

KODAIRA DIMENSION AND SYMPLECTIC SUMS

MICHAEL USHER

ABSTRACT. Modulo trivial exceptions, we show that symplectic sums of symplectic 4-manifolds along surfaces of positive genus are never rational or ruled, and we enumerate each case in which they have Kodaira dimension zero (*i.e.*, are blowups of symplectic 4-manifolds with torsion canonical class). In particular, a symplectic four-manifold of Kodaira dimension zero arises by such a surgery only if it is diffeomorphic to a blowup either of the $K3$ surface, the Enriques surface, or a member of a particular family of T^2 -bundles over T^2 each having $b_1 = 2$.

1. INTRODUCTION

Our understanding of the diversity of the world of symplectic four-manifolds has been greatly enriched by the introduction in [7] and [18] of the *symplectic sum*. Given symplectic four-manifolds $(X_1, \omega_1), (X_2, \omega_2)$ containing embedded, two-dimensional symplectic submanifolds $F_1 \subset X_1, F_2 \subset X_2$ of equal area and genus and an orientation-reversing isomorphism $\Phi: N_{X_1}F_1 \rightarrow N_{X_2}F_2$ of their normal bundles (which of course exists if and only if F_1 and F_2 have opposite self-intersection), the symplectic sum operation provides a natural isotopy class of symplectic structures on the normal connect sum

$$Z = X_1 \#_{F_1=F_2} X_2 = (X_1 \setminus \nu_1) \cup_{\partial\nu_1 \sim_{\Phi} \partial\nu_2} (X_2 \setminus \nu_2),$$

where the ν_i are tubular neighborhoods of F_i and we use the restriction of Φ to the unit normal circle bundles of the F_i to glue the boundaries of the manifolds $X_i \setminus \nu_i$. Using the symplectic sum along surfaces of positive genus, various authors over the years have constructed symplectic four-manifolds satisfying an impressive array of properties; see for instance Theorem 6.2 of [7], which for any finitely presented group G gives a number $r(G)$ such that whenever $a + b \equiv 0 \pmod{12}$ and $0 \leq a \leq 2(b - r(G))$ there is a symplectic 4-manifold $M_{a,b,G}$ with $\pi_1(M_{a,b,G}) = G$, $c_1^2(M_{a,b,G}) = a$, and $c_2(M_{a,b,G}) = b$. While Gompf's examples were distinguished by their classical topological invariants, the symplectic sum also gives rise to infinite families of mutually homeomorphic but nondiffeomorphic symplectic four-manifolds, since if K is a fibered knot the operation of knot surgery with K [3] amounts to a symplectic sum.

The purpose of this note is to show that, notwithstanding the diversity of symplectic four-manifolds that can be constructed via symplectic sum, there are significant topological restrictions on the manifolds that can be obtained in this way. Our results may perhaps best be understood in terms of the notion of (symplectic) *Kodaira dimension*, a notion which dates from [20] and is discussed in some detail in [14]. We

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shall recall the definition of Kodaira dimension below. First, recall that a symplectic four-manifold is called *minimal* if it does not contain any embedded symplectic spheres of square -1 , and that if (X, ω) is any symplectic four-manifold one may obtain a minimal symplectic four-manifold (X', ω') by blowing down a maximal disjoint collection of symplectic (-1) -spheres in X ; (X', ω') is then called a minimal model for (X, ω) .

Definition 1.1. *Let (X, ω) be a symplectic four-manifold with minimal model (X', ω') , and let $\kappa_{X'} \in H^2(X'; \mathbb{Z})$ denote the canonical class of (X', ω') . Then the Kodaira dimension of (X, ω) is*

$$\kappa(X, \omega) = \begin{cases} -\infty & \text{if } \kappa_{X'} \cdot [\omega'] < 0 \text{ or } \kappa_{X'}^2 < 0 \\ 0 & \text{if } \kappa_{X'} \cdot [\omega'] = \kappa_{X'}^2 = 0 \\ 1 & \text{if } \kappa_{X'} \cdot [\omega'] > 0 \text{ and } \kappa_{X'}^2 = 0 \\ 2 & \text{if } \kappa_{X'} \cdot [\omega'] > 0 \text{ and } \kappa_{X'}^2 > 0 \end{cases}$$

In Section 2 of [14] and references therein it is shown that $\kappa(X, \omega)$ is well-defined for any symplectic four-manifold (in particular it is independent of the choice of minimal model, and one of the four possibilities listed above always holds); coincides with the classical notion of Kodaira dimension in cases when X happens to admit the structure of a complex surface; is equal to $-\infty$ if and only if X is a rational or ruled surface;¹ and is equal to zero if and only if the canonical class of the minimal model X' is torsion. Moreover Theorem 2.6 of [14] shows that the Kodaira dimension $\kappa(M, \omega)$ depends only on the diffeomorphism type of M , and not on the symplectic form.

A common feature of the numerous interesting new symplectic four-manifolds that the symplectic sum operation has provided to us is that they have always had Kodaira dimension 1 or 2. For instance, knot surgery on the K3 surface with a nontrivial fibered knot as in [3] always yields a symplectic four-manifold of Kodaira dimension 1 (even though the result is homeomorphic to the K3 surface, which has Kodaira dimension zero), and (at least aside from some very trivial cases) Gompf's manifolds $M_{a,b,G}$ have Kodaira dimension 1 if $a = 0$ and 2 if $a > 0$. Our main theorem below will demonstrate that this is not a coincidence. To state it, we make the following definitions.

Definition 1.2. *Let $(X_1, \omega_1), (X_2, \omega_2)$ be symplectic four-manifolds with $F_i \subset X_i$ embedded symplectic submanifolds of equal area and genus and opposite square.*

- (1) *The symplectic sum $X_1 \#_{F_1=F_2} X_2$ is called smoothly trivial if, for some $i \in \{1, 2\}$, X_i the total space of an S^2 -bundle of which F_i is a section. Otherwise, the symplectic sum is called smoothly nontrivial.*
- (2) *The symplectic sum $X_1 \#_{F_1=F_2} X_2$ is said to be of blowup type if, for some $i \in \{1, 2\}$, the pair (X_i, F_i) may be obtained from a pair (E, F) consisting of the total space E of an S^2 -bundle of which F is a section by a sequence of zero or more blowups at points not lying on F .*

Remark 1.3. *It is stated without proof in [7] that if $X_1 \#_{F_1=F_2} X_2$ is a smoothly trivial symplectic sum, say with (X_2, F_2) consisting of an S^2 -bundle and a section, then the sum $X_1 \#_{F_1=F_2} X_2$ is diffeomorphic to X_1 . It is not difficult to prove this:*

¹Here and below we adopt the convention that a ruled surface is a symplectic manifold obtained by (possibly) blowing up the total space of an S^2 -bundle over some Riemann surface. When we want to assume that no blowups have been carried out, we shall refer instead to an " S^2 -bundle."

simply note that $X_2 \setminus \nu_2$ will be diffeomorphic to a neighborhood of F_1 in X_1 , so that for at least one choice of the gluing map $\Phi|_{\partial\nu_1}$ the sum will be diffeomorphic to X_1 ; further, the gluing maps $\Phi|_{\partial\nu_1}: \partial\nu_1 \rightarrow \partial\nu_2$ that we are allowed to use in forming the symplectic sum are precisely the restrictions of orientation reversing bundle isomorphisms, and so any two of them differ by precomposing with an orientation preserving diffeomorphism of $\partial\nu_1$ which extends over ν_1 , implying therefore that the diffeomorphism type of $X_1 \#_{F_1=F_2} X_2$ is independent of the gluing map and so is X_1 in any event. Of course, this argument is dependent on the fact that the gluing map is required to preserve the fibers of the normal circle bundles, an issue which seems to have caused a certain amount of confusion in the literature, where one occasionally finds mistaken claims that symplectic sums with S^2 -bundles along sections sometimes change the diffeomorphism type.

At any rate, the above fact justifies our use of the term “smoothly trivial” to describe such symplectic sums, and by Theorem 2.6 of [14] implies that performing a smoothly trivial symplectic sum leaves the Kodaira dimension unchanged. Incidentally, while these sums are trivial from a smooth standpoint, they generally do alter the symplectic structure in a manner equivalent to the “inflation” technique of [13], a fact which is exploited in [16].

Definition 1.4. *If (X_1, ω_1) , (X_2, ω_2) are symplectic four-manifolds with $F_i \subset X_i$ embedded symplectic submanifolds of equal area and genus and opposite square, the symplectic sum $X_1 \#_{F_1=F_2} X_2$ is called relatively minimal if for each $i = 1, 2$, there are no embedded symplectic spheres of square -1 in $X_i \setminus F_i$.*

Remark 1.5. *If a symplectic sum $Z = X_1 \#_{F_1=F_2} X_2$ is not relatively minimal, then if we blow down maximal disjoint collections of spheres of square -1 in $X_1 \setminus F_1$ and $X_2 \setminus F_2$ to obtain symplectic manifolds X'_1, X'_2 , then the F_i survive in the blowdowns and the areas, genera, and self-intersections of the F_i are left unchanged. Hence we may form a symplectic sum $Z' = X'_1 \#_{F_1=F_2} X'_2$, and Z may be recovered from Z' by a sequence of blowups. $X'_1 \#_{F_1=F_2} X'_2$ will be smoothly trivial if and only if $X_1 \#_{F_1=F_2} X_2$ is of blowup type. Thus any symplectic 4-manifold which arises as a symplectic sum which is not of blowup type is a blowup of a symplectic 4-manifold which arises as a smoothly nontrivial, relatively minimal symplectic sum. Moreover, symplectic sums which are of blowup type are diffeomorphic to blowups of one of their summands.*

Remark 1.6. *In this language, the main result of [27] may be rephrased as stating that any symplectic 4-manifold arising as a smoothly nontrivial, relatively minimal symplectic sum along surfaces of positive genus is minimal.*

Our main result is the following:

Theorem 1.7. *Suppose that (X_1, ω_1) , (X_2, ω_2) , F_1 , and F_2 are such that the symplectic sum $Z = X_1 \#_{F_1=F_2} X_2$ is smoothly nontrivial and relatively minimal and the genus of the F_i is positive. Then:*

- (a) Z does not have Kodaira dimension $-\infty$.
- (b) If Z has Kodaira dimension 0, then the diffeomorphism types of X_1 , X_2 , and Z are given by one of the rows in the following table, where the notation $M(A, B; \vec{v})$ denotes a T^2 -bundle over T^2 as described below or in [24]. Moreover, each entry in the third column of this table can in fact be constructed as a smoothly nontrivial, relatively minimal symplectic sum along a torus.

X_1	X_2	possible diffeomorphism types of $X_1 \#_{F_1=F_2} X_2$
$\mathbb{C}P^2 \# (18-k)\overline{\mathbb{C}P^2}$	$\mathbb{C}P^2 \# k\overline{\mathbb{C}P^2}$	<i>K3 surface</i>
$S^2 \times S^2$	$\mathbb{C}P^2 \# 17\overline{\mathbb{C}P^2}$	<i>K3 surface</i>
$\mathbb{C}P^2 \# (9-k)\overline{\mathbb{C}P^2}$	$(S^2 \times T^2) \# k\overline{\mathbb{C}P^2}$	<i>Enriques surface</i>
$S^2 \times S^2$	$(S^2 \times T^2) \# 8\overline{\mathbb{C}P^2}$	<i>Enriques surface</i>
$\mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$	$S^2 \tilde{\times} T^2$	<i>Enriques surface</i>
$S^2 \times T^2$	$S^2 \times T^2$	$M \left(I, \begin{pmatrix} -1 & z \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right),$ $M \left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right),$ $M \left(I, \begin{pmatrix} -1 & 2y \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right),$ $M \left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right) \quad (y, z \in \mathbb{Z})$
$S^2 \times T^2$	$S^2 \tilde{\times} T^2$	$M \left(-I, \begin{pmatrix} 1 & 2y+1 \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right),$ $M \left(-I, \begin{pmatrix} 1 & 2y+1 \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right) \quad (y \in \mathbb{Z})$
$S^2 \tilde{\times} T^2$	$S^2 \tilde{\times} T^2$	$M \left(I, \begin{pmatrix} -1 & z \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right),$ $M \left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right)$ $M \left(I, \begin{pmatrix} -1 & 2y+1 \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right) \quad (y, z \in \mathbb{Z})$

Here $S^2 \tilde{\times} T^2$ refers to the smoothly nontrivial S^2 -bundle over the torus. The *K3* surface is, of course, the smooth four-manifold underlying a quartic hypersurface of $\mathbb{C}P^3$, while the Enriques surface can be realized either as the quotient of a *K3* surface by a free involution which is holomorphic for an appropriate complex structure, or, equivalently, as the result of performing logarithmic transformations of multiplicity 2 on two fibers of the rational elliptic surface $E(1)$; pp. 590–599 of [9] provide a concise description of the complex geometry of these manifolds. The notation $M(A, B; \vec{v})$ ($A, B \in SL(2; \mathbb{Z}), \vec{v} \in \mathbb{Z}^2, AB = BA$) above is as in [24]: identifying $T^2 = \mathbb{R}^2/\mathbb{Z}^2$ and writing the coset of $(x, y) \in \mathbb{R}^2$ as $\begin{bmatrix} x \\ y \end{bmatrix}$, we define

$$M \left(A, B; \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right) = \frac{\mathbb{R}^2 \times T^2}{\left(\begin{matrix} s+1, t, \begin{bmatrix} x \\ y \end{bmatrix} \\ s, t+1, \begin{bmatrix} x \\ y \end{bmatrix} \end{matrix} \right) \sim \left(\begin{matrix} s, t, \begin{bmatrix} A \begin{pmatrix} x \\ y \end{pmatrix} \\ B \begin{pmatrix} x \\ y \end{pmatrix} \end{matrix} \right)},$$

and let $M(A, B; (m, n))$ be obtained from $M(A, B; (0, 0))$ by removing a neighborhood of a torus fiber of the projection $[s, t, x, y] \mapsto [s, t]$ and regluing it by the map

$$\begin{aligned} \partial D^2 \times T^2 &\rightarrow \partial D^2 \times T^2 \\ (e^{2\pi i\theta}, [x, y]) &\mapsto (e^{2\pi i\theta}, [x + m\theta], [y + n\theta]). \end{aligned}$$

Since manifolds obtained by general symplectic sums are blowups of those obtained by relatively minimal ones, and since Kodaira dimension is preserved under blowups, Theorem 1.7 has the following corollary:

Corollary 1.8. *No symplectic 4-manifold of Kodaira dimension $-\infty$ arises as a symplectic sum along surfaces of positive genus which is not of blowup type, and the only symplectic 4-manifolds of Kodaira dimension 0 which arise as symplectic sums which are not of blowup type along surfaces of positive genus are blowups of symplectic manifolds diffeomorphic to either the K3 surface, the Enriques surface, or a T^2 -bundle over T^2 having the form $M\left(I, \begin{pmatrix} -1 & z \\ 0 & -1 \end{pmatrix}; \vec{v}\right)$ or $M\left(-I, \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix}; \vec{v}\right)$, where $z \in \mathbb{Z}$ and $\vec{v} \in \{(0, 0), (0, 1), (1, 0)\}$.*

Symplectic 4-manifolds of Kodaira dimension $-\infty$ are of course well understood since they are all rational or ruled. In light of Gompf's manifolds $M_{a,b,G}$ mentioned above, the classes of symplectic 4-manifolds of Kodaira dimension either 1 or 2 are each at least as complicated as the class of all finitely presented groups, which have been known to be unclassifiable since the 1950's. The classification of symplectic 4-manifolds of Kodaira dimension zero, meanwhile, is a very interesting open problem. The only presently-known such manifolds are blowups of the K3 surface, the Enriques surface, or an orientable T^2 -bundle over T^2 (all of the latter were proven to admit symplectic structures in [5]), and a recent striking result independently proven in [1] and [15] implies that any minimal symplectic 4-manifold of Kodaira dimension zero necessarily has the same rational homology as one of the known minimal examples. Theorem 1.7 thus shows that (up to diffeomorphism) if any new symplectic 4-manifolds of Kodaira dimension zero do exist, then they cannot be found by performing symplectic sums along surfaces of positive genus. Note that since blowing down a (-1) -sphere amounts to performing a symplectic sum with $\mathbb{C}P^2$ along a line, any symplectic 4-manifold arises (in a somewhat trivial fashion) as a smoothly non-trivial symplectic sum along spheres. It would be interesting to know whether or not new symplectic 4-manifolds of Kodaira dimension zero can arise by symplectic sum with $\mathbb{C}P^2$ along a quadric (*i.e.*, by blowing down a (-4) -sphere), or more generally whether or not new symplectic 4-manifolds of Kodaira dimension zero can arise via the rational blowdown procedure of [2].

Theorem 1.7 pins down the diffeomorphism type of the symplectic sums in question; it would be somewhat preferable to have a result specifying the symplectic deformation type (though it's worth noting that this may be a moot point, since any two symplectic structures on any of the manifolds in the last column of the table in Theorem 1.7 have the same canonical class, and there are not currently any known examples of smooth four-manifolds admitting deformation inequivalent symplectic structures that have the same canonical class). In the case that the symplectic sum is a T^2 -bundle over T^2 , our proof can be seen to imply that the symplectic form will be positive on the fibers, and so will be deformation equivalent to a form obtained by the Thurston trick. When the sum is diffeomorphic to the K3 surface or the Enriques surface, the situation is perhaps more subtle, since in our proofs we use, among other things, the fact that any orientation-preserving diffeomorphism of the boundary of the complement of a tubular neighborhood of a fiber in the rational elliptic surface $E(1)$ extends to the whole complement, and so since such a diffeomorphism cannot always be made symplectic we lose control of the symplectic form.

We should mention that, as in Remark 1.3, although the conclusion of Theorem 1.7 only concerns diffeomorphism types the result is sensitive to the fact that the sum operation is symplectic and so the gluing map $\Phi: \partial\nu_1 \rightarrow \partial\nu_2$ is required to be the restriction of an anti-isomorphism of complex line bundles (rather than just an arbitrary diffeomorphism). Of course, if Φ were replaced by an arbitrary diffeomorphism, the sum might not admit a symplectic structure; for instance for $n \geq 2$ a degree-zero logarithmic transformation of a fiber of the elliptic surface $E(n)$ (which results from an appropriate gluing of the complement of the symplectic torus fiber of $E(n)$ to the complement of a symplectic torus in $T^2 \times S^2$) is diffeomorphic to the non-symplectic manifold $(2n-1)\mathbb{C}P^2 \# (10n-1)\overline{\mathbb{C}P^2}$ (Theorem 6.1 of [6]). In other cases, though, a more general gluing map gives rise to a manifold that happens to admit a symplectic structure, which may even have Kodaira dimension zero: for instance, any of the T^2 -bundles over T^2 given in our notation above as $M(I, I; (m, n))$ may be obtained by an appropriate gluing of the complement of a symplectic torus in T^4 to the complement of a symplectic torus in $T^2 \times S^2$; these all admit symplectic structures by [5] (or indeed by earlier work; the case $(m, n) = (0, 1)$ is the Kodaira-Thurston manifold) with trivial canonical class and so Kodaira dimension zero. However, for $(m, n) \neq (0, 0)$ $b_1(M(I, I; (m, n))) = 3$, whereas all of the T^2 -bundles over T^2 appearing in Theorem 1.7 have $b_1 = 2$, so none of the manifolds $M(I, I; (m, n))$ occur as smoothly nontrivial symplectic sums.

In the next section, we prove part (a) of Theorem 1.7, which might best be seen as a corollary of the arguments of [27]. The rest of the paper consists of the proof of part (b), which relies on a result describing the behavior of the canonical class of a symplectic sum in order to reduce the result to a small number of cases which can be dispensed with in turn. A useful tool in two of the cases is Lemma 3.3, which states that if F is a symplectic torus in $\mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$ Poincaré dual to the first Chern class, then there is a diffeomorphism of pairs taking $(\mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}, F)$ to the pair consisting of a rational elliptic surface together with one of its regular fibers. This should be contrasted with various non-isotopy results for symplectic tori Poincaré dual to multiples of the first Chern class, *e.g.*, in [4].

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2. RATIONAL AND RULED SURFACES

Part (a) of Theorem 1.7 is an easy consequence of two results proven in [27]. On the one hand, from Section 2 of that paper, we find (based largely on [12]), that if $Z = X_1 \#_{F_1=F_2} X_2$ is a symplectic sum, and if $A \in H_2(Z; \mathbb{Z})$ is any nonzero homology class having a nontrivial Gromov–Witten invariant counting genus-zero holomorphic curves, then there are classes $A_1 \in H_2(X_1; \mathbb{Z})$, $A_2 \in H_2(X_2; \mathbb{Z})$, each represented by a union of genus zero stable maps which are pseudoholomorphic for some almost complex structure J_i on X_i ($i = 1, 2$) which preserves TF_i such that

$$(1) \quad \langle \kappa_{X_1} + PD[F_1], A_1 \rangle + \langle \kappa_{X_2} + PD[F_2], A_2 \rangle = \langle \kappa_Z, A \rangle < 0,$$

where the final inequality results from the fact that the expected dimension of genus-zero pseudoholomorphic representatives of A , namely $-1 - \langle \kappa_Z, A \rangle$, must be nonnegative in order for the corresponding Gromov–Witten invariant to be nonvanishing.

On the other hand, Proposition 3.9 of [27], translated into the terminology of the introduction, states that if the symplectic sum $Z = X_1 \#_{F_1=F_2} X_2$ is smoothly

nontrivial and relatively minimal, and if the F_i have positive genus, then the F_i are “rationally K -nef,” which is to say, for $i = 1, 2$, if $A \in H_2(X_i; \mathbb{Z})$ is represented by a J_i -holomorphic sphere for some almost complex structure J_i preserving TF_i , then we necessarily have $\langle \kappa_{X_i} + PD[F_i], A \rangle \geq 0$.

As such, if the symplectic sum is smoothly nontrivial and relatively minimal, and if the genus of the surfaces involved is positive, then (1) cannot hold, and so Z cannot admit any nonvanishing genus zero Gromov–Witten invariants in any nontrivial homology classes. In [27] this was used to conclude that Z is minimal; in our present case, we simply note that any rational or ruled surface does admit a nonvanishing genus-zero Gromov–Witten invariant in a nontrivial homology class (the proper transform of the hyperplane class for blowups of $\mathbb{C}P^2$, or the class of the fiber of a ruling for ruled surfaces; see, *e.g.*, [19]). Thus rational and ruled surfaces (*i.e.*, symplectic 4-manifolds of Kodaira dimension $-\infty$) cannot arise as smoothly nontrivial, relatively minimal symplectic sums along surfaces of positive genus, proving part (a) of Theorem 1.7.

3. 4-MANIFOLDS OF KODAIRA DIMENSION ZERO

The proof of part (b) of Theorem 1.7 depends on the following result.

Theorem 3.1. *Let $(X_1, \omega_1), (X_2, \omega_2)$ be symplectic 4-manifolds, $F_i \subset X_i$ ($i = 1, 2$) embedded symplectic submanifolds of equal positive genus, equal area, and opposite self-intersection, and $(Z = X_1 \#_{F_1=F_2} X_2, \omega)$ the symplectic sum of the X_i along the F_i . Assume that the symplectic sum is smoothly nontrivial and that (Z, ω) has Kodaira dimension zero and is minimal. Then the F_i are both tori, and are Poincaré dual to $-\kappa_{X_i}$.*

Proof. According to Theorem 2.1 of [12], there is a symplectic 6-manifold (\mathcal{Z}, Ω) equipped with a projection $\pi: \mathcal{Z} \rightarrow D^2$ with the property that, for $\lambda \neq 0$, $(\pi^{-1}(\lambda), \Omega|_{\pi^{-1}(\lambda)})$ is isotopic to the symplectic sum Z , while $(\pi^{-1}(0), \Omega|_{\pi^{-1}(0)})$ is the singular symplectic manifold obtained by directly gluing the X_i along the F_i , so that the two pieces intersect in a copy F of the F_i . As seen in the proof of Lemma 2.2 of [12], one has (for $\lambda \neq 0$) $\kappa_{\mathcal{Z}|_{\pi^{-1}(\lambda)}} = \kappa_{\pi^{-1}(\lambda)}$, while for $i = 1, 2$ $c_1(T\mathcal{Z}|_{X_i}) = c_1(X_i) - PD_{X_i}[F_i]$.

We claim now that, where $i_\lambda: \pi^{-1}(\lambda) \rightarrow \mathcal{Z}$, $i_j: X_j \rightarrow \mathcal{Z}$ ($j = 1, 2$) are the inclusions, $i_{\lambda*}[\pi^{-1}(\lambda)]$ is equal to $i_{1*}[X_1] + i_{2*}[X_2]$ in $H_4(\mathcal{Z}; \mathbb{Z})$. This essentially follows from the description of \mathcal{Z} in Section 2 of [12]. Namely, as seen there, $\pi^{-1}(\lambda)$ for $0 < \lambda \ll 1$ may (up to isotopy) be obtained from $\pi^{-1}(0) = X_1 \cup_F X_2$ as follows: a neighborhood of $F \subset \mathcal{Z}$ is diffeomorphic to a neighborhood U of the zero section in $L \oplus L^* \rightarrow F$ where $L \rightarrow F$ is a complex line bundle of degree $[F_1]^2$ and L^* is its dual; putting a Hermitian metric $|\cdot|$ on L (which then induces one on L^*) and arranging that $U = \{(\alpha, v, x) \in L \oplus L^* \mid |\alpha|, |v| \leq 1\}$, up to smooth isotopy $\pi^{-1}(\lambda)$ coincides with $\pi^{-1}(0)$ outside U and its intersection with U is given by $\{(\alpha, v, x) \in L \oplus L^* \mid \langle \alpha, v \rangle = \chi(|\alpha| + |v|)\lambda\}$ where $\chi: [0, 1] \rightarrow [0, 1]$ is a bump function supported in $[0, 2\lambda^{1/4}]$ and equal to 1 on $[0, \lambda^{1/4}]$. Observe that X_1 is homologous to the chain obtained by replacing $X_1 \cap U$ by (in hopefully self-explanatory notation)

$$\{(\bar{v}, v, x) \mid |v| \leq \lambda^{1/2}\} + \{(\alpha, v, x) \in \pi^{-1}(\lambda) \mid \lambda^{1/2} \leq |v| \leq 1\}$$

and likewise X_2 is homologous to the chain obtained by replacing $X_2 \cap U$ by

$$\{(\alpha, \bar{\alpha}, x) \mid |\alpha| \leq \lambda^{1/2}\} + \{(\alpha, v, x) \in \pi^{-1}(\lambda) \mid \lambda^{1/2} \leq |\alpha| \leq 1\}.$$

But adding these two chains together and passing to homology just recovers $i_{\lambda*}[Z_\lambda]$ (as the first terms in the two expressions above now cancel), verifying that indeed $i_{\lambda*}[\pi^{-1}(\lambda)] = i_{1*}[X_1] + i_{2*}[X_2] \in H_4(\mathcal{Z}; \mathbb{Z})$.

As such, we have

$$\begin{aligned}
\langle \kappa_{\mathcal{Z}} \cup [\omega], [Z] \rangle &= \langle i_{\lambda}^*(\kappa_{\mathcal{Z}} \cup [\Omega]), [\pi^{-1}(\lambda)] \rangle = \langle \kappa_{\mathcal{Z}} \cup [\Omega], i_{\lambda*}[\pi^{-1}(\lambda)] \rangle \\
&= \langle \kappa_{\mathcal{Z}} \cup [\Omega], i_{1*}[X_1] \rangle + \langle \kappa_{\mathcal{Z}} \cup [\Omega], i_{2*}[X_2] \rangle \\
&= \langle \kappa_{\mathcal{Z}}|_{X_1} \cup [\Omega]|_{X_1}, [X_1] \rangle + \langle \kappa_{\mathcal{Z}}|_{X_2} \cup [\Omega]|_{X_2}, [X_2] \rangle \\
&= \langle (\kappa_{X_1} + PD_{X_1}[F_1]) \cup [\omega_1], [X_1] \rangle + \langle (\kappa_{X_2} + PD_{X_2}[F_2]) \cup [\omega_2], [X_2] \rangle \\
(2) \quad &= \langle \kappa_{X_1} \cup [\omega_1], [X_1] \rangle + \langle \kappa_{X_2} \cup [\omega_2], [X_2] \rangle + \int_{F_1} \omega_1 + \int_{F_2} \omega_2.
\end{aligned}$$

Note that nothing that we've done so far makes any use of the assumption that (Z, ω) is minimal with Kodaira dimension zero. However, when we do implement that assumption, the left hand side of (2) becomes zero. Hence

$$\left(\langle \kappa_{X_1} \cup [\omega_1], [X_1] \rangle + \int_{F_1} \omega_1 \right) + \left(\langle \kappa_{X_2} \cup [\omega_2], [X_2] \rangle + \int_{F_2} \omega_2 \right) = 0.$$

We claim now that each κ_{X_i} is proportional to $PD[F_i]$ in $H^2(X_i; \mathbb{R})$. Indeed, suppose that this were not the case, say for $i = 1$. Then we could find an element $\beta \in H^2(X_1; \mathbb{R})$ such that $\langle \kappa_{X_1} \cup \beta, [X_1] \rangle = 1$ but $\langle \beta, [F_1] \rangle = 0$. Moreover, since small closed perturbations of symplectic forms are still symplectic, for any sufficiently small $\epsilon > 0$ the cohomology class $[\omega_1] + \epsilon\beta$ would admit a symplectic form, say ω_1^ϵ , which (assuming ϵ is small enough) would continue to make F_1 symplectic, and would induce the same canonical class κ_{X_1} as does ω_1 by virtue of being deformation equivalent to ω_1 . We would then have

$$\int_{F_1} \omega_1^\epsilon = \int_{F_1} \omega_1, \quad \langle \kappa_{X_1} \cup [\omega_1^\epsilon], [X_1] \rangle = \langle \kappa_{X_1} \cup [\omega_1], [X_1] \rangle + \epsilon.$$

But then we could apply the symplectic sum operation to the symplectic manifolds (X_1, ω_1^ϵ) , (X_2, ω_2) along the F_i to obtain a new symplectic manifold $(Z^\epsilon, \omega^\epsilon)$, diffeomorphic (indeed deformation equivalent) to (Z, ω) , and by (2) we would have

$$\langle \kappa_{Z^\epsilon} \cup [\omega], [Z^\epsilon] \rangle = \epsilon > 0.$$

So $(Z^\epsilon, \omega^\epsilon)$ is not a minimal symplectic manifold of Kodaira dimension zero. But by Theorem 2.6 of [14], the Kodaira dimension of a symplectic four-manifold is a diffeomorphism invariant, so since Z^ϵ is diffeomorphic to Z (and since the minimality or nonminimality of Z is also a diffeomorphism invariant; see, *e.g.*, Proposition 2.1 of [14]) this is impossible. This contradiction shows that, for some $\mu_1, \mu_2 \in \mathbb{R}$, we have $PD(\kappa_{X_i}) = \mu_i[F_i] \in H_2(X; \mathbb{R})$ for $i = 1, 2$.

Evidently, since $\langle \kappa_{\mathcal{Z}} \cup [\omega], [Z] \rangle = 0$, we must have

$$(2 + \mu_1 + \mu_2) \int_{F_1} \omega_1 = \left(\langle \kappa_{X_1} \cup [\omega_1], [X_1] \rangle + \int_{F_1} \omega_1 \right) + \left(\langle \kappa_{X_2} \cup [\omega_2], [X_2] \rangle + \int_{F_2} \omega_2 \right) = 0,$$

so since $\int_{F_1} \omega_1 > 0$ we have

$$\mu_1 + \mu_2 = -2.$$

In particular, at least one of the μ_i , say μ_1 , is negative. Then $\langle \kappa_{X_1} \cup [\omega_1], [X_1] \rangle = \mu_1 \int_{F_1} \omega_1 < 0$, so by Theorem B of [17] and results of [26] (X_1, ω_1) must be either a rational surface or an irrational ruled surface.

Now if $X_1 = \mathbb{C}P^2 \# k \overline{\mathbb{C}P^2}$, then where H is the hyperplane class and E_1, \dots, E_k are the classes of the exceptional spheres of the blowups, we have $PD(\kappa_{X_1}) = -3H + \sum_{i=1}^k E_i$; from this it's easy to see from the adjunction formula that if F_1 is a symplectic surface of positive genus representing $\frac{1}{\mu_1} PD(\kappa_X)$ we necessarily have $-\frac{1}{\mu_1} \geq 1$, so that $\mu_1 \geq -1$; similarly if $X_1 = S^2 \times S^2$ then $PD(\kappa_{X_1}) = -2[S^2 \times \{pt\}] - 2[\{pt\} \times S^2]$, and again our assumptions on F_1 force $\mu_1 \geq -1$ ($\mu_1 = -2$ is ruled out both by the assumption that F_1 has positive genus and by the assumption that the sum is smoothly nontrivial, so that F_1 is not a section of an S^2 -bundle). Thus if X_1 is rational then $\mu_1 \geq -1$.

Suppose now that X_1 is an irrational ruled surface; say $X_1 = (S^2 \times \Sigma_h) \# k \overline{\mathbb{C}P^2}$ ($h \geq 1, k \geq 0$). Then where σ is the homology class of the proper transform of a section of $S^2 \times \Sigma_h \rightarrow \Sigma_h$ and f is the class of the proper transform of a generic fiber, we have $PD(\kappa_{X_1}) = -2\sigma + (2h - 2)f + \sum_{i=1}^k e_i$. If $k > 0$, then in order for $[F_1]$ to be an integral class we necessarily have $\mu_1 \geq -1$. If $k = 0$, we have either $\mu_1 \geq -1$ or $\mu_1 = -2$, but if $\mu_1 = -2$ then by Proposition 3.3 of [27] there is a ruling on X_1 of which F_1 is a section, which is forbidden by the assumption that the sum is smoothly nontrivial. Finally, if X_1 is a nontrivial S^2 -bundle $S^2 \tilde{\times} \Sigma_h$ over a surface of genus $h > 0$, then where s^+, s^- are sections of square $+1$ and -1 respectively, we have $PD(\kappa_X) = (2h - 3)[s^+] - (2h - 1)[s^-]$, so that since $[F_1] = \frac{1}{\mu_1} PD(\kappa_X) \in H_2(X_1; \mathbb{Z})$, we get $|\frac{1}{\mu_1}| \geq 1$, so $\mu_1 \geq -1$.

Summing up, we've shown that since $\mu_1 < 0$, X_1 is rational or ruled, and that (because X_1 is rational or ruled) by the hypothesis of the theorem we have $\mu_1 \geq -1$. But then since $\mu_1 + \mu_2 = -2$, we must have $\mu_2 < 0$, which then forces X_2 to be rational or ruled, and so by the same arguments $\mu_2 \geq -1$. So since $\mu_1 + \mu_2 = -2$ and $\mu_1, \mu_2 \geq -1$, we in fact have $\mu_1 = \mu_2 = -1$, *i.e.*, $[F_i] = -PD(\kappa_{X_i})$ for $i = 1, 2$.

To see that the F_i are tori, simply note that the adjunction formula gives

$$2g(F_i) - 2 = [F_i]^2 + \langle \kappa_{X_i}, [F_i] \rangle = \kappa_{X_i}^2 - \kappa_{X_i}^2 = 0.$$

□

Theorem 3.1 and its proof show that, in order for a smoothly nontrivial symplectic sum $X_1 \#_{F_1=F_2} X_2$ along a surface of positive genus to be minimal and of Kodaira dimension zero, the X_i necessarily are rational or ruled, and the F_i are tori Poincaré dual to $-\kappa_{X_i}$. The main theorem of [27] shows that the sum will automatically be minimal provided that the X_i and F_i satisfy the hypotheses of Theorem 1.7. The problem of determining the diffeomorphism types of such sums now naturally splits into 3 cases, which we address in turn.

3.1. Case 1: X_1 and X_2 are rational. Note that, since the F_i are tori, we have $\kappa_{X_1 \#_{F_1=F_2} X_2}^2 = 3\sigma(X_1 \#_{F_1=F_2} X_2) + 2\chi(X_1 \#_{F_1=F_2} X_2) = \kappa_{X_1}^2 + \kappa_{X_2}^2$. Now the rational surfaces have $\kappa_{\mathbb{C}P^2 \# k \overline{\mathbb{C}P^2}}^2 = 9 - k$ and $\kappa_{S^2 \times S^2}^2 = 8$, in light of which, in order for $\kappa_{X_1 \#_{F_1=F_2} X_2}^2$ to be zero, the unordered pair $\{X_1, X_2\}$ must be either $\{\mathbb{C}P^2 \# k \overline{\mathbb{C}P^2}, \mathbb{C}P^2 \# (18 - k) \overline{\mathbb{C}P^2}\}$ ($0 \leq k \leq 9$) or $\{S^2 \times S^2, \mathbb{C}P^2 \# 17 \overline{\mathbb{C}P^2}\}$. Note that since $[F_i] = -PD(\kappa_{X_i})$, F_i has intersection number 1 with each embedded symplectic (-1) -sphere in X_i . Choosing an almost complex structure J_i on X_i generic among those making F_i pseudoholomorphic, each homology class in X_i that is represented by an embedded symplectic (-1) -sphere will be represented by a J_i -holomorphic (-1) -sphere, which will then intersect F_i transversely and once. Blowing down such a

(-1) -sphere will then result in a symplectic manifold X'_i together with an embedded torus F'_i , with $[F'_i]^2 = [F_i]^2 + 1$.

Now according to Lemma 5.1 of [7] (respectively, Proposition 1.6 of [22]), if $(M_1, \omega_1), (M_2, \omega_2)$ are symplectic 4-manifolds containing surfaces Σ_1, Σ_2 of equal genus and area such that $[\Sigma_1]^2 + [\Sigma_2]^2 = 1$, and if $(\tilde{M}_i, \tilde{\Sigma}_i)$ denotes the pair consisting of a symplectic 4-manifold and symplectic surface that results from blowing up M_i at a point of Σ_i , then $\tilde{M}_1 \#_{\tilde{\Sigma}_1 = \Sigma_2} \tilde{M}_2$ is diffeomorphic (respectively, symplectic deformation equivalent) to $M_1 \#_{\Sigma_1 = \tilde{\Sigma}_2} \tilde{M}_2$.

Applying this to the cases under consideration enables us to replace the pair $\{\mathbb{C}P^2 \# k\overline{\mathbb{C}P^2}, \mathbb{C}P^2 \# (18 - k)\overline{\mathbb{C}P^2}\}$ ($0 \leq k \leq 9$) by $\{\mathbb{C}P^2 \# (k + 1)\overline{\mathbb{C}P^2}, \mathbb{C}P^2 \# (18 - k - 1)\overline{\mathbb{C}P^2}\}$ (since if $X_2 = \mathbb{C}P^2 \# (18 - k)$ where $k \leq 9$, X_2 contains (-1) -spheres meeting F_2 transversely once, any one of which may be blown down to give a torus of square one larger in $\mathbb{C}P^2 \# (18 - k - 1)\overline{\mathbb{C}P^2}$, and we may then apply Gompf's and McDuff-Symington's results mentioned above). Repeatedly "trading blowups" in this fashion enables us to reduce to the case that $k = 18 - k = 9$. Similarly, if $X_1 = S^2 \times S^2$, then $X_2 = \mathbb{C}P^2 \# 17\overline{\mathbb{C}P^2}$, so "trading blowups" once reduces us to the case that $X_1 = (S^2 \times S^2) \# \overline{\mathbb{C}P^2} = \mathbb{C}P^2 \# 2\overline{\mathbb{C}P^2}$ and $X_2 = \mathbb{C}P^2 \# 16\overline{\mathbb{C}P^2}$, and then doing so seven more times reduces to the case that $X_1 = X_2 = \mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$.

So we assume for the rest of this subsection that $X_1 = X_2 = \mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$. The X_i are then both diffeomorphic to the total space of a rational elliptic surface $E(1)$, and the F_i are homologous to a fiber of $E(1)$. In fact, we can make a stronger statement about the F_i ; we begin with the following lemma.

Lemma 3.2. *Let $B \subset \mathbb{C}^2$ be a closed ball around the origin, and let $\phi: B \rightarrow \mathbb{C}^2$ be an orientation preserving diffeomorphism onto a closed subset of \mathbb{C}^2 which maps $\{(w, z) \in B \mid z = 0\}$ orientation-preservingly to $\mathbb{C} \times \{0\}$. Then there is a diffeomorphism $\phi': B \rightarrow \phi(B)$ which is isotopic to ϕ by an isotopy which is the identity on a neighborhood of ∂B , such that ϕ' maps $\{(w, z) \in B \mid z = 0\}$ to $\mathbb{C} \times \{0\}$ and is holomorphic on a neighborhood of the origin.*

Proof. With respect to the splitting $\mathbb{R}^4 = \mathbb{C}^2 = \mathbb{R}^2 \times \mathbb{R}^2$, the Jacobian J of ϕ at the origin has the 2×2 block form $\begin{pmatrix} A & M \\ 0 & C \end{pmatrix}$. The orientation-preserving conditions ensure that A and J both have positive determinant, in light of which C also has positive determinant. Let $\chi: B \rightarrow [0, 1]$ be a smooth function which is equal to 1 on a neighborhood of the origin and to 0 on a neighborhood of ∂B . Let V_1 be the vector field on $B \subset \mathbb{R}^4$ whose value at $v \in B$ is $\chi(v) \begin{pmatrix} -\log A & 0 \\ 0 & -\log C \end{pmatrix} v$; by composing ϕ with the time-1 map of V_1 we reduce to the case where the Jacobian at the origin has form $\begin{pmatrix} I & A^{-1}M \\ 0 & I \end{pmatrix}$. Then where $V_2(v) = \chi(v) \begin{pmatrix} 0 & -A^{-1}M \\ 0 & 0 \end{pmatrix} v$ composing with the time-1 map of V_2 reduces us to the case that the Jacobian of ϕ at the origin is the identity. (Note that both V_1 and V_2 are tangent to $\mathbb{C} \times \{0\}$, so the condition that this set be preserved is not disturbed). But in this case there is a constant C (depending on the second derivatives of ϕ) such we have $|\phi(w, z) - (w, z)| \leq C(|w|^2 + |z|^2)$ and $|(D\phi)_{(w,z)} - I| \leq C(|w|^2 + |z|^2)^{1/2}$. Let $\beta: [0, \infty) \rightarrow [0, 1]$ be a smooth, monotone function such that $\beta(r) = 0$ for $r \leq 1/3$, $\beta(r) = 1$ for $r \geq 1$, and $\beta'(r) \leq 2$. Then if $\delta > 0$ defining

$$\phi'(w, z) = (w, z) + \beta((|w|^2 + |z|^2)^{1/2}/\delta)(\phi(w, z) - (w, z))$$

yields a smooth map which coincides with ϕ outside the ball of radius δ around the origin, is holomorphic in the ball of radius $\delta/3$ around the origin, and differs from ϕ in C^1 norm by at most $(3 + \delta)C\delta$ and therefore is a diffeomorphism as long as δ is taken small enough. Also, since ϕ preserves $\{z = 0\}$, ϕ' evidently does as well, and ϕ' is isotopic to ϕ by the isotopy $\phi + t(\phi' - \phi)$. \square

Lemma 3.3. *Let (M, ω) be a symplectic manifold obtained by blowing up $(\mathbb{C}P^2, \omega_{FS})$ at nine distinct points, and let $F \subset M$ be an embedded symplectic submanifold Poincaré dual to the anticanonical class $-\kappa_M$. Then there exists an elliptic fibration $\pi: E(1) \rightarrow S^2$ with no multiple fibers and a diffeomorphism $\Phi: M \rightarrow E(1)$ with the property that $\Phi(F)$ is a fiber of π .*

Proof. Let \tilde{J}_0 be an almost complex structure which makes F pseudoholomorphic. Provided that \tilde{J}_0 is chosen generically from among such almost complex structures, there are unique, embedded \tilde{J}_0 -holomorphic representatives E_1, \dots, E_9 , respectively, of the homology classes of the nine exceptional divisors of the blowup $M \rightarrow \mathbb{C}P^2$. Each of the E_i has a tubular neighborhood N_i modeled (symplectically) on a neighborhood of the zero section of the holomorphic line bundle $\mathcal{O}(-1)$ over $\mathbb{C}P^1$; we may shrink the N_i if necessary to make them pairwise disjoint. Now, for each i , the \tilde{J}_0 -holomorphic curves F and E_i have homological intersection number 1, so they meet transversely, positively, and in just one point. Hence as in Lemma 2.3 of [7], we may isotope F rel $M \setminus \cup N_i$ by symplectomorphisms to a surface F' such that, for some smaller neighborhoods N'_i of E_i , $F' \cap N'_i$ coincides with a fiber of the bundle projection $\mathcal{O}(-1) \rightarrow E_i$. Further, during this isotopy, we can change the almost complex structure \tilde{J}_0 to an almost complex structure \tilde{J} which agrees with \tilde{J}_0 outside N_i , makes F' holomorphic, and coincides on N'_i with the standard integrable complex structure on the tautological line bundle $\mathcal{O}(-1)$.

We now symplectically blow down the E_i (see Section 7.1 of [21] for a detailed description of this process); doing so amounts to symplectically identifying an annular neighborhood $L_i = D(\delta_{1,i}) \setminus D(\delta_{2,i}) \subset N'_i \subset \mathcal{O}(-1)$ of the zero section E_i with a spherical shell $B(r_{1,i}) \setminus B(r_{2,i})$ in \mathbb{C}^2 , and filling in this shell by a standard ball (centered at a point p_i with radius $r_{2,i}$) to replace the $\delta_{2,i}$ -neighborhood of E_i . This process is compatible with the complex blowdown in the sense that the annulus fibers of L_i are taken to annuli in the complex lines that they correspond to under the identification of $\mathcal{O}(-1)$ with the tautological line bundle of \mathbb{C}^2 , so in the blowdown these annuli may be filled in to form discs by adding in the disc of radius $r_{2,i}$ in the corresponding complex line. So since F' meets each L_i in one of these annulus fibers, filling these annuli in as above gives rise to a compact symplectic surface S whose intersection with each $B(r_{1,i})$ coincides with a complex line.

As a result of all this, blowing down the E_i results in $\mathbb{C}P^2$ equipped with an almost complex structure J which is integrable near each of the points p_i (and coincides with \tilde{J} outside the blow-up neighborhoods), a J -holomorphic curve $S \subset \mathbb{C}P^2$ which coincides with F' outside the blow-up neighborhoods, and a symplectic form ω' (induced by ω and the blowdown procedure) which is compatible with J . ω' is easily seen to be cohomologous to the Fubini-Study form (for instance, the proper transform of the hyperplane class under the original blowups that were done to obtain M from $\mathbb{C}P^2$ has a nonvanishing Gromov–Witten invariant, and so may be represented by a symplectic surface \tilde{H} which we can arrange to miss the L_i and so gives rise to a

symplectic surface in $(\mathbb{C}P^2, \omega')$ with the same area as \tilde{H} has in (M, ω) . Hence by a result of [10] ω' is symplectomorphic to the Fubini-Study form. Also, for a similar reason as above, $S \subset \mathbb{C}P^2$ has degree 3. So by Theorem 3 of [25], S is symplectically isotopic to some complex cubic curve C . The isotopy extension theorem then ensures that there is an ambient isotopy $\phi_t : \mathbb{C}P^2 \rightarrow \mathbb{C}P^2$ such that $\phi_1(S) = C$. Our intention now is to modify ϕ_1 to some other diffeomorphism ϕ_2 so that (i) $\phi_2(S) = C$, (ii) $\mathbb{C}P^2$ carries an elliptic pencil with fiber C and base locus $\{\phi_2(p_1), \dots, \phi_2(p_9)\}$, and (iii) ϕ_2 lifts to a diffeomorphism of the appropriate blowups which takes F' to the proper transform of C .

To achieve this, first note that since the sheaf of sections of the holomorphic normal bundle to C which vanish at the eight points $\phi_1(p_1), \dots, \phi_1(p_8)$ has degree 1, it admits global nonvanishing sections by Riemann-Roch; perturbing ϕ_1 by composing with a small diffeomorphism which preserves C we can arrange that $\phi_1(p_1), \dots, \phi_1(p_8)$ are generic in the sense that none of these sections vanishes to order 2. Such a section results in another smooth cubic C' which meets C transversely at the eight points $\phi_1(p_1), \dots, \phi_1(p_8)$, and also at some other point q_9 . Now let v be a vector field on C which vanishes on neighborhoods of the $\phi_1(p_i)$ for $1 \leq i \leq 8$ and whose time-1 flow maps $\phi_1(p_9)$ to q_9 . Using a partition of unity subordinate to a set of local trivializations of the normal bundle to C and a bump function supported on a tubular neighborhood of C , extend v to a vector field V on $\mathbb{C}P^2$ whose restriction to C is v ; let ψ be the time-1 flow of V , and let $\phi_0 = \psi \circ \phi_1$. Then $\phi_0 : \mathbb{C}P^2 \rightarrow \mathbb{C}P^2$ is a diffeomorphism which maps S to C and $p_1, \dots, p_9 \in S$ to the 9 intersection points between C and another smooth cubic C' .

Now ϕ_0 will not lift to a diffeomorphism on blowups, because it's not holomorphic near the points being blown up and so doesn't map complex lines to complex lines. However, around each p_i there are complex coordinates (w, z) in which S is given by $\{z = 0\}$ and likewise near each $\phi_0(p_i)$ there are complex coordinates in which C is given by $\{z = 0\}$. Hence, in terms of these local holomorphic coordinates, ϕ_0 is given in these neighborhoods by a diffeomorphism which satisfies the hypothesis of Lemma 3.2. So ϕ_0 may be modified by an isotopy supported in the union of these neighborhoods to an orientation-preserving diffeomorphism $\phi_2 : \mathbb{C}P^2 \rightarrow \mathbb{C}P^2$ which maps S to C and is holomorphic on (smaller) neighborhoods of p_1, \dots, p_9 . Consequently, if Y is the (complex) blowup of $(\mathbb{C}P^2, J)$ at the 9 points p_1, \dots, p_9 (which makes sense because J is integrable near the p_i), and if $E(1)$ is the complex blowup of $(\mathbb{C}P^2, J_{std})$ at $\phi_2(p_1), \dots, \phi_2(p_9)$, ϕ_2 lifts to a diffeomorphism $Y \rightarrow E(1)$ taking the proper transform of S to the proper transform of C . If f and f' are homogeneous cubic polynomials with vanishing loci C and C' respectively, the vanishing loci $C_{[\lambda:\mu]}$ of $\lambda f + \mu f'$ ($[\lambda:\mu] \in \mathbb{C}P^1$) provide an elliptic pencil on $\mathbb{C}P^2$ with base locus $\{\phi(p_1), \dots, \phi(p_9)\}$. Blowing up the base locus to form $E(1)$ thus gives an elliptic fibration with the proper transform of C as a fiber.

To compare Y to X , note that in order to put a symplectic form on the complex blowup Y in such a way that the map ϕ_2 lifts to Y we need to cut out balls B'_i around p_i that are smaller than the balls $B(r_{2,i})$ that were created by the blow-down $X \rightarrow \mathbb{C}P^2$. X and Y hence can't be symplectomorphic. However, there is an obvious diffeomorphism between the blowups corresponding to balls of different size which simply changes the radius of the disc bundle involved; in particular this diffeomorphism has a restriction to the neighborhood of the exceptional sphere which preserves the fibers of the normal bundle $\mathcal{O}(-1)$. Recalling that F' coincided with a

fiber of the normal bundle on the neighborhood N'_i it then follows that the natural diffeomorphism $X \rightarrow Y$ takes F' to the proper transform of S in Y .

We hence have a diffeomorphism $X \rightarrow E(1)$ which takes F' to the proper transform of C ; precomposing this with a symplectomorphism of X which isotopes F to F' gives us the promised map $\Phi: X \rightarrow E(1)$ taking F to a fiber of an elliptic fibration. \square

Corollary 3.4. *If the symplectic sum Z of two rational surfaces along a positive genus surface is a minimal symplectic four-manifold of Kodaira dimension zero, then Z is diffeomorphic to the K3 surface.*

Proof. Denote the two summands by X_i ($i = 1, 2$) and the surfaces in question by F_i . We've shown that we may assume that $X_i = \mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$ and that the F_i are tori Poincaré dual to $-PD(\kappa_{X_i})$. Hence by Lemma 3.3, we have $X_i \setminus \nu F_i \cong E(1) \setminus \nu F$ where $E(1)$ is the total space of a rational elliptic fibration having fiber F (and where " \cong " denotes diffeomorphism). Hence

$$Z \cong (E(1) \setminus \nu F) \cup_{\Phi} (E(1) \setminus \nu F)$$

for some orientation-reversing diffeomorphism Φ of the boundary $\partial(E(1) \setminus \nu F) = T^3$. But according to Proposition 1 of Appendice 4 of [11], every orientation preserving diffeomorphism of $\partial(E(1) \setminus \nu F)$ extends to $E(1) \setminus \nu F$, so the diffeomorphism type of $(E(1) \setminus \nu F) \cup_{\Phi} (E(1) \setminus \nu F)$ is independent of Φ . So since one choice of Φ (namely the one corresponding to taking the standard fiber sum of $E(1)$ with itself) gives rise to the K3 surface, Z is evidently diffeomorphic to the K3 surface independently of Φ . \square

3.2. Case 2: X_1 is rational and X_2 is irrational and ruled. Assume that X_2 is a ruled surface over a curve C of positive genus; we'll show shortly that C is a torus in the cases of interest. Then X_2 is symplectomorphic either to the nontrivial S^2 -bundle over C , which we denote $S^2 \tilde{\times} C$, or else $X_2 = (S^2 \times C) \# k\overline{\mathbb{C}P^2}$ for some $k \geq 0$. Suppose that X_1 is rational and $F_i \subset X_i$ ($i = 1, 2$) are embedded symplectic submanifolds with the property that the smoothly nontrivial symplectic sum $X_1 \#_{F_1=F_2} X_2$ is minimal and of Kodaira dimension zero. Then Theorem 3.1 shows that the F_i are tori Poincaré dual to $-\kappa_{F_i}$. In particular, if X_2 is nonminimal and J_2 is an almost complex structure preserving TF_2 , then each member of a maximal disjoint collection of embedded J_2 -holomorphic (-1) -spheres meets F_2 transversely and once; hence the results of [7] and [22] alluded to in the previous subsection show that, up to deformation equivalence, the symplectic sum is left unchanged if we simultaneously blow down each member of this maximal collection and blow up X_1 at a corresponding number of points on F_1 . This reduces us to the case that X_2 is minimal, and so is either $S^2 \times C$ or $S^2 \tilde{\times} C$.

Lemma 3.5. *Let $\pi: E \rightarrow C$ be an S^2 -bundle over a positive-genus surface C with symplectic form $\omega \in \Omega^2(E)$, and let $\Sigma \subset E$ be an embedded, connected, symplectic representative of $-PD(\kappa_E) \in H_2(E; \mathbb{Z})$, with tubular neighborhood $\nu\Sigma$. Then C is a torus and there is another bundle map $\pi': E \rightarrow C$ whose fibers are symplectic spheres such that $\pi'|_{E \setminus \nu\Sigma}$ defines a fiber bundle with fibers diffeomorphic to the annulus $S^1 \times I$.*

Proof. First, note that if J is an almost complex structure compatible with ω with respect to which Σ is pseudoholomorphic, and if \mathcal{M} is the moduli space of unparametrized pseudoholomorphic spheres representing the class of the fiber of π , then results of [19] show that the map $\pi': E \rightarrow \mathcal{M}$ which takes $e \in E$ to the point of

\mathcal{M} representing the unique J -holomorphic representative of the fiber class on which e lies is an S^2 -bundle with fibers homologous to the fibers of π ; fundamental group considerations then imply that \mathcal{M} has the same genus as C . By construction the fibers of π' are J -holomorphic and hence symplectic.

We now claim that Σ is isotopic to some surface $\Sigma' \subset E$ such that there is an almost complex structure J' which makes Σ' pseudoholomorphic and with respect to which $\pi': E \rightarrow \mathcal{M}$ is a pseudoholomorphic map (with respect to some almost complex structure on \mathcal{M}). Indeed, as in the proof of Lemma 3.2 of [16], using the parametrized Riemann mapping theorem we can find complex coordinates (z, w) on a suitable open set U_i of E centered around any critical point p_i of $\pi'|_{\Sigma}$ in terms of which the projection $\pi': E \rightarrow \mathcal{M}$ is given by $(z, w) \mapsto w$ and $\partial_{\bar{z}}$ lies in the J -antiholomorphic tangent space $T_J^{0,1}$. The intersection of Σ with this neighborhood will then be given by $\Sigma \cap U_i = \{w = g_i(z)\}$ where $g_i(z) = c_i z^{k_i} + O(|z|^{k_i+1})$ and $c_i \neq 0$; that $\pi'|_{\Sigma}$ has a critical point at $(0, 0)$ amounts to the statement that $k_i > 1$. Note that since Σ has intersection number 2 with the fibers of π' (as $[\Sigma] = -\kappa_E$ and the fibers are square-zero spheres), we in fact have $k_i = 2$, and moreover there can only be one critical point of $\pi'|_{\Sigma}$ in any given fiber of π' ; accordingly we can and do choose the U_i so that the $\pi'(U_i)$ are disjoint as i varies. We can then use a cutoff function supported in U_i and equal to 1 on some smaller neighborhood U'_i of the critical point p_i to isotope $\Sigma \text{ rel } U_i$ to some new surface Σ' whose intersection with U'_i is given by $\Sigma' \cap U'_i = \{w = c_i z^{k_i}\}$; further, using the same cutoff, we can isotope $J \text{ rel } U_i$ to a new almost complex structure J' which coincides with the standard integrable complex structure with holomorphic coordinates (z, w) on U'_i , and with respect to which both Σ' and the fibers of π' are J' -holomorphic. Repeating this near every critical point of $\pi'|_{\Sigma}$, Σ' and the fibers of π' are now J' -holomorphic and $\pi': E \rightarrow \mathcal{M}$ restricts to a pseudoholomorphic map on a neighborhood of $\text{Crit}(\pi'|_{\Sigma'})$ with respect to J' on E and a suitable complex structure on $\cup_i \pi'(U'_i) \subset \mathcal{M}$. But then extending this complex structure to all of \mathcal{M} , since $\pi'|_{\Sigma \setminus \cup_i U'_i}$ is an unbranched cover a simple patching argument may be used to further modify J' so that it continues to make Σ' pseudoholomorphic and now also makes the whole projection $\pi': E \rightarrow \mathcal{M}$ pseudoholomorphic. This proves the claim at the start of this paragraph.

But now $\pi'|_{\Sigma'}: \Sigma' \rightarrow \mathcal{M}$ is a holomorphic map from a torus to \mathcal{M} with degree 2; we know that \mathcal{M} has the same positive genus as C , so it follows that that genus is one. Hurwitz's formula then implies that $\pi'|_{\Sigma'}$ has no critical points; since the critical points of $\pi'|_{\Sigma'}$ were constructed to be just the same as those of $\pi'|_{\Sigma}$ it then follows that $\pi'|_{\Sigma}$ has no critical points. Thus Σ meets every fiber of π' transversely, and hence exactly twice by the positivity of intersections of J -holomorphic curves. Hence

$$\pi'|_{E \setminus \nu\Sigma}: E \setminus \nu\Sigma \rightarrow T^2$$

is a fibration with fiber given by the complement of two discs in S^2 , *i.e.*, by $S^1 \times I$. \square

Consequently, in all cases of interest, we have $X_2 = S^2 \times T^2$ or $X_2 = S^2 \tilde{\times} T^2$; these both have $c_1^2 = 0$, and so if $X_1 \#_{F_1=F_2} X_2$ is to be minimal of Kodaira dimension zero then $c_1^2(X_1) = 0$. Since the only rational surface with $c_1^2 = 0$ is $\mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$, evidently $X_1 = \mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$.

The above lemma makes the diffeomorphism classification of annulus bundles over T^2 relevant to us; specifically we are interested in those annulus bundles with orientable total space and having just one boundary component. Identify $S^1 \times I$ with

$A = \overline{D(2)} \setminus D(1/2) \subset \mathbb{C}$. Any annulus bundle over T^2 is isomorphic to one of the form $M(f, g; \{h_t\})$ where $f, g \in \pi_0(Diff(A))$ commute, $\{h_t\}_{t \in S^1} \in \pi_1(Diff(A))$,

$$M(f, g; \{1\}) = \frac{R^2 \times A}{(x+1, y, z) \sim (x, y, f(z)), (x, y+1, z) \sim (x, y, g(z))}$$

and $M(f, g; \{h_t\})$ is obtained from $M(f, g; \{1\})$ by removing a trivial neighborhood $D^2 \times A$ from $M(f, g; \{1\})$ and gluing it back by the map

$$\begin{aligned} \partial D^2 \times A &\rightarrow \partial D^2 \times A \\ (t, z) &\rightarrow (t, h_t(z)). \end{aligned}$$

Since changing the choice of basis $\{u, v\}$ of $H_1(T^2; \mathbb{Z})$ to, respectively, $\{u+v, v\}$ or $\{v, u\}$ corresponds to replacing (f, g) by $(f \circ g, g)$ or (g, f) , we can assume that f maps each respective boundary component of A to itself (if f doesn't initially, then either g or $f \circ g$ does). Now $\pi_0(Diff(A)) = \mathbb{Z}_2 \oplus \mathbb{Z}_2$, with generators given by $z \mapsto z^{-1}$ and $z \mapsto \bar{z}$.

We're interested in orientable annulus bundles over T^2 having just one boundary component. The orientability condition restricts us to the case that the monodromies f and g preserve the orientation of $A = \overline{D(2)} \setminus D(1/2)$. f is assumed to map each boundary component to itself, so this forces f to be isotopic to the identity. But then in order for the bundle to have just one boundary component g must swap the boundary components of A , forcing g to be isotopic to $z \mapsto z^{-1}$.

Now as explained after the statement of Theorem 2.3 in [28], it follows from a theorem of Smale that the identity component of $Diff(A)$ retracts to S^1 (and indeed the map $Diff_0(A) \rightarrow Diff_0(S^1)$ given by restriction to one boundary component is a homotopy equivalence), so $\pi_1(Diff(A))$ is generated by the loop of diffeomorphisms $r_t: A \rightarrow A$ where for $t \in S^1$ r_t is given by rotation through the angle t . Thus, any orientable annulus bundle over T^2 with one boundary component has form

$$Y_n = M(I, z \mapsto z^{-1}; \{r_t^n\})$$

In fact, arguing exactly as in Lemma 7 of Section 8 of [23], where $l, m \in \pi_1(\partial D^2 \times A)$ are, respectively, the generators of the images of the inclusion-induced maps $\pi_1(A) \rightarrow \pi_1(\partial D^2 \times A)$ and $\pi_1(\partial D^2) \rightarrow \pi_1(\partial D^2 \times A)$, one finds that for any $n \in \mathbb{Z}$ there is a fiber preserving diffeomorphism $Y_0 \setminus D^2 \times A \rightarrow Y_0 \setminus D^2 \times A$ whose restriction to the boundary $\partial D^2 \times A$ takes a representative of m to a representative of $m + 2nl$ (an explicit formula for such a diffeomorphism may easily be found by adapting the proof of Proposition 2(3) of [24] to the case where the fibers of the bundles involved are annuli rather than tori). Thus, every orientable annulus bundle over the torus having just one boundary component is isomorphic as a smooth fiber bundle to either Y_0 or Y_1 .

By definition, we have

$$(3) \quad Y_0 = S^1 \times \frac{\mathbb{R} \times A}{(x+1, z) \sim (x, z^{-1})}$$

Meanwhile, we see easily that

$$(4) \quad Y_1 = \frac{\mathbb{R} \times S^1 \times A}{(x+1, e^{i\theta}, z) \sim (x, e^{i\theta}, e^{i\theta} z^{-1})},$$

since the right hand side above obviously admits the structure of an annulus bundle and so by our earlier remarks is isomorphic either to Y_0 or to Y_1 ; computation of the fundamental group then shows that it is distinct from Y_0 .

Lemma 3.6. *Let $\pi: E \rightarrow T^2$ be an S^2 -bundle with symplectic form $\omega \in \Omega^2(E)$, and let $\Sigma \subset E$ be an embedded, connected, symplectic representative of $-PD(\kappa_E) \in H_2(E; \mathbb{Z})$, with tubular neighborhood $\nu\Sigma$. Then $E \setminus \nu\Sigma$ is diffeomorphic to Y_0 if and only if E is symplectomorphic to $S^2 \times T^2$ (with some split symplectic form).*

Proof. By Lemma 3.5, possibly after redefining π we may assume that π has symplectic fibers and that $\pi|_{\Sigma \setminus \nu\Sigma}$ defines an annulus bundle over T^2 .

For the forward implication, simply note that the annulus bundle Y_0 admits a section $(\theta, x) \mapsto [\theta, x, 1]$; if $E \setminus \nu\Sigma$ is diffeomorphic to Y_0 this section includes into E as a torus which intersects the fibers of $E \rightarrow T^2$ once transversely and which misses Σ . Now the total space of E is, by results of [19], symplectomorphic by a fiber-preserving map to the projectivization of a complex line bundle over T^2 of degree either 0 or 1; however, in the projectivization of a line bundle of degree 1 over the torus there are no homology classes having intersection number 1 with the fibers and 0 with the anticanonical class. Hence E must be the projectivization of the trivial complex line bundle over T^2 , *i.e.* $S^2 \times T^2$.

Conversely, suppose that E is symplectomorphic to $S^2 \times T^2$. As in Lemma 3.5, we can assume that Σ meets each fiber of $\pi: E \rightarrow T^2$ transversely twice. Now let $p: M \rightarrow S^2$ be a nontrivial S^2 -bundle over S^2 , and let $F \subset M$ be the disjoint union of a section of square -1 and a section of square 1 of p , each of which is symplectic with respect to some symplectic form on F which restricts nondegenerately to the fibers of π . Then by the pairwise sum construction in [7], the fiber sum E' of M and E carries a symplectic form and admits a symplectic torus Σ' obtained by gluing Σ to the section of square -1 in F at one of its intersection points with the fiber and to the section of square 1 in F at the other. Now the induced S^2 -fibration $\pi': E' \rightarrow T^2$ on the fiber sum is easily seen to admit sections of odd square (glue a section of even square in E to a section of odd square in M), so E' is diffeomorphic to the nontrivial S^2 -bundle over T^2 . Hence by the previous paragraph $E' \setminus \nu\Sigma'$ is not diffeomorphic to Y_0 , so it is diffeomorphic to Y_1 .

Now M is diffeomorphic to $\mathbb{C}P^2 \# \overline{\mathbb{C}P^2}$; the complement $M \setminus \nu F$ of a neighborhood of the disjoint union F of a section of square 1 and a section of square -1 is then diffeomorphic to the complement of a neighborhood of the union of a point and a line in $\mathbb{C}P^2$, *i.e.* to a region $\{(z, w) \in \mathbb{C}P^2 \mid r \leq |z|^2 + |w|^2 \leq R\}$ in \mathbb{C}^2 . In these terms, $\pi|_{M \setminus \nu F}: M \setminus \nu F \rightarrow \mathbb{C}P^1$ is the Hopf map $(z, w) \mapsto [z : w]$. This shows that the annulus fibration $p|_{M \setminus \nu F}: M \setminus \nu F \rightarrow S^2$ is obtained from the trivial annulus fibration over S^2 by removing the neighborhood of a fiber and regluing it by the diffeomorphism $(e^{i\theta}, z) \mapsto (e^{i\theta}, e^{i\theta}z)$ of $\partial D^2 \times A$.

But the annulus fibration $\pi': E' \setminus \nu\Sigma' \rightarrow T^2$ is obtained by taking the fiber sum of $\pi: E \setminus \nu\Sigma \rightarrow T^2$ with $p: M \setminus \nu F \rightarrow S^2$, so this implies that $\pi': E' \setminus \nu\Sigma' \rightarrow T^2$ may be constructed from $\pi: E \setminus \nu\Sigma \rightarrow T^2$ by removing the neighborhood of a fiber and regluing it by the diffeomorphism $(e^{i\theta}, z) \mapsto (e^{i\theta}, e^{i\theta}z)$ of $\partial D^2 \times A$. Now performing this operation on the annulus bundle Y_0 yields Y_1 , while performing it on Y_1 yields $Y_2 \cong Y_0$. So since we've already established that $E' \setminus \nu\Sigma'$ is diffeomorphic to Y_1 , it must be that $E \setminus \nu\Sigma$ is diffeomorphic to Y_0 . \square

Theorem 3.7. *Let X be an S^2 -bundle over T^2 , let $F \subset X$ be an embedded symplectic representative of $-PD(\kappa_X)$, and let $F' \subset E(1)$ be an embedded symplectic representative of $-PD(\kappa_{E(1)})$. Then the symplectic sum $E(1) \#_{F'=F} X$ is diffeomorphic to the Enriques surface.*

Proof. First, we notice that we can reduce to the case that X is symplectomorphic to $S^2 \times T^2$ (with some split symplectic form). Indeed, if X is instead diffeomorphic to the nontrivial S^2 -bundle over T^2 , we shall twice apply the result of [7] and [22] which allows us to “trade blowups” as discussed in Case 1. First, if (M_1, F_1) is the result of blowing down a (-1) -sphere passing once positively and transversely through F' (to find such a sphere, use an almost complex structure preserving TF' to evaluate the Gromov–Witten invariant of one of the classes of the exceptional spheres of $E(1) = \mathbb{C}P^2 \# 9\overline{\mathbb{C}P^2}$) and if $(M_2, F_2) = (X, F)$, we see that $E(1) \#_{F'=F} X$ is deformation equivalent to $M_1 \#_{F_1=\tilde{F}_2} \tilde{M}_2$. Now the ruling $X \rightarrow T^2$ induces a genus-0 (not relatively minimal) Lefschetz fibration $\pi: \tilde{M}_2 \rightarrow T^2$ each of whose fibers meets the symplectic square- (-1) torus \tilde{F}_2 twice; π has just one singular fiber, whose components C_1 and C_2 are two embedded (-1) -spheres (one of which, say C_1 , is the exceptional sphere of the blowup, and the other of which is the proper transform of the fiber of $X \rightarrow S^2$ that passes through the blown-up point), each of which intersects \tilde{F}_2 once. Now blowing down C_2 produces a manifold symplectomorphic to $S^2 \times T^2$, and $\tilde{F}_2 \subset M_2$ is isotopic to the proper transform of a symplectic representative F'' of $-PD(\kappa_{S^2 \times T^2})$. Hence $M_1 \#_{F_1=\tilde{F}_2} \tilde{M}_2$ is in turn deformation equivalent to $\tilde{M}_1 \#_{\tilde{F}_1=F''}(S^2 \times T^2)$. Since $(\tilde{M}_1, \tilde{F}_1)$ is obtained by first blowing down a sphere passing once positively and transversely through $F' \subset E(1)$ and then blowing up a point on the image of F' under the blowdown, it follows that \tilde{M}_1 is deformation equivalent to $E(1)$ and \tilde{F}_1 represents $-PD(\kappa_{\tilde{M}_1})$. This allows us to hereinafter assume that $X = S^2 \times T^2$.

By Lemma 3.3, $E(1) \setminus \nu F'$ is diffeomorphic to the manifold with boundary N obtained by deleting a neighborhood of a regular fiber of an elliptic fibration on $E(1)$, while $X \setminus \nu F$ is, by Lemma 3.6 and our reduction to the case that $X = S^2 \times T^2$, diffeomorphic to Y_0 .

So the symplectic sum in question is diffeomorphic to

$$X_0 = N \cup_{\partial} Y_0;$$

note that since by Proposition 1 of Appendice 4 of [11] every orientation preserving diffeomorphism of ∂N extends to N , the diffeomorphism type of X_0 is determined independently of the boundary gluing maps.

We claim now that X_0 is diffeomorphic to the Enriques surface. In fact, this is essentially a remark on p. 50 of [11]; for a direct proof, recall that $Y_0 = S^1 \times Z_0$ where $Z_0 = \mathbb{R} \times A/(x+1, z) \sim (x, z^{-1})$. Now projecting Z_0 onto its *second* factor gives Z_0 the structure of a Seifert fibration over D^2 with two multiple fibers each having multiplicity 2; hence $Y_0 = S^1 \times Z_0$ is the result of performing two multiplicity two logarithmic transformations on the trivial elliptic fibration $T^2 \times D^2$. Thus $X_0 = N \cup_{\partial} Y_0$ is obtained from $E(1)$ by deleting a neighborhood of a smooth fiber and replacing that neighborhood with the result of two multiplicity two logarithmic transformations on $T^2 \times D^2$, *i.e.*, X_0 is obtained from $E(1)$ by performing two multiplicity-two logarithmic transformations. But this is precisely the definition of the Enriques surface. □

3.3. Case 3: X_1 and X_2 are irrational and ruled. Since a k -fold blowup of an S^2 -bundle over a surface of genus h has $c_1^2 = 8 - 8h - k$, in order for the symplectic sum of irrational ruled surfaces X_1 and X_2 along a torus to have $c_1^2 = 0$, both X_1

and X_2 must be S^2 -bundles over T^2 . By Theorem 3.1, the surfaces F_i are embedded symplectic tori representing $-PD(\kappa_{X_i})$. As in the proof of Lemma 3.5, results of [19] imply that there are projections $\pi_i: X_i \rightarrow T^2$ such that $\pi_i|_{F_i}$ is an unramified double cover of T^2 by F_i ; the deck transformation of this cover is then a free orientation-preserving involution $\tau_i: F_i \rightarrow F_i$. By considering these involutions, we shall realize any symplectic sum of the X_i along the F_i as the total space of some torus bundle over T^2 .

Lemma 3.8. *Let $\tau_1, \tau_2: T^2 \rightarrow T^2$ be free orientation-preserving involutions, and let $\phi: T^2 \rightarrow T^2$ be any diffeomorphism. Then ϕ is isotopic to a diffeomorphism $\phi': T^2 \rightarrow T^2$ with the property that*

$$\phi'^{-1} \circ \tau_2 \circ \phi' \circ \tau_1 \text{ is either the identity or a free involution.}$$

Proof. First of all, note that any two free orientation-preserving involutions $\tau, \tau': T^2 \rightarrow T^2$ are conjugate. Indeed, letting E be the quotient of T^2 by τ , E' the quotient of T^2 by τ' , and $\pi: T^2 \rightarrow E, \pi': T^2 \rightarrow E'$ the projections, E and E' are both tori, so that there exists a diffeomorphism $\psi: E \rightarrow E'$. The images of $\pi_1(T^2)$ in $\pi_1(E')$ by π' and $\psi \circ \pi$ are both index 2 lattices in $\pi_1(E') \cong \mathbb{Z}^2$, so there is an element A of $SL(2; \mathbb{Z})$ taking one to the other; hence by composing ψ with a diffeomorphism of E' that induces A on π_1 we can assume that the maps induced on π_1 by π' and by $\psi \circ \pi$ have the same image. Hence $\psi \circ \pi: T^2 \rightarrow E'$ lifts to a diffeomorphism $f: T^2 \rightarrow T^2$ such that $\pi' \circ f = \psi \circ \pi$. Since τ (resp. τ') takes $x \in T^2$ to the unique other point in $\pi^{-1}(\pi(x))$ (resp. $\pi'^{-1}(\pi'(x))$) it follows that $\tau' \circ f = f \circ \tau$, so τ' and τ are indeed conjugate.

In light of this, identifying $T^2 = \mathbb{R}^2/\mathbb{Z}^2$ and conjugating τ_1, τ_2, ϕ by some diffeomorphism, we can assume that $\tau_1([x, y]) = [x + 1/2, y]$ (where $[x, y] \in T^2$ is the equivalence class of $(x, y) \in \mathbb{R}^2$ under the relations $(x + 1, y) \sim (x, y + 1) \sim (x, y)$). By the previous paragraph, since $\phi^{-1} \circ \tau_2 \circ \phi$ and τ_1 are free involutions, there is some $\alpha \in Diff(T^2)$ such that $\phi^{-1} \circ \tau_2 \circ \phi = \alpha^{-1} \circ \tau_1 \circ \alpha$. Now α is isotopic to some linear diffeomorphism $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2; \mathbb{Z})$; say $A = \alpha \circ f_1$ where $\{f_t\}_{t \in [0, 1]}$ is a smooth family of diffeomorphisms such that $f_0 = 1$. Then where $\phi' = \phi \circ f_1$, ϕ is isotopic to ϕ' and we have $\phi'^{-1} \circ \tau_2 \circ \phi' = A^{-1} \circ \tau_1 \circ A$.

Now since $\tau_1([x, y]) = [x + 1/2, y]$, one easily computes

$$A^{-1} \circ \tau_1 \circ A \circ \tau_1([x, y]) = \left[x + \frac{d+1}{2}, y - \frac{c}{2} \right],$$

which defines the identity if c is even (forcing d to be odd since $A \in SL(2; \mathbb{Z})$) and a free involution if c is odd. \square

Theorem 3.9. *Let $\pi_i: X_i \rightarrow T^2$ ($i = 1, 2$) be S^2 -bundles over T^2 , $F_i \subset X_i$ embedded tori with the property that $\pi_i|_{F_i}$ is an unramified double cover. Let ν_i be tubular neighborhoods of F_i (each identified with $D^2 \times F_i$), and let $\Phi: \partial\nu_1 \rightarrow \partial\nu_2$ be a diffeomorphism which (viewing $\partial\nu_i$ as an S^1 -bundle over F_i) covers some diffeomorphism $\phi: F_1 \rightarrow F_2$. Then the normal connect sum*

$$(X_1 \setminus \nu_1) \cup_{\partial\nu_1 \sim_{\Phi} \partial\nu_2} (X_2 \setminus \nu_2)$$

is diffeomorphic to the total space of a T^2 -bundle over T^2 .

Proof. First, note that (after performing isotopies which don't change the diffeomorphism type of the normal connect sum), we can assume that, for $i = 1, 2$, the S^2 -bundle projection π_i is constant on each fiber of the disc bundle projection $\nu_i \rightarrow F_i$, and that (using Lemma 3.8) $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ is either the identity or a free involution, where $\tau_i: F_i \rightarrow F_i$ is the deck transformation induced by the cover $\pi_i|_{F_i}$. Let $Z = (X_1 \setminus \nu_1) \cup_{\partial\nu_1 \sim_{\Phi} \partial\nu_2} (X_2 \setminus \nu_2)$.

Suppose that $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ is the identity. We define a bundle map $\pi: Z \rightarrow T^2$ as follows. If $x \in X_1 \setminus \nu_1 \subset Z$, put $\pi(x) = \pi_1(x)$. If $x \in X_2 \setminus \nu_2 \subset Z$, then there are two points $x_2, \tau_2(x_2) \in F_2 \cap \pi_2^{-1}(\{\pi_2(x)\})$, and since $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ is the identity we have $\tau_1(\phi^{-1}(x_2)) = \phi^{-1}(\tau_2(x_2))$, so that $\pi_1(\phi^{-1}(x_2)) = \pi_1(\phi^{-1}(\tau_2(x_2)))$ and we set

$$\pi(x) = \pi_1(\phi^{-1}(x_2)) = \pi_1(\phi^{-1}(\tau_2(x_2))).$$

Since, for each $p \in F_i$, the fiber of the circle bundle $\partial\nu_i \rightarrow F_i$ over p is mapped by π_i to $\pi_i(p)$, our map π is defined consistently on the identified boundary components $\partial\nu_1, \partial\nu_2$ in $Z = (X_1 \setminus \nu_1) \cup_{\partial\nu_1 \sim_{\Phi} \partial\nu_2} (X_2 \setminus \nu_2)$. One easily sees that $\pi: Z \rightarrow T^2$ is a T^2 -fibration; the point here is that since $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1 = 1$, $\phi: F_1 \rightarrow F_2$ descends to a map $f: T^2 \rightarrow T^2$ such that $\pi_2|_{F_2} \circ \phi = f \circ \pi_1|_{F_1}$; the fiber of π over $t \in T^2$ is formed by gluing the annulus $\pi_1^{-1}(\{t\}) \cap (X_1 \setminus \nu_1)$ to the annulus $\pi_2^{-1}(\{f(t)\}) \cap (X_2 \setminus \nu_2)$.

It remains to consider the case that $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ is a free involution. Then $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ commutes with τ_1 and their composition (namely $\phi^{-1} \circ \tau_2 \circ \phi$) is also a free involution. Let $E = F_1 / \langle \tau_1, \phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1 \rangle$ and let $p: F_1 \rightarrow E$ be the projection (which is an unramified quadruple covering of a torus by a torus). We shall define a torus fibration $\pi: Z \rightarrow E$ rather similarly to the previous case, except that here the fibers will be formed by gluing four annuli rather than two. If $x \in X_1 \setminus \nu_1 \subset Z$, set $\pi(x) = p(x_1)$ where $x_1 \in F_1 \cap \pi_1^{-1}(\{\pi_1(x)\})$; this is a coherent definition since the two elements of $\pi_1^{-1}(\{\pi_1(x)\})$ are intertwined by τ_1 . If $x \in X_2 \setminus \nu_2 \subset Z$, we intend to set $\pi(x) = p(\phi^{-1}(x_2))$ where $x_2 \in F_2 \cap \pi_2^{-1}(\{\pi_2(x)\})$; we need to see that the two possible choices of x_2 (either of which is taken to the other by τ_2) give the same value for $p(x)$. In other words, we need to check that if $x_2 \in F_2$ then $p(\phi^{-1}(x_2)) = p(\phi^{-1}(\tau_2(x_2)))$. Now since $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ has order 2,

$$\phi^{-1}(\tau_2(\phi(\tau_1(\phi^{-1}(x_2)))))) = \tau_1(\phi^{-1}(\tau_2(x_2)))$$

so since E is the quotient of F_1 by τ_1 and $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ it is indeed the case that $p(\phi^{-1}(x_2)) = p(\phi^{-1}(\tau_2(x_2)))$ for each $x_2 \in F_2$. We have thus defined $\pi: Z \rightarrow E$; it is again easily seen to be a torus bundle, with its fibers of the shape

$$\frac{A_0 \amalg A_1 \amalg A_2 \amalg A_3}{\partial_+ A_i \sim \partial_- A_{i+1} (i \in \mathbb{Z}/4\mathbb{Z})}$$

where A_0 and A_2 are annulus fibers of $\pi_2|_{X_2 \setminus \nu_2}$ and A_1 and A_3 are annulus fibers of $\pi_1|_{X_1 \setminus \nu_1}$ (the fact that $\phi^{-1} \circ \tau_2 \circ \phi \circ \tau_1$ is free serves to ensure that, in each of these torus fibers, A_0 and A_2 are distinct, as are A_1 and A_3). \square

This shows that any symplectic 4-manifold obtained as the symplectic sum of two S^2 -bundles over T^2 along a pair of bi-sections is diffeomorphic to a T^2 -bundle over T^2 . In fact, we can be quite specific about which T^2 -bundles over T^2 are obtained in this fashion. T^2 -bundles over T^2 were classified in [24]; in particular, Theorem 5 of that paper shows that the total spaces of such bundles are distinguished from one another up to diffeomorphism by their fundamental groups. As such, finding the

diffeomorphism type of the manifold $(X_1 \setminus \nu_1) \cup_{\partial\nu_1 \sim_{\Phi} \partial\nu_2} (X_2 \setminus \nu_2)$ in Theorem 3.9 is just a matter of applying van Kampen's theorem.

We know that, for $i = 1, 2$, the manifold $X_i \setminus \nu_i$ is diffeomorphic to one of the manifolds Y_0 or Y_1 of (3),(4); more specifically, if X_i is diffeomorphic to $S^2 \times T^2$ then $X_i \setminus \nu_i \cong Y_0$, and otherwise $X_i \setminus \nu_i \cong Y_1$. Note that

$$(5) \quad \pi_1(Y_j) = \frac{\langle \alpha, \beta, m \rangle}{\alpha^{-1}m\alpha = m^{-1}, \beta m = m\beta, \alpha\beta\alpha^{-1}\beta^{-1} = m^j} \quad (j = 0, 1),$$

with ∂Y_j being spanned by the subgroup generated by α^2, β, m . m here is the generator of the fundamental group of the annulus fiber of the bundle map $Y_j \rightarrow T^2$. Where F denotes the torus F_1 or F_2 whose neighborhood we have removed from X_1 or X_2 to get Y_j , we have a trivial circle bundle $p_j: \partial Y_j \rightarrow F$ whose action on π_1 has kernel $\langle m \rangle$. There is, of course, some flexibility in the choice of the generators: first, we get the same presentation if we replace β by βm^j and then m by m^{-1} ; secondly, if $\begin{pmatrix} p & q \\ r & s \end{pmatrix} \in SL(2, \mathbb{Z})$ and q is even (so that p and s are odd; say $s = 2t + 1$), then we get the same presentation by replacing α with $\alpha' = \alpha^p \beta^r$ and β with $\beta' = \alpha^q \beta^s m^{jt}$. One convenient consequence of this is that if $\gamma \in \pi_1(\partial Y_j)$ is any element with the property that $(p_j)_* \gamma$ is primitive in $\mathbb{Z}^2 = \pi_1(F)$ then the generators α, β in the presentation (5) may be chosen so that γ takes one of the forms

$$\gamma = \alpha^2 \beta^{2c} m^e \text{ or } \gamma = \alpha^{2a} \beta m^e.$$

We now consider the manifold resulting from gluing two of these manifolds Y_j, Y_k ($j, k \in \{0, 1\}$) together along their boundaries in a way consistent with the symplectic sum operation. Now in terms of bases $\{\alpha_1^2, \beta_1, m_1\}, \{\alpha_2^2, \beta_2, m_2\}$ for the fundamental groups of the boundaries ∂Y_j and ∂Y_k respectively, since the gluing map Φ is required to cover an isomorphism of the normal bundles it will identify m_1 with m_2 (possibly after replacing one of the m_i with its inverse, which as mentioned earlier can be done without affecting the presentation (5) at the cost of possibly multiplying β_i by m_i); also α_1^2 , since it projects via p_j to a primitive element in $\pi_1(F)$, will be taken to some element in the fundamental group of ∂Y_k which likewise projects via p_k to a primitive element. Hence by the remark at the end of the previous paragraph, possibly after renaming the generators α_2, β_2 , and m_2 in the presentation of $\pi_1(Y_k)$, the action of the gluing map on the fundamental groups of the boundaries in terms of the bases $\{\alpha_i^2, \beta_i, m_i\}$ takes one of the forms

$$\begin{pmatrix} 1 & b & 0 \\ 2c & d & 0 \\ e & f & 1 \end{pmatrix} (d - 2bc = 1) \text{ or } \begin{pmatrix} a & b & 0 \\ 1 & d & 0 \\ e & f & 1 \end{pmatrix} (ad - b = 1).$$

Hence van Kampen's theorem gives the fundamental group of the glued manifold $Y_j \cup_{\Phi} Y_k$ as either

$$(6) \quad \pi_1(Y_j \cup_{\Phi} Y_k) = \frac{\langle \alpha_1, \beta_1, \alpha_2, \beta_2, m \rangle}{\alpha_1^{-1}m\alpha_1 = \alpha_2^{-1}m\alpha_2 = m^{-1}, \beta_1 m = m\beta_1, \beta_2 m = m\beta_2, \alpha_1 \beta_1 \alpha_1^{-1} \beta_1^{-1} = m^j, \alpha_2 \beta_2 \alpha_2^{-1} \beta_2^{-1} = m^k, \alpha_1^2 = \alpha_2^2 \beta_2^{2c} m^e, \beta_1 = \alpha_2^{2b} \beta_2^d m^f}$$

or

(7)

$$\pi_1(Y_j \cup_{\Phi} Y_k) = \frac{\langle \alpha_1, \beta_1, \alpha_2, \beta_2, m \rangle}{\alpha_1^{-1} m \alpha_1 = \alpha_2^{-1} m \alpha_2 = m^{-1}, \beta_1 m = m \beta_1, \beta_2 m = m \beta_2, \alpha_1 \beta_1 \alpha_1^{-1} \beta_1^{-1} = m^j, \alpha_2 \beta_2 \alpha_2^{-1} \beta_2^{-1} = m^k, \alpha_1^2 = \alpha_2^{2a} \beta_2 m^e, \beta_1 = \alpha_2^{2b} \beta_2^d m^f}$$

The reader may verify that the group on the right hand side of (6) may be rewritten, by identifying $\gamma = \alpha_1^{-1} \alpha_2 \beta_2^c$, as

$$\frac{\langle \alpha_1, \beta_2, m, \gamma \rangle}{m\gamma = \gamma m, \alpha_1 \beta_2 \alpha_1^{-1} \beta_2^{-1} = m^{j+2(f-be)}, \alpha_1^{-1} m \alpha_1 = m^{-1}, \alpha_1^{-1} \gamma \alpha_1 = m^{kc-e} \gamma^{-1}, \beta_2^{-1} m \beta_2 = m, \beta_2^{-1} \gamma \beta_2 = m^{j-k+2(f-be)} \gamma}$$

which we recognize as the fundamental group of the T^2 -bundle over T^2 given in the notation of the introduction as

$$M \left(\left(\begin{array}{cc} -1 & kc - e \\ 0 & -1 \end{array} \right), \left(\begin{array}{cc} 1 & j - k + 2(f - be) \\ 0 & 1 \end{array} \right); \left(\begin{array}{c} j + 2(f - be) \\ 0 \end{array} \right) \right).$$

Similarly, the group on the right hand side of (7) may be identified, by taking $\sigma = \alpha_1 \alpha_2 \alpha_1^{-1} \alpha_2^{-1}$ and then using the relations $\alpha_1 \alpha_2^2 = \alpha_2^2 \alpha_1 m^{j+2(f-de)}$ and $\alpha_2 \alpha_1^2 = \alpha_1^2 \alpha_2 m^{2e-k}$ to obtain commutation relations between the α_i and σ , as

$$\frac{\langle \alpha_1, \alpha_2, m, \sigma \rangle}{m\sigma = \sigma m, \alpha_1 \alpha_2 \alpha_1^{-1} \alpha_2^{-1} = \sigma, \alpha_1^{-1} m \alpha_1 = m^{-1}, \alpha_1^{-1} \sigma \alpha_1 = m^{k-2e} \sigma^{-1}, \alpha_2^{-1} m \alpha_2 = m^{-1}, \alpha_2^{-1} \sigma \alpha_2 = m^{j+2(f-de)} \sigma^{-1}}$$

which is precisely the fundamental group of the T^2 -bundle over T^2

$$M \left(\left(\begin{array}{cc} -1 & k - 2e \\ 0 & -1 \end{array} \right), \left(\begin{array}{cc} -1 & j + 2(f - de) \\ 0 & -1 \end{array} \right); \left(\begin{array}{c} 0 \\ 1 \end{array} \right) \right).$$

Now by changing the basis for the homology of the base by $\begin{pmatrix} p & q \\ r & s \end{pmatrix} \in SL(2; \mathbb{Z})$, a T^2 -bundle over T^2 of form $M(A, B; \vec{v})$ may be equated with $M(A^p B^r, A^q B^s; \vec{v})$; also, the bundles $M(A, B; \vec{v})$ and $M(A, B; \vec{v}')$ are equivalent if $\vec{v}' - \vec{v}$ lies in the submodule of \mathbb{Z}^2 spanned by the columns of $A - I$ and $B - I$ (where I is the identity; these statements are proven in Proposition 2 of [24]). As such, given a bundle of form

$$M \left(\left(\begin{array}{cc} -1 & \delta \\ 0 & -1 \end{array} \right), \left(\begin{array}{cc} 1 & \zeta \\ 0 & 1 \end{array} \right); \left(\begin{array}{c} j + 2x \\ 0 \end{array} \right) \right),$$

by letting $z = \gcd(\delta, \zeta)$, $p = \zeta/z$, $r = \delta/z$, and (since p and r are then relatively prime) q and s be such that $ps - qr = 1$, so that $-q\delta + s\zeta = z$, we obtain

$$M \left(\left(\begin{array}{cc} -1 & \delta \\ 0 & -1 \end{array} \right), \left(\begin{array}{cc} 1 & \zeta \\ 0 & 1 \end{array} \right); \left(\begin{array}{c} j + 2x \\ 0 \end{array} \right) \right) = M \left((-1)^p I, (-1)^q \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix}; \left(\begin{array}{c} j \\ 0 \end{array} \right) \right)$$

(note also that p and q can't both be even since $ps - qr = 1$, and if p is odd then a further basis change for the homology of the base identifies $M(-I, -A; \vec{v})$ with $M(-I, A; \vec{v})$). This gives rise to the following list of possibilities for the diffeomorphism type of $Y_j \cup_{\Phi} Y_k$ when its fundamental group is given by (6):

j	k	possible diffeomorphism types of $Y_j \cup_{\Phi} Y_k$
0	0	$M\left(I, \begin{pmatrix} -1 & z \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix}\right), M\left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix}\right) (y, z \in \mathbb{Z})$
0	1	$M\left(-I, \begin{pmatrix} 1 & 2y+1 \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 0 \end{pmatrix}\right) (y \in \mathbb{Z})$
1	1	$M\left(I, \begin{pmatrix} -1 & z \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}\right), M\left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}\right) (y, z \in \mathbb{Z})$

Similarly, a bundle of form

$$M\left(\begin{pmatrix} -1 & \delta \\ 0 & -1 \end{pmatrix}, \begin{pmatrix} -1 & \zeta \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right)$$

is equivalent to

$$M\left((-1)^{p+r}I, (-1)^{q+s} \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right)$$

(where $z = \gcd(\delta, \zeta)$, $p = \zeta/z$, $r = -\delta/z$, and $ps - qr = 1$). From this, we deduce the following list of possibilities for the diffeomorphism type of $Y_j \cup_{\Phi} Y_k$ when its fundamental group is given by (7):

j	k	possible diffeomorphism types of $Y_j \cup_{\Phi} Y_k$
0	0	$M\left(I, \begin{pmatrix} -1 & 2y \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right), M\left(-I, \begin{pmatrix} 1 & 2y \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right) (y \in \mathbb{Z})$
0	1	$M\left(-I, \begin{pmatrix} 1 & 2y+1 \\ 0 & 1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right) (y \in \mathbb{Z})$
1	1	$M\left(I, \begin{pmatrix} -1 & 2y+1 \\ 0 & -1 \end{pmatrix}; \begin{pmatrix} 0 \\ 1 \end{pmatrix}\right) (y \in \mathbb{Z})$

In both of the above tables, it's easy to see that any of the indicated diffeomorphism types can in fact be realized by means of an appropriate choice of the gluing map Φ . Since if X is a ruled surface over T^2 and $F \subset X$ is an embedded representative of $-PD(\kappa_X)$, we've seen that $X \setminus \nu F \cong Y_0$ if $X = S^2 \times T^2$ and $X \setminus \nu F \cong Y_1$ if $X = S^2 \tilde{\times} T^2$, this completes the proof that the diffeomorphism types of the symplectic sums in question are as claimed in the introduction.

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DEPARTMENT OF MATHEMATICS, PRINCETON UNIVERSITY, PRINCETON, NJ 08540
E-mail address: musher@math.princeton.edu