Inflation, dark energy, and the string theory landscape

Andrei Linde

In collaboration with Renata Kallosh, Yashar Akrami,

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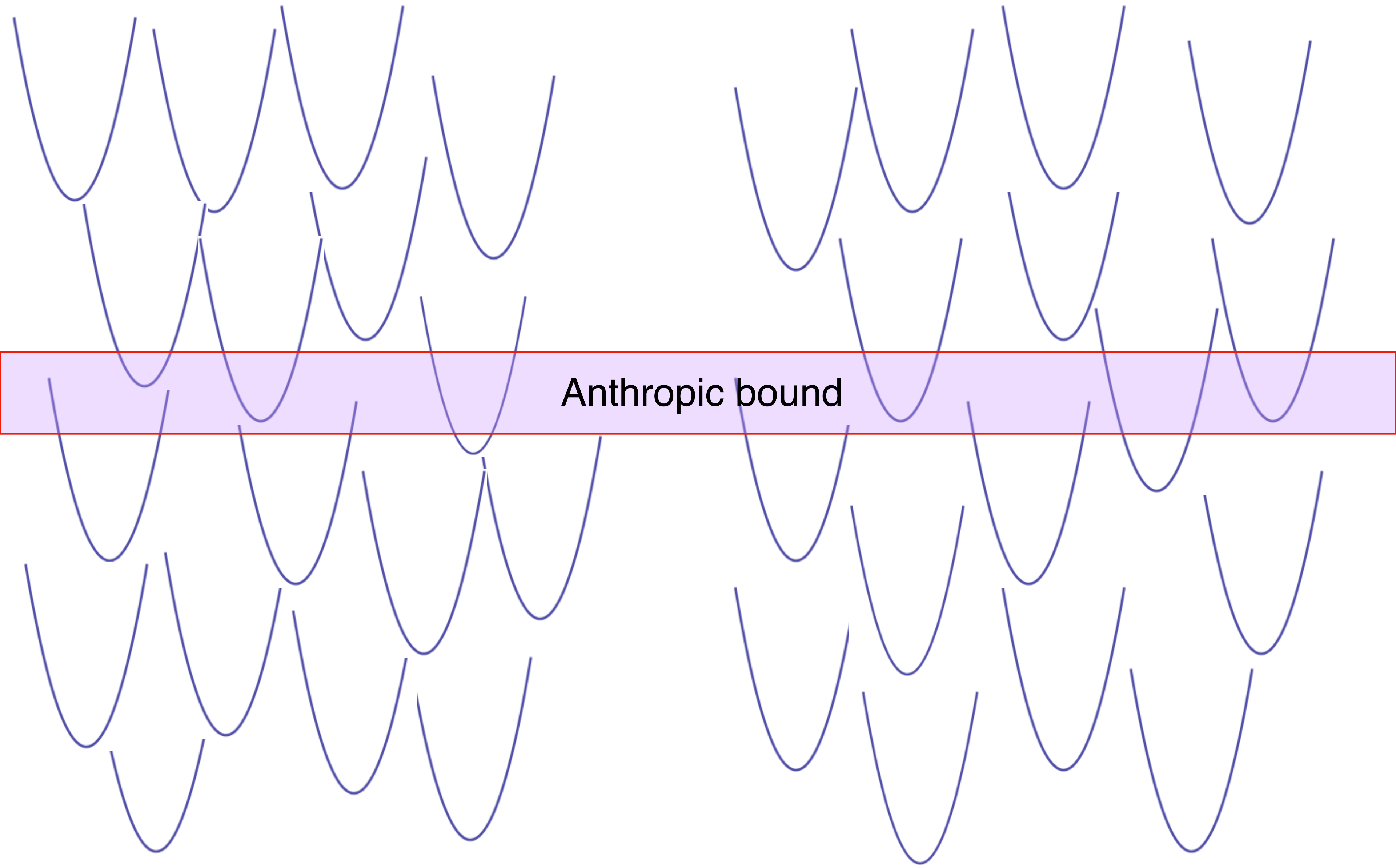
Anthropic approach to Λ in string theory:



Before quantum corrections

After quantum corrections

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

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

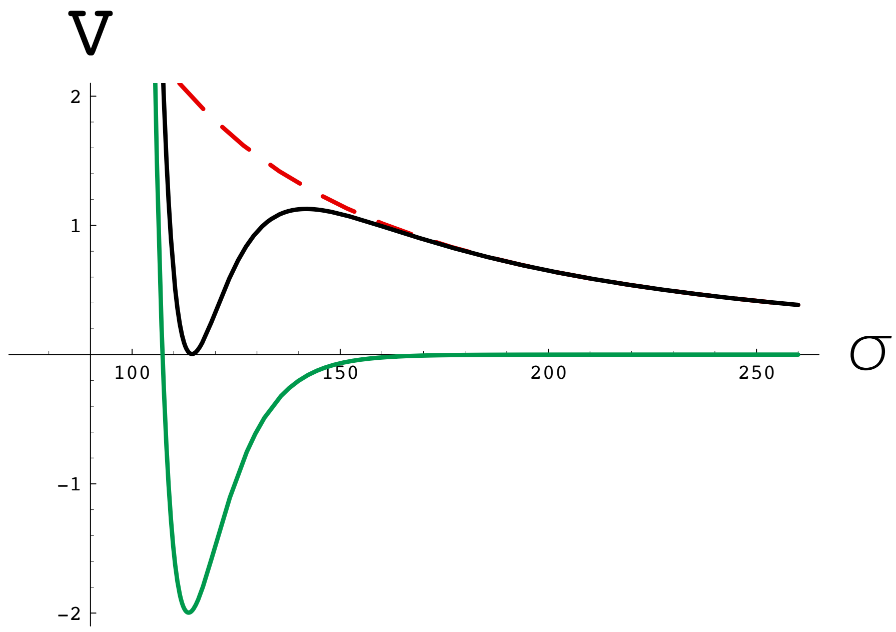
Note that the sign of the inequality is OPPOSITE to the one required for successful dark energy models.

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.

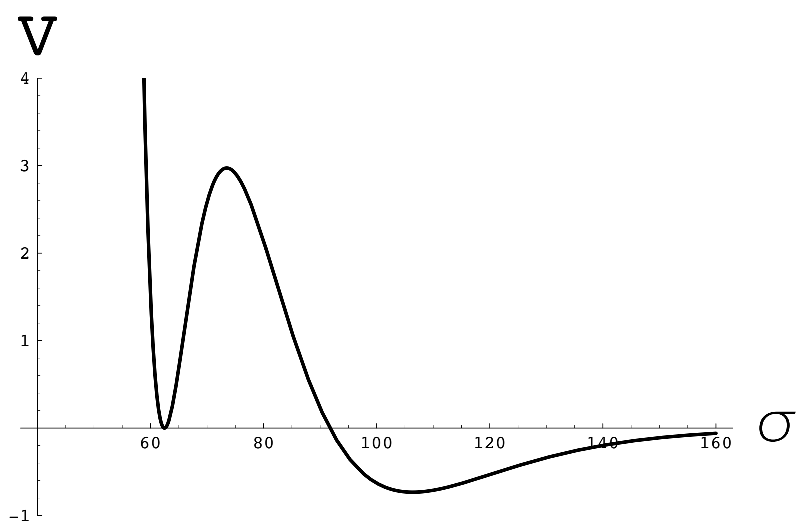
KL stabilization

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?

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

Planned cosmological observations such as CMB-S4, Simons Observatory, LiteBird, PICO are supposed to search for r ~ 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 $O(1)$

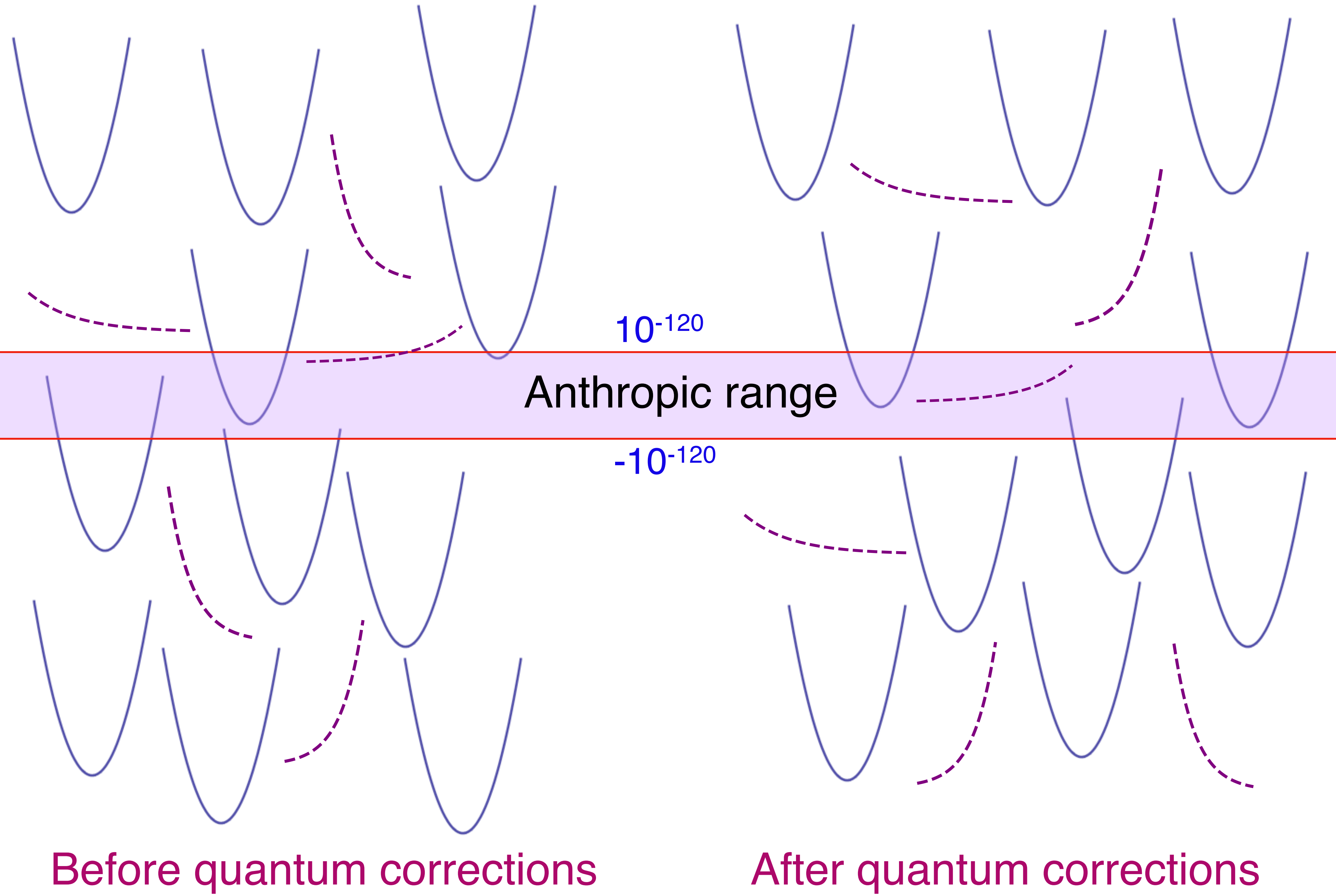
Is the string theory quintessence in the swampland?

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



Inflation after Planck 2018

Predictions of inflation and the possibility to test it

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

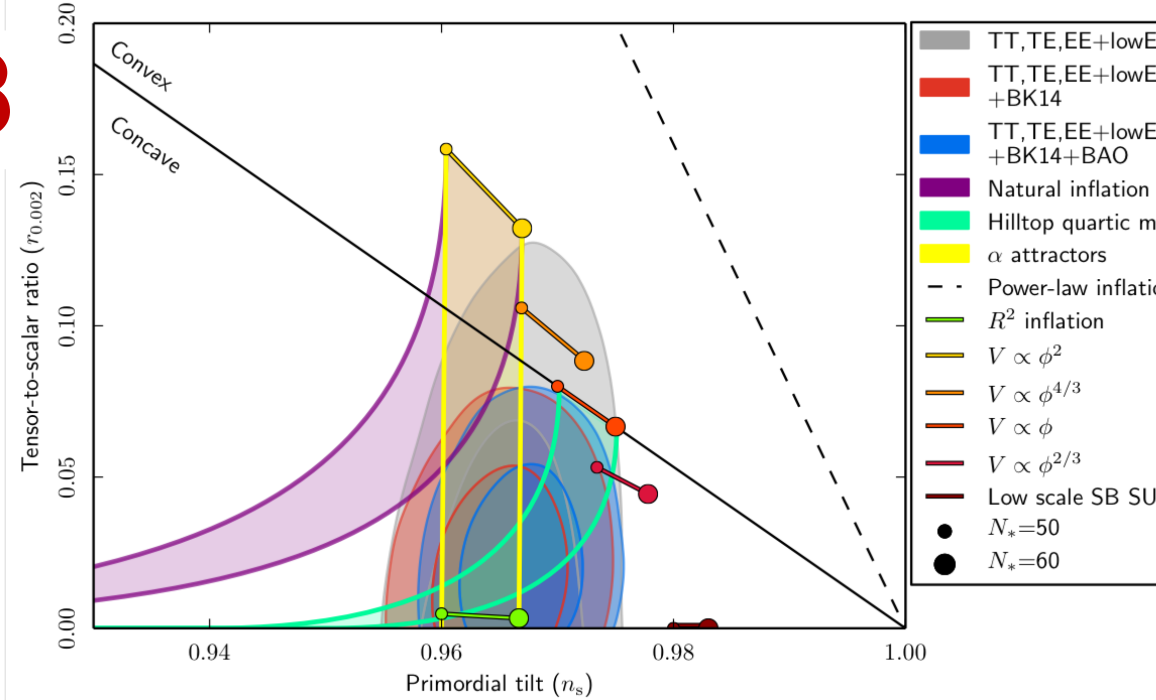
7) The large angle TE anti-correlation (WMAP, Planck) is a distinctive signature of superhorizon fluctuations (Spergel, Zaldarriaga 1997), ruling out many alternative possibilities

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

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

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

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

The potential becomes

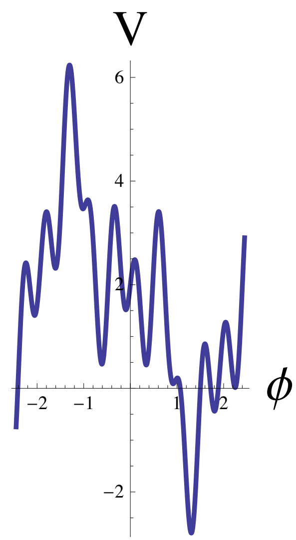
$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

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

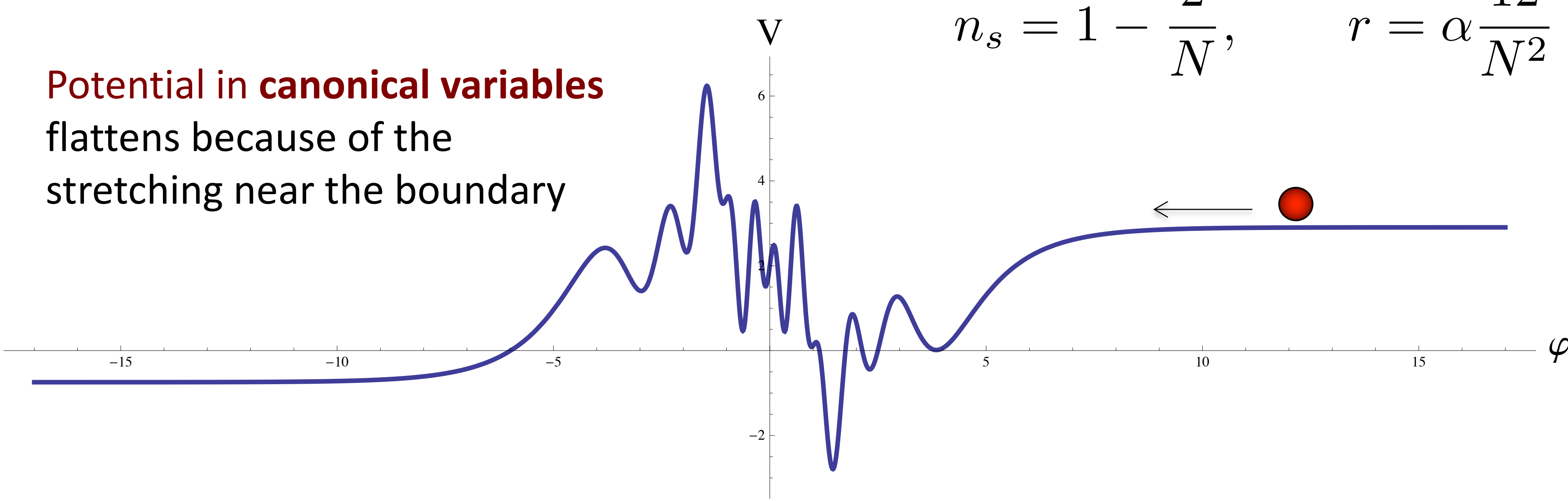
$$\frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



All of these models predict

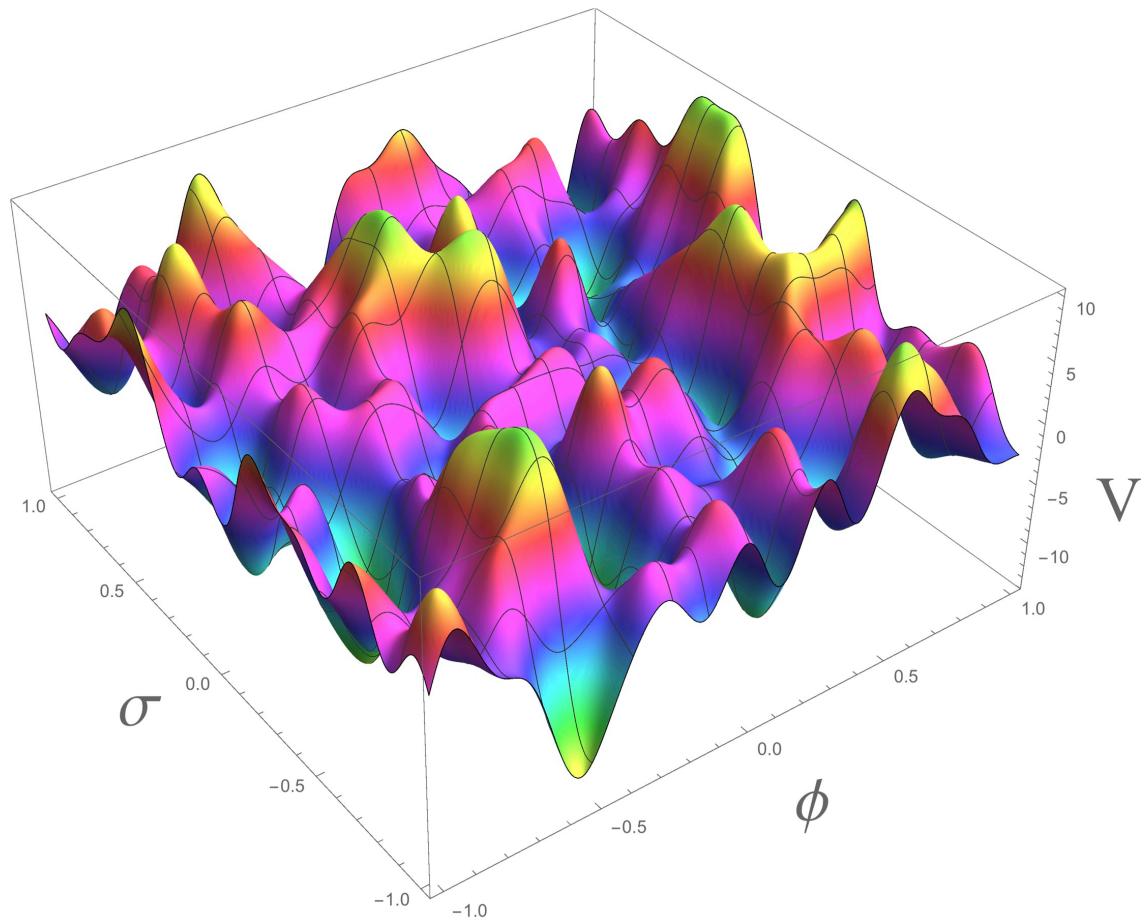
$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

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



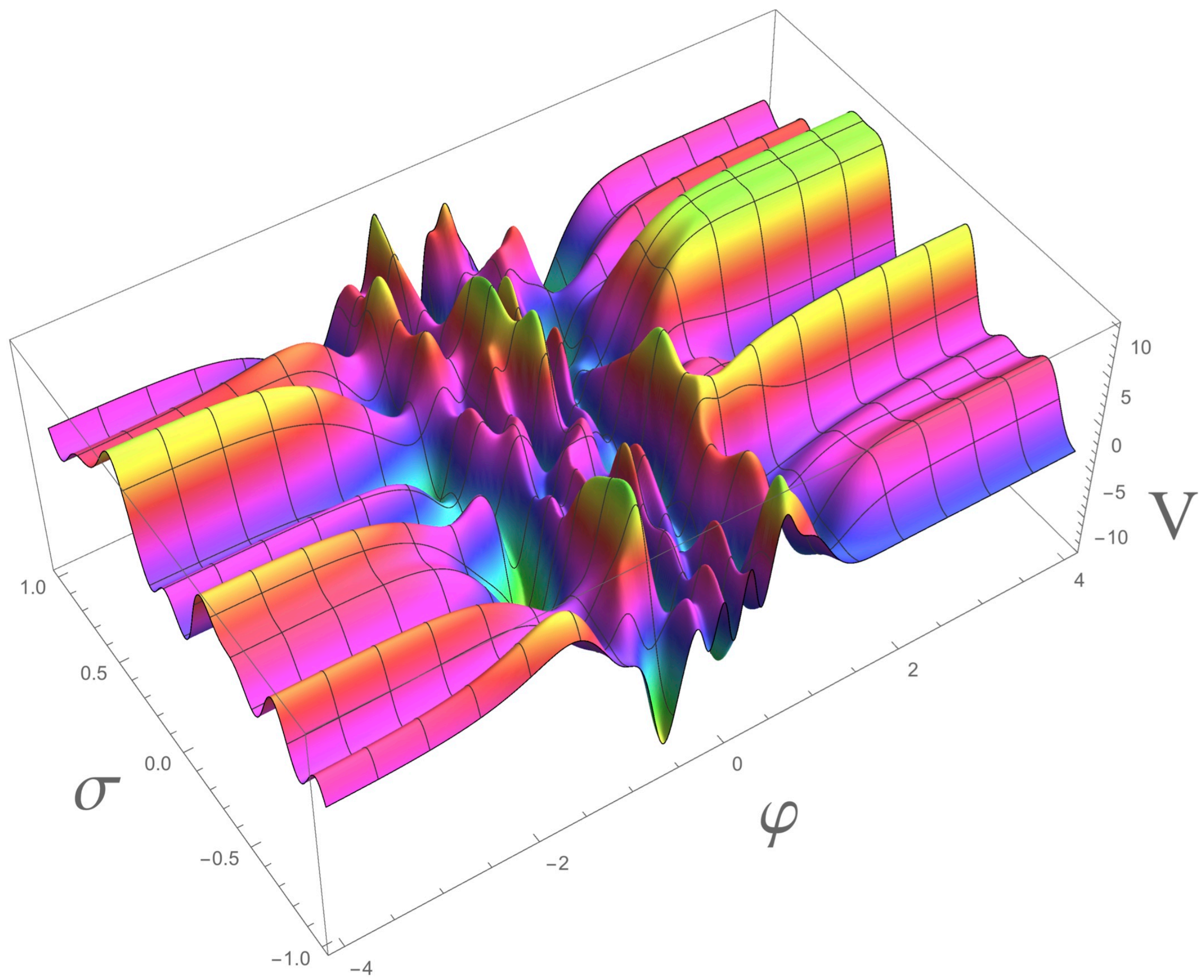
Inflation with Random Potentials and Cosmological Attractors

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



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

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



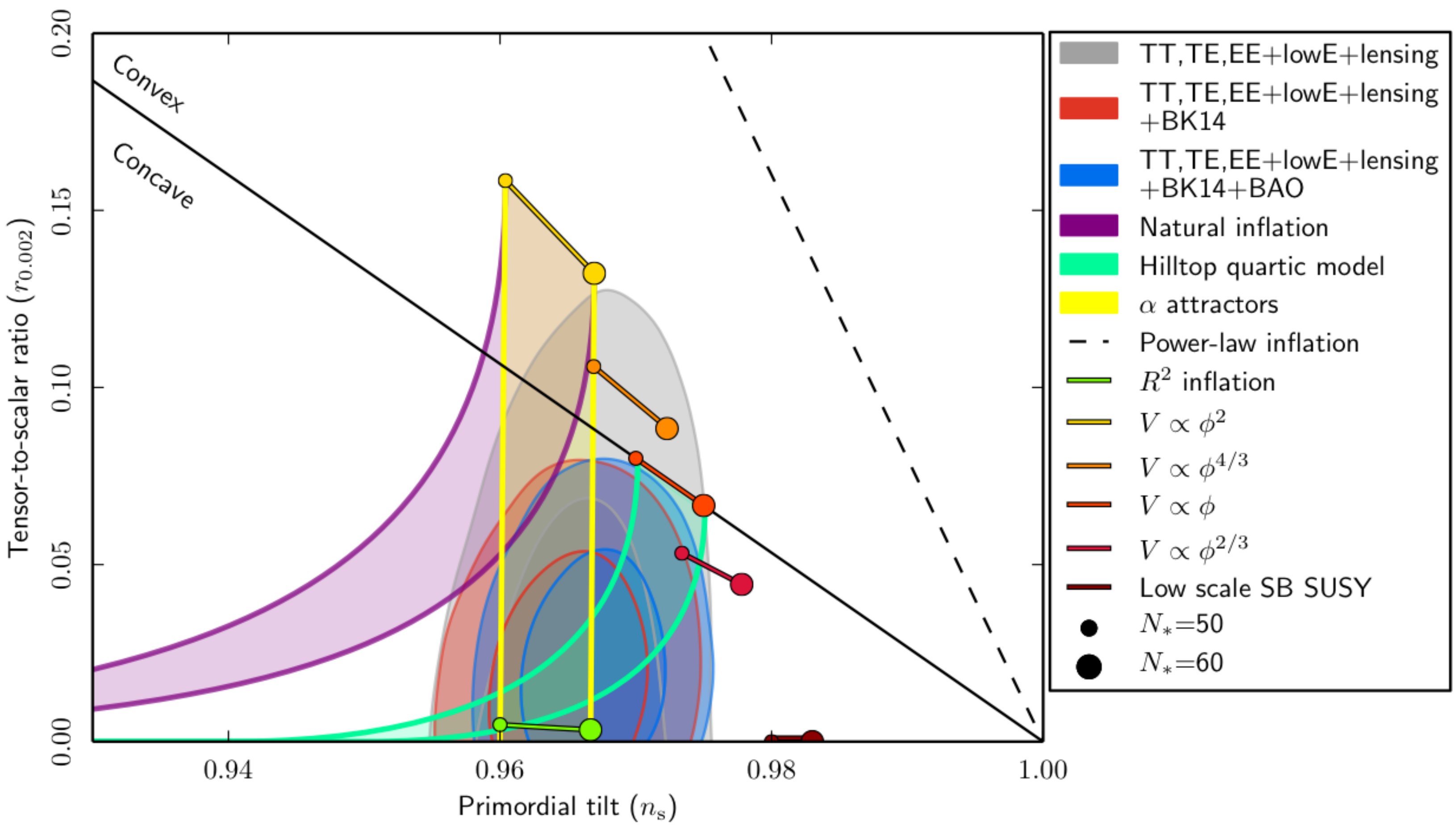
α-attractor mechanism makes the potentials flat, which makes inflation possible, which, in its turn, makes the universe flat

Planck 2018 and the Hilltop Mystery

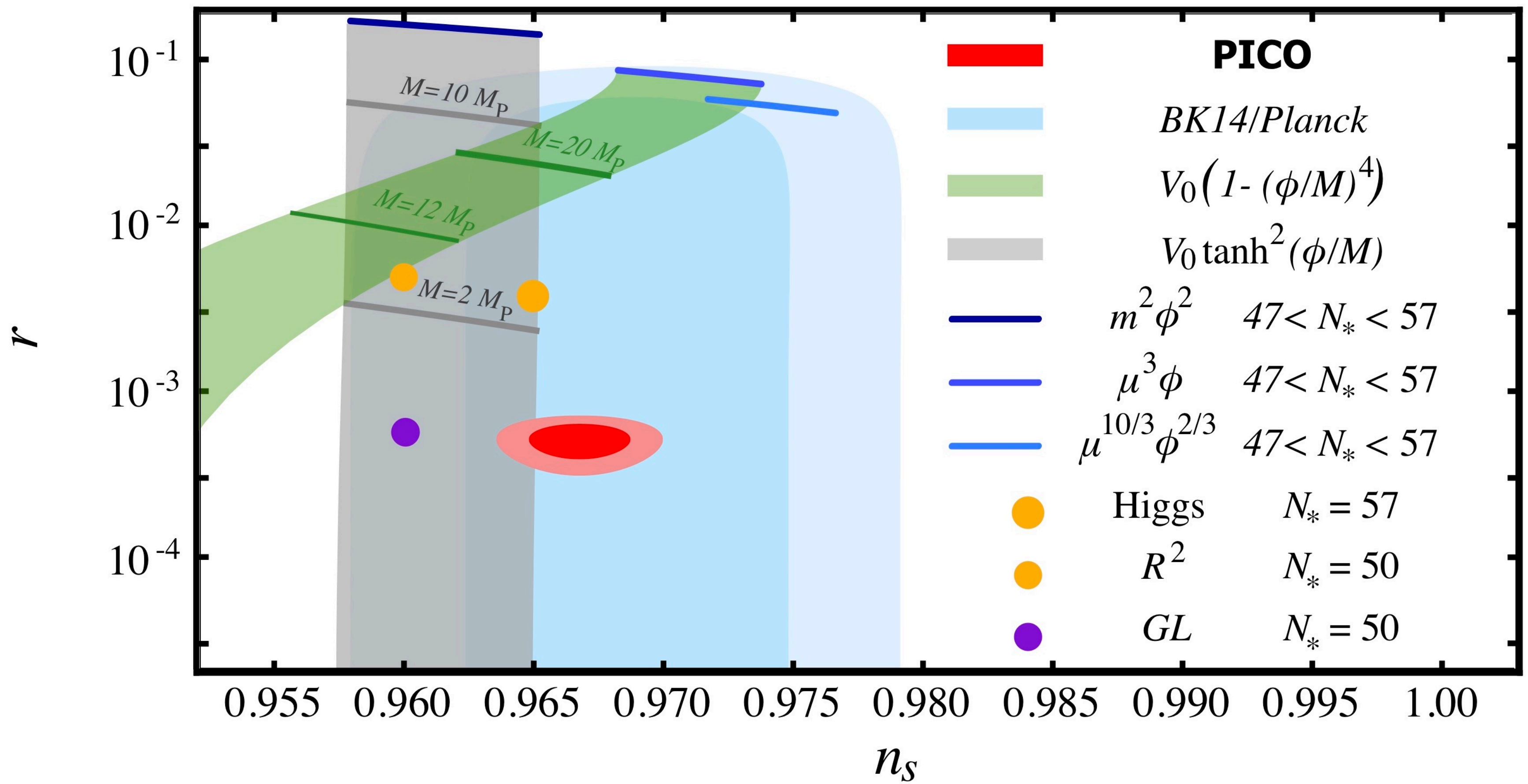
$$V = V_0 \left(1 - \frac{\phi^n}{m^n}\right)$$

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.

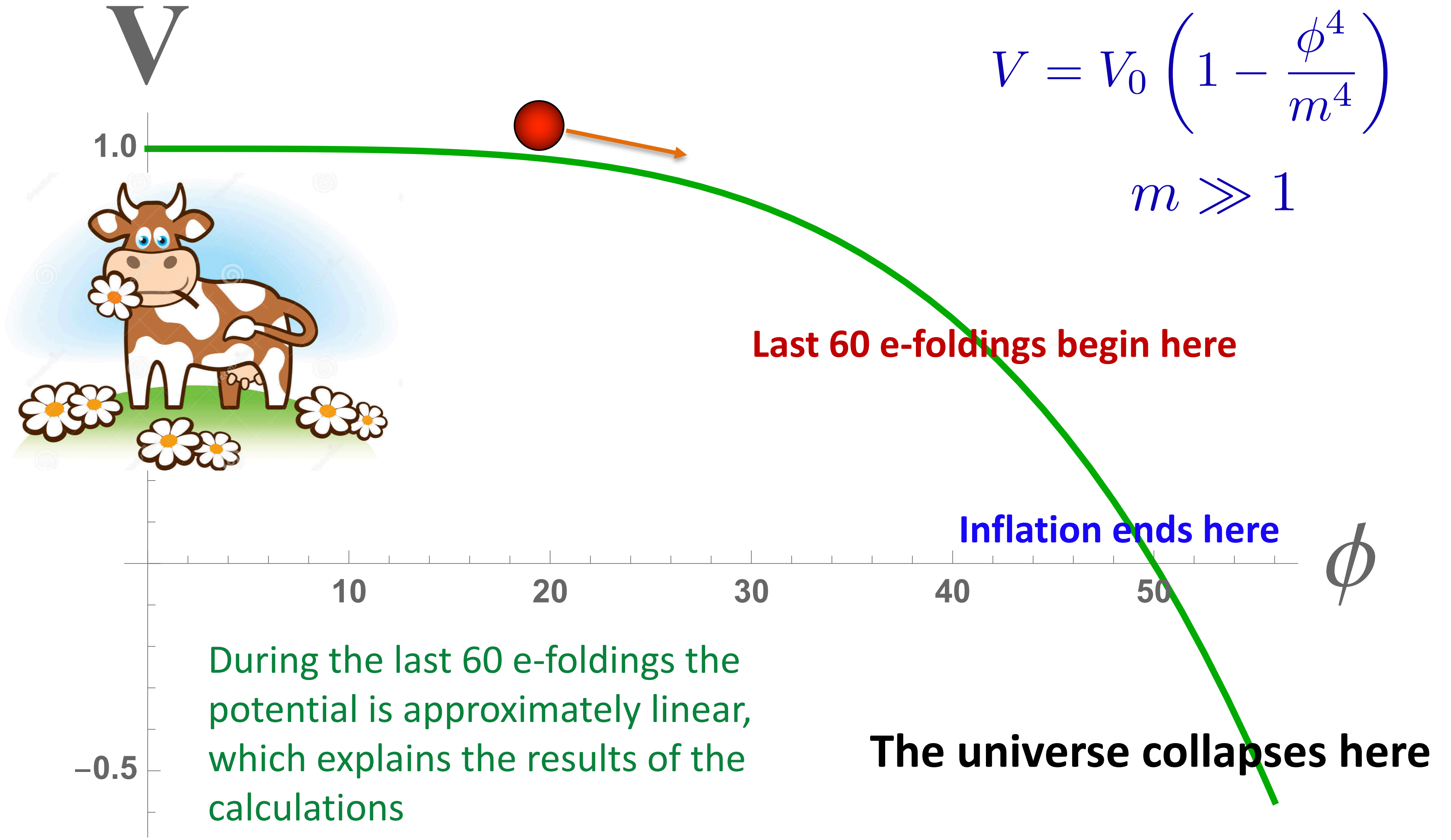
But n_s = 1-3/N is too small, the models with m < 1 are ruled out by Planck 2015 and 2018.

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?

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

$$m \gg 1$$

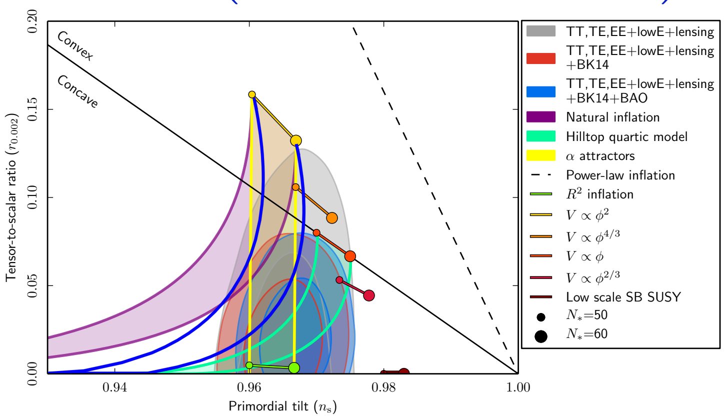


During the last 60 e-foldings the potential is approximately linear, which explains the results of the calculations

Saving hilltop models ?

Coleman-Weinberg

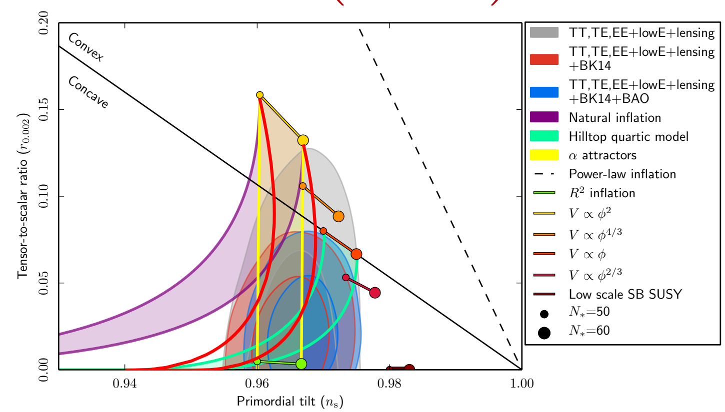
$$V = V_0 \left(1 + \frac{\phi^4}{m^4}(2\log\frac{\phi^2}{m^2} - 1)\right)$$



Motivation OK, agreement with data poor

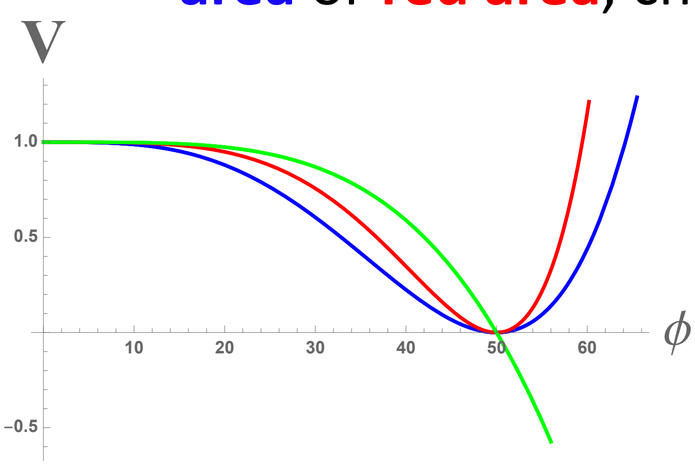
Squared hilltop

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



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



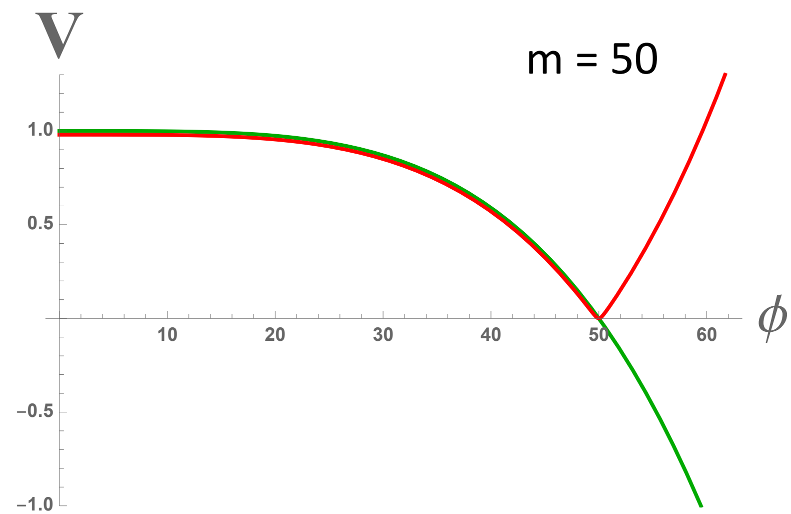
We conclude that the green hilltop area is not reproduced by analysis of simple consistent inflationary models

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

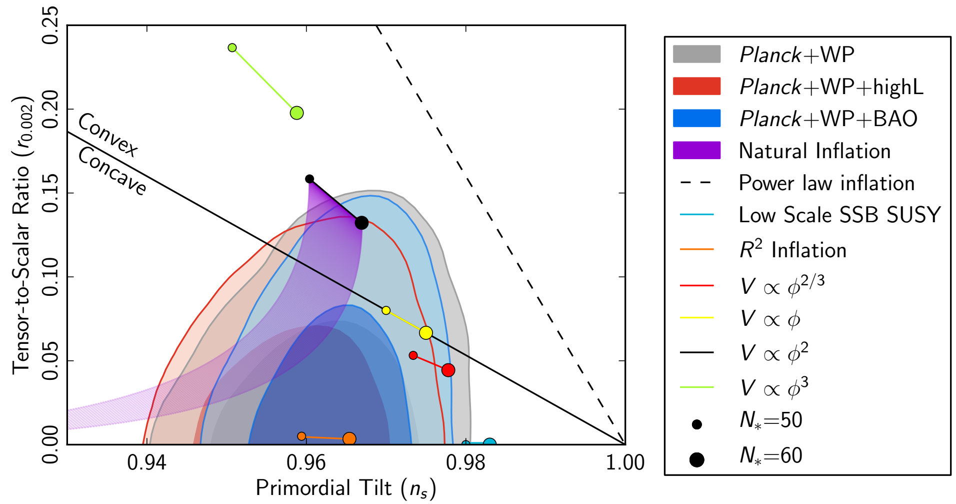
$$V = V_0 \left(\sqrt{\frac{1}{m^2} + \left(1 - \frac{\phi^4}{m^4}\right)^2} - \frac{1}{m} \right)$$



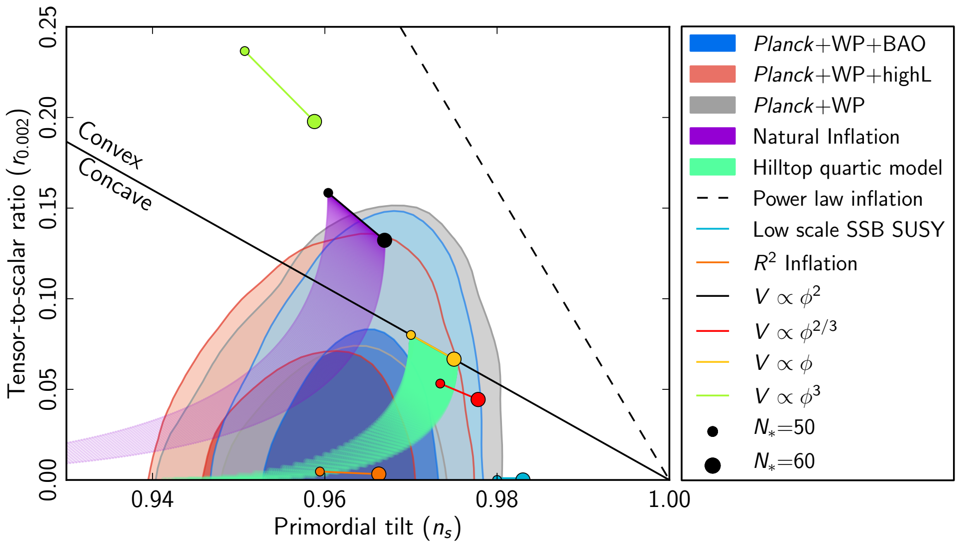
Does this *ad hoc* handmade model have any physical motivation? Should we put it on the list of the best inflationary models favored by Planck and suggest its further exploration by CMB-S4?

How did the green hilltop area appeared in these pictures?

Planck 2013 version 1



Version 2, after the referee report...

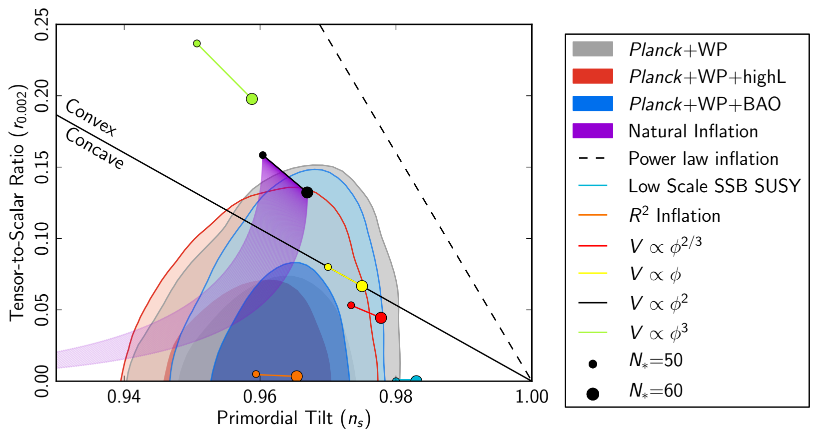


That is why the green hilltop area is in every subsequent Planck data release, in CMB-S4, in PICO, for the last 6 years...

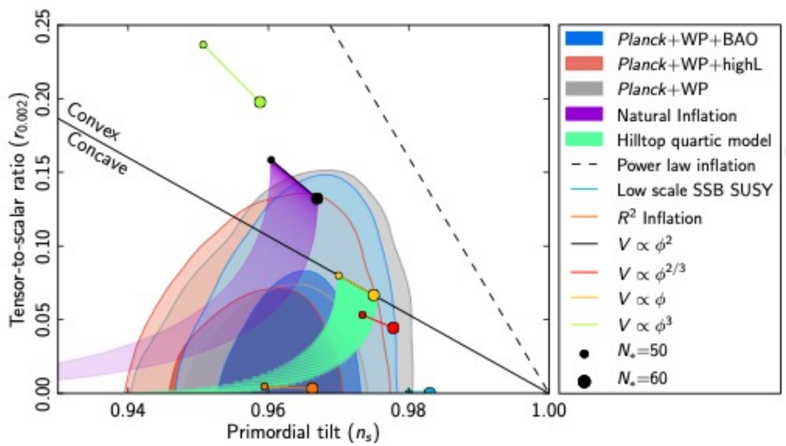
From Planck 2013 to PICO 2019

Planck 2013

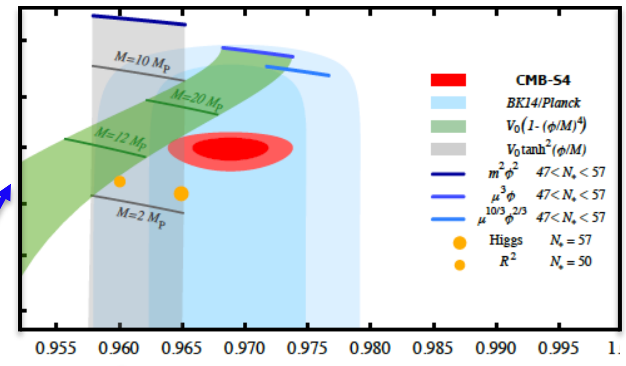
v1



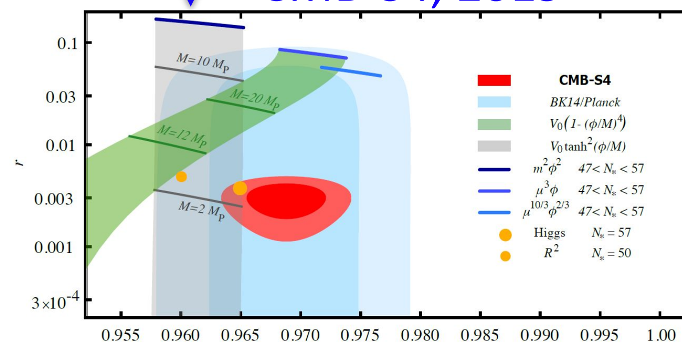
v2



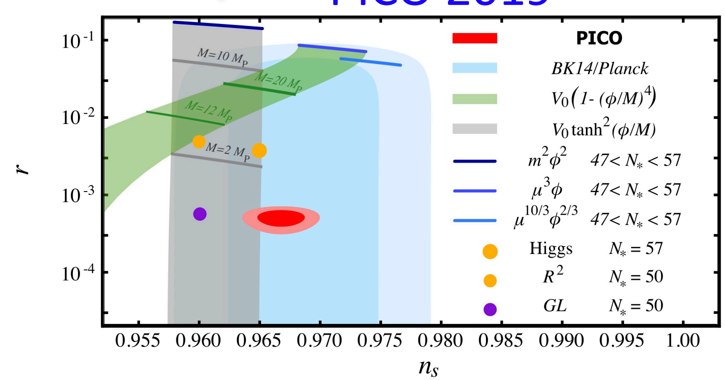
CMB-S4, 2016



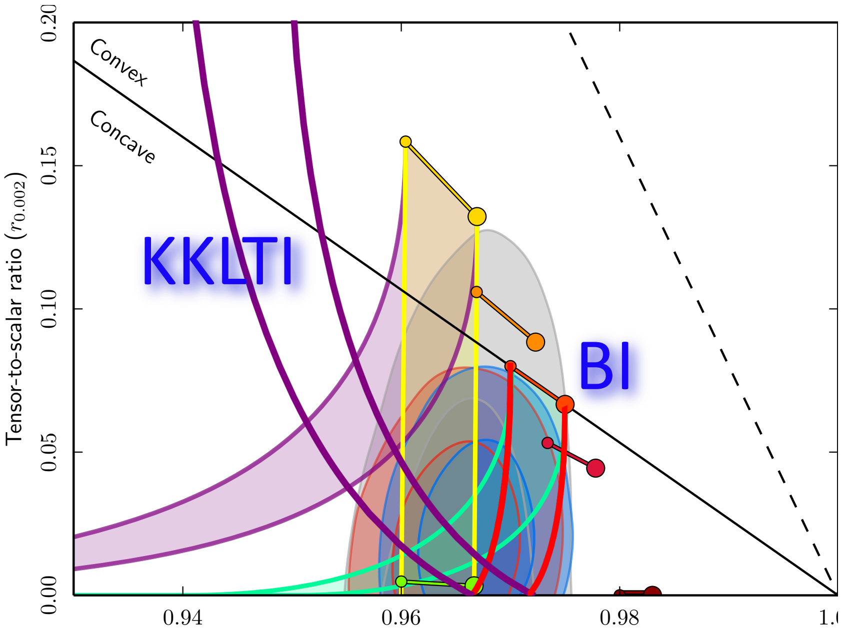
CMB-S4, 2019



PICO 2019



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

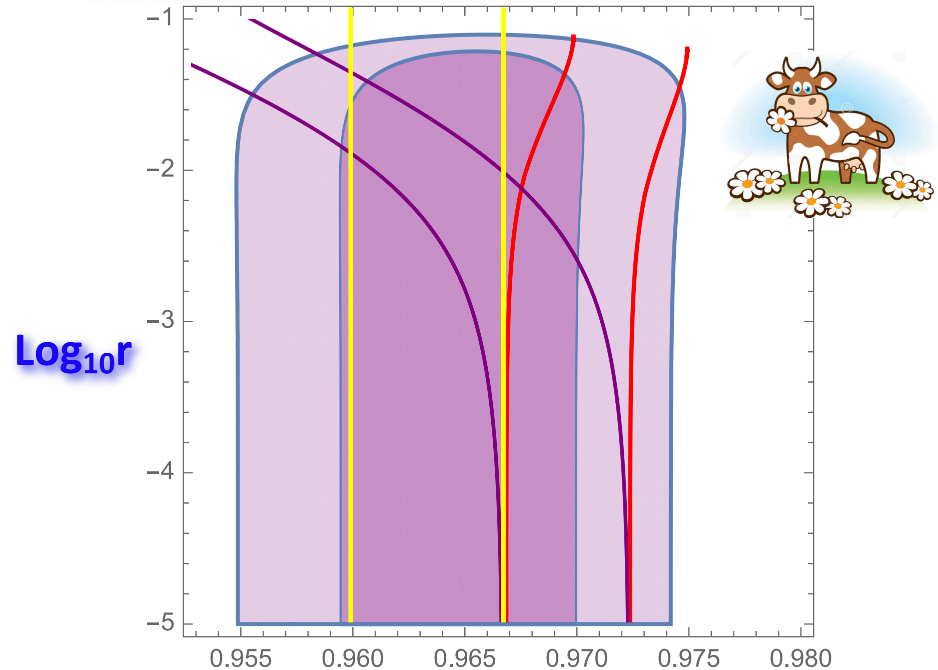


Towards $V \sim \varphi^n$

KKLTI

Towards $V \sim \varphi$

BI



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

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

towards

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

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

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

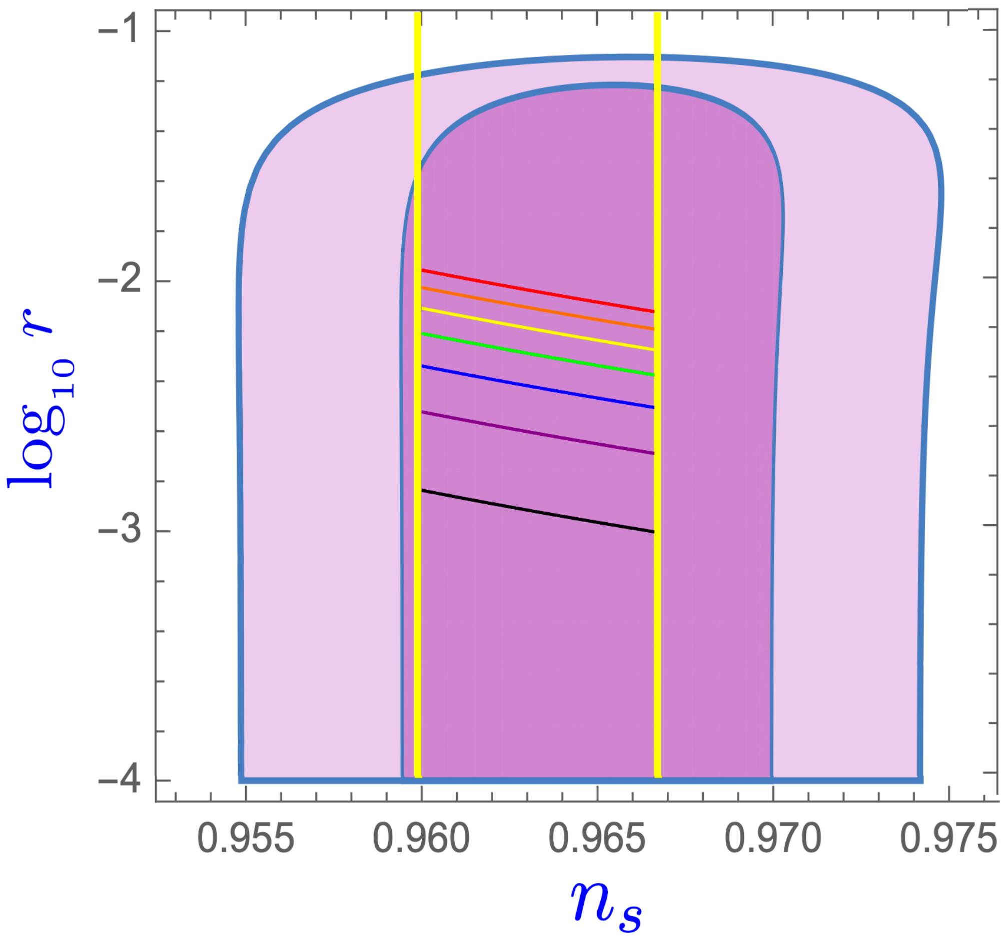
improved

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

U-duality symmetry benchmarks for α-attractors

Maximal supersymmetry

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



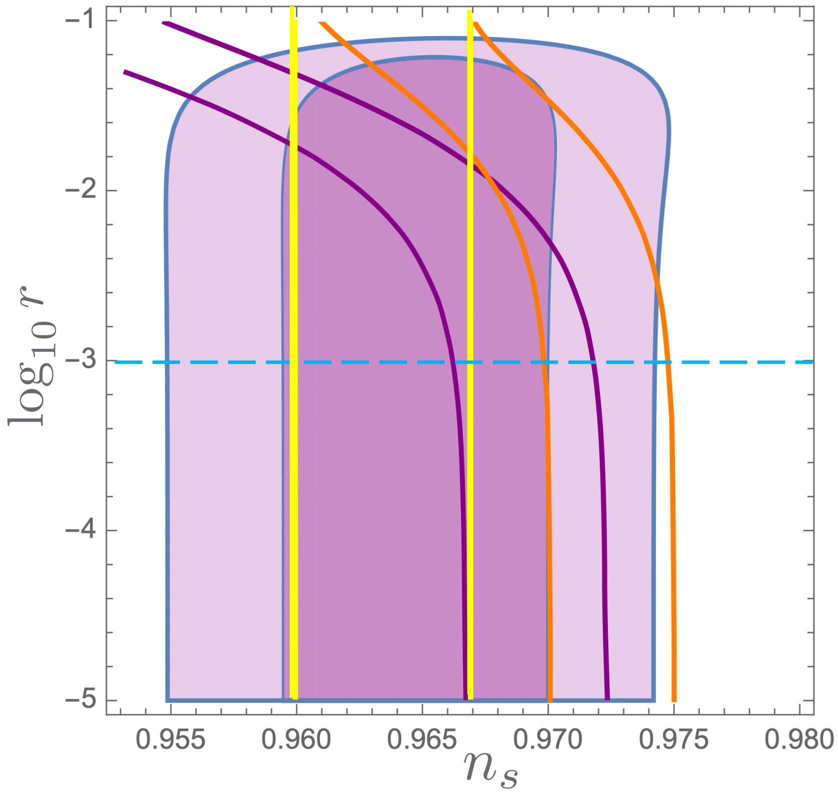
Special cases:

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	$n_s = 1 - \dfrac{2}{N}$	α-attractor
Purple stripe	$n_s = 1 - \dfrac{5}{3}\dfrac{1}{N}$	D3-brane
Orange stripe	$n_s = 1 - \dfrac{3}{2}\dfrac{1}{N}$	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: $\sigma(n_s) = 0.0015$

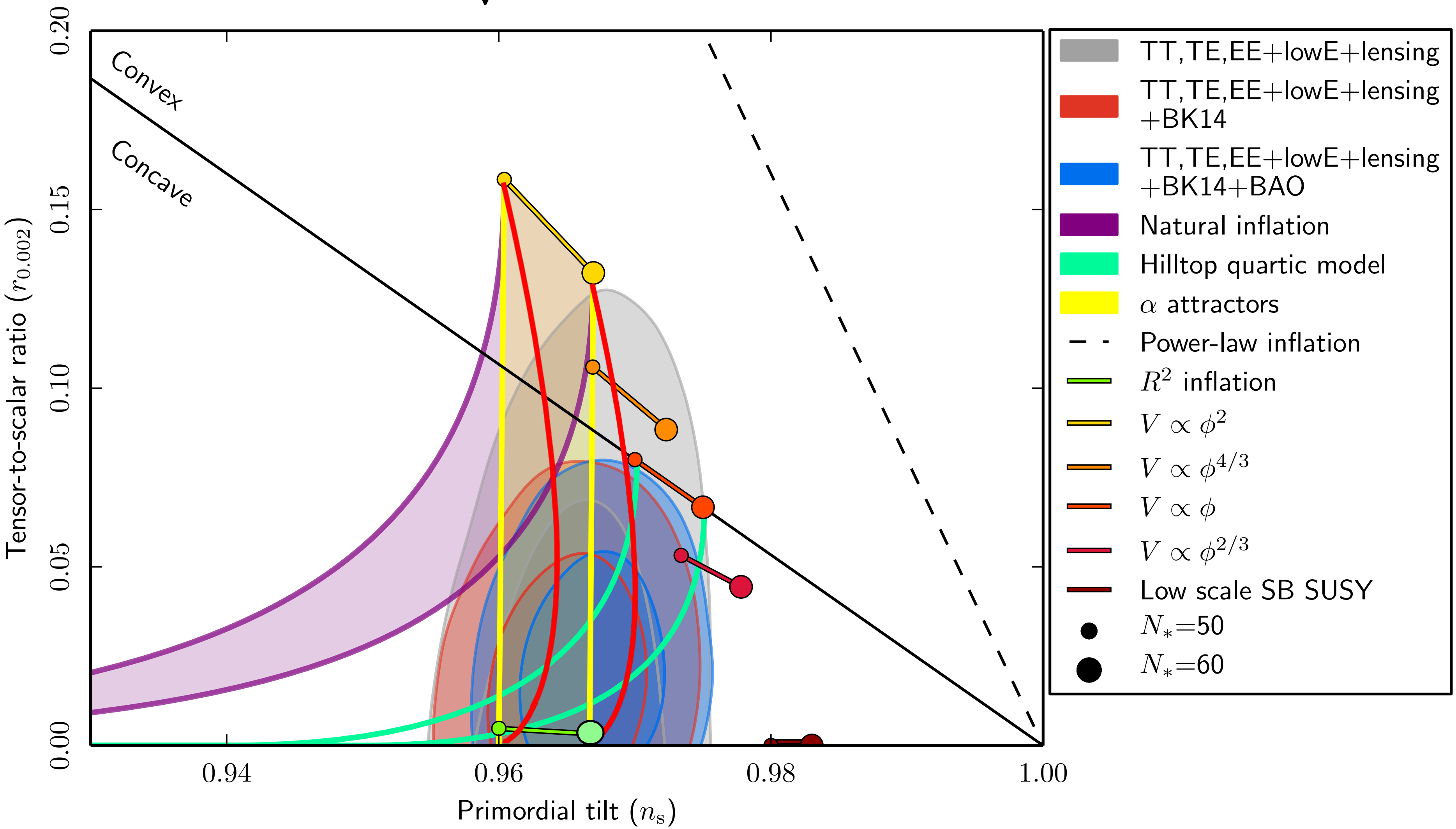
Which of the stripes will be the favorite?

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

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

$$V_T = V_0 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}}$$

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



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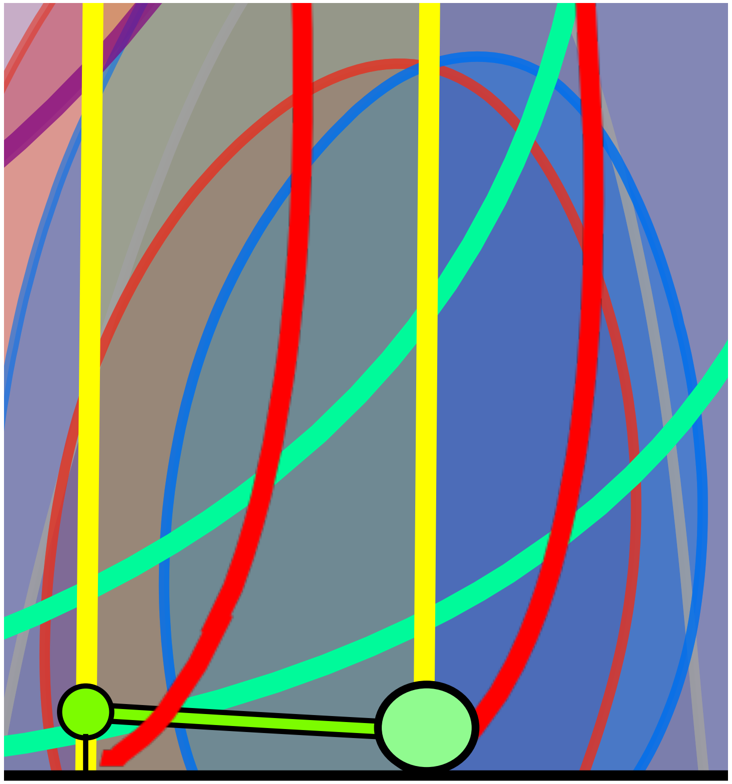
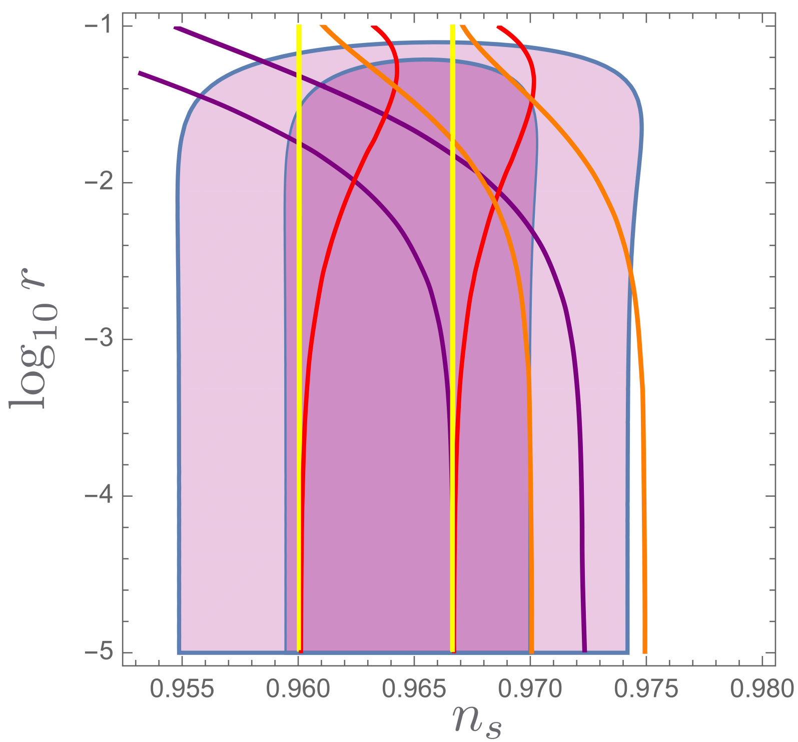
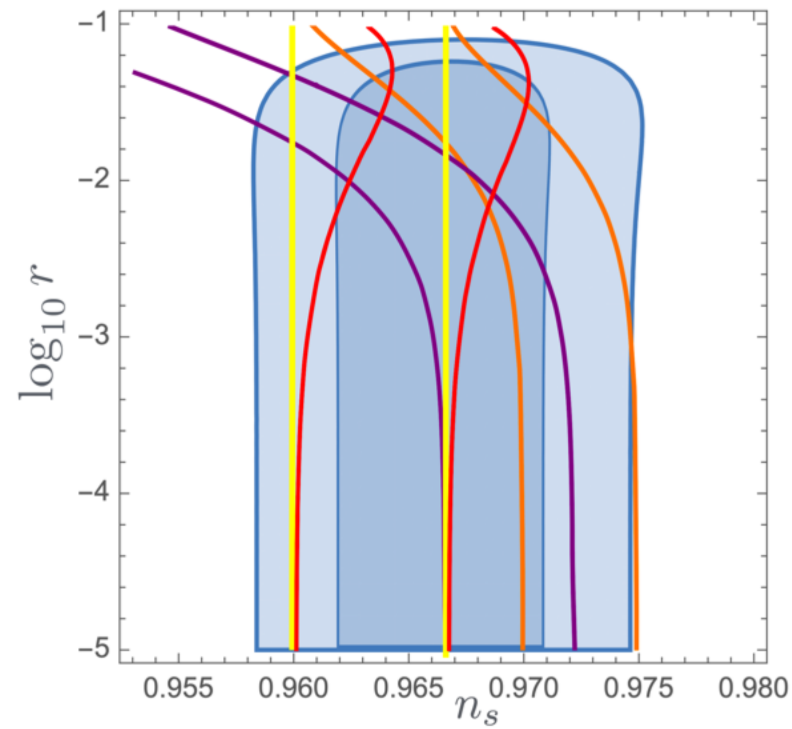


By zooming at the 1σ area (dark pink or dark blue), we see that most of it is covered by two simplest models of α-attractors

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

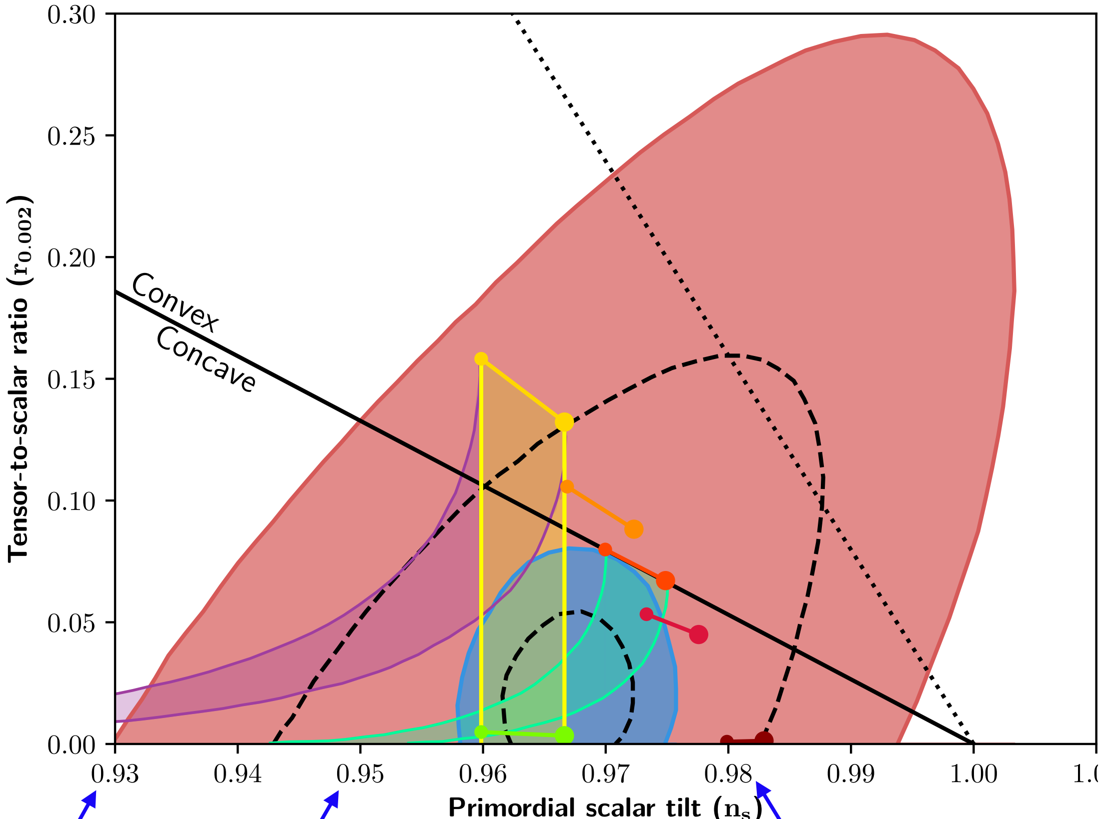




A combination of the simplest α-attractors and KKLTI models of D-brane inflation covers most of the area favored by Planck 2018, all the way down to r = 0.

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