Future of Inflation

Andrei Linde

in collaboration with Renata Kallosh

Why Inflation?

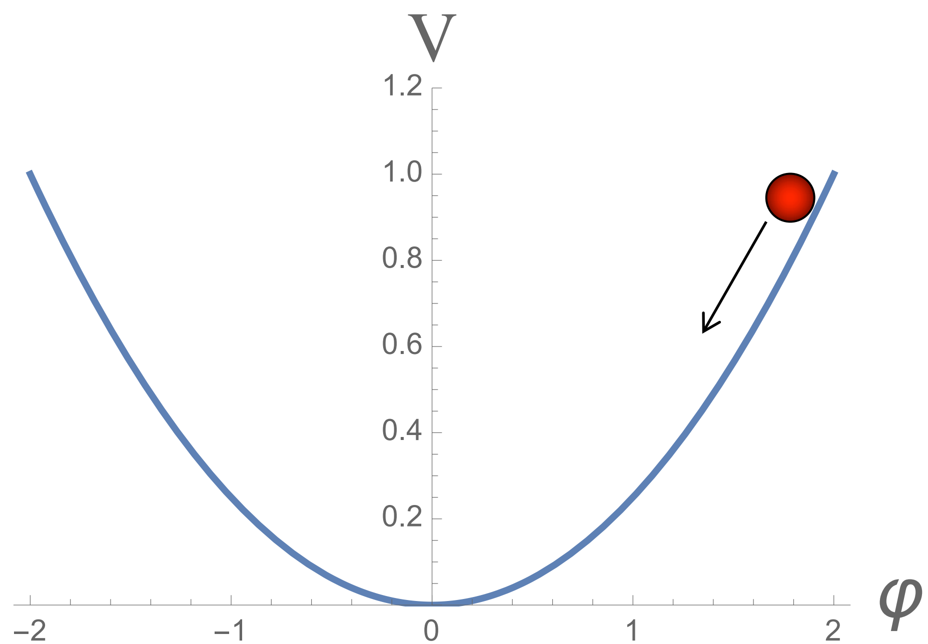
Hard Art of the Universe Creation

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 universe consisted of 10^{90} causally disconnected parts of size $ct = O(1)$. These 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.**

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 requires across **10^{90} Planck size domains**.



But this simple model is disfavored by Planck. What can we do?

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

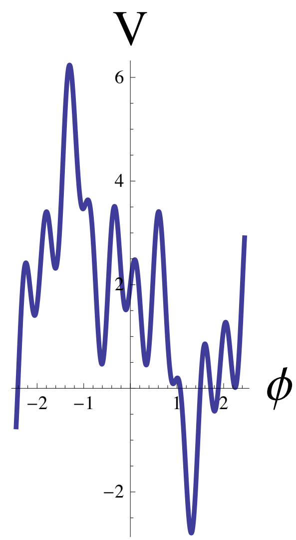
$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

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

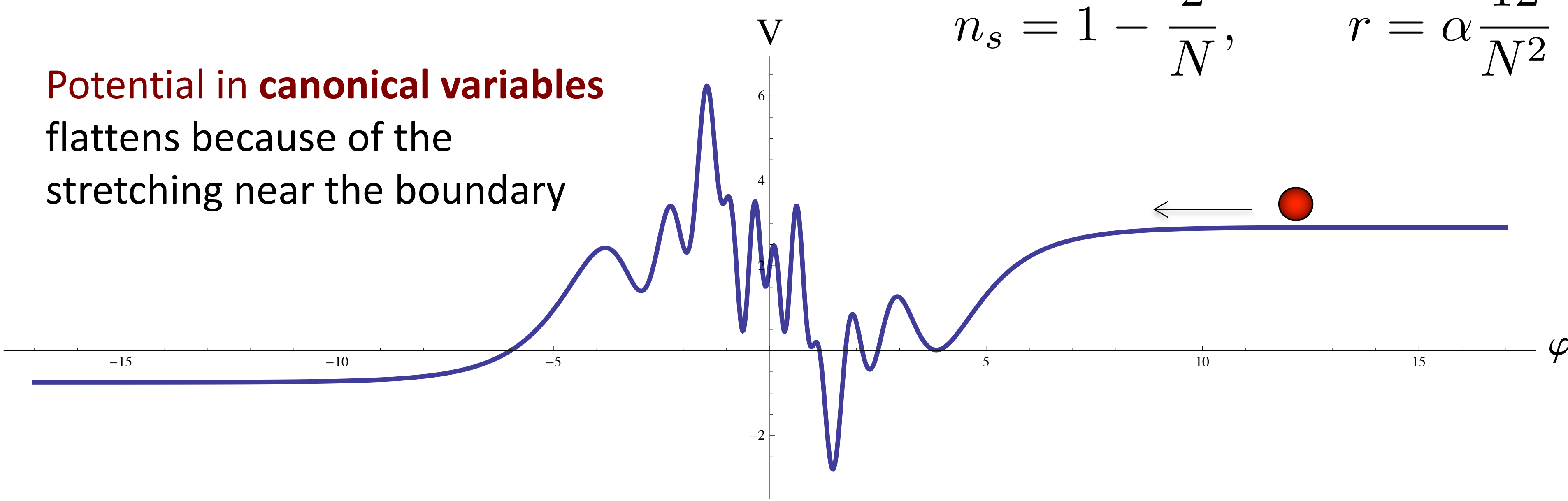
$$\frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



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

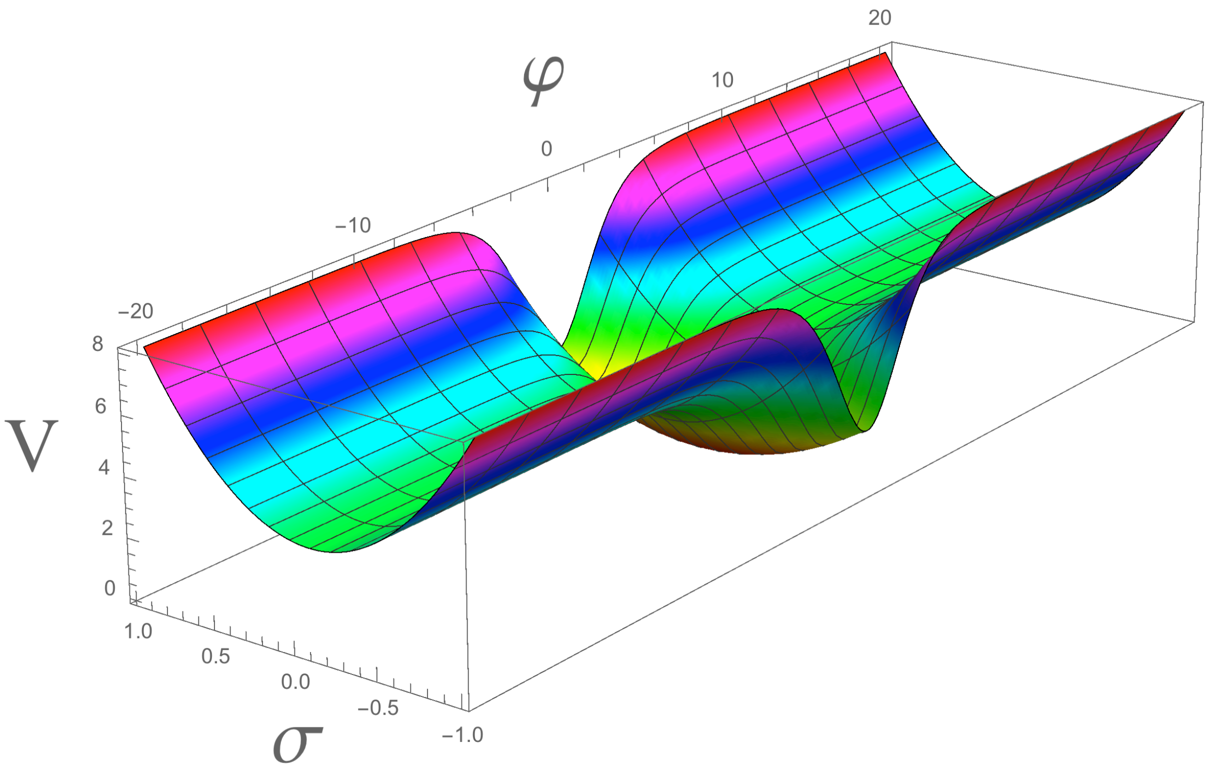


But in this model, as well as in the Starobinsky model and in Higgs inflation, the inflaton potential is 10 orders of magnitude below Planck density. It could seem that we have a problem with initial conditions.

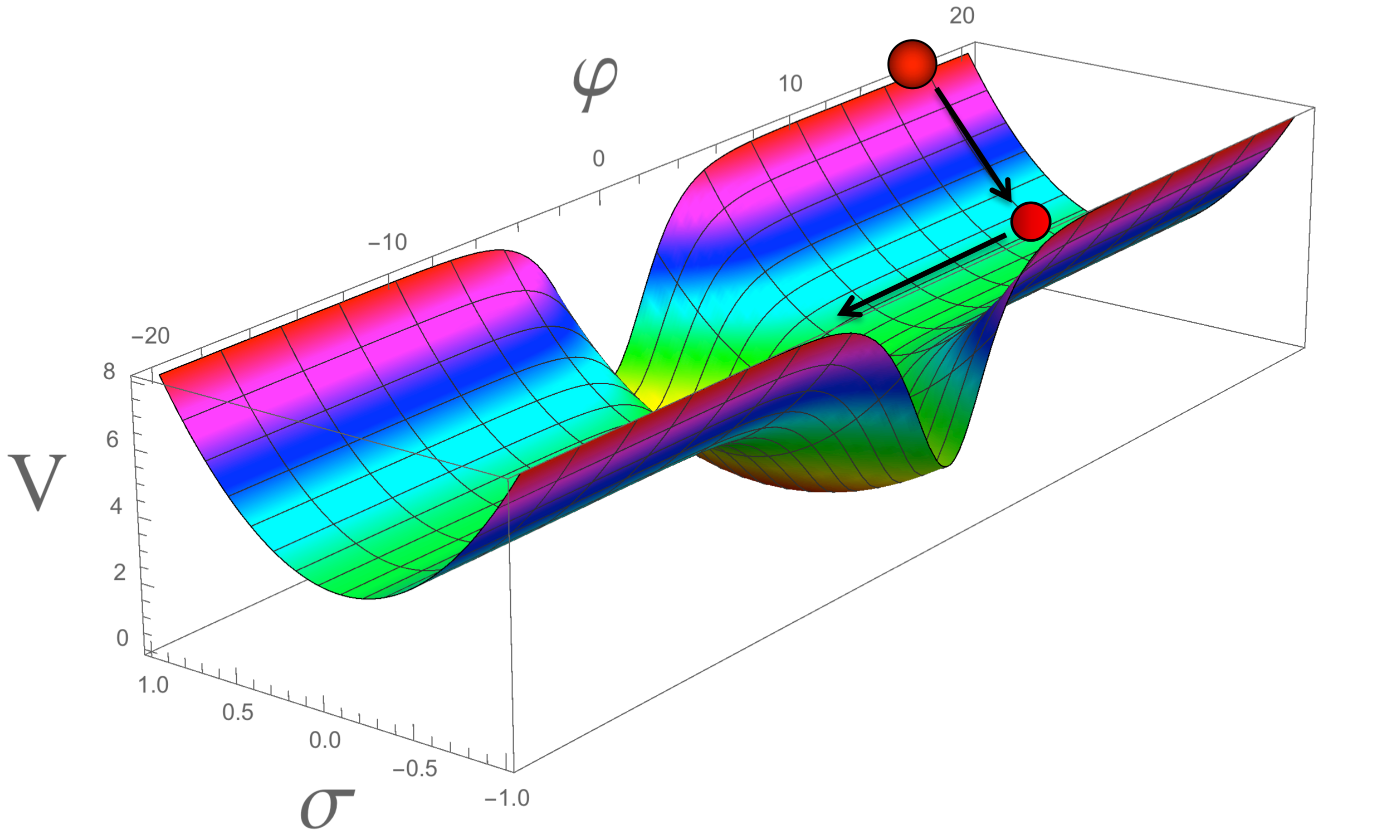
α-attractors and the simplest quadratic model

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

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 σ rolls down, the plateau inflation begins.

No problem with initial conditions

There is a simpler and more general way to solve the problem of initial conditions for inflation, without using additional fields.
Please ask me about it after the talk.

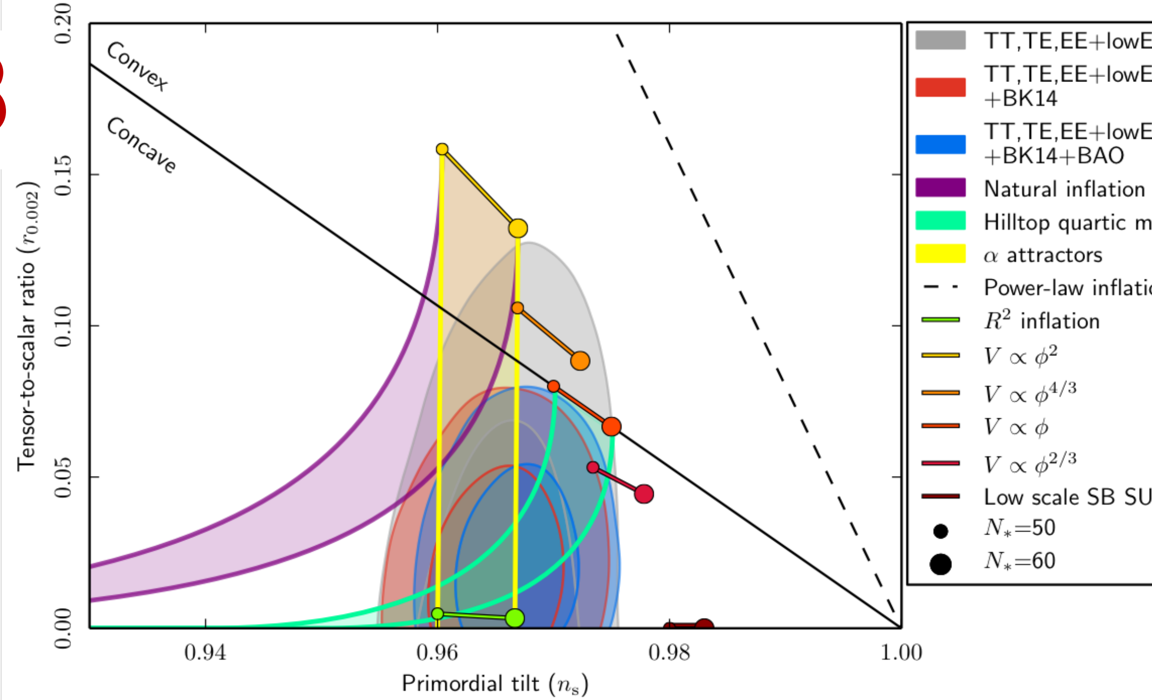
East, Kleban, AL, Senatore 1511.05143
Kleban, Senatore 1602.53520
Clough, Lim, DiNunno, Fischler, Flauger, Paban 1608.04408
AL 1710.04278

Inflation after Planck 2018

Recent work with Renata Kallosh and Yusuke Yamada,
1811.01023, 1906.02156, 1906.04729, 1909.04687

The main goal is to use Planck results and identify possible CMB targets for future observational missions

Planck 2018



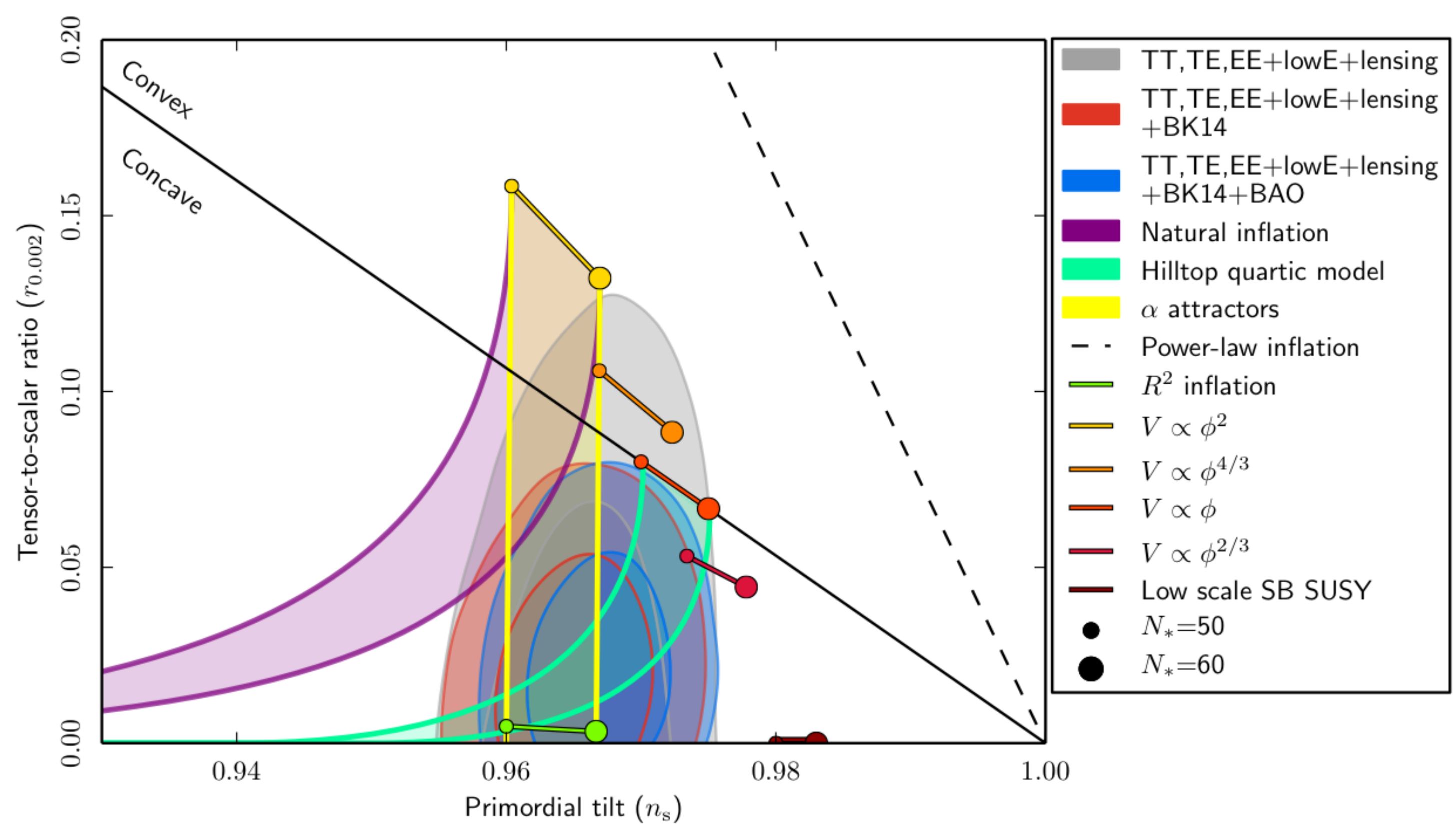
$R + R^2/(6M^2)$				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Power-law potential				
Non-minimal coupling				
Natural inflation				
Hilltop quadratic model				
Hilltop quartic model	$\Lambda^4\left(1 - \phi^4/\mu_4^4 + \ldots\right)$	$-2 < \log_{10}(\mu_4/M_{\rm Pl}) < 2$	-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

Hilltop Mystery

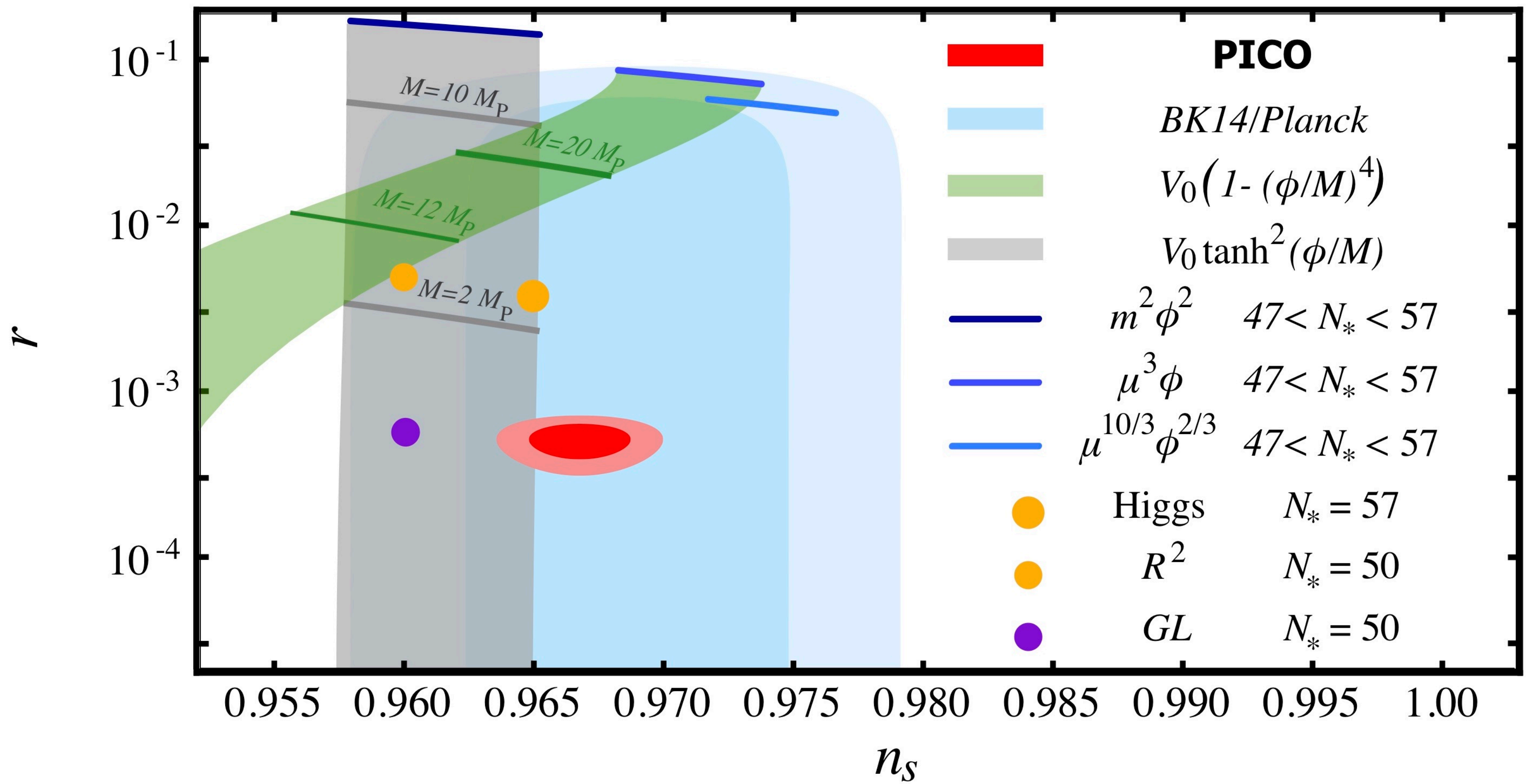
$$V = V_0 \left(1 - \frac{\phi^n}{m^n}\right)$$

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.

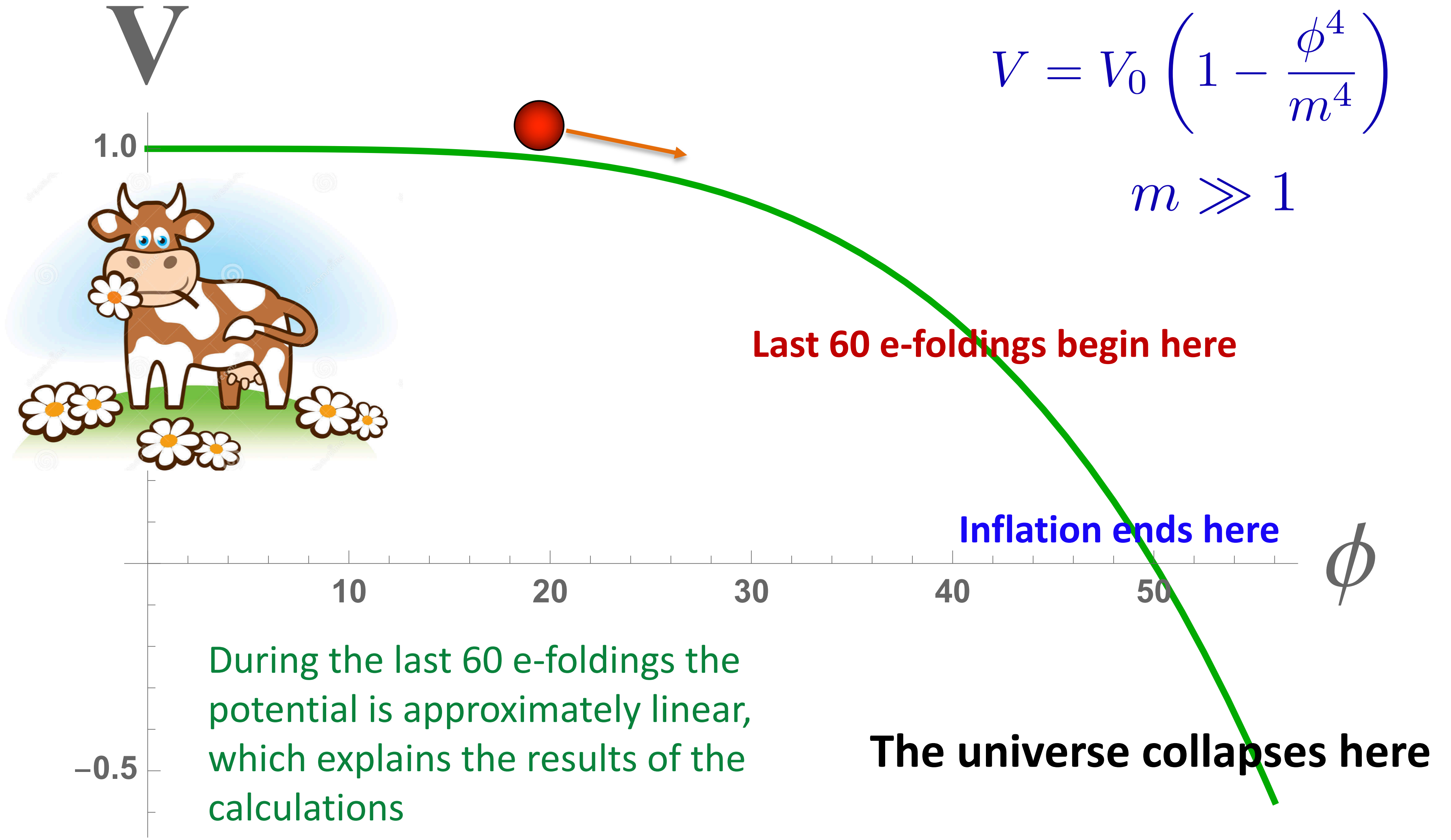
But n_s = 1-3/N is too small, the models with m < 1 are ruled out by Planck 2015 and 2018.

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?

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

$$m \gg 1$$

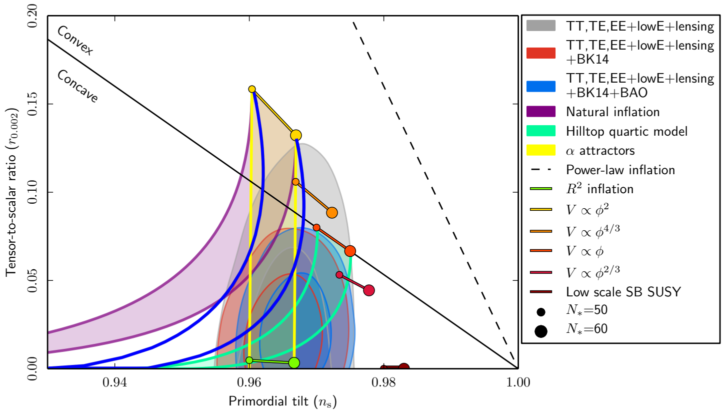


During the last 60 e-foldings the potential is approximately linear, which explains the results of the calculations

Saving hilltop models ?

Coleman-Weinberg

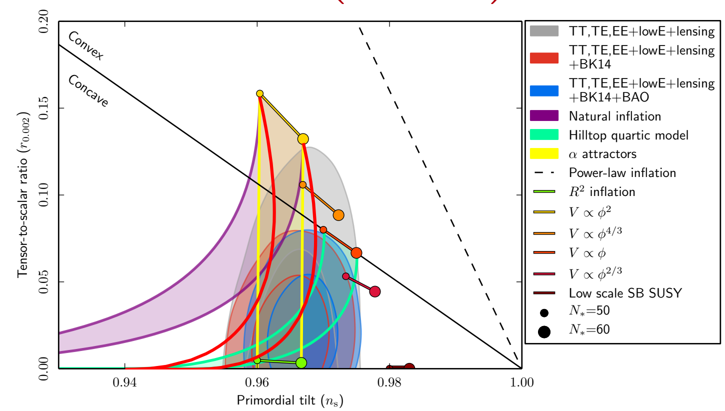
$$V = V_0\left(1 + \frac{\phi^4}{m^4}(2\log\frac{\phi^2}{m^2} - 1)\right)$$



Motivation OK, agreement with data poor

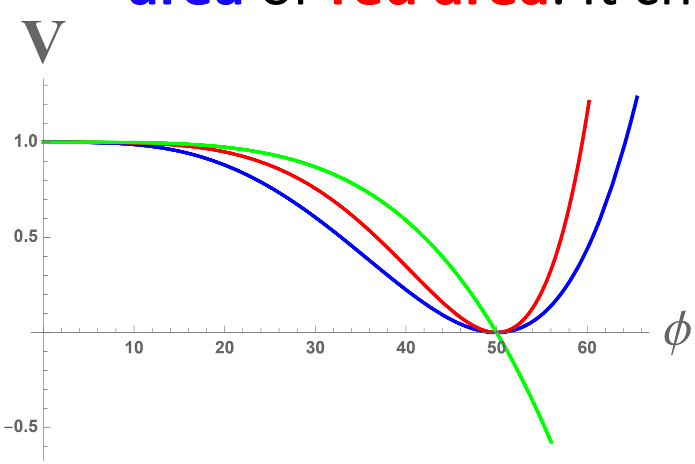
Squared hilltop

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



Agreement with data OK, motivation poor

Consistent hilltop models change the **green area** into the **blue area** or **red area**. It changes n_s and significantly increases r

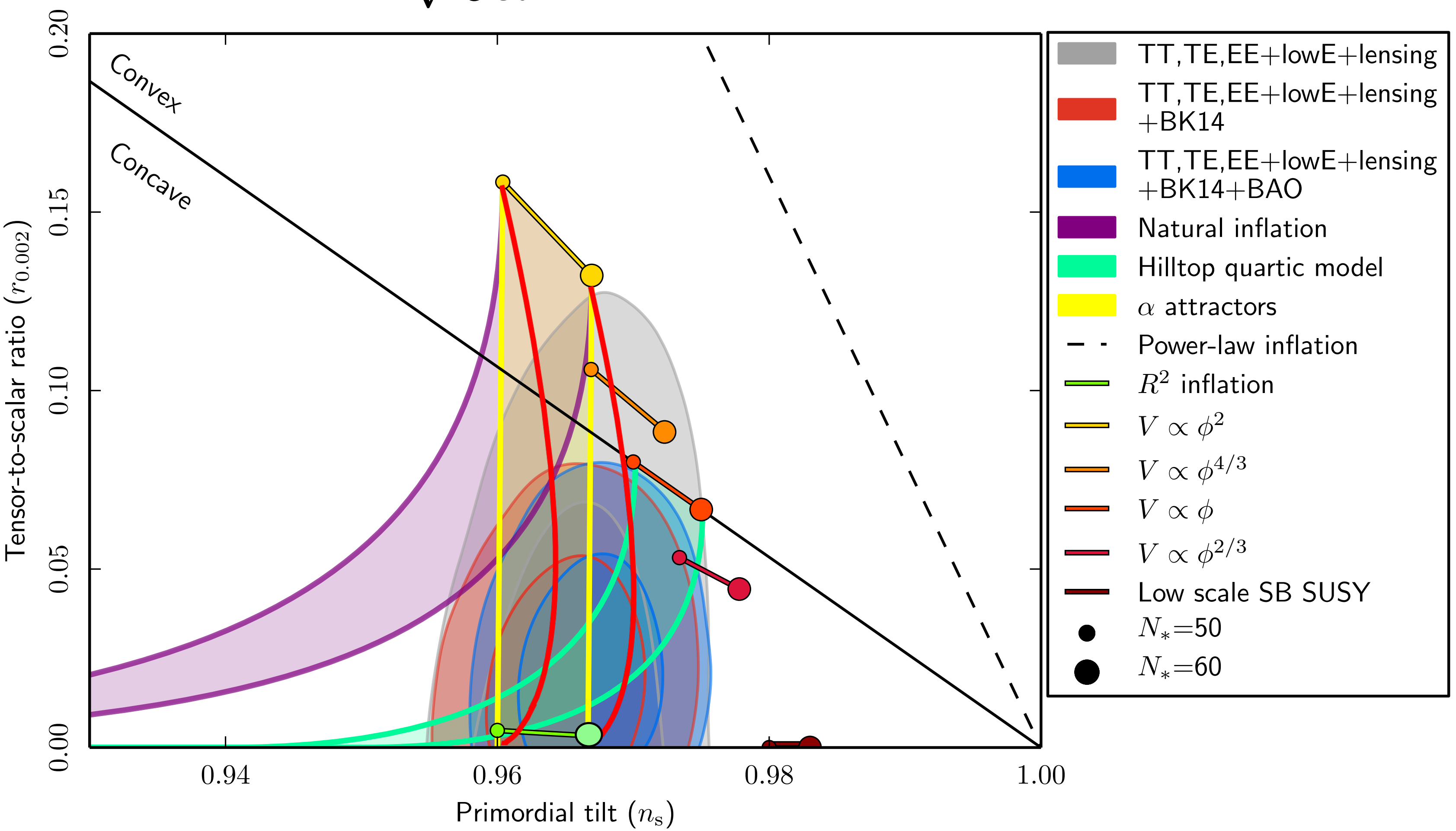


We conclude that the green hilltop area is not predicted by any simple consistent inflationary models

α-attractors and Planck 2018

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

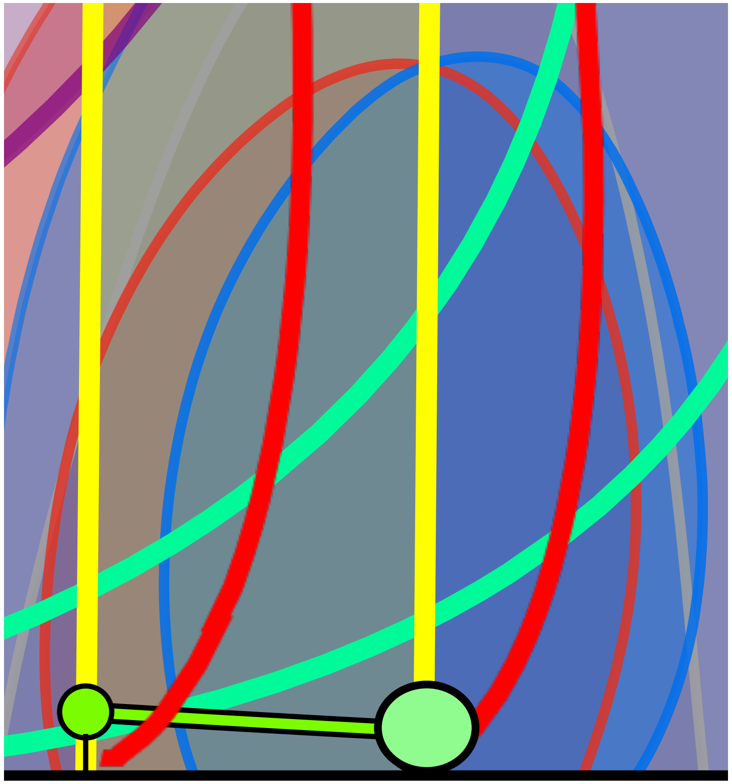
$$V_T = V_0 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}} \qquad V_E = V_0 \left(1 - e^{\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2$$



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

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

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

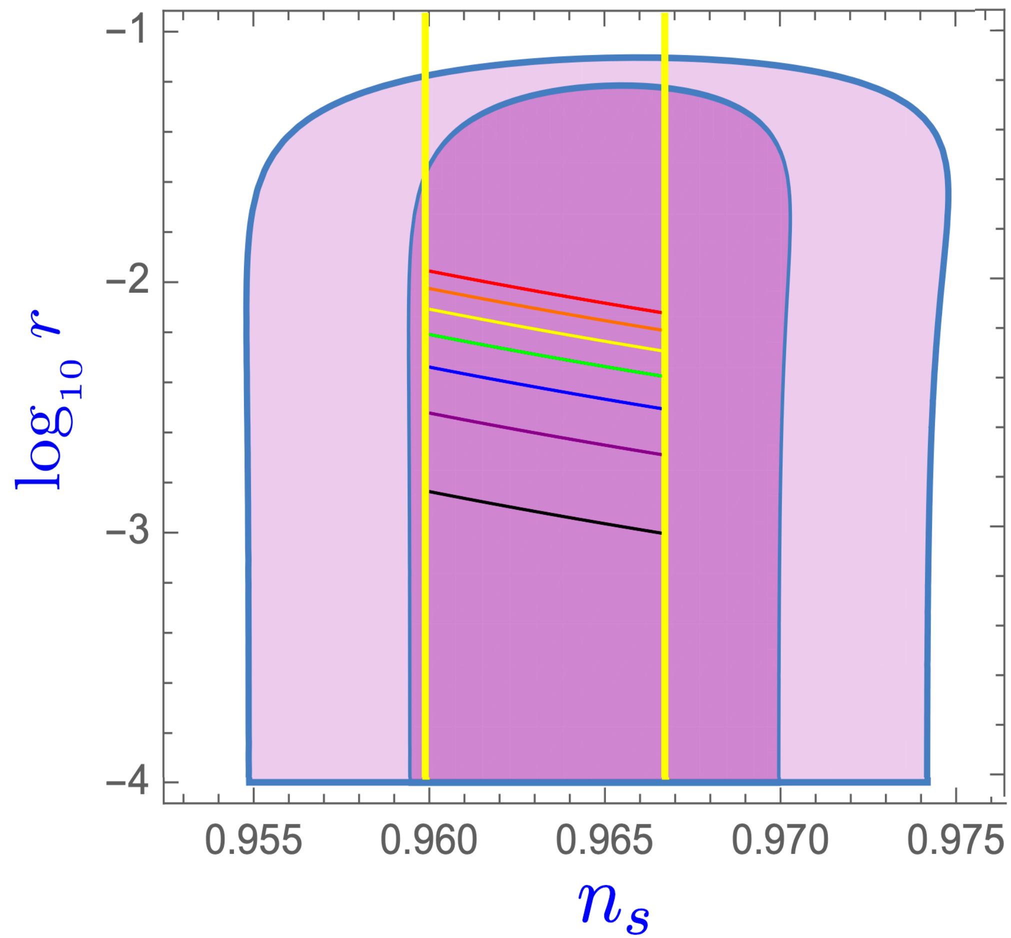


By zooming at the 1σ area (dark pink or dark blue), we see that most of it is covered by two simplest models of α-attractors

U-duality symmetry benchmarks for α-attractors

Maximal supersymmetry

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



Special cases:

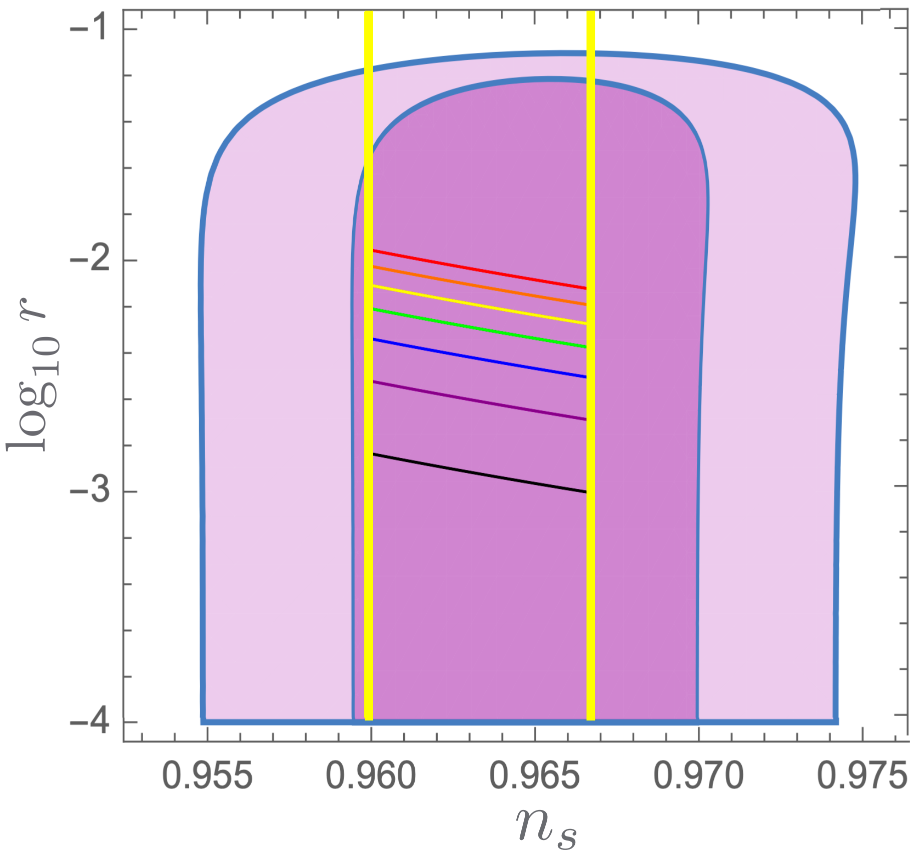
α = 2, **orange**, also fibre inflation, Cicoli et al

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

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

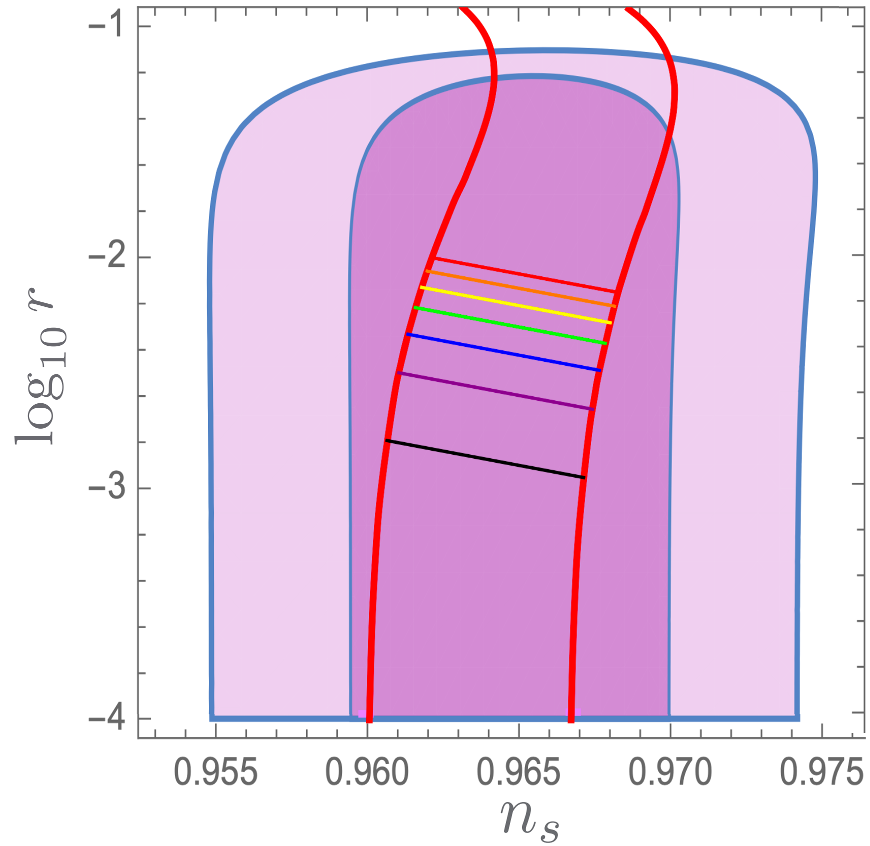
Benchmarks for T-models and E-models

T-models

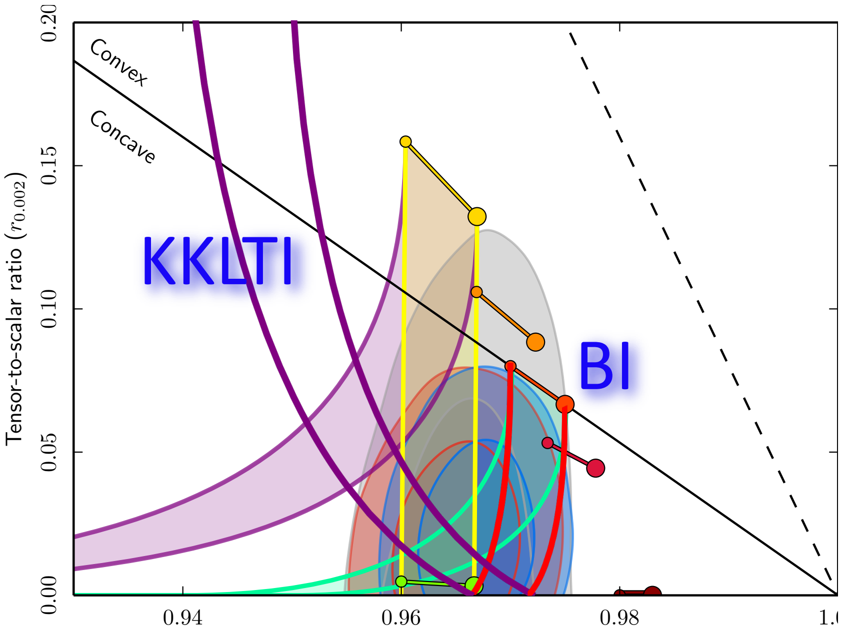


$$V_T = V_0 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}}$$

E-models



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

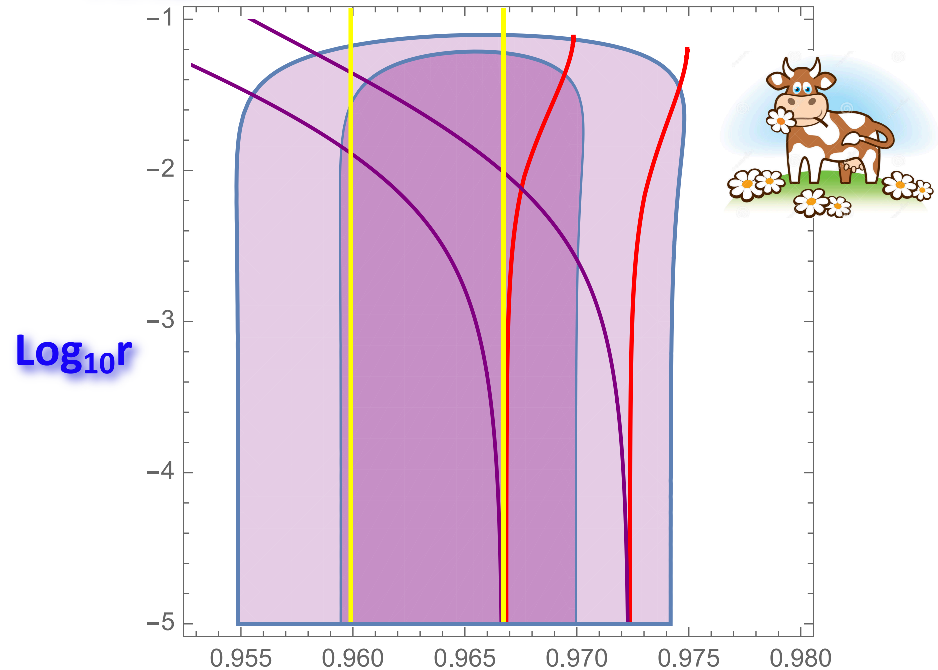


Towards $V \sim \varphi^n$

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

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

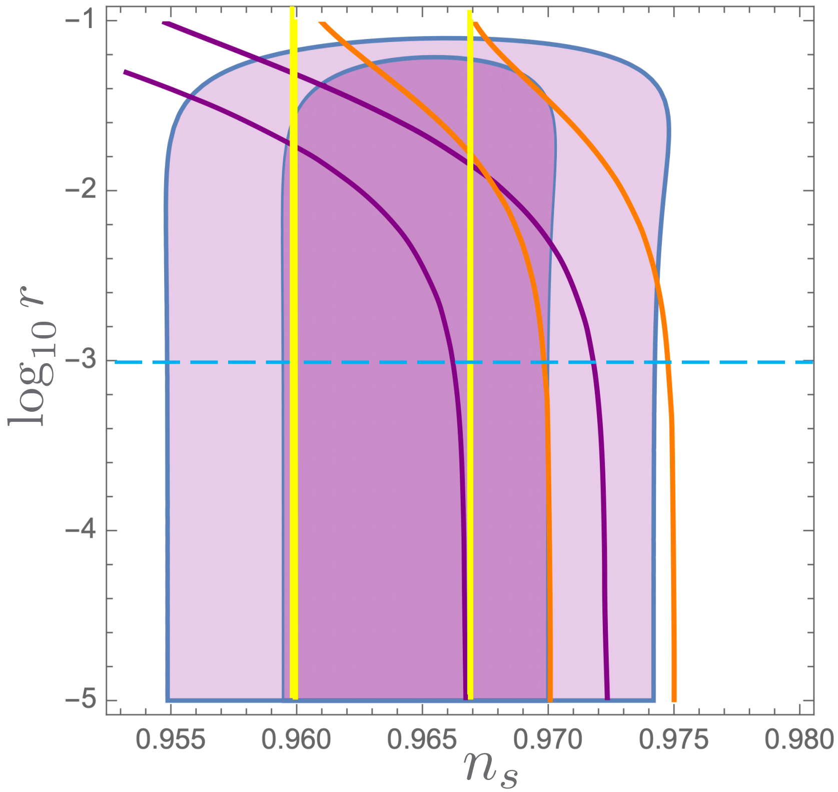
$$1 - \frac{\varphi^n}{m^n} \qquad 1 - \frac{m^n}{\varphi^n}$$

improved

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

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

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

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

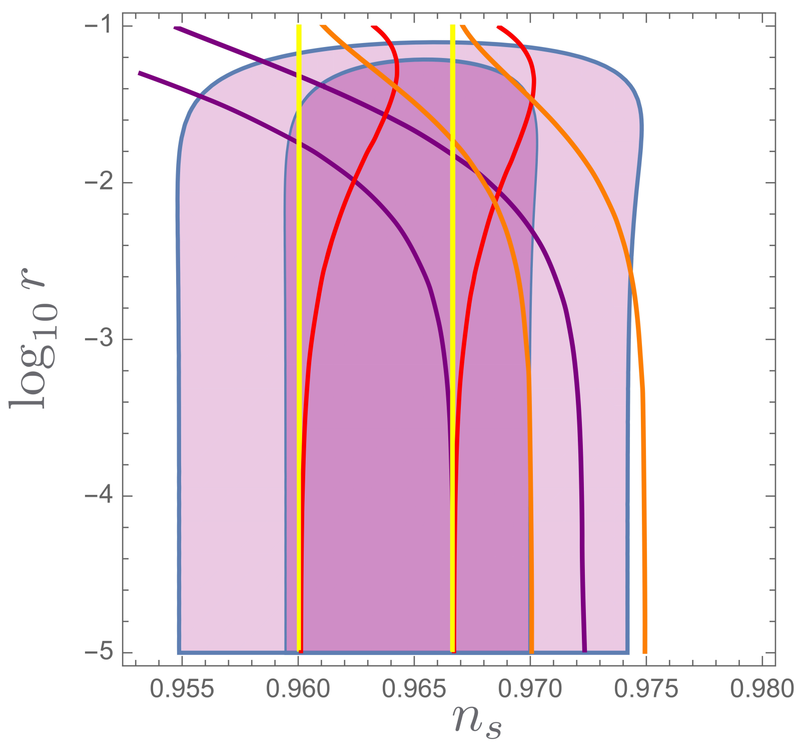
n_s precision data?

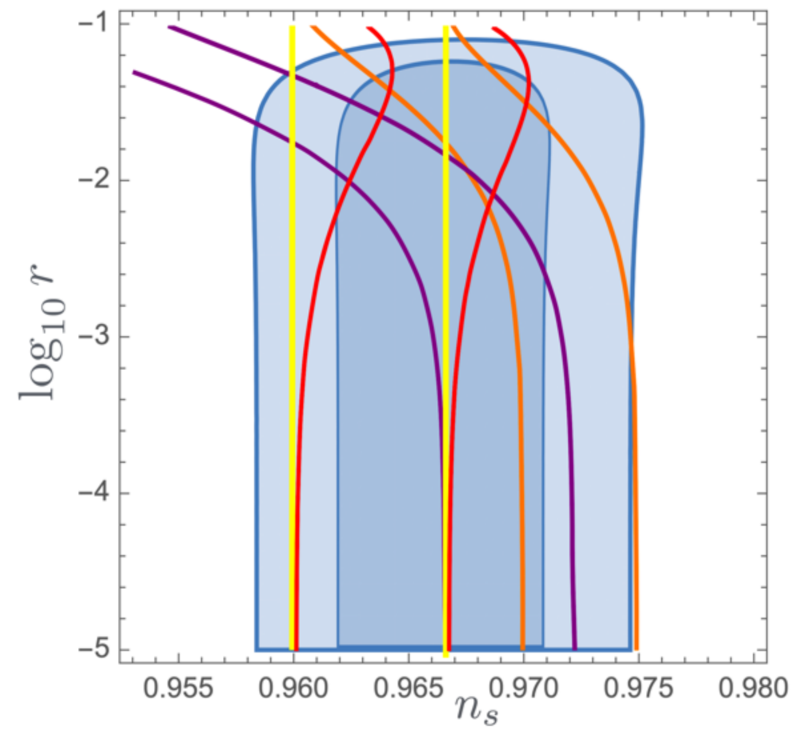
PICO: $\sigma(n_s) = 0.0015$

Which of the stripes will be the favorite?

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

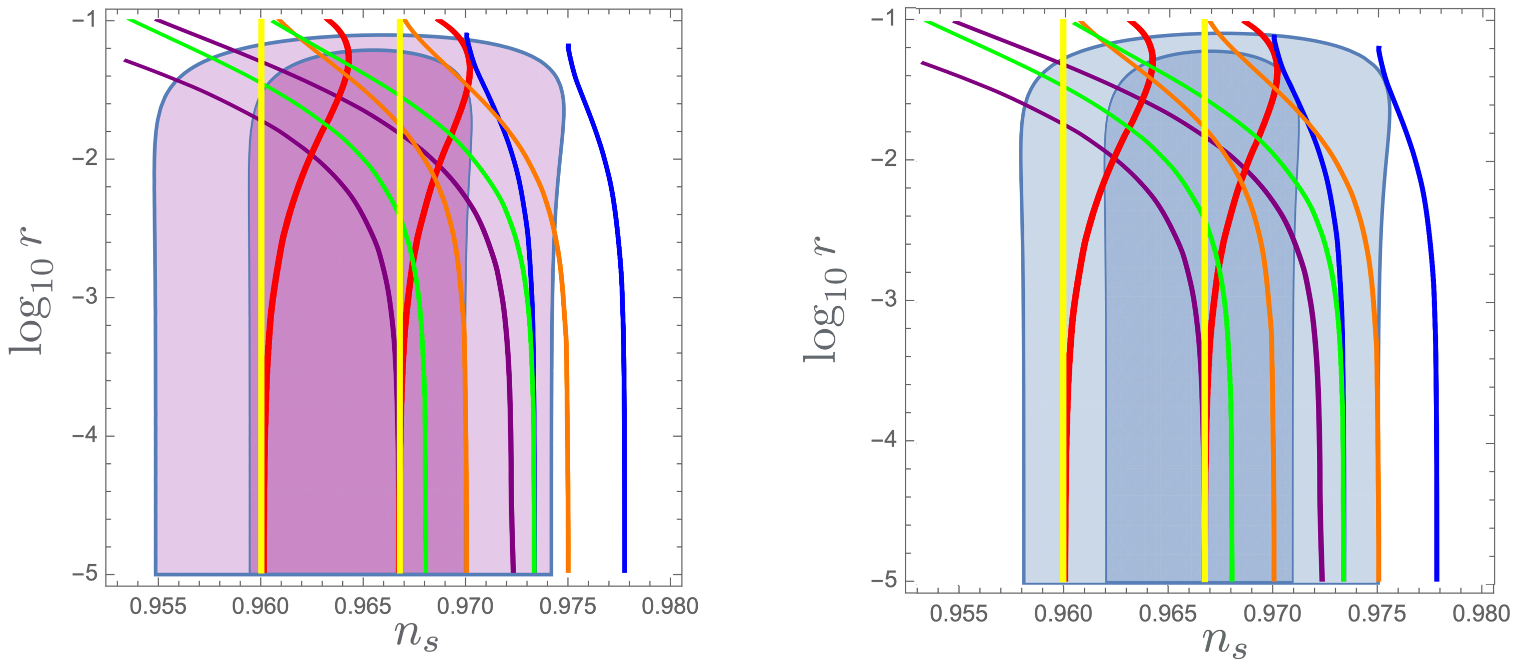
T-models, E-models and KKLTI models on Log r scale:





A combination of the simplest α-attractors and KKLTI models of Dp-brane inflation with p = 3 and p = 5 covers most of the area favored by Planck 2018, all the way down to r = 0.

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



α-attractors and KKLTI models of Dp-brane inflation with p = 3, 4, 5, 6 form a set of β – stripes, which become vertical at small r:

$$1 - n_s = \frac{\beta}{N}\,, \qquad \beta = 2,\ \frac{5}{3},\ \frac{8}{5},\ \frac{4}{3},\ \frac{3}{2}$$

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.

α-attractors and KKLTI models of D-brane inflation form a subclass of physically motivated (in SUGRA and string theory) models of pole inflation with

$$\mathcal{L} = \mathcal{L}_{\rm kin} - V = -\frac{1}{2}\frac{a_q}{\rho^q}(\partial\rho)^2 - V(\rho)$$

α-attractors correspond to pole inflation with q = 2 (supported by SUGRA)

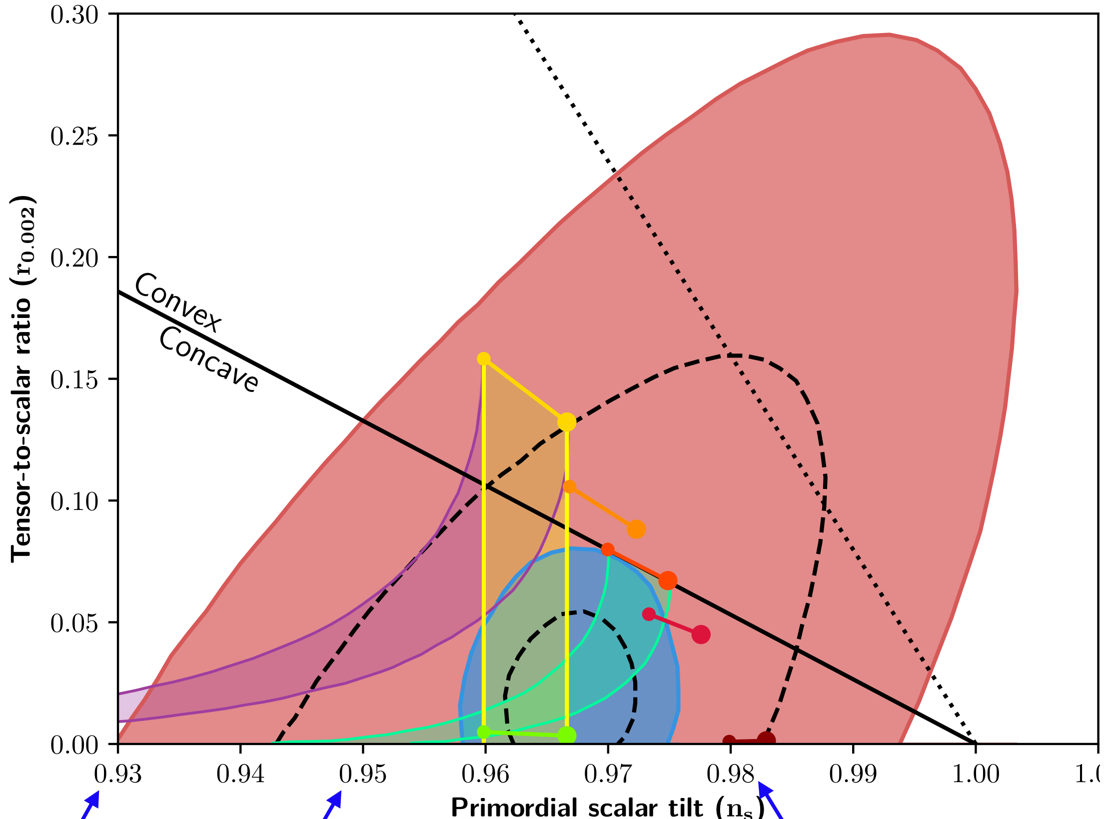
D-brane inflation form a subclass of physically motivated models of pole inflation with $q = \frac{5}{3}, \ \frac{8}{5}, \ \frac{4}{3}, \ \frac{3}{2}$

All of these models describe a set of $\beta -$ stripes with $1 - n_s = \frac{\beta}{N}$ where

$$\beta = \frac{q}{q-1}$$

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

Conclusions

Renata Kallosh and AL 1909.04687

- A combination of the simplest α-attractors and D-brane inflation models covers most of the area in the $(n_s,\, r)$ space favored by Planck 2018. For α-attractor models, there are discrete targets $3\alpha = 1, 2, ..., 7$, predicting 7 different values of $r = 12\alpha/N^2$ in the range $10^{-2} \gtrsim r \gtrsim 10^{-3}$.

- In the small r limit, α-attractors and D-brane inflation models describe vertical β-stripes in the $(n_s,\, r)$ space, with $n_s = 1 - \beta/N$, $\beta = 2, \frac{5}{3}, \frac{8}{5}, \frac{3}{2}, \frac{4}{3}$. A phenomenological description of these models and their generalizations can be achieved in the context of pole inflation.

- Future precision data on n_s may help to discriminate between these models even if the precision of the measurement of r is insufficient for the discovery of gravitational waves produced during inflation.