Testing String Theory by CMB

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Stanford

Strings 2007

Madrid, June 29

Based on RK, Linde, 0704.0647,
RK , hep-th/0702059,
Kachru, RK, Soroush, Sivanandam, work in progress
Grimm, work in progress

Standard Cosmological Model, LambdaCDM, is in good agreement with observations

One can compare the situation with the Standard Model in Particle Physics in early 80's when an essential agreement was observed. However, it required 20 more years for a complete confirmation based on precision data of all but neutrino parts of the standard model

Similarly, many features of the standard cosmological model, which include inflation and current acelleration, may require many years of precision data for a complete confirmation

Now, 6 parametrs describe well the WMAP3 observations of ~2000 points in the sky and agree with other independent (not CMB) observations

Future experiments/observations may be related to a discovery of supersymmetry. Anticipating such discovery, one can use the framework of d=4 supergravity and, if possible, derive it from d=11/10 M/string theory

Crucial future data for fundamental physics:

- Scale of gravitino mass: LSP, 1TeV, 10^{13} GeV ?
- Detection/non-detection of tensor B-modes: gravity waves from inflation

  $r = T/S$ current experimental bound $r < 0.3$

  2011 detection or bound $r < 0.1$

  2020 detection or bound $r < 0.01$

One has to work with closed (and open) string theory, derive the effective 4-dimensional supergravity and make predictions

In the supersymmetric gauge theory limit of supergravity

$$G_N \to 0 \qquad\qquad M_{Pl} \to \infty$$

we have no gravitino and no gravity waves

We already have analogous experience with the positive cosmological constant- **DARK ENERGY-** where such limit is not acceptable

It is easy to get a positive energy **Fayet-Illiopoulos** terms in supersymmetric gauge theory

Somewhat complicated in d=4 supergravity

Impossible in effective d=4 supergravity derived from M/string theory by compactification from d=11/10

$$E \sim \frac{c}{(\text{Volume})^{\alpha}}$$

KKLMMT

The energy of anti-branes or fluxes on branes

One can have consistent moduli-dependent D-terms: constant positive energy only after moduli stabilization

Burgess, RK, Quevedo;
Villadoro, Zwirner
Achucarro, de Carlos, Casas, Doplicher
Kiwoon Choi, Kwang Sik Jeong
Dudas, Mambrini
Haack, Krefl, Lust, Van Proeyen, Zagermann
Cremades, Garcia del Moral, Quevedo, Suruliz

Supersymmetric gauge theory-> open string theory decoupled from closed string theory-> is not useful for issues of gravitino and cosmology:

Gravity effects are crucial.

In the era of precision cosmology a clear identification of the Planck mass and string mass/length is required

In gravity we often used

$$M_{Pl}^{old} = \frac{1}{\sqrt{G_N}} = 1.221 \times 10^{19} GeV$$

In supergravity and string theory we use

$$M_{Pl} = \frac{M_{Pl}^{old}}{\sqrt{8\pi}} = 2.436 \times 10^{18} GeV$$

Why one has to be clear which of the two Planck masses are used?

For example, slow roll parameters in inflation

$$\eta = M_{Pl}^2 \frac{V''}{V} \qquad \epsilon = \frac{M_{Pl}^2}{2} \left(\frac{V'}{V}\right)^2$$

Current experimental value of the spectral index (WMAP3+SDSS)

$$n_s = 1 + 2\eta - 6\epsilon = 0.948 \pm 0.018$$

$8\pi \approx 25$

Clearly, one cannot ignore the difference between the old and the "supergravity type" Planck mass

Relation between Planck mass and string mass/length

$$l_s \Leftrightarrow l_{Pl}$$

The analogous clarification still has to take place in string theory with regard to string units and translation to Planck units via the volume of compactified extra dimensions

$$l_s = \sqrt{\alpha'} \qquad \tilde{l}_s = \sqrt{2\alpha'} \qquad l'_s = 2\pi\sqrt{\alpha'}$$

If one does not specify which one is used, one can make an error by a factor

$$(2\pi)^6 \sim 10^4$$

There was no good explanation of inflation and dark energy in string theory until recently

- 2003: Flux compactification and moduli stabilization: landscape of vacua, some of them are de Sitter vacua

- Simplest model: KKLT stabilization of the volume of the internal six-dimensional space

Now string theory has one explanation of **dark energy**:

metastable cosmological constant with equation of state

$$w = -1$$

- So far in agreement with the data.
- No other compelling models are available

There are several models of inflation in string theory. They are flexible enough to describe $n_s \sim 0.95$ but typically predict low level of gravitational waves and low non-gaussianity. They may explain light cosmic strings.

Observations of GW, cosmic strings or non-gaussianity can help us to test string theory

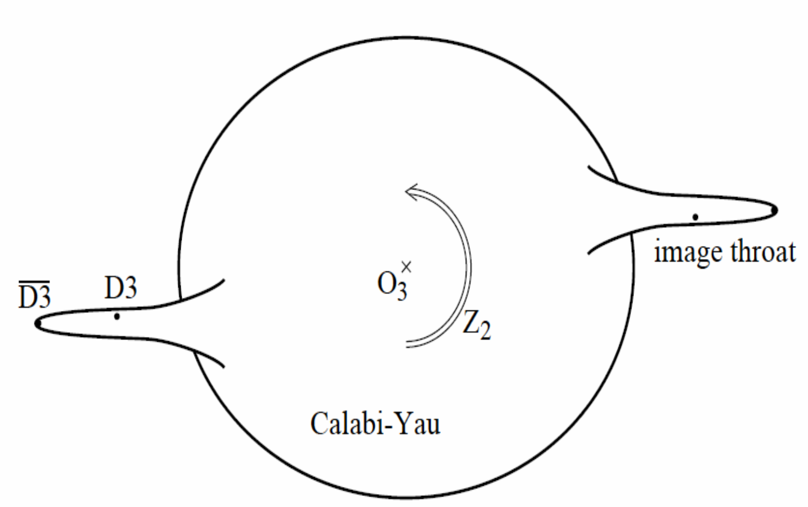
Here we will focus of GW

Two types of string inflation models:

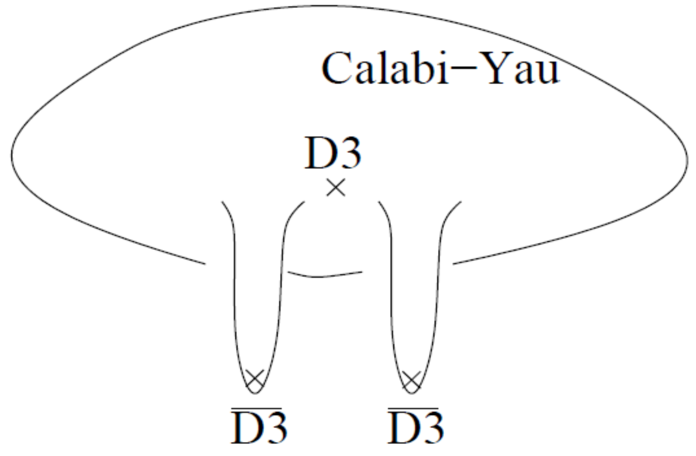
- **Modular Inflation.** The simplest class of models. They use only the fields that are already present in generalized KKLT model.

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

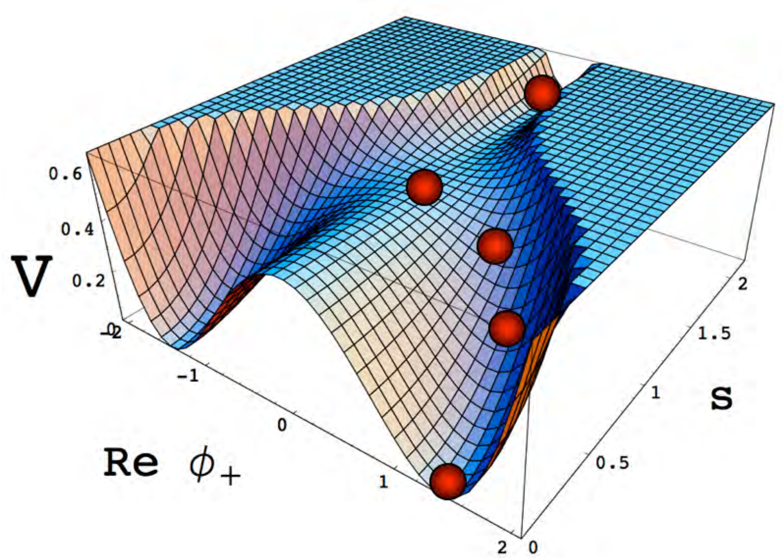
Brane Inflation in string theory



KKLMMT brane-anti-brane inflation



Two-throat model



Hybrid D3/D7 brane inflation

(Stringy D-term inflation)

Dirac-Born-Infeld inflation

$$\sqrt{1 + f(\phi) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}$$

Racetrack Inflation

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

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

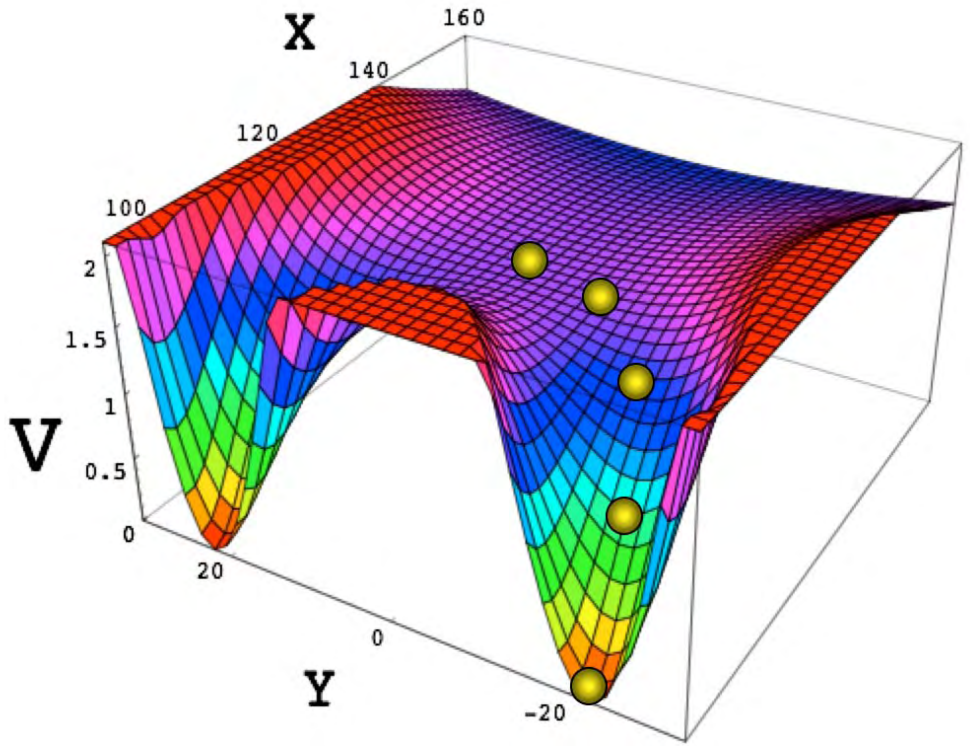
Superpotential: $$W = W_0 + A\, e^{-aT} + B\, e^{-bT}$$

Kähler potential: $$K = -3\log(T + T^*)$$

KKLT Uplifting term:

$$\delta V = \frac{E}{(T+T^*)^2}$$

Requires fine-tuning



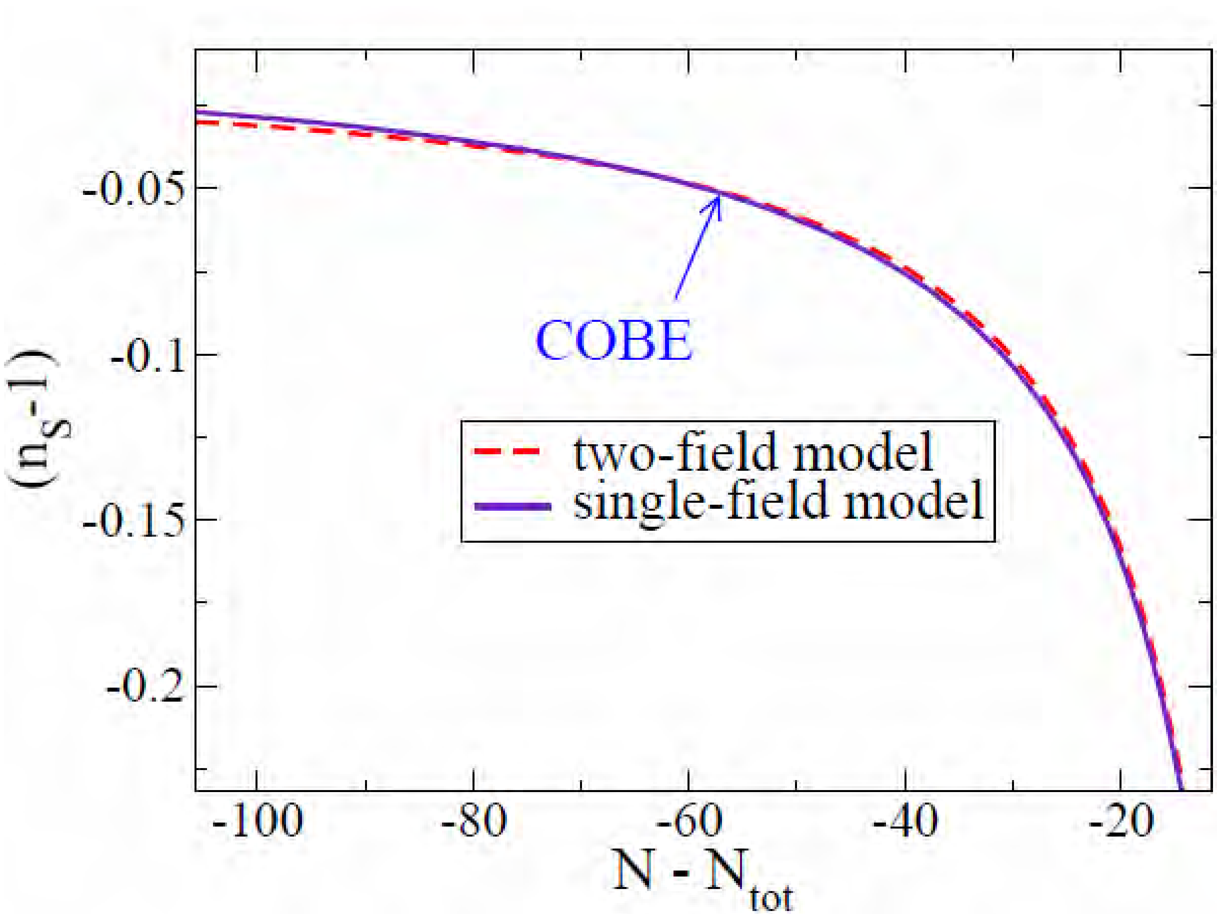
Same group

"Better Racetrack" Model of Inflation is based on explicit construction of string theory, where the KKLT-type stabilization of moduli was performed by Denef, Douglas, Florea (DDF) in 2004

$$\text{The orientifold of } \mathbb{P}^4_{[1,1,1,6,9]}$$

The model is a Calabi-Yau threefold with 2 Kahler moduli and 272 complex structure moduli. The moduli space admits an orientifold action which allows to reduce the moduli space of the Calabi-Yau complex structures to just 2 parameters.

$$f = x_1^{18} + x_2^{18} + x_3^{18} + x_4^3 + x_5^2 - 18\psi x_1 x_2 x_3 x_4 x_5 - 3\phi x_1^6 x_2^6 x_3^6$$



No cosmic strings

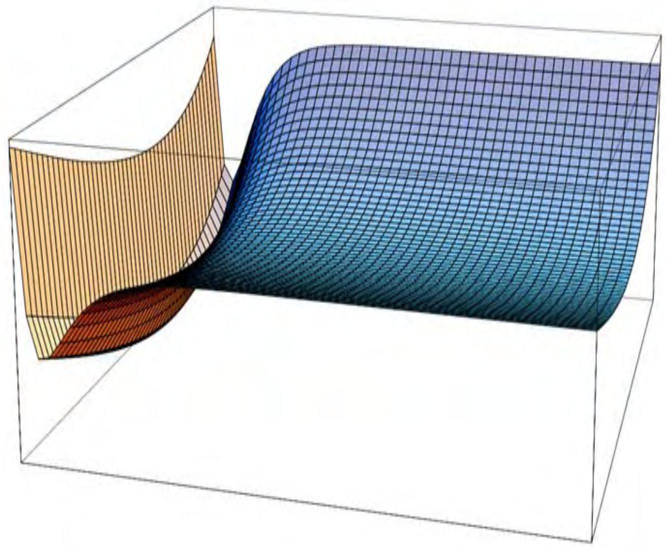
n_s=0.95

No grav. waves

Spectral index as a function of the number of e-foldings
(minus the total number of e-foldings)

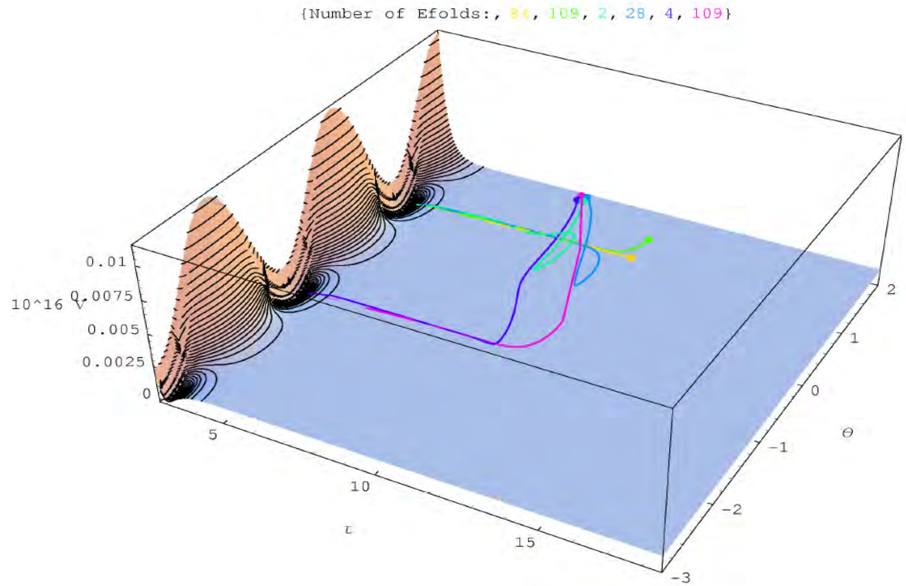
Inflationary models with Large Volume Compactification

Becker[2], Haack, Louis; Balasubramanian, Berglund, Conlon, Quevedo



Kahler modular inflation

Conlon, Quevedo



Roulette inflation

Bond, Kofman, Prokushkin, Vaudrevange

Less fine tunig, more moduli, more parameters

n_s =0.96, no cosmic strings, no GW

- All known brane inflation models and modular inflation models in string theory predict a non-detectable level of tensor modes

- These include the known versions of DBI models

- N-flation model (Dimopoulos, Kachru, McGreevy, Wacker) could predict detectable tensor modes, but this model still has to be derived from string theory

New models, or new versions of known models, may lead to different results, but this has to be established!

Silverstein et al, work in progres on generalized DBI models

Several possibilities for the future:

We have to fit n_s and we may find:

- No tensor modes
- No cosmic strings
- No non-gaussianity

- Tensor modes detected:
  Great challenge for string theory!
- Cosmic strings detected:
  No problem for string theory, a welcome effect, a potential window into physics at the string scale
- Non-gaussianity detected:
  some solutions maybe possible

Cosmology ⟶ **Mass of gravitino** ⟵ **Particle physics** ⟵ **LHC**

Planck + polarization experiments

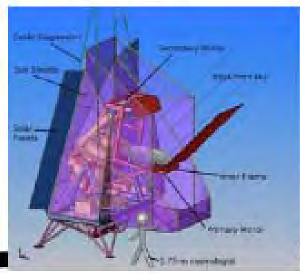
???

Dark matter searches

The CMB Polarization Programme

PLANCK

EBEX



SPIDER

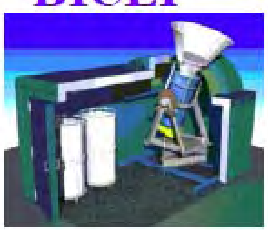
SPTpol

CMBpol ??
Satellite

2018

QUAD

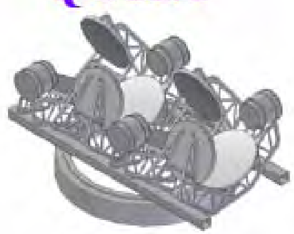
BICEP



POLARBEAR

ACTpol

QUIET



2011

now

time

What if tensor modes are detected?

Current bound: r = T/S < 0.3 from WMAP and SDSS

- What will detection mean for the fundamental physics, string theory and supergravity?

$$0.1 < r < 0.3$$ by 2011

$$10^{-2} < r < 0.1$$ by 2020

Tensor Modes and GRAVITINO

$$r \sim 10^8 H^2$$

- In KKLT models of moduli stabilization

$$H \leq M_{3/2}$$

RK, Linde 2004

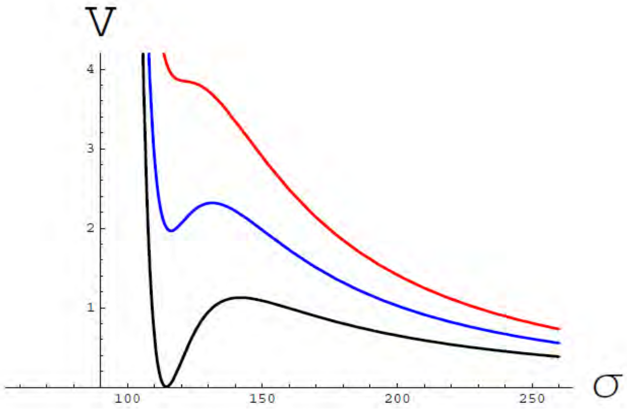
Therefore $$r \leq 10^8 M_{3/2}^2$$

$$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$$

superheavy gravitino

For $M_{3/2} \sim 1 TeV$ one has undetectable GW with

$$r \sim 10^{-24}$$



Models of inflation predicting GW

- Chaotic inflation

$$V = a\phi^2 + h\phi^3 + b\phi^4$$

- Natural inflation

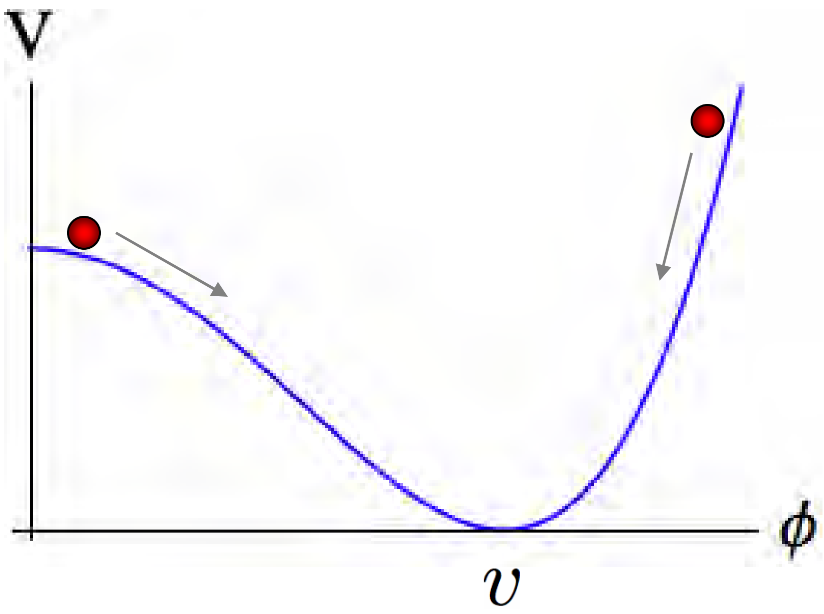
$$V = \Lambda(1 - \cos(\phi/f))$$

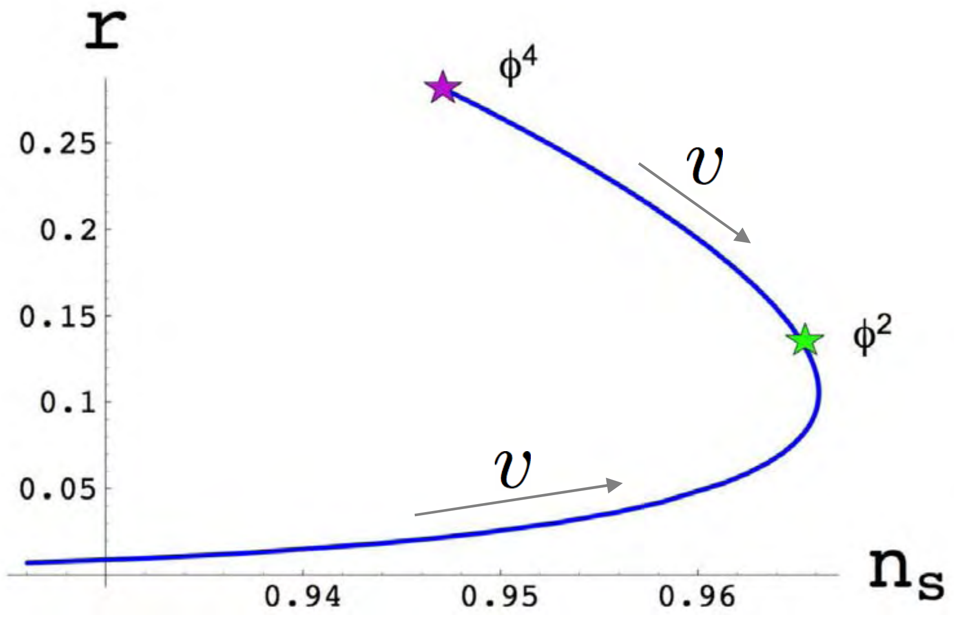
Can we derive these models from supergravity and string theory?

Tensor modes:

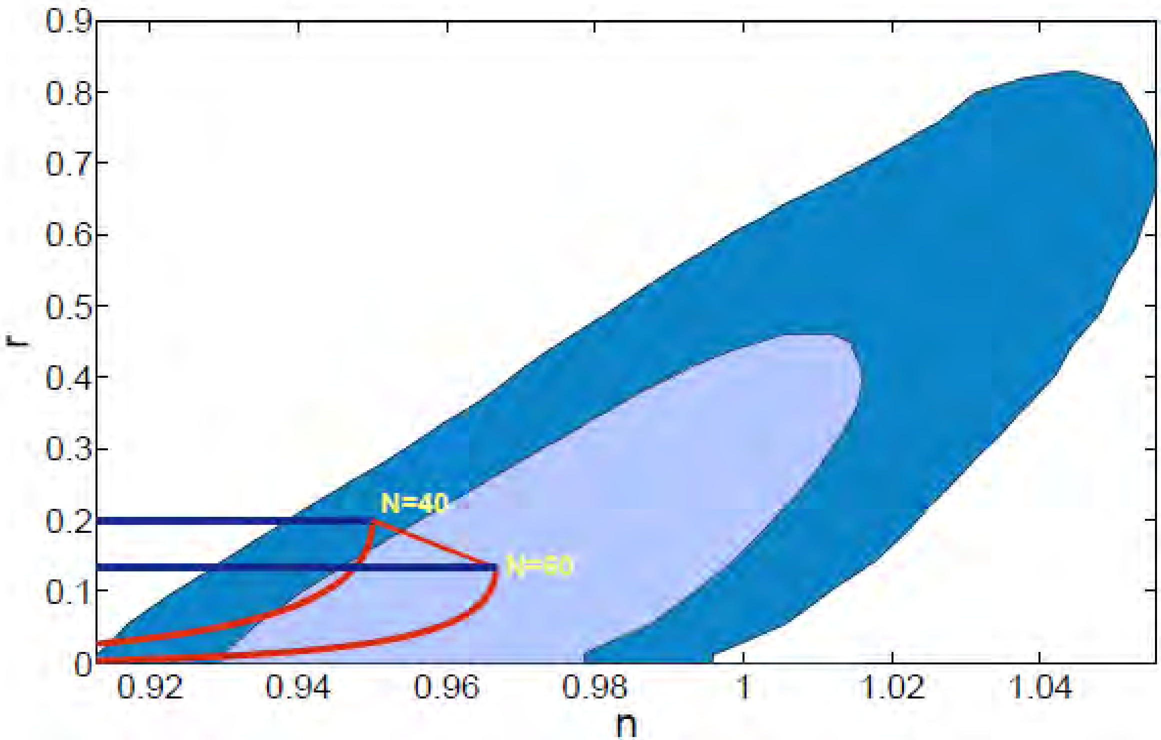
$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

RK, Linde, 2007





It <u>does</u> make sense to look for tensor modes even if none are found at the level r ~ 0.1 (Planck)



D. Lyth

Red curved lines correspond to natural inflation and a straight red line corresponds to quadratic chaotic inflation

The goal of cosmology community for a long time was to reconstruct from the data some information on the inflationary potential $V(\phi)$

This is still a valuable goal. However, in the context of string theory and effective N=1 supergravity the goal is to get some information on the Kähler potential $K(\Phi^i, \bar{\Phi}^i)$ and the Superpotential $W(\Phi^i)$, $i = 1, 2..., n.$

Generic potential of N=1 supergravity depends on a number of complex scalar fields which have a geometric meaning of coordinates in Kähler geometry

$$V(\phi) = e^K \left(K^{-1}_{\Phi\bar{\Phi}} \, |D_\Phi W|^2 - 3|W|^2\right)$$ **+ D-terms**

Chaotic inflation in supergravity

Main problem:

$$V(\phi) = e^K \left(K^{-1}_{\Phi\bar{\Phi}} \, |D_\Phi W|^2 - 3|W|^2\right)$$

Canonical Kähler potential is $K = \Phi\bar{\Phi}$

Therefore the potential blows up at large |φ|, and slow-roll inflation is impossible:

$$V \sim e^{|\Phi|^2}$$

Too steep, no inflation…

A solution: shift symmetry

Kawasaki, Yamaguchi, Yanagida 2000

Equally good Kähler potential $K = \frac{1}{2}(\Phi + \bar{\Phi})^2 + X\bar{X}$

and superpotential $W = m\Phi X$

The potential is very curved with respect to X and Re φ, so these fields vanish.

But Kähler potential does not depend on

$$\phi = \sqrt{2}\,\mathrm{Im}\,\Phi = (\Phi - \bar{\Phi})/\sqrt{2}$$

The effective potential is

$$V = \frac{m^2}{2}\phi^2$$

Axion Valley Model:
Effective Natural Inflation in Supergravity

- Shift symmetric quadratic Kähler potential

$$K = \frac{1}{2}(\Phi + \bar{\Phi})^2 \qquad \Phi = x + i\beta$$

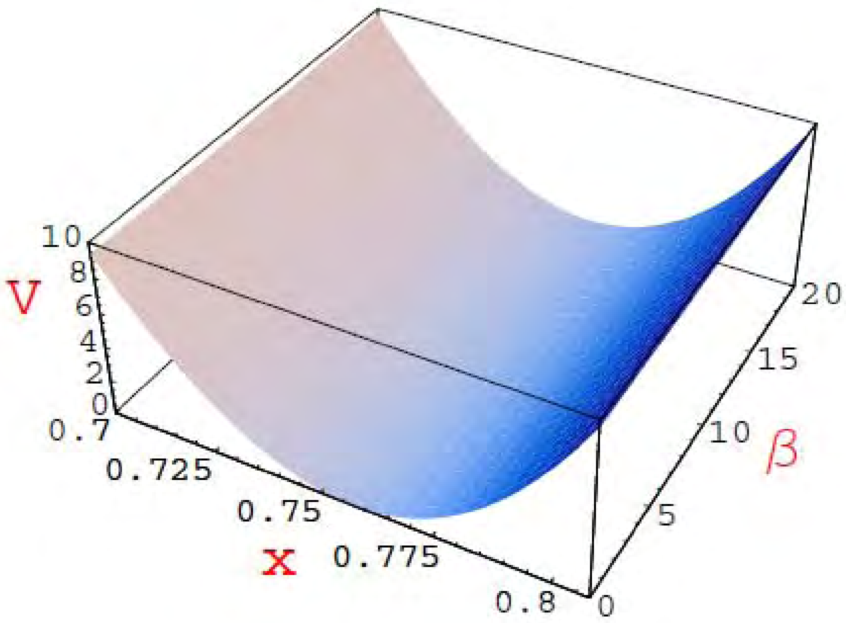
- KKLT-type superpotential

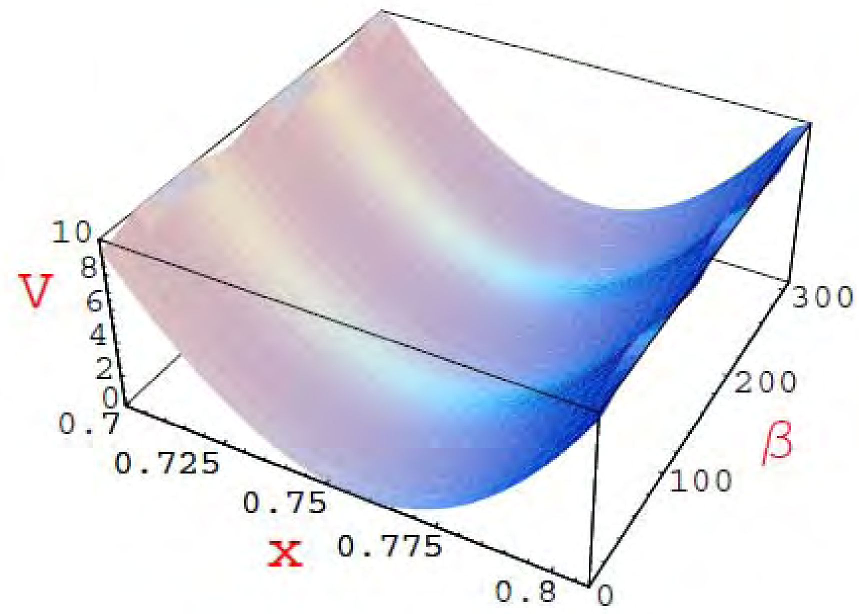
$$W = W_0 + Be^{-b\Phi}$$

- The potential after the KKLT-type uplifting $V(x, \beta)$ has a minimum at some value of the radial variable x_0. The radial direction is very steep. At this minimum the potential is that of natural inflation

$$V(x, \beta)|_{x_0} = \Lambda(1 - \cos(b\beta))$$

Axion Valley Potential





Sharp minimum in radial direction x, very shallow minimum for the axion

$$0 < \beta < 20$$

The potential shows the periodic structure for

$$0 < \beta < 300$$

Natural Inflation potential is the slice at the bottom of the valley

There are models of inflation in supergravity which predict tensor modes with

$$5 \cdot 10^{-3} < r < 0.3$$

- **In all known cases they have shift-symmetric quadratic Kähler potentials**

We may have to wait till 2011+ before we know if such supergravity models are valid

We anticipate learning new things about supersymmetry at that time

In string theory the computable Kähler potentials in known cases of Calabi-Yau compactification have shift symmetry

- However, they are logarithmic, not quadratic

$$K = -\ln\left(C_{ijk}(\Phi+\bar{\Phi})^i(\Phi+\bar{\Phi})^j(\Phi+\bar{\Phi})^k+\ldots\right)$$

Ferrara, RK, Strominger

KKLT, $C_{111}=1$

- These models predict undetectably small tensor modes in inflation.

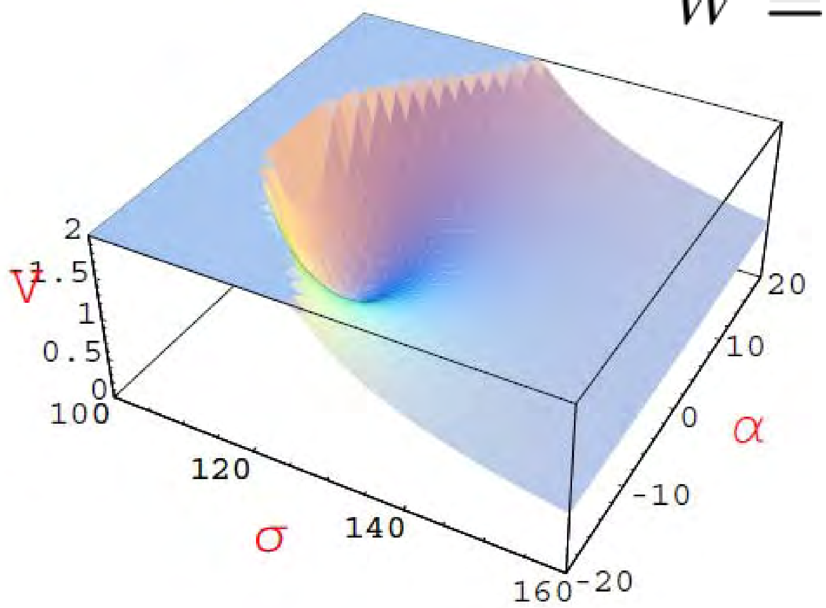
Kachru, RK, Soroush, Sivanandam, work in progress

Simplest example of KKLT potential

- One modulus

$$K = -\ln(T + \bar{T})^3$$

$$W = W_0 + Ae^{-aT}$$



RK, Prokushkin
hep-th/0403060
SuperCosmology
Mathematica code
for any # of moduli

Axion is as step as the radial modulus. This is an obstruction to N-flation model of assisted inflation in known models of string theory

No detectable GW in models with stringy logarithmic Kähler potentials

Can we derive axion valley supergravity models from string theory and predict GW?

Work in progress,
Kachru, RK, Soroush, Sivanandam, Grimm

Banks, Dine, Fox, Gorbatov Svrcek, Witten

Issues in axion physics in string theory: axion decay constant

Candidate models in type IIB orientifold with hypermultiplets cut down to chiral superfields by orientifolding

Simplest examples $K3 \times \frac{T^3}{\mathbf{Z_2}}$ $\frac{K3 \times T_2}{\mathbf{Z_2}}$

General case of IIB orientifold with hypers
Grimm, Louis

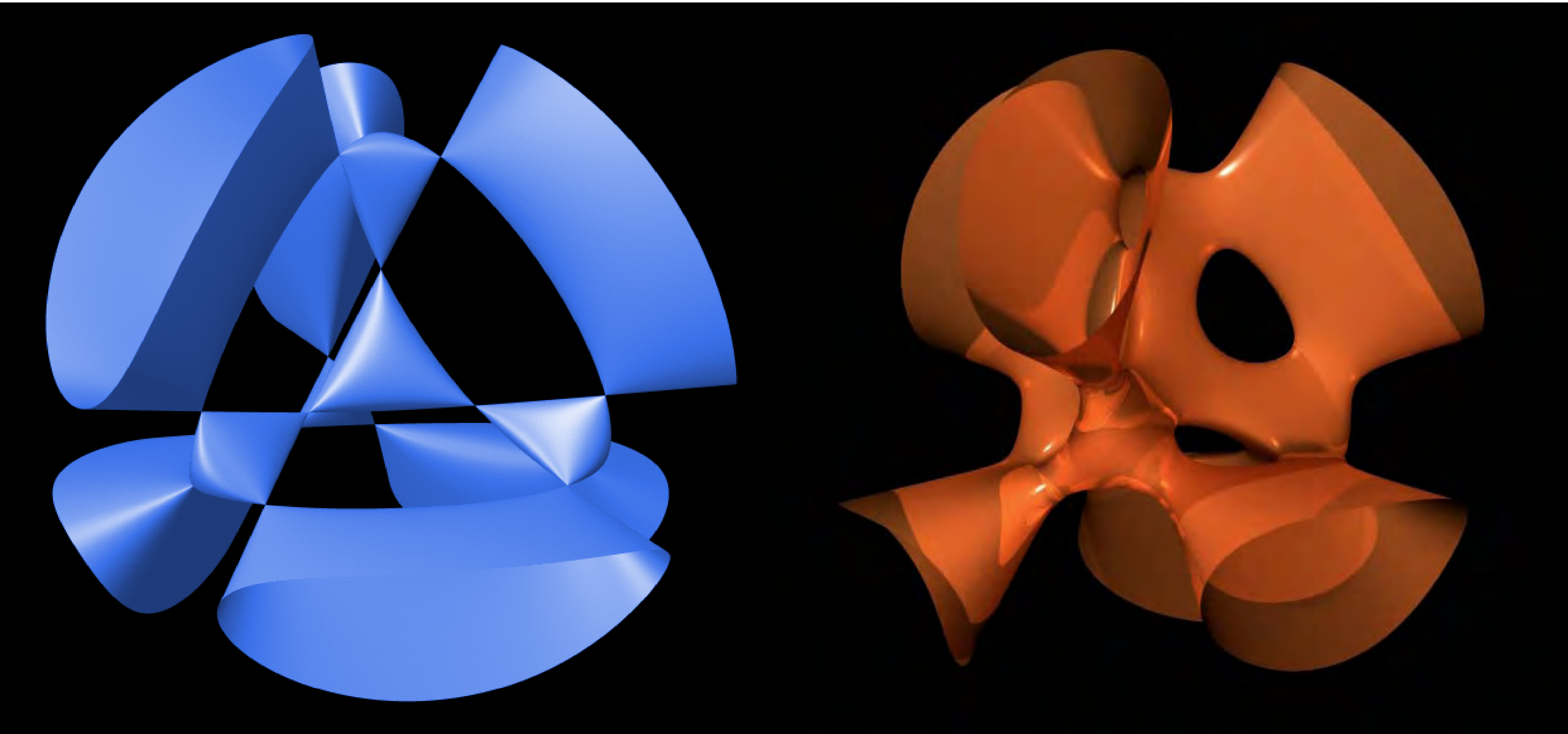
Type IIB string theory on K3 x $\frac{T^2}{Z_2}$ orientifold

Tripathy, Trivedi; Ferrara, Trigiante et al

Bergshoeff, RK, Kashani-Poor, Sorokin, Tomasiello

All moduli stabilized **Aspinwall, RK**

- **In F-theory compactifications on K3 x K3 one of the attractive K3 must be a Kummer surface to describe an orientifold in IIB, the second attractive K3 can be regular.**



Hodge-Kahler manifold

$$\frac{SO(2,n)}{SO(2)\times SO(n)}$$

$$K = -\ln(T+\bar{T}) - \ln[(x_0+\bar{x}_0)^2 - \sum_{i=1}^{i=19}(x_i+\bar{x}_i)^2]$$

At fixed T and $x_0 + \bar{x}_0 = v$

$$K \sim \frac{\sum_{i=1}^{i=19}(x_i+\bar{x}_i)^2}{v^2}$$

$$W \sim e^{-a x_i}$$

Small $x_i + \bar{x}_i$

Will this string theory model provide
the axion valley potential predicting GW ???

Two issues with regard to most crucial future data

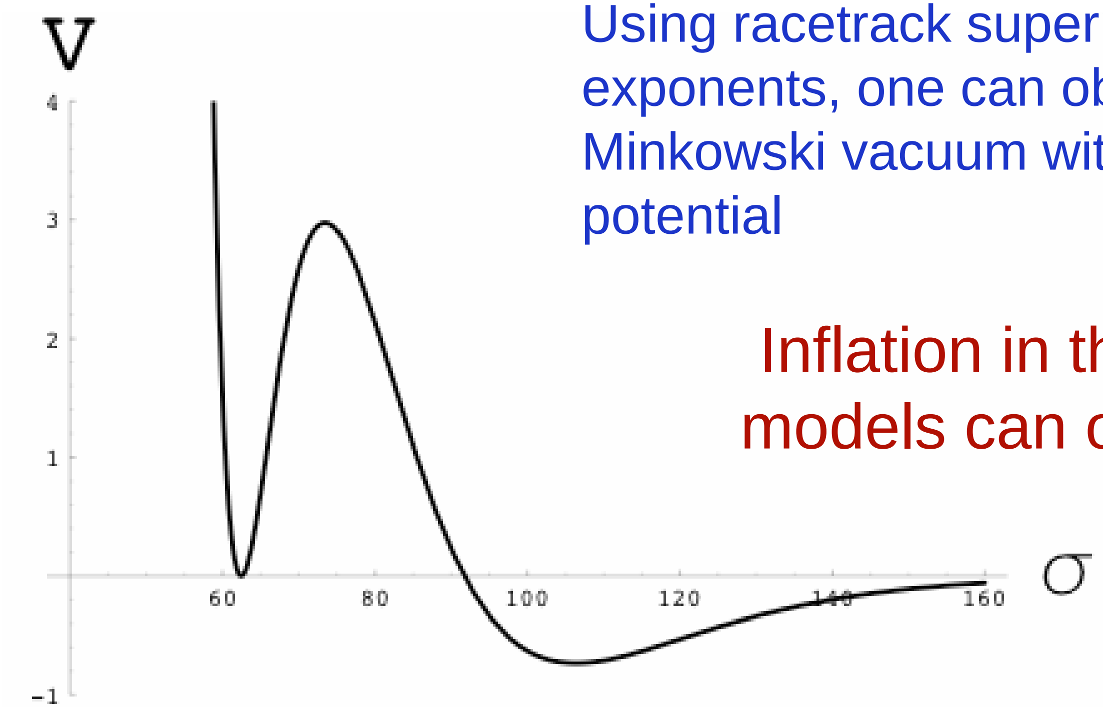
- To find inflationary models in string theory predicting the detectable level of B-modes or prove a no-go theorem

- To relate inflationary models to particle physics via the mass of gravitino in view of the bound

$H^2 \leq M_{3/2}^2$	$H^2 \leq \frac{M_{3/2}^2}{\mathcal{V}}$	No bound, fine-tuning
KKLT	**LVC**	**KL**
TeV gravitino, TeV H	TeV gravitino $\mathcal{V} \sim 10^{15}$ $H \sim 10^{-4}$ GeV	

KL model

RK, Linde, hep-th/0411011



Using racetrack superpotential with two exponents, one can obtain a supersymmetric Minkowski vacuum without any uplifting of the potential

Inflation in this class of KKLT models can occur at $H >> m_{3/2}$

Small mass of gravitino, no correlation with the height of the barrier and with the Hubble constant during inflation

In the context of inflation in string theory and supergravity, the detection (or non-detection) of the tensor modes from inflation is of crucial importance!

- At the present level of understanding there seem to be a unique way to read the features of the Kähler potential from the sky.
- No detection: Calabi-Yau 3-folds logarithmic Kähler potentials prediction $r \ll 10^{-3}$
- Detection: shift symmetric quadratic Kähler potentials

$$5 \times 10^{-3} < r < 0.3$$

- Derivable from string theory?

- The mass of the gravitino is tied to future detection or non-detection of the tensor modes in the most developed string theory models.

Scale of gravitino mass: LSP, 1TeV, 10^{13} GeV

KL models or need new ideas Racetrack Inflation, …

Conclusions

When we learned that our universe is accelerating, it was a creative crisis, which forced us to reconsider many issues in string theory, including the issue of moduli stabilization and metastable vacua.

If tensor modes are found, this may be equally important. It may provide us with information about the Kahler potential and force us to consider SUSY phenomenology with superheavy gravitino, or invent new methods of moduli stabilization.