On the present status of inflationary cosmology

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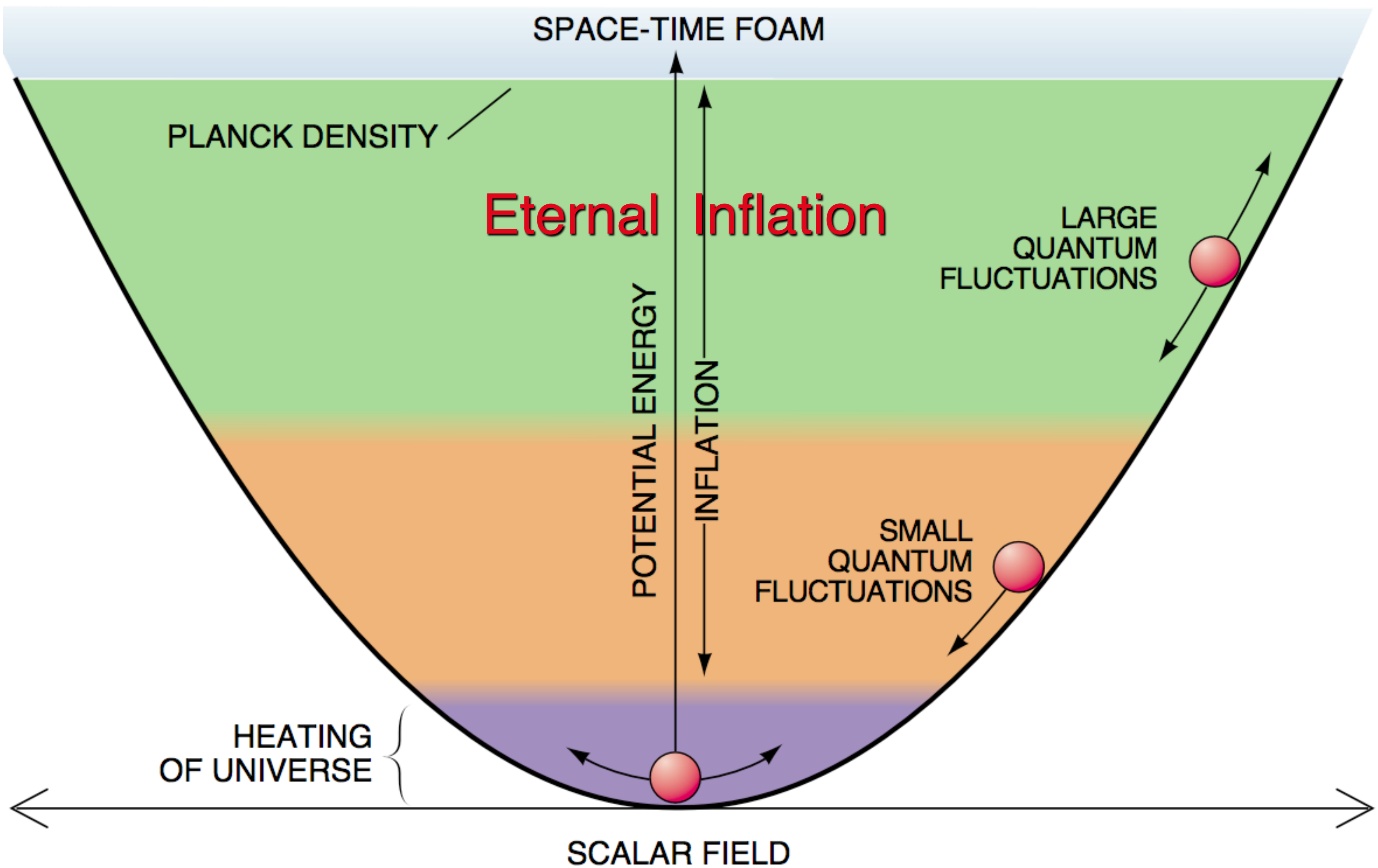
The simplest inflationary model

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

1983



Equations of motion:

Einstein equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{m^2}{6}\phi^2$$

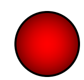
Klein-Gordon equation:

$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

Compare with equation for the harmonic oscillator with friction:

$$\ddot{x} + \alpha\dot{x} = -kx$$

A newborn universe could be as small as 10^{-33} cm (Planck length) and as light as 10^{-5} g (Planck mass). If its energy density is dominated by V, inflation immediately begins



$$l \sim 10^{-33} \text{ cm}$$

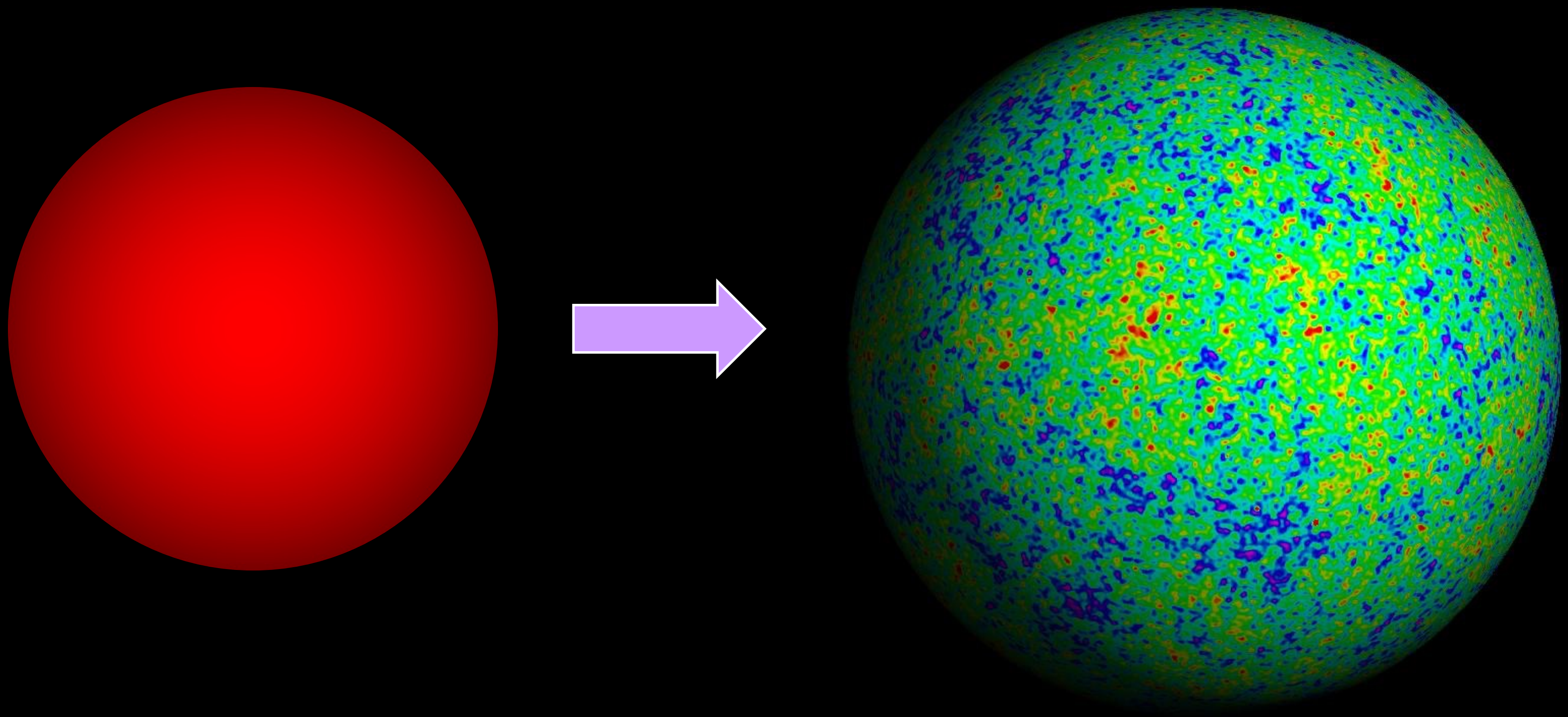
$$m \sim 10^{-5} \text{ g}$$

Inflationary universe 10^{-35} seconds old

$$10^{10000000000}$$

in ANY units of length

The universe after inflation becomes huge and almost absolutely uniform, but quantum fluctuations make it slightly non-uniform. This leads to formation of galaxies and tiny perturbations of the temperature of the universe



Origin of structure:

In this theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations,** which are amplified and stretched exponentially during inflation.

Galaxies are children of quantum fluctuations produced in the first 10^{-35} seconds after the birth of the universe.

Mukhanov and Chibisov 1981

The limits of classical cosmology

By observing distant parts of the universe, we see the universe close and closer to the Big Bang. If expansion of the universe was reversible, by playing the movie back, we would see galaxies moving closer to each other, particles collide, but we would never see 10^{90} particles merge into nothing and disappear, we would never see their origin in a vacuum-like state containing no particles at all.

Indeed, according to the inflationary theory, all particles were produced in the process of reheating after inflation. This is an irreversible quantum mechanical process.

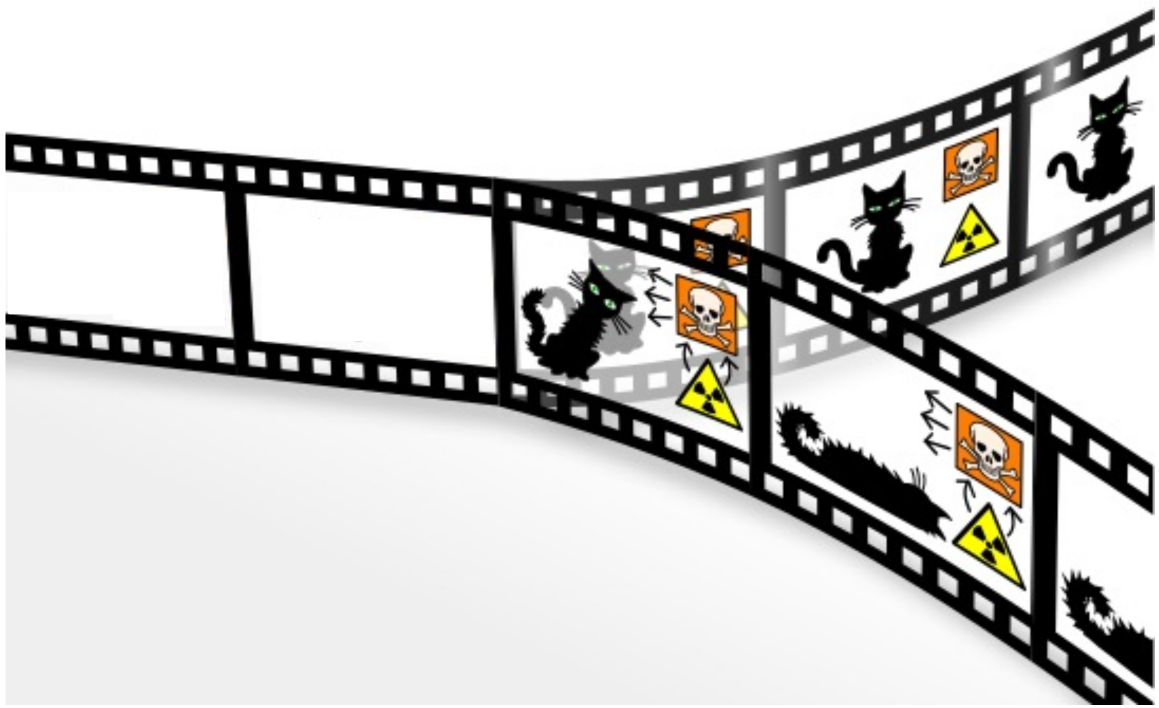
Remember the Schrodinger cat

Two consistent movies with one common element:

in the beginning, there was a cat

The Universe is similar to the Schrodinger cat, but without the cat to start with…

By playing the "movie" back, we would expect to see 10^{90} elementary particles all the way back to the Big Bang. But in inflationary cosmology everything could be born from a tiny Planck-size domain with **no particles at all**. All particles and galaxies were born due to quantum effects during or after inflation.



Thus, positions of the galaxies in the universe and their properties are determined by quantum fluctuations. These positions are completely different in different parts of the universe.

The same is true for the values of light scalar fields such as axions. These values determine local values of dark matter and dark energy density, which may take different values in different parts of the world.

More generally, different branches of the wave function of the universe may describe the universe with properties dramatically different from ours.

Welcome to the multiverse

Can we see the moment of creation?

In the old Big Bang theory, by looking at the sky we were looking back in time, all the way to the Big Bang. Gravitational waves could come to us directly from the Big Bang – one could see the singularity.

In inflationary theory, we can study only the last stages of inflation, when the density of the universe was about 9 orders below the Planck density. Indeed, there is a relation between the tensor to scalar ratio

$$r \approx 3 \times 10^7\ V$$

According to Plank/BICEP/Keck/ACT data, $r < 0.038$, which means that $V < 10^{-9}$ at the edge of visibility. To see what happen at $V = O(1)$ one would need to look beyond the horizon.

Thus, we will never see the moment of creation. But this also means that **the absence of full knowledge of the processes near the cosmological singularity should not affect the basic observational predictions of inflation.**

This is very similar to the cosmic censorship conjecture: The singularity may exist, but it should be invisible, hidden from us by a horizon.

Testing predictions of inflation

1) **The universe is flat, $\Omega = 1$**. (In the mid-90's, the consensus was that $\Omega = 0.3$, until the discovery of dark energy confirming inflation.)

2) The observable part of the universe is **uniform** (homogeneous).

3) It is **isotropic**. In particular, it does not rotate. (Back in the 80's we did not know that it is uniform and isotropic at such an incredible level.)

4) Perturbations produced by inflation are **adiabatic**

5) Unlike perturbations produced by cosmic strings, inflationary perturbations lead to many **peaks in the spectrum**

6) The large angle TE anti-correlation (WMAP, Planck) is a distinctive signature of **superhorizon fluctuations** (Spergel, Zaldarriaga 1997), ruling out many alternative possibilities

7) Inflationary perturbations should have a **nearly flat (but not exactly flat) spectrum**. A small deviation from flatness is one of the distinguishing features of inflation. It is as significant for inflationary theory as the asymptotic freedom for the theory of strong interactions

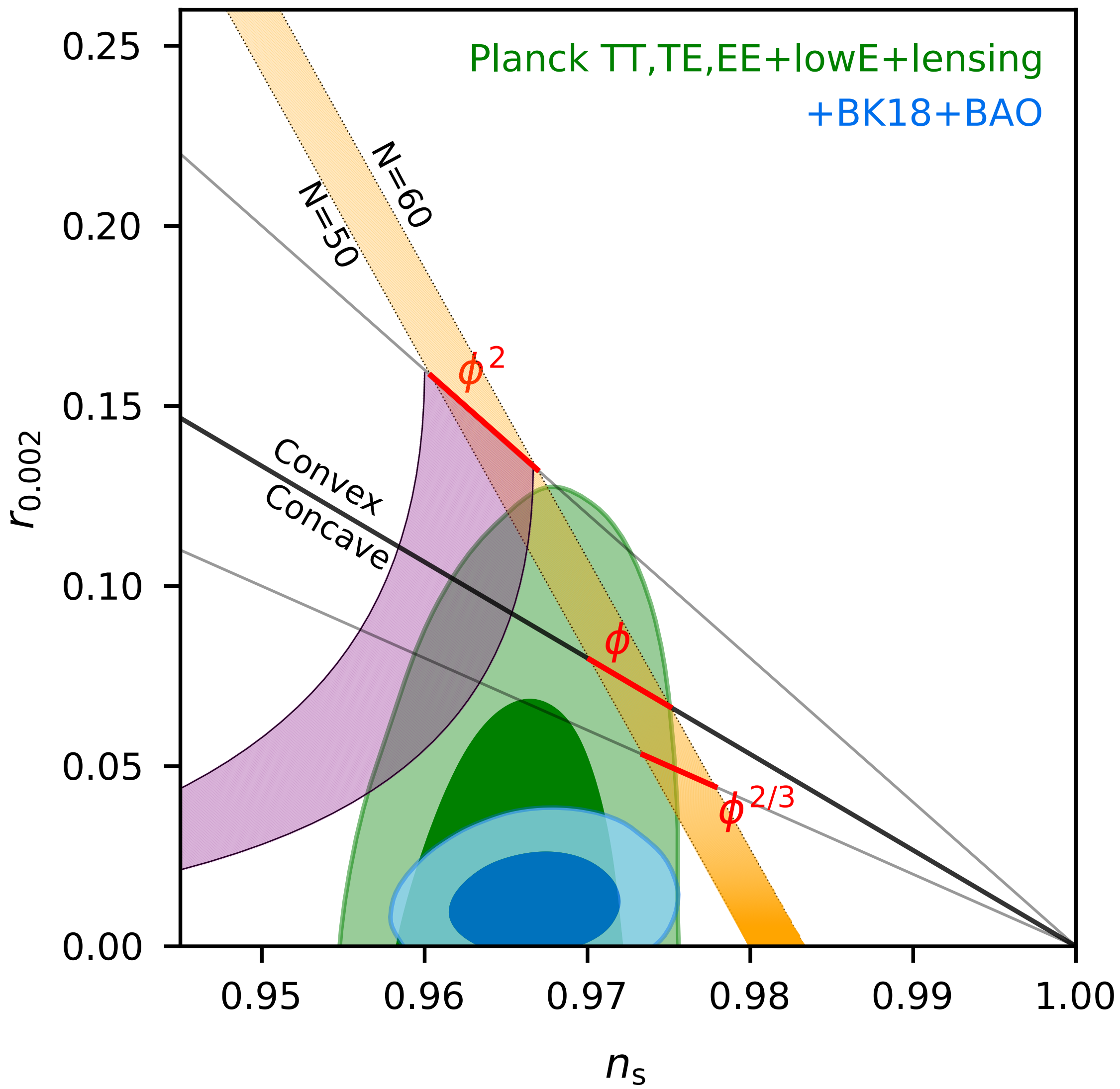
8) **Inflation produces scalar perturbations** and **tensor perturbations** with nearly flat spectrum, and it **does not produce vector perturbations**.

9) In the early 80's it could seem that inflation is ruled out because scalar perturbations are not observed at the expected level 10^{-3} required for galaxy formation. Thanks to dark matter, smaller perturbations are sufficient, and they were **found by COBE**.

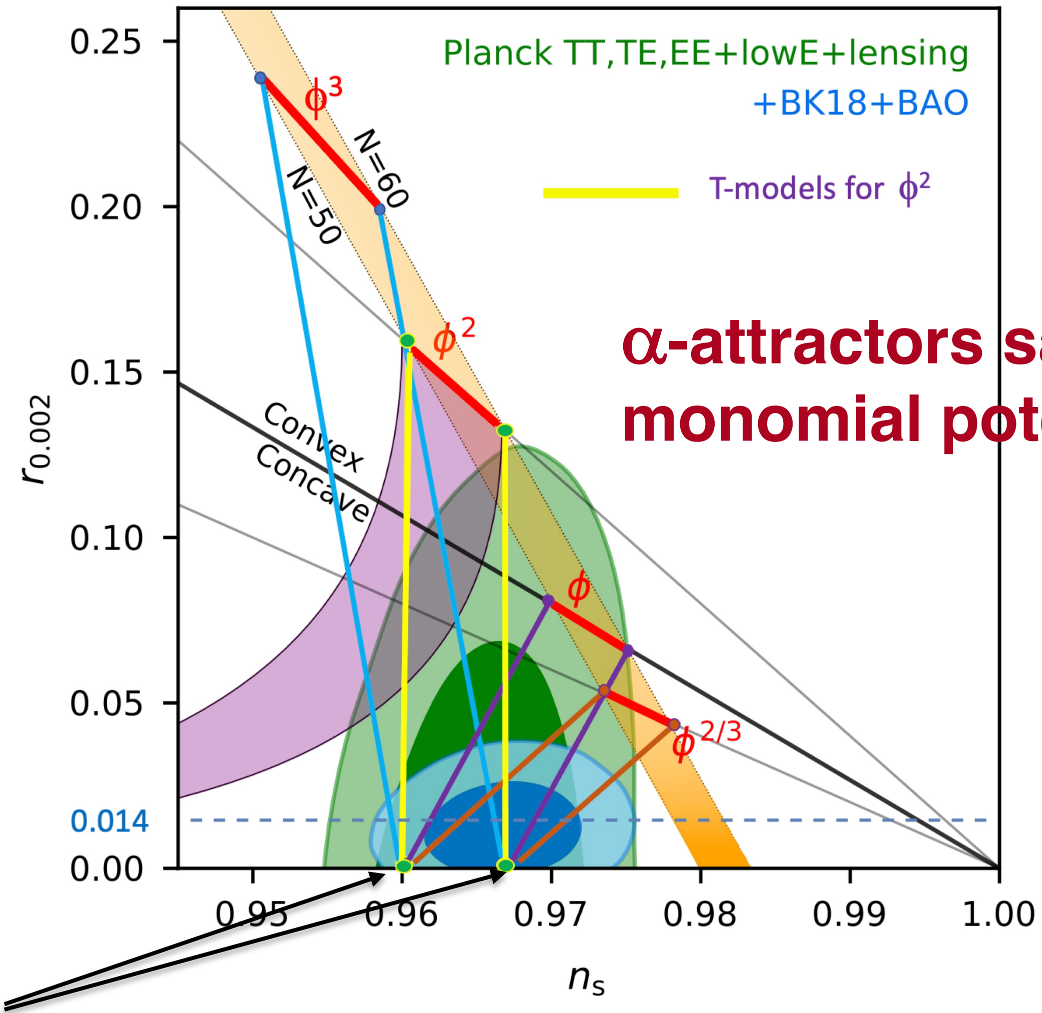
10) Scalar perturbations are **Gaussian**. In non-inflationary models, the parameter f_{NL}^{local} describing the level of local non-Gaussianity can be as large as 10^4, but it is predicted to be O(1) in all single-field inflationary models. **Confirmed by Planck.** Prior to the Planck2013 data release, there were rumors that $f_{NL}^{local} \gg O(1)$, which would rule out **all** single field inflationary models

Natural inflation and all monomial potentials are disfavored by Planck + BICEP/Keck 2021

What remains?



Predictions for n_s in α-attractor models at α< O(1) practically do not depend on the choice of the potential, and they match the Planck/BICEP/Keck data



α-attractors saving monomial potentials

Starobinsky model and Higgs inflation

α-attractors

Kallosh, AL, Roest 2013

To match observations, the simplest chaotic inflation model

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\phi^2 - \frac{1}{2}m^2\phi^2$$

should be modified:

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\underline{\frac{\phi^2}{6\alpha}})^2} - \frac{1}{2}m^2\phi^2$$

Switch to canonical variables $\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}$

The potential becomes

$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

This model (**α-attractor T-model**) is consistent with observational data for m ~ 10^{-5} and **<u>any</u>** value of α smaller than O(5).

What is the meaning of α-attractors?

More generally:

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{R}{2} - \frac{(\partial_\mu \phi)^2}{2\left(1 - \frac{\phi^2}{6\alpha}\right)^2} - V(\phi)$$

In canonical variables

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{R}{2} - \frac{(\partial_\mu \varphi)^2}{2} - V\left(\sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}\right)$$

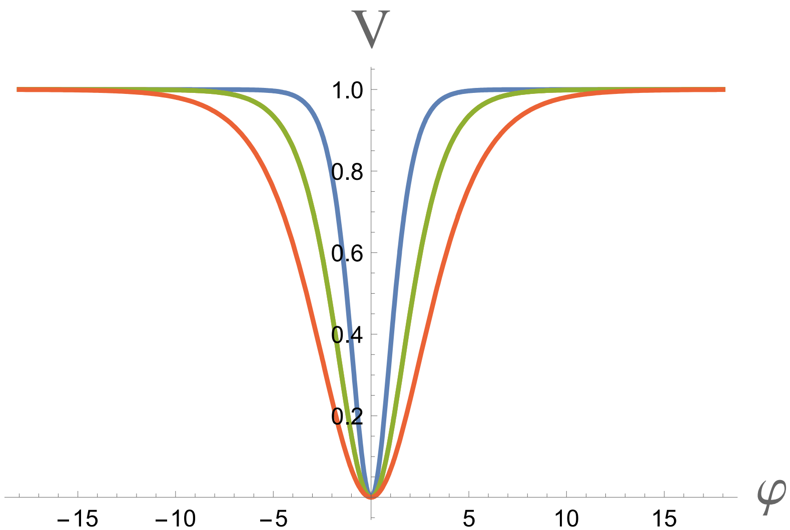
Asymptotically at large values of the field

$$V(\varphi) = V_0 - 2\sqrt{6\alpha}\,V_0'\,e^{-\sqrt{\frac{2}{3\alpha}}\varphi}$$

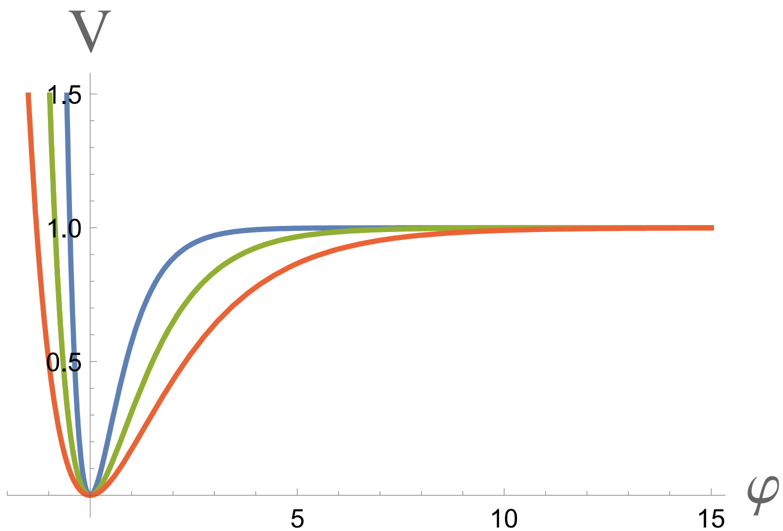
Here $V_0' = \partial_\phi V|_{\phi=\sqrt{6\alpha}}$ This factor can be absorbed in the redefinition (shift) of the field. **Therefore, at small α, values of n_s and r depend only on V_0 and α**, not on the shape of V(ϕ).

$$n_s = 1 - \frac{2}{N_e}\,, \qquad r = \frac{12\alpha}{N_e^2}$$

T-models for different α, or **Higgs inflation** for α=1



E-models for different α, or **Starobinsky model** for α=1



$$n_s = 1 - \frac{2}{N_e}\,, \qquad r = \frac{12\alpha}{N_e^2}$$

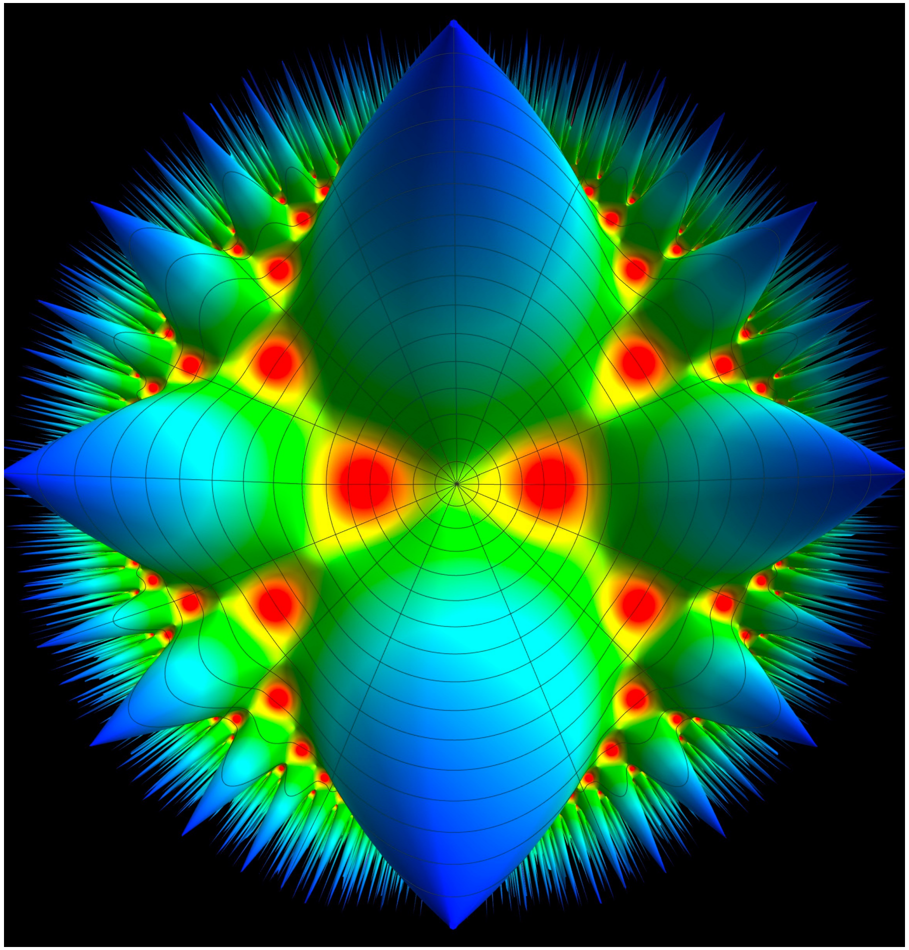
Exponential approach to the plateau

$$V = V_0\left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi} + \ldots\right)$$

Recent developments:

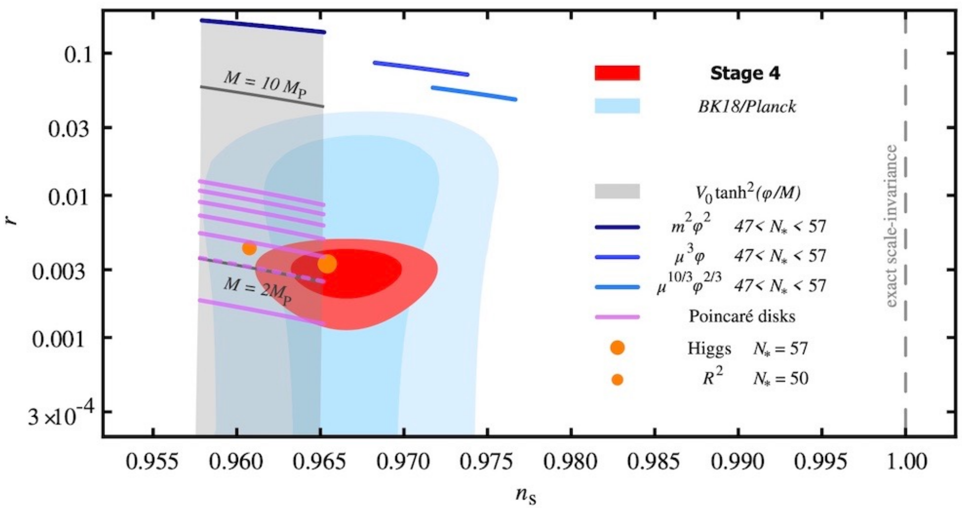
SL(2,Z) symmetric cosmological α-attractors

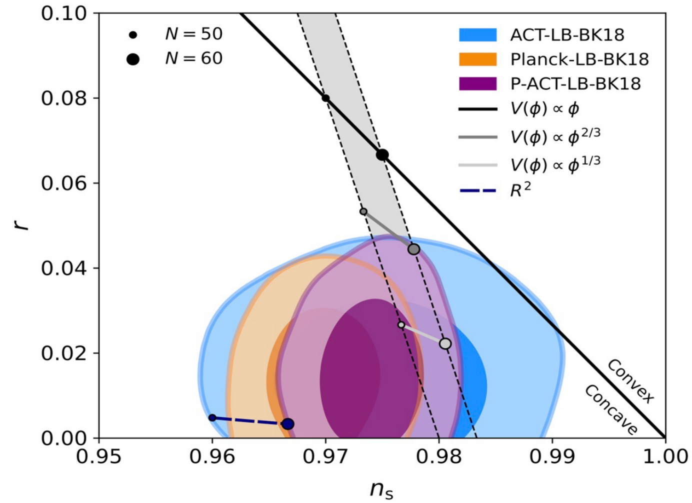
Casas, Ibanez, 2407.12081, Kallosh, AL, 2408.05203, 2411.07552, Carrasco, Kallosh, AL, Roest, 2503.14904



This theory describes *infinitely many* inflationary α-attractor plateaus

ACT+DESI suggest that $n_s > 0.965$, but CMB-S4 and LiteBIRD figures do not show any targets with $n_s > 0.965$





P-ACT-LB n_s=0.9743 ± 0.0034

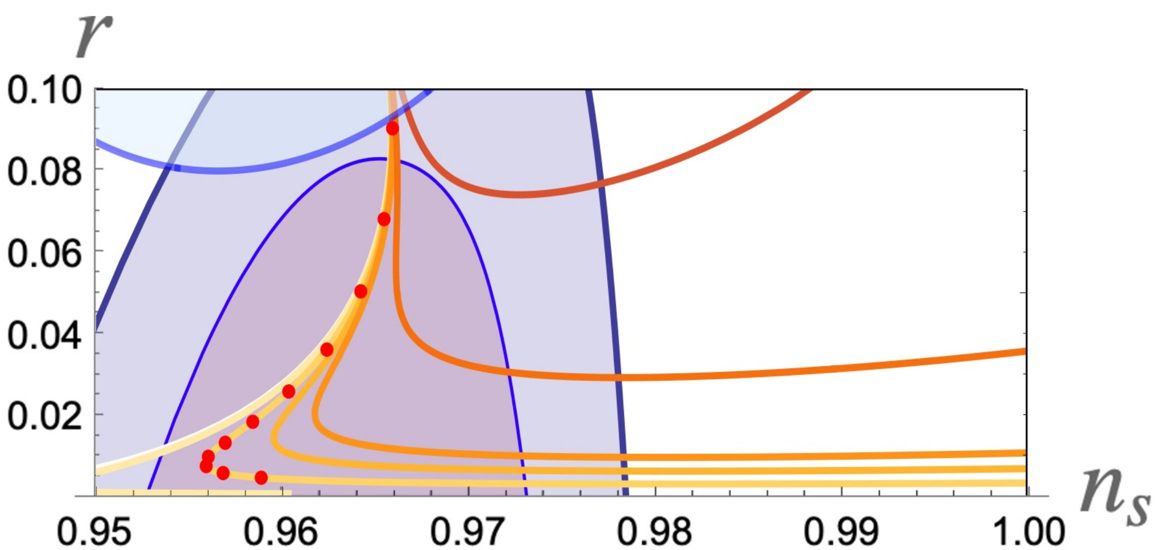
Before discussing **r** we have to understand that ACT shift of $\mathbf{n_s}$ to the right, **if correct**, is highly significant. As we will see, it disfavors inflationary models with an **exponential** approach to plateau with $\mathbf{n_s \sim 0.965}$ and favors models with a **power-law** approach to plateau and $\mathbf{n_s > 0.965}$

But first – a general question: Do we have any simple, comprehensive inflationary models that work no matter what?

A simple polynomial potential with 3 parameters can describe the full range of all possible values of A_s, n_s and r, all the way to r = 0 and n_s = 1

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

Destri, de Vega, Sanchez, 2007
Nakayama, Takahashi and Yanagida, 2013
Kallosh, AL, Westphal 2014



Example: For **b** = 0.34, we have **r** = 0.01. By increasing **a** from 0.13 to 0.17, we move from $\mathbf{n_s}$ = 0.967 (Planck) to 0.974 (ACT), and all the way to $\mathbf{n_s}$ = 1.

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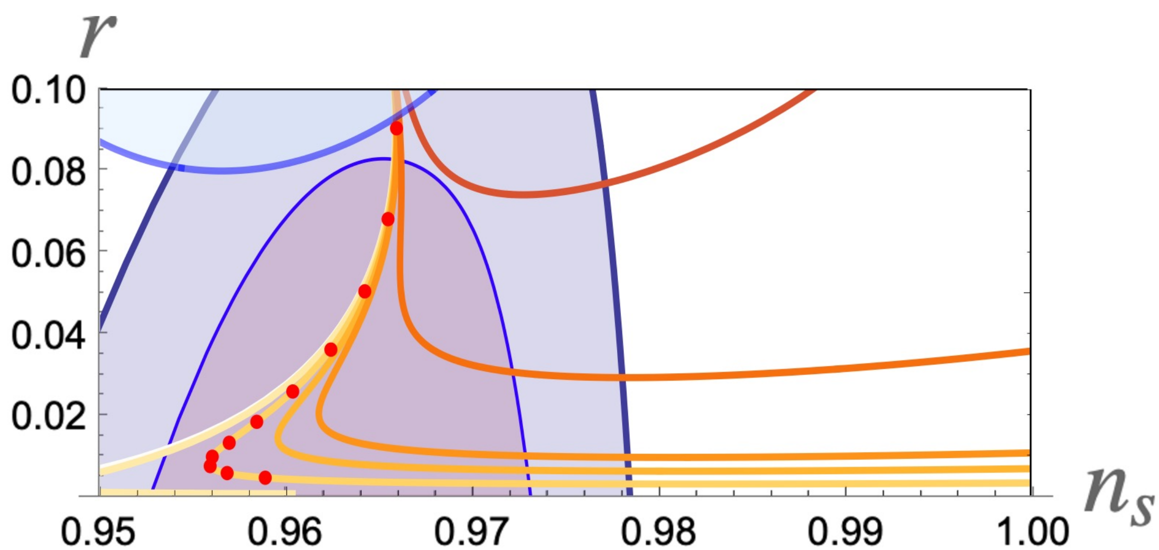
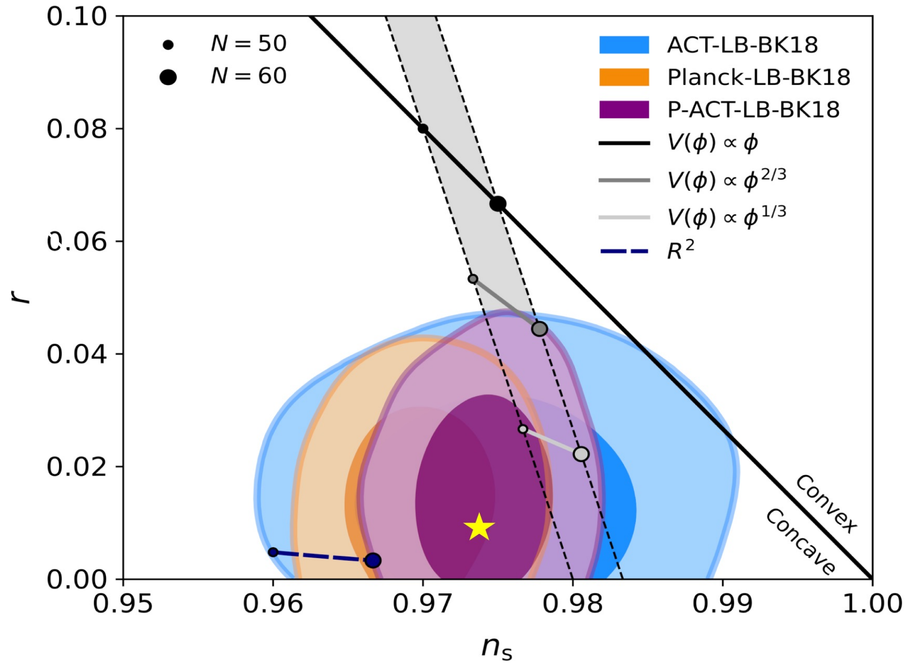


But it is better to have models with **no more than 1 or 2 parameters**

A non-minimal version of chaotic inflation

$$\frac{1}{2}(1+\underline{\phi)R} - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$$

Kallosh, AL, Roest
2503.21030



This simple generalization of the chaotic inflation model is compatible with ACT+SPT+DESI

Its prediction is shown by the yellow star

In the Einstein frame, this theory has a potential with a power-law approach to the plateau

$$V = \frac{m^2}{2}\left(1 - 8\varphi^{-2} + \ldots\right)$$

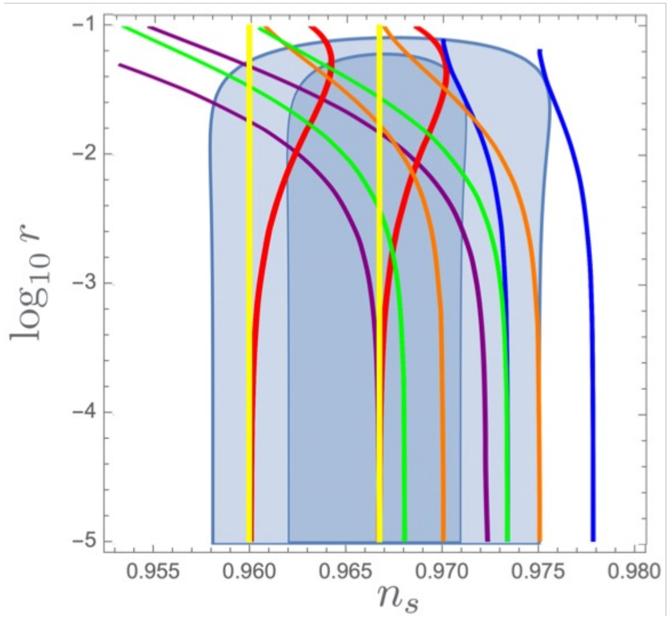
Pole inflation, polynomial α-attractors, KKLTI models, BI models

Power-law approach to the plateau

$$V = V_0\left(1 - \frac{m^k}{\varphi^k} + \dots\right)$$

$$n_s = 1 - \frac{2}{N_e}\frac{k+1}{k+2}$$

Example: $$V = V_0\,\frac{\varphi^k}{\varphi^k + m^k}$$



These models can cover a wide range of n_s

$$1 - \frac{2}{N_e} < n_s < 1 - \frac{1}{N_e}$$

For $N_e = 60$, this range is $0.967 < n_s < 0.983$

Fully compatible with ACT

A more detailed discussion of the simple models compatible with the recent data will be in the talk by Renata Kallosh