Title: Codimension-2 brane inflation

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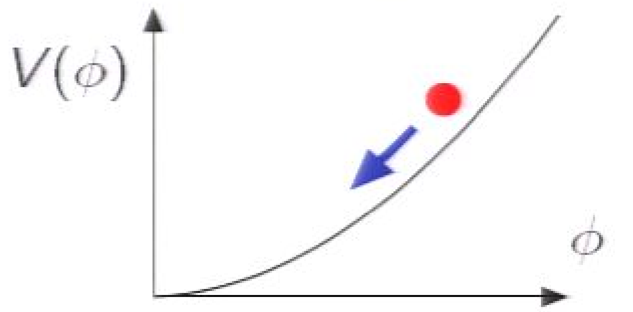
Abstract: We consider a probe codimension-2 brane inflation scenario in a warped six-dimensional flux compactification. First, we stabilise the modulus of the model by means of a cap regularisation of the codimension-2 singularities of the background solution. Then, we discuss the cosmological evolution of the world-volume of a probe codimension-2 brane when it moves along the radial direction of the internal space. In order to have slow-roll inflation, one needs the warping of the internal space to be weak, in contrast to the recent string inflation constructions with strong warping. We discuss the parameter range that the inflation is in agreement with the observationally inferred parameters and which furthermore is consistent with the probe brane approximation. We show that this scenario is falsifiable if substantial tensor modes are detected.

Inflation

- A period of accelerated expansion triggered (typically) by one or more slowly-rolling scalar fields



$$H = \frac{\dot{a}}{a} \approx \sqrt{\frac{V(\phi)}{M_{Pl}^2}} \approx const$$

- Comoving Hubble length decreasing with time
- Solves flatness, horizon, relics problems

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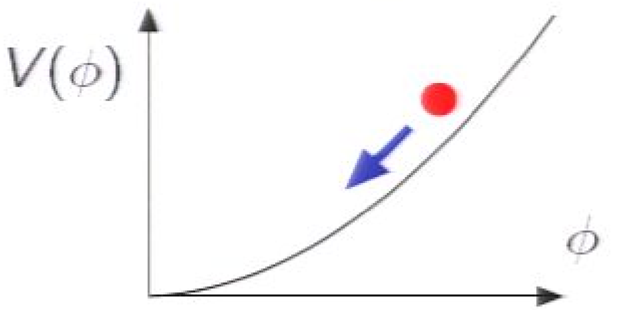
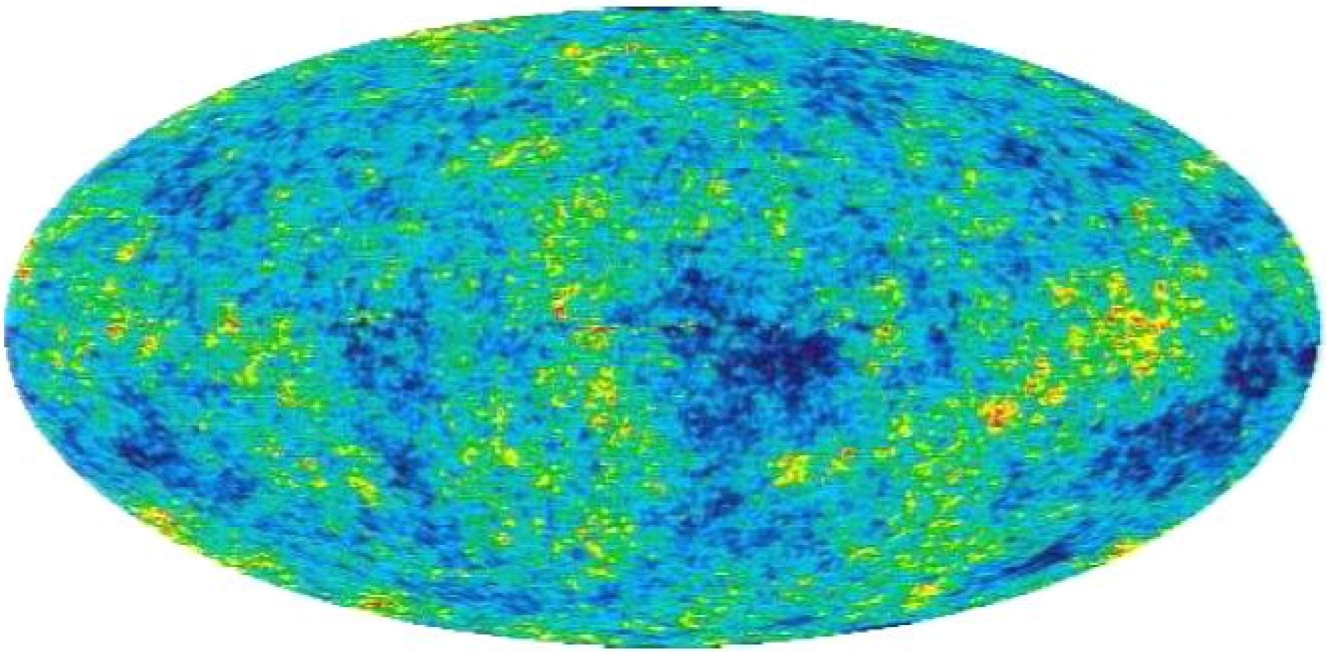


$$H = \frac{\dot{a}}{a} \approx \sqrt{\frac{V(\phi)}{M_{Pl}^2}} \approx const$$

- Comoving Hubble length decreasing with time
- Solves flatness, horizon, relics problems
- Predicts nearly scale-invariant and Gaussian spectrum of perturbations
- Quantum fluctuations of inflaton provide the seeds of structure formation

Cosmic Microwave Background



- Basic observed quantities

$$\delta_H = (1.91 \pm 0.17) \cdot 10^{-5} \quad , \quad n_s = 0.960 \pm 0.013$$
$$\text{(COBE)} \qquad\qquad \text{(WMAP, BAO, SN)}$$

Which model of inflation?

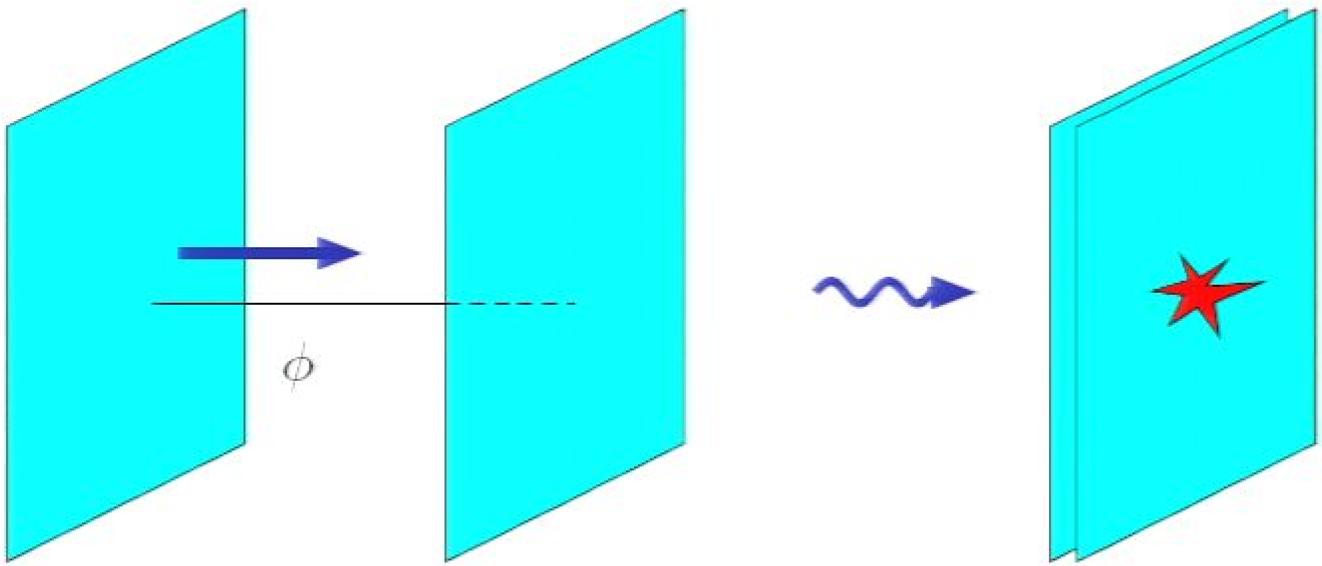
- There is a wealth of models for inflation ($\sim$ 3000 papers in SPIRES whose title includes "inflation")
- Two points of view
  - Phenomenological approach:
    Find the simplest model fitting the data
  - Theory approach:
    Test constructions motivated by theory
- It would be attractive to embed inflation in a more fundamental higher dimensional theory

$$
\begin{aligned}
&D = 10 \quad \text{string theory} \\
&D = 11 \quad \mathrm{M-theory} \\
&4 < D < 10 \quad \text{string compactifications} \\
&\qquad\qquad\quad \text{higher dim supergravitites}
\end{aligned}
$$

Brane inflation

- Branes are ubiquitous objects in higher dimensional theories $\equiv$ dynamical hypersurfaces living in the higher dimensional bulk
- Inflaton can be the field describing the interbrane separation

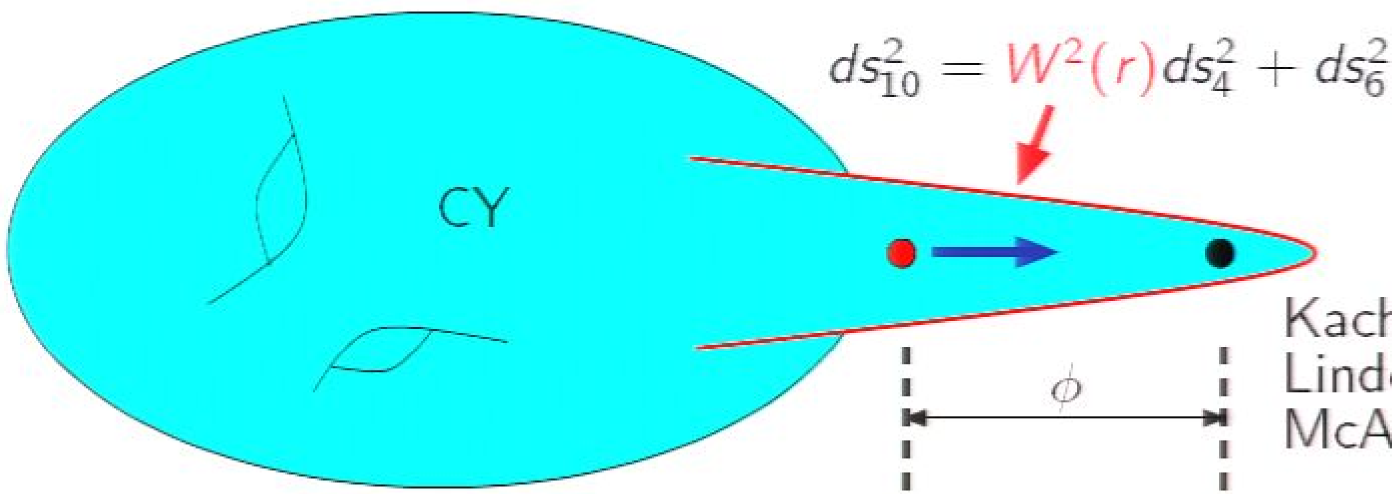
Dvali, Tye '98



- Branes approach each other (slow-roll inflation) followed by collision (reheating)
- Potential $V(\phi)$ calculable from the higher dimensional theory

String theory inflation

- The most realistic model in string theory ($D = 10$) has
  - 6 dimensions compactified in a Calabi-Yau manidold
  - fluxes of "magnetic" fields that stabilise the internal space
  - a highly warped throat



Kachru, Kallosh, Linde,Maldacena, McAllister,Trivedi '0

- Production of cosmic strings may lead to detectable gravitational waves and be visible in CMB polarization

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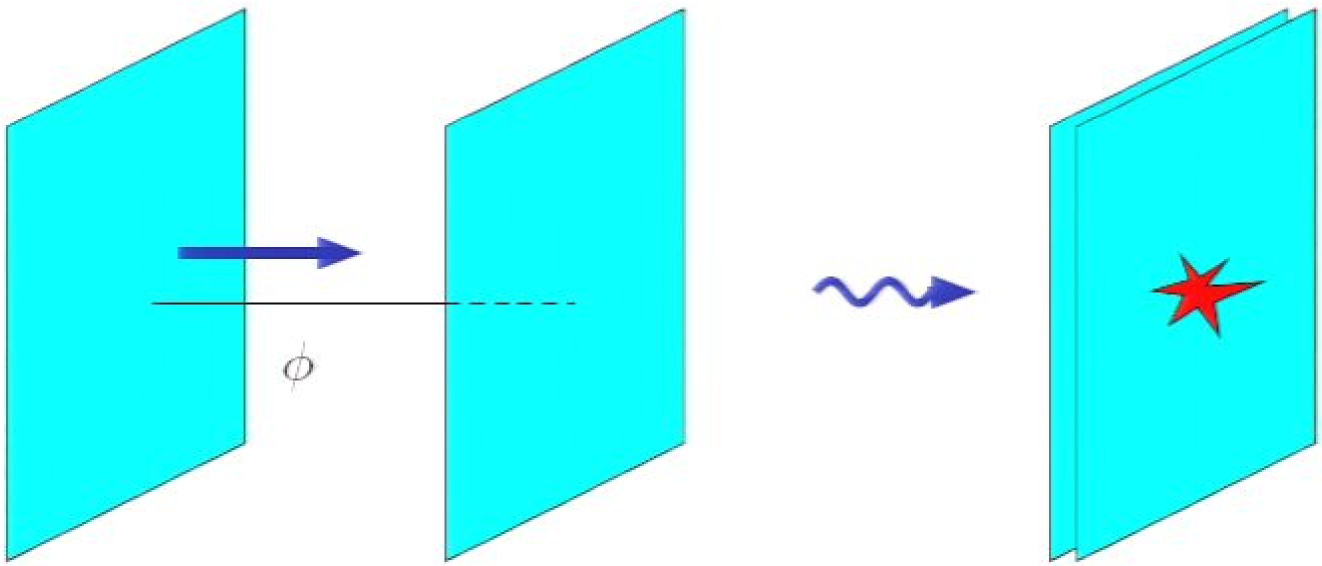

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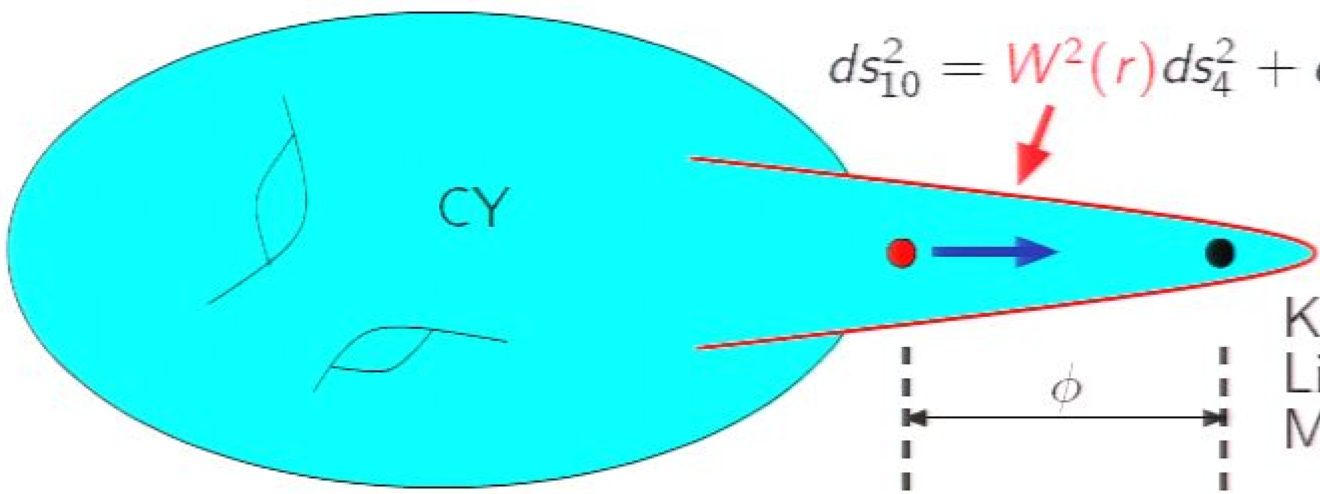
$$ds_{10}^2 = W^2(r)ds_4^2 + ds_6^2$$



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Outline

6D Gauged Supergravity

- Need a suitable background geometry in which the branes will move
- We consider the geometry generated by 6D gauged supergravity

Salam, Sezgin '84

- Field content

$$\text{Bosonic}: \quad g_{MN} \quad , \quad A_M \quad , \quad \phi \quad , \quad B_{MN}$$
$$\text{Fermionic}: \quad \psi_M \quad , \quad \lambda \quad , \quad \chi$$

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- Dynamics (bosonic sector w/t B_{MN})

$$S = \frac{M_6^4}{2} \int d^6x \sqrt{-g_6} \left[R_6 - \frac{1}{4}(\partial_M \phi)^2 - \frac{1}{2M_6^4} e^{\frac{1}{2}\phi} F_{MN} F^{MN} - 4g^2 M_6^4 e^{-\frac{1}{2}\phi} \right.$$

- Dilaton coupling to A_M + potential fixed by $\mathcal{N} = 2$ SUSY

6D Gauged Supergravity (contd)

- Turning on a gauge flux in the internal 2D space $F_{mn} = q\sqrt{g_2}\varepsilon_{mn}$, it is spontaneously compactified

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$$ds_6^2 = \eta_{\mu\nu}\,dx^\mu\,dx^\nu + ds_2^2$$

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- Need to add brane sources (of codimension-2)

$$S_i = -T_i \int d^4x \sqrt{g_4}$$

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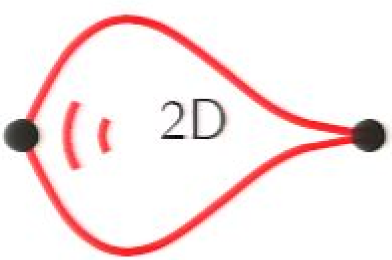


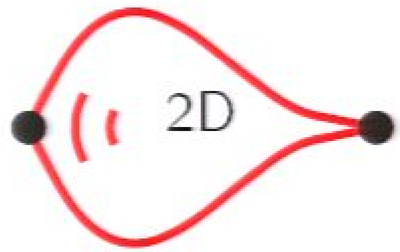
$T_2 = f(T_1, q/g)$

modulates warping

6D Gauged Supergravity with brane sources (contd)

- SUSY of the background solution

$\mathcal{N} = 0$ $\quad$ T_1



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For general g/q $\qquad$ $ds_6^2 = W^2(r)\eta_{\mu\nu}dx^\mu dx^\nu + ds_2^2$

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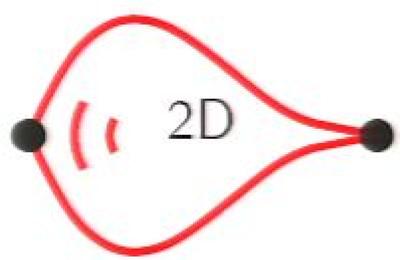

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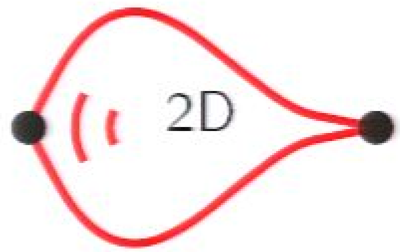

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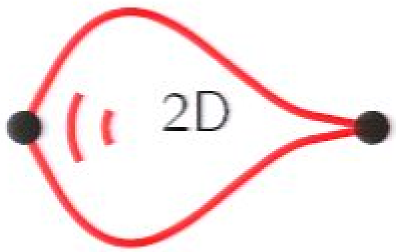

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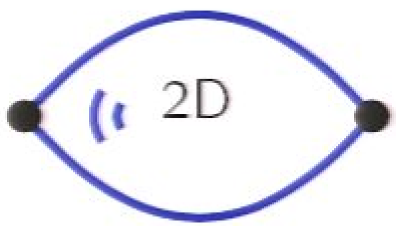


T

For $g/q = 1/(2M_6^4)$ $\quad ds_6^2 = \eta_{\mu\nu}dx^\mu dx^\nu + ds_2^2$

- For very weak warping, the solution is approximately supersymmetric

Modulus stabilization

- The solutions have a scaling symmetry

$$g_{MN} \longrightarrow e^{\frac{1}{2}\phi_0} g_{MN} \quad , \quad \phi \longrightarrow \phi + \phi_0$$

- There exists a modulus corresponding to the freedom of ϕ_0
- Needs to be fixed so that it does not spoil inflation

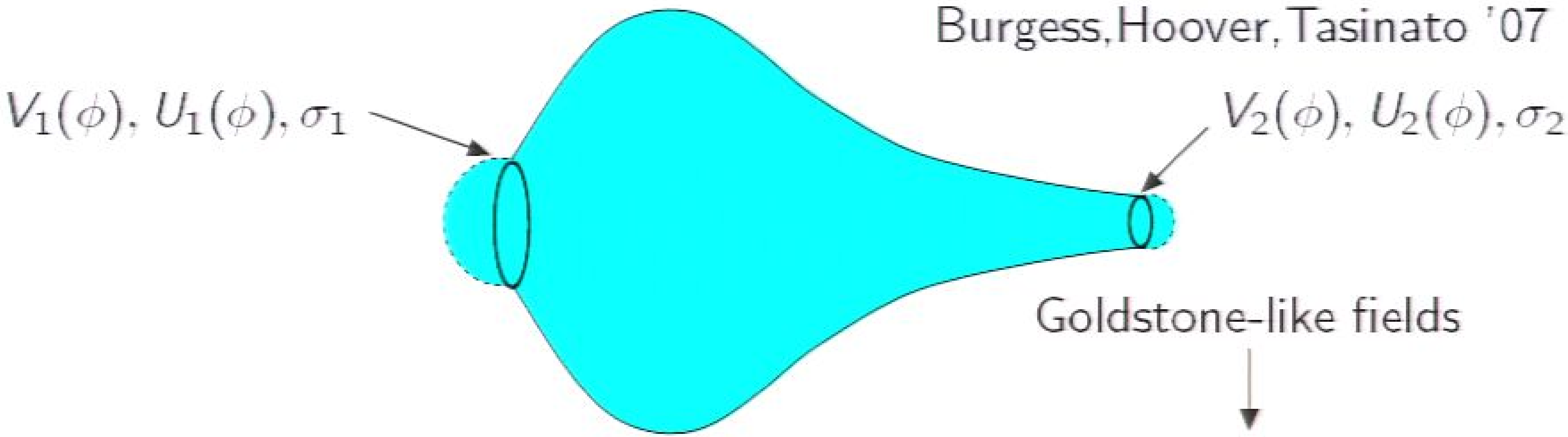
$$m^2_{modulus} > 0$$

- The stabilisation mechanism should not change much the background solution

Modulus stabilization (contd)

- **Example:** Stabilisation via the regularisation of the background branes as rings

Papantonopoulos,AP,Zamarias '06
Burgess,Hoover,Tasinato '07



- Ring actions $S_i = -\int d^5x \sqrt{-g_{(i)}} \Big[V_i(\phi) + \frac{1}{2} U_i(\phi)(D_{\hat{\mu}}\sigma_i D^{\hat{\mu}}\sigma_i) \Big]$
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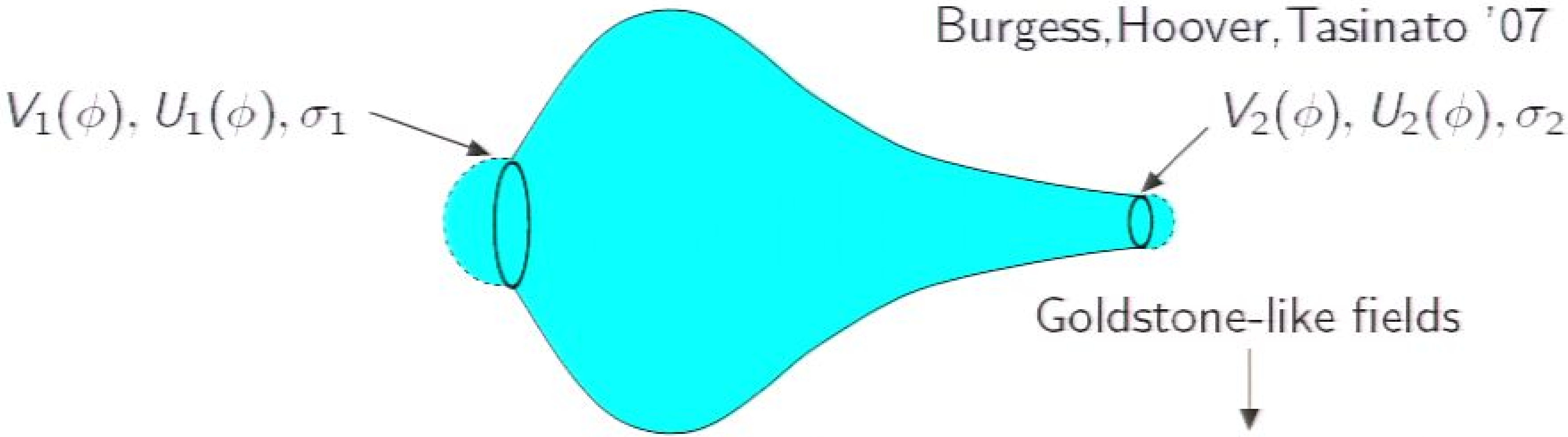

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Probe branes

- We will add one moving non-SUSY brane in the setup whose position in the bulk will be the inflaton
- We will consider the brane as probe $\equiv$ no backreaction to the background geometry !
- Two types of probes possible: Codimension-2 , Codimension-1

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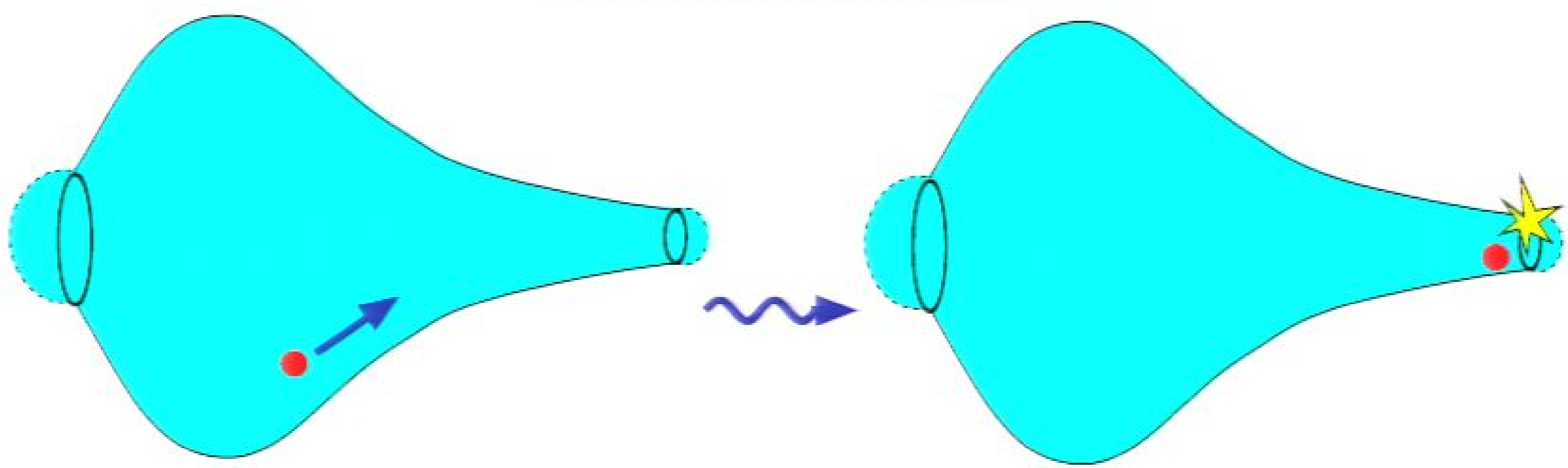
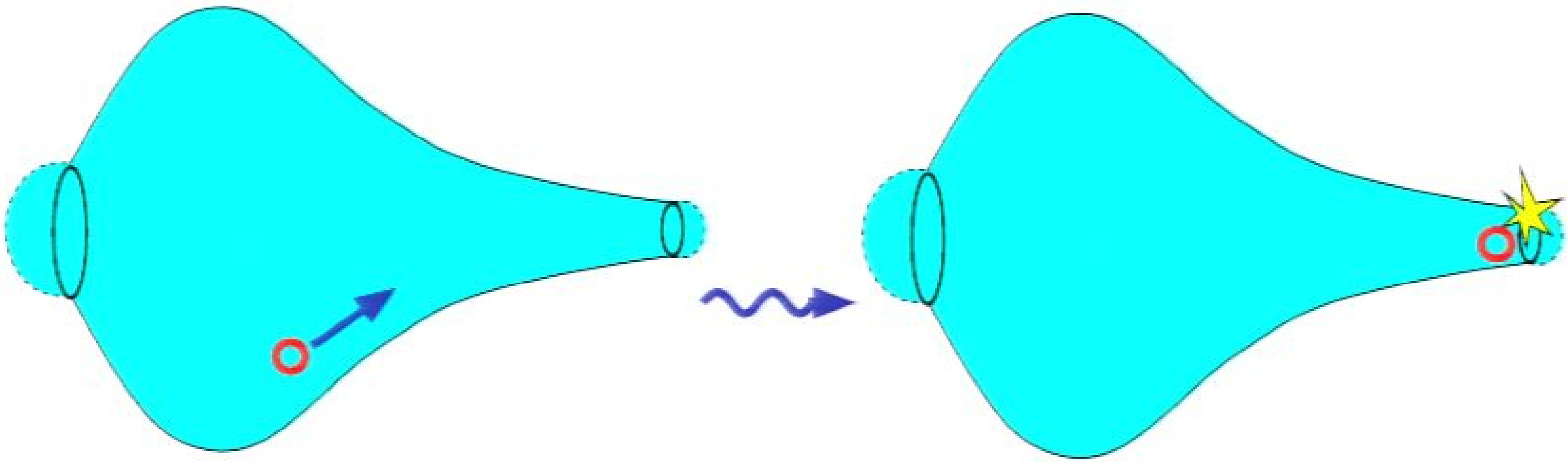
Codimension-2



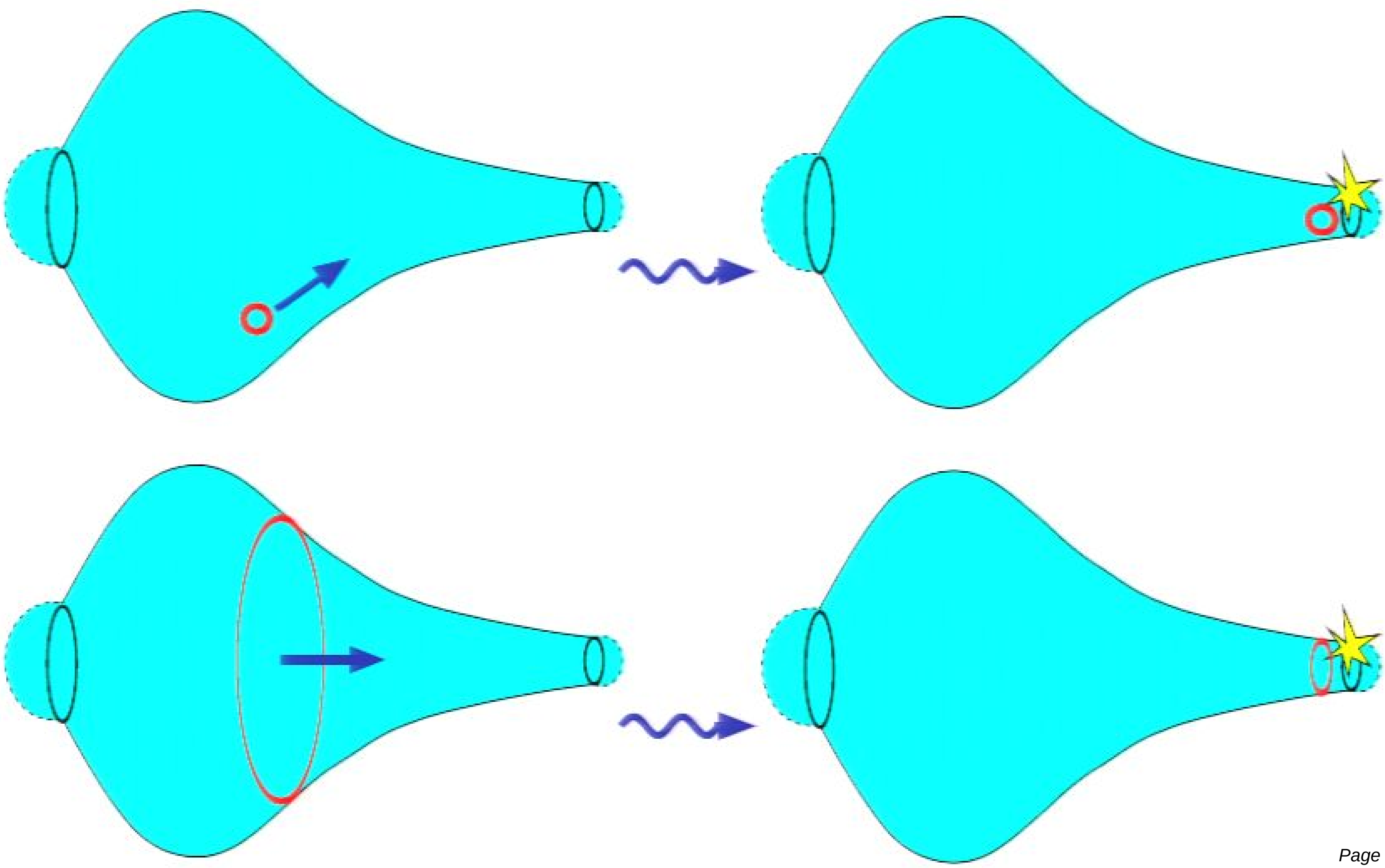
Probe branes (contd)

Codimension-1



Probe branes (contd)

Codimension-1

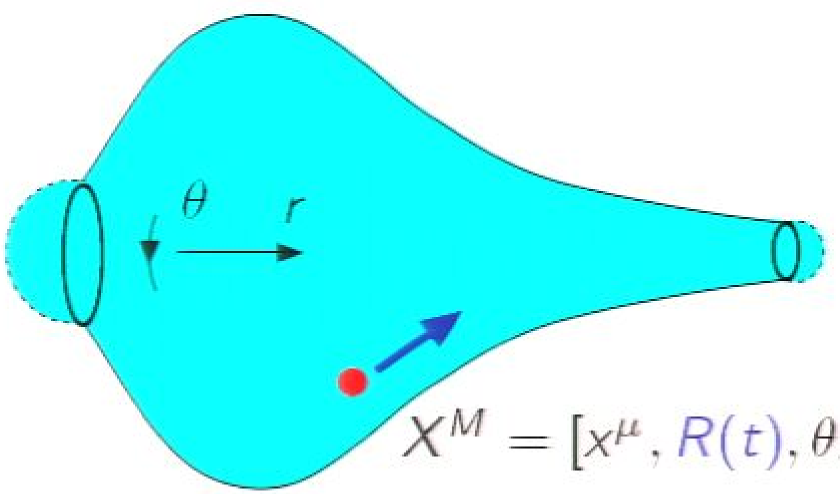


Probe branes (contd)

- Interested in the effective theory for a codim-2 or a small radius codim-1 probe
- Influence of the probe in the effective theory taken by the DBI-action

$$S_{probe} = -T_3 \int d^4x \sqrt{-\det \gamma_{\mu\nu}}$$

where $\gamma_{\mu\nu} = g_{MN}\partial_\mu X^M \partial_\nu X^N$ the induced metric on the probe



$$\gamma_{00} = g_{00} + g_{rr}\dot{R}^2$$

$$\gamma_{ij} = g_{ij}$$

$$X^M = [x^\mu, R(t), \theta_c]$$

Inflaton

Probe branes (contd)

- Integrating out the heavy modes we obtain the 4D effective action

$$S_{eff} \approx \int d^4x \sqrt{-g_4} \left[\frac{M_{Pl}^2}{2} R_4 - (\partial_\mu \psi)^2 - m_\psi^2 \psi^2 \right]$$

ψ : Stabilised modulus

Probe branes (contd)

- Integrating out the heavy modes we obtain the 4D effective action for $|\dot{R}| \ll 1$

$$S_{eff} \approx \int d^4x \sqrt{-g_4} \left[\frac{M_{Pl}^2}{2} R_4 - (\partial_\mu \psi)^2 - m_\psi^2 \psi^2 - \frac{T_3}{2} W^2 g_{rr} (\partial_\mu R)^2 - T_3 W^4 e^{-2\psi} \right]$$

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$W(r)$: Warping

- The potential is fixed by the background warping

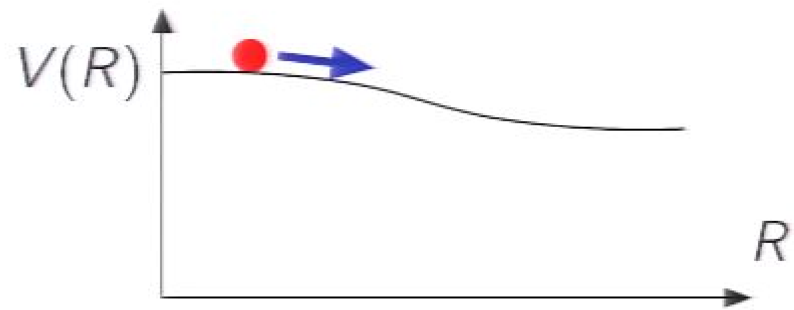
$$W^4 = \frac{1 + \frac{q^2}{4M_6^8 g^2} (R/r_0)^2}{1 + (R/r_0)^2} \quad , \quad r_0^2 = \frac{1}{M_6^4 g^2}$$

Mean internal space radius

Outline

Slow-roll

- If inflation happens below the scale of the ψ-stabilisation, we can consider ψ fixed
- The inflaton potential for $q/g < 2M_6^4$



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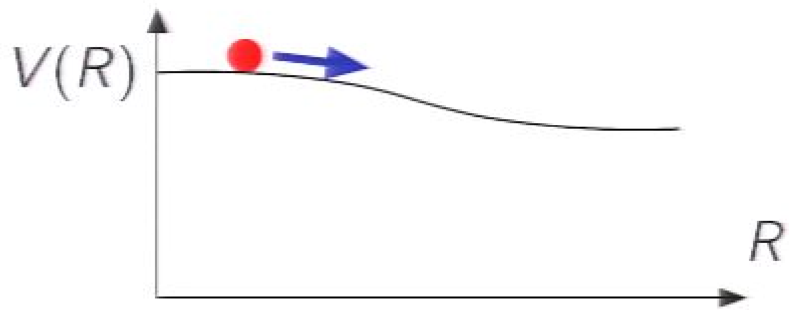

- The slow-roll parameters are

$$\epsilon \propto \delta^2 \frac{M_{Pl}^2}{r_0^4 T_3} \quad , \quad \eta \propto \delta \frac{M_{Pl}^2}{r_0^2 T_3} \quad \text{with} \quad \delta \equiv \frac{q^2}{4M_6^8 g^2} - 1$$

- For small warping $|\delta| \ll 1 \Rightarrow$ Slow-roll in all field space
- Weak warping, *i.e.*, we are close to the SUSY $\mathcal{N} = 1$ vacuum

Comparison with data

- Fit δ_H and n_s

$$\delta_H = \frac{1}{\sqrt{150\pi M_{Pl}^2}} \frac{V^{1/2}}{\epsilon^{1/2}} \approx 1.91 \cdot 10^{-5} \quad , \quad n_s = 1 - 6\epsilon + 2\eta \approx 0.960$$

- One should have $\delta < 0$, $|\delta| < 10^{-2}$ and

$$r_0^{-1} \sim 10^{13}\mathrm{GeV} \quad , \quad M_6 \sim 10^{15}\mathrm{GeV} \quad , \quad T_3^{1/4} \sim |\delta|^{1/4} 10^{16}\mathrm{GeV}$$

- Inflationary parameters

$$|\eta_{exit}| \lesssim 0.02 \quad , \quad \epsilon_{exit} \lesssim 0.02|\delta| \quad , \quad N_{COBE} \gtrsim 50 \ln(R_f/R_i) > 60$$

- Checking bounds on other observables

$$r \lesssim 0.06|\delta| \quad , \quad \frac{dn_s}{d\ln k} \lesssim 10^{-4}$$

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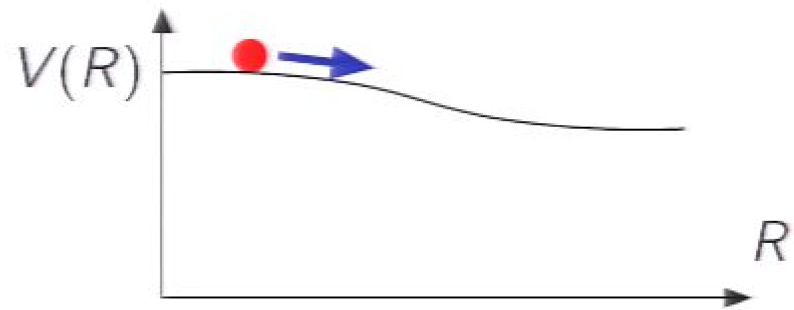

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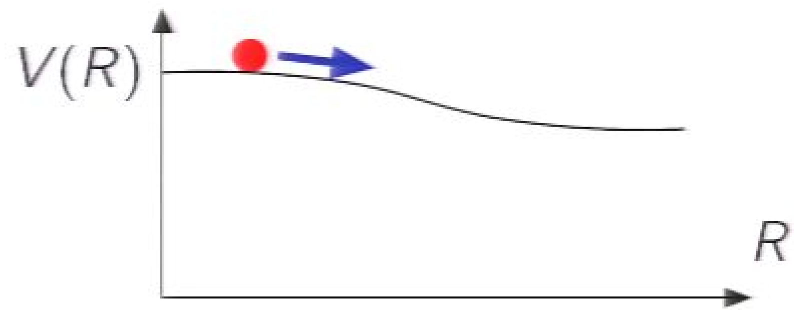

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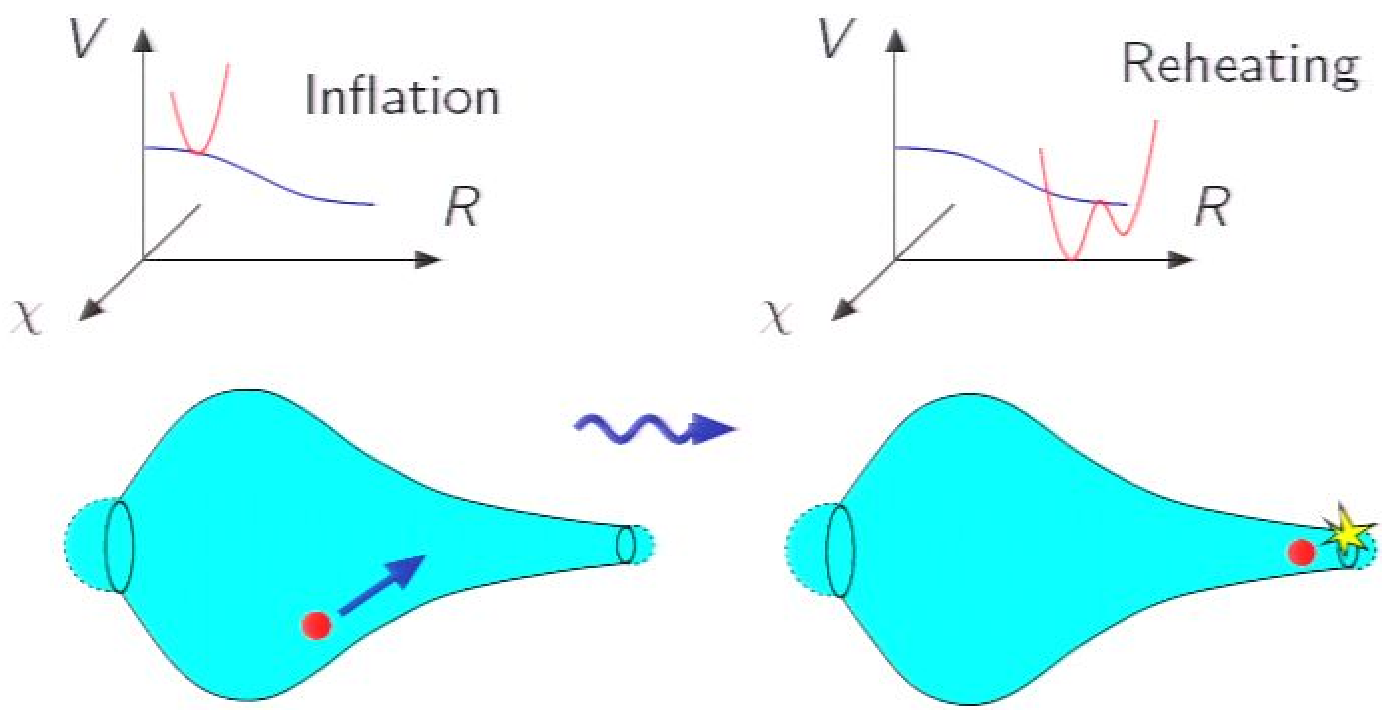
Exit from Inflation

- During inflation the probe travels from the one background brane to the other
- Close to collision the potential is altered to hybrid-like (R, χ)

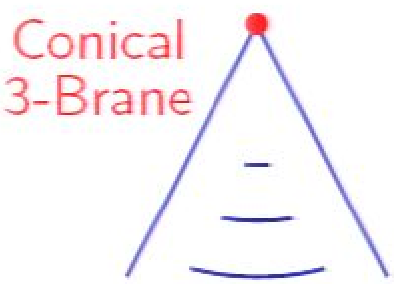


Outline

The DBI approximation

- Using the DBI action to account for the probe codimension-2 brane contribution to the effective 4D action dangerous
- Conical branes "hide" vacuum energy (tension)

Chen,Luty,Ponton '00



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$$V_{eff} \approx \underbrace{\lambda T_3}_{T_3^{eff}} W^4 \left[1 + \lambda \ln W \right]$$

Backreaction to modulus and warping

Modulus

- The modulus should be stabilised at a scale higher than the inflation scale

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- In this realisation of inflation, $T_3 \ll T_{1,2}$, but $T_3 > |T_1 - T_2|$
- Static multibrane solution with backreaction possible

Lee,Lüdeling '05

- T_3 does not change $T_1 - T_2$ that is needed for the warping
- In the adiabatic approximation can trust the solution

Conclusions

- Studied codimension-2 probe brane inflation in 6D gauged supergravity background
- Inflation happens for weak warping ($\neq$ strong warping of string models)
- Basic parameters

$$r_0^{-1} \sim 10^{13}\mathrm{GeV} \quad , \quad M_6 \sim 10^{15}\mathrm{GeV} \quad , \quad H \sim |\delta|^{1/2} 10^{14}\mathrm{GeV}$$

- To control backreaction we need $|\delta| \ll 10^{-2}$, *i.e.*, close to SUSY $\mathcal{N} = 1$ vacuum
- This scenario is falsifiable if substantial tensor modes are detected

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- If angular motion is taken into account we would obtain richer phenomenology, *e.g.*, isocurvature perturbations, f_{NL}

Langlois, Renaux-Petel, Steer, Tanaka '08