Arithmetic Geometry and Stacky Curves

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UGA Number Theory/Arithmetic Geometry Seminar

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Introduction

Believe women.

Believe your colleagues.

Stop the cruelty.

Generalized Fermat Equations

Motivation: Find all integer solutions (x, y, z) to the generalized Fermat equation

$$Ax^p + Bx^q = Cz^r$$

for $A, B, C \in \mathbb{Z}$ and $p, q, r \geq 2$.

Generalized Fermat Equations

Motivation: Find integer solutions to $Ax^p + Bx^q = Cz^r$.

Example $((A, B, C) = (1, 1, 1), (p, q, r) = (2, 2, 2))$

Famously, there are infinitely many integer solutions to $x^2 + y^2 = z^2$, with primitive $(\gcd(x, y, z) = 1)$ solutions parametrized by

$$(x, y, z) = \left(\frac{s^2 - t^2}{2}, st, \frac{s^2 + t^2}{2}\right) \quad \text{for odd, coprime } s > t \geq 1.$$

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P.
@p_blade_

Wow. Another day as an adult without using the Pythagorean Theorem.

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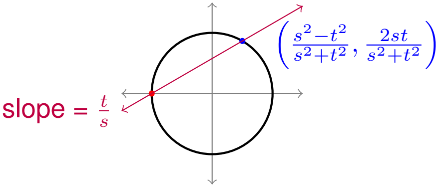

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Example $((A, B, C) = (1, 1, 1), (p, q, r) = (n, n, n))$

Also famously, there are *no* integer solutions to $x^n + y^n = z^n$ for $n > 2$.

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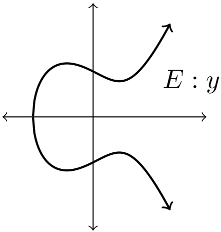
Example $((A, B, C) = (1, 1, 1), (p, q, r) = (n, n, n))$

Also famously, there are *no* integer solutions to $x^n + y^n = z^n$ for $n > 2$. Assume n is prime. If (x_0, y_0, z_0) were such a solution, it would determine an elliptic curve



$$E : y^2 = x(x - x_0^n)(x + y_0^n)$$

Ribet showed E is not modular. However, Wiles showed all such elliptic curves are modular, a contradiction.

Generalized Fermat Equations

Takeaway: Integer solutions to $Ax^p + Bx^q = Cz^r$ can be studied using geometry.

Generalized Fermat Equations

Here are some more known cases of $Ax^p + Bx^q = Cz^r$.

- (Beukers, Darmon–Granville) Let $\chi = \frac{1}{p} + \frac{1}{q} + \frac{1}{r} - 1$. The equation $x^p + y^q = z^r$ has infinitely many primitive solutions when $\chi > 0$ and finitely many when $\chi < 0$.

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- (Mordell, Zagier, Edwards) When $\chi > 0$, the primitive solutions to $x^p + y^q = z^r$ may always be parametrized explicitly (as in the $(2, 2, 2)$ case).
- (Fermat, Euler, et al.) The case $\chi = 0$ only occurs for $(2, 3, 6), (4, 4, 2), (3, 3, 3)$ and permutations of these. In each case, descent proves there are finitely many primitive solutions.
- $(2, 3, 7)$ was solved by Poonen–Schaeffer–Stoll (2007).
- $(2, 3, 8), (2, 3, 9)$ were solved by Bruin (1999, 2004).
- etc.

Generalized Fermat Equations

Question: How do we count solutions to such equations?

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One strategy is to form the scheme theoretic locus of nontrivial, primitive solutions in 3-dimensional space over $\mathbb{Z}$:

$$S = \operatorname{Spec}(\mathbb{Z}[x,y,z]/(Ax^p + By^q - Cz^r)) \smallsetminus \{x = y = z = 0\} \subseteq \mathbb{A}^3_{\mathbb{Z}}.$$

For any ring R, this keeps track of the R-solutions:

$$S(R) = \{x, y, z \in R \mid Ax^p + By^q = Cz^r, \text{ nontrivial, primitive}\}.$$

Generalized Fermat Equations

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Let G be the group of symmetries of S. $(G = \mathbb{G}_m \cdot (\mu_p \times \mu_q \times \mu_r))$

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Let G be the group of symmetries of S. $(G = \mathbb{G}_m \cdot (\mu_p \times \mu_q \times \mu_r))$

We can form the quotient $X = S/G$ whose points are exactly the equivalence classes of solutions:

$$X(R) = \{x, y, z \in R \mid Ax^p + By^q = Cz^r, \text{ nontriv., prim.}\}/\sim$$
$$\text{where } g \cdot (x,y,z) \sim (x,y,z).$$

Upside: these are easier to count than $S(R)$.
Downside: the geometry of X is bad!

Generalized Fermat Equations

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Let G be the group of symmetries of S. $(G = \mathbb{G}_m \cdot (\mu_p \times \mu_q \times \mu_r))$

We can form the quotient **stack** $\mathcal{X} = [S/G]$ whose points are exactly the **groupoid** of solutions:

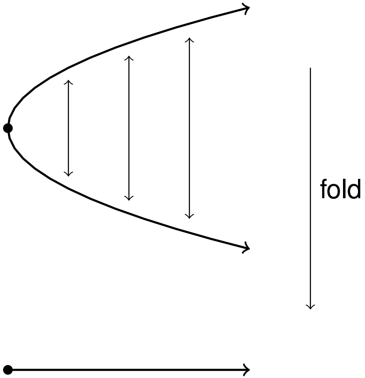
$\mathcal{X}(R)$: objects: nontriv., prim. solutions to $Ax^p + By^q = Cz^r$

morphisms: $(x,y,z) \xrightarrow{g} g \cdot (x,y,z)$.

Upside: these are easier to count than $S(R)$.
Downside: **none - stacks are awesome!**

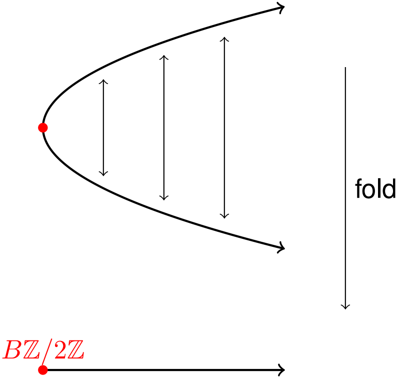
Stacks

Problem: all sorts of information is lost when we consider quotients.



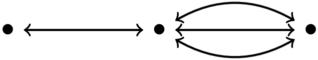
Stacks

Solution: Keep track of extra automorphisms using *groupoids*.

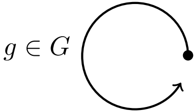


Stacks

A groupoid is a category with only isomorphisms.



Main example: for a group G, BG has one object • and one morphisms for every $g \in G$:



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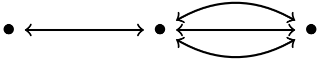

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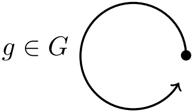


A stack is a functor $\mathcal{X} : \texttt{Ring} \to \texttt{Groupoid}$ that assigns to each ring R a groupoid $\mathcal{X}(R)$.

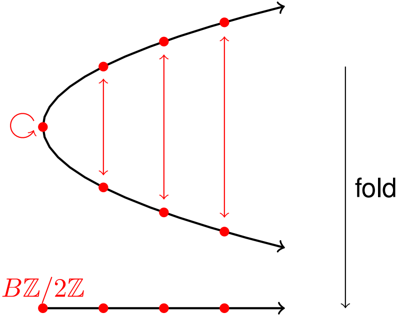
Moreover, it must satisfy *descent*: for any cover* $\{R \to S_i\}$, the objects/morphisms of $\mathcal{X}(R)$ are determined by those of $\{\mathcal{X}(S_i)\}$.

Stacks

A stack is a functor $\mathcal{X} : \texttt{Ring} \to \texttt{Groupoid}$ satisfying descent.

Example

For our plane curve $X : y^2 = x$, groupoids remember automorphisms like $(x, y) \leftrightarrow (x, -y)$



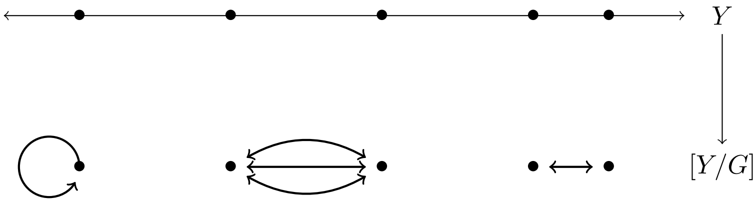
Here, each downstairs "point" is obtained by collapsing upstairs points together and identifying morphisms.

Stacks

A stack is a functor $\mathcal{X} : \texttt{Ring} \to \texttt{Groupoid}$ satisfying descent.

Example

More generally, for a group G acting on a space Y, we can form the *quotient stack* $[Y/G]$ whose R-points are the groupoid of G-orbits:



Special case: $[*/G] = BG$.

Stacky Curves

Here’s a technical definition of a stacky curve:

Definition

A **stacky curve** is a smooth, separated, connected stack $\mathcal{X} : \texttt{Ring} \to \texttt{Groupoid}$ satisfying:

1. $\mathcal{X}$ has an underlying *coarse moduli scheme* X with a map $\pi : \mathcal{X} \to X$ (collapse the groupoid to a set).
2. π is an isomorphism away from a finite set of points.
3. X is 1-dimensional (aka a curve).
4. There is an étale surjection $U \to \mathcal{X}$ where U is a scheme.
5. The diagonal $\Delta_{\mathcal{X}} : \mathcal{X} \to \mathcal{X} \times \mathcal{X}$ is representable.

Stacky Curves

Here's a more informal definition though:

A stacky curve $\mathcal{X}$ consists of an ordinary curve X, together with a finite number of marked points $P_1, \ldots, P_n$, each of which is decorated with a finite automorphism group G_i.

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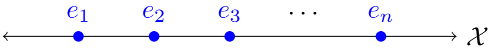
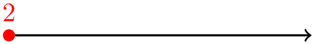
A stacky curve $\mathcal{X}$ consists of an ordinary curve X, together with a finite number of marked points $P_1, \ldots, P_n$, each of which is decorated with a finite automorphism group G_i.

Over $\mathbb{C}$ (or $\mathbb{Q}$, or a number field), the groups G_i are cyclic, so $G_i \cong \mathbb{Z}/e_i\mathbb{Z}$ and we can keep track of this data with a cartoon like this:



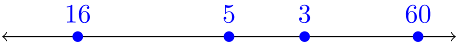
Stacky Curves

Here's a cartoon of our folded parabola:



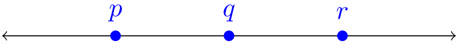
Stacky Curves

Here's a cartoon of a stacky curve with coarse space $\mathbb{P}^1$:



Stacky Curves

Here's a cartoon of our stacky curve $[S/G]$, where $S =$ primitive integer solutions to $Ax^p + Bx^q = Cz^r$:



Generalized Fermat Equations, Revisited

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$$\begin{tikzcd} C_0 \arrow[d] \\ \mathcal{X} \end{tikzcd}$$

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(2) Compute all twists of C_0 and their points.

(3) Use descent to identify points on $\mathcal{X}$.

Generalized Fermat Equations, Revisited

Example

For $\mathcal{X} : x^2 + y^2 = z^2$, there is an étale map

$$\begin{tikzcd}\mathbb{P}^1 \arrow[d] \\ \mathcal{X}\end{tikzcd}$$

and $\mathbb{P}^1$ has infinitely many points which descend, so there are infinitely many primitive Pythagorean triples.

Generalized Fermat Equations, Revisited

Example (Poonen–Schaeffer–Stoll)

For $\mathcal{X} : x^2 + y^3 = z^7$, there is an étale map

$$\begin{tikzcd}
C_1 \arrow[drr] & & C \arrow[ll, dashed, "\text{twist}"'] \arrow[rr, dashed, "\text{twist}"] \arrow[d] & & C_2 \arrow[dll] & \cdots & C_{10} \arrow[dllll] \\
& & \mathcal{X} & & & &
\end{tikzcd}$$

where C is the Klein quartic, defined by $x^3y + y^3 + x = 0$. Descending points from C and its 10 twists gives 16 primitive solutions:

$$(\pm 1, -1, 0), \quad (\pm 1, 0, 1), \quad (0, \pm 1, \pm 1), \quad (\pm 3, -2, 1),$$
$$(\pm 71, -17, 2), \quad (\pm 2213459, 1414, 65), \quad (\pm 15312283, 9262, 113),$$
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Local-Global Principle for Algebraic Curves

The classic local-global principle for an algebraic curve X asks if $X(\mathbb{Q}) \neq \varnothing$ is equivalent to $X(\mathbb{Q}_p) \neq \varnothing$ for all completions $\mathbb{Q}_p$, $p \leq \infty$.

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Let $g = g(X)$ be the genus of X. It is known that:

- (Hasse–Minkowski) If $g = 0$, the LGP holds for X.
- There are counterexamples to the LGP for all $g > 0$. For example, $X : 2y^2 = 1 - 17x^4$.

Local-Global Principle for Stacky Curves

For a stacky curve $\mathcal{X}$, we pose the *local-global principle for integral points*:

is $\mathcal{X}(\mathbb{Z}) \neq \varnothing$ equivalent to $\mathcal{X}(\mathbb{Z}_p) \neq \varnothing$ for all completions $\mathbb{Z}_p$?

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This time, the genus $g = g(\mathcal{X})$ can be *rational*:

$$g(\mathcal{X}) = g(X) + \frac{1}{2}\sum_{i=1}^{n} \frac{e_i - 1}{e_i}$$

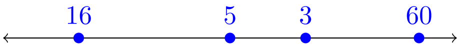
where X is the coarse space and $e_1, \ldots, e_n$ are the orders of the automorphisms groups at the finite number of stacky points.

When $\mathcal{X}$ is a *wild* stacky curve, I proved a more general formula for $g(\mathcal{X})$.

Local-Global Principle for Stacky Curves

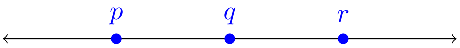
Example

Our cartoon from before is a stacky curve with genus $g = \frac{1}{2}\left(\frac{15}{16} + \frac{4}{5} + \frac{2}{3} + \frac{59}{60}\right) = \frac{271}{160}$.



Example

Our stacky curve $[S/G]$, where $S =$ primitive integer solutions to $Ax^p + Bx^q = Cz^r$, has genus $g = \frac{1}{2}\left(3 - \frac{1}{p} - \frac{1}{q} - \frac{1}{r}\right)$.



For example, the $(2,3,7)$ curve has genus $g = \frac{85}{84}$.

Local-Global Principle for Stacky Curves

For $\mathcal{X} = [S/G]$ where $S : Ax^p + By^q = Cz^r$, $g = \frac{1}{2}\left(3 - \frac{1}{p} - \frac{1}{q} - \frac{1}{r}\right)$.

Theorem (Bhargava–Poonen)

1. *If $g < \frac{1}{2}$, the LGP holds.*
2. *There are counterexamples to the LGP when $g = \frac{1}{2}$.*

Theorem (Darmon–Granville)

In the $(2, 2, n)$ case, with $g = \frac{n-1}{n}$, there are counterexamples to the LGP.

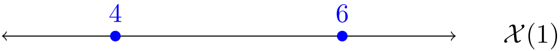
Joint work with Duque-Rosero, Keyes, Roy, Sankar, Wang (in progress): a complete solution in the $(2, 2, n)$ case.

Thank you!

Questions?

Another Example of a Stacky Curve

Here's another important stacky curve:



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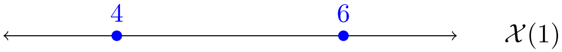

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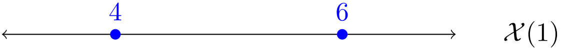

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More generally, there are modular curves $\mathcal{X}(N), \mathcal{X}_0(N), \mathcal{X}_1(N)$, etc. parametrizing elliptic curves with *level structure*.

Enough about those for now, but remember the Klein quartic?

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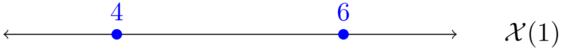

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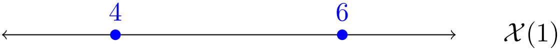

Fact: $\mathcal{X}(1) \cong \overline{\mathcal{M}}_{1,1}$, the compactified moduli stack of elliptic curves.

Fact 2: Modular curves give rise to *modular forms*.

Modular Forms

Let $\mathfrak{h} = \{z \in \mathbb{C} : \mathrm{im}(z) > 0\}$ be the upper half-plane in $\mathbb{C}$.

Definition

A **modular form** of weight $2k$ is a holomorphic function $f : \mathfrak{h} \to \mathbb{C}$ such that

1. For all $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL_2(\mathbb{Z})$, $f(z) = (cz + d)^{-2k} f(gz)$.
2. f is holomorphic at ∞.

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A **modular form** of weight $2k$ is a holomorphic function $f : \mathfrak{h} \to \mathbb{C}$ such that

1. For all $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL_2(\mathbb{Z})$, $f(z) = (cz+d)^{-2k} f(gz)$.
2. f is holomorphic at ∞.

Informal version: modular forms are highly symmetric holomorphic functions on the upper half-plane in $\mathbb{C}$.

Modular Forms

Given a modular form $f : \mathfrak{h} \to \mathbb{C}$, we can define a differential form $\omega = f(z)\, dz^k$.

By the symmetry of f, ω is not just defined on the upper half-plane, but on the quotient $\mathfrak{h}/SL_2(\mathbb{Z})$.

Compactifying by adding a point at ∞, this quotient $\overline{\mathfrak{h}/SL_2(\mathbb{Z})}$ becomes isomorphic to $\mathcal{X}(1)$, the moduli stack of elliptic curves.

Upshot: modular forms act like “functions” on the moduli stack $\mathcal{X}(1)$.

Katz Modular Forms

This allows one to define modular forms over any field K, as differential forms on the moduli stack $\mathcal{X}(1)$ of elliptic curves over K.

For an elliptic curve E over an arbitrary field K, let $\omega_{E/K}$ be the pullback of the canonical line bundle $\Omega^1_{E/K}$ to $\operatorname{Spec} K$.

Definition

A **Katz modular form** of weight k over K is a choice of section $f(E/A)$ of $\omega_{E/A}^{\otimes k/2}$ for every K-algebra A and elliptic curve E/A satisfying:

1. $f(E/A)$ is constant on isomorphism class of E/A.
2. (Naturality) f commutes with pullback along $A \to B$.
3. (Holomorphic condition) The "q-expansion" $f(E_{\mathrm{Tate}})$ has coefficients in $K \otimes \mathbb{Z}[[q]]$.

Cusp forms are modular forms with q-expansion coefficients in $K \otimes q\mathbb{Z}[[q]]$.

Katz Modular Forms

Pocket version:

- Pull back $\Omega^1_{E/K}$ along basepoint $O : \operatorname{Spec} K \hookrightarrow E$ to get $\omega_{E/K}$.
- Choose compatible sections $f(E/A) \in H^0(A, \omega_{E/A}^{\otimes k/2})$.
- Enforce holomorphic (and cusp) conditions with a geometric version of q-expansion principle.

Katz Modular Forms

Pocket version:

- Pull back $\Omega^1_{E/K}$ along basepoint $O : \operatorname{Spec} K \hookrightarrow E$ to get $\omega_{E/K}$.
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- Enforce holomorphic (and cusp) conditions with a geometric version of q-expansion principle.

Theorem

Let $\mathcal{M}_k$ be the space of weight k modular forms over K. Then there is an isomorphism

$$\mathcal{M}_k \xrightarrow{\sim} H^0(\mathcal{X}(1), \Omega_{\mathcal{X}(1)/K}(\Delta)^{k/2}), \quad f \longmapsto f\, dz^{k/2}$$

where $\mathcal{X}(1)$ is the moduli stack of elliptic curves and $\Delta = \infty$ is the cusp divisor.

Since $\mathcal{X}(1) \cong \mathbb{P}(4,6)$***, the graded ring of modular forms is

$$\bigoplus_{k \geq 0} \mathcal{M}_k \cong K[x_4, x_6].$$

Modular Forms Mod p

Joint work with D. Zureick-Brown (in progress): describe the space of mod p modular forms using the stacky structure of $\mathcal{X}(1)$ and other modular curves over $\mathbb{F}_p$.

Modular Forms Mod p

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For $p > 3$, the story for $\mathcal{X}(1)$ is the same as before:

and $\bigoplus \mathcal{M}_k \cong \mathbb{F}_p[x_4, x_6]$ (originally due to Edixhoven).

However, over $\mathbb{F}_2$ and $\mathbb{F}_3$, the stacky structure of $\mathcal{X}(1)$ looks different:

Modular Forms Mod p

Joint work with D. Zureick-Brown (in progress): describe the space of mod p modular forms using the stacky structure of $\mathcal{X}(1)$ and other modular curves over $\mathbb{F}_p$.

Even before considering the stacky structure, we have:

Theorem (Katz–Mazur)

There is a modular form $A \in \mathcal{M}_{p-1}(1; \mathbb{F}_p)$ (the Hasse invariant) satisfying $\operatorname{Frob}_p^* f = Af$ for every $f \in \mathcal{M}_k$. Moreover,

- *For $p \neq 2, 3$, $A \cong E_{p-1} \bmod p$, the weight $p-1$ Eisenstein series.*
- *For $p = 2, 3$, A is not the mod p reduction of any classical modular form.*

Modular Forms Mod p

Joint work with D. Zureick-Brown (in progress): describe the space of mod p modular forms using the stacky structure of $\mathcal{X}(1)$ and other modular curves over $\mathbb{F}_p$.

Recall: $\mathcal{M}_k \cong H^0(\mathcal{X}(1), \Omega(\Delta)^{k/2})$. Main tool to compute $\Omega = \mathcal{O}(K_{\mathcal{X}})$:

Theorem (K. 2021)

For a (tame or wild) stacky curve $\mathcal{X}$ with coarse moduli space $\pi : \mathcal{X} \to X$, their canonical divisors satisfy

$$K_{\mathcal{X}} = \pi^* K_X + \sum_{P \in \mathcal{X}(K)} \sum_{i=0}^{\infty} (|G_{P,i}| - 1)P$$

where $G_{P,i}$ are the higher ramification groups at P.

Modular Forms Mod p

Theorem (K. 2021)

$$K_{\mathcal{X}} = \pi^* K_X + \sum_{P \in \mathcal{X}(K)} \sum_{i=0}^{\infty} (|G_{P,i}| - 1)P.$$

Corollary

For the tame stacky curve $\mathcal{X}(1)$ *over* $\mathbb{F}_p, p > 3$,

we have $K_{\mathcal{X}(1)} = -2\infty + 3P + 5Q$.

Therefore $\bigoplus \mathcal{M}_k \cong \bigoplus H^0\left(\mathcal{X}(1), \mathcal{O}\left(\frac{7}{12}\right)\right) \cong K[x_4, x_6]$.

Modular Forms Mod p

Theorem (K. 2021)

$$K_{\mathcal{X}} = \pi^* K_X + \sum_{P \in \mathcal{X}(K)} \sum_{i=0}^{\infty} (|G_{P,i}| - 1) P.$$

Corollary (K.–Zureick-Brown 2023+ϵ)

For the ***wild*** *stacky curve $\mathcal{X}(1)$ over $\mathbb{F}_3$,*

we have $K_{\mathcal{X}(1)} = -2\infty + 7P$.

Therefore $\bigoplus \mathcal{M}_k \cong \bigoplus H^0\left(\mathcal{X}(1), \mathcal{O}\left(\frac{1}{6}\right)\right) \cong K[x_1, x_6]$.

Modular Forms Mod p

Theorem (K. 2021)

$$K_{\mathcal{X}} = \pi^* K_X + \sum_{P \in \mathcal{X}(K)} \sum_{i=0}^{\infty} (|G_{P,i}| - 1)P.$$

Corollary (K.–Zureick-Brown 2023$+\epsilon$)

For the **wild** *stacky curve* $\mathcal{X}(1)$ *over* $\mathbb{F}_2$,

we have $K_{\mathcal{X}(1)} = -2\infty + 14P$.

Therefore $\bigoplus \mathcal{M}_k \cong \bigoplus H^0\left(\mathcal{X}(1), \mathcal{O}\left(\frac{1}{6}\right)\right) \cong K[x_1, x_6]$.

Thank you!

Questions?