

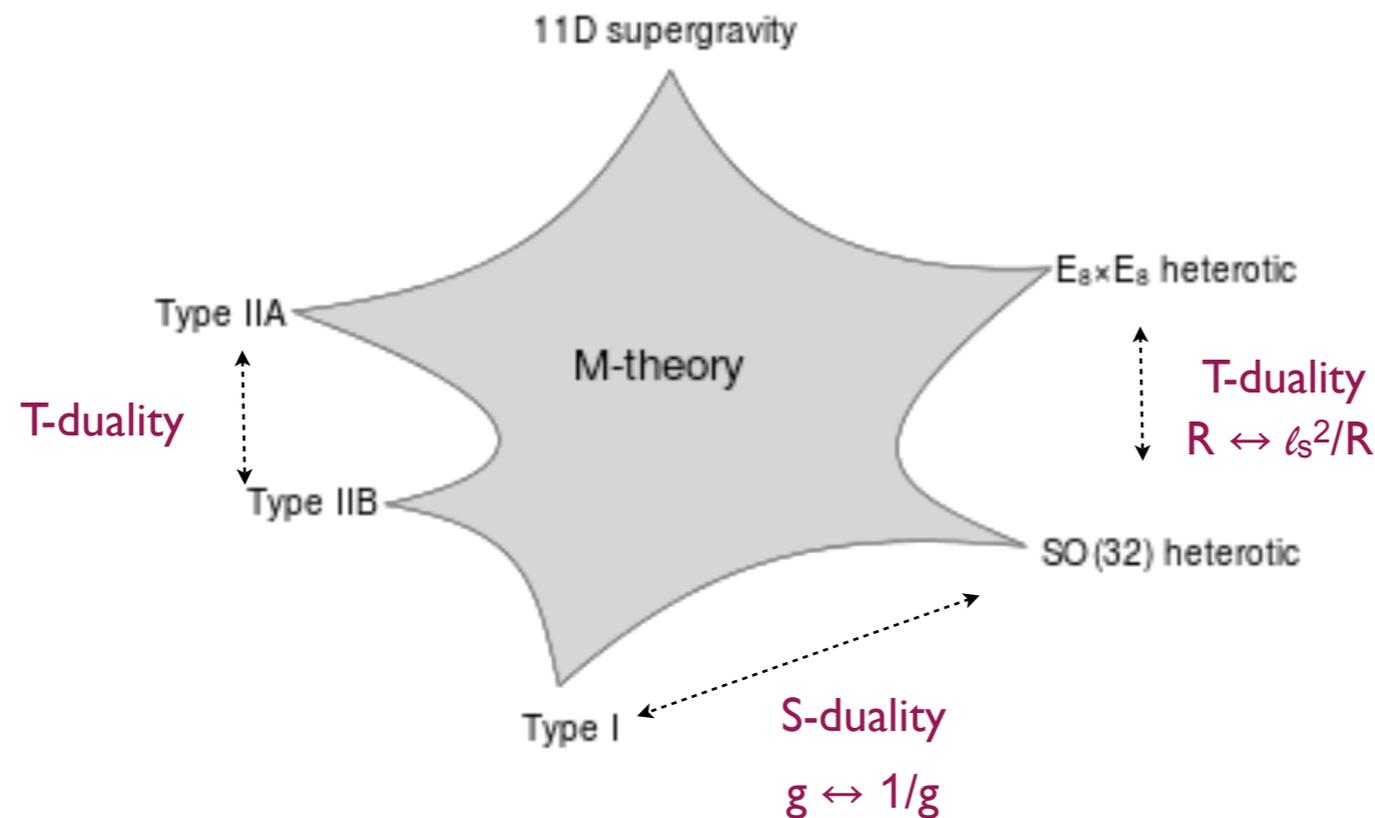
de Sitter vacua in string theory: from the landscape to the swampland

Mariana Graña
IPhT
CEA / Saclay

Itzykson 2019: Effective field theory in cosmology, gravitation and particle physics.
IPhT, CEA/Saclay 2018

String theory

- A remarkable theory of **quantum gravity**, calculable
- Second superstring revolution ('95): **unique theory!**



Different limits
connected
by dualities

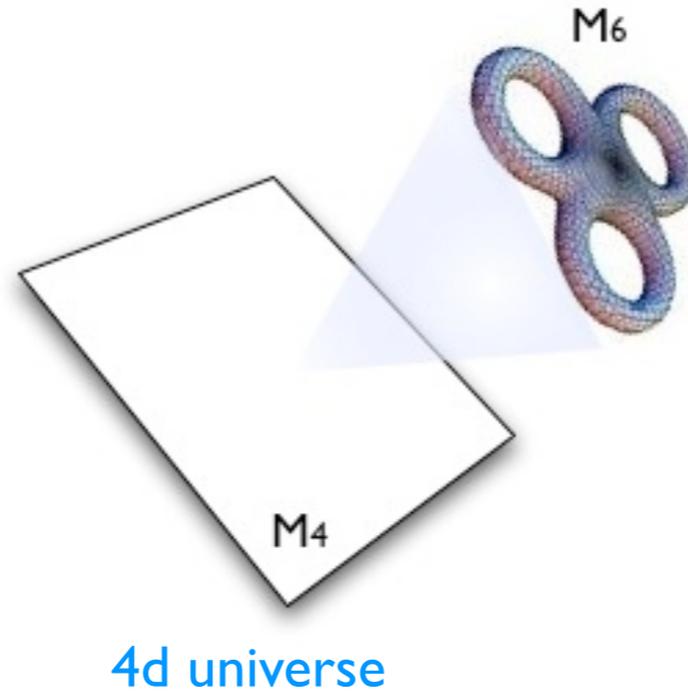
But

Unique theory 10d



6d compact space

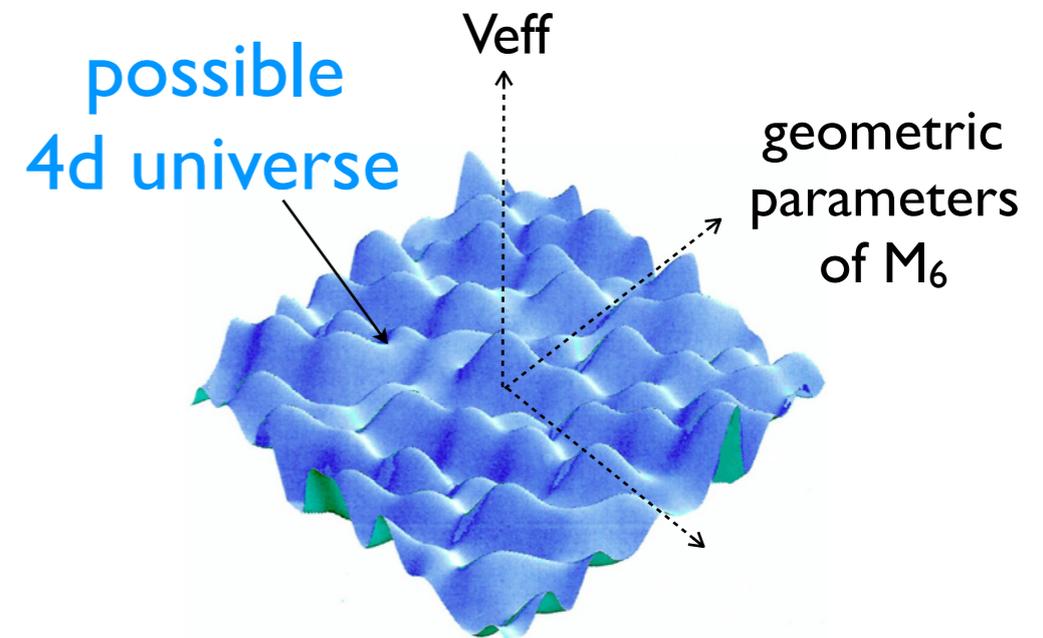
$$M_{10} = M_4 \times M_6$$



Geometry of M_6
determines physics
in 4d

Multiple solutions : 10^{500}

10^{500} possible 4d “de Sitter universes”



Kachru Kallosh
Linde Trivedi (KKLT) 2003

Since 2003

- Not a single explicit realisation
- Many **problems** in the construction pointed out

Bena, MG, Halmagyi, Kuperstein, Massai,
Retolaza, Van Riet @ IPhT

- ...

Fine, ...

- ...

Fine, ...

- **Tachyon**

Fine, vacuum is not exactly where we thought it was, but somewhere close

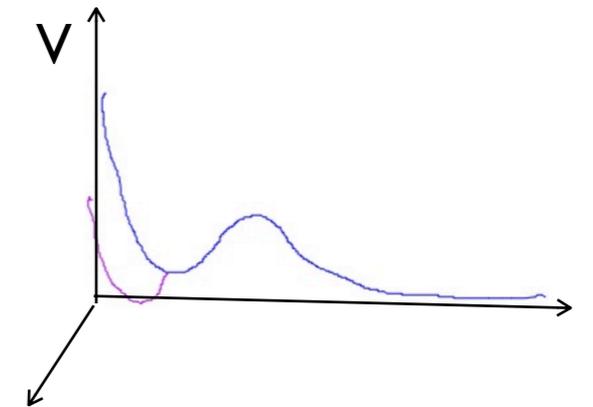
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Bena, MG, Kuperstein, Massai 14



- Is there a landscape with 10^{500} dS vacua in string theory?

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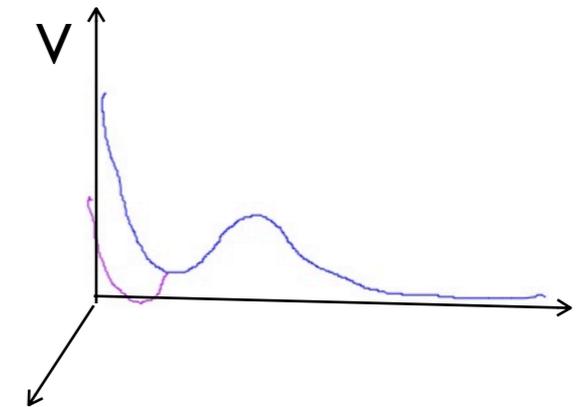
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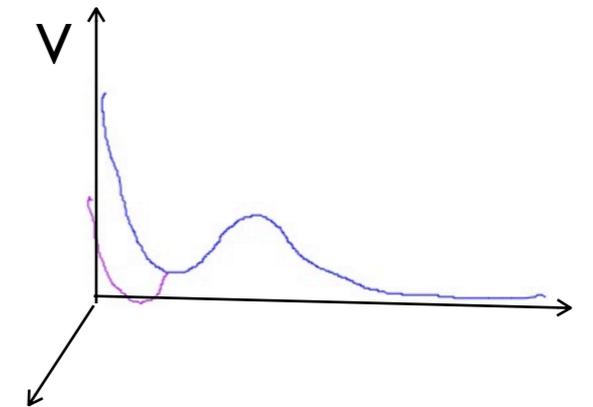
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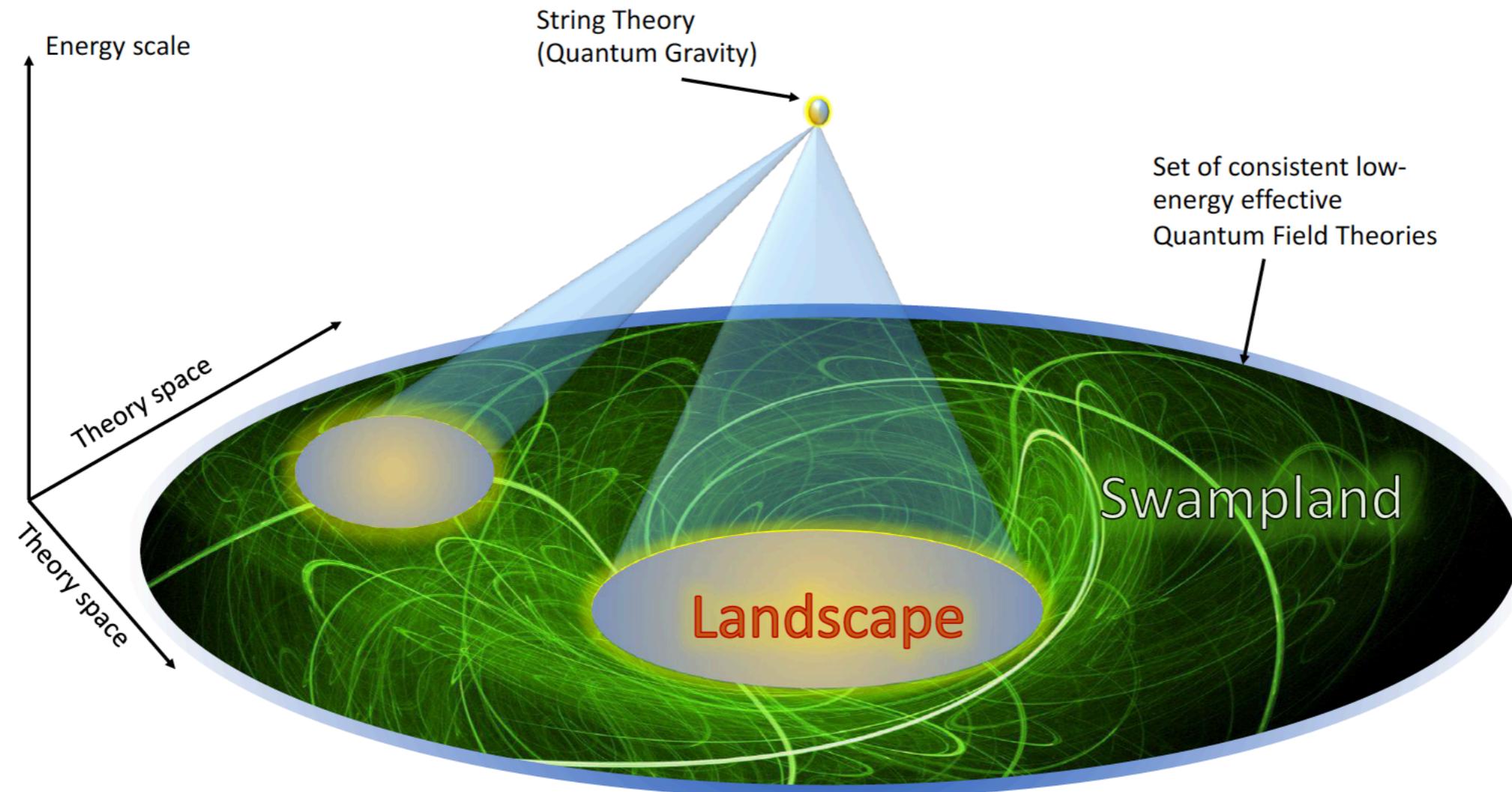
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Bena, MG, Kuperstein, Massai 14



- Is there a landscape with 10^{500} dS vacua in string theory?

The landscape and the swampland



- Series of conjectures on properties of EFT to be in the landscape

- No continuous global symmetries

⋮

- de Sitter conjecture

Obied, Ooguri, Spodyneiko, Vafa 07/18

In a theory on the landscape

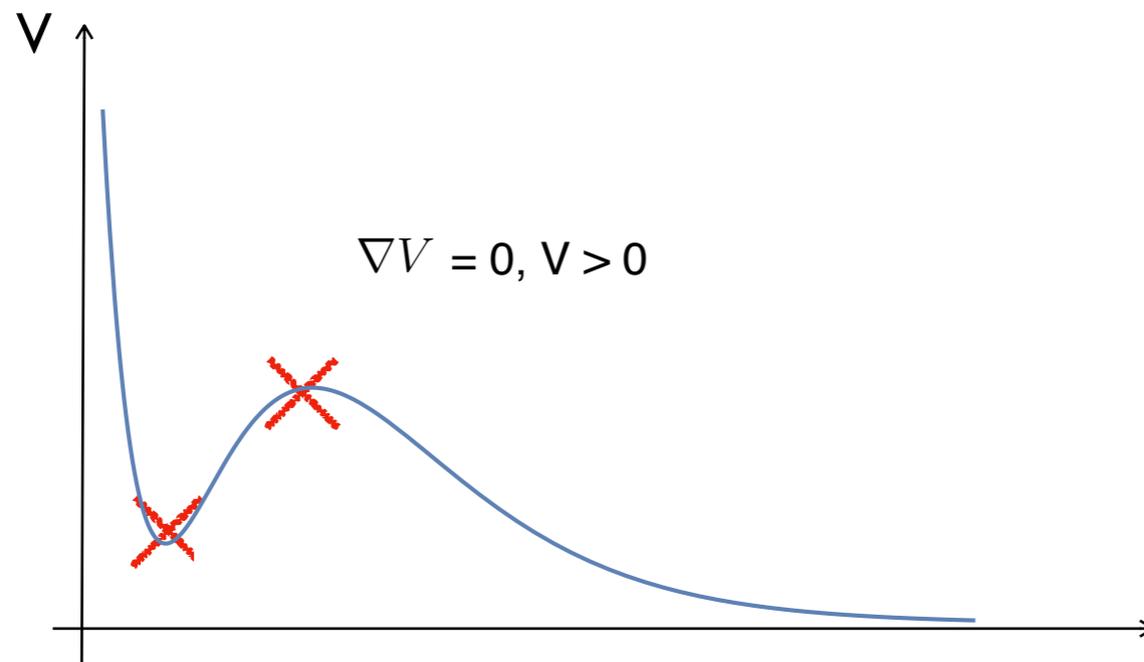
The potential satisfies $|\nabla V| \geq cV$ with $c > 0$ ($\mathcal{O}(1)$ in Planck units)

- de Sitter conjecture

Obied, Ooguri, Spodyneiko, Vafa 07/18

In a theory on the landscape

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- refined de Sitter conjecture

Obied, Ooguri, Spodyneiko, Vafa 07/18

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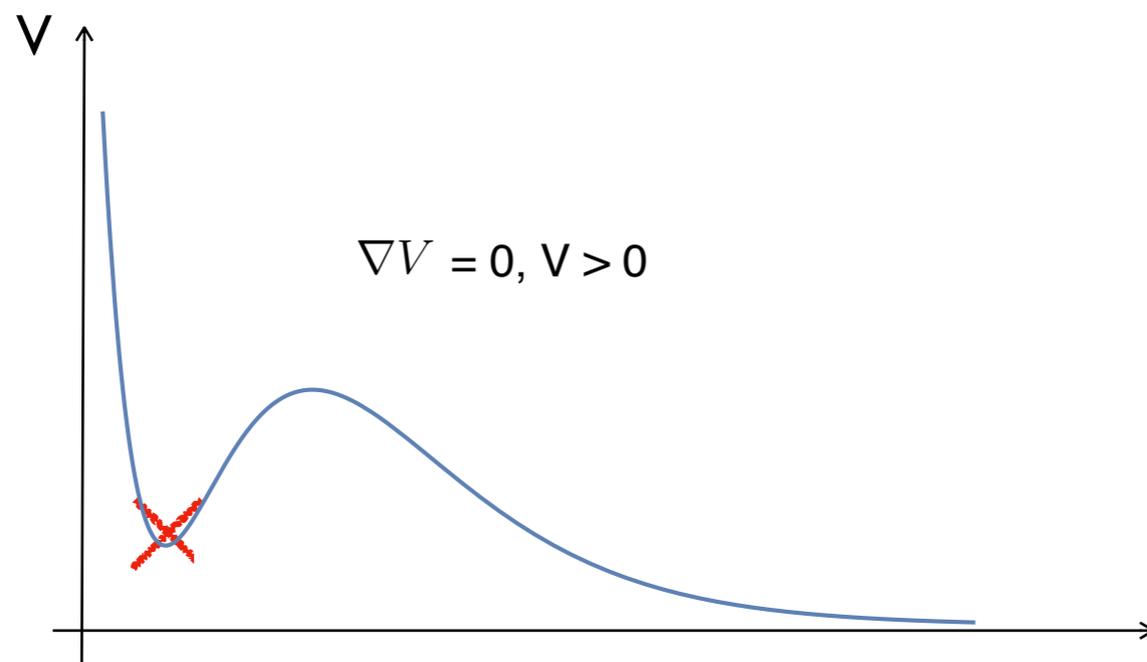
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or

$$\min(\nabla_i \nabla_j V) \leq -c'V$$

no metastable dS vacua

Ooguri, Palti, Shiu, Vafa 10/18



- refined de Sitter conjecture

Obied, Ooguri, Spodyneiko, Vafa 07/18

In a theory on the landscape

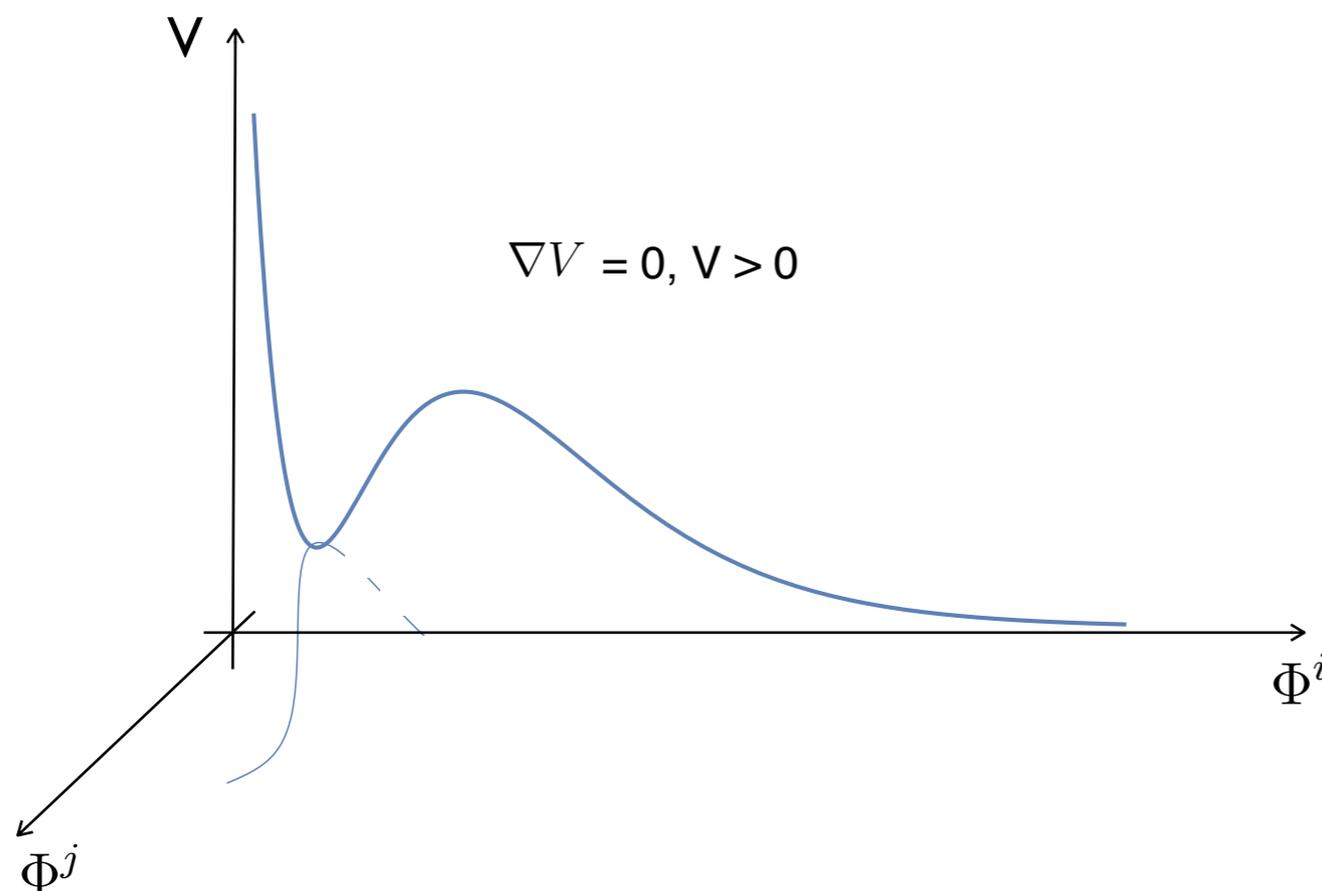
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or

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Ooguri, Palti, Shiu, Vafa 10/18



Metastable dS vacua
are in the swampland

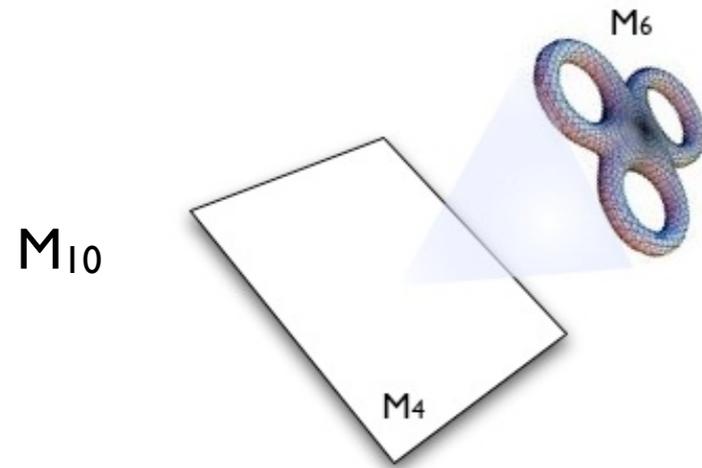
de Sitter vacua in string theory: from 10^{500} to none

Outline

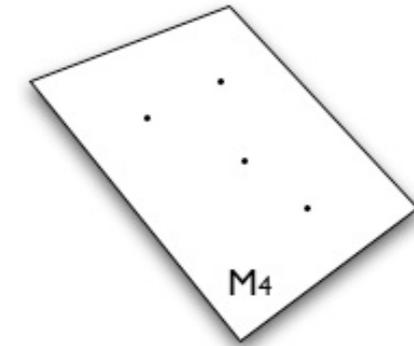
- 10^{500} de Sitter solutions
- 10^{500} problems
- Conclusions

String theory vacua: compactifications

$$M_{10} = M_4 \times M_6$$

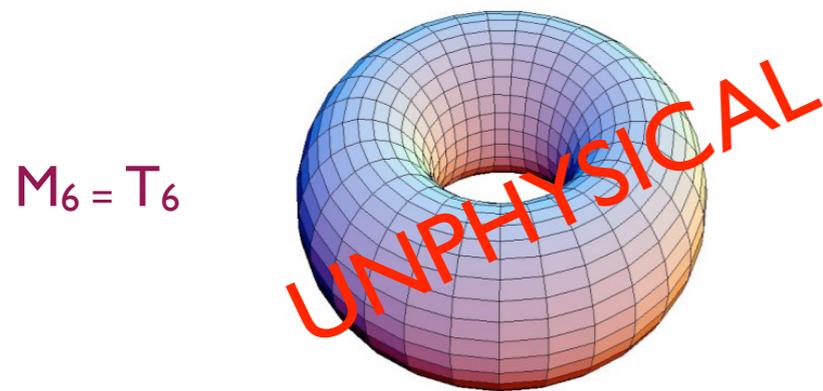


Properties of 6D space determine 4D physics



Observable world

Simplest solution to EOM



Supersymmetric



supersymmetric spectrum

BUT

4D space = Minkowski



no cosmological constant

Radii of circles not fixed



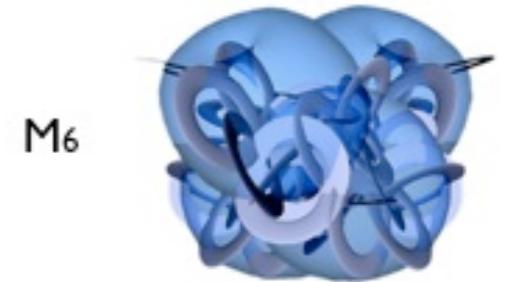
Massless scalars (moduli)

Next simplest solution: Calabi-Yau manifolds

$$M_{10} = M_4 \times M_6$$

EoM $\Rightarrow M_6 : R_{mn} = 0$ Ricci-flat

Calabi-Yau
manifolds



Algebraic techniques to construct them

Many (in 6D ~ more than 30.000 known, finite number of them?)

→ supersymmetric (though $N=2$ or 1 in 4D)

Better than tori, but still → massless scalars

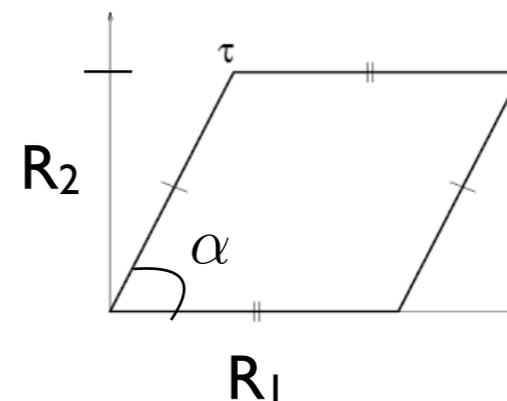
→ 4D space Minkowski

Unlike tori, CY manifolds rich enough to overcome these problems

Massless scalars in the 4d effective theory for CY compactifications

T^2 : R_1, R_2, α or instead $R_1 R_2 \rightarrow \text{vol}$; $\tau \rightarrow \text{shape}$

$T^6 = T^2 \times T^2 \times T^2$: $\text{vol}_1, \text{vol}_2, \text{vol}_3$ and τ_1, τ_2, τ_3



volume moduli : as many as independent 2 cycles = b^2

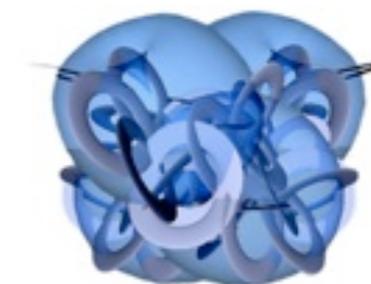
Same for CY:

shape moduli: as many as independent 3 cycles = b^3

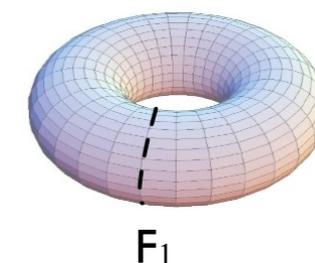
topological numbers
~ 100 in typical CY

Effective 4d theory for CY compactifications:

$N=1$ sugra theory with $b^2 + b^3$ massless scalars with no potential
~ 200 scalars



Partial Solution: **Turn on fluxes**
(higher dimensional versions of electromagnetic flux)



Topological flux

- Fluxes back-react \Rightarrow 6D geometries get far more complicated

Unless only some fluxes (3-form fluxes F_3, H_3) turned on

String theory vacua with fluxes

- Take a given CY manifold, add 3-form fluxes

$$\int_{\alpha_I} F_3 = e^I \quad \int_{\alpha_I} H_3 = \tilde{e}^I$$

$I = 1, \dots, b^3$



- Gravitational attraction vs electromagnetic repulsion: equilibrium point where **sizes of 3-cycles are fixed**

- Infinite number of solutions??

- No!! Cannot add as much flux as we want

Fluxes have **positive** tension

Maldacena-Nuñez 00

From Einstein's eq trace reversed

(**eom for space-time metric in string theory at classical level, leading order in der. expansion**)

$$\int_{M_6} \tilde{R} + \hat{T} = \nabla^2 e^{2A}$$

> 0 for fluxes $= 0$ on a **compact** manifold

$$M_{10} = M_4 \times_w M_6$$

$$ds^2 = e^{2A(y)} \tilde{g}_{\mu\nu} dx^\mu dx^\nu + g_{mn} dy^m dy^n$$

Minkowski, AdS₄ or dS₄ any M₆

$$\hat{T} = \frac{1}{2} (T_m^m - T_\mu^\mu)$$

-No dS! (or Minkowski) for any M6 if one adds fluxes

-D-brane sources do not help, they have $\hat{T} \geq 0$

-No dS or Minkowski with fluxes unless one adds **sources of negative tension**

∃ in string theory: **orientifold planes**

-Take a given CY manifold, add orientifold planes (quotient out by symmetry with fixed pts)

M₆



-Add 3-form fluxes

Sizes of 3-cycles are fixed

$$\int_{\alpha_I} F_3 = e^I$$

$$\int_{\alpha_I} H_3 = \tilde{e}^I$$

I=1,..., b³

b³~ 200 in typical CY

-How many solutions?

$$T_{3\text{-flux}} = |T_{\text{Orientifolds}}|$$

∥ ∥

$$Q_{3\text{-flux}} = |Q_{\text{Orientifolds}}| \sim 30$$

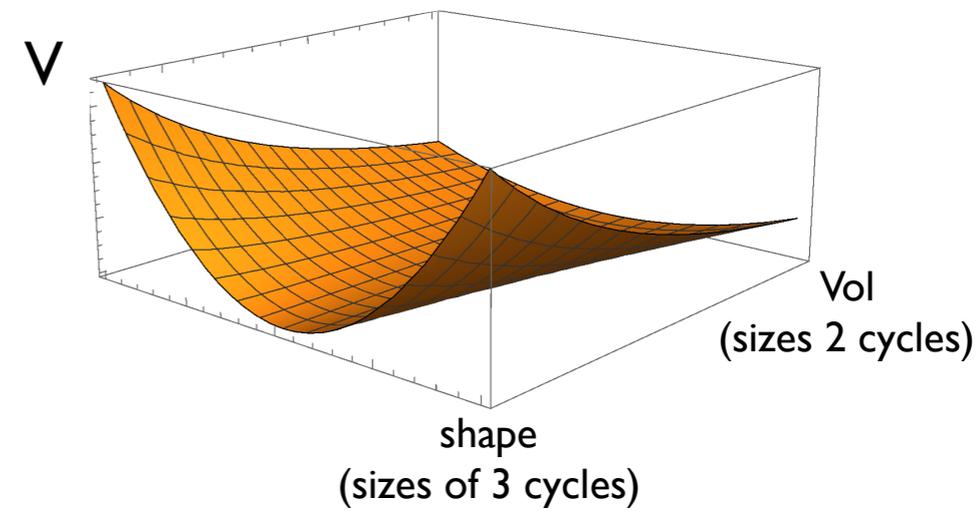
$$N_{\text{solutions}} \sim Q_{3\text{-flux}}^{\# \text{ cycles}} \sim 10^{500} \quad !!$$

**TADPOLE CANCELLATION
CONDITION**
(no net charge)

Landscape of string theory solutions BUT...

To get no massless scalars & V>0 at minimum

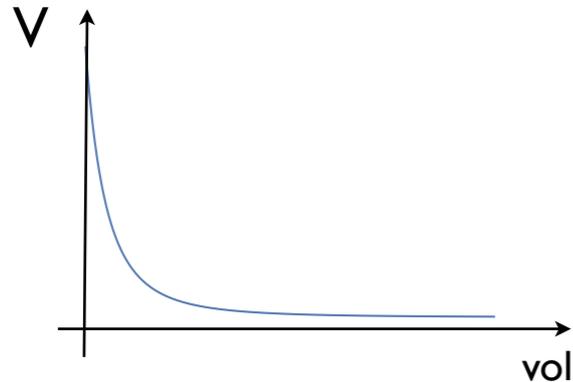
Need **fluxes** (step 1) + “**exotic**” ingredients
(steps 2 and 3)



de Sitter vacua, step 2 : non-perturbative quantum corrections

- Shape moduli massive: integrate them out (replace them by vevs)

Get an effective theory for volume moduli (sizes of 2 cycles)



CY with one single 2-cycle \Rightarrow

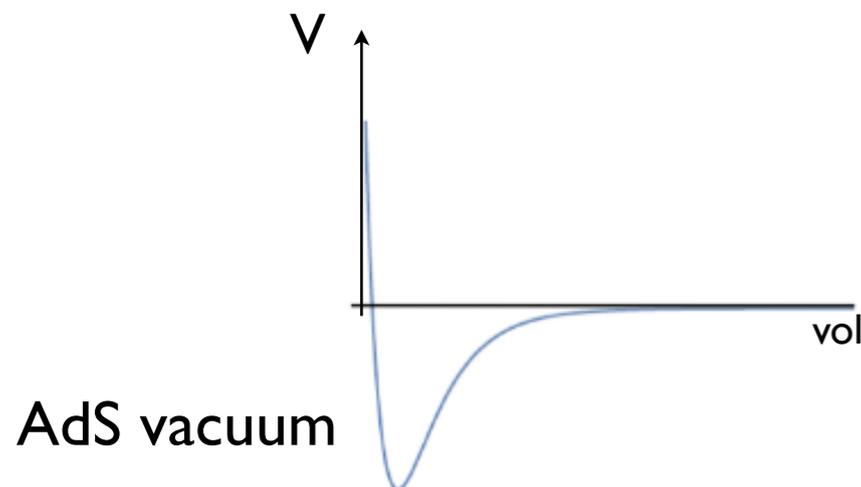
$$\text{Vol}(\text{CY}) = \text{vol}(\text{2-cycle})^3 = (\sqrt{\rho})^3$$

- **Gaugino condensation** on D7-branes wrapped on 4 cycles of CY

Kachru, Kallosh, Linde, Trivedi 03

Give non-perturbative contribution to the potential $\sim e^{-\rho}$

Get susy AdS vacuum with size of 4 cycle (~ 2 cycle) fixed



de Sitter vacua, step 3 : anti-D3-branes

- $\overline{D3}$ branes: same as D3-branes but opposite charge (\Rightarrow opposite charge of fluxes)

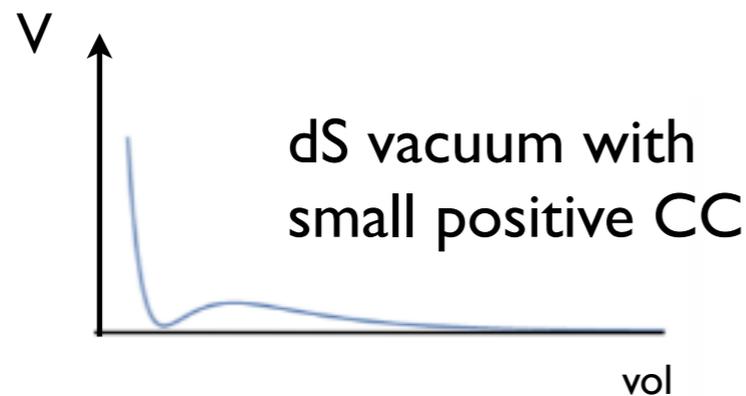
break susy

(meta) stable in probe approximation

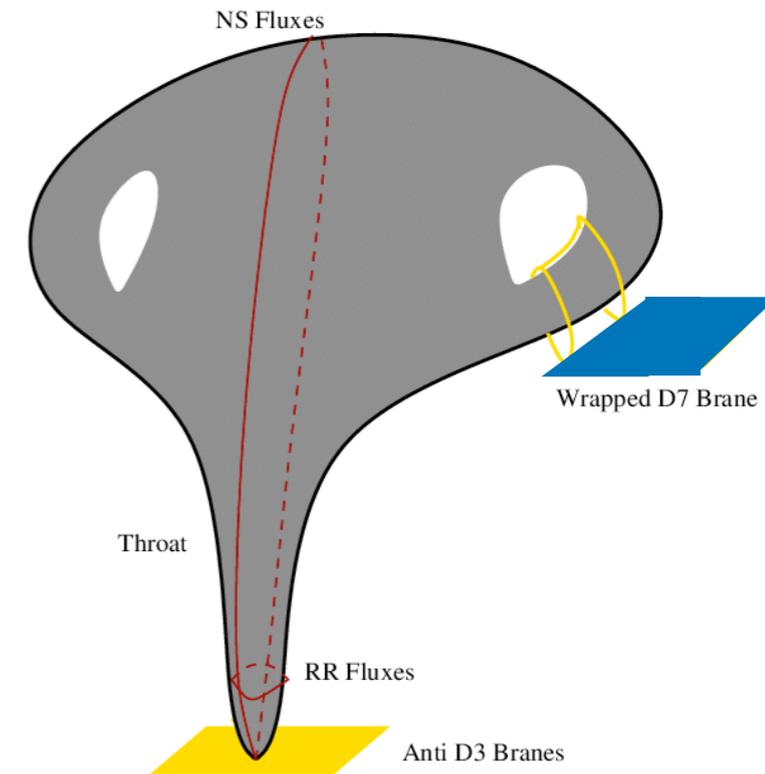
- attracted to bottom of throat where $e^{2A} \ll 1$
- non-perturbative decay via brane-flux annihilation

- Total potential

$$V = \frac{e^{-\rho}}{\rho^2} \left((\rho + 1) \overbrace{e^{-\rho}}^{\text{gaugino condensate}} + \underbrace{W_0}_{\text{fluxes}} \right) + \frac{D}{\rho^3} \underbrace{\overline{D3}}_{\sim e^{2A} \text{ (bottom)}}$$



Kachru, Pearson, Velinde 01



Generic mechanism

Landscape of string theory solutions with positive cosmological constant ?

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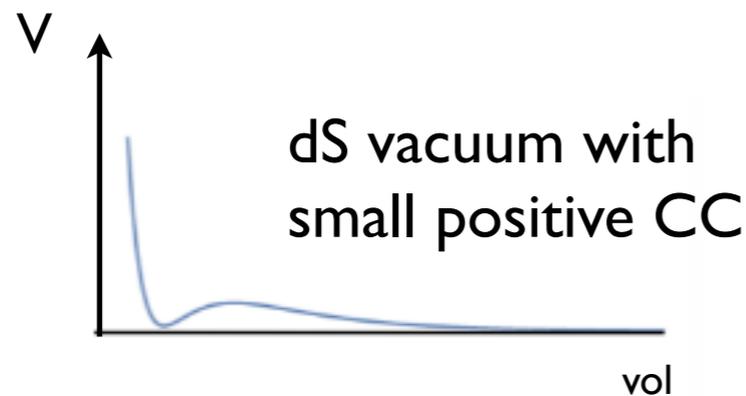
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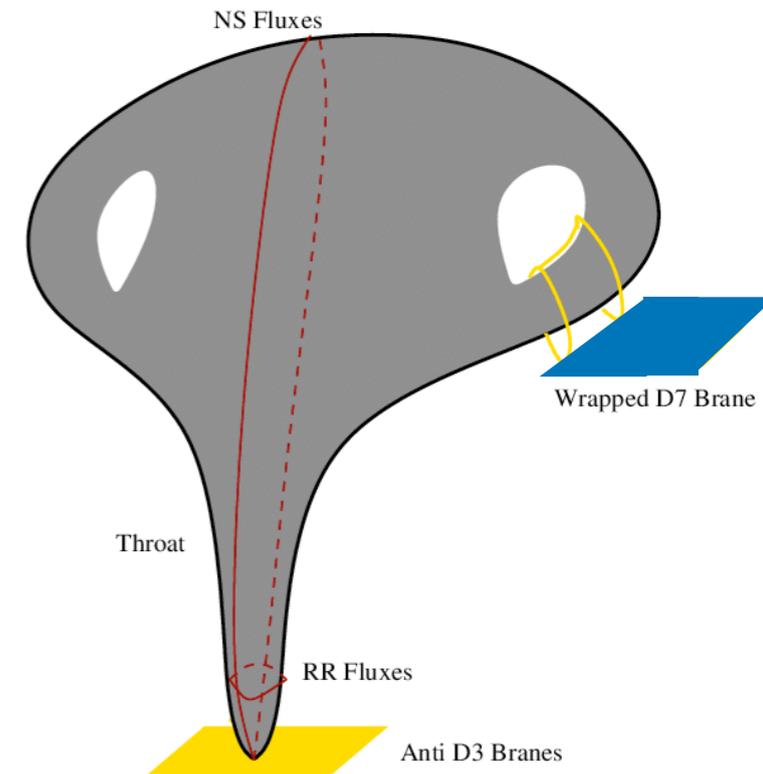
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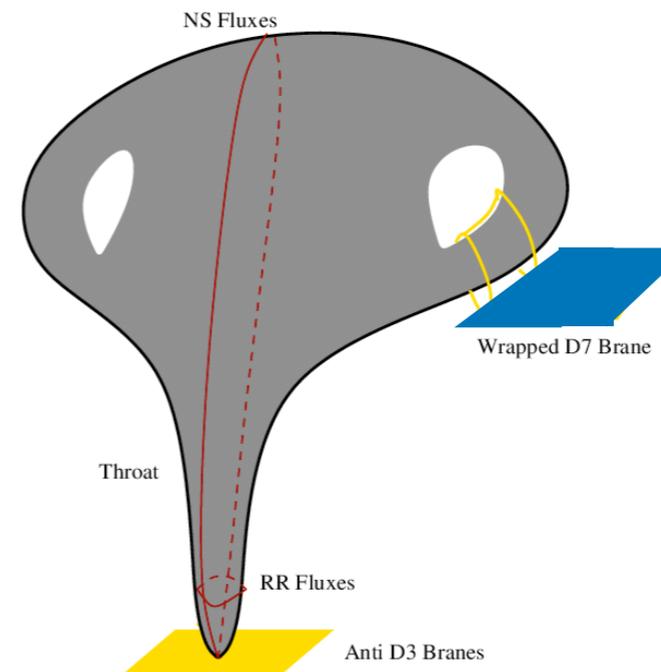
Generic mechanism

Landscape of string theory solutions with positive cosmological constant ?

In the landscape??

10^{500} problems

- **First step**: Needs fine-tuning: W_0, D
 - Constrained by **tadpole cancelation condition**
 - No explicit model constructed so far
- **Second step** in effective theory for ρ
 - Can we trust this effective theory?
 - 10D description of susy KKLT AdS sol
 - The EFT for ρ seems to give right vacuum
 - But EFT much more complicated! (light modes not included)
- **Second and third step**: $\overline{D3}$ in the EFT for ρ
 - Computed the 4d curvature sourced by **fluxes**, “**gaugino source term**” and $\overline{D3} \rightarrow$ negative !
 - Interpretation: interplay between $\overline{D3}$ and **gaugino condensate** flattens the potential for ρ (whose mass is $m_\rho^2 \sim \Lambda_{AdS}$)



Bena, Grana, Kovensky, Retolaza in progress

Moritz, Retolaza, Westphal 18

3rd step: $\overline{D3}$

- $\overline{D3}$ back-reaction (not in probe approximation): metastable vacuum? Bena, M.G., Halmagy, Kuperstein, Massai 09-14

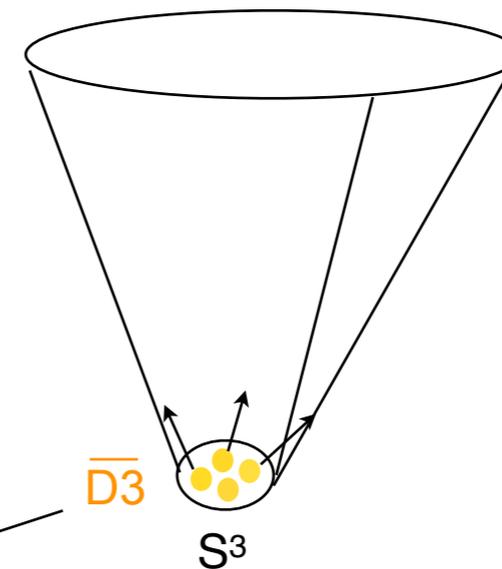
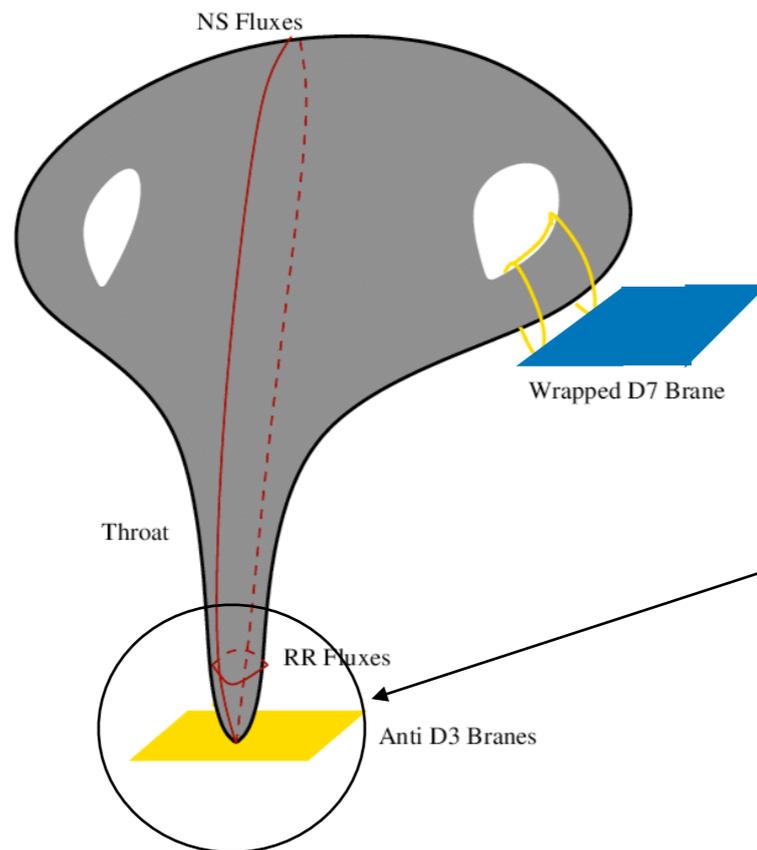
-Back-reacted solution is singular

Singularity expected, sources

Singularity not of the form expected

Singularity cannot be cloaked by horizon Bena, Buchel, Dias 12

-Tachyon on D3-branes: they repel each other



direction not considered in EFT

End point of instability?

$\overline{D3}$ close to bottom...

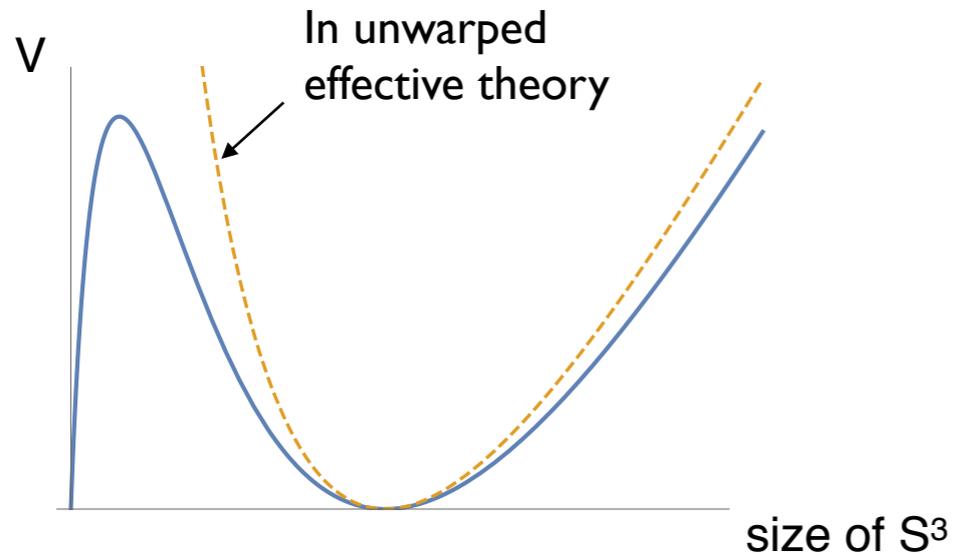
True??

- **First** step

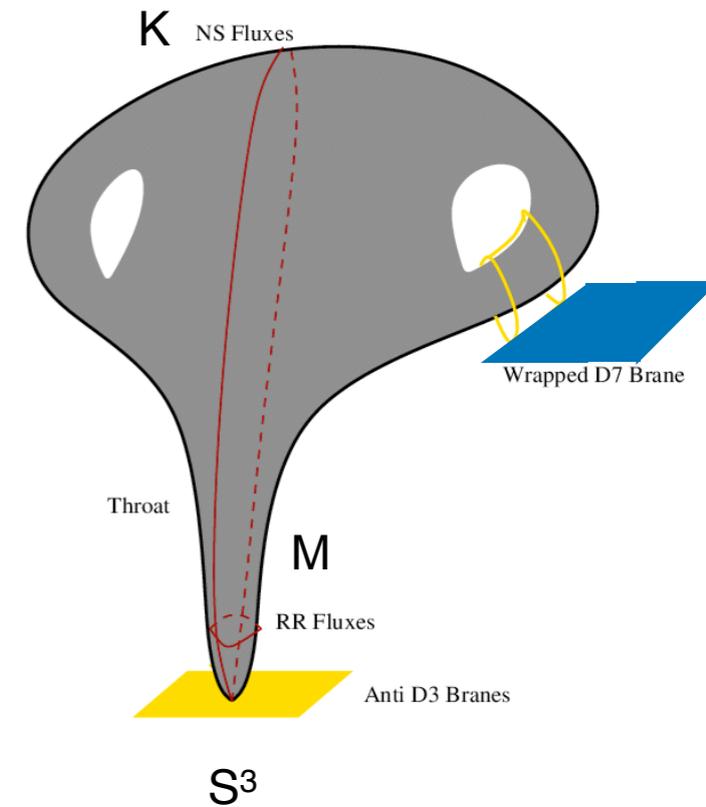
Using warped effective field theory

Douglas, Torroba 08

$$ds^2 = e^{2A} ds_4^2 + e^{-2A} ds_{CY}^2$$

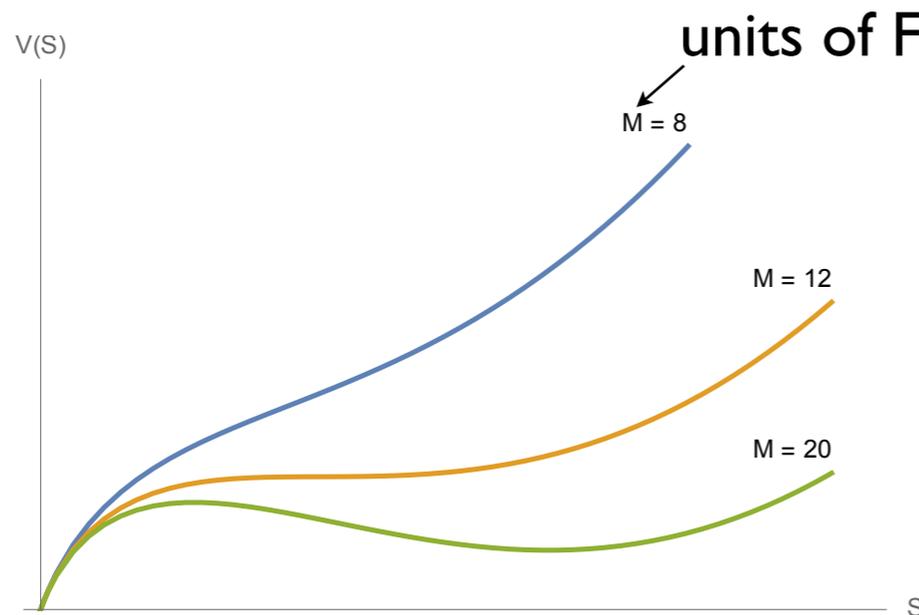


Bena, Dudas, M.G., Lust 18



- **First** and **third step**: $\overline{D3}$ wants to collapse the S^3 !

Full flux + $\overline{D3}$
warped
potential
for size of S^3



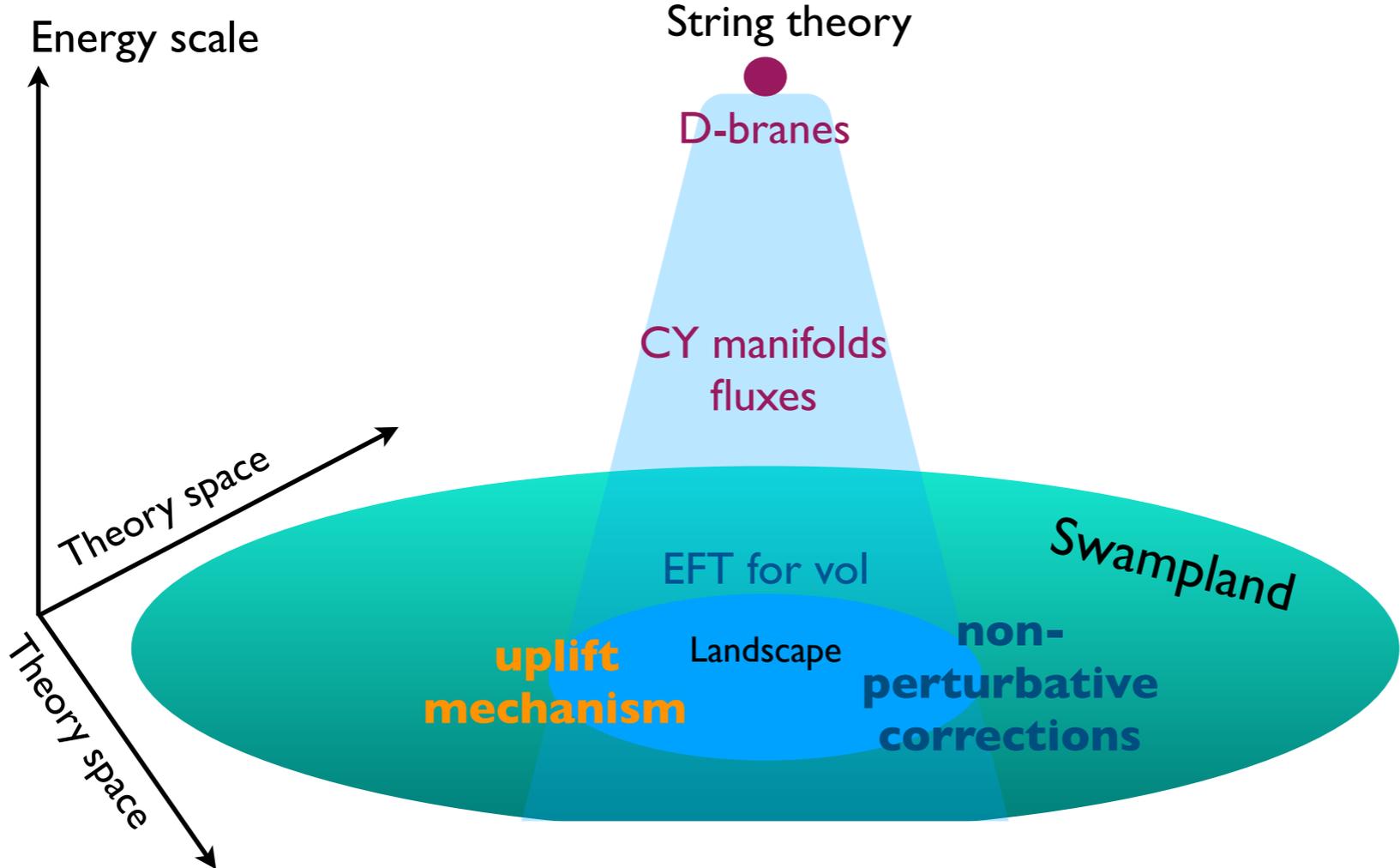
Need large flux on S^3 to avoid collapse, but not allowed by tadpole cancellation condition!!

Add other **D7-branes** wrapped on (very very highly curved) cycles: give extra negative **D3-charge**...

Allowed??

Bena, Dudas, M.G., Lust in progress

dS vacua à la KKLT more likely to be in the swampland than in the landscape



- Other dS solutions are less generic and much more questionable

Conclusions

String theory is a remarkable theory of quantum gravity

- Unique, but many solutions (10^{500})

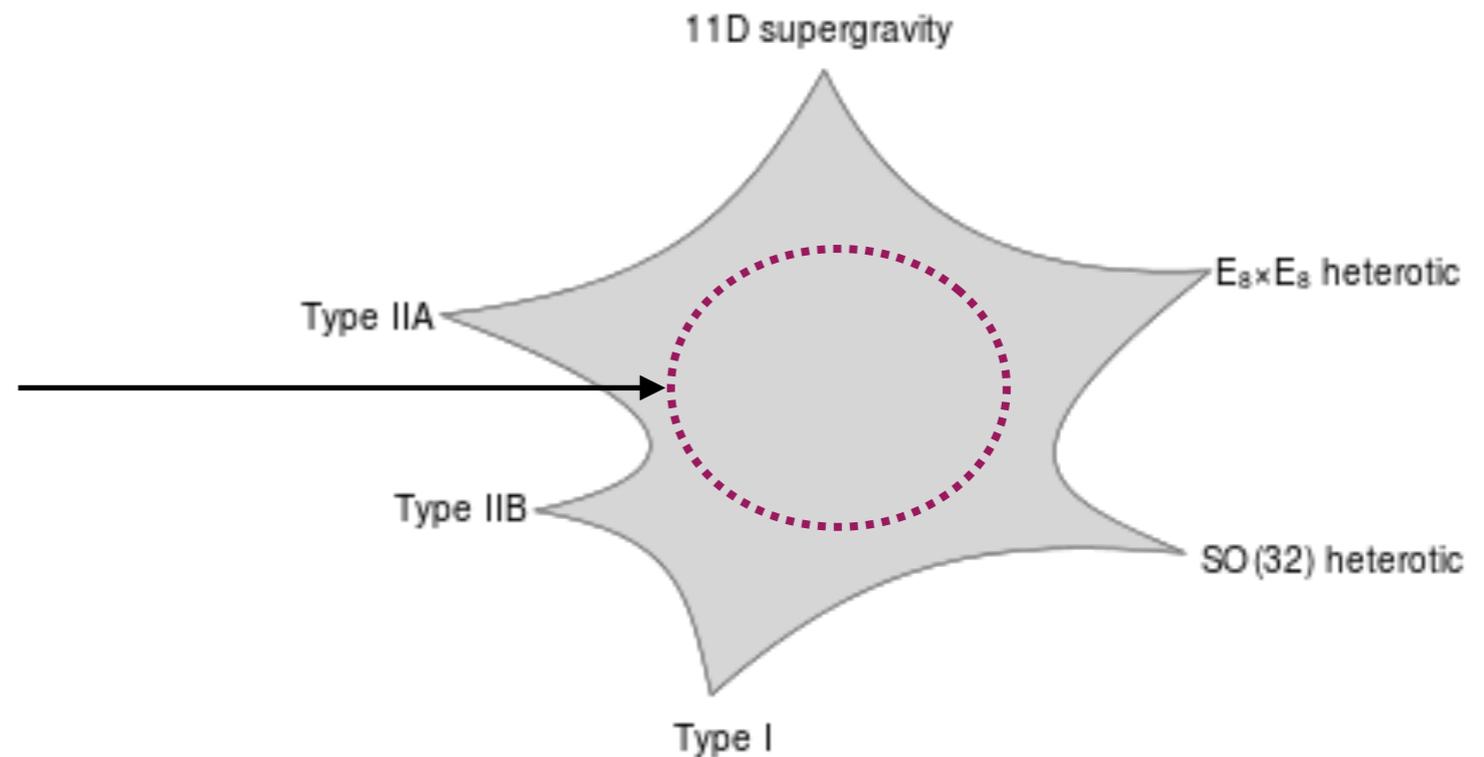
- Landscape of string theory vacua

 - Minkowski or AdS

- As for de Sitter vacua...

 - “My” weaker dS conjecture

If \exists any dS vacua in string theory



- Still need to work hard to (dis)prove the dS swampland conjecture