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General extension theorem for cohomology classes on non reduced analytic subspaces

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References

This is a joint work with Junyan Cao & Shin-ichi Matsumura

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The extension problem

Let (X, ω) be a possibly noncompact n-dimensional Kähler manifold, $\mathcal{J} \subset \mathcal{O}_X$ a coherent ideal sheaf, $Y = V(\mathcal{J})$ its zero variety and

$$\mathcal{O}_Y = \mathcal{O}_X/\mathcal{J}.$$

Here Y may be non reduced, i.e. $\mathcal{O}_Y$ may have nilpotent elements.

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Here Y may be non reduced, i.e. $\mathcal{O}_Y$ may have nilpotent elements.

Also, let (L, h_L) be a hermitian holomorphic line bundle on X, and

$$\Theta_{L,h_L} = i\,\partial\overline{\partial} \log h_L^{-1}$$

its curvature current (we allow singular metrics, $h_L = e^{-\varphi}$, $\varphi \in L^1_{\mathrm{loc}}$, Θ_{L,h_L} being computed in the sense of currents).

Question

Under which conditions on X, $Y = V(\mathcal{J})$, (L, h_L) is

$H^q(X, K_X \otimes L) \to H^q(Y, (K_X \otimes L)_{|Y}) = H^q(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{O}_X/\mathcal{J})$

a surjective restriction morphism?

Motivation: abundance conjecture and MMP

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For a line bundle L, one defines the Kodaira-Iitaka dimension $\kappa(L) = \limsup_{m\to+\infty} \log \dim H^0(X, L^{\otimes m})/\log m$ and the numerical dimension $\mathrm{nd}(L) =$ maximum exponent p of non zero "positive intersections" $\langle T^p\rangle$ of a positive current $T \in c_1(L)$ when L is psef (pseudoeffective), and $\mathrm{nd}(L) = -\infty$ otherwise. They always satisfy

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A line bundle L is said to be abundant if $\kappa(L) = \mathrm{nd}(L)$.

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The fundamental abundance conjecture can be stated: for each nonsingular klt pair (X, Δ) the $\mathbb{Q}$-line bundle $K_X + \Delta$ is abundant.

Generalized base point free theorem ?

One can try to investigate the abundance of $L = K_X + \Delta$ by induction on the dimension $n = \dim X$, by extending sections of $K_X + L_m$, $L_m = (m-1)K_X + m\Delta$ from subvarieties (noticing that $K_X + \Delta$ psef implies L_m psef, and even $L_m - \Delta$ psef).

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Standard base point free theorem

Let (X, Δ) be a projective klt pair, and L be a nef line bundle such that $L - (K_X + \Delta)$ is nef and big. Then L is semiample, i.e. $|mL|$ is BPF for some $m > 0$.

Question (weak positivity variant of the BPF property ?)

Assume that X is not uniruled, i.e. that K_X is pseudoeffective, and let L be a line bundle such that $L - \varepsilon K_X$ is pseudoeffective for some $0 < \varepsilon \ll 1$. Does there exist $G \in \mathrm{Pic}^0(X)$ such that $L + G$ is abundant ?

First naive (and too restrictive) technique

Consider the exact sequence

$$0 \to \mathcal{J} \to \mathcal{O}_X \to \mathcal{O}_X/\mathcal{J} \to 0$$

twisted by $\mathcal{O}_X(K_X \otimes L)$,

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$$\cdots \to H^q(X, K_X \otimes L) \to H^q(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{O}_X/\mathcal{J}) \to H^{q+1}(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{J}) \cdots$$

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It is therefore enough to have

$$H^{q+1}(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{J}) = 0.$$

In order to kill H^{q+1} it is enough to make a strict positivity (ampleness) assumption, e.g. by the Kodaira-Nakano / Nadel vanishing theorems.

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But we only want to make a weak semipositivity assumption!

In that case, one cannot expect to kill the cohomology group H^{q+1}.

Assumptions (1)

We assume X to be holomorphically convex. By the Cartan-Remmert theorem, this is the case iff X admits a proper holomorphic map $p : X \to S$ only a Stein complex space S.

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Observation : cohomology is then always Hausdorff

Let X be a holomorphically convex complex space and $\mathcal{F}$ a coherent analytic sheaf over X. Then all cohomology groups $H^q(X, \mathcal{F})$ are Hausdorff with respect to their natural topology (local uniform convergence of holomorphic Čech cochains)

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Proof. $H^q(X, \mathcal{F}) \simeq H^0(S, R^q p_* \mathcal{F})$ is a Fréchet space.

Corollary

To solve an equation $\overline{\partial} u = v$ on a holomorphically convex manifold X, it is enough to solve it approximately:

$$\overline{\partial} u_\varepsilon = v + w_\varepsilon, \qquad w_\varepsilon \to 0 \text{ as } \varepsilon \to 0$$

Assumptions (2)

We assume that the subvariety $Y \subset X$ is defined by

$$Y = V(\mathcal{I}(e^{-\psi})), \qquad \mathcal{O}_Y := \mathcal{O}_X/\mathcal{I}(e^{-\psi})$$

where ψ is a quasi-psh function with *analytic singularities*, i.e. locally on a neighborhood V of an arbitrary point $x_0 \in X$ we have

$$\psi(z) = c\log\sum|g_j(z)|^2 + v(z), \quad g_j{\in}\mathcal{O}_X(V),\ c{>}0,\ v{\in}C^\infty(V),$$

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and $\mathcal{I}(e^{-\psi}) \subset \mathcal{O}_X$ is the multiplier ideal sheaf

$$\mathcal{I}(e^{-\psi})_{x_0} = \Big\{ f \in \mathcal{O}_{X,x_0}\,;\ \exists U \ni x_0\,,\ \int_U |f|^2 e^{-\psi} d\lambda < +\infty \Big\}$$

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Moreover $\mathcal{I}(e^{-\psi})$ is always an integrally closed ideal.

Typical choice: $\psi(z) = c \log |s(z)|^2_{h_E},\ c > 0,\ s \in H^0(X, E).$

Log resolution / reduction to the divisorial case

The simplest case is when $Y = \sum m_j Y_j$ is an effective simple normal crossing divisor and $\mathcal{O}_Y = \mathcal{O}_X/\mathcal{O}_X(-Y)$. We can then take

$$\psi(z) = \sum c_j \log |\sigma_{Y_j}|^2_{h_j}, \quad c_j > 0,\ \lfloor c_j \rfloor = m_j,$$

for some smooth hermitian metric h_j on $\mathcal{O}_X(Y_j)$. Then

$$\mathcal{I}(e^{-\psi}) = \mathcal{O}_X\big(-\sum m_j Y_j\big), \qquad i\partial\overline{\partial}\psi = \sum c_j(2\pi[Y_j] - \Theta_{\mathcal{O}(Y_j),h_j})$$

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The case of a higher codimensional multiplier ideal scheme $\mathcal{I}(e^{-\psi})$ can easily be reduced to the divisorial case by using a suitable log resolution (a composition of blow ups, thanks to Hironaka's desingularization theorem).

Main results

Theorem (JY. Cao, D– , S-i. Matsumura, January 2017)

Take (X,ω) to be Kähler and holomorphically convex,
and let (L, h_L) be a hermitian line bundle such that

$$(**) \qquad \Theta_{L,h_L} + (1+\alpha\delta) i\partial\overline{\partial}\psi \geq 0 \qquad \text{in the sense of currents}$$

for some $\delta(x) > 0$ continuous and $\alpha = 0, 1$. Then:

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for some $\delta(x) > 0$ continuous and $\alpha = 0, 1$. Then:
the morphism induced by the natural inclusion $\mathcal{I}(h_L e^{-\psi}) \to \mathcal{I}(h_L)$

$$H^q(X, K_X \otimes L \otimes \mathcal{I}(h_L e^{-\psi})) \to H^q(X, K_X \otimes L \otimes \mathcal{I}(h_L))$$

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is injective for every $q \geq 0$, in other words, the sheaf morphism
$\mathcal{I}(h) \to \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi})$ yields a surjection

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Corollary (take h_L smooth $\Rightarrow \mathcal{I}(h_L) = \mathcal{O}_X$, and $Y = V(\mathcal{I}(e^{-\psi}))$)

If h_L is smooth, $\mathcal{O}_Y = \mathcal{O}_X/\mathcal{I}(e^{-\psi})$ and h_L, ψ satisfy $(**)$, then
$H^q(X, K_X \otimes L) \to H^q(Y, (K_X \otimes L)_{|Y})$ is surjective.

Comments / algebraic consequences

The exact sequence $0 \to \mathcal{I}(h_L e^{-\psi}) \to \mathcal{I}(h_L) \to \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi}) \to 0$ implies that both injectivity and surjectivity hold when

$$H^q(X, K_X \otimes L \otimes \mathcal{I}(h_L e^{-\psi}) = 0,$$

and for this it is enough to have a strict curvature assumption

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Corollary (purely algebraic)

Assume that X is projective (or that one has a projective morphism $X \to S$ over an affine algebraic base S). Let $Y = \sum m_j Y_j$ be an effective divisor and $\mathcal{O}_Y = \mathcal{O}_X/\mathcal{O}_X(-Y)$. If (as $\mathbb{Q}$-divisors)

$$(**) \qquad L - (1+\delta)\sum c_j Y_j = G_\delta + U_\delta, \quad \lfloor c_j \rfloor = m_j$$

with $\delta = 0$ or $\delta_0 \in \mathbb{Q}_+^*$, G_δ semiample and $U_\delta \in \mathrm{Pic}^0(X)$, then

$$H^q(X, K_X \otimes L) \to H^q(Y, (K_X \otimes L)_{|Y})$$

is surjective.

Twisted Bochner-Kodaira-Nakano inequality (Ohsawa-Takegoshi)

Let (X,ω) be a Kähler manifold and let $\eta,\ \lambda > 0$ be smooth functions on X.

For every compacted supported section $u \in \mathcal{C}^\infty_c(X,\Lambda^{p,q}T^*_X \otimes L)$ with values in a hermitian line bundle (L, h_L), one has

$$\|(\eta+\lambda)^{\frac12}\overline\partial^* u\|^2 + \|\eta^{\frac12}\overline\partial u\|^2 + \|\lambda^{\frac12}\partial u\|^2 + 2\|\lambda^{-\frac12}\partial\eta\wedge u\|^2 \ge \int_X \langle B^{p,q}_{L,h_L,\omega,\eta,\lambda} u, u\rangle dV_{X,\omega}$$

where $dV_{X,\omega} = \frac{1}{n!}\omega^n$ is the Kähler volume element and $B^{p,q}_{L,h_L,\omega,\eta,\lambda}$ is the Hermitian operator on $\Lambda^{p,q}T^*_X \otimes L$ such that

$$B^{p,q}_{L,h_L,\omega,\eta,\lambda} = [\eta\, i\Theta_L - i\,\partial\overline\partial\eta - i\lambda^{-1}\partial\eta\wedge\overline\partial\eta\ ,\ \Lambda_\omega].$$

Approximate solutions to $\overline{\partial}$-equations

Main L^2 estimate

Let (X, ω) be a Kähler manifold possessing a complete Kähler metric let (E, h_E) be a Hermitian vector bundle over X. Assume that $B = B^{n,q}_{E,h,\omega,\eta,\lambda}$ satisfies $B + \varepsilon \,\mathrm{Id} > 0$ for some $\varepsilon > 0$ (so that B can be just semi-positive or even slightly negative).

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Take a section $v \in L^2(X, \Lambda^{n,q}T^*_X \otimes E)$ such that $\overline{\partial} v = 0$ and

$$M(\varepsilon) := \int_X \langle (B+\varepsilon\,\mathrm{Id})^{-1} v, v\rangle \, dV_{X,\omega} < +\infty.$$

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$$M(\varepsilon) := \int_X \langle (B + \varepsilon\,\mathrm{Id})^{-1} v, v\rangle \, dV_{X,\omega} < +\infty.$$

Then there exists an approximate solution $u_\varepsilon \in L^2(X, \Lambda^{n,q-1} T^*_X \otimes E)$ and a correction term $w_\varepsilon \in L^2(X, \Lambda^{n,q} T^*_X \otimes E)$ such that

$$\overline{\partial} u_\varepsilon = v + w_\varepsilon \qquad \text{and}$$

$$\int_X (\eta + \lambda)^{-1} |u_\varepsilon|^2 \, dV_{X,\omega} + \frac{1}{\varepsilon} \int_X |w_\varepsilon|^2 \, dV_{X,\omega} \le M(\varepsilon).$$

Proof: setting up the relevant $\overline{\partial}$ equation (1)

Every cohomology class in

$$H^q(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi}))$$

is represented by a holomorphic Čech q-cocycle with respect to a Stein covering $\mathcal{U} = (U_i)$, say $(c_{i_0 \dots i_q})$,

$$c_{i_0 \dots i_q} \in H^0\big(U_{i_0} \cap \dots \cap U_{i_q}, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi})\big).$$

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$$H^q(X, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi}))$$

is represented by a holomorphic Čech q-cocycle with respect to a Stein covering $\mathcal{U} = (U_i)$, say $(c_{i_0 \ldots i_q})$,

$$c_{i_0 \ldots i_q} \in H^0\big(U_{i_0} \cap \ldots \cap U_{i_q}, \mathcal{O}_X(K_X \otimes L) \otimes \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi})\big).$$

By the standard sheaf theoretic isomorphism with Dolbeault cohomology, this class is represented by a smooth (n, q)-form

$$f = \sum_{i_0,\ldots,i_q} c_{i_0 \ldots i_q} \rho_{i_0} \overline{\partial} \rho_{i_1} \wedge \ldots \overline{\partial} \rho_{i_q}$$

by means of a partition of unity (ρ_i) subordinate to (U_i). This form is to be interpreted as a form on the (non reduced) analytic subvariety Y associated with the colon ideal sheaf $\mathcal{J} = \mathcal{I}(he^{-\psi}) : \mathcal{I}(h)$ and the structure sheaf $\mathcal{O}_Y = \mathcal{O}_X/\mathcal{J}$.

Proof: setting up the relevant $\overline{\partial}$ equation (2)

We get an extension of f as a smooth (no longer $\overline{\partial}$-closed) (n, q)-form on X by taking

$$\widetilde{f} = \sum_{i_0,\ldots,i_q} \widetilde{c}_{i_0\ldots i_q} \rho_{i_0} \overline{\partial}\rho_{i_1} \wedge \ldots \overline{\partial}\rho_{i_q}$$

where $\widetilde{c}_{i_0\ldots i_q}$ = extension of $c_{i_0\ldots i_q}$ from $U_{i_0} \cap \ldots \cap U_{i_q} \cap Y$ to $U_{i_0} \cap \ldots \cap U_{i_q}$

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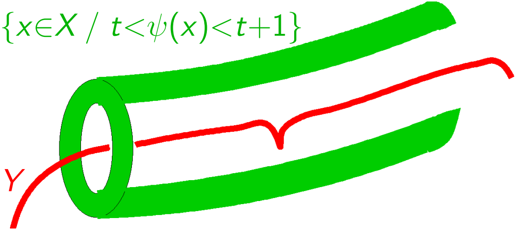

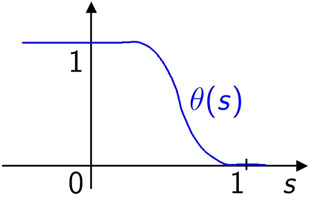

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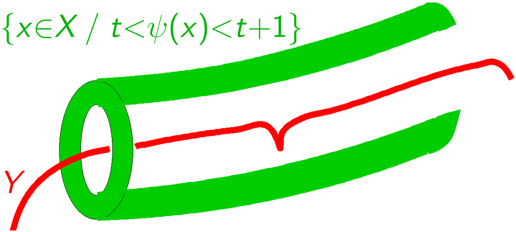

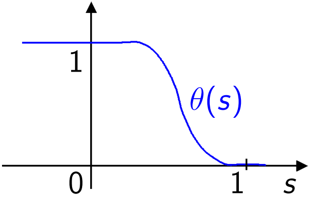

Now, truncate $\widetilde{f}$ as $\theta(\psi - t)\cdot\widetilde{f}$ on the green hollow tubular neighborhood, and solve an approximate $\overline{\partial}$-equation

$$(*) \qquad \overline{\partial} u_{t,\varepsilon} = \overline{\partial}(\theta(\psi - t)\cdot\widetilde{f}) + w_{t,\varepsilon}$$

Proof: setting up the relevant $\overline{\partial}$ equation (3)

Here we have

$$\overline{\partial}(\theta(\psi - t) \cdot \widetilde{f}) = \theta'(\psi - t)\overline{\partial}\psi \wedge \widetilde{f} + \theta(\psi - t) \cdot \overline{\partial}\widetilde{f}$$

where the first term vanishes near Y and the second one is L^2 with respect to $h_L e^{-\psi}$ (as the image of $\overline{\partial}\widetilde{f}$ in $\mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi})$ is $\overline{\partial}f = 0$).

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With ad hoc "twisting functions" $\eta = \eta_t := 1 - \delta\chi_t(\psi)$, $\lambda := \pi(1 + \delta^2\psi^2)$ and a suitable adjustment $\varepsilon = e^{(1+\beta)t}$, $\beta \ll 1$, we can find approximate L^2 solutions of the $\overline{\partial}$-equation such that

$$\overline{\partial}u_{t,\varepsilon} = \overline{\partial}(\theta(\psi - t)\cdot\widetilde{f}) + w_{t,\varepsilon}\ , \qquad \int_X |u_{t,\varepsilon}|^2_{\omega,h_L} e^{-\psi} dV_{X,\omega} < +\infty$$

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The estimate on $u_{t,\varepsilon}$ with respect to the weight $h_L e^{-\psi}$ shows that $\theta(\psi - t) \cdot \widetilde{f} - u_{t,\varepsilon}$ is an approximate extension of f. □

Can one get estimates for the extension ?

The answer is yes if ψ is log canonical, namely $\mathcal{I}(e^{-(1-\varepsilon)\psi}) = \mathcal{O}_X$ for all $\varepsilon > 0$. Then $Y = V(\mathcal{I}(e^{-\psi}))$ is easily seen to be reduced.

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Ohsawa's residue measure

If ψ is log canonical, one can also associate in a natural way a measure $dV_{Y^\circ,\omega}[\psi]$ on the set Y° of regular points of Y as follows. If $g \in \mathcal{C}_c(Y^\circ)$ is a compactly supported continuous function on Y° and $\widetilde{g}$ a compactly supported extension of g to X, one sets

$$\int_{Y^\circ} g\, dV_{Y^\circ,\omega}[\psi] = \lim_{t\to-\infty} \int_{\{x\in X\,,\; t<\psi(x)<t+1\}} \widetilde{g} e^{-\psi}\, dV_{X,\omega}$$

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Theorem

If ψ is lc and the curvature hypothesis is satisfied, for any f in $H^0(Y, K_X \otimes L \otimes \mathcal{I}(h_L)/\mathcal{I}(h_L e^{-\psi}))$ s.t. $\int_{Y^\circ} |f|^2_{\omega,h_L} dV_{Y^\circ,\omega}[\psi] < +\infty$, there exists $\widetilde{f} \in H^0(X, K_X \otimes L \otimes \mathcal{I}(h_L))$ which extends f, such that

$$\int_X (1+\delta^2\psi^2)^{-1} e^{-\psi} |\widetilde{f}|^2_{\omega,h_L} dV_{X,\omega} \le \frac{34}{\delta} \int_{Y^\circ} |f|^2_{\omega,h_L} dV_{Y^\circ,\omega}[\psi].$$

Can one get estimates for the extension ? (sequel)

If ψ is not log canonical, consider the "last jumps" $m_{p-1} < m_p \le 1$ such that $\mathcal{I}(h_L e^{-m_{p-1}\psi}) \supsetneq \mathcal{I}(h_L e^{-m_p\psi}) = \mathcal{I}(h_L e^{-\psi})$ and assume

$$f \in H^0(Y, K_X \otimes L \otimes \mathcal{I}(h_L e^{-m_{p-1}\psi})/\mathcal{I}(h_L e^{-m_p\psi})),$$

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Higher multiplicity residue measure

If f is as above, and $\widetilde{f}$ is a local extension, one can associate a higher multiplicity residue measure $|f|^2 dV_{Y^\circ,\omega}[\psi]$ (formal notation) as follows. If $g \in \mathcal{C}_c(Y^\circ)$ and $\widetilde{g}$ a compactly supported extension of g to X, one sets

$$\int_{Y^\circ} g\,|f|^2 dV_{Y^\circ,\omega}[\psi] = \lim_{t\to-\infty} \int_{\{x\in X\,,\ t<\psi(x)<t+1\}} \widetilde{g}\,|\widetilde{f}|^2 e^{-m_p\psi}\, dV_{X,\omega}$$

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Then a global extension $\widetilde{f} \in H^0(X, K_X \otimes L \otimes \mathcal{I}(h_L e^{-m_{p-1}\psi}))$ exists, that satisfies the expected L^2 estimate.

Special case / limitations of the L^2 estimates

In the special case when ψ is given by $\psi(z) = r\log|s(z)|^2_{h_E}$ for a section $s \in H^0(X, E)$ generically transverse to the zero section of a rank r vector vector E on X, the subvariety $Y = s^{-1}(0)$ has codimension r, and one can check easily that

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Thus one sees that the residue measure takes into account in a very precise manner the singularities of Y. It may happen that $dV_{Y^\circ,\omega}[\psi]$ has infinite mass near the singularities of Y, as is the case when Y is a simple normal crossing divisor.

Therefore, sections $s \in H^0(Y, (K_X \otimes L)_{|Y}$ may not be L^2 with respect to $dV_{Y^\circ,\omega}[\psi]$), and the L^2 estimate of the approximate extension can blow up as $\varepsilon \to 0$. The surprising fact is this is however sufficient to prove the qualitative extension theorem, but without any effective L^2 estimate in the limit.

Remarks: optimal L^2 estimates

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In fact, this result can be seen to hold under the sole assumption that there is only one jump, by a variation of the known methods (Błocki, Guan-Zhou, Berndtsson-Lempert).

The end