Reverse Engineering the Universe

Andrei Linde

Suppose we want to create the universe suitable for life, and we want to do it in the simplest possible way.

Is it possible to develop a fool-proof design?

Let us look at our own universe at present, and then “play the movie back in time”.

How big was the Big Bang?

The distance from Earth to the edge of the observable part of the universe is about 46.5 billion light years, or 4.4 x 10^{28} cm, in any direction. It contains about 10^{90} elementary particles. The total mass is about 10^{50} tons.

Big Bang universe at the Planck time and density

In quantum gravity it is very convenient to use system of units where

$$c = \hbar = G = 1$$

In these units, the density of matter in the expanding universe was

$$\rho \sim \frac{1}{t^2}$$

At $t < 1$, density was > O(1), and quantum fluctuations were too strong. The time $t = 1$ (or 10^{-43} seconds, in more conventional units) is called the Planck time, and the density equal to 1 (or 10^{94} g/cm^3) is called the Planck density. At that time, each part of the universe of size O(1) (Planck length ~ 10^{-33} cm) contained O(1) particles, each of them with kinetic energy O(1).

One can talk about classical space - time only at $t > 1$ and at density smaller than the Planck density.

Hard Art of the Universe Creation

According to the standard hot Big Bang universe, the total number of particles during its expansion did not change much, so the universe at the Planck time was supposed to contain about 10^{90} particles. At the Planck time $t = O(1)$, there was one particle per Planck length $ct = O(1)$.

Thus, at the Planck time $t = 1$, the whole universe consisted of 10^{90} causally disconnected parts of size $ct = O(1)$. Such parts did not know about each other. If someone wanted to create the universe at the Planck time, he/she could only make **a Very Small Bang** in his/her own tiny part of the universe of a Planck size $ct = O(1)$. **Everything else was beyond causal control.**

Is it possible to make a miracle, start with less than a milligram of matter (Planck mass), in a tiny speck of space of Planck size O(1), and produce 10^{90} particles from it?

Basic idea:

One of the Einstein equations for the empty universe with vacuum energy density V_0 (cosmological constant) is

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V_0^2}{3}$$

It has a solution describing an exponentially growing (inflating) universe:

$$a = a_0\, e^{Ht}$$

The total vacuum energy of such universe grows even faster, as volume

$$E = E_0\, e^{3Ht}$$

If eventually this vacuum state decays, it produces exponentially many elementary particles with exponentially large energy. Problem solved!

Alan Guth 1980

If something looks too good to be true...

If the universe is empty, how can one tell that it expands?

The universe with a constant positive vacuum energy V_0 is de Sitter space. It looks expanding in one system of coordinates, collapsing in another system of coordinates, and static in yet another coordinates.

If there is no preferable coordinate system in the vacuum, then there is no preferable time when the vacuum state decays. Therefore vacuum decays chaotically, and the universe becomes grossly inhomogeneous. After a year of investigation, Alan Guth and Stephen Hawking concluded that this scenario cannot be improved.

Moreover, in the original scenario, it was assumed that the universe was large from the very beginning, started its evolution in the hot Big Bang, and inflation began only at $t > 10^5$. Does not fully address the problem.

Breaking the rules

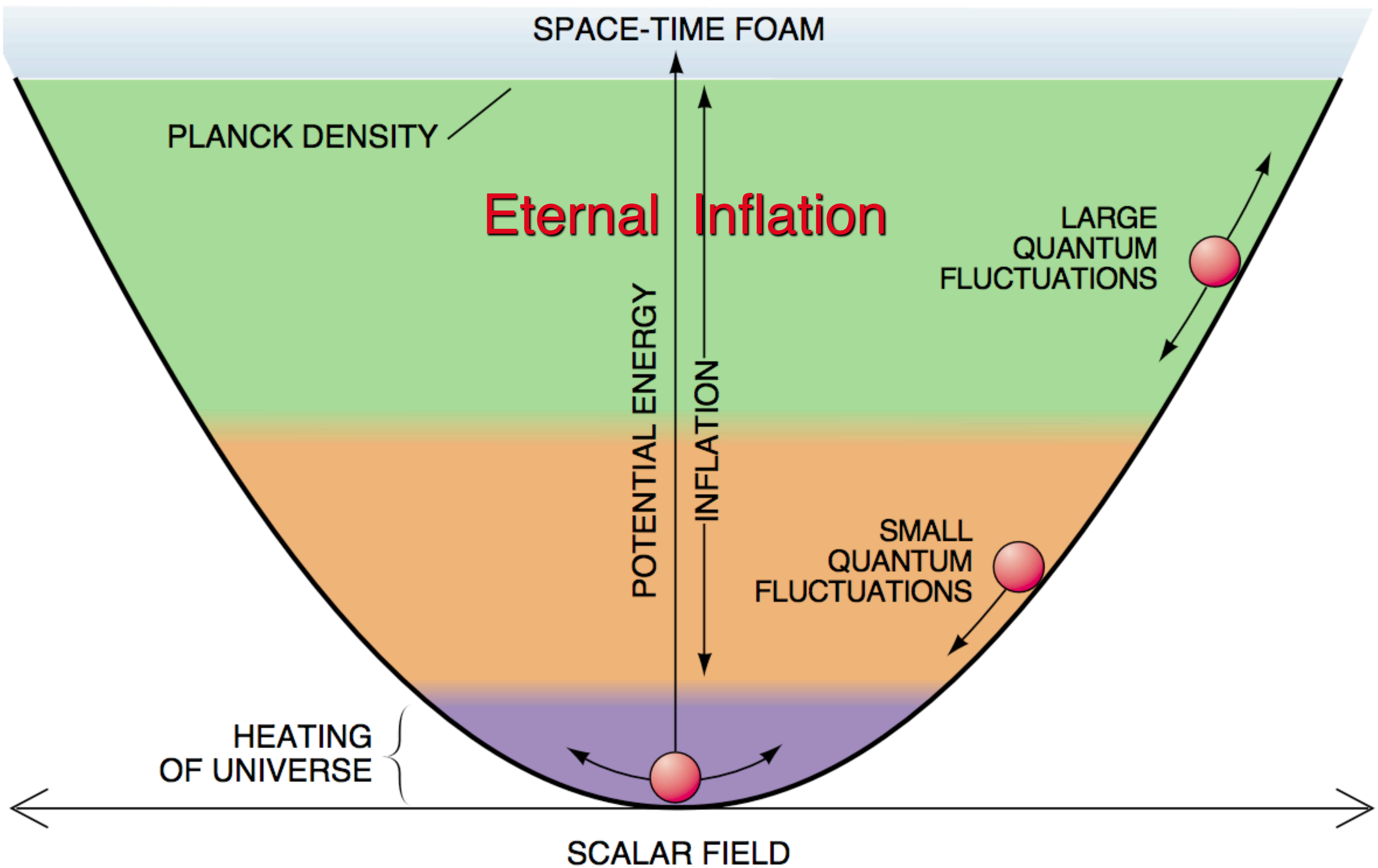
A solution was found in 1981-1983: Instead of a vacuum state with a constant vacuum energy V_0, one should consider a slowly changing scalar field with a sufficiently flat potential $V(\phi)$. If the potential is too steep – no inflation. If it is too flat – the universe becomes inhomogeneous.

And then it was realized that it is better to completely abandon the idea that the universe was born in the hot Big Bang.

The simplest inflationary model

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

AL 1983



Equations of motion:

- **Einstein equation:**

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

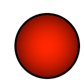
- **Klein-Gordon equation:**

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

Compare with equation for the harmonic oscillator with friction:

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

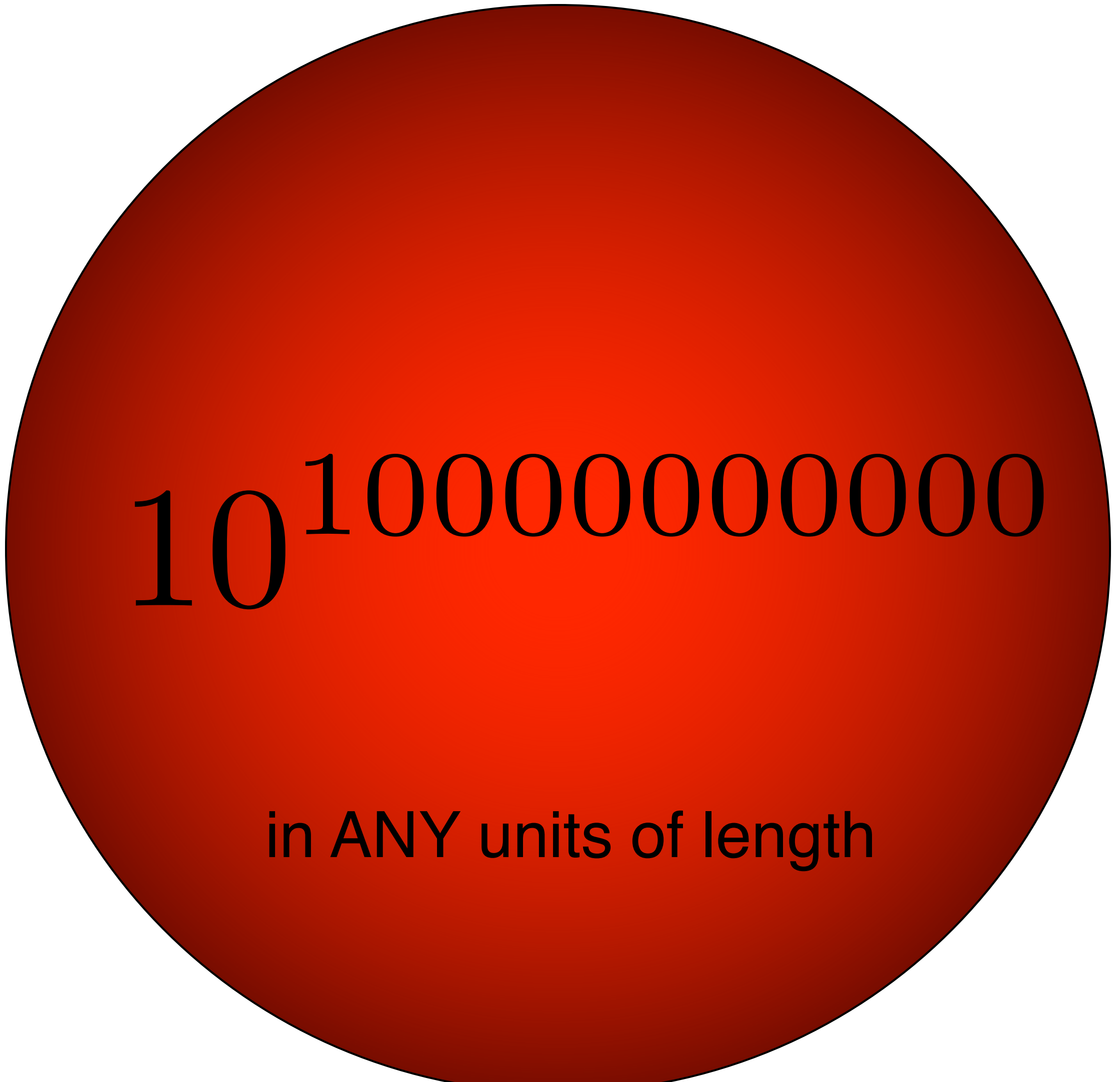
A newborn universe could be as small as 10^{-33} cm (Planck length) and as light as 10^{-5} g (Planck mass). If its energy density is dominated by V, inflation immediately begins



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

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

Inflationary universe 10^{-35} seconds old



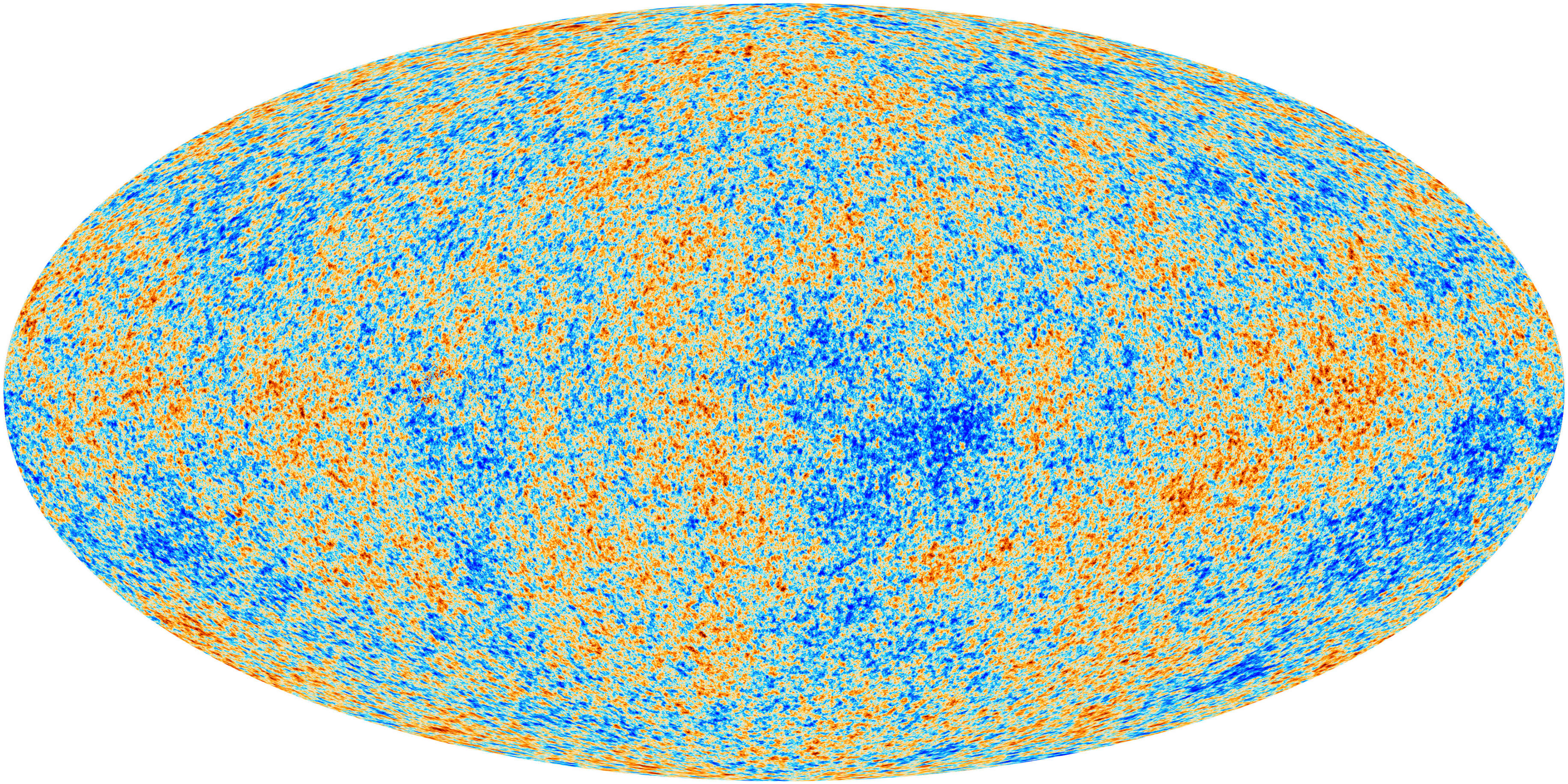
Origin of structure:

In this theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations** amplified during the exponential growth of the universe.

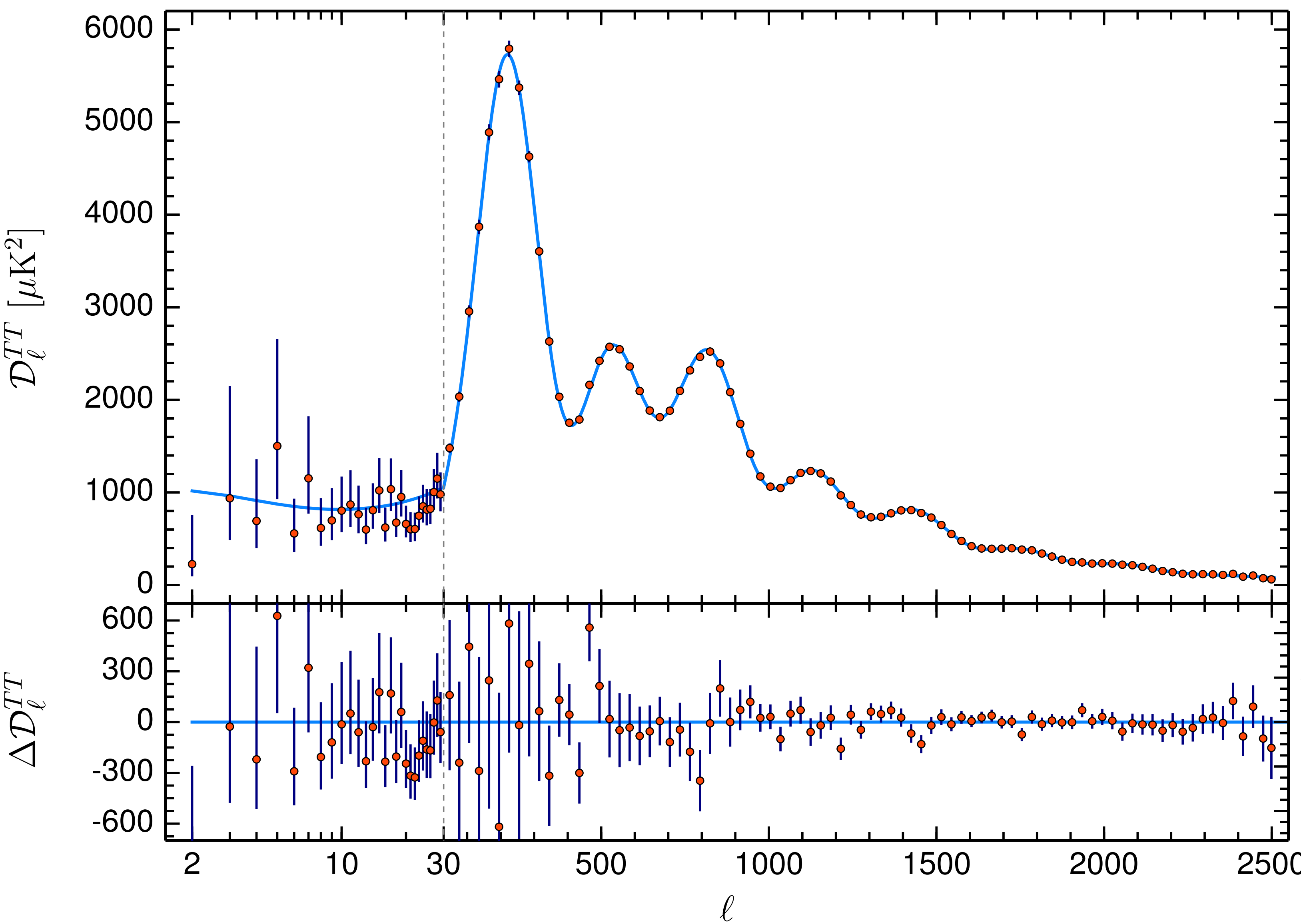
Galaxies are children of quantum fluctuations produced in the first 10^{-35} seconds after the birth of the universe.

Planck satellite: Perturbations of temperature

This is an image of **quantum fluctuations produced by inflation 10^{-35} seconds after the Big Bang**. These tiny fluctuations were **stretched by inflation** to incredibly large size, and now we can observe them **using all sky as a giant photographic plate**



Planck 2018: Perturbations of temperature (red dots) and predictions of inflationary theory (blue line)



Testing inflation

1) In the early 80's it seemed that inflation is ruled out because inflationary perturbations are not observed at the expected level 10^{-3}. The problem disappeared thanks to dark matter.

2) 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.)

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

4) 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.)

5) Perturbations produced by inflation are adiabatic

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

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

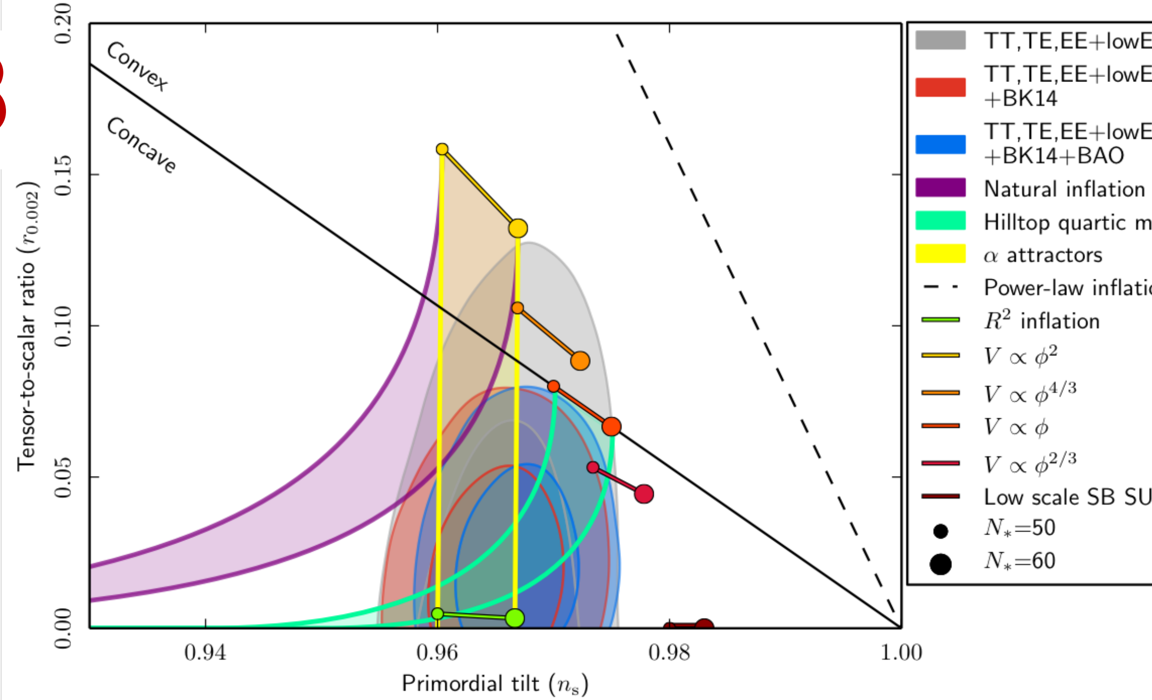
8) Inflationary perturbations should have a nearly flat, but not exactly flat spectrum. A small deviation from flatness is one of the distinguishing features of inflation. It is as significant for inflationary theory as the asymptotic freedom for the theory of strong interactions

9) Inflation produces scalar perturbations, but it also produces tensor perturbations with nearly flat spectrum, and it does not produce vector perturbations (matches observations). There are certain relations between the properties of scalar and tensor perturbations

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. 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

Inflation after Planck 2018

Planck 2018



$R + R^2/(6M^2)$				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Non-minimal coupling				
Natural inflation				
Hilltop quadratic model				
Hilltop quartic model	$\Lambda^4\left(1-\phi^4/\mu_4^4+\ldots\right)$	$-2<\log_{10}(\mu_4/M_{\rm Pl})<2$	-0.3	-1.4
D-brane inflation ($p=2$)	$\Lambda^4\left(1-\mu_{\rm D\,2}^2/\phi^p+\ldots\right)$	$-6<\log_{10}(\mu_{\rm D\,2}/M_{\rm Pl})<0.3$	-2.3	1.6
D-brane inflation ($p=4$)	$\Lambda^4\left(1-\mu_{\rm D\,4}^4/\phi^p+\ldots\right)$	$-6<\log_{10}(\mu_{\rm D\,4}/M_{\rm Pl})<0.3$	-2.2	0.8
Potential with exponential tails	$\Lambda^4\left[1-\exp\left(-q\phi/M_{\rm Pl}\right)+\ldots\right]$	$-3<\log_{10}q<3$	-0.5	-1.0
Spontaneously broken SUSY	$\Lambda^4\left[1+\alpha_h\log\left(\phi/M_{\rm Pl}\right)+\ldots\right]$	$-2.5<\log_{10}\alpha_h<1$	9.0	-5.0
E-model ($n=1$)	$\Lambda^4\left\{1-\exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_1^{\rm E}}M_{\rm Pl}\right)^{-1}\right]\right\}^{2n}$	$-2<\log_{10}\alpha_1^{\rm E}<4$	0.2	-1.0
E-model ($n=2$)	$\Lambda^4\left\{1-\exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_2^{\rm E}}M_{\rm Pl}\right)^{-1}\right]\right\}^{2n}$	$-2<\log_{10}\alpha_2^{\rm E}<4$	-0.1	0.7
T-model ($m=1$)	$\Lambda^4\tanh^{2m}\left[\phi\left(\sqrt{6\alpha_1^{\rm T}}M_{\rm Pl}\right)^{-1}\right]$	$-2<\log_{10}\alpha_1^{\rm T}<4$	-0.1	0.1
T-model ($m=2$)	$\Lambda^4\tanh^{2m}\left[\phi\left(\sqrt{6\alpha_2^{\rm T}}M_{\rm Pl}\right)^{-1}\right]$	$-2<\log_{10}\alpha_2^{\rm T}<4$	-0.4	0.1

What is the meaning of α-attractors?

Kallosh, AL, Roest 2014

Start with the simplest chaotic inflation model

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

Modify its kinetic term

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

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

The potential becomes

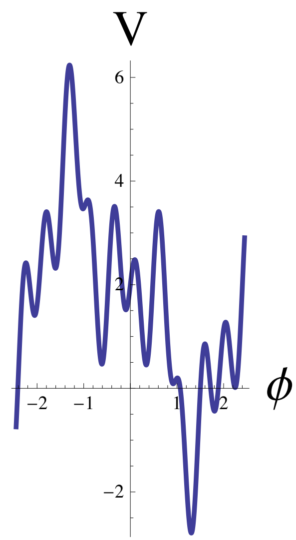
$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

Stretching and flattening of the potential is similar to stretching of inhomogeneities during inflation

Kallosh, AL 2013

Potential in the **original variables** with kinetic term

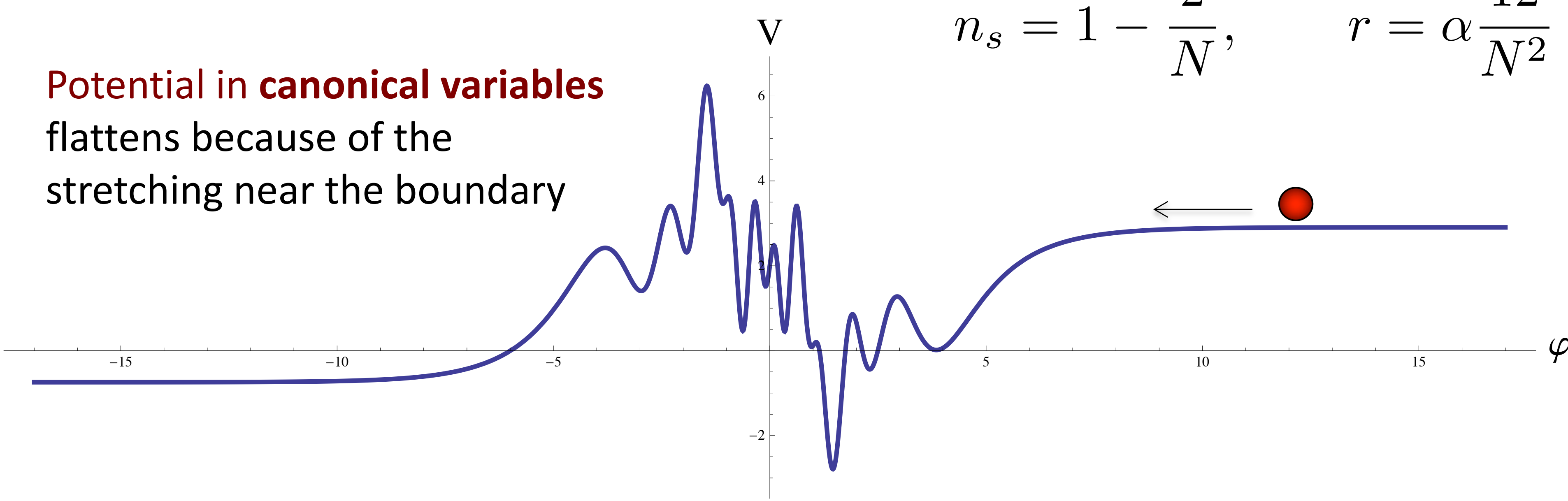
$$\frac{1}{2}\,\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



All of these models predict

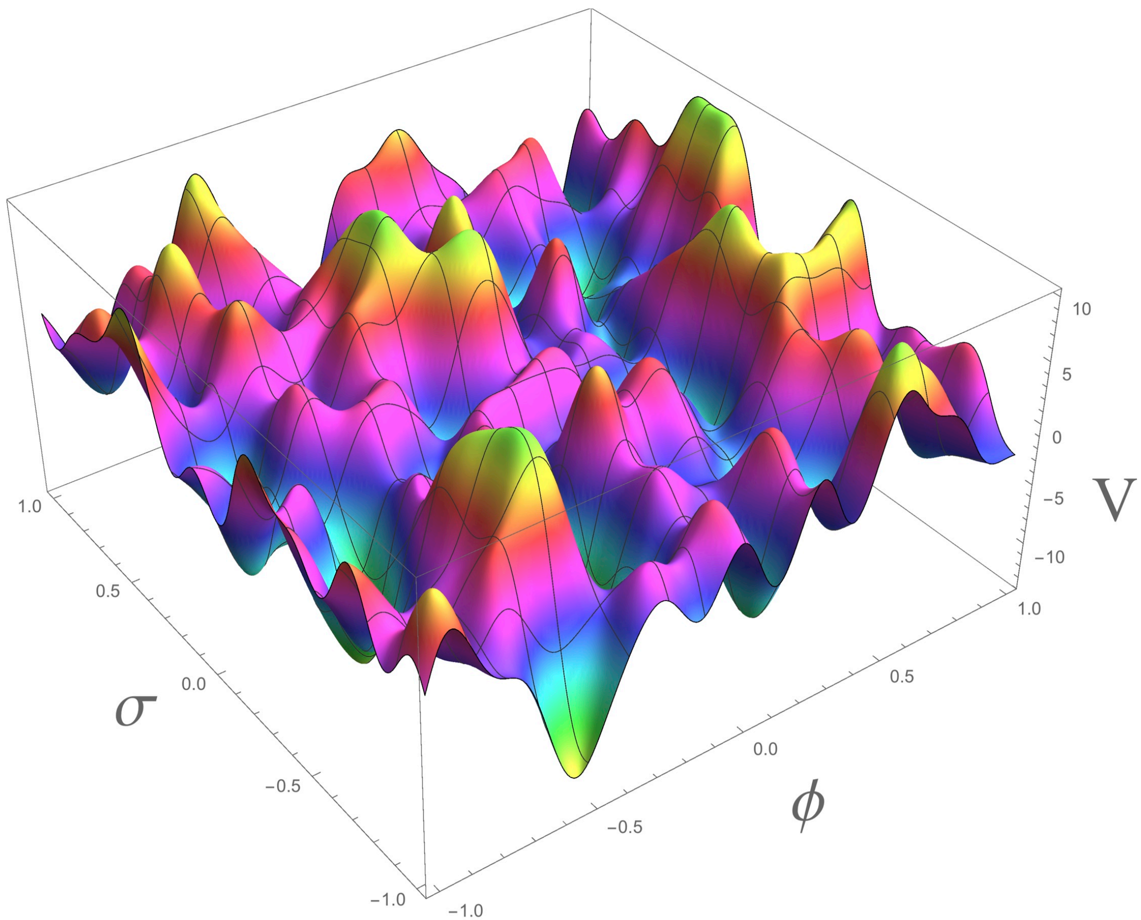
$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

Potential in **canonical variables** flattens because of the stretching near the boundary



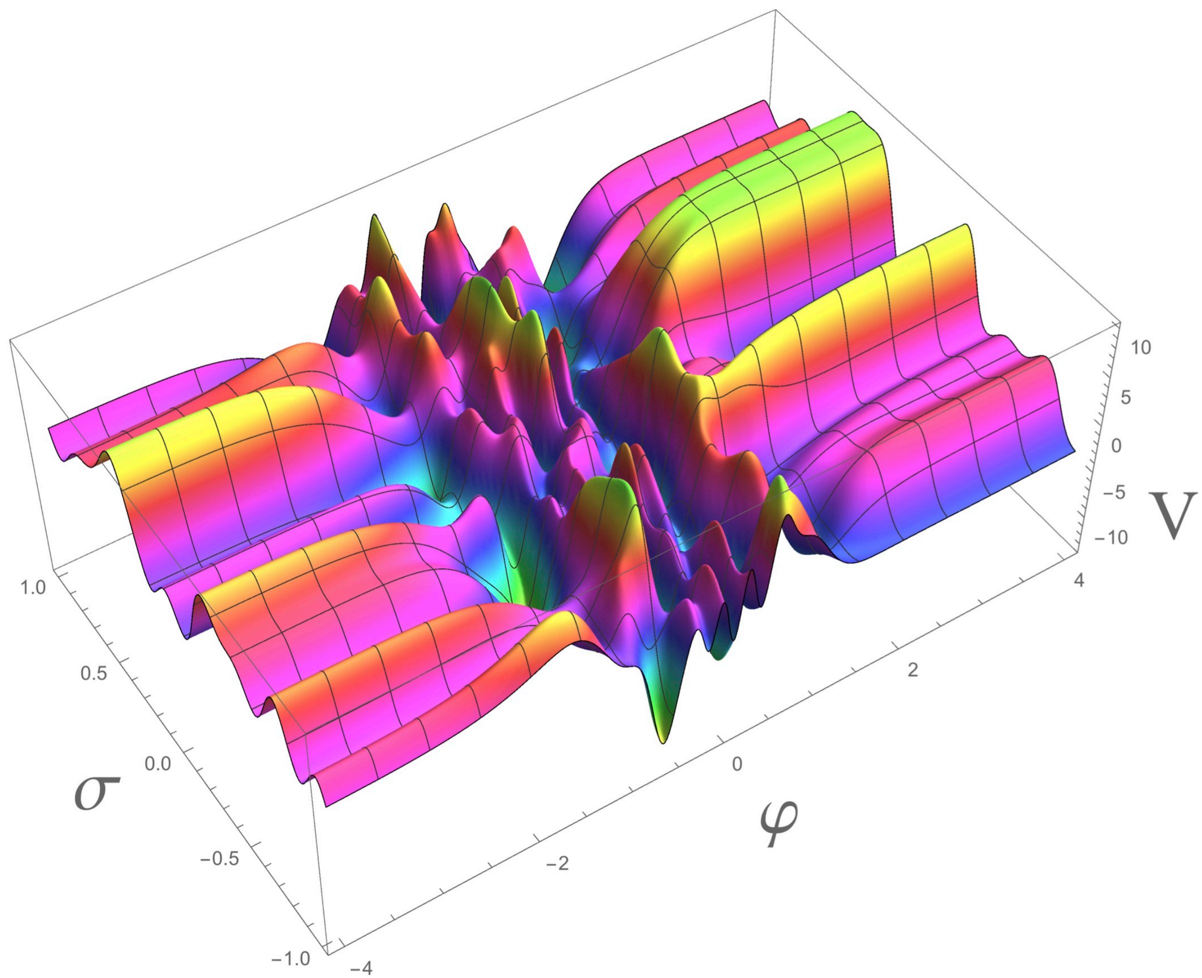
Inflation with Random Potentials and Cosmological Attractors

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



In terms of canonical fields φ with the kinetic term $\frac{(\partial_\mu \varphi)^2}{2}$, the potential is

$$V(\varphi, \sigma) = V(\sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}, \sigma)$$



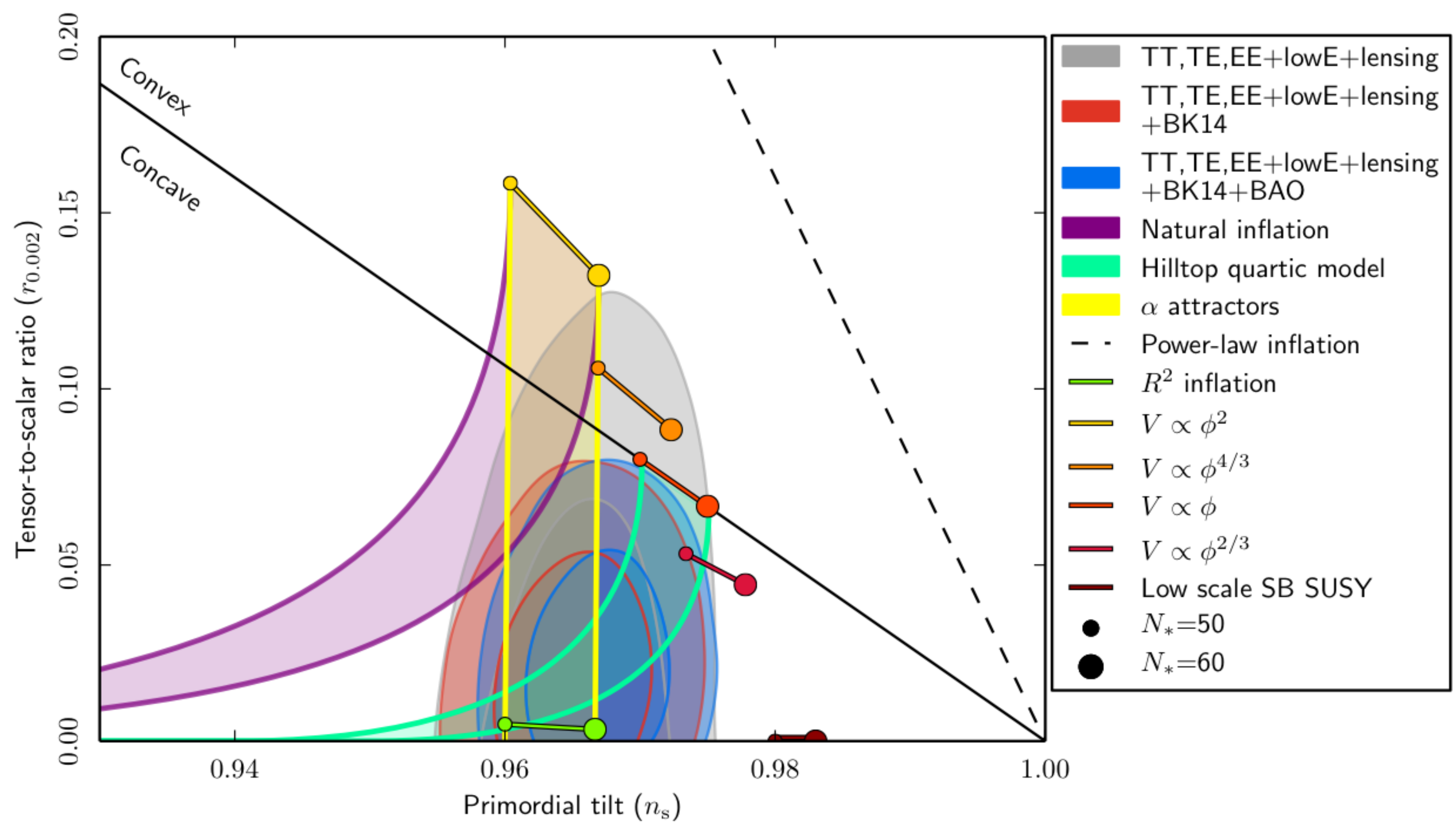
α-attractor mechanism makes the potentials flat, which makes inflation possible, which, in its turn, makes the universe flat

Planck 2018 and the Hilltop Mystery

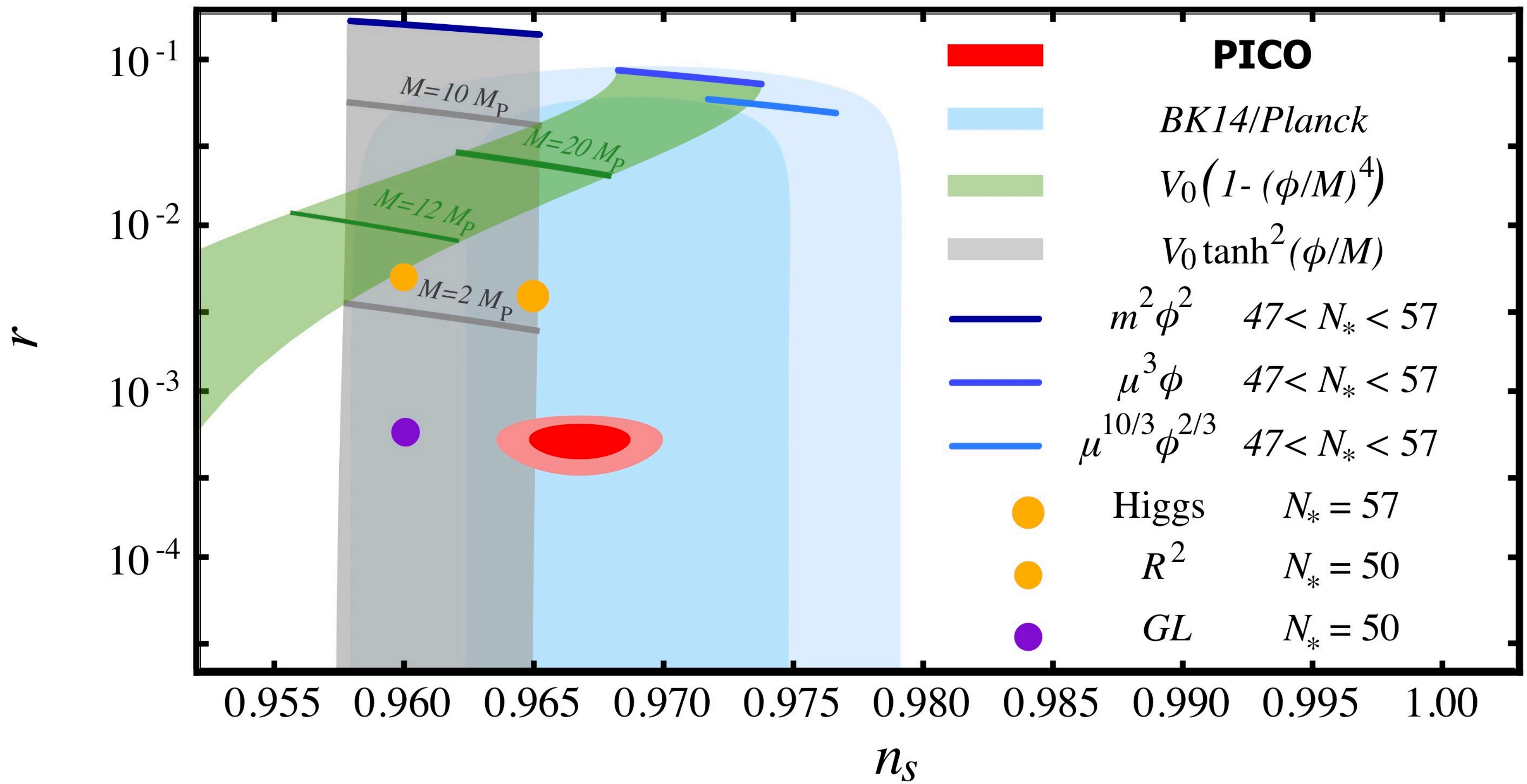
$$V = V_0 \left(1 - \frac{\phi^n}{m^n}\right)$$

RK, Linde, 1906.02156

The potential is very non-linear, but the predictions, **shown by the green area**, in the large m limit converge to the predictions of a theory with a linear potential, **for any n**. **What is going on?**



The same green hilltop area in PICO



Short happy life at the hilltop

$$V = V_0\left(1 - \frac{\phi^4}{m^4}\right) \qquad m \lesssim 1$$

For m < 1, the hilltop inflation is an attractor: n_s = 1-3/N for all m < 1. Nice model, for m << 1 inflation occurs at the top, at ϕ << m. Adding higher order terms one can easily modify the potential without affecting inflation.

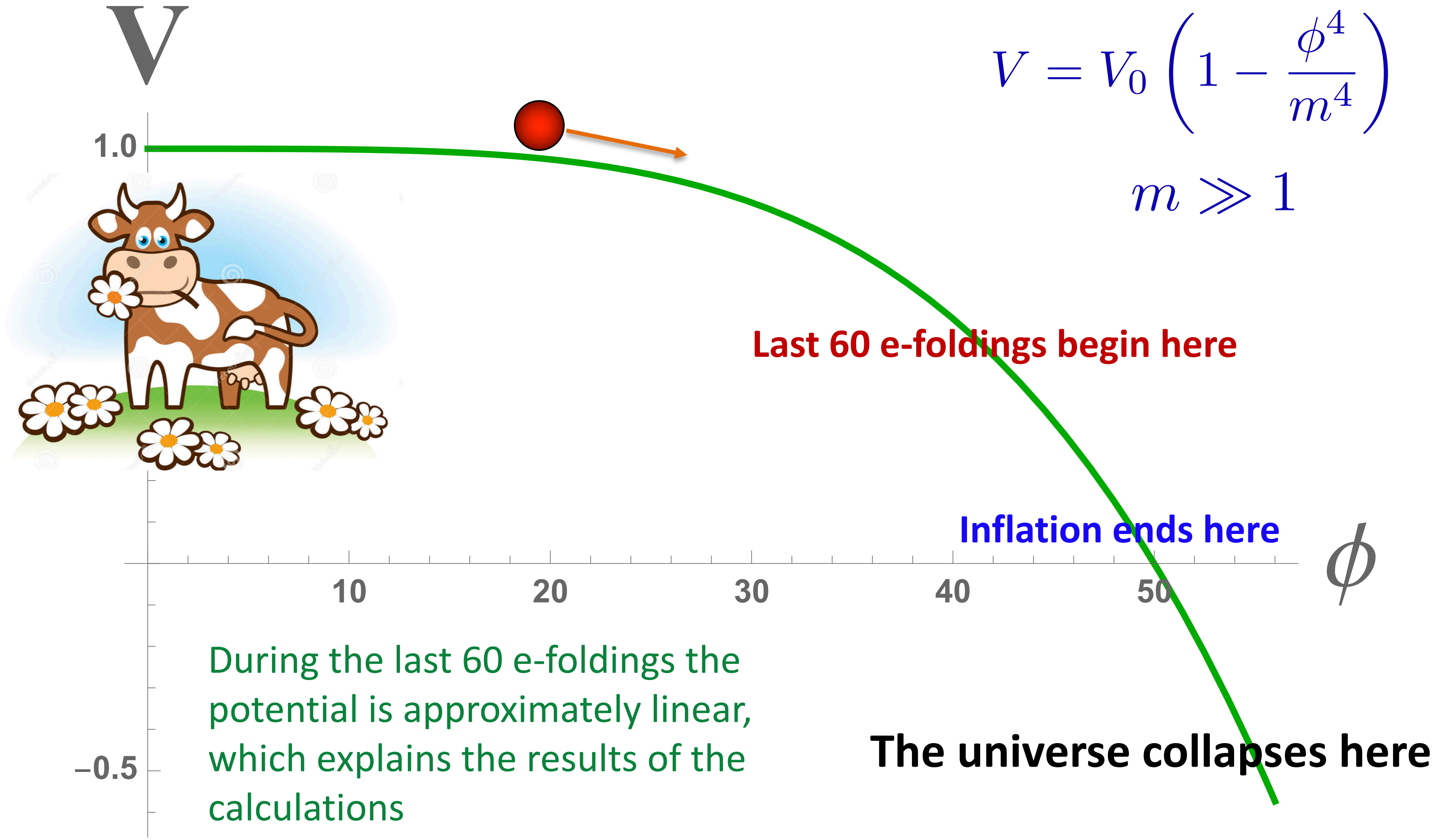
But n_s = 1-3/N is too small, the models with m < 1 are ruled out by Planck 2015 and 2018.

Most of the green area in the Planck figures corresponds to m > 10. The linear regime corresponds to m >> 10. Last stages of inflation occur far away from the top, at ϕ ~ m > 10. Unspecified higher order terms in ϕ/m determine <u>everything</u>, initial beauty is gone.

Hilltop inflation starts at the top but where does it end?

$$V = V_0 \left(1 - \frac{\phi^4}{m^4}\right)$$

$$m \gg 1$$

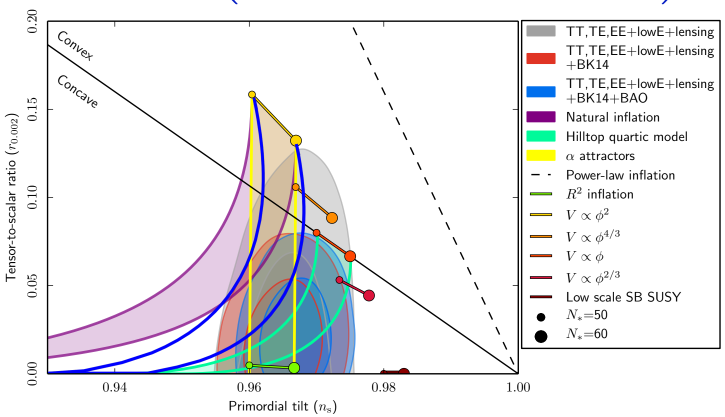


During the last 60 e-foldings the potential is approximately linear, which explains the results of the calculations

Saving hilltop models ?

Coleman-Weinberg

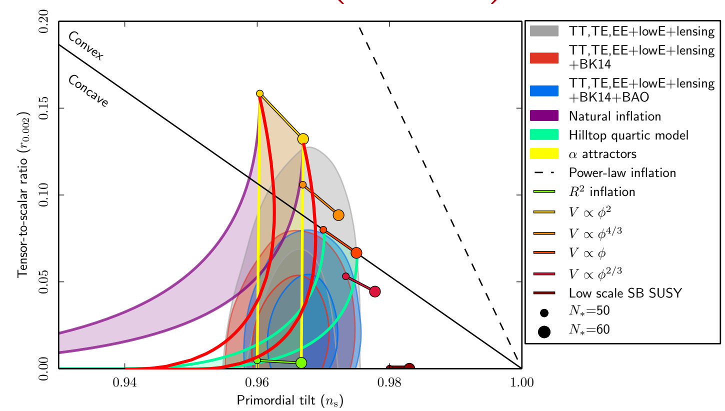
$$V = V_0\left(1+\frac{\phi^4}{m^4}(2\log\frac{\phi^2}{m^2}-1)\right)$$



Motivation OK, agreement with data poor

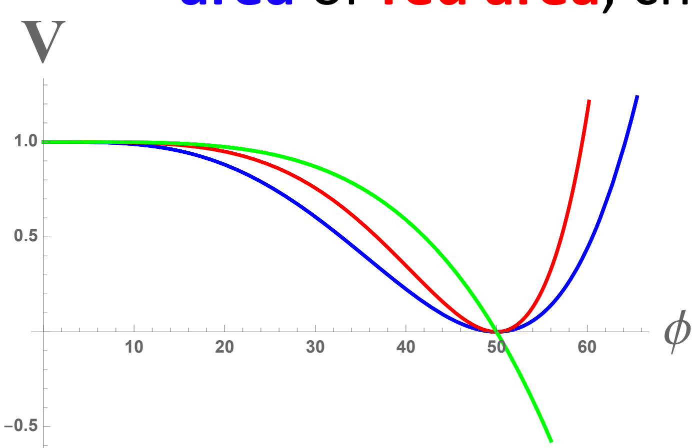
Squared hilltop

$$V = V_0\left(1-\frac{\phi^4}{m^4}\right)^2$$



Agreement with data OK, motivation poor

Thus, consistent models change the **green area** into the **blue area** or **red area**, change n_s and significantly increase r



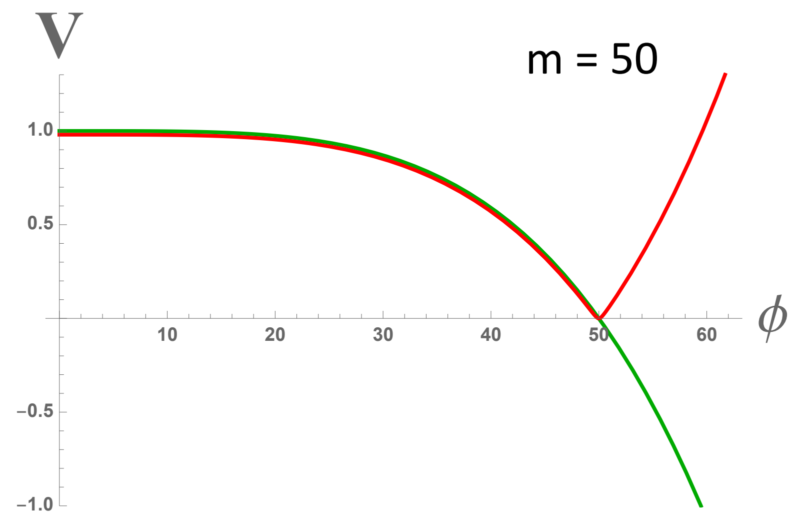
We conclude that the green hilltop area is not reproduced by analysis of simple consistent inflationary models

But what if one desperately wants to preserve the predictions of the inconsistent hilltop models?

It can be done. *Up and down, positive and negative, heaven and hell differ only by the sign. So just take the* ***absolute value*** *of the hilltop potential, make it smooth, and you will get*

the hilltop bottom

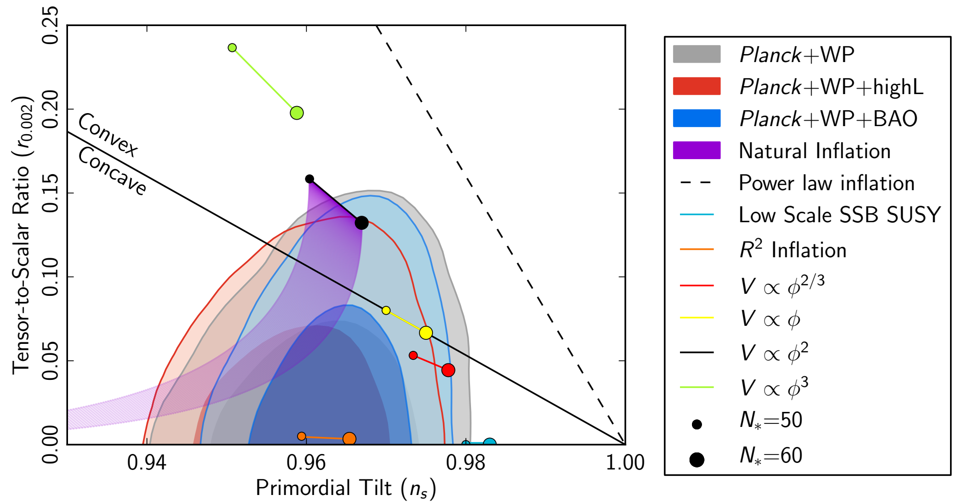
$$V = V_0 \left(\sqrt{\frac{1}{m^2} + \left(1 - \frac{\phi^4}{m^4}\right)^2} - \frac{1}{m} \right)$$



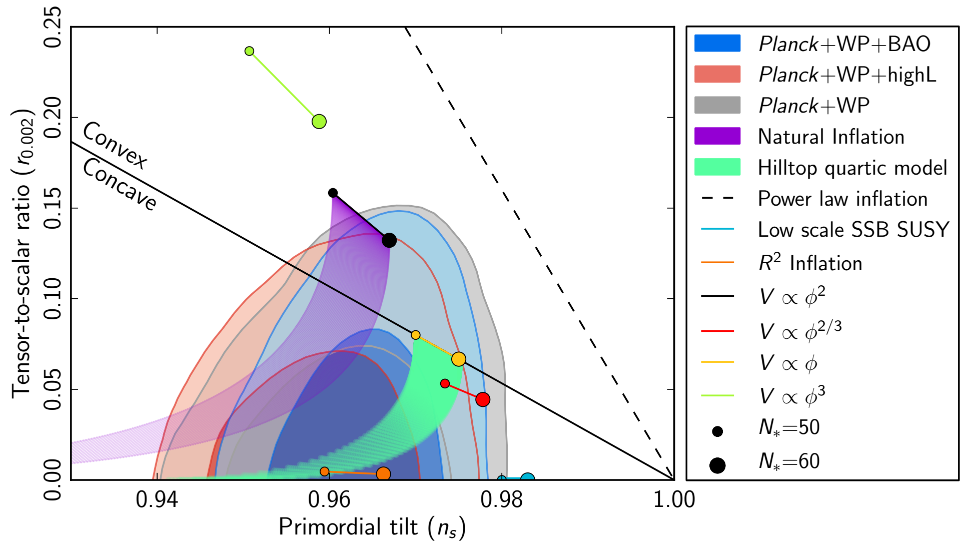
Does this *ad hoc* handmade model have any physical motivation? Should we put it on the list of the best inflationary models favored by Planck and suggest its further exploration by CMB-S4?

How did the green hilltop area appeared in these pictures?

Planck 2013 version 1



Version 2, <u>after the referee report...</u>

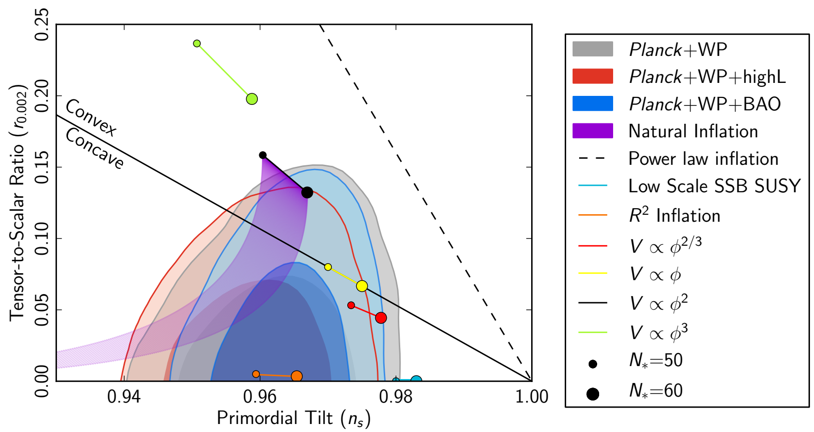


Thanks to the referee, the green hilltop area appears in every Planck data release, in CMB-S4, in PICO, for the last 6 years...

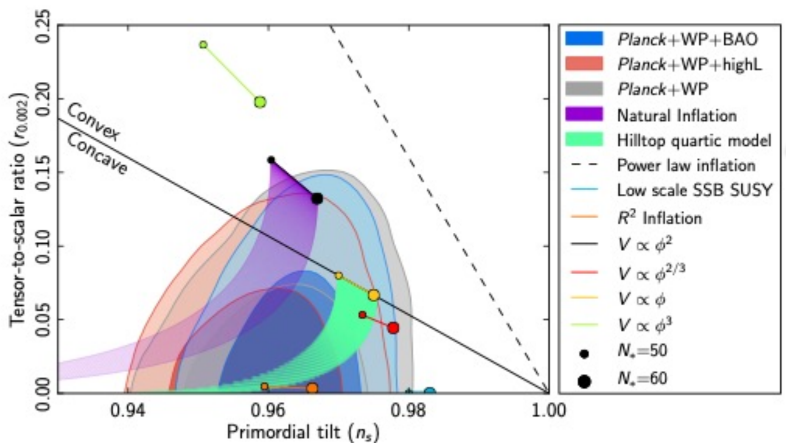
From Planck 2013 to PICO 2019

Planck 2013

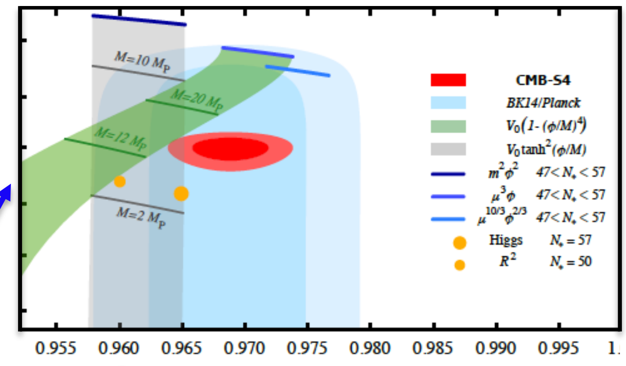
v1



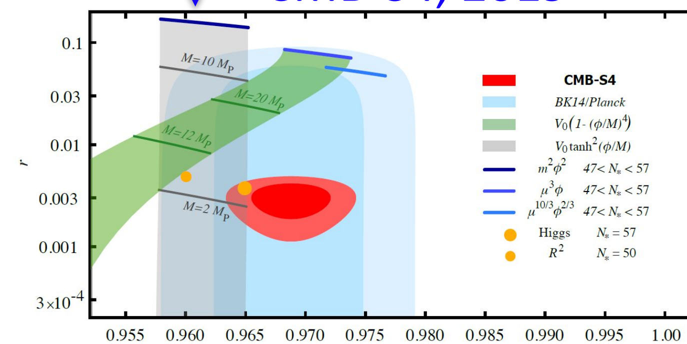
v2



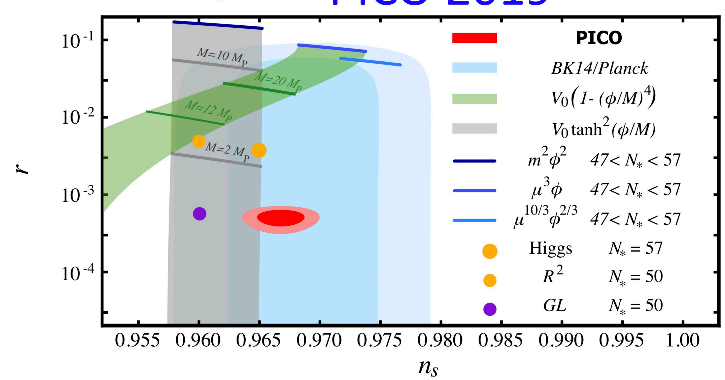
CMB-S4, 2016



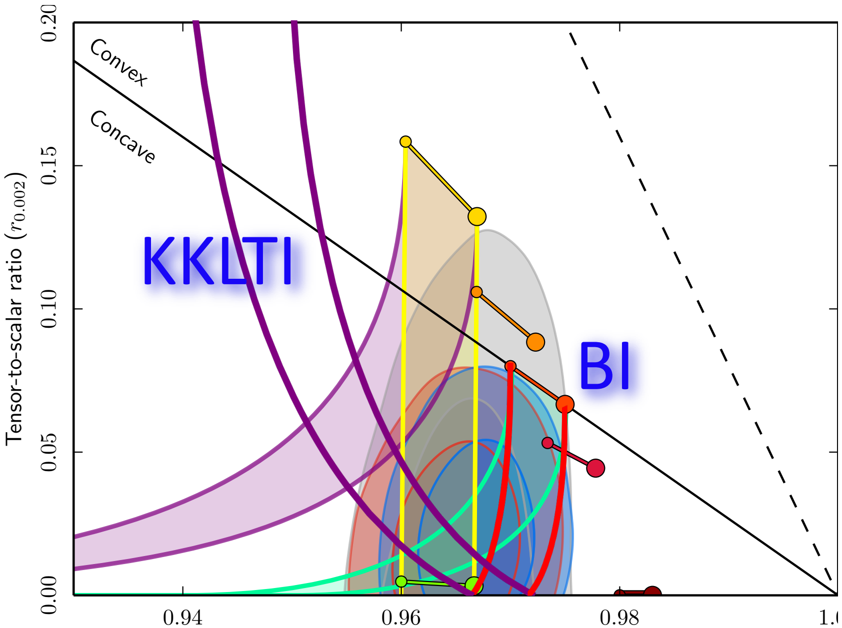
CMB-S4, 2019



PICO 2019



At the moment there are no simple, well-motivated and consistent hilltop models describing the green area in these figures

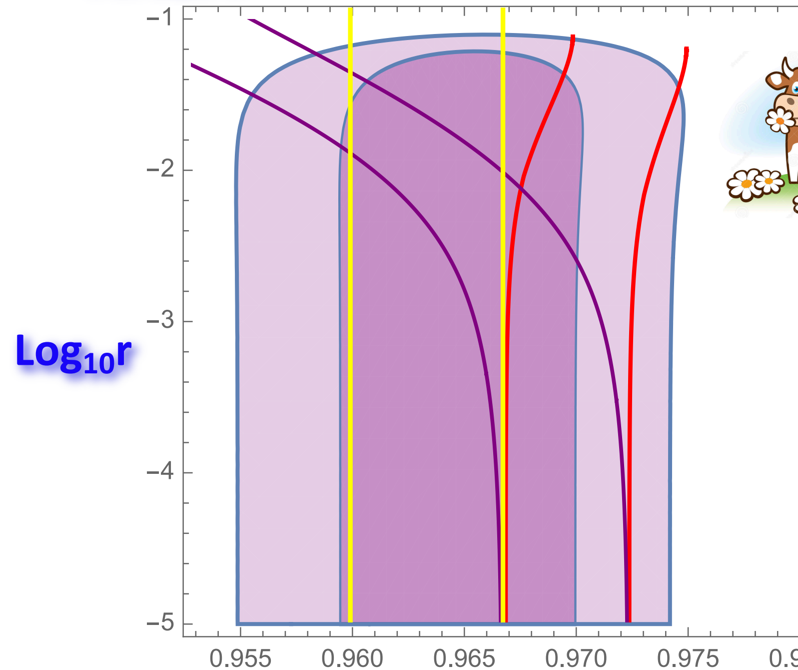


Towards $V \sim \varphi^n$

KKLTI

Towards $V \sim \varphi$

BI



$$\boxed{n_s = 1 - \frac{2}{N}}$$

towards

$$n_s = 1 - \frac{2}{N}\frac{n+1}{n+2}$$

Predictions of a potential with a linear potential $V \sim \varphi$ is an attractor of hilltop and BI models and large m

$$1 - \frac{\varphi^n}{m^n} \qquad 1 - \frac{m^n}{\varphi^n}$$

Hard to improve: no simple well motivated data-consistent hill-top model reproduces the green area

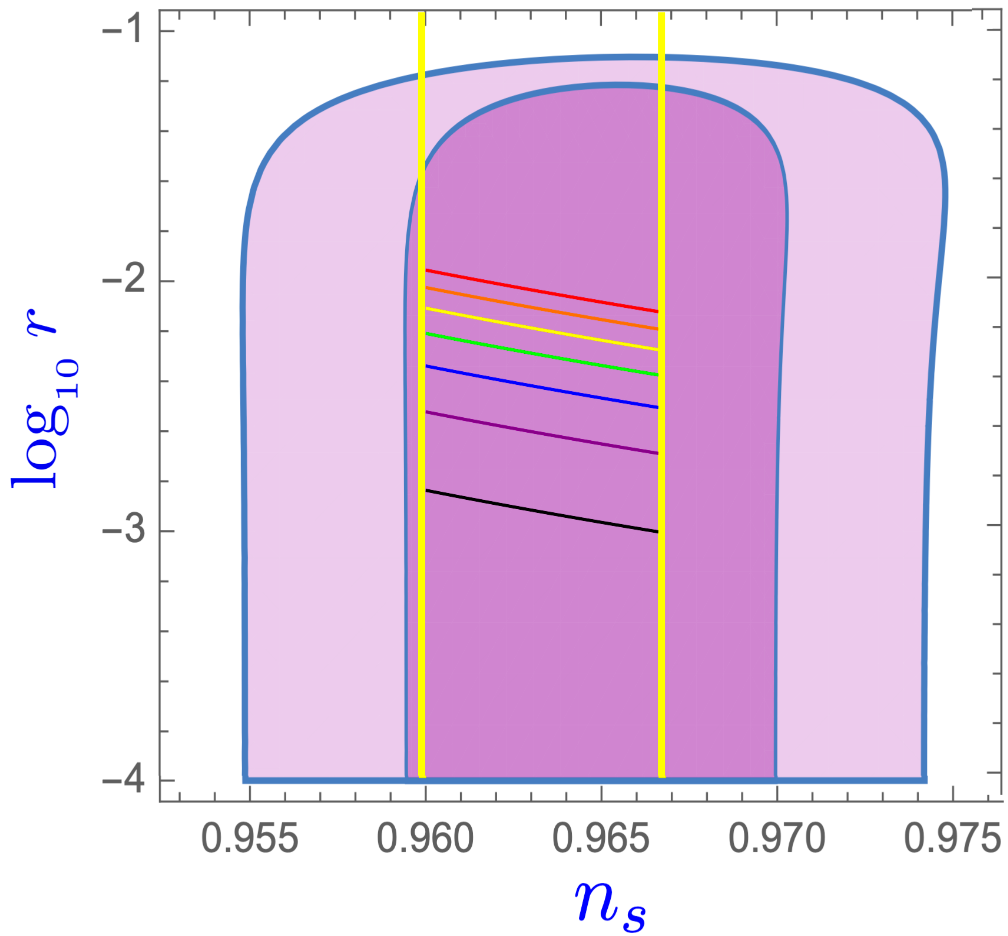
improved

$$V_{KKLTI} \sim \left(1 + \frac{m^n}{\varphi^n}\right)^{-1}$$

U-duality symmetry benchmarks for α-attractors

Maximal supersymmetry

$$E_{7(7)}(\mathbb{R}) \supset [SL(2,\mathbb{R})]^7$$



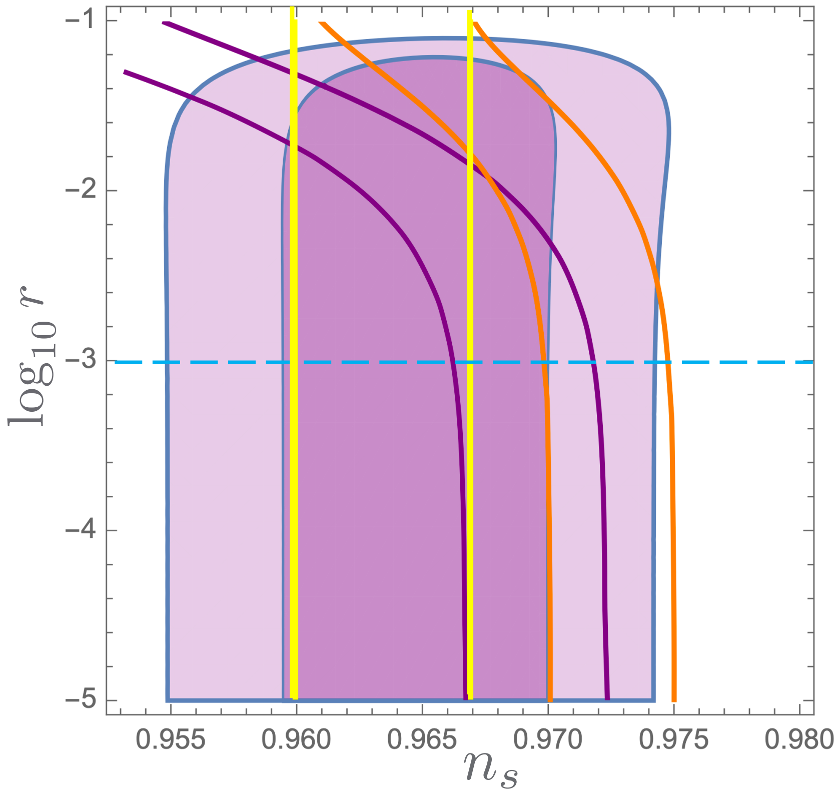
Special cases:

α = 2, **orange**, also fibre inflation, Cicoli et al

α = 1, **blue**, also Higgs, Starobinsky and conformal attractors

α = 1/3, **black**, also maximal superconformal theory

Attractor stripes at $r \lesssim 10^{-3}$



Plateau potentials and the position of the attractor stripes at small r

Yellow stripe	$n_s = 1 - \frac{2}{N}$	α-attractor
Purple stripe	$n_s = 1 - \frac{5}{3}\frac{1}{N}$	D3-brane
Orange stripe	$n_s = 1 - \frac{3}{2}\frac{1}{N}$	D5-brane

asymptotic formula at small r for α-attractor models

$$(1 - n_s)|_{r\to 0} = \frac{2}{N}$$

asymptotic formula at small r for Dp-brane models

$$(1 - n_s)|_{r\to 0} = \frac{2}{N}\,\frac{8-p}{9-p}$$

n_s precision data?

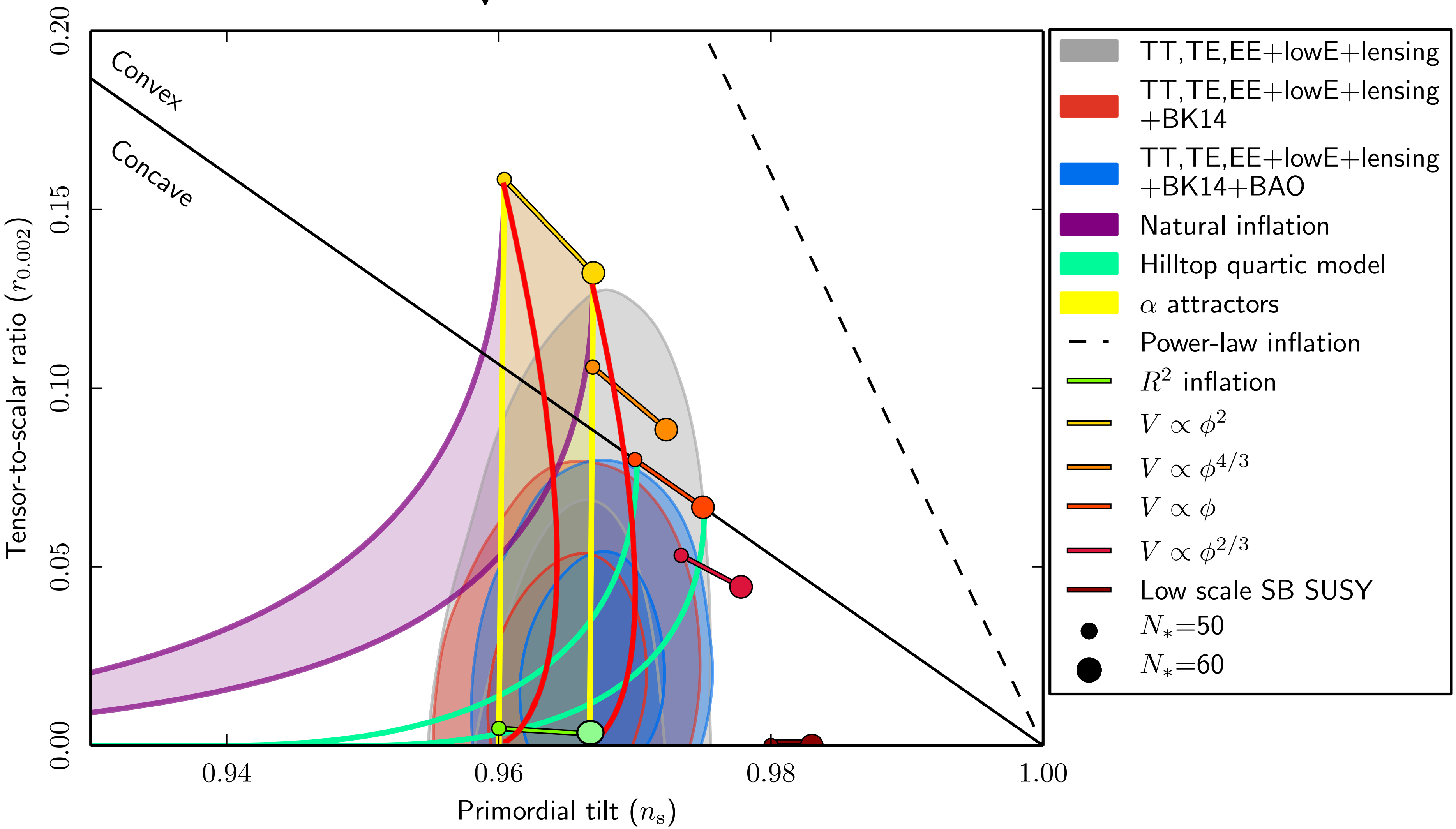
PICO: $\sigma(n_s) = 0.0015$

Which of the stripes will be the favorite?

Even not detecting B-modes one will be able to distinguish between these models!

T-models (yellow) and E-models (red)

$$V_T = V_0 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}} \qquad V_E = V_0 \left(1 - e^{\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2$$



T-models (yellow) and E-models (red)

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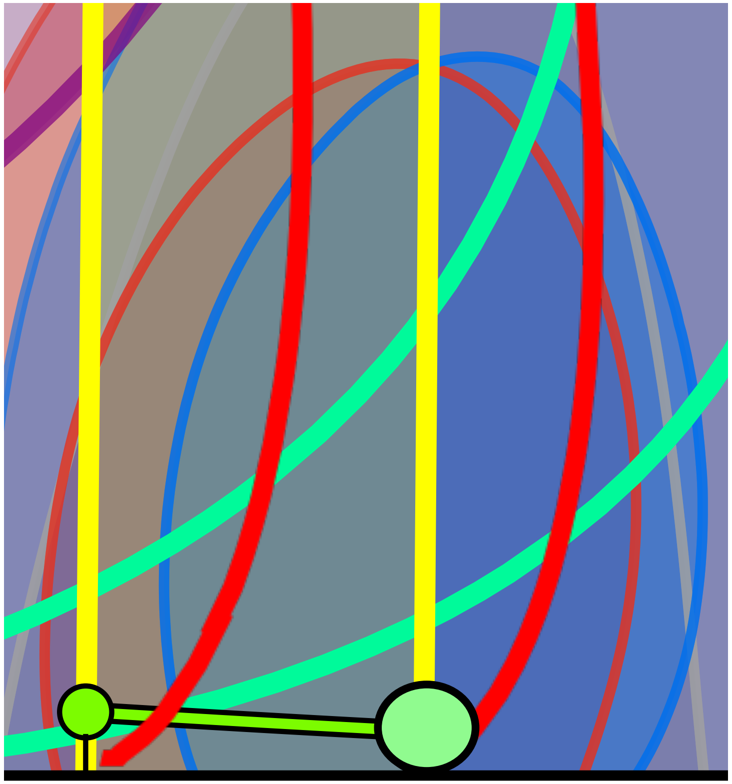
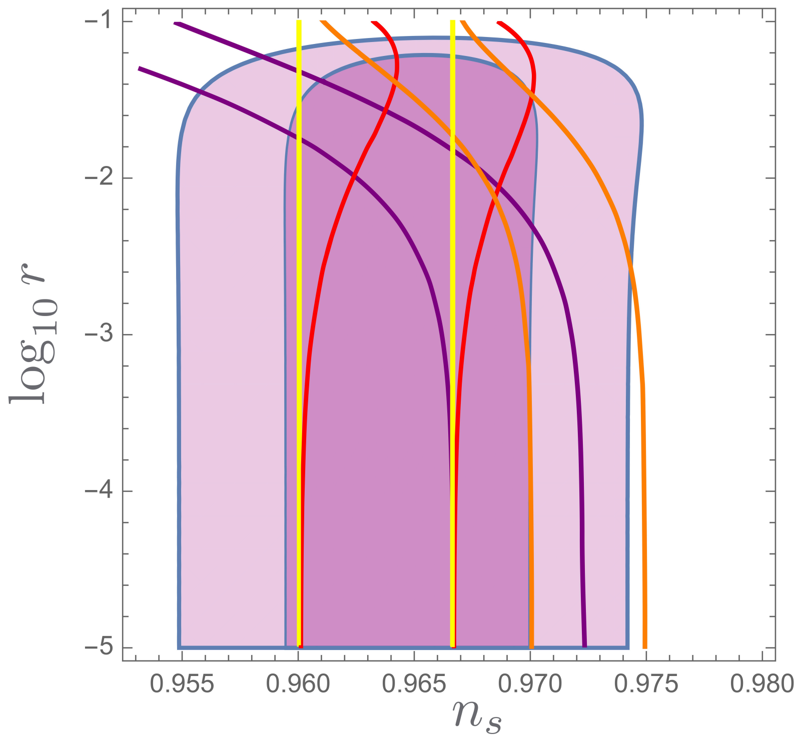
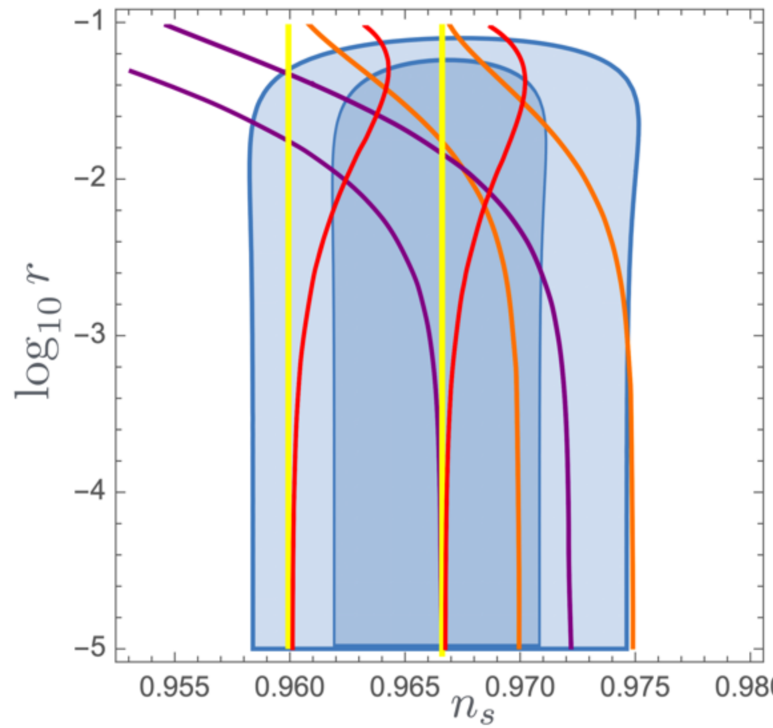


By zooming at the 1σ area (dark pink or dark blue), we see that most of it is covered by two simplest models of α-attractors

T-models, E-models and KKLTI models on Log r scale:

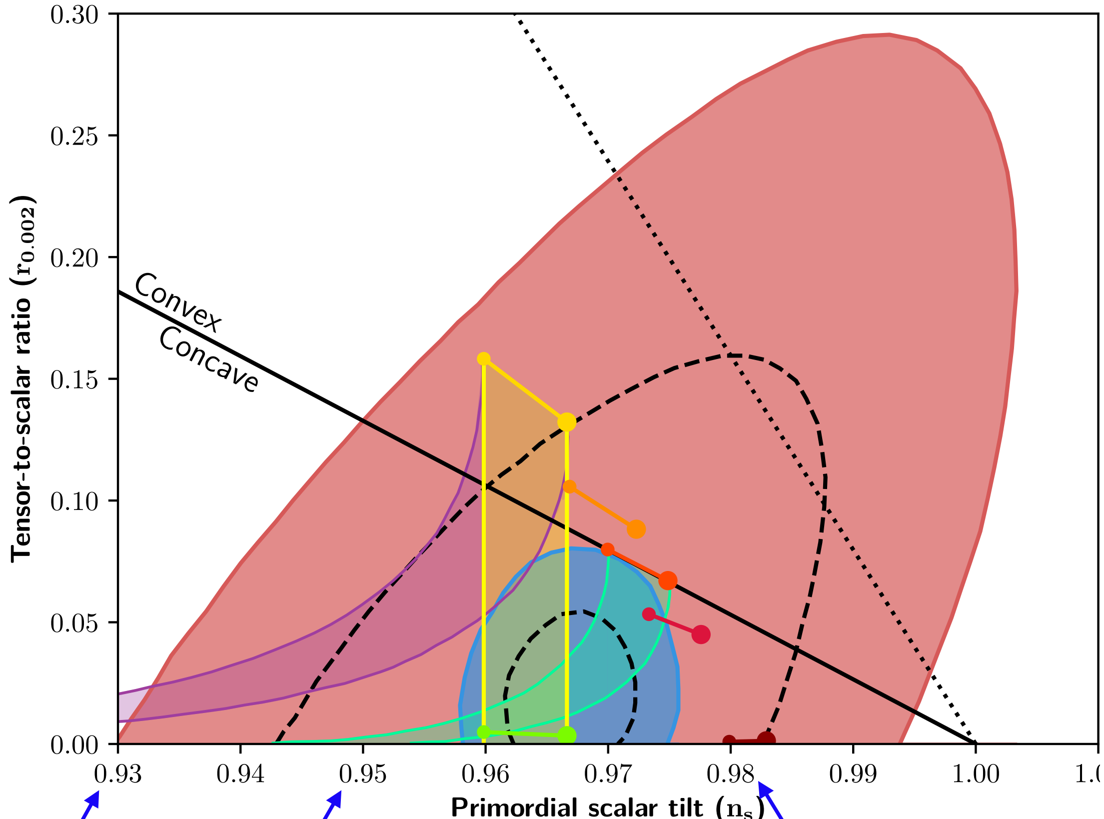




A combination of the simplest α-attractors and KKLTI models of D-brane inflation covers most of the area favored by Planck 2018, all the way down to r = 0.

The era of precision cosmology: history lessons

Akrami, RK, Linde, and Vardanyan, 2018



Inflection point

Racetrack inflation

D3/D7 brane inflation

Many versions of string theory inflation with extremely small r were ruled out by the increasing precision of data related to n_s

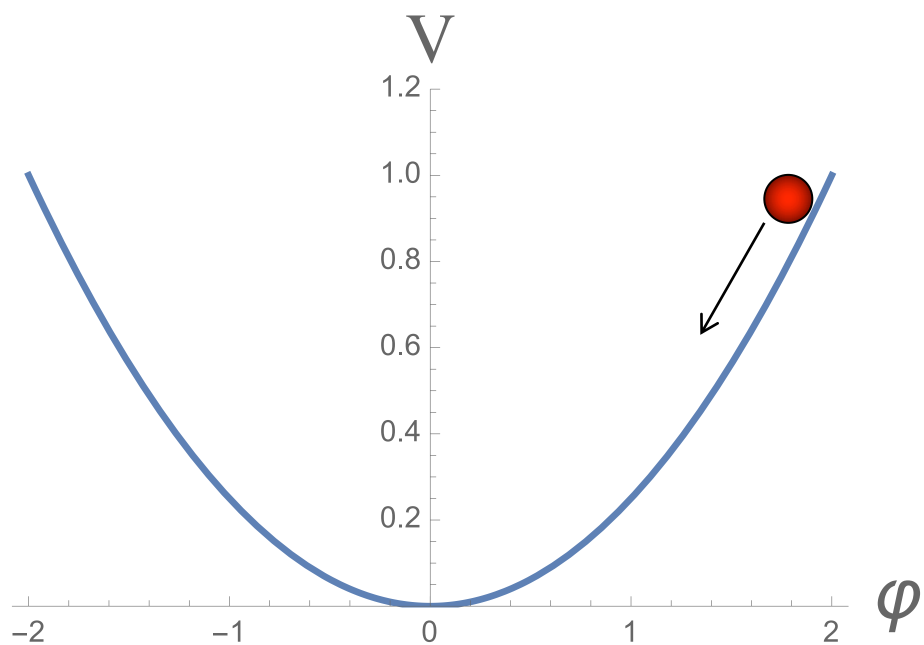
Initial conditions for inflation

For any set of 3 cosmologists there are at least 9 different opinions on the problem of initial conditions, and even more suggestions about what the word “initial” means. It is especially true in quantum cosmology, where the wave function of the universe does not depend on time, and the meaning of the “beginning” should be clarified.

A much easier question is whether we are better with inflation or without it. And the answer is pretty simple.

Simplest inflationary model: $V = \frac{m^2\phi^2}{2}$

Inflation can start at the Planck density if there is **a single Planck size domain** with a potential energy V of the same order as kinetic and gradient density. This is the minimal requirement, compared to standard Big Bang, where initial homogeneity is required across **10^{90} Planck size domains**.



Inflation may start in the universe of the Planck mass (energy) $E \sim M_P \sim 10^{-5}$ g, at the Planck time $t_P \sim M_P \sim 1 \sim 10^{-43}$ s.

But where did these initial 10^{-5} g of matter come from?

Uncertainty relation (in units $c = \hbar = 1$):

$$\Delta E \cdot \Delta t = M_P \cdot M_p^{-1} = 1$$

Thus the emergence of the initial 10^{-5} g of matter is a simple consequence of the quantum mechanical uncertainty principle. And once we have 10^{-5} g of matter in form of a scalar field, inflation begins, and energy becomes exponentially large.

One can fit all Planck data by a polynomial, with inflation starting at the Planck density

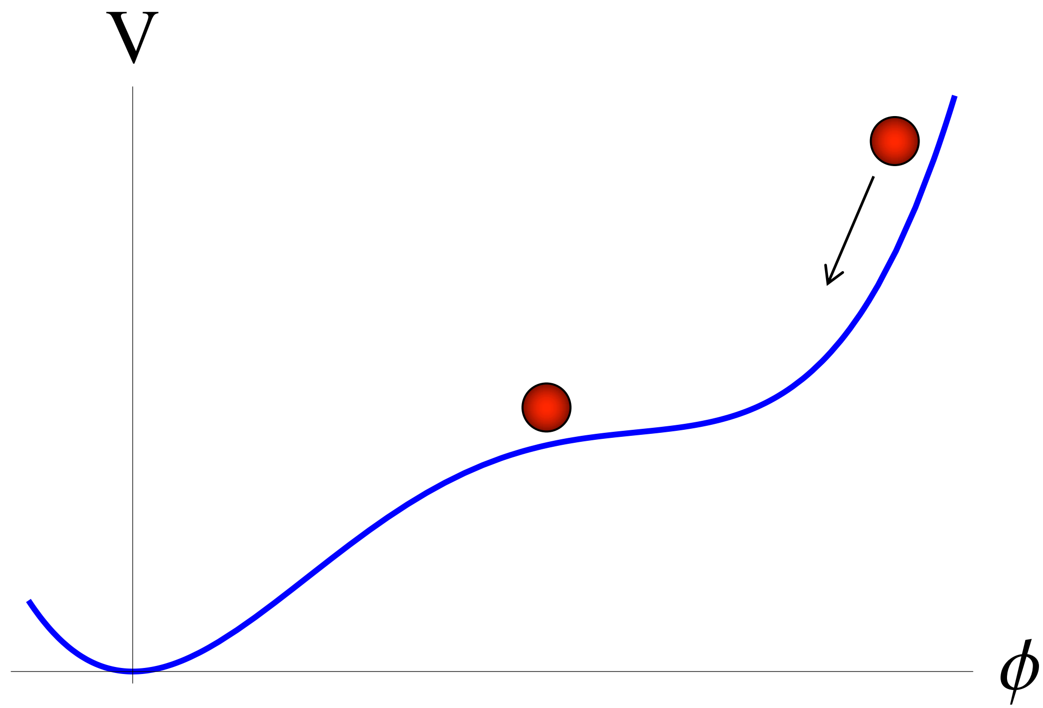
$$V = \frac{m^2\phi^2}{2}\left(1 - a\phi + b\phi^2\right)$$

Destri, de Vega, Sanchez, 2007
Nakayama, Takahashi and Yanagida, 2013
Kallosh, AL, Westphal 2014
Kallosh, AL, Roest, Yamada **1705.09247**

3 observables: A_s, n_s, r

3 parameters: m, a, b

Example: m =10^{-5}, a = 0.12, b=0.29



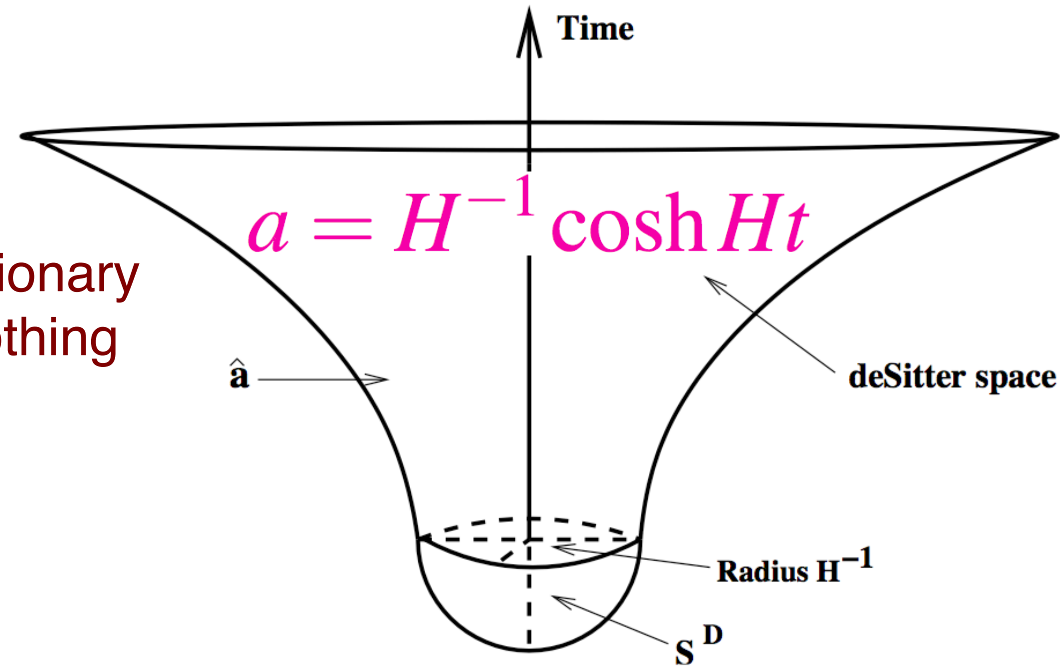
But the best fit is provided by models with plateau potentials with V < 10^{-10}

But what if $V \ll 1$ as in the models providing the best fit to Planck 2018??

Quantum creation of a closed universe

Creation of inflationary universe from nothing

Vilenkin 1982,
A.L. 1984,
Vilenkin 1984



<u>Closed</u> 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. (Remember, $\Delta E\ \Delta t \sim 1$ is OK.) 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

In string theory, beginning of a low-scale inflation is not necessarily a problem: Inflation may start at Planck/string scale, and then it continues until tunneling brings us down to regions with smaller Hubble constant.

Our goal here is to understand the situation in simpler models without appealing to string theory. If we are able to do it, it will further confirm that inflation is robust.

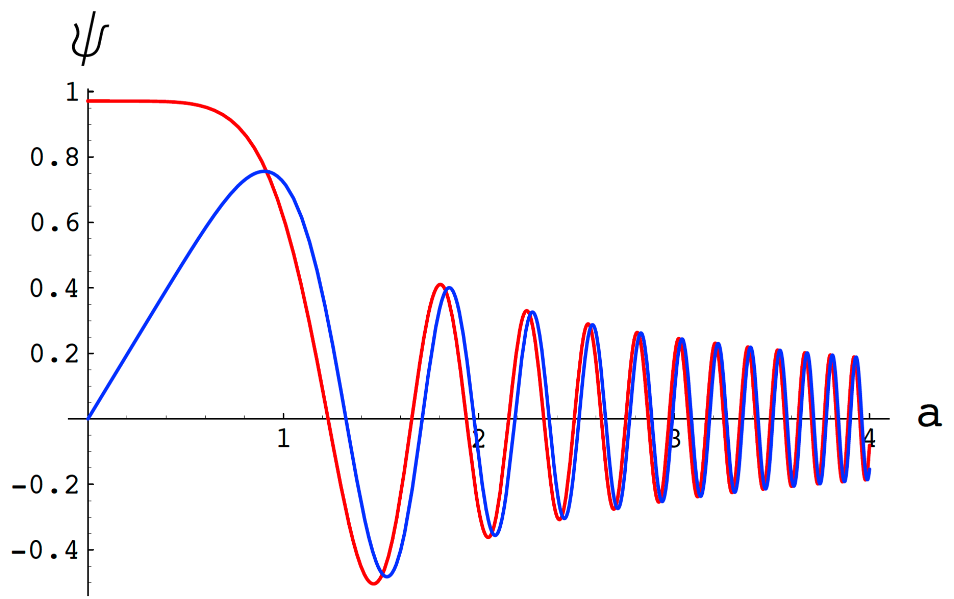
Universe as a bagel

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 can be arbitrarily small

$$\left[\frac{d^2}{da^2} + 12a^4 V\right]\Psi(a) = 0$$

$$\Psi(a) = \beta\sqrt{a}\Big(\mathrm{J}_{-\frac{1}{6}}\Big(\frac{2\sqrt{V}a^3}{\sqrt{3}}\Big) + \gamma\,\mathrm{J}_{\frac{1}{6}}\Big(\frac{2\sqrt{V}a^3}{\sqrt{3}}\Big)\Big)$$



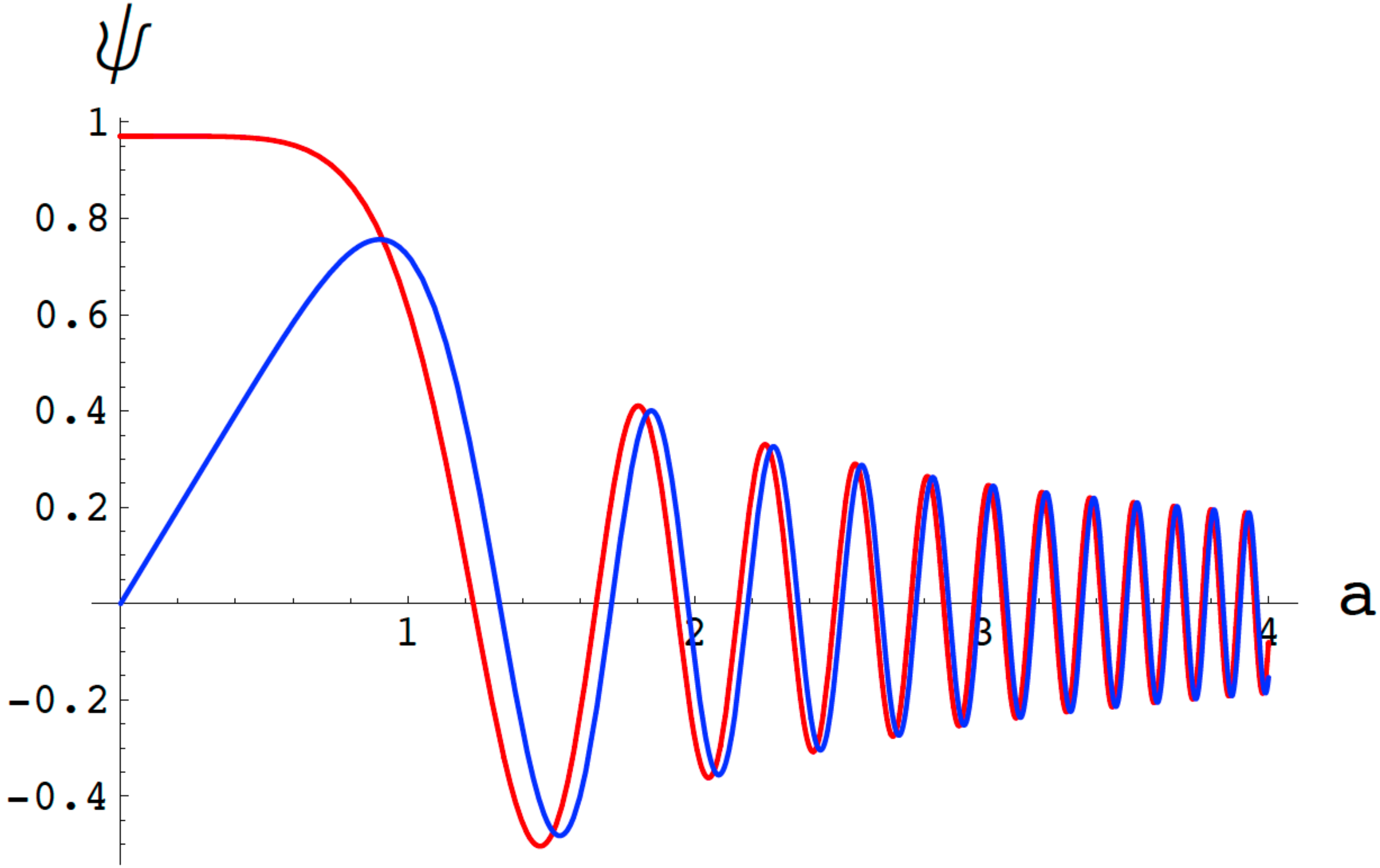


FIG. 1: Two eigenmodes of the Wheeler-DeWitt equation for the wave function of the flat compact toroidal universe. The scale factor a is given in units of $V^{-1/6}$. The description of the evolution of the universe in terms of classical space-time begins at $a \gtrsim V^{-1/6}$ ($a \gtrsim 1$ in our figure), when the semiclassical approximation becomes valid and the "cosmic clock" starts ticking.

Alternative interpretation:

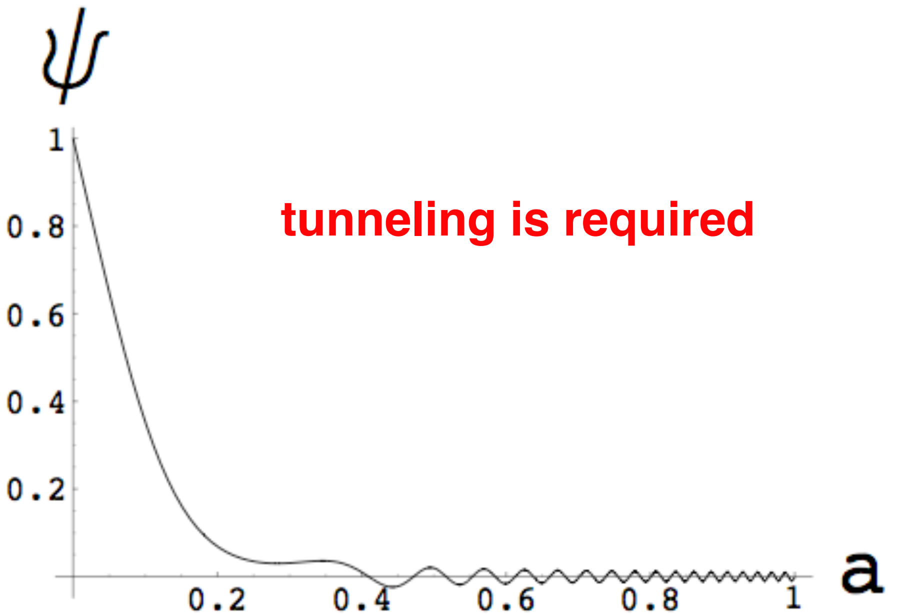
$$S = \int dt\, d^3x \sqrt{-g} \left(-\frac{1}{2} R + \frac{1}{2} \partial_\mu \phi\, \partial^\mu \phi - V(\phi) \right)$$

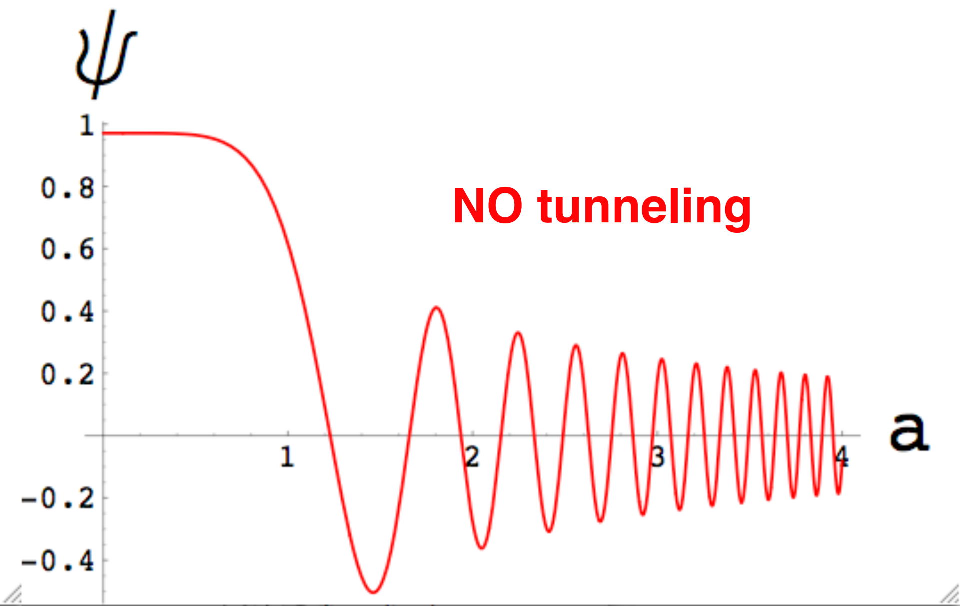
It is finite and proportional to $\sqrt{V} a^3(t) \sim \sqrt{V} a^3(t) e^{3Ht}$

For $a < V^{-1/6}$, the action is smaller than 1

At the moment when the size of the universe becomes $V^{-1/6}$ its total energy is given by the energy of a single inflationary fluctuations in dS space $T_H = O(H)$

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 <u>not</u> exponentially suppressed

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

Consider a particular example, $V = 10^{-12}$ as in new inflation

For a closed universe, the cosmic clock starts ticking at

$$a \sim V^{-1/2} \sim 10^6$$

Big baby, born in pain, against the laws of classical physics (quantum tunneling is required). Its initial mass is

$$E = a^3 V \sim V^{-1/2} \sim 10^6$$

For a flat compact universe, the cosmic clock starts ticking much earlier, at

$$a \sim V^{-1/6} \sim 10^2$$

At that time the total energy is much smaller than Planckian

$$E = H \sim V^{1/2} \sim 10^{-6}$$

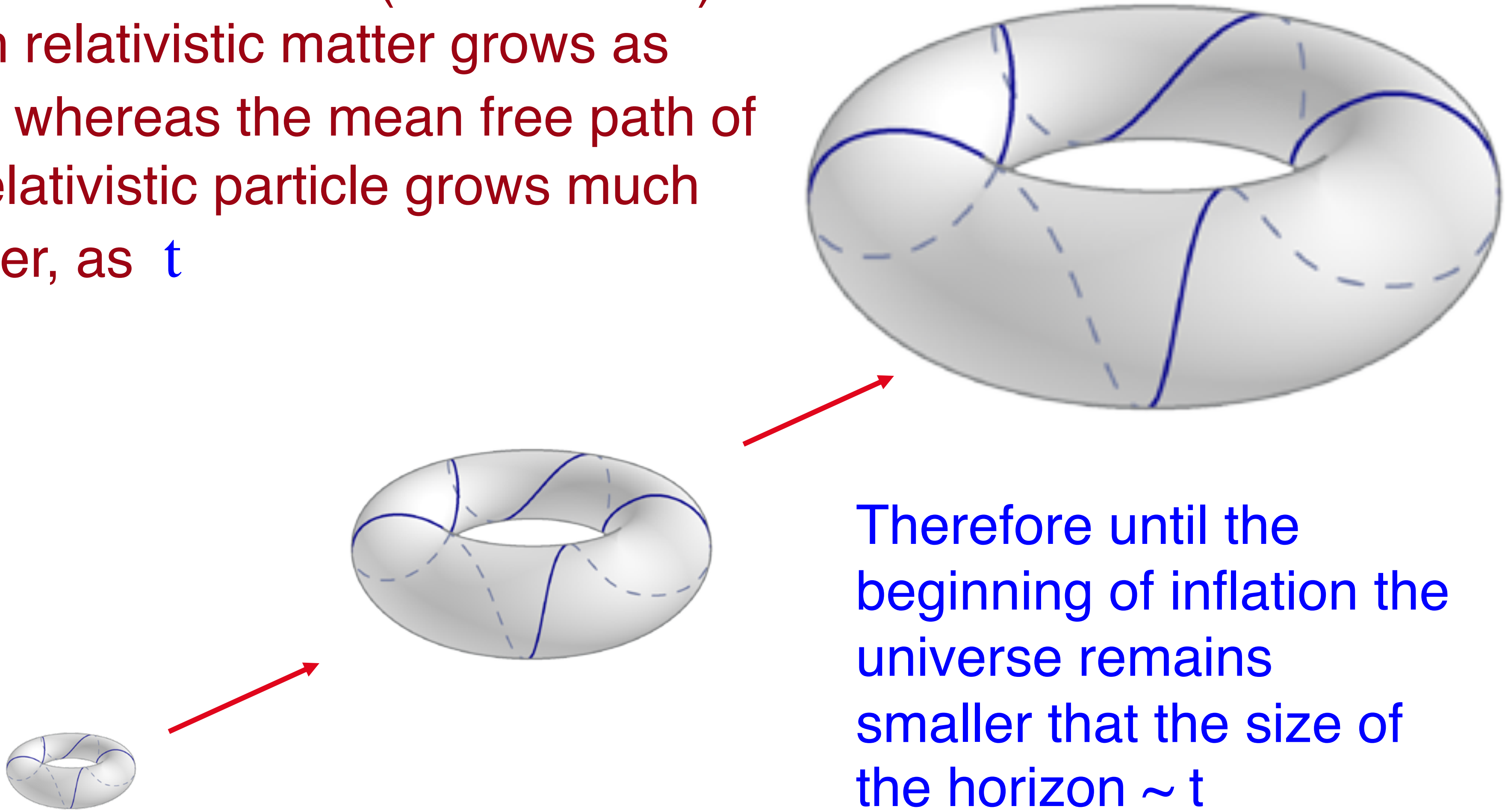
Creation of a closed inflationary universe, and of an infinite flat or open universe is **exponentially less probable** than creation of a compact topologically nontrivial flat or open universe

Spheres are expensive, bagels are free

Chaotic mixing

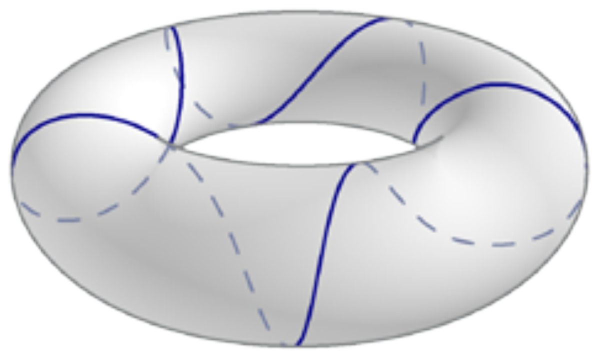
Cornish, Starkman, Spergel 1996; A.L. 2004

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 $\sim t$

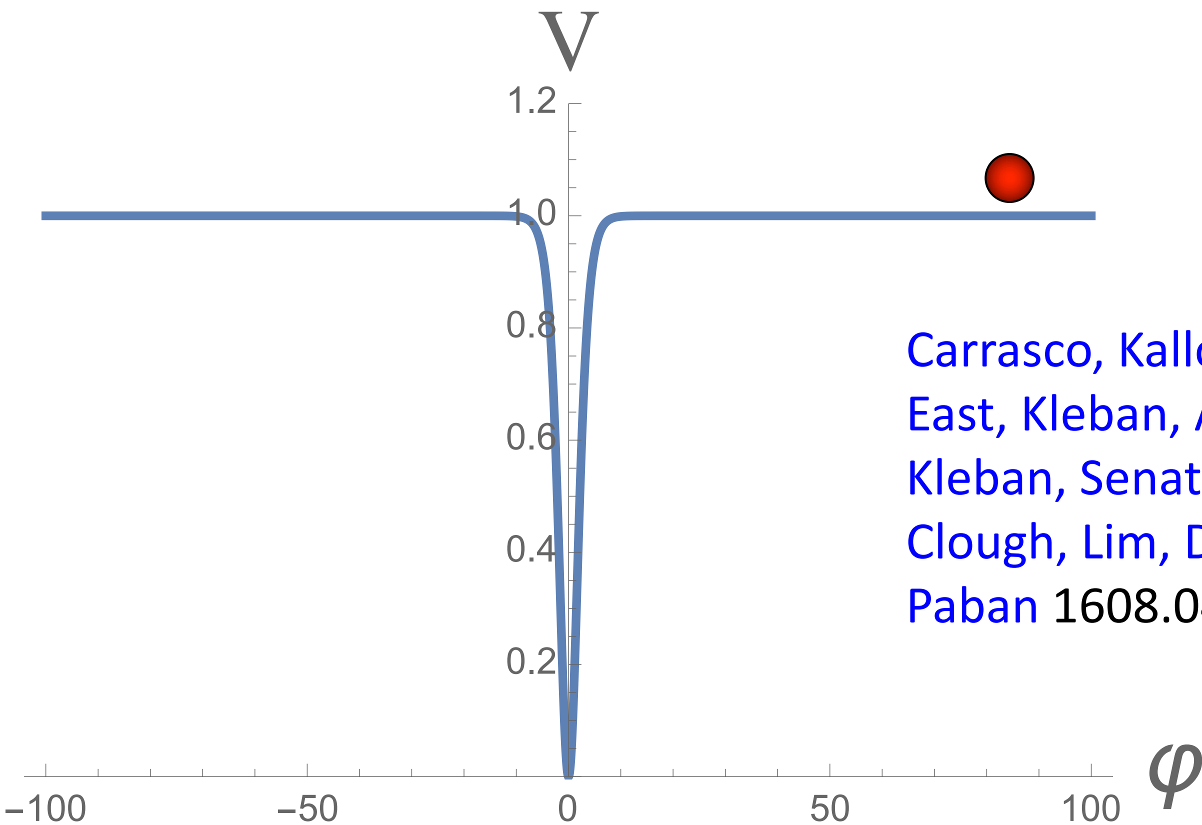
If the universe initially had a Planck size, then within the cosmological time $t \gg 1$ each particle runs around the torus **many times** and appear in all parts of the universe with equal probability, which makes the universe homogeneous and keeps it homogeneous until the beginning of inflation



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.

α-attractors: Initial conditions for inflation

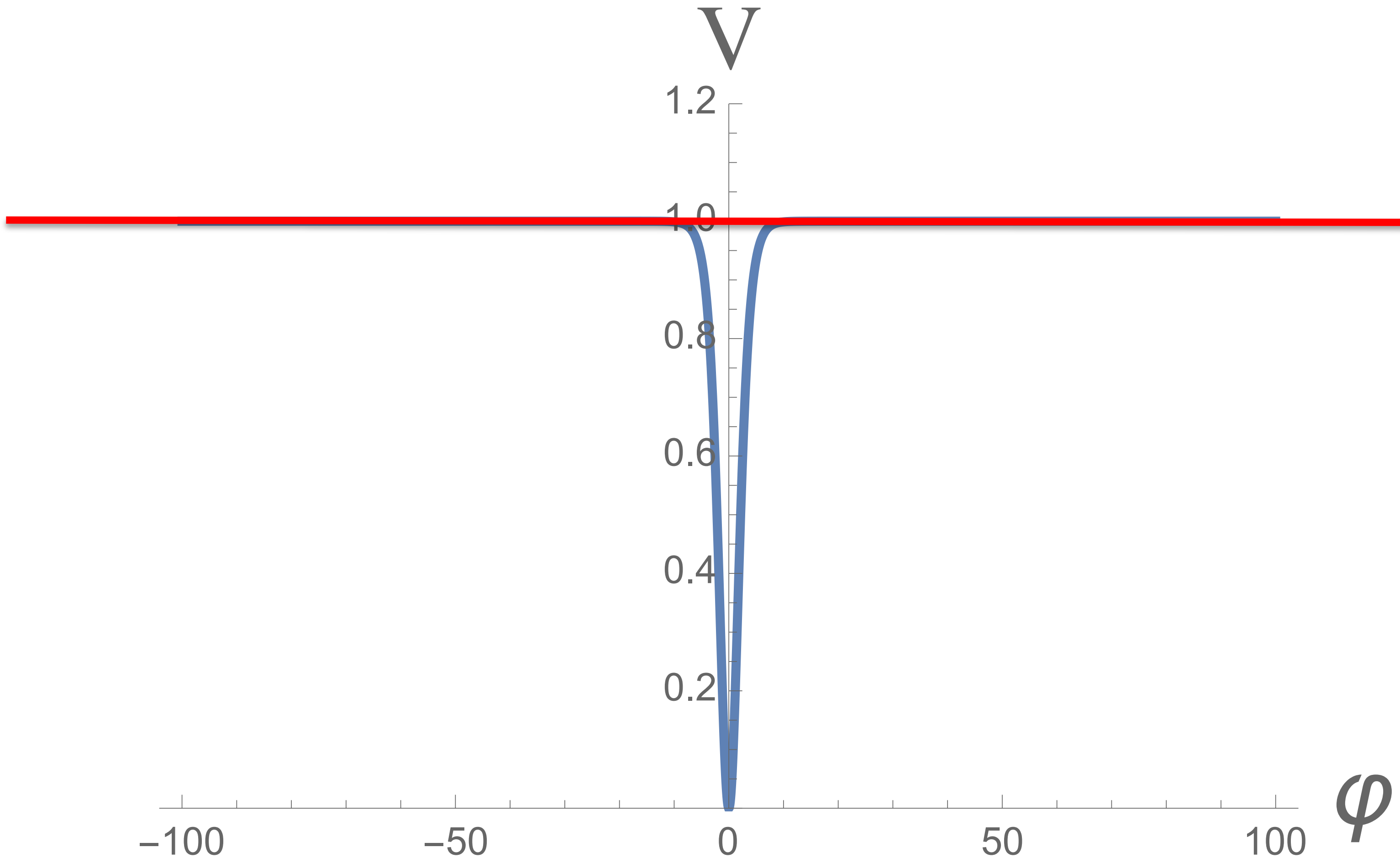
At large fields, the α-attractor potential remains 10 orders of magnitude below Planck density. Can we have inflation with natural initial conditions here? The same question applies for the Starobinsky model and Higgs inflation.



Carrasco, Kallosh, AL 1506.00936
East, Kleban, AL, Senatore 1511.05143
Kleban, Senatore 1602.03520
Clough, Lim, DiNunno, Fischler, Flauger, Paban 1608.04408

To explain the main idea, note that this potential coincides with the cosmological constant <u>almost everywhere</u>.

Carrasco, Kallosh, AL 1506.00936



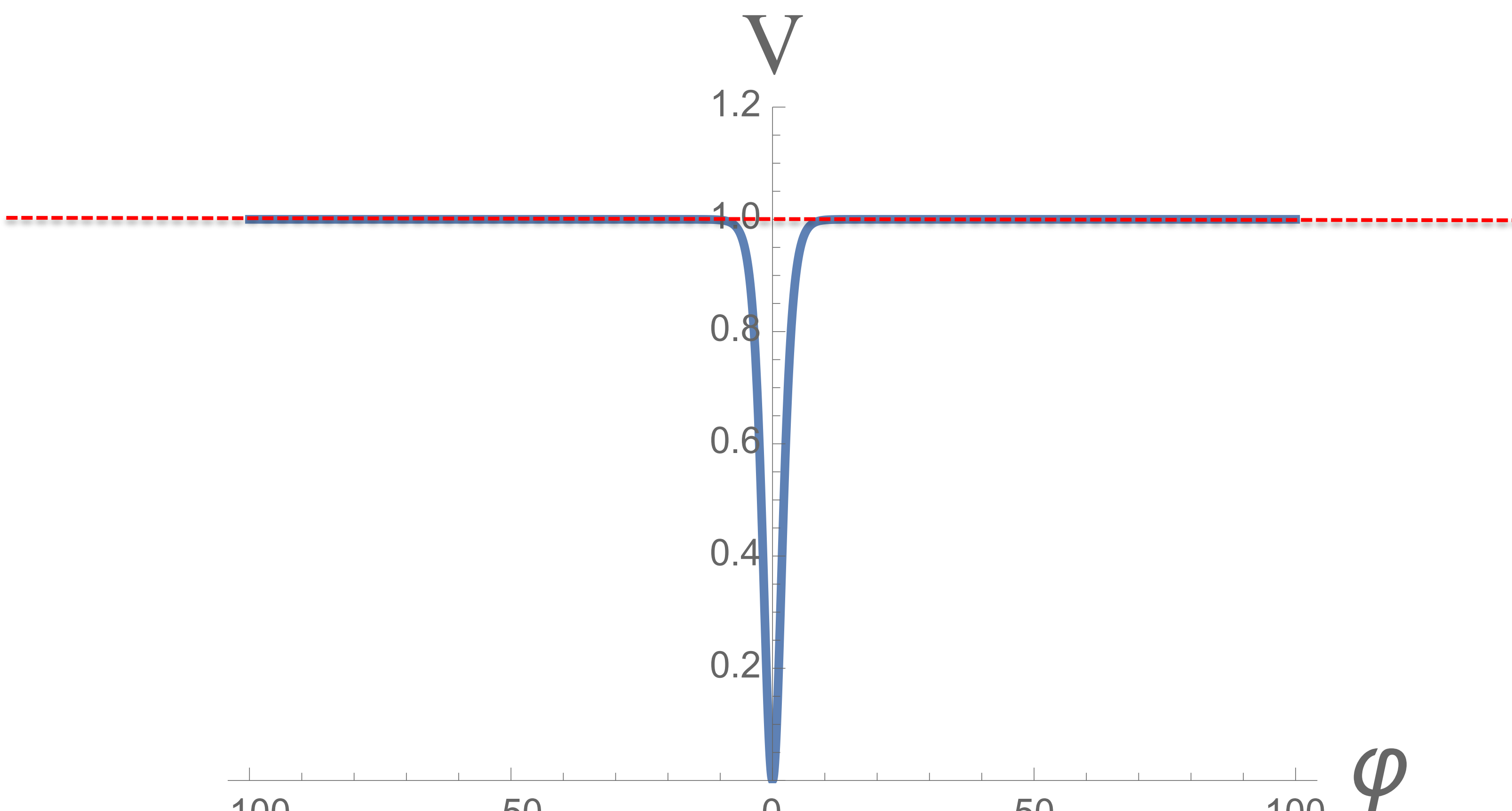
For the universe with a cosmological constant, the problem of initial conditions is nearly trivial.

Start at the Planck density, in an expanding universe dominated by inhomogeneities. The energy density of matter is diluted by the cosmological expansion as $1/t^2$. **What could prevent the exponential expansion of the universe which becomes dominated by the cosmological constant Λ after the time t = $\Lambda^{-1/2}$?**

Inflation does NOT happen in the universe with the cosmological constant $\Lambda = 10^{-10}$ only if the whole universe collapses within 10^{-28} seconds after its birth.

In other words, only instant global collapse could allow the universe to avoid exponential expansion dominated by the cosmological constant. If the universe does not instantly collapse, it inflates.

This optimistic conclusion related to the cosmological constant applies to α-attractors as well, because their potential coincides with the cosmological constant almost everywhere.

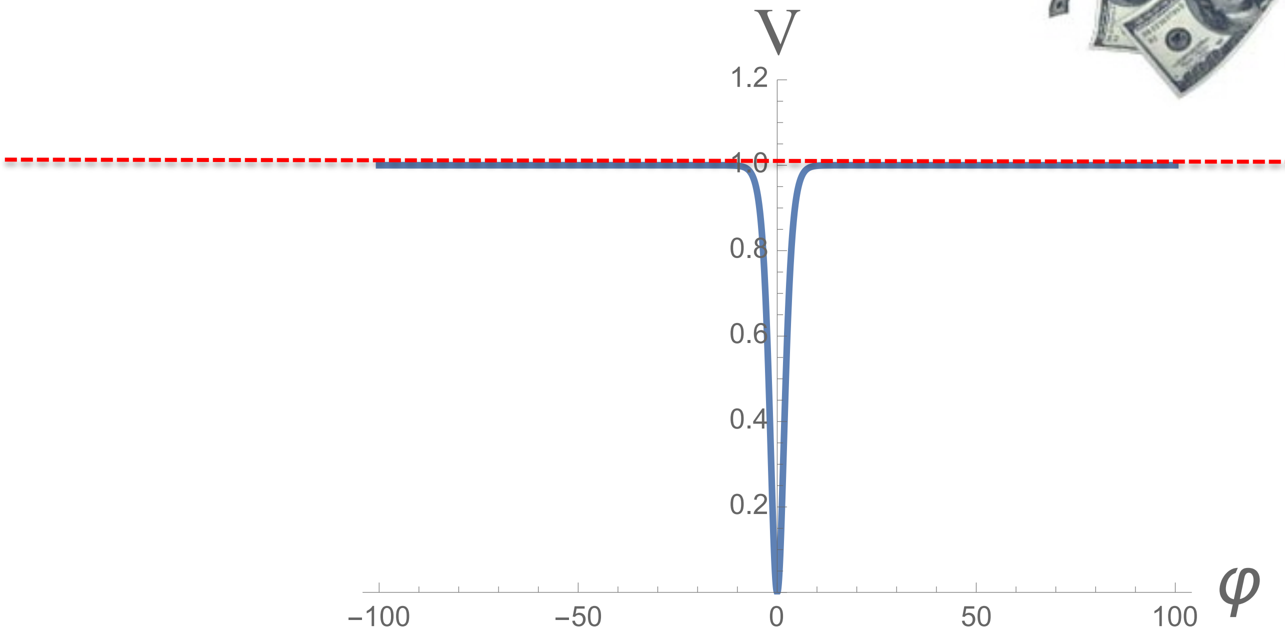


It is well known that dropping money from a helicopter may lead to inflation, unless all money miss the target

A simple interpretation of our results

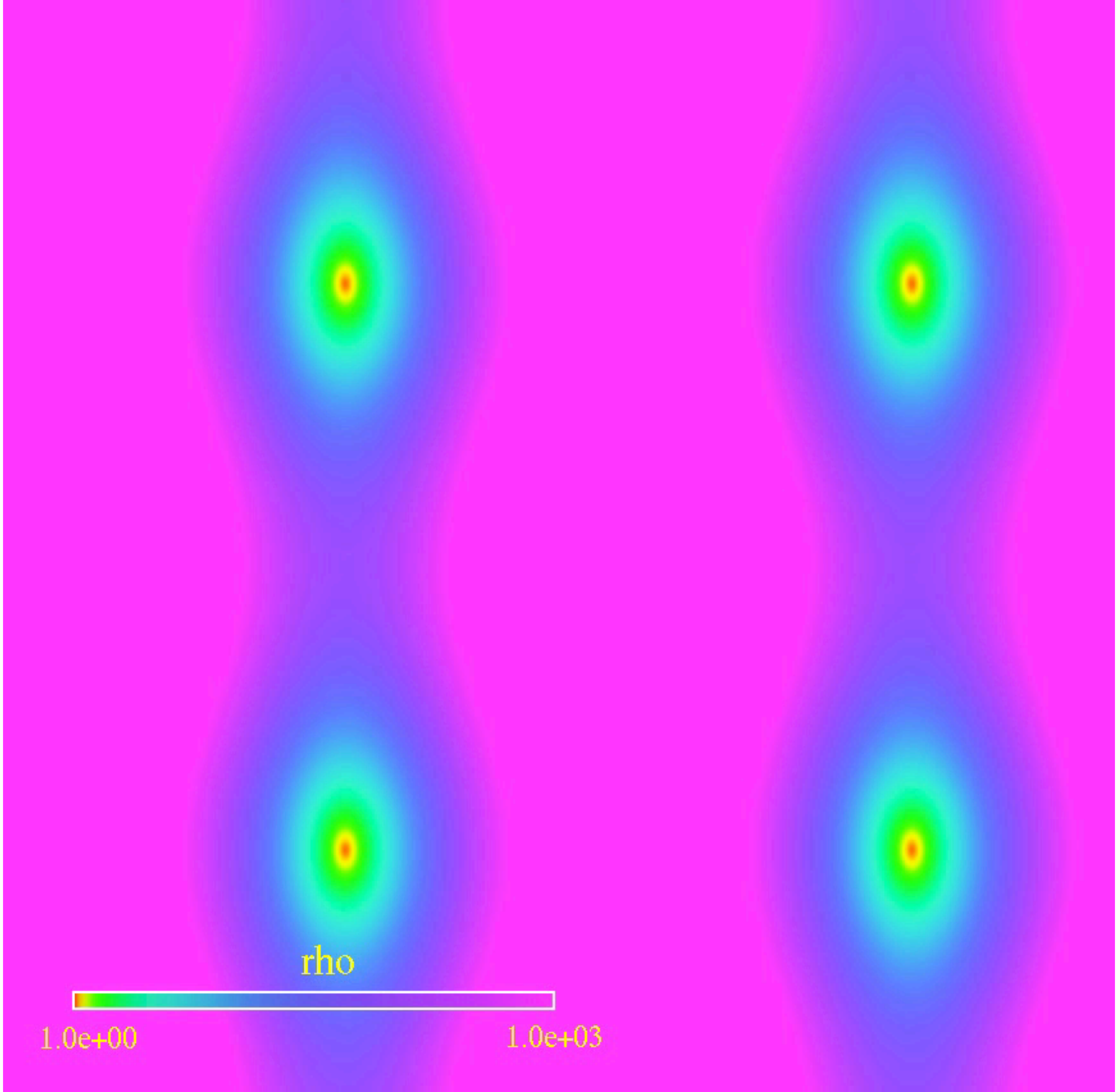
suggested by Starobinsky

Money dropped from a helicopter have no choice but lend on an infinitely long plateau. This inevitably leads to inflation



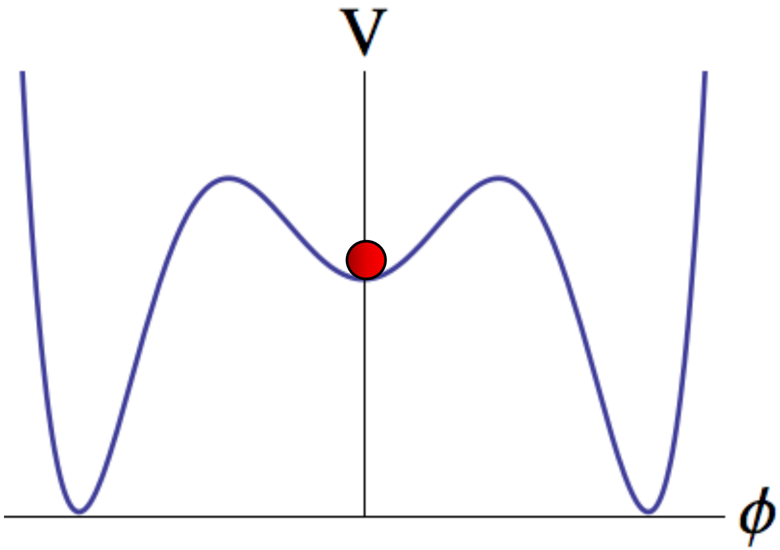
These arguments are valid for general large field inflationary models as well. Recently they have been confirmed by the same methods of numerical GR as the ones used in simulations of BH evolution and merger. The simulations show how BHs are produced from large super-horizon initial inhomogeneities, while the rest of the universe enters the stage of inflation.

East, Kleban, AL, Senatore 1511.05143
Kleban, Senatore 1602.53520
Clough, Lim, DiNunno, Fischler, Flauger, Paban 1608.04408

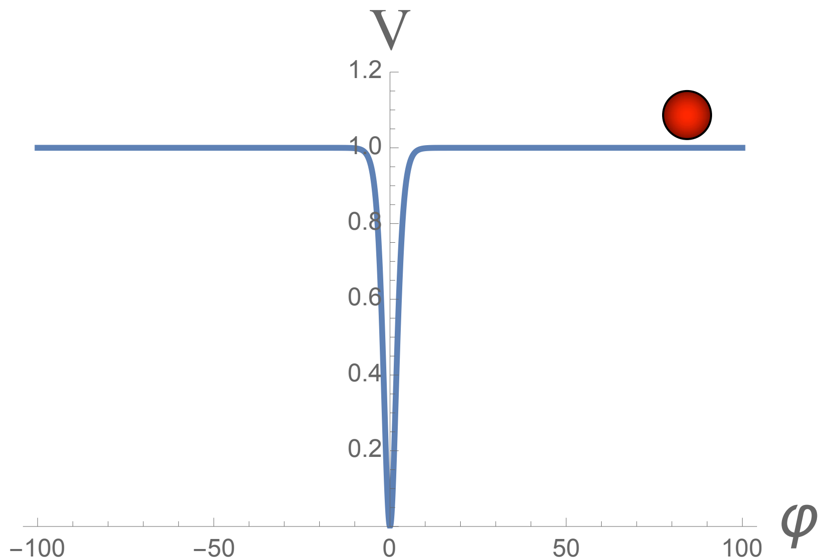

rho
1.0e+00
1.0e+03

Initial conditions for plateau inflation

Two independent stages of inflation:



"Old inflation" in string landscape



plateau inflation

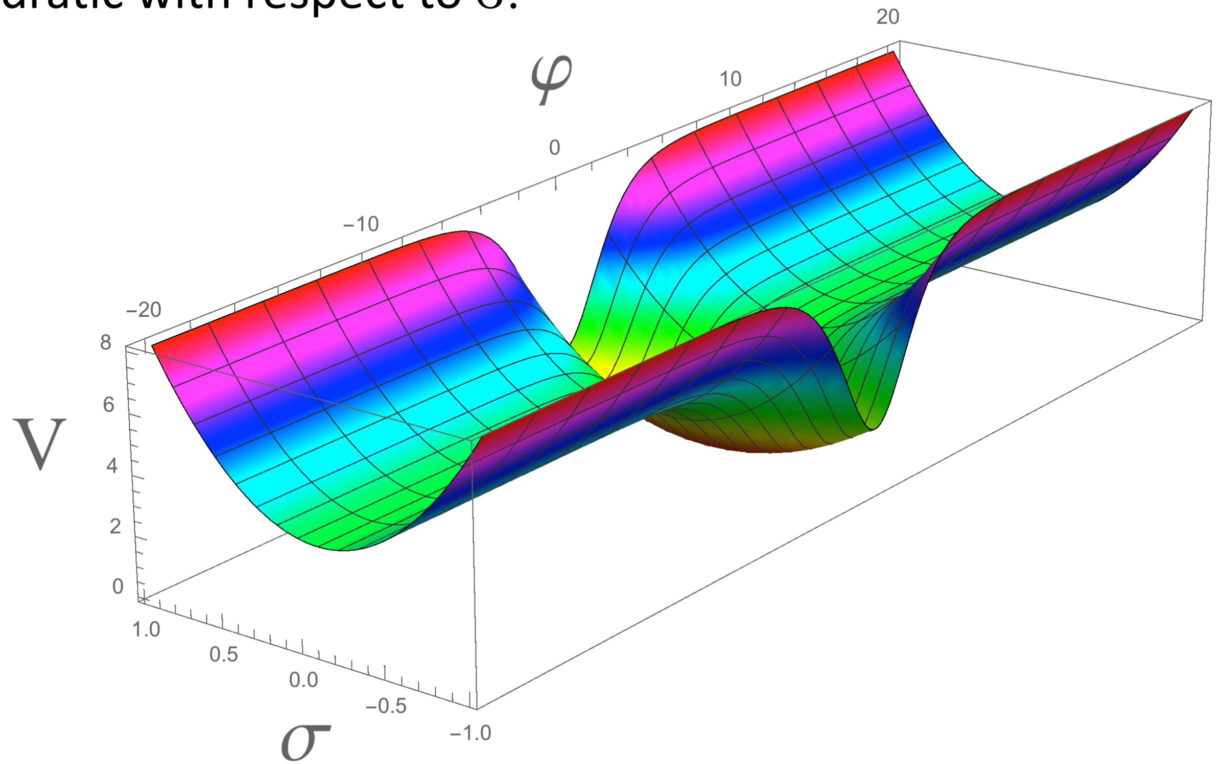
Old inflation goes first, at nearly Planckian density. Fluctuations in the light field φ triggered by "old inflation" in string theory landscape spread this field along the plateau of the potential. After the end of "old inflation", the plateau inflation begins.

No problem with initial conditions

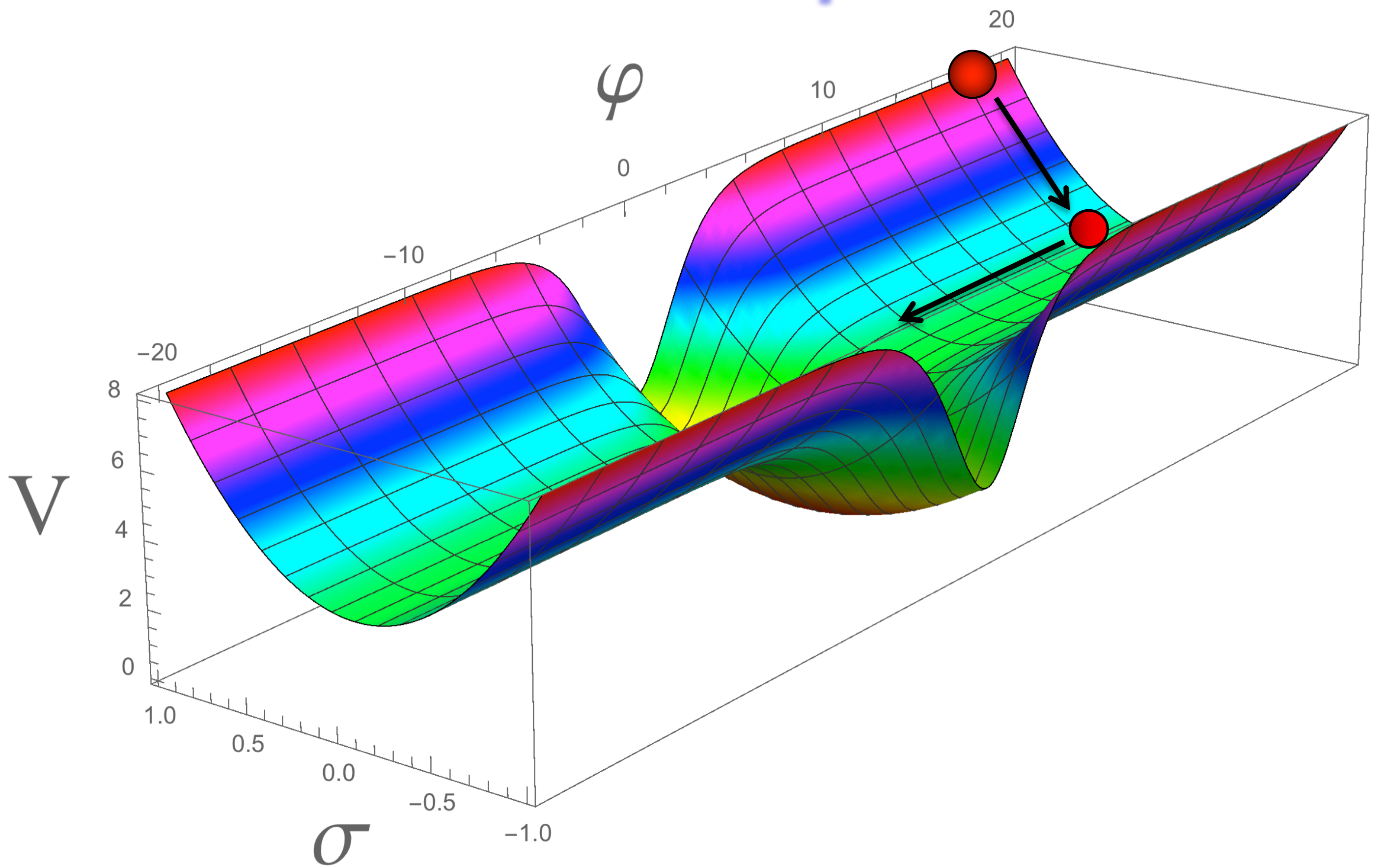
Even simpler, no need for quantum fluctuations

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

Potential in canonical variables has a plateau at large values of the inflaton field, and it is quadratic with respect to σ.



Initial conditions for plateau inflation



Chaotic inflation with a parabolic potential goes first, starting at nearly Planckian density. When the field down, the plateau inflation begins.

No problem with initial conditions

Conclusions:

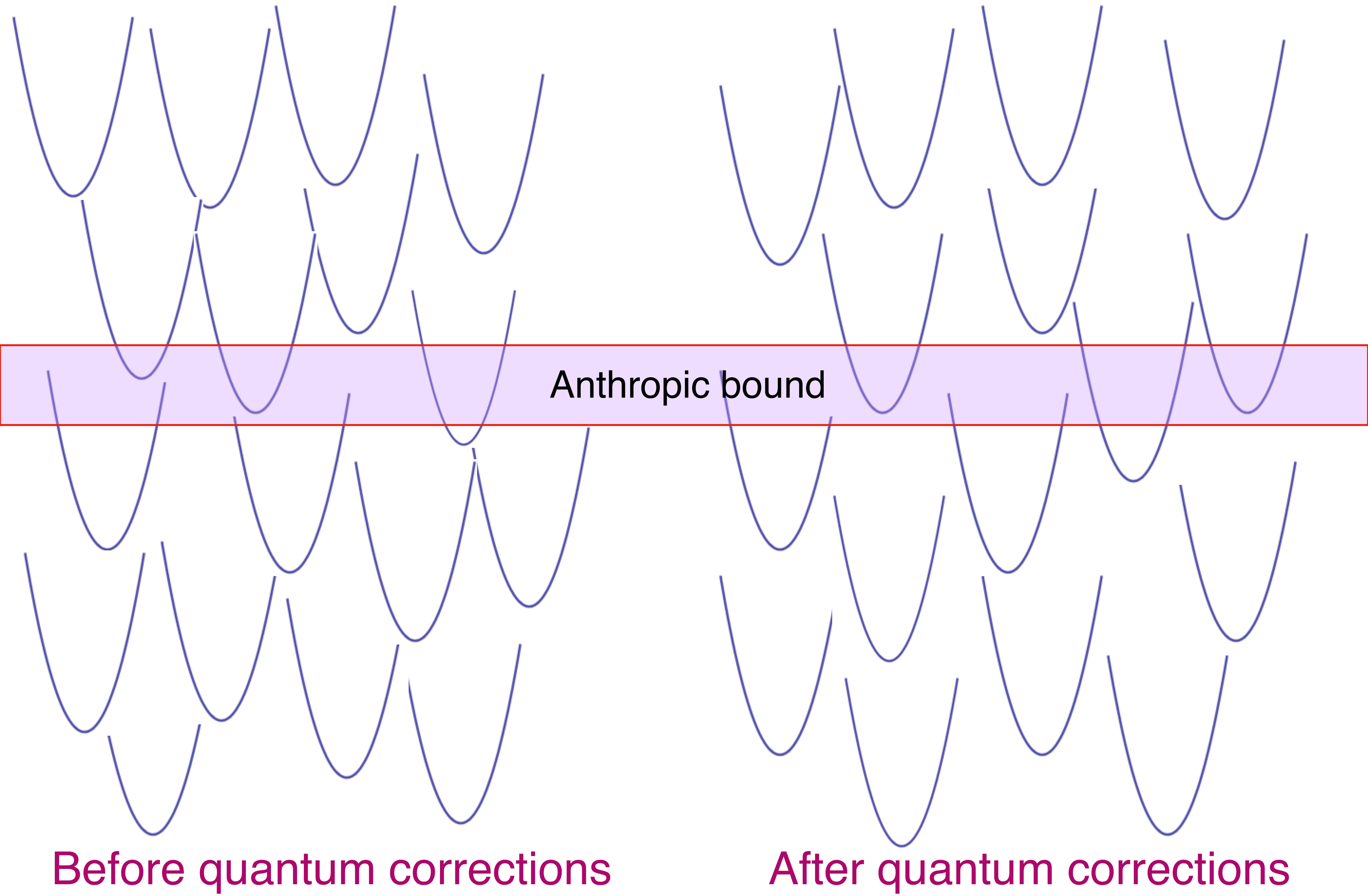
Cosmological attractors and other models with plateau potentials allow us to reconsider many usual assumptions with respect to the large field models, resolving some of their often discussed problems, and offering new solutions to the problem of initial conditions in inflationary cosmology.

The simplest α-attractors and D-brane models cover most of the n_s- r space favored by Planck 2018

Many simple ways to solve the problem of initial conditions.

Landscape or swampland ?

Anthropic approach to Λ in string theory:



dS and the new swampland conjectures

G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, 1806.08362

1) dS is incompatible with string theory (see also Vafa's lectures and a review by Daniellson and Van Riet)

2) Potentials in string theory should satisfy the swampland conjecture

$$\frac{|\nabla_\phi V|}{V} \geq c\,, \qquad c \sim 1$$

Example of a "legitimate" potential

$$V(\phi) = V_0\, e^{\lambda\phi} \qquad \text{with} \;\; \lambda > 1$$

Note that the sign of the inequality is OPPOSITE to the one required for successful dark energy models.

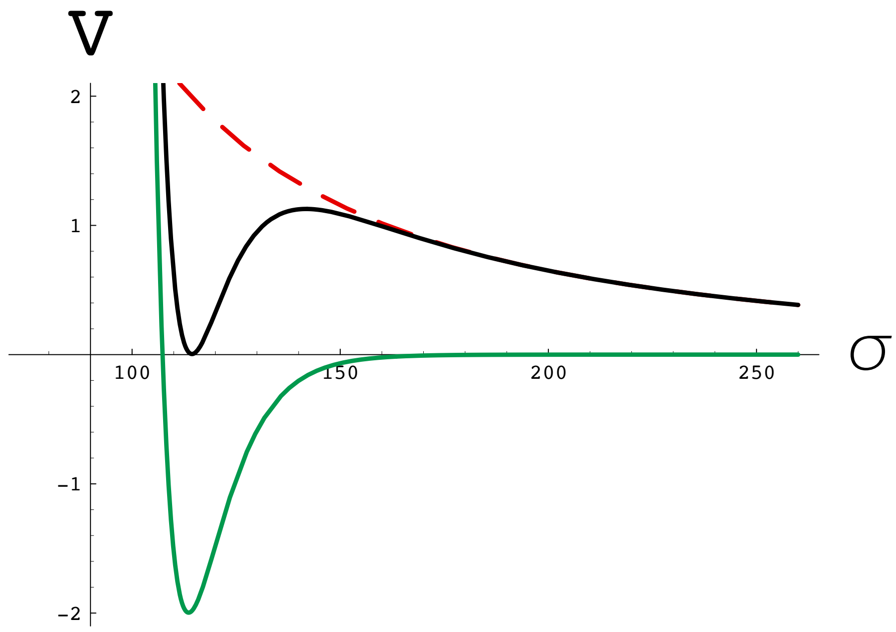
Why no dS? Why large slope of V?

KKLT

Kachru, Kallosh, AL, Trivedi 2003

$$K = -3\log\left(T+\bar{T}\right) + S\bar{S}\,,$$

$$W = W_0 + A\exp(-aT) + b\ S$$



S is the nilpotent field describing uplifting due to the anti-D3 brane

Kallosh, AL, Vercnocke, Wrase 2014
Ferrara, Kallosh, AL 2014
Kallosh, Wrase 2014
Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase 2015

De Sitter Vacua with a Nilpotent Superfield

Kallosh, AL, McDonough, Scalisi, 1808.09428, 1809.09018,1901.02022

One of the main papers supporting the swampland conjecture was 1707.08678 by Westphal et al suggesting that the uplifting procedure in the KKLT construction is not valid.

We found that the modification of the SUSY breaking sector of the nilpotent superfield proposed in 1707.08678 is not consistent with non-linearly realized local supersymmetry of de Sitter supergravity.

Keeping this issue aside, we found that the corresponding bosonic potential does actually describe de Sitter uplifting.

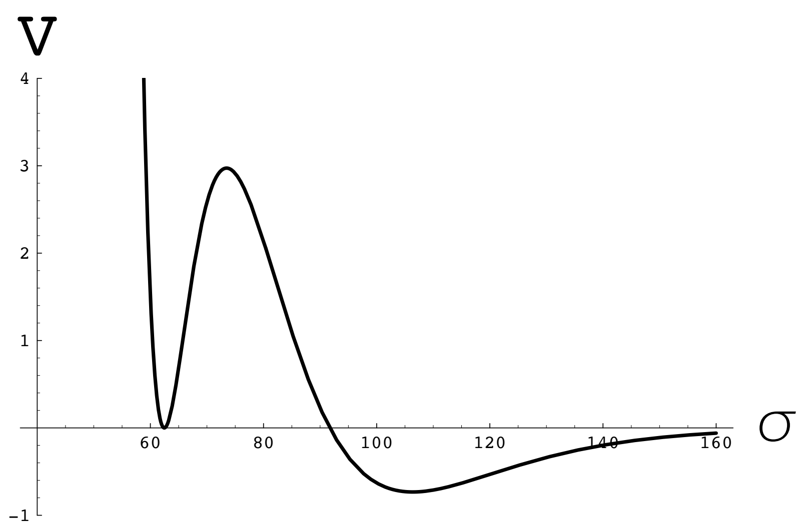
KL stabilization

Kallosh, AL 2004

$$W = W_0 + Ae^{-a\rho} + Be^{-b\rho} + \mu^2 S$$

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

The minimum for b = 0 is at V=0. By a different choice of W_0 and b, the potential at the minimum can take any value. Only extremely small uplift is required. The height of the barrier is not related to SUSY breaking, so the moduli can be stabilized with arbitrary strength.



KL model, which requires parametrically small uplifting

Kallosh, AL, McDonough, Scalisi, 1901.02022

KL version of the KKLT scenario does not have any problems with uplifting, but Moritz and Van Riet in 1805.00944 argued that it might violate the weak gravity conjecture.

We found in 1901.02022 that KL mechanism is consistent with the WGC.

Quintessence and the new swampland conjecture

G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, 1806.08362

$$V(\phi) = V_0\, e^{\lambda\phi}$$

In all models of superstring quintessence proposed there $\lambda > 1.4$. We found that $\lambda > 1$ is ruled out with confidence level better than 99.7%, and $\lambda > 1.4$ is ruled out even much stronger.

Yashar Akrami, Renata Kallosh, AL, Valeri Vardanyan, 1808.09440

And there are many conceptual issues, such as **quantum corrections** for extremely flat potentials, **fifth force** problem, **decompactification** of 6 dimensions, etc. For example, in the first of the models proposed by Obied et al the internal space completely decompactifies, in the second model, its volume grows by 180 orders of magnitude during the cosmological evolution.

Any constraints from inflation?

The amplitude of density perturbations is small only if

$$|\nabla_\phi V| \gtrsim V^{3/2}$$

Observations:

$$|\nabla_\phi V| \gtrsim 10^5\, V^{3/2}$$

This means that the basic no-dS conjecture is automatically satisfied for slow-roll inflation: Slow roll inflation occurs only in space different from dS. There is no need to impose the swampland constraint

$$\frac{|\nabla_\phi V|}{V} \geq c\,, \qquad c \sim 1$$

But if one extends this conjecture to inflation, it would strongly disfavor this conjecture, because according to Planck2018, for 99.9% of all inflationary models one has

$$\frac{|\nabla_\phi V|}{V} < 0.09$$

Any constraints from inflation?

$$r = 8\left(\frac{V'}{V}\right)^2 = 8c^2$$

Planned cosmological observations such as CMB-S4, Simons Observatory, LiteBird, PICO are supposed to search for $r \sim 10^{-2}$ - 10^{-3}. If the tensor modes are not found in this range, this may imply that

$$c < 10^{-2}$$

Is $c = 10^{-1} = O(1)$?

Is $10^{-2} = O(1)$?

The answer of the authors of the swampland conjecture:

10^{-10} is not $O(1)$

Is the string theory quintessence in the swampland?

Consider exponential potential with λ =0.7 (all higher values are ruled out with 95% confidence). How large should the excursion of the field be to span the distance between the Planck density V =O(1) and the present value of dark energy V =O(10^{-120}) = e^{-276}

$$\Delta\phi \sim 400$$

This would strongly contradict the weak gravity conjecture. If only the Planck excursions O(1) are allowed, then the quintessence potential can be valid only for V =O(10^{-120}). How can we use such a theory in cosmology?

Anthropic approach to Λ in string theory