Supergravity and Cosmology

Renata Kallosh, Stanford

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Guadeloupe islands
University of Antilles

For cosmology we need General Relativity

Supergravity is next natural step after General Relativity

Superstring theory is believed to be the most fundamental theory we know

However, string theory has an emergent concept of space-time. To use it in the context of the 4-dimensional General Relativity and cosmology requires many intermediate steps

If in these steps some amount of supersymmetry, maximal or minimal or intermediate, is preserved, one finds consequences for cosmology, potentially supportable or falsifiable by observations

- De Sitter/near de Sitter supergravity

- Inflationary model building

- New M-theory/String theory inspired targets for B-modes beyond the well known satellite targets like R^2 and Higgs inflation, with r of the order 3×10^{-3}

- Cosmological data and the String Swampland
  A comment to very recent papers by Vafa et al

- Dark Energy and Quintessential Inflation
  models with w equal or close to -1, but allowing a shift of n_s, if new data requires it

Fundamental idea following the discovery of General Relativity: local supersymmetry

Einstein's dream of unifying electromagnetism and gravity was realized starting with extended **$\mathcal{N}$=2 supergravity**. The model does so by adding **two real gravitino** to the photon and the graviton. The first breakthrough into finiteness of quantum supergravity occurred via this unification: an explicit calculation of **photon—photon scattering** which was known to be divergent in the coupled Maxwell—Einstein system yielded a dramatic result : the new diagrams involving gravitinos cancelled the divergences found previously, 1976.

More such cancellation were found later in higher $\mathcal{N}$.

LHC did not discover low-energy $\mathcal{N}$=1 supersymmetry yet, nor gave evidence of extra dimensions.

However, the idea of a **maximal supersymmetry, spontaneously broken to minimal supersymmetry, can be tested in cosmology**

$\mathcal{N}$=8 in d=4 supergravity,	}	**B-mode targets**
M-theory , $\mathcal{N}$=1 in d=11		
Superstring theory, $\mathcal{N}$=2 in d=10		**Hidden symmetries**

Cosmological Constant in Supergravity

Known to be negative in pure supergravity, without scalar fields (1977)

$$\Lambda < 0 \quad \textbf{AdS}$$

Supergravity with a positive cosmological constant without scalars was not known

$$\Lambda > 0 \quad \textbf{dS}$$

What is the problem with de Sitter supergravity ?

$\mathcal{N}=1$

- Anti- de Sitter: $$[P_\mu,\, P_\nu] = \mp\frac{1}{4L^2}M_{\mu\nu}$$

  SO(3,2) is SO(4,1)

- Superalgebra ? $$\begin{aligned}[P_\mu,\, Q_\alpha] &= \frac{1}{4L}(\gamma_\mu Q)_\alpha \\ \{Q_\alpha,\, Q_\beta\} &= -\frac{1}{2}(\gamma^\mu)_{\alpha\beta}P_\mu - \frac{1}{8L}(\gamma^{\mu\nu})_{\alpha\beta}M_{\mu\nu}\end{aligned}$$

- Jacobi identities: only with lower sign (Anti-de Sitter)
  Supergroup OSp(1|4); sp(4)=so(3,2)

$\mathcal{N}>1$ Jacobi ok, but non-unitary reps

No-go theorems prohibit linearly realized supersymmetry.

New $\mathcal{N}$=1 dS supergravity has a non-linearly realized supersymmetry.

Bergshoeff, Freedman, RK, Van Proeyen
Hasegawa, Yamada

2015

Standard linear $\mathcal{N}$=1 SUSY

1 Majorana fermion   1 complex scalar

$$\mathcal{L} = -\tfrac{1}{2}(\partial_\mu A)^2 - \tfrac{1}{2}(\partial_\mu B)^2 - \tfrac{1}{2} i \bar{\psi}\gamma^\mu \partial_\mu \psi - \tfrac{1}{2} m^2 A^2 - \tfrac{1}{2} m^2 B^2 - \tfrac{1}{2} i m \bar{\psi}\psi - g m A (A^2 + B^2) - \tfrac{1}{2} g^2 (A^2 + B^2)^2 - i g \bar{\psi}(A - \gamma_5 B)\psi .$$

Wess-Zumino, 1974: minimal SUSY with a

Majorana fermion and a complex scalar

Gravity NO-GO for de Sitter

AdS/CFT studies

$$\sqrt{|g|}\,\Lambda \leq 0$$

LHC, as of June 2018

No SUSY partners yet

Non-linear $\mathcal{N}$=1 SUSY

1 Majorana fermion   2 Majorana fermions

$$\mathcal{L} = -f^2 + i\partial_\mu \overline{G}\bar{\sigma}^\mu G + \frac{1}{4f^2}\overline{G}^2 \partial^2 G^2 - \frac{1}{16 f^6} G^2 \overline{G}^2 \partial^2 G^2 \partial^2 \overline{G}^2$$

Volkov, Akulov, 1972   Non-linearly realized

supersymmetry: only fermions are present

Pure supergravity, with de Sitter vacua was constructed in 2015

Bergshoeff, Freedman, RK, Van Proeyen;
Hasegawa, Yamada;

$$\sqrt{|g|}\,\Lambda = \sqrt{|g|}\, f^2 > 0$$

The hints came from inflationary model building: in α-attractor models (yellow lines on Planck r/n_s plot).

Non-linear supersymmetry is a nice feature that allows to stabilize extra moduli and reduce the evolution to the one driven by a single scalar inflaton.

The advanced version of these models are based on a supersymmetry which is not a standard linear susy but includes also a non-linear susy.

A feature known in non-perturbative string theory:
D-branes with Born-Infeld vectors and Volkov-Akulov spinors

Nilpotent chiral multiplet action

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

$$\mathcal{L}_{s^2(x,\theta)=0} = -f^2 + \partial_a \bar{\chi} \bar{\sigma}^a \chi + \frac{1}{4f^2} \bar{\chi}^2 \partial^2 \chi^2 - \frac{1}{16 f^6} \chi^2 \bar{\chi}^2 \partial^2 \chi^2 \partial^2 \bar{\chi}^2$$

Goldstino action in absence of fermions
just adds a positive term to energy

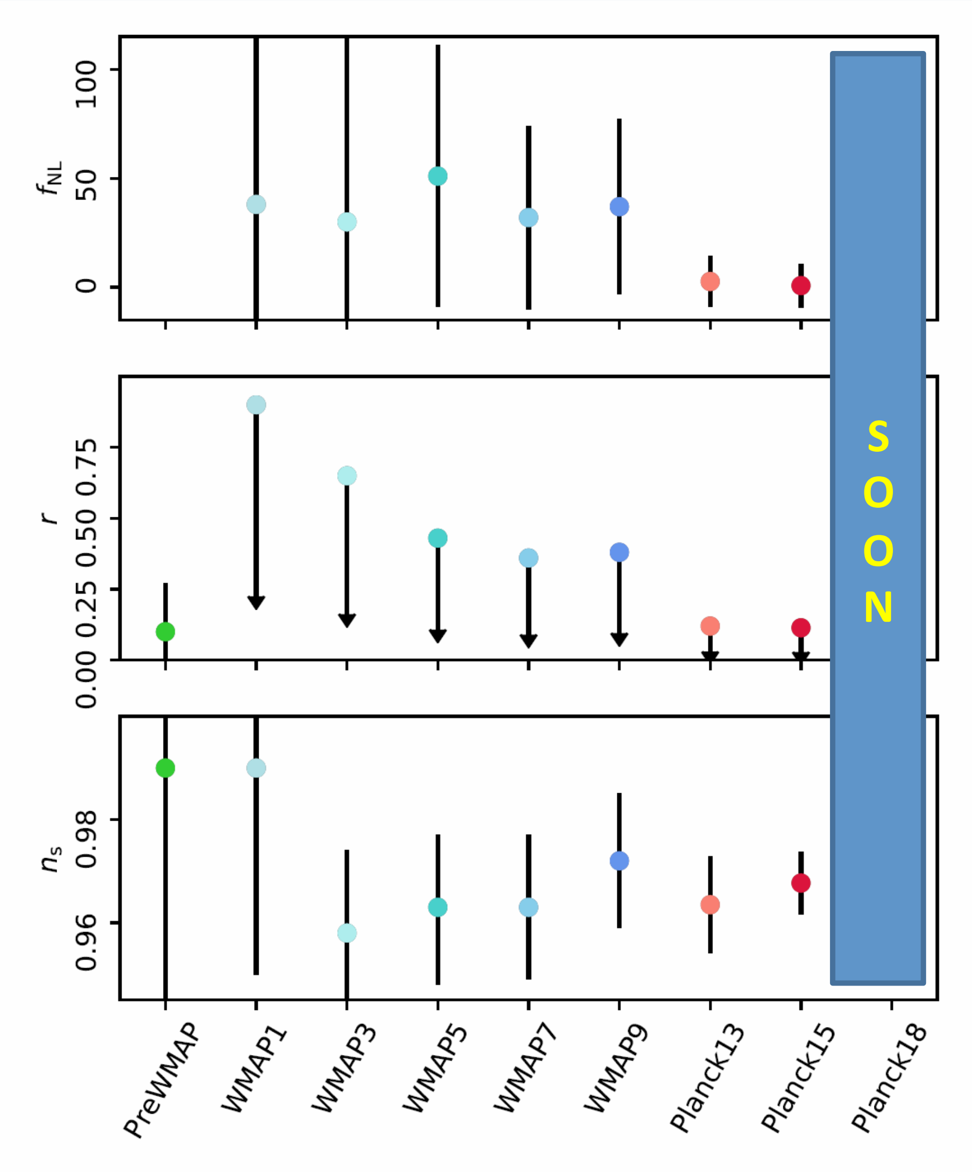
Non-linearly realized supersymmetry:

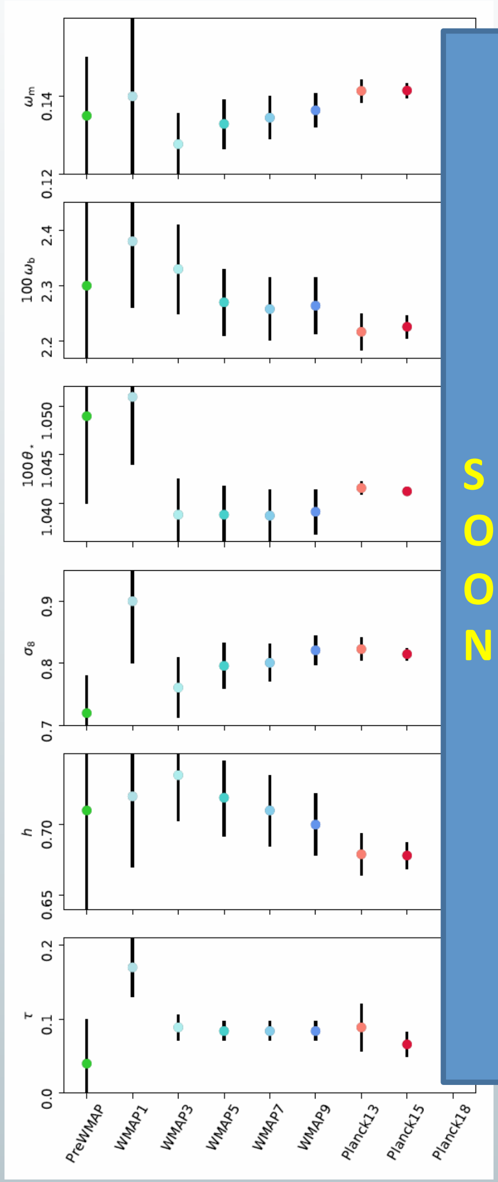
only fermions present

Supersymmetric KKLT uplift

In supergravity inlation a stabilizer superfield

LCDM parameters vs time





Focus on inflationary parameters f_{NL} and r-n_s plane

Absence of non-Gaussianity: easy to explain with a single inflaton field. This requires stabilization of many other scalars fields. We learned how to do it.

Surprisingly, even in multi-α-attractor models, we find a very small non-Gaussianity

If we see in Planck 2018 that n_s is still about $0.96 - 0.97$

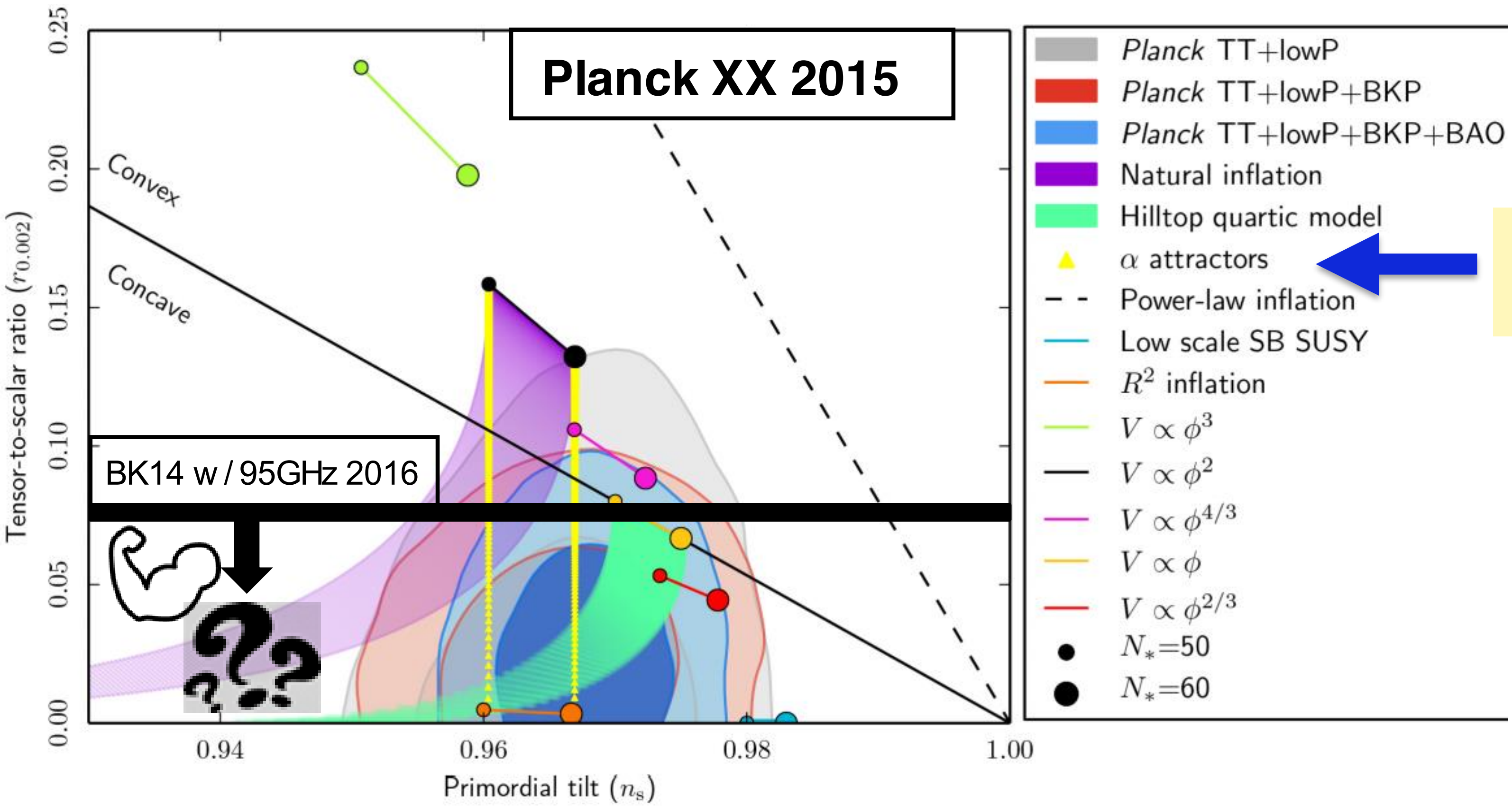
If we see in Planck 2018 and BICEP-KEK 2018 that $r < 0.07$

Can we find one simple reason why

$$n_s \approx 1 - \frac{2}{N}$$

N is the number of e-foldings

Cosmology: from the sky to the fundamental physics



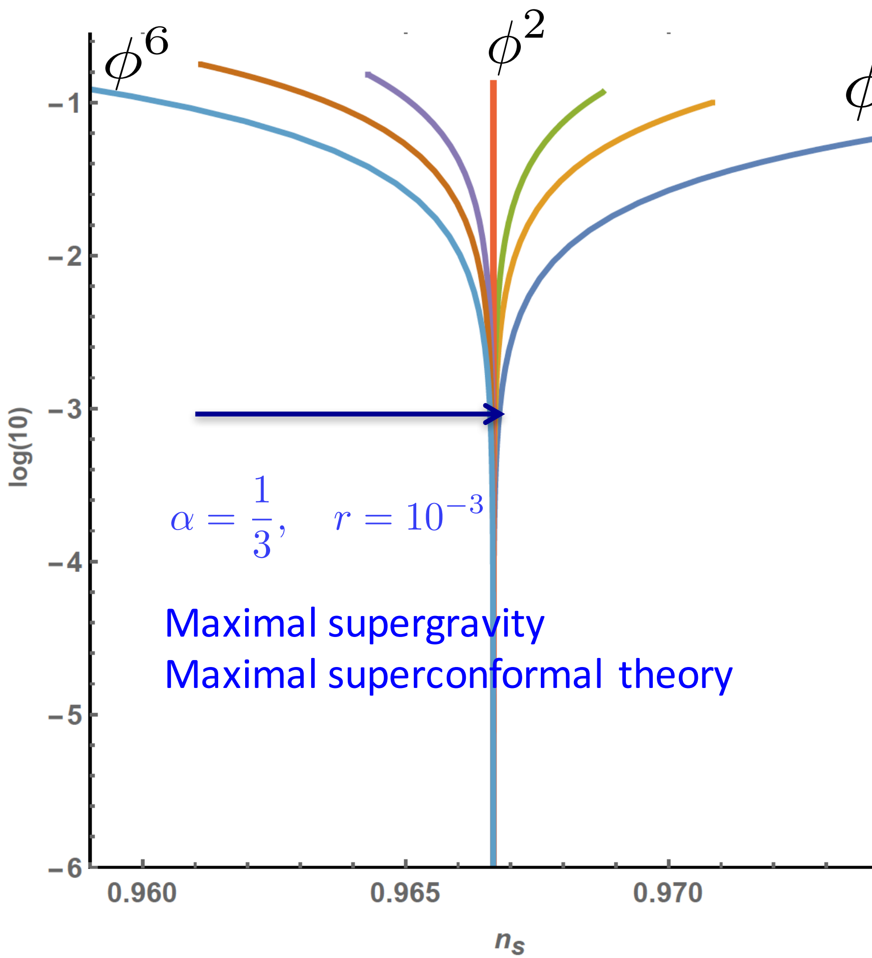
RK, Linde, Roest, 2013

If B-modes are discovered soon with $r > 10^{-2}$ natural inflation models, axion monodromy models, α-attractor models,…, will be validated - no need to worry about log scale r

Otherwise, we switch to log r to see $10^{-3} < r < 10^{-2}$

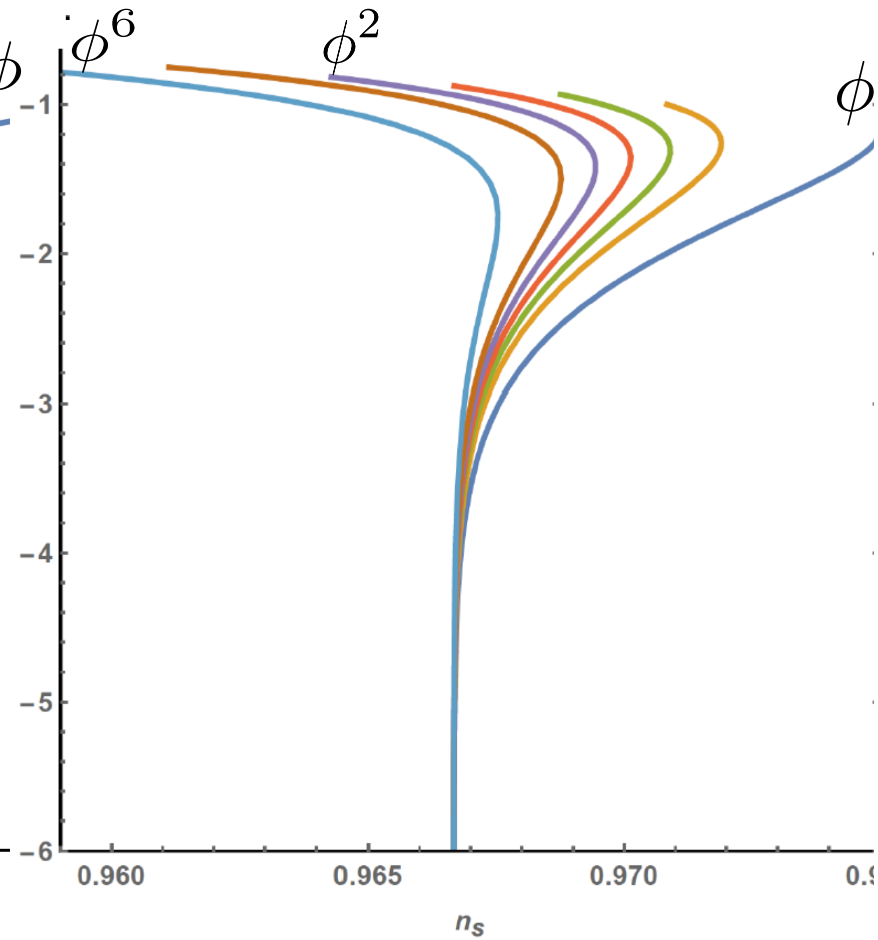
α-attractors

Simple Fanned T-models



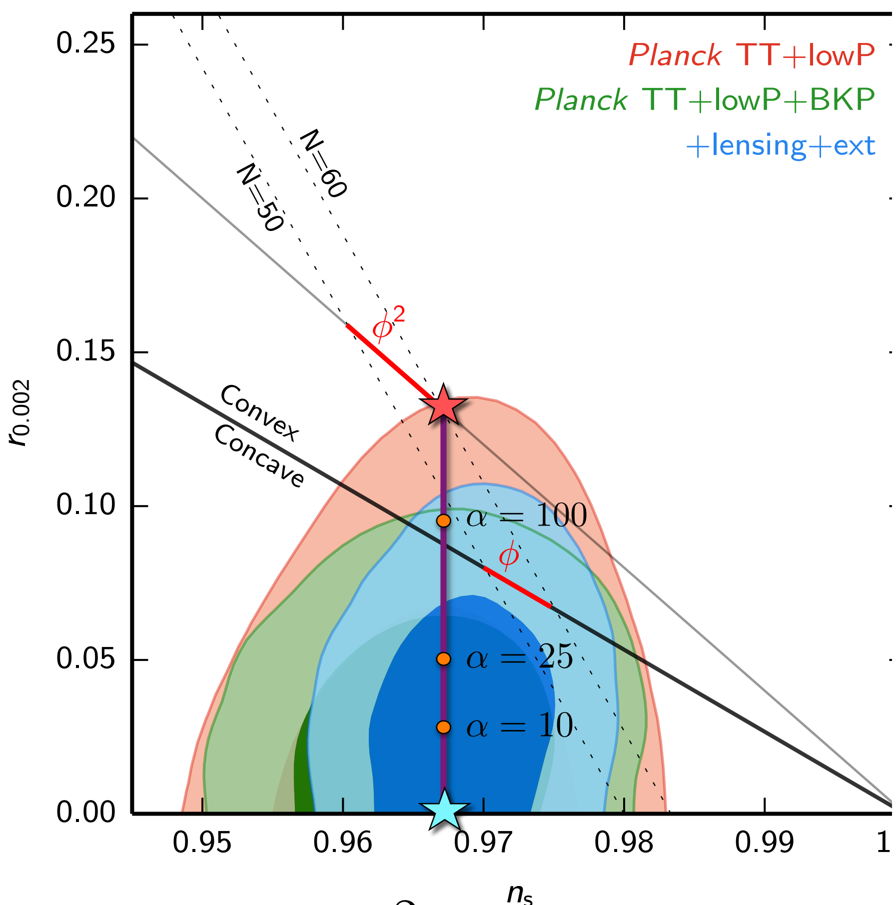
$$\left(\tanh\frac{\varphi}{\sqrt{6\alpha}}\right)^{2n}$$

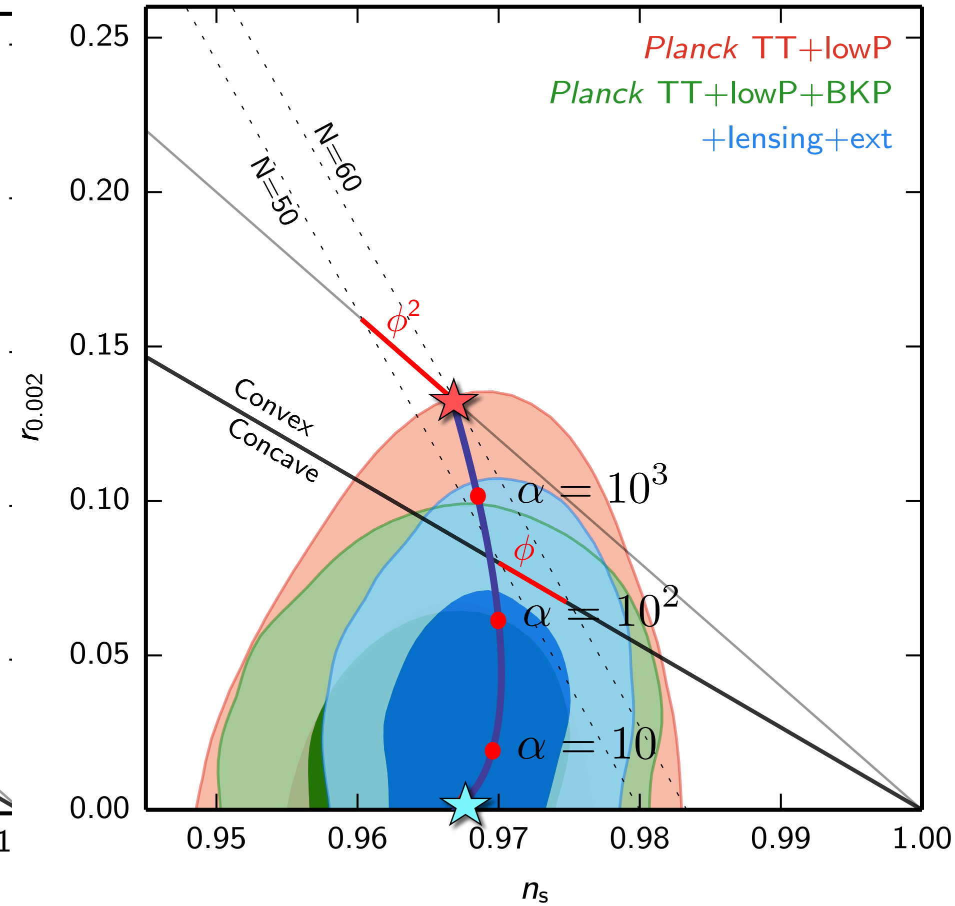
Simple Fanned E-models



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

Starobinsky and Higgs, α=1, n=1





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

$$\frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\frac{\phi^2}{(1+\frac{\phi}{\sqrt{6\alpha}})^2}$$

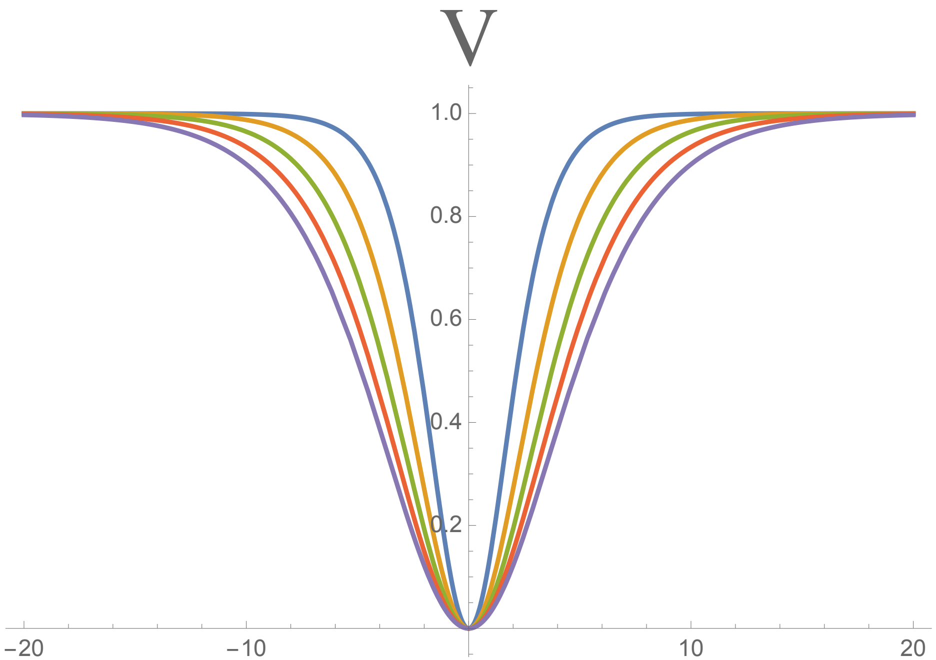
Simplest T-models

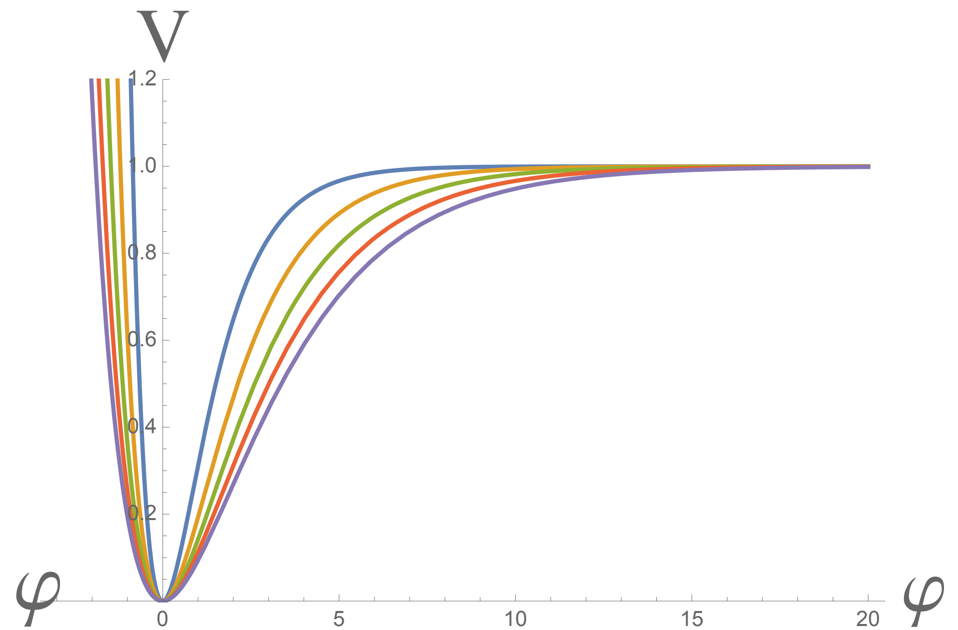
RK, Linde, Roest 2013

Simplest E-models

Ferrara, RK, Linde, Porrati, 2013

Plateau potentials of α-attractors





$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \;\; - \alpha\mu^2\Big(\tanh\frac{\varphi}{\sqrt{6\alpha}}\Big)^2$$

$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \;\; - \alpha\mu^2\Big(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi}\Big)^2$$

Simplest T-model   in canonical variables   Simplest E-model

$$\frac{1}{2}R - 3\alpha\frac{\partial Z\partial\bar{Z}}{(1-Z\bar{Z})^2} - V_0 Z\bar{Z}$$

$$\frac{1}{2}R - 3\alpha\frac{\partial T\partial\bar{T}}{(T+\bar{T})^2} - V_0(T-1)^2$$

In geometric variables

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

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

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

For a unit size Poincare disk:

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

Next CMB satellite mission target

α-attractors in supergravity

$SL(2,\mathbb{R})$ symmetry

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

$$ds^2 = \frac{3\alpha}{(T + \bar{T})^2} dT d\bar{T}$$

$$\mathcal{R}_K = -\frac{2}{3\alpha}$$

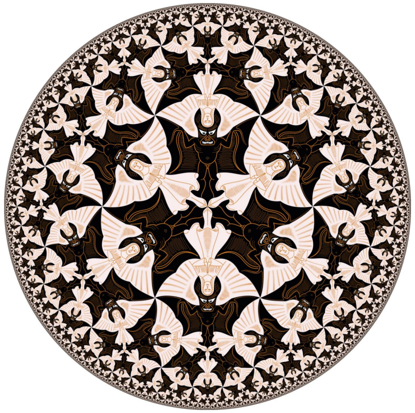
Curvature of the moduli space in Kahler geometry

$$Z\bar{Z} < 1$$

Hyperbolic geometry of a Poincaré disk

Disk or **half-plane**

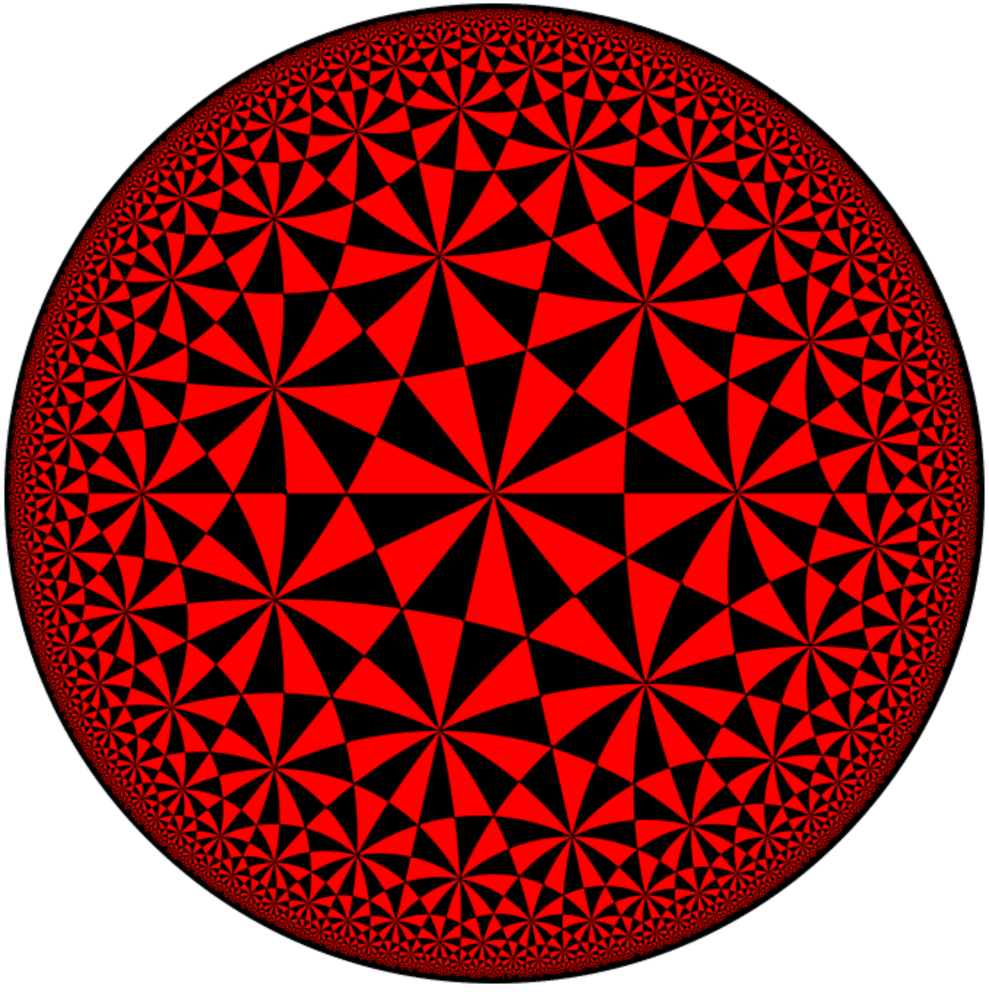
$$T + \bar{T} > 0$$



Escher in the Sky, RK, Linde 2015

$$3\alpha = R^2_{\rm Escher} \approx 10^3 r$$

Möbius transformations applied to hyperbolic tilings



Meaning of the measurement of the curvature of the 3d space

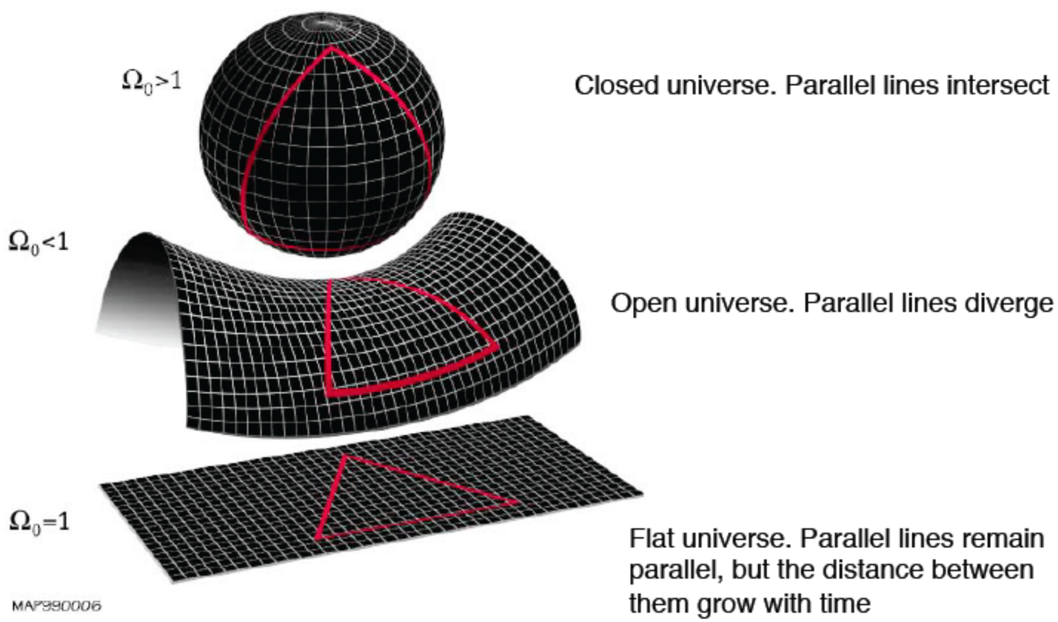
k=+1, k=-1, k=0

Spatial curvature parameter

$$ds^2 = -dt^2 + a(t)^2 \gamma_{ij} dx^i dx^j$$

$$\Omega_K = -0.0004 \pm 0.00036$$

Closed, open or flat universe



In the context of new supergravity cosmological models, measuring r means measuring the curvature of the hyperbolic geometry of the moduli space

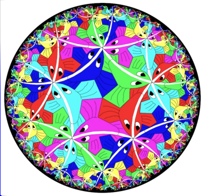
$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha \frac{12}{N^2}$$

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

scalar fields are coordinates of the Kahler geometry

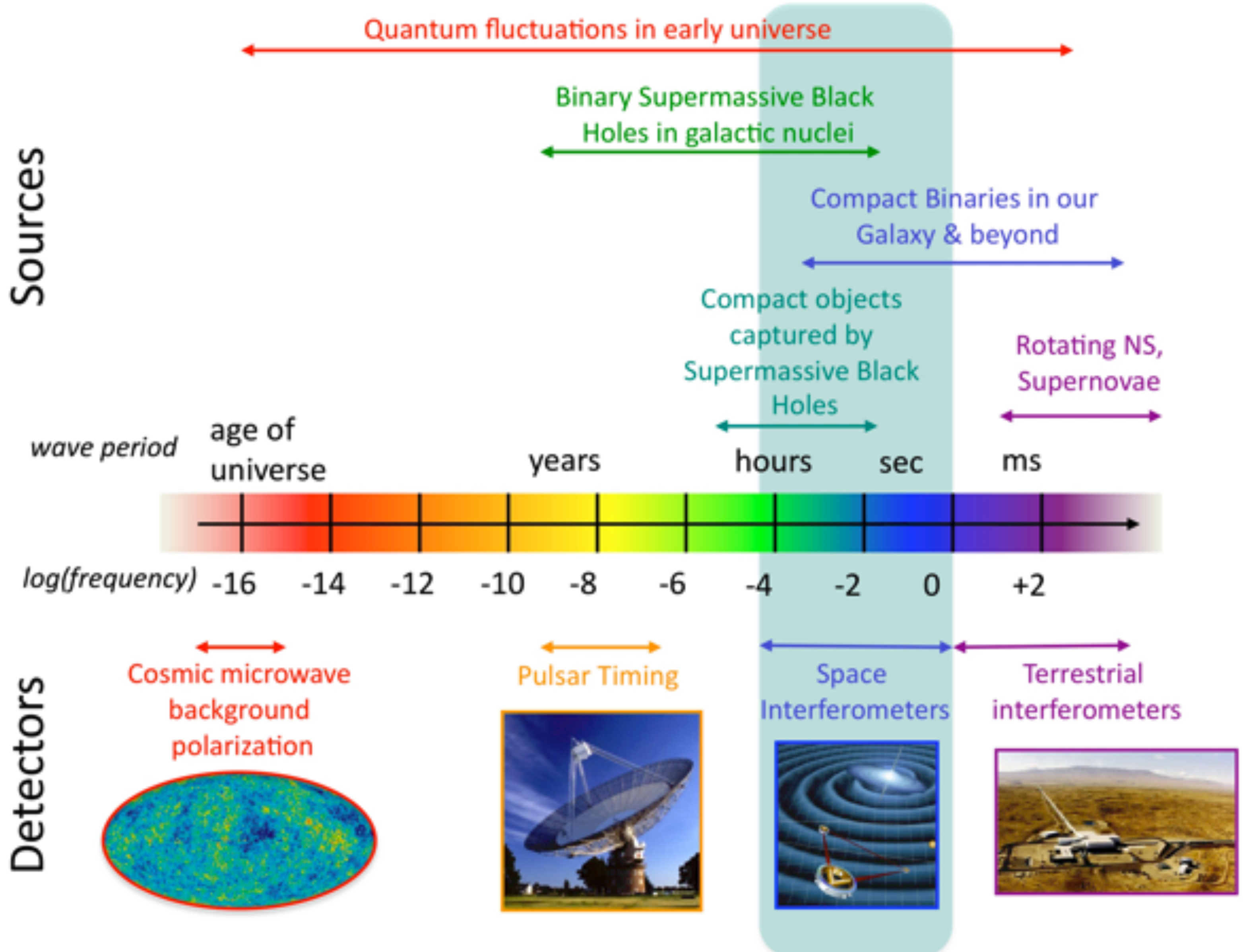
Decreasing r, decreasing α, increasing curvature R_K

$$3\alpha = R^2_{\text{Escher}} \approx 10^3 r$$



Hyperbolic geometry of a Poincaré disk

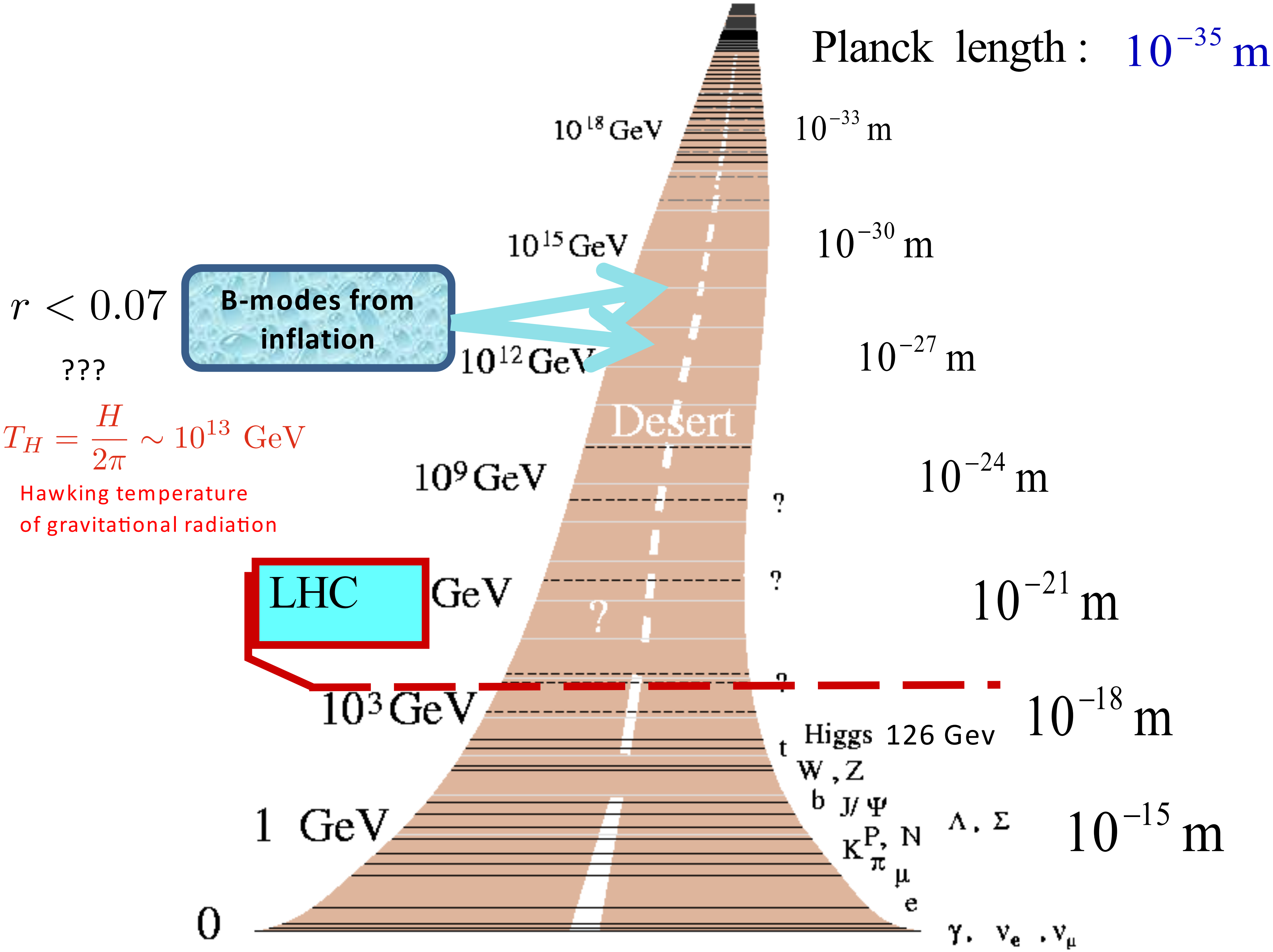
The Gravitational Wave Spectrum



Test of Quantum Gravity **Test of General Relativity**

LIGO detected GW from binary black holes and neutron stars, with the wavelength of thousands of kilometers

But the primordial GW affecting the CMB have wavelengths of billions of light-years!!!



Planck length : 10^−35 m
10^18 GeV
10^−33 m
10^15 GeV
10^−30 m
r < 0.07
B-modes from inflation
10^12 GeV
10^−27 m
???
T_H = H/2π ~ 10^13 GeV
Hawking temperature
of gravitational radiation
Desert
10^9 GeV
10^−24 m
?
LHC
GeV
?
10^−21 m
?
?
10^3 GeV
10^−18 m
Higgs 126 Gev
t
W , Z
b
J/ Ψ
Λ , Σ
1 GeV
10^−15 m
K
P, N
π
μ
e
0
γ , ν_e , ν_μ

The energy scale of inflation

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

GUT

The energy of inflationary perturbations

$$H = \frac{1}{M_{Pl}}\sqrt{V/3} \sim 2.6 \times 10^{13} \text{GeV} \left(\frac{r}{0.01}\right)^{\frac{1}{2}}$$

If primordial gravitational waves are detected

$$r \approx 10^{-2} \qquad H \approx 2.6 \times 10^{13} \text{GeV}$$

$$r \approx 10^{-3} \qquad H \approx 0.8 \times 10^{13} \text{GeV}$$

we will probe energies billion times higher than the energies probed at LHC

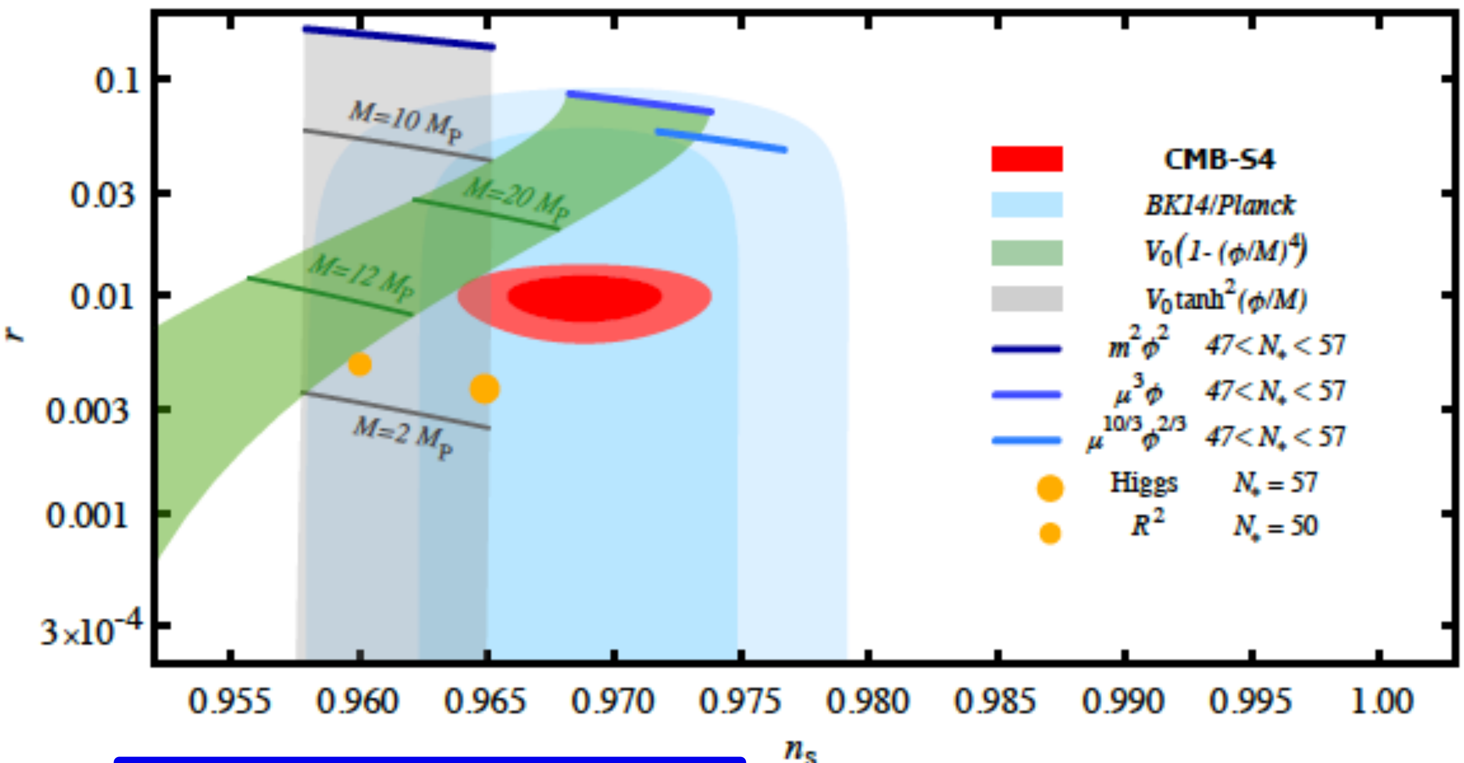
CMB-S4 Concept Definition Task force

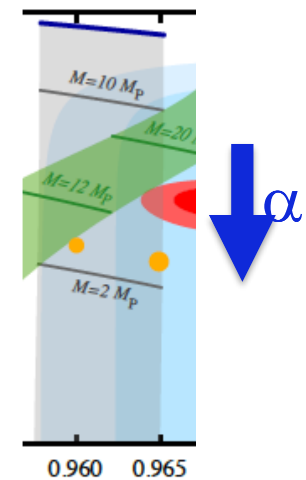
From the Executive Summary of the CDT Report

The first goal and requirement for CMB-S4 is to measure the imprint of primordial gravitational waves on the CMB polarization anisotropy, quantified by the tensor-to-scalar ratio r. Specifically, CMB-S4 will be designed to provide a detection of $r \geq 0.003$. In the absence of a signal, CMB-S4 will be designed to constrain $r < 0.001$ at the 95% confidence level, nearly two orders of magnitude more stringent than current constraints. This will test many of the simplest models of inflation, including those based on symmetry principles, that occur at high energy and large inflaton field range. The r requirements have been translated into measurement requirements consistent with projecting out foregrounds and other contamination as detailed in Appendix A.

Alpha-Attractors and B-mode Targets

CMB-S4





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

LiteBIRD

M. Hazumi, March 2018

What is LiteBIRD ?

◆ Post-Planck CMB Satellite

- ◆ JAXA-led international mission w/ strong European participation
- ◆ The most-advanced status (Phase-A) among all post-Planck proposals
- ◆ CMB polarization sky survey w/ Planck x ~100 sensitivity

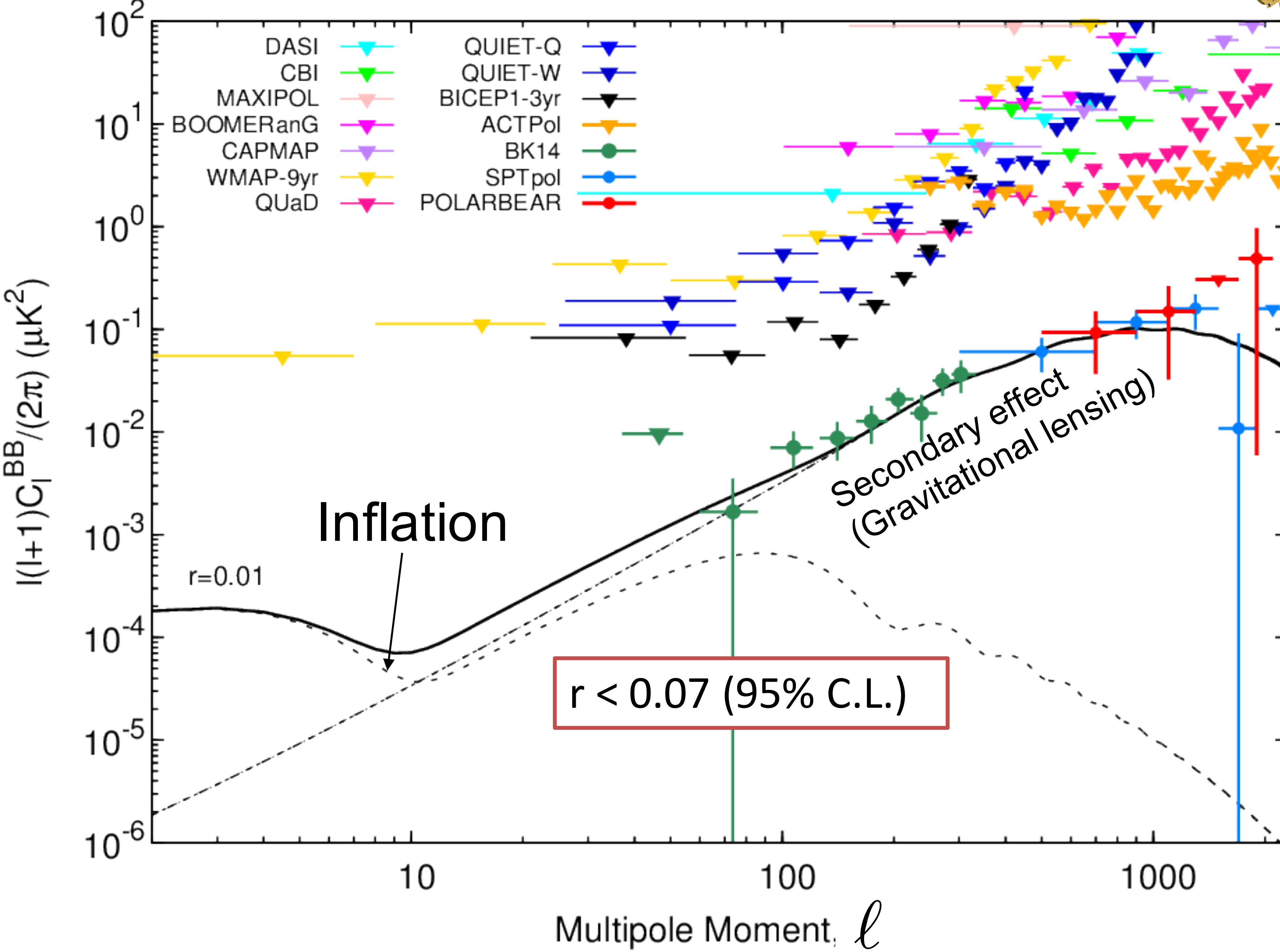
◆ Primordial Cosmology

- ◆ A definitive search for signal from cosmic inflation in CMB polarization map
- ◆ Either making a discovery or ruling out well-motivated inflationary models

◆ Fundamental Physics

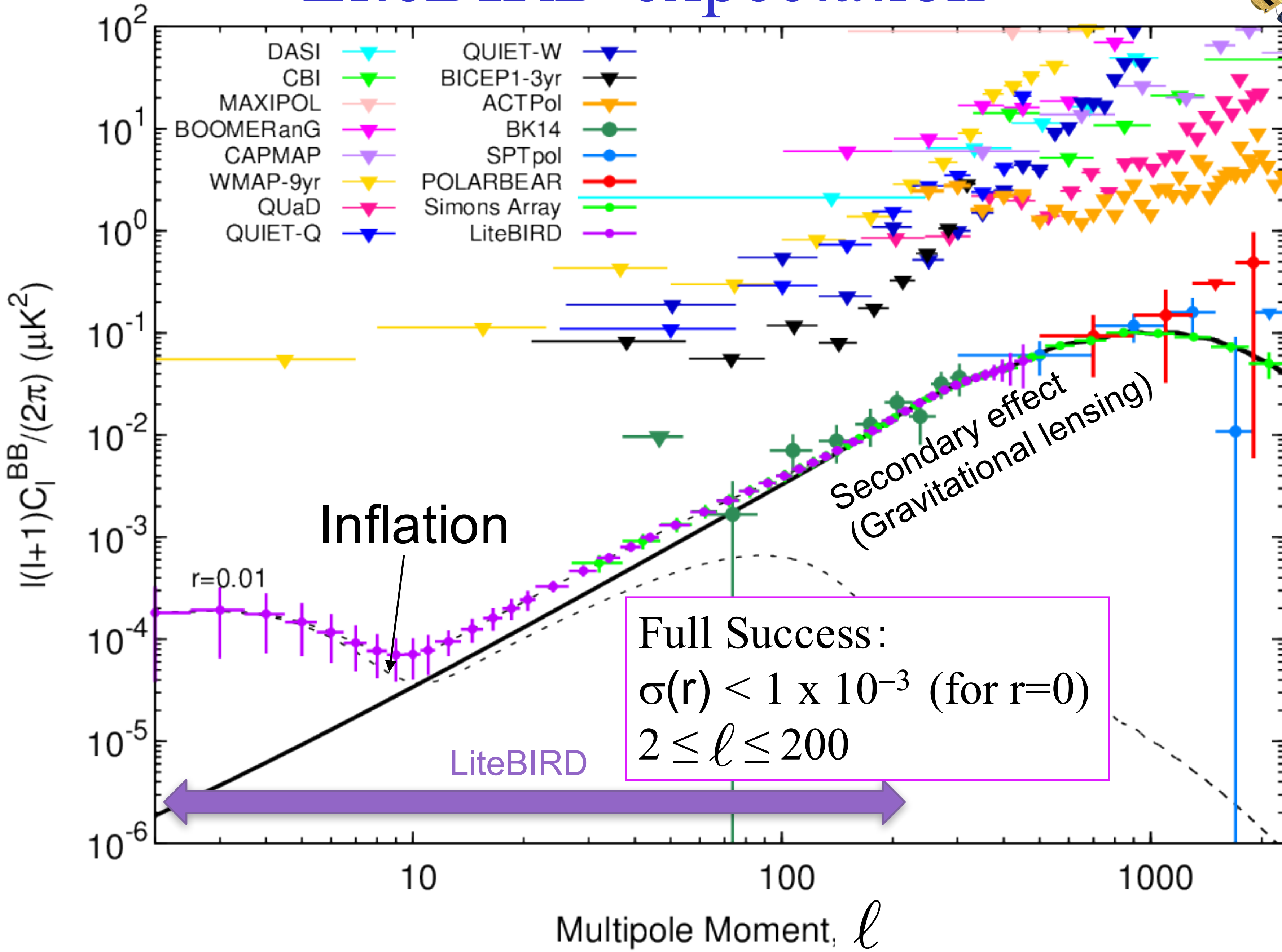
- ◆ Giving insight into the quantum nature of gravity and other new physics

B-mode power spectrum (2016)



LiteBIRD expectation

LiteBIRD
Yuji Chinone



- **Maximal supersymmetry and B-modes**
- M-theory in d=11
- Superstring theory in d=10
- $\mathcal{N}$=8 supergravity in d=4

2016, Ferrara and RK

Scalars are coordinates of the coset space in $\mathcal{N}$=8 supergravity in d=4

$$\frac{G}{H} = \frac{E_{7(7)}}{SU(8)}$$

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

Geometries with discreet number of unit size Poincaré disks are possible when consistent reduction of supersymmetry is performed. Upon identification of their moduli one finds

$$ds^2 = k\frac{dTd\bar{T}}{(T+\bar{T})^2}, \qquad k = 1,2,3,4,5,6,7 \quad = 3\alpha$$

At least one disk and no more than seven

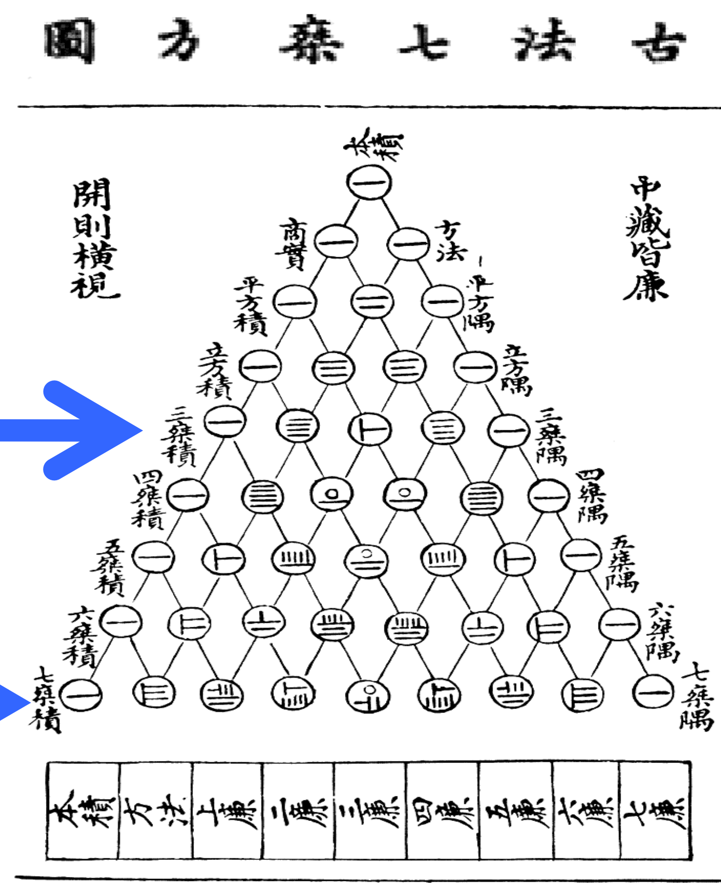
N=55 e-foldings

$$r \approx \{1.3,\ 2.6,\ 3.9,\ 5.2,\ 6.5,\ 7.8,\ 9.1\} \times 10^{-3}$$

$$n_s \approx 0.963$$

Yanghui triangle

13th century

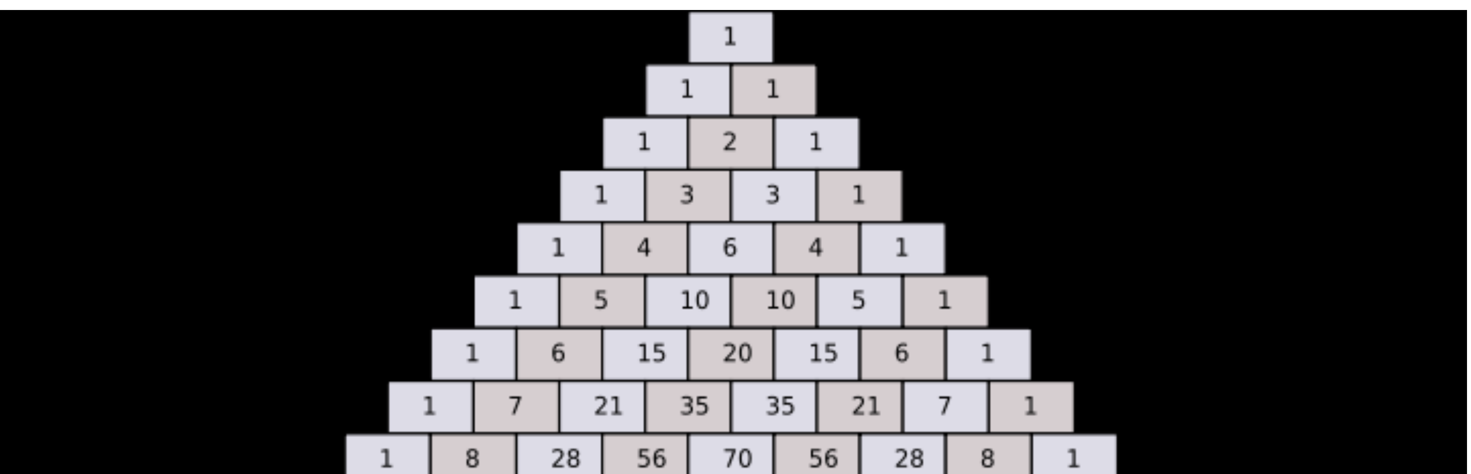


$(x+y)^4$ N=4 SYM

$(x+y)^8$ N=8 SG

Pascal's triangle determines the coefficients which arise in binomial expansions.

Each number in the triangle is the sum of the two directly above it.



Maximal $\mathcal{N} = 8$ supergravity

DeWit, Freedman (1977); Cremmer, Julia, Scherk (1978);
Cremmer, Julia (1978,1979); De Wit, Nicolai (1982)

- Theory has $2^8 = 256$ massless states.
- Multiplicity of states, vs. helicity, from coefficients in binomial expansion of $(x+y)^8$ – 8^{th} row of Pascal's triangle

$\mathcal{N} = 8$: 1 ✶ 8 ✶ 28 ✶ 56 ✶ 70 ✶ 56 ✶ 28 ✶ 8 ✶ 1

helicity : -2 $\quad -\frac{3}{2}$ $\quad -1$ $\quad -\frac{1}{2}$ $\quad 0$ $\quad \frac{1}{2}$ $\quad 1$ $\quad \frac{3}{2}$ $\quad 2$

h^- $\quad \psi_i^-$ $\quad v_{ij}^-$ $\quad \chi_{ijk}^-$ $\quad s_{ijkl}$ $\quad \chi_{ijk}^+$ $\quad v_{ij}^+$ $\quad \psi_i^+$ $\quad h^+$

SUSY charges Q_a, a=1,2,…,8 shift helicity by 1/2 ✶

- Ungauged theory, in flat spacetime

Anti-D3 Brane Induced Geometric Inflation:

Model Building Paradise — RK, Linde, Roest, Yamada, 2017

$\mathcal{G}$ **Kahler function** — Cremmer, Ferrara, Girardello, Julia, Scherk, van Nieuwenhuizen, Van Proeyen, from 1978

We are interested in anti-D3 brane interaction with Calabi-Yau moduli T_i. In supergravity we expect some interaction between the nilpotent superfield S, **representing KKLT type anti-D3 brane,** and Calabi-Yau moduli T_i

$$\mathcal{G}(T^i, \bar{T}^i; S, \bar{S})$$

$$\mathcal{G} \equiv K + \log W + \log \bar{W}\,, \qquad \mathbf{V} = e^{\mathcal{G}}(\mathcal{G}^{\alpha\bar{\beta}}\mathcal{G}_\alpha \mathcal{G}_{\bar{\beta}} - 3)$$

simple relation between the potential and the nilpotent field geometry

$$\mathcal{G}^{S\bar{S}}(T_i, \bar{T}_i) = \frac{\mathbf{V}(T_i, \bar{T}_i) + 3|m_{3/2}|^2}{|m_{3/2}|^2}$$

From the sky to fundamental physics

7-disk cosmological model

3α=7 example

1. Start with M-theory, or String theory, or $\mathcal{N}$=8 supergravity

2. Perform a consistent truncation to $\mathcal{N}$=1 supergravity in d=4 with a 7-disk manifold

$$\mathcal{G} = \log W_0^2 - \frac{1}{2}\sum_{i=1}^{7} \log \frac{(1 - Z_i\overline{Z}_i)^2}{(1 - Z_i^2)(1 - \overline{Z}_i^2)} + S + \overline{S} + \mathcal{G}_{S\overline{S}} S\overline{S},$$

$$\mathcal{G}^{S\overline{S}} = \frac{1}{W_0^2}(3W_0^2 + \mathbf{V}).$$

corresponding to the **merger of seven disks** of unit size

The scalar potential defining geometry is

$$\mathbf{V} = \Lambda + \frac{m^2}{7}\sum_i |Z_i|^2 + \frac{M^2}{7^2}\sum_{1\leq i\leq j\leq 7}\Big((Z_i + \overline{Z}_i) - (Z_j + \overline{Z}_j)\Big)^2,$$

De Sitter exit

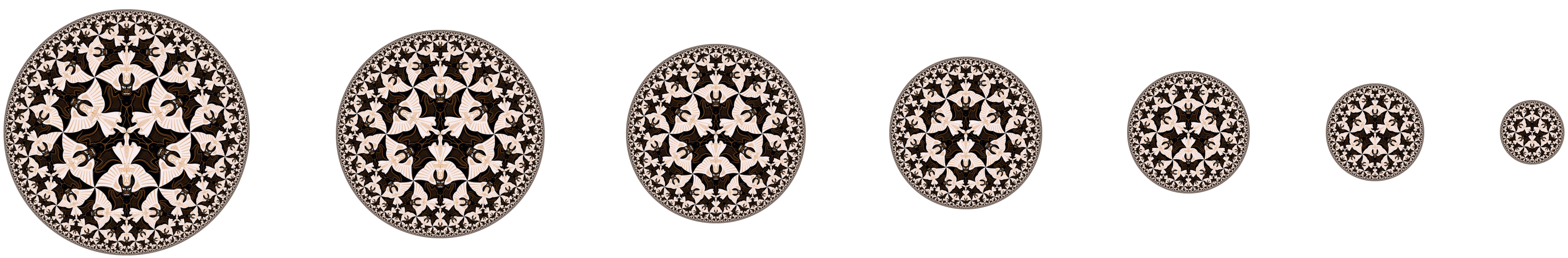
During inflation $\mathbf{V}(\varphi) = \Lambda + m^2 \tanh^2 \frac{\varphi}{\sqrt{14}},$

$r \approx 10^{-2}$

Based on CMB data on the value of the tilt of the spectrum n_s as a function of N we deduced that hyperbolic geometry of a Poincaré disk  suggests a way to explain the experimental formula

$$n_s \approx 1 - \frac{2}{N}$$

Using a consistent reduction from maximal $\mathcal{N}=8$ supersymmetry theories: M-theory in d=11, String theory in d=10, maximal supergravity in d=4, to the minimal $\mathcal{N}=1$ supersymmetry we have deduced the favorite models with hyperbolic geometry with $R^2_{Escher} = 3\alpha = 7,6,5,4,3,2,1$



$r \approx 0.9 \times 10^{-2}$ $r \approx 1.3 \times 10^{-3}$

B-mode targets from disks merger

In contrast with $\mathcal{N}=1$ supersymmetry models where 3α is arbitrary

Short summary on B-modes

- B-mode detection, if it takes place, will probe energies at about 10^{13} GeV, billion times higher than the energies probed at LHC

- Whereas LIGO discovery of gravitational waves confirms General Relativity, a discovery of primordial gravitational waves will confirm our understanding of Quantum Gravity, up to energies of inflation, since we describe inflationary perturbations using both General Relativity and Quantum field Theory

- The range of B-mode space detectors $10^{-3} < r < 10^{-2}$ is particularly interesting since it has targets from the fundamental physics: string theory, M-theory, maximal supergravity

Seven values scanning the range between 10^{-3} and 10^{-2}

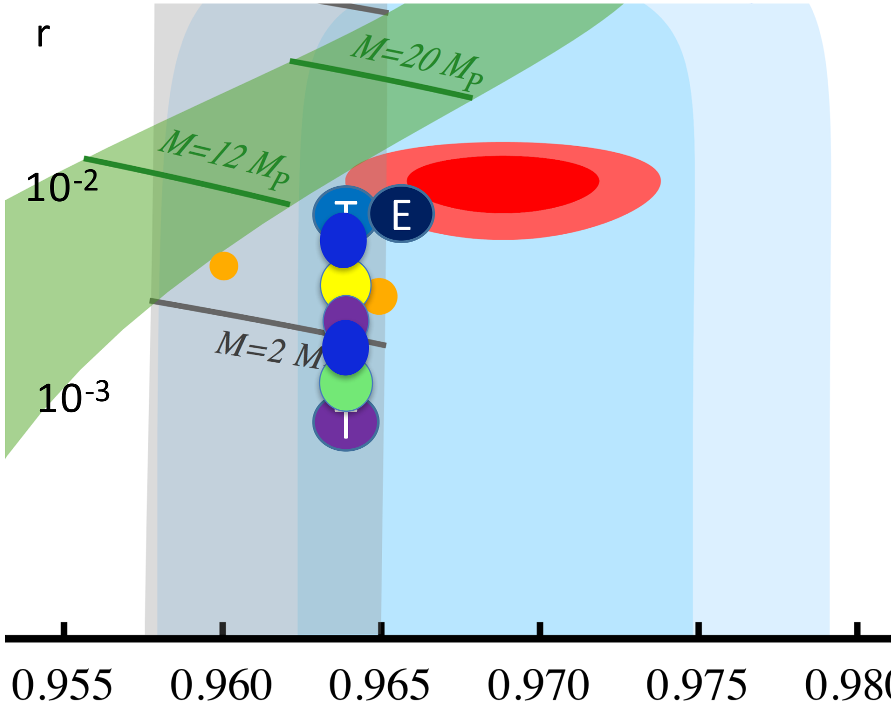
$$r \approx 3\alpha \frac{4}{N^2} \qquad n_s \approx 1 - \frac{2}{N}$$

α-attractor models

Example
$$n_s \approx 0.963$$
N=55 e-foldings

3α= 7,6,5,4,3,2,1

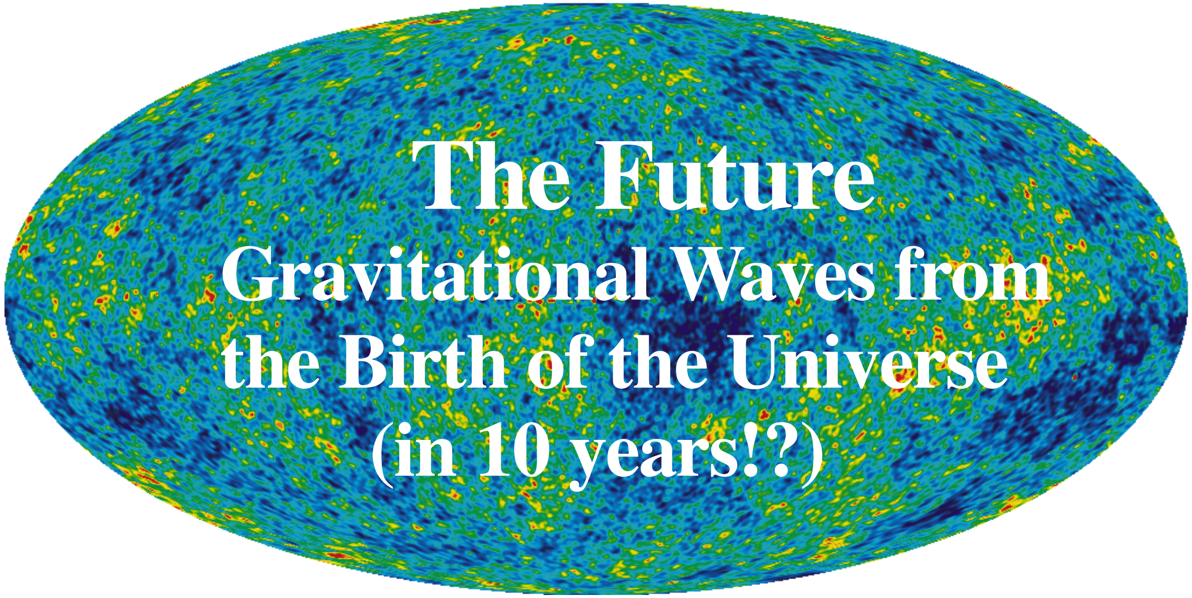
Starobinsky and Higgs, α=1



Higgs $N_* = 57$

R^2 $N_* = 50$

Seven new targets



L. Page, talk at the Breakthrough Prize Symposium, December 4, 2017 at Stanford

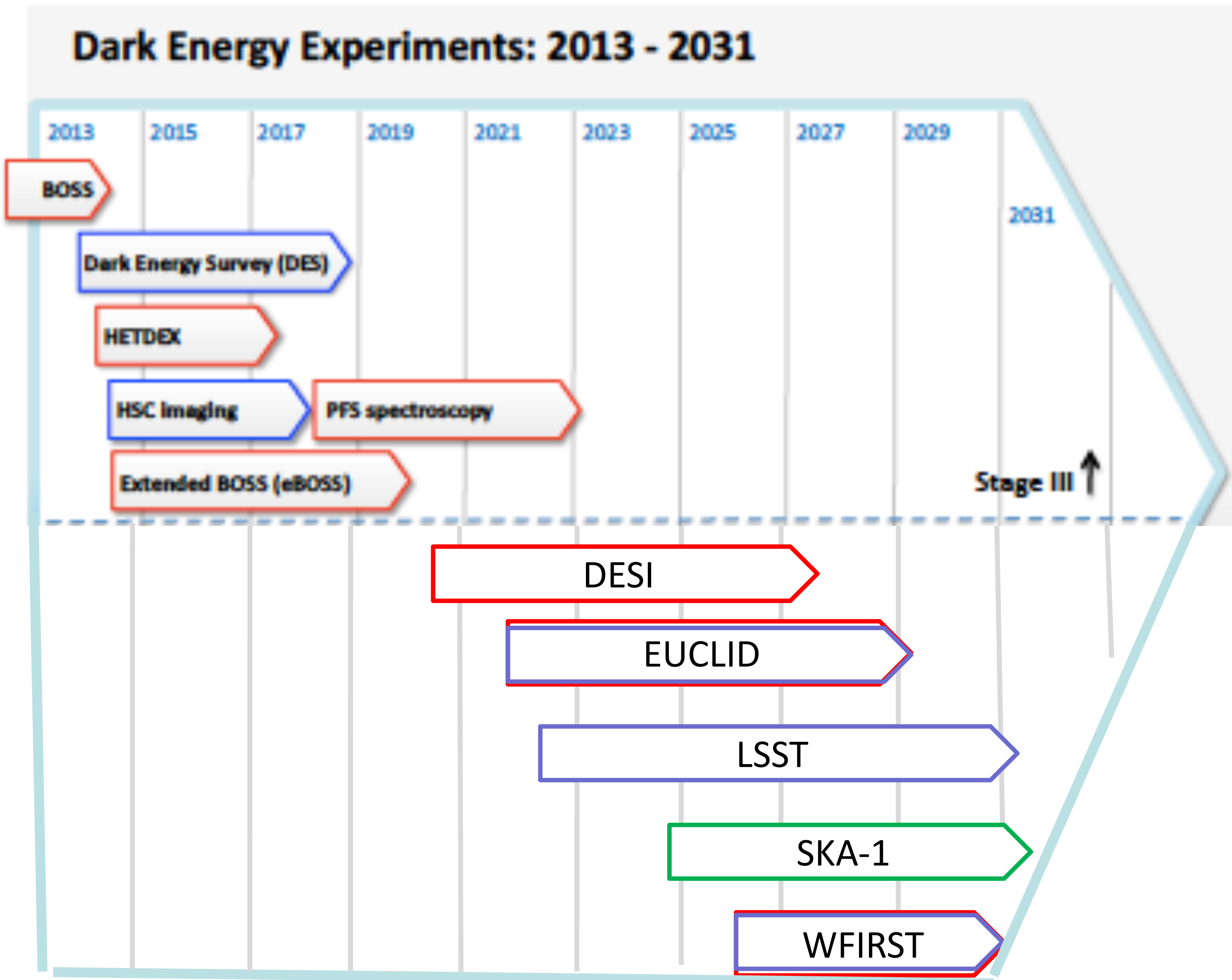
Primordial gravitational waves would be a direct connection between gravitation and quantum mechanical processes

….a test of cosmology

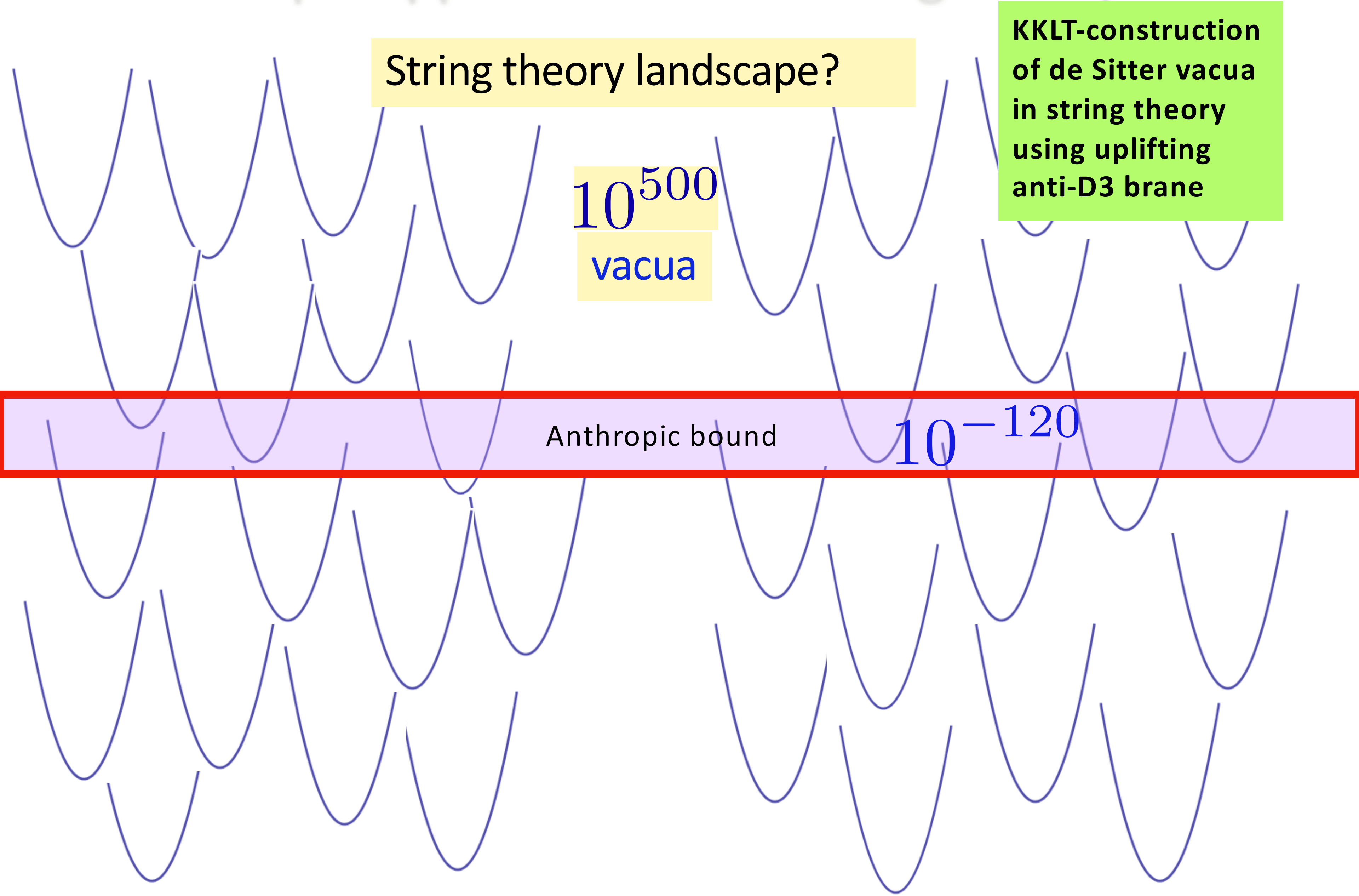
….and a link between Einstein and Bohr that has eluded physics for 100 years

$40 Million Grant Establishes Simons Observatory, a New Investigation into the Formation of the Early Universe

The DE road map past to future



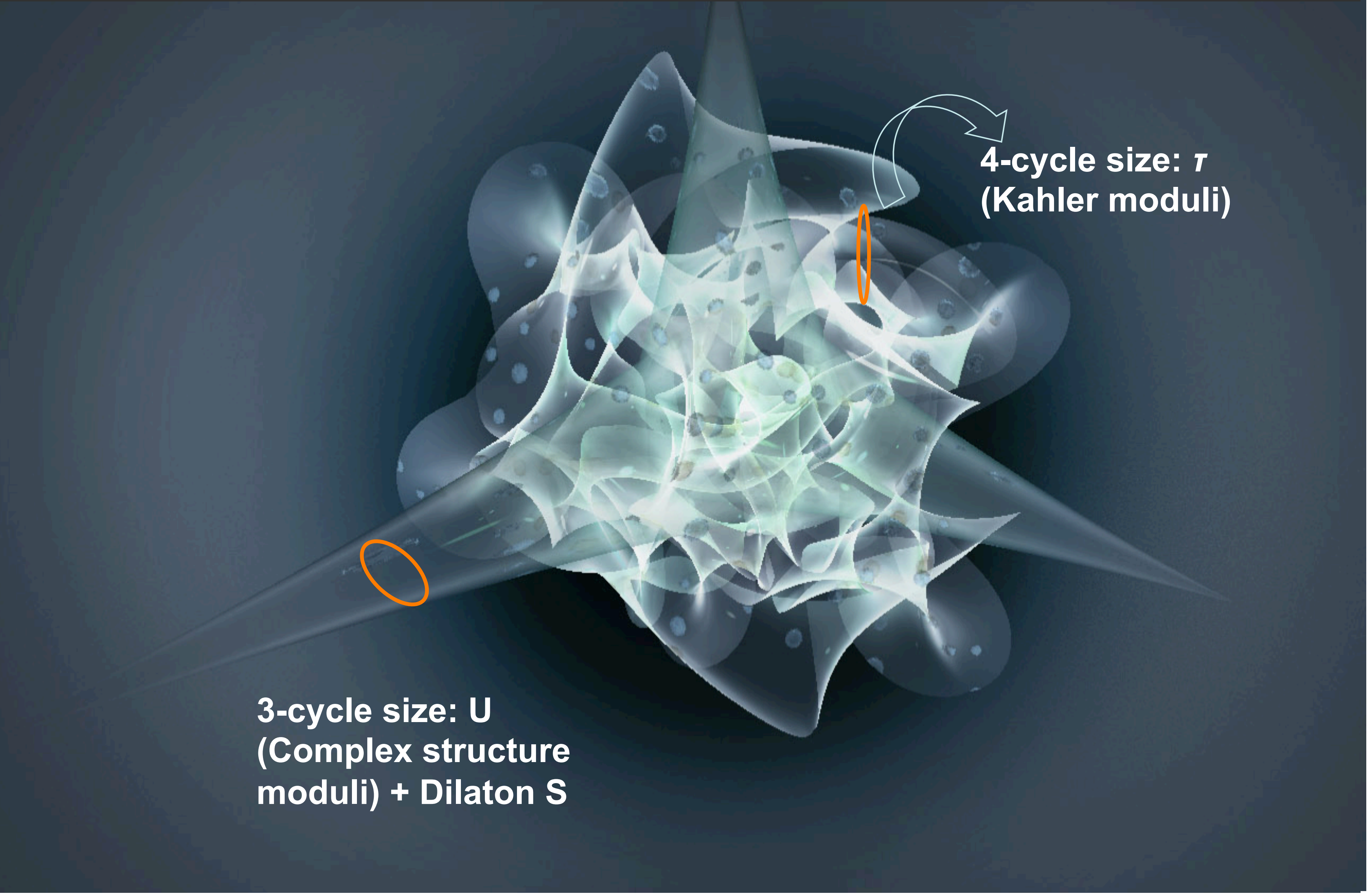
Anthropic approach to Λ in string theory:



Before quantum corrections

After quantum corrections

IIB MODULI STABILISATION



Dark Energy, ΛCDM, wCDM

String landscape picture: many moduli, one has to stabilize many scalars to produce the (metastable) de Sitter vacua with positive CC

KKLT construction, 2003 **Anti-D3-brane** in Giddings-Kachru-Polchinski backgrounc

De Sitter vacua in string theory
Kachru, RK, Linde, Trivedi 2530 refs.

Towards inflation in string theory
Kachru, RK, Linde, Maldacena, McAllister, Trivedi 1050 refs.

Supergravity approximation: starting 2002, how to construct **de Sitter vacua inspired by string theory**.

String theory and supergravity prefer AdS or Minkowski vacua with unbroken supersymmetry

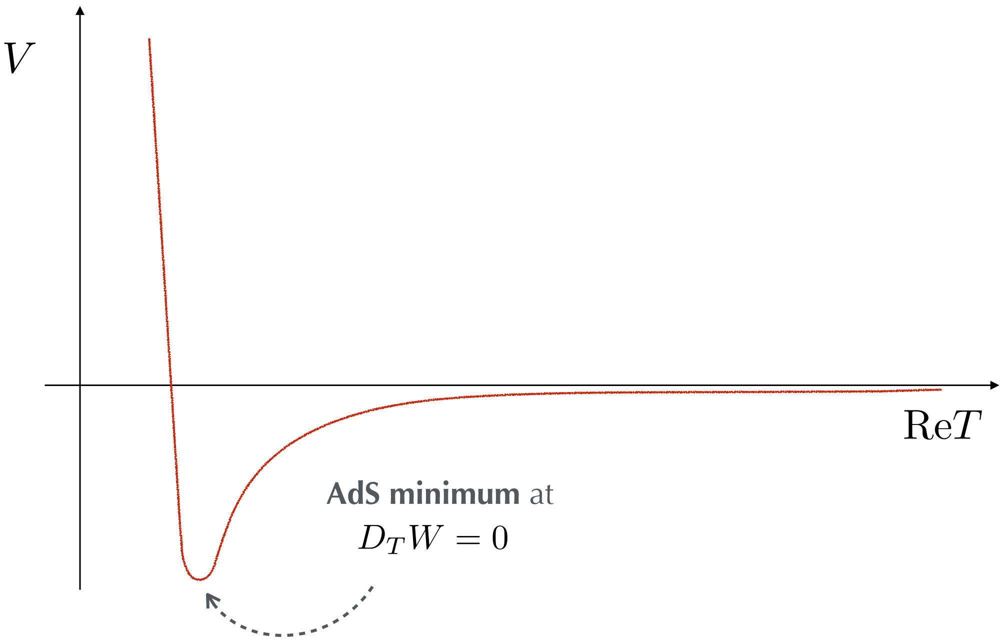
KKLT

Kachru, Kallosh, Linde, Trivedi 2003

$$K = -3\log(T+\bar{T})$$

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

$$V = V_T$$

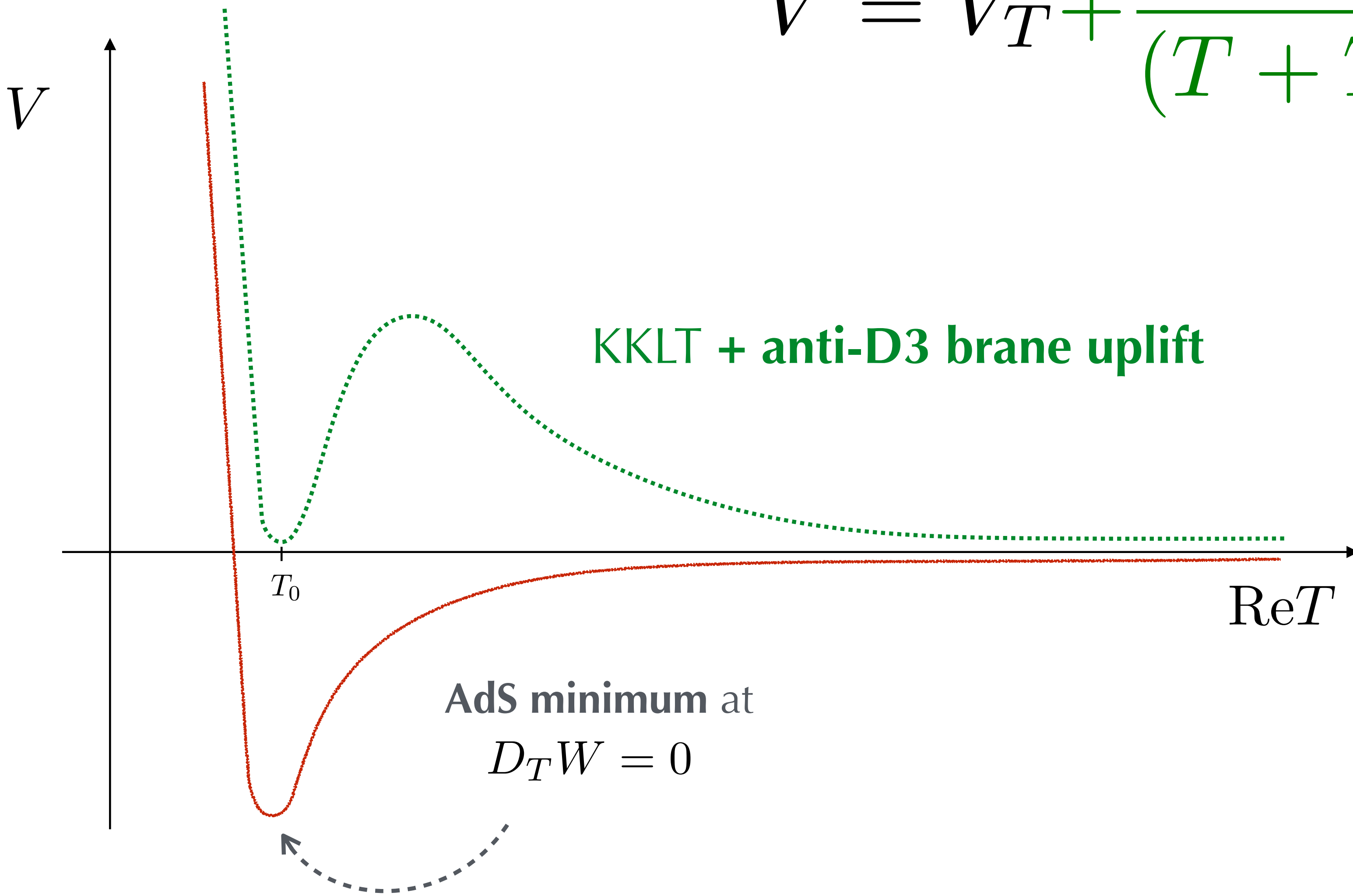


Negative CC

Stabilization of the volume of the extra six dimensions (Calabi-Yau manifold)

Still 2003, positive energy from the anti-D3 brane

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



D=4 Supergravity Language

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

$$W = W_0 + A\exp(-aT) + \mu^2 S$$

The nilpotent superfield

Represents anti-D3 brane

$$S(x,\theta) = s(x) + \sqrt{2}\lambda(x)\theta + F(x)\theta^2$$

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

$$\Downarrow$$

$$S(x,\theta) = \frac{\lambda\lambda}{2F} + \sqrt{2}\lambda\theta + F\theta^2$$

no scalar! **just fermions!**

Volkov, Akulov 1972,1973
Rocek; Ivanov, Kapustnikov 1978
Lindstrom, Rocek 1979
Casalbuoni, De Curtis, Dominici, Feruglio, Gatto 1989
Komargodski, Seiberg 2009

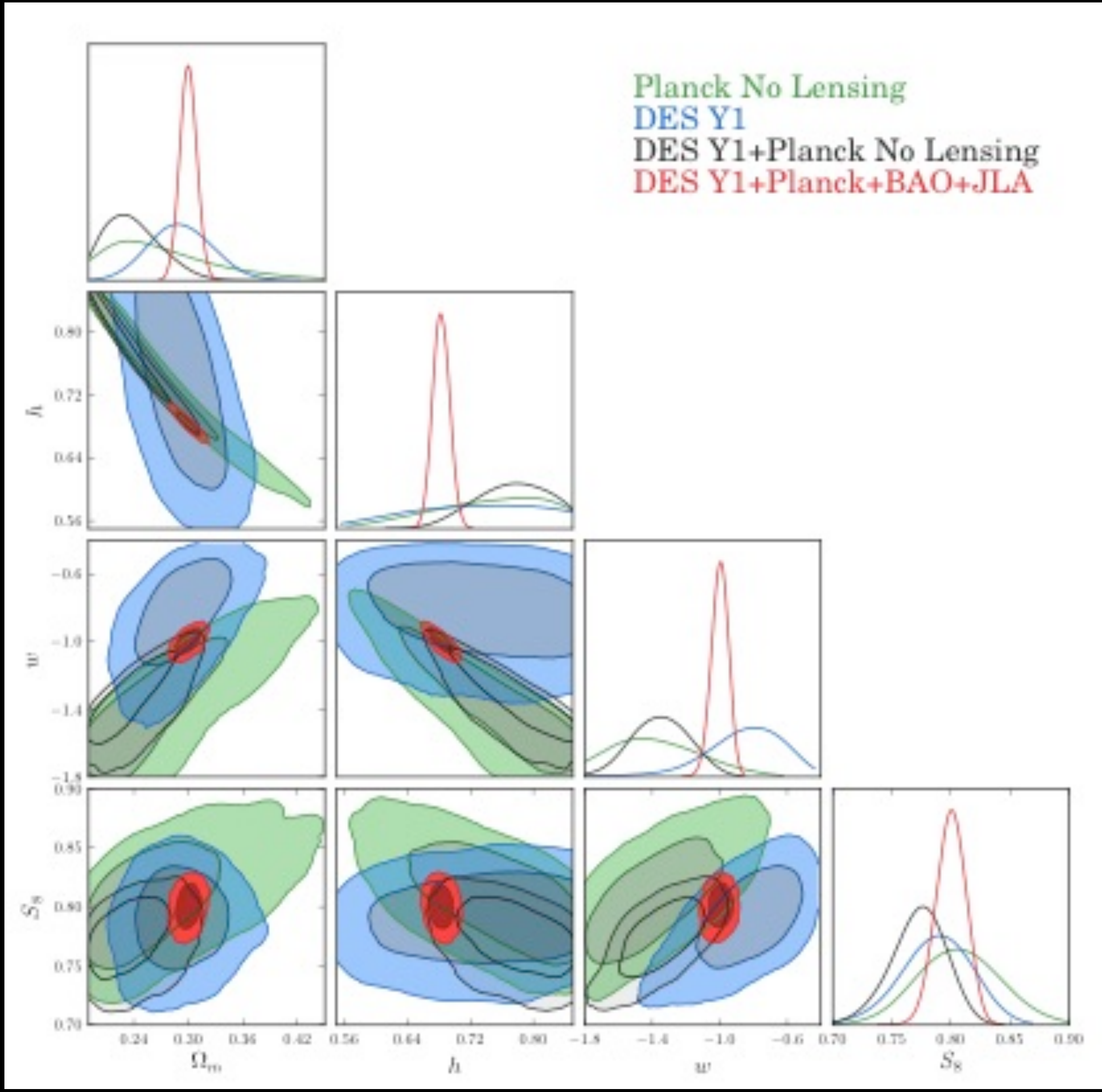
The scalar is a bilinear of a goldstino fermions, not a fundamental field

Supersymmetric uplift!

Combine multiple data sets: wCDM

- DES-3x2pt+Planck does not favor wCDM
- (w,h, M_ν) highly degenerate for DES-3x2pt/Planck alone
- DES-3x2pt+BAO+SN consistent with Planck in wCDM
- combination disfavors wCMD (R_w =0.1), yields

$$w = -1.00^{+0.04}_{-0.05}.$$



DES Collaboration 1708.01530 – revised numbers

C. Vafa et al

De Sitter Space and the Swampland   June 21, 2018

proposed a swampland criterion

accelerating universes

$$|\nabla V| \geq c \cdot V,$$

Vafa, Steinhardt et al

On the Cosmological Implications of the String Swampland   June 25, 2018

$$|\nabla V| \geq c \cdot V,$$

Excludes de Sitter vacua, ΛCDM

V'=0

The problem with Vafa et al proposal: all string theory examples have

$$c \geq 1$$

$$w + 1 \geq 0.33$$

Ruled out by current data

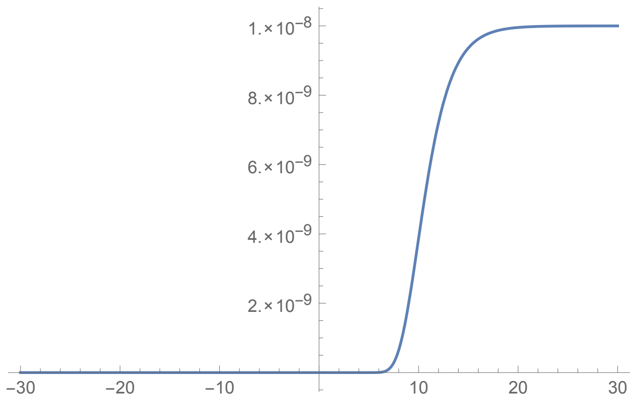
Kind of admitted in the second paper, that one needs c < 0.6

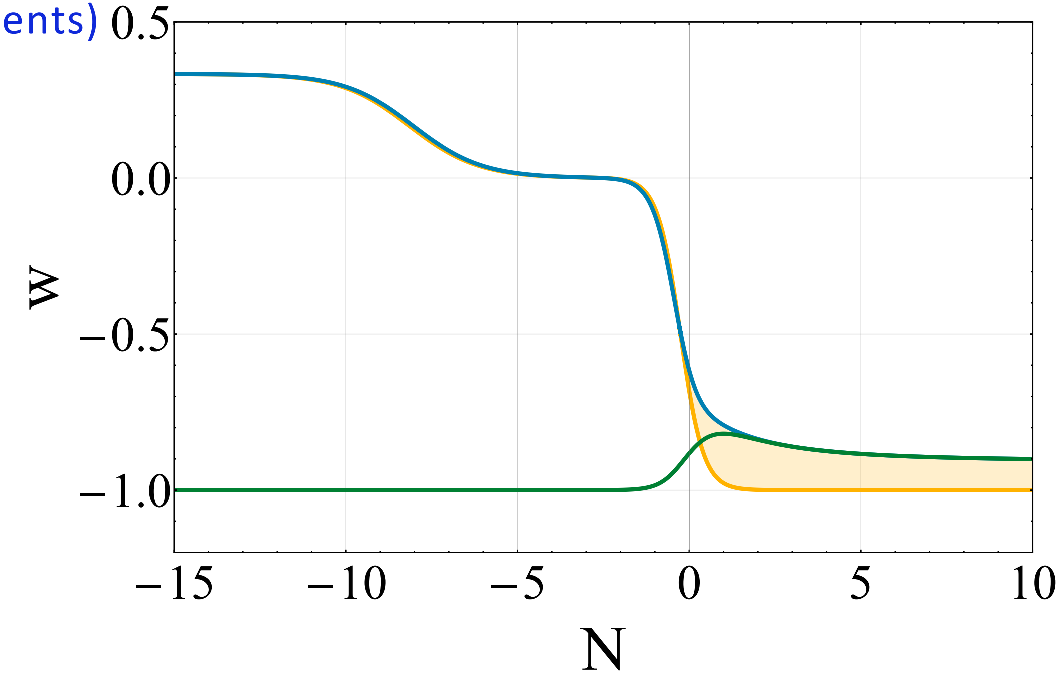
$$w + 1 < 0.12$$

Dark Energy with α-attractors : w= -1, in most cases

Dec 2017, Akrami, RK, Linde, Vardanyan

A simple quintessential inflation 2-shoulder α-attractor model (requires large exponents)





$$r = 4\,\frac{3\alpha}{N^2}$$

$$w_\infty = -1 + \frac{2}{3}\,\frac{1}{3\alpha}$$

$$3\alpha = 7 \qquad r \approx 10^{-2} \qquad w_\infty \approx -0.9$$

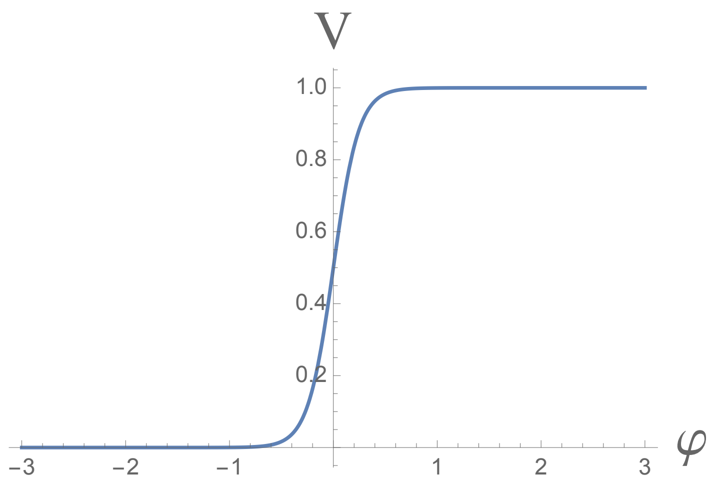
LiteBird? Euclid?

Quintessential α-attractor model with linear potential:

$$V(\phi) = \gamma\phi + \Lambda$$

In canonical variables:

$$V(\varphi) = \Lambda + \gamma\sqrt{6\alpha}(\tanh\frac{\varphi}{\sqrt{6\alpha}} + 1) \approx \Lambda + 2\gamma\sqrt{6\alpha}\, e^{\sqrt{\frac{2}{3\alpha}}\varphi}$$



Very simple potential, predictions for w depend on efficiency of reheating. Requires $\alpha = 10^{-2}$.

Thus there is nothing simpler than the cosmological constant, but if the data show that **w** is different from **-1**, we can account for it without modifying GR.

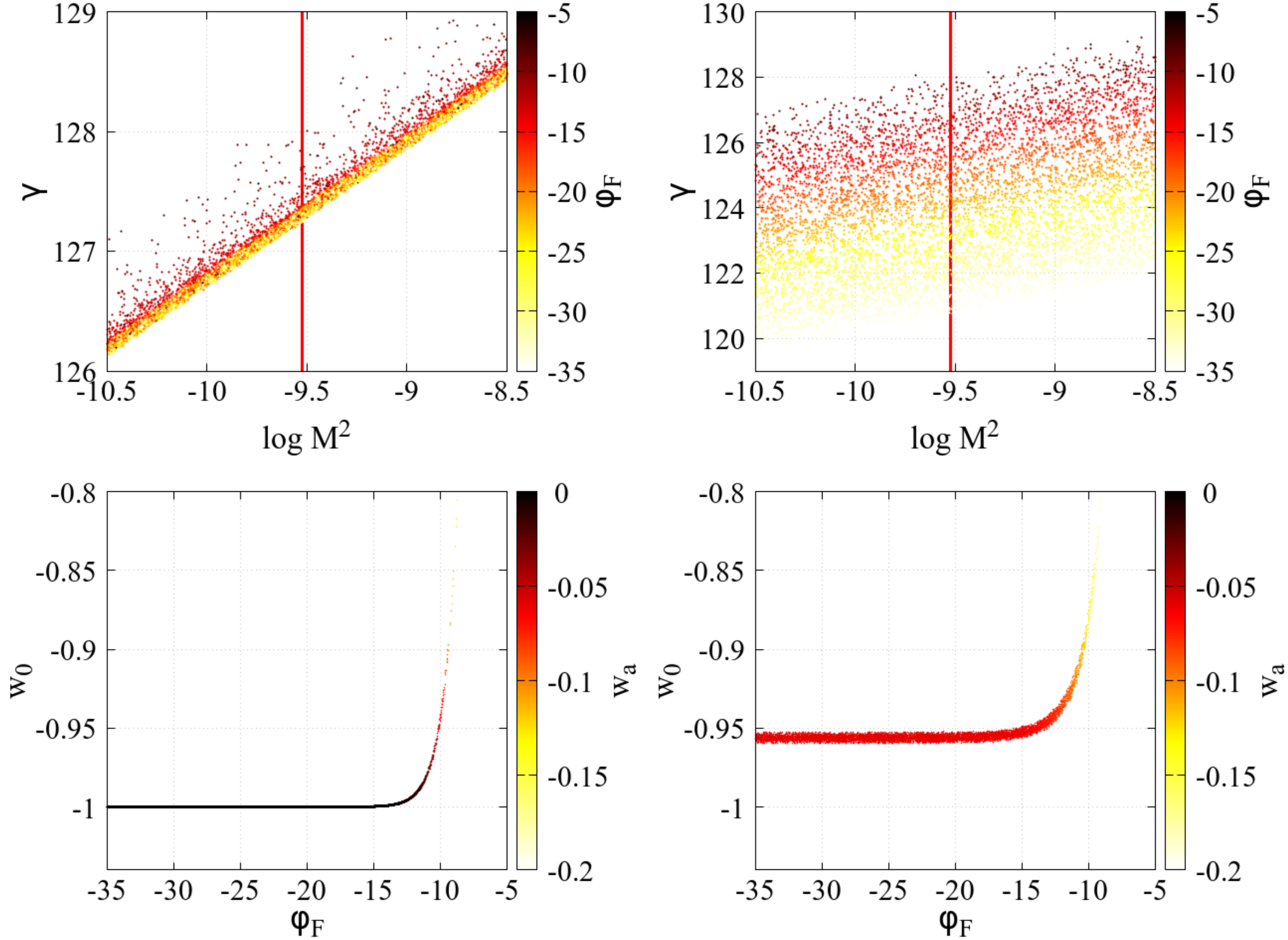


Figure 15. *Upper panels:* Cosmological constraints on $\log M^2$ and γ for Exp-model I (left panel) and Exp-model II (right panel) in term of $\varphi_{\rm F}$, when it is allowed to vary between -35 and $+8$. $\log M^2$ has been scanned over only in a range around the COBE/Planck normalization value depicted by the vertical, red lines. *Lower panels:* CPL parameters w_0 and w_a for the dark energy equation of state, for Exp-models I (left panel) and II (right panel) as functions of $\varphi_{\rm F}$. The points cluster around $w_0 = -1$ (model I) and $w_0 \sim -0.96$ (model II) for large, negative values of $\varphi_{\rm F}$.

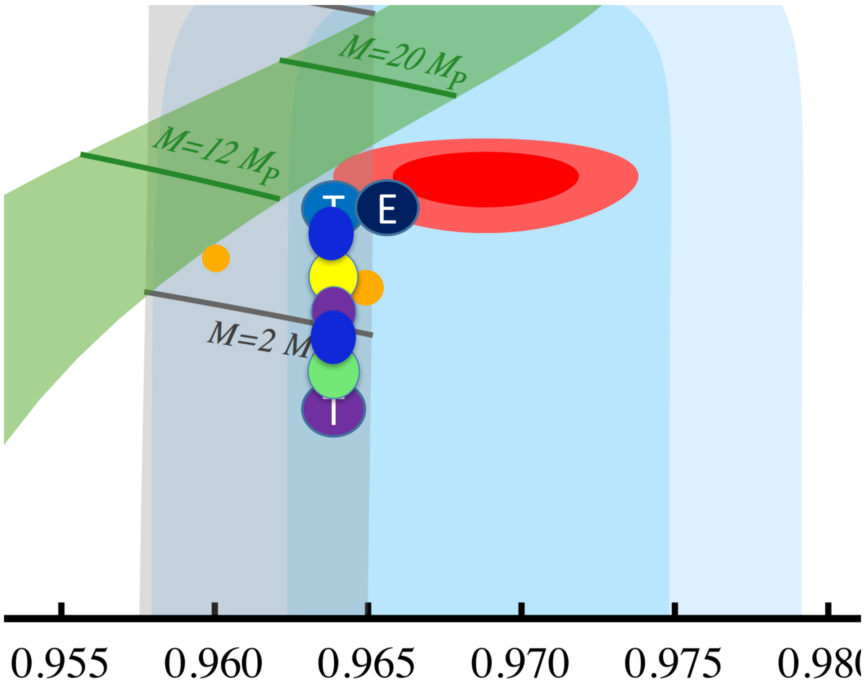
In quintessential α-attractors with gravitational preheating and a long stage of kinetic energy dominance, inflation must be longer than in the conventional α-attractors with a long stage of oscillations at about

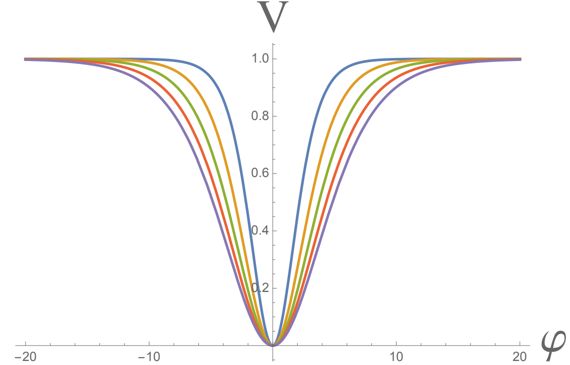
$$\Delta N \sim \frac{1}{6} \ln \left(\frac{\rho_{\rm end}}{\rho_{\rm reh}} \right)$$

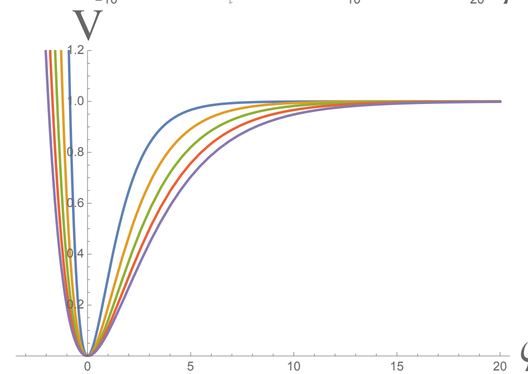
The required number of e-folds N in the quintessential α-attractor models can be greater than in the conventional α-attractors, or in the Starobinsky model, by

$$\Delta N \sim 10$$

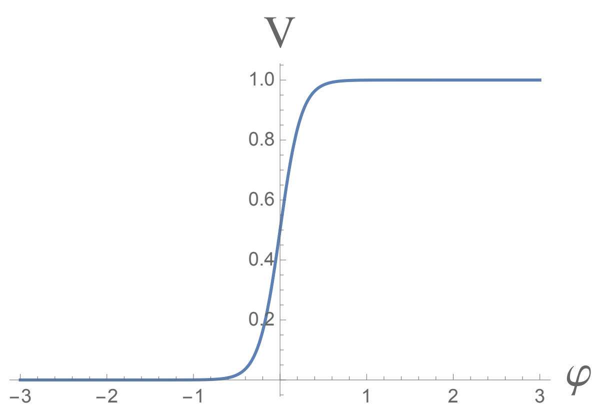
As a result, the value of $\mathbf{n_s}$ in the quintessential α-attractors with gravitational preheating is typically greater than in more traditional models by about 0.006 or so. This number coincides with one standard deviation in the Planck results. Thus by a more precise determination of $\mathbf{n_s}$ to be achieved in the future, we may be able to distinguish between the quintessential α-attractors and conventional models with a cosmological constant, even if we cannot tell the difference between **w** and **-1**. This emphasizes importance of precise measurement of $\mathbf{n_s}$.







Quintessential inflation allows to increase the number of e-foldings N, which slightly increases **n_s** for α-attractor models. With better precision on spectral index **n_s** we may differentiate in the future between inflation ending at the minimum of the potential, and the one ending at a second plateau, even if the equation of state there is **w = -1**



Looking forward for the new data