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for non-scalar split residual representations

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THE BREUIL-MÉZARD CONJECTURE FOR NON-SCALAR SPLIT RESIDUAL REPRESENTATIONS

BY YONGQUAN HU AND FUCHENG TAN

ABSTRACT. – We prove the Breuil-Mézard conjecture for split non-scalar residual representations of $\text{Gal}(\overline{\mathbb{Q}_p}/\mathbb{Q}_p)$ by local methods. Combined with the cases previously proved in [20] and [26], this completes the proof of the conjecture (when $p \geq 5$). As a consequence, the local restriction in the proof of the Fontaine-Mazur conjecture in [20] is removed.

RÉSUMÉ. – Nous prouvons la conjecture de Breuil-Mézard pour les représentations résiduelles scindées non-scalaires de $\text{Gal}(\overline{\mathbb{Q}_p}/\mathbb{Q}_p)$ par des méthodes locales. Combiné avec les cas déjà prouvés dans [20] et [26], cela complète la preuve de la conjecture (lorsque $p \geq 5$). Par conséquent, la restriction locale dans la preuve de la conjecture de Fontaine-Mazur dans [20] est levée.

Notation

- $p \geq 5$ is a prime number. The p -adic valuation is normalized as $v_p(p) = 1$.
- $E/\mathbb{Q}_p$ is a sufficiently large finite extension with ring of integers $\mathcal{O}$, a (fixed) uniformizer ϖ , and residue field $\mathbb{F}$. Its subring of Witt vectors is denoted by $W(\mathbb{F})$.
- For a number field F , the completion at a place v is written as F_v , for which we fix a uniformizer denoted by ϖ_v .
- For a local or global field L , $G_L = \text{Gal}(\overline{L}/L)$. The inertia subgroup for the local field is written as I_L .
- For each finite place v in a number field F , fix a map $G_{F_v} \rightarrow G_F$ by choosing an inclusion $\overline{F} \hookrightarrow \overline{F}_v$ of algebraic closures.
- $\epsilon : G_{\mathbb{Q}_p} \rightarrow \mathbb{Z}_p^\times$ is the cyclotomic character, $\omega : G_{\mathbb{Q}_p} \rightarrow \mathbb{F}_p^\times$ is its reduction mod p , and $\tilde{\omega}$ is the Teichmüller lifting of ω .
- $\mathbb{1} : G_{\mathbb{Q}_p} \rightarrow \mathbb{F}_p^\times$ is the trivial character. We also let $\mathbb{1}$ denote other trivial representations, if no confusion arises.
- Normalize the local class field map $\mathbb{Q}_p^\times \rightarrow G_{\mathbb{Q}_p}^{\text{ab}}$ so that uniformizers correspond to geometric Frobenii. Then a character of $G_{\mathbb{Q}_p}$ will also be regarded as a character of $\mathbb{Q}_p^\times$.
- For a ring R , $\text{m-Spec} R$ denotes the set of maximal ideals.

- For R a Noetherian ring and M a finite R -module of dimension at most d , let $\ell_{R_{\mathfrak{p}}}(M_{\mathfrak{p}})$ denote the length of the $R_{\mathfrak{p}}$ -module $M_{\mathfrak{p}}$, and let $Z_d(M) = \sum_{\mathfrak{p}} \ell_{R_{\mathfrak{p}}}(M_{\mathfrak{p}}) \mathfrak{p}$ for all $\mathfrak{p} \in \operatorname{Spec} R$ such that $\dim R/\mathfrak{p} = d$. When the context is clear, we simply denote it by $Z(M)$.
- For R a Noetherian local ring with maximal ideal $\mathfrak{m}$ and M a finite R -module, and for an $\mathfrak{m}$ -primary ideal $\mathfrak{q}$ of R , let $e_{\mathfrak{q}}(R, M)$ denote the Hilbert-Samuel multiplicity of M with respect to $\mathfrak{q}$. We abbreviate $e_{\mathfrak{m}}(R, M) = e(R, M)$ and $e_{\mathfrak{q}}(R, R) = e_{\mathfrak{q}}(R)$.
- For $r \geq 0$, we let $\operatorname{Sym}^r E^2$ (resp. $\operatorname{Sym}^r \mathbb{F}^2$) be the usual symmetric power representation of $\operatorname{GL}_2(\mathbb{Z}_p)$ (resp. of $\operatorname{GL}_2(\mathbb{F}_p)$), but viewed as a representation of $\operatorname{GL}_2(\mathbb{Z}_p)$.

1. Introduction

Consider the following data:

- an integer $k \geq 2$,
- a representation $\tau : I_{\mathbb{Q}_p} \rightarrow \operatorname{GL}_2(E)$ with open kernel,
- a continuous character $\psi : G_{\mathbb{Q}_p} \rightarrow \mathcal{O}^{\times}$ such that $\psi|_{I_{\mathbb{Q}_p}} = \epsilon^{k-2} \det \tau$.

We call such a triple (k, τ, ψ) a p -adic Hodge type. We say a 2-dimensional continuous representation $\rho : G_{\mathbb{Q}_p} \rightarrow \operatorname{GL}_2(E)$ is of type (k, τ, ψ) if ρ is potentially semi-stable (i.e., de Rham) such that its Hodge-Tate weights are $(0, k-1)$, $\operatorname{WD}(\rho)|_{I_{\mathbb{Q}_p}} \simeq \tau$, and $\det \rho \simeq \psi \epsilon$. Here $\operatorname{WD}(\rho)$ is the Weil-Deligne representation associated to ρ by Fontaine [12].

By a result of Henniart [14], there is a unique finite dimensional smooth irreducible $\overline{\mathbb{Q}_p}$ -representation $\sigma(\tau)$ (resp. $\sigma^{\operatorname{cr}}(\tau)$) of $\operatorname{GL}_2(\mathbb{Z}_p)$ associated to τ , such that for any infinite dimensional smooth absolutely irreducible representation π of $\operatorname{GL}_2(\mathbb{Q}_p)$ and the associated Weil-Deligne representation $LL(\pi)$ via classical local Langlands correspondence, we have $\operatorname{Hom}_{\operatorname{GL}_2(\mathbb{Z}_p)}(\sigma(\tau), \pi) \neq 0$ if and only if $LL(\pi)|_{I_{\mathbb{Q}_p}} \simeq \tau$ (resp. $\operatorname{Hom}_{\operatorname{GL}_2(\mathbb{Z}_p)}(\sigma^{\operatorname{cr}}(\tau), \pi) \neq 0$ if and only if $LL(\pi)|_{I_{\mathbb{Q}_p}} \simeq \tau$ and the monodromy operator is trivial). We remark that $\sigma(\tau)$ and $\sigma^{\operatorname{cr}}(\tau)$ differ only when $\tau = \chi \oplus \chi$ is scalar, in which case

$$\sigma(\tau) = \tilde{\operatorname{st}} \otimes \chi \circ \det, \quad \sigma^{\operatorname{cr}}(\tau) = \chi \circ \det$$

where $\tilde{\operatorname{st}}$ is the inflation to $\operatorname{GL}_2(\mathbb{Z}_p)$ of the Steinberg representation of $\operatorname{GL}_2(\mathbb{F}_p)$.

Enlarging E if needed, we may and do assume $\sigma(\tau)$ is defined over E . Form the finite dimensional $\operatorname{GL}_2(\mathbb{Z}_p)$ -representation

$$\sigma(k, \tau) = \operatorname{Sym}^{k-2} E^2 \otimes_E \sigma(\tau)$$

and the semi-simplification $\overline{\sigma(k, \tau)}^{\operatorname{ss}}$ of the reduction modulo ϖ of a $\operatorname{GL}_2(\mathbb{Z}_p)$ -stable $\mathcal{O}$ -lattice inside $\sigma(k, \tau)$. Then $\overline{\sigma(k, \tau)}^{\operatorname{ss}}$ does not depend on the choice of the lattice.

Recall that the finite dimensional irreducible $\mathbb{F}$ -representations of $\operatorname{GL}_2(\mathbb{Z}_p)$ are of the form

$$\sigma_{n,m} := \operatorname{Sym}^n \mathbb{F}^2 \otimes \det^m, \quad n \in \{0, \dots, p-1\}, m \in \{0, \dots, p-2\}.$$

For each $\sigma_{n,m}$ let $a_{n,m} = a_{n,m}(k, \tau)$ be the multiplicity with which $\sigma_{n,m}$ occurs in $\overline{\sigma(k, \tau)}^{\operatorname{ss}}$. We have the obvious analogue in the crystalline case by considering

$$\sigma^{\operatorname{cr}}(k, \tau) := \operatorname{Sym}^{k-2} E^2 \otimes_E \sigma^{\operatorname{cr}}(\tau)$$

and denote the resulting numbers by $a_{n,m}^{\operatorname{cr}} = a_{n,m}^{\operatorname{cr}}(k, \tau)$.

Let $\bar{\rho} : G_{\mathbb{Q}_p} \rightarrow \mathrm{GL}_2(\mathbb{F})$ be a continuous representation and $R^\square(\bar{\rho})$ be its universal framed deformation ring ([19]). The following results on the structure of potentially semi-stable framed deformation rings are known.

THEOREM 1.1 (Kisin, [19]). – *There is a unique (possibly trivial) quotient $R^{\square,\psi}(k, \tau, \bar{\rho})$ (resp. $R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})$) of $R^\square(\bar{\rho})$ such that*

(i) *A map $x : R^\square(\bar{\rho}) \rightarrow E'$, for any finite extension E'/E , factors through $R^{\square,\psi}(k, \tau, \bar{\rho})$ (resp. $R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})$) if and only if the Galois representation ρ_x corresponding to x is of type (k, τ, ψ) (resp. and is potentially crystalline).*

(ii) *$R^{\square,\psi}(k, \tau, \bar{\rho})$ (resp. $R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})$) is p -torsion free.*

(iii) *$R^{\square,\psi}(k, \tau, \bar{\rho})[1/p]$ (resp. $R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})[1/p]$) is reduced, all of whose irreducible components are smooth of dimension 4.*

The following conjecture, the so-called Breuil-Mézard conjecture, relates the Hilbert-Samuel multiplicity of $R^{\square,\psi}(k, \tau, \bar{\rho})/\varpi$ (resp. $R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})/\varpi$) with the numbers $a_{n,m}$ (resp. $a_{n,m}^{\mathrm{cr}}$).

CONJECTURE 1.2 (Breuil-Mézard, [4]). – *For any (k, τ, ψ) as above, we have*

$$(1) \quad e(R^{\square,\psi}(k, \tau, \bar{\rho})/\varpi) = \sum_{n,m} a_{n,m}(k, \tau) \mu_{n,m}(\bar{\rho}),$$

$$(2) \quad e(R_{\mathrm{cr}}^{\square,\psi}(k, \tau, \bar{\rho})/\varpi) = \sum_{n,m} a_{n,m}^{\mathrm{cr}}(k, \tau) \mu_{n,m}(\bar{\rho})$$

for some integers $\mu_{n,m}(\bar{\rho})$ which are independent of k, τ and ψ .

In particular, the conjecture implies that

$$\mu_{n,m}(\bar{\rho}) = e\left(R_{\mathrm{cr}}^{\square,\psi}(n+2, (\tilde{\omega}^m)^{\oplus 2}, \bar{\rho})/\varpi\right)$$

which can be computed. We refer the reader to [20, 1.1.6] for these numbers, and remark that when $n = p - 2$ and $\bar{\rho}$ is scalar, $\mu_{p-2,m}(\bar{\rho}) = 4$, as is shown in [28].

Conjecture 1.2 was proved by Kisin [20] in the cases that $\bar{\rho}$ is not (a twist of) an extension of $\mathbb{1}$ by ω . He first proved the “ $\leq$ ” part of (1) and (2) using the p -adic local Langlands [6], and then combined it with the (global) modularity lifting method to deduce the “ $\geq$ ” part. Years later, the conjecture was proved by Paškūnas [26] for all $\bar{\rho}$ with only scalar endomorphisms, using the p -adic local Langlands and his previous (local) results in [25]. We prove, also using local methods (except for one global input due to Emerton [9], see the introduction of [26]), the following theorem (in the language of cycles of [10]), which in particular includes the remaining case of the conjecture (when $p \geq 5$).

THEOREM 1.3 (Remark 5.7, Theorem 5.11, Theorem 5.12). – *For any continuous representation $\bar{\rho} : G_{\mathbb{Q}_p} \rightarrow \mathrm{GL}_2(\mathbb{F})$ which is isomorphic to the direct sum of two distinct characters, and for any (k, τ, ψ) as above, there are 4-dimensional cycles $\mathcal{Z}_{n,m}$ of $R^\square(\bar{\rho})$ which are independent of (k, τ, ψ) such that*

$$\mathcal{Z}(R^{\square,\psi}(k, \tau, \bar{\rho})/\varpi) = \sum_{n,m} a_{n,m}(k, \tau) \mathcal{Z}_{n,m}.$$