ON FOLIATIONS WITH NEF ANTI-CANONICAL BUNDLE

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Abstract. In this paper we prove that the anti-canonical bundle of a holomorphic foliation \( \mathcal{F} \) on a complex projective manifold cannot be nef and big if either \( \mathcal{F} \) is regular, or \( \mathcal{F} \) has a compact leaf. Then we address codimension one regular foliations whose anti-canonical bundle is nef with maximal Kodaira dimension.

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1. Introduction

In the last few decades, much progress has been made in the classification of complex projective varieties. The general viewpoint is that complex projective manifolds \( X \) should be classified according to the behavior of their canonical class \( K_X \). Similar ideas can be applied in the context of foliations on complex projective manifolds. If \( \mathcal{F} \subset T_X \) is a foliation on a complex projective manifold, we define its canonical class to be \( K_\mathcal{F} = -c_1(\mathcal{F}) \). In analogy with the case of projective manifolds, one expects the numerical properties of \( K_\mathcal{F} \) to reflect geometric aspects of \( \mathcal{F} \) (see for instance [Dru04], [LPT11], [AD13], [AD14a], [AD14b]).

In [PS14], Popa and Schnell proved that the canonical bundle of a codimension one regular foliation with trivial normal bundle cannot be big. In this paper we propose to investigate regular foliations on complex projective manifolds with \( -K_\mathcal{F} \) nef. Codimension one regular foliations with trivial canonical bundle were classified by Touzet in [Tou08]. More recently, Pereira and Touzet have investigated regular foliations \( \mathcal{F} \) of arbitrary rank on complex projective manifolds with \( c_1(\mathcal{F}) = 0 \) and \( c_2(\mathcal{F}) = 0 \).

In [Miy93, Theorem 2], Miyaoka proved that the anticanonical bundle of a smooth projective morphism \( f : X \to C \) onto a smooth proper curve cannot be ample. In [Zha96, Proposition 1] (see also [Deb01, Theorem 3.12]), this result was generalized by dropping the smoothness assumption on \( f \). In this note, we give a further generalization of this result to foliations (see also Theorem 7.1).

Theorem 1.1. Let \( X \) be a complex projective manifold, and let \( \mathcal{F} \subset T_X \) be a codimension \( q \) foliation with \( 0 < q < \dim X \). Suppose that either \( \mathcal{F} \) is regular, or that \( \mathcal{F} \) has a compact leaf. Then \( -K_\mathcal{F} \) is not nef and big.

In [AD14a, Theorem 1.5], the authors proved that the anti-canonical bundle of a codimension one foliation on a complex projective manifold whose singular set has codimension \( \geq 3 \) cannot be nef and big.

The following example show that the statement of Theorem 1.1 becomes wrong if one relaxes the assumption on \( K_\mathcal{F} \).

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Example 1.2. Fix an integer \( m \) such that \( m \geq 2 \). Let \( A \) be an abelian variety with \( \dim A \geq 1 \), and let \( L \) be an ample line bundle on \( A \). Set \( X := \mathbb{P}(L \oplus L^\otimes m) \) with natural morphism \( \varphi : X \to A \), and tautological line bundle \( \mathcal{O}_X(1) \). We have

\[
\mathcal{O}_X(-K_{X/A}) \cong \left( \mathcal{O}_X(1) \otimes \varphi^*L_{\text{ample}}^{-1} \right) \otimes \left( \mathcal{O}_X(1) \otimes \varphi^*L_{\text{ample}}^{-m} \right).
\]

Note that \( h^0(X, \mathcal{O}_X(1) \otimes \varphi^*L_{\text{ample}}^{-m}) = 1 \), and that for any positive integer \( k \), we have

\[
h^0(X, \mathcal{O}_X(k) \otimes \varphi^*L_{\text{ample}}^{-k}) = \begin{cases} h^0(A, S^k(O_A \oplus L_{\text{ample}}^{m-1})) & \text{by the projection formula,} \\ \sum_{0 \leq i \leq k} h^0(A, L_{\text{ample}}^{i(m-1)}) & \text{by the G-R-R theorem,} \\ \frac{1}{(n-1)!}(m-1)^n n^{-1} k^n & \text{by Faulhaber’s formula.} \end{cases}
\]

Thus \( \mathcal{O}_X(1) \otimes \varphi^*L_{\text{ample}}^{-1} \) is big, and so is \(-K_{X/A}\). Let \( \mathcal{G} \) be a linear foliation on \( A \) of codimension \( 0 < q \leq \dim A \), and let \( \mathcal{F} \) be the pull-back of \( \mathcal{G} \) via \( \varphi \) (see [2.9]). Then \( \mathcal{F} \) is a regular foliation with \(-K_{\mathcal{F}} \sim -K_{X/A}\), big.

The next example shows that Theorem [1.1] is wrong if one drops the integrability assumption on \( \mathcal{F} \).

Example 1.3. The null correlation bundle \( \mathcal{N} \) on \( \mathbb{P}^{2n+1} \) (see [OSS80, 4.2]) yields a contact distribution \( \mathcal{D} = \mathcal{N} \otimes O_{\mathbb{P}^{2n+1}}(1) \subset \mathcal{T}_{\mathbb{P}^{2n+1}} \) on \( \mathbb{P}^{2n+1} \) corresponding to a twisted 1-form \( \theta \in H^0(\mathbb{P}^{2n+1}, \Omega_{\mathbb{P}^{2n+1}}^1(\mathcal{D})) \).

Recall that a contact structure on a complex manifold \( X \) is a co-rank 1 subbundle \( \mathcal{D} \subset \mathcal{T}_X \) such that the bivector form \( \theta \) with values in the quotient line bundle \( \mathcal{L} = \mathcal{T}_X/\mathcal{D} \) deduced from the Lie bracket on \( \mathcal{T}_X \) is everywhere non-degenerate. This implies that the dimension of \( X \) is odd, say \( \dim X = 2n + 1 \), that the canonical bundle \( \mathcal{O}_X(K_X) \) is isomorphic to \( \mathcal{L}^\otimes n \), and that \( \det(\mathcal{T}) \cong \mathcal{L}^\otimes n \). Alternatively, the contact structure can be described by the twisted 1-form \( \theta \in H^0(X, \Omega_X^1 \otimes \mathcal{L}) \) corresponding to the natural projection \( \mathcal{T}_X \to \mathcal{L} \).

An immediate consequence of Theorem [1.1] is the following upper bound on the Kodaira dimension of the anti-canonical bundle of a holomorphic codimension 1 foliation.

Corollary 1.4. Let \( X \) be a complex projective manifold, and let \( \mathcal{F} \subset \mathcal{T}_X \) be a codimension 1 foliation. Suppose that either \( \mathcal{F} \) is regular, or that \( \mathcal{F} \) has a compact leaf. Suppose furthermore that \(-K_{\mathcal{F}} \) is nef. Then \( \kappa(X, -K_{\mathcal{F}}) \leq \dim X - 1 \).

Next, we investigate regular codimension one foliations with \(-K_{\mathcal{F}} \) nef and \( \kappa(X, -K_{\mathcal{F}}) = \dim X - 1 \). Note that \(-K_{\mathcal{F}} \) is then nef and abundant.

Theorem 1.5. Let \( X \) be a complex projective manifold, and let \( \mathcal{F} \subset \mathcal{T}_X \) be a codimension \( q \) foliation with \( 0 < q < \dim X \). Suppose that either \( \mathcal{F} \) is regular, or that \( \mathcal{F} \) has a compact leaf. Suppose furthermore that \(-K_{\mathcal{F}} \) is nef and abundant. Then \( \kappa(X, -K_{\mathcal{F}}) \leq \dim X - q \), and equality holds only if \( \mathcal{F} \) is algebraically integrable.

The following example shows to what extent Theorem [1.5] is optimal.

Example 1.6. Let \( T \) be a positive-dimensional projective manifold with \(-K_T \) nef, and let \( A \) be a positive-dimensional abelian variety. Consider a linear foliation \( \mathcal{G} \) on \( A \), and let \( \mathcal{F} \) be the pull-back of \( \mathcal{G} \) on \( \mathcal{T} \times A \). Then \(-K_{\mathcal{F}} \sim -K_{T \times A/A} \) is nef and \( \nu(-K_{\mathcal{F}}) = \kappa(T \times A, -K_{\mathcal{F}}) = \kappa(T, -K_T) = \nu(-K_T) \). Moreover, if \( \mathcal{G} \) is general enough, then \( \mathcal{F} \) has no algebraic leaf.

Theorem 1.7. Let \( X \) be a complex projective manifold with \( h^1(X, \mathcal{O}_X) = 0 \), and let \( \mathcal{F} \subset \mathcal{T}_X \) be a regular codimension \( 1 \) foliation. Suppose that \(-K_{\mathcal{F}} \) is nef and \( \kappa(X, -K_{\mathcal{F}}) = \dim X - 1 \). Then \( X \cong \mathbb{P}^1 \times F \), and \( \mathcal{F} \) is induced by the natural morphism \( X \cong \mathbb{P}^1 \times F \to \mathbb{P}^1 \).

The proof of the main results rely on the following observation (see also Proposition [0.1]).

Proposition 1.8. Let \( X \) be a complex projective manifold, and let \( \mathcal{F} \subset \mathcal{T}_X \) be a foliation. Suppose that \(-K_{\mathcal{F}} \) is nef. Suppose furthermore that either \( \mathcal{F} \) is regular, or that \( \mathcal{F} \) has a compact leaf. There exist a foliation \( \mathcal{H} \) on \( X \) induced by an almost proper map \( \varphi : X \to Y \), and a foliation \( \mathcal{G} \) on \( Y \) such that

1. there is no positive-dimensional algebraic subvariety passing through a general point of \( Y \) that is tangent to \( \mathcal{G} \),
(2) \( \mathcal{F} = \varphi^{-1} \mathcal{G} \), and
(3) \( K_{\mathcal{F}} \equiv K_{\mathcal{G}} \).

The paper is organized as follows. In section 2, we review basic definitions and results about holomorphic foliations. In section 3, we extend a number of known results on slope-semistable sheaves to the classical case to the setting where polarisations are given by movable complete intersection curve classes. As application, we obtain a generalization of Metha-Ramananathan’s theorem. In sections 4 and 5, we study the anti-canonical divisor of algebraically integrable foliations, and provide applications to the study of singularities of those foliations with \(-K_{\mathcal{F}}\) nef. Section 6 is devoted to the proof of Proposition 1.8. Section 7 is devoted to the proofs of Theorem 1.14 and Corollary 1.13. In section 8 we prove Theorems 1.5 and 1.7.

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2. Recollection: Foliations

In this section we recall the basic facts concerning foliations.

2.1. Foliations.

Definition 2.1. A foliation on a normal variety \( X \) is a coherent subsheaf \( \mathcal{F} \subset T_X \) such that
- \( \mathcal{F} \) is closed under the Lie bracket, and
- \( \mathcal{F} \) is saturated in \( T_X \). In other words, the quotient \( T_X/\mathcal{F} \) is torsion-free.

The rank \( r \) of \( \mathcal{F} \) is the generic rank of \( \mathcal{F} \). The codimension of \( \mathcal{F} \) is defined as \( q := \dim X - r \).

Let \( X^\circ \subset X_{ns} \) be the maximal open set where \( \mathcal{F}|_{X_{ns}} \) is a subbundle of \( T_{X_{ns}} \). A leaf of \( \mathcal{F} \) is a connected, locally closed holomorphic submanifold \( L \subset X^\circ \) such that \( T_L = \mathcal{F}|_L \). A leaf is called algebraic if it is open in its Zariski closure.

Definition 2.2. Let \( X \) be a complex manifold, and let \( \mathcal{F} \) be a foliation on \( X \). We say that \( \mathcal{F} \) is regular if \( \mathcal{F} \) is a subbundle of \( T_X \).

Next, we define the algebraic and transcendental parts of a holomorphic foliation (see [AD14a] Definition 2).

Definition 2.3. Let \( \mathcal{F} \) be a holomorphic foliation on a normal variety \( X \). There exist a normal variety \( Y \), unique up to birational equivalence, a dominant rational map \( \varphi : X \dashrightarrow Y \), and a holomorphic foliation \( \mathcal{G} \) on \( Y \) such that the following holds (see [LPT11] Section 2.4).

1. \( \mathcal{G} \) is purely transcendental, i.e., there is no positive-dimensional algebraic subvariety through a general point of \( Y \) that is tangent to \( \mathcal{G} \); and
2. \( \mathcal{F} \) is the pullback of \( \mathcal{G} \) via \( \varphi \) (see [2.9] for this notion).

The foliation on \( X \) induced by \( \varphi \) is called the algebraic part of \( \mathcal{F} \).

2.4 (Foliations defined by \( q \)-forms). Let \( \mathcal{F} \) be a codimension \( q \) foliation on an \( n \)-dimensional complex manifold \( X \). Suppose that \( q \geq 1 \). The normal sheaf of \( \mathcal{F} \) is \( \mathcal{N} := (T_X/\mathcal{F})^\ast \). The \( q \)-th wedge product of the inclusion \( \mathcal{N}^\ast \hookrightarrow \Omega_X^1 \) gives rise to a nonzero global section \( \omega \in H^0(X, \Omega_X^q \otimes \text{det}(\mathcal{N})) \) whose zero locus has codimension at least 2 in \( X \). Such \( \omega \) is locally decomposable and integrable. To say that \( \omega \) is locally decomposable means that, in a neighborhood of a general point of \( X \), \( \omega \) decomposes as the wedge product of \( q \) local 1-forms \( \omega = \omega_1 \wedge \cdots \wedge \omega_q \). To say that it is integrable means that for this local decomposition one has \( d\omega_i \wedge \omega = 0 \) for every \( i \in \{1, \ldots, q\} \). The integrability condition for \( \omega \) is equivalent to the condition that \( \mathcal{F} \) is closed under the Lie bracket.

Conversely, let \( \mathcal{L} \) be a line bundle on \( X \), \( q \geq 1 \), and \( \omega \in H^0(X, \Omega_X^q \otimes \mathcal{L}) \) a global section whose zero locus has codimension at least 2 in \( X \). Suppose that \( \omega \) is locally decomposable and integrable. Then one defines a foliation of rank \( r = n - q \) on \( X \) as the kernel of the morphism \( T_X \to \Omega_X^{q-1} \otimes \mathcal{L} \) given by the contraction with \( \omega \). These constructions are inverse of each other.

We will use the following notation.

Notation 2.5. Let \( \varphi : X \to Y \) be a dominant morphism of normal varieties. Assume either that \( K_Y \) is \( \mathbb{Q} \)-Cartier or that \( \varphi \) is equidimensional. Write \( K_{X/Y} := K_X - \varphi^*K_Y \). We refer to it as the relative canonical divisor of \( X \) over \( Y \).
Remark 2.6. Let \( \varphi : X \to Y \) be an equidimensional morphism of normal varieties, and let \( D \) be a Weil \( \mathbb{Q} \)-divisor on \( Y \). The pull-back \( \varphi^*D \) of \( D \) is defined as follows. We define \( \varphi^*D \) to be the unique \( \mathbb{Q} \)-divisor on \( X \) whose restriction to \( \varphi^{-1}(Y_{ns}) \) is \( (\varphi|_{ns})^*D|_{ns} \). This construction agrees with the usual pull-back if \( D \) itself is \( \mathbb{Q} \)-Cartier.

Notation 2.7. Let \( \varphi : X \to Y \) be a dominant morphism of normal varieties. Let \( Y^\circ \subset Y \) be a dense open subset with \( \text{codim} \ Y \setminus Y^\circ \geq 2 \) such that \( \varphi \) restricts to an equidimensional morphism \( \varphi^\circ : X^\circ \to Y^\circ \), where \( X^\circ := \varphi^{-1}(Y^\circ) \). Set

\[
R(\varphi^\circ) = \sum_{D^\circ} \left( (\varphi^\circ)^*D^\circ - ((\varphi^\circ)^*D^\circ)_{\text{red}} \right)
\]

where \( D^\circ \) runs through all prime divisors on \( Y^\circ \), and let \( R(\varphi) \) denotes the Zariski closure of \( R(\varphi^\circ) \) in \( X \). We refer to it as the \textit{ramification divisor} of \( \varphi \).

Definition 2.8. Let \( \mathcal{F} \) be a foliation on a normal projective variety \( X \). The \textit{canonical class} \( K_{\mathcal{F}} \) of \( \mathcal{F} \) is any Weil divisor on \( X \) such that \( \mathcal{O}_X(-K_{\mathcal{F}}) \cong \det(\mathcal{F}) \).

We say that \( \mathcal{F} \) is \( \mathbb{Q} \)-Gorenstein if \( K_{\mathcal{F}} \) is a \( \mathbb{Q} \)-Cartier divisor.

2.9 (Foliations described as pull-backs). Let \( X \) and \( Y \) be normal varieties, and let \( \varphi : X \to Y \) be a dominant rational map that restricts to a morphism \( \varphi^\circ : X^\circ \to Y^\circ \), where \( X^\circ \subset X \) and \( Y^\circ \subset Y \) are smooth open subsets.

Let \( \mathcal{G} \) be a codimension \( q \) foliation on \( Y \) with \( q \geq 1 \). Suppose that the restriction \( \mathcal{G}^\circ \) of \( \mathcal{G} \) to \( Y^\circ \) is defined by a twisted \( q \)-form \( \omega_{Y^\circ} \in H^0(Y^\circ, \Omega^q_{Y^\circ} \otimes \det(\mathcal{N}_{\mathcal{G}^\circ})) \). Then \( \omega_{Y^\circ} \) induces a nonzero twisted \( q \)-form \( \omega_{X^\circ} \in H^0(X^\circ, \Omega^q_{X^\circ} \otimes (\varphi^\circ)^*\left( \det(\mathcal{N}_{\mathcal{G}^\circ})_{|Y^\circ} \right) \) \)), which in turn defines a codimension \( q \) foliation \( \mathcal{F}^\circ \) on \( X^\circ \). We say that the saturation \( \mathcal{F} \) of \( \mathcal{F}^\circ \) in \( T_X \) is the pull-back of \( \mathcal{G} \) via \( \varphi \), and write \( \mathcal{F} = \varphi^{-1}\mathcal{G} \).

Suppose that \( X^\circ \) is such that \( \varphi^\circ \) is an equidimensional morphism. Let \( (B_i)_{i \in I} \) be the (possibly empty) set of hypersurfaces in \( Y^\circ \) contained in the set of critical values of \( \varphi^\circ \) and invariant by \( \mathcal{G} \). A straightforward computation shows that

\[
(2.1) \quad \det(\mathcal{N}_{\mathcal{G}^\circ}) \cong (\varphi^\circ)^* \det(\mathcal{N}_{\mathcal{G}})_{|Y^\circ} \otimes \mathcal{O}_{X^\circ} \left( \sum_{i \in I} ((\varphi^\circ)^*B_i)|_{\text{red}} - (\varphi^\circ)^*B_i \right).
\]

In particular, if \( \mathcal{F} \) is induced by \( \varphi \), then (2.1) gives

\[
(2.2) \quad K_{\mathcal{F}^\circ} = K_{X^\circ/Y^\circ} - R(\varphi^\circ),
\]

where \( R(\varphi^\circ) \) denotes the ramification divisor of \( \varphi^\circ \).

Conversely, let \( \mathcal{F} \) be a foliation on \( X \), and suppose that the general fiber of \( \varphi \) is tangent to \( \mathcal{F} \). This means that, for a general point \( x \) on a general fiber \( F \) of \( \varphi \), the linear subspace \( \mathcal{F}_x \subset T_xX \) determined by the inclusion \( \mathcal{F}_x \subset T_xX \) contains \( T_xF \). Suppose moreover that \( \varphi^\circ \) is smooth with connected fibers. Then, by [AD13 Lemma 6.7], there is a holomorphic foliation \( \mathcal{F} \) on \( Y \) such that \( \mathcal{F} = \varphi^{-1}\mathcal{G} \).

2.2. Algebraically integrable foliations.

Definition 2.10. Let \( X \) be normal variety. A foliation \( \mathcal{F} \) on \( X \) is said to be \textit{algebraically integrable} if the leaf of \( \mathcal{F} \) through a general point of \( X \) is an algebraic variety.

Definition 2.11. Let \( \mathcal{F} \) be an algebraically integrable \( \mathbb{Q} \)-Gorenstein foliation on a normal projective variety \( X \). Let \( i : F \to X \) be the normalization of the closure of a general leaf of \( \mathcal{F} \). There is an effective \( \mathbb{Q} \)-divisor \( \Delta \) on \( F \) such that \( K_F + \Delta \sim i^*K_{\mathcal{F}} \) (AD14b Definition 3.6)). The pair \( (F, \Delta) \) is called a \textit{general log leaf} of \( \mathcal{F} \).

The case when \( (F, \Delta) \) is \textit{log canonical} is specially interesting (see AD13 and AD14b). We refer to [KM98 section 2.3] for the definition of klt and log canonical pairs. Here we only remark that if \( F \) is smooth and \( \Delta \) is a reduced simple normal crossing divisor, then \( (F, \Delta) \) is log canonical.

The same argument used in the proof of AD14b Proposition 3.13] shows that the following holds. We leave the details to the reader. In particular, Proposition 2.12 below says that an algebraically integrable \( \mathbb{Q} \)-Gorenstein foliation with mild singularities and big anti-canonical divisor has a very special property: there is a common point contained in the closure of a general leaf.
Proposition 2.12. Let $X$ be a normal projective variety, let $\mathcal{F}$ be a $\mathbb{Q}$-Gorenstein algebraically integrable foliation on $X$, and let $(F, \Delta)$ be its general log leaf. Suppose that $-K_\mathcal{F} = A + E$ where $A$ is a $\mathbb{Q}$-ample $\mathbb{Q}$-divisor and $E$ is an effective $\mathbb{Q}$-divisor. Suppose furthermore that $(F, \Delta + E|_F)$ is log canonical. Then there is a closed irreducible subset $T \subset X$ satisfying the following property. For a general log leaf $(F, \Delta)$, there exists a log canonical center $S$ of $(F, \Delta + E|_F)$ whose image in $X$ is $T$.

2.13 (The family of log leaves). Let $X$ be a normal projective variety, and let $\mathcal{F}$ be an algebraically integrable foliation on $X$. We describe the family of leaves of $\mathcal{F}$ (see [AD14a, Remark 3.12]). There is a unique normal projective variety $Y$ contained in the normalization of the Chow variety of $X$ whose general point parametrizes the closure of a general leaf of $\mathcal{F}$ (viewed as a reduced and irreducible cycle in $X$). Let $Z \to Y \times X$ denotes the normalization of the universal cycle. It comes with morphisms:

$$
Z \xrightarrow{\nu} X,
$$

where $\nu: Z \to X$ is birational and, for a general point $y \in Y$, $\nu(\psi^{-1}(y)) \subset X$ is the closure of a leaf of $\mathcal{F}$. The variety $Y$ is called the family of leaves of $\mathcal{F}$.

Suppose moreover that $\mathcal{F}$ is $\mathbb{Q}$-Gorenstein. Denote by $\mathcal{F}|_Z$ the foliation induced by $\mathcal{F}$ (or $\psi$) on $Z$. There is a canonically defined effective Weil $\mathbb{Q}$-divisor $B$ on $Z$ such that

$$
(2.3) \quad K_{\mathcal{F}|_Z} + B = K_{Z/Y} - R(\psi) + B \sim_\mathbb{Q} \nu^* K_\mathcal{F},
$$

where $R(\psi)$ denotes the ramification divisor of $\psi$. Note that the equality $K_{\mathcal{F}|_Z} = K_{Z/Y} - R(\psi)$ follows from from (2.2). Suppose that $y \in Y$ is a general point, and set $Z_y := \psi^{-1}(y)$ and $\Delta_y := B|_{U_y}$. Then $(Z_y, \Delta_y)$ coincides with the general log leaf $(F, \Delta)$ defined above.

Remark 2.14. In the setup of 2.13 we claim that $B$ is $\nu$-exceptional. This is an immediate consequence of the equality $\nu_* K_{\mathcal{F}|_Z} = K_\mathcal{F}$.

Remark 2.15. In the setup of 2.13 suppose furthermore that $K_\mathcal{F}$ is a Cartier divisor. Then $B$ is a Weil divisor, and (2.3) reads

$$
K_{\mathcal{F}|_Z} + B = K_{Z/Y} - R(\psi) + B \sim \nu^* K_\mathcal{F}.
$$

We end this subsection with a useful criterion of algebraic integrability for foliations.

Theorem 2.16 ([BM01, Theorem 0.1], [Bos01, Theorem 3.5]). Let $X$ be a normal complex projective variety, and let $\mathcal{F}$ be a foliation on $X$. Let $C \subset X$ be a complete curve disjoint from the singular loci of $X$ and $\mathcal{F}$. Suppose that the restriction $\mathcal{F}|_C$ is an ample vector bundle on $C$. Then the leaf of $\mathcal{F}$ through any point of $C$ is an algebraic variety.

3. Movable complete intersection curves and semistable sheaves

In order to prove our results, we construct subfoliations of the foliation $\mathcal{F}$ which inherit some of the positivity properties of $\mathcal{F}$. One way to construct such subfoliations is via Harder-Narasimhan filtrations (see Proposition 3.12 below).

The notion of slope-stability with respect to the choice of an ample line bundle is not flexible enough to allow for applications in birational geometry. The paper [GKP14] (see also [CP11]) extends a number of known results from the classical case to the setting where the ambient variety is normal and $\mathbb{Q}$-factorial, and polarisations are given by movable curve classes. Recall that a numerical curve class $\alpha$ on a normal projective variety is movable if $D \cdot \alpha \geq 0$ for all effective Cartier divisors $D$. In this paper, it is advantageous to generalize the notion of slope, replacing movable curve classes with movable complete intersection curve classes.

Let $X$ be an $n$-dimensional normal projective variety. Consider the space $N_1(X)_{\mathbb{R}}$ of numerical curve classes on $X$.

Notation 3.1. Let $X$ be an $n$-dimensional normal projective variety, and let $\alpha$ be a numerical curve class on $X$. We say that $\alpha$ is a complete intersection numerical curve class if $\alpha = [D_1, \ldots, D_{n-1}] \in N_1(X)_{\mathbb{R}}$ for some Cartier divisors $D_1, \ldots, D_{n-1}$ on $X$. 
Remark 3.2. Let $D_1, \ldots, D_{n-1}$ be Cartier divisors on $X$. Suppose that $D_i$ is nef for all $i$. Then $\alpha := [D_1 \cdot \cdots \cdot D_{n-1}]$ is a movable complete intersection numerical curve class.

Definition 3.3. Let $X$ be a normal projective variety. Let $\alpha$ be a complete intersection numerical curve class on $X$, and let $\mathcal{F}$ be a torsion-free sheaf of positive rank $r$.

We define the slope of $\mathcal{F}$ with respect to $\alpha$ to be $\mu_\alpha(\mathcal{F}) = \frac{\text{det} \mathcal{F}}{\alpha}$.

We say that $\mathcal{F}$ is $\alpha$-semistable if for any subsheaf $\mathcal{E} \neq 0$ of $\mathcal{F}$ we have $\mu_\alpha(\mathcal{E}) \leq \mu_\alpha(\mathcal{F})$.

The same argument used in the proof of [GKPT14 Corollary 2.26] shows that the following holds.

Proposition 3.4. Given a torsion-free sheaf $\mathcal{F}$ on a normal projective variety $X$, and a movable complete intersection numerical curve class $\alpha$, there exists a unique filtration of $\mathcal{F}$ by saturated subsheaves

$$0 = \mathcal{F}_0 \subsetneq \mathcal{F}_1 \subsetneq \cdots \subsetneq \mathcal{F}_k = \mathcal{F},$$

with $\alpha$-semistable quotients $\mathcal{Q}_i = \mathcal{F}_i/\mathcal{F}_{i-1}$, and such that $\mu_\alpha(\mathcal{Q}_1) > \mu_\alpha(\mathcal{Q}_2) > \cdots > \mu_\alpha(\mathcal{Q}_k)$.

This is called the Harder-Narasimhan filtration of $\mathcal{F}$. The sheaf $\mathcal{F}_1$ is called the maximally destabilizing subsheaf of $\mathcal{F}$, and it satisfies

$$\mu_\alpha(\mathcal{F}_1) = \mu_\alpha^{\max}(\mathcal{F}) := \sup\{\mu_\alpha(\mathcal{E}) | 0 \neq \mathcal{E} \subsetneq \mathcal{F} \text{ a coherent subsheaf}\}.$$

We will need the following easy observations.

Lemma 3.5. Let $\mathcal{F}$ be a torsion-free sheaf on a normal projective $X$, and let $\alpha$ be a complete intersection numerical curve class on $X$. Then $\mathcal{F}$ is $\alpha$-semistable if and only if so is $\mathcal{F}^{\ast\ast}$.

Notation 3.6. Let $\varphi : X \to Y$ be any birational morphism of projective normal varieties, and let $\alpha = [D_1 \cdots D_{n-1}] \in N_1(X)_{\mathbb{R}}$ be complete intersection numerical curve class. Set $\varphi^\ast \alpha := [\varphi^\ast D_1 \cdots \varphi^\ast D_{n-1}] \in N_1(X)_{\mathbb{R}}$. We refer to it as the numerical pull-back of $\alpha$.

Remark 3.7. In the setup of Notation 3.6 we have $D \cdot \varphi^\ast \alpha = \varphi_\ast D \cdot \alpha$ for any Weil $\mathbb{Q}$-divisor $D$ on $X$ by the projection formula. It follows that this construction agrees with the usual numerical pull-back if $X$ and $Y$ are $\mathbb{Q}$-factorial.

Remark 3.8. The pull-back of any movable complete intersection numerical curve class is again a movable complete intersection numerical curve class.

Lemma 3.9. Let $\varphi : X \to Y$ be any birational morphism of projective normal varieties, and let $\mathcal{F}$ be a torsion-free sheaf on $X$. Let $\alpha$ be a complete intersection numerical curve class on $Y$. Then $\mathcal{F}$ is $\varphi^\ast \alpha$-semistable if and only if the torsion-free sheaf $\varphi_\ast \mathcal{F}$ is $\alpha$-semistable.

The proof of the next lemma is similar to that of [HL97 Lemma 3.2.2], and so we leave the details to the reader.

Lemma 3.10. Let $\varphi : X \to Y$ be a finite surjective morphism of projective normal varieties, and let $\mathcal{F}$ be a torsion-free sheaf on $Y$. Let $\alpha$ be a complete intersection numerical curve class on $Y$. Then $\mathcal{F}$ is $\alpha$-semistable if and only if $\varphi^\ast \mathcal{F}/\text{Tor}(\varphi^\ast \mathcal{F})$ is $\varphi^\ast \alpha$-semistable.

We will make use of the following notation.

Notation 3.11. Let $X$ be an $n$-dimensional normal projective variety, and let $|H|$ be a basepoint-free complete linear system on $X$. For each $1 \leq i \leq n-1$, let $D_i \in |H|$ be a general hypersurface, and set $C = D_1 \cap \cdots \cap D_{n-1}$. We say that $C$ is a general complete intersection curve on $X$ of type $H$.

We now provide a technical tool for the proof of the main results. The following result is a generalization of [AD13 Lemma 4.7] (see also [DPT13 Lemma 12]).

Proposition 3.12. Let $\psi : Z \to Y$ be a dominant morphism of normal projective varieties, let $X$ be a normal projective variety, and let $\nu : Z \to X$ be a birational morphism. Let $H$ be a very ample divisor on $X$, and let $\mathcal{F}$ be a torsion-free sheaf on $Y$. Then there exists a saturated subsheaf $\mathcal{E} \subsetneq \mathcal{F}$ satisfying the following property. For a general complete intersection curve $C$ on $Z$ of type $\nu^\ast H$ with $m$ large enough, $\psi^\ast \mathcal{E}_{|C}$ is the maximally destabilizing subsheaf of $\psi^\ast \mathcal{F}_{|C}$.
Proof. Set $n = \dim Z = \dim X$ and $l = \dim Y$.

Let $m$ be a positive integer, and consider general hypersurfaces $H_i \in |mH|$ for $1 \leq i \leq n-1$. By replacing $m$ with a larger integer, we may assume that the Harder-Narasimhan filtration of $\mathcal{F} := (\nu_*(\psi^*\mathcal{L}))^{**}$ with respect to $H$ commutes with restriction to all complete intersections $H_i \cap \cdots \cap H_i$, $1 \leq i \leq n-1$ (see [Fle84]).

Set $D_i := \nu^{-1}(H_i) \in |m\nu^*H|$, $Z_1 := D_1 \cap \cdots \cap D_{n-1}$, and $X_1 := H_1 \cap \cdots \cap H_{n-1}$. The restriction of $\nu$ to $Z_1$ yields a surjective birational morphism $\nu_1 : Z_1 \to X_1$ of normal varieties. Denote by $\psi_1 : Z_1 \to Y$ the restriction of $\psi$ to $Z_1$. Note that $\psi_1$ is generically finite. Let $\psi_2 : Z_1 \to Y_1$ be its Stein factorization. It comes with a birational morphism $\mu_1 : Y_1 \to Y$.

Set $B = H_1 \cap \cdots \cap H_{n-1}$. Up to replacing $H_{n-i+1}, \ldots, H_{n-1}$ by linearly equivalent divisors on $X$, we may assume that $B \subset X \setminus \nu_1(\text{Exc}(\nu_1))$. Set $C = \nu_1^{-1}(B) = \nu_1^{-1}(B) = D_1 \cap \cdots \cap D_{n-1} \cong B$.

Set $\mathcal{F}_1 := \mu_1^*\mathcal{L}/\text{Tor}(\mu_1^*\mathcal{L})$, $\mathcal{F} := (\psi^*\mathcal{L})^{**}$, $\mathcal{F}_2 = (\psi_*\mathcal{L})^{**} \cong (\psi_*\mathcal{L})^{**}$, and $\mathcal{F}_1 := ((\nu_1)_*, \mathcal{F}_1)^{**}$. Since $\mathcal{F}_1|_{X_1}$ is reflexive, we must have

$$\mathcal{F}_1 \cong \mathcal{F}_1|_{X_1}.$$ 

Let $\mathcal{X}$ be the maximally destabilizing subsheaf of $\mathcal{F}$ with respect to $H$. By Flenner’s version of the Mehta-Ramanan theorem and the choice of $m$, $\mathcal{X}_1 := \mathcal{X}|_{X_1}$ is the maximally destabilizing subsheaf of $\mathcal{F}_1 \cong \mathcal{F}_1|_{X_1}$ with respect to $H|_{X_1}$. Note that $\mathcal{X}_1$ is reflexive by [AD13, Remark 2.3]. Let $\mathcal{F}_1 \subset \mathcal{F}_2$ such that $((\nu_1)_*, \mathcal{X}_1)^{**} = \mathcal{X}_1 \subset \mathcal{F}_1$. We may assume that $\mathcal{F}_1$ is saturated in $\mathcal{F}_2$. Since $B \subset X \setminus \nu_1(\text{Exc}(\nu_1))$, we have

$$\mathcal{F}_1|_{B} = \mathcal{X}_1|_{B} = ((\nu_1)_*, \mathcal{X}_1)^{**}|_{B} \cong (\nu_1)_*, \mathcal{F}_1|_{B} \cong \mathcal{F}_1|_{C_1}$$

and

$$\mathcal{F}_2|_{B} = \mathcal{X}_1|_{B} = ((\nu_1)_*, \mathcal{X}_1)^{**}|_{B} \cong (\nu_1)_*, \mathcal{F}_2|_{B} \cong \mathcal{F}_2|_{C_1}.$$ 

By Flenner’s version of the Mehta-Ramanan theorem and the choice of $m$, we conclude as above that $\mathcal{F}_1|_{C_1}$ is the maximally destabilizing subsheaf of $\mathcal{F}_1|_{C_1}$.

Let $K$ be a splitting field of the function field $\mathbb{C}(Z_1)$ over $\mathbb{C}(Y_1)$, and let $\nu_2 : Z_2 \to Z_1$ be the normalization of $Z_1$ in $K$. Set $\psi_3 := \psi_2 \circ \nu_2 : Z_2 \to Y_1$, and denote by $G$ the Galois group of $\mathbb{C}(Z_2)$ over $\mathbb{C}(Y_1)$. We obtain a commutative diagram

\[
\begin{array}{ccc}
Z_2 & \xrightarrow{\psi_2, \text{finite}} & Z_1 \\
\psi_3, \text{finite} & & \psi_2, \text{finite} \\
Y_1 & \xrightarrow{\mu_1, \text{birational}} & Y \\
\end{array}
\]

\[
\begin{array}{ccc}
& & \xleftarrow{\nu_1, \text{birational}} \\
& & \xleftarrow{X_1} \\
& & \xleftarrow{\nu, \text{birational}} \\
& & \xleftarrow{X} \\
Y & \xrightarrow{\psi} & Z_1 \\
\end{array}
\]

The numerical curve class $[C_1] \in N_1(Z_1)_R$ is a movable complete intersection curve class by Remark 3.2. By Lemmas 3.3 and 3.9, $\mathcal{F}_1$ is the maximally destabilizing sheaf of $\mathcal{F}_1$ with respect to the movable class $[C_1] = [\nu_1^*H|_{X_1}]^{-1} \in N_1(Z_1)_R$. From Lemmas 3.3 and 3.10, we deduce that $\mathcal{F}_2 := (\nu_2^*\mathcal{F}_1)^{**}$ is the maximally destabilizing sheaf of $(\nu_2^*\mathcal{F}_1)^{**} \cong (\psi_*\mathcal{F}_1)^{**} = : \mathcal{F}_2$ with respect to the movable class $\nu_2^*[C_1] = [(\nu_1 \circ \nu_2)^*H|_{X_1}]^{-1} \in N_1(Z_2)_R$.

Let $Y_1^0 \subset Y_1$ be a dense open subset with codim $Y_1 \setminus Y_1^0 \geq 2$ such that $G$ acts on $Z_2^0 := \psi_2^{-1}(Y_1^0)$ and such that $\mathcal{F}_2|_{Z_2^0}$ is locally free. Note that $Z_2^0/G \cong Y_1^0$. Because of its uniqueness, $\mathcal{F}_2|_{Z_2^0}$ is invariant under the natural action of $G$ on $\mathcal{F}_2|_{Z_2^0} \cong \mathcal{F}_2|_{Z_2^0}$). Therefore there exists a saturated subsheaf $\mathcal{E}_1 \subset \mathcal{F}_2$ such that $\psi_3^*\mathcal{E}_1|_{Z_2^0} \cong \mathcal{F}_2|_{Z_2^0}$. By Lemma 3.11 again, we have that $(\nu_2^*\mathcal{E}_1)^{**} \cong \mathcal{E}_1$.

Consider $\mathcal{E} = (\mu_1)_*\mathcal{E}_1 \subset \mathcal{F}_1$. Then $\mathcal{E}$ is saturated in $\mathcal{F}_1$, and $\mathcal{F}_1|_{C_1} \cong \mathcal{F}_1|_{C_1}$ is the maximally destabilizing subsheaf of $\psi_*\mathcal{F}_1 \cong \mathcal{F}_1|_{C_1}$. This completes the proof of the proposition. \qed

4. The anti-canonical divisor of an algebraically integrable foliation

In this section, we apply Viehweg’s weak positivity theorem to algebraically integrable foliations. We refer to [Vie85] for the definition of weak positivity. This notion was introduced by Viehweg, as a kind of birational version of being nef.

The following is a generalization of [Hor12, Lemma 2.14] and [CP13, Theorem 2.11] (see also Proposition 3.8 below). Recall that a $Q$-divisor $D$ on a normal projective variety $X$ is said to be pseudo-effective if, for
any big \(\mathbb{Q}\)-divisor \(B\) on \(X\) and any rational number \(\varepsilon > 0\), there exists an effective \(\mathbb{Q}\)-divisor \(E\) on \(X\) such that \(D + \varepsilon B \sim_{\mathbb{Q}} E\).

**Proposition 4.1.** Let \(X\) be a normal projective variety, let \(\mathcal{F}\) be a \(\mathbb{Q}\)-Gorenstein algebraically integrable (possibly singular) foliation on \(X\), and let \((F, \Delta)\) be its general log leaf. Let \(L\) be an effective \(\mathbb{Q}\)-Cartier \(\mathbb{Q}\)-divisor on \(X\). Suppose that \((F, \Delta + L|_F)\) is log canonical, and that \(\kappa(F, K_F + \Delta + L|_F) \geq 0\). Then \(K_{\mathcal{F}} + L\) is pseudo-effective.

**Proof.** Let \(\psi: Z \to Y\) be the family of leaves, and let \(\nu: Z \to X\) be the natural morphism (see 2.13). By Lemma 4.2 below, there exists a finite surjective morphism \(Y_1 \to Y\) with \(Y_1\) normal and connected satisfying the following property. If \(Z_1\) denotes the normalization of the product \(Y_1 \times_Y Z\), then the induced morphism \(\psi_1: Z_1 \to Y_1\) has reduced fibers over codimension one points in \(Y_1\).

By 2.13 there is a canonically defined effective \(\mathbb{Q}\)-Weil divisor \(B\) on \(Z\) such that

\[
K_{Z/Y} - R(\psi) + B \sim_{\mathbb{Q}} \nu^*K_{\mathcal{F}}
\]

where \(R(\psi)\) denotes the ramification divisor of \(\psi\). A straightforward computation shows that

\[
\nu_1^*(K_{Z/Y} - R(\psi)) = K_{Z_1/Y_1}.
\]

Set \(\Gamma_1 = \nu_1^*B + (\nu \circ \nu_1)^*L\). Let \(F_1\) be a general fiber of \(\psi_1\). Note that \((F_1, \Gamma_1|_{F_1})\) has log canonical singularities by assumption. It follows that \((Z_1, \Gamma_1)\) has log canonical singularities over the generic point of \(Y_1\) by inversion of adjunction (see Kaw07). Let \(\mu_2: Y_2 \to Y_1\) be a resolution of singularities, and let \(Z_2\) be a resolution of singularities of the product \(Y_2 \times_{Y_1} Z_1\). Up to replacing \(Z_2\) with a birational model, we may assume that \(Z_2\) is a log resolution of \((Z_1, \Gamma_1)\). We have a commutative diagram

\[
\begin{array}{ccc}
Z_2 & \xrightarrow{\nu_2, \text{bireal}} & Z_1 & \xrightarrow{\nu_1, \text{finite}} & Z & \xrightarrow{\nu, \text{bireal}} & X \\
\downarrow \psi_2 & & \downarrow \psi_1 & & \downarrow \psi & & \\
Y_2 & \xrightarrow{\mu_2, \text{bireal}} & Y_1 & \xrightarrow{\mu_1, \text{finite}} & Y & & \\
\end{array}
\]

We write

\[
K_{Z_2} + \Gamma_2 = \nu_2^*(K_{Z_1} + \Gamma_1) + E
\]

where \(\Gamma_2\) and \(E\) are effective, with no common components, \((\nu_2)^*, \Gamma_2 = \Gamma_1\), and \(E\) is \(\nu_2\)-exceptional. Then \((Z_2, \Gamma_2)\) has log canonical singularities over the generic point of \(Y_2\). Let \(F_2\) denote a general fiber of \(\psi_2\).

Thus, for any positive integer \(m\) which is sufficiently divisible, the natural morphism

\[
\psi_2^*(\mathcal{O}_{Z_2}(m(K_{Z_2/Y_2} + \Gamma_2))) \to \mathcal{O}_{Z_2}(m(K_{Z_2/Y_2} + \Gamma_2))
\]

is generically surjective. The sheaf \((\psi_2)_*\mathcal{O}_{Z_2}(m(K_{Z_2/Y_2} + \Gamma_2))\) is weakly positive by Cam04 Theorem 4.13. Therefore, \(K_{Z_2/Y_2} + \Gamma_2\) is pseudo-effective, and hence so is \((\nu \circ \nu_1 \circ \nu_2)_*(K_{Z_2/Y_2} + \Gamma_2)\). Since \(\psi_2\) is equidimensional, there exist dense open subsets \(Y_1^\circ \subset Y_1\) and \(Z_1^\circ \subset Z_1\) with codim \(Y_1 \setminus Y_1^\circ \geq 2\) and codim \(Z_1 \setminus Z_1^\circ \geq 2\) such that \(\psi_1(Z_1 \setminus Z_1^\circ) \subset Y_1 \setminus Y_1^\circ\), and such that \(\nu_2\) (respectively, \(\mu_2\)) induces an isomorphism \(\nu_2^{-1}(Z_1 \setminus Z_1^\circ) \cong Z_1 \setminus Z_1^\circ\) (respectively, \(\mu_2^{-1}(Y_1 \setminus Y_1^\circ) \cong Y_1 \setminus Y_1^\circ\)). Hence, \((\nu_2)_*(K_{Z_2/Y_2} + \Gamma_2) = K_{Z_1/Y_1} + \Gamma_1\).

From 4.11 and 4.12, we conclude that

\[
(\nu \circ \nu_1 \circ \nu_2)_*(K_{Z_2/Y_2} + \Gamma_2) = \deg(\nu_1)(K_{\mathcal{F}} + L)
\]

is pseudo-effective, completing the proof of the proposition.

\[
\square
\]

**Lemma 4.2.** Let \(\psi: Z \to Y\) be a dominant equidimensional morphism of normal varieties. There exists a finite surjective morphism \(Y_1 \to Y\) with \(Y_1\) normal and connected satisfying the following property. If \(Z_1\) denotes the normalization of the product \(Y_1 \times_Y Z\), then the induced morphism \(\psi_1: Z_1 \to Y_1\) has reduced fibers over codimension one points in \(Y_1\).

**Proof.** This follows easily from BLR95 Theorem 2.1' (see also AK00 Section 5)].

\[
\square
\]
As a first application of Proposition 4.1, we obtain a generalization of [Hör12 Lemma 2.14] and [CP13 Theorem 2.11].

**Proposition 4.3.** Let $\psi: X \rightarrow Y$ be a dominant morphism of normal projective varieties with general fiber $F$. Suppose that $\psi$ is smooth, and that $\varphi$ has connected fibers. Let $L$ be an effective $\mathbb{Q}$-divisor on $X$ such that $K_X + L$ is $\mathbb{Q}$-Cartier in a neighborhood of $F$. Suppose furthermore that $(F, L|_F)$ is log canonical, and that $\kappa(F, K_F + L|_F) \geq 0$. Then $K_{X/Y} - R(\varphi) + L$ is pseudo-effective, where $R(\varphi)$ denotes the ramification divisor of $\varphi$.

**Proof.** Let $\nu: X_1 \rightarrow X$ be a log resolution of $(X, L)$, and set $\varphi_1 := \varphi \circ \nu: X_1 \rightarrow Y$. Let $Y^0 \subset Y$ be a dense open subset such that $K_{X^0} + L|_{X^0}$ is $\mathbb{Q}$-Cartier, where $X^0 := \varphi^{-1}(Y^0)$. Set $X_1^0 := \nu^{-1}(X^0)$. We write

\[(4.4) \quad K_{X_1^0} + L_1^0 = (\nu|_{X_1^0})^*(K_{X^0} + L|_{X^0}) + E^0\]

where $L_1^0$ and $E^0$ are effective, with no common components, $(\nu|_{X_1^0})_L, L_1^0 = L|_{X_1^0}$, and $E^0$ is $\nu$-exceptional. Denote by $L_1$ the Zariski closure of $L_1^0$ in $X_1$. Note that $\nu_* L_1 = L$. Let $F_1$ denote a general fiber of $\varphi_1$. Then $(F_1, L_1|_{F_1})$ has log canonical singularities, and $\kappa(F_1, K_{F_1} + L_1|_{F_1}) = \kappa(F, K_F + L|_F) \geq 0$ by (4.4). By Proposition 4.1 applied to the foliation $\mathcal{F}$ on $X_1$ induced by $\nu_1$ and $L = L_1$, we conclude that $K_{\mathcal{F}_1} + L_1$ is pseudo-effective. There is an exact sequence

\[0 \rightarrow \mathcal{F}_1 \rightarrow T_{X_1} \rightarrow \varphi_1^* T_Y,\]

and thus $K_{\mathcal{F}_1} = K_{X_1/Y} - R(\varphi_1) - G$, where $R(\varphi_1)$ denotes the ramification divisor of $\varphi_1$ and $G$ is an effective divisor. This in turn implies that $K_{X/Y} - R(\varphi) + L$ is pseudo-effective since $K_{X/Y} - R(\varphi) - \nu_*(K_{X_1/Y} - R(\varphi_1) - G) = \nu_* G$ is effective. \qed

**Remark 4.4.** It should be noted that Proposition 4.3 does not require $K_{X/Y} - R(\varphi) + L$ to be $\mathbb{Q}$-Cartier.

**Corollary 4.5.** Let $\psi: Z \rightarrow Y$ be a dominant morphism of normal projective varieties with general fiber $F$. Suppose that $\psi$ is equidimensional with connected fibers. Let $L$ be an effective $\mathbb{Q}$-divisor on $Z$ such that $K_Z + L$ is $\mathbb{Q}$-Cartier in a neighborhood of $F$. Suppose furthermore that $(F, L|_F)$ is log canonical, and that $\kappa(F, K_F + L|_F) \geq 0$. Then $K_{Z/Y} - R(\psi) + L$ is pseudo-effective, where $R(\psi)$ denotes the ramification divisor of $\psi$.

**Proof.** Let $\mu_1: Y_1 \rightarrow Y$ be a resolution of singularities, and let $Z_1$ be the normalization of the product $Y_1 \times_Y Z$, with natural morphisms $\psi_1: Z_1 \rightarrow Y_1$ and $\nu_1: Z_1 \rightarrow Z$. Apply Proposition 4.3 to $\psi_1$ and $\nu_1^* L$. We conclude that $K_{Z_1/Y_1} - R(\psi_1) + \nu_1^* L$ is pseudo-effective, where $R(\psi_1)$ denotes the ramification divisor of $\psi_1$. It follows that $(\nu_1)_*(K_{Z_1/Y_1} - R(\psi_1) + \nu_1^* L)$ is pseudo-effective as well. Since $\psi$ is equidimensional, there exist dense open subsets $Y^0 \subset Y$ and $Z^0 \subset Z$ with codim $Y \setminus Y^0 \geq 2$ and codim $Z \setminus Z^0 \geq 2$ such that $\psi(Z \setminus Z^0) \subset Y \setminus Y^0$, and such that $\nu_1$ (respectively, $\mu_1$) induces an isomorphism $\nu_1^{-1}(Z \setminus Z^0) \cong Z \setminus Z^0$ (respectively, $\mu_1^{-1}(Y \setminus Y^0) \cong Y \setminus Y^0$). Hence, $(\nu_1)_*(K_{Z_1/Y_1} - R(\psi_1) + \nu_1^* L) = K_{Z/Y} - R(\psi) + L$, where $R(\psi)$ denotes the ramification divisor of $\psi$. This completes the proof of the Corollary 4.3. \qed

Next, we obtain a generalization of [AD13 Proposition 5.8].

**Proposition 4.6.** Let $X$ be a normal projective variety, let $\mathcal{F}$ a $\mathbb{Q}$-Gorenstein algebraically integrable foliation on $X$, and let $(F, \Delta)$ be its general log leaf. Suppose that $-K_{\mathcal{F}} = A + E$ where $A$ is a $\mathbb{Q}$-ample $\mathbb{Q}$-divisor and $E$ is an effective $\mathbb{Q}$-divisor. Then $(F, \Delta + E|_F)$ is klt.

**Proof.** We argue by contradiction, and assume that $(F, \Delta + E|_F)$ is klt. Let $\psi: Z \rightarrow Y$ be the family of leaves, and let $\nu: Z \rightarrow X$ be the natural morphism (see [2.13]). There is a canonically defined effective $\mathbb{Q}$-Weil divisor $B$ on $Z$ such that

\[K_{Z/Y} - R(\psi) + B \sim_\mathbb{Q} \nu^* K_{\mathcal{F}}\]

where $R(\psi)$ denotes the ramification divisor of $\psi$. We view $F$ as a (general) fiber of $\psi$. Recall that $B|_F = \Delta$, and that $K_{Z/Y} - R(\psi)$ is a canonical divisor of the foliation $\mathcal{F}|_Z$ on $Z$ induced by $\mathcal{F}$ (or $\psi$). We write $\nu^* A = H + N$ where $H$ is a $\mathbb{Q}$-ample $\mathbb{Q}$-divisor and $N$ is an effective $\mathbb{Q}$-divisor. Let $0 < \varepsilon \ll 1$ be a rational number such that $(F, \Delta + E|_F + \varepsilon N|_F)$ is klt, and set $H_\varepsilon = \nu^* A - \varepsilon N$. Note that $H_\varepsilon$ is $\mathbb{Q}$-ample. Finally, let $D \neq 0$ be an effective $\mathbb{Q}$-Cartier $\mathbb{Q}$-divisor on $Y$, such that $H'_\varepsilon := H_\varepsilon - \psi^* D$ is $\mathbb{Q}$-ample. Then
yielding a contradiction.

\[ K_F + \Delta + E_{|F} + H_{E_{|F}} + \varepsilon N_{|F} \sim_{Q} 0 \]. Now, apply Proposition 4.1 to conclude that \( K_{\mathcal{F}_2} + B + \nu^* E + H_{E} + \varepsilon N \) is pseudo-effective. But

\[ K_{\mathcal{F}_2} + B + \nu^* E + H_{E} + \varepsilon N \sim_{Q} -\psi^* D, \]

yielding a contradiction. \( \square \)

**Remark 4.7.** Note that Proposition 4.7 also follows Proposition 2.12. We decided to include a proof to keep our exposition as self-contained as possible.

5. **Singularities of foliations**

In this section, we provide another application of Proposition 4.1. We study singularities of algebraically integrable foliations (see Proposition 5.3). First, we recall the definition of terminal and canonical singularities, inspired by the theory of singularities of pairs, developed in the context of the minimal model program.

5.1 ([McQ08 Definition I.1.2]). Let \( \mathcal{F} \) be a foliation on a normal variety \( X \). Given a birational morphism \( \nu_1 : X_1 \to X \) of normal varieties, there is a unique foliation \( \mathcal{F}_1 \) on \( X_1 \) that agrees with \( \nu_1^* \mathcal{F} \) on the open subset of \( X_1 \) where \( \nu_1 \) is an isomorphism. Let \( B = \sum_{i \in I} a_i B_i \) be a (not necessarily effective) \( \mathbb{Q} \)-divisor on \( X \). Suppose that \( B_i \) is not invariant by \( \mathcal{F} \) for any \( i \in I \).

Suppose moreover that \( K_{\mathcal{F}} + B \) is \( \mathbb{Q} \)-Cartier and that \( \nu_1 \) is projective. Then there are uniquely defined rational numbers \( a_E(X, \mathcal{F}, B) \)'s such that

\[ K_{\mathcal{F}_1} + B_1 = \nu_1^*(K_{\mathcal{F}} + B) + \sum_E a_E(X, \mathcal{F}, B) E, \]

where \( E \) runs through all exceptional prime divisors for \( \nu_1 \), and where \( B_1 \) denotes the proper transform of \( B \) in \( X_1 \). The \( a_E(X, \mathcal{F}, B) \)'s do not depend on the birational morphism \( \nu_1 \), but only on the valuations associated to the \( E \)'s.

We say that \((\mathcal{F}, B)\) is terminal (respectively, canonical) if \( a_E(X, \mathcal{F}, B) > 0 \) (respectively, \( a_E(X, \mathcal{F}, B) \geq 0 \)) for all \( E \) exceptional over \( X \).

We say that \( \mathcal{F} \) is terminal (respectively, canonical) if so is \((\mathcal{F}, 0)\).

**Remark 5.2.** A regular foliation on a smooth variety is canonical by [AD13 Lemma 3.10].

The following example shows that a regular foliation on a smooth variety may not be (log) terminal.

**Example 5.3.** Let \( F \) and \( T \) be smooth varieties with \( \dim F \geq 1 \), and \( \dim T \geq 2 \). Let \( \mathcal{F} \) be the foliation on \( X := F \times T \) induced by the projection \( X \to T \). Fix a point \( t \in T \), and let \( T_1 \) be the blow-up of \( T \) at \( t \). Set \( X_1 := F \times T_1 \), with natural morphism \( \nu_1 : X_1 \to X \). Note that \( \nu_1 : X_1 \to X \) is the blow-up of \( X \) along \( F \times \{t\} \subset F \times T \). Denote by \( E \) its exceptional set. Observe that \( E \) is invariant by \( \mathcal{F}_1 \). The foliation \( \mathcal{F}_1 \) induced by \( \mathcal{F} \) on \( X_1 \) is given by the natural morphism \( X_1 \to T_1 \). We have \( \mathcal{F}_1 = \nu_1^* \mathcal{F} \), and hence \( a_E(X, \mathcal{F}, 0) = 0 \).

The following result is probably well-known to experts, though as far as we can see, the statement does not appear in the literature.

**Lemma 5.4.** Let \( \psi : Z \to Y \) be a dominant equidimensional morphism of normal varieties, and denote by \( \mathcal{H} \) the foliation on \( Z \) induced by \( \psi \). Suppose that \( Y \) is smooth. Let \( B = \sum_{i \in I} a_i B_i \) be a \( \mathbb{Q} \)-Cartier \( \mathbb{Q} \)-divisor on \( Z \). Suppose that \( B_i \) is not invariant by \( \mathcal{H} \) for every \( i \in I \). Suppose furthermore that \((\mathcal{H}, B)\) is terminal (respectively, canonical). Then \((Z, -R(\psi) + B)\) has terminal singularities (respectively, canonical singularities).

**Proof.** By [2.9] we have \( K_{\mathcal{H}} = K_{Z/Y} - R(\psi) \), and thus \( K_Z - R(\psi) \) is \( \mathbb{Q} \)-Cartier. Let \( \nu_1 : Z_1 \to Z \) be a resolution of singularities, and set \( \psi_1 := \psi \circ \nu_1 \). Denote by \( \mathcal{H}_1 \) the foliation induced by \( \mathcal{H} \) (or \( \psi_1 \)) on \( Z_1 \). Write \( K_{\mathcal{H}_1} + B_1 = \nu_1^*(K_{\mathcal{H}} + B) + E \) where \( E \) is a \( \nu \)-exceptional \( \mathbb{Q} \)-divisor, and \( B_1 \) denotes the proper transform of \( B \) in \( Z_1 \). There is an exact sequence

\[ 0 \to \mathcal{H}_1 \to T_{Z_1} \to \psi_1^* T_Y, \]

and thus \( K_{\mathcal{H}_1} = K_{Z_1/Y} - R(\psi)_1 + G \), where \( R(\psi)_1 \) denotes the proper transform of \( R(\psi) \) in \( Z_1 \) and \( G \) is an effective \( \nu \)-exceptional \( \mathbb{Q} \)-divisor. We obtain

\[ K_{Z_1} - R(\psi)_1 + B_1 = \nu_1^* (K_Z - R(\psi) + B) + E + G. \]
The lemma follows easily.

\textbf{Proposition 5.5.} Let $X$ be a normal projective variety, let $\mathcal{H}$ be a $\mathbb{Q}$-Gorenstein algebraically integrable foliation on $X$, and let $(F, \Delta)$ be its general log leaf. Suppose that $\Delta = 0$. Suppose moreover that $-K_{\mathcal{H}} \sim_{\mathbb{Q}} P + N$ where $P$ is a nef $\mathbb{Q}$-divisor and $N = \sum_{i \in I} N_i$ is an effective $\mathbb{Q}$-divisor such that $(F, N_{iF})$ is canonical. Suppose furthermore that $N_i$ is not invariant by $\mathcal{H}$ for any $i \in I$. Then $(\mathcal{H}, N)$ is canonical.

\textbf{Proof.} Let $\psi: Z \to Y$ be the family of leaves, and let $\nu: Z \to X$ be the natural morphism (see \ref{prop:natural-morphism}). Let $\nu_1: Z_1 \to Z$ be a birational morphism with $Z_1$ smooth and projective. We obtain a commutative diagram

$$
\begin{array}{ccc}
Z_1 & \xrightarrow{\nu_1, \text{birational}} & Z \\
\downarrow{\psi_1} & & \downarrow{\psi} \\
Y & \xrightarrow{\nu} & X
\end{array}
$$

Denote by $\mathcal{H}_{Z_1}$ the foliation on $Z_1$ induced by $\mathcal{H}$. Let $E_1$ be the $\nu \circ \nu_1$-exceptional $\mathbb{Q}$-divisor such that

$$
K_{\mathcal{H}_{Z_1}} + N_1 = (\nu \circ \nu_1)^*(K_{\mathcal{H}} + N) + E_1,
$$

where $N_1$ denotes the proper transform of $N$ in $Z_1$. To prove the lemma, it is enough to show that $E_1$ is effective. Denote by $F_1$ the proper transform of $F$ in $Z_1$. Note that we have $K_{\mathcal{H}_{|F}} \sim_{\mathbb{Q}} K_{F}$ since $\Delta = 0$. Since $(F, N_{iF})$ is canonical, the restriction $E_{1F}$ of $E_1$ to $F$ is effective, and $(F_1, N_{iF_1})$ is canonical as well (see [Ko97] Lemma 3.10). Let $H$ be an ample (effective) divisor on $Z_1$, let $\varepsilon > 0$ be a rational number, and let $A_{\varepsilon} \sim_{\mathbb{Q}} (\nu \circ \nu_1)^*P + \varepsilon H$ such that $(F_1, N_{iF_1} + A_{\varepsilon})$ is canonical. We have

$$
K_{F_1} + N_{1F_1} = (\nu_1|F_1)^*(K_{F} + N_{F}) + E_{1F_1} \sim_{\mathbb{Q}} (\nu|F_1)^*(P_{F}) + E_{1F_1}
$$

by \ref{lem:divisor-properties} using \ref{thm:canonical-properties}, and the fact that $\Delta = 0$, and hence

$$
\kappa(F_1, K_{F_1} + N_{1F_1} + A_{\varepsilon}) = \kappa(F_1, E_{1F_1} + \varepsilon H_{F_1}) = \dim F_1 \geq 0.
$$

By Proposition \ref{prop:effective-conditions} applied to $\mathcal{H}_{Z_1}$, and $L = A_{\varepsilon} + N_1 \sim_{\mathbb{Q}} (\nu \circ \nu_1)^*P + \varepsilon H + N_1$, we conclude that

$$
K_{\mathcal{H}_{Z_1}} + A_{\varepsilon} + N_1 \sim_{\mathbb{Q}} K_{\mathcal{H}_{Z_1}} + (\nu \circ \nu_1)^*P + \varepsilon H + N_1
$$

is pseudo-effective for any $0 < \varepsilon \ll 1$, and hence $K_{\mathcal{H}_{Z_1}} + (\nu \circ \nu_1)^*P + N_1$ is pseudo-effective as well. Also, by \ref{lem:divisor-properties}, we have

$$
K_{\mathcal{H}_{Z_1}} + (\nu \circ \nu_1)^*P + N_1 = E_1.
$$

By a result of Lazarsfeld ([KL10] Corollary 13), the $\nu \circ \nu_1$-exceptional $\mathbb{Q}$-divisor $E_1$ is pseudo-effective if and only if it is effective, completing the proof of the proposition. \hfill \Box

The proof of the next Proposition is similar to that of Proposition \ref{prop:canonical-conditions}. One only needs to replace the use of Proposition \ref{prop:natural-morphism} with Proposition \ref{prop:birational-morphisms}.

\textbf{Proposition 6.1.} Let $\varphi: X \to Y$ be a dominant morphism of normal projective varieties with general fiber $F$. Suppose that $Y$ is smooth, and that $\varphi$ has connected fibers. Suppose moreover that $-K_{X/Y} \sim_{\mathbb{Q}} P + N$ where $P$ is a nef $\mathbb{Q}$-divisor and $N$ is an effective $\mathbb{Q}$-divisor such that $(F, N_{iF})$ is canonical. Then $(X, N)$ has canonical singularities.

\section{Foliations with Nef Anti-Canonical Bundle}

In this section, we provide another technical tool for the proof of the main results. The following result is the main observation of this paper. Note that Proposition \ref{prop:birational-morphisms} is an immediate consequence of Proposition \ref{prop:effective-conditions} and Lemma \ref{lem:divisor-properties} below.

\textbf{Proposition 6.1.} Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a foliation. Suppose that $-K_{\mathcal{F}} \equiv P + N$ where $P$ is a nef $\mathbb{Q}$-divisor and $N$ is an effective $\mathbb{Q}$-divisor such that $(X, N)$ is log canonical. Suppose that the algebraic part $\mathcal{H}$ of $\mathcal{F}$ has a compact leaf. Let $\psi: Z \to Y$ be the family of leaves of $\mathcal{H}$, and let $\nu: Z \to X$ be the natural morphism. Set $\varphi := \psi \circ \nu^{-1}: X \to Y$, let $\mathcal{G}$ be the foliation on $Y$ such that $\mathcal{F} = \varphi^{-1}\mathcal{G}$, and let $\mathcal{H}_Z$ be the foliation on $Z$ induced by $\mathcal{H}$. Then

\begin{enumerate}
\item $\varphi^*K_{\mathcal{G}} \equiv 0$,
\item $K_{\mathcal{H}} \equiv K_{\mathcal{F}}$, and
\item $K_{\mathcal{H}_Z} \sim \nu^*K_{\mathcal{F}}$.
\end{enumerate}
Proof. We subdivide the proof into a number of relatively independent steps.

**Step 1.** By assumption, \( \varphi \) is an almost proper map: there exist dense Zariski open sets \( X^* \subset X \) and \( Y^* \subset Y \) such that the the restriction \( \varphi^* \) of \( \varphi \) to \( X^* \) induces a proper morphism \( \varphi^*: X^* \to Y^* \). Moreover, the following holds:

\[ \odot \] there is no positive-dimensional algebraic subvariety passing through a general point of \( Y \) that is tangent to \( \mathcal{G} \).

**Step 2.** Let \( A \) be an ample divisor on \( X \). Note that \( F \) is smooth. There exists an open set \( U \supset F \) such that \( \mathcal{H}_U \) is a subbundle of \( \mathcal{F}_U \), \( \mathcal{G}_U \) is locally free, and \( (\mathcal{F} / \mathcal{H})|_U \cong \mathcal{G}^*|_U \). In particular, \( K_{\mathcal{H}|F} \sim K_{\mathcal{F}|F} \sim K_F \). Let \( \varepsilon > 0 \) be a rational number. Then \( K_F - K_{\mathcal{H}|F} + \varepsilon A|_F \equiv \varepsilon A|_F \) is \( \mathbb{Q} \)-ample, and hence \( \kappa(F, K_F + P|_F + N|_F + \varepsilon A|_F) \geq 0 \). Since \( P + \varepsilon A \) is \( \mathbb{Q} \)-ample, there exists an effective \( \mathbb{Q} \)-divisor \( A_\varepsilon \sim_\mathbb{Q} P + \varepsilon A \) such that the pair \((X, N + A_\varepsilon)\) is log canonical. From [Kol97, Theorem 4.8], we conclude that \((F, N|_F + A|_F)\) is log canonical.

By Proposition 4.1 applied to the foliation \( H \) on \( X \) and \( L := A_\varepsilon + N \), we conclude that \( K_{\mathcal{H}} + P + N + \varepsilon A \equiv K_{\mathcal{H}} - K_{\mathcal{G}} + \varepsilon A \) is pseudo-effective for any positive rational number \( \varepsilon > 0 \). It follows that \( K_{\mathcal{H}} - K_{\mathcal{G}} \) is pseudo-effective.

**Step 3.** We will show that \( (K_{\mathcal{H}} - K_{\mathcal{G}}) \cdot A^{\dim X - 1} \leq 0 \). Note that \( \psi: Z \to Y \) is equidimensional. Thus, by 2.9 there is an effective divisor \( R \) on \( X \) such that

\[ K_{\mathcal{H}} - K_{\mathcal{G}} = -(\varphi^* K_{\mathcal{G}} + R). \]

To prove that \( (K_{\mathcal{H}} - K_{\mathcal{G}}) \cdot A^{\dim X - 1} \leq 0 \), it is enough to show that \( \varphi^* K_{\mathcal{G}} \cdot A^{\dim X - 1} \geq 0 \). We argue by contradiction, and we assume that \( \varphi^* K_{\mathcal{G}} \cdot A^{\dim X - 1} < 0 \). By Proposition 3.12 there exists a saturated subsheaf \( \mathcal{E} \subset \mathcal{G} \) satisfying the following property. Let \( C \) be a general complete intersection curve of type \( m \nu^* A \) with \( m \) sufficiently large. Then \( \psi^* \mathcal{E}_C \) is the maximally destabilizing subsheaf of \( \psi^* \mathcal{G}_C \). By our current assumption, we have \( \deg(\psi^* \mathcal{G}_C) > 0 \) so that we must have \( \deg(\psi^* \mathcal{E}_C) > 0 \). This implies that \( \psi^* \mathcal{E}_C \) is ample. We conclude that \( \mathcal{E}|_B \) is an ample vector bundle, where \( B := \psi(C) \). By [KSC10, Proposition 30], we have \( \text{Hom}_C(\psi^* \mathcal{E}_C \otimes \psi^* \mathcal{G}_C, \psi^* \mathcal{G}_C/\psi^* \mathcal{E}_C) = 0 \) and thus \( \text{Hom}_C(\mathcal{E} \otimes \mathcal{E}, \mathcal{G} / \mathcal{E}) = 0 \). Since \( \mathcal{G} \) is closed under the Lie bracket, it follows that \( \mathcal{E} \) is a foliation. By Theorem 3.10 we conclude that the leaf of \( \mathcal{E} \) through any point of \( B \) is algebraic. But this contradicts \( \odot \) above. This proves that \( \varphi^* K_{\mathcal{G}} \cdot A^{\dim X - 1} \geq 0 \), and \( (K_{\mathcal{H}} - K_{\mathcal{G}}) \cdot A^{\dim X - 1} \leq 0 \).

**Step 4.** By Steps 2 and 3, we must have \( (K_{\mathcal{H}} - K_{\mathcal{G}}) \cdot A^{\dim X - 1} = 0 \). From [GT13, Proposition 6.5], we conclude that

\[ K_{\mathcal{H}} \equiv K_{\mathcal{G}}. \]

This proves (2). Note also that we must have \( \varphi^* K_{\mathcal{G}} = 0 \), proving (1).

**Step 5.** Let \( \mathcal{H}_Z \) be the foliation on \( Z \) induced by \( \mathcal{H} \). We show that

\[ K_{\mathcal{H}_Z} \sim \nu^* K_{\mathcal{H}}. \]

Note that \( K_{\mathcal{H}_Z} = K_{Z/Y} - R(\psi) \) by 2.9. Up to replacing \( P \) with \( K_{\mathcal{H}} - N \) if necessary, we may assume that \( K_{\mathcal{H}} = P + N \). By 2.13 there is an effective Weil \( \mathbb{Q} \)-divisor \( B \) on \( Z \) such that

\[ K_{\mathcal{H}_Z} + B \sim \nu^* K_{\mathcal{H}}, \]

and hence

\[ K_{\mathcal{H}_Z} + \nu^* P + \nu^* N \sim -B. \]

Note that \( \text{Supp}(B) \cap F = \emptyset \). The same argument used in Step 2 shows that \( K_{\mathcal{H}_Z} + \nu^* P + \nu^* N \) is pseudo-effective. One only needs to replace the use of Proposition 1.11 with Corollary 1.3. Since \( K_{\mathcal{H}_Z} + \nu^* P + \nu^* N \sim -B \), we conclude that \( B = 0 \). This completes the proof of the proposition.

**Lemma 6.2.** Let \( X \) be a complex projective manifold, and let \( \mathcal{F} \subset T_X \) be a foliation. Suppose that either \( \mathcal{F} \) is regular, or that \( \mathcal{F} \) has a compact leaf. Then the algebraic part \( \mathcal{H} \) of \( \mathcal{F} \) has a compact leaf.

**Proof.** By [LPT11, Section 2.4], there exist a normal projective variety \( Y \), a dominant rational map \( \varphi: X \dashrightarrow Y \), and a foliation \( \mathcal{G} \) on \( Y \) such that the following holds:
(a) there is no positive-dimensional algebraic subvariety passing through a general point of $Y$ that is tangent to $\mathcal{G}$; and

(b) $\mathcal{F}$ is the pull-back of $\mathcal{G}$ via $\varphi$.

Note that $\mathcal{H}$ is the foliation on $X$ induced by $\varphi$. After replacing $Y$ with a birationally equivalent variety, we may assume that $Y$ is the family of leaves of $\mathcal{H}$. Let $Z$ be the normalization of the universal cycle over $Y$. It comes with morphisms $\psi: Z \to Y$, and $\nu: Z \to X$ (see [2.13]).

To prove the lemma, we have to show that $\psi(\text{Exc}(\nu)) \subseteq Y$. We argue by contradiction and assume that $\psi(\text{Exc}(\nu)) = Y$.

Let $F$ be the closure of a general fiber of $\varphi$. Denote by $S$ the (possibly empty) singular locus of $\mathcal{F}$. Then $F \cap S = \emptyset$. Indeed, suppose that $S \neq \emptyset$, and consider a compact $L$ leaf of $\mathcal{F}$. Pick $y \in Y$ such that $Z_y \cap L \neq \emptyset$. Then $Z_y \subset L$, and hence $Z_y \cap S = \emptyset$. Thus, if $y'$ is sufficiently close to $y$, then $Z_{y'} \cap S = \emptyset$, proving our claim.

By Zariski's Main Theorem, there is an integral (complete) curve $C \subset Z$ with $\dim \nu(C) = 0$ and $\nu(C) \in F$. Set $B := \psi(C)$, and note that $\dim B = 1$. Then $\nu(\psi^{-1}(B)) \supseteq F$ is tangent to $\mathcal{F}$ since $\mathcal{F}$ is regular in a neighborhood of $F$, and $\dim \nu(\psi^{-1}(B)) = \dim F + 1$. This implies that $B$ is tangent to $\mathcal{G}$, yielding a contradiction and proving the lemma. \qed

We believe that the following result will be useful when considering arbitrary (regular) foliations.

**Proposition 6.3.** Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a foliation. Let $\mathcal{H}$ be the algebraic part of $\mathcal{F}$. Suppose that $\mathcal{H}$ is induced by an almost proper map $\varphi: X \to Y$, and let $\mathcal{G}$ be the foliation on $Y$ such that $\mathcal{F} = \varphi^{-1}\mathcal{G}$. Then $\mu_{\text{top}}^\mathcal{H}(\mathcal{G})$ $\leq$ 0 for any ample divisor $A$ on $X$.

**Proof.** This follows easily from Steps 1 and 3 of the proof of Proposition 6.1 using the Mehta-Ramanathan theorem. \qed

7. Proofs

In this section we prove Theorem 7.1 and Corollary 7.3.

**Theorem 7.1.** Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a codimension $q$ foliation with $0 < q < \dim X$. Suppose that the algebraic part $\mathcal{H}$ of $\mathcal{F}$ has a compact leaf. Suppose furthermore that $-K_{\mathcal{F}} \equiv A + E$ where $A$ is a $\mathbb{Q}$-ample $\mathbb{Q}$-divisor and $E$ is an effective $\mathbb{Q}$-divisor. Then $(X, E)$ is not log canonical.

**Proof.** Argue by contradiction, and assume that $(X, E)$ is log canonical. There exist a dense open subset $X^0 \subset X$, a normal variety $Y^0$, and a proper morphism $\varphi^0: X^0 \to Y^0$ such that $\mathcal{H}$ is the foliation on $X$ induced by $\varphi^0$. By Proposition 6.1, we have $K_{\mathcal{H}} \equiv K_{\mathcal{F}}$. Note that $\dim Y^0 < \dim X^0$ since $K_{\mathcal{F}} \not\equiv 0$. Set $A' := -K_{\mathcal{F}} - E$. Then $A'$ is $\mathbb{Q}$-ample, and $-K_{\mathcal{F}} = A' + E$.

Let $y$ be a general point in $Y$, and denote by $X_y$ the corresponding fiber of $\varphi$. The pair $(X_y, E|_{X_y})$ is log canonical by [Kol87, Theorem 4.8]. Also, note that $X_y$ is smooth. Let $0 < \varepsilon < 1$ a rational number such that $A' + \varepsilon E$ is $\mathbb{Q}$-ample, and such that $(X_y, (1 - \varepsilon)E|_{X_y})$ is klt. Then $-K_{\mathcal{F}} = (A' + \varepsilon E) + (1 - \varepsilon)E$. But this contradicts Proposition 4.6 applied to $\mathcal{H}$. \qed

Note that Theorem 7.1 and Corollary 7.3 are consequences of Theorem 7.2 and Corollary 7.3 respectively using Lemma 6.2.

**Theorem 7.2.** Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a codimension $q$ foliation with $0 < q < \dim X$. Suppose that the algebraic part $\mathcal{H}$ of $\mathcal{F}$ has a compact leaf. Then $-K_{\mathcal{F}}$ is not nef and big.

**Proof.** Write $-K_{\mathcal{F}} = A + E$ where $A$ is a $\mathbb{Q}$-ample $\mathbb{Q}$-divisor, and $E$ is an effective $\mathbb{Q}$-divisor. Let $0 < \varepsilon < 1$ be a rational number such that $(X, \varepsilon E)$ is klt. Note that $A_\varepsilon := -K_{\mathcal{F}} - \varepsilon E$ is $\mathbb{Q}$-ample. This contradicts Theorem 7.1 proving Theorem 7.1. \qed

**Corollary 7.3.** Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a codimension 1 foliation. Suppose that the algebraic part $\mathcal{H}$ of $\mathcal{F}$ has a compact leaf. Suppose furthermore that $-K_{\mathcal{F}}$ is nef. Then $\kappa(X, -K_{\mathcal{F}}) \leq \dim X - 1$.

**Proof.** By Theorem 7.2 we must have $\nu(-K_{\mathcal{F}}) \leq \dim X - 1$. Thus $\kappa(X, -K_{\mathcal{F}}) \leq \nu(-K_{\mathcal{F}}) \leq \dim X - 1$ by [Kaw85, Proposition 2.2]. \qed
Lemma 8.2. Let $\kappa$ and $\nu$. Recall that the numerical dimension $Q$ of $P$ is the largest positive integer $k$ such that $P^k \neq 0$. We have $\kappa(X, P) \leq \nu(P)$ by [Kaw85, Proposition 2.2], and we say that $P$ is abundant if equality holds.

By [Kaw85, Proposition 2.1], $P$ is abundant if and only if there is a diagram of normal projective varieties

$$
\begin{array}{ccc}
Z & \xrightarrow{f} & T \\
\downarrow & & \downarrow \\
X & \xrightarrow{\nu} & Y
\end{array}
$$

and a nef and big $Q$-Cartier $Q$-divisor $D$ on $T$ such that $\nu^* P \sim Q f^* D$, where $\nu$ is a birational morphism, and $f$ is surjective.

We will need the following easy observation.

**Lemma 8.2.** Let $P$ be a nef and abundant $Q$-Cartier $Q$-divisor on a normal projective variety $X$. With the above notation, write $D = A + E$ where $A$ is a $Q$-ample $Q$-divisor, and $E$ is an effective $Q$-divisor. Let $F \subseteq X$ be a subvariety not contained in $\nu(P_{Z/Y} \cup f^{-1}(\text{Supp}(E)))$. Then $P_{1/F}$ is nef and abundant, and $\nu(P_{1/F}) = \dim f(\tilde{F})$, where $\tilde{F}$ denotes the proper transform of $F$ in $Z$.

**Proof.** Note that $f(\tilde{F}) \not\subseteq E$, and thus $D_{1/F}(\tilde{F})$ is nef and big. The lemma follows easily. \qed

The following observation will prove to be crucial.

**Lemma 8.3.** Let $X$ and $Y$ be normal projective varieties, and let $\varphi: X \dashrightarrow Y$ be an almost proper map with general fiber $F$. Let $\mathcal{F}$ be the induced foliation on $X$. Suppose that $\mathcal{F}$ is $Q$-Gorenstein. Suppose moreover that $-K_{\mathcal{F}} \equiv P$ where $P$ is nef and abundant, and that $-K_{\mathcal{F}1/F} = -K_F$ is nef and abundant. Then $\nu(-K_{\mathcal{F}}) \leq \nu(-K_F)$.

**Proof.** Let $\psi: Z \to Y$ be the family of leaves of $\mathcal{F}$, and let $\nu: Z \to X$ be the natural morphism (see 2.13). By Lemma 4.2 there exists a finite surjective morphism $\mu_1: Y_1 \to Y$ with $Y_1$ normal and connected satisfying the following property. If $Z_1$ denotes the normalization of the product $Y_1 \times_Y Z$, then the induced morphism $\psi_1: Z_1 \to Y_1$ has reduced fibers over codimension one points in $Y_1$. Denote by $\nu_1: Z_1 \to Z$ the natural morphism.

By Proposition 6.1 and 2.9 we have

$$
K_{Z/Y} - R(\psi) \sim \nu^* K_{\mathcal{F}}.
$$

A straightforward computation shows that

$$
\nu_1^*(K_{Z_1/Y_1} - R(\psi)) = K_{Z_1/Y_1}.
$$

We conclude that $-K_{Z_1/Y_1} \equiv Q$-Cartier, and that $-K_{Z_1/Y_1} \equiv P_1$, where $P_1 := (\nu_1 \circ \nu)^* P$.

By [Kaw85, Proposition 2.1] applied to $P_1$, there exist an almost proper morphism $f_3: Z_3 \to T_3$ of normal projective varieties, a birational morphism $\nu_3: Z_3 \to Z_1$, and a nef and big $Q$-Cartier $Q$-divisor $D_3$ on $T_3$ such that $\nu_3^* P_1 \sim Q f_3^* D_3$. We obtain a commutative diagram

$$
\begin{array}{ccc}
Z_3 & \xrightarrow{\nu_3, \text{ birational}} & Z_1 & \xrightarrow{\nu_1, \text{ finite}} & Z & \xrightarrow{\nu, \text{ birational}} & X \\
\downarrow f_3 & & \downarrow \psi_1 & & \downarrow \psi & & \downarrow \psi \\
T_3 & \xrightarrow{\mu_1, \text{ finite}} & Y_1 & \xrightarrow{\psi_1} & Y
\end{array}
$$

We view $F$ as a fiber of $\psi$. Let $F_1$ be a fiber of $\psi_1$ such that $\nu_1(F_1) = F$. Note that the restriction of $\nu_1$ to $F_1$ induces an isomorphism $F_1 \cong F$. Let $\tilde{F}_1$ be the proper transform of $F_1$ in $Z_3$. We also have that $P_1|_{F_1} = P_{1/F} = -K_F$. By Lemma 8.2 above, we obtain that $\dim f_3(\tilde{F}_1) = \nu(P_1|_{F_1}) = \nu(-K_F)$.  

---

**Question 7.4.** Given a regular foliation $\mathcal{F}$ of rank $r$ on a complex projective manifolds with $-K_{\mathcal{F}}$ nef, do we have $\kappa(X, -K_{\mathcal{F}}) \leq r$?
We argue by contradiction, and assume that $\dim T_2 = \nu(-K_\mathcal{F}) > \nu(-K_F)$. Let $Y_2 \subset Y_1$ be a general complete intersection curve, and set $Z_2 := \psi_Y^{-1}(Y_2) \subset Z_1$. It comes with a morphism $\psi_2: Z_2 \to Y_2$. Let $\tilde{Z}_2$ be the proper transform of $Z_2$ in $Z_3$. Then $\dim f_3(\tilde{Z}_2) = \dim f_3(F) + 1 = \nu(-K_F) + 1$, and thus $\nu(-K_{Z_2/Y_1}|_{Z_2}) = \nu(P|_{Z_2}) = \nu(-K_F) + 1$ by Lemma 8.2 again. By the adjunction formula, we have $K_{Z_2/Y_1}|_{Z_2} \sim K_{\tilde{Z}_2/Y_2}$. This gives
$$\nu(-K_{\tilde{Z}_2/Y_2}) = \nu(-K_F) + 1.$$  
By proposition 5.6, $Z_2$ has canonical singularities, and by [Fuj11, Theorem 1.1], $-K_{Z_2/Y_2}$ is $\psi_2$-semi-ample. Therefore, there exist a $Y_2$-morphism $f_2: Z_2 \to T_2$ with connected fibers onto a normal projective variety, and a $\mathbb{Q}$-Cartier $\mathbb{Q}$-divisor $M$ on $T_2$ ample over $Y_2$ such that $-K_{Z_2/Y_2} \sim f_2^* M$.

By Ambro’s canonical bundle formula [Amb05, Theorem 4.1], there exists an effective $\mathbb{Q}$-divisor $B_2$ on $T_2$ such that $(T_2, B_2)$ is klt and $K_{Z_2} \sim Q f_2^*(K_{T_2} + B_2)$.

Thus $K_{Z_2/Y_2} \sim f_2^*(K_{T_2/Y_2} + B_2)$, and hence $-(K_{T_2/Y_2} + B_2)$ is nef with
$$\nu(-(K_{T_2/Y_2} + B_2)) = \nu(-K_{Z_2/Y_2}) = \nu(-K_F) + 1 = \dim T_2.$$  
But this contradicts [AD13, Theorem 5.1] (see also Proposition 1.6), completing the proof of the lemma. □

Corollary 8.4. Let $X$ be a complex projective manifold, let $Y$ be a normal projective variety, and let $\varphi: X \dashrightarrow Y$ be an almost proper map with general fiber $F$. Let $\mathcal{F}$ be the induced foliation on $X$. Suppose that $\mathcal{F}$ is $\mathbb{Q}$-Gorenstein. Suppose furthermore that $-K_\mathcal{F}$ is nef and abundant with $\nu(-K_\mathcal{F}) = \dim X - \dim Y$. Then $-K_F$ is nef and big, and $-K_\mathcal{F}$ is semiample.

Proof. Note first that $-K_F$ is nef and abundant by Lemma 8.2. Then, apply Lemma 8.3 to conclude that $-K_F$ is nef and big. In particular, $-K_\mathcal{F}$ is semiample. By [Kaw88, Proposition 2.1] applied to $-K_\mathcal{F}$, there exist a surjective morphism $f: Z \to T$ of normal projective varieties, a birational morphism $\nu: Z \to X$, and a nef and big $\mathbb{Q}$-Cartier $\mathbb{Q}$-divisor $D$ on $T$ such that

$$\nu^*(-K_\mathcal{F}) \sim Q f^* D.$$  
Let $\tilde{F}$ denote the proper transform of $F$ in $Z$. The restriction $f|_{\tilde{F}}: \tilde{F} \to T$ of $f$ to $\tilde{F}$ is generically finite by Lemma 8.2 and 8.1 reads
$$-\nu|_{\tilde{F}}^* K_F \sim Q f|_{\tilde{F}}^* D.$$  
Since $-K_F$ is semiample, we conclude that $D$ is semiample as well, and hence so is $-K_\mathcal{F}$. □

Corollary 8.5. Let $X$ be a complex projective manifold, and let $\varphi: X \to Y$ be a morphism onto a smooth complete curve with connected general fiber $F$. Denote by $\mathcal{F}$ the induced foliation on $X$. Suppose that $-K_\mathcal{F}$ is nef and $\kappa(X, -K_\mathcal{F}) = \dim X - 1$. Then $-K_F$ is nef and big, and $-K_\mathcal{F}$ is semiample.

Proof. Note that $-K_\mathcal{F}$ is nef and abundant by Theorem 1.1. The claim then follows from Corollary 8.4. □

The proof of the next lemma is similar to that of Lemma 8.3.

Lemma 8.6. Let $\varphi: X \to Y$ be a morphism of normal projective varieties with general fiber $F$. Suppose that there exists a $\mathbb{Q}$-Cartier divisor $K$ on $X$ such that $K|_{\varphi^{-1}(Y_m)} \sim K_{\varphi^{-1}(Y_m)}/Y_m$. Suppose furthermore that $K$ is nef and abundant. Then $\nu(-K) \leq \nu(-K_F)$.

The same argument used in the proof of Corollary 8.5 shows that the following holds. One only needs to replace the use of Theorem 1.1 with [AD13, Theorem 5.1], and the use of Lemma 8.3 with Lemma 8.6.

Corollary 8.7. Let $X$ be a complex projective manifold, and let $\varphi: X \to Y$ be a morphism onto a smooth complete curve with connected general fiber $F$. Suppose that $-K_X/Y$ is nef and $\kappa(X, -K_X/Y) = \dim X - 1$. Then $-K_F$ is nef and big, and $-K_X/Y$ is semiample.

Note that Theorem 1.5 is an immediate consequence of Theorem 8.8 and Lemma 6.2.
Proof. By assumption, $\mathcal{F}$ is induced by an almost proper map $\varphi: X \to Y$. By Proposition 6.1 we have $K_{\mathcal{F}} \equiv K_{\mathcal{F}}$. Let $\mathcal{G}$ be the foliation on $Y$ such that $\mathcal{F} = \varphi^{-1}\mathcal{G}$. There exists an open set $U \supset \mathcal{F}$ contained in $X$ such that $\mathcal{H}|_{\mathcal{G}}$ is a subbundle of $\mathcal{F}|_{\mathcal{U}}$, $\mathcal{G}|_{\mathcal{U}}$ is locally free, and $(\mathcal{F}/\mathcal{H})|_{\mathcal{U}} \cong \varphi^*\mathcal{G}|_{\mathcal{U}}$. In particular, we have $K_{\mathcal{F}}|_{\mathcal{F}} \sim K_{\mathcal{G}}|_{\mathcal{F}}$, and hence $-K_{\mathcal{F}}$ is nef and abundant by Lemma 8.2. Then

$$
\kappa(X, -K_{\mathcal{F}}) = \nu(-K_{\mathcal{F}}) \quad \text{since } -K_{\mathcal{F}} \text{ is nef and abundant}
$$

$$
= \nu(-K_{\mathcal{F}}) \quad \text{since } K_{\mathcal{G}} \equiv K_{\mathcal{F}}
$$

$$
\leq \nu(-K_{\mathcal{F}}) \quad \text{by Lemma 8.3}
$$

$$
\leq \dim F = \text{rank } \mathcal{H}
$$

$$
\leq \text{rank } \mathcal{F} = \dim X - q \quad \text{since } \mathcal{H} \subset \mathcal{F}.
$$

Suppose that $\kappa(X, -K_{\mathcal{F}}) = \dim X - q$. Then we must have rank $\mathcal{H} = \text{rank } \mathcal{F}$. Thus $\mathcal{H} = \mathcal{F}$, and hence $\mathcal{F}$ is algebraically integrable. This completes the proof of Theorem 8.8.

Corollary 8.9. Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a codimension 1 foliation. Suppose that either $\mathcal{F}$ is regular, or that $\mathcal{F}$ has a compact leaf. Suppose furthermore that $-K_{\mathcal{F}}$ is nef and $\kappa(X, -K_{\mathcal{F}}) = \dim X - 1$. Then $\mathcal{F}$ is algebraically integrable.

Proof. Note that $-K_{\mathcal{F}}$ is abundant by Corollary 1.4. The claim then follows from Theorem 1.5.

The remainder of the present section is devoted to the proof of Theorem 1.7.

Lemma 8.10. Let $X$ be a complex projective manifold, and let $\mathcal{F} \subset T_X$ be a regular codimension 1 foliation. Suppose that $-K_{\mathcal{F}}$ is nef and $\kappa(X, -K_{\mathcal{F}}) = \dim X - 1$. Then $\mathcal{F}$ is induced by a smooth morphism $X \to Y$ onto a smooth complete curve $Y$ of genus $g(Y) = h^1(X, \mathcal{O}_X)$.

Proof. By Corollary 8.9, $\mathcal{F}$ is algebraically integrable. So let $\varphi: X \to Y$ be a first integral, with general fiber $F$. By Corollary 8.3, $-K_{\mathcal{F}}$ is nef and big. Let $F_1 = mF_0$ be any fiber of $\varphi$, where $m$ is a positive integer. By the adjunction formula, we have $K_{F_0} = (K_X + F_0)|_{F_0}$, and hence

$$
K_{F_0}^{\dim X - 1} = (K_X + F_0)^{\dim X - 1} : F_0 = (K_{X/Y} - (m - 1)F_0)^{\dim X - 1} : F_0
$$

$$
= K_{\mathcal{F}}^{\dim X - 1} : F_0 = \frac{1}{m}K_{\mathcal{F}}^{\dim X - 1} : F_1 = \frac{1}{m}K_{\mathcal{F}}^{\dim X - 1} : F = \frac{1}{m}K_{\mathcal{F}}^{\dim X - 1} > 0.
$$

Moreover, $K_{F_0} = (K_X + F_0)|_{F_0} \sim (K_X - (m - 1)F_0)|_{F_0} \sim K_{\mathcal{F}}|_{F_0}$ is nef by assumption. In particular, $\pi_1(F_0) = \{1\}$ (see [Zha06]). By the holomorphic version of Reeb stability theorem, we conclude that $\varphi$ is a smooth morphism.

By the Kawamata-Viehweg vanishing theorem, we have $R^1\varphi_*\mathcal{O}_X = 0$. The Leray spectral sequence then yields $h^1(X, \mathcal{O}_X) = h^1(Y, \mathcal{O}_Y)$. This completes the proof of the lemma.

Proof of Theorem 1.7. Let $X$ be a complex projective manifold with $h^1(X, \mathcal{O}_X) = 0$, and let $\mathcal{F} \subset T_X$ be a codimension 1 regular foliation. Suppose that $-K_{\mathcal{F}}$ is nef and $\kappa(X, -K_{\mathcal{F}}) = \dim X - 1$.

By Lemma 8.10, $\mathcal{F}$ is induced by a smooth morphism $\varphi: X \to \mathbb{P}_1$. In particular, $K_{\mathcal{F}} = K_{X/\mathbb{P}_1}$. Now, observe that $-K_X = -K_{X/\mathbb{P}_1} - \varphi^*K_{\mathbb{P}_1}$ is nef, and that

$$
(-K_X)^{\dim X} = (-K_{X/\mathbb{P}_1} - \varphi^*K_{\mathbb{P}_1})^{\dim X} = 2 \dim X(-K_{F})^{\dim F} > 0.
$$

In other words, $X$ is a weak Fano manifold. Let $F$ be a general fiber of $\varphi$. Let $R = \mathbb{R}_{\geq 0}[\ell] \subset \text{NE}(X)$ be an extremal ray with $F \cdot \ell > 0$. Let $\psi_R: X \to Z$ be the corresponding contraction. Note that any fiber of $\psi_R$ has dimension $\leq 1$. Thus, $Z$ is smooth and either $\psi_R: X \to Z$ is the blow up of a codimension 2 subvariety, or $\psi_R: X \to Z$ is a conic bundle by [Wis91, Theorem 1.2].

Suppose first that $\psi_R: X \to Z$ is the blow up of a codimension 2 subvariety. Then, up to replacing $\ell$ with a numerically equivalent curve on $X$, we may assume that $-K_X \cdot \ell = 1$. On the other hand,

$$
-K_X \cdot \ell = (-K_{X/\mathbb{P}_1} - \varphi^*K_{\mathbb{P}_1}) \cdot \ell \geq 2F \cdot \ell \geq 2,
$$

...
yielding a contradiction. This proves that $\psi_R : X \to Z$ is a conic bundle. Arguing as above, we conclude that $\psi_R : X \to Z$ is a smooth conic bundle, and that $F \cdot \ell = 1$. This implies that the morphism $\varphi \times \psi_R : X \to \mathbb{P}^1 \times Z$ is birational. On the other hand, it is finite, and hence $X \cong \mathbb{P}^1 \times F$, proving the theorem.

**Question 8.11.** Given a smooth morphism $X \to Y$ onto a smooth complete curve $Y$ with $g(Y) \geq 1$ such that $-K_{X/Y}$ is nef and $\kappa(X, -K_{X/Y}) = \dim X - 1$, do we have $X \cong Y \times F$?

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