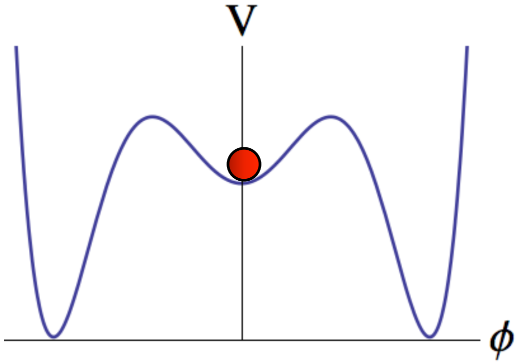
Inflation in string theory and supergravity

Andrei Linde

Inflation

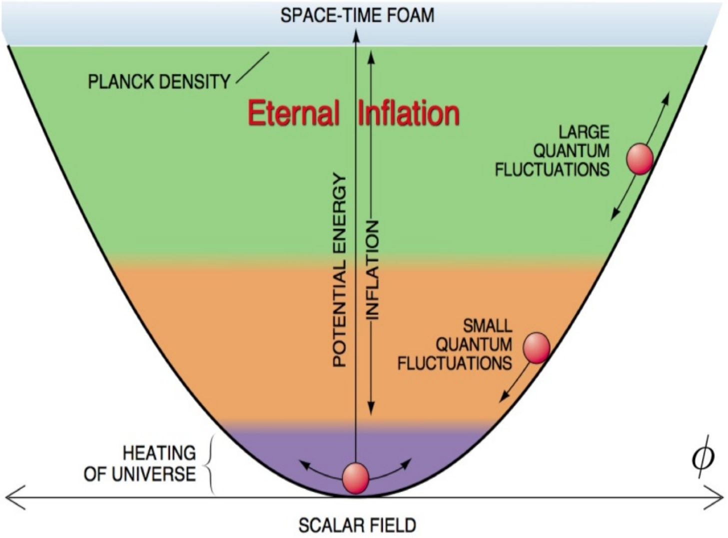
Starobinsky, 1980 – modified gravity, R + R^2 a complicated but almost working model

Guth, 1981 - old inflation. Great idea, first outline of the new paradigm, but did not quite work, and did not predict inflationary perturbations

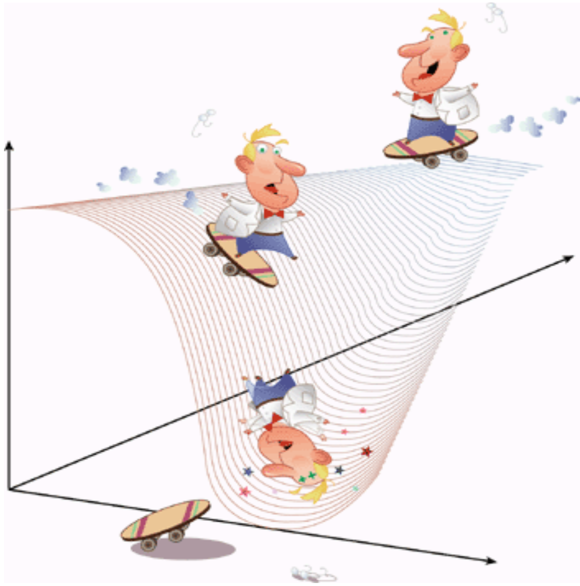


A.L., 1982 - new inflation
(also Albrecht, Steinhardt)

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



1983 - chaotic inflation



1991 - hybrid inflation

Inflation and Planck2013

$$\Omega = 1 + 0.0005 \pm 0.0066$$

$$n_s = 0.959 \pm 0.007$$

Non-inflationary HZ spectrum with n = 1 is ruled out at a better than 5σ level, just as predicted in 1981 by Mukhanov and Chibisov

$$f_{\mathrm{NL}}^{\mathrm{local}} = 2.7 \pm 5.8$$

Perturbations are Gaussian with 0.01% accuracy !!!

Apart for possible anomalies to be studied separately, an incredible success of the simplest inflationary models

Inflation

INFLATIONARY PARADIGM IN TROUBLE AFTER PLANCK2013

IJJAS, STEINHARDT, LOEB

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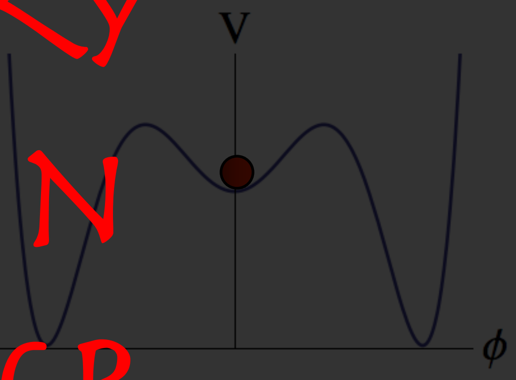

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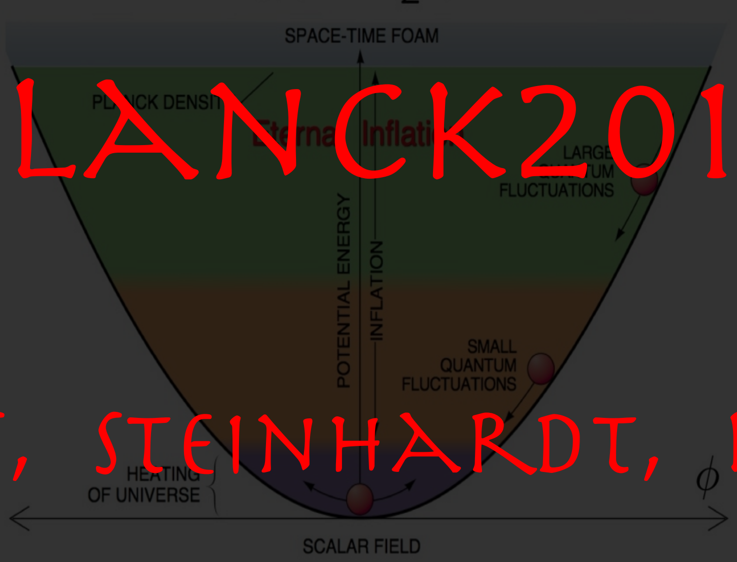

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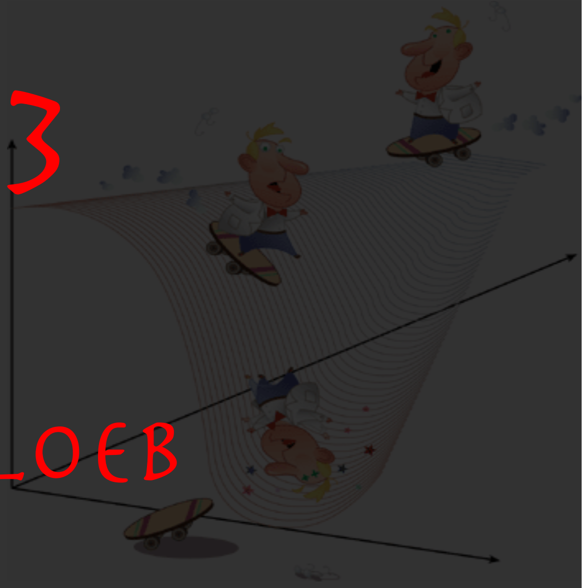


1991 - hybrid inflation

Do you want to know my opinion, or you think that you already know it?

I believe that it is much, much better than the article two years ago:

SCIENTIFIC AMERICAN

April 2011 ScientificAmerican.com

Quantum Gaps in Big Bang Theory

Why our best explanation of how the universe evolved must be fixed—or replaced

Antibiotics

New Threat from Lethal Bacteria

Imaging

Neuroscience in the Courts

Seismology

Earthquake Warning System

Main points of Steinhardt et al:

The authors believe (incorrectly) that Planck2013 rules out chaotic inflation

They **strongly dislike new inflation** and other remaining inflationary models

This is what they do not like

1**) Problem of initial conditions:** Planck rules out inflation at Planck density. Low scale inflation is absolutely improbable.

Each of these statements is incorrect. This is an important scientific issue, so we will discuss it now.

2) **The curse of the multiverse**: After Planck, eternal inflation becomes unavoidable, which is a disaster

Many people believe that this is an advantage. If cyclic scenario is based on string theory, as the authors claim, it suffers from the same “problem”

3) **Unlikeliness of inflation** (The authors do not like it)

Shall we call it unluckiness problem? If one has problems constructing good inflationary models, others may try to help

4) **LHC does not like inflation too** (instability of Higgs vacuum during inflation)

Existing studies may be relevant for Higgs inflation, but not in general. In many cases, metastable or unstable vacua are STABILIZED during inflation. Remember hybrid inflation?

Initial conditions for chaotic inflation

Take our universe back to the Planck time in the Big Bang theory. It consisted of 10^{90} different causally disconnected domains of Planck size. The probability that all of them had the same density at the same time is less than $e^{-10^{90}}$ (horizon and homogeneity problems)

Now instead of that, take a single Planck-size **closed** universe with Planck density

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\phi_i^2 + V(\phi) \sim 1$$

A typical universe with $\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\phi_i^2 \gg V(\phi)$ instantly collapses. Nobody can observe such universes (and reduce their wave function).

A typical universe with $\frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\phi_i^2 \ll V(\phi)$ inflates and becomes huge, uniform and flat.

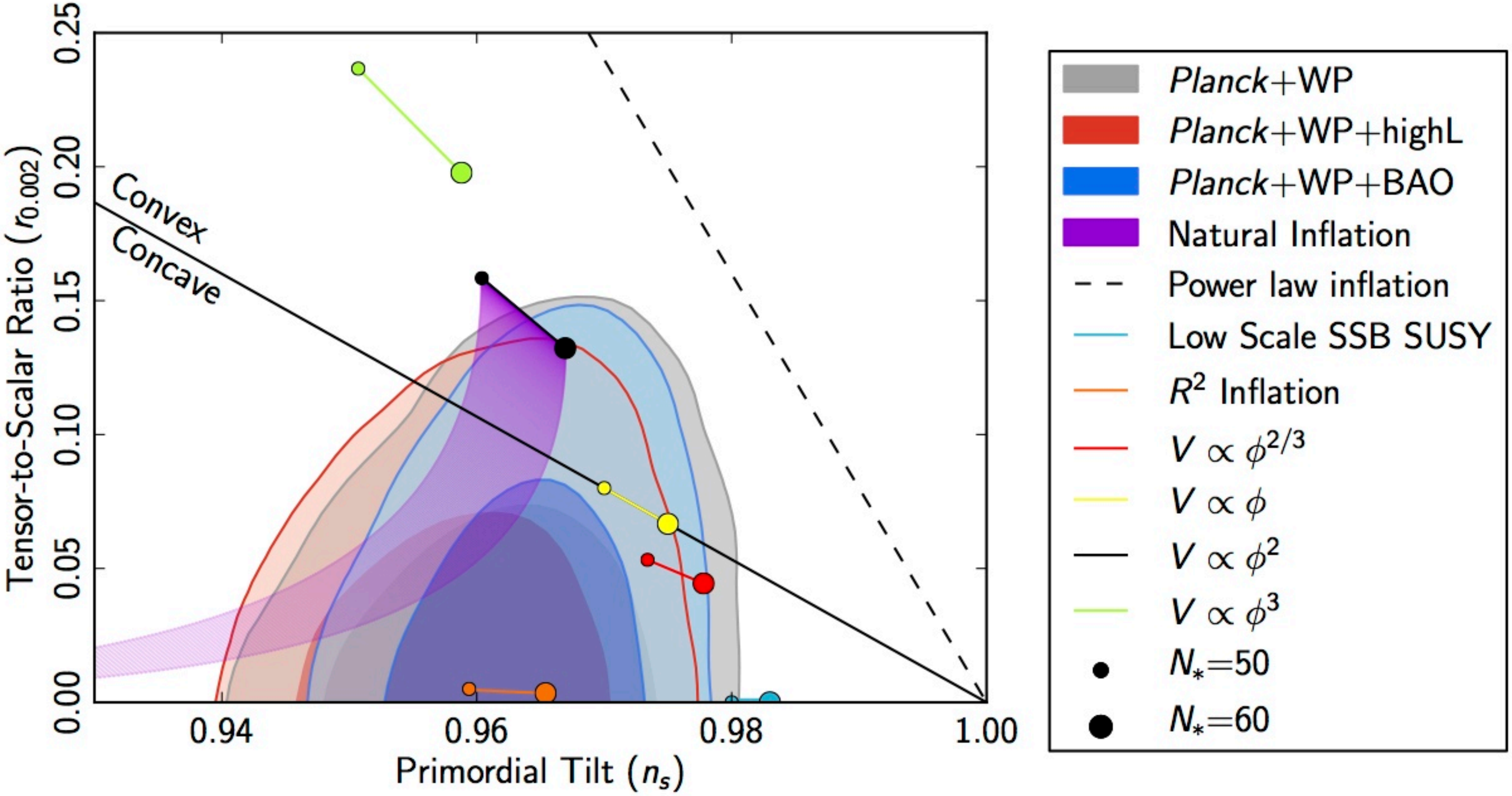
Thus it is easy to start chaotic inflation, if inflation may occur for V = O(1). And the authors seem to agree with it.

Looking at the Planck results, Steinhardt et all say:

1) chaotic inflation with V = O(1) does not work

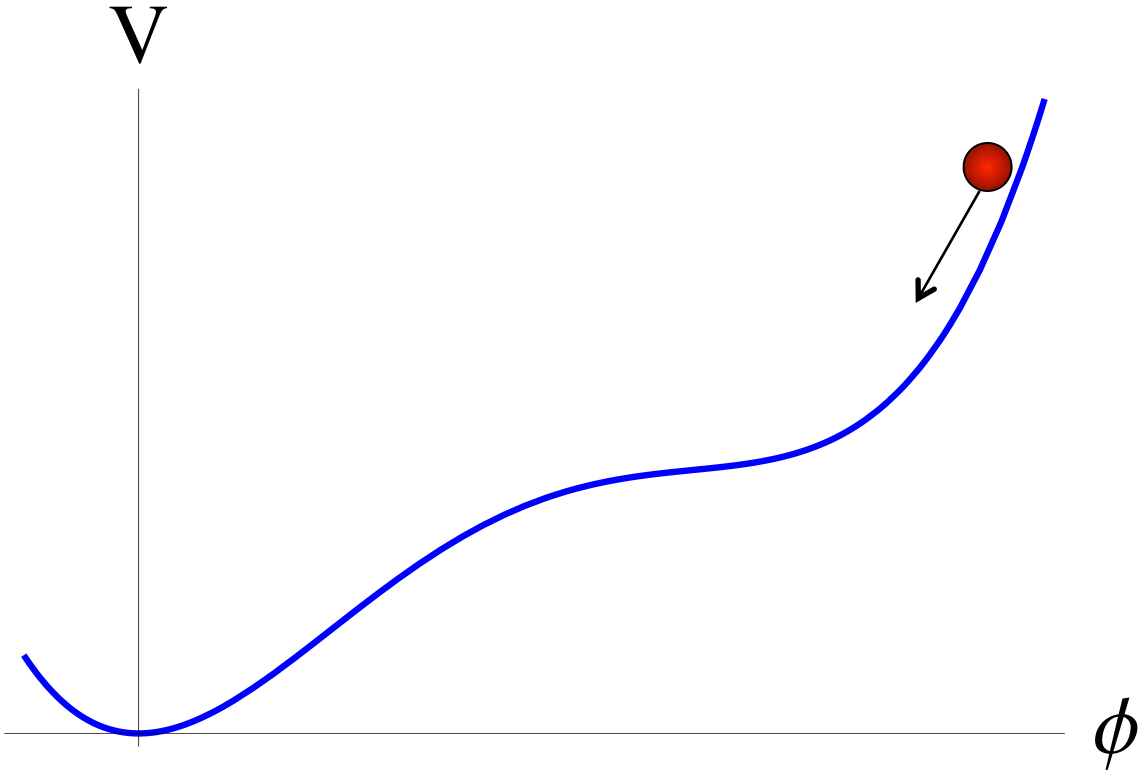
2) the only remaining models are the ones with V <<< 1, for which initial conditions for inflation are extremely improbable

Let us show that **each of these statements is incorrect**

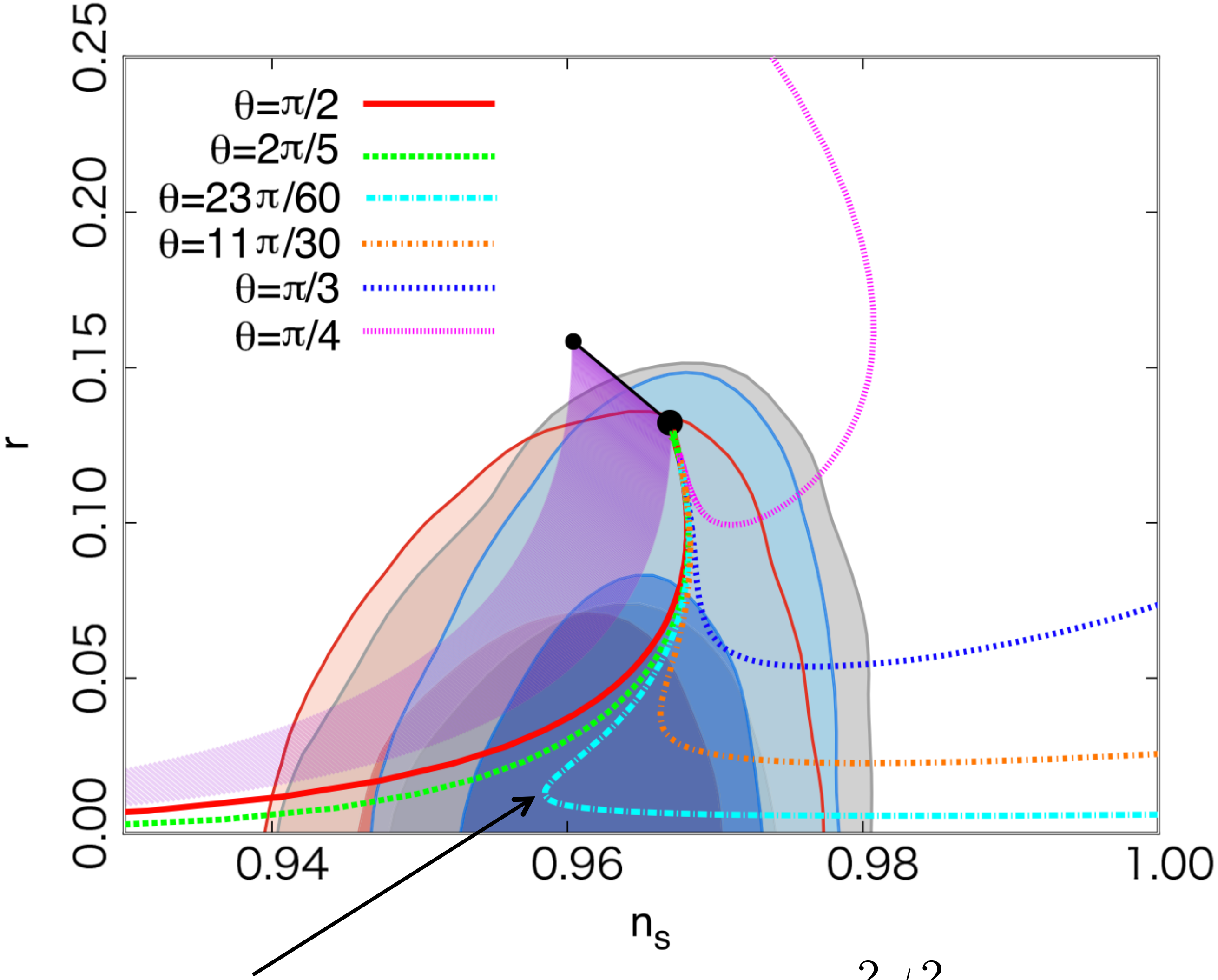


Example: $V = \frac{m^2\phi^2}{2}\left(1 - a(b\phi) + (b\phi)^2\right)$

As an example, take a ~ 1.87 and consider a family of such potentials for different b. The change of b does not change the overall shape of the potential, but stretches it horizontally.



Destri, de Vega and Sanchez, 2007 Nakayama, Takahashi, Yanagida 2013

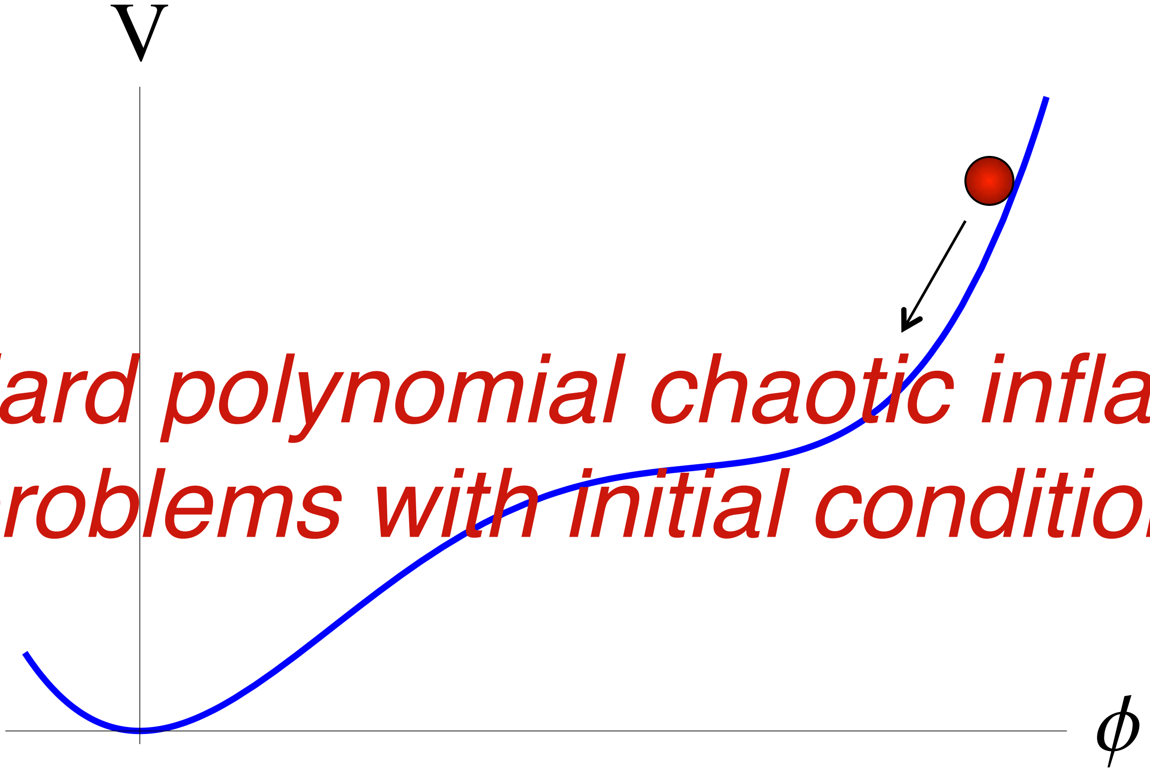


This line corresponds to potential $V = \dfrac{m^2\phi^2}{2}\Big(1 - a(b\phi) + (b\phi)^2\Big)$
for a ~ 1.87 and various values of b

Example:

$$V = \frac{m^2\phi^2}{2}\left(1 - a(b\phi) + (b\phi)^2\right)$$

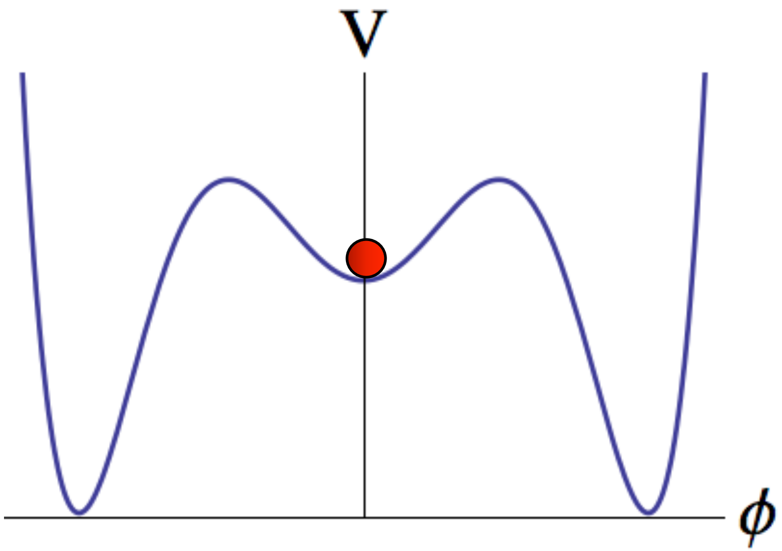
Just as an example, take a ~ 1.87 and consider a family of such potentials for different b. The change of b does not change the overall shape of the potential, but stretches it horizontally.



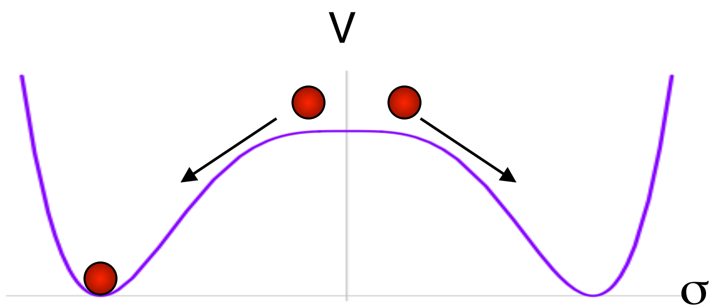
Standard polynomial chaotic inflation, no problems with initial conditions

What could seem “unlikely” about this potential?

Initial conditions for hilltop inflation



“Old inflation” in string landscape



Hilltop inflation

Fluctuations in the light field σ triggered by “old inflation” in string theory landscape put this field to the top of the potential in some parts of the universe. After the end of “old inflation” the new inflation begins.

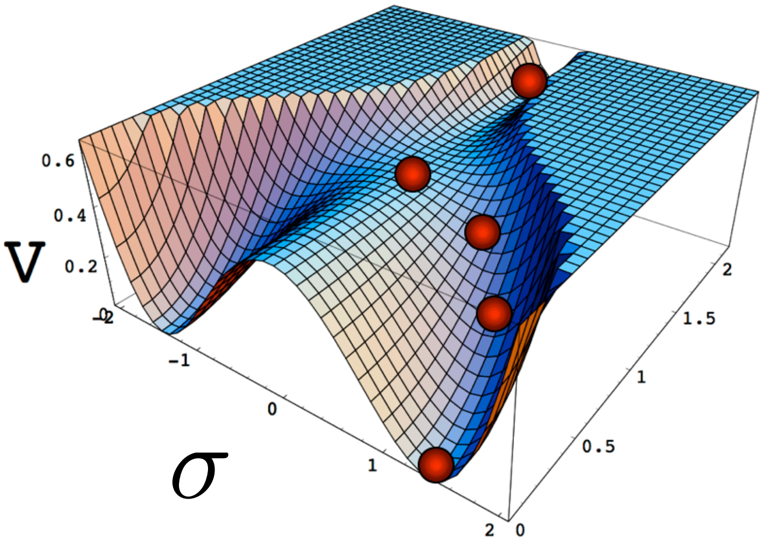
No problem with initial conditions!

Initial conditions for hilltop inflation, even simpler:

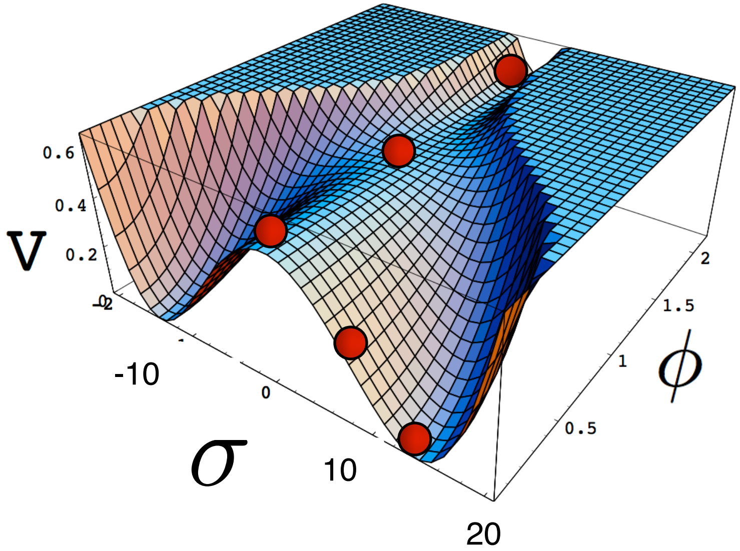
$$V(\sigma,\phi)=\frac{1}{4\lambda}(M^2-\lambda\sigma^2)^2+\frac{m^2}{2}\phi^2+\frac{g^2}{2}\phi^2\sigma^2$$

Like in hybrid inflation, but with symmetry breaking $\sigma \gg 1$

Inflation begins naturally, as in large field chaotic inflation

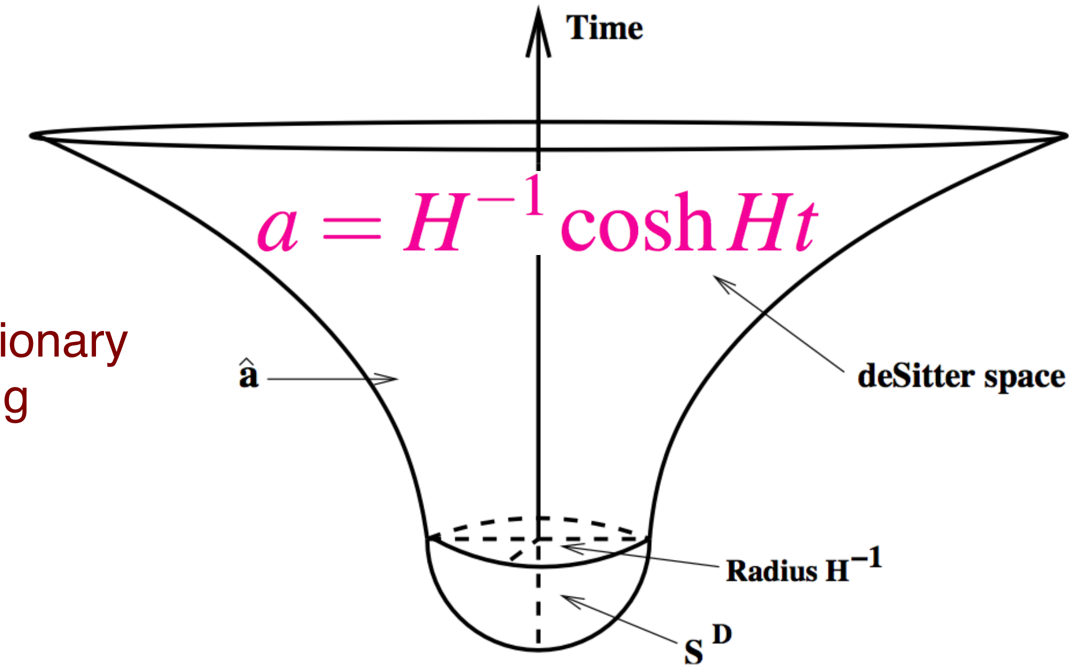


Hybrid



Hilltop

Quantum creation of the universe



Creation of the inflationary universe from nothing

Vilenkin 1982,
A.L. 1984,
Vilenkin 1984

Closed dS space cannot continuously grow from the state with a = 0, it must tunnel. For the Planckian H, as in chaotic inflation, the action is O(1), tunneling is easy. For very small H, creation of a closed universe is **exponentially suppressed**.

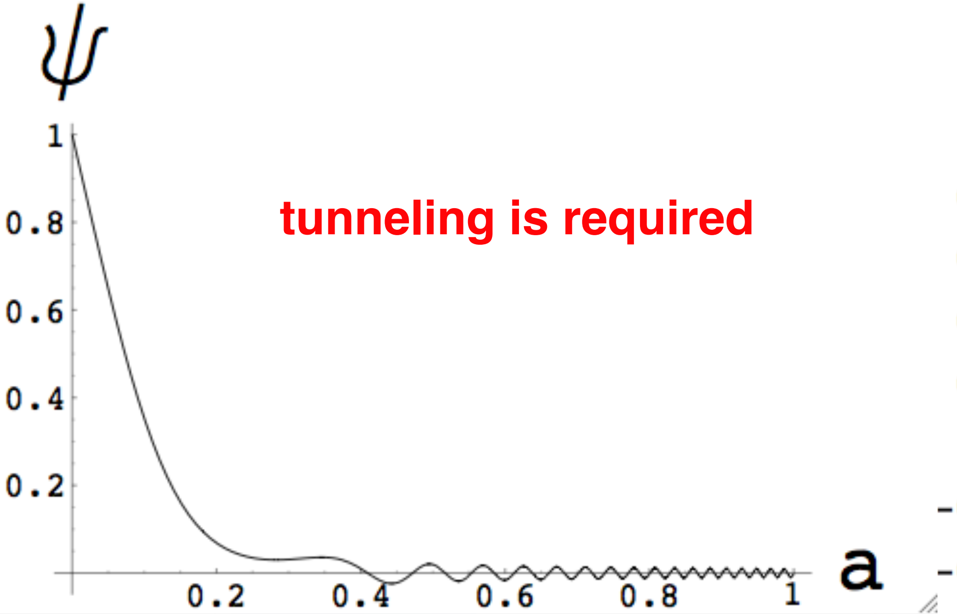
Thus it is difficult to start expansion of a **closed** universe with $V \ll 1$

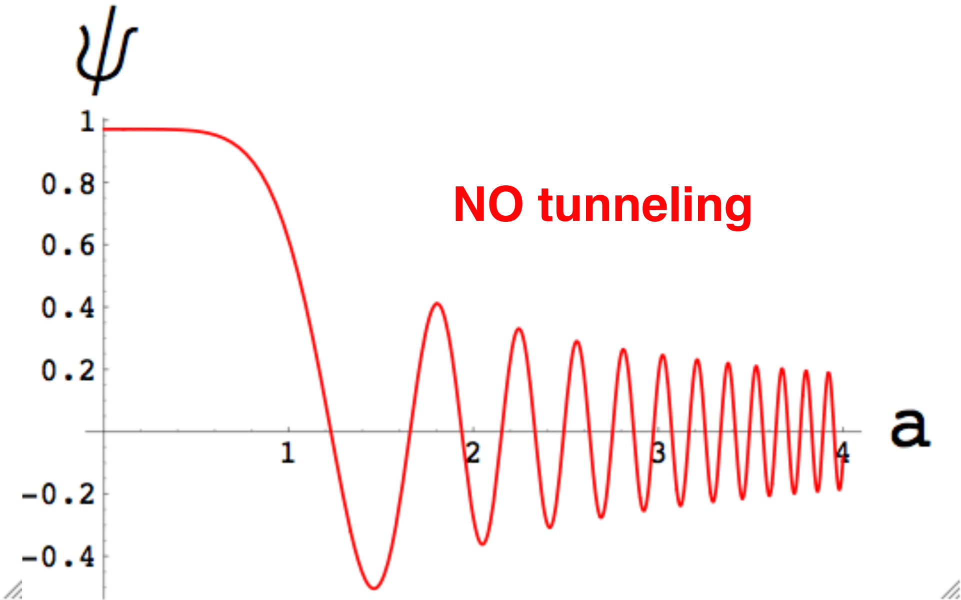
Not a problem!

Take a box (a part of a flat universe) and glue its opposite sides to each other. What we obtain is a **torus**, which is a topologically nontrivial flat universe.

No need to tunnel: A compact open inflationary universe may be arbitrarily small

Closed versus compact flat universe in quantum cosmology





Closed universe

Wave function of the universe is exponentially suppressed at large scale factor a

A.L. 1984, Vilenkin 1984

Compact flat universe

Wave function is not exponentially suppressed

Zeldovich, Starobinsky 1984, Coule, Martin 2000, A.L. 2004

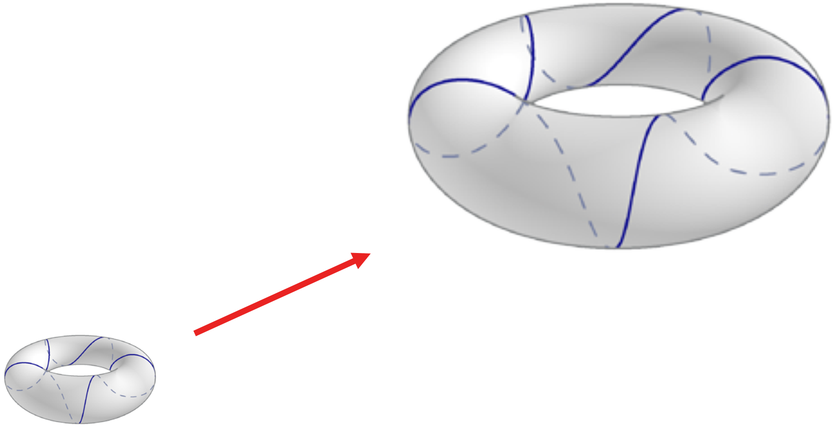
Thus there is NO exponential suppression of the probability of quantum creation of a compact flat (or open) inflationary universe corresponding to a top of the potential, so there is no problem with initial conditions for the low energy inflation.

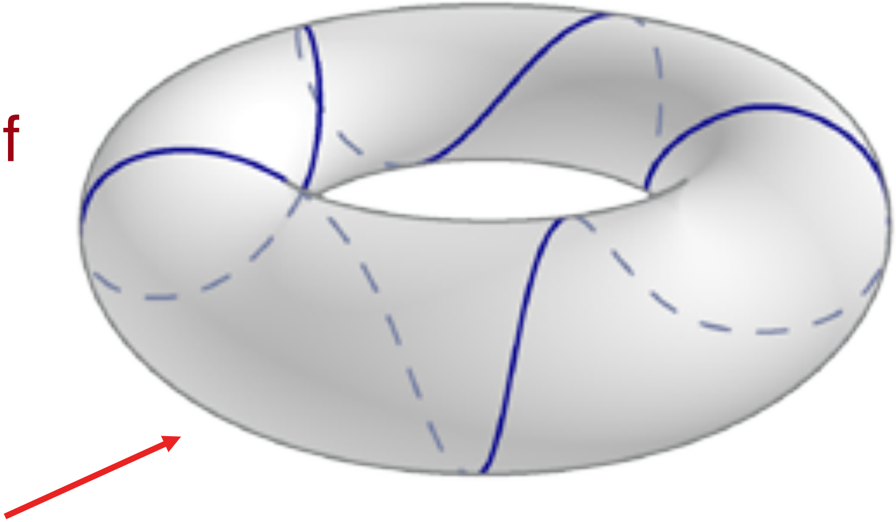
But what if you do not want to talk about quantum cosmology, and about models with more than one scalar field?

Chaotic mixing

Cornish, Starkman, Spergel 1996; A.L. 2004

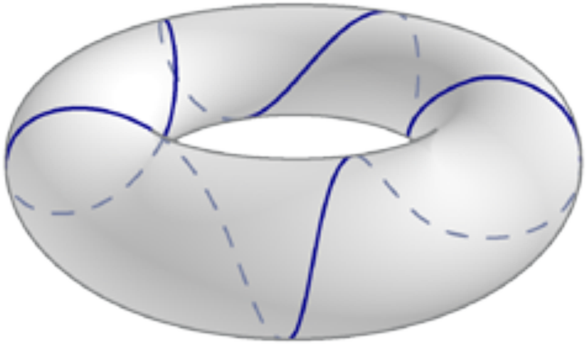
The size of a torus (our universe) with relativistic matter grows as $t^{1/2}$, whereas the mean free path of a relativistic particle grows much faster, as t





Therefore until the beginning of inflation the universe remains smaller that the size of the horizon ~ t

If the universe initially had a Planck size, then within the cosmological time t >> 1 each particle runs around the torus **many times** and appear in all parts of the universe with equal probability, which makes the universe homogeneous and keeps it homogeneous until the beginning of inflation



Thus chaotic mixing keeps the universe uniform until the onset of inflation, even if it can occur only at V<< 1. This is another solution of the problem of initial conditions.

Conclusion on initial conditions:

1) Planck data are perfectly compatible with simple chaotic inflation models, such as $V = a\,\phi + b\,\phi^2 + c\,\phi^3$, which do not suffer from any problems with initial conditions.

2) There are many different solutions of the initial conditions problem even for the low energy scale (hilltop) inflation, for example: Fluctuations generated at an earlier stage of inflation (e.g. dS expansion in the landscape), hybrid inflation type initial conditions following an earlier chaotic inflation regime, quantum creation of a compact open of flat universe, chaotic mixing.

So who is in trouble after Planck?

Back to reality – and to my originally planned talk:

Many inflationary models. Which ones can be implemented in the context of string theory and supergravity?

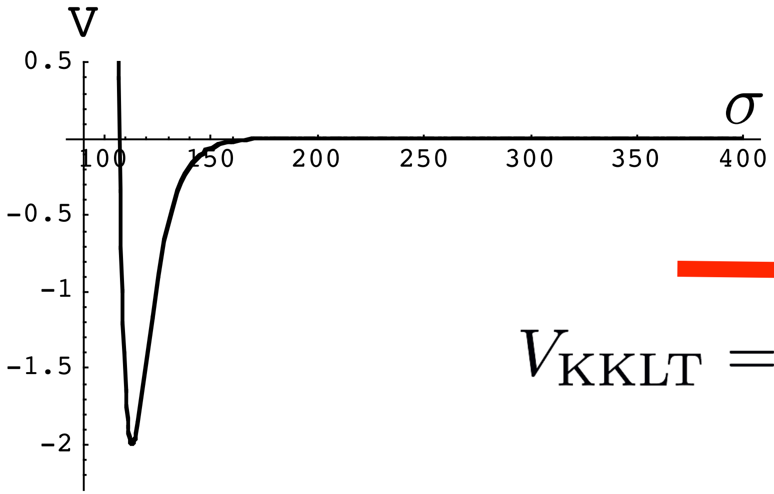
We will give only a small sample of available models.

String Theory

First step – vacuum stabilization. Several different approaches; perhaps the simplest one is the KKLT construction.

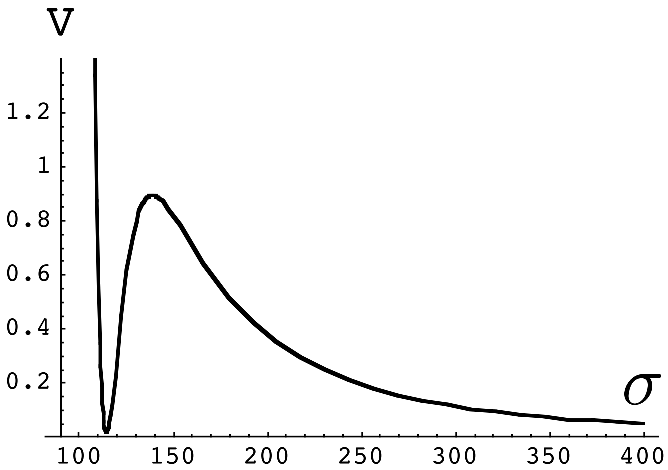
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

$$\rho = \sigma + i\alpha$$



Stabilization in a supersymmetric AdS minimum

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

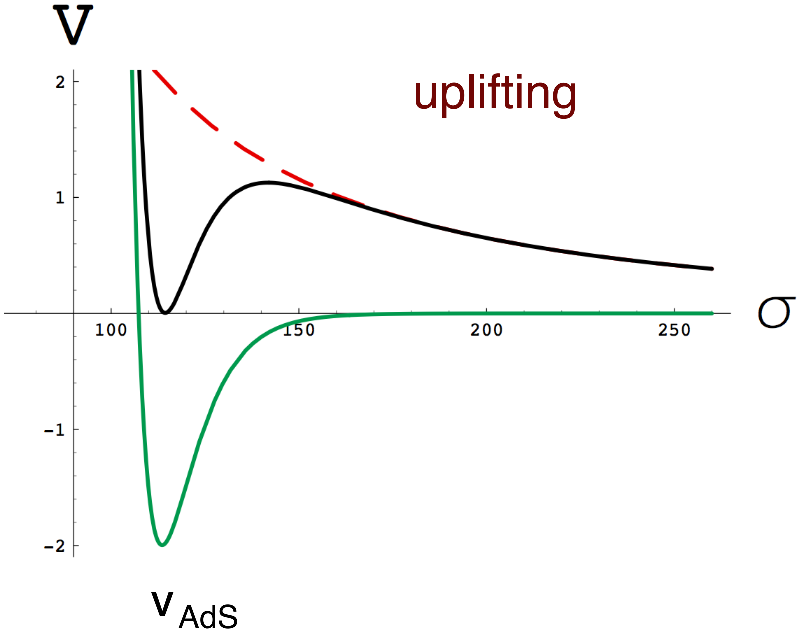


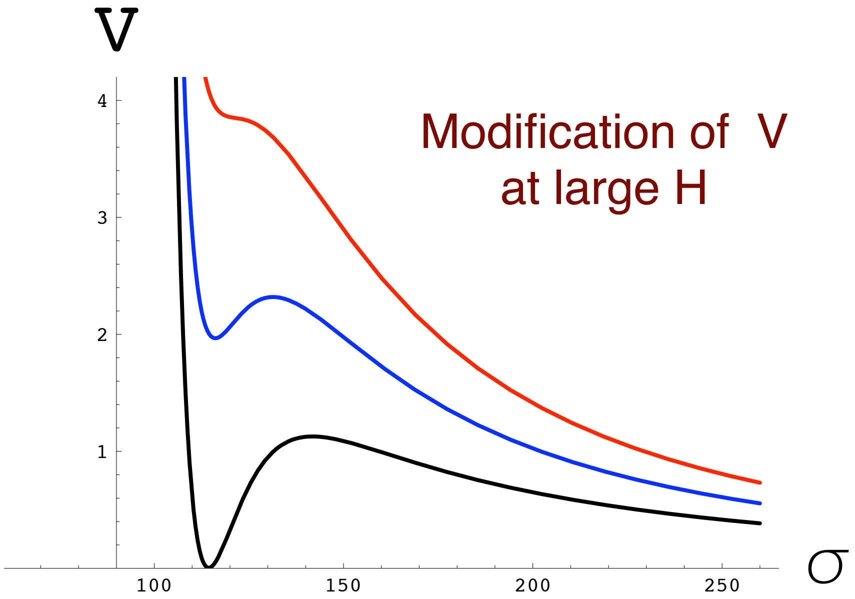
Uplifting to dS breaks SUSY

Vacuum destabilization during inflation

Kallosh, A.L. 2004

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





Constraint on the Hubble constant in this class of models:

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

Tensor modes in CMB and gravitino

Kallosh, A.L. 2007

$$H \lesssim m_{3/2}$$

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

unobservable

A discovery or non-discovery of tensor modes would be a crucial test for string theory and SUSY phenomenology

KL model

Kallosh, A.L. 2004

$$\mathcal{K} = -3\ln[(\rho+\bar\rho)]$$

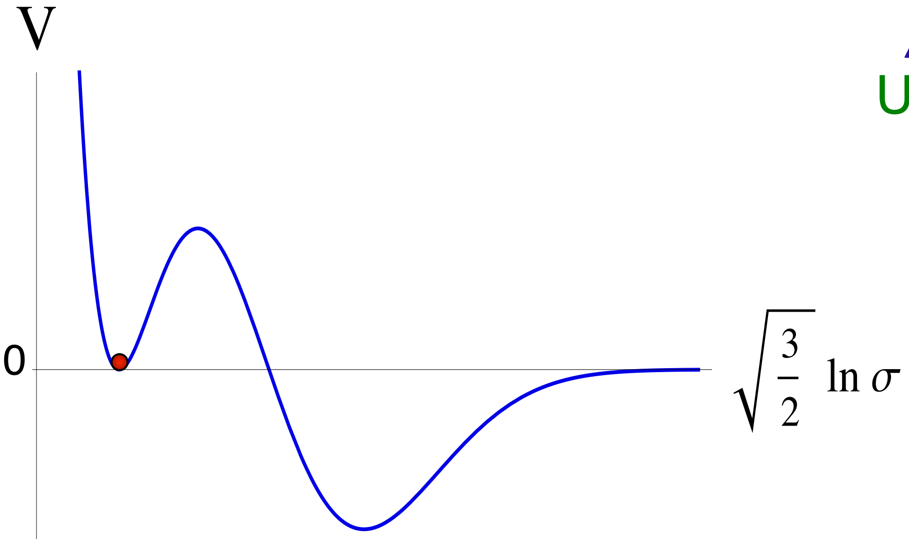
$$W = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

$$W_0 = -A\left(\frac{a\,A}{b\,B}\right)^{\frac{a}{b-a}} + B\left(\frac{a\,A}{b\,B}\right)^{\frac{b}{b-a}} + \Delta$$

It has a supersymmetric Minkowski vacuum for $\Delta = 0$, with a **high barrier**.

Δ makes it a supersymmetric AdS.

Uplifting breaks SUSY



$$m_{3/2} \sim \Delta$$

Thus one **can** have a high barrier and a tiny gravitino mass

H can be arbitrarily large, r becomes observable

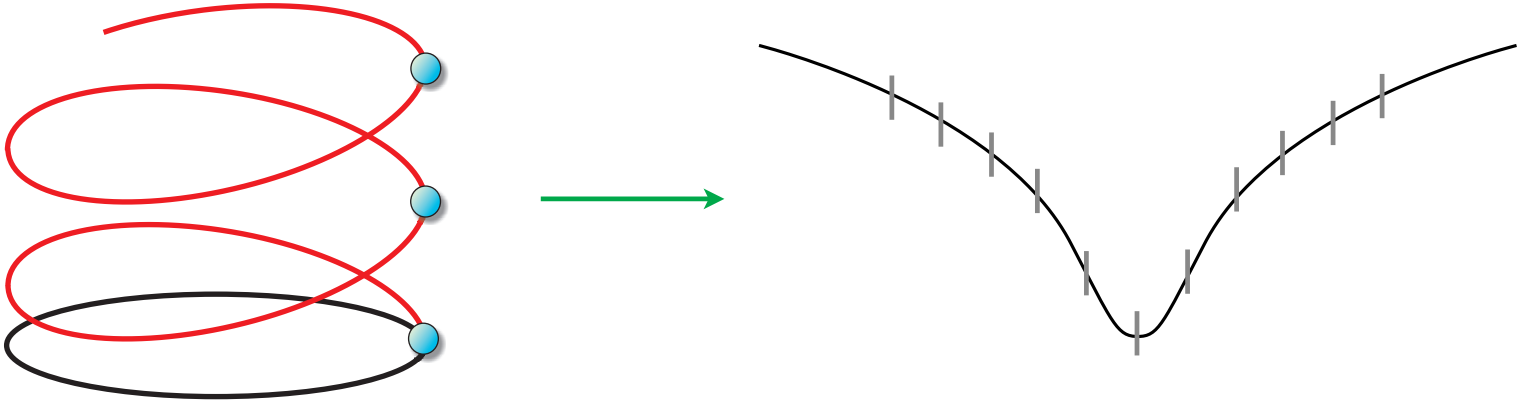
Chaotic Inflation in String Theory

An elegant example: Axion monodromy

Silverstein, Westphal   0803.3085
McAllister, Silverstein, Westphal 0808.0706

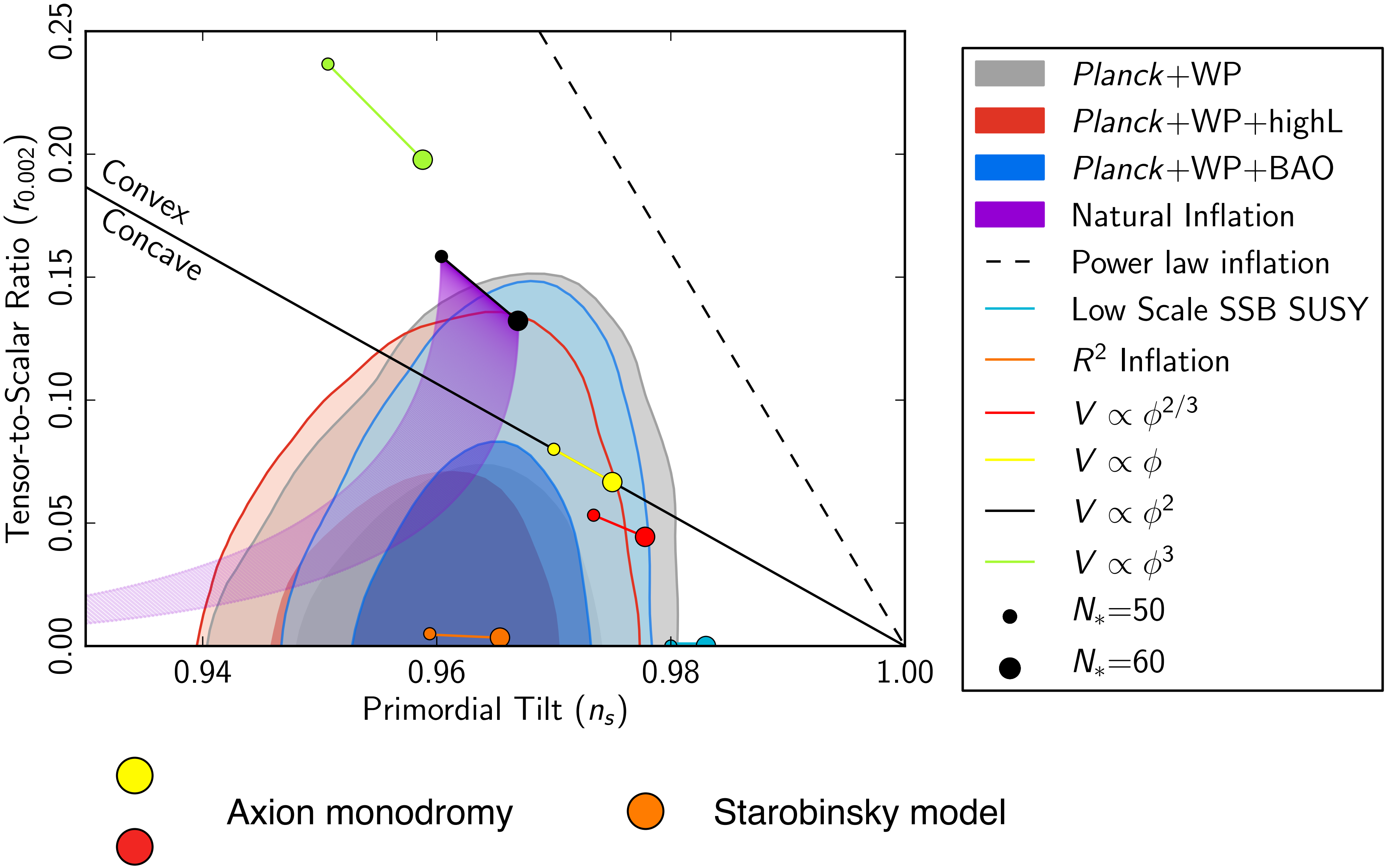
- unwind a periodic field direction into a *monodromy*

→   e.g. by employing a wrapped brane



$$V \sim \phi^{2/3} \quad \text{or} \quad V \sim \phi$$

Requires something like KL mechanism of strong moduli stabilization



Convex
Concave
Tensor-to-Scalar Ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60
Axion monodromy
Starobinsky model

Problems with 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…

Chaotic inflation in supergravity

Kawasaki, Yamaguchi, Yanagida 2000

Kahler potential $\mathcal{K} = S\bar{S} - \frac{1}{2}(\Phi - \bar{\Phi})^2$

and superpotential $W = mS\Phi$

The potential is very curved with respect to S and Im Φ, so these fields vanish. But Kahler potential does not depend on

$$\phi = \sqrt{2}\,\mathrm{Re}\ \Phi = (\Phi + \bar{\Phi})/\sqrt{2}$$

The potential of this field has the simplest form, as in chaotic inflation, without any exponential terms:

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

Quantum corrections do not change this result

More general models

Kallosh, A.L. 1008.3375, Kallosh, A.L., 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

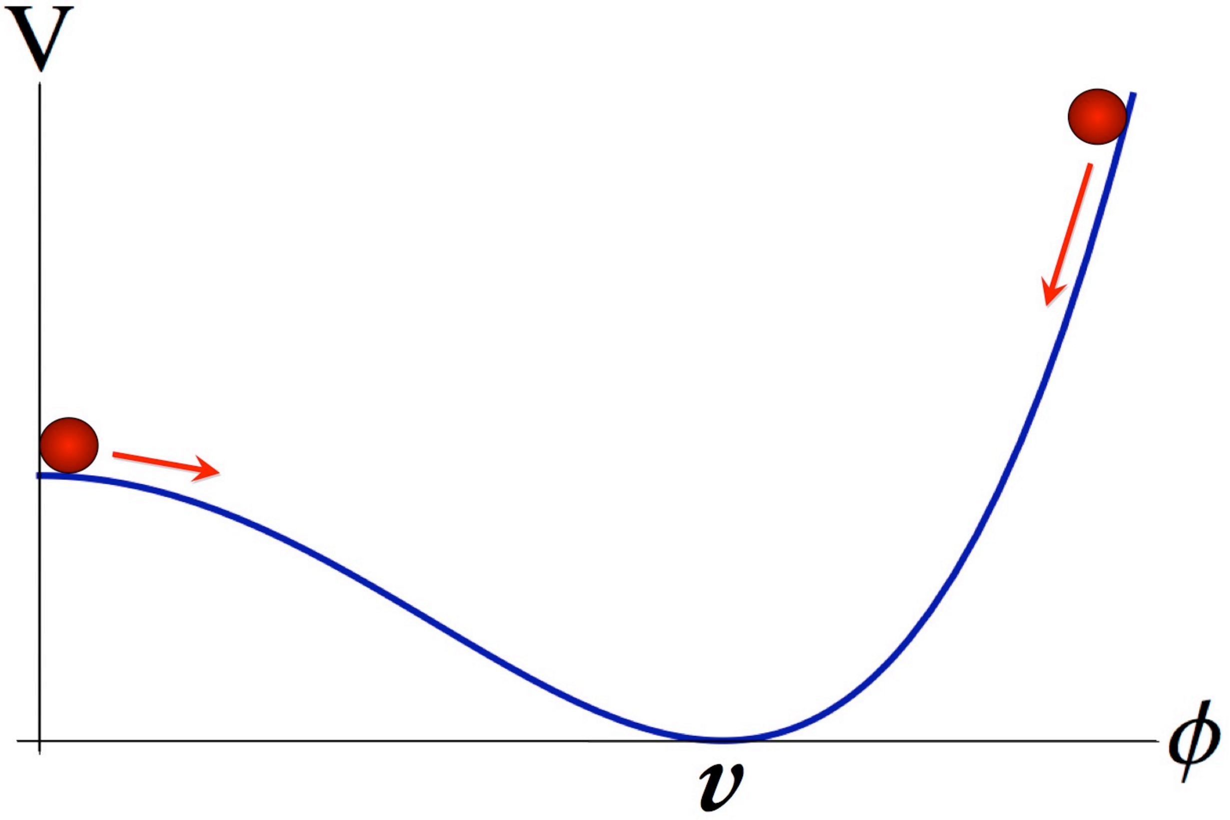
In this new class of supergravity inflation models, one can have **arbitrary potential for the inflaton field**.

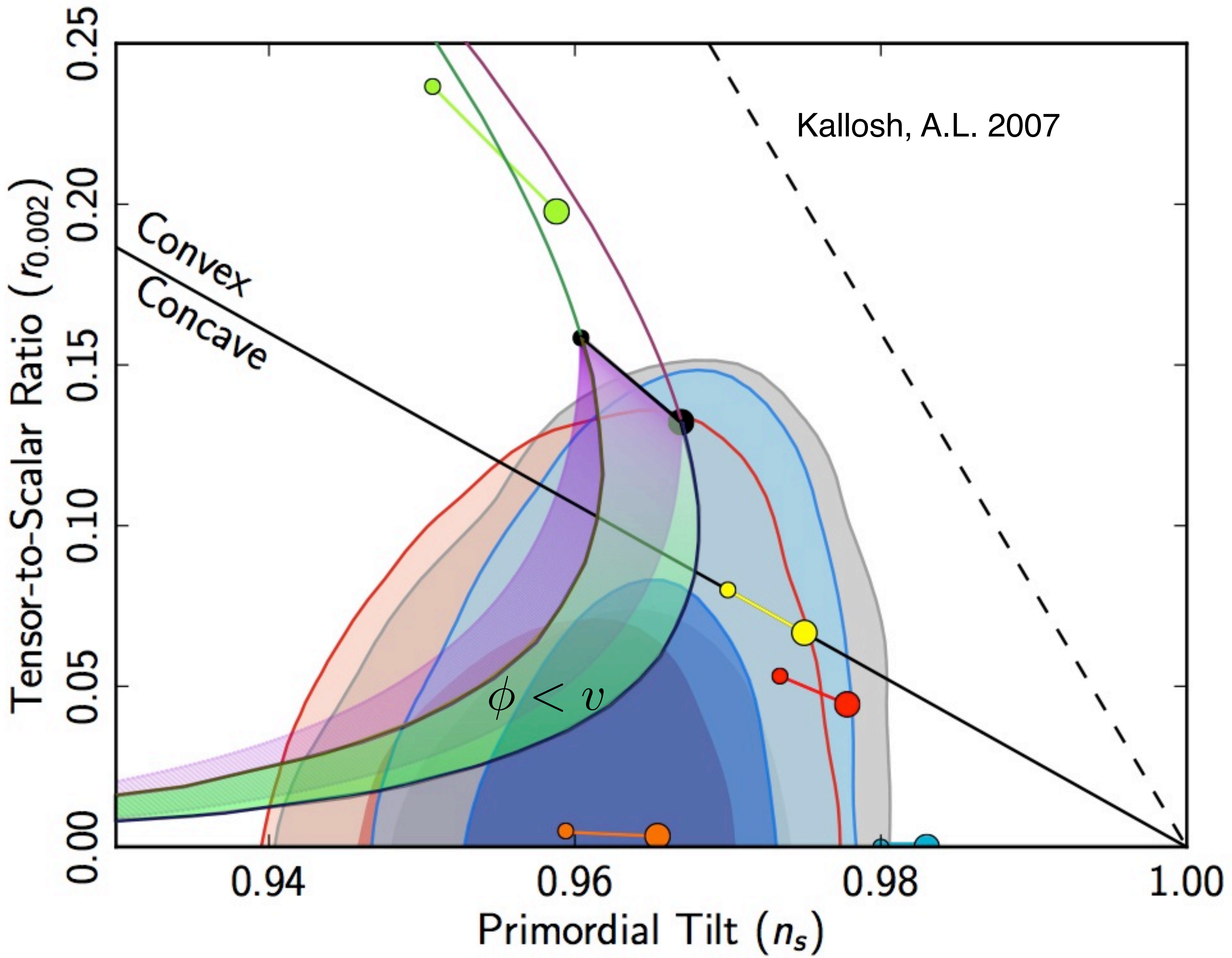
Thus one can have **ANY desirable values of n_s and r.** Moreover, one can generalize this scenario to describe production of non-gaussian perturbations and cosmic strings.

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

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

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




Kallosh, A.L. 2007
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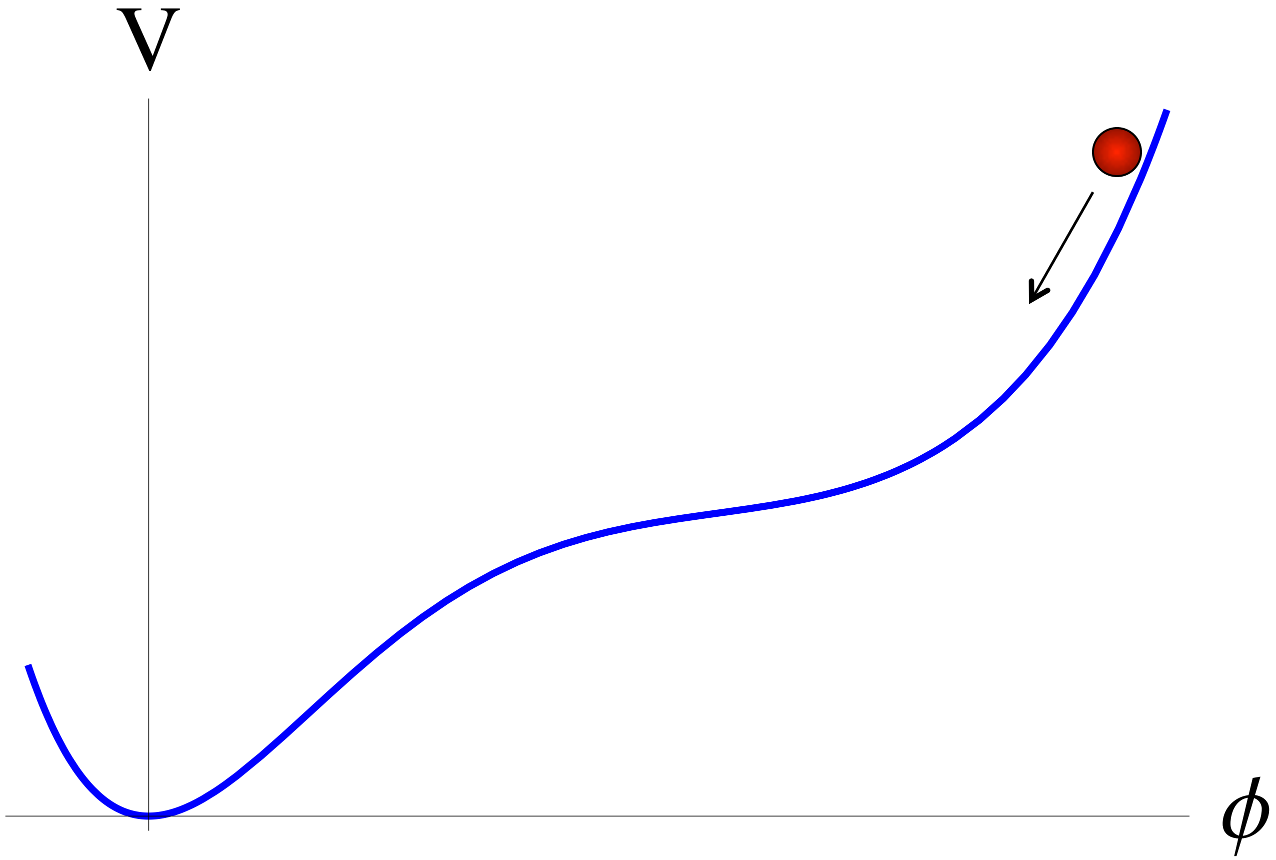
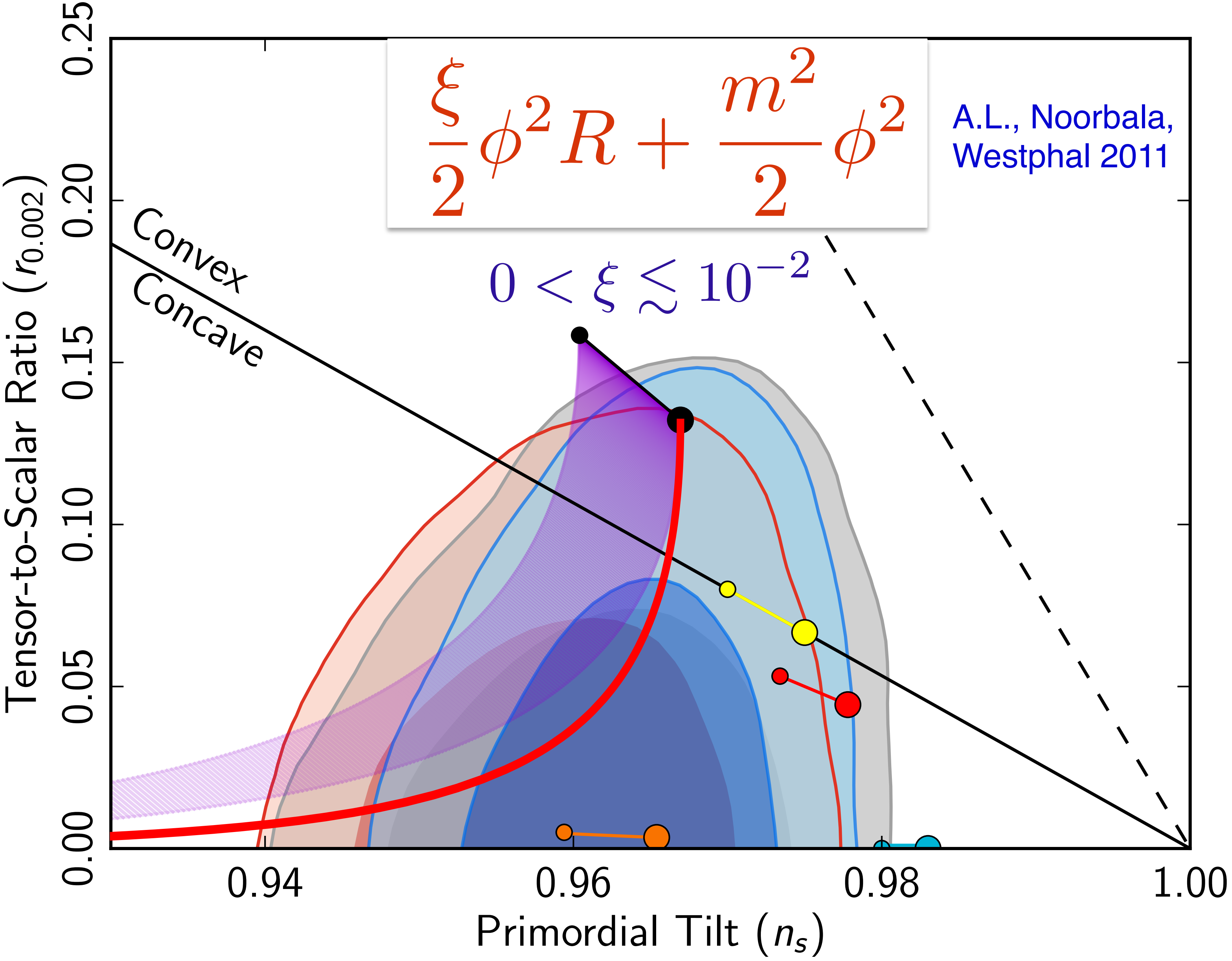
0.25
0.20
0.15
0.10
0.05
0.00
Primordial Tilt (n_s)
0.94
0.96
0.98
1.00

Similar, in SUGRA: $W = mS\phi\Big(1 - a(b\phi) + (b\phi)^2\Big)$

$$V = m^2\phi^2\Big(1 - a(b\phi) + (b\phi)^2\Big)^2$$



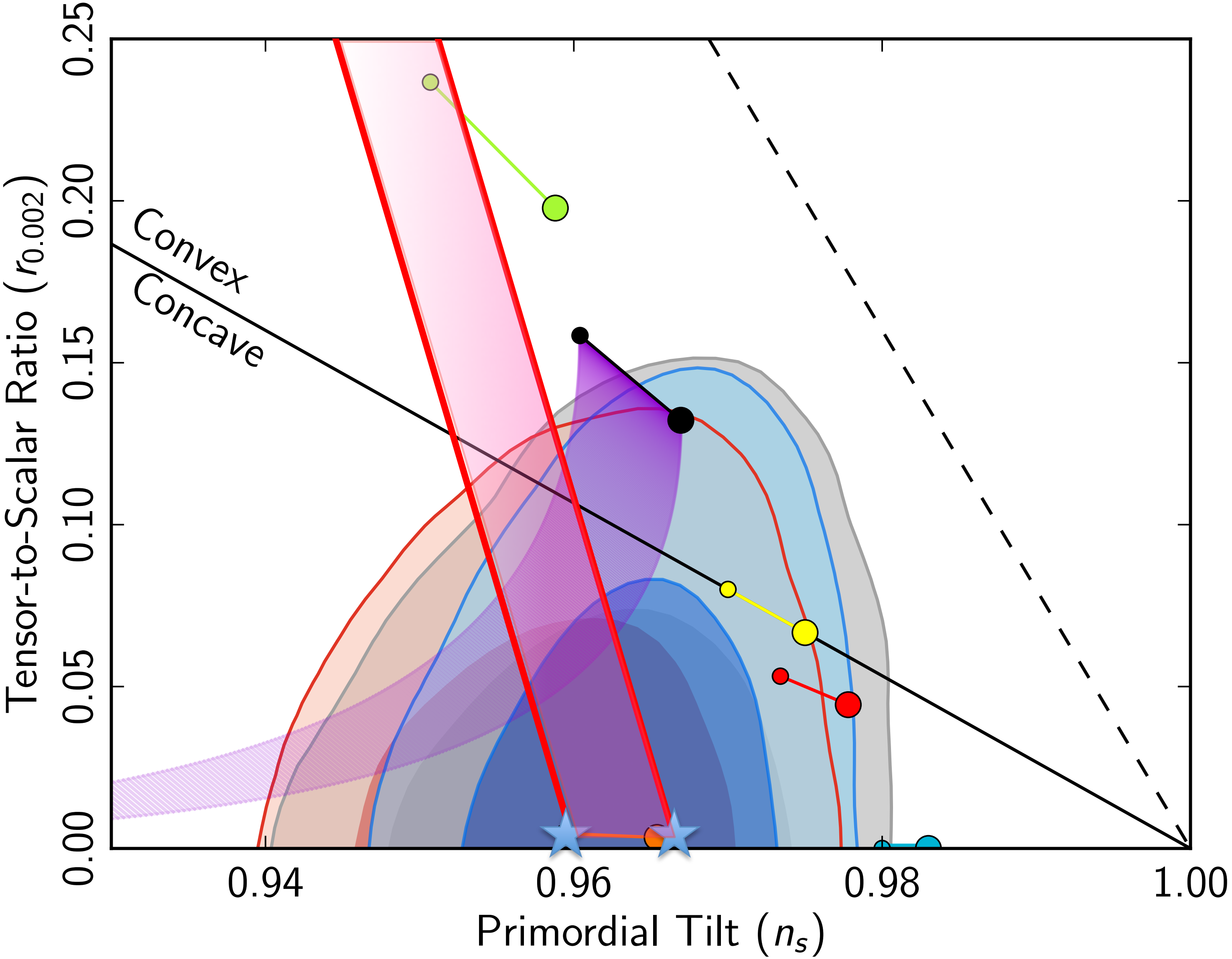


$$\frac{\xi}{2}\phi^2 R + \frac{m^2}{2}\phi^2$$

A.L., Noorbala, Westphal 2011

$$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}\phi^4$$

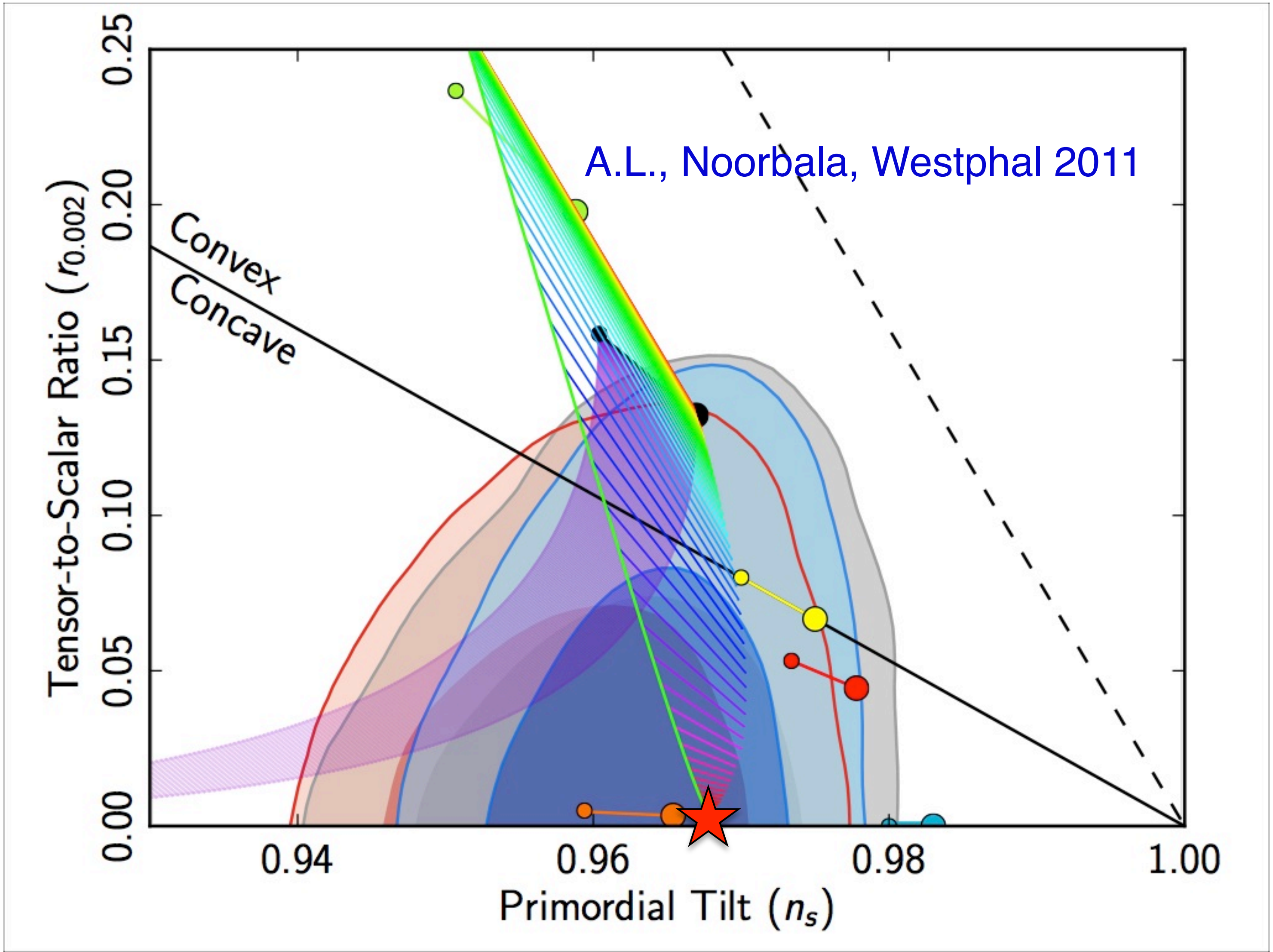
Okada, Rehman, Shafi 2010



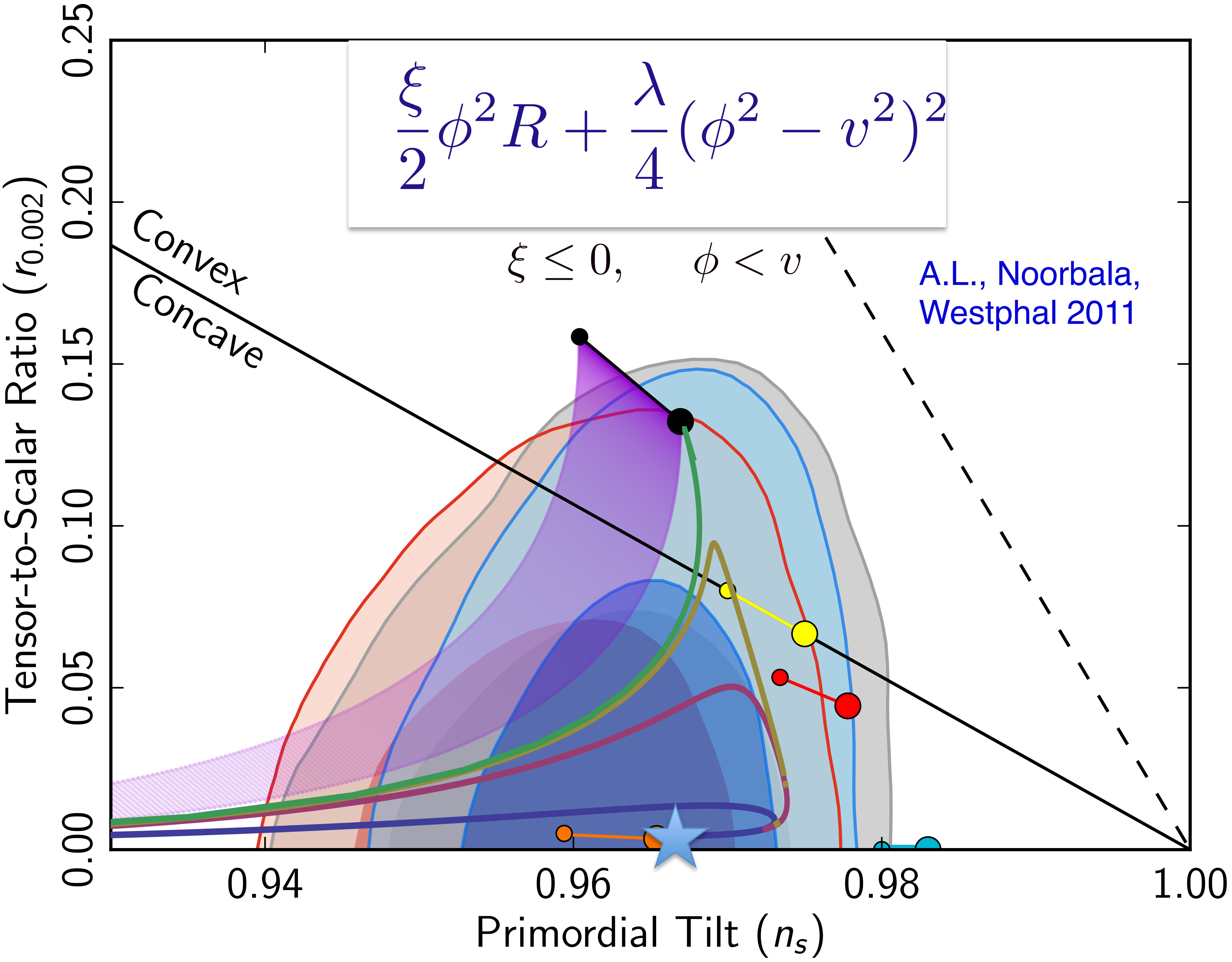
“Higgs Inflation” ★

$$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Salopek, J. R. Bond and J. M. Bardeen, 1989
Bezrukov, Shaposhnikov 2008
Ferrara, Kallosh, A.L., Marrani, Van Proeyen 2011



A.L., Noorbala, Westphal 2011

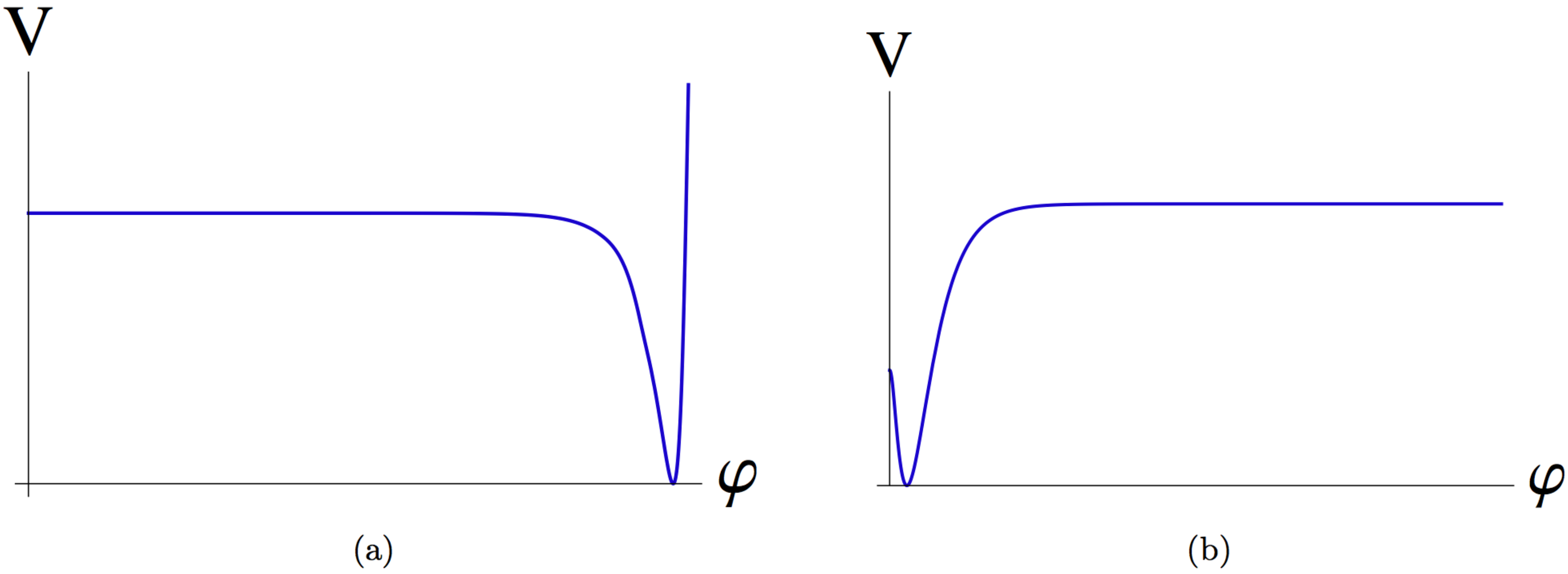


$$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$$

$\xi \leq 0, \quad \phi < v$

A.L., Noorbala, Westphal 2011

Potential for non-minimal Higgs inflation in Einstein frame for $\xi < 0$, $\phi < v$, and for $\xi > 0$, $\phi > v$



(a)

(b)

Potential for Starobinsky model is very similar, the same prediction for n_s and r.

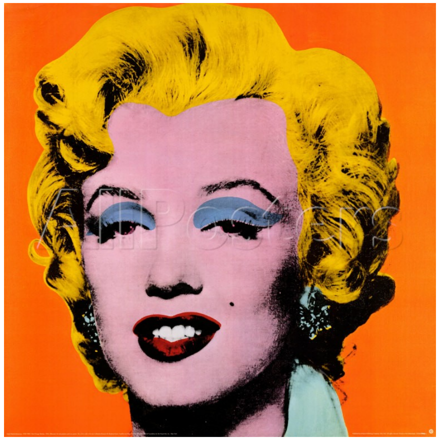
Actually, predictions are the same for the same N, but N may be different for different models because of different reheating.

Thus for ANY Planck-compatible set of n_s and r one can find MANY sets of supergravity based inflationary models nicely fitting the data. Degeneracy can be removed by a possible discovery of a tiny non-flatness of the universe, non-Gaussianity, cosmic strings, anomalies, etc.

For example, in some models of open inflation, one may suppress the quadrupole. In some versions of chaotic inflation in supergravity one can realize the curvaton mechanism, generate non-Gaussianities due to vector field production, produce superhorizon (or nearly superhorizon) cosmic strings, and may do many other “bad things” to our universe, in order to produce tiny imperfections which may appeal to certain people ☺

Indeed, some claim that the secret of beauty is in a slight asymmetry between left and right sides of a face, which may become enhanced by a dark spot of a proper size.

This observation was confirmed by measurements in all channels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Feeling lucky…

Our present position is extremely fine-tuned in terms of the cosmological evolution. 10^{-8} AU (age of the universe) ago we did not even know that other galaxies exist. 3×10^{-9} AU ago we did not see the CMB anisotropy. 10^{-9} AU ago we did not know about dark energy. 3×10^{-10} AU ago the Planck satellite did not yet fly. Happy epoch of great cosmological discoveries probably will be over in 10^{-8} AU. We are creating the map of the universe which is not going to change much during the next billion years…

The fact that we were born just in time to participate in this magnificent process and witness great cosmological discoveries is a 6 σ anomaly, the one that we should be very happy about.

But is it actually an anomaly or a superselection rule? Cosmologists can only live at the time when investigation of the universe is possible and financially feasible.

Efstathiou, private communication ☺