String Inflation

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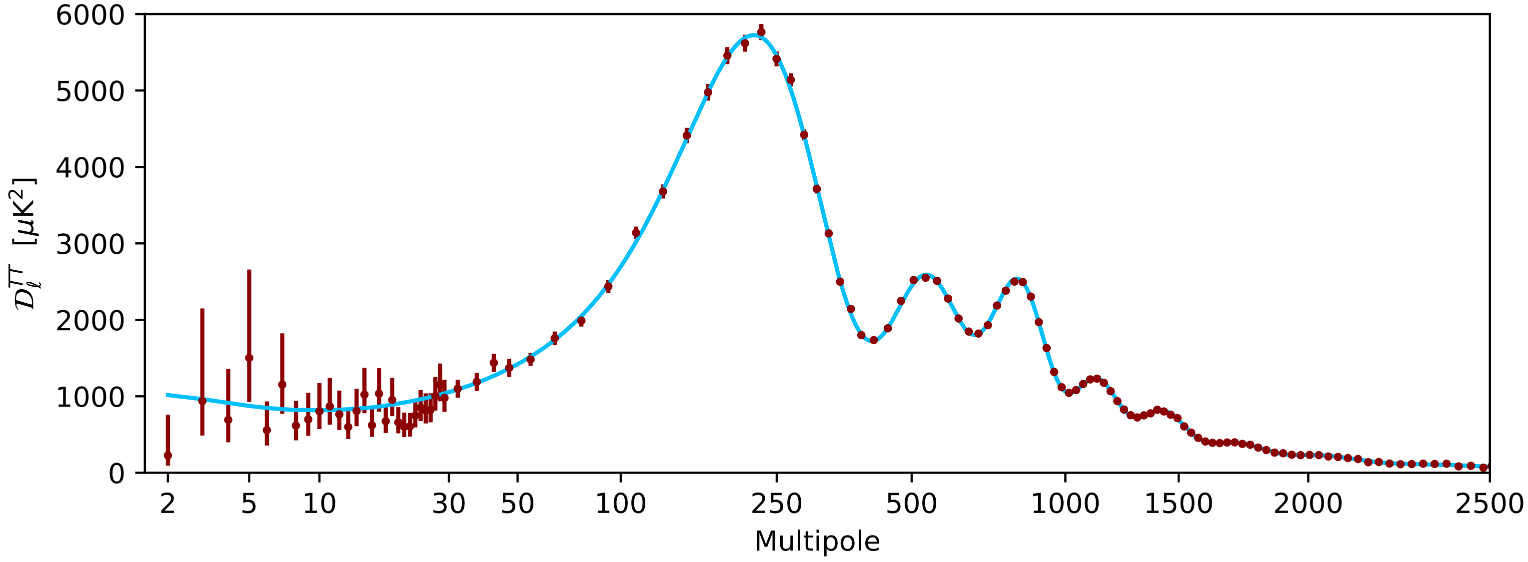
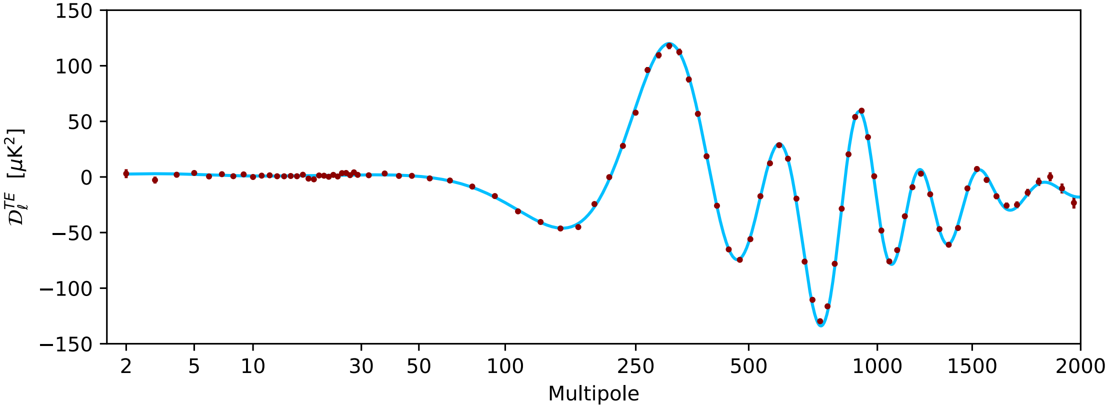
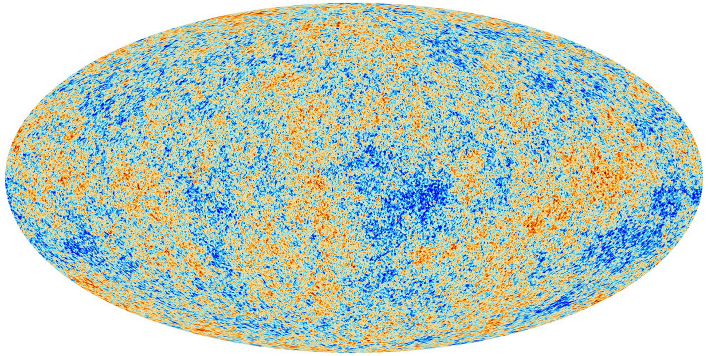
SUSY 2021

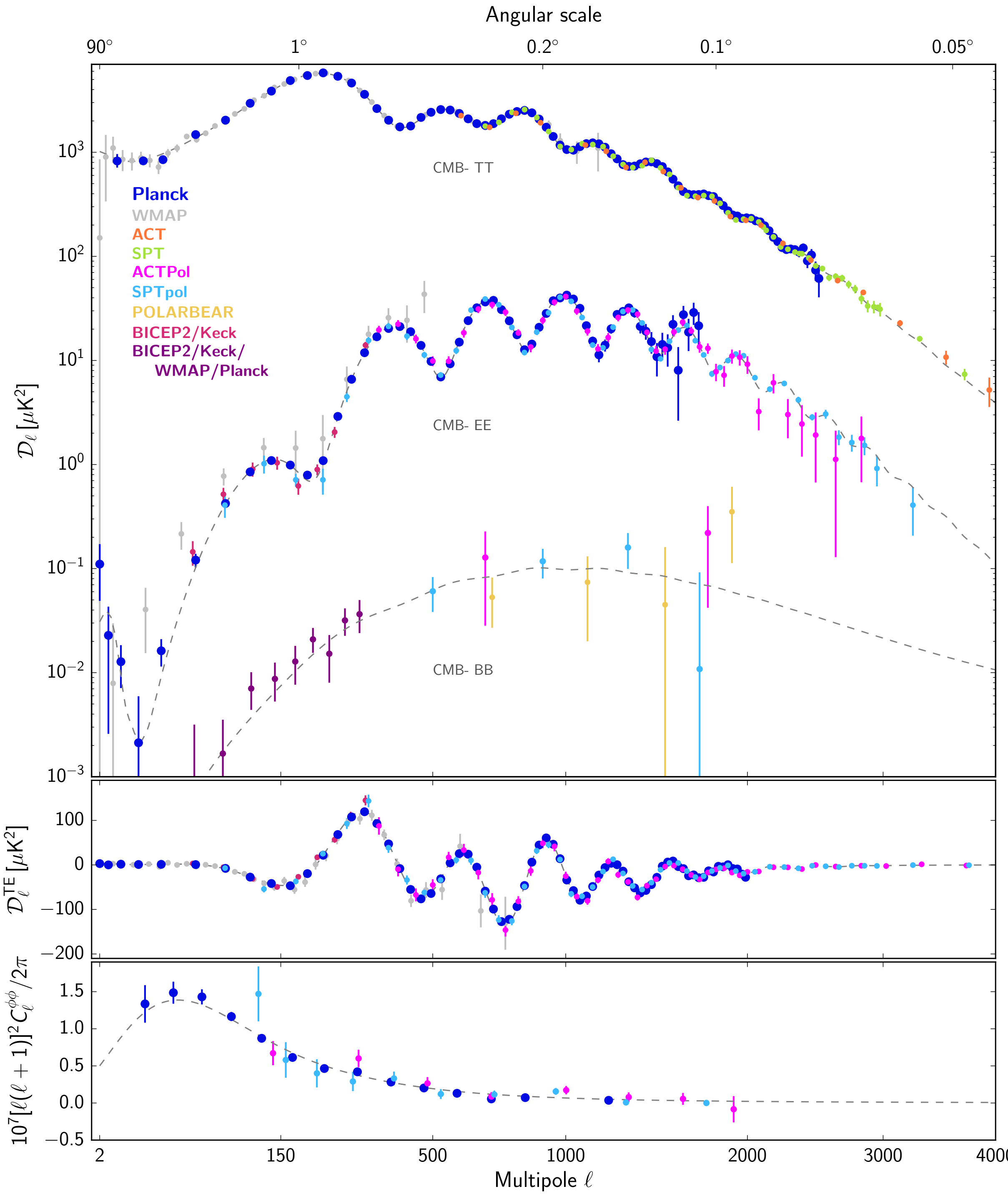
2013-2019	BK15/Planck
2021, August 9-13	CMB-S4
	BK18 ?
2028-2029	Future missions

Theoretical physics
vis-à-vis
cosmological data on inflation







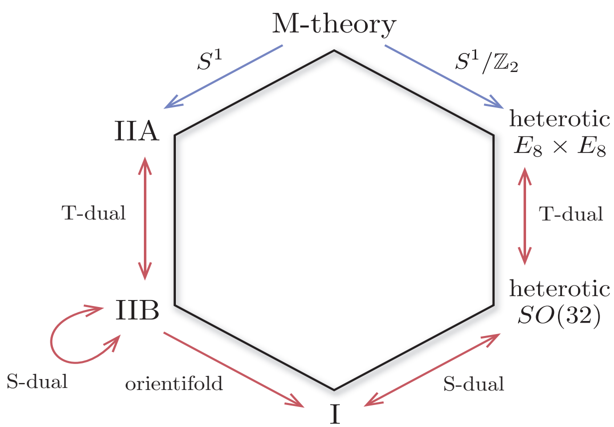

Angular scale
90°
1°
0.2°
0.1°
0.05°
CMB- TT
CMB- EE
CMB- BB
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/
WMAP/Planck
$\mathcal{D}_\ell\,[\mu\mathrm{K}^2]$
$\mathcal{D}_\ell^{\mathrm{TE}}\,[\mu\mathrm{K}^2]$
$10^7[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
Multipole ℓ

Inflation and String Theory

textbook

Baumann, McAllister

2015



From Worldsheet to Spacetime

UV completion ?

String Inflation After Planck 2013

Burgess, Cicoli, Quevedo 1306.3512

TASI lectures on cosmological observables and string theory Silverstein 1606.03640

CMB targets after Planck 2018 RK, Linde 1909.04687

Supergravity limit of **critical superstring theory**.—The low-energy limit is a D=10 supergravity theory with local sources, D-branes and O-planes. Compactification to D=4 supergravity to explain the observations

Cosmology/supergravity talks at this conference:

Microscopic description of brane gauginos, talk by Shiu

Challenges in supersymmetric cosmology, talk by Antoniadis

On anomalous production of slow gravitinos in minimal supergravity inflation and its resolution, talk by Terada

Gravitino production during inflation, talk by Sorbo

String cosmology can be also studied without supersymmetry. **Non-critical string theory** D-10 $\neq 0$ see talk by Silverstein on (Non-)SUSY 2021 and Cosmology

String Inflation After Planck 2013

Burgess, Cicoli, Quevedo

Most models of string inflation either are already ruled out by n_s or have a very small r, will not be tested during the next decades

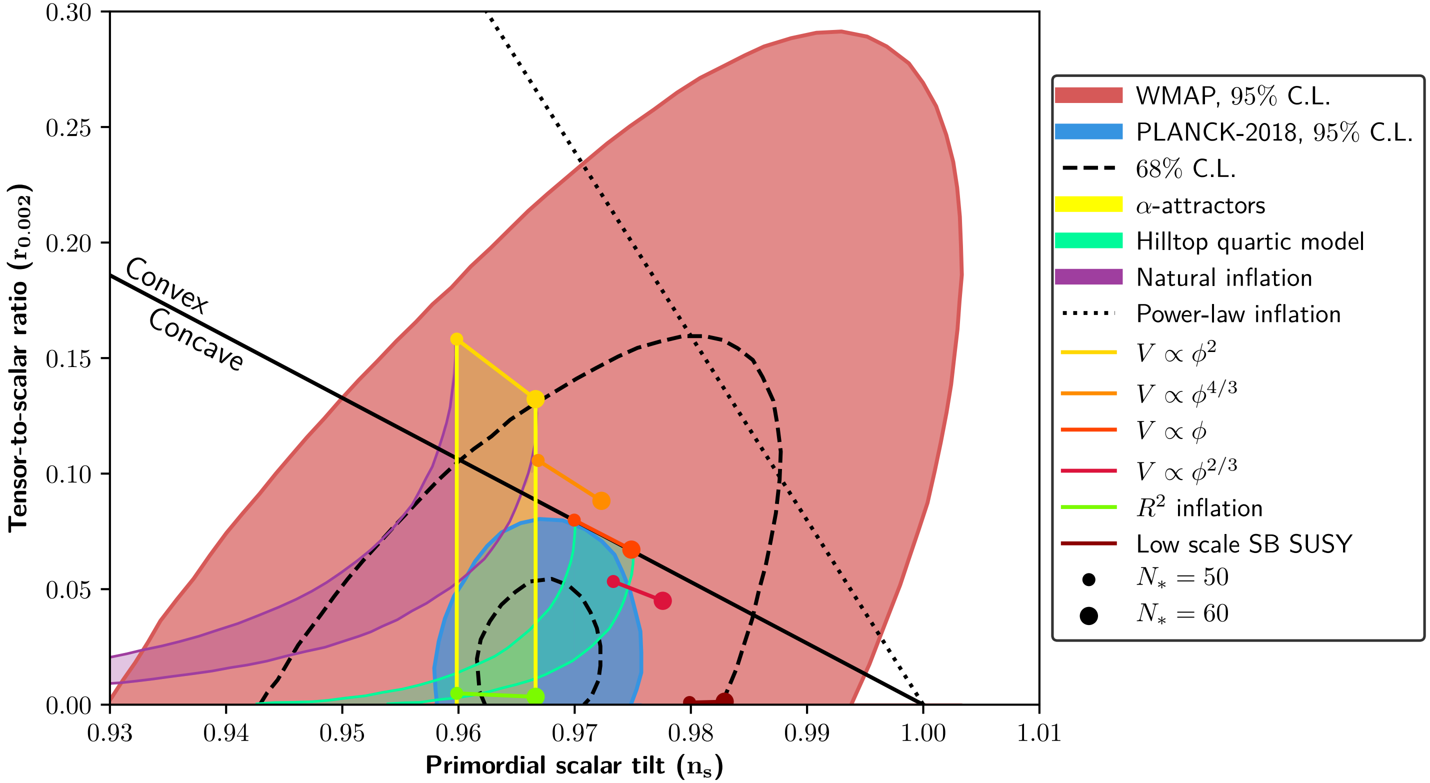
String Scenario	n_s	r	
D3/$\overline{\text{D3}}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$	r very small
Inflection Point Inflation	$\cancel{0.92 \leq n_s \leq 0.93}$	$r \leq 10^{-6}$	r very small
DBI Inflation	$\cancel{0.93 \leq n_s \leq 0.93}$	$r \leq 10^{-7}$	r very small
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$	r very small
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$	r very small
Racetrack Inflation	$\cancel{0.95 \leq n_s \leq 0.96}$	$r \leq 10^{-8}$	r very small
N − flation	$\cancel{0.93 \leq n_s \leq 0.95}$	$\cancel{r \leq 10^{-3}}$	r=0.13
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$	Testable soon
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$	r very small
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$	Testable
Poly − instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$	r very small

arXiv:2010.01139v2 **[astro-ph.CO]**

r < 0.44 at 95% CL

Early Universe, CMB: PLANCK 2018 versus WMAP 2010

(after billion dollars spent)



~~2004 Racetrack~~
~~Inflation in String theory~~

$\cancel{n_s \leq 0.95}$

~~1994 F-term, 1996 D-term Inflation in supergravity~~
~~D3/D7 model in String theory, 2007~~

$\cancel{n_s \approx 0.98}$

2018

~~2003 KKLMMT~~
~~2010 inflection model~~

$\cancel{n_s \leq 0.93}$

~~2005 N-flation~~

~~r=0.13~~

One of the ways to explain flatness of the potentials in inflationary theory is to start with the theory with shift symmetry. The famous example is the shift symmetry of the axion potential, which may lead to realization of the natural inflation scenario, or of the axion monodromy scenario.

These mechanisms do not require supersymmetry.

Yet another possibility is to use Goldstone shift symmetry of supersymmetric flat directions in supergravity, and then uplift these flat directions to plateau inflationary potentials. They might correspond to saxion flat directions.

When the nilpotent multiplet is present, we can build such models in string theory inspired supergravity. These are known as α-attractors.

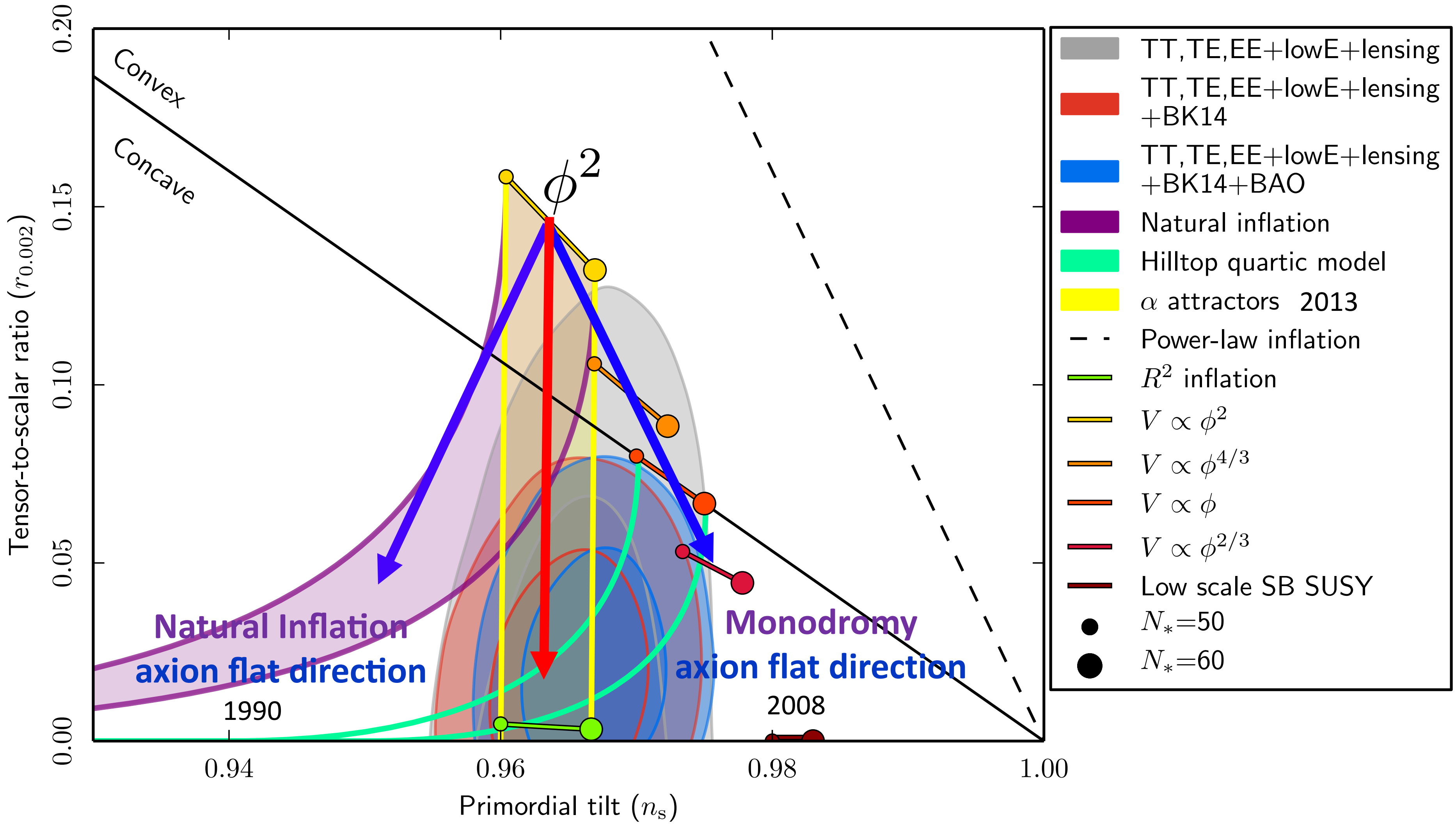
Also in Fiber inflation, Higgs and R^2 inflation, the inflaton is a scalar, not a pseudoscalar.

In early supergravity inflation models, starting with Kawasaki, Yamaguchi, Yanagida, 2000, it was realized that an extra superfield in addition to an inflaton multiplet, is a tool for model building.

It become even more clear now that the nilpotent chiral multiplet, representing Volkov-Akulov supersymmetry/anti-D3 brane in string theory, is a powerful tool in cosmology to describe both dark energy and inflation.

Planck 2018

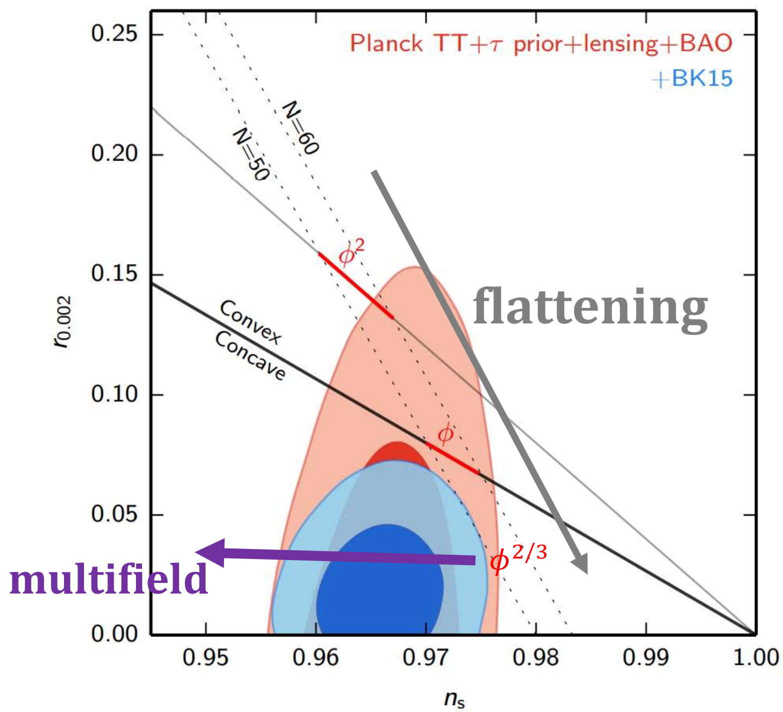
α-attractors, Starobinsky, Higgs, fiber inflation
saxion flat direction: **plateau potentials**



Silverstein Strings **2021** slide

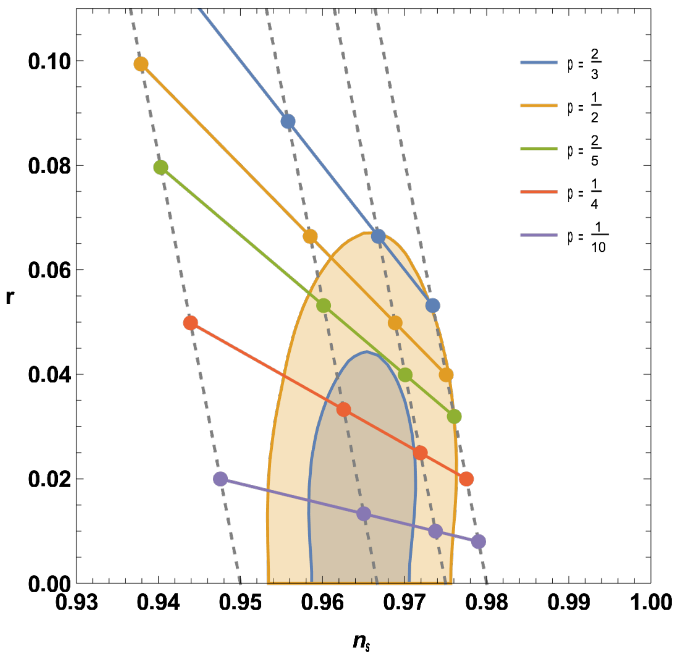
Comments on observables:

r, n_s: flattening and multifield effects



Integrating out heavy fields flattens V (energetics)

Dong et al, Dimopoulos et al,..., Wenren (before data)



Double Monodromy Inflation arXiv:2101.05861

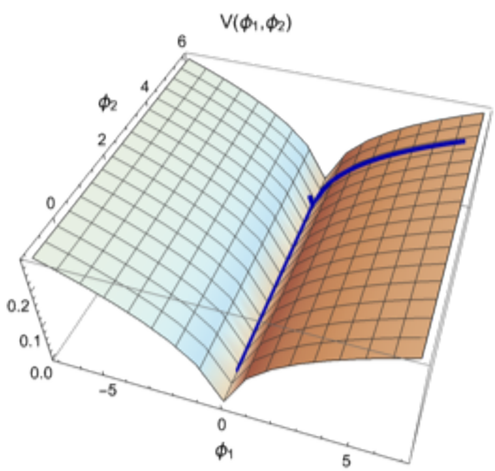
Rollercoaster Cosmology arXiv:2011.09489

D'Amico, Kaloper and Westphal

A short rollercoaster cosmology based on two stages of monodromy inflation separated by a stage of matter domination, generated after the early inflaton falls out of slow roll

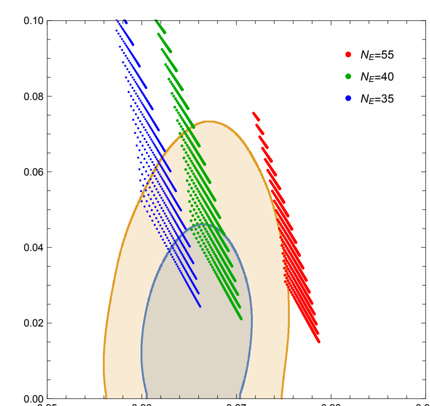
The blobs correspond to,from left to right,N =20, N =30, N =40 and N =50 e-folds before the end of the 1st accelerating stage

Two-stage inflationary trajectory, where the field ϕ_1 slides down the slope first, oscillates while decaying near the bottom of the "gutter", and then ϕ_2 starts to move along the "gutter".



If the **first stage** is controlled by a flat potential, $V \sim \phi^p$ with $p < 1$ and lasts **N ~ 30 – 40 e-folds**, the scalar and tensor perturbations at the largest scales will fit the CMB perfectly, and produce relic gravity waves with $0.02 < r < 0.06$

$$\phi^{\frac{1}{10}}, \phi^{\frac{1}{4}} \quad ?$$

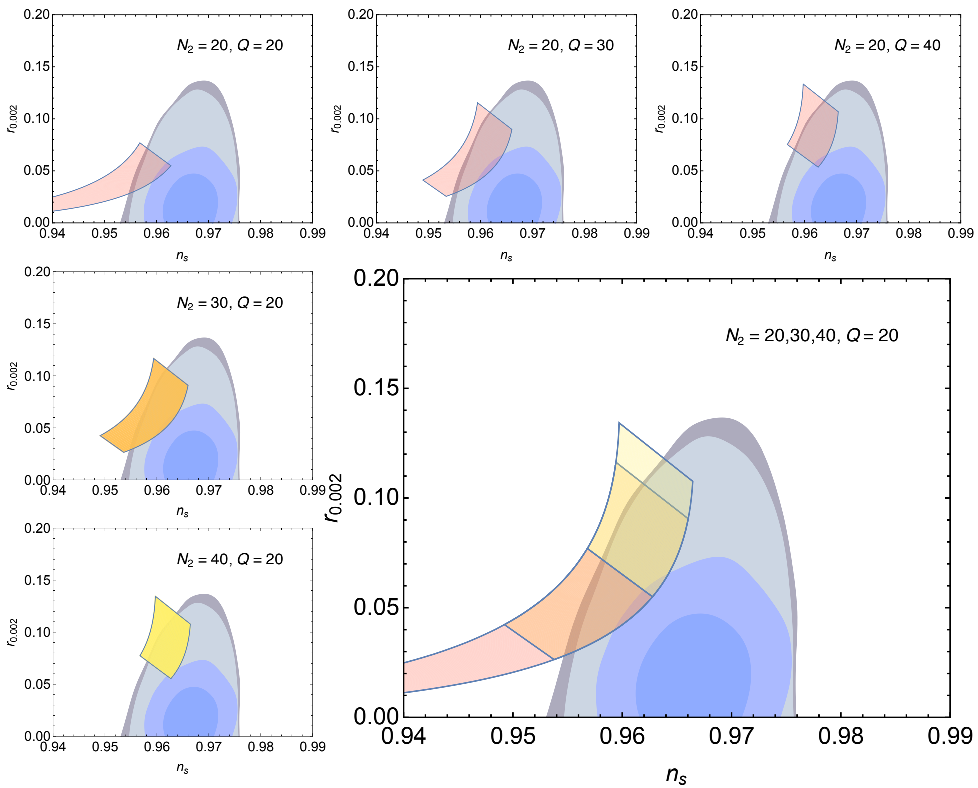


Aligned Natural Inflation in the Large Volume Scenario

arXiv:2106.09853

Stephen Angus, Kang-Sin Choi, and Chang Sub Shin

We embed natural inflation in an explict string theory model and derive observables in cosmology. We achieve this by compactifying the type IIB string on a Calabi–Yau orientifold, stabilizing moduli via the Large Volume Scenario, and configuring axions using D7-brane stacks. In order to obtain a large effective decay constant, we employ the Kim–Nilles–Peloso alignment mechanism, with the required multiple axions arising naturally from anisotropic bulk geometries.



Plot of the spectral index n_s and the tensor-to-scalar ratio r

Significant effort, but all models are still far from the sweet spot of data

Planck constraints on the tensor-to-scalar ratio

arXiv:2010.01139

Use the latest release of Planck maps, PR4

New Planck constraint $r < 0.056$

Combining Planck with BICEP2/Keck 2015 data yields an upper limit of

$r < 0.044$ at 95% C. L.

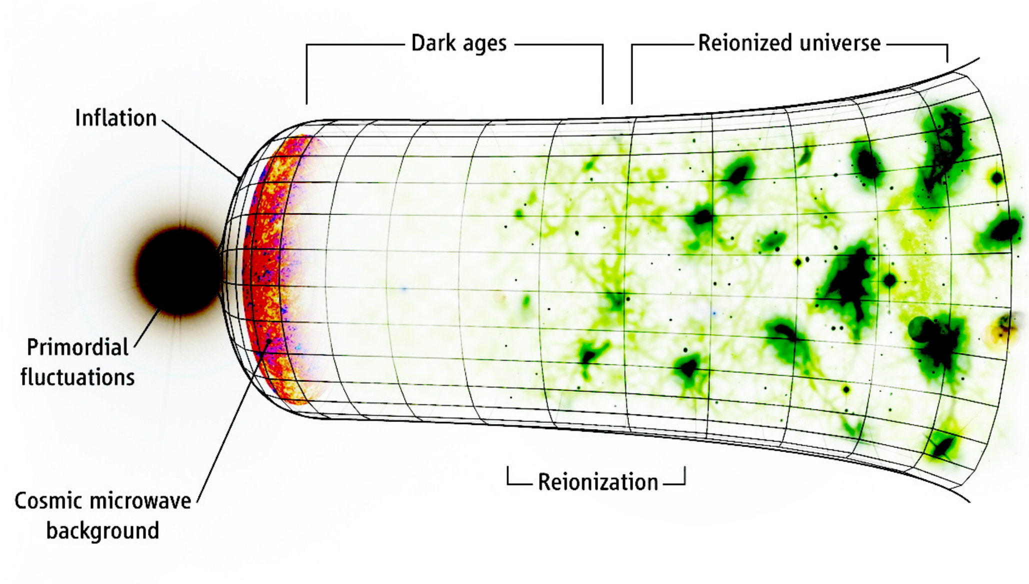
the tightest limit on *r* to date

CMB-S4 2021 Summer Collaboration Meeting

Gravitational waves provide an unobstructed view of the dynamics of the universe through cosmic history.

The inflationary paradigm

- Period of accelerated expansion
- Simplest model Single-Field Slow-Roll (SFSR)
- Solves several Big Bang Theory problems
- Predictions:
  - Flat universe ✓
  - Density perturbations with ~ scale-invariant red-tilted power-law spectrum ✓
  - Gaussian/adiabatic scalar perturbations ✓
  - Tensor (and scalar) perturbations from quantum vacuum fluctuations



P. Campeti slide

Why hunting for the primordial GW?

- Tensor-to-scalar ratio $r = \frac{A_T}{A_S}$
- r directly connected to the energy scale of inflation

$$V^{1/4} = 1.04 \times 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

- No detection yet of primordial B, only upper limits $r < 0.044$ at $95\,\%\,C.L.$

The goal of the recent work with Linde, Yamada, Wrase

My talk at Supergravity session of SUSY 2021

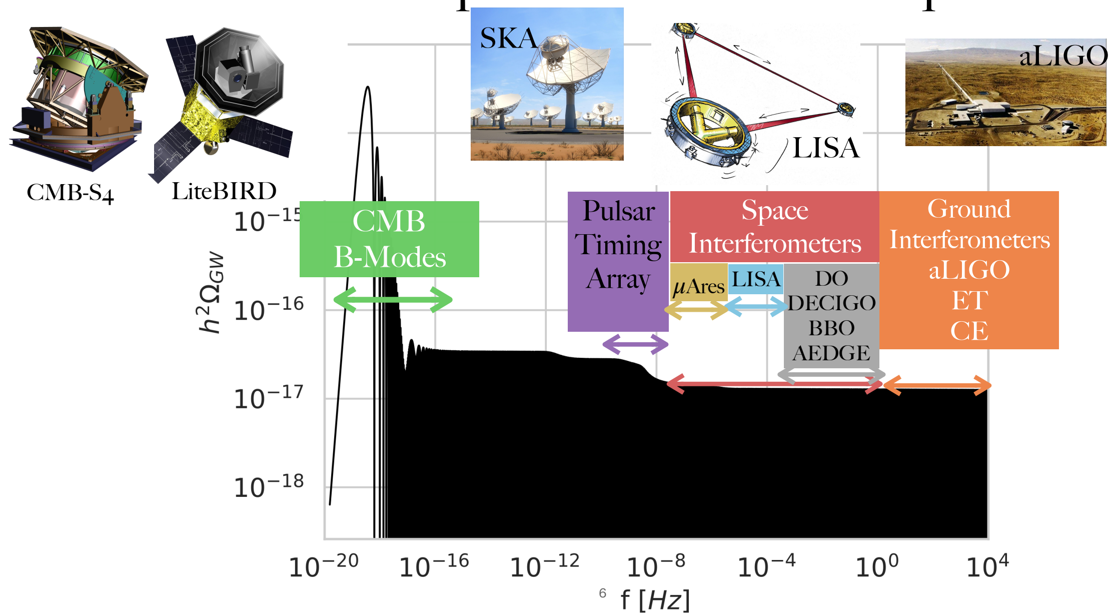
- Which models of inflation will fit the data?
- What we will learn about fundamental physics?

- Unique information on the early universe
- Probe energy scales unreachable by particle colliders

B-modes state-of-the-art (2028-2029)

Ground based and satellite mission, Highly complimentary experiments

Observational probes at different frequencies



From P. Campeti talk

6

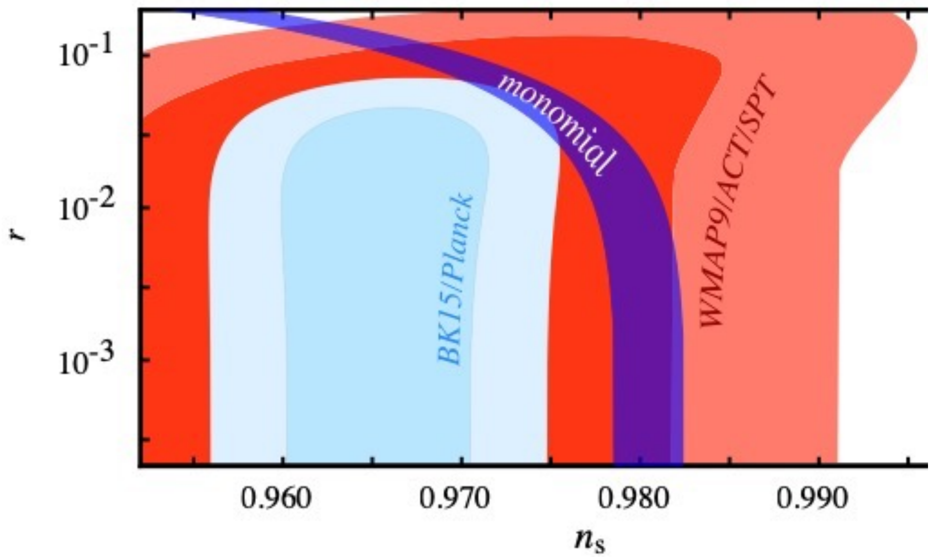
Science goals for CMB-S4 August 9-13, 2021

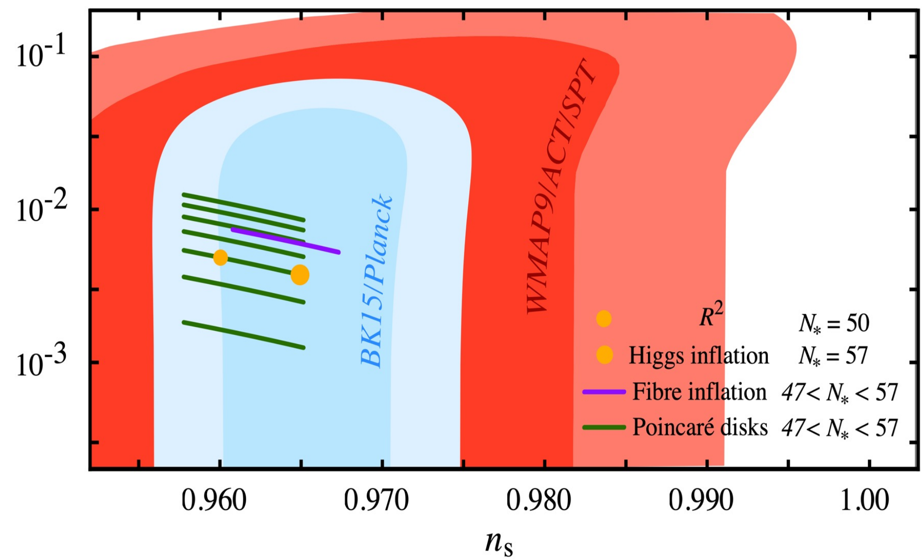
From R. Flauger talk

- detect gravitational waves provided $r > 3 \times 10^{-3}$

or

- provide an upper limit of $r < 10^{-3}$ **at 95% CL**





Monomial models are about to be excluded by current data

BK18 maps about to be released

In addition to all time favorite plateau potentials: R^2 and Higgs

B-mode targets: 7 Poincare disks, α-attractors with 3a=1,2,3,4,5,6,7

Ferrara, RK, 2016

RK, Linde, Wrase, Yamada, 2017

RK, Linde, Roest, Yamada, 2017

McDonough , Scalisi, 2016

$$ds^2 = \frac{dx^2 + dy^2}{(1 - x^2 - y^2)^2}$$

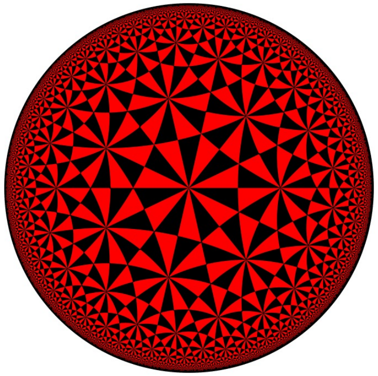
http://mathworld.wolfram.com/PoincareHyperbolicDisk.html

Kahler space curvature

$$R_K = -\frac{2}{3\alpha}$$

$$K = -3\alpha \log(1 - Z\overline{Z})$$

$$ds^2 = 3\alpha \frac{dZ\, d\bar{Z}}{(1 - Z\bar{Z})^2}$$



For a unit size Poincare Hyperbolic disk:

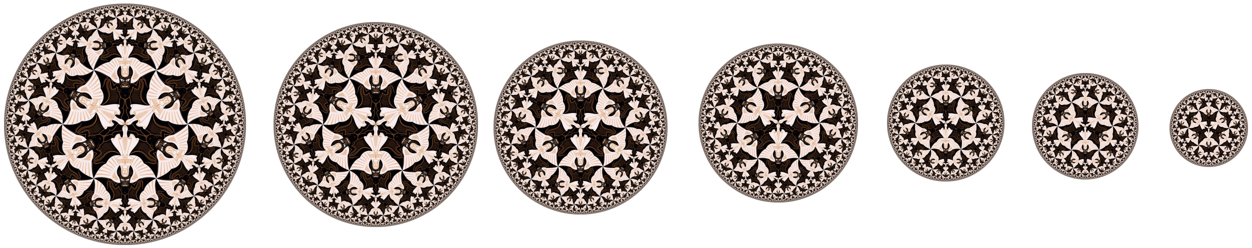
$$r \sim 10^{-3} \qquad \alpha = \frac{1}{3}$$

Next CMB satellite mission targets: 7 Poincare disks

Escher in the Sky

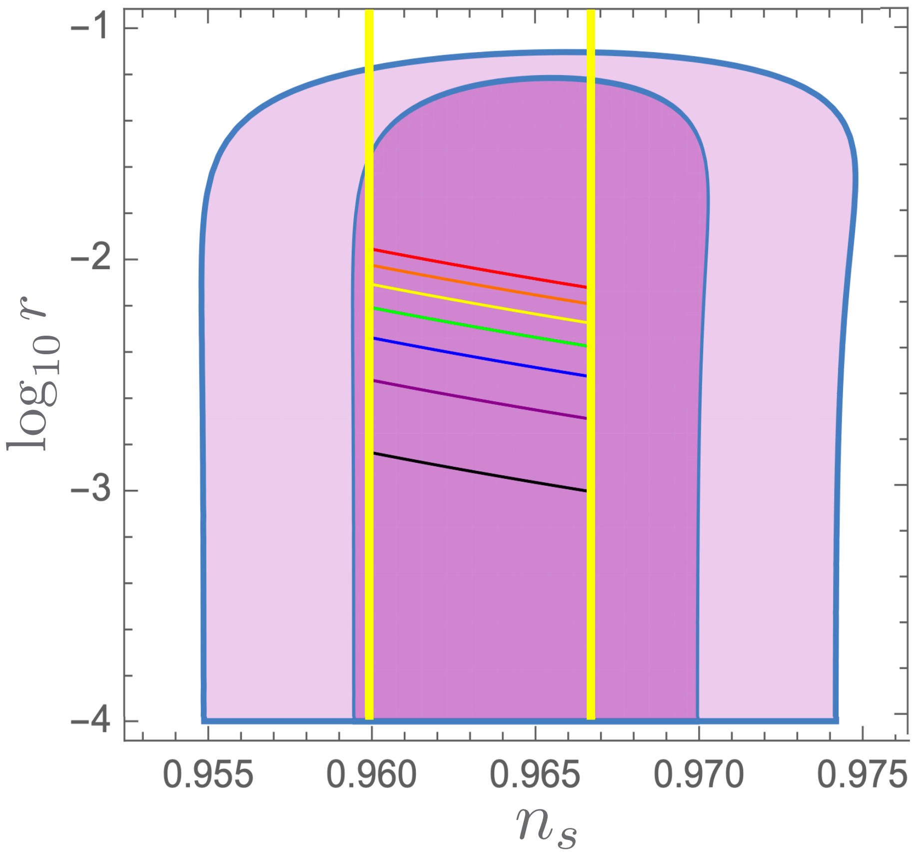
3α is R^2 of the Escher disk

3α=1,2,3,4,5,6,7



Benchmarks for T-models and E-models

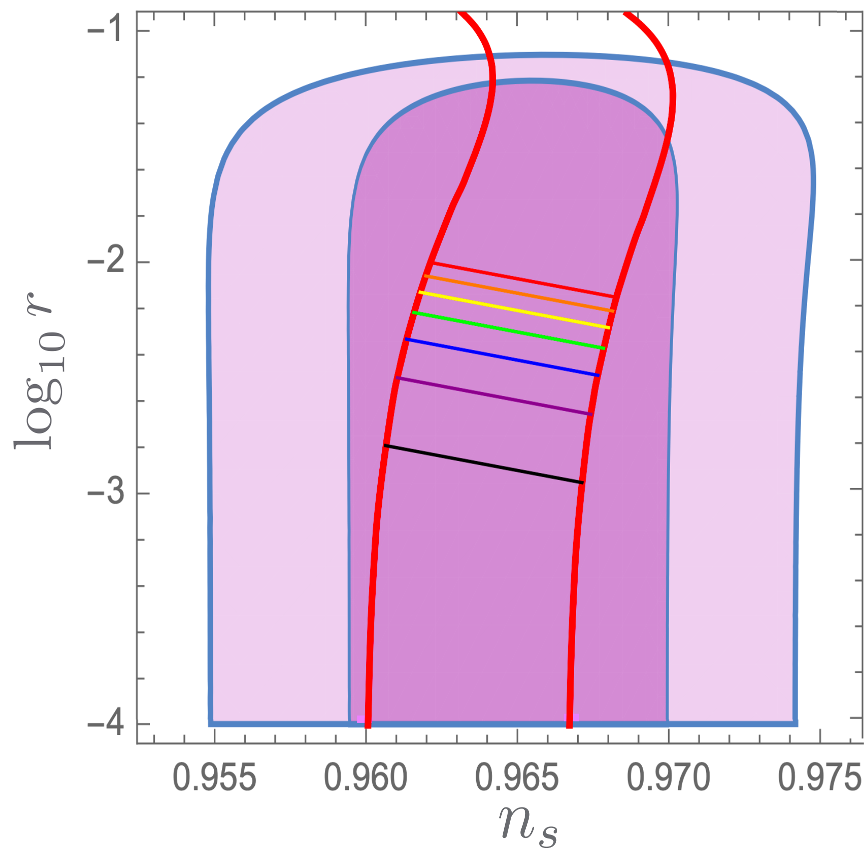
T-models



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

Yellow band: continuous 3α,
7 lines: discrete 3α

E-models



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

Red band: continuous 3α,
7 lines: discrete 3α

$50<N_e<60$

Sequestered Inflation

RK, A. Linde, Y. Yamada, T. Wrase, 2021

2108.08491 2108.08492

We construct **supergravity models** which allow one to sequester the phenomenology of inflation from the Planckian energy scale physics which can be associated with string theory or M-theory.

The procedure consists of two steps: At **Step I** we use $W_{\rm flux}$ in string theory or M-theory to obtain a 4D supergravity with some number of chiral multiplets and scalar potentials that have supersymmetric Minkowski vacua with flat directions (Goldstone supermultiplets).

At **Step II** we uplift these Goldstones to plateau inflationary potentials. We find certain conditions which ensure that the superheavy fields involved in the stabilization of the Minkowski vacua at Step I are completely decoupled from the inflationary phenomenology.

Technical tools beyond well known in Supergravity

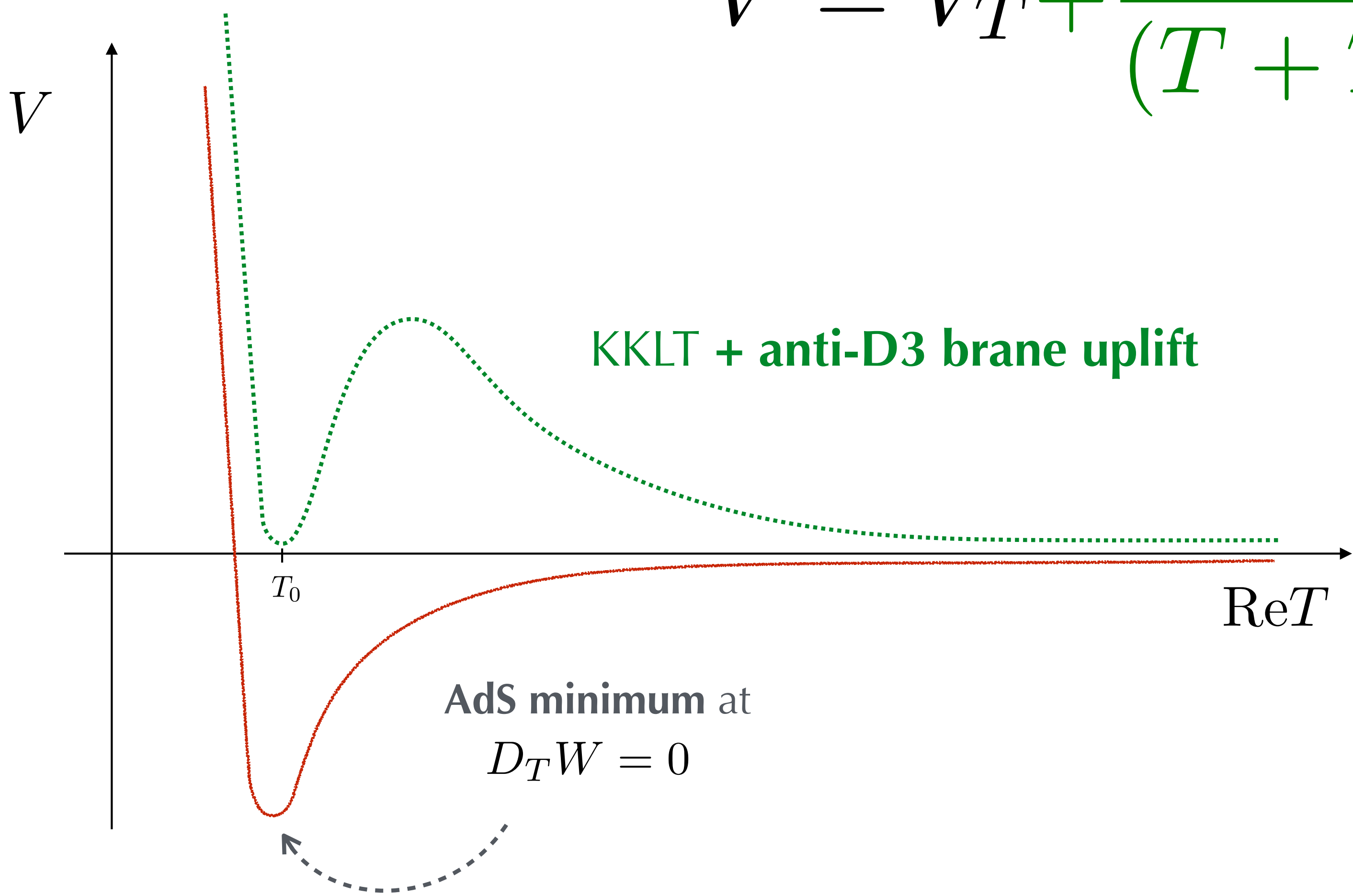
At **Step I**: **Goldstone multiplets** in Supergravity $\Leftrightarrow$ Symmetries of Flux Superpotentials

At **Step II**: **Nilpotent multiplet** to make a massless Godstone into a plateau potential

2003, positive energy from the anti-D3 brane

Volkov-Akulov non-linear realization of supersymmetry

$$V = V_T + \frac{\mu^4}{(T+\bar{T})^2}$$



D=4 Supergravity Language

$$K = -3\ln(T + \bar{T} - X\overline{X})$$

$$W = W_0 + A\exp^{-aT} + \mu^2 X$$

The nilpotent superfield represents anti-D3 brane

$$X(x,\theta) = s(x) + \sqrt{2}\psi(x)\theta + F_X\theta^2$$

$$X^2(x,\theta) = 0$$

$$X(x,\theta) = \frac{\psi\psi}{2F_X} + \sqrt{2}\psi\theta + F_X\theta^2$$

The scalar is a bilinear of a goldstino fermions, not a fundamental field

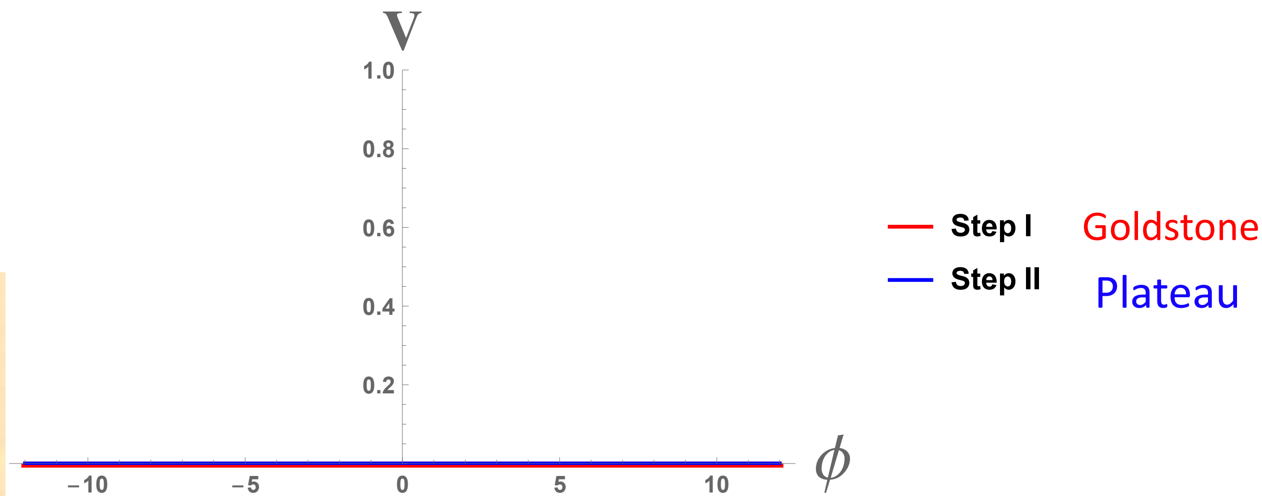
Supersymmetric uplift!

Stringy origin of plateau potentials

$M_{Pl} = 1$

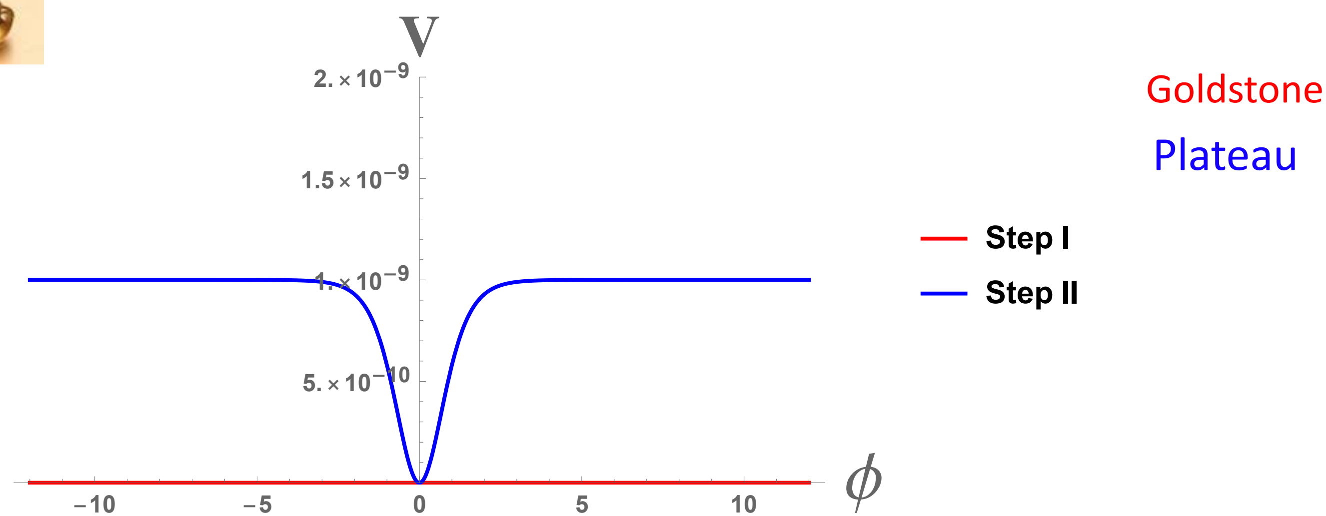
IIB String Theory and Sequestered Inflation

RK, Linde, Yamada, Wrase



With magnifying glass: looking at H_{infl}^2 scale, 9 orders below Planckian density

T-models in Sequestered Inflation



$$n_s \approx 1 - \frac{2}{N}, \qquad r \approx 3\,\alpha \frac{4}{N^2}$$

The **discrete set of values 3α = *n*** with an integer *n* in the range [**1,2,3,4,5,6,7**] motivated by **maximal supersymmetry** is compatible with the current data.

Maximal supersymmetry ⟷ M-theory, string theory

11D, 10D supergravity + local sources: D-branes and O-planes

Minimal supersymmetry ⟷ 4D supergravity

Continuous set of values 3α

Minimal supersymmetry $\mathcal{N}$=1 supergravity prediction: a continuous band, **any r is possible**, **n_s** fits the data

Maximal supersymmetry, string theory: **7 hyperbolic disks scan the region**

$$1 \leq 3\alpha \leq 7$$

$$10^{-3} \lesssim r \lesssim 10^{-2}$$

What we may learn about SUSY/M-theory and string theory from the detection/non-detection of gravitational waves from inflation?

The models with **discrete values of the 3α**-parameter are associated with string theory, M-theory and maximal $\mathcal{N}$=8 supergravity. These are the seven targets shown in LiteBIRD figure, at the specific seven values of the parameter r which defines the B-modes **(purple lines in the figure)**

For continuous values of the 3α-parameter there is a band of values of r as we see below. It is possible that the B-modes will be discovered above or below the seven hyperbolic disks targets, and still fit the data on n_s. This would support the idea of a minimal $\mathcal{N}$=1 supergravity with hyperbolic geometry.

B-modes may not even be detected if $r \ll 10^{-3}$. If, however, the future data on B-modes will fit one of the seven discrete targets, the cosmological models associated with **string theory, M-theory, maximal supergravity** will get a strong support as the favorite models of theoretical physics which fit the cosmological observations.

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