

# QUADRIC SURFACE BUNDLES OVER SURFACES AND STABLE RATIONALITY

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ABSTRACT. We prove a general specialization theorem which implies stable irrationality for a wide class of quadric surface bundles over rational surfaces. As an application, we solve, with the exception of two cases, the stable rationality problem for any very general complex projective quadric surface bundle over  $\mathbb{P}^2$ , given by a symmetric matrix of homogeneous polynomials. Both exceptions degenerate over a plane sextic curve and the corresponding double cover is a K3 surface.

## 1. INTRODUCTION

Recently, Hassett, Pirutka and Tschinkel [15, 16, 17] found the first three examples of families of quadric surface bundles over  $\mathbb{P}^2$ , where the very general member is not stably rational. In each case, the degeneration locus is a plane octic curve. Smooth quadric surface bundles over rational surfaces typically deform to smooth bundles with a section, hence to smooth rational fourfolds. This allowed them to produce the first examples of non-rational varieties with rational deformation types.

In [23], we introduced a variant of the method of Voisin [25] and Colliot-Thélène–Pirutka [12], which allowed us to disprove stable rationality via a degeneration argument where a universally  $\mathrm{CH}_0$ -trivial resolution of the special fibre is not needed. The purpose of this paper is to show that one can use this technique to simplify the arguments in [15, 16, 17] and to apply them to large classes of quadric surface bundles.

The main result is the following general specialization theorem without resolutions.

**Theorem 1.** *Let  $X$  be a projective fourfold which specializes to a complex projective fourfold  $Y$  with a morphism  $f : Y \rightarrow S$  to a rational surface  $S$ , such that:*

- (1) *the generic fibre of  $f$  is a smooth quadric surface  $Q$  over  $K = \mathbb{C}(S)$ ;*
- (2) *the discriminant  $d \in K^*/(K^*)^2$  of  $Q$  is nontrivial;*
- (3)  *$H_{nr}^2(K(Q)/\mathbb{C}, \mathbb{Z}/2) \neq 0$ .*

*Then  $X$  is not stably rational.*

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Note that the assumptions in the above theorem concern only the generic fibre of  $f$ . In particular,  $f$  does not need to be flat and there is no assumption on the singularities of  $Y$  at points which do not dominate  $S$ . A universally  $\text{CH}_0$ -trivial resolution of  $Y$  is not needed. For a more general version which works also if the discriminant of  $Q$  is possibly trivial,  $X$  and  $Y$  have arbitrary dimension and the generic fibre of  $f$  is only stably birational to  $Q$ , see Theorem 9 below.

The second unramified cohomology group in item (3) coincides with the Brauer group of any resolution of singularities of  $Y$ . Pirutka computed this group explicitly for any quadric surface over  $\mathbb{C}(\mathbb{P}^2)$  which satisfies (2), see [22, Theorem 3.17]. This gives rise to many examples to which the above theorem applies. In this paper we will apply it only to a single example of Hassett, Pirutka and Tschinkel [15, Proposition 11].

The proof of Theorem 1 uses Pirutka's results [22] on the unramified cohomology of quadric surfaces over  $\mathbb{C}(\mathbb{P}^2)$ , together with our aforementioned method from [23], which builds on [25] and [12].

To illustrate an application of Theorem 1, let us consider a generically non-degenerate line bundle valued quadratic form  $q : \mathcal{E} \rightarrow \mathcal{O}_{\mathbb{P}^2}(n)$ , where  $\mathcal{E} = \bigoplus_{i=0}^3 \mathcal{O}_{\mathbb{P}^2}(-r_i)$  is split and such that the quadratic form  $q_s$  on the fibre  $\mathcal{E}_s$  is nonzero for all  $s \in \mathbb{P}^2$ . Then,  $X = \{q = 0\} \subset \mathbb{P}(\mathcal{E})$  defines a quadric surface bundle over  $\mathbb{P}^2$ . We may also regard  $q$  as a symmetric matrix  $A = (a_{ij})$ , where  $a_{ij}$  is a global section of  $\mathcal{O}_{\mathbb{P}^2}(r_i + r_j + n)$ . Locally over  $\mathbb{P}^2$ ,  $X$  is given by

$$(1) \quad \sum_{i,j=0}^3 a_{ij} z_i z_j = 0,$$

where  $z_i$  denotes a local coordinate which trivializes  $\mathcal{O}_{\mathbb{P}^2}(-r_i) \subset \mathcal{E}$ .

If  $X$  is smooth, its deformation type depends only on the integers  $d_i := 2r_i + n$ ; we call any such quadric surface bundle of type  $(d_0, d_1, d_2, d_3)$ . The degeneration locus of  $X \rightarrow \mathbb{P}^2$  is a plane curve of degree  $\sum_i d_i$ , which is always even. If some  $d_i$  is negative, then  $X \rightarrow \mathbb{P}^2$  admits a section and so  $X$  is rational. We may thus from now on restrict ourselves to the case  $d_i \geq 0$  for all  $i$ .

**Corollary 2.** *Let  $d_0, d_1, d_2$  and  $d_3$  be non-negative integers of the same parity, and let  $X \rightarrow \mathbb{P}^2$  be a very general complex projective quadric surface bundle of type  $(d_0, d_1, d_2, d_3)$ . If  $\sum_i d_i \neq 6$ , then the following holds:*

- (1)  $X$  is rational if  $\sum_i d_i \leq 4$  or if  $d_i = d_j = 0$  for  $i \neq j$ ;
- (2)  $X$  is not stably rational otherwise.

The bundles in item (1) of the above corollary have a rational section, and so already the generic fibre of  $X$  over  $\mathbb{P}^2$  is rational.

Up to reordering, the only cases left open by the above corollary are types  $(1, 1, 1, 3)$  and  $(0, 2, 2, 2)$ . The former corresponds to blow-ups of cubic fourfolds containing a plane (see [4]) and the latter are Verra fourfolds [9, 18], i.e. double covers of  $\mathbb{P}^2 \times \mathbb{P}^2$ , branched along a hypersurface of bidegree  $(2, 2)$ . In both exceptions, the degeneration locus of the quadric bundle is a sextic curve in  $\mathbb{P}^2$ , and so the associated double cover is a K3 surface.

Specializing to  $a_{33} = 0$  in (1) shows that all examples in the above corollary deform to smooth quadric surface bundles with a section, hence to smooth rational fourfolds.

Many quadric surface bundles over  $\mathbb{P}^2$  are birational to fourfolds which arise naturally in projective geometry. For instance, Corollary 2 implies the following, cf. [23, §3.5]:

- (I) a very general complex hypersurface of bidegree  $(d, 2)$  in  $\mathbb{P}^2 \times \mathbb{P}^3$  is not stably rational if  $d \geq 2$ ;
- (II) a very general complex hypersurface  $X \subset \mathbb{P}^5$  of degree  $d + 2$  and with multiplicity  $d$  along a 2-plane is not stably rational if  $d \geq 2$ .
- (III) a double cover  $X \xrightarrow{2:1} \mathbb{P}^4$ , branched along a very general complex hypersurface  $Y \subset \mathbb{P}^4$  of even degree  $d + 2$  and with multiplicity  $d$  along a line is not stably rational if  $d \geq 2$ ;

The case  $d = 2$  in items (I) and (III) corresponds to the aforementioned results in [15] and [16], respectively. For stable rationality properties of smooth hypersurfaces and double covers, see [7, 12, 13, 16, 21, 24, 25]; for results on conic bundles, see [1, 3, 6, 7, 8, 14, 25].

In [23], we studied rationality properties of quadric bundles with arbitrary fibre dimensions. Our uniform treatment sufficed to prove (I) and (II) for  $d \geq 5$ , and (III) for  $d \geq 8$ . On the other hand, the results in [23] left open infinitely many cases in Corollary 2. For instance, the types  $(1, 1, d_2, d_3)$  and  $(0, 2, d_2, d_3)$  with  $d_2 \leq 7$  and arbitrary  $d_3$  are not covered by [23, Theorem 40] and there are more cases which were not accessible, see [23, Remark 35].

Our method applies also to quadric surface bundles over other rational surfaces  $S$ . We treat in this paper the case  $S = \mathbb{P}^1 \times \mathbb{P}^1$  and obtain similar results as those in Corollary 2 above, see Corollaries 11 and 12 below.

**1.1. Conventions and notations.** All schemes are separated. A variety is an integral scheme of finite type over a field. A very general point of some scheme is a closed point which is contained in a countable intersection of dense open subsets.

We say that a variety  $X$  over a field  $L$  specializes (or degenerates) to a variety  $Y$  over a field  $k$ , if there is a discrete valuation ring  $R$  with residue field  $k$  and fraction field  $F$  with an injection of fields  $F \hookrightarrow L$ , together with a flat proper morphism  $\mathcal{X} \rightarrow \text{Spec } R$  of finite type, such that  $Y$  is isomorphic to the special fibre  $Y \simeq \mathcal{X} \times k$  and  $X \simeq \mathcal{X} \times L$  is isomorphic to a base change of the generic fibre. If  $\mathcal{Y} \rightarrow B$  is a flat proper morphism

of complex varieties with integral fibres, then for any closed points  $0, t \in B$  with  $t$  very general, the fibre  $Y_t$  specializes to  $Y_0$  in the above sense, see [23, Lemma 8].

A morphism  $f : X \rightarrow Y$  of varieties over a field  $k$  is universally  $\mathrm{CH}_0$ -trivial, if  $f_* : \mathrm{CH}_0(X \times L) \xrightarrow{\cong} \mathrm{CH}_0(Y \times L)$  is an isomorphism for all field extensions  $L$  of  $k$ .

A quadric surface bundle is a flat morphism  $f : X \rightarrow S$  between projective varieties such that the generic fibre is a smooth quadric surface; the degeneration locus is given by all  $s \in S$  such that  $f^{-1}(s)$  is singular. If  $f$  is not assumed flat, then we call  $X$  a weak quadric surface bundle over  $S$ . Quadric surface bundles over surfaces have been studied in detail in [5].

We denote by  $\mu_2 \subset \mathbb{G}_m$  the group of second roots of unity. If  $X$  is a variety over a field  $k$  of characteristic different from 2, the unramified cohomology group  $H_{nr}^i(X, \mu_2^{\otimes i})$  is the subgroup of all elements of the Galois cohomology group  $H^i(k(X), \mu_2^{\otimes i})$  which have trivial residue at any divisor over  $X$ , see [11]. This is a stable birational invariant of  $X$  and it depends only on the field extension  $k(X)/k$ , see [11, Proposition 1.2]; if we want to emphasize the base field, we also denote this group by  $H_{nr}^i(k(X)/k, \mu_2^{\otimes i})$ .

## 2. SECOND UNRAMIFIED COHOMOLOGY OF QUADRIC SURFACES

Let  $K$  be a field of characteristic different from 2. It will be convenient to identify the Galois cohomology group  $H^i(K, \mu_2^{\otimes i})$  with the étale cohomology group  $H_{\text{ét}}^i(\mathrm{Spec}(K), \mu_2^{\otimes i})$ . We also use the identification  $H^1(K, \mu_2) \simeq K^*/(K^*)^2$ , induced by the Kummer sequence. For  $a, b \in K^*$ , we denote by  $(a, b) \in H^2(K, \mu_2^{\otimes 2})$  the cup product of the classes given by  $a$  and  $b$ . If  $S$  is a normal variety with fraction field  $K$ , then, for any  $\alpha \in H^2(K, \mu_2^{\otimes 2})$ , the ramification divisor  $\mathrm{ram}(\alpha) \subset S$  is given by (the closure of) all codimension one points  $x \in S^{(1)}$  with  $\partial_x^2 \alpha \neq 0$ . Here,  $\partial_x^2 : H^2(K, \mu_2^{\otimes 2}) \rightarrow H^1(\kappa(x), \mu_2)$  denotes the residue induced by the local ring  $\mathcal{O}_{S,x} \subset K$ .

To any quadratic form  $q$  over  $K$ , one associates the discriminant  $\mathrm{discr}(q) \in K^*/(K^*)^2$  and the Clifford invariant  $\mathrm{cl}(q) \in H^2(K, \mu_2^{\otimes 2})$ . These invariants depend only on the isomorphism type of the corresponding quadric hypersurface  $Q = \{q = 0\}$  in projective space. If  $Q$  is a surface, then, up to similarity,  $q \simeq \langle 1, -a, -b, abd \rangle$  for some  $a, b, d \in K^*$ . In this case,  $\mathrm{discr}(q) = d$  and  $\mathrm{cl}(q) = (-a, -b) + (ab, d)$ . We will need the following, see [2] and [19, Corollary 8].

**Theorem 3.** *Let  $K$  be a field with  $\mathrm{char}(K) \neq 2$ , and let  $f : Q \rightarrow \mathrm{Spec} K$  be a smooth projective quadric surface over  $K$ . Denote by  $d \in K^*/(K^*)^2$  the discriminant of  $Q$  and by  $\beta \in H^2(K, \mu_2^{\otimes 2})$  the Clifford invariant. Then,*

$$f^* : H^2(K, \mu_2^{\otimes 2}) \rightarrow H_{nr}^2(K(Q)/K, \mu_2^{\otimes 2})$$

*is an isomorphism if  $d$  is nontrivial. If  $d \in (K^*)^2$ , then  $\ker(f^*) = \{1, \beta\}$ .*

Pirutka computed completely the unramified cohomology group  $H_{nr}^2(K(Q)/\mathbb{C}, \mu_2^{\otimes 2})$  of a smooth quadric surface  $Q$  with nonzero discriminant over the function field  $K = \mathbb{C}(\mathbb{P}^2)$ , see [22, Theorem 3.17]; most of her arguments work even for arbitrary discriminant, see Remark 5 below. The following reflects one half of her result.

**Theorem 4** (Pirutka). *Let  $f : Q \rightarrow \text{Spec } K$  be a smooth projective quadric surface over the function field  $K$  of some smooth rational surface  $S$  over  $\mathbb{C}$ . Let  $d \in K^*/(K^*)^2$  denote the discriminant and  $\beta \in H^2(K, \mu_2^{\otimes 2})$  the Clifford invariant of  $Q$ . If for some  $\alpha \in H^2(K, \mu_2^{\otimes 2})$  the pullback  $f^*\alpha \in H_{nr}^2(K(Q)/\mathbb{C}, \mu_2^{\otimes 2})$  is unramified over  $\mathbb{C}$ , then the following holds:*

- (\*) *If the residue  $\partial_x^2 \alpha$  at some codimension one point  $x \in S^{(1)}$  is nonzero, then*
  - (a)  $\partial_x^2 \alpha = \partial_x^2 \beta$ ;
  - (b)  $d$  becomes a square in the fraction field of the completion  $\widehat{\mathcal{O}_{S,x}}$ .

*Proof.* The condition on  $d$  is by Hensel's lemma equivalent to asking that, up to multiplication by a square,  $d$  is a unit in  $\mathcal{O}_{S,x}$  whose image in  $\kappa(x)$  is a square. The theorem follows therefore from [22, Section 3.6.2]. (In [22, Theorem 3.17], the assumption that  $d$  is not a square is only used to invoke bijectivity of  $f^*$  via Theorem 3; the assumption that  $\text{ram}(\beta)$  is a simple normal crossing divisor on  $S$  is only used in [22, Section 3.6.1].)  $\square$

**Remark 5.** *Up to replacing  $S$  by some blow-up, one can always assume that  $\text{ram}(\beta)$  is a simple normal crossing divisor on  $S$ . Under this assumption, Pirutka's analysis in [22, Section 3.6.1] shows that the following converse of the above theorem is also true: if  $\alpha \in H^2(K, \mu_2^{\otimes 2})$  is such that condition (\*) holds, then  $f^*\alpha \in H_{nr}^2(K(Q)/\mathbb{C}, \mu_2^{\otimes 2})$  is unramified over  $\mathbb{C}$ ; non-triviality can be checked via Theorem 3.*

Pirutka's result [22, Theorem 3.17] applies to the following important example, due to Hassett, Pirutka and Tschinkel [15, Proposition 11]; for a reinterpretation in terms of conic bundles, see [6].

**Proposition 6** (Hassett–Pirutka–Tschinkel). *Let  $K = \mathbb{C}(x, y)$  be the function field of  $\mathbb{P}^2$  and consider the quadratic form  $q = \langle y, x, xy, F(x, y, 1) \rangle$  over  $K$ , where*

$$F(x, y, z) = x^2 + y^2 + z^2 - 2(xy + xz + yz).$$

*If  $f : Q \rightarrow \text{Spec } K$  denotes the corresponding projective quadric surface over  $K$ , then*

$$0 \neq f^*(x, y) \in H_{nr}^2(K(Q)/\mathbb{C}, \mu_2^{\otimes 2}).$$

### 3. A VANISHING RESULT

The following general vanishing result allows us to avoid any explicit resolution of singularities.

**Proposition 7.** *Let  $Y$  be a smooth complex projective variety and let  $S$  be a smooth complex projective rational surface. Let  $f : Y \dashrightarrow S$  be a dominant rational map whose generic fibre  $Y_\eta$  is stably birational to a smooth quadric surface  $Q$  over  $K = \mathbb{C}(S)$ . Suppose that there is some  $\alpha \in H^2(K, \mu_2^{\otimes 2})$ , such that  $\alpha' := f^*\alpha \in H_{nr}^2(Y, \mu_2^{\otimes 2})$  is unramified over  $\mathbb{C}$ . Then, for any prime divisor  $E \subset Y$  which does not dominate  $S$ , the restriction of  $\alpha'$  to  $E$  vanishes:*

$$\alpha'|_E = 0 \in H^2(\mathbb{C}(E), \mu_2^{\otimes 2}).$$

*Proof.* Since unramified cohomology is a functorial stable birational invariant (see [11]), we may up to replacing  $Y$  by  $Y \times \mathbb{P}^m$  assume that  $Y_\eta \dashrightarrow Q$  is dominant.

We denote by  $d \in K^*/(K^*)^2$  and  $\beta \in H^2(K, \mu_2^{\otimes 2})$ , the discriminant and the Clifford invariant of  $Q$  respectively. Since  $Y$  is smooth,  $f$  is defined at the generic point  $y$  of  $E$ . By [23, Lemma 28], we may up to replacing  $S$  by a different smooth projective model assume that the image  $x := f(y) \in S^{(1)}$  is a codimension one point on  $S$ . Consider the local ring  $A := \mathcal{O}_{S,x}$  and let  $\widehat{A}$  be its completion with field of fractions  $\widehat{K} := \text{Frac}(\widehat{A})$ . The local ring  $B := \mathcal{O}_{Y,y}$  contains  $A$ . We let  $\widehat{B}$  be the completion of  $B$  and  $\widehat{L} := \text{Frac}(\widehat{B})$  be its field of fractions. Since  $Y_\eta \dashrightarrow Q$  is dominant, inclusion of fields induces the following sequence

$$(2) \quad H^2(K, \mu_2^{\otimes 2}) \xrightarrow{\varphi_1} H^2(\widehat{K}, \mu_2^{\otimes 2}) \xrightarrow{\varphi_2} H^2(\widehat{K}(Q), \mu_2^{\otimes 2}) \xrightarrow{\varphi_3} H^2(\widehat{L}, \mu_2^{\otimes 2}).$$

**Lemma 8.** *If  $\gamma \in H^2(K, \mu_2^{\otimes 2})$  satisfies  $\partial_x^2 \gamma = 0$ , then  $\varphi_1(\gamma) = 0 \in H^2(\widehat{K}, \mu_2^{\otimes 2})$ .*

*Proof.* Since  $\partial_x^2 \gamma = 0$ , the image of  $\gamma$  in  $H^2(\widehat{K}, \mu_2^{\otimes 2})$  is contained in  $H_{\text{ét}}^2(\text{Spec } \widehat{A}, \mu_2^{\otimes 2}) \subset H^2(\widehat{K}, \mu_2^{\otimes 2})$ , see [10, §3.3 and §3.8]. It thus suffices to show that  $H_{\text{ét}}^2(\text{Spec } \widehat{A}, \mu_2^{\otimes 2})$  vanishes. Since  $\widehat{A}$  is a henselian local ring, restriction to the closed point gives an isomorphism  $H_{\text{ét}}^2(\text{Spec } \widehat{A}, \mu_2^{\otimes 2}) \simeq H^2(\kappa(x), \mu_2^{\otimes 2})$ , see [20, Corollary VI.2.7]. By Tsen's theorem,  $H^2(\kappa(x), \mu_2^{\otimes 2}) = 0$ . This concludes the lemma.  $\square$

Since  $f^*\alpha$  is unramified, we know that

$$(3) \quad \varphi_3 \circ \varphi_2 \circ \varphi_1(\alpha) \in H_{\text{ét}}^2(\text{Spec } \widehat{B}, \mu_2^{\otimes 2}) \subset H^2(\widehat{L}, \mu_2^{\otimes 2}),$$

see [10, §3.3 and §3.8] and the compatibility of the residue map illustrated in [11, p. 143]. We aim to show that this class vanishes, which is enough to conclude the proposition, because  $\alpha'|_E$  is obtained as restriction of the above class to the closed point  $\text{Spec } \mathbb{C}(E)$ .

If  $\partial_x^2 \alpha = 0$ , then (3) vanishes by Lemma 8. If  $\partial_x^2 \alpha \neq 0$ , then  $\partial_x^2(\alpha - \beta) = 0$  by Theorem 4. By Lemma 8, it then suffices to show that  $\beta$  maps to zero via (2). By Theorem 4,  $d$  becomes a square in  $\widehat{K}$ , and so the latter follows from Theorem 3, applied to  $\varphi_2$  in (2). This concludes the proof of the proposition.  $\square$

## 4. PROOF OF THEOREM 1

The following is a generalization of Theorem 1, stated in the introduction. For what it exactly means that a variety specializes to another variety, see Section 1.1 above .

**Theorem 9.** *Let  $X$  be a proper variety which specializes to a complex projective variety  $Y$ . Suppose that there is a dominant rational map  $f : Y \dashrightarrow \mathbb{P}^2$  with the following properties:*

- (a) *some Zariski open and dense subset  $U \subset Y$  admits a universally  $\text{CH}_0$ -trivial resolution of singularities  $\tilde{U} \rightarrow U$  such that the induced rational map  $\tilde{U} \dashrightarrow \mathbb{P}^2$  is a morphism whose generic fibre is proper over  $\mathbb{C}(\mathbb{P}^2)$ .*
- (b) *the generic fibre  $Y_\eta$  of  $f$  is stably birational to a smooth projective quadric surface  $g : Q \rightarrow \text{Spec } K$  over  $K = \mathbb{C}(\mathbb{P}^2)$ , such that there is a class  $\alpha \in H^2(K, \mu_2^{\otimes 2})$  with  $0 \neq g^*\alpha \in H_{nr}^2(K(Q)/\mathbb{C}, \mu_2^{\otimes 2})$ .*

*Then, no resolution of singularities of  $X$  admits an integral decomposition of the diagonal. In particular,  $X$  is not stably rational.*

*Proof.* Since  $g^*\alpha \neq 0$  is unramified and unramified cohomology is a stable birational invariant,  $\alpha' := f^*\alpha \in H_{nr}^n(Y, \mu_2^{\otimes n})$  is a nontrivial unramified class as well. Condition (a) ensures that there is a log resolution  $\tau : \tilde{Y} \rightarrow Y$  such that  $\tau^{-1}(U) = \tilde{U}$  and such that  $E := \tilde{Y} \setminus \tilde{U}$  is a simple normal crossing divisor. Our assumptions on  $\tilde{U}$  then imply that  $\tau^{-1}(U) \rightarrow U$  is universally  $\text{CH}_0$ -trivial. Moreover, each component  $E_i$  of  $E$  is smooth and does not dominate  $\mathbb{P}^2$ . Therefore, Proposition 7 implies that the nontrivial class  $\alpha'$  restricts to zero on  $E_i$  for all  $i$  and so Theorem 9 follows from [23, Proposition 25].  $\square$

*Proof of Theorem 1.* Condition (1) in Theorem 1 clearly implies condition (a) in Theorem 9. By Theorem 3, conditions (1), (2) and (3) in Theorem 1 imply condition (b) in Theorem 9. Theorem 1 follows therefore from Theorem 9.  $\square$

## 5. APPLICATIONS

**5.1. Quadric surface bundles over  $\mathbb{P}^2$ .** If the symmetric matrix  $A = (a_{ij})$  in (1) is of diagonal form, i.e.  $a_{ij} = 0$  for all  $i \neq j$ , then we say that the corresponding quadric surface bundle  $X$  is given by the quadratic form  $q = \langle a_{00}, \dots, a_{33} \rangle$ . The condition that  $X$  is flat over  $\mathbb{P}^2$  means that the  $a_{ii}$  have no common zero. If the homogeneous polynomials  $a_{ii}$  degenerate and acquire common zeros, then the same formula still defines a weak quadric bundle as long as the  $a_{ii}$  are nonzero and have no common factor. We will use such degenerations in the proofs below.

*Proof of Corollary 2.* In the notation of (1), let  $A = (a_{ij})_{0 \leq i, j \leq 3}$  be the symmetric matrix which corresponds to the very general quadric surface bundle  $X$  of type  $(d_0, d_1, d_2, d_3)$

over  $\mathbb{P}^2$ . We may without loss of generality assume  $0 \leq d_0 \leq d_1 \leq d_2 \leq d_3$ . If  $d_1 = 0$ , then also  $d_0 = 0$  and  $a_{ij} \in \mathbb{C}$  is constant for  $i, j \in \{0, 1\}$ . The quadric  $\{a_{00}z_0^2 + 2a_{01}z_0z_1 + a_{11}z_1^2 = 0\}$  has thus a point over  $\mathbb{C}$  and so  $X \rightarrow \mathbb{P}^2$  has a section. Hence  $X$  is rational. If  $d_i = 1$  for all  $i$ , then  $X$  is a hypersurface of bidegree  $(1, 2)$  in  $\mathbb{P}^2 \times \mathbb{P}^3$  and so projection to the second factor shows that  $X$  is rational. Since the  $d_i$  have all the same parity, this shows that  $X$  is rational if  $\sum d_i \leq 4$  or  $d_1 = 0$ .

The case  $d_i = 2$  for all  $i$  is due to [15]; a quick proof follows from [15, Proposition 11] (see Proposition 6 above) and Theorem 1.

It remains to deal with the case where  $\sum_i d_i \geq 8$ ,  $d_1 \geq 1$  and  $d_3 \geq 3$ . Recall that all  $d_i$  are either even or odd. Consider the weak quadric surface bundle  $Y_i := \{q_i = 0\} \subset \mathbb{P}(\mathcal{E})$  of type  $(d_0, d_1, d_2, d_3)$ , given by the diagonal forms

$$\begin{aligned} q_1 &:= \langle z^{d_0}, x^{d_1}, xyz^{d_2-2}, yz^{d_3-3}F(x, y, z) \rangle, \\ q_2 &:= \langle z^{d_0}, xz^{d_1-1}, x^{d_2-1}y, yz^{d_3-3}F(x, y, z) \rangle, \\ q_3 &:= \langle z^{d_0}, x^{d_1}, yz^{d_2-1}, xyz^{d_3-4}F(x, y, z) \rangle, \end{aligned}$$

where  $F$  is the quadratic polynomial from Proposition 6.

Note that  $Y_i$  is integral, because the entries in the diagonal form are coprime. Consider the natural projection  $Y_i \rightarrow \mathbb{P}^2$ . The generic fibre is a smooth quadric surface  $Q_i$  over  $K = \mathbb{C}(\mathbb{P}^2)$ . Setting  $z = 1$  shows that  $Q_1$  is given by the quadratic form  $q'_1 = \langle 1, x^{d_1}, xy, yF(x, y, 1) \rangle$ ,  $Q_2$  is given by  $q'_2 = \langle 1, x, x^{d_2-1}y, yF(x, y, 1) \rangle$ , and  $Q_3$  is given by  $q'_3 = \langle 1, x^{d_1}, y, xyF(x, y, 1) \rangle$ .

If  $d_0$  is even, then so is  $d_2$ . Multiplying through by  $y$ , absorbing squares and re-ordering the entries shows thus in this case that  $q'_2$  is similar to the quadratic form  $q = \langle y, x, xy, F(x, y, 1) \rangle$  from Proposition 6. If  $d_0$  is odd, then so is  $d_1$  and so  $q'_1$  is isomorphic to  $\langle 1, x, xy, yF(x, y, 1) \rangle$  and  $q'_3$  is isomorphic to  $\langle 1, x, y, xyF(x, y, 1) \rangle$ . Again,  $q'_1$  and  $q'_3$  are both similar to  $q$ . Hence,  $H_{nr}^2(K(Q_i)/\mathbb{C}, \mu_2^{\otimes 2}) \neq 0$  for  $i \equiv d_0 \pmod{2}$  by [15, Proposition 11].

Since  $d_1, d_2 \geq 1$  and  $d_3 \geq 3$ , the very general quadric surface bundle  $X \subset \mathbb{P}(\mathcal{E})$  as in Corollary 2 degenerates to  $Y_2$ . If  $d_0$  is odd,  $X$  also degenerates to  $Y_1$  or  $Y_3$ , depending on whether  $d_2 \geq 3$  or  $d_2 = 1$ . Depending on the parity of  $d_0$  and the size of  $d_2$ , we can choose one of the three degenerations together with Theorem 1 (or 9) to conclude.  $\square$

**Remark 10.** *Pirutka informed us that for any total degree  $d := \sum_i d_i \geq 8$ , she can reprove some cases of Corollary 2 via degenerations to similar quadric surface bundles as in [15], for which [22, Theorem 3.17] applies, and for which she can compute universally  $\text{CH}_0$ -trivial resolutions explicitly, using and extending further the local computations from [15, 16]. While the resolutions are not needed by Theorem 1, her approach gives a complete answer only for  $d = 8$ .*



**5.2. Quadric surface bundles over  $\mathbb{P}^1 \times \mathbb{P}^1$ .** As a second example where Theorem 1 applies, we consider quadric surface bundles  $X$  over  $\mathbb{P}^1 \times \mathbb{P}^1$  that are given by a line bundle valued quadratic form  $q : \mathcal{E} \rightarrow \mathcal{O}(m, n)$ , where  $\mathcal{E} = \bigoplus_{i=0}^3 \mathcal{O}(-p_i, -q_i)$  is split. Locally,  $X := \{q = 0\} \subset \mathbb{P}(\mathcal{E})$  is given by (1) where  $a_{ij}$  is a global section of  $\mathcal{O}(p_i + p_j + m, q_i + q_j + n)$ . If  $a_{ij} = 0$  for  $i \neq j$ , we say that  $X$  is given by the quadratic form  $q = \langle a_{00}, \dots, a_{33} \rangle$ . If the  $a_{ii}$  degenerate and acquire common zeros, then the same formulas define still a hypersurface in  $\mathbb{P}(\mathcal{E})$  which is a weak quadric surface bundle over  $\mathbb{P}^2$  as long as the  $a_{ii}$  are nonzero and have no common factor. The deformation type of  $X$  depends only on the integers  $d_i := m + 2p_i$  and  $e_i := n + 2q_i$ , and we call  $(d_i, e_i)_{0 \leq i \leq 3}$  the type of  $X$ . Note that the  $d_i$ , as well as the  $e_i$  have the same parity for all  $i$ . We say that the type  $(d_i, e_i)_{0 \leq i \leq 3}$  is lexicographically ordered, if  $d_i < d_{i+1}$  or  $d_i = d_{i+1}$  and  $e_i \leq e_{i+1}$ .

**Corollary 11.** *Let  $X \rightarrow \mathbb{P}^1 \times \mathbb{P}^1$  be a very general quadric surface bundle of lexicographically ordered type  $(d_i, e_i)_{0 \leq i \leq 3}$ , with  $d_i, e_i \geq 0$  and  $d_3, e_3 \geq 3$ . Then,*

- (1)  $X$  is rational if  $d_2 = 0$ ,  $d_1 = e_1 = e_0 = 0$  or  $e_0 = e_1 = e_2 = 0$ ;
- (2)  $X$  is not stably rational otherwise.

All examples in Corollary 11 have the deformation types of smooth rational fourfolds, see for instance [23, Lemma 19]. The condition  $d_3, e_3 \geq 3$  in the above theorem could be replaced by a weaker but more complicated assumption; we collect in Corollary 12 below the remaining cases where our method works.

*Proof of Corollary 11.* Let  $A = (a_{ij})_{0 \leq i, j \leq 3}$  be a symmetric matrix, where  $a_{ij}$  is a very general global section of  $\mathcal{O}_{\mathbb{P}^1 \times \mathbb{P}^1}(p_i + p_j + m, q_i + q_j + n)$  and consider the corresponding quadric surface bundle  $X$  over  $\mathbb{P}^1 \times \mathbb{P}^1$ . Here the integers  $d_i := 2p_i + m$  and  $e_i := 2q_i + n$  are assumed to satisfy the assumptions of Corollary 11, i.e.  $(d_i, e_i)_{0 \leq i \leq 3}$  is lexicographically ordered with  $d_i, e_i \geq 0$  and  $d_3, e_3 \geq 3$ .

If  $d_1 = e_1 = e_0 = 0$ , then  $(a_{ij})_{0 \leq i, j \leq 1}$  is a constant matrix and so  $X$  has a section. If  $d_2 = 0$ , then  $(a_{ij})_{0 \leq i, j \leq 2}$  is a matrix of polynomials which are constant along the first factor. Since any conic bundle over  $\mathbb{P}^1$  has a section,  $X$  admits also a section. If  $e_0 = e_1 = e_2 = 0$ , then  $(a_{ij})_{0 \leq i, j \leq 2}$  is a matrix of polynomials, constant along the second factor, and so  $X$  has a section as before. Since  $X$  is general and  $d_i, e_i \geq 0$ , the generic fibre of  $X$  over  $\mathbb{P}^1 \times \mathbb{P}^1$  is a smooth quadric surface and so  $X$  is rational in each of the above cases.

The case where  $(e_0, e_1, e_2) \neq (0, 0, 0)$ ,  $(d_1, e_0, e_1) \neq (0, 0, 0)$  and  $d_2 \neq 0$  is similar to the proof of Corollary 2. The main point is that we can always degenerate  $X$  to weak quadric surface bundle  $Y$  over  $\mathbb{P}^1 \times \mathbb{P}^1$  whose generic fibre is isomorphic to the example in Proposition 6. To find such a degeneration, we consider coordinates  $x_0, x_1$  and  $y_0, y_1$  on

the first respectively second factor of  $\mathbb{P}^1 \times \mathbb{P}^1$  and consider the bidegree  $(2, 2)$  polynomial

$$(4) \quad h := x_1^2 y_0^2 + x_0^2 y_1^2 + x_0^2 y_0^2 - 2(x_1 y_1 x_0 y_0 + x_1 x_0 y_0^2 + y_1 y_0 x_0^2).$$

We then start with the quadratic form  $q = \langle 1, y_1, x_1, x_1 y_1 h \rangle$ . Putting  $x_0 = y_0 = 1$  shows that the corresponding quadric surface over  $K = \mathbb{C}(\mathbb{P}^1 \times \mathbb{P}^1)$  is isomorphic to the one in Proposition 6. The point is that the isomorphism type of this quadric surface does not change if we perform any of the following operations to the quadratic form  $q$ :

- multiply some entries with even powers of  $x_1$  and  $y_1$ ;
- multiply some entries with arbitrary powers of  $x_0$  and  $y_0$ ;
- reorder the entries of the quadratic form.

Our aim is to produce a quadratic form of given type  $(e_i, d_i)_{0 \leq i \leq 3}$  whose entries are coprime, since the latter guarantees that the associated quadratic form defines a weak quadric surface bundle  $Y$  over  $\mathbb{P}^1 \times \mathbb{P}^1$ . Once this is achieved, Corollary 11 will follow from [15, Proposition 11] and Theorem 1.

By assumptions,  $d_2 \geq 1$ , and if  $e_0 = e_1 = 0$ , then  $d_1 \geq 1$  and  $e_2 \geq 1$ . This leads to Cases A, B and C below. We divide into further subcases and provide each time a quadratic form (produced via the above process) with the properties we want. Recall that the  $d_i$ , as well as the  $e_i$ , have the same parity.

**Case A:**  $e_1 \geq 1$ .

*Subcase A.1.* If  $d_0$  and  $e_0$  are even, then we take

$$\langle x_1^{d_0} y_1^{e_0}, x_0^{d_1} y_0^{e_1-1} y_1, x_0^{d_2-1} x_1 y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

*Subcase A.2.* If  $d_0$  is odd and  $e_0$  is even, then we take

$$\langle x_0^{d_0} y_1^{e_0}, x_0^{d_1} y_0^{e_1-1} y_1, x_1^{d_2} y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

*Subcase A.3.* If  $d_0$  is even and  $e_0$  is odd, then we take

$$\langle x_1^{d_0} y_0^{e_0}, x_0^{d_1} y_1^{e_1}, x_0^{d_2-1} x_1 y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

*Subcase A.4.* If  $d_0$  and  $e_0$  are odd, then we take

$$\langle x_0^{d_0} y_0^{e_0}, x_0^{d_1} y_1^{e_1}, x_1^{d_2} y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

**Case B:**  $e_0 \geq 1$  and  $e_1 = 0$  (hence  $e_i$  is even for all  $i$ ).

*Subcase B.1.* If  $d_0$  is even, then we take

$$\langle x_1^{d_0} y_0^{e_0-1} y_1, x_0^{d_1}, x_0^{d_2-1} x_1 y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

*Subcase B.2.* If  $d_0$  is odd, then we take

$$\langle x_0^{d_0} y_0^{e_0-1} y_1, x_0^{d_1}, x_1^{d_2} y_0^{e_2}, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

**Case C:**  $d_1, e_2 \geq 1$  and  $e_0 = e_1 = 0$  (hence  $e_i$  is even for all  $i$ ).

*Subcase C.1.* If  $d_0$  is even, then we take

$$\langle x_1^{d_0}, x_0^{d_1-1} x_1, x_0^{d_2} y_0^{e_2-1} y_1, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

*Subcase C.2.* If  $d_0$  is odd, then we take

$$\langle x_0^{d_0}, x_1^{d_1}, x_0^{d_2} y_0^{e_2-1} y_1, x_0^{d_3-3} y_0^{e_3-3} x_1 y_1 h \rangle.$$

In each of the above cases, putting  $x_0 = y_0 = 1$  and reordering the factors if necessary shows that the corresponding weak quadric surface bundle  $Y$  over  $\mathbb{P}^1 \times \mathbb{P}^1$  has generic fibre which is isomorphic to  $\langle 1, y_1, x_1, x_1 y_1 F(x_1, y_1, 1) \rangle$ . Corollary 11 follows therefore from [15, Proposition 11] (see Proposition 6 above) and Theorem 1.  $\square$

**Corollary 12.** *Let  $(d_i, e_i)_{0 \leq i \leq 3}$  be a lexicographically ordered tuple of pairs of non-negative integers with  $d_i + d_j$  and  $e_i + e_j$  even for all  $i, j$ . Suppose that one of the following holds:*

- (1)  $d_1 \geq 1, d_3 \geq 2, e_1 + e_2 \geq 1$  and  $e_3 \geq 3$ ;
- (2)  $d_1 \geq 1, d_3 \geq 2, e_0 \geq 1, e_1 + e_2 \geq 1$  and  $e_2 \geq 2$ .

*Then a very general complex projective quadric surface bundle  $X$  over  $\mathbb{P}^1 \times \mathbb{P}^1$  of type  $(d_i, e_i)_{0 \leq i \leq 3}$  is not stably rational.*

*Proof.* We start with the quadratic forms  $q_1 := \langle 1, x_1, x_1 y_1, y_1 h \rangle$  and  $q_2 := \langle y_1, x_1, x_1 y_1, h \rangle$ , where  $h$  is as in (4). If condition (1) holds, then we can use  $q_1$  and if (2) holds, then we can use  $q_2$  to obtain via the procedure, explained in the proof of Corollary 11, a quadratic form of type  $(d_i, e_i)_{0 \leq i \leq 3}$  whose coefficients are coprime. This yields a special fibre to which Theorem 1 applies. The details are similar as in the proof of Corollary 11 and we leave them to the reader.  $\square$

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