Title: Inflation in String Theory

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Abstract: TBA

Microscopic Aspects of Inflation in String Theory

Daniel Baumann

Princeton University

Perimeter Institute, March 2008

Inflation

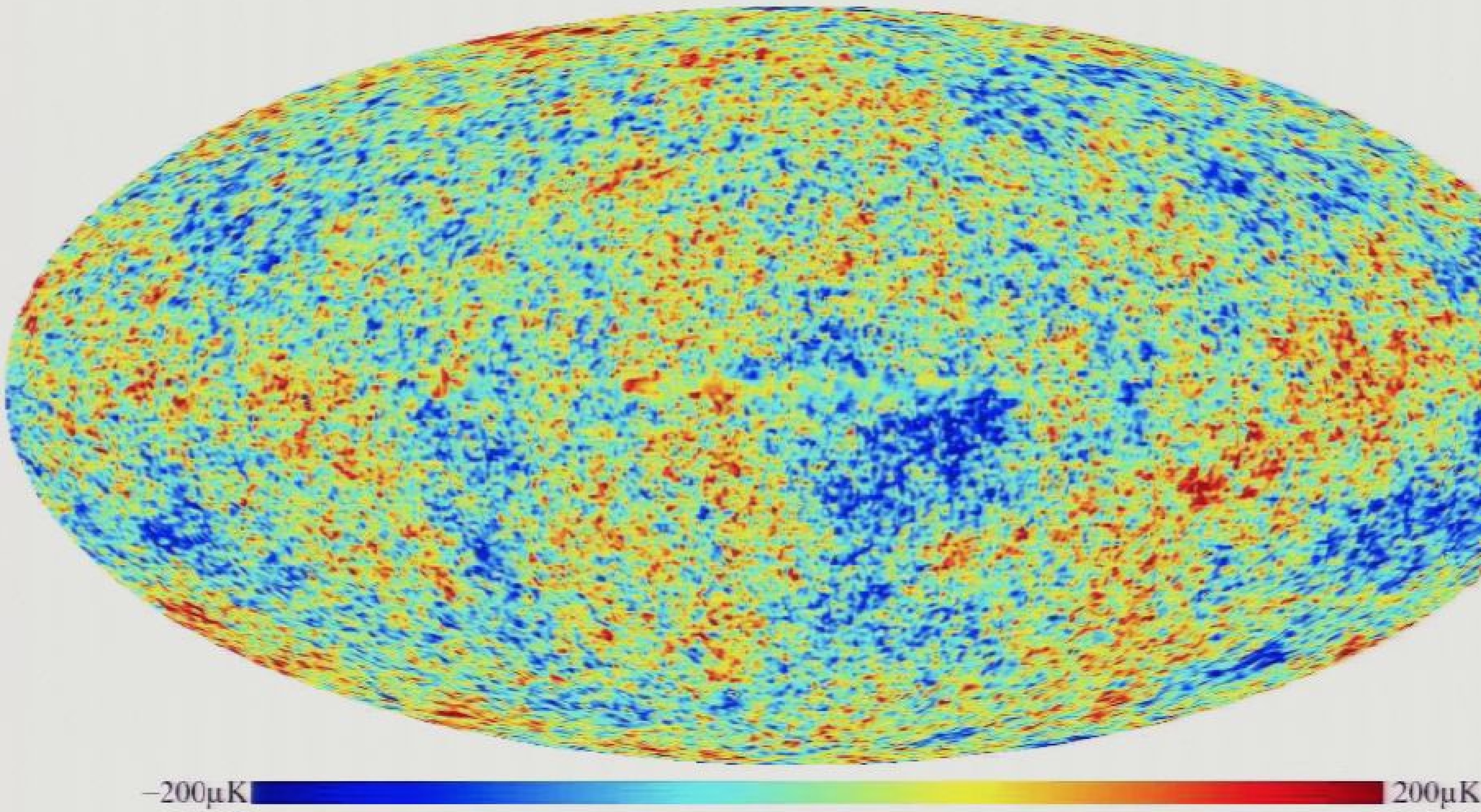
A period of accelerated expansion

Guth; Linde; Albrecht & Steinhardt.

$$ds^2 = -dt^2 + e^{2Ht} d\mathbf{x}^2 \qquad H \approx \text{const.}$$

- Solves horzion, flatness and monopole problems, *i.e.* explains why the universe is so large, so flat and so empty.
- Predicts scalar fluctuations in CMB temperature:
  - approximately, but not exactly, scale-invariant
  - approximately Gaussian
- Predicts primordial tensor fluctuations $=$ gravitational waves

The Golden Age of Cosmology



Standard Model of Cosmology

Observations:

- Homogeneous Background

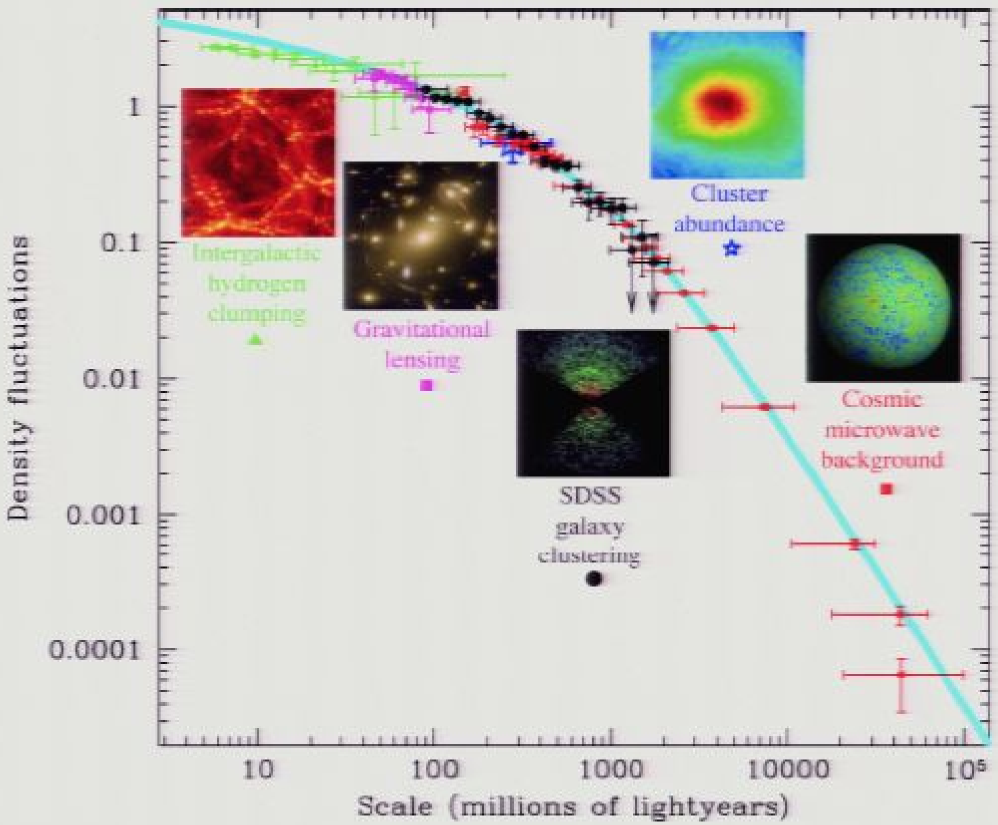
  $\Omega_b,\ \Omega_{dm},\ \Omega_\Lambda,\ h,\ \tau$

  - Atoms 4%
  - Dark Matter 23%
  - Dark Energy 72%

- Fluctuations

  $A_s,\ n_s,\ r,\ f_{\rm NL}$

  - (nearly) scale-invariant
  - adiabatic
  - Gaussian (?)



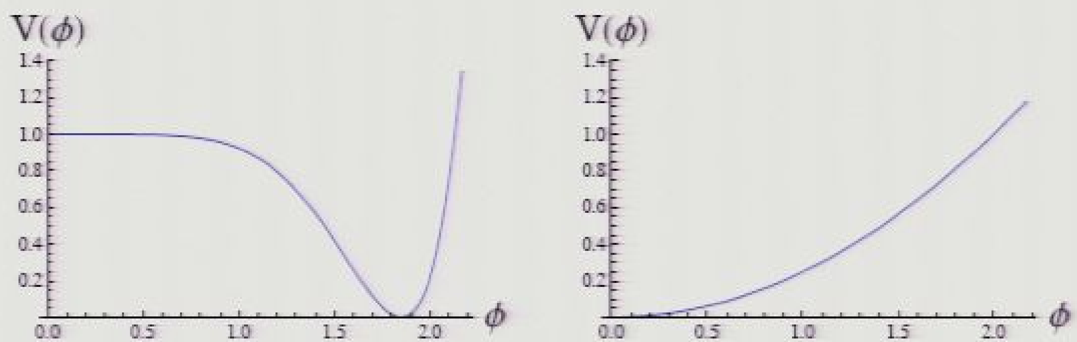
Standard Model of Cosmology

Theory:

- ΛCDM
  - Dark matter?
  - Dark energy?
- **Inflation**

  What is the physics of inflation?

  - Potential $V(\phi)$?



  - Tensors r?

    r will be strongly constrained in the near future. Models which produce an observable signal require a proper UV understanding.

Today's Talk

- Focus on a specific, concrete model of string inflation:

  warped D-brane inflation.

- Understand the predictions for

  $V(\phi)$ and r

  as fully and explicitly as possible.

Outline

Based on

- D.B., McAllister,
  A Microscopic Limit on Gravitational Waves from D-brane Inflation

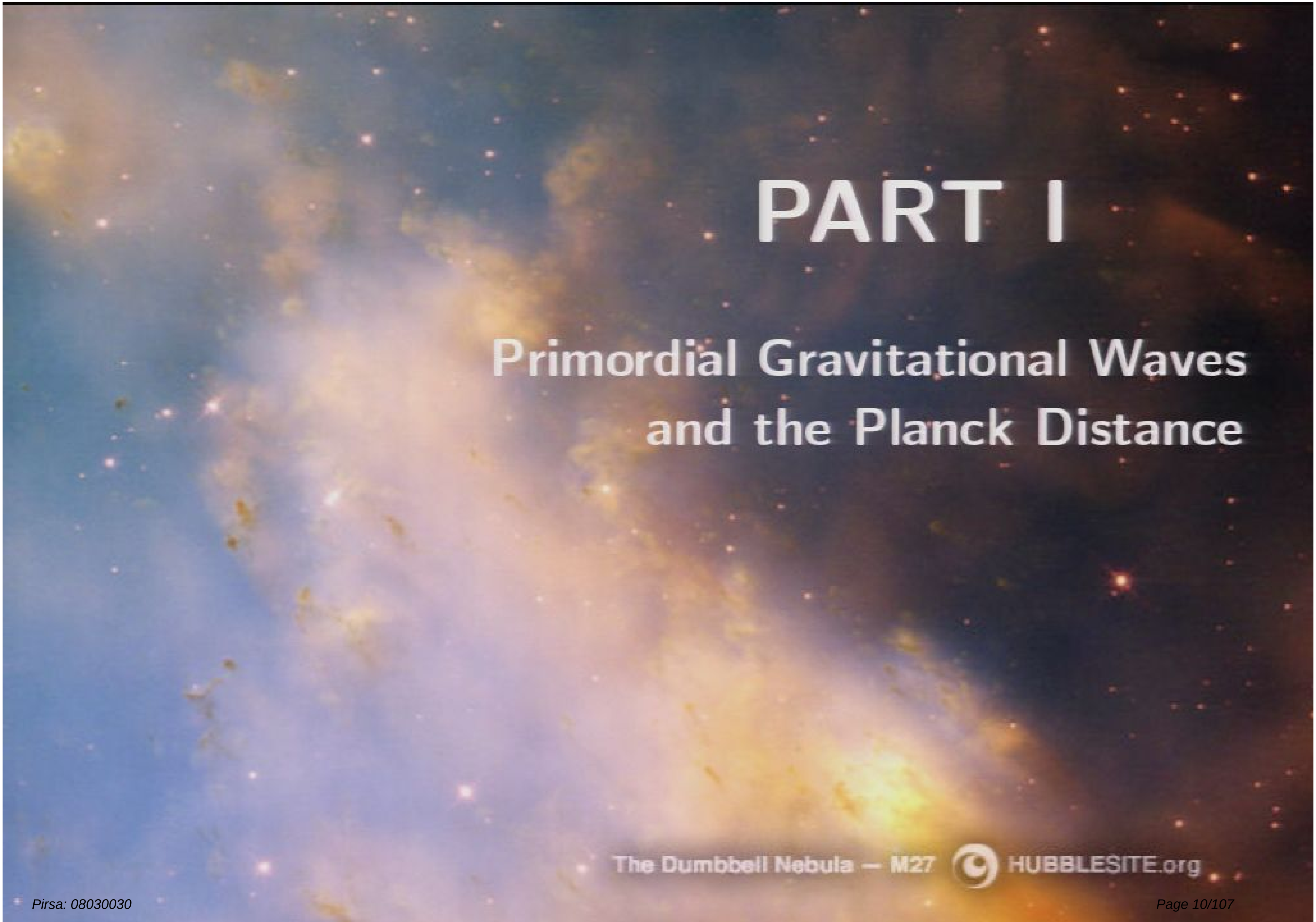
- D.B., Dymarsky, Klebanov, McAllister,
  Towards an Explicit Model of D-brane Inflation
- D.B., Dymarsky, Klebanov, McAllister, Steinhardt,
  A Delicate Universe: Compactification Obstacles to D-brane Inflation
- D.B., Dymarsky, Klebanov, Maldacena, McAllister, Murugan,
  On D3-brane Potentials in Compactifications with Fluxes and Wrapped D-branes

- D.B., Dymarsky, Kachru, Klebanov, McAllister,
  work in progress

- D.B.,
  Aspects of Inflation in String Theory (PhD thesis)

PART I

Primordial Gravitational Waves and the Planck Distance



Quantum Fluctuations in de Sitter

tensors (δg_{ij})

$$P_t \propto \frac{H^2}{M_{\rm pl}^2}$$

scalars $(\delta\rho)$

$$P_s \propto H^2 \left(\frac{H}{\dot\phi}\right)^2$$

$$\delta\phi \times (\delta\phi \to \delta\rho)$$

tensor-to-scalar ratio

$$r \equiv \frac{P_t}{P_s} = 8\left(\frac{1}{M_{\rm pl}}\frac{{\rm d}\phi}{{\rm d}N_e}\right)^2$$

where

$${\rm d}N_e \equiv {\rm d}\ln a = H{\rm d}t = \left(\frac{H}{\dot\phi}\right){\rm d}\phi$$

The Lyth Bound

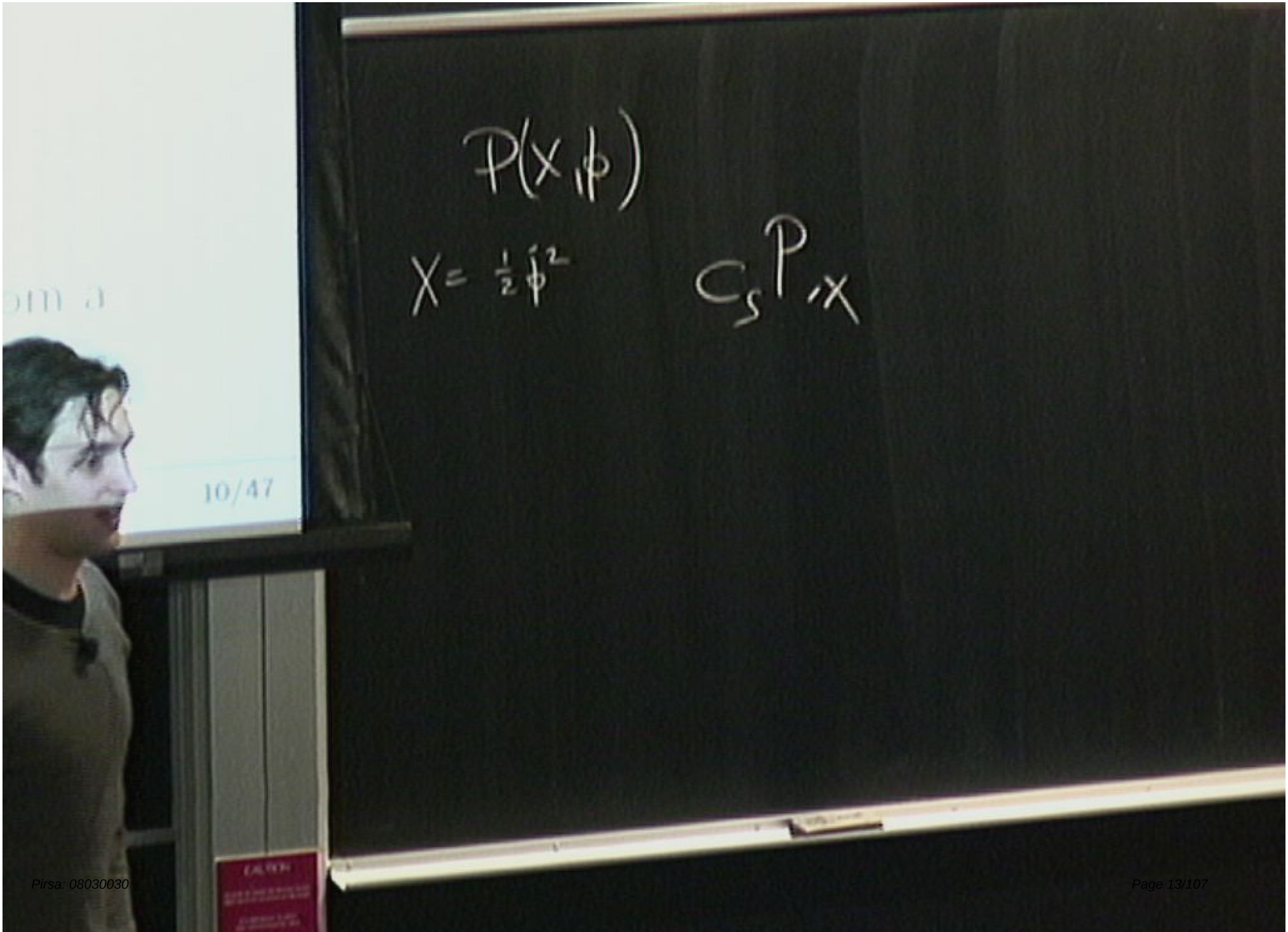
$$r = 8\left(\frac{1}{M_{\rm pl}}\frac{\mathrm{d}\phi}{\mathrm{d}N_e}\right)^2$$

$$\frac{\Delta\phi}{M_{\rm pl}} = \int_{\phi_{\rm end}}^{\phi_\star} \mathrm{d}N_e \sqrt{\frac{1}{8} r(N_e)}$$

Let $r_\star$ be the value of r on observable scales $(N_e(\phi_\star) \sim 60)$ and the Lyth bound follows

$$\frac{r_\star}{0.01} < \frac{8}{9}\left(\frac{\Delta\phi}{M_{\rm pl}}\right)^2$$

- This is a useful constraint if we can compute $\left(\frac{\Delta\phi}{M_{\rm pl}}\right)_{\rm max}$ from a microscopic theory.


P(X, φ)
X = ½ φ̇²
c_s P_{,X}
10/47

$$P(X, \phi) = X - V$$

$$X = \frac{1}{2}\dot{\phi}^2$$

$$c_s \quad P_{,X}$$

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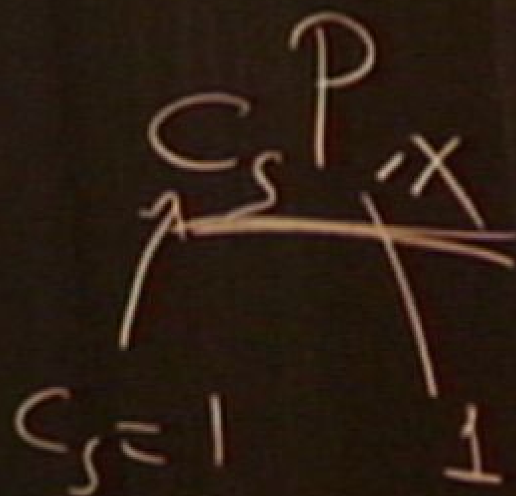

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What if we see tensors?

Current constraint on tensors: $r_\star \lesssim 0.4$.

Realistically observable: $r_\star \gtrsim 0.01$.

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Two pieces of information will result from a measurement of r:

1. **Energy-scale of Inflation**

   The measured amplitude of scalar perturbations $P_s \sim \left(\frac{\delta\rho}{\rho}\right)^2 \sim 10^{-10}$ (and $H^2 \approx \frac{1}{3M_{\rm pl}^2} V$) implies:

$$V^{1/4} \sim \left(\frac{r_\star}{0.01}\right)^{1/4} 10^{16}\ \mathrm{GeV}$$

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2. **Super-Planckian Field Variation**

   Observable gravitational waves require $\Delta\phi > M_{\rm pl}$ during inflation:

   $$\frac{\Delta\phi}{M_{\rm pl}} > \mathcal{O}(1) \left(\frac{r_\star}{0.01}\right)^{1/2}$$

   e.g. $V(\phi) = \frac{1}{2}m^2\phi^2$ requires $\Delta\phi \sim 15 M_{\rm pl}$.

The Microphysics of Observable Tensors

- Observable tensors ($r_\star > 0.01$) require

  $\Delta\phi > M_{\rm pl}$ *and* **controllably flat potentials:**

  Is this realizable in a **consistent microscopic theory** like string theory?

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- *Controversial* Effective Field Theory Arguments: (cut-off $\Lambda \leq M_{\rm pl}$)
  - $V(\phi)$ can be reliably computed only over $\Delta\phi < M_{\rm pl}$
  - Flat potential and inflation only likely over $\Delta\phi < M_{\rm pl}$

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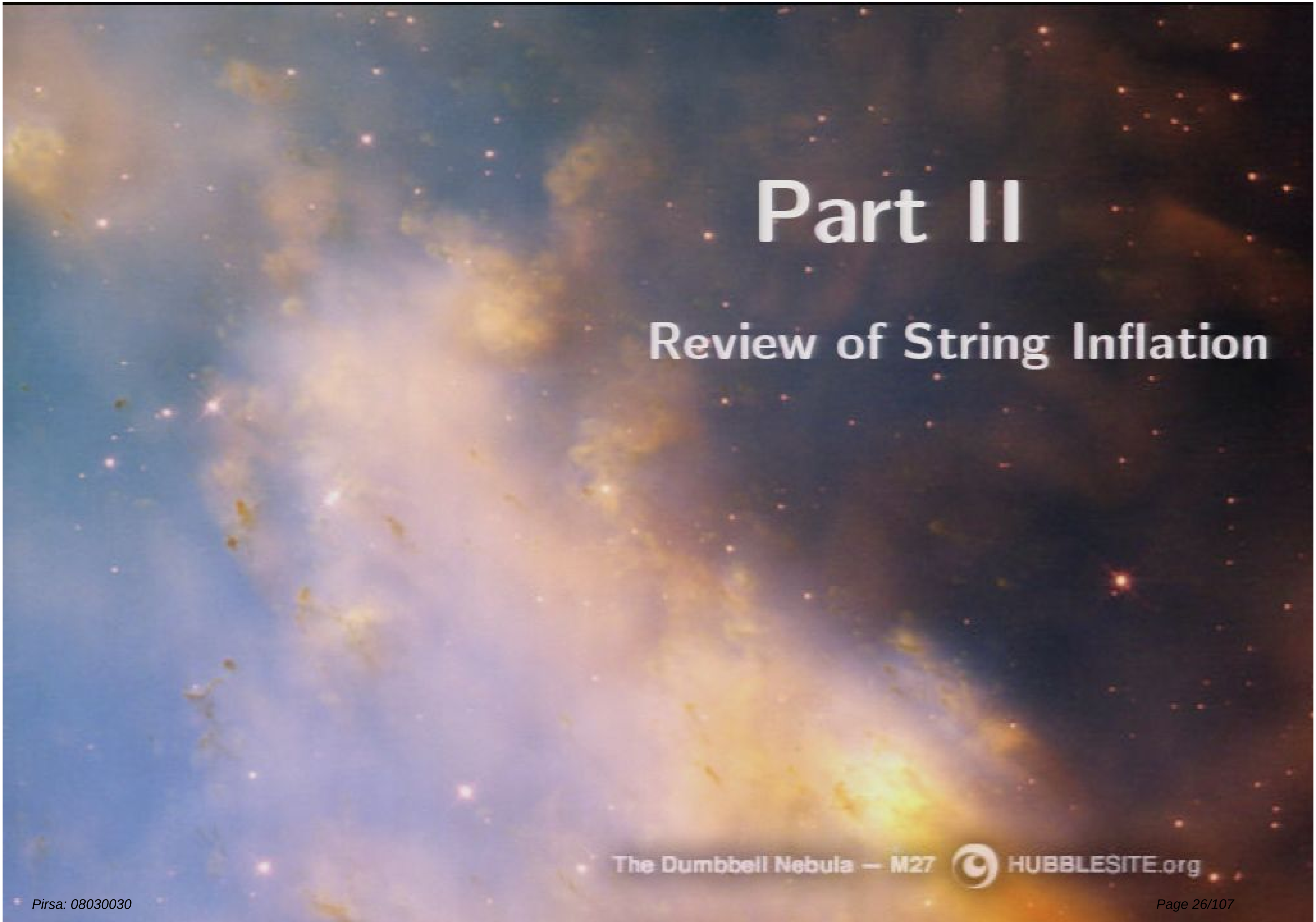
  Arguments are controversial/UV-sensitive.

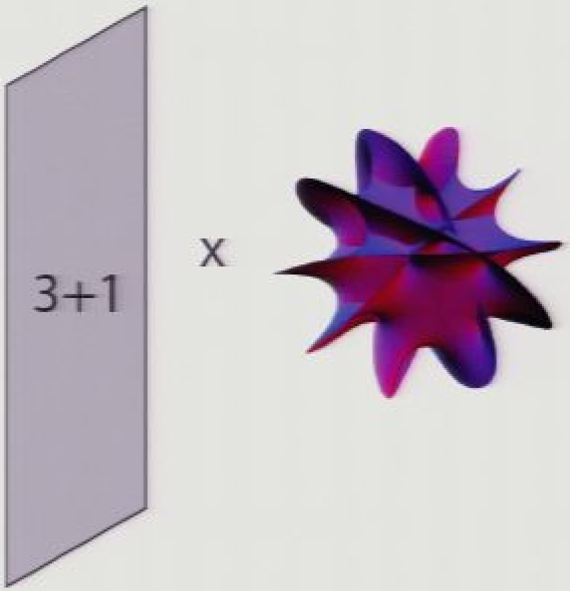
- Need UV-complete theory (e.g. string theory) to resolve the argument.

Part II

Review of String Inflation



Moduli Fields: "Blessing and Curse"



- **Moduli**:
  Scalar fields in the effective 4d theory:
  - dilaton
  - complex structure moduli
  - Kähler moduli
  - D-brane positions
- "Blessing":
  Dynamics of moduli may be a natural way to explain inflation.
- "Curse":
  Unfixed moduli are "bad news".
  Moduli stabilization in string theory was a major breakthrough.

KKLT:
Kachru, Kallosh, Linde and Trivedi

Moduli are stabilized by **fluxes** (complex structure) and **non-perturbative** (*quantum*) **effects** on **wrapped branes** (Kähler).

Models of Inflation in String Theory

Moduli dynamics can lead to inflation:

"Dynamics *OF* or *IN* the extra dimensions is reflected in a change in the inflationary energy in the 4d spacetime"

- Closed string models

  Role of the inflaton is played by moduli fields which control "size and shape" of the compact space.

  - Racetrack
  - Kähler moduli
  - Roulette
  - N-flation
  - ...

- Open string models

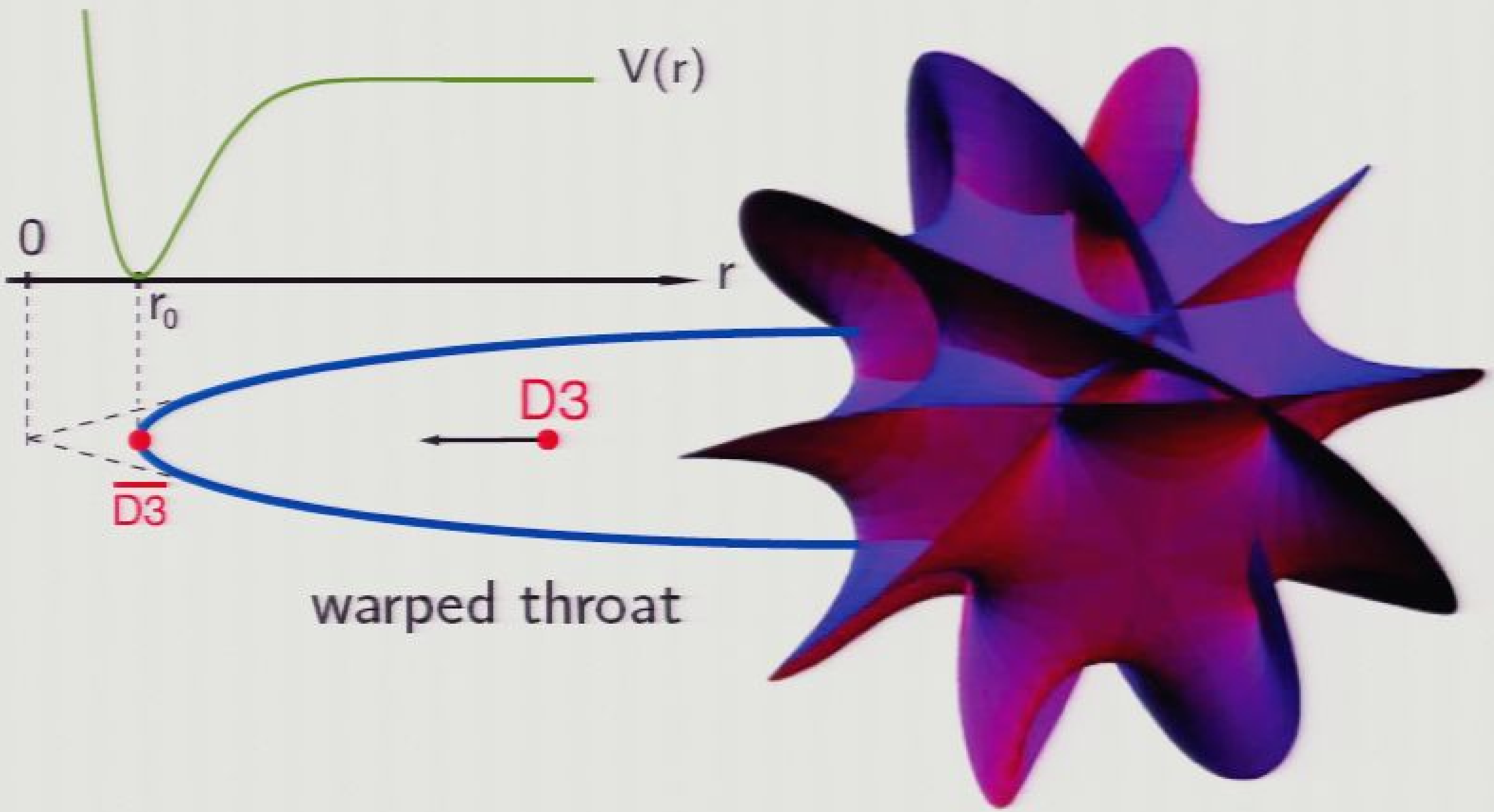
  Role of the inflaton is played by D-brane positions or orientations.

  - Brane-antibrane
  - Branes at angles
  - D3-D7
  - Warped brane-antibrane
  - M5-brane
  - DBI
  - ...

Warped D-Brane Inflation

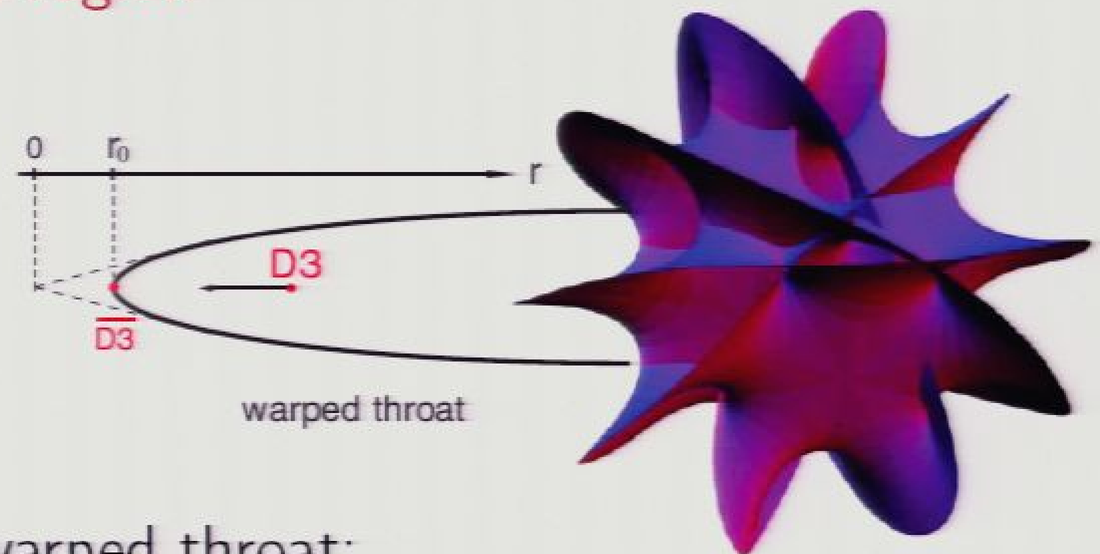
KKLMMT Scenario

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi



Warped D-Brane Inflation

Fluxes backreact on the Calabi-Yau metric to produce a "warped throat region"



Advantages of warped throat:

- Warping suppresses the force between the branes. Coulomb potential is exponentially flat.
- Stringy realization of Randall-Sundrum scenario; Hierarchy of scales.
- Local model ⇒ explicit metrics ⇒ **computable**

cf. general Calabi-Yau metrics are not known.

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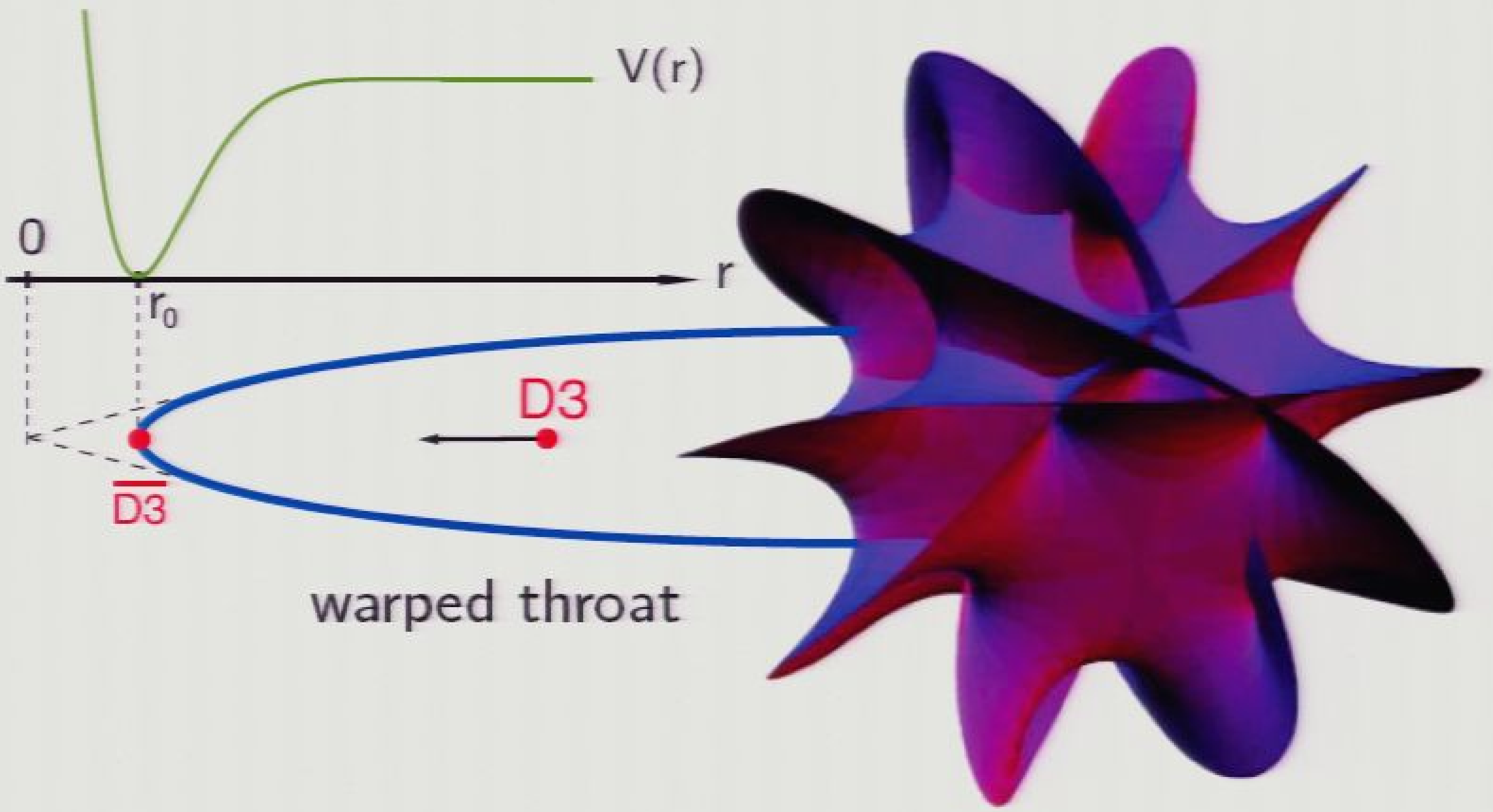

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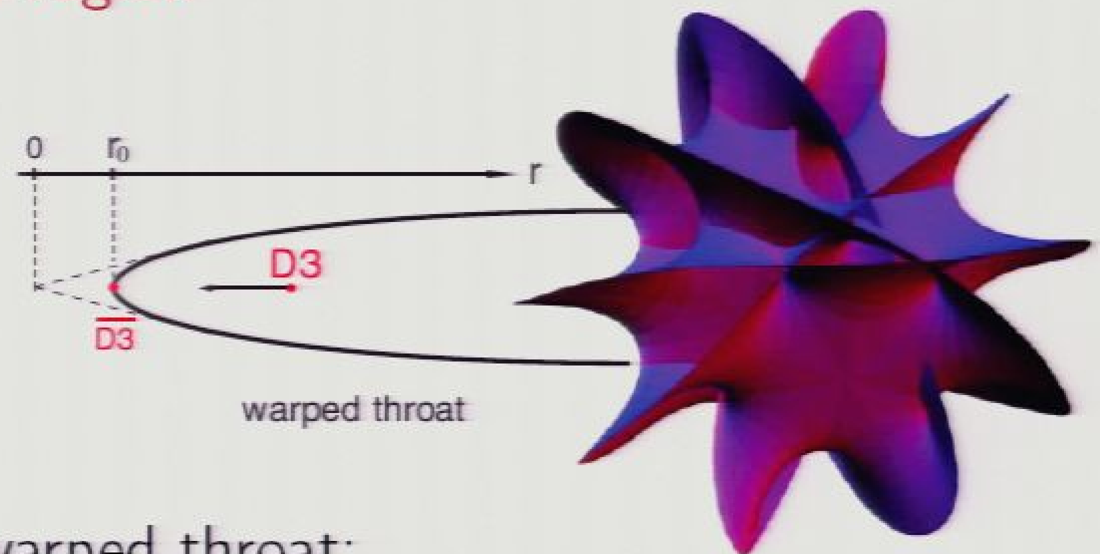

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The Field Range Bound

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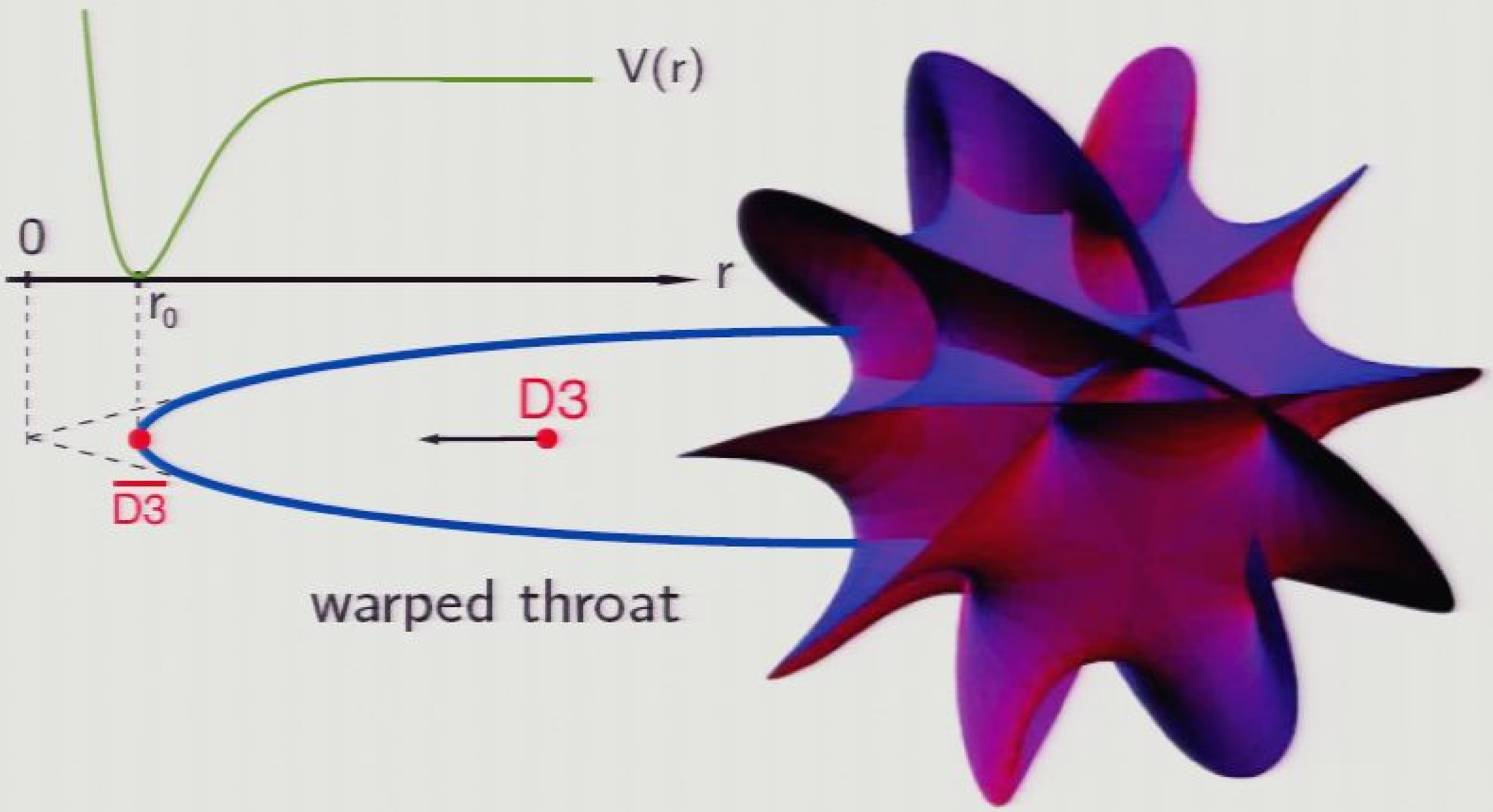

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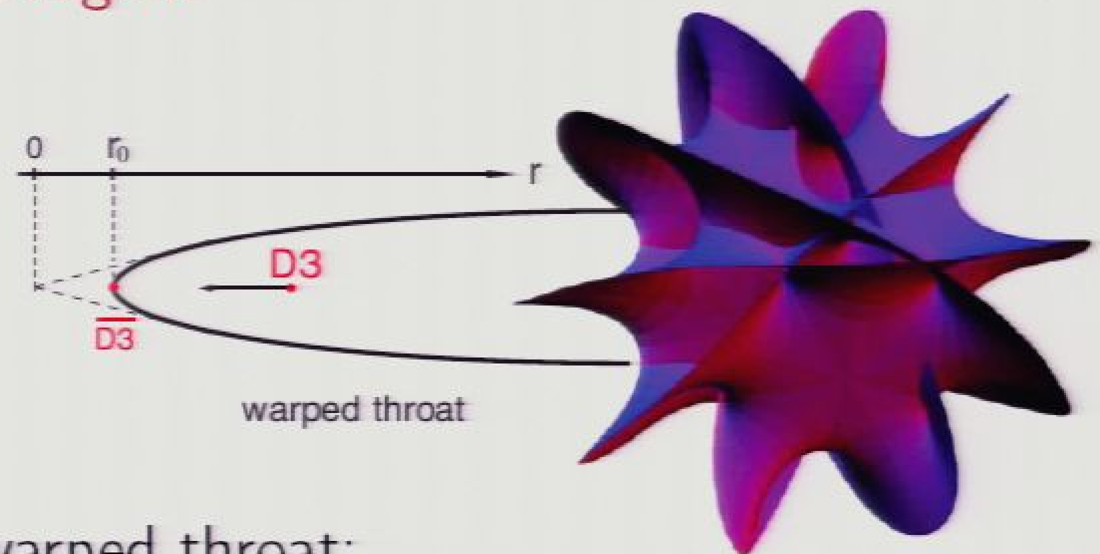

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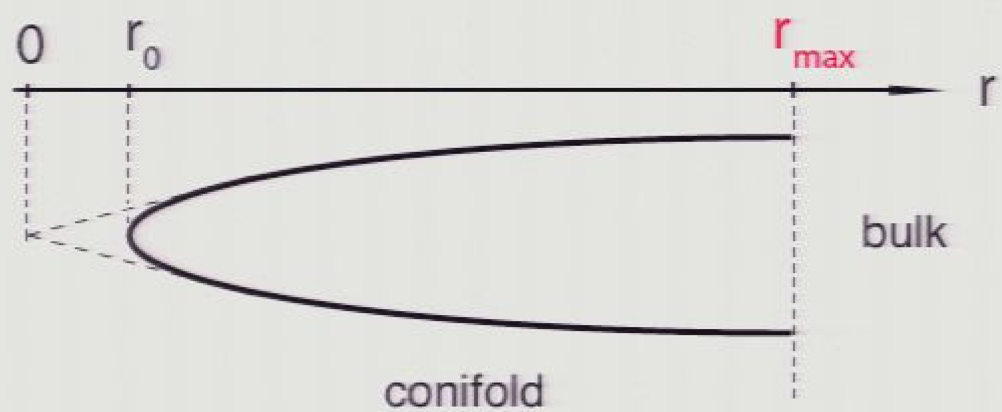
Warped Geometry



A warped cone over the base X_5 has the following metric:

$$\mathrm{d}s^2 = h^{-1/2}(r) g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu + h^{1/2}(r)(\mathrm{d}r^2 + r^2 \mathrm{d}s_{X_5}) \,,$$

where the warp factor follows from supergravity

$$h^{-1} = \left(\frac{r}{R}\right)^4 , \qquad T_3 R^4 = \frac{\pi}{2} \frac{N}{\mathrm{Vol}(X_5)} \,.$$

The supergravity approximation requires large value of the flux integer $N \gg 1$.

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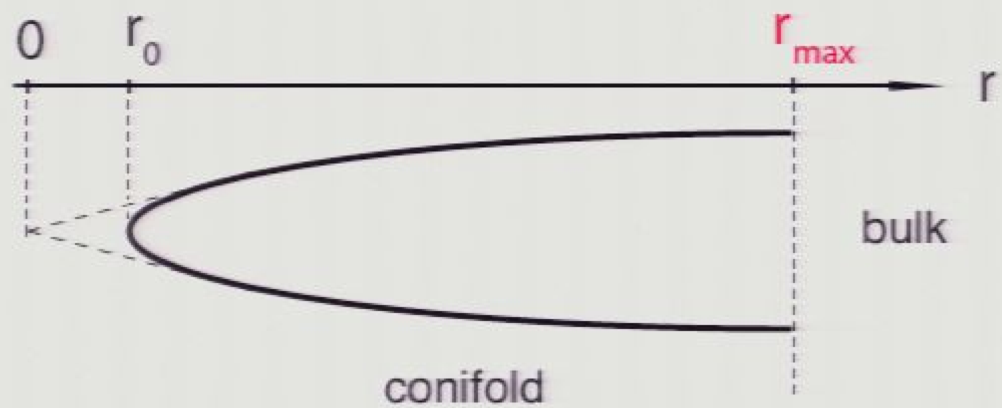

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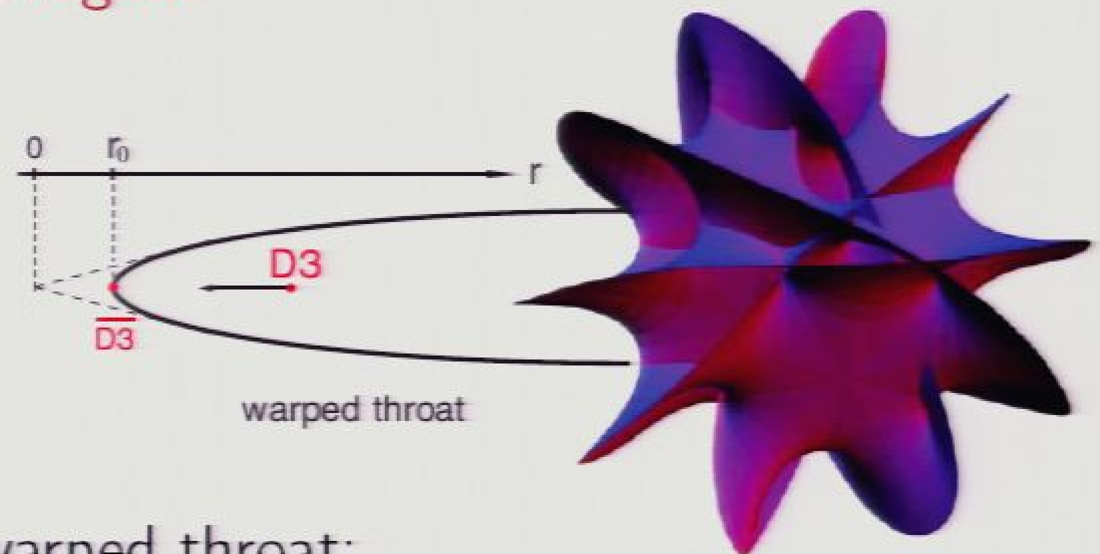

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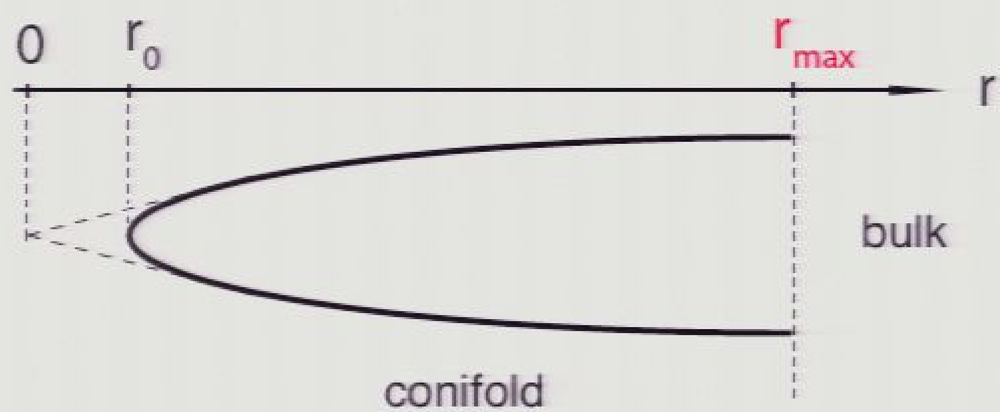

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Compactification Volume and 4d Planck Mass

Dimensional reduction

$$M_{\rm pl}^2 = M_{10}^8 V_6^w$$

where $M_{10}^8 \equiv \frac{2}{(2\pi)^7 g_s^2 (\alpha')^4} = \frac{1}{\pi}(T_3)^2$ and

$$V_6^w \equiv \int {\rm d}y^6 \sqrt{-g}\, h(y) = (V_6^w)_{\rm throat} + (V_6^w)_{\rm bulk} \; > \; (V_6^w)_{\rm throat}$$

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Get conservative constraint by ignoring the (unknown) bulk volume and computing the **warped throat volume**

$$(V_6^w)_{\rm throat} = \frac{1}{2}{\rm Vol}(X_5) R^4 r_{\rm max}^2 = \frac{\pi}{T_3}\frac{N}{4} r_{\rm max}^2$$

$$M_{\rm pl}^2 > T_3 r_{\rm max}^2 \frac{N}{4}$$

Compactification Constraint on the Field Variation

4d-Planck Mass

$$M_{\rm pl}^2 > T_3 r_{\rm max}^2 \frac{N}{4}$$

$$+$$

Canonical Inflaton Field

$$\phi^2 = T_3 r^2 < T_3 r_{\rm max}^2$$

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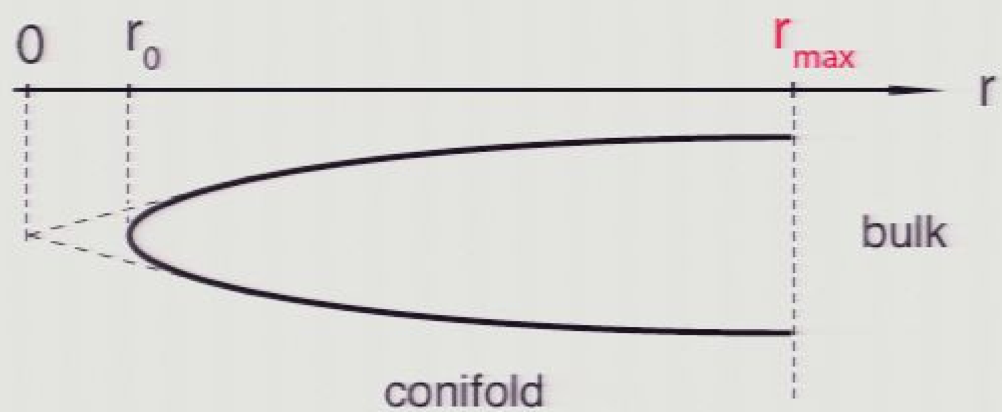

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A Microscopic Limit on Gravitational Waves from D-brane Inflation

Primordial Tensors?

$$\frac{\Delta\phi}{M_{\rm pl}} < \frac{2}{\sqrt{N}}$$

Consistency requires

$$N \gg 1$$

i.e.

$$\Delta\phi \ll M_{\rm pl}$$

NO observable tensors from brane inflation!

Notice that our field range bound
did not require use of any genericity argument like:

> "it would be very fine tuned to have such a flat potential over such a large distance in the throat"

The bound follows from *pure geometry*.

Also notice that *longer throats have shorter canonical field range in 4d Planck units!*

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Dramatic Constraint on DBI Inflation

Silverstein and Tong

Relativistic limit of brane motion:

- DBI action allows inflation even for steep potentials.
- Non-gaussianity is large.

Dramatic Constraint on DBI Inflation

Observations ($f_{\rm NL} < 100$) require super-Planckian field variation

$$\phi > M_{\rm pl}$$

This is inconsistent with our microscopic constraint!

D.B., McAllister
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Summary

Implications of the field range bound:

1. Detectable tensors impossible in slow roll of D3-branes.
2. Rules out DBI inflation from D3-branes on Calabi-Yau cones.
   (D.B., McAllister; see also: Lidsey, Huston; Bean et al.; Peiris, D.B., Friedman, Cooray)

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Canonical Inflaton Field

$$\phi^2 = T_3 r^2 < T_3 r_{\rm max}^2$$

D.B., McAllister

A Microscopic Limit on Gravitational Waves from D-brane Inflation

Dramatic Constraint on DBI Inflation

Observations ($f_{\rm NL} < 100$) require super-Planckian field variation

$$\phi > M_{\rm pl}$$

This is inconsistent with our microscopic constraint!

D.B., McAllister
A Microscopic Limit on Gravitational Waves from D-brane Inflation

Summary

Implications of the field range bound:

1. Detectable tensors impossible in slow roll of D3-branes.
2. Rules out DBI inflation from D3-branes on Calabi-Yau cones.
   (D.B., McAllister; see also: Lidsey, Huston; Bean et al.; Peiris, D.B., Friedman, Cooray)

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- Expect similar field range bounds for most D-brane models.
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  But, ...
- Similar results easily found in most closed string models.
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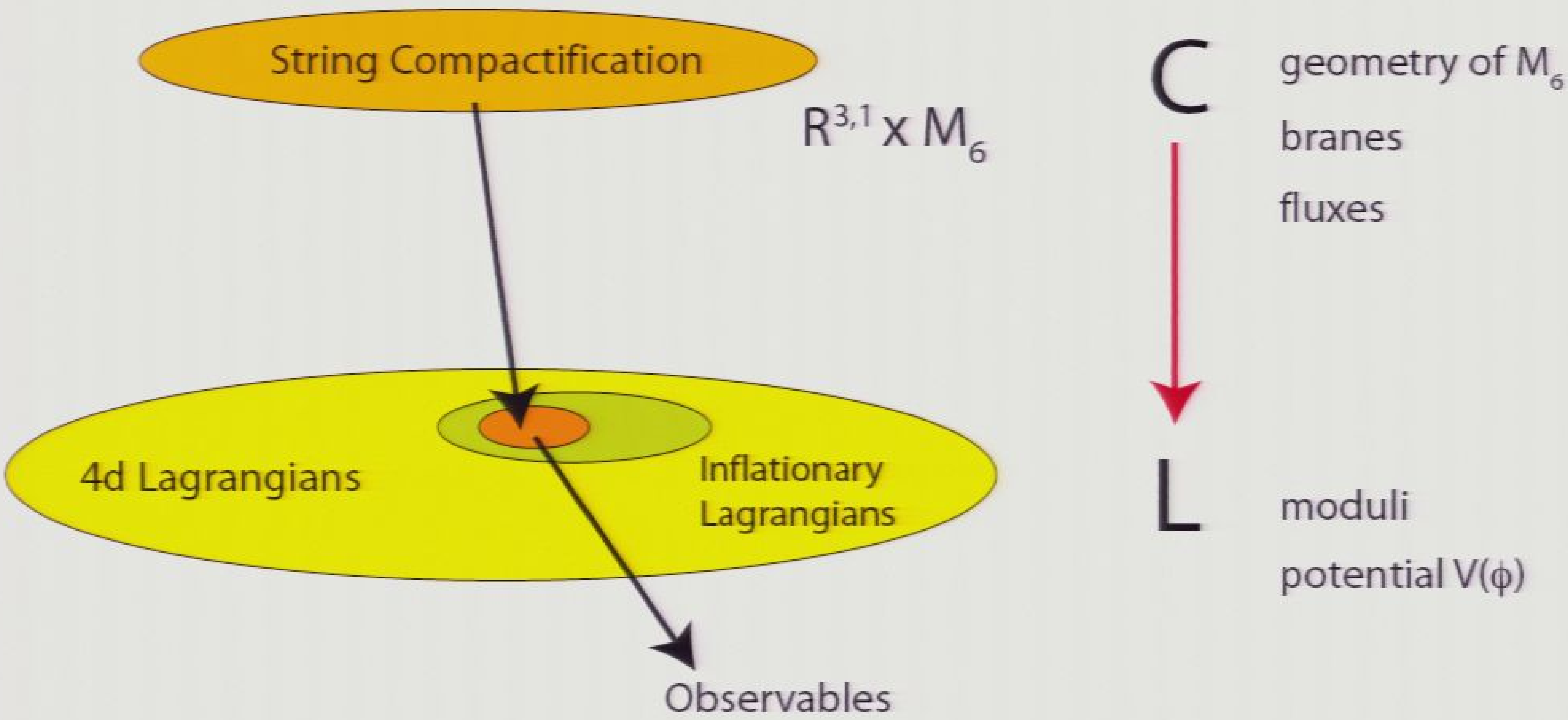
Question:

Can large-field inflation be realized in a consistent string compactification?

PART IV

Towards *Explicit* D-brane Inflation

From String Compactification to Low Energy Lagrangian



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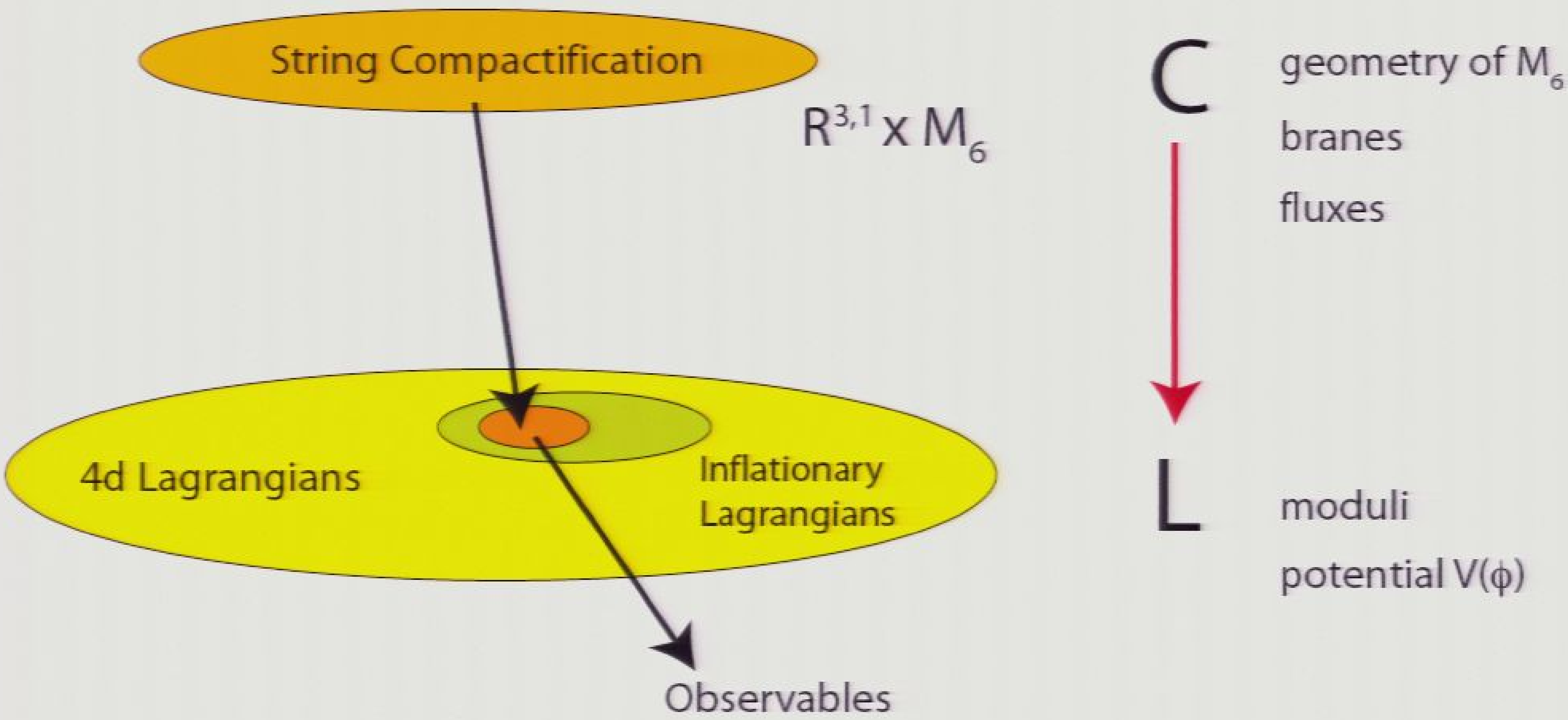

String Theory and Inflationary Cosmology

1. Short-Term Goal

   Existence Proof of Inflation in String Theory

2. Mid-Term Goal

   Classification of Possible Inflationary Models in String Theory
   e.g. large field vs. small field

   Understand Microscopic Constraints
   Understand Naturalness

3. Long-Term Goal

   Compute Observational Signatures

What is required for an Existence Proof?

"The hard part is not to find a flat potential,
but to show that it is *THE* potential."

What is required for an Existence Proof?

Consider an inflation model with some $V(\phi)$.

A robust model requires understanding gravity corrections up to dimension 6

$$\delta V \sim \frac{V}{M_{\rm pl}^2}\phi^2 \,.$$

These can induce order Hubble corrections to the inflaton mass,

$$\Delta\eta \sim \mathcal{O}(1)\,.$$

i.e. for a controllable model one needs to demonstrate explicitly that these dangerous terms are *absent*, *suppressed* or *cancel*.

This requires some knowledge of Planck scale physics or quantum gravity.

e.g. $V(\phi)$ for Brane Inflation

- **Before** moduli stabilization:

  Brane-antibrane Coulomb potential is exponentially flat.

- **After** moduli stabilization:

  Moduli stabilization induces $\Delta\eta = \mathcal{O}(1)$ terms and spoils flatness of the inflaton potential!

- Obliged to compute corrected potential in **stabilized vacuum**.

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$V(\phi)$ and Moduli Stabilization

KKLT compactification: Effects on mobile D3-branes?

1. **FLUXES**

Type IIB on CY_3 orientifold with $G_3 \equiv F_3 - \tau H_3$ flux.

- GKP compactification: eom enforces ISD flux:

$$\star_6 G_3 = i G_3$$

- Graña:
scalars governing motion of a spacetime-filling D3-brane couple only to IASD flux

$$(\star_6 - i) G_3$$

NO force on D3-branes from ISD fluxes.

- systematic study of IASD effects from UV perturbations:
D.B., Dymarsky, Kachru, Klebanov, McAllister, *work in progress*

$V(\phi)$ and Moduli Stabilization

KKLT compactification: Effects on mobile D3-branes?

2. **Non-perturbative effects** on wrapped branes
induce dangerous $\Delta\eta \sim \mathcal{O}(1)$ corrections to the inflaton potential.

$$W_{\rm np} = \underline{\underline{A(\phi)}} e^{-a\rho}$$

The Physics of the Brane Inflation Potential

Two physical effects lead to $\Delta\eta \sim \mathcal{O}(1)$ corrections to the Coulomb potential:

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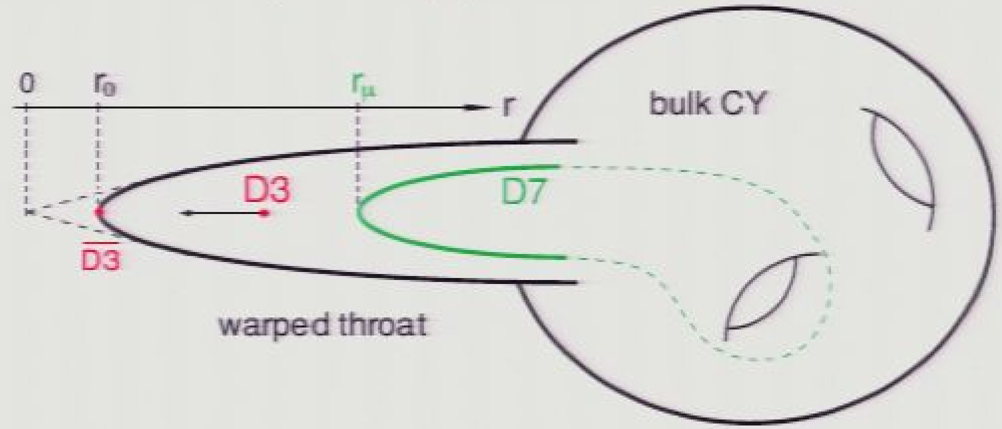

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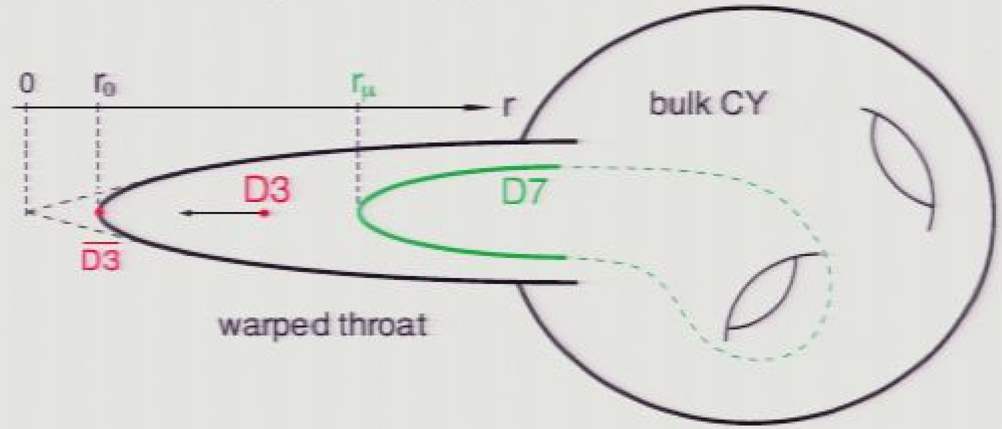

1. **D3-brane backreaction on the compactification volume**
   The physical volume of the compact space depends on the position of the D3-brane, $\mathcal{V}(\phi)$.

$$\mathcal{L}_{\rm Einstein} \sim \frac{1}{\mathcal{V}(\phi)^{\#}} \mathcal{L}_{\rm String} \quad \Rightarrow \quad \delta V(\phi)\,.$$

First computed by KKLMMT.

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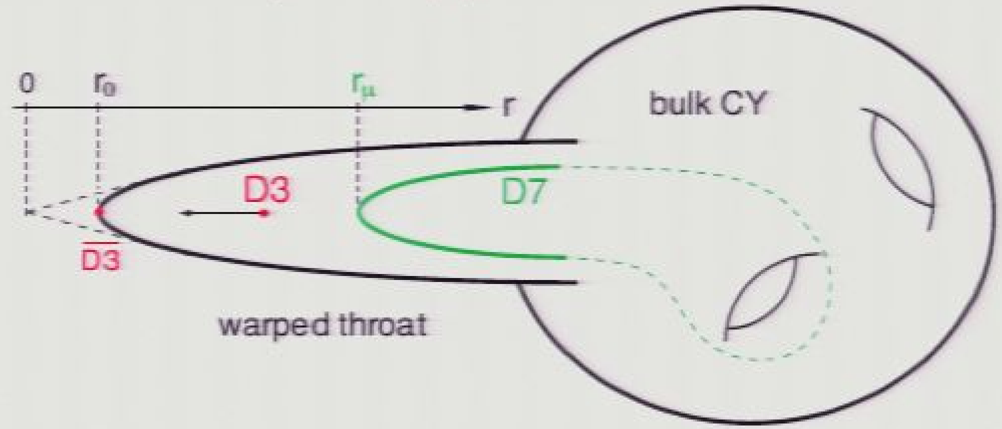

1. **D3-brane backreaction on the compactification volume**
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2. **D3/D7 interaction**
   The presence of the D3-brane changes the *warped* volume of the 4-cycle wrapped by the D7-branes, $\mathcal{V}_4^w(\phi) \equiv \int d^4y \sqrt{g}\, h(\phi)$.

$$\frac{1}{g^2} \propto \mathcal{V}_4^w(\phi) \quad \Rightarrow \quad W_{\rm np} \propto e^{-c\mathcal{V}_4^w(\phi)} \equiv A(\phi) e^{-a\rho} \quad \Rightarrow \quad \delta V(\phi)\,.$$

First computed by D.B., Dymarsky, Klebanov, Maldacena, McAllister, Murugan.
(see also: Ganor; Berg, Haack and Körs; Giddings & Maharana)

Eta–Problem from Compactification Effects

Both the **D3-backreaction on the volume** and the **D3/D7 interaction** give large contributions to the inflaton mass:

$$\eta = \frac{V''}{V} = \frac{2}{3} + \eta_{3/7}(\phi)$$

Can η ever be small?

Recap of the Situation

- The potential in the KKLMMT model is not naturally flat enough for inflation, despite initial hopes.
- Depending on the function $\eta_{3/7}(\phi)$, it may sometimes, or never, be flat enough.
- To determine whether this model can ever work, we need to compute $\eta_{3/7}(\phi)$.

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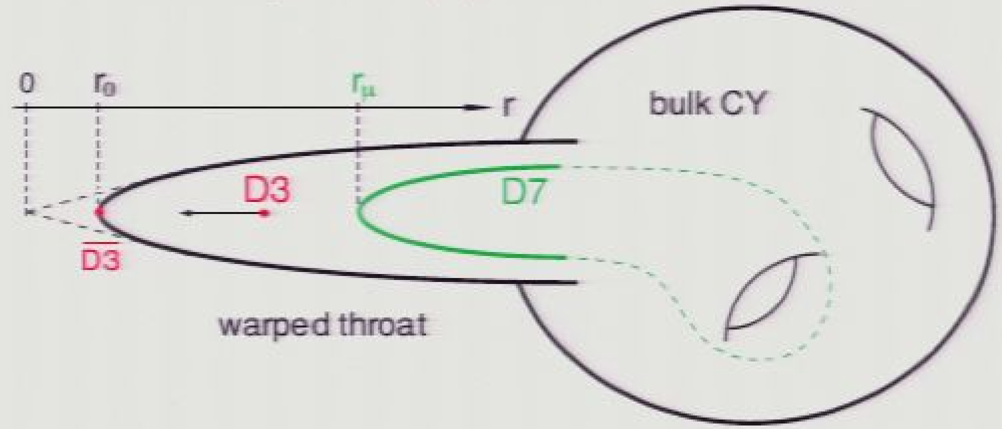

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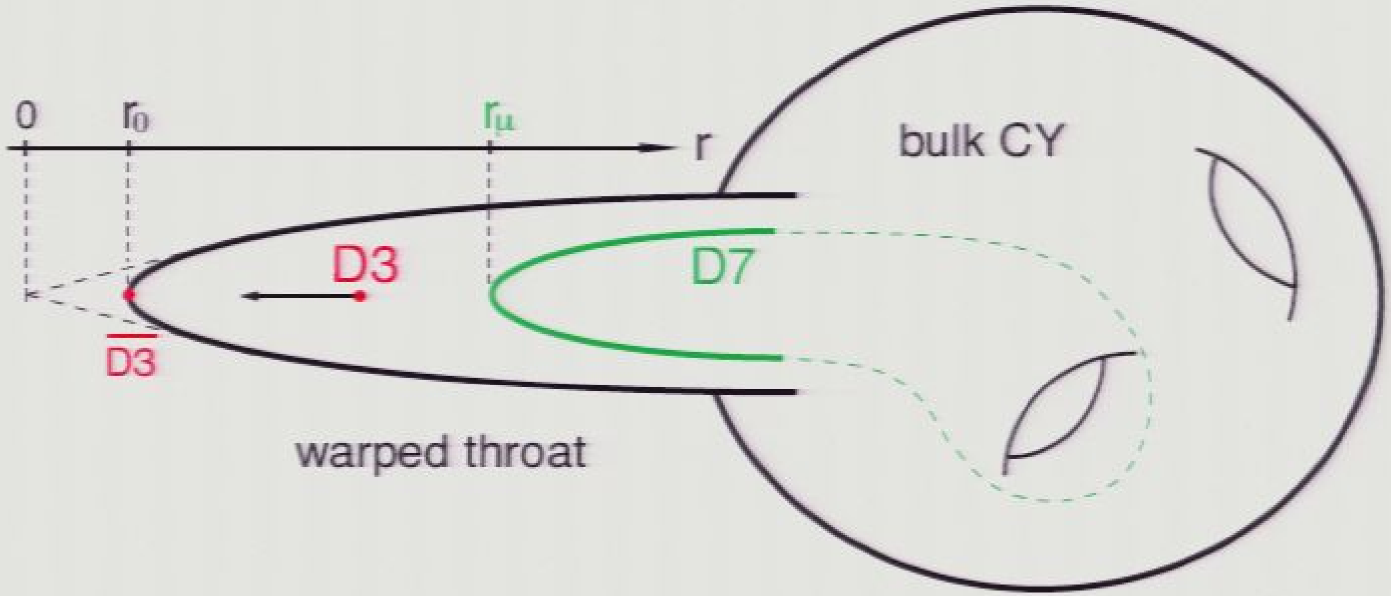
D3/D7-Interaction

Setup



$$\delta\mathcal{V}_4^w \equiv \int \mathrm{d}^4 y \sqrt{g}\, \delta h\,, \quad \nabla^2 \delta h = \mathcal{C}\, \delta(r - r')$$

$\Rightarrow$ D3/D7 interaction:

D.B., Dymarsky, Klebanov, Maldacena, McAllister, Murugan,
On D3-brane Potentials in Compactifications with Fluxes and Wrapped Branes.
JHEP 0611 (2006) 031

see also: Ganor

Effective Single Field Potential

- Potential depends on 8 real fields.

Integrating out the angles and the compactification volume gives the effective single field potential for radial motion.

D.B., Dymarsky, Klebanov, McAllister
Towards an Explicit Model of D-brane Inflation.

see also: Burgess et al., Krause & Pajer

$$\frac{\partial V}{\partial \rho}\Big|_{\rho=\rho_\star(\phi)} = \frac{\partial V}{\partial \Psi}\Big|_{\Psi=\Psi_\star(\phi)} \equiv 0 \quad \Rightarrow \quad \mathbb{V}(\phi) \equiv V(\phi, \rho_\star(\phi), \Psi_\star(\phi))$$

Microscopic Input and Fine-Tuning

Microscopic Parameters:

- n:
  No. of D7-branes.
- ϕ_μ:
  Minimal radius of embedding.
- ρ_0:
  4-cycle volume.
  Related to flux (N).
- h_0:
  Warp factor at the tip.
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Compactification Constraints:

- Field Range Bound
  $\phi_\mu < \Delta\phi < \frac{2}{\sqrt{N}}$
- Four-Cycle Volume
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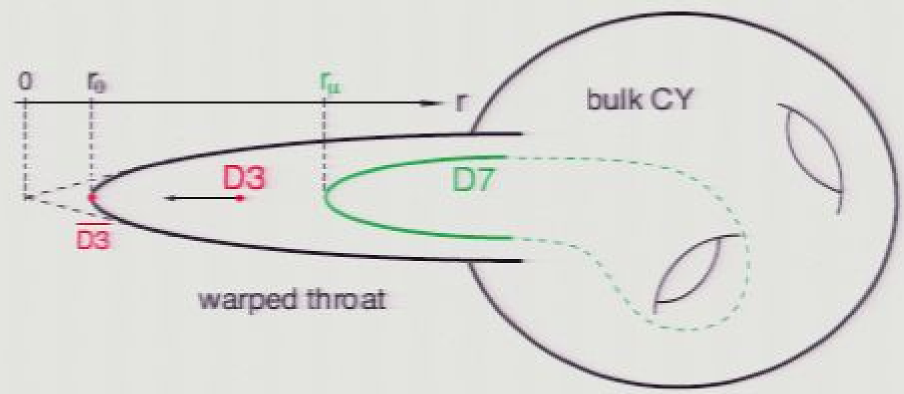
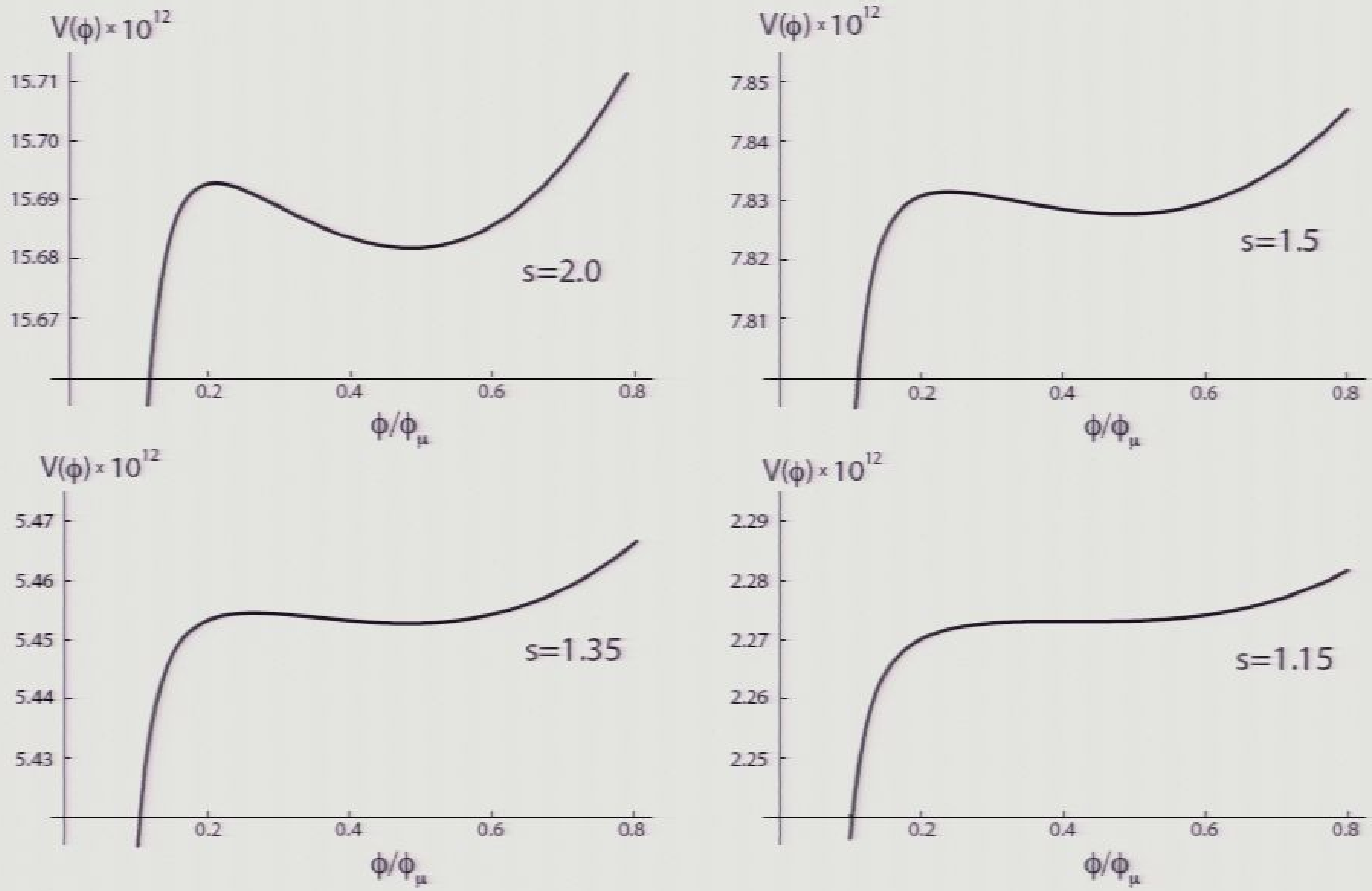


From Metastable to Monotonic



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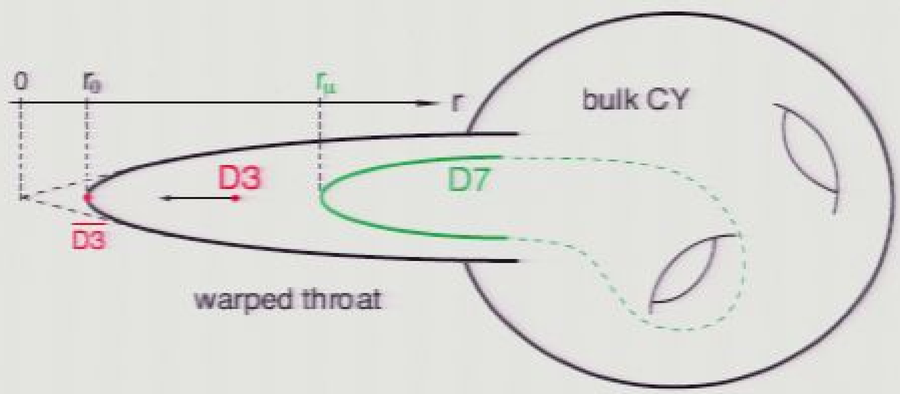

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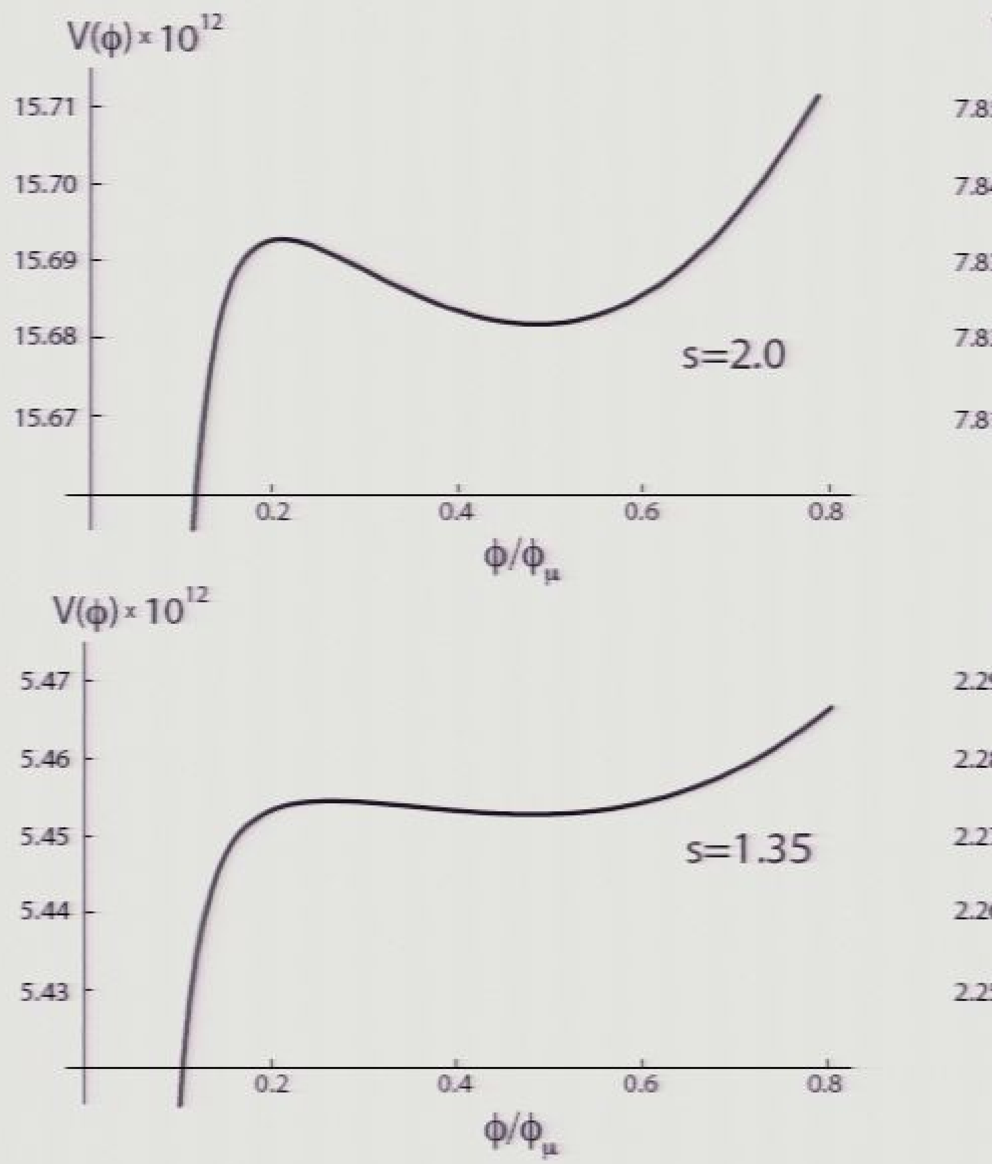

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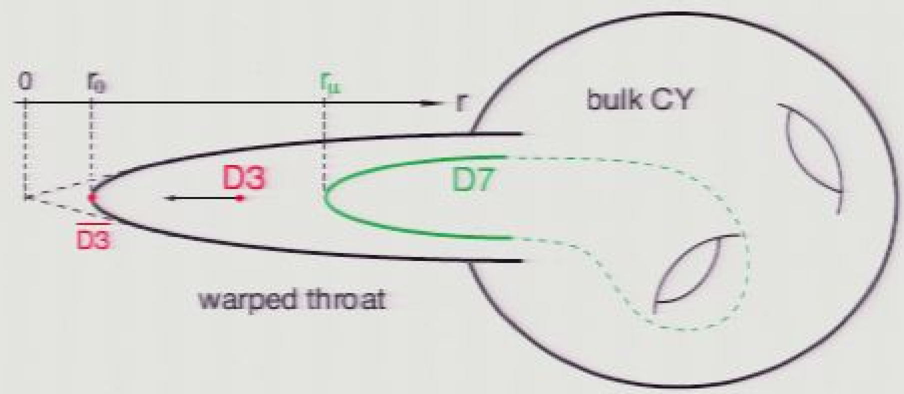

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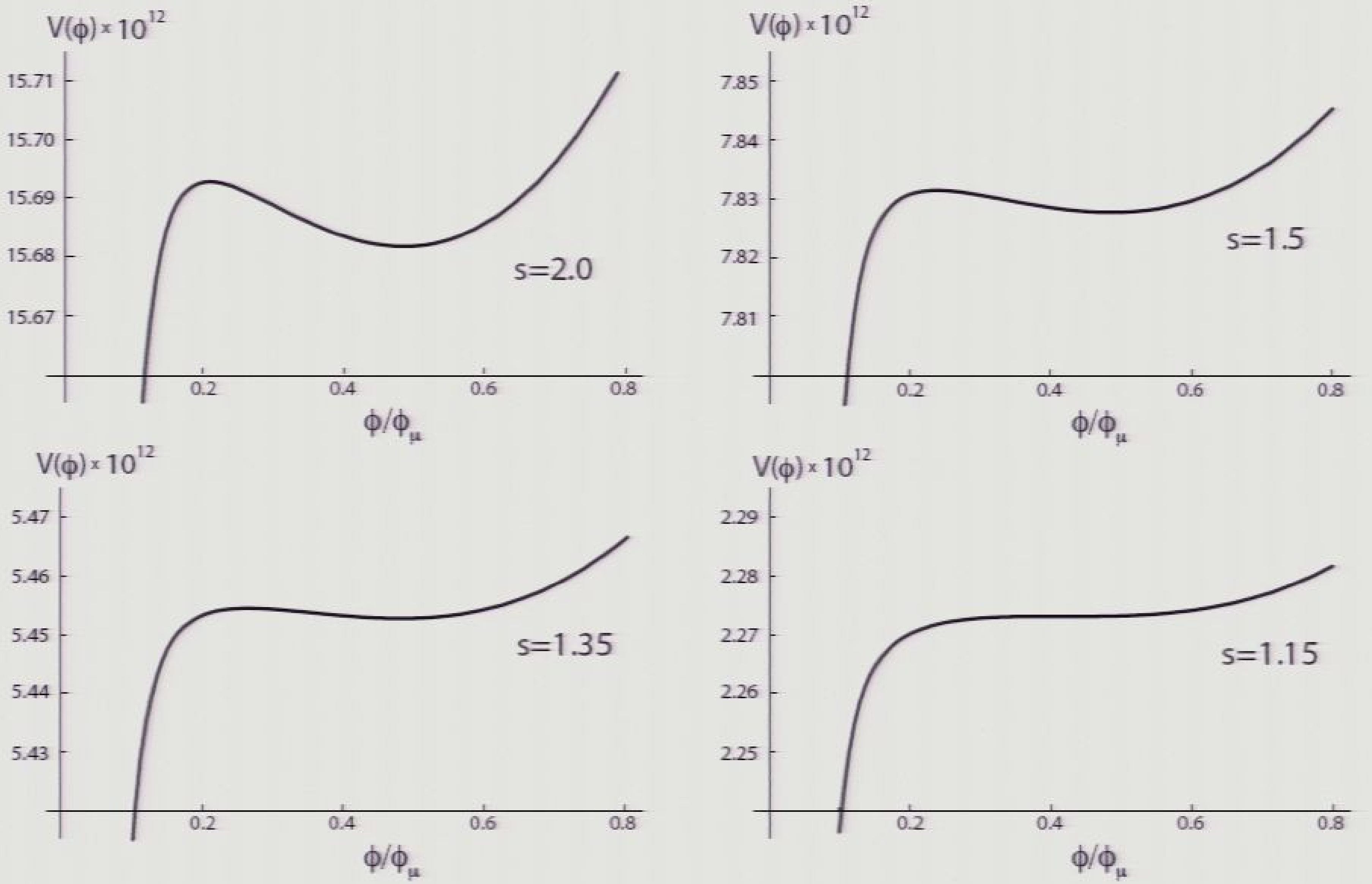

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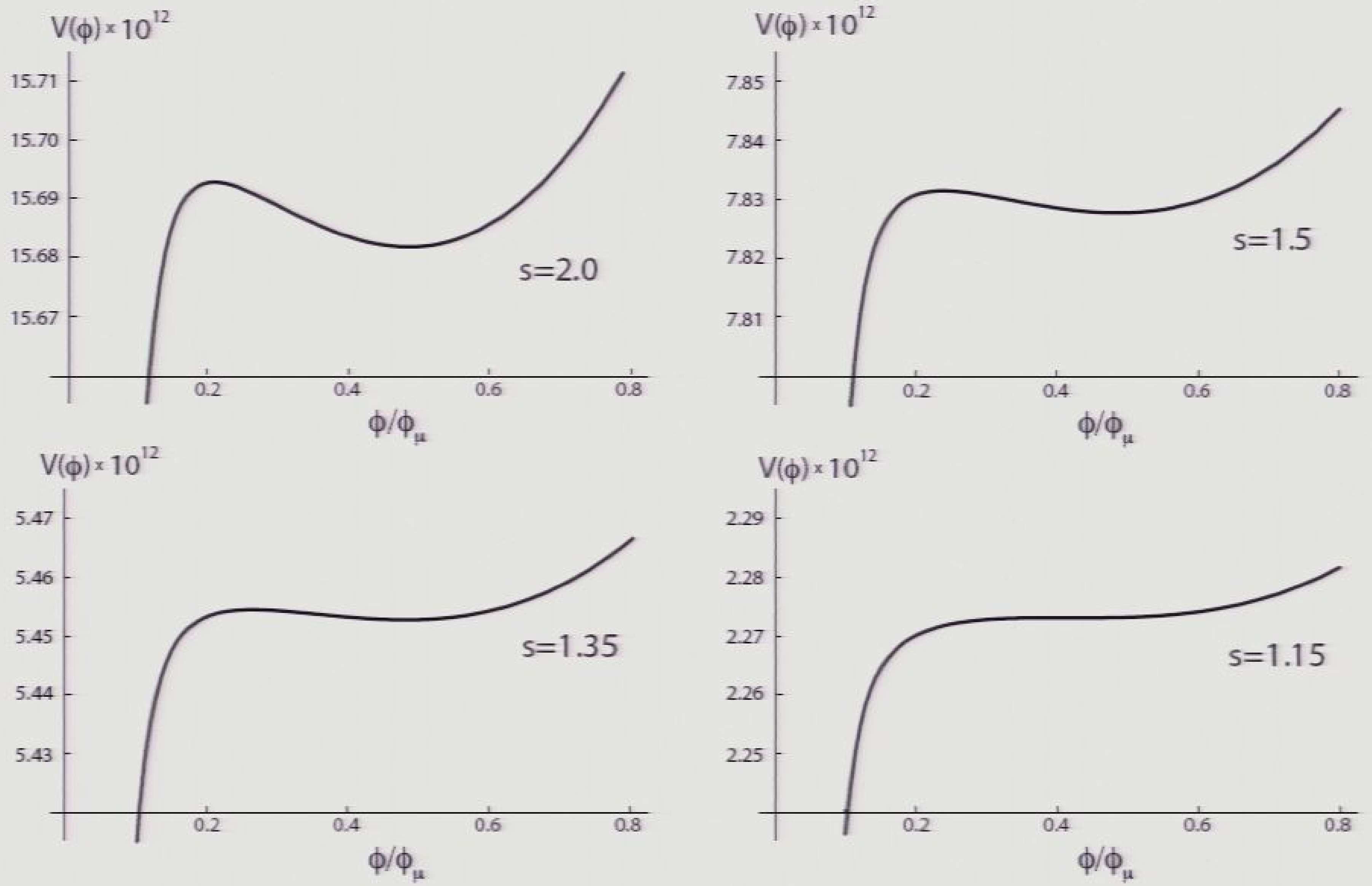

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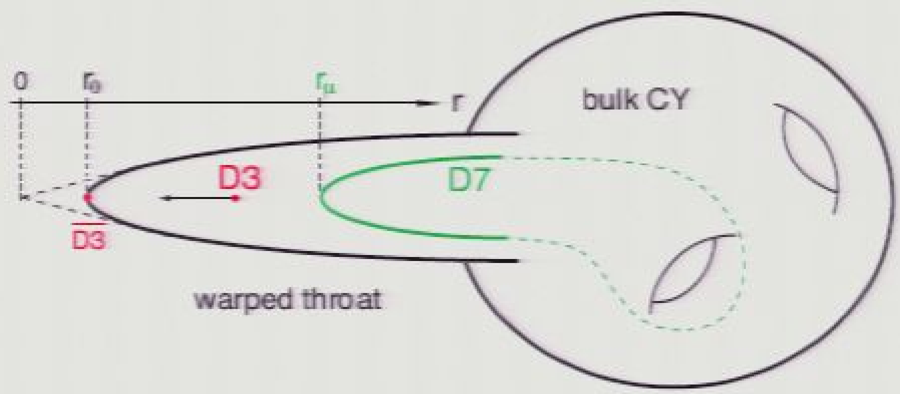

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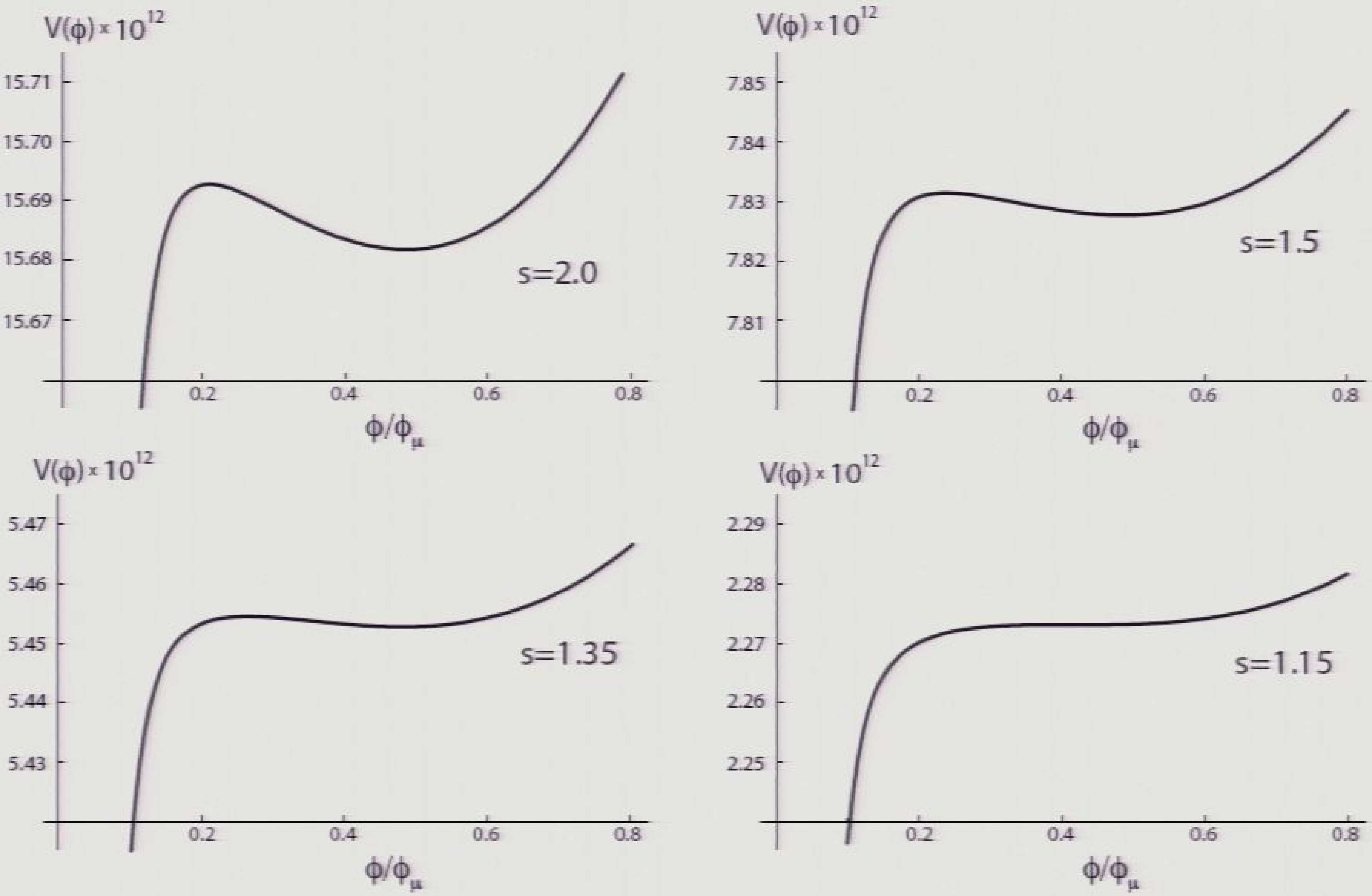

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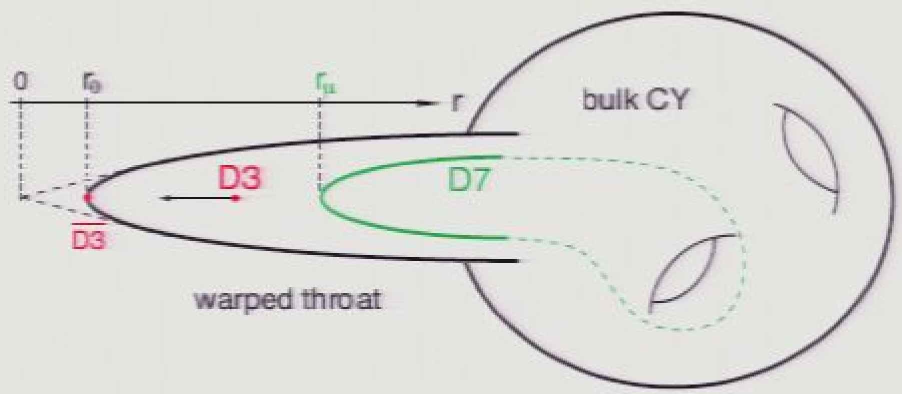

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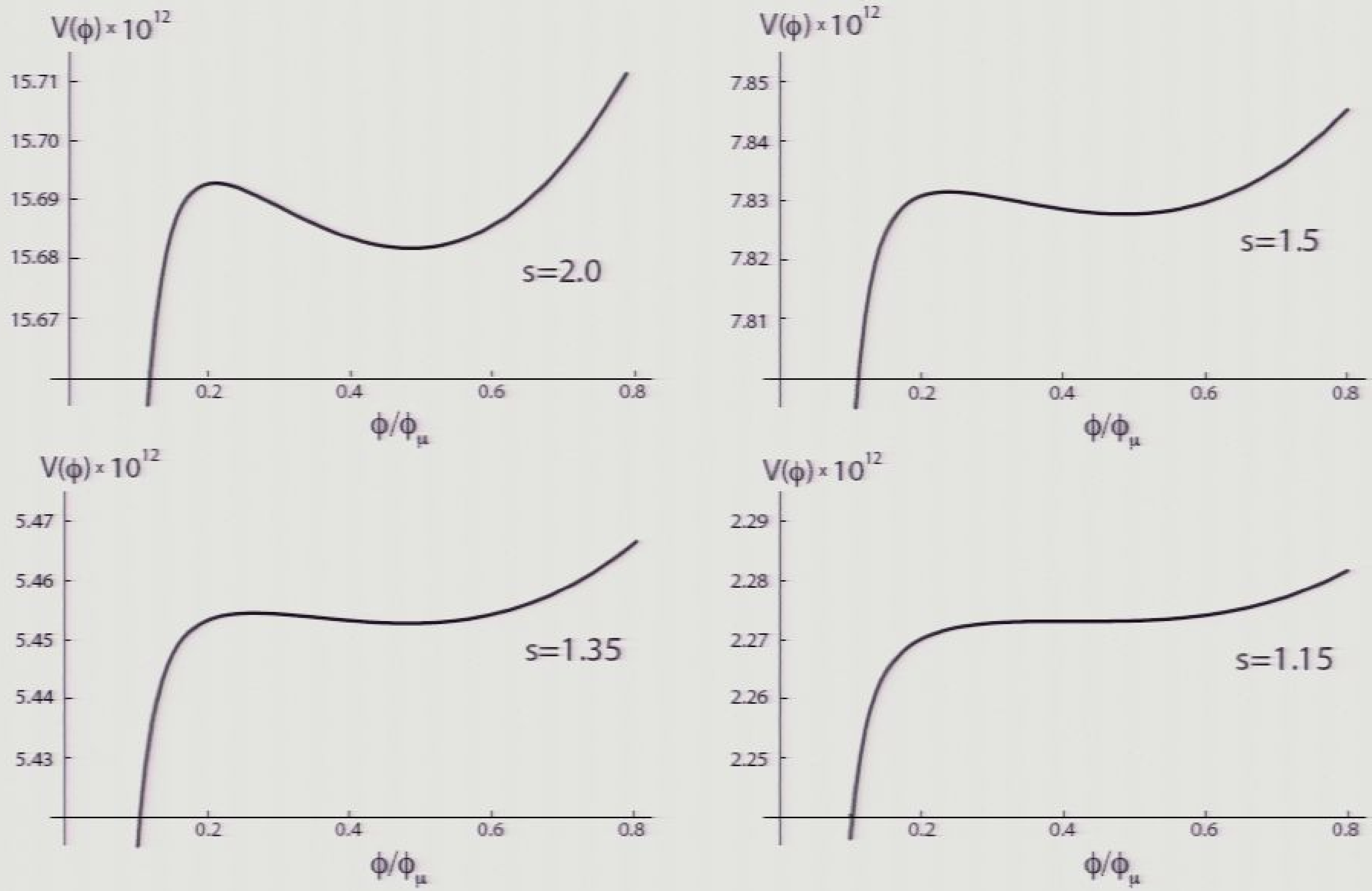

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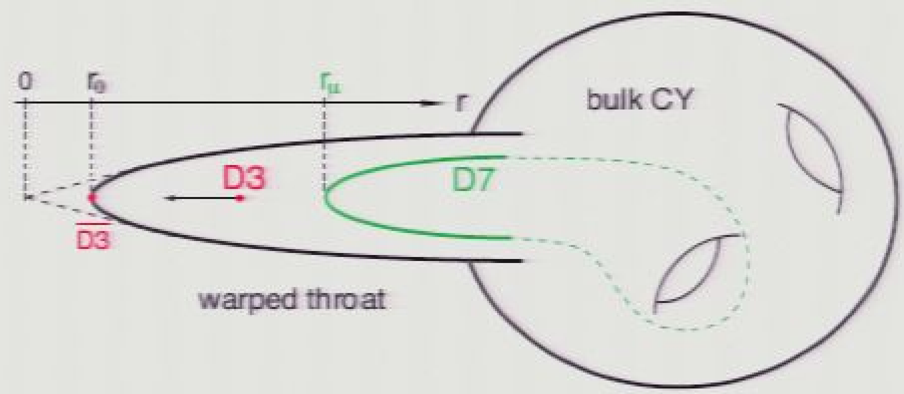

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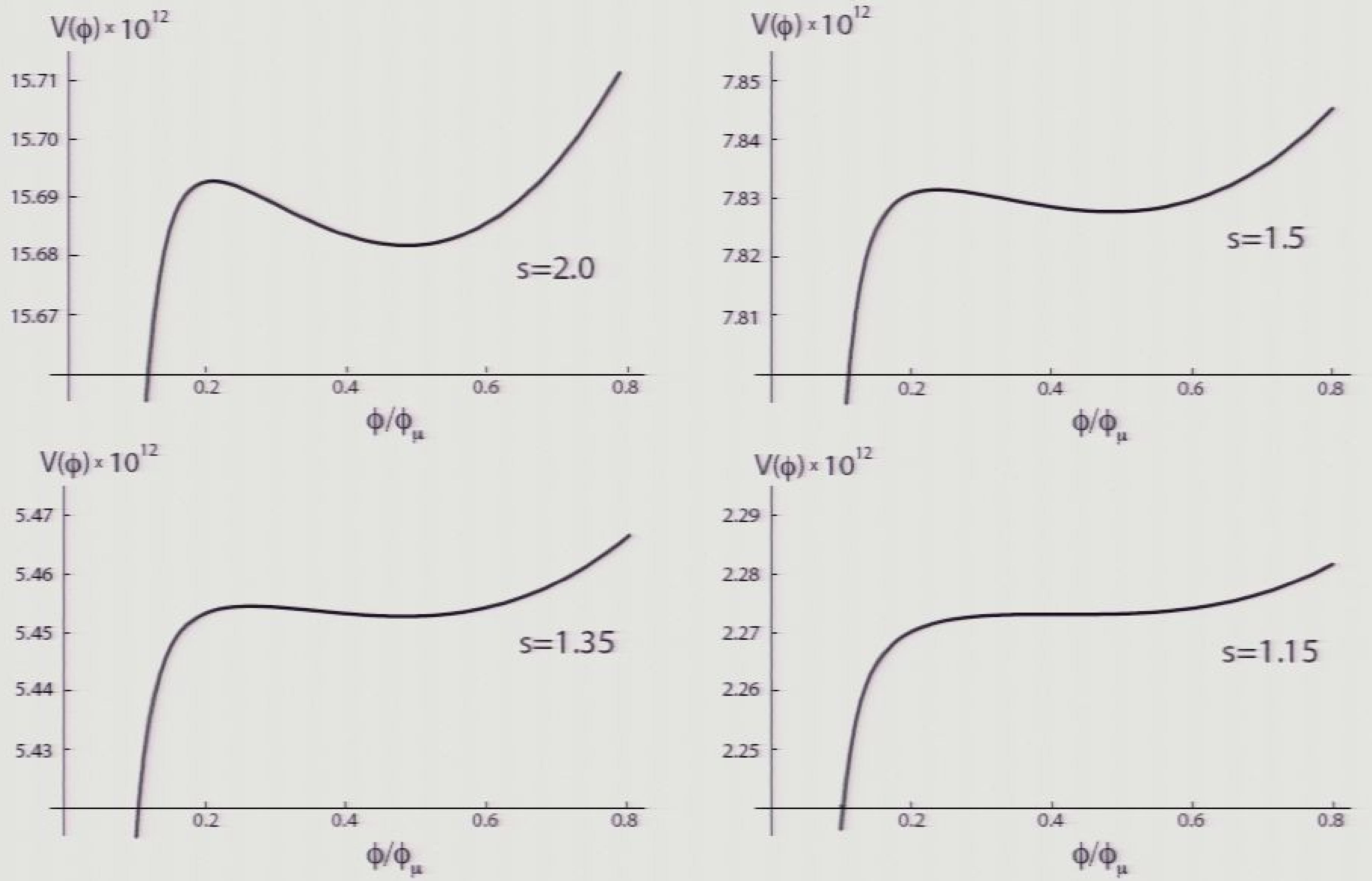
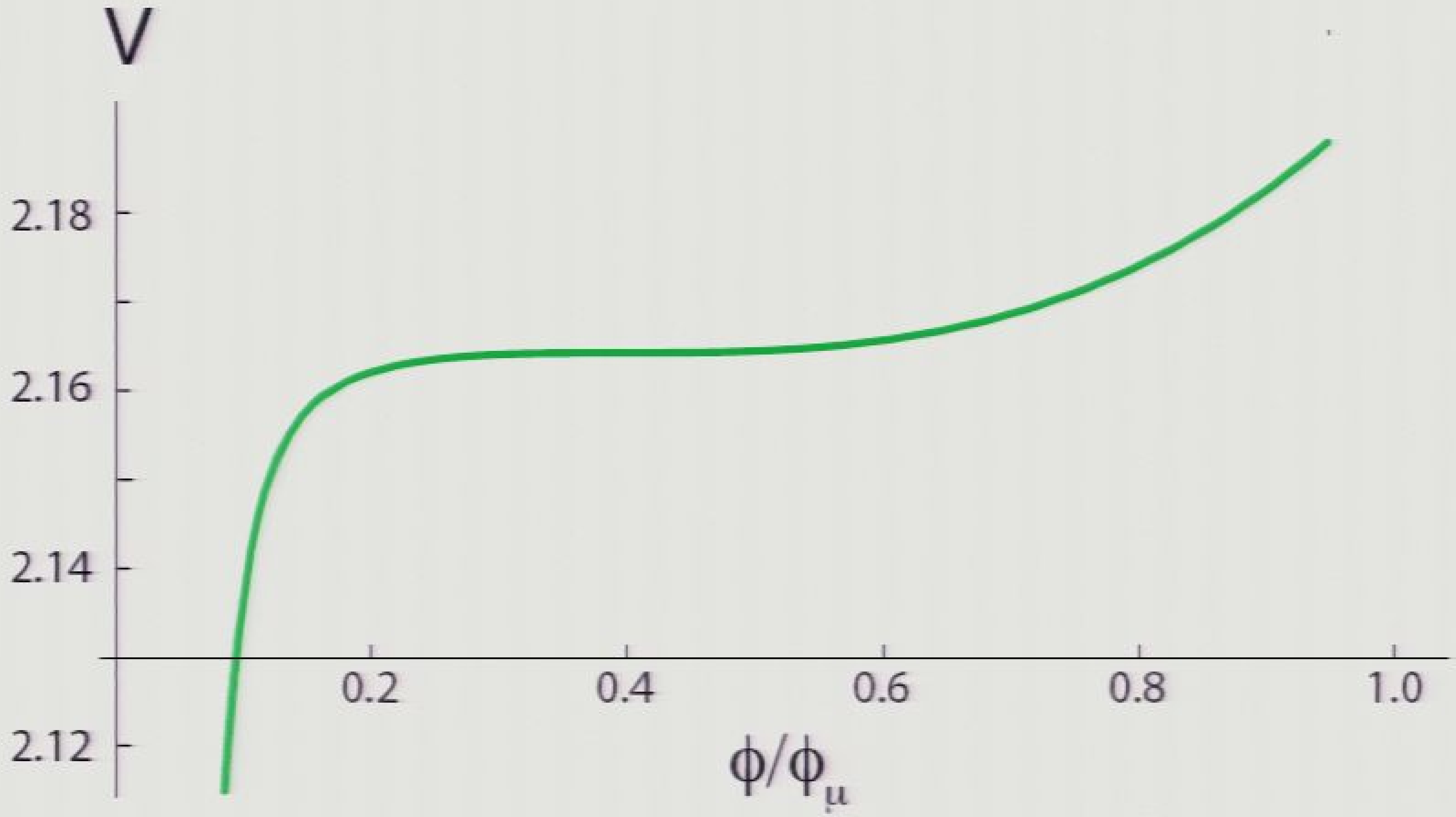
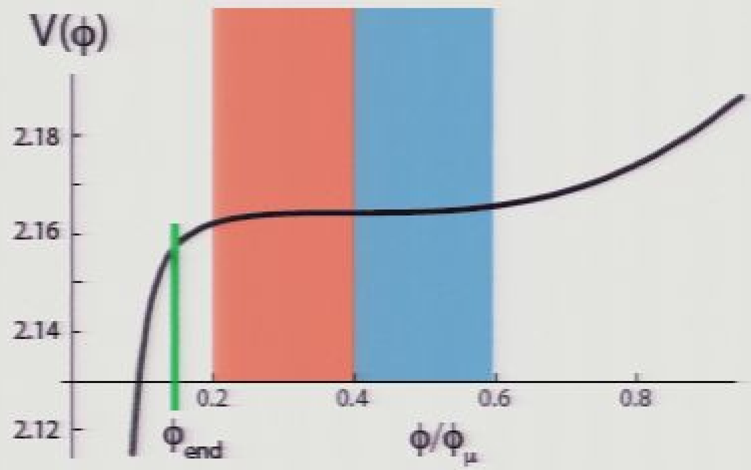


Inflection Point Inflation



D.B., Dymarsky, Klebanov, McAllister, Steinhardt
A Delicate Universe: Compactification Obstacles to D-brane Inflation
PRL 99, 141601 (2007)

Scalar Spectrum



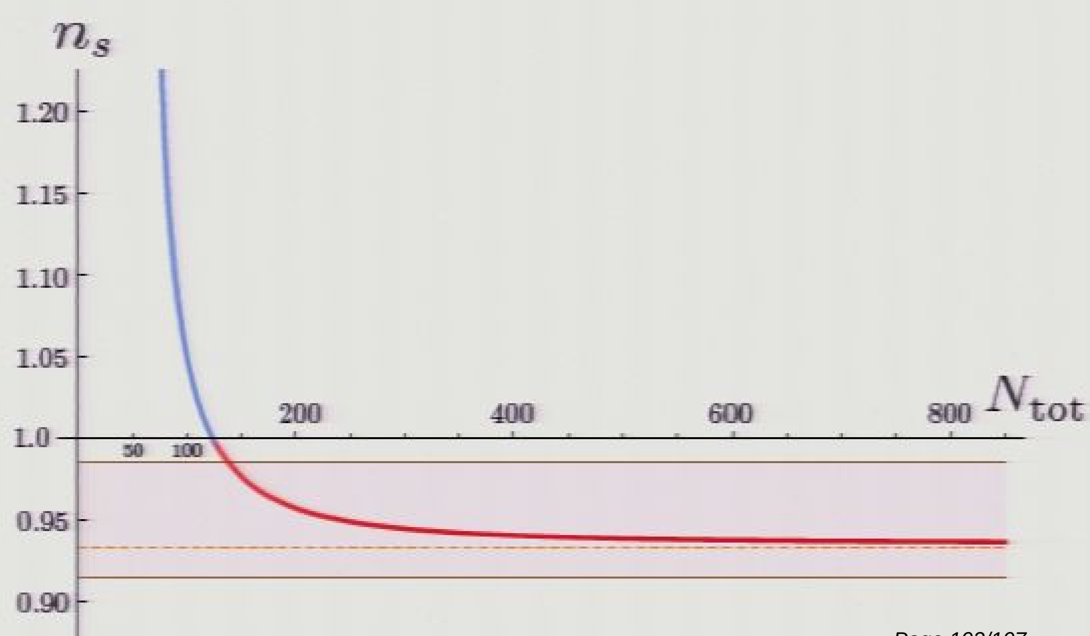
$$V(\phi) = V_0 + \lambda_1 \phi + \frac{1}{3!}\lambda_3 \phi^3$$

Total number of e-folds is finite: $N_{\rm tot} = \pi \sqrt{\frac{2V_0^2}{\lambda_1 \lambda_3}}$.

$$n_s - 1 = -\frac{4\pi}{N_{\rm tot}} \cot\left(\frac{\pi N_\star}{N_{\rm tot}}\right)$$

- n_s can be red or blue;
- lower limit on n_s:

$$n_s \geq 1 - \frac{4}{N_\star} \approx 0.9\bar{3}$$



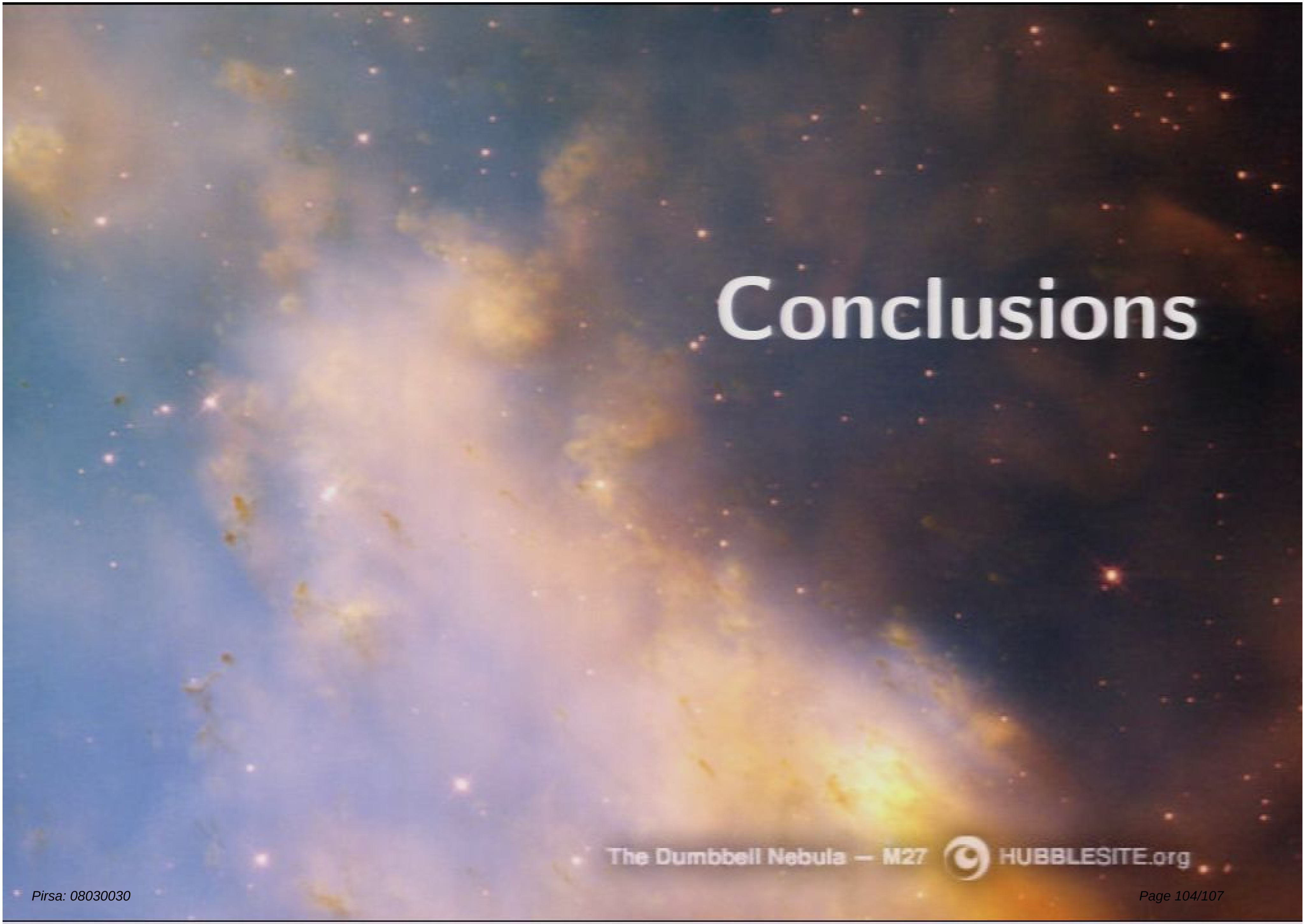
A Critical Assessment

- Brane-inflation is fine-tuned and delicate.
- Scale-invariant scalar spectrum requires extra tuning not required by a solution to the horizon problem.
- Initial conditions and overshoot problems.

  But see: Itzhaki & Kovetz *Inflection Point Inflation* Underwood *Brane Inflation is Attractive*
- Model lacks embedding into an honest compactification:
  $\Rightarrow$ parameterize with UV perturbations to KS geometry

  D.B., Dymarsky, Kachru, Klebanov, McAllister,
  work in progress

Conclusions



Inflationary UV Challenges/Opportunities

Three problems in inflationary cosmology scream out for a UV completion:

- **$V(\phi)$ and the η–Problem**
  Satisfactory theory must come with a sufficient degree of UV completeness to estimate corrections to the inflationary potential and prove absence of the η–problem.

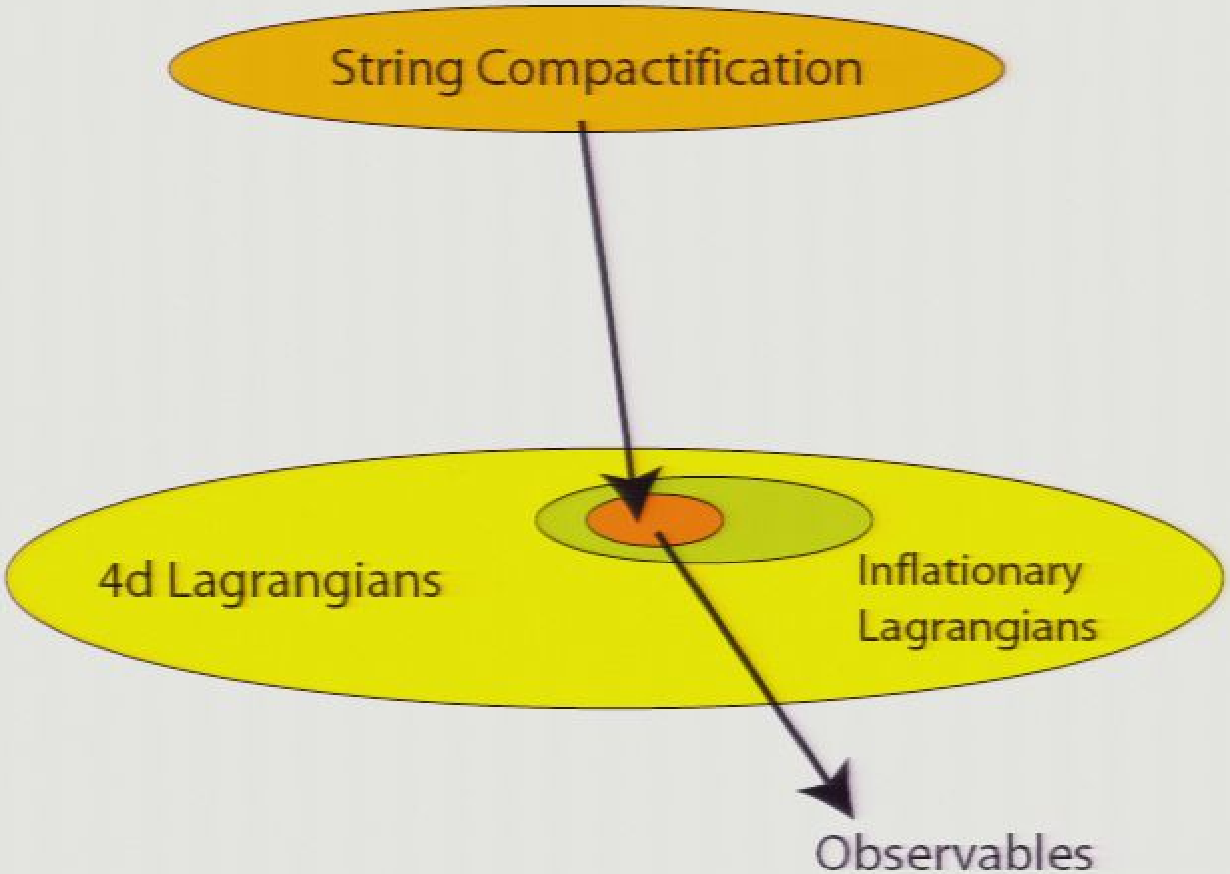
- **Gravitational Waves**

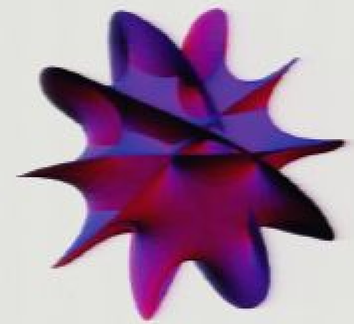
$$\frac{\Delta\phi}{M_{\rm pl}} \sim \mathcal{O}(1)\left(\frac{r}{0.01}\right)^{1/2}$$

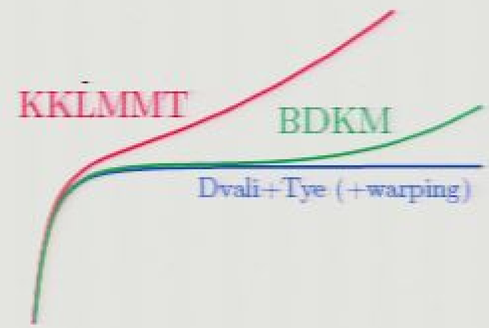
  Detection of tensors implies super-Planckian field variation.

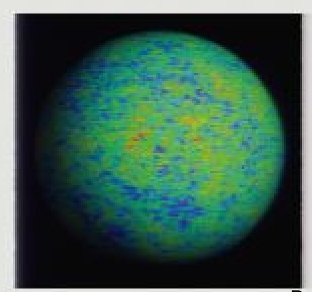
- **Non-Gaussianity**
  In single-field models non-Gaussianity can only be large if higher derivative terms, $((\partial\phi)^2)^n$, play a crucial role during inflation. Of course, this requires a plausible UV completion, e.g. DBI inflation.

From Compactification Data to Low-Energy Lagrangian







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Igor Klebanov, Juan Maldacena, Arvind Murugan,
Paul Steinhardt
The Helix Nebula — NGC 7293
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