

GEOMETRIC EISENSTEIN SERIES, INTERTWINING OPERATORS, AND SHIN'S AVERAGING FORMULA

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ABSTRACT. In the geometric Langlands program over function fields, Braverman-Gaitsgory [BG02] and Laumon [Lau90] constructed geometric Eisenstein functors which geometrize the classical construction of Eisenstein series over function fields by replacing the Eisenstein series with an automorphic sheaf on the moduli stack Bun_G of G -bundles of the smooth projective curve defined by the function field. These sheaves are Hecke Eigensheaves, encode the completed Eisenstein series under the function-sheaf dictionary, and satisfy a functional equation with respect to the action of the Weyl group. Fargues and Scholze [FS] very recently constructed a general candidate for the local Langlands correspondence, via a geometric Langlands correspondence occurring over the Fargues-Fontaine curve. In this note, we carry some of the theory of geometric Eisenstein series over to the Fargues-Fontaine setting. Namely, given a quasi-split connected reductive group $G/\mathbb{Q}_p$ with maximal torus T , we study the geometric Eisenstein functor $\mathrm{nEis}(-)$, carrying sheaves on the moduli stack Bun_T to sheaves on the moduli stack Bun_G . We show that, given a sufficiently nice L -parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T$ with induced parameter ϕ given by composing with the natural embedding ${}^L T \rightarrow {}^L G$, there is a Hecke eigensheaf on Bun_G with eigenvalue ϕ , given by applying $\mathrm{nEis}(-)$ to the Hecke eigensheaf $\mathcal{S}_{\phi_T}$ on Bun_T attached to ϕ_T constructed by Fargues [Far16; Far20] and Zou [Zou22]. We show that the object $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ interacts well with Verdier duality, and, assuming compatibility of the Fargues-Scholze correspondence with a suitably nice form of the local Langlands correspondence, provide an explicit formula for the stalks of the eigensheaf in terms of parabolic inductions of the character χ attached to ϕ_T assuming the regularity of χ . This explicit description of the eigensheaf has several surprising consequences. First, it recovers special cases of an averaging formula of Shin [Shi12; Ber21] for the cohomology of local Shimura varieties with rational coefficients, and generalizes it to the non-minuscule case. Moreover, it refines the averaging formula in the cases where the parameter ϕ is sufficiently nice, giving an explicit formula for the degrees of cohomology that certain parabolic inductions sit in, and this refined formula holds even with torsion coefficients. The sufficiently nice condition on ϕ_T is related to zeros and poles of the intertwining operators attached to the normalized parabolic induction $i_B^G(\chi)$, and we analogously see that the refined averaging formula actually gives a geometric construction of such intertwiners.

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1. INTRODUCTION

1.1. Geometric Eisenstein Series over Function Fields. In the Langlands program, Eisenstein series are a way of describing the non-cuspidal automorphic spectrum of a group in terms of the cuspidal automorphic spectrum of its proper Levi subgroups. Over function fields these objects have several geometric incarnations, as first studied extensively by Laumon [Lau90] in the case of GL_n and later refined by Braverman-Gaitsgory [BG02] for general reductive groups. In particular, if one is interested in the function field of a curve Y over a finite field k then one replaces the functions defining Eisenstein series by certain automorphic sheaves. Namely, let G/k be a split connected reductive group; then one wishes to construct "Eisenstein sheaves" on Bun_G the moduli stack of G -bundles on Y . To do this, for $P \subset G$ a proper parabolic subgroup with Levi factor M one considers the following diagram of moduli stacks of bundles

$$\begin{array}{ccc} \mathrm{Bun}_P & \xrightarrow{\mathfrak{p}_P} & \mathrm{Bun}_G \\ \downarrow \mathfrak{q}_P & & \\ \mathrm{Bun}_M & & \end{array}$$

where Bun_P is the moduli stack of P -bundles $\mathcal{G}_P$ on Y and the maps $\mathfrak{p}_P$ (resp. $\mathfrak{q}_P$) send $\mathcal{G}_P$ to the G -bundle (resp. M -bundle) $\mathcal{G}_P \times^P G$ (resp. $\mathcal{G}_P \times^P M$). Using this, one can define an Eisenstein functor which (up to shifts and twists) is given by

$$\mathrm{Eis}_P(-) := \mathfrak{p}_P! \mathfrak{q}_P^*(-),$$

and it takes ℓ -adic sheaves on Bun_M to ℓ -adic sheaves on Bun_G . Under the function-sheaf dictionary, the values of this functor give rise to the classical Eisenstein series.

In this geometric context, one can ask for even more. Namely, in the geometric Langlands correspondence one is interested in constructing Hecke eigensheaves on Bun_G , and it is natural to ask whether one could upgrade Eis_P to a functor that is well-behaved with respect to the eigensheaf property. In particular, if $\hat{M}$ (resp. $\hat{G}$) denotes the Langlands dual group of M (resp. G) one can consider a $\hat{M}$ -local system $E_{\hat{M}}$ and a Hecke eigensheaf $\mathcal{S}_{E_{\hat{M}}}$ with eigenvalue $E_{\hat{M}}$. One then considers the induced $\hat{G}$ local system $E_{\hat{G}}$ given by the natural embedding $\hat{M} \hookrightarrow \hat{G}$, and one would like to construct a functor that produces a eigensheaf with eigenvalue $E_{\hat{G}}$ from the Hecke eigensheaf $\mathcal{S}_{E_{\hat{M}}}$. One might hope that $\mathrm{Eis}_P(\mathcal{S}_{E_{\hat{M}}})$ works; however, this is too naive. Namely, one expects such sheaves to be well-behaved under Verdier duality, and one can easily check that $\mathrm{Eis}_P(-)$ will not commute with Verdier duality, since the map $\mathfrak{p}_P$ is not proper. To remedy this, one considers relative Drinfeld compactifications of the map $\mathfrak{p}_P$, denoted $\widetilde{\mathrm{Bun}}_P$ and $\overline{\mathrm{Bun}}_P$, respectively. These compactifications are equipped with open immersions $\tilde{j} : \mathrm{Bun}_P \hookrightarrow \widetilde{\mathrm{Bun}}_P$ and $j : \mathrm{Bun}_P \hookrightarrow \overline{\mathrm{Bun}}_P$, which realize Bun_P as an open subspace, and are defined by considering parabolic structures with torsion at finitely many Cartier divisors. Moreover, they both have maps

$$\overline{\mathfrak{p}}_P : \overline{\mathrm{Bun}}_P \rightarrow \mathrm{Bun}_G$$

and

$$\tilde{\mathfrak{p}}_P : \widetilde{\mathrm{Bun}}_P \rightarrow \mathrm{Bun}_G$$

which are proper after restricting to finitely many connected components and extend $\mathfrak{p}_P$, as well as maps $\tilde{\mathfrak{q}}_P : \widetilde{\mathrm{Bun}}_P \rightarrow \mathrm{Bun}_M$ and $\bar{\mathfrak{q}}_P : \overline{\mathrm{Bun}}_P \rightarrow \mathrm{Bun}_{M^{ab}}$ extending the natural maps $\mathfrak{q}_P : \mathrm{Bun}_P \rightarrow \mathrm{Bun}_M$ and $\mathfrak{q}_P^\dagger : \mathrm{Bun}_P \xrightarrow{\mathfrak{q}_P} \mathrm{Bun}_M \rightarrow \mathrm{Bun}_{M^{ab}}$, respectively.

To obtain a sheaf that interacts well with Verdier duality, one needs to take account for the singularities of the compactification. Namely, if one considers the intersection cohomology sheaf $\mathrm{IC}_{\widetilde{\mathrm{Bun}}_P}$ of $\widetilde{\mathrm{Bun}}_P$ then the desired functor is given by

$$\widetilde{\mathrm{Eis}}_P(-) := \tilde{\mathfrak{p}}_{P*}(\tilde{\mathfrak{q}}_P^*(-) \otimes \mathrm{IC}_{\widetilde{\mathrm{Bun}}_P})$$

One of the main results of Braverman-Gaitsgory [BG02] is that this satisfies the desired Hecke eigensheaf property when applied to $\mathcal{S}_{E_{\hat{M}}}$. One may also wonder what this corresponds to at the level of functions. We recall that the classical Eisenstein series is known to satisfy a functional equation after multiplying by an appropriate ratio of L -values. The compactified Eisenstein series corresponds to this completed Eisenstein series under the function-sheaf dictionary. In fact, in certain cases one can see the usual functional equation at the sheaf-theoretic level. If $P = B$ is the Borel and we consider the appropriately normalized Hecke eigensheaf $\mathcal{S}_{E_{\hat{T}}}$ associated to $E_{\hat{T}}$ via geometric class field theory then $\widetilde{\mathrm{Eis}}(\mathcal{S}_{\phi_T})$ satisfies a functional equation under a regularity hypothesis on the local system $E_{\hat{T}}$. Now let $w \in W_G$ be an element of the Weyl group of G with $\tilde{w} \in N(T)$ a choice of representative. Then $\tilde{w}$ acts on Bun_T , and, if we write $\mathcal{S}_{E_{\hat{T}}}^w$ for the pullback of $\mathcal{S}_{E_{\hat{T}}}$ along this automorphism, we have the following result.

Theorem 1.1. [BG02, Theorem 2.2.4] *For $E_{\hat{T}}$ a regular $\hat{T}$ -local system on Y and a choice of representative $\tilde{w} \in N(\hat{T})$ of $w \in W_G$, we have an isomorphism*

$$\widetilde{\mathrm{Eis}}_B(\mathcal{S}_{E_{\hat{T}}}) \simeq \widetilde{\mathrm{Eis}}_B(\mathcal{S}_{E_{\hat{T}}}^w)$$

of ℓ -adic sheaves on Bun_G .

As alluded to above, one can see that, after passing to functions, this gives precisely the well-known functional equation for the Eisenstein series multiplied by the appropriate ratio of L -values

([BG02, Section 2.2]). Moreover, by [BG08, Theorem 1.5], under the regularity assumption the sheaf $\widetilde{\text{Eis}}_B(\mathcal{S}_{E_{\tilde{T}}})$ is perverse.

The main goal of this note is to explore what this theory of geometric Eisenstein series has to tell us in the context of the recent geometric Langlands correspondence constructed by Fargues and Scholze.

1.2. Hecke Eigensheaves over the Fargues-Fontaine Curve. Consider two distinct primes $\ell \neq p$. Let $G/\mathbb{Q}_p$ be a quasi-split connected reductive group over the p -adic numbers, and set $\check{\mathbb{Q}}_p$ to be the completion of the maximal unramified extension of $\mathbb{Q}_p$ with Frobenius σ . Let $W_{\mathbb{Q}_p} \subset \Gamma := \text{Gal}(\check{\mathbb{Q}}_p/\mathbb{Q}_p)$ denote the Weil group. In [FS], Fargues and Scholze developed the geometric framework required to make sense of objects like Bun_G , the moduli stack of G -bundles on the Fargues-Fontaine curve X , and show that the local Langlands correspondence for G can be viewed as a geometric Langlands correspondence over X . Namely, they prove a version of Geometric Satake in this setup, allowing them to construct Hecke operators and in turn excursion operators. Their Hecke operators take sheaves on Bun_G to sheaves on Bun_G with a continuous $W_{\mathbb{Q}_p}$ -action, via some version of Drinfeld's Lemma. As a consequence, they were able to construct semi-simple Langlands parameters $\phi_\pi^{\text{FS}} : W_{\mathbb{Q}_p} \rightarrow {}^L G(\overline{\mathbb{Q}}_\ell)$ attached to any smooth irreducible representation π of $G(\mathbb{Q}_p)$.

Predating the construction of the Fargues-Scholze local Langlands correspondence was Fargues' conjecture as formulated in [Far16, Conjecture 4.4]. This asserted the existence of Hecke Eigensheaves attached to supercuspidal L -parameters $\phi : W_{\mathbb{Q}_p} \rightarrow {}^L G(\overline{\mathbb{Q}}_\ell)$, where ${}^L G = \hat{G} \rtimes W_{\mathbb{Q}_p}$ is the L -group of G . More precisely, given such a ϕ , Fargues conjectured the existence of a $\overline{\mathbb{Q}}_\ell$ -sheaf $\mathcal{S}_\phi$ on Bun_G such that, if one acts via a Hecke operator T_V corresponding to a representation $V \in \text{Rep}_{\overline{\mathbb{Q}}_\ell}({}^L G)$ then there is an isomorphism

$$T_V(\mathcal{S}_\phi) \simeq \mathcal{S}_\phi \boxtimes r_V \circ \phi$$

of sheaves on Bun_G with continuous $W_{\mathbb{Q}_p}$ -action satisfying natural compatibilities. The moduli stack Bun_G is stratified by elements of the Kottwitz set $B(G) := G(\check{\mathbb{Q}}_p)/(b \sim gb\sigma(g)^{-1})$, giving rise to Harder-Narasimhan (abbrev. HN)-strata Bun_G^b for all $b \in B(G)$. It was conjectured that the sheaf $\mathcal{S}_\phi$ must be supported on the basic locus $\bigsqcup_{b \in B(G)_{\text{basic}}} \text{Bun}_G^b$ or, in bundle-theoretic terms, the locus defined by semistable bundles. Each of the basic strata Bun_G^b are isomorphic to the classifying stack $[\ast/J_b(\mathbb{Q}_p)]$, where J_b is the σ -centralizer attached to $b \in B(G)$. The σ -centralizers of the basic elements parameterize extended pure inner forms of G in the sense of Kottwitz [Kot97], and the restrictions of the sheaf to these classifying stacks can be interpreted as smooth representations of $J_b(\mathbb{Q}_p)$. Using this, Fargues also gave a conjectural description for what the restrictions of the sheaf should be given by. In particular, for $b \in B(G)_{\text{basic}}$ the restriction to Bun_G^b should be a direct sum (up to multiplicities)¹ $\bigoplus_{\pi \in \Pi_\phi(J_b)} \pi$, where $\Pi_\phi(J_b)$ is the L -packet over ϕ as conjectured by Kaletha's refined local Langlands correspondence for G [Kal16]. Assuming the refined local Langlands, the verification of the Hecke eigensheaf property ultimately reduces to a strong form of the Kottwitz conjecture for the cohomology of a space of shtukas parameterizing modifications

$$\mathcal{F}_b \rightarrow \mathcal{F}_{b'}$$

on X bounded by a geometric dominant cocharacter μ , where $b, b' \in B(G)_{\text{basic}}$ are appropriately chosen basic elements with respect to μ , and $\mathcal{F}_b$ and $\mathcal{F}_{b'}$ denote the bundles on X corresponding to $b, b' \in B(G)$.

Since the work of Fargues-Scholze, the construction of this eigensheaf has been carried out in several cases. For tori, it follows from the work of Fargues [Far16; Far20], and Zou [Zou22]. For $G = \text{GL}_n$, this is a result of Anschütz and Le-Bras [AL21]. For general reductive groups, a somewhat general strategy for constructing this eigensheaf in the particular case of the group GSp_4 is laid

¹There are no higher multiplicities if the centralizer of ϕ is abelian.

out in [Ham25], by showing compatibility of the Fargues-Scholze correspondence with the refined local Langlands correspondence of Kaletha [Kal16], and then using this to deduce the non-minuscule cases of the Kottwitz conjecture required for the verification of the Hecke eigensheaf property via the spectral action [FS, Section X.2]. This strategy is carried out for odd unitary groups in the paper [BHN22]. We recall that the fibers of the local Langlands correspondence over supercuspidal parameters should solely consist of supercuspidal representations. Therefore, the above eigensheaves can be thought of as analogous to supercuspidal representations in the classification of smooth irreducible representations. To have a more definitive connection between the theory of smooth representations and Fargues' eigensheaves, it becomes desirable to construct eigensheaves that serve as the analogues of parabolic inductions of supercuspidals, which will analogously be "parabolically induced" from the eigensheaves attached to supercuspidal parameters. This will be precisely what carrying over the theory of the previous section to the Fargues-Fontaine setting gives us.

1.3. Geometric Eisenstein Series over the Fargues-Fontaine Curve. We will assume that G is a quasi-split group. Let $A \subset T \subset B \subset G$ be a choice of maximal split torus, maximal torus, and Borel, respectively. In this paper, we will be concerned with studying the geometric Eisenstein functor over the Fargues-Fontaine curve in the principal case (i.e where the parabolic $P \subset G$ is the Borel). Restricting to the principal case has several advantages. For one, one can unconditionally speak about the Hecke eigensheaf attached to a parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T$ valued in the maximal torus. Additionally, in this case there exists only one Drinfeld compactification $\overline{\text{Bun}}_B$ of the moduli space of B -structures Bun_B , which has a fairly manageable geometry. As mentioned in §1.1, there are in general two compactifications $\overline{\text{Bun}}_P$ and $\widetilde{\text{Bun}}_P$. The compactification $\overline{\text{Bun}}_P$ has a relatively simple geometry and can be understood more or less the same as $\overline{\text{Bun}}_B$. The problem is that $\overline{\text{Bun}}_P$ admits only a map to $\text{Bun}_{M^{ab}}$ and not to Bun_M . This means we can prove analogous results for the Hecke eigensheaves attached to characters induced from $\phi : W_{\mathbb{Q}_p} \rightarrow {}^L M^{ab}$ which correspond to generalized principal series representations induced from M . We have chosen not to do this in this note for simplicity. However, if one wants to consider inductions of Hecke eigensheaves attached to a general supercuspidal parameter $\phi_M : W_{\mathbb{Q}_p} \rightarrow {}^L M$ then one is forced to understand the much more complicated geometry of the space $\widetilde{\text{Bun}}_P$. Certainly, some analogues of the results proven in this paper should be possible, but there are many technical hurdles that need to be overcome (for some partial geometric results in this directions see [HHS24]).

1.3.1. Geometric Eisenstein Series. Throughout, we will let $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ be a continuous parameter valued in the L -group of T , where $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$ has the discrete topology. Our aim is to construct an eigensheaf (Definition 3.1) with eigenvalue ϕ , the composition of ϕ_T with the natural embedding ${}^L T(\Lambda) \rightarrow {}^L G(\Lambda)$. This will be an object in $\text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$ the category of lisse-étale solid Λ -sheaves, as defined in [FS, Chapter VII]. We do not work directly with this category of solid sheaves in our argument, as the usual six functors are not as well behaved in this case. Instead, we will first restrict to the case where $\Lambda = \overline{\mathbb{F}}_\ell$ and one has an isomorphism $\text{D}_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{F}}_\ell) \simeq \text{D}_{\text{ét}}(\text{Bun}_G, \overline{\mathbb{F}}_\ell)$ with the usual category of étale $\overline{\mathbb{F}}_\ell$ sheaves as defined in [Sch]. We then construct the lisse-étale sheaves with $\overline{\mathbb{Z}}_\ell$ and $\overline{\mathbb{Q}}_\ell$ coefficients from this sheaf. For the first part of this section, we will always assume that $\Lambda = \overline{\mathbb{F}}_\ell$ unless otherwise stated, and to simplify the notation, we adopt the convention that, when working with $\Lambda = \overline{\mathbb{F}}_\ell$, we will denote the derived category of étale sheaves on a v -stack or diamond Z by simply writing $\text{D}(Z)$. We will additionally assume that ℓ is very decent throughout in the following sense:

- (1) We have that $\ell \nmid \pi_0(Z(G))$, where $Z(G)$ denotes the center of G .
- (2) We have that $\ell \nmid |Q|$, where Q is the smallest quotient through which the $W_{\mathbb{Q}_p}$, the Weil group of $\mathbb{Q}_p$, acts on the Langlands dual group $\hat{G}$.

In order to avoid complications in the ℓ -modular setting. In particular, the former assumption will guarantee that we have access to the spectral action constructed in Fargues-Scholze and more

notably the excursion algebra, and the latter assumption will guarantee that various categories of tilting modules of algebraic representations are well-behaved.

We let $\mathcal{S}_{\phi_T}$ be the eigensheaf on the moduli stack Bun_T parameterizing T -bundles on X attached to ϕ_T by Fargues [Far20; Far20] and Zou [Zou22]. Our aim is to construct an eigensheaf with respect to the parameter ϕ by applying a geometric Eisenstein functor to $\mathcal{S}_{\phi_T}$. To do this, one needs to show that the relevant geometric objects used in defining geometric Eisenstein series are well-behaved in this framework. Namely, one can show that the moduli stack of B -bundles on X , denoted Bun_B , gives rise to an Artin v -stack and the maps in the natural diagram

$$(1) \quad \begin{array}{ccc} & \text{Bun}_B & \\ & \downarrow \mathfrak{q} & \searrow \mathfrak{p} \\ & \text{Bun}_T & \text{Bun}_G \end{array}$$

have good geometric properties; $\mathfrak{q}$ is a cohomologically smooth (non-representable) map of Artin v -stacks, and $\mathfrak{p}$ is compactifiable and representable in locally spatial diamonds (See §5.1). It follows that one has a well-defined functor given by $\mathfrak{p}_! \mathfrak{q}^* : D(\text{Bun}_T) \rightarrow D(\text{Bun}_G)$ using the functors constructed in [Sch].

In order to make the functor $\mathfrak{p}_! \mathfrak{q}^*$ behave well with respect to Verdier duality, one needs to take into account the appropriate shifts and twists coming from the dualizing object on Bun_B . Namely, using the cohomological smoothness of $\mathfrak{q}$ and Bun_T , it is easy to see that the moduli stack Bun_B is cohomologically smooth of some ℓ -dimension given by a locally constant function $\dim(\text{Bun}_B) : |\text{Bun}_B| \rightarrow \mathbb{Z}$, where $|\text{Bun}_B|$ is the underlying topological space of Bun_B . It follows that, v -locally on Bun_B , the dualizing object is given by $\Lambda[2\dim(\text{Bun}_B)]$. This leads us to our first attempt to define the Eisenstein functor as $\text{Eis}(-) := \mathfrak{p}_!(\mathfrak{q}^*(-)[\dim(\text{Bun}_B)])$. While this definition is closer to what we want, it has one key flaw; even though the dualizing object on Bun_B is v -locally isomorphic to $\Lambda[2\dim(\text{Bun}_B)]$ it is not equal to this sheaf on the nose. In particular, there are certain modulus character twists.

These modulus character twists can be encoded by the sheaf $\Delta_B^{1/2}$ on Bun_T , which will be the Hecke eigensheaf attached to the L -parameter

$$\hat{\rho} \circ |\cdot| : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$$

where $\hat{\rho}$ denotes the character of ${}^L T$ defined by the positive roots of G , and we abusively write $|\cdot| : W_{\mathbb{Q}_p} \rightarrow \Lambda^*$ for the norm character of $W_{\mathbb{Q}_p}$ and we fix a square root in Λ . As a sheaf on Bun_T , the stalks on the connected components $\text{Bun}_T' \simeq [*/T(\mathbb{Q}_p)]$ will just be given by the character $\delta_B^{1/2} : T(\mathbb{Q}_p) \rightarrow \Lambda^*$. Similarly, we write Δ_B for the Hecke eigensheaf with eigenvalue given by the L -parameter $2\hat{\rho} \circ |\cdot|$. It now follows from [HI25, Theorem 1.6] that the dualizing complex on Bun_B is isomorphic to $\mathfrak{q}^*(\Delta_B)[2\dim(\text{Bun}_B)]$, and it follows that the sheaf $\text{IC}_{\text{Bun}_B} := \mathfrak{q}^*(\Delta_B^{1/2})[\dim(\text{Bun}_B)]$ is Verdier self-dual. Therefore, we define the normalized Eisenstein functor to be

$$\text{nEis}(-) := \mathfrak{p}_!(\mathfrak{q}^*(-) \otimes \text{IC}_{\text{Bun}_B})$$

This is already very suggestive. Indeed, the (unnormalized) Eisenstein functor will have stalks related to the unnormalized parabolic induction of the characters χ , and the normalized Eisenstein series will have stalks related to the normalized parabolic induction. Moreover, just as smooth duality interacts nicely with normalized parabolic induction so too does Verdier duality with the normalized Eisenstein functor. In order to study how the normalized Eisenstein functor interacts with Verdier duality, it becomes very natural to want a nice compactification of the morphism $\mathfrak{p}$, as Eis involves the functor $\mathfrak{p}_!$. As seen in §1.1, this can be accomplished by considering an analogue of the Drinfeld compactification $\overline{\text{Bun}}_B$. This object was studied in the Fargues-Scholze context for more general parabolics in [HHS24]. In particular, it was shown there that there exists an Artin

v -stack $\overline{\text{Bun}}_B$ equipped with an open immersion

$$j : \text{Bun}_B \hookrightarrow \overline{\text{Bun}}_B$$

such that the map $\bar{p} : \overline{\text{Bun}}_B \rightarrow \text{Bun}_G$ is proper (after restricting to finitely many connected components of Bun_T).

Now, we would like to claim that the sheaf $\text{nEis}(\mathcal{S}_{\phi_T})$ is a Hecke eigensheaf with respect to the parameter ϕ given by composing ϕ_T with the natural embedding ${}^L T \rightarrow {}^L G$; however, in analogy with §1.1, the right object to consider in this case is not $\text{nEis}(\mathcal{S}_{\phi_T})$, but rather a compactified version $\overline{\text{Eis}}(\mathcal{S}_{\phi_T})$. Unfortunately, there is currently no well-behaved formalism for intersection cohomology in the context of diamonds and v -stacks. This prevents us from even defining the kernel sheaf $\text{IC}_{\overline{\text{Bun}}_B}$ typically used in the definition of $\overline{\text{Eis}}(-)$ in any naive way. There is however a way out if we impose some conditions on our parameter ϕ_T . We write $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$ for the set of Γ -orbits of geometric cocharacters. Given an element $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$, we can attach to it a representation of ${}^L T$ by inducing the representation of $\hat{T}$ defined by a representative of the orbit ν in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$. We consider the composition $\nu \circ \phi_T$, and we will say that ϕ_T is generic if the Galois cohomology complexes

$$R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$$

are trivial for all $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$ defined by the Γ -orbits of coroots in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$. This condition may appear mysterious; but there are several ways to see why it is the morally correct condition. Perhaps the most compelling comes from local representation theory. As mentioned in §1.1, the compactified Eisenstein series in the function field setting corresponds to the completed Eisenstein series under the function sheaf dictionary, while the non-compactified Eisenstein series corresponds to just the usual Eisenstein series. In particular, the sheaf $\text{IC}_{\overline{\text{Bun}}_B}$ encodes the zeros and poles of the meromorphic continuation of the Eisenstein series. If χ denotes the character of $T(\mathbb{Q}_p)$ attached to ϕ_T via local class field theory then we recall that, if $w \in W_G$ is an element of the relative Weyl group, the local analogue of the meromorphic continuation of Eisenstein series is the theory of intertwining operators. In particular, suppose that $\Lambda = \overline{\mathbb{Q}}_\ell$, then we have maps

$$i_{\chi, w} : i_B^G(\chi) \rightarrow i_B^G(\chi^w)$$

of smooth $G(\mathbb{Q}_p)$ -representations, which can be viewed as meromorphic functions on the set of complex unramified characters by twisting χ . Now, using local Tate-duality, it is easy to see that the vanishing of the above complexes will imply that χ pre-composed with coroots is not trivial or isomorphic to a power of the norm character. These are precisely the type of conditions one expects to guarantee that the intertwining operators are holomorphic and give rise to an isomorphism. In fact in the appendix, we show that, for χ attached to a generic parameter ϕ_T , we always have an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^w)$ for any $w \in W_G$ (Proposition A.2).

This suggests that, at least heuristically, we should always have an isomorphism $\text{nEis}(\mathcal{S}_{\phi_T}) \simeq \overline{\text{Eis}}(\mathcal{S}_{\phi_T})$, for ϕ_T satisfying some version of genericity and regularity and any reasonable definition of $\overline{\text{Eis}}(\mathcal{S}_{\phi_T})$. Indeed, this makes sense when we look at the geometry of $\overline{\text{Bun}}_B$; in particular, the stack $\overline{\text{Bun}}_B$ admits a locally closed stratification given by $\text{Div}^{(\bar{\nu})} \times \text{Bun}_B$, where $\text{Div}^{(\bar{\nu})}$ is a certain partially symmetrized version of the mirror curve Div^1 parameterizing effective Cartier divisors in X attached to $\bar{\nu}$ inside the coinvariant lattice $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$. We recall that there is a natural map $(-)_\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, from Γ -orbits to coinvariants. This map defines an injection on the Γ -orbits of the simple positive coroots. In particular, for each vertex $i \in \mathcal{J}$ of the relative Dynkin diagram of G , we get an element α_i in the coinvariant lattice, which corresponds to a Γ -orbit of positive simple coroots. The natural strata of $\overline{\text{Bun}}_B$ are specified by elements $\bar{\nu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ lying in the positive span of these α_i , and each strata corresponds to the locus of B -bundles with torsion specified by $\bar{\nu}$. Now, the restriction of $\bar{\mathfrak{q}}^*(\mathcal{S}_{\phi_T})$ to this strata is given by pulling back a Hecke

operator on Bun_T applied to $\mathcal{S}_{\phi_T}$ along $\mathfrak{q}$. One can deduce that the factor appearing on the divisor curve $\text{Div}^{(\bar{v})}$ will be related to $\alpha_i \circ \phi_T$, via the Hecke eigensheaf property $T_{\alpha_i}(\mathcal{S}_{\phi_T}) \simeq \alpha_i \circ \phi_T \boxtimes \mathcal{S}_{\phi_T}$ for $\mathcal{S}_{\phi_T}$, where we have identified α_i with its associated Γ -orbit via $(-)_\Gamma$. This implies that the complex $R\Gamma(W_{\mathbb{Q}_p}, \alpha_i \circ \phi_T)$ appears in $\bar{\mathfrak{p}}_!$ applied to this restriction as a tensor factor, and will in turn vanish for ϕ_T generic, suggesting an isomorphism of the form $\text{nEis}(\mathcal{S}_{\phi_T}) \simeq \overline{\text{Eis}}(\mathcal{S}_{\phi_T})$ in this case.

We can turn these heuristics into actual math. In particular, since we expect an isomorphism of the form $\text{nEis}(\mathcal{S}_{\phi_T}) \simeq \overline{\text{Eis}}(\mathcal{S}_{\phi_T})$ under some version of genericity and regularity, we should expect for such parameters that $\text{nEis}(\mathcal{S}_{\phi_T})$ behaves well under Verdier duality, is a perverse Hecke eigensheaf with eigenvalue ϕ , and satisfies the analogue of the functional equation seen in Theorem 1.1 in this case. The precise conditions on ϕ_T that we will need to prove our results will depend on the result and the particular group G . For this reason, we break up our condition into two parts.

Condition/Definition 1.2. (*Condition/Definition 3.6*) *Given a parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$, we impose the following conditions on ϕ_T in what follows.*

- (1) *For all $\alpha \in \mathbb{X}_*(T_{\mathbb{Q}_p})/\Gamma$ defined by the Γ -orbits of coroots in $\mathbb{X}_*(T_{\mathbb{Q}_p})$, the Galois cohomology complex $R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$ is trivial.*
- (2) *If χ is the character attached to ϕ_T under local class field theory. We have, for all $w \neq 1$ in the relative Weyl group W_G of G , that χ is regular. I.e*

$$\chi \not\simeq \chi^w$$

If ϕ_T satisfies (1) then we say it is generic, and if it satisfies (1) and (2) then we say it is generic regular.

Remark 1.3. These conditions are related to the behavior of the principal series representations $i_B^G(\chi)$ of G . Roughly speaking, Condition (1) guarantees the irreducibility of non-unitary principal series representations and that the intertwining operators for $i_B^G(\chi)$ are isomorphisms, while Condition (2) guarantees the irreducibility of unitary principal series representations (See Lemma A.4). As we will see in Appendix A, genericity is enough to guarantee that one has an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^w)$ for all $w \in W_G$. However, one could still have an isomorphism of this form if $i_B^G(\chi)$ is the reducible induction of a unitary character χ . This can happen if the character χ is not regular (i.e it is fixed by some $w \in W_G$). To illustrate this, note that, for $G = \text{GL}_n$, if we write $\phi_T = \bigoplus_{i=1}^n \phi_i$ as a sum of characters then genericity is equivalent to supposing that

$$R\Gamma(W_{\mathbb{Q}_p}, \phi_i^\vee \otimes \phi_j)$$

is trivial for all $i \neq j$. We note that, by local Tate-duality and using that the Euler-Poincaré characteristic of this complex is 0, genericity is equivalent to assuming that ϕ_i is not isomorphic to ϕ_j or $\phi_j(1)$. If we write $\chi = \chi_1 \otimes \dots \otimes \chi_n$ as a product of characters of $\mathbb{Q}_p^*$ then this implies that $\chi_i^{-1} \chi_j \not\simeq |\cdot|^{\pm 1}$ for all $i > j$, which is precisely the condition guaranteeing irreducibility. On the other hand, if $G = \text{SL}_2$, and we write χ for the character of $\mathbb{Q}_p^*$ attached to ϕ_T via local class field theory, we need that $\chi \not\simeq |\cdot|^{\pm 1}$ and $\chi^2 \not\simeq \mathbf{1}$ to guarantee irreducibility of $i_B^G(\chi)$. The condition $\chi \not\simeq |\cdot|^{\pm 1}$ is guaranteed by Condition (1), and Condition (2) is equivalent to $\chi^2 \not\simeq \mathbf{1}$.

Remark 1.4. The choice of calling a parameter satisfying Condition (1) generic is motivated by the analogous notion of decomposed generic considered by Caraiani and Scholze [CS17, Definition 1.9]. In particular, we note that if ϕ_T is unramified and $G = \text{GL}_n$ then, by the previous remark, we see that Condition (1) is precisely equivalent to ϕ_T being decomposed generic.

Genericity will be used to limit possible stalks of $\text{nEis}(\mathcal{S}_{\phi_T})$ using some assumed properties of the Fargues-Scholze local Langlands correspondence, while regularity will be needed to show the geometric Eisenstein series commutes with Verdier duality, as well as fully compute the stalks and show that it satisfies the analogous functional equation to Theorem 1.1. Unfortunately, in general to get

the Hecke eigensheaf property for $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ we still need more. Write $(-)^{\Gamma} : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$ for the natural map from geometric cocharacters to their Galois orbits. Given a geometric dominant cocharacter $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ with Galois orbit $\mu^{\Gamma} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+/\Gamma$, we have an associated representation $V_{\mu^{\Gamma}} \in \mathrm{Rep}_{\Lambda}({}^L G)$. The weights of $V_{\mu^{\Gamma}}|_{L_T}$ can be interpreted in terms of the representations corresponding to the Galois orbits of weights in the usual highest weight representation V_{μ} of $\hat{G}$. The following condition will guarantee the Hecke eigensheaf property for $\mathrm{nEis}(\mathcal{S}_{\phi_T})$, and the Hecke operator defined by $V_{\mu^{\Gamma}}$.

Definition 1.5. (Definition 3.10) For a toral parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ and a geometric dominant cocharacter μ , we say ϕ_T is strongly μ -regular if the Galois cohomology complexes

$$R\Gamma(W_{\mathbb{Q}_p}, (\nu - \nu')^{\Gamma} \circ \phi_T)$$

are trivial for ν, ν' defining distinct Γ -orbits of weights the highest weight representation of $\hat{G}$ of highest weight μ .

Remark 1.6. We note that genericity usually implies strong μ -regularity for some suitably chosen cocharacters $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$. In particular, note that if $\mu = (1, 0, \dots, 0, 0)$ and $G = \mathrm{GL}_n$ then, since μ is minuscule, the possible weights of V_{μ} in $\hat{T}$ are all given by Weyl group orbits of μ , and the possible differences between the weights will consequently be precisely the coroots of GL_n .

Let's now see how these conditions manifest in our results on Eisenstein series. We begin with the Hecke eigensheaf property. In particular, consider a finite index set I and a representation $V \in \mathrm{Rep}_{\Lambda}({}^L G^I)$. Given $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma)^I$, we write $V((\nu_i)_{i \in I})$ for the multiplicity of the weight space of the corresponding representation of ${}^L T^I$ in $V|_{L_T^I}$, and write $T_{(\nu_i)_{i \in I}}$ for the associated Hecke operator. By applying excision to the aforementioned locally closed stratification of $\overline{\mathrm{Bun}}_B$ and combining it with the geometric Satake correspondence of Fargues-Scholze [FS, Chapter VI], we can show the following result.

Theorem 1.7. (Theorem 6.1) For $\mathcal{F} \in \mathrm{D}(\mathrm{Bun}_T)$, I a finite index set, and $V \in \mathrm{Rep}_{\Lambda}({}^L G^I)$ with associated Hecke operator T_V , the sheaf $T_V(\mathrm{nEis}(\mathcal{F}))$ on Bun_G with continuous $W_{\mathbb{Q}_p}^I$ -action has a $W_{\mathbb{Q}_p}^I$ -equivariant filtration indexed by $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma)^I$. The filtration's graded pieces are isomorphic to

$$\bigoplus_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma)^I} \mathrm{nEis}(T_{(\nu_i)_{i \in I}}(\mathcal{F})) \otimes V((\nu_i)_{i \in I})$$

Moreover, the filtration is natural in I and V , as well as compatible with compositions and exterior tensor products.

The argument for proving this "filtered eigensheaf property" is very similar to that given by [BG02] in their proof of the Hecke eigensheaf property for the compactified geometric Eisenstein functor in the function field setting. However, there Braverman and Gaitsgory rely on the decomposition theorem applied to the perverse sheaf $\mathrm{IC}_{\overline{\mathrm{Bun}}_B}$, which would not make sense in this context. Nevertheless, we still have access to the excision spectral sequence one usually uses in proving the decomposition theorem. In particular, in the proof of the decomposition theorem one uses the excision spectral sequence and then invokes the theory of weights to show that it degenerates. Something similar happens here. Namely, if we apply this to the sheaf $\mathcal{F} = \mathcal{S}_{\phi_T}$ then we see that $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a filtered eigensheaf in the sense that, up to passing to the graded pieces of this filtration, it is an eigensheaf with eigenvalue ϕ , and later we can see, by looking at the Weil group action, this filtration must always split under some version of genericity on ϕ_T .

Even without knowing that the filtration on $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ splits, the filtered eigensheaf property can already be used to tell us a lot about the structure of $\mathrm{nEis}(\mathcal{S}_{\phi_T})$. In particular, given $b \in$

$B(G)$, the restriction $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b}$ to the HN-strata Bun_G^b defines a complex of smooth $J_b(\mathbb{Q}_p)$ -representations, and we are interested in describing this restriction. Here J_b is the σ -centralizer of b and it is an extended pure inner form of a Levi subgroup M_b of G . The fact that $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a filtered Hecke eigensheaf with eigenvalue ϕ implies that, if ρ is an irreducible constituent of this restriction then the Fargues-Scholze parameter ϕ_ρ^{FS} must be equal to ϕ under the twisted embedding ${}^L J_b \rightarrow {}^L G$. If we believe that the Fargues-Scholze local Langlands correspondence is the true local Langlands correspondence then this seems to suggest that ρ should be given by a normalized parabolic induction of the character χ attached to ϕ_T via local class field theory. In particular, we note, by deformation theory, that a toral parameter being generic implies that every lift of ϕ_T to $\overline{\mathbb{Z}}_\ell$ factors through ${}^L T$ and that the induced $\mathbb{Q}_\ell$ -parameter cannot come from the semi-simplification of a parameter with non-trivial monodromy (Lemma 3.14). This imposes a very rigid constraint on J_b . In particular, the Borel $B \cap M_b$ of M_b should transfer to a Borel B_b of J_b . The elements where this occurs are the elements in the image of the map $B(T) \rightarrow B(G)$, called the unramified elements $B(G)_{\mathrm{un}}$, as studied in the work of Xiao-Zhu [XZ17].

Corollary 1.8. (*Corollary 6.7*) *For ϕ_T a generic parameter and $b \in B(G)$, assuming compatibility of the Fargues-Scholze and the conjectural local Langlands correspondence (Assumption 6.5), the restriction $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b}$ vanishes unless $b \in B(G)_{\mathrm{un}}$.*

We now assume compatibility (Assumption 6.5) for the rest of the section. The previous corollary tells us that if we are interested in understanding the complex of $J_b(\mathbb{Q}_p)$ -representations defined by the stalks $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b}$ then we can restrict to the case where $b \in B(G)_{\mathrm{un}}$, and here we expect the stalks to be given by the inductions $i_{B_b}^{J_b}(\chi) \otimes \delta_{P_b}^{-1/2}$, where δ_{P_b} is the modulus character of the parabolic P_b with Levi factor M_b transferred to J_b .² This is indeed the case. To understand this, we use that each element $b \in B(G)_{\mathrm{un}}$ has a unique reduction $b_T \in B(T)$ such that the slopes are G -dominant. Similarly, we write b_T^- for the unique element whose isocrystal slopes are anti-dominant and will refer to it as the HN-dominant element, where we recall that the isocrystal slopes are the negative of the Harder-Narasimhan slopes of the associated bundles. The set of elements in $B(T)$ mapping to b can be described as $w(b_T^-)$, where we identify $w \in W_b := W_G/W_{M_b}$ with a set of representatives of minimal length in W_G . The connected components of Bun_B and Bun_T are indexed by elements in $B(T) \simeq \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, giving a direct sum decomposition:

$$\mathrm{nEis}(\mathcal{S}_{\phi_T}) = \bigoplus_{\bar{\nu} \in B(T)} \mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T})$$

After restricting to Bun_G^b , the point is that only the summands indexed by $\bar{\nu} = w(b_T^-)$ for $w \in W_b$ survive. It is fairly easy to see this when $\bar{\nu} = b_T^-$. In particular, the connected component $\mathrm{Bun}_B^{b_T^-}$ will parametrize split B -structures since the HN-slopes are dominant, and the diagram (1) (essentially) becomes

$$\begin{array}{ccc} \left[*/B_b(\mathbb{Q}_p) \right] & & \\ \downarrow \mathfrak{q} & \searrow \mathfrak{p} & \\ \left[*/T(\mathbb{Q}_p) \right] & & \left[*/J_b(\mathbb{Q}_p) \right] \end{array}$$

²These twists by the modulus character come from the fact that the excursion algebra on Bun_G acts on a smooth irreducible representation $\rho \in D(J_b(\mathbb{Q}_p), \Lambda) \simeq D(\mathrm{Bun}_G^b) \subset D(\mathrm{Bun}_G)$ via the Fargues-Scholze parameter $\phi_\rho^{\mathrm{FS}} : W_{\mathbb{Q}_p} \rightarrow {}^L J_b(\Lambda)$ of a smooth irreducible representation ρ of J_b , composed with the *twisted* embedding ${}^L J_b(\Lambda) \rightarrow {}^L G(\Lambda)$, as in [FS, Section IX.7.1].

Using this, it is easy to see that $\mathfrak{p}!\mathfrak{q}^*(\chi)$ will be given by compactly supported functions of $J_b/B_b(\mathbb{Q}_p)$ which transform under $B_b(\mathbb{Q}_p)$ via χ . In other words, the unnormalized induction $\text{Ind}_{B_b}^{J_b}(\chi)$. When one accounts for the twists coming from the dualizing object as well as the sign switch between isocrystals and G -bundles, one finds that the exact formula becomes

$$\text{nEis}^{b_T^-}(\mathcal{S}_{\phi_T}) \simeq j_{b!}(i_{B_b}^{J_b}(\chi^{w_0}) \otimes \delta_{P_b}^{-1/2})[-\langle 2\hat{\rho}, \nu_b \rangle]$$

where $j_b : \text{Bun}_G^b \rightarrow \text{Bun}_G$ is the inclusion of the HN-strata corresponding to b and $w_0 \in W_b$ is a minimal length representative of the element of longest length. Now, what about the connected components $\bar{\nu} = w(b_T^-)$ with w non-trivial? Here the HN-slopes of $\bar{\nu}$ are at least partially anti-dominant, and therefore $\text{Bun}_B^{w(b_T^-)}$ will parameterize some non-split extensions. Nonetheless, one finds that $\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T})$ behaves similarly to the contribution of the connected component given by the HN-dominant reduction. Note that, a priori, the complex $\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T})$ could be supported on all $b' \in B(G)$ with $b \succeq b'$ in the natural partial ordering on $B(G)$. If one imposes the previous compatibility assumption and assumes ϕ_T is generic then one can use the previous corollary to assume that $b' \in B(G)_{\text{un}}$. In this case, the complex $\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$ can be computed in terms of the cohomology of the space of simultaneous reductions of a G -bundle $\mathcal{F}_G$ to two B -bundles with underlying T -bundles given by $w(b_T^-)$ and a Weyl group translate of b'_T , where b'_T is the HN-dominant reduction of b' . This space admits a locally closed stratification by the generic relative position of these two reductions coming from the Bruhat decomposition of $B \backslash G/B$. If $b' \neq b$ then each of the non-empty strata admit a map to a positive symmetric power of the mirror curve Div^1 , and are locally modelled by a semi-infinite flag space called a Zastava space, as studied in the function field setting by Feign, Finkelberg, Kusnetzov, and Mirković [Fei+99]. By combining a study of these Zastava spaces with a regularity condition on ϕ_T and induction on b , we can show that the restriction of $\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T})$ to each of the locally closed strata indexed by $b' \neq b$ vanishes, from which we can conclude that the restriction $\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$ vanishes unless $b' = b$, where again only the contribution of the split B -structure matters. All in all, we conclude an isomorphism:

$$\text{nEis}^{w(b_T^-)}(\mathcal{S}_{\phi_T}) \simeq j_{b!}(i_{B_b}^{J_b}(\chi^{w_0}) \otimes \delta_{P_b}^{-1/2})[-\langle 2\hat{\rho}, \nu_b \rangle]$$

This parallel behavior between the HN-dominant connected component and the connected components in its Weyl group orbit is no accident. In analogy with §1.1, we expect, for a choice of representative $\tilde{w} \in N(T)$ of $w \in W_G$ in the relative Weyl group, to have an isomorphism

$$\text{nEis}(\mathcal{S}_{\phi_T}) \simeq \text{nEis}(\mathcal{S}_{\phi_T}^{\tilde{w}})$$

where $\mathcal{S}_{\phi_T}^{\tilde{w}}$ is the pullback of $\mathcal{S}_{\phi_T}$ along the map $\text{Bun}_T \rightarrow \text{Bun}_T$ induced by $\tilde{w}$, assuming $\mathcal{S}_{\phi_T}$ or equivalently χ is regular. This involution sends the connected component $\text{Bun}_T^{b_T}$ to $\text{Bun}_T^{w(b_T)}$ and sends the character χ to χ^w . In particular, we see that, by our previous description of stalks, this gives the precise analogue of Theorem 1.1 recalling that genericity should guarantee an isomorphism $\text{nEis}(\mathcal{S}_{\phi_T}) \simeq \overline{\text{nEis}}(\mathcal{S}_{\phi_T})$ for any good definition of the RHS.

Lastly, we discuss how our Eisenstein functor interacts with Verdier duality. We saw above that for a dominant reduction b_T of b , $w \in W_b$, and generic regular ϕ_T , that we have an isomorphism

$$\text{nEis}^{w(b_T)}(\mathcal{S}_{\phi_T}) \simeq j_{b!}(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}).$$

Therefore, in order to see that the Eisenstein functor commutes with Verdier duality, we need to exhibit that the natural map

$$j_{b!}(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}) \rightarrow j_{b*}(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2})$$

is an isomorphism. This would follow from showing that $j_{b*}(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2})$ is only supported on the HN-strata corresponding to $b \in B(G)$, and this can be accomplished through a very similar argument to that explained above for showing that $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ was only supported on one strata. In particular, if, for a Artin v -stack Z , we denote Verdier duality by $\mathbb{D}_Z$ then we have the following.

Theorem 1.9. (Theorem 8.11) *For ϕ_T a generic regular parameter, there is an isomorphism of objects in $\mathrm{D}(\mathrm{Bun}_G)$*

$$\mathbb{D}_{\mathrm{Bun}_G}(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathbb{D}_{\mathrm{Bun}_T}(\mathcal{S}_{\phi_T}))$$

where we note that $\mathbb{D}_{\mathrm{Bun}_T}(\mathcal{S}_{\phi_T}) \simeq \mathcal{S}_{\phi_T^\vee}$, if $\phi_T^\vee$ is the parameter dual to ϕ_T .

We summarize the above discussion as follows.

Theorem 1.10. (Corollary 8.2) *Consider ϕ_T a generic regular parameter with associated character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$. Given $b \in B(G)_{\mathrm{un}}$, we consider J_b , M_b , B_b , and W_b as defined above. For $b \in B(G)$, the stalk $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \in \mathrm{D}(\mathrm{Bun}_G^b) \simeq \mathrm{D}(J_b(\mathbb{Q}_p), \Lambda)$ is given by*

- (1) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq \bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$ if $b \in B(G)_{\mathrm{un}}$,*
- (2) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq 0$ if $b \notin B(G)_{\mathrm{un}}$.*

In particular, $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a perverse sheaf on Bun_G with respect to the standard t -structure defined by the HN-strata using Theorem 8.11.

We note that the previous Corollaries imply that the stalks of the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ are valued in smooth admissible representation when ϕ_T is generic regular. This implies that the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is ULA with respect to the structure map $\mathrm{Bun}_G \rightarrow *$, using the characterization given in [FS, Theorem V.7.1]. This ULA property allows us to extend the construction of $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ to $\overline{\mathbb{Z}}_\ell$ and $\overline{\mathbb{Q}}_\ell$ -coefficients, where passing to the world of lisse-étale solid sheaves is a non-trivial matter because of the difference between ℓ -adic and discrete topologies. We will need to work with ϕ_T that is integral in the sense that, if $\Lambda = \overline{\mathbb{Q}}_\ell$, it is of the form $\overline{\phi}_T \otimes_{\overline{\mathbb{Z}}_\ell} \overline{\mathbb{Q}}_\ell$ for a $\overline{\mathbb{Z}}_\ell$ -valued parameter $\overline{\phi}_T$. Given an integral parameter ϕ_T such that the mod ℓ -reduction is generic regular, we get a sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T}) \in \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$ for all $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$. The description of the stalks, the filtered eigensheaf property with eigenvalue ϕ , and the commutation with Verdier duality all extend in a natural way to these coefficient systems, and we would now like to say that the filtered eigensheaf property implies it is a genuine eigensheaf under the conditions on ϕ_T . For a representation $V \in \mathrm{Rep}_\Lambda({}^L G)$, the filtered eigensheaf property tells us that $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ has a filtration whose graded pieces have Weil group action given by $\nu^\Gamma \circ \phi_T$, for $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ a non-zero weight of V in $\hat{T}$. In order to see this splits, it suffices to show for ν, ν' defining distinct Galois orbits of weights of V in $\hat{T}$ that the extension group $H^1(W_{\mathbb{Q}_p}, (\nu - \nu')^\Gamma \circ \phi_T)$ vanishes for the Γ -orbit $(\nu - \nu')^\Gamma$ defined by $\nu - \nu'$. However, this is equivalent to saying that the entire complex

$$R\Gamma(W_{\mathbb{Q}_p}, (\nu - \nu')^\Gamma \circ \phi_T)$$

is trivial, and this was precisely the kind of vanishing result that strong μ -regularity of ϕ_T guaranteed. Moreover, by the vanishing of the H^0 the splitting will be unique. In particular, if $V = V_{\mu_\Gamma}$ for $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ such that ϕ_T is strongly μ -regular then this allows us to see that we get a unique splitting for $V = V_{\mu_\Gamma}$. Now, as noted in Remark 1.6, we see that strong μ -regularity is usually guaranteed under generic for a sufficiently nicely chosen cocharacter. We would like to use this to conclude that the filtration on $T_{V_{\mu_\Gamma}}$ splits in more generality. Suppose we are given cocharacters $\mu_1, \dots, \mu_k$ and we know that the filtration splits for the V_{μ_i} then, using the compatibilities of the filtration, we can show the splitting for any representation V realized as a direct summand of $\bigotimes_{k=1}^m V_{\mu_k}^{\otimes n_i}$, but in this case we cannot guarantee that this splitting is unique.

We need to be a bit careful when running the argument sketched above. In particular, if $\Lambda = \overline{\mathbb{Q}}_\ell$, then the category $\mathrm{Rep}_\Lambda({}^L G)$ is semi-simple with irreducible objects parametrized by Γ -orbits of

dominant cocharacters $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+/\Gamma$ and the above argument goes through. If $\Lambda \in \{\overline{\mathbb{Z}}_\ell, \overline{\mathbb{F}}_\ell\}$ this is no longer true. However, in these cases, we can replace $\text{Rep}_\Lambda(LG)$ by a sub-category of tilting modules $\text{Tilt}_\Lambda(LG)$ ([Mat00], [Jan03, Appendix E]), which will be semi-simple with indecomposable objects parameterized by $\mu^\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+/\Gamma$, denoted $\mathcal{T}_{\mu^\Gamma} \in \text{Tilt}_\Lambda(LG)$. Extending the theory of tilting modules to the full L -group ${}^L G$ is a bit subtle. However, this is precisely what our assumption that $\ell \nmid |Q|$ appearing in the very decent condition above will allow us to do. This category is preserved under taking tensor products, and therefore we can define the notion of a "tilting eigensheaf" (Definition 9.5) by replacing $\text{Rep}_\Lambda(LG)$ with $\text{Tilt}_\Lambda(LG)$ in the usual definition. For $V \in \text{Rep}_\Lambda(LG^I)$, we write $r_V : {}^L G^I \rightarrow \text{GL}(V)$ for the associated map. This allows us to define the following.

Definition 1.11. For a finite index set I , we say a tuple of cocharacters $(\mu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$ is $(\mu_i)_{i \in I}$ -regular if the filtration on $T_V(\text{nEis}(\mathcal{S}_{\phi_T}))$ splits for the tilting module $V = \boxtimes_{i \in I} \mathcal{T}_{\mu_i^\Gamma}$.

Remark 1.12. The argument sketched above allows us to show if ϕ_T is $(\mu_{1i})_{i \in I}$ and $(\mu_{2i})_{i \in I}$ regular then this implies that ϕ_T is regular for the cocharacter attached to any highest weight tilting module occurring in the tensor product $\boxtimes_{i \in I} \mathcal{T}_{\mu_{1i}^\Gamma} \otimes \mathcal{T}_{\mu_{2i}^\Gamma}$ (Proposition 9.12). In particular, this implies that ϕ_T is $(\mu_{1i} + \mu_{2i})_{i \in I}$ -regular by considerations of highest weight. This property often allows us to see that we get μ -regularity just under the generic hypothesis on ϕ_T . For example, for $G = \text{GL}_n$, and $\Lambda = \overline{\mathbb{Q}}_\ell$ then, as observed in Remark 1.6, genericity will imply strong μ -regularity for $\mu = (1, 0, \dots, 0)$, and this will imply the filtration splits uniquely for this cocharacter. This allows us to see that the filtration splits uniquely for the standard representation, and this in turn allows us to see that we get a splitting for the representations corresponding to the other fundamental coweights $\omega_i = (1_i, 0_{n-i})$ using the decomposition $V_{\text{std}}^{\otimes i} = \text{Sym}^i(V) \oplus \dots \oplus \Lambda^i(V)$ of the tensor powers of the standard representation V_{std} of GL_n . From here, we can show μ -regularity for all μ using the fact that we can realize $\mathcal{T}_\mu$ as a direct summand of a tensor product of the representations corresponding to fundamental coweights. This argument also works with torsion coefficients since $\Lambda^i(V) = V_{\omega_i}$ will always be tilting by virtue of ω_i being minuscule for all $i = 1, \dots, n$ when $G = \text{GL}_n$ (Corollary 9.16).

Our main theorem is then as follows.

Theorem 1.13. (Theorem 9.10) For $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$, we consider $\phi_T : W_{\overline{\mathbb{Q}}_p} \rightarrow {}^L T(\Lambda)$ an integral parameter such that its mod ℓ -reduction is generic regular. There then exists a perverse sheaf $\text{nEis}(\mathcal{S}_{\phi_T}) \in \text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$ which is a filtered eigensheaf with eigenvalue ϕ . If $V \in \text{Tilt}_\Lambda(LG)$ is a direct sum of tilting modules $\boxtimes_{i \in I} \mathcal{T}_{\mu_i^\Gamma}$ for geometric dominant cocharacters μ_i , and ϕ_T is μ_i -regular (resp. strongly μ_i -regular), the filtration on $T_V(\text{nEis}(\mathcal{S}_{\phi_T}))$ splits (resp. splits uniquely), and we have a natural isomorphism

$$T_V(\text{nEis}(\mathcal{S}_{\phi_T})) \simeq \text{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_V \circ \phi$$

of sheaves in $\text{D}_{\text{lis}}(\text{Bun}_G)^{BW_{\overline{\mathbb{Q}}_p}^I}$. In particular, if ϕ_T is μ -regular (resp. strongly μ -regular) for all geometric dominant cocharacters μ then $\text{nEis}(\mathcal{S}_{\phi_T})$ is a weak tilting eigensheaf (resp. tilting eigensheaf). For $b \in B(G)$, the stalk $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b} \in \text{D}(\text{Bun}_G^b) \simeq \text{D}(J_b(\overline{\mathbb{Q}}_p), \Lambda)$ is given by

- (1) an isomorphism $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b} \simeq \bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$ if $b \in B(G)_{\text{un}}$,
- (2) an isomorphism $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b} \simeq 0$ if $b \notin B(G)_{\text{un}}$.

Moreover, if $\mathbb{D}_{\text{Bun}_G}$ denotes Verdier duality on Bun_G , we have an isomorphism

$$\mathbb{D}_{\text{Bun}_G}(\text{nEis}(\mathcal{S}_{\phi_T})) \simeq \text{nEis}(\mathcal{S}_{\phi_T}^\vee)$$

of sheaves in $\text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$.

Remark 1.14. The notion of a weak tilting eigensheaf means that we always have isomorphisms

$$\eta_{V,I} : T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_V \circ \phi$$

for $V \in \mathrm{Tilt}({}^L G^I)$ and a finite index set I , but do not necessarily know that the desired compatibilities with respect to I and V . Even though we know these compatibilities for the filtration, it is not necessarily clear that the splitting we produce through our argument respects these compatibilities without assuming strong μ -regularity. Only knowing the compatibilities of the splittings under such restrictive conditions is a bit unfortunate; fortunately, for most of the applications to local Shtuka spaces with one leg it suffices to only know a splitting exists.

This eigensheaf has several suprising applications to the cohomology of local Shimura varieties and shtuka spaces. To formalize this, we define, for $b \in B(G)$, a complex of $J_b(\mathbb{Q}_p)$ -representations denoted $\mathrm{Red}_{b,\phi}$. If $b \notin B(G)_{\mathrm{un}}$ we set this to be equal to 0 and if $b \in B(G)_{\mathrm{un}}$ to be equal to $\bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$. Now let's consider μ a geometric dominant cocharacter of G with reflex field E and set $B(G, \mu) \subset B(G)$ to be the subset of μ -admissible elements (Definition 2.5). We let $\mathcal{T}_\mu$ be the associated highest weight tilting module of $\hat{G}$. This defines a representation of $W_E \ltimes \hat{G}$ with associated Hecke operator T_μ . We write $r_\mu : W_E \ltimes \hat{G} \rightarrow \mathrm{GL}(\mathcal{T}_\mu)$ for the associated map. We consider the cohomology of the local shtuka spaces $\mathrm{Sht}(G, b, \mu)_\infty$, as defined in [SW20]. In particular, the representation $\mathcal{T}_\mu$ attached to a dominant inverse defines a sheaf $\mathcal{S}_\mu$ on $\mathrm{Sht}(G, b, \mu)_\infty$ via geometric Satake, and we can consider the complex $R\Gamma_c(G, b, \mu)$ of $J_b(\mathbb{Q}_p) \times G(\mathbb{Q}_p) \times W_E$ -modules attached to cohomology valued in this sheaf.

Remark 1.15. We note that, since we have used the tilting module $\mathcal{T}_\mu$ in the definition of $R\Gamma_c(G, b, \mu)$ instead of the usual highest weight representation V_μ this is slightly different than the usual definition appearing in the literature. The two definitions will coincide when the representation V_μ defines a tilting module, which is equivalent to V_μ being irreducible with coefficients in Λ . We say such a μ is tilting if this holds. This will always hold if $\Lambda = \overline{\mathbb{Q}_\ell}$ or if μ is minuscule, and we study this notion more carefully in Appendix B.

We can use $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ to describe the cohomology of $R\Gamma_c(G, b, \mu)$. Assume that ϕ_T is μ -regular, the Hecke eigensheaf property then tells us that we have an isomorphism

$$T_\mu(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_\mu \circ \phi|_{W_E}$$

of sheaves with continuous W_E -action. If we restrict to the open HN-strata $j_1 : \mathrm{Bun}_G^1 \rightarrow \mathrm{Bun}_G$ defined by the trivial element $1 \in B(G)$ then this gives an isomorphism

$$j_1^* T_\mu(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq i_B^G(\chi) \boxtimes r_\mu \circ \phi|_{W_E}$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules. Now the point is that only the elements $b \in B(G, \mu)$ occur as a modifications $\mathcal{F}_b \rightarrow \mathcal{F}_G^0$ of type μ , where $\mathcal{F}_G^0$ is the trivial G -bundle. Therefore, only these stalks contribute to the LHS. By applying excision to the locally closed stratification given by Bun_G^b for $b \in B(G, \mu)$, we find that the LHS has a filtration with graded pieces isomorphic to $j_1^* T_\mu(j_{b!}(\mathrm{Red}_{b,\phi}))$, but these are related to the isotypic parts $R\Gamma_c^b(G, b, \mu)[\mathrm{Red}_{b,\phi}]$. From the above analysis, we deduce the following.

Theorem 1.16. (*Theorem 10.7*) *For $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ an integral toral parameter such that its mod ℓ -reduction is generic regular and any geometric dominant cocharacter μ such that ϕ_T is μ -regular, we have an equality*

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^b(G, b, \mu)[\mathrm{Red}_{b,\phi}]] = [r_\mu \circ \phi|_{W_E} \boxtimes i_B^G(\chi)]$$

in the Grothendieck group $K_0(G(\mathbb{Q}_p) \times W_E, \Lambda)$ of smooth admissible $G(\mathbb{Q}_p)$ -representations with a continuous action of W_E .

If we now consider the case where $\Lambda = \overline{\mathbb{Q}}_\ell$ then it follows that the averaging formula is valid for all generic regular and μ -regular parameters $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}}_\ell)$, which admit a $\overline{\mathbb{Z}}_\ell$ -lattice. Moreover, with $\overline{\mathbb{Q}}_\ell$ -coefficients, we can interpret both sides as trace forms on $K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}}_\ell)$, and use that the set of characters obtained from such parameters is Zariski dense in the variety of unramified characters to conclude the following more general claim.

Theorem 1.17. *(Theorem 10.10) For $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}}_\ell)$ any toral parameter and μ any geometric dominant cocharacter of G , we have an equality*

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^b(G, b, \mu)[\text{Red}_{b, \phi}]] = [r_\mu \circ \phi|_{W_E} \boxtimes i_B^G(\chi)]$$

in $K_0(G(\mathbb{Q}_p) \times W_E, \overline{\mathbb{Q}}_\ell)$.

If μ is minuscule and $G = \text{GL}_n$ then this recovers special cases of an averaging formula of Shin [Shi12], which was formalized for more general reductive groups by Alexander Bertolini-Meli [Ber21]. In particular, for all χ the induction $i_B^G(\chi)$ defines a class $[i_B^G(\chi)] \in K_0^{st}(G(\mathbb{Q}_p), \overline{\mathbb{Q}}_\ell)$ in the subgroup of the Grothendieck group with stable character sum. To such a class, the averaging formula gives a description of the RHS in terms of an average over $B(G, \mu)$ of the isotypic parts of $R\Gamma_c(G, b, \mu)$ with respect to $\text{Red}_b^c(i_B^G(\chi))$, where $\mathfrak{c}$ is a refined endoscopic datum (Definition C.1). In Appendix C, we verify that this indeed agrees with the conjectured averaging formula when $\mathfrak{c}$ is the trivial endoscopic datum. This is rather remarkable. Such formulae are typically proven in the minuscule case by stabilizing the trace formula on the Igusa varieties indexed by $b \in B(G, \mu)$, and our analysis gives a more conceptual explanation for them. By combining our work here with the compatibility results proven in [Ham25] and [BHN22], this gives a proof of this averaging formula in cases where the non-basic Igusa varieties haven't even been properly defined yet!³ We recall that, in the proof of the averaging formula, we used excision to produce a filtration whose graded pieces were isomorphic to

$$j_1^* T_\mu(j_{b!}(\text{Red}_{b, \phi})) \simeq j_1^* T_\mu(j_{b!}(\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b}))$$

By using the isomorphism $\mathbb{D}_{\text{Bun}_G}(\text{nEis}(\mathcal{S}_{\phi_T})) \simeq \text{nEis}(\mathcal{S}_{\phi_T^\vee})$, we can show (See Corollary 10.14) that we have an isomorphism: $j_1^* T_\mu(j_{b!}(\text{Red}_{b, \phi})) \simeq j_1^* T_\mu(j_{b*}(\text{Red}_{b, \phi}))$ of objects in $\text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$. This implies that the excision spectral sequence degenerates, allowing us to conclude the following refined averaging formula.

Theorem 1.18. *(Theorem 10.15) For ϕ_T an integral parameter with generic regular mod ℓ -reduction, and μ any geometric dominant cocharacter such that ϕ_T is μ -regular, we have an isomorphism*

$$\bigoplus_{b \in B(G, \mu)_{\text{un}}} \bigoplus_{w \in W_b} R\Gamma_c^b(G, b, \mu)[\rho_{b, w}][-\langle 2\hat{\rho}, \nu_b \rangle] \simeq i_B^G(\chi) \boxtimes r_\mu \circ \phi|_{W_E}$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules, where $\rho_{b, w} := i_{P_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$.

We now assume that ϕ_T is an integral parameter with generic regular mod ℓ reduction in all that follows. The previous theorem leads to a very explicit descriptions of the complexes $R\Gamma_c(G, b, \mu)[\rho_{b, w} \otimes \delta_{P_b}]$ and the degrees of cohomology they sit in.

Corollary 1.19. *(Corollary 10.16) For μ a geometric dominant cocharacter with reflex field E such that ϕ_T is μ -regular, fixed $b \in B(G, \mu)_{\text{un}}$, and varying $w \in W_b$, the complex $R\Gamma_c^b(G, b, \mu)[\rho_{b, w}]$ is*

³However, in the case where G is split and μ is minuscule this formula can actually be checked by hand (See Proposition 10.19), but in the case of unitary groups or restrictions of scalars of a split group and μ minuscule this already gives new information.

isomorphic to $\phi_{b,w}^\mu \boxtimes \sigma[\langle 2\hat{\rho}, \nu_b \rangle]$, for $\phi_{b,w}^\mu$ a representation of W_E and σ a sub-quotient of $i_B^G(\chi)$. Moreover, we have an isomorphism

$$\bigoplus_{b \in B(G, \mu)_{\text{un}}} \bigoplus_{w \in W_b} \phi_{b,w}^\mu \simeq r_\mu \circ \phi|_{W_E}$$

of W_E -representations.

It is now natural to wonder what the representations $\phi_{b,w}^\mu$ exactly are. It was already observed by Xiao-Zhu [XZ17] that the elements of the set $B(G, \mu)_{\text{un}}$ correspond to Weyl group orbits of weights of the highest weight module $\mathcal{T}_\mu$ or rather its restriction $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ (Corollary 2.9). If we let $b_T \in B(T)$ be the dominant reduction of an element $b \in B(G, \mu)_{\text{un}}$ then the orbit of the character b_T under the Weyl group W_G can be described as $w(b_T)$ for $w \in W_b$ varying. For varying $b \in B(G, \mu)_{\text{un}}$, this describes the set of non-zero weights which can occur in the representation $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$. In particular, given such a $\bar{\nu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, we can look at the direct sum of weight spaces

$$\bigoplus_{\substack{\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \nu_\Gamma = \bar{\nu}}} \mathcal{T}_\mu(\nu)$$

and this coincides with the weight space of $\mathcal{T}_\mu|_{\hat{G}^\Gamma}(\bar{\nu})$ via the isomorphism $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma \simeq \mathbb{X}^*(\hat{T}^\Gamma)$. The refined averaging formula suggests the following relationship.

Conjecture 1.20. (*Conjecture 10.17*) *For all geometric dominant cocharacters μ such that ϕ_T is μ -regular, an unramified element $b \in B(G, \mu)_{\text{un}}$, and a Weyl group element $w \in W_b$, we have an isomorphism*

$$\bigoplus_{\substack{\widetilde{w(b_T)} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \widetilde{w(b_T)}_\Gamma = w(b_T)}} \widetilde{w(b_T)} \circ \phi_T|_{W_{E'}} \otimes \mathcal{T}_\mu(\widetilde{w(b_T)}) \simeq \phi_{b,w}^\mu|_{W_{E'}}$$

of $W_{E'}$ -representations, where $E'|E$ denotes the splitting field of G .

We verify this conjecture in some particular cases, by noting that the contribution from the μ -ordinary locus can be explicitly computed using a shtuka analogue of Boyer's trick [Boy99], as studied by Gaisin-Imai [GI16]. To do this, we note that we have a distinguished element in $B(G, \mu)_{\text{un}}$ called the μ -ordinary element, which we denote by b_μ . It is the maximal element in the partial ordering on $B(G, \mu)$, and we let b_{μ_T} be its dominant reduction. The conjecture suggests that this should correspond to the Weyl group orbit of the highest weight of $\mathcal{T}_\mu$. In this case, the space $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ with its $G(\mathbb{Q}_p) \times J_b(\mathbb{Q}_p)$ -action is determined by the space $\text{Sht}(T, b_{\mu_T}, \mu)_{\infty, \mathbb{C}_p}$ with its $T(\mathbb{Q}_p) \times T(\mathbb{Q}_p)$ -action. In particular, using this we can deduce the following isomorphism (See Proposition 10.19):

$$R\Gamma_c^\flat(G, b_\mu, \mu)[\rho_{b_\mu, w}] \simeq i_B^G(\chi^{w w_0}) \boxtimes w(\mu) \circ \phi_T|_{W_E}[\langle 2\hat{\rho}, \nu_b \rangle],$$

where w and w_0 are minimal length representatives of W_b in W_G . This calculation has a very interesting consequence. In particular, when combined with the refined averaging formula, we see that we must have an isomorphism $i_B^G(\chi^w) \simeq i_B^G(\chi)$. So, by choosing μ to be sufficiently regular so that $W_{b_\mu} = W_G$, we can deduce the following.

Theorem 1.21. (*Corollary 10.21*) *For ϕ_T an integral parameter with generic regular mod ℓ -reduction such that there exists a μ which is not fixed under W_G and ϕ_T is μ -regular, we have an isomorphism*

$$i_{\chi, w} : i_B^G(\chi) \simeq i_B^G(\chi^w)$$

of smooth $G(\mathbb{Q}_p)$ -representations for all $w \in W_G$.

This showcases the strong connection between the theory of geometric Eisenstein series and the theory of intertwining operators and the Langlands quotient that has been our philosophical guide throughout. A relation that holds even with mod ℓ -coefficients! With mod ℓ coefficients, there is no good theory of intertwining operators or the Langlands quotient (See however [Dat05], for the current state of the art), and we suspect that further developing the theory of geometric Eisenstein series should provide some insights into these notions in the ℓ -modular setting.

We saw above that our previous conjecture on $\phi_{b,w}^\mu$ can be completely verified using Boyer's trick in the case that the only weights of $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ are orbits of the highest weight. This will be the case when the image $\mu_\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma^+ \simeq \mathbb{X}^*(\hat{T}^\Gamma)^+$ of μ is minuscule with respect to the pairing with $\mathbb{X}_*(\hat{T}^\Gamma)$. If we combine this with the refined averaging formula then we can also deduce the claim when $B(G, \mu)$ has two elements. I.e the case where $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ has two weight spaces; one corresponding to the μ -ordinary element and the other corresponding to the basic element. This will prove the previous conjecture in all cases where $\mu_\Gamma \in \mathbb{X}^*(\hat{T}^\Gamma)^+$ is minuscule or quasi-minuscule with respect to the pairing with the cocharacters $\mathbb{X}_*(\hat{T}^\Gamma)$.

Theorem 1.22. (Corollary 10.24) *For μ a geometric dominant cocharacter and ϕ_T strongly μ -regular such that $\mu_\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma^+$ is minuscule or quasi-minuscule with respect to the pairing with $\mathbb{X}_*(\hat{T}^\Gamma)$, the previous conjecture is true.*

Remark 1.23. Even for μ minuscule it can be the case that the image $\mu_\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma^+$ is no longer minuscule with respect to the above pairing, as this corresponds to restricting the highest weight representation of $\hat{G}$ defined by μ to $\hat{G}^\Gamma$. Therefore, even for μ minuscule, we can still have that the basic element $b \in B(G, \mu)$ is unramified (See [XZ17, Remark 4.2.11]) In these cases, a very analogous result was proven by [XZ17], where they describe the irreducible components of affine Deligne-Lusztig varieties in terms of the weight space defined by the basic element. These affine Deligne-Lusztig varieties describe the special fibers of the local shtuka spaces $\text{Sht}(G, b, \mu)_\infty/\overline{K}$ in the case that G is unramified, and K is a hyperspecial level. Moreover, we suspect that, by using nearby cycles, one could deduce some special cases of their result from ours.

Throughout our results, we have introduced various technical conditions on ϕ_T . We suspect that some of these conditions (in particular, the μ -regularity) are artifacts of the proofs we have used to overcome the technical geometry of Bun_B and its compactifications in the context of analytic geometric and diamonds. While the conditions are manageable for specific applications to specific groups it leaves one wanting for a more conceptually clear picture. In particular, we conjecture that the following is true, which (modulo checking the compatibilities of the isomorphisms in the eigensheaf property) our methods show for GL_n and integral generic regular parameters (Corollary 9.16)

Conjecture 1.24. *For $\Lambda \in \{\overline{\mathbb{F}_\ell}, \overline{\mathbb{Z}_\ell}, \overline{\mathbb{Q}_\ell}\}$ and $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ a generic regular L -parameter, there exists a sheaf $\text{nEis}(\mathcal{S}_{\phi_T}) \in \text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$ which is a perverse Hecke eigensheaf with eigenvalue ϕ such that one has an isomorphism $\mathbb{D}_{\text{Bun}_G}(\text{nEis}(\mathcal{S}_{\phi_T})) \simeq \text{nEis}(\mathcal{S}_{\phi_T^\vee})$, and its stalk at all $b \in B(G)$ is isomorphic to $\text{Red}_{b,\phi} \otimes \delta_{P_b}^{-1}$.*

This conjecture would follow from knowing the existence of $\text{IC}_{\overline{\text{Bun}_B}}$ and in turn the compactified Eisenstein functor $\overline{\text{Eis}}$ with all the various desiderata proven by Braverman-Gaitsgory [BG02] in the function field setting. In particular, we expect that $\overline{\text{Eis}}(-)$ should commute with Verdier duality, and satisfy the functional equation under condition 3.6 (2). Moreover, by the analogue of the results of [BG08], there should be a natural map

$$\text{nEis}(\mathcal{S}_{\phi_T}) \rightarrow \overline{\text{Eis}}(\mathcal{S}_{\phi_T})$$

whose cone should be given by Eisenstein functors tensored with complexes admitting a filtration isomorphic to $R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$ for α a Γ -orbit of coroots of G . In particular, we should have an

isomorphism $\overline{\text{Eis}}(\mathcal{S}_{\phi_T}) \simeq \text{nEis}(\mathcal{S}_{\phi_T})$ precisely when ϕ_T is generic. It follows by our above analysis that this would imply an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^w)$ for all generic regular χ . We show that this is true for generic χ in the appendix (Proposition A.2) at least with $\overline{\mathbb{Q}}_\ell$ -coefficients.

In §2, we start by defining the set of unramified elements in $B(G)$ and discussing their relationship with highest weight theory, as in [XZ17]. In §3, we review the construction of eigensheaves on Bun_T attached to parameters ϕ_T , introducing the conditions on our parameter ϕ_T and working through some useful lemmas and examples related to them. In §4, we review the geometric Satake correspondence of Fargues-Scholze, recalling the key results and relating the highest weight theory of ${}^L G$ to the cohomology of semi-infinite Schubert cells. In §5, we introduce Drinfeld's compactifications over the Fargues-Fontaine curve and recall its basic geometric properties and discuss a key diagram that will be used in the proof of the Hecke eigensheaf property. In §6, we will study how the Eisenstein functor interacts with Hecke operators, establishing Theorem 1.7. In §7, we review some important results from the paper [HHS24] on geometric second adjointness and the preservation of ULA objects. In §8, we will carry out the computation of the stalks of the Eisenstein series $\text{nEis}(\mathcal{S}_{\phi_T})$ and show the commutation with Verdier duality, establishing Theorem 1.9 and Theorem 1.10. In §9, we describe the theory of tilting modules for the L -group ${}^L G$, constructing $\text{nEis}(\mathcal{S}_{\phi_T})$ with $\overline{\mathbb{Z}}_\ell$ and $\overline{\mathbb{Q}}_\ell$ -coefficients and showing Theorem 1.15. Finally, in §10, we deduce the applications to the cohomology of local shtuka spaces showing Theorems 1.16, 1.17, 1.18, and Corollary 1.19.

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2. NOTATION

- Let $\ell \neq p$ be distinct primes.
- Let G be a quasi-split connected reductive group.
- We let $\overline{\mathbb{Q}}_\ell$ denote the algebraic closure of the ℓ -adic numbers, with residue field $\overline{\mathbb{F}}_\ell$ and ring of integers $\overline{\mathbb{Z}}_\ell$, endowed with the discrete topology.
- Let Γ be the absolute Galois group of $\mathbb{Q}_p$, and let $W_{\mathbb{Q}_p} \subset \Gamma$ be the Weil group of $\mathbb{Q}_p$.
- We set $\mathcal{L}_{\mathbb{Q}_p} := W_{\mathbb{Q}_p} \times \text{SL}_2(\overline{\mathbb{Q}}_\ell)$ to be the Weil-Deligne group.
- Fix choices $A \subset T \subset B \subset G$ of maximal split torus, maximal non-split torus, and Borel. We use U to denote the unipotent radical of B .
- We let W_G be the relative Weyl group of G and w_0 be the element of longest length.
- We write $\text{Ind}_B^G(-)$ for the unnormalized parabolic induction functor from B to G . We let δ_B be the modulus character defined by B so that $i_B^G(-) := \text{Ind}_B^G(- \otimes \delta_B^{1/2})$ is the normalized induction. In other words, δ_B is defined by the transformations of the space of right Haar measures.
- Let $\check{\mathbb{Q}}_p$ be the completion of the maximal unramified extension of $\mathbb{Q}_p$ with Frobenius σ . For $E/\mathbb{Q}_p$ a finite extension, we set $\check{E}$ to be the compositum $E\check{\mathbb{Q}}_p$.
- Set $\mathbb{C}_p$ to be the completion of the algebraic closure of $\mathbb{Q}_p$.
- Let $B(G) = G(\check{\mathbb{Q}}_p)/(g \sim hg\sigma(h)^{-1})$ denote the Kottwitz set of G .
- For $b \in B(G)$, we write J_b for the σ -centralizer of b .

- We will always work over the fixed base $* := \mathrm{Spd} \overline{\mathbb{F}}_p$, unless otherwise stated.
- Let Perf denote the category of (affinoid) perfectoid spaces in characteristic p over $*$ endowed with the v -topology. For $S \in \mathrm{Perf}$, let Perf_S denote the category of affinoid perfectoid spaces over it.
- For $S \in \mathrm{Perf}$, let X_S denote the relative (schematic) Fargues-Fontaine curve over S .
- For $\mathrm{Spa}(F, \mathcal{O}_F) \in \mathrm{Perf}$ a geometric point, we will often drop the subscript on X_F and just write X for the associated Fargues-Fontaine curve.
- For $b \in B(G)$, we write $\mathcal{F}_b$ for the associated G -bundle on X .
- For $S \in \mathrm{Perf}$, we let $\mathcal{F}_G^0$ denote the trivial G -bundle on X_S .
- We consider coefficient systems $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$, with a fixed choice of square root of $p \in \Lambda$. We define all half Tate twists with respect to this choice.
- For an Artin v -stack X , we write $\mathrm{D}_\blacksquare(X, \Lambda)$ for the condensed ∞ -category of solid Λ -valued sheaves on X , and write $\mathrm{D}_{\mathrm{lis}}(X, \Lambda) \subset \mathrm{D}_\blacksquare(X, \Lambda)$ for the full sub-category of Λ -valued lisse-étale sheaves, as defined in [FS, Chapter VII].
- For a v -stack or diamond X , when working with torsion coefficients, we will indicate this by just writing $\mathrm{D}(X) := \mathrm{D}_{\mathrm{ét}}(X, \Lambda)$ for the category of étale Λ -sheaves on X , as defined [Sch]. If X is an Artin v -stack ([FS, Definition IV.V.1]) admitting a separated cohomologically smooth surjection $U \rightarrow X$ from a locally spatial diamond U such that the étale site has a basis with bounded ℓ -cohomological dimension (which will always be the case for our applications) then we will regard it as a condensed ∞ -category via the identification $\mathrm{D}_{\mathrm{lis}}(X, \Lambda) \simeq \mathrm{D}(X)$ when viewed as objects in $\mathrm{D}_\blacksquare(X, \Lambda)$ [FS, Proposition VII.6.6].
- We let $\hat{G}$ denote the Langlands dual group of G with fixed splitting $(\hat{T}, \hat{B}, \{X_\alpha\})$.
- If E denotes the splitting field of G then the action of $W_{\mathbb{Q}_p}$ factors through $Q := W_{\mathbb{Q}_p}/W_E$. We let ${}^L G := \hat{G} \rtimes Q$ denote the L -group.
- Throughout, we will assume that, for our fixed G , ℓ is very decent in the sense mentioned in the introduction that $\ell \nmid \pi_0(Z(G))$ and that $\ell \nmid |Q|$. We will also occasionally make reference to the notion of ℓ being very good, as defined in [FS, Page 33]⁴, which in addition to being very decent imposes additional constraints depending on the type of group.
- For I a finite index set, we let $\mathrm{Rep}_\Lambda({}^L G^I)$ denote the category of finite-dimensional algebraic representations of ${}^L G^I$.
- To any condensed ∞ -category $\mathcal{C}$, we write $\mathcal{C}^{BW_{\mathbb{Q}_p}^I}$ for the category of objects with continuous $W_{\mathbb{Q}_p}^I$ -action, as defined in [FS, Section IX.1].
- We will let $\mathrm{Div}^1 := \mathrm{Spd} \check{\mathbb{Q}}_p / \mathrm{Frob}^{\mathbb{Z}}$ denote the mirror curve, and, for a finite extension $E/\mathbb{Q}_p$, we write Div_E^1 for the base-change to E .
- For I a finite index set, we let Div^I denote $|I|$ -copies of the mirror curve. For $n \in \mathbb{N}_{\geq 1}$, we let $\mathrm{Div}^{(n)} = (\mathrm{Div}^1)^n / S_n$, denote the n th symmetric power of the mirror curve, where S_n is the symmetric group on n letters.
- For a reductive group $H/\mathbb{Q}_p$, we write $\mathrm{D}(H(\mathbb{Q}_p), \Lambda)$ for the unbounded derived category of smooth Λ -representations.
- We say a map of v -stacks $f : X \rightarrow Y$ is representable in nice diamonds if it is representable in locally spatial diamonds, is compactifiable, and (locally) $\mathrm{tr.deg}(f) < \infty$.
- All 6-functors will be implicitly derived unless otherwise stated.
- For a locally pro- p group H , we write $\underline{H}$ for the functor sending $S \in \mathrm{Perf}$ to $\mathrm{Cont}(|S|, H)$, the set of continuous maps from the underlying topological space of S to H .

Remark 2.1. At various points, we will need to consider the functors $f_! : \mathrm{D}(X) \rightarrow \mathrm{D}(Y)$ and $f^! : \mathrm{D}(Y) \rightarrow \mathrm{D}(X)$ for certain "stacky" morphisms of Artin v -stacks $f : X \rightarrow Y$. The correct definitions of these functors in this case are given in the work of [GHW22]. In particular,

⁴Here we emphasize that we are referring to is ArXiv v2.

they extend the 6-functors studied in [Sch; FS] to fine maps [GHW22, Definition 1.3] of decent v -stacks [GHW22, Definition 1.2]. In general being a decent v -stack is stronger than being Artin. However, it is easy to check that for all the stacks (resp. morphisms) we consider these functors for they will be decent (resp. fine). To see this, one can use which states that if $f : X \rightarrow Y$ is a map of v -stacks which is representable in nice diamonds and Y is decent then X is also decent and f is fine. In the cases we consider, one can apply this if one takes $Y = \text{Bun}_G$. To see that Bun_G is decent, one can use the charts studied in [FS, Section V.3], and take advantage of the fact that the maps defining the charts are formally smooth [FS, Definition IV.3.1] by [FS, Proposition IV.4.24]. This in particular allows one to see that these charts map strictly surjectively [GHW22, Defintion 4.1] to Bun_G . It remains to explain why the maps appearing in our context are fine, to do this one can combine the previous analysis with [GHW22, Proposition 4.10 (iii)], which says that fine morphisms satisfy the 2 out of 3 property.

- When speaking about such fine maps of decent v -stacks we will often just cite theorems that only apply to the setting where f is representable in nice diamonds, and leave it to the reader to check that one can deduce the analogous results from the cited result and the formal properties of the 6-functors defined in [GHW22].
- Given a decent v -stack $X \rightarrow *$ such that X is fine over $*$, we let $K_X := f^!(\Lambda) \in D(X)$ denote the dualizing object of X . Similarly, for $\mathcal{F} \in D(X)$, we will write $R\Gamma_c(X, \mathcal{F}) := f_!(\mathcal{F}) \in D(\Lambda)$. We write $\mathbb{D}_X(-) := R\mathcal{H}om(-, K_X)$ for the Verdier duality functor. For a fine map $f : X \rightarrow S$ of decent v -stacks, we write $\mathbb{D}_{X/S} := R\mathcal{H}om(-, f^!(\Lambda))$ for relative Verdier duality.
- We will use the geometric normalization of local class field theory. For $n \in \mathbb{Z}$, we write (n) for the n th power of the ℓ -adic cyclotomic character of $W_{\mathbb{Q}_p}$. We note that, under this normalization, (1) is sent to the norm character $|\cdot| : \mathbb{Q}_p^* \rightarrow \Lambda^*$, which acts trivially on $\mathbb{Z}_p^*$ and sends p to $p^{-1} \in \Lambda^*$.

Before introducing the rest of the notation, we discuss the relationship between unramified elements in $B(G)$ and the representation theory of the dual group.

2.1. Unramified Elements in $B(G)$ and Highest Weight Theory. In this section, we will study the set of unramified elements in the Kottwitz set of G . As we will show, these elements are connected to the highest weight theory of the Langlands dual group $\hat{G}$, as discussed in [XZ17, Section 4.2.1]. First, we recall that the Kottwitz set $B(G)$ of a connected reductive group $G/\mathbb{Q}_p$ is equipped with two maps:

- The slope homomorphism

$$\begin{aligned} \nu : B(G) &\rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_{\mathbb{Q}}^{+, \Gamma} \\ b &\mapsto \nu_b \end{aligned}$$

where $\Gamma := \text{Gal}(\overline{\mathbb{Q}_p}/\mathbb{Q}_p)$ and $\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_{\mathbb{Q}}^+$ is the set of rational dominant cocharacters of G .

- The Kottwitz invariant

$$\kappa_G : B(G) \rightarrow \pi_1(G)_{\Gamma}$$

where $\pi_1(G)$ denotes the algebraic fundamental group of Borovoi.

Now, given a geometric cocharacter μ of G with reflex field E , we can define the element:

$$\tilde{\mu} := \frac{1}{[E : \mathbb{Q}_p]} \sum_{\gamma \in \text{Gal}(E/\mathbb{Q}_p)} \gamma(\mu) \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_{\mathbb{Q}}^{+, \Gamma}$$

We let μ^b be the image of μ in $\pi_1(G)_{\Gamma} \simeq X^*(Z(\hat{G})^{\Gamma})$. Via the isomorphism $B(G)_{\text{basic}} \simeq \pi_1(G)_{\Gamma}$, we regard it as a basic element of $B(G)$, which are the minimal elements in the natural partial ordering

on $B(G)$. Now we recall that, for a torus T , we have an isomorphism $B(T) \simeq \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$. We can use this isomorphism to give a nice description of a certain piece of $B(G)$.

Definition 2.2. [XZ17, Section 4.2.1] We let $B(G)_{\text{un}} \subset B(G)$ denote the image of the natural map $B(T) \rightarrow B(G)$. We refer to this as the set of unramified elements.

We now have the following Lemma. We write $(-)_\Gamma$ for the natural quotient map $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$.

Lemma 2.3. [XZ17, Lemma 4.2.2] Let $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma \simeq B(T) \rightarrow B(G)$ be the natural map. Then this induces an isomorphism:

$$\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma / W_G \simeq B(G)_{\text{un}}$$

Proof. Strictly speaking, the proof given by Xiao-Zhu is only in the case that G is unramified. We remedy this now. Note that it is clear that this map is surjective, so it suffices to check injectivity. Let $\mu_1, \mu_2 \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ be two elements with b_1, b_2 their images in $B(G)$ under the natural composite

$$\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma \simeq B(T) \rightarrow B(G),$$

and suppose that $b_1 = b_2$. Since $\kappa_G(b_1) = \kappa_G(b_2)$, it follows that we have $\mu_1 - \mu_2 = (\gamma - 1)\nu + \alpha$ for some coroot $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ and $\gamma \in \Gamma$. We may, without loss of generality, replace μ_1 by $\mu_1 + (\gamma - 1)\nu$, and therefore assume that $\mu_1 - \mu_2 = \alpha$. Since the slope homomorphisms of ν_{b_1} and ν_{b_2} are equal by assumption, we can assume, after conjugating by an element of W_G , that $\tilde{\mu}_1 = \tilde{\mu}_2$. Therefore, it follows that, if E_α denotes the reflex field of α , we have an equality

$$\sum_{g \in \text{Gal}(E_\alpha/\mathbb{Q}_p)} g(\alpha) = 0$$

which in turn implies that

$$\sum_{g \in \text{Gal}(E_\alpha/\mathbb{Q}_p)} (1 - g)(\alpha) = |\text{Gal}(E_\alpha/\mathbb{Q}_p)|\alpha$$

This would imply that α_Γ vanishes in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ assuming that α_Γ isn't torsion. However, Γ permutes the simple coroots, which form a basis of all coroots. Therefore, it follows that α_Γ is not torsion. $\square$

Now we would like to describe $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma / W_G$ slightly differently. To do this, we consider the natural pairing

$$\langle -, - \rangle : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma \times \mathbb{X}^*(T_{\overline{\mathbb{Q}}_p})^\Gamma \rightarrow \mathbb{Z}$$

induced by the usual pairing between cocharacters and characters. We let $\hat{\Delta} \subset \mathbb{X}^*(T_{\overline{\mathbb{Q}}_p})$ (resp. $\Delta \subset \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$) be the set of (absolute) simple roots (resp. coroots) of G . Then we define $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma^+$ to be the set of elements in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ whose inner product with $\text{Im}(\hat{\Delta} \rightarrow \mathbb{X}^*(T_{\overline{\mathbb{Q}}_p})^\Gamma)$ under the natural averaging map is positive. The natural map

$$\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma^+ \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma / W_G$$

is an isomorphism. We also note that we have a natural partial ordering on $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$. In particular, given $\bar{\nu}, \bar{\nu}' \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ we say that $\bar{\nu} \geq \bar{\nu}'$ if $\bar{\nu} - \bar{\nu}'$ is a positive integral combination of α_Γ for $\alpha \in \Delta$. We note that we have a natural injective order preserving map:

$$\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma^+ \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\mathbb{Q}^{\Gamma,+} \times \pi_1(G)_\Gamma$$

With this, we can reformulate the previous lemma as follows.

Lemma 2.4. *[XZ17, Lemma 4.2.3] The following diagram is commutative and respects the partial ordering*

$$\begin{array}{ccc} B(G)_{\text{un}} & \xrightarrow{\simeq} & \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+ \\ \downarrow & & \downarrow \\ B(G) & \xrightarrow{\nu \times \kappa} & \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\mathbb{Q}}^{\Gamma,+} \times \pi_1(G)_{\Gamma} \end{array}$$

Now recall that, for μ a geometric dominant cocharacter of G , we have the following.

Definition 2.5. We define $B(G, \mu) \subset B(G)$ to be subset of $b \in B(G)$ for which $\nu_b \leq \tilde{\mu}$ with respect to the Bruhat ordering and $\kappa(b) = \mu^b$.

The previous lemma allows us to interpret the unramified elements in this set as follows.

Corollary 2.6. *[XZ17, Corollary 4.2.4] Under the identifications $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+ \simeq \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}/W_G \simeq B(G)_{\text{un}}$, we have an equality:*

$$B(G, \mu)_{\text{un}} := B(G)_{\text{un}} \cap B(G, \mu) = \{\lambda_{\Gamma} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+ \mid \lambda_{\Gamma} \leq \mu_{\Gamma}\}$$

We now would like to connect this set with the highest weight theory for $\hat{G}$. If the group is not split then the unramified elements are naturally connected with the highest weight theory of the subgroup $\hat{G}^{\Gamma}$. Even though $\hat{G}^{\Gamma}$ is possibly disconnected its representation theory behaves like a connected reductive group. To see this, first we note that the subgroup $\hat{T}^{\Gamma}$ defined by the maximal torus has character group isomorphic to $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}$, and the partial order described above allows one to talk about the highest weight of a representation. In particular, if we let $\hat{T}^{\Gamma, \circ}$ (resp. $\hat{G}^{\Gamma, \circ}$) denote the neutral component of $\hat{T}^{\Gamma}$ (resp. $\hat{G}^{\Gamma}$). Then one can use that the natural map $\hat{T}^{\Gamma}/\hat{T}^{\Gamma, \circ} \rightarrow \hat{G}^{\Gamma}/\hat{G}^{\Gamma, \circ}$ is an isomorphism ([Zhu15, Lemma 4.6]) to see that usual highest weight theory extends to $\hat{G}^{\Gamma}$. In particular, we have the following.

Lemma 2.7. *[Zhu15, Lemma 4.10] For $\bar{\mu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+$, there is a unique up to isomorphism irreducible representation of $V_{\bar{\mu}} \in \text{Rep}_{\overline{\mathbb{Q}}_p}(\hat{G}^{\Gamma})$ of highest weight $\bar{\mu}$, which give rise to all the irreducible representations in $\text{Rep}_{\overline{\mathbb{Q}}_p}(\hat{G}^{\Gamma})$ for varying $\bar{\mu}$. Moreover, the multiplicity of the $\bar{\mu}$ weight space in $V_{\bar{\mu}}$ is 1, and the non-zero weights $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}$ of $V_{\bar{\mu}}$ lie in the convex hull of the W_G -orbit of $\bar{\mu}$.*

To a geometric dominant cocharacter μ , we can attach an irreducible representation $V_{\mu} \in \text{Rep}_{\overline{\mathbb{Q}}_p}(\hat{G})$. This defines a natural representation of $\hat{G} \rtimes W_{E_{\mu}}$ as in [Kot84, Lemma 2.1.2], where E_{μ} is the reflex field of μ . An element $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ defines a representation of $\hat{T}$, and we write $V_{\mu}(\nu)$ for the corresponding weight space of V_{μ} . If we consider the restriction $V_{\mu}|_{\hat{G}^{\Gamma}}$ then the weight space $V_{\mu}(\nu)$ gives rise to a ν_{Γ} weight space, where we write $(-)\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}$ for the map given by taking coinvariants. Using this, it is easy to see we have the following relationship.

Lemma 2.8. *For $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ and $\bar{\nu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}$, we have the following equality:*

$$\dim(V_{\mu}(\bar{\nu})) = \sum_{\substack{\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \nu_{\Gamma} = \bar{\nu}}} \dim(V_{\mu}(\nu))$$

We will combine this lemma with the following, which follows from the above discussion.

Corollary 2.9. *([XZ17, Lemma 4.26]) For μ a geometric dominant cocharacter, under the identification $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+ \simeq B(G)_{\text{un}}$ the elements $\bar{\nu} \in B(G, \mu)_{\text{un}}$ correspond to W_G -orbits of the possible non-zero weights in $V_{\mu}|_{\hat{G}^{\Gamma}}$.*

Let's study this now more carefully. For $b \in B(G)$, we want to use the above discussion to understand the fiber of the map:

$$i : B(T) \rightarrow B(G)_{\text{un}} \subset B(G)$$

Recall that, given $b \in B(G)$, since G is quasi-split the σ -centralizer J_b is an extended pure inner form (in the sense of [Kot97, Section 5.2]) of a Levi subgroup M_b of G [Kot97, Section 6.2], which is the centralizer of the slope homomorphism ν_b of b . We make the following definition.

Definition 2.10. For $b \in B(G)$, we let W_{M_b} denote the relative Weyl group of M_b and set $W_b := W_G/W_{M_b}$. We will fix a set of representatives $w \in W_G$ of minimal length, as in [BZ77, Section 2.11], and abuse notation by writing w for both the representative and the corresponding element.

When combining the above discussion with Lemma 2.3, we can deduce the following Corollary.

Corollary 2.11. *For fixed $b \in B(G)_{\text{un}}$, the fiber $i^{-1}(b)$ has a unique element, denoted b_T , whose κ -invariant lies in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_{\Gamma}^+$. Moreover, we have an equality $i^{-1}(b) = \{w(b_T) \mid w \in W_b\}$.*

Now, given a parabolic P with Levi factor M , the element $b \in B(G)$ admits a reduction to a Levi subgroup M if and only if the parabolic $P \cap M_b$ of M_b transfers to a parabolic of J_b under the inner twisting (apply [CFS21, Page 259] to the basic reduction of b to M_b). We record this specialized to the case of the Borel for future use.

Lemma 2.12. *An element $b \in B(G)$ lies in $B(G)_{\text{un}}$ if and only if $B \cap M_b$ defines, via the inner twisting, a Borel subgroup of J_b .*

Remark 2.13. We note that, when $b \in B(G)_{\text{un}}$, we have an isomorphism $M_b \simeq J_b$ because J_b will be a quasi-split inner form of M_b .

We will end with an important observation about the map $(-)_\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ from orbits to coinvariants. Let $\tilde{\mathcal{J}}$ (resp. $\mathcal{J}$) denote the vertices of the absolute (resp. relative) Dynkin diagram of G . For $i \in \tilde{\mathcal{J}}$, we write $\tilde{\alpha}_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ for the corresponding simple absolute coroot. We recall that Γ permutes the $\tilde{\alpha}_i$, and the orbits under Γ are in bijection with elements of $\mathcal{J}$; namely, the average over the orbit is the (reduced) positive coroot corresponding to $i \in \mathcal{J}$. Therefore, for each $i \in \mathcal{J}$, we obtain an element $\alpha_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ given by the common image of the elements in the orbit corresponding to $i \in \mathcal{J}$ under the map $(-)_\Gamma$. This allows us to make the following definition.

Definition 2.14. We denote the group of coinvariants by $\Lambda_{G,B} := \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, and set $\Lambda_{G,B}^{\text{pos}}$ to be the semi-group spanned by the elements $\alpha_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$ corresponding to the Γ -orbit of coroots indexed by $i \in \mathcal{J}$.

Now we introduce the rest of the notation motivated by the discussion above.

- We let $\hat{\Lambda}_G^+ := \mathbb{X}^*(T_{\overline{\mathbb{Q}}_p})_{\Gamma,+}^+$ be the set of Galois invariant dominant characters.
- To a dominant character $\hat{\lambda} \in \hat{\Lambda}_G^+$, we get an associated highest weight Weyl G -module, denoted $\mathcal{V}^{\hat{\lambda}}$. It has a fixed highest weight vector $v^{\hat{\lambda}} \in \mathcal{V}^{\hat{\lambda}}$, and, given a pair of such weights $\hat{\lambda}_1, \hat{\lambda}_2$, there is a canonical map

$$\mathcal{V}^{\hat{\lambda}_1 + \hat{\lambda}_2} \rightarrow \mathcal{V}^{\hat{\lambda}_1} \otimes \mathcal{V}^{\hat{\lambda}_2}$$

which takes $v^{\hat{\lambda}_1 + \hat{\lambda}_2}$ to $v^{\hat{\lambda}_1} \otimes v^{\hat{\lambda}_2}$.

- Let $\mathcal{J}$ be the set of vertices of the relative Dynkin diagram of $G/\mathbb{Q}_p$. For each $i \in \mathcal{J}$, we denote the corresponding element in the coinvariant lattice by $\alpha_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, as in Definition 2.14. We denote the (reduced) simple coroots corresponding to $i \in \mathcal{J}$ by $\alpha_{i,A} \in X_*(A)$. Similarly, for $i \in \mathcal{J}$, we denote the reduced simple roots by $\hat{\alpha}_i \in \mathbb{X}^*(A)^+$.

- We consider the natural pairing

$$\langle -, - \rangle : \hat{\Lambda}_G \times \Lambda_{G,B} \rightarrow \mathbb{Z}.$$

- We will regularly use the natural quotient map

$$(-)_\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$$

as well as the map

$$(-)^\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$$

from cocharacters to their Galois orbits. We note that $(-)_\Gamma$ factorizes over $(-)^\Gamma$ as a map of sets.

- For a geometric dominant cocharacter $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ with reflex field E , we write V_μ for the natural representation of $W_E \rtimes \hat{G}$ of highest weight μ , as in [Kot84, Lemma 2.1.2]. We also write $V_{\mu^\Gamma} \in \text{Rep}_\Lambda({}^L G)$ for the induction of this representation to ${}^L G$, which only depends on the associated Γ -orbit μ^Γ of μ .
- For $b \in B(G)$, we let J_b be the extended pure inner form of M_b considered above. If $b \in B(G)_{\text{un}}$, we write B_b for the Borel defined by $B \cap M_b$ under the inner twisting, as in Lemma 2.12.
- Given $b \in B(G)_{\text{un}}$, we note that, by Lemma 2.3, there exists a unique element $b_T \in B(T)$ with dominant slope homomorphism with respect to the choice of Borel. We refer to this as the dominant reduction. Similarly, we write b_T^- for the unique element with anti-dominant slopes and will refer to this as the HN-dominant reduction of b (Recall that there is a minus sign when comparing isocrystal slopes and HN-slopes).
- We set $W_b := W_G/W_{M_b}$, where W_{M_b} (resp. W_G) is the relative Weyl group of M_b (resp. G). We identify $w \in W_b$ with a representative of minimal length in W_G throughout.

3. GEOMETRIC LOCAL CLASS FIELD THEORY

3.1. Hecke Eigensheaves for Tori. In this section, we want to talk about geometric local class field theory. Namely, given a torus T with L -parameter

$$\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$$

where ${}^L T$ denotes the Langlands dual group of T , we want to construct a Hecke eigensheaf, denoted $\mathcal{S}_{\phi_T}$, on the moduli stack Bun_T . We recall that, for a representation $V \in \text{Rep}_\Lambda({}^L G^I)$ of I -copies of the L -group of G for some finite index set I , a Hecke operator is a map defined by the correspondence

$$\begin{array}{ccc} & \text{Hck}_G^I & \\ h^\leftarrow \times \pi \swarrow & & \searrow h^\rightarrow \\ \text{Bun}_G \times \text{Div}^I & & \text{Bun}_G \end{array}$$

where Hck_G^I is the functor that parametrizes, for $S \rightarrow \text{Div}^I$ defining a tuple of Cartier divisors in the relative Fargues-Fontaine X_S over S , corresponding to characteristic 0 untilts $S_i^\sharp$ for $i \in I$ of S , a pair of G -torsors $\mathcal{E}_1, \mathcal{E}_2$ together with an isomorphism

$$\beta : \mathcal{E}_1|_{X_S \setminus \bigcup_{i \in I} S_i^\sharp} \xrightarrow{\cong} \mathcal{E}_2|_{X_S \setminus \bigcup_{i \in I} S_i^\sharp}$$

where $h^\rightarrow((\mathcal{E}_1, \mathcal{E}_2, (S_i^\sharp)_{i \in I})) = \mathcal{E}_1$ and $h^\leftarrow \times \pi((\mathcal{E}_1, \mathcal{E}_2, \beta, (S_i^\sharp)_{i \in I})) = (\mathcal{E}_2, (S_i^\sharp)_{i \in I})$. For an algebraic representation $V \in \text{Rep}_\Lambda({}^L G^I)$, the geometric Satake correspondence of Fargues-Scholze [FS, Chapters VI, IX.2] furnishes a sheaf $\mathcal{S}_V \in \text{D}_\bullet(\text{Hck}, \Lambda)$. Using this, we can define the Hecke operator as

$$T_V : \text{D}_{\text{lis}}(\text{Bun}_G, \Lambda) \rightarrow \text{D}_\bullet(\text{Bun}_G \times \text{Div}^I, \Lambda)$$

$$\mathcal{F} \mapsto (h^\leftarrow \times \pi)_\sharp((h^\rightarrow)^*(\mathcal{F}) \otimes \mathcal{S}_V)$$

where $(h^\leftarrow \times \pi)_\sharp$ is the natural push-forward (we note that with torsion coefficients this can be replaced with usual pushforward using [FS, Proposition VII.5.3] and the properness of $h^\leftarrow \times \pi$ after restricting to the support of $\mathcal{S}_V$). I.e the left adjoint to the restriction functor in the category of solid Λ -sheaves [FS, Proposition VII.3.1]. This induces a functor

$$T_V : \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda) \rightarrow \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)^{BW_{\mathbb{Q}_p}^I}$$

via a version of Drinfeld's Lemma [FS, Theorem I.7.2, Proposition IX.2.1, Corollary IX.2.3]. When $\Lambda = \overline{\mathbb{F}}_\ell$, this is essentially the statement that Λ -valued local systems on Div^I are equivalent to continuous representations of $W_{\mathbb{Q}_p}^I$ on finite projective Λ -modules [FS, Proposition VI.9.2]. In this case, we will freely pass between this perspective of local systems and $W_{\mathbb{Q}_p}^I$ -representations.

With this in hand, we can define what it means for a sheaf on Bun_G to be a Hecke eigensheaf.

Definition 3.1. Given a continuous L -parameter $\phi : W_{\mathbb{Q}_p} \rightarrow {}^L G(\Lambda)$, we say a sheaf $\mathcal{S}_\phi \in \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$ is a Hecke eigensheaf with eigenvalue ϕ if, for all $V \in \mathrm{Rep}_\Lambda({}^L G^I)$ with associated map $r_V : {}^L G^I \rightarrow \mathrm{GL}(V)$, we are given isomorphisms

$$\eta_{V,I} : T_V(\mathcal{S}_\phi) \simeq \mathcal{S}_\phi \boxtimes r_V \circ \phi$$

of sheaves in $\mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)^{BW_{\mathbb{Q}_p}^I}$, that are natural in I and V , and compatible with compositions and exterior tensor products in V . We will similarly say that $\mathcal{S}_\phi$ is a weak eigensheaf with eigenvalue ϕ if we only know the existence of these isomorphisms.

Remark 3.2. We recall that Hecke operators are monoidal and functorial in (V, I) . In particular, given two representations $V, W \in \mathrm{Rep}_\Lambda({}^L G)$, we have a natural isomorphism

$$(T_V \times \mathrm{id})(T_W)(\cdot)|_\Delta \simeq T_{V \otimes W}(\cdot)$$

where $\Delta : \mathrm{Div}^1 \rightarrow (\mathrm{Div}^1)^2$ is the diagonal map. The compatibilities for the isomorphisms $\eta_{V,I}$ are defined with respect to such isomorphisms.

Now let's elucidate what this means for tori. Recall that an irreducible representation of ${}^L T^I$ is parametrized by a tuple of Galois orbits $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I$. Similarly, one has a decomposition

$$\mathrm{Hck}_T^I = \bigcup_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I} \mathrm{Hck}_{T,(\nu_i)_{i \in I}}^I$$

of Hck_T^I into closed substacks, where $\mathrm{Hck}_{T,(\nu_i)_{i \in I}}^I$ parametrizes a modification $\mathcal{E}_1 \dashrightarrow \mathcal{E}_2$ of meromorphism given by the Galois orbit ν_i over the I Cartier divisors in Div^I . If one lets $\mathcal{S}_{(\nu_i)_{i \in I}}$ be the sheaf defined by the representation of ${}^L T^I$ corresponding to $(\nu_i)_{i \in I}$, then this sheaf is simply the constant sheaf supported on the subspace $\mathrm{Hck}_{T,(\nu_i)_{i \in I}}^I$. Therefore, for studying the Hecke operator $T_{(\nu_i)_{i \in I}}$, we can restrict the Hecke correspondence to the diagram:

$$\begin{array}{ccc} & \mathrm{Hck}_{T,(\nu_i)_{i \in I}}^I & \\ \swarrow h_{(\nu_i)_{i \in I}}^\leftarrow \times \pi & & \searrow h_{(\nu_i)_{i \in I}}^\rightarrow \\ \mathrm{Bun}_T \times \mathrm{Div}^I & & \mathrm{Bun}_T \end{array}$$

Let E_{ν_i} denote the reflex field of the Γ -orbit $\nu_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma$. We can consider the following base-change of Div^I :

$$\mathrm{Div}_{E_{(\nu_i)_{i \in I}}}^I := \prod_{i \in I} \mathrm{Div}_{E_{\nu_i}}^1$$

We note that, since a modification of T -bundles is uniquely determined by the locus of meromorphy, we have an isomorphism $\mathrm{Hck}_{T,(\nu_i)_{i \in I}}^I \simeq \mathrm{Bun}_T \times \mathrm{Div}_{E(\nu_i)_{i \in I}}^I$. Under this identification, we have a map

$$h_{(\nu_i)_{i \in I}}^{\rightarrow} : \mathrm{Bun}_T \times \mathrm{Div}_{E(\nu_i)_{i \in I}}^I \rightarrow \mathrm{Bun}_T$$

where, given $(\mathcal{F}_T, (D_i)_{i \in I})$, we denote the resulting T -bundle under applying this map as $\mathcal{F}_T(\sum_{i \in I} -\nu_i D_i)$. We note that the isomorphism class of this bundle is only determined by the image of $\nu_i \Gamma$ in the coinvariant lattice, and this will be important in the next section. The map $h_{(\nu_i)_{i \in I}}^{\leftarrow} \times \pi$ is defined by the natural finite étale morphism $q_{(\nu_i)_{i \in I}} : \mathrm{Div}_{E(\nu_i)_{i \in I}}^I \rightarrow \mathrm{Div}^I$, and pushing forward corresponds to inducing the $\prod_{i \in I} W_{E_{\nu_i}}$ action to $\prod_{i \in I} W_{\mathbb{Q}_p}$.

Now, via local class field theory, there is a character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$ attached to ϕ_T . Moreover, each connected component Bun_T^ν for varying $\nu \in B(T) \simeq \Lambda_{G,B}$ is isomorphic to the classifying stack $[*/T(\mathbb{Q}_p)]$. As a consequence, we may interpret χ as a sheaf on the connected components $j_{\bar{\nu}} : \mathrm{Bun}_T^{\bar{\nu}} \rightarrow \mathrm{Bun}_T$ for $\bar{\nu} \in B(T)$. One might hope that considering

$$\mathcal{S}_{\phi_T} := \bigoplus_{\bar{\nu} \in B(T)} j_{\bar{\nu}}^*(\chi)$$

the sheaf on Bun_T whose restriction to each connected component is equal to χ gives rise to the desired Hecke eigensheaf. This is indeed the case. In particular, via the realization of local class field theory in the torsion of Lubin-Tate formal groups, we have the following proposition.

Proposition 3.3. *[Far16, Section 9.2], [Zou22] The sheaf $\mathcal{S}_{\phi_T}$ is an eigensheaf with eigenvalue ϕ_T . In particular, for all $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\mathbb{Q}_p})/\Gamma)^I$, we have an isomorphism*

$$T_{(\nu_i)_{i \in I}}(\mathcal{S}_{\phi_T}) \simeq \boxtimes_{i \in I} \nu_i \circ \phi_T \otimes \mathcal{S}_{\phi_T}$$

of objects in $\mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_T, \Lambda)^{BW_{\mathbb{Q}_p}^I}$. More precisely, if $\tilde{\nu}_i$ is a representative of the Γ -orbit of ν_i for all $i \in I$, we have an isomorphism

$$(h_{(\nu_i)_{i \in I}}^{\rightarrow})^*(\mathcal{S}_{\phi_T}) \simeq \boxtimes_{i \in I} \tilde{\nu}_i \circ \phi_T|_{W_{E_{\nu_i}}} \otimes \mathcal{S}_{\phi_T}$$

which after applying $q_{(\nu_i)_{i \in I}^*}$ gives rise to the previous identification of induced representations.

A special role will be played by the eigensheaf attached to the parameter

$$2\hat{\rho} \circ |\cdot|^{1/2} : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$$

where $2\hat{\rho}$ denotes the character of ${}^L T(\Lambda)$ defined by the sum of all positive roots with respect to the choice of Borel and $|\cdot| : W_{\mathbb{Q}_p} \rightarrow \Lambda^*$ is the norm character. We note that the value of this sheaf on each connected component is given by the character $\delta_B^{1/2}$, where δ_B denotes the modulus character defined by B . This leads to the following definition.

Definition 3.4. We let $\Delta_B^{1/2}$ be the eigensheaf on Bun_T attached to the parameter

$$2\hat{\rho} \circ |\cdot|^{1/2} : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$$

via Proposition 3.3. Similarly, we write Δ_B for the eigensheaf attached to $2\hat{\rho} \circ |\cdot|$, where the stalks of this sheaf are given by δ_B .

The key point is that (up to shifts) the pullback of this eigensheaf to the moduli stack Bun_B gives rise to a sheaf which we will denote by $\mathrm{IC}_{\mathrm{Bun}_B}$. We will see later that this sheaf is Verdier self-dual on Bun_B and therefore tensoring by it will give rise to the morally correct definition of the Eisenstein functor. We note that, given a parameter ϕ_T with associated eigensheaf $\mathcal{S}_{\phi_T}$, the tensor product $\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2}$ will be the eigensheaf attached to the tensor product $\phi_T \otimes 2\hat{\rho} \circ |\cdot|^{1/2}$ of L -parameters (the L -parameter whose value is equal to the product of the parameters). It therefore follows from Proposition 3.3 that the following is true.

Corollary 3.5. *For all $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma)^I$, we have an isomorphism*

$$T_{(\nu_i)_{i \in I}}(\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2}) \simeq \boxtimes_{i \in I} (\nu_i \circ \phi_T)(\langle \hat{\rho}, \nu_i \Gamma \rangle) \otimes (\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2})$$

of objects in $D_{\text{lis}}(\text{Bun}_T, \Lambda)^{BW_{\mathbb{Q}_p}^I}$.

Now we discuss the various conditions that we will impose on our parameter ϕ_T , as well as discuss their relationship with the irreducibility of principal series through various examples.

3.2. Genericity, Regularity, and the Irreducibility of Principal Series. Consider the functor

$$R\Gamma(W_{\mathbb{Q}_p}, -) : D_{\text{lis}}(\text{Bun}_T, \Lambda)^{BW_{\mathbb{Q}_p}} \rightarrow D_{\text{lis}}(\text{Bun}_T, \Lambda)$$

given by taking continuous cohomology with respect to $W_{\mathbb{Q}_p}$. As we will see later, computing the Eisenstein functor applied to the eigensheaf $\mathcal{S}_{\phi_T}$ will reduce to computing the values of $R\Gamma(W_{\mathbb{Q}_p}, (h_\nu^\leftarrow)^*(\mathcal{S}_{\phi_T}))$ and $R\Gamma(W_{\mathbb{Q}_p}, (h_\nu^\leftarrow)^*(\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2}))$ for $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$. In this note, we will want to restrict to the simplest case where these contributions all vanish. The exact conditions we will need are as follows.

Condition/Definition 3.6. *Given a parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$, we impose the following conditions on ϕ_T in what follows.*

- (1) *For all Γ -orbits $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$ of simple coroots in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$, the Galois cohomology complex $R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$ is trivial.*
- (2) *If χ is the character attached to ϕ_T under local class field theory. We have, that χ is regular, i.e for all $w \in W_G$ non-trivial, we have that*

$$\chi \neq \chi^w$$

If it satisfies (1) then we say ϕ_T is generic. If it satisfies (1)-(2) we say that ϕ_T is generic regular.

These conditions are related to the irreducibility of the induction $i_B^G(\chi)$. To explain this, let's translate all these conditions to the character χ . Let $E/\mathbb{Q}_p$ denote the splitting field of G . Then the action of $W_{\mathbb{Q}_p}$ on $\hat{G}$ factors through $W_{\mathbb{Q}_p}/W_E$. Given $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma$ a Γ -orbit of coroots with reflex field E_α , local class field theory [Lan97] gives us a map

$$E_\alpha^* \rightarrow T(E_\alpha)$$

attached to $\tilde{\alpha} \circ \phi_T|_{W_{E_\alpha}}$, for a representative $\tilde{\alpha}$ in the Γ -orbit of α . If we post-compose with the norm map $\text{Nm}_{E_\alpha/\mathbb{Q}_p}$ then we get a map

$$E_\alpha^* \rightarrow T(\mathbb{Q}_p)$$

which only depends on the Galois orbit α . We further precompose with the norm map $\text{Nm}_{E/E_\alpha} : E^* \rightarrow E_\alpha^*$, giving a character:

$$E^* \rightarrow T(\mathbb{Q}_p)$$

We write $\chi_\alpha : E^* \rightarrow \Lambda^*$ for the precomposition of χ with this map. Now, consider the complex $R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$, where ϕ_T is the parameter attached to χ . It follows by Schapiro's lemma that we have an isomorphism:

$$R\Gamma(W_{E_\alpha}, \tilde{\alpha} \circ \phi_T|_{W_{E_\alpha}}) \simeq R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T).$$

Moreover, under our assumption that ℓ is very decent with respect to G , we have that $\ell \nmid [E : E_\alpha]$. In particular, by consideration of the corestriction and restriction sequence, we see that the vanishing of $R\Gamma(W_{E_\alpha}, \tilde{\alpha} \circ \phi_T|_{W_{E_\alpha}})$ is equivalent to the vanishing of $R\Gamma(W_E, \tilde{\alpha} \circ \phi_T|_{W_E})$. By local Tate-duality and the fact that the Euler-Poincaré characteristic of this complex is 0, we note that the vanishing of $R\Gamma(W_E, \tilde{\alpha} \circ \phi_T|_{W_E})$ is the same as saying that $\tilde{\alpha} \circ \phi_T|_{W_E}$ is not isomorphic to the trivial or cyclotomic character. Using this, we can see that the above conditions on ϕ_T are equivalent to the following conditions on χ .

Condition/Definition 3.7. *Given a smooth character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$ consider the following conditions on χ .*

- (1) *For all Γ -orbits $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma$ of positive coroots in $\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})$, the character χ_α is not isomorphic to the trivial representation $\mathbf{1}$ or $|\cdot|_E^{\pm 1}$, where $|\cdot|_E$ is the norm character on E the splitting field of G .*
- (2) *We have that χ is regular, i.e for all $w \in W_G$ non-trivial, we have that*

$$\chi \neq \chi^w.$$

We say that χ is generic if (1) holds, and that it is generic regular if (1)-(2) hold.

We now illustrate how this condition is related to irreducibility of $i_B^G(\chi)$ in some examples. We will assume that $\Lambda = \overline{\mathbb{Q}_\ell}$ in all of the examples for simplicity.

Example 3.8. ($G = \mathrm{GL}_n$) We can write $\chi := \chi_1 \otimes \chi_2$ for $\chi_i : \mathbb{Q}_p^* \rightarrow \overline{\mathbb{Q}_\ell}^*$ smooth characters and $i = 1, 2$. We see that χ being generic implies that $\chi_1 \chi_2^{-1} \neq \mathbf{1}$ and $\chi_1 \chi_2^{-1} \neq |\cdot|_E^{\pm 1}$, and this latter condition guarantees that the normalized parabolic induction $i_B^{\mathrm{GL}_2}(\chi_1 \otimes \chi_2)$ is irreducible. Let's also look at Condition (2) in this case. Suppose it fails, then we have an isomorphism:

$$\chi_1(t_1) \chi_2(t_2) \simeq \chi_1(t_2) \chi_2(t_1)$$

Evaluating at $(t_1, t_2) = (t, 1)$ this would imply that $\chi_1 \chi_2^{-1} \simeq \mathbf{1}$, which would contradict χ being generic.

In particular, we see that χ being generic is enough to guarantee irreducibility and regularity for GL_2 and similarly for GL_n .

In general, genericity does not always imply regularity. In particular, Condition 3.6 (2) seems to be related to the irreducibility of some unitary principal series representations.

Example 3.9. ($G = \mathrm{SL}_2$) In this case, $\chi : \mathbb{Q}_p^* \rightarrow \overline{\mathbb{Q}_\ell}^*$ is a character of $\mathbb{Q}_p^*$. The induction $i_B^G(\chi)$ will be irreducible if and only if $\chi \neq |\cdot|_E^{\pm 1}$ and $\chi^2 \neq \mathbf{1}$. The condition that $\chi \neq |\cdot|_E^{\pm 1}$ is guaranteed by χ being generic but the condition $\chi^2 \neq \mathbf{1}$ is not. However, we note that χ being regular enforces the additional condition that $\chi^2 \neq \mathbf{1}$ guaranteeing irreducibility in this case.

We now come to the last condition on our parameter ϕ_T . In particular, the exact condition we will need is as follows.

Definition 3.10. For a toral parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ and a geometric dominant cocharacter μ , we say ϕ_T is strongly μ -regular if the Galois cohomology complexes

$$R\Gamma(W_{\mathbb{Q}_p}, (\nu - \nu')^\Gamma \circ \phi_T)$$

are trivial for ν, ν' distinct weights of the highest weight representation of $\hat{G}$ of highest weight μ_k for all $k = 1, \dots, n$.

To give some flavor for this condition, we prove the following Proposition.

Lemma 3.11. *Suppose that $G = \mathrm{GL}_n$ and let $\mu = (1, \dots, 0)$ denote the standard character then strong μ -regularity is implied by generic.*

Proof. We note that since μ is minuscule the standard representation V_μ has weights given by Weyl group orbits of the highest weight. From here, it easily follows that the difference of distinct weights of V_μ in $\hat{T}$ are given by coroots of G and the claim follows. $\square$

As mentioned in the introduction, weak normalized regularity and μ -regularity for a geometric dominant cocharacter which isn't fixed under any element of W_G , will imply the existence of isomorphisms $i_{\chi, w} : i_B^G(\chi) \xrightarrow{\sim} i_B^G(\chi^w)$ for all $w \in W_G$ once the theory of geometric Eisenstein series has been developed. Similarly, we will show the following.

Proposition 3.12. (*Proposition A.2*) If $\chi : T(\mathbb{Q}_p) \rightarrow \overline{\mathbb{Q}_\ell}^*$ is a generic character then, for all $w \in W_G$, we have an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^w)$.

In fact, for regular characters χ , the existence of such isomorphisms is equivalent to irreducibility. More generally, we show that such isomorphisms exist assuming χ is generic (Proposition A.2), but this does not guarantee irreducibility of certain unitary principal series as seen when $G = \mathrm{SL}_2$. This only follows from generic regularity.

Using the Langlands classification, the proof of this proposition will essentially reduce to a calculation of reducibility points in rank 1, where it reduces to Example 3.9 and the following example, which illustrates the behavior of our conditions in the non-split case.

Example 3.13. ($G = \mathrm{U}_3/E$) Let $E/\mathbb{Q}_p$ be a quadratic extension. We write $\overline{(-)}$ for the non-trivial automorphism of E over $\mathbb{Q}_p$. If e_1, e_2, e_3 is the standard basis for the cocharacter lattice $\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})$ then $\overline{(-)}$ acts by

$$e_1 \longleftrightarrow -e_3$$

$$e_2 \longleftrightarrow -e_2$$

It follows that the simple coroot $\alpha_1 := e_1 - e_2$ is sent to the simple coroot $\alpha_2 := e_2 - e_3$ under $\overline{(-)}$. Thus, the Γ -orbits of positive coroots in $\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})$ are given by $\{\alpha_1, \alpha_2\}$ with reflex field E and $\alpha_1 + \alpha_2$ with reflex field $\mathbb{Q}_p$. Now recall that the maximal torus $T(\mathbb{Q}_p) \subset \mathrm{U}_3(\mathbb{Q}_p)$ is isomorphic to $E^* \times E^1$, via the embedding

$$\begin{aligned} E^* \times E^1 &\rightarrow \mathrm{U}_3(\mathbb{Q}_p) \\ t &\mapsto \begin{pmatrix} t & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & \bar{t}^{-1} \end{pmatrix} \end{aligned}$$

where E^1 denotes the set of norm 1 elements. Then if we write the character $\chi(t, s) : E^* \times E^1 \rightarrow \Lambda^*$ as $\chi(t, s) = \chi_1(t)\chi_2(ts\bar{t}^{-1})$ the reducibility of $i_B^G(\chi)$ depends solely on χ_1 , as in [Rog90, Page 173], where here it reduces to the analogous question for SU_3 , and there the reducibility points were studied in [Key84, Section 7]. The induction $i_B^G(\chi)$ is reducible if and only if one of the following hold:

- (1) $\chi_1 = \eta| \cdot |_E^{\pm 1/2}$, where $\eta|_{\mathbb{Q}_p^*} = \eta_{E/\mathbb{Q}_p}$,
- (2) $\chi_1 = | \cdot |_E^{\pm 1}$,
- (3) $\chi_1|_{\mathbb{Q}_p^*}$ is trivial, but χ is not.

Here $| \cdot |_E$ is the norm character of E which is in particular the splitting field of G , and $\eta_{E/\mathbb{Q}_p} : \mathbb{Q}_p^* \rightarrow \Lambda^*$ is the unique quadratic character with kernel given by $\mathrm{Nm}_{E/\mathbb{Q}_p}(E^*)$. We note that the cocharacters of $T(\mathbb{Q}_p)$ given by the Γ -orbits of positive roots are

$$\begin{aligned} \{\alpha_1, \alpha_2\} : E^* &\rightarrow T(\mathbb{Q}_p) = E^* \times E^1 \\ t &\mapsto (t, t^{-1}\bar{t}) \end{aligned}$$

and

$$\begin{aligned} \{\alpha_1 + \alpha_2\} : E^* &\rightarrow E^* \times E^1 \\ t &\mapsto (\mathrm{Nm}_{E/\mathbb{Q}_p}(t), 1) \end{aligned}$$

By precomposing χ with the first character, we see that χ being generic implies $\chi_1 \not\equiv \mathbf{1}$ and $\chi_1 \not\equiv | \cdot |_E^{\pm 1}$, which implies reducibility point (2) cannot occur. By precomposing χ with the second character, we see that χ being generic implies that $\chi(\mathrm{Nm}_{E/\mathbb{Q}_p}(t)) \simeq \chi_1(\mathrm{Nm}_{E/\mathbb{Q}_p}(t)) \not\equiv \mathbf{1}$ and $\chi_1(\mathrm{Nm}_{E/\mathbb{Q}_p}(t)) \not\equiv |t|_E^{\pm 1}$. Note that if $\chi \simeq \eta| \cdot |_E^{\pm 1/2}$ then we have, for all $t \in E^*$, an isomorphism:

$$\chi(\mathrm{Nm}_{E/\mathbb{Q}_p}(t)) = \chi_1(t\bar{t}) \simeq \eta(\mathrm{Nm}_{E/\mathbb{Q}_p}(t))|\mathrm{Nm}_{E/\mathbb{Q}_p}(t)|_E^{\pm 1/2} \simeq |t|_E^{\pm 1}$$

Summarizing, we see again that χ being generic guarantees irreducibility of the two non-unitary inductions. Now, if $\chi|_{\mathbb{Q}_p^*}$ is trivial then we have that

$$\chi(\mathrm{Nm}_{E/\mathbb{Q}_p}(t)) = \chi_1(t\bar{t}) \simeq \mathbf{1}$$

Thus, we see χ being generic guarantees the irreducibility of all principal series. Moreover, χ being generic regular enforces the additional constraint that

$$\chi(t\bar{t}) \not\simeq \mathbf{1}$$

which we just saw follows from χ being generic, so regularity follows from generic in this case.

The connection between genericity and irreducibility of non-unitary principal series fits in nicely with the general Langlands philosophy. In particular, since we are inducing from a Borel, we expect that a parameter should have monodromy if it arises as a constituent of the reducible induction of a non-unitary character. We saw in the above examples that this shouldn't occur when the parameter ϕ_T attached to χ is generic. We can analyze when a parameter comes from the semi-simplification of a parameter with non-trivial monodromy and relate this to genericity.

Lemma 3.14. *We let $\phi : \mathcal{L}_{\mathbb{Q}_p} \rightarrow {}^L G(\overline{\mathbb{Q}_\ell})$ be an L -parameter (not necessarily Frobenius semi-simple). Suppose that $\phi : \mathcal{L}_{\mathbb{Q}_p} \rightarrow {}^L G(\overline{\mathbb{Q}_\ell})$ has non-trivial monodromy, and that the semi-simplification ϕ^{ss} (See Assumption 6.5) factors through ${}^L T \rightarrow {}^L G$ via the natural embedding. If we write $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}_\ell})$ for the parameter induced by ϕ^{ss} then ϕ_T is not generic.*

Proof. If ϕ has non-trivial monodromy and the semi-simplification factors through ${}^L T$, there exists a lift

$$\begin{array}{ccc} & & {}^L B(\overline{\mathbb{Q}_\ell}) \\ & \nearrow \tilde{\phi} & \downarrow \\ W_{\mathbb{Q}_p} & \xrightarrow{\phi_T} & {}^L T(\overline{\mathbb{Q}_\ell}) \end{array}$$

of ϕ_T , which is not given by the inclusion ${}^L T(\overline{\mathbb{Q}_\ell}) \rightarrow {}^L B(\overline{\mathbb{Q}_\ell})$. Such an extension implies that there exists a non-trivial class in $R\Gamma(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$, which would in turn imply ϕ_T is not generic. $\square$

We finish this section by describing the Hecke eigensheaf property on symmetric powers of the curve for the sheaf $\mathcal{S}_{\phi_T}$ attached to a parameter ϕ_T .

3.3. The Symmetrized Hecke Eigensheaf Property. We let $\bar{\nu}$ be an element of $\Lambda_{G,B}^{\mathrm{pos}} \setminus \{0\}$. We can write this as a linear combination $\sum_{i \in \mathcal{J}} n_i \alpha_i$ for positive integers n_i , where the α_i correspond to the Galois orbits of simple absolute roots as in Definition 2.14. Given such an α_i , we can consider the reflex field E_i of the associated Galois orbit, and define the following partially symmetrized curve:

$$\mathrm{Div}^{(\bar{\nu})} := \prod_{i \in \mathcal{J}} \mathrm{Div}_{E_i}^{(n_i)}.$$

Points of this curve correspond to tuples of Cartier divisors D_i over E_i of degree n_i for all $i \in \mathcal{J}$. We can consider the map

$$h_{(\bar{\nu})}^{\rightarrow} : \mathrm{Bun}_T \times \mathrm{Div}^{(\bar{\nu})} \rightarrow \mathrm{Bun}_T$$

given by sending $(\mathcal{F}_T, (D_i)_{i \in \mathcal{J}})$ to $\mathcal{F}_T(\sum_{i \in \mathcal{J}} -\alpha_i \cdot D_i)$, where we are identifying α_i with its corresponding Γ -orbit.

This partially symmetrized mirror curve $\mathrm{Div}^{(\bar{\nu})}$ behaves a bit strangely if G is not split. To illustrate this, consider the following example.

Example 3.15. Let $G = \mathrm{U}_3$ be a unitary group in 3 variables attached to a quadratic extension $E/\mathbb{Q}_p$ and write α_1 and α_2 for the two absolute positive simple roots. We recall, as in Example 3.13, that the Galois group exchanges α_1 and α_2 . Therefore, they both map to a unique element $\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma$ which spans the lattice $\Lambda_{G,B}^{pos}$ by Definition. Consider the element $\bar{\nu} := 2\alpha \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma$.

We note that we have an equality $\mathrm{Div}^{(\bar{\nu})} = \mathrm{Div}_E^{(2)}$ in this case. The pre-image of 2α under the natural map $(-)_\Gamma : \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma \rightarrow \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma$ consists of two elements: the Γ -orbit $\{2\alpha_1, 2\alpha_2\}$ with reflex field E and the Γ -orbit of $\{\alpha_1 + \alpha_2\}$ with reflex field $\mathbb{Q}_p$. We saw in the previous section that the space of modifications defined by the Γ -orbit $\{2\alpha_1, 2\alpha_2\}$ is given by $\mathrm{Bun}_T \times \mathrm{Div}_E^1$, correspondingly we have a natural map

$$\Delta_{\{2\alpha_1, 2\alpha_2\}} : \mathrm{Div}_E^1 \xrightarrow{\Delta} \mathrm{Div}_E^2 \rightarrow \mathrm{Div}_E^{(2)}$$

given by the diagonal embedding composed with the quotient map. It is easy to check we have an equality $h_{\{2\alpha_1, 2\alpha_2\}}^\rightarrow(-) = h_{\bar{\nu}}^\rightarrow \circ (\mathrm{id} \times \Delta_{\{2\alpha_1, 2\alpha_2\}})$. Perhaps more interestingly, attached to the Γ -orbit $\{\alpha_1 + \alpha_2\}$, we have a twisted diagonal map

$$\Delta_{\{\alpha_1 + \alpha_2\}} : \mathrm{Div}_{\mathbb{Q}_p}^1 \rightarrow \mathrm{Div}_E^{(2)}$$

given by sending a Cartier divisor D to its pre-image under the natural finite-étale covering $X_{S,E} \rightarrow X_S$ of Fargues-Fontaine curves induced by the extension $E/\mathbb{Q}_p$. By [Li-22, Proposition 1.5], this map defines a closed embedding whose image lies in the complement of the image of $\Delta_{\{2\alpha_1, 2\alpha_2\}}$ in $\mathrm{Div}_E^{(2)}$, and we similarly see that we have a relationship $h_{(\bar{\nu})}^\rightarrow \circ (\mathrm{id} \times \Delta_{\{\alpha_1 + \alpha_2\}})(-) = h_{\{\alpha_1 + \alpha_2\}}^\rightarrow(-)$.

The previous example illustrates that we can understand $\mathrm{Bun}_T \times \mathrm{Div}^{(\bar{\nu})}$ as realizing the set of all modifications specified by Galois orbits $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma$ such that $\nu_\Gamma = \bar{\nu}$. This is indeed a general phenomenon. In particular, using that Γ permutes the simple absolute coroots of G , given any such ν with reflex field E_ν , we can define a twisted diagonal embedding

$$\Delta_\nu : \mathrm{Div}_{E_\nu}^1 \rightarrow \mathrm{Div}^{(\bar{\nu})}$$

such that we have a relationship $h_\nu^\rightarrow(-) := h_{\bar{\nu}}^\rightarrow \circ (\mathrm{id} \times \Delta_\nu)(-)$.

If $\bar{\nu} = \alpha_i$ for $i \in \mathcal{J}$ the map Δ_ν is an isomorphism for the unique Γ -orbit of simple coroots corresponding to α_i . Therefore, the pullback of $\mathcal{S}_{\phi_T}$ along $h_{(\bar{\nu})}^\leftarrow$ is isomorphic to $\mathcal{S}_{\phi_T} \boxtimes \tilde{\alpha}_i \circ \phi_T$ for a choice of representative $\tilde{\alpha}_i$ of the Γ -orbit corresponding to α_i . In general, recall that given a local system $\mathbb{L}$ and n a positive integer, we can consider the symmetric powers

$$\mathbb{L}^{(n)} := \pi_*(\boxtimes_{i=1}^n \mathbb{L})^{S_n}$$

where π denotes the push-forward along the S_n -torsor:

$$\pi : (\mathrm{Div}^1)^n \rightarrow \mathrm{Div}^{(n)}$$

Using this, we can define a local system on $\mathrm{Div}^{(\bar{\nu})}$ given by

$$E_{\phi_T}^{(\bar{\nu})} := \boxtimes_{i \in \mathcal{J}} E_{\phi_i}^{(n_i)}$$

where ϕ_i is the local system on $\mathrm{Div}_{E_i}^1$ corresponding to the character $\tilde{\alpha}_i \circ \phi_T|_{W_{E_i}}$ of W_{E_i} for E_i the reflex field of the Galois orbit corresponding to α_i . With this in hand, we can describe the pullback of $\mathcal{S}_{\phi_T}$ along $h_{(\bar{\nu})}^\leftarrow$ as the sheaf $E_{\phi_T}^{(\bar{\nu})} \boxtimes \mathcal{S}_{\phi_T}$ by using that Hecke operators are monoidal, and the natural compatibilities of the eigensheaf.

We will now review the next ingredient in our calculations of geometric Eisenstein series, the Geometric Satake correspondence.

4. GEOMETRIC SATAKE AND THE AFFINE GRASSMANNIAN

4.1. The Geometric Satake Correspondence. We will now recall some facts about the geometric Satake correspondence for the B_{dR}^+ Grassmannian, as proven in [FS, Chapter VI]. For any finite set I , we consider the local Hecke stack

$$\pi_G : \mathcal{Hck}_G^I \rightarrow \mathrm{Div}^I$$

For a point $S \rightarrow \mathrm{Div}^I$, we can consider the completion of the structure sheaf $\mathcal{O}_{X_S}$ at the union of the I Cartier divisors in X_S defined by S . This defines a ring which we denote by B^+ , and inverting D , we get a ring which we denote by B . The mapping sending $S \in \mathrm{Div}^I$ to $G(B^+)$ and $G(B)$ defines étale sheaves on Perf , which we denote by $L_{\mathrm{Div}^I}^+ G$ and $L_{\mathrm{Div}^I} G$, respectively. We note that, for $I = \{*\}$ and $S = \mathrm{Spa}(F, \mathcal{O}_F) \rightarrow \mathrm{Div}^I$ a geometric point with associated untilt $(C, \mathcal{O}_C)$, we have $B^+ = B_{dR}^+(C, \mathcal{O}_C)$ and $B = B_{dR}(C, \mathcal{O}_C)$, the usual de-Rham period rings attached to the untilt. For simplicity, we will often just drop the subscript Div^I and just write $L^+ G$ and LG for these étale sheaves. By [SW20, Proposition 19.1.2], the Hecke stack can be described as the quotient:

$$[L^+ G \backslash LG / L^+ G] \rightarrow \mathrm{Div}^I$$

In other words, for $S \in \mathrm{Perf}$ mapping to Div^I , $\mathcal{Hck}_G^I$ will parameterize a pair of G -bundles over the formal completion of the tuple of divisors $D_{S,i}$ defined by the map $S \rightarrow \mathrm{Div}^I$ together with a trivialization away from the $D_{S,i}$. It follows that this has a map to the global Hecke stack considered in §3, by restricting to formal completions. Later on in the paper, we will use the analogous notations introduced here for the local Hecke stack to denote their pullback to the global Hecke stack $\mathcal{Hck}_G$ along this map.

To study this, we can uniformize this by the quotient

$$\mathrm{Gr}_G^I := LG / L^+ G \rightarrow \mathrm{Div}^I$$

which is the Fargues-Fontaine analogue of the Beilinson-Drinfeld Grassmannian. Using Beauville-Laszlo [SW20, Lemma 5.29], this can be interpreted as parameterizing modifications $\mathcal{F}_G \dashrightarrow \mathcal{F}_G^0$ over X_S away from the tuple of Cartier divisors defined by the projection to Div^I . It follows by the results of [SW20, Lecture XX] that the Beilinson-Drinfeld Grassmannian is a well-behaved geometric object; it can be written as a closed union of subsheaves that are proper and representable in spatial diamonds over Div^I , given by bounding the meromorphy of the modifications. We can consider the category

$$\mathrm{D}(\mathcal{Hck}_G^I)^{bd}$$

of objects with support in one of the aforementioned quasi-compact subsets. This carries a monoidal structure coming from the diagram:

$$\mathcal{Hck}_G^I \times_{\mathrm{Div}^I} \mathcal{Hck}_G^I \xleftarrow{(p_1, p_2)} L^+ G \backslash LG \times^{L^+ G} LG / L^+ G \xrightarrow{m} \mathcal{Hck}_G^I$$

Here the middle space can be interpreted as parameterizing a pair of G -bundles $\mathcal{E}_1, \mathcal{E}_2$ together with a pair of modifications $\beta_1 : \mathcal{E}_1 \dashrightarrow \mathcal{E}_0$ and $\beta_2 : \mathcal{E}_0 \dashrightarrow \mathcal{E}_2$ to/from the trivial bundle with the same locus of meromorphy. The maps p_i are the natural projections remembering only the data $(\mathcal{E}_i, \beta_i)$ for $i = 1, 2$, and m is defined by sending $(\mathcal{E}_i, \beta_i)_{i=1,2}$ to $\beta_2 \circ \beta_1 : \mathcal{E}_1 \dashrightarrow \mathcal{E}_2$. Given $A, B \in \mathrm{D}(\mathcal{Hck}_G^I)^{bd}$, we define

$$A \star B := Rm_*(p_1^*(A) \otimes p_2^*(B)) \in \mathrm{D}(\mathcal{Hck}_G^I)^{bd}$$

the convolution of A and B [FS, Section VI.8]. Since the map m is a fibration in Gr_G^I it is proper over any quasi-compact subset, so by proper base-change it gives a well-defined associative monoidal structure. One can further refine our category of sheaves as follows. In particular, we note that the locus of $\mathcal{Hck}_G^I$ where the meromorphy is equal to the Galois orbit of $\mu_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ at the i th Cartier divisor for $i \in I$ is uniformized by a cohomologically smooth diamond of relative dimension

$\sum_{i \in I} \langle 2\hat{\rho}, \mu_i \rangle$ over Div^I by [FS, Proposition VI.2.4]. One can check that this gives rise to a well-defined perverse t -structure on $D(\mathcal{Hck}_G^I)^{bd}$ over Div^I given by insisting that $!$ -restriction (resp. $*$ -restriction) to these strata sit in cohomological degrees $\geq$ (resp. $\leq$) $-\sum_{i \in I} \langle 2\hat{\rho}, \mu_i \rangle$, and that convolution preserves perversity [FS, Proposition VI.8.1]. With this in hand, we arrive at the key definition.

Definition 4.1. [FS, Definition I.6.2] We define the Satake category

$$\text{Sat}_G^I \subset D(\mathcal{Hck}_G^I)^{bd}$$

as the category of all $A \in D(\mathcal{Hck}_G^I)^{bd}$ which are perverse, flat (i.e for all Λ -modules M $A \otimes M$ is also perverse), and ULA over Div^I , as defined in [FS, Chapter V.7].

The ULA and flatness property in the above definition has the key consequence that the pullback of $A \in \text{Sat}_G^I$ to Gr_G^I composed with the push-forward to Div^I has cohomology sheaves valued in Λ -valued local systems on Div^I . In particular, using an analogue of Drinfeld's lemma [FS, Proposition VI.9.2], this gives rise to a fiber functor

$$F_G^I : \text{Sat}_G^I \rightarrow \text{Rep}_{W_{\mathbb{Q}_p}^I}(\Lambda)$$

$$A \mapsto \bigoplus_i \mathcal{H}^i(R\pi_{G*}(A))$$

where $\text{Rep}_{W_{\mathbb{Q}_p}^I}(\Lambda)$ denotes the category of continuous representations of $W_{\mathbb{Q}_p}^I$ on finite projective Λ -modules, and $R\pi_{G*}$ is the functor given by pulling back to Gr_G^I and taking the push-forward to Div^I , as in [FS, Definition/Proposition VI.7.10]. Now, by using the factorization structure on these Grassmannians, one can also construct an analogue of the fusion product [FS, Section VI.9]. Let us recall its construction. We consider a partition $I = I_1 \sqcup \dots \sqcup I_k$ of this index set. We consider the open subspace

$$\text{Div}^{I; I_1, \dots, I_k} \subset \text{Div}^I$$

parameterizing a tuple of Cartier divisors $(D_i)_{i \in I}$ such that D_i and $D_{i'}$ are disjoint whenever $i, i' \in I = I_1 \sqcup \dots \sqcup I_k$ lie in different I_j s, and let $\mathcal{Hck}_G^{I; I_1, \dots, I_k}$ be the base-change of $\mathcal{Hck}_G^I$ to this open subspace. We can define the subcategory $\text{Sat}_G^{I; I_1, \dots, I_k} \subset D(\mathcal{Hck}_G^{I; I_1, \dots, I_k})^{bd}$ in an analogous manner to Definition 4.1. We have a natural restriction map

$$\text{Sat}_G^I \rightarrow \text{Sat}_G^{I; I_1, \dots, I_k}$$

which, by [FS, Proposition VI.9.3], defines a fully faithful embedding. There is also an identification

$$\mathcal{Hck}_G^I \times_{\text{Div}^I} \text{Div}^{I; I_1, \dots, I_k} \simeq \prod_{j=1}^k \mathcal{Hck}_G^{I_j} \times_{\prod_j \text{Div}^{I_j}} \text{Div}^{I; I_1, \dots, I_k}$$

giving a natural map

$$\text{Sat}_G^{I_1} \times \dots \times \text{Sat}_G^{I_k} \rightarrow \text{Sat}_G^{I; I_1, \dots, I_k}$$

via taking exterior products. Then, by [FS, Definition/Proposition VI.9.4], this lies in the full subcategory Sat_G^I , and the resulting map

$$\text{Sat}_G^{I_1} \times \dots \times \text{Sat}_G^{I_k} \rightarrow \text{Sat}_G^I$$

is called the fusion product. Now consider the composite

$$\text{Sat}_G^I \times \text{Sat}_G^I \rightarrow \text{Sat}_G^{I \sqcup I} \rightarrow \text{Sat}_G^I$$

where the first map is the fusion product, and the last map is given by restricting along the diagonal embedding $\mathcal{Hck}^I \rightarrow \mathcal{Hck}^{I \sqcup I}$. Then this is naturally isomorphic to the convolution product. By this comparison between fusion and convolution, one can deduce that the convolution product is in fact

symmetric monoidal, and that the functor F_G^I takes this monoidal structure to the usual tensor product on $\text{Rep}_{W_{\mathbb{Q}_p}^I}(\Lambda)$. Now, using Tannakian duality, one deduces the following.

Theorem 4.2. *[FS, Theorem I.6.3] For a finite index set I , the category Sat_G^I is naturally in I identified with $\text{Rep}_\Lambda(^L G^I)$ the category of representations of ${}^L G^I$ on finite projective Λ -modules.*

Remark 4.3. One needs to be a bit careful here. In particular, ${}^L G$ as defined here differs from the usual definition of the L -group; namely, the usual action of $W_{\mathbb{Q}_p}$ on $\hat{G}$ is twisted by a cyclotomic character (See [FS, Section VI.11] for more details).

One of the key points that also plays an important role in the proof of this theorem is that this construction respects the natural map

$$\text{res}_T^{I,G} : \text{Rep}_\Lambda(^L G^I) \rightarrow \text{Rep}_\Lambda(^L T^I)$$

given by restricting a representation of ${}^L G^I$ to ${}^L T^I$ along the natural embedding:

$${}^L T^I \rightarrow {}^L G^I$$

To explain this, we need to explain how this functor is realized in the geometry of Beilinson-Drinfeld Grassmannians. First note that, as in §3, we have an identification

$$\text{Gr}_T^I = \bigcup_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I} \text{Gr}_{T,(\nu_i)_{i \in I}}^I \simeq \bigcup_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I} \text{Div}_{E(\nu_i)_{i \in I}}^I$$

into closed subspaces, where $\text{Gr}_{T,(\nu_i)_{i \in I}}$ parametrizes modifications of T -bundles with meromorphy equal to the Galois orbit defined by ν_i at a Cartier divisor D_i for all $i \in I$, and $\text{Div}^I := \prod_{i \in I} \text{Div}_{E_{\nu_i}}^1$, where E_{ν_i} denotes the reflex field of ν_i . In particular, we see that Theorem 4.2 is trivial in this case, as F_T^I will induce an equivalence between Sat_T^I and $(\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I$ -graded objects in $\text{Rep}_\Lambda(W_{\mathbb{Q}_p}^I)$ under this isomorphism. We consider the diagram

$$\begin{array}{ccc} & \text{Gr}_B^I & \\ p \swarrow & & \searrow q \\ \text{Gr}_T^I & & \text{Gr}_G^I \end{array}$$

and define the functor:

$$p_! q^* : D(\text{Gr}_G^I)^{bd} \rightarrow D(\text{Gr}_T^I)^{bd}$$

As we will discuss further in the next section, the fibers of the morphism p over the connected components $\text{Gr}_{T,(\nu_i)_{i \in I}}^I$ give rise to a locally closed stratification of Gr_G^I which embed via the morphism q (cf. [FS, Example VI.3.4]). These are the so called semi-infinite Schubert cells. If one considers $\mathbb{G}_m$ acting on Gr_G^I via a suitably chosen cocharacter μ composed with the $L^+ G$ action on Gr_G^I then one can identify these semi-infinite cells with a union $\mathbb{G}_m$ -orbits (the attractor of the $\mathbb{G}_m$ -action), and the fixed points will be precisely the closed subspaces components:

$$\text{Gr}_T^I = \bigcup_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})/\Gamma)^I} \text{Gr}_{T,(\nu_i)_{i \in I}}^I$$

This allows one to apply a diamond analogue [FS, Theorem IV.6.5] of Braden's hyperbolic localization theorem [Bra03]. In particular, since sheaves in Sat_G^I pullback to $L^+ G$ -equivariant sheaves on Gr_G^I , they will be $\mathbb{G}_m$ -equivariant. From this, one can deduce that $p_! q^*$ is a hyperbolic localization

with respect to this $\mathbb{G}_m$ -action and will therefore preserve perverse, flat, and ULA objects over Div^I . We therefore get an induced functor

$$\text{CT} : \text{Sat}_G^I \rightarrow \text{Sat}_T^I$$

called the constant term functor, as in [FS, Proposition VI.7.13]. We now consider the following function

$$\deg : |\text{Gr}_T^I| \rightarrow \mathbb{Z}$$

which has value $\langle 2\hat{\rho}, |(\nu_i)_{i \in I}| \rangle$ on the connected component indexed by $(\nu_i)_{i \in I}$, where $|(\nu_i)_{i \in I}| := \sum_{i \in I} \bar{\nu}_i \Gamma \in \Lambda_{G,B}$. Now, by applying excision with respect to the stratification by semi-infinite cells one can show that, for all $A \in \text{Sat}_G$, one has an isomorphism $\bigoplus_i \mathcal{H}^i(\pi_{G*}(A)) \simeq \mathcal{H}^0(\pi_{T*}(\text{CT}(A)[\deg]))$ (See the proof of [FS, Proposition VI.7.10]). This in particular gives us the following Proposition.

Proposition 4.4. *For all finite index sets I , there exists a commutative diagram*

$$\begin{array}{ccc} \text{Sat}_G^I & \xrightarrow{\text{CT}[\deg]} & \text{Sat}_T^I \\ \downarrow F_G^I & & \downarrow F_T^I \\ \text{Rep}_\Lambda({}^L G^I) & \xrightarrow{\text{res}_T^{I,G}} & \text{Rep}_\Lambda({}^L T^I) \end{array}$$

where here F_G^I (resp. F_T^I) is the equivalence given by Theorem 4.2 for G (resp. T).

Moreover, it follows by [FS, Proposition VI.9.6], that the fusion product respects the constant term functors.

Proposition 4.5. *For all finite index sets I , with a partition $I_1 \sqcup \dots \sqcup I_k$, we have a commutative diagram*

$$\begin{array}{ccc} \text{Sat}_G^{I_1} \times \dots \times \text{Sat}_G^{I_k} & \longrightarrow & \text{Sat}_G^I \\ \downarrow \text{CT}^{I_1}[\deg] \times \dots \times \text{CT}^{I_k}[\deg] & & \downarrow \text{CT}^I[\deg] \\ \text{Sat}_T^{I_1} \times \dots \times \text{Sat}_T^{I_k} & \longrightarrow & \text{Sat}_T^I \end{array}$$

which commutes functorially in I , where the top (resp. bottom) vertical arrow is given by the fusion product for G (resp. T).

We now turn our attention to the semi-infinite cells.

4.2. The Cohomology of Semi-Infinite Cells. Theorem 4.2, Proposition 4.4, and Proposition 4.5 have implications for the cohomology of spaces related to moduli spaces of B -structures. We will record this now. We let $E/\mathbb{Q}_p$ be the splitting field of G . Then we have an identification $\text{Gr}_{G,E}^I \simeq \text{Gr}_{G_E}^I$ over the base change Div_E^I of Div^I to E . Sheaves on this space will be equivalent algebraic representations of I copies of the dual group $\hat{G}$. First, we recall that we have the following natural stratification of $\text{Gr}_{G,E}^I$.

Definition 4.6. For $(\lambda_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$, we let $\text{Gr}_{G,(\lambda_i)_{i \in I},E}^I$ (resp. $\text{Gr}_{G,\leq(\lambda_i)_{i \in I},E}^I$) be the locally closed (resp. closed) subfunctor of Gr_G parameterizing modifications

$$\mathcal{F}_G^0 \rightarrow \mathcal{F}_G$$

between the trivial G -bundle $\mathcal{F}_G^0$ and a G -bundle $\mathcal{F}_G$ of meromorphy equal to (resp. less than) $\sum_{D_i=D_j} \lambda_i$ at a Cartier divisor D_j , for some fixed $j \in I$.

As mentioned in the previous section, $\mathrm{Gr}_{G,(\lambda_i)_{i \in I},E}^I$ is representable in nice diamonds and is cohomologically smooth of dimension equal to $\sum_{i \in I} \langle 2\hat{\rho}, \lambda_i \rangle$ over Div_E^I , by [FS, Proposition VI.2.4]. Similarly, by [SW20, Proposition 19.2.3], $\mathrm{Gr}_{G,\leq(\lambda_i)_{i \in I},E}$ is representable in nice diamonds and proper over Div_E^I . Fix $\boxtimes_{i \in I} V_i = V \in \mathrm{Rep}_\Lambda(\hat{G}^I)$ with fixed central character, and suppose the highest weight of V_i is given by λ_i for $\lambda_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$. Attached to this, we get a Λ -valued perverse sheaf $\mathcal{S}_V$ supported on $\mathrm{Gr}_{G,\leq(\lambda_i)_{i \in I},E}^I$ by Theorem 4.2 and [FS, Proposition VI.7.5]. We now fix a geometric point $x \rightarrow \mathrm{Div}_E^I$. In what follows, for a space $?$ over Div_E^I we write ${}_x?$ for the base-change to x . Since a local system on Div_E^I will be determined by the W_E^I -representation given by its pullback to this geometric point, looking at this pullback will be sufficient for most calculations. We now consider another stratification of $\mathrm{Gr}_{G,E}^I$.

Definition 4.7. Consider the natural map:

$$q : \mathrm{Gr}_{B,E}^I \rightarrow \mathrm{Gr}_{T,E}^I$$

For $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, we set $S_{G,(\nu_i)_{i \in I},E}^I$ to be the fiber of $\mathrm{Gr}_{B,E}^I$ over the closed subspace $\mathrm{Gr}_{T,(\nu_i)_{i \in I},E}^I$ in $\mathrm{Gr}_{T,E}^I$ parameterizing modifications of type $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$. We note, by [FS, Proposition VI.3.1], that the natural map

$$p : \mathrm{Gr}_{B,E}^I \rightarrow \mathrm{Gr}_{G,E}^I$$

is a bijection on geometric points and it defines a locally closed embedding on the $S_{G,(\nu_i)_{i \in I},E}^I$. Therefore, the spaces $S_{G,(\nu_i)_{i \in I},E}^I$ for varying $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, form locally-closed subspaces of $\mathrm{Gr}_{G,E}^I$ and every geometric point lies in a strata (though not necessarily a unique one!).

Remark 4.8. In particular, given a modification $\beta : \mathcal{F}_G^0 \dashrightarrow \mathcal{F}_G$ of G -bundles, by the Tannakian formalism this is equivalent to specifying a set of meromorphic maps

$$\mathcal{V}_{\mathcal{F}_G^0}^\lambda \dashrightarrow \mathcal{V}_{\mathcal{F}_G}^\lambda$$

for all dominant characters $\hat{\lambda} \in \hat{\Lambda}_G^+$ satisfying the Plücker relations (cf. Definition 5.9)⁵. The trivial G -bundle $\mathcal{F}_G^0$ admits a natural split B -structure whose associated T -bundle is the trivial T -bundle $\mathcal{F}_T^0$, and this defines a set of maps

$$\mathcal{L}_{\mathcal{F}_T^0}^\lambda \hookrightarrow \mathcal{V}_{\mathcal{F}_G^0}^\lambda$$

where $\mathcal{L}^\lambda := (\mathcal{V}^\lambda)^U$ and U is the unipotent radical of B . For a set of divisors $(D_i)_{i \in I} \in \mathrm{Div}_E^I$, we can also consider the meromorphic map

$$\mathcal{L}_{\mathcal{F}_T^0}^\lambda \left(\sum_{i \in I} -\langle \hat{\lambda}, \nu_{i\Gamma} \rangle \cdot D_i \right) \dashrightarrow \mathcal{L}_{\mathcal{F}_T^0}^\lambda \rightarrow \mathcal{V}_{\mathcal{F}_G^0}^\lambda \dashrightarrow \mathcal{V}_{\mathcal{F}_G}^\lambda$$

defined by modifying the T -bundles by ν_i at D_i for all $i \in I$. We claim that β defines a point in $S_{G,(\nu_i)_{i \in I},E}^I$ if and only if this map does not have a zero or pole for all $\hat{\lambda}$. This is easy to see. In particular, if this map does not have a zero or a pole then the maps

$$\mathcal{L}_{\mathcal{F}_T^0}^\lambda \left(- \sum_{i \in I} \langle \hat{\lambda}, \nu_{i\Gamma} \rangle \cdot D_i \right) \rightarrow \mathcal{V}_{\mathcal{F}_G}^\lambda$$

define a B -structure $\mathcal{F}_B$ on $\mathcal{F}_G$ whose underlying T -bundle is given by $\mathcal{F}_T^0(-\sum_{i \in I} \langle \hat{\lambda}, \nu_{i\Gamma} \rangle \cdot D_i)$. Moreover, the construction induces a map of B -bundles

$$\mathcal{F}_B^0 \dashrightarrow \mathcal{F}_B$$

⁵Here we note that $\mathcal{V}^\lambda$ is defined by Galois descent from $\overline{\mathbb{Q}}_p$, recalling that $\hat{\Lambda}_G^+ = \mathbb{X}^*(T_{\overline{\mathbb{Q}}_p})^{\Gamma,+}$.

which when applying $\times^B G$ gives the modification β and when applying $\times^B T$ gives rise to a modification defining a point in the closed subspace $\mathrm{Gr}_{T,(\nu_i)_{i \in I},E}^I$ over the point attached to $(D_i)_{i \in I}$ in Div_E^I . In other words, $\mathcal{F}_B^0 \dashrightarrow \mathcal{F}_B$ defines an element of the locally closed stratum $S_{G,(\nu_i)_{i \in I},E}^I$.

For $V \in \mathrm{Rep}_\Lambda(\hat{G}^I)$, we again consider the sheaf $\mathcal{S}_V$ on $\mathrm{Gr}_{G,\leq(\lambda_i)_{i \in I},E}^I$, and pullback to a fixed geometric point $x \rightarrow \mathrm{Div}_E^I$ defined by $\mathrm{Spa}(C)$ for C an algebraically closed perfectoid field. If we write $p_{(\nu_i)_{i \in I}} : xS_{G,(\nu_i)_{i \in I},E}^I \rightarrow x\mathrm{Gr}_{T,(\nu_i)_{i \in I},E}^I \simeq \mathrm{Spa}(C)$ for the induced map on the closed subspaces indexed by $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, we note that we have an isomorphism

$$p_! q^*(\mathcal{S}_V) \simeq \bigoplus_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I} p_{(\nu_i)_{i \in I}}!(\mathcal{S}_V|_{xS_{G,(\nu_i)_{i \in I},E}^I}) = \bigoplus_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I} \mathbb{H}_c^*(xS_{G,(\nu_i)_{i \in I},E}^I, \mathcal{S}_V|_{xS_{G,(\nu_i)_{i \in I},E}^I})$$

(cf. [FS, Example VI.3.6]). However, this is simply the constant term functor in the previous section. In particular, by Proposition 4.4, we deduce the following.

Corollary 4.9. *For $V = \boxtimes_{i \in I} V_i \in \mathrm{Rep}(\hat{G}^I)$, a geometric point $x \rightarrow \mathrm{Div}_E^I$, and all tuples $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, we have an isomorphism*

$$\mathbb{H}_c^{(2\hat{\rho}, |(\nu_i)_{i \in I}|)}(xS_{G,(\nu_i)_{i \in I},E}^I, \mathcal{S}_V|_{xS_{G,(\nu_i)_{i \in I},E}^I}) \simeq \boxtimes_{i \in I} V_i(\nu_i)(-\langle \hat{\rho}, \nu_i \rangle)$$

of W_E^I -modules.

Remark 4.10. The Tate twists appearing here are due to the difference between the standard definition of ${}^L G$ and the one used in the geometric Satake equivalence, as in the remark proceeding Theorem 4.2.

This will be the key proposition required for the proof of the filtered Hecke eigensheaf property. More specifically, to show the compatibilities of the filtered eigensheaf property, we need to show that this isomorphism is functorial in I . In particular, consider a map of finite index sets $\pi : I \rightarrow J$. For $j \in J$, we set $I_j := \pi^{-1}(j)$ and consider the natural map $\Delta_{IJ} : \mathrm{Div}_E^J \rightarrow \mathrm{Div}_E^I$, which diagonally embeds the j th copy of Div_E^1 in Div_E^J into Div_E^I . Then, by the relationship between fusion product and tensor product under Theorem 4.2, we have a identification

$$\Delta_{IJ}^*(\mathcal{S}_V) \simeq \mathcal{S}_{\Delta_{IJ}^*(V)}$$

of sheaves on $\mathrm{Gr}_{G,E}^J$, where $\Delta_{IJ}^*(V)$ is given by restriction along the corresponding map $\hat{G}^J \rightarrow \hat{G}^I$. Now, by Proposition 4.5, we have the following.

Corollary 4.11. *For all finite index sets I, J with a map $f : I \rightarrow J$, a tuple $(\nu_j)_{j \in J} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^J$, a representation $V \in \mathrm{Rep}(\hat{G}^I)$, and a geometric point $x \rightarrow \mathrm{Div}_E^J$, the identification $\Delta_{IJ}^*(\mathcal{S}_V) \simeq \mathcal{S}_{\Delta_{IJ}^*(V)}$ induces an isomorphism*

$$\mathbb{H}_c^*(xS_{G,(\nu_j)_{j \in J},E}^J, \mathcal{S}_{\Delta_{IJ}^*(V)}|_{xS_{G,(\nu_j)_{j \in J},E}^J}) \simeq \bigoplus_{\substack{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I \\ \sum_{i \in I_j} \nu_i = \nu_j}} \mathbb{H}_c^*(xS_{G,(\nu_i)_{i \in I},E}^I, \mathcal{S}_V|_{xS_{G,(\nu_i)_{i \in I},E}^I})$$

of W_E^J -modules, where the action on the RHS is via the natural map $\Delta_{IJ} : W_E^J \rightarrow W_E^I$. This is compatible with the identification

$$\Delta_{IJ}^*(V((\nu_j)_{j \in J})) \simeq \bigoplus_{\substack{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I \\ \sum_{i \in I_j} \nu_i = \nu_j}} V((\nu_i)_{i \in I})$$

under the isomorphisms of Corollary 4.9.

We note that the previous result has some very useful geometric consequences. Let's explain this in the case that $I = \{*\}$ is a singleton for a fixed geometric point $x \rightarrow \mathrm{Div}_E^1$. Fix $\lambda \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$, and consider the highest weight representation $V_\lambda \in \mathrm{Rep}_\Lambda(\hat{G})$ defined by λ . Since the sheaf $\mathcal{S}_\lambda$ is supported on ${}_x\mathrm{Gr}_{G, \leq \lambda}$, we can deduce the following.

Corollary 4.12. *For $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ and $\lambda \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ with associated highest weight representation $V_\lambda \in \mathrm{Rep}_\Lambda(\hat{G})$, if the weight space $V_\lambda(\nu)$ is non-trivial then the intersection ${}_x\mathrm{S}_{G, \nu, E} \cap {}_x\mathrm{Gr}_{G, \leq \lambda, E}$ is non-empty.*

Remark 4.13. One can also see this by using the Iwasawa decomposition of G and working explicitly with the loop group of G (See the analysis proceeding [She23, Proposition 6.4] and [She23, Remark 6.5]). For example, one can show that the intersection ${}_x\mathrm{Gr}_{G, \leq \lambda, E} \cap {}_x\mathrm{S}_{G, w_0(\lambda), E}$ is simply the point given by ξ^λ , where $\xi \in B_{dR}^+(C, \mathcal{O}_C)$ is the uniformizing parameter defined by the geometric point x . This corresponds to the lowest weight space $V_\lambda(w_0(\lambda))$.

5. MODULI STACKS OF B -STRUCTURES

In the first part of the section, we review the structure of the moduli stack of B -structures Bun_B and its basic geometric properties. This will allow us to define the geometric Eisenstein functor. For the proof of the Hecke eigensheaf property, it will be natural to consider a compactification of Bun_B , denoted $\overline{\mathrm{Bun}}_B$ which is the Drinfeld compactification. We will review the basic properties of this compactification in the second part.

5.1. The Geometry of Bun_B . We will start by collecting some basic facts about the moduli stack Bun_B parameterizing, for $S \in \mathrm{Perf}$, the groupoid of B -bundles on X_S . Given a B -bundle $\mathcal{G}_B$, we can send it to the induced T -bundle and G -bundle via the natural maps

$$\begin{array}{ccc} B & \longrightarrow & G \\ \downarrow & & \\ T & & \end{array}$$

which induces a diagram of v -stacks:

$$\begin{array}{ccc} \mathrm{Bun}_B & \xrightarrow{\mathfrak{p}} & \mathrm{Bun}_G \\ \downarrow \mathfrak{q} & & \\ \mathrm{Bun}_T & & \end{array}$$

Let's first start by breaking this up into connected components. As seen in §3, the connected components of Bun_T are indexed by elements $\bar{\nu} \in B(T) \simeq \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma = \Lambda_{G, B}$. This allows us to define the following.

Definition 5.1. For $\bar{\nu} \in B(T)$, we write $\mathrm{Bun}_B^{\bar{\nu}}$ for the pre-image of the connected component $\mathrm{Bun}_T^{\bar{\nu}}$ defined by $\bar{\nu}$ under the map $\mathfrak{q}^{\bar{\nu}}$. We write $\mathfrak{p}^{\bar{\nu}} : \mathrm{Bun}_B^{\bar{\nu}} \rightarrow \mathrm{Bun}_G$ and $\mathfrak{q}^{\bar{\nu}} : \mathrm{Bun}_B^{\bar{\nu}} \rightarrow \mathrm{Bun}_T^{\bar{\nu}}$ for the restriction of $\mathfrak{p}$ and $\mathfrak{q}$ to $\mathrm{Bun}_B^{\bar{\nu}}$, respectively.

We claim that this induces a decomposition of the moduli stack Bun_B into connected components. To each element $\bar{\nu}$, we define the integer $d_{\bar{\nu}} := \langle 2\hat{\rho}, \bar{\nu} \rangle$, where $2\hat{\rho}$ is the sum of all positive roots with respect to the choice of Borel. We note that, if $\bar{\nu}$ is anti-dominant with respect to the choice of Borel, $d_{\bar{\nu}}$ is negative. This will be the case where the HN-slopes are dominant so the B -bundles will split, and the negative dimension comes from quotienting out by the torsor of splittings. On the other hand, if $\bar{\nu}$ is dominant then the connected component will parametrize non-split B -structures and we see that the dimension will be positive. We have the following claim.

Proposition 5.2. *The map $\mathfrak{q}$ is a cohomologically smooth (non-representable) morphism of Artin v -stacks in the sense of [FS, Definition IV.1.11]. In particular, for $\bar{\nu} \in \Lambda_{G,B}$, the map $\mathfrak{q}^{\bar{\nu}}$ is pure of ℓ -dimension equal to $d_{\bar{\nu}}$, in the sense of [FS, Definition IV.1.17].*

Proof. This follows from [Ham21, Proposition 4.7], where we note that Bun_T is an Artin v -stack that is cohomologically smooth of ℓ -dimension 0 (See also [AL21, Lemma 4.1 (ii)]). $\square$

In particular, this implies using [Sch, Proposition 23.11], that $\mathfrak{q}$ is a universally open morphism of Artin v -stacks. Moreover, one can check that the fibers of this morphism are connected (See the proof of [AL21, Lemma 4.1 (ii)] and [Ham21, Proposition 3.16]). As a consequence, we can deduce that, since $\bigsqcup_{\bar{\nu} \in \Lambda_{G,B}} \text{Bun}_T^{\bar{\nu}}$ is a decomposition of Bun_T into connected components, the following is true.

Corollary 5.3. *The connected components of Bun_B are given by $\text{Bun}_B^{\bar{\nu}}$, for varying $\bar{\nu} \in B(T)$.*

We now comment briefly on the geometry of the map $\mathfrak{p}$. In particular, we have the following.

Lemma 5.4. *[AL21, Lemma 4.1 (ii)] The map $\mathfrak{p}$ is representable in nice diamonds.*

These properties allow us to define the Eisenstein functor using the derived functors defined in [Sch].

Definition 5.5. We define a locally constant function

$$\begin{aligned} \dim(\text{Bun}_B) : |\text{Bun}_B| &\rightarrow \mathbb{Z} \\ x \in |\text{Bun}_B^{\bar{\nu}}| &\mapsto d_{\bar{\nu}} \end{aligned}$$

and with it the unnormalized Eisenstein functor

$$\begin{aligned} \text{Eis} : \text{D}(\text{Bun}_T) &\rightarrow \text{D}(\text{Bun}_G) \\ \mathcal{F} &\mapsto \mathfrak{p}_!(\mathfrak{q}^*(\mathcal{F})[\dim(\text{Bun}_B)]) \end{aligned}$$

Even though Bun_B is cohomologically smooth (by the smoothness of Bun_T and Proposition 5.2), the sheaf $\Lambda[\dim(\text{Bun}_B)]$ is not Verdier self-dual. In particular, the dualizing object K_{Bun_B} on Bun_B is not isomorphic to $\Lambda[2\dim(\text{Bun}_B)]$; this is only v -locally true on Bun_B . To elucidate the problem, note that, given $\bar{\nu} \in \Lambda_{G,B}$, we can consider the natural map $\mathfrak{q}^{\bar{\nu}} : \text{Bun}_B^{\bar{\nu}} \rightarrow \text{Bun}_T^{\bar{\nu}} = [* / T(\mathbb{Q}_p)]$. Given a character $\kappa_{\bar{\nu}}$ of $T(\mathbb{Q}_p)$, we can pull this character back along $\mathfrak{q}^{\bar{\nu}}$ to get a sheaf on $\text{Bun}_B^{\bar{\nu}}$. These characters give us sheaves on $\text{Bun}_B^{\bar{\nu}}$, which v -locally will be constant, but are not constant on the nose. The main result of [HI25] specialized to the case of the Borel is as follows.

Theorem 5.6. *[HI25, Theorem 1.6] The dualizing object on Bun_B is isomorphic to $\mathfrak{q}^*(\Delta_B)[2\dim(\text{Bun}_B)]$, with $\Delta_B \in \text{D}(\text{Bun}_T)$ as in Definition 3.4.*

The key consequence of this theorem for us.

Corollary 5.7. *The sheaf $\mathfrak{q}^*(\Delta_B^{1/2})[\dim(\text{Bun}_B)]$ on Bun_B is Verdier self-dual.*

This motivates the definition of the normalized Eisenstein functor.

Definition 5.8. We let $\text{IC}_{\text{Bun}_B} := \mathfrak{q}^*(\Delta_B^{1/2})[\dim(\text{Bun}_B)]$. We define the normalized Eisenstein functor:

$$\begin{aligned} \text{nEis} : \text{D}(\text{Bun}_T) &\rightarrow \text{D}(\text{Bun}_G) \\ \mathcal{F} &\mapsto \mathfrak{p}_!(\mathfrak{q}^*(\mathcal{F}) \otimes \text{IC}_{\text{Bun}_B}) \end{aligned}$$

In particular, we note that we have a natural isomorphism:

$$\text{nEis}(-) \simeq \text{Eis}(- \otimes \Delta_B^{1/2}).$$

Since the definition of the Eisenstein functor involves the functor $\mathfrak{p}_!$, it is natural to consider a compactification of the morphism $\mathfrak{p}$ in order to study its finer properties. This leads us to the Drinfeld compactification.

5.2. The Drinfeld Compactification.

5.2.1. *The Definition and Basic Properties.* We recall that classically (curve over a finite or complex field) there is a rather straight-forward way of compactifying the map:

$$\mathfrak{p} : \text{Bun}_B \rightarrow \text{Bun}_G$$

This is called a Drinfeld Compactification of $\mathfrak{p}$, denoted $\overline{\text{Bun}}_B$. Its main property is that there exists an open immersion $\text{Bun}_B \rightarrow \overline{\text{Bun}}_B$, and it has a map $\bar{\mathfrak{p}} : \overline{\text{Bun}}_B \rightarrow \text{Bun}_G$ extending $\mathfrak{p}$, which is proper after restricting to finitely many connected components. First, as a warm up, let us explain the construction when $G = \text{GL}_2$. For this, we recall that Bun_B can be viewed as parameterizing tuples $(\mathcal{M}, \mathcal{L}, \kappa : \mathcal{L} \hookrightarrow \mathcal{M})$, where $\mathcal{E}$ is a rank 2 vector bundle, $\mathcal{L}$ is a rank 1 vector bundle, and κ is an injective bundle map. To compactify this space, we will allow κ to be a map of $\mathcal{O}_{X_S}$ -modules whose pullback to each geometric point is an injective map of coherent sheaves on X . In other words, we allow $\mathcal{M}/\mathcal{L}$ to have torsion. For a general G , the idea is to apply the Tannakian formalism. In particular, given a G -bundle $\mathcal{F}_G$ we get, for all $\hat{\lambda} \in \hat{\Lambda}_G^+$, an induced highest weight bundle, denoted $\mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$. A point of Bun_B mapping to $\mathcal{F}_G$ via $\mathfrak{p}$ then defines a set of line subbundles $\kappa^{\hat{\lambda}} : \mathcal{L}^{\hat{\lambda}} \hookrightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$ which satisfy some Plücker relations. Using this interpretation, $\overline{\text{Bun}}_B$ can then be defined as classifying G -bundles $\mathcal{F}_G$ together with a system of maps $\bar{\kappa}^{\hat{\lambda}} : \mathcal{L}^{\hat{\lambda}} \rightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$ for all $\hat{\lambda} \in \Lambda_G^+$, which are injective after pulling back to a geometric point and satisfy the same Plücker relations.

We now explain how to construct the aforementioned compactification $\overline{\text{Bun}}_B$ of Bun_B over Bun_G in the Fargues-Fontaine setting. In order to describe the Drinfeld compactification, we note that, for $S \in \text{Perf}$, Bun_B can be viewed as a stack parameterizing triples:

- (1) A G -bundle $\mathcal{F}_G$ on X_S .
- (2) A T -bundle $\mathcal{F}_T$ on X_S .
- (3) A G -equivariant map $\kappa : \mathcal{F}_G \rightarrow G/U \times^T \mathcal{F}_T$.

By the Tannakian formalism, (3) can be described as a collection of injective bundle maps on X_S , $\kappa^{\mathcal{V}} : (\mathcal{V}^U)_{\mathcal{F}_T} \rightarrow \mathcal{V}_{\mathcal{F}_G}$ for every G -module $\mathcal{V}$ satisfying the following Plücker relations:

- (1) For the trivial representation $\mathcal{V}$, $\kappa^{\mathcal{V}}$ must be the identity map $\mathcal{O}_{X_S} \rightarrow \mathcal{O}_{X_S}$.
- (2) For a G -module map $\mathcal{V}^1 \rightarrow \mathcal{V}^2$, the induced square

$$\begin{array}{ccc} ((\mathcal{V}^1)^U)_{\mathcal{F}_T} & \xrightarrow{\kappa^{\mathcal{V}^1}} & \mathcal{V}_{\mathcal{F}_G}^1 \\ \downarrow & & \downarrow \\ ((\mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\kappa^{\mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^2 \end{array}$$

commutes.

- (3) For two G -modules $\mathcal{V}^1$ and $\mathcal{V}^2$, we have that the diagram

$$\begin{array}{ccc} ((\mathcal{V}^1)^U \otimes (\mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\kappa^{\mathcal{V}^1} \otimes \kappa^{\mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^1 \otimes \mathcal{V}_{\mathcal{F}_G}^2 \\ \downarrow & & \downarrow \text{id} \\ ((\mathcal{V}^1 \otimes \mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\kappa^{\mathcal{V}^1 \otimes \mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^1 \otimes \mathcal{V}_{\mathcal{F}_G}^2 \end{array}$$

commutes.

As mentioned above, the idea will now be to introduce torsion in the above definition. In particular, we have the following definition for $\overline{\text{Bun}}_B$.

Definition 5.9. We define $\overline{\text{Bun}}_B$ to be the v -stack parameterizing, for $S \in \text{Perf}$, triples $(\mathcal{F}_G, \mathcal{F}_T, \bar{\kappa}^\mathcal{V})$, where $\bar{\kappa}^\mathcal{V}$ is a map of $\mathcal{O}_{X_S}$ -modules defined for every G -module $\mathcal{V}$

$$(\mathcal{V}^U)_{\mathcal{F}_T} \rightarrow \mathcal{V}_{\mathcal{F}_G}$$

satisfying the following conditions:

- For every geometric point $s \rightarrow S$, the pullback of $\bar{\kappa}^\mathcal{V}$ to the Fargues-Fontaine curve over s is an injection of coherent sheaves.
- The Plücker relations hold in the following sense:
 - (1) For the trivial representation $\mathcal{V}$, $\bar{\kappa}^\mathcal{V}$ is the identity map $\mathcal{O} \rightarrow \mathcal{O}$.
 - (2) For a G -module map $\mathcal{V}^1 \rightarrow \mathcal{V}^2$, the induced square

$$\begin{array}{ccc} ((\mathcal{V}^1)^U)_{\mathcal{F}_T} & \xrightarrow{\bar{\kappa}^{\mathcal{V}^1}} & \mathcal{V}_{\mathcal{F}_G}^1 \\ \downarrow & & \downarrow \\ ((\mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\bar{\kappa}^{\mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^2 \end{array}$$

commutes.

- (3) For two G -modules $\mathcal{V}^1$ and $\mathcal{V}^2$, we have that the diagram

$$\begin{array}{ccc} ((\mathcal{V}^1)^U \otimes (\mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\bar{\kappa}^{\mathcal{V}^1} \otimes \bar{\kappa}^{\mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^1 \otimes \mathcal{V}_{\mathcal{F}_G}^2 \\ \downarrow & & \downarrow \text{id} \\ ((\mathcal{V}^1 \otimes \mathcal{V}^2)^U)_{\mathcal{F}_T} & \xrightarrow{\bar{\kappa}^{\mathcal{V}^1 \otimes \mathcal{V}^2}} & \mathcal{V}_{\mathcal{F}_G}^1 \otimes \mathcal{V}_{\mathcal{F}_G}^2 \end{array}$$

commutes.

Remark 5.10. To simplify the notation, we will write $\mathcal{L}^{\hat{\lambda}} := (\mathcal{V}^{\hat{\lambda}})^U$ and $\bar{\kappa}^{\hat{\lambda}}$ for the embedding attached to the highest weight module of G of highest weight $\hat{\lambda} \in \hat{\Lambda}_G^+$.

This gives rise to a well-defined v -stack, and, using this description, we get well-defined morphisms $\bar{\mathfrak{p}} : \overline{\text{Bun}}_B \rightarrow \text{Bun}_G$ and $\bar{\mathfrak{q}} : \overline{\text{Bun}}_B \rightarrow \text{Bun}_T$ via projecting the data $(\mathcal{F}_G, \mathcal{F}_T, \bar{\kappa})$ to the first and second factor, respectively. We also get a natural map $j : \text{Bun}_B \rightarrow \overline{\text{Bun}}_B$, which will be an open immersion by [HHS24, Theorem 1.2.2 (i)]. We now recall the stratification of $\overline{\text{Bun}}_B$. For an element $\bar{\nu} \in \Lambda_{G,B}^{\text{pos}} \setminus \{0\}$, we write $\bar{\nu} = \sum_{i \in \mathcal{J}} n_i \alpha_i$ as a positive linear combination of the elements corresponding to Γ -orbits of simple positive coroots α_i . We let $\text{Div}^{(\bar{\nu})}$ be the partially symmetrized power of the mirror curve attached to it, as in §3.3. We have a map of Artin v -stacks

$$j_{\bar{\nu}} : \text{Div}^{(\bar{\nu})} \times \text{Bun}_B \rightarrow \overline{\text{Bun}}_B$$

sending a tuple $(\{(D_i)_{i \in \mathcal{J}}\}, \mathcal{F}_G, \mathcal{F}_T, \kappa^{\hat{\lambda}})$, to the tuple

$$(\mathcal{F}_G, \mathcal{F}_T(-\sum_{i \in \mathcal{J}} \alpha_i \cdot D_i), \bar{\kappa}^{\hat{\lambda}})$$

where $\bar{\kappa}^{\hat{\lambda}}$ is the natural composition

$$(\mathcal{L}^{\hat{\lambda}})_{\mathcal{F}_T}(-\sum_{i \in \mathcal{J}} \langle \alpha_i, \hat{\lambda} \rangle \cdot D_i) \rightarrow \mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}} \xrightarrow{\kappa^{\hat{\lambda}}} (\mathcal{V}^{\hat{\lambda}})_{\mathcal{F}_G}$$

defined by the unique effective modification of T -bundles of the specified meromorphy and support. We now make the following definition.

Definition 5.11. For $\bar{\nu} \in \Lambda_{G,B}^{\text{pos}} \setminus \{0\}$, we define the ν -stack $\overline{\nu\text{Bun}}_B$ (resp. $\geq_{\bar{\nu}} \overline{\nu\text{Bun}}_B$) to be the locus where, for all $\hat{\lambda} \in \hat{\Lambda}_G^+$, the cokernels $\mathcal{V}^{\hat{\lambda}}/\text{Im}(\bar{\kappa}^{\hat{\lambda}})$ have torsion of length equal to (resp. greater than) $\langle \hat{\lambda}, \bar{\nu} \rangle$ after pulling back to any geometric point. By [HHS24, Lemma 4.14 (i)], $\overline{\nu\text{Bun}}_B$ is a locally closed substack of $\overline{\text{Bun}}_B$, and the closure of $\overline{\nu\text{Bun}}_B$ in $\overline{\text{Bun}}_B$ is contained in $\geq_{\bar{\nu}} \overline{\nu\text{Bun}}_B$. Moreover, it follows by [HHS24, Proposition 4.2.8] that the map $j_{\bar{\nu}} : \text{Div}^{(\bar{\nu})} \times \text{Bun}_B \rightarrow \overline{\text{Bun}}_B$ is a locally closed embedding with image isomorphic to $\overline{\nu\text{Bun}}_B$.

With these strata defined, we now discuss a key diagram that will be important for proving the filtered Hecke eigensheaf property.

5.2.2. The Key Diagram. We would now like to describe how Hecke correspondences on Bun_G interact with pullback along the map $\bar{p} : \overline{\text{Bun}}_B \rightarrow \text{Bun}_G$. This will be used in §7 to show the filtered Hecke eigensheaf property for the geometric Eisenstein series, analogous to the analysis carried out in [BG02, Section 3]. We fix a finite index set I , and consider the Hecke stacks $\text{Hck}_{G,E}^I$ base-changed to the field E over which G splits. We consider the usual diagram

$$\text{Bun}_G \times \text{Div}_E^I \xleftarrow{h_G^{\leftarrow} \times \pi} \text{Hck}_{G,E}^I \xrightarrow{h_G^{\rightarrow}} \text{Bun}_G$$

as in §3 and §4. We now fix a tuple of geometric dominant cocharacters $(\lambda_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$, and restrict to the locus $\text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}$ where the meromorphy of this modification is bounded by $(\lambda_i)_{i \in I}$. We define the ν -stack $\overline{Z}_{(\lambda_i)_{i \in I}}^I$ by the Cartesian diagram:

$$\begin{array}{ccc} \overline{Z}_{(\lambda_i)_{i \in I}}^I & \xrightarrow{'h_G^{\rightarrow}} & \overline{\text{Bun}}_B \\ \downarrow \bar{p} & & \downarrow \bar{p} \\ \text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I & \xrightarrow{h_G^{\rightarrow}} & \text{Bun}_G \end{array}$$

By definition, $\overline{Z}_{(\lambda_i)_{i \in I}}^I$ parametrizes pairs of G -bundles $(\mathcal{F}_G, \mathcal{F}'_G)$ together with a modification $\mathcal{F}_G \dashrightarrow \mathcal{F}'_G$ with meromorphy bounded by λ_i at Cartier divisors D_i for $i \in I$ and an enhanced B -structure on $\mathcal{F}'_G$ specified by maps $\bar{\kappa}'^{\hat{\lambda}}$ for $\hat{\lambda} \in \hat{\Lambda}_G^+$. The fact that the modification $\mathcal{F}_G \dashrightarrow \mathcal{F}'_G$ has meromorphy bounded by $(\lambda_i)_{i \in I}$ implies that, for all $\hat{\lambda} \in \hat{\Lambda}_G^+$, we have an inclusion:

$$\mathcal{V}_{\mathcal{F}'_G}^{\hat{\lambda}} \subset \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}} \left(\sum_{i \in I} \langle \hat{\lambda}, -w_0(\lambda_{i\Gamma}) \rangle \cdot D_i \right)$$

Therefore, the embeddings

$$\bar{\kappa}'^{\hat{\lambda}} : \mathcal{L}_{\mathcal{F}'_G}^{\hat{\lambda}} \hookrightarrow \mathcal{V}_{\mathcal{F}'_G}^{\hat{\lambda}}$$

give rise to a map:

$$\bar{\kappa}^{\hat{\lambda}} : \mathcal{L}_{\mathcal{F}_G}^{\hat{\lambda}} \left(\sum_{i \in I} \langle \hat{\lambda}, w_0(\lambda_{i\Gamma}) \rangle \cdot D_i \right) \hookrightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$$

This defines for us a morphism

$$\phi_{(\lambda_i)_{i \in I}} : \overline{Z}_{(\lambda_i)_{i \in I}}^I \rightarrow \overline{\text{Bun}}_B \times \text{Div}_E^I$$

which records the point in $\overline{\text{Bun}}_B \times \text{Div}_E^I$ defined by the pair $(\bar{\kappa}^{\hat{\lambda}}, (D_i)_{i \in I})$. This sits in a commutative diagram

$$(2) \quad \begin{array}{ccccc} \overline{\text{Bun}}_B \times \text{Div}_E^I & \xleftarrow{\phi_{(\lambda_i)_{i \in I}}} & \overline{Z}_{(\lambda_i)_{i \in I}}^I & \xrightarrow{'h_G^{\rightarrow}} & \overline{\text{Bun}}_B \\ \downarrow \bar{p} \times \text{id} & & \downarrow \bar{p} & & \downarrow \bar{p} \\ \text{Bun}_G \times \text{Div}_E^I & \xleftarrow{h_G^{\leftarrow} \times \pi} & \text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I & \xrightarrow{h_G^{\rightarrow}} & \text{Bun}_G \end{array}$$

where we note that left square is not Cartesian. We will not use the space $\overline{Z}_{(\lambda_i)_{i \in I}}^I$ at all in our arguments, but it should be important for future applications. For our purposes, we consider $Z_{(\lambda_i)_{i \in I}}^I$, the space obtained by replacing $\overline{\text{Bun}}_B$ with Bun_B on the right hand side of the diagram. This sits in an analogous diagram

$$(3) \quad \begin{array}{ccccc} \overline{\text{Bun}}_B \times \text{Div}_E^I & \xleftarrow{\phi_{(\lambda_i)_{i \in I}}} & Z_{(\lambda_i)_{i \in I}}^I & \xrightarrow{{}'h_G^\rightarrow} & \text{Bun}_B \\ \downarrow \bar{p} \times \text{id} & & \downarrow {}'p & & \downarrow p \\ \text{Bun}_G \times \text{Div}_E^I & \xleftarrow{h_G^\leftarrow \times \pi} & \text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I & \xrightarrow{h_G^\rightarrow} & \text{Bun}_G \end{array}$$

As we will see, the proof of the filtered Hecke eigensheaf Property will ultimately reduce to contemplating the fibers of the morphism $\phi_{(\lambda_i)_{i \in I}}$. For our purposes, it will suffice to consider the pullback of this diagram to a geometric point $\text{Spa}(F, \mathcal{O}_F) \rightarrow \text{Div}_E^I$. We denote the resulting space by $x\overline{Z}_{(\lambda_i)_{i \in I}}^I$. It sits in a diagram of the form

$$\begin{array}{ccccc} x\overline{\text{Bun}}_B & \xleftarrow{\phi_{(\lambda_i)_{i \in I}}} & x\overline{Z}_{(\lambda_i)_{i \in I}}^I & \xrightarrow{{}'h_G^\rightarrow} & \overline{\text{Bun}}_B \\ \downarrow \bar{p} & & \downarrow {}'p & & \downarrow p \\ x\text{Bun}_G & \xleftarrow{h_G^\leftarrow \times \pi} & x\text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I & \xrightarrow{h_G^\rightarrow} & \text{Bun}_G \end{array}$$

where $x\text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I$ is the Hecke stack parameterizing modifications at the tuple of Cartier divisors $(D_i)_{i \in I}$ corresponding to x and $x\overline{\text{Bun}}_B$ (resp. $x\text{Bun}_G$) denotes the base change of $\overline{\text{Bun}}_B$ (resp. Bun_G) to $\text{Spa}(F, \mathcal{O}_F)$. Consider a tuple $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$ lying in the span of the positive coroots and write $\bar{\nu} := \sum_{i \in I} \nu_i \Gamma$. Let E_{ν_i} denote the reflex field of ν_i . We view the geometric point $x \rightarrow \text{Div}^I$ as a geometric point of $\text{Div}^{(\bar{\nu})}$ via composing with the map

$$\Delta_{(\nu_i)_{i \in I}} : \text{Div}_E^I \xrightarrow{\prod_{i \in I} \Delta_{\nu_i}} \prod_{i \in I} \text{Div}^{(\nu_i \Gamma)} \rightarrow \text{Div}^{(\bar{\nu})}$$

where the last map is given by taking the union of Cartier divisors and Δ_{ν_i} is the twisted diagonal embedding described in §3.3. We set $x_{(\nu_i)_{i \in I}} \overline{\text{Bun}}_B$ to be the pullback of the locally closed stratum $\bar{\nu} \overline{\text{Bun}}_B \simeq \text{Div}^{(\bar{\nu})} \times \text{Bun}_B$ to this geometric point. The substack $x_{(\nu_i)_{i \in I}} \overline{\text{Bun}}_B$ corresponds to the locus where the embeddings

$$\mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}} \rightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$$

have a zero of order given by $\langle \nu_i, \hat{\lambda} \rangle$ at D_i for all dominant characters $\hat{\lambda}$ of G and all $i \in I$, and a zero nowhere else. We now consider the open substack $x_{,0} \overline{\text{Bun}}_B = x\text{Bun}_B$. Since the maps κ have no zero at the Cartier divisors corresponding to x , it follows that they define an L^+B torsor over $x_{,0} \overline{\text{Bun}}_B$, which we denote by $x\mathcal{B}$. We then consider the map

$$i_{(\nu_i)_{i \in I}} : \overline{\text{Bun}}_B \times \text{Div}_E^I \rightarrow \overline{\text{Bun}}_B \times \text{Div}_E^I$$

given by sending $(\mathcal{F}_G, \mathcal{F}_T, \bar{\kappa}^{\hat{\lambda}}, (D_i)_{i \in I})$ to the object $(\mathcal{F}_G, \mathcal{F}_T(-\sum_{i \in I} \nu_i \cdot D_i), \mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}}(-\sum_{i \in I} \langle \nu_i \Gamma, \hat{\lambda} \rangle \cdot D_i) \hookrightarrow \mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}} \hookrightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}, (D_i)_{i \in I})$, where the map $\mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}}(-\sum_{i \in I} \langle \nu_i \Gamma, \hat{\lambda} \rangle \cdot D_i) \hookrightarrow \mathcal{L}_{\mathcal{F}_T}^{\hat{\lambda}}$ is specified by the ν_i at the D_i . Note that the map $i_{(\nu_i)_{i \in I}}$ defines an isomorphism between the pullbacks $x_{,0} \overline{\text{Bun}}_B$ and $x_{(\nu_i)_{i \in I}} \overline{\text{Bun}}_B$. Therefore, by transport of structure, we get a L^+B -torsor, denoted $x\mathcal{B}^{(\nu_i)_{i \in I}}$, over $x_{(\nu_i)_{i \in I}} \overline{\text{Bun}}_B$. For $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$ lying in the span of the positive coroots, we let $xZ_{(\lambda_i)_{i \in I}}^{I, *, (\nu_i)_{i \in I}}$ (resp. $xZ_{(\lambda_i)_{i \in I}}^{I, (\nu_i)_{i \in I}, *}$) be the fibers of $'h_G^\rightarrow$ (resp. $\phi_{(\lambda_i)_{i \in I}}$) over $x_{(\nu_i)_{i \in I}} \overline{\text{Bun}}_B$. We now have the following Lemma describing these subspaces, which is an analogue of [BG02, Lemma 3.3.6].

Lemma 5.12. *For tuples $(\nu_i)_{i \in I}, (\nu'_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$ lying in the span of the positive coroots, geometric dominant cocharacters $(\lambda_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$, and a geometric point $x \rightarrow \text{Div}_E^I$, the following is true.*

(1) *There is an isomorphism*

$${}_x Z_{(\lambda_i)_{i \in I}}^{I,*,(\nu'_i)_{i \in I}} \simeq {}_x \text{Gr}_{G, \leq (-w_0(\lambda_i))_{i \in I}}^I \times^{L^+B} {}_x \mathcal{B}^{(\nu'_i)_{i \in I}}$$

where the L^+B action on ${}_x \text{Gr}_{G, \leq (-w_0(\lambda_i))_{i \in I}}^I$ is given by the inclusion $L^+B \hookrightarrow L^+G$.

(2) *Under the identification in (1), the substack ${}_x Z_{(\lambda_i)_{i \in I}}^{I,(\nu_i)_{i \in I},(\nu'_i)_{i \in I}} \hookrightarrow {}_x Z_{(\lambda_i)_{i \in I}}^{I,*,(\nu'_i)_{i \in I}}$ identifies with the substack*

$${}_x \text{Gr}_{G, \leq (-w_0(\lambda_i))_{i \in I}, E}^I \cap {}_x \text{S}_{G, (-w_0(\lambda_i) - \nu_i + \nu'_i)_{i \in I}, E}^I \times^{L^+B} {}_x \mathcal{B}^{(\nu'_i)_{i \in I}} \subset {}_x \text{Gr}_{G, \leq (-w_0(\lambda_i))_{i \in I}, E}^I \times^{L^+B} {}_x \mathcal{B}^{(\nu'_i)_{i \in I}}$$

(3) *When viewed as a stack projecting to ${}_{x, (\nu_i)_{i \in I}} \overline{\text{Bun}}_B$, the stack ${}_x Z_{(\lambda_i)_{i \in I}}^{I,(\nu_i)_{i \in I},(\nu'_i)_{i \in I}}$ identifies with*

$${}_x \text{Gr}_{G, \leq (\lambda_i)_{i \in I}, E}^I \cap {}_x \text{S}_{G, (\nu_i - \nu'_i + w_0(\lambda_i))_{i \in I}, E}^I \times^{L^+B} {}_x \mathcal{B}^{(\nu_i)_{i \in I}}$$

Proof. Follows from the definitions and the description of the semi-infinite cells mentioned in the remark proceeding Definition 4.7. $\square$

We now apply this diagram to prove the filtered eigensheaf property.

6. THE FILTERED EIGENSHEAF PROPERTY

6.1. Proof of the Filtered Eigensheaf Property. We would now like to describe how Hecke correspondences on Bun_G interact with the Eisenstein functor. This will be used to show the Hecke eigensheaf property. Our analysis is heavily inspired by [BG02, Section 3], where an analogous claim is proven in the classical case. However, unlike the arguments there, we cannot appeal to the decomposition theorem, as the usual formalism of weights doesn't exist in this context. Nonetheless, we still have the excision spectral sequence, which will give us a filtration on the Eisenstein series. In §9, we will show that, under the condition of μ -regularity (Definition 3.10), this filtration splits for the Hecke operator defined by $V_{\mu\Gamma} \in \text{Rep}_\Lambda(LG)$ when applied to $\mathcal{F} = \mathcal{S}_{\phi_T}$.

Our goal is the following Theorem.

Theorem 6.1. *For $\mathcal{F} \in \text{D}(\text{Bun}_T)$, I a finite index set, and $V \in \text{Rep}_\Lambda(LG^I)$, the sheaf $T_V(\text{Eis}(\mathcal{F}))$ has a $W_{\overline{\mathbb{Q}}_p}^I$ -equivariant filtration indexed by $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})/\Gamma)^I$. The filtration's graded pieces are isomorphic to*

$$\text{Eis}(T_{(\nu_i)_{i \in I}}(\mathcal{F})) \otimes V((\nu_i)_{i \in I})(-\langle \hat{\rho}, \sum_{i \in I} \nu_i \Gamma \rangle)$$

as sheaves in $\text{D}(\text{Bun}_G)^{BW_{\overline{\mathbb{Q}}_p}^I}$. Moreover, the filtration is natural in I and V , as well as compatible with compositions and exterior tensor products in V .

Let $E/\overline{\mathbb{Q}}_p$ be an extension over which G splits. The value of $T_V(\text{nEis}(\mathcal{S}_{\phi_T}))$ is determined by the value of the Hecke correspondence base-changed to E , using [FS, Corollary V.2.3] (See [FS, Page 314]). Here the correspondence is determined by a representation $V = \boxtimes_{i \in I} V_i \in \text{Rep}_\Lambda(\hat{G}^I)$ of I -copies of the dual group. We let $\lambda_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ be the highest weight of V_i . By taking direct sums, we can assume WLOG that V has a fixed central character. We let $\mathcal{S}_V$ be the Λ -valued sheaf on $\text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I$ defined via Theorem 4.2. Our aim is to construct a W_E^I -equivariant filtration on the sheaf:

$$T_V(\text{Eis}(\mathcal{F})) = (h_G^\rightarrow \times \pi)_!(h_G^{\rightarrow*}(\mathfrak{p}!q^*(\mathcal{F})[\dim(\text{Bun}_B)])) \otimes \mathcal{S}_V \in \text{D}(\text{Bun}_G)^{BW_E^I}$$

This will be accomplished by contemplating the diagram

$$\begin{array}{ccccc}
 \overline{\text{Bun}}_B \times \text{Div}_E^I & \xleftarrow{\phi_{(\lambda_i)_{i \in I}}} & Z_{(\lambda_i)_{i \in I}}^I & \xrightarrow{{}'h_G^\rightarrow} & \text{Bun}_B \\
 \downarrow \bar{p} \times \text{id} & & \downarrow {}'\mathfrak{p} & & \downarrow \mathfrak{p} \\
 \text{Bun}_G \times \text{Div}_E^I & \xleftarrow{h_G^\rightarrow \times \pi} & \text{Hck}_{G, \leq (\lambda_i)_{i \in I}, E}^I & \xrightarrow{h_G^\rightarrow} & \text{Bun}_G
 \end{array}$$

as defined in §5.2.2 (3). Using base-change on the right Cartesian square, we get an isomorphism

$$T_V(\text{Eis}(\mathcal{F})) \simeq (h_G^\rightarrow \times \pi)_! ({}'\mathfrak{p}_! {}'h_G^{\rightarrow*} \mathfrak{q}^*(\mathcal{F})[\dim(\text{Bun}_B)] \otimes \mathcal{S}_V)$$

but, applying the projection formula with respect to $\mathfrak{p}'$, this becomes

$$T_V(\text{Eis}(\mathcal{F})) \simeq (h_G^\rightarrow \times \pi)_! ({}'\mathfrak{p}_! ({}'h_G^{\rightarrow*} (\mathfrak{q}^*(\mathcal{F})[\dim(\text{Bun}_B)])) \otimes {}'\mathfrak{p}^*(\mathcal{S}_V))$$

We define

$$K_V := {}'h_G^{\rightarrow*}(\Lambda[\dim(\text{Bun}_B)]) \otimes {}'\mathfrak{p}^*(\mathcal{S}_V)$$

allowing us to rewrite our formula nicely as

$$(4) \quad T_V(\text{Eis}(\mathcal{F})) \simeq (h_G^\rightarrow \times \pi)_! {}'\mathfrak{p}_! ({}'h_G^{\rightarrow*} \mathfrak{q}^*(\mathcal{F}) \otimes K_V) = (\bar{p} \times \text{id})_! \phi_{(\lambda_i)_{i \in I}} ({}'h_G^{\rightarrow*} \mathfrak{q}^*(\mathcal{F}) \otimes K_V)$$

Now we would like to reduce the claim to applying excision to $\phi_{(\lambda_i)_{i \in I}}(K_V)$ with respect to a locally closed stratification of $\overline{\text{Bun}}_B \times \text{Div}_E^I$. The claim should then follow from Corollary 4.9 and Lemma 5.12. In order to do this, let's further rewrite the formula. We recall that, for $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, we have a map

$$i_{(\nu_i)_{i \in I}} : \overline{\text{Bun}}_B \times \text{Div}_E^I \rightarrow \overline{\text{Bun}}_B \times \text{Div}_E^I$$

sending the tuple $(\mathcal{F}_G, \mathcal{F}_T, \bar{\kappa}^\lambda, (D_i)_{i \in I})$ to the tuple $(\mathcal{F}_G, \mathcal{F}_T(-\sum_{i \in I} \nu_i \cdot D_i), \mathcal{L}_{\mathcal{F}_T}^\lambda(-\sum_{i \in I} \langle \nu_i, \hat{\lambda} \rangle \cdot D_i) \hookrightarrow \mathcal{L}_{\mathcal{F}_T}^\lambda \hookrightarrow \mathcal{V}_{\mathcal{F}_G}^\lambda, (D_i)_{i \in I})$. We also have the map

$$h_{(\nu_i)_{i \in I}}^\rightarrow : \text{Bun}_T \times \text{Div}_E^I \simeq \text{Hck}_{T, (\nu_i)_{i \in I}}^I \rightarrow \text{Bun}_T$$

as in §3 which is given by modifying a T -bundle by $(\nu_i)_{i \in I}$ at a tuple of divisors $(D_i)_{i \in I}$ defining a point in Div_E^I . Then, for $\mathcal{F} \in \text{D}(\text{Bun}_T)$, we recall that we have an identification $(h_{(\nu_i)_{i \in I}}^\rightarrow)^*(\mathcal{F}) = T_{(\nu_i)_{i \in I}}(\mathcal{F})$ of sheaves in $\text{D}(\text{Bun}_T)^{BW_E^I}$. Now, we can verify the following easy Lemma, which follows from the definition of $\phi_{(\lambda_i)_{i \in I}}$.

Lemma 6.2. *The following is true.*

- (1) *The maps $h_{(w_0(\lambda_i))_{i \in I}}^\rightarrow \circ (\bar{q} \times \text{id}) \circ \phi_{(\lambda_i)_{i \in I}}$ and $\mathfrak{q} \circ {}'h_G^\rightarrow$ from $Z_{(\lambda_i)_{i \in I}}^I$ to Bun_T coincide.*
- (2) *For every $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, the maps $(\bar{q} \times \text{id}) \circ i_{(\nu_i)_{i \in I}}$ and $(h_{(\nu_i)_{i \in I}}^\rightarrow \times \text{id}) \circ (\bar{q} \times \text{id})$ from $\overline{\text{Bun}}_B \times \text{Div}_E^I$ to $\text{Bun}_T \times \text{Div}_E^I$ coincide.*

Now, with this in hand, let's revisit equation (4):

$$T_V(\text{Eis}(\mathcal{F})) \simeq (\bar{p} \times \text{id})_! \phi_{(\lambda_i)_{i \in I}} ({}'h_G^{\rightarrow*} \mathfrak{q}^*(\mathcal{F}) \otimes K_V)$$

Using Lemma 6.2 (1), we have that

$${}'h_G^{\rightarrow*} \mathfrak{q}^*(\mathcal{F}) \simeq \phi_{(\lambda_i)_{i \in I}}^* (\bar{q} \times \text{id})^* (h_{(w_0(\lambda_i))_{i \in I}}^\rightarrow)^*(\mathcal{F})$$

substituting this in and applying projection formula with respect to $\phi_{(\lambda_i)_{i \in I}}$, we can rewrite the RHS as

$$(\bar{p} \times \text{id})_! ((\bar{q} \times \text{id})^* (h_{(w_0(\lambda_i))_{i \in I}}^\rightarrow)^*(\mathcal{F}) \otimes \phi_{(\lambda_i)_{i \in I}}(K_V))$$

Now we claim that we have the following description of $\phi_{(\lambda_i)_{i \in I}}(K_V)$.

Theorem 6.3. *The sheaf $\phi_{(\lambda_i)_{i \in I}!}(K_V) \in D(\overline{\text{Bun}}_B)^{BW_E^I}$ has a W_E^I -equivariant filtration indexed by $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$. The graded pieces of this filtration are given by*

$$\boxtimes_{i \in I} (i_{\nu_i}!(j \times \text{id})!(\Lambda[\dim(\text{Bun}_B)])) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle \hat{\rho}, w_0(\lambda) + \nu_i \rangle]$$

Assuming this for now, we get that $T_V(\text{Eis}(\mathcal{F}))$ has a W_E^I -equivariant filtration with graded pieces given by

$$\boxtimes_{i \in I} (\bar{\mathbf{p}} \times \text{id})_!(\bar{\mathbf{q}} \times \text{id})^* h_{w_0(\lambda_i)}^{\rightarrow*}(\mathcal{F}) \otimes (i_{\nu_i}!(j \times \text{id})!(\Lambda[\dim(\text{Bun}_B)])) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle \hat{\rho}, w_0(\lambda) + \nu_i \rangle]$$

Applying projection formula with respect to i_{ν_i} , we obtain

$$\boxtimes_{i \in I} (\bar{\mathbf{p}} \times \text{id})_! i_{\nu_i}^* (i_{\nu_i}^* (\bar{\mathbf{q}} \times \text{id})^* h_{w_0(\lambda_i)}^{\rightarrow*}(\mathcal{F}) \otimes (j \times \text{id})!(\Lambda[\dim(\text{Bun}_B)])) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle \hat{\rho}, w_0(\lambda) + \nu_i \rangle]$$

but now, by Lemma 6.2 (2), we have

$$i_{\nu_i}^* (\bar{\mathbf{q}} \times \text{id})^* h_{w_0(\lambda_i)}^{\rightarrow*}(\mathcal{F}) \simeq (\bar{\mathbf{q}} \times \text{id})^* h_{w_0(\lambda_i) + \nu_i}^{\rightarrow*}(\mathcal{F}) \simeq (\bar{\mathbf{q}} \times \text{id})^*(T_{w_0(\lambda_i) + \nu_i}(\mathcal{F}))$$

so substituting this into the previous formula we get

$$\boxtimes_{i \in I} (\bar{\mathbf{p}} \times \text{id})_! i_{\nu_i}^* ((\bar{\mathbf{q}} \times \text{id})^*(T_{w_0(\lambda_i) + \nu_i}(\mathcal{F}) \otimes (j \times \text{id})!(\Lambda[\dim(\text{Bun}_B)]))) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle \hat{\rho}, w_0(\lambda) + \nu_i \rangle]$$

Now i_{ν_i} does nothing to the G -bundle $\mathcal{F}_G$ and the copy of Div_E^I . Therefore, this becomes

$$\boxtimes_{i \in I} (\bar{\mathbf{p}} \times \text{id})_! ((\bar{\mathbf{q}} \times \text{id})^*(T_{w_0(\lambda_i) + \nu_i}(\mathcal{F})) \otimes (j \times \text{id})!(\Lambda[\dim(\text{Bun}_B)])) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle \hat{\rho}, w_0(\lambda) + \nu_i \rangle]$$

which is just

$$\boxtimes_{i \in I} (\text{Eis} \boxtimes \text{id})(T_{w_0(\lambda_i) + \nu_i}(\mathcal{F})) \otimes V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)$$

by an application of projection formula to $j \times \text{id}$. Since $w_0(\lambda_i)$ is the lowest weight of V_i this implies the desired result. Thus, to construct the filtration all we have to do is prove Theorem 6.3.

Proof. (Theorem 6.3) For $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$, let $\bar{\nu} := \sum_{i \in I} \nu_i \Gamma$. Consider the locally closed stratum ${}_{\bar{\nu}}\overline{\text{Bun}}_B \times \text{Div}_E^I \simeq \text{Bun}_B \times \text{Div}(\bar{\nu}) \times \text{Div}_E^I \subset \overline{\text{Bun}}_B \times \text{Div}_E^I$. We have the natural projection

$$p_1 : {}_{\bar{\nu}}\overline{\text{Bun}}_B \times \text{Div}_E^I \simeq \text{Bun}_B \times \text{Div}(\bar{\nu}) \times \text{Div}_E^I \rightarrow \text{Div}(\bar{\nu})$$

as well as the map

$$p_2 : {}_{\bar{\nu}}\overline{\text{Bun}}_B \times \text{Div}_E^I \rightarrow \text{Div}_E^I \xrightarrow{\Delta_{(\nu_i)_{i \in I}}} \text{Div}(\bar{\nu})$$

where the first map is the natural projection and $\Delta_{(\nu_i)_{i \in I}}$ is as defined in §5.2.2. Since $\text{Div}(\bar{\nu})$ is proper using [FS, Proposition II.1.21] and in particular separated, it follows that if we let ${}_{(\nu_i)_{i \in I}}(\overline{\text{Bun}}_B \times \text{Div}_E^I) \rightarrow {}_{\bar{\nu}}\overline{\text{Bun}}_B \times \text{Div}_E^I$ be the pullback of the diagonal morphism $\Delta_{\text{Div}(\bar{\nu})}$ along (p_1, p_2) that this is a closed immersion. Therefore, we see that the composite ${}_{(\nu_i)_{i \in I}}(\overline{\text{Bun}}_B \times \text{Div}_E^I) \rightarrow {}_{\bar{\nu}}\overline{\text{Bun}}_B \times \text{Div}_E^I \rightarrow \overline{\text{Bun}}_B \times \text{Div}_E^I$ is a locally closed immersion parameterizing $(\bar{\kappa}^{\hat{\lambda}} : (\mathcal{L}^{\hat{\lambda}})_{\mathcal{F}_T} \rightarrow (\mathcal{V}^{\hat{\lambda}})_{\mathcal{F}_G}, \hat{\lambda} \in \hat{\Lambda}_G^+, (D_i)_{i \in I})$ such that $\text{Coker}(\bar{\kappa}^{\hat{\lambda}})$ has torsion of length $\langle \hat{\lambda}, \nu_{i\Gamma} \rangle$ supported at D_i , and a 0 nowhere else for all $\hat{\lambda} \in \hat{\Lambda}_G^+$ and $i \in I$. If we let $j_{(\nu_i)_{i \in I}} := i_{(\nu_i)_{i \in I}} \circ (j \times \text{id})$ then we see that this maps isomorphically onto ${}_{(\nu_i)_{i \in I}}(\overline{\text{Bun}}_B \times \text{Div}_E^I)$, and for varying $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}))^I$ these form a locally closed stratification of $\overline{\text{Bun}}_B \times \text{Div}_E^I$. Now, by applying the excision with respect to this locally closed stratification, we obtain a filtration on $\phi_{(\lambda_i)_{i \in I}!}(K_Z)$ whose graded pieces are isomorphic to:

$$j_{(\nu_i)_{i \in I}}! j_{(\nu_i)_{i \in I}}^* \phi_{(\lambda_i)_{i \in I}!}(K_V)$$

Moreover, since the maps $j_{(\nu_i)_{i \in I}}$ are defined over the projection to Div_E^I , it follows that this filtration is W_E^I -equivariant. It remains to determine the W_E^I -action on the graded pieces. To do this, we can

consider the pullback to a geometric point $x = \mathrm{Spa}(C, \mathcal{O}_C) \rightarrow \mathrm{Div}_E^I$, where we can regard x as a point of $\mathrm{Div}^{(\bar{\nu})}$, as in §5.2.2. We recall that by definition

$$K_V := {}^{\prime}\mathfrak{p}^*(\mathcal{S}_V) \otimes ({}^{\prime}h_G^{\rightarrow})^*(\Lambda[\dim(\mathrm{Bun}_B)])$$

so, by Lemma 5.12 (3), the pullback to x identifies with

$$R\Gamma_c(x \mathrm{Gr}_{G, \leq (\lambda_i)_{i \in I}, E} \cap x \mathrm{S}_{G, (\nu_i + w_0(\lambda_i))_{i \in I}, E}, \mathcal{S}_V|_{x \mathrm{Gr}_{G, \leq (\lambda_i)_{i \in I}, E} \cap x \mathrm{S}_{G, (\nu_i + w_0(\lambda_i))_{i \in I}, E}})[\dim(\mathrm{Bun}_B)]$$

Now, by Corollary 4.9, $j_{(\nu_i)_{i \in I}}^* \phi_{(\lambda_i)_{i \in I}}(K_V)$ identifies with

$$\boxtimes_{i \in I} V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, (w_0(\lambda_i) + \nu_i) \rangle)[-\langle 2\hat{\rho}, \sum_{i \in I} (w_0(\lambda_i) + \nu_i) \rangle + \dim(\mathrm{Bun}_B)],$$

as desired $\square$

It remains to see that this filtration satisfies the desired compatibilities. Consider a map of finite index sets $\pi : I \rightarrow J$. For $j \in J$, we set $I_j := \pi^{-1}(j)$ and consider the natural map $\Delta_{IJ} : \mathrm{Div}_E^J \rightarrow \mathrm{Div}_E^I$, which diagonally embeds the j th copy of Div_E^1 in Div_E^J into Div_E^I . Attached to this, we have a Cartesian diagram

$$\begin{array}{ccc} \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^J & \xleftarrow[\phi_{(\lambda_j)_{j \in J}}]{} & Z_{(\lambda_j)_{j \in J}}^J \\ \downarrow \mathrm{id} \times \Delta_{IJ} & & \downarrow \tilde{\Delta}_{IJ} \\ \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^I & \xleftarrow[\phi_{(\lambda_i)_{i \in I}}]{} & Z_{(\lambda_i)_{i \in I}}^I \end{array}$$

where $\lambda_j := \sum_{i \in I_j} \lambda_i$ for all $j \in J$. Base change gives us a natural isomorphism:

$$(5) \quad (\mathrm{id} \times \Delta_{IJ})^* \phi_{(\lambda_i)_{i \in I}}(K_{\boxtimes_{i \in I} V_i}) \simeq \phi_{(\lambda_j)_{j \in J}} \tilde{\Delta}_{IJ}^*(K_{\boxtimes_{i \in I} V_i})$$

However, by the relationship between fusion product and tensor product under Theorem 4.2, we deduce that $\tilde{\Delta}_{IJ}^*(K_{\boxtimes_{i \in I} V_i}) \simeq K_{\boxtimes_{j \in J} V_j}$, where $V_j := \otimes_{i \in I_j} V_i$. We now compare the two filtrations on the LHS and the RHS of this isomorphism. To do this, we define $(\nu_j)_{j \in J}$ by $\nu_j := \sum_{i \in I_j} \nu_i$. We note that we have a natural Cartesian diagram

$$\begin{array}{ccc} \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^J & \xrightarrow{i_{(\nu_j)_{j \in J}}} & \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^J \\ \downarrow \mathrm{id} \times \Delta_{IJ} & & \downarrow \mathrm{id} \times \Delta_{IJ} \\ \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^I & \xrightarrow{i_{(\nu_i)_{i \in I}}} & \overline{\mathrm{Bun}}_B \times \mathrm{Div}_E^I \end{array}$$

On the LHS of (5), we have a filtration with graded pieces isomorphic to

$$(\mathrm{id} \times \Delta_{IJ})^* i_{(\nu_i)_{i \in I}}(j \times \mathrm{id})!(\Lambda[\dim(\mathrm{Bun}_B)]) \otimes \boxtimes_{i \in I} V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle 2\hat{\rho}, (w_0(\lambda_i) + \nu_i) \rangle]$$

which is naturally isomorphic to

$$i_{(\nu_j)_{j \in J}}(\mathrm{id} \times \Delta_{IJ})^* (j \times \mathrm{id})!(\Lambda[\dim(\mathrm{Bun}_B)]) \otimes \boxtimes_{i \in I} V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle 2\hat{\rho}, (w_0(\lambda_i) + \nu_i) \rangle]$$

by base-change applied to the previous Cartesian square. We can further rewrite this as

$$i_{(\nu_j)_{j \in J}} \circ (j \times \mathrm{id})!(\Lambda[\dim(\mathrm{Bun}_B)]) \otimes \boxtimes_{j \in J} \otimes_{i \in I_j} V_i(w_0(\lambda_i) + \nu_i)(-\langle \hat{\rho}, w_0(\lambda_i) + \nu_i \rangle)[-\langle 2\hat{\rho}, (w_0(\lambda_i) + \nu_i) \rangle]$$

On the other hand, for such a $(\nu_j)_{j \in J}$, the RHS of (5) has a filtration with graded pieces isomorphic to

$$i_{(\nu_j)_{j \in J}}(j \times \mathrm{id})!(\Lambda[\dim(\mathrm{Bun}_B)]) \otimes \boxtimes_{j \in J} V_j(w_0(\lambda_j) + \nu_j)(-\langle \hat{\rho}, w_0(\lambda_j) + \nu_j \rangle)[-\langle 2\hat{\rho}, w_0(\lambda_j) + \nu_j \rangle]$$

but now note that

$$V_j(w_0(\lambda_j) + \nu_j) = \bigoplus_{\substack{(\nu_i)_{i \in I} \in \Lambda_{G,B}^I \\ \sum_{i \in I_j} \nu_i = \nu_j}} \bigotimes_{i \in I_j} V_i(w_0(\lambda_i) + \nu_i)$$

for all $j \in J$. Therefore, the graded piece indexed by $(\nu_j)_{j \in J}$ on the RHS of (5) have a split filtration with graded pieces isomorphic to the graded pieces coming from the filtration on the LHS on (5). The compatibility of these two filtrations now follows from Corollary 4.11, and the fact that the filtration came from restricting the sheaf $\mathcal{S}_V$ to semi-infinite cells. Now, we can reap the fruit of this section using the filtered eigensheaf property to get some control on the stalks of $\mathrm{nEis}(\mathcal{S}_{\phi_T})$.

6.2. Consequences of the Filtered Eigensheaf Property. First, we note, by applying Theorem 6.1 when $\mathcal{F} = \mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2}$ together with Corollary 3.5, we obtain the following.

Corollary 6.4. *For all finite index sets I and $V = \boxtimes_{i \in I} V_i \in \mathrm{Rep}_\Lambda({}^L G^I)$, the sheaf $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ admits a $W_{\mathbb{Q}_p}^I$ -equivariant filtration indexed by $(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\mathbb{Q}_p})/\Gamma)^I$. The filtration's graded pieces are isomorphic to $\mathrm{nEis}(\mathcal{S}_{\phi_T}) \otimes \boxtimes_{i \in I} (\nu_i \circ \phi_T) \otimes V_i(\nu_i)$. The filtration is natural in I and V , as well as compatible with compositions and exterior tensor products in V .*

In particular, we note that the direct sum of the graded pieces of the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ is isomorphic to

$$\mathrm{nEis}(\mathcal{S}_{\phi_T}) \otimes \bigoplus_{(\nu_i)_{i \in I} \in (\mathbb{X}_*(T_{\mathbb{Q}_p})/\Gamma)^I} \boxtimes_{i \in I} \nu_i \circ \phi_T \otimes V_i(\nu_i) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_V \circ \phi$$

as sheaves in $D(\mathrm{Bun}_G)^{BW_{\mathbb{Q}_p}^I}$, where ϕ is the parameter ϕ_T composed with the natural embedding ${}^L T \rightarrow {}^L G$. In other words, $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ is a filtered eigensheaf with eigenvalue ϕ . We now would like to use this to deduce some consequences about the stalks of the Eisenstein series $\mathrm{nEis}(\mathcal{S}_{\phi_T})$. In particular, consider some Schur irreducible subquotient A of some cohomology sheaf of $\mathrm{nEis}(\mathcal{S}_{\phi_T})$. We will now need our assumption that the prime ℓ is very decent; more specifically, the assumption that $\ell \nmid |\pi_0(Z(G))|$. Under this assumption, the excursion algebra will define endomorphisms of A which determine and are determined by the parameter ϕ_A^{FS} , as in [FS, Propositions I.9.1, I.9.3]. Since the excursion algebra is determined by natural transformations of Hecke operators, the filtered Hecke eigensheaf property tells us that these scalars must be specified by ϕ , so that we have an equality: $\phi = \phi_A^{\mathrm{FS}}$, as conjugacy classes of semi-simple parameters. In particular, if we consider $b \in B(G)$ and look at the restriction $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b}$ to the locally closed HN-strata $\mathrm{Bun}_G^b \subset \mathrm{Bun}_G$ indexed by b . Then, by [FS, Proposition V.2.2], we have a natural isomorphism $D(\mathrm{Bun}_G^b) \simeq D(J_b(\mathbb{Q}_p), \Lambda)$. By the previous discussion and compatibility of the Fargues-Scholze correspondence with restriction to J_b [FS, Section IX.7.1], we deduce that any irreducible constituent ρ of the restriction $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b}$ has Fargues-Scholze parameter $\phi_\rho^{\mathrm{FS}} : W_{\mathbb{Q}_p} \rightarrow {}^L J_b(\Lambda)$ equal to ϕ under the appropriately Tate twisted embedding:

$${}^L J_b(\Lambda) \rightarrow {}^L G(\Lambda)$$

Now, since our parameter ϕ is induced from the maximal torus, we would like to say that this is impossible unless J_b itself admits a maximal torus, which is in turn equivalent to assuming that b is unramified. Here we need to be a bit careful. In particular, if we consider $G = \mathrm{GL}_2$ and b the element of slope $\frac{1}{2}$ then $J_b = D_{\frac{1}{2}}^*$ the units in the quaternion division algebra. The trivial representation $\mathbf{1}$ of $D_{\frac{1}{2}}^*$ has Fargues-Scholze parameter given by

$$W_{\mathbb{Q}_p} \rightarrow \mathrm{GL}_2(\Lambda)$$

$$g \mapsto \begin{pmatrix} |g|^{1/2} & 0 \\ 0 & |g|^{-1/2} \end{pmatrix}$$

This parameter is induced from a maximal torus of GL_2 ; however, it is not generic. In particular, the composite of this parameter with the unique simple root defined by the upper triangular Borel gives a Galois representation isomorphic to the norm/cyclotomic character $|\cdot|$. Therefore, one might hope that assuming compatibility of some suitably nice form of the local Langlands correspondence for G with the Fargues-Scholze correspondence together with genericity of ϕ_T is enough to give us the desired description of the stalks. This is indeed the case. The assumption we need is as follows.

Assumption 6.5. *For a connected reductive group $H/\mathbb{Q}_p$, we have*

- *the set $\Pi(H)$ of smooth irreducible $\overline{\mathbb{Q}_\ell}$ -representations of $H(\mathbb{Q}_p)$,*
- *the set $\Phi(H)$ of conjugacy classes of continuous maps*

$$W_{\mathbb{Q}_p} \times \mathrm{SL}(2, \overline{\mathbb{Q}_\ell}) \rightarrow {}^L H(\overline{\mathbb{Q}_\ell})$$

where $\overline{\mathbb{Q}_\ell}$ has the discrete topology, $\mathrm{SL}(2, \overline{\mathbb{Q}_\ell})$ acts via an algebraic representation, $W_{\mathbb{Q}_p}$ acts through a semi-simple homomorphism (in the sense that if it factors through ${}^L P$ for a proper parabolic $P \subset G$ then it also factors through the associated Levi ${}^L M$), and the map respects the action of $W_{\mathbb{Q}_p}$ on ${}^L H(\overline{\mathbb{Q}_\ell})$, the L -group of H ,

- *the set $\Phi^{\mathrm{ss}}(H)$ of continuous (where again $\overline{\mathbb{Q}_\ell}$ has the discrete topology) semi-simple homomorphisms,*

$$W_{\mathbb{Q}_p} \rightarrow {}^L H(\overline{\mathbb{Q}_\ell}),$$

- *and the semi-simplification map $(-)^{\mathrm{ss}} : \Phi(H) \rightarrow \Phi^{\mathrm{ss}}(H)$ defined by precomposition with*

$$W_{\mathbb{Q}_p} \rightarrow W_{\mathbb{Q}_p} \times \mathrm{SL}(2, \overline{\mathbb{Q}_\ell})$$

$$g \mapsto (g, \begin{pmatrix} |g|^{1/2} & 0 \\ 0 & |g|^{-1/2} \end{pmatrix}).$$

Then, we assume that there exists a collection of maps

$$\mathrm{LLC}_b : \Pi(J_b) \rightarrow \Phi(J_b)$$

$$\rho \mapsto \phi_\rho,$$

for all $b \in B(G)$, satisfying the following properties:

- (1) *The diagram*

$$\begin{array}{ccc} \Pi(J_b) & \xrightarrow{\mathrm{LLC}_b} & \Phi(J_b) \\ & \searrow \mathrm{LLC}_b^{\mathrm{FS}} & \downarrow (-)^{\mathrm{ss}} \\ & & \Phi^{\mathrm{ss}}(J_b) \end{array}$$

commutes, where $\mathrm{LLC}_b^{\mathrm{FS}}$ is the Fargues-Scholze local Langlands correspondence for J_b .

- (2) *For ρ a non-zero smooth irreducible representation of $J_b(\mathbb{Q}_p)$ for some $b \in B(G)$, consider ϕ_ρ as an element of $\Phi(G)$ given by composing with the twisted embedding ${}^L J_b(\overline{\mathbb{Q}_\ell}) \simeq {}^L M_b(\overline{\mathbb{Q}_\ell}) \rightarrow {}^L G(\overline{\mathbb{Q}_\ell})$ (as defined in [FS, Section IX.7.1]). Then ϕ_ρ factors through the natural (up to $\hat{G}$ -conjugacy) embedding ${}^L T \rightarrow {}^L G$ if and only if $b \in B(G)_{\mathrm{un}}$.*
- (3) *If ρ is a non-zero representation such that $W_{\mathbb{Q}_p} \times \mathrm{SL}(2, \overline{\mathbb{Q}_\ell}) \xrightarrow{\phi_\rho} {}^L J_b(\overline{\mathbb{Q}_\ell}) \rightarrow {}^L G(\overline{\mathbb{Q}_\ell})$ factors through the embedding ${}^L T \rightarrow {}^L G$ with induced parameter ϕ_T , then, by (2), the element b is unramified, and we require that ρ is isomorphic to an irreducible subquotient of $i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$ for $w \in W_b$, where $\chi : T(\mathbb{Q}_p) \rightarrow \overline{\mathbb{Q}_\ell}^*$ is the character attached to ϕ_T by class field theory and δ_{P_b} is the character defined in [HI25, Definition 3.14]. Here the map ${}^L T \rightarrow {}^L G$ is the non-twisted embedding and the map ${}^L J_b \rightarrow {}^L G$ is the twisted embedding.*

Remark 6.6. This assumption might seem a bit daunting, but is verifiable in many cases. In particular, the first assumption follows from the compatibility of the Fargues-Scholze correspondence with the Harris-Taylor correspondence for groups of type A_n and its inner forms ([HKW22, Theorem 1.0.3]). Similarly, for groups of type C_2 and their inner forms over a unramified extension L with $p > 2$, this follows from the main theorem of [Ham25], and, for odd unramified unitary groups over $\mathbb{Q}_p$ this follows from the main theorem of [BHN22]. The methods employed in these two papers should generalize to at least a few other cases.

Assumption (2) is also a standard and verifiable conjecture in the cases where the local Langlands correspondence is known to exist. If ρ is a representation such that ϕ_ρ factors through ${}^L T$ then we are claiming that J_b has a Borel subgroup. For non quasi-split groups, it is conjectured that one should only consider L -parameters coming from the L -groups of the Levi subgroups of the non quasi-split group. These are referred to as relevant L -parameters. In particular, one expects the L -packets of LLC_b over irrelevant ϕ to be empty (See for example [Kal16, Conjecture A.2]), so if ϕ_ρ factors through ${}^L T$ for some ρ under LLC_b it should imply that the group J_b has a Borel B_b . Assumption (3) is just the expectation that, when ϕ_ρ factors through ${}^L T$, the members of the L -packet should be given by the irreducible constituents of the parabolic inductions from T to J_b . The Weyl group twists appear since the Weyl group conjugates of $\phi_\rho : W_{\mathbb{Q}_p} \rightarrow {}^L J_b(\overline{\mathbb{Q}_\ell}) \simeq {}^L M_b(\overline{\mathbb{Q}_\ell})$ all map to the same parameter when viewed as a parameter valued in ${}^L G$, and the modulus twist by $\delta_{P_b}^{-1/2}$ appears since we are comparing this to an L -parameter of G via the twisted embedding ${}^L J_b(\overline{\mathbb{Q}_\ell}) \simeq {}^L M_b(\overline{\mathbb{Q}_\ell}) \rightarrow {}^L G(\overline{\mathbb{Q}_\ell})$ (cf. [HI25, Page 24-25]).

Under this assumption, we will deduce our main Corollary of the filtered eigensheaf property.

Corollary 6.7. *Under Assumption 6.5, consider $b \in B(G)$ with corresponding locally closed HN-strata $\text{Bun}_G^b \subset \text{Bun}_G$. For ϕ a generic parameter, the following is true.*

- (1) *If $b \notin B(G)_{\text{un}}$ the restriction*

$$\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b}$$

vanishes.

- (2) *If $b \in B(G)_{\text{un}}$ is an unramified element and ρ is a smooth irreducible $\overline{\mathbb{F}_\ell}$ -representation occurring as a constituent of $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b}$ then ρ is an irreducible constituent of $i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$ for some $w \in W_b$.*

Proof. As noted above, $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b}$ will be valued in an unbounded complex of smooth $\overline{\mathbb{F}_\ell}$ -representations of the σ -centralizer J_b of b . If we consider a smooth irreducible constituent of this restriction ρ then, as already discussed above, it follows that the Fargues-Scholze parameter $\phi_\rho^{\text{FS}} : W_{\mathbb{Q}_p} \rightarrow {}^L J_b(\overline{\mathbb{F}_\ell})$ under the twisted embedding

$${}^L J_b(\overline{\mathbb{F}_\ell}) \rightarrow {}^L G(\overline{\mathbb{F}_\ell})$$

agrees with ϕ . Using [Dat05, Lemma 6.8], we can choose $\tilde{\rho}$ a lift of ρ to a smooth irreducible $\overline{\mathbb{Q}_\ell}$ -representation admitting a $J_b(\mathbb{Q}_p)$ -stable $\overline{\mathbb{Z}_\ell}$ -lattice such that ρ occurs as a subquotient of $\tilde{\rho} \bmod \ell$. Since the Fargues-Scholze correspondence is compatible with reduction mod ℓ (by the Λ -linearity of the maps appearing in [FS, Theorem IX.5.2]), it follows that the Fargues-Scholze parameter $\phi_{\tilde{\rho}}^{\text{FS}}$ factors through ${}^L G(\overline{\mathbb{Z}_\ell})$ and that it equals $\phi_\rho^{\text{FS}} \bmod \ell$. Now, since ϕ_ρ^{FS} factors through ${}^L T$ and induces a generic parameter, we claim that the same is true for $\phi_{\tilde{\rho}}^{\text{FS}}$. This follows through standard deformation theory. In particular, if

$$H^1(W_{\mathbb{Q}_p}, \alpha \circ \phi_T)$$

vanishes for all Γ -orbits α of roots, then any lift of ϕ_ρ^{FS} will factor through ${}^L T$, but this vanishing is guaranteed by ϕ_T being generic (cf. [CS17, Lemma 6.2.2]). It is also easy to see that $\phi_{\tilde{\rho}}^{\text{FS}}$ must

be generic since its mod ℓ reduction is. Now, by Assumption 6.5, we note that $\phi_{\tilde{\rho}}^{\text{FS}}$ is the semi-simplification of $\phi_{\tilde{\rho}}$, the L -parameter attached to $\tilde{\rho}$, but by Lemma 3.14 and genericity that implies that $\phi_{\tilde{\rho}}|_{W_{\mathbb{Q}_p}} = \phi_{\tilde{\rho}}^{\text{FS}}$. The two claims now follow from Assumptions 6.5 (2) and (3), respectively. $\square$

This statement will allow us to give a complete description of the eigensheaf $\text{nEis}(\mathcal{S}_{\phi_T})$ for ϕ_T satisfying the slightly stronger condition of generic regularity. In particular, as we will see in §9, for the restrictions of the sheaf to Bun_G^b for $b \in B(G)_{\text{un}}$, we will always be able to evaluate the stalks in terms of normalized parabolic inductions of Weyl group translates of the character χ , and, by the previous Corollary, we know these are the only possible non-zero stalks.

Now we turn our attention to studying how the geometric Eisenstein functor interacts with Verdier duality.

7. SECOND ADJOINTNESS AND THE ULA PROPERTY

In this section, we recall two important results from the paper [HHS24]. First, we recall the statement of geometric second adjointness. We will consider the following geometric constant term functors.

$$\text{nCT}_* : \text{D}(\text{Bun}_G) \rightarrow \text{D}(\text{Bun}_T)$$

$$A \mapsto \mathbf{q}_*(\mathbf{p}^!(A) \otimes \text{IC}_{\text{Bun}_B}^{-1})$$

and

$$\text{nCT}_! : \text{D}(\text{Bun}_G) \rightarrow \text{D}(\text{Bun}_T)$$

$$A \mapsto \mathbf{q}_!(\mathbf{p}^*(A) \otimes \text{IC}_{\text{Bun}_B}).$$

These satisfy adjunction relationships

$$(\text{nEis}(-), \text{nCT}_*(-))$$

and

$$(\text{nCT}_!(-), \text{nEis}_*(-)).$$

Here we recall $\text{nEis}_*(-) := \mathbf{p}_*(\mathbf{q}^*(-) \otimes \text{IC}_{\text{Bun}_B})$, and for the second relationship, we have used that $\mathbf{q}^!(\Lambda) \simeq \text{IC}_{\text{Bun}_B}^{\otimes 2}$, by Theorem 5.6.

We will use the subscripts $(-)_-$ to denote the analogous functors formed with respect to the diagram attached to Bun_{B^-} , where B^- denotes the opposite Borel. We now have the following result, which is a geometric analogue of the classical second adjointness result.

Theorem 7.1. *[HHS24, Theorem 1.1.1 (3)], [Tak24, Theorem 2.5] There is a natural isomorphism*

$$\text{nCT}_{-!}(-) \simeq \text{nCT}_*(-)$$

of functors $\text{D}(\text{Bun}_G) \rightarrow \text{D}(\text{Bun}_T)$.

This expression will be used in the next section to show the commutation of Eisenstein series with Verdier duality, by allowing us to rewrite certain constant term functors. We also have the following key finiteness result.

Theorem 7.2. *[HHS24, Theorem 1.1.2 (1)] The functor*

$$\text{nEis}(-) : \text{D}(\text{Bun}_T) \rightarrow \text{D}(\text{Bun}_G)$$

preserves ULA objects after restricting to finitely many connected components of Bun_T .

In particular, this will be used in the next section to show that the Eisenstein functor $\text{nEis}(\mathcal{S}_{\phi_T})$ has stalks valued in finite length representations after restricting to connecting components and assuming 6.5.

8. STALKS OF GEOMETRIC EISENSTEIN SERIES AND VERDIER DUALITY

8.1. Stalks of Geometric Eisenstein Series. Now our aim is to explicitly determine the stalks of the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T})$, when ϕ_T is generic regular. Recall this means that ϕ_T is generic, and, for all $w \in W_G$ non-trivial, $\chi \not\sim \chi^w$. Genericity will allow us to apply the results of Corollary 6.7, and the second condition will appear naturally in the computation of the stalks. It is helpful to treat each connected component separately. In particular, using Corollary 5.3, we consider the decomposition:

$$\mathrm{nEis}(\mathcal{S}_{\phi_T}) = \bigoplus_{\bar{\nu} \in B(T)} \mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T})$$

The main result of this section is as follows.

Theorem 8.1. *Consider ϕ_T a generic regular parameter with associated character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$. We fix $\bar{\nu} \in B(T)$ with image $b \in B(G)_{\mathrm{un}}$, dominant reduction b_T , and associated Borel B_b . Using Corollary 2.11, we can write $\bar{\nu} = w(b_T)$ for a unique $w \in W_b$. Then we have an isomorphism*

$$\mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T}) \simeq j_b!(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2})[-\langle 2\hat{\rho}, \nu_b \rangle]$$

under the identification $D(J_b(\mathbb{Q}_p), \Lambda) \simeq D(\mathrm{Bun}_G^b)$, where $j_b : \mathrm{Bun}_G^b \rightarrow \mathrm{Bun}_G$ is the locally closed immersion defined by the HN-stratum corresponding to b , and P_b is the standard parabolic with Levi factor $M_b \simeq J_b$.

By varying $\bar{\nu}$ over all connected components, we obtain the following.

Corollary 8.2. *Consider ϕ_T a generic regular parameter, with associated character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$. Assume 6.5. For $b \in B(G)$, the stalk $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \in D(\mathrm{Bun}_G^b) \simeq D(J_b(\mathbb{Q}_p), \Lambda)$ is given by*

- (1) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq \bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$ if $b \in B(G)_{\mathrm{un}}$,*
- (2) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq 0$ if $b \notin B(G)_{\mathrm{un}}$.*

First, consider the following easy Lemma.

Lemma 8.3. *For $\bar{\nu} \in B(T)$ with image b in $B(G)$, the restriction*

$$\mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^{b'}}$$

for $b' \in B(G)$ vanishes unless $b \succeq b'$ in the natural partial ordering on $B(G)$.

Proof. This follows from the observation that the image of $\mathrm{Bun}_B^{\bar{\nu}}$ under $\mathbf{p}^{\bar{\nu}}$ is contained in the open substack $\mathrm{Bun}_B^{\leq b}$ parametrizing bundles with associated Kottwitz element less than b . In particular, using the Tannakian formalism [Zie15, Theorems 4.42, 4.43], this reduces to the observation that, for GL_n , a bundle $\mathcal{E}$ with a filtration by vector subbundles has Harder-Narasimhan polygon less than or equal to Harder-Narasimhan polygon of the direct sum of the graded pieces of the filtration, which is an easy consequence of the formalism of Harder-Narasimhan reductions (See for example [Ked17, Corollary 3.4.18]). $\square$

Thus, for a fixed $b' \in B(G)$, Lemma 8.3 tells us that $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^{b'}}$ is a direct sum of $\mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^{b'}}$ for $\bar{\nu}$ whose image $b \in B(G)$ satisfies $b \succeq b'$. Now the key point is that, under the generic regularity assumption, all the contributions will vanish except when $b' = b$. This is one of the many reasons that generic regularity is absolutely necessary to get a reasonable eigen-sheaf. In general, all possible $\bar{\nu}$ contribute to $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^{b'}}$, and $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^{b'}}$ will be equal to an infinite direct sum of smooth irreducible representations sitting in infinitely many degrees. We now reduce Theorem 8.1 to two propositions. We first have the following proposition describing the contribution of the split reduction in the connected components $\mathrm{Bun}_B^{\bar{\nu}}$, which is a special case of [HI25, Theorem 4.26].

Proposition 8.4. *Let $\bar{v} \in B(T)$ be an element mapping to $b \in B(G)_{\text{un}}$. We write $\bar{v} = w(b_T)$ as above. If ϕ_T is any toral parameter, we have an isomorphism*

$$\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b} \simeq i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$$

of complexes of smooth $J_b(\mathbb{Q}_p)$ -modules, under the identification $D(\text{Bun}_G^b) \simeq D(J_b(\mathbb{Q}_p), \Lambda)$, where $w \in W_b$ is identified with a representative of minimal length and δ_{P_b} is as in assumption 6.5.

This tells us that all the claimed contributions to the restriction $\text{nEis}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^b}$ appear. All that remains is to show is that there are no additional contributions, and this is precisely what generic regularity will allow us to do.

Proposition 8.5. *Assume ϕ_T is generic regular and 6.5, then, for all $\bar{v} \in B(T)$ mapping to $b \in B(G)_{\text{un}}$, the sheaf $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})$ is only supported on the HN-strata Bun_G^b .*

We now prove this Proposition.

8.1.1. *The Proof of Proposition 8.5.* We argue by induction on $b \in B(G)_{\text{un}}$ with respect to the partial ordering on $B(G)$ and the following stronger statement.

"For $b \in B(G)_{\text{un}}$ with dominant reduction b_T , and $\bar{v} = w(b_T) \in B(T)$ mapping to b for varying $w \in W_b$, we have an isomorphism

$$\text{nEis}^{w(b_T)}(\mathcal{S}_{\phi_T}) \simeq j_{b!}(i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2})[-\langle 2\hat{\rho}, \nu_b \rangle]$$

of sheaves in $D(\text{Bun}_G)$."

The base case will be when b is such that any $b' \in B(G)_{\text{un}}$ satisfying $b \succeq b'$ is equal to b . Since the stalk of $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$ will only be non-trivial for $b' \in B(G)$ such that $b \succeq b'$ by Lemma 8.3, the result in this case follows from Proposition 8.4 and Corollary 6.7 (1), where we note that ϕ_T is generic regular and therefore generic. For the inductive step, assume the claim is true for all $b' \in B(G)_{\text{un}}$ such that $b \succeq b'$. Let $\bar{v} \in B(T)$ be an element mapping to b . By Proposition 8.4 and Corollary 6.7 (1) again, it suffices to show that the restriction of $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})$ to $\text{Bun}_G^{b'}$ vanishes for all such b' . By Corollary 6.7 (2), it suffices to show, for all $w \in W_{b'}$, that the complex

$$R\mathcal{H}om(\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}, i_{B_{b'}}^{J_{b'}}(\chi^w) \otimes \delta_{P_{b'}}^{-1/2}) = R\mathcal{H}om(\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T}), j_{b'*}(i_{B_{b'}}^{J_{b'}}(\chi^w) \otimes \delta_{P_{b'}}^{-1/2}))$$

is trivial. In particular, since, by Corollary 7.2, we know that $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})$ is ULA and it follows that $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$ is admissible in the sense that, for all compact open $K \subset J_b(\mathbb{Q}_p)$, $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})^K|_{\text{Bun}_G^{b'}}$ is a perfect complex. By Corollary 6.7 (2) and [Vig96, p. II.5.13], we know that there are only finitely many possibilities for smooth irreducible constituents of $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$. Therefore, by choosing $K \subset G(\mathbb{Q}_p)$ sufficiently small (so that every such constituent has a non-zero fixed vector), we deduce that $\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T})|_{\text{Bun}_G^{b'}}$ is a complex with finite length cohomology, which reduces us to showing that the previous complex is trivial. To do this, let $\bar{v}' = w(b'_T)$ be the element mapping to $b' \in B(G)$ defined by $w \in W_{b'}$. Our inductive hypothesis tells us that we have an isomorphism

$$j_{b'!}(i_{B_{b'}}^{J_{b'}}(\chi^w) \otimes \delta_{P_{b'}}^{-1/2})[-\langle 2\hat{\rho}, \nu_{b'} \rangle] \simeq \text{nEis}^{\bar{v}'}(\mathcal{S}_{\phi_T})$$

varying over $\bar{v}'$ mapping to $b' \in B(G)$. Using Theorem 5.6 and our inductive hypothesis together with the fact that generic regularity is stable under replacing ϕ_T by $\phi_T^\vee$, it follows that we have an isomorphism $\text{nEis}^{\bar{v}'}(\mathcal{S}_{\phi_T}) \simeq j_{b'*}(i_{B_{b'}}^{J_{b'}}(\chi^w) \otimes \delta_{P_{b'}}^{-1/2})[-\langle 2\hat{\rho}, \nu_b \rangle]$. Therefore, it then suffices to show, for all $\bar{v}'$ mapping to $b' \in B(G)_{\text{un}}$ and $\bar{v}$ mapping to $b \in B(G)_{\text{un}}$, that

$$R\mathcal{H}om(\text{nEis}^{\bar{v}}(\mathcal{S}_{\phi_T}), \text{nEis}_*^{\bar{v}'}(\mathcal{S}_{\phi_T}))$$

is trivial. To aid our analysis, we consider the following unnormalized version of the constant term functor

$$\mathrm{CT}_*^{\bar{\nu}}(-) := \mathbf{q}_*^{\bar{\nu}} \circ \mathbf{p}^{\bar{\nu}!}(-)[- \dim(\mathrm{Bun}_B^{\bar{\nu}})] : \mathrm{D}(\mathrm{Bun}_G) \rightarrow \mathrm{D}(\mathrm{Bun}_T^{\bar{\nu}})$$

which is in particular the right adjoint of the unnormalized Eisenstein functor $\mathrm{Eis}^{\bar{\nu}}(-) := \mathbf{p}_!(\mathbf{q}^*(-)[\dim(\mathrm{Bun}_B^{\bar{\nu}})])$. The unnormalized version of the functors considered in §8. Writing $\mathrm{nEis}^{\bar{\nu}}(\mathcal{S}_{\phi_T})$ as $\mathrm{Eis}^{\bar{\nu}}(\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2})$ and using adjunction, it suffices to show that the complex

$$R\mathcal{H}om_{T(\mathbb{Q}_p)}(\chi \otimes \delta_B^{1/2}, \mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T}))$$

is trivial in $\mathrm{D}(\mathrm{Bun}_T^{\bar{\nu}}) \simeq \mathrm{D}(T(\mathbb{Q}_p), \Lambda)$. To show this, we first look at the diagram

$$\begin{array}{ccccc} \mathrm{Bun}_B^{\bar{\nu}} \times_{\mathrm{Bun}_G} \mathrm{Bun}_B^{\bar{\nu}'} & \xrightarrow{\mathbf{p}^{\bar{\nu}'}} & \mathrm{Bun}_B^{\bar{\nu}'} & \xrightarrow{\mathbf{q}^{\bar{\nu}'}} & \mathrm{Bun}_T^{\bar{\nu}'} \\ \downarrow \mathbf{p}^{\bar{\nu}'} & & \downarrow \mathbf{p}^{\bar{\nu}'} & & \\ \mathrm{Bun}_B^{\bar{\nu}} & \xrightarrow{\mathbf{p}^{\bar{\nu}}} & \mathrm{Bun}_G & & \\ \downarrow \mathbf{q}^{\bar{\nu}} & & & & \\ \mathrm{Bun}_T^{\bar{\nu}} & & & & \end{array}$$

and note, by base-change, that we have a natural isomorphism

$$\mathbf{q}_*^{\bar{\nu}} \circ \mathbf{p}^{\bar{\nu}!} \circ \mathbf{p}_*^{\bar{\nu}'} \circ \mathbf{q}^{\bar{\nu}'*}(-) \simeq \mathbf{q}_*^{\bar{\nu}} \circ \mathbf{p}_*^{\bar{\nu}'} \circ \mathbf{p}^{\bar{\nu}!} \circ \mathbf{q}^{\bar{\nu}'*}(-)$$

of derived functors $\mathrm{D}(\mathrm{Bun}_T^{\bar{\nu}'}) \rightarrow \mathrm{D}(\mathrm{Bun}_T^{\bar{\nu}})$. This tells us that $\mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T})$ is the direct image of the complex

$$\mathbf{p}^{\bar{\nu}!}(\mathbf{q}^{\bar{\nu}'*}(\mathcal{S}_{\phi_T} \otimes \Delta_B^{1/2}))[\dim(\mathrm{Bun}_B^{\bar{\nu}'} - \dim(\mathrm{Bun}_B^{\bar{\nu}}))]$$

on $\mathrm{Bun}_B^{\bar{\nu}} \times_{\mathrm{Bun}_G} \mathrm{Bun}_B^{\bar{\nu}'}$ onto $\mathrm{Bun}_T^{\bar{\nu}}$. By [Ham21, Lemma 4.9], the space $\mathrm{Bun}_B^{\bar{\nu}} \times_{\mathrm{Bun}_G} \mathrm{Bun}_B^{\bar{\nu}'}$ has a locally closed stratification given by the generic relative position of the two bundles

$$\bigsqcup_{w \in W_G} (\mathrm{Bun}_B^{\bar{\nu}} \times_{\mathrm{Bun}_G} \mathrm{Bun}_B^{\bar{\nu}'})_w$$

which we denote by $Z_w^{\bar{\nu}, \bar{\nu}'}$ for varying $w \in W_G$. Using the excision spectral sequence, this implies that $\mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T})$ also admits a filtration whose graded pieces we write as $(\mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T}))_w$. Consider the following claim.

Proposition 8.6. *Let $\bar{\nu}$ and $\bar{\nu}'$ be two elements mapping to b and b' in $B(G)_{\mathrm{un}}$, respectively.*

- (1) *Suppose that $b \neq b'$ then the stack $Z_w^{\bar{\nu}, \bar{\nu}'}$ is empty if $w = 1$.*
- (2) *If $w \neq 1$ then $(\mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T}))_w$ in $\mathrm{D}(T(\mathbb{Q}_p), \Lambda)$ is isomorphic to $\chi^w \otimes \delta_B^{1/2}$ tensored by a complex of $\mathbb{F}_\ell$ -vector spaces.*

First, let's finish the proof of Proposition 8.5 assuming this. By the above discussion, it suffices to show that the complex

$$R\mathcal{H}om_{T(\mathbb{Q}_p)}(\chi \otimes \delta_B^{1/2}, (\mathrm{CT}_*^{\bar{\nu}} \circ \mathrm{nEis}_*^{\bar{\nu}'}(\mathcal{S}_{\phi_T}))_w)$$

is trivial for all $w \in W_G$. This is trivial if $w = 1$ by point (1). If $w \neq 1$, then it follows from point (2) and the fact that the existence of an isomorphism $\chi \otimes \delta_B^{1/2} \simeq \chi^w \otimes \delta_B^{1/2}$ would imply an isomorphism $\chi \simeq \chi^w$, which contradict Condition 3.6 (2), the regularity component of the definition of generic regularity. Therefore, since ϕ_T is generic regular by assumption, the claim follows. Let's now finish up by reducing this Proposition to a simpler claim, which we will prove in the next section. Proposition 8.6 is an analogue of [BG08, Proposition 10.8] and the idea behind its proof is the same.

Proof. (Proposition 8.6) We first begin by elucidating the geometry of the spaces $Z_w^{\bar{\nu}, \bar{\nu}'}$ a bit more. For $S \in \text{Perf}$, note that a S -point of $\text{Bun}_B^{\bar{\nu}} \times_{\text{Bun}_G} \text{Bun}_B^{\bar{\nu}'}$ corresponds to a pair of B -structures on a G -bundle $\mathcal{F}_G$ on X_S . Namely, it parametrizes a pair $\mathcal{F}_B^1$ (resp. $\mathcal{F}_B^2$) of two B -structures on a G -bundle $\mathcal{F}_G$ whose reduction to T , denoted $\mathcal{F}_T^1$ (resp. $\mathcal{F}_T^2$) is isomorphic to $\mathcal{F}_{\bar{\nu}}$ (resp. $\mathcal{F}_{\bar{\nu}'}$) after pulling back to any geometric point of S . We can think of it as parameterizing sections

$$X_S \rightarrow B \backslash G/B$$

such that the degree is of the specified form. More transparently, we can think of a point of $\text{Bun}_B^{\bar{\nu}} \times_{\text{Bun}_G} \text{Bun}_B^{\bar{\nu}'}$ as the B -bundle $\mathcal{F}_B^2$ together with a section

$$s : X_S \rightarrow \mathcal{F}_B^2 \times^B G/B$$

where B acts via conjugation on G/B . For $\hat{\lambda} \in \hat{\Lambda}_G^+$, we recall that by interpreting $\mathcal{V}^{\hat{\lambda}}$ as global sections of the appropriately twisted bundle on G/B corresponding to $\hat{\lambda}$ under Borel-Weil-Bott, every point in G/B gives rise to a line $\ell^{\hat{\lambda}} \subset \mathcal{V}^{\hat{\lambda}}$. We consider the B -stable subspace $\mathcal{V}_{\geq w}^{\hat{\lambda}} \subset \mathcal{V}^{\hat{\lambda}}$ consisting of weights greater than or equal to $w(\hat{\lambda})$ and $\mathcal{V}_{> w}^{\hat{\lambda}} \subset \mathcal{V}_{\geq w}^{\hat{\lambda}}$ the codimension 1 subspace consisting of weights strictly greater than $w(\hat{\lambda})$. We let $(G/B)_w := BwB/B$ be the locally closed Schubert cell attached to $w \in W_G$. We write $(G/B)_{\geq w}$ for its closure. The closure is stratified by the Schubert cells indexed by elements $w' \in W_G$ with length less than or equal to w . Then the line $\ell^{\hat{\lambda}} \subset \mathcal{V}^{\hat{\lambda}}$ will correspond to a point in $(G/B)_{\geq w}$ if and only if it belongs to $\mathcal{V}_{\geq w}^{\hat{\lambda}}$ for all $\hat{\lambda} \in \hat{\Lambda}_G^+$. Moreover, the point belongs to the stratum $(G/B)_w$ if and only if the projection to $\mathcal{V}_{\geq w}^{\hat{\lambda}}/\mathcal{V}_{> w}^{\hat{\lambda}}$ is non-zero. This allows us to explain what it means to lie in the locally closed stratum $Z_w^{\bar{\nu}, \bar{\nu}'}$. In particular, by definition [Ham21, Page 26], lying in this stratum is equivalent to the condition that s factors through $\mathcal{F}_B^2 \times^B (G/B)_{\geq w}$ and is not contained in any closed strata defined by $\mathcal{F}_B^2 \times^B (G/B)_{\geq w'}$ for any $w' > w$ in the Bruhat order. This implies that the section s determines a set of line subbundles

$$\mathcal{L}_{\mathcal{F}_T^1}^{\hat{\lambda}} \rightarrow (\mathcal{V}_{\geq w}^{\hat{\lambda}})_{\mathcal{F}_B^2}$$

for all $\hat{\lambda} \in \hat{\Lambda}_G^+$. Moreover, via the inclusion $\mathcal{V}_{\geq w}^{\hat{\lambda}} \subset \mathcal{V}^{\hat{\lambda}}$, these give the Plücker description of the B -structure $\mathcal{F}_B^1$ such that $\mathcal{F}_G \simeq \mathcal{F}_B^1 \times^B G \simeq \mathcal{F}_B^2 \times^B G$. For this to define a point in $Z_w^{\bar{\nu}, \bar{\nu}'}$, these need to satisfy the condition that the induced map

$$\mathcal{L}_{\mathcal{F}_T^1}^{\hat{\lambda}} \rightarrow (\mathcal{V}_{\geq w}^{\hat{\lambda}})_{\mathcal{F}_B^2} \rightarrow (\mathcal{V}_{\geq w}^{\hat{\lambda}}/\mathcal{V}_{> w}^{\hat{\lambda}})_{\mathcal{F}_B^2} = (\mathcal{L}^{\hat{\lambda}})_{(\mathcal{F}_T^2)^w}$$

is non-zero map of $\mathcal{O}_{X_S}$ -modules (cf. [Bra+02, Page 14], [BG08, Page 48], [Sch15, Propositions 4.3.2, 4.4.2]). In particular, since $\mathcal{L}_{\mathcal{F}_T^1}^{\hat{\lambda}}$ is a line bundle, the map being non-zero implies it is a fiberwise injective map of line bundles. Now, recalling our choice of Borel, if we define $\theta := \bar{\nu} - w(\bar{\nu}')$ then the support of the torsion of the cokernel of this map of line bundles determines a point in $\text{Div}^{(\theta)}$, by the assumptions on the degrees and [HHS24, Lemma 4.2.9]. For this strata to be non-empty, we must have that $\theta \in \Lambda_{G,B}^{\text{pos}}$. Therefore, for all non-empty strata, we have a map:

$$\pi_w : Z_w^{\bar{\nu}, \bar{\nu}'} \rightarrow \text{Div}^{(\theta)}.$$

Now, with these preparations out of the way, let's start with the proof. For Point (1), note that if $w = 1$ then we have an injective map of line bundles

$$\mathcal{L}_{\mathcal{F}_T^1}^{\hat{\lambda}} \rightarrow \mathcal{L}_{\mathcal{F}_T^2}^{\hat{\lambda}}$$

for all $\hat{\lambda}$, which give rise to the embeddings defined by $\mathcal{F}_B^1$ when composed with the injections of bundles $\mathcal{L}_{\mathcal{F}_T^2}^{\hat{\lambda}} \rightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$ defined by $\mathcal{F}_B^2$, by construction. However, since the composition $\mathcal{L}_{\mathcal{F}_T^1}^{\hat{\lambda}} \rightarrow \mathcal{V}_{\mathcal{F}_G}^{\hat{\lambda}}$ is also a map of vector bundles, this is impossible unless $\mathcal{F}_T^1 \simeq \mathcal{F}_T^2$, which would contradict our

assumption that $\bar{v}, \bar{v}' \in B(T)$ map to $b \neq b'$ in $B(G)$. Therefore, we have established point (1). For point (2), we write $\mathbf{q}_1$ (resp. $\mathbf{q}_2$) for the natural projections of $Z_w^{\bar{v}, \bar{v}'}$ to $\text{Bun}_T^{\bar{v}}$ (resp. $\text{Bun}_T^{\bar{v}'}$). We note, by the above discussion, that $\mathbf{q}_2$ is equal to the composition

$$Z_w^{\bar{v}, \bar{v}'} \xrightarrow{\mathbf{q}_1 \times \pi_w} \text{Bun}_T^{\bar{v}} \times \text{Div}^{(\theta)} \xrightarrow{\text{op} h_{(\bar{\theta})}^{\rightarrow}} \text{Bun}_T^{w(\bar{v}')} \xrightarrow{w^{-1}} \text{Bun}_T^{\bar{v}'}$$

where $\text{op} h_{(\bar{\theta})}^{\rightarrow}$ is the map sending $(\mathcal{F}_T, (D_i)_{i \in \mathcal{I}})$ to the bundle $\mathcal{F}_T(\sum_{i \in \mathcal{I}} \alpha_i \cdot D_i)$ and the last map is given by conjugation by w on Bun_T . Recall, $(\text{CT}_*^{\bar{v}} \circ \text{nEis}_*^{\bar{v}'}(\mathcal{S}_{\phi_T}))_w$ is given (up to a shift) by the sheaf

$$\mathbf{q}_{1*} \circ {}' \mathbf{p}^{\bar{v}'} \circ \mathbf{q}^{\bar{v}'}(\chi \otimes \delta_B^{1/2}).$$

We can write this as the Verdier dual of $\mathbf{q}_{1!} \circ {}' \mathbf{p}^{\bar{v}'} \circ \mathbf{q}^{\bar{v}'}(\chi^{-1} \otimes (\delta_B^{1/2})^{-1}) \simeq \mathbf{q}_{1!} \circ {}' \mathbf{p}^{\bar{v}'} \circ \mathbf{q}^{\bar{v}'}(\chi^{-1} \otimes \delta_B^{1/2})$, where the last isomorphism is Theorem 5.6. Replacing χ by χ^{-1} , this reduces us to showing that $\mathbf{q}_{1!} \circ {}' \mathbf{p}^{\bar{v}'} \circ \mathbf{q}^{\bar{v}'}(\chi \otimes \delta_B^{1/2}) \simeq \mathbf{q}_{1!} \circ \mathbf{q}_2^*(\chi \otimes \delta_B^{1/2})$ is isomorphic to $\chi^w \otimes \delta_B^{-1/2}$ tensored by a complex of $\mathbb{F}_\ell$ -vector spaces. Using the above factorization of $\mathbf{q}_2$, we rewrite this as

$$\mathbf{q}_{1!} \circ (\mathbf{q}_1 \times \pi_w)^* \circ (\text{op} h_{(\bar{\theta})}^{\rightarrow})^* \circ (w^{-1})^*(\chi \otimes \delta_B^{1/2}) \simeq \mathbf{q}_{1!} \circ (\mathbf{q}_1 \times \pi_w)^*((\chi^w \otimes (\delta_B^{1/2})^w) \boxtimes (E_{\phi_T^w \otimes (\hat{\rho}^w \circ |\cdot|)}^{(\theta)})^\vee)$$

but now, we claim, we are reduced to the following, which is an analogue of [BG08, Proposition 10.10]

Proposition 8.7. *The direct image $(\mathbf{q}_1 \times \pi_w)_!(\Lambda)$ is isomorphic to a pullback of a complex on $\text{Div}^{(\theta)}$ along the projection map $\text{Bun}_T^{\bar{v}} \times \text{Div}^{(\theta)} \rightarrow \text{Div}^{(\theta)}$ tensored by $\delta_B^{-1} \otimes \delta_{B'}$, where $B' := TU' \subset B$ for $U' \subset U$ the subgroup generated by $\alpha > 0$ such that $w(\alpha) < 0$.*

□

In particular, by applying projection formula, this tells us that $\mathbf{q}_{1!} \circ \mathbf{q}_2^*(\chi \otimes \delta_B^{1/2})$ is isomorphic to $\chi^w \otimes (\delta_B^{1/2})^w \otimes \delta_B^{-1} \otimes \delta_{B'}$ tensored by the pullback of a complex on $\text{Div}^{(\theta)}$. However, we now easily check that we have an equality

$$(\delta_B^{1/2})^w \otimes \delta_B^{-1} \otimes \delta_{B'} \simeq \delta_B^{-1/2},$$

so that we indeed conclude that $\mathbf{q}_{1!} \circ \mathbf{q}_2^*(\chi \otimes \delta_B^{1/2})$ is isomorphic to $\chi^w \otimes \delta_B^{-1/2}$ tensored by the pullback of a complex on $\text{Div}^{(\theta)}$, as desired.

We will now prove Proposition 8.7 by relating the spaces $Z_w^{\bar{v}, \bar{v}'}$ to some variants of what are called Zastava or semi-infinite flag spaces in the classical literature, as first studied over function fields by Feign, Finkelberg, Kusnetsov, and Mirković [Fei+99; FM99].

8.1.2. Zastava Spaces. We recall that the unipotent part U' of the subgroup $B' \subset B$ appearing in proposition 8.7 acts simply transitively on the closed Schubert cell $(G/B)_{\geq w}$ and use this to define the w -twisted version of the Zastava space.

Definition 8.8. For $\theta \in \Lambda_{G,B}^{\text{pos}}$, we let $W_w^\theta \rightarrow \text{Div}^{(\theta)}$ be the v -sheaf parameterizing, for $S \in \text{Perf}$, a triple

$$(\mathcal{F}_{U'}, s, D)$$

of the datum:

- A U' -bundle $\mathcal{F}_{U'}$ on X_S .
- A section $s : X_S \rightarrow \mathcal{F}_{U'} \times^{U'} (G/B)_{\geq w}$ that does not lie in $(G/B)_{\geq w'}$ for any $w' > w$ in the Bruhat order.
- A divisor $D \in \text{Div}^{(\theta)}$ such that the induced non-zero ($\implies$ fiberwise injective) maps of line bundles

$$\mathcal{L}^{\hat{\lambda}} \rightarrow (\mathcal{V}_{\geq w}^{\hat{\lambda}})_{\mathcal{F}_{U'}} \rightarrow (\mathcal{V}_{\geq w}^{\hat{\lambda}} / \mathcal{V}_{> w}^{\hat{\lambda}})_{\mathcal{F}_{U'}} = \mathcal{O}_{X_S}$$

for all $\hat{\lambda} \in \hat{\Lambda}_G^+$ have cokernel with torsion supported on D .

Classically, the usual Zastava space in the literature is the same datum as above in the case that $w = w_0$ together with a level structure on the bundle $\mathcal{L}^\lambda$ so that it encodes information about enhanced B -structures on one of the factors. It's importance is that it provides a local model for the singularities of the Drinfeld compactification $\overline{\text{Bun}}_B$. The space we have defined above in the case that $w = w_0$ is the open part of the Zastava space which models just the space Bun_B . As seen in our description of $Z_w^{\bar{\nu}, \bar{\nu}'}$ in the previous section, this will clearly have a relationship to the spaces we are interested in describing. Let us first just consider the case of the element of longest length. We claim that the following is true.

Lemma 8.9. *For $w = w_0$ the element of longest length and $\theta = \bar{\nu} - w(\bar{\nu}') \in \Lambda_{G,B}^{\text{pos}}$ for $\bar{\nu}'$ and $\bar{\nu}$ as above, there exists a commutative diagram*

$$\begin{array}{ccc} Z_w^{\bar{\nu}, \bar{\nu}'} & \longrightarrow & W_w^\theta \\ \downarrow \mathfrak{q}_1 \times \pi_w & & \downarrow \\ \text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)} & \xrightarrow{p_2} & \text{Div}^{(\theta)} \end{array}$$

which is a Cartesian square.

Proof. When $w = w_0$, we have that $U' = U$ and $B' = B$. Given an S -point of W_w^θ , the maps

$$\mathcal{L}^\lambda \rightarrow (\mathcal{V}_{\geq w}^\lambda)_{\mathcal{F}_U} \hookrightarrow (\mathcal{V}^\lambda)_{\mathcal{F}_G}$$

of vector bundles on X_S define a B -structure $\mathcal{F}_B$ on the G -bundle $\mathcal{F}_U \times^U G$. We note that the induced map

$$\mathcal{L}^\lambda \rightarrow (\mathcal{V}_{\geq w}^\lambda)_{\mathcal{F}_U} \rightarrow (\mathcal{V}_{\geq w}^\lambda / \mathcal{V}_{> w}^\lambda)_{\mathcal{F}_U} = \mathcal{O}_{X_S}$$

with torsion cokernel of support given by $D \in \text{Div}^{(\theta)}$ induces an identification $\mathcal{L}^\lambda \simeq \mathcal{O}_{X_S}(-\langle \hat{\lambda}, \theta \rangle \cdot D)$ implying that $\mathcal{F}_B \times^B T$ has Kottwitz invariant given by $\theta = \bar{\nu} - w(\bar{\nu}')$ after pulling back to a geometric point. Given a bundle $\mathcal{F}_T^1 \in \text{Bun}_T^{\bar{\nu}}$ of degree $\bar{\nu}$, we can dualize the above maps to get a fiberwise injection

$$\mathcal{O}_{X_S} \rightarrow (\mathcal{L}^\lambda)^\vee \simeq \mathcal{O}_{X_S}(\langle \hat{\lambda}, \theta \rangle \cdot D)$$

of line bundles, and then tensor by $\mathcal{L}_{\mathcal{F}_T^1}^\lambda$ to get an injection

$$\mathcal{L}_{\mathcal{F}_T^1}^\lambda \rightarrow \mathcal{L}_{\mathcal{F}_T^1}^\lambda(\langle \hat{\lambda}, \theta \rangle \cdot D)$$

Similarly, by taking duals and twisting the U -torsor $\mathcal{F}_U$ by $\mathcal{F}_T^1$, we obtain $B = T \ltimes U$ -bundles $\mathcal{F}_B^1$ and $\mathcal{F}_B^2$ defining points in $Z_w^{\bar{\nu}, \bar{\nu}'}$, giving rise to a map

$$(\text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)}) \times_{\text{Div}^{(\theta)}} W_w^\theta \rightarrow Z_w^{\bar{\nu}, \bar{\nu}'}$$

which we can see is an isomorphism. In particular, given a point in $Z_w^{\bar{\nu}, \bar{\nu}'}$ corresponding to B -bundles $\mathcal{F}_B^1$ and $\mathcal{F}_B^2$ then we can define a U -bundle $\mathcal{F}_B^2 \times^B U$, and, as already seen in the previous section, we get a section $s : X_S \rightarrow \mathcal{F}_U \times^U (G/B)_{\geq w}$, $D \in \text{Div}^{(\theta)}$, and a T -bundle $\mathcal{F}_T^1$ of the desired form. $\square$

Now this lemma implies Proposition 8.7 in the case that $w = w_0$. In particular, under the isomorphism

$$(\text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)}) \times_{\text{Div}^{(\theta)}} W_w^\theta \simeq Z_w^{\bar{\nu}, \bar{\nu}'}$$

$\text{Bun}_T^{\bar{\nu}}$ splits off as direct factor, and so, by K nneth, we deduce the claim. Now we would like to apply a similar argument using the spaces W_w^θ in the case that w is a general element. However, we run into a problem that, in general, all we get is a map

$$(\text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)}) \times_{\text{Div}^{(\theta)}} W_w^\theta \rightarrow Z_w^{\bar{\nu}, \bar{\nu}'}$$

where attached to a point in $(\text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)}) \times_{\text{Div}^{(\theta)}} W_w^\theta$ we only get a B' -torsor $\mathcal{F}_{B'}^1$ with T -factor of degree $\bar{\nu}$. The above map is then given by a base-change of the natural map $f_{\bar{\nu}} : \text{Bun}_{B'}^{\bar{\nu}} \rightarrow \text{Bun}_B^{\bar{\nu}}$. In particular, if we let $\tilde{Z}_w^{\bar{\nu}, \bar{\nu}'} \rightarrow Z_w^{\bar{\nu}, \bar{\nu}'}$ be the base-change of $Z_w^{\bar{\nu}, \bar{\nu}'}$ along the map $f_{\bar{\nu}}$ then the analogue of this Lemma holds with $\tilde{Z}_w^{\bar{\nu}, \bar{\nu}'}$ in place of $Z_w^{\bar{\nu}, \bar{\nu}'}$ by the same argument. Now let's study the map $f_{\bar{\nu}} : \text{Bun}_{B'}^{\bar{\nu}} \rightarrow \text{Bun}_B^{\bar{\nu}}$ in a particular example and see how to prove Proposition 8.7 in this case.

Example 8.10. Suppose that $G = \text{GL}_3$ and let $\bar{\nu}$ correspond to a tuple of integers $(-e, -f, -g) \in \mathbb{Z}^3 \simeq B(T)$ via the Kottwitz invariant. We suppose w corresponds to the simple reflection exchanging the first and second basis vectors. After rigidifying the T -bundle $\mathcal{F}_T$ to be isomorphic to $(\mathcal{O}(e), \mathcal{O}(f), \mathcal{O}(g))$, we can view $\text{Bun}_B^{\bar{\nu}}$ as the moduli space of torsors under the U -torsor

$$\begin{pmatrix} 1 & \mathcal{O}(e) \otimes \mathcal{O}(f)^\vee & \mathcal{O}(e) \otimes \mathcal{O}(g)^\vee \\ 0 & 1 & \mathcal{O}(f) \otimes \mathcal{O}(g)^\vee \\ 0 & 0 & 1 \end{pmatrix}$$

over X , where the automorphisms (up to rigidification) of a point in $\text{Bun}_B^{\bar{\nu}}$ are given by considering the $\mathcal{H}^0$ Banach-Colmez spaces attached to these bundles. Similarly, after rigidification, we can view $\text{Bun}_{B'}^{\bar{\nu}}$ as the moduli space of torsors under the U' -torsor

$$\begin{pmatrix} 1 & \mathcal{O}(e) \otimes \mathcal{O}(f)^\vee & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

over X , and the map $f_{\bar{\nu}}$ is given by taking direct sums of the extension of $\mathcal{O}(e)$ by $\mathcal{O}(f)$ defined by the point in $\text{Bun}_{B'}^{\bar{\nu}}$ with $\mathcal{O}(g)$. In particular, we can see that the fibers of the map $f_{\bar{\nu}} : \text{Bun}_{B'}^{\bar{\nu}} \rightarrow \text{Bun}_B^{\bar{\nu}}$ are an iterated fibration in the Banach-Colmez spaces $\mathcal{H}^0(\mathcal{O}(e) \otimes \mathcal{O}(g)^\vee)$ and $\mathcal{H}^0(\mathcal{O}(f) \otimes \mathcal{O}(g)^\vee)$. If we assume that these Banach-Colmez spaces are positive it follows from the proof of [FS, Proposition V.2.1] that the adjunction

$$f_{\bar{\nu}}^! f_{\bar{\nu}} \rightarrow \text{id}$$

is an equivalence. In particular, combining this with the above discussion would give us the proof of Proposition 8.7 in this case. We now consider $d \in \mathbb{N}_{>0}$ and fix a closed point $\infty \in X$ in the Fargues-Fontaine curve over an algebraically closed complete field F in characteristic p . We look at the short-exact sequence of $\mathcal{O}_X$ -modules

$$0 \rightarrow \mathcal{O}_X(-d) \rightarrow \mathcal{O}_X \rightarrow \mathcal{O}_{X, \infty}/t_\infty^d \rightarrow 0$$

where $\mathcal{O}_{X, \infty}$ is the completed local ring and t_∞ is the uniformizing parameter corresponding to an untilt C of F . Tensoring by $\mathcal{O}(g)$, we get a short exact sequence:

$$0 \rightarrow \mathcal{O}_X(g-d) \rightarrow \mathcal{O}_X(g) \rightarrow \mathcal{O}_{X, \infty}/t_\infty^d \rightarrow 0$$

Let $\bar{\nu}_d$ correspond to the tuple of integers $(e, f, g-d) \in \mathbb{Z}^3$. Then we consider the natural map $f_{\bar{\nu}_d} : \text{Bun}_{B'}^{\bar{\nu}_d} \rightarrow \text{Bun}_B^{\bar{\nu}_d}$. If we choose d sufficiently large such that the spaces $\mathcal{H}^0(\mathcal{O}(e) \otimes \mathcal{O}_X(g-d)^\vee)$ and $\mathcal{H}^0(\mathcal{O}(f) \otimes \mathcal{O}_X(g-d)^\vee)$ are positive Banach-Colmez spaces then the fibers of $f_{\bar{\nu}_d}$ will be an iterated fibration in these positive Banach-Colmez spaces, and therefore we can again conclude that the adjunction

$$f_{\bar{\nu}_d}^! f_{\bar{\nu}_d} \rightarrow \text{id}$$

is an isomorphism. Now we claim that we have a map:

$$\text{Bun}_B^{\bar{\nu}} \rightarrow \text{Bun}_B^{\bar{\nu}_d}$$

Explicitly, given a point $\text{Bun}_{B'}^{\bar{\nu}}$, we have an exact sequence

$$0 \rightarrow \mathcal{E}_2 \rightarrow \mathcal{E} \rightarrow \mathcal{O}(g) \rightarrow 0$$

of bundles, where $\mathcal{E}_2$ is an extension of $\mathcal{O}(e)$ and $\mathcal{O}(f)$. We can then consider the pullback of this exact sequence with respect to the map $\mathcal{O}(g-d) \rightarrow \mathcal{O}(g)$ given by the modification, which will give

us a point in $\text{Bun}_B^{\bar{\nu}_d}$. We write $f_{\bar{\nu}, d\infty} : \text{Bun}_B^{\bar{\nu}, d\infty} := \text{Bun}_B^{\bar{\nu}} \times_{\text{Bun}_B^{\bar{\nu}_d}} \text{Bun}_{B'}^{\bar{\nu}_d} \rightarrow \text{Bun}_B^{\bar{\nu}}$ for the pullback of $f_{\bar{\nu}_d}$ along this map. We again conclude that the adjunction

$$f_{\bar{\nu}, d\infty}! f_{\bar{\nu}, d\infty}^! \rightarrow \text{id}$$

is an isomorphism. If we could use this map instead of $f_{\bar{\nu}}$, we could prove the claim by arguing as above. Indeed, consider $\mathbf{q}_1 \times \pi_w : Z_w^{\bar{\nu}, \bar{\nu}'} \rightarrow \text{Bun}_T^{\bar{\nu}} \times \text{Div}^{(\theta)}$. If we base-change all the above spaces to F , and let $(\text{Div} \setminus \infty)^{(\theta)}$ be the partially symmetrized power defined by $\text{Div}^1 \setminus \infty$, the open complement of the closed point $\infty \rightarrow \text{Div}^1$ defined by the fixed untillt, then, if we consider the map $\mathbf{q}_1 \times \pi_w : Z_w^{\bar{\nu}, \bar{\nu}'} \rightarrow \text{Bun}_T^{\bar{\nu}} \times (\text{Div} \setminus \infty)^{(\theta)}$ restricted to this locus, we can show that the base-change $Z_w^{\bar{\nu}, \bar{\nu}'}$ along $f_{\bar{\nu}, d\infty}$ sits in an analogous Cartesian square to Lemma 8.9, and deduce Proposition 8.7 for the restriction of $(\mathbf{q}_1 \times \pi_w)! f_{\bar{\nu}, d\infty}^! f_{\bar{\nu}, d\infty}^! (\Lambda) \simeq (\mathbf{q}_1 \times \pi_w)_! (\Lambda)$ to the open strata $(\text{Div} \setminus \infty)^{(\theta)} \subset \text{Div}^{(\theta)}$.

Therefore, this allows us to reduce Proposition 8.7 to studying this restriction by varying the untillt ∞ . More precisely, to see why the character twist by $\delta_{B'} \otimes \delta_B^{-1}$ appears in Proposition 8.7, we note that $\bar{f}_{\bar{\nu}_d} : \text{Bun}_{B'} \rightarrow \text{Bun}_B$ is ℓ -cohomologically smooth. In particular, one can show, by the exact same argument as [HI25, Proposition 3.9], that the dualizing complex of $\text{Bun}_{B'}$ is isomorphic to the sheaf $\Delta_{B'}$ on Bun_T given by the modulus character of $\delta_{B'}$ pulled back to $\text{Bun}_{B'}$ and given appropriate shifts, just as in Theorem 5.6. One can in turn compute the relative dualizing complex of $\bar{f}_{\bar{\nu}_d}$ in terms of the pullback of $\Delta_{B'} \otimes \Delta_B^{-1}$. We then see that $f_{\bar{\nu}, d\infty}$ is also ℓ -cohomologically smooth as a base-change of $\bar{f}_{\bar{\nu}_d}$ [Sch, Proposition 23.16] with dualizing object $f_{\bar{\nu}, d\infty}^! (\Lambda)$ computed in terms of $\Delta_{B'} \otimes \Delta_B^{-1}$ pulled back to the fiber product $\text{Bun}_B^{\bar{\nu}, d\infty}$. The claim in this case follows.

With this motivating example, all that remains is to formalize the above argument. In particular, first off note, by [FS, Corollary V.2.3], that for the proof of Proposition 8.7 it suffices to consider the base-change of all the above spaces to the base $* = \text{Spd}(F)$ for F an algebraically closed perfectoid field in characteristic p . We consider such a field with fixed characteristic 0 untillt C , and let $\infty \rightarrow \text{Div}^1$ be the closed F -point defined by this untillt. We consider the open complement $\text{Div}^1 \setminus \infty$, and the partially symmetrized powers $(\text{Div}^1 \setminus \infty)^{(\theta)}$ defined by the open subset. By applying excision, it suffices to verify Proposition 8.7 over this open subset with the claim over the closed complement being trivial. We abuse notation and write $Z_w^{\bar{\nu}, \bar{\nu}'}$ and W_w^θ for the base-change to this open subspace for the rest of the section. Now let's consider the spaces defined by the locally pro-finite sets $\underline{B}(\mathbb{Q}_p)$ (resp. $\underline{B}'(\mathbb{Q}_p)$), and the natural map

$$f_0 : \text{Bun}_{B'}^0 \simeq [*/\underline{B}'(\mathbb{Q}_p)] \rightarrow \text{Bun}_B^0 \simeq [*/\underline{B}(\mathbb{Q}_p)]$$

of v -stacks. The fibers of this map are an iterated fibration in $\mathcal{H}^0(\mathcal{O}_X) = \mathbb{Q}_p$ indexed by the positive roots $\hat{\alpha} > 0$ such that $w(\hat{\alpha}) > 0$. We choose $\bar{\nu}_\infty \in \mathbb{X}_*(T_{\mathbb{Q}_p})_\Gamma$ to be an element such that $\langle \bar{\nu}_\infty, \hat{\alpha} \rangle < 0$ for all $\hat{\alpha} > 0$ such that $w(\hat{\alpha}) > 0$. Recalling our choice of Borel, this implies that the map

$$f_{\bar{\nu}_\infty} : \text{Bun}_{B'}^{\bar{\nu}_\infty} \rightarrow \text{Bun}_B^{\bar{\nu}_\infty}$$

is a fibration in iterated positive Banach-Colmez spaces. We consider a modification $\mathcal{F}_T^0 \dashrightarrow \mathcal{F}_{\bar{\nu}_\infty}$ at ∞ of meromorphy $\bar{\nu}_\infty$. This modification induces a map

$$\text{Bun}_B^0 \rightarrow \text{Bun}_B^{\bar{\nu}_\infty}$$

which we precompose with the map

$$\text{Bun}_B^{\bar{\nu}} \rightarrow \text{Bun}_B^0$$

also given by an appropriate modification. This allows us to define

$$\text{Bun}_{B'}^{\bar{\nu}, \infty} := \text{Bun}_{B'}^{\bar{\nu}_\infty} \times_{\text{Bun}_B^{\bar{\nu}_\infty}} \text{Bun}_B^{\bar{\nu}}$$

by base-changing $f_{\bar{\nu}_\infty}$. We write

$$f_{\bar{\nu}, \infty} : \text{Bun}_{B'}^{\bar{\nu}, \infty} \rightarrow \text{Bun}_B^{\bar{\nu}}$$

for the base-change of $f_{\bar{\nu}\infty}$. By the proof of [FS, Proposition V.2.1], we have that the adjunction

$$f_{\bar{\nu},\infty}! f_{\bar{\nu},\infty}^! \rightarrow \text{id}$$

is an isomorphism, since $f_{\bar{\nu}\infty}$ and in turn $f_{\bar{\nu},\infty}$ is an iterated fibration of positive Banach-Colmez spaces. Now we define

$$\tilde{Z}_w^{\bar{\nu},\bar{\nu}'} := Z_w^{\bar{\nu},\bar{\nu}'} \times_{\text{Bun}_{\bar{B}}} \text{Bun}_{B'}^{\bar{\nu},\infty}$$

By the previous adjunction, it suffices to show the analogue of Proposition 8.7 for the composition

$$\tilde{Z}_w^{\bar{\nu},\bar{\nu}'} \rightarrow Z_w^{\bar{\nu},\bar{\nu}'} \xrightarrow{q_1 \times \pi_w} \text{Bun}_T^{\bar{\nu}} \times (\text{Div} \setminus \infty)^{(\theta)}$$

and the shriek pullback of the constant sheaf along the first map. However, by now arguing exactly as in the proof of Lemma 8.9, with B' and its unipotent radical U' replacing B and U , we can deduce that the base-change of $W_w^\theta \rightarrow (\text{Div} \setminus \infty)^{(\theta)}$ along $p_2 : \text{Bun}_T^{\bar{\nu}} \times (\text{Div} \setminus \infty)^{(\theta)} \rightarrow (\text{Div} \setminus \infty)^{(\theta)}$ is precisely the space $\tilde{Z}_w^{\bar{\nu},\bar{\nu}'}$. This concludes the proof of Proposition 8.7 by Künneth, where the twist by $\delta_{B'} \otimes \delta_B^{-1}$ comes from the relative dualizing complex of $f_{\bar{\nu}\infty}$ and in turn $f_{\bar{\nu},\infty}$ just as in the previous Example.

8.2. Commutation with Verdier Duality. In this section, we will establish the following.

Theorem 8.11. *For ϕ_T a generic regular parameter and assuming 6.5, we have that*

$$\mathbb{D}_{\text{Bun}_G} \text{nEis}(\mathcal{S}_{\phi_T}) \simeq \text{nEis} \mathbb{D}_{\text{Bun}_T}(\mathcal{S}_{\phi_T}),$$

where $\mathbb{D}_{\text{Bun}_T}(\mathcal{S}_{\phi_T}) \simeq \mathcal{S}_{\phi_T}^\vee$.

For $b \in B(G)_{\text{un}}$ and $w \in W_b$, we set $\rho_{b,w} := i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$. Using Theorem 8.2, we reduce Theorem 8.11 to the following claim.

Theorem 8.12. *For all $b \in B(G)_{\text{un}}$, $w \in W_b$, and χ associated to a generic regular parameter ϕ_T , assuming 6.5 the natural map*

$$j_{b!}(\rho_{b,w}) \rightarrow Rj_{b*}(\rho_{b,w})$$

is an isomorphism.

Proof. By [FS, Section IX.7.1], any irreducible constituent of $Rj_{b*}(\rho_{b,w})|_{\text{Bun}_G^{b'}}$ in $D(J_{b'}(\mathbb{Q}_p), \Lambda)$ must have Fargues-Scholze parameter equal to ϕ . Therefore, by the argument for Corollary 6.7 and Assumption 6.5, the restriction $Rj_{b*}(\rho_{b,w})|_{\text{Bun}_G^{b'}}$ will only be non-zero if $b' \in B(G)_{\text{un}}$, and any irreducible constituent must be an irreducible constituent of $\rho_{b',w'}$, for some $b' \in B(G)_{\text{un}}$ and $w' \in W_{b'}$.

Moreover, the sheaf $Rj_{b*}(\rho_{b,w})$ is ULA over the point since it is the Verdier dual of a complex which is ULA over the point using [FS, Theorem V.7.1] and [FS, Corollary IV.2.25]. As in the proof of Proposition 8.5, this allows us to deduce that $Rj_{b*}(\rho_{b,w})|_{\text{Bun}_G^{b'}}$ is a complex with finite length cohomology. This reduces us to showing that the complex

$$\text{RHom}_{J_{b'}(\mathbb{Q}_p)}(j_{b*}(\rho_{b,w})|_{\text{Bun}_G^{b'}}, \rho_{b',w'}) \simeq \text{RHom}(j_{b*}(\rho_{b,w}), j_{b'*}(\rho_{b',w'}))$$

is trivial for all $b' \in B(G)_{\text{un}}$ and $w' \in W_{b'}$ with $b' \neq b$. We set $\bar{\nu} = w(b_T)$. By using Theorem 5.6, Corollary 8.2, and the fact that generic regularity is a condition stable under switching B and B^- and χ and χ^{-1} , we obtain that it suffices to show that

$$\text{RHom}(\text{nEis}_*^{\bar{\nu}}(\mathcal{S}_{\phi_T}), \text{nEis}_{-*}^{\bar{\nu}'}(\mathcal{S}_{\phi_T}))$$

for all $\bar{\nu}' \in B(T)$ such that its image $b' \in B(G)$ satisfies that $b \neq b'$. We can now rewrite this as

$$\text{RHom}(\text{nCT}_{-!}^{\nu'} \text{nEis}_*^{\nu}(\mathcal{S}_{\phi_T}), \chi) \simeq \text{RHom}(\text{nCT}_*^{\nu'} \text{nEis}_*^{\nu}(\mathcal{S}_{\phi_T}), \chi),$$

using Theorem 7.1. Using projection formula and the smoothness of the map $\mathfrak{q}$, we can further rewrite this as

$$\mathrm{RHom}(\mathrm{CT}_*^{\nu'} \mathrm{nEis}_*^{\nu'}(\mathcal{S}_{\phi_T}), \chi \otimes \delta_B^{1/2}).$$

The claim now follows by Proposition 8.6 as in the proof of Proposition 8.5. $\square$

9. THE HECKE EIGENSHEAF PROPERTY

9.1. Tilting Eigensheaves. We would now like to combine our work in the previous sections and use it to construct eigensheaves. We would like to do this in a uniform way for coefficient systems $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$, where Λ has the discrete topology unless otherwise stated. One of the issues is that the representation theory of ${}^L G/\Lambda$ is substantially different in each of these three cases. The structure of the representation theory of $\mathrm{Rep}_{\overline{\mathbb{Q}}_\ell}({}^L G)$ was described in §2. With $\overline{\mathbb{Q}}_\ell$ -coefficients, the category is semisimple with simple objects given by V_{μ^Γ} for $\mu^\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+/\Gamma$ a Γ -orbit of a geometric dominant cocharacter μ . If $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell\}$ this is no longer so straightforward; the representation V_{μ^Γ} can fail to be irreducible. To develop a good theory of algebraic representations with these coefficients, we will need to invoke our assumption that ℓ is very decent with respect to G and use the theory of tilting modules. We first discuss the general notion of a tilting module. Fix H a split connected reductive group over $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$. We consider the involution

$$\mathbb{D} : \mathrm{Rep}_\Lambda(H) \rightarrow \mathrm{Rep}_\Lambda(H)$$

$$V \mapsto (V^*)^\sigma$$

where V^* is the dual representation and σ is the Chevalley involution. For $\lambda \in \mathbb{X}^*(H)^+$ a dominant character, we let V^λ denote the highest weight representation attached to λ by Borel-Weil-Bott, and we write $V_\lambda := \mathbb{D}(V^\lambda)$. We now come to our key definition.

Definition 9.1. Given $V \in \mathrm{Rep}_\Lambda(H)$, we say that V has a Weyl (resp. good) filtration if it admits a filtration whose successive quotients are isomorphic to V^λ (resp. V_λ). We say V is tilting if it admits both a good and a Weyl filtration. We write $\mathrm{Tilt}_\Lambda(H) \subset \mathrm{Rep}_\Lambda(H)$ for the full sub-category of tilting modules.

The category of tilting modules is additive, but usually not abelian. If $\Lambda = \overline{\mathbb{Q}}_\ell$ the highest weight modules are simple, and $\mathrm{Tilt}_\Lambda(H) = \mathrm{Rep}_\Lambda(H)$. Therefore, this is only an interesting notion if $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell\}$. The key point of moving to this sub-category is that we have the following generalization of usual highest weight theory due Ringel and Donkin [Rin91], [Don93].

Theorem 9.2. *For each $\lambda \in \mathbb{X}^*(H)^+$, there exists a unique indecomposable tilting module $\mathcal{T}_\lambda \in \mathrm{Tilt}_\Lambda(H)$ with highest weight λ . We have that $\dim(\mathcal{T}_\lambda(\lambda)) = 1$, and, for varying λ , this parametrizes all indecomposable tilting modules.*

We also get the usual classification of all tilting modules in terms of highest weight tilting modules.

Proposition 9.3. *[Jan03, Section E.22], [Mat00, Lemma 7.3] For all $V \in \mathrm{Tilt}_\Lambda(H)$, there exists unique integers $n(\lambda) \in \mathbb{N}_{\geq 0}$ for all $\lambda \in \mathbb{X}^*(H)^+$ and an isomorphism*

$$V \simeq \bigoplus_{\lambda \in \mathbb{X}^*(H)^+} (\mathcal{T}_\lambda)^{n(\lambda)}$$

of tilting modules.

Now we come to a difficult result which was proven by [Wan82] for groups of type A_n , [Don93] for almost all groups, and [Mat00] in general.

Theorem 9.4. *If we have two tilting modules $V, V' \in \mathrm{Tilt}_\Lambda(H)$ then the tensor product $V \otimes V'$ is tilting.*

We can now extend this to the L -group using our assumption that ℓ is very decent with respect to G ; in particular, our assumption that $\ell \nmid |Q|$. By Theorem 9.2 applied to $H = \hat{G}$, we deduce that we have a well-defined category $\text{Tilt}_\Lambda(\hat{G})$ of tilting modules, where each object can be written as a direct sum of highest weight tilting modules $\mathcal{T}_\mu$ for $\mu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ using Proposition 9.3. Now, given such a μ , we consider the reflex field E_μ , and extend this to a representation of $W_{E_\mu} \times \hat{G}$, as in [Kot84, Lemma 2.1.2]. We define the tilting module $\mathcal{T}_{\mu\Gamma}$ as the induction of this representation from $W_{E_\mu} \times \hat{G}$ to $W_{\mathbb{Q}_p} \times \hat{G}$, and let $\text{Tilt}_\Lambda({}^L G) \subset \text{Rep}_\Lambda({}^L G)$ be the full sub-category given by direct sums of such modules, where we note that $\mathcal{T}_{\mu\Gamma}$ only depends on the Γ -orbit of $\mu^\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+/\Gamma$ of μ . Now, since ℓ is very decent, it follows that $W_{\mathbb{Q}_p}$ acts on $\hat{G}$ via a quotient Q that is prime to ℓ by definition, and therefore $W_{\mathbb{Q}_p}/W_{E_\mu}$ is also of order prime to ℓ . Combing this observation, Frobenius Reciprocity/Mackey theory, and Theorem 9.4, we conclude that $\mathcal{T}_{\mu\Gamma}$ is indeed an irreducible representation of ${}^L G$, and that $\text{Tilt}({}^L G)$ is preserved under tensor products. This allows us to define the following.

Definition 9.5. Given a continuous L -parameter $\phi : W_{\mathbb{Q}_p} \rightarrow {}^L G(\Lambda)$, we say a sheaf $\mathcal{S}_\phi \in \text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)$ is a tilting eigensheaf with eigenvalue ϕ if, for all $V \in \text{Tilt}_\Lambda({}^L G^I)$, we are given isomorphisms

$$\eta_{V,I} : T_V(\mathcal{S}_\phi) \simeq \mathcal{S}_\phi \boxtimes r_V \circ \phi$$

of sheaves in $\text{D}_{\text{lis}}(\text{Bun}_G, \Lambda)^{BW_{\mathbb{Q}_p}^I}$, which are natural in I and V , and compatible with compositions and exterior tensor products in V . If $\Lambda = \overline{\mathbb{Q}}_\ell$ this recovers Definition 3.1. We similarly say $\mathcal{S}_\phi$ is a weak tilting eigensheaf if only the isomorphisms $\eta_{V,I}$ exist.

Remark 9.6. Our discussion of highest weight theory in §2.1 for $\hat{G}^\Gamma$ also extends to the tilting modules $\mathcal{T}_\mu$ under our assumption that ℓ is very decent. In particular, using Proposition 9.2, we can understand the possible weights occurring in $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ in terms of $\bar{\nu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, which lie in the convex hull of the W_G orbit of $\mu_\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma^+$, and the $\bar{\nu}$ weight space of $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ will be a direct sum over the weight spaces $\mathcal{T}_\mu(\nu)$ for $\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})$ mapping to $\bar{\nu}$, as in Lemma 2.8. To see this, we note, by [FS, Proposition VIII.5.11]⁶ and our assumption that ℓ is very decent, that we have the following:

- (1) $\hat{G}^\Gamma$ is a smooth linear algebraic group, and $\hat{G}^{\Gamma,\circ}$ is reductive.
- (2) $\hat{G}^\Gamma/\hat{G}^{\Gamma,\circ} \simeq \hat{T}^\Gamma/\hat{T}^{\Gamma,\circ}$ is of order prime to ℓ , where $\hat{G}^{\Gamma,\circ}$ (resp. $\hat{T}^{\Gamma,\circ}$) denotes the neutral component of $\hat{G}^\Gamma$ (resp. $\hat{T}^\Gamma$), and the isomorphism follows as in [Zhu15, Lemma 4.6].

These observations allows us to see the highest weight theory of the (possibly disconnected) group $\hat{G}^\Gamma$ behaves as expected with modular coefficients by mimicking the proof of Lemma 2.7.

We now define our candidate tilting eigensheaf for each of the possible coefficient systems $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$.

9.2. The Construction of the Eigensheaf. We fix a toral parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$, with induced parameter $\phi : W_{\mathbb{Q}_p} \xrightarrow{\phi_T} {}^L T(\Lambda) \rightarrow {}^L G(\Lambda)$. Our goal is to construct a candidate tilting eigensheaf with respect to the parameter ϕ . If $\Lambda = \overline{\mathbb{F}}_\ell$, we have already carried this out. It is simply the sheaf $\text{nEis}(\mathcal{S}_{\phi_T}) \in \text{D}(\text{Bun}_G)$ viewed as a sheaf in $\text{D}_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{F}}_\ell)$ via the identification $\text{D}(\text{Bun}_G) \simeq \text{D}_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{F}}_\ell)$ [FS, Proposition VII.6.6], obtained by embedding both categories into $\text{D}_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{F}}_\ell)$. To move beyond this case, we need to invoke the following Lemma.

Lemma 9.7. *For $\Lambda = \overline{\mathbb{F}}_\ell$, ϕ_T generic regular, and assuming 6.5, the sheaf $\text{nEis}(\mathcal{S}_{\phi_T}) \in \text{D}(\text{Bun}_G)$ is ULA with respect to the structure map $\text{Bun}_G \rightarrow *$.*

⁶Here we are citing version 2 on the ArXiv

Proof. Given $A \in D(\text{Bun}_G)$, we recall that A being ULA with respect to the map $\text{Bun}_G \rightarrow *$ is equivalent to saying that its stalks $A|_{\text{Bun}_G^b}$ are valued in a complex of smooth representations such that $A^K|_{\text{Bun}_G^b}$ is a perfect complex of Λ -modules for all open pro- p subgroups $K \subset J_b(\mathbb{Q}_p)$ [FS, Theorem V.7.1]. In particular, the result follows from Corollary 8.2. $\square$

Now, if $\Lambda = \overline{\mathbb{Z}}_\ell$ then, by taking inverse limits with respect to the mod ℓ^n reductions of ϕ_T , and considering the systems of sheaves given by applying the Eisenstein functor to the eigensheaf attached to these reductions, we obtain a sheaf

$$\widehat{\text{nEis}(\mathcal{S}_{\phi_T})} \in D_{\text{ét}}^{\text{ULA}}(X, \overline{\mathbb{Z}}_\ell)$$

Now, we have a fully faithful embedding

$$D_{\text{ét}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell) \hookrightarrow D_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$$

given as in [FS, Page 261]. This embedding is used to define the Hecke operators in the setting of solid sheaves (See [FS, Page 264]), utilizing that sheaves in the Satake category are ULA over Div^I . In particular, this embedding is Hecke equivariant in the appropriate sense, and so the filtered eigensheaf property transfers to the image of $\widehat{\text{nEis}(\mathcal{S}_{\phi_T})}$ in $D_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$. We also have a natural embedding $D_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell) \hookrightarrow D_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$, and we can analogously define the set of ULA objects in it [FS, Definition VII.7.8], denoted $D_{\text{lis}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$. We have the following claim.

Lemma 9.8. *Under the embeddings of $D_{\text{lis}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ and $D_{\text{ét}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ into $D_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ described above, these two full subcategories are isomorphic.*

Proof. We have a semi-orthogonal decomposition of $D_{\text{lis}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ ([FS, Proposition VII.7.3]) and $D_{\text{ét}}^{\text{ULA}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ into $D(J_b(\mathbb{Q}_p), \overline{\mathbb{Z}}_\ell)_{\text{adm}}$ and $\hat{D}(J_b(\mathbb{Q}_p), \overline{\mathbb{Z}}_\ell)_{\text{adm}}$ by excision, respectively. Here $\hat{D}(J_b(\mathbb{Q}_p), \overline{\mathbb{Z}}_\ell)$ denotes the derived category of ℓ -complete smooth representations of $J_b(\mathbb{Q}_p)$, and the subscript adm is used to denote the full subcategory of objects such that its invariants under an open compact $K \subset J_b(\mathbb{Q}_p)$ is a perfect complex. Since the semi-orthogonal decompositions are compatible with the two embeddings into $D_{\blacksquare}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ it suffices to show that we have an identification

$$D(J_b(\mathbb{Q}_p), \overline{\mathbb{Z}}_\ell)_{\text{adm}} \simeq \hat{D}(J_b(\mathbb{Q}_p), \overline{\mathbb{Z}}_\ell)_{\text{adm}},$$

but this follows from [Han20, Proposition 2.6]. $\square$

Using the isomorphism supplied by the previous Lemma, we can regard $\widehat{\text{nEis}(\mathcal{S}_{\phi_T})} \in D_{\text{ét}}^{\text{ULA}}(X, \overline{\mathbb{Z}}_\ell)$ as an object in $D_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$, which we denote by $\text{nEis}(\mathcal{S}_{\phi_T})$. Since these isomorphisms are compatible with Hecke operators it follows that Corollary 6.4 transfers to this sheaf. It now remains to describe the desired sheaf when $\Lambda = \overline{\mathbb{Q}}_\ell$. In this case, we need to assume the parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}}_\ell)$ is of the form $\overline{\phi}_T \otimes \overline{\mathbb{Q}}_\ell$, where $\overline{\phi}_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Z}}_\ell)$ is a parameter with generic regular mod ℓ -reduction. Assume 6.5. Then we consider the sheaf $\text{nEis}(\mathcal{S}_{\phi_T}) \in D_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{Z}}_\ell)$ constructed above, and define

$$\text{nEis}(\mathcal{S}_{\phi_T}) := \text{nEis}(\mathcal{S}_{\overline{\phi}_T})\left[\frac{1}{\ell}\right] \in D_{\text{lis}}(\text{Bun}_G, \overline{\mathbb{Q}}_\ell)$$

by taking the colimit over the multiplication by ℓ maps. Now with the candidate eigensheaf defined, we begin the proof of the eigensheaf property. To capture the necessary integrality conditions, we define the following.

Definition 9.9. For $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$ with the discrete topology and a continuous toral parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ we say that ϕ_T is integral if it admits a mod ℓ -reduction. In particular, if $\Lambda = \overline{\mathbb{Q}}_\ell$, we assume it is of the form $\overline{\phi}_T \otimes_{\overline{\mathbb{Z}}_\ell} \overline{\mathbb{Q}}_\ell$ for some continuous parameter $\overline{\phi}_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Z}}_\ell)$.

9.3. The Hecke Eigensheaf Property.

We start with the following Theorem.

Theorem 9.10. *For $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$ with the discrete topology, we consider $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ an integral parameter with generic regular mod ℓ reduction. There then exists a perverse sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T}) \in \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$ which is a filtered eigensheaf with eigenvalue ϕ as in Corollary 6.4. If V is a direct sum of $\boxtimes_{i \in I} \mathcal{T}_{\mu_i}^\Gamma$ for geometric dominant cocharacters μ_i , and ϕ_T is strongly μ_i -regular (Definition 3.10), the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ splits uniquely, and we have a natural isomorphism*

$$T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_V \circ \phi$$

of sheaves in $\mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G)^{BW_{\mathbb{Q}_p}^I}$. In particular, if ϕ_T is strongly μ -regular for all geometric dominant cocharacters μ then $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a tilting eigensheaf. For $b \in B(G)$, the stalk $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \in \mathrm{D}(\mathrm{Bun}_G^b) \simeq \mathrm{D}(J_b(\mathbb{Q}_p), \Lambda)$ is given by

- (1) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq \bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle]$ if $b \in B(G)_{\mathrm{un}}$,*
- (2) *an isomorphism $\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{\mathrm{Bun}_G^b} \simeq 0$ if $b \notin B(G)_{\mathrm{un}}$.*

Moreover, if $\mathbb{D}_{\mathrm{Bun}_G}$ denotes Verdier duality on Bun_G , we have an isomorphism

$$\mathbb{D}_{\mathrm{Bun}_G}(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}^\vee)$$

of sheaves in $\mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$.

Proof. The existence of $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ and the transfer of the filtered Hecke eigensheaf property to this sheaf was discussed in the previous section. The claim on Verdier duality follows from Theorem 8.11, and the discussion in [FS, Section VII.5]. The description of the stalks follows from the construction and Corollary 8.2. It remains to show that the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ splits uniquely for $\boxtimes_{i \in I} \mathcal{T}_{\mu_i}^\Gamma = V \in \mathrm{Rep}_\Lambda({}^L G)$ such that ϕ_T is strongly μ_i -regular for all $i \in I$. To do this, we note that an extension between the graded pieces of the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ is specified by a cohomology class in the H^1 of $R\Gamma(W_{\mathbb{Q}_p}^I, \boxtimes_{i \in I} (\nu_i - \nu'_i)^\Gamma \circ \phi_T) \simeq \bigotimes_{i \in I}^\mathbb{L} R\Gamma(W_{\mathbb{Q}_p}, (\nu_i - \nu'_i)^\Gamma \circ \phi_T)$ for ν_i and ν'_i defining two distinct Γ -orbits of weights of the representation $\mathcal{T}_\mu$ in $\hat{T}$ for all $i \in I$. In particular, we note if ϕ_T is strongly μ_i -regular then the H^1 vanishes and the filtration splits, and similarly the H^0 vanishes so the splitting is unique. In particular, since we know the filtration satisfies all the desired compatibilities for the eigensheaf property if we know strong μ -regularity for all μ , it follows from the splitting being unique that $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a tilting eigensheaf. $\square$

We now fix an integral parameter ϕ_T with generic regular mod ℓ -reduction and consider the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T}) \in \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$ supplied by the previous theorem. We come to the following definition.

Definition 9.11. Given a tuple of geometric dominant cocharacters $(\mu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$ for all $i \in I$, we say that $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ is $(\mu_i)_{i \in I}$ -regular if the filtration on

$$T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$$

splits (but not necessarily uniquely) for the tilting module $V = \boxtimes_{i \in I} \mathcal{T}_{\mu_i}^\Gamma \in \mathrm{Tilt}_\Lambda({}^L G^I)$.

As seen in the proof of Theorem 9.10, if the μ_i are such that ϕ_T is strongly μ_i -regular then it follows that ϕ_T is $(\mu_i)_{i \in I}$ -regular. For certain μ_i , strong μ_i -regularity will be implied by genericity, and the following Proposition allows us to deduce that the filtration splits in more cases.

Proposition 9.12. *Suppose that $(\mu_{1i})_{i \in I}, (\mu_{2i})_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$ are tuples of characters such that ϕ_T is $(\mu_{1i})_{i \in I}$ and $(\mu_{2i})_{i \in I}$ -regular. Then if $V \simeq \boxtimes_{i \in I} \mathcal{T}_{\mu_i}^\Gamma \in \mathrm{Tilt}_\Lambda({}^L G^I)$ occurs as a direct summand of the tensor product $\boxtimes_{i \in I} \mathcal{T}_{\mu_{1i}}^\Gamma \otimes \mathcal{T}_{\mu_{2i}}^\Gamma \in \mathrm{Tilt}({}^L G^I)$ it follows that ϕ_T is $(\mu_i)_{i \in I}$ -regular.*

Proof. It suffices to show that, given $(\mu_{1i})_{i \in I}, (\mu_{2i})_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$ with $V_1 := \boxtimes_{i \in I} \mathcal{T}_{\mu_{1i}}^\Gamma$ and $V_2 := \boxtimes_{i \in I} \mathcal{T}_{\mu_{2i}}^\Gamma$ such that we know the filtration on $T_{V_1}(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ and $T_{V_2}(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ splits, the same is true for the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$, where $V \in \mathrm{Tilt}_\Lambda(LG^I)$ is a direct summand of $V_1 \otimes V_2$. To do this, we can use the isomorphism

$$T_{V_1} T_{V_2}(\mathrm{nEis}(\mathcal{S}_{\phi_T}))|_\Delta \simeq T_{V_1 \otimes V_2}(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$$

coming from the fusion product, where $\Delta : \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)^{BW_{\overline{\mathbb{Q}}_p}^{I \sqcup I}} \rightarrow \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)^{BW_{\overline{\mathbb{Q}}_p}^I}$ is the natural map given by diagonal restriction. By assumption, the diagonal restriction of the filtration on the LHS splits. Moreover, by the compatibilities of the filtration, we know that the filtration on the LHS refines the filtration on the RHS. In particular, we deduce that the filtration on $T_{V_1 \otimes V_2}(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ has a splitting, and since V is a direct summand of $V_1 \otimes V_2$, we know that the filtration also splits on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$. $\square$

In particular, by considerations of highest weight, the tilting module $\boxtimes_{i \in I} \mathcal{T}_{(\mu_{1i} + \mu_{2i})^\Gamma}$ is always a direct summand of $\boxtimes_{i \in I} \mathcal{T}_{\mu_{1i}}^\Gamma \otimes \mathcal{T}_{\mu_{2i}}^\Gamma$. Using this, we deduce the following Corollary.

Corollary 9.13. *If ϕ_T is $(\mu_{1i})_{i \in I}$ and $(\mu_{2i})_{i \in I}$ -regular then it is also $(\mu_{1i} + \mu_{2i})_{i \in I}$ -regular.*

This motivates the following definition.

Definition 9.14. We say a parameter ϕ_T is normalized regular if it is integral with generic regular mod ℓ reduction and if there exists a set of elements μ_k for $k = 1, \dots, n$ such that:

- (1) The μ_k generate $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ in the sense that any $\mu = \sum_{k=1}^n n_k \mu_k$ as elements in $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$ for some $n_k \in \mathbb{Z}$.
- (2) ϕ_T is strongly μ_k -regular, for all $k = 1, \dots, n$.

This allows us to state the following corollary.

Corollary 9.15. *Suppose that ϕ_T is normalized regular then it is $(\mu_i)_{i \in I}$ -regular for all finite index sets I and $\mu_i \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$. In particular, the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a (weak) tilting eigensheaf with eigenvalue ϕ given by the composite of ϕ_T with the natural map ${}^L T \rightarrow {}^L G$.*

Proof. We recall that $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ being a (weak) tilting eigensheaf means that, for all $V \in \mathrm{Tilt}_\Lambda(LG^I)$, we know that we have an isomorphism

$$T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T})) \simeq \mathrm{nEis}(\mathcal{S}_{\phi_T}) \boxtimes r_V \circ \phi$$

but we do not know that these isomorphisms satisfy the desired compatibilities. To show this, it suffices to show the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ just splits (not necessarily uniquely) for all highest weight tilting modules $V = \boxtimes_{i \in I} \mathcal{T}_{\mu_i}^\Gamma$ corresponding to the Γ -orbits of varying $(\mu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$. Since ϕ_T is strongly μ_k -regular for the $k = 1, \dots, n$ appearing in the definition of normalized regularity, it follows, as in the proof of Theorem 9.10, that the filtration on $T_V(\mathrm{nEis}(\mathcal{S}_{\phi_T}))$ splits for any tuple of the generating cocharacters $(\mu_i)_{i \in I}$ such that $\mu_i = \mu_k$ for all $i \in I$ and varying $k = 1, \dots, n$ appearing in Definition 9.14. However, since every tuple of cocharacters μ_i , can be written as a linear combination of μ_k for $k = 1, \dots, n$, this follows from Corollary 9.13. $\square$

By choosing μ_k for $k = 1, \dots, n$ to be, for example a set of minuscule/quasi-minuscule generators of $\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+$, this allows to see that μ -regularity for all μ is actually an open condition on the variety of unramified twists of a fixed ϕ_T . This will be sufficient for most applications of the Eisenstein series to describing the cohomology of local shtukas and Shimura varieties in the Grothendieck group. However, for more refined applications of our results it becomes important to spell out the precise assumptions needed to deduce μ -regularity for all μ . Ideally, it should be implied by generic regularity for all μ , as is suggested by Conjecture 1.24. For $G = \mathrm{GL}_n$, we show how to verify this from the results proven above.

Corollary 9.16. *For $G = \mathrm{GL}_n$, if ϕ_T is an integral generic L -parameter then the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T})$ is a (weak) tilting eigensheaf.*

Proof. We give the proof for $\Lambda = \overline{\mathbb{F}}_\ell$, with the other cases being strictly easier. It is easy to see that generic implies regular, so that if ϕ_T is generic then it is automatically generic regular. It suffices to show for all tuples $(\mu_i)_{i \in I} \in (\mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})^+)^I$ that ϕ_T is $(\mu_i)_{i \in I}$ regular. By Lemma 3.11, we know that if ϕ_T is generic then it is strongly μ -regular for the cocharacter $\mu = (1, 0, \dots, 0)$ corresponding to the standard representation V_{std} of $\hat{G} \simeq \mathrm{GL}_n$. By Proposition 9.13, it suffices to show that if ϕ_T is generic then μ -regularity holds for the fundamental coweights $\mu = \omega_i = (1^i, 0^{n-i})$ for $i = 1, \dots, n$. We recall that the ω_i are minuscule in this case and therefore it follows by Lemma B.1 that the representation $\Lambda^i(V_{\mathrm{std}}) \simeq V_{\omega_i}$ is irreducible and thereby equal to the tilting module $\mathcal{T}_{\omega_i}$. However, now the result follows from Proposition 9.12 and the fact that $\Lambda^i(V_{\mathrm{std}})$ is a direct summand of $V_{\mathrm{std}}^{\otimes n}$. The fact that assumption 6.5 is satisfied follows from the compatibility of Fargues-Scholze with Harris-Taylor [FS, Theorem I.9.6 (ix)] and Jacquet Langlands [HKW22, Theorem I.0.3] together with other standard properties of the Fargues-Scholze correspondence. $\square$

With our main results in hand, we can move into applications.

10. APPLICATIONS

Now we will deduce some applications to the cohomology of local shtuka spaces. In §9.1, we will use our eigensheaf to derive an analogue of an averaging formula of Shin for the cohomology of local shtuka spaces. In §9.2 and §9.3, we will discuss a refined version of this averaging formula, and use it to derive a very explicit formula for the isotypic parts of local shtuka spaces with respect to parabolic inductions of characters coming from normalized regular parameters. By combining this with a shtuka analogue of Boyer's trick, we will show that this gives rise to a geometric construction of intertwining operators, and recovers a result analogous to a result of Xiao and Zhu [XZ17] on the irreducible components of affine Deligne-Lusztig varieties, but on the generic fiber.

Let's first recall the key definitions. We say a local shtuka datum is a triple (G, b, μ) for μ a geometric dominant cocharacter of G and $b \in B(G, \mu)$ an element of the μ -admissible locus of the Kottwitz set of G (Definition 2.5). We let E be the reflex field of μ . The triple (G, b, μ) defines a diamond

$$\mathrm{Sht}(G, b, \mu)_\infty \rightarrow \mathrm{Spd}(\check{E})$$

parameterizing modifications $\mathcal{F}_b \rightarrow \mathcal{F}_G^0$ with meromorphy bounded by μ on X^7 . It carries an action of $G(\mathbb{Q}_p) \times J_b(\mathbb{Q}_p)$ and a (non-effective) descent datum from $\check{E}$ down to E . This allows us to consider the tower of quotients

$$\mathrm{Sht}(G, b, \mu)_\infty / \underline{K} =: \mathrm{Sht}(G, b, \mu)_K$$

for varying open compact subgroups $K \subset G(\mathbb{Q}_p)$. We write $\mathcal{S}_\mu$ for the Λ -valued sheaf attached to the highest weight tilting module $\mathcal{T}_\mu$ of $W_E \rtimes \hat{G}$ as in the previous section. This is given by pulling back the sheaf on $\mathrm{Hck}_{G,E}$ defined by $\mathcal{T}_\mu$ and Theorem 4.2 along the natural map $\mathrm{Sht}(G, b, \mu) \rightarrow \mathrm{Hck}_{G,E}$. In particular, the sheaf $\mathcal{S}_\mu$ is equivariant with respect to the actions of $G(\mathbb{Q}_p)$ and $J_b(\mathbb{Q}_p)$ by construction. Letting $\mathrm{Sht}(G, b, \mu)_{K, \mathbb{C}_p}$ denote the base-change of these spaces to $\mathbb{C}_p$, we can now define the complex

$$R\Gamma_c(G, b, \mu) := \mathrm{colim}_{K \rightarrow \{1\}} R\Gamma_c(\mathrm{Sht}(G, b, \mu)_{K, \mathbb{C}_p}, \mathcal{S}_\mu)$$

of $G(\mathbb{Q}_p) \times J_b(\mathbb{Q}_p) \times W_E$ -modules. We now want to disentangle the $G(\mathbb{Q}_p)$ and $J_b(\mathbb{Q}_p)$ action. To do this, for π (resp. ρ) a smooth irreducible representation of $G(\mathbb{Q}_p)$ (resp. $J_b(\mathbb{Q}_p)$) on Λ -modules,

⁷Note that this is the space denoted $\mathrm{Sht}(G, b, \mu^{-1})$ in [SW20]. We find that our convention simplifies certain formulae.

we define the π (resp. ρ)-isotypic part. I.e the complexes

$$R\Gamma_c(G, b, \mu)[\pi] := R\Gamma_c(G, b, \mu) \otimes_{\mathcal{H}(G)} \pi$$

and

$$R\Gamma_c(G, b, \mu)[\rho] := R\Gamma_c(G, b, \mu) \otimes_{\mathcal{H}(J_b)} \rho$$

where $\mathcal{H}(G) := C_c^\infty(G(\mathbb{Q}_p), \Lambda)$ (resp. $\mathcal{H}(J_b)$) is the usual smooth Hecke algebra of G (resp. J_b). We recall that $\text{Sht}(G, b, \mu)_\infty$ has dimension equal to $\langle 2\hat{\rho}, \mu \rangle =: d$. The complexes $R\Gamma_c(G, b, \mu)[\pi]$ (resp. $R\Gamma_c(G, b, \mu)[\rho]$) are concentrated in degrees $-d \leq i \leq d$ and are valued in admissible $J_b(\mathbb{Q}_p)$ (resp. $G(\mathbb{Q}_p)$) representations, which are moreover of finite length with $\overline{\mathbb{Q}_\ell}$ -coefficients [FS, Page 317]. Similarly, we define the complexes

$$R\Gamma_c^\flat(G, b, \mu)[\pi] := R\mathcal{H}om(R\Gamma_c(G, b, \mu), \pi)$$

and

$$R\Gamma_c^\flat(G, b, \mu)[\rho] := R\mathcal{H}om(R\Gamma_c(G, b, \mu), \rho).$$

We will make regular use of the relationship between these complexes and Hecke operators. For simplicity, we will mostly stick to the isotypic parts $R\Gamma_c^\flat(G, b, \mu)[\rho]$, as it removes various annoying twists and shifts⁸; however, one can easily translate to the isotypic parts $R\Gamma_c^\flat(G, b, \mu)[\pi]$ in the cases we consider, using Corollary 10.14. We write

$$T_\mu : D_{\text{lis}}(\text{Bun}_G, \Lambda) \rightarrow D_{\text{lis}}(\text{Bun}_G, \Lambda)^{BW_E}$$

for the Hecke operator defined by the representation $\mathcal{T}_\mu$. For $b \in B(G)$, consider the natural map

$$f : \mathcal{J}_b^{>0} \rightarrow *,$$

where $\text{Aut}(\mathcal{E}_b) \simeq J_b(\mathbb{Q}_p) \ltimes \mathcal{J}_b^{>0}$, and the semidirect product structures is given by allowing $\text{Aut}(\mathcal{E}_b)$ to act on the canonical reduction of $\mathcal{E}_b$. Since f is an iterated fibration of Banach-Colmez spaces and $\mathcal{J}_b^{>0}$ has an action of $J_b(\mathbb{Q}_p)$ on the right coming from the canonical reduction of $\mathcal{E}_b$. We have an isomorphism

$$f_!(\Lambda) \simeq \kappa[-2\langle 2\hat{\rho}_G, \nu_b \rangle]$$

for some character $\kappa : J_b(\mathbb{Q}_p) \rightarrow \Lambda^*$ (cf. [GI16, Lemma 4.18]). We have the following relationship between isotypic parts of shtuka spaces and Hecke operators.

Lemma 10.1. *[FS, Section IX.3] Given a local shtuka datum (G, b, μ) as above and π (resp. ρ) a smooth representation of $G(\mathbb{Q}_p)$ (resp. $J_b(\mathbb{Q}_p)$) on Λ -modules, we can consider the associated sheaves $\rho \in D(J_b(\mathbb{Q}_p), \Lambda) \simeq D_{\text{lis}}(\text{Bun}_G^b, \Lambda)$ and $\pi \in D(G(\mathbb{Q}_p), \Lambda) \simeq D_{\text{lis}}(\text{Bun}_G^1, \Lambda)$ on the HN-strata $j_b : \text{Bun}_G^b \hookrightarrow \text{Bun}_G$ and $j_1 : \text{Bun}_G^1 \hookrightarrow \text{Bun}_G$, respectively. There then exists an isomorphism*

$$R\Gamma_c(G, b, \mu)[\rho \otimes \kappa^{-1}][2\langle 2\hat{\rho}_G, \nu_b \rangle] \simeq j_{1*} T_\mu j_{b!}(\rho)$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules and an isomorphism

$$R\Gamma_c(G, b, \mu)[\pi] \simeq j_b^* T_{\mu^{-1}} j_{1!}(\pi)$$

of complexes of $J_b(\mathbb{Q}_p) \times W_E$ -modules, where $\mu^{-1} := -w_0(\mu)$ is a dominant inverse of μ . Similarly, we have an isomorphism

$$R\Gamma_c^\flat(G, b, \mu)[\rho] \simeq j_{1*} T_\mu j_{b*}(\rho)$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules, and an isomorphism

$$R\Gamma_c^\flat(G, b, \mu)[\pi][2\langle 2\hat{\rho}_G, \nu_b \rangle] \simeq j_b^! T_{\mu^{-1}} j_{1*}(\pi) \otimes \kappa^{-1}$$

of complexes of $J_b(\mathbb{Q}_p) \times W_E$ -modules.

⁸We thank Naoki Imai for drawing our attention to this.

Remark 10.2. This comparison comes from the fact that when comparing Hecke operators and isotypic parts of shtuka spaces, that, after several applications of base-change, the difference will be controlled by the ! pushforward of the constant sheaf along the map

$$\mathrm{Sht}(G, b, \mu)_\infty \rightarrow \mathrm{Gr}_{G, \mu^{-1}}^b$$

from the Shtuka space to the adic Newton strata of the B_{dR}^+ affine Grassmannian. This is in particular a $\mathcal{J}_b$ -torsor. The third and fourth relationship can be obtained from the first and second by acting via Verdier duality and using Hom-Tensor duality.

We can be more explicit about this character. In particular, we have the following, which follows from [HI25, Corollary 1.8].

Proposition 10.3. *We have an isomorphism $\kappa \simeq \delta_{P_b}^{-1}$, where δ_{P_b} is the modulus character of the standard parabolic P_b with Levi factor M_b transferred to J_b along the inner twisting. In particular, we have, by Lemma 10.1, isomorphisms*

$$R\Gamma_c(G, b, \mu)[\rho \otimes \delta_{P_b}][2\langle 2\hat{\rho}_G, \nu_b \rangle] \simeq j_1^* T_\mu j_{b!}(\rho)$$

and

$$R\Gamma_c^\flat(G, b, \mu)[\rho] \simeq j_1^* T_\mu j_{b*}(\rho)$$

of $G(\mathbb{Q}_p) \times W_E$ -modules.

We note that, since we used the tilting module $\mathcal{T}_\mu$ in the definition of $R\Gamma_c(G, b, \mu)$ and the Hecke operator T_μ , the complex $R\Gamma_c(G, b, \mu)$ will in general be different from the usual complex defined with respect to the highest weight module V_μ . However, they will agree when we impose the following condition on μ with respect to our coefficient system Λ .

Definition 10.4. For $\Lambda \in \{\overline{\mathbb{F}}_\ell, \overline{\mathbb{Z}}_\ell, \overline{\mathbb{Q}}_\ell\}$, we will say μ is tilting if the representation $V_\mu \in \mathrm{Rep}_\Lambda(\hat{G})$ lies in the full subcategory $\mathrm{Tilt}_\Lambda(\hat{G})$ of tilting modules or equivalently if it is irreducible with coefficients in Λ .

Remark 10.5. If $\Lambda = \overline{\mathbb{Q}}_\ell$ this condition always holds. Moreover, by Lemma B.1, this always holds if μ is minuscule. In Appendix B, we give more insight into this notion.

We now consider a toral parameter $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ with associated smooth character $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$. Unless otherwise stated, we will assume that ϕ_T is integral with generic regular mod ℓ -reduction. Given such a ϕ_T , we set ϕ to be the L -parameter of G induced via the natural embedding ${}^L T(\Lambda) \rightarrow {}^L G(\Lambda)$ and consider the sheaf $\mathrm{nEis}(\mathcal{S}_{\phi_T}) \in \mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)$ given by Theorem 9.10. We begin our analysis by relating our eigensheaves to an averaging formula of Shin. From now on, we will assume 6.5.

10.1. The Averaging Formula. For μ a geometric dominant cocharacter with reflex field E , we write $r_\mu : W_E \times \hat{G} \rightarrow \mathrm{GL}(\mathcal{T}_\mu)$ for the map defined by $\mathcal{T}_\mu$. Since the Hecke operator T_{μ^Γ} attached to $\mathcal{T}_{\mu^\Gamma} \in \mathrm{Rep}_\Lambda({}^L G)$ factors through the Hecke operator T_μ attached to $\mathcal{T}_\mu$ (cf. [FS, Pages 313-315]) if ϕ_T is μ -regular then, by definition, we have an isomorphism

$$T_\mu \mathrm{nEis}(\mathcal{S}_{\phi_T}) \simeq r_\mu \circ \phi|_{W_E} \boxtimes \mathrm{nEis}(\mathcal{S}_{\phi_T})$$

of objects in $\mathrm{D}_{\mathrm{lis}}(\mathrm{Bun}_G, \Lambda)^{BW_E}$. Now let's apply the restriction functor $j_1^*(-)$ to both sides of this isomorphism. By the description of the stalks, we know that the RHS is equal to $r_\mu \circ \phi|_{W_E} \boxtimes \pi$, where $\pi := i_B^G(\chi)$ is the normalized parabolic induction of the character χ attached to ϕ_T by class field theory. We can also simplify the RHS. In particular, first off note that, since any G -bundle $\mathcal{F}_G$ on X that occurs as a modification $\mathcal{F}_G \dashrightarrow \mathcal{F}_G^0$ of type μ lies in the set $B(G, \mu)$ by [Rap18, Proposition A.9], we have an isomorphism

$$j_1^*(T_\mu(\mathrm{nEis}(\mathcal{S}_{\phi_T}))) \simeq j_1^* T_\mu(\mathrm{nEis}(\mathcal{S}_{\phi_T})|_{B(G, \mu)})$$

where here we view $B(G, \mu)$ as the open subset of Bun_G defined by the identification $B(G) \simeq |\text{Bun}_G|$ describing the underlying topological space $|\text{Bun}_G|$ of Bun_G [Vie, Theorem 1.1], where $B(G)$ has the natural topology given by the partial ordering. We can further refine this by applying excision with respect to the locally closed stratification by the Harder-Narasimhan strata $\text{Bun}_G^b \subset \text{Bun}_G$ for $b \in B(G, \mu)$, using [FS, Proposition VII.7.3]. The excision spectral sequence then tells us that the LHS has a filtration whose graded pieces are isomorphic to:

$$j_1^*(T_\mu(j_b!j_b^*(\text{nEis}(\mathcal{S}_{\phi_T})))),$$

which, using Proposition 10.12, and the description of the stalks of the Eigensheaf one can show is isomorphic to $j_1^*(T_\mu(j_b!j_b^*(\text{nEis}(\mathcal{S}_{\phi_T}))))$. In particular, in $K_0(G(\mathbb{Q}_p) \times W_E, \Lambda)$, the Grothendieck group of Λ -valued smooth admissible $G(\mathbb{Q}_p)$ -representations with a continuous action of W_E , this tells us that we have an equality:

$$(6) \quad \sum_{b \in B(G, \mu)} [j_1^*(T_\mu(j_b!j_b^*(\text{nEis}(\mathcal{S}_{\phi_T}))))] = [r_\mu \circ \phi|_{W_E} \boxtimes \pi]$$

Now, using the description of the stalks of $\text{nEis}(\mathcal{S}_{\phi_T})$ and Lemma 10.1, we can spell out the LHS more clearly. In particular, we define the following.

Definition 10.6. For ϕ_T an arbitrary toral parameter with induced parameter ϕ and $b \in B(G)$, we define the complex of smooth admissible $J_b(\mathbb{Q}_p)$ -representations $\text{Red}_{b, \phi}$ as follows. If $b \notin B(G)_{\text{un}}$, we set $\text{Red}_{b, \phi}$ to be equal to 0, and, if $b \in B(G)_{\text{un}}$, we set $\text{Red}_{b, \phi}$ to be equal to

$$\bigoplus_{w \in W_b} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}[-\langle 2\hat{\rho}, \nu_b \rangle] \in \text{D}(J_b(\mathbb{Q}_p), \Lambda)$$

where δ_{P_b} is the modulus character of J_b defined by the standard parabolic $P_b \subset G$ with Levi factor $M_b \simeq J_b$, as before.

This allows us to deduce the following from equation (8).

Theorem 10.7. For $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ an integral parameter with generic regular mod ℓ reduction, if $\pi := i_B^G(\chi)$ is the normalized parabolic induction of the smooth character χ attached to ϕ_T then, for any geometric dominant cocharacter μ such that ϕ_T is μ -regular, we have an equality

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^\flat(G, b, \mu)[\text{Red}_{b, \phi}]] = [r_\mu \circ \phi|_{W_E} \boxtimes \pi]$$

in $K_0(G(\mathbb{Q}_p) \times W_E, \Lambda)$.

Remark 10.8. We note that, in the above analysis, we didn't necessarily have to restrict to the HN-strata Bun_G^1 or even a single cocharacter. In particular, by considering Hecke operators defined by representations in $\text{Tilt}_\Lambda({}^L G^I)$ for a finite index set I , we could have deduced an analogous formula for shtuka spaces with I legs for an arbitrary finite index set I . We could have also restricted to any HN-stratum; however, if the HN-stratum is not defined by a basic element, the answer is not as clean as above. In particular, given a G -bundle $\mathcal{F}_b$ on X corresponding to a general element $b \in B(G)$, it is to the best of our knowledge completely unknown exactly which G -bundles $\mathcal{F}_G$ occur as modifications $\mathcal{F}_G \dashrightarrow \mathcal{F}_b$ of type μ . It would be interesting to understand this question better. We leave it to the reader to work out the precise statements of these more general implications.

We can use this claim to deduce the averaging formula for an arbitrary toral parameter ϕ_T when $\Lambda = \overline{\mathbb{Q}_\ell}$, by viewing both sides as trace forms on $K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ and using a continuity argument. We note that, in this case, the cocharacter μ is always tilting so we have that $R\Gamma_c(G, b, \mu)$ and $R\Gamma_c^\flat(G, b, \mu)$ are just the usual complexes. We recall that $f : K_0(G(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell}) \rightarrow \overline{\mathbb{Q}_\ell}$ is a trace form if

it can be written as $\text{tr}(\delta| -)$ for $\delta \in C_c^\infty(G(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$. We now fix a $\delta \in C_c^\infty(G(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ and $\gamma \in W_E$, we define the following functions attached to this datum:

$$\begin{aligned} f_L^{\delta, \gamma} &: K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell}) \rightarrow \overline{\mathbb{Q}_\ell} \\ \chi &\mapsto \text{tr}(\delta \times \gamma | i_B^G(\chi) \boxtimes r_\mu \circ \iota(\chi)|_{W_E}) \\ f_R^{\delta, \gamma} &: K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell}) \rightarrow \overline{\mathbb{Q}_\ell} \\ \chi &\mapsto \sum_{b \in B(G, \mu)_{\text{un}}} \sum_{w \in W_b} \text{tr}(\delta \times \gamma | R\Gamma_c^b(G, b, \mu) [i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}]) (-1)^{\langle 2\hat{\rho}_G, \nu_b \rangle}, \end{aligned}$$

where $\iota(\chi) \simeq \phi_T$ is given by local class field theory. We have the following lemma.

Lemma 10.9. *The functions $f_L^{\delta, \gamma}$ and $f_R^{\delta, \gamma}$ define trace forms on $K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$.*

Proof. This follows from the fact that normalized parabolic induction takes trace forms to trace forms as can be checked from the characterization of trace forms in the trace Paley-Wiener theorem [BDK86], and the fact that $\text{tr}(\delta \times \gamma | R\Gamma_c(G, b, \mu) [-])$ defines a trace form on $K_0(J_b(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ by [HKW22, Theorem 6.5.4]. $\square$

This gives the following.

Theorem 10.10. *For $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}_\ell})$ an arbitrary toral parameter with associated character χ , and $i_B^G(\chi) =: \pi$, we have an equality*

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^b(G, b, \mu) [\text{Red}_{b, \phi}]] = [r_\mu \circ \phi|_{W_E} \boxtimes \pi]$$

in $K_0(G(\mathbb{Q}_p) \times W_E, \overline{\mathbb{Q}_\ell})$.

Proof. It suffices to show that the trace forms $f_L^{\delta, \gamma}(\chi)$ and $f_R^{\delta, \gamma}(\chi)$ agree for varying δ and γ and all $\chi \in K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$. We define the difference $\Delta_{\delta, \gamma} := f_L^{\delta, \gamma}(\chi) - f_R^{\delta, \gamma}(\chi)$. We say that a subset $S \in K_0(T(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ is dense if $\Delta_{\delta, \gamma}(x) = 0$ for all $x \in S$ implies that $\Delta_{\delta, \gamma} = 0$. Using Theorem 10.7 and Lemma 9.15, we can reduce to showing that the subset S of all characters χ which are normalized regular and admit a $\overline{\mathbb{Z}_\ell}$ -lattice is dense. This is relatively easy to show. In particular, if we view $\Delta_{\delta, \gamma}$ as a regular function on the variety of unramified twists of a fixed character χ then the set of characters admitting a $\overline{\mathbb{Z}_\ell}$ lattice is Zariski-dense. Moreover, the locus where χ is normalized regular is also clearly Zariski dense, since it is implied by insisting that χ precomposed with sums of coroots is not the norm or trivial character for the sums of coroots appearing in differences of distinct weights of V_{μ_k} , for a finite list of generating cocharacters μ_k with $k = 1, \dots, n$ appearing in the definition of μ -regularity, and it is also clear for the condition of generic regularity. Therefore, the claim follows, using the previous Lemma. $\square$

This theorem is compatible with existing results. We recall that Shin [Shi12] and Bertoloni-Meli [Ber21], have described similar averaging formulas. In particular, given a refined endoscopic datum $\mathfrak{e} = (H, \mathcal{H}, s, \eta)$ (Definition C.1), Shin and Bertoloni-Meli define maps

$$\text{Red}_b^{\mathfrak{e}}(-) : K_0^{st}(H(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell}) \rightarrow K_0(J_b(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$$

where $K_0^{st}(H(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ denotes the Grothendieck group of stable virtual $\overline{\mathbb{Q}_\ell}$ -representations of $H(\mathbb{Q}_p)$. If we are given an L -parameter ϕ which factors as $\mathcal{L}_{\mathbb{Q}_p} \xrightarrow{\phi^H} \mathcal{H} \xrightarrow{L\eta} {}^L G$ then, using the local Langlands correspondence for G , we are able to attach a stable distribution $S\Theta_\phi \in K_0^{st}(H(\mathbb{Q}_p), \overline{\mathbb{Q}_\ell})$ which should satisfy the endoscopic character identities as in [Kal16, Conjecture D]. The averaging formula (Conjecture C.2) is a conjectural formula for

$$\sum_{b \in B(G, \mu)} R\Gamma_c^b(G, b, \mu) [\text{Red}_b^{\mathfrak{e}}(S\Theta_\phi)]$$

in $K_0(G(\mathbb{Q}_p) \times W_E, \overline{\mathbb{Q}}_\ell)$. Our averaging formula is related to the case when $\mathfrak{c}_{\text{triv}} = (G, 1, {}^L G, \text{id})$ is the trivial endoscopic datum. In particular, if ϕ_T is a generic toral parameter then, by Lemma 3.14, ϕ should define an actual L -parameter with trivial monodromy, and we can consider the L -packet $\Pi_\phi(G)$ under the local Langlands correspondence for G appearing in Assumption 6.5. By Assumption 6.5 (3), the members of the L -packet will be given by the irreducible constituents of $i_B^G(\chi)$. Therefore, we have that $S\Theta_\phi = [\pi]$ in $K_0^{st}(G(\mathbb{Q}_p), \overline{\mathbb{Q}}_\ell)$, and in the appendix we verify that the following is true.

Proposition 10.11. *Let $\chi : W_{\mathbb{Q}_p} \rightarrow \overline{\mathbb{Q}}_\ell^*$ be a smooth generic character, so that, using Lemma 3.14, we have an equality*

$$S\Theta_\phi = [\pi]$$

in $K_0(G(\mathbb{Q}_p), \overline{\mathbb{Q}}_\ell)^{st}$ under the local Langlands correspondence appearing in Assumption 6.5. Then we always have

$$[\text{Red}_{b,\phi}] = \text{Red}^{\mathfrak{c}_{\text{triv}}}([\pi])$$

in the Grothendieck group $K_0(J_b(\mathbb{Q}_p), \overline{\mathbb{Q}}_\ell)$, and Conjecture C.2 holds true for the L -parameter ϕ attached to χ .

We would now like to refine our averaging formula further. In particular, using Theorem 8.11, we can upgrade this equality in the Grothendieck group to a genuine isomorphism of complexes.

10.2. The Refined Averaging Formula and Intertwining Operators. Consider an element $b \in B(G)_{\text{un}}$ with dominant reduction $b_T \in B(T)$. For $w \in W_b$, we set $\rho_{b,w} := i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$ to be the twisted normalized parabolic induction, and consider $j_b : \text{Bun}_G^b \hookrightarrow \text{Bun}_G$, the inclusion of the locally closed HN-strata corresponding to b . We let ϕ_T be an integral parameter with weakly generic mod ℓ -reduction and consider the sheaf $\text{nEis}(\mathcal{S}_{\phi_T})$ furnished by Theorem 9.10. We have an isomorphism

$$(7) \quad j_{b!}(\rho_{b,w})[-\langle 2\hat{\rho}, \nu_b \rangle] \simeq \text{nEis}^{w(b_T)}(\mathcal{S}_{\phi_T}).$$

We can act by $\mathbb{D}_{\text{Bun}_G}(-)$ on both sides of (12). By the commutation of Eisenstein series with Verdier duality, the RHS of (12) becomes

$$\text{nEis}^{w(b_T)}(\mathcal{S}_{\phi_T}^\vee) \simeq j_{b!}(\rho_{b,w}^*)[-\langle 2\hat{\rho}, \nu_b \rangle]$$

where $\rho_{b,w}^* = (i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2})^* = i_{B_b}^{J_b}((\chi^w)^{-1}) \otimes \delta_{P_b}^{1/2}$ denotes the contragradient. On the other hand, the LHS of (12) becomes

$$j_{b*}(\mathbb{D}_{\text{Bun}_G^b}(\rho_{b,w_0}))[\langle 2\hat{\rho}, \nu_b \rangle]$$

We now need to be a bit careful. In particular, we recall that $\text{Bun}_G^b \simeq [*/\mathcal{J}_b]$, where $\mathcal{J}_b$ is the group diamond parameterizing automorphisms of $\mathcal{F}_b$, and we are implicitly using the identification $\text{D}_{\text{lis}}(\text{Bun}_G^b, \Lambda) \simeq \text{D}(J_b(\mathbb{Q}_p), \Lambda)$ given by pullback along the map $p : [*/\mathcal{J}_b] \rightarrow [*/J_b(\mathbb{Q}_p)]$, as in [FS, Proposition V.2.2, VII.7.1]. Therefore, we need to account for the shifts and twists given by $p^!$. We can use that the natural section s of p is an iterated fibration of positive Banach-Colmez space and Proposition 10.3, to show that $p^!(-) \simeq p^*(- \otimes \delta_{P_b}^{-1})[-2\langle 2\hat{\rho}, \nu_b \rangle]$, and therefore the LHS of (12) becomes $j_{b*}(\rho_{b,w}^* \otimes \delta_{P_b}^{-1})[\langle 2\hat{\rho}, \nu_b \rangle - 2\langle 2\hat{\rho}, \nu_b \rangle] = j_{b*}(\rho_{b,w}^* \otimes \delta_{P_b}^{-1})[-\langle 2\hat{\rho}, \nu_b \rangle]$. In conclusion, we have an isomorphism:

$$j_{b*}(\rho_{b,w}^* \otimes \delta_{P_b}^{-1})[-\langle 2\hat{\rho}, \nu_b \rangle] \simeq j_{b!}(\rho_{b,w}^* \otimes \delta_{P_b}^{-1})[-\langle 2\hat{\rho}, \nu_b \rangle]$$

Relaxing the contragredients and cancelling the shifts, we deduce an isomorphism:

$$j_{b*}(\rho_{b,w}) \simeq j_{b!}(\rho_{b,w}).$$

In conclusion, we deduce the following, which was already mentioned in Theorem 8.12, but we have now also handled the case of more general coefficient systems using the discussion in §10.

Proposition 10.12. *For $b \in B(G)_{\text{un}}$, $w \in W_b$, ϕ_T an integral toral parameter with generic regular reduction, and $\rho_{b,w} = i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}$, we have an isomorphism*

$$j_{b!}(\rho_{b,w}) \simeq j_{b*}(\rho_{b,w})$$

of objects in $D_{\text{lis}}(\text{Bun}_G, \Lambda)$.

Remark 10.13. If b is basic then this precisely says that the sheaf defined by $\rho_{b,w}$ is inert in the sense of [Han20, Definition 2.19]. In particular, this Proposition, in conjunction with [Han20, Theorem 2.22] and Lemma 3.14, seems to suggest that inert sheaves should correspond precisely to the representations whose semi-simplified L -parameter comes from the semi-simplification of a parameter with non-trivial monodromy. For example, if one takes the constant sheaf on Bun_G^1 and considers $j_{1!}(\Lambda)$ then we have that $\mathbb{D}_{\text{Bun}_G}(j_{1!}(\Lambda)) \simeq j_{1*}(\Lambda)$ which one can check is not isomorphic to $j_!(\Lambda)$ (See the proof of [HI25, Proposition 3.16]). Similarly, we see that the L -parameter attached to the trivial representation comes from the semi-simplification of a parameter with non-trivial monodromy (the Steinberg parameter).

Now consider μ a geometric dominant cocharacter of G with reflex field E and an element $b \in B(G, \mu)$. Applying $j_1^* T_\mu(-)$ to both sides of the previous isomorphism, we conclude, using Proposition 10.3, an isomorphism

$$R\Gamma_c(G, b, \mu)[\rho_{b,w} \otimes \delta_{P_b}] \simeq R\Gamma_c^\flat(G, b, \mu)[\rho_{b,w}][-2\langle 2\rho_G, \nu_b \rangle].$$

Corollary 10.14. *Let (G, b, μ) be a local shtuka datum. For $b \in B(G)_{\text{un}}$, $w \in W_b$, and ϕ_T an integral toral parameter such that ϕ_T has generic regular mod ℓ reduction, there is an isomorphism*

$$R\Gamma_c(G, b, \mu)[\rho_{b,w} \otimes \delta_{P_b}] \simeq R\Gamma_c^\flat(G, b, \mu)[\rho_{b,w}][-2\langle 2\rho_G, \nu_b \rangle]$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules.

We now claim that the cohomology of $R\Gamma_c(G, b, \mu)[\rho_{b,w} \otimes \delta_{P_b}]$ should be concentrated in degree $\langle 2\hat{\rho}, \nu_b \rangle$, for $\rho_{b,w}$ as above. To do this, let's put ourselves back in the position of an integral ϕ_T with generic regular mod ℓ reduction. We saw that in the previous section that the excision spectral sequence applied to $\text{nEis}(\mathcal{S}_{\phi_T})|_{B(G, \mu)}$ gives rise to a filtration whose graded pieces are isomorphic to $j_{b!}j_b^*(\text{nEis}(\mathcal{S}_{\phi_T}))$, but Lemma 10.12 implies that these graded pieces are also isomorphic to $j_{b*}j_b^*(\text{Eis}(\mathcal{S}_{\phi_T}))$. In particular, this allows us to deduce that the edge maps in the excision spectral sequence split, and therefore the sequence degenerates, giving an isomorphism:

$$\bigoplus_{b \in B(G, \mu)} j_{b*}j_b^* \text{nEis}(\mathcal{S}_{\phi_T}) \simeq \text{nEis}(\mathcal{S}_{\phi_T})|_{B(G, \mu)}.$$

We now would like to apply the eigensheaf property. So fix a geometric dominant cocharacter, and assume that ϕ_T is μ -regular. If $\pi = i_B^G(\chi)$ is the normalized parabolic induction of χ as above then, using our description of the stalks, we deduce the following "refined averaging formula".

Theorem 10.15. *For $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\Lambda)$ an integral toral parameter with generic regular mod ℓ -reduction and μ a geometric dominant cocharacter such that ϕ_T is μ -regular, we have an isomorphism*

$$\bigoplus_{b \in B(G, \mu)_{\text{un}}} \bigoplus_{w \in W_b} R\Gamma_c^\flat(G, b, \mu)[\rho_{b,w}][-2\langle 2\hat{\rho}_G, \nu_b \rangle] \simeq (i_B^G(\chi) \boxtimes r_\mu \circ \phi|_{W_E})$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -modules.

Unless otherwise stated, we will from now on assume that ϕ_T is integral with generic regular mod ℓ reduction. Using the previous formula, we can give a very explicit description of the complexes $R\Gamma_c^\flat(G, b, \mu)[\rho_{b,w}]$, for $b \in B(G, \mu)_{\text{un}}$ and $w \in W_b$.

Corollary 10.16. *For μ a geometric dominant cocharacter with reflex field E such that ϕ_T is μ -regular, fixed $b \in B(G, \mu)_{\text{un}}$, and varying $w \in W_b$, the complex $R\Gamma_c^b(G, b, \mu)[\rho_{b,w}]$ is isomorphic to $\phi_{b,w}^\mu \boxtimes \sigma[\langle 2\hat{\rho}, \nu_b \rangle]$, for $\phi_{b,w}^\mu$ a representation of W_E and σ a subrepresentation of $i_B^G(\chi)$. Moreover, we have an isomorphism*

$$\bigoplus_{b \in B(G, \mu)_{\text{un}}} \bigoplus_{w \in W_b} \phi_{b,w}^\mu \simeq r_\mu \circ \phi|_{W_E}$$

of W_E -representations.

This leads to a natural question. How can we describe the W_E -representations $\phi_{b,w}^\mu$ in terms of the weights appearing in $r_\mu \circ \phi|_{W_E}$. We recall, by Corollary 2.9, that the orbit of b_T under the Weyl group W_G can be described as $w(b_T)$ for $w \in W_b$ varying; moreover, using Corollary 2.9 and Remark 9.6, we see that we have a correspondence between $B(G, \mu)_{\text{un}}$ and the set of Weyl orbits of weights which can occur in the representation $\mathcal{T}_\mu|_{\hat{G}\Gamma}$. In particular, given $\bar{\nu} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p})_\Gamma$, we consider the subspace

$$\bigoplus_{\substack{\nu \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \bar{\nu}_\Gamma = \bar{\nu}}} \tilde{\nu} \circ \phi_T|_{W_E} \otimes \mathcal{T}_\mu(\nu)$$

of $(r_\mu \circ \phi)|_{W_E}$, where we note that if we forget the Galois action then this identifies with the $\bar{\nu}$ weight space of $\mathcal{T}_\mu|_{\hat{G}\Gamma}$ by Lemma 2.8. Now the refined averaging formula suggests the following.

Conjecture 10.17. *For all geometric dominant cocharacters μ such that ϕ_T is μ -regular, an unramified element $b \in B(G, \mu)_{\text{un}}$, and a Weyl group element $w \in W_b$, we have an isomorphism*

$$\bigoplus_{\substack{\widetilde{w(b_T)} \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \widetilde{w(b_T)}_\Gamma = w(b_T)}} \widetilde{w(b_T)} \circ \phi_T|_{W_{E'}} \otimes \mathcal{T}_\mu(\widetilde{w(b_T)}) \simeq \phi_{b,w}^\mu|_{W_{E'}}$$

of $W_{E'}$ -representations, where b_T is a dominant reduction of b and $E'|E$ denotes the splitting field of G .

For the rest of this section, let us look at some cases where this can be shown explicitly, using a shtuka analogue of Boyer's trick. To illustrate the idea, we begin with a particularly nice example, where Theorem 10.15 and Conjecture 10.17 can be checked by hand.

Example 10.18. Let $G = \text{GL}_2$ and $\mu = (1, 0)$. Write $\phi_T = \phi_1 \oplus \phi_2$, and consider the set $B(G, \mu)$. It consists of two elements: the μ -ordinary element and the basic element. Only the μ -ordinary element lies in $B(G, \mu)_{\text{un}}$; therefore, only this element contributes to the expression in Theorem 10.15. Namely, if b_μ denotes the μ -ordinary element, we note that $\langle 2\hat{\rho}, \nu_{b_\mu} \rangle = \langle 2\hat{\rho}, \mu \rangle = 1$. We conclude that Theorem 10.15 is an isomorphism

$$R\Gamma_c^b(G, b_\mu, \mu)[\chi \otimes \delta_B^{-1/2}] \oplus R\Gamma_c^b(G, b_\mu, \mu)[\chi^{w_0} \otimes \delta_B^{-1/2}] \simeq i_B^{GL_2}(\chi) \boxtimes \phi[1]$$

of $G(\mathbb{Q}_p) \times W_{\mathbb{Q}_p}$ -representations. This can be seen through direct computation. In particular, we have an isomorphism $J_{b_\mu} \simeq T$, and, since μ is minuscule, we have that $\mathcal{S}_\mu \simeq \Lambda[1](\frac{1}{2})$. The space $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ is the moduli space parameterizing modifications $\mathcal{O}(-1) \oplus \mathcal{O} \dashrightarrow \mathcal{O}^2$ of type $(1, 0)$. Every such modification is determined by an injection $\mathcal{O}(-1) \hookrightarrow \mathcal{O}$ of line bundles. Formally, this implies that the space $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ as a space with $\text{GL}_2(\mathbb{Q}_p)$ -action is parabolically induced from the space parameterizing such injections as a space with $T(\mathbb{Q}_p)$ action. Here $T(\mathbb{Q}_p)$ acts on the space of injections $\mathcal{O}(-1) \hookrightarrow \mathcal{O}$ via the scaling action precomposed with projection to the first factor of $T(\mathbb{Q}_p)$. This is a manifestation of the fact that $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ is a $\mathcal{J}_b$ -torsor over the flag variety $(G/B)(\mathbb{Q}_p) \simeq \mathbb{P}^1(\mathbb{Q}_p) \subset \mathbb{P}_{\mathbb{C}_p}^1 \simeq \text{Gr}_{G, \leq \mu^{-1}, \mathbb{C}_p}$, where the last isomorphism is the Bialynicki-Birula map. In particular, note that the compactly supported cohomology of $G/B(\mathbb{Q}_p)$ is precisely

the space of compactly supported functions on $(G/B)(\mathbb{Q}_p)$. All in all, this allows us to conclude isomorphisms

$$\begin{aligned} R\Gamma_c^b(G, b_\mu, \mu)[\chi \otimes \delta_B^{-1/2}] &= \text{Ind}_{B^-}^G(\chi \otimes \delta_B^{-1/2}) \boxtimes \phi_1[1] = i_B^G(\chi^{w_0}) \boxtimes \phi_1[1] \\ R\Gamma_c^b(G, b_\mu, \mu)[\chi^{w_0} \otimes \delta_B^{-1/2}] &= \text{Ind}_{B^-}^G(\chi^{w_0} \otimes \delta_B^{-1/2}) \boxtimes \phi_2[1] = i_B^G(\chi) \boxtimes \phi_2[1], \end{aligned}$$

where there is a cancellation of the $\frac{1}{2}$ Tate twist in $\mathcal{S}_\mu$ and the Tate twist coming from $\delta_B^{-1/2}$, as in §3. the compactly supported cohomology of $\mathcal{J}_b^{>0}$ contribute. Now, if χ is attached to a generic parameter ϕ_T , this implies that $i_B^G(\chi)$ is irreducible as in Example 3.8, and it follows that we have an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^{w_0})$, which allows us to conclude the result.

Now let's generalize this example. In particular, recall that $B(G, \mu)$ has a distinguished μ -ordinary element, denoted b_μ , which is the maximal element with respect to the partial ordering on $B(G, \mu)$, and has the property that $\tilde{\mu} = \nu_{b_\mu}$, where $\tilde{\mu}$ is the weighted average over the Galois orbit of μ as in §2.1. If we write μ_T for μ viewed as a geometric cocharacter of T in the negative Weyl chamber defined by the choice of Borel, we can see that b_μ admits a dominant reduction to the unique element $b_{\mu_T} \in B(T, \mu_T)$. In other words, the element b_μ always lies in $B(G, \mu)_{\text{un}} := B(G, \mu) \cap B(G)_{\text{un}}$. Conjecture 10.17 suggests to us that this should give rise to the contribution given by the highest weight of $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$, which will have multiplicity one. We now prove the following result using a shtuka analogue of Boyer's trick [Boy99] proven by Gaisin-Imai [GI16].

Proposition 10.19. *For μ any geometric dominant cocharacter with reflex field E , $b_\mu \in B(G, \mu)_{\text{un}}$ the μ -ordinary element with dominant reduction b_{μ_T} , $w \in W_b$ varying, and ϕ_T any toral parameter, we have an isomorphism*

$$R\Gamma_c^b(G, b_\mu, \mu)[\rho_{b_\mu, w}] \simeq w(\mu_T) \circ \phi_T|_{W_E} \boxtimes i_B^G(\chi^{ww_0})[\langle 2\hat{\rho}, \nu_{b_\mu} \rangle]$$

of $W_E \times G(\mathbb{Q}_p)$ -representations, where $w, w_0 \in W_b$ are representatives of minimal length.

Proof. We note that the element $b_\mu \in B(G, \mu)$ is Hodge-Newton reducible in the sense of [RV14, Definition 4.5]. In particular, b_μ is induced from the unique element $b_{\mu_T} \in B(T, \mu_T)$ via the natural map $B(T) \rightarrow B(G)$. Consider a rank k vector bundle of the form $\bigoplus_{i=1}^k \mathcal{O}(n_i)$ for $n_i \in \mathbb{Z}$ and suppose we have a modification:

$$\bigoplus_{i=1}^k \mathcal{O}(n_i) \dashrightarrow \mathcal{O}^n$$

Then it is easy to see that such a modification will be determined by a tuple of modifications

$$\mathcal{O}(n_i) \dashrightarrow \mathcal{O}$$

for all $i = 1, \dots, k$. If we apply the Tannakian formalism [GI16, Lemma 4.11], this tells us that the space $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ parameterizing modifications of the form

$$\mathcal{F}_{b_\mu} \dashrightarrow \mathcal{F}_G^0$$

will be determined by the spaces $\text{Sht}(T, w(b_{\mu_T}), w(\mu_T))_{\infty, \mathbb{C}_p}$ parametrizing modifications of the form

$$\mathcal{F}_{w(b_{\mu_T})} \dashrightarrow \mathcal{F}_T^0$$

with meromorphy equal to $w(\mu_T)$ for varying $w \in W_{b_\mu}$. In particular, this tells us that the moduli space $\text{Sht}(G, b_\mu, \mu)_{\infty, \mathbb{C}_p}$ parameterizing modifications of meromorphy $\leq \mu$ is actually equal to the open subspace $\text{Sht}(G, b_\mu, \mu)_{\infty}^\mu$ parameterizing modifications of meromorphy equal to μ . This is because any modification induced from a modification

$$\mathcal{F}_{b_{\mu_T}} \dashrightarrow \mathcal{F}_T^0$$

of type μ_T will be of type μ , which implies that we have an isomorphism $\mathcal{S}_\mu \simeq \Lambda[d](\frac{d}{2})$, where $d = \langle 2\hat{\rho}, \nu_{b_\mu} \rangle = \langle 2\hat{\rho}, \mu \rangle$ using [FS, Proposition VI.7.5]. Here we need to be a bit careful since $\mathcal{S}_\mu$

is the pullback of the sheaf associated to the tilting module $\mathcal{T}_\mu$ not V_μ as per usual. However, we note that the above discussion tells us that the Newton strata in the Schubert cell/variety $\mathrm{Gr}_{G, \leq \mu^{-1}, \mathbb{C}_p}^{b_\mu} = \mathrm{Gr}_{G, \mu^{-1}, \mathbb{C}_p}^{b_\mu}$ has only non-empty intersection with the semi-infinite cells $S_{G, w(\mu_T), \mathbb{C}_p}$ indexed by the Weyl group orbits of the highest weight, using the Remark proceeding 4.7. Since both $\mathcal{T}_\mu$ and V_μ have highest weight with multiplicity one, the discrepancy doesn't matter via Corollary 4.9. It remains to describe the complex $R\Gamma_c^b(G, b_\mu, \mu)[\rho_{b_\mu, w}]$. Using our above observations, [GI16, Theorem 4.26] (as in the proof [HI25, Theorem 4.21]), it follows that we have an isomorphism

$$R\Gamma_c^b(G, b_\mu, \mu)[\rho_{b_\mu, w}] \simeq \mathrm{Ind}_{P_{b_\mu}^-}^G (R\Gamma_c^b(M, b_{\mu_M}, \mu_M)[i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_{b_\mu}}^{-1/2}][\langle 2\hat{\rho}, \mu \rangle](\langle \hat{\rho}, \mu \rangle))$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -representation, where $M = M_{b_\mu}$ is the centralizer of the slope homomorphism, μ_M is the G -dominant choice of μ viewed as a cocharacter of M , and $b_{\mu_M} \in B(M, \mu_M)$ is the μ -ordinary element. We note that, since $b_\mu \in B(G)_{\mathrm{un}}$, it follows that $B(M, \mu_M)$ is a singleton and that μ_M is central with respect to M . In particular, $\mathrm{Sht}(M, \mu_M, b_{\mu_M})$ is 0-dimensional and identifies with the profinite set $\underline{M}(\mathbb{Q}_p)$ (recall that $M \simeq J_{b_\mu} \simeq J_{b_{\mu_M}}$ in this case). This allows us to identify

$$R\Gamma_c^b(M_b, \mu_M, b_{\mu_M})[i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_{b_\mu}}^{-1/2}] \simeq i_{B \cap M_b}^{M_b}(\chi^w) \otimes \delta_{P_{b_\mu}}^{-1/2} \boxtimes w(\mu_T) \circ \phi_T(-\langle \hat{\rho}, \mu \rangle)|_{W_E},$$

where we can identify the 1-dimensional Weil group action through excursion algebra considerations. Therefore, we get an isomorphism

$$\begin{aligned} R\Gamma_c^b(G, b_\mu, \mu)[\rho_{b_\mu, w}] &\simeq \mathrm{Ind}_{P_{b_\mu}^-}^G (i_{B \cap M_b}^{M_b}(\chi^w) \otimes \delta_{P_{b_\mu}}^{-1/2}) \boxtimes w(\mu_T) \circ \phi_T|_{W_E}[\langle 2\hat{\rho}, \mu \rangle](\langle -\hat{\rho}, \mu \rangle + \langle \hat{\rho}, \mu \rangle) \simeq \\ &i_B^G(\chi^{ww_0}) \boxtimes w(\mu_T) \circ \phi_T|_{W_E}[\langle 2\hat{\rho}, \mu \rangle] \end{aligned}$$

of complexes of $G(\mathbb{Q}_p) \times W_E$ -representations which gives the desired result by transitivity of parabolic induction. $\square$

Remark 10.20. We note that in the proof we did not use any of our results on geometric Eisenstein series. It would be interesting to generalize some of these computations to some non-principal situations. In particular, if one works with a general parabolic P with Levi factor M and a supercuspidal parameter $\phi_M : W_{\mathbb{Q}_p} \rightarrow {}^L M$ and assumes that Fargues' conjecture holds on the Levi subgroup M , then the results of [GI16] guarantee that one has similar formulas relating the cohomology of the shtuka spaces of G to basic local shtuka spaces of M for Hodge-Newton reducible $b \in B(G, \mu)$ admitting a reduction to M . The description of the eigensheaf in Fargues' conjecture, as described for odd unramified unitary groups in [BHN22] and partially for GSp_4 in [Ham25], gives one a very explicit description of these basic local shtuka spaces, which would in turn give a computational approach to understanding and generalizing these formulas beyond the principal case. We fully anticipate that some of the methods we use in the principal case generalize to the non-principal case; however, the results seem much more technical, and these computations would give a nice foothold into the problem.

This explicit calculation has some interesting consequences. In particular, we already saw in Example 10.18 that relating Proposition 10.19 to Theorem 10.15 required using the existence of an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^w)$; i.e. intertwining operators. This phenomenon actually persists. In particular, we deduce the following.

Corollary 10.21. *Let $\chi : T(\mathbb{Q}_p) \rightarrow \Lambda^*$ be a character obtained from an integral toral parameter ϕ_T whose mod ℓ -reduction is generic regular. For $\mu \in \mathbb{X}_*(T_{\mathbb{Q}_p})^+$, let W_μ be the stabilizer of the action of W_G on $\mathbb{X}_*(T_{\mathbb{Q}_p})^+$ and assume that ϕ_T is μ -regular. Then, for all $w \in W_G/W_\mu$ a minimal length representative, we have an isomorphism*

$$i_B^G(\chi) \simeq i_B^G(\chi^{ww_0})$$

of $G(\mathbb{Q}_p)$ -representations.

Proof. Since M_{b_μ} will be by construction the centralizer of μ , we have an isomorphism $W_{M_{b_\mu}} \simeq W_\mu$. The previous proposition then tells us that we have an isomorphism

$$R\Gamma_c^b(G, b_\mu, \mu)[i_{B_{b_\mu}}^{J_{b_\mu}}(\chi^w) \otimes \delta_{P_{b_\mu}}^{1/2}] \simeq w(\mu_T) \circ \phi_T|_{W_E} \boxtimes i_B^G(\chi^{ww_0})[\langle 2\hat{\rho}, \nu_{b_\mu} \rangle]$$

for all $w \in W_G/W_\mu$ a minimal length representative. On the other hand, since ϕ_T is μ -regular, Corollary 10.16 tells us that the LHS must be isomorphic as a $G(\mathbb{Q}_p)$ representation to some copies of subrepresentations of $i_B^G(\chi)$. To show that $i_B^G(\chi) \simeq i_B^G(\chi^{ww_0})$, it therefore suffices to show that they are equal in the Grothendieck group. However, we claim that $[i_B^G(\chi)] \simeq [i_B^G(\chi^{ww_0})]$ in $K_0(G(\mathbb{Q}_p), \Lambda)$ for any $\Lambda \in \{\overline{\mathbb{Q}_\ell}, \overline{\mathbb{Z}_\ell}, \overline{\mathbb{F}_\ell}\}$ and $w \in W_G$. With $\overline{\mathbb{Q}_\ell}$ -coefficients, this is classical [Dij72a, Theorem 4]. It suffices to treat the case of $\overline{\mathbb{F}_\ell}$ -coefficients. In this case, after choosing a lift $\tilde{\chi}$ of χ , we have an equality $[i_B^G(\tilde{\chi}) \otimes \overline{\mathbb{Q}_\ell}] = [i_B^G(\tilde{\chi}^{ww_0}) \otimes \overline{\mathbb{Q}_\ell}]$. So we can find $\overline{\mathbb{Z}_\ell}$ -lattices in both representations such that this equality is also true in the Grothendieck group $K_0(G(\mathbb{Q}_p), \overline{\mathbb{Z}_\ell})$. However, the semi-simplification mod ℓ doesn't depend on the choice of $\overline{\mathbb{Z}_\ell}$ -lattice, by the strong Brauer-Nesbitt principle of Vignéras [Vig96, Section 2.5]. It follows that the equality $[i_B^G(\chi)] = [i_B^G(\chi^{ww_0})]$ holds in $K_0(G(\mathbb{Q}_p), \overline{\mathbb{F}_\ell})$ as well. $\square$

In particular, the refined averaging formula, together with the direct computation of provided above, gives rise to an isomorphism: $i_{\chi, w} : i_B^G(\chi) \simeq i_B^G(\chi^w)$. If $\Lambda = \overline{\mathbb{Q}_\ell}$ this recovers the following special case of Proposition A.2.

Corollary 10.22. *Suppose that $\chi : T(\mathbb{Q}_p) \rightarrow \overline{\mathbb{Q}_\ell}^*$ is a normalized regular character admitting a $\overline{\mathbb{Z}_\ell}$ -lattice then we have isomorphisms $i_B^G(\chi) \simeq i_B^G(\chi^w)$ for all $w \in W_G$.*

This suggests an interesting relationship between the theory of geometric Eisenstein series over the Fargues-Fontaine curve and the classical theory of intertwining operators and the Langlands quotient, which we hope is explored more in the future. This prospect becomes even more exciting in the ℓ -modular situation. The theory of intertwining operators in this context has been partially explored by Dat [Dat05, Sections 6-8], and the Langlands quotient theorem does not naively hold in this context, as the following example illustrates.

Example 10.23. Suppose that $\ell \neq 2$, $\ell \mid p-1$, and $G = \mathrm{GL}_2$. We let $\chi = \delta_B^{-1/2}$ be the modulus character. We note that, by our assumption that $\ell \mid p-1$, we have an isomorphism $|\cdot| \simeq \mathbf{1}_T$. It follows that we have that $\delta_B^{-1/2} \simeq \delta_B^{1/2}$. We consider the usual short exact sequence

$$0 \rightarrow \mathbf{1}_G \rightarrow i_B^G(\delta_B^{-1/2}) \rightarrow \mathrm{St}_G \rightarrow 0$$

where St_G denotes the Steinberg representation. Acting by smooth duality actually gives a splitting of the short exact sequence and in turn a chain of isomorphisms

$$i_B^G(\delta_B^{-1/2}) \simeq \mathrm{St}_G \oplus \mathbf{1}_G \simeq i_B^G(\delta_B^{1/2})$$

of smooth $G(\mathbb{Q}_p)$ -representations. In particular, we see that $i_B^G(\delta_B^{1/2})$ does not have a unique irreducible quotient in this case, so that the Langlands quotient theorem cannot naively hold.

Let's now explore a case in which Proposition 10.19 can be used to verify Conjecture 10.17. Suppose that μ is a geometric dominant cocharacter such that the image $\mu_\Gamma \in \mathbb{X}_*(T_{\overline{\mathbb{Q}_p}})_\Gamma^+$ is quasisemiuscual or minuscule with respect to the pairing with $\mathbb{X}_*(\hat{T}^\Gamma)$. In this case, we recall that the orbit of the highest weight space $\mathcal{T}_\mu|_{\hat{G}^\Gamma}(b_\mu)$ forms a closed orbit under the relative Weyl group W_G , where $b_\mu \in B(G, \mu)_{\mathrm{un}}$ is the μ -ordinary element. It then follows that all the weight spaces of $\mathcal{T}_\mu|_{\hat{G}^\Gamma}$ in this orbit will be given by the κ -invariants of $w(b_{\mu_T}) \in B(T) \simeq \mathbb{X}^*(\hat{T}^\Gamma)$, for $w \in W_G$ varying. However, by Proposition 10.19, we see that all the weight spaces of this form come from the contribution

of the μ -ordinary element to the refined averaging formula. If μ_Γ is minuscule with respect to the above pairing this is the only weight space in $\mathcal{T}_\mu|_{\hat{G}_\Gamma}$, and we see that Conjecture 10.17 is true. If μ_Γ is quasi-minuscule, the only other element in $B(G, \mu)_{\text{un}}$ is the basic element, denoted μ^b . By Corollary 2.9, the highest weight representation $\mathcal{T}_\mu|_{\hat{G}_\Gamma}$ admits a central weight space $\mathcal{T}_\mu|_{\hat{G}_\Gamma}(\mu_T^b)$ in this case, where $\mu_T^b \in B(T) \simeq \mathbb{X}^*(\hat{T}^\Gamma)$ is the (unique) reduction to T of $\mu^b \in B(G, \mu)_{\text{un}}$. We deduce the following from the refined averaging formula.

Corollary 10.24. *Let μ be a geometric dominant cocharacter such that ϕ_T is strongly μ -regular with reflex field E . Assume that μ_Γ is quasi-minuscule with respect to the pairing with $\mathbb{X}_*(\hat{T}^\Gamma)$. Let $\mu^b \in B(G, \mu)$ be the unique basic element. It follows by Corollary 2.9 that μ^b is unramified in this case. We let μ_T^b be its unique reduction to $B(T)$. There is an isomorphism*

$$R\Gamma_c(G, b, \mu^b)[i_{B_b}^{J_b}(\chi)]|_{W_{E'}} \simeq R\Gamma_c^b(G, b, \mu^b)[i_{B_b}^{J_b}(\chi)]|_{W_{E'}} \simeq \bigoplus_{\substack{\tilde{\mu}_T^b \in \mathbb{X}_*(T_{\overline{\mathbb{Q}}_p}) \\ \tilde{\mu}_{T\Gamma}^b = \mu_T^b}} \tilde{\mu}_T^b \circ \phi_T|_{W_{E'}} \otimes \mathcal{T}_\mu(\tilde{\mu}_T^b) \boxtimes i_B^G(\chi)$$

of complexes of $W_{E'} \times G(\mathbb{Q}_p)$ -modules, where $E'|E$ denotes the splitting field of G .

Proof. The isomorphism of the b isotypic part with the non- b isotypic part follows from Proposition 10.14, noting that for b basic the shifts and twists do not occur. The rest follows from combining Theorem 10.15 and Proposition 10.19. Noting that, by the strong μ -regularity assumption on ϕ_T , the Weil group action of the contribution of the highest weight to the refined averaging formula must be distinct from the Weil group action on the contribution of the central weight spaces, by the vanishing of the H^0 s for the differences of these weight spaces. $\square$

Remark 10.25. If G is split then the condition that the central weight space of $\mathcal{T}_\mu|_{\hat{G}_\Gamma}$ is non-zero cannot occur if μ is minuscule. However, if G is not split then it can occur that the central weight space is non-trivial even if μ is minuscule. For example, if one considers an odd quasi-split unitary group U_n and the cocharacter $(1, 0, \dots, 0, 0)$ then the σ -centralizer will be isomorphic to U_n , and therefore the basic element $b \in B(G, \mu)$ lies in $B(G)_{\text{un}}$. A more in depth characterization of when this can occur is given in [XZ17, Remark 4.2.11]. This result is in some sense a generic fiber manifestation of some of the results in [XZ17]. Here, in the case that G is unramified, Xiao and Zhu relate the irreducible components of affine Deligne-Lusztig varieties to the central weight spaces appearing above, and use these irreducible components to construct cohomological correspondences on the special fibers of certain Shimura varieties using uniformization. These affine Deligne-Lusztig varieties are precisely the special fibers of a natural integral model of $\text{Sht}(G, \mu^b, \mu)_\infty / \underline{K}$ for a choice of hyperspecial subgroup $K \subset G(\mathbb{Q}_p)$.

APPENDIX A. INTERTWINING OPERATORS AND THE IRREDUCIBILITY OF PRINCIPAL SERIES

We want to show the irreducibility of principal series representations obtained from the characters χ attached to parameters $\phi_T : W_{\mathbb{Q}_p} \rightarrow {}^L T(\overline{\mathbb{Q}}_\ell)$ satisfying the conditions in 3.7. We let $\chi : T(\mathbb{Q}_p) \rightarrow \mathbb{C}^*$ be the character attached to ϕ_T via local class field theory and a fixed isomorphism $\overline{\mathbb{Q}}_\ell \simeq \mathbb{C}$ sending $p^{1/2}$ to the fixed choice of square root in $\overline{\mathbb{Q}}_\ell$. Our goal will be to show the following two facts.

Proposition A.1. *Suppose that χ is a regular character in the sense that it is not fixed under any $w \in W_G$ then if we have an isomorphism*

$$i_B^G(\chi) \simeq i_B^G(\chi^{w_0})$$

the representation $i_B^G(\chi)$ is irreducible.

Proposition A.2. *If $\chi : T(\mathbb{Q}_p) \rightarrow \mathbb{C}^*$ is a generic character then, for all $w \in W_G$, we have an isomorphism*

$$i_B^G(\chi) \simeq i_B^G(\chi^w)$$

of smooth $G(\mathbb{Q}_p)$ -representations.

By combining these two Propositions, we deduce the following.

Corollary A.3. *For χ a generic regular character, the induction $i_B^G(\chi)$ is always irreducible.*

The idea behind proving such results is due to Speh and Vogan [SV80, Theorem 3.14] in the archimedean case. They study the reducibility of principal series using the Langlands classification [BW80, Section IV]. Strictly speaking, their analysis is for the archimedean place, but it is easy to see that it extends to the case of a p -adic group using the analogous Langlands classification there [BW80, Section XI.2]. They (roughly) break the problem of understanding the reducibility points of principal series representations into two parts:

- (1) ([SV80, Theorem 3.14(a)]) Understanding the reducibility points of non-unitary principal series with respect to the parabolic inductions from T to M_i for $i \in \mathcal{J}$, where M_i is the rank 1 Levi subgroup of G whose relative Dynkin diagram is given by $\{i\} \subset \mathcal{J}$.
- (2) ([SV80, Theorem 3.14(b)]) Understanding the reducibility points of unitary principal series representations with respect to induction from T to a (not necessarily rank 1) proper Levi subgroup of G .

We will now explain this heuristic in our case. To see analogous analysis worked out more explicitly for specific p -adic reductive groups, we point the reader to [Tad94, Section 7], [Mui97, Section 3], [Mat10, Section 3] for a small sample. For (2), a very definitive answer to such questions can be found in the paper of Keys [Key82]. In particular, by [Key82, Corollary 1] the number of irreducible components of such a unitary parabolic induction can be computed in terms of the Knapp-Stein R-Group [KS72; Kna73a; Kna73b], which Keys determines for all split groups. While this is very interesting, we will not address this here. In particular, we have the following.

Lemma A.4. *If χ is a regular unitary character then the normalized parabolic induction $i_B^G(\chi)$ is irreducible.*

Proof. This follows from the Bruhat decomposition and the fact that $i_B^G(\chi)$ is unitary and therefore fully decomposable (See [Cas95, Theorem 6.6.1] or [Bru61]). $\square$

Now consider $\mathbb{X}^*(T_{\mathbb{Q}_p})^\Gamma \otimes \mathbb{R} \simeq \mathbb{X}_*(A) \otimes \mathbb{R} \simeq \mathbb{R}^d$ the set of unramified characters. For $s \in \mathbb{R}^d$, we write ν^s for the associated unramified character. We will say that ν^s is positive (resp. strictly positive) if, for all simple (reduced) positive coroots $\alpha_{i,A}$, the precomposition of ν^s with $\alpha_{i,A}$ is positive (resp. strictly positive), or in other words that s lies in the positive Weyl chamber of $\mathbb{X}_*(A) \otimes \mathbb{R}$ defined by the Borel. We write $\chi = \mu_\chi \nu^{s_\chi}$, where μ_χ is a unitary character and ν^{s_χ} is an unramified character of T , for some $s_\chi \in \mathbb{R}^d$. We now consider intertwining operators. Recall that, for $w \in W_G$ and $s \in \mathbb{R}^d$, we have the intertwining operator

$$I_w(\mu_\chi, s) : i_B^G(\mu_\chi \nu^s) \rightarrow i_B^G((\mu_\chi \nu^s)^w)$$

$$f(g) \mapsto \int_{U_w} f(w^{-1}ug)du$$

where $U_w := U \cap wU^-w^{-1}$ and U^- is the unipotent radical of the opposite Borel. This integral will converge if ν^s lies sufficiently deep in the dominant Weyl chamber, and admits a meromorphic continuation as a function of s (where one imposes this constraint on the real part). Away from these poles, it gives rise to an intertwining operator between $i_B^G(\mu_\chi \nu^s)$ and $i_B^G((\mu_\chi \nu^s)^w)$ in the usual representation theory sense. For our purposes, we will be interested in the intertwining operator $I_{w_0}(\mu_\chi, s)$ for the element of longest length w_0 . In this case, one can see that the operator is

convergent for all s which are strictly positive, and the image of the operator is the unique irreducible Langlands quotient of $i_B^G(\mu_\chi \nu^s)$ (See [BW80, Sections XI.2.6, XI.2.7]). This quotient has multiplicity one and therefore the intertwining space between $i_B^G(\chi)$ and $i_B^G(\chi^{w_0})$ is one-dimensional. It follows that, if ν^{s_χ} is strictly positive, it suffices to exhibit an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^{w_0})$ to show irreducibility. We will now use this kind of analysis to prove Proposition A.1.

Proof. (Proposition A.1) First off note that, for all χ , we have an equality

$$[i_B^G(\chi)] = [i_B^G(\chi^{w_0})]$$

in $K_0(G(\mathbb{Q}_p))$ (See for example [Dij72b, Theorem 4]). This allows us to, without loss of generality, assume that ν^{s_χ} is positive. Now, consider the set of $i \in \mathcal{J}$ such that the precomposition of ν^{s_χ} with $\alpha_{i,A}$ is equal to 0. This defines a parabolic P_χ of G which we decompose as $P_\chi = M_\chi A_\chi N_\chi$, where A_χ is the maximal split torus in the center of M_χ . If $\mathcal{J}_{M_\chi}$ denotes the vertices of the relative Dynkin diagram of M_χ then $\mathcal{J}_{M_\chi} \subset \mathcal{J}$ corresponds to the set of simple positive coroots where this precomposition vanishes. Now, set $\nu_1 := \nu^{s_\chi}|_{A \cap M_\chi}$ and $\nu_2 := \nu^{s_\chi}|_{A_\chi}$. We consider the parabolic induction

$$i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)$$

where we now note that $\mu_\chi \otimes \nu_1$ is unitary by construction. Therefore, $i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)$ is unitary and thereby fully decomposable. It follows that, since $i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)$ and $i_{B \cap M_\chi}^{M_\chi}((\mu_\chi \otimes \nu_1)^{w_0^{M_\chi}})$ are equal in the Grothendieck group, we have an isomorphism $i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1) \simeq i_{B \cap M_\chi}^{M_\chi}((\mu_\chi \otimes \nu_1)^{w_0^{M_\chi}})$, where $w_0^{M_\chi}$ is the element of longest length of the Weyl group of M_χ . Now, we have an isomorphism:

$$i_B^G(\chi) \simeq i_{P_\chi}^G((i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)) \otimes \nu_2)$$

Since χ is regular then, it follows by Lemma A.4, that the unitary induction $i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)$ is irreducible. Therefore, the RHS is the induction of an irreducible tempered representation times an unramified character ν_2 satisfying the property that $\langle \alpha_{i,A}, \nu_2 \rangle > 0$ for all $i \in \mathcal{J} \setminus \mathcal{J}_{M_\chi}$ by construction. Again applying the Langlands classification [BW80, Sections XI.2.6, XI.2.7], the intertwining operator attached to the parabolic P_χ and the element $w_0 w_0^{M_\chi}$ converges for $s = s_\chi$, and since it maps to a unique quotient of multiplicity one it suffices to exhibit an isomorphism between $i_{P_\chi}^G((i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)) \otimes \nu_2)$ and the induction twisted by $w_0 w_0^{M_\chi}$. However, since we just saw that $i_{B \cap M_\chi}^{M_\chi}((\mu_\chi \otimes \nu_1)^{w_0^{M_\chi}}) \simeq i_{B \cap M_\chi}^{M_\chi}(\mu_\chi \otimes \nu_1)$, it suffices to show we have an isomorphism $i_B^G(\chi) \simeq i_B^G(\chi^{w_0})$. This establishes the claim. $\square$

Now we just need to show Proposition A.2.

Proof. We claim that this reduces to the analogous question for G a group of rank 1. In particular, let's consider for $i \in \mathcal{J}$ the simple positive (reduced) coroot $\alpha := \alpha_{i,A}$ and the rank 1 parabolic $P_\alpha = M_\alpha N_\alpha A_\alpha$ attached to it. As before, we write $\nu_1^\alpha := \nu^{s_\chi}|_{A \cap M_\alpha}$ and $\nu_2^\alpha := \nu^{s_\chi}|_{A_\alpha}$. For all simple positive coroots α , we have an isomorphism

$$i_B^G(\chi) \simeq i_{P_\alpha}^G((i_{B \cap M_\alpha}^{M_\alpha}(\mu_\chi \otimes \nu_1^\alpha)) \otimes \nu_2^\alpha)$$

However, if w_α is the simple reflection corresponding to α , we have that

$$i_B^G(\chi^{w_\alpha}) \simeq i_{P_\alpha}^G((i_{B \cap M_\alpha}^{M_\alpha}((\mu_\chi \otimes \nu_1^\alpha)^{w_\alpha})) \otimes \nu_2^\alpha)$$

Therefore, if we can show the existence of an isomorphism:

$$i_{B \cap M_\alpha}^{M_\alpha}(\mu_\chi \otimes \nu_1^\alpha) \simeq i_{B \cap M_\alpha}^{M_\alpha}((\mu_\chi \otimes \nu_1^\alpha)^{w_\alpha})$$

It will imply that we have an isomorphism:

$$i_B^G(\chi) \simeq i_B^G(\chi^{w_\alpha})$$

Now we can proceed by induction on the length of Weyl group elements. We just described the base case, but then, by replacing χ with χ^{w_α} we can proceed by considering another simple reflection attached to another simple positive coroot distinct from α . We note that, since χ being generic is a condition for all coroots (not just simple), at each step of the induction we are tasked with showing the following.

Proposition A.5. *Let G be a absolutely simple, simply connected, quasi-split connected reductive group of split rank 1. Let α be the unique simple (reduced) positive coroot of G and w_α the corresponding simple reflection. Then, for all χ a generic character of $T(\mathbb{Q}_p)$, we have an isomorphism*

$$i_B^G(\chi) \simeq i_B^G(\chi^{w_\alpha})$$

of smooth $G(\mathbb{Q}_p)$ -representations.

It remains to justify the absolutely simple simply connected assumption. To do this, note that given a G not satisfying these conditions, we can find a surjective central isogeny $f : \tilde{G} \rightarrow G$, where $\tilde{G}$ is a product of torii and absolutely simple simply connected groups. If we let $\tilde{B}$ be the preimage of the Borel B with maximal torus given by $\tilde{T}$ the preimage of T then, since $\text{Ker}(f)$ is contained in the center, we have an isomorphism $\tilde{G}/\tilde{B} \simeq G/B$. This implies that we have an isomorphism:

$$i_B^G(\chi)|_{\tilde{G}(\mathbb{Q}_p)} \simeq i_{\tilde{B}}^{\tilde{G}}(\chi|_{\tilde{T}(\mathbb{Q}_p)})$$

Moreover, since f will induce an isomorphism on the root spaces, it follows that if χ is generic with respect to G then $\chi|_{\tilde{T}(\mathbb{Q}_p)}$ is generic with respect to $\tilde{G}$. This reduces us to exhibiting the desired isomorphism for $\tilde{G}$. Now, we prove Proposition A.5 through brute force. In particular, we will use Tits' classification theorem [Tit79] (See also [Car01] for the classification in rank 1). We adopt the same notation as in [Tit79]. Since we are assuming the group to be quasi-split, there are two cases.

A.0.1. ${}^1A_{1,1}$. In this case, we have that $G = \text{SL}_2$. We saw in Example 3.9 that genericity guaranteed irreducibility aside from the case where $\chi^2 \simeq \mathbf{1}$, but since this is a unitary character it still follows that we have the desired isomorphism.

A.0.2. ${}^2A_{2,1}$. In this case, the group cannot be split; in particular, we have that $G = \text{SU}_3$ is a quasi-split special unitary group attached to a quadratic extension $E/\mathbb{Q}_p$. We saw in Example 3.13 that χ being generic guaranteed irreducibility and hence the desired isomorphism. $\square$

APPENDIX B. TILTING COCHARACTERS

We consider a general quasi-split connected reductive group $G/\mathbb{Q}_p$, and a geometric dominant cocharacter $\mu \in \mathbb{X}_*(T_{\mathbb{Q}_p})^+$. For $\Lambda \in \{\overline{\mathbb{Q}_\ell}, \overline{\mathbb{Z}_\ell}, \overline{\mathbb{F}_\ell}\}$, we are interested in understanding the condition of μ being tilting (Definition 10.4). Recall that this means that the representation $V_\mu \in \text{Rep}_\Lambda(\hat{G})$ attached to μ lies in the subcategory $\text{Tilt}_\Lambda(\hat{G})$. If $\Lambda = \overline{\mathbb{Q}_\ell}$ this is always true, and so we fix $\Lambda \in \{\overline{\mathbb{F}_\ell}, \overline{\mathbb{Z}_\ell}\}$ in what follows. Since this only involves the representation theory $\hat{G}$ we may, without loss of generality, assume G is split in what follows. This is simply the question of when the highest weight module V_μ of $\hat{G}$ is irreducible with Λ -coefficients. This question has been studied extensively (See for example [Jan03, Pages 283-286] for a comprehensive overview). In the first two sections, we discuss some general theory to determine when μ is tilting in this split case, and then provide a table summarizing when μ is tilting in the case that μ is a fundamental coweight.

B.1. General Theory. We assume G is a split connected reductive group throughout this section, with Langlands dual group $\hat{G}$. For μ a dominant cocharacter, the condition that μ is tilting is equivalent to showing that the highest weight G -module $V_\mu \in \text{Rep}_\Lambda(\hat{G})$ is simple. We begin with the following lemma.

Lemma B.1. *If μ is minuscule then it is tilting.*

Proof. In this case, the weights of V_μ form a closed Weyl group orbit. It follows that V_μ is always irreducible and therefore tilting. $\square$

We would now like to provide a finer criterion for irreducibility. To do this, we will introduce some notation. Given a coroot ν and $r \in \mathbb{Z}$, we consider the affine reflection of $\mathbb{X}_*(T) \otimes \mathbb{R}$ given as

$$s_{\nu,r}(\mu) := s_\nu(\mu) + r\nu$$

where $s_\nu \in W_G$ is the reflection attached to ν . We set W_ℓ to be the subgroup generated by reflections $s_{\nu,n\ell}$, where ν is a coroot and $n \in \mathbb{Z}$, and write ρ for the sum of all coroots of G . Elements $w \in W_\ell$ act on $\mu \in \mathbb{X}_*(T) \otimes \mathbb{R}$, via the standard dot action $w \cdot \mu := w(\mu + \rho) - \rho$. In other words, we regard $s_{\nu,n\ell}$ as a reflection around the hyperplane:

$$\{\mu \in \mathbb{X}_*(T) \otimes \mathbb{R} \mid \langle \mu + \rho, \nu^\vee \rangle = n\ell\}$$

It follows that the standard alcove for this action is given by

$$C = \{\mu \in \mathbb{X}_*(T) \otimes \mathbb{R} \mid 0 < \langle \mu + \rho, \nu^\vee \rangle < \ell\}$$

and we denote the closure by $\overline{C}$. We now have the following slightly more general criterion for the irreducibility of V_μ .

Proposition B.2. *[Jan03, Corollary 5.6] Suppose that $\mu \in \overline{C} \cap \mathbb{X}_*(T)^+$ then μ is tilting.*

For a given μ , this will give us a lower bound on the ℓ for which μ is tilting. However, it is only a sufficient condition and not necessary. In particular, note that we have the following.

Theorem B.3. *[Mat00, Theorem 2.6] If $\mu = (\ell - 1)(\rho)$ then μ is tilting.*

So $V_{(\ell-1)(\rho)}$ will always be simple, but $(\ell - 1)(\rho)$ will not usually lie in $\overline{C} \cap \mathbb{X}_*(T)^+$. Moreover, if we define the Coxeter number $h = \max_\nu \{\langle \rho, \nu^\vee \rangle + 1\}$ ranging over all coroots ν then it is easy to see that $C \cap \mathbb{X}_*(T) \neq \emptyset$ is equivalent to $\ell \geq h$, and so, for small ℓ , Proposition B.2 tells us nothing. To tackle these more general cases, we introduce a sum formula for the characters of the representations. Namely, for $V \in \text{Rep}_\Lambda(\hat{G})$, we write $\text{ch}(V) := \sum_{\nu \in \mathbb{X}_*(T)} \dim(V(\nu))e^\nu$ for the character of V . For μ a dominant cocharacter, we write $\chi(\mu) := \text{ch}(V_\mu)$ for the character of V_μ . Then we have the following.

Proposition B.4. *[Jan03, Section 8.19] For each $\mu \in \mathbb{X}_*(T)^+$, there is a filtration of $\hat{G}$ -modules*

$$\cdots \subset V_\mu^2 \subset V_\mu^1 \subset V_\mu^0 = V_\mu$$

such that

$$\sum_{i>0} \text{ch}(V_\mu^i) = \sum_{\nu} \sum_{0 < m\ell < \langle \mu + \rho, \nu^\vee \rangle} \nu_\ell(m\ell) \chi(s_{\nu,m\ell} \cdot \mu)$$

where $\nu_\ell(-)$ is the ℓ -adic valuation and ν ranges over all coroots. Moreover, we have that V_μ/V_μ^1 is isomorphic to the irreducible socle of V_μ . In particular, we see that μ is tilting if and only if

$$\sum_{\nu} \sum_{0 < m\ell < \langle \mu + \rho, \nu^\vee \rangle} \nu_\ell(m\ell) \chi(s_{\nu,m\ell} \cdot \mu) = 0$$

This generalizes Proposition B.2 and gives a computational method for verifying when μ is tilting. See for example [Jan03, Section 8.20] for this worked out for $G = \text{SL}_4$ and $\ell > 3$, [GS88] for a table answering this question for G an exceptional group and certain μ , and [BW71] for an analogous table for certain exceptional groups and low rank classical groups. In general, a precise classification of when μ is tilting for all G seems to be quite complicated, and to the best of our knowledge is unknown. However, when G is of type A_{n-1} , there exists a complete classification.

Proposition B.5. [Jan91, Page 113] For G of type A_{n-1} , μ is tilting if and only if for each coroot ν of G the following is satisfied. Write $\langle \mu + \rho, \nu^\vee \rangle = a\ell^s + b\ell^{s+1}$, with $a, b, s \in \mathbb{N}$ and $0 < a < \ell$. Then there have to be positive coroots $\beta_0, \beta_1, \dots, \beta_b$ such that $\langle \mu + \rho, \beta_i^\vee \rangle = \ell^{s+1}$ for $1 \leq i \leq b$, $\langle \mu + \rho, \beta_0^\vee \rangle = a\ell^s$, $\nu = \sum_{i=0}^b \beta_i$, and $\sum_{i=1}^b \beta_i$ is a coroot.

For general types, we will content ourselves with describing the fundamental coweights, where we can give a full description of the tilting condition.

B.2. The Tilting Condition for Fundamental Coweights. We assume that G is a split adjoint group, and let $\hat{\alpha}_j$ denote the simple roots, where we use the enumeration as in [Bou68, Pages 250-275]. We choose fundamental coweights characterized by $\langle \varpi_i, \hat{\alpha}_j \rangle = \delta_{ij}$. We will be interested in the question of when the representation V_{ϖ_i} is irreducible. In this case, we have a complete classification [Jan03, Pages 286-287], [Jan91, Section 4.6]. We note that, if ϖ_i is minuscule, this is automatic by Lemma B.1, so in what follows we simply provide a list of ℓ for the non-minuscule ϖ_i (See [LR08, Page 221] for a classification). This namely implies the case of A_n is trivial, since all fundamental coweights are minuscule. A common condition in modular representation theory is that of being very good, so we have also enumerated the condition that ℓ is very good for the different types.

Type of G	Type of $\tilde{G}$	μ	ℓ	ℓ very good
$B_n, n \geq 2$	C_n	$\varpi_i, 1 < i \leq n$	$\ell \mid \binom{n+1-(i+j)/2}{(i-j)/2}, 0 \leq j < i, j \cong i \pmod{2}$	$\ell \neq 2$
$C_n, n \geq 2$	B_n	$\varpi_i, 1 \leq i < n$	$\ell = 2$	$\ell \neq 2$
$D_n, n \geq 4$	D_n	$\varpi_i, 1 < i < n-1$	$\ell = 2$	$\ell \neq 2$
E_6	E_6	ϖ_1, ϖ_6 ϖ_3, ϖ_5 ϖ_2 ϖ_4	$\emptyset$ $\ell = 2$ $\ell = 3$ $\ell = 2, 3$	$\ell \neq 2, 3$
E_7	E_7	ϖ_1 ϖ_2 ϖ_3, ϖ_5 ϖ_4 ϖ_6 ϖ_7	$\ell = 2$ $\ell = 3$ $\ell = 2, 3$ $\ell = 2, 3, 13$ $\ell = 2, 7$ $\emptyset$	$\ell \neq 2, 3$
E_8	E_8	ϖ_1 ϖ_2 ϖ_3 ϖ_4 ϖ_5 ϖ_6 ϖ_7 ϖ_8	$\ell = 2$ $\ell = 2, 3, 7$ $\ell = 2, 3, 19$ $\ell = 2, 3, 5, 13, 19$ $\ell = 2, 3, 5$ $\ell = 2, 3, 5, 7$ $\ell = 2, 3, 5$ $\emptyset$	$\ell \neq 2, 3, 5$
F_4	F_4	ϖ_1 ϖ_2, ϖ_3 ϖ_4	$\ell = 2$ $\ell = 2, 3$ $\ell = 3$	$\ell \neq 2, 3$
G_2	G_2	ϖ_1 ϖ_2	$\ell = 3$ $\ell = 2$	$\ell \neq 2, 3$

By comparing the fourth and fifth columns, we deduce the following.

Proposition B.6. For G a split adjoint connected reductive group over $\mathbb{Q}_p$, if ℓ is very good then ϖ_i for any $i \in \mathcal{J}$ is tilting for all G of type A_n, C_n, D_n, E_6, F_4 , and G_2 .

APPENDIX C. RELATIONSHIP TO THE CLASSICAL AVERAGING FORMULA, BY ALEXANDER BERTOLONI-MELI

In this appendix, we show that the averaging formula proven in Theorem 10.10 is compatible with existing formulas and conjectures in the literature.

C.1. Averaging Formulas. To begin, we recall the general statement of these averaging formulas. Such formulas first appeared in the book of Harris–Taylor ([HT01]) and are classically deduced by studying the geometry of the mod- p fibers of Shimura varieties. These fibers admit a Newton stratification in terms of the set $B(G, \mu)$ and the strata are uniformized by Rapoport–Zink spaces and Igusa varieties. The cohomological consequence of this is the formula of Mantovan ([Man05]) which up to twists is given as

$$(8) \quad \sum_i \varinjlim_{K \subset G(\mathbb{A}_f)} (-1)^i H_c^i(\mathrm{Sh}(G, X)_K, \overline{\mathbb{Q}}_\ell) = \sum_{b \in B(G, \mu)} R\Gamma_c^b(G, b, \mu) \left[\sum_j (-1)^j \varinjlim_{K^p \subset G(\mathbb{A}_f^p)} H_c^j(\mathrm{Ig}_{K^p}^b, \overline{\mathbb{Q}}_\ell) \right],$$

in $K_0(G(\mathbb{A}_f) \times W_{E_\mu})$, where $\mathrm{Sh}(G, X)_K$ (resp. $\mathrm{Ig}_{K^p}^b$) is the Shimura variety (resp. Igusa variety) determined by the associated data. Averaging formulas can then be deduced by studying isotypic pieces of the above formula.

In order to precisely state these averaging formulas, we first recall some facts about stable characters following [Hir04]. Let G be a connected reductive group with Levi subgroup M and parabolic P . Let $K_0(G(\mathbb{Q}_p), \mathbb{C})^{st} \subset K_0(G(\mathbb{Q}_p), \mathbb{C})$ denote the subgroup of virtual representations with stable character. Then the normalized Jacquet module and parabolic induction functors induce morphisms

$$i_P^G : K_0(M(\mathbb{Q}_p), \mathbb{C}) \rightarrow K_0(G(\mathbb{Q}_p), \mathbb{C}), \quad r_P^G : K_0(G(\mathbb{Q}_p), \mathbb{C}) \rightarrow K_0(M(\mathbb{Q}_p), \mathbb{C}).$$

Moreover, one can show these operations preserve stability so that we get homomorphisms

$$i_P^G : K_0(M(\mathbb{Q}_p), \mathbb{C})^{st} \rightarrow K_0(G(\mathbb{Q}_p), \mathbb{C})^{st}, \quad r_P^G : K_0(G(\mathbb{Q}_p), \mathbb{C})^{st} \rightarrow K_0(M(\mathbb{Q}_p), \mathbb{C})^{st}.$$

Now let G^* denote the unique quasi-split group that is an inner form of G . We assume that G arises as an extended pure inner twist of G^* and fix this extra structure (G, ϱ, z) . One can work with more general G using Kaletha's theory of rigid inner twists, but this is not necessary to explore the connections to this paper where G is always quasi-split.

We also need to introduce endoscopy for G . For convenience, we recall:

Definition C.1. A *refined endoscopic datum* for a connected reductive group G over a local field F is a tuple $(H, \mathcal{H}, s, \eta)$ which consists of

- a quasi-split group H over F ,
- an extension $\mathcal{H}$ of W_F by $\widehat{H}$ such that the map $W_F \rightarrow \mathrm{Out}(\widehat{H})$ coincides with the map $\rho_H : W_F \rightarrow \mathrm{Out}(\widehat{H})$ induced by the action of W_F on $\widehat{H} \subset {}^L H$,
- an element $s \in Z(\widehat{H})^\Gamma$,
- an L -homomorphism $\eta : \mathcal{H} \rightarrow {}^L G$,

satisfying the condition:

- we have $\eta(\widehat{H}) = Z_{\widehat{G}}(s)^\circ$.

Now suppose that $(H, \mathcal{H}, s, \eta)$ is a refined endoscopic datum for G . Then after fixing splittings of $G, H, \widehat{G}, \widehat{H}$, there is a canonical endoscopic transfer of distributions inducing a morphism

$$\mathrm{Trans}_H^G : K_0(H(\mathbb{Q}_p), \mathbb{C})^{st} \rightarrow K_0(G(\mathbb{Q}_p), \mathbb{C}).$$

Furthermore, suppose we have a refined endoscopic datum $(H_M, \mathcal{H}_M, s, \eta_M)$ of M such that $\mathcal{H}_M$ is a Levi subgroup of $\mathcal{H}$ and the following diagram commutes:

$$\begin{array}{ccc} \mathcal{H} & \xrightarrow{\eta} & {}^L G \\ \uparrow & & \uparrow \\ \mathcal{H}_M & \xrightarrow{\eta_M} & {}^L M. \end{array}$$

The datum $(H_M, \mathcal{H}_M, H, M, s, \eta)$ along with these compatibilities is called an *embedded* endoscopic datum in [Ber21; BS22]. Our fixed choice of splittings of G , H and their duals determines from P a parabolic subgroup P_{H_M} of H with Levi subgroup H_M . We then have an equality

$$(9) \quad \text{Trans}_H^G \circ i_{P_{H_M}}^H = i_P^G \circ \text{Trans}_{H_M}^M.$$

There is also a compatibility of Trans and r which we now recall. A refined endoscopic datum $\mathfrak{e} = (H, \mathcal{H}, s, \eta)$ of G and a Levi subgroup $M \subset G$ can be upgraded to the structure of an embedded endoscopic datum in potentially many non-equivalent ways and these are parametrized by a set $D(M, \mathfrak{e}) \cong W(\widehat{H}) \backslash W(M, H) / W(\widehat{M})$, where $W(M, H)$ is defined to be the subset of the Weyl group $W(\widehat{G})$ of $\widehat{G}$ such that $Z_{L_H}((w \circ \eta)^{-1}(Z(\widehat{M})^\Gamma))$ surjects onto W_F , and where $W(\widehat{H})$ is identified with a subgroup of $W(\widehat{G})$ via η . Then we have

$$r_P^G \circ \text{Trans}_H^G = \sum_{D(M, \mathfrak{e})} \text{Trans}_{H_M}^M \circ r_{P_{H_M}}^H.$$

We now define the map $\text{Red}_b^\mathfrak{e}$ which plays a crucial role in the statement of the averaging formula. We define

$$(10) \quad \text{Red}_b^\mathfrak{e} : K_0(H(\mathbb{Q}_p), \mathbb{C})^{st} \rightarrow K_0(J_b(\mathbb{Q}_p), \mathbb{C})$$

by

$$\text{Red}_b^\mathfrak{e} = \left(\sum_{D(M, \mathcal{H})} \text{Trans}_{J_b}^{H_M} \circ r_{P_{H_M}}^H \right) \otimes \bar{\delta}_P^{-\frac{1}{2}} e(J_b),$$

where $\bar{\delta}_P$ is the transport of the modulus character for P to J_b , and $e(J_b) \in \{\pm 1\}$ is the Kottwitz sign.

Then the (still largely conjectural) averaging formula gives a relation satisfied by $R\Gamma_c^\flat(G, b, \mu)$ at Langlands (or Arthur) parameters ϕ for which there is an associated stable distribution $S\Theta_{\phi, G}$ on G satisfying endoscopic character identities as in [Kal16, Conjecture D]. In particular, this is the case for all tempered L -parameters. To describe the expected formula, fix such a parameter ϕ and suppose that $(H, \mathcal{H}, s, \eta)$ is an endoscopic datum such that ϕ factors as $\mathcal{L}_F \xrightarrow{\phi^H} \mathcal{H} \rightarrow {}^L G$. Then we expect

Conjecture C.2 (Averaging Formula). *We expect the following equality in $K_0(G(\mathbb{Q}_p) \times W_{E_\mu})$:*

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^\flat(G, b, \mu) [\text{Red}_b^\mathfrak{e}(S\Theta_{\phi^H, H})]] = \text{Trans}_H^G(S\Theta_{\phi^H, H}) \boxtimes \text{tr}(r_\mu \circ \phi|_{W_{E_\mu}} | s).$$

In particular, when $\mathfrak{e}$ is the trivial endoscopic datum given by $\mathfrak{e}_{\text{triv}} = (G^*, {}^L G^*, 1, \text{id})$ then we expect

$$\sum_{b \in B(G, \mu)} [R\Gamma_c^\flat(G, b, \mu) [\text{Red}_b^{\mathfrak{e}_{\text{triv}}}(S\Theta_{\phi, G^*})]] = S\Theta_{\phi, G} \boxtimes r_\mu \circ \phi|_{W_{E_\mu}}.$$

For GL_n , this is known in the trivial endoscopic case for all representations by [Shi12]. Because L -packets are singletons for GL_n , the trivial endoscopic case implies the endoscopic versions of the formula. In [BN21], the formula is proven for discrete parameters and elliptic endoscopy of unramified GU_n , for n odd. In [Ber21], a strategy is outlined to prove this formula in the elliptic endoscopic

cases using the cohomology of Igusa and Shimura varieties. This strategy should (eventually) yield results comparable to [BN21] whenever adequate global results are known about the Langlands correspondence and the cohomology of Shimura and Igusa varieties.

The averaging formulas imply strong results about $R\Gamma_c^b(G, b, \mu)$. For instance, in [BN21, §6] it is shown that the averaging formula for each elliptic endoscopic group and for ϕ a supercuspidal parameter implies the Kottwitz conjecture as in [RV14, Conjecture 7.3].

C.2. Proof of Proposition 10.11. The averaging formula in §10.1 corresponds to the case of the trivial endoscopic triple $\mathfrak{e}_{\text{triv}} = (G^*, {}^L G^*, 1, \text{id})$. Hence to check that Theorem 10.10 agrees with C.2, we just need to check that $\text{Red}_b^{\mathfrak{e}_{\text{triv}}}(S\Theta_{\phi, G^*})$ coincides with $\text{Red}_{b, \phi}$ for ϕ induced from ϕ_T generic. Since ϕ_T is generic, by Lemma 3.14 ϕ should give rise to a well-defined L -parameter with trivial monodromy. Therefore, under the LLC $_G$ appearing in Assumption 6.5, we are assuming the parameter ϕ has an L -packet given by the irreducible constituents of the multiplicity free representation $i_B^G(\chi)$, by Assumption 6.5 (3). Suppose first that $b \in B(G)_{\text{un}}$. Then we have

$$[\text{Red}_{b, \phi}] = \sum_{w \in W_G/W_{M_b}} i_{B_b}^{J_b}(\chi^w) \otimes \delta_{P_b}^{-1/2}(-1)^{\langle 2\hat{\rho}_G, \nu_b \rangle}.$$

in $K_0(G(\mathbb{Q}_p))$. The set $D(M, \mathfrak{e})$ is a singleton and corresponds to the trivial embedded datum where $H_M = M$. Note that $r_{P_b^{op}}^G(i_B^G(\chi)) = r_{P_b}^G(i_B^G(\chi))$ and that the latter term can be simplified by the geometric lemma of [BZ77].

$$\begin{aligned} \text{Red}_b^{\mathfrak{e}_{\text{triv}}}(S\Theta_{\phi, G^*}) &= (\text{Trans}_{M_b}^{J_b} \circ r_{P_b^{op}}^G)(i_B^G(\chi)) \otimes \bar{\delta}_P^{-\frac{1}{2}} e(J_b) \\ &= \text{Trans}_{M_b}^{J_b} \circ \left(\sum_{w \in W_G/W_{M_b}} i_{B \cap M_b}^{M_b} \chi^w \right) \otimes \bar{\delta}_P^{-\frac{1}{2}} e(J_b) \\ &= \left(\sum_{w \in W_G/W_{M_b}} i_{B_b}^{J_b} \right) \circ \text{Trans}_T^{T_b} \chi^w \otimes \bar{\delta}_P^{-\frac{1}{2}}(-1)^{\langle 2\hat{\rho}_G, \nu_b \rangle} \\ &= \text{Red}_{b, \phi}. \end{aligned}$$

where the third equality is (9) combined with an application of [HKW22, Lemma A.2.1].

Now consider the case where $b \notin B(G)_{\text{un}}$. We must show that $\text{Red}_b^{\mathfrak{e}_{\text{triv}}}(i_B^G(\chi)) = 0$, for which it suffices to show that $\text{Trans}_{M_b}^{J_b}(i_{B \cap M_b}^{M_b}(\chi^w)) = 0$ for each $w \in W_G/W_{M_b}$. This follows from the fact that T does not transfer to J_b by assumption and the character of $i_{B \cap M_b}^{M_b}(\chi^w)$ is supported on the conjugates of T as per [Dij72b, Theorem 3].

REFERENCES

- [AL21] Johannes Anschütz and Arthur-César Le-Bras. “Averaging Functors in Fargues’ Program for GL_n ”. In: *Preprint* (2021). arXiv:2104.04701.
- [BDK86] J. Bernstein, P. Deligne, and D. Kazhdan. “Trace Paley-Wiener theorem for reductive p -adic groups”. In: *J. Analyse Math.* 47 (1986), pp. 180–192. ISSN: 0021-7670. DOI: 10.1007/BF02792538. URL: <https://doi.org/10.1007/BF02792538>.
- [Ber21] Alexander Bertoloni-Meli. *An averaging formula for the cohomology of PEL-type Rapoport–Zink spaces*. 2021. DOI: 10.48550/ARXIV.2103.11538. URL: <https://arxiv.org/abs/2103.11538>.
- [BG02] A. Braverman and D. Gaitsgory. “Geometric Eisenstein series”. In: *Invent. Math.* 150.2 (2002), pp. 287–384. ISSN: 0020-9910. DOI: 10.1007/s00222-002-0237-8. URL: <https://doi.org/10.1007/s00222-002-0237-8>.

- [BG08] Alexander Braverman and Dennis Gaiety. “Deformations of local systems and Eisenstein series”. In: *Geom. Funct. Anal.* 17.6 (2008), pp. 1788–1850. ISSN: 1016-443X. DOI: 10.1007/s00039-007-0645-4. URL: <https://doi.org/10.1007/s00039-007-0645-4>.
- [BHN22] Alexander Bertoloni-Meli, Linus Hamann, and Kieu-Hieu Nguyen. “Compatibility of Fargues-Scholze correspondence for unitary groups”. In: *Preprint* (2022). arXiv:2207.13193.
- [BN21] A. Bertoloni-Meli and K.H. Nguyen. “The Kottwitz conjecture for unitary PEL-type Rapoport–Zink spaces”. In: *Preprint* (2021). arXiv:2104.05912.
- [Bou68] N. Bourbaki. *Éléments de mathématique. Fasc. XXXIV. Groupes et algèbres de Lie. Chapitre IV: Groupes de Coxeter et systèmes de Tits. Chapitre V: Groupes engendrés par des réflexions. Chapitre VI: systèmes de racines*. Actualités Scientifiques et Industrielles [Current Scientific and Industrial Topics], No. 1337. Hermann, Paris, 1968, 288 pp. (loose errata).
- [Boy99] P. Boyer. “Mauvaise réduction des variétés de Drinfeld et correspondance de Langlands locale”. In: *Invent. Math.* 138.3 (1999), pp. 573–629. ISSN: 0020-9910. DOI: 10.1007/s002220050354. URL: <https://doi.org/10.1007/s002220050354>.
- [Bra+02] A. Braverman et al. “Intersection cohomology of Drinfeld’s compactifications”. In: *Selecta Math. (N.S.)* 8.3 (2002), pp. 381–418. ISSN: 1022-1824. DOI: 10.1007/s00029-002-8111-5. URL: <https://doi.org/10.1007/s00029-002-8111-5>.
- [Bra03] Tom Braden. “Hyperbolic localization of intersection cohomology”. In: *Transform. Groups* 8.3 (2003), pp. 209–216. ISSN: 1083-4362. DOI: 10.1007/s00031-003-0606-4. URL: <https://doi.org/10.1007/s00031-003-0606-4>.
- [Bru61] François Bruhat. “Distributions sur un groupe localement compact et applications à l’étude des représentations des groupes p -adiques”. In: *Bull. Soc. Math. France* 89 (1961), pp. 43–75. ISSN: 0037-9484. URL: http://www.numdam.org/item?id=BSMF_1961__89__43_0.
- [BS22] Alexander Bertoloni-Meli and Sug Woo Shin. *The stable trace formula for Igusa varieties, II*. 2022. DOI: 10.48550/ARXIV.2205.05462. URL: <https://arxiv.org/abs/2205.05462>.
- [BW71] N. Burgoyne and C. Williamson. “Some Computations involving simple Lie algebras”. In: *Proc. 2nd Symposium of Symbolica and Algebraic Manipulation* (1971).
- [BW80] Armand Borel and Nolan R. Wallach. *Continuous cohomology, discrete subgroups, and representations of reductive groups*. Annals of Mathematics Studies, No. 94. Princeton University Press, Princeton, N.J.; University of Tokyo Press, Tokyo, 1980, pp. xvii+388. ISBN: 0-691-08248-0; 0-691-08249-9.
- [BZ77] I. N. Bernstein and A. V. Zelevinsky. “Induced representations of reductive p -adic groups. I”. In: *Ann. Sci. École Norm. Sup. (4)* 10.4 (1977), pp. 441–472. ISSN: 0012-9593. URL: http://www.numdam.org/item?id=ASENS_1977_4_10_4_441_0.
- [Car01] L. Carbone. “On the classification of rank 1 groups over non-archimedean local fields”. In: *Online Notes* (2001). URL: <https://sites.math.rutgers.edu/~carbone1/pdfs/Classification.pdf>.
- [Cas95] W. Casselman. “Theory of admissible representations”. In: *Online Notes* (1995). URL: <https://personal.math.ubc.ca/~cass/research/pdf/p-adic-book.pdf>.
- [CFS21] Miaofen Chen, Laurent Fargues, and Xu Shen. “On the structure of some p -adic period domains”. In: *Camb. J. Math.* 9.1 (2021), pp. 213–267. ISSN: 2168-0930. DOI: 10.4310/CJM.2021.v9.n1.a4. URL: <https://doi.org/10.4310/CJM.2021.v9.n1.a4>.
- [CS17] Ana Caraiani and Peter Scholze. “On the generic part of the cohomology of compact unitary Shimura varieties”. In: *Ann. of Math. (2)* 186.3 (2017), pp. 649–766. ISSN: 0003-486X. DOI: 10.4007/annals.2017.186.3.1. URL: <https://doi.org/10.4007/annals.2017.186.3.1>.

- [Dat05] J.-F. Dat. “ v -tempered representations of p -adic groups. I. l -adic case”. In: *Duke Math. J.* 126.3 (2005), pp. 397–469. ISSN: 0012-7094. DOI: 10.1215/S0012-7094-04-12631-4. URL: <https://doi.org/10.1215/S0012-7094-04-12631-4>.
- [Dij72a] G. van Dijk. “Computation of certain induced characters of p -adic groups”. In: *Math. Ann.* 199 (1972), pp. 229–240. ISSN: 0025-5831. DOI: 10.1007/BF01429876. URL: <https://doi.org/10.1007/BF01429876>.
- [Dij72b] G. van Dijk. “Computation of certain induced characters of p -adic groups”. In: *Math. Ann.* 199 (1972), pp. 229–240. ISSN: 0025-5831. DOI: 10.1007/BF01429876. URL: <https://doi.org/10.1007/BF01429876>.
- [Don93] Stephen Donkin. “On tilting modules for algebraic groups”. In: *Math. Z.* 212.1 (1993), pp. 39–60. ISSN: 0025-5874. DOI: 10.1007/BF02571640. URL: <https://doi.org/10.1007/BF02571640>.
- [Far16] L. Fargues. “Geometrization of the Local Langlands correspondence: An Overview”. In: *Preprint* (2016). arXiv: 1602.00999.
- [Far20] Laurent Fargues. “Simple connexité des fibres d’une application d’Abel-Jacobi et corps de classes local”. In: *Ann. Sci. Éc. Norm. Supér. (4)* 53.1 (2020), pp. 89–124. ISSN: 0012-9593. DOI: 10.24033/asens.2418. URL: <https://doi.org/10.24033/asens.2418>.
- [Fei+99] Boris Feigin et al. “Semi-infinite flags. II. Local and global intersection cohomology of quasimaps’ spaces”. In: *Differential topology, infinite-dimensional Lie algebras, and applications*. Vol. 194. Amer. Math. Soc. Transl. Ser. 2. Amer. Math. Soc., Providence, RI, 1999, pp. 113–148. DOI: 10.1090/trans2/194/06. URL: <https://doi.org/10.1090/trans2/194/06>.
- [FM99] Michael Finkelberg and Ivan Mirković. “Semi-infinite flags. I. Case of global curve $\mathbf{P}^1$ ”. In: *Differential topology, infinite-dimensional Lie algebras, and applications*. Vol. 194. Amer. Math. Soc. Transl. Ser. 2. Amer. Math. Soc., Providence, RI, 1999, pp. 81–112. DOI: 10.1090/trans2/194/05. URL: <https://doi.org/10.1090/trans2/194/05>.
- [FS] L. Fargues and P. Scholze. “Geometrization of the local Langlands Correspondence”. In: *to appear in Asterisque* (). arXiv:2102.13459 v2.
- [GHW22] Daniel Gulotta, David Hansen, and Jared Weinstein. “An enhanced six-functor formalism for diamonds and v -stacks”. In: *Preprint* (2022). arXiv:2201.12467.
- [GI16] I. Gaisan and N. Imai. “Non-semi-stable loci in Hecke stacks and Fargues’ Conjecture”. In: *Preprint* (2016). arXiv:1608.07446.
- [GS88] Peter B. Gilkey and Gary M. Seitz. “Some representations of exceptional Lie algebras”. In: vol. 25. 1-3. Geometries and groups (Noordwijkerhout, 1986). 1988, pp. 407–416. DOI: 10.1007/BF00191935. URL: <https://doi.org/10.1007/BF00191935>.
- [Ham21] Linus Hamann. “A Jacobian Criterion for Artin v -stacks”. In: *Preprint* (2021). arXiv:2209.07495 (to appear in *Selecta*).
- [Ham25] Linus Hamann. “Compatibility of the Fargues–Scholze and Gan–Takeda local Langlands”. In: *Compos. Math.* 161.9 (2025), pp. 2202–2271. ISSN: 0010-437X,1570-5846. DOI: 10.1112/S0010437X25102455. URL: <https://doi-org.ezp-prod1.hul.harvard.edu/10.1112/S0010437X25102455>.
- [Han20] D. Hansen. “On the supercuspidal cohomology of basic local Shimura varieties”. In: (2020). Available at home page of first named author.
- [HHS24] L. Hamann, D. Hansen, and Peter Scholze. *Geometric Eisenstein Series I: Finiteness Theorems*. 2024.
- [HI25] Linus Hamann and Naoki Imai. “Dualizing complexes on the moduli of parabolic bundles”. In: *J. Reine Angew. Math.* 825 (2025), pp. 139–183. ISSN: 0075-4102,1435-5345. DOI: 10.1515/crelle-2025-0031. URL: <https://doi-org.ezp-prod1.hul.harvard.edu/10.1515/crelle-2025-0031>.

- [Hir04] Kaoru Hiraga. “On functoriality of Zelevinski involutions”. In: *Compos. Math.* 140.6 (2004), pp. 1625–1656. ISSN: 0010-437X. DOI: 10.1112/S0010437X04000892. URL: <https://doi.org/10.1112/S0010437X04000892>.
- [HKW22] David Hansen, Tasho Kaletha, and Jared Weinstein. “On the Kottwitz conjecture for local shtuka spaces”. In: *Forum Math. Pi* 10 (2022), Paper No. e13, 79. DOI: 10.1017/fmp.2022.7. URL: <https://doi.org/10.1017/fmp.2022.7>.
- [HT01] Michael Harris and Richard Taylor. *The geometry and cohomology of some simple Shimura varieties*. Vol. 151. Annals of Mathematics Studies. With an appendix by Vladimir G. Berkovich. Princeton University Press, Princeton, NJ, 2001, pp. viii+276. ISBN: 0-691-09090-4.
- [Jan03] Jens Carsten Jantzen. *Representations of algebraic groups*. Second. Vol. 107. Mathematical Surveys and Monographs. American Mathematical Society, Providence, RI, 2003, pp. xiv+576. ISBN: 0-8218-3527-0.
- [Jan91] Jens C. Jantzen. “First cohomology groups for classical Lie algebras”. In: *Representation theory of finite groups and finite-dimensional algebras (Bielefeld, 1991)*. Vol. 95. Progr. Math. Birkhäuser, Basel, 1991, pp. 289–315.
- [Kal16] Tasho Kaletha. “The local Langlands conjectures for non-quasi-split groups”. In: *Families of automorphic forms and the trace formula*. Simons Symp. Springer, [Cham], 2016, pp. 217–257.
- [Ked17] K. Kedlaya. “Sheaves, stacks, and shtukas”. In: *Lecture Notes* (2017). URL: <http://swc.math.arizona.edu/aws/2017/2017KedlayaNotes.pdf>.
- [Key82] Charles David Keys. “On the decomposition of reducible principal series representations of p -adic Chevalley groups”. In: *Pacific J. Math.* 101.2 (1982), pp. 351–388. ISSN: 0030-8730. URL: <http://projecteuclid.org/euclid.pjm/1102724780>.
- [Key84] David Keys. “Principal series representations of special unitary groups over local fields”. In: *Compositio Math.* 51.1 (1984), pp. 115–130. ISSN: 0010-437X. URL: http://www.numdam.org/item?id=CM_1984__51_1_115_0.
- [Kna73a] A. W. Knap. “Commutativity of intertwining operators”. In: *Bull. Amer. Math. Soc.* 79 (1973), pp. 1016–1018. ISSN: 0002-9904. DOI: 10.1090/S0002-9904-1973-13308-7. URL: <https://doi.org/10.1090/S0002-9904-1973-13308-7>.
- [Kna73b] A. W. Knap. “Determination of intertwining operators”. In: *Harmonic analysis on homogeneous spaces (Proc. Sympos. Pure Math., Vol. XXVI, Williams Coll., Williamstown, Mass., 1972)*. 1973, pp. 263–268.
- [Kot84] Robert E. Kottwitz. “Shimura varieties and twisted orbital integrals”. In: *Math. Ann.* 269.3 (1984), pp. 287–300. ISSN: 0025-5831. DOI: 10.1007/BF01450697. URL: <https://doi.org/10.1007/BF01450697>.
- [Kot97] Robert E. Kottwitz. “Isocrystals with additional structure. II”. In: *Compositio Math.* 109.3 (1997), pp. 255–339. ISSN: 0010-437X. DOI: 10.1023/A:1000102604688. URL: <https://doi.org/10.1023/A:1000102604688>.
- [KS72] A. W. Knap and E. M. Stein. “Irreducibility theorems for the principal series”. In: *Conference on Harmonic Analysis (Univ. Maryland, College Park, Md., 1971)*. 1972, 197–214. Lecture Notes in Math., Vol. 266.
- [Lan97] R. P. Langlands. “Representations of abelian algebraic groups”. In: Special Issue. Olga Taussky-Todd: in memoriam. 1997, pp. 231–250. DOI: 10.2140/pjm.1997.181.231. URL: <https://doi.org/10.2140/pjm.1997.181.231>.
- [Lau90] G. Laumon. “Faisceaux automorphes liés aux séries d’Eisenstein”. In: *Automorphic forms, Shimura varieties, and L -functions, Vol. I (Ann Arbor, MI, 1988)*. Vol. 10. Perspect. Math. Academic Press, Boston, MA, 1990, pp. 227–281.
- [Li-22] Daniel Siyuan Li-Huerta. *The plectic conjecture for local fields*. 2022. URL: <https://arxiv.org/abs/2205.05462>.

- [LR08] Venkatramani Lakshmibai and Komaranapuram N. Raghavan. *Standard monomial theory*. Vol. 137. Encyclopaedia of Mathematical Sciences. Invariant theoretic approach, Invariant Theory and Algebraic Transformation Groups, 8. Springer-Verlag, Berlin, 2008, pp. xiv+265. ISBN: 978-3-540-76756-5.
- [Man05] Elena Mantovan. “On the cohomology of certain PEL-type Shimura varieties”. In: *Duke Math. J.* 129.3 (2005), pp. 573–610. ISSN: 0012-7094. DOI: 10.1215/S0012-7094-05-12935-0. URL: <https://doi.org/10.1215/S0012-7094-05-12935-0>.
- [Mat00] Olivier Mathieu. “Tilting modules and their applications”. In: *Analysis on homogeneous spaces and representation theory of Lie groups, Okayama–Kyoto (1997)*. Vol. 26. Adv. Stud. Pure Math. Math. Soc. Japan, Tokyo, 2000, pp. 145–212. DOI: 10.2969/aspm/02610145. URL: <https://doi.org/10.2969/aspm/02610145>.
- [Mat10] Ivan Matić. “The unitary dual of p -adic $\mathrm{SO}(5)$ ”. In: *Proc. Amer. Math. Soc.* 138.2 (2010), pp. 759–767. ISSN: 0002-9939. DOI: 10.1090/S0002-9939-09-10065-5. URL: <https://doi.org/10.1090/S0002-9939-09-10065-5>.
- [Mui97] Goran Muić. “The unitary dual of p -adic G_2 ”. In: *Duke Math. J.* 90.3 (1997), pp. 465–493. ISSN: 0012-7094. DOI: 10.1215/S0012-7094-97-09012-8. URL: <https://doi.org/10.1215/S0012-7094-97-09012-8>.
- [Rap18] Michael Rapoport. “Appendix to On the p -adic cohomology of the Lubin-Tate tower”. In: *Ann. Sci. Éc. Norm. Supér. (4)* 51.4 (2018), pp. 811–863. ISSN: 0012-9593. DOI: 10.24033/asens.2367. URL: <https://doi.org/10.24033/asens.2367>.
- [Rin91] Claus Michael Ringel. “The category of modules with good filtrations over a quasi-hereditary algebra has almost split sequences”. In: *Math. Z.* 208.2 (1991), pp. 209–223. ISSN: 0025-5874. DOI: 10.1007/BF02571521. URL: <https://doi.org/10.1007/BF02571521>.
- [Rog90] Jonathan D. Rogawski. *Automorphic representations of unitary groups in three variables*. Vol. 123. Annals of Mathematics Studies. Princeton University Press, Princeton, NJ, 1990, pp. xii+259. ISBN: 0-691-08586-2; 0-691-08587-0. DOI: 10.1515/9781400882441. URL: <https://doi.org/10.1515/9781400882441>.
- [RV14] Michael Rapoport and Eva Viehmann. “Towards a theory of local Shimura varieties”. In: *Münster J. Math.* 7.1 (2014), pp. 273–326. ISSN: 1867-5778.
- [Sch] P. Scholze. “Étale Cohomology of Diamonds”. In: *to appear in Asterisque* (). arXiv:1709.07343.
- [Sch15] Simon Schieder. “The Harder-Narasimhan stratification of the moduli stack of G -bundles via Drinfeld’s compactifications”. In: *Selecta Math. (N.S.)* 21.3 (2015), pp. 763–831. ISSN: 1022-1824. DOI: 10.1007/s00029-014-0161-y. URL: <https://doi.org/10.1007/s00029-014-0161-y>.
- [She23] Xu Shen. “Harder-Narasimhan strata and p -adic period domains”. In: *Trans. Amer. Math. Soc.* 376.5 (2023), pp. 3319–3376. ISSN: 0002-9947, 1088-6850. DOI: 10.1090/tran/8859. URL: <https://doi.org/10.1090/tran/8859>.
- [Shi12] Sug Woo Shin. “On the cohomology of Rapoport-Zink spaces of EL-type”. In: *Amer. J. Math.* 134.2 (2012), pp. 407–452. ISSN: 0002-9327. DOI: 10.1353/ajm.2012.0009. URL: <https://doi.org/10.1353/ajm.2012.0009>.
- [SV80] Birgit Speh and David A. Vogan Jr. “Reducibility of generalized principal series representations”. In: *Acta Math.* 145.3-4 (1980), pp. 227–299. ISSN: 0001-5962. DOI: 10.1007/BF02414191. URL: <https://doi.org/10.1007/BF02414191>.
- [SW20] P. Scholze and J. Weinstein. *Berkeley lectures on p -adic Geometry*. Vol. 389. Annals of Mathematics Studies. Princeton University Press, 2020.
- [Tad94] Marko Tadić. “Representations of p -adic symplectic groups”. In: *Compositio Math.* 90.2 (1994), pp. 123–181. ISSN: 0010-437X. URL: http://www.numdam.org/item?id=CM_1994__90_2_123_0.

- [Tak24] Yuta Takaya. “Second Adjointness and cuspidal supports at the categorical level”. In: *Preprint* (2024). arXiv:2408.04582.
- [Tit79] J. Tits. “Reductive groups over local fields”. In: *Automorphic forms, representations and L-functions (Proc. Sympos. Pure Math., Oregon State Univ., Corvallis, Ore., 1977), Part 1*. Proc. Sympos. Pure Math., XXXIII. Amer. Math. Soc., Providence, R.I., 1979, pp. 29–69.
- [Vie] Eva Viehmann. *On Newton strata in the B_{dR}^+ -Grassmannian*. DOI: 10.48550/ARXIV.2101.07510. URL: <https://arxiv.org/abs/2101.07510>.
- [Vig96] Marie-France Vignéras. *Représentations l -modulaires d’un groupe réductif p -adique avec $l \neq p$* . Vol. 137. Progress in Mathematics. Birkhäuser Boston, Inc., Boston, MA, 1996, xviii and 233. ISBN: 0-8176-3929-2.
- [Wan82] Jian Pan Wang. “Sheaf cohomology on G/B and tensor products of Weyl modules”. In: *J. Algebra* 77.1 (1982), pp. 162–185. ISSN: 0021-8693. DOI: 10.1016/0021-8693(82)90284-8. URL: [https://doi.org/10.1016/0021-8693\(82\)90284-8](https://doi.org/10.1016/0021-8693(82)90284-8).
- [XZ17] Liang Xiao and Xinwen Zhu. “Cycles on Shimura varieties via Geometric Satake”. In: *Preprint* (2017). arXiv. 1707.05700.
- [Zhu15] Xinwen Zhu. “The geometric Satake correspondence for ramified groups”. In: *Ann. Sci. Éc. Norm. Supér. (4)* 48.2 (2015), pp. 409–451. ISSN: 0012-9593. DOI: 10.24033/asens.2248. URL: <https://doi.org/10.24033/asens.2248>.
- [Zie15] Paul Ziegler. “Graded and filtered fiber functors on Tannakian categories”. In: *J. Inst. Math. Jussieu* 14.1 (2015), pp. 87–130. ISSN: 1474-7480. DOI: 10.1017/S1474748013000376. URL: <https://doi.org/10.1017/S1474748013000376>.
- [Zou22] K. Zou. “The Categorical Form of Fargues’ conjecture for Tori”. In: *Preprint* (2022). arXiv:2202.13238.