REVIEW TALK:
DE SITTER VACUA AND BEYOND

Severin Lüst

L2C, Montpellier

Deconstructing the String Landscape

IPhT, CEA Saclay, Nov 30, 2023

LITERATURE

- I. Bena, M. Graña, T. van Riet (2023):
  “Trustworthy de Sitter compactifications of string theory: a comprehensive review”

THANK YOU!

LITERATURE

- U. Danielsson, T. van Riet (2018):
  "What if string theory has no de Sitter vacua?"
- M. Cicoli et al. (2023):
  "String Cosmology: from the Early Universe to Today"
- T. van Riet, G. Zoccarato (2023):
  "Beginners lectures on flux compactifications and related Swampland topics"
- L. McAllister, F. Quevedo (2023):
  "Moduli Stabilisation in String Theory"
- M. Graña (2005):
  "Flux compactifications in string theory: a comprehensive review"
- F. Denef (2008):
  "Lectures on constructing string vacua"

REALISTIC STRING VACUA

Any realistic string theory vacuum should have:

- four macroscopic spacetime dimensions (obviously)
- broken / no supersymmetry
- dark energy / positive cosmological constant
- and many other properties

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- and many other properties

KNOWN STRING VACUA

String vacua that we understand well have:

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

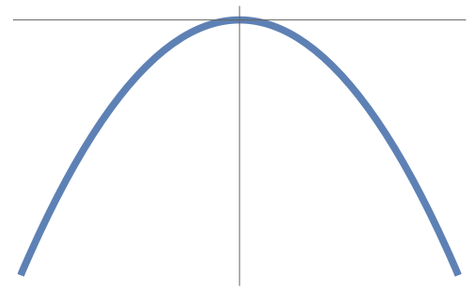
side note:

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

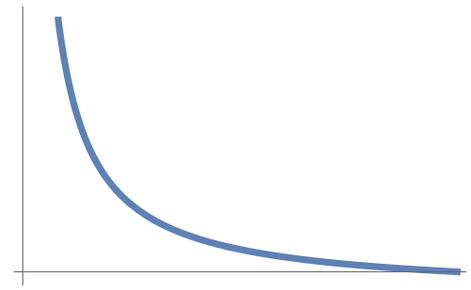
Unknown whether string theory has stable { non-SUSY vacua! / de Sitter vacua!

NON-SUPERSYMMETRIC STRING THEORY

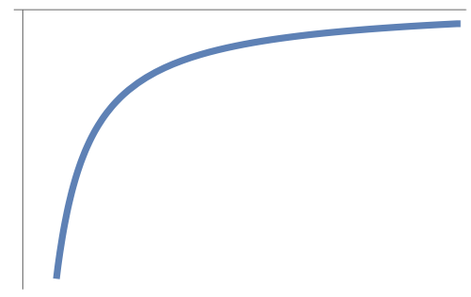
- Bosonic string
  - Target space tachyon!



- 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: $V \sim -\frac{1}{R^{\alpha}}$ (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 effects: generate a potential for moduli!

assume:

$\phi \to \infty$:
weakly coupled regime, SUSY restored,
effective tree-level description valid

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

(see also recent swampland efforts)

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[Dine, Seiberg '85]

potential from first order quantum corrections:

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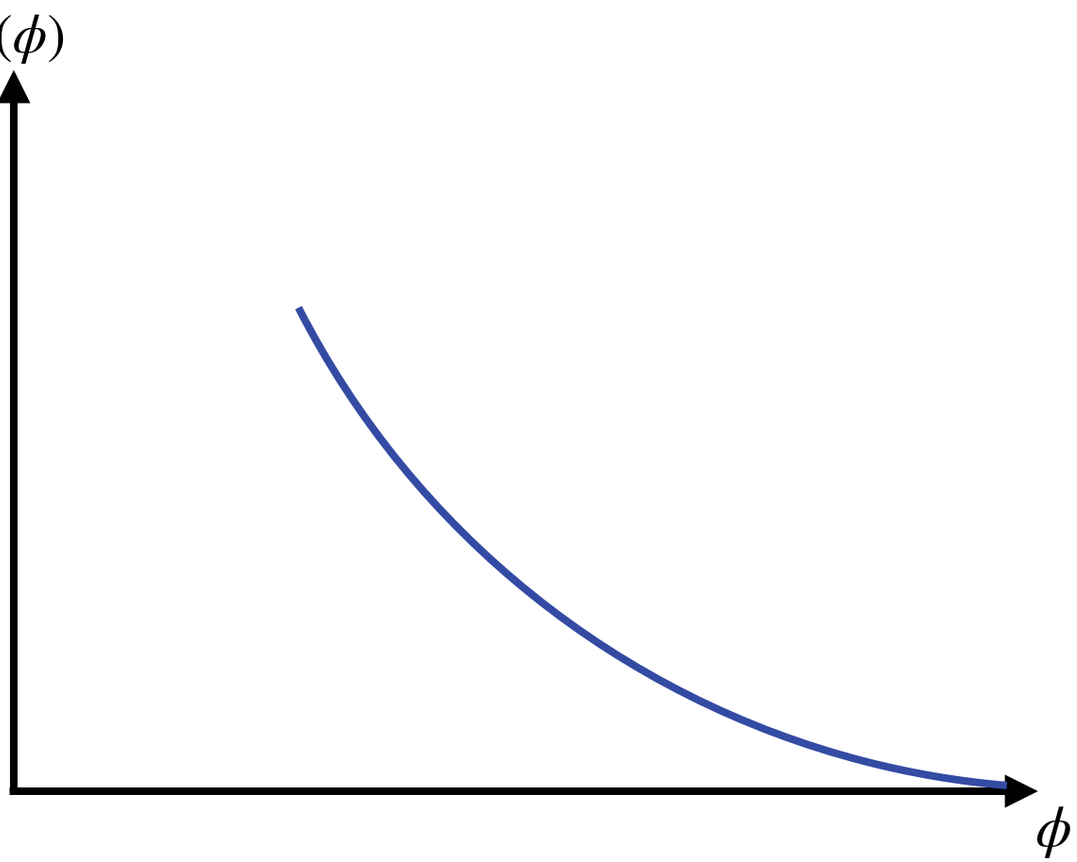

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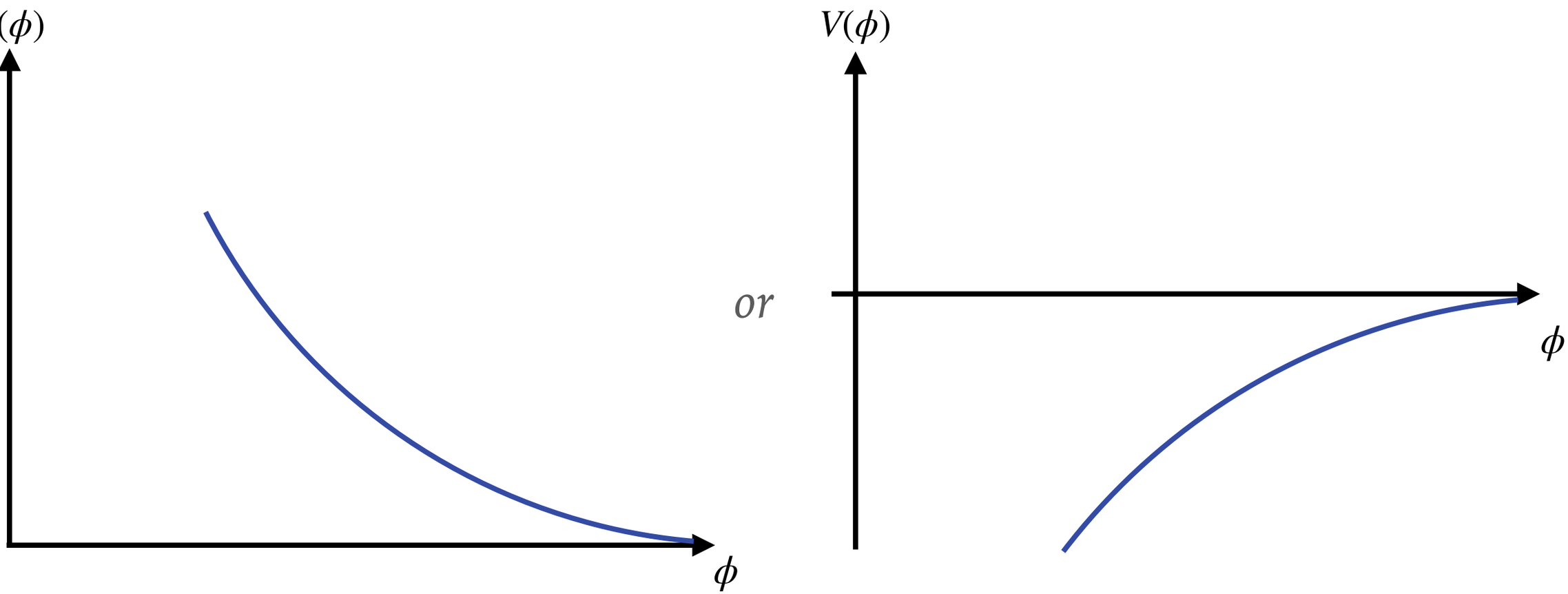

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take higher order corrections into account:

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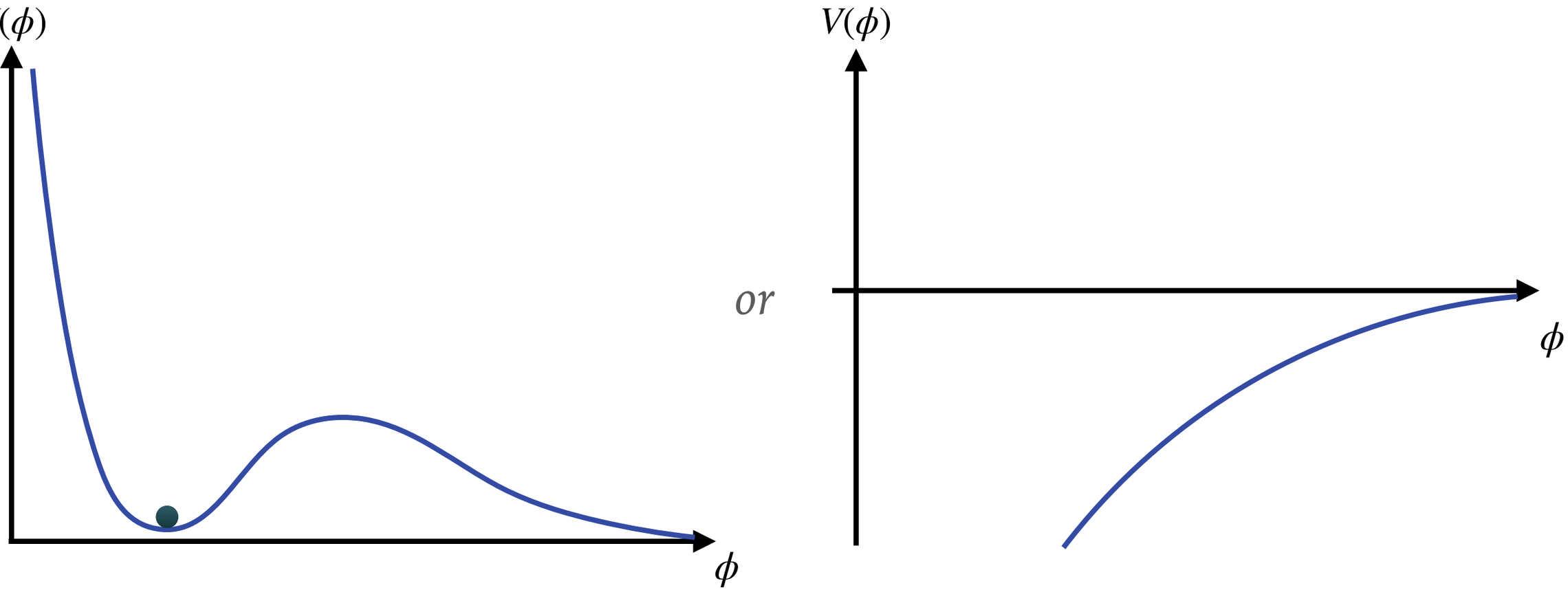

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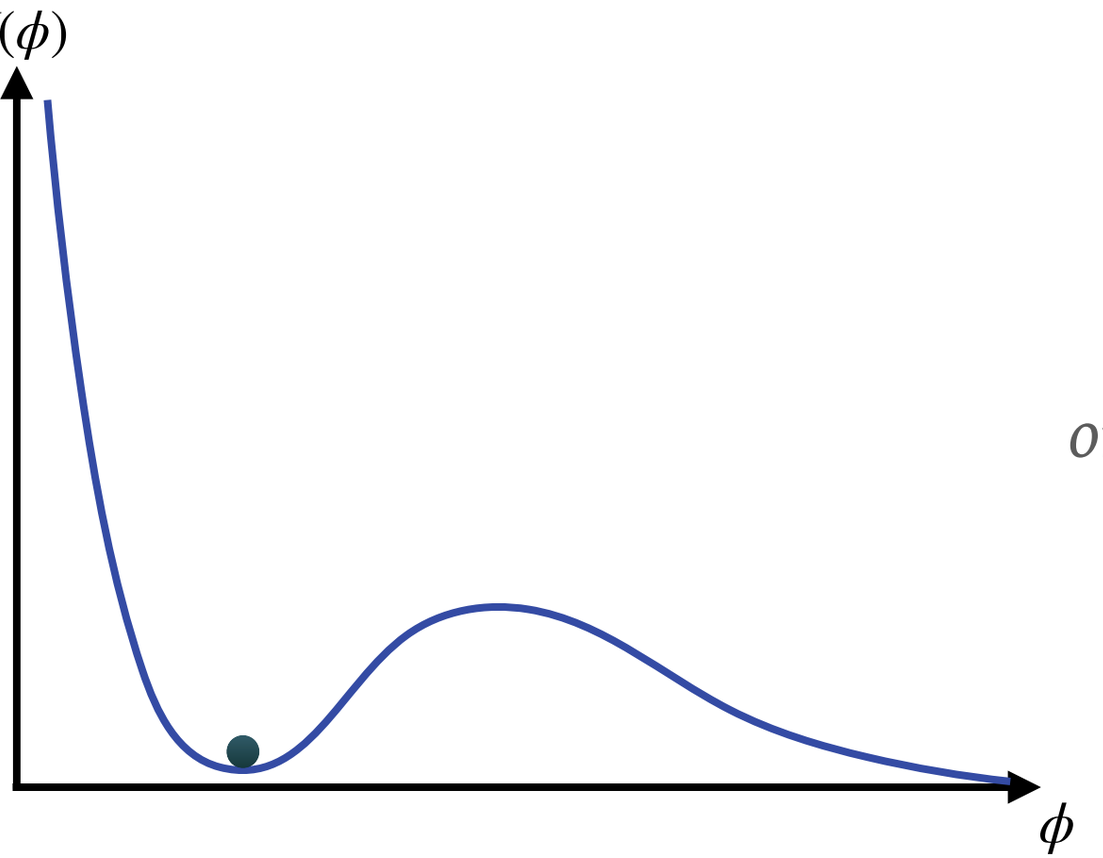

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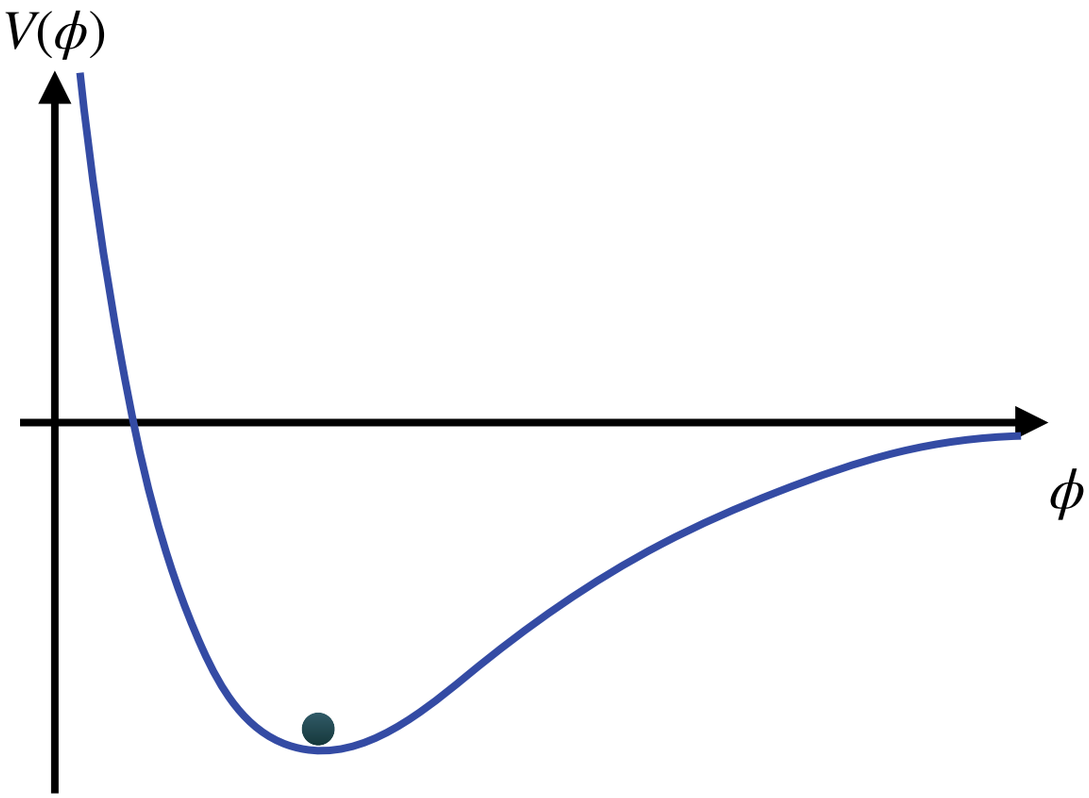

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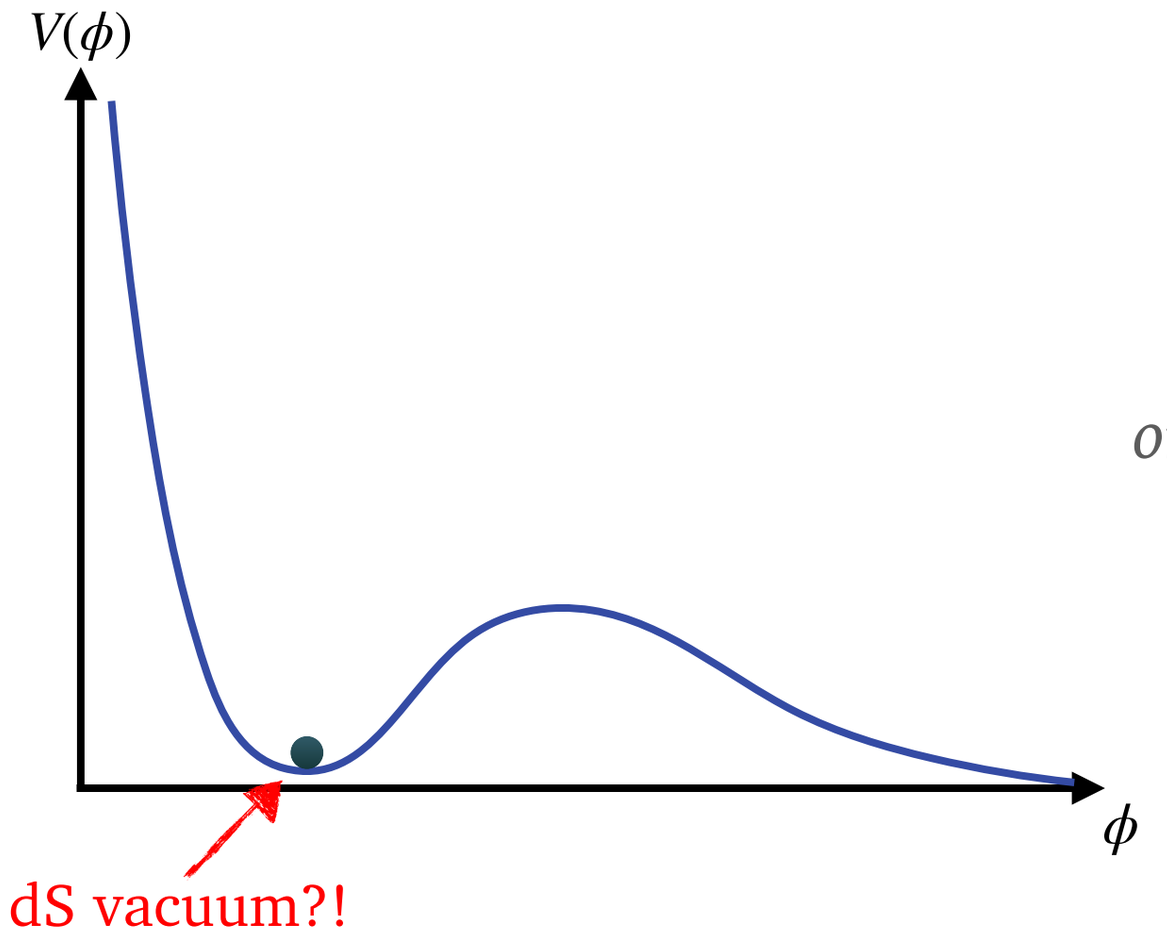

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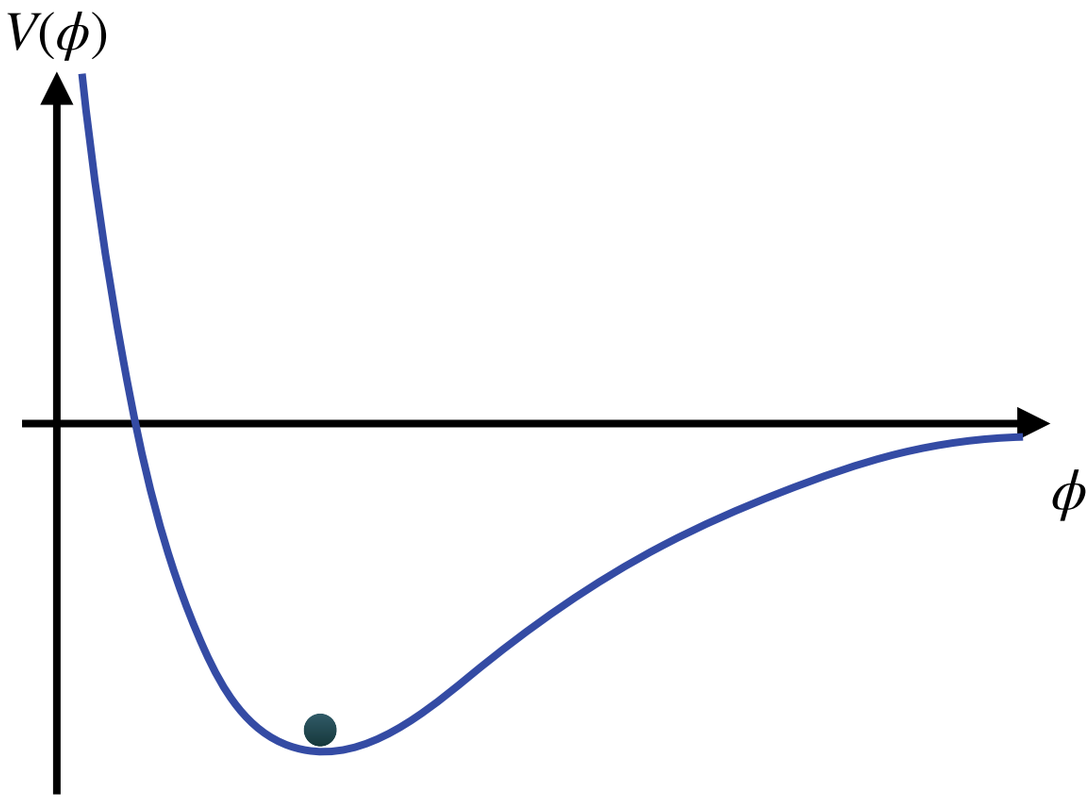

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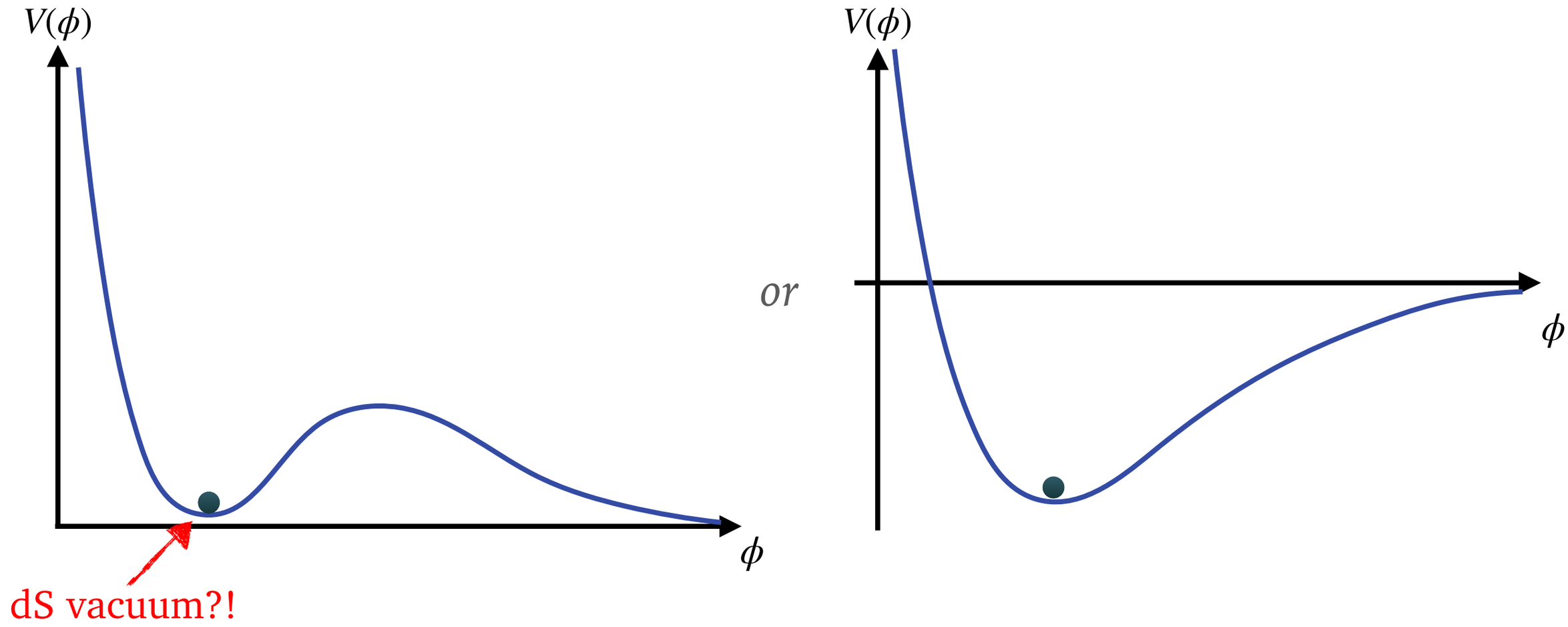

at minimum of V:

$$\text{higher order corrections} \approx \text{first order corrections} \longrightarrow$$

strong coupling!

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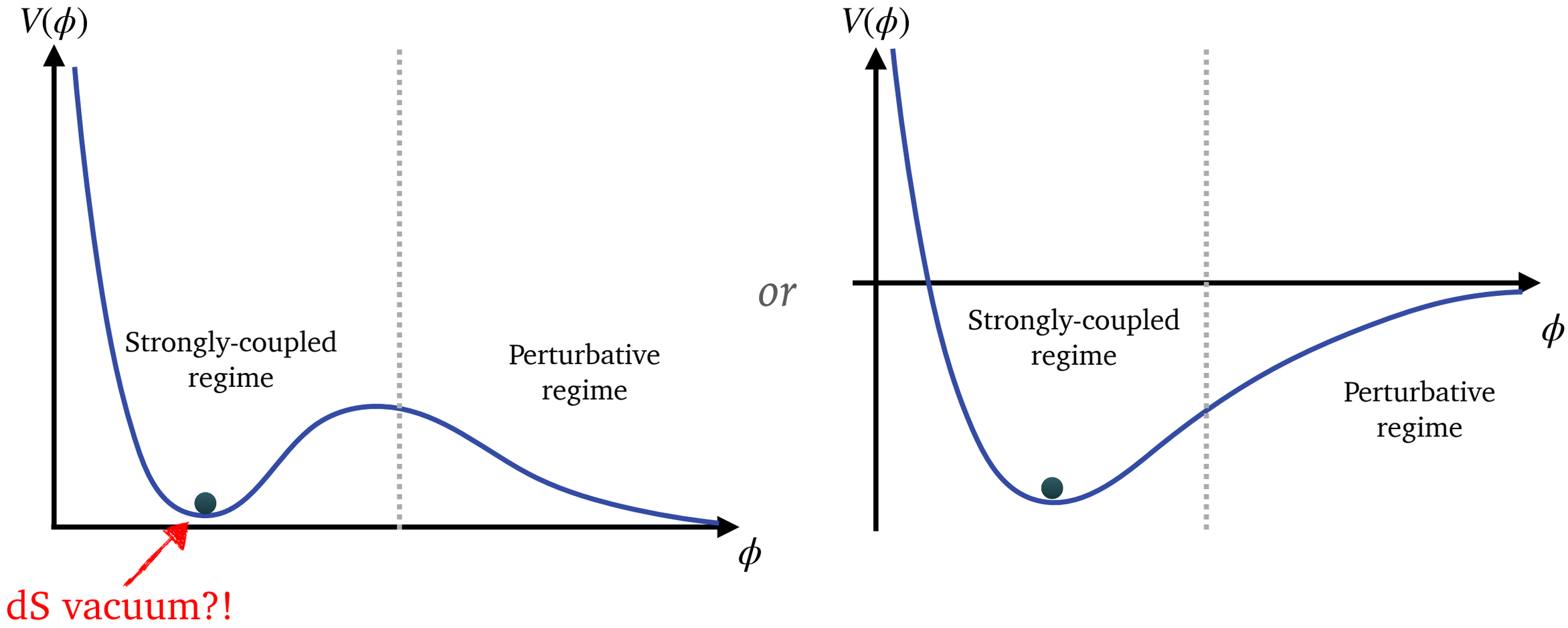


at minimum of V:

higher order corrections $\approx$ first order corrections $\rightarrow$ *strong coupling!*

DINE-SEIBERG PROBLEM

de Sitter vacua from quantum corrections only at strong coupling!

higher order corrections:
mostly unknown

"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:

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

- 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

$$\frac{|V'|}{V} \geq \frac{d+2}{\phi} \quad \rightarrow \textit{no de Sitter minima!}$$

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

DE SITTER NO-GO

- [Maldacena, Nuñez '00] (and many others):

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

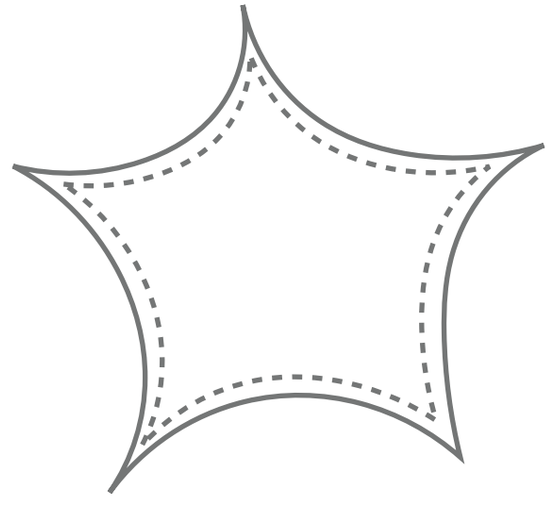
- de Sitter vacua from String Theory must involve:

  a) quantum effects

  or

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

  → Danger of Dine-Seiberg like control issues!



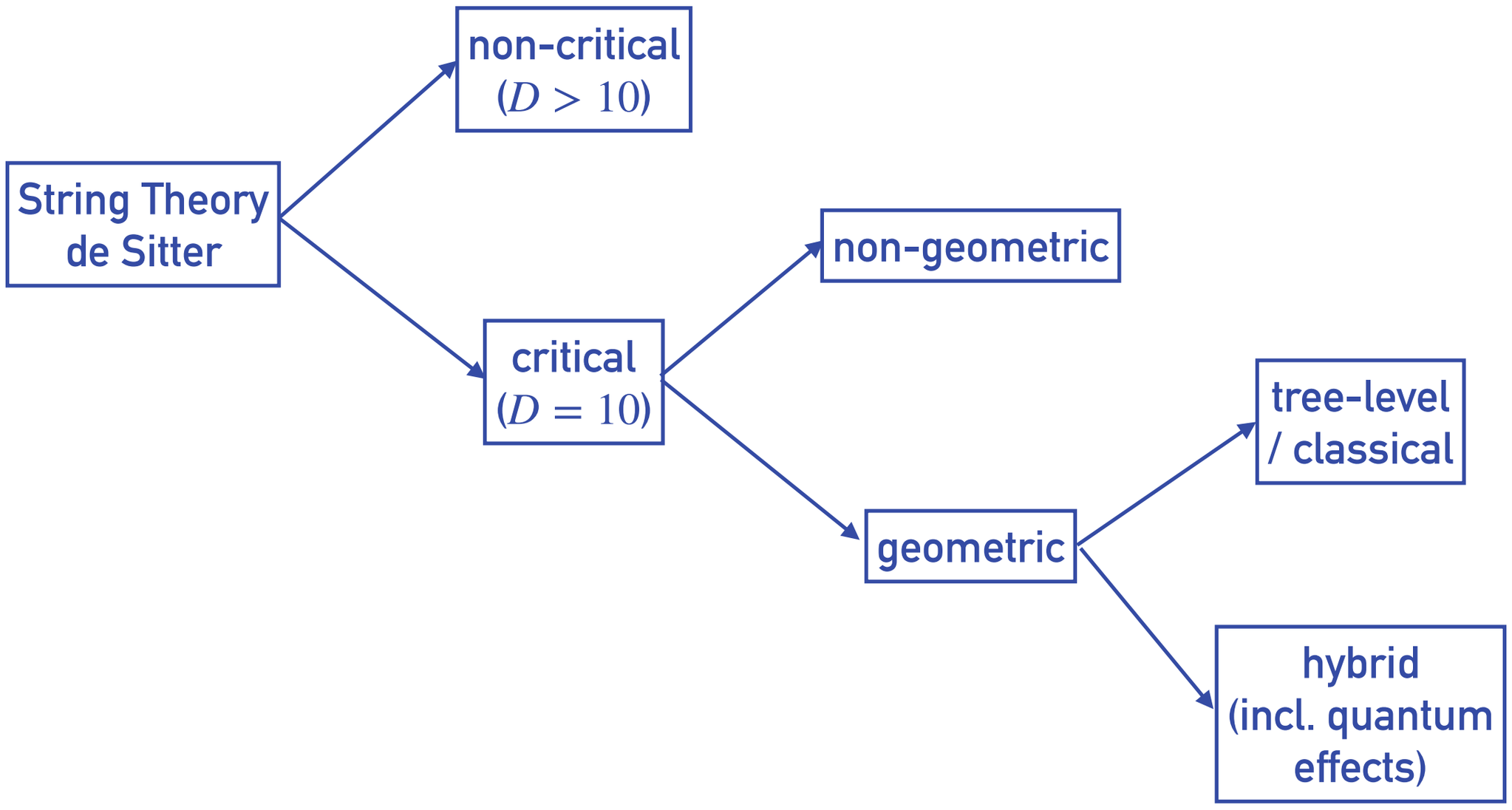
- most promising strategy:

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

STRING THEORY DE SITTER CONSTRUCTIONS

SYSTEMATICS OF DE SITTER CONSTRUCTIONS

[Danielsson, van Riet '18]:



NON-CRITICAL STRING THEORY

➤ Effective action of non-critical string theory ($D \neq D_c$):

$$S = \frac{1}{2\kappa_D^2} \int d^D x \sqrt{-g} e^{-2\phi} \left(R - \frac{D - D_c}{\alpha'} + \dots \right)$$

positive for $D \geq D_c$

→ facilitates compactification to de Sitter

➤ Early models:

[Silverstein '01][Maloney, Silverstein, Strominger '02]

➤ Recent critical analysis: [Junghans '23]

- generalisation of Maldacena-Nuñez like no-go theorems
- no parametric control over O-plane backreaction (and higher derivative corrections) in the large D limit

NON-GEOMETRIC CONSTRUCTIONS

- Applying (chains) of string dualities (e.g. T-duality) allows for the construction of non-geometric backgrounds / fluxes.
- Resulting four-dimensional potentials often have de Sitter minima.

see e.g. [Shelton, Taylor, Wecht '05][Dibitetto et al. '12];
for a recent review: [Plauschinn '18]

- However:
  - *intrinsically string theoretical*
  - *unclear if treatment in supergravity is justified*
  - *difficult to define a notion of (perturbative) control*

CLASSICAL DE SITTER VACUA

- Find a solution to the classical, 10D supergravity EOMs with 4D de Sitter
    - must contain O-plane / D-brane singularities
    - breaks SUSY at the level of the classical geometry

reduced control, unclear if actually string backgrounds

- extensive body of literature

(see e.g. [Silverstein '08], [Danielsson et al.], [Andriot et al.] and many others)

- existing solutions:
    - all are classically unstable / tachyonic
    - not under perturbative control (e.g. small volume, large g_s, …)
    - contain O-planes in smeared approximation

NON-SUPERSYMMETRIC STRING THEORY

- perturbative worksheet CFT:

  Problem: Run-away for dilaton!
  (→ Dine-Seiberg Problem)

- Powerful no-go theorems for heterotic string
  [Kutasov, Maxfield, Melnikov, Sethi '15]

- Stabilisation of other moduli also challenging
  [Fraiman, Graña, Parra de Freitas, Sethi '20], talk by H. Parra de Freitas

- Target space perspective:
  - positive dilaton potential: similar to non-critical strings
  - no-go theorems [Basile, Lanza '20]

(see also talk by S. Raucci)

HYBRID MODELS

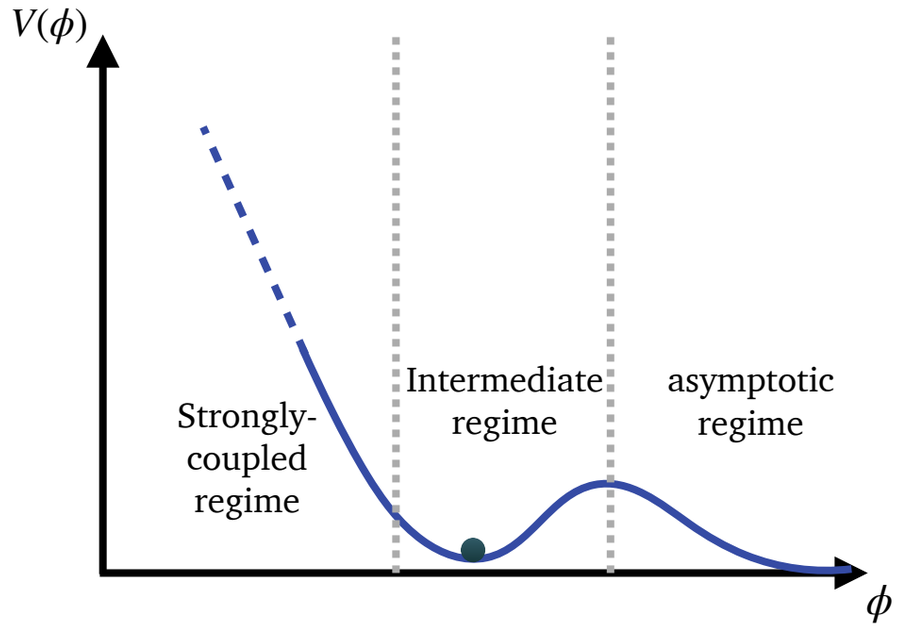
➤ most promising strategy:

combine different effects (fluxes + quantum corrections)
to avoid no-go theorems
while maintaining maximal control

➤ two main competitors (both in IIB or F-theory):

- *KKLT* [Kachru, Kallosh, Linde, Trivedi '03]
- *Large Volume Scenario (LVS)*
  [Balasubramanian, Berglund, Conlon, Quevedo '05]

start from well understood Calabi-Yau
compactifications $\mathcal{N} = 2$
$\rightarrow$ *break SUSY gradually*



➤ see also: M-theory on hyperbolic manifolds + Casimir energies
[Bruno de Luca, Silverstein, Torroba '21], talk by G. Bruno De Luca

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)
   → (supersymmetric) AdS-vacuum

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

(see also talk by J. Moritz)

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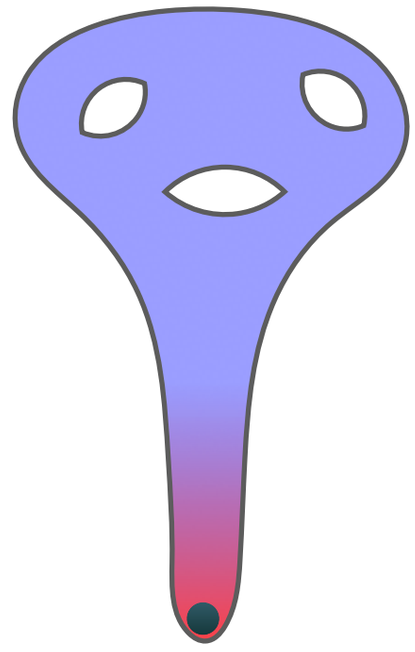

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THE FLUX LANDSCAPE (STEP 1)

- Huge flux landscape:
  required for sufficiently high statistical probability to find meta-stable KKLT / LVS de Sitter vacua (e.g. $|W_0| \ll 1$)

until recently:

- few concrete realizations but statistical arguments
  [Ashok, Douglas '03], [Denef, Douglas '04]

now:

- systematic construction of flux vacua with $|W_0| \ll 1$
  [Demirtas, Kim, McAllister, Moritz '21, '20] (see talk by J. Moritz)
  [Álvarez-Garcia, Blumenhagen, Brinkmann, Schlechter '20]
- Tadpole conjecture [Bena, Blåbäck, Graña, SL '20]
  [Marchesano, Prieto, Wiesner '21][Plauschinn '21][Graña, Grimm, van de Heisteeg, Herraez, Plauschinn '22][Becker, Gonzalo, Walcher, Wrase '22][Grimm, Monnee '23][Becker, Brady, Sengupta '23] (see also talk by N. Brady, A. Sengupta)
- Relations to asymptotic Hodge theory [Grimm et al.]
- advances in automatized (computer aided) constructions
  [Cole, Schachner, Shiu '19][Bena, Blåbäck, Graña, SL '21][McAllister et al.][Dubey, Krippendorf, Schachner '23][Plauschinn, Schlechter '23] and many more (see also talk by J. Halverson)

SUPERSYMMETRIC ADS VACUA (STEP 2)

- Kähler moduli stabilization by non-perturbative effects:

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

- Gaugino condensation in 10D
  [Moritz, Retolaza, Westphal '17][Gautason, Van Hemelryck, Van Riet, Venken '19][Hamada, Hebecker, Soler '18-21][Graña, Kovensky, (Retolaza), (Toulikas) '19-'22]
- Corrections on top of classically running solution? [Sethi '17]
- highly explicit constructions with large $h^{1,1}$
  [Demirtas, Kim, McAllister, Moritz, Rios-Tascon '21], see talk by J. Moritz
- no systematic understanding of genuine $\mathcal{N} = 1$ compactifications / corrections (see talk by M. Wiesner)
- holographically dual brane CFT: incompatible with $|\Lambda_{\text{AdS}}| \ll 1$? [SL, Vafa, Wiesner, Xu '22]

ANTIBRANE UPLIFT / BACKREACTION EFFECTS (STEP 3)

- antibrane uplift requires strongly warped geometry (e.g. Klebanov-Strassler throat)
- backreaction effects of antibrane in KS throat
  [Bena, Graña, (Halmagyi), (Kuperstein, Massai) '09-'12][Blåbäck, Danielsson, Van Riet, '12-'14] [Gautason, Junghans, Zagermann '13][Michel, Mintun, Polchinski, Puhm, Saad '14][Cohen-Maldonado, Diaz, Van Riet, Vercnocke '15][Bena, Dudas, Graña, SL, '18][SL, Randall, '22]
- curvature corrections to KPV? [(Hebecker), Schreyer, Venken '22]
- singular bulk problem:
  no control over O-plane backreaction unless $h^{1,1} \gg 1$
  (throat too large to fit into Calabi-Yau)
  [Gao, Hebecker, Junghans '20][Carta, Moritz, Westphal '18]
  see also [Carta, Moritz '20]
- control over mass scales?
  [Blumenhagen, Kläwer, Schlechter '19][Dudas, SL '19][Blumenhagen, Gligovic, Kaddachi '22] [SL, Wiesner '22]
- What about uplift by fluxes (non-ISD fluxes)?
  [Saltman, Silverstein '04][Krippendorf, Schachner '23]

LARGE VOLUME SCENARIO (LVS)

- Kähler potential with leading α'-correction:

$$K = -2\log\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right)$$

→ non-supersymmetric AdS vacuum
at exponentially large volume $\mathcal{V}$

- control over corrections requires $g_s \ll 1, \mathcal{V} \gg 1$
  (no SUSY: not all corrections explicitly known!)
  see e.g. [Cicoli, Quevedo, Savelli, Schachner, Valandro '21]
- Systematic estimate of size of corrections:
  no control unless large tadpole!
  [Junghans '22 (2x)][Gao, Hebecker, Schreyer, Venken '22]
- Holographic duality (and Swampland)
  [de Alwis, Gupta, Quevedo, Valandro '15][Conlon, Quevedo '18]
  [Conlon, (Ning), Revello '20, '21]

DE SITTER AND QUANTUM GRAVITY

DE SITTER AND QUANTUM GRAVITY

The difficulty of realising meta-stable de Sitter vacua is

a) a computational / control problem.

b) a conceptual problem.

If b)

What is the fundamental reason why String Theory / Quantum Gravity and de Sitter vacua are incompatible?

If a)

How can we access de Sitter vacua in the context of String Theory / Quantum Gravity?

THE SWAMPLAND POINT OF VIEW

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

$$|\nabla V| \gtrsim cV \qquad (\mathcal{O}(10^3) \text{ follow up papers})$$

- Trans-Planckian Censorship conjecture (TCC) [Bedroya, Vafa '19]:

no sub-Planckian mode grows larger than the Hubble radius

→ implies the de Sitter conjecture in the asymptotic

- species scale [Dvali '07]: satisfies similar bounds
  [van de Heisteeg, Vafa, Wiesner, Wu '22, '23][Cribiori, D. Lüst '23]
  [(Caldéron-Infante), Castellano, Ruiz, Valenzuela '23]

- scale separation and (A)dS distance conjecture (see talk by T. Van Riet)

- Festina-Lente: lower bound on mass of charged particles in dS
  [Montero, Van Riet, Venken '19][Montero, Vafa, Van Riet, Venken '21]

QUANTUM CONSISTENCY OF DE SITTER

- finite quantum break-time of de Sitter might put severe constraints on consistency of de Sitter quantum gravity
  [Dvali, Gómez, Zell '17, '18]

- absence of S-matrix in de Sitter see e.g. [Buosso '05]
  see e.g. also holographic argument for TCC by [Bedroya '23]

- de Sitter Holography? [Strominger '01] and many others
  - dual to Euclidean CFTs
  - higher spin theory
  - matrix models

BEYOND DE SITTER

DARK ENERGY BEYOND DE SITTER

➤ Dark Dimension scenario [Montero, Vafa, Valenzuela '22]

tiny cosmological constant / (asymptotic) dark energy
implies a large extra dimension

[Anchordoqui, Antoniadis, D. Lüst '22, '23][Gonzalo, Montero, Obied, Vafa '22]
[Blumenhagen, Brinkmann, Makridou '22] and many others

➤ What about other forms of Dark Energy / Accelerated Expansion?

- In asymptotic regions?
- As difficult as de Sitter vacua?

[Dasgupta, Emelin, Faruk, Tatar 19'][Rudelius '22][Calderón-Infante, Ruiz, Valenzuela '22]
[Marconnet, Tsimpis '22][Shiu, Tonioni, Tran '23][Cremonini, Gonzalo, Rajaguru, Tang, Wrase '23]
[Hebecker, Schreyer, Venken '23][Andriot, Tsimpis, Wars '23][Revello '23]
[Gomes, Hardy, Parameswaran '23] (see also talk by S. Parameswaran)

THANK YOU!