

THE Λ -ADIC
SHIMURA-SHINTANI-WALDSPURGER CORRESPONDENCE

MATTEO LONGO, MARC-HUBERT NICOLE

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ABSTRACT. We generalize the Λ -adic Shintani lifting for $\mathrm{GL}_2(\mathbb{Q})$ to indefinite quaternion algebras over \mathbb{Q} .

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1. INTRODUCTION

Langlands's principle of functoriality predicts the existence of a staggering wealth of transfers (or lifts) between automorphic forms for different reductive groups. In recent years, attempts at the formulation of p -adic variants of Langlands's functoriality have been articulated in various special cases. We prove the existence of the Shimura-Shintani-Waldspurger lift for p -adic families. More precisely, Stevens, building on the work of Hida and Greenberg-Stevens, showed in [21] the existence of a Λ -adic variant of the classical Shintani lifting of [20] for $\mathrm{GL}_2(\mathbb{Q})$. This Λ -adic lifting can be seen as a formal power series with coefficients in a finite extension of the Iwasawa algebra $\Lambda := \mathbb{Z}_p[[X]]$ equipped with specialization maps interpolating classical Shintani lifts of classical modular forms appearing in a given Hida family.

Shimura in [19], resp. Waldspurger in [22] generalized the classical Shimura-Shintani correspondence to quaternion algebras over \mathbb{Q} , resp. over any number field. In the p -adic realm, Hida ([7]) constructed a Λ -adic Shimura lifting, while Ramsey ([17]) (resp. Park [12]) extended the Shimura (resp. Shintani) lifting to the overconvergent setting.

In this paper, motivated by ulterior applications to Shimura curves over \mathbb{Q} , we generalize Stevens's result to any non-split rational indefinite quaternion algebra B , building on work of Shimura [19] and combining this with a result of Longo-Vigni [9]. Our main result, for which the reader is referred to Theorem 3.8 below, states the existence of a formal power series and specialization maps interpolating Shimura-Shintani-Waldspurger lifts of classical forms in a given

p -adic family of automorphic forms on the quaternion algebra B . The Λ -adic variant of Waldspurger's result appears computationally challenging (see remark in [15, Intro.]), but it seems within reach for real quadratic fields (cf. [13]).

As an example of our main result, we consider the case of families with trivial character. Fix a prime number p and a positive integer N such that $p \nmid N$. Embed the set $\mathbb{Z}^{\geq 2}$ of integers greater or equal to 2 in $\text{Hom}(\mathbb{Z}_p^\times, \mathbb{Z}_p^\times)$ by sending $k \in \mathbb{Z}^{\geq 2}$ to the character $x \mapsto x^{k-2}$. Let f_∞ be an Hida family of tame level N passing through a form f_0 of level $\Gamma_0(Np)$ and weight k_0 . There is a neighborhood U of k_0 in $\text{Hom}(\mathbb{Z}_p^\times, \mathbb{Z}_p^\times)$ such that, for any $k \in \mathbb{Z}^{\geq 2} \cap U$, the weight k specialization of f_∞ gives rise to an element $f_k \in S_k(\Gamma_0(Np))$. Fix a factorization $N = MD$ with $D > 1$ a square-free product of an even number of primes and $(M, D) = 1$ (we assume that such a factorization exists). Applying the Jacquet-Langlands correspondence we get for any $k \in \mathbb{Z}^{\geq 2} \cap U$ a modular form f_k^{JL} on Γ , which is the group of norm-one elements in an Eichler order R of level Mp contained in the indefinite rational quaternion algebra B of discriminant D . One can show that these modular forms can be p -adically interpolated, up to scaling, in a neighborhood of k_0 . More precisely, let \mathcal{O} be the ring of integers of a finite extension F of \mathbb{Q}_p and let \mathbb{D} denote the \mathcal{O} -module of \mathcal{O} -valued measures on \mathbb{Z}_p^2 which are supported on the set of primitive elements in \mathbb{Z}_p^2 . Let Γ_0 be the group of norm-one elements in an Eichler order $R_0 \subseteq B$ containing R . There is a canonical action of Γ_0 on \mathbb{D} (see [9, §2.4] for its description). Denote by F_k the extension of F generated by the Fourier coefficients of f_k . Then there is an element $\Phi \in H^1(\Gamma_0, \mathbb{D})$ and maps $\rho_k : H^1(\Gamma_0, \mathbb{D}) \rightarrow H^1(\Gamma, F_k)$ such that $\rho(k)(\Phi) = \phi_k$, the cohomology class associated to f_k^{JL} , with k in a neighborhood of k_0 (for this we need a suitable normalization of the cohomology class associated to f_k^{JL} , which we do not touch for simplicity in this introduction). We view Φ as a quaternionic family of modular forms. To each ϕ_k we may apply the Shimura-Shintani-Waldspurger lifting ([19]) and obtain a modular form h_k of weight $k + 1/2$, level $4Np$ and trivial character. We show that this collection of forms can be p -adically interpolated. For clarity's sake, we present the liftings and their Λ -adic variants in a diagram, in which the horizontal maps are specialization maps of the p -adic family to weight k ; JL stands for the Jacquet-Langlands correspondence; SSW stands for the Shimura-Shintani-Waldspurger lift; and the dotted arrows are constructed in this paper:

$$\begin{array}{ccc}
 f_\infty & \xrightarrow{\quad} & f_k \\
 \Lambda\text{-adic JL} \downarrow & & \downarrow \text{JL} \\
 \Phi & \xrightarrow{\rho_k} & \phi_k \\
 \Lambda\text{-adic SSW} \downarrow \cdots & & \downarrow \text{SSW} \\
 \Theta & \xrightarrow{\cdots} & h_k
 \end{array}$$

More precisely, as a particular case of our main result, Theorem 3.8, we get the following

THEOREM 1.1. *There exists a p -adic neighborhood U_0 of k_0 in $\mathrm{Hom}(\mathbb{Z}_p^\times, \mathbb{Z}_p^\times)$, p -adic periods Ω_k for $k \in U_0 \cap \mathbb{Z}^{\geq 2}$ and a formal expansion*

$$\Theta = \sum_{\xi \geq 1} a_\xi q^\xi$$

with coefficients a_ξ in the ring of \mathbb{C}_p -valued functions on U_0 , such that for all $k \in U_0 \cap \mathbb{Z}^{\geq 2}$ we have

$$\Theta(k) = \Omega_k \cdot h_k.$$

Further, $\Omega_{k_0} \neq 0$.

2. SHINTANI INTEGRALS AND FOURIER COEFFICIENTS OF HALF-INTEGRAL WEIGHT MODULAR FORMS

We express the Fourier coefficients of half-integral weight modular forms in terms of period integrals, thus allowing a cohomological interpretation which is key to the production of the Λ -adic version of the Shimura-Shintani-Waldspurger correspondence. For the quaternionic Shimura-Shintani-Waldspurger correspondence of interest to us (see [15], [22]), the period integrals expressing the values of the Fourier coefficients have been computed generally by Prasanna in [16].

2.1. THE SHIMURA-SHINTANI-WALDSPURGER LIFTING. Let $4M$ be a positive integer, $2k$ an even non-negative integer and χ a Dirichlet character modulo $4M$ such that $\chi(-1) = 1$. Recall that the space of half-integral weight modular forms $S_{k+1/2}(4M, \chi)$ consists of holomorphic cuspidal functions h on the upper-half plane \mathfrak{H} such that

$$h(\gamma(z)) = j^{1/2}(\gamma, z)^{2k+1} \chi(d)h(z),$$

for all $\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \Gamma_0(4M)$, where $j^{1/2}(\gamma, z)$ is the standard square root of the usual automorphy factor $j(\gamma, z)$ (cf. [15, 2.3]).

To any quaternionic integral weight modular form we may associate a half-integral weight modular form following Shimura's work [19], as we will describe below.

Fix an odd square free integer N and a factorization $N = M \cdot D$ into coprime integers such that $D > 1$ is a product of an even number of distinct primes. Fix a Dirichlet character ψ modulo M and a positive even integer $2k$. Suppose that

$$\psi(-1) = (-1)^k.$$

Define the Dirichlet character χ modulo $4N$ by

$$\chi(x) := \psi(x) \left(\frac{-1}{x} \right)^k.$$

Let B be an indefinite quaternion algebra over \mathbb{Q} of discriminant D . Fix a maximal order \mathcal{O}_B of B . For every prime $\ell|M$, choose an isomorphism

$$i_\ell : B \otimes_{\mathbb{Q}} \mathbb{Q}_\ell \simeq \mathbb{M}_2(\mathbb{Q}_\ell)$$

such that $i_\ell(\mathcal{O}_B \otimes_{\mathbb{Z}} \mathbb{Z}_\ell) = \mathbb{M}_2(\mathbb{Z}_\ell)$. Let $R \subseteq \mathcal{O}_B$ be the Eichler order of B of level M defined by requiring that $i_\ell(R \otimes_{\mathbb{Z}} \mathbb{Z}_\ell)$ is the suborder of $\mathbb{M}_2(\mathbb{Z}_\ell)$ of upper triangular matrices modulo ℓ for all $\ell|M$. Let Γ denote the subgroup of the group R_1^\times of norm 1 elements in R^\times consisting of those γ such that $i_\ell(\gamma) \equiv \begin{pmatrix} 1 & * \\ 0 & 1 \end{pmatrix} \pmod{\ell}$ for all $\ell|M$. We denote by $S_{2k}(\Gamma)$ the \mathbb{C} -vector space of weight $2k$ modular forms on Γ , and by $S_{2k}(\Gamma, \psi^2)$ the subspace of $S_{2k}(\Gamma)$ consisting of forms having character ψ^2 under the action of R_1^\times . Fix a Hecke eigenform

$$f \in S_{2k}(\Gamma, \psi^2)$$

as in [19, Section 3].

Let V denote the \mathbb{Q} -subspace of B consisting of elements with trace equal to zero. For any $v \in V$, which we view as a trace zero matrix in $\mathbb{M}_2(\mathbb{R})$ (after fixing an isomorphism $i_\infty : B \otimes \mathbb{R} \simeq \mathbb{M}_2(\mathbb{R})$), set

$$G_v := \{\gamma \in \mathrm{SL}_2(\mathbb{R}) \mid \gamma^{-1}v\gamma = v\}$$

and put $\Gamma_v := G_v \cap \Gamma$. One can show that there exists an isomorphism

$$\omega : \mathbb{R}^\times \xrightarrow{\sim} G_v$$

defined by $\omega(s) = \beta^{-1} \begin{pmatrix} s & 0 \\ 0 & s^{-1} \end{pmatrix} \beta$, for some $\beta \in \mathrm{SL}_2(\mathbb{R})$. Let \mathfrak{t}_v be the order of $\Gamma_v \cap \{\pm 1\}$ and let γ_v be an element of Γ_v which generates $\Gamma_v \setminus \{\pm 1\} / \{\pm 1\}$. Changing γ_v to γ_v^{-1} if necessary, we may assume $\gamma_v = \omega(t)$ with $t > 0$. Define V^* to be the \mathbb{Q} -subspace of V consisting of elements with strictly negative norm. For any $\alpha = \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \in V^*$ and $z \in \mathcal{H}$, define the quadratic form

$$Q_\alpha(z) := cz^2 - 2az - b.$$

Fix $\tau \in \mathcal{H}$ and set

$$P(f, \alpha, \Gamma) := -\left(2(-\mathrm{nr}(\alpha))^{1/2}/\mathfrak{t}_\alpha\right) \int_\tau^{\gamma_\alpha(\tau)} Q_\alpha(z)^{k-1} f(z) dz$$

where $\mathrm{nr} : B \rightarrow \mathbb{Q}$ is the norm map. By [19, Lemma 2.1], the integral is independent on the choice τ , which justifies the notation.

Remark 2.1. The definition of $P(f, \alpha, \Gamma)$ given in [19, (2.5)] looks different: the above expression can be derived as in [19, page 629] by means of [19, (2.20) and (2.22)].

Let $R(\Gamma)$ denote the set of equivalence classes of V^* under the action of Γ by conjugation. By [19, (2.6)], $P(f, \alpha, \Gamma)$ only depends on the conjugacy class of α , and thus, for $\mathcal{C} \in R(\Gamma)$, we may define $P(f, \mathcal{C}, \Gamma) := P(f, \alpha, \Gamma)$ for any choice of $\alpha \in \mathcal{C}$. Also, $q(\mathcal{C}) := -\mathrm{nr}(\alpha)$ for any $\alpha \in \mathcal{C}$.

Define \mathcal{O}'_B to be the maximal order in B such that $\mathcal{O}'_B \otimes_{\mathbb{Z}} \mathbb{Z}_\ell \simeq \mathcal{O}_B \otimes_{\mathbb{Z}} \mathbb{Z}_\ell$ for all $\ell \nmid M$ and $\mathcal{O}'_B \otimes_{\mathbb{Z}} \mathbb{Z}_\ell$ is equal to the local order of $B \otimes_{\mathbb{Q}} \mathbb{Q}_\ell$ consisting of

elements γ such that $i_\ell(\gamma) = \begin{pmatrix} a & b/M \\ cM & d \end{pmatrix}$ with $a, b, c, d \in \mathbb{Z}_\ell$, for all $\ell|M$. Given $\alpha \in \mathcal{O}'_B$, we can find an integer b_α such that

$$(1) \quad i_\ell(\alpha) \equiv \begin{pmatrix} * & b_\alpha/M \\ * & * \end{pmatrix} \pmod{i_\ell(R \otimes_{\mathbb{Z}} \mathbb{Z}_\ell)}, \quad \forall \ell|M.$$

Define a locally constant function η_ψ on V by $\eta_\psi(\alpha) = \psi(b_\alpha)$ if $\alpha \in \mathcal{O}'_B \cap V$ and $\eta(\alpha) = 0$ otherwise, with $\psi(a) = 0$ if $(a, M) \neq 1$ (for the definition of locally constant functions on V in this context, we refer to [19, p. 611]).

For any $\mathcal{C} \in R(\Gamma)$, fix $\alpha_{\mathcal{C}} \in \mathcal{C}$. For any integer $\xi \geq 1$, define

$$a_\xi(\tilde{h}) := (2\mu(\Gamma \backslash \mathfrak{H}))^{-1} \cdot \sum_{\mathcal{C} \in R(\Gamma), q(\mathcal{C})=\xi} \eta_\psi(\alpha_{\mathcal{C}}) \xi^{-1/2} P(f, \mathcal{C}, \Gamma).$$

Then, by [19, Theorem 3.1],

$$\tilde{h} := \sum_{\xi \geq 1} a_\xi(\tilde{h}) q^\xi \in S_{k+1/2}(4N, \chi)$$

is called the Shimura-Shintani-Waldspurger lifting of f .

2.2. COHOMOLOGICAL INTERPRETATION. We introduce necessary notation to define the action of the Hecke action on cohomology groups; for details, see [9, §2.1]. If G is a subgroup of B^\times and S a subsemigroup of B^\times such that (G, S) is an Hecke pair, we let $\mathcal{H}(G, S)$ denote the Hecke algebra corresponding to (G, S) , whose elements are written as $T(s) = GsG = \coprod_i Gs_i$ for $s, s_i \in S$ (finite disjoint union). For any $s \in S$, let $s^* := \text{norm}(s)s^{-1}$ and denote by S^* the set of elements of the form s^* for $s \in S$. For any $\mathbb{Z}[S^*]$ -module M we let $T(s)$ act on $H^1(G, M)$ at the level of cochains $c \in Z^1(G, M)$ by the formula $(c|T(s))(\gamma) = \sum_i s_i^* c(t_i(\gamma))$, where $t_i(\gamma)$ are defined by the equations $Gs_i\gamma = Gs_j$ and $s_i\gamma = t_i(\gamma)s_j$. In the following, we will consider the case of $G = \Gamma$ and

$$S = \{s \in B^\times | i_\ell(s) \text{ is congruent to } \begin{pmatrix} 1 & * \\ 0 & * \end{pmatrix} \pmod{\ell} \text{ for all } \ell|M\}.$$

For any field L and any integer $n \geq 0$, let $V_n(L)$ denote the L -dual of the L -vector space $\mathcal{P}_n(L)$ of homogeneous polynomials in 2 variables of degree n . We let $\mathbb{M}_2(L)$ act from the right on $P(x, y)$ as $P|\gamma(x, y) := P(\gamma(x, y))$, where for $\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ we put

$$\gamma(x, y) := (ax + yb, cx + dy).$$

This also equips $V_n(L)$ with a left action by $\gamma \cdot \varphi(P) := \varphi(P|\gamma)$. To simplify the notation, we will write $P(z)$ for $P(z, 1)$.

Let F denote the finite extension of \mathbb{Q} generated by the eigenvalues of the Hecke action on f . For any field K containing F , set

$$\mathbb{W}_f(K) := H^1(\Gamma, V_{k-2}(K))^f$$

where the superscript f denotes the subspace on which the Hecke algebra acts via the character associated with f . Also, for any sign \pm , let $\mathbb{W}_f^\pm(K)$ denote the \pm -eigenspace for the action of the archimedean involution ι . Remember that ι is defined by choosing an element ω_∞ of norm -1 in R^\times such that such

that $i_\ell(\omega_\infty) \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \pmod M$ for all primes $\ell|M$ and then setting $\iota := T(\omega_\infty)$ (see [9, §2.1]). Then $\mathbb{W}_f^\pm(K)$ is one dimensional (see, e.g., [9, Proposition 2.2]); fix a generator ϕ_f^\pm of $\mathbb{W}_f^\pm(F)$.

To explicitly describe ϕ_f^\pm , let us introduce some more notation. Define

$$f|\omega_\infty(z) := (Cz + D)^{-k/2} \overline{f(\omega_\infty(\bar{z}))}$$

where $i_\infty(\omega_\infty) = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$. Then $f|\omega_\infty \in S_{2k}(\Gamma)$ as well. If the eigenvalues of the Hecke action on f are real, then we may assume, after multiplying f by a scalar, that $f|\omega_\infty = f$ (see [19, p. 627] or [10, Lemma 4.15]). In general, let $I(f)$ denote the class in $H^1(\Gamma, V_{k-2}(\mathbb{C}))$ represented by the cocycle

$$\gamma \mapsto \left[P \mapsto I_\gamma(f)(P) := \int_\tau^{\gamma(\tau)} f(z)P(z)dz \right]$$

for any $\tau \in \mathcal{H}$ (the corresponding class is independent on the choice of τ). With this notation,

$$P(f, \alpha, \Gamma) = -(2(-\text{nr}(\alpha))^{1/2}/\mathfrak{t}_\alpha) \cdot I_{\gamma_{\alpha c}}(f)(Q_{\alpha c}(z)^{k-1}).$$

Denote by $I^\pm(f) := (1/2) \cdot I(f) \pm (1/2) \cdot I(f)|\omega_\infty$, the projection of $I(f)$ to the eigenspaces for the action of ω_∞ . Then $I(f) = I^+(f) + I^-(f)$ and $I_f^\pm = \Omega_f^\pm \cdot \phi_f^\pm$, for some $\Omega_f^\pm \in \mathbb{C}^\times$.

Given $\alpha \in V^*$ of norm $-\xi$, put $\alpha' := \omega_\infty^{-1}\alpha\omega_\infty$. By [19, 4.19], we have

$$\eta(\alpha)\xi^{-1/2}P(f, \alpha, \Gamma) + \eta(\alpha')\xi^{-1/2}P(f, \alpha', \Gamma) = -\eta(\alpha) \cdot \mathfrak{t}_\alpha^{-1} \cdot I_{\gamma_\alpha}^+(Q_{\alpha c}(z)^{k-1}).$$

We then have

$$a_\xi(\tilde{h}) = \sum_{c \in R_2(\Gamma), q(c)=\xi} \frac{-\eta_\psi(\alpha c)}{2\mu(\Gamma \backslash \mathcal{H}) \cdot \mathfrak{t}_{\alpha c}} \cdot I_{\gamma_{\alpha c}}^+(Q_{\alpha c}(z)^{k-1}).$$

We close this section by choosing a suitable multiple of h which will be the object of the next section. Given $Q_\alpha(z) = cz^2 - 2az - b$ as above, with α in V^* , define $\tilde{Q}_\alpha(z) := M \cdot Q_\alpha(z)$. Then, clearly, $I^\pm(f)(\tilde{Q}_{\alpha c}(z)^{k-1})$ is equal to $M^{k-1}I^\pm(f)(Q_{\alpha c}(z)^{k-1})$. We thus normalize the Fourier coefficients by setting

$$a_\xi(h) := -\frac{a_\xi(\tilde{h}) \cdot M^{k-1} \cdot 2\mu(\Gamma \backslash \mathcal{H})}{\Omega_f^+} = \sum_{c \in R(\Gamma), q(c)=\xi} \frac{\eta_\psi(\alpha c)}{\mathfrak{t}_{\alpha c}} \cdot \phi_f^+(\tilde{Q}_{\alpha c}(z)^{k-1}).$$

So

$$(3) \quad h := \sum_{\xi \geq 1} a_\xi(h)q^\xi$$

belongs to $S_{k+1/2}(4N, \chi)$ and is a non-zero multiple of \tilde{h} .

3. THE Λ -ADIC SHIMURA-SHINTANI-WALDSPURGER CORRESPONDENCE

At the heart of Stevens’s proof lies the control theorem of Greenberg-Stevens, which has been worked out in the quaternionic setting by Longo–Vigni [9]. Recall that $N \geq 1$ is a square free integer and fix a decomposition $N = M \cdot D$ where D is a square free product of an even number of primes and M is coprime to D . Let $p \nmid N$ be a prime number and fix an embedding $\bar{\mathbb{Q}} \hookrightarrow \bar{\mathbb{Q}}_p$.

3.1. THE HIDA HECKE ALGEBRA. Fix an ordinary p -stabilized newform

$$(4) \quad f_0 \in S_{k_0}(\Gamma_1(Mp^{r_0}) \cap \Gamma_0(D), \epsilon_0)$$

of level $\Gamma_1(Mp^{r_0}) \cap \Gamma_0(D)$, Dirichlet character ϵ_0 and weight k_0 , and write \mathcal{O} for the ring of integers of the field generated over \mathbb{Q}_p by the Fourier coefficients of f_0 .

Let Λ (respectively, $\mathcal{O}[[\mathbb{Z}_p^\times]]$) denote the Iwasawa algebra of $W := 1 + p\mathbb{Z}_p$ (respectively, \mathbb{Z}_p^\times) with coefficients in \mathcal{O} . We denote group-like elements in Λ and $\mathcal{O}[[\mathbb{Z}_p^\times]]$ as $[t]$. Let $\mathfrak{h}_\infty^{\text{ord}}$ denote the p -ordinary Hida Hecke algebra with coefficients in \mathcal{O} of tame level $\Gamma_1(N)$. Denote by $\mathcal{L} := \text{Frac}(\Lambda)$ the fraction field of Λ . Let \mathcal{R} denote the integral closure of Λ in the primitive component \mathcal{K} of $\mathfrak{h}_\infty^{\text{ord}} \otimes_\Lambda \mathcal{L}$ corresponding to f_0 . It is well known that the Λ -algebra \mathcal{R} is finitely generated as Λ -module.

Denote by \mathcal{X} the \mathcal{O} -module $\text{Hom}_{\mathcal{O}\text{-alg}}^{\text{cont}}(\mathcal{R}, \bar{\mathbb{Q}}_p)$ of continuous homomorphisms of \mathcal{O} -algebras. Let $\mathcal{X}^{\text{arith}}$ the set of arithmetic homomorphisms in \mathcal{X} , defined in [9, §2.2] by requiring that the composition

$$W \hookrightarrow \Lambda \xrightarrow{\kappa} \bar{\mathbb{Q}}_p$$

has the form $\gamma \mapsto \psi_\kappa(\gamma)\gamma^{n_\kappa}$ with $n_\kappa = k_\kappa - 2$ for an integer $k_\kappa \geq 2$ (called the weight of κ) and a finite order character $\psi_\kappa : W \rightarrow \bar{\mathbb{Q}}_p$ (called the wild character of κ). Denote by r_κ the smallest among the positive integers t such that $1 + p^t\mathbb{Z}_p \subseteq \ker(\psi_\kappa)$. For any $\kappa \in \mathcal{X}^{\text{arith}}$, let P_κ denote the kernel of κ and \mathcal{R}_{P_κ} the localization of \mathcal{R} at κ . The field $F_\kappa := \mathcal{R}_{P_\kappa}/P_\kappa\mathcal{R}_{P_\kappa}$ is a finite extension of $\text{Frac}(\mathcal{O})$. Further, by duality, κ corresponds to a normalized eigenform

$$f_\kappa \in S_{k_\kappa}(\Gamma_0(Np^{r_\kappa}), \epsilon_\kappa)$$

for a Dirichlet character $\epsilon_\kappa : (\mathbb{Z}/Np^{r_\kappa}\mathbb{Z})^\times \rightarrow \bar{\mathbb{Q}}_p$. More precisely, if we write $\psi_{\mathcal{R}}$ for the character of \mathcal{R} , defined as in [6, Terminology p. 555], and we let ω denote the Teichmüller character, we have $\epsilon_\kappa := \psi_\kappa \cdot \psi_{\mathcal{R}} \cdot \omega^{-n_\kappa}$ (see [6, Cor. 1.6]). We call $(\epsilon_\kappa, k_\kappa)$ the signature of κ . We let κ_0 denote the arithmetic character associated with f_0 , so $f_0 = f_{\kappa_0}$, $k_0 = k_{\kappa_0}$, $\epsilon_0 = \epsilon_{\kappa_0}$, and $r_0 = r_{\kappa_0}$. The eigenvalues of f_κ under the action of the Hecke operators T_n ($n \geq 1$ an integer) belong to F_κ . Actually, one can show that f_κ is a p -stabilized newform on $\Gamma_1(Mp^{r_\kappa}) \cap \Gamma_0(D)$.

Let Λ_N denote the Iwasawa algebra of $\mathbb{Z}_p^\times \times (\mathbb{Z}/N\mathbb{Z})^\times$ with coefficients in \mathcal{O} . To simplify the notation, define $\Delta := (\mathbb{Z}/Np\mathbb{Z})^\times$. We have a canonical isomorphism of rings $\Lambda_N \simeq \Lambda[\Delta]$, which makes Λ_N a Λ -algebra, finitely generated as

Λ -module. Define the tensor product of Λ -algebras

$$\mathcal{R}_N := \mathcal{R} \otimes_{\Lambda} \Lambda_N,$$

which is again a Λ -algebra (resp. Λ_N -algebra) finitely generated as a Λ -module, (resp. as a Λ_N -module). One easily checks that there is a canonical isomorphism of Λ -algebras

$$\mathcal{R}_N \simeq \mathcal{R}[\Delta]$$

(where Λ acts on \mathcal{R}); this is also an isomorphism of Λ_N -algebras, when we let $\Lambda_N \simeq \Lambda[\Delta]$ act on $\mathcal{R}[\Delta]$ in the obvious way.

We can extend any $\kappa \in \mathcal{X}^{\text{arith}}$ to a continuous \mathcal{O} -algebra morphism

$$\kappa_N : \mathcal{R}_N \longrightarrow \bar{\mathbb{Q}}_p$$

setting

$$\kappa_N \left(\sum_{i=1}^n r_i \cdot \delta_i \right) := \sum_{i=1}^n \kappa(r_i) \cdot \psi_{\mathcal{R}}(\delta_i)$$

for $r_i \in \mathcal{R}$ and $\delta_i \in \Delta$. Therefore, κ_N restricted to \mathbb{Z}_p^{\times} is the character $t \mapsto \epsilon_{\kappa}(t)t^{n\kappa}$. If we denote by \mathcal{X}_N the \mathcal{O} -module of continuous \mathcal{O} -algebra homomorphisms from \mathcal{R}_N to $\bar{\mathbb{Q}}_p$, the above correspondence sets up an injective map $\mathcal{X}^{\text{arith}} \hookrightarrow \mathcal{X}_N$. Let $\mathcal{X}_N^{\text{arith}}$ denote the image of $\mathcal{X}^{\text{arith}}$ under this map. For $\kappa_N \in \mathcal{X}_N^{\text{arith}}$, we define the signature of κ_N to be that of the corresponding κ .

3.2. THE CONTROL THEOREM IN THE QUATERNIONIC SETTING. Recall that B/\mathbb{Q} is a quaternion algebra of discriminant D . Fix an auxiliary real quadratic field F such that all primes dividing D are inert in F and all primes dividing Mp are split in F , and an isomorphism $i_F : B \otimes_{\mathbb{Q}} F \simeq \mathbb{M}_2(F)$. Let \mathcal{O}_B denote the maximal order of B obtained by taking the intersection of B with $\mathbb{M}_2(\mathcal{O}_F)$, where \mathcal{O}_F is the ring of integers of F . More precisely, define

$$\mathcal{O}_B := \iota^{-1}(i_F^{-1}(i_F(B \otimes 1) \cap \mathbb{M}_2(\mathcal{O}_F)))$$

where $\iota : B \hookrightarrow B \otimes_{\mathbb{Q}} F$ is the inclusion defined by $b \mapsto b \otimes 1$. This is a maximal order in B because $i_F(B \otimes 1) \cap \mathbb{M}_2(\mathcal{O}_F)$ is a maximal order in $i_F(B \otimes 1)$. In particular, i_F and our fixed embedding of $\bar{\mathbb{Q}}$ into $\bar{\mathbb{Q}}_p$ induce an isomorphism

$$i_p : B \otimes_{\mathbb{Q}} \mathbb{Q}_p \simeq \mathbb{M}_2(\mathbb{Q}_p)$$

such that $i_p(\mathcal{O}_B \otimes_{\mathbb{Z}} \mathbb{Z}_p) = \mathbb{M}_2(\mathbb{Z}_p)$. For any prime $\ell|M$, also choose an embedding $\bar{\mathbb{Q}} \hookrightarrow \bar{\mathbb{Q}}_{\ell}$ which, composed with i_F , yields isomorphisms

$$i_{\ell} : B \otimes_{\mathbb{Q}} \mathbb{Q}_{\ell} \simeq \mathbb{M}_2(\mathbb{Q}_{\ell})$$

such that $i_p(\mathcal{O}_B \otimes_{\mathbb{Z}} \mathbb{Z}_{\ell}) = \mathbb{M}_2(\mathbb{Z}_{\ell})$. Define an Eichler order $R \subseteq \mathcal{O}_B$ of level M by requiring that for all primes $\ell|M$ the image of $R \otimes_{\mathbb{Z}} \mathbb{Z}_{\ell}$ via i_{ℓ} consists of upper triangular matrices modulo ℓ . For any $r \geq 0$, let Γ_r denote the subgroup of the group R_1^{\times} of norm-one elements in R consisting of those γ such that $i_{\ell}(\gamma) = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ with $c \equiv 0 \pmod{Mp^r}$ and $a \equiv d \equiv 1 \pmod{Mp^r}$,

for all primes $\ell \nmid Mp$. To conclude this list of notation and definitions, fix an embedding $F \hookrightarrow \mathbb{R}$ and let

$$i_\infty : B \otimes_{\mathbb{Q}} \mathbb{R} \simeq \mathbb{M}_2(\mathbb{R})$$

be the induced isomorphism.

Let $\mathbb{Y} := \mathbb{Z}_p^2$ and denote by \mathbb{X} the set of primitive vectors in \mathbb{Y} . Let \mathbb{D} denote the \mathcal{O} -module of \mathcal{O} -valued measures on \mathbb{Y} which are supported on \mathbb{X} . Note that $\mathbb{M}_2(\mathbb{Z}_p)$ acts on \mathbb{Y} by left multiplication; this induces an action of $\mathbb{M}_2(\mathbb{Z}_p)$ on the \mathcal{O} -module of \mathcal{O} -valued measures on \mathbb{Y} , which induces an action on \mathbb{D} . The group R^\times acts on \mathbb{D} via i_p . In particular, we may define the group:

$$\mathbb{W} := H^1(\Gamma_0, \mathbb{D}).$$

Then \mathbb{D} has a canonical structure of $\mathcal{O}[[\mathbb{Z}_p^\times]]$ -module, as well as $\mathfrak{h}_\infty^{\text{ord}}$ -action, as described in [9, §2.4]. In particular, let us recall that, for any $[t] \in \mathcal{O}[[\mathbb{Z}_p^\times]]$, we have

$$\int_{\mathbb{X}} \varphi(x, y) d([t] \cdot \nu) = \int_{\mathbb{X}} \varphi(tx, ty) d\nu,$$

for any locally constant function φ on \mathbb{X} .

For any $\kappa \in \mathcal{X}^{\text{arith}}$ and any sign $\pm \in \{-, +\}$, set

$$\mathbb{W}_\kappa^\pm := \mathbb{W}_{f_\kappa^{\text{JL}}}^\pm(F_\kappa) = H^1(\Gamma_{r_\kappa}, V_{n_\kappa}(F_\kappa))^{f_\kappa, \pm}$$

where f_κ^{JL} is any Jacquet-Langlands lift of f_κ to Γ_{r_κ} ; recall that the superscript f_κ denotes the subspace on which the Hecke algebra acts via the character associated with f_κ , and the superscript \pm denotes the \pm -eigenspace for the action of the archimedean involution ι . Also, recall that \mathbb{W}_κ^\pm is one dimensional and fix a generator ϕ_κ^\pm of it.

We may define specialization maps

$$\rho_\kappa : \mathbb{D} \longrightarrow V_{n_\kappa}(F_\kappa)$$

by the formula

$$(5) \quad \rho_\kappa(\nu)(P) := \int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} \epsilon_\kappa(y) P(x, y) d\nu$$

which induces (see [9, §2.5]) a map:

$$\rho_\kappa : \mathbb{W}^{\text{ord}} \longrightarrow \mathbb{W}_\kappa^{\text{ord}}.$$

Here \mathbb{W}^{ord} and $\mathbb{W}_\kappa^{\text{ord}}$ denote the ordinary submodules of \mathbb{W} and \mathbb{W}_κ , respectively, defined as in [3, Definition 2.2] (see also [9, §3.5]). We also let $\mathbb{W}_{\mathcal{R}} := \mathbb{W} \otimes_{\Lambda} \mathcal{R}$, and extend the above map ρ_κ to a map

$$\rho_\kappa : \mathbb{W}_{\mathcal{R}}^{\text{ord}} \longrightarrow \mathbb{W}_\kappa^{\text{ord}}$$

by setting $\rho_\kappa(x \otimes r) := \rho_\kappa(x) \cdot \kappa(r)$.

THEOREM 3.1. *There exists a p -adic neighborhood \mathcal{U}_0 of κ_0 in \mathcal{X} , elements Φ^\pm in $\mathbb{W}_{\mathcal{R}}^{\text{ord}}$ and choices of p -adic periods $\Omega_\kappa^\pm \in F_\kappa$ for $\kappa \in \mathcal{U}_0 \cap \mathcal{X}^{\text{arith}}$ such that, for all $\kappa \in \mathcal{U}_0 \cap \mathcal{X}^{\text{arith}}$, we have*

$$\rho_\kappa(\Phi^\pm) = \Omega_\kappa^\pm \cdot \phi_\kappa^\pm$$

and $\Omega_{\kappa_0}^{\pm} \neq 0$.

Proof. This is an easy consequence of [9, Theorem 2.18] and follows along the lines of the proof of [21, Theorem 5.5], cf. [10, Proposition 3.2]. \square

We now normalize our choices as follows. With \mathcal{U}_0 as above, define

$$\mathcal{U}_0^{\text{arith}} := \mathcal{U}_0 \cap \mathcal{X}^{\text{arith}}.$$

Fix $\kappa \in \mathcal{U}_0^{\text{arith}}$ and an embedding $\bar{\mathbb{Q}}_p \hookrightarrow \mathbb{C}$. Let f_{κ}^{JL} denote a modular form on $\Gamma_{r_{\kappa}}$ corresponding to f_{κ} by the Jacquet-Langlands correspondence, which is well defined up to elements in \mathbb{C}^{\times} . View ϕ_{κ}^{\pm} as an element in $H^1(\Gamma_{r_{\kappa}}, V_n(\mathbb{C}))^{\pm}$. Choose a representative Φ_{γ}^{\pm} of Φ^{\pm} , by which we mean that if $\Phi^{\pm} = \sum_i \Phi_i^{\pm} \otimes r_i$, then we choose a representative $\Phi_{i,\gamma}^{\pm}$ for all i . Also, we will write $\rho_{\kappa}(\Phi)(P)$ as

$$\int_{\mathbb{Z}_p \times \mathbb{Z}_p^{\times}} \epsilon_{\kappa}(y) P(x, y) d\Phi_{\gamma}^{\pm} := \sum_i \kappa(r_i) \cdot \int_{\mathbb{Z}_p \times \mathbb{Z}_p^{\times}} \epsilon_{\kappa}(y) P(x, y) d\Phi_{i,\gamma}^{\pm}.$$

With this notation, we see that the two cohomology classes

$$\gamma \mapsto \int_{\mathbb{Z}_p \times \mathbb{Z}_p^{\times}} \epsilon_{\kappa}(y) P(x, y) d\Phi_{\gamma}^{\pm}(x, y)$$

and

$$\gamma \mapsto \Omega_{\kappa}^{\pm} \cdot \int_{\tau}^{\gamma(\tau)} P(z, 1) f_{\kappa}^{\text{JL}, \pm}(z) dz$$

are cohomologous in $H^1(\Gamma_{r_{\kappa}}, V_{n_{\kappa}}(\mathbb{C}))$, for any choice of $\tau \in \mathcal{H}$.

3.3. METAPLECTIC HIDA HECKE ALGEBRAS. Let $\sigma : \Lambda_N \rightarrow \Lambda_N$ be the ring homomorphism associated to the group homomorphism $t \mapsto t^2$ on $\mathbb{Z}_p^{\times} \times (\mathbb{Z}/N\mathbb{Z})^{\times}$, and denote by the same symbol its restriction to Λ and $\mathcal{O}[[\mathbb{Z}_p^{\times}]]$. We let Λ_{σ} , $\mathcal{O}[[\mathbb{Z}_p^{\times}]]_{\sigma}$ and $\Lambda_{N,\sigma}$ denote, respectively, Λ , $\mathcal{O}[[\mathbb{Z}_p^{\times}]]$ and Λ_N viewed as algebras over themselves via σ . The ordinary metaplectic p -adic Hida Hecke algebra we will consider is the Λ -algebra

$$\tilde{\mathcal{R}} := \mathcal{R} \otimes_{\Lambda} \Lambda_{\sigma}.$$

Define as above

$$\tilde{\mathcal{X}} := \text{Hom}_{\mathcal{O}\text{-alg}}^{\text{cont}}(\tilde{\mathcal{R}}, \bar{\mathbb{Q}}_p)$$

and let the set $\tilde{\mathcal{X}}^{\text{arith}}$ of arithmetic points in $\tilde{\mathcal{X}}$ to consist of those $\tilde{\kappa}$ such that the composition

$$W \hookrightarrow \Lambda \xrightarrow{\lambda \mapsto 1 \otimes \lambda} \tilde{\mathcal{R}} \xrightarrow{\tilde{\kappa}} \bar{\mathbb{Q}}_p$$

has the form $\gamma \mapsto \psi_{\tilde{\kappa}}(\gamma) \gamma^{n_{\tilde{\kappa}}}$ with $n_{\tilde{\kappa}} := k_{\tilde{\kappa}} - 2$ for an integer $k_{\tilde{\kappa}} \geq 2$ (called the weight of $\tilde{\kappa}$) and a finite order character $\psi_{\tilde{\kappa}} : W \rightarrow \bar{\mathbb{Q}}$ (called the wild character of $\tilde{\kappa}$). Let $r_{\tilde{\kappa}}$ the smallest among the positive integers t such that $1 + p^t \mathbb{Z}_p \subseteq \ker(\psi_{\tilde{\kappa}})$.

We have a map $p : \tilde{\mathcal{X}} \rightarrow \mathcal{X}$ induced by pull-back from the canonical map $\mathcal{R} \rightarrow \tilde{\mathcal{R}}$. The map p restricts to arithmetic points.

As above, define the Λ -algebra (or Λ_N -algebra)

$$(6) \quad \tilde{\mathcal{R}}_N := \mathcal{R} \otimes_{\Lambda} \Lambda_{N,\sigma}$$

via $\lambda \mapsto 1 \otimes \lambda$.

We easily see that $\tilde{\mathcal{R}}_N \simeq \tilde{\mathcal{R}}[\Delta]$ as Λ_N -algebras, where we enhance $\tilde{\mathcal{R}}[\Delta]$ with the following structure of $\Lambda_N \simeq \Lambda[\Delta]$ -algebra: for $\sum_i \lambda_i \cdot \delta_i \in \Lambda[\Delta]$ (with $\lambda_i \in \Lambda$ and $\delta_i \in \Delta$) and $\sum_j r_j \cdot \delta'_j \in \tilde{\mathcal{R}}[\Delta]$ (with $r_j = \sum_h r_{j,h} \otimes \lambda_{j,h} \in \tilde{\mathcal{R}}$, $r_{j,h} \in \mathcal{R}$, $\lambda_{j,h} \in \Lambda_{\sigma}$, and $\delta'_j \in \Delta$), we set

$$\left(\sum_i \lambda_i \cdot \delta_i \right) \cdot \left(\sum_j r_j \cdot \delta'_j \right) := \sum_{i,j,h} (r_{j,h} \otimes (\lambda_i \lambda_{j,h})) \cdot (\delta_i \delta'_j).$$

As above, extend $\tilde{\kappa} \in \tilde{\mathcal{X}}^{\text{arith}}$ to a continuous \mathcal{O} -algebra morphism

$$\tilde{\kappa}_N : \tilde{\mathcal{R}}_N \longrightarrow \bar{\mathbb{Q}}_p$$

by setting

$$\tilde{\kappa}_N \left(\sum_{i=1}^n x_i \cdot \delta_i \right) := \sum_{i=1}^n \tilde{\kappa}(x_i) \cdot \psi_{\mathcal{R}}(\delta_i)$$

for $x_i \in \tilde{\mathcal{R}}$ and $\delta_i \in \Delta$, where $\psi_{\mathcal{R}}$ is the character of \mathcal{R} . If we denote by $\tilde{\mathcal{X}}_N$ the \mathcal{O} -module of continuous \mathcal{O} -linear homomorphisms from $\tilde{\mathcal{R}}_N$ to $\bar{\mathbb{Q}}_p$, the above correspondence sets up an injective map $\tilde{\mathcal{X}}^{\text{arith}} \hookrightarrow \tilde{\mathcal{X}}_N$ and we let $\tilde{\mathcal{X}}_N^{\text{arith}}$ denote the image of $\tilde{\mathcal{X}}^{\text{arith}}$. Put $\epsilon_{\tilde{\kappa}} := \psi_{\tilde{\kappa}} \cdot \psi_{\mathcal{R}} \cdot \omega^{-n\tilde{\kappa}}$, which we view as a Dirichlet character of $(\mathbb{Z}/Np^{r_{\tilde{\kappa}}}\mathbb{Z})^{\times}$, and call the pair $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$ the signature of $\tilde{\kappa}_N$, where $\tilde{\kappa}$ is the arithmetic point corresponding to $\tilde{\kappa}_N$.

We also have a map $p_N : \tilde{\mathcal{X}}_N \rightarrow \mathcal{X}_N$ induced from the map $\mathcal{R}_N \rightarrow \tilde{\mathcal{R}}_N$ taking $r \mapsto r \otimes 1$ by pull-back. The map p_N also restricts to arithmetic points. The maps p and p_N make the following diagram commute:

$$\begin{array}{ccc} \tilde{\mathcal{X}}^{\text{arith}} & \hookrightarrow & \tilde{\mathcal{X}}_N^{\text{arith}} \\ \downarrow p & & \downarrow p_N \\ \mathcal{X}^{\text{arith}} & \hookrightarrow & \mathcal{X}_N^{\text{arith}} \end{array}$$

where the projections take a signature (ϵ, k) to $(\epsilon^2, 2k)$.

3.4. THE Λ -ADIC CORRESPONDENCE. In this part, we combine the explicit integral formula of Shimura and the fact that the toric integrals can be p -adically interpolated to show the existence of a Λ -adic Shimura-Shintani-Waldspurger correspondence with the expected interpolation property. This follows very closely [21, §6].

Let $\tilde{\kappa}_N \in \tilde{\mathcal{X}}_N^{\text{arith}}$ of signature $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$. Let L_r denote the order of $\mathbb{M}_2(F)$ consisting of matrices $\begin{pmatrix} a & b/Mp^f \\ Mp^r c & d \end{pmatrix}$ with $a, b, c, d \in \mathcal{O}_F$. Define

$$\mathcal{O}_{B,r} := \iota^{-1}(i_F^{-1}(i_F(B \otimes 1) \cap L_r))$$

Then $\mathcal{O}_{B,r}$ is the maximal order introduced in §2.1 (and denoted \mathcal{O}'_B there) defined in terms of the maximal order \mathcal{O}_B and the integer Mp^r . Also,

$$S := \mathcal{O}_B \cap \mathcal{O}_{B,r}$$

is an Eichler order of B of level Mp containing the fixed Eichler order R of level M . With $\alpha \in V^* \cap \mathcal{O}_{B,1}$, we have

$$(7) \quad i_F(\alpha) = \begin{pmatrix} a & b/(Mp) \\ c & -a \end{pmatrix}$$

in $\mathbb{M}_2(F)$ with $a, b, c \in \mathcal{O}_F$ and we can consider the quadratic forms

$$Q_\alpha(x, y) := cx^2 - 2axy - (b/(Mp))y^2,$$

and

$$(8) \quad \tilde{Q}_\alpha(x, y) := Mp \cdot Q_\alpha(x, y) = Mpcx^2 - 2Mpa xy - by^2.$$

Then $\tilde{Q}_\alpha(x, y)$ has coefficients in \mathcal{O}_F and, composing with $F \hookrightarrow \mathbb{R}$ and letting $x = z, y = 1$, we recover $Q_\alpha(z)$ and $\tilde{Q}_\alpha(z)$ of §2.1 (defined by means of the isomorphism i_∞). Since each prime $\ell | Mp$ is split in F , the elements a, b, c can be viewed as elements in \mathbb{Z}_ℓ via our fixed embedding $\bar{\mathbb{Q}} \hookrightarrow \bar{\mathbb{Q}}_\ell$, for any prime $\ell | Mp$ (we will continue writing a, b, c for these elements, with a slight abuse of notation). So, letting $b_\alpha \in \mathbb{Z}$ such that $i_\ell(\alpha) \equiv \begin{pmatrix} * & b_\alpha/(Mp) \\ * & * \end{pmatrix}$ modulo $i_\ell(S \otimes_{\mathbb{Z}} \mathbb{Z}_\ell)$, for all $\ell | Mp$, we have $b \equiv b_\alpha$ modulo $Mp\mathbb{Z}_\ell$ as elements in \mathbb{Z}_ℓ , for all $\ell | Mp$, and thus we get

$$(9) \quad \eta_{\epsilon_{\bar{\kappa}}}(\alpha) = \epsilon_{\bar{\kappa}}(b_\alpha) = \epsilon_{\bar{\kappa}}(b)$$

for b as in (7).

For any $\nu \in \mathbb{D}$, we may define an \mathcal{O} -valued measure $j_\alpha(\nu)$ on \mathbb{Z}_p^\times by the formula:

$$\int_{\mathbb{Z}_p^\times} f(t) dj_\alpha(\nu)(t) := \int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} f(\tilde{Q}_\alpha(x, y)) d\nu(x, y).$$

for any continuous function $f : \mathbb{Z}_p^\times \rightarrow \mathbb{C}_p$. Recall that the group of \mathcal{O} -valued measures on \mathbb{Z}_p^\times is isomorphic to the Iwasawa algebra $\mathcal{O}[[\mathbb{Z}_p^\times]]$, and thus we may view $j_\alpha(\nu)$ as an element in $\mathcal{O}[[\mathbb{Z}_p^\times]]$ (see, for example, [1, §3.2]). In particular, for any group-like element $[\lambda] \in \mathcal{O}[[\mathbb{Z}_p^\times]]$ we have:

$$\int_{\mathbb{Z}_p^\times} f(t) d([\lambda] \cdot j_\alpha(\nu))(t) = \int_{\mathbb{Z}_p^\times} \left(\int_{\mathbb{Z}_p^\times} f(ts) d[\lambda](s) \right) dj_\alpha(\nu)(t) = \int_{\mathbb{Z}_p^\times} f(\lambda t) dj_\alpha(\nu)(t).$$

On the other hand,

$$\int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} f(\tilde{Q}_\alpha(x, y)) d(\lambda \cdot \nu) = \int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} f(\tilde{Q}_\alpha(\lambda x, \lambda y)) d\nu = \int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} f(\lambda^2 \tilde{Q}_\alpha(x, y)) d\nu$$

and we conclude that $j_\alpha(\lambda \cdot \nu) = [\lambda^2] \cdot j_\alpha(\nu)$. In other words, j_α is a $\mathcal{O}[[\mathbb{Z}_p^\times]]$ -linear map

$$j_\alpha : \mathbb{D} \longrightarrow \mathcal{O}[[\mathbb{Z}_p^\times]]_\sigma.$$

Before going ahead, let us introduce some notation. Let χ be a Dirichlet character modulo Mp^r , for a positive integer r , which we decompose accordingly

with the isomorphism $(\mathbb{Z}/Np^r\mathbb{Z})^\times \simeq (\mathbb{Z}/N\mathbb{Z})^\times \times (\mathbb{Z}/p^r\mathbb{Z})^\times$ into the product $\chi = \chi_N \cdot \chi_p$ with $\chi_N : (\mathbb{Z}/N\mathbb{Z})^\times \rightarrow \mathbb{C}^\times$ and $\chi_p : (\mathbb{Z}/p^r\mathbb{Z})^\times \rightarrow \mathbb{C}^\times$. Thus, we will write $\chi(x) = \chi_N(x_N) \cdot \chi_p(x_p)$, where x_N and x_p are the projections of $x \in (\mathbb{Z}/Np^r\mathbb{Z})^\times$ to $(\mathbb{Z}/N\mathbb{Z})^\times$ and $(\mathbb{Z}/p^r\mathbb{Z})^\times$, respectively. To simplify the notation, we will suppress the N and p from the notation for x_N and x_p , thus simply writing x for any of the two. Using the isomorphism $(\mathbb{Z}/N\mathbb{Z})^\times \simeq (\mathbb{Z}/M\mathbb{Z})^\times \times (\mathbb{Z}/D\mathbb{Z})^\times$, decompose χ_N as $\chi_N = \chi_M \cdot \chi_D$ with χ_M and χ_D characters on $(\mathbb{Z}/M\mathbb{Z})^\times$ and $(\mathbb{Z}/D\mathbb{Z})^\times$, respectively. In the following, we only need the case when $\chi_D = 1$.

Using the above notation, we may define a $\mathcal{O}[\mathbb{Z}_p^\times]$ -linear map $J_\alpha : \mathbb{D} \rightarrow \mathcal{O}[\mathbb{Z}_p^\times]$ by

$$J_\alpha(\nu) = \epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot j_\alpha(\nu)$$

with b as in (7). Set $\mathbb{D}_N := \mathbb{D} \otimes_{\mathcal{O}[\mathbb{Z}_p^\times]} \Lambda_N$, where the map $\mathcal{O}[\mathbb{Z}_p^\times] \rightarrow \Lambda_N$ is induced from the map $\mathbb{Z}_p^\times \rightarrow \mathbb{Z}_p^\times \times (\mathbb{Z}/N\mathbb{Z})^\times$ on group-like elements given by $x \mapsto x \otimes 1$. Then J_α can be extended to a Λ_N -linear map $J_\alpha : \mathbb{D}_N \rightarrow \Lambda_{N,\sigma}$. Setting $\mathbb{D}_{\mathcal{R}_N} := \mathcal{R}_N \otimes_{\Lambda_N} \mathbb{D}_N$ and extending by \mathcal{R}_N -linearity over Λ_N we finally obtain a \mathcal{R}_N -linear map, again denoted by the same symbol,

$$J_\alpha : \mathbb{D}_{\mathcal{R}_N} \longrightarrow \tilde{\mathcal{R}}_N.$$

For $\nu \in \mathbb{D}_N$ and $r \in \mathcal{R}_N$ we thus have

$$J_\alpha(r \otimes \nu) = \epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot r \otimes j_\alpha(\nu).$$

For the next result, for any arithmetic point $\kappa_N \in \mathcal{X}_N^{\text{arith}}$ coming from $\kappa \in \mathcal{X}^{\text{arith}}$, extend ρ_κ in (5) by \mathcal{R}_N -linearity over $\mathcal{O}[\mathbb{Z}_p^\times]$, to get a map

$$\rho_{\kappa_N} : \mathbb{D}_{\mathcal{R}_N} \longrightarrow V_{n_\kappa}$$

defined by $\rho_{\kappa_N}(r \otimes \nu) := \rho_\kappa(\nu) \cdot \kappa_N(r)$, for $\nu \in \mathbb{D}$ and $r \in \mathcal{R}_N$. To simplify the notation, set

$$(10) \quad \langle \nu, \alpha \rangle_{\kappa_N} := \rho_{\kappa_N}(\nu)(\tilde{Q}_\alpha^{n_{\tilde{\kappa}}/2}).$$

The following is essentially [21, Lemma (6.1)].

LEMMA 3.2. *Let $\tilde{\kappa}_N \in \tilde{\mathcal{X}}_N^{\text{arith}}$ with signature $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$ and define $\kappa_N := p_N(\tilde{\kappa}_N)$. Then for any $\nu \in \mathbb{D}_{\mathcal{R}_N}$ we have:*

$$\tilde{\kappa}_N(J_\alpha(\nu)) = \eta_{\epsilon_{\tilde{\kappa}}}(\alpha) \cdot \langle \nu, \alpha \rangle_{\kappa_N}.$$

Proof. For $\nu \in \mathbb{D}_N$ and $r \in \mathcal{R}_N$ we have

$$\begin{aligned} \tilde{\kappa}_N(J_\alpha(r \otimes \nu)) &= \tilde{\kappa}_N(\epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot r \otimes j_\alpha(\nu)) \\ &= \epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot \tilde{\kappa}_N(r \otimes 1) \cdot \tilde{\kappa}_N(1 \otimes j_\alpha(\nu)) \\ &= \epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot \kappa_N(r) \cdot \int_{\mathbb{Z}_p^\times} \tilde{\kappa}_N(t) dj_\alpha(\nu) \end{aligned}$$

and thus, noticing that $\tilde{\kappa}_N$ restricted to \mathbb{Z}_p^\times is $\tilde{\kappa}_N(t) = \epsilon_{\tilde{\kappa},p}(t)t^{n_{\tilde{\kappa}}}$, we have

$$\tilde{\kappa}_N(J_\alpha(r \otimes \nu)) = \epsilon_{\tilde{\kappa},M}(b) \cdot \epsilon_{\tilde{\kappa},p}(-1) \cdot \kappa_N(r) \int_{\mathbb{Z}_p \times \mathbb{Z}_p^\times} \epsilon_{\tilde{\kappa},p}(\tilde{Q}_\alpha(x, y)) \tilde{Q}_\alpha(x, y)^{n_{\tilde{\kappa}}/2} d\nu.$$

Recalling (8), and viewing a, b, c as elements in \mathbb{Z}_p , we have, for $(x, y) \in \mathbb{Z}_p \times \mathbb{Z}_p^\times$, $\epsilon_{\tilde{\kappa}, p}(\tilde{Q}_\alpha(x, y)) = \epsilon_{\tilde{\kappa}, p}(-by^2) = \epsilon_{\tilde{\kappa}, p}(-b)\epsilon_{\tilde{\kappa}, p}(y^2) = \epsilon_{\tilde{\kappa}, p}(-b)\epsilon_{\tilde{\kappa}, p}^2(y) = \epsilon_{\tilde{\kappa}, p}(-b)\epsilon_{\kappa, p}(y)$.

Thus, since $\epsilon_{\tilde{\kappa}}(-1)^2 = 1$, we get:

$$\tilde{\kappa}_N(J_\alpha(r \otimes \nu)) = \kappa_N(r) \cdot \epsilon_{\tilde{\kappa}, M}(b) \cdot \epsilon_{\tilde{\kappa}, p}(b) \cdot \rho_\kappa(\nu)(\tilde{Q}_\alpha^{n_{\tilde{\kappa}}/2}) = \eta_{\epsilon_\kappa}(\alpha) \cdot \langle \nu, \alpha \rangle_{\kappa_N}$$

where for the last equality use (9) and (10). □

Define

$$\mathbb{W}_{\mathcal{R}_N} := \mathbb{W} \otimes_{\mathcal{O}[\mathbb{Z}_p^\times]} \mathcal{R}_N,$$

the structure of $\mathcal{O}[\mathbb{Z}_p^\times]$ -module of \mathcal{R}_N being that induced by the composition of the two maps $\mathcal{O}[\mathbb{Z}_p^\times] \rightarrow \Lambda_N \rightarrow \mathcal{R}_N$ described above. There is a canonical map

$$\vartheta : \mathbb{W}_{\mathcal{R}_N} \longrightarrow H^1(\Gamma_0, \mathbb{D}_{\mathcal{R}_N})$$

described as follows: if ν_γ is a representative of an element ν in \mathbb{W} and $r \in \mathcal{R}_N$, then $\vartheta(\nu \otimes r)$ is represented by the cocycle $\nu_\gamma \otimes r$.

For $\nu \in \mathbb{W}_{\mathcal{R}_N}$ represented by ν_γ and $\xi \geq 1$ an integer, define

$$\theta_\xi(\nu) := \sum_{\mathcal{C} \in R(\Gamma_1), q(\mathcal{C})=\xi} \frac{J_{\alpha \mathcal{C}}(\nu_{\gamma_{\alpha \mathcal{C}}})}{t_{\alpha \mathcal{C}}}.$$

DEFINITION 3.3. For $\nu \in \mathbb{W}_{\mathcal{R}_N}$, the formal Fourier expansion

$$\Theta(\nu) := \sum_{\xi \geq 1} \theta_\xi(\nu) q^\xi$$

in $\mathcal{R}_N[[q]]$ is called the Λ -adic Shimura-Shintani-Waldspurger lift of ν . For any $\tilde{\kappa} \in \tilde{\mathcal{X}}^{\text{arith}}$, the formal power series expansion

$$\Theta(\nu)(\tilde{\kappa}_N) := \sum_{\xi \geq 1} \tilde{\kappa}_N(\theta_\xi(\nu)) q^\xi$$

is called the $\tilde{\kappa}$ -specialization of $\Theta(\nu)$.

There is a natural map

$$\mathbb{W}_{\mathcal{R}} \longrightarrow \mathbb{W}_{\mathcal{R}_N}$$

taking $\nu \otimes r$ to itself (use that \mathcal{R} has a canonical map to $\mathcal{R}_N \simeq \mathcal{R}[\Delta]$, as described above). So, for any choice of sign, $\Phi^\pm \in \mathbb{W}_{\mathcal{R}}$ will be viewed as an element in $\mathbb{W}_{\mathcal{R}_N}$.

From now on we will use the following notation. Fix $\tilde{\kappa}_0 \in \tilde{\mathcal{X}}^{\text{arith}}$ and put $\kappa_0 := p(\tilde{\kappa}_0) \in \mathcal{X}^{\text{arith}}$. Recall the neighborhood \mathcal{U}_0 of κ_0 in Theorem 3.1. Define $\tilde{\mathcal{U}}_0 := p^{-1}(\mathcal{U}_0)$ and

$$\tilde{\mathcal{U}}_0^{\text{arith}} := \tilde{\mathcal{U}}_0 \cap \tilde{\mathcal{X}}^{\text{arith}}.$$

For each $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$ put $\kappa = p(\tilde{\kappa}) \in \mathcal{U}_0^{\text{arith}}$. Recall that if $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$ is the signature of $\tilde{\kappa}$, then $(\epsilon_\kappa, k_\kappa) := (\epsilon_{\tilde{\kappa}}^2, 2k_{\tilde{\kappa}})$ is that of κ_0 . For any $\kappa := p(\tilde{\kappa})$ as above, we may consider the modular form

$$f_\kappa^{\text{JL}} \in S_{k_\kappa}(\Gamma_{r_\kappa}, \epsilon_\kappa)$$

and its Shimura-Shintani-Waldspurger lift

$$h_\kappa = \sum_{\xi} a_\xi(h_\kappa)q^\xi \in S_{k_\kappa+1/2}(4Np^{r_\kappa}, \chi_\kappa), \quad \text{where } \chi_\kappa(x) := \epsilon_{\tilde{\kappa}}(x) \left(\frac{-1}{x}\right)^{k_\kappa},$$

normalized as in (2) and (3). For our fixed κ_0 , recall the elements $\Phi := \Phi^+$ chosen as in Theorem 3.1 and define $\phi_\kappa := \phi_\kappa^+$ and $\Omega_\kappa := \Omega_\kappa^+$ for $\kappa \in \mathcal{U}_0^{\text{arith}}$.

PROPOSITION 3.4. *For all $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$ such that $r_\kappa = 1$ we have*

$$\tilde{\kappa}_N(\theta_\xi(\Phi)) = \Omega_\kappa \cdot a_\xi(h_\kappa) \quad \text{and} \quad \Theta(\Phi)(\tilde{\kappa}_N) = \Omega_\kappa \cdot h_\kappa.$$

Proof. By Lemma 3.2 we have

$$\tilde{\kappa}_N(\theta_\xi(\Phi)) = \sum_{\mathcal{C} \in R(\Gamma_1), q(\mathcal{C})=\xi} \frac{\eta_{\epsilon_{\tilde{\kappa}}}(\alpha_{\mathcal{C}})}{\mathfrak{t}_{\alpha_{\mathcal{C}}}} \rho_{\kappa_N}(\Phi)(\tilde{Q}_{\alpha_{\mathcal{C}}}^{n_{\tilde{\kappa}}/2}).$$

Using Theorem 3.1, we get

$$\tilde{\kappa}_N(\theta_\xi(\Phi)) = \sum_{\mathcal{C} \in R(\Gamma_1), q(\mathcal{C})=\xi} \frac{\eta_{\epsilon_{\tilde{\kappa}}}(\alpha_{\mathcal{C}}) \cdot \Omega_\kappa}{\mathfrak{t}_{\alpha_{\mathcal{C}}}} \phi_\kappa(\tilde{Q}_{\alpha_{\mathcal{C}}}^{k_\kappa-1}).$$

Now (2) shows the statement on $\tilde{\kappa}_N(\theta_\xi(\Phi))$, while that on $\Theta(\Phi)(\tilde{\kappa}_N)$ is a formal consequence of the previous one. \square

COROLLARY 3.5. *Let a_p denote the image of the Hecke operator T_p in \mathcal{R} . Then $\Theta(\Phi)|T_p^2 = a_p \cdot \Theta(\Phi)$.*

Proof. For any $\kappa \in \mathcal{X}^{\text{arith}}$, let $a_p(\kappa) := \kappa(T_p)$, which is a p -adic unit by the ordinarity assumption. For all $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$ with $r_\kappa = 1$, we have

$$\Theta(\Phi)(\tilde{\kappa}_N)|T_p^2 = \Omega_\kappa \cdot h_\kappa|T_p^2 = a_p(\kappa) \cdot \Omega_\kappa \cdot h_\kappa = a_p(\kappa) \cdot \Theta(\Phi)(\tilde{\kappa}_N).$$

Consequently,

$$\tilde{\kappa}_N(\theta_{\xi p^2}(\Phi)) = a_p(\kappa) \cdot \tilde{\kappa}_N(\theta_\xi(\Phi))$$

for all $\tilde{\kappa}$ such that $r_\kappa = 1$. Since this subset is dense in $\tilde{\mathcal{X}}_N$, we conclude that $\theta_{\xi p^2}(\Phi) = a_p \cdot \theta_\xi(\Phi)$ and so $\Theta(\Phi)|T_p^2 = a_p \cdot \Theta(\Phi)$. \square

For any integer $n \geq 1$ and any quadratic form Q with coefficients in F , write $[Q]_n$ for the class of Q modulo the action of $i_F(\Gamma_n)$. Define $\mathcal{F}_{n,\xi}$ to be the subset of the F -vector space of quadratic forms with coefficients in F consisting of quadratic forms \tilde{Q}_α such that $\alpha \in V^* \cap \mathcal{O}_{B,n}$ and $-\text{nr}(\alpha) = \xi$. Writing $\delta_{\tilde{Q}_\alpha}$ for the discriminant of Q_α , the above set can be equivalently described as

$$\mathcal{F}_{n,\xi} := \{\tilde{Q}_\alpha \mid \alpha \in V^* \cap \mathcal{O}_{B,n}, \delta_{\tilde{Q}_\alpha} = Np^n \xi\}.$$

Define $\mathcal{F}_{n,\xi}/\Gamma_n$ to be the set $\{[\tilde{Q}_\alpha]_n \mid \tilde{Q}_\alpha \in \mathcal{F}_{n,\xi}\}$ of equivalence classes of $\mathcal{F}_{n,\xi}$ under the action of $i_F(\Gamma_n)$. A simple computation shows that $Q_{g^{-1}\alpha g} = Q_\alpha|g$ for all $\alpha \in V^*$ and all $g \in \Gamma_n$, and thus we find

$$\mathcal{F}_{n,\xi}/\Gamma_n = \{[\tilde{Q}_{\mathcal{C}_\alpha}]_n \mid \mathcal{C} \in R(\Gamma_n), \delta_{\tilde{Q}_\alpha} = Np^n \xi\}.$$

We also note that, in the notation of §2.1, if f has weight character ψ , defined modulo Np^n , and level Γ_n , the Fourier coefficients $a_\xi(h)$ of the Shimura-Shintani-Waldspurger lift h of f are given by

$$(11) \quad a_\xi(h) = \sum_{[Q] \in \mathcal{F}_{n,\xi}/\Gamma_n} \frac{\psi(Q)}{\mathfrak{t}_Q} \phi_f^+(Q(z)^{k-1})$$

and, if $Q = \tilde{Q}_\alpha$, we put $\psi(Q) := \eta_\psi(b_\alpha)$ and $\mathfrak{t}_Q := \mathfrak{t}_\alpha$. Also, if we let

$$\mathcal{F}_n/\Gamma_n := \prod_{\xi} \mathcal{F}_{n,\xi}/\Gamma_n$$

we can write

$$(12) \quad h = \sum_{[Q] \in \mathcal{F}_n/\Gamma_n} \frac{\psi(Q)}{\mathfrak{t}_Q} \phi_f^+(Q(z)^{k-1}) q^{\delta_Q/(Np^n)}.$$

Fix now an integer $m \geq 1$ and let $n \in \{1, m\}$. For any $t \in (\mathbb{Z}/p^n\mathbb{Z})^\times$ and any integer $\xi \geq 1$, define $\mathcal{F}_{n,\xi,t}$ to be the subset of $\mathcal{F}_{n,\xi}$ consisting of forms such that $Np^n b_\alpha \equiv t \pmod{Np^m}$. Also, define $\mathcal{F}_{n,\xi,t}/\Gamma_n$ to be the set of equivalence classes of $\mathcal{F}_{n,\xi,t}$ under the action of $i_F(\Gamma_n)$. If $\alpha \in V^* \cap \mathcal{O}_{B,m}$ and

$$i_F(\alpha) = \begin{pmatrix} a & b \\ c & -a \end{pmatrix},$$

then

$$(13) \quad \tilde{Q}_\alpha(x, y) = Np^n cx^2 - 2Np^n axy - Np^n by^2$$

from which we see that there is an inclusion $\mathcal{F}_{m,\xi,t} \subseteq \mathcal{F}_{1,\xi p^{m-1},t}$. If \tilde{Q}_α and $\tilde{Q}_{\alpha'}$ belong to $\mathcal{F}_{m,\xi,t}$, and $\alpha' = g\alpha g^{-1}$ for some $g \in \Gamma_m$, then, since $\Gamma_m \subseteq \Gamma_1$, we see that \tilde{Q}_α and $\tilde{Q}_{\alpha'}$ represent the same class in $\mathcal{F}_{1,\xi p^{m-1},t}/\Gamma_1$. This shows that $[\tilde{Q}_\alpha]_m \mapsto [\tilde{Q}_\alpha]_1$ gives a well-defined map

$$\pi_{m,\xi,t} : \mathcal{F}_{m,\xi,t}/\Gamma_m \longrightarrow \mathcal{F}_{1,\xi p^{m-1},t}/\Gamma_1.$$

LEMMA 3.6. *The map $\pi_{m,\xi,t}$ is bijective.*

Proof. We first show the injectivity. For this, suppose \tilde{Q}_α and $\tilde{Q}_{\alpha'}$ are in $\mathcal{F}_{m,\xi,t}$ and $[\tilde{Q}_\alpha]_1 = [\tilde{Q}_{\alpha'}]_1$. So there exists $g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$ in $i_F(\Gamma_1)$ such that $\tilde{Q}_\alpha = \tilde{Q}_{\alpha'}|g$. If $\tilde{Q}_\alpha = cx^2 - 2axy - by^2$, and easy computation shows that $\tilde{Q}_{\alpha'} = c'x^2 - 2a'xy - b'y^2$ with

$$\begin{aligned} c' &= c\alpha^2 - 2a\alpha\gamma - b\gamma^2 \\ a' &= -c\alpha\beta + a\beta\gamma + a\alpha\delta + b\gamma\delta \\ b' &= -c\beta^2 + 2a\beta\delta + b\delta^2. \end{aligned}$$

The first condition shows that $\gamma \equiv 0 \pmod{Np^m}$. We have $b \equiv b' \equiv t \pmod{Np^m}$, so $\delta^2 \equiv 1 \pmod{Np^m}$. Since $\delta \equiv 1 \pmod{Np}$, we see that $\delta \equiv 1 \pmod{Np^m}$ too.

We now show the surjectivity. For this, fix $[\tilde{Q}_{\alpha c}]_1$ in the target of π , and choose a representative

$$\tilde{Q}_{\alpha c} = cx^2 - 2axy - by^2$$

(recall $Mp^m \xi | \delta_{\tilde{Q}_{\alpha c}}$, $Np|c$, $Np|a$, and $b \in \mathcal{O}_F^\times$, the last condition due to $\eta_\psi(\alpha c) \neq 0$). By the Strong Approximation Theorem, we can find $\tilde{g} \in \Gamma_1$ such that

$$i_\ell(\tilde{g}) \equiv \begin{pmatrix} 1 & 0 \\ ab^{-1} & 1 \end{pmatrix} \pmod{Np^m}$$

for all $\ell|Np$. Take $g := i_F(\tilde{g})$, and put $\alpha := g^{-1}\alpha c g$. An easy computation, using the expressions for a', b', c' in terms of a, b, c and $g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$ as above, shows that $\alpha \in V^* \cap \mathcal{O}_{B,m}$, $\eta_\psi(\alpha) = t$ and $\delta_{\tilde{Q}_\alpha} = Np^m \xi$, and it follows that $\tilde{Q}_\alpha \in \mathcal{F}_{m,\xi,t}$. Now

$$\pi([\tilde{Q}_\alpha]_m) = [\tilde{Q}_\alpha]_1 = [\tilde{Q}_{g^{-1}\alpha c g}]_1 = [\tilde{Q}_{\alpha c}]_1$$

where the last equality follows because $g \in \Gamma_1$. □

PROPOSITION 3.7. *For all $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$ we have*

$$\Theta(\Phi)(\tilde{\kappa}_N) | T_p^{r_\kappa - 1} = \Omega_\kappa \cdot h_\kappa.$$

Proof. For $r_\kappa = 1$, this is Proposition 3.4 above, so we may assume $r_\kappa \geq 2$. As in the proof of Proposition 3.4, combining Lemma 3.2 and Theorem 3.1 we get

$$\Theta(\Phi)(\tilde{\kappa}_N) = \sum_{\xi \geq 1} \left(\sum_{\mathcal{C} \in R(\Gamma_1), q(\mathcal{C}) = \xi} \frac{\eta_{\epsilon_{\tilde{\kappa}}}(\alpha \mathcal{C}) \cdot \Omega_\kappa}{t_{\alpha \mathcal{C}}} \phi_\kappa(\tilde{Q}_{\alpha \mathcal{C}}^{k_\kappa - 1}) \right) q^\xi$$

which, by (11) and (12) above we may rewrite as

$$\Theta(\Phi)(\tilde{\kappa}_N) = \sum_{[Q] \in \mathcal{F}_1/\Gamma_1} \frac{\epsilon_{\tilde{\kappa}}(Q) \cdot \Omega_\kappa}{t_Q} \phi_\kappa(Q^{k_\kappa - 1}) q^{\delta_Q/(Np)}$$

By definition of the action of T_p on power series, we have

$$\Theta(\Phi)(\tilde{\kappa}_N) | T_p^{r_\kappa - 1} = \sum_{[Q] \in \mathcal{F}_1/\Gamma_1, p^{r_\kappa} | \delta_Q} \frac{\epsilon_{\tilde{\kappa}}(Q) \cdot \Omega_\kappa}{t_Q} \phi_\kappa(Q^{k_\kappa - 1}) q^{\delta_Q/(Np^{r_\kappa})}.$$

Setting $\mathcal{F}_{n,t}/\Gamma_n := \coprod_{\xi \geq 1} \mathcal{F}_{n,t,\xi}/\Gamma_n$ for $n \in \{1, r_\kappa\}$, Lemma 3.6 shows that

$$\mathcal{F}_{1,t}^* := \{[Q] \in \mathcal{F}_{1,t}/\Gamma_{1,t} \text{ such that } p^{r_\kappa} | \delta_Q\}$$
 is equal to $\mathcal{F}_{r_\kappa,t}$.

Therefore, splitting the above sum over $t \in (\mathbb{Z}/Np^{r_\kappa}\mathbb{Z})^\times$, we get

$$\begin{aligned} \Theta(\Phi)(\tilde{\kappa}_N) | T_p^{r_\kappa - 1} &= \sum_{t \in (\mathbb{Z}/p^{r_\kappa - 1}\mathbb{Z})^\times} \sum_{[Q] \in \mathcal{F}_{1,t}^*} \frac{\epsilon_{\tilde{\kappa}}(Q) \cdot \Omega_\kappa}{t_Q} \phi_\kappa(Q^{k_\kappa - 1}) q^{\delta_Q/(Np^{r_\kappa})} \\ &= \sum_{t \in (\mathbb{Z}/p^{r_\kappa - 1}\mathbb{Z})^\times} \sum_{[Q] \in \mathcal{F}_{m,t}/\Gamma_m} \frac{\epsilon_{\tilde{\kappa}}(Q) \cdot \Omega_\kappa}{t_Q} \phi_\kappa(Q^{k_\kappa - 1}) q^{\delta_Q/(Np^{r_\kappa})} \\ &= \sum_{[Q] \in \mathcal{F}_m/\Gamma_m} \frac{\epsilon_{\tilde{\kappa}}(Q) \cdot \Omega_\kappa}{t_Q} \phi_\kappa(Q^{k_\kappa - 1}) q^{\delta_Q/(Np^{r_\kappa})}. \end{aligned}$$

Comparing this expression with (12) gives the result. □

We are now ready to state the analogue of [21, Thm. 3.3], which is our main result. For the reader's convenience, we briefly recall the notation appearing below. We denote by \mathcal{X} the points of the ordinary Hida Hecke algebra, and by $\mathcal{X}^{\text{arith}}$ its arithmetic points. For $\kappa_0 \in \mathcal{X}^{\text{arith}}$, we denote by \mathcal{U}_0 the p -adic neighborhood of κ_0 appearing in the statement of Theorem 3.1 and put $\mathcal{U}_0^{\text{arith}} := \mathcal{U}_0 \cap \mathcal{X}^{\text{arith}}$. We also denote by $\Phi = \Phi^+ \in \mathbb{W}_{\mathcal{R}}^{\text{ord}}$ the cohomology class appearing in Theorem 3.1. The points $\tilde{\mathcal{X}}$ of the metaplectic Hida Hecke algebra defined in §3.3 are equipped with a canonical map $p : \tilde{\mathcal{X}}^{\text{arith}} \rightarrow \mathcal{X}^{\text{arith}}$ on arithmetic points. Let $\tilde{\mathcal{U}}_0^{\text{arith}} := \tilde{\mathcal{U}}_0 \cap \tilde{\mathcal{X}}^{\text{arith}}$. For each $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$, put $\kappa = p(\tilde{\kappa}) \in \mathcal{U}_0^{\text{arith}}$. Recall that if $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$ is the signature of $\tilde{\kappa}$, then the signature of κ is $(\epsilon_{\kappa}, k_{\kappa}) := (\epsilon_{\tilde{\kappa}}^2, 2k_{\tilde{\kappa}})$. For any $\kappa := p(\tilde{\kappa})$ as above, we may consider the modular form

$$f_{\kappa}^{\text{JL}} \in S_{k_{\kappa}}(\Gamma_{r_{\kappa}}, \epsilon_{\kappa})$$

and its Shimura-Shintani-Waldspurger lift

$$h_{\kappa} = \sum_{\xi} a_{\xi}(h_{\kappa})q^{\xi} \in S_{k_{\kappa}+1/2}(4Np^{r_{\kappa}}, \chi_{\kappa}), \quad \text{where } \chi_{\kappa}(x) := \epsilon_{\tilde{\kappa}}(x) \left(\frac{-1}{x}\right)^{k_{\kappa}},$$

normalized as in (2) and (3). Finally, for $\tilde{\kappa} \in \tilde{\mathcal{X}}^{\text{arith}}$, we denote by $\tilde{\kappa}_N$ its extension to the metaplectic Hecke algebra $\tilde{\mathcal{R}}_N$ defined in §3.3.

THEOREM 3.8. *Let $\kappa_0 \in \mathcal{X}^{\text{arith}}$. Then there exists a choice of p -adic periods Ω_{κ} for $\kappa \in \mathcal{U}_0$ such that the Λ -adic Shimura-Shintani-Waldspurger lift of Φ*

$$\Theta(\Phi) := \sum_{\xi \geq 1} \theta_{\xi}(\Phi)q^{\xi}$$

in $\mathcal{R}_N[[q]]$ has the following properties:

- (1) $\Omega_{\kappa_0} \neq 0$.
- (2) For any $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$, the $\tilde{\kappa}$ -specialization of $\Theta(\Phi)$

$$\Theta(\nu)(\tilde{\kappa}_N) := \sum_{\xi \geq 1} \tilde{\kappa}(\theta_{\xi}(\Phi))q^{\xi} \text{ belongs to } S_{k_{\kappa}+1/2}(4Np^{r_{\kappa}}, \chi'_{\kappa}),$$

where $\chi'_{\kappa}(x) := \chi_{\kappa}(x) \cdot \left(\frac{p}{x}\right)^{k_{\kappa}-1}$, and satisfies

$$\Theta(\Phi)(\tilde{\kappa}_N) = \Omega_{\kappa} \cdot h_{\kappa}|T_p^{1-r_{\kappa}}.$$

Proof. The elements Ω_{κ} are those Ω_{κ}^+ appearing in Theorem 3.1, which we used in Propositions 3.4 and 3.7 above, so (1) is clear. Applying $T_p^{r_{\kappa}-1}$ to the formula of Proposition 3.7, using Corollary 3.5 and applying $a_p(\kappa)^{1-r_{\kappa}}$ on both sides gives

$$\Theta(\Phi)(\tilde{\kappa}_N) = a_p(\kappa)^{1-r_{\kappa}} \Omega_{\kappa} \cdot h_{\kappa}|T_p^{r_{\kappa}-1}.$$

By [18, Prop. 1.9], each application of T_p has the effect of multiplying the character by $\left(\frac{p}{x}\right)$, hence

$$h'_{\kappa} := h_{\kappa}|T_p^{r_{\kappa}-1} \in S_{k_{\kappa}+1/2}(4Np^{r_{\kappa}}, \chi'_{\kappa})$$

with χ'_κ as in the statement. This gives the first part of (2), while the last formula follows immediately from Proposition 3.7. \square

Remark 3.9. Theorem 1.1 is a direct consequence of Theorem 3.8, as we briefly show below.

Recall the embedding $\mathbb{Z}^{\geq 2} \hookrightarrow \text{Hom}(\mathbb{Z}_p^\times, \mathbb{Z}_p^\times)$ which sends $k \in \mathbb{Z}^{\geq 2}$ to the character $x \mapsto x^{k-2}$. Extending characters by \mathcal{O} -linearity gives a map

$$\mathbb{Z}^{\geq 2} \hookrightarrow \mathcal{X}(\Lambda) := \text{Hom}_{\mathcal{O}\text{-alg}}^{\text{cont}}(\Lambda, \bar{\mathbb{Q}}_p).$$

We denote by $k^{(\Lambda)}$ the image of $k \in \mathbb{Z}^{\geq 2}$ in $\mathcal{X}(\Lambda)$ via this embedding. We also denote by $\varpi : \mathcal{X} \rightarrow \mathcal{X}(\Lambda)$ the finite-to-one map obtained by restriction of homomorphisms to Λ . Let $k^{(\mathcal{R})}$ be a point in \mathcal{X} of signature $(k, 1)$ such that $\varpi(k^{(\mathcal{R})}) = k^{(\Lambda)}$. A well-known result by Hida (see [6, Cor. 1.4]) shows that \mathcal{R}/Λ is unramified at $k^{(\Lambda)}$. As shown in [21, §1], this implies that there is a section $s_{k^{(\Lambda)}}$ of ϖ which is defined on a neighborhood $\mathcal{U}_{k^{(\Lambda)}}$ of $k^{(\Lambda)}$ in $\mathcal{X}(\Lambda)$ and sends $k^{(\Lambda)}$ to $k^{(\mathcal{R})}$.

Fix now k_0 as in the statement of Theorem 1.1, corresponding to a cuspform f_0 of weight k_0 with trivial character. The form f_0 corresponds to an arithmetic character $k_0^{(\mathcal{R})}$ of signature $(1, k_0)$ belonging to \mathcal{X} . Let \mathcal{U}'_0 be the inverse image of \mathcal{U}_0 under the section $s_{k_0^{(\Lambda)}}$, where $\mathcal{U}_0 \subseteq \mathcal{X}$ is the neighborhood of $k_0^{(\mathcal{R})}$ in Theorem 3.8. Extending scalars by \mathcal{O} gives, as above, an injective continuous map $\text{Hom}(\mathbb{Z}_p^\times, \mathbb{Z}_p^\times) \hookrightarrow \mathcal{X}(\Lambda)$, and we let U_0 be any neighborhood of the character $x \mapsto x^{k_0-2}$ which maps to \mathcal{U}'_0 and is contained in the residue class of k_0 modulo $p-1$. Composing this map with the section $\mathcal{U}'_0 \hookrightarrow \mathcal{U}_0$ gives a continuous injective map

$$\varsigma : U_0 \hookrightarrow \mathcal{U}'_0 \hookrightarrow \mathcal{U}_0$$

which takes k_0 to $k_0^{(\mathcal{R})}$, since by construction the image of k_0 by the first map is $k_0^{(\Lambda)}$. We also note that, more generally, $\varsigma(k) = k^{(\mathcal{R})}$ because by construction $\varsigma(k)$ restricts to $k^{(\Lambda)}$ and its signature is $(1, k)$, since the character of $\varsigma(k)$ is trivial. To show the last assertion, recall that the character of $\varsigma(k)$ is $\psi_k \cdot \psi_{\mathcal{R}} \cdot \omega^{-k}$, and note that ψ_k is trivial because $k^{(\Lambda)}(x) = x^{k-1}$, and $\psi_{\mathcal{R}} \cdot \omega^{-k}$ is trivial because the same is true for k_0 and $k \equiv k_0$ modulo $p-1$. In other words, arithmetic points in $\varsigma(U_0)$ correspond to cuspforms with trivial character. This is the Hida family of forms with trivial character that we considered in the Introduction.

We can now prove Theorem 1.1. For all $k \in U_0 \cap \mathbb{Z}^{\geq 2}$, put $\Omega_k := \Omega_{k^{(\mathcal{R})}}$ and define $\Theta := \Theta(\Phi) \circ \varsigma$ with Φ as in Theorem 3.8 for $\kappa_0 = k_0^{(\mathcal{R})}$. Applying Theorem 3.8 to $k_0^{(\mathcal{R})}$, and restricting to $\varsigma(U_0)$, shows that U_0 , Ω_k and Θ satisfy the conclusion of Theorem 1.1.

Remark 3.10. For $\tilde{\kappa} \in \tilde{\mathcal{U}}_0^{\text{arith}}$ of signature $(\epsilon_{\tilde{\kappa}}, k_{\tilde{\kappa}})$ with $r_{\tilde{\kappa}} = 1$ as in the above theorem, $h_{\tilde{\kappa}}$ is trivial if $(-1)^{k_{\tilde{\kappa}}} \neq \epsilon_{\tilde{\kappa}}(-1)$. However, since $\phi_{\kappa_0} \neq 0$, it follows that h_{κ_0} is not trivial as long as the necessary condition $(-1)^{k_0} = \epsilon_0(-1)$ is verified.

Remark 3.11. This result can be used to produce a quaternionic Λ -adic version of the Saito-Kurokawa lifting, following closely the arguments in [8, Cor. 1].

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Matteo Longo
Dipartimento di Matematica
Università di Padova
Via Trieste 63
35121 Padova
Italy
mlongo@math.unipd.it

Marc-Hubert Nicole
Institut de mathématiques
de Luminy
Université d'Aix-Marseille
campus de Luminy, case 907
13288 Marseille cedex 9
France
nicole@iml.univ-mrs.fr

