Inflationary multiverse and string theory landscape

Andrei Linde

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Many, many questions:

What was before the Big Bang?

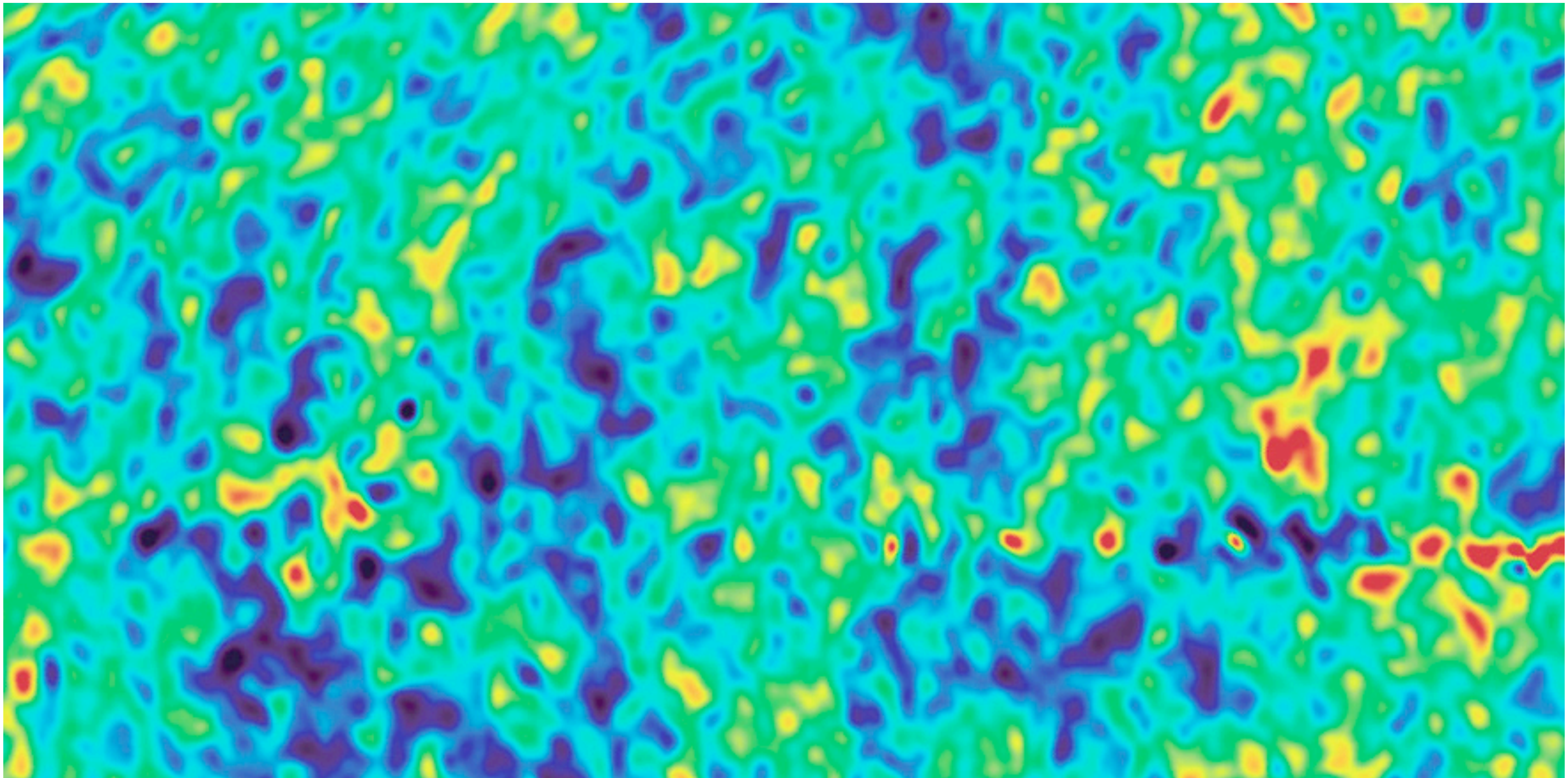
We do not know yet

Why is our universe so **homogeneous**?
Why is it **not exactly** homogeneous?
Why is it **isotropic** (same in all directions)?
Why all of its parts started expanding simultaneously?
Why is it **flat** **($\Omega = 1$)**?
Why is it so **large**?
Where are monopoles and other unwanted relics?

Answered by inflation

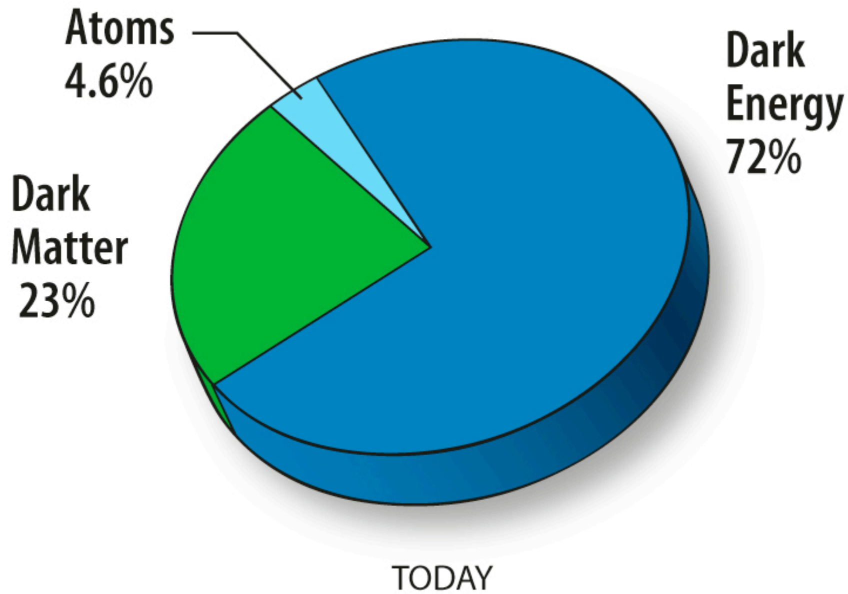
Why vacuum (dark) energy is so small but not zero?
Why there is 5 times more dark matter than normal matter?
Why there is about 4 times more dark energy than dark matter?
Why **$w = -1$**?

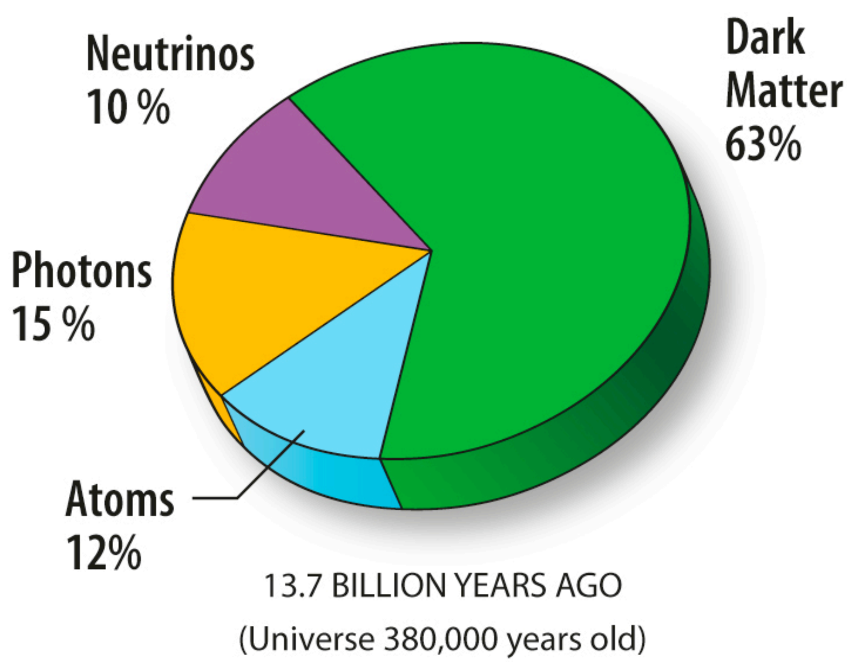
Possible answers are given by a combination of particle physics, string theory and eternal inflation



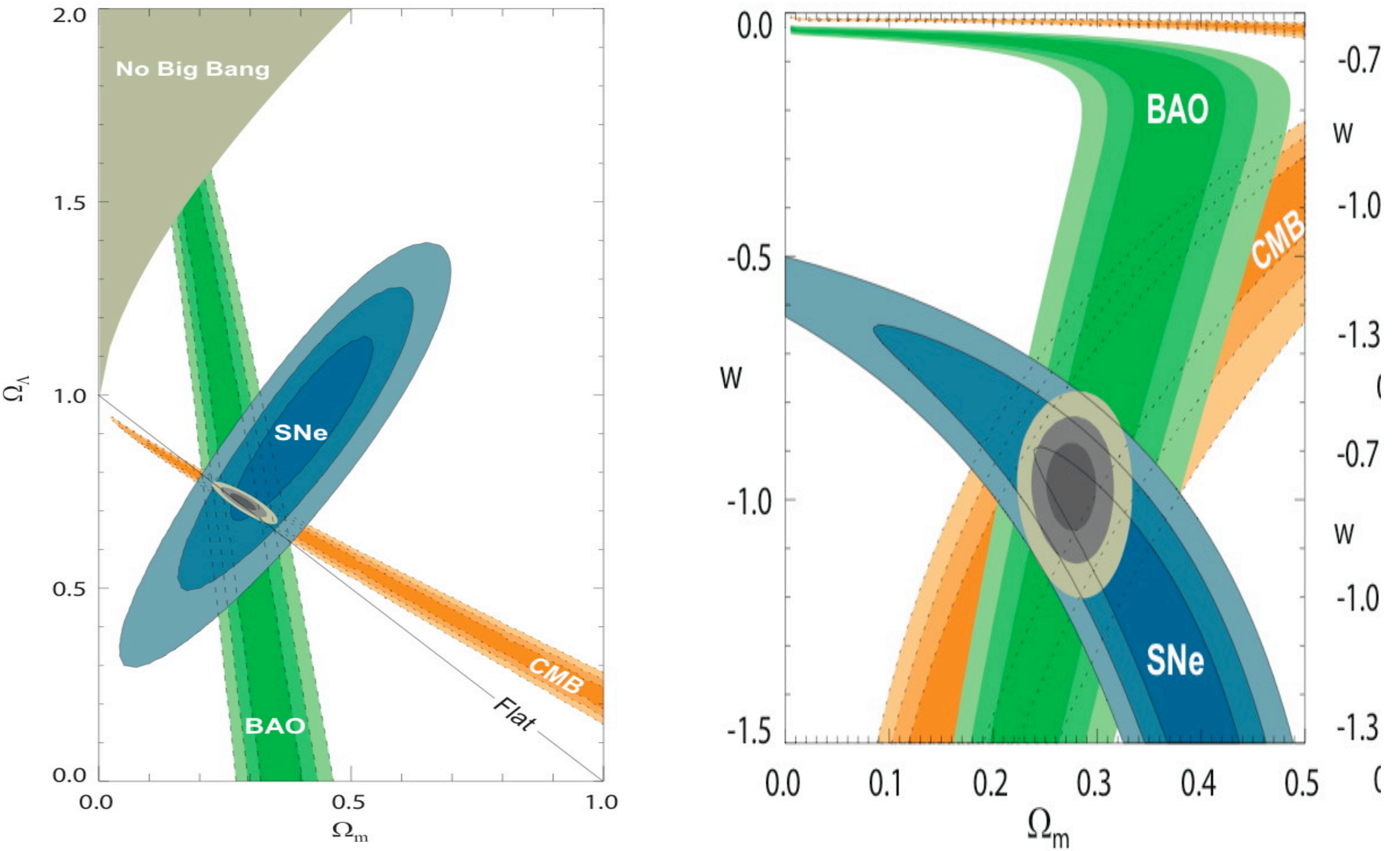

Observations

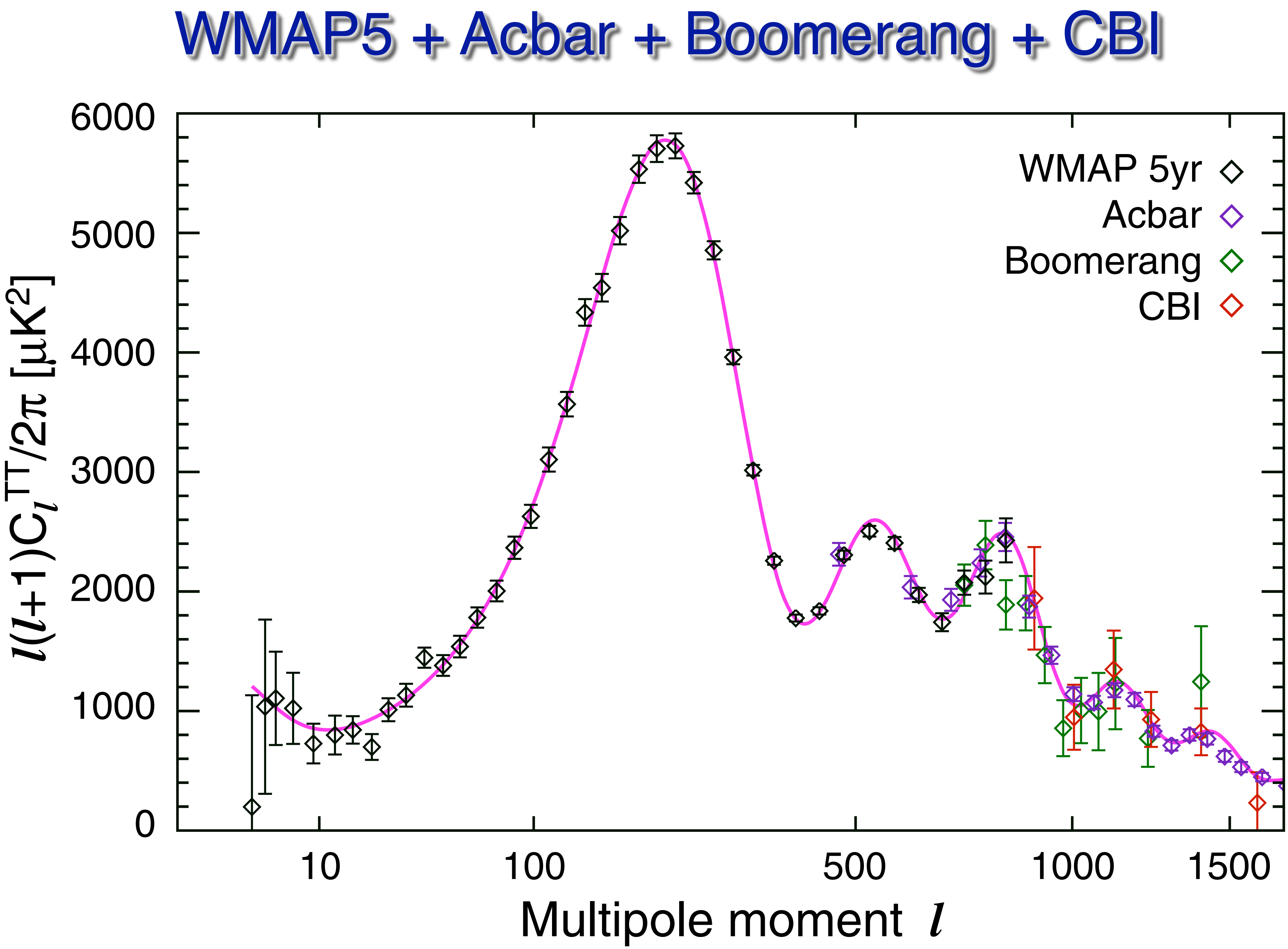
WMAP 5-Year Pie Chart





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





WMAP5 + Acbar + Boomerang + CBI
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
10
100
500
1000
1500
Multipole moment l
WMAP 5yr
Acbar
Boomerang
CBI

Predictions of Inflation:

1) The universe should be homogeneous, isotropic and flat,

$$\Omega = 1 + O(10^{-4}) \qquad [\Omega=\rho/\rho_0]$$

Observations: it is homogeneous, isotropic and flat:

$$\Omega = 1.005 \pm 0.013$$

2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-1})$. Spectral index n_s slightly differs from 1. (This is an important prediction, similar to asymptotic freedom in QCD.)

Observations: perturbations are gaussian with accuracy 0.1% (but this is not the end of the story) and adiabatic, with flat spectrum:

$$n_{\mathrm{s}} = 0.959 \pm 0.013$$

Gaussianity is confirmed at 0.1% level, but there are interesting developments when we increase precision even further.

Current constraints from WMAP and LSS:

$$f_{NL} = 30 \pm 15$$

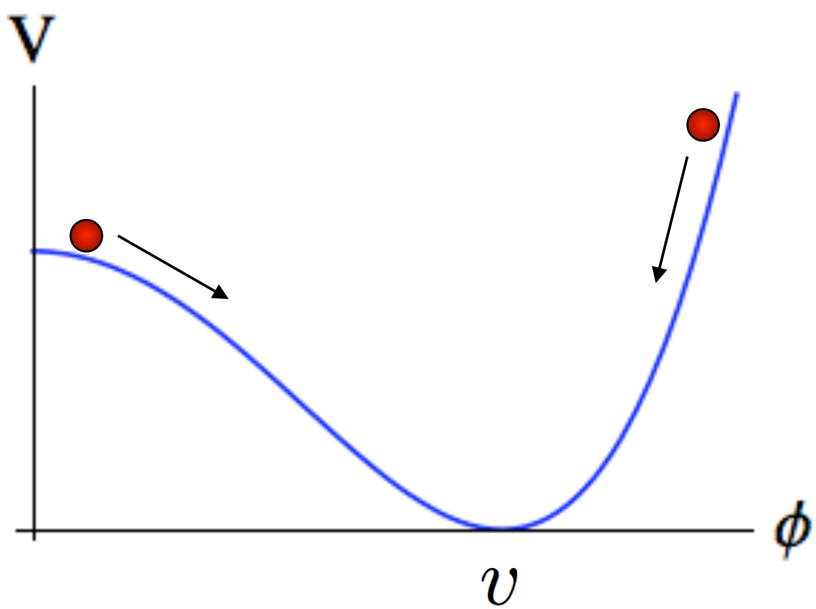
In ALL single-field inflationary models $|f_{NL}| < 1$, so we may need to switch to two-field models if nongaussianity is found.

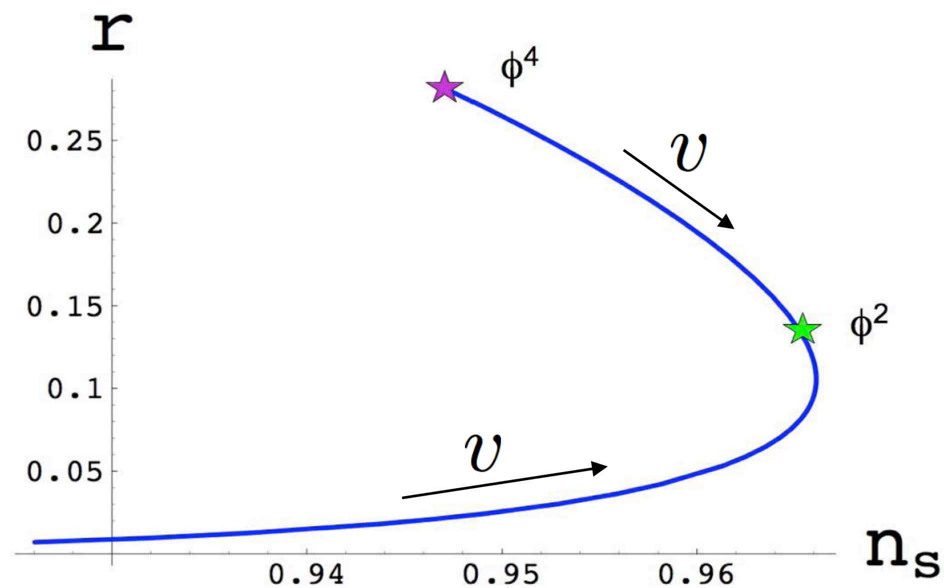
- –In 5-10 years, we will know **flatness** to **0.1%** level.
- –In 5-10 years, we will know **Gaussianity** to **0.01%** level (f_{NL}~10), or even to **0.005%** level (f_{NL}~5), at 95% CL.

Tensor modes:

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

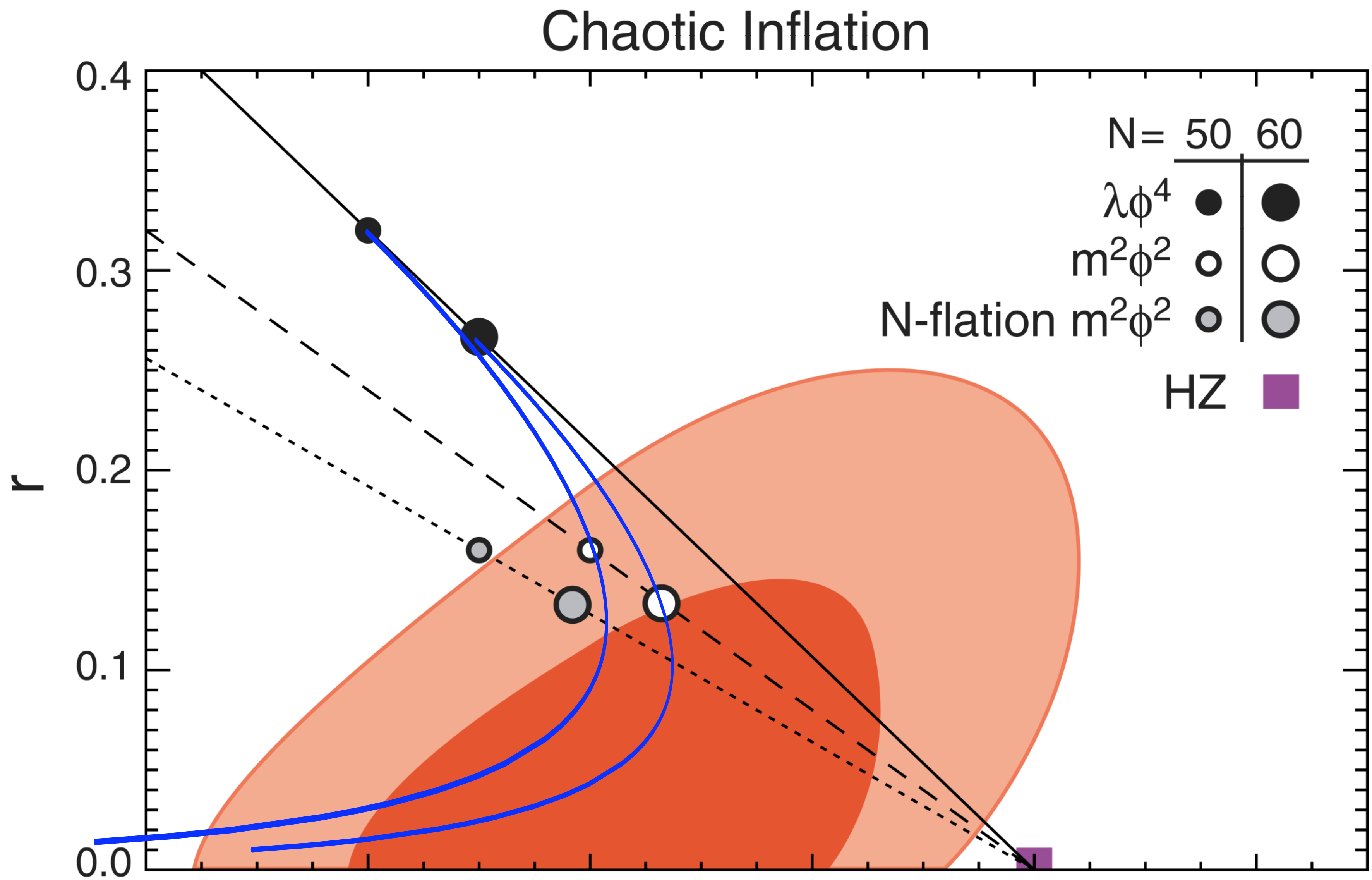
Kallosh, A.L. 2007





It does make sense to look for tensor modes even if none are found at the level r ~ 0.1 (Planck). Best bound now is r < 0.2.

Observers are more optimistic now than a year ago about the possibility to measure r at the level r ~ 0.01 after 2011



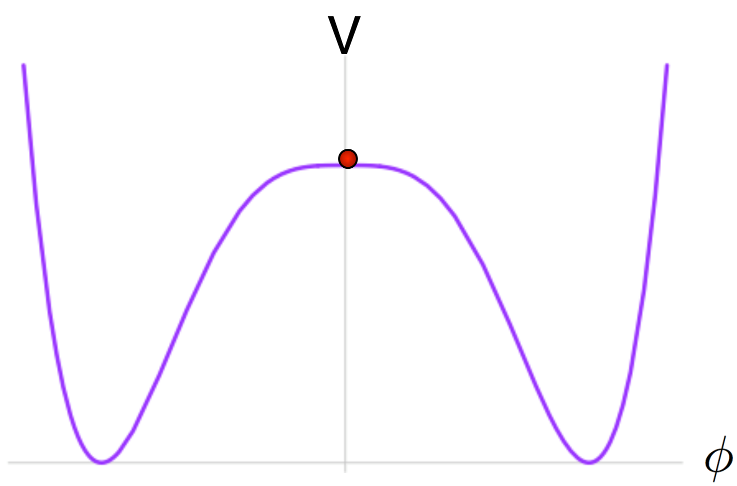
Blue lines – chaotic inflation with the simplest spontaneous symmetry breaking potential $-m^2\phi^2 + \lambda\phi^4$ for N = 50 and N = 60

Can we have large nongaussianity ?

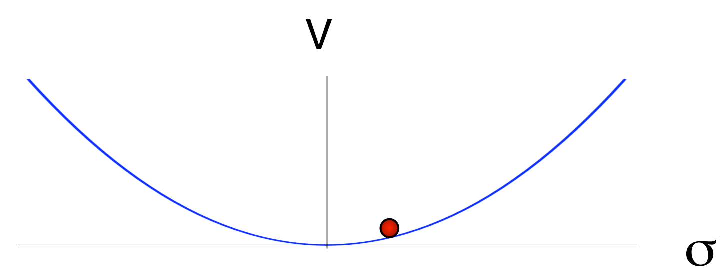
A.L., Mukhanov, 1996

Lyth, Wands, Ungarelli, 2002

Lyth, Wands, Sasaki and collaborators - many papers up to 2008



Inflaton



Curvaton

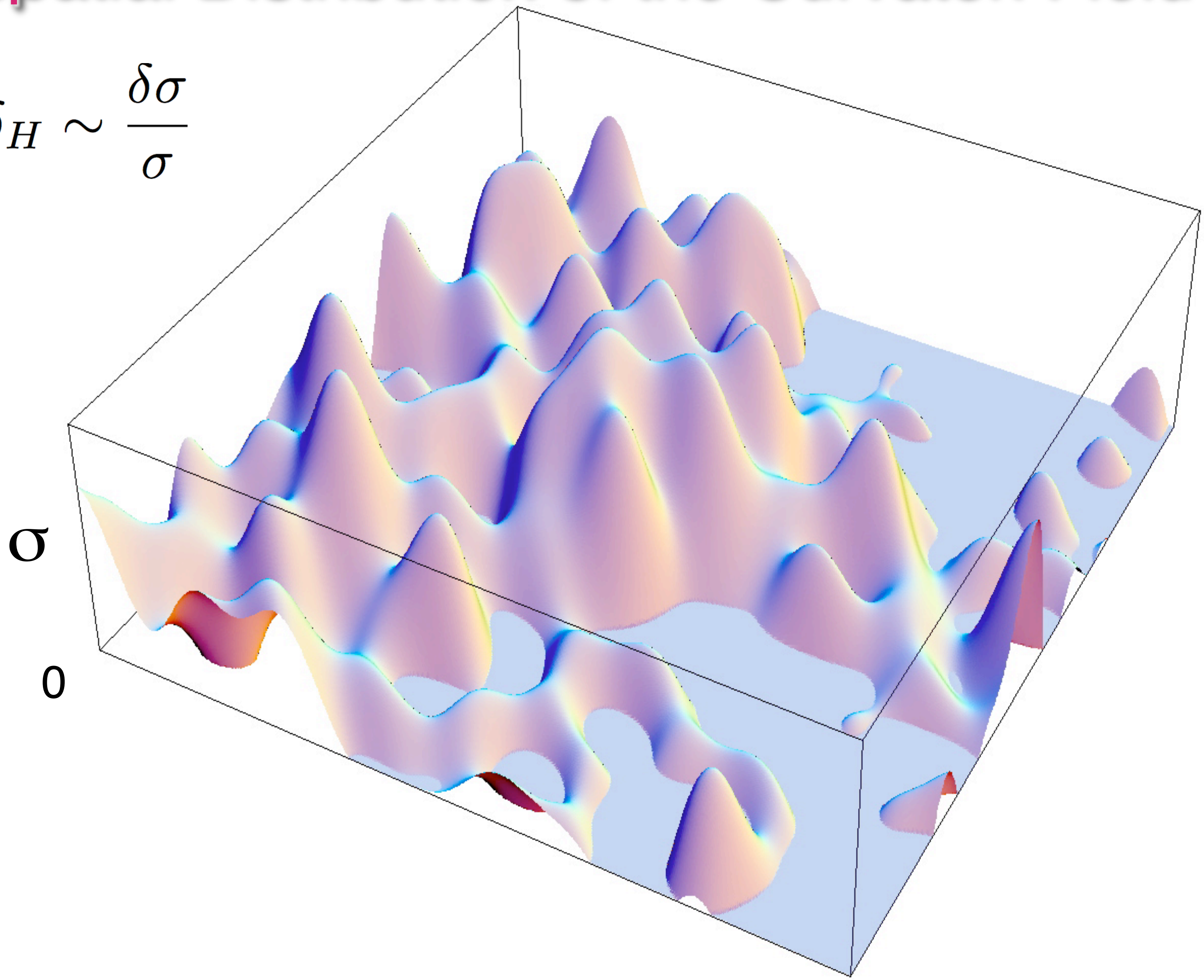
Isocurvature perturbations $\longrightarrow$ adiabatic perturbations

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

σ is determined by quantum fluctuations, so the amplitude of perturbations is different in different places

Spatial Distribution of the Curvaton Field

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$



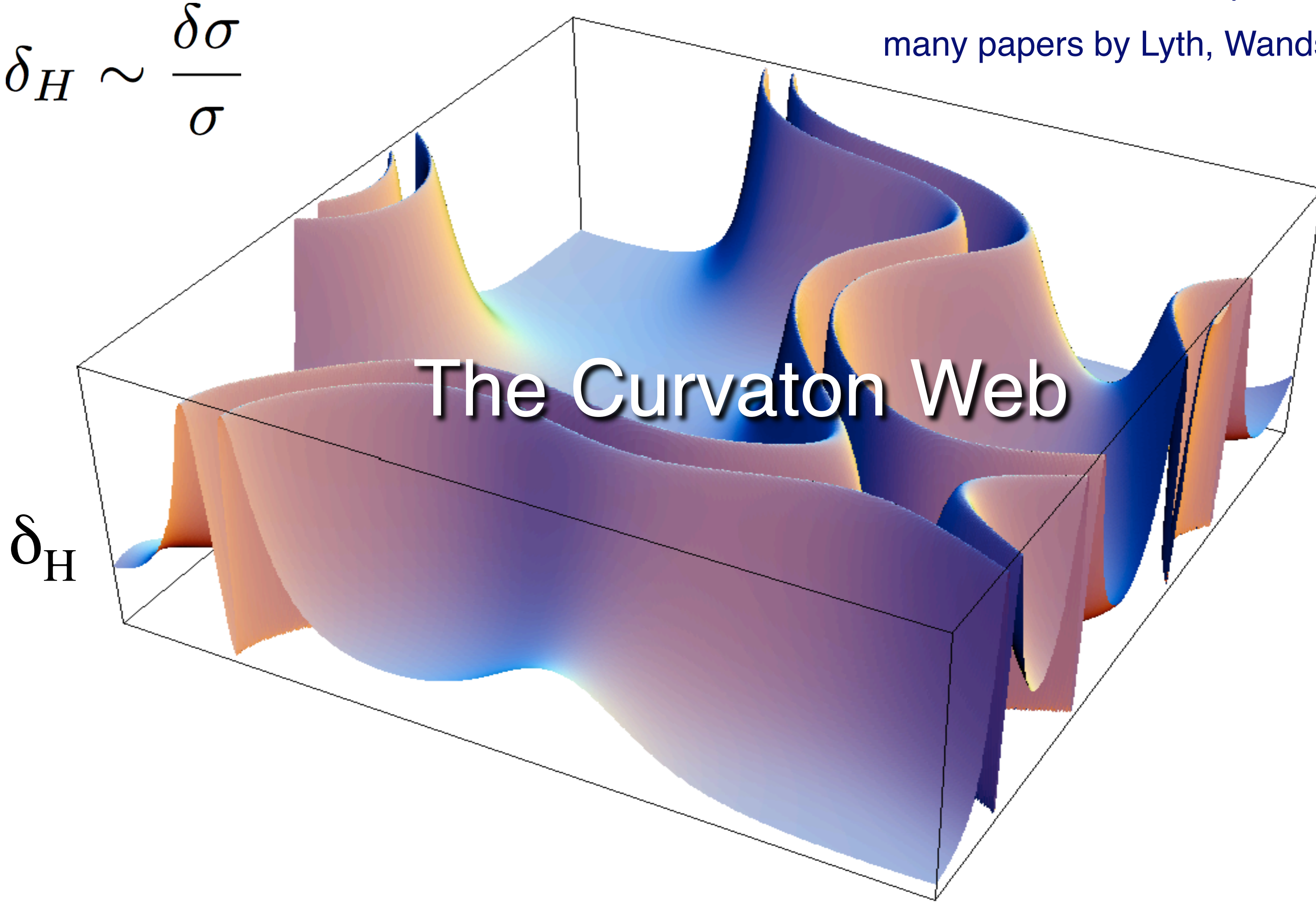
The Curvaton Web and Nongaussianity

Usually we assume that the amplitude of inflationary perturbations is constant, $\delta_H \sim 10^{-5}$ everywhere. However, in the curvaton scenario δ_H can be different in different parts of the universe. This is a clear sign of nongaussianity.

A.L., Mukhanov, astro-ph/0511736

many papers by Lyth, Wands, Sasaki

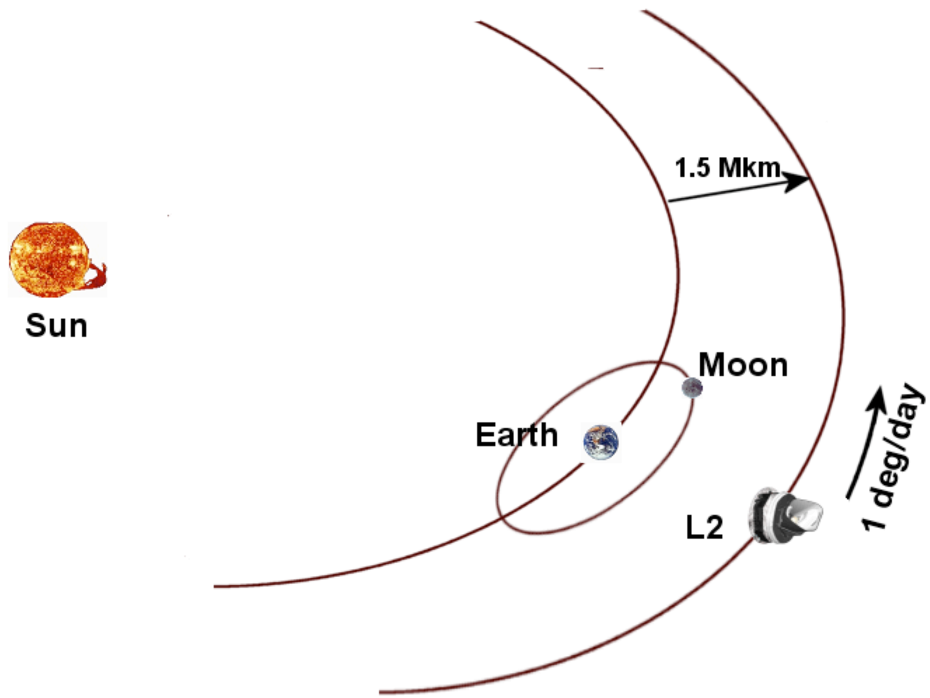
$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

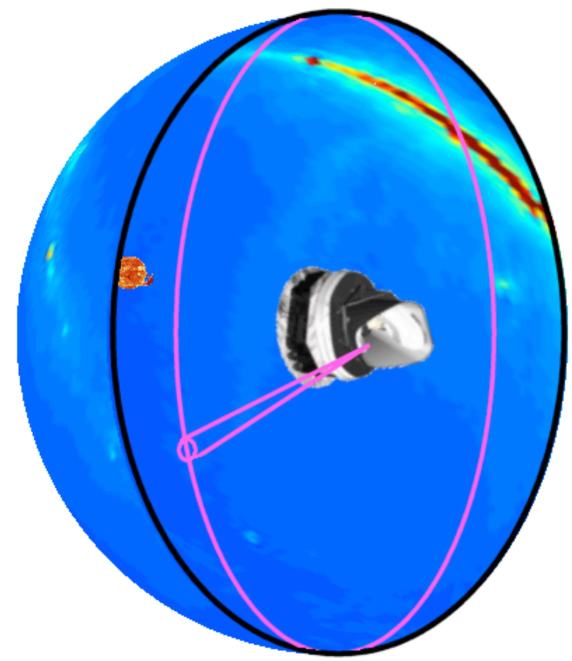


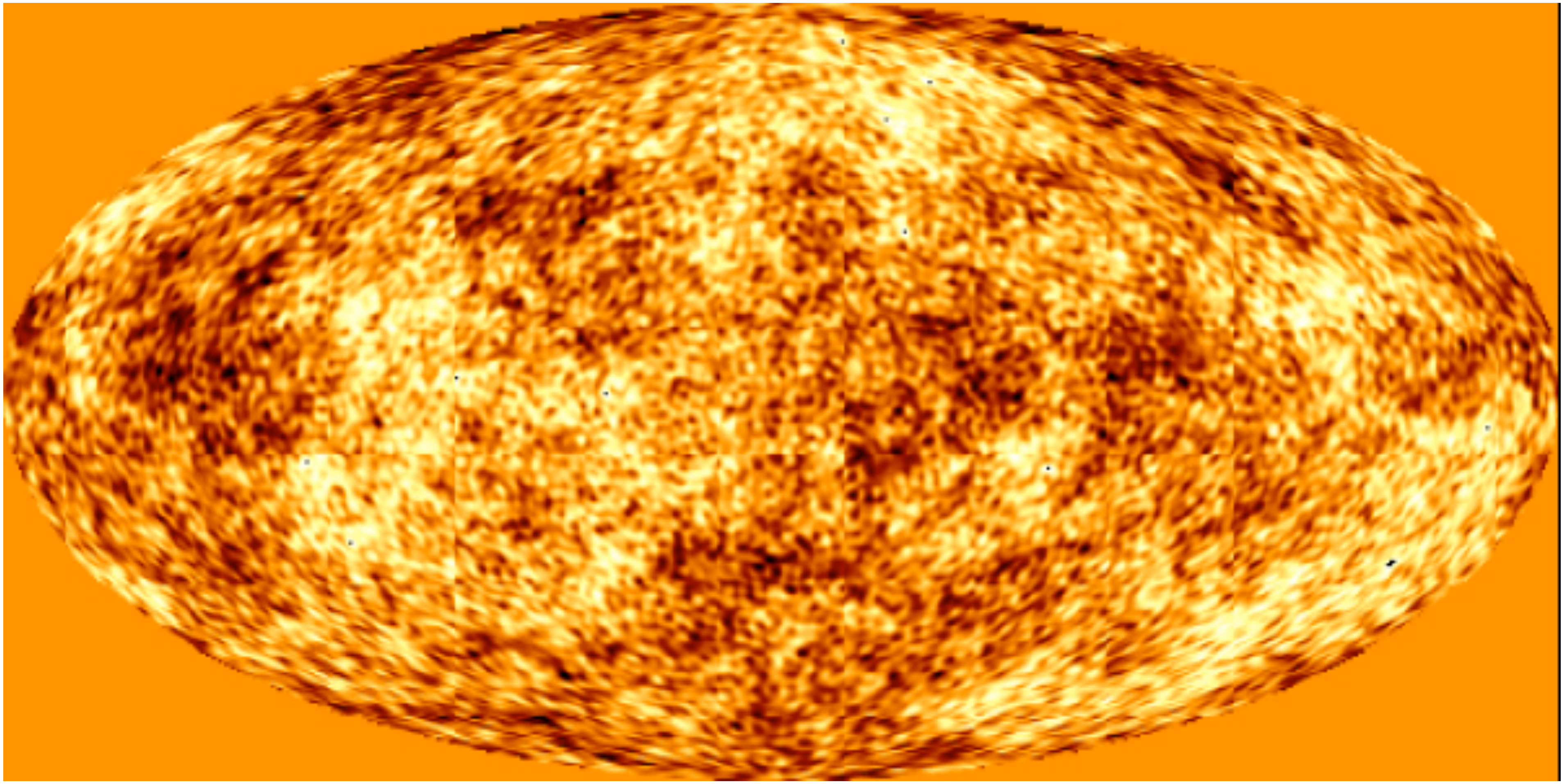
Can we have large nongaussianity in the curvaton scenario?

Yes, if the amplitude of the curvaton perturbations δ is large, but the relative contribution of the curvaton to the total energy density was small. Then large curvaton perturbations $\delta \gg 10^{-5}$ produce small perturbations of metric $\sim 10^{-5}$, but the level of nongaussianity can be very high.

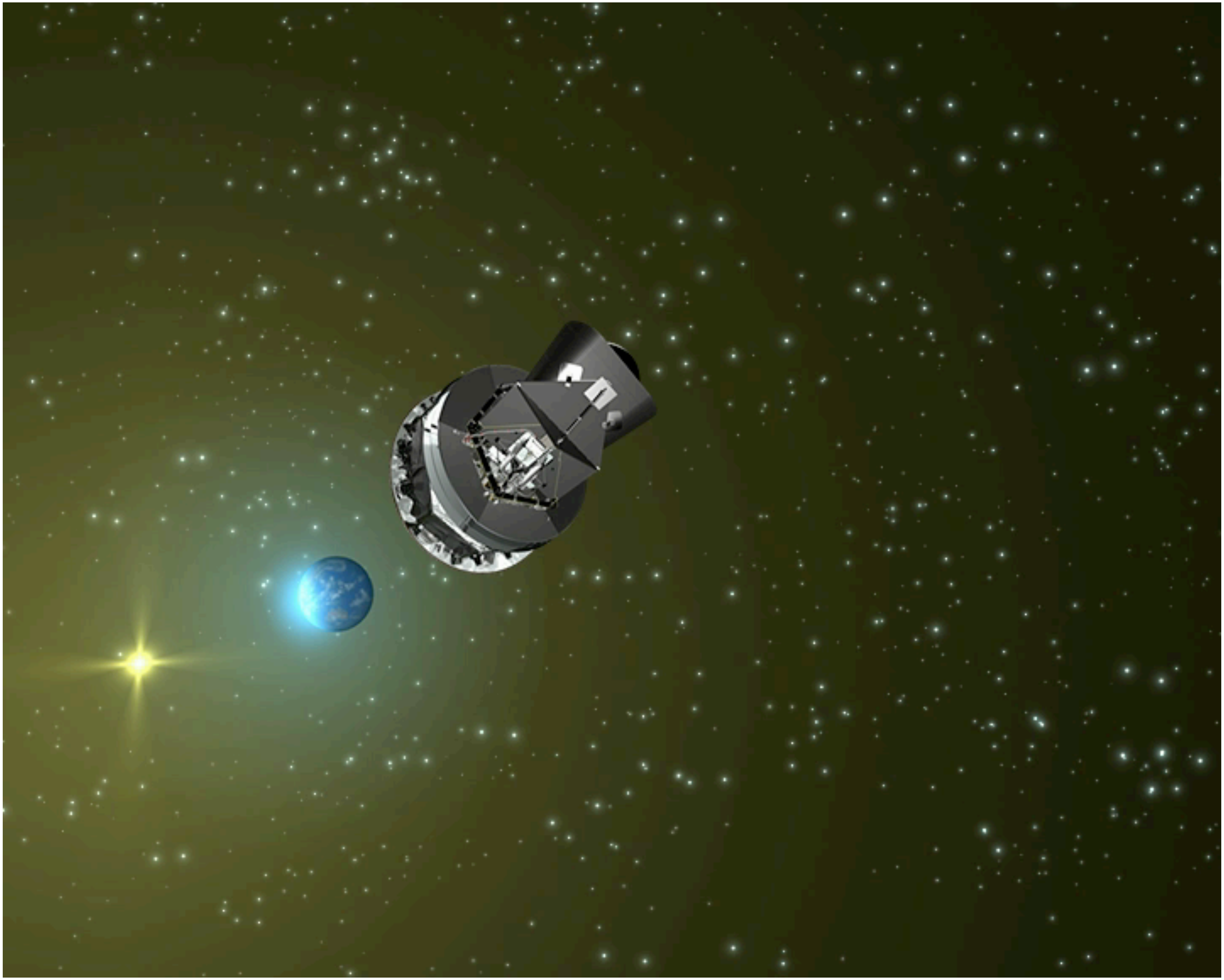
Planck satellite was launched few days ago, on May 14, 2009

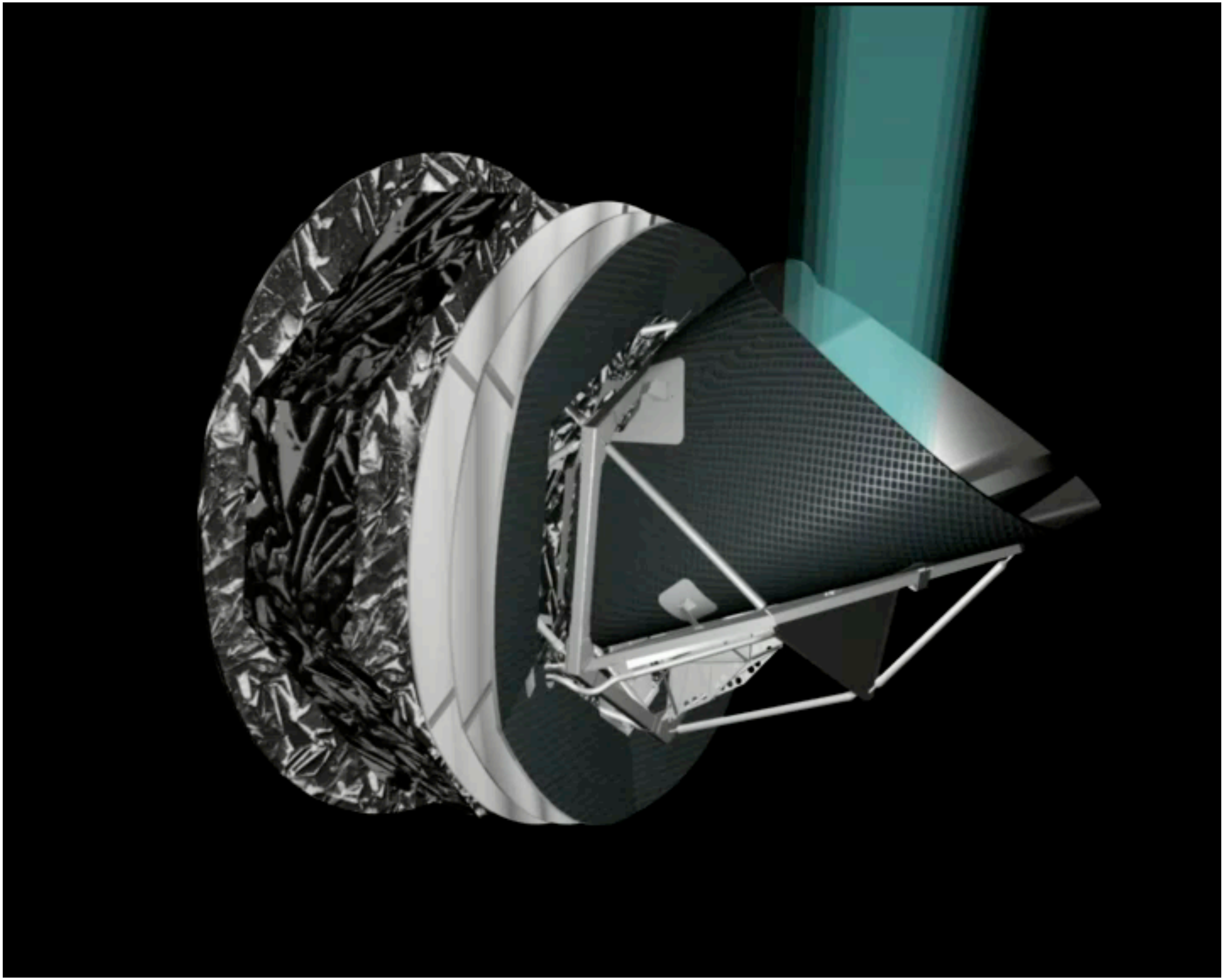






Planck will be able to measure tiny fluctuations of CMB temperature, up to 5 millionths of a degree





Inflation in String Theory

The volume stabilization problem:

A potential of the theory obtained by compactification in string theory of type IIB:

$$V(X, Y, \phi) \sim e^{\sqrt{2}X - \sqrt{6}Y}\ V(\phi)$$

X and Y are canonically normalized field corresponding to the dilaton field and to the volume of the compactified space; ϕ is the field driving inflation

The potential with respect to X and Y is very steep, these fields rapidly run down, and the potential energy V vanishes. We must stabilize these fields.

Dilaton stabilization: Giddings, Kachru, Polchinski 2001

Volume stabilization: KKLT construction

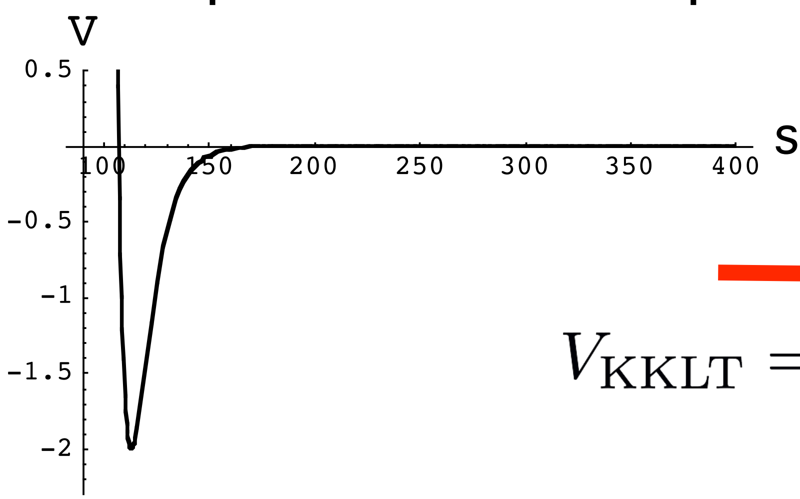
Kachru, Kallosh, A.L., Trivedi 2003

Basic steps of the KKLT scenario:

1) Start with a theory with runaway potential discussed above

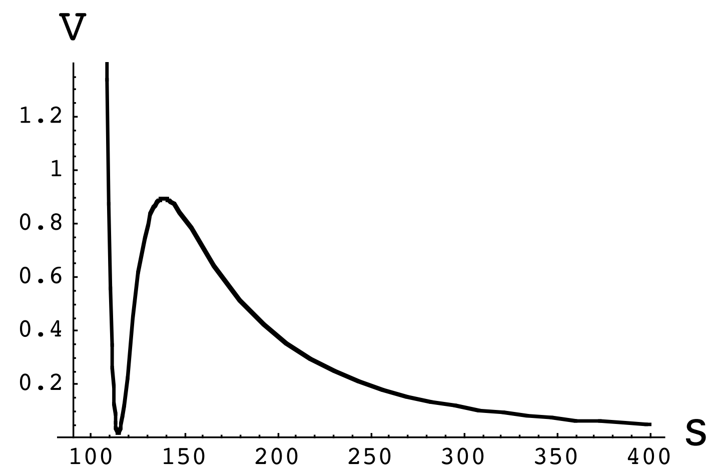
2) Bend this potential down due to nonperturbative quantum effects in a compactified 4D theory (this step is not described by compactification of an effective 10D Einstein theory; introducing orientifolds is insufficient)

3) Uplift the minimum to the state with a positive vacuum energy by adding a positive energy of an anti-D3 brane in warped Calabi-Yau space



AdS minimum

$$V_{\mathrm{KKLT}} = V_{\mathrm{AdS}} + \frac{D}{\sigma^2}$$



Metastable dS minimum

A toy model of SUGRA inflation:

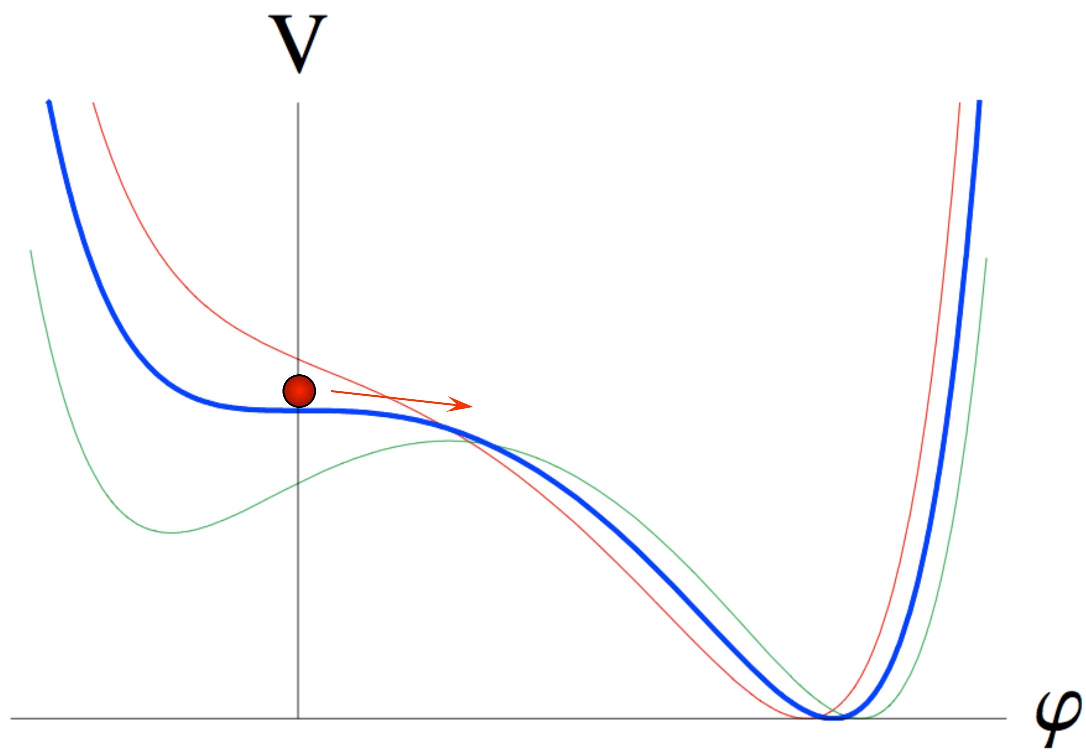
Holman, Ramond, Ross, 1984

Superpotential: $$W = c\,(\Phi - \Phi_0)^2$$

Kahler potential: $$K = \Phi\bar{\Phi}$$

Inflation occurs for $\Phi_0 = 1$

Requires fine-tuning, but it is simple, and it works

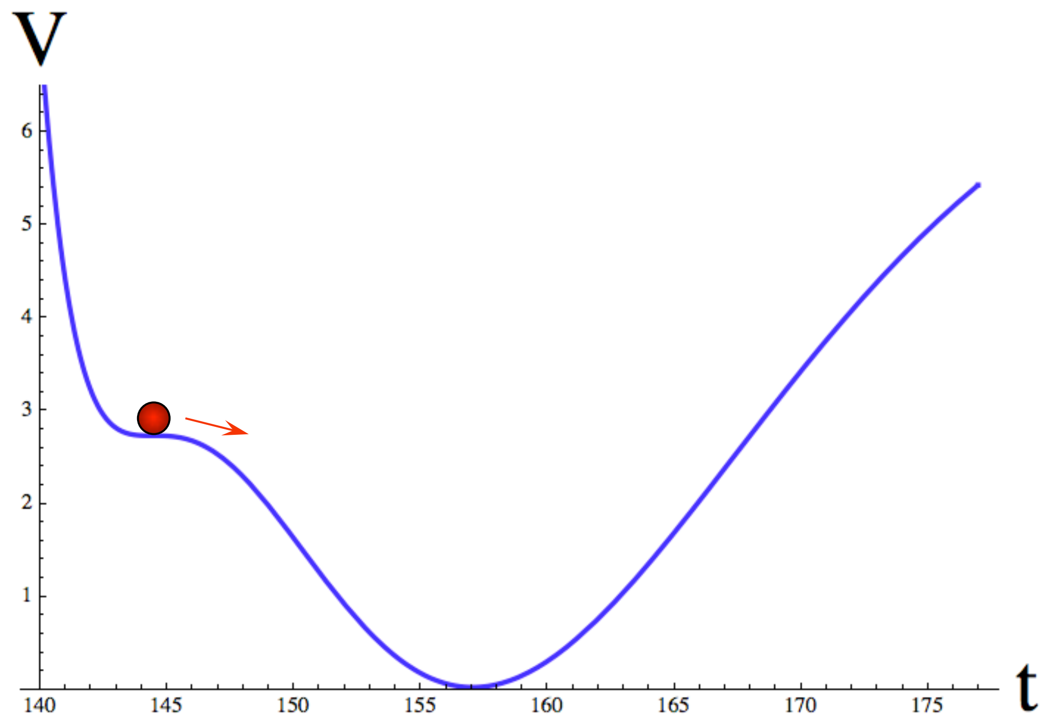


String volume modulus inflation

A.L., Westphal, 2007

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

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

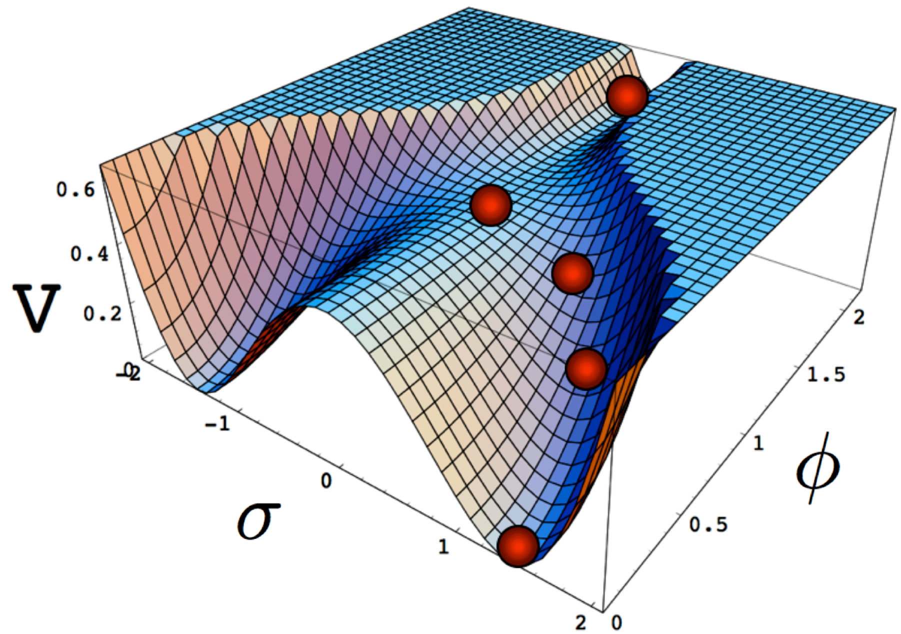


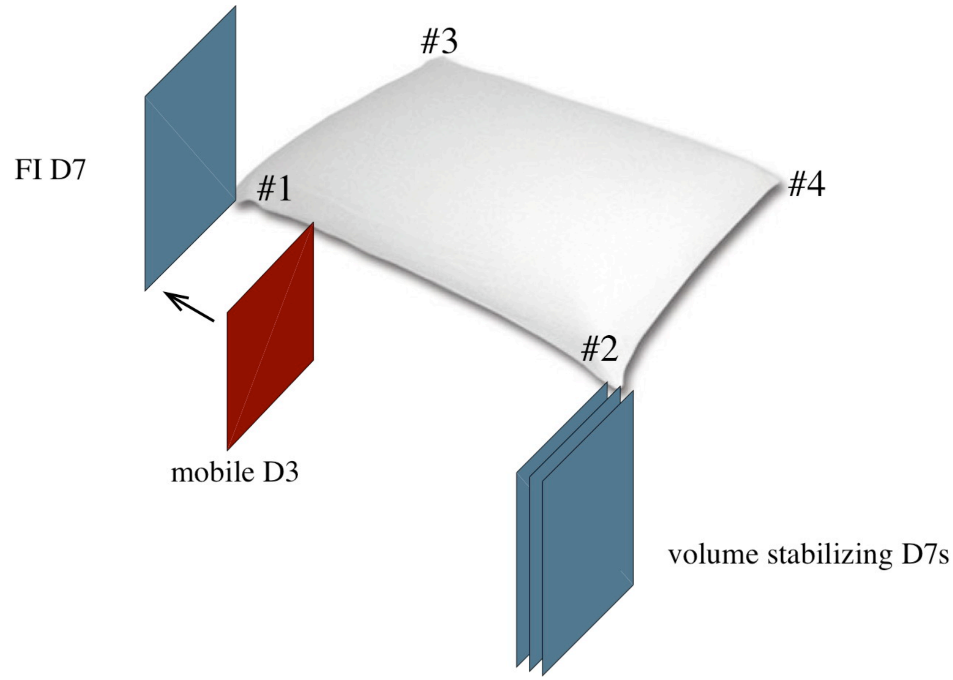
Volume modulus inflation

Requires fine-tuning, but works without any need to study complicated brane dynamics

D3/D7 hybrid inflation

Haack, Kallosh, Krause, A.L., Lust, Zagermann 2008



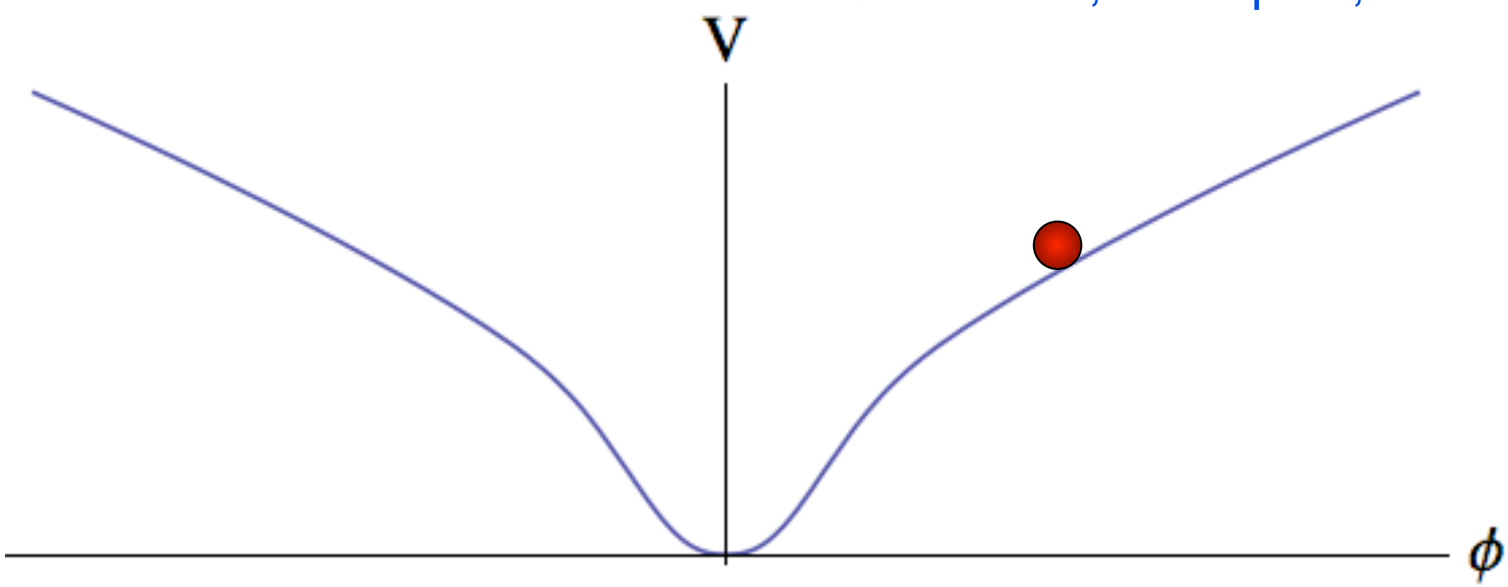


Naturally flat inflaton direction, string theory corrections under control, eternal inflation regime, a controllably small amount of cosmic strings.

Can we have chaotic inflation in string theory?

The answer is “yes”; the potential is ϕ^2 at small ϕ and $\phi^{2/3}$ at large ϕ:

Silverstein, Westphal, 2008



Type IIA models, based on Nil manifolds, rather than on the CY spaces. Large SUSY breaking.

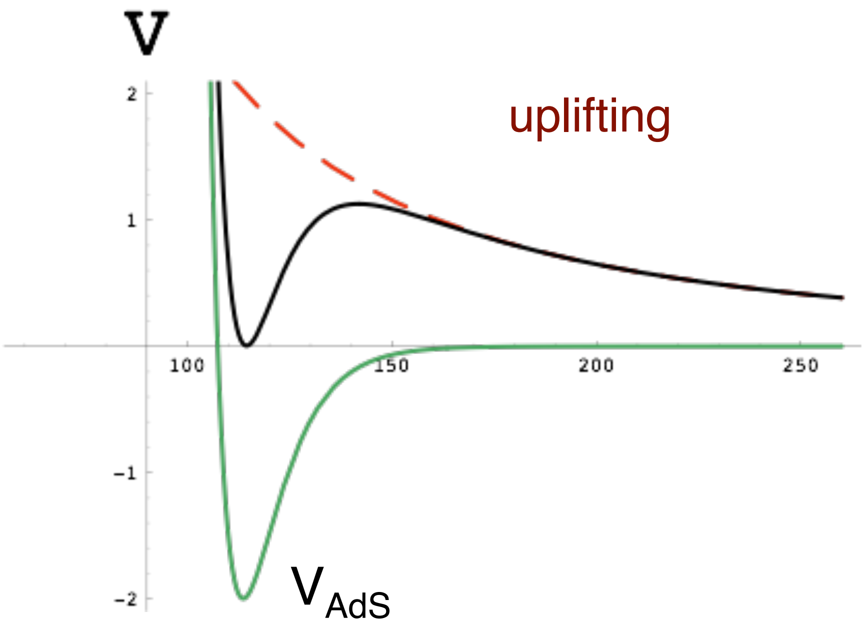
Can be done in type IIB as well.

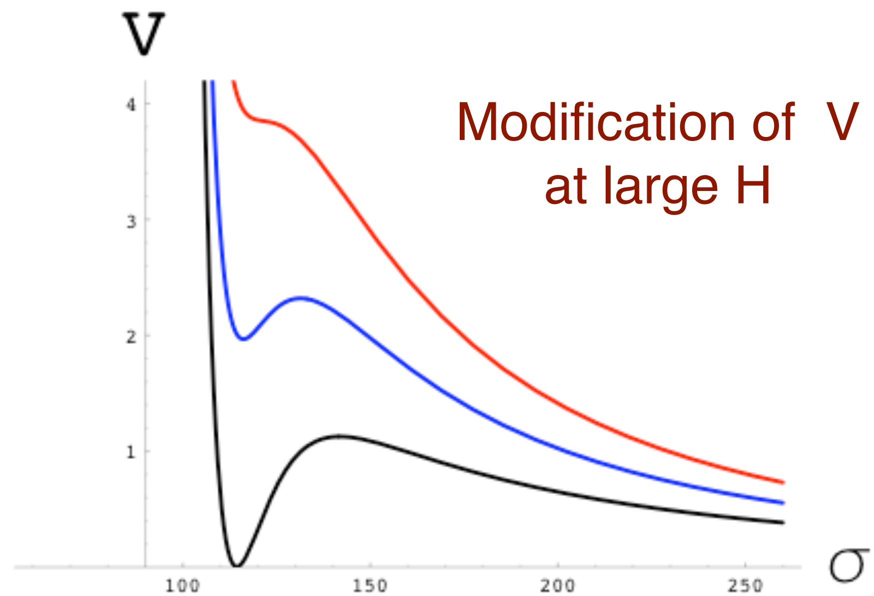
McAllister, Silverstein, Westphal 2008

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

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





Constraint on the Hubble constant in this class of models:

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

Can we avoid these conclusions?

Recent model of chaotic inflation is string theory (Silverstein and Westphal, 2008) also requires $m_{3/2} > H \sim 10^{13}$ GeV.

In more complicated theories one can have $H \gg m_{3/2}$. But this requires fine-tuning (Kallosh, A.L. 2004, Badziak, Olechowski, 2007)

In models with large volume of compactification (Quevedo et al) the situation is even more dangerous: $H < m_{3/2}^{3/2} < 1\ KeV$

It is possible to solve this problem, but it is rather nontrivial, and, once again, it requires fine tuning.

Conlon, Kallosh, A.L., Quevedo, 2008

Remember that we are suffering from the light gravitino and the cosmological moduli problem for the last 25 years.

Tensor Modes and GRAVITINO

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

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

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

Kallosh, A.L. 2007

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

superheavy gravitino

$$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$$

unobservable

If we find tensor modes AND light superpartners of normal particles at LHC, it might have as important consequences for string theory as the discovery of the cosmological constant

Why multiverse ?

It was proposed more than 25 years ago. Why so much interest NOW ?

Historicaly, the question was opposite: Why UNIverse?

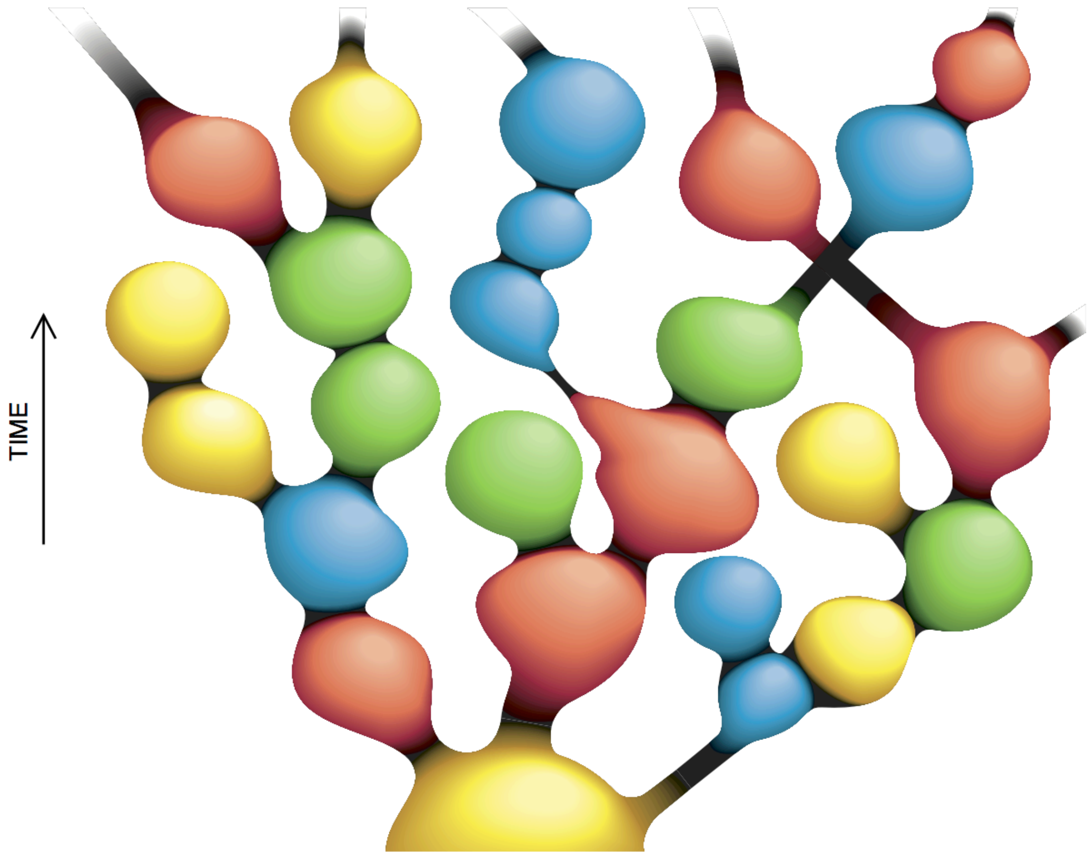
Uniformity of our world is explained by **inflation**:
Exponential stretching of the new-born universe makes it almost exactly uniform.

However, inflationary fluctuations eternally produce new parts of the universe with different properties.

Inflationary **universe** becomes a **multiverse**

Inflationary Multiverse

Inflationary universe may consist of many parts with different properties depending on the local values of the scalar fields, compactification, fluxes, etc.



In our own words:

"It is said that there is no such thing as a free lunch. But the universe is the ultimate free lunch".

Alan Guth, 1981

"Now we can add that inflationary universe is the only lunch at which **ALL** possible dishes are served".

A.L. 1982

Eternal inflation and string theory landscape

An enormously large number of possible types of compactification which exist e.g. in the theories of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear.

A.L. 1986

Now, Dr. Witten allowed, dark energy might have transformed this from a vice into a virtue, a way to generate universes where you can find any cosmological constant you want. We just live in one where life is possible, just as fish only live in water.

The New York Times

June 3, 2008

Why the multiverse suddenly became popular?

1. **Inflationary theory** received strong observational support

2. **Acceleration of the universe** and existence of dark energy (cosmological constant) was firmly established

3. **String theory** could not explain these observational data. This was a **creative crisis** which was resolved in 2003 with finding the mechanism of vacuum stabilization in string theory (KKLT construction and other related mechanisms).

4. Immediately after that, we learned that **this mechanism allows vacuum to be in 10^{500} different states**, with different values of vacuum energy (cosmological constant).

5. This established the picture of **inflationary multiverse consisting of infinitely many "universes" of 10^{500} types** (string theory landscape).

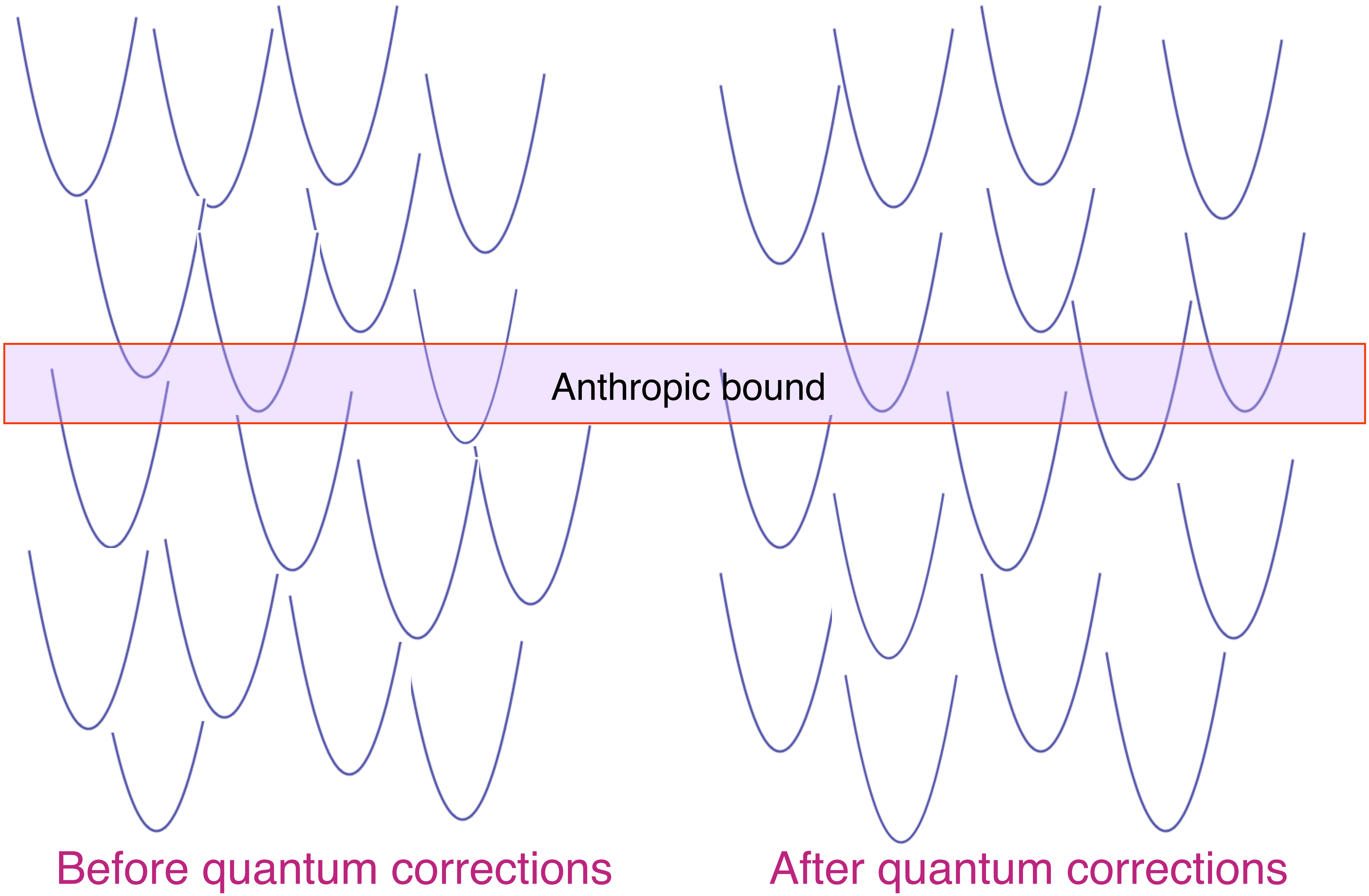
6. These developments provided **the framework for solving the cosmological constant problem using anthropic principle**, along the lines proposed in the 80's.

A.L. 1984, CC as a function of fluxes

A. Sakharov 1984, CC as a function of compactification

S. Weinberg 1987, anthropic bound on CC

Anthropic approach to Λ in string theory:

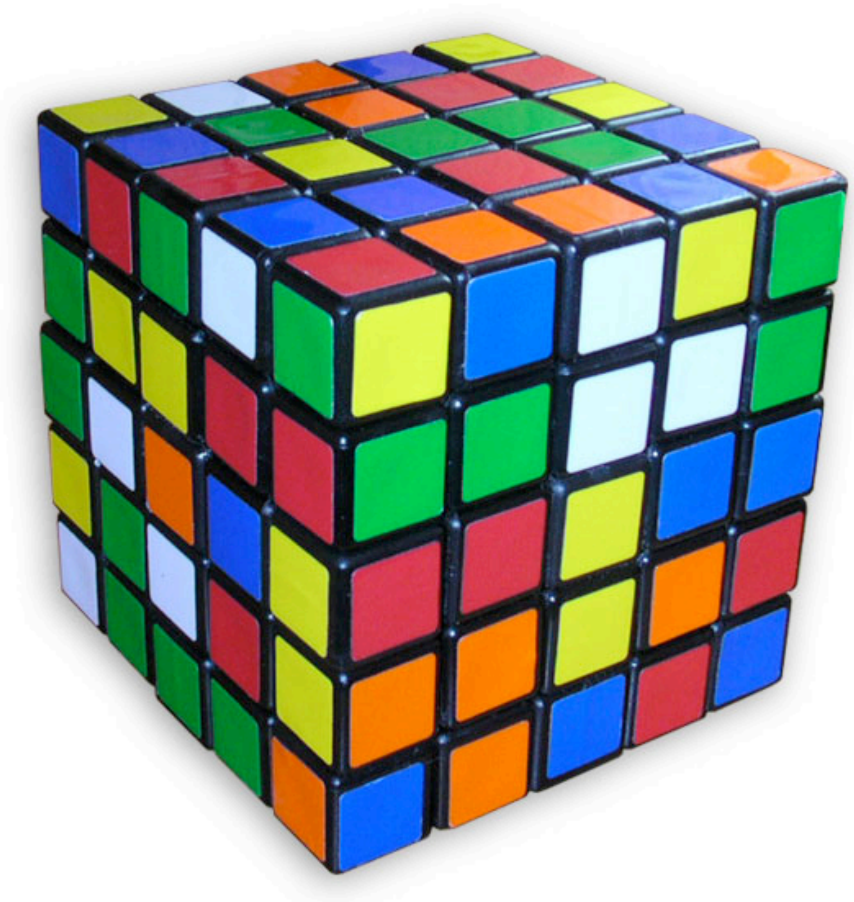


How many different universes are in the multiverse

There are perhaps $\sim 10^{500}$ vacua in string theory landscape

If these vacua appear as a result of bubble formation which is not followed by slow roll inflation, then each of these vacua is equally unimportant, because nobody can live there. Thus one could think that the number of possibilities is much smaller than 10^{500}. However, the number of different universes which may emerge as a result of eternal slow roll inflation is much greater than 10^{500}.

The universe at the end of inflation consists of e^{3N} independent domains of size H^{-1}, in each of which the scalar field jumps either upwards or downwards.



In this sense, each of the stringy vacua experiencing N e-folds of a **slow roll** inflation can produce

$$e^{e^{3N}}$$

different geometries.

For $N > 60$ we get

$$e^{e^{180}} \sim 10^{10^{77}}$$

This is much greater than the number of vacua in the landscape.

Application: Dark matter in the axion field

Old lore: If the axion mass is smaller than 10^{-5} eV, the amount of dark matter in the axion field contradicts observations, for a typical initial value of the axion field.

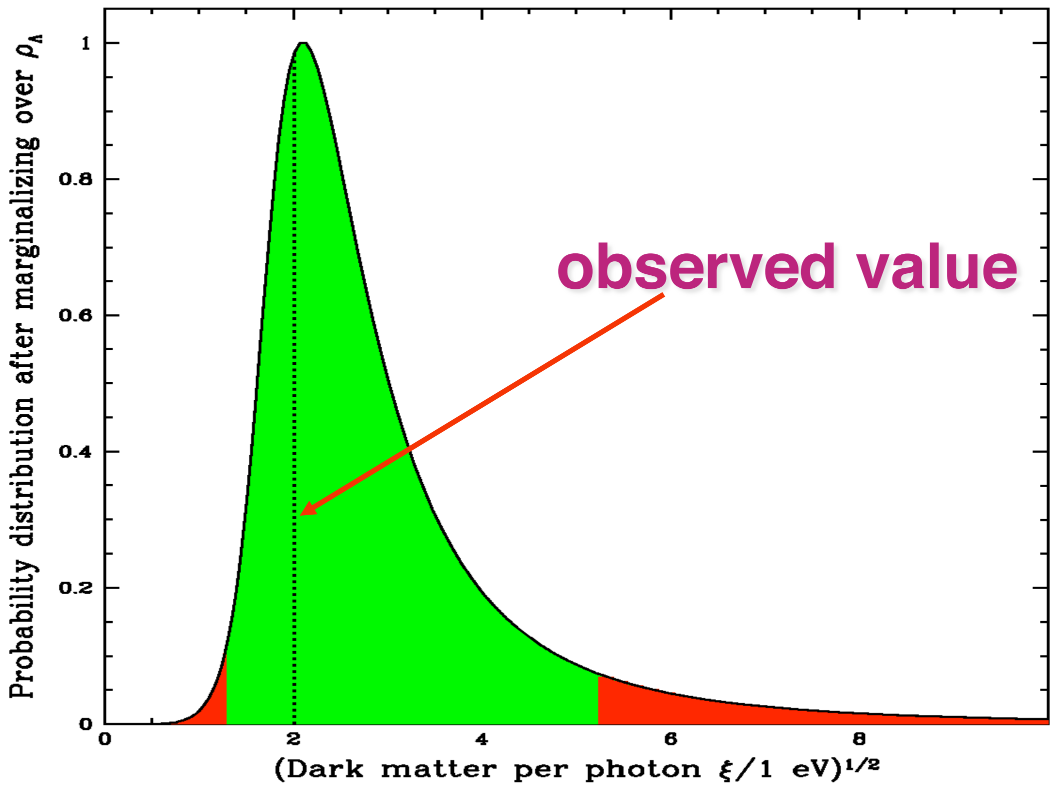
Can we give a scientific definition of "typical" ?

Anthropic argument: Inflationary fluctuations make the amount of the axion dark matter a RANDOM PARAMETER. We can live only in those parts of the universe where the initial value of the axion field was sufficiently small (A.L. 1988).

This argument is not sensitive to the choice of the probability measure

Anthropic Constraints on the Axion Dark Matter

Aguirre, Rees, Tegmark, and Wilczek, astro-ph/0511774



This is a possible answer to the question why there is 5 times more dark matter than the ordinary matter.

Can we return back to the <u>uni</u>verse?

No, unless we can do <u>all</u> of these things simultaneously:

- Find an alternative to string theory
- Find an alternative to inflation
- Find an alternative solution of the cosmological constant problem and of many other coincidence problems