Challenges for inflationary model building after Planck

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Aim of the talk

Discuss theoretical challenges for building models of inflation after Planck results

`Current situation:`

The spectrum of curvature fluctuations is almost (but not exactly) scale invariant, and is characterized to a high degree by a Gaussian statistics.

No hints of contributions isocurvature fluctuations, nor of gravitational waves.

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- Single field, slow roll inflation (with simple potentials, characterized by a minimal number of parameters) fit well data. Focus on this set-up.

  Predictions:

  - No non-G detected in the foreseeable future
  - No isocurvature modes
  - Tensor modes detectable depending on the model (small or large field)

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  Predictions detectable in a not too distant future (combining with LSS etc):

  - Non-G bispectrum parameter $f_{\rm NL}$ is of order one-ten, might be detectable.
  - Non-G trispectrum parameters might be quite large
  - Hints of isocurvature might be detected.
  - Other features (glitches in the power spectrum, etc)

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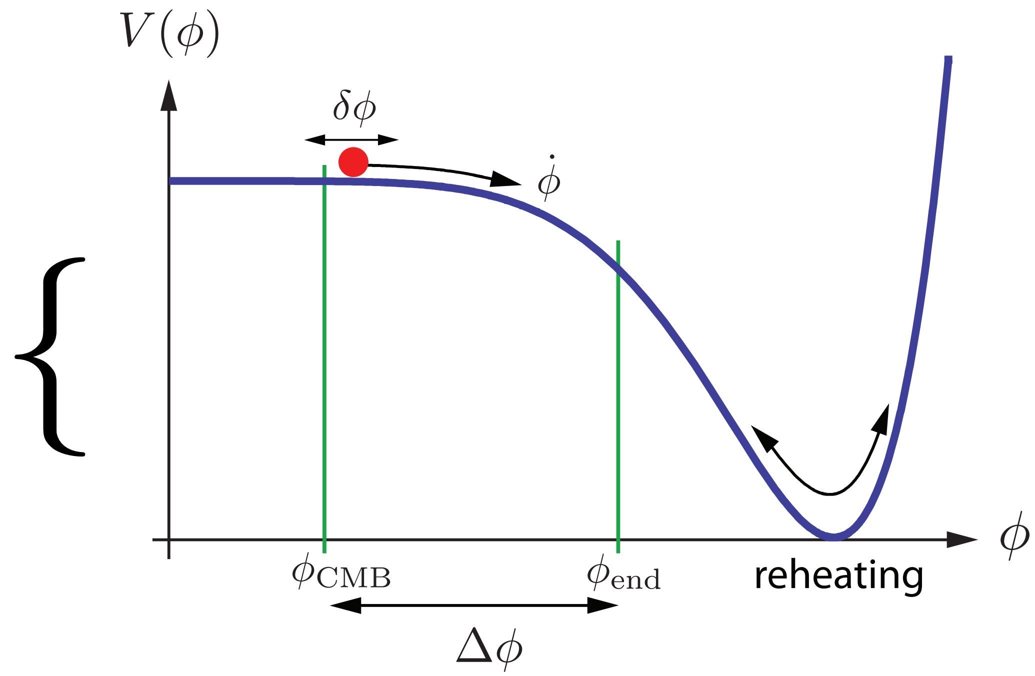
`Do naturalness arguments help to decide?`

Opportunities and challenges in building models of inflation

$$V \simeq M_{Pl}^2\, M_{GUT}^2$$



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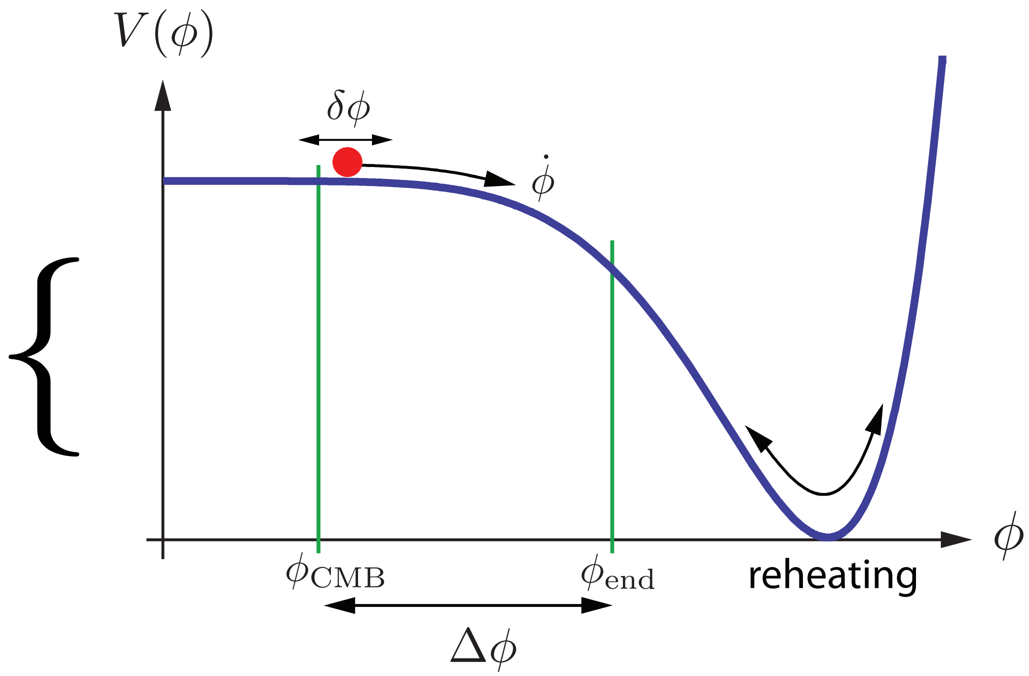

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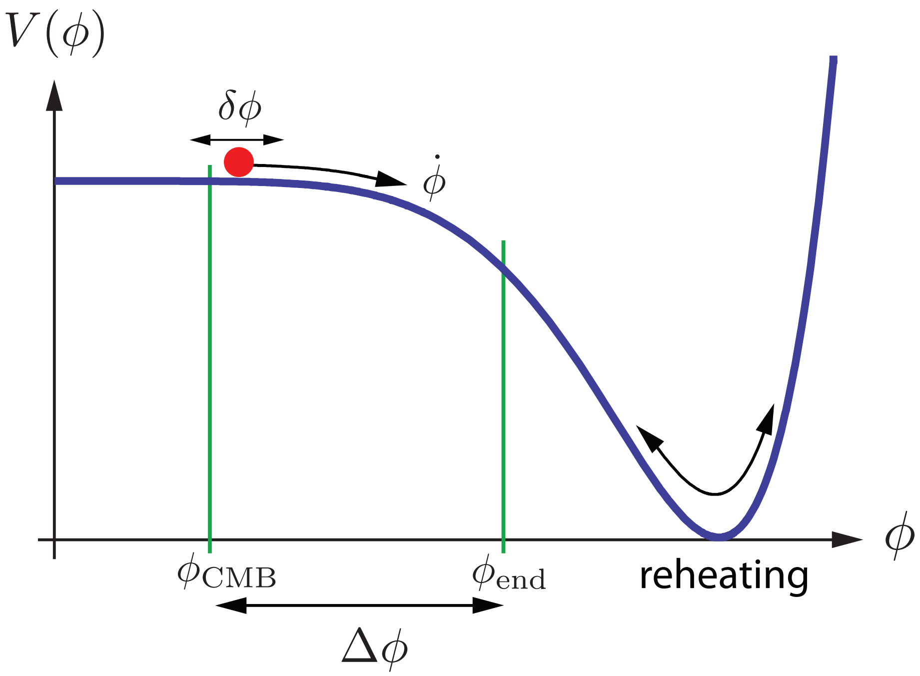

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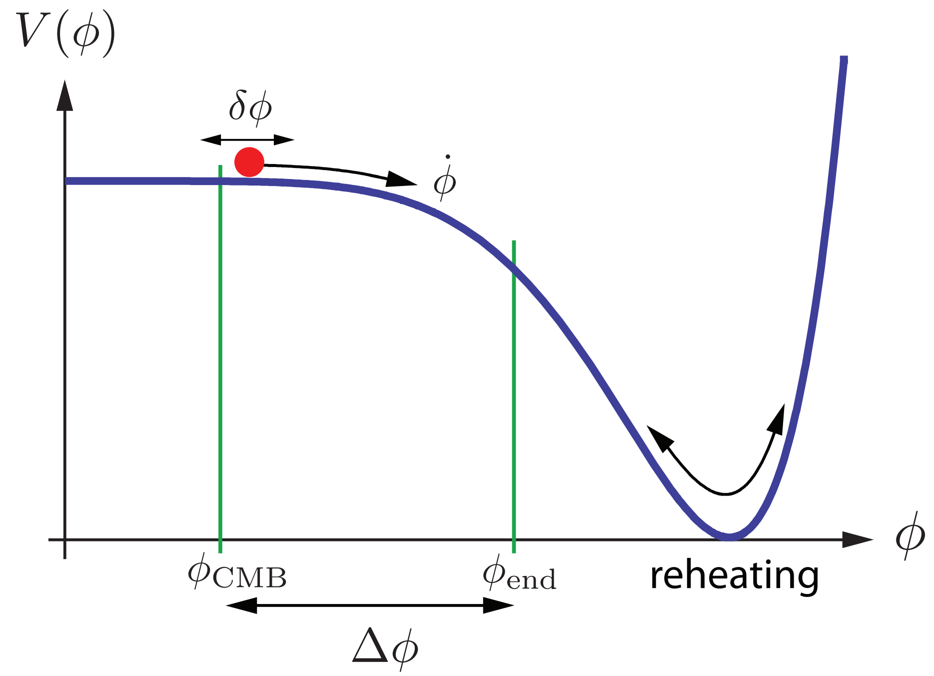

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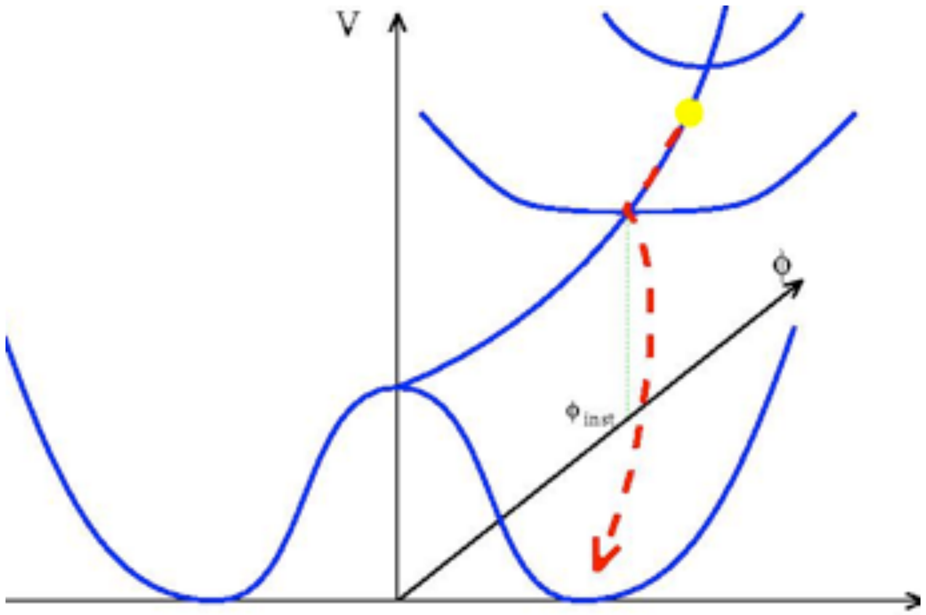

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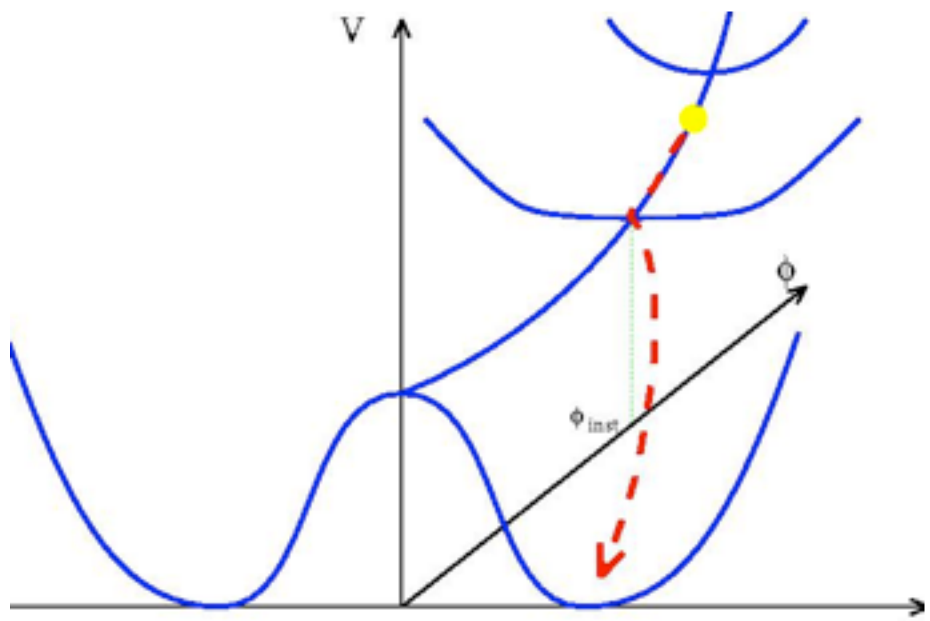

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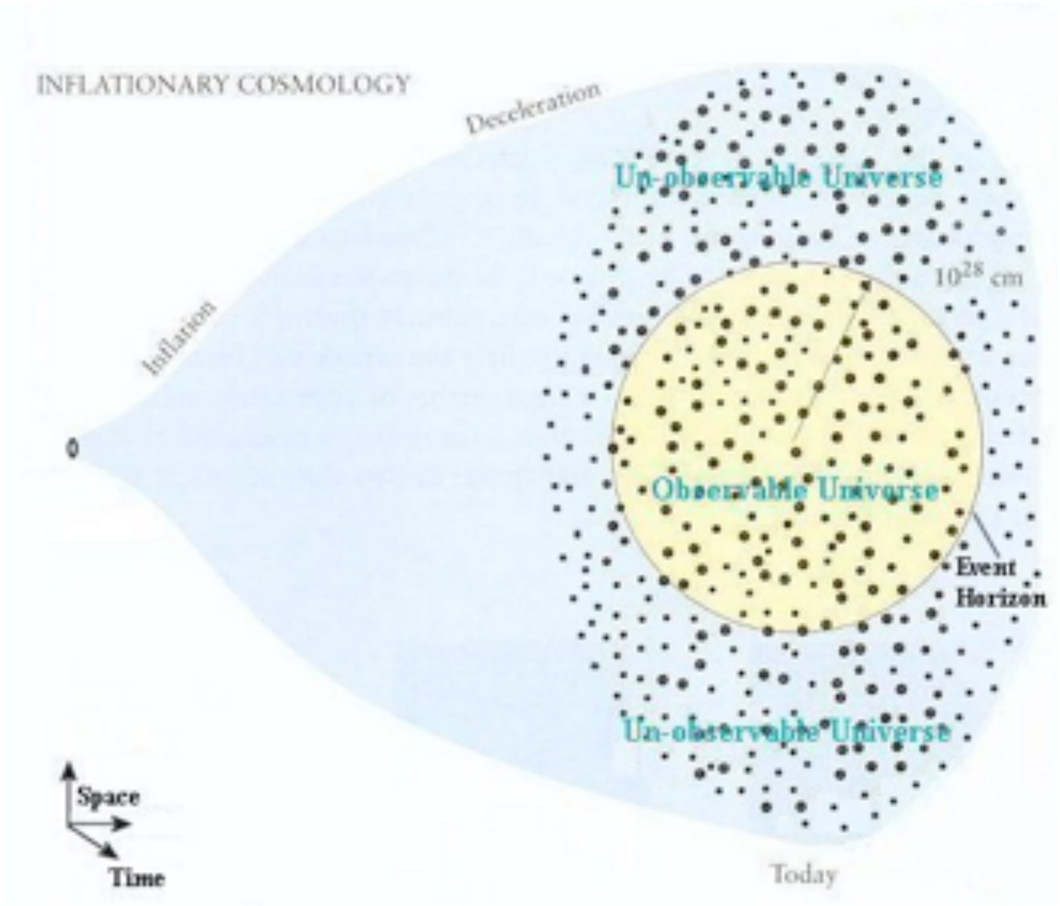

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Inflation is a delicate process

`Inflation is very sensitive to interactions of inflaton with itself and with other fields`

Technically, this manifests in the so called η**-problem**

Slow-roll parameters
$$\begin{cases} \epsilon = -\dfrac{\dot{H}}{H^2} \\[2em] \eta = \dfrac{\dot{\epsilon}}{\epsilon\, H} \end{cases}$$

The condition to have inflation is $\epsilon < 1$. In order to have a sufficiently prolonged period of inflation, $\eta < 1$. These parameters can be expressed in terms of the inflaton potential as

$$\epsilon_V \equiv \frac{M_{\rm P}^2}{2}\left(\frac{V'}{V}\right)^2 \ll \mathcal{O}(1)\ , \quad \eta_V \equiv M_{\rm P}^2 \frac{V''}{V} \ll \mathcal{O}(1)$$

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Additional challenges for **large field models**

- Since the inflaton does super-Planckian excursions $\Delta\phi \geq M_{Pl}$, we must worry about high dimension contributions to the potential $\sim \phi^p/M_{Pl}^{p-4}$
- These models are able to produce large tensor-to-scalar ratio: Lyth bound.

A guide for model building ?

These naturalness issues shouldn't be ignored, and may offer a guide for theoretical model building.

Similar to hierarchy problem of particle physics, that motivates going beyond SM

▷ Some sort of interesting (new?) physics is controlling inflationary potential?

Ideas available on the theory market to address these tuning issues:

Flatness of inflationary potential is due to:

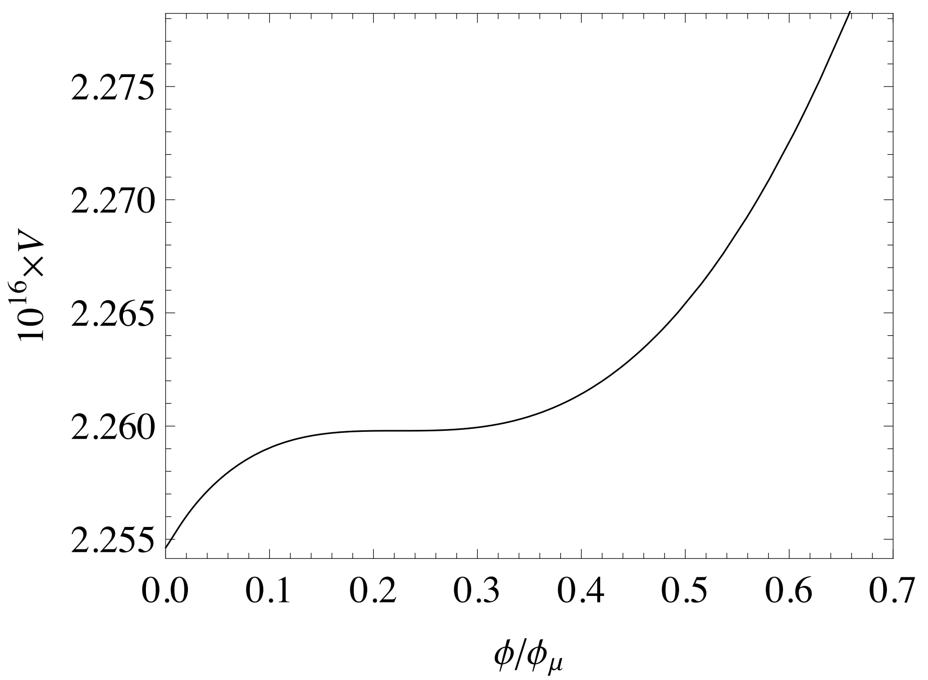
- `Accident`
- `Large self-interactions`
  Inflaton dynamics is very different with respect to the simplest scenario
- `Symmetries`

The hope is that, along the way, we find interesting ideas to further explore ....

Accident

Conceptually simple idea

Inflection point inflation: different contributions to the inflaton potential accidentally cancel, leaving a potential sufficiently flat to sustain enough inflation.



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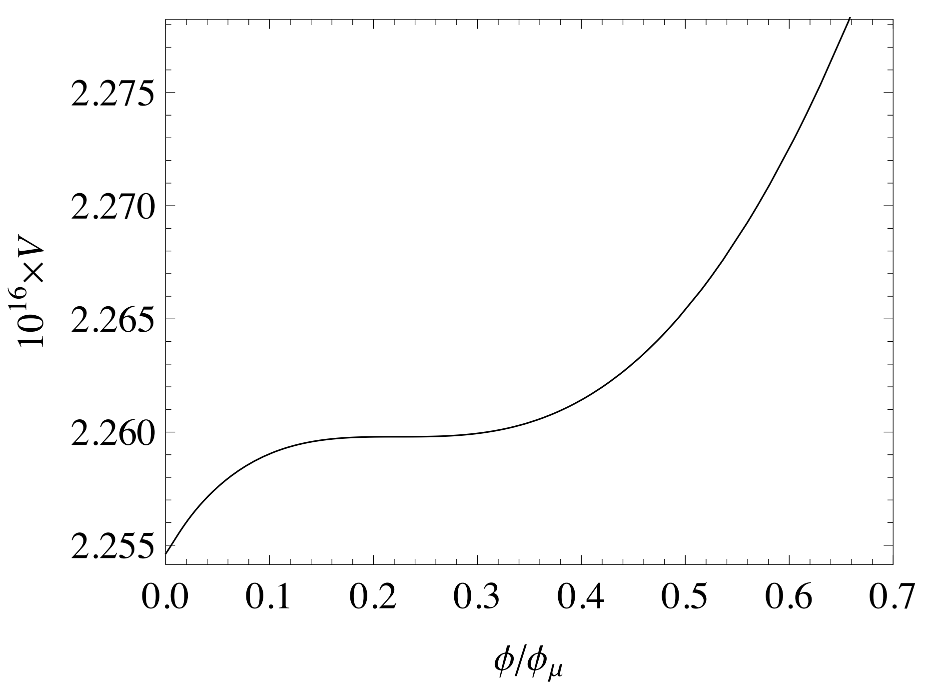

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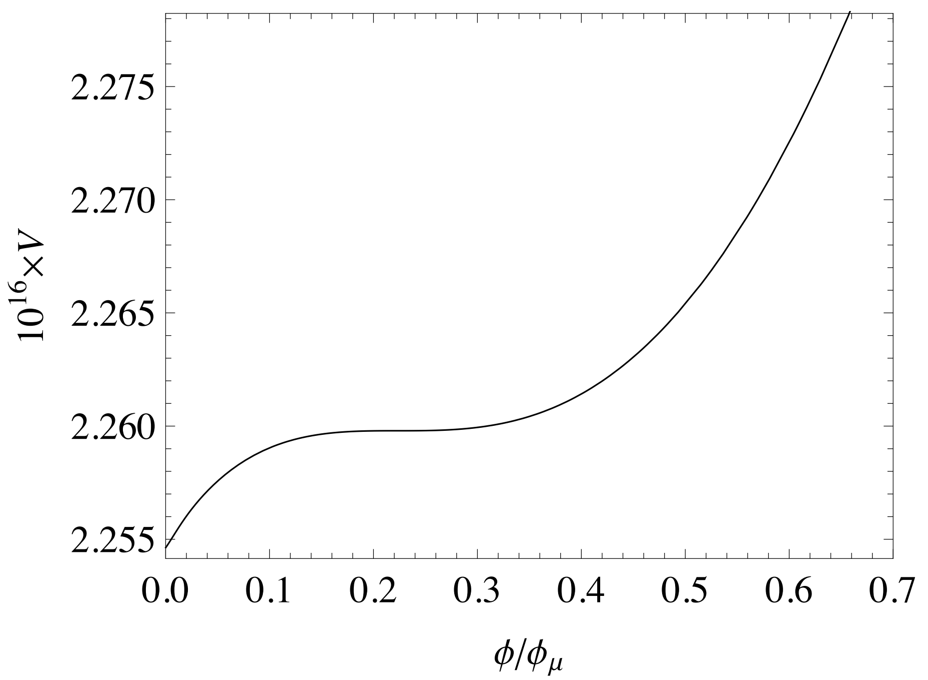

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String inflation realizes inflation within a fundamental theory of nature providing settings to `test` this possibility.

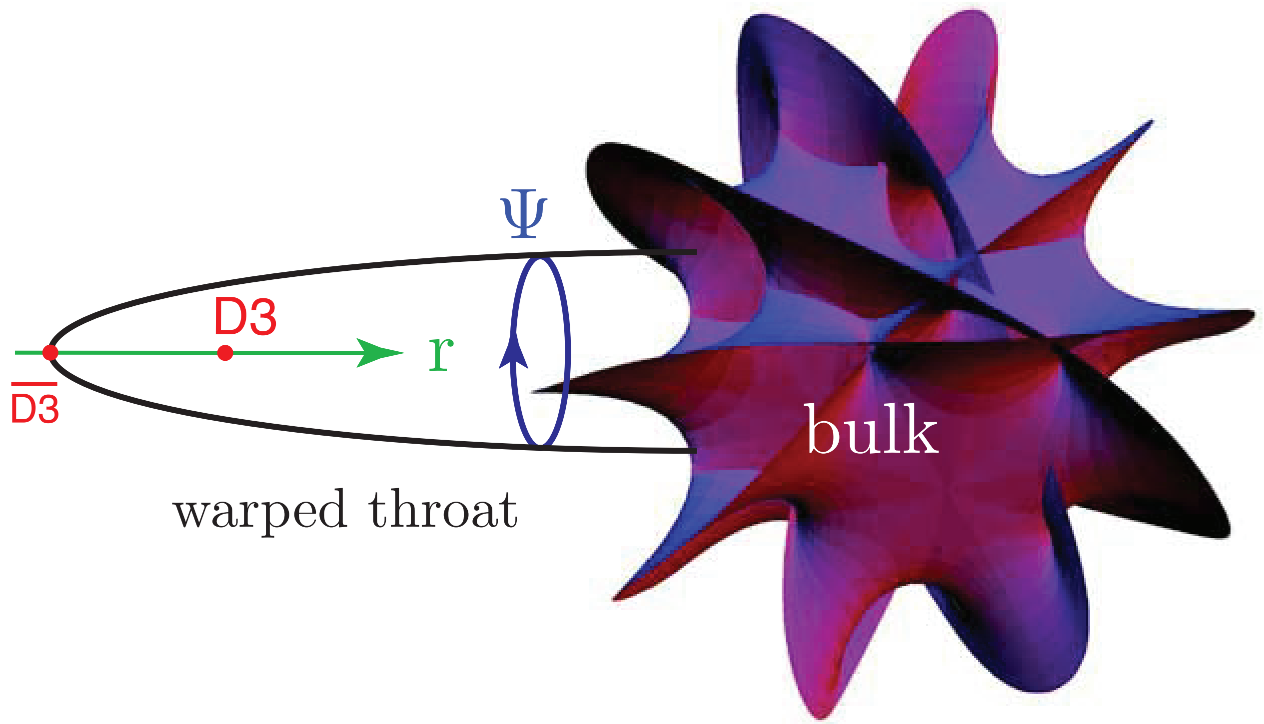
- String theory contains plenty of `light scalars` that can drive inflation

D-brane inflation:

`D3-brane embedded in a warped throat (KS space-time, throat with fluxes turned on)`

`The position of the moving D3 brane corresponds to the rolling inflaton`

- The brane feels a force associated with presence of anti-brane as well as fluxes (KKLMMT)
- Inflaton feels the influence of additional light scalars, that have to be fixed by adding wrapped D7



Burgess et al, Baumann, Klebanov et al, + others have studied in detail this system, showing that, with tunings of order of percent, sufficient inflation can be realized. } **Delicate inflation**

$$V(\phi) = V_0(\phi) + M_{\rm pl}^2 H_0^2 \left[\left(\frac{\phi}{M_{\rm pl}} \right)^2 - a_{3/2} \left(\frac{\phi}{M_{\rm pl}} \right)^{3/2} \right]$$

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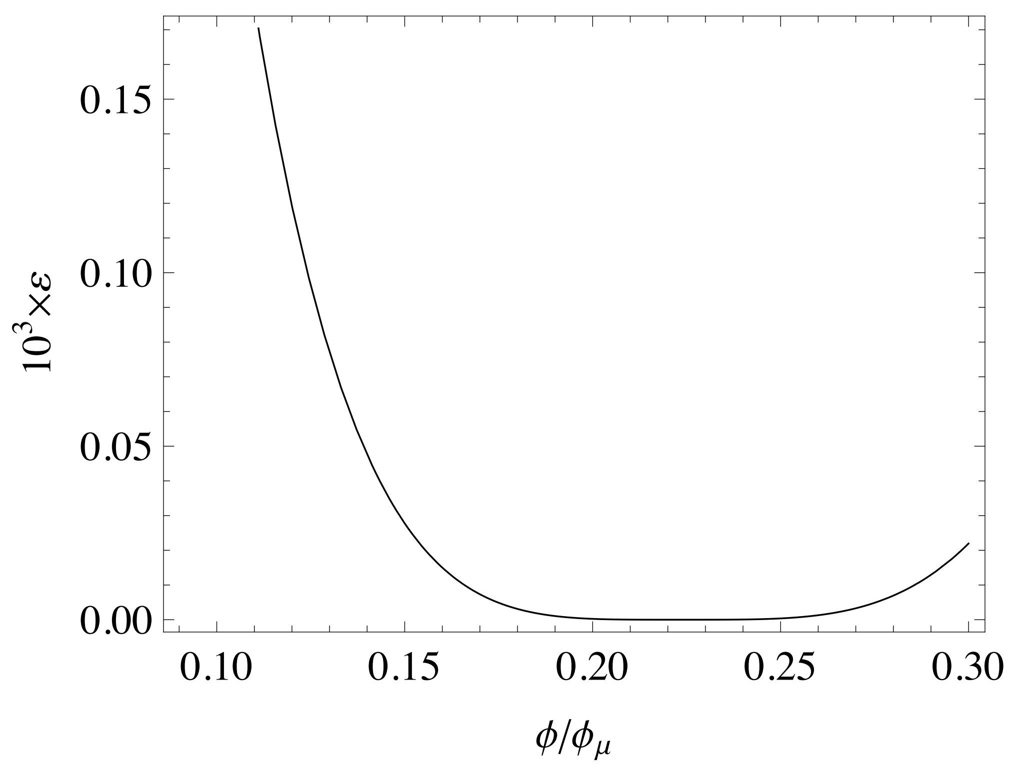
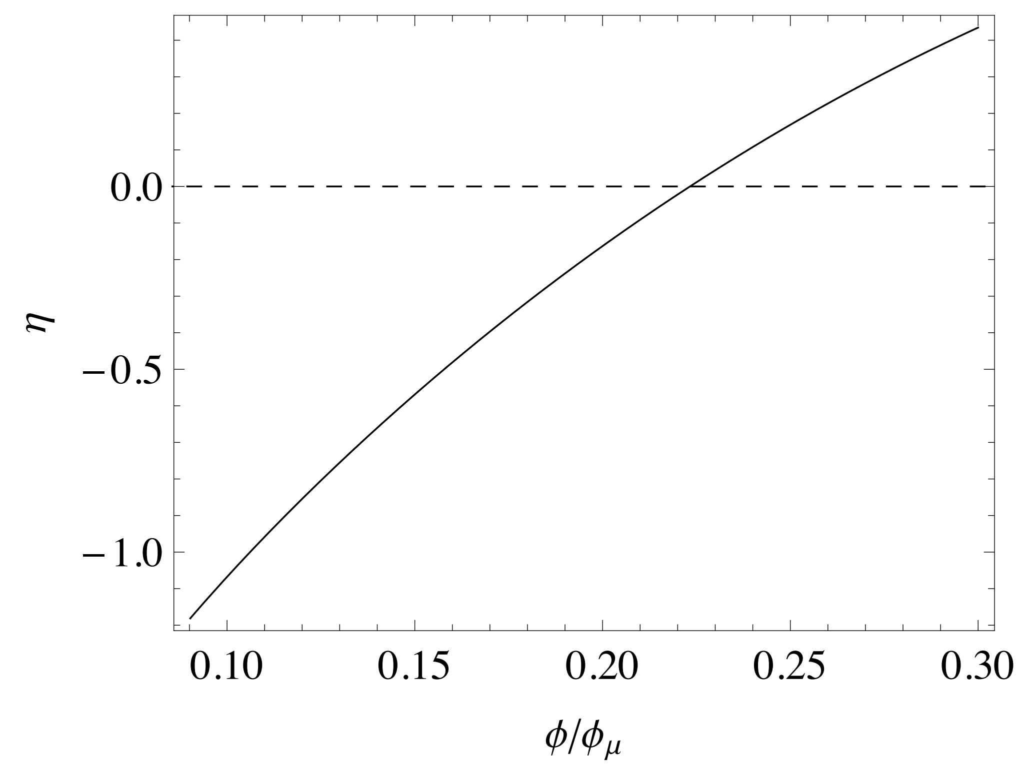
Many variations on this idea can be done:

- Warped geometries have been very well studied by string theorists to understand properties of **QCD in terms of gravity duals (AdS/CFT)**

- With Chen, Gong, Koyama we realized a multi-field version (hybrid inflation) of the original model





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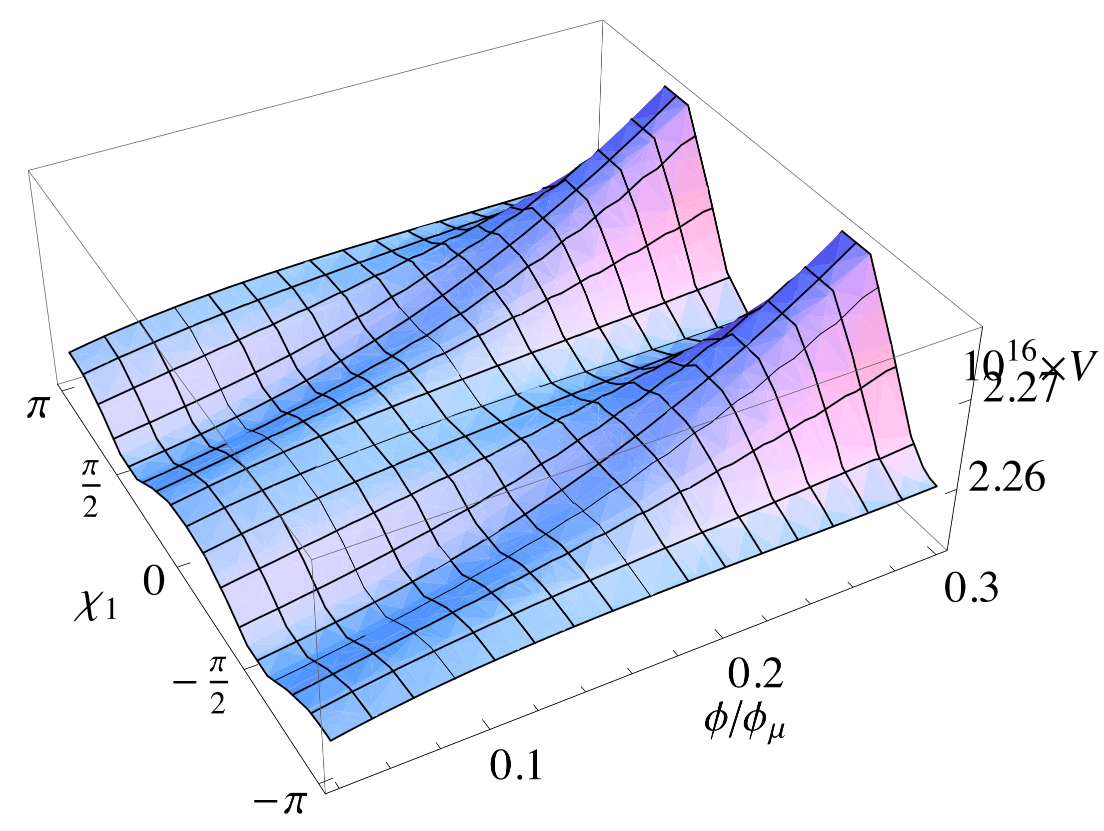

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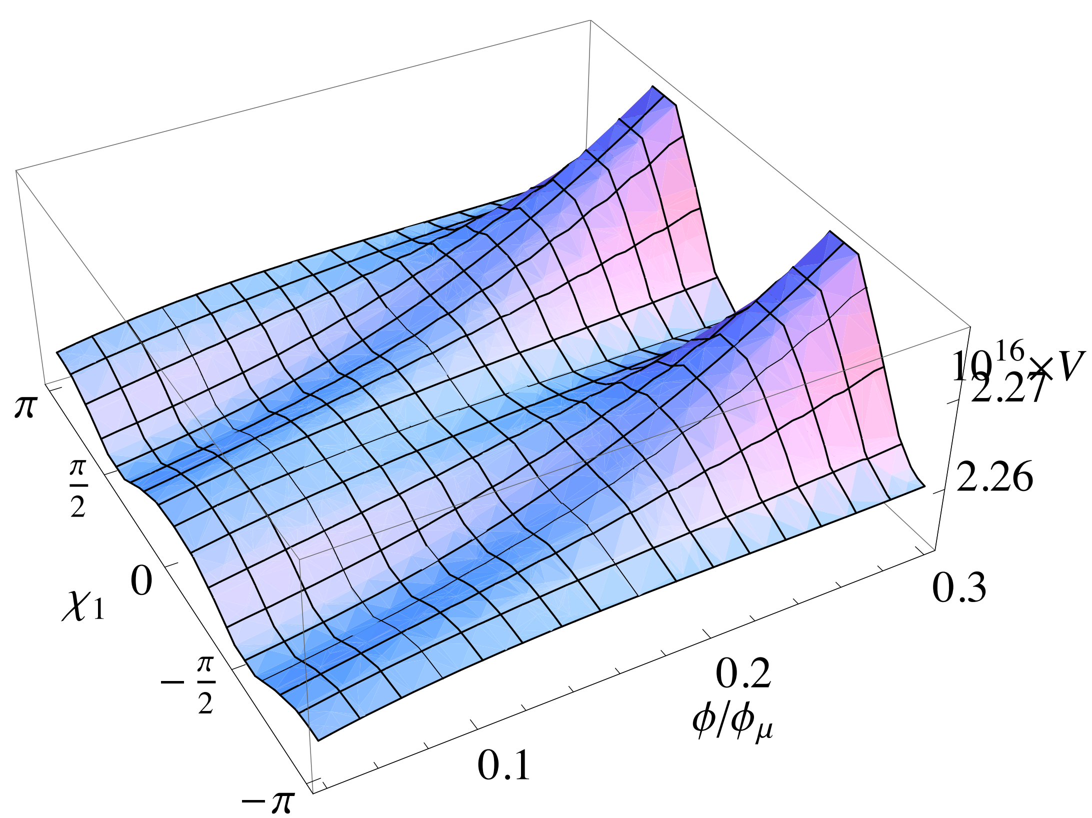

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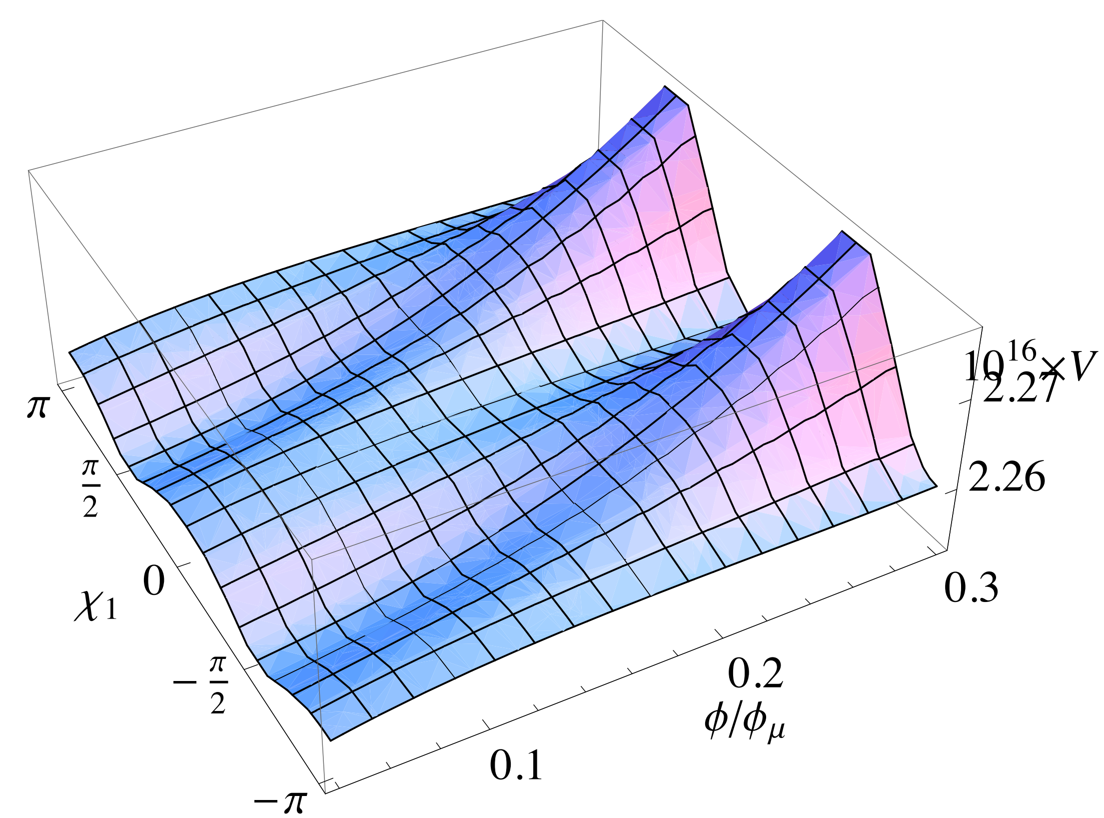

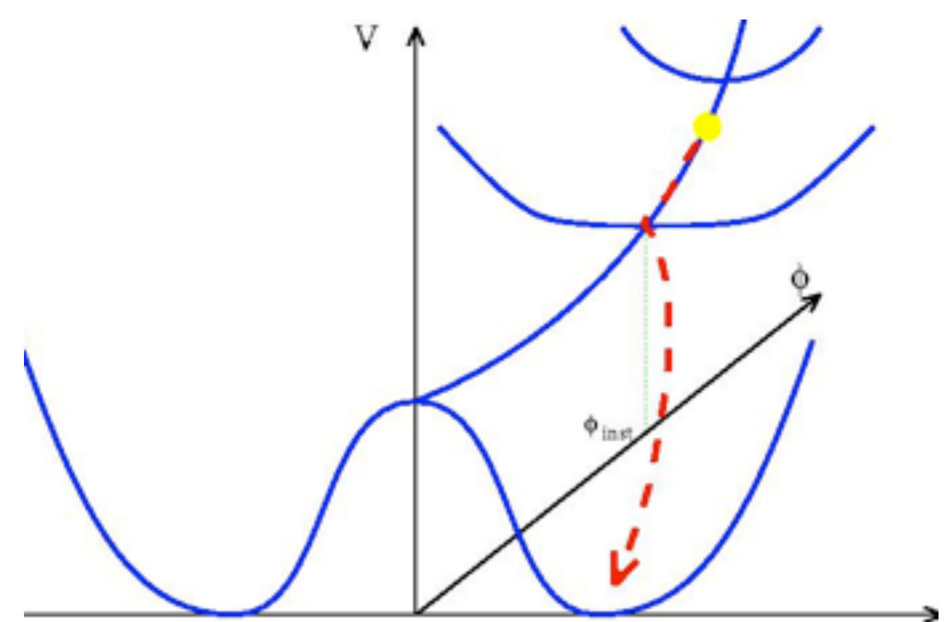

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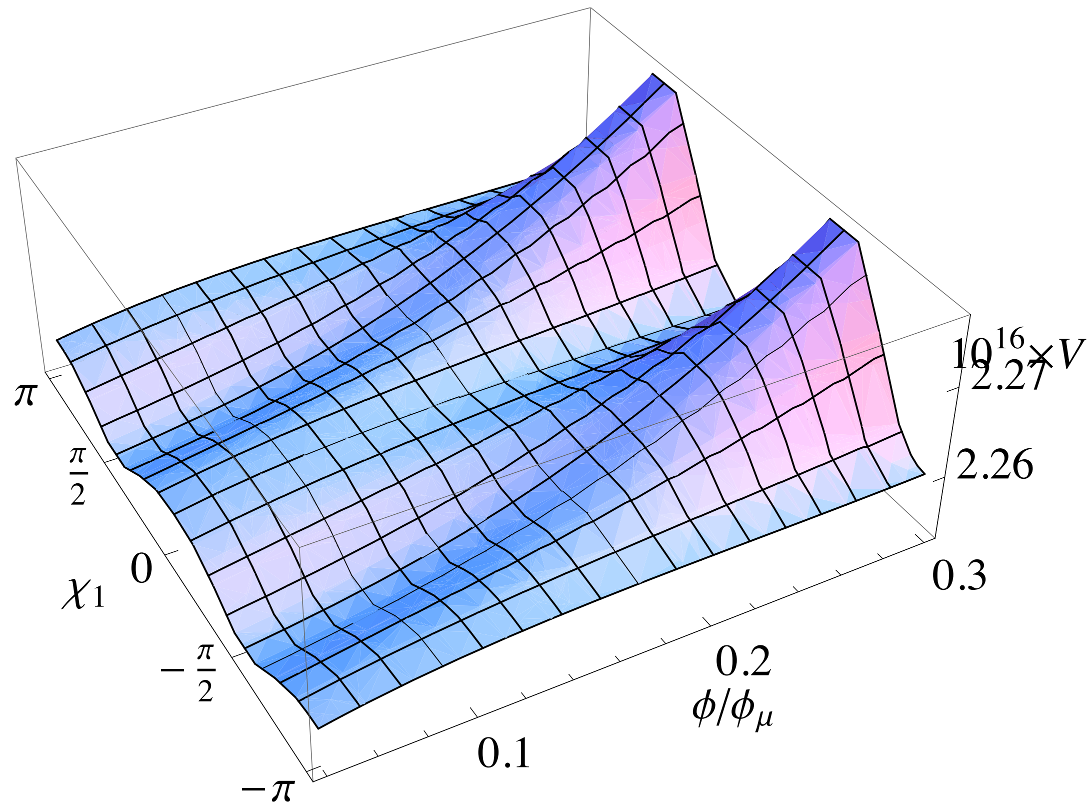
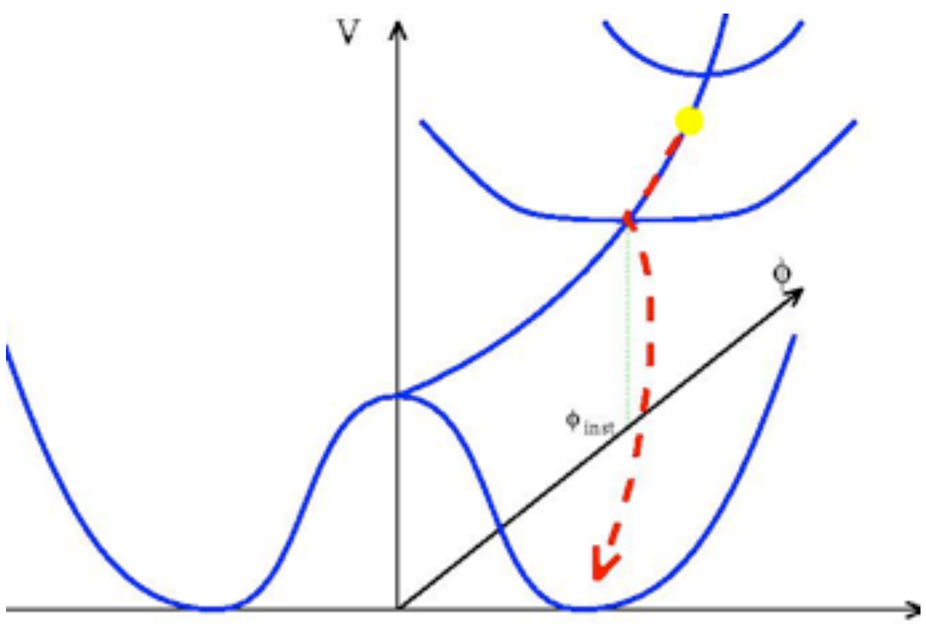
$\Rightarrow$ Use a set-up where angular directions become tachyonic towards the IR





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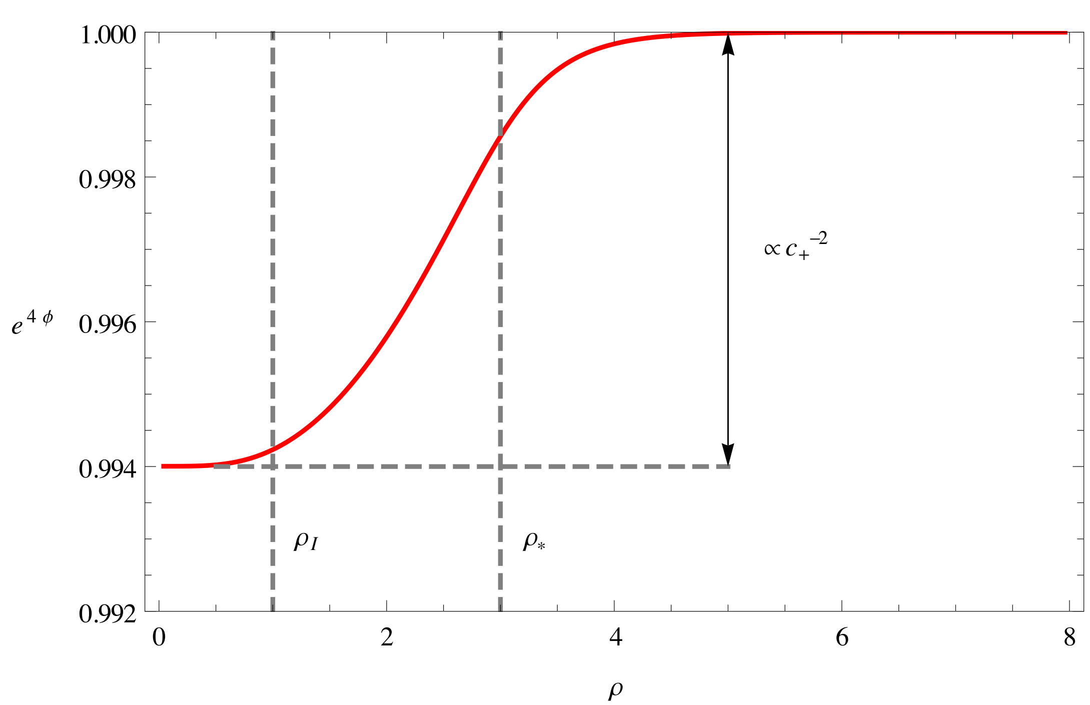

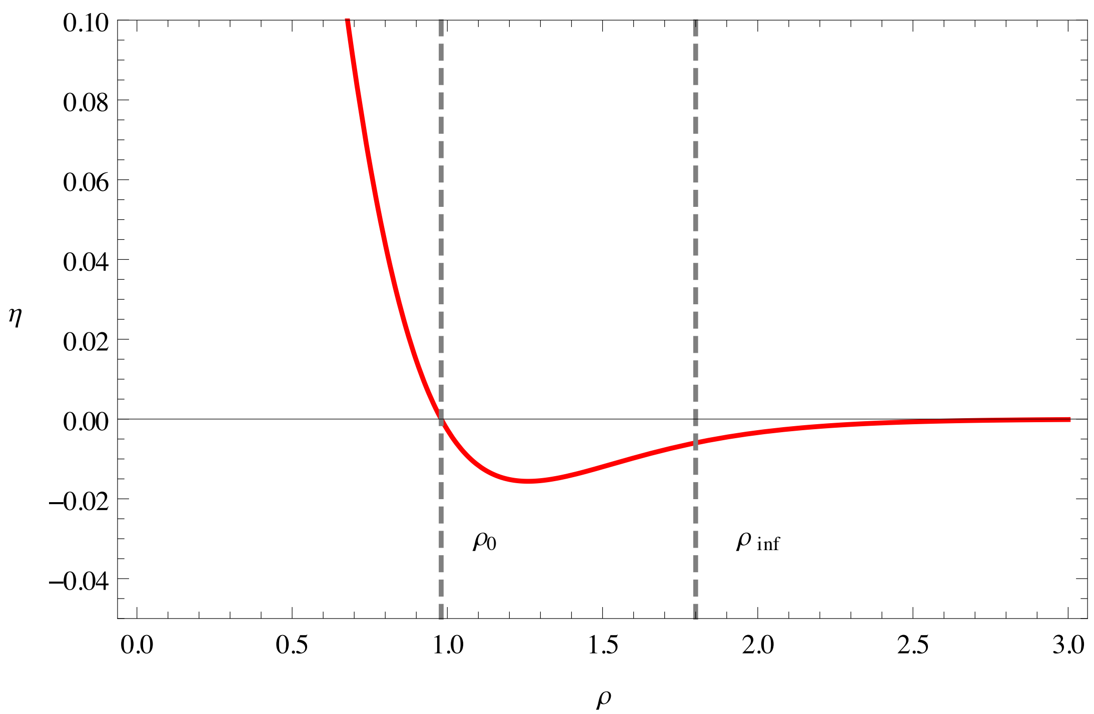

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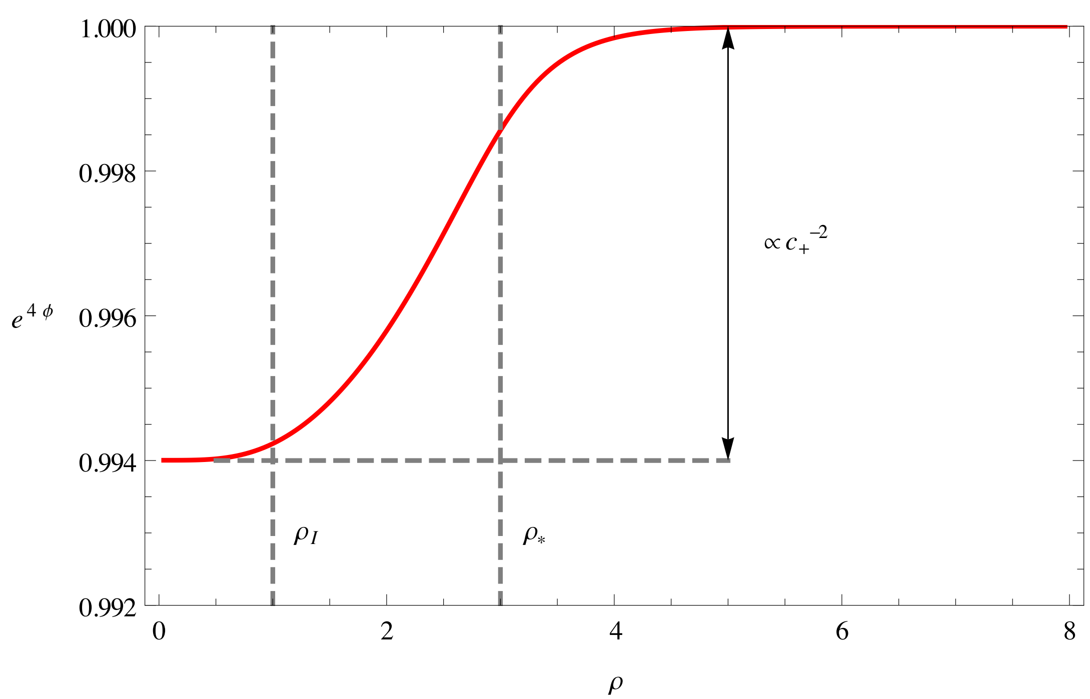

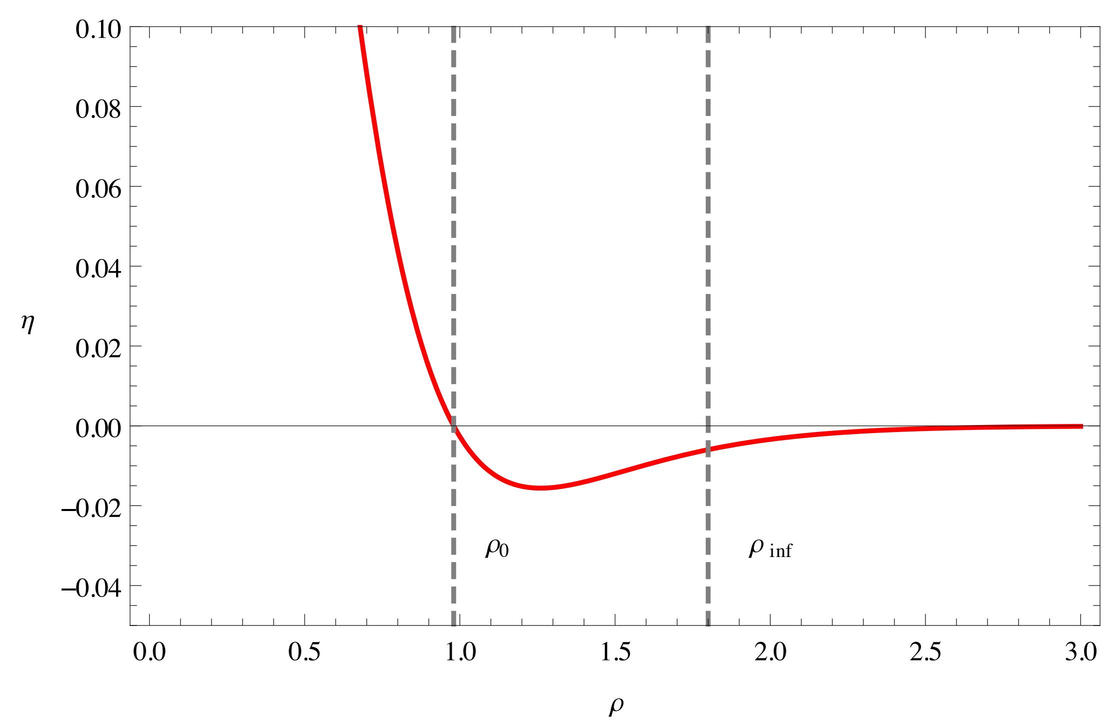

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– Strong coupling in cosmology $\Rightarrow$ Weakly coupled, computable setting in QFT side?

D-brane inflation:

- String brane inflation can realize inflection point inflation

  $\Rightarrow$ Exploits and applies the **most modern string theory techniques** for cosmology

Very interesting to exploit connections between AdS/CFT tools and cosmology

- Skenderis et al attempt to use AdS/CFT to analytically calculate dynamics of cosmological fluctuations in strongly coupled scenarios

New tools to study cosmological regimes that are difficult to analyze by analytical methods

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Predictions:

- Consistent with single field inflation, no tensor modes.
- But controllable complications can be added, that leads to features to power-spectrum or non-G

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Idea: since $f(\phi)\,\dot{\phi}^2 \leq 1$ then if $f(\phi)$ is large then inflaton velocity is bounded:

Large derivative self-interactions

Imagine that the inflaton is **not** weakly coupled, and assume one can find a realization of inflation that exploits this feature.

Then, large (expected) corrections to the inflaton mass should be **harmless** (or even welcome) for inflaton dynamics.

In order to realize this idea, we need derivative self-interactions:

hard to build consistent (ghost-free) theories containing them, but possible: DBI inflation; G-inflation; Galileon inflation.

DBI inflation can be **motivated** from string theory: a high energy completion that allows to analyze naturalness issues in this context.

$$S_{DBI} = -\int d^4x\,\sqrt{-g}\,\left[\frac{1}{f(\phi)}\left(\sqrt{1-f(\phi)\,\dot{\phi}^2}-1\right)+V(\phi)\right]$$

Idea: since $f(\phi)\,\dot{\phi}^2 \leq 1$ then if $f(\phi)$ is large then inflaton velocity is bounded:

No matter how large the inflaton mass is!

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Great idea for our eta problem:

- Mass of inflaton can become arbitrarily large without spoiling inflation $c_s = \sqrt{1 - f(\phi)\,\dot{\phi}^2} \leq 1$
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- Couplings between different branes might be enough to avoid the previous problem.

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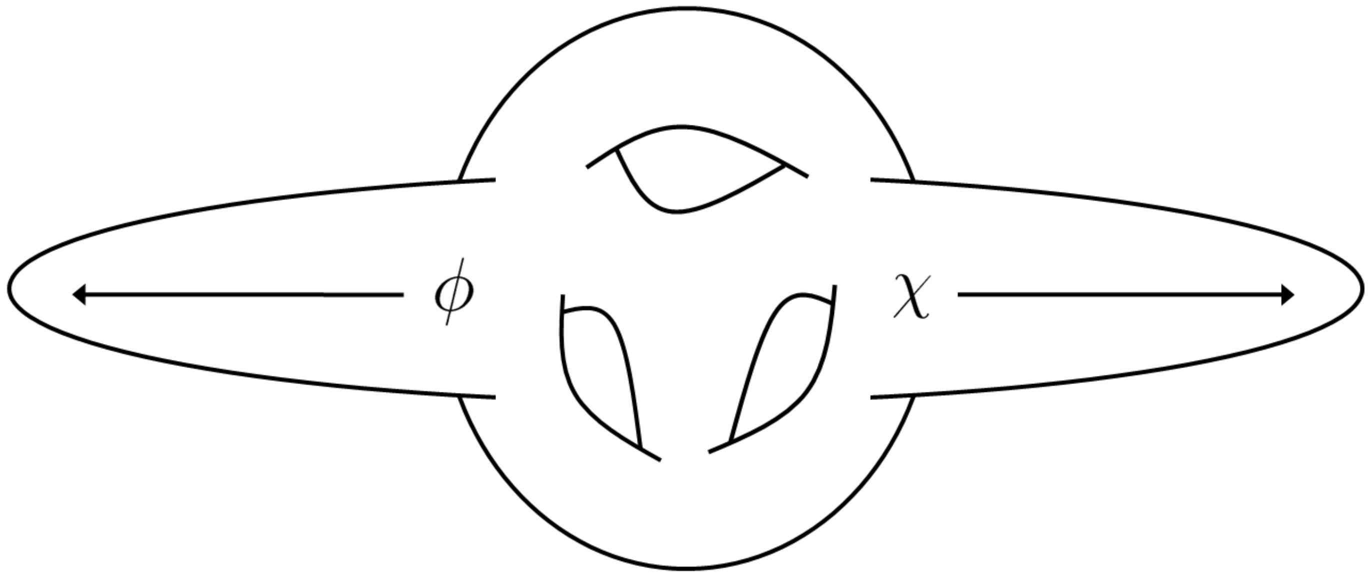
- **Dynamics of cosmological perturbations change, due to conversion of isocurvature into adiabatic fluctuations**

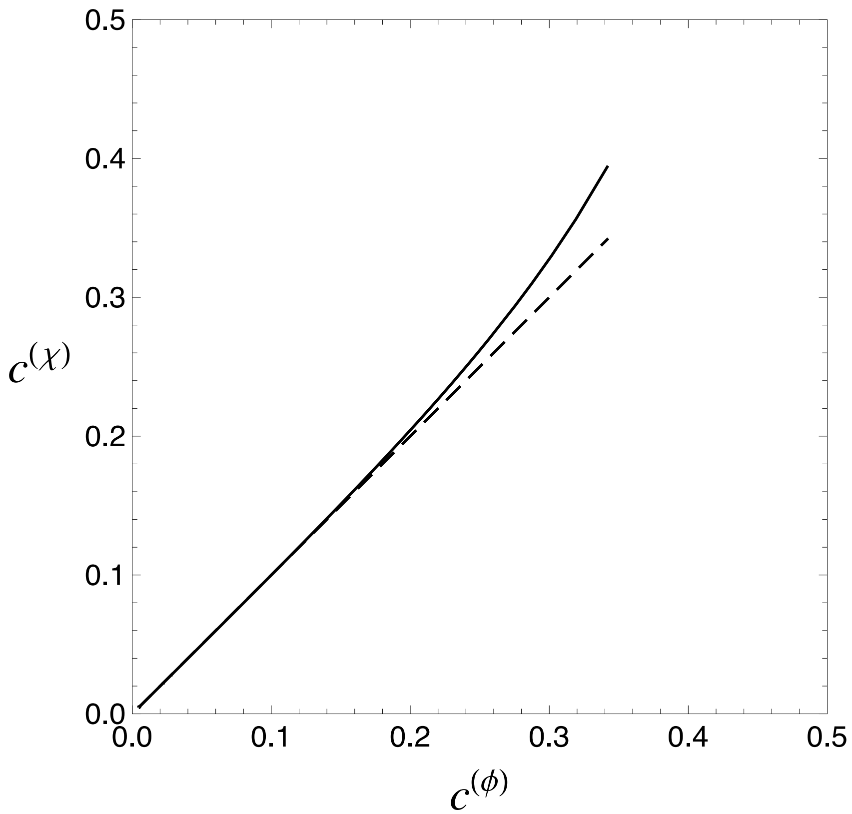
Large derivative self-interactions



- **Both** `local` and `equilateral` non-G can be generated.

- Equilateral nonG produced at horizon exit, that must then be evolved at superhorizon scales; at the same time local non-G is produced

Large derivative self-interactions



- With Emery and Wands we studied in detail a set-up in which large (but tunable) non-G of both shapes can be produced depending on initial conditions and choice of model parameters

$$f_{\rm NL}^{(3)}(k_1,k_2,k_3) = \frac{5}{6}\frac{\Lambda(k_1,k_2,k_3)}{\sum_i k_i^3}\frac{1}{c_\star^2}\frac{\left(\frac{u^3}{\epsilon_\star^{(\phi)2}}+\frac{v^3}{\epsilon_\star^{(\chi)2}}\right)}{\left(\frac{u^2}{\epsilon_\star^{(\phi)}}+\frac{v^2}{\epsilon_\star^{(\chi)}}\right)^2},$$

$$\frac{6}{5}f_{\rm NL}^{(4)} = \frac{\frac{u^2}{\epsilon_\star^{(\phi)}}\left(1-\frac{(\eta_\star^{(\phi)}+s_\star^{(\phi)})}{\epsilon_\star^{(\phi)}}u\right)+\frac{v^2}{\epsilon_\star^{(\chi)}}\left(1-\frac{(\eta_\star^{(\chi)}+s_\star^{(\chi)})}{\epsilon_\star^{(\chi)}}v\right)+2\left(\frac{u}{\epsilon_\star^{(\phi)}}-\frac{v}{\epsilon_\star^{(\chi)}}\right)^2\mathcal{A}}{\left(\frac{u^2}{\epsilon_\star^{(\phi)}}+\frac{v^2}{\epsilon_\star^{(\chi)}}\right)^2}.$$

Large derivative self-interactions

DBI, Hordenski, Galileon, etc etc

- Very nice theoretical idea to address naturalness issues
- It exploits large derivative self-interactions
  - General prediction: large non-Gaussianity are produced
  - **But** this conclusion can be avoided: non-Gaussianities might result of a size that's just below Planck sensitivity

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  - General prediction: large non-Gaussianity are produced
  - **But** this conclusion can be avoided: non-Gaussianities might result of a size that's just below Planck sensitivity
- Maybe correct, but sounds very strange....

  Analogy: Technicolor scenario for explaining EWSB in particle physics models

Symmetries

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What are the possibilities?

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- **Supersymmetry** Doesn't work: susy breaking scale is of order Hubble parameter

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Question: Can you find a UV completion?

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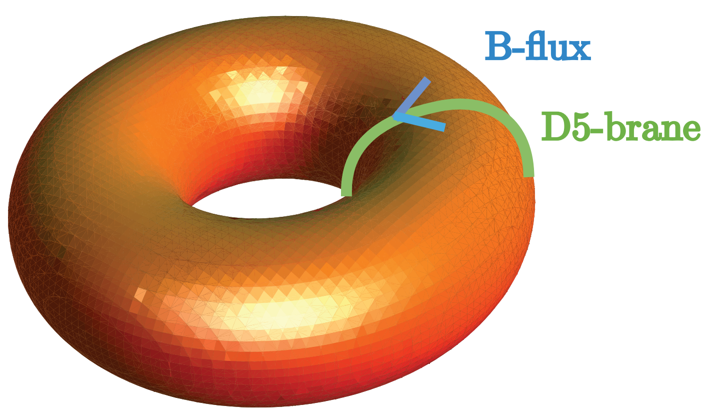

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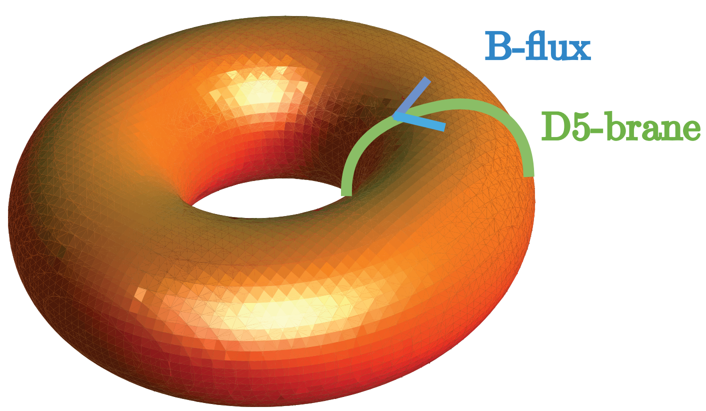

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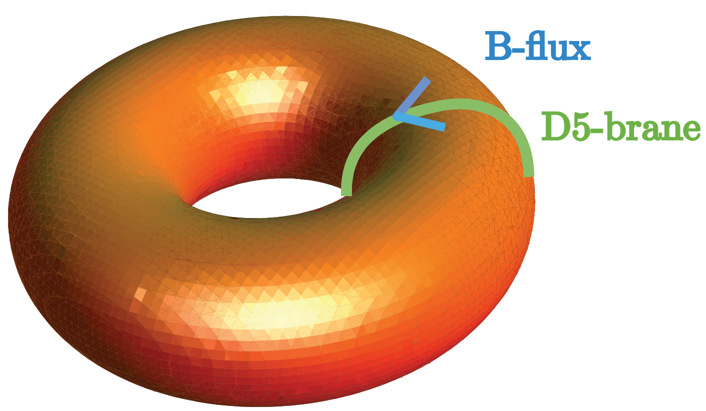

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Problems?

- The mechanism works for NS5 branes: delicate issues of backreaction...
- What about **reheating**? how does the inflaton couple to matter without spoiling shift symmetry?

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▷ **No-scale symmetry** Low energy limit of string theory is supergravity. F-term potential for $\mathcal{N} = 1$ sugra is

$$V_F = e^{K/M_{Pl}^2} \left(K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - \frac{3\,|W|^2}{M_{Pl}^2} \right)$$

Consider case in which

$$\sum_{i\bar{j}} K^{i\bar{j}} K_i K_{\bar{j}} = 3 \qquad \text{(no-scale condition)}$$

$$W = W_0$$

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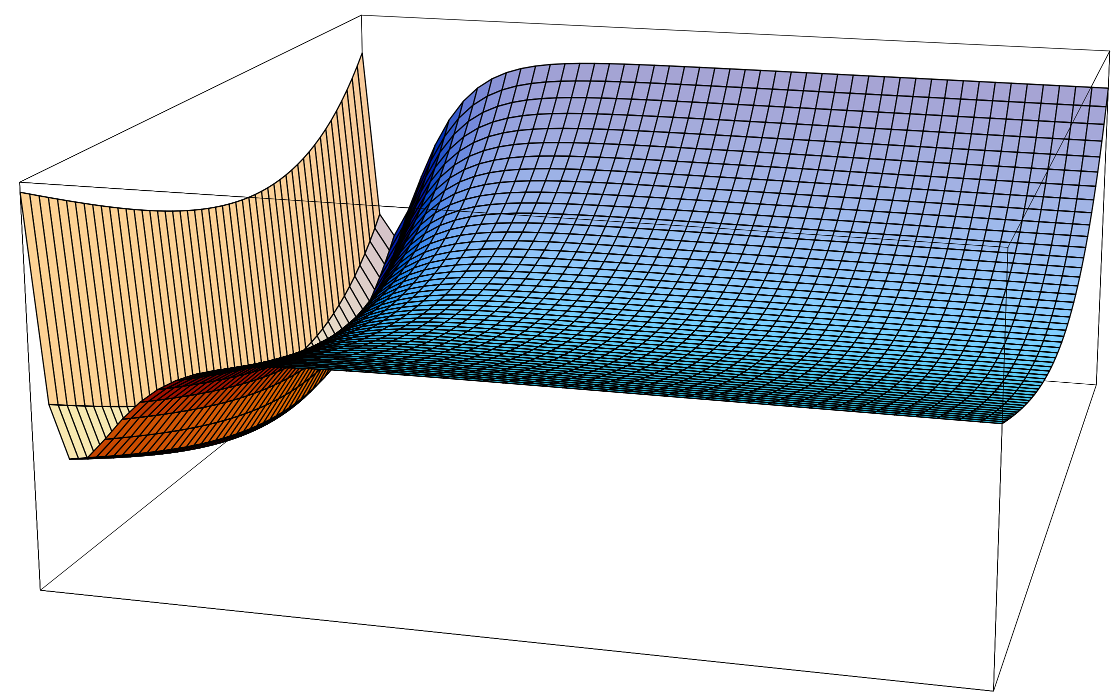
Inflaton: Kähler (closed) modulus in IIB string theory

$$V = V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\exp\left[-a_n\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\right]$$



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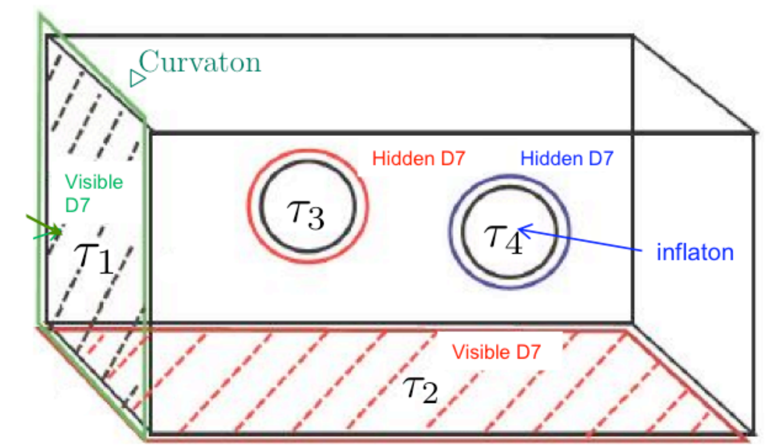
In this scenario **modulation mechanisms** can be implemented

– There are other light moduli associated with features of the geometry: they `do not directly couple to the inflaton field`



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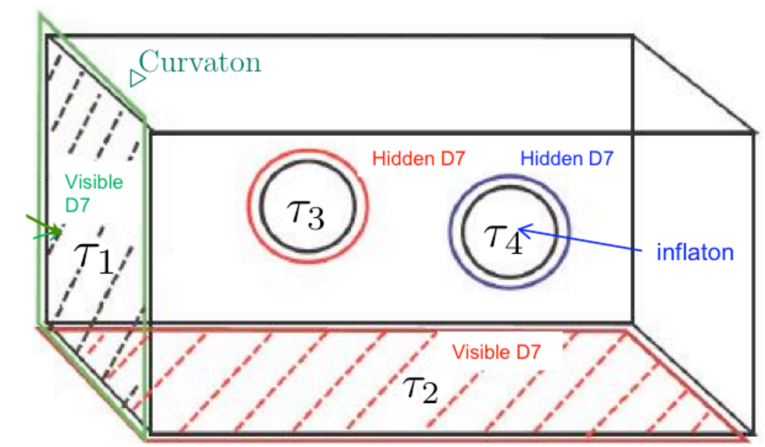

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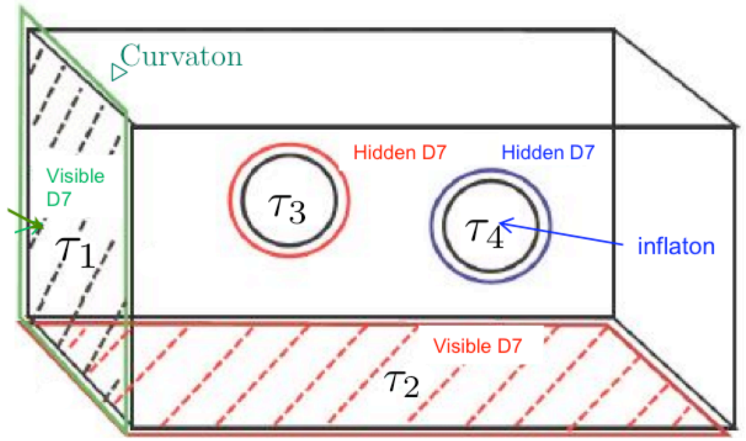

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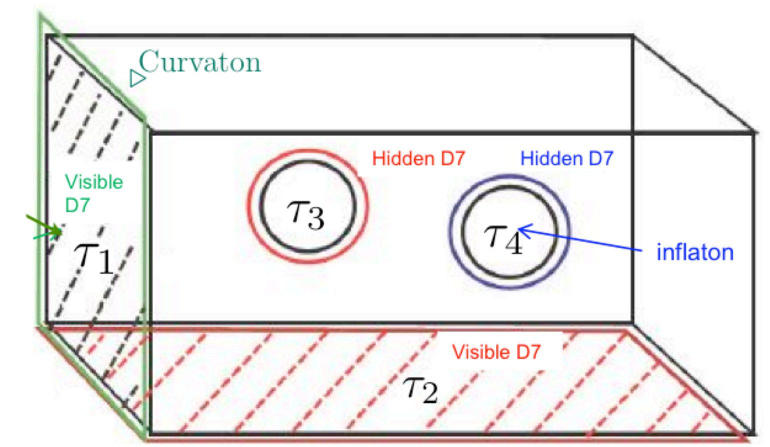

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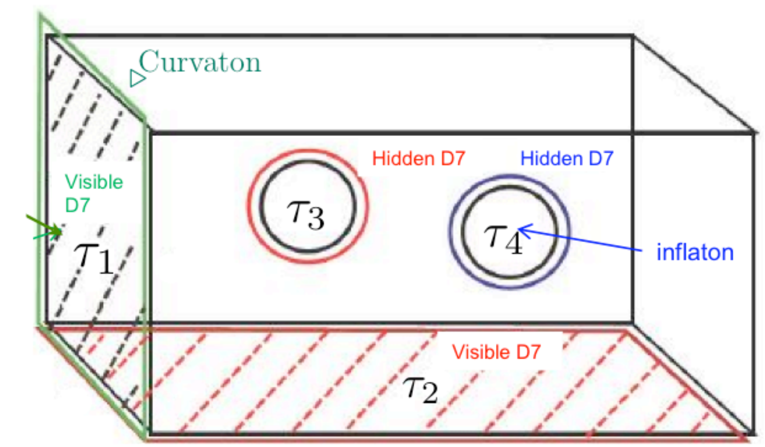

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– It is possible to **explicitly compute** couplings between these moduli and SM-like fields, living on wrapped D7 branes

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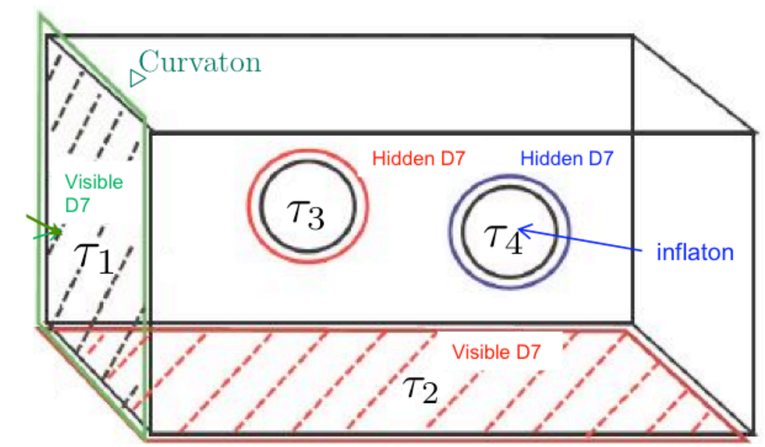

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$$V_{cur}(\hat{\chi}_1) = \frac{g_s\, W_0^2}{8\pi\, \mathcal{V}^{10/3}} \left[C_0\, e^{\frac{2}{\sqrt{3}}\hat{\chi}_1} - C_1\, e^{-\frac{1}{\sqrt{3}}\,\hat{\chi}_1} + C_2\, e^{-\frac{4}{\sqrt{3}}\,\hat{\chi}_1} \right] ,$$

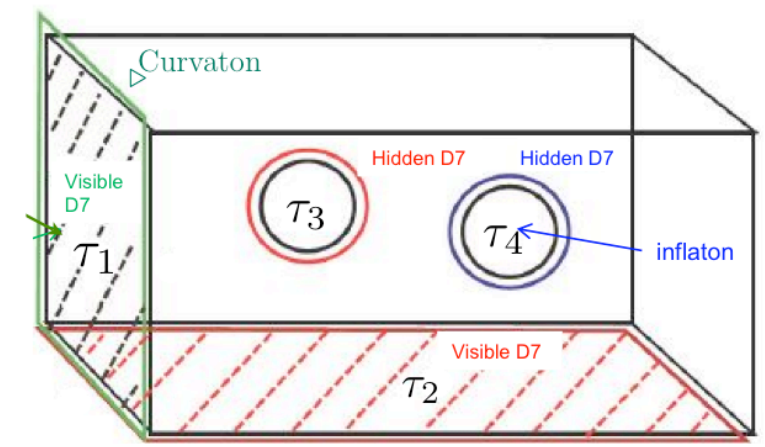
– It is possible to **explicitly compute** couplings between these moduli and SM-like fields, living on wrapped D7 branes

$$\mathcal{L}_{gauge} = -\frac{\tau}{M_p} F_{\mu\nu} F^{\mu\nu} ,$$

Curvaton in LV scenarios

In this scenario **modulation mechanisms** can be implemented

– There are other light moduli associated with features of the geometry: they `do not directly couple to the inflaton field`



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Computing non-Gaussianity, we find non-G of local shape with

$$f_{\rm NL}^{loc} = 2 \qquad (\texttt{Planck value } f_{\rm NL}^{loc} = 2.7 \pm 5.8)$$