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A note on Iwasawa μ-invariants of elliptic curves

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Abstract. Suppose that E_1 and E_2 are elliptic curves defined over $\mathbb{Q}$ and p is an odd prime where E_1 and E_2 have good ordinary reduction. In this paper, we generalize a theorem of Greenberg and Vatsal [3] and prove that if $E_1[p^i]$ and $E_2[p^i]$ are isomorphic as Galois modules for $i = \mu(E_1)$, then $\mu(E_1) \leq \mu(E_2)$. If the isomorphism holds for $i = \mu(E_1) + 1$, then both the curves have same μ-invariants. We also discuss one numerical example.

Keywords: elliptic curves, Iwasawa μ-invariants, Selmer groups.

Mathematical subject classification: Primary: 11G05, 14H52.

1 Introduction

Let E be an elliptic curve defined over $\mathbb{Q}$ with good ordinary reduction at p. Let Σ denote any finite set of primes containing p, ∞, and the primes of bad reduction for E. Let $\mathbb{Q}_\infty$ be the cyclotomic-$\mathbb{Z}_p$ extension of $\mathbb{Q}$. Let η_p be the unique prime of $\mathbb{Q}_\infty$ lying over p, and I_{η_p} be the inertia subgroup of $G_{(\mathbb{Q}_\infty)_{\eta_p}}$. The Selmer group $S_{E[p^\infty]}(\mathbb{Q}_\infty)$ is defined as, following [3],

$$S_{E[p^\infty]}(\mathbb{Q}_\infty) := \ker\Big(H^1(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty, E[p^\infty]) \to \prod_{l\in\Sigma} \mathcal{H}_l(\mathbb{Q}_\infty, E[p^\infty])\Big), \quad (1.1)$$

where for $l \neq p$, $\mathcal{H}_l(\mathbb{Q}_\infty, E[p^\infty]) := \prod_{\eta|l} H^1((\mathbb{Q}_\infty)_\eta, E[p^\infty])$, with η running over the primes of $\mathbb{Q}_\infty$ lying over l, and

$$\mathcal{H}_p\big(\mathbb{Q}_\infty, E[p^\infty]\big) := H^1\big((\mathbb{Q}_\infty)_{\eta_p}, E[p^\infty]\big)/L_{\eta_p}$$

where $L_{\eta_p} = \ker\Big(H^1((\mathbb{Q}_\infty)_{\eta_p}, E[p^\infty]) \to H^1(I_{\eta_p}, \widetilde{E}[p^\infty])\Big)$. This is in fact the classical Selmer group of E over $\mathbb{Q}_\infty$. Since it is the object one usually works with, there is a lot of interest in gaining information about its mu-invariant.

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Let Σ_0 be any subset of Σ which does not contain p. We also consider a "non-primitive" Selmer group, following [3], defined by

$$S^{\Sigma_0}_{E[p^\infty]}(\mathbb{Q}_\infty) = \ker\Big(H^1(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty, E[p^\infty]) \to \prod_{l\in\Sigma-\Sigma_0} \mathcal{H}_l(\mathbb{Q}_\infty, E[p^\infty])\Big).$$

We now define a Selmer group for $E[p^i]$ where $i \geq 1$ in the following way. Let

$$S^{\Sigma_0}_{E[p^i]}(\mathbb{Q}_\infty) := \ker\Big(H^1(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty, E[p^i]) \to \prod_{l\in\Sigma-\Sigma_0} \mathcal{H}_l(\mathbb{Q}_\infty, E[p^i])\Big).$$

For

$$l \neq p,\ \mathcal{H}_l\big(\mathbb{Q}_\infty, E[p^i]\big) := \prod_{\eta | l} H^1\big(I_\eta, E[p^i]\big),$$

and for

$$l = p,\ \mathcal{H}_p\big(\mathbb{Q}_\infty, E[p^i]\big) := H^1\big(I_{\eta_p}, \widetilde{E}[p^i]\big).$$

Both $S_{E[p^\infty]}(\mathbb{Q}_\infty)$ and $S^{\Sigma_0}_{E[p^\infty]}(\mathbb{Q}_\infty)$ are modules over the Iwasawa algebra $\Lambda := \mathbb{Z}_p[[\Gamma]]$, where $\Gamma = G(\mathbb{Q}_\infty/\mathbb{Q})$. It is a deep theorem of Kato that $S_{E[p^\infty]}(\mathbb{Q}_\infty)$ is cotorsion over Λ. This allows us to define the μ-invariant which is the largest power of p dividing the characteristic polynomial.

Theorem 1.1 (See [3]). *We have* $\mu\Big(\widehat{S_{E[p^\infty]}(\mathbb{Q}_\infty)}\Big) = \mu\Big(\widehat{S^{\Sigma_0}_{E[p^\infty]}(\mathbb{Q}_\infty)}\Big)$.

Suppose that E_1 and E_2 are elliptic curves defined over $\mathbb{Q}$. Let p be an odd prime where E_1 and E_2 have good ordinary reduction. If $E_1[p] \cong E_2[p]$ as $G_{\mathbb{Q}}$-modules, then in [3], Greenberg and Vatsal proved that $S_{E_1[p^\infty]}(\mathbb{Q}_\infty)[p]$ is finite if and only if $S_{E_2[p^\infty]}(\mathbb{Q}_\infty)[p]$ is finite. Consequently, if $\mu(S_{E_1[p^\infty]}(\mathbb{Q}_\infty)) = 0$ then $\mu(S_{E_2[p^\infty]}(\mathbb{Q}_\infty)) = 0$. The aim of this paper is to prove the following main result and to discuss a numerical example. The proof of the main result is a simple generalization of the one given by Greenberg and Vatsal [3].

Theorem 1.2. *Suppose that E_1 and E_2 are elliptic curves defined over $\mathbb{Q}$. Let p be an odd prime where E_1 and E_2 have good ordinary reduction. Assume that $E_1[p^i] \cong E_2[p^i]$ as $G_{\mathbb{Q}}$-modules for $i = \mu(E_1)$. Also assume that both $E_1(\mathbb{Q})[p]$ and $E_2(\mathbb{Q})[p]$ are trivial. Then $\mu(E_1) \leq \mu(E_2)$. If $E_1[p^i] \cong E_2[p^i]$ as $G_{\mathbb{Q}}$-modules for $i = \mu(E_1) + 1$, then $\mu(E_1) = \mu(E_2)$.*

2 Proof of the Main Result

Before giving the proof of the Theorem 1.2, we first state a lemma.

Lemma 2.1. *Let $S = \mathrm{S}_{E[p^\infty]}(\mathbb{Q}_\infty)$ and $X_E(\mathbb{Q}_\infty)$ be the Pontryagin dual. Let p be a prime where E has good ordinary reduction. Then*

$$\mu(X_E(\mathbb{Q}_\infty)) = \sum_{i=1}^{\infty} \mathrm{corank}_{\mathbb{F}_p[[T]]} \frac{S[p^i]}{S[p^{i-1}]}.$$

Proof. The proof follows without difficulty from the following exact sequences and comparing $\mathbb{F}_p[[T]]$-coranks

$$0 \to \widehat{\left(\frac{S}{p^r S}\right)} \to \widehat{\left(\frac{S}{p^{r+1} S}\right)} \to \widehat{\left(\frac{p^r S}{p^{r+1} S}\right)} \to 0. \tag{2.1}$$

$$0 \to \big(p^{r-1} S\big)[p] \to \big(p^{r-1} S\big) \to (p^{r-1} S) \to \frac{p^{r-1} S}{p^r S} \to 0. \tag{2.2}$$

□

The following result is an easy generalization of Proposition 2.8 in [3] (also see [1]).

Theorem 2.2. *Let p be an odd prime. Assume that Σ_0 is a subset of $\Sigma - \{p, \infty\}$. Assume that $E(\mathbb{Q})[p] = 0$ and $i \geq 1$. Then*

$$S^{\Sigma_0}_{E[p^\infty]}(\mathbb{Q}_\infty)[p^i] \cong S^{\Sigma_0}_{E[p^i]}(\mathbb{Q}_\infty).$$

Proof. Since $H^0(\mathbb{Q}, E[p]) = E(\mathbb{Q})[p] = 0$ and $\mathrm{Gal}(\mathbb{Q}_\infty/\mathbb{Q})$ is a pro-p group, we have $H^0(\mathbb{Q}_\infty, E[p^\infty]) = 0$. Consider the exact sequence

$$0 \to E[p^i] \to E[p^\infty] \xrightarrow{p^i} E[p^\infty] \to 0$$

of $\mathrm{Gal}(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty)$-modules. Taking $\mathrm{Gal}(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty)$ cohomology and using the fact that $H^0(\mathbb{Q}_\infty, E[p^\infty]) = 0$, we find the following isomorphism

$$H^1\big(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty, E[p^i]\big) \cong H^1\big(\mathbb{Q}_\Sigma/\mathbb{Q}_\infty, E[p^\infty]\big)[p^i].$$

Comparing the local conditions defining $S^{\Sigma_0}_{E[p^\infty]}(\mathbb{Q}_\infty)[p^i]$ and $S^{\Sigma_0}_{E[p^i]}(\mathbb{Q}_\infty)$, we complete the proof of the result. □

Let Σ be a finite set of primes containing p, ∞, and all primes where either E_1 or E_2 has bad reduction. Let $\Sigma_0 = \Sigma - \{p, \infty\}$.

Proof of the Theorem 1.2. From Theorem 2.1 and Theorem 1.1, we have

$$\begin{aligned}
\mu(E_1) &= \sum_{i=1}^{\mu(E_1)} \operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{S^{\Sigma_0}_{E_1[p^\infty]}(\mathbb{Q}_\infty)[p^i]}{S^{\Sigma_0}_{E_1[p^\infty]}(\mathbb{Q}_\infty)[p^{i-1}]} \\
&= \sum_{i=1}^{\mu(E_1)} \operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{S^{\Sigma_0}_{E_1[p^i]}(\mathbb{Q}_\infty)}{S^{\Sigma_0}_{E_1[p^{i-1}]}(\mathbb{Q}_\infty)} \\
&= \sum_{i=1}^{\mu(E_1)} \operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{S^{\Sigma_0}_{E_2[p^i]}(\mathbb{Q}_\infty)}{S^{\Sigma_0}_{E_2[p^{i-1}]}(\mathbb{Q}_\infty)} \\
&= \sum_{i=1}^{\mu(E_1)} \operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{\mathrm{S}^{\Sigma_0}_{E_2[p^\infty]}(\mathbb{Q}_\infty)[p^i]}{\mathrm{S}^{\Sigma_0}_{E_2[p^\infty]}(\mathbb{Q}_\infty)[p^{i-1}]} \\
&\leq \mu(E_2).
\end{aligned}$$

The equalities follow directly from Theorem 2 and the isomorphisms $E_1[p^i] \cong E_2[p^i]$ as $G_{\mathbb{Q}}$-modules for $i = \mu(E_1)$. Indeed, since $E_1[p^i] \cong E_2[p^i]$ as $G_{\mathbb{Q}}$-modules for $i = \mu(E_1) + 1$, so

$$\operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{\mathrm{S}^{\Sigma_0}_{E_1[p^i]}(\mathbb{Q}_\infty)}{\mathrm{S}^{\Sigma_0}_{E_1[p^{i-1}]}(\mathbb{Q}_\infty)} = 0$$

implies

$$\operatorname{corank}_{\mathbb{F}_p[[T]]} \frac{\mathrm{S}^{\Sigma_0}_{E_2[p^i]}(\mathbb{Q}_\infty)}{\mathrm{S}^{\Sigma_0}_{E_2[p^{i-1}]}(\mathbb{Q}_\infty)} = 0$$

for $i = \mu(E_1) + 1$. Hence if $E_1[p^i] \cong E_2[p^i]$ as $G_{\mathbb{Q}}$-modules for $i = \mu(E_1) + 1$, then $\mu(E_1) = \mu(E_2)$. $\square$

3 Numerical examples

Consider the following elliptic curves:

$$E_1 : y^2 = x^3 - x^2 - 2858x - 10163, \qquad [4900a1] \tag{3.1}$$

$$E_2 : y^2 = x^3 - x^2 - 174358x - 27964663, \qquad [4900a2] \tag{3.2}$$

$$E_3 : y^2 = x^3 - x^2 - 24908x + 1522312, \qquad [4900b1] \tag{3.3}$$

$$E_4 : y^2 = x^3 - x^2 + 24092x + 6422312. \qquad [4900b2] \tag{3.4}$$

Here the labels in the square brackets denote the Cremona numbers of the curves. We begin with some facts about these curves. There is a single 3-isogeny $\phi\colon E_1 \longrightarrow E_2$ and $\psi\colon E_3 \longrightarrow E_4$, defined over $\mathbb{Q}$. All the curves have good ordinary reduction at 3. A computation using 3-division polynomials shows that there is no non-trivial 3-torsion point over $\mathbb{Q}$ on these curves. Recall that for an elliptic curve $E\colon y^2 = x^3 + ax + b$ over $\mathbb{Q}$, its 3-division polynomial is given by $\psi(x) = 3x^4 + 6ax^2 + 12bx - a^2$. Let x_0, x_1 be two different roots of ψ, so that

$$\psi(x) = 3(x - x_0)\big(x^3 + x_0x^2 + \big(2a + x_0^2\big)x + 4b + 2ax_0 + x_0^3\big).$$

Let $y_1^2 = x_1^3 + ax_1 + b$. Then $-4y_1^2x_0 = (x_0^2 + a + 2x_0x_1)^2$. Hence

$$y_1 = \pm\sqrt{-x_0}\left(x_1 + \frac{x_0^2 + a}{2x_0}\right).$$

Similarly,

$$y_0 = \pm\sqrt{-x_1}\left(x_0 + \frac{x_1^2 + a}{2x_1}\right).$$

Therefore, $\mathbb{Q}(E[3]) = \mathbb{Q}(\sqrt{-x_0}, \sqrt{-x_1}, \sqrt{-x_2}, \sqrt{-x_3})$, which is nothing but the splitting field of $\psi(-X^2) = 3X^8 + 6aX^4 - 12bX^2 - a^2$.

Lemma 3.1. *Suppose that for an elliptic curve $E/\mathbb{Q}$, $\mathbb{Q}(E[3])$ denotes the field of 3-torsion points. Then $\mathbb{Q}(E_1[3]) = \mathbb{Q}(E_3[3])$ and $\mathbb{Q}(E_2[3]) = \mathbb{Q}(E_4[3])$. Moreover, these fields are of degree 12 over $\mathbb{Q}$. There is a 3-torsion point of E_1 and E_3 defined over $\mathbb{Q}(\sqrt{5})$, while E_2 and E_4 have a 3-torsion point defined over $\mathbb{Q}(i\sqrt{15})$.*

Proof. Let $\psi_i(X)$ denote the 3-division polynomial for the Weierstrass equation of $E_i : i = 1, \ldots, 4$. Using MAGMA the splitting fields of $\psi_1(-X^2)$ and $\psi_3(-X^2)$ as well as $\psi_2(-X^2)$ and $\psi_4(-X^2)$ are found to be equal. Further, the degree of the extensions $\mathbb{Q}(E_i[3])$ over $\mathbb{Q}$ is also found to be 12 for each i. Along with this, we also find 3-torsion points

$$P_1 = (2940, 2^3 3^3 7^2 5\sqrt{5}), \qquad P_2 = (-8820, 2^3 3.5.7^2\sqrt{15}i),$$
$$P_3 = (2940, 2^4 3^3.5.7\sqrt{5}), \qquad P_4 = (-8820, 2^4.3.5^4.7\sqrt{15}i)$$

on E_1, E_2, E_3, E_4 respectively. Therefore E_1 and E_3 have a 3-torsion point over $L = \mathbb{Q}(\sqrt{5})$, while E_2 and E_4 have a 3-torsion point over $K = \mathbb{Q}(\sqrt{15}i)$. $\square$

Our next goal is to show that $E_1[3] \cong E_3[3]$ and $E_2[3] \cong E_4[3]$ as $G_{\mathbb{Q}}$-modules.

Theorem 3.2. *As $G_{\mathbb{Q}}$-modules, $E_1[3] \cong E_3[3]$ and $E_2[3] \cong E_4[3]$.*

Proof. Let ρ_i denote the $G_{\mathbb{Q}}$-representation associated to $E_i[3]$, for $i = 1, \ldots, 4$ and $L = \mathbb{Q}(\sqrt{5})$ and $K = \mathbb{Q}(i\sqrt{15})$. Since each of these curves admit a 3-isogeny, we get

$$\rho_1(g) \sim \begin{pmatrix} \epsilon(g) & b(g) \\ 0 & \eta(g) \end{pmatrix} \quad \text{and} \quad \rho_3(g) \sim \begin{pmatrix} \epsilon'(g) & b'(g) \\ 0 & \eta'(g) \end{pmatrix} \ \forall g \in G_{\mathbb{Q}},$$

where $\epsilon, \epsilon', \eta, \eta'$ are all characters of $G_{\mathbb{Q}}$. Since there is 3-torsion point in L, we have

$$\rho_1|_{G_L} \sim \begin{pmatrix} 1 & * \\ 0 & \chi \end{pmatrix} \quad \text{and} \quad \rho_3|_{G_L} \sim \begin{pmatrix} 1 & * \\ 0 & \chi \end{pmatrix}.$$

where $\chi = \chi_3 \pmod 3$ is the mod 3 cyclotomic character. Suppose that $\Delta := G_{\mathbb{Q}}/G_L =< \tau >$, then $\epsilon(\tau) = -1$ as there is no non-trivial rational 3-torsion. Therefore, $\eta(\tau) = -\chi(\tau)$.

Comparing the traces of $\rho_1(g)\ |_{G_L}$, we get $\epsilon(g) + \eta(g) = 1 + \chi(g)$, for $g \in G_L$. Therefore, by Artin's theorem on linear independence of characters, either $\epsilon(g) = \chi(g)$ or 1 for $g \in G_L$. Suppose that $\epsilon(g) = \chi(g)$. Then

$$\rho_1\ |_{G_L}\ (g) \sim \begin{pmatrix} \chi(g) & b(g) \\ 0 & \eta(g) \end{pmatrix},$$

which means that there is a point in $E_1[3]$, say P' such that $gP' = \chi(g)P'$. There is also a point P_1 in $E_1[3]$ such that $gP_1 = P_1$. It is easy to see that P_1 is not in the span of P'. Hence with respect to these points as basis, we have

$$\rho_1\ |_{G_L}\ (g) \sim \begin{pmatrix} \chi(g) & 0 \\ 0 & \eta(g) \end{pmatrix}.$$

Therefore the kernel of $\rho_1\ |_{G_L}$ cuts out a field whose extension degree over L is 2 or 4. This is not possible as the extension degree over L is computed to be 6 in the previous lemma. Hence, $\epsilon(g) = 1$ and $\eta(g) = \chi(g)$ for $g \in G_L$.

Similarly, for the $G_{\mathbb{Q}}$-representation ρ_3, we have $\epsilon'(\tau) = -1$ and $\eta'(\tau) = -\chi(\tau)$. As above, $\epsilon'\ |_{G_L}\ (g) = 1$ and $\eta'\ |_{G_L}\ (g) = \chi(g)$. Now, for any $\gamma = h\tau \in G_{\mathbb{Q}}$ with $h \in G_L$, we have $\epsilon'(h\tau) = -1 = \epsilon(h\tau)$ and $\eta'(h\tau) = \chi(h\tau) = \eta(h\tau)$. This implies that

$$\rho_1 \sim \begin{pmatrix} \epsilon & b \\ 0 & \eta \end{pmatrix} \quad \text{and} \quad \rho_3 \sim \begin{pmatrix} \epsilon & b' \\ 0 & \eta \end{pmatrix}.$$

Let $\mathbf{F} = \mathbb{Z}/3\mathbb{Z}$ as a vector space over itself. For $g, h \in G_{\mathbb{Q}}$, using $\rho_1(gh) = \rho_1(g)\rho_2(h)$, it is easy to see that $u := \eta^{-1}b$, and $v := \eta^{-1}b'$ are 1-cocycles in $Z^1(G_{\mathbb{Q}}, \mathbf{F}(\epsilon\eta^{-1}))$. If u, v differ by a 1-coboundary in $B^1(G_{\mathbb{Q}}, \mathbf{F}(\epsilon\eta^{-1}))$, then it is easy to see that $\rho_1 \sim \rho_3$. Using the inflation-restriction sequence with respect to $G_L \subset G_{\mathbb{Q}}$, we get

$$\begin{aligned} 0 &\to H^1\big(\Delta, \mathbf{F}(\epsilon\eta^{-1})^{G_L}\big) \to H^1\big(G_{\mathbb{Q}}, \mathbf{F}(\epsilon\eta^{-1})\big) \\ &\to H^1\big(G_L, \mathbf{F}(\epsilon\eta^{-1})\big)^{\Delta} \to H^2\big(\Delta, \mathbf{F}(\epsilon\eta^{-1})^{G_L}\big). \end{aligned}$$

Since Δ acts non-trivially on the one dimensional space $\mathbf{F}(\epsilon\eta^{-1})$ and Δ is cyclic, therefore the first term of this sequence vanishes. Hence we have an inclusion

$$H^1\big(G_{\mathbb{Q}}, \mathbf{F}(\epsilon\eta^{-1})\big) \hookrightarrow H^1\big(G_L, \mathbf{F}(\chi^{-1})\big)^{\Delta} \hookrightarrow H^1\big(G_L, \mathbf{F}(\chi^{-1})\big), \tag{3.5}$$

where we have used the fact that $\epsilon\ |_{G_L} = 1$ and $\eta\ |_{G_L} = \chi$. Let M be the extension over L cut out by χ, $H = G_M$ and $D = G(M/L)$. Then $M = K(\mu_3)$ so that D has order 2. Using the inflation restriction sequence again, but with respect to $H \subset G_L$, we get

$$\begin{aligned} 0 &\longrightarrow H^1\big(D, \mathbf{F}(\chi^{-1})^H\big) \longrightarrow H^1\big(G_L, \mathbf{F}(\chi^{-1})\big) \\ &\longrightarrow H^1\big(H, \mathbf{F}(\chi^{-1})\big)^D \longrightarrow H^2\big(D, \mathbf{F}(\chi^{-1})^H\big). \end{aligned}$$

As D is cyclic and H acts trivially on $\mathbf{F}$, the first term is trivial.

Combining this injection with the injection in (3.5), we get

$$H^1\big(G_{\mathbb{Q}}, \mathbf{F}(\epsilon\eta^{-1})\big) \hookrightarrow H^1\big(G_L, \mathbf{F}(\chi^{-1})\big) \hookrightarrow H^1\big(H, \mathbf{F}(\chi^{-1})\big)^D.$$

Let $b\ |_{G_L} = a, b'\ |_{G_L} = a'$. By the first injectivity, to show that b, b' are cohomologous it is enough to show that a, a' differ by a co-boundary. We give a proof of this below.

Since H acts trivially on $\mathbf{F}(\chi^{-1})$ therefore $H^1(H, \mathbf{F}(\chi^{-1}))^D = \mathrm{Hom}(H, \mathbf{F})^D$. Hence the image of a, which is $a|_H$, gives a homomorphism $H \longrightarrow \mathbf{F}$.

Since $\mathbb{Q}(E_1[3]) = \mathbb{Q}(E_3[3])$, therefore the field cut out by $a|_H$ and $a'|_H$ are the same. Hence $J := ker(a|_H) = ker(a'|_H) =: J'$. Further, as $a|_H$, and $a'|_H$ are non-trivial, they are surjective. Hence $a|_H$, and $a'|_H$ are isomorphisms from H/J onto $\mathbf{F}$. Finally, since $|H/J| = |\mathbf{F}| = 3$, therefore $|\mathrm{Isom}(H/J, \mathbf{F})| = 2$, and hence either $a|_H = a'|_H$ or $a|_H = -a'|_H$.

If $a|_H = a'|_H$, then by injectivity of the above exact sequence, it follows that $[a] = [a']$ and we are done.

Let $a|_H = -a'|_H = 2a'|_H$, then $[a] = [2a']$. Therefore $[b] = [2b']$. As $[2b'] = 2[b']$, so

$$\begin{pmatrix} \epsilon & b \\ 0 & \eta \end{pmatrix} \sim \begin{pmatrix} \epsilon & 2b' \\ 0 & \eta \end{pmatrix}.$$

Now,

$$\begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} \epsilon & b' \\ 0 & \eta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix}^{-1} = \begin{pmatrix} \epsilon & 2b' \\ 0 & \eta \end{pmatrix}.$$

Therefore

$$\begin{pmatrix} \epsilon & b \\ 0 & \eta \end{pmatrix} \sim \begin{pmatrix} \epsilon & b' \\ 0 & \eta \end{pmatrix}.$$

Hence $\rho_1 \sim \rho_3$. This proves that $E_1[3]$ and $E_3[3]$ are isomorphic as $G_{\mathbb{Q}}$-modules.

In a similar manner, since the elliptic curves E_2 and E_4 have a 3-torsion point over $K = \mathbb{Q}(i\sqrt{15})$ and $\mathbb{Q}(E_2[3]) = \mathbb{Q}(E_4[3])$, along with the fact that $\mathbb{Q}(E_2[3])$ has degree 12 over $\mathbb{Q}$, we see that $\rho_2 \sim \rho_4$, thereby completing the proof. □

Theorem 3.3. *As $G_{\mathbb{Q}}$-modules, $E_1[9] \cong E_3[9]$ and $E_2[9] \ncong E_4[9]$.*

Proof. Using Sage, William Stein has checked that $E_1[9]$ and $E_3[9]$ are isomorphic, in fact "equal", as subvarieties of $J_0(4900)$. The 9-division polynomials of E_2 and E_4 have factors of degree $1 + 3 + 9 + 27$. Using Sage it can be checked that the two degree 27 polynomials (the largest factors of the two 9-division polynomials) do not define isomorphic fields. Let $f \colon E_2[9] \longrightarrow E_4[9]$ be an isomorphism of Galois modules. Then for each $P \in E_2[9]$ its field of definition $\mathbb{Q}(P)$ is equal to $\mathbb{Q}(f(P))$. Clearly subgroup of $G_{\mathbb{Q}}$ fixing $\{P, -P\}$ is the same subgroup for P as for $f(P)$. The fixed field of this subgroup is $\mathbb{Q}(x(P))$, hence $\mathbb{Q}(x(P)) = \mathbb{Q}(x(f(P))$. Since the last fact holds for every (nonzero) $P \in E_2[9]$, it follows that the two 9-division polynomials (whose roots are all the $x(P)$ for nonzero P) match up, in the sense that there is a bijection from the irreducible factors of the first to those of the second such that for each irreducible factor h_2 of the first which matches the factor h_4 of the second, the fields $\mathbb{Q}[x]/(h_2)$ and $\mathbb{Q}[x]/(h_4)$ are isomorphic. But $E_2[9]$ and $E_4[9]$ have a single irreducible factor of degree 27 in its 9-division polynomial, but these do not define isomorphic number fields. This proves that $E_2[9] \ncong E_4[9]$ as Galois modules. □

Using MAGMA, we find that the first coefficients of the p-adic L-functions of E_1 and E_3 are not divisible by 3. Therefore, assuming the *main conjecture*, the μ-invariant of E_1 and E_3 are 0. Moreover, since the ratio of the periods is 3 in each isogeny class, so the μ-invariant of E_2 and E_4 are 1. This numerically verifies our Main theorem.

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