String Theory Vacua with Positive Cosmological Constant

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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1. Introduction

Easy to imagine:

IR modifications of GR (E.g. f(R) gravity etc.) ⟷ (constrained by) Observations at cosmological length scales

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This talk:

UV modifications of GR (String theory) ⟷ constrained by ⟷ Observations at cosmological length scales

How is this possible?

String theory is a unified UV-completion of SM interactions and GR

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Basic idea:

Apparently point-like particle = "String"

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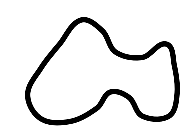

or

closed open

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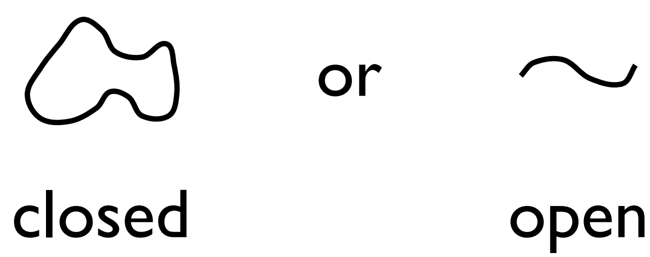
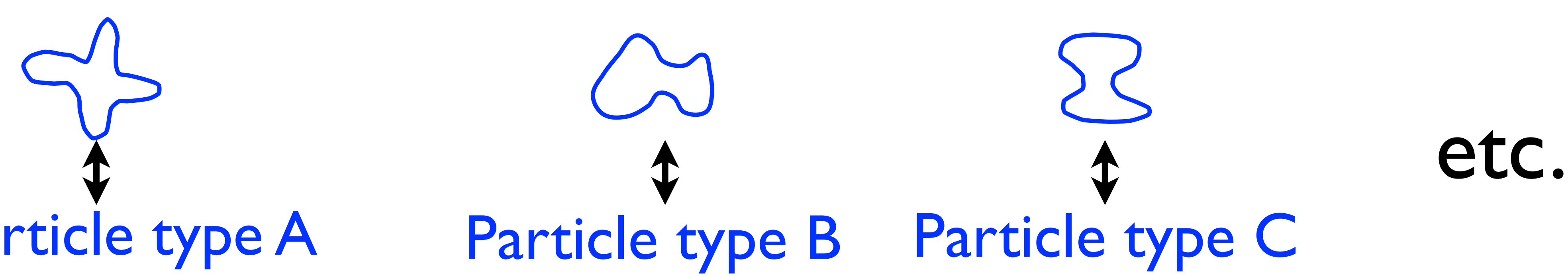
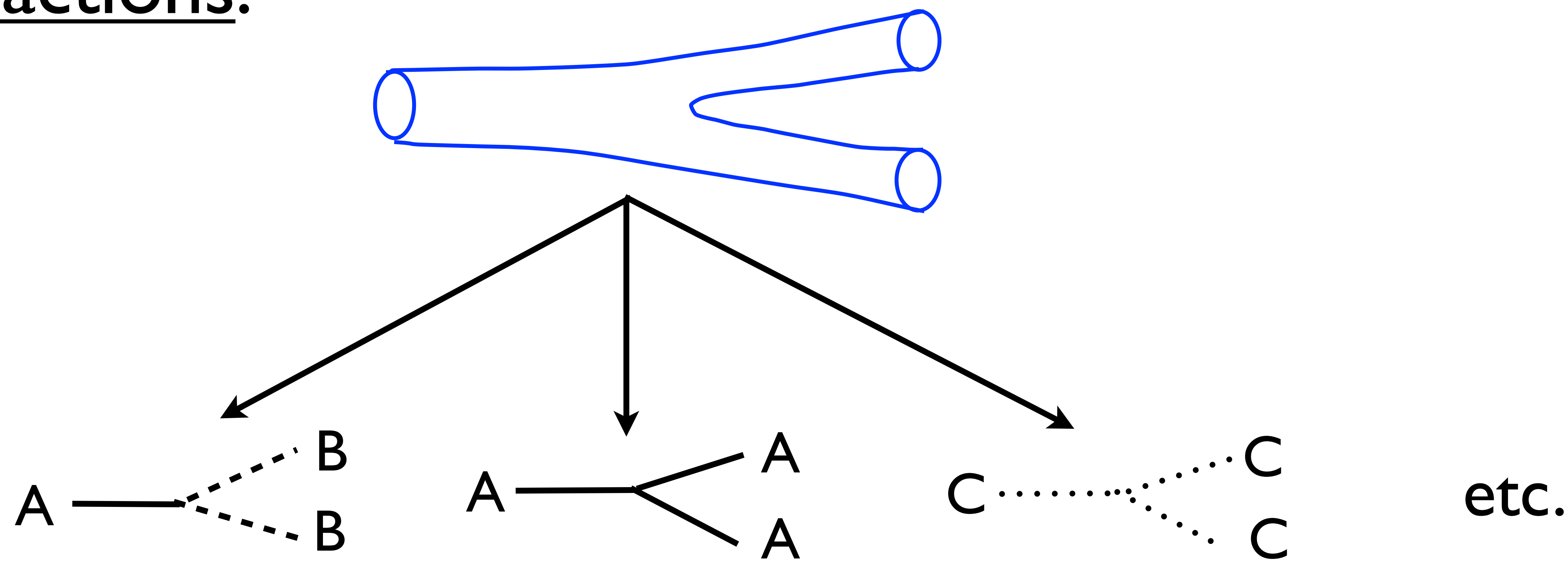


Different point particle species ⟷ Different string vibration modes



Interactions:



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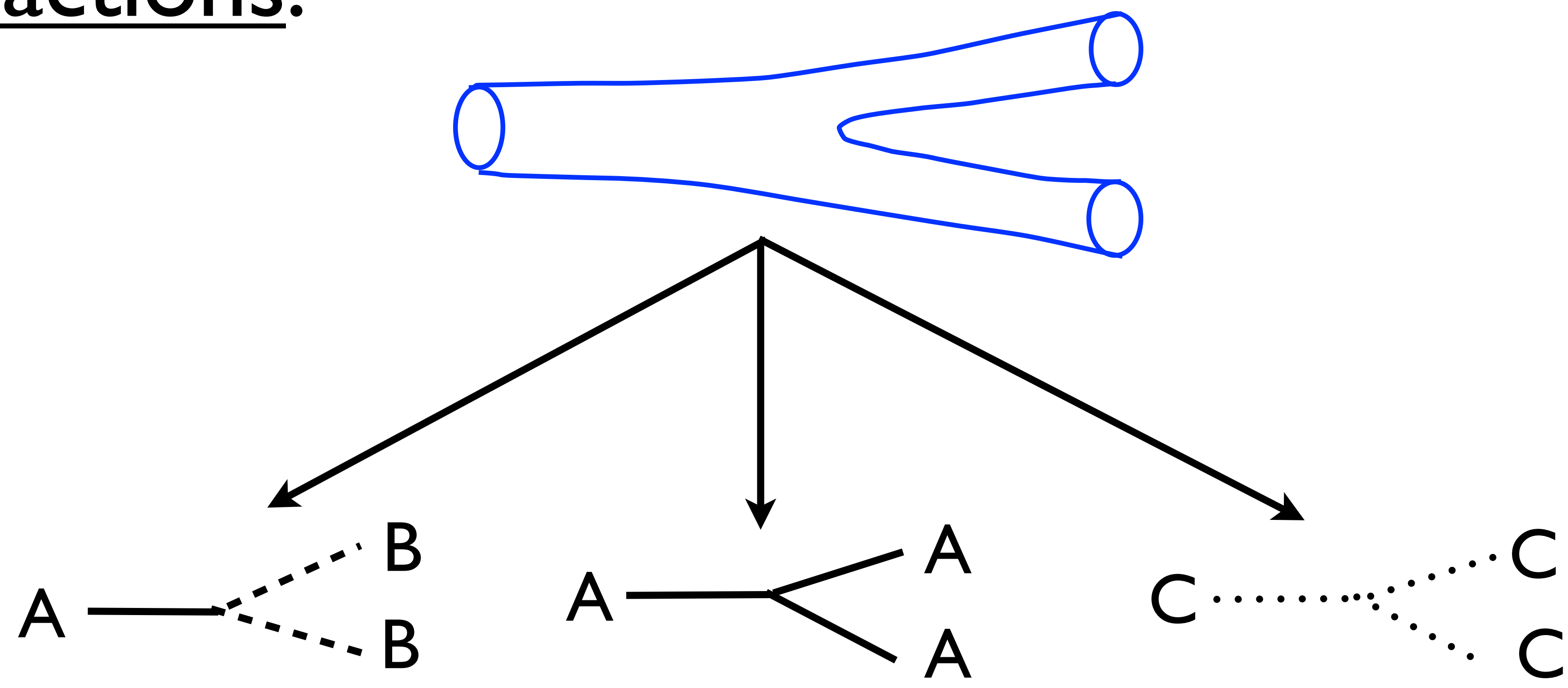

etc.

$\ni$ gravity, Yang-Mills, Yukawa etc.

at large length scales (small energies)

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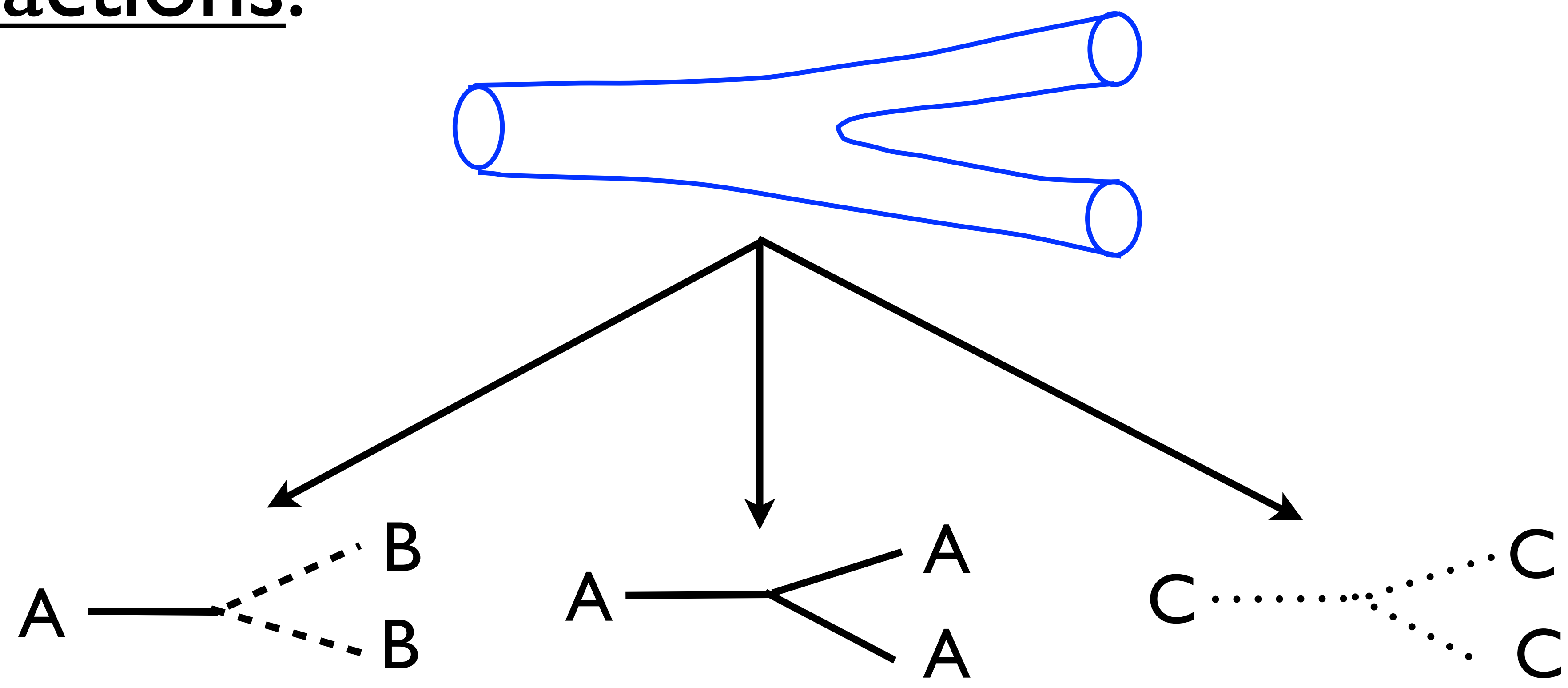

etc.

∋ gravity, Yang-Mills, Yukawa etc.

at large length scales (small energies)

→ Unified, UV-finite description of all particles and interactions

So far: No deviations from point particle behavior in particle physics experiments

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Consistent with

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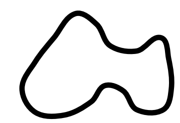
Consistent with ·

Hence:

string size $< 10^{-19}\mathrm{m} \sim (1\ \mathrm{TeV})^{-1}$



$\uparrow$

ΔL_{LHC}

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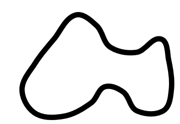

$\uparrow$

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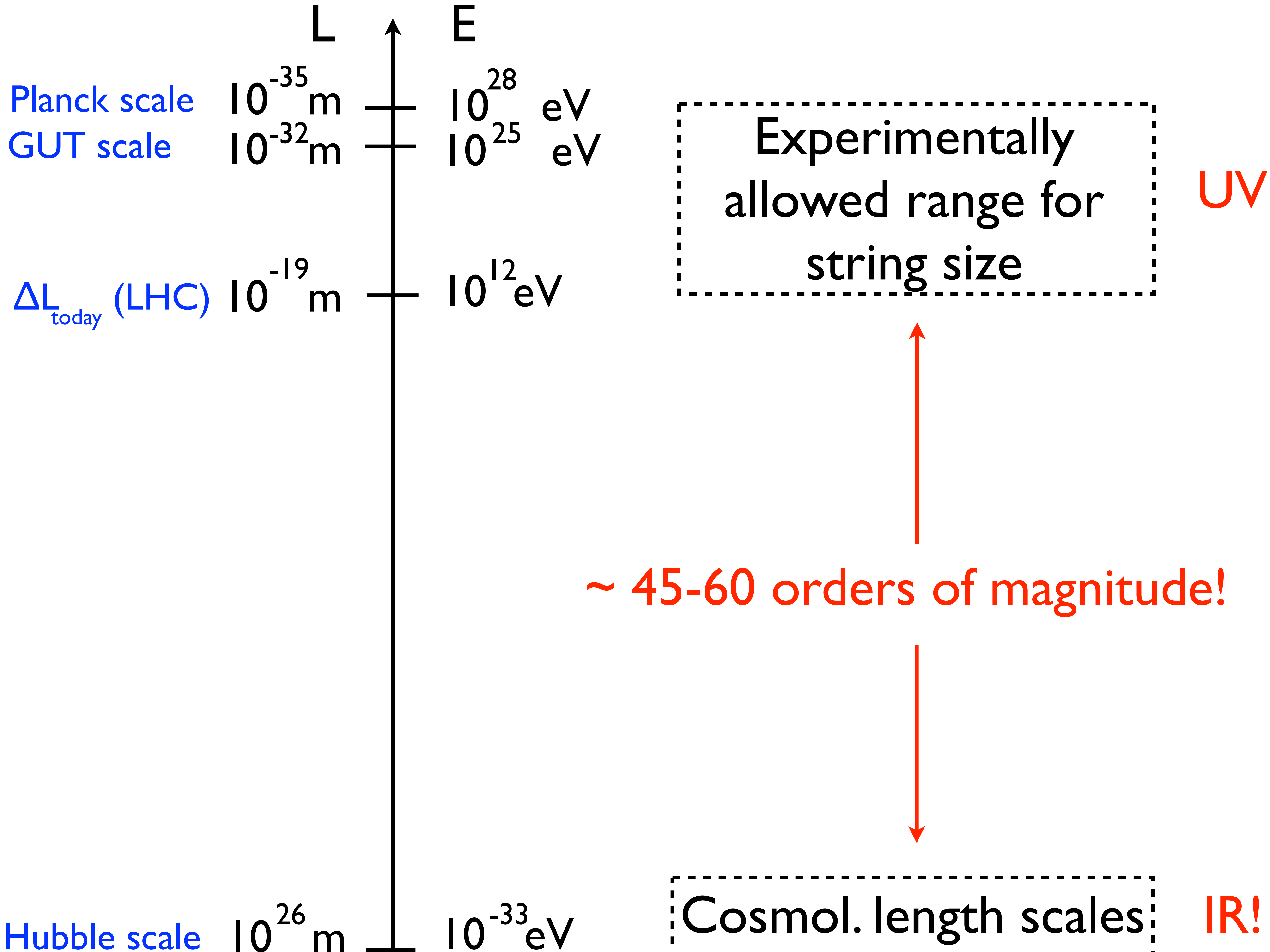
Consistent with

→ Strings must be tiny and directly only affect physics in the deep UV


L
E
Planck scale
10^{-35} m
10^{28} eV
GUT scale
10^{-32} m
10^{25} eV
ΔL_{today} (LHC)
10^{-19} m
10^{12} eV
Hubble scale
10^{26} m
10^{-33} eV
Experimentally allowed range for string size
UV!
~ 45-60 orders of magnitude!
Cosmol. length scales
IR!

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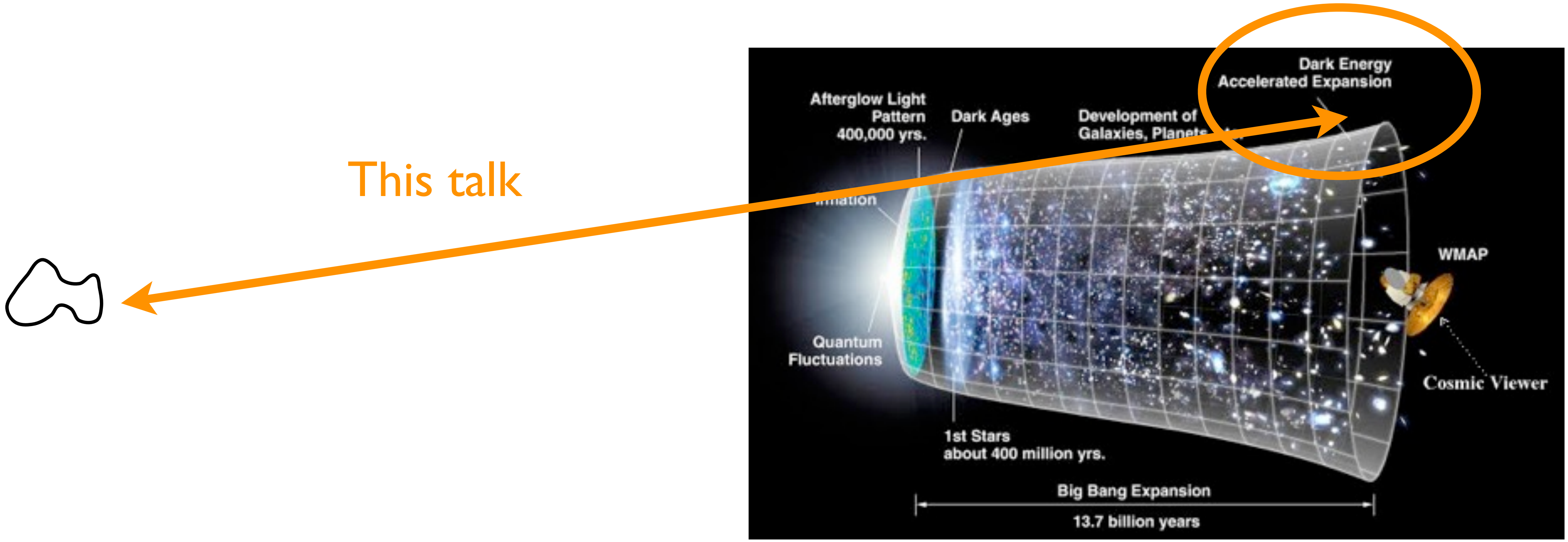

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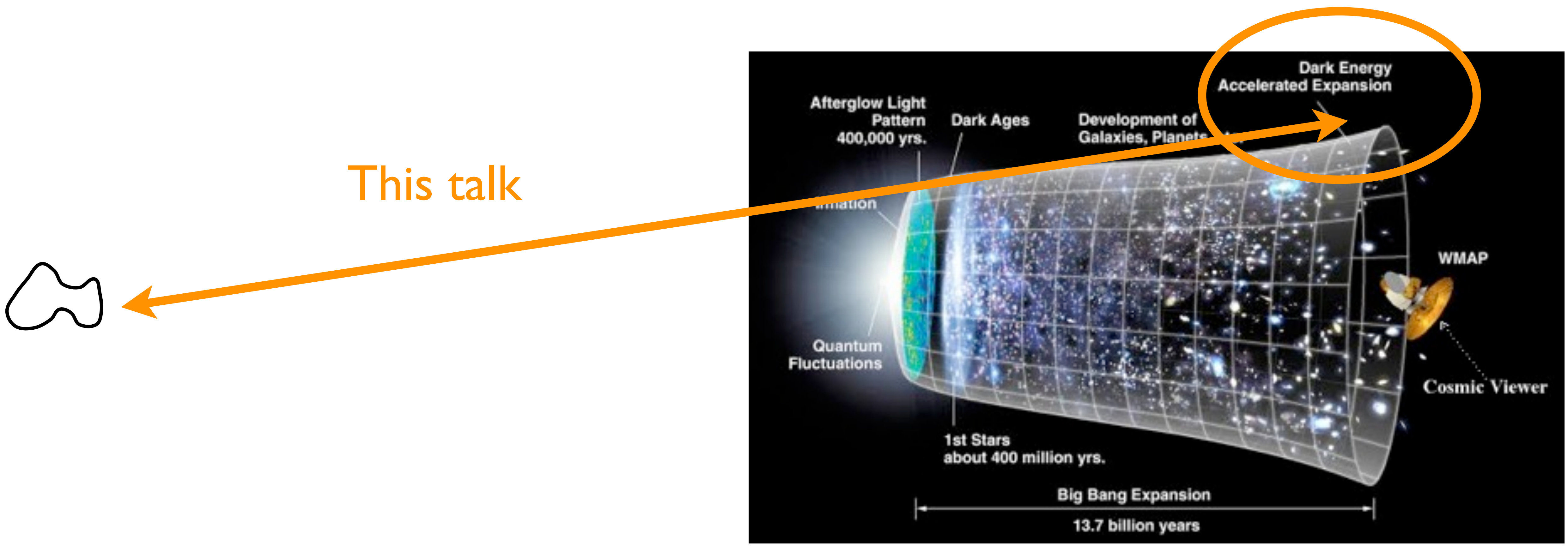

Implementing a positive cosmological constant ("dark energy") in string theory is surprisingly non-trivial!

Why is that?

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→ Standard scenario: "Compactification"

$$\mathcal{M}^{(10)} = \mathcal{M}^{(4)} \times \mathcal{M}^{(6)}$$

Large & non-compact (= our familiar 4D world)

small & compact (Size R_c)

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small & compact

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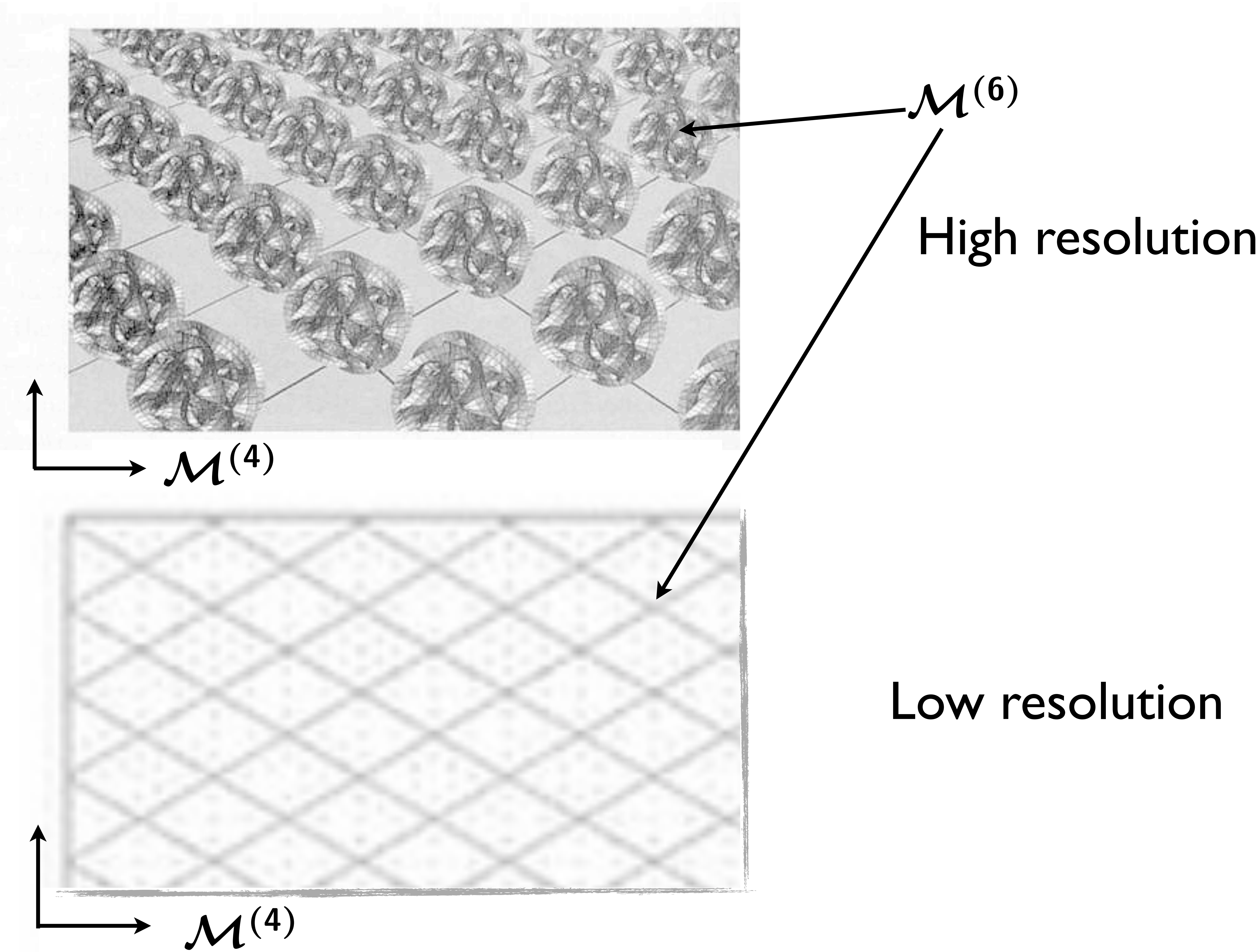
At length scales $\Delta L >> R_c$ the world looks effectively 4D



$\mathcal{M}^{(6)}$
High resolution
$\mathcal{M}^{(4)}$
Low resolution
$\mathcal{M}^{(4)}$

An important consequence of the extra dimensions:

Moduli fields

= One of the few model independent predictions of string theory

Moduli fields:

Light 4D scalar fields from higher dimensional field components:

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E.g. metric fluctuations:

M,N= 0,...,9

μ,ν = 0,1,2,3

m,n = 4,...,9

$$\delta \mathbf{g}_{\mathrm{MN}} \longrightarrow \delta \mathbf{g}_{\mu\nu}\ ,\ \delta \mathbf{g}_{\mu \mathrm{m}}\ ,\ \delta \mathbf{g}_{\mathrm{mn}}$$

- $\delta \mathbf{g}_{\mu\nu}$ → 4D Metric
- $\delta \mathbf{g}_{\mu \mathrm{m}}$ → 4D Vector fields
- $\delta \mathbf{g}_{\mathrm{mn}}$ → 4D Scalars

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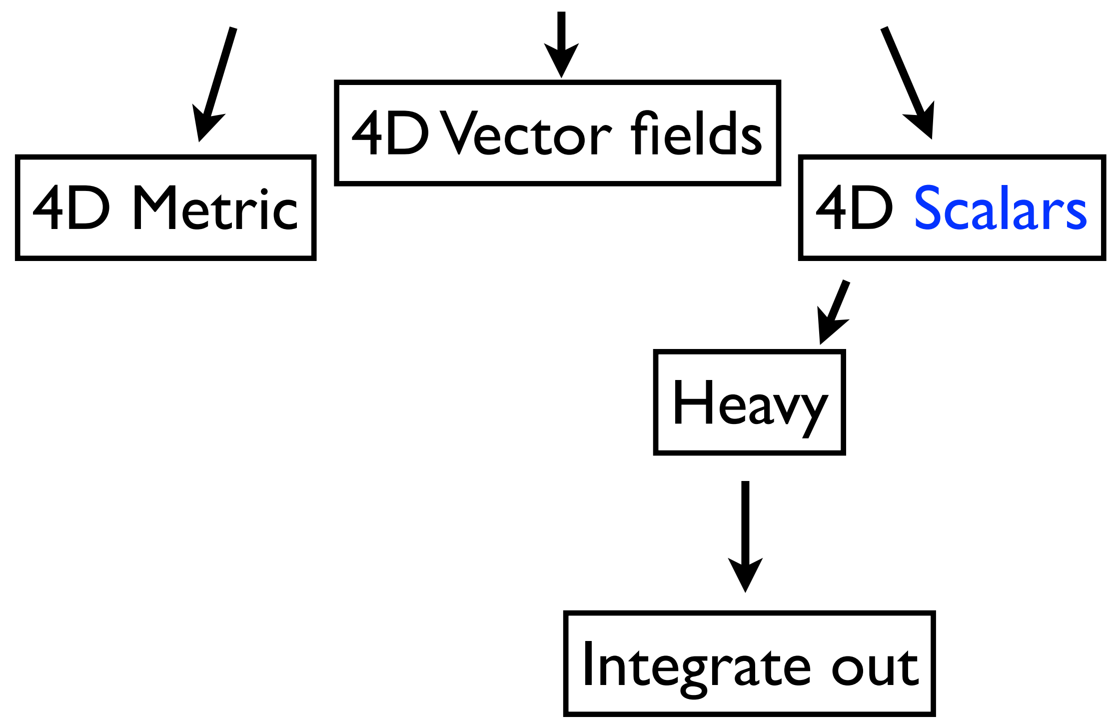

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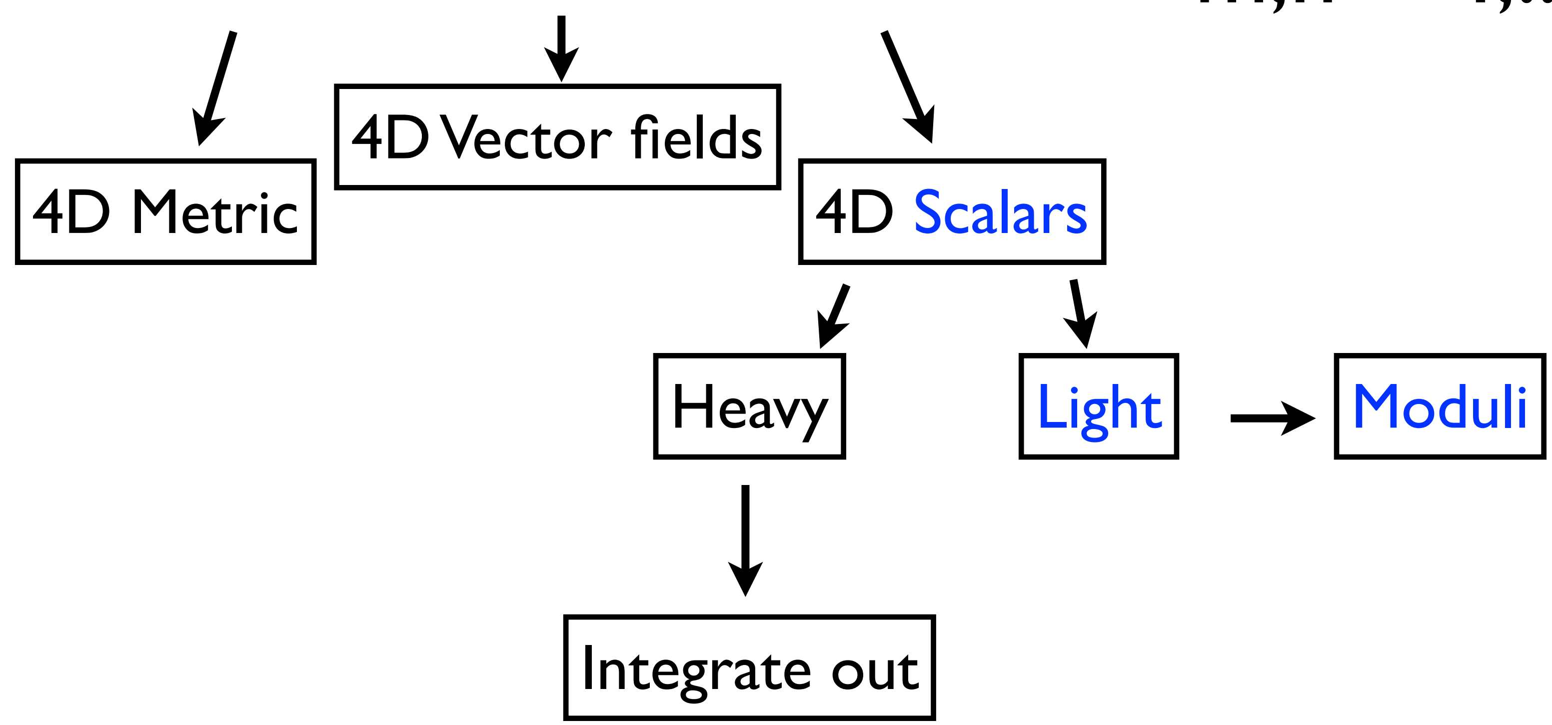

- Moduli vevs parameterize background deformations that cost no/little energy

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- Light moduli cause phenomenological problems

(5th force, varying fund. constants, BBN, overclosure,...)

Avoided for $\mathbf{M^2_{mod} \gtrsim (30TeV)^2}$

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Topic of this talk

Rest of the talk

2. de Sitter vacua in string theory

3. Computational control and classical dS vacua

4. The stability problem

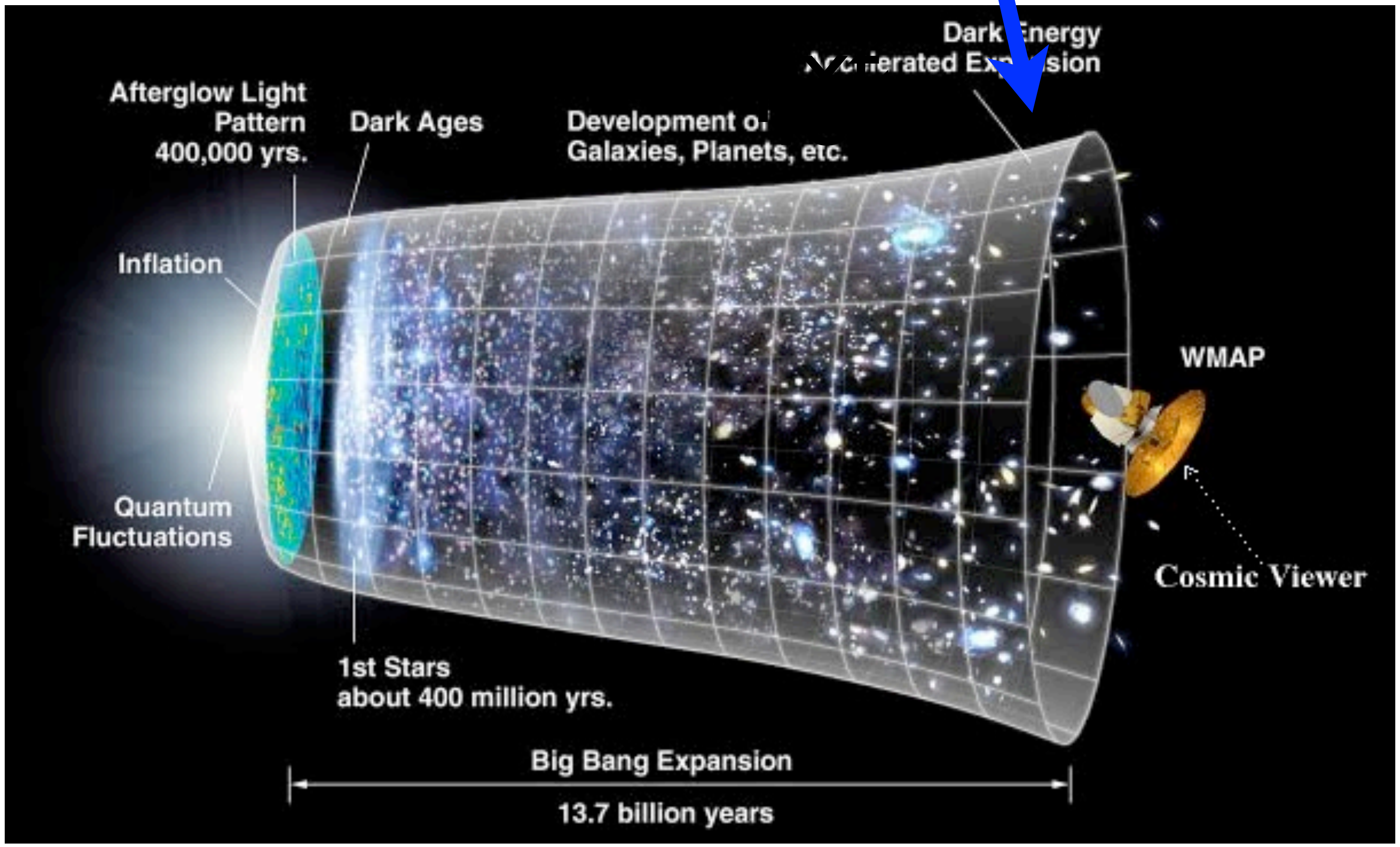
5. Conclusions

2. de Sitter vacua in string theory

Our assumption:

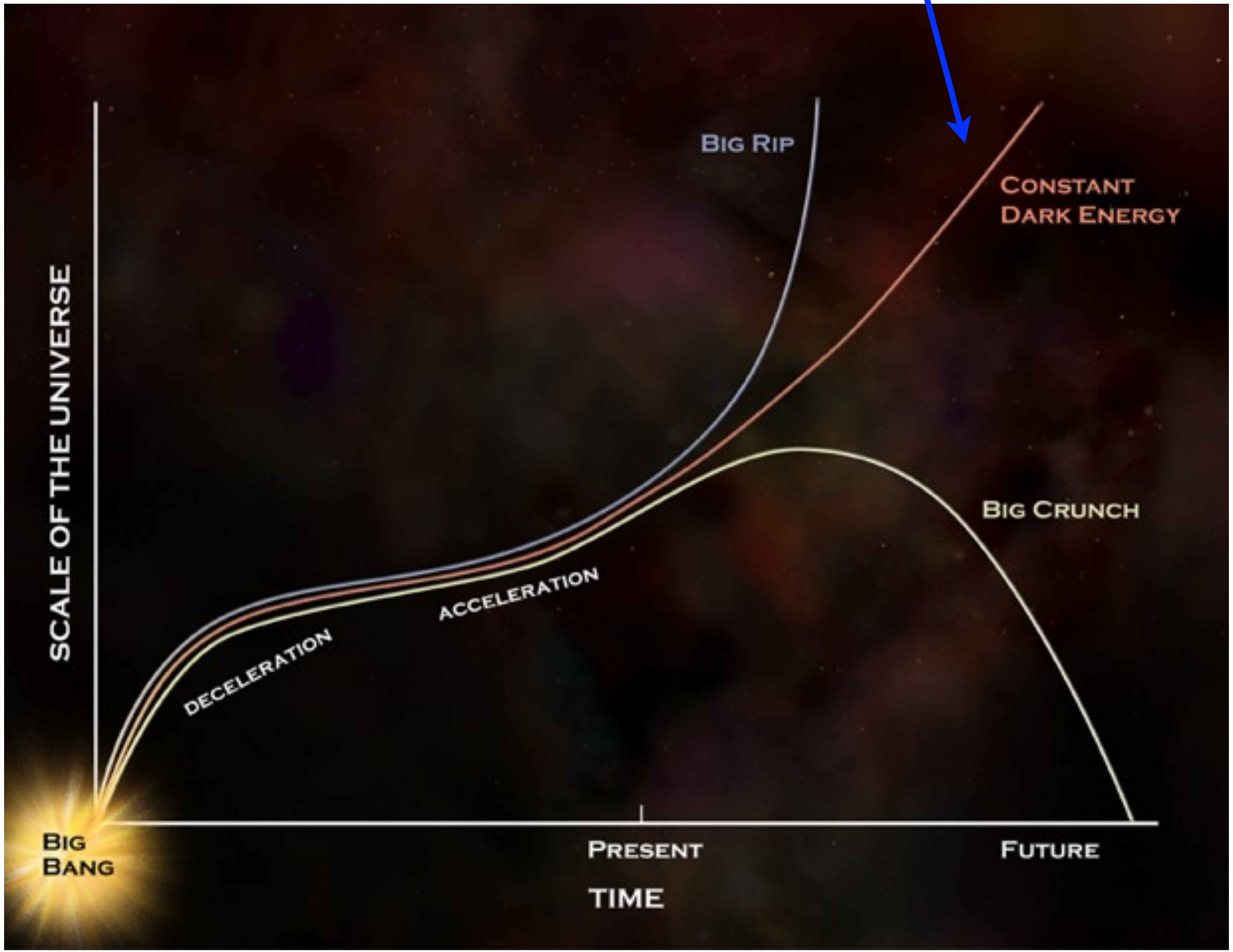
Today's accelerated expansion of the Universe is due to a positive vacuum energy density

$$\rho_{\text{vac}} \sim (1\,\text{meV})^4 > 0$$



For $\rho_{vac} = \textbf{const.}$: $\rho_{vac} \sim \Lambda > 0$ (cosmological constant)

⇒ Universe asymptotes 4D de Sitter spacetime



$\mathbf{a(t) = e^{\kappa t}}$

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Main focus of this talk

A priori two issues:

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Find a consistent and perturbatively stable compactification of string theory of the form

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- Connection to familiar 4D physics less immediate

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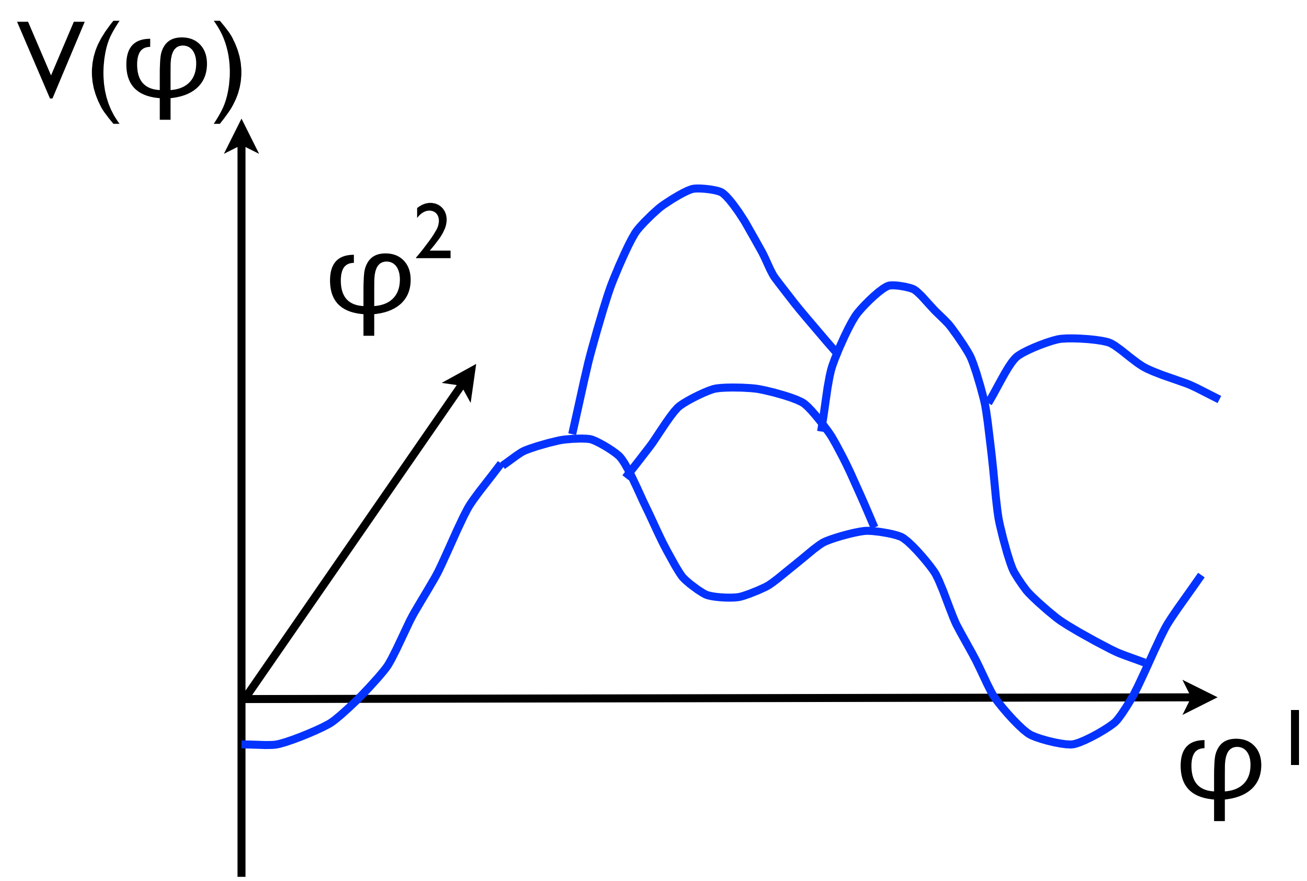

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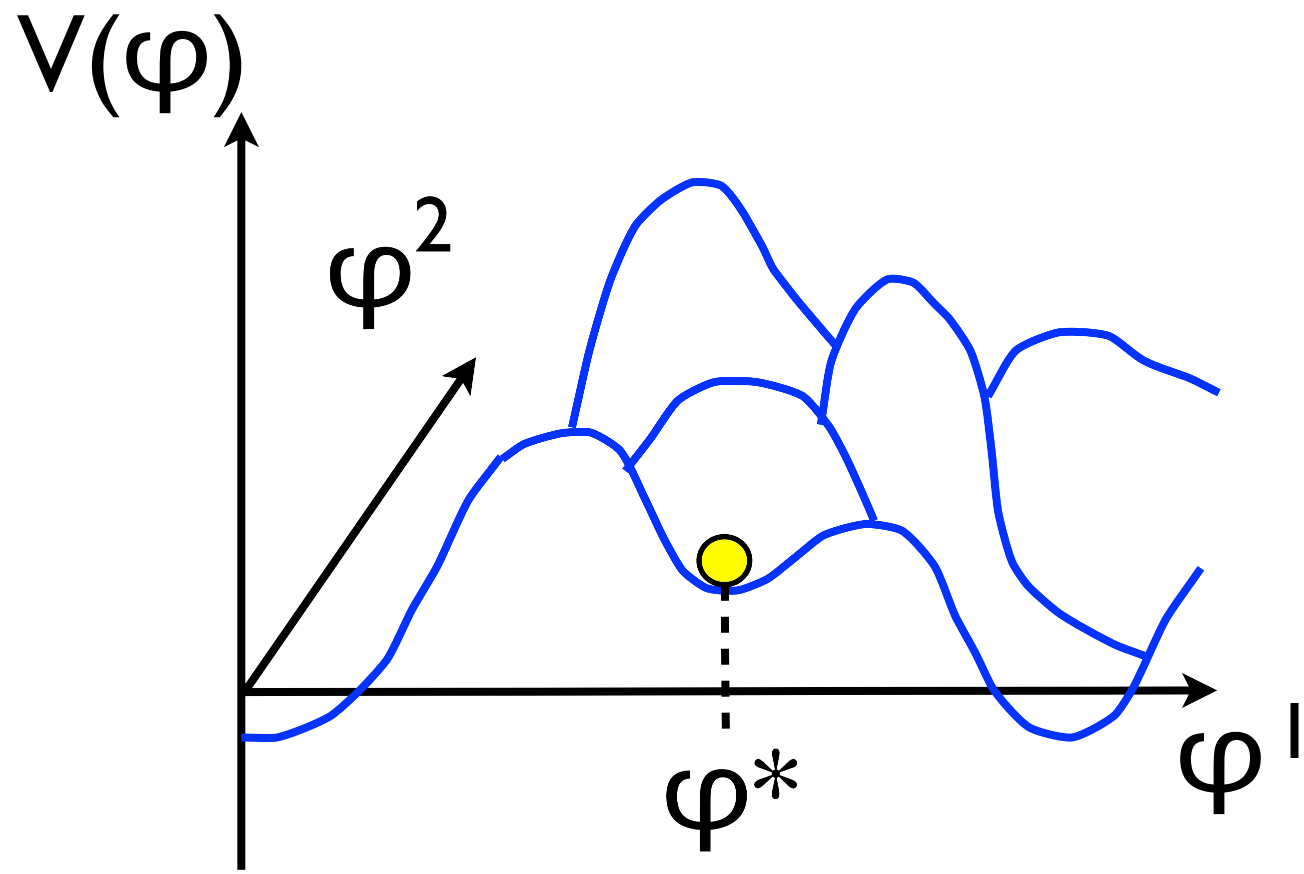

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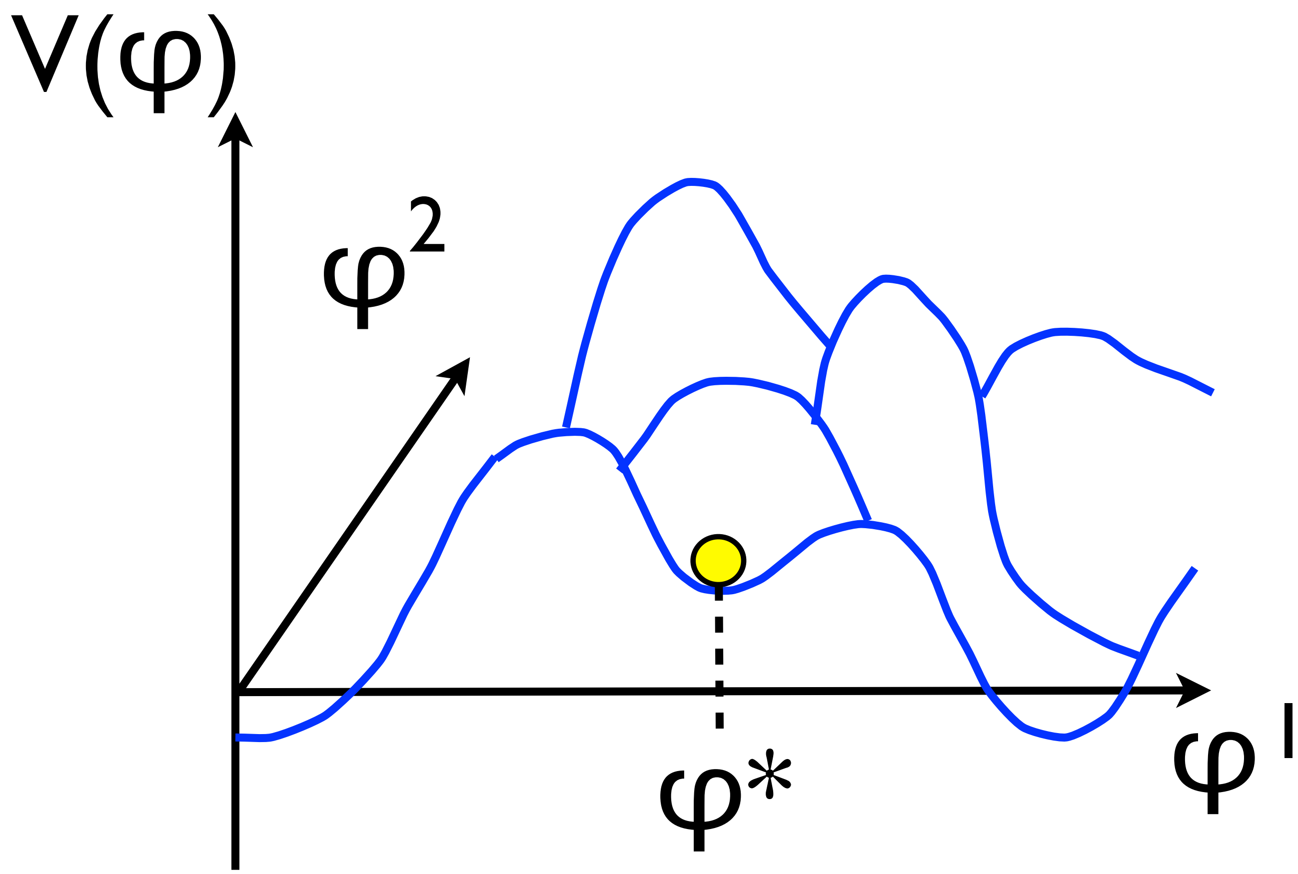

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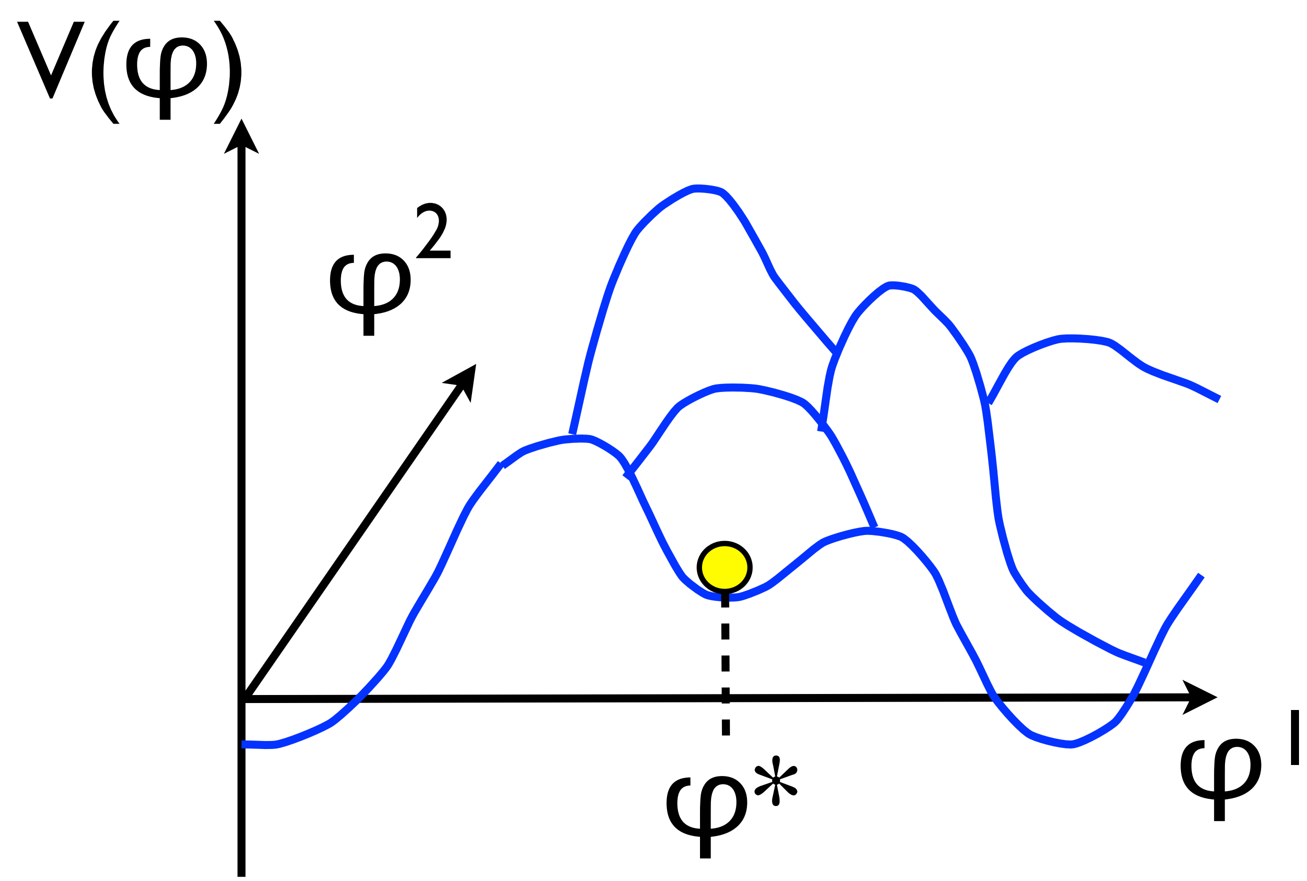

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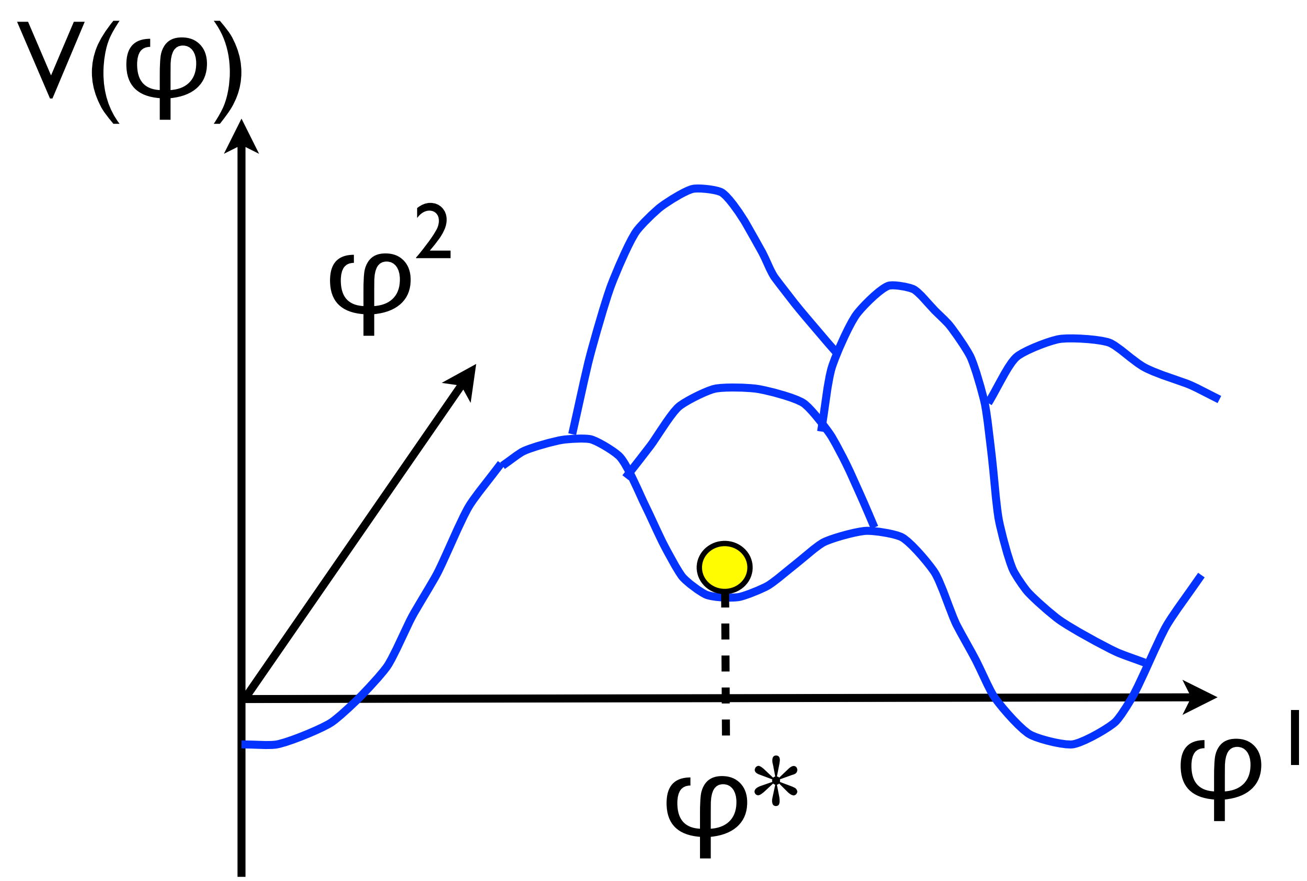

Goal: A local minimum at $V(\varphi^*) > 0$ ← Main topic of this talk (surprisingly difficult)

Ideally: $V(\varphi^*) = \rho_{vac} \approx (1\ \text{meV})^4$ $\mathbf{M_{moduli}} > \mathcal{O}(\mathbf{30\ TeV})$

3. Computational control and classical de Sitter vacua

How does one compute $V(\varphi)$?

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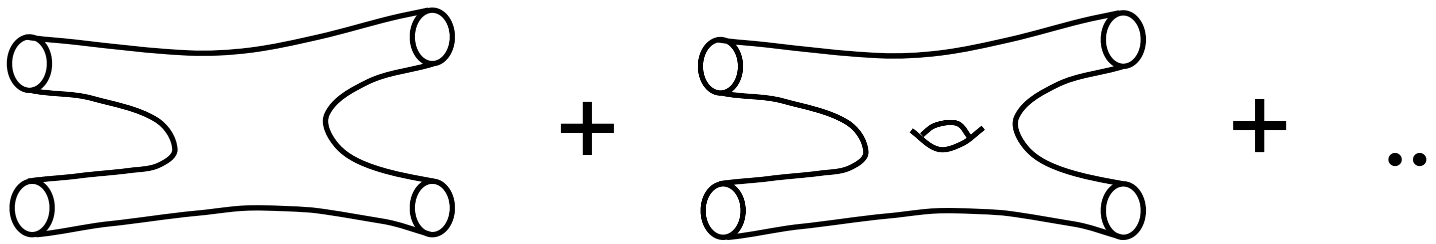
g_s (string coupling) $\leftrightarrow$ Loop expansion



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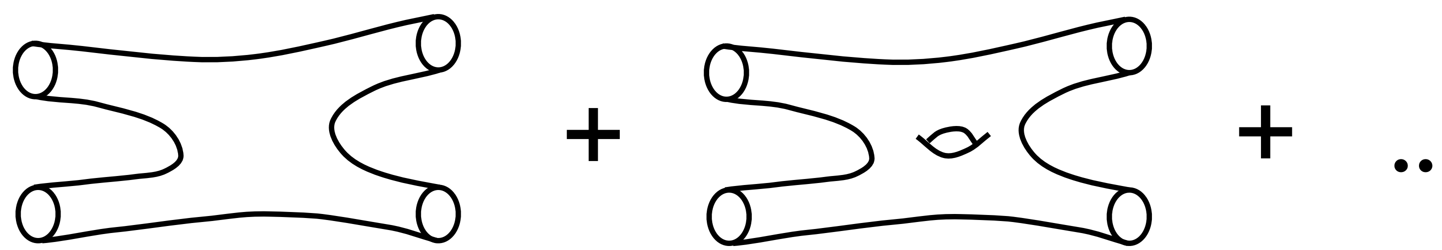
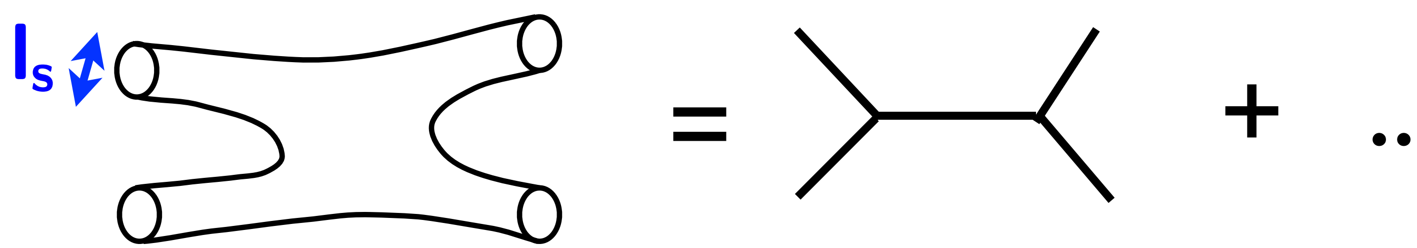


$\sim g_s^{2(L-1)}$

$\alpha' = l_s^2$ =(string length)^2 $\leftrightarrow$ Deviation from point particle limit



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Classical 10D supergravity

$$S_{sugra} = \int d^{10}x \sqrt{g}\, R + \ldots$$

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α´ corrections →

g_s corrections ↓

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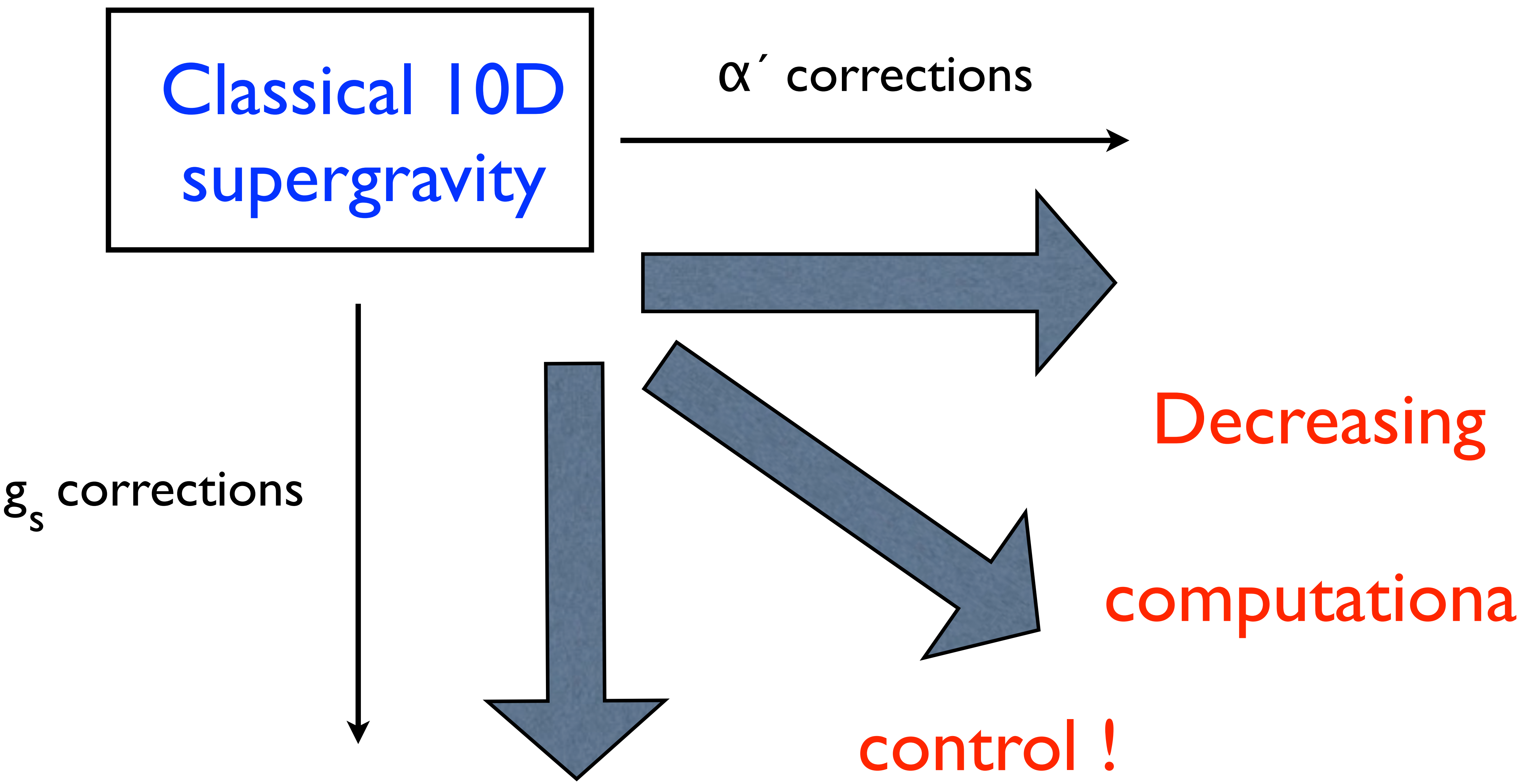

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Classical 10D supergravity

$$S_{sugra} = \int d^{10}x \sqrt{g}\, R + \ldots$$

↑

Natural first attempt:
Try to find de Sitter vacua using only this!

$\Rightarrow$ "Classical" de Sitter vacua

Unfortunately, there is a serious problem!

$\exists$ powerful no-go theorems against de Sitter compactifications in the supergravity approximation !

E.g.: Gibbons (1984);
de Wit, Smit, Hari Dass (1987)
Maldacena, Nuñez (2000)
Steinhardt, Wesley (2008)

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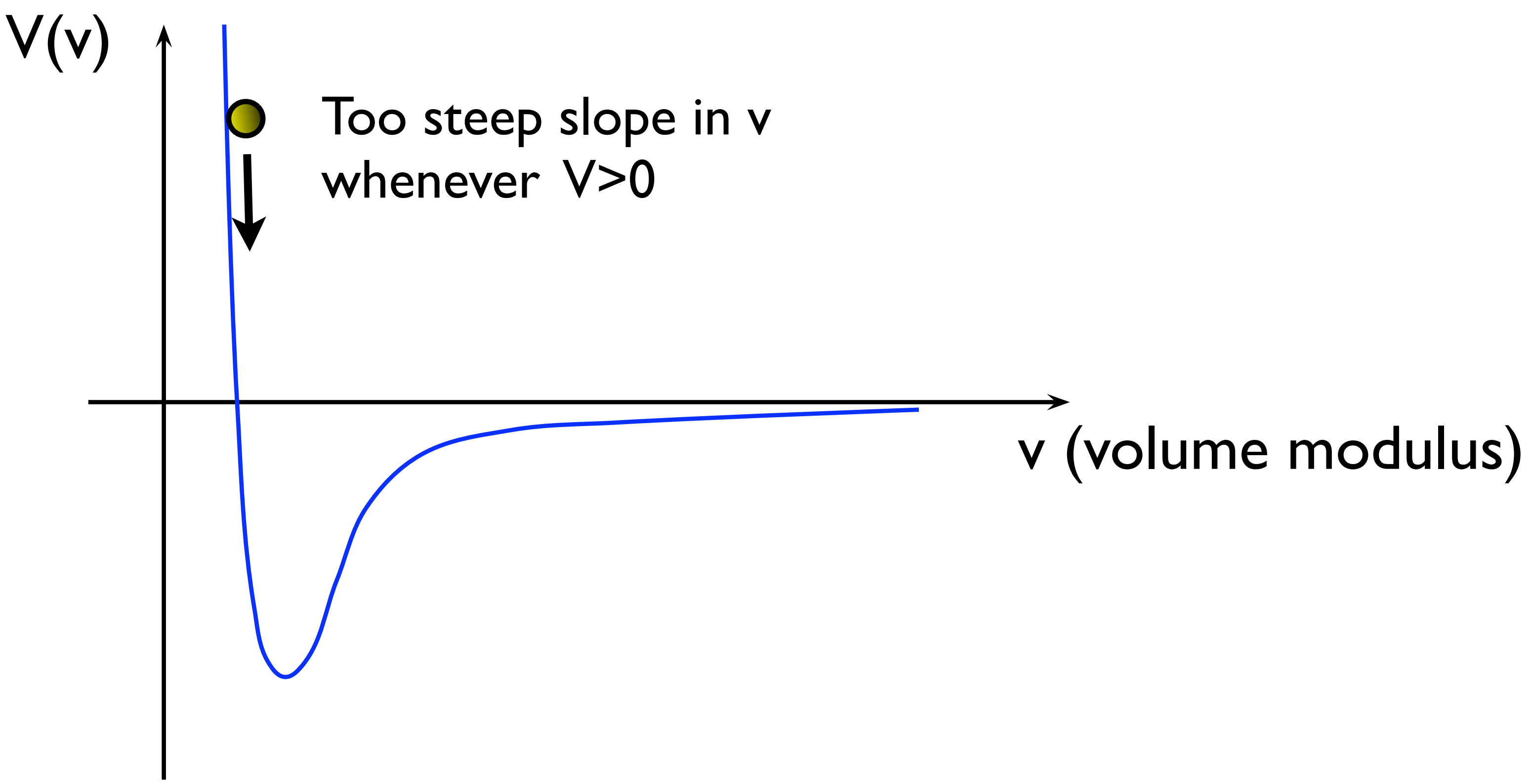
Simplest version:

If null energy condition (NEC) is satisfied, i.e. if

$$\mathsf{T}_{\mathsf{MN}}\, \mathbf{n}^{\mathsf{M}} \mathbf{n}^{\mathsf{N}} \geq 0, \quad \mathbf{n} \cdot \mathbf{n} = 0$$

$\mathbf{dS_4} \times_{\mathsf{w}} \mathcal{M}^{(6)}$ is not a solution of the supergravity approximation!

Manifestation in 4D field theory:



⇒ No de Sitter vacua possible (and no slow roll inflation)

Two ways out: (or a combination thereof)

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(see below)

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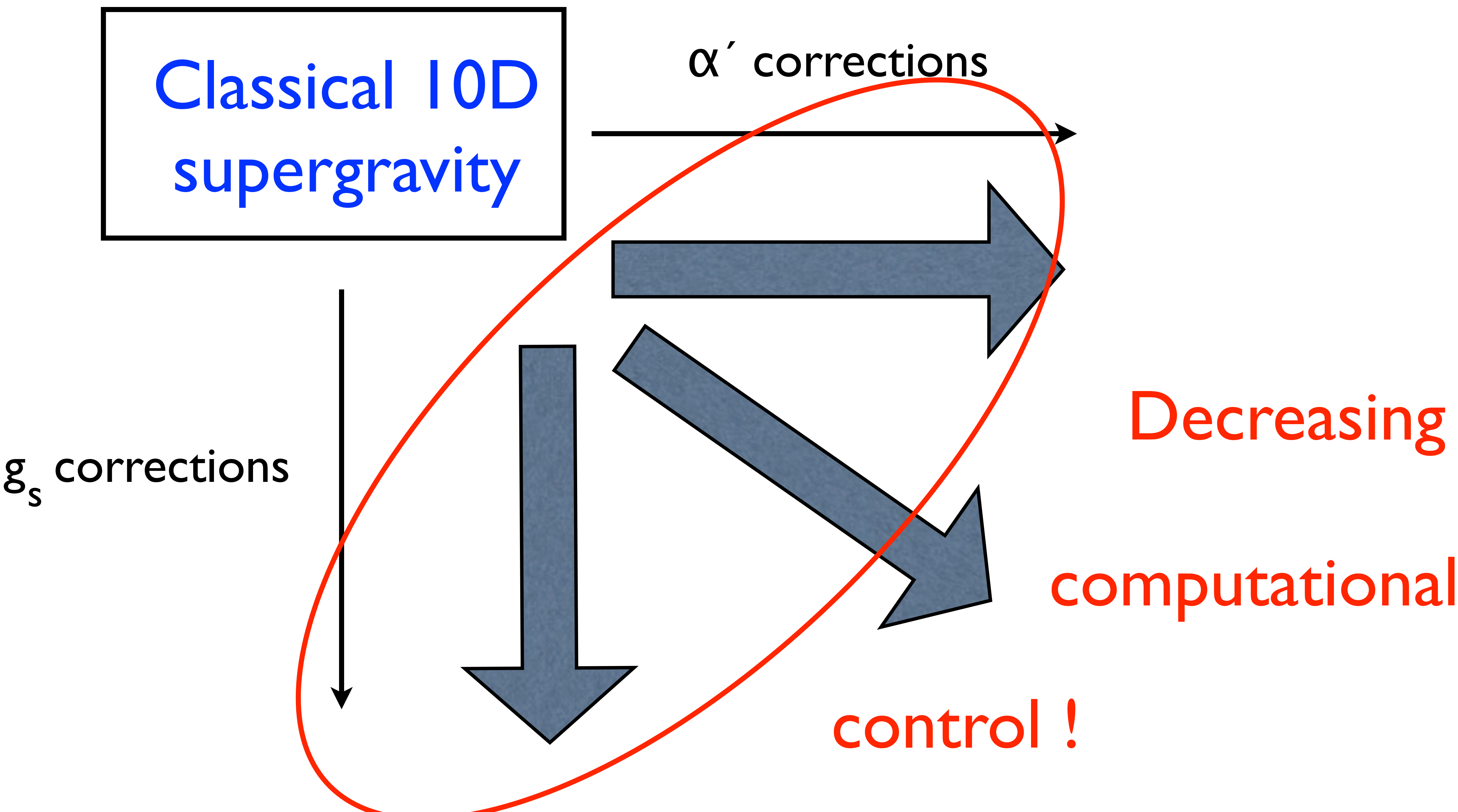

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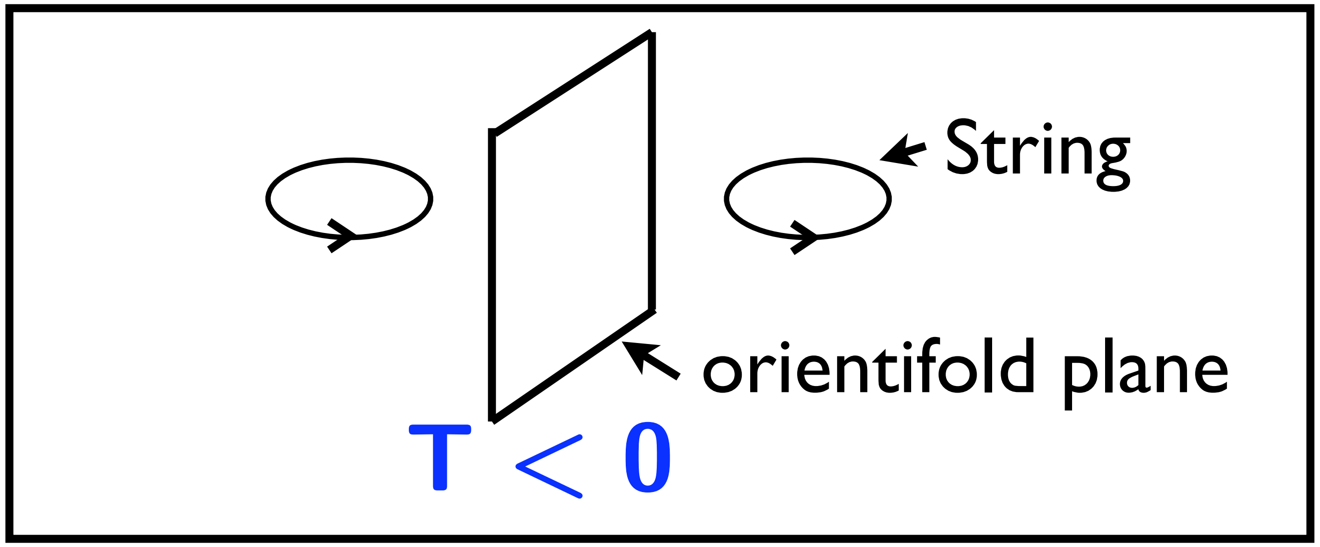

$\Rightarrow$ Try:

Classical supergravity + orientifold planes

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One finds: New no-go's unless $\int \sqrt{g}\, R^{(6)} < 0$

Hertzberg, Kachru, Taylor, Tegmark (2007)
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(negative (integrated) internal curvature)

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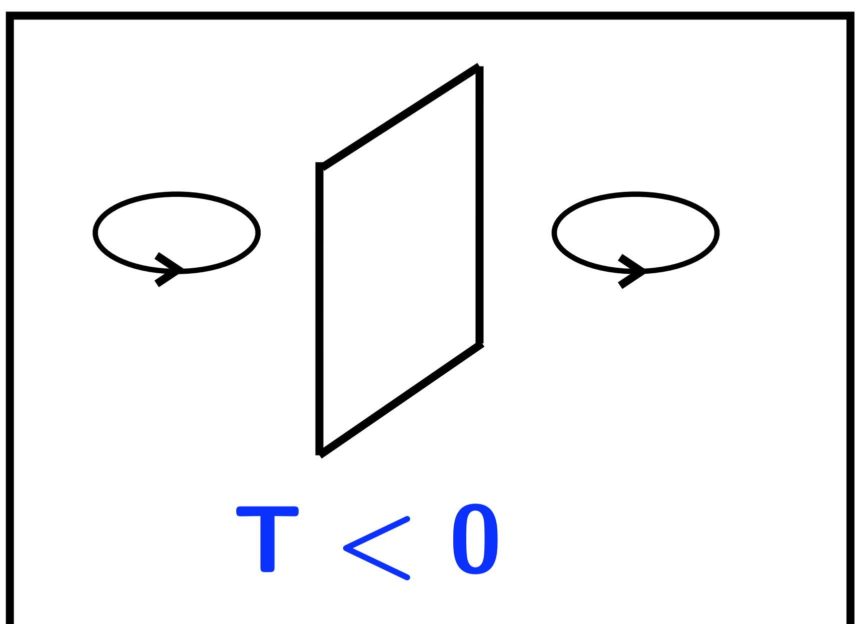

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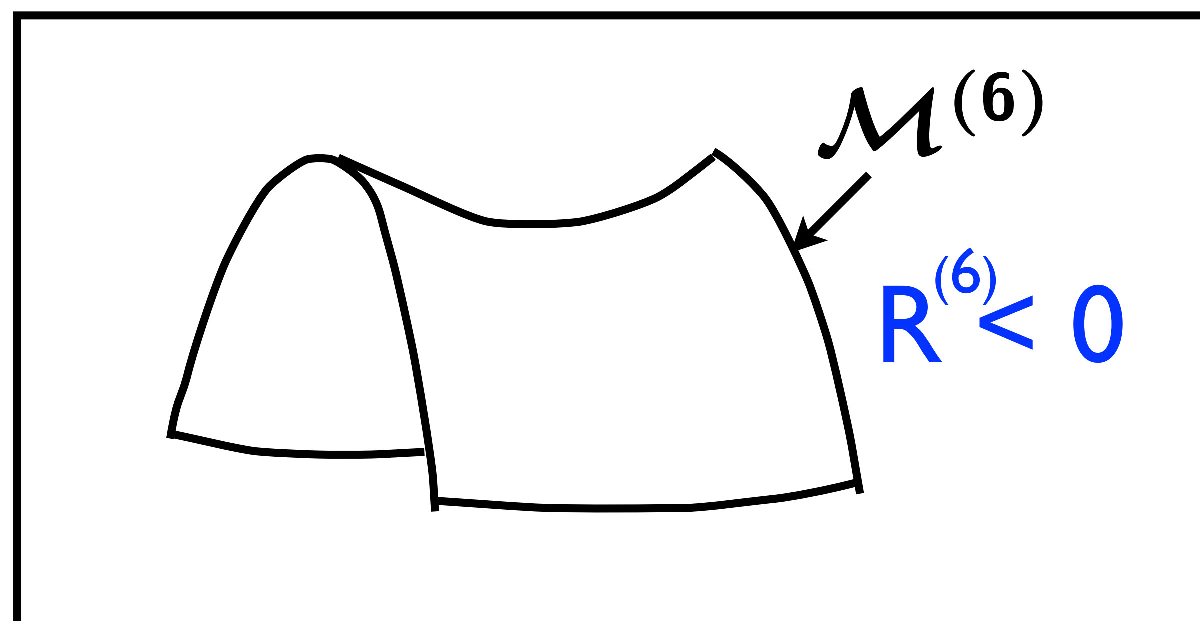

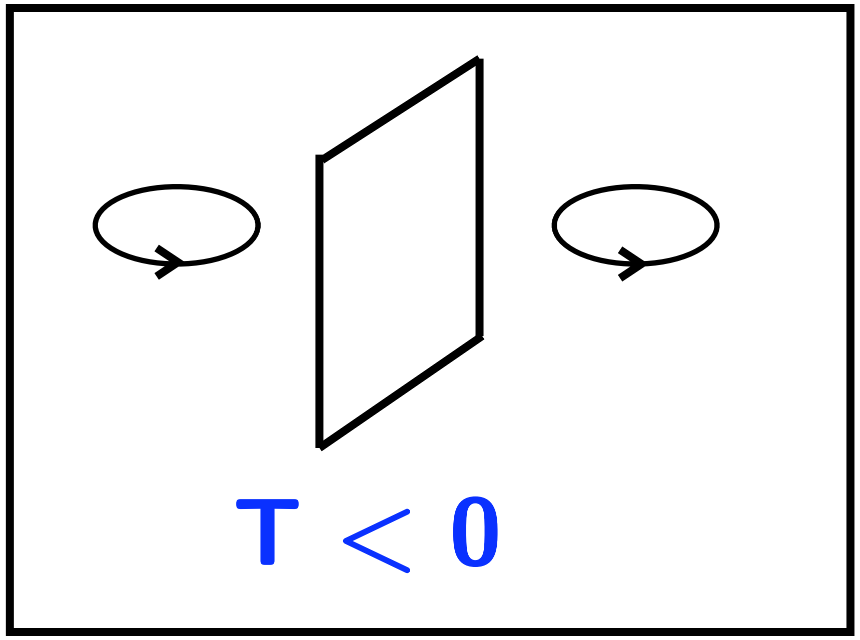

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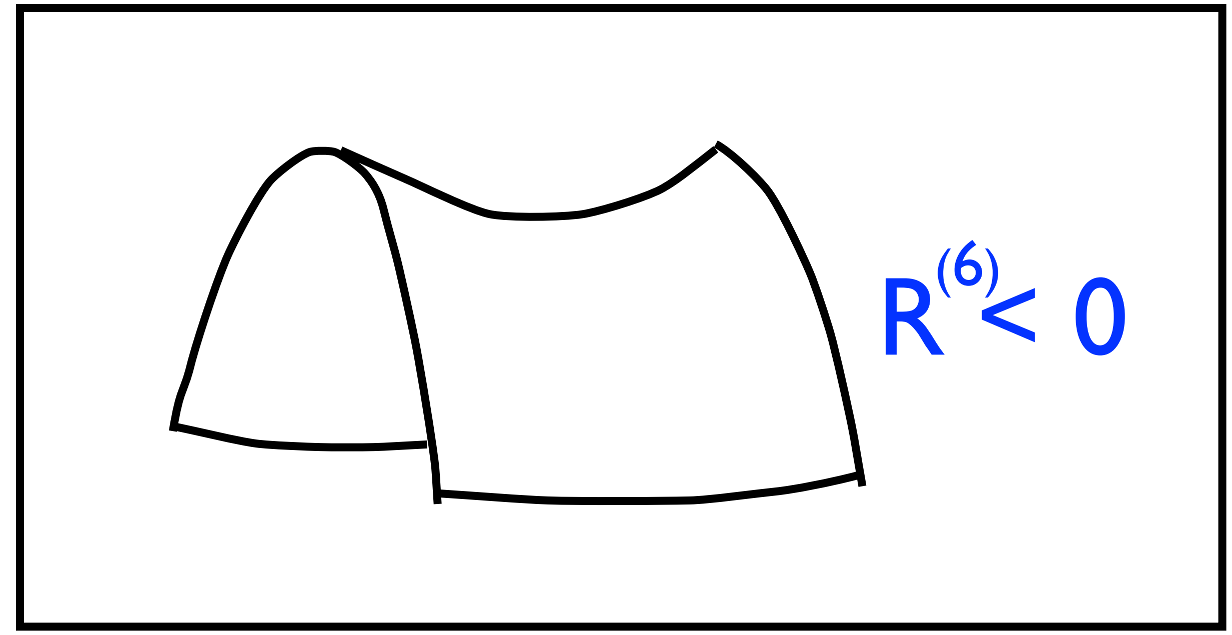
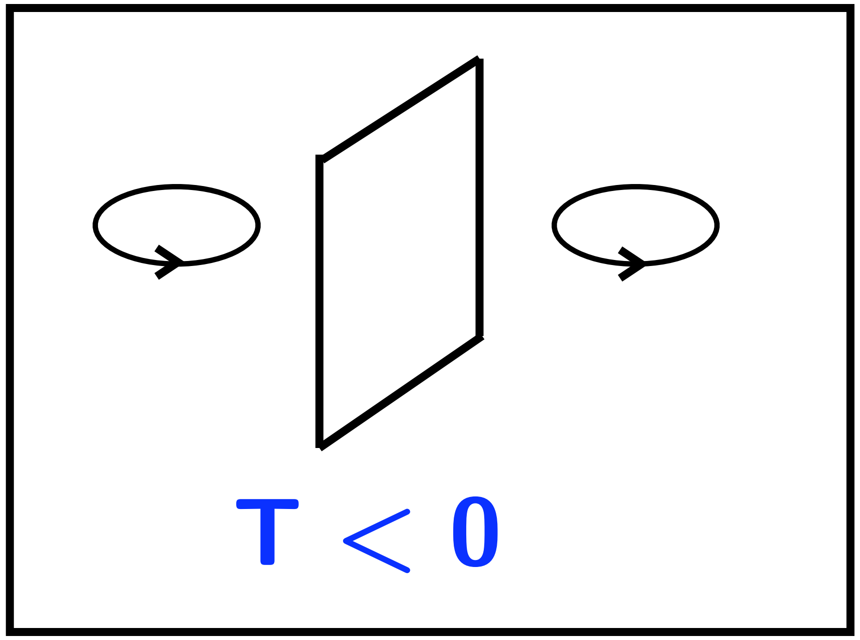


O-planes

Negative internal curvature

There are two problems with these ingredients



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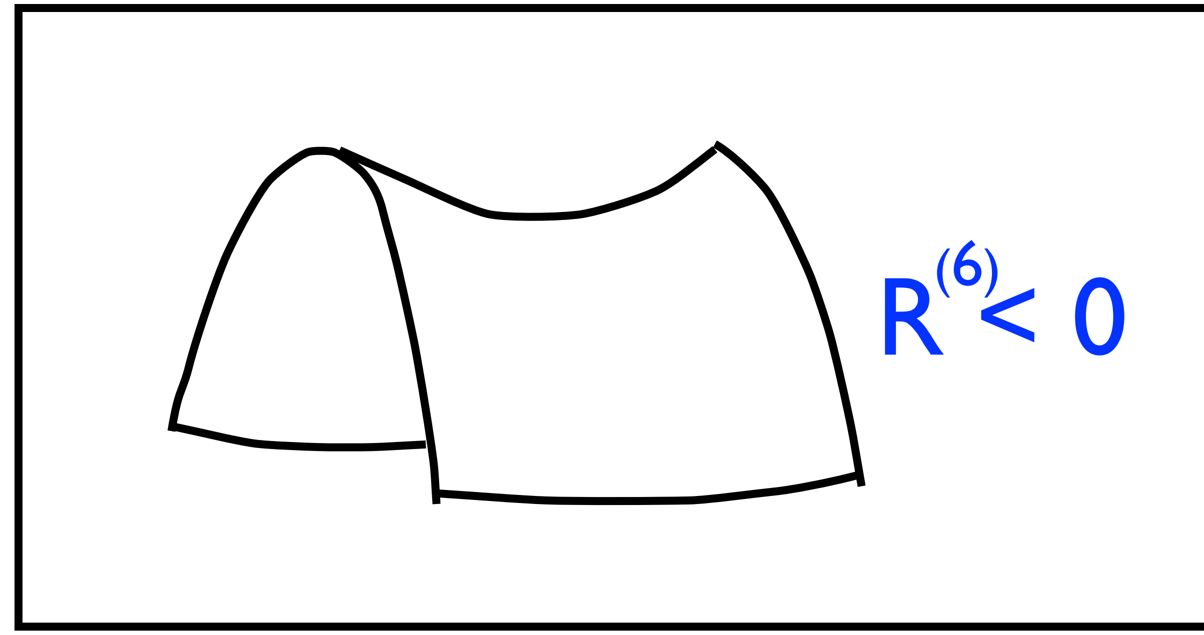

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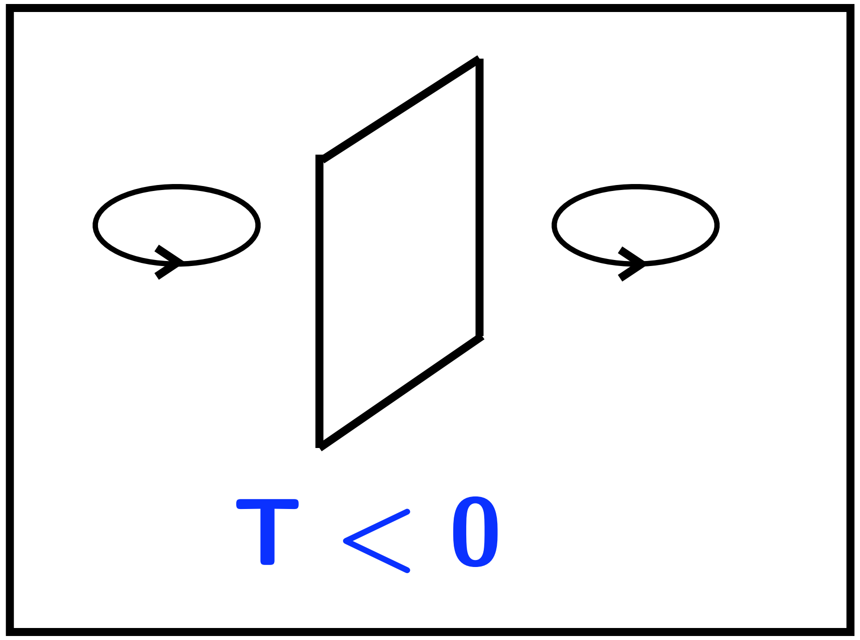

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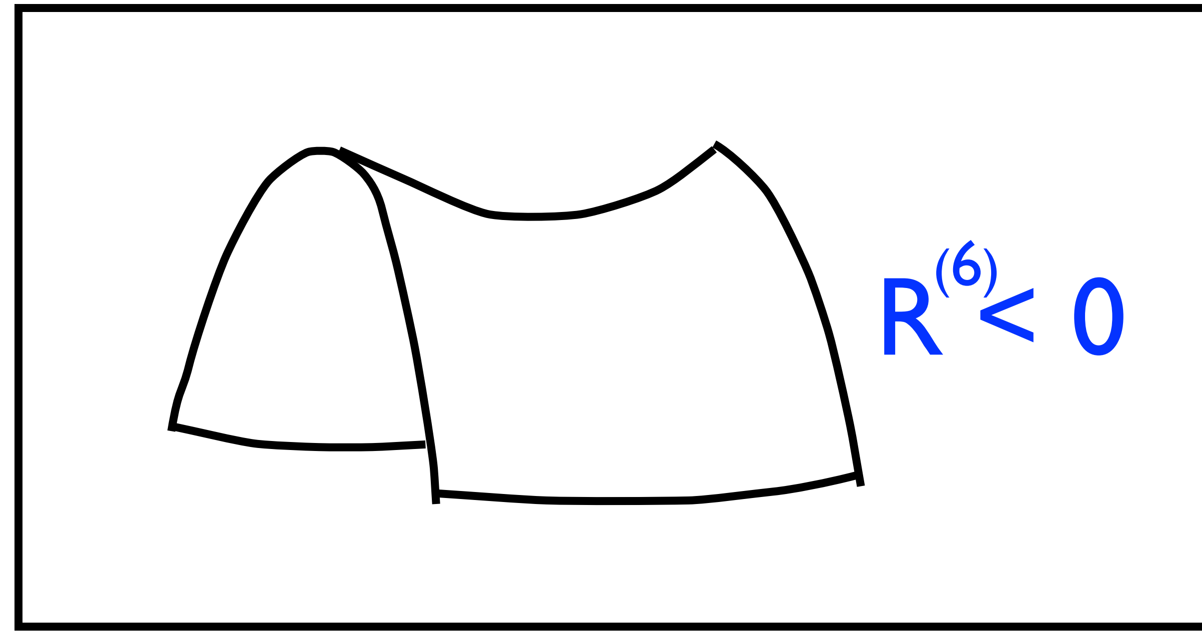

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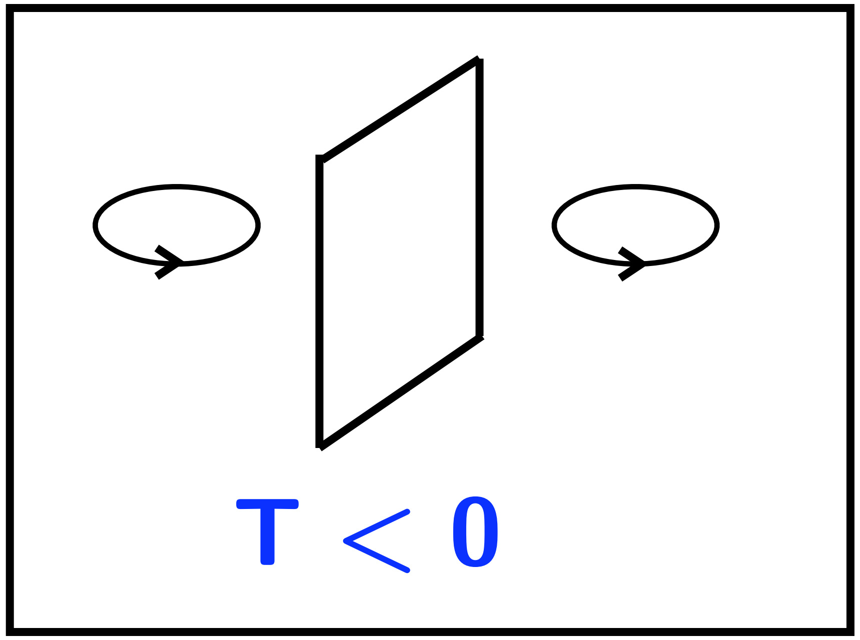
Localized energy and charge density on O-plane



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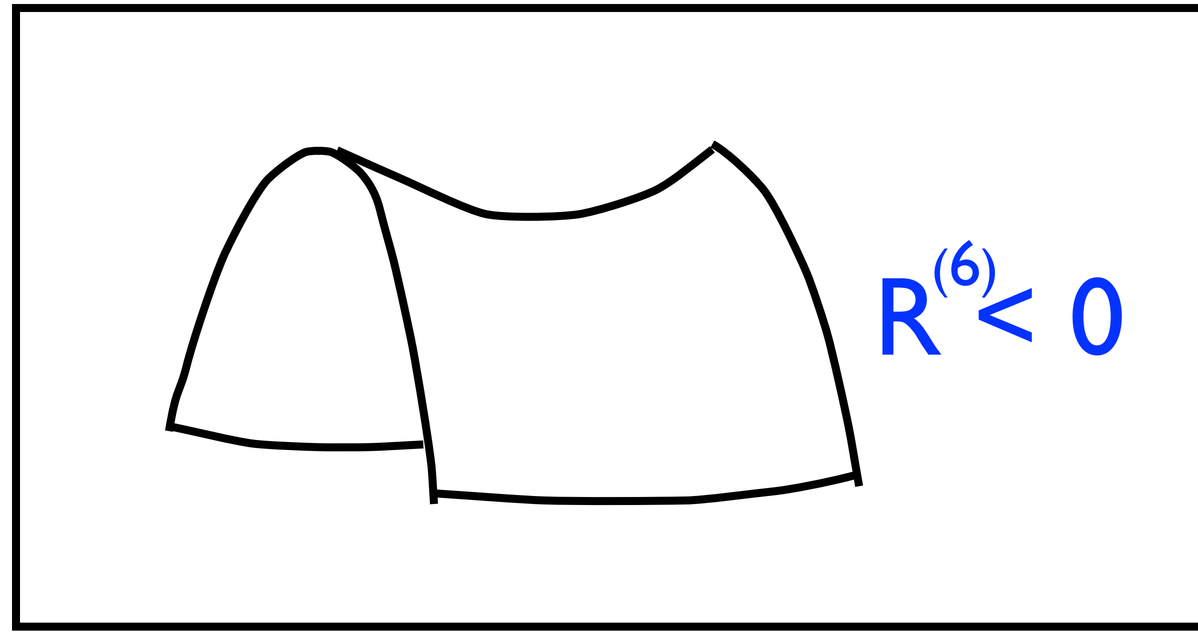


O-planes

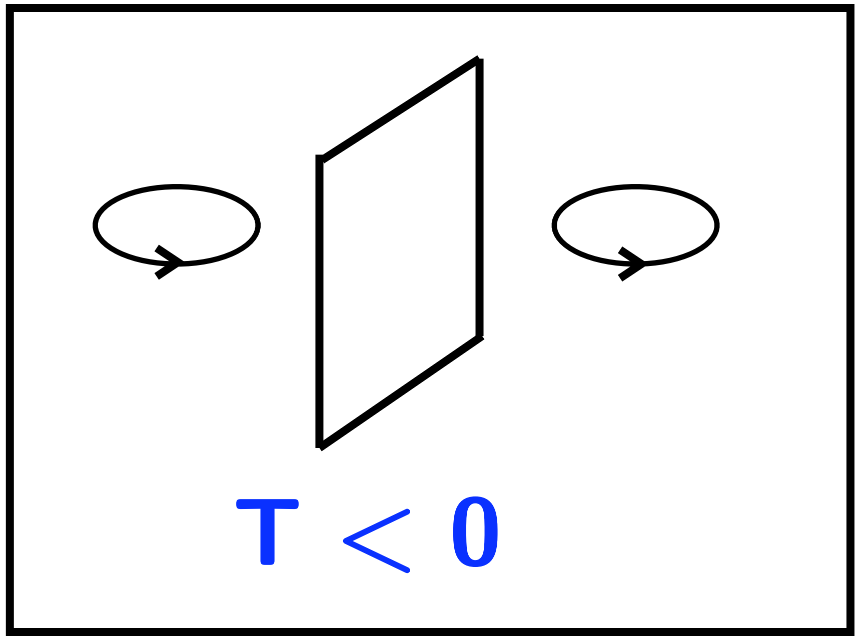
Negative internal curvature

↓

Localized energy and charge density on O-plane

↓

Complicated dynamical back-reaction



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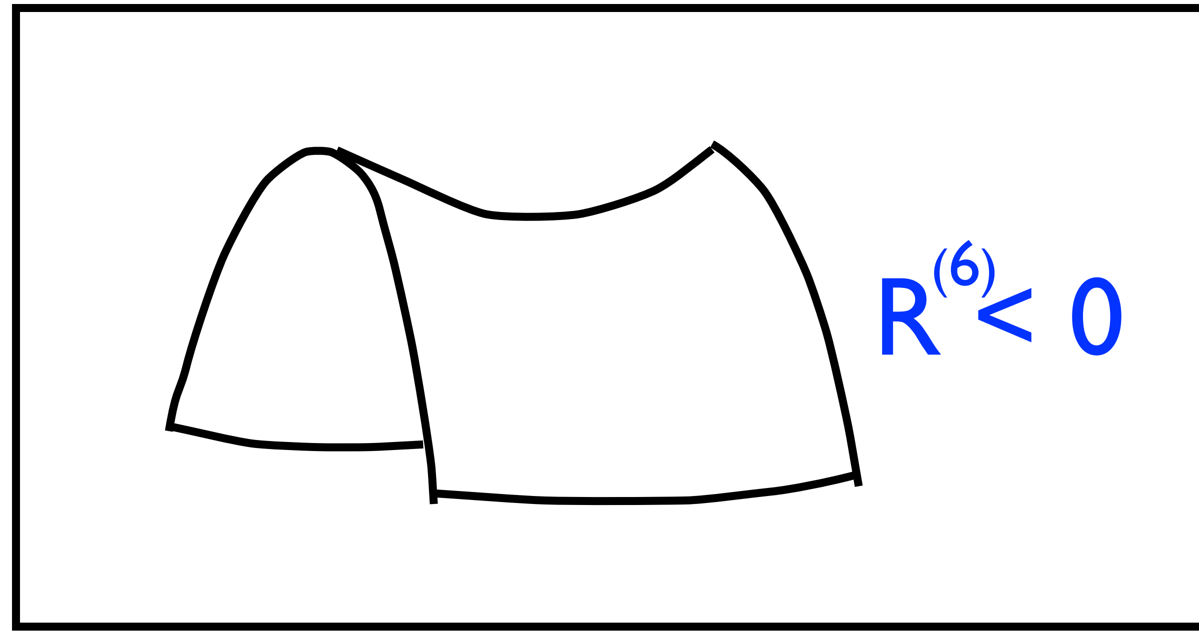

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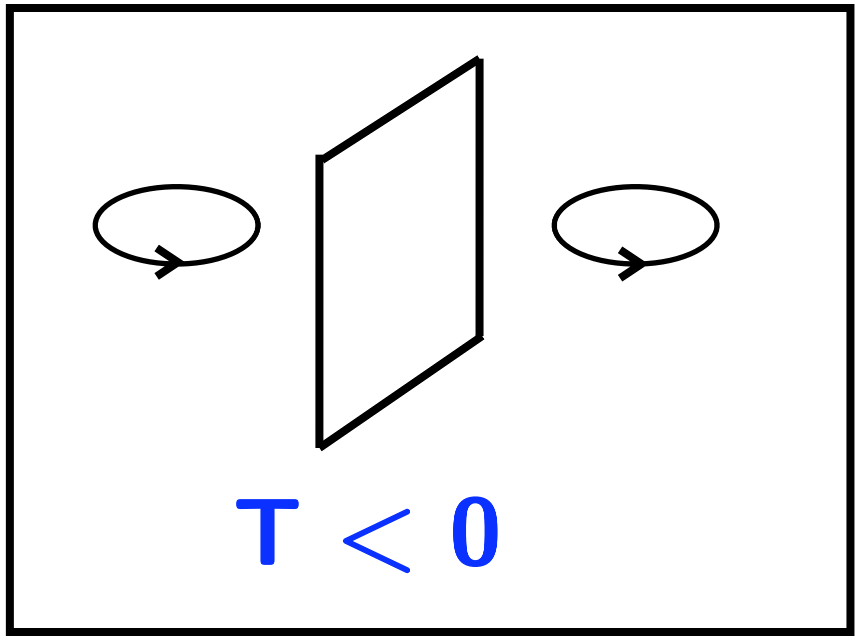

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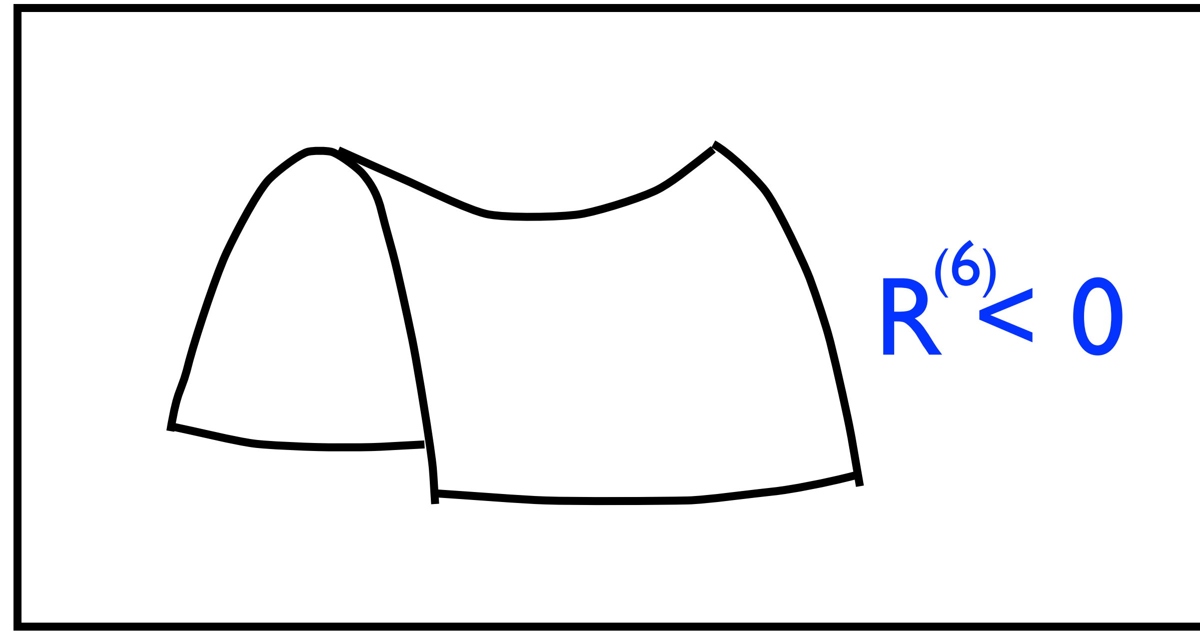

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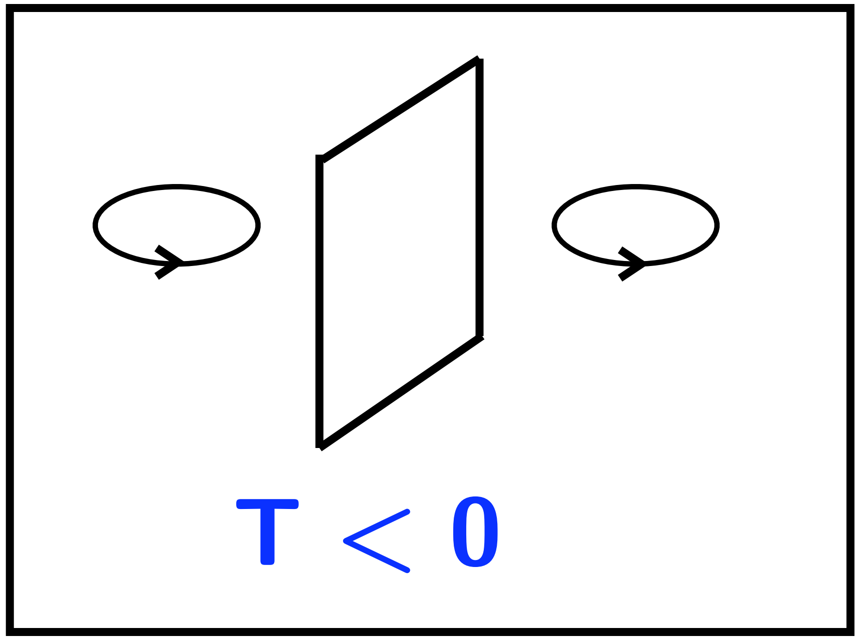

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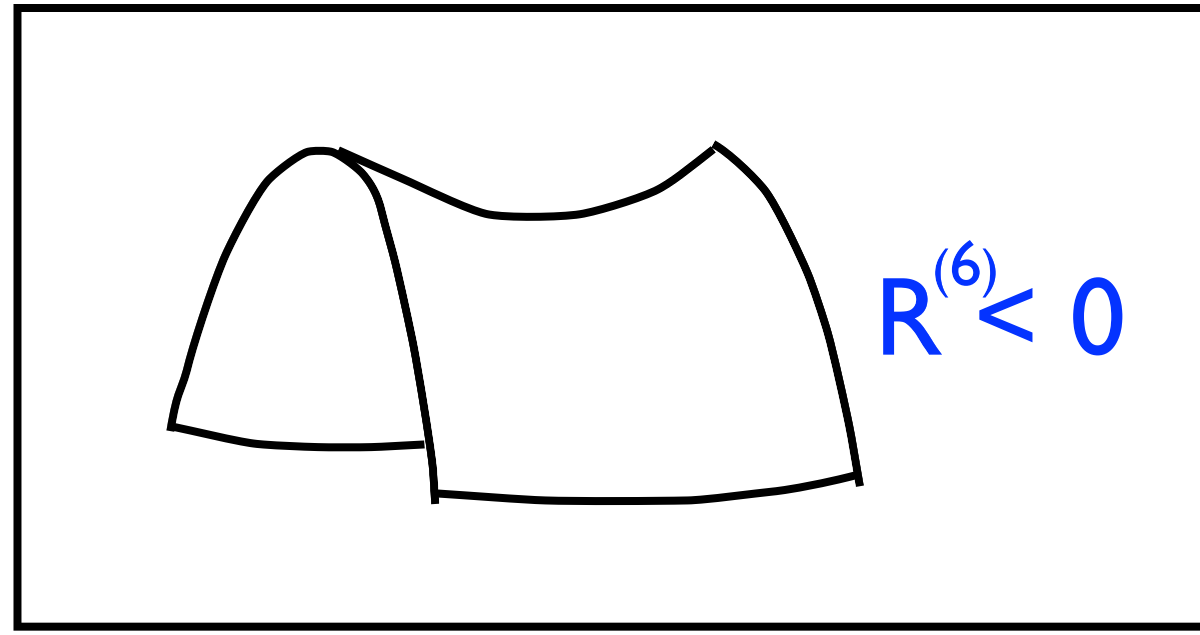

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$\mathcal{L}_{\text{eff}}^{(4D)} = ??$

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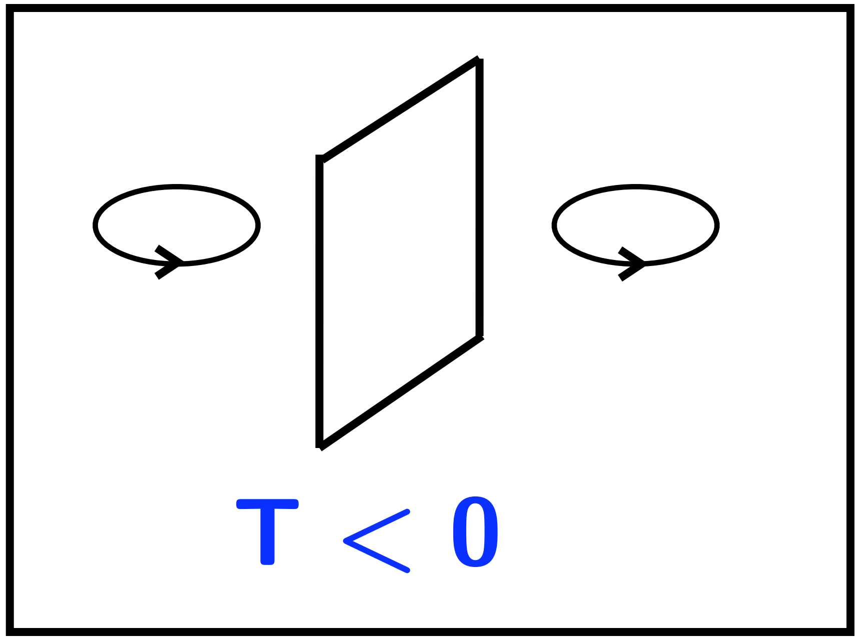

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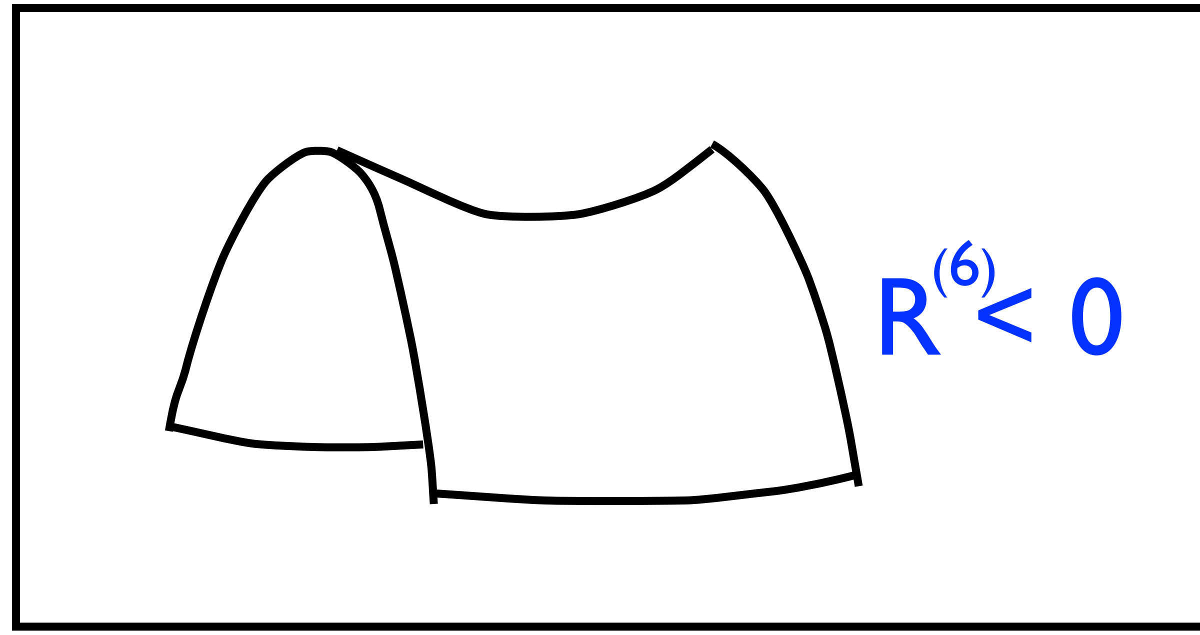

O-planes → Localized energy and charge density on O-plane → Complicated dynamical back-reaction

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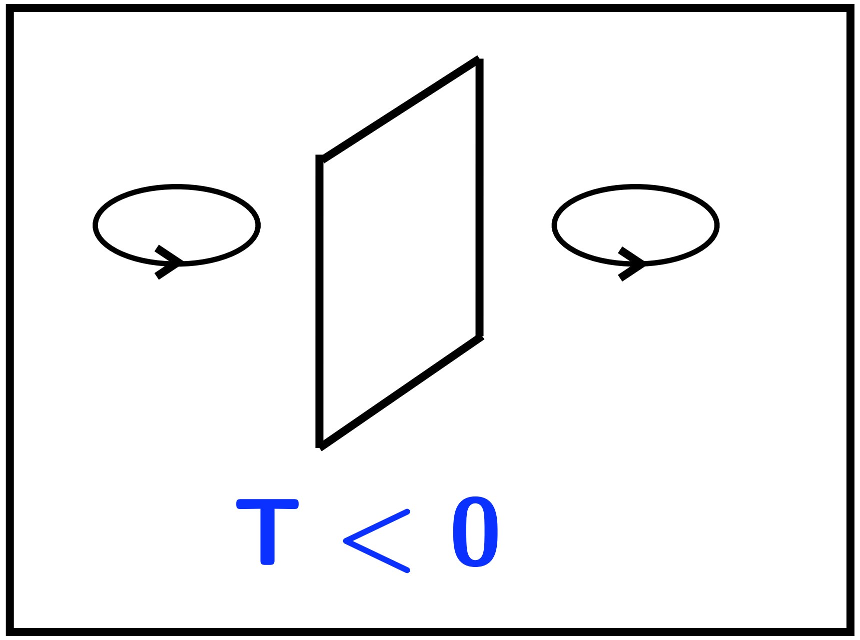

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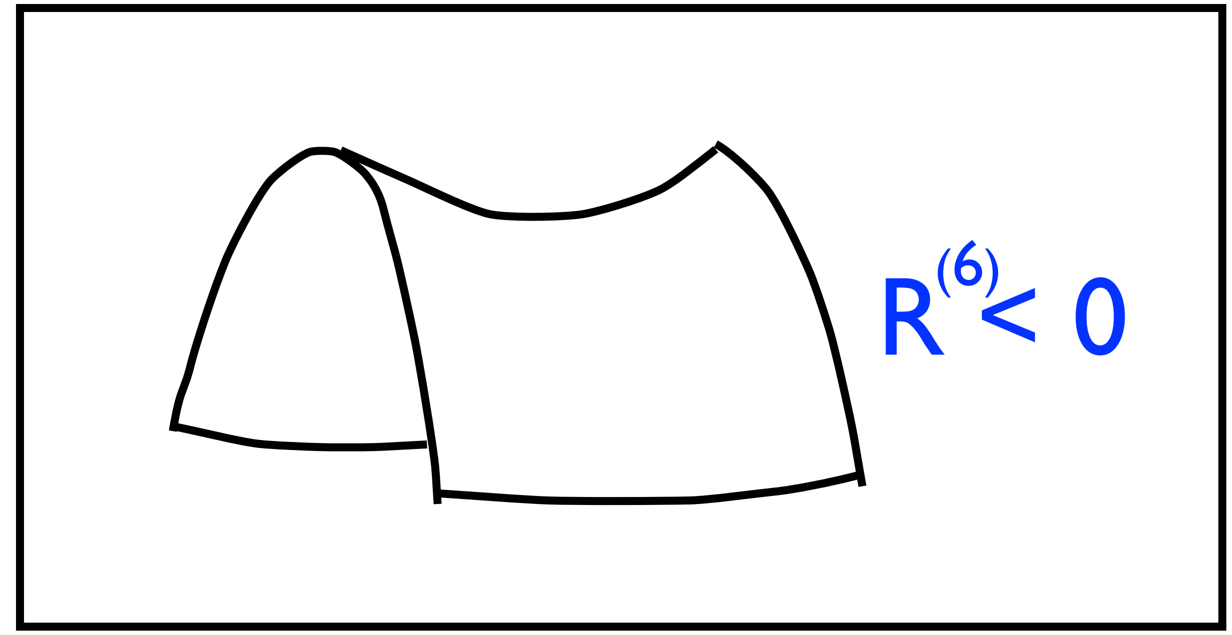
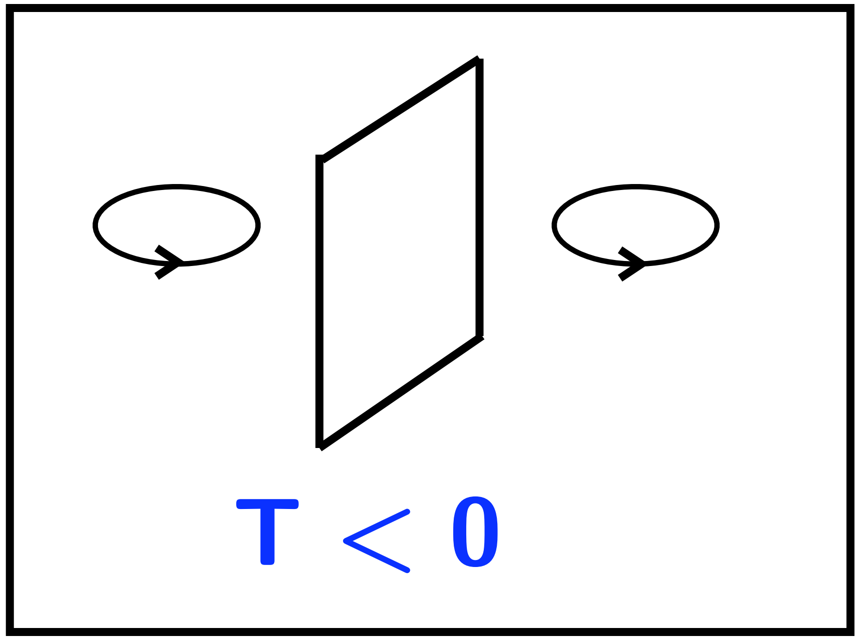


O-planes

Negative internal curvature

A strategy:



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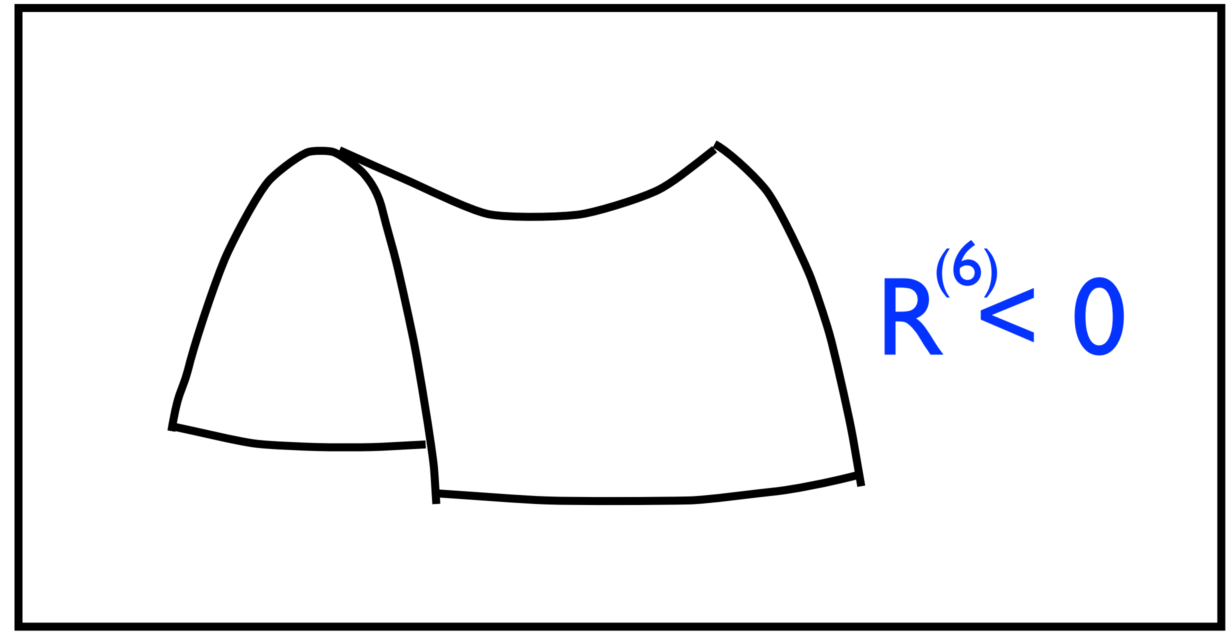

O-planes

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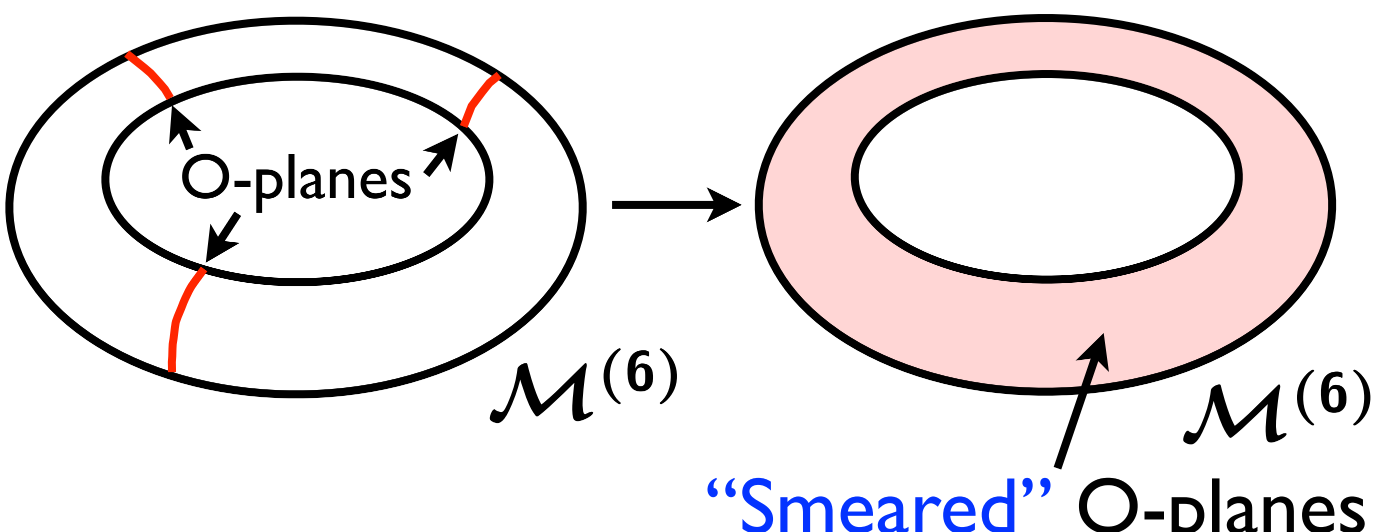
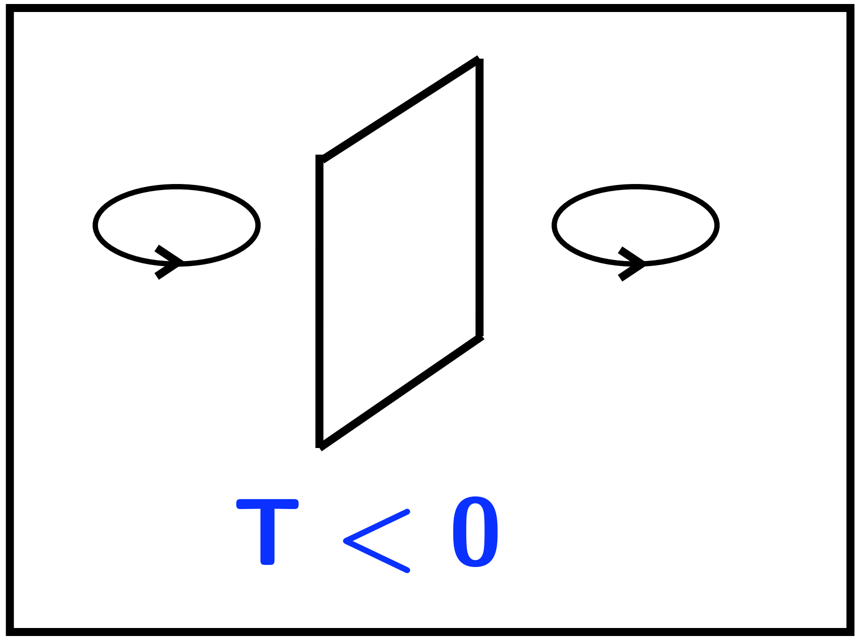
A strategy:

(i) “Smear” the O-planes:





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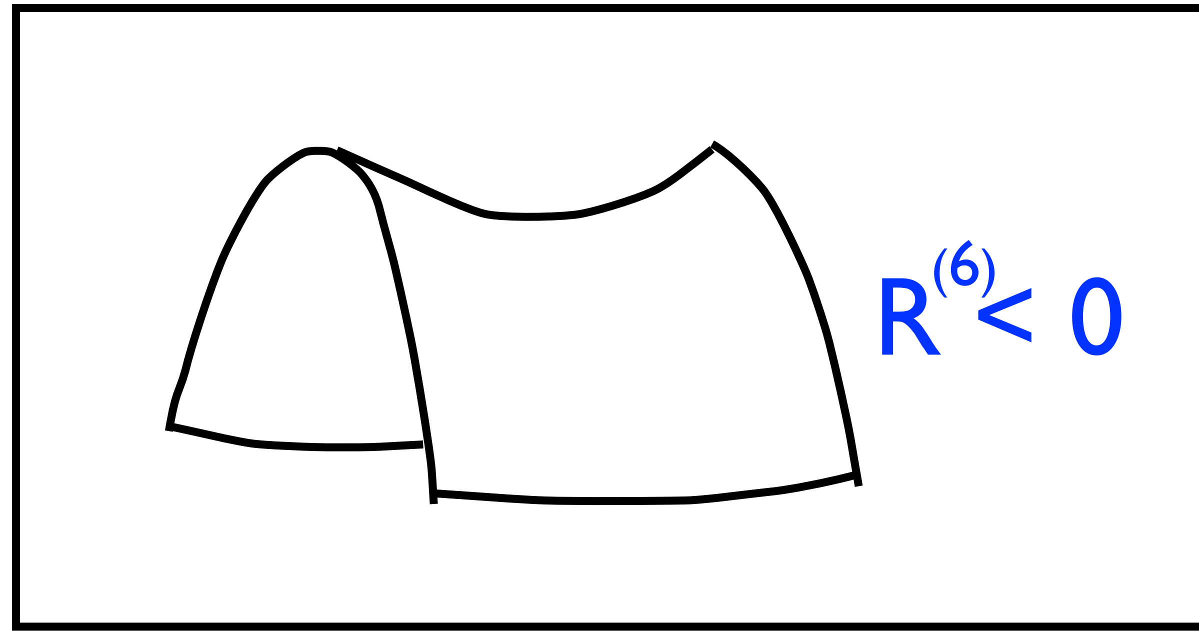

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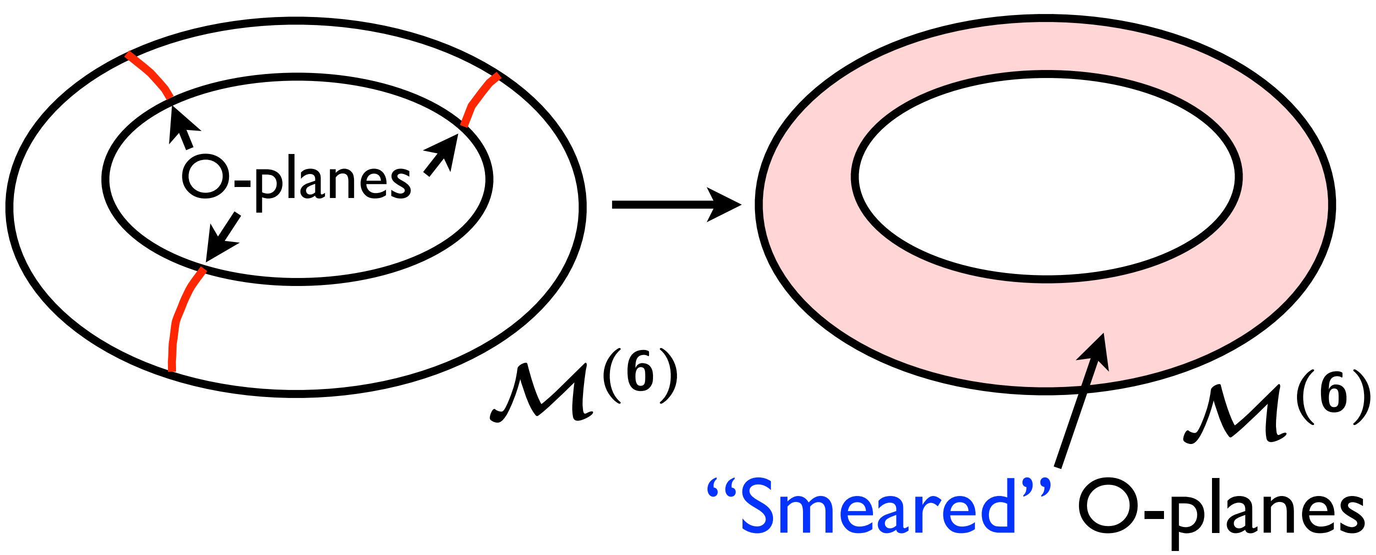
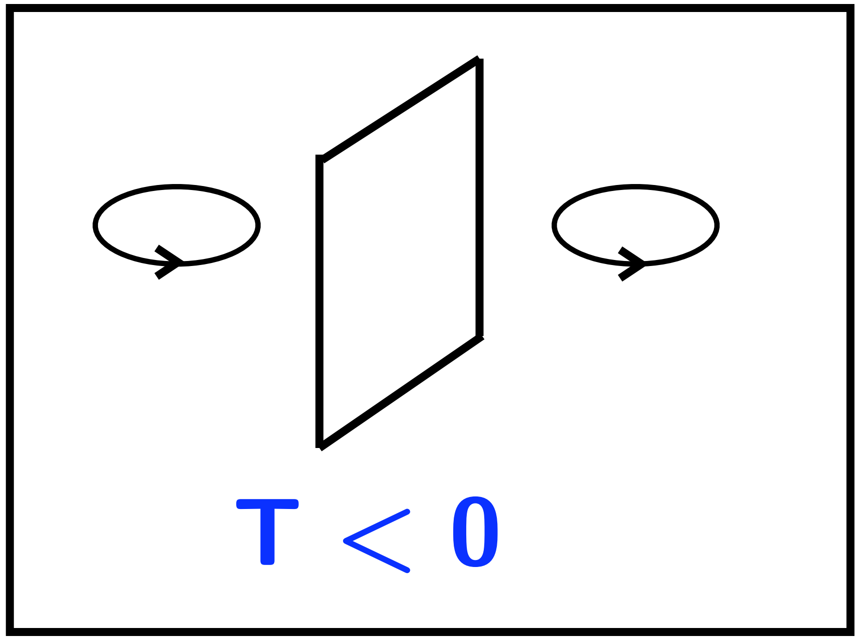


(ii) Use group or coset manifolds for $\mathcal{M}^{(6)}$

$$\mathcal{M}^{(6)} = \mathbf{G} \text{ or } \mathbf{G}/\mathbf{H}$$



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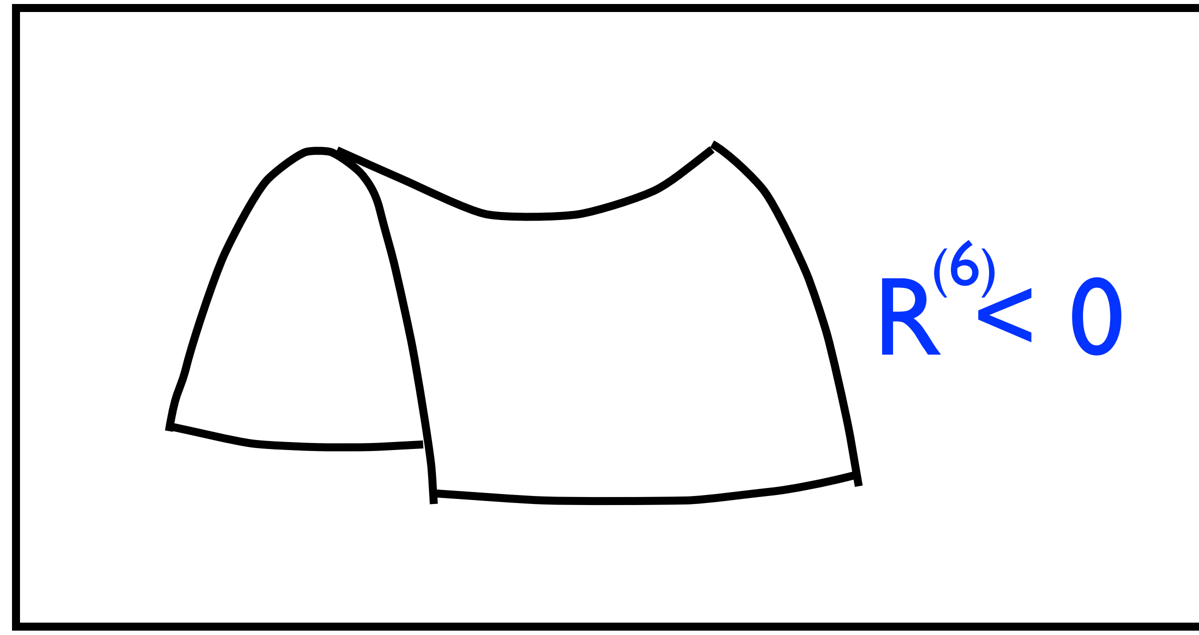

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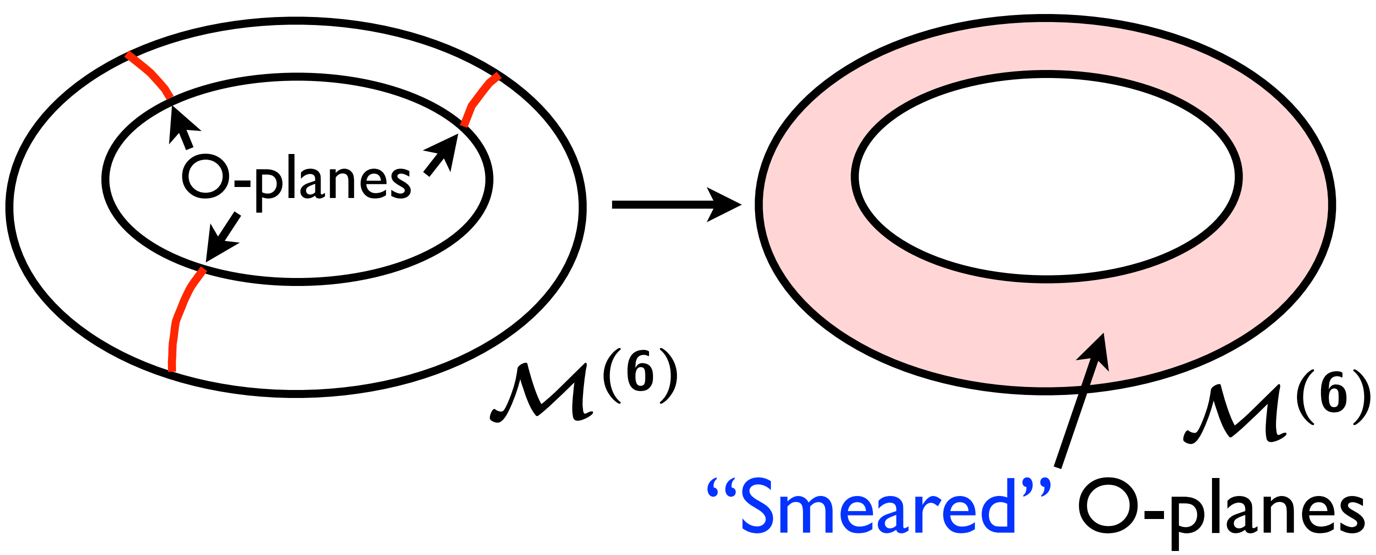

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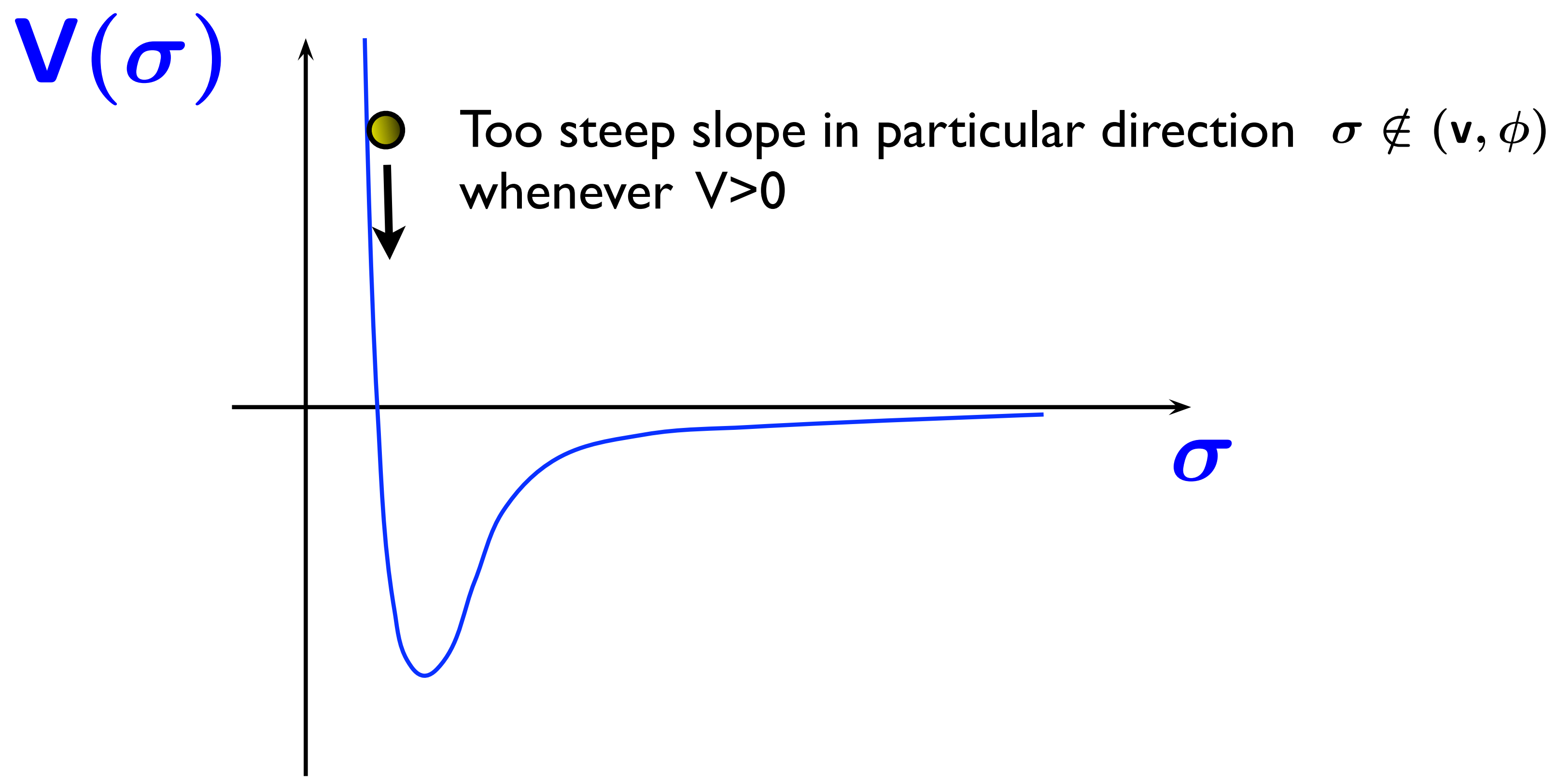
$\rightarrow$ Back-reaction & dimensional reduction well-understood

Despite these simplifications, one finds:

Most models can be ruled out by weaker no-go theorems along other field directions



But also: First working example with a de Sitter extremum:

Caviezel, Koerber, Körs, Lüst, Wrase, MZ (2008)

$$\mathcal{M}^{(6)} = \mathbf{SU}(2) \times \mathbf{SU}(2)$$

Flauger, Paban, Robbins, Wrase (2008)

More (early) examples:

Caviezel, Wrase, MZ (2009)

Danielsson, Haque, Koerber, Shiu, Van Riet, Wrase (2011)

Related important early works:

Silverstein (2007)

Haque, Shiu, Underwood, Van Riet (2008)

Danielsson, Haque, Shiu, Van Riet (2009)

Andriot, Goi, Minasian, Petrini (2010)

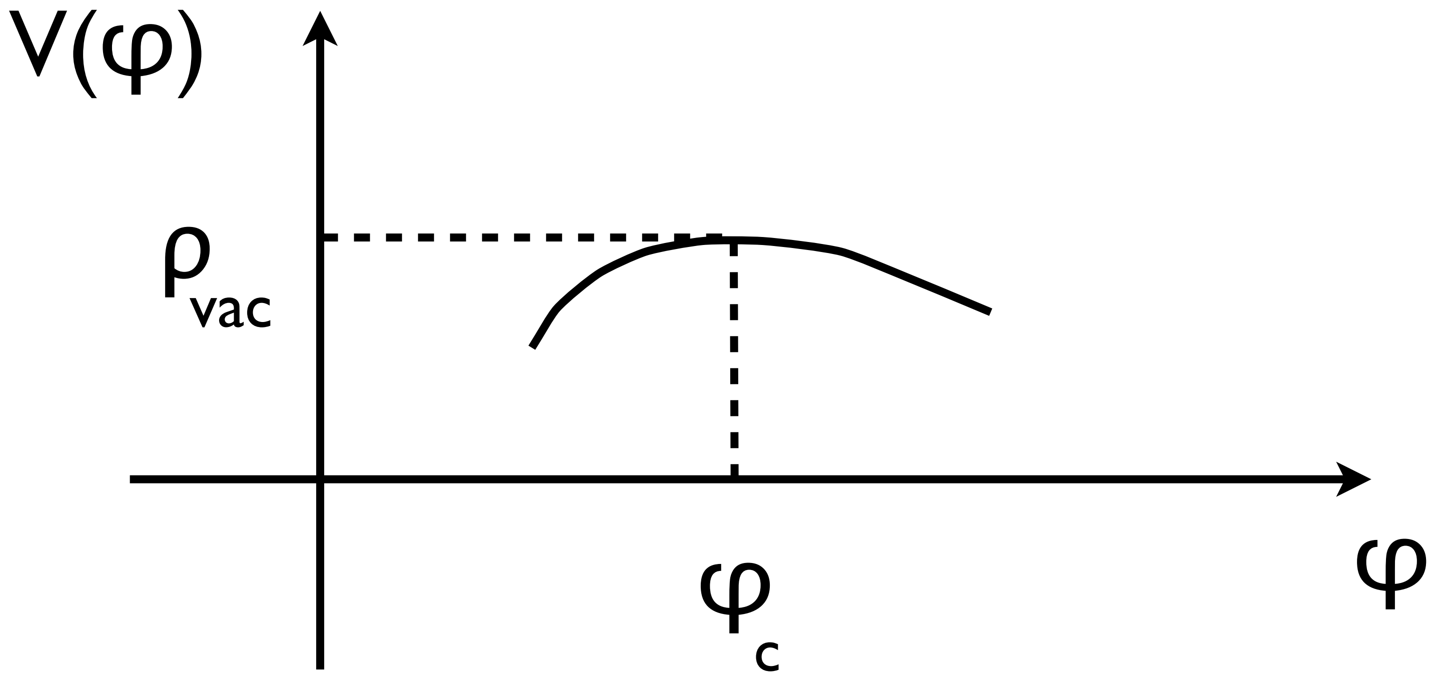
Dong, Horn, Silverstein, Torroba (2010)

Danielsson, Koerber, Van Riet (2010)

Problems:

(i) So far, all examples have at least one tachyonic instability

(Saddle points, not minima)



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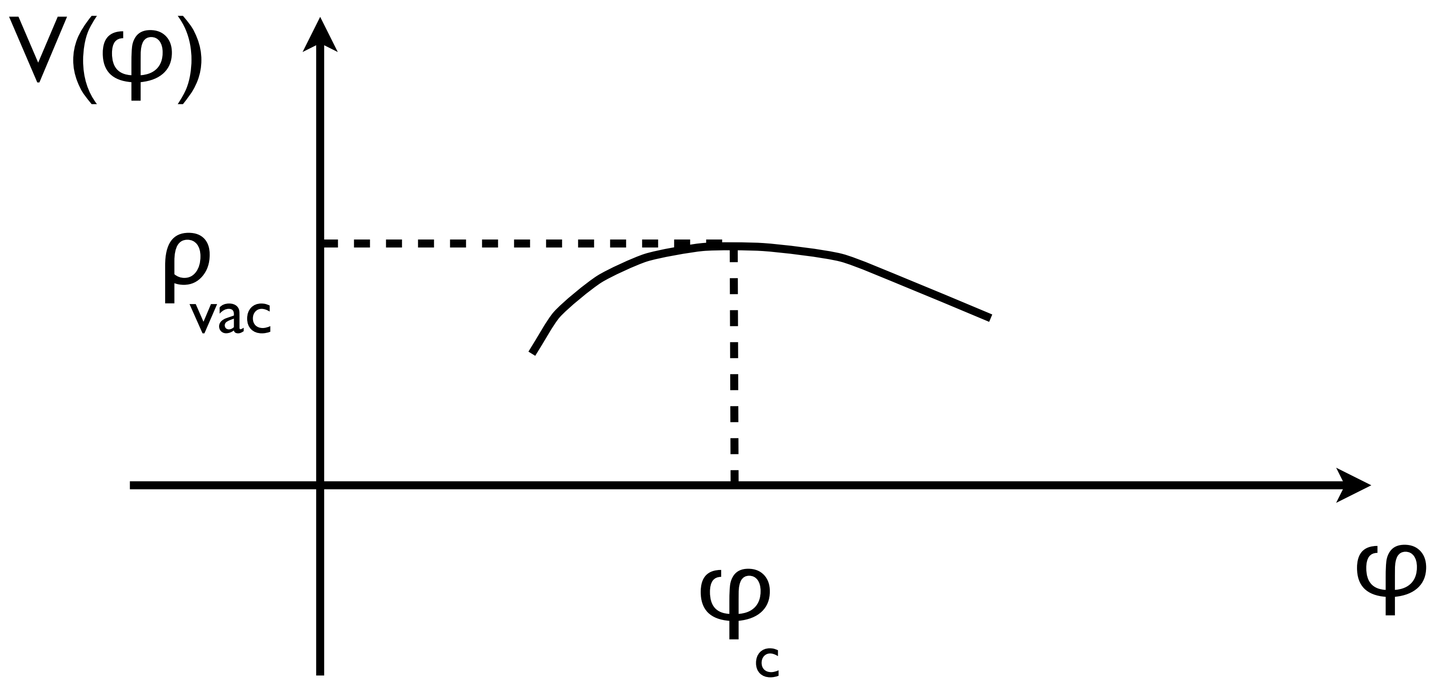

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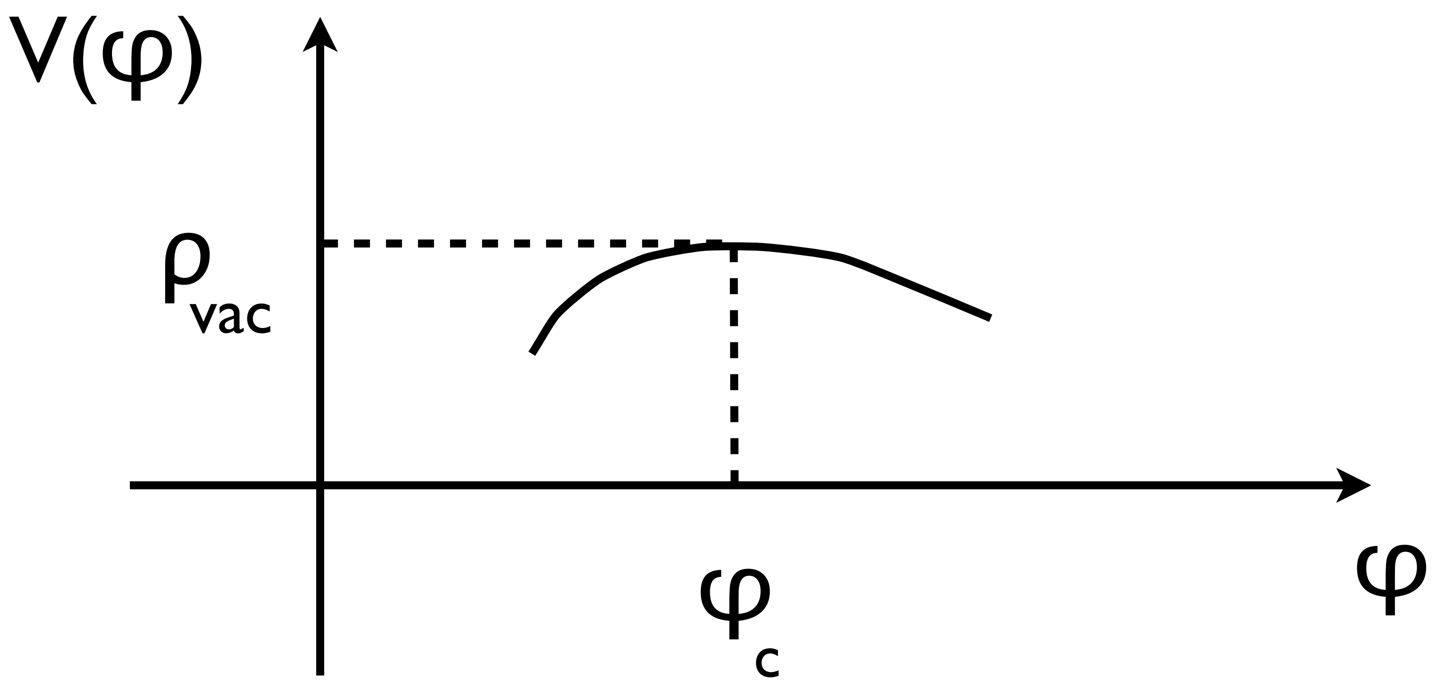

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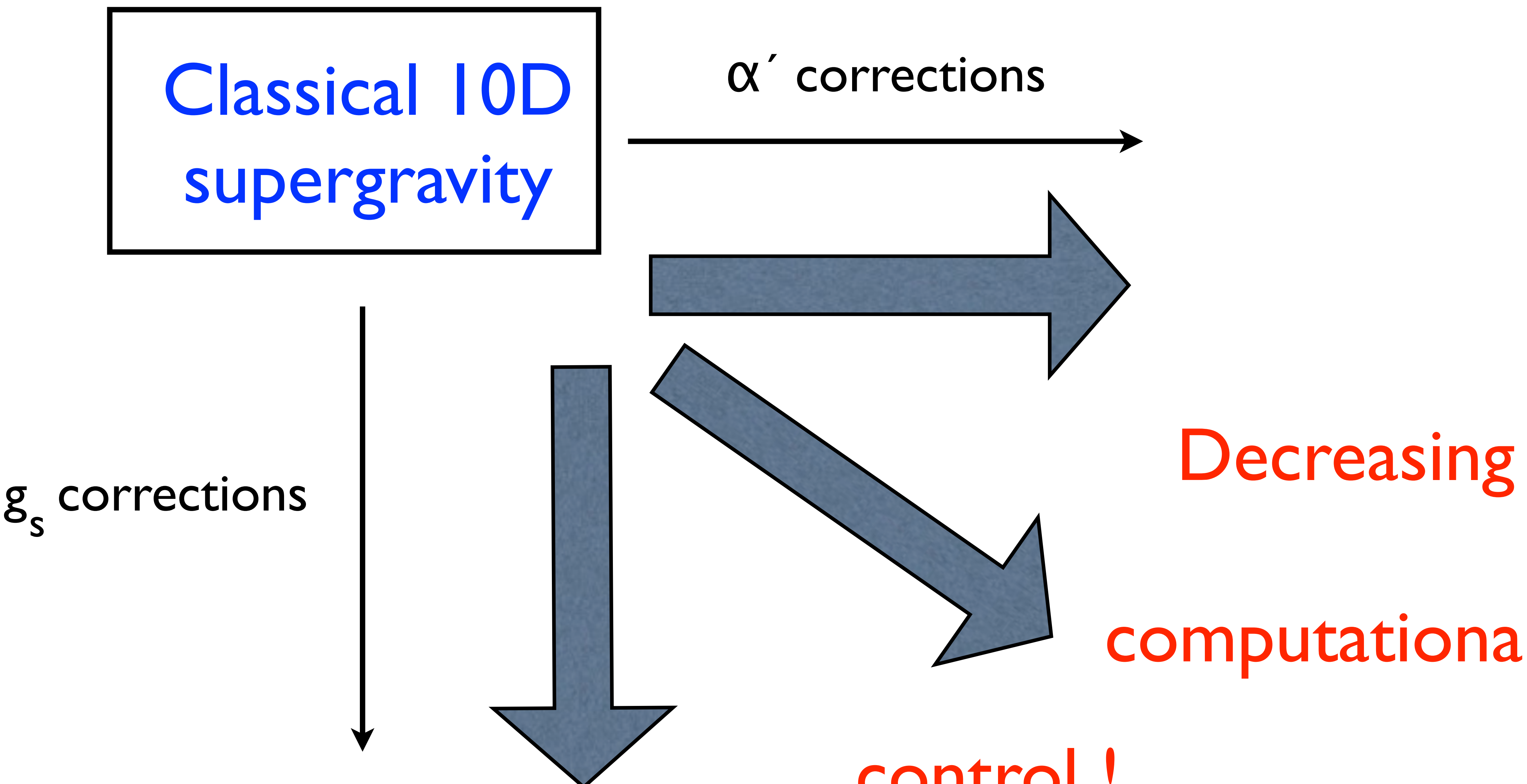
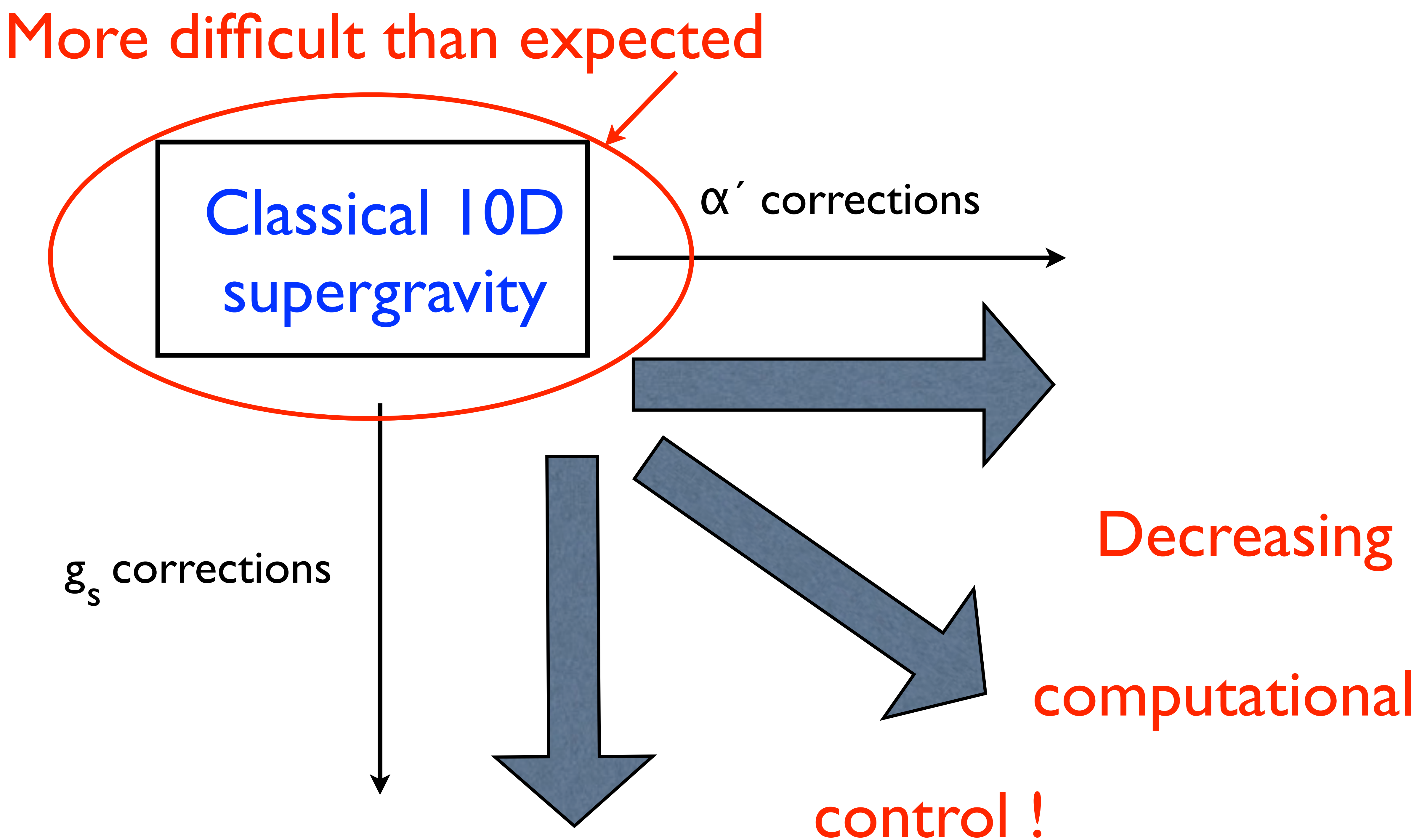
(iii) No naturally small parameter $\Rightarrow$ $\rho_{vac} \gg (1\,\mathrm{meV})^4$


Classical 10D
supergravity
α´ corrections
g_s corrections
Decreasing
computational
control !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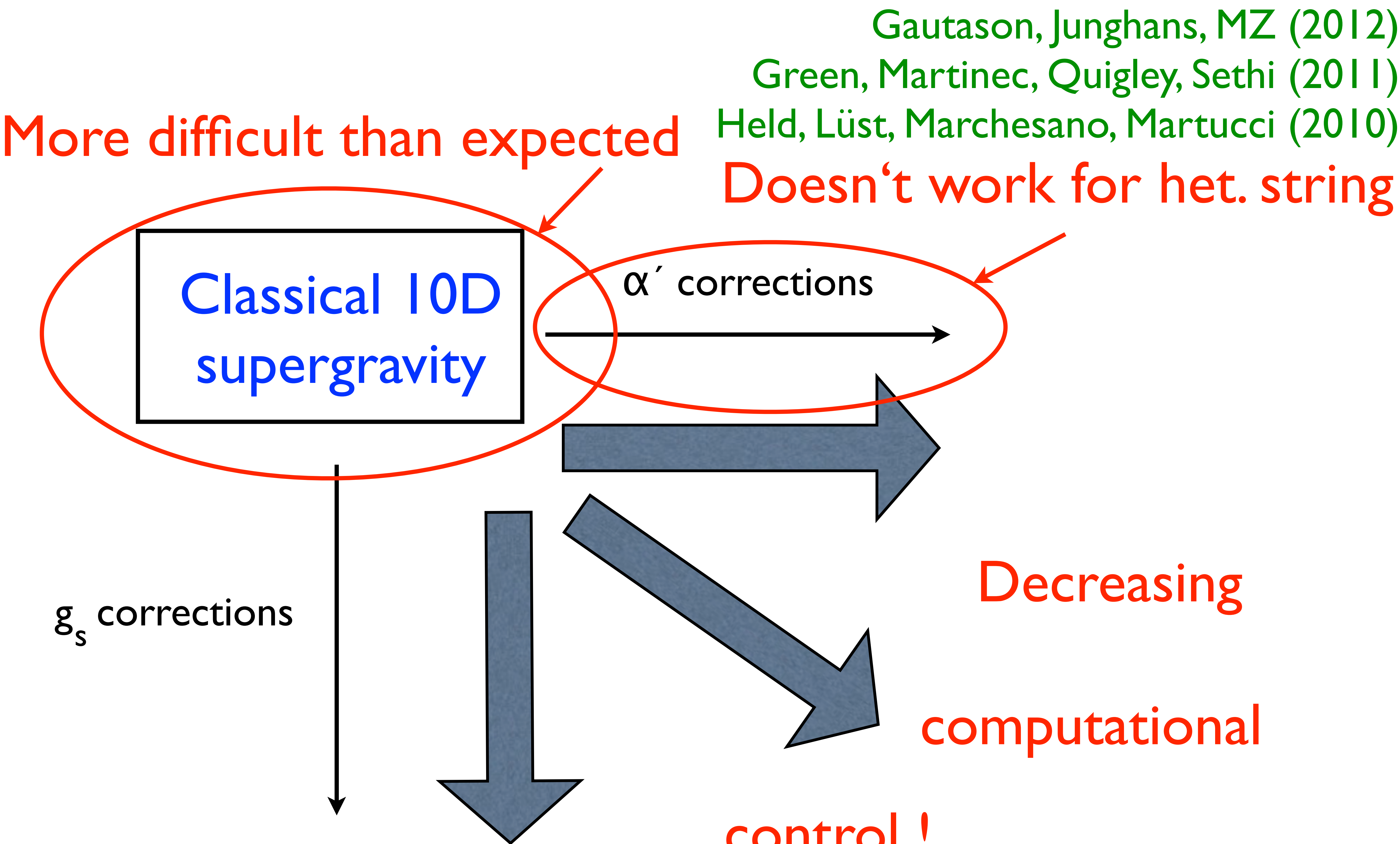
Gautason, Junghans, MZ (2012)
Green, Martinec, Quigley, Sethi (2011)
Held, Lüst, Marchesano, Martucci (2010)
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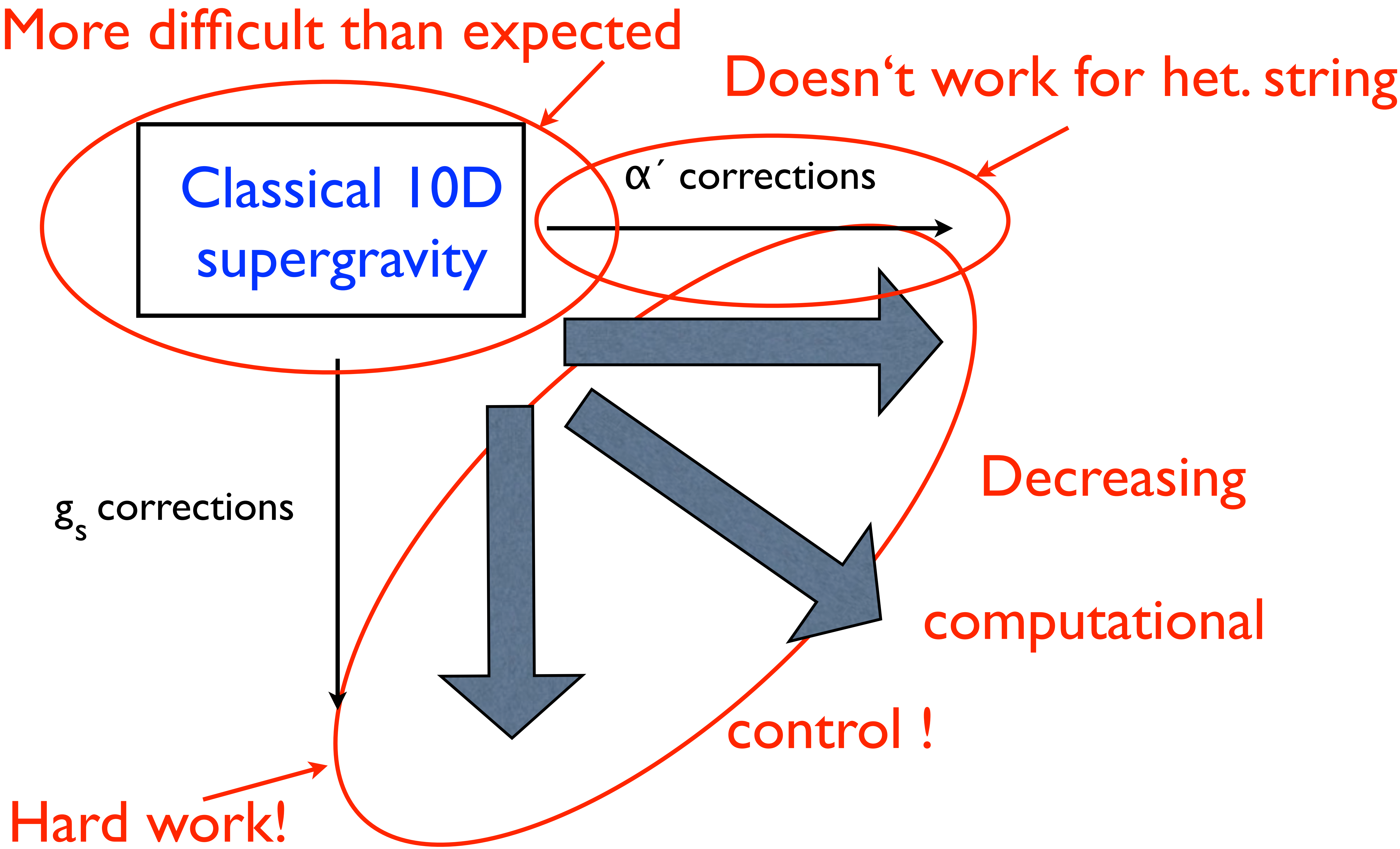
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Hard work!

An incomplete list of approaches:

Kachru, Kallosh, Linde, Trivedi (2003)
Burgess, Kallosh, Quevedo (2003)
Choi, Falkowski, Nilles, Olechowski, Pokorski (2004)
Parameswaran, Westphal (2006)
Westphal (2006)
Balasubramanian, Berglund, Conlon, Quevedo (2005)
Parameswaran, Ramos-Sanchez, Zavala (2010)
Rummel, Westphal (2011)
Louis, Rummel, Valandro, Westphal (2012)
Cicoli, Maharana, Quevedo, Burgess (2012)
Cicoli, Klevers, Krippendorf, Mayrhover, Quevedo, Valandro (2013)
Blåbäck, Roest, Zavala (2013)
Danielsson, Dibitetto (2013)
Rummel, Sumimoto (2014)
Braun, Rummel, Sumumoto, Valandro (2015)
Kallosh, Linde, Vercnocke, Wrase (2014)
Marsh, Vercnocke, Wrase (2014)
Guarino, Inverso (2015)
Retolaza, Uranga (2015)
Buchmüller, Dierigl, Ruehle, Schweizer (2016)

4. The stability problem

A serious problem:

Perturbative stability!

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A critical point in the effective potential need not be a local minimum

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More likely for many scalar fields:
Saddle points with tachyonic directions

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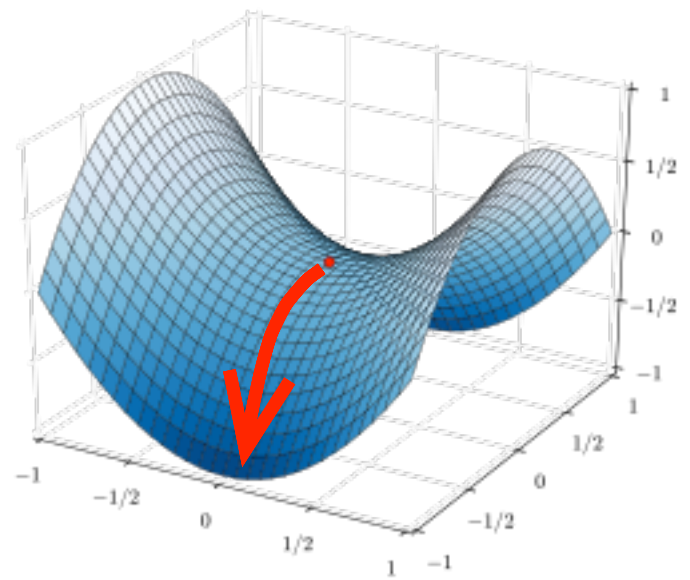

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But: de Sitter vacua cannot preserve supersymmetry!
→ No general protection against instability

More scalars → Tachyonic instability more likely

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- Naively:

$$\mathbf{P(no\ tachyons)} \sim 2^{-N_{scalars}}$$

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- More sophisticated estimates (in "random supergravity"):

Marsh, McAllister, Wrase (2011)
Chen, Shiu, Sumitomo, Tye (2011)
Sumitomo, Tye (2012)

$$\mathbf{P}(\textbf{no tachyon}) \sim \exp[-\mathbf{c}\mathbf{N}_{\textbf{scalars}}^{1.3\ldots1.5}]$$

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$$\mathbf{P}(\text{no tachyon}) \sim \exp[-c N_{\text{scalars}}^{1.3\ldots1.5}]$$

- Typically: $N_{\text{scalars}} = \mathcal{O}(10)\ldots\mathcal{O}(100)$

⇒ Perturbatively stable de Sitter vacua extremely rare ?

However, statistical arguments based on random potentials need not necessarily be accurate.

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There may be setups with special potentials in which tachyons are unlikely

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Conversely, there may be setups with unavoidable (universal) tachyons (e.g. the sGoldstino)

E.g. Covi, Gomez-Reino, Gross, Louis, Palma, Scrucca (2008)

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Junghans, MZ (2016)

The observed tachyons in classical de Sitter vacua might be structural tachyons and not statistical tachyons.

5. Conclusions

The extra dimensions of string theory may have observable consequences even if we can‘t resolve the extra dimensions or the strings with accelerator experiments.

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These consequences can often be understood in terms of the moduli fields (and axions) induced by the extra dimensions and involve topics such as inflation, supersymmetry breaking, dark matter or dark energy

Focus in this talk:

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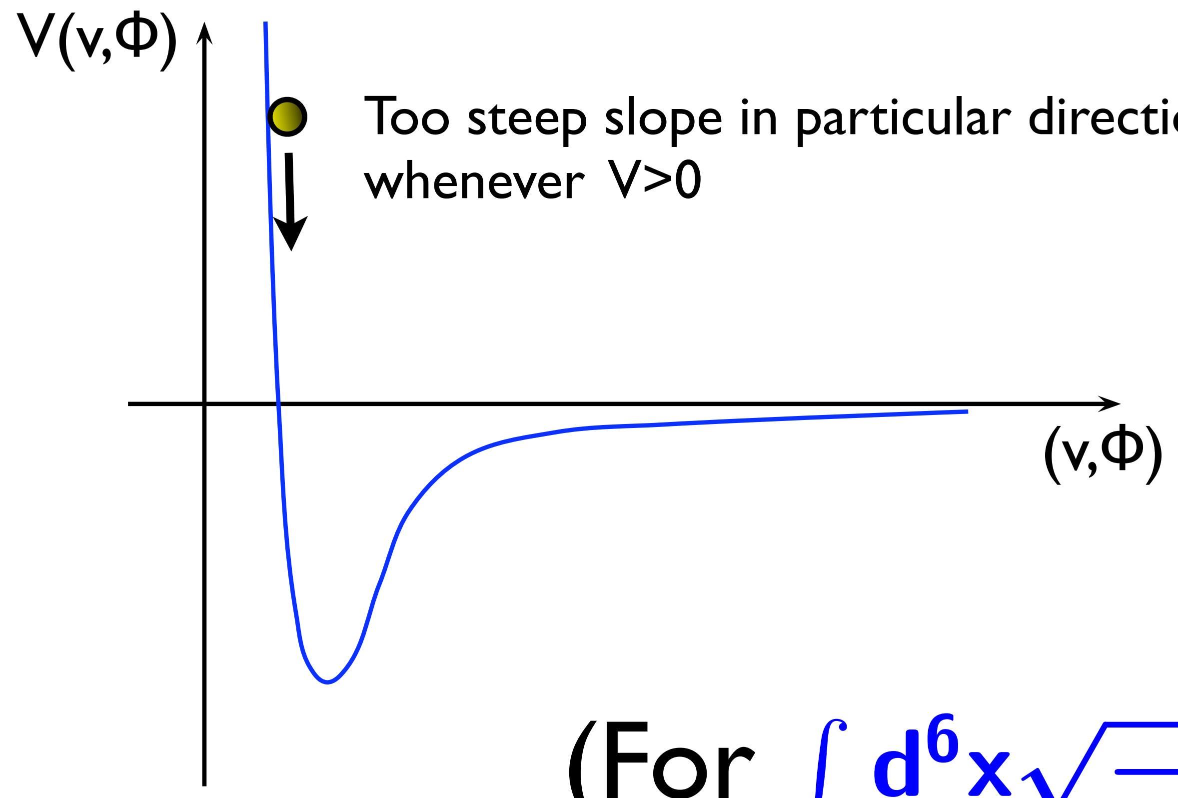
→ Strong filters for realistic string compactifications?

10D proof uses Einstein and dilaton equation

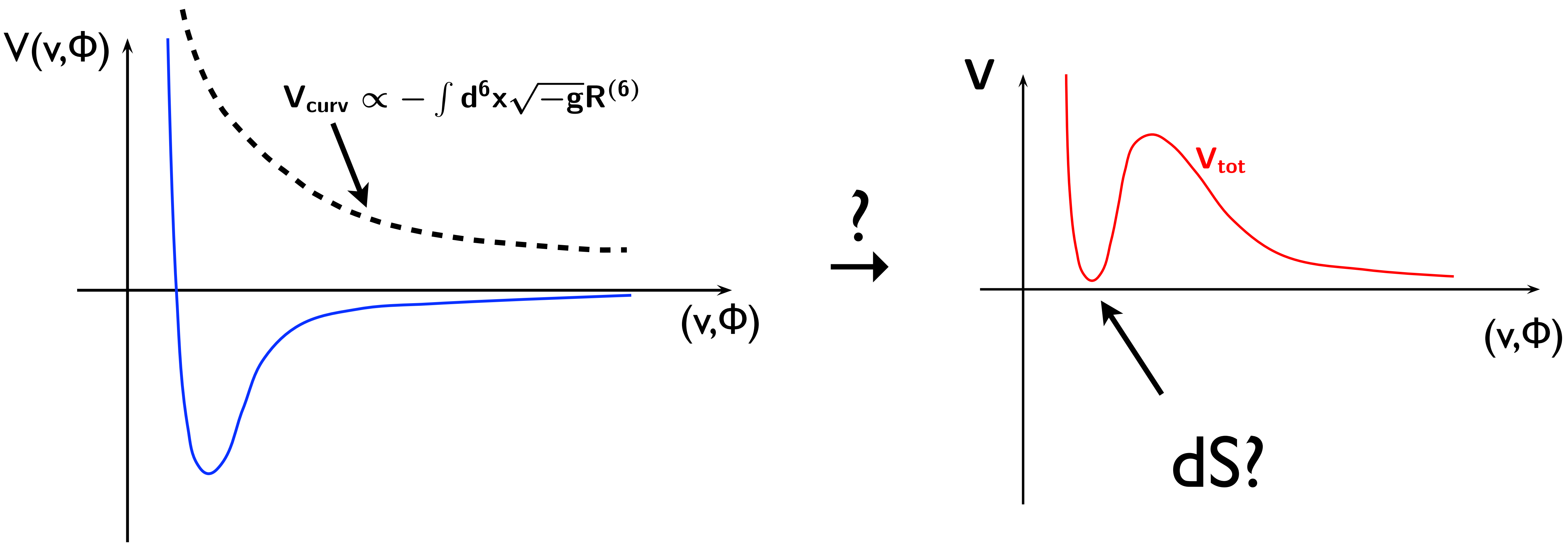
4D manifestation:



(For $\int \mathbf{d^6x}\sqrt{-\mathbf{g}}\ \mathbf{R^{(6)}} \geq \mathbf{0}$)

10D proof uses Einstein and dilaton equation

But for $\int d^6x\sqrt{-g}\, R^{(6)} < 0$:



⇒ Use O-planes & negative internal curvature

Based on:

Apruzzi, Gautason, Parameswaran, MZ (2014)
Junghans, Schmidt, MZ (2014)
Bena, Junghans, Kuperstein, Van Riet, Wrase, MZ (2012)
Gautason, Junghans, MZ (2012, 2013)
Blåbäck, Danielsson, Junghans, Van Riet, Wrase, MZ (2010,2011)

As well as

Wrase, MZ (2010)
Caviezel, Wrase, MZ (2009)
Caviezel, Koerber, Körs, Lüst, Wrase, MZ (2008)
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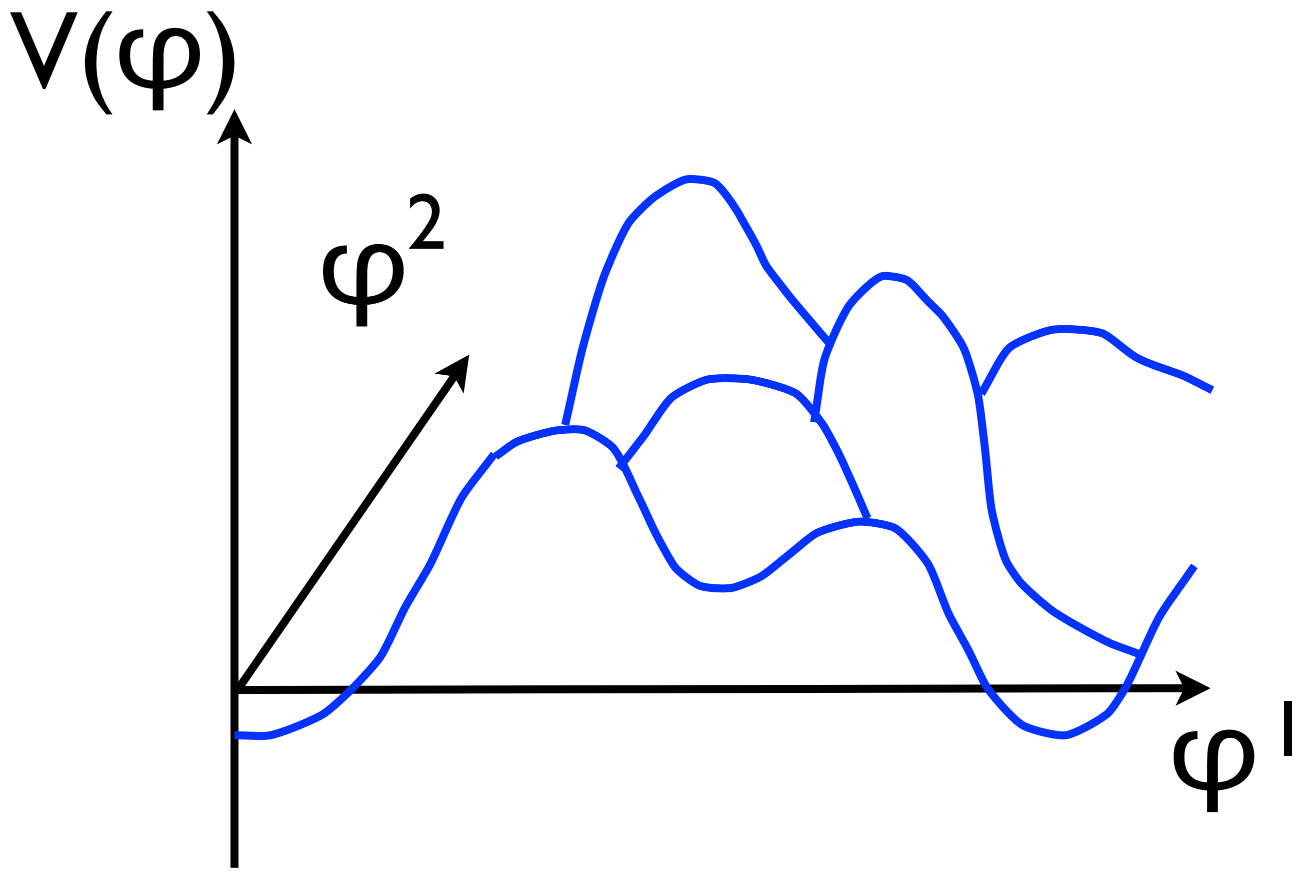
Various effects (tree-level + quantum corrections) generate an effective 4D scalar potential for the moduli



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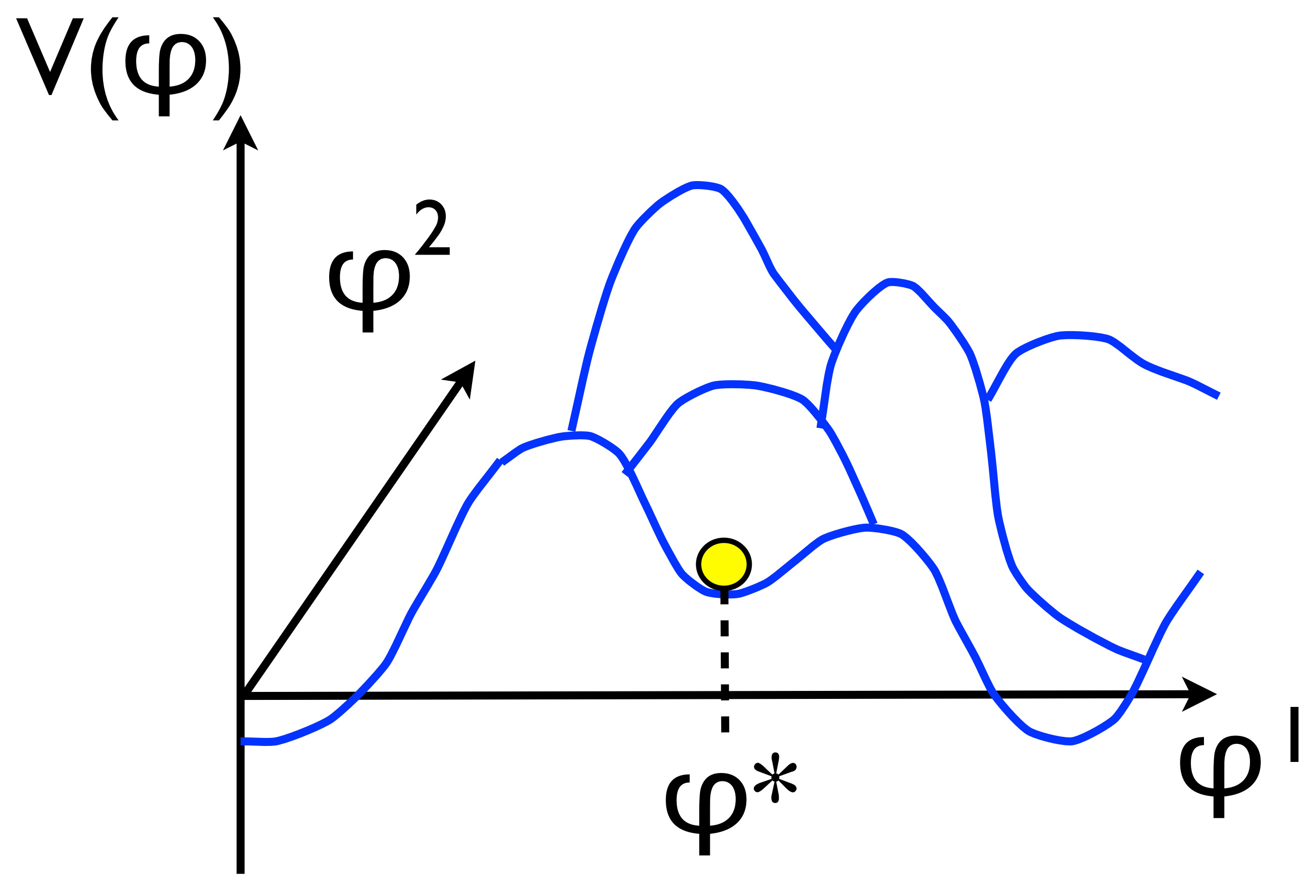

Positive CC ⟷ Local minimum at $V(\varphi^*) > 0$

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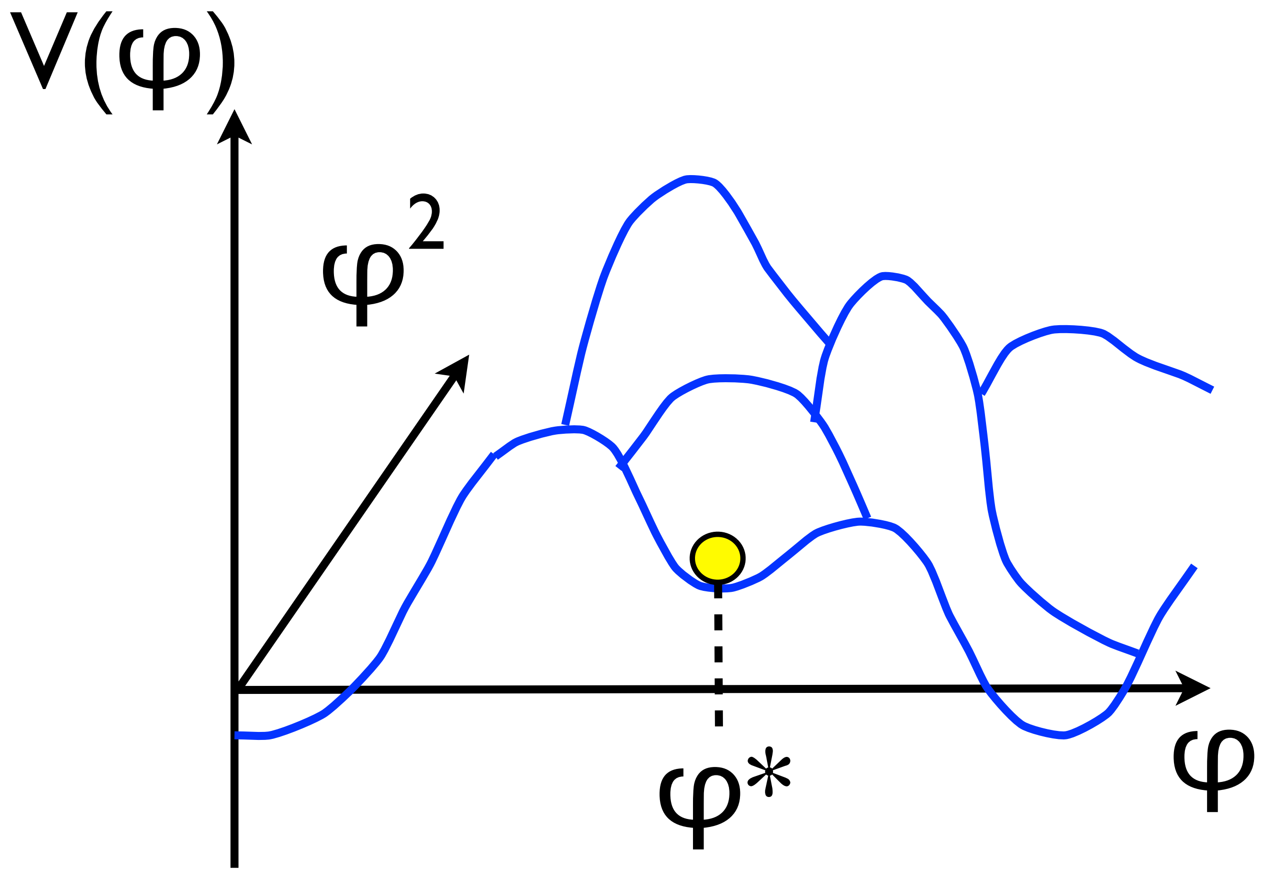

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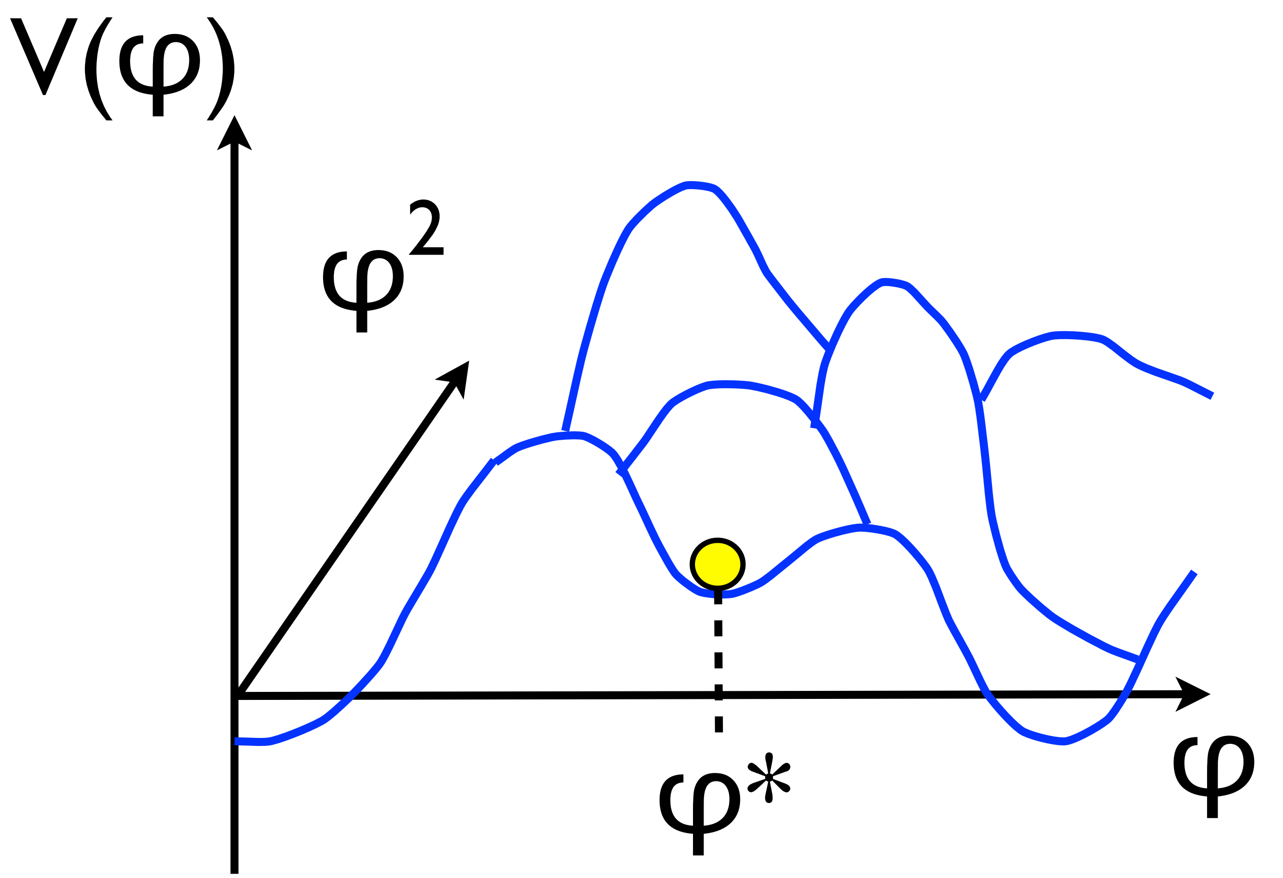

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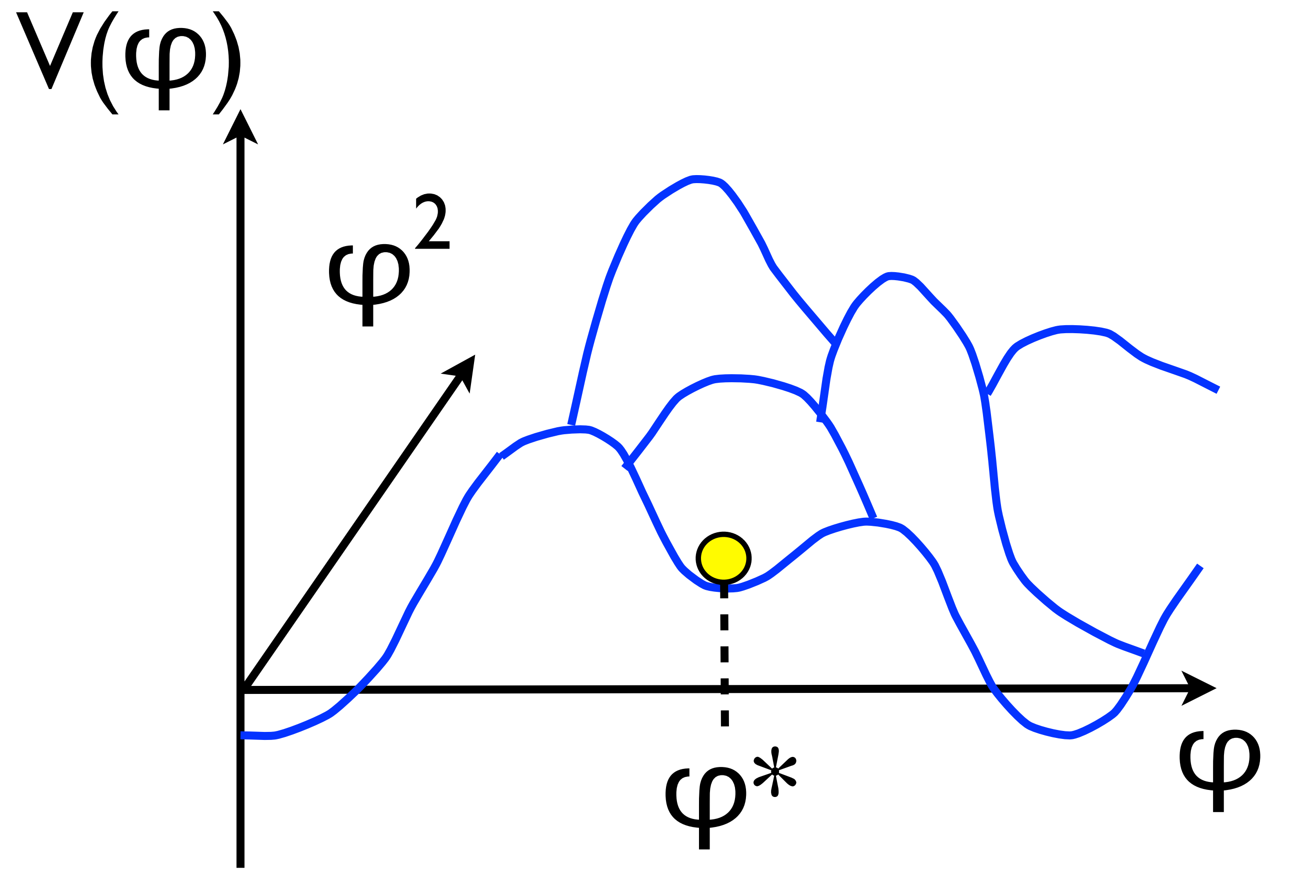

Main topic of this talk (surprisingly difficult!)

Positive CC ⟷ Local minimum at $V(\varphi^*) > 0$

Ideally: $V(\varphi^*) = \rho_{vac} \approx (1\ \text{meV})^4$

$M_{moduli} > \mathcal{O}(30\ \text{TeV})$

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E.g.: Gibbons (1984);
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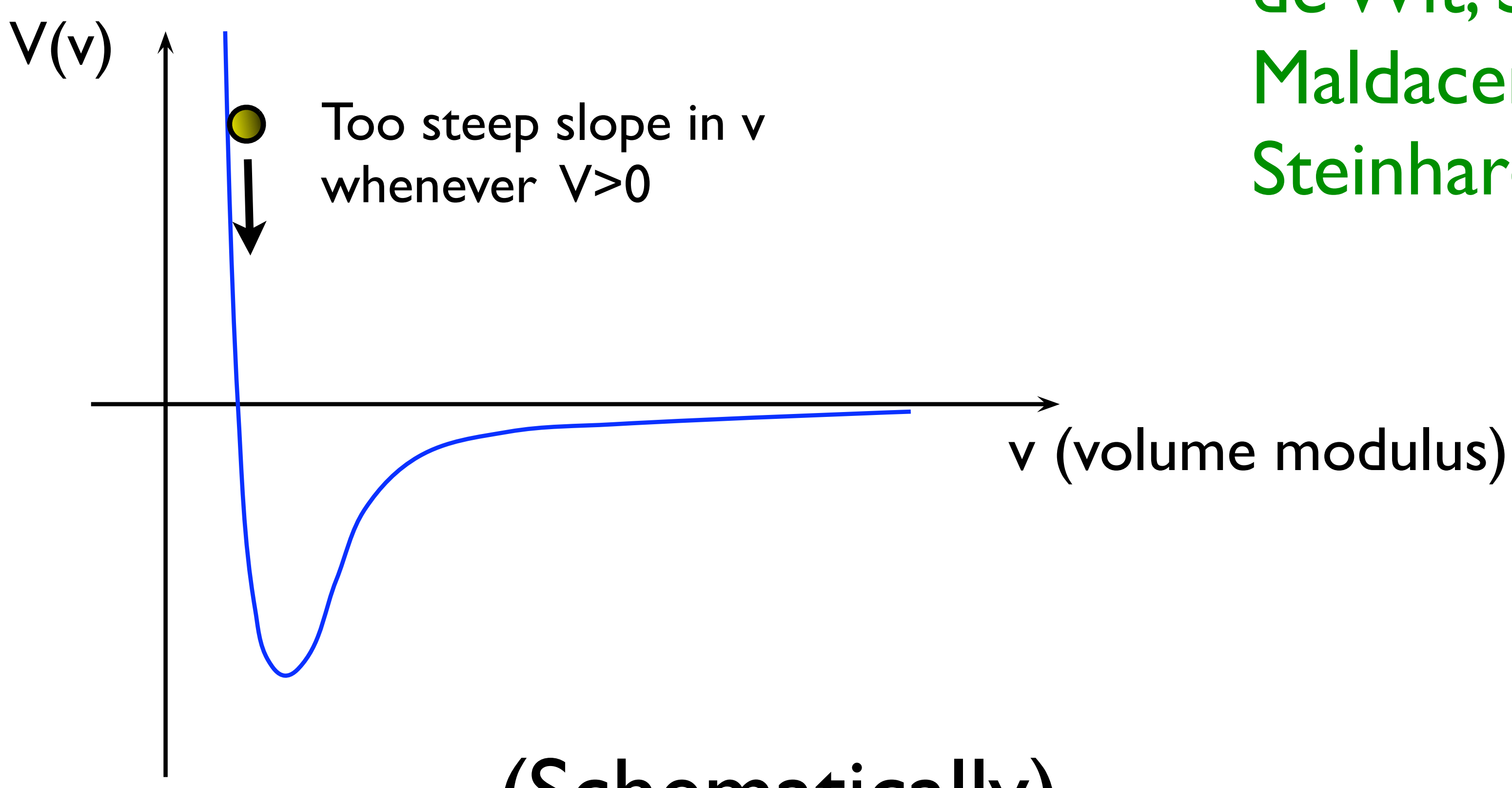

(Schematically)

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→ Need more complicated compactification setups:

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1. "Classical de Sitter vacua"

(Tree-level with orientifolds planes and negative 6D curvature)

To evade no-go

Two problems:

1. Find a critical point with $V(\varphi^*) > 0$

<u>Problem</u>: Simple setups ruled out by no-go theorems

→ Need more complicated compactification setups:

1. "Classical de Sitter vacua"

   (Tree-level with orientifolds planes and negative 6D curvature)

   To evade no-go

or

2. "Quantum de Sitter vacua"

   (Perturbative and non-perturbative quantum corrections relevant)

   To evade no-go

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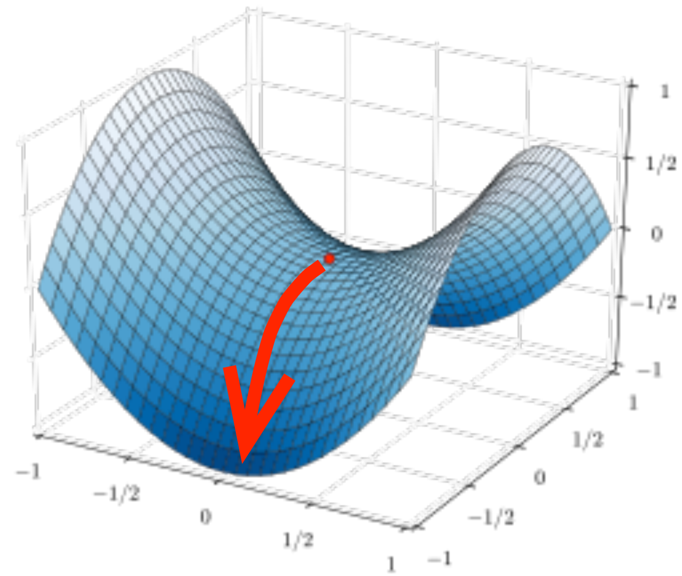

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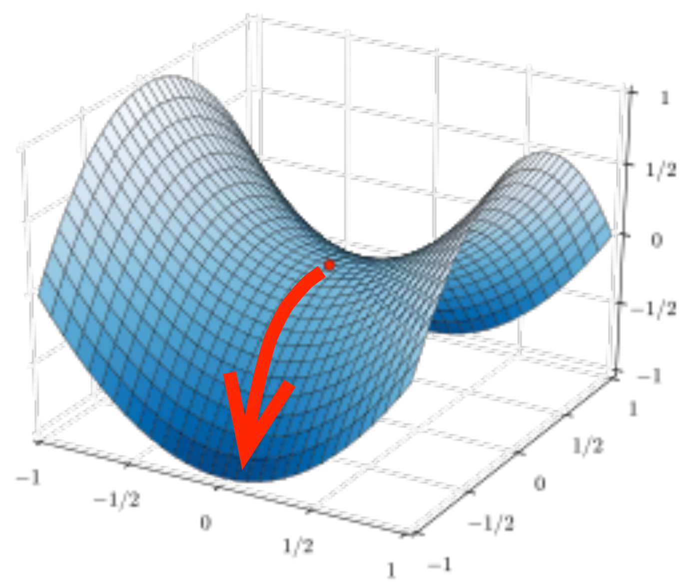

→ Tachyonic instabilities generic!

(No protection from SUSY in de Sitter)

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