REALISTIC VACUA IN THE STRING LANDSCAPE

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PERSONAL INTRODUCTION

Since Jan. 2023:

L2C
in Montpellier

LABORATOIRE CHARLES COULOMB MONTPELLIER

UNIVERSITÉ DE MONTPELLIER

Spring 2025:

LPTHE

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

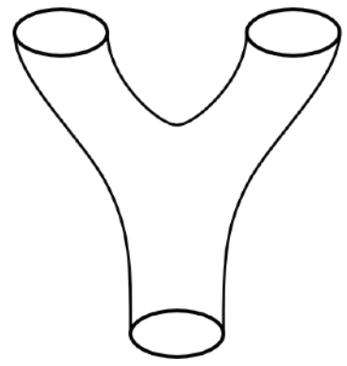
SORBONNE UNIVERSITÉ

Research interests:

String Theory & String Phenomenology, Supergravity,
AdS/CFT Holography, Black Holes, Swampland Constraints, …

STRING THEORY

- Fully consistent theory of quantum gravity



- Provides important insights on formal aspects of QFT, Quantum Gravity, Holography, …

- many highly non-trivial connection to Mathematics

- However: Contact with experiment is challenging!
  - stringy effects at almost arbitrarily high energy scales $\lesssim M_{pl}$
  - huge Landscape of possible models
  - unclear if it allows for realistic backgrounds

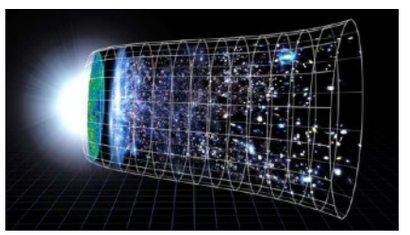
REALISTIC STRING VACUA

Any realistic string theory vacuum should have (at least):

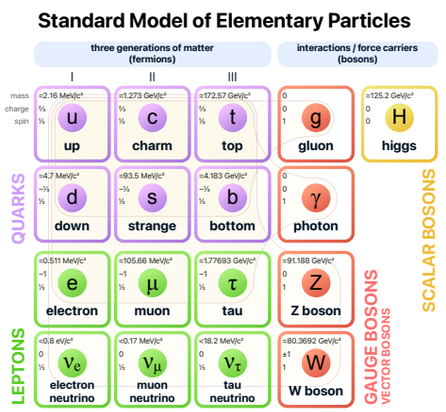
- four macroscopic spacetime dimensions

- broken / no supersymmetry

- dark energy / positive cosmological constant



- Standard Model matter
  (gauge groups, chiral fermions, …)



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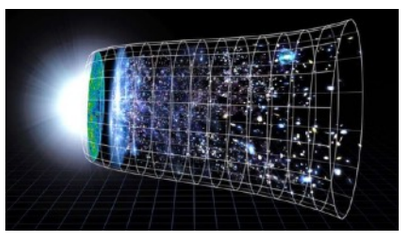
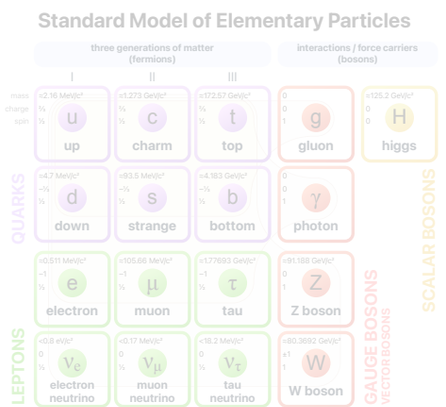




KNOWN STRING VACUA

String theory backgrounds that we understand well have:

- extended ($\mathcal{N} \geq 2$) supersymmetry
- negative or vanishing cosmological constant (AdS or Mink.)

side note:

SUSY breaking and positive vacuum energy (e.g. de Sitter) are related
(no SUSY algebra with unitary representations in de Sitter)

Unknown
whether string theory has (meta-)stable { non-SUSY vacua!
de Sitter vacua!

COMPACTIFICATION AND MODULI

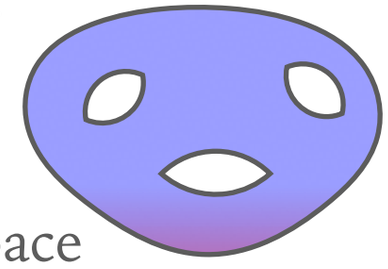
- Compactification: 4D physics from higher dimensions:

$$M_{4+d} = M_4 \times Y_d$$

higher-dim. spacetime

"our" 4D spacetime

compact "internal" space

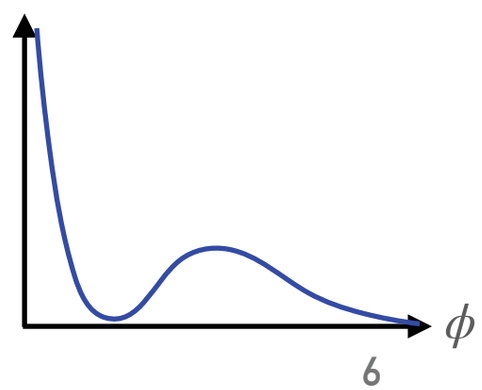


- Fundamental problem of string compactifications:

deformations / moduli of Y_d $\delta g_{ij}(\phi)$ = massless scalar fields ϕ *(at tree/classical level)* = coupling constants $g(\phi)$

Broken Supersymmetry:

- Quantum effects: generate a potential for moduli!



DINE-SEIBERG PROBLEM

[Dine, Seiberg '85]

potential from first order quantum corrections:

$$\lim_{\phi \to \infty} V = 0$$

$$(assume\ \phi \to \infty \Leftrightarrow g(\phi) \to 0)$$

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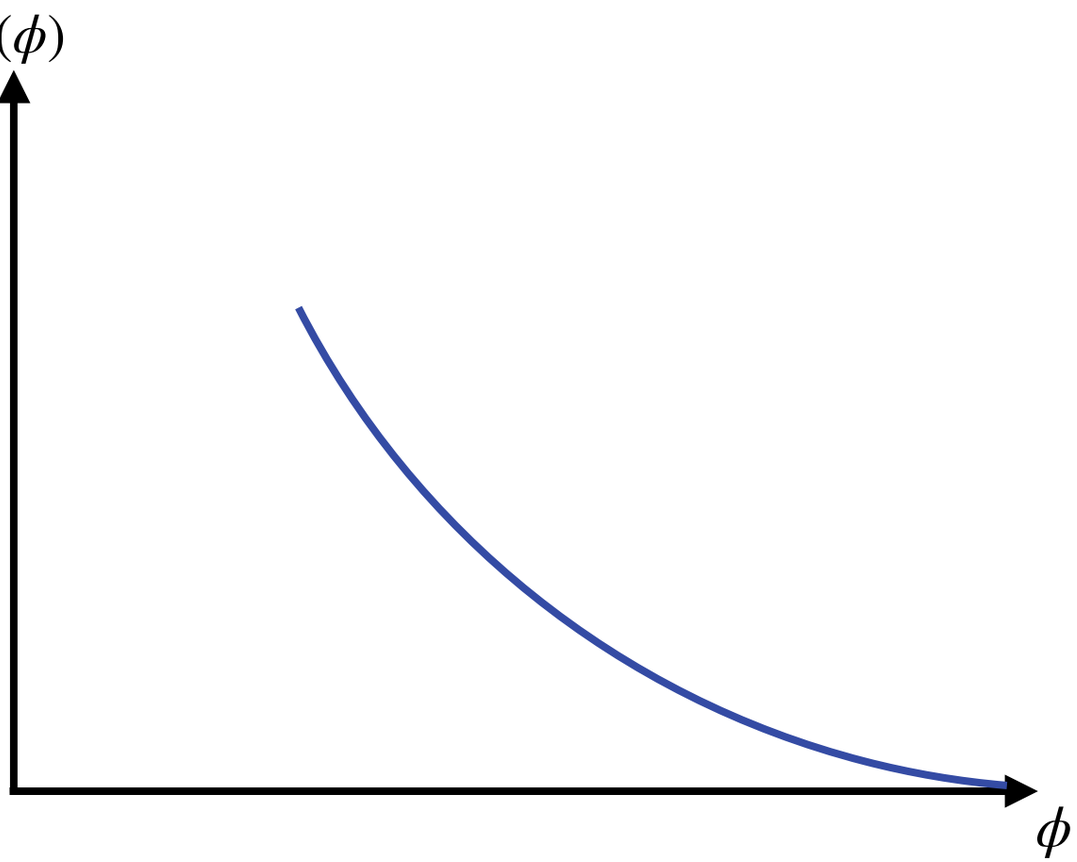

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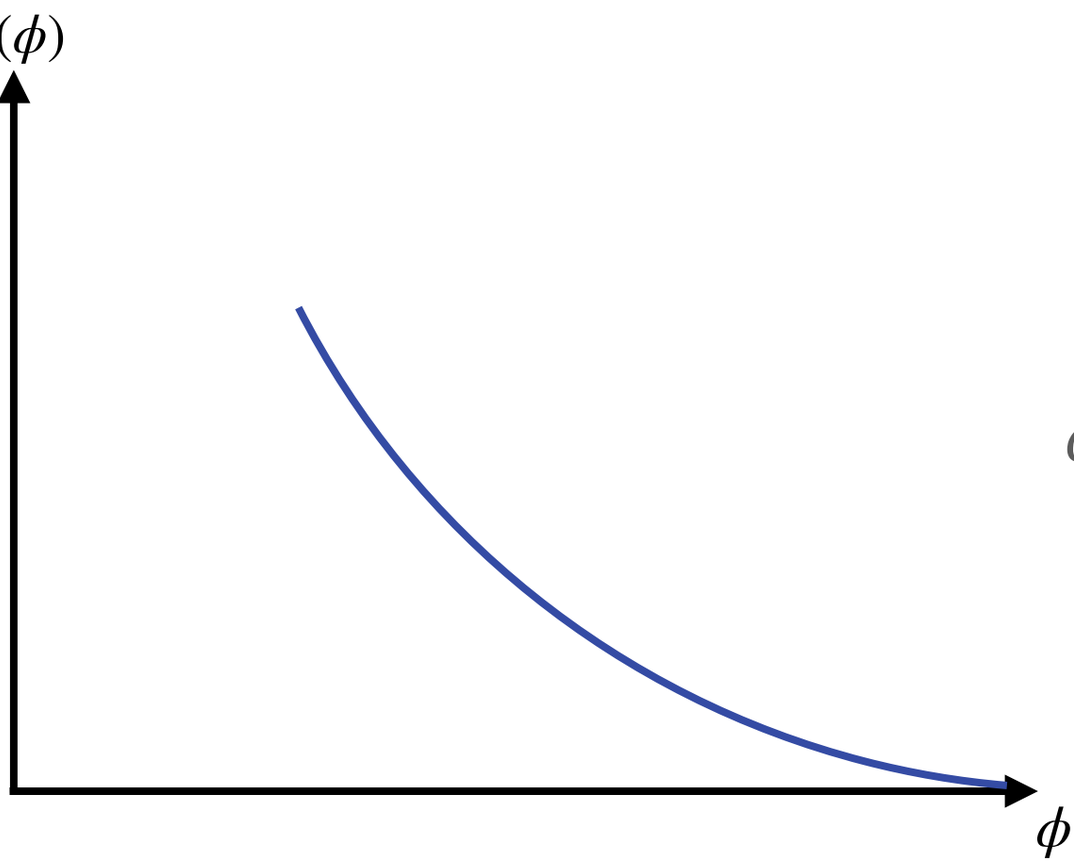

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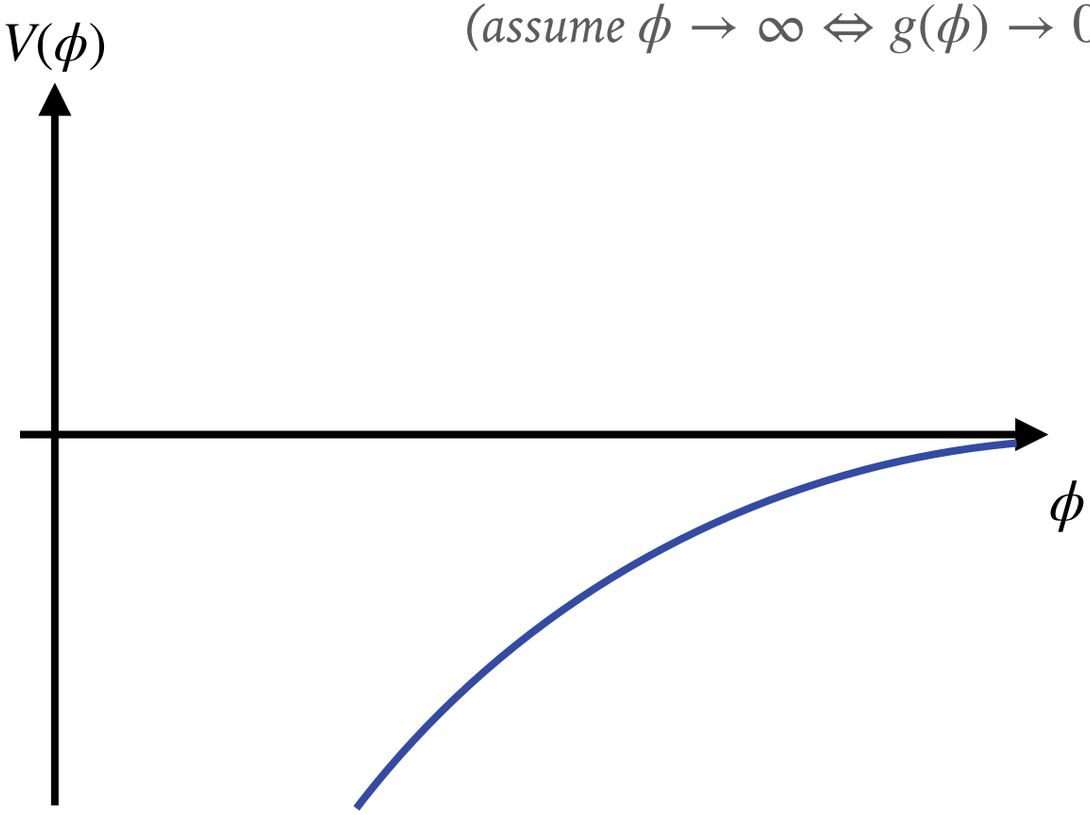

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take higher order corrections into account:

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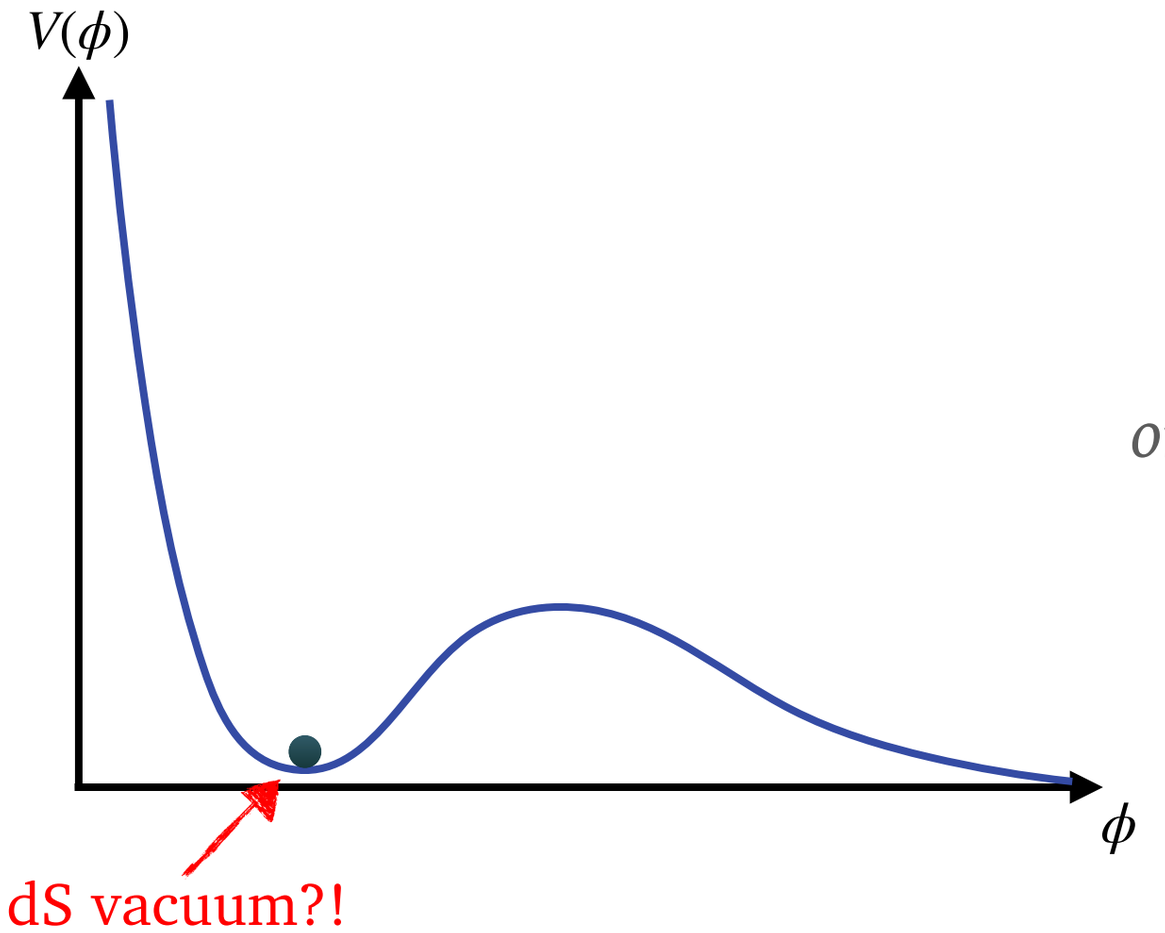

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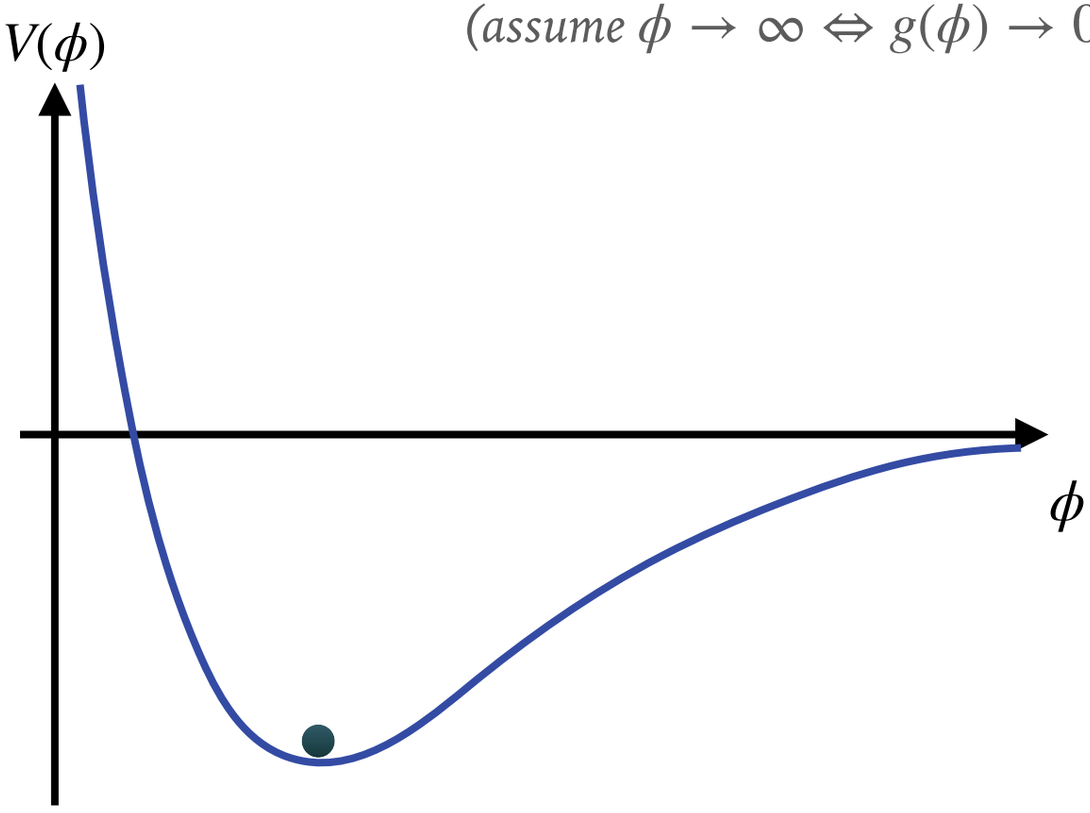

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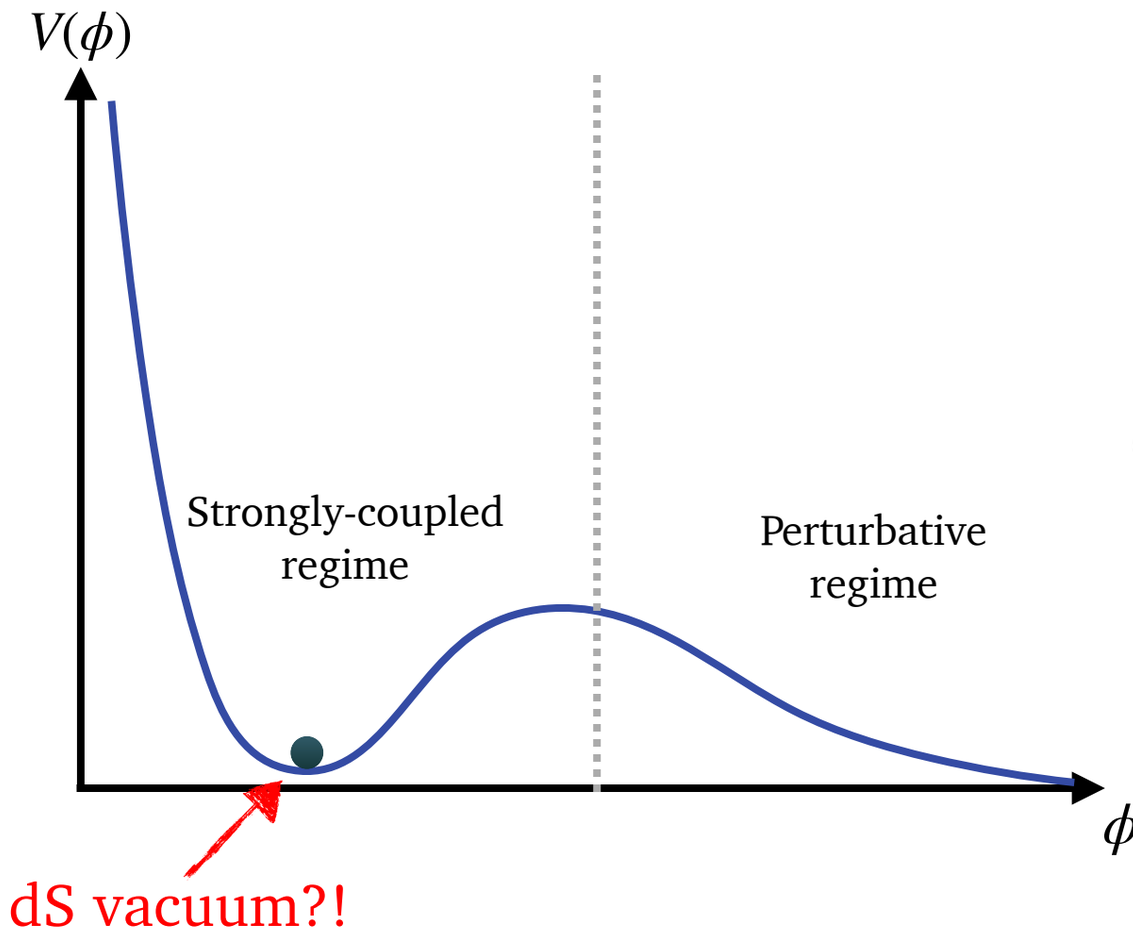

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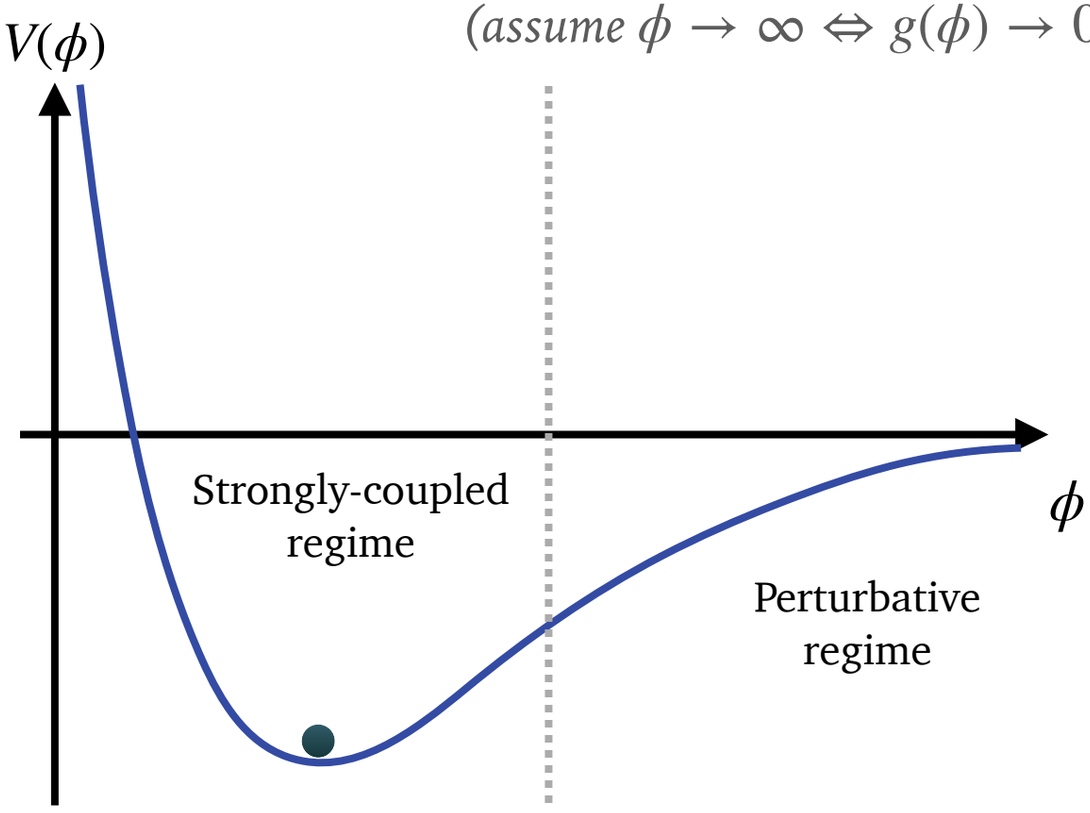


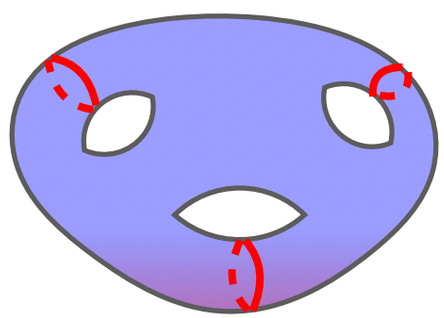
at minimum of V: higher order corrections $\approx$ first order corrections $\rightarrow$ *strong coupling! no perturbative control!*

FLUX COMPACTIFICATION

➤ Possible solution to the Dine-Seiberg problem:

Generate a potential at the
classical / tree-level

→ *Fluxes!*



non-vanishing p-form field strengths $F_{m_1 \ldots m_p} \neq 0$
along cycles of the internal geometry

➤ Fluxes generate a potential:

$$V_F \sim \int \sqrt{g} g^{m_1 n 1} \ldots g^{m_p n_p} F_{m_1 \ldots m_p} F_{n_1 \ldots n_p}$$

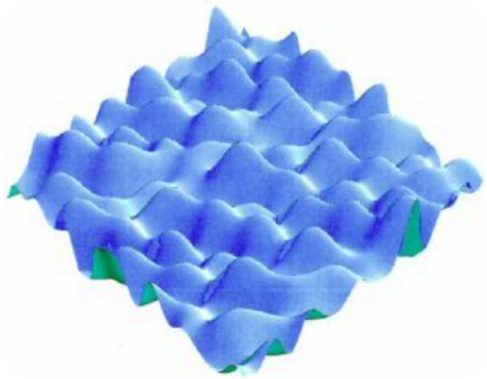
→ *fixes size of cycles (= moduli) classically*

→ *avoid Dine-Seiberg if* V_F *has minimum at* $|\phi| \gg 1$

THE FLUX LANDSCAPE

Many different
compactification spaces
(Calabi-Yau manifolds)

Many different fluxes
per compactification space
(complicated topology)



HUGE Landscape of
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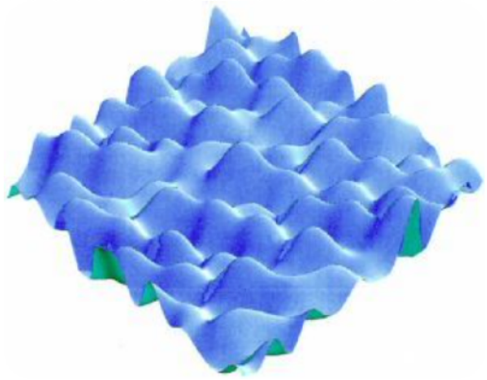


HUGE Landscape of string theory vacua!

Claim:

→ High probability for vacua with:
[Bousso, Polchinski '00]

a) positive but tiny cosmological constant $(0 < \Lambda \ll 1)$

b) control over quantum corrections $(|\phi| \gg 1)$

THE TADPOLE PROBLEM

[Bena, Blåbäck, Graña, SL '20]

- Problem A:

  most flux vacua not computed explicitly!

- Problem B:

  not all flux choices give a consistent vacuum!

→ *How large is the Landscape of consistent vacua?*

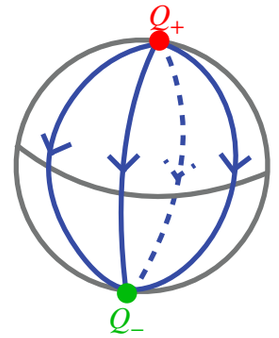
- Constraint on fluxes: Fluxes carry a positive charge!

  example: 3-form flux on Calabi-Yau manifold Y_6:

$$Q_{flux} = \int_{Y_6} F_3 \wedge H_3$$

- Tadpole cancellation: total charge in compact space = 0

  (flux lines need to end somewhere)



THE TADPOLE PROBLEM

[Bena, Blåbäck, Graña, SL '20]

- Tadpole cancellation: total charge in compact space = 0

$$Q_{\text{flux}} = Q_{\text{top}}$$

flux to stabilize N moduli in internal space — Q_{flux} — Q_{top} — *negative topological charge*

- Scaling of both charges with number of moduli:

Tadpole Conjecture:

$$Q_{\text{flux}} \gtrsim \alpha\, N_{\text{moduli}}$$

Topology:

$$Q_{\text{top}} = \frac{\chi}{24} \sim \frac{1}{4} N_{\text{moduli}} + \mathcal{O}(1)$$

(χ: *Euler number of internal space*)

empirical data:

$$\alpha \approx 0.44 > \frac{1}{4} \quad \Rightarrow Q_{\text{flux}} \sim N_{\text{moduli}} \sim \mathcal{O}(1)$$ ↯

→ no stabilization if $N_{\text{moduli}} \gg 1$ →

Landscape much smaller than expected?!

HOLOGRAPHY AND FLUX VACUA

[SL, Vafa, Wiesner, Xu '22]

Are there vacua in the Landscape with a very small cosmological constant?

Laboratory: Supersymmetric flux vacua

Flux vacua without SUSY breaking: ⟶ negative cosmological constant $\Lambda < 0$ Anti de Sitter (AdS) vacuum

Idea: Use AdS/CFT holography!

Gravity on Anti-de Sitter space in d-dimensions ⟷ *exact (holographic) duality* ⟷ conformal field theory (QFT) in (d-1)-dimensions

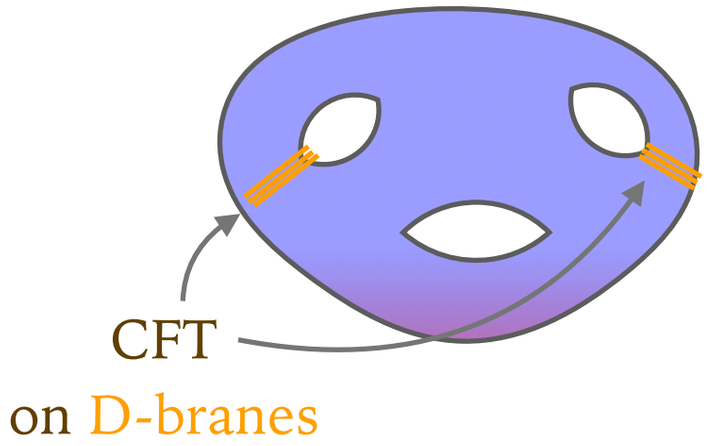
HOLOGRAPHY AND KKLT

[SL, Vafa, Wiesner, Xu '22]

- flux vacuum (without susy breaking):

  4D SUSY AdS

  $$\left|\Lambda_{AdS}\right| \ll 1$$



- Holographic dual:

  (2+1)D Conformal Field Theory (CFT)

  $$\left|\Lambda_{AdS}\right|^2 \sim \frac{1}{c}$$ ← *central charge* (# degrees of freedom of CFT)

  → D-branes wrapped on internal space

- Degrees of freedom of D-branes:

  Result: $c \lesssim \chi \sim N_{\text{moduli}}$ (χ: *Euler number*) $\Rightarrow$

  Tadpole Problem

$$\left|\Lambda\right| \ll 1$$

impossible!

OUTLOOK: STRING VACUA IN THE INTERIOR OF MODULI SPACE?

No realistic vacua in weak coupling / supergravity limit of string theory?

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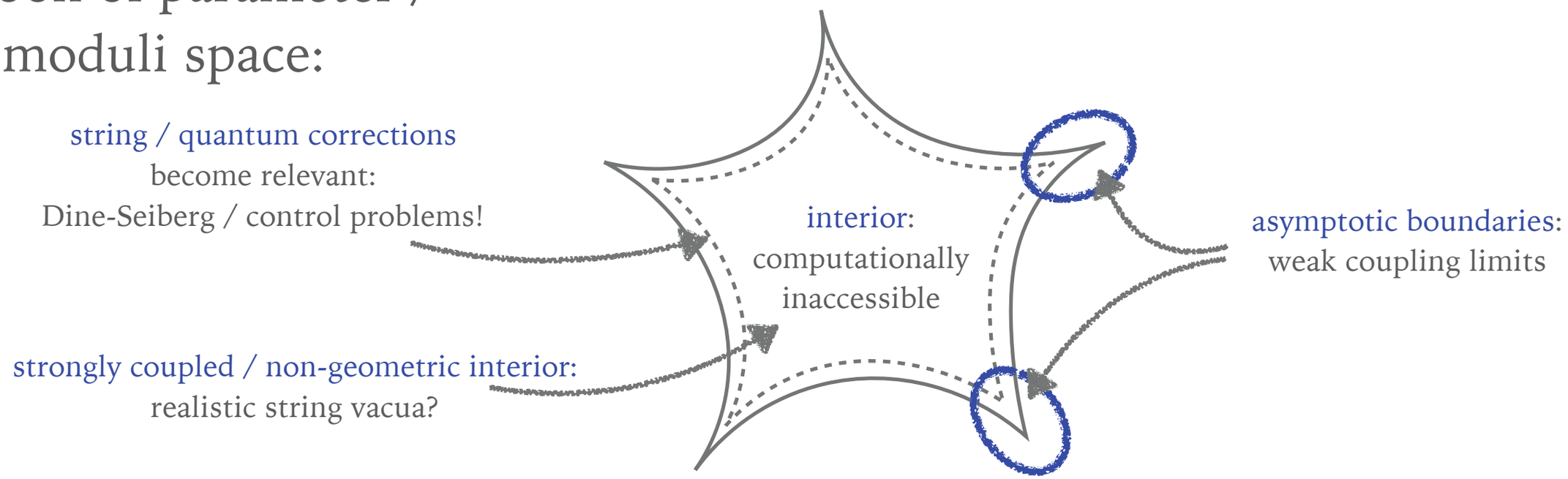
Cartoon of parameter / moduli space:



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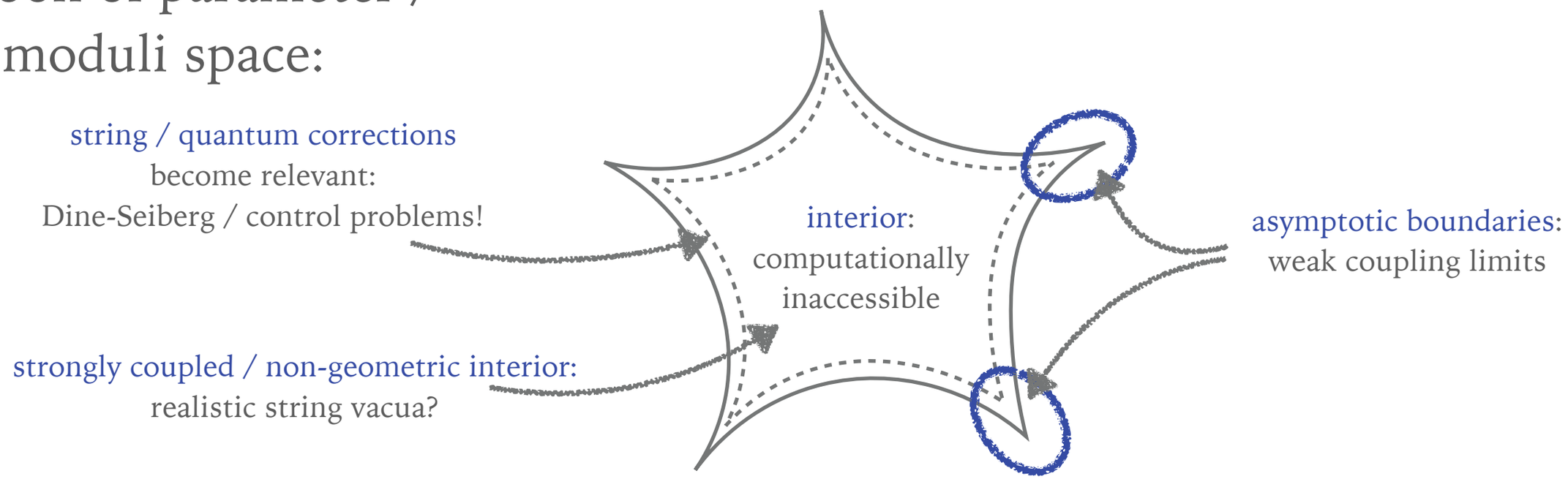

Outlook:

weak coupling behaviour of potential $V(\phi)$ → [SL '24] → information on string vacua in the interior of moduli space?

THANK YOU!