String Cosmology

Recent developments

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Stanford

Cosmology, Strings, and Phenomenology

Stockholm , June 20, 2007

Based on R. K., A. Linde, 0704.0647,
R. K. , hep-th/0702059,
work in progress

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: GKP-KKLT stabilization of the volume of the internal six-dimensional space

Volume stabilization

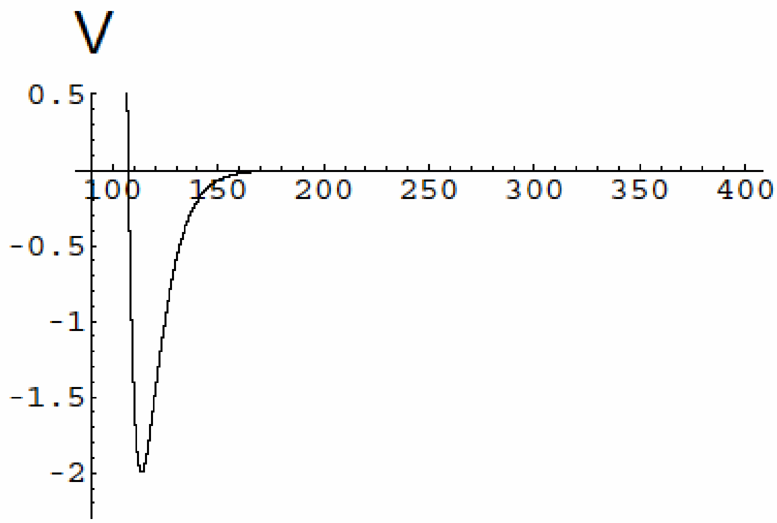
KKLT

Kachru,R.K.,Linde, Trivedi

Basic steps:

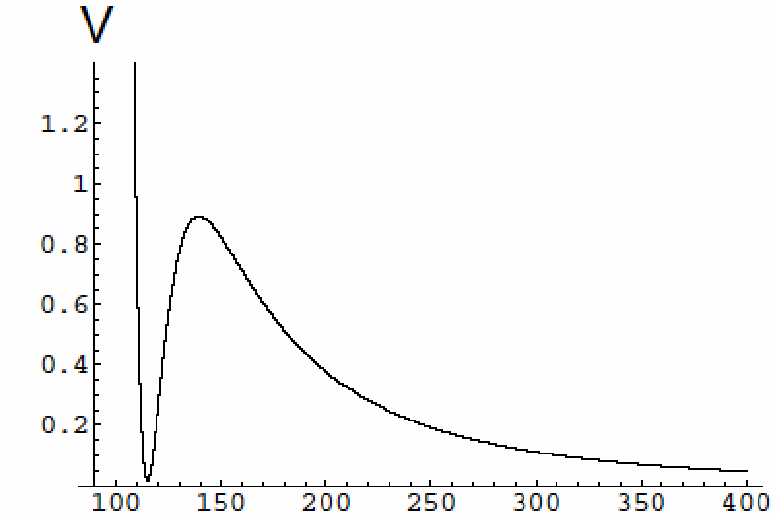
Warped geometry of the compactified space and nonperturbative effects (gaugino condensation, instantons) lead to AdS space (negative vacuum energy) with unbroken SUSY and stabilized volume

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

$$\frac{c}{\sigma^n} \longrightarrow$$



Metastable dS minimum

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.

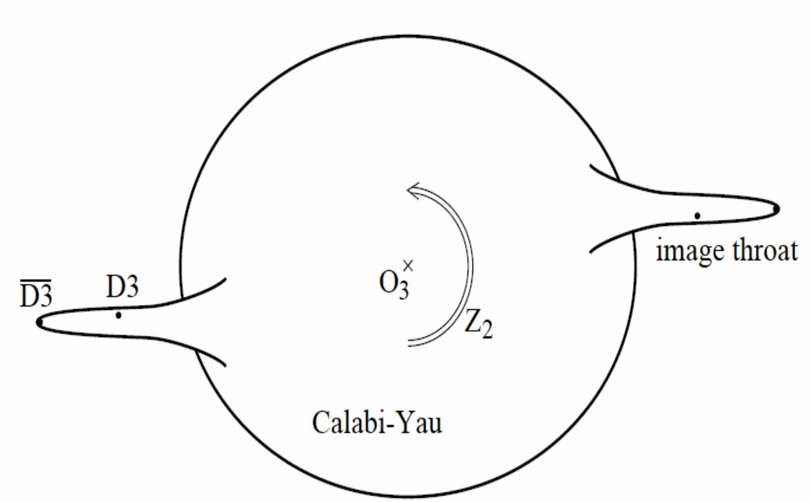
Observations of GW, cosmic strings or non-gaussianity can help us to test string theory

Two types of string inflation models:

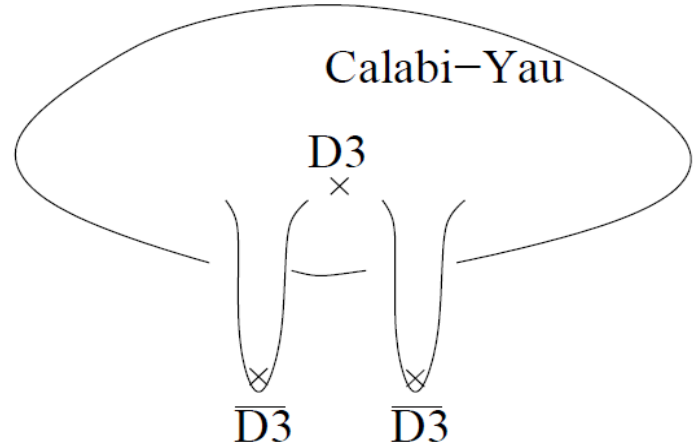
- **Modular Inflation.** The simplest class of models. They use only the fields that are already present in generalized KKLT model.

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

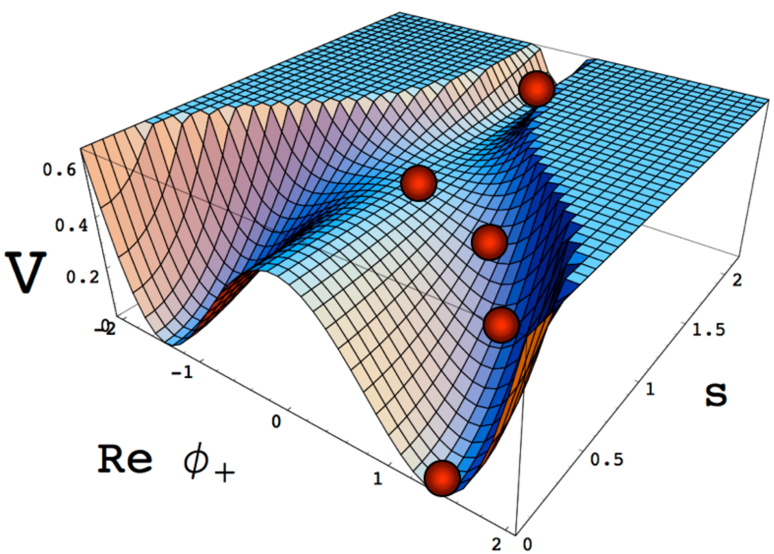
Brane Inflation in string theory



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

2004

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

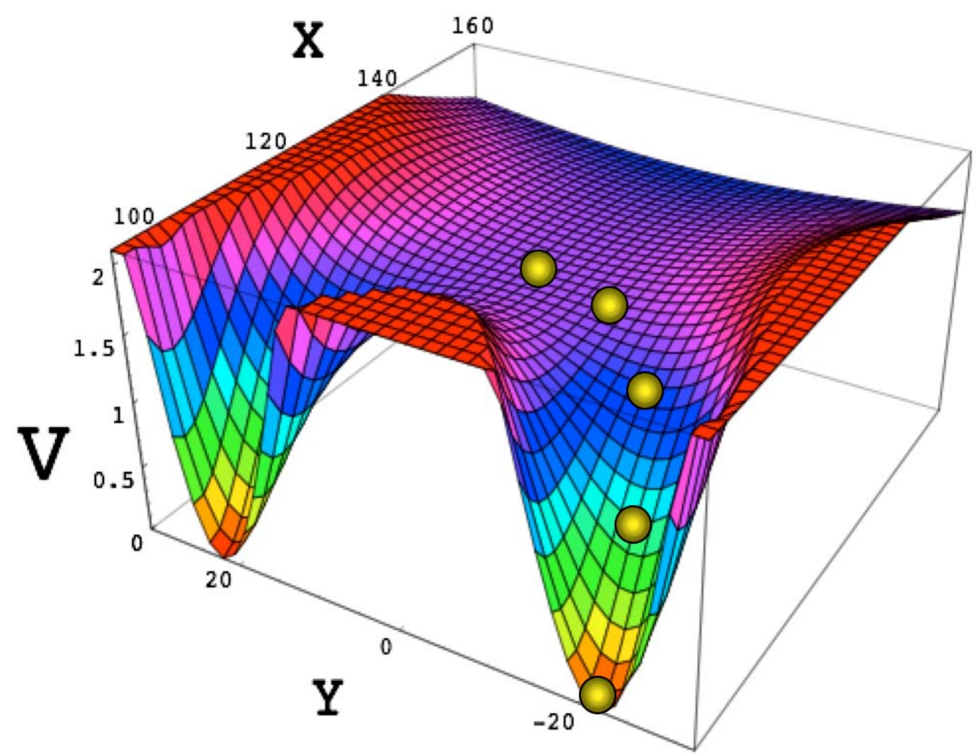
Blanco-Pilado, Burgess, Cline, Escoda, Gomes-Reino, Kallosh, Linde, Quevedo

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

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

KKLT Uplifting term:

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



Same group 2006

“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

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.

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

Two complex moduli: the simplest known case of realistic stringy KKLT stabilization

- Kähler potential

$$K = -2\ln[(\tau_2+\bar{\tau}_2)^{3/2} - (\tau_1+\bar{\tau}_1)^{3/2}]$$

- Superpotential

$$W = W_0 + Ae^{-a\tau_1} + Be^{-b\tau_2}$$

This inflationary model requires a fine-tuning of the parameters

stringy landscape conjecture

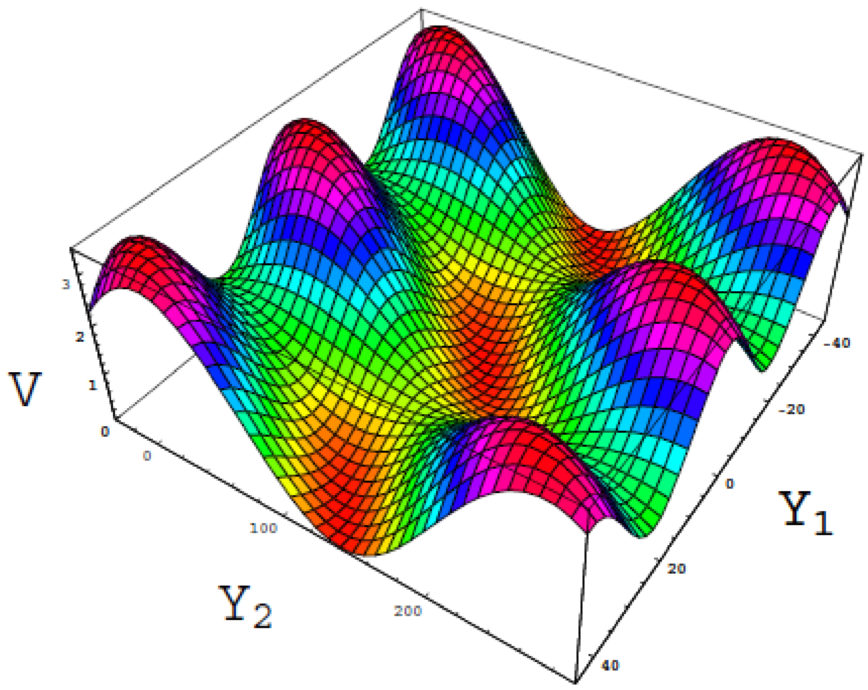


Figure 1: The potential as a function of the axion variables Y_1, Y_2 at the minimum of the radial variables X_1, X_2, , in units 10^{-15} of the Planck density.

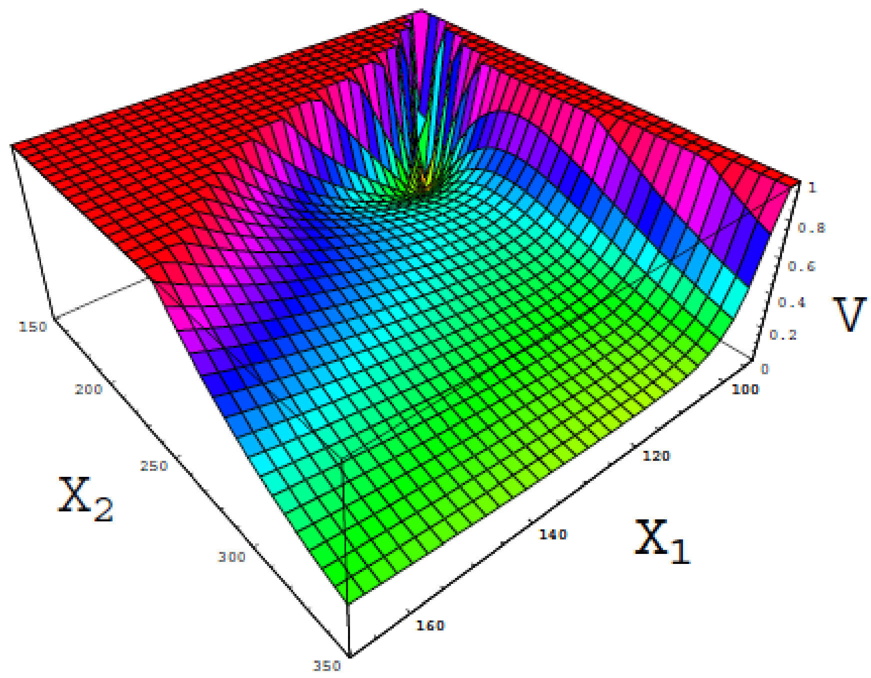
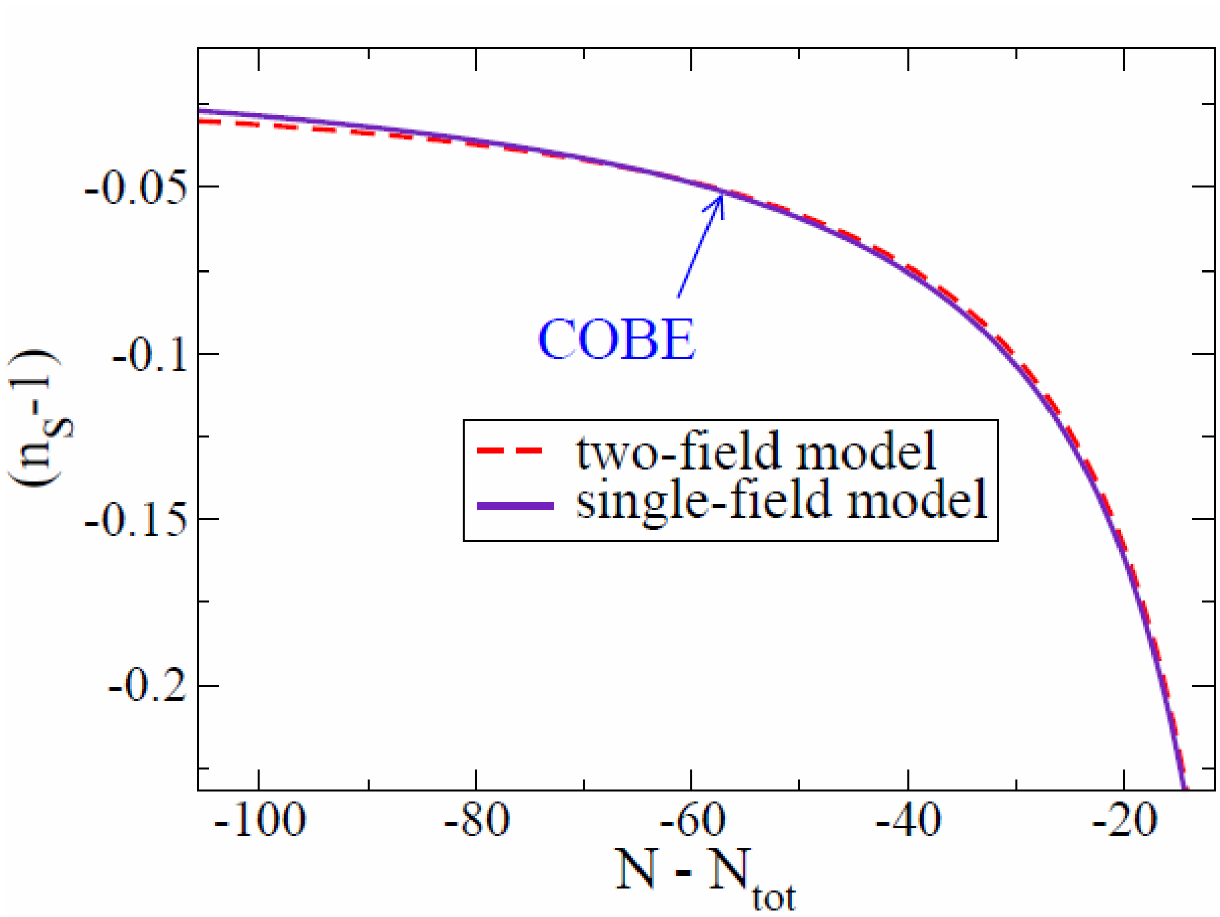


Figure 2: The potential as a function of the radial variables X_1, X_2 at the minimum of the angular variables Y_1, Y_2, in units 10^{-14} of the Planck density.



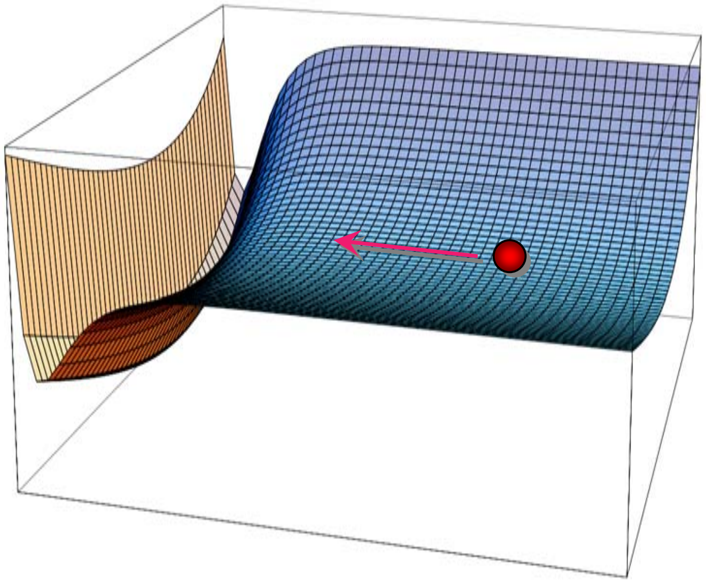
No cosmic strings

n_s=0.95

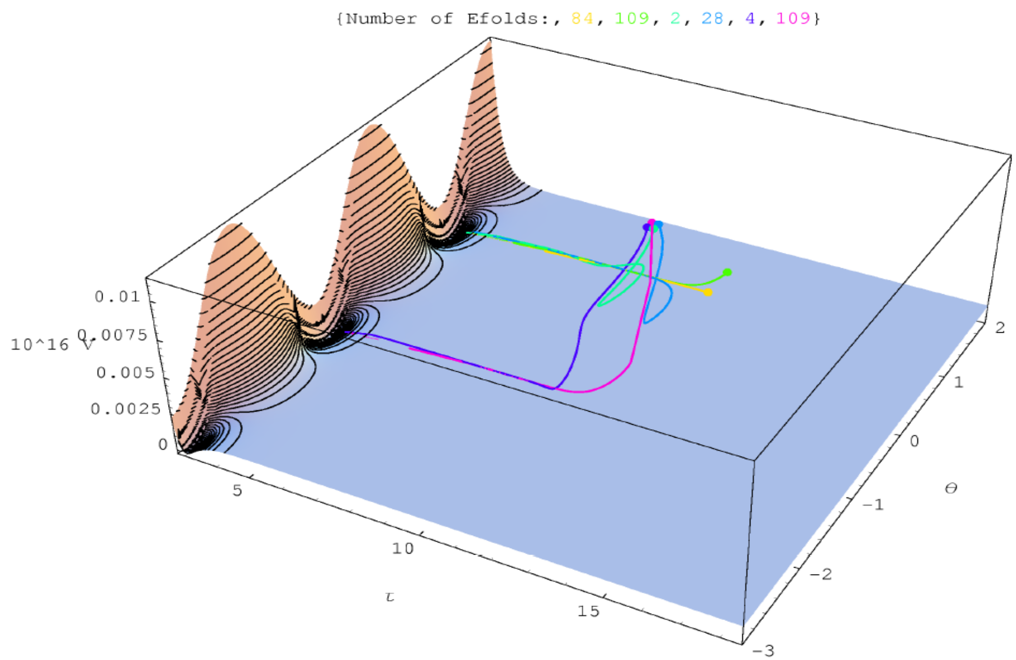
No grav. waves

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

Inflationary models with Large Volume Compactification



Kahler modular inflation



Roulette inflation

Less fine tunig, more moduli, more parameters

Quevedo's talk

- 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 still has to be derived from string theory

  Dimopoulos, Kachru, McGreevy, Wacker, 2005

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

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	

Tensor Modes and GRAVITINO

Discovery of GW $\quad r \sim 10^8 H^2$

- In KKLT models of moduli stabilization

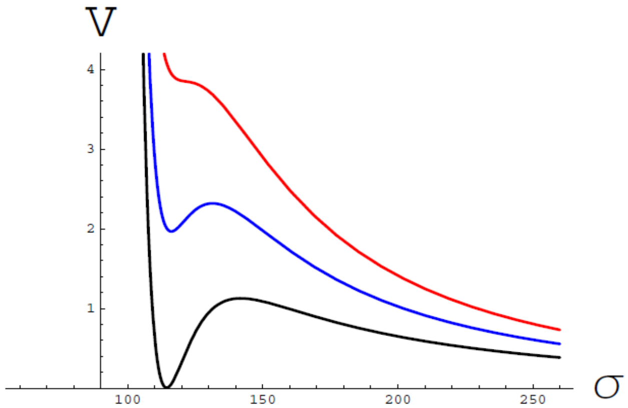
$$H \leq M_{3/2}$$

- Detection of GW $\longrightarrow$ $r \leq 10^8 M_{3/2}^2$

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

Extremely heavy gravitino

- If $M_{3/2} \sim 1 TeV$ the prediction of these models: undetectable GW

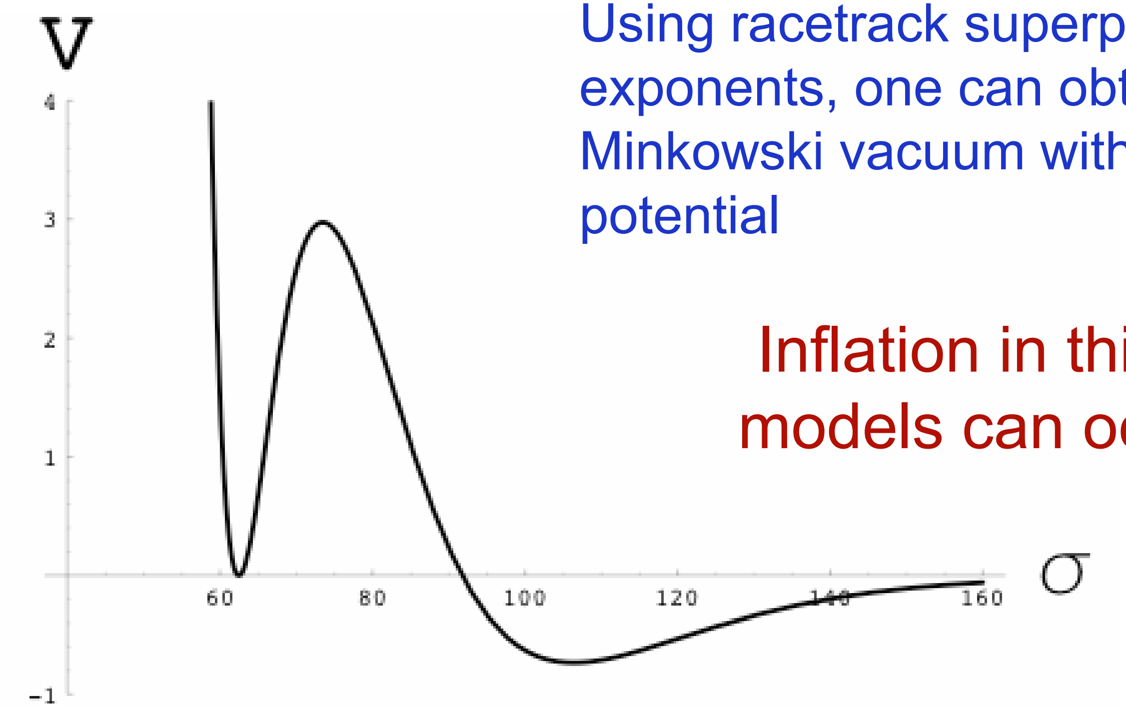


Extremely small H ???

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

KL model

Kallosh, A.L. 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 $H \gg m_{3/2}$

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

Several possibilities:

After we fit n_s, 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 $\longrightarrow$ **Mass of gravitino** $\longleftarrow$ **Particle physics** $\longleftarrow$ **LHC**

Planck + polarization experiments

???

Dark matter searches

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

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

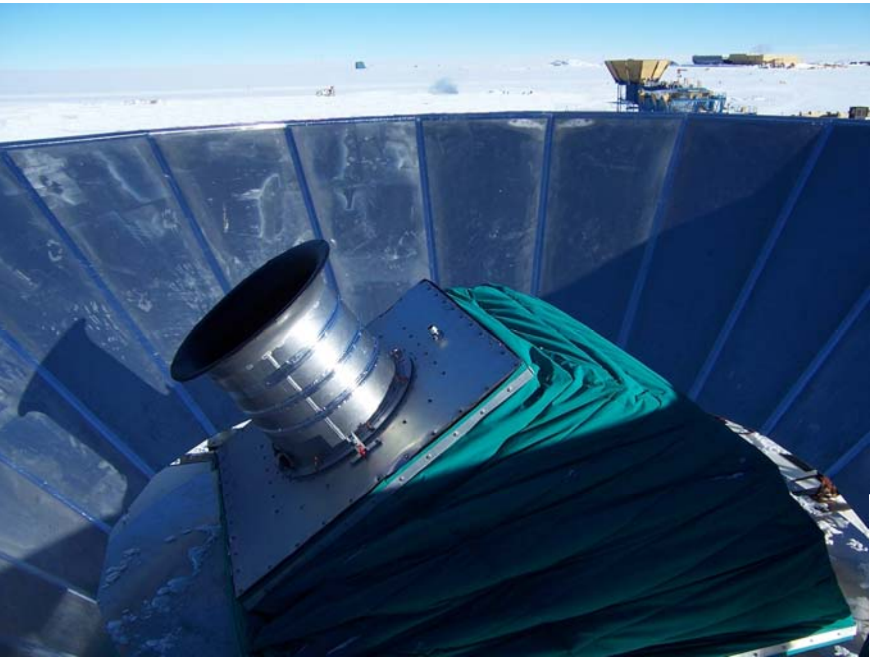
By 2020

Experiments taking data now...

BICEP

CalTech, JPL
UCSD, Berkeley
Cardiff, IAS

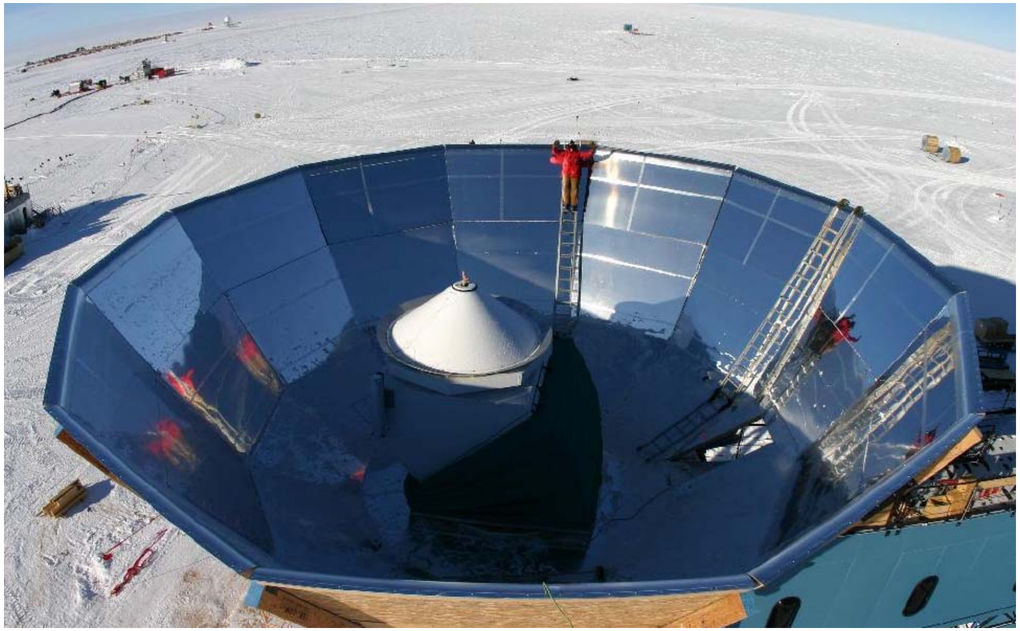
~40' beam
90 & 150 Ghz



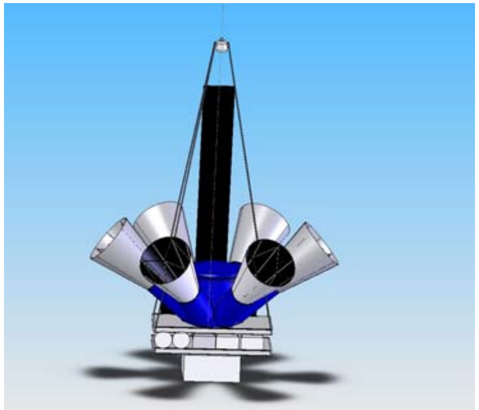
QUAD

Stanford, CalTech
JPL, Cardiff, Chicago,
Edinburgh, Maynooth

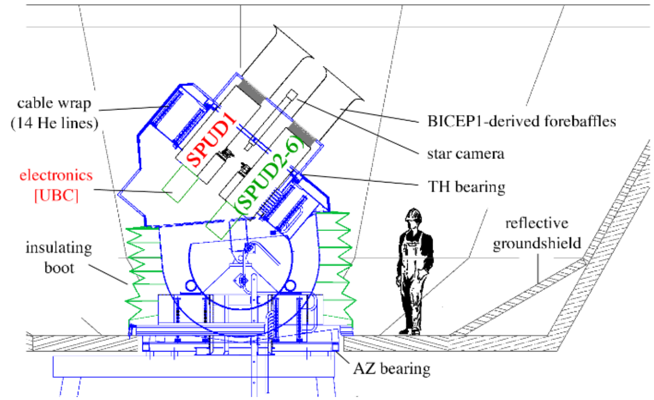
~5' beam
90 & 150 Ghz
High Precision E Mode determination



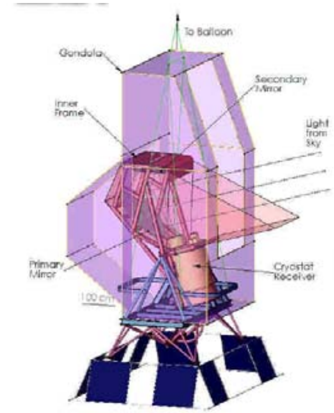
The Next Generation: 6+ Machines!



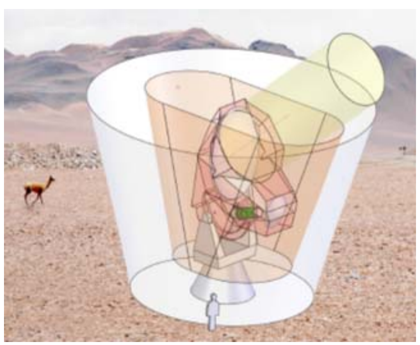
Spider: CalTech, CWRU, ICL, JPL, NIST, UBC, U Toronto



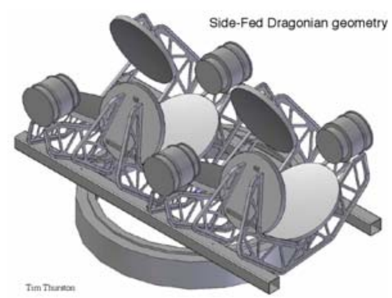
SPUD: CalTech, JPL, UCSD, Berkeley, Cardiff, IAS, Toronto



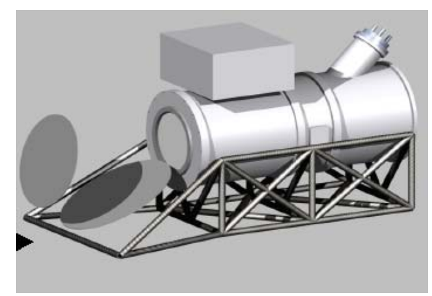
EBEX: Brown, Cardiff, Columbia,APC, Harvard, IAS, ISAS, McGill, Oxford, UCB/LBNL, UCSD, Minnesota, Toronto, Weizmann



polarBear: Berkeley, LBNL, UCSD, McGill Colorado



QUIET: Chicago, JPL, Miami, Princeton, CalTech, Columbia, Stanford, Oxford, MPI



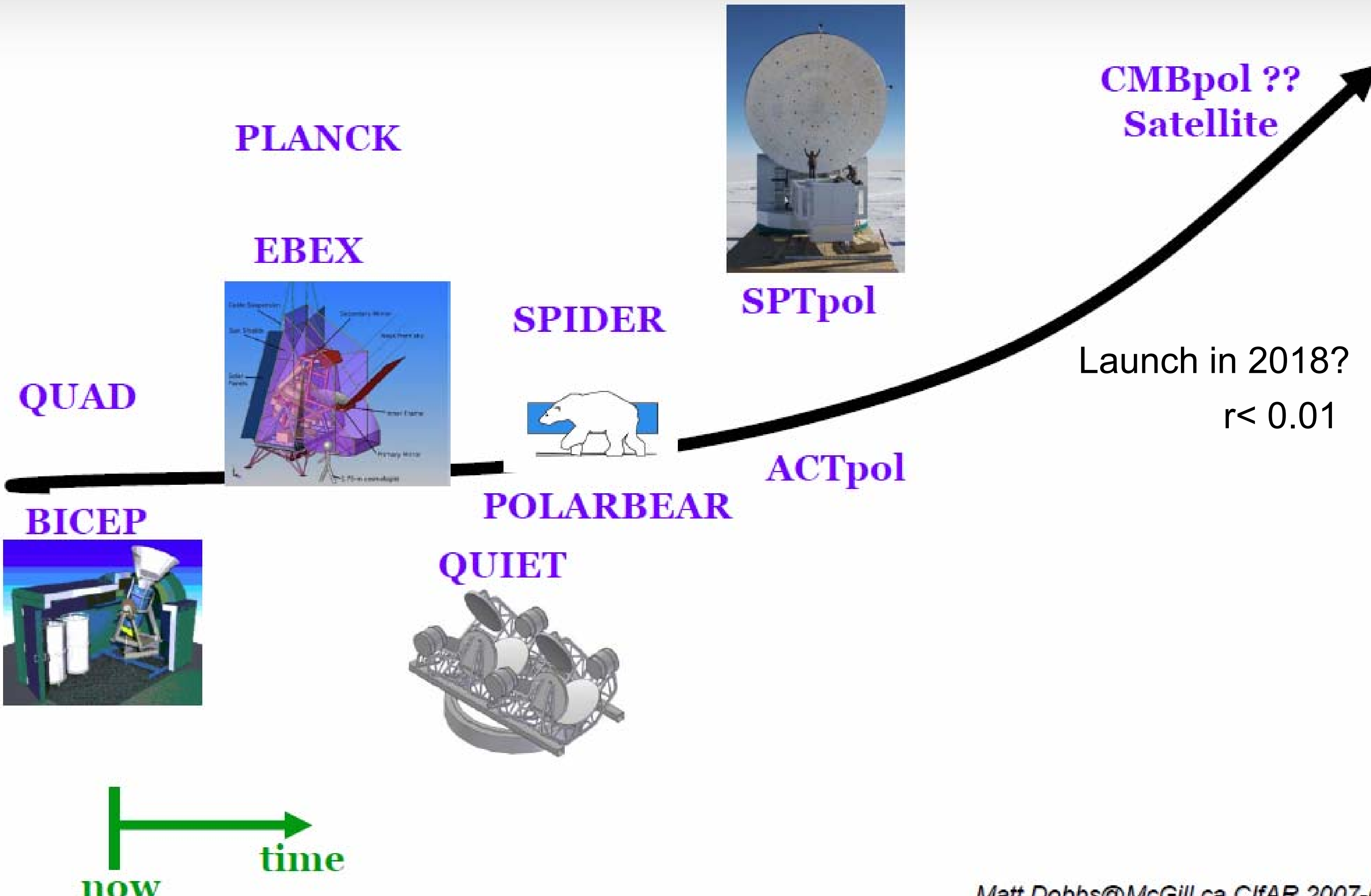
Clover: Cambridge, Cardiff, Oxford, NIST, CalTech, UBC

Barth Netterfield

Status:

- All have begun construction
- All hope to detect or put the bound, r <
- All plan to have results by 2011

The CMB Polarization Programme



Models of inflation predicting GW

- Chaotic inflation

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

- Natural inflation

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

Freese, Freeman, Olinto, 1990

- Assisted inflation:

chaotic inflation with many fields

$$V = \sum_i^N m_i^2 \phi_i^2$$

Liddle, Mazumdar, Schunk, 1998

$$\phi_i \geq \frac{M_{Pl}}{\sqrt{N}}$$

A bit of relaxation for N= 10^{2n} $\quad \phi_i \geq \frac{M_{Pl}}{10^n}$

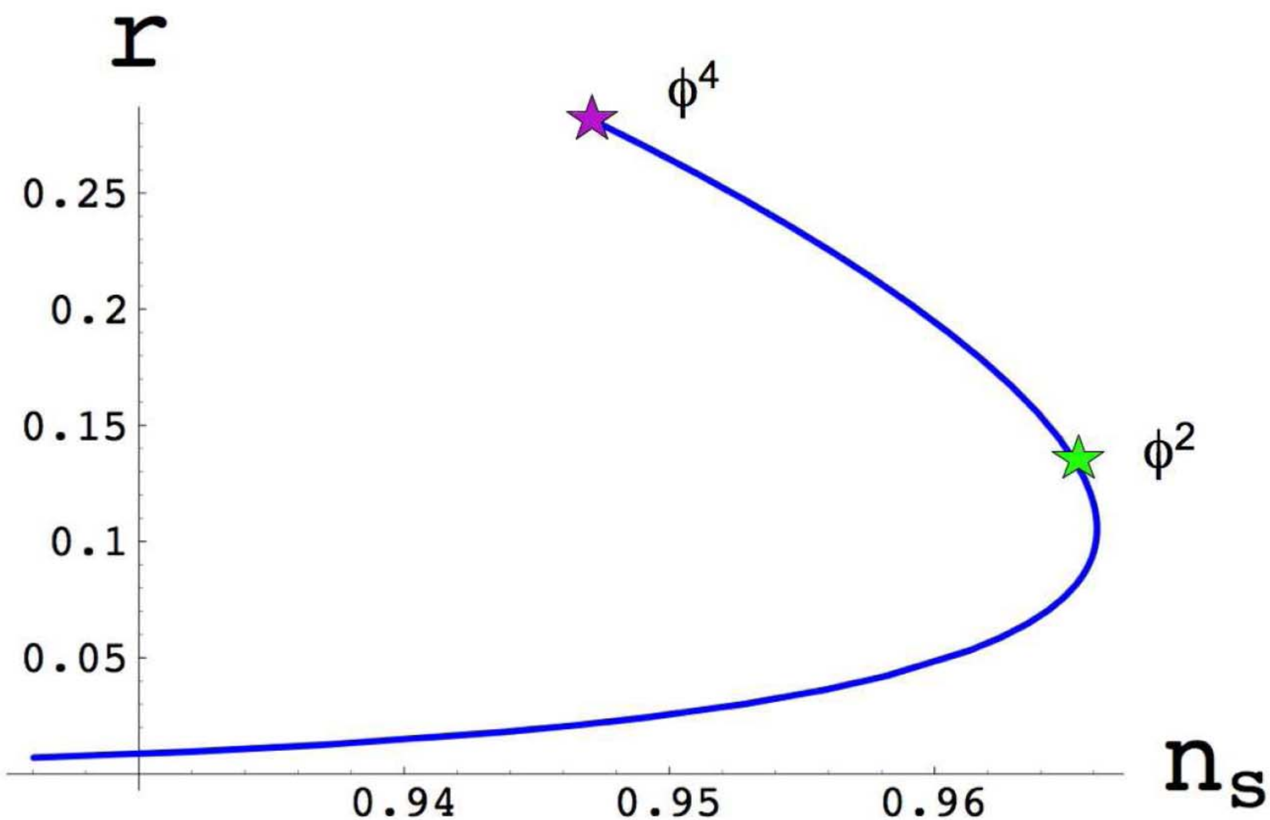
- Field theory models

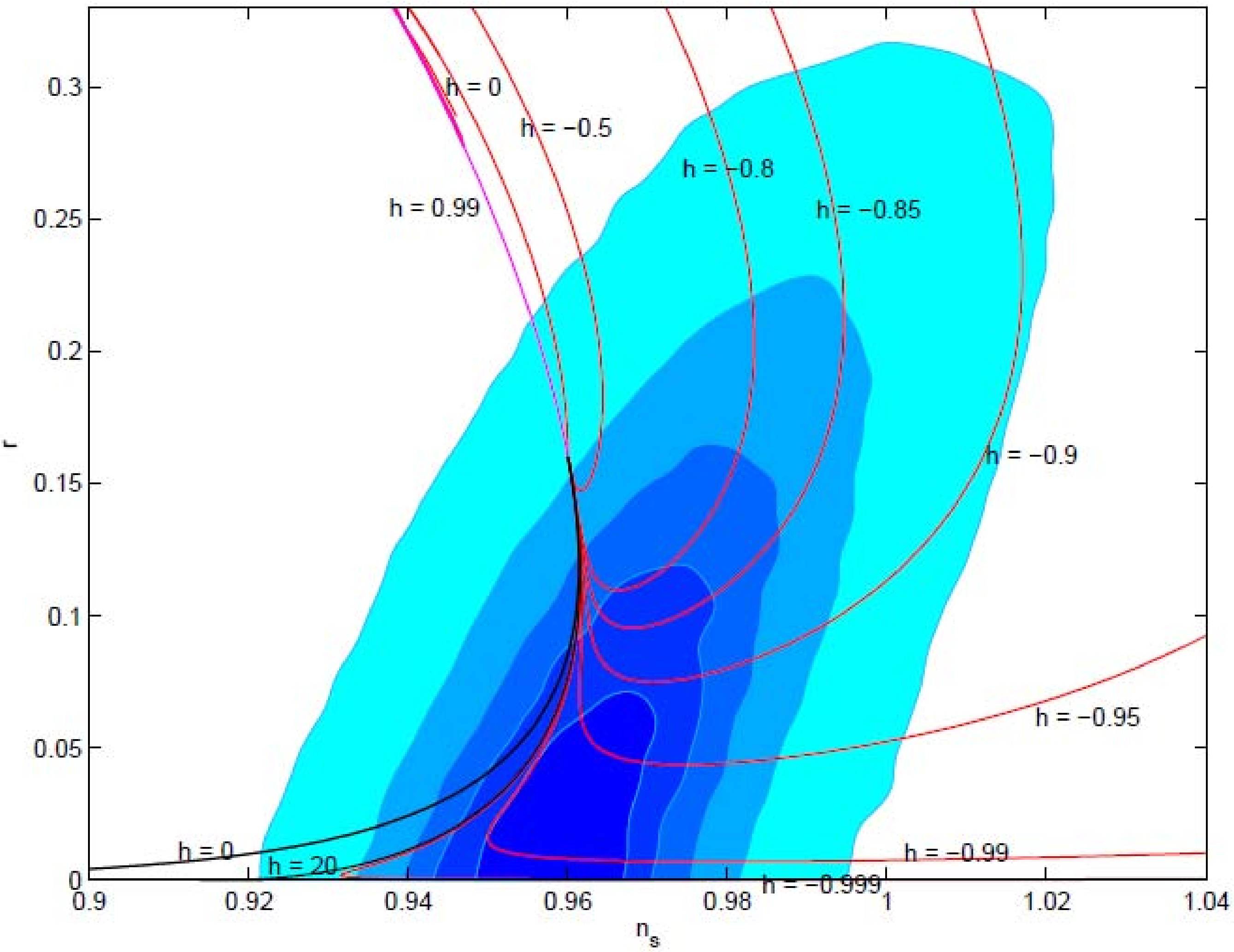
Relation to supersymmetry, supergravity, string theory?

If any of these models are related to string theory/supergravity, it becomes a particularly important issue of the fundamental physics: we need new data from

Planck+ pol. exp and CMBPOL

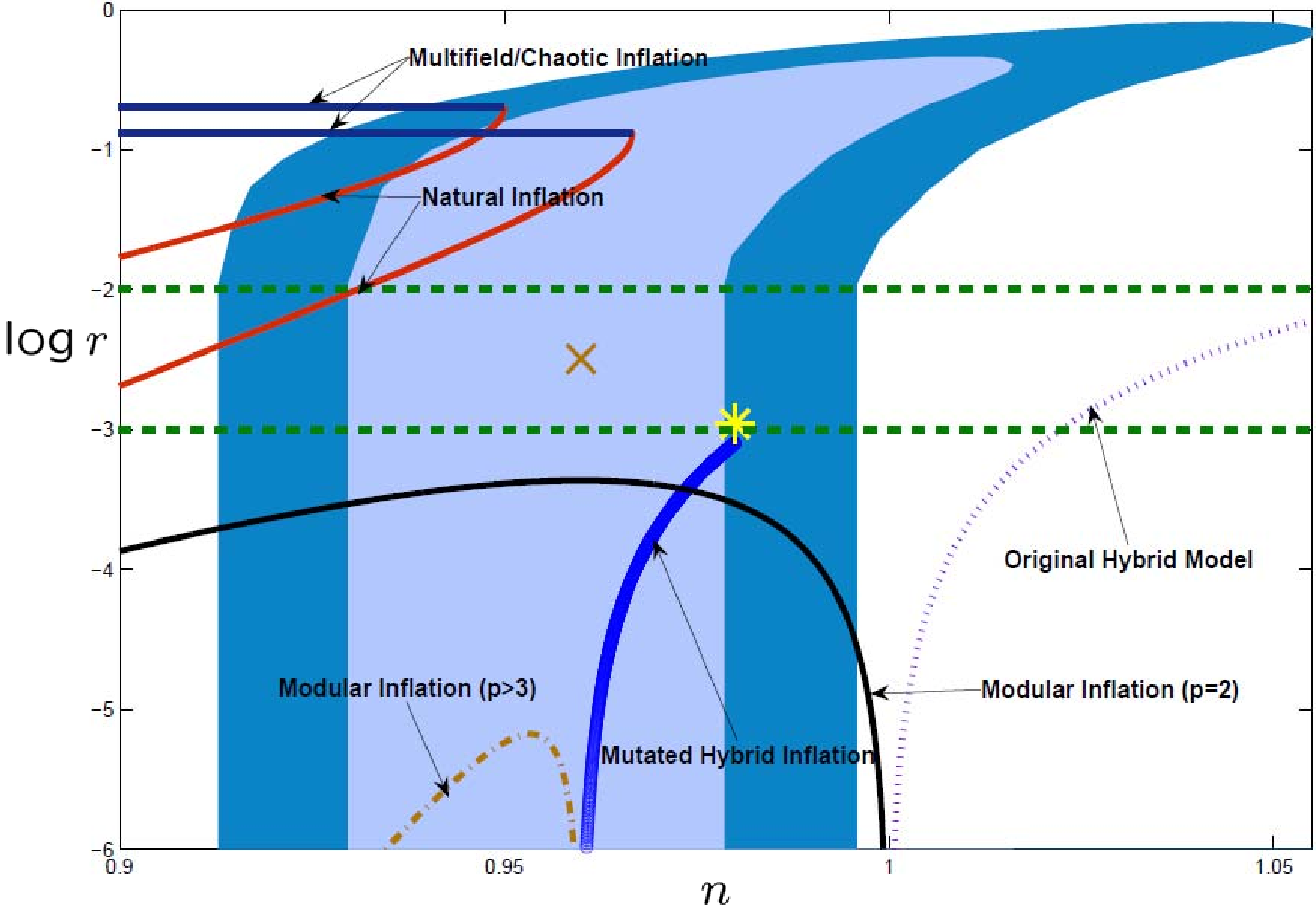
$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$





Destri, de Vega, Sanchez, 2007

Possible values of r and n_s for chaotic inflation with a potential including terms ϕ^2, ϕ^3, ϕ^4 for N = 50. The color-filled areas correspond to various confidence levels according to the WMAP3 and SDSS data.


Multifield/Chaotic Inflation
Natural Inflation
Original Hybrid Model
Modular Inflation (p>3)
Modular Inflation (p=2)
Mutated Hybrid Inflation
log r
n
0
−1
−2
−3
−4
−5
−6
0.9
0.95
1
1.05

D. Lyth, 2007

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 some number of complex scalar fields which have a geometric meaning of coordinates in Kähler geometry

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

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 potential of this field has the simplest form, without any exponential terms, even including the radiative corrections:

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

Axion Valley Model:
Effective Natural Inflation in Supergravity

- Shift symmetric quadratic Kähler potential

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

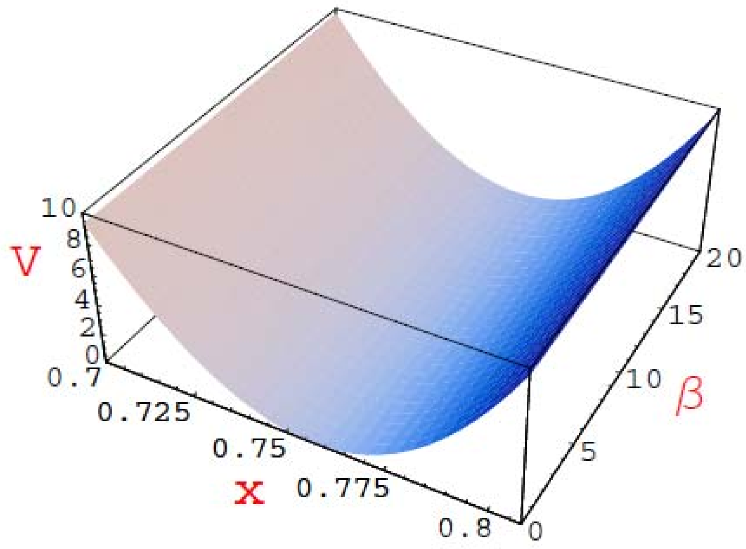
- KKLT-type superpotential

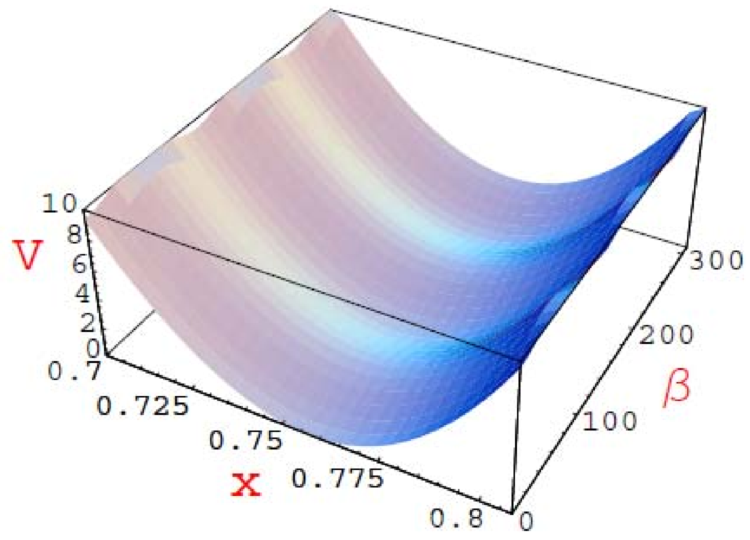
$$W = W_0 + Be^{-b\Phi}$$

- 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

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

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

$$0 < \beta < 300$$

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 will have to wait till 2018+ before we know if such supergravity models are valid

We anticipate learning new things about supersymmetry at this time

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

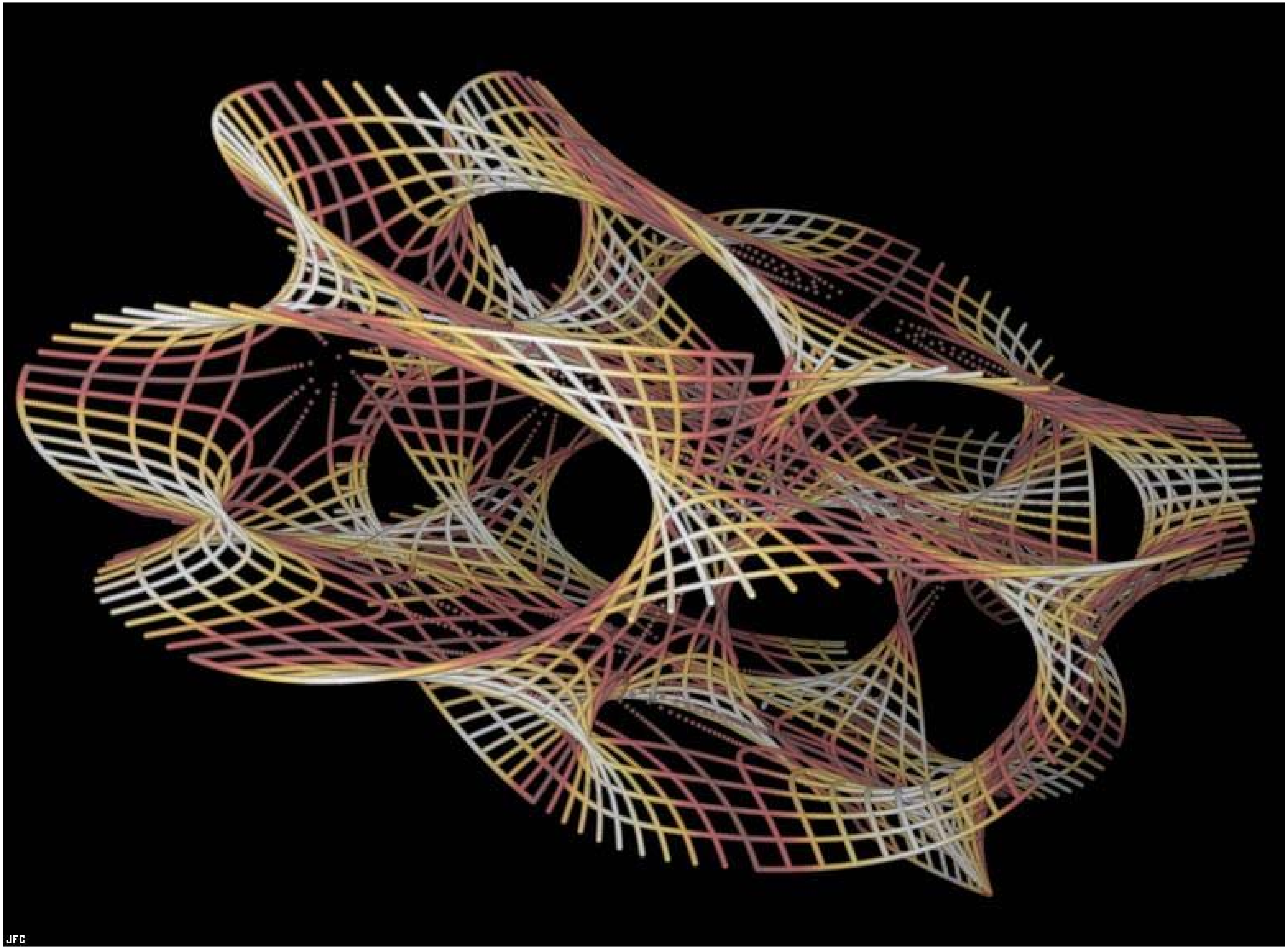
- However, they are logarithmic, not quadratic

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

KKLT, $C_{111}=1$

- These models generically predict undetectably small tensor modes in inflation.

A slice of quintic



$T = \sigma + i\alpha$ Total volume σ fixed by gaugino condensation/instantons

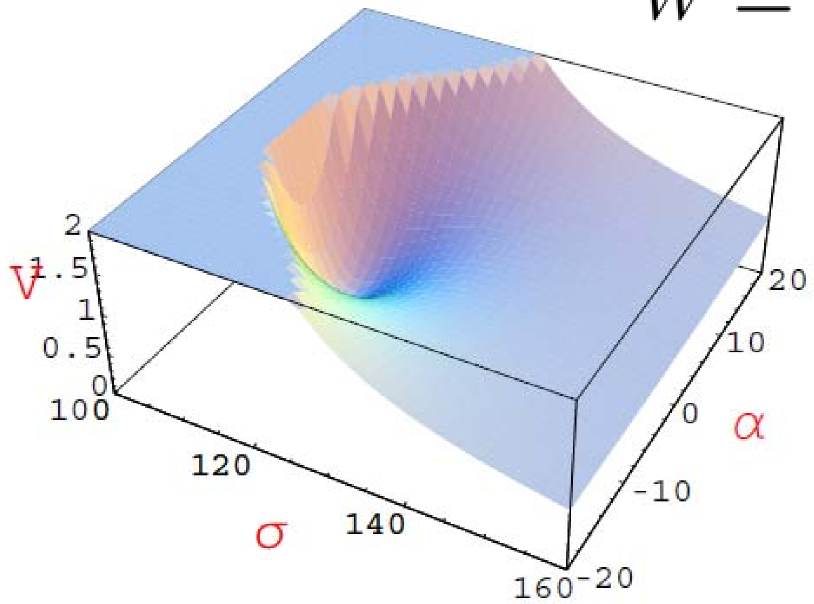
Shape moduli and axion-dilaton fixed by fluxes

Simplest example of KKLT potential

- One modulus

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

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



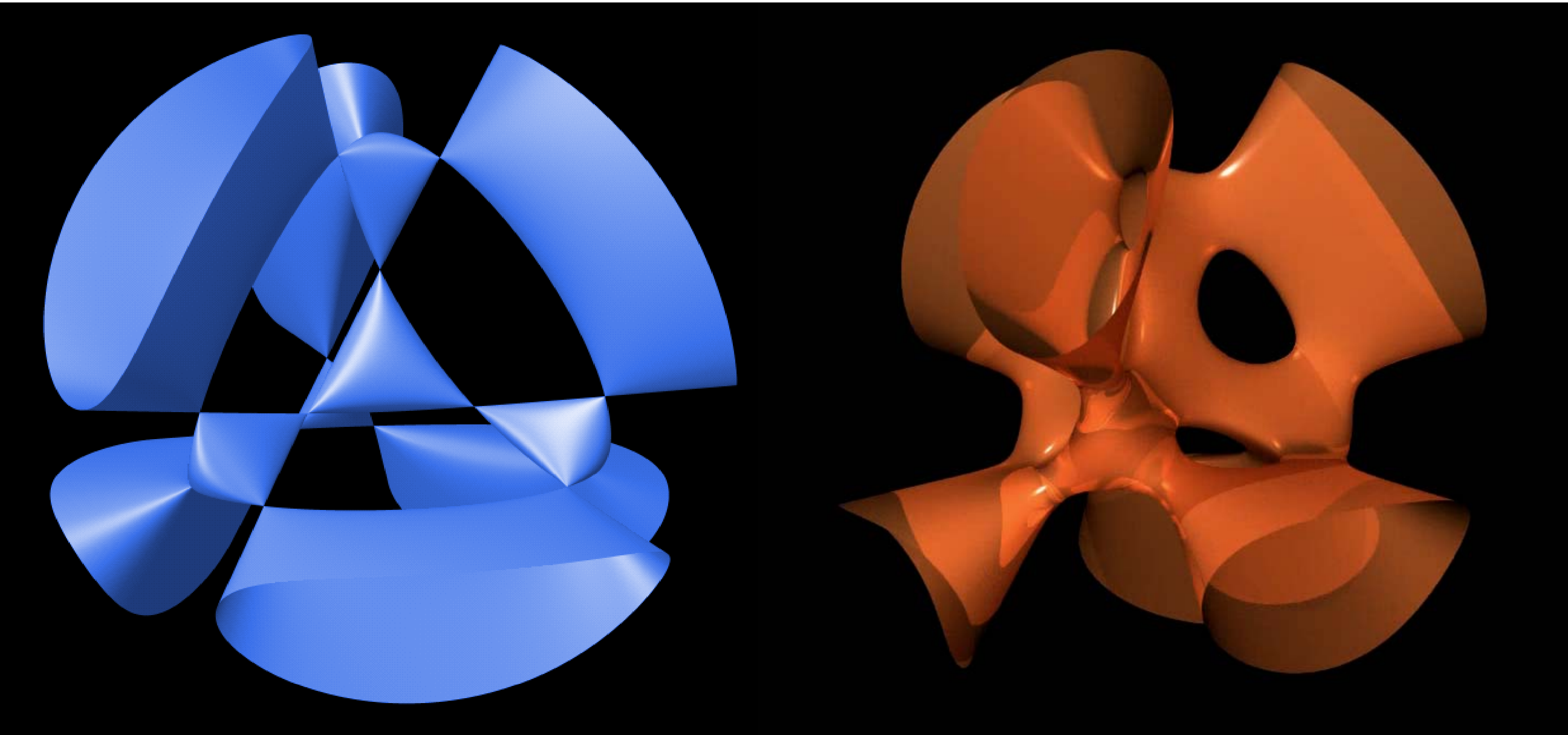
Axion is as step as the radial modulus. This is an obstruction to N-flation model of assisted inflation in known models of string theory

No detectable GW in models with stringy logarithmic Kähler potentials

Type IIB string theory on K3 x $\frac{T^2}{\mathbf{Z}_2}$ orientifold

Aspinwall, R. K. , 2005

- **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

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

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

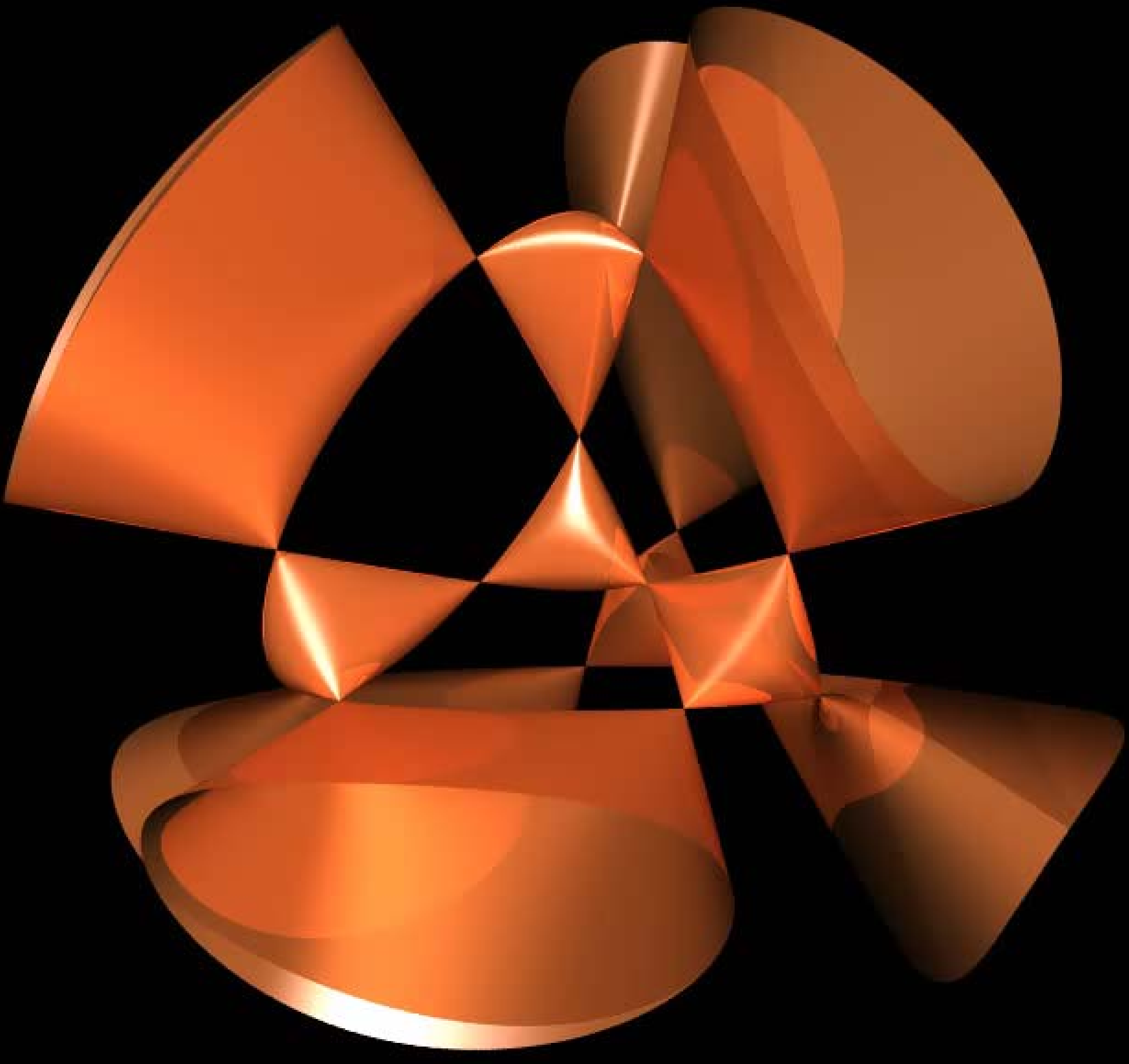
At fixed T and $x_0 + \bar{x}_0 = v$

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

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

Small $x_i + \bar{x}_i$

Will this string theory model provide
the axion valley potential predicting GW?
Work in progress.



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

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

- 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, superheavy, 10^{13} GeV

KL models or need new ideas Racetrack, LVC, … Inflation,