

# On the Eisenstein ideal for imaginary quadratic fields

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## ABSTRACT

For certain algebraic Hecke characters  $\chi$  of an imaginary quadratic field  $F$  we define an Eisenstein ideal in a  $p$ -adic Hecke algebra acting on cuspidal automorphic forms of  $\mathrm{GL}_{2/F}$ . By finding congruences between Eisenstein cohomology classes (in the sense of G. Harder) and cuspidal classes we prove a lower bound for the index of the Eisenstein ideal in the Hecke algebra in terms of the special  $L$ -value  $L(0, \chi)$ . We further prove that its index is bounded from above by the  $p$ -valuation of the order of the Selmer group of the  $p$ -adic Galois character associated to  $\chi^{-1}$ . This uses the work of R. Taylor *et al.* on attaching Galois representations to cuspforms of  $\mathrm{GL}_{2/F}$ . Together these results imply a lower bound for the size of the Selmer group in terms of  $L(0, \chi)$ , coinciding with the value given by the Bloch-Kato conjecture.

## Introduction

The aim of this work is to demonstrate the use of Eisenstein cohomology, as developed by Harder, in constructing elements of Selmer groups for Hecke characters of an imaginary quadratic field  $F$ . The strategy of first finding congruences between Eisenstein series and cuspforms and then using the Galois representations attached to the cuspforms to prove lower bounds on the size of Selmer groups goes back to Ribet [Rib76], and has been applied and generalized in [Wil90] in his proof of the Iwasawa main conjecture for characters over totally real fields, and more recently by [SU02] and [BC04] amongst others. These all used for the congruences integral structures coming from algebraic geometry. In our case the symmetric space associated to  $\mathrm{GL}_{2/F}$  is not hermitian and we therefore use the integral structure arising from Betti cohomology. This alternative, more general approach was outlined for  $\mathrm{GL}_{2/\mathbf{Q}}$  in [HP92].

In [Har87] G. Harder constructed Eisenstein cohomology as a complement to the cuspidal cohomology for the groups  $\mathrm{GL}_2$  over number fields and proved that this decomposition respects the rational structure of group cohomology. The case interesting for congruences is when this decomposition is not integral, i.e., when there exists an Eisenstein class with integral restriction to the boundary that has a denominator. In [Ber08] such classes were constructed for imaginary quadratic fields and their denominator was bounded from below by the special  $L$ -value of a Hecke character. In §3 we give a general set-up in which cohomological congruences between Eisenstein and cuspidal classes can be proven (Proposition 9) and then apply this to the classes constructed in [Ber08]. The result can be expressed as a lower bound for the index of the Eisenstein ideal of the title in a Hecke algebra in terms of the special  $L$ -value. The main obstacle to obtaining a congruence from the results in [Ber08] is the occurrence of torsion in higher degree cohomology, which is not very well understood (see the discussion in §3.4). However, we manage to solve this “torsion problem” for unramified characters in §4.

The other main ingredient are the Galois representations associated to cohomological cuspidal

automorphic forms, constructed by R. Taylor *et al.* by means of a lifting to the symplectic group in [Tay94]. Assuming the existence of congruences between an Eisenstein series and cuspforms we use these representations in §2 to construct elements in the Selmer group of a Galois character. In fact, we prove that its size is bounded from below by the index of the Eisenstein ideal.

These two results are combined in §5 to prove a lower bound on the size of Selmer groups of Hecke characters of an imaginary quadratic field in terms of a special  $L$ -value, coinciding with the value given by the Bloch-Kato conjecture.

To give a more precise account, let  $p > 3$  be a prime unramified in the extension  $F/\mathbf{Q}$  and let  $\mathfrak{p}$  be a prime of  $F$  dividing  $(p)$ . Fix embeddings  $\overline{F} \hookrightarrow \overline{F}_{\mathfrak{p}} \hookrightarrow \mathbf{C}$ . Let  $\phi_1, \phi_2 : F^* \backslash \mathbf{A}_F^* \rightarrow \mathbf{C}^*$  be two Hecke characters of infinity type  $z$  and  $z^{-1}$ , respectively, with conductors coprime to  $(p)$ . Let  $\mathcal{R}$  be the ring of integers in a sufficiently large finite extension of  $F_{\mathfrak{p}}$ . Let  $\mathbf{T}$  be the  $\mathcal{R}$ -algebra generated by Hecke operators acting on cuspidal automorphic forms of  $\mathrm{GL}_{2/F}$ . For  $\phi = (\phi_1, \phi_2)$  we define in §2 an Eisenstein ideal  $\mathbf{I}_{\phi}$  in  $\mathbf{T}$ . Following previous work of Wiles and Urban we construct elements in the Selmer group of  $\chi_{\mathfrak{p}}\epsilon$ , where  $\chi_{\mathfrak{p}}$  is the  $p$ -adic Galois characters associated to  $\chi := \phi_1/\phi_2$  and  $\epsilon$  is the  $p$ -adic cyclotomic character. We obtain a lower bound on the size of the Selmer group in terms of that of the congruence module  $\mathbf{T}/\mathbf{I}_{\phi}$ . A complication that arises in the application of Taylor's theorem is that we need to work with cuspforms with cyclotomic central character. This is achieved by a twisting argument (see Lemma 8).

To prove the lower bound on the congruence module in terms of the special  $L$ -value (the first step described above), we use the Eisenstein cohomology class  $\mathrm{Eis}(\phi)$  constructed in [Ber08] in the cohomology of a symmetric space  $S$  associated to  $\mathrm{GL}_{2/F}$ . The class is an eigenvector for the Hecke operators at almost all places with eigenvalues corresponding to the generators of  $\mathbf{I}_{\phi}$ , and its restriction to the boundary of the Borel-Serre compactification of  $S$  is integral. The main result of [Ber08], which we recall in §5, is that the denominator  $\delta$  of  $\mathrm{Eis}(\phi) \in H^1(S, \overline{F}_{\mathfrak{p}})$  is bounded from below by  $L^{\mathrm{alg}}(0, \chi)$ . As mentioned above, Proposition 9 gives a general setup for cohomological congruences. It implies the existence of a cuspidal cohomology class congruent to  $\delta \cdot \mathrm{Eis}(\phi)$  modulo the  $L$ -value supposing that there exists an integral cohomology class with the same restriction to the boundary as  $\mathrm{Eis}(\phi)$ . The latter can be replaced by the assumption that  $H_c^2(S, \mathcal{R})_{\mathrm{torsion}} = 0$ , and this result is given in Theorem 13. In §4 we prove that the original hypothesis is satisfied for unramified  $\chi$ , avoiding the issue of torsion freeness. We achieve this by a careful analysis of the restriction map to the boundary  $\partial\overline{S}$  of the Borel-Serre compactification. Starting with a group cohomological result for  $\mathrm{SL}_2(\mathcal{O})$  due to Serre [Ser70] (which we extend to all maximal arithmetic subgroups of  $\mathrm{SL}_2(F)$ ) we define an involution on  $H^1(\partial\overline{S}, \mathcal{R})$  such that the restriction map

$$H^1(S, \mathcal{R}) \xrightarrow{\mathrm{res}} H^1(\partial\overline{S}, \mathcal{R})^-,$$

surjects onto the  $-1$ -eigenspace. We apply the resulting criterion to  $\mathrm{res}(\mathrm{Eis}(\phi))$  to deduce the existence of a lift to  $H^1(S, \mathcal{R})$ .

Note that the restriction to constant coefficient systems and therefore weight 2 automorphic forms is important only for §4. It was applied throughout to simplify the exposition. In particular, the results of Theorems 10 and 13 extend (for split  $p$ ) to characters  $\chi$  with infinity type  $z^{m+2}\overline{z}^{-m}$  for  $m \in \mathbf{N}_{\geq 0}$ . See [Ber08] for the necessary modifications and results.

Combining the two steps we obtain in §5 a lower bound for the size of the Selmer group of  $\chi_{\mathfrak{p}}\epsilon$  in terms of  $L^{\mathrm{alg}}(0, \chi)$  and relate this result to the Bloch-Kato conjecture. This conjecture has been proven in our case (at least for class number 1) starting from the Main Conjecture of Iwasawa theory for imaginary quadratic fields (see [Han97], [Guo93]). Similar results have also been obtained by Hida in [Hid82] for split primes  $p$  and  $\overline{\chi} = \chi^c$  using congruences of classical elliptic modular forms between CM and non-CM forms. We seem to recover base changes of his congruences in this case (but see §3.6 for a discussion when our congruences do not arise from base change).

However, our method of constructing elements in Selmer groups using cohomological congruences is very different and should be more widely applicable. The analytic theory of Eisenstein cohomology has been developed for many groups, and rationality results are known, e.g. for  $GL_n$  by the work of [FS98]. Our hope is that the method presented here generalizes to these higher rank groups.

To conclude, we want to mention two related results. In [Fel00] congruences involving degree 2 Eisenstein cohomology classes for imaginary quadratic fields were constructed but only the  $L$ -value of the quadratic character associated to  $F/\mathbf{Q}$  was considered. The torsion problem we encounter does not occur for degree 2, but the treatment of the denominator of the Eisenstein classes is more difficult. For cases of the Bloch-Kato conjecture when the Selmer groups are infinite see [BC04]. Their method is similar to ours in that they use congruences between Eisenstein series and cuspforms, however, they work with  $p$ -adic families on  $U(3)$  and do not use Eisenstein cohomology.

## 1. Notation and Definitions

### 1.1 General notation

Let  $F/\mathbf{Q}$  be an imaginary quadratic extension and  $d_F$  its absolute discriminant. Denote the class-group by  $Cl(F)$  and the ray class group modulo a fractional ideal  $\mathfrak{m}$  by  $Cl_{\mathfrak{m}}(F)$ . For a place  $v$  of  $F$  let  $F_v$  be the completion of  $F$  at  $v$ . We write  $\mathcal{O}$  for the ring of integers of  $F$ ,  $\mathcal{O}_v$  for the closure of  $\mathcal{O}$  in  $F_v$ ,  $\mathfrak{P}_v$  for the maximal ideal of  $\mathcal{O}_v$ ,  $\pi_v$  for a uniformizer of  $F_v$ , and  $\hat{\mathcal{O}}$  for  $\prod_{v \text{ finite}} \mathcal{O}_v$ . We use the notations  $\mathbf{A}, \mathbf{A}_f$  and  $\mathbf{A}_F, \mathbf{A}_{F,f}$  for the adèles and finite adèles of  $\mathbf{Q}$  and  $F$ , respectively, and write  $\mathbf{A}^*$  and  $\mathbf{A}_F^*$  for the respective group of ideles. We often identify elements  $a_v$  of  $F_v^*$  for any place  $v$  with their image in  $\mathbf{A}_F^*$  under the canonical injective homomorphism  $a_v \mapsto (1, \dots, 1, a_v, 1, \dots, 1)$ . Let  $p > 3$  be a prime of  $\mathbf{Z}$  that does not ramify in  $F$ , and let  $\mathfrak{p} \subset \mathcal{O}$  be a prime dividing  $(p)$ . Let  $\Sigma_p$  be the set of places of  $F$  above  $p$ .

Denote by  $G_F$  the absolute Galois group of  $F$ . For  $\Sigma$  a finite set of places of  $F$  let  $G_{\Sigma}$  be the Galois group of the maximal extension of  $F$  unramified at all places not in  $\Sigma$ . We fix an embedding  $\bar{F} \hookrightarrow \bar{F}_v$  for each place  $v$  of  $F$ . Denote the corresponding decomposition and inertia groups by  $G_v$  and  $I_v$ , respectively. Let  $g_v = G_v/I_v$  be the Galois group of the maximal unramified extension of  $F_v$ . For each finite place  $v$  we also fix an embedding  $\bar{F}_v \hookrightarrow \mathbf{C}$  that is compatible with the fixed embeddings  $i_v : \bar{F} \hookrightarrow \bar{F}_v$  and  $i_{\infty} : \bar{F} \hookrightarrow \mathbf{C} (= \bar{F}_{\infty})$ . For a topological  $G_F$ -module (resp.  $G_v$ -module)  $M$  write  $H^1(F, M)$  for the continuous Galois cohomology group  $H^1(G_F, M)$ , and  $H^1(F_v, M)$  for  $H^1(G_v, M)$ .

### 1.2 Hecke characters

A Hecke character of  $F$  is a continuous group homomorphism  $\lambda : F^* \backslash \mathbf{A}_F^* \rightarrow \mathbf{C}^*$ . Such a character corresponds uniquely to a character on ideals prime to the conductor, which we also denote by  $\lambda$ . Define the character  $\lambda^c$  by  $\lambda^c(x) = \lambda(\bar{x})$ .

LEMMA 1 (Lemma 3.16 of [Ber05]). *If  $\lambda$  is an unramified Hecke character then  $\lambda^c = \bar{\lambda}$ .* □

For Hecke characters  $\lambda$  of type  $(A_0)$ , i.e., with infinity type  $\lambda_{\infty}(z) = z^m \bar{z}^n$  with  $m, n \in \mathbf{Z}$  we define (following Weil) a  $p$ -adic Galois character

$$\lambda_{\mathfrak{p}} : G_F \rightarrow \bar{F}_{\mathfrak{p}}^*$$

associated to  $\lambda$  by the following rule: For a finite place  $v$  not dividing  $p$  or the conductor of  $\lambda$ , put  $\lambda_{\mathfrak{p}}(\text{Frob}_v) = i_{\mathfrak{p}}(i_{\infty}^{-1}(\lambda(\pi_v)))$  where  $\text{Frob}_v$  is the *arithmetic* Frobenius at  $v$ . It takes values in the integer ring of a finite extension of  $F_{\mathfrak{p}}$ .

Let  $\epsilon : G_F \rightarrow \mathbf{Z}_p^*$  be the  $p$ -adic cyclotomic character defined by the action of  $G_F$  on the  $p$ -power roots of unity:  $g \cdot \xi = \xi^{\epsilon(g)}$  for  $\xi$  with  $\xi^{p^m} = 1$  for some  $m$ . Our convention is that the Hodge-Tate

weight of  $\epsilon$  at  $\mathfrak{p}$  is 1 and we use the arithmetic Frobenius normalization for the Artin reciprocity map  $\text{rec}$  which implies that  $\epsilon(\text{rec}(u)) = \text{Nm}_{\mathcal{O}_{\mathfrak{p}}/\mathbf{Z}_p}(u)^{-1}$  for  $u \in \mathcal{O}_{\mathfrak{p}}^*$ .

Let  $\lambda$  a Hecke character of infinity type  $z^a (\frac{z}{\bar{z}})^b$  with conductor prime to  $p$ . Write  $L(s, \lambda)$  for the Hecke  $L$ -function of  $\lambda$ . Assume  $a, b \in \mathbf{Z}$  and  $a > 0$  and  $b \geq 0$ . Put

$$L^{\text{alg}}(0, \lambda) := \Omega^{-a-2b} \left( \frac{2\pi}{\sqrt{d_F}} \right)^b \Gamma(a+b) \cdot L(0, \lambda),$$

where  $\Omega$  is a complex period. In most cases, this normalization is integral, i.e., lies in the integer ring of a finite extension of  $F_{\mathfrak{p}}$ . See [Ber08] Theorem 3 for the exact statement. Put

$$L^{\text{int}}(0, \lambda) = \begin{cases} L^{\text{alg}}(0, \lambda) & \text{if } \text{val}_{\mathfrak{p}}(L^{\text{alg}}(0, \lambda)) \geq 0 \\ 1 & \text{otherwise.} \end{cases}$$

### 1.3 Selmer groups

Let  $\rho : G_F \rightarrow \mathcal{R}^*$  be a continuous Galois character taking values in the ring of integers  $\mathcal{R}$  of a finite extension  $L$  of  $F_{\mathfrak{p}}$ . Write  $\mathfrak{m}_{\mathcal{R}}$  for its maximal ideal and put  $\mathcal{R}^{\vee} = L/\mathcal{R}$ . Let  $\mathcal{R}_{\rho}$ ,  $L_{\rho}$ , and  $W_{\rho} = L_{\rho}/\mathcal{R}_{\rho} = \mathcal{R}_{\rho} \otimes_{\mathcal{R}} \mathcal{R}^{\vee}$  be the free rank one modules on which  $G_F$  acts via  $\rho$ .

Following Bloch and Kato [BK90] we define the following Selmer groups: Let

$$H_f^1(F_v, L_{\rho}) = \begin{cases} \ker(H^1(F_v, L_{\rho}) \rightarrow H^1(I_v, L_{\rho})) & \text{for } v \nmid p, \\ \ker(H^1(F_v, L_{\rho}) \rightarrow H^1(F_v, B_{\text{cris}} \otimes L_{\rho})) & \text{for } v \mid p, \end{cases}$$

where  $B_{\text{cris}}$  denotes Fontaine's ring of  $p$ -adic periods. Put

$$H_f^1(F_v, W_{\rho}) = \text{im}(H_f^1(F_v, L_{\rho}) \rightarrow H^1(F_v, W_{\rho})).$$

For a finite set of places  $\Sigma$  of  $F$  define

$$\text{Sel}^{\Sigma}(F, \rho) = \ker \left( H^1(F, W_{\rho}) \rightarrow \prod_{v \notin \Sigma} \frac{H^1(F_v, W_{\rho})}{H_f^1(F_v, W_{\rho})} \right).$$

We write  $\text{Sel}(F, \rho)$  for  $\text{Sel}^{\emptyset}(F, \rho)$ .

If  $p$  splits in  $F/\mathbf{Q}$  and  $\rho = \lambda_{\mathfrak{p}}$  for a Hecke character  $\lambda$  of infinity type  $z^a \bar{z}^b$  with  $a, b \in \mathbf{Z}$  then one can show (see [Hid82] (1.6a)) that

$$\rho(\text{rec}(u_1, u_2)) = u_1^a \bar{u}_2^b \text{ for } (u_1, u_2) \in \mathcal{O}_{\mathfrak{p}}^* \times \mathcal{O}_{\bar{\mathfrak{p}}}^* \text{ with } (u_1, u_2) \equiv (1, 1) \pmod{\mathfrak{f}_{\lambda} \mathcal{O}_{\mathfrak{p}} \times \mathfrak{f}_{\lambda} \mathcal{O}_{\bar{\mathfrak{p}}}}, \quad (1)$$

where  $\mathfrak{f}_{\lambda}$  is the conductor of  $\lambda$ . The character  $\rho$  is therefore ‘‘locally algebraic’’ in the sense of [Ser68], and a Theorem of Tate ([Ser68] III A7, Theorem 3) implies that the local Galois representations  $\rho|_{G_{\mathfrak{p}}}$  and  $\rho|_{G_{\bar{\mathfrak{p}}}}$  are of Hodge-Tate type with weights  $-a$  and  $-b$ , respectively. Following Greenberg we define in this ‘‘ordinary case’’

$$F_{\mathfrak{p}}^+ L_{\rho} = \begin{cases} L_{\rho} & \text{if } a < 0 \text{ (i.e., HT-wt of } \rho > 0), \\ \{0\} & \text{if } a \geq 0 \text{ (i.e., HT-wt of } \rho \leq 0) \end{cases}$$

and

$$F_{\bar{\mathfrak{p}}}^+ L_{\rho} = \begin{cases} L_{\rho} & \text{if } b < 0, \\ \{0\} & \text{if } b \geq 0. \end{cases}$$

In the ordinary case we have  $H_f^1(F_v, L_{\rho}) = \text{im}(H^1(F_v, F_v^+ L_{\rho}) \rightarrow H^1(F_v, L_{\rho}))$  for  $v \mid p$  (see [Guo96] p.361, [Fla90] Lemma 2).

LEMMA 2. *Let  $\rho$  be unramified at  $v \nmid p$ . If  $\rho(\text{Frob}_v) \not\equiv \epsilon(\text{Frob}_v) \pmod{p}$  then*

$$\text{Sel}^{\Sigma}(F, \rho) = \text{Sel}^{\Sigma \setminus \{v\}}(F, \rho).$$

*Proof.* By definition  $\text{Sel}^{\Sigma \setminus \{v\}}(F, \rho) \subset \text{Sel}^{\Sigma}(F, \rho)$  for any  $v$ . For places  $v$  as in the lemma we have

$$H_f^1(F_v, W_\rho) = \ker(H^1(F_v, W_\rho) \rightarrow H^1(I_v, W_\rho)^{g_v}).$$

It is clear that  $H^1(I_v, W_\rho)^{g_v} = \text{Hom}_{g_v}(I_v^{\text{tame}}, W_\rho) = \text{Hom}_{g_v}(I_v^{\text{tame}}, W_\rho[\mathfrak{m}_{\mathcal{R}}^n])$  for some  $n$ . By our assumption therefore  $H^1(I_v, W_\rho)^{g_v} = 0$  since  $\text{Frob}_v$  acts on  $I_v^{\text{tame}}$  by  $\epsilon(\text{Frob}_v)$ .  $\square$

#### 1.4 Cuspidal automorphic representations

We refer to [Urb95] §3.1 as a reference for the following: For  $K_f = \prod_v K_v \subset \text{GL}_2(\mathbf{A}_{F,f})$  a compact open subgroup, denote by  $S_2(K_f)$  the space of cuspidal automorphic forms of  $\text{GL}_2(F)$  of weight 2, right-invariant under  $K_f$ . For  $\omega$  a finite order Hecke character write  $S_2(K_f, \omega)$  for the forms with central character  $\omega$ . This is isomorphic as a  $\text{GL}_2(\mathbf{A}_{F,f})$ -module to  $\bigoplus \pi_f^{K_f}$  for automorphic representations  $\pi$  of a certain infinity type (see Theorem 3 below) with central character  $\omega$ . For  $g \in \text{GL}_2(\mathbf{A}_{F,f})$  we have the Hecke action of  $[K_f g K_f]$  on  $S_2(K_f)$  and  $S_2(K_f, \omega)$ . For places  $v$  with  $K_v = \text{GL}_2(\mathcal{O}_v)$  we define  $T_v = [K_f \begin{pmatrix} \pi_v & 0 \\ 0 & 1 \end{pmatrix} K_f]$ .

#### 1.5 Cohomology of symmetric space

Let  $G = \text{Res}_{F/\mathbf{Q}} \text{GL}_2/F$  and  $B$  the restriction of scalars of the Borel subgroup of upper triangular matrices. For any  $\mathbf{Q}$ -algebra  $R$  we consider a pair of characters  $\phi = (\phi_1, \phi_2)$  of  $R^* \times R^*$  as character of  $B(R)$  by defining  $\phi \left( \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \right) = \phi_1(a)\phi_2(b)$ . Put  $K_\infty = U(2) \cdot \mathbf{C}^* \subset G(\mathbf{R})$ . For an open compact subgroup  $K_f \subset G(\mathbf{A}_f)$  we define the adelic symmetric space

$$S_{K_f} = G(\mathbf{Q}) \backslash G(\mathbf{A}) / K_\infty K_f.$$

Note that  $S_{K_f}$  has several connected components. In fact, strong approximation implies that the fibers of the determinant map

$$S_{K_f} \rightarrow \pi_0(K_f) := \mathbf{A}_{F,f}^* / \det(K_f) F^*$$

are connected. Any  $\gamma \in G(\mathbf{A}_f)$  gives rise to an injection

$$G_\infty \hookrightarrow G(\mathbf{A})$$

$$g_\infty \mapsto (g_\infty, \gamma)$$

and, after taking quotients, to a component  $\Gamma_\gamma \backslash G_\infty / K_\infty \rightarrow S_{K_f}$ , where

$$\Gamma_\gamma := G(\mathbf{Q}) \cap \gamma K_f \gamma^{-1}.$$

This component is the fiber over  $\det(\gamma)$ . Choosing a system of representatives for  $\pi_0(K_f)$  we therefore have

$$S_{K_f} \cong \coprod_{[\det(\gamma)] \in \pi_0(K_f)} \Gamma_\gamma \backslash \mathbf{H}_3,$$

where  $G_\infty / K_\infty$  has been identified with three-dimensional hyperbolic space  $\mathbf{H}_3 = \mathbf{R}_{>0} \times \mathbf{C}$ .

We denote the Borel-Serre compactification of  $S_{K_f}$  by  $\overline{S}_{K_f}$  and write  $\partial \overline{S}_{K_f}$  for its boundary. The Borel-Serre compactification  $\overline{S}_{K_f}$  is given by the union of the compactifications of its connected components. For any arithmetic subgroup  $\Gamma \subset G(\mathbf{Q})$ , the boundary of the Borel-Serre compactification of  $\Gamma \backslash \mathbf{H}_3$ , denoted by  $\partial(\Gamma \backslash \overline{\mathbf{H}}_3)$ , is homotopy equivalent to

$$\coprod_{[\eta] \in \mathbf{P}^1(F)/\Gamma} \Gamma_{B\eta} \backslash \mathbf{H}_3, \quad (2)$$

where we identify  $\mathbf{P}^1(F) = B(\mathbf{Q}) \backslash G(\mathbf{Q})$ , take  $\eta \in G(\mathbf{Q})$ , and put  $\Gamma_{B\eta} = \Gamma \cap \eta^{-1} B(\mathbf{Q}) \eta$ .

For  $X \subset \overline{S}_{K_f}$  and  $R$  an  $\mathcal{O}$ -algebra we denote by  $H^i(X, R)$  (resp.  $H_c^i(X, R)$ ) the  $i$ -th (Betti) cohomology group (resp. with compact support), and the interior cohomology, i.e., the image of  $H_c^i(X, R)$  in  $H^i(X, R)$ , by  $H_i^i(X, R)$ .

There is a Hecke action of double cosets  $[K_f g K_f]$  for  $g \in G(\mathbf{A}_f)$  on these cohomology groups (see [Urb98] §1.4.4 for the definition). We put  $T_{\pi_v} = [K_f \begin{pmatrix} \pi_v & 0 \\ 0 & 1 \end{pmatrix} K_f]$  and  $S_{\pi_v} = [K_f \begin{pmatrix} \pi_v & 0 \\ 0 & \pi_v \end{pmatrix} K_f]$ .

The connection between cohomology and cuspidal automorphic forms is given by the Eichler-Shimura-Harder isomorphism (in this special case see [Urb98] Theorem 1.5.1): For any compact open subgroup  $K_f \subset G(\mathbf{A}_f)$  we have

$$S_2(K_f) \xrightarrow{\sim} H_!^1(S_{K_f}, \mathbf{C}) \quad (3)$$

and the isomorphism is Hecke-equivariant.

One knows (see for example, [Ber08] Proposition 4) that for any  $\mathcal{O}[\frac{1}{6}]$ -algebra  $R$  there is a natural  $R$ -functorial isomorphism

$$H^1(\Gamma \backslash \mathbf{H}_3, R) \cong H^1(\Gamma, R), \quad (4)$$

where the group cohomology  $H^1(\Gamma, R)$  is just given by  $\text{Hom}(\Gamma, R)$ .

### 1.6 Galois representations associated to cuspforms for imaginary quadratic fields

Combining the work of Taylor, Harris, and Soudry with results of Friedberg-Hoffstein and Laumon/Weissauer, one can show the following (see [BH07]):

**THEOREM 3.** *Given a cuspidal automorphic representation  $\pi$  of  $\text{GL}_2(\mathbf{A}_F)$  with  $\pi_\infty$  isomorphic to the principal series representation corresponding to*

$$\begin{pmatrix} t_1 & * \\ 0 & t_2 \end{pmatrix} \mapsto \begin{pmatrix} t_1 \\ |t_1| \end{pmatrix} \begin{pmatrix} |t_2| \\ t_2 \end{pmatrix}$$

and cyclotomic central character  $\omega$  (i.e.  $\omega^c = \omega$ ), let  $\Sigma_\pi$  denote the set of places above  $p$ , the primes where  $\pi$  or  $\pi^c$  is ramified, and primes ramified in  $F/\mathbf{Q}$ .

Then there exists a continuous Galois representation

$$\rho_\pi : G_F \rightarrow \text{GL}_2(\overline{F}_{\mathfrak{p}})$$

such that if  $v \notin \Sigma_\pi$ , then  $\rho_\pi$  is unramified at  $v$  and the characteristic polynomial of  $\rho_\pi(\text{Frob}_v)$  is  $x^2 - a_v(\pi)x + \omega(\mathfrak{P}_v)\text{Nm}_{F/\mathbf{Q}}(\mathfrak{P}_v)$ , where  $a_v(\pi)$  is the Hecke eigenvalue corresponding to  $T_v$ . The image of the Galois representation lies in  $\text{GL}_2(L)$  for a finite extension  $L$  of  $F_{\mathfrak{p}}$  and the representation is absolutely irreducible.  $\square$

*Remark.* i) Taylor relates  $\pi$  to a low weight Siegel modular form via a theta lift and uses the Galois representation attached to this form (via pseudorepresentations and the Galois representations of cohomological Siegel modular forms) to find  $\rho_\pi$ .

ii) Taylor had some additional technical assumption in [Tay94] and only showed the equality of Hecke and Frobenius polynomial outside a set of places of zero density. For this strengthening of Taylor's result see [BH07].

iii) Conjecture 3.2 in [CD06] describes for cuspforms of general weight a conjectural extension of Taylor's theorem.

Urban studied in [Urb98] the case of ordinary automorphic representations  $\pi$ , and together with results in [Urb05] on the Galois representations attached to ordinary Siegel modular forms shows:

THEOREM 4 (Corollaire 2 of [Urb05]). *If  $\pi$  is unramified at  $\mathfrak{p}$  and ordinary at  $\mathfrak{p}$ , i.e.,  $|a_{\mathfrak{p}}(\pi)|_p = 1$ , then the Galois representation  $\rho_{\pi}$  is ordinary at  $\mathfrak{p}$ , i.e.,*

$$\rho_{\pi}|_{G_{\mathfrak{p}}} \cong \begin{pmatrix} \Psi_1 & * \\ 0 & \Psi_2 \end{pmatrix},$$

where  $\Psi_2|_{I_{\mathfrak{p}}} = 1$ , and  $\Psi_1|_{I_{\mathfrak{p}}} = \det(\rho_{\pi})|_{I_{\mathfrak{p}}} = \epsilon$ .

For  $p$  inert we will need a stronger statement (we refer the reader to [DFG04] Section 1.1.2 for the definition of a short crystalline Galois representation, and note that we assume  $p > 3$ ):

CONJECTURE 5. *If  $\pi$  is unramified at  $\mathfrak{p}$  then  $\rho_{\pi}|_{G_{\mathfrak{p}}}$  is crystalline and short.*

## 2. Selmer group and Eisenstein ideal

In this section we define an Eisenstein ideal in a Hecke algebra acting on cuspidal automorphic forms of  $\mathrm{GL}_2/F$  and show that its index gives a lower bound on the size of the Selmer group of a Galois character.

Let  $\phi_1$  and  $\phi_2$  be two Hecke characters with infinity type  $z$  and  $z^{-1}$ , respectively. Assume that their conductors are coprime to  $(p)$ . Let  $\mathcal{R}$  be the ring of integers in the finite extension  $L$  of  $F_{\mathfrak{p}}$  containing the values of the finite parts of  $\phi_i$  and  $L^{\mathrm{alg}}(0, \phi_1/\phi_2)$ . Denote its maximal ideal by  $\mathfrak{m}_{\mathcal{R}}$ . Let  $\Sigma_{\phi}$  be the finite set of places dividing the conductors of the characters  $\phi_i$  and their complex conjugates and the places dividing  $pd_F$ . Let  $K_f = \prod_v K_v \subset G(\mathbf{A}_f)$  be a compact open subgroup such that  $K_v = \mathrm{GL}_2(\mathcal{O}_v)$  if  $v \notin \Sigma_{\phi} \setminus \Sigma_p$ . In Section 3.2 we will specify  $K_v$  at the other ‘‘bad’’ places  $v \in \Sigma_{\phi} \setminus \Sigma_p$ . We will leave this open for now since we focus on the places dividing  $p$  in this section.

Because of the condition on the central character in Theorem 3 we assume that there exists a finite order Hecke character  $\eta$  unramified outside  $\Sigma_{\phi}$  such that

$$(\phi_1\phi_2\eta^2)^c = \phi_1\phi_2\eta^2. \quad (5)$$

Denote by  $\mathbf{T}$  the  $\mathcal{R}$ -algebra generated by the Hecke operators  $T_v, v \notin \Sigma_{\phi} \setminus \Sigma_p$  acting on  $S_2(K_f, \phi_1\phi_2)$ . Call the ideal  $\mathbf{I}_{\phi} \subseteq \mathbf{T}$  generated by

$$\{T_v - \phi_1(\mathfrak{P}_v)\mathrm{Nm}(\mathfrak{P}_v) - \phi_2(\mathfrak{P}_v) | v \notin \Sigma_{\phi} \setminus \Sigma_p\}$$

the *Eisenstein ideal associated to  $\phi = (\phi_1, \phi_2)$* .

Using the notation of §1.2, we define Galois characters

$$\begin{aligned} \rho_1 &= \phi_{1,\mathfrak{p}}\epsilon, \\ \rho_2 &= \phi_{2,\mathfrak{p}}, \\ \rho &= \rho_1 \otimes \rho_2^{-1}. \end{aligned}$$

Notice that  $\rho$  depends only on the quotient  $\phi_1/\phi_2$ . Our first main result is the following inequality:

THEOREM 6. *Assuming Conjecture 5 if  $p$  is inert in  $F/\mathbf{Q}$ , we have*

$$\mathrm{val}_p(\#\mathrm{Sel}^{\Sigma_{\phi} \setminus \Sigma_p}(F, \rho)) \geq \mathrm{val}_p(\#(\mathbf{T}/\mathbf{I}_{\phi})).$$

*Proof.* We can assume that

$$\mathbf{T}/\mathbf{I}_{\phi} \neq 0.$$

Let  $\mathfrak{m} \subset \mathbf{T}$  be a maximal ideal containing  $\mathbf{I}_{\phi}$ . Localising at  $\mathfrak{m}$  we write

$$S_2(K_f, \phi_1\phi_2)_{\mathfrak{m}} = \bigoplus_{i=1}^n V_{\pi_{i,f}}^{K_f},$$

where  $V_{\pi_f}$  denotes the representation space of the (finite part) of a cuspidal automorphic representation  $\pi$ .

By twisting the cuspforms by the finite order character  $\eta$  of (5) we can ensure that their central character is cyclotomic. Hence we can apply Theorem 3 to associate Galois representations  $\rho_{\pi_i \otimes \eta} : G_{\Sigma_\phi} \rightarrow \mathrm{GL}_2(L_i)$  to each  $\pi_i \otimes \eta, i = 1 \dots n$  for some finite extensions  $L_i/F_p$ . Taking all of them together (and untwisting by  $\eta$ ) we obtain a continuous, absolutely irreducible Galois representation

$$\rho_T := \bigoplus_{i=1}^n \rho_{\pi_i \otimes \eta} \otimes \eta^{-1} : G_{\Sigma_\phi} \rightarrow \mathrm{GL}_2(\mathbf{T}_m \otimes_{\mathcal{R}} L).$$

Here we use that  $\mathbf{T}_m \otimes_{\mathcal{R}} L = \prod_{i=1}^n L_i$ , which follows from the strong multiplicity one theorem. We have an embedding

$$\begin{aligned} \mathbf{T}_m &\hookrightarrow \prod_{i=1}^n L_i \\ T_v &\mapsto ((a_v(\pi_i)), \end{aligned}$$

where  $a_v(\pi_i)$  is the  $T_v$ -eigenvalue of  $\pi_i$ . The coefficients of the characteristic polynomial  $\mathrm{char}(\rho_T)$  lie in  $\mathbf{T}_m$  and by the Chebotarev density theorem

$$\mathrm{char}(\rho_T) \equiv \mathrm{char}(\rho_1 \oplus \rho_2) \pmod{\mathbf{I}_\phi}.$$

For any finite free  $\mathbf{T}_m \otimes L$ -module  $\mathcal{M}$ , any  $\mathbf{T}_m$ -submodule  $\mathcal{L} \subset \mathcal{M}$  that is finite over  $\mathbf{T}_m$  and such that  $\mathcal{L} \otimes L = \mathcal{M}$  is called a  $\mathbf{T}_m$ -lattice. Specializing to our situation Theorem 1.1 of [Urb01] we get:

**THEOREM 7 (Urban).** *Given a Galois representation  $\rho_T$  as above there exists a  $G_{\Sigma_\phi}$ -stable  $\mathbf{T}_m$ -lattice  $\mathcal{L} \subset (\mathbf{T}_m \otimes L)^2$  such that  $G_{\Sigma_\phi}$  acts on  $\mathcal{L}/\mathbf{I}_\phi \mathcal{L}$  via the short exact sequence*

$$0 \rightarrow \mathcal{R}_{\rho_1} \otimes_{\mathcal{R}} (\mathcal{N}/\mathbf{I}_\phi) \rightarrow \mathcal{L}/\mathbf{I}_\phi \mathcal{L} \rightarrow \mathcal{R}_{\rho_2} \otimes_{\mathcal{R}} (\mathbf{T}_m/\mathbf{I}_\phi) \rightarrow 0,$$

where  $\mathcal{N} \subset \mathbf{T}_m \otimes L$  is a  $\mathbf{T}_m$ -lattice with  $\mathrm{val}_p(\#\mathbf{T}_m/\mathbf{I}_\phi) \leq \mathrm{val}_p(\#\mathcal{N}/\mathbf{I}_\phi \mathcal{N}) < \infty$  and no quotient of  $\mathcal{L}$  is isomorphic to  $\bar{\rho}_1 := \rho_1 \pmod{\mathfrak{m}_{\mathcal{R}}}$ .

*Proof.* Note that the  $\mathcal{R}$ -algebra map  $\mathcal{R} \twoheadrightarrow \mathbf{T}_m/\mathbf{I}_\phi$  is surjective and that  $\mathcal{L}/\mathbf{I}_\phi \mathcal{L} \cong \mathcal{L} \otimes_{\mathcal{R}} \mathbf{T}_m/\mathbf{I}_\phi$ . Hence this short exact sequence recovers the one in the statement of Theorem 1.1 of [Urb01]. For the statement about  $\mathrm{val}_p(\#\mathcal{N}/\mathbf{I}_\phi \mathcal{N})$  see [Urb01] p. 519 and use that any  $\mathcal{R}$ -submodule of  $\mathbf{T}_m/\mathbf{I}_\phi$  or  $\mathcal{N}/\mathbf{I}_\phi \mathcal{N}$  is a  $\mathbf{T}_m$ -submodule.

See [Ber05] §7.3.2 for an alternative construction of such a lattice using arguments of Wiles ([Wil86] and [Wil90]).  $\square$

Using the properties of the Galois representations attached to cuspforms listed in §1.6 we can now conclude the proof of Theorem 6 by similar arguments as in [Urb01]. To ease notation we put  $\mathcal{T} := \mathcal{N}/\mathbf{I}_\phi$  and  $\Sigma := \Sigma_\phi$ .

Identifying  $\mathcal{R}_\rho$  with  $\mathrm{Hom}_{\mathcal{R}}(\mathcal{R}_{\rho_2}, \mathcal{R}_{\rho_1})$  and writing  $s : \mathcal{R}_{\rho_2} \otimes \mathbf{T}_m/\mathbf{I}_\phi \rightarrow \mathcal{L} \otimes \mathbf{T}_m/\mathbf{I}_\phi$  for the section as  $\mathbf{T}_m/\mathbf{I}_\phi$ -modules we define a 1-cocycle  $c : G_F \rightarrow G_\Sigma \rightarrow \mathcal{R}_\rho \otimes \mathcal{T}$  by

$$c(g)(m) = \text{the image of } s(m) - g.s(g^{-1}.m) \text{ in } \mathcal{R}_{\rho_1} \otimes \mathcal{T}.$$

Consider the  $\mathcal{R}$ -homomorphism

$$\varphi : \mathrm{Hom}_{\mathcal{R}}(\mathcal{T}, \mathcal{R}^\vee) \rightarrow H^1(F, W_\rho), \varphi(f) = \text{the class of } (1 \otimes f) \circ c.$$

We will show that

- (i)  $\mathrm{im}(\varphi) \subset \mathrm{Sel}^{\Sigma \setminus \Sigma_p}(F, \rho)$ ,

(ii)  $\ker(\varphi) = 0$ .

From (i) it follows that

$$\mathrm{val}_p(\#\mathrm{Sel}^{\Sigma \setminus \Sigma_p}(F, \rho)) \geq \mathrm{val}_p(\#\mathrm{im}(\varphi)).$$

From (ii) it follows that

$$\begin{aligned} \mathrm{val}_p(\#\mathrm{im}(\varphi)) &\geq \mathrm{val}_p(\#\mathrm{Hom}_{\mathcal{R}}(\mathcal{T}, \mathcal{R}^\vee)) \\ &= \mathrm{val}_p(\#\mathcal{T}) \\ &\geq \mathrm{val}_p(\#\mathbf{T}_m/\mathbf{I}_\phi). \end{aligned}$$

To prove (ii) we use an argument explained to us by Chris Skinner. We first observe that for any  $f \in \mathrm{Hom}_{\mathcal{R}}(\mathcal{T}, \mathcal{R}^\vee)$ ,  $\ker(f)$  has finite index in  $\mathcal{T}$  since  $\mathcal{T}$  is a finite  $\mathcal{R}$ -module, and so  $f \in \mathrm{Hom}_{\mathcal{R}}(\mathcal{T}, \mathcal{R}^\vee[\mathfrak{m}_{\mathcal{R}}^n])$  for some  $n$ . Suppose now that  $f \in \ker(\varphi)$ . We claim that the class of  $c$  in  $H^1(G_\Sigma, \mathcal{R}_\rho \otimes_{\mathcal{R}} \mathcal{T}/\ker(f))$  is zero. To see this, let  $X = \mathcal{R}^\vee/\mathrm{im}(f)$  and observe that there is an exact sequence

$$H^0(G_\Sigma, \mathcal{R}_\rho \otimes_{\mathcal{R}} X) \rightarrow H^1(G_\Sigma, \mathcal{R}_\rho \otimes_{\mathcal{R}} \mathcal{T}/\ker(f)) \rightarrow H^1(G_\Sigma, \mathcal{R}_\rho \otimes_{\mathcal{R}} \mathcal{R}^\vee).$$

Since  $f \in \ker(\varphi)$  and the second arrow in the sequence comes from the inclusion  $\mathcal{T}/\ker(f) \hookrightarrow \mathcal{R}^\vee$  induced by  $f$ , the image in the right module of the class of  $c$  in the middle is zero. Our claim follows therefore if the module on the left is trivial. But the dual of this module is a subquotient of  $\mathrm{Hom}_{\mathcal{R}}(\mathcal{R}_\rho, \mathcal{R})$  on which  $G_\Sigma$  acts trivially. By assumption, however,  $\mathcal{R}_\rho$  is a rank one module on which  $G_\Sigma$  acts non-trivially.

Suppose in addition that  $f$  is non-trivial, i.e.,  $\ker(f) \subsetneq \mathcal{T}$ . Note that any  $\mathcal{R}$ -submodule of  $\mathcal{T}$  is actually a  $\mathbf{T}_m$ -submodule since  $\mathcal{R} \rightarrow \mathbf{T}_m/\mathbf{I}_\phi$ . Hence there exists a  $\mathbf{T}_m$ -module  $A$  with  $\ker(f) \subset A \subset \mathcal{T}$  such that  $\mathcal{T}/A \cong \mathcal{R}/\mathfrak{m}_{\mathcal{R}}$ . Since  $c$  represents the trivial class in  $H^1(G_\Sigma, \mathcal{R}_\rho \otimes_{\mathcal{R}} \mathcal{T}/\ker(f))$  it follows that the  $\mathbf{T}_m[G_\Sigma]$ -extension

$$0 \rightarrow \mathcal{R}_{\rho_1} \otimes_{\mathcal{R}} \mathcal{R}/\mathfrak{m}_{\mathcal{R}} \cong \mathcal{R}_{\rho_1} \otimes_{\mathcal{R}} \mathcal{T}/A \rightarrow (\mathcal{L}/\mathbf{I}_\phi \mathcal{L})/(\mathcal{R}_{\rho_1} \otimes_{\mathcal{R}} A) \rightarrow \mathcal{R}_{\rho_2} \otimes_{\mathcal{R}} (\mathbf{T}_m/\mathbf{I}_\phi) \rightarrow 0$$

is split. But this would give a  $\mathbf{T}_m[G_\Sigma]$ -quotient of  $\mathcal{L}$  isomorphic to  $\bar{\rho}_1$ , which contradicts one of the properties of the lattice constructed by Urban. Hence  $\ker(\varphi)$  is trivial.

For (i) we have to show that the local conditions of the Selmer group are satisfied. Firstly, if  $v \notin \Sigma$  then  $v \nmid p$  and  $\rho$  is unramified at  $v$ , so we have

$$H_f^1(F_v, W_\rho) = \ker(H^1(F_v, W_\rho) \rightarrow H^1(I_v, W_\rho))$$

by Lemma 1.3.5 (iv) of [Rub00]. Since the extension in Theorem 7 is unramified outside  $\Sigma$  the image of  $\varphi$  maps to zero in  $H^1(I_v, W_\rho)$ .

For the places  $v \mid p$  we divide into the split and inert cases: For split  $p$  we claim that we only have a non-trivial condition at  $\mathfrak{p}$  since  $H_f^1(F_{\bar{\mathfrak{p}}}, W_\rho) = H^1(F_{\bar{\mathfrak{p}}}, W_\rho)_{\mathrm{div}} = H^1(F_{\bar{\mathfrak{p}}}, W_\rho)$ . For this we use that  $\rho = \epsilon$  on  $I_{\bar{\mathfrak{p}}}$  by (1). Then we know by [NSW08] Proposition 7.3.10 that  $H^1(F_{\bar{\mathfrak{p}}}, W_\epsilon)$  is divisible and  $W_\epsilon^{I_{\bar{\mathfrak{p}}}} = \{1\}$  since  $p > 3$ , so by applying the inflation-restriction sequence for both  $W_\rho$  and  $W_\epsilon$  we get

$$H^1(F_{\bar{\mathfrak{p}}}, W_\rho) \cong H^1(I_{\bar{\mathfrak{p}}}, W_\rho)^{g_{\bar{\mathfrak{p}}}} \cong H^1(F_{\bar{\mathfrak{p}}}, W_\epsilon).$$

At  $\mathfrak{p}$  it suffices to prove that the extension in Theorem 7 is split when considered as an extension of  $\mathbf{T}_m[G_{\mathfrak{p}}]$ -modules, because then the class in  $H^1(F_{\mathfrak{p}}, \mathcal{R}_\rho \otimes \mathcal{T})$  determined by  $c$  is the zero class. In this case the Hecke eigenvalues  $a_{\mathfrak{p}}(\pi_i) \equiv p \cdot \phi_1(\mathfrak{p}) + \phi_2(\mathfrak{p}) \not\equiv 0 \pmod{\mathfrak{m}_{\mathcal{R}}}$ , hence the cuspforms  $\pi_i \otimes \eta$  are ordinary at  $\mathfrak{p}$ , so Theorem 4 applies and  $\rho_T$  is ordinary. Observing that the Hodge-Tate weights at  $\mathfrak{p}$  of  $\rho_1$  and  $\rho_2$  are 0 and 1, respectively, the splitting of the extension as  $\mathbf{T}_m[G_{\mathfrak{p}}]$ -modules follows from comparing the basis given by Theorem 7 with the one coming from ordinarity.

For inert  $p$  we use the observation from the proof of (ii) that  $\text{im}(\varphi) \subset H^1(F, W_\rho[\mathfrak{m}_{\mathcal{R}}^n])$  for some  $n$ . Following [DFG04] p.697 we define  $H_f^1(F_{\mathfrak{p}}, W_\rho[\mathfrak{m}_{\mathcal{R}}^n]) \subset H^1(F_{\mathfrak{p}}, W_\rho[\mathfrak{m}_{\mathcal{R}}^n])$  to be the subset consisting of those cohomology classes which correspond to extensions of  $\mathcal{R}/\mathfrak{m}_{\mathcal{R}}^n[G_{\mathfrak{p}}]$ -modules

$$0 \rightarrow \mathcal{R}_{\rho_1}^\vee[\mathfrak{m}_{\mathcal{R}}^n] \rightarrow \mathcal{E} \rightarrow \mathcal{R}_{\rho_2}^\vee[\mathfrak{m}_{\mathcal{R}}^n] \rightarrow 0$$

such that  $\mathcal{E}$  is in the essential image of the functor  $\mathbf{V}$  defined in [DFG04] Section 1.1.2 (extended using the Tate twist [DFG04] p. 711). We will not need the precise definition of  $\mathbf{V}$ , just that its essential image is closed under taking subobjects, quotients and finite direct sums, and contains all short crystalline  $G_{\mathfrak{p}}$ -representations. Conjecture 5 therefore implies that  $\text{im}(\varphi) \subset H_f^1(F_{\mathfrak{p}}, W_\rho[\mathfrak{m}_{\mathcal{R}}^n])$  (see [Klo08] Lemma 9.19). Since by [DFG04] Proposition 2.2 and [Klo08] Proposition 9.20

$$\varinjlim_j H_f^1(F_{\mathfrak{p}}, W_\rho[\mathfrak{m}_{\mathcal{R}}^j]) \cong H_f^1(F_{\mathfrak{p}}, W_\rho),$$

this proves that  $\text{im}(\varphi)$  satisfies the required local condition in this case, too.  $\square$

The following Lemma will later provide us with the finite order character  $\eta$  of (5) used in the twisting above.

LEMMA 8. *If  $\chi = \phi_1/\phi_2$  satisfies  $\chi^c = \bar{\chi}$  then there exists a finite order character  $\eta$  unramified outside  $\Sigma_\phi$  such that  $(\phi_1\phi_2\eta^2)^c = \phi_1\phi_2\eta^2$ .*

*Proof.* In the lemma on p.81 of [Gre83] Greenberg defines a Hecke character  $\mu_G : F^* \backslash \mathbf{A}_F^* \rightarrow \mathbf{C}^*$  of infinity type  $z^{-1}$  such that  $\mu_G^c = \bar{\mu}_G$  and  $\mu_G$  is ramified exactly at the primes ramified in  $F/\mathbf{Q}$ . We claim that there exists a finite order Hecke character  $\mu$  unramified outside  $\Sigma_\phi$  such that

$$\chi' := \chi\mu_G^2 = \mu/\mu^c.$$

Given such a character  $\mu$  we then define  $\eta = \mu_G/\mu\phi_2$  and one checks that  $\phi_1\phi_2\eta^2 = (\mu\mu^c)^{-1}$ .

Since  $\chi'^{-1} = \bar{\chi}' = \chi'^c$  we have that

$$\chi' \equiv 1 \text{ on } \text{Nm}_{F/\mathbf{Q}}(\mathbf{A}_F^*) \subset \mathbf{A}_{\mathbf{Q}}^* \subset \mathbf{A}_F^*.$$

Thus  $\chi'$  restricted to  $\mathbf{Q}^* \backslash \mathbf{A}_{\mathbf{Q}}^*$  is either the quadratic character of  $F/\mathbf{Q}$  or trivial. Since our finite order character has trivial infinite component,  $\chi'$  has to be trivial on  $\mathbf{Q}^* \backslash \mathbf{A}_{\mathbf{Q}}^*$ .

Looking at the exact sequence

$$1 \rightarrow F^* \rightarrow \mathbf{A}_F^* \rightarrow F^* \backslash \mathbf{A}_F^* \rightarrow 1,$$

by Hilbert's Theorem 90 applied to  $F^*$  and  $\text{Gal}(F/\mathbf{Q})$  we find that  $H^0(\text{Gal}(F/\mathbf{Q}), F^* \backslash \mathbf{A}_F^*) = \mathbf{Q}^* \backslash \mathbf{A}_{\mathbf{Q}}^*$ . Thus the kernel of  $x \mapsto x/x^c$  is given by  $\mathbf{Q}^* \backslash \mathbf{A}_{\mathbf{Q}}^*$ . Since we showed that  $\chi'$  vanishes on  $\mathbf{Q}^* \backslash \mathbf{A}_{\mathbf{Q}}^*$  it therefore factors through  $\mathbf{A}_F^* \rightarrow A$ , where  $A$  is the subset of  $\mathbf{A}_F^*$  of elements of the form  $x/x^c$  and the map is  $x \mapsto x/x^c$ . If  $y \in A \cap F^*$  then  $y$  has trivial norm and so by Hilbert's Theorem 90,  $y = x/x^c$  for some  $x \in F^*$ . Thus the induced character  $A \rightarrow \mathbf{C}^*$  vanishes on  $A \cap F^*$ . This implies that there is a continuous finite order character  $\mu : F^* \backslash \mathbf{A}_F^* \rightarrow \mathbf{C}^*$  which restricts to this character on  $A$  and  $\chi' = \mu/\mu^c$  (this argument is taken from the proof of Lemma 1 in [Tay94]).

By the following argument we can further conclude that the induced character vanishes on  $A \cap \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*$  (recall our identification  $F_v^* \hookrightarrow \mathbf{A}_F^*$  from Section 1.1) and therefore find  $\mu$  on  $F^* \backslash \mathbf{A}_F^* / \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*$  restricting to the character  $A \rightarrow \mathbf{C}^*$ . Writing  $U_{F,\ell} = \prod_{v|\ell} \mathcal{O}_v^*$  for a prime  $\ell$  in  $\mathbf{Q}$  we have an injection

$$H^1(\text{Gal}(F/\mathbf{Q}), \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*) \hookrightarrow \prod_{\ell \notin \Sigma_\phi} H^1(\text{Gal}(F/\mathbf{Q}), U_{F,\ell}),$$

where " $\ell \notin \Sigma_\phi$ " denotes those  $\ell \in \mathbf{Z}$  such that  $v \mid \ell \Rightarrow v \notin \Sigma_\phi$ . Here we use that by our definition of  $\Sigma_\phi$  we know that  $v \in \Sigma_\phi \Rightarrow \bar{v} \in \Sigma_\phi$ . In fact, all these groups are trivial since all  $\ell \notin \Sigma_\phi$  are

unramified in  $F/\mathbf{Q}$  and so

$$H^1(\mathrm{Gal}(F/\mathbf{Q}), U_{F,\ell}) \cong H^1(G_v, \mathcal{O}_v^*) = 1.$$

If  $y \in A \cap \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*$  then  $y$  has trivial norm in  $\prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*$ . But as shown,  $H^1(\mathrm{Gal}(F/\mathbf{Q}), \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^*)$  is trivial so there exists  $x \in \prod_{v \notin \Sigma_\phi} \mathcal{O}_v^* \cap \mathbf{A}_F^*$  such that  $y = x/x^c$ . Since  $\chi'$  is unramified outside  $\Sigma_\phi$  the image of  $y$  under the induced character therefore equals  $\chi'(x) = 1$ , as claimed above.  $\square$

### 3. Bounding the Eisenstein ideal

In [Ber08] we constructed a class  $\mathrm{Eis}(\phi)$  in the cohomology of a symmetric space associated to  $\mathrm{GL}_{2/F}$  that has integral non-zero restriction to the boundary of the Borel-Serre compactification, and is an eigenvector for the Hecke operators at almost all places. By a result of Harder one knows that  $\mathrm{Eis}(\phi)$  is rational. The main result of [Ber08] is a lower bound on its denominator (defined in (6) below) in terms of the  $L$ -value of a Hecke character. In this section we show that if there exists an integral cohomology class with the same restriction to the boundary as  $\mathrm{Eis}(\phi)$  then there exists a congruence modulo the  $L$ -value between  $\mathrm{Eis}(\phi)$ , multiplied by its denominator, and a cuspidal cohomology class.

#### 3.1 The Eisenstein cohomology set-up

Recall the notation and definitions introduced in Section 1.5. Let  $\mathcal{R}$  denote the ring of integers in the finite extension  $L$  of  $F_{\mathfrak{p}}$  obtained by adjoining the values of the finite part of both  $\phi_i$  and  $L^{\mathrm{alg}}(0, \phi_1/\phi_2)$ . We write

$$\tilde{H}^1(X, \mathcal{R}) := H^1(X, \mathcal{R})_{\mathrm{free}} = \mathrm{im}(H^1(X, \mathcal{R}) \rightarrow H^1(X, L))$$

for  $X = S_{K_f}$  or  $\partial\bar{S}_{K_f}$ . For  $c \in H^1(S_{K_f}, L)$  define the denominator (ideal) by

$$\delta(c) := \{a \in \mathcal{R} : a \cdot c \in \tilde{H}^1(S_{K_f}, \mathcal{R})\}. \quad (6)$$

We have the long exact sequence of relative cohomology (see e.g. [Bre97] II.12 (22))

$$\dots \rightarrow H_c^1(S_{K_f}, R) \rightarrow H^1(S_{K_f}, R) \xrightarrow{\mathrm{res}} H^1(\partial\bar{S}_{K_f}, R) \rightarrow H_c^2(S_{K_f}, R) \rightarrow \dots$$

for any  $\mathcal{R}$ -algebra  $R$ .

3.1.1 *The set-up* Suppose we are given a pair of Hecke characters  $\phi = (\phi_1, \phi_2)$  as in Section 2 and a class  $\mathrm{Eis}(\phi) \in H^1(S_{K_f}, L)$  satisfying the following properties:

(E1) The image of  $\mathrm{Eis}(\phi)$  under  $\mathrm{res}$  lies in  $\tilde{H}^1(\partial\bar{S}_{K_f}, \mathcal{R})$ .

(E2) For all places  $v$  outside the conductors of the  $\phi_i$  the class  $\mathrm{Eis}(\phi)$  is an eigenvector for the Hecke operator  $T_{\pi_v} = [K_f \begin{pmatrix} \pi_v & 0 \\ 0 & 1 \end{pmatrix} K_f]$  with eigenvalue

$$\phi_2(\mathfrak{P}_v) + \mathrm{Nm}(\mathfrak{P}_v)\phi_1(\mathfrak{P}_v).$$

(E3) The central character of  $\mathrm{Eis}(\phi)$  is given by  $\phi_1\phi_2$ , i.e., the Hecke operators

$$S_{\pi_v} = [K_f \begin{pmatrix} \pi_v & 0 \\ 0 & \pi_v \end{pmatrix} K_f]$$

act on it by multiplication by  $(\phi_1\phi_2)(\pi_v)$ .

(E4) The denominator of  $\mathrm{Eis}(\phi)$  is bounded below by  $L^{\mathrm{int}}(0, \phi_1/\phi_2)$ , i.e.,

$$\delta(\mathrm{Eis}(\phi)) \subseteq (L^{\mathrm{int}}(0, \phi_1/\phi_2)).$$

Suppose we are also given:

(H1) There exists  $c_\phi \in \tilde{H}^1(S_{K_f}, \mathcal{R})$  with

$$\text{res}(c_\phi) = \text{res}(\text{Eis}(\phi)) \in \tilde{H}^1(\partial\bar{S}_{K_f}, \mathcal{R}).$$

(H2) There exists an idempotent  $e_\omega$  acting on  $H^1(S_{K_f}, \mathbf{C})$  such that  $S_{\pi_v}e_\omega = (\phi_1\phi_2)(\pi_v)e_\omega$  for  $v$  not dividing the conductors of the  $\phi_i$ .

The following provides a bound on the congruence module introduced in the previous section:

PROPOSITION 9. *Given the above setup there is an  $\mathcal{R}$ -algebra surjection*

$$\mathbf{T}/\mathbf{I}_\phi \twoheadrightarrow \mathcal{R}/(L^{\text{int}}(0, \phi_1/\phi_2)).$$

*Proof.* Put  $\tilde{H}_!^1(S_{K_f}, \mathcal{R}) = H_!^1(S_{K_f}, L) \cap \tilde{H}^1(S_{K_f}, \mathcal{R})$  and  $\omega = \phi_1\phi_2$ . Under the Eichler-Shimura-Harder isomorphism (see (3)) we have

$$e_\omega H_!^1(S_{K_f}, \mathbf{C}) \cong S_2(K_f, \omega).$$

Hence the Hecke algebra  $\mathbf{T}$  from Section 2 is isomorphic to the  $\mathcal{R}$ -subalgebra of

$$\text{End}_{\mathcal{R}}(e_\omega \tilde{H}_!^1(S_{K_f}, \mathcal{R}))$$

generated by the Hecke operators  $T_{\pi_v}$  for all primes  $v \notin \Sigma_\phi$ , and we will identify the two.

Note that for  $c_\phi \in \tilde{H}^1(S_{K_f}, \mathcal{R})$  given by (H1) we have

$$\text{res}(e_\omega c_\phi) = e_\omega \text{res}(c_\phi) = e_\omega \text{res}(\text{Eis}(\phi)) = \text{res}(\text{Eis}(\phi))$$

since  $S_v(\text{Eis}(\phi)) = \omega(\pi_v)\text{Eis}(\phi)$  by (E3).

Without loss of generality, we can assume that  $\delta(\text{Eis}(\phi)) \neq \mathcal{R}$ ; there is nothing to prove otherwise by (E4). Let  $\delta$  be a generator of  $\delta(\text{Eis}(\phi))$ . Then  $\delta \cdot \text{Eis}(\phi)$  is an element of an  $\mathcal{R}$ -basis of  $e_\omega \tilde{H}_!^1(S_{K_f}, \mathcal{R})$ . By construction,  $c_0 := \delta \cdot (e_\omega c_\phi - \text{Eis}(\phi)) \in e_\omega H_!^1(S_{K_f}, L)$  is a nontrivial element of an  $\mathcal{R}$ -basis of  $e_\omega \tilde{H}_!^1(S_{K_f}, \mathcal{R})$ . Extend  $c_0$  to an  $\mathcal{R}$ -basis  $c_0, c_1, \dots, c_d$  of  $e_\omega \tilde{H}_!^1(S_{K_f}, \mathcal{R})$ . For each  $t \in \mathbf{T}$  write

$$t(c_0) = \sum_{i=0}^d a_i(t)c_i, \quad a_i(t) \in \mathcal{R}.$$

Then

$$\mathbf{T} \twoheadrightarrow \mathcal{R}/(\delta), \quad t \mapsto a_0(t) \pmod{\delta} \tag{7}$$

is an  $\mathcal{R}$ -module surjection. We claim that it is a homomorphism of  $\mathcal{R}$ -algebras with the Eisenstein ideal  $\mathbf{I}_\phi$  contained in its kernel. To prove this it suffices to check that each  $a_0(T_{\pi_v} - \phi_2(\mathfrak{P}_v) - \text{Nm}(\mathfrak{P}_v)\phi_1(\mathfrak{P}_v))$ ,  $v \notin \Sigma_\phi$  is contained in  $\delta\mathcal{R}$ . This is an easy calculation using (E2). Since  $\mathcal{R}/(\delta) \twoheadrightarrow \mathcal{R}/(L^{\text{int}}(0, \chi))$  by (E4), this concludes the proof.  $\square$

In the following sections, we will indicate how to produce the elements in the set-up of the proposition. Under certain conditions on the characters  $\phi_i$ , to be reviewed in Section 3.2, we constructed in [Ber08] a class  $\text{Eis}(\phi)$  satisfying (E1)-(E4) using Harder's Eisenstein cohomology. Assumption (H2) is of a technical nature and will be discussed in Section 3.3. We are interested in controlling the central character via (H2) because of the restriction in Theorem 3. The most difficult ingredient to procure is (H1), see Sections 3.4 and 4.

*Remark.* i) As already remarked in the introduction, the constant cohomology coefficients above can be replaced by coefficient systems arising from finite dimensional representations of  $\text{GL}_{2/F}$ . See [Ber08] §2.4 and 3.1 for the necessary modifications.

- ii) Note also that except for the explicit Hecke operators we did not use any information specific to  $\mathrm{GL}_{2/F}$ , i.e.,  $S_{K_f}$  could be replaced by a symmetric space associated to a different group  $G$  and  $\phi$  by a tuple of automorphic forms on the Levi part of a parabolic subgroup of  $G$ . Since the analytic theory of Eisenstein cohomology has been developed for a wide variety of groups, and rationality results are known, e.g. for  $\mathrm{GL}_n$  by the work of [FS98], we hope that these techniques generalize to these groups.

### 3.2 Construction of Eisenstein class

Following Harder we constructed in [Ber08] Eisenstein cohomology classes in the Betti cohomology group  $H^1(S_{K_f}, \mathbf{C})$ . Given a pair of Hecke characters  $\phi = (\phi_1, \phi_2)$  with  $\phi_{1,\infty}(z) = z$  and  $\phi_{2,\infty}(z) = z^{-1}$  these depend on a choice of a function  $\Psi_{\phi_f}$  in the induced representation

$$V_{\phi_f, \mathbf{C}}^{K_f} = \{ \Psi : G(\mathbf{A}_f) \rightarrow \mathbf{C} \mid \Psi(bg) = \phi_f(b)\Psi(g) \ \forall b \in B(\mathbf{A}_f), \Psi(gk) = \Psi(g) \ \forall k \in K_f \}.$$

In the notation of [Ber08] we take  $K_f = K_f^S$  and  $\Psi_{\phi_f} = \Psi_{\phi}^0$ . We recall the definition of the compact open  $K_f$ . Denote by  $S$  the finite set of places where both  $\phi_i$  are ramified, but  $\phi_1/\phi_2$  is unramified. Write  $\mathfrak{M}_i$  for the conductor of  $\phi_i$ . For an ideal  $\mathfrak{N}$  in  $\mathcal{O}$  and a finite place  $v$  of  $F$  put  $\mathfrak{N}_v = \mathfrak{N}\mathcal{O}_v$ . We define

$$K^1(\mathfrak{N}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{GL}_2(\widehat{\mathcal{O}}), a-1, c \equiv 0 \pmod{\mathfrak{N}} \right\},$$

$$K^1(\mathfrak{N}_v) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{GL}_2(\mathcal{O}_v), a-1, c \equiv 0 \pmod{\mathfrak{N}_v} \right\},$$

and

$$U^1(\mathfrak{N}_v) = \{ k \in \mathrm{GL}_2(\mathcal{O}_v) : \det(k) \equiv 1 \pmod{\mathfrak{N}_v} \}.$$

Now put

$$K_f := \prod_{v \in S} U^1(\mathfrak{M}_{1,v}) \prod_{v \notin S} K^1((\mathfrak{M}_1 \mathfrak{M}_2)_v).$$

The exact definition of  $\Psi_{\phi_f}$  will not be required in the following; we refer the interested reader to [Ber08] Section 3.2. Let  $\mathrm{Eis}(\phi)$  be the cohomology class denoted by  $[\mathrm{Eis}(\Psi_{(\phi_1, \phi_2)_f}^0)]$  in [Ber08].

The rationality of  $\mathrm{Eis}(\phi)$ , i.e., the fact that  $\mathrm{Eis}(\phi) \in H^1(S_{K_f}, L)$  was proven by Harder, see [Ber08] Proposition 13. Properties (E2) and (E3) are satisfied by construction, see [Ber08] Lemma 9. The integrality of the constant term (E1) is analyzed in [Ber08] Proposition 16. The main result of [Ber08] is the bound on the denominator (E4). The latter two require certain conditions on the characters  $\phi_1$  and  $\phi_2$ . However, since in the combination of Theorem 6 and Proposition 9 the main object of interest is the character  $\chi = \phi_1/\phi_2$ , we will from now on focus on  $\chi$  and view  $\phi_1$  and  $\phi_2$  as auxiliary.

**THEOREM 10** ([Ber08] Proposition 16, Theorem 29). *Let  $\chi$  be a Hecke character  $\chi$  of infinity type  $z^2$  with conductor  $\mathfrak{M}$  coprime to  $(p)$ . Assume in addition that either*

(i)  *$p$  splits in  $F$ ,  $\chi$  has split conductor, and  $\frac{L(0, \bar{\chi})}{L(0, \chi)} \in \mathcal{R}$*

or

(ii)  *$\chi^c = \bar{\chi}$ , no ramified primes divide  $\mathfrak{M}$  and no inert primes congruent to  $-1 \pmod{p}$  divide  $\mathfrak{M}$  with multiplicity one, and*

$$\omega_{F/\mathbf{Q}}(\mathfrak{M}) \frac{\tau(\tilde{\chi})}{\sqrt{\mathrm{Nm}(\mathfrak{M})}} = 1,$$

where  $\omega_{F/\mathbf{Q}}$  is the quadratic Hecke character associated to the extension  $F/\mathbf{Q}$  and  $\tau(\tilde{\chi})$  the Gauss sum of the unitary character  $\tilde{\chi} := \chi/|\chi|$ .

Then there exists a factorization  $\chi = \phi_1/\phi_2$  such that  $\text{Eis}(\phi)$  satisfies (E1)-(E4).  $\square$

*Remark.* i) Proposition 16 of [Ber08] shows that  $\frac{L(0, \bar{\chi})}{L(0, \chi)} \in L$ .

ii) By considering non-constant coefficient systems [Ber08] in fact proves this for characters  $\chi$  of infinity type  $z^{m+2}\bar{z}^{-m}$  for  $m \in \mathbf{N}_{\geq 0}$  if  $p$  splits in  $F/\mathbf{Q}$ .

### 3.3 Existence of an idempotent (H2)

LEMMA 11. *Let  $K_f$  be the compact open defined in Section 3.2. If  $p \nmid \#\text{Cl}_{\mathfrak{M}_1\mathfrak{M}_2}(F)$  then (H2) is satisfied.*

*Proof.* By [Urb98] §1.2 and 1.4.5 the action of the diamond operators  $S_{\pi_v}, v \nmid \mathfrak{M}_1\mathfrak{M}_2$  on  $H^1(S_{K_f}, \mathbf{C})$  is determined by the class in  $\text{Cl}_{\mathfrak{M}_1\mathfrak{M}_2}(F)$  of the ideal determined by  $\pi_v$  and induces an  $\mathcal{R}$ -linear action of  $\text{Cl}_{\mathfrak{M}_1\mathfrak{M}_2}(F)$  on  $H^1(S_{K_f}, \mathbf{C})$ . Here we use that

$$K_f \supset K(\mathfrak{M}_1\mathfrak{M}_2) := \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{GL}_2(\hat{\mathcal{O}}) : \begin{pmatrix} a & b \\ c & d \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \pmod{\mathfrak{M}_1\mathfrak{M}_2} \right\}.$$

By assumption the ray class group has order prime to  $p$ , so  $\mathcal{R}[\text{Cl}_{\mathfrak{M}_1\mathfrak{M}_2}(F)]$  is semisimple. For  $\omega := \phi_1\phi_2$ , which can be viewed as a character of  $\text{Cl}_{\mathfrak{M}_1\mathfrak{M}_2}(F)$ , let  $e_\omega$  be the idempotent associated to  $\omega$ , so that  $S_v e_\omega = \omega(\pi_v) e_\omega$ .  $\square$

*Remark.* By enlarging  $K_f$  the condition  $p \nmid \#(\mathcal{O}/\mathfrak{M}_1\mathfrak{M}_2)^*$  can be weakened to the order of  $\phi_i|_{\hat{\mathcal{O}}^*}$  being coprime to  $p$ , see [Ber05] §6.1.

### 3.4 Torsion problem (H1)

Hypothesis (H1) is related to the question of the occurrence of torsion classes in  $H_c^2(S_{K_f}, \mathcal{R})$  as follows: There exists  $c_\phi \in \tilde{H}^1(S_{K_f}, \mathcal{R})$  with  $\text{res}(c_\phi) = \text{res}(\text{Eis}(\phi)) \in \tilde{H}^1(\partial\bar{S}_{K_f}, \mathcal{R})$  if and only if  $\text{res}(\text{Eis}(\phi))$  maps to zero in  $\tilde{H}_c^2(S_{K_f}, \mathcal{R})$ . Let  $d_\phi \in \tilde{H}_c^2(S_{K_f}, \mathcal{R})$  be the image of  $\text{res}(\text{Eis}(\phi))$  and write  $\delta$  for a generator of the denominator  $\delta(\text{Eis}(\phi))$ . Since  $\delta\text{Eis}(\phi) \in \tilde{H}^1(S_{K_f}, \mathcal{R})$  we know that  $\delta d_\phi$  is trivial in  $\tilde{H}_c^2(S_{K_f}, \mathcal{R})$ . So if we knew that  $H_c^2(S_{K_f}, \mathcal{R})_{\text{torsion}} = 0$  then hypothesis (H1) would be satisfied.

This problem does not arise for  $\text{GL}_{2/\mathbf{Q}}$  because no such torsion classes exist with the Hecke eigenvalues under consideration (see [HP92]). In our situation, we know by Lefschetz duality (see [Gre67] (28.18) or [Mau80] Theorem 5.4.13) that

$$H_c^2(S_{K_f}, \mathcal{R}) \cong H_1(S_{K_f}, \mathcal{R}),$$

so this question reduces to the problem of torsion in  $\Gamma^{\text{ab}}$  for arithmetic subgroups  $\Gamma \subset G(\mathbf{Q})$ . This has been studied in [EGM82], [SV83], and [GS93] (see also [EGM98] §7.5). An arithmetic interpretation or explanation for the torsion has not been found yet in general (but see [EGM82] for examples in the case of  $\mathbf{Q}(\sqrt{-1})$ ). Based on computer calculations [GS93] (2) suggests that for  $\Gamma \subset \text{PSL}_2(\mathcal{O})$ , apart from 2 and 3 only primes less than or equal to  $\frac{1}{2}[\text{PSL}_2(\mathcal{O}) : \Gamma]$  occur in the torsion of  $\Gamma^{\text{ab}}$ . Even restricting to the ordinary part there can be torsion, see [Tay]§4. In all cases calculated so far,  $\text{PSL}_2(\mathcal{O})^{\text{ab}}$  has only 2 or 3-torsion (see also [Swa71], [Berk06]) but this is not known in general, hence our different approach in the following section, where we will prove:

PROPOSITION 12. *Let  $\chi = \phi_1/\phi_2$  be an unramified Hecke character of infinity type  $z^2$ . Assume that 1 is the only unit in  $\mathcal{O}^*$  congruent to 1 modulo the conductor of  $\phi_1$ . If (E1) holds for  $K_f$  and  $\text{Eis}(\phi)$  as defined in Section 3.2 then (H1) is satisfied.*

### 3.5 Congruence results

We will summarize in this section the conditions under which we can procure the ingredients for Proposition 9 and hence prove the existence of cohomological congruences.

**THEOREM 13.** *Assume  $p$  splits in  $F/\mathbf{Q}$ . Let  $\chi$  be a Hecke character of infinity type  $z^2$  with split conductor  $\mathfrak{M}$  coprime to  $(p)$ . Assume  $\frac{L(0, \bar{\chi})}{L(0, \chi)} \in \mathcal{R}$  and*

$$p \nmid \#(\mathcal{O}/\mathfrak{M})^* \cdot \#\mathrm{Cl}(F).$$

*Let  $q > \#(\mathcal{O}^*)$  be any rational prime coprime to  $(p)\mathfrak{M}$  and split in  $F$  such that  $p \nmid q - 1$  and  $\mathfrak{q}$  a prime of  $F$  dividing  $(q)$ . If  $H_c^2(S_{\tilde{K}_f}, \mathbf{Z}_p)_{\mathrm{torsion}} = 0$ , where*

$$\tilde{K}_f = \{k \in K^1(\mathfrak{M}) : \det(k) \equiv 1 \pmod{\mathfrak{q}}\},$$

*then there exists a pair of characters  $\phi = (\phi_1, \phi_2)$  such that  $\chi = \phi_1/\phi_2$  and there is an  $\mathcal{R}$ -algebra surjection*

$$\mathbf{T}/\mathbf{I}_\phi \twoheadrightarrow \mathcal{R}/(L^{\mathrm{int}}(0, \chi)).$$

*Remark.* As noted before, this result is true, in fact, for characters  $\chi$  of infinity type  $z^{m+2}\bar{z}^{-m}$  for  $m \in \mathbf{N}_{\geq 0}$ .

*Proof.* Let  $\phi_1$  be a Hecke character with conductor  $\mathfrak{q}$  of infinity type  $z$  (for existence see, e.g. Lemma 24 of [Ber08]). This is the character used in the proof of [Ber08] Theorem 29 and  $K_f = \tilde{K}_f$  for this pair  $(\phi_1, \phi_1/\chi)$ , so the theorem follows from Proposition 9, Theorem 10, and Lemma 11, together with the comments at the beginning of Section 3.4.  $\square$

A similar result can be deduced for characters  $\chi$  satisfying  $\bar{\chi} = \chi^c$  by taking as  $\phi_1$  the character used in the proof of [Ber08] Theorem 29. Its construction is more involved and we refer the reader to the account in [Ber08] §5.2 and 5.3. The conductor  $\mathfrak{M}_1$  of  $\phi_1$  in this case is given by  $r\mathcal{D}$  for  $\mathcal{D}$  the different of  $F$  and  $r \in \mathbf{Z}$  any integer coprime to  $(p)\mathfrak{M}$ , but such that no inert prime congruent to  $-1$  modulo  $p$  divides  $r$  with multiplicity one.

To be able to apply Lemma 2 in Section 5 and to satisfy the assumption in Proposition 12 we want to impose the following extra condition on the conductor  $\mathfrak{M}_1$ :

( $\phi$ ) 1 is the only unit in  $\mathcal{O}^*$  congruent to 1 modulo  $\mathfrak{M}_1$ , and

$$v \mid \mathfrak{M}_1 \Rightarrow v = \bar{v} \text{ and } \#\mathcal{O}_v/\mathfrak{P}_v \not\equiv \pm 1 \pmod{p},$$

We therefore assume in addition that  $p \nmid \#\mathrm{Cl}(F)$  and that  $\ell \not\equiv \pm 1 \pmod{p}$  for  $\ell \mid d_F$ . Also we choose  $r$  appropriately such that  $p \nmid (\mathcal{O}/r)^*$  and that ( $\phi$ ) holds.

We leave the counterpart of Theorem 13 for characters  $\chi$  satisfying  $\bar{\chi} = \chi^c$  to the interested reader and instead give the following result, which does not require torsion freeness. By Lemma 1 unramified characters  $\chi$  satisfy  $\chi^c = \bar{\chi}$ , so we deduce from Proposition 9 together with Lemma 11, Theorem 10, and Proposition 12:

**THEOREM 14.** *Assume in addition that  $p \nmid \#\mathrm{Cl}(F)$  and that  $\ell \not\equiv \pm 1 \pmod{p}$  for  $\ell \mid d_F$ . Let  $\chi$  be an unramified Hecke character of infinity type  $z^2$ . Then there exists a pair of characters  $\phi = (\phi_1, \phi_2)$  satisfying ( $\phi$ ) such that  $\chi = \phi_1/\phi_2$  and there is an  $\mathcal{R}$ -algebra surjection*

$$\mathbf{T}/\mathbf{I}_\phi \twoheadrightarrow \mathcal{R}/(L^{\mathrm{int}}(0, \chi)).$$

$\square$

### 3.6 Discussion of results

These are the first such cohomological congruences between Eisenstein series and cuspforms for  $\mathrm{GL}_2$  over an imaginary quadratic field, except for the results for degree 2 Eisenstein classes associated to unramified characters in [Fel00]. There are two options: either these congruences first arise for  $\mathrm{GL}_2/F$  or they show that congruences over  $\mathbf{Q}$  can be lifted, in accordance with Langlands functoriality. The congruences constructed in [Fel00] turn out to be base changes of congruences over  $\mathbf{Q}$  (see [Fel00] Satz 3.3).

Recall from [GL79] Theorem 2 and [Cre92] p. 413 that a cuspform over  $F$  is a base change if and only if its Hecke eigenvalues at complex conjugate places coincide. Observe that if  $\bar{\chi} \neq \chi^c$  then the Hecke eigenvalues of our Eisenstein cohomology class  $\mathrm{Eis}(\phi)$  (and all twists by a character) are distinct at complex conjugate places (see (E2) for the definition of the eigenvalues). Therefore in this case our congruences are new, i.e., are not base changed.

If  $\bar{\chi} = \chi^c$  then the proof of Lemma 8 implies that there exists a twist of the Eisenstein class such that its eigenvalues at conjugate places coincide. However, we cannot determine if the congruences are base changed, as for cohomology in degree 1 the arguments of [HLR86] do not apply. We plan to investigate this question further. We refer the reader to Remark 4.6 of [BeK08], where we exhibit conditions under which this question can be answered: Consider split  $p$  and let  $\rho_0 : G_{\Sigma_\phi} \rightarrow \mathrm{GL}_2(\mathcal{R}/\mathfrak{m}_{\mathcal{R}})$  be a continuous representation of the form

$$\begin{pmatrix} 1 & * \\ 0 & \chi_{\mathfrak{p}} \epsilon \pmod{\mathfrak{m}_{\mathcal{R}}} \end{pmatrix}$$

with scalar centralizer. Under assumptions ensuring the uniqueness of  $\rho_0$  up to isomorphism we then prove that no character twist of the congruent cuspforms of Section 3.5 arises from base change.

## 4. The case of unramified characters

In this section we will prove Proposition 12, i.e., show the existence of an integral lift of the constant term of the Eisenstein cohomology class  $\mathrm{Eis}(\phi)$ , as defined in §3.2. Our strategy is to find an involution on the boundary cohomology such that the restriction map surjects onto the  $-1$ -eigenspace of this involution, i.e., such that (for each connected component of  $\bar{S}_{K_f}$ )

$$H^1(\Gamma \backslash \bar{\mathbf{H}}_3, \mathcal{R}) \xrightarrow{\mathrm{res}} H^1(\partial(\Gamma \backslash \bar{\mathbf{H}}_3), \mathcal{R})^- \subset H^1(\partial(\Gamma \backslash \bar{\mathbf{H}}_3), \mathcal{R}),$$

where the superscript ‘ $-$ ’ indicates the  $-1$ -eigenspace. We prove the existence of such an involution for all maximal arithmetic subgroups of  $\mathrm{SL}_2(F)$ , extending a result of Serre for  $\mathrm{SL}_2(\mathcal{O})$ . Proposition 12 is then proven by showing that  $\mathrm{res}(\mathrm{Eis}(\phi))$  lies in this  $-1$ -eigenspace.

### 4.1 Involutions and the image of the restriction map

Let  $\Gamma \subset G(\mathbf{Q})$  be an arithmetic subgroup. Given an involution  $\iota$  on  $X = \Gamma \backslash \bar{\mathbf{H}}_3$  or  $\partial(\Gamma \backslash \bar{\mathbf{H}}_3)$  we define an involution on  $H^1(X, \mathcal{R})$  via the pullback of  $\iota$  on the level of singular cocycles. Assuming that we have an orientation-reversing involution on  $\Gamma \backslash \bar{\mathbf{H}}_3$  such that

$$H^1(\Gamma \backslash \bar{\mathbf{H}}_3, \mathcal{R}) \xrightarrow{\mathrm{res}} H^1(\partial(\Gamma \backslash \bar{\mathbf{H}}_3), \mathcal{R})^- \subset H^1(\partial(\Gamma \backslash \bar{\mathbf{H}}_3), \mathcal{R})$$

we show that the map is, in fact, surjective. The existence of such an involution will be shown for maximal arithmetic subgroups in the following sections. We first recall:

**THEOREM 15** (Poincaré and Lefschetz duality). *Let  $R$  be a Dedekind domain in which 2 and 3 are invertible. Let  $\iota$  be an orientation-reversing involution on  $\Gamma \backslash \bar{\mathbf{H}}_3$ . Denoting by a superscript  $+$  (resp.  $-$ ) the  $+1$ - (resp.  $-1$ -) eigenspaces for the induced involutions on cohomology groups, we have*

perfect pairings

$$H_c^r(\Gamma \backslash \overline{\mathbf{H}}_3, R)^\pm \times H^{3-r}(\Gamma \backslash \overline{\mathbf{H}}_3, R)^\mp \rightarrow R \text{ for } 0 \leq r \leq 3$$

and

$$H^r(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R)^\pm \times H^{2-r}(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R)^\mp \rightarrow R \text{ for } 0 \leq r \leq 2.$$

Furthermore, the maps in the exact sequence

$$H^1(\Gamma \backslash \overline{\mathbf{H}}_3, R) \xrightarrow{\text{res}} H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R) \xrightarrow{\partial} H_c^2(\Gamma \backslash \overline{\mathbf{H}}_3, R)$$

are adjoint, i.e.,

$$\langle \text{res}(x), y \rangle = \langle x, \partial(y) \rangle.$$

*References.* Serre states this in the proof of Lemma 11 in [Ser70] for field coefficients, [AS86] Lemma 1.4.3 proves the perfectness for fields  $R$  and [Urb95] Theorem 1.6 for Dedekind domains as above. Other references for this Lefschetz or “relative” Poincaré duality for oriented manifolds with boundary are [May99] Chapter 21, §4 and [Gre67] (28.18). The pairings are given by the cup product and evaluation on the respective fundamental classes. We use that  $\overline{\mathbf{H}}_3$  is an oriented manifold with boundary and that  $\Gamma$  acts on it properly discontinuously and without reversing orientation. The lemma in [Fel00] §1.1 shows that the order of any finite subgroup of  $G(\mathbf{Q})$  is divisible only by 2 or 3. See also [Ber05] Theorem 5.1 and Lemma 5.2.  $\square$

LEMMA 16. *Suppose in addition to the conditions of the previous theorem that  $R$  is a complete discrete valuation ring with finite residue field of characteristic  $p > 2$ . Suppose that we have an involution  $\iota$  as in the theorem such that*

$$H^1(\Gamma \backslash \overline{\mathbf{H}}_3, R) \xrightarrow{\text{res}} H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R)^\epsilon,$$

where  $\epsilon = +1$  or  $-1$ . Then, in fact, the restriction map is surjective.

*Proof.* Let  $\mathfrak{m}$  denote the maximal ideal of  $R$ . Since the cohomology modules are finitely generated (so the Mittag-Leffler condition is satisfied for  $\varprojlim H^1(\cdot, R/\mathfrak{m}^r)$ ), it suffices to prove the surjectivity for each  $r \in \mathbf{N}$  of

$$H^1(\Gamma \backslash \overline{\mathbf{H}}_3, R/\mathfrak{m}^r) \rightarrow H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r)^\epsilon.$$

For these coefficient systems we are dealing with finite groups and can count the number of elements in the image and the eigenspace of the involution; they turn out to be the same. We observe that  $H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r) = H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r)^+ \oplus H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r)^-$  and that, by the last lemma,

$$\#H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r)^+ = \#H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r)^-.$$

Similarly we deduce from the adjointness of  $\text{res}$  and  $\partial$  and the perfectness of the pairings that  $\text{im}(\text{res})^\perp = \text{im}(\text{res})$  and so

$$\#\text{im}(\text{res}) = \frac{1}{2} \#H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R/\mathfrak{m}^r).$$

$\square$

## 4.2 Involutions for maximal arithmetic subgroups of $\text{SL}_2(F)$

For  $\eta \in G(\mathbf{Q})$  let  $B^\eta$  be the parabolic subgroup defined by  $B^\eta(\mathbf{Q}) = \eta^{-1}B(\mathbf{Q})\eta$ . Let  $\Gamma \subset G(\mathbf{Q})$  be an arithmetic subgroup. The set  $\{B^\eta : [\eta] \in B(\mathbf{Q}) \backslash G(\mathbf{Q})/\Gamma\}$  is a set of representatives for the  $\Gamma$ -conjugacy classes of Borel subgroups. Let  $U^\eta$  be the unipotent radical of  $B^\eta$ . For  $D \in \mathbf{P}^1(F)$  let  $\Gamma_D = \Gamma \cap U_D$ , where  $U_D$  is the unipotent subgroup of  $\text{SL}_2(F)$  fixing  $D$ . Note that if  $D_\eta \in \mathbf{P}^1(F)$  corresponds to  $[\eta] \in B(\mathbf{Q}) \backslash G(\mathbf{Q})$  under the isomorphism of  $B(\mathbf{Q}) \backslash G(\mathbf{Q}) \cong \mathbf{P}^1(F)$  given by right action on  $[0 : 1] \in \mathbf{P}^1(F)$  then we have that  $U_{D_\eta} = U^\eta(\mathbf{Q})$  and  $\Gamma_{D_\eta} = \Gamma \cap U^\eta(\mathbf{Q}) =: \Gamma_{U^\eta}$ .

Let  $U(\Gamma)$  be the direct sum  $\bigoplus_{[D] \in \mathbf{P}^1(F)/\Gamma} \Gamma_D$ . Up to canonical isomorphism this is independent of the choice of representatives  $[D] \in \mathbf{P}^1(F)/\Gamma$ . Since  $U(\Gamma)$  is abelian we use additive notation in the following. The inclusions  $\Gamma_D \hookrightarrow \Gamma$  define a homomorphism

$$\alpha : U(\Gamma) \rightarrow \Gamma^{\text{ab}}.$$

For  $\Gamma = \text{SL}_2(\mathcal{O})$  [Ser70] shows that there is a well-defined action of complex conjugation on  $U(\text{SL}_2(\mathcal{O}))$  induced by the complex conjugation action on the matrix entries of  $G_\infty = \text{GL}_2(\mathbf{C})$ . Denoting by  $U^+$  the set of elements of  $U(\text{SL}_2(\mathcal{O}))$  invariant under the involution and by  $U'$  the set of elements  $u + \bar{u}$  for  $u \in U(\text{SL}_2(\mathcal{O}))$ , Serre proves:

**THEOREM 17** (Serre [Ser70] Théorème 9). *For imaginary quadratic fields  $F$  other than  $\mathbf{Q}(\sqrt{-1})$  or  $\mathbf{Q}(\sqrt{-3})$  the kernel of the homomorphism  $\alpha : U(\text{SL}_2(\mathcal{O})) \rightarrow \text{SL}_2(\mathcal{O})^{\text{ab}}$  satisfies the inclusions*

$$6U' \subseteq \ker(\alpha) \subseteq U^+.$$

In the following we generalize this theorem to all maximal arithmetic subgroups. After we had discovered this generalization we found out that it had already been stated in [BN92], but for our application we need more detail than is provided there.

For  $\mathfrak{b}$  a fractional ideal let

$$H(\mathfrak{b}) := \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{SL}_2(F) \mid a, d \in \mathcal{O}, b \in \mathfrak{b}, c \in \mathfrak{b}^{-1} \right\}.$$

This is a maximal arithmetic subgroup of  $\text{SL}_2(F)$  and any maximal arithmetic subgroup is conjugate to  $H(\mathfrak{b})$  (see [EGM98] Prop. 7.4.5). In order to study the structure of  $U(H(\mathfrak{b}))$  we define  $j : \mathbf{P}^1(F) \rightarrow \text{Cl}(F)$  to be the map

$$j([z_1 : z_2]) = [z_1 \mathfrak{b} + z_2 \mathcal{O}].$$

**THEOREM 18.** *For  $\Gamma = H(\mathfrak{b})$ , the induced map*

$$j : \mathbf{P}^1(F)/\Gamma \rightarrow \text{Cl}(F)$$

*is a bijection.*

*Proof.* Let  $(x_1, x_2), (y_1, y_2) \in F \times F$ . It is easy to check (see [EGM98] Theorem VII 2.4 for  $\text{SL}_2(\mathcal{O})$ , [Ber05] Lemma 5.10 for the general case) that the following are equivalent:

- (1)  $x_1 \mathfrak{b} + x_2 \mathcal{O} = y_1 \mathfrak{b} + y_2 \mathcal{O}$ .
- (2) There exists  $\sigma \in H(\mathfrak{b})$  such that  $(x_1, x_2) = (y_1, y_2) \sigma$ .

It remains to show the surjectivity of  $j$ . Given a class in  $\text{Cl}(F)$  take  $\mathfrak{a} \subset \mathcal{O}$  representing it. By the Chinese Remainder Theorem one can choose  $z_2 \in \mathcal{O}$  such that

- $\text{ord}_\varphi(z_2) = \text{ord}_\varphi(\mathfrak{a})$  if  $\varphi \mid \mathfrak{a}$ .
- $\text{ord}_\varphi(z_2) = 0$  if  $\varphi \nmid \mathfrak{a}$ ,  $\text{ord}_\varphi(\mathfrak{b}) \neq 0$ .

Then one chooses  $z_1$  such that

- $\text{ord}_\varphi(z_1 \mathfrak{b}) > \text{ord}_\varphi(z_2)$  if  $\varphi \mid \mathfrak{a}$  or  $\text{ord}_\varphi(\mathfrak{b}) \neq 0$ .
- $\text{ord}_\varphi(z_1 \mathfrak{b}) = 0$  if  $\varphi \nmid z_2$ ,  $\varphi \nmid \mathfrak{a}$ , and  $\text{ord}_\varphi(\mathfrak{b}) = 0$ .

These choices ensure that  $\text{ord}_\varphi(z_1 \mathfrak{b} + z_2 \mathcal{O}) = \text{ord}_\varphi(\mathfrak{a})$  for all prime ideals  $\varphi$ . □

Following Serre [Ser70] we now calculate explicitly  $\Gamma_{[z_1 : z_2]}$  for  $\Gamma = H(\mathfrak{b})$  and  $[z_1 : z_2] \in \mathbf{P}^1(F)$ .

LEMMA 19. For  $\Gamma = H(\mathfrak{b})$ ,  $\Gamma_{[z_1:z_2]}$  is conjugate in  $H(\mathfrak{b})$  to

$$\left\{ \theta \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} \theta^{-1} : t \in \mathfrak{a}^{-2}\mathfrak{b} \right\},$$

where  $\mathfrak{a} = z_1\mathfrak{b} + z_2\mathcal{O}$  and  $\theta$  is an isomorphism  $\mathcal{O} \oplus \mathfrak{b} \xrightarrow{\sim} \mathfrak{a} \oplus \mathfrak{a}^{-1}\mathfrak{b}$  of determinant 1, i.e., such that its second exterior power

$$\Lambda^2\theta : \Lambda^2(\mathcal{O} \oplus \mathfrak{b}) = \mathfrak{b} \rightarrow \Lambda^2(\mathfrak{a} \oplus \mathfrak{a}^{-1}\mathfrak{b}) = \mathfrak{a} \otimes \mathfrak{a}^{-1}\mathfrak{b} = \mathfrak{b}$$

is the identity.

*Proof.* The main change to [Ser70] §3.6 is that we consider the lattice  $L := \mathcal{O} \oplus \mathfrak{b}$  instead of  $\mathcal{O}^2$ . We claim there exists a projective rank 1 submodule  $E$  of  $L$  containing a multiple of  $(z_1, z_2)$ . Let  $E$  be the kernel of the  $\mathcal{O}$ -homomorphism  $L = \mathcal{O} \oplus \mathfrak{b} \rightarrow F$  given by  $(x, y) \mapsto yz_1 - xz_2$ . Since the image is  $\mathfrak{a} = z_1\mathfrak{b} + z_2\mathcal{O}$ , we get  $L/E \cong \mathfrak{a}$ , so  $L/E$  is projective of rank 1 and  $L$  decomposes as  $E \oplus L/E$ .

By definition  $\Gamma_{[z_1:z_2]}$  fixes  $L \cap \{\lambda(z_1, z_2), \lambda \in F\}$ , but this is exactly  $E$ . Since  $\Gamma_{[z_1:z_2]}$  is unipotent it can therefore be identified with  $\text{Hom}_{\mathcal{O}}(L/E, E)$ . For any fractional ideal  $\mathfrak{a}$ ,  $\Lambda^2(\mathfrak{a}) = 0$  and so  $\mathfrak{b} = \Lambda^2(L) = \Lambda^2(E \oplus L/E) = E \otimes_{\mathcal{O}} L/E$  so  $E$  is isomorphic to  $(L/E)^{-1} \otimes \mathfrak{b}$ . This implies an isomorphism  $\text{Hom}_{\mathcal{O}}(L/E, E) = (L/E)^{-1} \otimes E \cong (L/E)^{-1} \otimes (L/E)^{-1} \otimes \mathfrak{b} \cong \mathfrak{a}^{-2}\mathfrak{b}$ . Choosing an isomorphism  $\theta : L \rightarrow L/E \oplus E \cong \mathfrak{a} \oplus \mathfrak{a}^{-1}\mathfrak{b}$  of determinant 1 we can represent  $\Gamma_{[z_1:z_2]}$  as stated above.  $\square$

Note that since  $H(\mathfrak{b})$  is the stabilizer of any lattice  $\mathfrak{m} \oplus \mathfrak{n}$  with  $\mathfrak{m}$  and  $\mathfrak{n}$  fractional ideals of  $F$  such that  $\mathfrak{m}^{-1}\mathfrak{n} = \mathfrak{b}$ , one can deduce

LEMMA 20. Let  $\mathfrak{a}, \mathfrak{b}$  be two fractional ideals of  $F$ . If  $[\mathfrak{a}] = [\mathfrak{b}]$  in  $\text{Cl}(F)/\text{Cl}(F)^2$ , then  $H(\mathfrak{a}) = H(\mathfrak{b})^\gamma$  with  $\gamma \in \text{GL}_2(F)$ . If the fractional ideals differ by the square of an  $\mathcal{O}$ -ideal, then  $\gamma$  can be taken to be in  $\text{SL}_2(F)$ .

If the class of  $\mathfrak{b}$  in  $\text{Cl}(F)$  is a square,  $H(\mathfrak{b})$  is isomorphic to  $\text{SL}_2(\mathcal{O})$  by Lemma 20, and the involution on  $U(\text{SL}_2(\mathcal{O}))$  induced by complex conjugation and Serre's Théorème 9 can easily be transferred to  $U(H(\mathfrak{b}))$ . We therefore turn our attention to the case when

$$[\mathfrak{b}] \text{ is not a square in } \text{Cl}(F).$$

Note that this implies that  $[\mathfrak{b}]$  has even order, since any odd order class can be written as a square.

Define an involution on  $H(\mathfrak{b})$  to be the composition of complex conjugation with an Atkin-Lehner involution, i.e., by

$$H = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mapsto A\bar{H}A^{-1} = \begin{pmatrix} \bar{d} & -\text{Nm}(\mathfrak{b})\bar{c} \\ -\bar{b}\text{Nm}(\mathfrak{b})^{-1} & \bar{a} \end{pmatrix},$$

$$\text{where } A = \begin{pmatrix} 0 & 1 \\ -\text{Nm}(\mathfrak{b})^{-1} & 0 \end{pmatrix}.$$

Like Serre, we will choose a set of representatives for the cusps  $\mathbf{P}^1(F)/H(\mathfrak{b})$  on which this involution acts. For this we observe that if  $\Gamma_{[z_1:z_2]}$  fixes  $[z_1 : z_2]$  then  $A\bar{\Gamma}_{[z_1:z_2]}A^{-1}$  fixes  $[\bar{z}_1 : \bar{z}_2]A^{-1} = [\bar{z}_2 : -\text{Nm}(\mathfrak{b})\bar{z}_1]$ . We use the isomorphism  $j : \mathbf{P}^1(F)/H(\mathfrak{b}) \rightarrow \text{Cl}(F)$  to show that this action on the cusps is fixpoint-free. We observe that if  $j([z_1 : z_2]) = \mathfrak{a}$  then  $j([\bar{z}_1 : \bar{z}_2]A^{-1}) = [\bar{z}_2\mathfrak{b} + \text{Nm}(\mathfrak{b})\bar{z}_1\mathcal{O}] = [\bar{\mathfrak{a}}\mathfrak{b}]$ . Note that  $[\mathfrak{a}] \neq [\bar{\mathfrak{a}}\mathfrak{b}]$  in  $\text{Cl}(F)$  since otherwise  $[\mathfrak{a}^2] = [\text{Nm}(\mathfrak{a})\mathfrak{b}] = [\mathfrak{b}]$ , i.e.,  $[\mathfrak{b}]$  a square, contradicting our hypothesis. So  $\text{Cl}(F)$  can be partitioned into pairs  $(\mathfrak{a}_i, \bar{\mathfrak{a}}_i\mathfrak{b})$ .

Choosing  $[z_1^i : z_2^i] \in \mathbf{P}^1(F)$  such that  $\mathfrak{a}_i = z_1^i\mathfrak{b} + z_2^i\mathcal{O}$  we obtain

$$U(H(\mathfrak{b})) = \bigoplus_{(\mathfrak{a}_i, \bar{\mathfrak{a}}_i\mathfrak{b})} (\Gamma_{[z_1^i:z_2^i]} \oplus A\bar{\Gamma}_{[z_1^i:z_2^i]}A^{-1}).$$

Our choice of representatives of  $\mathbf{P}^1(F)/H(\mathfrak{b})$  shows that the involution operates on  $U(H(\mathfrak{b}))$  and, in fact, by identifying  $\Gamma_{[z_1^i:z_2^i]}$  with  $\left\{ \theta \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \theta^{-1} : s \in \mathfrak{a}_i^{-2}\mathfrak{b} \right\}$  for  $\theta : \mathcal{O} \oplus \mathfrak{b} \rightarrow \mathfrak{a}_i \oplus \mathfrak{a}_i^{-1}\mathfrak{b}$  and  $A\bar{\Gamma}_{[z_1^i:z_2^i]}A^{-1}$  with  $\left\{ \theta' \begin{pmatrix} 1 & 0 \\ -t & 1 \end{pmatrix} \theta'^{-1} : t \in \bar{\mathfrak{a}}_i^{-2}\mathfrak{b}^{-1} \right\}$  for  $\theta' = A\bar{\theta}A^{-1} : \mathcal{O} \oplus \mathfrak{b} \rightarrow \bar{\mathfrak{a}}_i^{-1} \oplus \bar{\mathfrak{a}}_i\mathfrak{b}$ , we can describe the involution on each of the pairs as

$$(s, t) \in \mathfrak{a}_i^{-2}\mathfrak{b} \oplus \bar{\mathfrak{a}}_i^{-2}\mathfrak{b}^{-1} \mapsto (\bar{t}\text{Nm}(\mathfrak{b}), \bar{s}\text{Nm}(\mathfrak{b})^{-1}).$$

Now denote by  $U^+$  the set of elements of  $U(H(\mathfrak{b}))$  invariant under the involution  $H \mapsto A\bar{H}A^{-1}$ , and by  $U'$  the set of elements  $u + A\bar{u}A^{-1}$  for  $u \in U(H(\mathfrak{b}))$ .

**THEOREM 21.** *For  $\Gamma = H(\mathfrak{b})$  with  $[\mathfrak{b}]$  a non-square in  $\text{Cl}(F)$ , the kernel  $N$  of the homomorphism*

$$\alpha : U(\Gamma) \rightarrow \Gamma^{\text{ab}}$$

*coming from the inclusion  $\Gamma_D \hookrightarrow \Gamma$  for  $D \in \mathbf{P}^1(F)$  satisfies  $6U' \subset N \subset U^+$ .*

*Proof.* With small modifications, we follow Serre's proof of his Théorème 9. As in Serre's case, it suffices to prove the inclusion  $6U' \subset N$ , i.e., that  $6(u + A\bar{u}A^{-1})$  maps to an element of the commutator  $[H(\mathfrak{b}), H(\mathfrak{b})]$ :

Suppose that we have  $6U' \subset N$ , but that there exists an element  $u \in N$  not contained in  $U^+$ . Then the subgroup of  $N$  generated by  $6U'$  and  $u$  has rank  $\#\text{Cl}(F) + 1$ . This contradicts the fact that the kernel of  $\alpha$  has rank  $\#\text{Cl}(F)$  (see [Ser70] Théorème 7). (The latter is proven by showing dually that the rank of the image of the restriction map  $H^1(H(\mathfrak{b}) \setminus \bar{\mathbf{H}}_3, R) \rightarrow H^1(\partial(H(\mathfrak{b}) \setminus \bar{\mathbf{H}}_3), R)$  has half the rank of that of the boundary cohomology. This we showed in the proof of Lemma 16).

To prove  $6U' \subset N$  we make use of Serre's Proposition 6:

**PROPOSITION 22** ([Ser70] Proposition 6). *Let  $\mathfrak{q}$  be a fractional ideal of  $F$  and let  $t \in \mathfrak{q}$  and  $t' = \bar{t}/\text{Nm}(\mathfrak{q})$  so that  $t' \in \mathfrak{q}^{-1}$ . Put  $x_t = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$  and  $y_{t'} = \begin{pmatrix} 1 & 0 \\ -t' & 1 \end{pmatrix}$ . Then  $(x_t y_{t'})^6$  lies in the commutator subgroup of  $H(\mathfrak{q})$ .*

Put  $\mathfrak{a} := z_1\mathfrak{b} + z_2\mathcal{O}$ . If  $u \in \Gamma_{[z_1:z_2]}$ , identify it with  $\theta^{-1} \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} \theta$  for some  $t \in \mathfrak{a}^{-2}\mathfrak{b}$  and  $\theta : \mathcal{O} \oplus \mathfrak{b} \rightarrow \mathfrak{a} \oplus \mathfrak{a}^{-1}\mathfrak{b}$  of determinant 1. One easily checks that  $A\bar{u}A^{-1}$  then corresponds to  $(A\bar{\theta}A^{-1}) \begin{pmatrix} 1 & 0 \\ -\bar{t}\text{Nm}(\mathfrak{b})^{-1} & 1 \end{pmatrix} (A\bar{\theta}A^{-1})$ . Like Serre, we use that since  $[\bar{\mathfrak{a}}] = [\mathfrak{a}^{-1}]$ ,  $A\bar{u}A^{-1}$  is also given by Theorem 18 by  $B^{-1}\theta^{-1} \begin{pmatrix} 1 & 0 \\ -t' & 1 \end{pmatrix} \theta B$  for  $t' = \bar{t}\text{Nm}(\mathfrak{b})^{-1}\text{Nm}(\mathfrak{a})^2$  and  $B \in H(\mathfrak{b})$  taking  $\begin{pmatrix} \text{Nm}(\mathfrak{b})\bar{z}_2 \\ \bar{z}_1 \end{pmatrix}$  to  $\text{Nm}(\mathfrak{a})^{-1} \begin{pmatrix} \text{Nm}(\mathfrak{b})\bar{z}_2 \\ \bar{z}_1 \end{pmatrix}$ .

Since  $\theta^{-1}x_t y_{t'}\theta$  is a representative of  $u + BA\bar{u}A^{-1}B^{-1}$ , we deduce from the above proposition with  $\mathfrak{q} = \mathfrak{a}^{-2}\mathfrak{b}$  that  $6(u + BA\bar{u}A^{-1}B^{-1})$  and therefore  $6(u + A\bar{u}A^{-1})$  lie in  $[H(\mathfrak{b}), H(\mathfrak{b})]$ .  $\square$

The following observation links  $U(\Gamma)$  to the cohomology of the boundary components:

**LEMMA 23.** *For imaginary quadratic fields  $F$  other than  $\mathbf{Q}(\sqrt{-1})$  or  $\mathbf{Q}(\sqrt{-3})$ ,  $\Gamma \subset \text{SL}_2(F)$  an arithmetic subgroup,  $P$  a parabolic subgroup of  $\text{Res}_{F/\mathbf{Q}}(\text{SL}_{2/F})$  with unipotent radical  $U_P$ , and  $R$  a ring in which 2 is invertible we have*

$$H^1(\Gamma_P, R) \cong H^1(\Gamma_{U_P}, R),$$

where  $\Gamma_P = \Gamma \cap P(\mathbf{Q})$  and  $\Gamma_{U_P} = \Gamma \cap U_P(\mathbf{Q})$ .

*Proof.* Serre shows in [Ser70] Lemme 7 that  $\Gamma_{U_P} \triangleleft \Gamma_P$  and that the quotient  $W_P = \Gamma_P/\Gamma_{U_P}$  can be identified with a subgroup of the roots of unity of  $F$ , i.e., of  $\{\pm 1\}$  since  $F \neq \mathbf{Q}(\sqrt{-1}), \mathbf{Q}(\sqrt{-3})$ . The Lemma follows from the Inflation-Restriction sequence. See also [Tay] p.110.  $\square$

By (2), (4) (in Section 1.5), and Lemma 23 we have

$$H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R) \cong \coprod_{[\eta] \in \mathbf{P}^1(F)/\Gamma} H^1(\Gamma_{U_P}, R) = H^1(U(\Gamma), R). \quad (8)$$

We now reinterpret Serre's Theorem and its generalization as follows:

**PROPOSITION 24.** *For imaginary quadratic fields  $F$  other than  $\mathbf{Q}(\sqrt{-1})$  or  $\mathbf{Q}(\sqrt{-3})$  and  $R$  a ring in which 2 and 3 is invertible, the image of the restriction map*

$$H^1(\Gamma \backslash \overline{\mathbf{H}}_3, R) \xrightarrow{\text{res}} H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R)$$

*is contained in the  $-1$ -eigenspace of the involution induced by*

$$\begin{aligned} \iota : \mathbf{H}_3 &\rightarrow \mathbf{H}_3 : (z, t) \mapsto (\bar{z}, t) \text{ if } \Gamma = \text{SL}_2(\mathcal{O}); \\ \iota : \mathbf{H}_3 &\rightarrow \mathbf{H}_3 : (z, t) \mapsto A.(\bar{z}, t) \text{ for } A = \begin{pmatrix} 0 & 1 \\ -\text{Nm}(\mathfrak{b})^{-1} & 0 \end{pmatrix} \text{ if } \Gamma = H(\mathfrak{b}) \text{ with } [\mathfrak{b}] \text{ a non-square in } \\ &\text{Cl}(F), \end{aligned}$$

*and these involutions are orientation-reversing.*

By Lemma 16 this immediately implies:

**COROLLARY 25.** *For imaginary quadratic fields  $F$  other than  $\mathbf{Q}(\sqrt{-1})$  or  $\mathbf{Q}(\sqrt{-3})$ ,  $\Gamma = \text{SL}_2(\mathcal{O})$  or  $H(\mathfrak{b})$  with  $[\mathfrak{b}]$  a non-square in  $\text{Cl}(F)$ , and  $R$  a complete discrete valuation ring in which 2 and 3 are invertible and with finite residue field of characteristic  $p > 2$ , the restriction map*

$$H^1(\Gamma \backslash \overline{\mathbf{H}}_3, R) \xrightarrow{\text{res}} H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R)^-$$

*surjects onto the  $-1$ -eigenspace of the involutions defined in the proposition.*

*Proof of Proposition 24.* Write  $I : \Gamma \rightarrow \Gamma$  for the involution

$$\begin{cases} \gamma \mapsto \bar{\gamma} & \text{if } \Gamma = \text{SL}_2(\mathcal{O}), \\ \gamma \mapsto A\bar{\gamma}A^{-1} & \text{if } \Gamma = H(\mathfrak{b}). \end{cases}$$

The involutions  $\iota$  extend canonically to  $\overline{\mathbf{H}}_3$ . One checks that for  $\gamma \in \Gamma$  we have

$$\iota(\gamma.(z, t)) = I(\gamma)\iota(z, t). \quad (9)$$

This implies that the involutions operate on  $\Gamma \backslash \mathbf{H}_3$  and  $\Gamma \backslash \overline{\mathbf{H}}_3$ , and hence on  $\partial(\Gamma \backslash \overline{\mathbf{H}}_3)$ . To show that they act by reversing the orientation note that complex conjugation corresponds to reflection in a half-plane of  $\mathbf{H}_3$  and therefore reverses the orientation. Furthermore,  $\text{GL}_2(\mathbf{C})$  acts on  $\mathbf{H}_3$  via  $A' = (\det(A)^{-\frac{1}{2}})A \in \text{SL}_2(\mathbf{C})$  and  $\text{SL}_2(\mathbf{C})$  acts without reversing orientation, as can be seen from the geometric definition of its action via the Poincaré extension of the action on  $\mathbf{P}^1(\mathbf{C})$  (see [EGM98] pp.2-3).

Using (9) one shows that under the isomorphism

$$H^1(\partial(\Gamma \backslash \overline{\mathbf{H}}_3), R) \stackrel{(8)}{\cong} H^1(U(\Gamma), R)$$

$\iota$  corresponds to the involution on  $H^1(U(\Gamma), R) = \text{Hom}(U(\Gamma), R)$  given by  $\varphi \mapsto I(\varphi)$ , where  $I(\varphi)(u) := \varphi(I(u))$ .

We can therefore check that the image of the restriction maps is contained in the  $-1$ -eigenspace on the level of group cohomology: The restriction map is given by

$$\mathrm{Hom}(\Gamma^{\mathrm{ab}}, R) \rightarrow \mathrm{Hom}(U(\Gamma), R) : \varphi \mapsto \varphi \circ \alpha.$$

By Serre's theorem and Theorem 21,  $0 = \varphi(\alpha(uI(u))) = \varphi(\alpha(u)) + \varphi(\alpha(I(u)))$ , so  $I(\varphi \circ \alpha)(u) = \varphi(\alpha(I(u))) = -\varphi(\alpha(u))$  for any  $u \in U(\Gamma)$ .  $\square$

### 4.3 Integral lift of constant term

Recall the statement of Proposition 12:

PROPOSITION 26 (=Proposition 12). *Let  $\chi = \phi_1/\phi_2$  be an unramified Hecke character of infinity type  $z^2$ . Assume that 1 is the only unit in  $\mathcal{O}^*$  congruent to 1 modulo the conductor of  $\phi_1$ . Let  $K_f$  and  $\mathrm{Eis}(\phi)$  be defined as in Section 3.2. Assume  $\mathrm{res}(\mathrm{Eis}(\phi)) \in \tilde{H}^1(\partial\bar{S}_{K_f}, \mathcal{R})$ . Then there exists  $c_\phi \in \tilde{H}^1(S_{K_f}, \mathcal{R})$  with*

$$\mathrm{res}(c_\phi) = \mathrm{res}(\mathrm{Eis}(\phi)) \in \tilde{H}^1(\partial\bar{S}_{K_f}, \mathcal{R}).$$

First observe that everywhere unramified characters with infinity type  $z^2$  exist only for  $F \neq \mathbf{Q}(\sqrt{-1}), \mathbf{Q}(\sqrt{-3})$ . For unramified  $\chi$  we have

$$K_f = \prod_{v|\mathfrak{M}_1} U^1(\mathfrak{M}_{1,v}) \prod_{v \nmid \mathfrak{M}_1} \mathrm{GL}_2(\mathcal{O}_v).$$

Recall that  $U^1(\mathfrak{M}_{1,v}) = \{k \in \mathrm{GL}_2(\mathcal{O}_v) : \det(k) \equiv 1 \pmod{\mathfrak{M}_{1,v}}\}$ . By assumption, 1 is the only unit in  $\mathcal{O}^*$  congruent to 1 modulo  $\mathfrak{M}_1$  so we get  $K_f \cap \mathrm{GL}_2(F) = \mathrm{SL}_2(\mathcal{O})$ .

Recall from §1.5 the decomposition of  $S_{K_f}$  into its connected components. The above implies that we can write  $S_{K_f}$  as a disjoint union of  $\Gamma \backslash \mathbf{H}_3$  with  $\Gamma = H(\mathfrak{b})$  for suitable fractional ideals  $\mathfrak{b}$ : For a finite idele  $a$ , denote by  $(a)$  the corresponding fractional ideal. Write

$$S_{K_f} \cong \coprod_{i=1}^{\#\pi_0(K_f)} \Gamma_{t_i} \backslash \mathbf{H}_3,$$

where  $\Gamma_{t_i} = G(\mathbf{Q}) \cap t_i K_f t_i^{-1}$  and the  $t_i \in G(\mathbf{A}_f)$  are given by  $t_i = \begin{pmatrix} \gamma_j a_k b_m & 0 \\ 0 & b_m \end{pmatrix}$ , with

- $\{\gamma_j\}$  a system of representatives of

$$\ker(\pi_0(K_f) \rightarrow \mathrm{Cl}(F)) \cong \mathcal{O}^* \backslash \prod_v \mathcal{O}_v^* / \det(K_f),$$

- $\{a_k\}$  a set of representatives of  $\mathrm{Cl}(F)/(\mathrm{Cl}(F))^2$  in  $\mathbf{A}_{F,f}^*$  (and we represent the principal ideals by (1)),
- $\{b_m^2\}$  a set representing  $\mathrm{Cl}(F)^2$ .

Note that for these choices  $\Gamma_{t_i} = H((a_k))$  and either  $a_k = 1$  or  $[(a_k)]$  is not a square in  $\mathrm{Cl}(F)$ . This allows us to apply our results for maximal arithmetic subgroups from the previous section by considering the restriction maps to the boundary separately for each connected component.

PROPOSITION 27.

$$[\mathrm{res}(\mathrm{Eis}(\phi))] \in (H^1(\partial\bar{S}_{K_f}, \mathcal{R})^-)_{\mathrm{free}},$$

where  $H^1(\partial\bar{S}_{K_f}, \mathcal{R})^-$  is defined via the isomorphism to

$$\bigoplus_{i=1}^{\#\pi_0(K_f)} H^1(\partial(\Gamma_{t_i} \backslash \bar{\mathbf{H}}_3), \mathcal{R})^-$$

where ‘-’ indicates the  $-1$ -eigenspace of the involutions defined in Proposition 24.

*Remark.* Together with Corollary 25 this shows the existence of an integral lift of the constant term and proves Proposition 12.

*Proof.* We will consider the restriction maps to the boundary separately for each connected component  $\Gamma_{t_i} \backslash \mathbf{H}_3$ :

$$H^1(\Gamma_{t_i} \backslash \mathbf{H}_3, \mathcal{R}) \xrightarrow{\text{res}} H^1(\partial(\Gamma_{t_i} \backslash \overline{\mathbf{H}}_3), \mathcal{R}) \stackrel{(2)}{\cong} \bigoplus_{[\eta] \in \mathbf{P}^1(F)/\Gamma_{t_i}} H^1(\Gamma_{t_i, B\eta} \backslash \mathbf{H}_3, \mathcal{R}),$$

where  $\Gamma_{t_i, B\eta} = \Gamma_{t_i} \cap \eta^{-1}B(\mathbf{Q})\eta$ . By (4) and Lemma 23 we have  $H^1(\Gamma_{t_i, B\eta} \backslash \mathbf{H}_3, \mathcal{R}) \cong H^1(\Gamma_{t_i, U\eta}, \mathcal{R})$ . We recall from [Ber08] Proposition 10, Lemma 11, and Proof of Proposition 16 that  $\text{res}(\text{Eis}(\phi))$  restricted to this boundary component is represented by

$$\eta_\infty^{-1} \begin{pmatrix} 1 & x \\ 0 & 1 \end{pmatrix} \eta_\infty \mapsto x \Psi_\phi(\eta_f t_i) - \frac{L(0, \bar{\chi})}{L(0, \chi)} W(\chi) \cdot \bar{x} \Psi_{w_0 \cdot \phi}(\eta_f t_i), \quad (10)$$

where  $W(\chi)$  is the root number of  $\chi$ ,  $\eta_f$  and  $\eta_\infty$  denote the images of  $\eta \in G(\mathbf{Q})$  in  $G(\mathbf{A}_f)$  and  $G(\mathbf{R})$ , respectively,  $w_0 \cdot (\phi_1, \phi_2) = (\phi_2 \cdot |\cdot|, \phi_1 \cdot |\cdot|^{-1})$ , and  $\Psi_\phi : G(\mathbf{A}_f) \rightarrow \mathbf{C}$  satisfies

$$\Psi_\phi \left( \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} k \right) = \phi_1(a) \phi_2(d) \text{ for } \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \in B(\mathbf{A}_f), k \in \prod_v \text{SL}_2(\mathcal{O}_v) \subset K_f.$$

Note that, in particular,  $\Psi_\phi(bg) = \phi_\infty^{-1}(b) \Psi_\phi(g)$  for  $b \in B(F) \subset G(\mathbf{A}_f)$ , where we use the convention introduced in §1.5 for considering  $\phi$  as a character of  $B(\mathbf{A})$ . By Lemma 1,  $\chi^c = \bar{\chi}$ , so  $L(0, \chi) = L(0, \bar{\chi})$ . Furthermore,  $W(\chi) = i^2(\chi/|\chi|)(\delta_F^{-1})$  for  $\delta_F$  the different ideal of  $F/\mathbf{Q}$  (see e.g. the proof of Proposition 2.1.7 of [AH06]). Since  $\delta_F = g'(\alpha)\mathcal{O}$ , where  $\mathcal{O} = \mathbf{Z}[\alpha]$  and  $g \in \mathbf{Z}[x]$  is the minimal polynomial of  $\alpha$  (see [Neu99] Proposition III.2.4) one checks that for all imaginary quadratic fields there exists a generator  $\delta$  of  $\delta_F$  satisfying  $\bar{\delta} = -\delta$ . We deduce therefore that in our case  $W(\chi) = 1$ .

We need to prove that (10) lies in the  $-1$ -eigenspace of the involution induced by  $u \mapsto \bar{u}$  for  $\Gamma_{t_i} = \text{SL}_2(\mathcal{O})$  and by  $u \mapsto A\bar{u}A^{-1}$  for  $\Gamma_{t_i} = H(\mathfrak{b})$ , where  $A = \begin{pmatrix} 0 & 1 \\ -N^{-1} & 0 \end{pmatrix}$  with  $N = \text{Nm}(\mathfrak{b})$ .

Case  $\Gamma_{t_i} = \text{SL}_2(\mathcal{O})$ : Recall that in this case  $t_i = \begin{pmatrix} \gamma_i b_i & 0 \\ 0 & b_i \end{pmatrix}$  for some  $\gamma_i \in \hat{\mathcal{O}}^*$  and  $b_i \in \mathbf{A}_{F,f}^*$ .

It suffices to prove that  $\Psi_\phi(\eta_f t_i) = \Psi_{w_0 \cdot \phi}(\bar{\eta}_f t_i)$ . For this we use the Bruhat decomposition of matrices in  $\text{GL}_2(F)$  given by:

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{cases} \begin{pmatrix} 1 & b/d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix} & \text{if } c = 0, \\ \begin{pmatrix} 1 & a/c \\ 0 & 1 \end{pmatrix} \begin{pmatrix} ad-bc & 0 \\ 0 & -c \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & d/c \\ 0 & 1 \end{pmatrix} & \text{otherwise.} \end{cases}$$

Since  $\Psi_\phi \left( \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} g \right) = \Psi_\phi \left( \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \right) \Psi_\phi(g)$  we can consider separately the cases

- (a)  $\eta = \begin{pmatrix} a & b \\ 0 & d \end{pmatrix}$  for  $a, b, d \in F$  and
- (b)  $\eta = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & e \\ 0 & 1 \end{pmatrix}$  for  $e \in F$ .

We check that for (a)  $\Psi_\phi \left( \eta_f \begin{pmatrix} \gamma_i b_i & 0 \\ 0 & b_i \end{pmatrix} \right) = \phi_1(\gamma_i b_i) \phi_2(b_i) \Psi_\phi(\eta_f)$  and  $\Psi_{w_0 \cdot \phi} \left( \bar{\eta}_f \begin{pmatrix} \gamma_i b_i & 0 \\ 0 & b_i \end{pmatrix} \right) =$

$\phi_2(\gamma_i)|\gamma_i|\phi_1(b_i)\phi_2(b_i)\Psi_{w_0,\phi}(\bar{\eta}_f)$ . Since  $\gamma_i \in \hat{\mathcal{O}}^*$  and  $\chi = \phi_1/\phi_2$  is unramified it suffices to show that  $\Psi_\phi(\eta_f) = \Psi_{w_0,\phi}(\bar{\eta}_f)$ . In case (b) we similarly reduce to this assertion.

In (a) we get  $\Psi_\phi(\eta_f) = \phi_{1,\infty}^{-1}(a)\phi_{2,\infty}^{-1}(d) = \frac{d}{a}$ . Since  $w_0.\phi$  has infinity type  $(\bar{z}, \bar{z}^{-1})$  this equals  $\Psi_{w_0,\phi}(\bar{\eta}_f)$ . In (b) we need to calculate the Iwasawa decomposition of  $\eta$  in  $\mathrm{GL}_2(F_v)$  if  $e \notin \mathcal{O}_v$  (at all other places  $\Psi_\phi(\eta_v) = \Psi_{w_0,\phi}(\bar{\eta}_{\bar{v}}) = 1$ ). It is given by

$$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & e \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} e^{-1} & 0 \\ 0 & e \end{pmatrix} \begin{pmatrix} -1 & 0 \\ -e^{-1} & -1 \end{pmatrix}.$$

So, if  $e \notin \mathcal{O}_v$  then  $\Psi_\phi(\eta_v) = (\phi_2/\phi_1)_v(e) = \chi_v^{-1}(e)$ , which matches  $\Psi_{w_0,\phi}(\bar{\eta}_{\bar{v}}) = (\phi_1/\phi_2)_{\bar{v}}(\bar{e})|\bar{e}|_{\bar{v}}^{-2}$  because  $\chi^c = \bar{\chi}$  and  $\chi\bar{\chi} = |\cdot|^2$ .

Case  $\Gamma_{t_i} = H(\mathfrak{b})$ : The involution maps the cusp corresponding to  $B^n$  to  $B^{\bar{\eta}A^{-1}}$ . We therefore have to prove that

$$\Psi_\phi(\eta_f t_i) = \Psi_{w_0,\phi}(\bar{\eta}_f A^{-1} t_i). \quad (11)$$

Recall that  $t_i = \begin{pmatrix} x_i b_i & 0 \\ 0 & b_i \end{pmatrix}$  for some  $x_i, b_i \in \mathbf{A}_{F,f}^*$ . Again making use of the Bruhat decomposition, we need to only consider  $\eta$  as in cases (a) and (b) above. Following the arguments used for Case (1), Case(a) reduces immediately to showing that  $\Psi_\phi(t_i) = \Psi_{w_0,\phi}(A^{-1} t_i)$ . The left hand side equals  $\phi_{1,f}(x_i b_i)\phi_{2,f}(b_i)$ , the right hand side is

$$\begin{aligned} \Psi_{w_0,\phi} \left( \begin{pmatrix} N & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} x_i b_i & 0 \\ 0 & b_i \end{pmatrix} \right) &= N^{-1} \Psi_{w_0,\phi} \left( \begin{pmatrix} b_i & 0 \\ 0 & x_i b_i \end{pmatrix} \right) \\ &= N^{-1} \phi_{1,f}(x_i b_i)\phi_{2,f}(b_i)|x_i|_f^{-1}. \end{aligned}$$

Equality follows from  $|x_i|_f^{-1} = \mathrm{Nm}(\mathfrak{b})$ .

For (b), one quickly checks that for  $\eta = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$  the two sides in (11) agree. For general  $\eta = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & e \\ 0 & 1 \end{pmatrix}$  one shows that, on the one hand,

$$\eta_f \begin{pmatrix} x_i b_i & 0 \\ 0 & b_i \end{pmatrix} = \begin{pmatrix} b_i & 0 \\ 0 & x_i b_i \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & e x_i \\ 0 & 1 \end{pmatrix},$$

and on the other hand,

$$\bar{\eta}_f A^{-1} \begin{pmatrix} x_i b_i & 0 \\ 0 & b_i \end{pmatrix} = \begin{pmatrix} x_i b_i & 0 \\ 0 & b_i N \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 & \bar{e} x_i / N \\ 0 & 1 \end{pmatrix}.$$

Since  $(x_i \bar{x}_i) = (N)$  the valuations of  $\bar{e} x_i / N$  agrees with that of  $\bar{e} x_i$ . Repeating the calculation for  $\eta = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$  and then applying the argument from Case 1(b) (since  $\chi$  is unramified we are only concerned about the valuation of the upper right hand entry) we also obtain equality.  $\square$

## 5. Bloch-Kato Conjecture for Hecke characters

Combining Theorem 6 with Theorem 13 or 14 we get lower bounds on the size of the Selmer group of Hecke characters. We want to demonstrate this application under the particular conditions of Theorem 14 and relate it to the Bloch-Kato conjecture.

**THEOREM 28.** *Assume that  $p > 3$ ,  $p \nmid d_F \# \mathrm{Cl}(F)$  and that  $\ell \not\equiv \pm 1 \pmod{p}$  for  $\ell \mid d_F$ . If  $p$  is inert in  $F/\mathbf{Q}$  then assume Conjecture 5. Let  $\chi$  be an unramified Hecke character of infinity type  $z^2$ . Then*

we have

$$\mathrm{val}_p \# \mathrm{Sel}(F, \chi_p \epsilon) \geq \mathrm{val}_p(\# \mathcal{R}/L^{\mathrm{int}}(0, \chi))$$

*Proof.* Put  $\rho := \chi_p \epsilon$ . Theorem 6 together with Lemma 8 and Theorem 14 imply

$$\mathrm{val}_p \# \mathrm{Sel}^{\Sigma_\phi \setminus \Sigma_p}(F, \chi_p \epsilon) \geq \mathrm{val}_p(\# \mathcal{R}/L^{\mathrm{int}}(0, \chi)),$$

where  $\phi = (\phi_1, \phi_2)$  is given by Theorem 14. For the definition of  $\Sigma_\phi$  see the start of §2. Recall that by  $(\phi)$  the set  $\Sigma_\phi \setminus \Sigma_p$  contains only places  $v$  such that  $\bar{v} = v$  and  $\# \mathcal{O}_v/\mathfrak{P}_v \not\equiv \pm 1 \pmod{p}$ . By Lemma 1 we have  $\chi^c = \bar{\chi}$ , which implies that  $\rho$  is anticyclotomic, and so we get  $\rho(\mathrm{Frob}_v) = \rho(\mathrm{Frob}_v^c) = \rho^{-1}(\mathrm{Frob}_v)$ , or  $\rho(\mathrm{Frob}_v) = \pm 1$ . Hence we have ensured that

$$\rho(\mathrm{Frob}_v) \not\equiv \epsilon(\mathrm{Frob}_v) \pmod{p}$$

for all  $v \in \Sigma_\phi \setminus \Sigma_p$ , so the theorem follows from applying Lemma 2.  $\square$

*Example 29.* A numerical example in which the conditions of our theorem are satisfied and a non-trivial lower bound on a Selmer group is obtained is given by the following: Let  $F = \mathbf{Q}(\sqrt{-67})$  and  $p = 19$ . One checks that 19 splits in  $F$ . Since the class number is 1, there is only one unramified Hecke character of infinity type  $z^2$ . Up to  $p$ -adic units  $L^{\mathrm{alg}}(0, \chi)$  is given by  $\frac{L(0, \chi)}{\Omega^2}$  where  $\Omega$  is the Neron period of the elliptic curve  $y^2 + y = x^3 - 7370x + 243582$ , which has conductor  $67^2$  and complex multiplication by  $\mathcal{O}$ . Using MAGMA and ComputeL [Dok04] one calculates that  $L^{\mathrm{alg}}(0, \chi) \in \mathbf{Z}_{19}$  and

$$\mathrm{val}_{19}(L^{\mathrm{alg}}(0, \chi)) = 1.$$

### 5.1 Comparison with other results

Assume from now on that  $\#\mathrm{Cl}(F) = 1$ . Let  $\Psi : F^* \setminus \mathbf{A}_F^* \rightarrow \mathbf{C}^*$  be a Hecke character of infinity type  $z^{-1}$  which satisfies  $\Psi^c = \bar{\Psi}$ . Then there exists an elliptic curve  $E$  over  $\mathbf{Q}$  with complex multiplication by  $\mathcal{O}$  and associated Grössencharacter  $\Psi$ . Consider

$$\rho = (\Psi^k \bar{\Psi}^{-j})_p \text{ for } k > 0, j \geq 0.$$

We now have the following proposition from [Dee99] (Proposition 4.4.3 and §5.3):

**PROPOSITION 30** (Dee). *The group  $\mathrm{Sel}(F, \rho)$  is finite if and only if  $\mathrm{Sel}(F, \rho^{-1}\epsilon)$  is finite. If this is the case then*

$$\#\mathrm{Sel}(F, \rho) = \#\mathrm{Sel}(F, \rho^{-1}\epsilon) < \infty.$$

By considering  $\chi = \Psi^{-2}$  for some  $\Psi$  as above and  $(k, j) = (2, 0)$ , compare therefore Theorem 28 with the following:

**THEOREM 31** (Han, [Han97]). *Suppose  $k > j + 1$ . For inert  $p$  also assume that  $\rho$  is non-trivial when restricted to  $\mathrm{Gal}(F(E_p)/F)$ . Then  $\mathrm{Sel}(F, \rho)$  is finite and*

$$\mathrm{val}_p \# \mathrm{Sel}(F, \rho) = \mathrm{val}_p(\# \mathcal{R}/L^{\mathrm{alg}}(0, \Psi^{-k} \bar{\Psi}^j)).$$

Previously, Kato proved this in the case  $k > 0$  and  $j = 0$ , cf. [Kat93]. For a similar result in the case of split  $p$  see [Guo93]. Han claims that his method extends to general class numbers. All proofs take as input the proof of the Main Conjecture of Iwasawa theory by Rubin [Rub91].

We refer to [Guo96] §3 for the proof that this statement on the size of the Selmer group is equivalent to the (critical case of the)  $p$ -part of the Bloch-Kato Tamagawa number conjecture for the motives associated to the Hecke characters.

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