Supersymmetry, String Theory and Cosmology

P A C I F I C 2011

Renata Kallosh

Stanford

Outline

- How current and future observations in cosmology and experiments in particle physics have affected and will affect our understanding of `foundations' of theoretical physics

- String cosmology

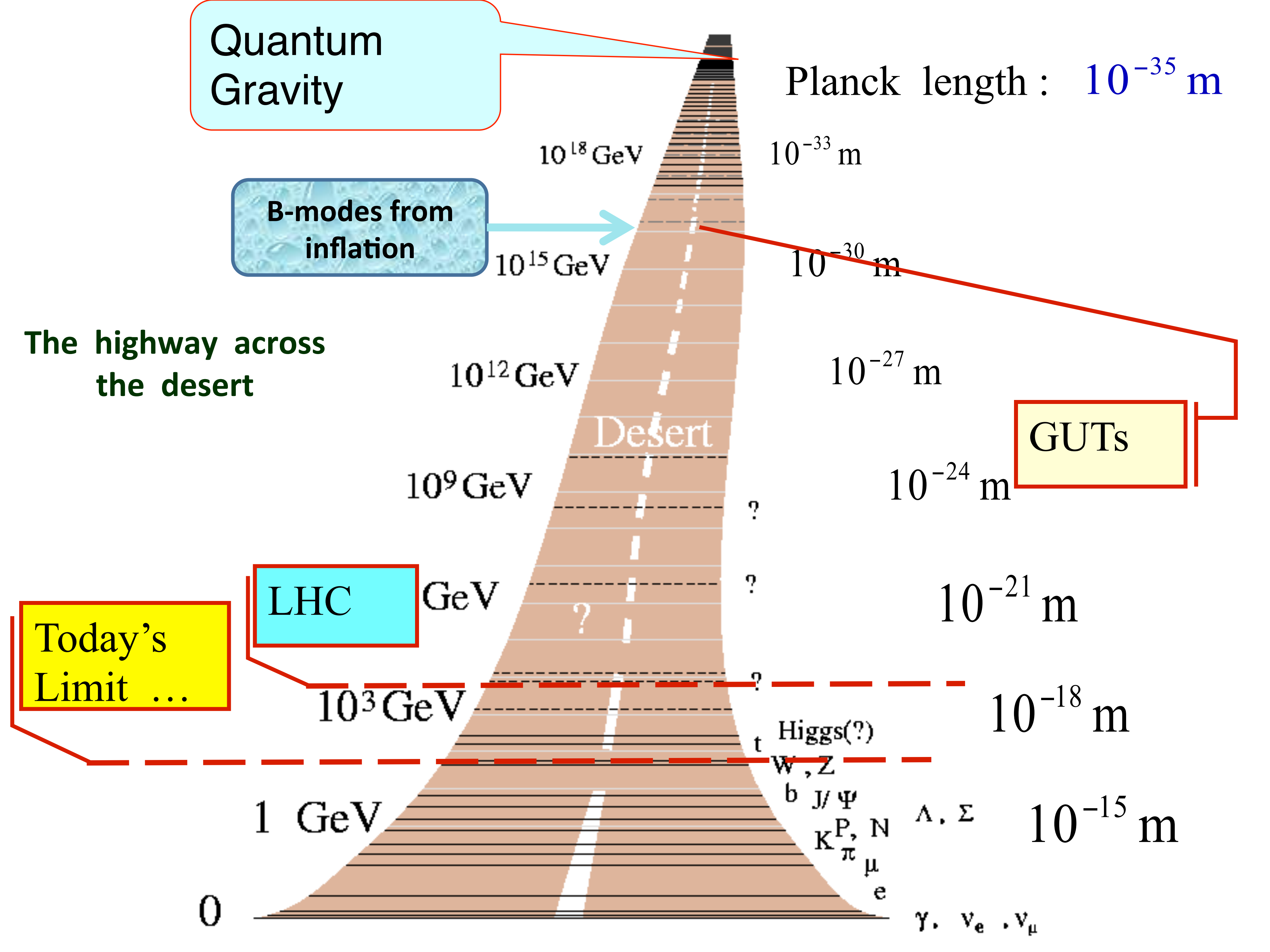
  String Landscape and the issue of Cosmological Constant

  B-modes and Gravitino

  Cosmic strings?

- Higgs Inflation and supersymmetry
- Supergravity with generic inflaton potential: ready for any n_s and r

- Recent dramatic progress in N=8 four-dimensional supergravity



Quantum Gravity
Planck length : 10^−35 m
10^18 GeV
10^−33 m
B-modes from inflation
10^15 GeV
10^−30 m
The highway across the desert
10^12 GeV
10^−27 m
Desert
GUTs
10^9 GeV
10^−24 m
?
LHC
GeV
?
10^−21 m
?
?
Today's Limit …
10^3 GeV
10^−18 m
Higgs(?)
t
W, Z
b
J/Ψ
Λ, Σ
1 GeV
K
P,
N
π
10^−15 m
μ
e
0
γ, νe, νμ

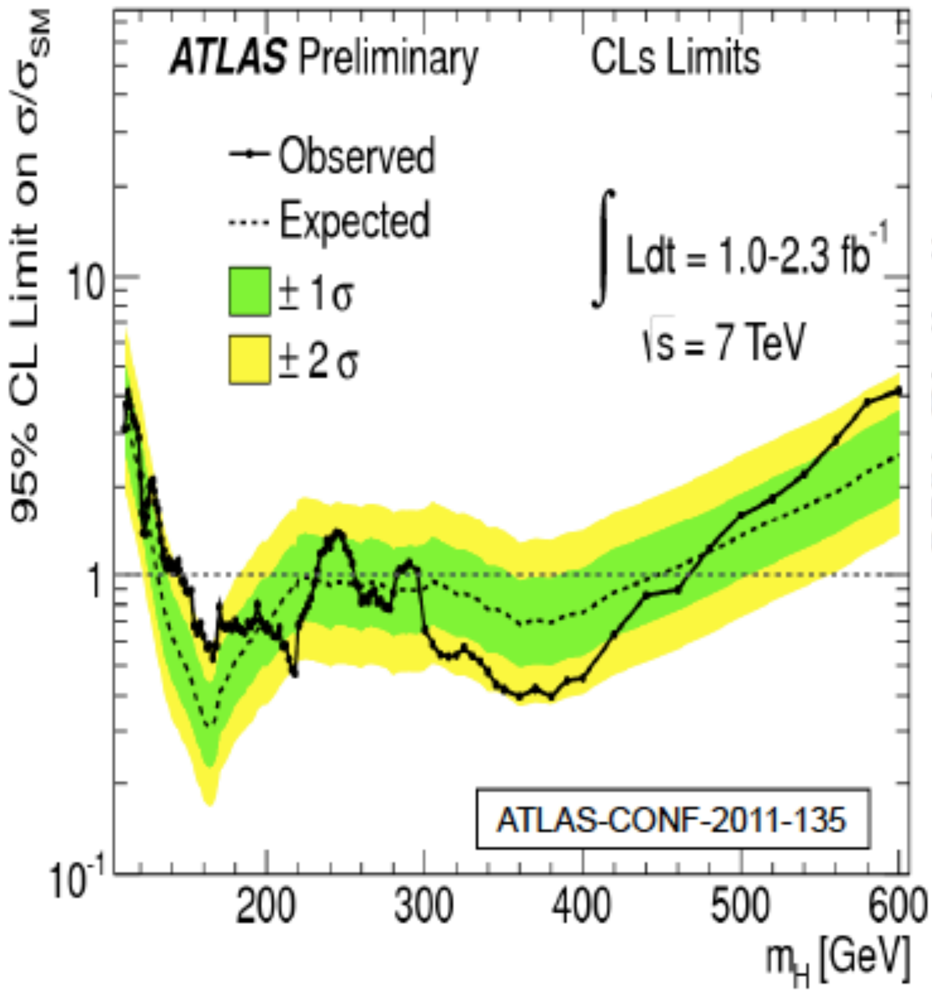
LHC Seminar
Higgs searches with CMS
by Marco Zanetti (Massachusetts Inst. of Technology (US))
Monday 12 September 2011 from **11:00** to **12:00** (Europe/Zurich)
at CERN
Description

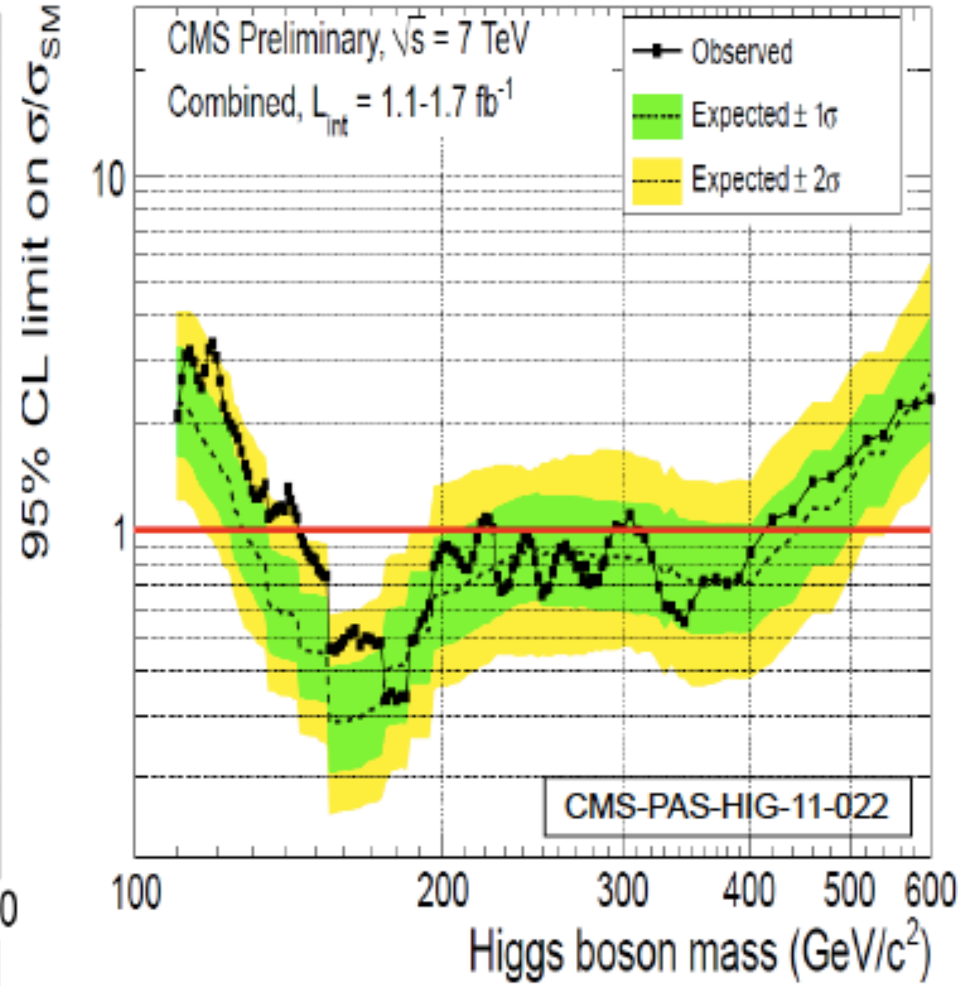
The excellent performances of the LHC in the 2011 run are setting the grounds for the final chase of the Higgs boson.

We probed the entire possible Higgs mass spectrum, from 110 to 600 GeV

The data places already tight limits and excludes large fractions of the Higgs mass range, leaving however still open the search in the theoretically favored low mass region.

Status of Lepton Photon Conference Mumbai, 22nd Aug 2011





95% CL exclusions SM Higgs mass ranges (GeV)

	ATLAS	CMS
Expected	**131 – 447**	**130 – 447**
Data	**146 – 232, 256 – 282, 296 – 466**	**145 – 216, 226 – 288, 310 - 400**

IF SUPERSYMMETRY 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

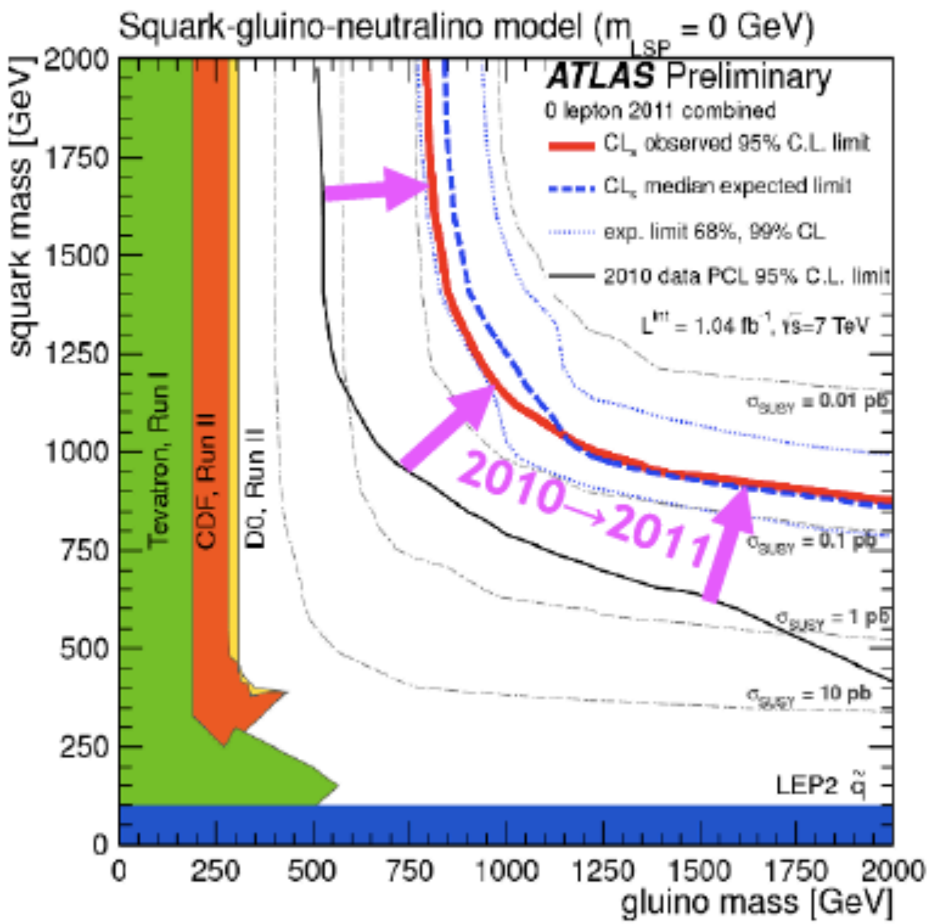
$$(t, \vec{x}) \to (t', \vec{x}') \Longrightarrow x^\mu \to (x^\mu)'$$

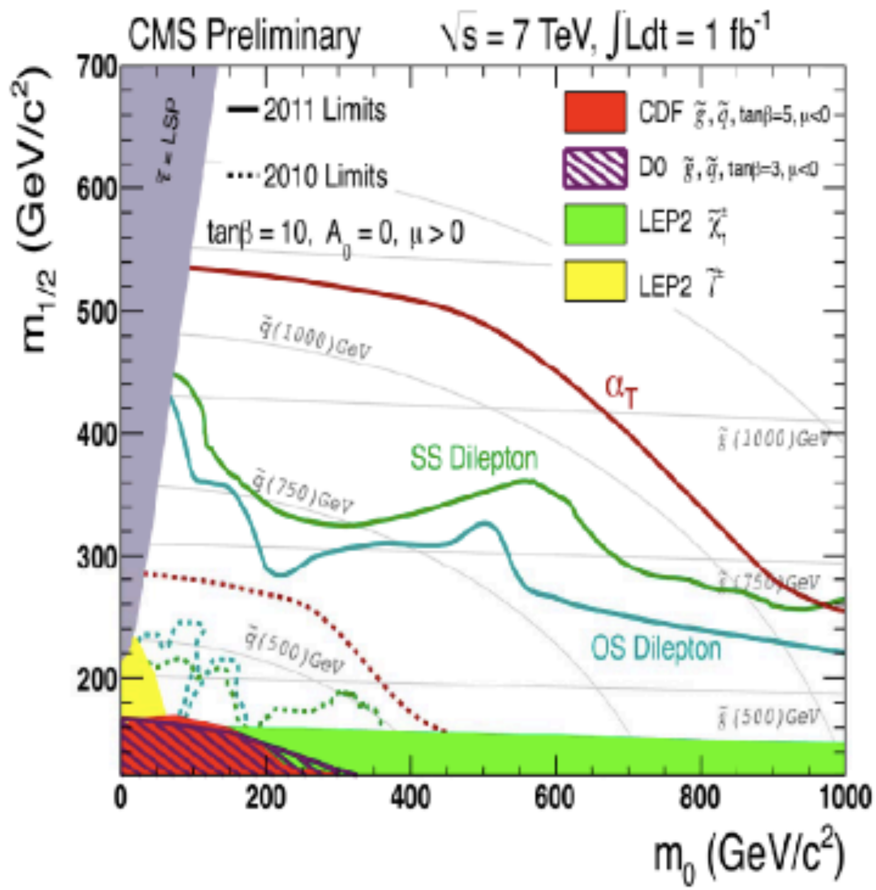
SUPERSYMMETRY

$$(x^\mu, \theta_\alpha) \to ((x^\mu)', \theta'_\alpha) \Longrightarrow Z^M \to (Z^M)'$$

Gravity ⟶ **Supergravity/String theory**

Sample SUSY exclusion limits as presented by ATLAS and CMS

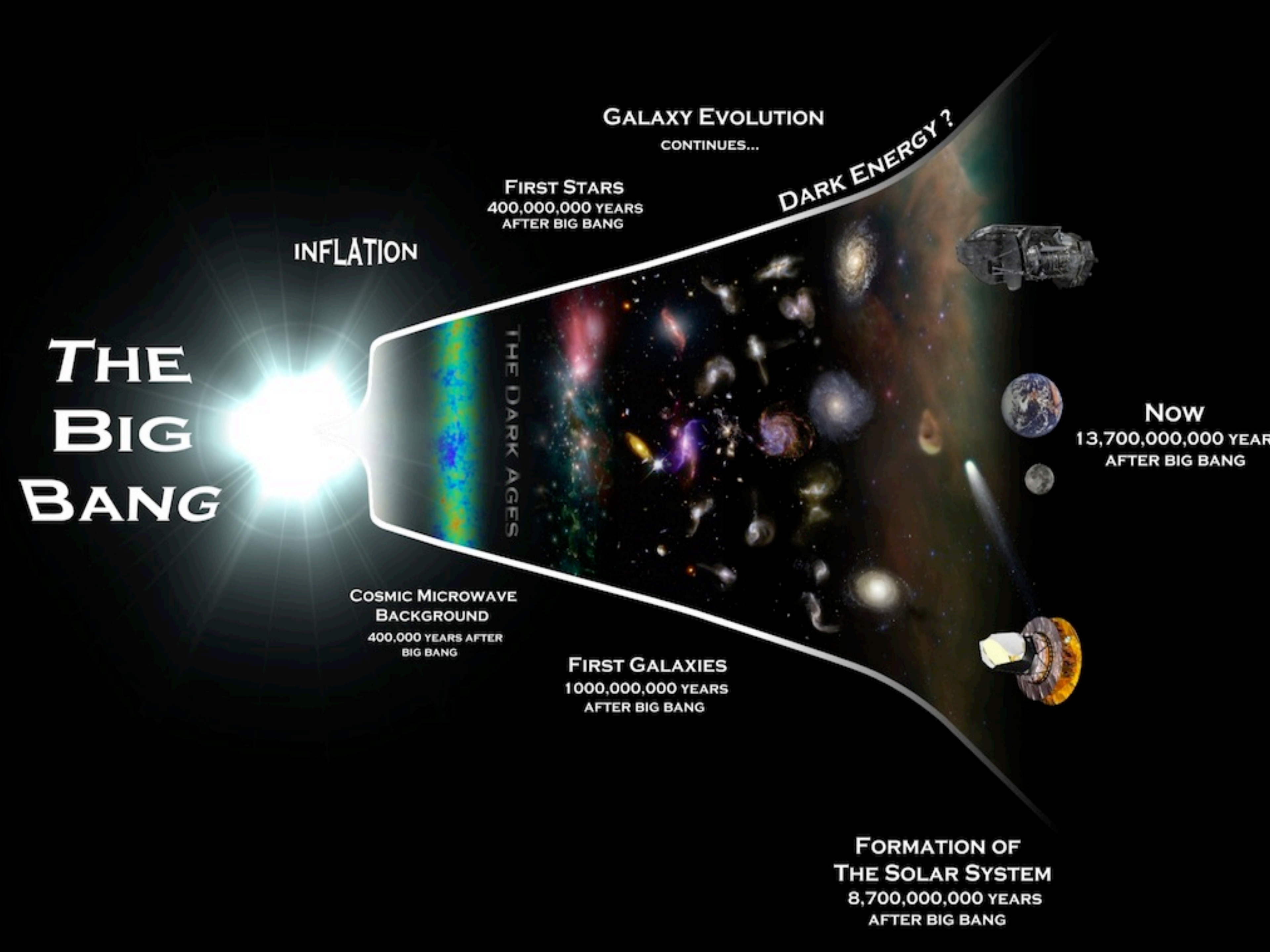




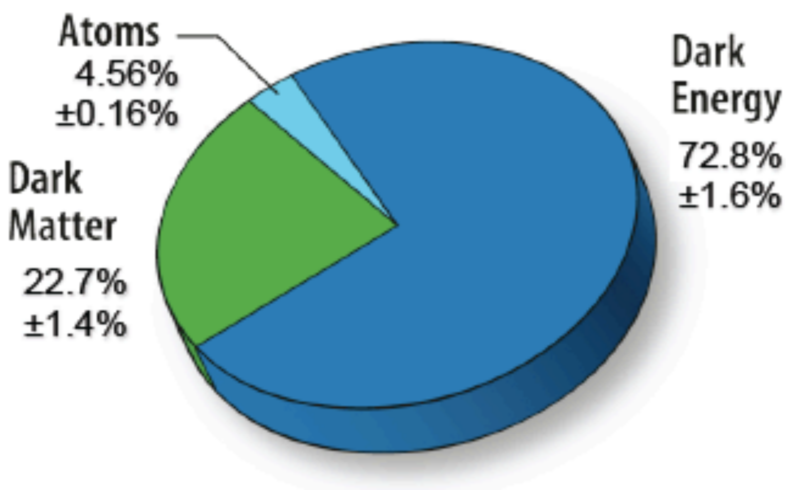
Simplified model with two q generations, $m(\chi_1^0)\sim 0$
m_g>800 GeV, m_q>850 GeV (valid for m_{LSP} < 200 GeV)
Equal mass case: $m_g=m_q$>1.075 TeV

α_T = 2[nd] jet E_T / Trans. Mass

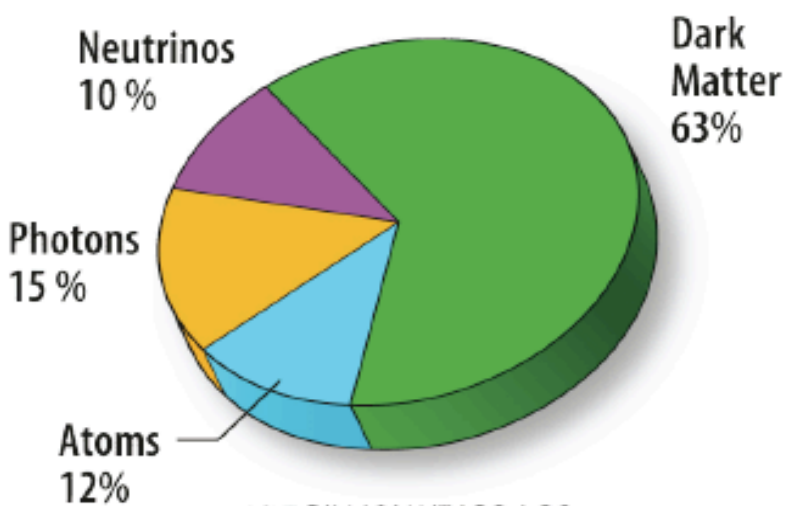
Desperately seeking SUSY


The Big Bang
Inflation
Cosmic Microwave Background
400,000 years after big bang
The Dark Ages
First Stars
400,000,000 years after big bang
First Galaxies
1000,000,000 years after big bang
Galaxy Evolution
continues...
Dark Energy ?
Formation of The Solar System
8,700,000,000 years after big bang
Now
13,700,000,000 YEAR
after big bang

ΛCDM – c. 2011



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Hubble –

$H_0 = 70.4 \pm 1.4$ km s^{-1} Mpc^{-1}

Age –

$t_0 = 13.75 \pm 0.11$ Gyr

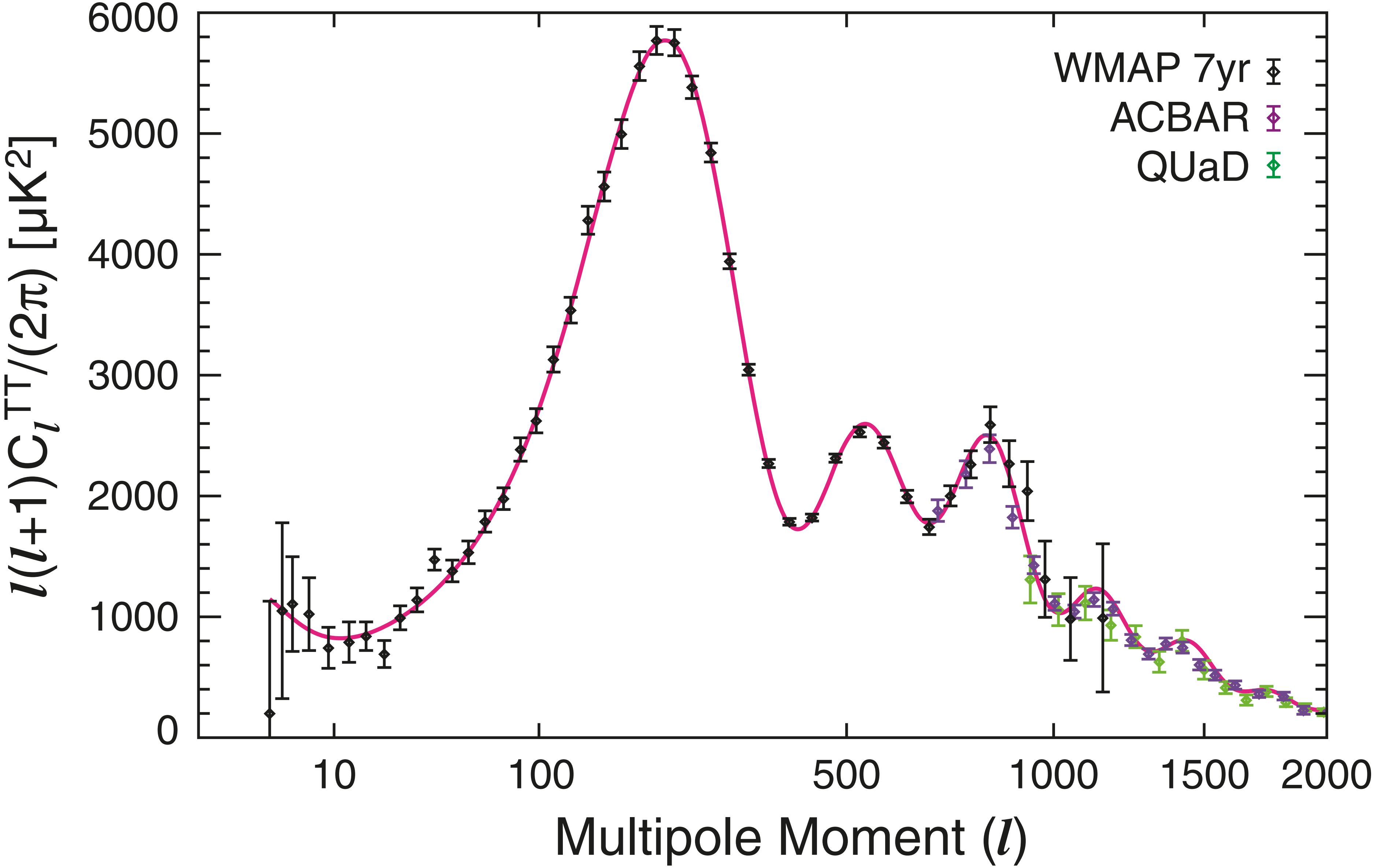
Cosmology: Next Decade?

- Astro2010: Astronomy & Astrophysics Decadal Survey
  - Report from *Cosmology and Fundamental Physics* Panel (Panel Report, Page T-3):

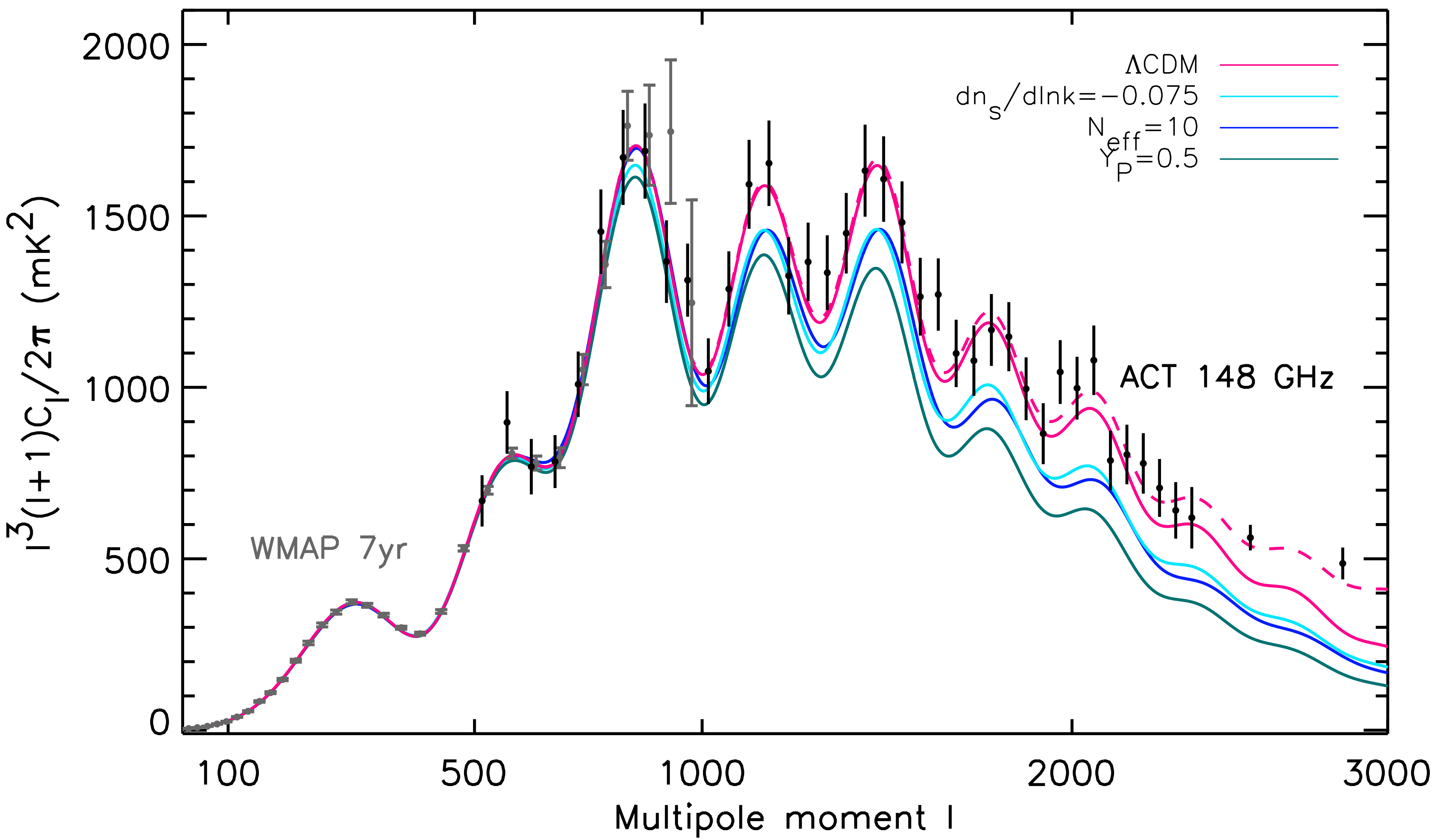
TABLE I Summary of Science Frontiers Panels' Findings

Panel		Science Questions
Cosmology and Fundamental Physics	CFP 1	How Did the Universe Begin?
	CFP 2	Why Is the Universe Accelerating?
	CFP 3	What Is Dark Matter?
	CFP 4	What Are the Properties of Neutrinos?

WMAP7 + Acbar + QUaD

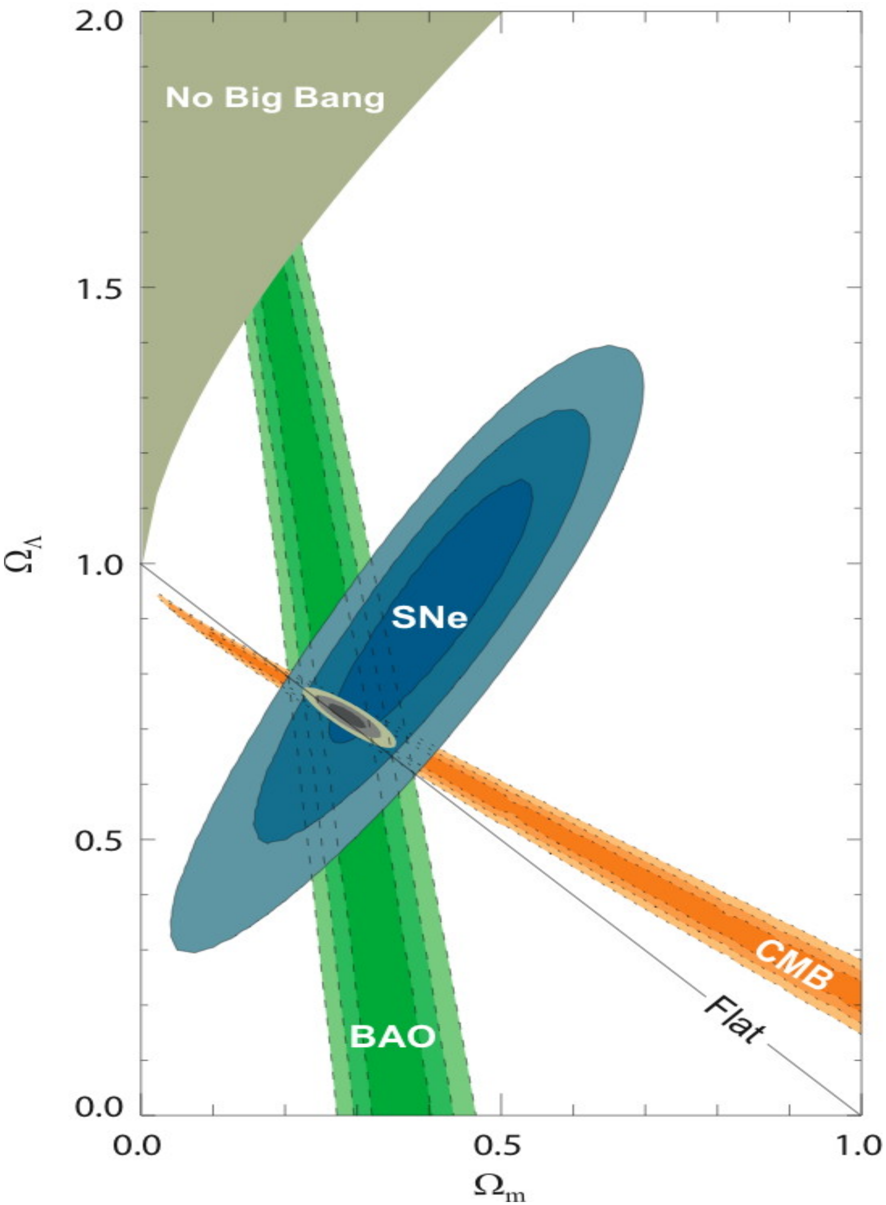


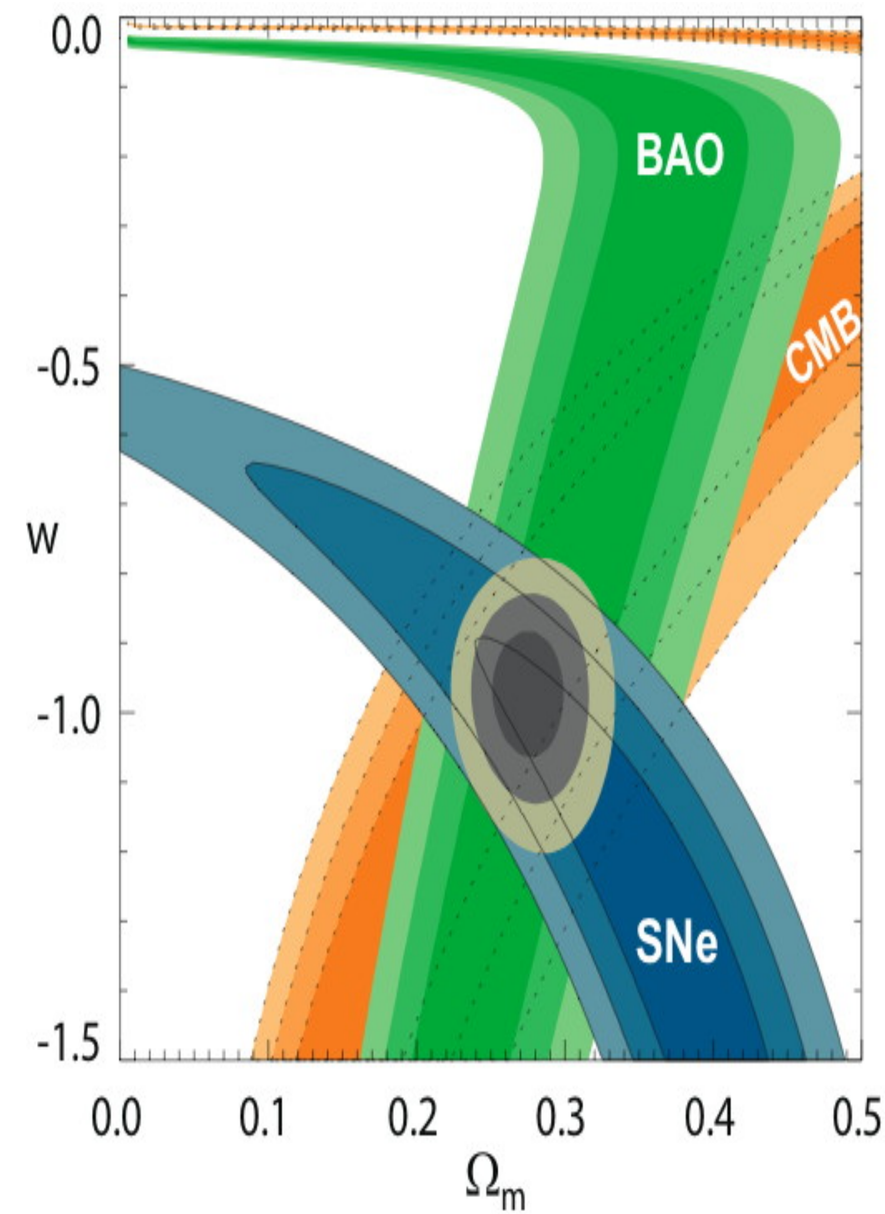
WMAP7 + Atacama



2008

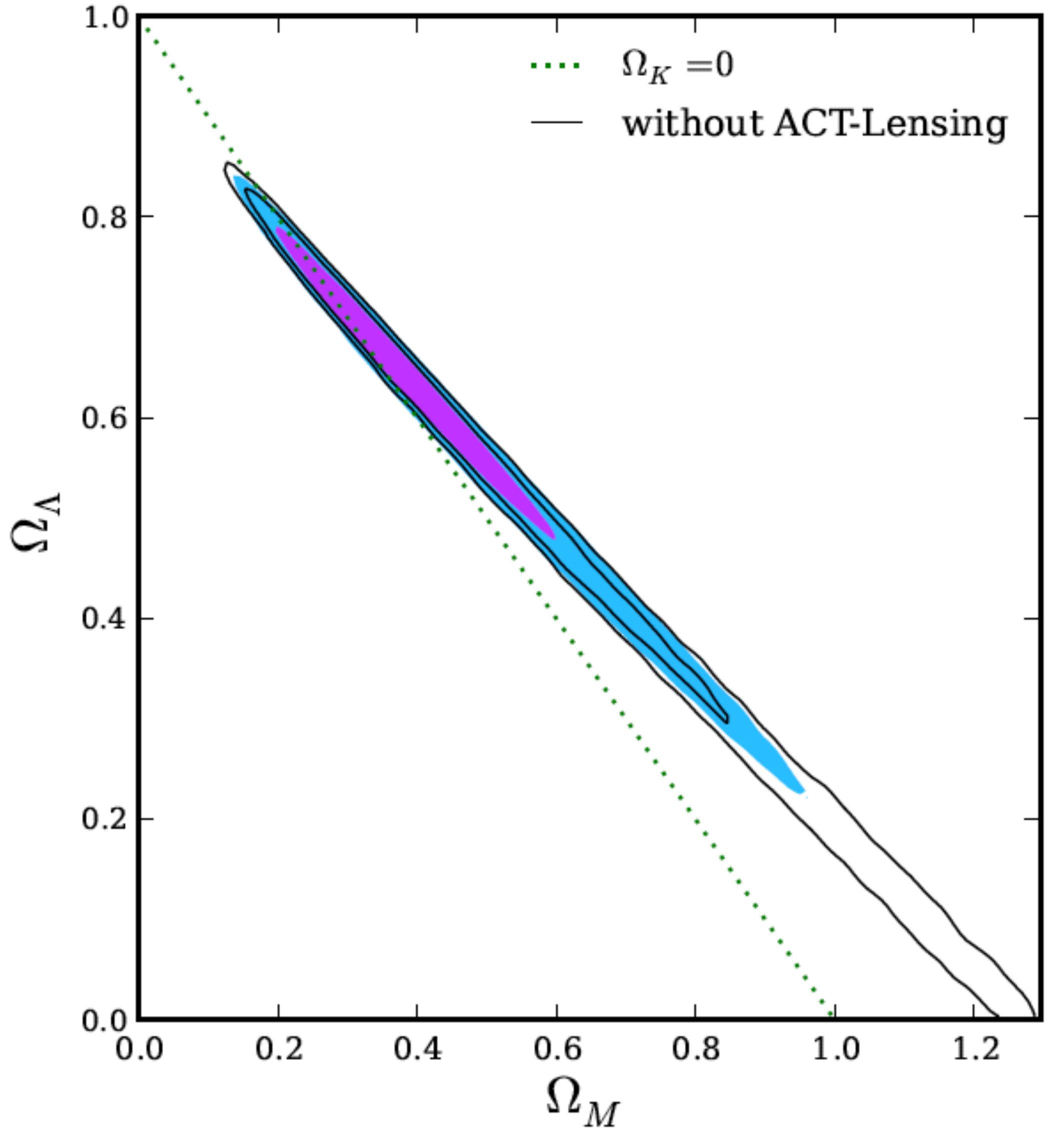
Concordance and simplicity: $\Omega = 1$, $w = -1$





Evidence for dark energy from the CMB alone

using the Atacama Cosmology Telescope lensing measurements

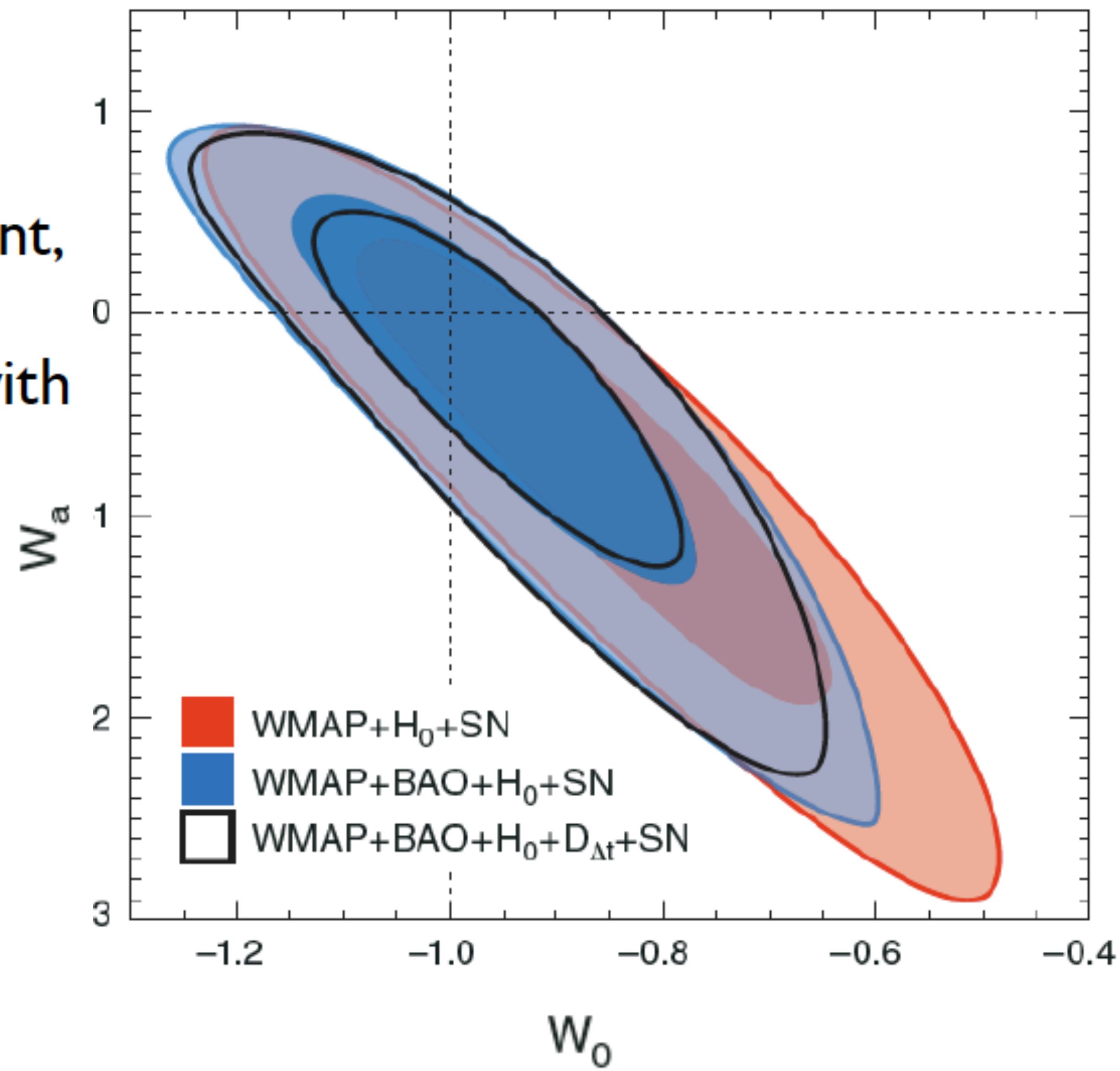


For the first time measurements of CMB alone favor cosmologies with w=-1 dark energy over models without dark energy at a 3.2-sigma level

August 2011

2011

- Cosmological constant, w_0=–1 and w_a=0, are perfectly consistent with data.



The unbearable lightness of space-time

Einstein's cosmological constant is the simplest explanation for dark energy and so far it fits all the data. It describes dark energy with equation of state w = -1.

Other explanations of dark energy based on modification of Einstein's gravity, are hard to make work and raise more questions than they answer.

But if dark energy is the cosmological constant, it is smaller than the theoretically predicted one by a shocking factor 10^{-120}

$$\Lambda \sim 10^{-120} \left(M_{Planck}\right)^4$$

No fundamental principles can explain why the cosmological constant, or any other physical parameter, could be so small without being zero.

Zero can be a fundamental number, due to some symmetries, but not a 1 with 120 zeroes between it and the decimal point.

String Theory Landscape

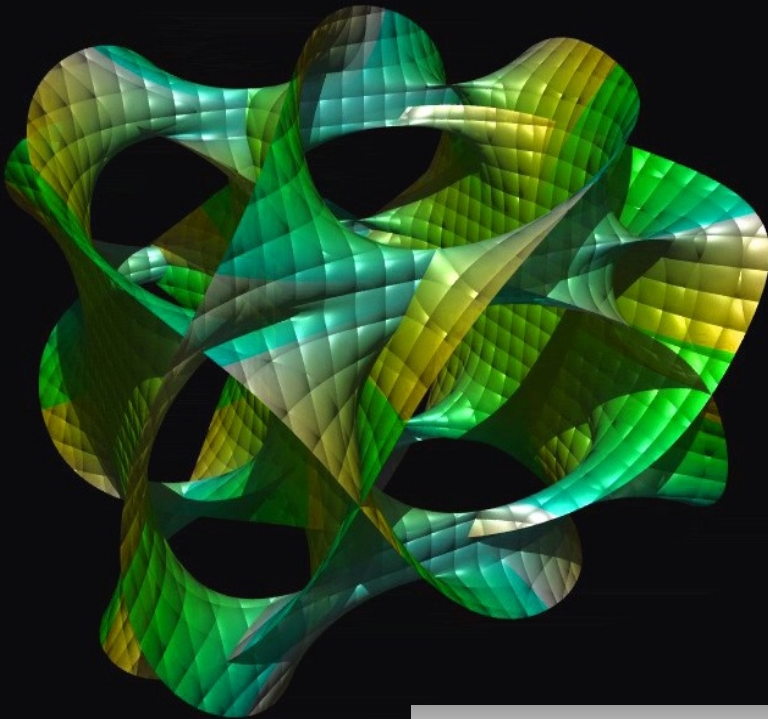
String Theory

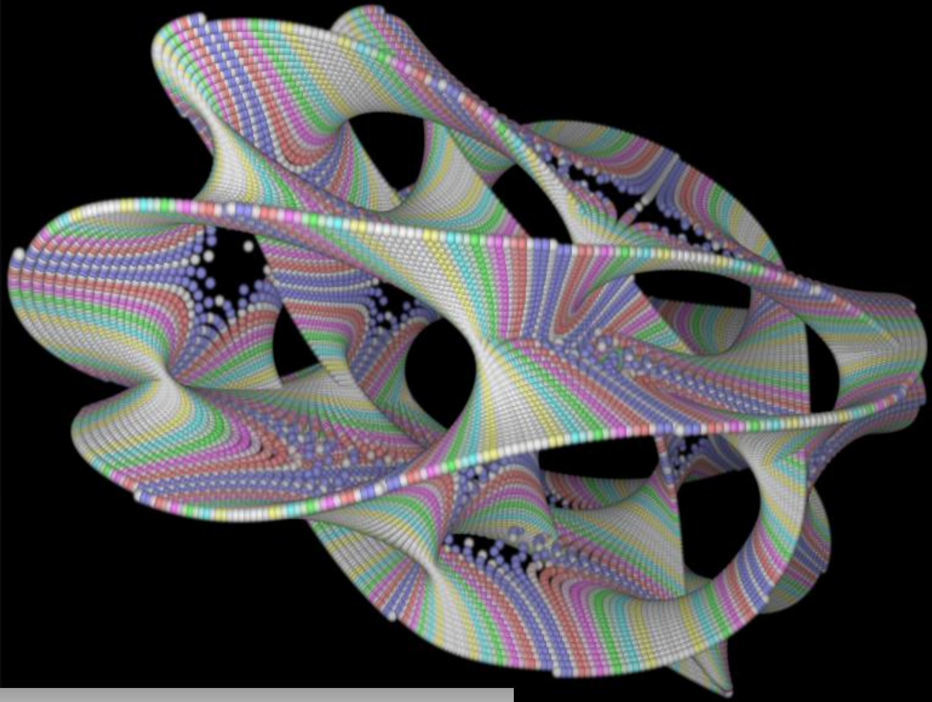
- String theory is the best known candidate for the theory of all interactions, including gravity.

- Since 1987 it was known that string theory has many (10^{500}-10^{1500}) solutions defining string theory vacua (Lerche, Lust, Schellekens 1987; Bousso, Polchinsky 2000). This was a source of embarrassment for string theory, attempting to explain our universe in the best traditions of the old paradigm: a dream to explain just one world we live in.

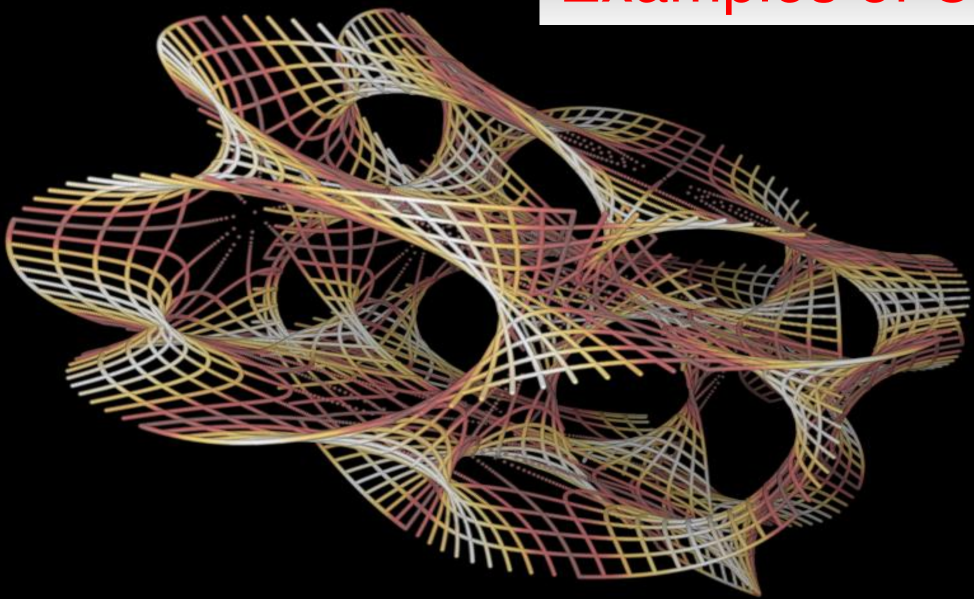
- However, all of these vacua were **unstable**, they had **negative** energy density, and therefore they could not describe our world. This problem became especially urgent when cosmologists found that the vacuum energy density (the cosmological constant) is **positive**.

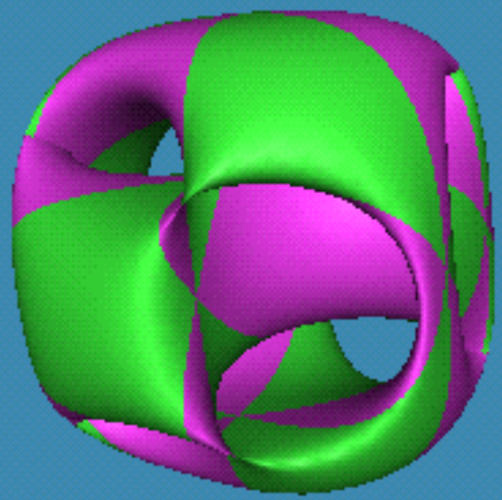
- This problem was resolved in 2003 in the **KKLT scenario based on many other efforts of string community in this direction**.





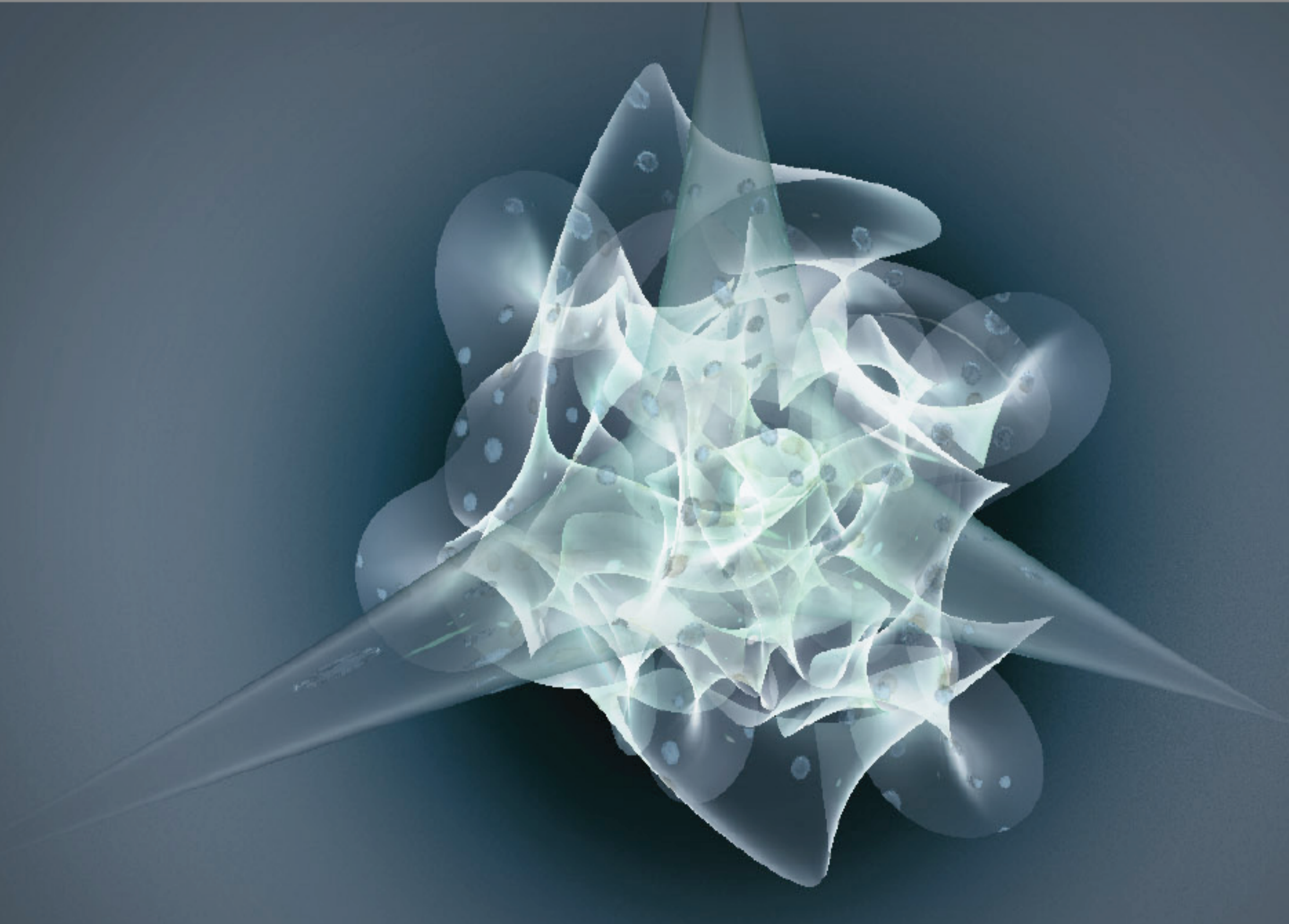
Examples of Calabi-Yau 3-folds





Other moduli: size of cycles

ALL MODULI STABILISED !



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

String Theory Landscape

Solving the cosmological constant problem

Among 10^{500} vacua one can always find many vacua with vacuum energy smaller than 10^{-120}. We cannot live in the vacua with vacuum energy much greater than 10^{-120}.

Thus a combination of inflationary theory, string theory and anthropic reasoning can solve the cosmological constant problem.

At the moment, we do not have any alternative solutions.

Inflation in string theory

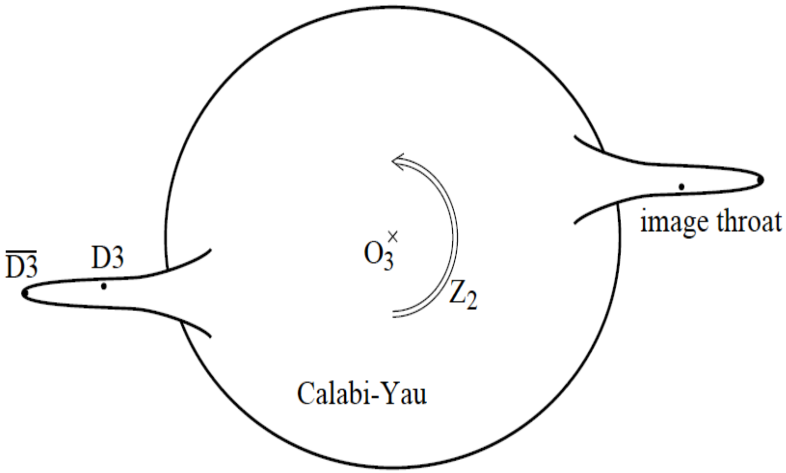
To produce a reasonable cosmology in string theory it was **necessary to stabilize all moduli but the inflaton (or two, for non-gaussianity)**. In 4d theory such moduli are scalar fields. In string theory and supergravity they often have physical and geometrical meaning as volumes of extra dimensions and various cycles in topologically non-trivial extra dimensions. The inflaton can also be related to a distance between branes.

Brane inflation

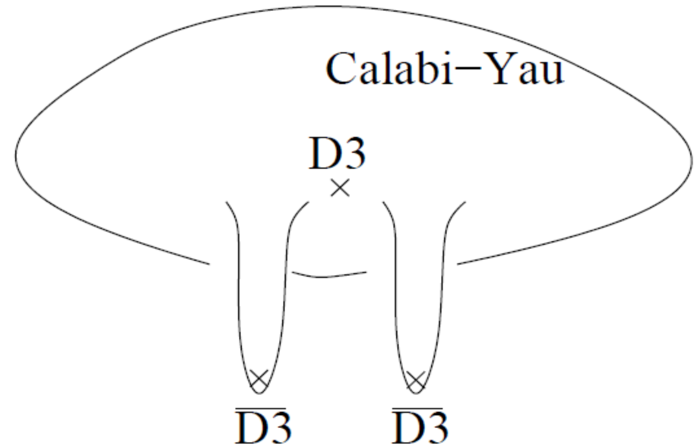
Modular inflation

Brane inflation with monodromy

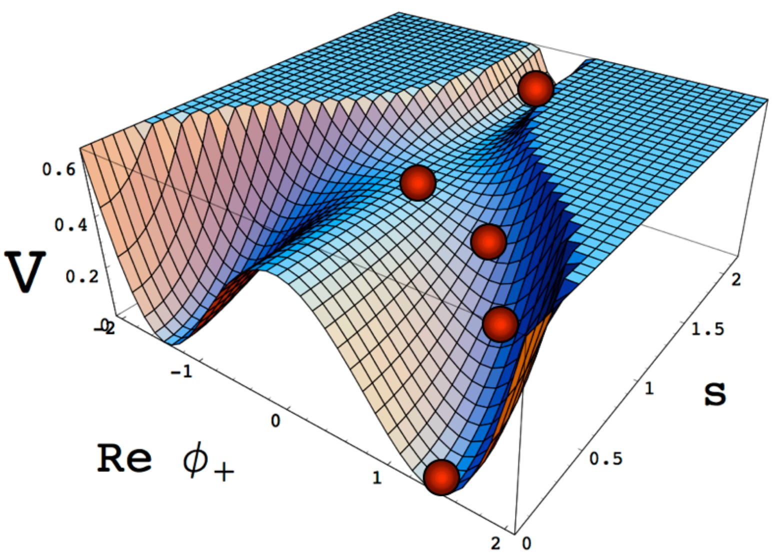
Brane Inflation in string theory



KKLMMT brane-anti-brane inflation



Two-throat model



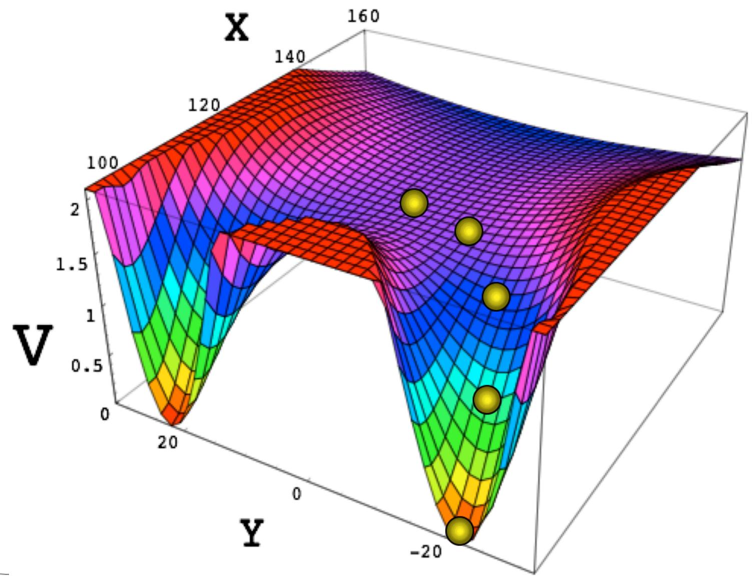
Hybrid D3/D7 brane inflation

(Stringy D-term inflation)

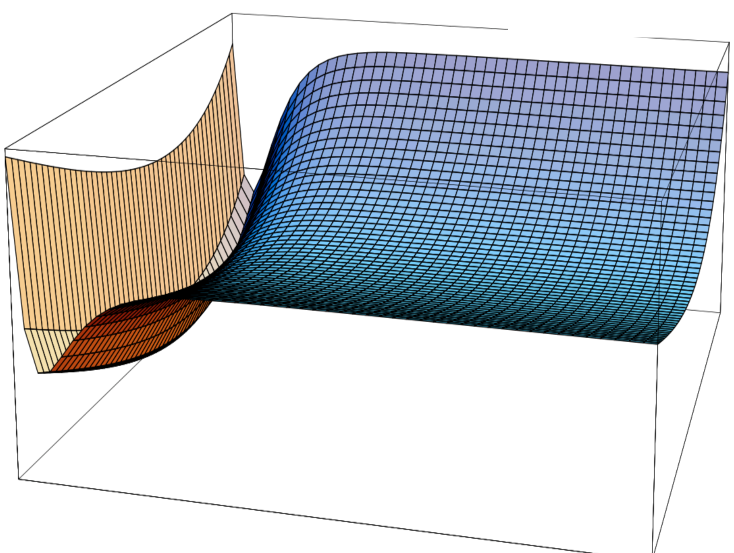
Dirac-Born-Infeld inflation

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

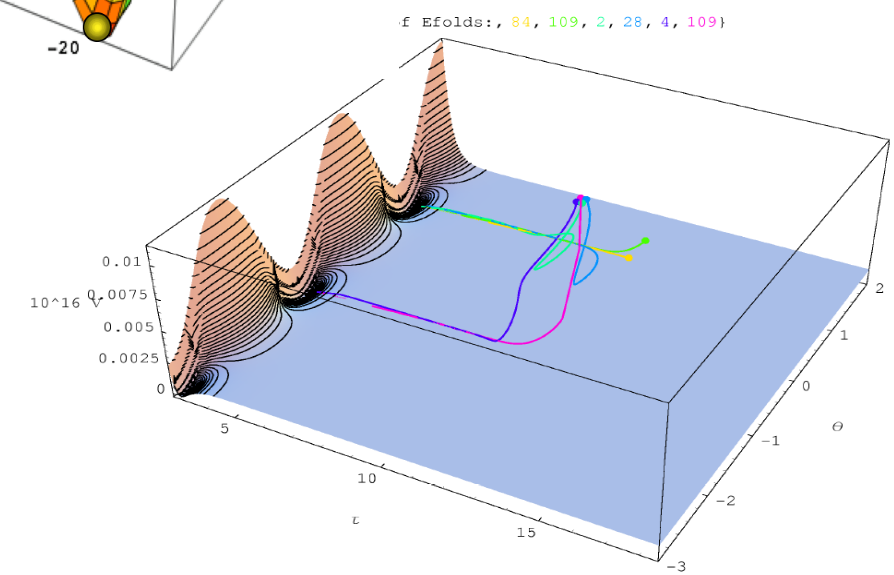
Modular Inflation models



Racetrack inflation



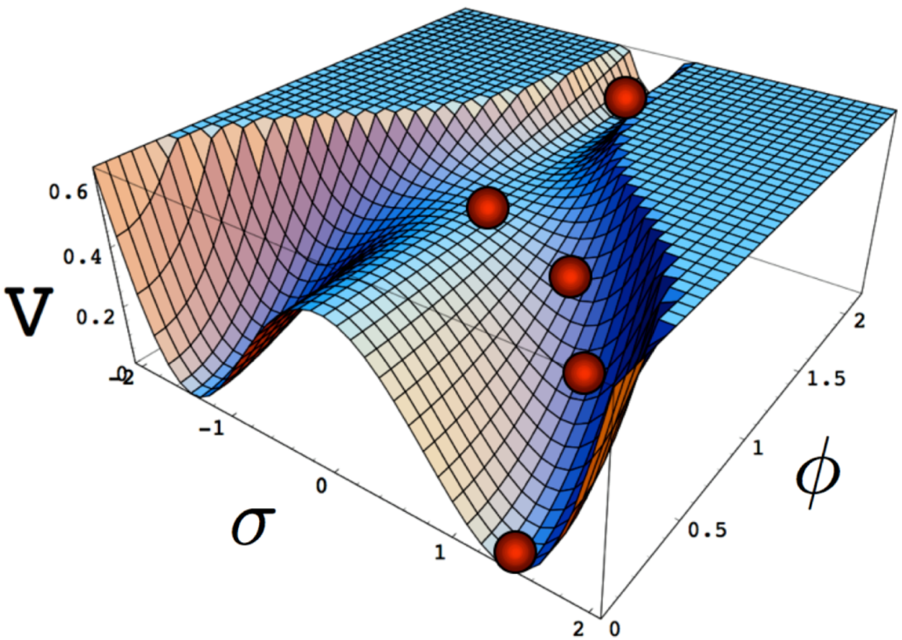
Kahler modular inflation

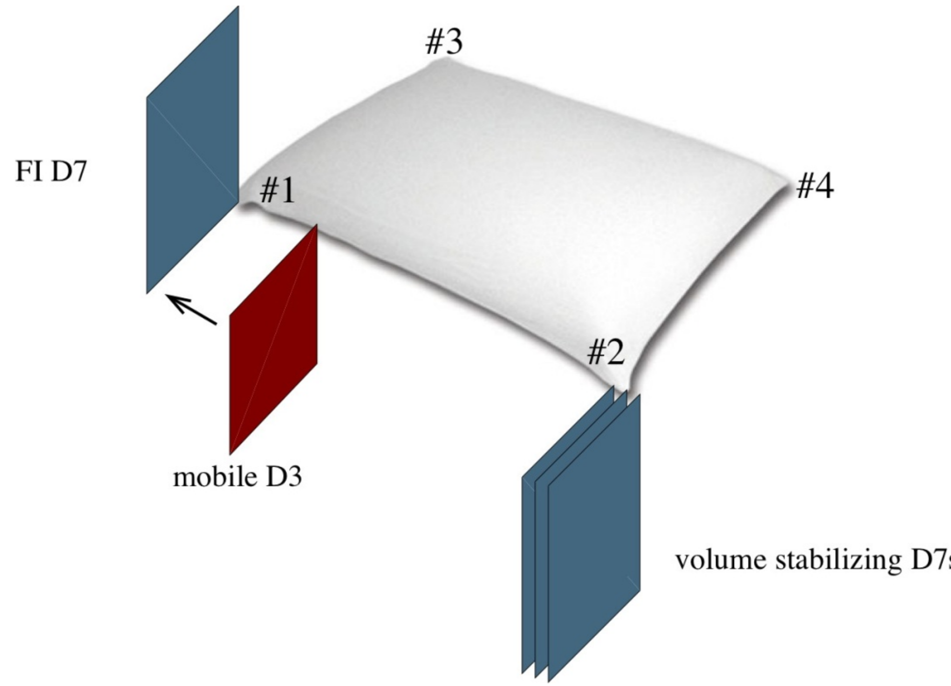


Roulette inflation

D3/D7 hybrid inflation

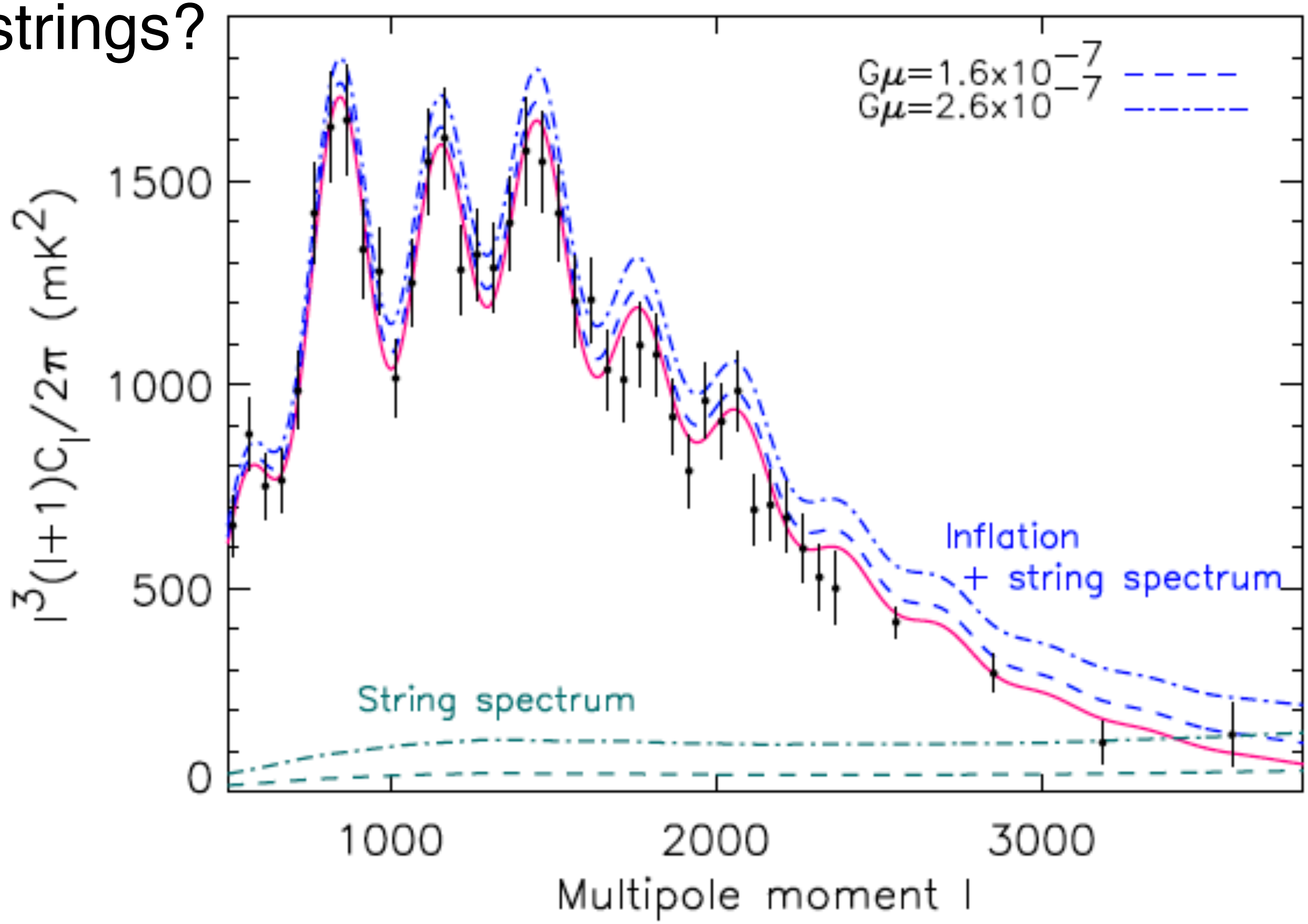
Haack, RK, Krause, Linde, Lust, Zagermann 2008





Stringy version of the D-term inflation. Naturally flat inflaton direction, string theory corrections under control, eternal inflation regime, a controllably small amount of cosmic strings.

Cosmic strings?



ATACAMA, 2010

Models with cosmic strings overpredict the observed power for $1500 < l < 4000$

August 2011, Hindmarsh et al

Update of the constraints on the cosmic string tension by CMB data, enabled both by the use of new, high-resolution CMB data and by improved predictions for the impact of Abelian Higgs cosmic strings on the CMB power spectra.

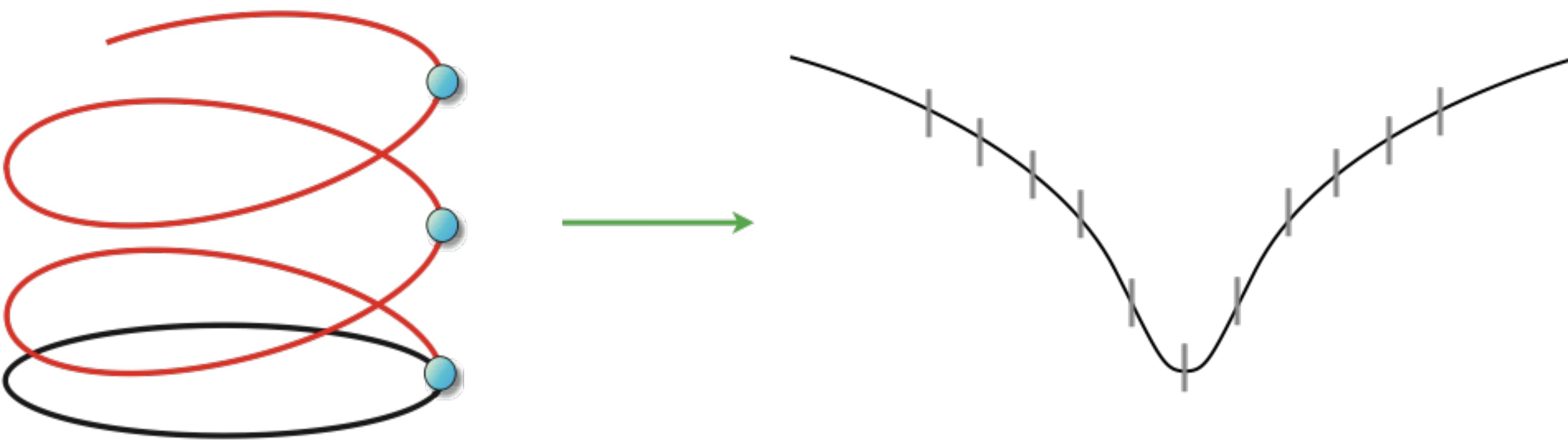
Using all the CMB data, a scale invariant initial perturbation spectrum, $n_s = 1$, is now disfavoured at 2.4σ even if strings are present. A Bayesian model selection analysis no longer indicates a preference for strings.

central idea ...

Silverstein, Westphal, 2008, McAllister, Silverstein, Westphal 2008

- unwind a periodic field direction into a *monodromy*

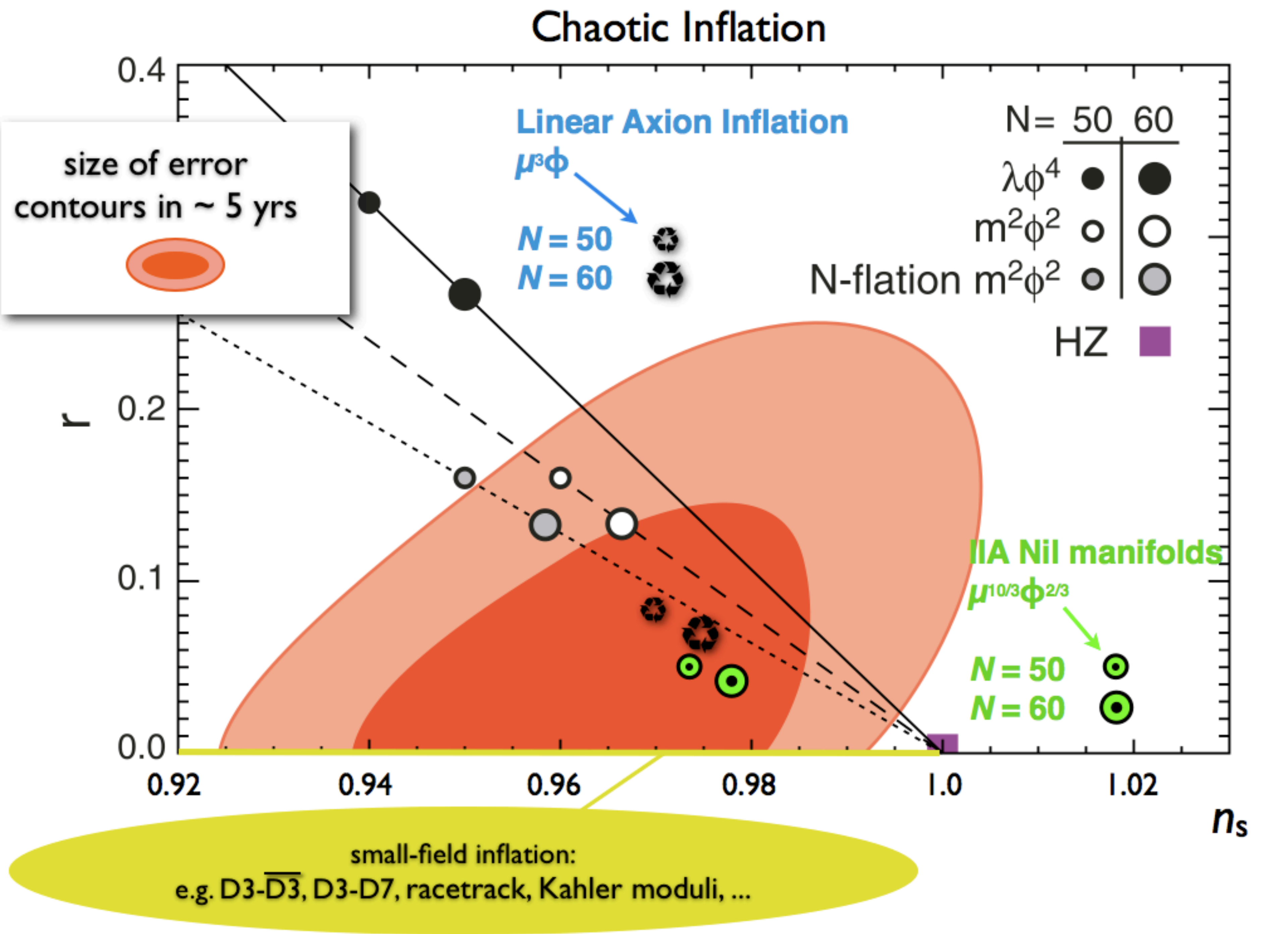
→ e.g. by employing a wrapped brane



Type IIA string

$$\mathbf{V}(\phi > \mathbf{M_P}) \sim \begin{cases} \phi^{2/3}\,, & \text{moving D4} - \text{brane in a Nil manifold} \\ \phi\,, & 2 - \text{form axions on a } 5 - \text{brane} \end{cases}$$

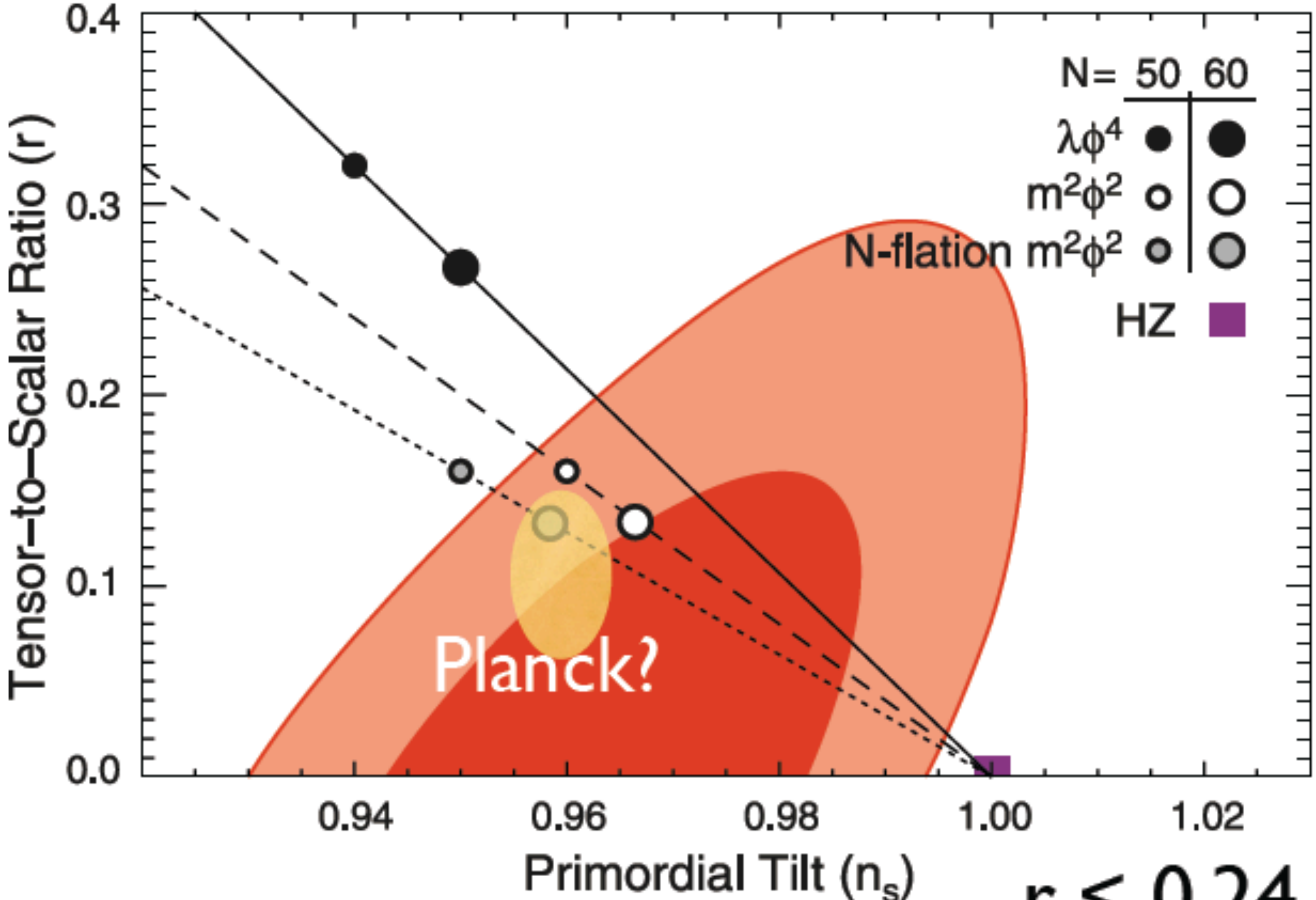
Type IIB,



Chaotic Inflation
size of error contours in ~ 5 yrs
Linear Axion Inflation
$\mu^3\phi$
$N = 50$
$N = 60$
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
HZ
IIA Nil manifolds
$\mu^{10/3}\phi^{2/3}$
$N = 50$
$N = 60$
r
0.4
0.2
0.1
0.0
0.92
0.94
0.96
0.98
1.0
1.02
n_s
small-field inflation:
e.g. D3-$\overline{\text{D3}}$, D3-D7, racetrack, Kahler moduli, ...

Probing Inflation

2011



$r < 0.24$ (95%CL)

Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.

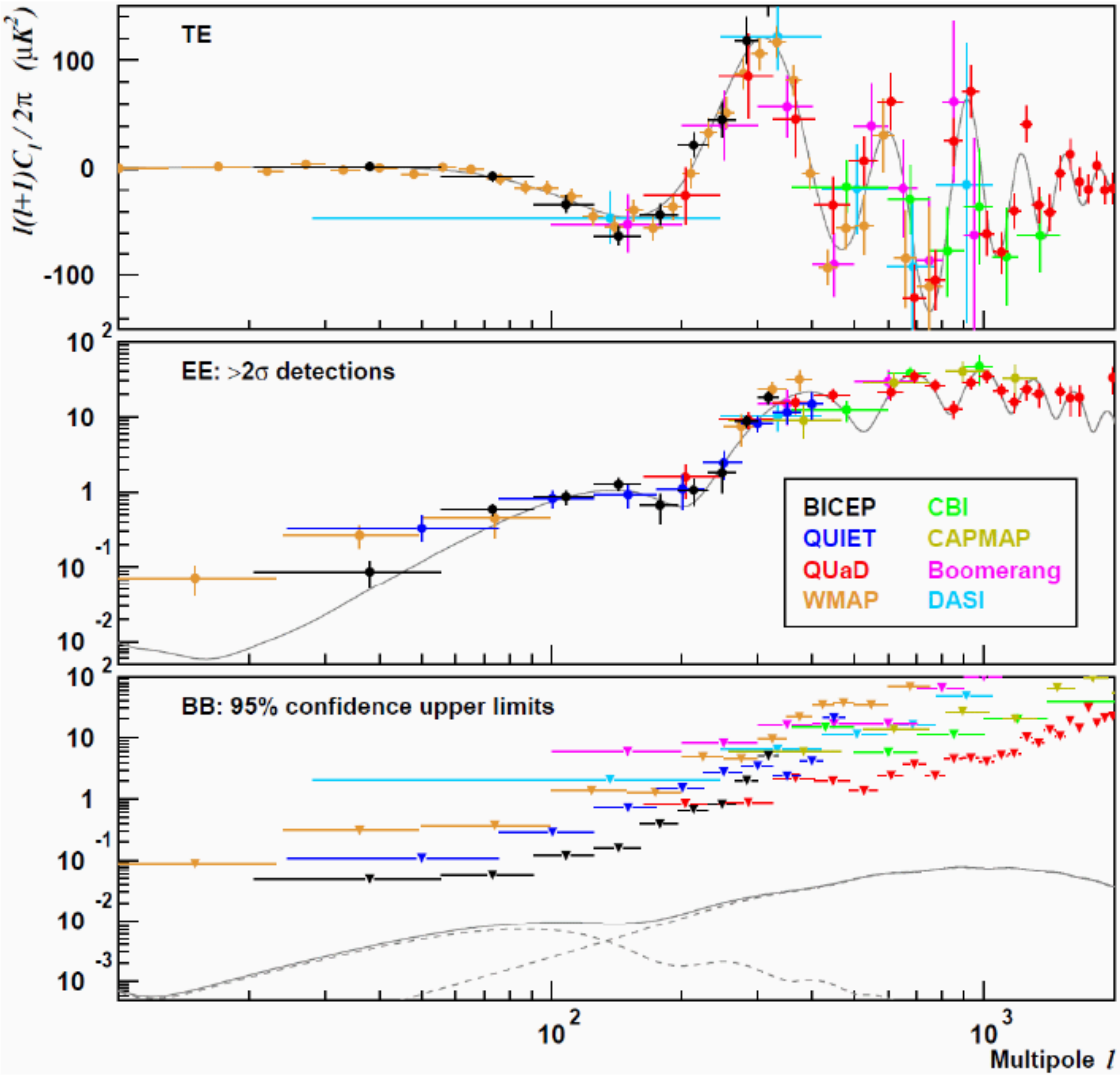
$n_s=0.968\pm0.012$ (68%CL)

The search for B-modes

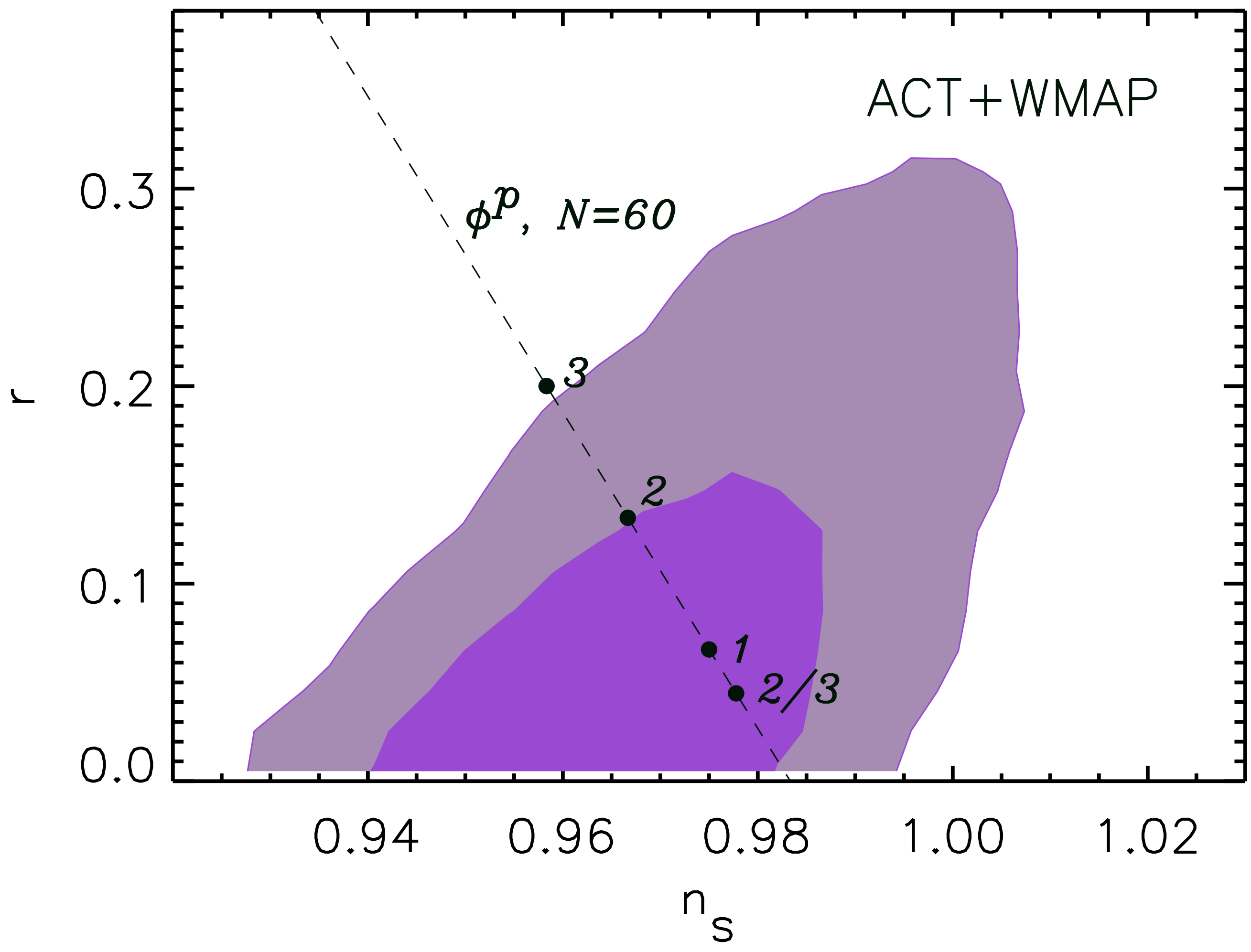
- Inflation generates a tensor mode perturbation whose amplitude is proportional to the energy scale of inflation

- There is a real hope for improving the sensitivity on T/S by nearly 2 orders of magnitude during the next 3-10 years

Experimental measurements, as of 07/2011



WMAP7 + Atacama



Harrison-Zeldovich $n_s = 1$ excluded at 99.7% CL (3 sigma)

Our goal is to develop a theoretical framework which would give us maximal flexibility to describe upcoming observational data in the context of supergravity/string theory motivated models:

1) Functional freedom in the choice of the potential, to adjust n_s and r.
2) The possibility to go beyond the single-field models to describe a possible non-gaussianity, to tune f_{NL}.
3) Solving the cosmological moduli problem and the gravitino problem

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 Kahler 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…

Kawasaki, Yamaguchi, Yanagida 2000

More general models

RK, Linde 1008.3375, RK, Linde, Rube,1011.5945

$$W = S\, f(\Phi)$$

The Kahler potential is any function of the type

$$\mathcal{K}((\Phi - \bar{\Phi})^2,\, S\bar{S})$$

The potential as a function of the real part of Φ at S = 0 is

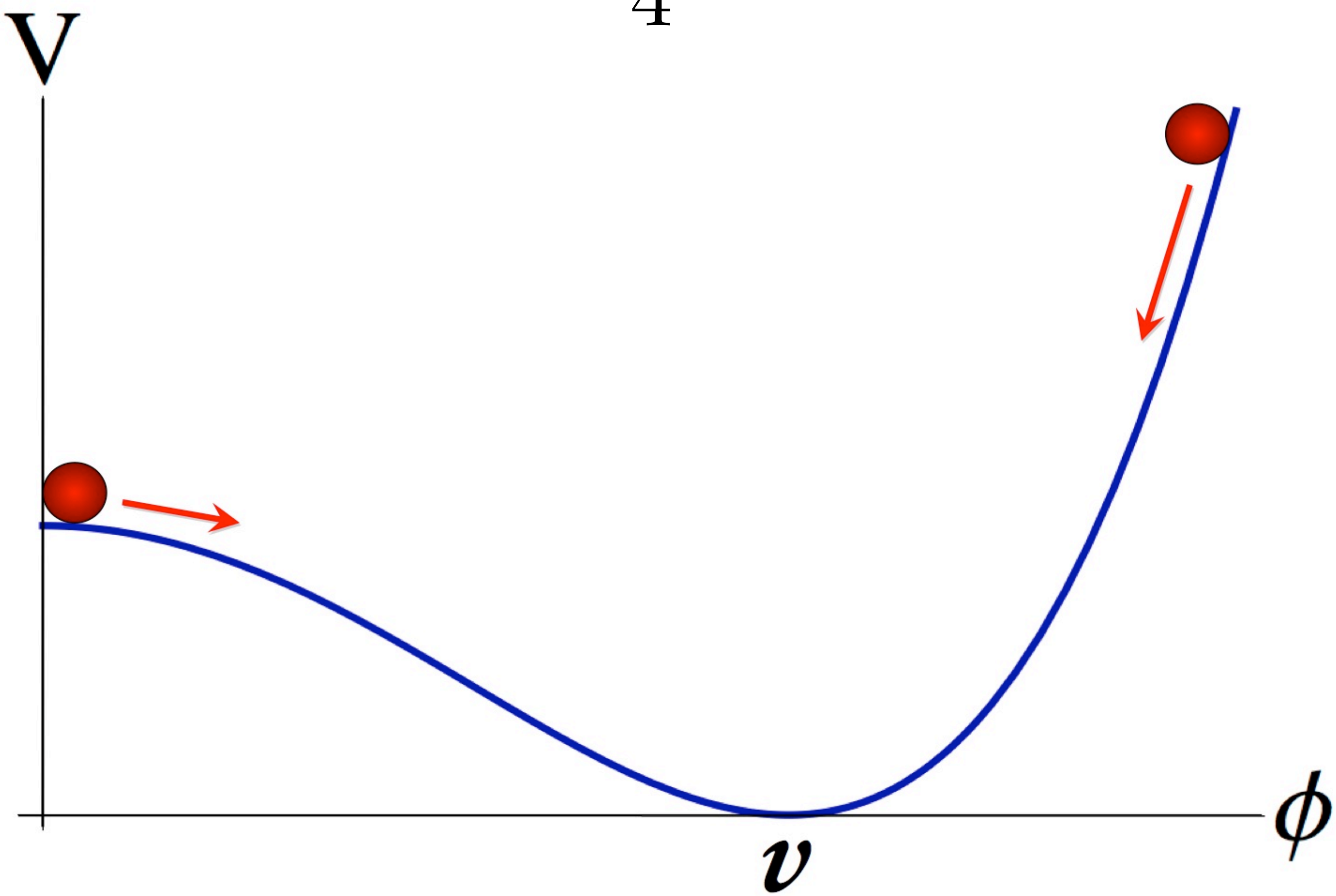
$$V = |f(\Phi)|^2$$

FUNCTIONAL FREEDOM in choosing inflationary potential

Example: $W = -\lambda S(\Phi^2 - v^2/2)$

During inflation $S = 0,\ \mathrm{Im}\,\Phi = 0,\ \mathrm{Re}\,\Phi = \sqrt{2}\,\phi$

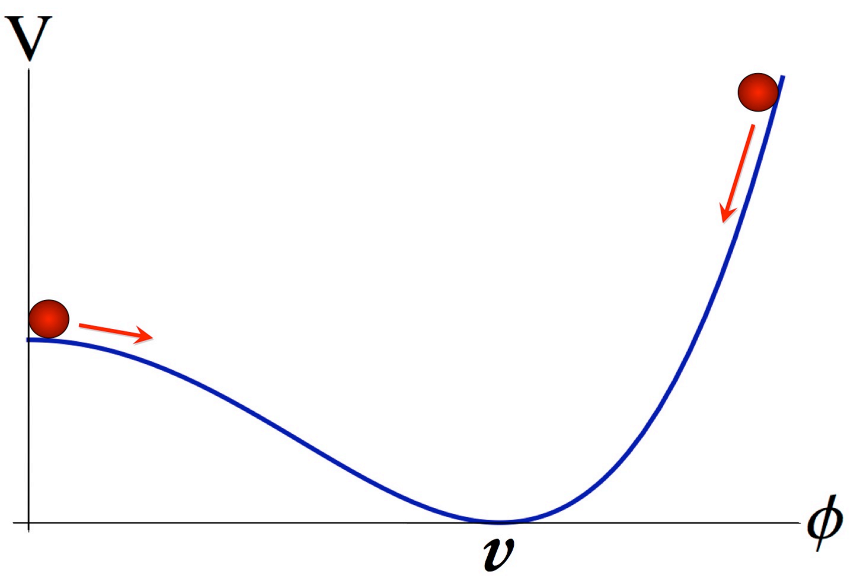
$$V(\phi) = \frac{\lambda^2}{4}(\phi^2 - v^2)^2$$

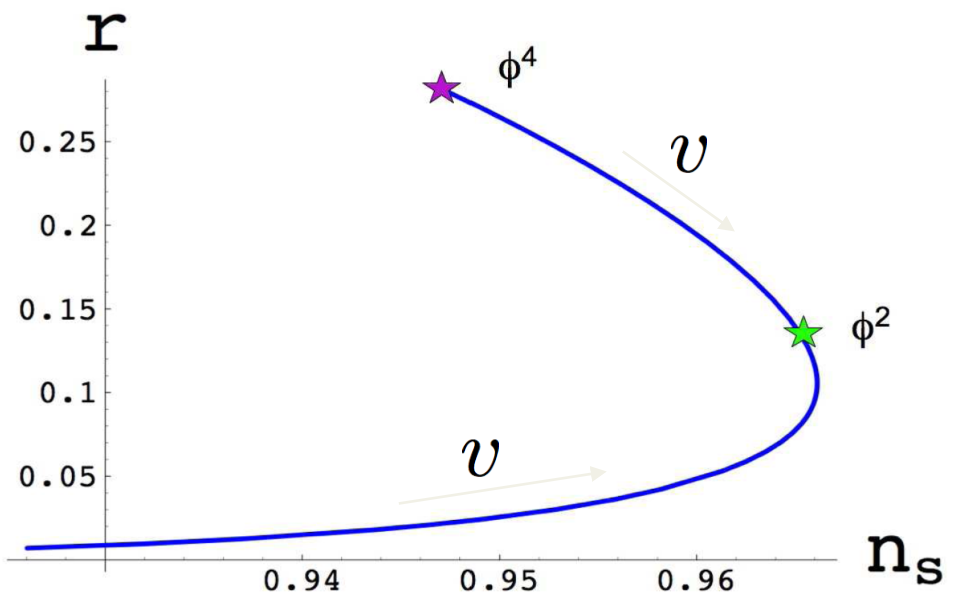


Tensor modes:

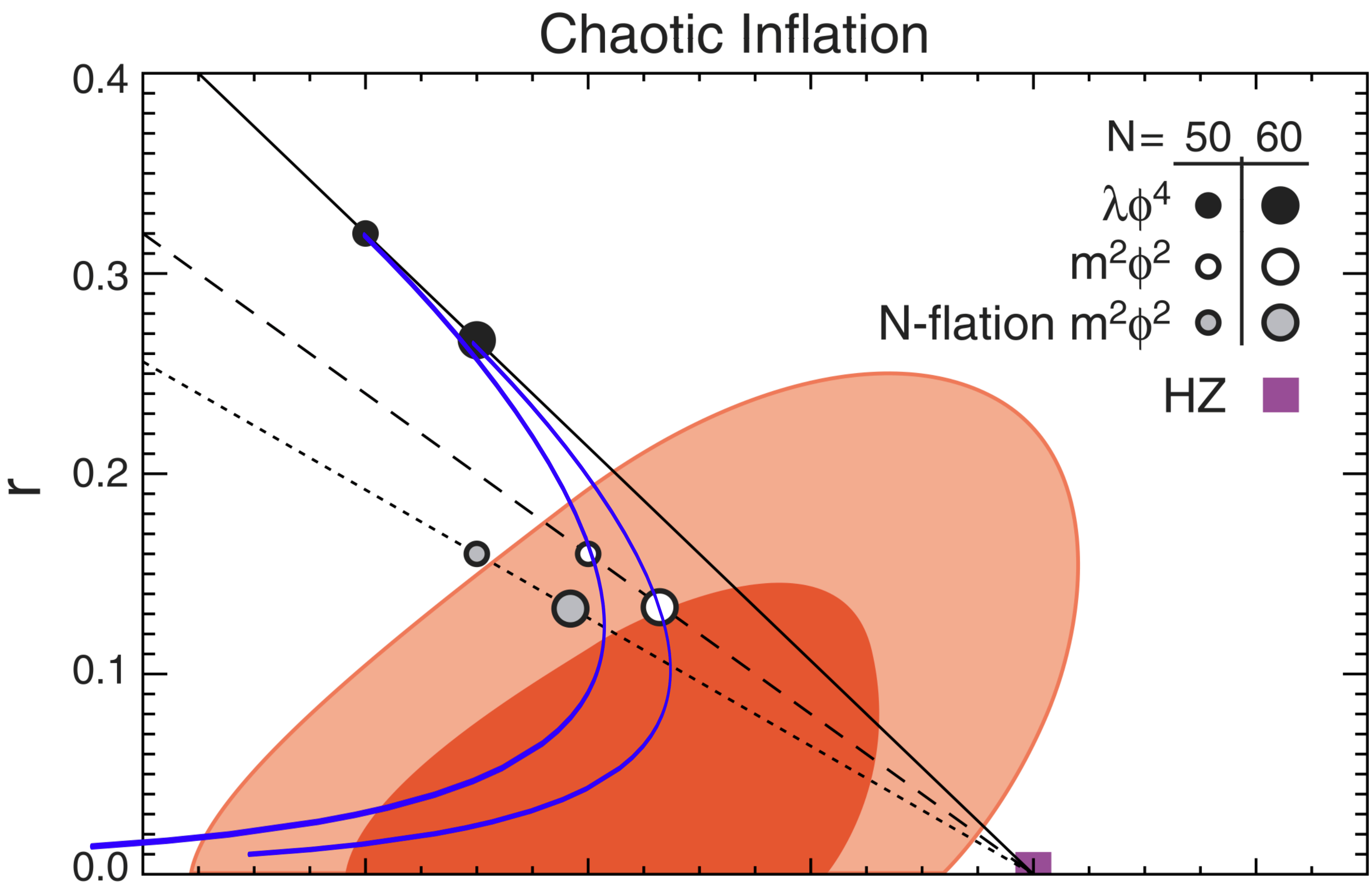
$$V = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Kallosh, A.L. 2007





Observers are optimistic now about measuring r at the level approaching r ~ 0.01 after 2011-2012 (BICEP2, other experiments)



Blue lines – chaotic inflation with the simplest spontaneous symmetry breaking potential $-m^2\phi^2 + \lambda\phi^4$ for N = 50 and N = 60

Supersymmetry breaking after inflation

Kallosh, A.L., Olive, Rube, 1106.6025

$$W = S\, f(\Phi) \qquad \mathcal{K}((\Phi - \bar{\Phi})^2,\, S\bar{S})$$

In this class of models one can get a theory with ANY type of inflationary potential of the real part of the field Φ

$$V = |f(\Phi)|^2$$

To have SUSY breaking on TeV scale one can add to this model a hidden sector with light Polonyi-type fields. But this leads to the cosmological moduli problem, which plagues SUGRA cosmology for the last 30 years.

In string theory, **SUSY breaking is a part of the KKLT construction**. Do we need to add Polonyi fields? Can we avoid the moduli problem?

Work in progress

Near future: theory and data
LHC and COSMOLOGY:

- Supersymmetry?
- Is dark energy a cosmological constant?
- Non-gaussianity
- More on spectral index
- Cosmic strings
- B-modes ?
- Mass of gravitino ?

- **Test of superstring theory?**

We are waiting for LHC and Planck, dark matter and B-mode experiments data