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► **To cite this version:**

Vincent Guedj, Henri Guenancia, Ahmed Zeriahi. Continuity of singular Kähler-Einstein potentials. International Mathematics Research Notices, In press. hal-03039820v1

**HAL Id: hal-03039820**

**<https://hal.science/hal-03039820v1>**

Submitted on 4 Dec 2020 (v1), last revised 6 Oct 2021 (v2)

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# CONTINUITY OF SINGULAR KÄHLER-EINSTEIN POTENTIALS

by

Vincent Guedj, Henri Guenancia & Ahmed Zeriahi

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*Abstract.* — In this note, we investigate some regularity aspects for solutions of degenerate complex Monge-Ampère equations (DCMAE) on singular spaces.

First, we study the Dirichlet problem for DCMAE on singular Stein spaces, showing a general continuity result. A consequence of our results is that Kähler-Einstein potentials are continuous at isolated singularities.

Next, we establish the global continuity of solutions to DCMAE when the reference class belongs to the real Néron-Severi group. This yields in particular the continuity of Kähler-Einstein potentials on any irreducible Calabi-Yau variety. We show that the associated singular Kähler-Einstein metrics are strictly positive when the variety is moreover smoothable.

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## Introduction

Generalizing Yau’s solution of the Calabi conjecture [Yau78], singular Kähler-Einstein metrics on mildly singular Kähler varieties  $X$  have been constructed in [EGZ09] and further studied by many authors (see [GZ17, Bou18, Don18] and the references therein). These are honest Kähler forms  $\omega_{\text{KE}} = \omega + dd^c \varphi_{\text{KE}}$  on the regular part  $X_{\text{reg}}$  of  $X$ , where  $c_1(X) = \lambda[\omega]$  is proportional to a reference Kähler class  $[\omega]$ , s.t.

$$\text{Ric}(\omega_{\text{KE}}) = \lambda\omega_{\text{KE}}.$$

One constructs  $\omega_{\text{KE}} = \omega + dd^c \varphi_{\text{KE}}$  by solving a degenerate complex Monge-Ampère equation

$$(0.1) \quad (\omega + dd^c \varphi_{\text{KE}})^n = e^{-\lambda\varphi_{\text{KE}}} \mu_X,$$

where  $n = \dim_{\mathbb{C}} X$  and  $\mu_X$  is an appropriate volume form.

Understanding the asymptotic behavior of  $\varphi_{\text{KE}}$  near  $X_{\text{sing}}$  is a major open problem. A very precise description has been obtained by Hein-Sun in [HS17], when the singularities are isolated and furthermore isomorphic to a smoothable strongly regular Calabi-Yau cone. It would be highly desirable to extend this description to more general contexts, but this seems presently out of reach.

It has been shown in [EGZ09] that  $\varphi_{\text{KE}}$  is always uniformly bounded across  $X_{\text{sing}}$ . The viscosity approach developed in [EGZ11] fails to establish continuity at the singularities (see [EGZ17]). In this article we use both local (Dirichlet problem analysis) and global (stability estimates) arguments to establish continuity properties of  $\varphi_{\text{KE}}$  and positivity of  $\omega_{\text{KE}}$  across  $X_{\text{sing}}$ , in various geometrical contexts that we now describe.

**Isolated singularities.** — Let  $X$  be a Stein complex space which is reduced and locally irreducible, of complex dimension  $n \geq 1$ , equipped with a hermitian metric whose fundamental form is a positive  $(1,1)$ -form denoted by  $\beta$ . Let  $\Omega \Subset X$  be a strongly pseudoconvex domain in  $X$ , i.e.  $\Omega$  admits a smooth defining function  $\rho$  which is strictly plurisubharmonic in a neighborhood of  $\bar{\Omega}$ .

Let  $\phi$  be a continuous function on  $\partial\Omega$  and  $0 \leq f \in L^p(\Omega)$  with  $p > 1$ . The Dirichlet problem with boundary datum  $\phi$  and right hand side  $\mu := f\beta^n$  consists in finding a bounded plurisubharmonic function  $U$  satisfying the following properties :

$$(0.2) \quad \begin{cases} (dd^c U)^n = \mu & \text{in } \Omega, \\ U|_{\partial\Omega} = \phi, & \text{on } \partial\Omega, \end{cases}$$

where the equation is here understood in the sense of Bedford-Taylor [BT76, BT82, Bed82], as we briefly recall in Section 1.2.

When  $X$ ,  $\phi$  and  $f$  are smooth and  $f$  is positive, this problem has been addressed by several authors (see notably [CH99, GL10]) following the fundamental work of Caffarelli-Kohn-Nirenberg-Spruck [CKNS85]. When  $f$  merely belongs to  $L^p$ ,  $p > 1$ , a unique continuous solution has been constructed by Kolodziej [Kol98]. When  $X$  has singularities, we are not aware of any contribution besides [Wik09] which studies maximal plurisubharmonic functions, [EGZ09] which deals with global Monge-Ampère equations on mildly singular compact Kähler varieties and [DLS17] which seeks for solutions in Cegrell finite energy classes.

Our first main result is the following.

**Theorem A.** — *The Dirichlet problem (0.2) admits a unique solution  $U \in \text{PSH}(\Omega) \cap C^0(\bar{\Omega})$ .*

We apply this local theory to establish the continuity of singular Kähler-Einstein potentials at isolated singularities as a consequence of Theorem A:

**Corollary B.** — *A Kähler-Einstein potential  $\varphi_{\text{KE}}$ , i.e. a solution of (0.1), is continuous at any isolated singularity of  $X$ .*

We show more generally that the results holds for Kähler-Einstein metrics on pairs, cf. Theorem 3.4.

**Non-isolated singularities.** — In order to deal with non-isolated singularities we require the reference class  $[\omega]$  to belong to the real Néron-Severi group, cf Section 3.3 for the notation and Theorem 3.9.

**Theorem C.** — Let  $(X, \omega)$  be a compact normal Kähler space such that  $[\omega] \in \widetilde{\text{NS}}_{\mathbb{R}}(X) \subset H^1(X, \text{PH}_X)$ . Let  $f \geq 0$  be a function in  $L^p(X)$  for some  $p > 1$  such that  $\int_X f \omega^n = \int_X \omega^n$ . Let  $\varphi \in \text{PSH}(X, \omega) \cap L^\infty(X)$  be the unique solution of the equation

$$(\omega + dd^c \varphi)^n = f \omega^n$$

such that  $\sup_X \varphi = 0$ . Then  $\varphi$  is continuous on  $X$ .

Note that if  $X$  has rational singularities (e.g. if  $X$  has klt singularities), the natural map  $\beta : H^1(X, \text{PH}_X) \rightarrow H^2(X, \mathbb{R})$  is an injection and identifies  $\widetilde{\text{NS}}_{\mathbb{R}}(X)$  with the usual Néron-Severi group  $\text{NS}_{\mathbb{R}}(X)$ .

The continuity of  $\varphi$  when  $[\omega] \in \widetilde{\text{NS}}_{\mathbb{Q}}(X)$  is a (rational) Hodge class follows from the extension result of [CGZ13] (some particular cases were obtained by Zhang [DZ10]). This shows, in particular, the continuity of Kähler-Einstein potentials  $\varphi_{\text{KE}}$  in negative or positive curvature since the reference class  $[\omega]$  is rational in this case.

We finally apply Theorem C to the case where  $X$  is an irreducible Calabi-Yau variety  $X$  (cf. Definition 3.10 and Corollary 3.11) and show furthermore that  $\omega_{\text{KE}}$  is a Kähler current provided that  $X$  is smoothable.

**Theorem D.** — Let  $X$  be an irreducible Calabi-Yau variety, and let  $\alpha$  be a Kähler class. Then, the unique singular Ricci-flat metric  $\omega_{\text{KE}} \in \alpha$  has continuous potentials on  $X$ . Moreover, if  $X$  is smoothable then  $\omega_{\text{KE}}$  dominates a Kähler form.

The strict positivity result actually holds in more general contexts (negative curvature, pairs) as we explain in Theorem 4.3.

**Acknowledgements.** — This work has benefited from State aid managed by the ANR under the "PIA" program bearing the reference ANR-11-LABX-0040, in connection with the research project HERMETIC.

## 1. Preliminaries

**1.1. Plurisubharmonic functions on complex spaces.** — Let  $X$  be a reduced complex analytic space of pure dimension  $n \geq 1$ . We will denote by  $X_{\text{reg}}$  the complex manifold of regular points of  $X$ . The set

$$X_{\text{sing}} := X \setminus X_{\text{reg}}$$

of singular points is an analytic subset of  $X$  of complex codimension  $\geq 1$ .

By definition for each point  $x_0 \in X$  there exists a neighborhood  $U$  of  $x_0$  and a local embedding  $j : U \hookrightarrow \mathbb{C}^N$  onto an analytic subset of  $\mathbb{C}^N$  for some  $N \geq 1$ .

Using these local embeddings, it is possible to define the spaces of smooth forms of given degree on  $X$ . The notion of currents on  $X$  is then defined by duality by their action on compactly supported smooth forms on  $X$ . The operators  $\partial$  and  $\bar{\partial}$ ,  $d$ ,  $d^c$  and  $dd^c$  are then well defined by duality (see [Dem85] for a careful treatment).

In the same way one can define the analytic notions of holomorphic and plurisubharmonic functions. There are essentially two different notions :

**Definition 1.1.** — Let  $u : X \rightarrow \mathbb{R} \cup \{-\infty\}$  be a given function.

1. We say that  $u$  is plurisubharmonic on  $X$  if it is locally the restriction of a plurisubharmonic function on a local embedding of  $X$  onto an analytic subset of  $\mathbb{C}^N$ .
2. We say that  $u$  is weakly plurisubharmonic on  $X$  if  $u$  is locally bounded from above on  $X$  and its restriction to the complex manifold  $X_{\text{reg}}$  is plurisubharmonic.

Fornaess and Narasimhan proved in [FN80] that  $u$  is plurisubharmonic on  $X$  if and only if for any analytic disc  $h : \mathbb{D} \rightarrow X$ , the restriction  $u \circ h$  is subharmonic on  $\mathbb{D}$  or identically  $-\infty$ .

If  $u$  is weakly plurisubharmonic on  $X$ ,  $u$  is plurisubharmonic on  $X_{\text{reg}}$ , hence upper semi-continuous on  $X_{\text{reg}}$ . Since no assumption is made on  $u$  at singular points, its natural to extend  $u$  to  $X$  by the following formula :

$$(1.1) \quad u^*(x) := \limsup_{X_{\text{reg}} \ni y \rightarrow x} u(y), \quad x \in X.$$

The function  $u^*$  is upper semi-continuous, locally integrable on  $X$  and satisfies  $dd^c u^* \geq 0$  in the sense of currents on  $X$ . By Demailly [Dem85], the two notions are equivalent when  $X$  is locally irreducible. More precisely we will need the following result :

**Theorem 1.2.** — [Dem85] *Assume that  $X$  is a locally irreducible analytic space and  $u : X \rightarrow \mathbb{R} \cup \{-\infty\}$  is a weakly plurisubharmonic function on  $X$ , then the function  $u^*$  defined by (1.1) is plurisubharmonic on  $X$ .*

Observe that since  $u$  is plurisubharmonic on  $X_{\text{reg}}$ , we have  $u^* = u$  on  $X_{\text{reg}}$ . Hence  $u^*$  is the upper semi-continuous extension of  $u|_{X_{\text{reg}}}$  to  $X$ . We note the following important consequence :

**Corollary 1.3.** — *Let  $\mathcal{U} \subset \text{PSH}(X)$  be a non empty family of plurisubharmonic functions which is locally bounded from above on  $X$ . Then its upper envelope*

$$U := \sup\{u ; u \in \mathcal{U}\},$$

*is a well-defined Borel function whose upper semi-continuous regularization  $U^*$  is plurisubharmonic on  $X$ .*

This result is an extension of a classical result of P. Lelong concerning envelopes of plurisubharmonic functions on open sets in  $\mathbb{C}^n$  (see [Lel61, GZ17]).

Following [FN80] we say that  $X$  is Stein if it admits a  $\mathcal{C}^2$ -smooth strongly plurisubharmonic exhaustion. We will use the following definition :

**Definition 1.4.** — A domain  $\Omega \Subset X$  is strongly pseudoconvex if it admits a negative  $\mathcal{C}^2$ -smooth strongly plurisubharmonic exhaustion, i.e. a function  $\rho$  strongly plurisubharmonic in a neighborhood  $\Omega'$  of  $\bar{\Omega}$  such that  $\Omega := \{x \in \Omega' ; \rho(x) < 0\}$  and for any  $c < 0$ ,

$$\Omega_c := \{x \in \Omega' ; \rho(x) < c\} \Subset \Omega$$

is relatively compact.

Our complex spaces will be assumed to be reduced, locally irreducible of dimension  $n \geq 1$ . We denote by  $\text{PSH}(X)$  the set of plurisubharmonic functions on  $X$ .

**1.2. Monge-Ampère operator on singular spaces.** — The complex Monge-Ampère measure  $(dd^c u)^n$  of a smooth psh function in a domain of  $\mathbb{C}^n$  is the Radon measure

$$(dd^c u)^n = c \det \left( \frac{\partial^2 u}{\partial z_i \partial \bar{z}_j} \right) dV_{\text{eucl}},$$

where  $c > 0$  is a normalizing constant. The definition has been extended to any bounded psh function by Bedford-Taylor, who laid down the foundations of *pluripotential theory* in [BT76, BT82] (see [GZ17] for a recent treatment).

The complex Monge-Ampère operator has been defined and studied on complex spaces by Bedford in [Bed82] and later by Demailly in [Dem85]. It turns out that if  $u \in \text{PSH}(X) \cap L_{\text{loc}}^\infty(X)$ , the Monge-Ampère measure  $(dd^c)^n$  is well defined on  $X_{\text{reg}}$  and can be extended to  $X$  as a Borel measure with zero mass on  $X_{\text{sing}}$ .

Thus all standard properties of the complex Monge-Ampère operator acting on  $\text{PSH}(X) \cap L_{\text{loc}}^\infty(X)$  extend to this setting (see [Bed82, Dem85]). In particular :

**Proposition 1.5.** — *Let  $\Omega \Subset X$  a relatively compact open set and  $u, v \in \text{PSH}(\Omega) \cap L^\infty(\Omega)$ . Assume that  $\liminf_{x \rightarrow \zeta} (u(x) - v(x)) \geq 0$  for any  $\zeta \in \partial\Omega$ . Then*

$$\int_{\{u < v\}} (dd^c v)^n \leq \int_{\{u < v\}} (dd^c u)^n.$$

*In particular, if  $(dd^c u)^n \leq (dd^c v)^n$  weakly on  $\Omega$ , then  $v \leq u$  on  $\Omega$ .*

The proof relies on Stokes formula (see [Bed82]). We now recall an important stability estimate that we shall use in the sequel:

**Proposition 1.6.** — *Let  $\Omega, u, v$  as in Proposition 1.5 above. Let  $\beta$  be a smooth positive  $(1, 1)$ -form on  $X$  and let  $f \in L^p(\Omega)$  for some  $p > 1$ . Assume that*

$$(dd^c u)^n \leq f\beta^n \quad \text{on } \Omega.$$

*Then for any  $0 < \gamma < 1/(nq + 1)$ , there exists a constant  $C = C(\gamma, \|f\|_p) > 0$  such that*

$$\sup_{\Omega} (v - u)_+ \leq \sup_{\partial\Omega} (v - u)_+^* + C \|(v - u)_+\|_1^\gamma.$$

*where  $\|(v - u)_+\|_1 := \int_{\Omega} (v - u)_+ \beta^n$*

Here  $w_+ := \sup\{w, 0\}$  and  $w^*$  means the upper semi-continuous extension of a bounded function  $w$  on  $\Omega$  to the boundary i.e.  $w(\zeta) := \limsup_{z \rightarrow \zeta} w(z)$ .

This result is proved in [GKZ08, Theorem 1.1]) when the ambient space is  $X = \mathbb{C}^n$  (see also [EGZ09, Proposition 3.3] for a similar result in the context of compact Kähler varieties). The proof relies on capacity estimates and the use of the comparison principle Proposition 1.5, it can be reproduced identically in our present context.

## 2. Dirichlet problem on singular complex spaces

In this Section, we will work in the following

**Setting 2.1.** — Let  $X$  be a Stein space of dimension  $n \geq 1$ , reduced and locally irreducible. We fix a smooth positive  $(1,1)$ -form  $\beta$  on  $X$ . Let  $\Omega \Subset X$  be a pseudoconvex domain with  $C^2$ -smooth exhaustion function  $\rho$ , let  $f \in L^p(\Omega)$  for some  $p > 1$  and let  $\mu := f\beta^n$ . Finally, let  $\phi \in C^0(\partial\Omega)$ .

By the comparison principle Proposition 1.5, if the Dirichlet problem (0.2) admits a solution, it dominates any subsolution. We will now prove that the maximal subsolution is psh, hence coincides with the solution in that case.

**Definition 2.2.** — A plurisubharmonic function  $v \in \text{PSH}^\infty(\Omega) := \text{PSH}(\Omega) \cap L^\infty(\Omega)$  is a subsolution to the Dirichlet problem (0.2) with data  $(\phi, \mu)$  if the following two conditions are satisfied :

1.  $v^*(\zeta) := \limsup_{\Omega \ni z \rightarrow \zeta} v(z) \leq \phi(\zeta)$ , for any  $\zeta \in \partial\Omega$ ,
2.  $(dd^c v)^n \geq \mu$  weakly in  $\Omega$ .

It is natural to consider the family  $\mathcal{S}_{\phi, \mu} = \mathcal{S}_{\phi, \mu}(\Omega)$  of all subsolutions to the Dirichlet problem (0.2) with data  $(\phi, \mu)$  and its upper envelope when it exists.

**2.1. The subsolution property.** — We start with the following standard observation.

**Lemma 2.3.** — In Setting 2.1, assume that the Dirichlet problem (0.2) with data  $(\phi, \mu)$  admits a subsolution  $v_0 \in \mathcal{S}_{\phi, \mu}(\Omega)$ . Then the upper envelope of subsolutions

$$U := U_{\phi, \mu} := \sup\{v ; v \in \mathcal{S}_{\phi, \mu}(\Omega)\}$$

is a subsolution to the Dirichlet problem (0.2), i.e.  $U_{\phi, \mu} \in \mathcal{S}_{\phi, \mu}(\Omega)$ . Moreover, if  $v_0 = \phi$  on  $\partial\Omega$  then

$$(2.1) \quad \lim_{z \rightarrow \zeta} U(z) = \phi(\zeta), \quad \text{for any } \zeta \in \partial\Omega.$$

The proof of the lemma will actually not make use of the assumption  $f \in L^p(\Omega)$ , but we chose to stick to Setting 2.1 throughout this section for clarity.

*Proof.* — Observe that for any  $u \in \mathcal{S}_{\phi, \mu}(\Omega)$  we have  $u \leq M_\phi := \max_{\partial\Omega} \phi$  on  $\Omega$ . Therefore, the envelope  $U := U_{\phi, \mu}$  is a well-defined bounded function on  $\Omega$  and  $U^*$  is a bounded plurisubharmonic function on  $\Omega$  by Corollary 1.3. It follows then from a topological lemma of Choquet and the comparison principle Proposition 1.5, that  $U^*$  satisfies the inequality  $(dd^c U^*)^n \geq \mu$  in  $\Omega$  (see [BT76, GZ17]). It remains to show that  $U = U^* \in \text{PSH}(\Omega)$  and that the boundary values of  $U$  are  $\leq \phi$  (resp.  $= \phi$  in the second case).

*Claim.* Let  $U_\phi := U_{\phi, 0}$  be the maximal plurisubharmonic function on  $\Omega$  with boundary values  $\leq \phi$ . Then,  $U_\phi = U_\phi^* \in \text{PSH}(\Omega)$  and it satisfies

$$(2.2) \quad \lim_{z \rightarrow \zeta} U_\phi(z) = \phi(\zeta), \quad \text{for any } \zeta \in \partial\Omega.$$

For the time being, assume that the claim holds and let us finish the proof of Lemma 2.3. Since we have

$$(2.3) \quad v_0 \leq U \leq U_\phi \quad \text{on } \Omega$$

the claim would imply  $v_0 \leq U^* \leq U_\phi$  on  $\Omega$ . Thus, one would get  $U^* \in \mathcal{S}_{\phi, \mu}(\Omega)$ , hence  $U^* \leq U$  on  $\Omega$ , and finally  $U^* = U$  on  $\Omega$ . The boundary condition follows from (2.3).

It now remains to prove the claim. To establish (2.2), we fix  $\varepsilon > 0$  and let  $\psi$  be a  $\mathcal{C}^2$  function on  $\partial\Omega$  such that  $\psi - \varepsilon \leq \phi \leq \psi$  on  $\partial\Omega$ . By definition

$$U_\psi - \varepsilon \leq U_\phi \leq U_\phi^* \leq U_\psi^* \quad \text{on } \Omega,$$

reducing the problem to the case when  $\phi$  is  $\mathcal{C}^2$  on  $\partial\Omega$ . In this case we can extend  $\phi$  as a  $\mathcal{C}^2$  function in a neighborhood of  $\bar{\Omega}$ . Choosing  $A > 1$  large enough, we can assume that  $v_\phi := A\rho + \phi$  is plurisubharmonic and smooth in a neighborhood of  $\bar{\Omega}$  and  $v_\phi = \phi$  on  $\partial\Omega$ . Hence  $v_\phi \leq U_\phi$ . Similarly we choose  $B > 1$  large enough so that  $w_\phi := -B\rho + \phi$  is a smooth plurisuperharmonic function in a neighborhood of  $\bar{\Omega}$  such that  $w_\phi = \phi$  on  $\partial\Omega$ . It follows from the maximum principle that  $v_\phi \leq U_\phi \leq U_\phi^* \leq w_\phi$  on  $\Omega$ . This implies that  $U_\phi^*$  is a subsolution hence  $U_\phi^* \leq U_\phi$  and finally  $U_\phi = U_\phi^* \in \text{PSH}(\Omega)$ . At the same time, we get that  $U_\phi$  satisfies (2.2). The claim and lemma follow.  $\square$

**2.2. Balayage.** — We now show that  $U_{\phi, \mu}$  is a solution of the Dirichlet problem (0.2) using Lemma 2.3 and a balayage process in  $\Omega_{\text{reg}}$ , adapting the proofs of [BT76, Theorem 8.3] and [GZ17, Theorem 5.16].

**Theorem 2.4.** — *In Setting 2.1, we have  $\mathcal{S}_{\phi, \mu}(\Omega) \neq \emptyset$ . Moreover, its upper envelope*

$$(2.4) \quad U := \sup\{v; v \in \mathcal{S}_{\phi, \mu}(\Omega)\}$$

*satisfies  $U \in \text{PSH}(\Omega) \cap \mathcal{C}(\Omega)$ . Moreover,  $U$  admits a continuous extension to  $\bar{\Omega}$  and it solves the Dirichlet problem (0.2).*

When  $f \equiv 0$ , a similar result has been obtained by Wikström [Wik09, Theorem 1.8].

*Proof.* — We proceed in several steps.

*Step 1:* Assume first that  $\phi \in \mathcal{C}^2(\partial\Omega)$  and  $\mu = f\beta^n$  with  $f \in L^\infty(\Omega)$ . We claim that there exists a subsolution  $v$  plurisubharmonic and smooth in a neighborhood of  $\bar{\Omega}$  such that  $v = \phi$  on  $\partial\Omega$ . Indeed consider any smooth extension of  $\phi$  to a neighborhood of  $\bar{\Omega}$ . For  $A > 1$  large enough, the function  $v_\phi = v_\phi^A := A\rho + \phi$  is plurisubharmonic and smooth in a neighborhood of  $\bar{\Omega}$  and satisfies  $(dd^c v_\phi)^n \geq f\beta^n$  in  $\Omega$ , since  $f$  is bounded from above. Since  $v_\phi = \phi$  on  $\partial\Omega$  we can apply Lemma 2.3 to conclude that  $(dd^c U)^n \geq \mu$  on  $\Omega$  and

$$\lim_{z \rightarrow \zeta} U(z) = \phi(\zeta) \quad \text{for any } \zeta \in \partial\Omega.$$

It remains to show that  $(dd^c U)^n = \mu$  in  $\Omega_{\text{reg}}$ . Choose a chart  $(B, z)$  in a neighborhood of given regular point  $a \in \Omega_{\text{reg}}$  such that there exists an isomorphism  $F : B \rightarrow \mathbb{B}$  from a neighborhood of  $\bar{B}$  onto a neighborhood of the closed euclidean unit ball  $\bar{\mathbb{B}}$  with  $F(B) = \mathbb{B}$ . We consider the Dirichlet problem  $(dd^c u)^n = f\beta^n$  on  $B$  with boundary



values  $u = U$  on  $\partial B$ . Observe that  $U$  is a subsolution to this problem. Using [BT76, Theorem 8.3] (together with its generalization by Cegrell [Ceg84]), we can find a solution  $u \in \text{PSH}(B) \cap L^\infty(B)$  to this problem (see also [GZ17, Theorem 5.17]). It follows from Proposition 1.5 that  $U \leq u$  on  $B$ .

The function  $\tilde{u}$  defined on  $\Omega$  by  $\tilde{u} = u$  on  $B$  and  $\tilde{u} = U$  on  $\Omega \setminus B$  is a plurisubharmonic subsolution to the Dirichlet problem (0.2) since  $\mu = f\beta^n$  puts no mass on  $\partial B$ . Therefore,  $\tilde{u} \leq U$  on  $\Omega$ . This yields  $u = U$  on  $B$ , hence  $(dd^c U)^n = f\beta^n$  in  $B$ . Since  $B \subset \Omega_{\text{reg}}$  was arbitrary, it follows that  $(dd^c U)^n = f\beta^n$  on  $\Omega_{\text{reg}}$ , hence on the whole  $\Omega$ .

To show the continuity of  $U$  on  $\bar{\Omega}$  we first observe that  $U$  can be extended as a plurisubharmonic function on a neighborhood  $\Omega'$  of  $\bar{\Omega}$ . Indeed since  $v_\phi$  is plurisubharmonic on a neighborhood  $\Omega'$  of  $\bar{\Omega}$  and  $v_\phi \leq U$  on  $\Omega$  with  $v_\phi = \phi = U$  on  $\partial\Omega$ , the function  $V$  defined by  $V = U$  on  $\Omega$  and  $V := v_\phi$  on  $\Omega' \setminus \Omega$  is plurisubharmonic on  $\Omega'$ . We can always assume that  $\Omega'$  is a Stein space. By Fornaess-Narasimhan approximation Theorem [FN80, Theorem 5.5] there exists a decreasing sequence  $(V_j)$  of plurisubharmonic functions on  $\Omega'$  which converges to  $V$  on  $\Omega'$ . Consider now  $v_j := V_j$  on  $\bar{\Omega}$ . Then  $v_j \in \text{PSH}(\Omega) \cap C^0(\bar{\Omega})$  and  $(v_j)$  decreases to  $U$  on  $\bar{\Omega}$ . It follows from Proposition 1.6 that

$$(2.5) \quad \sup_{\Omega} (v_j - U) \leq \sup_{\partial\Omega} (v_j - U) + C \|v_j - U\|_1^\gamma,$$

where  $0 < \gamma < 1/(nq + 1)$ . Since  $(v_j)$  decreases to  $U = \phi$  on  $\partial\Omega$ , Dini's lemma ensures that the convergence is uniform on  $\partial\Omega$ . It follows therefore from (2.5) that  $(v_j)$  uniformly converges to  $U$  on  $\bar{\Omega}$ , hence  $U$  is continuous on  $\bar{\Omega}$ .

*Step 2 :* Assume  $\phi \in C^0(\partial\Omega)$  and  $\mu = f\beta^n$  with  $f \in L^\infty(\Omega)$ . Take a decreasing sequence of smooth functions  $(\phi_j)_{j \in \mathbb{N}^*}$  converging to  $\phi$  on  $\partial\Omega$  so that  $\phi_j - 1/j \leq \phi \leq \phi_j$  on  $\partial\Omega$  for any  $j \geq 1$ . Then from the definitions we see that

$$U_{\phi_j, \mu} - 1/j \leq U_{\phi, \mu} \leq U_{\phi_j, \mu}, \quad \text{on } \bar{\Omega}.$$

This implies that the sequence  $(U_{\phi_j, \mu})$  uniformly converges to  $U_{\phi, \mu}$  on  $\bar{\Omega}$ . Hence  $U = U_{\phi, \mu}$  is continuous on  $\bar{\Omega}$ ,  $U = \phi$  on  $\partial\Omega$  and satisfies the equation  $(dd^c U)^n = \mu$  on  $\Omega$ .

*Step 3 :* Assume  $\phi \in C^0(\partial\Omega)$  and  $\mu = f\beta^n$  with  $f \in L^p(\Omega)$ , with  $p > 1$ . Define  $f_j := \min\{f, j\}$  for  $j \in \mathbb{N}$ . The bounded densities  $(f_j)$  increase to  $f$  in  $L^p(\Omega)$ . Set  $U_j := U_{\phi, \mu_j}$  where  $\mu_j := f_j\beta^n$  for  $j \in \mathbb{N}$ . By the comparison principle Proposition 1.5,  $(U_j)_{j \in \mathbb{N}}$  is a decreasing sequence of bounded plurisubharmonic functions on  $\Omega$  that are continuous up to the boundary.

We first show that the  $U_j$ 's are uniformly bounded. Let  $v := U_{\phi, 0}$  denote the maximal plurisubharmonic function on  $\Omega$  with boundary value  $\phi$  (whose properties have been established the proof of Lemma 2.3). The comparison principle Proposition 1.5 ensures that  $U_j \leq v$  on  $\Omega$ . It follows from Proposition 1.6 that for all  $j \in \mathbb{N}$ ,

$$\|v - U_j\|_{L^\infty} \leq C \|v - U_j\|_{L^1}^\gamma,$$

where  $0 < \gamma < 1$  and  $C > 0$  is a uniform constant depending only on a uniform bound of  $\|f_j\|_p \leq \|f\|_p$ . This implies in particular that  $\|v - U_j\|_{L^\infty}^{1-\gamma} \leq C'$ , where  $C' > 0$  is a uniform constant, hence  $\sup_j \|U_j\|_{L^\infty} < +\infty$ .

The sequence  $(U_j)_{j \in \mathbb{N}}$  of continuous functions on  $\bar{\Omega}$  therefore decreases to a bounded function  $V$  such that  $V|_\Omega$  is plurisubharmonic and  $V|_{\partial\Omega} = \phi$  since  $U_j|_{\partial\Omega} = \phi$  for all  $j$ . Moreover  $(dd^c V)^n = \mu$ , as follows from the continuity property of the complex Monge-Ampère operator along monotone sequences. Thus  $V$  is a subsolution to (0.2). By Lemma 2.3, the function  $U = U_{\mu, \phi}$  is a subsolution to (0.2). Since  $U$  is the maximal subsolution we have  $V \leq U$ . On the other hand  $(dd^c U)^n \geq (dd^c V)^n$  so Proposition 1.5 ensures  $U \leq V$  on  $\Omega$ . Therefore  $U = V$  and  $(dd^c U)^n = \mu$ .

The continuity of  $U$  again follows from the stability estimate (Proposition 1.6) : there exists a constant  $C > 0$  such that for all  $j \in \mathbb{N}$

$$\sup_{\Omega} (U_j - U) \leq C \|U_j - U\|_1^\gamma,$$

showing that  $(U_j)$  uniformly converges to  $U$  on  $\bar{\Omega}$ , hence  $U$  is continuous on  $\bar{\Omega}$  and solves the Dirichlet problem (0.2).  $\square$

### 3. Continuity of Kähler-Einstein potentials

**3.1. Generalities.** — Let  $X$  be a normal compact space. We say that  $X$  is Kähler if it admits a Kähler form in the following sense

*Definition 3.1.* — A Kähler form  $\omega$  on a normal complex space  $X$  can be defined as a Kähler form on  $X_{\text{reg}}$  which extends to a smooth, closed  $(1, 1)$ -form under local embeddings  $X \xrightarrow[\text{loc}]{\hookrightarrow} \mathbb{C}^N$ . In particular, one can cover  $X$  with open subsets  $U_\alpha$ , find embeddings  $j_\alpha : U_\alpha \hookrightarrow \mathbb{C}^N$  as well as smooth, strictly psh functions  $\varphi_\alpha$  defined on a neighborhood of  $j_\alpha(U_\alpha)$  such that  $\omega|_{U_\alpha} = j_\alpha^* dd^c \varphi_\alpha$ .

The study of complex Monge-Ampère equations in this context has been initiated in [EGZ09], providing a way of constructing singular Kähler-Einstein metrics and extending Yau's fundamental solution to the Calabi conjecture [Yau78]. More precisely, it is proven there that given a Kähler metric  $\omega$  on  $X$  and a non-negative function  $f \in L^p(X)$  for some  $p > 1$  satisfying  $\int_X f \omega^n = \int \omega^n$ , then the equation

$$(3.1) \quad (\omega + dd^c \varphi^n) = f \cdot \omega^n$$

has a unique solution  $\varphi \in \text{PSH}(X, \omega) \cap L^\infty(X)$  such that  $\sup_X \varphi = 0$ .

Let us now explain the relation between the equation (3.1) above and the existence of singular Kähler-Einstein metrics.

We choose a pair  $(X, D)$  consisting of an  $n$ -dimensional compact Kähler variety  $X$  and a divisor  $D = \sum a_i D_i$  with  $a_i \in [0, 1] \cap \mathbb{Q}$ . We assume that there exists an integer  $m \geq 1$  such that  $m(K_X + D)$  is a line bundle.

Given a hermitian metric  $h$  on  $K_X + D$  and the singular metric  $e^{-\phi_D}$  (only unique up to a positive multiple), one constructs a measure  $\mu_{(X, D), h}$  on  $X$  as follows. If  $U$  is any

open set where  $m(K_X + D)$  admits a trivialization  $\sigma$  on  $U_{\text{reg}}$ , then the expression

$$\frac{i^{n^2} (\sigma \wedge \bar{\sigma})^{\frac{1}{m}}}{|\sigma|_{h^{\otimes m}}^{\frac{2}{m}}} e^{-\phi_D}$$

defines a measure on  $U_{\text{reg}}$  which is independent of  $m$  as well as the choice of  $\sigma$  and can thus be patched to a measure on  $X_{\text{reg}}$ . Its extension by 0 on  $X_{\text{sing}}$  is by definition  $\mu_{(X,D),h}$ . We recall the following properties satisfied by the measure  $\mu := \mu_{(X,D),h}$ , cf [EGZ09, Lemma 6.4].

- The Ricci curvature of  $\mu$  on  $X_{\text{reg}}$  is equal to  $-i\Theta(h) + [D]$ .
- The mass  $\int_X d\mu$  is finite if and only if  $(X, D)$  has klt singularities.
- If  $\mu$  has finite mass, then the density  $f$  of  $\mu$  wrt  $\omega^n$  (i.e.  $\mu = f \cdot \omega^n$ ) satisfies  $f \in L^p(X)$  for some  $p > 1$ .

From now on, we work in the following

**Setting 3.2.** — Let  $(X, D)$  be a pair where  $X$  is a compact normal Kähler space and  $D$  is an effective  $\mathbb{Q}$ -divisor. Assume that  $(X, D)$  has klt singularities, pick a Kähler metric  $\omega$  and a hermitian metric  $h$  on  $K_X + D$ , normalized so that  $\int_X d\mu_{(X,D),h} = \int_X \omega^n$ . We assume either

- $K_X + D$  is ample and  $\omega = i\Theta(h)$ ; or
- $K_X + D \equiv 0$  and  $h$  satisfies  $i\Theta(h) = 0$ ; or
- $K_X + D$  is anti-ample and  $\omega = -i\Theta(h)$ .

**Definition 3.3.** — In the Setting 3.2 above, a Kähler-Einstein metric is a solution  $\omega_{\text{KE}} := \omega + dd^c \varphi_{\text{KE}}$  of the Monge-Ampère equation

$$(3.2) \quad (\omega + dd^c \varphi_{\text{KE}})^n = e^{-\lambda \varphi_{\text{KE}}} \mu_{(X,D),h}$$

where  $\lambda = \{-1, 0, 1\}$  according to whether we are in the first, second or third case. It satisfies

$$(3.3) \quad \text{Ric}(\omega_{\text{KE}}) = \lambda \omega_{\text{KE}} + [D]$$

in the weak sense.

By the results [EGZ09] recalled above, (3.2) admits a unique solution  $\omega_{\text{KE}}$  whenever  $\lambda \in \{-1, 0\}$ . Its potential  $\varphi_{\text{KE}}$  is globally bounded on  $X$  and  $\omega_{\text{KE}}$  is a honest Kähler-Einstein metric on  $X_{\text{reg}} \setminus \text{Supp}(D)$  and it has cone singularities along  $D$  generically [Gue13]. For  $\lambda = +1$  we refer the reader to [BBE<sup>+</sup>19, Bou18].

Understanding the asymptotic behavior of  $\varphi_{\text{KE}}$  (resp.  $\omega_{\text{KE}}$ ) near  $X_{\text{sing}}$  is a major open problem. A breakthrough has been obtained in [HS17] for special type of Calabi-Yau varieties, but a lack of local models prevent us from a good understanding in more general situations. We discuss below two different tools that allow one to show -in many contexts- global continuity of the Kähler-Einstein potential  $\varphi_{\text{KE}}$ , a statement that was overlooked in [EGZ11].

### 3.2. Isolated singularities. —

**Theorem 3.4.** — *Let  $(X, D)$  be a pair as in Setting 3.2. Then the potential  $\varphi_{\text{KE}}$  of any Kähler-Einstein metric in the sense of Definition 3.3 is continuous near an isolated singularity of  $X$ .*

*Proof.* — We work near an isolated singular point  $a$ . We let  $B$  denote a small strictly pseudoconvex neighborhood of  $a$  in  $X$ , isomorphic to the trace of a ball in some local embedding in  $\mathbb{C}^N$ , and let  $\rho$  denote a local smooth potential for  $\omega = dd^c\rho$  in  $B$ .

Recall from [EGZ17] that the Kähler-Einstein potential  $\varphi_{\text{KE}}$  is continuous in  $B \setminus \{a\}$ . We can apply the local theory developed in Section 2 to obtain that  $\psi = \rho + \varphi_{\text{KE}}$  is the unique solution of the Dirichlet problem

$$(dd^c\psi)^n = e^{-\lambda\varphi_{\text{KE}}}\mu_{(X,D),h} \text{ in } B, \quad \text{with } \psi|_{\partial B} = (\rho + \varphi_{\text{KE}})|_{\partial B}.$$

Recall that  $\mu_{(X,D),h}$  has an  $L^p$  density wrt  $\omega^n$  since  $(X, D)$  is klt. It follows therefore from Theorem 2.4 that  $\psi$  is continuous, hence so is  $\varphi_{\text{KE}}$  at point  $a$ .  $\square$

**3.3. Hodge classes vs transcendental classes.** — Let  $X$  be a compact Kähler space. In  $H^2(X, \mathbb{R})$ , an important subgroup is made up by the first Chern class of line bundles  $L$  on  $X$  via the map

$$c_1 : H^1(X, \mathcal{O}_X^*) \rightarrow H^2(X, \mathbb{R})$$

induced by the exponential exact sequence

$$(3.4) \quad 0 \longrightarrow \underline{\mathbb{Z}} \longrightarrow \mathcal{O}_X \xrightarrow{e^{2\pi i \cdot}} \mathcal{O}_X^* \longrightarrow 0$$

and the sheaf injection  $\underline{\mathbb{Z}} \hookrightarrow \underline{\mathbb{R}}$ .

**Definition 3.5.** — The group  $\text{Im}(c_1) \subset H^2(X, \mathbb{R})$  is called Néron-Severi group of  $X$  and denoted by  $\text{NS}(X)$ . One defines the vector spaces  $\text{NS}_{\mathbb{Q}}(X) := \text{NS}(X) \otimes \mathbb{Q} \subset H^2(X, \mathbb{R})$  and  $\text{NS}_{\mathbb{R}}(X) := \text{NS}(X) \otimes \mathbb{R} \subset H^2(X, \mathbb{R})$ .

A Kähler metric  $\omega$  (cf Definition 3.1) is canonically attached to an element in  $H^0(X, \mathcal{C}_X^\infty / \text{PH}_X)$  where  $\mathcal{C}_X^\infty$  (resp.  $\text{PH}_X$ ) is the subsheaf of continuous functions on  $X$  that are local restrictions of smooth functions (resp. pluriharmonic functions) under local embeddings  $X \xrightarrow[\text{loc}]{\hookrightarrow} \mathbb{C}^N$ . It can be proved that a pluriharmonic function is locally the real part of a holomorphic function, [BEG13, §4.6.1]. The exact sequences

$$0 \longrightarrow \text{PH}_X \longrightarrow \mathcal{C}_X^\infty \longrightarrow \mathcal{C}_X^\infty / \text{PH}_X \longrightarrow 0$$

$$0 \longrightarrow \underline{\mathbb{R}} \longrightarrow \mathcal{O}_X \xrightarrow{\text{Im}(\cdot)} \text{PH}_X \longrightarrow 0$$

yield a map

$$H^0(X, \mathcal{C}_X^\infty / \text{PH}_X) \xrightarrow{[\cdot]} H^1(X, \text{PH}_X) \xrightarrow{\beta} H^2(X, \mathbb{R})$$

**Definition 3.6.** — A class  $\alpha \in H^1(X, \text{PH}_X)$  is called Kähler if there exists a Kähler metric  $\omega$  on  $X$  such that  $\alpha = [\omega]$ . The Kähler cone of  $X$  is the set  $\mathcal{K}_X \subset H^1(X, \text{PH}_X)$  made out of Kähler classes. It is an open, convex set.

**Remark 3.7.** — When  $X$  has rational singularities, it is proved in [GK20, Remark 3.2 (2)] that  $\beta$  is an injection and that we have an exact sequence

$$0 \longrightarrow H^1(X, \text{PH}_X) \xrightarrow{\beta} H^2(X, \mathbb{R}) \longrightarrow H^2(X, \mathcal{O}_X) \longrightarrow 0.$$

In particular, under those assumptions, one can alternatively view the Kähler cone  $\mathcal{K}_X \subset H^2(X, \mathbb{R})$  without any ambiguity.

Finally, the logarithm map yields an exact sequence

$$0 \longrightarrow \underline{\mathbb{R}/\mathbb{Z}} \xrightarrow{e^{2\pi i \cdot}} \mathcal{O}_X^* \xrightarrow{\log|\cdot|} \text{PH}_X \longrightarrow 0$$

hence a map

$$H^1(X, \mathcal{O}_X^*) \xrightarrow{\gamma} H^1(X, \text{PH}_X)$$

such that  $\beta \circ \gamma = c_1$ .

**Definition 3.8.** — One set  $\widetilde{\text{NS}}(X) := \text{Im}(\gamma) \subset H^1(X, \text{PH}_X)$ . One also defines the vector spaces  $\widetilde{\text{NS}}_{\mathbb{Q}}(X) := \widetilde{\text{NS}}(X) \otimes \mathbb{Q} \subset H^1(X, \text{PH}_X)$  and  $\widetilde{\text{NS}}_{\mathbb{R}}(X) := \widetilde{\text{NS}}(X) \otimes \mathbb{R} \subset H^1(X, \text{PH}_X)$ .

The relation between the two groups introduced is that

$$(3.5) \quad \text{NS}(X) = \beta(\widetilde{\text{NS}}(X))$$

and when  $X$  has rational singularities, then Remark 3.7 implies that  $\beta$  induces an isomorphism between the two groups and, in particular, between their tensorization by  $\mathbb{Q}$  or  $\mathbb{R}$ .

A generalization of Kodaira theorem shows that a line bundle  $L \rightarrow X$  on a normal compact space  $X$  such that  $\gamma(L) \in \mathcal{K}_X$  is automatically ample, cf e.g. [EGZ09, Proposition 5.12]. In particular, there exists an embedding  $f : X \hookrightarrow \mathbb{P}^N$  such that  $f^* \mathcal{O}_{\mathbb{P}^N}(1) = L$  and  $[f^* \omega_{\text{FS}}] = \gamma(L)$ .

One can slightly extend the result above by asserting that if  $\widetilde{\text{NS}}_{\mathbb{R}}(X) \cap \mathcal{K}_X \neq \emptyset$ , then  $X$  is projective. Indeed,  $\mathcal{K}_X$  is open and  $\widetilde{\text{NS}}_{\mathbb{Q}}(X)$  is dense in  $\widetilde{\text{NS}}_{\mathbb{R}}(X)$ , so  $\widetilde{\text{NS}}_{\mathbb{Q}}(X) \cap \mathcal{K}_X \neq \emptyset$ . Since  $\mathcal{K}_X$  is a cone, we further deduce  $\widetilde{\text{NS}}(X) \cap \mathcal{K}_X \neq \emptyset$  and we can apply the result above.

Coming back to Equation (3.1), it is proved in [CGZ13] that if  $[\omega] \in \widetilde{\text{NS}}_{\mathbb{Q}}(X)$ , then the potential solution  $\varphi$  can be approximated by a decreasing sequence of smooth  $\omega$ -psh functions, hence [EGZ09, Theorem 2.1] ensures that  $\varphi$  is globally continuous on  $X$ .

In particular, the previous discussion applies to show that if  $(X, D)$  is a klt pair such that  $K_X + D$  has a sign, then a solution  $\varphi_{\text{KE}}$  of (3.2) is continuous on  $X$  as soon as  $\lambda \neq 0$ . That is, singular Kähler-Einstein metrics  $\omega_{\text{KE}}$  with positive or negative Ricci curvature have continuous potentials.

The remaining case of interest is when the curvature is zero (i.e.  $\lambda = 0$ ) and  $[\omega]$  is an arbitrary Kähler class in  $H^1(X, \text{PH}_X)$ . The following results deals with the case  $[\omega] \in \widetilde{\text{NS}}_{\mathbb{R}}(X)$ .

**Theorem 3.9.** — Let  $(X, \omega)$  be a compact normal Kähler space such that  $[\omega] \in \widetilde{\text{NS}}_{\mathbb{R}}(X) \subset H^1(X, \text{PH}_X)$ . Let  $f \geq 0$  be a function in  $L^p(X)$  for some  $p > 1$  such that  $\int_X f \omega^n = \int_X \omega^n$ . Let  $\varphi \in \text{PSH}(X, \omega) \cap L^\infty(X)$  be the unique solution of the equation

$$(\omega + dd^c \varphi)^n = f \omega^n$$

such that  $\sup_X \varphi = 0$ . Then  $\varphi$  is continuous on  $X$ .

Generalizing the celebrated Beauville-Bogomolov decomposition, it was recently proved in [BGL20] that compact Kähler spaces  $X$  with klt singularities such that  $K_X$  is numerically trivial should admit a finite cover  $X' \rightarrow X$ , unramified in codimension one and such that  $X' = T \times \prod Y_i \times \prod Z_j$  where  $T$  is a (smooth) torus,  $Y_i$  are irreducible Calabi-Yau varieties and  $Z_j$  are irreducible holomorphic symplectic varieties, cf. also [Dru18, GKG19, HP19, CGGN20] for related anterior results. We will focus on the irreducible Calabi-Yau factors, whose definition we now recall.

**Definition 3.10.** — Let  $X$  be a compact, normal Kähler space of dimension  $n \geq 3$ . We say that  $X$  is an irreducible Calabi-Yau variety if  $X$  has canonical singularities, trivial canonical bundle and is such that for any finite quasi-étale cover  $X' \rightarrow X$ , we have  $h^0(X', \Omega_{X'}^{[p]}) = 0$  for any  $1 \leq p \leq n - 1$ .

Since there are no reflexive two-forms on an irreducible Calabi-Yau variety  $X$ , it is automatically projective. From Theorem 3.9, we deduce the following

**Corollary 3.11.** — Let  $X$  be an irreducible Calabi-Yau variety and let  $\alpha \in \mathcal{K}_X$  be a Kähler class. Then, the unique singular Ricci-flat metric  $\omega \in \alpha$  has continuous potentials on  $X$ .

*Proof of Corollary 3.11.* — Let  $p : \tilde{X} \rightarrow X$  be a resolution of singularities. Since  $X$  has rational singularities and  $\tilde{X}$  is compact Kähler, we have for any  $p \leq n$

$$h^p(X, \mathcal{O}_X) = h^p(\tilde{X}, \mathcal{O}_{\tilde{X}}) = h^0(\tilde{X}, \Omega_{\tilde{X}}^p).$$

By [KS18], we have  $p_* \Omega_{\tilde{X}}^p = \Omega_X^{[p]}$ , and therefore

$$h^p(X, \mathcal{O}_X) = h^0(X, \Omega_X^{[p]}) = 0$$

for  $p = 1, 2$ . The exact sequence (3.4) shows that the integral first Chern class yields an isomorphism  $H^1(X, \mathcal{O}_X^*) \simeq H^2(X, \mathbb{Z})$  so, in particular, one has

$$(3.6) \quad \text{NS}_{\mathbb{R}}(X) = H^2(X, \mathbb{R}).$$

By (3.5) and the remark below it, it follows that  $\widetilde{\text{NS}}_{\mathbb{R}}(X) = H^1(X, \text{PH}_X)$ . The Corollary is now proved.  $\square$

*Proof of Theorem 3.9.* — It follows from [EGZ09, Theorem 4.1] that there is a unique solution  $u \in \text{PSH}(X, \omega) \cap L^\infty(X)$  of the equation

$$(3.7) \quad (\omega + dd^c u)^n = e^u \cdot f \omega^n$$

We claim it is continuous. If that claim holds, we can apply it to  $\varphi$  which is the solution of the equation

$$(\omega + dd^c u)^n = e^u \cdot (f e^{-\varphi}) \omega^n$$

This is indeed legitimate since  $f e^{-\varphi} \in L^p(X)$  as  $\varphi$  is bounded.

We are now going to prove the claim. Since  $\widetilde{\text{NS}}_{\mathbb{Q}}(X)$  is dense in  $\widetilde{\text{NS}}_{\mathbb{R}}(X)$ , one can find a family of Kähler metrics  $\omega_\varepsilon$  such that

- $[\omega_\varepsilon] \in \widetilde{\text{NS}}_{\mathbb{Q}}(X)$
- $[\omega_\varepsilon] \rightarrow [\omega]$  in  $H^1(X, \text{PH}_X)$ .

Moreover, since the map  $H^0(X, \mathcal{C}_X^\infty / \text{PH}_X) \rightarrow H^1(X, \text{PH}_X)$  is continuous, one can assume additionally that  $\omega_\varepsilon \rightarrow \omega$  smoothly on  $X$ . Since  $\omega$  is Kähler, there is no loss of generality in assuming that we have the following set of inequalities

$$(3.8) \quad (1 - \varepsilon)\omega \leq \omega_\varepsilon \leq (1 + \varepsilon)\omega$$

We consider the unique function  $u_\varepsilon \in \text{PSH}(X, \omega) \cap L^\infty(X)$  solution of the equation

$$(3.9) \quad (\omega_\varepsilon + dd^c u_\varepsilon)^n = e^{u_\varepsilon} \cdot f\omega^n$$

As we explained above,  $u_\varepsilon \in \mathcal{C}^0(X)$  since  $[\omega_\varepsilon] \in \widetilde{\text{NS}}_{\mathbb{Q}}(X)$ . Moreover, by Jensen's inequality, it follows easily that

$$(3.10) \quad \sup_X u_\varepsilon \leq C$$

for some  $C > 0$  independent of  $\varepsilon$ . Moreover, it follows from (3.8) that the function  $v_\varepsilon := (1 - \varepsilon)u + n \log(1 - \varepsilon) - \varepsilon \|u\|_\infty$  is  $\omega_\varepsilon$ -psh and satisfies

$$\begin{aligned} (\omega_\varepsilon + dd^c v_\varepsilon)^n &\geq (1 - \varepsilon)^n (\omega + dd^c u)^n \\ &= e^{(1-\varepsilon)u + n \log(1-\varepsilon) + \varepsilon u} \cdot f\omega^n \\ &\geq e^{v_\varepsilon} \cdot f\omega^n. \end{aligned}$$

This shows that  $v_\varepsilon$  is a subsolution of (3.9) and we get

$$(3.11) \quad v_\varepsilon = (1 - \varepsilon)u + n \log(1 - \varepsilon) - \varepsilon \|u\|_\infty \leq u_\varepsilon$$

In particular, we have a uniform lower bound for  $u_\varepsilon$  independent of  $\varepsilon$ . Combined with (3.10) we obtain, up to adjusting  $C$ , the following control

$$(3.12) \quad \|u_\varepsilon\|_\infty \leq C$$

Finally, we consider  $w_\varepsilon := \frac{1}{1+\varepsilon}u_\varepsilon - n \log(1 + \varepsilon) - \frac{\varepsilon}{1+\varepsilon}\|u_\varepsilon\|_\infty$ . By (3.8), the function  $w_\varepsilon$  is  $\omega$ -psh and satisfies

$$\begin{aligned} (\omega + dd^c w_\varepsilon)^n &\geq (1 + \varepsilon)^{-n} (\omega_\varepsilon + dd^c u_\varepsilon)^n \\ &= e^{\frac{1}{1+\varepsilon}u_\varepsilon - n \log(1+\varepsilon) + \frac{\varepsilon}{1+\varepsilon}u_\varepsilon} \cdot f\omega^n \\ &\geq e^{w_\varepsilon} \cdot f\omega^n. \end{aligned}$$

This shows that  $w_\varepsilon$  is a subsolution of (3.7) and we get

$$(3.13) \quad w_\varepsilon = \frac{1}{1+\varepsilon}u_\varepsilon - n \log(1 + \varepsilon) - \frac{\varepsilon}{1+\varepsilon}\|u_\varepsilon\|_\infty \leq u.$$

Combining (3.11)-(3.13) and (3.12), we see that

$$\|u - u_\varepsilon\|_\infty \leq -n \log(1 - \varepsilon) + 2\varepsilon \max(\|u\|_\infty, \|u_\varepsilon\|_\infty) = O(\varepsilon).$$

That is,  $u$  is the uniform limit of the continuous functions  $u_\varepsilon$  when  $\varepsilon \rightarrow 0$ . In particular, it is continuous.  $\square$

#### 4. Strict positivity of singular Kähler-Einstein metrics

Kähler-Einstein theory in positive curvature is notoriously more complicated than in non-positive curvature. For that reason, we will make additional assumptions when working in the log Fano case and introduce the following

**Setting 4.1.** — *In the Setting 3.2, we assume additionally in the case where  $-(K_X + D)$  is ample that we have*

- $K_X$  is  $\mathbb{Q}$ -Cartier and  $D \in |-mK_X|$  for some  $m \in \mathbb{Z}_{>0}$ .
- There exists a Kähler-Einstein metric  $\omega_{\text{KE}}$ .
- $\text{Aut}^\circ(X) = 0$  if  $D = \emptyset$ .

The assumption on the automorphism group is to ensure uniqueness of the KE metric. Note that by Kodaira vanishing, one has always  $\text{Aut}^\circ(X, [D]) = 0$  if  $D \neq \emptyset$ , cf [SW16, Theorem 2.8].

The first assumption is mainly here because we will later use results in the literature which for historical reasons only deal with anti-canonical divisors.

In summary, in Setting 4.1 above, there exists in each three cases a unique Kähler-Einstein metric  $\omega_{\text{KE}} \in [\omega]$ . This is by [EGZ09] if  $K_X + D \geq 0$  and by [BBE<sup>+</sup>19, Theorem 5.1] if  $K_X + D < 0$ .

An alternative approach to the continuity of Kähler-Einstein potentials  $\varphi_{\text{KE}}$  consists in showing that  $\omega_{\text{KE}}$  dominates a Kähler form on  $X$  (this is so far only known locally in  $X_{\text{reg}}$ ). In this case  $\varphi_{\text{KE}}$  is  $(1 - \varepsilon)\omega$ -psh and this should help in finding global extensions of  $\varphi_{\text{KE}}$  (see [CGZ13, CT14, WZ20] for partial results in this direction).

The purpose of this final section is thus to study when  $\omega_{\text{KE}}$  is a Kähler current, by using a smoothability assumption. Our results are inspired by [RZ11, Lemma 5.2]. To that end, we introduce the following definition

**Definition 4.2.** — Let  $(X, D)$  be a klt pair with  $X$  compact and let  $\omega$  be a Kähler metric. We say that  $(X, D, [\omega])$  admits a  $\mathbb{Q}$ -Goreinstein smoothing if there exists a triplet  $(\mathcal{X}, \mathcal{D}, [\omega_{\mathcal{X}}])$  consisting of a normal complex space  $\mathcal{X}$ , an effective  $\mathbb{Q}$ -divisor  $\mathcal{D}$ , and a smooth,  $(1, 1)$ -form  $\omega_{\mathcal{X}}$  on  $\mathcal{X}$  admitting a proper holomorphic map  $\pi : \mathcal{X} \rightarrow \mathbb{D}$  satisfying:

1.  $K_{\mathcal{X}/\mathbb{D}} + \mathcal{D}$  is a  $\mathbb{Q}$ -line bundle.
2. Every irreducible component of  $\mathcal{D}$  surjects onto  $\mathbb{D}$ .
3.  $(\mathcal{X}, \mathcal{D})|_{\pi^{-1}(0)} \simeq (X, D)$ .
4. For  $t \neq 0$ ,  $(X_t, D_t) = (\mathcal{X}, \mathcal{D})|_{\pi^{-1}(t)}$  is log smooth.
5. For  $t \in \mathbb{D}$ ,  $\omega_t := \omega_{\mathcal{X}}|_{X_t}$  is Kähler and  $[\omega_0] = [\omega]$ .

If  $K_X$  is  $\mathbb{Q}$ -Cartier and  $D \in |-mK_X|$  for some  $m \in \mathbb{Z}_{>0}$ , we require additionally that  $K_{\mathcal{X}/\mathbb{D}}$  is  $\mathbb{Q}$ -Cartier and  $\mathcal{D} \in |-mK_{\mathcal{X}/\mathbb{D}}|$ .

Let us make few remarks:

- If  $K_X + D$  is ample or anti-ample, then so is  $K_{X_t} + D_t$  for  $t$  small. Then, the last condition in the definition above is automatic if  $\omega \in \pm c_1(K_X + D)$ , by using an embedding of  $\mathcal{X}$  into  $\mathbb{P}^N \times \mathbb{D}$  via sections of  $\pm m(K_{X_t} + D_t)$  for  $m$  large.



- If  $K_X + D$  is numerically trivial, then so is  $K_{X_t} + D_t$  for  $t$  small, cf e.g. [DG18, Lemma 2.12].
- The pair  $(X_t, D_t)$  is automatically klt for any  $t \in \mathbb{D}$ .

**Theorem 4.3.** — *Let  $(X, D, [\omega])$  as in Setting 4.1 and assume that  $(X, D, [\omega])$  admits a  $\mathbb{Q}$ -Gorenstein smoothing. Then, the Kähler-Einstein metric  $\omega_{\text{KE}}$  is a Kähler current. That is, there exists  $C > 0$  such that*

$$\omega_{\text{KE}} \geq C^{-1}\omega.$$

**Remark 4.4.** — Along the same lines, one can obtain the result above assuming instead that  $(X, D)$  admits a crepant resolution, i.e. a proper bimeromorphic map  $p : \tilde{X} \rightarrow X$  such that  $K_{\tilde{X}} + \tilde{D} = p^*(K_X + D)$  where  $\tilde{D}$  is the proper transform of  $D$ .

*Proof.* — We consider the smoothing  $\pi : (\mathcal{X}, \mathcal{D}) \rightarrow \mathbb{D}$ . Up to shrinking  $\mathbb{D}$  slightly and adding  $\pi^* dd^c |t|^2$  to  $\omega_{\mathcal{X}}$ , one can assume that the later form is strictly positive. Since  $\omega_{\mathcal{X}}$  is the restriction of a smooth positive  $(1, 1)$ -form under local embedding  $\mathcal{X} \hookrightarrow \mathbb{C}^N$ , one can assume that the bisectional curvature of  $\omega_{\mathcal{X}}|_{\mathcal{X}^{\text{reg}}}$  is bounded above by a given constant  $C_1$ , maybe up to shrinking  $\mathbb{D}$  just a little more. This is because the bisectional curvature decreases when passing to holomorphic submanifolds. By the same argument, we see the bisectional curvature of  $\omega_t = \omega_{\mathcal{X}}|_{X_t}$  is bounded above by  $C_1$ , for any  $t \in \mathbb{D}$ .

Assume  $\lambda \leq 0$ . For  $t \in \mathbb{D}$ , we consider  $\tilde{\omega}_t = \omega_t + dd^c \varphi_t$  the unique Kähler-Einstein metric of the pair  $(X_t, D_t)$ . It solves

$$(4.1) \quad (\omega_t + dd^c \varphi_t)^n = e^{-\lambda \varphi_t} f_t \omega_t^n$$

for some non-negative function  $f_t$  on  $X_t$  satisfying  $\int_{X_t} f_t^p \omega_t^n \leq C(p, \omega)$  for some  $p > 1$  and some constant  $C(p, \omega)$  independent of  $t \in \mathbb{D}$ , cf the klt version of [DGG20, Lemma 4.4]. If  $\lambda = 0$ , we normalize  $\varphi_t$  by  $\sup_{X_t} \varphi_t = 0$ . By [DGG20], we know that up to shrinking  $\mathbb{D}$ , there exists a constant  $C_2 > 0$  such that

$$(4.2) \quad \|\varphi_t\|_{L^\infty(X_t)} \leq C_2$$

for any  $t \in \mathbb{D}$ .

If  $\lambda > 0$ , there is still a unique KE metric  $\tilde{\omega}_t$  satisfying the estimate (4.2) but the proof requires considerable more work, cf. [SSY16, Proposition 2.23] or [LWX19, Theorem 1.2 (iii)].

Set  $E := \text{Supp}(\mathcal{D})$ . We choose a smooth hermitian metric  $h$  on  $\mathcal{O}_{\mathcal{X}}(E)$ , a section  $s$  of that line bundle cutting out  $E$ , and we introduce the function  $\psi := \log |s|_h^2$ . It satisfies  $dd^c \psi = -i\Theta_h(E)$  on  $\mathcal{X} \setminus E$ , hence there exists a constant  $C_3 > 0$  such that

$$(4.3) \quad \psi \leq C_3 \quad \text{and} \quad dd^c \psi \geq -C_3 \omega \quad \text{on} \quad \mathcal{X} \setminus E.$$

We introduce a number  $\varepsilon > 0$  (meant to go to zero) and we assume wlog that  $\varepsilon C_3 \leq 1$ . We also define  $v_t := \log \text{tr}_{\tilde{\omega}_t} \omega_t$ , which is smooth on  $X_t \setminus E$  and globally bounded (for  $t \neq 0$ ). We want to quantify that bound.

On  $X_t \setminus E$ , we have  $\text{Ric } \tilde{\omega}_t \geq -\tilde{\omega}_t$  and  $\text{Bisec}(X_t, \omega_t) \leq C_1$ . By Chern-Lu formula (cf. [Che68], [Lu68, Theorem 4.2] or [Rub14, Proposition 7.2]), we get

$$\Delta_{\tilde{\omega}_t} v_t \geq -1 - 2C_1 e^{v_t}$$

Using the identity  $\tilde{\omega}_t = \omega_t + dd^c \varphi_t$  and the inequality (4.3), we get

$$\Delta_{\tilde{\omega}_t} (v_t - A\varphi_t + \varepsilon\psi) \geq e^{v_t} - C_4.$$

where  $A = 2(C_1 + 1)$  and  $C_4 = An + 1$ . The maximum of the term inside the Laplacian is attained on  $X_t \setminus E$ , and an easy application of the maximum principle shows

$$v_t(x) \leq C_5 - \varepsilon\psi(x)$$

for any  $x \in X_t \setminus E$  and  $\varepsilon > 0$ , and where  $C_5 = \log C_4 - 2AC_2 + 1$ . Passing to the limit when  $\varepsilon \rightarrow 0$ , we find

$$(4.4) \quad \tilde{\omega}_t \geq C_5^{-1} \omega_t \quad \text{on } X_t, \text{ for any } t \in \mathbb{D}^*.$$

Next, we choose a continuous family of smooth maps  $F_t : X_{\text{reg}} \rightarrow X_t$  inducing a diffeomorphism onto their image and such that  $F_0 = \text{Id}_{X_{\text{reg}}}$ . We claim that  $F_t^* \tilde{\omega}_t$  converges locally smoothly to  $\omega_{\text{KE}}$  on  $X_{\text{reg}} \setminus E$  when  $t \rightarrow 0$ . Thanks to (4.4), this would imply that

$$\omega_{\text{KE}} \geq C_5^{-1} \omega \quad \text{on } X_{\text{reg}} \setminus E$$

hence everywhere since neither  $\omega_{\text{KE}}$  nor  $\omega$  charges the pluripolar set  $X_{\text{sing}} \cup E$  (since they have bounded local potentials).

Set  $X^\circ := X_{\text{reg}} \setminus E$ . In order to show the convergence, we claim successively:

- The family of functions  $F_t^* \varphi_t$  is precompact in the  $C_{\text{loc}}^2(X^\circ)$ -topology.
- Each cluster value  $\omega_\infty = \omega + dd^c \varphi_\infty$  of  $F_t^* \tilde{\omega}_t$  solves the Monge-Ampère equation

$$(\omega + dd^c \varphi_\infty)^n = e^{-\lambda \varphi_\infty} f_0 \omega^n \quad \text{on } X^\circ.$$

- Each cluster value  $\varphi_\infty$  is globally bounded on  $X^\circ$ , hence its unique  $\omega$ -psh extension to  $X$  solves the equation above on  $X$ .

By uniqueness of the Kähler-Einstein metric, it would then follow that  $\omega_\infty = \omega_{\text{KE}}$ , concluding the proof of the convergence. Let us briefly justify each of the items above.

The first point follows from the local Laplacian estimate on  $X^\circ$  obtained from (4.4). Indeed, once the laplacian estimates are obtained, one can invoke Evans-Krylov and Schauder estimates, since  $F_t^* \omega_t$  (resp.  $F_t^* J_t, F_t^* f_t$ ) converges locally smoothly on  $X^\circ$  to  $\omega$  (resp.  $J, f_0$ ) when  $t \rightarrow 0$ . The second item is an immediate consequence of the first one. As for the last one, it is a consequence of (4.2).  $\square$

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*December 3, 2020*

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