

Michael Klaput (University of Oxford) based on work togehter with Andre Lukas and Eirik Svanes

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Why flux?

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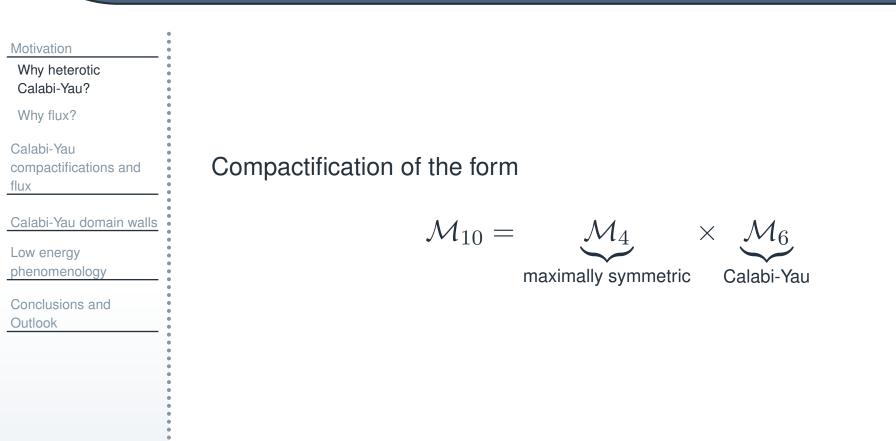
Motivation: Why flux on Calabi-Yau?



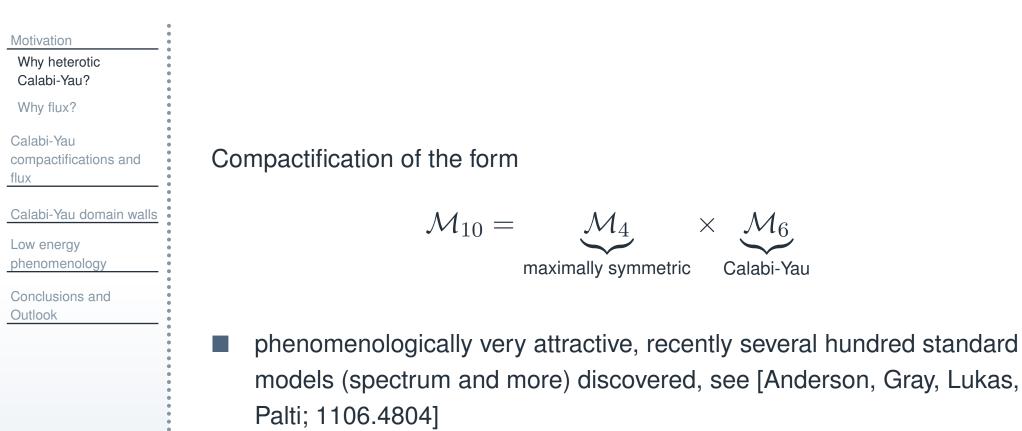
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powerful tools of algebraic geometry available



Why flux?

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Models attractive, but: moduli stabilisation is a problem

- \rightarrow in type IIA/B fluxes can help to resovle this
- \rightarrow heterotic has NS flux available (NS5 branes)



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Models attractive, but: moduli stabilisation is a problem

- \rightarrow in type IIA/B fluxes can help to resovle this
- \rightarrow heterotic has NS flux available (NS5 branes)

Problem: NS flux on Calabi-Yau is very constrained (no-go, see below)



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Models attractive, but: moduli stabilisation is a problem

- \rightarrow in type IIA/B fluxes can help to resovle this
- \rightarrow heterotic has NS flux available (NS5 branes)

Problem: NS flux on Calabi-Yau is very constrained (no-go, see below) These approaches have been tried in the past:

- geometric flux [Gurrieri, Lukas, Micu 0408121], but: \mathcal{M}_6 no longer Calabi-Yau)
- recent progress on this in standard CY compactifications without flux [Anderson, Gray, Lukas, Ovrut]
- this talk: Calabi-Yau and flux



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Make a compactification ansatz:

 $\mathcal{M}_{10} = \mathcal{M}_4 \times \mathcal{M}_6$

maximally symmetric



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Make a compactification ansatz:

$$\mathcal{M}_{10} = \underbrace{\mathcal{M}_4}_{\text{maximally symmetric}} \times \mathcal{M}_6$$

then requiring unbroken supersymmetry gives [Wit, Smit, Dass, Nucl.Phys B283 1987]

 $H = 0 \qquad \Leftrightarrow \qquad \mathcal{M}_6$ is Calabi-Yau

This means either we give up Calabi-Yau or we have no flux.



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? Why is there such a tension between Calabi-Yau and flux? simple argument to illuminate this [Gauntlett, Martelli, Waldram 0302158]: look at dilaton equation of motion

$$\nabla^2 e^{-2\phi} = e^{-2\phi} * (H \wedge *H)$$



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$$\nabla^2 e^{-2\phi} = e^{-2\phi} * (H \wedge *H)$$

integrating gives

$$\underbrace{-\int_{X_6} d_6 \left(e^{4A} *_6 d_6 e^{-2\phi} \right)}_{=0} = \int_{X_6} e^{4A} e^{-2\phi} (H \wedge *_6 H) = \| e^{2A} e^{-\phi} H \|^2$$



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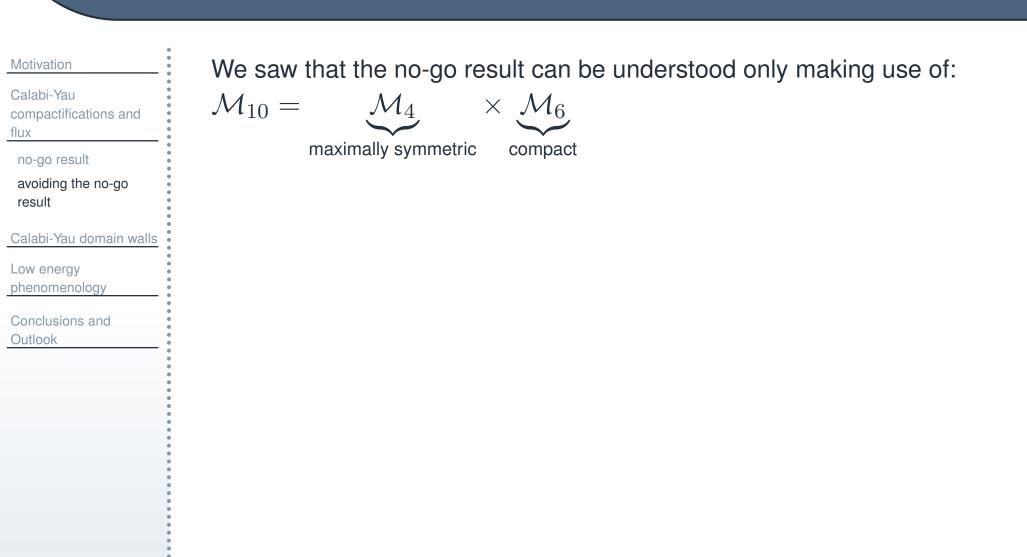
 $\underbrace{-\int_{X_6} d_6 \left(e^{4A} *_6 d_6 e^{-2\phi} \right)}_{=0} = \int_{X_6} e^{4A} e^{-2\phi} (H \wedge *_6 H) = \| e^{2A} e^{-\phi} H \|^2$

 $\Rightarrow H = 0 \qquad \forall \mathcal{M}_6 \text{ compact}$

i.e. we did not use Calabi-Yau, nor supersymmetry! (of course, α' corrections avoid this argument, however: again no CY! [Strominger])



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We saw that the no-go result can be understood only making use of:

 $\mathcal{M}_{10} =$



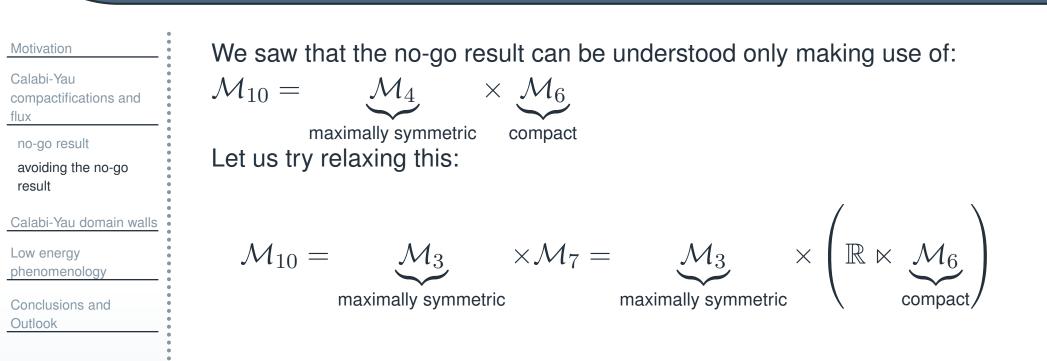


maximally symmetric compact Let us try relaxing this:

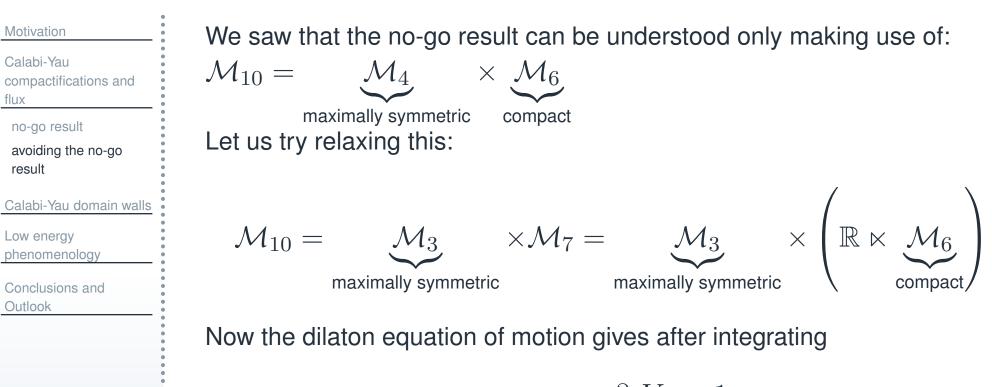
 $\mathcal{M}_{10} = \mathcal{M}_3$ $\times \mathcal{M}_7 =$

maximally symmetric

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$$-\partial_y^2 e^{-2\phi} - \partial_y e^{-2\phi} \frac{\partial_y V}{V} = \frac{1}{V} \|e^{-\phi}H\|^2$$

 \rightarrow giving ϕ an appropriate y dependence allows for non-zero flux!



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Supersymmetry conditions

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We have motivated the existence of Calabi-Yau domain walls with flux. Let us make this more explicit:

$$\left(\nabla_M + \frac{1}{8}\mathcal{H}_M\right)\epsilon = 0 \qquad \left(\nabla\!\!\!/\phi + \frac{1}{12}\mathcal{H}\right)\epsilon = 0$$



Supersymmetry conditions

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$$\left(\nabla_M + \frac{1}{8}\mathcal{H}_M\right)\epsilon = 0 \qquad \left(\nabla\!\!\!/\phi + \frac{1}{12}\mathcal{H}\right)\epsilon = 0$$

using 6d spinors we define the forms on \mathcal{M}_6 :

$$J := \eta_{-}^{\dagger} \gamma_{uv} \eta_{-} e^{uv} \qquad \Omega := \eta_{+}^{\dagger} \gamma_{uvw} \eta_{-} e^{uvw}$$

with the domain wall ansatz $\mathcal{M}_{10} = \mathcal{M}_3 \times \mathbb{R} \ltimes \mathcal{M}_6$ this leads to

 $d\Omega_{-} = 2d\phi \wedge \Omega_{-} \qquad \qquad J \wedge dJ = J \wedge J \wedge d\phi$ $dJ = 2\phi'\Omega_{-} - \Omega'_{-} - 2d\phi \wedge J + *H$ $d\Omega_{+} = J \wedge J' - \phi'J \wedge J + 2d\phi \wedge \Omega_{+} \qquad \qquad \Omega_{-} \wedge H = 2\phi' * 1$ $\Omega_{+} \wedge H = 0 ,$

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The Killing spinor equations then reduce for a Calabi-Yau (i.e. dJ = 0, $d\Omega = 0$) to the following flow equations

$$\Omega'_{+} = 2\phi'\Omega_{+} - H$$
$$J \wedge J' = \phi'J \wedge J$$
$$\Omega_{-} \wedge H = 2\phi' * 1 ,$$

together with the constraint

S

 $\Omega_+ \wedge H = 0 \; .$



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 $\Omega_+ \wedge H = 0 \; .$

 \rightarrow existence of solutions guaranteed by [Hitchin math.DG 0107101]



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$$\Omega = Z^{A} \Big[\alpha_{A} - \mathcal{G}_{AB}(Z^{A})\beta^{B} \Big]$$
$$J = v^{i}\omega_{i}$$
$$H = \mu^{A}\alpha_{A} + \epsilon_{B}\beta^{B}$$

Here Z^A are the $h^{2,1} + 1$ projective complex moduli and \mathcal{G} their prepotential, v^i the $h^{1,1}$ Kähler moduli and μ^A , ϵ_A y-independent flux parameters.



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The flow equations for the forms can be easily integrated if we define $X^A := e^{-2\phi}Z^A$ and a new coordinate z via $dy/dz = e^{2\phi}$:

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$$\begin{aligned} &\operatorname{Re} \, X^A = -\mu^A z - \gamma^A \\ &\operatorname{Re} \, \mathcal{G}_B(X^A) = \epsilon_B z + \eta_B \\ & v^i = e^\phi v_0^i \;, \end{aligned}$$

with integration constants $\{\gamma^A, \eta_B\}$, such that $\gamma^A \epsilon_A + \eta_B \mu^B = 0$. $2(h^{2,1}+1)$ equations for $h^{2,1}+1$ complex $X^A \Rightarrow X^A = X^A(z)$.

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$$X^A = -\mu^A z - \gamma^A$$

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$$\operatorname{Im} X^{A} \epsilon_{A} + \operatorname{Im} \mathcal{G}_{B} \mu^{B} = -2V_{0} \partial_{z} (e^{-\phi})$$



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$$\operatorname{Im} X^{A} \epsilon_{A} + \operatorname{Im} \mathcal{G}_{B} \mu^{B} = -2V_{0} \partial_{z} (e^{-\phi})$$

for any given Calabi-Yau such a solution can be constructed
it allows for any harmonic flux to be present (no α' corrections needed)



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We saw that relaxing the 4d spacetime to a domain wall gave us enough freedom to add flux to a given Calabi-Yau compactification but: did we lose all potential to do realistic phenomenology?



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to think further about this, let us look at the low-energy theory:



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 $\mathcal{N}=1$ SUGRA, moduli fields (S,T^i,X^A) [Gurrieri, Lukas, Micu 0408121]

$$K = -\ln i(\bar{S} - S) - \ln 8V - \ln i(X^A \bar{\mathcal{G}}_A - \bar{X}^A \mathcal{G}_A)$$

(so far: this is the same theory as for a maximally symmetric CY compactification)



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new: superpotential

$$W = \epsilon_A X^A + \mu^A \mathcal{G}_A$$



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domain wall ground states

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The theory described above has for non-vanishing flux a 1/2-BPS domain wall [Lukas, Matti 1005.5302].



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→ for the more general case half-flat: Yes, in the large complex structure limit [Lukas, Matti]



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Matching requires field redefinitions:

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$$e^{2\phi} = e^{2\phi_4} V / V_0$$
 $Z^A = e^{2\phi} X^A$ $v^i = t^i$

We also know something about the asymptotics:

weak coupling limit as $y \to \infty$

 X^A approach constant value as $y \to \infty$



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Therfore, want to take the viewpoint:

$$\begin{array}{ccc} {\sf CY} \mbox{ max. sym.} & \longrightarrow & {\sf CY} \mbox{ domain wall} \\ & \downarrow & & \downarrow \\ \mbox{ some nice model} & \longrightarrow & \mbox{ some nice model with W} \end{array}$$



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Let us return to the question whether the domain wall spoils the phenomenological success of the original Calabi-Yau model.



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domain wall is a perturbative solution and unstable: at least dilaton is still unfixed



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- in standard Calabi-Yau compactification the situation is similar: at least dilaton unfixed



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- ightarrow add non-perturbative effects to lift the ground state to a stable vacuum



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However, why shouldn't the domain wall itself be lifted in this process, leading to a vacuum with a maximally symmetric spacetime in 4d? In fact, for half-flat domain walls it was shown that the domain wall can indeed be lifted to a maximally symmetric and stable vacuum (moduli at consistent values) [M.K., Lukas, Matti, Svanes 1210.5933]



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Conclusions:

- heterotic CY compactifications offer a fertile ground for phenomenology
- \rightarrow but: moduli stabilisation problematic



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Conclusions:

- heterotic CY compactifications offer a fertile ground for phenomenology
- \rightarrow but: moduli stabilisation problematic
 - relaxing assumptions on 4d spacetime allows for flux
- \rightarrow in particular CY domain walls allow for arbitrary harmonic flux



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Conclusions:

- heterotic CY compactifications offer a fertile ground for phenomenology
- \rightarrow but: moduli stabilisation problematic
 - relaxing assumptions on 4d spacetime allows for flux
- \rightarrow in particular CY domain walls allow for arbitrary harmonic flux
 - this results in a model which has a domain wall, so it seems no realistic phenomenology possible
- \rightarrow however, we believe that past work has shown that there is justified reason to believe that such a model can be lifted to a maximally symmetric vacuum



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Paradigm:

make compactification ansatz as close as possible to our universe (in particular 4d spacetime should be maximally symmetric)

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make compactification ansatz as close as possible to our universe (in particular 4d spacetime should be maximally symmetric)

However:

- it seems very hard to actually find stable vacuua with this approach
- it almost seems unavoidable to introduce non-perturbative effects to stabilise the dilaton



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What if we take a different point of view:



start with some ansatz that allows for enough freedom to stabilise all moduli but the dilaton (= switch on a superpotential)



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- it seems very hard to actually find stable vacuua with this approach
- I it almost seems unavoidable to introduce non-perturbative effects to stabilise the dilaton

What if we take a different point of view:



- start with some ansatz that allows for enough freedom to stabilise all moduli but the dilaton (= switch on a superpotential)
- $\rightarrow\,$ lift to non-perturbative stable vacuum, with a maximally symmetric spacetime

After all, it is the final lifted vacuum which we want to look like our universe.



Heterotic Calabi-Yau Flux Compactifications - 19

Outlook

Motivation	
Calabi-Yau compactifications and flux	
Calabi-Yau domain walls	Still many things left to do:
phenomenology	study lifting and moduli stabilisation for an explicit model
Conclusions and Outlook	try supersymmetric cosmic string, black hole,



Thank you!

Motivation
Calabi-Yau compactifications and flux
Calabi-Yau domain walls
Low energy phenomenology
Conclusions and
Outlook

