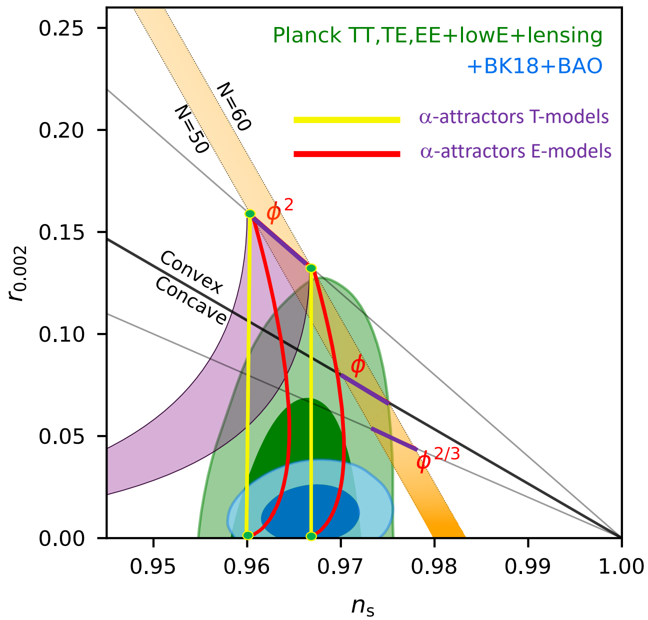
Inflationary Cosmology 2025:

Where is n_s and how low r can go?

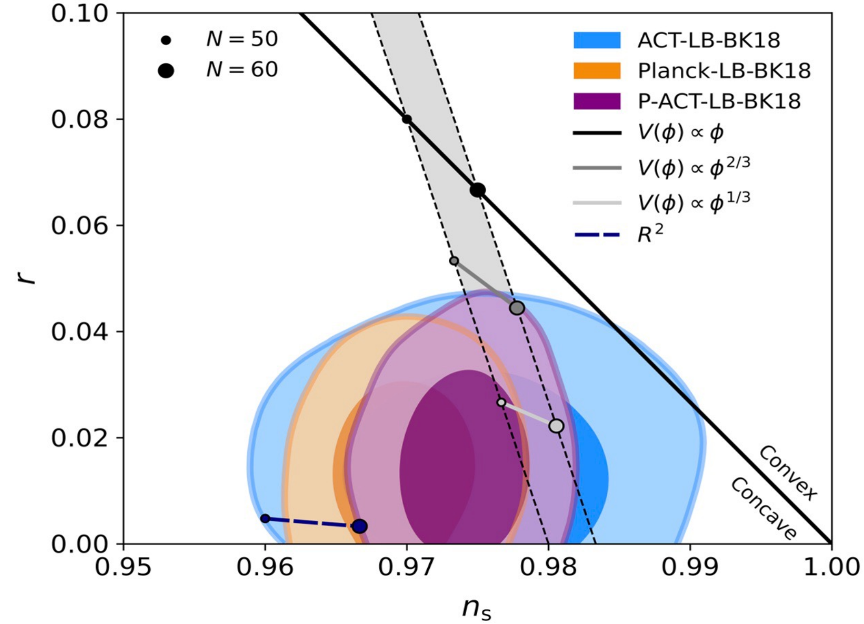
Andrei Linde

Where is n_s?

Planck/BICEP/Keck 2021



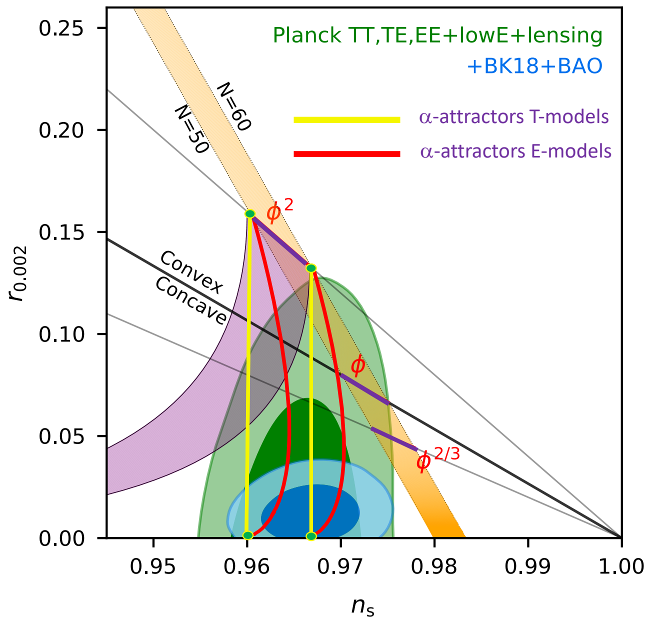
P-ACT-LB-BK18



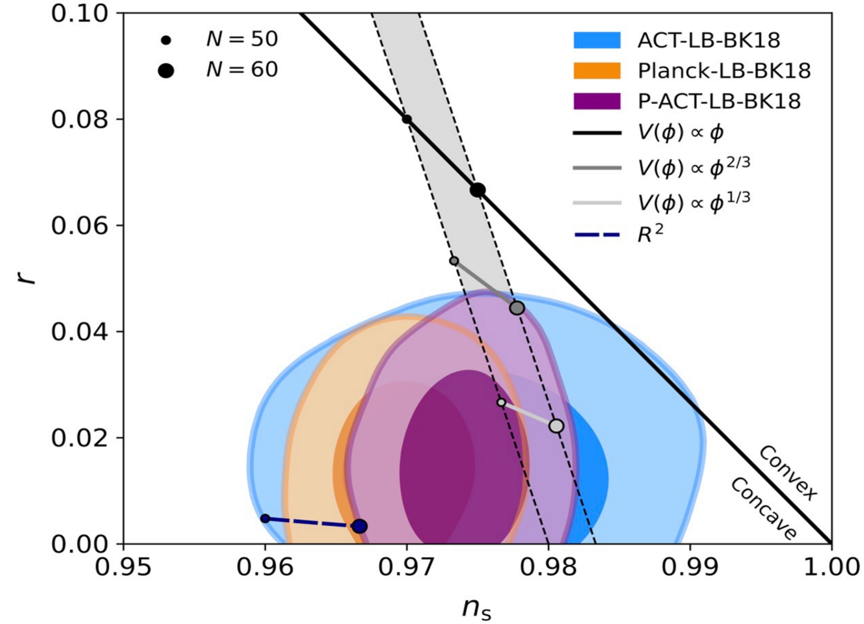
Planck	0.9666 ± 0.0077
P-ACT	0.9709 ± 0.0038
P-ACT-LB	0.9743 ± 0.0034

Where is n_s?

Planck/BICEP/Keck 2021



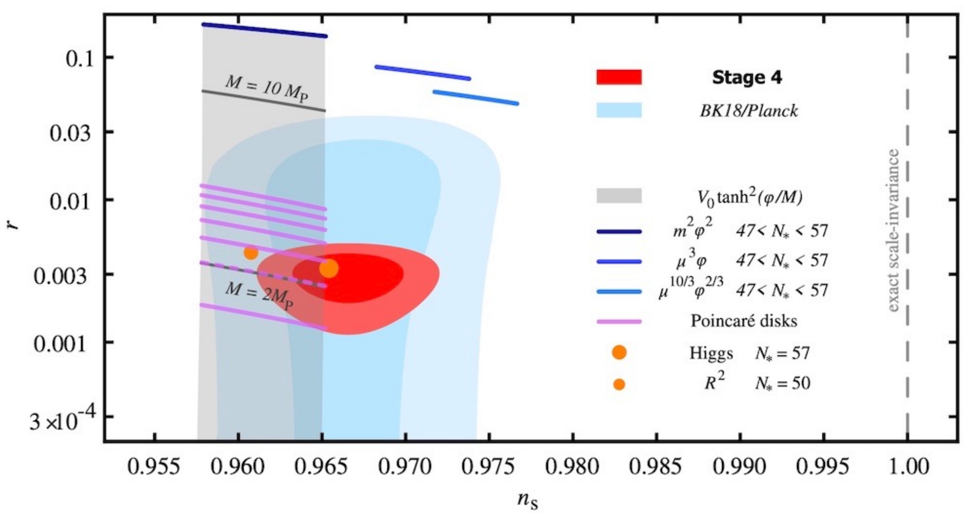
P-ACT-LB-BK18

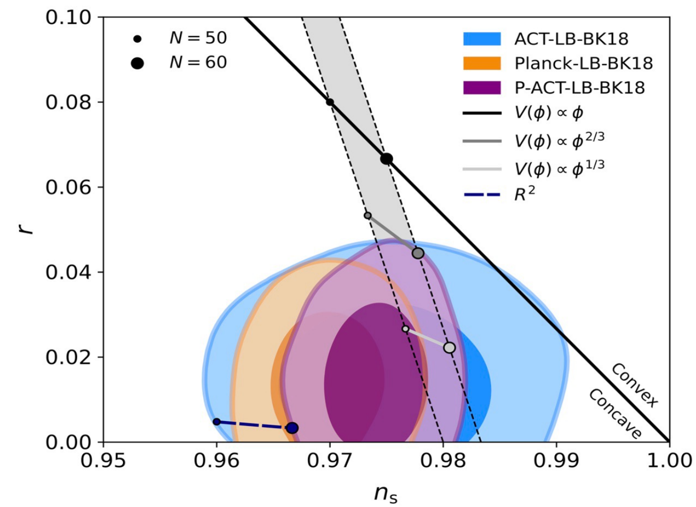


Planck	$0.9\underline{666} \pm 0.0077$
P-ACT	$0.9\underline{709} \pm 0.0038$
P-ACT-LB	$0.9\underline{743} \pm 0.0034$

Is it "just a small shift"?

CMB-S4 and LiteBIRD figures do not show any targets with $n_s > 0.965$

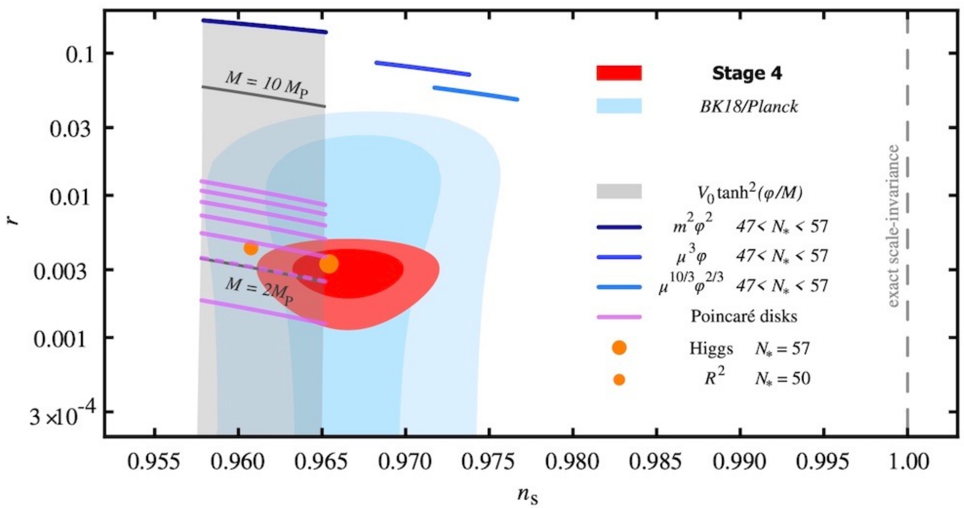


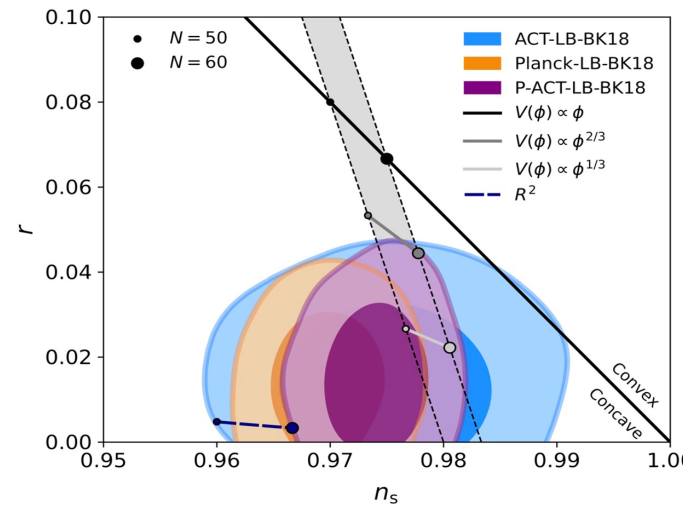


P-ACT-LB n_s=0.9743 ± 0.0034

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 $\mathbf{n_s > 0.965}$

CMB-S4 and LiteBIRD figures do not show any targets with $n_s > 0.965$





P-ACT-LB $n_s = 0.9743 \pm 0.0034$

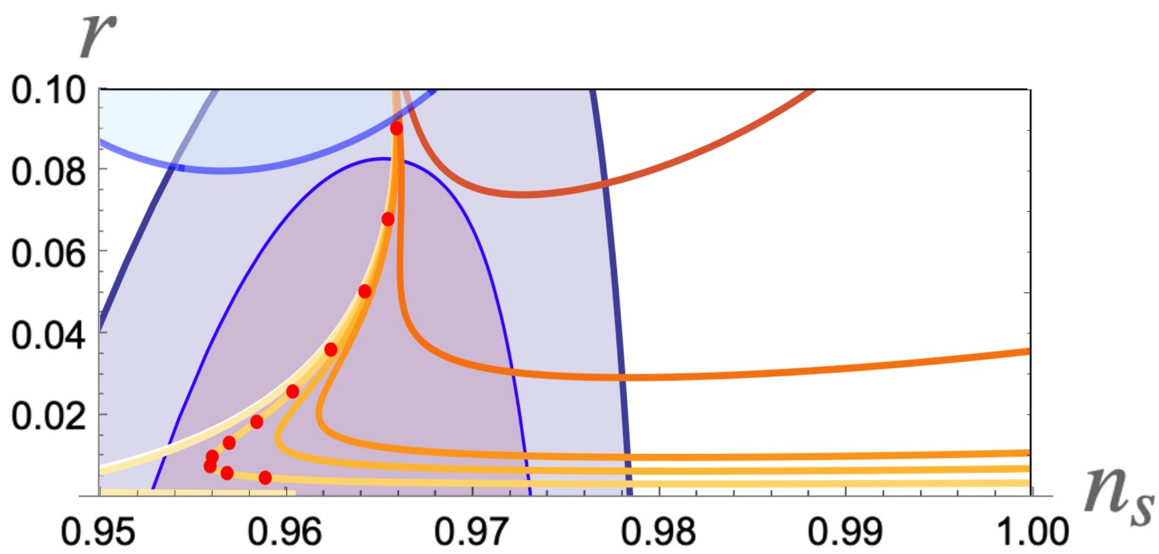
Before discussing **r** we have to understand that ACT shift of $\mathbf{n_s}$ to the right, **if correct**, is highly significant. As we will see, it disfavors inflationary models with an **exponential** approach to plateau with $\mathbf{n_s \sim 0.965}$ and favors models with a **power-law** approach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

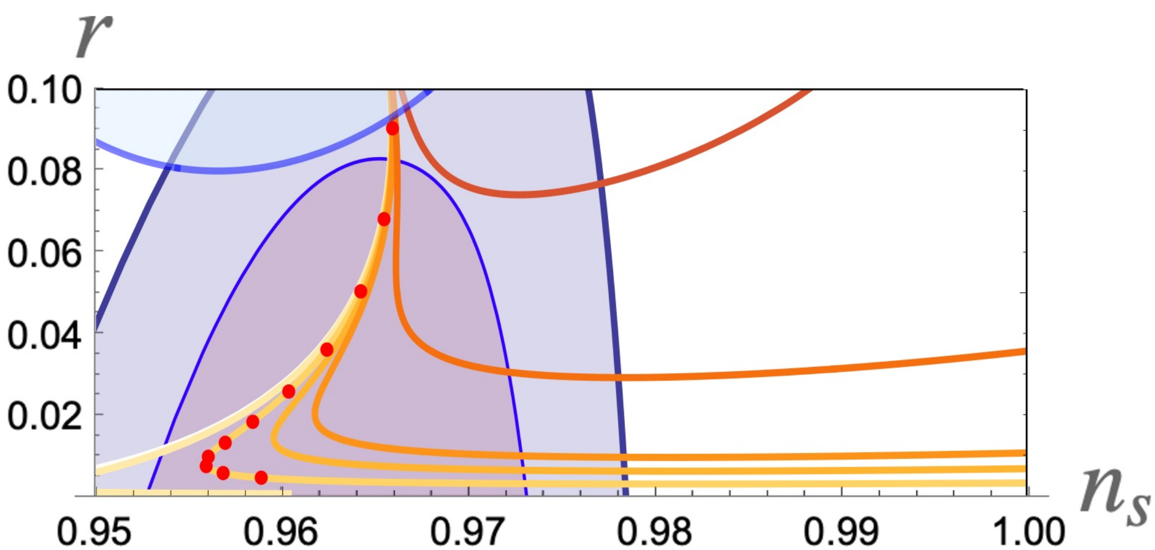


Example: For **b** = 0.34, we have **r** = 0.01. By increasing **a** from 0.13 to 0.17, we move from $\mathbf{n_s}$ = 0.967 (Planck) to 0.974 (ACT), and all the way to $\mathbf{n_s}$ = 1.

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

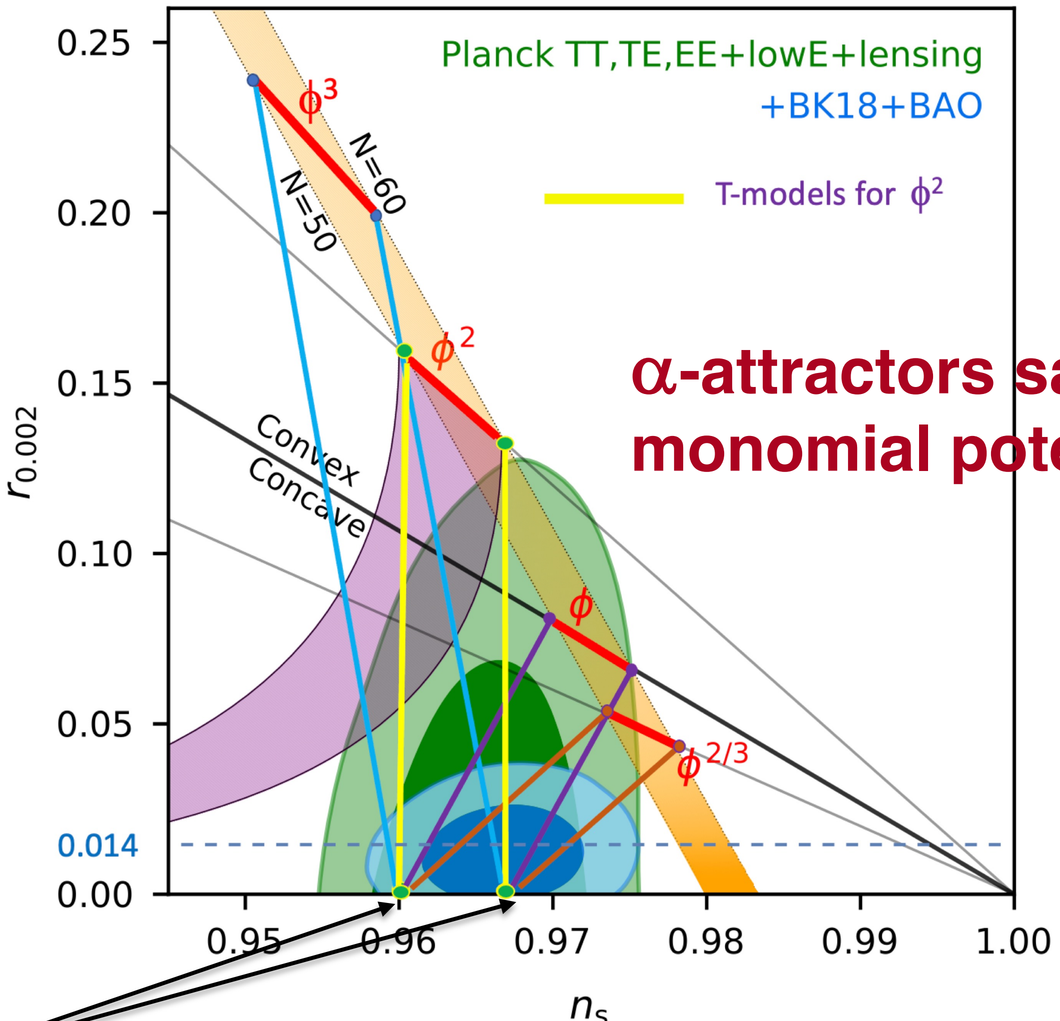
$$V = \frac{m^2\phi^2}{2}(1 - a\phi + b(a\phi)^2)^2$$

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



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

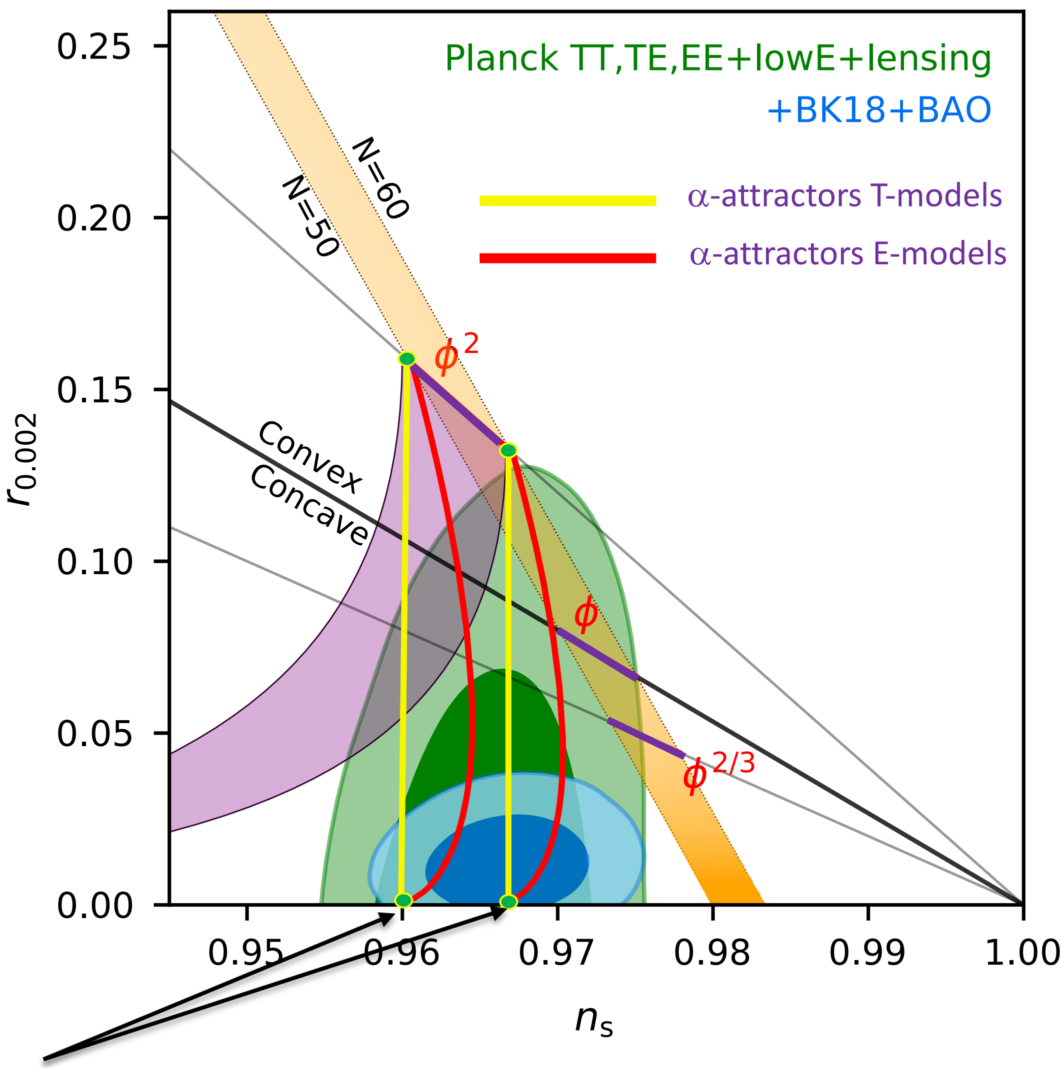
Predictions for n_s in α-attractor models at $\alpha < O(1)$ practically do not depend on the choice of the potential



α-attractors saving monomial potentials

Starobinsky model and **Higgs inflation**

Planck2018 – BICEP/Keck2021 constraints

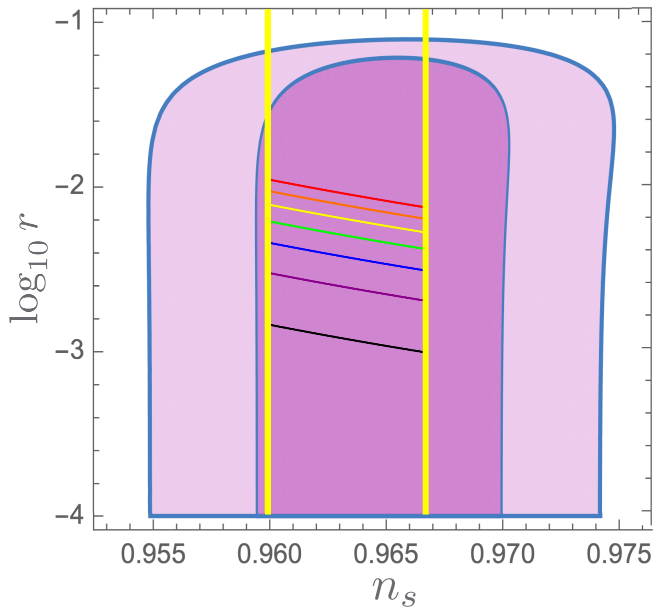


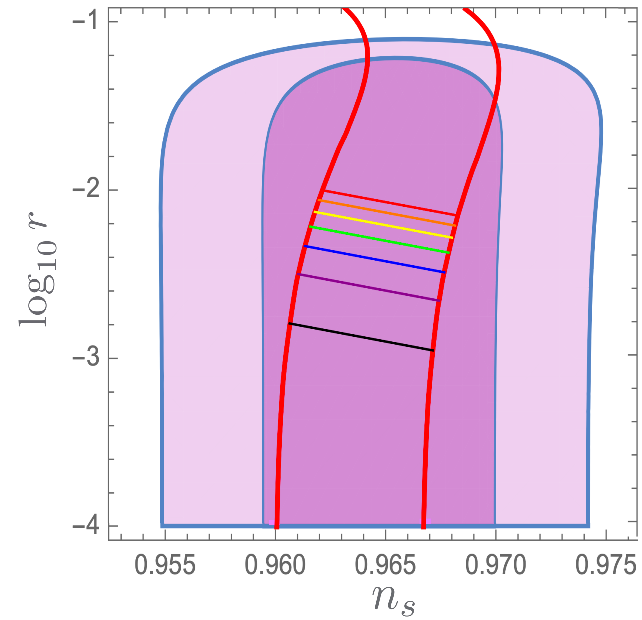
Starobinsky model and **Higgs inflation**

Benchmarks for T-models and E-models

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

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





String theory interpretation of **7 discrete targets for α-attractors**

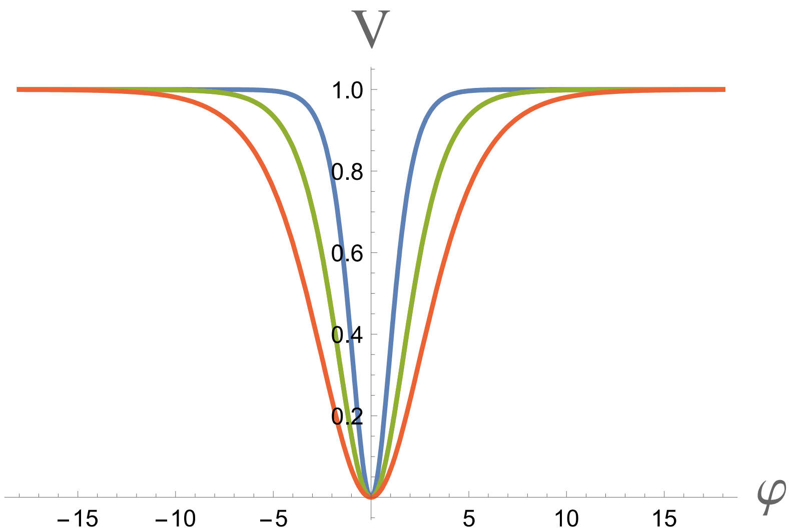
$$3\alpha = 1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7$$

Ferrara, Kallosh 1610.04163

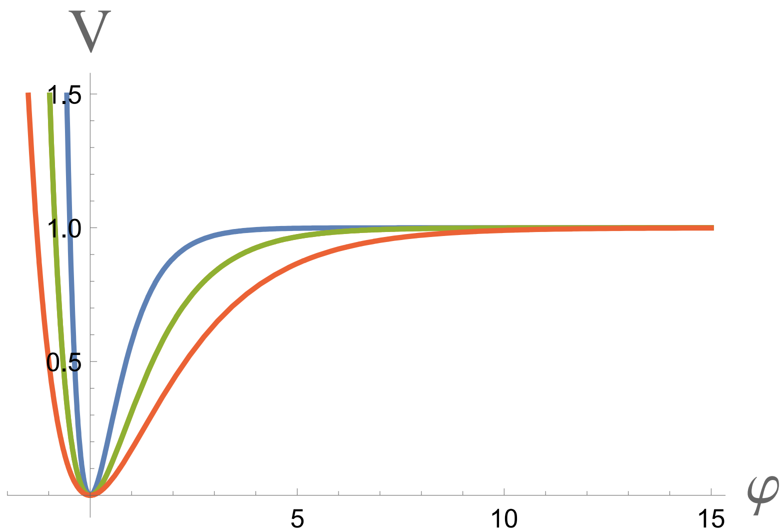
Kallosh, A.L., Wrase, Yamada 1704.04829

Interesting range: $r = 10^{-2} - 10^{-3}$

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



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



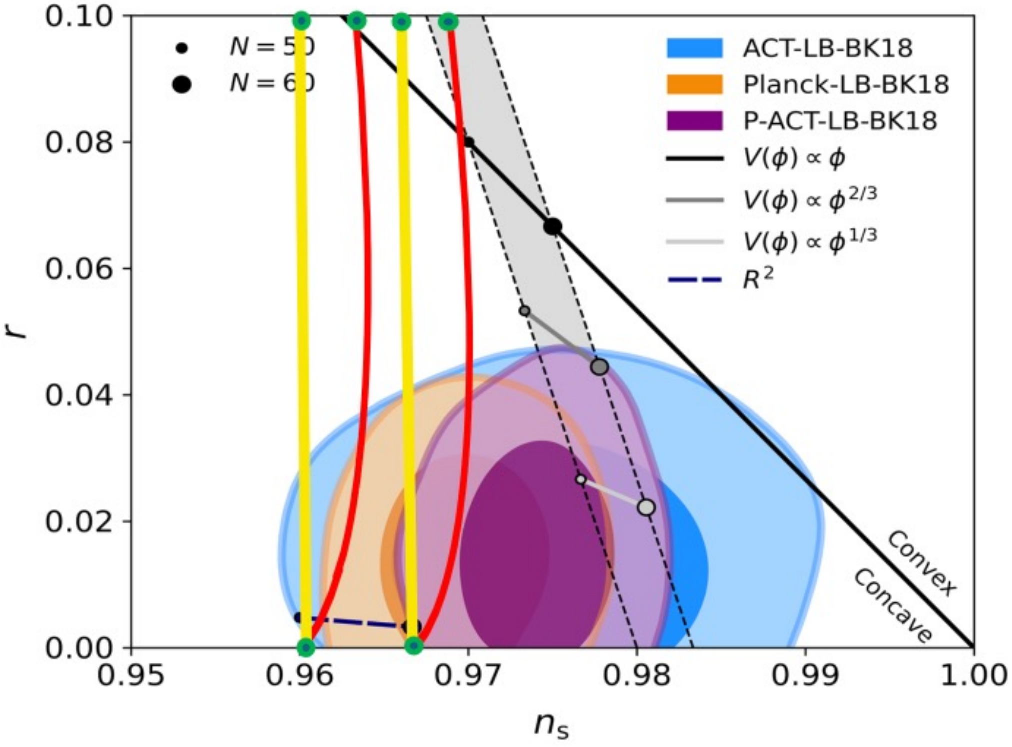
$$\boxed{n_s = 1 - \frac{2}{N_e}\,, \qquad r = \frac{12\alpha}{N_e^2}}$$

Exponential approach to the plateau

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

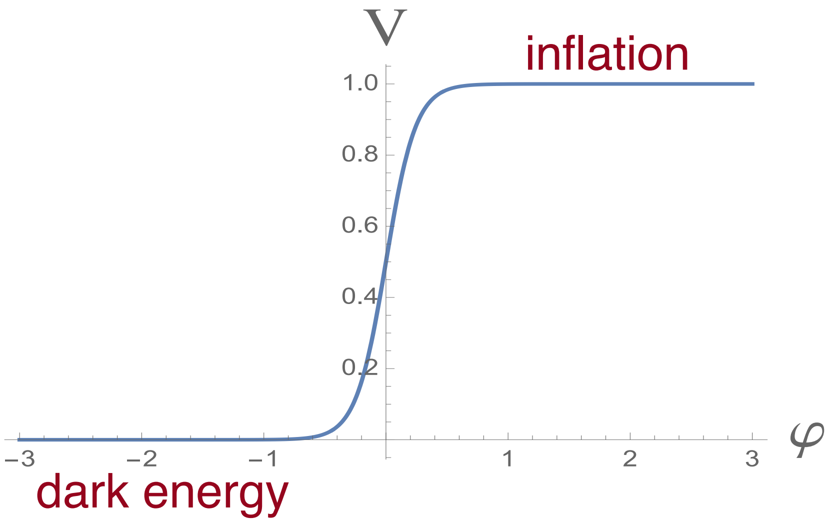
CMB-S4 and LiteBIRD targets and P-ACT-LB

P-ACT-LB:
n_s=0.9743 ± 0.0034



E-models of α-attractors (red lines) are compatible with P-ACT, but only marginally compatible with P-ACT-LB, depending on details of reheating.

Increasing N_e and n_s in quintessential α-attractors



In models of quintessential α-attractors, the transition from inflation to dark energy domination goes through a long stage of reheating with domination of kinetic energy (kination) with equation of state $w \sim 1$

$$N_e = \cdots + \frac{1-3w}{12(1+w)} \ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right)$$

This may lead to an increase of N_e by about 10, as compared with the standard reheating during oscillations with w = 0. As a result, n_s may increase by about 0.006.

Depending on the model, one can end up in a state dominated by a small cosmological constant or by a dynamical dark energy.

1703.00305, 1712.09693

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

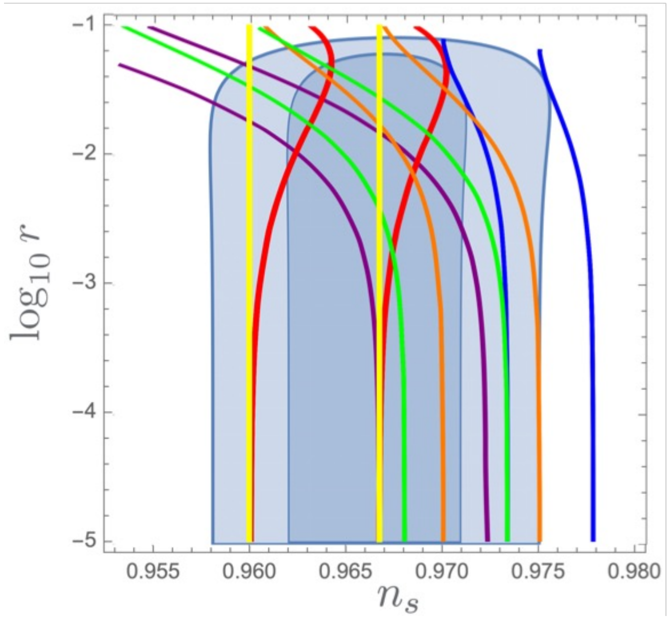
Power-law approach to the plateau

$$V = V_0\Big(1 - \frac{m^k}{\varphi^k} + \ldots\Big)$$

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

Example:

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



These models can cover a wide range of n_s

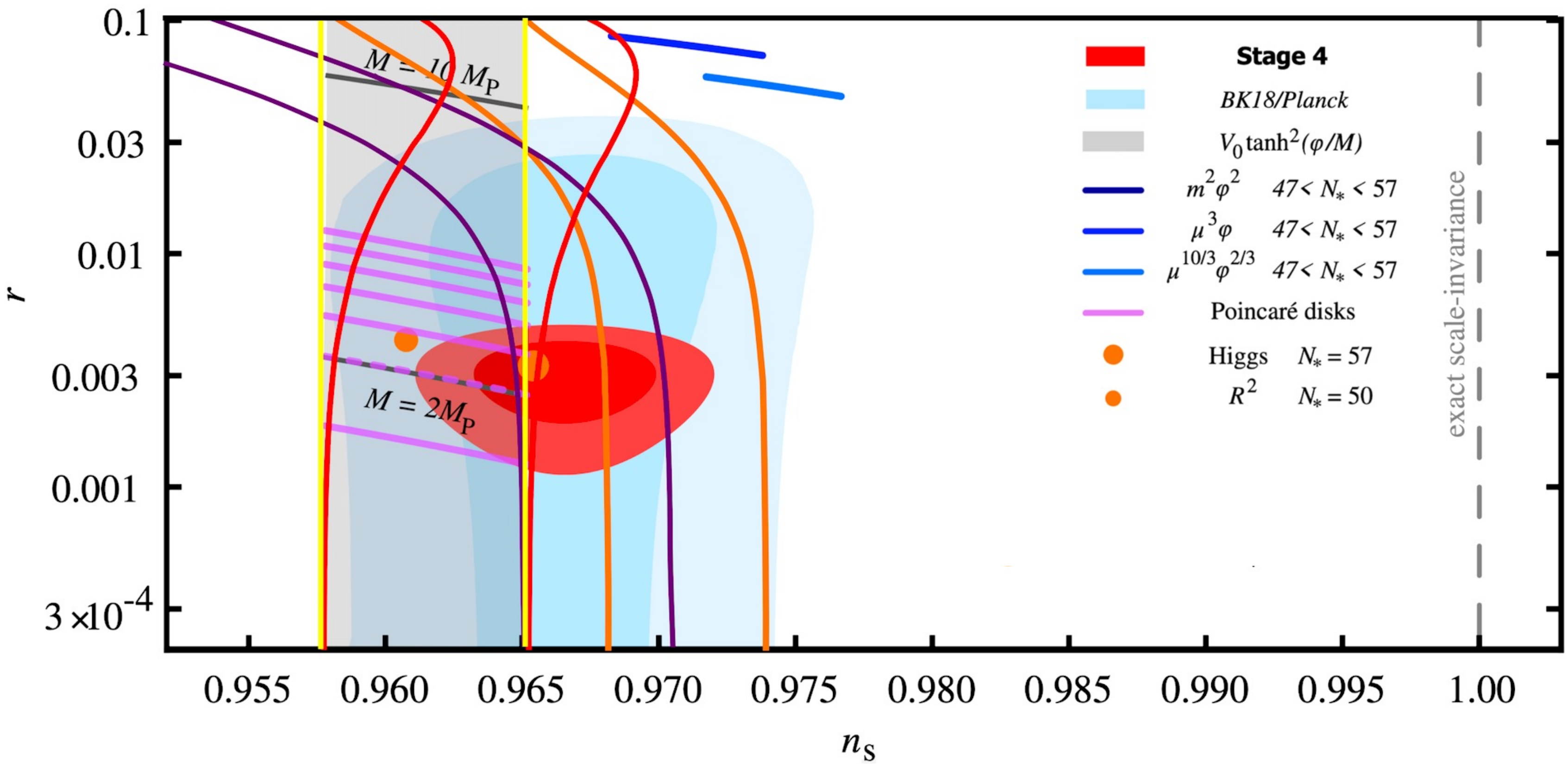
$$1 - \frac{2}{N_e} < n_s < 1 - \frac{1}{N_e}$$

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

Fully compatible with ACT

CMB-S4 and LiteBIRD

Snowmass2021 Cosmic Frontier + power law attractors

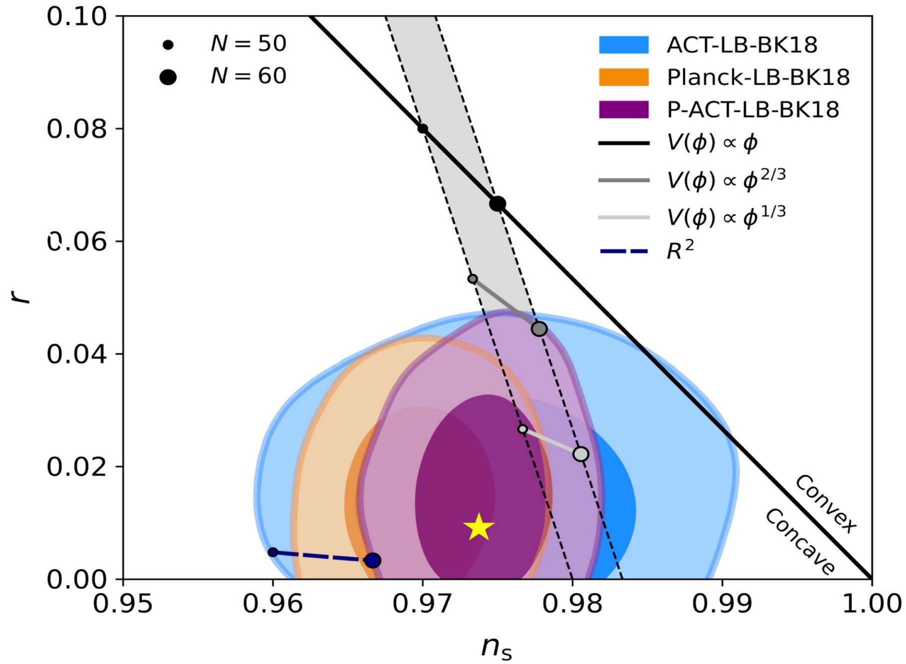


The gray area shows predictions of T-models. The two red lines show predictions of E-models. The purple and orange lines correspond to the polynomial α-attractors $\frac{\varphi^4}{\varphi^4+\mu^4}$ and $\frac{\varphi^2}{\varphi^2+\mu^2}$. These models completely cover the dark blue area favored by Planck/BICEP/Keck

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



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

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

String theory inflation

M. Cicoli, J.P. Conlon, A. Maharana, S. Parameswaran, F. Quevedo and I. Zavala, *String cosmology: From the early universe to today*, *Phys. Rept.* **1059** (2024) 1 [2303.04819].

String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ Inflation	0.968	10^{-7}
Inflection Point Inflation	0.923	10^{-6}
D3-D7 Inflation	0.981	10^{-6}
Racetrack Inflation	0.942	10^{-8}
Volume Inflation	0.965	10^{-9}
DBI Inflation	0.923	10^{-7}

String theory inflation

M. Cicoli, J.P. Conlon, A. Maharana, S. Parameswaran, F. Quevedo and I. Zavala, *String cosmology: From the early universe to today*, *Phys. Rept.* **1059** (2024) 1 [2303.04819].

UPDATED

String model	n_s	r
Fibre Inflation	0.963	0.007
Blow-up Inflation	0.965	2×10^{-5}
Poly-instanton Inflation	0.958	10^{-5}
~~Aligned Natural Inflation~~	~~0.960~~	~~0.098~~
~~*N*-Flation~~	~~0.960~~	~~0.13~~
Axion Monodromy	0.978	0.044
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ Inflation	0.968	10^{-7}
~~Inflection Point Inflation~~	~~0.923~~	~~10^{-6}~~
D3-D7 Inflation	0.981	10^{-6}
~~Racetrack Inflation~~	~~0.942~~	~~10^{-8}~~
Volume Inflation	0.965	10^{-9}
~~DBI Inflation~~	~~0.923~~	~~10^{-7}~~

String theory inflation

1) **If tensor modes are found** with $\mathbf{n_s}$ = 0.963 and **r** = 0.007, it will be a triumph of Fibre Inflation, and α-attractors with $\alpha = 2$, which make the same prediction. (This option matches Planck, but is in tension with ACT.)

2) **If tensor modes are found** with ANY **r** smaller than the ACT bound 0.038 but different from 0.007, it will be a triumph of inflationary cosmology, but it will rule out ALL string inflation models mentioned above and discussed at the conference Strings 2025.

This is yet another argument for the search for inflationary tensor modes.

Conclusions

1) Precise measurement of n_s can distinguish between the models with exponential or power-law approach to a plateau.

2) Tensor to scalar ratio r can take any value, all the way down to zero, but there is a series of interesting discrete values of r in the range $10^{-2} – 10^{-3}$.

3) <u>If tensor modes are found</u> with any r below the ACT bound 0.038, but different from ~0.007, it will rule out ALL available string inflation models.

For a more detailed discussion, see
Kallosh, AL, 2505.13646