REVIEW TALK:
REALISTIC VACUA IN THE STRING THEORY LANDSCAPE

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REALISTIC STRING VACUA

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

- four macroscopic spacetime dimensions (obviously)
- broken / no supersymmetry
- dark energy / positive cosmological constant
- Standard Model matter (gauge groups, chiral fermions, …)

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KNOWN STRING VACUA

String vacua that we understand well have:

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

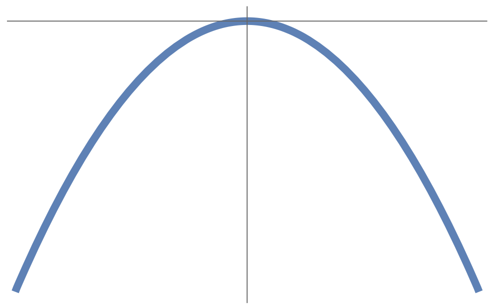
side note:

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

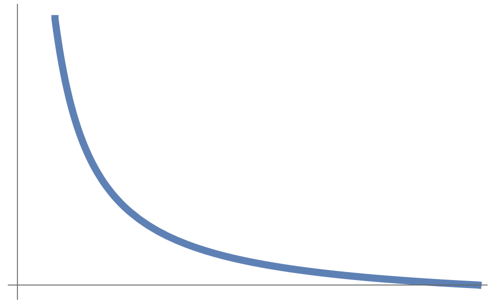
Unknown whether string theory has stable $\left\{ \begin{array}{l} \text{non-SUSY vacua!} \\ \text{de Sitter vacua!} \end{array} \right.$

NON-SUPERSYMMETRIC STRING THEORY

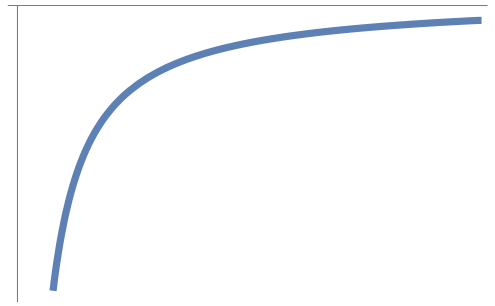
- Bosonic string
  - Target space tachyon!



- Type 0 string
  - Target space tachyon!
- $O(16) \times O(16)$ Heterotic string
  - String frame: positive cosmological constant
  - Einstein frame: $V \sim e^{-5\phi/2}$ (run-away!)



- Scherk-Schwarz supersymmetry breaking
  - anti-periodic fermion boundary conditions on circle
  - Potential for radius: $V \sim -\dfrac{1}{R^{\alpha}}$ (run-away!)



DINE-SEIBERG PROBLEM

[Dine, Seiberg '85]

- Fundamental problem of string compactifications:

Moduli! (*e.g. dilaton, comp. volume, …*) = *massless scalar fields at tree (classical) level*

Broken Supersymmetry:

- Quantum effect: generate a potential for moduli!

assume:

$\phi \to \infty$: *weakly coupled regime, SUSY restored, effective tree-level description valid* $\Rightarrow$ $\lim_{\phi\to\infty} V = 0$

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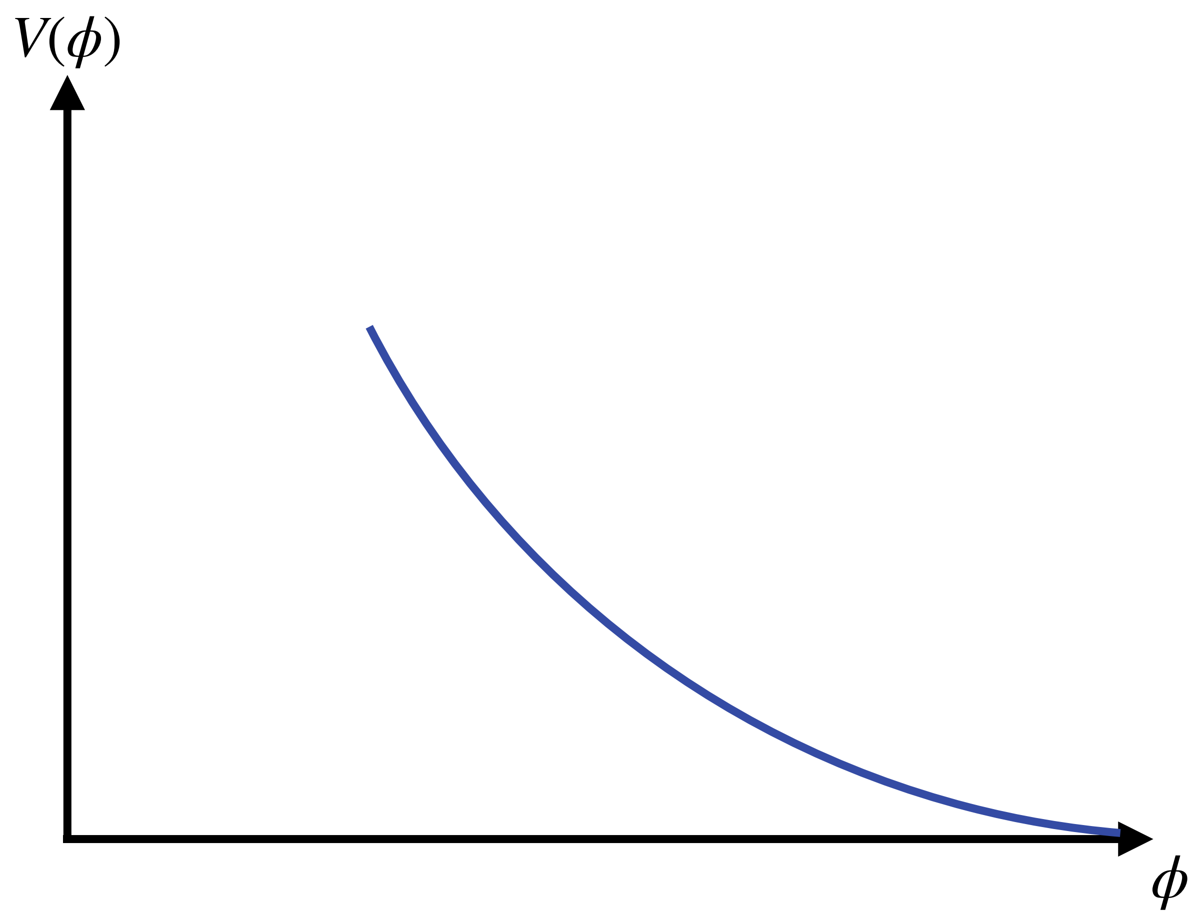

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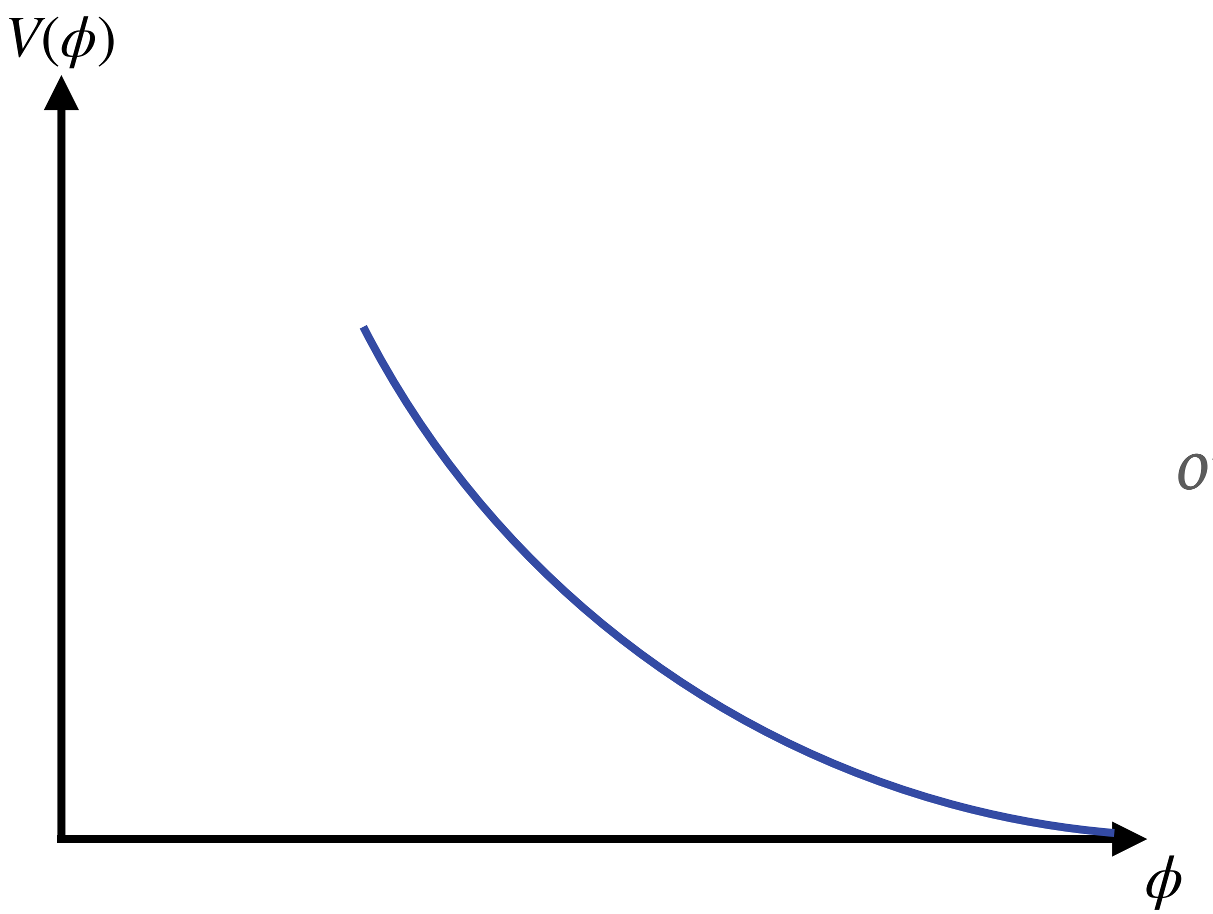

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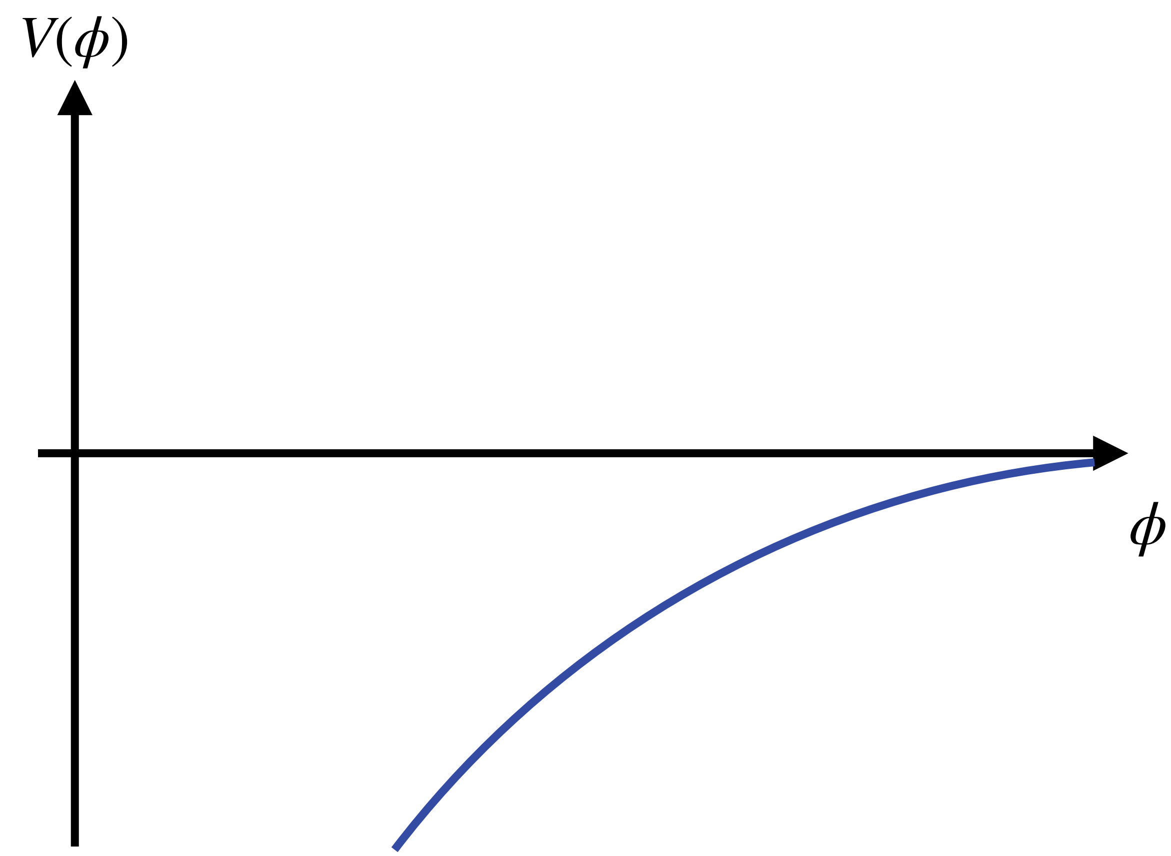

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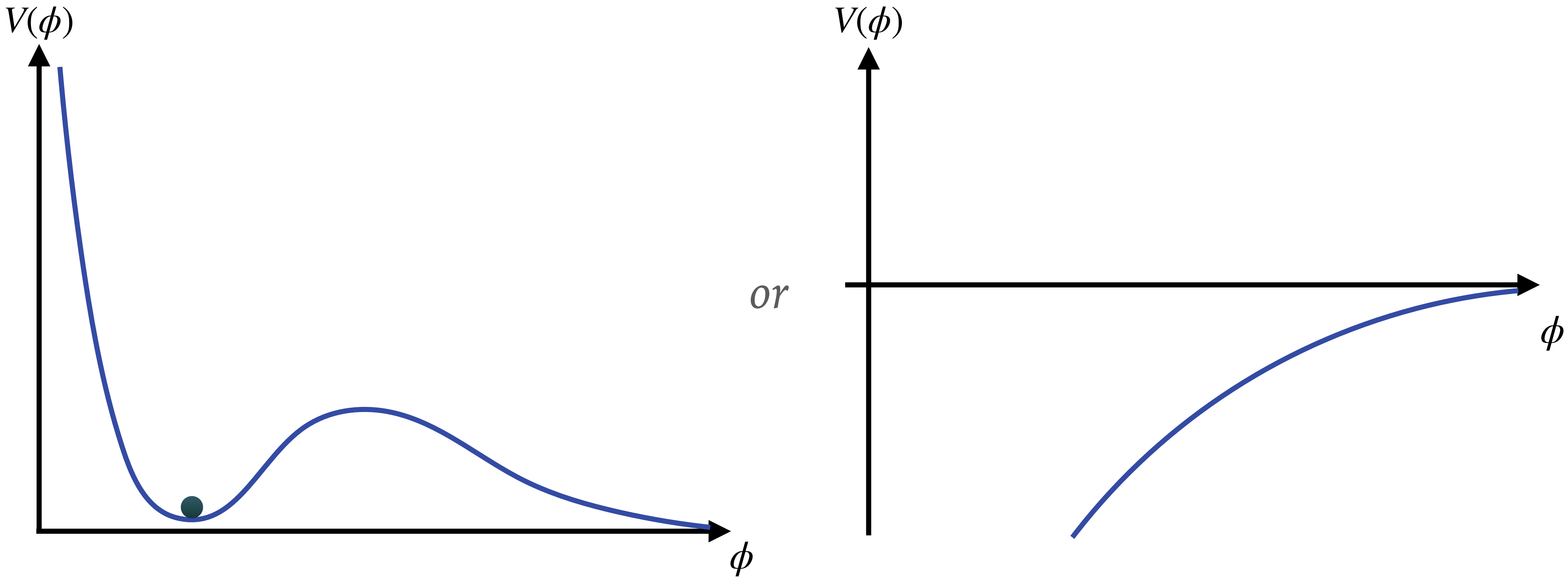

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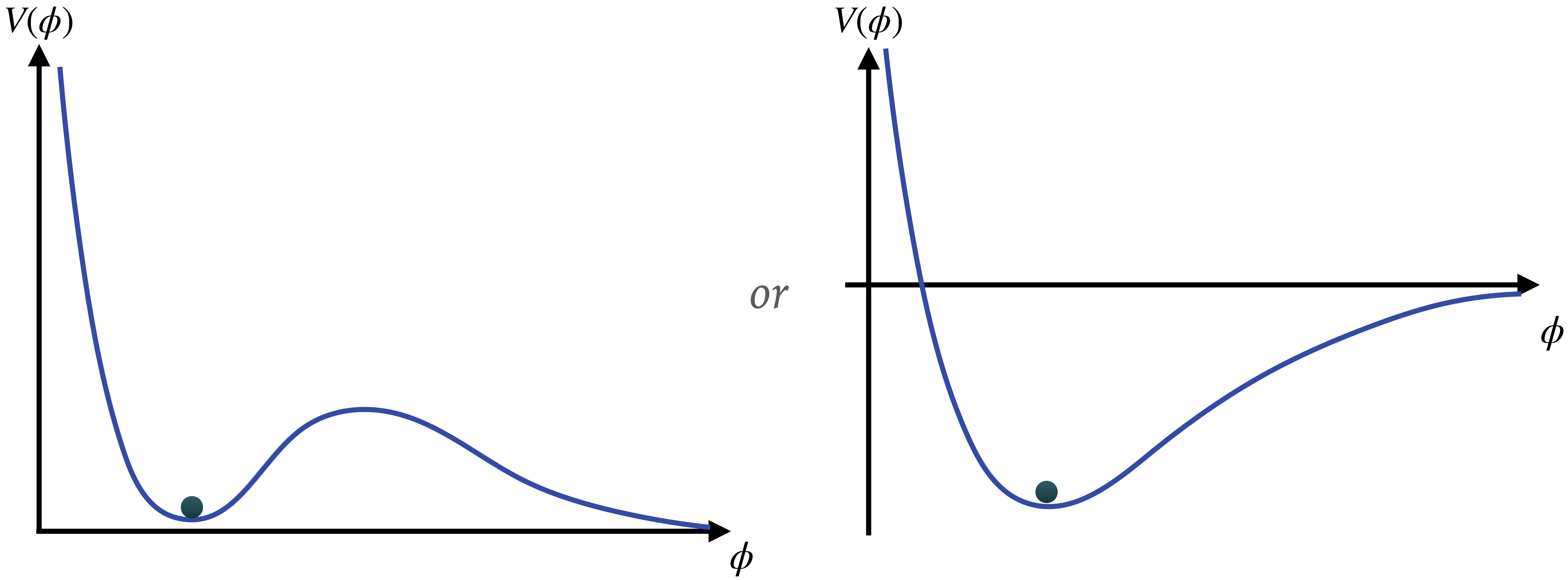

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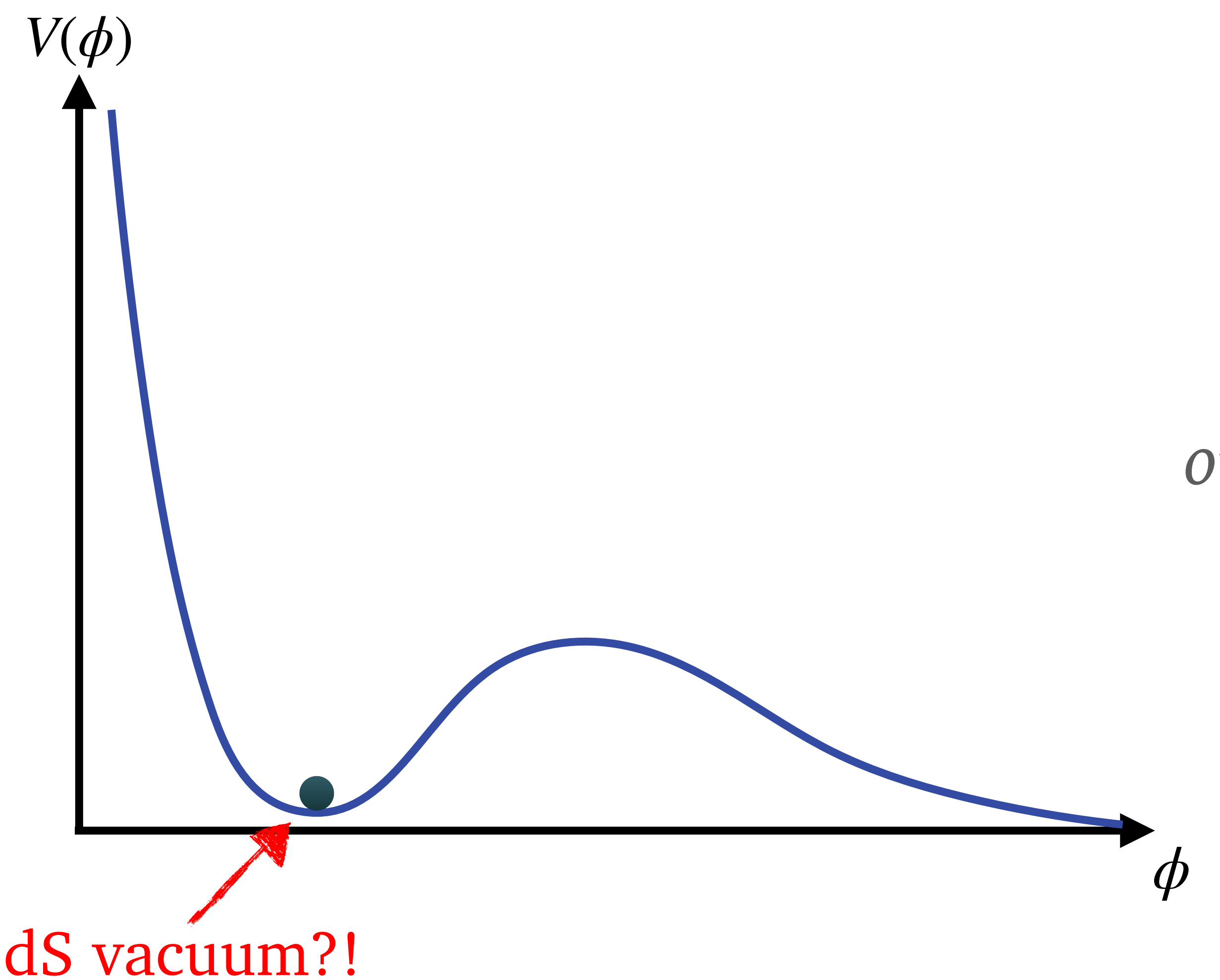

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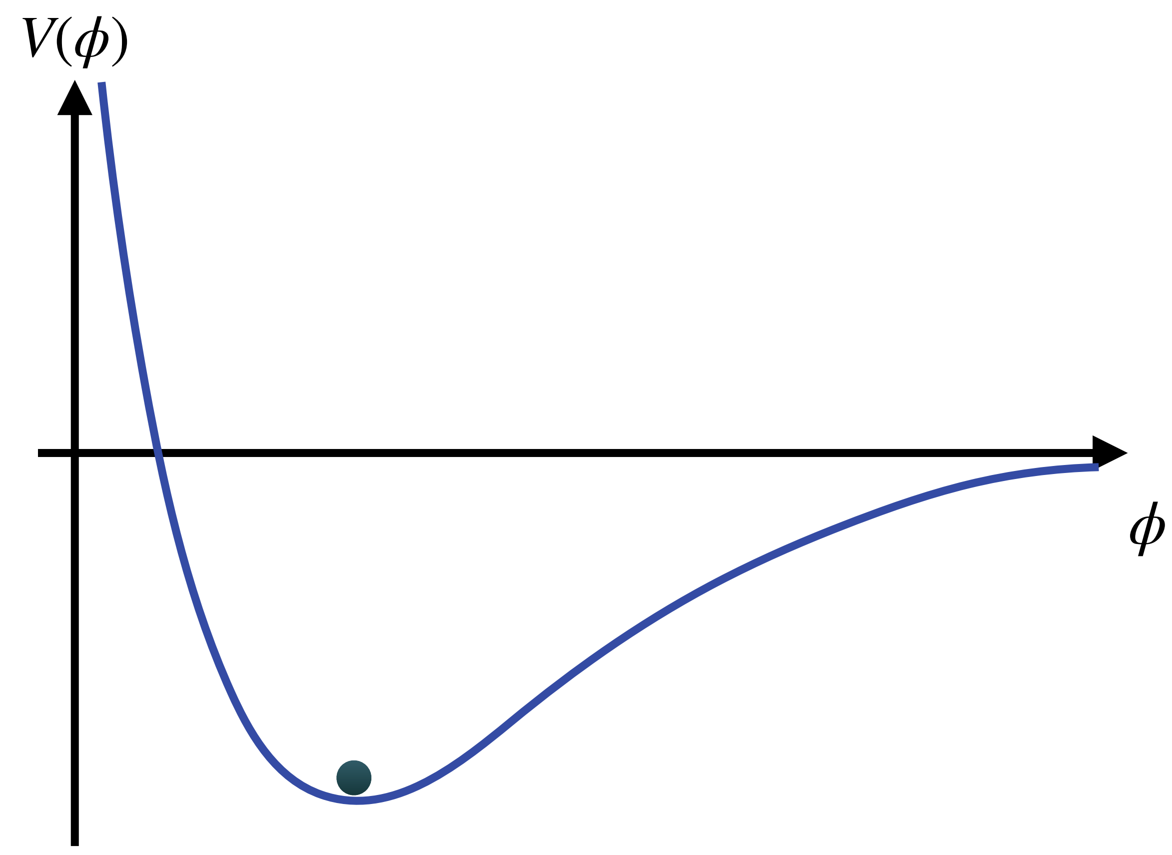

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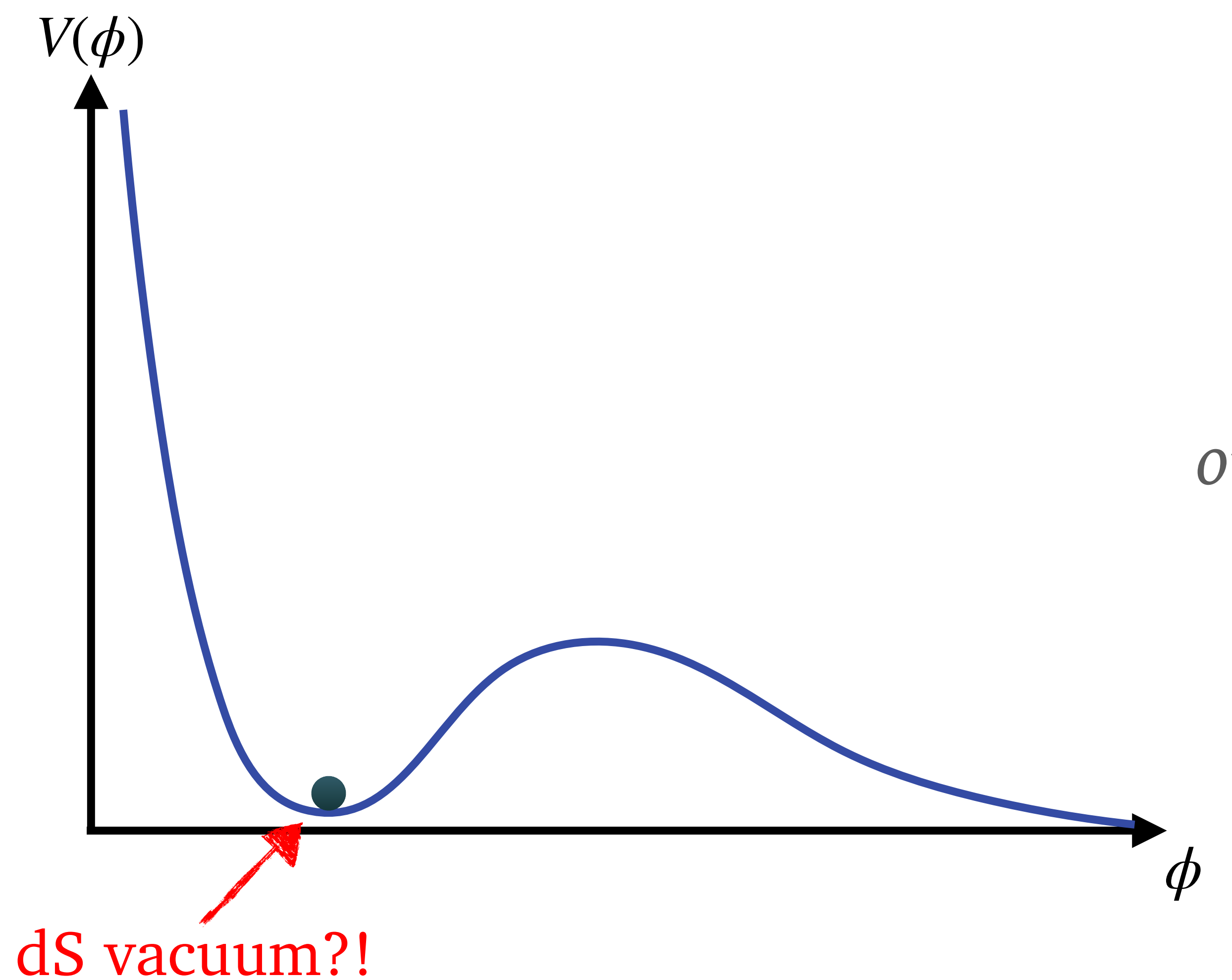

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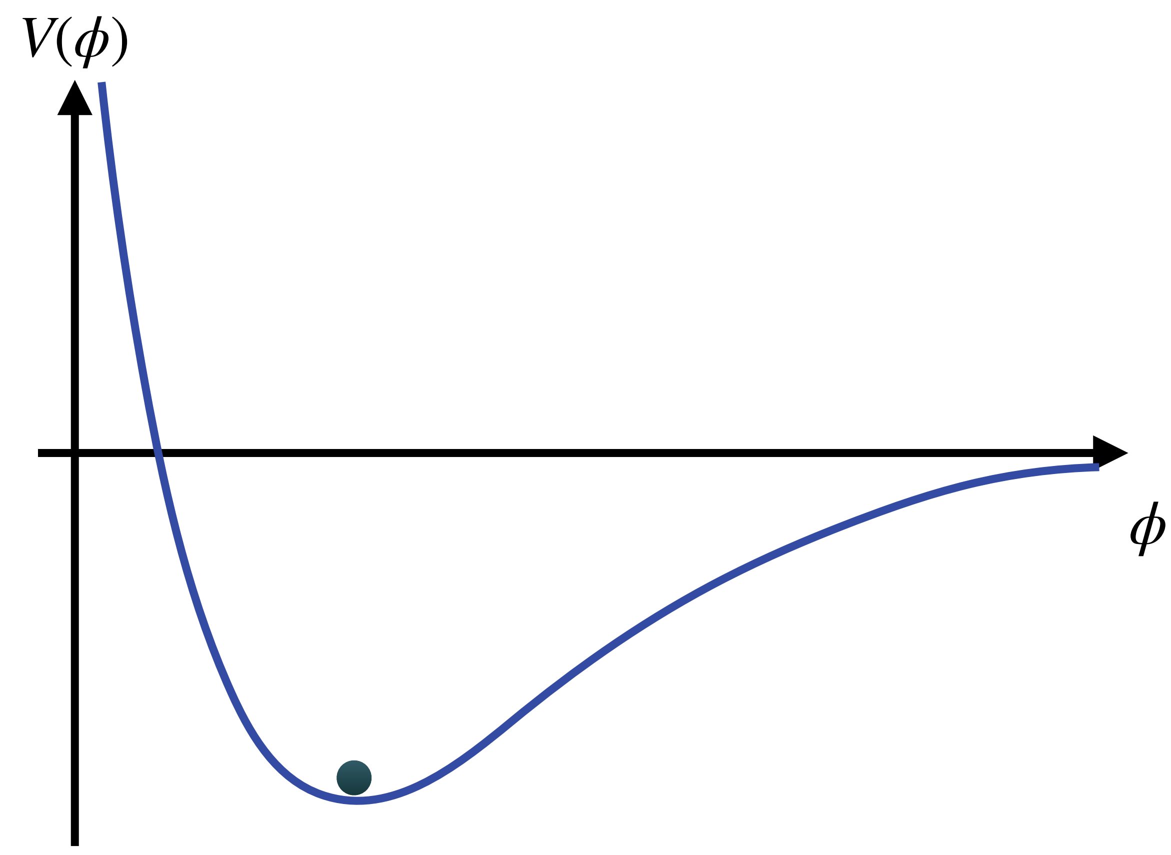

at minimum of V: higher order corrections $\approx$ first order corrections $\longrightarrow$ *strong coupling!*

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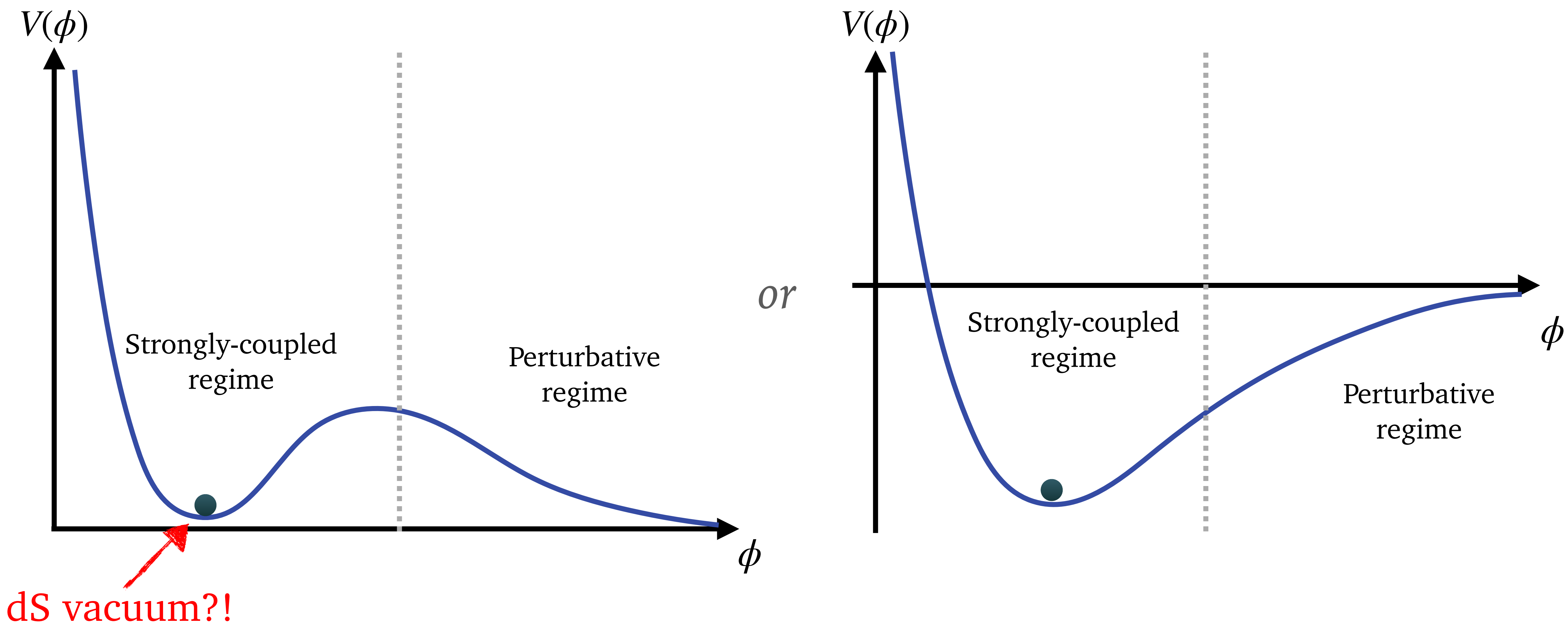

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DINE-SEIBERG PROBLEM

de Sitter vacua from quantum corrections only at strong coupling!

higher order corrections:
generally only known for extended SUSY ($\mathcal{N} \geq 2$)!

*"when corrections can be computed, they are not important,
and when they are important, they cannot be computed"*

F. Denef, Les Houches Lecture, 2008

FLUX COMPACTIFICATION:

- Alternative strategy:

Stabilize moduli at the classical 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:

$$V_F \sim \int \sqrt{g}\, g^{m_1 n1} \ldots g^{m_p n_p} F_{m_1 \ldots m_p} F_{n_1 \ldots n_p}$$

- Dependence on volume $V \sim r^d$:

$$V_F \sim r^{-d-2p} \int F^2$$

→ *runaway towards decompactification!*

FLUX COMPACTIFICATION AND DE SITTER NO-GO

- Balance against potential from internal curvature:

$$V_R \sim r^{-2-d} \int R$$

- Schematic form of the overall potential (fluxes + curvature):

$$V = \sum_p r^{-2p-d} \int F_p^2 - r^{-2-d} \int R$$

- For $V > 0$ (and $p \geq 1$) this potential satisfies

$$\frac{|V'|}{V} \geq \frac{d+2}{\phi}$$

→ *no de Sitter minima!*

(AdS minima are easily possible, e.g. Freund-Rubin type $AdS_{D-d} \times S^d$)

DE SITTER NO-GO

- [Maldacena, Nuñez '00]:

From any two-derivative supergravity there is no smooth compactification to de Sitter!

- de Sitter vacua from String Theory must involve:

  a) quantum effects

  or

  b) stringy ingredients (higher-derivative terms, O-planes, …)

  → Danger of Dine-Seiberg like control issues!

- Swampland de Sitter conjecture [Obied, Ooguri, Spodyneiko, Vafa '18]

$$\frac{|\nabla V|}{V} \geq \mathcal{O}(1)$$

→ *Likely true in asymptotic limits but not necessarily everywhere in field space*

DE SITTER CONSTRUCTIONS

- new strategy:

  combine different effects (classical + corrections)
  to avoid Dine-Seiberg!

- two main competitors (both in IIB or F-theory):
  - *KKLT* [Kachru, Kallosh, Linde, Trivedi '03]
  - *Large Volume Scenario (LVS)* [Balasubramanian, Berglund, Conlon, Quevedo '05]

- many other ideas (not in this talk)
  - *classical* [Danielson et al. '11], [Andriot '19] for reviews
  - *non-geometric* e.g. [de Carlos, Guarino, Moreno '09]

DE SITTER FROM IIB

KKLT (AND LVS)

IIB DE SITTER VACUA

Three step procedure [KKLT '03]

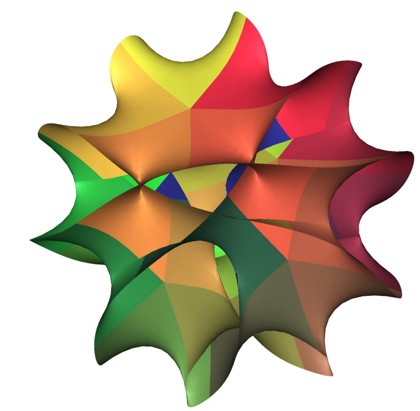
1. Calabi-Yau orientifold with complex structure-moduli stabilized by three-form fluxes

2. Stabilize Kähler moduli by
   a) non-perturbative quantum effects (KKLT)
   b) α' corrections (LVS)
   $\rightarrow$ (supersymmetric) AdS-vacuum

3. Supersymmetry breaking by an anti-D3-brane at the bottom of a warped throat
   $\rightarrow$ exp. suppressed uplift to dS due to strong warping

COMPACTIFICATION ON CALABI-YAU MANIFOLDS

➤ IIB on Calabi-Yau:



$$M_{10} = M_4 \times CY_3$$

➡ 4d N=2 supergravity

➡ many massless scalar fields (moduli):

- $h^{1,1}$ Kähler moduli (volumes of 2 or 4-cycles)
- $h^{2,1}$ complex structure moduli (volumes of 3-cycles)

→ *very well understood!*

(moduli space geometry, quantum corrections, Mirror symmetry, BPS states, …)

SUPERSYMMETRY BREAKING FROM ORIENTIFOLDING

- divide CY_3 by a discrete involution (i.e. $\mathbb{Z}_2$ action) combined with world sheet parity Ω_p (and $(-1)^F$)

- effect A: break SUSY from $\mathcal{N} = 2$ to $\mathcal{N} = 1$!
- effect B: fixed points of $\mathbb{Z}_2$ action:

→ orientifold planes ($O3$ and $O7$)

O-planes carry charge!

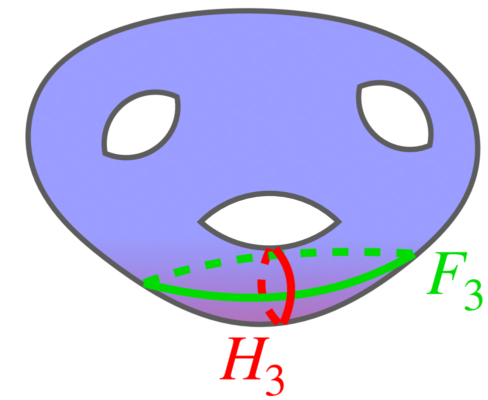
Tadpole cancellation condition:
(for O3-planes; generally includes also O7 and D7)

$$N_{D3} - \frac{1}{4} N_{O3} + \frac{1}{2} \int H_3 \wedge F_3 = 0$$

Need D3-branes and/or fluxes!

FLUX COMPACTIFICATION

- 3-form fluxes: $\langle F_3 \rangle \neq 0$, $\langle H_3 \rangle \neq 0$



fix volume of 3-cycles
(i.e. complex structure moduli!)

- Kinetic term for $G_3 = F_3 - \tau H_3$:

$$\mathscr{L}_{kin} \sim \int G_3 \wedge \star \overline{G}_3 \sim \int d^6y \sqrt{g}\, g^{il} g^{jm} g^{kn} G_{ijk} \overline{G}_{lmn}$$

depends on CY-metric g_{ij} $\longrightarrow$ Classical potential for complex structure moduli!

THE NO-SCALE POTENTIAL

- classical superpotential from fluxes (GVW): [Gukov, Vafa, Witten '99]

$$W = \int G_3 \wedge \Omega \qquad (G_3 = F_3 - \tau H_3)$$

- W depends on complex structure moduli but not on Kähler moduli!

$$\partial_\rho W = 0 \quad \Rightarrow \quad D_\rho W \sim \frac{1}{\rho - \bar{\rho}} W$$

ρ: volume modulus

no-scale structure:

$$K(\rho, \bar{\rho}) = -2\log(\mathcal{V}) = -3\log\left[-i(\rho - \bar{\rho}\right]$$

- $\mathcal{N} = 1$ supergravity potential:

$$V = e^K \left(g^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W} - 3|W|^2 \right) = e^K g^{i\bar{j}} D_i W \bar{D}_{\bar{j}} \bar{W}$$

all moduli

complex structure moduli

KÄHLER MODULI: THE NO-SCALE POTENTIAL (2)

- No-scale potential from fluxes:

$$V = e^K g^{i\bar{j}} D_i W \bar{D}_{\bar{j}} \bar{W}$$

→ depends only on *complex structure* moduli!

potential for Kähler moduli only from quantum or stringy corrections!

- KKLT: non-perturbative corrections to superpotential

$$W = \int G_3 \wedge \Omega + \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, G_3)\ e^{-2\pi k^\alpha T_\alpha}$$

Kähler moduli

- LVS: perturbative corrections to Kähler potential

$$K(\rho, \bar{\rho}) = -2\log\left[\mathscr{V} + g_s^{-3/2}\xi\right]$$

$\xi \sim \chi(CY_3)$

→ *avoid control problems à la Dine-Seiberg by balancing corrections against classical terms?*

KKLT: KÄHLER MODULI STABILIZATION [Kachru, Kallosh, Linde, Trivedi '03]

- Example: one Kähler modulus $\rho = i\sigma$

$$W_0 = \langle W_{\rm flux} \rangle = \left\langle \int G_3 \wedge \Omega \right\rangle$$

$$W = W_0 + Ae^{ia\rho}$$

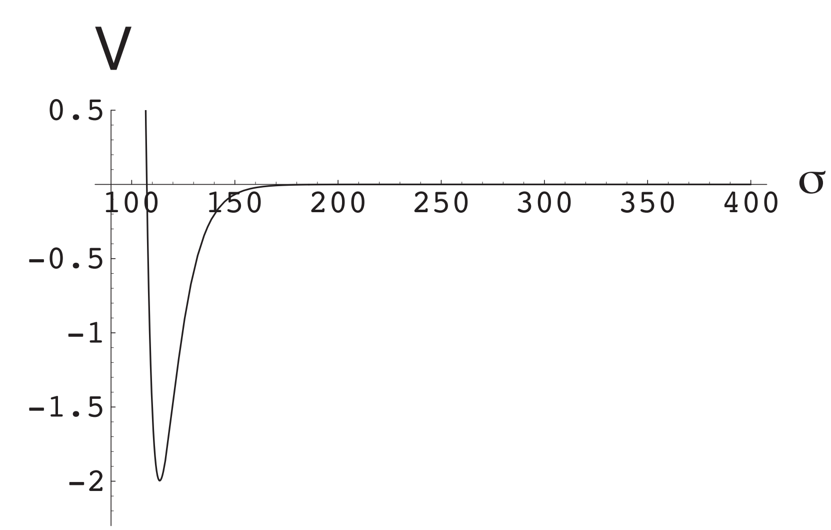
- F-term condition: $D_\rho W = 0$

$$W_0 = -Ae^{-a\sigma}\left(1 + \frac{2}{3}a\sigma\right)$$

Balance classical W_0 against non-pert. $e^{-a\sigma}$ $\rightarrow$ avoid Dine-Seiberg

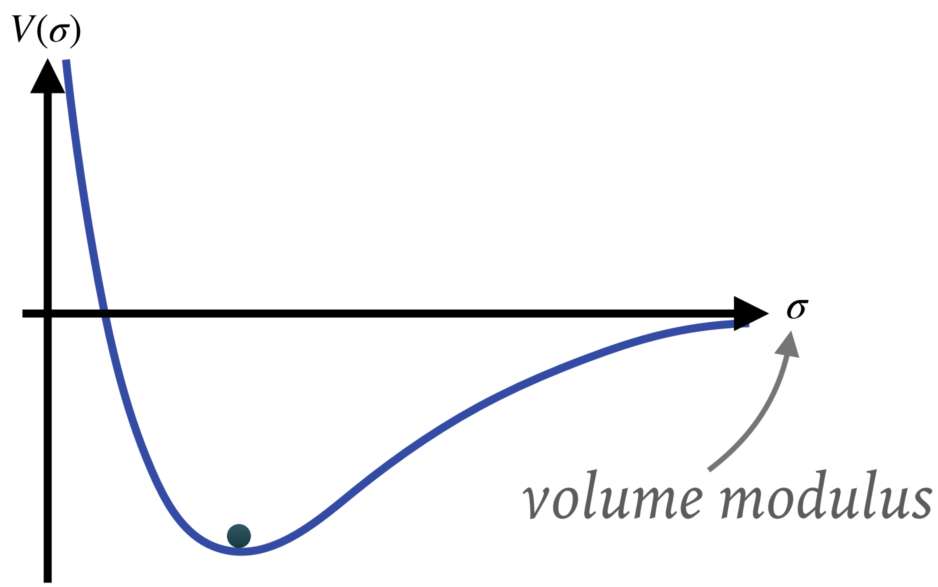
- AdS minimum:

$$V_{AdS} = -3e^K W^2 = -\frac{a^2A^2e^{-2a\sigma}}{6\sigma}$$



ANTI-BRANE UPLIFT

- so far: AdS vacuum ($\mathcal{N} = 1$ supersymmetric for KKLT)



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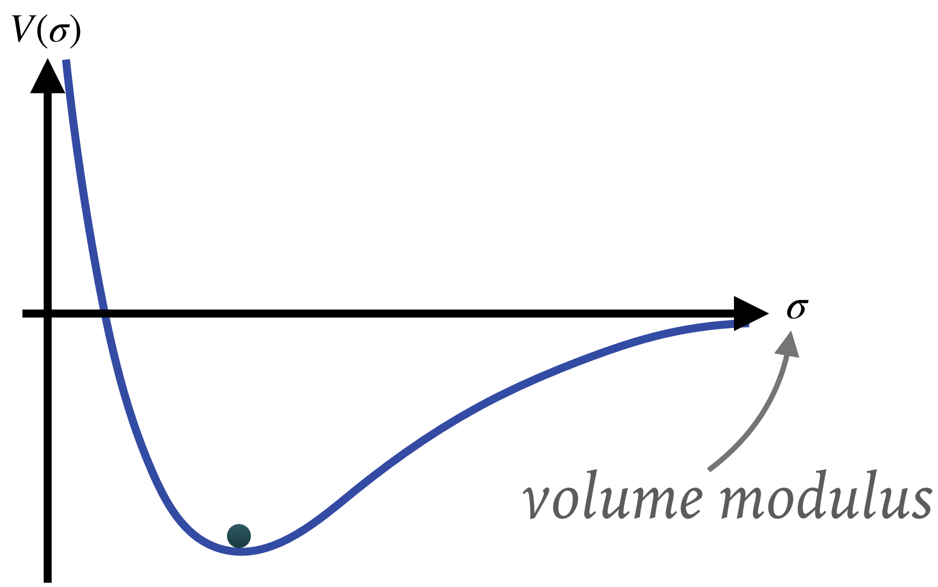

- next: raise vacuum energy (and break SUSY)

add an anti-D3-brane:

(D3-brane with negative charge) →

contribution to potential:

$$V_{\overline{D3}} \sim \frac{1}{\sigma^3} T_{D3}$$

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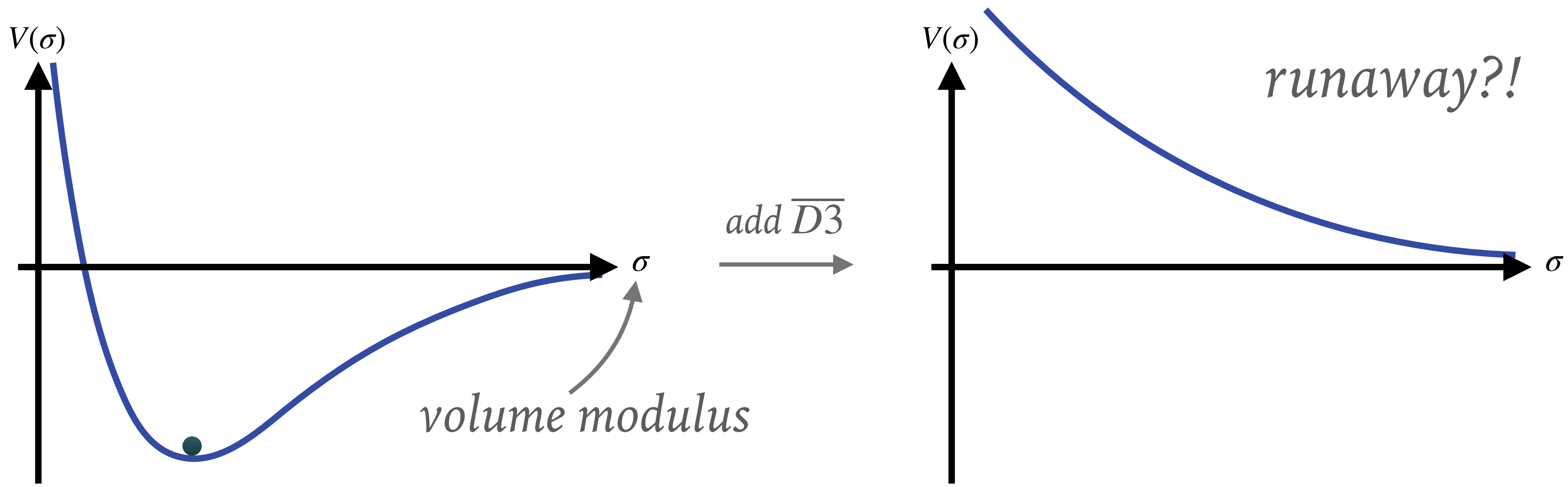

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- Problem: potential for σ too shallow, $\overline{D3}$ too heavy!

BACKREACTION OF FLUXES

[Graña, Polchinski ’00, ’01]
[Giddings, Kachru, Polchinski ’02]

- Three-form fluxes in IIB

$$\int_{(A_I,B^I)} F_3 = (M^I, M_I) \in \mathbb{Z} \qquad \int_{(A_I,B^I)} H_3 = (K^I, K_I) \in \mathbb{Z}$$

A_I, B^I: symplectic basis of 3-cycles on the CY
($I = 0,\ldots,h^{2,1}$)

- back-reaction: warped background:

A: warp factor

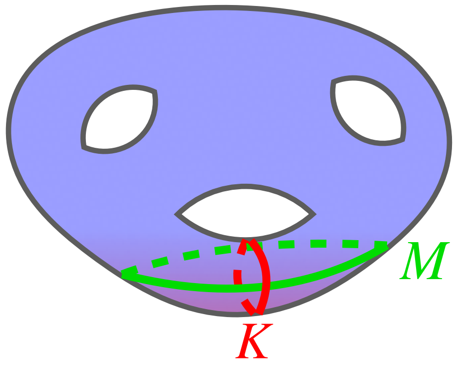
Calabi-Yau
(orbifold) metric

$$ds_{10}^2 = e^{2A} ds_4^2 + e^{-2A} ds_6^2$$

$$F_5 = (1 + \star\ ) vol_4 \wedge de^{4A}$$

ANTI-BRANE UPLIFT AND WARPED THROATS

➤ Solution: use back-reaction of fluxes to create region with large redshift in Calabi-Yau

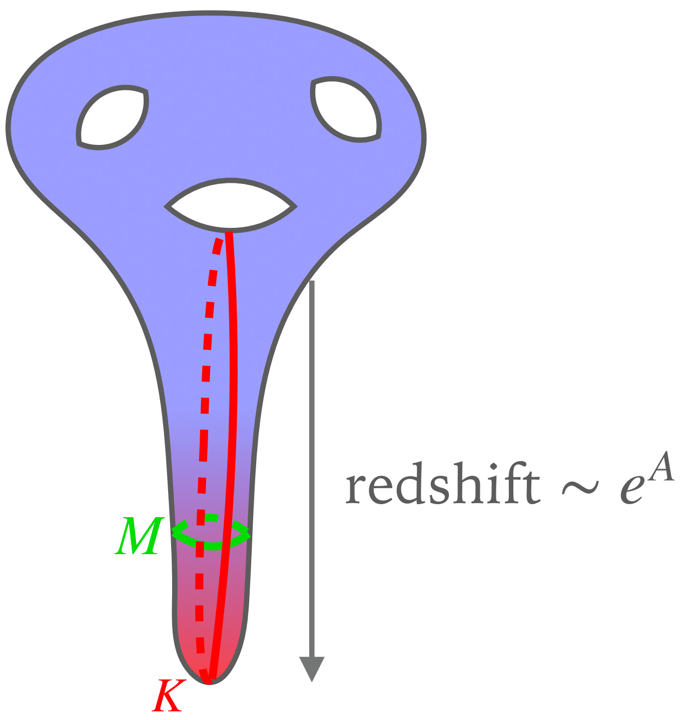


ANTI-BRANE UPLIFT AND WARPED THROATS

- Solution: use back-reaction of fluxes to create region with large redshift in Calabi-Yau

(local) geometry described by *Klebanov-Strassler* throat:

$$e^{4A} \sim \exp\left(-\frac{8\pi K}{g_s M}\right)$$



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→

$\overline{D3}$ *potential in warped throat:*

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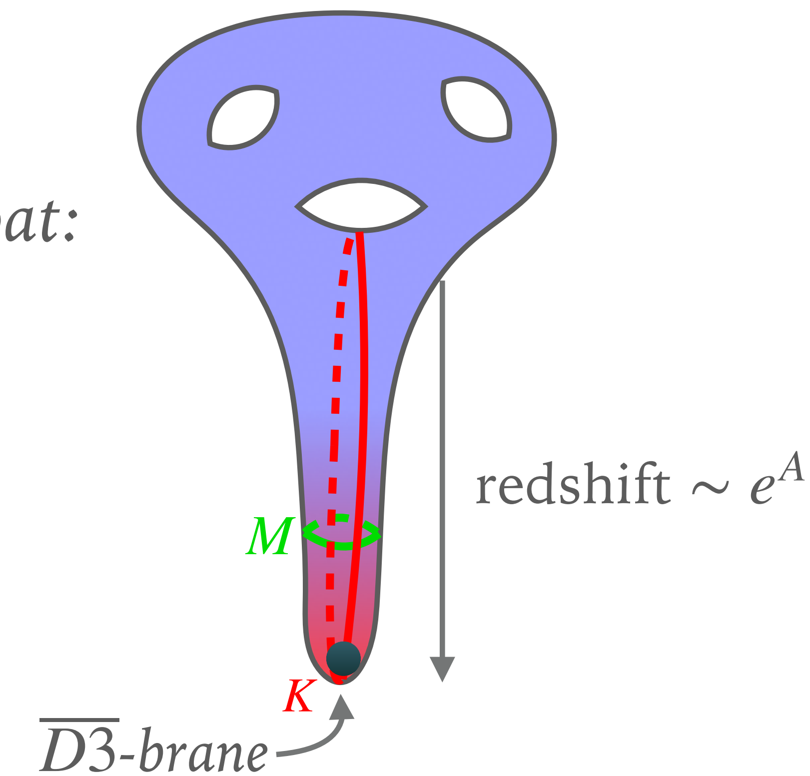

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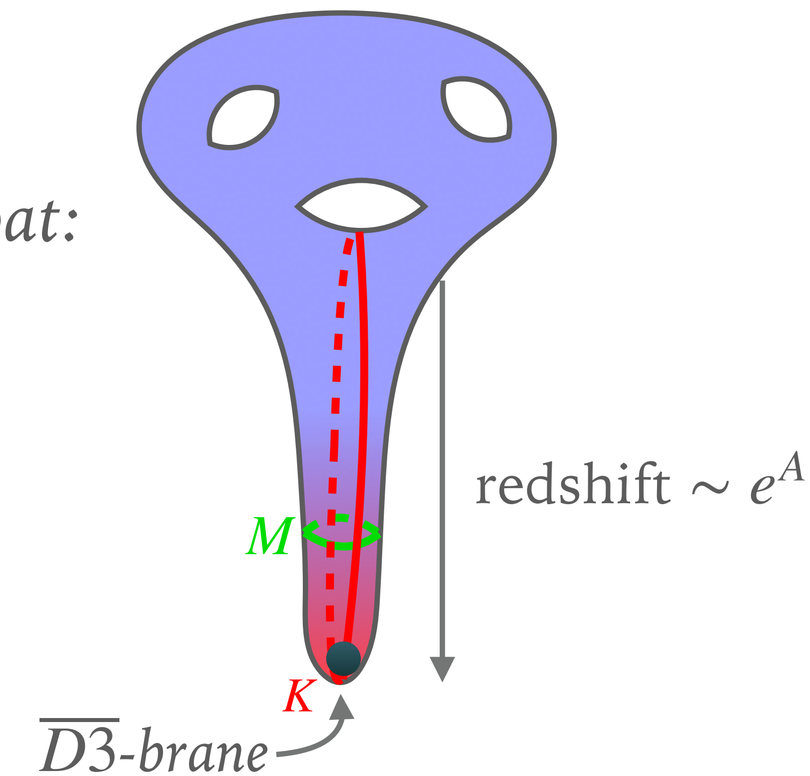
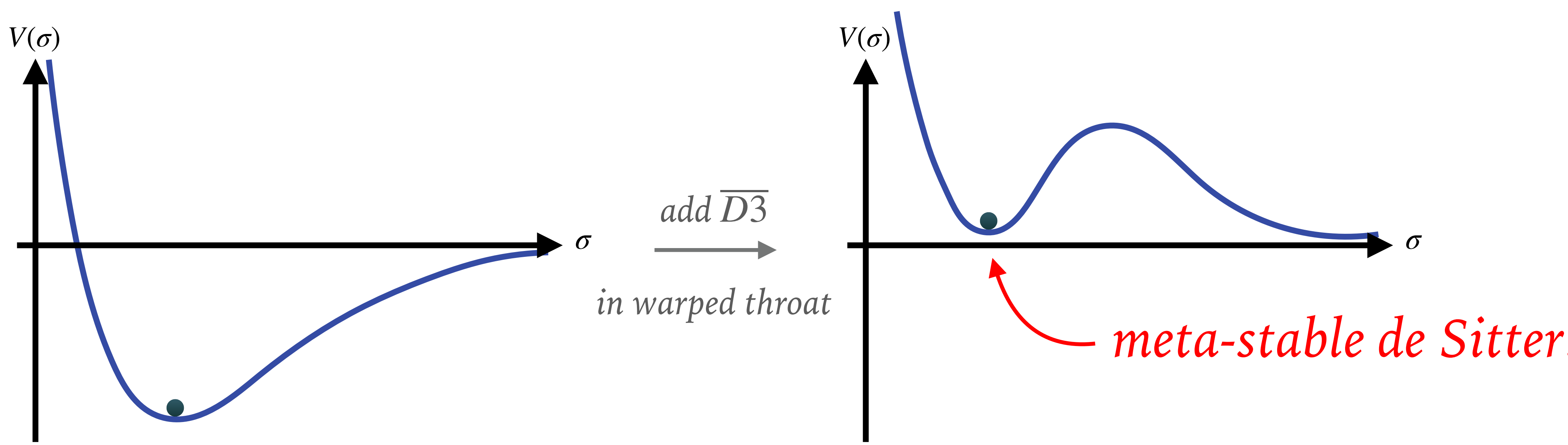


➤ Effect on volume modulus potential:

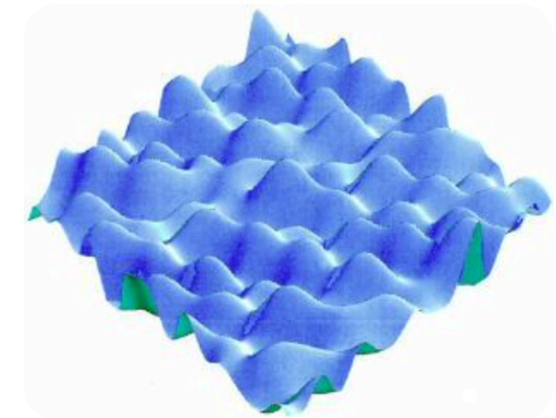


DISCUSSION

RECENT DEVELOPMENTS AND ISSUES

CONCRETE REALISATIONS IN THE LANDSCAPE

- Flux Landscape:



Huge combinatorial number of possible Calabi-Yau and flux choices

$$> 10^{500}$$

- Promises high statistical probability to find meta-stable KKLT / LVS de Sitter vacuum [Ashok, Douglas '03], [Denef, Douglas '04]

- Only few concrete realisations (difficult for models with many moduli)

KKLT/LVS are rather scenarios than concrete models

- Impressive recent efforts for KKLT AdS vacua

[Demirtas, Kim, McAllister, Moritz, Rios-Tascon '21]

TADPOLE BOUNDS

- Fluxes are constraint by tadpole cancellation condition:

$$\frac{1}{2}\int H_3 \wedge F_3 + Q_{loc} = 0$$

- Tadpole conjecture: [Bena, Blåbäck, Graña, SL '20]

$$\frac{1}{2}\int H_3 \wedge F_3 \text{ grows faster than } Q_{\text{loc}} \text{ with the number of moduli}$$

- If, true: Landscape much smaller than anticipated!

➞ *more difficult to obtain required fine-tuning*

[Graña, Grimm, van de Heisteeg, Herraez, Plauschinn '22]

- Confirmed in asymptotic limits in moduli space
- also in deep interior? [SL, Wiesner '22]

[Marchesano, Prieto, Wiesner '21]
[Plauschinn '21] [SL '21]

CONTROL ISSUES

Careful estimates of the size of relevant corrections:

- KKLT: "Fit" warped throat into Calabi-Yau [Carta, Moritz, Westphal '18] [Gao, Hebecker, Junghans '20]

"Singular bulk problem"

Control over supergravity approximation only if $Q_{\text{loc}} \gg 1$

(possible resolution: [Carta, Moritz '20])

- LVS: [Junghans '22 (2x)] [Gao, Hebecker, Schreyer, Venken '22]

Simultaneous control over all correction requires large Q_{loc}

- KKLT with fluxes along the lines of [Demirtas, Kim, McAllister, Moritz '20]:

Controlled mass-hierarchy only if $Q_{\text{loc}} \gg 1$?

[Blumenhagen, Gligovic, Kaddachi '22]

MODULAR CONSTRUCTION

- Bottom-up (EFT) construction that combines different top-down (string theory) ingredients

  (fluxes, quantum effects, warped throats, anti-branes, …)

- Individual ingredients well understood but interaction between ingredients often neglected

- incomplete list of possible issues:
  - warped throats and Kähler moduli stabilisation
    [Carta, Moritz, Westphal '18] [Gao, Hebecker, Junghans '20]
  - anti-brane uplift and complex structure moduli stabilisation
    [Bena, Dudas, Graña, SL '18] [Blumenhagen, Kläwer, Schlechter '18]
  - backreaction of fluxes
    [Randall, SL '22]

- related: no genuine $\mathcal{N} = 1$ formulation, instead treatment as approximative $\mathcal{N} = 2$

SCALE SEPARATION

- When can we trust a lower-dimensional EFT description?

[Gautason, Schillo, Van Riet, Williams '15]

necessary condition: $|\Lambda| \ll m_{KK}$ *"Scale separation"*

cosmological constant → $|\Lambda|$; Kaluza-Klein scala = size of the extra-dimension → m_{KK}

→ violated for many AdS vacua with extended SUSY (e.g. $AdS \times S$)!

- Swampland AdS conjecture: [D. Lüst, Palti, Vafa '19]
  AdS vacua: tower of states with mass $m_{tower} \sim |\Lambda|^{\alpha}$

  ➔ same for dS?!

  → *dark dimension scenario* [Montero, Vafa, Valenzuela '19]

- KKLT / LVS: appear to satisfy scale separation
  but: maybe presence of similar tower from warped throat?
  [Blumenhagen, Gligovic, Kaddachi '22]

HOLOGRAPHY

- KKLT: Before de Sitter-uplift: SUSY AdS vacuum

→ *holographically dual CFT?!*

[Minasian, Tsimpis '99]
[Kounnas, Lüst, Petropoulos, Tsimpis '07]

- CFT dual to flux vacuum (+ non pert. effects) as system of D5/NS5-branes

[SL, Vafa, Wiesner, Xu '22]

central charge

count degrees of freedom: $c_{CFT} \lesssim Q_{loc}$

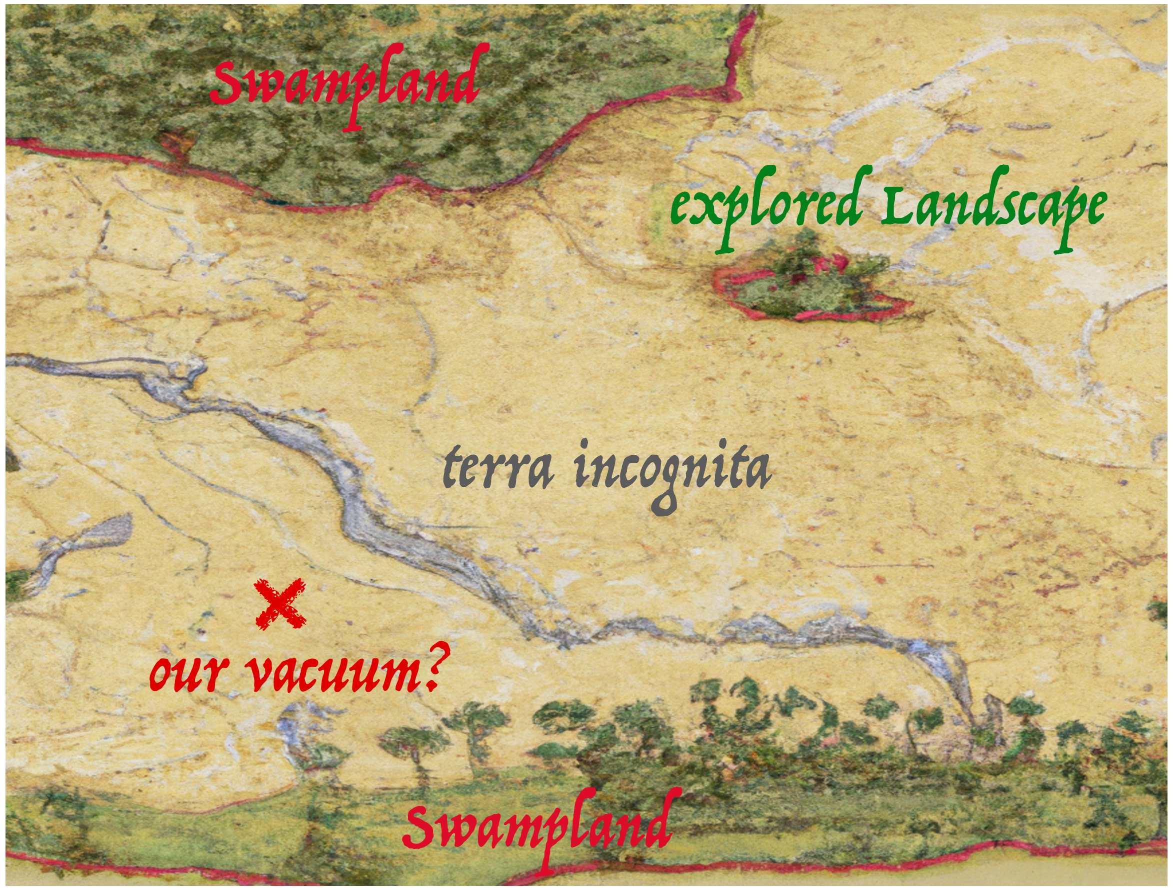
localised D3-charge in tadpole cancellation condition

- AdS/CFT holography: $|\Lambda_{AdS}| \sim \frac{1}{c_{CFT}^2} \gtrsim \frac{1}{Q_{loc}^2}$ bounded from below!

→ *no weakly coupled, scale-separated AdS vacua from KKLT?!*

DE SITTER VACUA UNDER THE LAMPPOST?

- weakly coupled, geometric, supersymmetric vacua
  → only a small fraction of the Landscape
- but: no phenomenological reason to focus on these vacua!



We study supersymmetric Calabi-Yau vacua
not because we should but because we can…

THANK YOU!