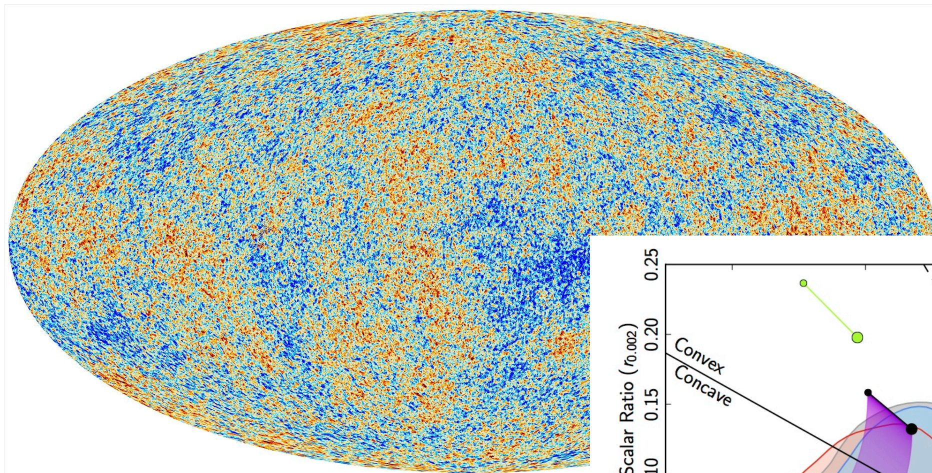
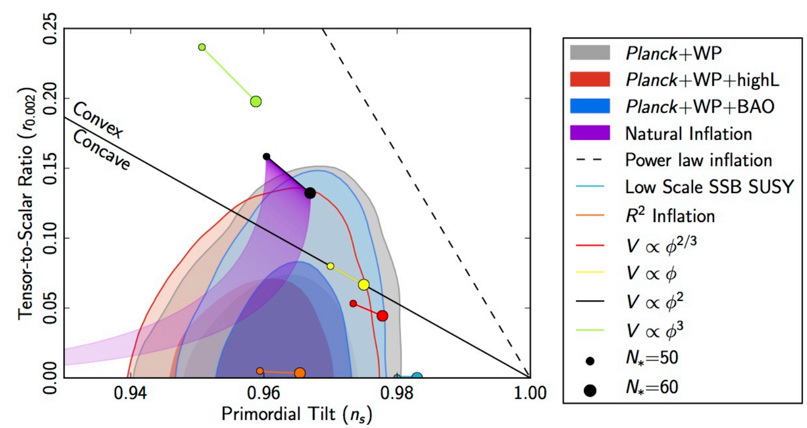
Shortcomings of the inflationary paradigm





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Phys. Lett. B 723 (2013), 261-266 (arXiv: 1304.2785) &

work in progress

Why inflation?

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

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(Received 11 August 1980)

The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

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.

Andrei Linde, KITP April 23, 2013

The idea

$$H^2 = \frac{8\pi G}{3}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \dots - \frac{k}{a^2}\right)$$

$$\boxed{+\frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(w+1)}}}$$

expanding universe

$$\epsilon \equiv \frac{3}{2}(w+1) < 1$$

inflationary cosmology

contracting universe

$$\epsilon \equiv \frac{3}{2}(w+1) > 3$$

ekpyrotic/cyclic cosmology

conditions for inflation to work

(1) inflation occurs, i.e. there is a stage with

$$\epsilon < 1$$

(2) inflation lasts "long enough", i.e.

$$\epsilon < 1 \quad \text{for} \quad 60 > N > 0$$

(3) inflation ends, i.e.

$$\epsilon > 1 \quad \text{for} \quad N = 0$$

(4) inflation gives the right spectrum of density fluctuations, i.e.

$$\delta\rho/\rho \sim 10^{-5}$$

from the equation-of-state to the potential

$$\boxed{w = \frac{\rho}{p} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}}$$

(1) inflation occurs, i.e. there is a stage with

$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 < 1\,, \quad |\eta| = M_{\rm Pl}^2 \left|\frac{V''}{V}\right| < 1$$

(2) inflation lasts “long enough”, i.e.

$$N \sim \frac{1}{M_{\rm Pl}^2}\frac{V}{V''} \sim 60$$

(3) inflation ends, i.e. (1) breaks down for N = 0,

(4) inflation gives the right spectrum of density fluctuations, i.e.

$$\frac{\delta\rho}{\rho} \sim \frac{1}{M_{\rm Pl}^{1/3}}\frac{V^{2/3}}{V'} \sim 10^{-5}$$

classifying inflationary scenarios

$$n_s - 1 = 2\eta - 6\epsilon$$

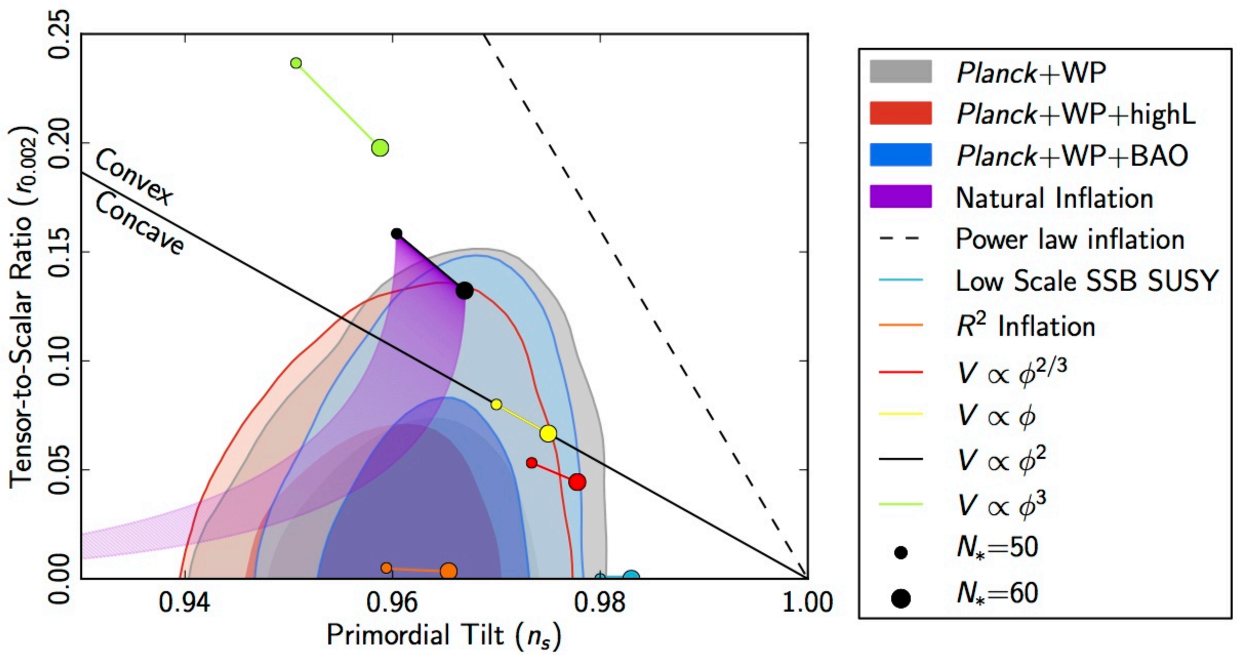
$$r = 16\epsilon$$

$$f_{\rm NL}$$

Predictions?

Planck2013 in combination with WMAP+SPT+ACT+BAO

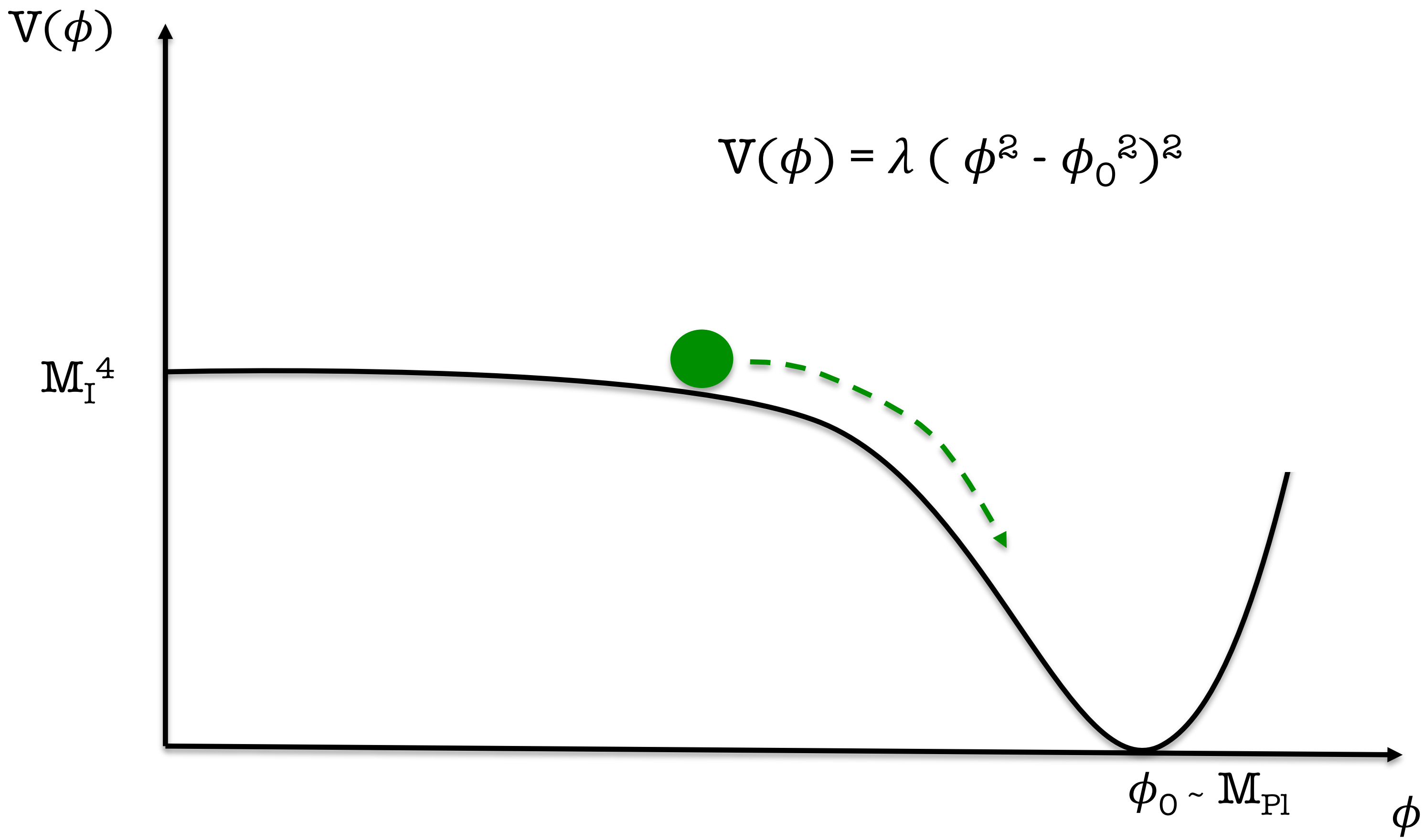
1. non-Gaussianity is small



2. Planck2013 independently confirms results obtained previously by combining WMAP with other observations.

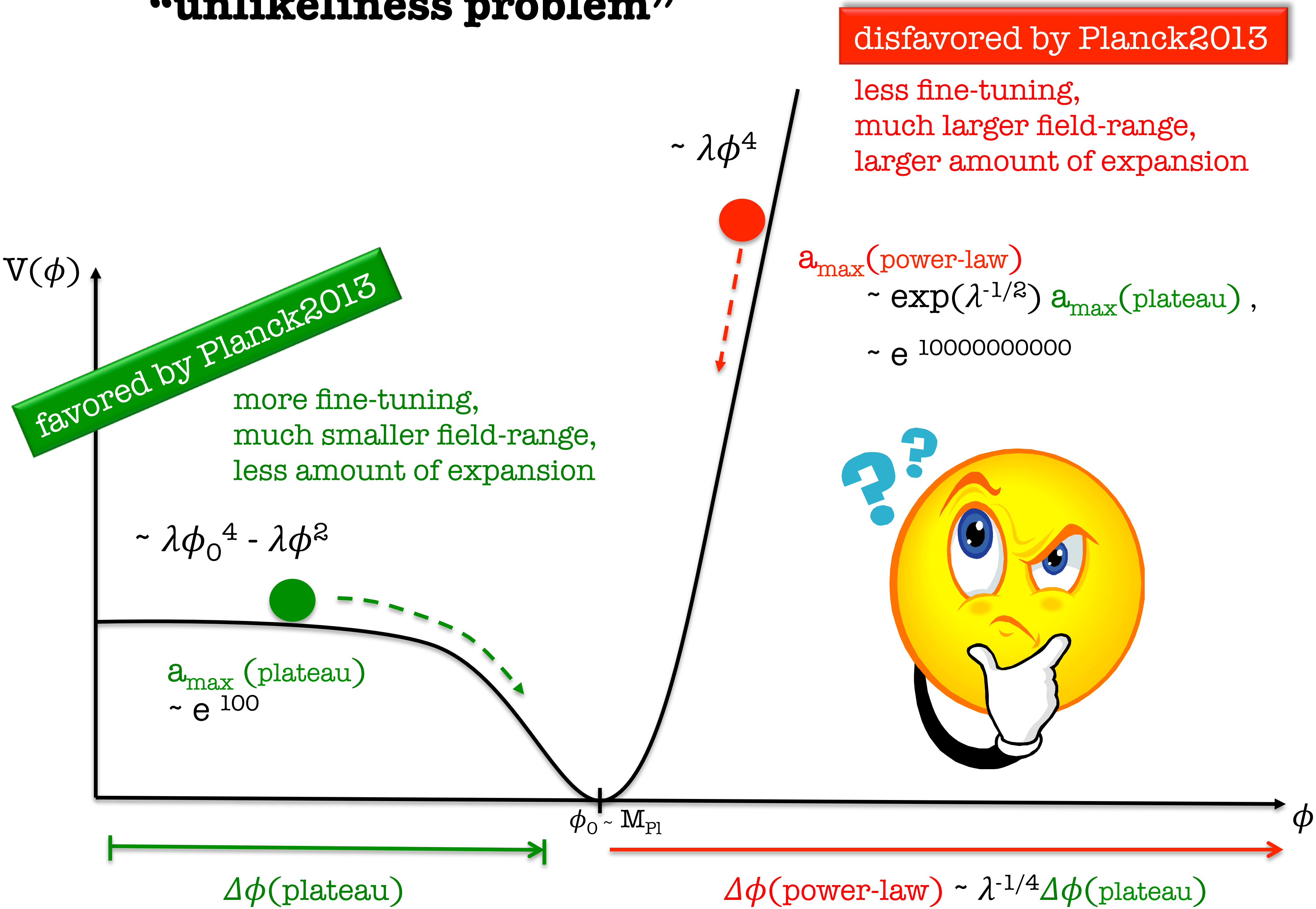
3. Planck2013 favors a special class of inflationary models: plateau-like potentials

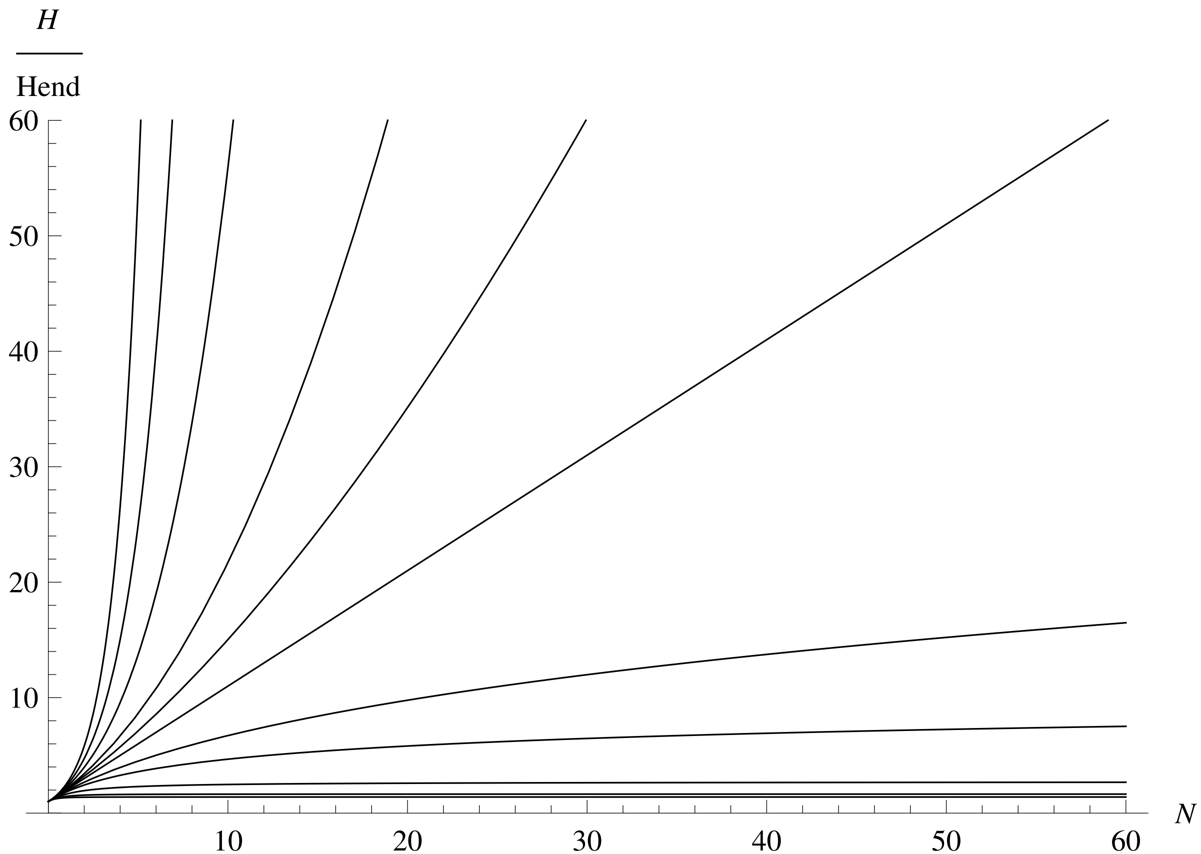
Example: „new inflation“ (Albrecht & Steinhardt 1982, Linde 1982)



Note: energy scale of the plateau is at least 12 orders of magnitude below the Planck scale

“unlikeliness problem”





H
Hend
60
50
40
30
20
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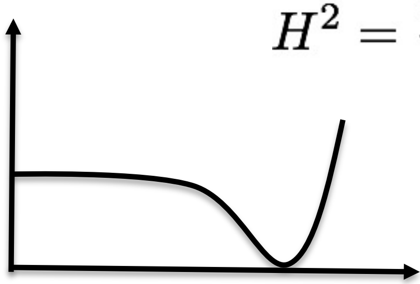
10
20
30
40
50
60
N

* new initial conditions problem:

$$H^2 = \frac{8\pi G}{3}\left(\frac{\rho_m^0}{a^3} + \frac{\rho_r^0}{a^4} + \frac{\sigma^2}{a^6} + \ldots - \frac{k}{a^2}\right) + \frac{8\pi G}{3}\frac{\rho_\phi^0}{a^{3(w+1)}}$$

$M_I{}^4$

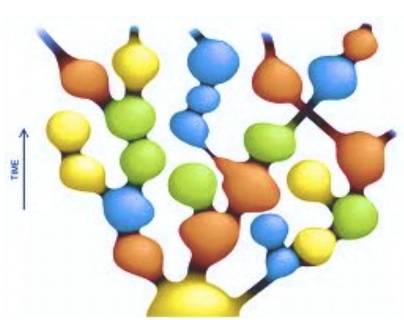


$$\boxed{r^3(t_{Pl}) > (10^{19}\,\mathrm{GeV} / M_I)^3\, H^{-3}(t_{Pl})}$$

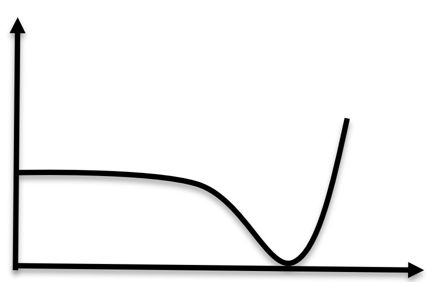
For inflation to start we need huge homogeneous initial volumes

Recall that inflation was supposed to explain smoothness, not to assume it!

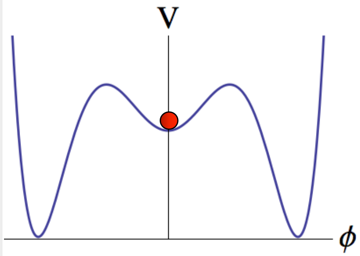
* new multiverse problem:



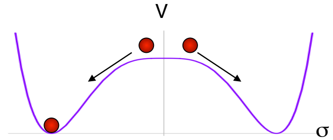
$M_I{}^4$



Initial conditions for hilltop inflation



"Old inflation" in string landscape



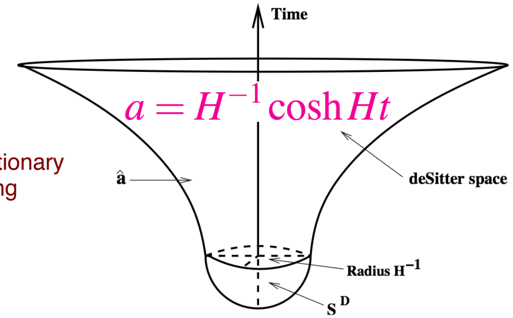
Hilltop inflation

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!

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**.

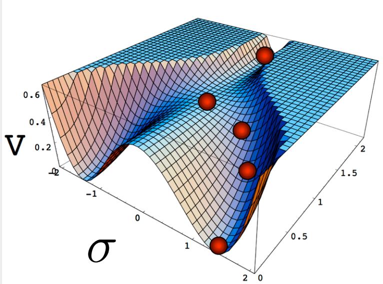
Initial conditions for hilltop inflation, even simpler:

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

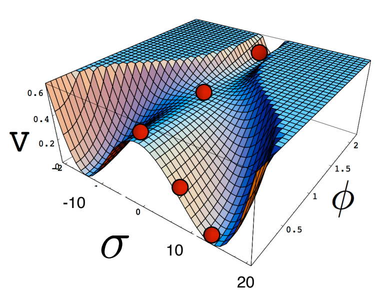
Like in hybrid inflation, but with symmetry breaking σ >> 1

Inflation begins naturally, as in large field chaotic inflation

Hybrid



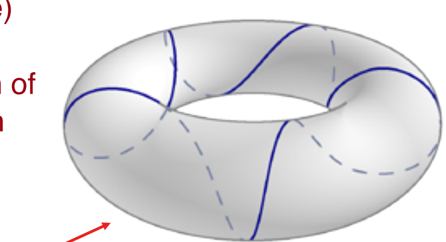
Hilltop

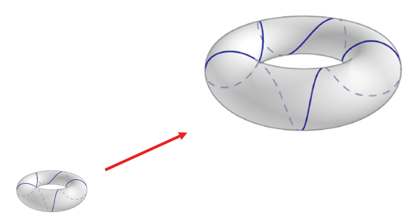


Chaotic mixing

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

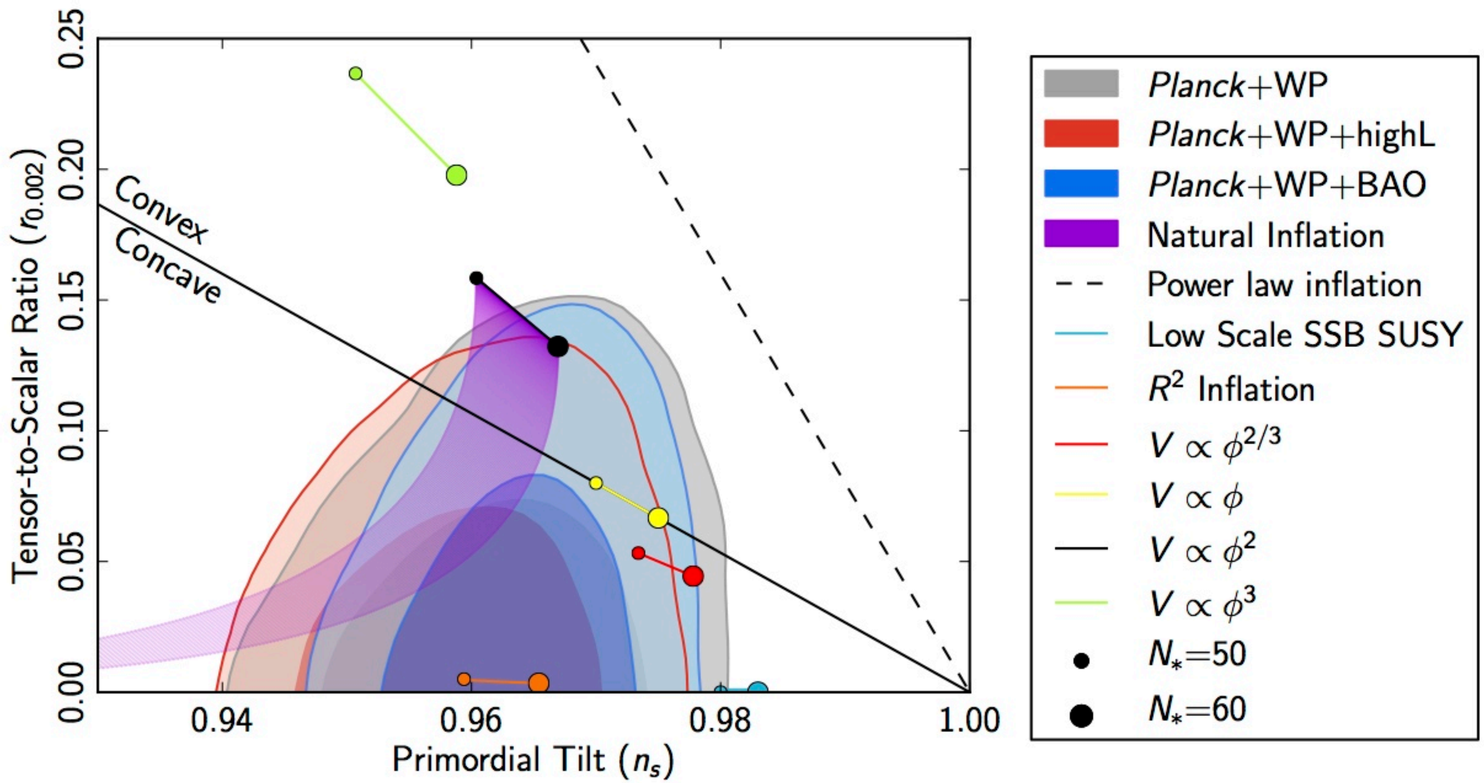




Therefore until the beginning of inflation the universe remains smaller that the size of the horizon ~ t

Future data will ...

(a) diffuse the problems, (b) confirm the problems, or (c) amplify the problems.



Thank you!