Inflation in String Theory

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Stanford

Texas Symposium, Stanford, December 13, 2004

Outline

Recent progress in string theory cosmology

Flux Compactification and Stabilization of Moduli,

Metastable de Sitter Space in String Theory

Landscape of String Theory, CC problem

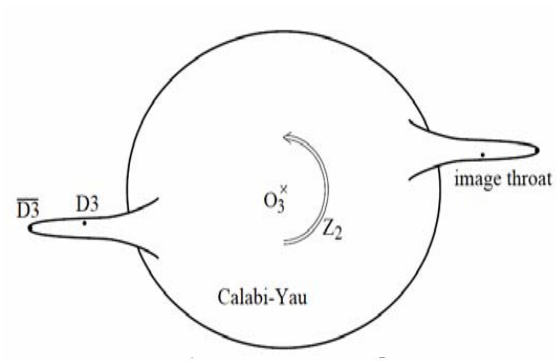
(More in a talk by L. Susskind on December 15)

Inflation in String Theory

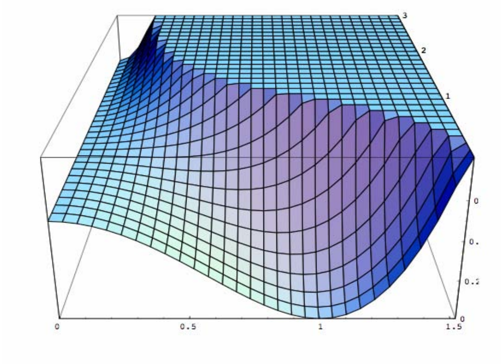
Cosmic Strings

How cosmology has affected string theory and particle physics

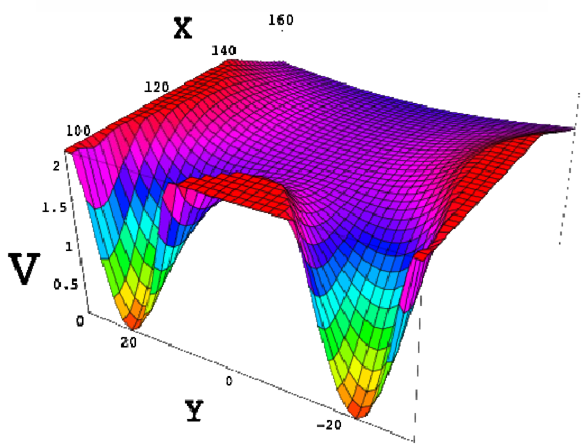
New class of inflationary models in string theory



KKLMMT brane-anti-brane inflation



D3/D7 brane inflation



Racetrack modular inflation

DBI inflation, Silverstein et al

Our Universe is an Ultimate Test of Fundamental Physics

- High-energy accelerators will probe the scale of energies way below GUT scales

- **Cosmology and astrophysics are sources of data in the gravitational sector of the fundamental physics (above GUT, near Planck scale)**

Cosmological Concordance Model

- Early Universe Inflation
- Near de Sitter space
- 13.7 billion years ago
- During 10^{-35} sec

- Current Acceleration
- Near de Sitter space
- Now
- During few billion years

$$\frac{\dot{a}}{a} = H \approx \mathrm{const}$$

$$V \sim H^2 M_P^2 \qquad V \sim H^2 M_P^2$$

$$H_{infl} \leq 10^{-5} M_p \qquad H_{accel} \sim 10^{-60} M_P$$

$$\frac{\ddot{a}}{a} > 0$$

Impact of the discovery of acceleration of the universe

Until recently, string theory could not describe acceleration of the early universe (inflation)

The discovery of current acceleration made the problem even more severe, but also helped to identify the root of the problem

String Theory and Cosmology

How to get de Sitter or near de Sitter 4d space
from the compactified 10d string theory or 11d M-theory?

$$H_{infl} \leq 10^{-5} M_p \qquad H_{accel} \sim 10^{-60} M_P$$

No-Go Theorems for 4d de Sitter Space

from 10/11d string/M theory

- Gibbons **1985**
- de Wit, Smit, Hari Dass, **1987**
- Maldacena, Nunez, **2001**

How to go around the conditions for de Sitter no-go theorems?

How to perform a compactification from 10/11 dimensions to 4 dimensions and stabilize the moduli?

Can string theory afford runaway moduli: a dilaton and the total volume of the compact 6d space?

$$-\frac{1}{2}(\partial\tilde{\phi})^2 - \frac{1}{2}(\partial\tilde{\sigma})^2 - e^{-\sqrt{2}\,\tilde{\phi}-\sqrt{6}\,\tilde{\sigma}}V_0$$

Both stringy moduli have very steep potentials incompatible with the data for inflation and even for the current acceleration of the universe, particularly the total volume

Recent proposal

Towards cosmology in type IIB string theory

Dilaton stabilization **Giddings, Kachru and Polchinski**

Volume stabilization, <u>KKLT construction of de Sitter space</u> **Kachru, R.K., Linde, Trivedi**

Maloney, Silverstein, Strominger,
in non-critical string theory

Kachru, R. K., Maldacena, McAllister, Linde, Trivedi

INFLATION The KLMT model

FLUX COMPACTIFICATION

FLUXES $\Rightarrow$ small numbers in string theory for cosmology

- **Best understood example: resolved conifold**

$$w_1^2 + w_2^2 + w_3^2 + w_4^2 = z$$

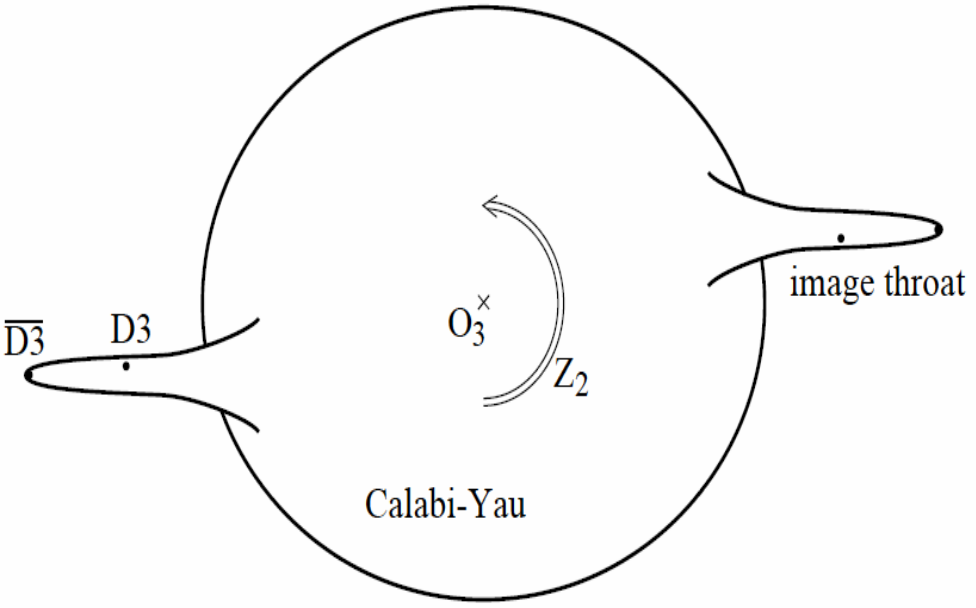
K and M are integer fluxes

$$\int F_{(3)} = 2\pi M$$

$$\int H_{(3)} = -2\pi K$$

$$z \sim e^{-\frac{2K}{Mgs}}$$

The throat geometry has a highly warped region



$$e^{A_{min}} \sim z^{1/3} \sim e^{-\frac{2\pi K}{3Mg_s}}$$

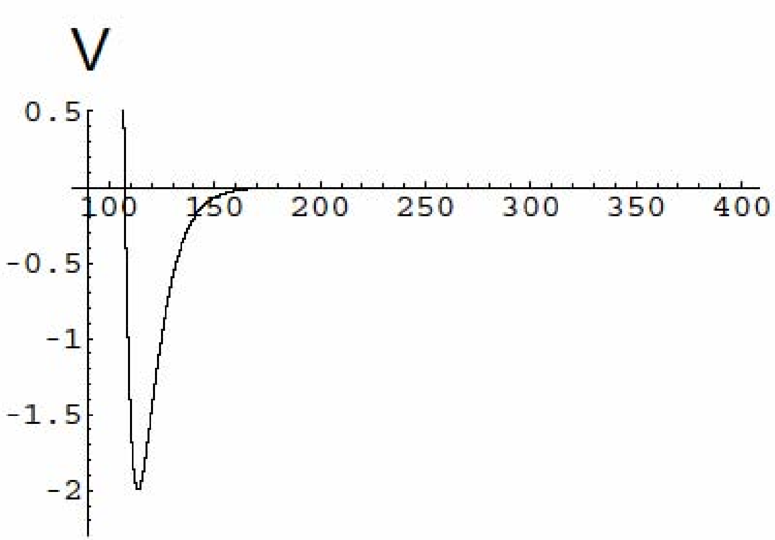
$$ds^2 = e^{2A(y)} ds_4^2 + ds_y^2 \qquad e^{2A} \ll 1$$

Volume stabilization

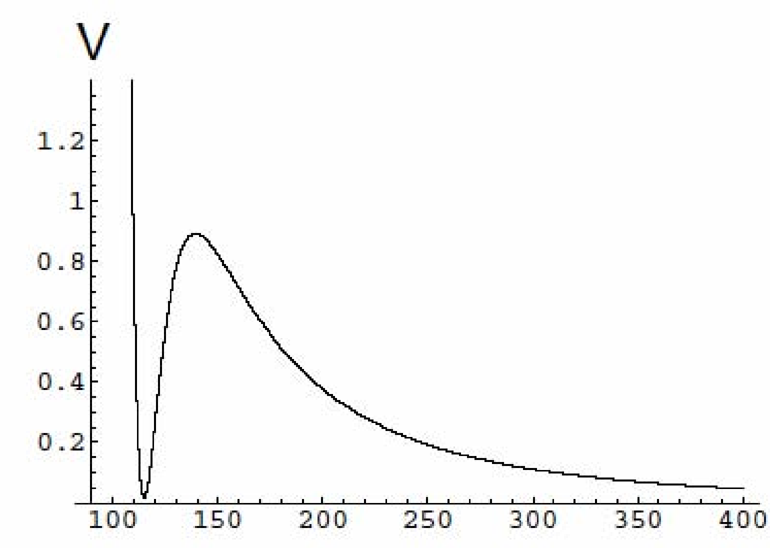
Basic steps:

Warped geometry of the compactified space and nonperturbative effects (instantons, gaugino condensation) lead to AdS space negative vacuum energy) with unbroken SUSY and stabilized volume

Uplifting AdS space to a metastable dS space (positive vacuum energy) by adding anti-D3 brane at the tip of the conifold (or D7 brane with fluxes)

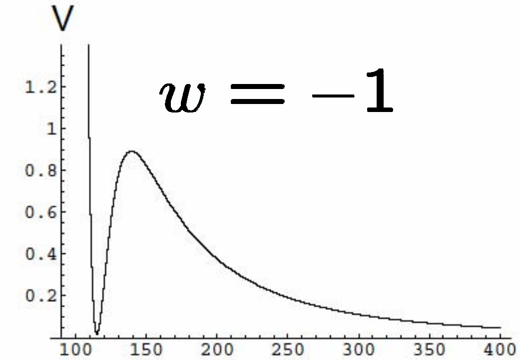


AdS minimum



Metastable dS minimum

LIFETIME



$w = -1$

- **KKLT** model starts with an AdS minimum due to non-perturbative effects. It can be uplifted to dS minimum with the barrier protecting it from the decay. This dS is metastable, observationally indistinguishable from CC

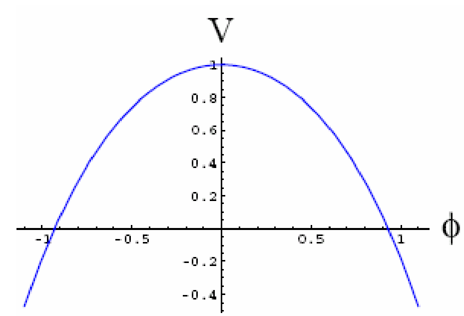
$$t \sim 10^{10^{120}} \text{ years}$$

- Exact solutions of 11d M/string-supergravity with fluxes: **ghost-free dS supergravities**. Unstable since dS is a saddle point.

$w(t)$

R. K., Linde, Prokushkin, Shmakova

$$t \sim 10^{10} - 10^{11} \text{ years}$$



KKLT based new ideas

String Landscape **Susskind** (talk on Wedensday)

Statistics of Flux Vacua **Douglas, Dine, Kachru,…**

Cosmic Strings Produced by the end of Inflation

Dvali, R. K. , Van Proeyen; Copeland, Myers, Polchinski

Eternal Inflation
Vilenkin, Linde
KKLT

Landscape Idea

Bousso, Polchinski; Susskind; Douglas

- With account of loop corrections each vacuum will change. However, the total lanscape picture with many vacua will survive
- There are many vacua with negative, vanishing and positive energies
- Somewhere there is our vacuum with

$$\Lambda \sim 1/N$$

where N, the number of vacua, is required to be $N > 10^{120}$

The number of phenomenologically (or anthropically) acceptable vacua is smaller than the number of total vacua

Is there a better idea?

String Theory Landscape

Two types of string inflation models:

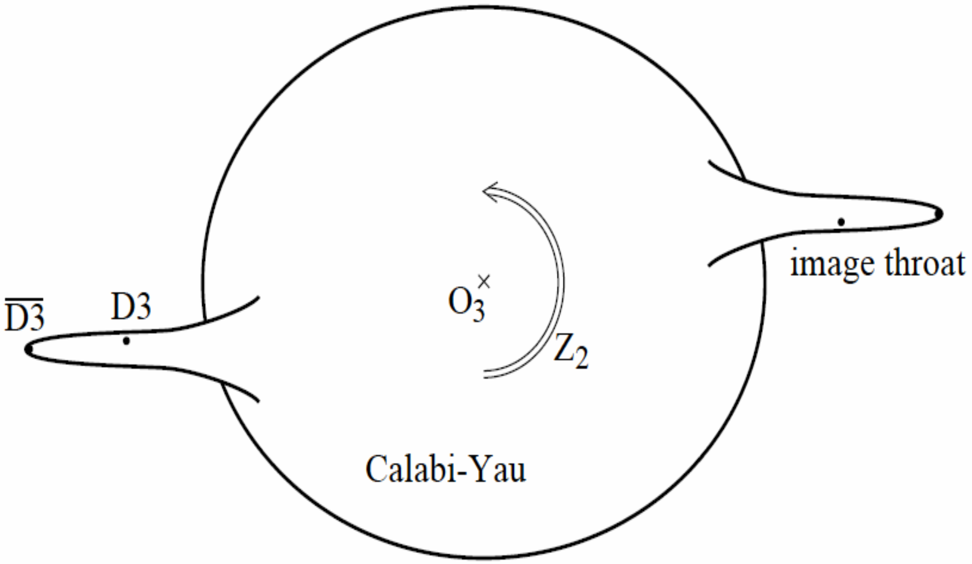
- **Brane inflation** (Dvali-Tye) The inflaton field corresponds to the distance between branes in Calabi-Yau space.

  KKLMMT and D3/D7

- **Modular Inflation.** The simplest class of models. Only moduli that are already present in the KKLT model.

The KLMT model

D3 anti-D3 brane inflation in the throat geometry



Branes feel a potential which depends on gravitational redshift (warp factor) in the compact directions

The redshift in the throat plays the key role in KLMT

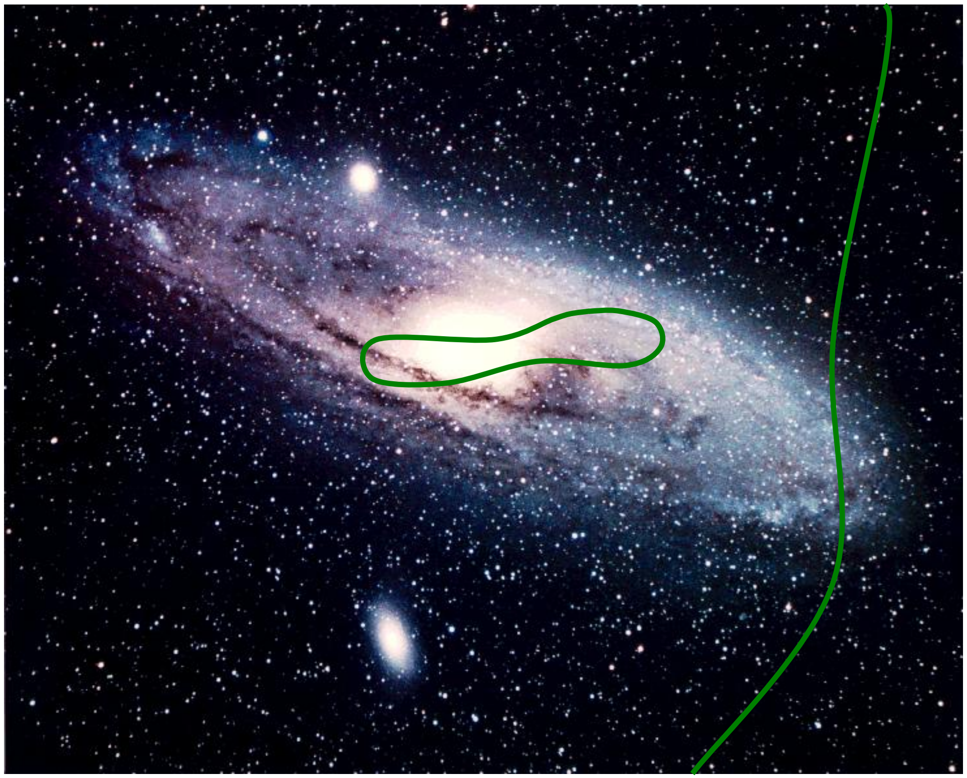
Advantages:

1) source of small parameters,

2) cosmic strings produced by the end of inflation are light: no contradiction with the data, possible discovery in the future

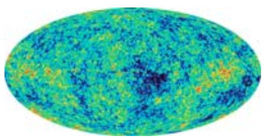
Disadvantage: conformal coupling of the inflaton field (position of D3-brane in the throat region): **requires fine-tuning**

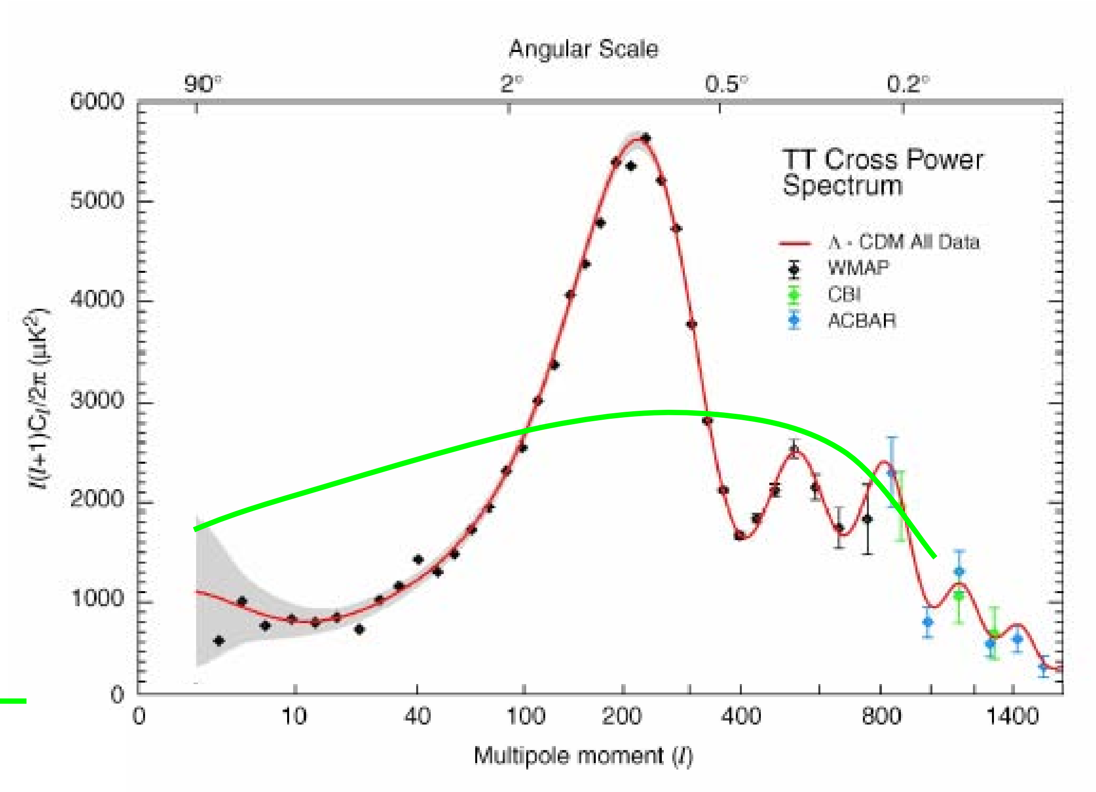
Cosmic Superstrings



Generic in hybrid inflation models

CMB power spectrum





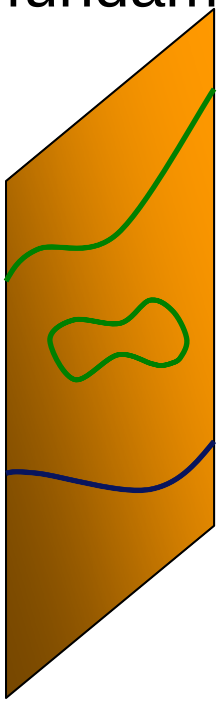
WMAP data

strings

Acoustic peaks come from temporal coherence. Inflation has it, strings don't. String contribution < 10% implies $G\mu \lesssim 10^{-6}$.

For D-brane/antibrane, there is a $U(1) \mathrm{x} U(1)$ symmetry, which disappears when the branes annihilate. This leads to production of strings just as in field theory. One $U(1)$ gives Dirichlet strings, the other gives `fundamental' strings

radiation + D-strings + F-strings



In various brane inflation models one finds

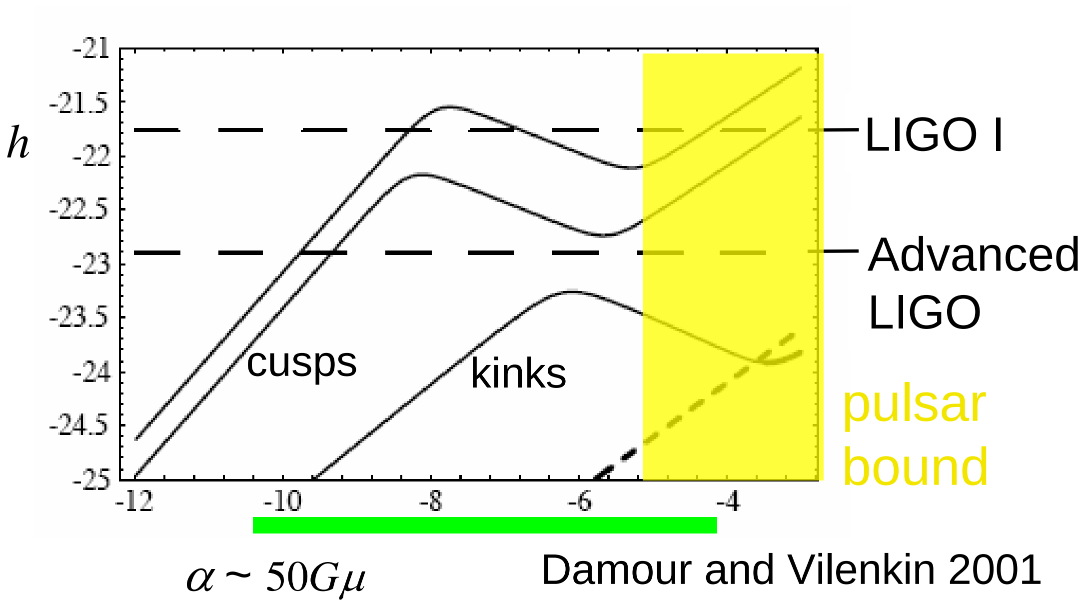
$10^{-12} < G\mu < 10^{-6}$ (Tye et al)

The KKLMMT model is near the middle of this range.

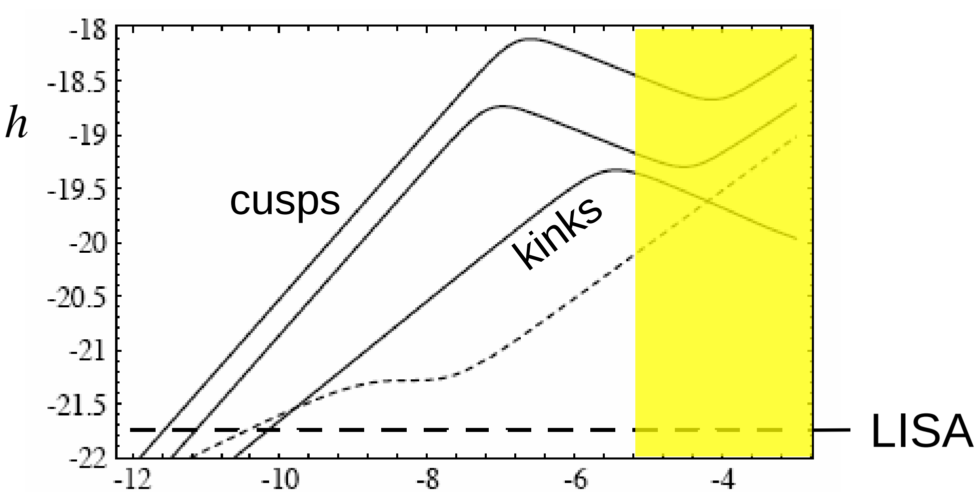
LIGO/LISA signals from string cusps

Polchinski, 2004

Cosmic strings could be the brightest GW sources, over a wide range of $G\mu$



Damour and Vilenkin 2001



Field theory strings?

String theory strings?

Issues of fine-tuning

- KKLMMT (warped flux compactification models)

$$K = -3 \ln \left((\rho - \bar{\rho}) - \bar{\phi}\phi \right)$$

$$\mathcal{G}(\rho, \bar{\rho}, \bar{\phi}\phi)$$

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

D3-anti-D3 brane inflation with volume stabilization
In the warped deformed conifold KS geometry leads to:

$$M_{\mathrm{infl}}^2 \sim H^2$$

Without fine-tuning

KKLMMT-type models with fine-tuning

One can fine-tune the parameters in some models to provide a flat potential with volume stabilization.

Can we do better in string theory? Use symmetries?

Shift Symmetry of $\mathcal{G}$

Flatness of the effective supergravity inflaton potential follows from the shift symmetry of $\mathcal{G} \equiv K + \ln |W|^2$

$$V = e^{\mathcal{G}}[|\mathcal{G}_{,z}|^2 - 3]$$

We need models where the position of the D3 brane after stabilization of the volume is still a modulus

Supersymmetry and Inflation

- Hybrid Inflation

Linde, 91

- F-term, D-term Inflation

Copeland, Liddle, Lyth, Stewart, Wands;
Dvali, Shafi, Shafer, 94
Binetruy, Dvali; Halyo, 96

- **D3/D7 Brane Inflation as D-term Inflation**

Dasgupta, Herdeiro, Hirano, R.K., 2002

- **Include Volume Stabilization:**

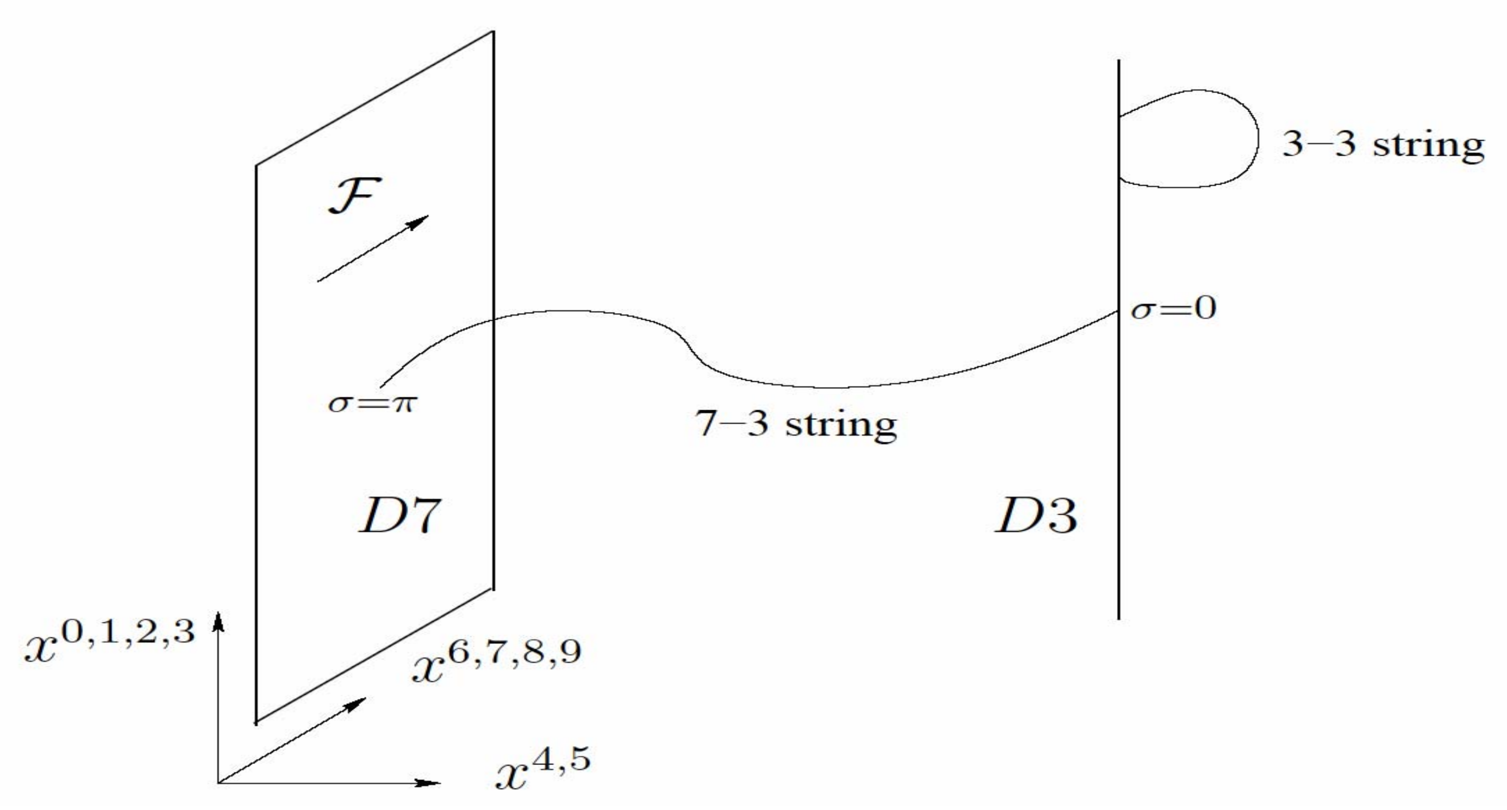
  F-term for KKLT+ Shift Symmetry slightly broken by quantum corrections

Dasgupta, Hsu,R.K.,Prokushkin, Linde,Zagerman; Koyama, Tachkawa, Watari, 2003-2004

- Effective D-term Inflation with type IIB string theory parameters

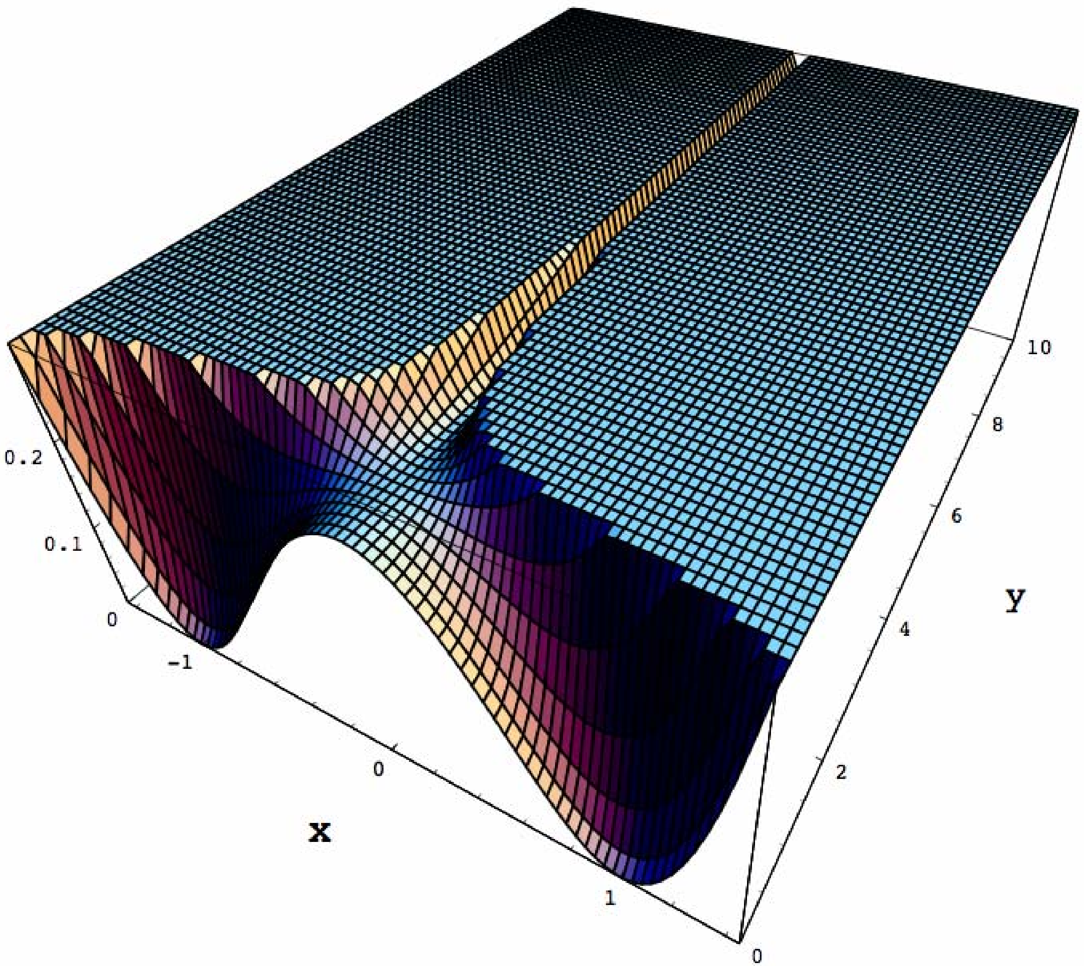
Kachru, R. K., Linde, in preparation

D3/D7 BRANE INFLATION MODEL



The mass of D3-D7 strings (hypers) is split due to the presence of the anti-self-dual flux on D7

Hybrid D3/D7 Inflation Model



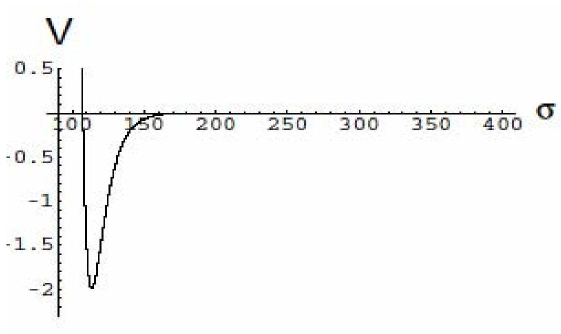
How to make this model valid in string theory with the volume stabilization

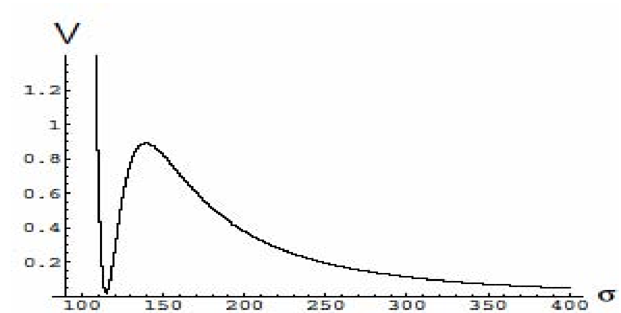
String theory does not have constant FI terms!

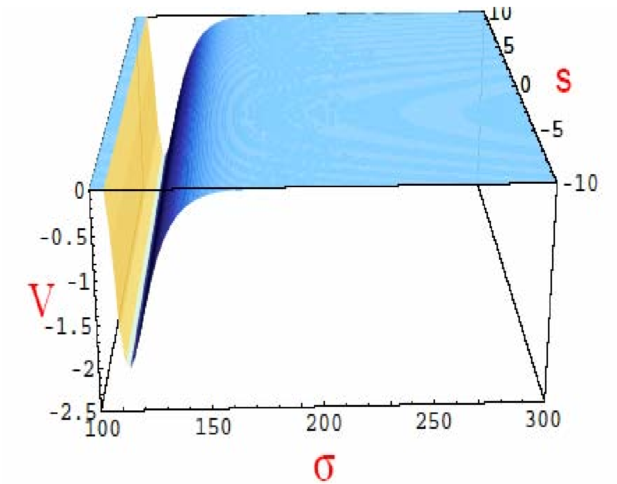
Shift Symmetry?

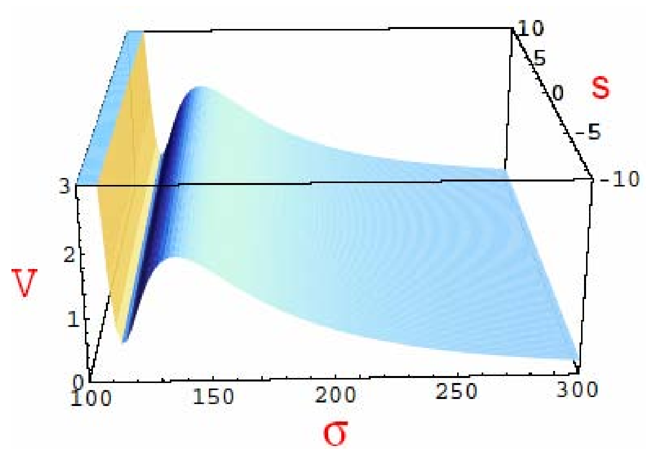
Inflaton Trench

$$\mathcal{G}(\rho, \bar{\rho}, \bar{\phi} + \phi)$$









- Supersymmetric Ground State of Branes in Stabilized Volume

SHIFT SYMMETRY

The motion of branes does not destabilize the volume

Isometry of the compactified space provides shift symmetry slightly broken by quantum corrections

- Type IIB string theory compactified on

$$K3 \times \frac{T^2}{Z^2}$$

- orientifold with fluxes, mobile D3 branes and heavy D7 brane

$$V = \frac{g^2 \xi^2}{2} [1 + \frac{g^2}{8\pi^2} \ln \frac{S^2}{S_{cr}^2}]$$

Unlike in the brane-antibrane scenario, inflation in D3/D7 model does not require fine-tuning

D3/D7 Phenomenology with Stabilized Volume and Inflation

$$V = \frac{g^2\xi^2}{2}[1 + \frac{g^2}{8\pi^2} \ln \frac{S^2}{S_{cr}^2}]$$

The conditions for successful slow-roll inflation require

$$\xi \sim 1.5 \times 10^{-5}$$

To find other parameters one should use the dictionary between brane construction and D-term model

Dasgupta, Hsu, R.K., Linde, Zagermann

This is possible for quantized fluxes, and realistic values of volume and string coupling

$$\mathcal{F} \sim 2\pi 10^{-7} \frac{\sigma^3}{g_s} \sim 2\pi$$

$$n_s \sim 0.98$$

KKL

Racetrack Inflation

the first working model of the **modular inflation**

Early attempts
Banks, Berkooz, Shenker, Moore, Steinhardt, 1995

Blanco-Pilado, Burgess, Cline, Escoda, Gomes-Reino, Kallosh, Linde, Quevedo

hep-th/0406230

Superpotential: $$W = W_0 + Ae^{-a\rho} + Be^{-b\rho}$$

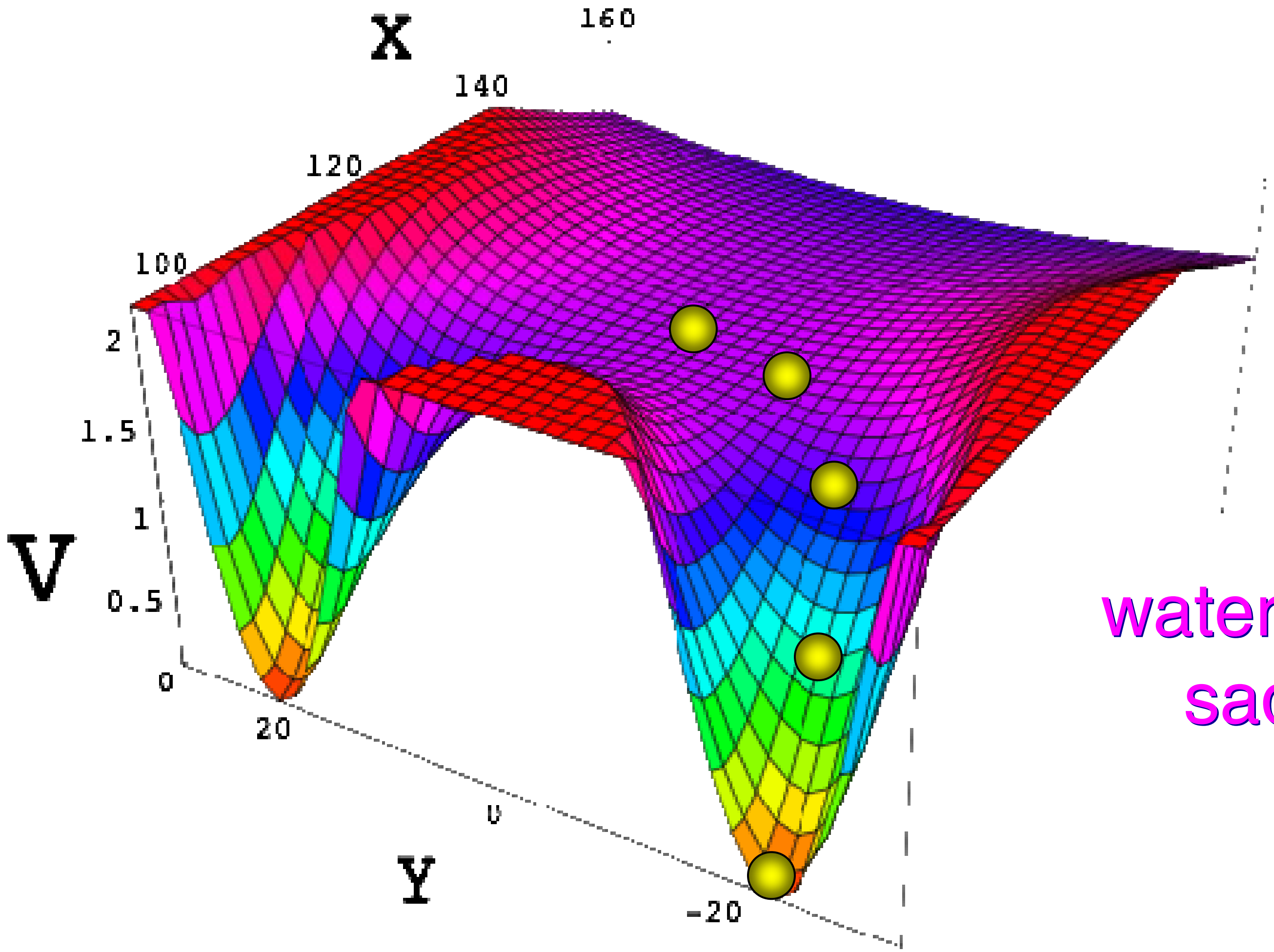
Kahler potential: $$K = -3\log(\rho + \bar{\rho})$$

Effective potential for a complex field:
volume of the compact manifold and its axionic partner

Eternal topological inflation

Parameters and Potential

$$A = \frac{1}{50}, \qquad B = -\frac{35}{1000}, \qquad a = \frac{2\pi}{100}, \qquad b = \frac{2\pi}{90}, \qquad W_0 = -\frac{1}{25000}$$



waterfall from the saddle point

INFLATIONARY PREDICTIONS for the modular racetrack inflation:

Flat spectrum of metric perturbations with

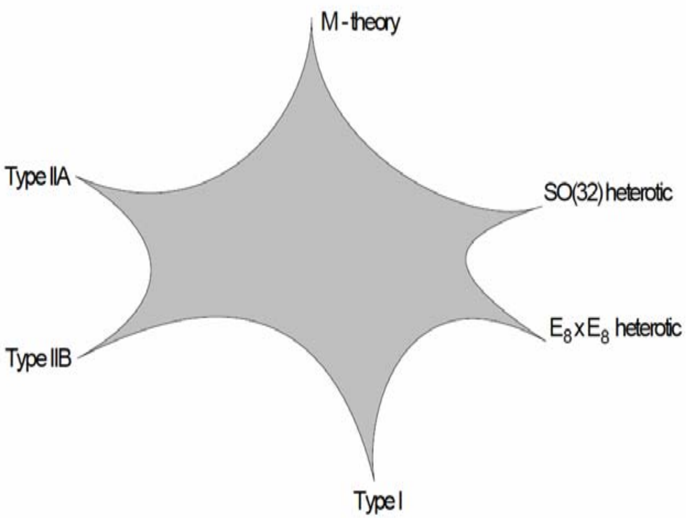
$$n_s \sim 0.95$$

Marginally consistent with data, but may be ruled out by future observations

Parameters require fine-tuning with accuracy O(0.1%), which may not be a problem if one takes into account

The string theory landscape

Possible profound changes in string theory paradigm and particle physics



Old favorite, heterotic string, requires **non-Kahler compactification** for volume moduli stabilization; may stabilize at strong string coupling

Becker, Becker, Dasgupta, Prokushkin

Old heterotic phenomenology ?

Type IIA string ?

Scale of susy breaking?

If we have to fine-tune CC we may as well fine-tune the Higgs mass,

the low scale susy may not be valid: **Split supersymmetry**

Arkani-Hamed, Dimopoulos

Summary on String Cosmology

- Over the last few years we were able to construct the first model of the cosmological constant/dark energy in the context of string theory

- Several models of string theory inflation are available now, much more work is required

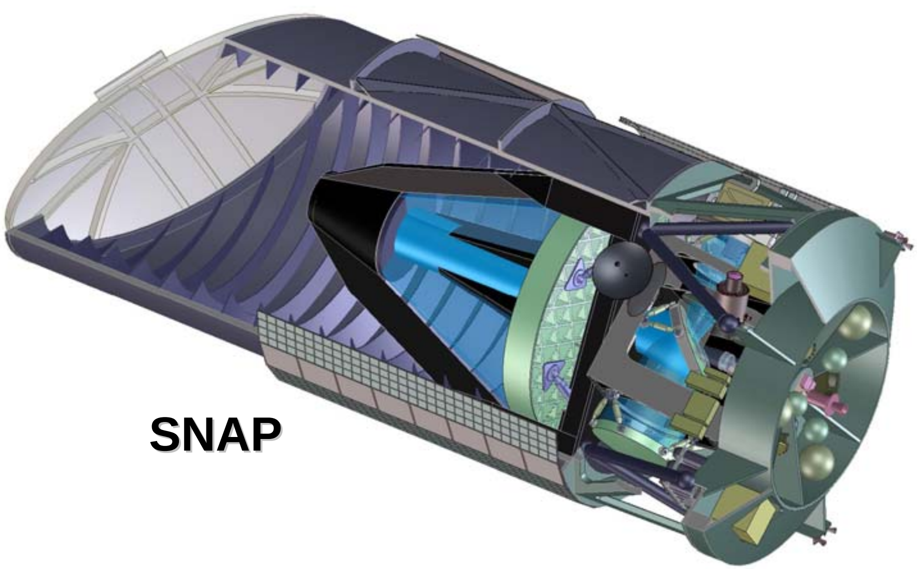
- Future cosmological data will help us to test the new ideas in string theory and cosmology

Physics beyond the Standard Model at LHC

Start : summer 2007

- Introduction (main parameters, machine, experiments …)
- Experimental challenges and techniques
- Examples of potential for physics beyond SM

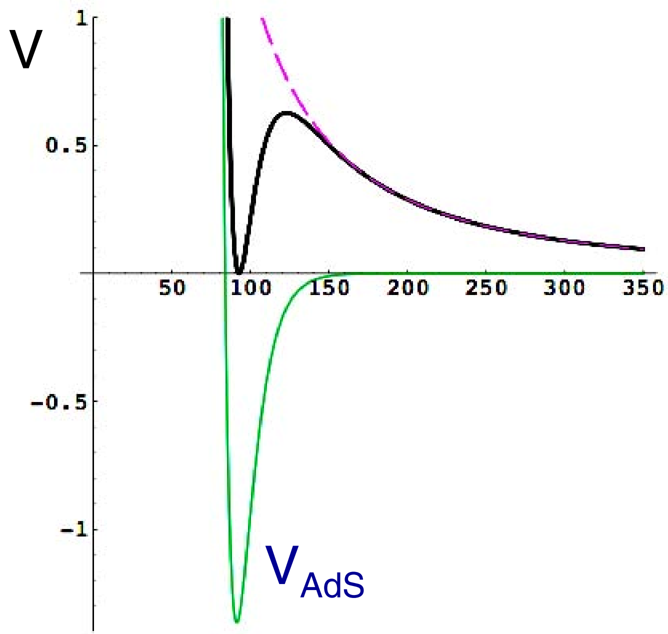
PLANCK

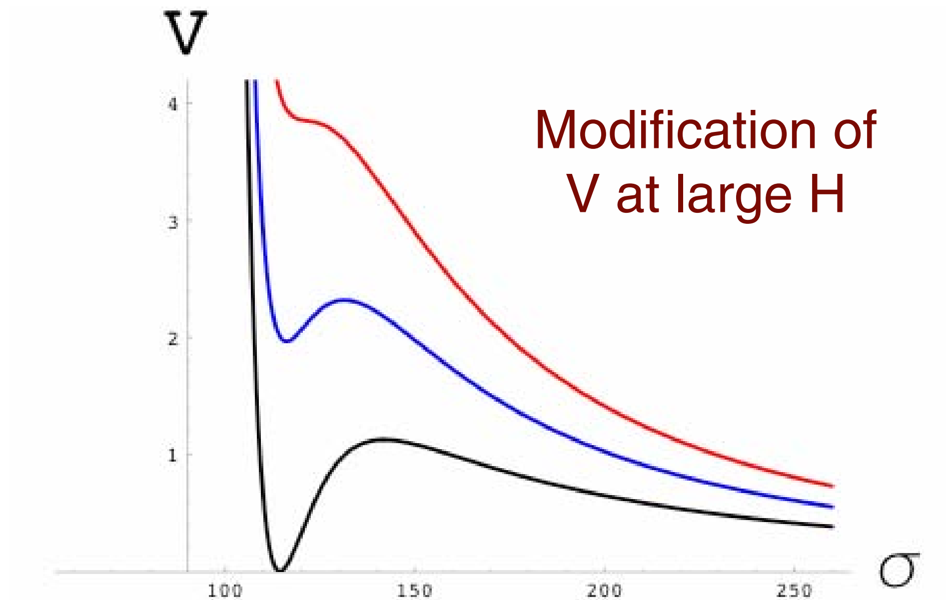


SNAP

GRAVITINO IN STRING COSMOLOGY

The height of the KKLT barrier is smaller than V_{AdS}. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is given by $H^2 = V_{infl} /3$.



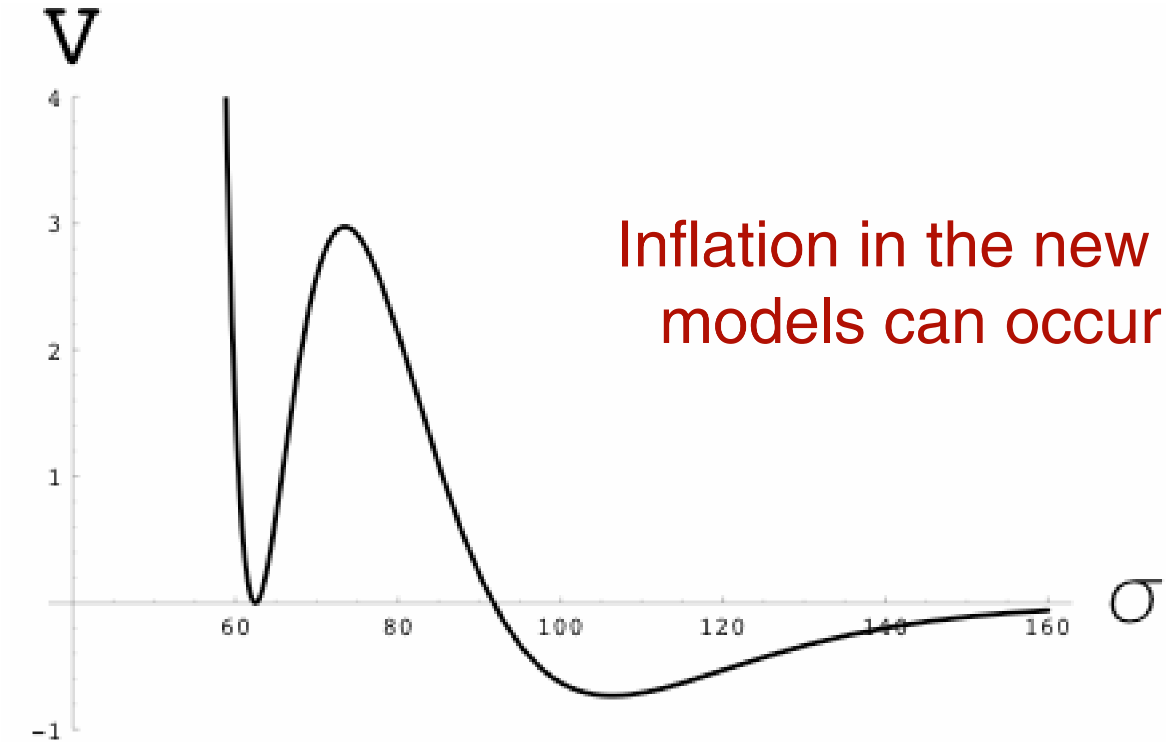


Constraint on the Hubble constant in this class of models:

$$H < m_{3/2}$$

A new class of KKLT models

R.K, Linde, hep-th/0411011



Inflation in the new class of KKLT models can occur at $H \gg m_{3/2}$

Small mass of gravitino, no correlation with the height of the barrier