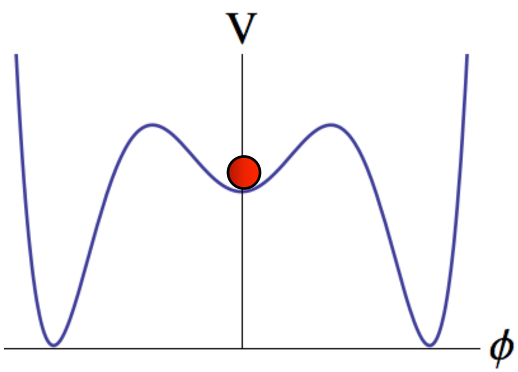
Inflation after Planck2013

Andrei Linde

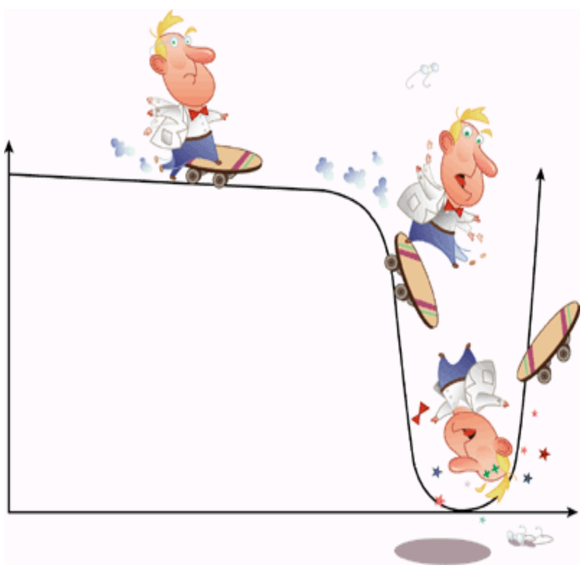
Inflation

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

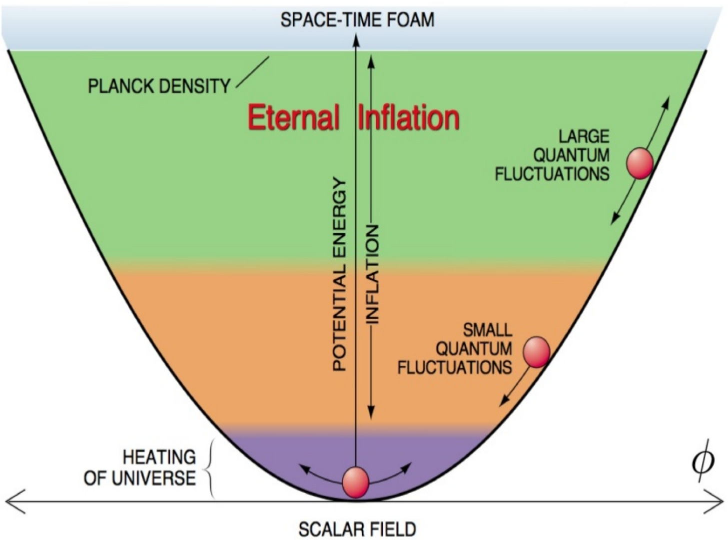
Guth, 1981 - old inflation. Great idea, first outline of the new paradigm, but did not quite work, and did not predict inflationary perturbations



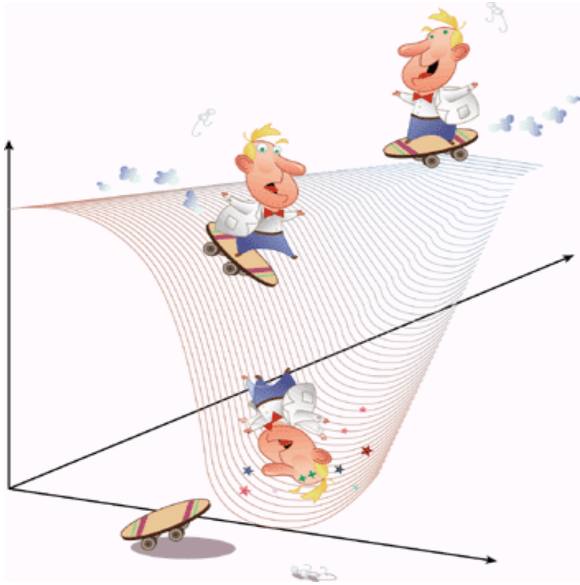
$$V(\phi) = \frac{m^2}{2}\phi^2$$



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



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, as predicted in 1981 by Mukhanov and Chibisov

No contribution from isocurvature perturbations and cosmic strings above few %

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

Perturbations are Gaussian with 0.01% accuracy !!!

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

Not everyone agrees:

Ijjas, Steinhardt, Loeb 1304.2785

“Inflationary paradigm in trouble after Planck2013”

“In sum, we find that recent experimental data disfavors all the best-motivated inflationary scenarios and introduces new, serious difficulties that cut to the core of the inflationary paradigm.”

Main points:

The authors believe that Planck2013 rules out chaotic inflation

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

Detailed arguments:

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

I believe that 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 faces the same "problem"

3) **Unlikeliness of inflation**

Subjective criterion. Some of the authors did not like inflation even before Planck.

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.

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.

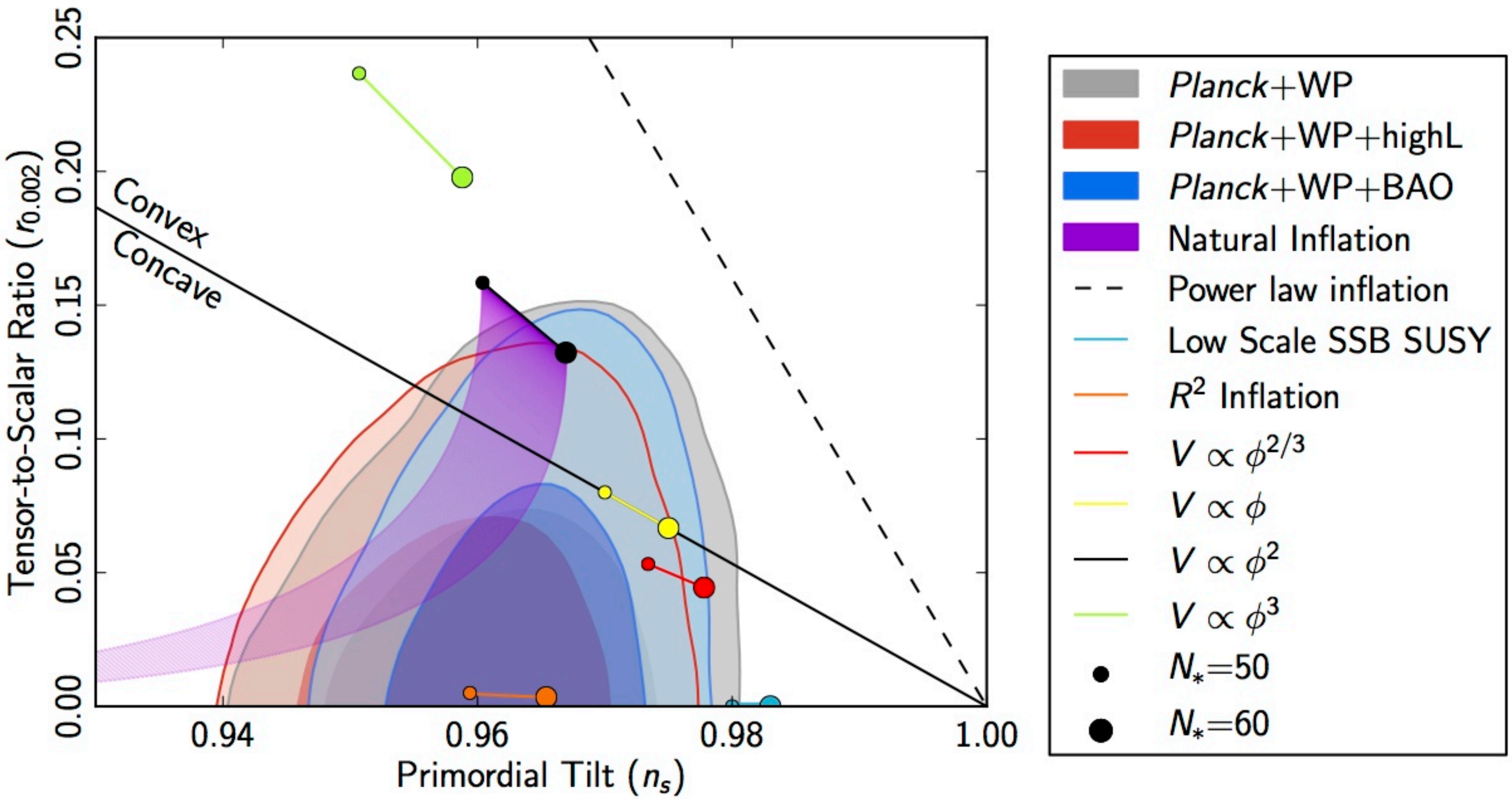
Thus it is easy to start chaotic inflation, if inflation may occur for V = O(1). The authors seem to agree with it.

Looking at the Planck results, Ijjas et al say:

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

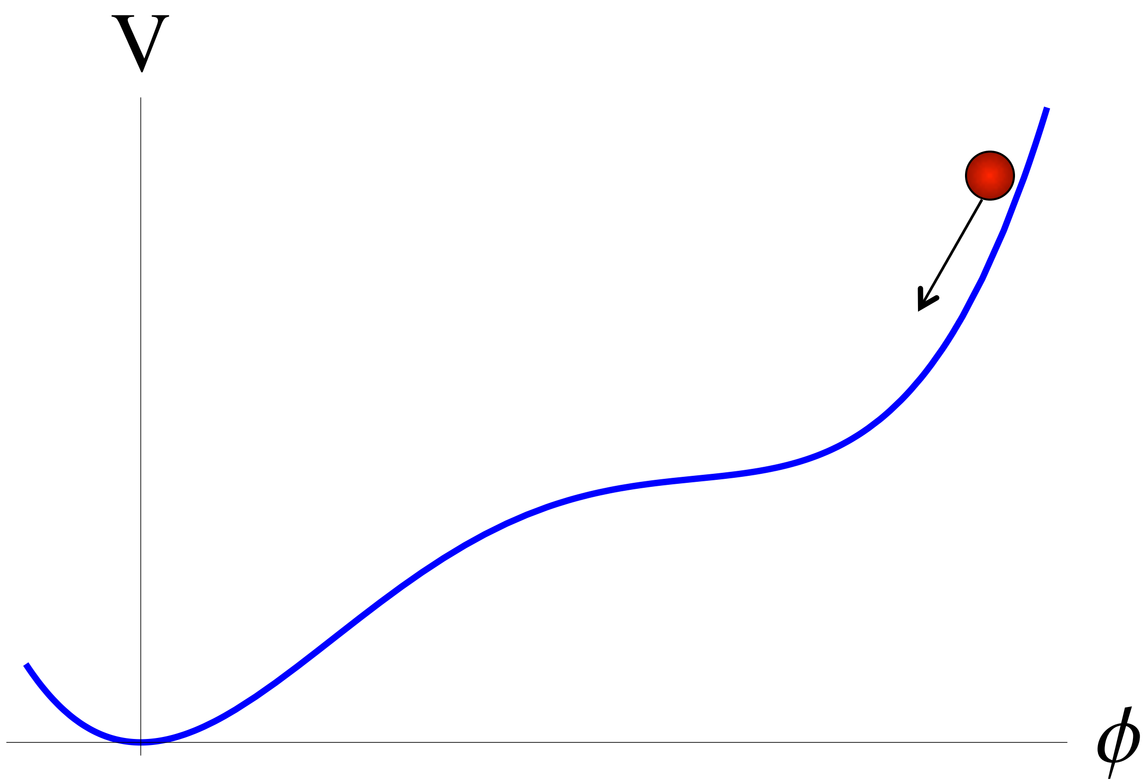
2) the only remaining models are the ones with V <<< 1 (e.g. **new inflation**) for which initial conditions for inflation are extremely improbable

Let us check these statements

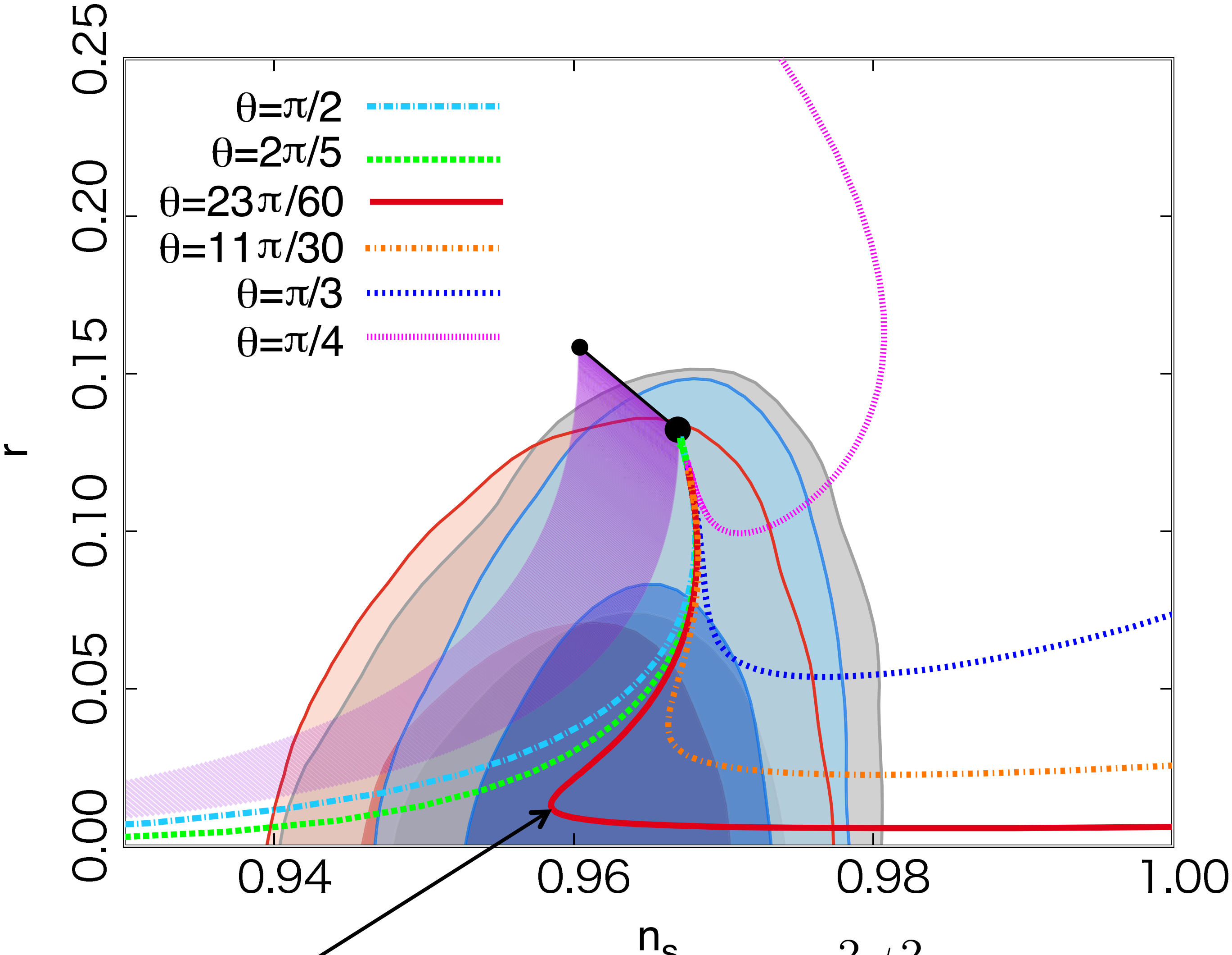


Example: $$V = \frac{m^2\phi^2}{2}\left(1 - a(b\phi) + (b\phi)^2\right)$$

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

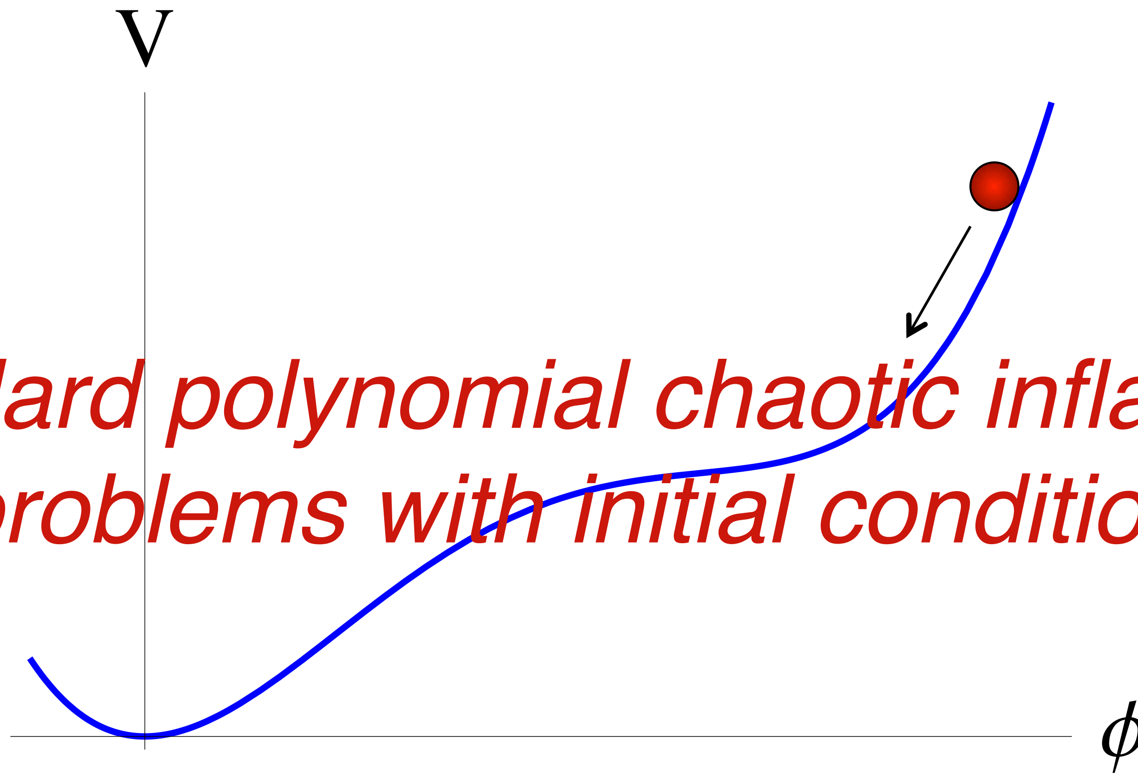


This line corresponds to potential $V = \frac{m^2\phi^2}{2}\Big(1 - a(b\phi) + (b\phi)^2\Big)$

for a ~ 1.87 and various values of b

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

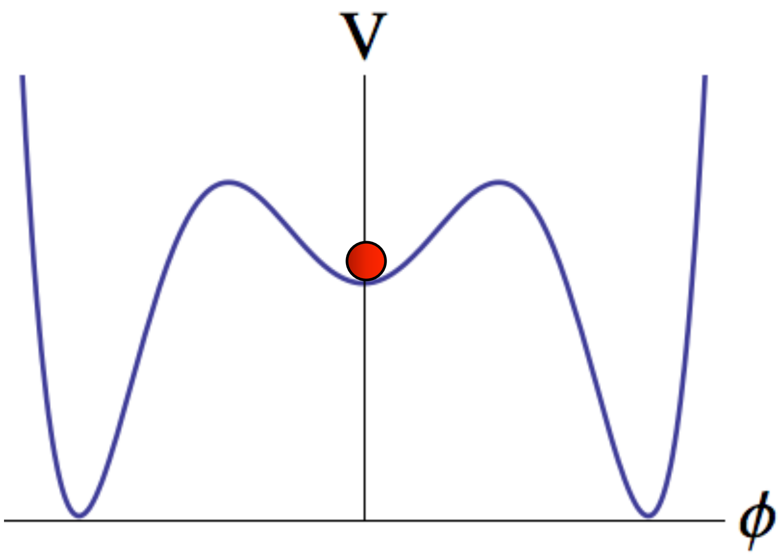
Just as an example, take a ~ 1.87 and consider a family of such potentials for different b. The change of b does not change the overall shape of the potential, but stretches it horizontally.



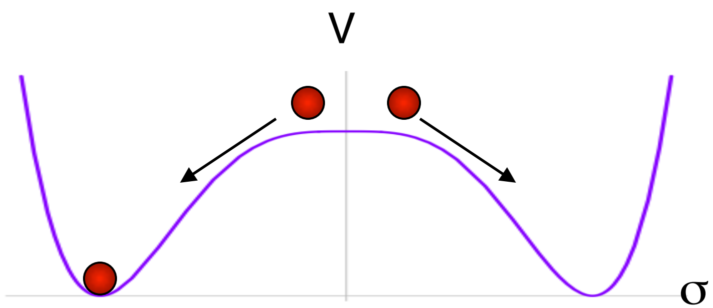
Standard polynomial chaotic inflation, no problems with initial conditions

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!

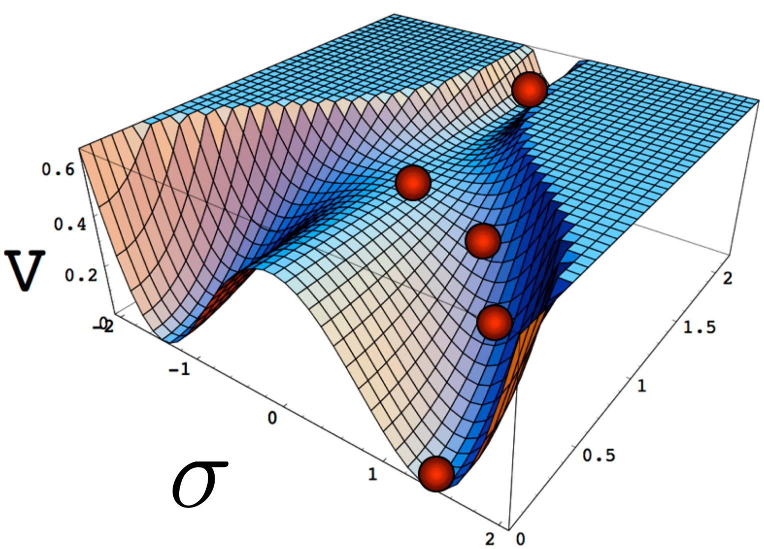
Initial conditions for hilltop inflation, even simpler:

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

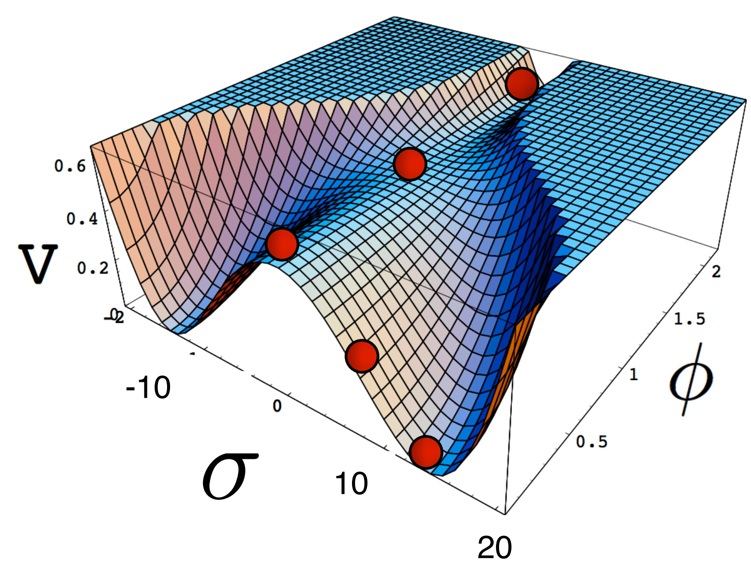
Like in hybrid inflation, but with symmetry breaking $\sigma >> 1$

Inflation begins naturally, as in large field chaotic inflation

Hybrid



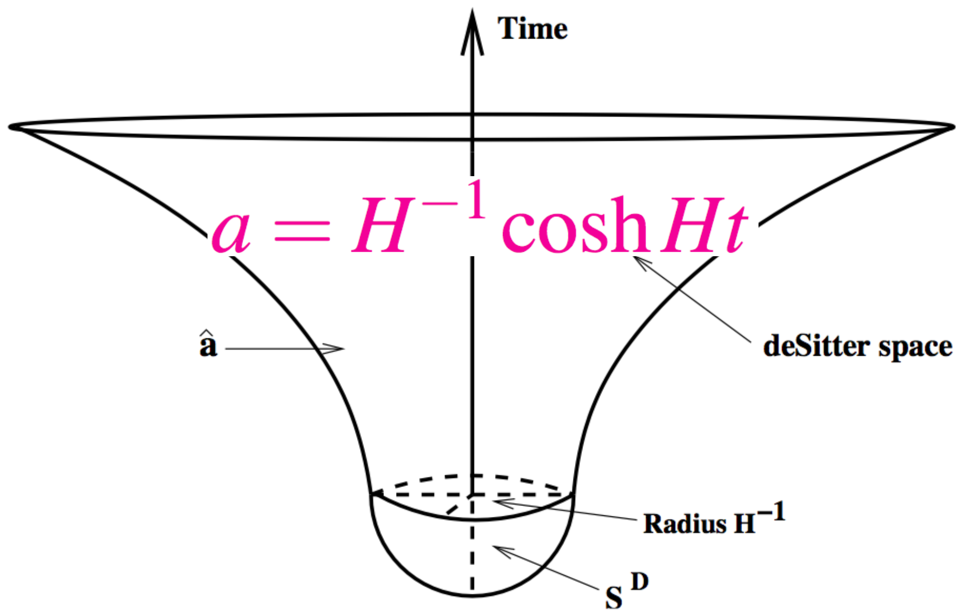
Hilltop



Quantum creation of the universe

Creation of a **closed** 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 Planckian H ~ 1, as in chaotic inflation, the action is O(1), tunneling is easy. For H << 1, creation of a closed universe is exponentially suppressed.

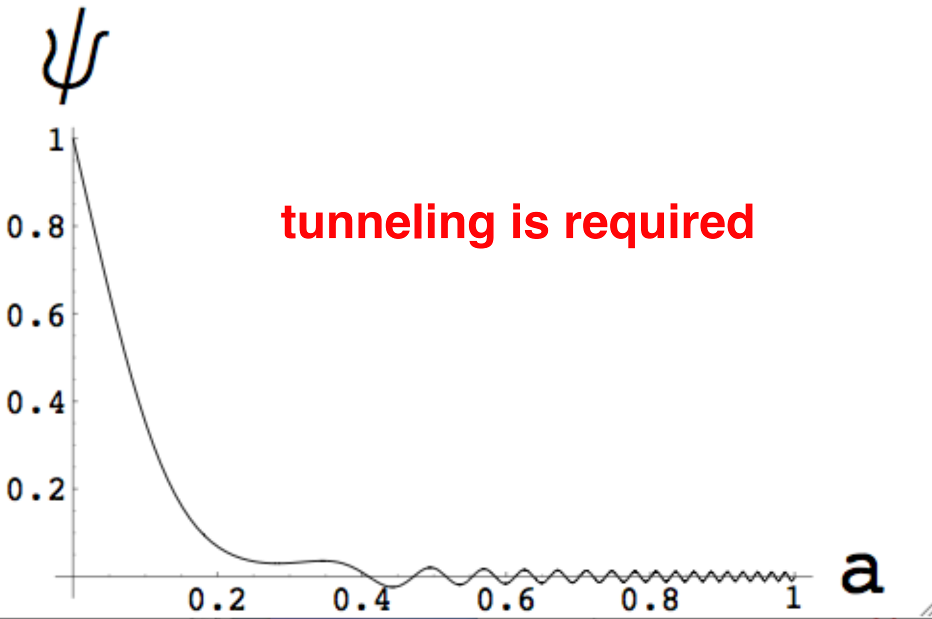
This agrees with the general expectation that it is better to start inflation near Planck density. However, in fact it only means that the universe is created near the highest maximum of V.

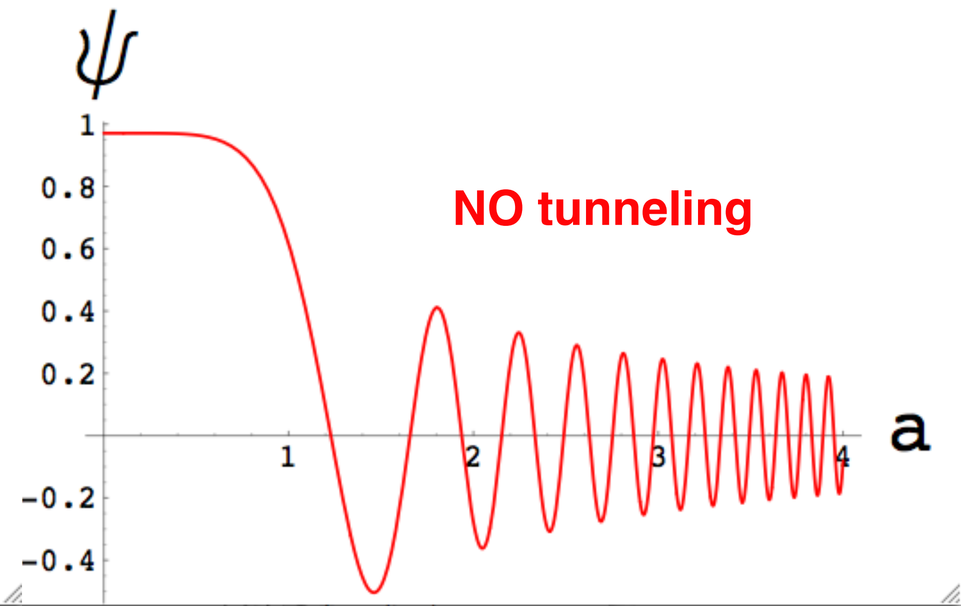
Not a problem!

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

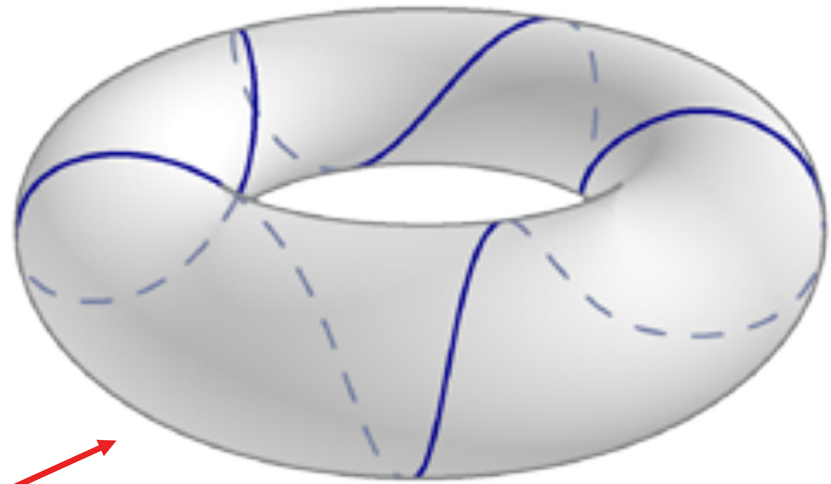
Thus there is **no** exponential suppression of the probability of quantum creation of a compact flat (or open) inflationary universe corresponding to a top of the potential, so there is no problem with initial conditions for the low energy inflation.

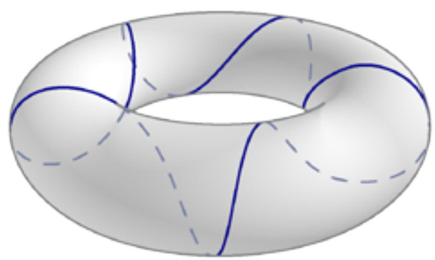
But what if we do not want to talk about quantum cosmology, and about models with more than one scalar field?

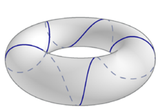
Chaotic mixing

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

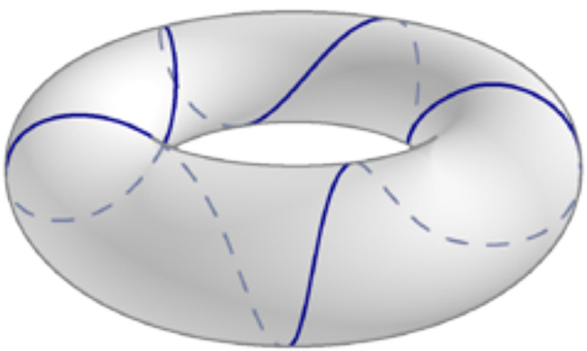






Therefore until the beginning of inflation the universe remains smaller that the size of the horizon $\sim t$

If the universe initially had a Planck size, then within the cosmological time $t \gg 1$ 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 $V \ll 1$. This is yet 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 Planck2013:

Many inflationary models. Many of them can fit the same n_s and r. Which ones can be implemented in the context of string theory and supergravity?

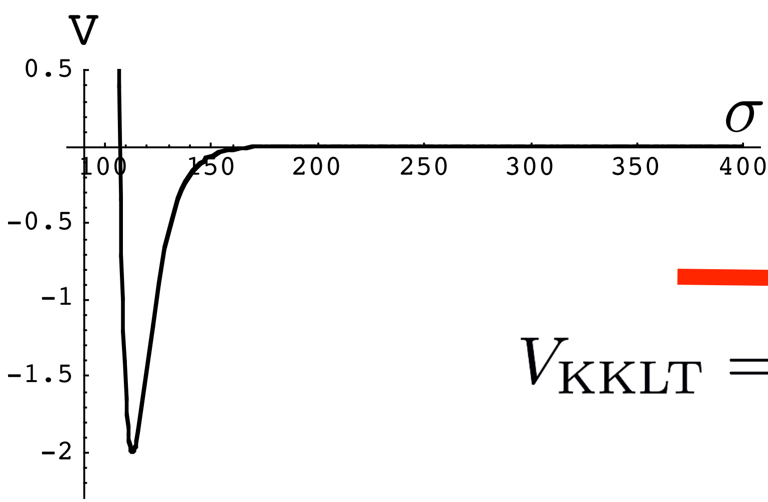
We will give only a small sample of available models.

String Theory

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

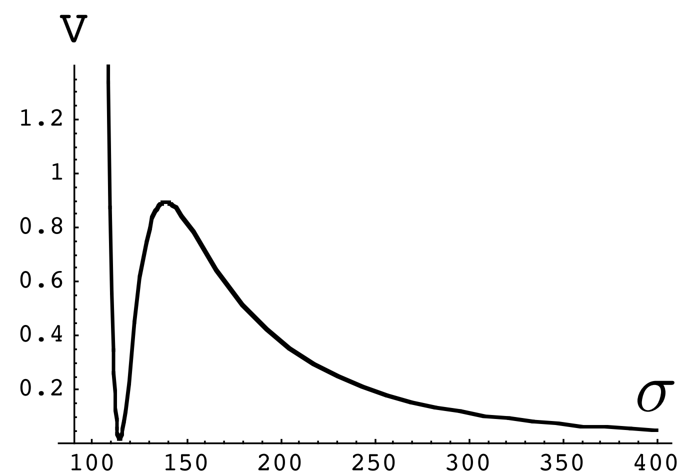
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

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



Stabilization in a supersymmetric AdS minimum

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

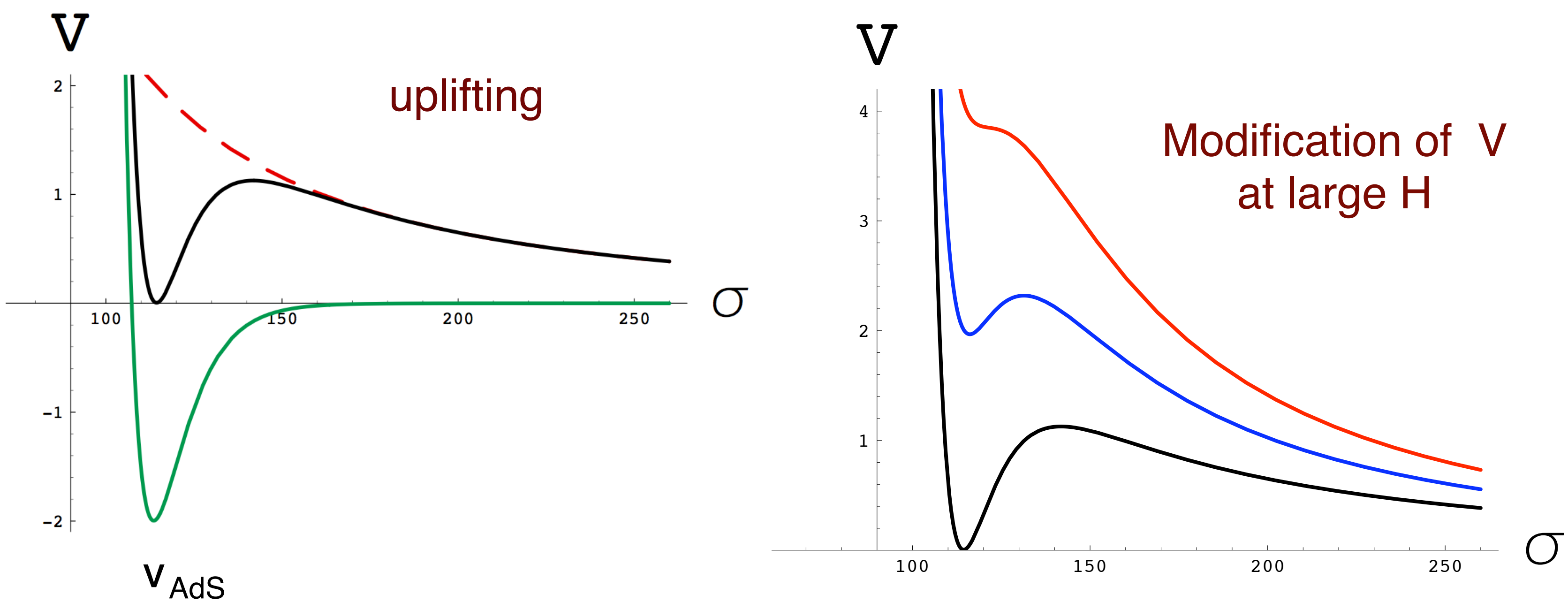


Uplifting to dS breaks SUSY

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

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

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

unobservable

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

Modern versions of string theory

Discovery of SUSY particles at LHC

Discovery of gravity waves

Any 2 of these 3 items are compatible with each other. Can all 3 of them live in peace?

We will describe the simplest way to address this issue

KL model

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

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

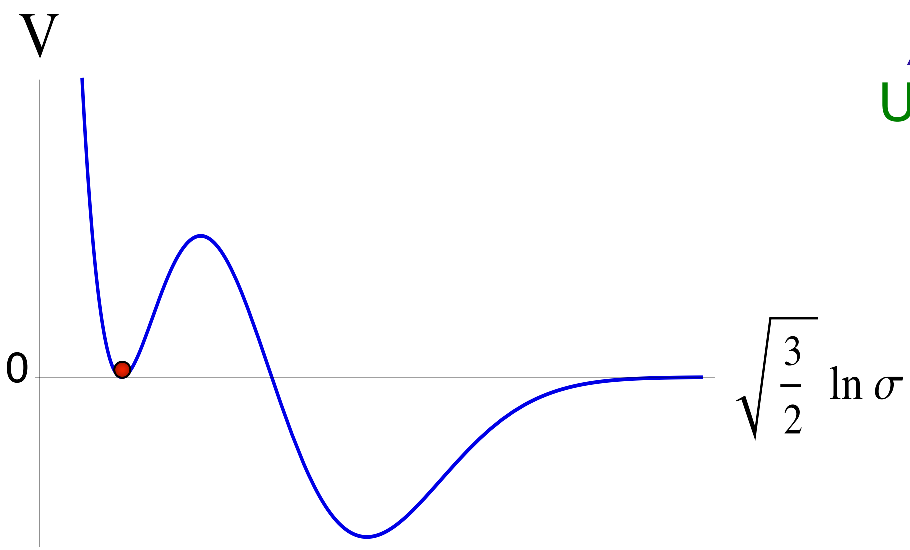
$$W_0 = -A\left(\frac{a\,A}{b\,B}\right)^{\frac{a}{b-a}} + B\left(\frac{a\,A}{b\,B}\right)^{\frac{b}{b-a}} + \Delta$$

Kallosh, A.L. 2004

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 <u>high barrier</u> and a <u>tiny gravitino mass</u>

H can be arbitrarily large, r becomes observable

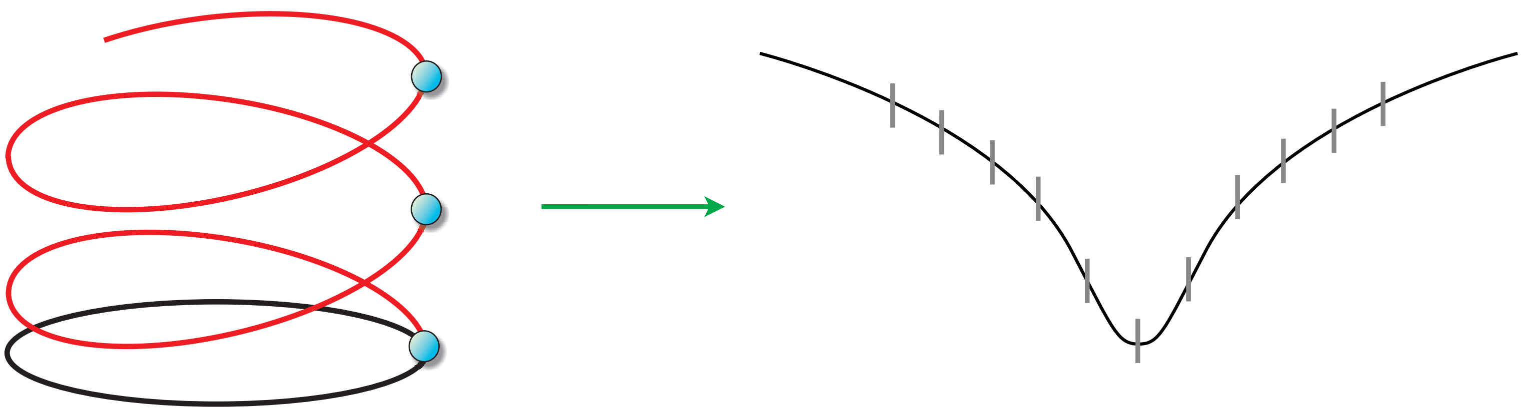
Chaotic Inflation in String Theory

An elegant example: Axion monodromy

Silverstein, Westphal 0803.3085
McAllister, Silverstein, Westphal 0808.0706

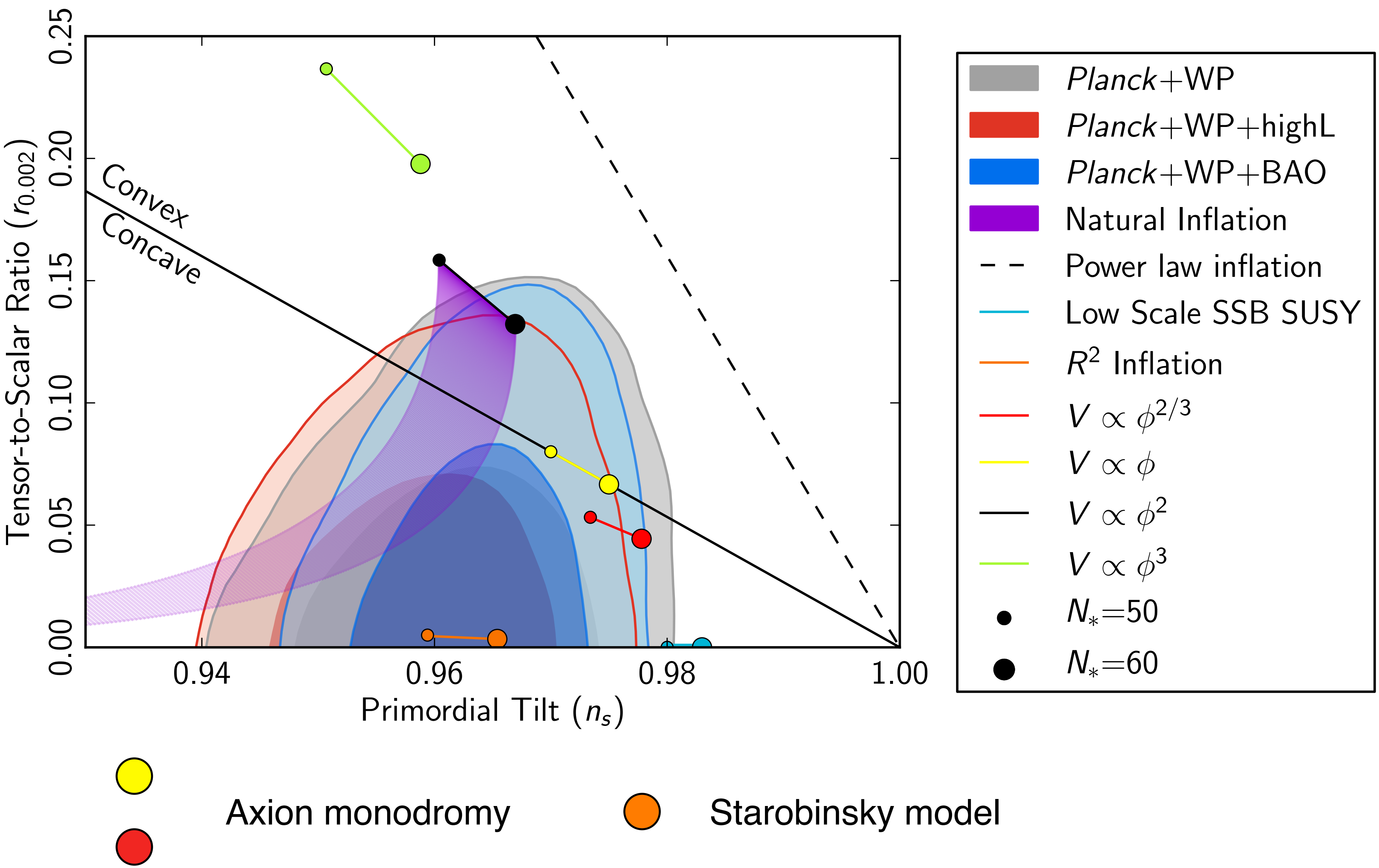
- unwind a periodic field direction into a *monodromy*

  → 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



Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
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

Natural Inflation in supergravity/string theory

One could expect it to be readily available, but stabilization of the large radius of the axion potential was a problem. A consistent version was constructed only relatively recently (Kallosh 2007).

$R + R^2$ in supergravity

Work in progress, see Ketov et al 2012.

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

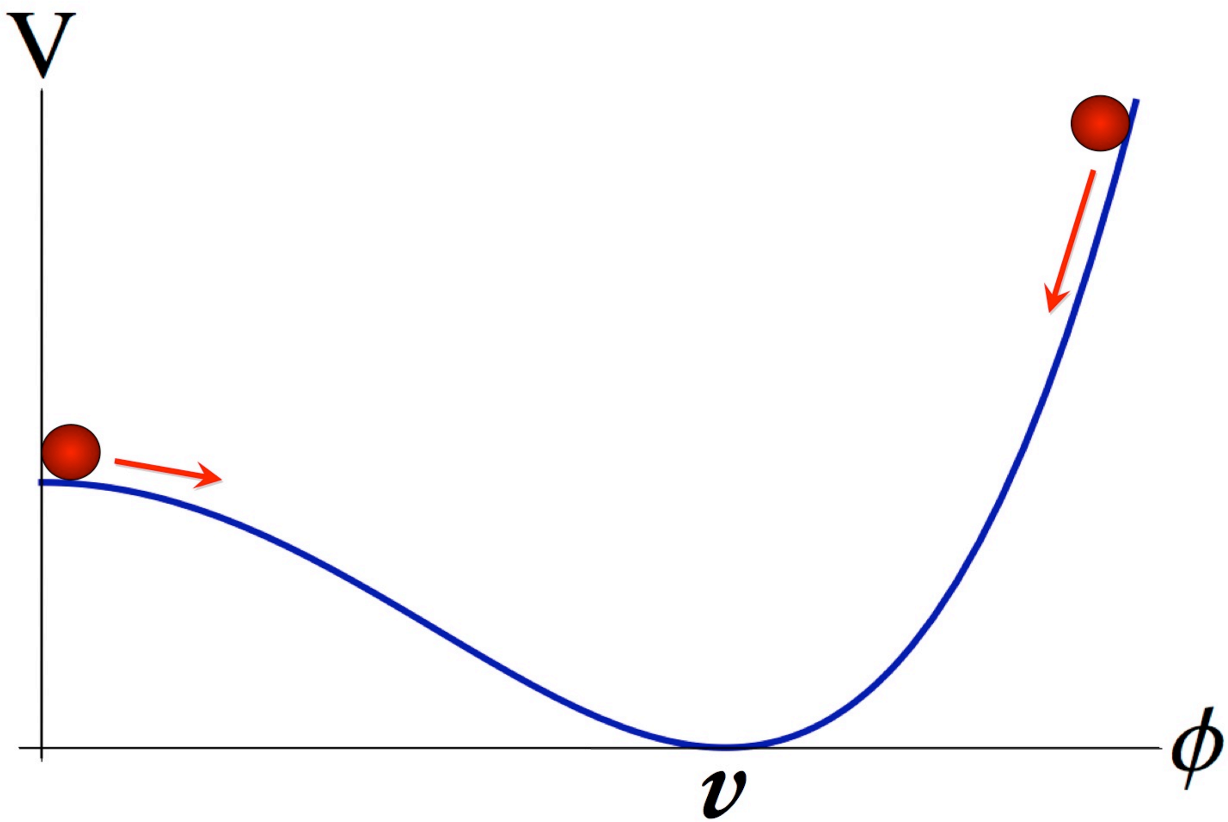
In this new class of supergravity inflation models, one can have **arbitrary potential for the inflaton field**.

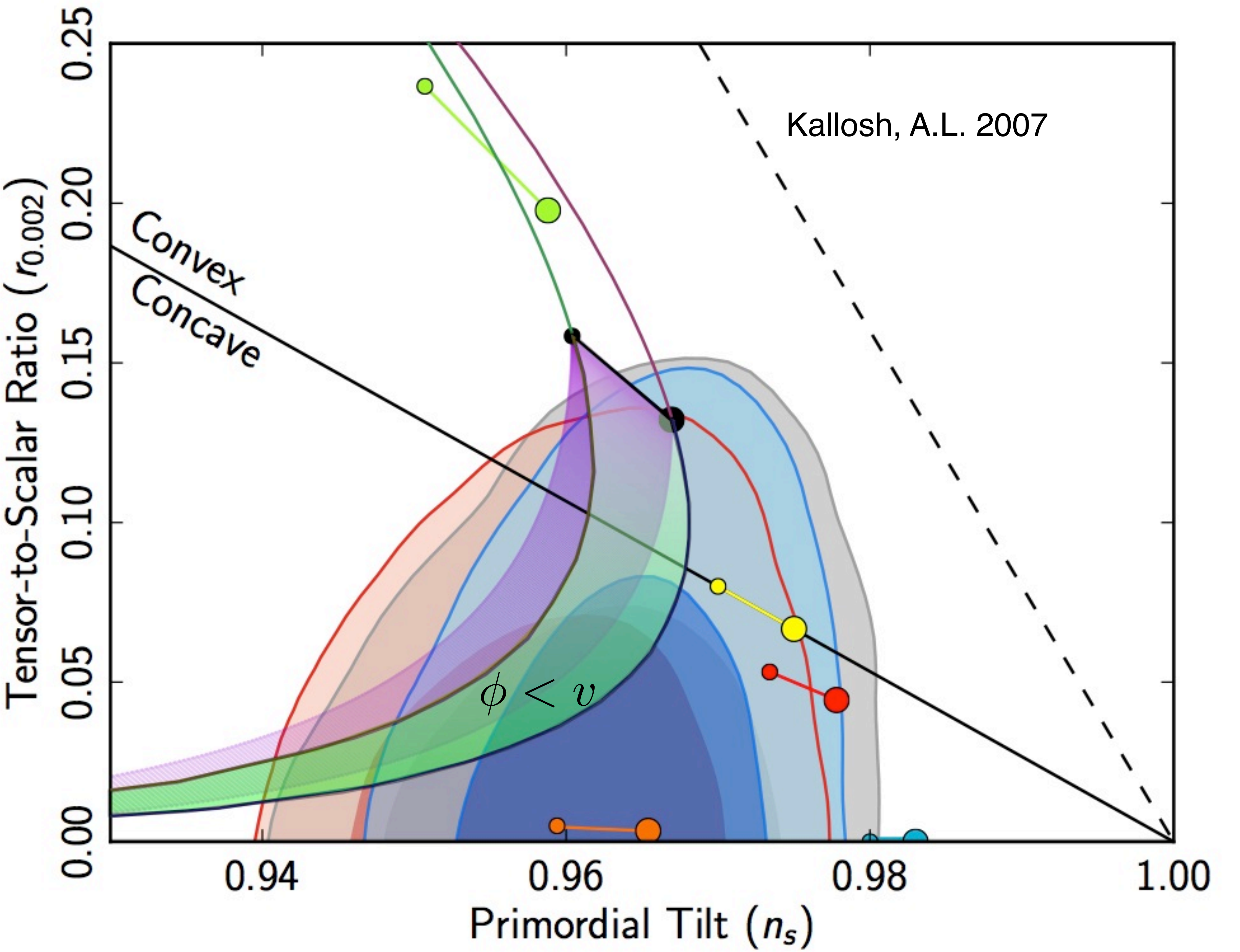
Thus one can have **ANY desirable values of n_s and r.** Moreover, one can generalize this scenario to describe production of non-gaussian perturbations and cosmic strings, to be discussed on Thursday.

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

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

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





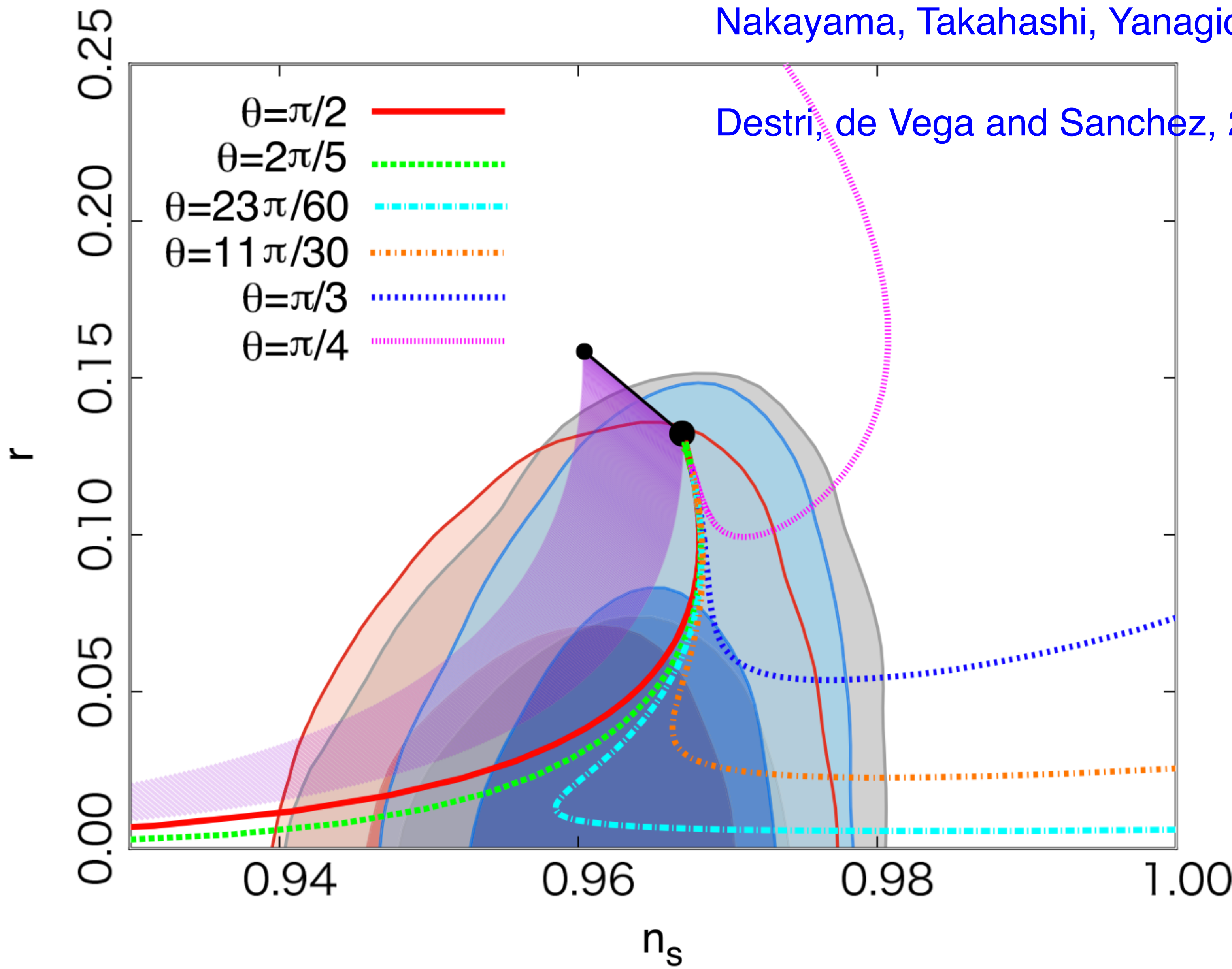
Kallosh, A.L. 2007
Convex
Concave
$\phi < v$
Tensor-to-Scalar Ratio ($r_{0.002}$)
0.25
0.20
0.15
0.10
0.05
0.00
Primordial Tilt (n_s)
0.94
0.96
0.98
1.00

Polynomial non-SUGRA

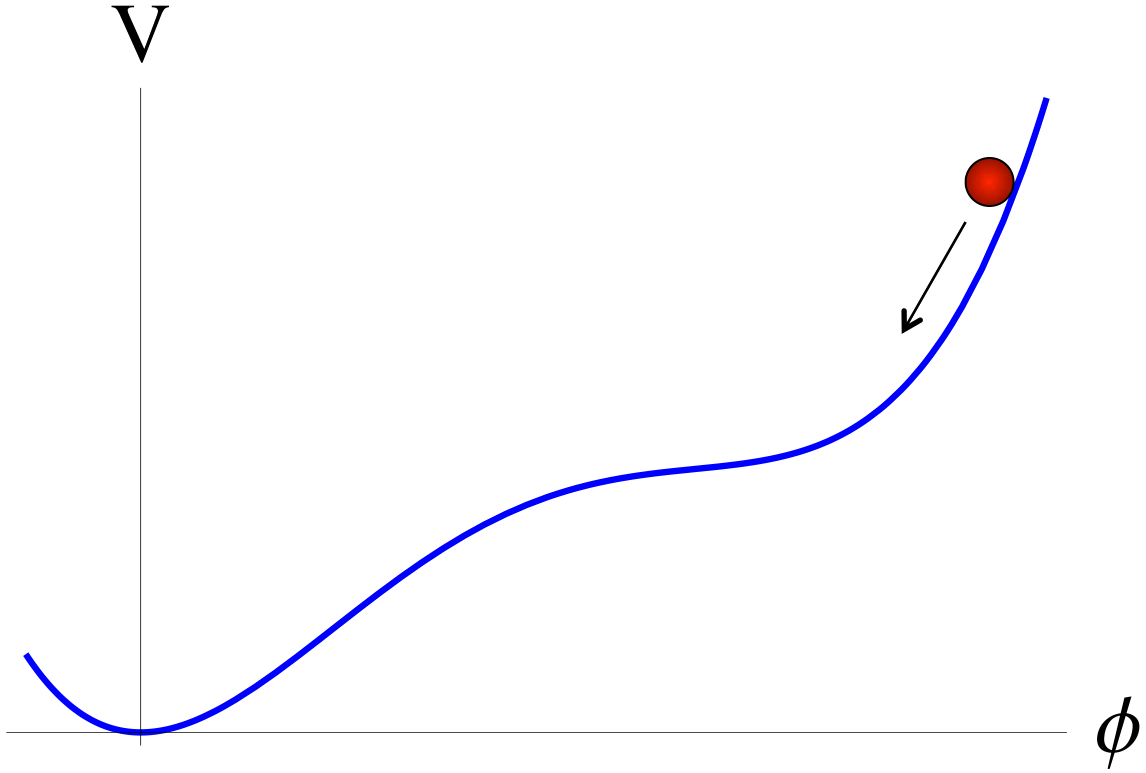
$$V = \frac{\phi^2}{2}\left(m^2 - \sqrt{2}m\lambda \sin\theta\,\phi + \frac{\lambda^2}{2}\phi^2\right)$$

Nakayama, Takahashi, Yanagida 2013

Destri, de Vega and Sanchez, 2007

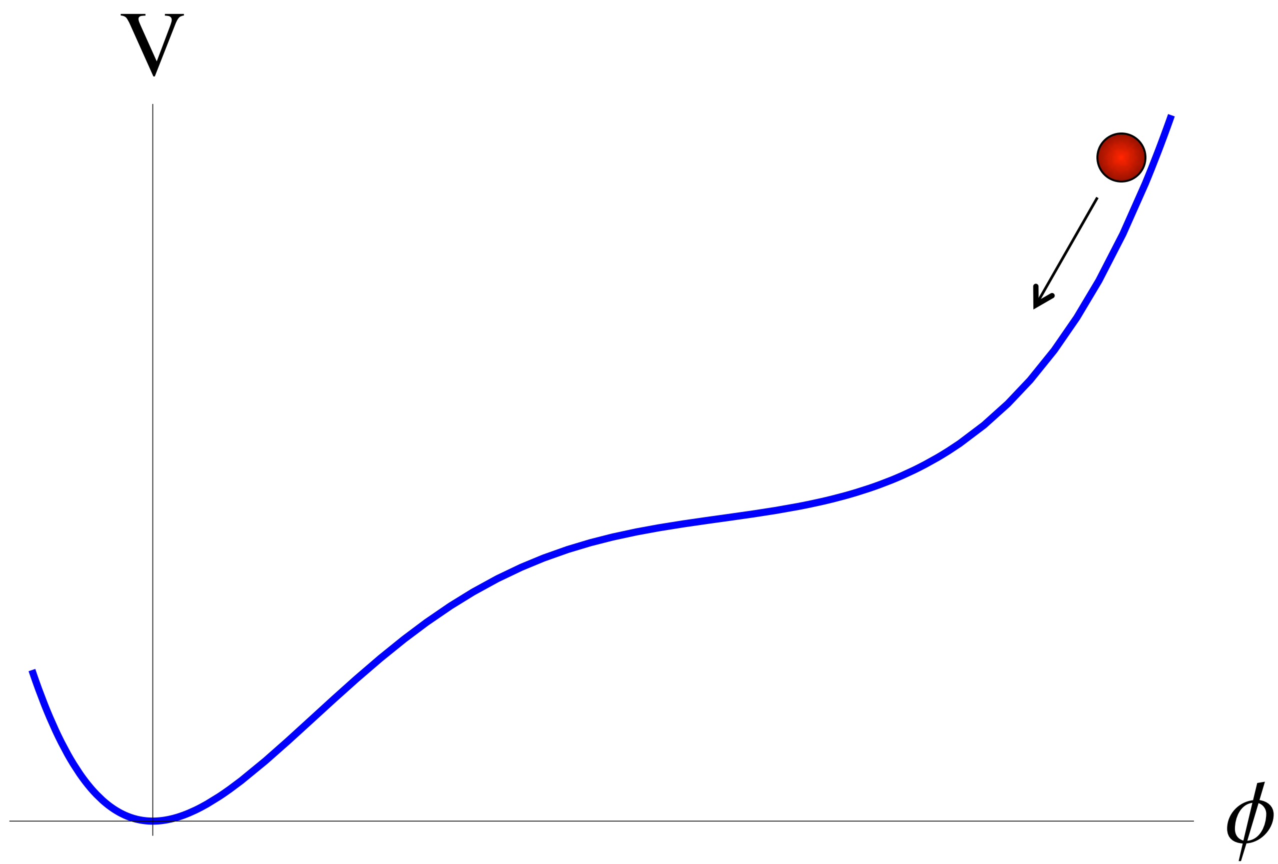


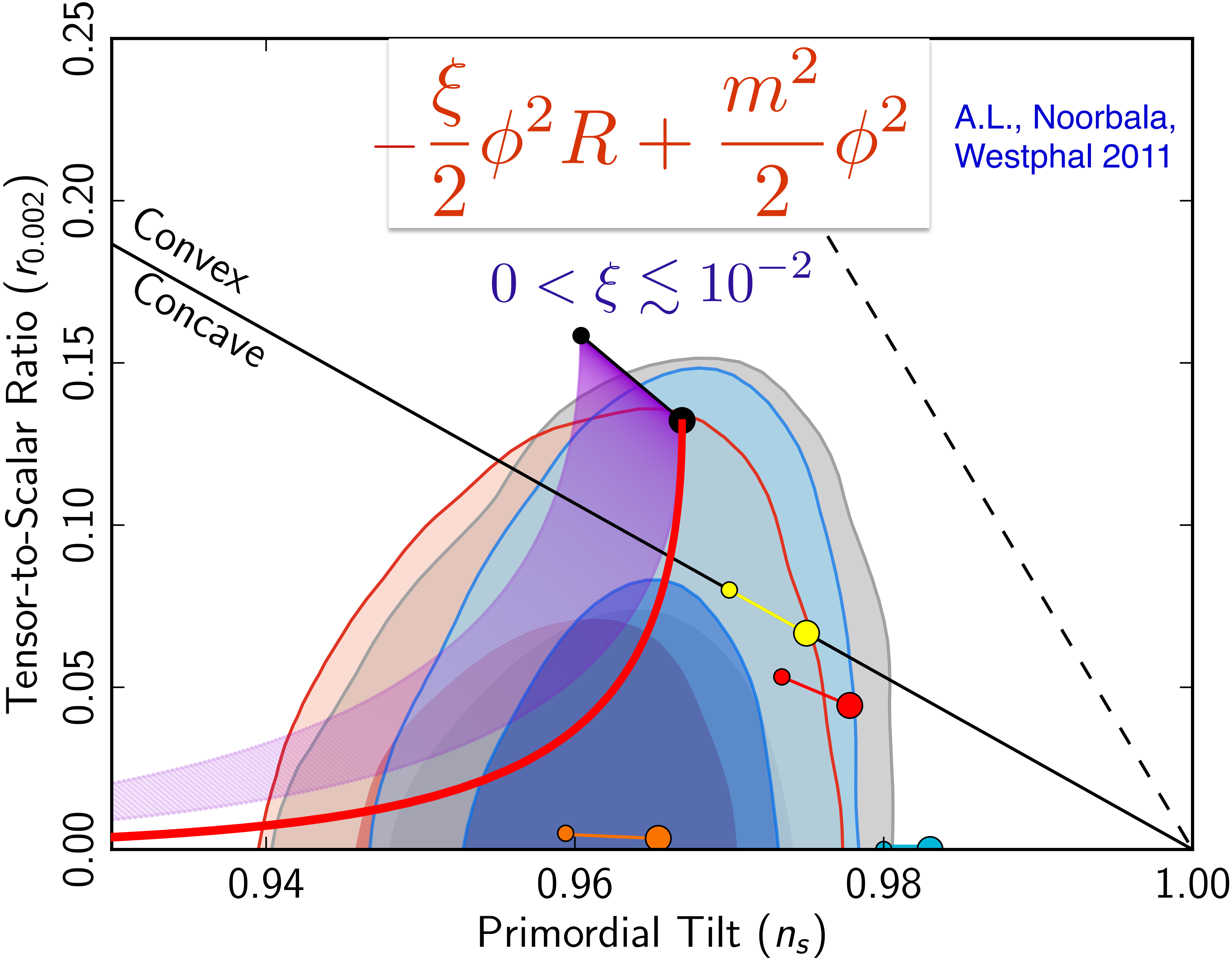
$$V = \frac{m^2\phi^2}{2}\left(1 - a(b\phi) + (b\phi)^2\right)$$



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
$0 < \xi \lesssim 10^{-2}$
Convex
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Tensor-to-Scalar Ratio ($r_{0.002}$)
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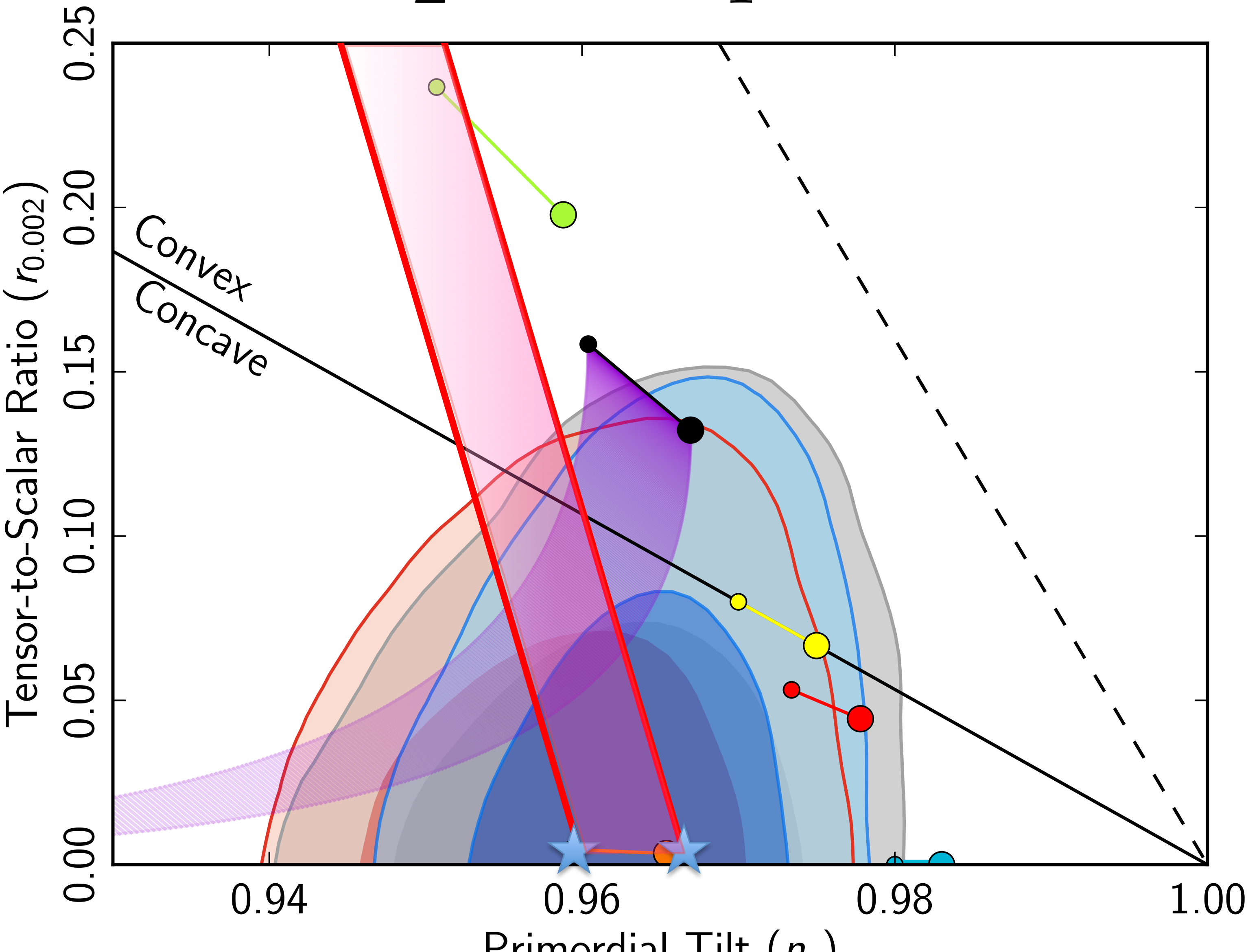
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

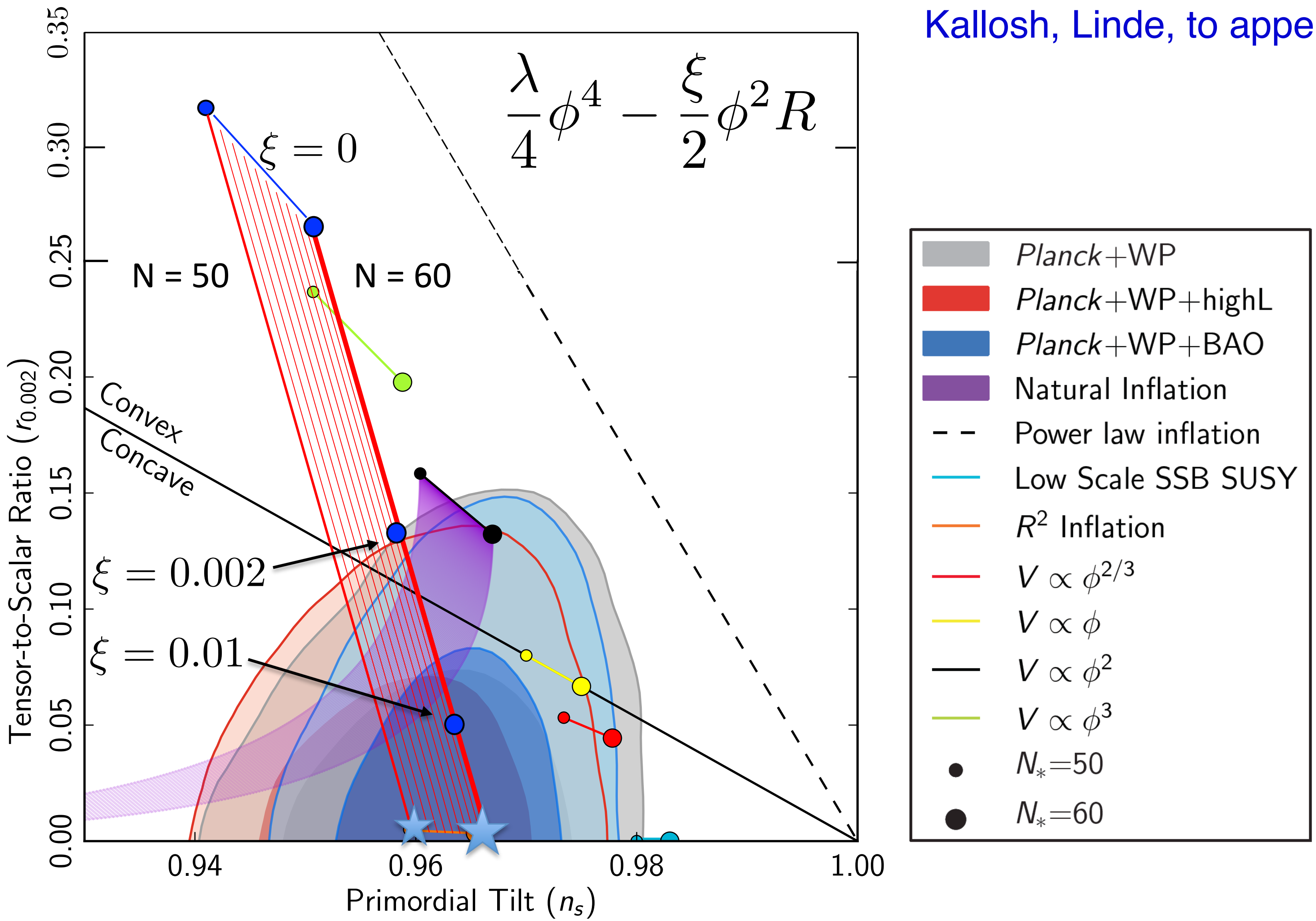
$$-\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}\phi^4$$

Okada, Rehman, Shafi 2010



Inflation and superconformal symmetry

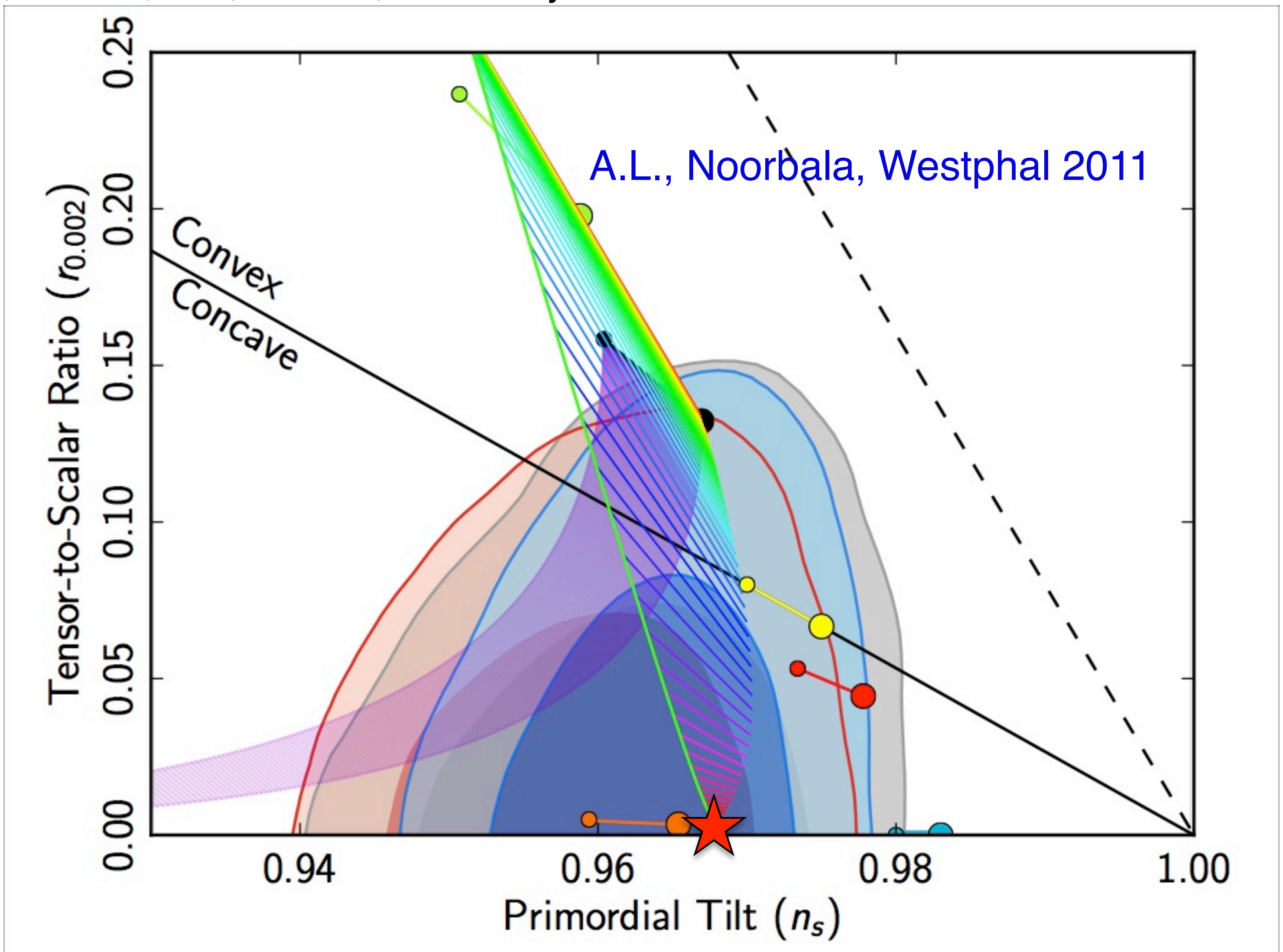
Kallosh, Linde, to appear

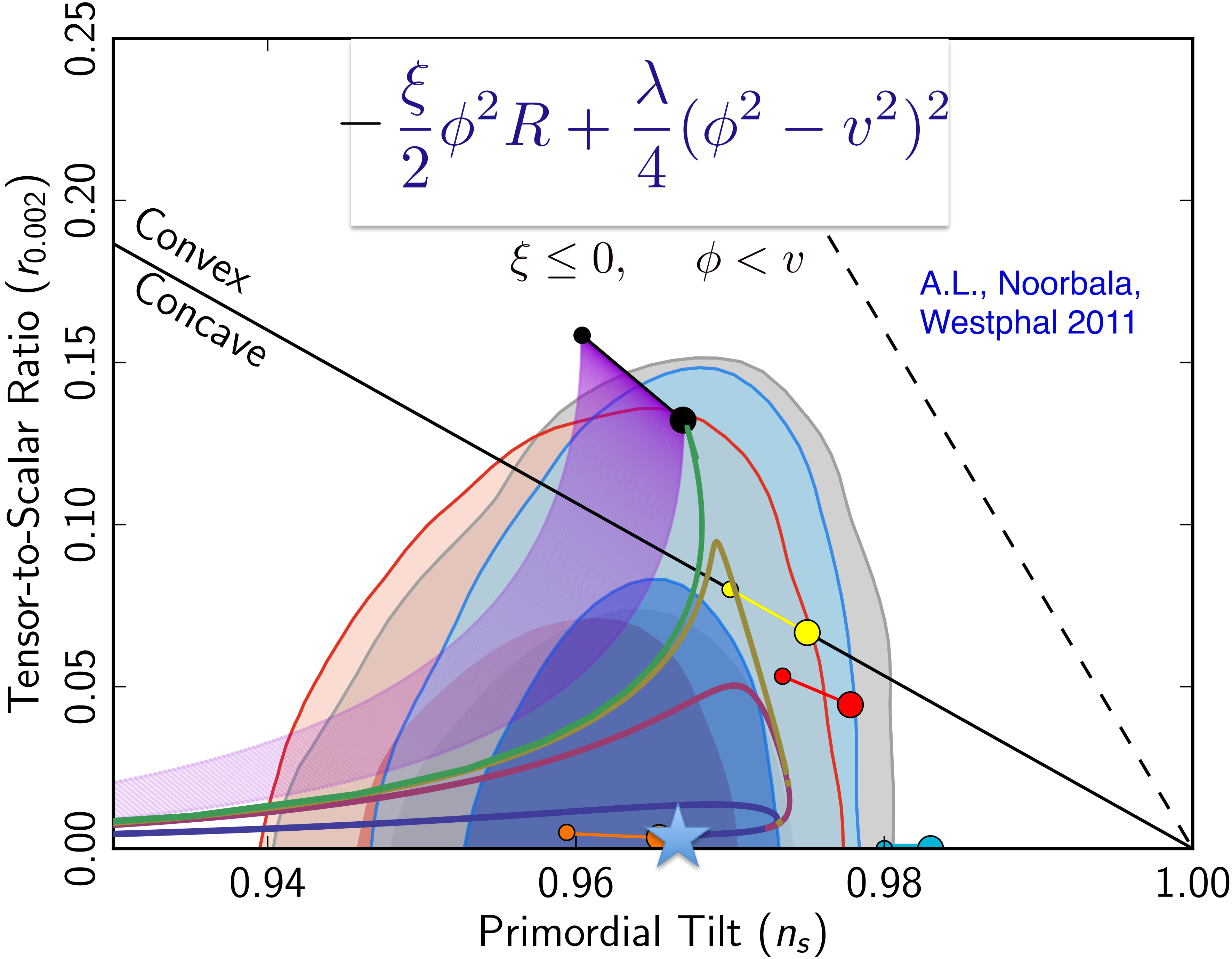


“Higgs Inflation”

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

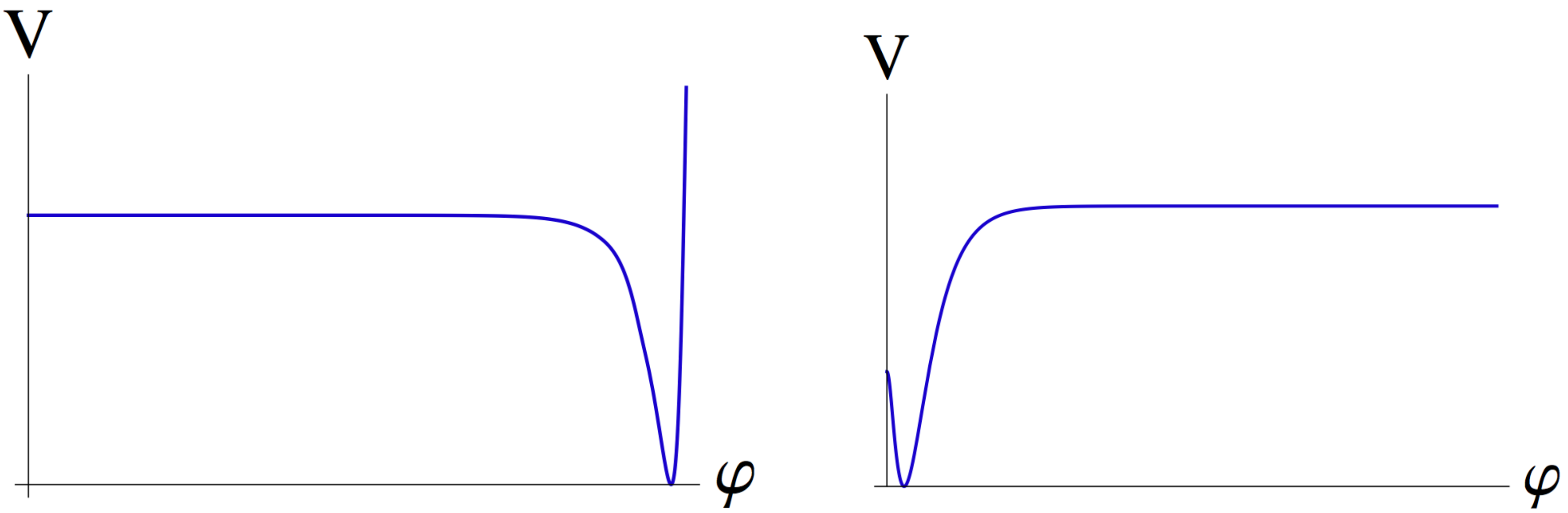
$$-\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$$





$-\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$
$\xi \leq 0, \quad \phi < v$
Convex
Concave
A.L., Noorbala, Westphal 2011
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

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☺

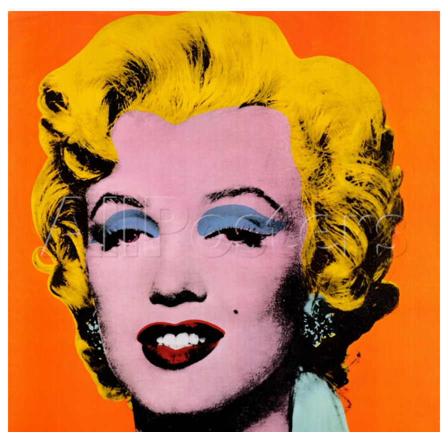
Indeed, some claim that the secret of beauty is in a slight asymmetry between left and right sides of a face, which may become enhanced by a dark spot of a proper size.

This observation was confirmed by measurements in all channels.







ti Design

Can we explain anomalies?

1) Domain walls with spontaneous symmetry breaking in MeV range?

2) Curvaton domain walls or super-horizon perturbations?

3) Quasi-open universe with Omega = 0.999?

4) Low magnitude hugely non-gaussian component of perturbations?

Whatever it is, it should probably go on top of the basic inflationary mechanism.

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 ☺