Cosmology of moving branes and spinflation

第8回 宇宙における時空・物質・構造の進化」研究会

'Dark Energy in the Universe' サマースクール

２００８年８月３０日（土）～９月２日（火）

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Outline

- Brane Inflation, Moduli Stabilization and Flux Compactifications
- Cyclic, Mirage cosmologies (using angular momentum)
- Spinflation

DE, Gregory, Tasinato, Zavala hep-th/0701252
DE, Gregory, Mota,Tasinato, Zavala 0709.2666
DE, Gregory in progress

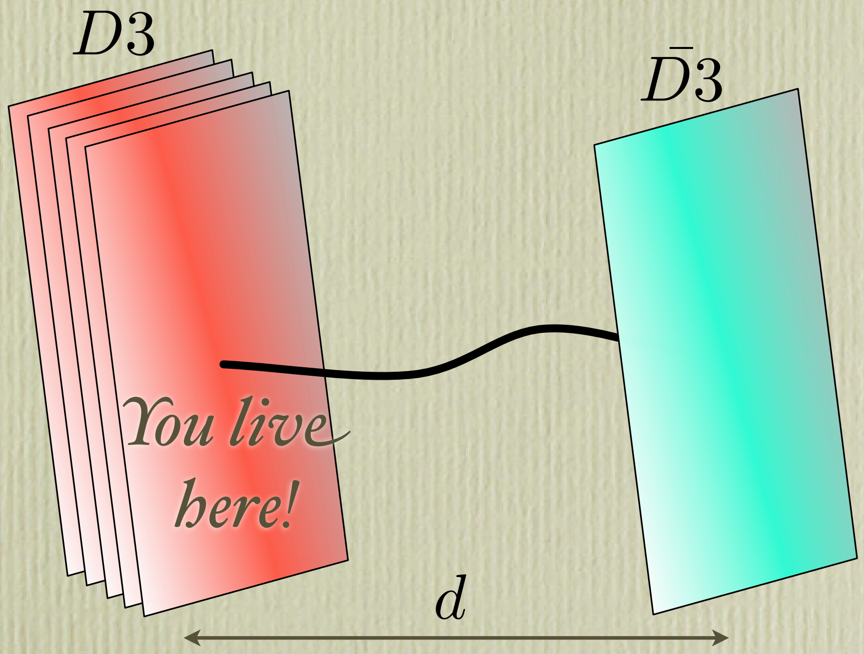
Inflationary Paradigm

- At early times the Universe experienced a short burst of extremely rapid (*accelerated*) expansion.
- Inflation solves conceptual and theoretical problems of the SBB model.
- Basic predictions are all supported by the data.

Brane Inflation *Dvali, Tye '99*

(geometric inflation)

- Coulomb attraction



lightest string =
4D particle, *Tachyon*

$$M_T^2 = d^2 M_s^4 - M_s^2$$

$$d \leq \ell_s \rightarrow M_T^2 \leq 0$$

Brane/anti-brane separation (in X_6) acts like an inflaton

...like Higgs in SM, T 'condenses,' ending inflation

Observational Predictions

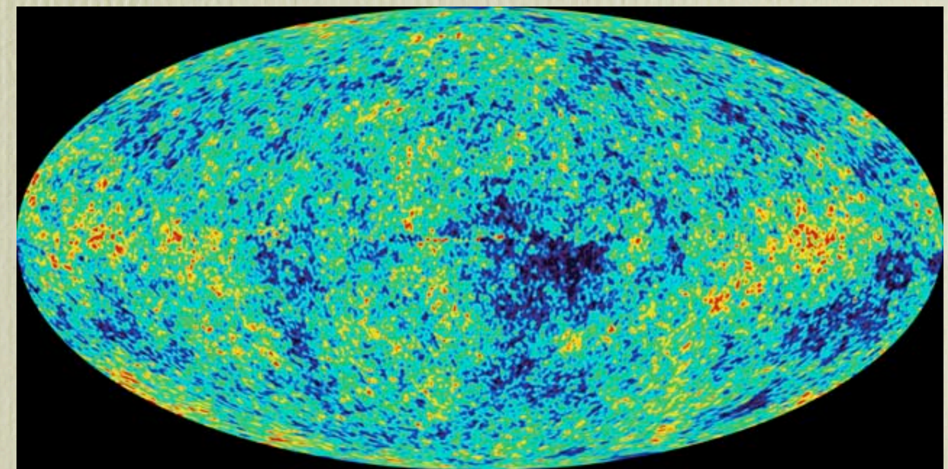
- In the annihilation the anti-brane destroys a brane and (observable) cosmic strings can be produced.

- There are also possible signatures in cosmological perturbations (*in the CMB*)....

• In ordinary slow roll inflation, perturbations are Gaussian.

• In brane inflation non-Gaussianities are possible and *Planck can see them*. *Garriga, Mukhanov '99* *Alishahiha, Silverstein, Tong '04*

• Significant non-Gaussianity detection would be strong evidence of new physics in the inflaton sector.



Moduli Fields

- The metric in the extra dimensions (sizes and shapes of cycles of Calabi-Yau space) depends on continuous parameters called *moduli*.

- The parameters of a solution correspond to scalar fields (unconstrained by EOM, i.e. *massless*) in four dimensions.

- In a realistic compactification there can be *many* of these moduli fields.

Moduli Problems

These scalar fields have nonuniversal couplings to matter:

$$f_i(\varphi_i)L_m(\psi_i)$$

Different types of matter get different accelerations from these forces, violating the equivalence principle.

"Fifth force" experiments constrain such forces to be very weak, but if fields remain massless we do not expect them to interact with matter more weakly than gravity.

Need to stabilize moduli using fluxes and branes.

Concrete Stringy Model

$$S_{\rm IIB} = \frac{1}{2\kappa^2}\int d^{10}x\sqrt{-g_{\rm s}}\Big\{e^{-2\phi}\left[\mathcal{R}+4(\nabla\phi)^2\right]$$

$$-\frac{F_{(1)}^2}{2} - \frac{1}{2\cdot 3!}G_{(3)}\cdot\bar{G}_{(3)} - \frac{\tilde{F}_{(5)}^2}{4\cdot 5!}\Big\}$$

$$+\frac{1}{8i\kappa^2}\int e^{\phi}C_{(4)}\wedge G_{(3)}\wedge\bar{G}_{(3)} \;+\; S_{\rm loc}$$

$$G_{(3)} = F_{(3)} - \tau H_{(3)}$$

$$\tau = C_{(0)} + ie^{-\phi}$$

$$S_{\rm loc} = -\int_{R^4\times\Sigma} d^{p+1}\xi\, T_p\sqrt{-g} + \mu_p \int_{R^4\times\Sigma} C_{p+1}$$

In IIB RR potentials are:

$$C_{(0)}, C_{(2)}, C_{(4)}, C_{(6)}, C_{(8)}$$

- Compactify this on a CY manifold and turn on fluxes and wrap branes to stabilze moduli fields.

Giddings, Kachru, Polchinski 2001
Kachru, Kallosh, Linde, Trivedi 2003

- Study dynamics of brane probes in this background

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi 2003

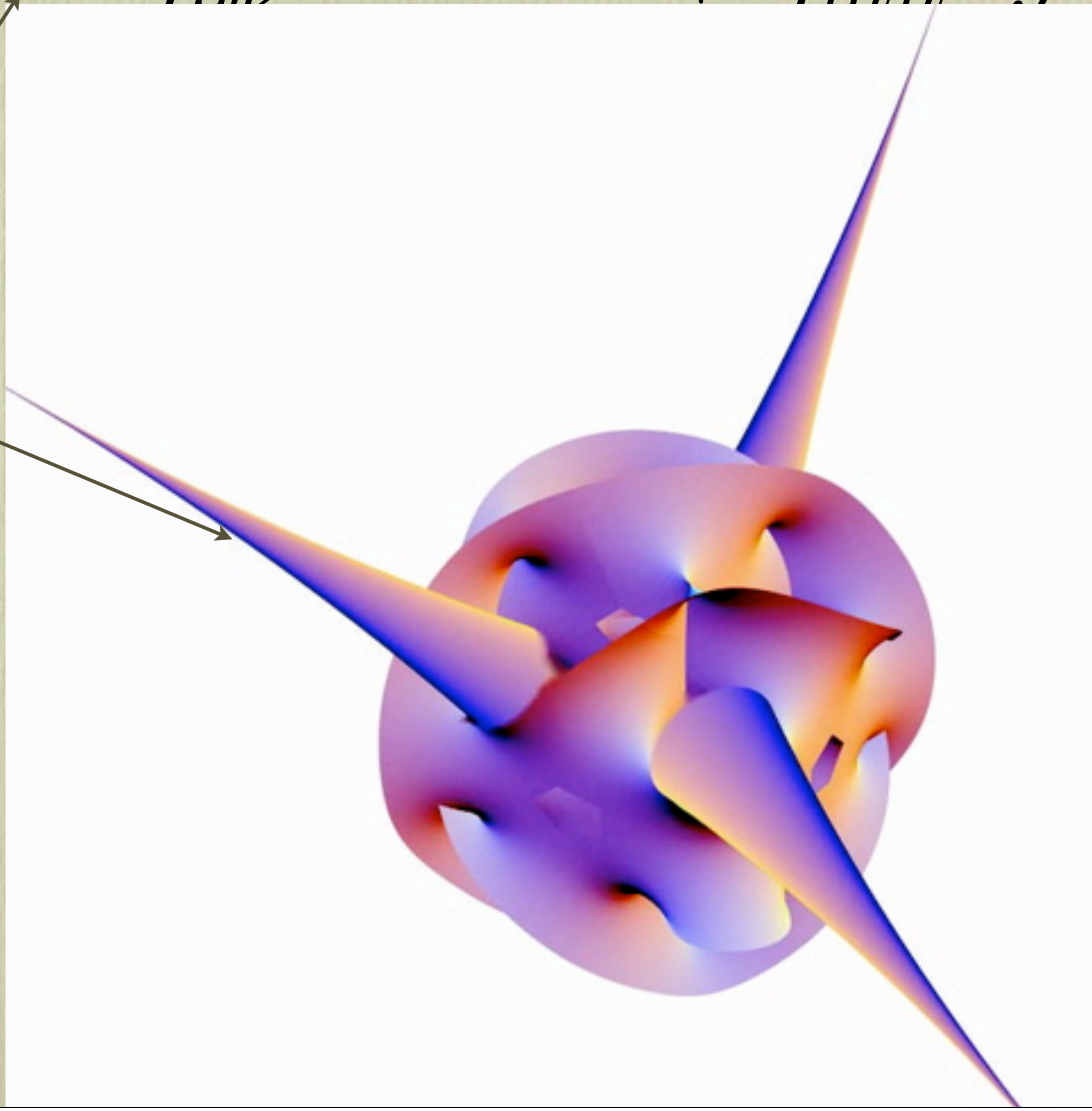
- Compactify on CY

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + \tilde{g}_{mn}dy^m dy^n$$

... Turn on the FLUX!!

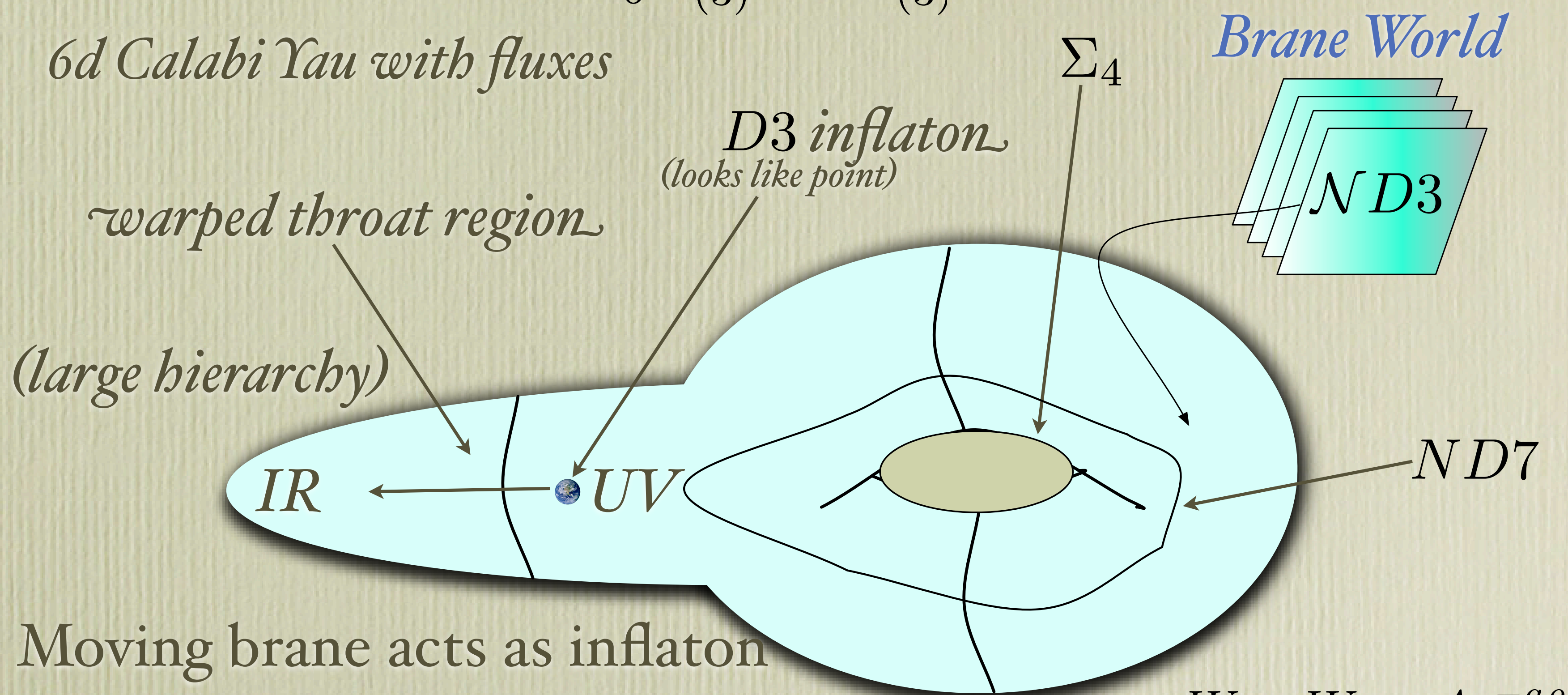
$$ds^2 = e^{A(y)} g_{\mu\nu}dx^\mu dx^\nu + e^{-A(y)} \tilde{g}_{mn}dy^m dy^n$$

Warping!



Brane Cosmologies

$$*_6 G_{(3)} = i G_{(3)}$$



- Moving brane acts as inflaton
- Moving branes experience expansion/contraction as they move in the throat - *mirage cosmology*

$$W = W_0 + A e^{-a\rho}$$

- Need nonperturbative effects to stabilize Kähler moduli

Klebanov Strassler

- Based on *deformed conifold*:

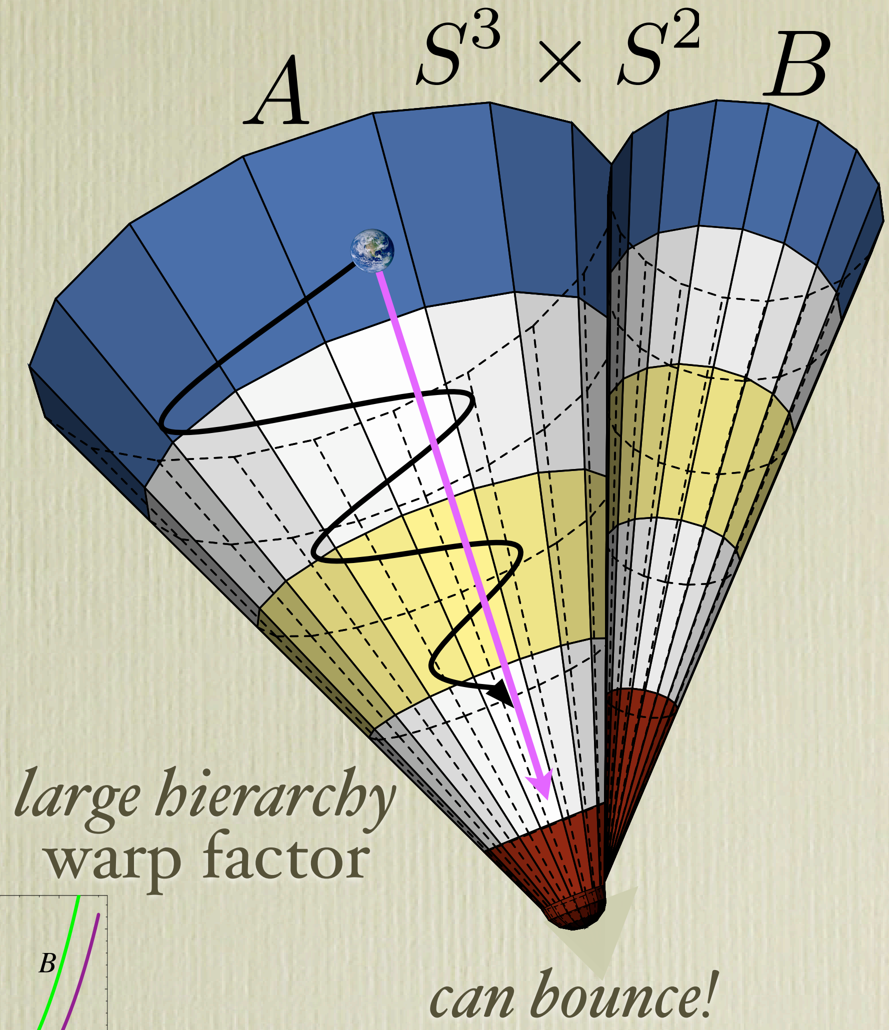
$$\sum_A (w^A)^2 = z$$

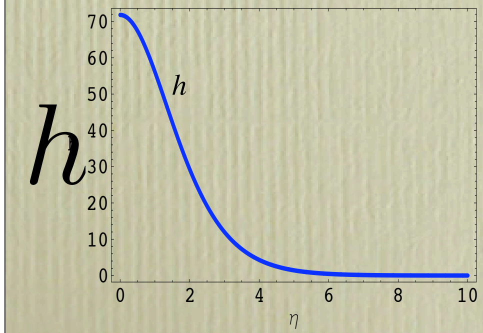
$$\frac{1}{2\pi\alpha'}\int_A F_3 = 2\pi M$$

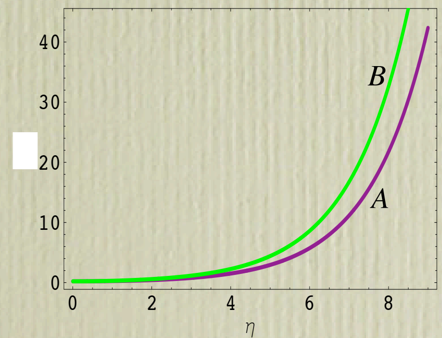
$$\frac{1}{2\pi\alpha'}\int_B H_3 = -2\pi K$$

$$W = \int G_3 \wedge \Omega \qquad z = \int_A \Omega$$

$$z = e^A \sim e^{-2\pi K/g_s M}$$







$$Vol(T^{(1,1)}) = \frac{16\pi^3}{27}$$

Brane Dynamics & Mirage Cosmology

DAE, Gregory, Tasinato, Zavala '07

- The probe brane evolves according to the DBI action:

$$S_{\rm DBI} = -m \int d^4x \left[h^{-1}(\sqrt{1-hv^2} - 1 \right]$$

Induced "mirage cosmology"

Kehagias, Kiritsis '99

$$ds^2 = h^{-1/2}\left(-(1-h\,v^2)\,dt^2 + dx_i dx^i\right) = -d\tau^2 + a^2(\tau) dx_i dx^i$$

- Bounces are possible. The *4D* effective theory on the brane is a scalar-tensor gravity that can violate the NEC.
- Represents a string theory resolution of a spacelike singularity.

Turning on angular momentum

- What if the brane *spins* as it moves in the throat?
- Conserved angular momentum: $l_r = \frac{g_{rs}\,\dot{\theta}^s}{\sqrt{1 - hv^2}}$

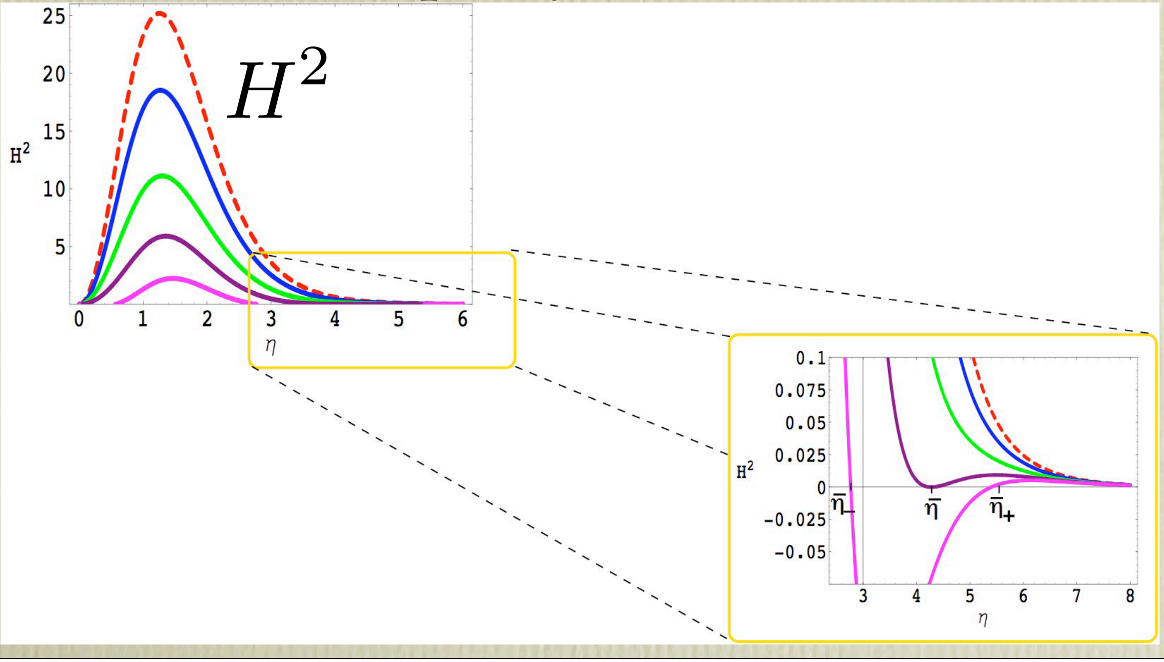
$$v^2 = \frac{g_{\eta\eta}\dot{\eta}^2 + \ell^2(\eta)}{1 + h\ell^2(\eta)} \qquad \ell^2(\eta) = g^{rs} l_r l_s$$

Mirage cyclic cosmology

$$ds_{10}^2 = h^{-1/2}(\eta)\, dx_\mu dx^\mu + h^{1/2}(\eta) ds_6^2$$

$$h(\eta) \propto \epsilon^{-8/3} \int_\eta^\infty dx\, \frac{x\,\coth x - 1}{\sinh^2 x}\, (\sinh(2\,x) - 2\,x)^{1/3}$$

- Introducing angular momentum generates a centrifugal barrier for the brane.
- Bound states near tip – cyclic Universes.



- The mirage pictures has serious drawbacks, but it does provide an example of a time-dependent bounce and cyclic toy cosmologies in string theory.

- Try using spinning moving branes as inflatons instead. (We live somewhere *off* the inflaton brane)

DE, Gregory, Mota, Tasinato, Zavala '07

Backreaction

- Easiest first step is to couple DBI to Einstein Hilbert action. *Silverstein, Tong 2003*
- There are *no NEC violating sources*, making cyclic cosmologies impossible.
- Can have bounces in the radial field due to angular momentum or passing through a nonsingular tip (KS).

Brane position: $\phi = \sqrt{T_3}\, r$

DBI(nflation) in the Throat

A moving brane sources inflation.

$$S = \frac{M_{Pl}^2}{2}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\,P(X,\,\phi^m)$$

$$P(X,\phi^m) = -g_s^{-1}\left[h^{-1}\sqrt{1+h\,g_{mn}g^{\mu\nu}\partial_\mu\phi^m\partial_\nu\phi^n} - q\,h^{-1} + V(\phi^m)\right]$$

For D3 moduli space is the internal space:

$$\{\eta,\psi,\theta_1,\theta_2,\phi_1,\phi_2\}$$

$$\gamma \equiv \frac{1}{\sqrt{1-hv^2}}$$

$$v^2 = g_{mn}\dot{\varphi}^m\dot{\varphi}^n$$

Brane speed limit!

$$E = \frac{1}{h}\left[\gamma - q\right] + V$$

$$P = \frac{1}{h}\left[q - \gamma^{-1}\right] - V$$

Position in throat given by field: ϕ

$$\dot{H} = -\frac{3\beta}{2h}\left(\frac{h^2\left(\frac{H^2}{\beta}-V\right)^2+2qH\left(\frac{H^2}{\beta}-V\right)+q^2-1}{q+h\left(\frac{H^2}{\beta}-V\right)}\right)$$

$$g_{\phi\phi}\dot{\phi}^2 = h^{-1}\left[1-\frac{1+h\frac{\ell(\phi)^2}{a^6}}{q+h\left(\frac{H^2}{\beta}-V\right)}\right]$$

- bounces due to angular momentum still possible but not with sufficient efoldings of inflation.

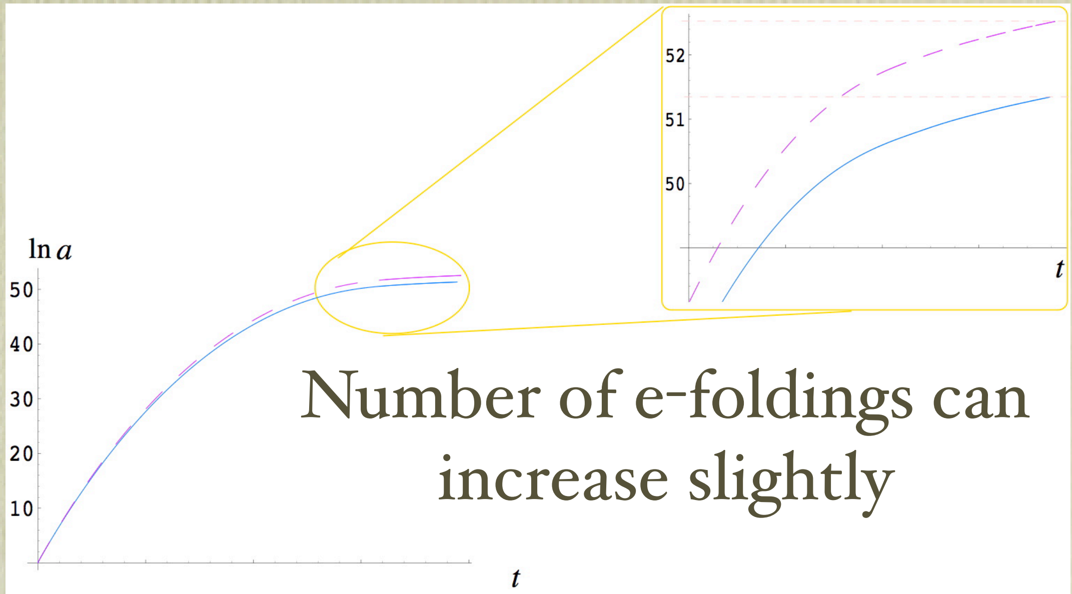
- *spinflatons prolong inflation*

$$\varepsilon = \frac{3\beta}{2H^2}\left\{\left[q+f\left(\frac{3H^2}{\beta}-V\right)\right]\dot{\phi}^2+\frac{l^2(\phi)}{a^6}\left[q+f\left(\frac{3H^2}{\beta}-V\right)\right]^{-1}\right\}$$

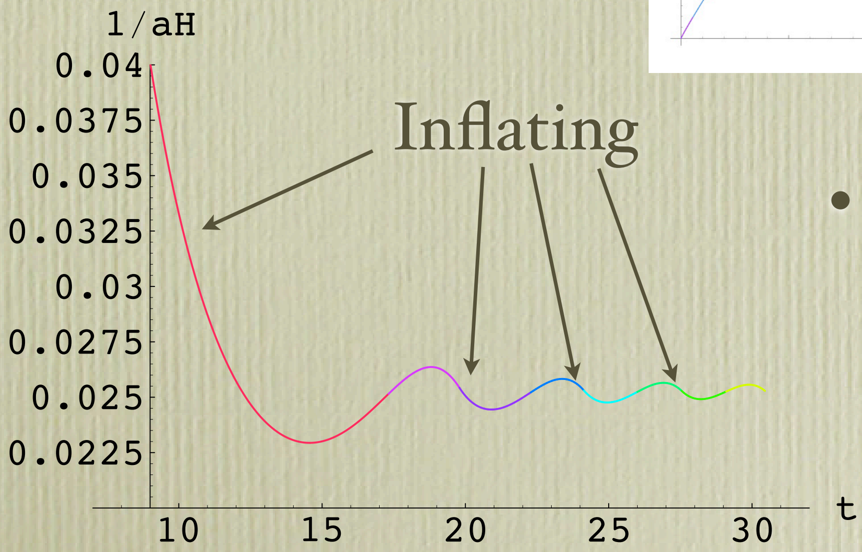
Inflationary trajectories

$$V(\phi) = m^2\phi^2$$

(using full KS)



Number of e-foldings can increase slightly



- inflaton couples to SM fields

reheating

$$\mathcal{L} = -\frac{1}{2}g^2\phi^2\chi^2 - h\bar{\psi}\psi\phi$$

Brodie, DE '03

Mukohyama '07

Non-Gaussianities

- For a brane moving through a warped background:

$$S_{DBI} = \int dt\, d\vec{x}\, h^{-1}(\phi)\sqrt{1 - h(\phi)\partial^{\mu}\phi\partial_{\mu}\phi}$$

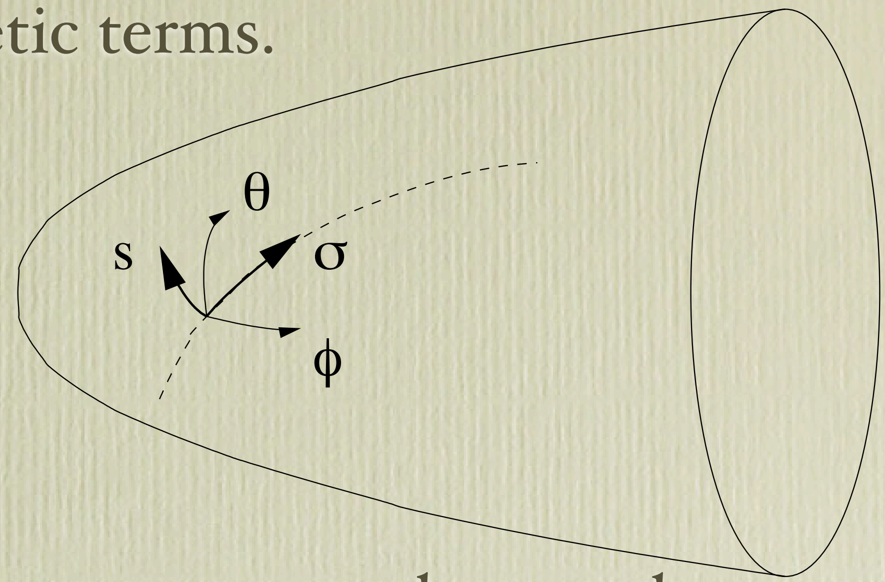
In standard slow roll inflation $|n_s - 1| << 1$

(gaussian ground state of QHO)

In DBI $f_{NL} \propto \gamma^2$ $\gamma \equiv \dfrac{1}{\sqrt{1 - hv^2}}$

Brane inflation *is* a multi field model with non-standard kinetic terms.

$$\{\eta, \psi, \theta_1, \theta_2, \phi_1, \phi_2\}$$



In general, adiabatic and isocurvature modes travel at different speeds (due to gammas)

DE, Gregory, Mota, Tasinato, Zavala '07
Arroja, Mizuno, Koyama '08

. . .but DBI is special

Langois, Renauz-Petel, Steer, Tanaka '08

Conclusions

- Considering brane dynamics with angular momentum and cycling behavior gives rich, new phenomenology.
- Models can make general observational predictions (e.g. cosmic strings, non-gaussianity, gravitational waves).
- Much more work needs to be done to build explicit stringy models.