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IHARA’S LEMMA IN HIGHER DIMENSION: THE LIMIT CASE

by

Pascal Boyer

Abstract. — Clozel, Harris and Taylor proposed in [CHT08] conjectural generalizations of the classical Ihara’s lemma for GL_2 , to higher dimensional similitude groups. We prove these conjectures in the so called *limit case* under some mild hypothesis coming from a level raising theorem of Gee in [Gee11].

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1. Introduction

1.1. Ihara's original Lemma: origin and proofs. — In the Taylor-Wiles method Ihara's lemma is the key ingredient to extend a $R = T$ property from the minimal case to a non minimal one. It is usually formulated by the injectivity of some map as follows.

Let $\Gamma = \Gamma_0(N)$ be the usual congruence subgroup of $SL_2(\mathbb{Z})$ for some $N > 1$, and for a prime p not dividing N let $\Gamma' := \Gamma \cap \Gamma_0(p)$. We then have two degeneracy maps

$$\pi_1, \pi_2 : X_{\Gamma'} \longrightarrow X_{\Gamma}$$

between the compactified modular curves of levels Γ' and Γ respectively, induced by the inclusion

$$\Gamma' \hookrightarrow \Gamma \text{ and } \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix} \Gamma' \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}^{-1} \hookrightarrow \Gamma.$$

For $l \neq p$, we then have a map

$$\pi^* := \pi_1^* + \pi_2^* : H^1(X_{\Gamma}, \mathbb{F}_l)^2 \longrightarrow H^1(X_{\Gamma'}, \mathbb{F}_l).$$

Theorem 1.1.1. — *Let \mathfrak{m} be a maximal ideal of the Hecke algebra acting on these cohomology groups which is non Eisenstein, i.e. that corresponds to an irreducible Galois representation. Then after localizing at \mathfrak{m} , the map π^* is injective.*

Diamond and Taylor in [DT94] proved an analogue of Ihara's lemma for Shimura curves over \mathbb{Q} . For a general totally real number field F with ring of integers \mathcal{O}_F , Manning and Shotton in [MS] succeeded to prove it under some large image hypothesis. Their strategy is entirely different from those of [DT94] but rather consists roughly

- to carry Ihara's lemma for a compact Shimura curve $Y_{\bar{K}}$ associated to a definite quaternion algebra \bar{D} ramified at some auxiliary place v of F , in level $\bar{K} = \bar{K}^v \bar{K}_v$ an open compact subgroup of $D \otimes \mathbb{A}_{F,f}$ unramified at v ,
- to the indefinite situation X_K relatively to a quaternion division algebra D ramified at all but one infinite place of F , and isomorphic to \bar{D} at all finite places of F different to v , and with level K agreeing with \bar{K}^v away from v .

Indeed in the definite case Ihara's statement is formulated by the injectivity of

$$\pi^* = \pi_1^* + \pi_2^* : H^0(Y_{\bar{K}}, \mathbb{F}_l)_{\mathfrak{m}} \oplus H^0(Y_{\bar{K}}, \mathbb{F}_l)_{\mathfrak{m}} \longrightarrow H^0(Y_{\bar{K}_0(w)}, \mathbb{F}_l)_{\mathfrak{m}}$$

where both \bar{D} and \bar{K} are unramified at the place w and $\bar{K}_0(w)_w$ is the subgroup of $GL_2(F_w)$ of elements which are upper triangular modulo p .

The proof goes like this, cf. [MS] theorem 6.8. Suppose $(f, g) \in \ker \pi^*$. Regarding f and g as K^v -invariant function on $\bar{G}(F) \backslash \bar{G}(\mathbb{A}_{F,f})$, then $f(x) = -g(x\omega)$ where $\omega = \begin{pmatrix} \varpi_w & 0 \\ 0 & 1 \end{pmatrix}$, ϖ_w being an uniformizer for F_w and \bar{G} being the algebraic group

over \mathcal{O}_F associated to \mathcal{O}_D^\times the inversible group of the maximal order $\mathcal{O}_{\overline{D}}$ of \overline{D} : note that $\overline{G}(F_w) \cong \mathrm{GL}_2(F_w)$. Then f is invariant under K^v and $\omega^{-1}K^v\omega$ so that, using the strong approximation theorem for the subgroup of \overline{G} of elements of reduced norm 1, then f factors through the reduced norm map, and so is supported on Eisenstein maximal ideals.

The link between X_K and Y_{K^v} is given by the geometry of the integral model of the Shimura curve $X_{K_0(v)}$ with $\Gamma_0(v)$ -level structure. The main new ingredient of [MS] to carry this geometric link to Ihara's lemma goes through the patching technology which allows to obtain maximal Cohen-Macaulay modules over deformation rings. Using a flatness property and Nakayama's lemma, there are then able to extend a surjective property, dual to the injectivity in the Ihara's lemma, from the maximal unipotent locus on the deformation space to the whole space, and recover the Ihara's statement reducing by the maximal ideal of the deformation ring.

Recently Caraiani and Tamiozzo following closely [MS] also obtained Ihara's lemma for Hilbert varieties essentially because Galois deformations rings are the same and so regular which is not the case outside the case of GL_2 .

1.2. Generalisations of Ihara's Lemma. — To generalize the classical Ihara's lemma in higher dimension, there are essentially two approaches.

- The first natural one developed by Clozel, Harris and Taylor in their first proof of Sato-Tate theorem [CHT08], focuses on the H^0 with coefficients in \mathbb{F}_l of a zero dimensional Shimura variety associated to higher dimensional definite division algebras. More precisely consider a totally real field F^+ and a imaginary quadratic extension E/\mathbb{Q} and define $F = F^+E$. We then consider \overline{G}/\mathbb{Q} a unitary group with $\overline{G}(\mathbb{Q})$ compact so that \overline{G} becomes an inner form of GL_d over F . This means, cf. §2.3, we have fixed a division algebra \overline{B} with center F , of dimension d^2 , provided with an involution of the second kind such that its restriction to F is the complex conjugation. We moreover suppose that at every place w of F , either \overline{B}_w is split or a local division algebra.

Let v be a place of F above a prime number p split in E and such that $\overline{B}_v^\times \cong \mathrm{GL}_d(F_v)$ where F_v is the associated local field with ring of integers \mathcal{O}_v and residue field $\kappa(v)$.

Notation 1.2.1. — Let q_v be the order of the residue field $\kappa(v)$.

Consider then an open compact subgroup \overline{K}^v infinite at v in the following sense: $\overline{G}(\mathbb{Q}_p) \cong \mathbb{Q}_p^\times \times \prod_{v_i^+} \overline{B}_{v_i^+}^{op,\times}$ where $p = \prod_i v_i^+$ in F^+ and we identify places of F^+ over $p = uu^c \in E$ with places of F over u . We then ask $\overline{K}_p^v = \mathbb{Z}_p^\times \times \prod_{w|u} \overline{K}_w$ to be such that \overline{K}_v is restricted to the identity element.

The associated Shimura variety in level $\overline{K} = \overline{K}^v \overline{K}_v$ for some finite level \overline{K}_v at v , denoted by $\overline{\text{Sh}}_{\overline{K}}$, is then such that its \mathbb{C} -points are $\overline{G}(\mathbb{Q}) \backslash \overline{G}(\mathbb{A}_{\mathbb{Q}}^{\infty}) / \overline{K}$ and for l a prime not divisible by v , its H^0 with coefficients in $\overline{\mathbb{F}}_l$ is then identified with the space

$$S_{\overline{G}}(\overline{K}, \overline{\mathbb{F}}_l) = \{f : \overline{G}(\mathbb{Q}) \backslash \overline{G}(\mathbb{A}_{\mathbb{Q}}^{\infty}) / \overline{K} \longrightarrow \overline{\mathbb{F}}_l \text{ locally constant}\}.$$

It is naturally an admissible smooth representation of $\text{GL}_d(F_v)$ and of the Hecke algebra $\mathbb{T}(\overline{K}^v)$ defined as the image of the abstract unramified Hecke algebra, cf. definition 2.4.1, inside $\text{End}(S_{\overline{G}}(\overline{K}^v, \overline{\mathbb{F}}_l))$.

To a maximal ideal \mathfrak{m} of $\mathbb{T}(\overline{K}^v)$ is associated a Galois $\overline{\mathbb{F}}_l$ -representation $\overline{\rho}_{\mathfrak{m}}$, cf. §3.1. We consider the case where this representation is irreducible. Note in particular that such an \mathfrak{m} is then not pseudo-Eisenstein in the usual terminology.

Conjecture 1.2.2. — (cf. conjecture B in [CHT08])

Any irreducible $\text{GL}_d(F_v)$ -submodule of $S_{\overline{G}}(\overline{K}^v, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ is generic.

- For rank 2 unitary groups, we recover the previous statement as the characters are exactly those representations which do not have a Whittaker model, i.e. are the non generic ones.

- For $d \geq 2$, over $\overline{\mathbb{Q}}_l$, the generic representations of $\text{GL}_d(F_v)$ are the irreducible parabolically induced representations $\text{st}_{t_1}(\pi_{v,1}) \times \cdots \times \text{st}_{t_r}(\pi_{v,r})$ where for $i = 1, \dots, r$,

- $\pi_{v,i}$ is an irreducible cuspidal representation of $\text{GL}_{g_i}(F_v)$,
- $\text{st}_{t_i}(\pi_{v,i})$ is a Steinberg representations, cf. definition 2.1.2,
- $\sum_{i=1}^r t_i g_i = d$ where the Zelevinsky segments $[\pi_{v,i}\{\frac{1-t_i}{2}\}, \pi_{v,i}\{\frac{t_i-1}{2}\}]$ are not linked in the sense of [Zel80].

- Over $\overline{\mathbb{F}}_l$ every irreducible generic representation is obtained as the unique generic subquotient of the modulo l reduction of a generic representation. It can also be characterized intrinsically using representation of the mirabolic subgroup, cf. §2.1.

Here we will be mainly interested in the following weak form of Ihara's lemma, except that we will allow ramification, see the main theorem below.

Definition 1.2.3. — (cf. definition of [CHT08] 5.1.9)

An admissible smooth $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module M is said to have the weak Ihara property if for every $m \in M^{\text{GL}_d(\mathcal{O}_v)}$ which is an eigenvector of $\overline{\mathbb{F}}_l[\text{GL}_d(\mathcal{O}_v) \backslash \text{GL}_d(F_v) / \text{GL}_d(\mathcal{O}_v)]$, every irreducible submodule of the $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module generated by m , is generic.

Remark. In particular if we ask about $S_{\overline{G}}(\overline{K}^v, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ having the weak Ihara property, then $S_{\overline{G}}(\overline{K}^v, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ should have non trivial unramified vectors so that the supercuspidal support of the restriction $\overline{\rho}_{\mathfrak{m},v}$ of $\overline{\rho}_{\mathfrak{m}}$ to the decomposition subgroup at v , is made of unramified characters.

- The second approach is to find a map playing the same role as $\pi^* = \pi_1^* + \pi_2^*$. It is explained in section 5.1 of [CHT08] with the help of the element

$$\theta_v \in \mathbb{Z}_l[K_1(v^n) \backslash \mathrm{GL}_d(F_v) / \mathrm{GL}_d(\mathcal{O}_{F_v})]$$

constructed by Russ Mann, cf. proposition 5.1.7 of [CHT08], where F_v is here a finite extension of \mathbb{Q}_p with ring of integers \mathcal{O}_v .

Definition 1.2.4. — An admissible smooth $\overline{\mathbb{F}}_l[\mathrm{GL}_d(F_v)]$ -module M is said to have the almost Ihara property if $\theta_v : M^{\mathrm{GL}_d(\mathcal{O}_v)} \rightarrow M$ is injective.

Recall that l is called quasi-banal for $\mathrm{GL}_d(F_v)$ if either $l \nmid \# \mathrm{GL}_d(\kappa_v)$ (the banal case) or $l > d$ and $q_v \equiv 1 \pmod{l}$ (the limit case).

Proposition 1.2.5. — (cf. [CHT08] lemma 5.1.10)

Suppose that l is quasi-banal and M is a $\overline{\mathbb{F}}_l[\mathrm{GL}_d(F_v)]$ -module verifying the Ihara property. If $\ker(\theta_v : M^{\mathrm{GL}_d(\mathcal{O}_v)} \rightarrow M)$ is a $\mathbb{F}_l[\mathrm{GL}_d(\mathcal{O}_{F_v}) \backslash \mathrm{GL}_d(F_v) / \mathrm{GL}_d(\mathcal{O}_{F_v})]$ -module, then M has the almost Ihara property.

Applications: the generalizations of the classical Ihara's lemma were introduced in [CHT08] to prove a non minimal $R = \mathbb{T}$ theorem. The weaker statement $R^{\mathrm{red}} = \mathbb{T}$ where R^{red} is the reduced quotient of R , was later obtained unconditionally using Taylor's *Ihara avoidance* method, cf. [Tay08] which was enough to prove the Sato-Tate conjecture. However, the full $R = \mathbb{T}$ theorem would have applications to special values of the adjoint L -function and would imply that R is a complete intersection. It should also be useful for generalizing the local-global compatibility results of [Eme].

In [Mos21], the author also proved that Ihara's property in the quasi-banal case is equivalent to the following result.

Proposition 1.2.6. — (cf. [Mos21] corollary 9.5)

Let \mathfrak{m} be a non-Eisenstein maximal ideal of \mathbb{T}^S and $f \in S_{\overline{G}}(\overline{K}^v \mathrm{GL}_d(\mathcal{O}_v), \overline{\mathbb{F}}_l)$. Let Iw_v be the Iwahori subgroup of $\mathrm{GL}_d(\mathcal{O}_v)$, then the $\overline{\mathbb{F}}_l[\mathrm{Iw}_v \backslash \mathrm{GL}_d(F_v) / \mathrm{GL}_d(\mathcal{O}_v)]$ -submodule of $S_{\overline{G}}(\overline{K}^v \mathrm{Iw}_v, \overline{\mathbb{F}}_l)$ generated by f is of dimension $d!$.

1.3. Main result. — With the previous notations, let q_v be the order of the residue field of F_v . We fix some prime number l unramified in F^+ and split in E and we place ourself in the limit case where $q_v \equiv 1 \pmod{l}$ with $l > d$, which is, at least by base change, the crucial case to consider.

Definition 1.3.1. — As in definition 2.5.1 of [CHT08], we say that a subgroup $H \subseteq \mathrm{GL}_d(\overline{\mathbb{F}}_l)$ is big if :

- H has no l -power order quotients;
- $H^i(H, \mathfrak{g}_d^0(\overline{\mathbb{F}}_l)) = (0)$ for $i = 0, 1$ and where $\mathfrak{g}_d := \mathrm{Lie} \mathrm{GL}_d$ and \mathfrak{g}_d^0 is the trace zero subspace of \mathfrak{g}_d ;

- for all irreducible $\overline{\mathbb{F}}_l[H]$ -submodules W of $\mathfrak{g}_d(\overline{\mathbb{F}}_l)$, we can find $h \in H$ and $\alpha \in \overline{\mathbb{F}}_l$ satisfying the following properties.
 - The α -generalized eigenspace $V(h, \alpha)$ of h on $\overline{\mathbb{F}}_l^d$ is one dimensional.
 - Let $\pi_{h,\alpha} : \overline{\mathbb{F}}_l^d \rightarrow V(h, \alpha)$ be the h -equivariant projection of $\overline{\mathbb{F}}_l^d$ to $V(h, \alpha)$ and let $i_{h,\alpha} : V(h, \alpha) \hookrightarrow \overline{\mathbb{F}}_l^d$ be the h -equivariant injection of $V(h, \alpha)$ into $\overline{\mathbb{F}}_l^d$. Then $\pi_{h,\alpha} \circ W \circ i_{h,\alpha} \neq (0)$.

Theorem 1.3.2. — *In the limit case, suppose moreover that there exists a prime $p_0 = u_0 \bar{u}_0$ split in E with a place $v_0 | u_0$ of F such that \overline{B}_{v_0} is a division algebra. Consider \mathfrak{m} such that*

$$\bar{\rho}_{\mathfrak{m}} : G_F \longrightarrow \mathrm{GL}_n(\overline{\mathbb{F}}_l)$$

is a strongly irreducible representation which is unramified at all places of F lying above primes which do not split in E and which satisfies the following hypothesis:

- *after semi-simplification $\bar{\rho}_{\mathfrak{m},v}$ is a direct sum of characters;*
- *$\overline{F}^{\ker \mathrm{ad} \bar{\rho}}$ does not contain $F(\zeta_l)$ where ζ_l is any primitive l -root of 1;*
- *$\bar{\rho}(G_{F^+(\zeta_l)})$ is big.*

Then Ihara's lemma of the conjecture 1.2.2 is true, i.e. every irreducible $\mathrm{GL}_d(F_v)$ -submodule of $S_{\overline{G}}(\overline{K}^v, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ is generic.

Remark. The first hypothesis, if you moreover suppose that the characters are unramified, corresponds to the weak form of Ihara's lemma of definition 1.2.3. The last two ones come from theorem 5.1.5 of [Gee11] which is some level raising statement, cf. theorem 3.1.2. Any other similar statement, for example theorem 4.4.1 of [BLGGT14], with different hypothesis can then be used to formulate another result about Ihara's lemma. The *strongly* irreducibility is needed to prove the semi-simplicity of the cohomology of the KHT Shimura variety in [NF19]: however note that if one believe in Tate's conjecture, the semi-simplicity should be true in general.

In [Boy20] we essentially proved conjecture 1.2.2 in the banal case under some restrictive hypothesis. The idea was mainly to transfer the property about irreducible subspaces to a similar one for the middle degree cohomology group of some KHT Shimura variety $\mathrm{Sh}_{K^v(\infty)}$ associated to some similitude group G/\mathbb{Q} such that $G(\mathbb{A}_{\mathbb{Q}}^{\infty,p}) \cong \overline{G}(\mathbb{A}_{\mathbb{Q}}^{\infty,p})$, cf. §2.3 for more details, and with level $K^v(\infty) := \overline{K}^v$ meaning finite level outside v and infinite level at v .

The localization at \mathfrak{m} of the cohomology groups of $\mathrm{Sh}_{K^v(\infty)}$ can be computed as the cohomology of the geometric special fiber $\mathrm{Sh}_{K^v(\infty), \bar{s}_v}$ of $\mathrm{Sh}_{K^v(\infty)}$, with coefficient in the complex of nearby cycles $\Psi_{K^v(\infty), v}$.

The Newton stratification of $\mathrm{Sh}_{K^v(\infty), \bar{s}_v}$ gives us a filtration of $\Psi_{K^v(\infty), v}$, cf. [Boy19], and so a filtration of $H^{d-1}(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, \overline{\mathbb{Z}}_l)_{\mathfrak{m}}$ and the main point of [Boy20] is to prove that each graded part of this filtration verifies the Ihara property, i.e.

each of their irreducible sub-space are generic. To realize this strategy we need first the cohomology groups of $\mathrm{Sh}_{K^v(\infty)}$ to be torsion free: this point is now essentially settled by the main result of [Boy23a]. More crucially the previous filtration should be strict, i.e. its graded parts have to be torsion free, cf. theorem 2.4.3.

It appears that these graded parts are parabolically induced and in the limit case when the order q_v of the residue field is such that $q_v \equiv 1 \pmod{l}$, the socle of these parabolic induced representations are no more irreducible and do not fulfill the Ihara property. It then appears that we have:

- first to verify that the first non trivial graded part of our filtration verifies the genericity property of its irreducible submodule. For this we need a level raising statement as theorem 5.1.5 in [Gee11], cf. theorem 3.1.2, or theorem 4.4.1 of [BLGGT14].
- Then we have to understand that the extensions between the graded parts of our filtration, are non split.

The idea here is to work with the Galois representation $\rho_{\mathfrak{m}}$ with values in the localized Hecke algebra $\mathbb{T}(K^v(\infty))_{\mathfrak{m}}$ and more precisely with $\rho_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$ which should be as far as possible from being semi-simple, i.e. the graded parts of its socle filtration should be irreducible. Over $\overline{\mathbb{Q}}_l$, $\rho_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$ is equipped with the action of the nilpotent monodromy operator N_v coming from a monodromy operator acting on $\Psi_{K^v(\infty),v}$ constructed from the fact that any $\overline{\mathbb{Q}}_l$ -representation with finite dimension is quasi-unipotent.

Over $\overline{\mathbb{F}}_l$ the usual arithmetic approach for defining the nilpotent monodromy operator, is hopeless because, up to consider a finite extension of F_v , such a $\overline{\mathbb{F}}_l$ -representation has a trivial action of the inertia group. We are then looking for a geometric definition of N_v which then exists whatever are the coefficients, $\overline{\mathbb{Q}}_l$, $\overline{\mathbb{Z}}_l$ and $\overline{\mathbb{F}}_l$, compatible with tensor products. One classical construction is known in the semi-stable reduction case, cf. [Ill94] §3, which corresponds to the case where the level at v of our Shimura variety is of Iwahori type: this implies that we deal with automorphic representations Π such that the cuspidal support of Π_v is made of unramified characters, and so with the weak form of Ihara's lemma of definition 1.2.3. Using our knowledge of the $\overline{\mathbb{Z}}_l$ -nearby cycles described completely in [Boy23b], it is quite easy to construct such a geometric nilpotent monodromy operator which generalizes the semi-stable case by allowing ramified characters, cf. §3.2.

Taking this geometric monodromy operator, we then obtain a cohomological monodromy operator $N_{v,\mathfrak{m}}^{\mathrm{coho}}$ acting on $H^0(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K^v(\infty),v})_{\mathfrak{m}}$ as soon as the irreducible constituents of $\bar{\rho}_{\mathfrak{m}}$ are characters. One of the main point, cf theorem 2.4.3, is that the graded parts of the filtration of $H^0(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K^v(\infty),v})_{\mathfrak{m}}$ induced by the Newton filtration on the nearby cycles spectral sequence, are all torsion free, so that in particular we are in position to understand quite enough the action of $\overline{N}_{v,\mathfrak{m}}^{\mathrm{coho}} := N_{v,\mathfrak{m}}^{\mathrm{coho}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$ on $H^0(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K^v(\infty),v})_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$, see *Main observation* at the end of §3.2, and prove that its nilpotency order is as large as possible.

Finally using typicity of $H^0(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K^v(\infty),v})_{\mathfrak{m}}$ in the sense of definition 3.3.2, we infer for every irreducible sub-quotient ϱ of $\bar{\rho}_{\mathfrak{m}}$, a monodromy operator $N_{\mathfrak{m},\varrho}$ on $\rho_{\mathfrak{m}}$. We then consider the image of $N_{\mathfrak{m},\varrho}^{r-1} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{F}}_l$ where r is the multiplicity of ϱ in $\bar{\rho}_{\mathfrak{m}}$:

- From the theorem of Gee and the *main observation*, we know both that this image is non zero
- and it is associated to ϱ -generic representations.

Varying ϱ we infer genericness of irreducible quotients of $H^0(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K^v(\infty),v})_{\mathfrak{m}} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{F}}_l$ and we conclude about its irreducible subspaces through Grothendieck-Verdier duality as in proposition 3.7 (3) of [NT16].

2. Preliminaries

2.1. Representations of $\mathrm{GL}_d(L)$. — Consider a finite extension L/\mathbb{Q}_p with residue field \mathbb{F}_q . We denote by $|\cdot|$ its absolute value. For a representation π of $\mathrm{GL}_d(L)$ and $n \in \frac{1}{2}\mathbb{Z}$, set

$$\pi\{n\} := \pi \otimes q^{-n\mathrm{val}_{\mathrm{det}}}.$$

Notation 2.1.1. — For π_1 and π_2 representations of respectively $\mathrm{GL}_{n_1}(L)$ and $\mathrm{GL}_{n_2}(L)$, we will denote by

$$\pi_1 \times \pi_2 := \mathrm{ind}_{P_{n_1, n_1+n_2}(L)}^{\mathrm{GL}_{n_1+n_2}(L)} \pi_1\left\{\frac{n_2}{2}\right\} \otimes \pi_2\left\{-\frac{n_1}{2}\right\},$$

the normalized parabolic induced representation where for any sequence $\underline{r} = (0 < r_1 < r_2 < \cdots < r_k = d)$, we write $P_{\underline{r}}$ for the standard parabolic subgroup of GL_d with Levi

$$\mathrm{GL}_{r_1} \times \mathrm{GL}_{r_2-r_1} \times \cdots \times \mathrm{GL}_{r_k-r_{k-1}}.$$

Recall that a representation ϱ of $\mathrm{GL}_d(L)$ is called *cuspidal* (resp. *supercuspidal*) if it is not a subspace (resp. subquotient) of a proper parabolic induced representation. When the field of coefficients is of characteristic zero, these two notions coincides, but this is no more true over $\bar{\mathbb{F}}_l$.

Definition 2.1.2. — (see [Zel80] §9 and [Boy10] §1.4) Let g be a divisor of $d = sg$ and π an irreducible cuspidal $\bar{\mathbb{Q}}_l$ -representation of $\mathrm{GL}_g(L)$. The induced representation

$$(1) \quad \pi\left\{\frac{1-s}{2}\right\} \times \pi\left\{\frac{3-s}{2}\right\} \times \cdots \times \pi\left\{\frac{s-1}{2}\right\}$$

holds a unique irreducible quotient (resp. subspace) denoted $\mathrm{st}_s(\pi)$ (resp. $\mathrm{Speh}_s(\pi)$); it is a generalized Steinberg (resp. Speh) representation. Their cuspidal support is the Zelevinsky segment

$$[\pi\left\{\frac{1-s}{2}\right\}, \pi\left\{\frac{s-1}{2}\right\}] := \left\{ \pi\left\{\frac{1-s}{2}\right\}, \pi\left\{\frac{3-s}{2}\right\}, \dots, \pi\left\{\frac{s-1}{2}\right\} \right\}.$$

More generally the set of sub-quotients of the induced representation (1) is in bijection with the following set.

$$\text{Dec}(s) = \{(t_1, \dots, t_r), \text{ such that } t_i \geq 1 \text{ and } \sum_{i=1}^r t_i = s\}.$$

For any $\underline{s} \in \text{Dec}(s)$, we denote by $\text{st}_{\underline{s}}(\pi)$ the associated irreducible sub-quotient of (1). Following Zelevinsky, we fix this bijection such that $\text{Speh}_s(\pi)$ corresponds to (s) and $\text{st}_s(\pi)$ to $(1, \dots, 1)$. The Lubin-Tate representation $LT_{h,s}(\pi)$ will also appear

in the following, it corresponds with $(\overbrace{1, \dots, 1}^h, s-h)$.

Proposition 2.1.3. — (cf. [Vig96] III.5.10) *Let π be an irreducible cuspidal representation of $\text{GL}_g(K)$ with a stable $\overline{\mathbb{Z}}$ -lattice⁽¹⁾, then its modulo l reduction is irreducible and cuspidal (but not necessary supercuspidal).*

We now suppose as explained in the introduction that

$$q \equiv 1 \pmod{l} \quad \text{and} \quad l > d$$

so the following facts are verified:

- the modulo l reduction of every irreducible cuspidal representation of $\text{GL}_g(L)$ for $g \leq d$, is supercuspidal.
- For a $\overline{\mathbb{F}}_l$ -irreducible supercuspidal representation ϱ of $\text{GL}_g(L)$, the parabolic induced representation $\varrho \times \dots \times \varrho$, with s copies of ϱ , is semi-simple with irreducible constituents the modulo l reduction of $\text{st}_{\underline{s}}(\pi)$ for $\underline{s} \in \text{Dec}(s)$ and π any cuspidal representation whose modulo l reduction is isomorphic to ϱ .

Concerning the notion of genericity, consider the mirabolic subgroup $M_d(L)$ of $\text{GL}_d(L)$ as the set of matrices with last row $(0, \dots, 0, 1)$: we denote by

$$V_d(L) = \{(m_{i,j}) \in M_d(L) : m_{i,j} = \delta_{i,j} \text{ for } j < d\}.$$

its unipotent radical. We fix a non trivial character ψ of L and let θ be the character of $V_d(L)$ defined by $\theta((m_{i,j})) = \psi(m_{d-1,d})$. For $G = \text{GL}_r(L)$ or $M_r(L)$, we denote by $\text{alg}(G)$ the abelian category of smooth representations of G and, following [BZ77], we introduce

$$\Psi^- : \text{alg}(M_d(L)) \longrightarrow \text{alg}(\text{GL}_{d-1}(L)),$$

and

$$\Phi^- : \text{alg}(M_d(L)) \longrightarrow \text{alg}(M_{d-1}(L)),$$

defined by $\Psi^- = r_{V_d,1}$ (resp. $\Phi^- = r_{V_d,\theta}$) the functor of V_d coinvariants (resp. (V_d, θ) -coinvariants), cf. [BZ77] 1.8. For $\tau \in \text{alg}(M_d(L))$, the representation

$$\tau^{(k)} := \Psi^- \circ (\Phi^-)^{k-1}(\tau)$$

⁽¹⁾We say that π is integral.

is called the k -th derivative of τ . If $\tau^{(k)} \neq 0$ and $\tau^{(m)} = 0$ for all $m > k$, then $\tau^{(k)}$ is called the highest derivative of τ . In the particular case where $k = d$, there is a unique irreducible representation τ_{nd} of $M_d(L)$ with derivative of order d .

Definition 2.1.4. — An irreducible representation π of $\mathrm{GL}_d(L)$ is said generic, if its restriction to the mirabolic subgroup admits τ_{nd} as a subquotient.

Let π be an irreducible generic representation of $\mathrm{GL}_d(L)$ and consider any stable lattice which gives us by modulo l reduction a $\overline{\mathbb{F}}_l$ -representation uniquely determined up to semi-simplification. Then this modulo l reduction admits a unique generic irreducible constituent.

2.2. Weil–Deligne inertial types. — Recall that a Weil–Deligne representation of W_L is a pair (r, N) where

- $r : W_L \longrightarrow \mathrm{GL}(V)$ is a smooth⁽²⁾ representation on a finite dimensional vector space V ; and
- $N \in \mathrm{End}(V)$ is nilpotent such that

$$r(g)Nr(g)^{-1} = \|g\|N,$$

where $\|\bullet\| : W_L \longrightarrow W_L/I_L \twoheadrightarrow q^{\mathbb{Z}}$ takes an arithmetic Frobenius element to q .

Remark. To a continuous⁽³⁾ representation on a finite dimensional \mathbb{Q}_l -vector space V , $\rho : W_L \longrightarrow \mathrm{GL}(V)$ is attached a Weil–Deligne representation denoted by $\mathrm{WD}(\rho)$. A Weil representation of W_L is also said of Galois type if it comes from a representation of G_L .

Main example: let $\rho : W_L \longrightarrow \mathrm{GL}(V)$ be a smooth irreducible representation on a finite dimensional vector space V . For $k \geq 1$ an integer, we then define a Weil–Deligne representation

$$\mathrm{Sp}(\rho, k) := (V \oplus V(1) \oplus \cdots \oplus V(k-1), N),$$

where for $0 \leq i \leq k-2$, the isomorphism $N : V(i) \cong V(i+1)$ is induced by some choice of a basis of $\overline{L}(1)$ and $N|_{V(k-1)}$ is zero. Then every Frobenius semi-simple Weil–Deligne representation of W_L is isomorphic to some $\bigoplus_{i=1}^r \mathrm{Sp}(\rho_i, k_i)$, for smooth irreducible representations $\rho_i : W_L \longrightarrow \mathrm{GL}(V_i)$ and integers $k_i \geq 1$. Up to obvious reorderings, such a writing is unique.

Let now ρ be a continuous representation of W_L , or its Weil–Deligne representation $\mathrm{WD}(\rho)$, and consider its restriction to I_L , $\tau := \rho|_{I_L}$. Such an isomorphism class of a finite dimensional continuous representation of I_L is then called *an inertial type*.

Notation 2.2.1. — Let \mathcal{I}_0 the set of inertial types that extend to a continuous irreducible representation of G_L .

⁽²⁾i.e. continuous for the discrete topology on V

⁽³⁾relatively to the l -adic topology on V

Remark. $\tau \in \mathcal{I}_0$ might not be irreducible.

Let Part be the set of decreasing sequences of positive integers $\underline{d} = (\underline{d}(1) \geq \underline{d}(2) \geq \dots)$ viewed as a partition of $\sum \underline{d} := \sum_i \underline{d}(i)$.

Notation 2.2.2. — Let $f : \mathcal{I}_0 \rightarrow \text{Part}$ with finite support. We then denote by τ_f the restriction to I_L of

$$\bigoplus_{\tau_0 \in \mathcal{I}_0} \bigoplus_i \text{Sp}(\rho_{\tau_0}, f(\tau_0)(i)),$$

where ρ_{τ_0} is a fixed extension of τ_0 to W_L .

Remark. By lemma 3.3 of [MS] the isomorphism class of τ_f is independent of the choices of the ρ_{τ_0} .

The map from $\{f : \mathcal{I}_0 \rightarrow \text{Part}\}$ to the set of inertial types given by $f \mapsto \tau_f$, is a bijection. The dominance order \preceq on Part induces a partial order on the set of inertial types.

We let rec_L denote the local reciprocity map of [HT01, Theorem A]. Fix an isomorphism $\iota : \overline{\mathbb{Q}}_\ell \xrightarrow{\sim} \mathbb{C}$. We normalize the local reciprocity map rec of [HT01, Theorem A], defined on isomorphism classes of irreducible smooth representations of $\text{GL}_n(L)$ over \mathbb{C} as follows: if π is the isomorphism class of an irreducible smooth representation of $\text{GL}_n(L)$ over $\overline{\mathbb{Q}}_\ell$, then

$$\rho_\ell(\pi) \stackrel{\text{def}}{=} \iota^{-1} \circ \text{rec}_L \circ \iota(\pi \otimes_{\overline{\mathbb{Q}}_\ell} |\det|^{(1-n)/2}).$$

Then $\rho_\ell(\pi)$ is the isomorphism class of an n -dimensional, Frobenius semisimple Weil–Deligne representation of W_L over $\overline{\mathbb{Q}}_\ell$, independent of the choice of ι . Moreover, if ρ is an isomorphism class of an n -dimensional, Frobenius semisimple Weil–Deligne representation of W_L over M , then $\rho_\ell^{-1}(\rho)$ is defined over M (cf. [CEG⁺16, §1.8]).

Recall the following compatibility of the Langlands correspondence.

Lemma 2.2.3. — *If π and π' are irreducible generic representations of $\text{GL}_d(L)$ such that $\rho_\ell(\pi)|_{I_L} \cong \rho_\ell(\pi')|_{I_L}$ then*

$$\pi|_{\text{GL}_d(\mathcal{O}_L)} \cong \pi'|_{\text{GL}_d(\mathcal{O}_L)}.$$

2.3. Kottwitz–Harris–Taylor Shimura varieties. — Let $F = F^+E$ be a CM field where E/\mathbb{Q} is a quadratic imaginary extension and F^+/\mathbb{Q} is totally real. We fix a real embedding $\tau : F^+ \hookrightarrow \mathbb{R}$. For a place v of F , we will denote by

- F_v the completion of F at v ,
- \mathcal{O}_v the ring of integers of F_v ,
- ϖ_v a uniformizer,
- q_v the cardinal of the residue field $\kappa(v) = \mathcal{O}_v/(\varpi_v)$.

Let B be a division algebra with center F , of dimension d^2 such that at every place v of F , either B_v is split or a local division algebra and suppose B provided with an involution of second kind $*$ such that $*|_F$ is the complex conjugation. For any $\beta \in B^{*-1}$, denote by \sharp_β the involution $v \mapsto v^\sharp_\beta = \beta v^* \beta^{-1}$ and let G/\mathbb{Q} be the group of similitudes, denoted by G_τ in [HT01], defined for every \mathbb{Q} -algebra R by

$$G(R) \cong \{(\lambda, g) \in R^\times \times (B^{op} \otimes_{\mathbb{Q}} R)^\times \text{ such that } gg^{\sharp_\beta} = \lambda\}$$

with $B^{op} = B \otimes_{F,c} F$. If x is a place of \mathbb{Q} split $x = yy^c$ in E then

$$(2) \quad G(\mathbb{Q}_x) \cong (B_y^{op})^\times \times \mathbb{Q}_x^\times \cong \mathbb{Q}_x^\times \times \prod_{v_i^+} (B_{v_i^+}^{op})^\times,$$

where $x = \prod_i v_i^+$ in F^+ and we identify places of F^+ over x with places of F over y .

Convention 2.3.1. — For $x = yy^c$ a place of \mathbb{Q} split in M and v a place of F over y , we shall make throughout the text the following abuse of notation: we denote $G(F_v)$ the factor $(B_{v|F^+}^{op})^\times$ in the formula (2) so that

$$G(\mathbb{A}_{\mathbb{Q}}^{\infty,v}) := G(\mathbb{A}_{\mathbb{Q}}^{\infty,p}) \times \left(\mathbb{Q}_p^\times \times \prod_{v_i^+ \neq v|F^+} (B_{v_i^+}^{op})^\times \right).$$

In [HT01], the authors justify the existence of some G like before such that moreover

- if x is a place of \mathbb{Q} non split in M then $G(\mathbb{Q}_x)$ is quasi split;
- the invariants of $G(\mathbb{R})$ are $(1, d-1)$ for the embedding τ and $(0, d)$ for the others.

As in [HT01, page 90], a compact open subgroup K of $G(\mathbb{A}_{\mathbb{Q}}^{\infty})$ is said to be *sufficiently small* if there exists a place x of \mathbb{Q} such that the projection from K^x to $G(\mathbb{Q}_x)$ does not contain any element of finite order except identity.

Notation 2.3.2. — Denote by \mathcal{K} the set of sufficiently small compact open subgroups of $G(\mathbb{A}^{\infty})$. For $K \in \mathcal{K}$, write $\text{Sh}_{K,\eta} \longrightarrow \text{Spec } F$ for the associated Shimura variety of Kottwitz-Harris-Taylor type.

Definition 2.3.3. — Denote by Spl the set of places w of F such that $p_w := w|_{\mathbb{Q}} \neq l$ is split in E and $B_w^\times \cong \text{GL}_d(F_w)$. For each $K \in \mathcal{K}$, we write $\text{Spl}(K)$ for the subset of Spl of places such that K_v is the standard maximal compact of $\text{GL}_d(F_v)$.

In the sequel, we fix a place v of F in Spl . The scheme $\text{Sh}_{K,\eta}$ has a projective model $\text{Sh}_{K,v}$ over $\text{Spec } \mathcal{O}_v$ with special geometric fiber Sh_{K,\bar{s}_v} . We have a projective system $(\text{Sh}_{K,\bar{s}_v})_{K \in \mathcal{K}}$ which is naturally equipped with an action of $G(\mathbb{A}_{\mathbb{Q}}^{\infty}) \times \mathbb{Z}$ such that any $w_v \in W_{F_v}$ acts by $-\deg(w_v) \in \mathbb{Z}$, where $\deg = \text{val} \circ \text{Art}_{F_v}^{-1}$ and $\text{Art}_{F_v} : F_v^\times \xrightarrow{\sim} W_{F_v}^{ab}$.

Notation 2.3.4. — For $K \in \mathcal{K}$, the Newton stratification of the geometric special fiber Sh_{K,\bar{s}_v} is denoted by

$$\text{Sh}_{K,\bar{s}_v} =: \text{Sh}_{K,\bar{s}_v}^{\geq 1} \supset \text{Sh}_{K,\bar{s}_v}^{\geq 2} \supset \cdots \supset \text{Sh}_{K,\bar{s}_v}^{\geq d}$$

where $\text{Sh}_{K,\bar{s}_v}^{\leq h} := \text{Sh}_{K,\bar{s}_v}^{\geq h} - \text{Sh}_{K,\bar{s}_v}^{\geq h+1}$ is an affine scheme, which is smooth and pure of dimension $d - h$. It is built up by the geometric points such that the connected part of the associated Barsotti–Tate group has rank h . For each $1 \leq h < d$, write

$$i_h : \text{Sh}_{K,\bar{s}_v}^{\geq h} \hookrightarrow \text{Sh}_{K,\bar{s}_v}^{\geq 1}, \quad j^{\geq h} : \text{Sh}_{K,\bar{s}_v}^{\leq h} \hookrightarrow \text{Sh}_{K,\bar{s}_v}^{\geq h},$$

and $j^=h = i_h \circ j^{\geq h}$.

For $n \geq 1$, with our previous abuse of notation, consider $K^v(n) := K^v K_v(n)$ where

$$K_v(n) := \ker(\text{GL}_d(\mathcal{O}_v) \twoheadrightarrow \text{GL}_d(\mathcal{O}_v/\mathcal{M}_v^n)).$$

Recall that $\text{Sh}_{K^v(n),\bar{s}_v}^{\leq h}$ is geometrically induced under the action of the parabolic subgroup $P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n)$, defined as the stabilizer of the first h vectors of the canonical basis of F_v^d . Concretely this means there exists a closed subscheme $\text{Sh}_{K^v(n),\bar{s}_v,1}^{\leq h}$ stabilized by the Hecke action of $P_{h,d}(F_v)$ and such that

$$\text{Sh}_{K^v(n),\bar{s}_v}^{\leq h} = \text{Sh}_{K^v(n),\bar{s}_v,1}^{\leq h} \times_{P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n)} \text{GL}_d(\mathcal{O}_v/\mathcal{M}_v^n),$$

meaning that $\text{Sh}_{K^v(n),\bar{s}_v}^{\leq h}$ is the disjoint union of copies of $\text{Sh}_{K^v(n),\bar{s}_v,1}^{\leq h}$ indexed by $\text{GL}_d(\mathcal{O}_v/\mathcal{M}_v^n)/P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n)$ and exchanged by the action of $\text{GL}_d(\mathcal{O}_v/\mathcal{M}_v^n)$. We will denote by $\text{Sh}_{K^v(n),\bar{s}_v,1}^{\geq h}$ the closure of $\text{Sh}_{K^v(n),\bar{s}_v,1}^{\leq h}$ inside $\text{Sh}_{K^v(n),\bar{s}_v}$.

Notation 2.3.5. — Let $1 \leq h \leq d$ and Π_h any representation of $\text{GL}_h(F_v)$. For χ_v a character of F_v^\times , we then denote by

$$\widetilde{HT}_1(\chi_v, \Pi_h) := \mathcal{L}(\chi_v, t)_1 \otimes \Pi_h^{K_v(n)} \otimes \Xi^{\frac{h-d}{2}}$$

the Harris-Taylor local system on the Newton stratum $\text{Sh}_{K^v(n),\bar{s}_v,1}^{\leq h}$ where

- $\mathcal{L}(\chi_v, t)_1$ is the constant sheaf $\overline{\mathbb{Z}}_l$ where the fundamental group acts through

$$\pi_1 \twoheadrightarrow \mathcal{D}_{v,h}^\times \xrightarrow{\chi_v} \mathcal{O}_v^\times$$

where $\mathcal{D}_{v,h}$ is the maximal order of the division algebra $D_{v,h}/F_v$ with invariant $1/h$, and the first surjection is given by the Igusa varieties of [HT01];

- $\Xi : \frac{1}{2}\mathbb{Z} \longrightarrow \overline{\mathbb{Z}}_l^\times$ is defined by $\Xi(\frac{1}{2}) = q^{1/2}$.

We also introduce the induced version

$$\widetilde{HT}(\chi_v, \Pi_h) := \left(\mathcal{L}(\chi_v, t)_1 \otimes \Pi_h^{K_v(n)} \otimes \Xi^{\frac{h-d}{2}} \right) \times_{P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n)} \text{GL}_d(\mathcal{O}_v/\mathcal{M}_v^n),$$

where the unipotent radical of $P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n)$ acts trivially and the action of

$$(g^{\infty,v}, \begin{pmatrix} g_v^c & * \\ 0 & g_v^{et} \end{pmatrix}, \sigma_v) \in G(\mathbb{A}^{\infty,v}) \times P_{h,d}(\mathcal{O}_v/\mathcal{M}_v^n) \times W_v$$

is given

- by the action of g_v^c on $\Pi_h^{K_v(n)}$ and $\deg(\sigma_v) \in \mathbb{Z}$ on $\Xi^{\frac{h-d}{2}}$, and

- the action of $(g^{\infty,v}, g_v^{et}, \text{val}(\det g_v^c) - \deg \sigma_v) \in G(\mathbb{A}^{\infty,v}) \times \text{GL}_{d-h}(\mathcal{O}_v/\mathcal{M}_v^n) \times \mathbb{Z}$ on $\mathcal{L}_{\overline{\mathbb{Q}}_l}(\chi_v)_1 \otimes \Xi^{\frac{h-d}{2}}$.

We also introduce

$$HT(\chi_v, \Pi_h)_1 := \widetilde{HT}(\chi_v, \Pi_h)_1[d - tg],$$

and the perverse sheaf

$$P(h, \chi_v)_1 := {}^p j_{1,!}^{\overline{h}} HT(\chi_v, \text{St}_h(\chi_v))_1 \otimes \chi_v^{-1},$$

and their induced version, $HT(\chi_v, \Pi_h)$ and $P(h, \chi_v)$.

Note that over $\overline{\mathbb{Z}}_l$, there are at least two notions of intermediate extension associated to the two classical t -structures p and $p+$. However in our situation they all coincide. Indeed as $\text{Sh}_{K^v(n), \overline{s}_v, 1}^{\geq h}$ is smooth over $\text{Spec } \overline{\mathbb{F}}_p$, then $HT(\chi_v, \Pi_h)_1$ is perverse for the two t -structures with

$$i_1^{h \leq +1,*} HT(\chi_v, \Pi_h)_1 \in {}^p \mathcal{D}^{<0} \text{ and } i_1^{h \leq +1,!} HT(\chi_v, \Pi_h)_1 \in {}^{p+} \mathcal{D}^{\geq 1}.$$

Let now denote by

$$\Psi_{K,v} := R\Psi_{\eta_v}(\overline{\mathbb{Z}}_l[d-1])(\frac{d-1}{2})$$

the nearby cycles autodual free perverse sheaf on $\text{Sh}_{K, \overline{s}_v}$. Recall, cf. [Boy23b] proposition 3.1.3, that

$$(3) \quad \Psi_{K,v} \cong \bigoplus_{1 \leq g \leq d} \bigoplus_{\varrho \in \text{Scusp}(g)} \Psi_{K,\varrho},$$

where

- $\text{Scusp}(g)$ is the set of equivalence classes of irreducible supercuspidal representations of $\text{GL}_g(F_v)$.
- The irreducible sub-quotients of $\Psi_{K,\varrho} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$ are the Harris-Taylor perverse sheaves of $\Psi_{K, \overline{\mathbb{Q}}_l}$ associated to irreducible cuspidal representations π_v with modulo l reduction having supercuspidal support a Zelevinsky segment associated to ϱ .

Remark. In the limit case when $q_v \equiv 1 \pmod l$ and $l > d$, recall that we do not have to bother about cuspidal $\overline{\mathbb{F}}_l$ -representation which are not supercuspidal. In particular in the previous formula we can

- replace $\text{Scusp}(g)$ by the set $\text{Cusp}(g)$ of equivalence classes of cuspidal representations,
- and the Harris-Taylor perverse sheaves of $\Psi_{K,\varrho} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$ are those associated to π_v such that its modulo l reduction is isomorphic to ϱ .

Moreover regarding the main statement about Ihara's lemma, we will only be concerned by $\Psi_{K,\varrho}$ for ϱ a character.

2.4. Filtrations of stratification. — Using the Newton stratification and following the constructions of [Boy14], we can define a $\overline{\mathbb{Z}}_l$ -filtration

$$\mathrm{Fil}_!^0(\Psi_{K,\varrho}) \hookrightarrow \cdots \hookrightarrow \mathrm{Fil}_!^d(\Psi_{K,\varrho}) = \Psi_{K,\varrho}$$

where each graded part $\mathrm{gr}_!^k(\Psi_{K,\varrho})$ admits a filtration, cf. [Boy14] corollary 3.4.5

$$\mathrm{Fil}^{-d}(\mathrm{gr}_!^k(\Psi_{K,\varrho})) \hookrightarrow \cdots \hookrightarrow \mathrm{Fil}^{-k}(\mathrm{gr}_!^k(\Psi_{K,\varrho})) = \mathrm{gr}_!^k(\Psi_{K,\varrho})$$

with

$$\mathrm{gr}^{-i}(\mathrm{gr}_!^k(\Psi_{K,\varrho})) \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l \cong \bigoplus_{\pi_v \in \mathrm{Cusp}(\varrho)} P(i, \pi_v) \left(\frac{i+1-2k}{2} \right),$$

where $\mathrm{Cusp}(\varrho)$ is the set of equivalence classes of irreducible cuspidal representations with modulo l reduction isomorphic to ϱ . We then have spectral sequences

$$(4) \quad E_1^{p,q} = H^{p+q}(\mathrm{Sh}_{K,\bar{s}_v}, \mathrm{gr}^{-p}(\mathrm{gr}_!^k(\Psi_{K,\varrho}))) \Rightarrow H^{p+q}(\mathrm{Sh}_{K,\bar{s}_v}, \mathrm{gr}_!^k(\Psi_{K,\varrho})),$$

and

$$(5) \quad E_1^{p,q} = H^{p+q}(\mathrm{Sh}_{K,\bar{s}_v}, \mathrm{gr}_!^{-p}(\Psi_{K,\varrho})) \Rightarrow H^{p+q}(\mathrm{Sh}_{K,\bar{s}_v}, \Psi_{K,\varrho}).$$

Definition 2.4.1. — For a finite set S of places of \mathbb{Q} containing the places where G is ramified, denote by $\mathbb{T}_{abs}^S := \prod'_{x \notin S} \mathbb{T}_{x,abs}$ the abstract unramified Hecke algebra where $\mathbb{T}_{x,abs} \cong \overline{\mathbb{Z}}_l[X^{un}(T_x)]^{W_x}$ for T_x a split torus, W_x the spherical Weyl group and $X^{un}(T_x)$ the set of $\overline{\mathbb{Z}}_l$ -unramified characters of T_x .

Example. For $w \in \mathrm{Spl}$, we have

$$\mathbb{T}_{v|\mathbb{Q},abs} = \overline{\mathbb{Z}}_l[T_{v',i} : i = 1, \dots, d, v'|(v|\mathbb{Q})]$$

where $T_{v',i}$ is the characteristic function of

$$\mathrm{GL}_d(\mathcal{O}_{v'}) \mathrm{diag}(\overbrace{\varpi_{v'}, \dots, \varpi_{v'}}^i, \overbrace{1, \dots, 1}^{d-i}) \mathrm{GL}_d(\mathcal{O}_{v'}) \subseteq \mathrm{GL}_d(F_{v'}).$$

Recall that \mathbb{T}_{abs}^S acts through correspondances on each of the $H^i(\mathrm{Sh}_{K,\bar{\eta}}, E)$ where $K \in \mathcal{K}$ is maximal at each places outside S .

Notation 2.4.2. — We denote by $\mathbb{T}(K)$ the image of \mathbb{T}_{abs}^S inside $\mathrm{End}_{\overline{\mathbb{Z}}_l}(H^{d-1}(\mathrm{Sh}_{K,\bar{\eta}}, \overline{\mathbb{Z}}_l))$.

We also denote

$$H^{d-1}(\mathrm{Sh}_{K^v(\infty),\bar{\eta}}, \overline{\mathbb{Z}}_l) := \varinjlim_{K_v} H^{d-1}(\mathrm{Sh}_{K^v K_v, \bar{\eta}}, \overline{\mathbb{Z}}_l),$$

where K_v describe the set of open compact subgroup of $\mathrm{GL}_d(\mathcal{O}_v)$. We also use similar notation for others cohomology groups.

Theorem 2.4.3. — Let \mathfrak{m} be a maximal ideal of $\mathbb{T}(K^v(\infty))$ such that $\bar{\rho}_{\mathfrak{m}}$ is irreducible and the irreducible constituents of its restriction to the decomposition group at the place v are characters. Recall also that $q_v \equiv 1 \pmod{l}$ and $l > d$. Then

(i) $H^i(\mathrm{Sh}_{K^v(\infty),\bar{\eta}}, \overline{\mathbb{Z}}_l)_{\mathfrak{m}}$ is zero if $i \neq d-1$ and otherwise torsion free.

(ii) Moreover the spectral sequences (4) and (5), localized at \mathfrak{m} , degenerate at E_1 and the $E_{1,\mathfrak{m}}^{p,q}$ are zero for $p + q \neq 0$ and otherwise torsion free.

Proof. — (i) It is the main theorem of [Boy23a].

(ii) From (3) we are led to study the initial terms of the spectral sequence given by the filtration of $\Psi_{K^v(\infty),\varrho}$ for ϱ a character which is a constituent of $\bar{\rho}_{\mathfrak{m},v}$. Recall also, as we are in the limit case, that

- as there do not exist irreducible $\overline{\mathbb{Q}}_l$ -cuspidal representation of $\mathrm{GL}_g(F_v)$ for $g \leq d$ with modulo l reduction not supercuspidal, the irreducible constituents of $\Psi_{K,\varrho} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$ are the Harris-Taylor perverse sheaves $P(h, \chi_v)^{(\frac{h-1-2k}{2})}$ where the modulo l reduction of χ_v is isomorphic to ϱ and $0 \leq k < h$.
- Over $\overline{\mathbb{Z}}_l$, we do not have to worry about the difference between p and $p+$ intermediate extensions.

From [Boy23b] §2.3, consider the following equivariant resolution

$$(6) \quad 0 \rightarrow j_!^{=d} HT(\chi_v, \Pi_h \{ \frac{h-d}{2} \} \times \mathrm{Speh}_{d-h}(\chi_v \{ h/2 \})) \otimes \Xi^{\frac{d-h}{2}} \rightarrow \dots$$

$$\rightarrow j_!^{=h+1} HT(\chi_v, \Pi_h \{ -1/2 \} \times \chi_v \{ h/2 \}) \otimes \Xi^{\frac{1}{2}} \rightarrow$$

$$j_!^{=h} HT(\chi_v, \Pi_h) \rightarrow {}^p j_{!*}^{=h} HT(\chi_v, \Pi_h) \rightarrow 0,$$

where Π_h is any representation of $\mathrm{GL}_h(F_v)$, also called the infinitesimal part of the perverse sheaf ${}^p j_{!*}^{=h} HT(\chi_v, \Pi_h)$.⁽⁴⁾

By adjunction property, for $1 \leq \delta \leq d - h$, the map

$$(7) \quad j_!^{=h+\delta} HT(\chi_v, \Pi_h \{ \frac{-\delta}{2} \} \times \mathrm{Speh}_{\delta}(\chi_v \{ h/2 \})) \otimes \Xi^{\delta/2}$$

$$\rightarrow j_!^{=h+\delta-1} HT(\chi_v, \Pi_h \{ \frac{1-\delta}{2} \} \times \mathrm{Speh}_{\delta-1}(\chi_v \{ h/2 \})) \otimes \Xi^{\frac{\delta-1}{2}}$$

is given by

$$(8) \quad HT(\chi_v, \Pi_h \{ \frac{-\delta}{2} \} \times \mathrm{Speh}_{\delta}(\chi_v \{ h/2 \})) \otimes \Xi^{\delta/2} \rightarrow$$

$$j^{=h+\delta,*} ({}^p i^{h+\delta,!} (j_!^{=h+\delta-1} HT(\chi_v, \Pi_h \{ \frac{1-\delta}{2} \} \times \mathrm{Speh}_{\delta-1}(\chi_v \{ h/2 \})) \otimes \Xi^{\frac{\delta-1}{2}}))$$

To compute this last term we use the resolution (6) for $h + \delta - 1$. Precisely denote by $\mathcal{H} := HT(\chi_v, \mathrm{st}_h(\chi \{ \frac{1-\delta}{2} \}) \times \mathrm{Speh}_{\delta-1}(\chi_v \{ h/2 \})) \otimes \Xi^{\frac{\delta-1}{2}}$, and write the previous resolution for $h + \delta - 1$ as follows

$$0 \rightarrow K \rightarrow j_!^{=h+\delta} \mathcal{H}' \rightarrow Q \rightarrow 0,$$

$$0 \rightarrow Q \rightarrow j_!^{=h+\delta-1} \mathcal{H} \rightarrow {}^p j_{!*}^{=h+\delta-1} \mathcal{H} \rightarrow 0,$$

⁽⁴⁾In $P(h, \chi_v)$ the infinitesimal part Π_h is $\mathrm{st}_h(\chi_v)$.

with

$$\mathcal{H}' := HT\left(\chi_v, \Pi_h\left\{\frac{1-\delta}{2}\right\} \times (\mathrm{Speh}_{\delta-1}(\chi_v\{-1/2\}) \times \chi_v\left\{\frac{\delta-1}{2}\right\})\{h/2\}\right) \otimes \Xi^{\delta/2}.$$

As the support of K is contained in $\mathrm{Sh}_{\bar{L}, \bar{s}_v}^{\geq h+\delta+1}$ then $p_i^{h+\delta,!}K = K$ and $j^{=h+\delta,*}(p_i^{h+\delta,!}K)$ is zero. Moreover $p_i^{h+\delta,!}(p_{j!}^{=h+\delta-1}\mathcal{H})$ is zero by construction of the intermediate extension. We then deduce that

$$\begin{aligned} (9) \quad j^{=h+\delta,*}(p_i^{h+\delta,!}(j!^{=h+\delta-1}HT(\chi_v, \Pi_h\left\{\frac{1-\delta}{2}\right\} \times \mathrm{Speh}_{\delta-1}(\chi_v\{h/2\}))) \otimes \Xi^{\frac{\delta-1}{2}})) \\ \cong HT\left(\chi_v, \Pi_h\left\{\frac{1-\delta}{2}\right\} \right. \\ \left. \times (\mathrm{Speh}_{\delta-1}(\chi_v\{-1/2\}) \times \chi_v\left\{\frac{\delta-1}{2}\right\})\{h/2\}\right) \otimes \Xi^{\delta/2} \end{aligned}$$

In particular, up to homothety, the map (8), and so (7), is unique. Finally as the maps of (6) are strict, the given maps (7) are uniquely determined, that is, if we forget the infinitesimal parts, these maps are independent of the chosen h in (6), i.e. only depends on $h + \delta$.

For every $1 \leq h \leq d$, let denote by $i(h)$ the smallest index i such that $H^i(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, p_{j!}^{=h}HT(\chi_v, \Pi_h)_{\mathfrak{m}})$ has non trivial torsion: if it does not exist then we set $i(h) = +\infty$ and note that it does not depend on the choice of the infinitesimal part Π_h . By duality, as $p_{j!} = p^+_{j!}$ for Harris-Taylor local systems associated to characters, note that when $i(h)$ is finite then $i(h) \leq 0$. Suppose by absurdity there exists h with $i(h)$ finite and denote h_0 the biggest such h .

Lemma 2.4.4. — *For $1 \leq h \leq h_0$ then $i(h) = h - h_0$.*

Note that a similar result is proved in [Boy17] when the level is maximal at v .

Proof. — a) We first prove that for every $h_0 < h \leq d$, the cohomology groups of $j!^{=h}HT(\chi_v, \Pi_h)$ are torsion free. Consider the following strict filtration in the category of free perverse sheaves

$$(10) \quad (0) = \mathrm{Fil}^{-1-d}(\chi_v, h) \hookrightarrow \mathrm{Fil}^{-d}(\chi_v, h) \hookrightarrow \dots \hookrightarrow \mathrm{Fil}^{-h}(\chi_v, h) = j!^{=h}HT(\chi_v, \Pi_h)$$

where the symbol \hookrightarrow means a strict monomorphism, with graded parts

$$\mathrm{gr}^{-k}(\chi_v, h) \cong p_{j!}^{=k}HT(\chi_v, \Pi_h\left\{\frac{h-k}{2}\right\} \otimes \mathrm{st}_{k-h}(\chi_v\{h/2\}))\left(\frac{h-k}{2}\right).$$

Over $\bar{\mathbb{Q}}_l$, the result is proved in [Boy09] §4.3. Over $\bar{\mathbb{Z}}_l$, the result follows from the general constructions of [Boy14] and the fact that the p and $p+$ intermediate extensions are isomorphic for Harris-Taylor perverse sheaves associated to characters. The associated spectral sequence localized at \mathfrak{m} , is then concentrated in middle degree and torsion free which gives the claim.

b) Before watching the cases $h \leq h_0$, note that the spectral sequence associated to (6) for $h = h_0 + 1$, has all its E_1 terms torsion free and degenerates at its E_2 terms. As by hypothesis the aims of this spectral sequence is free and equals to only one E_2 terms, we deduce that all the maps

$$(11) \quad H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h+\delta} HT_\xi(\chi_v, \mathrm{st}_h(\chi_v\{\frac{-\delta}{2}\}) \times \mathrm{Speh}_\delta(\chi_v\{h/2\})) \otimes \Xi^{\delta/2})_{\mathfrak{m}} \\ \longrightarrow \\ H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h+\delta-1} HT_\xi(\chi_v, \mathrm{st}_h(\chi_v\{\frac{1-\delta}{2}\}) \\ \times \mathrm{Speh}_{\delta-1}(\chi_v\{h/2\})) \otimes \Xi^{\frac{\delta-1}{2}})_{\mathfrak{m}}$$

are saturated, i.e. their cokernel are free $\overline{\mathbb{Z}}_l$ -modules. Then from the previous fact stressed after (9), this property remains true when we consider the associated spectral sequence for $1 \leq h' \leq h_0$.

c) Consider now $h = h_0$ and the spectral sequence associated to (6) where

$$(12) \quad E_2^{p,q} = H^{p+2q}(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h+q} HT_\xi(\chi_v, \mathrm{st}_h(\chi_v(-q/2)) \times \mathrm{Speh}_q(\chi_v\{h/2\})) \otimes \Xi^q)_{\mathfrak{m}}$$

By definition of h_0 , we know that some of the E_∞^{-p} should have a non trivial torsion subspace. We saw that

- the contributions from the deeper strata are torsion free and
- $H^i(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h_0} HT_\xi(\chi_v, \Pi_{h_0}))_{\mathfrak{m}}$ are zero for $i < 0$ and is torsion free for $i = 0$, whatever is Π_{h_0} .
- Then there should exist a non strict map $d_1^{p,q}$. But, we have just seen that it can not be maps between deeper strata.
- Finally, using the previous points, the only possibility is that the cokernel of

$$(13) \quad H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h_0+1} HT_\xi(\chi_v, \mathrm{st}_{h_0}(\chi_v\{\frac{-1}{2}\}) \times \chi_v\{h_0/2\})) \otimes \Xi^{1/2})_{\mathfrak{m}} \\ \longrightarrow \\ H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, j_!^{=h_0} HT_\xi(\chi_v, \mathrm{st}_{h_0}(\chi_v)))_{\mathfrak{m}}$$

has a non trivial torsion subspace.

In particular we have $i(h_0) = 0$.

d) Finally using the fact 2.18 and the previous points, for any $1 \leq h \leq h_0$, in the spectral sequence (12)

- by point a), $E_2^{p,q}$ is torsion free for $q \geq h_0 - h + 1$ and so it is zero if $p + 2q \neq 0$;
- by affiness of the open strata, cf. [Boy17] theorem 1.8, $E_2^{p,q}$ is zero for $p + 2q < 0$ and torsion free for $p + 2q = 0$;
- by point b), the maps $d_2^{p,q}$ are saturated for $q \geq h_0 - h + 2$;

- by point c), $d_2^{-2(h_0-h+1), h_0-h+1}$ has a cokernel with a non trivial torsion subspace.
- Moreover, over $\overline{\mathbb{Q}}_l$, the spectral sequence degenerates at E_3 and $E_3^{p,q} = 0$ if $(p, q) \neq (0, 0)$.

We then deduce that $H^i(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, {}^p j_{!*}^{-h} HT_\xi(\chi_v, \Pi_h))_{\mathfrak{m}}$ is zero for $i < h - h_0$ and for $i = h - h_0$ it has a non trivial torsion subspace. \square

Consider now the filtration of stratification of Ψ_ϱ constructed using the adjunction morphisms $j_!^{-h} j^{=h,*}$ as in [Boy14]

$$(14) \quad \mathrm{Fil}_!^1(\Psi_\varrho) \hookrightarrow \mathrm{Fil}_!^2(\Psi_\varrho) \hookrightarrow \cdots \hookrightarrow \mathrm{Fil}_!^d(\Psi_\varrho)$$

where $\mathrm{Fil}_!^h(\Psi_\varrho)$ is the saturated image of $j_!^{-h} j^{=h,*} \Psi_\varrho \rightarrow \Psi_\varrho$. For our fixed χ_v , let denote $\mathrm{Fil}_{!, \chi_v}^1(\Psi) \hookrightarrow \mathrm{Fil}_!^1(\Psi_\varrho)$ such that $\mathrm{Fil}_{!, \chi_v}^1(\Psi) \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l \cong \mathrm{Fil}_!^1(\Psi_{\chi_v})$ where Ψ_{χ_v} is the direct factor of $\Psi \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$ associated to χ_v , cf. [Boy14]. From [Boy23b] 3.3.5, we have the following resolution of $\mathrm{gr}_{!, \chi_v}^h(\Psi)$

$$(15) \quad 0 \rightarrow j_!^{=d} HT(\chi_v, LT_{h,d}(\chi_v)) \otimes \chi_v^*\left(\frac{d-h}{2}\right) \rightarrow \\ j_!^{=d-1} HT(\chi_v, LT_{h,d-1}(\chi_v)) \otimes \chi_v^*\left(\frac{d-h-1}{2}\right) \rightarrow \\ \cdots \rightarrow j_!^{=h} HT(\chi_v, \mathrm{st}_h(\chi_v)) \otimes \chi_v^* \rightarrow \mathrm{gr}_{!, \chi_v}^h(\Psi) \rightarrow 0,$$

where $LT_{h,h+\delta}(\chi_v) \hookrightarrow \mathrm{st}_h(\chi_v\{-\delta/2\}) \times \mathrm{Speh}_\delta(\chi_v\{h/2\})$, is the only irreducible subspace of this induced representation,

We can then apply the previous arguments a)-d) above: for $h \leq h_0$ (resp. $h > h_0$) the torsion of $H^i(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, \mathrm{gr}_{!, \chi_v}^h(\Psi_{v,\xi}))_{\mathfrak{m}}$ is trivial for any $i \leq h - h_0$ (resp. for all i) and the free parts are concentrated for $i = 0$. Using the spectral sequence associated to the previous filtration, we can then conclude that $H^{1-t_0}(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, \Psi_{v,\xi})_{\mathfrak{m}}$ would have non trivial torsion which is false as \mathfrak{m} is supposed to be KHT-free. \square

In particular the previous spectral sequence gives us a filtration of $H^{d-1}(\mathrm{Sh}_{K^v(\infty), \bar{\eta}_v}, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ whose graded parts are

$$H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_v}, \mathrm{gr}^{-p}(\mathrm{gr}_!^k(\Psi_{K,\varrho})))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l,$$

for ϱ describing the equivalence classes of irreducible $\overline{\mathbb{F}}_l$ -supercuspidal representation of $\mathrm{GL}_g(F_v)$ with $1 \leq g \leq d$, and then $1 \leq k \leq p \leq \lfloor \frac{d}{g} \rfloor$.

3. Genericity for KHT-Shimura varieties

As explained in the introduction, we follow the strategy of [Boy20] which consists to transfer the genericity property of Ihara's lemma concerning \overline{G} to the genericity of the cohomology of KHT-Shimura varieties.

Let \overline{G} be a similitude group as in the introduction such that moreover there exists a prime number p_0 split in E and v_0^+ a place of F^+ above p_0 , identified as before to a place v_0 of F , such that \overline{B}_{v_0} is a division algebra: in particular $v_0 \neq v$. Consider then, with the usual abuse of notation, G/\mathbb{Q} such that $G(\mathbb{A}_{\mathbb{Q}}^{\infty, v_0}) \cong \overline{G}(\mathbb{A}_{\mathbb{Q}}^{\infty, v_0})$ with $G(F_{v_0}) \cong \mathrm{GL}_d(F_{v_0})$ and $G(\mathbb{R})$ of signatures $(1, n-1), (0, n)^r$. The KHT Shimura variety $\mathrm{Sh}_{K, v_0} \rightarrow \mathrm{spec} \mathcal{O}_{v_0}$ associated to G with level K , has a Newton stratification of its special fiber with

$$\mathrm{Sh}_{K, \bar{s}_{v_0}}^=d = \coprod_{i \in \ker^1(\mathbb{Q}, G)} \mathrm{Sh}_{K, \bar{s}_{v_0}, i}^=d.$$

For a equivariant sheaf $\mathcal{F}_{K, i}$ on $\mathrm{Sh}_{K^v(\infty), \bar{s}_{v_0}, i}^=d$ seen as compatible system of $\mathrm{Sh}_{K^v K_v, \bar{s}_{v_0}, i}^=d$ for K_v describing the set of open compact subgroups of $\mathrm{GL}_d(\mathcal{O}_v)$, its fiber at a compatible system $z_{K^v(\infty), i}$ of supersingular point $z_{K^v K_v, i}$, has an action of $\overline{G}(\mathbb{A}_{\mathbb{Q}}^{\infty}) \times \mathrm{GL}_d(F_v)^0$ where $\mathrm{GL}_d(F_v)^0$ is the kernel of the valuation of the determinant so that, cf. [Boy09] proposition 5.1.1, as a $\mathrm{GL}_d(F_v)$ -module, we have

$$H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_{v_0}, i}^=d, \mathcal{F}_{K^v(\infty), i}) \cong \left(\mathrm{ind}_{\overline{G}(\mathbb{Q})}^{\overline{G}(\mathbb{A}^{\infty, v}) \times \mathbb{Z}} z_{K^{v_0}(\infty), i}^* \mathcal{F}_{K^{v_0}(\infty), i} \right)^{K^v},$$

with $\delta \in \overline{G}(\mathbb{Q}) \mapsto (\delta^{\infty, v_0}, \mathrm{val} \circ \mathrm{rn}(\delta_{v_0})) \in \overline{G}(\mathbb{A}^{\infty, v_0, v}) \times \mathbb{Z}$ and where the action of $g_{v_0} \in \mathrm{GL}_d(F_{v_0})$ is given by those of $(g_0^{-\mathrm{val} \det g_{v_0}} g_{v_0}, \mathrm{val} \det g_{v_0}) \in \mathrm{GL}_d(F_{v_0})^0 \times \mathbb{Z}$ where $g_0 \in \mathrm{GL}_d(F_{v_0})$ is any fixed element with $\mathrm{val} \det g_0 = 1$. Moreover, cf. [Boy09] corollaire 5.1.2, if $z_{K^{v_0}(\infty), i}^* \mathcal{F}_{K^{v_0}(\infty), i}$ is provided with an action of the kernel $(D_{v_0, d}^{\times})^0$ of the valuation of the reduced norm, action compatible with those of $\overline{G}(\mathbb{Q}) \hookrightarrow D_{v_0, d}^{\times}$, then as a $G(\mathbb{A}^{\infty})$ -module, we have

$$(16) \quad H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_{v_0}, i}^=d, \mathcal{F}_{K^v(\infty), i}) \cong \left(\mathcal{C}^{\infty}(\overline{G}(\mathbb{Q}) \backslash \overline{G}(\mathbb{A}^{\infty}), \Lambda) \otimes_{D_{v_0, d}^{\times}} \mathrm{ind}_{(D_{v_0, d}^{\times})^0}^{D_{v_0, d}^{\times}} z_i^* \mathcal{F}_{\mathcal{I}, i} \right)^{K^v}$$

In particular, cf. lemma 2.3.1 of [Boy20], let $\bar{\pi}$ be an irreducible sub- $\overline{\mathbb{F}}_l$ -representation of $\mathcal{C}^{\infty}(\overline{G}(\mathbb{Q}) \backslash \overline{G}(\mathbb{A})/K^v, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ for \mathfrak{m} such that $\bar{\rho}_{\mathfrak{m}}$ is irreducible. Write its local component $\bar{\pi}_{v_0} \cong \pi_{v_0}[s]_D$ with π_{v_0} an irreducible cuspidal representation of $\mathrm{GL}_g(F_{v_0})$ with $d = sg$. Then $(\bar{\pi}^{v_0})^{K^v}$ is a sub-representation of $H^0(\mathrm{Sh}_{K^v(\infty), \bar{s}_{v_0}}^=d, HT(\pi_{v_0}^{\vee}, s))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$ and, cf. proposition 2.3.2 of [Boy20], a sub- $\overline{\mathbb{F}}_l$ -representation of $H^{d-1}(\mathrm{Sh}_{K^v(\infty), \bar{\eta}_{v_0}}, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$. Indeed, cf. theorem 2.4.3,

- by the main result of [Boy23a], as $l > d \geq 2$ and $\bar{\rho}_{\mathfrak{m}}$ is irreducible, then \mathfrak{m} is KHT free so that hypothesis (H1) of [Boy20] is fulfilled.
- Theorem 2.4.3 gives us that the filtration of $H^{d-1}(\mathrm{Sh}_{K^v(\infty), \bar{\eta}_{v_0}}, \overline{\mathbb{Z}}_l)_{\mathfrak{m}}$ induced by the filtration of the nearby cycles at v_0 is strict, which was the reason to introduced hypothesis (H3) in [Boy20].

Finally if the analog of Ihara's lemma for $H^{d-1}(\mathrm{Sh}_{K^v(\infty), \bar{\eta}}, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ is true for the action of $\mathrm{GL}_d(F_v)$, then this is also the case for \overline{G} . We now focus on the genericity of irreducible sub- $\mathrm{GL}_d(F_v)$ -modules of $H^0(\mathrm{Sh}_{K^v(\infty), \bar{\eta}}, \overline{\mathbb{F}}_l)_{\mathfrak{m}}$ using the nearby cycles at the place v .

Using proposition 3.7 (3) of [NT16], through Verdier duality, this is also equivalent to prove the genericity of irreducible quotient of $\mathrm{GL}_d(F_v)$ -modules of $H^0(\mathrm{Sh}_{K^v(\infty), \bar{\eta}_v, \bar{\mathbb{F}}_l})_{\mathfrak{m}}$, which is the content of proposition 3.3.4 using 3.3.3.

3.1. Level raising. — To a cohomological minimal prime ideal $\tilde{\mathfrak{m}}$ of $\mathbb{T}(K)$, which corresponds to a maximal ideal of $\mathbb{T}(K)[\frac{1}{l}]$, is associated both a near equivalence class of $\bar{\mathbb{Q}}_l$ -automorphic representation $\Pi_{\tilde{\mathfrak{m}}}$ and a Galois representation

$$\rho_{\tilde{\mathfrak{m}}} : G_F := \mathrm{Gal}(\bar{F}/F) \longrightarrow \mathrm{GL}_d(\bar{\mathbb{Q}}_l)$$

such that the eigenvalues of the Frobenius morphism at an unramified place w are given by the Satake parameters of the local component $\Pi_{\tilde{\mathfrak{m}}, w}$ of $\Pi_{\tilde{\mathfrak{m}}}$. The semi-simple class $\bar{\rho}_{\mathfrak{m}}$ of the reduction modulo l of $\rho_{\tilde{\mathfrak{m}}}$ depends only of the maximal ideal \mathfrak{m} of \mathbb{T}_K^S containing $\tilde{\mathfrak{m}}$.

We now allow infinite level at v and we denote by $\mathbb{T}(K^v(\infty))$ the associated Hecke algebra. We fix a maximal ideal \mathfrak{m} in $\mathbb{T}(K^v(\infty))$ such that

- the associated Galois representation $\bar{\rho}_{\mathfrak{m}} : G_F \rightarrow \mathrm{GL}_d(\mathbb{F})$ is irreducible;
- $\bar{\rho}_{\mathfrak{m}}|_{W_{F_v}}$, after semi-simplification, is a direct sum of characters.

Remark. For every minimal prime $\tilde{\mathfrak{m}} \subseteq \mathfrak{m}$, note that $\Pi_{\tilde{\mathfrak{m}}, v}$ looks like $\mathrm{st}_{s_1}(\chi_{v,1}) \times \cdots \times \mathrm{st}_{s_r}(\chi_{v,r})$ with $s_1 + \cdots + s_r = d$.

Let $\mathcal{S}_v(\mathfrak{m})$ be the supercuspidal support of the modulo l reduction of any $\Pi_{\tilde{\mathfrak{m}}, v}$ in the near equivalence class associated to a minimal prime ideal $\tilde{\mathfrak{m}} \subseteq \mathfrak{m}$. Recall that $\mathcal{S}_v(\mathfrak{m})$ is a multi-set, i.e. a set with multiplicities which only depends on \mathfrak{m} . We decompose it according to the set \mathcal{Z} of Zelevinsky lines: as we supposed $q_v \equiv 1 \pmod l$ then every Zelevinsky line is reduced to a single equivalence class of an irreducible (super)cuspidal $\bar{\mathbb{F}}_l$ -representations ϱ of some $\mathrm{GL}_{g(\varrho)}(F_v)$ with $1 \leq g(\varrho) \leq d$. Moreover our second hypothesis tells us that we are only concerned with ϱ being a character:

$$\mathcal{S}_v(\mathfrak{m}) = \coprod_{\varrho \in \mathrm{Cusp}_{\bar{\mathbb{F}}_l}(1, v)} \mathcal{S}_{\varrho}(\mathfrak{m}),$$

where $\mathrm{Cusp}_{\bar{\mathbb{F}}_l}(1, v)$ is the set of $\bar{\mathbb{F}}_l$ -characters of F_v^\times .

Notation 3.1.1. — We denote by $l_{\varrho}(\mathfrak{m})$ the multiplicity of $\mathcal{S}_{\varrho}(\mathfrak{m})$.

For $\tilde{\mathfrak{m}} \subseteq \mathfrak{m}$, the local component $\Pi_{\tilde{\mathfrak{m}}, v}$ of $\Pi_{\tilde{\mathfrak{m}}}$ can then be written as a full induced representation $\bigtimes_{\varrho \in \mathrm{Cusp}_{\bar{\mathbb{F}}_l}(1, v)} \Pi_{\tilde{\mathfrak{m}}, \varrho}$ where each $\Pi_{\tilde{\mathfrak{m}}, \varrho}$ is also a full induced representation

$$\Pi_{\tilde{\mathfrak{m}}, \varrho} \cong \bigtimes_{i=1}^{r(\varrho)} \mathrm{St}_{l_{\varrho, i}(\tilde{\mathfrak{m}})}(\pi_{v, i})$$

where $r_l(\pi_{v, i}) \cong \varrho$, $l_{\varrho, 1}(\varrho) \geq \cdots \geq l_{\varrho, r(\varrho)}(\varrho)$ and $\sum_{i=1}^r l_{\varrho, i}(\tilde{\mathfrak{m}}) = l_{\varrho}(\mathfrak{m})$.

Suppose now that there exists $\varrho \in \text{Cusp}_{\overline{\mathbb{F}}_l}(1, v)$ with $r(\varrho) \geq 2$, then

$$H^0(\text{Sh}_{K, \bar{s}_v}, \text{gr}^{-l_{\varrho, 1}(\varrho)}(\text{gr}_!^1(\Psi_{K, \varrho})))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$$

is a subspace of $H^0(\text{Sh}_{K, \bar{s}_v}, \Psi_{K, v})_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$. Moreover this subspace, as a $\overline{\mathbb{F}}_l$ -representation of $\text{GL}_d(F_v)$, has a subspace of the following shape $\text{st}_{l_1(\varrho)}(\varrho) \times \tau$ where the supercuspidal support of τ contains ϱ . In particular as $q_v \equiv 1 \pmod{l}$ and $l > d$, this induced representation has both a generic and a non generic subspace.

We can then conclude that for the genericity property to be true for KHT Shimura varieties, one needs a level raising property as in proposition 3.3.1 of [Boy20]. Hopefully such statements exist under some rather mild hypothesis as for example the following result of T. Gee.

Theorem 3.1.2. — ([Gee11] theorem 5.1.5) *Let $F = F^+E$ be a CM field where F^+ is totally real and E is imaginary quadratic. Let $d > 1$ and $l > d$ be a prime which is unramified in F^+ and split in E . Suppose that*

$$\bar{\rho} : G_F \longrightarrow \text{GL}_n(\overline{\mathbb{F}}_l)$$

is an irreducible representation which is unramified at all places of F lying above primes which do not split in E and which satisfies the following properties.

- $\bar{\rho}$ is automorphic of weight \underline{a} , where we assume that for all $\tau \in (\mathbb{Z}^d)^{\text{hom}(F, \mathbb{C})}$ we have either

$$l - 1 - d \geq a_{\tau, 1} \geq \cdots \geq a_{\tau, d} \geq 0,$$

or

$$l - 1 - d \geq a_{c\tau, 1} \geq \cdots \geq a_{c\tau, d} \geq 0.$$

Note in particular that these conditions imply $\bar{\rho}^c \cong \bar{\rho}^\vee \epsilon^{1-d}$.

- $\overline{F}^{\ker \text{ad } \bar{\rho}}$ does not contain $F(\zeta_l)$.
- $\bar{\rho}(G_{F^+(\zeta_l)})$ is big.

Let u be a finite place of F^+ which split in F and not dividing l . Choose an inertial type τ_v and a place v of F above u . Assume that $\bar{\rho}|_{G_{F_v}}$ has a lift to characteristic zero of type τ_v .

Then there is an automorphic representation π of $\text{GL}_n(\mathbb{A}_F)$ of weight \underline{a} and level prime to l such that

- $\bar{r}_{l, u}(\pi) \cong \bar{\rho}$.
- $r_{l, u}(\pi)|_{G_{F_v}}$ has type τ_v .
- π is unramified at all places $w \neq v$ of F at which $\bar{\rho}$ is unramified.

Remark. In this text we focus only on the trivial coefficients $\overline{\mathbb{Z}}_l$, i.e. to the case $a_{\tau, 1} = \cdots = a_{\tau, d} = a_{c\tau, 1} = \cdots = a_{c\tau, d} = 0$, but we could also deal with others weights as in the previous theorem.

3.2. Local and global monodromy. — The previous filtrations on $\Psi_{K,\varrho}$ are compatible with the action of the monodromy operator N_v at v . More precisely, over $\overline{\mathbb{Q}}_l$, for $i \geq 2$, we have isomorphisms

$$N_v : \mathrm{gr}^{-i}(\mathrm{gr}_!^{k+1}(\Psi_{K,\varrho})) \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l \longrightarrow \mathrm{gr}^{-i}(\mathrm{gr}_!^k(\Psi_{K,\varrho}(1))) \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l.$$

As explained in the introduction, we seek for a geometric definition of N_v . In the semi-stable case, i.e. when the level K is such that K_v is the Iwahori subgroup Iw_v of upper triangular matrices modulo q_v , following Rapoport-Zink we obtained a geometric nilpotent monodromy operator $N_v^{geo} : \Psi_{K^v \mathrm{Iw}_v, v} \longrightarrow \Psi_{K^v \mathrm{Iw}_v, v}(1)$ over $\overline{\mathbb{Z}}_l$ whose tensor product with $\overline{\mathbb{Q}}_l$ coincides with the usual arithmetic nilpotent monodromy operator and such that, cf. [Ill94] 3.6.13, its modulo l reduction \overline{N}_v^{geo} share the same order of nilpotency with N_v^{geo} .

We want to obtain a similar definition in infinite level at v . Recall that, concerning our Ihara's lemma statement, we are only interested in automorphic representations Π such that Π_v looks like an irreducible parabolic induction $\mathrm{st}_{s_1}(\chi_{v,1}) \times \cdots \times \mathrm{st}_{s_r}(\chi_{v,r})$ for $\chi_{v,i}$ characters. We then know that these representations appears in the cohomology of $\mathrm{Sh}_{K,\overline{s}_v}$ with coefficient in Ψ_ϱ for ϱ a $\overline{\mathbb{F}}_l$ -character. Recall that for an open compact subgroup K , Ψ_{K,χ_v} is a direct factor of $\Psi_{K,\varrho} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l$. We then consider the pullback

$$\begin{array}{ccc} \Psi_{K,\chi_v,\overline{\mathbb{Z}}_l} & \hookrightarrow & \Psi_{K,\chi_v} \\ \downarrow & & \downarrow \\ \Psi_{K,\varrho} & \hookrightarrow & \Psi_{K,\varrho} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l, \end{array}$$

where the cokernel $\Psi_{K,\varrho}^{\chi_v}$ of $\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l} \hookrightarrow \Psi_{K,\varrho}$, is a free perverse sheaf. From [Boy19], $\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l}$ has, a $\overline{\mathbb{Z}}_l$ -bi-filtration with graded parts $\mathrm{gr}^{-i}(\mathrm{gr}_!^k(\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l}))$ where $1 \leq k \leq i \leq d$ such that⁽⁵⁾

$$\mathrm{gr}^{-i}(\mathrm{gr}_!^k(\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l})) \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{Q}}_l \cong P(i, \chi_v) \left(\frac{1-i+2(k-1)}{2} \right).$$

Note that, up to homothety and because the modulo l reduction of $\mathrm{st}_{k+i}(\chi_v)$ is irreducible for $k+i \leq d < l$, $P(k+i, \chi_v)$ admits a unique stable $\overline{\mathbb{Z}}_l$ -lattice. There exists then a unique $\overline{\mathbb{Z}}_l$ -monodromy operator $N_v(\chi_v)$ acting on $\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l}$ such that

- it coincides with the arithmetic monodromy operator over $\overline{\mathbb{Q}}_l$,
- it is of nilpotency order d modulo l , inducing isomorphisms

$$\mathrm{gr}^{-i}(\mathrm{gr}_!^{k+1}(\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l})) \longrightarrow \mathrm{gr}^{-i}(\mathrm{gr}_!^k(\Psi_{K,\chi_v,\overline{\mathbb{Z}}_l}(1))).$$

⁽⁵⁾Recall that, as $q_v \equiv 1 \pmod l$ with $l > d$, then there exists no cuspidal representation whose modulo l reduction has a supercuspidal support made of character except than characters.

Consider now the pushout $\tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l}$

$$\begin{array}{ccc} \Psi_{K,\varrho} & \dashrightarrow & \tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l} \\ \downarrow & & \downarrow \\ \Psi_{K,\varrho} \otimes_{\bar{\mathbb{Z}}_l} & \twoheadrightarrow & \Psi_{K,\chi_v} \end{array}$$

As explained in the introduction of [Boy23b], both $\Psi_{K,\chi_v,\bar{\mathbb{Z}}_l}$ and $\tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l}$ are constructed from the locally constant sheaf $j^{=1,*}\Psi_{K,\chi_v,\bar{\mathbb{Z}}_l}$ (resp. $j^{=1,*}\tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l}$) using the adjunction morphism $j_l^{=h}j^{=h,*}$ without any saturation process⁽⁶⁾ Then as these two local systems are $\bar{\mathbb{Z}}_l$ -lattices of the $F_v^\times \times F_v^\times \times W_v$ -representation, $\chi_v \otimes \chi_v \otimes \chi_v$, they are obviously isomorphic. We then deduce that $\Psi_{K,\chi_v,\bar{\mathbb{Z}}_l}$ and $\tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l}$ are isomorphic. Consider then the following nilpotent monodromy operator

$$N_{v,\chi_v} : \tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l} \xrightarrow{\sim} \Psi_{K,\chi_v,\bar{\mathbb{Z}}_l} \xrightarrow{N_v(\chi_v)} \Psi_{K,\chi_v,\bar{\mathbb{Z}}_l}.$$

Consider then the compositum N_v^{geo}

$$\begin{array}{ccc} \Psi_{K,\varrho} & \longrightarrow & \bigoplus_{\chi_v \in \text{Cusp}(\varrho)} \tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l} \\ & & \downarrow \bigoplus_{\chi_v} N_{v,\chi_v} \\ & & \bigoplus_{\chi_v \in \text{Cusp}(\varrho)} \Psi_{K,\chi_v,\bar{\mathbb{Z}}_l} \longrightarrow \Psi_{K,\varrho}, \end{array}$$

where $\text{Cusp}(\varrho)$ is the set of character whose modulo l reduction is isomorphic to ϱ . Note that the two horizontal maps are monomorphism which becomes isomorphisms after tensoring with $\bar{\mathbb{Q}}_l$ and $N_v^{geo} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{Q}}_l$ coincides with the usual arithmetic nilpotent monodromy operator.

Lemma 3.2.1. — *The order of nilpotency of $N_v^{geo} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{F}}_l$ is d .*

Proof. — Over $\bar{\mathbb{Z}}_l$, for any $\chi_v \in \text{Cusp}(\varrho)$ we have

$$\Psi_{K,\varrho} \twoheadrightarrow \tilde{\Psi}_{K,\chi_v,\bar{\mathbb{Z}}_l} \xrightarrow{N_{v,\chi_v}^d} \Psi_{K,\chi_v,\bar{\mathbb{Z}}_l} \hookrightarrow \Psi_{K,\varrho}.$$

The results then follows from the fact that all the above maps are strict, i.e. their cokernels are torsion free. \square

Consider a maximal ideal \mathfrak{m} of $\mathbb{T}^S(K^v(\infty))$ given by the level raising statement of theorem 3.1.2 and such that $H^{d-1}(\text{Sh}_{K^v \text{Iw}_v, \bar{\eta}}, \bar{\mathbb{Z}}_l)_{\mathfrak{m}}$ is torsion free and non zero. In

⁽⁶⁾In our case of a character, the proof is quite simple as we do not have to bother about the p -intermediate extensions, cf. lemma 2.1.6 of loc. cit., which is the main point to deal with in [Boy23b].

[**Boy14**] over $\overline{\mathbb{Q}_l}$, we proved that the filtration $\text{Fil}_!^\bullet(\Psi_{K,v})$ coincides with the kernel filtration of monodromy on $\Psi_{K,v}$. The spectral sequence

$$E_{1,!,\mathfrak{m}}^{i,j} := H^{i+j}(\text{Sh}_{K,\bar{s}_v}, \text{gr}_!^{-i}(\Psi_{K,v}))_{\mathfrak{m}} \Rightarrow H^{i+j}(\text{Sh}_{K,\bar{s}_v}, \Psi_{K,v})_{\mathfrak{m}}$$

is concentrated in $i + j = 0$ and so degenerates in E_1 . We denote by $N_{\mathfrak{m},\varrho}^{\text{coho}}$ the monodromy operator associated to N_v^{geo} on $H^*(\text{Sh}_{K^v(\infty),\bar{s}_v}, \Psi_{K^v(\infty),\varrho})_{\mathfrak{m}}$ as well as $\overline{N}_{\mathfrak{m},\varrho}^{\text{coho}}$ for its modulo l version.

Main observation: let ϱ be a character which is a subquotient of $\bar{\rho}_{\mathfrak{m},v}$, and consider $\tilde{\mathfrak{m}} \subseteq \mathfrak{m}$ such that, thanks to theorem 3.1.2:

- $(\Pi_{\tilde{\mathfrak{m}}}^\infty)^{K^v} \neq 0$ so that it appears in $H^{d-1}(\text{Sh}_{K^v \text{Iw}_v, \bar{\eta}}, \overline{\mathbb{Z}_l})_{\mathfrak{m}}$,
- $\Pi_{\tilde{\mathfrak{m}},v} \cong \text{st}_{l_\varrho(\mathfrak{m})}(\chi_v) \times \tau_v$, where $\chi_v \in \text{Cusp}(\varrho)$ and the supercuspidal support of the modulo l reduction of τ_v does not hold ϱ .

Recall that from theorem 2.4.3, the filtration of $\Psi_{K,\varrho}$ gives us a filtration of $H^{d-1}(\text{Sh}_{K^v(\infty),\bar{\eta}}, \overline{\mathbb{Z}_l})_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}_l}} \overline{\mathbb{F}_l}$ where the graded parts are the $H^0(\text{Sh}_{K^v(\infty),\bar{s}_v}, \text{gr}^{-i}(\text{gr}_!^k(\Psi_{K,\varrho})))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}_l}} \overline{\mathbb{F}_l}$. From the definition of N_v^{geo} , we then observe that the image of $(\overline{N}_v^{\text{coho}})^{l_\varrho(\mathfrak{m})-1}$

- is, by the previous lemma, non zero
- and its irreducible $\overline{\mathbb{F}_l}[\text{GL}_d(F_v)]$ -irreducible subquotients are, up to multiplicities, also subquotients of $H^0(\text{Sh}_{K^v(\infty),v}, P(\chi_v, l_\varrho(\mathfrak{m}))^{(\frac{l_\varrho(\mathfrak{m})-1}{2}))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}_l}} \overline{\mathbb{F}_l}$, for any $\chi_v \in \text{Cusp}(\varrho)$ as this modulo l reduction does not depend on the choice of such a lift of ϱ .

3.3. Typicity and monodromy. — As explained in [**HT01**], the $\overline{\mathbb{Q}_l}$ -cohomology of $\text{Sh}_{K,\bar{\eta}}$ can be written as

$$H^{d-1}(\text{Sh}_{K,\bar{\eta}}, \overline{\mathbb{Q}_l})_{\mathfrak{m}} \cong \bigoplus_{\pi \in \mathcal{A}_{\xi,K}(\mathfrak{m})} (\pi^\infty)^K \otimes V(\pi^\infty),$$

where

- $\mathcal{A}_K(\mathfrak{m})$ is the set of equivalence classes of automorphic representations of $G(\mathbb{A})$ with non trivial K -invariants and such that its modulo l Satake's parameters outside S are prescribed by \mathfrak{m} ,
- and $V(\pi^\infty)$ is a representation of $\text{Gal}_{F,S}$.

As $\bar{\rho}_{\mathfrak{m}}$ is supposed to be absolutely irreducible, then as explained in chapter VI of [**HT01**], if $V(\pi^\infty)$ is non zero, then π is a weak transfer of a cohomological automorphic representation (Π, ψ) of $\text{GL}_d(\mathbb{A}_F) \times \mathbb{A}_F^\times$ with $\Pi^\vee \cong \Pi^c$ where c is the complex conjugation. Attached to such a Π is a global Galois representation $\rho_{\Pi,l} : \text{Gal}_{F,S} \rightarrow \text{GL}_d(\overline{\mathbb{Q}_l})$ which is irreducible.

Theorem 3.3.1. — (cf. [NF19] theorem 2.20)

If $\rho_{\Pi,l}$ is strongly irreducible, meaning it remains irreducible when it is restricted to any finite index subgroup, then $V(\pi^\infty)$ is a semi-simple representation of $\text{Gal}_{F,S}$.

Remark. The Tate conjecture predicts that $V(\pi^\infty)$ is always semi-simple.

Definition 3.3.2. — (cf. [Sch18] §5) We say that \mathfrak{m} is KHT-typic for K if, as a $\mathbb{T}(K)_{\mathfrak{m}}[\text{Gal}_{F,S}]$ -module,

$$H^{d-1}(\text{Sh}_{K,\bar{\eta}}, \bar{\mathbb{Z}}_l)_{\mathfrak{m}} \cong \sigma_{\mathfrak{m},K} \otimes_{\mathbb{T}(K)_{\mathfrak{m}}} \rho_{\mathfrak{m},K},$$

for some $\mathbb{T}(K)_{\mathfrak{m}}$ -module $\sigma_{\mathfrak{m},K}$ on which $\text{Gal}_{F,S}$ acts trivially and

$$\rho_{\mathfrak{m},K} : \text{Gal}_{F,S} \longrightarrow \text{GL}_d(\mathbb{T}(K)_{\mathfrak{m}})$$

is the stable lattice of $\bigoplus_{\tilde{\mathfrak{m}} \subseteq \mathfrak{m}} \rho_{\tilde{\mathfrak{m}}}$ introduced in the introduction.

Proposition 3.3.3. — We suppose that for all $\pi \in \mathcal{A}_K(\mathfrak{m})$, the Galois representation $V(\pi^\infty)$ is semi-simple. Then \mathfrak{m} is KHT-typic for K .

Proof. — By proposition 5.4 of [Sch18] it suffices to deal with $\bar{\mathbb{Q}}_l$ -coefficients. From [HT01] proposition VII.1.8 and the semi-simplicity hypothesis, then $V(\pi^\infty) \cong \tilde{R}(\pi)^{\oplus n(\pi)}$ where $\tilde{R}(\pi)$ is of dimension d . We then write

$$(\pi^\infty)^K \otimes_{\bar{\mathbb{Q}}_l} R(\pi) \cong (\pi^\infty)^K \otimes_{\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l}} (\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l})^d,$$

and $(\pi^\infty)^K \otimes_{\bar{\mathbb{Q}}_l} V(\pi^\infty) \cong ((\pi^\infty)^K)^{\oplus n(\pi)} \otimes_{\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l}} (\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l})^d$ and finally

$$H^{d-1}(\text{Sh}_{K,\bar{\eta}}, \bar{\mathbb{Q}}_l)_{\mathfrak{m}} \cong \sigma_{\mathfrak{m},K,\bar{\mathbb{Q}}_l} \otimes_{\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l}} (\mathbb{T}(K)_{\mathfrak{m},\bar{\mathbb{Q}}_l})^d,$$

with $\sigma_{\mathfrak{m},K,\bar{\mathbb{Q}}_l} \cong \bigoplus_{\pi \in \mathcal{A}_K(\mathfrak{m})} ((\pi^\infty)^I)^{\oplus n(\pi)}$. The result then follows from [HT01] theorem VII.1.9 which insures that $R(\pi) \cong \rho_{\tilde{\mathfrak{m}}}$, if $\tilde{\mathfrak{m}}$ is the prime ideal associated to π , \square

Let ϱ be a $\bar{\mathbb{F}}_l$ -character with $l_\varrho(\mathfrak{m}) > 0$. Then $H^0(\text{Sh}_{K,\bar{\eta}_v}, \Psi_{K,\varrho})_{\mathfrak{m}}$ as a direct factor of $H^{d-1}(\text{Sh}_{K,\bar{\eta}}, \bar{\mathbb{Q}}_l)_{\mathfrak{m}}$, is also typic, i.e.

$$H^0(\text{Sh}_{K,\bar{\eta}_v}, \Psi_{K,\varrho})_{\mathfrak{m}} \cong \sigma_{\mathfrak{m},K,\varrho} \otimes_{\mathbb{T}(K)_{\mathfrak{m}}} \rho_{\mathfrak{m},K,\varrho}.$$

The monodromy operator $N_{\mathfrak{m},\varrho}^{\text{cho}}$ acting on $H^0(\text{Sh}_{K,\bar{\eta}_v}, \Psi_{K,\varrho})_{\mathfrak{m}}$ is such that

$$N_{\mathfrak{m},\varrho}^{\text{cho}} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{Q}}_l \cong \text{Id} \otimes N_{\mathfrak{m},\varrho,\bar{\mathbb{Q}}_l},$$

i.e. it acts trivially on the first factor $\sigma_{\mathfrak{m},K,\varrho}$. We then deduce that $N_{\mathfrak{m},\varrho}^{\text{cho}}$ induces a nilpotent operator $N_{\mathfrak{m},\varrho}$ (resp. $\bar{N}_{\mathfrak{m},\varrho}$) on $\rho_{\mathfrak{m}}$ (resp. $\rho_{\mathfrak{m}} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{F}}_l$).

Remark. For a K^v and \mathfrak{m} such that the irreducible constituent of $\bar{\rho}_{\mathfrak{m},v}$ are characters, we notice that $\rho_{\mathfrak{m},K}$ does not depend on the level K_v and we then denote it simply by $\rho_{\mathfrak{m}}$.

Proposition 3.3.4. — Let τ_v be an irreducible $\bar{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module which is a quotient of $\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\bar{\mathbb{Z}}_l} \bar{\mathbb{F}}_l$. Then τ_v is generic.

Proof. — Recall that τ_v can be written as a full parabolic induced representation

$$\bigtimes_{\varrho \in \text{Cusp}_{\overline{\mathbb{F}}_l}(1,v)} \tau_{\varrho}$$

where the (super)cuspidal support of τ_{ϱ} is a multiple of ϱ . We want to prove that τ_{ϱ} is generic which, as $q_v \equiv 1 \pmod l$ with $l > d$, means that $\tau_{\varrho} \cong \text{st}_{l_{\varrho}(\mathfrak{m})}(\varrho)$.

Recall that $R := \mathbb{T}(K^v(\infty))_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$ has a unique maximal ideal \mathfrak{N} which is topologically nilpotent. We then consider the image of $(N_{\mathfrak{m},\varrho}^{\text{coho}})^{l_{\varrho}(\mathfrak{m})-1} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l = \text{Id} \otimes \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}$

$$(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) \otimes_{R/\mathfrak{N}} (\rho_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) \xrightarrow{\text{Id} \otimes \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}} (\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) \otimes_{R/\mathfrak{N}} \text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}.$$

From theorem 3.1.2, we know there exists $\tilde{\mathfrak{m}} \subseteq \mathfrak{m}$ such that $\Pi_{\tilde{\mathfrak{m}},v} \cong \text{st}_{l_{\varrho}(\mathfrak{m})}(\chi_v) \times \tau_v$ where χ_v is isomorphic to ϱ modulo l , and the cuspidal support of τ_v modulo l does not contain ϱ . From the main observation at the end of §3.2, we then deduce that $\text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}$ is non zero.

Let denote by $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l)$, the cosocle of $\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$, i.e. its largest semi-simple quotient as a $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module. Note that this cosocle is a R -module and we first consider

$$\text{Top}_1(\sigma_{\mathfrak{m},K^v(\infty)}) := \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) \otimes_R R/\mathfrak{N},$$

which is obviously a quotient of $(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l)/\mathfrak{N}$, and

$$\text{Top}_1(\sigma_{\mathfrak{m},K^v(\infty)}) \otimes_{R/\mathfrak{N}} \text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}/\mathfrak{N}$$

is a quotient of $(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) \otimes_R \text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1}$. Write

$$\text{Top}_1(\sigma_{\mathfrak{m},K^v(\infty)}) \cong \bigoplus_{i=1}^r \overline{\pi}_{v,i}$$

as a $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ semi-simple module so that

$$\text{Top}_1(\sigma_{\mathfrak{m},K^v(\infty)}) \otimes_{\overline{\mathbb{F}}_l} (\text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1} \otimes_R \overline{\mathbb{F}}_l) \cong \bigoplus_{i=1}^r (\overline{\pi}_{v,i} \otimes_{\overline{\mathbb{F}}_l} (\text{Im } \overline{N}_{\mathfrak{m},\varrho}^{l_{\varrho}(\mathfrak{m})-1} \otimes_R \overline{\mathbb{F}}_l))$$

is a quotient of the image of $(N_{\mathfrak{m},\varrho}^{\text{coho}})^{l_{\varrho}(\mathfrak{m})-1} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$ on $H^0(\text{Sh}_{K^v(\infty),\tilde{s}_v}, \Psi_{K^v(\infty),\varrho})_{\mathfrak{m}} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l$. But we saw that this image, up to semi-simplification and multiplicities, is contained in

$$H^0(\text{Sh}_{K^v(\infty),\tilde{s}_v}, P(\varrho, l_{\varrho}(\mathfrak{m})))_{\mathfrak{m}} \cong (\bigoplus_i \overline{\phi}_{v,i}) \otimes \varrho,$$

where each $\overline{\phi}_{v,i}$ are of the following shape $\text{st}_{l_{\varrho}(\mathfrak{m})}(\varrho) \times \overline{\phi}_{v,i}^{\varrho}$ where ϱ does not belong to the (super)cuspidal support of $\overline{\phi}_{v,i}^{\varrho}$. We then deduce that the ϱ -part of any of

the irreducible constituents $\tau_v \cong \bigtimes_{\varrho \in \text{Cusp}(1,v)} \tau_\varrho$ of $\text{Top}_1(\sigma_{\mathfrak{m},K^v(\infty)})$ are such that τ_ϱ is generic. As it is true for all $\varrho \in \text{Cusp}(1,v)$, then τ_v is generic.

We now want to prove, by induction on δ , that $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^{\delta-1}$ is generic as a $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module, meaning that all its irreducible sub-quotients are generic. We just proved that the statement is true for $\delta = 1$. Consider

$$\begin{aligned} 0 \rightarrow \mathfrak{N}^{\delta-1} \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta &\longrightarrow \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta \\ &\longrightarrow \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^{\delta-1} \rightarrow 0. \end{aligned}$$

As $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l)$ is semi-simple as a $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module, let M_δ , which is no more a R -module, such that

$$\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta = \mathfrak{N}^{\delta-1} \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta \oplus M_\delta.$$

Consider then any $r \in \mathfrak{N}^{\delta-1}$: then multiplication by r in $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta$ induces a map

$$M_\delta \xrightarrow{\times r} \mathfrak{N}^{\delta-1} \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta,$$

with image $M_\delta(r)$ which, as a $\overline{\mathbb{F}}_l[\text{GL}_d(F_v)]$ -module is generic because M_δ is, by our induction hypothesis. Now as $\mathfrak{N}^{\delta-1} \text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta$ is generated by the $M_\delta(r)$ for r varying inside $\mathfrak{N}^{\delta-1}$, we then deduce that it is generic and $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta$ also.

Finally we conclude using the fact that, as \mathfrak{N} is topologically nilpotent, every quotient of $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l)$ has to be a quotient of some $\text{Top}(\sigma_{\mathfrak{m},K^v(\infty)} \otimes_{\overline{\mathbb{Z}}_l} \overline{\mathbb{F}}_l) / \mathfrak{N}^\delta$.

□

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