Towards String Cosmology. Stabilization of moduli in string theory I, II

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I. Towards String Cosmology

■ In this pedagogical lecture some basic part of the standard cosmological model which is most relevant for the fundamental theoretical physics will be explained. The common features and differences between early universe inflation and late-time acceleration will be stressed. Some recent attempts to address the issues of cosmology in string theory and higher dimensional supergravity with the emphasis on successes and still unsolved problems will be presented.

Outline of Lecture I

- 1. Cosmological Concordance Model and Problems of M/String Theory in Explaining the Observations.
- 2. Flux Compactification and Stabilization of Moduli, Metastable de Sitter Space in String Theory
- **3. Ghost-Free** de Sitter Supergravities as Consistent Reductions of String and M-theory: **collapsing universe**
- 4. Landscape of String Theory, Statistics of Flux Vacua, CC problem
- 5. Inflation in String Theory, Cosmic Strings, Scale of SUSY breaking

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)

In view of the recent cosmological observations supporting dark energy and inflation it is fair to say that we do not really know what is "fundamental physics"

"Most embarrassing observation in physics – that's the only quick thing I can say about dark energy that's also true." -- Edward Witten

What is so embarrassing about it?

Two general problems:

• Why is the cosmological constant so small, $\Lambda < 10^{-120}$ in Planck density units?

• Why $\wedge \sim \rho_{\text{matter}}$?
Coincidence problem.

addressed by anthropic principle, Weinberg 1987

The third problem:

Two years ago it was not clear how one could possibly incorporate a <u>positive</u> cosmological constant <u>in string theory</u>

addressed by KKLT, 2003

One can argue that M/String theory is fundamental

- Perturbative finiteness of quantum gravity
- Beyond standard model particle physics
- Supersymmetry, supergravity: d=10/d=11 maximal dimension, almost unique
- The best theory we have now (unless it can be ruled out by observations)
- Stringy Cloak for a Null Singularity

Physics beyond the Standard Model at LHC



Start: summer 2007

CMS cavern

Higgs, Standard Model Supersymmetry, SPLIT SUPERSYMMETRY

F Giano

LHC discovery reach

Time	reach in squark/gluino mass
1 month at 10 ³³	~ 1.3 TeV
1 year at 10 ³³	~ 1.8 TeV
1 year at 10 ³⁴	~ 2.5 TeV
ultimate (300 fb-1)	up to ~ 3 TeV

LHC should add many crucial pieces to our knowledge of fundamental physics

- → huge impact also on astroparticle physics and cosmology?
- → in ~ 3 years particle physics may enter the most glorious epoch of its history ...

IF SUSY IS THERE

The significance of discovery of supersymmetry in nature,

(which will manifests itself via existence of supersymmetric particles) is the discovery of the **fermionic dimensions** of spacetime.

It will be the most fundamental discovery in physics after Einstein's relativity

$$(t, \vec{x}) \rightarrow (t', \vec{x}') \longrightarrow x^{\mu} \rightarrow (x^{\mu})'$$

SUPERSYMMETRY

$$(x^{\mu}, \theta_{\alpha}) \rightarrow ((x^{\mu})', \theta'_{\alpha}) \longrightarrow Z^{M} \rightarrow (Z^{M})'$$

Gravity

Supergravity/String theory

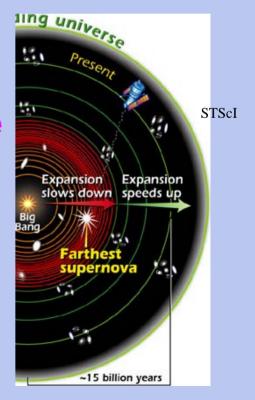
$\begin{array}{ccc} Fundamental \ Physics \\ \rightarrow & \text{Cosmology} \rightarrow & \text{Field Theory} \end{array}$

a(t) \rightarrow Equation of state w(z) \rightarrow V(ϕ)

CMB
LSS

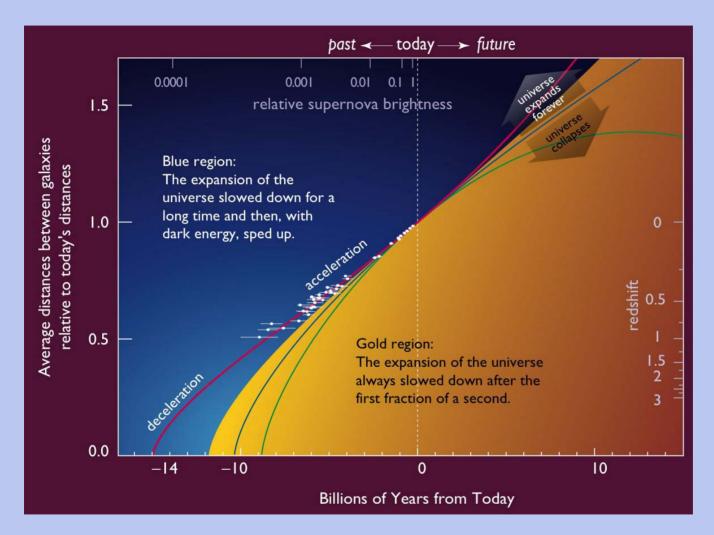


The subtle slowing and growth of scales with time – a(t) – map out the cosmic history like tree rings map out the Earth's climate history.



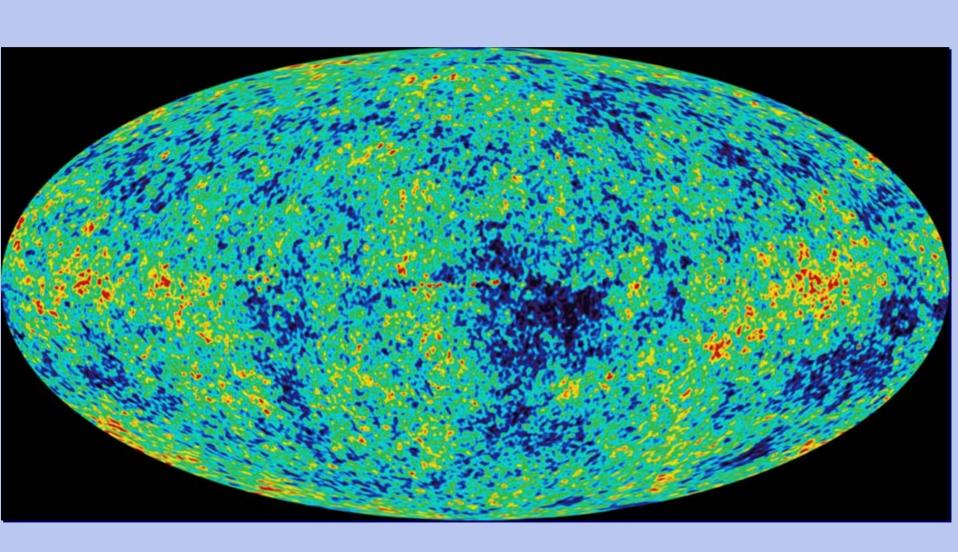
Map the expansion history of the universe

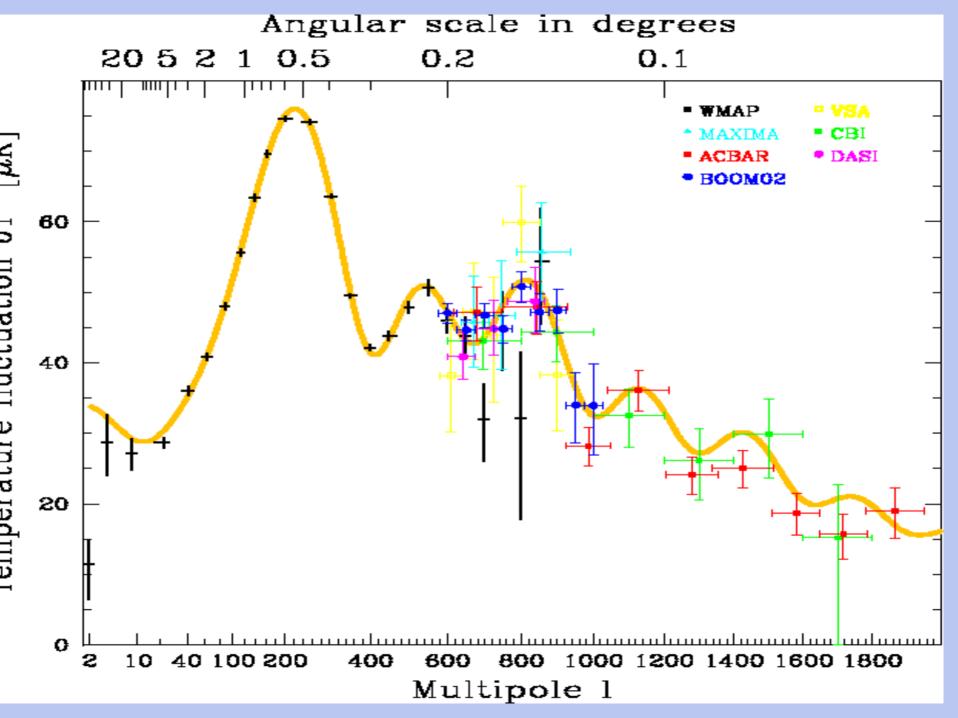
Discovery! Acceleration



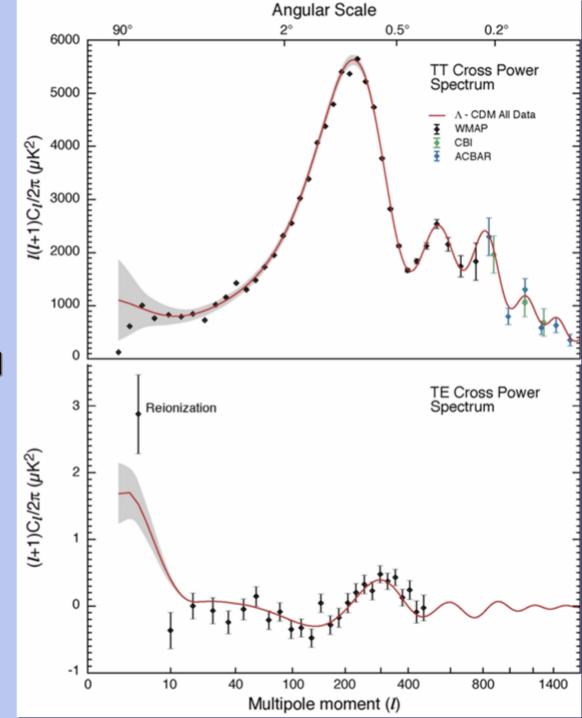
Exploding stars – supernovae – are bright beacons that allow us to measure precisely the expansion over the last 10 billion years.

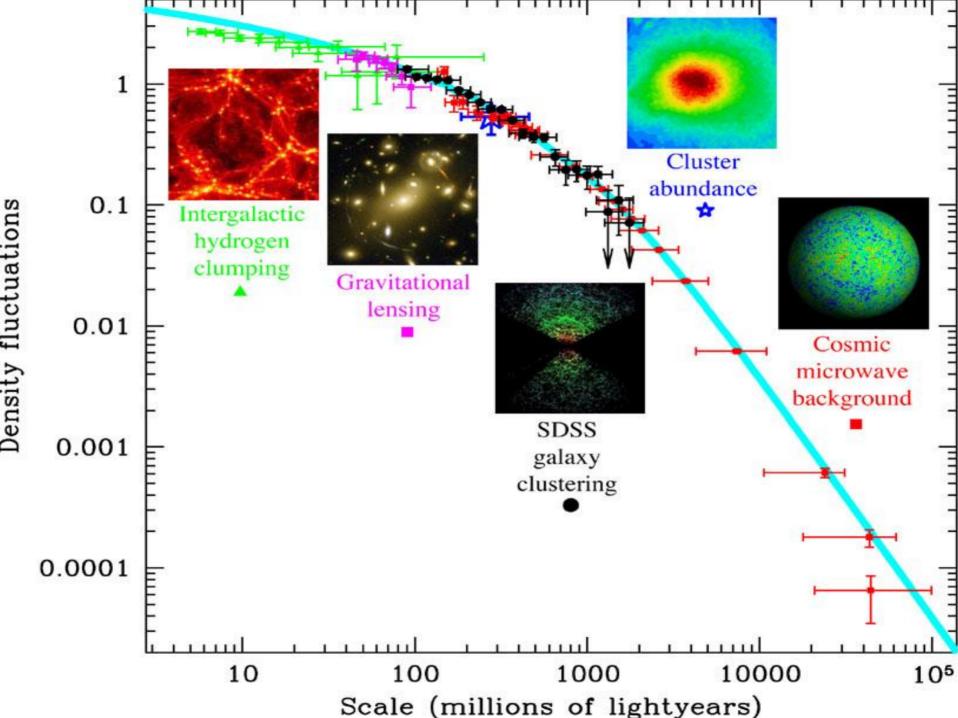
WMAP and the temperature of the sky





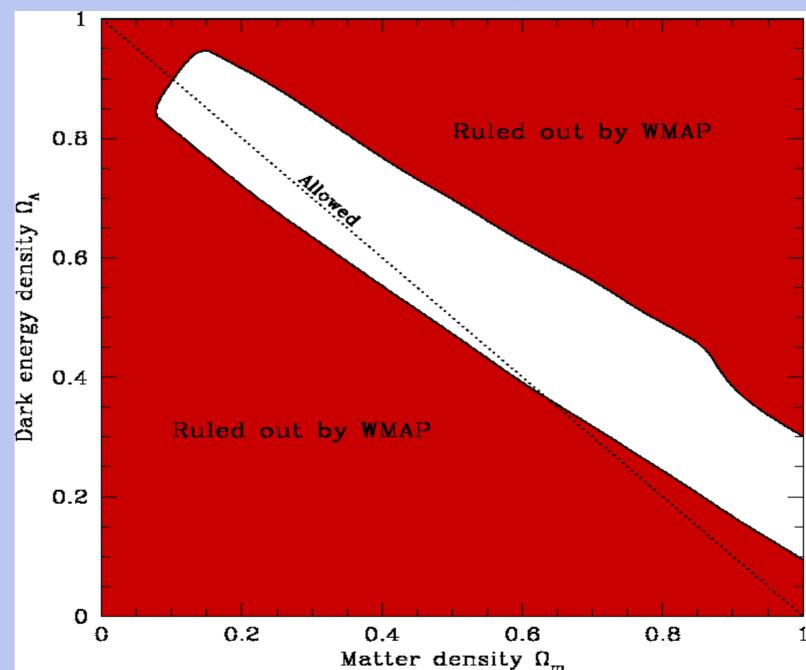
WMAP
and spectrum of the microwave background anisotropy



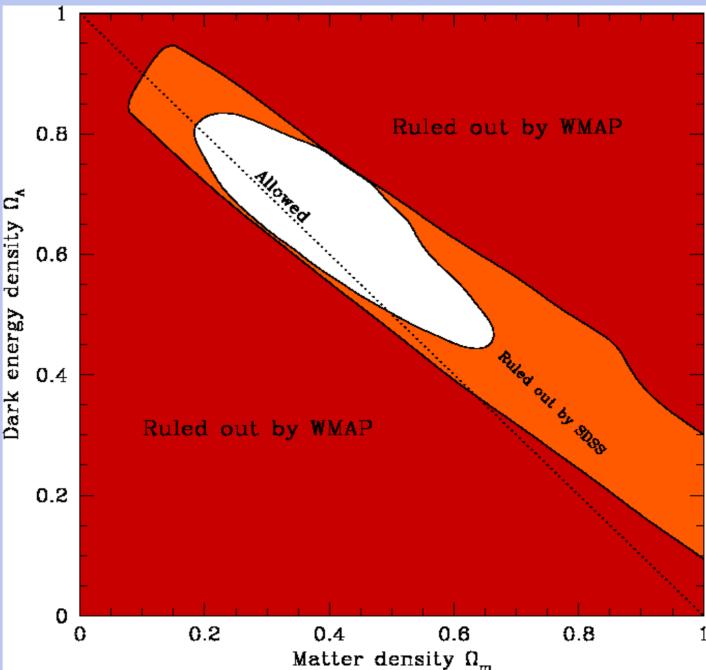


How much dark energy is there? 8.0 Dark energy density $\Omega_{\mathtt{A}}$ Closed 0.6 0.4 Open 0.2 0 0.2 0.4 0.6 8.0 Matter density Ω_m

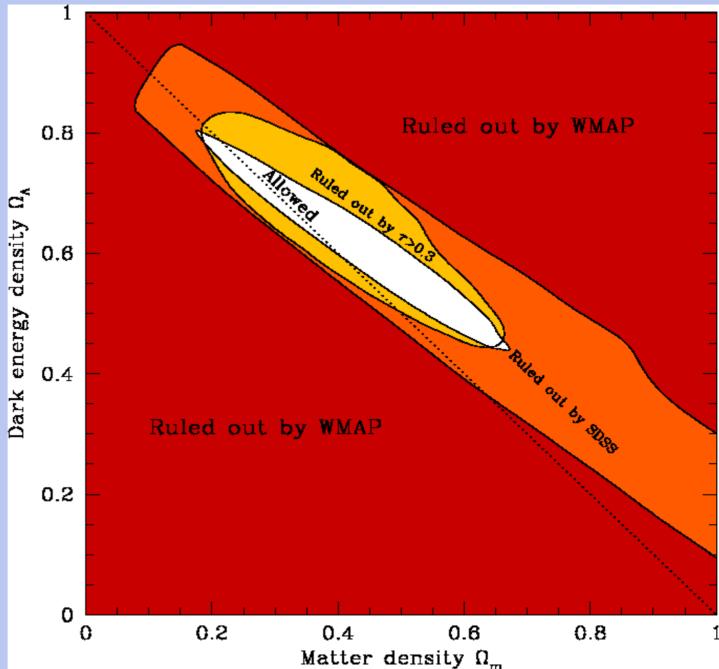




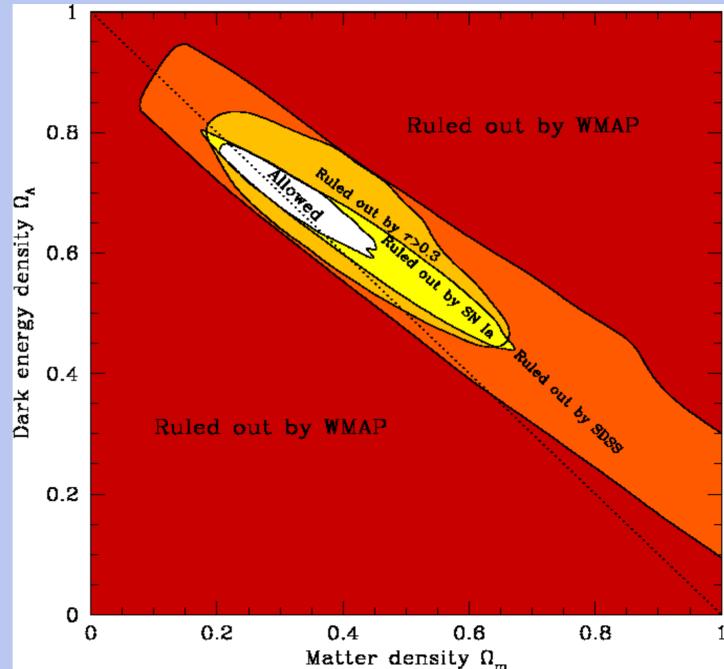






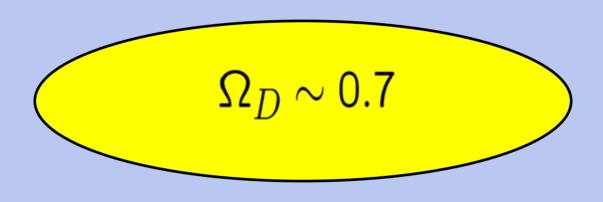






DARK ENERGY

Total energy in 3d flat FRW universe



$$\Omega_T = \Omega_D + \Omega_M = 1$$

70% of the total energy of the universe is DARK

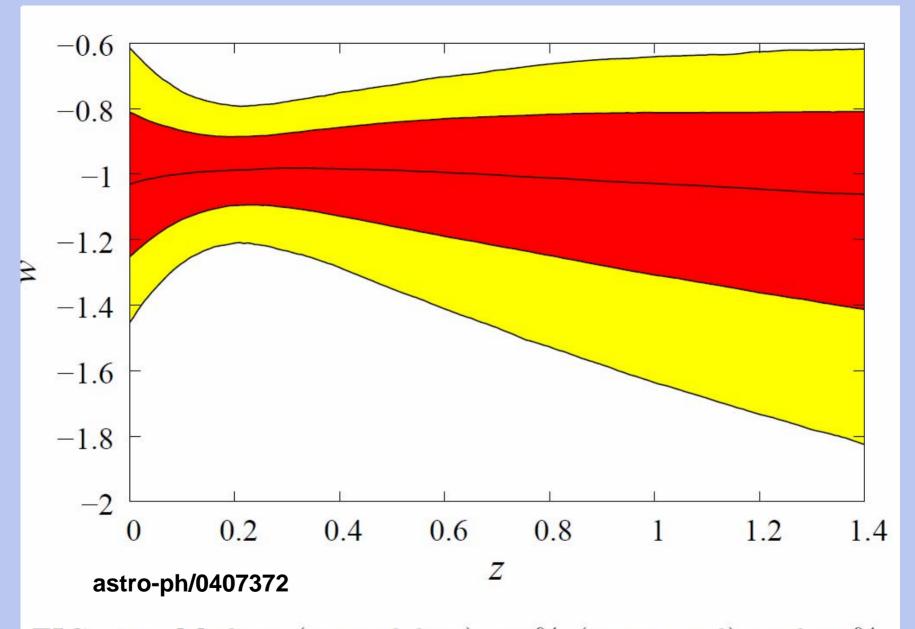
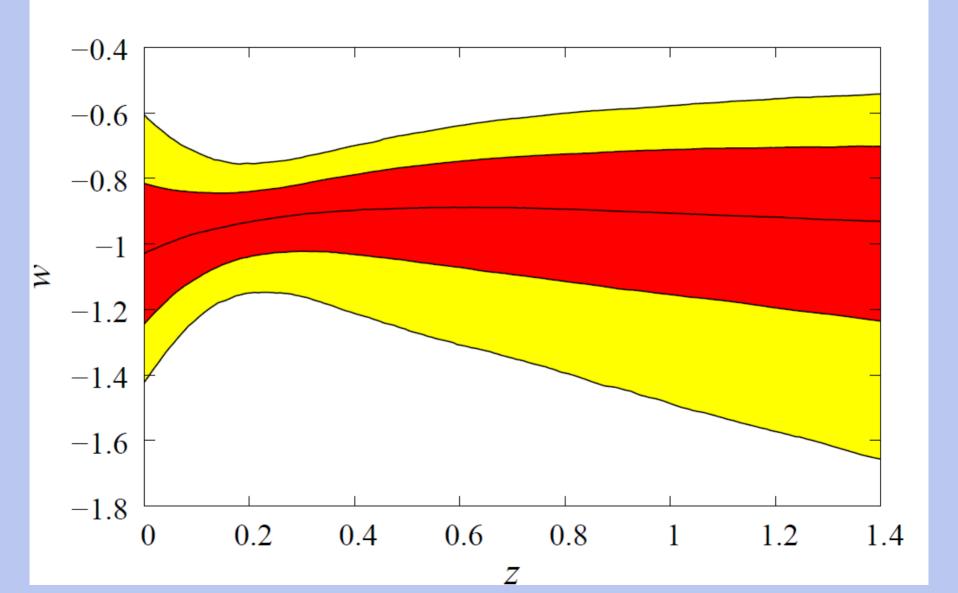


FIG. 10: Median (central line), 68% (inner, red) and 95% (outer, yellow) intervals of w(z) using all the data in the chains

constraints are reasonably model independent as long as w is a smooth function of redshift. We find that the simplest solution, w = -1, fits the data at all redshifts.



Constraining Dark Energy with X-ray Galaxy Clusters, Supernovae and the Cosmic Microwave Background

David Rapetti^{1,2,3*}, Steven W. Allen^{1,3} and Jochen Weller^{1,4,5}

Spring 2005

sets. We examine a series of dark energy models with up to three free parameters: the current dark energy equation of state w_0 , the early time equation of state $w_{\rm et}$ and the scale factor at transition, $a_{\rm t}$. From a combined analysis of all three data sets, assuming a constant equation of state and that the Universe is flat, we measure $w_0 = -1.05^{+0.10}_{-0.12}$. Including $w_{\rm et}$ as a free parameter and allowing the transition scale factor to vary over the range $0.5 < a_{\rm t} < 0.95$ where the data sets have discriminating power, we measure $w_0 = -1.27^{+0.33}_{-0.39}$ and $w_{\rm et} = -0.66^{+0.44}_{-0.62}$. We find no significant evidence for evolution in the dark energy equation of state parameter with redshift. Marginal hints of evolution in the supernovae data become less significant when the cluster constraints are also included in the analysis. The complementary nature of the data sets leads to a tight constraint on the mean matter density, $\Omega_{\rm m}$ and alleviates a number of other parameter degeneracies, including that between the scalar spectral index $n_{\rm s}$, the physical baryon density $\Omega_{\rm b}h^2$ and the optical depth τ . This complementary nature also allows us to ex-

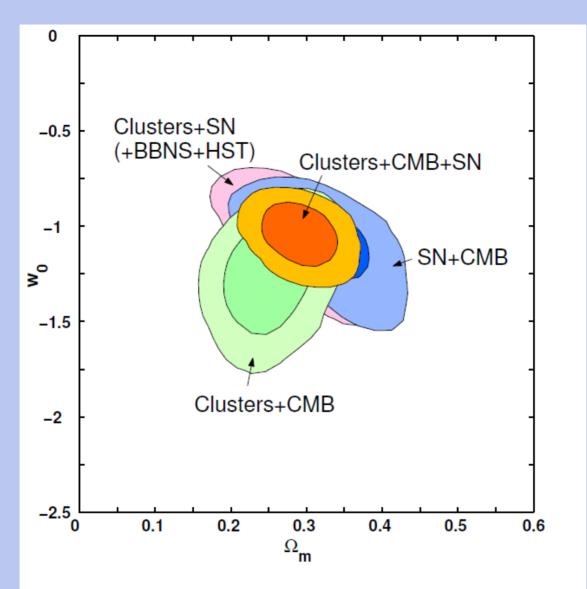


Figure 1. The 68.3 and 95.4 per cent confidence limits in the $(\Omega_{\rm m}, w_0)$ plane for the various pairs of data sets and for all three data sets combined. A constant dark energy equation of state parameter is assumed.

New data

Boomerang,..., WMAP, 2005 ??? Planck, SNAP, LSST ..., 2010-2012

It is likely that 70% of Dark Energy and Early Universe Inflation will be confirmed, but we have to wait

Cosmological Concordance Model

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

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

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

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

$$H_{infl} \le 10^{-5} M_p$$

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

$$H_{accel} \sim 10^{-60} M_P$$

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

String Theory and Cosmology

All observations so far seem to fit 4d Einstein GR. We need to know how to get this picture from the compactified 10d string theory or 11d M-theory and supergravity

How to get de Sitter or near de Sitter 4d space?

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

ADS/CFT CORRESPONDENCE

A major activity of string community from 1997 is AdS/CFT

$$\Lambda < 0$$

????

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

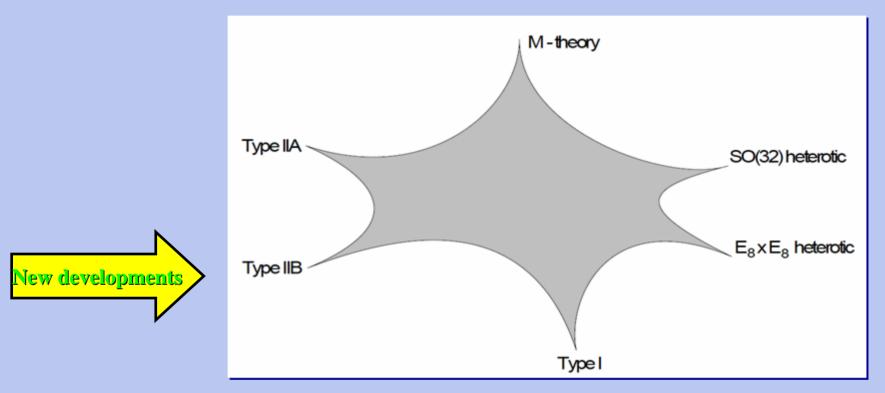


How to go around the conditions for de Sitter no-go theorems?



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

Space of M/String Theory vacua



- It was known for 20 years that string theory is not easily compatible with cosmology
- During the last few years this became a very serious issue

Recent proposal

Towards cosmology in type IIB string theory

Dilaton stabilization Giddings, Kachru and Polchinski 2001

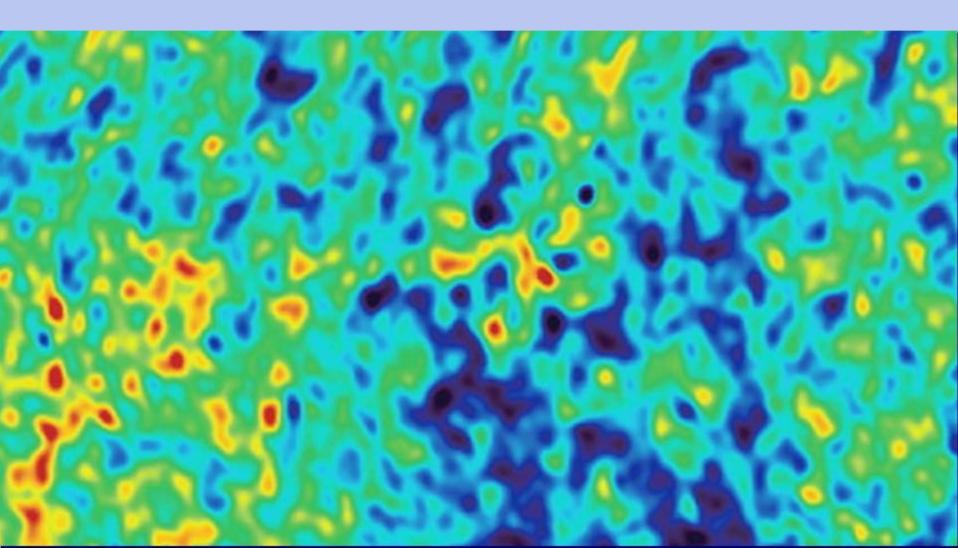
Volume stabilization, KKLT

Kachru, R. K, Linde, Trivedi 2003

Kachru, R. K., Maldacena, McAllister, Linde, Trivedi 2003

The KLMT model

A photographic image of quantum fluctuations blown up to the size of the universe



Inflationary slow roll parameters in units $M_P^2 \equiv 8\pi G_N = 1$

Primordial slope $n_s \equiv 1 - 6\epsilon + 2\eta$

$$\eta[\varphi] = \frac{V''}{V} \sim \text{const}$$
 $\epsilon[\varphi] = \frac{1}{2} \left(\frac{V'}{V}\right)^2 \sim \text{const}$

Derivatives w. r. to canonicaly normalized fields!

Observational data

$$n_s = 0.98 \pm 0.02$$

Can String Theory Afford the Runaway Moduli?

Compare with observations

$$-\frac{1}{2}(\partial\varphi)^2 - e^{-\lambda\varphi}$$

1. For early universe inflation

$$\lambda \leq 10^{-1}$$

2. For dark energy $\lambda \leq 1$

For the dilaton

$$\lambda = \sqrt{2}$$

For the total volume

$$\lambda = \sqrt{6}$$

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

FLUX COMPACTIFICATION, IIB STRING

■ Non-perturbative string theory, perturbative d=10 supergravity

Leads to stabilization of axion-dilaton and complex structure moduli

Kahler moduli stabilization cannot be achieved via flux compactification

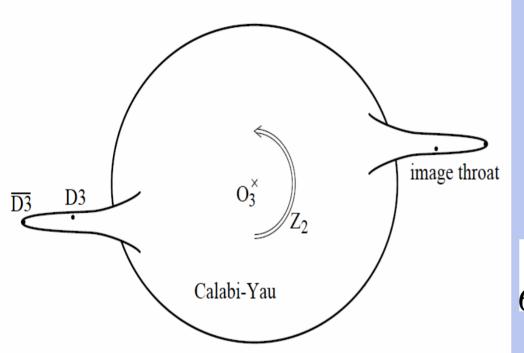
Flux compactification and moduli stabilization in IIB string theory (supergravity + local sources)

$$G_3 = F_3 - \tau H_3$$

$$\tau = C_0 + ie^{-\phi}$$

$$\tilde{F}_5 = F_5$$

The fluxes fix the shape of Calabi-Yau and the dilaton-axion



K and M are integer fluxes associated with the 3-forms in typellB theory

Deformed Conifold

$$e^{4A_{min}} \sim z^{4/3} \sim re^{-\frac{8\pi K}{3Mgs}}$$

The throat geometry has a highly warped region

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

No-scale Potential is Positive-Definite

No-scale
$$V = e^K(\sum_{\rho, z_{\alpha}, \tau} g^{k\bar{l}} D_k W \overline{D_l W} - 3|W|^2)$$

$$V = e^K \sum_{z_{\alpha}, \tau} g^{a\bar{b}} D_a W \overline{D_b W} \ge 0$$

Runaway potential for the volume moduli. Dilaton and shape moduli are generically fixed in Minkowski space!

Kahler moduli problem (in particular, overall volume)

KKLT proposal

i) non-perturbative superpotential from Euclidean D3-branes wrapped on special 4-cycles

$$W \sim e^{-\mathsf{Vol}(D)} \sim e^{i\rho}$$

ii) non-perturbative superpotential from pure SYM on a stack of D7's on $W \sim e^{-\text{Vol}(\Sigma_4)/C_2(G)} \sim e^{i\rho/C_2}$

Effective theory for the volume moduli

$$W = W_0(z_{cr}, \tau_{cr}) + Ae^{ia\rho} + \dots \qquad \rho = \alpha + i\sigma$$

Solve
$$D_{\rho}W = 0$$
 $\sigma_{cr} \sim \frac{1}{a} \ln W_0$

 $C_2(G) > 1$, $W_0 \ll 1$ the volume is stabilized in AdS critical point in the regime of validity of calculations!

$$V_{cr} = -3e^K |W_{cr}|^2$$
, $D_l W = 0$

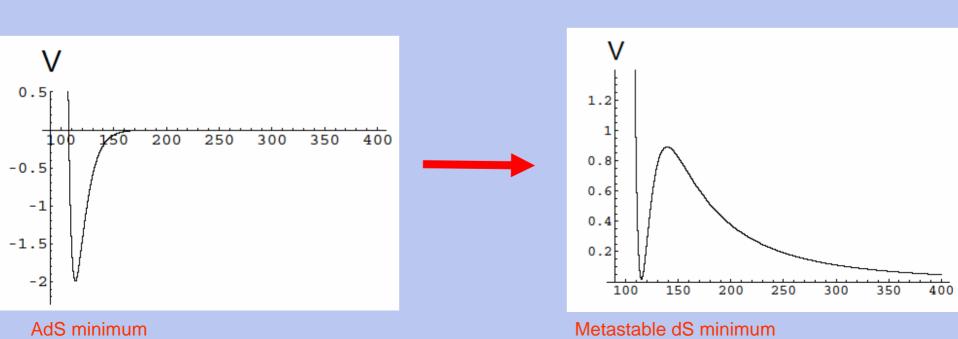
AdS minimum

Volume stabilization

Basic steps:

Warped geometry of the compactified space and nonperturbative effects 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 (or D7 brane with fluxes)



KKLT based new ideas

Landscape Susskind Statistics of Flux Vacua

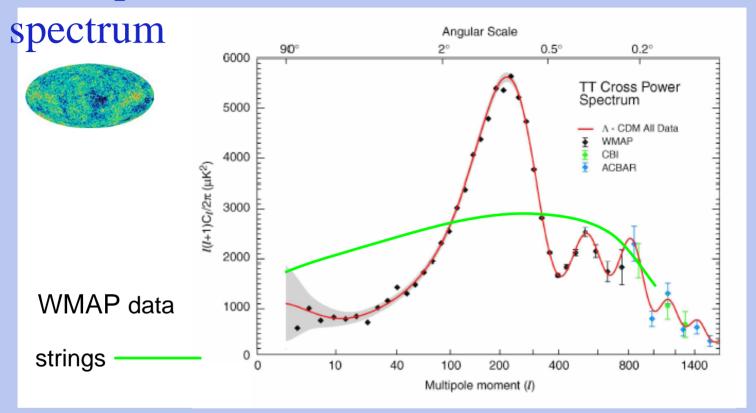
Douglas

Models of Inflation in String Theory

Cosmic Strings Produced by the end of Inflation, **OBSERVABLE IN THE FUTURE?**

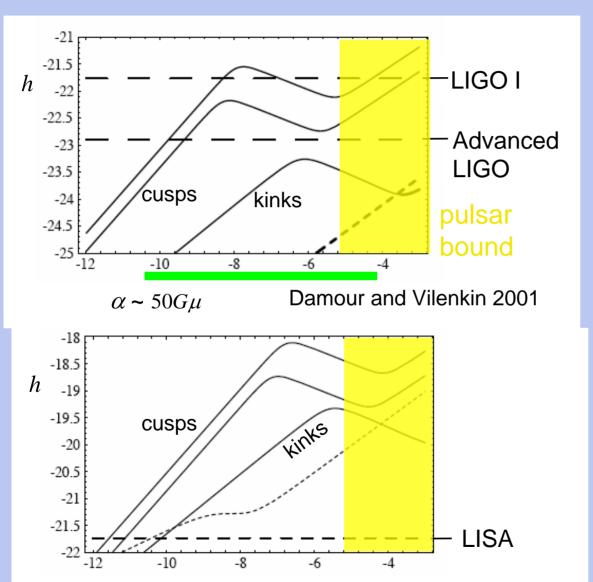
Copeland, Myers, Polchinski

CMB power



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

LIGO/LISA signals from string cusps



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

Field theory strings?

String theory strings?

A general Problem of Dark Energy:

$$V'/V \le 1$$
 $V''/V \le 1$ slow roll conditions

Dark energy can be observationally different from the cosmological constant only if an additional coincidence problem is resolved. In the language of the effective scalar theory, one should require that the slope of the quintessence potential is anomalously small,

$$V < 10^{-120}$$

To distinguish dark energy from the cosmological constant, the slope must be of the same order as the cosmological constant:

$$V' \approx 10^{-120}$$

This would be a **coincidence** (additional fine-tuning), which does not have any motivation (even anthropic) in most of the dark energy models.

An exception from this rule is provided by Ghost-Free de Sitter supergravities, consistent reductions from M/String Theory

De Sitter Gauged Supergravities

as a consistent Pauli reduction of M/String theory on hyperbolic spaces

 $\mathcal{H}^{p,q}$

11/10 d supergravities lead to ghost-free gauged 4d supergravities with extended supersymmetry

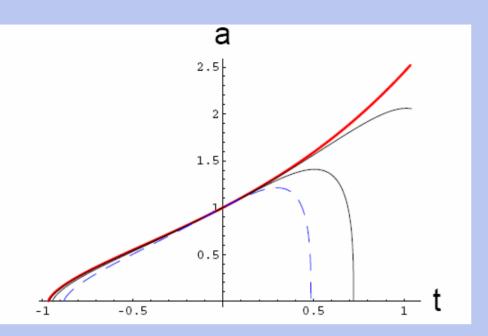
dS always correspond to saddle points

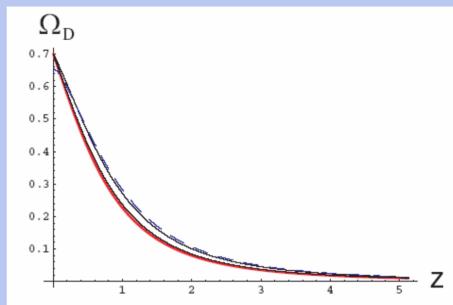
R. K., Linde, Prokushkin, Shmakova, 2002 Cvetic, Gibbons, Pope, 2004 Acharya, Denef, Valandro, 2005

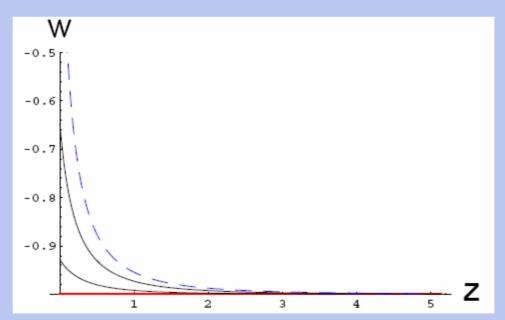
Toy models of dark energy with w > -1, with future collapse and anthropic explanation of the scale of CC

Dark energy slow-roll conditions are satisfied authomatically

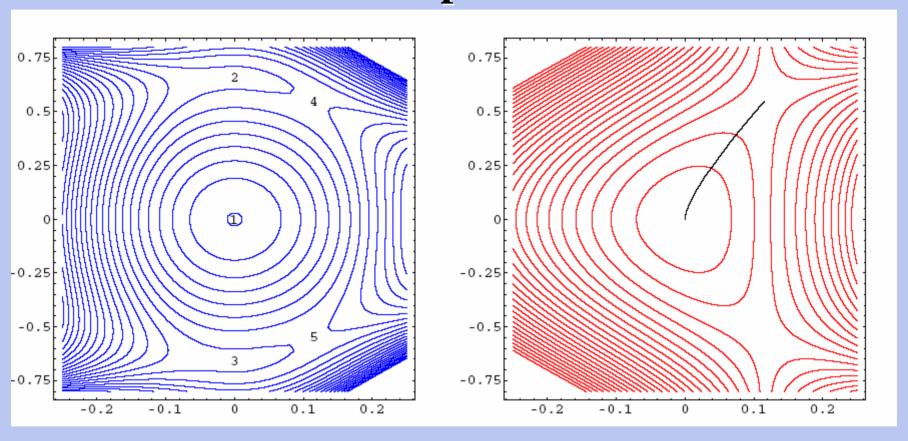
$$m^2 \sim -H^2$$





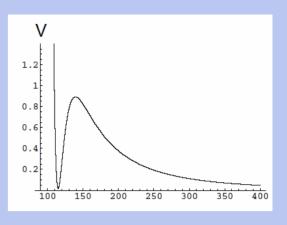


Typical AdS extrema, maximum and saddle points



LIFETIME

* KKLT model starts with an AdS minimum due to non-perturbative



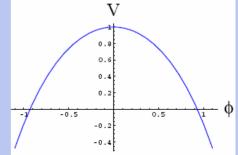
effects. It can be uplifted to dS minimum with the barrier protecting it from the decay. This dS is metastable, practically CC

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

❖ Exact solutions of 11d M/string-supergravity with fluxes: ghost-free dS supergravities. Unstable

since dS is a saddle point. Prediction

R. K., Linde $t \sim 10^{10} - 10^{11}$



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

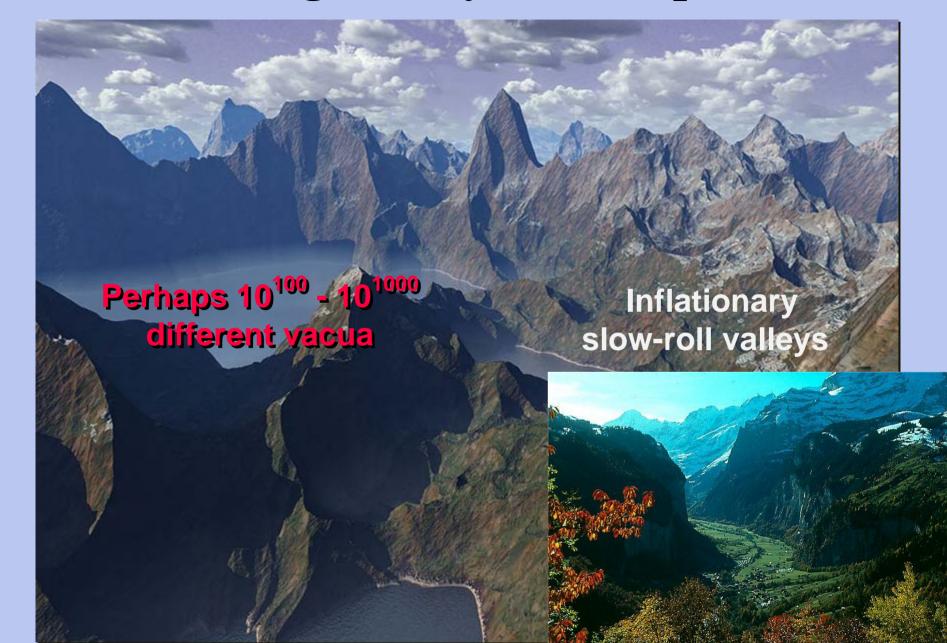
$$\Lambda \sim 1/N$$

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



With KKLT and other versions of dS we have found that vacua with positive CC are possible in string theory and equation of state with

$$w = -1$$

is consistent with string theory.

To explain any other equation of state of dark energy, like

$$w \neq -1$$
 $w' \neq 0$

remains extremely difficult

and, particularly, w < -1 does not seem possible in consistent string theory.

Modified gravity and other ideas (some do not seem to be consistent with SUSY)

Two types of string inflation models:

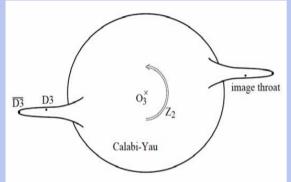
■ Brane inflation (Dvali-Tye) The inflaton field corresponds to the distance between branes in Calabi-Yau space.

KKLMMT and D3/D7

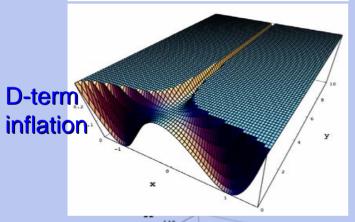
Modular Inflation. The simplest class of models. Only moduli that are already present in the KKLT model.

Racetrack Inflation

New: inflationary models in string theory



KKLMMT brane-anti-brane inflation



V

D3/D7 brane inflation

Dasgupta, Herdeiro, Hirano, R.K.



Racetrack modular inflation

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

DBI inflation, Silverstein et al

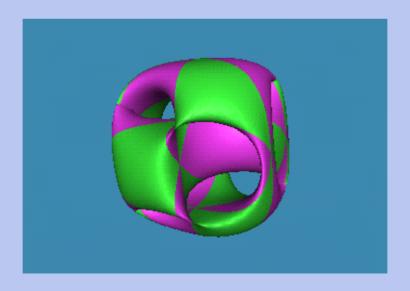
Important New Results and Consequences of the New Picture 2004-2005

- Denef, Douglas, Florea, Grassi, Kachru: examples of all moduli stabilization
- New models with all moduli fixed: Aspinwall, Bergshoeff, R. K. Kashani-Poor, Sorokin, Tomasiello
- Scale of susy breaking: if we have to finetune CC we may need to fine-tune the Higgs mass, the generic low scale susy may be not valid. Split supersymmetry

Arkani-Hamed, Dimopoulos

Major problem: moduli space

New mechanisms of volume stabilization



A Simple Example of Moduli Fixing

Aspinwall, R.K.

We analyze M-theory compactified on K3xK3 with fluxes and its F-theory limit, which is dual to an orientifold of the type IIB string on $K3 \times T^2/Z_2$

We argue that instanton effects will generically fix all of the moduli.

Moduli space is no more

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 and particle physics data will help us to test the new ideas in string theory and cosmology

