

RATIONAL POINTS ON K3 SURFACES AND DERIVED EQUIVALENCE

BRENDAN HASSETT AND YURI TSCHINKEL

The geometry of vector bundles and derived categories on complex K3 surfaces has developed rapidly since Mukai’s seminal work [Muk87]. Many foundational questions have been answered:

- the existence of vector bundles and twisted sheaves with prescribed invariants;
- geometric interpretations of isogenies between K3 surfaces [Orl97, Căl00];
- the global Torelli theorem for holomorphic symplectic manifolds [Ver13, Huy12b];
- the analysis of stability conditions and its implications for birational geometry of moduli spaces of vector bundles and more general objects in the derived category [BMT14, BM14, Bri07].

Given the precision and power of these results, it is natural to seek arithmetic applications of this circle of ideas. Questions about zero cycles on K3 surfaces have attracted the attention of Beauville-Voisin [BV04], Huybrechts [Huy12a], and other authors.

Our focus in this note is on *rational points* over non-closed fields of arithmetic interest. We seek to relate the notion of derived equivalence to arithmetic problems over various fields. Our guiding questions are:

Question 1. Let X and Y be K3 surfaces, derived equivalent over a field F . Does the existence/density of rational points of X imply the same for Y ?

Given $\alpha \in \text{Br}(X)$, let (X, α) denote the twisted K3 surface associated with α , i.e., if $\mathcal{P} \rightarrow X$ is an étale projective bundle representing α , of relative dimension $r - 1$ then $(X, \alpha) = [\mathcal{P} / \text{SL}_r]$.

Question 2. Suppose that (X, α) and (Y, β) are derived equivalent over F . Does the existence of a rational point on the former imply the same for the latter?

Note that an F -rational point of (X, α) corresponds to an $x \in X(F)$ such that $\alpha|x = 0 \in \mathrm{Br}(F)$. After this paper was released, Ascher, Dasaratha, Perry, and Zhou [ADPZ15] found that Question 2 has a negative answer, even over local fields.

We shall consider these questions for F finite, p -adic, real, and local with algebraically closed residue field. These will serve as a foundation for studying how the geometry of K3 surfaces interacts with Diophantine questions over local and global fields. For instance, is the Hasse/Brauer-Manin formalism over global fields compatible with (twisted) derived equivalence? See [HVAV11, HVA13, MSTVA14] for concrete applications to rational points problems.

In this paper, we first review general properties of derived equivalence over arbitrary base fields. We then offer examples which illuminate some of the challenges in applying derived category techniques. The case of finite and real fields is presented first—here the picture is well developed. Local fields of equicharacteristic zero are also fairly well understood, at least for K3 surfaces with semistable or other mild reduction. The analogous questions in mixed characteristic remain largely open, but comparison with the geometric case suggests a number of avenues for future investigation.

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1. GENERALITIES ON DERIVED EQUIVALENCE FOR K3 SURFACES

1.1. Definitions. Let X and Y denote K3 surfaces over a field F . Let p and q be the projections from $X \times Y$ to X and Y respectively.

Let $\mathcal{E} \in D^b(X \times Y)$ be an object of the bounded derived category of coherent sheaves, which may be represented by a perfect complex of

locally free sheaves. The *Fourier-Mukai transform* is defined

$$\begin{aligned}\Phi_{\mathcal{E}} : D^b(X) &\rightarrow D^b(Y) \\ \mathcal{F} &\mapsto q_*(\mathcal{E} \otimes p^*\mathcal{F}),\end{aligned}$$

where push forward and tensor product are the derived operations.

We say X and Y are *derived equivalent* if there exists an equivalence of triangulated categories over F

$$\Phi : D^b(X) \xrightarrow{\sim} D^b(Y).$$

A fundamental theorem of Orlov [Orl97] implies that Φ arises as the Fourier-Mukai transform $\Phi_{\mathcal{E}}$ for some perfect complex $\mathcal{E} \in D^b(X \times Y)$. When we refer to Fourier-Mukai transforms below they will induce derived equivalences.

1.2. Mukai lattices. Suppose X is a K3 surface defined over \mathbb{C} and consider its Mukai lattice

$$\tilde{H}(X, \mathbb{Z}) = \tilde{H}(X, \mathbb{Z}) := H^0(X, \mathbb{Z})(-1) \oplus H^2(X, \mathbb{Z}) \oplus H^4(X, \mathbb{Z})(1),$$

where we apply Tate twists to get a Hodge structure of weight two. Mukai vectors refer to type $(1, 1)$ vectors in $\tilde{H}(X, \mathbb{Z})$. Let $(,)$ denote the natural nondegenerate pairing on $\tilde{H}(X, \mathbb{Z})$; this coincides with the intersection pairing on $H^2(X, \mathbb{Z})$ and the negative of the intersection pairing on the other summands. There is an induced homomorphism on the level of cohomology:

$$\begin{aligned}\phi_{\mathcal{E}} : \tilde{H}(X, \mathbb{Z}) &\rightarrow \tilde{H}(Y, \mathbb{Z}) \\ \eta &\mapsto q_*(\sqrt{\text{Td}_{X \times Y}} \cdot \text{ch}(\mathcal{E}) \cup p^*\eta).\end{aligned}$$

Note that

$$\phi_{\mathcal{E}} \text{ch}(\mathcal{F}) = \text{ch}(\Phi_{\mathcal{E}}(\mathcal{F})).$$

For X defined over a non-closed field F , there are analogous constructions in ℓ -adic and other flavors of cohomology [LO11, § 2]. When working ℓ -adically, we interpret $\tilde{H}(X, \mathbb{Z}_{\ell})$ as a Galois representation rather than a Hodge structure. Observe that $\phi_{\mathcal{E}}$ is defined on Hodge structures, de Rham cohomologies, and ℓ -adic cohomologies—and these are all compatible.

1.3. Characterizations over the complex numbers.

Theorem 3. [Orl97, §3] *Let X and Y be K3 surfaces over \mathbb{C} , with transcendental cohomology groups*

$$T(X) := \text{Pic}(X)^{\perp} \subset H^2(X, \mathbb{Z}), \quad T(Y) := \text{Pic}(Y)^{\perp} \subset H^2(Y, \mathbb{Z}).$$

The following are equivalent

- there exists an isometry of Hodge structures $\tilde{H}(X, \mathbb{Z}) \simeq \tilde{H}(Y, \mathbb{Z})$;
- there exists an isometry of Hodge structures $T(X) \simeq T(Y)$;
- X and Y are derived equivalent;
- Y is isomorphic to a moduli space of stable vector bundles over X , admitting a universal family $\mathcal{E} \rightarrow X \times Y$, i.e., $Y = M_v(X)$ for a Mukai vector v such that there exists a Mukai vector w with $(v, w) = 1$.

See [Orl97, §3.8] and [Huy08, §3] for discussion of the fourth condition; for our purposes, we need not distinguish among various notions of stability. This has been extended to arbitrary fields as follows:

Theorem 4. [LO11, Th. 1.1] *Let X and Y be K3 surfaces over an algebraically closed field F of characteristic $\neq 2$. Then the third and the fourth statements are equivalent.*

Moreover, a derived equivalence between X and Y induces Galois-compatible isomorphisms between their ℓ -adic Mukai lattices. See [Huy15, §16.4] for more discussion.

1.4. Descending derived equivalence. Let F be a field of characteristic zero with algebraic closure \bar{F} . Given Y smooth and projective over F , let \bar{Y} denote the corresponding variety over \bar{F} . We say Y is *of K3 type* if \bar{Y} is deformation equivalent to the Hilbert scheme of a K3 surface.

Lemma 5. *Suppose Y_1 and Y_2 are of K3 type over F and there exists an isomorphism $\iota : \bar{Y}_1 \xrightarrow{\sim} \bar{Y}_2$ defined over \bar{F} inducing*

$$\iota^* : H^2(\bar{Y}_2, \mathbb{Z}_\ell) \xrightarrow{\sim} H^2(\bar{Y}_1, \mathbb{Z}_\ell)$$

compatible with the action of $\text{Gal}(\bar{F}/F)$. Then $Y_1 \simeq Y_2$ over F .

Proof. In characteristic zero, Galois fixed points of $\text{Isom}(\bar{Y}_1, \bar{Y}_2)$ correspond to isomorphisms between the varieties defined over F . Automorphisms of \bar{Y}_1 (resp. \bar{Y}_2) act transitively and faithfully on this set by pre-composition (resp. post-composition).

The Torelli theorem implies that the automorphism group of a K3 surface has a faithful representation in its second cohomology. This holds true for manifolds of K3 type as well—see [Mar10, Prop. 1.9] as well as previous work of Beauville and Kaledin-Verbitsky. The Galois invariance of ι^* implies that ι is Galois-fixed, hence defined over F . \square

Suppose that X and Y are K3 surfaces over F . Given a derived equivalence

$$\Phi : D(X) \xrightarrow{\sim} D(Y)$$

over F the induced

$$\phi : \tilde{H}(\bar{X}, \mathbb{Z}_\ell) \xrightarrow{\sim} \tilde{H}(\bar{Y}, \mathbb{Z}_\ell)$$

is compatible $\text{Gal}(\bar{F}/F)$ actions. We consider whether the converse holds.

We use the notation $\mathcal{M}_v(X)$ for the moduli *stack* of vector bundles/complexes over X ; this is typically a \mathbb{G}_m -gerbe over $M_v(X)$ due to homotheties.

Proposition 6. *Suppose that X and Y are K3 surfaces over F . Let $\Phi : D(\bar{X}) \xrightarrow{\sim} D(\bar{Y})$ be a derived equivalence over \bar{F} such that the induced*

$$\phi : \tilde{H}(\bar{X}, \mathbb{Z}_\ell) \xrightarrow{\sim} \tilde{H}(\bar{Y}, \mathbb{Z}_\ell)$$

is compatible with Galois actions. Write $v = \phi^{-1}(1, 0, 0)$ and $w = \phi(1, 0, 0)$.

Then we have isomorphisms $Y \simeq M_v(X)$ and $X \simeq M_w(Y)$ inducing the derived equivalence over \bar{F} . Moreover, there exist \mathbb{G}_m -gerbes $\mathcal{X} \rightarrow X$ and $\mathcal{Y} \rightarrow Y$ and isomorphisms $\mathcal{Y} \simeq \mathcal{M}_v(X)$ and $\mathcal{X} \simeq \mathcal{M}_w(Y)$ such that $\mathcal{X} \rightarrow X$ and $\mathcal{Y} \rightarrow Y$ admit trivializations over \bar{F} .

Proof. Choosing an appropriate polarization on X , the moduli space $M_v(\bar{X})$ is a K3 surface. This follows from [Muk87, Prop. 4.2]; Mukai's argument shows that the requisite polarization can be found over a non-closed field, as we just have to avoid walls orthogonal to certain Mukai vectors.

There exists a Mukai vector $v' \in \tilde{H}(\bar{X}, \mathbb{Z}_\ell)$ that is Galois invariant and satisfies $(v, v') = 1$, e.g., $v' = \phi^{-1}(0, 0, -1)$. Thus the universal sheaf

$$\mathcal{E} \rightarrow X \times \mathcal{M}_v(X)$$

has the following property: on basechange to \bar{F} it may be obtained as the pull-back of a universal sheaf on the coarse space

$$\bar{\mathcal{E}} \rightarrow \bar{X} \times M_v(\bar{X}).$$

Indeed, the universal sheaf exists wherever $M_{v'}(X)$ admits a rational point (see [LO11, Th. 3.16]).

We apply Lemma 5 to Y and $M_v(X)$. The Torelli Theorem implies $\bar{Y} \simeq M_v(\bar{X})$ with the induced isomorphism compatible with the Galois actions on ℓ -adic cohomology. Thus it descends to give $Y \simeq M_v(X)$ defined over F . \square

Remark 7. Can X and Y fail to be derived equivalent over F ? How do the pull-back homomorphisms

$$\mathrm{Br}(F) \rightarrow \mathrm{Br}(X), \quad \mathrm{Br}(F) \rightarrow \mathrm{Br}(Y)$$

compare? They must have the same kernel if X and Y are derived equivalent over F .

Remark 8. Sosna [Sos10] has given examples of complex K3 surfaces that are derived equivalent but not isomorphic to their complex conjugates.

1.5. Cycle-theoretic invariants of derived equivalence.

Proposition 9. *Let X and Y be derived equivalent K3 surfaces over a field F of characteristic $\neq 2$. Then $\mathrm{Pic}(X)$ and $\mathrm{Pic}(Y)$ are stably isomorphic as $\mathrm{Gal}(\bar{F}/F)$ -modules, and $\mathrm{Br}(X)[n] \simeq \mathrm{Br}(Y)[n]$ provided n is not divisible by the characteristic.*

Even over \mathbb{C} , this result does not extend to higher dimensional varieties [Add13].

Proof. The statement on the Picard groups follows from the Chow realization of the Fourier-Mukai transform—see [LO11, §2.7] for discussion. We write

$$\tilde{H}_{\mathrm{\acute{e}t}}(X, \mu_n) = H_{\mathrm{\acute{e}t}}^0(X, \mathbb{Z}/n\mathbb{Z}) \oplus H_{\mathrm{\acute{e}t}}^2(X, \mu_n) \oplus H_{\mathrm{\acute{e}t}}^4(X, \mu_n^{\otimes 2}).$$

The Chow-theoretic interpretation of the Fourier-Mukai kernel gives the realization

$$\phi : \tilde{H}_{\mathrm{\acute{e}t}}(X, \mu_n) \rightarrow \tilde{H}_{\mathrm{\acute{e}t}}(Y, \mu_n),$$

compatible with cycle class maps [LO11, Prop. 2.10]. Modding out by the images of the cycle class maps we get the desired equality of Brauer groups. \square

Recall that the *index* $\mathrm{ind}(X)$ of a smooth projective variety X over a field F is the greatest common divisor of the degrees of field extensions F'/F over which $X(F') \neq \emptyset$, or equivalently, the lengths of zero-dimensional subschemes $Z \subset X$.

Given a bounded complex of locally free sheaves on X

$$E = \{E_{-M} \rightarrow E_{-M+1} \rightarrow \cdots \rightarrow E_N\}$$

we may define the Chern character

$$\mathrm{ch}(E) = \sum_j (-1)^j \mathrm{ch}(E_j)$$

in Chow groups with \mathbb{Q} coefficients. The degree zero and one pieces yield the rank and first Chern class of E , expressed as alternating sums of the ranks and determinants of the terms, respectively. Similarly, we may define

$$c_2(E) = -\text{ch}_2(E) + \text{ch}_1(E)^2/2,$$

a quadratic expression in the Chern classes of the E_j with *integer* coefficients. Modulo the \mathbb{Z} algebra generated by the first Chern classes of the E_j , we may write

$$c_2(E) \equiv \sum_j (-1)^j c_2(E_j).$$

Lemma 10. *If (S, h) is a smooth projective surface over F then*

$$\begin{aligned} \text{ind}(S) &= \text{gcd}\{c_2(E) : E \text{ vector bundle on } S\} \\ &= \text{gcd}\{c_2(E) : E \in D^b(S)\}. \end{aligned}$$

Proof. Consider the ‘decomposable index’

$$\text{inddec}(S) := \text{gcd}\{D_1 \cdot D_2 : D_1, D_2 \text{ very ample divisors on } S\}$$

which is equal to

$$\text{gcd}\{D_1 \cdot D_2 : D_1, D_2 \text{ divisors on } S\},$$

because for any divisor D the divisor $D + Nh$ is very ample for $N \gg 0$. All three quantities in the assertion divide $\text{inddec}(S)$, so we work modulo this quantity.

By the analysis of Chern classes above, the second and third quantities agree. Given a reduced zero-dimensional subscheme $Z \subset S$ we have a resolution

$$0 \rightarrow E_{-2} \rightarrow E_{-1} \rightarrow \mathcal{O}_S \rightarrow \mathcal{O}_Z \rightarrow 0$$

with E_{-2} and E_{-1} vector bundles. This implies that

$$\text{gcd}\{c_2(E) : E \text{ vector bundle on } S\} \mid \text{ind}(S).$$

Conversely, given a vector bundle E there exists a twist $E \otimes \mathcal{O}_S(Nh)$ that is globally generated and

$$c_2(E \otimes \mathcal{O}_S(Nh)) \equiv c_2(E) \pmod{\text{inddec}(S)}.$$

Thus there exists a zero-cycle Z with degree $c_2(E \otimes \mathcal{O}_S(Nh))$ and

$$\text{ind}(S) \mid \text{gcd}\{c_2(E) : E \text{ vector bundle on } S\}.$$

□

Proposition 11. *If X is a K3 surface over a field F then*

$$\text{ind}(X) \mid \gcd\{24, D_1 \cdot D_2 \text{ where } D_1, D_2 \text{ are divisors on } X\}.$$

This follows from Lemma 10 and the fact that $c_2(T_X) = 24$. Beauville-Voisin [BV04] and Huybrechts [Huy10] have studied the corresponding subgroup of $\text{CH}_0(X_{\bar{F}})$.

Proposition 12. *Let X and Y be derived equivalent K3 surfaces over a field F . Then $\text{ind}(X) = \text{ind}(Y)$.*

The proof will require the notion of a *spherical object* on a K3 surface. This is an object $\mathcal{S} \in D^b(X)$ with

$$\text{Ext}^0(\mathcal{S}, \mathcal{S}) = \text{Ext}^2(\mathcal{S}, \mathcal{S}) = F, \quad \text{Ext}^i(\mathcal{S}, \mathcal{S}) = 0, \quad i \neq 0, 2.$$

These satisfy the following

- $(v(\mathcal{S}), v(\mathcal{S})) = -2$;
- rigid simple vector bundles are spherical;
- each spherical object \mathcal{S} has the associated spherical twist [Huy15, 16.2.4]:

$$T_{\mathcal{S}} : D^b(X) \rightarrow D^b(X),$$

an autoequivalence such that the induced homomorphism on the Mukai lattice is the reflection associated with $v(\mathcal{S})$;

- each spherical object $\bar{\mathcal{S}}$ on $X_{\bar{F}}$ is defined over a finite extension F'/F [Huy10, 5.4];
- over \mathbb{C} , each $v = (r, D, s) \in \tilde{H}(X, \mathbb{Z}) \cap H^{1,1}$ with $(v, v) = -2$ arises from a spherical object, which may be taken to be a rigid vector bundle E if $r > 0$ [Kul89];
- under the same assumptions, for each polarization h on X there is a *unique* h -slope stable vector bundle E with $v(E) = v$ [Huy12a, 5.1.iii].

Proof. Proposition 6 allows us to express $Y = M_v(X)$ for $v = (r, ah, s)$ where h is a polarization on X and $a^2h^2 = 2rs$. It also yields a Mukai vector $w = (r', bg, s') \in \tilde{H}(X, \mathbb{Z}_{\ell})$ with

$$(v, w) = abg \cdot h - rs' - sr' = 1.$$

Thus we have

$$(1.1) \quad \langle r, s \rangle = \langle 1 \rangle \pmod{g \cdot h}.$$

Consider a Fourier-Mukai transform realizing the equivalence

$$\Phi : D^b(X) \rightarrow D^b(Y)$$

and the induced homomorphism ϕ on the Mukai lattice. Note that

$$\phi(v) = (0, 0, 1)$$

reflecting the fact that a point on Y corresponds to a sheaf on X with Mukai vector v .

Suppose that Y has a rational point over a field of degree n over F ; let $Z \subset Y$ denote the corresponding subscheme of length n . Applying Φ^{-1} to \mathcal{O}_Z gives an element of the derived category with Mukai vector (nr, nah, ns) and

$$c_2(\Phi^{-1}(\mathcal{O}_Z)) = \frac{c_1(\Phi^{-1}(\mathcal{O}_Z))^2}{2} - \chi(\Phi^{-1}(\mathcal{O}_Z)) + 2 \operatorname{rank}(\Phi^{-1}(\mathcal{O}_Z))$$

which equals $n(nrs + r - s)$. Following the proof of Lemma 10, we compute

$$c_2(\Phi^{-1}(\mathcal{O}_Z)) \pmod{\operatorname{inddec}(X)}.$$

First suppose that r and s have different parity, so that

$$\gcd(nrs + r - s, 2rs) = \gcd(nrs + r - s, rs).$$

Then using (1.1) we obtain

$$\begin{aligned} \langle nrs + r - s, rs \rangle &= \langle r - s, rs \rangle = \langle r - s, r \rangle \langle r - s, s \rangle \\ &= \langle -s, r \rangle \langle r, s \rangle = \langle r, s \rangle^2 = \langle 1 \rangle \pmod{g \cdot h}. \end{aligned}$$

If r and s are both even then $g \cdot h$ must be odd and

$$\langle nrs + r - s, 2rs \rangle = \langle nrs + r - s, rs \rangle \pmod{g \cdot h}$$

and repeating the argument above gives the desired conclusion.

Now suppose that r and s are both odd. It follows that $h^2 \equiv 2 \pmod{4}$ and we write $h^2 = 2\gamma - 2$ for some even integer γ . Let \mathcal{S} denote the spherical object associated with h so that $v(\mathcal{S}) = (1, h, \gamma)$. Applying $T_{\mathcal{S}}$ to the Mukai vector

$$(r, ah, s) \mapsto (r, ah, s) + ((r, ah, s), (1, h, \gamma)) (1, h, \gamma),$$

we obtain a new vector with rank $r + (ah^2 - s - r\gamma)$, which is even. This reduces us to the previous situation.

In each case, we find

$$c_2(\Phi^{-1}(\mathcal{O}_Z)) \equiv n \pmod{\operatorname{inddec}(X)},$$

whence $\operatorname{ind}(X) | n$. Varying over all degrees n , we find

$$\operatorname{ind}(X) | \operatorname{ind}(Y)$$

and the Proposition follows. \square

The last result raises the question of whether spherical objects are defined over the ground field:

Question 13. Let X be a K3 surface over a field F . Suppose that $\bar{\mathcal{S}}$ is a spherical object on $X_{\bar{F}}$ such that $c_1(\bar{\mathcal{S}}) \in \text{Pic}(X_{\bar{F}})$ is a divisor defined over X . When does $\bar{\mathcal{S}}$ come from an object \mathcal{S} on X ?

Kuleshov [Kul89, Kul90] gives a partial description of how to generate all exceptional bundles on K3 surfaces of Picard rank one through ‘restructuring’ operations and ‘dragons’. It would be worthwhile to analyze which of these operations could be defined over the ground field.

Example 14. We give an example of a K3 surface X over a field F with

$$\text{Pic}(X) = \text{Pic}(X_{\bar{F}}) = \mathbb{Z}h$$

and a rigid sheaf E over $X_{\bar{F}}$ that fails to descend to F .

Choose (X, h) to be a degree fourteen K3 surface defined over \mathbb{R} with $X(\mathbb{R}) = \emptyset$. This may be constructed as follows: Fix a smooth conic C and quadric threefold Q with

$$C \subset Q \subset \mathbb{P}^4, \quad Q(\mathbb{R}) = \emptyset.$$

Let X' denote a complete intersection of Q with a cubic containing C ; we have $X'(\mathbb{R}) = \emptyset$ and X' admits a lattice polarization

$$\begin{array}{c|cc} & g & C \\ \hline g & 6 & 2 \\ C & 2 & -2 \end{array}.$$

Write $h = 2g - C$ so that (X', h) is a degree 14 K3 surface containing a conic. Let X be a small deformation of X' with $\text{Pic}(X_{\mathbb{C}}) = \mathbb{Z}h$.

The K3 surface X is Pfaffian if and only if it admits a vector bundle E with $v(E) = (2, h, 4)$ corresponding to the classifying morphism $X \rightarrow \text{Gr}(2, 6)$. However, note that

$$c_2(E) = 5$$

which would mean that $\text{ind}(X) = 1$. On the other hand, if $X(\mathbb{R}) = \emptyset$ then $\text{ind}(X) = 2$.

2. EXAMPLES OF DERIVED EQUIVALENCE

2.1. Elliptic fibrations. The paper [AKW14] has a detailed discussion of derived equivalences among genus one curves over function fields.

In this section we work over a field F of characteristic zero.

A K3 surface X is *elliptic* if it admits a morphism $X \rightarrow C$ to a curve of genus zero with fibers of genus one. We allow $C = \mathbb{P}^1$ or a non-split conic over F .

Lemma 15. *A K3 surface X is elliptic if and only if it admits a non-trivial divisor D with $D^2 = 0$.*

Proof. If X is elliptic then the pull back of a non-trivial divisor from C gives a square-zero class; we focus on the converse.

This is well-known if F is algebraically closed [PŠŠ71, §6, Th. 1]. Indeed, let $\mathcal{C}_+ \subset H^2(X, \mathbb{R})$ denote the component of the positive cone $\{\eta : (\eta, \eta) > 0\}$ containing an ample divisor and $\Gamma \subset \text{Aut}(H^2(X, \mathbb{Z}))$ the group generated by Picard-Lefschetz reflections ρ_R associated with (-2) -curves $R \in \text{Pic}(X)$. Then the Kähler cone of X is a fundamental domain for the action of Γ on \mathcal{C}_+ , in the sense that no two elements of the cone are in the same orbit and each orbit in \mathcal{C}_+ meets the closure of the Kähler cone. Cohomology classes in the interior of the cone have trivial Γ -stabilizer; classes on walls of the boundary associated with (-2) -curves are stabilized by the associated reflections.

Thus if $\text{Pic}(X)$ represents zero then there exists a non-zero divisor D in the closure of the Kähler cone with $D^2 = 0$, which induces an elliptic fibration $X \rightarrow \mathbb{P}^1$. Given a divisor $D \in \mathcal{C}_+$, we can be a bit more precise about the $\gamma \in \Gamma$ required to take D to a nef divisor. We can write

$$\gamma = \rho_{R_1} \cdots \rho_{R_m}$$

where each R_j is the class of an irreducible rational curve contained in the fixed part of the linear series $|D|$ (cf. proof in [PŠŠ71, §6], [SD74, §2]).

Now suppose F is not algebraically closed and D is defined over F . The group $\text{Gal}(\bar{F}/F)$ acts on the (-2) -curves on \bar{X} and thus on Γ and the orbit $\Gamma \cdot D$. The Galois action on R_1, \dots, R_m may be nontrivial. However, the fundamental domain description guarantees a unique $f \in \Gamma \cdot D$ in the nef cone of X , which is necessarily Galois invariant; some multiple of this divisor is defined over F . This semiample divisor induces our elliptic fibration. \square

Proposition 16. *Let X be an elliptic K3 surface over F and Y another K3 surface derived equivalent to X over F . Then Y is elliptic over F .*

Proof. By Proposition 9, the Picard groups of X and Y are stably isomorphic as lattices

$$\mathrm{Pic}(X) \oplus U \simeq \mathrm{Pic}(Y) \oplus U, \quad U = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

In particular, $\mathrm{Pic}(X)$ and $\mathrm{Pic}(Y)$ share the same discriminant and p -adic invariants. A rank-two indefinite lattice represents zero if and only if its discriminant is a square. In higher ranks, an indefinite lattice represents zero if and only if it represents zero p -adically for each p .

Thus $\mathrm{Pic}(Y)$ admits a square-zero class and is elliptic by Lemma 15. \square

An elliptic K3 surface $J \rightarrow C$ is *Jacobian* if it admits a section $C \rightarrow J$. It has geometric Picard group containing

$$(2.1) \quad \begin{array}{c|cc} & f & \Sigma \\ \hline f & 0 & 1 \\ \Sigma & 1 & -2 \end{array}$$

where f is a fiber and Σ is the section. Jacobian elliptic surfaces admit numerous autoequivalences [Bri98, §5]. Let $a, b \in \mathbb{Z}$ with $a > 0$ and $(a, b) = 1$. The moduli space of rank a degree b indecomposable vector bundles on fibers of $J \rightarrow C$ is an elliptic fibration with section, isomorphic to J over C . This reflects Atiyah's classification of vector bundles over elliptic curves [Ati57, Th. 7]. The associated Fourier-Mukai transform induces an autoequivalence of J acting on $\tilde{H}(J, \mathbb{Z})$ via an element of

$$\begin{pmatrix} c & a \\ d & b \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z})$$

obtained as in [Bri98, Th. 3.2, 5.3]. This acts on the Mukai vectors (or their ℓ -adic analogues)

$$(1, 0, 0), (0, 0, 1) \in H^0(J, \mathbb{Z})(-1) \oplus H^2(J, \mathbb{Z}) \oplus H^4(J, \mathbb{Z})(1)$$

by the formula

$$(1, 0, 0) \mapsto (0, af, c), \quad (0, 0, 1) \mapsto (b, d(f + \Sigma), 0).$$

The action is transitive on the (-2) -vectors in the lattice of algebraic classes

$$(2.2) \quad H^0(J, \mathbb{Z})(-1) \oplus H^4(J, \mathbb{Z})(1) \oplus \langle f, \Sigma \rangle \simeq \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} \oplus \begin{pmatrix} 0 & 1 \\ 1 & -2 \end{pmatrix}.$$

Thus we have established the following:

Proposition 17. *Let $J \rightarrow C$ be a Jacobian elliptic K3 surface over F . Then autoequivalences of J defined over F induce a representation of $\mathrm{SL}_2(\mathbb{Z})$ on (2.2) as above.*

The point is that here autoequivalences are defined over the ground field.

Over \mathbb{C} , the availability of autoequivalences has strong consequences for Jacobian elliptic K3 surfaces. For instance, orientation preserving automorphisms of the Mukai lattice of a complex K3 surface arise from autoequivalences [HLOY04a, Th. 1.6]. This implies that derived equivalent Jacobian elliptic K3 surfaces are isomorphic [HLOY04b, Cor. 2.7.3]. The autoequivalences are generated via spherical twists associated with rigid objects.

As we have seen (e.g., in Example 14), rigid objects over non-closed fields need not descend. It is natural to ask the following question:

Question 18. Let J_1 and J_2 denote Jacobian elliptic K3 surfaces over a field F of characteristic zero. If J_1 and J_2 are derived equivalent does it follow that $J_1 \simeq J_2$?

If the geometric Picard group has rank two then the isomorphism follows from Proposition 17.

We recall the classical Ogg-Shafarevich theory for elliptic fibrations, following [Căl00, 4.4.1, 5.4.5]: Let F be algebraically closed of characteristic zero and $J \rightarrow \mathbb{P}^1$ a Jacobian elliptic K3 surface. We may interpret

$$\mathrm{III}(J/\mathbb{P}^1) \simeq \mathrm{Br}(J)$$

and each α in this group may be realized by an elliptically fibered K3 surface $X \rightarrow \mathbb{P}^1$ with Jacobian fibration $J \rightarrow \mathbb{P}^1$. If α has order n then we have natural exact sequences

$$0 \rightarrow \mathbb{Z}/n\mathbb{Z} \rightarrow \mathrm{Br}(J) \rightarrow \mathrm{Br}(X) \rightarrow 0$$

and

$$0 \rightarrow T(X) \rightarrow T(J) \rightarrow \mathbb{Z}/n\mathbb{Z} \rightarrow 0.$$

Note that if $Y = \mathrm{Pic}^c(X/\mathbb{P}^1)$ then $[Y] = c[X] \in \mathrm{III}(J/\mathbb{P}^1)$. If c is relatively prime to n , so there exists an integer b with $bc \equiv 1 \pmod{n}$, then we have $\mathrm{Pic}^b(Y) = X$ as well. It follows that X and Y are derived equivalent with the universal sheaves inducing the Fourier-Mukai transform [Bri98, Th. 1.2].

Proposition 19. *Let F be algebraically closed of characteristic zero. Let $\phi : X \rightarrow \mathbb{P}^1$ be an elliptic K3 surface with Jacobian fibration $J(X) \rightarrow \mathbb{P}^1$. Let $\alpha \in \text{Br}(J(X))$ denote the Brauer class associated with $[X]$ in the Tate-Shafarevich group of $J(X) \rightarrow \mathbb{P}^1$. Then X is derived equivalent to the pair $(J(X), \alpha)$.*

This follows from the proof of Căldăraru's conjecture; see [HS06, 1.vi] as well as [Căl00, 4.4.1] for the fundamental identification between the twisting data and the Tate-Shafarevich group.

Question 20. Let X and Y be K3 surfaces derived equivalent over a field F . Suppose we have an elliptic fibration $X \rightarrow C$ over F . Does Y admit a fibration $Y \rightarrow C$ such that

$$\begin{array}{ccc} X & \xrightarrow{\sim} & \text{Pic}^b(Y/C) \\ \searrow & & \swarrow \\ C & & \end{array}$$

for some integer b ?

By symmetry we have $X \simeq \text{Pic}^b(Y/C)$ and $Y \simeq \text{Pic}^c(X/C)$ for $b, c \in \mathbb{Z}$. As before, if $n = \text{ord}([X]) = \text{ord}([Y])$ in the Tate-Shafarevich group then $bc \equiv 1 \pmod{n}$.

A positive answer to Question 20 would imply:

- X dominates Y over F and *vice versa*.
- If X and Y are elliptic K3 surfaces derived equivalent over a field F of characteristic zero then $X(F) \neq \emptyset$ if and only if $Y(F) \neq \emptyset$.

2.2. Rank one K3 surfaces. We recall the general picture:

Proposition 21. [Ogu02, Prop. 1.10], [Ste04] *Let X/\mathbb{C} be a K3 surface with $\text{Pic}(X) = \mathbb{Z}h$, where $h^2 = 2n$. Then the number m of isomorphism classes of K3 surfaces Y derived equivalent to X is given by*

$$m = 2^{\tau(n)-1}, \quad \text{where } \tau(n) = \text{number of prime factors of } n.$$

Example 22. The first case where there are multiple isomorphism classes is degree twelve. Let (X, h) be such a K3 surface and $Y = M_{(2,h,3)}(X)$ the moduli space of stable vector bundles $E \rightarrow X$ with

$$\text{rk}(E) = 2, \quad c_1(E) = h, \quad \chi(E) = 2 + 3 = 5,$$

whence $c_2(E) = 5$. Note that if $Y(F) \neq \emptyset$ then X admits an effective zero-cycle of degree five and therefore a zero-cycle of degree one. Indeed, if $E \rightarrow X$ is a vector bundle corresponding to $[E] \in Y(F)$ then a generic $\sigma \in \Gamma(X, E)$ vanishes at five points on X . As we vary σ , we

get a four-parameter family of such cycles. Moreover, the cycle h^2 has degree twelve, relatively prime to five.

Is $X(F) \neq \emptyset$ when $Y(F) \neq \emptyset$?

2.3. Rank two K3 surfaces. Exhibiting pairs of non-isomorphic derived equivalent complex K3 surfaces of rank two is a problem on quadratic forms [HLOY04b, §3]. Suppose that $\text{Pic}(X_{\mathbb{C}}) = \Pi_X$ and $\text{Pic}(Y_{\mathbb{C}}) = \Pi_Y$ and X and Y are derived equivalent. Orlov's Theorem implies $T(X) \simeq T(Y)$ which means that Π_X and Π_Y have isomorphic discriminant groups/ p -adic invariants. Thus we have to exhibit p -adically equivalent rank-two even indefinite lattices that are not equivalent over \mathbb{Z} . (Proposition 9 asserts this is a necessary condition over general fields of characteristic zero.)

Example 23. We are grateful to Sho Tanimoto and Letao Zhang for assistance with this example. Consider the lattices

$$\Pi_X = \begin{array}{c|cc} C & f \\ \hline C & 2 & 13 \\ f & 13 & 12 \end{array} \quad \Pi_Y = \begin{array}{c|cc} D & g \\ \hline D & 8 & 15 \\ g & 15 & 10 \end{array}$$

which both have discriminant 145. Note that Π_X represents -2

$$(2f - C)^2 = (25C - 2f)^2 = -2$$

but that Π_Y fails to represent -2 .

Let X be a K3 surface over F with split Picard group Π_X over a field F . We assume that C and f are ample. The moduli space

$$Y = M_{(2,C+f,10)}(X)$$

has Picard group

$$\begin{array}{c|cc} 2C & (C+f)/2 \\ \hline 2C & 8 & 15 \\ (C+f)/2 & 15 & 10 \end{array} \simeq \Pi_Y$$

while $M_{(2,D,2)}(Y)$ has Picard group

$$\begin{array}{c|cc} D/2 & 2g \\ \hline D/2 & 2 & 15 \\ 2g & 15 & 40 \end{array} \simeq \Pi_X$$

and is isomorphic to X .

These surfaces have the following properties:

- X and Y admit decomposable zero cycles of degree one over F ;

- $X(F) \neq \emptyset$: the rational points arise from the smooth rational curves with classes $2f - C$ and $25C - 2f$, both of which admit zero-cycles of odd degree and thus are $\simeq \mathbb{P}^1$ over F ;
- $Y(F')$ is dense for some finite extension F'/F , due to the fact that $|\text{Aut}(Y_{\mathbb{C}})| = \infty$.

We do not know whether

- $X(F')$ is dense for any finite extension F'/F ;
- $Y(F) \neq \emptyset$.

3. FINITE AND REAL FIELDS

The ℓ -adic interpretation of the Fourier-Mukai transform yields

Theorem 24. [LO11] [Huy15, 16.4.3] *Let X and Y be K3 surfaces derived equivalent over a finite field F . Then for each finite extension F'/F we have*

$$|X(F')| = |(Y(F'))|.$$

For the case of general surfaces see [Hon13].

We have a similarly complete picture over the real numbers. We review results of Nikulin [Nik79, §3] [Nik08, §2] on real K3 surfaces.

Let X be a K3 surface over \mathbb{R} , $X_{\mathbb{C}}$ the corresponding complex K3 surface, and φ the action of the anti-holomorphic involution (complex conjugation) of $X_{\mathbb{C}}$ on $H^2(X_{\mathbb{C}}, \mathbb{Z})$. Let $\Lambda_{\pm} \subset H^2(X_{\mathbb{C}}, \mathbb{Z})$ denote the eigenlattices where φ acts via ± 1 . If D is a divisor on X defined over \mathbb{R} then

$$\varphi([D]) = -D;$$

the sign reflects the fact that complex conjugation reverses the sign of $(1, 1)$ forms. In Galois-theoretic terms, the cycle class of a divisor lives naturally in $H^2(X_{\mathbb{C}}, \mathbb{Z}(1))$ and twisting by -1 accounts for the sign change. Let $\tilde{\Lambda}_{\pm}$ denote the eigenlattices of the Mukai lattice; note that $\tilde{\Lambda}_{-}$ contains the degree zero and four summands. Again, the sign change reflects the fact that these are twisted in the Mukai lattice.

We introduce the key invariants: Let \mathbf{r} denote the rank of Λ_{-} . The discriminant groups of Λ_{\pm} are two-elementary groups of order 2^a where a is a non-negative integer. Note that $\tilde{\Lambda}_{\pm}$ have discriminant groups of the same order. Finally, we set

$$\delta_{\varphi} = \begin{cases} 0 & \text{if } (\lambda, \varphi(\lambda)) \equiv 0 \pmod{2} \text{ for each } \lambda \in \Lambda \\ 1 & \text{otherwise.} \end{cases}$$

Note that δ_φ can be computed via the Mukai lattice

$$\delta_\varphi = 0 \text{ iff } (\lambda, \varphi(\lambda)) \equiv 0 \pmod{2} \text{ for each } \lambda \in \tilde{\Lambda},$$

as the degree zero and four summands always give even intersections.

We observe the following:

Proposition 25. *Let X and Y be K3 surfaces over \mathbb{R} , derived equivalent over \mathbb{R} . Then*

$$(\mathbf{r}(X), a(X), \delta_{\varphi, X}) = (\mathbf{r}(Y), a(Y), \delta_{\varphi, Y}).$$

Proof. The derived equivalence induces an isomorphism

$$\tilde{H}(X_{\mathbb{C}}, \mathbb{Z}) \simeq \tilde{H}(Y_{\mathbb{C}}, \mathbb{Z})$$

compatible with the conjugation actions. Since $(\mathbf{r}, a, \delta_\varphi)$ can be read off from the Mukai lattice, the equality follows. \square

The topological type of a real K3 surface is governed by these invariants. Let T_g denote a compact orientable surface of genus g .

Proposition 26. [Nik79, Th. 3.10.6] [Nik08, 2.2] *Let X be a real K3 surface with invariants $(\mathbf{r}, a, \delta_\varphi)$. Then the manifold $X(\mathbb{R})$ is orientable and*

$$X(\mathbb{R}) = \begin{cases} \emptyset & \text{if } (\mathbf{r}, a, \delta_\varphi) = (10, 10, 0) \\ T_1 \sqcup T_1 & \text{if } (\mathbf{r}, a, \delta_\varphi) = (10, 8, 0) \\ T_g \sqcup (T_0)^k & \text{otherwise, where} \\ & g = (22 - \mathbf{r} - a)/2, k = (\mathbf{r} - a)/2. \end{cases}$$

Corollary 27. *Let X and Y be K3 surfaces defined and derived equivalent over \mathbb{R} . Then $X(\mathbb{R})$ and $Y(\mathbb{R})$ are diffeomorphic. In particular, $X(\mathbb{R}) \neq \emptyset$ if and only if $Y(\mathbb{R}) \neq \emptyset$.*

The last statement also follows from Proposition 12: A variety over \mathbb{R} has a real point if and only if its index is one. (This was pointed out to us by Colliot-Thélène.)

Example 28. Let X and Y be derived equivalent K3 surfaces, defined over \mathbb{R} ; assume they have Picard rank one. Then $Y = M_v(X)$ for some isotropic Mukai vector $v = (r, f, s) \in \tilde{H}(X(\mathbb{C}), \mathbb{Z})$ with $(r, s) = 1$. For a vector bundle E of this type note that

$$c_2(E) = c_1(E)^2/2 + r\chi(\mathcal{O}_X) - \chi(E) = rs + r - s,$$

which is odd as r and s are not both even. Then a global section of E gives an odd-degree cycle on X over \mathbb{R} , hence an \mathbb{R} -point.

4. GEOMETRIC CASE: LOCAL FIELDS WITH COMPLEX RESIDUE FIELD

We start with a general definition: Let R be a discrete valuation ring with quotient field F . A K3 surface X over F has *good reduction* if there exists a smooth proper algebraic space $\mathcal{X} \rightarrow \text{Spec}(R)$ with generic fiber X . It has *ADE reduction* if the central fiber has (at worst) rational double points.

Let X be a projective K3 surface over $F = \mathbb{C}((t))$. Consider the monodromy action

$$T : H^2(X, \mathbb{Z}) \rightarrow H^2(X, \mathbb{Z})$$

associated with a loop about $t = 0$. This is *quasi-unipotent*, i.e., there exist $e, f \in \mathbb{N}$ such that $(T^e - I)^f = 0$ [Lan73]; we choose e, f minimal with this property.

Let $\Delta = \text{Spec } \mathbb{C}[[t]]$ and fix a projective model

$$\mathcal{X} \rightarrow \Delta$$

and a resolution

$$\varpi : \mathcal{X}' \rightarrow \Delta$$

such that the central fiber $\varpi^{-1}(0)$ is a normal crossings divisor, perhaps with multiplicities along some components. Let $\mathcal{X}'_{\circ} \subset \varpi^{-1}(0)$ denote the smooth locus of the central fiber, i.e., the points of multiplicity one. A'Campo [A'C75, Th. 1] proved that

$$\chi(\mathcal{X}'_{\circ}) = 2 + \text{trace}(T).$$

This may be interpreted as the alternating sum of the traces of the monodromy matrices on *all* the cohomology groups of X .

An application of Hensel's Lemma yields

Proposition 29. *If $\text{trace}(T) \neq -2$ then $\mathcal{X} \rightarrow \Delta$ admits a section, i.e., $X(F) \neq \emptyset$.*

This result was previously obtained by Nicaise [Nic11, Cor. 6.6]; his techniques are also applicable in mixed characteristic under appropriate tameness assumptions.

Proposition 29 applies when T is unipotent ($e = 1$). This is the case when there exists a resolution $\mathcal{X}' \rightarrow \Delta$ with central fiber *reduced* normal crossings. (See the Appendix and Theorem 35 for further analysis.)

If X and Y are derived equivalent over F then Orlov's Theorem and the discussion preceding Proposition 6 implies that their Mukai lattices admit a monodromy equivariant isomorphism. Thus the characteristic polynomials of their monodromy matrices are equal.

Corollary 30. *Suppose that X and Y are derived equivalent K3 surfaces with monodromy satisfying $\text{trace}(T) \neq -2$. Then both $X(F)$ and $Y(F)$ are nonempty.*

We also have results when T is semisimple:

Proposition 31. *Suppose that X and Y are derived equivalent K3 surfaces over $F = \mathbb{C}((t))$. Then the following conditions are equivalent:*

- X (equivalently, Y) has monodromy acting via an element of a product of Weyl groups;
- X and Y admit models with central fiber consisting of a K3 surface with ADE singularities.

Thus both $X(F)$ and $Y(F)$ are nonempty.

Proof. We elaborate on the first condition: Let T denote the monodromy of X . Then there exist vanishing cycles $\gamma_1, \dots, \gamma_s$ for X such that each $\gamma_i^2 = -2$, $\langle \gamma_1, \dots, \gamma_s \rangle$ is negative definite, and T is a product of reflections associated with the γ_i . If g is any polarization on X then the γ_i are orthogonal to g . Thus the Fourier-Mukai transform restricts to an isomorphism on the sublattice generated by the γ_i . In particular, the monodromy of Y admits the same interpretation as a product of reflections.

Let L denote the smallest saturated sublattice of $H^2(X, \mathbb{Z})$ containing $\gamma_1, \dots, \gamma_s$ —the classification of Dynkin diagrams implies it is a direct sum of lattices of ADE type. Let M denote the corresponding lattice in $H^2(Y, \mathbb{Z})$, which is isomorphic to L .

After a basechange

$$\text{Spec}(R_1) \rightarrow \text{Spec}(R), \quad t_1^e = t$$

where e is the order of T , the Torelli Theorem gives smooth (Type I Kulikov) models

$$\mathcal{X}_1, \mathcal{Y}_1 \rightarrow \text{Spec}(R_1)$$

with central fibers having ADE configurations of type M , consisting of smooth rational curves. Blowing these down yield models

$$\mathcal{X}'_1, \mathcal{Y}'_1 \rightarrow \text{Spec}(R_1)$$

which descend to

$$\mathcal{X}, \mathcal{Y} \rightarrow \text{Spec}(R),$$

i.e., ADE models of X and Y .

An application of Hensel's Lemma gives that $X(F), Y(F) \neq \emptyset$. \square

5. SEMISTABLE MODELS OVER p -ADIC FIELDS

Let F be a p -adic field with ring of integers R .

We start with the case of good reduction, which follows from Theorem 24 and Hensel's Lemma:

Corollary 32. *Let X and Y be K3 surfaces over F , which are derived equivalent and have good reduction over F . Then $X(F) \neq \emptyset$ if and only if $Y(F) \neq \emptyset$.*

We can extend this as follows:

Proposition 33. *Assume that the residue characteristic $p \geq 7$. Let X and Y be K3 surfaces over F , which are derived equivalent and have ADE reduction over F . Then $X(F) \neq \emptyset$ if and only if $Y(F) \neq \emptyset$.*

Proof. Let k be the finite residue field, $\mathcal{X}, \mathcal{Y} \rightarrow \text{Spec}(R)$ proper models of X and Y , \mathcal{X}_0 and \mathcal{Y}_0 denote the resulting reductions, and $\tilde{\mathcal{X}}_0$ and $\tilde{\mathcal{Y}}_0$ their minimal resolutions over \bar{k} . Applying Artin's version of Brieskorn simultaneous resolution [Art74, Th. 2], there exists a finite extension

$$\text{Spec}(R_1) \rightarrow \text{Spec}(R)$$

and proper models

$$\tilde{\mathcal{X}} \rightarrow \mathcal{X} \times_{\text{Spec}(R)} \text{Spec}(R') \rightarrow \text{Spec}(R'),$$

$$\tilde{\mathcal{Y}} \rightarrow \mathcal{Y} \times_{\text{Spec}(R)} \text{Spec}(R') \rightarrow \text{Spec}(R'),$$

in the category of algebraic spaces, with central fibers $\tilde{\mathcal{X}}_0$ and $\tilde{\mathcal{Y}}_0$.

The Fourier-Mukai transform induces isomorphisms

$$H_{\text{ét}}^2(\bar{X}, \mathbb{Q}_\ell) \rightarrow H_{\text{ét}}^2(\bar{Y}, \mathbb{Q}_\ell).$$

Indeed, there is a natural choice on the integral transcendental cohomology. The stable equivalence on Picard groups (see Proposition 9) guarantees the existence of a isomorphism on the algebraic classes after tensoring by \mathbb{Q} .

Specializing yields an isomorphism

$$\psi : H_{\text{ét}}^2(\tilde{\mathcal{X}}_0, \mathbb{Q}_\ell) \rightarrow H_{\text{ét}}^2(\tilde{\mathcal{Y}}_0, \mathbb{Q}_\ell).$$

Note that since $\tilde{\mathcal{X}}, \tilde{\mathcal{Y}}$ are not projective over $\text{Spec}(R')$, there is not an evident interpretation of this as a derived equivalence over $\text{Spec}(R')$. (See [BM02] for such interpretations for K3 fibrations over complex curves.) Furthermore ψ is far from unique, as we may compose with reflections arising from exceptional curves in either $\tilde{\mathcal{X}}_0 \rightarrow \mathcal{X}_0$ or $\tilde{\mathcal{Y}}_0 \rightarrow \mathcal{Y}_0$ associated with vanishing cycles of \mathcal{X} or \mathcal{Y} .

Let L (resp. M) denote the lattice of vanishing cycles in $H^2(X, \mathbb{Q}_\ell)$ (resp. $H^2(Y, \mathbb{Q}_\ell)$), with orthogonal complement L^\perp (resp. M^\perp). The isomorphism ψ does induce an isomorphism

$$L^\perp \simeq M^\perp$$

compatible with Galois actions. As in the proof of Proposition 31, the lattices L and M are isomorphic once we fix an interpretation via vanishing cycles of our models.

Our assumptions on p guarantee that the classification and deformations of rational double points over k coincides with the classification in characteristic 0 [Art77]. Choose new *regular* models for X and Y

$$\mathcal{X}'', \mathcal{Y}'' \rightarrow \mathrm{Spec}(R)$$

whose central fibers \mathcal{X}_0'' and \mathcal{Y}_0'' are obtained from $\tilde{\mathcal{X}}_0$ and $\tilde{\mathcal{Y}}_0$ by blowing down the (-2) -curves classes associated with L and M respectively. Let $\mathcal{X}_\circ \subset \mathcal{X}_0''$ and $\mathcal{Y}_\circ \subset \mathcal{Y}_0''$ denote the smooth loci, i.e., the complements of the rational curves associated with L and M respectively.

We claim that ψ induces an isomorphism on compactly supported cohomology

$$H_{c, \text{ét}}^2(\bar{\mathcal{X}}_\circ, \mathbb{Q}_\ell) \simeq H_{c, \text{ét}}^2(\bar{\mathcal{Y}}_\circ, \mathbb{Q}_\ell),$$

compatible with Galois actions. Indeed, these may be identified with L^\perp and M^\perp , respectively. The Weil conjectures yield then that

$$|\mathcal{X}_\circ(k)| = |\mathcal{Y}_\circ(k)|$$

and Hensel's Lemma implies our claim. \square

Question 34. Is admitting a model with good or ADE reduction a derived invariant?

Y. Matsumoto and C. Liedtke have recently addressed this. Having *potentially* good reduction is governed by whether $H_{\text{ét}}^2(\bar{X}, \mathbb{Q}_\ell)$ is unramified, under technical assumptions [Mat14, Th. 1.1]. These are satisfied if there exists a Kulikov model after some basechange [ML14, p. 2]. The ramification condition depends on the ℓ -adic cohomology and thus only on the derived equivalence class. Proposition 31 suggests a monodromy characterization of ADE reduction in mixed characteristic; under technical assumptions, there exists such a model if the cohomology is unramified [ML14, Th. 5.1].

APPENDIX: SEMISTABILITY AND DERIVED EQUIVALENCE

To understand the implications of derived equivalence for rational points over local fields, we must first describe how monodromy governs the existence of models with good properties. For K3 surfaces, it is widely expected that unipotent monodromy should suffice to guarantee the existence of a Kulikov model. Over \mathbb{C} this is widely known to experts; the referee advised us that this was addressed in correspondence among R. Friedman, D. Morrison, and F. Scattone in 1983. As we are unaware of a published account, we offer an argument:

Theorem 35. *Let X be a K3 surface over $F = \mathbb{C}((t))$. Then X admits a Kulikov model if and only if its monodromy is unipotent.*

Corollary 36. *Let X and Y be derived equivalent K3 surfaces over F . Then X admits a Kulikov model if and only if Y admits a Kulikov model.*

As we have seen, if X and Y are derived equivalent over F then their Mukai lattices admit a monodromy-equivariant isomorphism; thus the characteristic polynomials of their monodromy matrices are equal.

The remainder of this section is devoted the proof of Theorem 35. We start with a review of basic results on Kulikov models.

Let $R = \mathbb{C}[[t]]$, $\Delta = \text{Spec}(R)$, and $\Delta^\circ = \text{Spec}(F)$. The monodromy T of X over $\mathbb{C}((t))$ satisfies

$$(T^e - I)^f = 0$$

for some $e, f \in \mathbb{N}$. We take e and f minimal with this property.

The semistable reduction theorem [KKMSD73] implies there exists an integer $n \geq 1$ such that after basechange to

$$R_2 = \mathbb{C}[[t_2]], F_2 = \mathbb{C}((t_2)), \quad t_2^n = t,$$

there exists a flat proper

$$\pi_2 : \mathcal{X}_2 \rightarrow \Delta_2 = \text{Spec}(R_2)$$

such that

- the generic fiber is the basechange of X to F_2 ;
- the central fiber $\pi_2^{-1}(0)$ is a reduced normal crossings divisor.

We call this a *semistable model* for X . It is well-known that semistable reductions have unipotent monodromy so $e|n$.

By work of Kulikov and Persson-Pinkham [Kul77, PP81], there exists a semistable modification of \mathcal{X}_2

$$\varpi : \tilde{\mathcal{X}} \rightarrow \Delta_2$$

with trivial canonical class, i.e., there exists a birational map $\mathcal{X}_2 \dashrightarrow \tilde{\mathcal{X}}$ that is an isomorphism away from the central fibers. We call this a *Kulikov model* for X . Furthermore, the structure of the central fiber $\tilde{\mathcal{X}}_0$ can be described in more detail:

Type I $\tilde{\mathcal{X}}_0$ is a K3 surface and $f = 1$.

Type II $\tilde{\mathcal{X}}_0$ is a chain of surfaces glued along elliptic curves, with rational surfaces at the end points and elliptic ruled surfaces in between; here $f = 2$.

Type III $\tilde{\mathcal{X}}_0$ is a union of rational surfaces and $f = 3$.

We will say more about the Type III case: It determines a combinatorial triangulation of the sphere with vertices indexed by irreducible components, edges indexed by double curves, and ‘triangles’ indexed by triple points [Mor84]. We analyze this combinatorial structure of $\tilde{\mathcal{X}}_0$ in terms of the integer m .

Let $\tilde{\mathcal{X}}_0 = \cup_{i=1}^n V_i$ denote the irreducible components, \tilde{V}_i their normalizations, and $D_{ij} \subset \tilde{V}_i$ the double curves over $V_i \cap V_j$.

Definition 37. $\tilde{\mathcal{X}}_0$ is in *minus-one* form if for each double curve D_{ij} we have $(D'_{ij})^2_{V_i} = -1$ if D'_{ij} is a smooth component of D_{ij} and $(D_{ij}^2)_{V_i} = 1$ if D_{ij} is nodal.

Miranda-Morrison [MM83] have shown that after elementary transformation of $\tilde{\mathcal{X}}$, we may assume that $\tilde{\mathcal{X}}$ is in minus-one form.

The following are equivalent [Fri83, §3],[FS85, 0.5,7.1]:

- the logarithm of the monodromy is m times a primitive matrix;
- $\tilde{\mathcal{X}}_0$ admits a ‘special μ_m action’, i.e., acting trivially on the sets of components, double/triple points, and Picard groups of the irreducible components;
- $\tilde{\mathcal{X}}_0$ admits ‘special m -bands of hexagons’, i.e., the triangulation coming from the components of $\tilde{\mathcal{X}}_0$ arises as a degree m refinement of another triangulation.

In other words, $\tilde{\mathcal{X}}_0$ ‘looks like’ it is obtained from applying semistable reduction to the degree m basechange of a Kulikov model. Its central fiber $\tilde{\mathcal{X}}'_0$ can readily be described [Fri83, 4.1]—its triangulation is the one with refinement equal to the triangulation of $\tilde{\mathcal{X}}_0$, and its components are contractions of the corresponding components of $\tilde{\mathcal{X}}_0$. (When we refer to $\tilde{\mathcal{X}}'_0$ below in the Type III case, we mean the surface defined by this process.)

For Type II we can do something similar [Fri84, §2]. After elementary modifications, we may assume the elliptic surfaces are minimal. Then following are equivalent:

- the logarithm of the monodromy is m times a primitive matrix;
- $\tilde{\mathcal{X}}_0 = V_0 \cup_E \dots \cup_E V_m$ is a chain of $m+1$ surfaces glued along copies of an elliptic curve E , where V_0 and V_m are rational and V_1, \dots, V_{m-1} are minimal surfaces ruled over E .

Again $\tilde{\mathcal{X}}_0$ ‘looks like’ it is obtained from applying semistable reduction to another Kulikov model with central fiber $\tilde{\mathcal{X}}'_0 = V_0 \cup_E V_m$. Moreover $(E^2)_{V_0} + (E^2)_{V_m} = 0$ and $\tilde{\mathcal{X}}'_0$ is d -semistable in the sense of Friedman [Fri84, 2.1]. (When we refer to $\tilde{\mathcal{X}}'_0$ below in the Type II case, we mean the surface defined by this process.)

There are refined Kulikov models taking into account polarizations: Let (X, g) be a polarized K3 surface over F of degree $2d$. Shepherd-Barron [SB83] has shown there exists a Kulikov model $\varpi : \tilde{\mathcal{X}} \rightarrow \Delta_2$ with the following properties:

- there exists a specialization of g to a nef Cartier divisor on the central fiber $\tilde{\mathcal{X}}_0$;
- g is semi-ample relative to Δ_2 , inducing

$$\begin{array}{ccc} \tilde{\mathcal{X}} & \xrightarrow{|g|} & \mathcal{Z} \\ \searrow & & \swarrow \\ & \Delta_2 & \end{array}$$

where $\tilde{\mathcal{X}}_0 \rightarrow \mathcal{Z}_0$ is birational and \mathcal{Z}_0 has rational double points, normal crossings, or singularities with local equations

$$xy = zt = 0.$$

These will be called *quasi-polarized Kulikov models* and their central fibers *admissible degenerations of degree $2d$* .

Recall the construction in sections five and six of [FS85]: Let \mathcal{D} denote the period domain for degree $2d$ K3 surfaces and Γ the corresponding arithmetic group—the orientation-preserving automorphisms of the cohomology lattice $H^2(X, \mathbb{Z})$ fixing g . Fix an admissible degeneration (\mathcal{Y}_0, g) of degree $2d$ and its image (\mathcal{Z}_0, h) , with deformation spaces $\text{Def}(\mathcal{Y}_0, g) \rightarrow \text{Def}(\mathcal{Z}_0, h)$; the morphism arises because g is semiample over the deformation space. Let

$$\overline{\Gamma \backslash \mathcal{D}}_{N_{\mathcal{Y}_0}} \supset \Gamma \backslash \mathcal{D}$$

denote the partial toroidal compactification parametrizing limiting mixed Hodge structures with monodromy weight filtration given by a nilpotent $N_{\mathcal{Y}_0}$ associated with \mathcal{Y}_0 (see [FS85, p.27]). We do keep track of the stack structure. Given a holomorphic mapping

$$f : \{t : 0 < |t| < 1\} \rightarrow \Gamma \setminus \mathcal{D},$$

that is locally liftable (lifting locally to \mathcal{D}), with unipotent monodromy Γ -conjugate to $N_{\mathcal{Y}_0}$, then f extends to

$$f : \{t : |t| < 1\} \rightarrow \overline{\Gamma \setminus \mathcal{D}}.$$

The period map extends to an étale morphism [FS85, 5.3.5, 6.2]

$$\text{Def}(\mathcal{Y}_0, g) \rightarrow \overline{\Gamma \setminus \mathcal{D}}.$$

Thus the partial compactification admits a (local) universal family.

Theorem 35 thus boils down to

The smallest positive integer n for which we have a Kulikov model equals the smallest positive integer e such that T^e is unipotent.

Proof. We show that a Kulikov model exists provided the monodromy is unipotent. Suppose we have unipotent monodromy over

$$R_1 = \mathbb{C}[[t_1]], t_1^e = t,$$

and semistable reduction

$$\mathcal{X}_2 \rightarrow \Delta_2 = \text{Spec}(R_2), \quad R_2 = \text{Spec}(\mathbb{C}[[t_2]]), t_2^{me} = t.$$

Let $\tilde{\mathcal{X}} \rightarrow \Delta_2$ denote a Kulikov model, obtained after applying elementary transformations as specified above. Write

$$mN = \log(T^e) = (T^e - I) - \frac{1}{2}(T^e - I)^2$$

where $m \in \mathbb{N}$ and N is primitive (cf. [FS85, 1.2] for the Type III case).

Let $\tilde{\mathcal{X}}'_0$ be the candidate for the ‘replacement’ Kulikov model, i.e., the central fiber of the Kulikov model we expect to find

$$\tilde{\mathcal{X}}' \rightarrow \Delta_1.$$

In the Type I case $\tilde{\mathcal{X}}'_0 = \tilde{\mathcal{X}}_0$ by Torelli, so we focus on the Type II and III cases.

Lemma 38. *Suppose that $\tilde{\mathcal{X}}_0$ admits a degree $2d$ semiample divisor g . Then $\tilde{\mathcal{X}}'_0$ admits one as well, denoted by g' .*

Proof. In the Type II case, this follows from [Fri84, Th. 2.3]. The discussion there shows how (after elementary modification) the divisor can be chosen to induce the morphism $\tilde{\mathcal{X}}_0 \rightarrow \tilde{\mathcal{X}}'_0$ collapsing $V_1 \cup_E \dots \cup_E V_{m-1}$ to E , interpreted as the normal crossings locus of $\tilde{\mathcal{X}}'_0$.

For Type III, we rely on Proposition 4.2 of [Fri83], which gives an analogous process for modifying the coefficients of h so that it is trivial or a sum of fibers on the special bands of hexagons. However, Friedman's result does not indicate whether the resulting line bundle is nef. This can be achieved after birational modifications of the total space [SB83, Th. 1]. \square

We can apply the Friedman-Scattone compactification construction to both $(\tilde{\mathcal{X}}_0, g)$ and $(\tilde{\mathcal{X}}'_0, g')$, with $N = N_{\tilde{\mathcal{X}}'_0}$ and $mN = N_{\tilde{\mathcal{X}}_0}$. Thus we obtain *two* compactifications

$$\overline{\Gamma \setminus \mathcal{D}}_{mN} \rightarrow \overline{\Gamma \setminus \mathcal{D}}_N \supset \Gamma \setminus \mathcal{D},$$

both with universal families of degree $2d$ K3 surfaces and admissible degenerations.

To construct $\tilde{\mathcal{X}}' \rightarrow \Delta_1 = \text{Spec}(R_1)$ we use the diagram

$$\begin{array}{ccc} \Delta_2 & \rightarrow & \overline{\Gamma \setminus \mathcal{D}}_{mN} \\ \downarrow & & \downarrow \\ \Delta_1 & & \overline{\Gamma \setminus \mathcal{D}}_N. \end{array}$$

The liftability criterion for mappings to the toroidal compactifications gives an arrow

$$\Delta_1 \rightarrow \overline{\Gamma \setminus \mathcal{D}}_N$$

making the diagram commute. The induced universal family on this space induces a family

$$\tilde{\mathcal{X}}' \rightarrow \Delta_1,$$

agreeing with our original family for $t_1 \neq 0$ by the Torelli Theorem. More precisely, the monodromies of the two families over $\Delta_1^\circ = \text{Spec}(R_1) \setminus \{0\}$ are identified and automorphisms of K3 surfaces act faithfully on cohomology, so they are isomorphic over Δ_1° . Thus $\tilde{\mathcal{X}}' \rightarrow \Delta_1$ is the desired model. \square

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DEPARTMENT OF MATHEMATICS, RICE UNIVERSITY, MS 136, HOUSTON, TX 77251-1892, USA

Current address: Department of Mathematics, Brown University, Box 1917, 151 Thayer Street Providence, RI 02912, USA

E-mail address: `bhassett@math.brown.edu`

COURANT INSTITUTE, NEW YORK UNIVERSITY, NEW YORK, NY 10012, USA

E-mail address: `tschinkel@cims.nyu.edu`

SIMONS FOUNDATION, 160 FIFTH AVENUE, NEW YORK, NY 10010, USA