Alpha-attractors and B-mode targets

Renata Kallosh, Stanford, May 18, 2017

Keith Olive Fest

University of Minnesota

Based on work with A. Linde and
S. Ferrara, D. Roest, T. Wrase, Y. Yamada

Keith:
a friend and a collaborator

Talks by J. Ellis and D. Nanopoulos
and many other collaborators

My personal interest

K.A. Olive *et al.* (Particle Data Group)

Best source of information for teaching QFT III


KCL-PH-TH/2015-23, LCTS/2015-13, CERN-PH-TH/2015-122
ACT-04-15, MI-TH-1513
UMN-TH-3438/15, FTPI-MINN-15/26

Calculations of Inflaton Decays and Reheating: with Applications to No-Scale Inflation Models

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ABSTRACT

We discuss inflaton decays and reheating in no-scale Starobinsky-like models of inflation, calculating the effective equation-of-state parameter, w, during the epoch of inflaton decay, the reheating temperature, T_{reh}, and the number of inflationary e-folds, N_*, comparing analytical approximations with numerical calculations. We then illustrate these results with applications to models based on no-scale supergravity and motivated by generic string compactifications, including scenarios where the inflaton is identified as an untwisted-sector matter field with direct Yukawa couplings to MSSM fields, and where the inflaton decays via gravitational-strength interactions. Finally, we use our results to discuss the constraints on these models imposed by present measurements of the scalar spectral index n_s and the tensor-to-scalar perturbation ratio r, converting them into constraints on N_*, the inflaton decay rate and other parameters of specific no-scale inflationary models.

May 2015

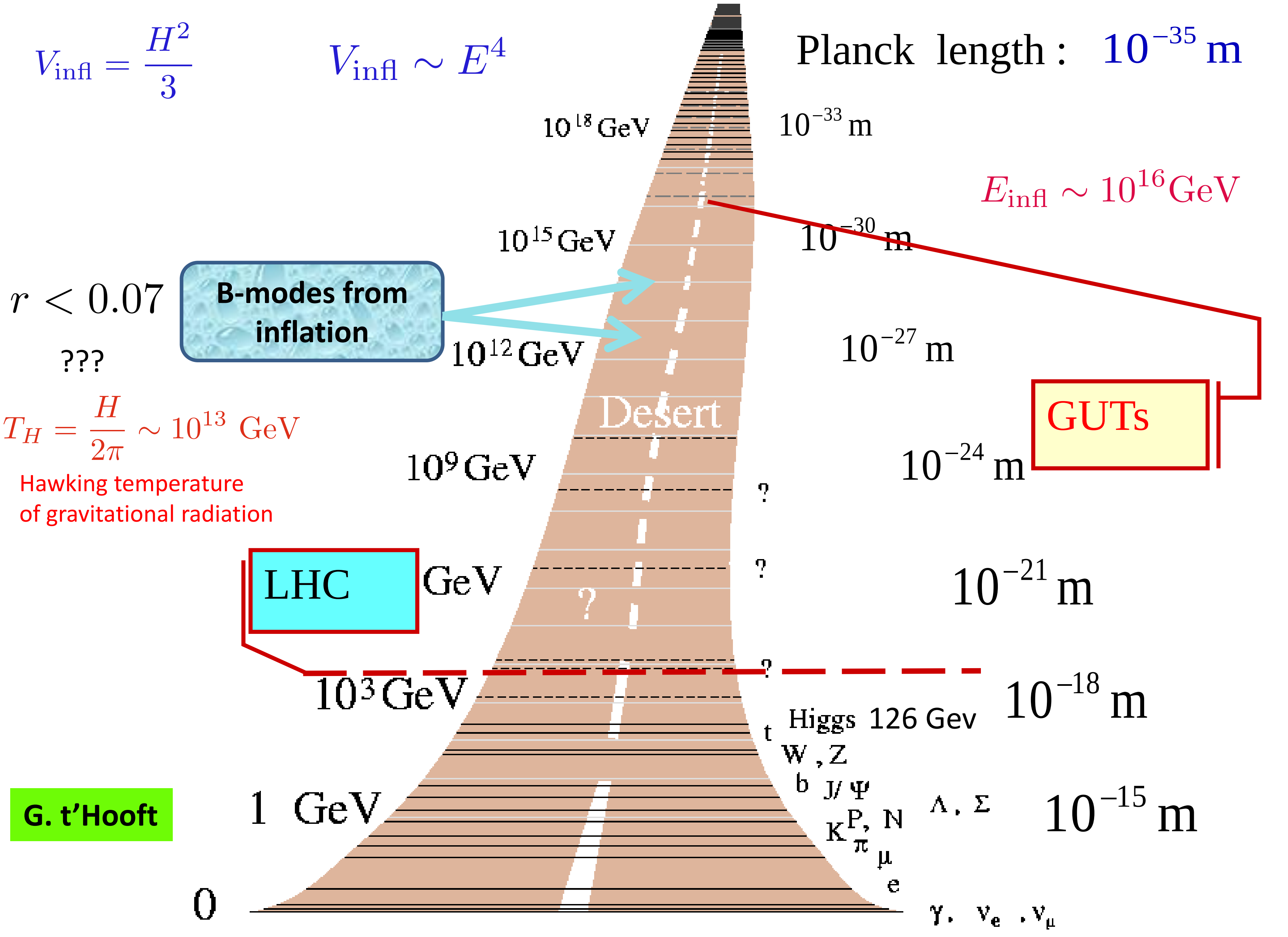
1

2015

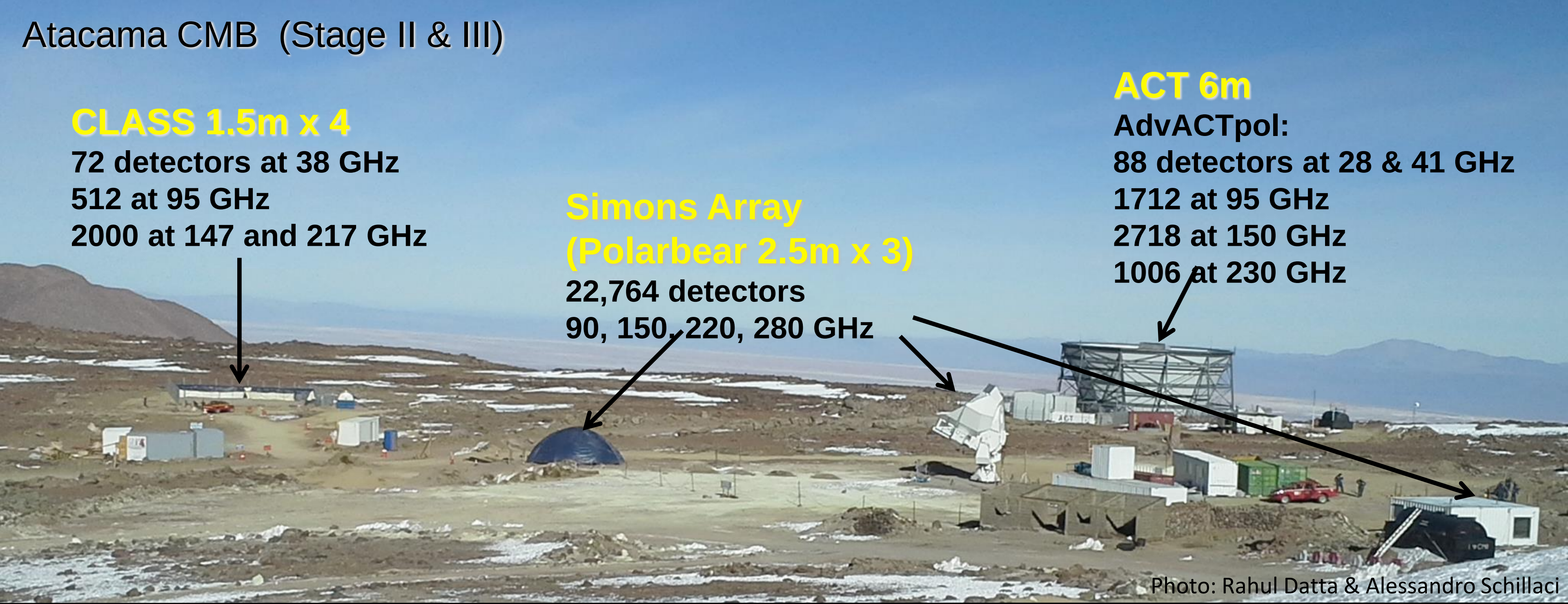
Creation of Matter in the Universe

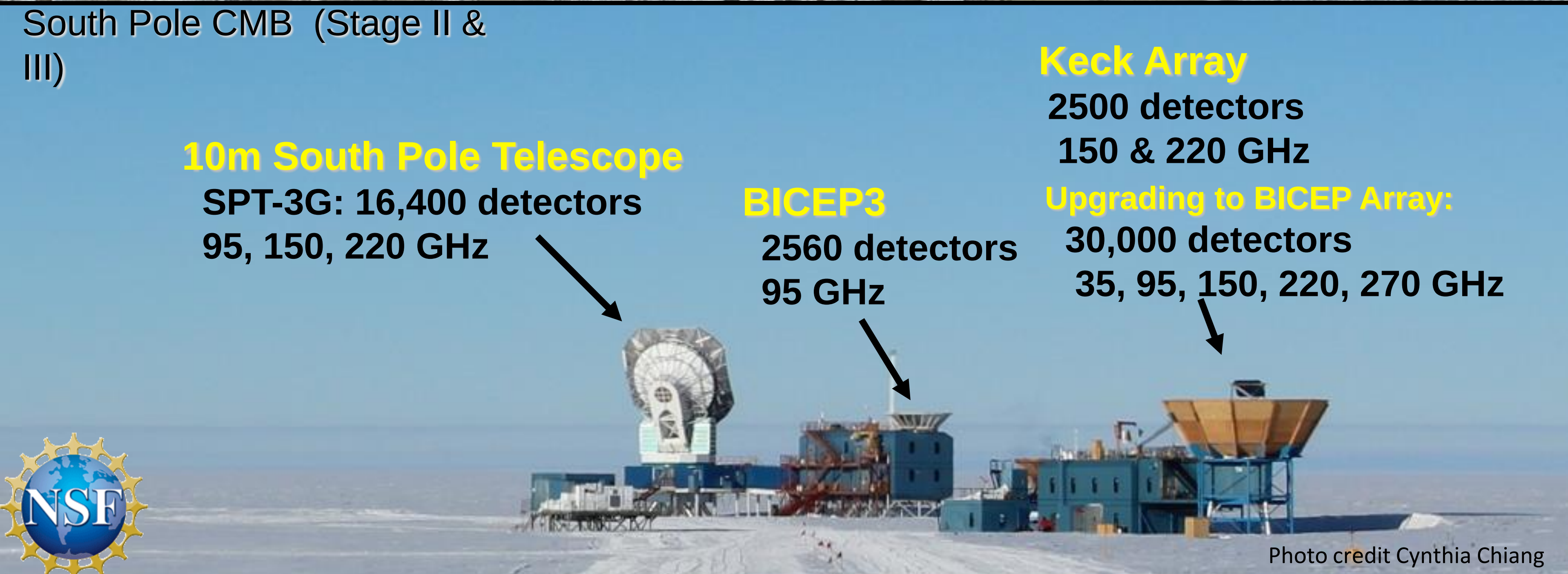
Particularly important for the analysis of the future precision cosmological data on n_s and r with regard to a number of e-foldings in inflation, N.

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



$V_{\rm infl} = \frac{H^2}{3}$
$V_{\rm infl} \sim E^4$
Planck length : 10^{-35} m
10^{18} GeV
10^{-33} m
$E_{\rm infl} \sim 10^{16}$GeV
10^{15} GeV
10^{-30} m
$r < 0.07$
B-modes from inflation
???
10^{12} GeV
10^{-27} m
$T_H = \frac{H}{2\pi} \sim 10^{13}$ GeV
Desert
GUTs
Hawking temperature
of gravitational radiation
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
G. t'Hooft
1 GeV
10^{-15} m
K P, N
π
μ
e
0
γ , ν_e , ν_μ

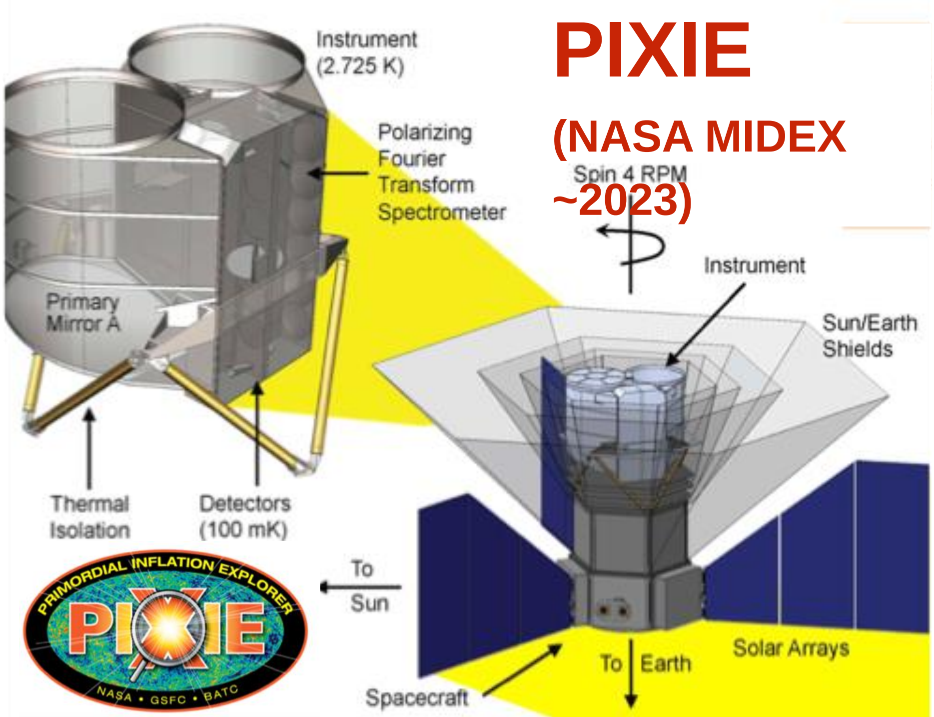

Atacama CMB (Stage II & III)
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (Stage II & III)
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
Keck Array
2500 detectors
150 & 220 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz
NSF
Photo credit Cynthia Chiang

CMB satellite proposals

PIXIE

(NASA MIDEX ~2023)



LiteCORE

(ESA M5 ~2026-2030)

LiteBIRD (JAXA, ~2025)

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

All targeting $\sigma(r) \sim$ few 10^{-4}

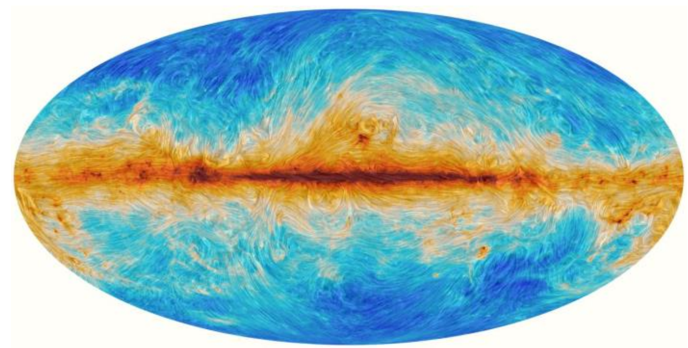
Why so many detectors for primordial gravitational waves?

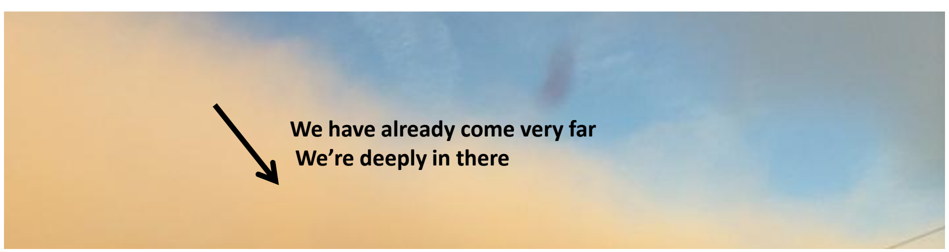
Hard to detect B-modes: removal of foregrounds, control of systematics, achieving required sensitivity

The March toward *r*=0.001

Chao-Lin Kuo **Stanford/SLAC**

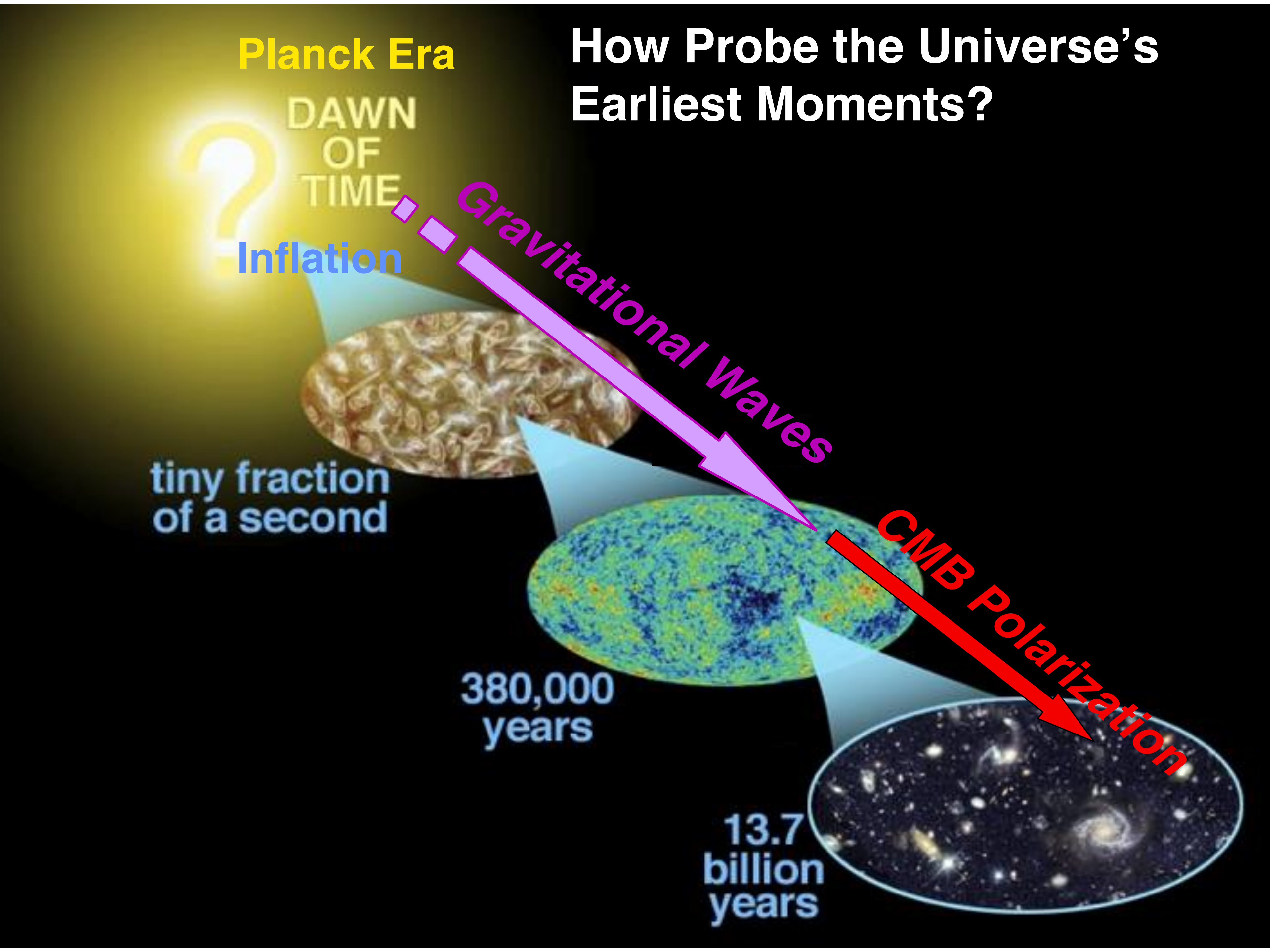
New Horizons in Inflationary Cosmology, SITP, March 3, 2017

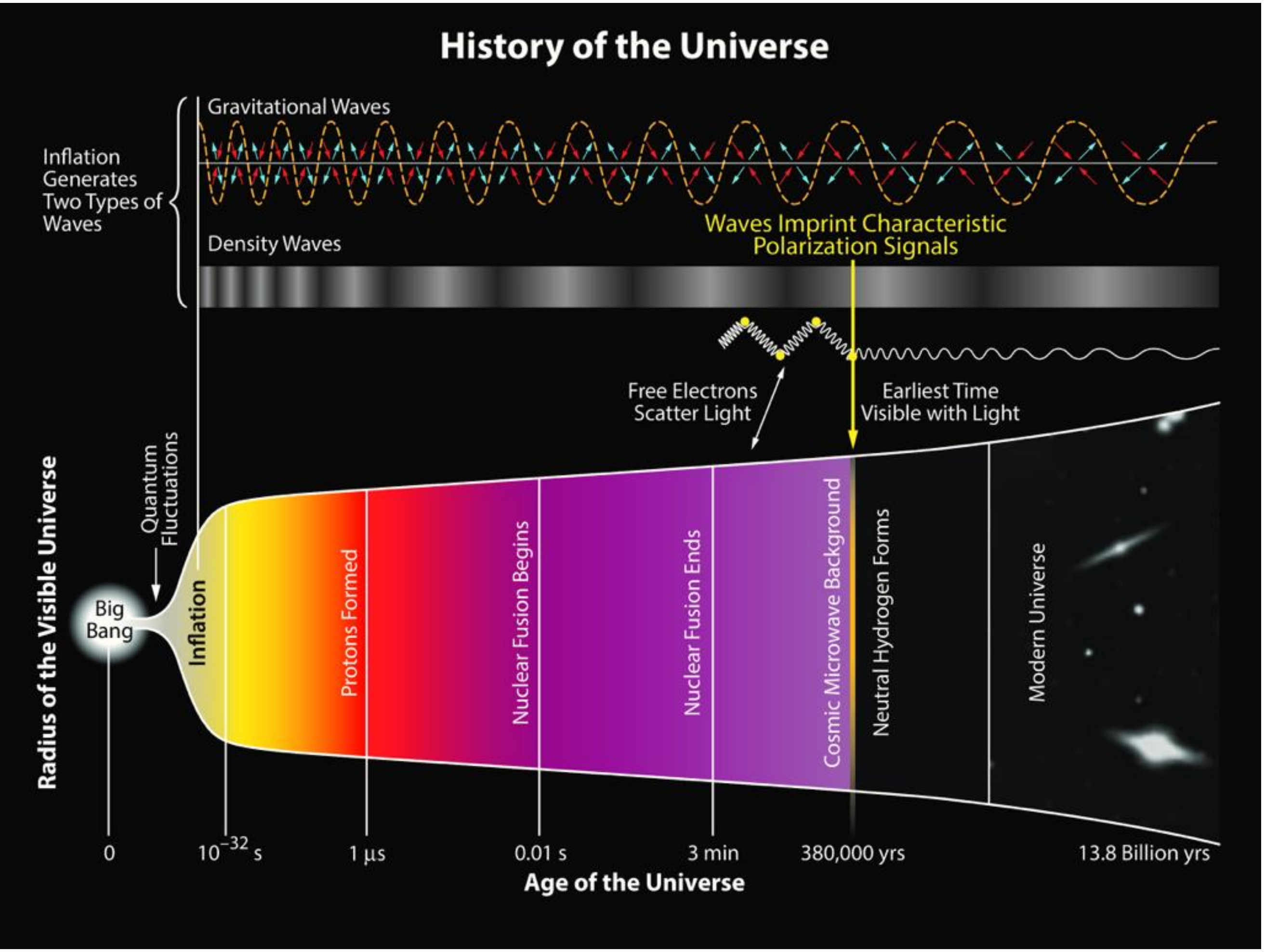




Detection would be of fundamental importance for understanding Quantum Gravity

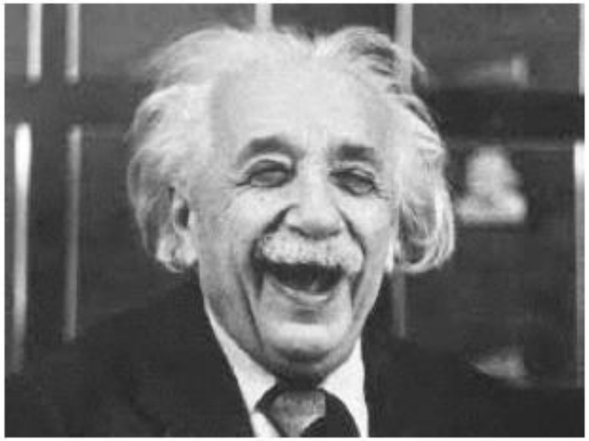
How Probe the Universe's Earliest Moments?





Primordial gravitational Waves, B-modes. Created during early universe inflation, about 13.8 billion years ago. Not yet detected.

Gravitational waves detected by LIGO from the binary black hole merger at about 1.3 billion years ago

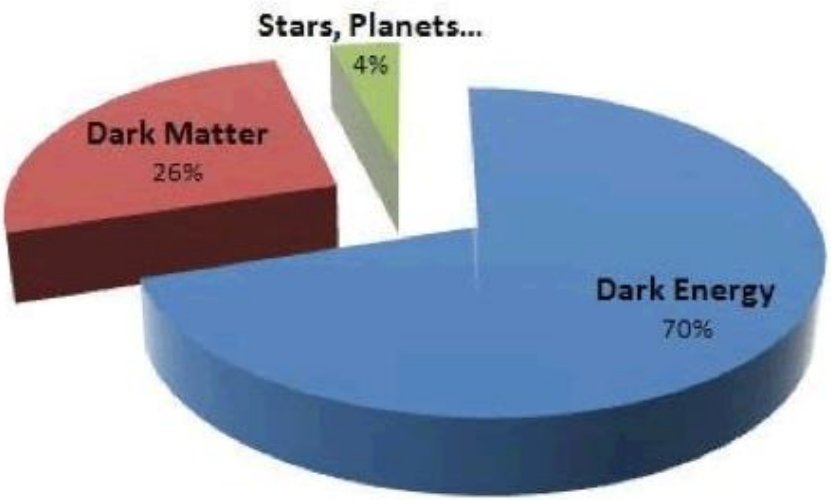


String theory landscape?

ΛCDM

$$w = -0.99 \pm 0.06$$

$$\Lambda \sim (10^{-30} M_{Pl})^4 \sim 10^{-120}\, M_{Pl}^4$$

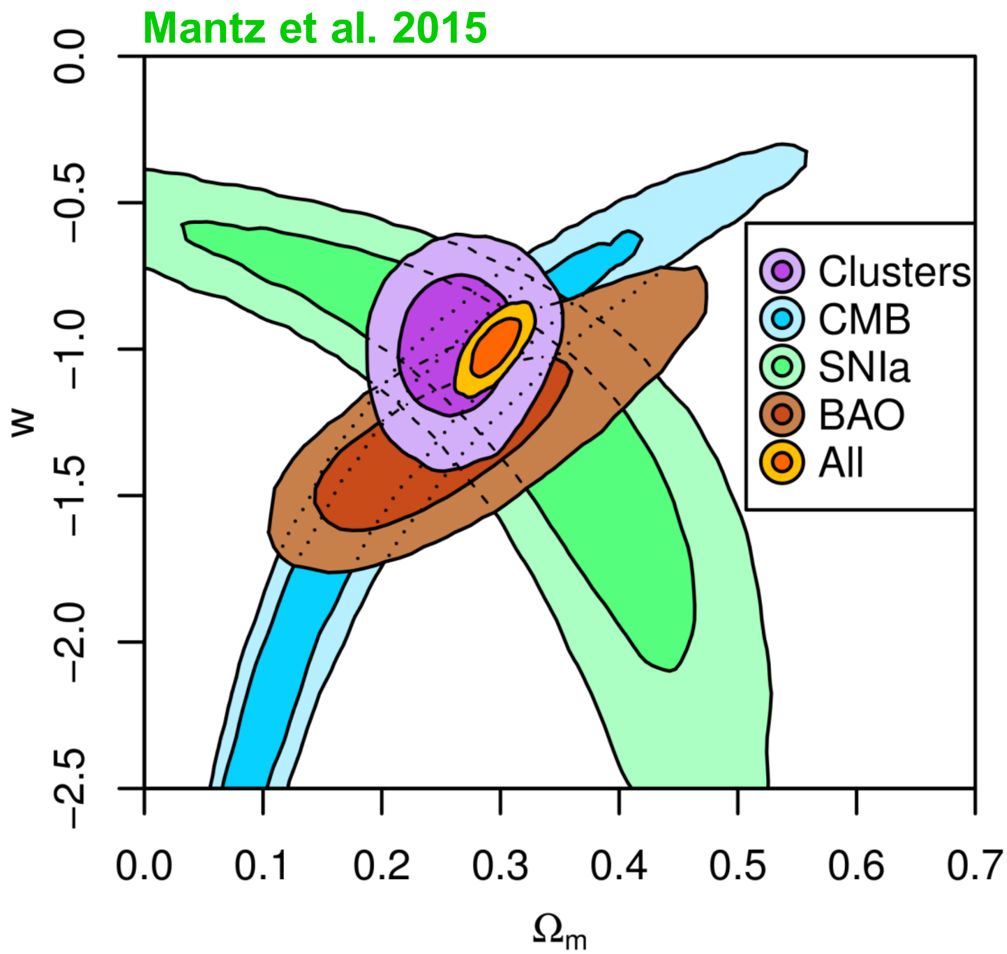


$$\Lambda \sim (10^{-3} eV)^4$$

ΛCDM cosmology

Dark energy: clusters vs. independent techniques

From S. Allen talk at CMBS4, Feb2017



Flat, constant w model:

Clusters (Mantz et al. '15)
CMB (WMAP9+SPT+ACT)
SNIa (Suzuki et al. '12)
BAO (Anderson et al. '14)

Combined constraint (68%)

$\Omega_m = 0.295 \pm 0.013$
$\sigma_8 = 0.819 \pm 0.026$
$w = -0.99 \pm 0.06$

Cluster constraints from 224 massive clusters at z<0.5 (+ Chandra X-ray + WTG weak lensing) competitive with other leading cosmological methods.

Recent data (non CMB)

The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample

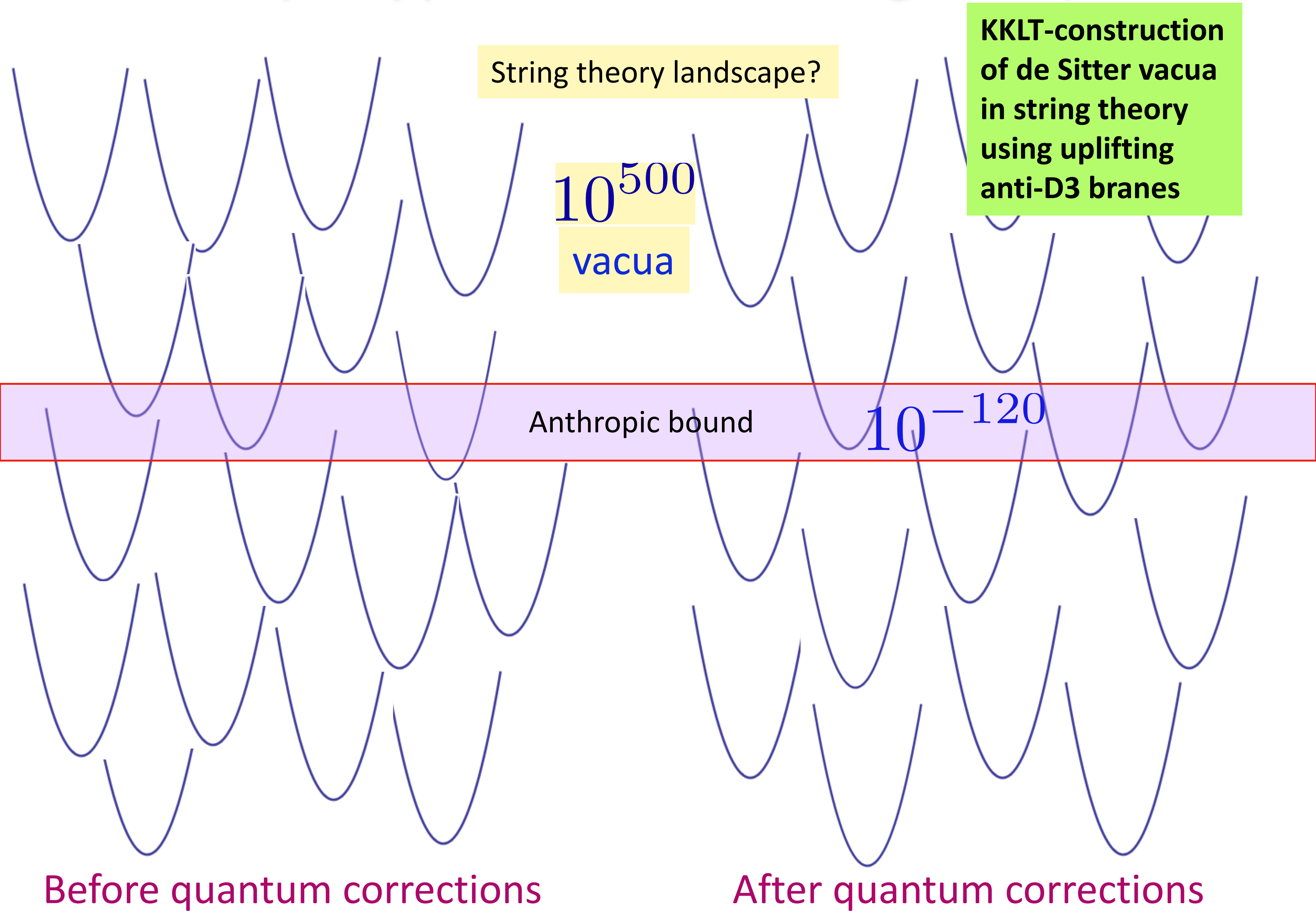
2016

$$\Omega_K = 0.0003 \pm 0.0026$$

$$w = 1.01 \pm 0.06$$

strong affirmation of the spatially flat cold dark matter model with a cosmological constant (ΛCDM)

Anthropic approach to Λ in string theory:

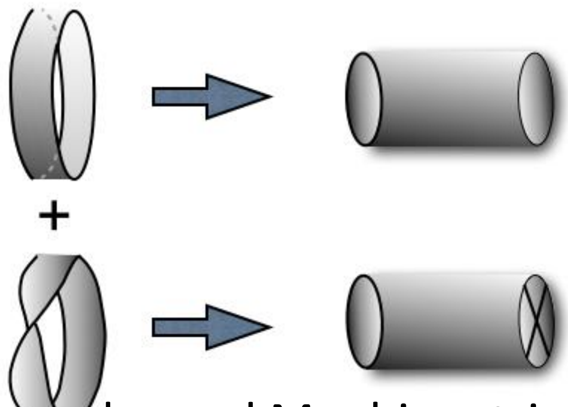


String Theory Realizations of the Nilpotent Goldstino

RK, Quevedo, Uranga 2015
Earlier work by Dudas et al

A technical tool for the string theory landscape construction and for inflationary model building

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



The one-loop open string annulus and Moebius strip diagrams turn into closed string channel diagrams describing tree level exchange of NSNS and RR states between two boundaries (branes or antibranes), or between one boundary and one crosscap (O3-plane)

Non-linear supersymmetry: not of the kind which was not found at LHC

Volkov-Akulov, 1972

Allows de Sitter vacua in Supergravity without scalars

The Cosmic Microwave Background Stage 4 Concept Definition Task force

- A subset of the CMB-S4 community set up to do a specific job

- A Task Force set up by the Astronomy and Astrophysics Advisory Committee (AAAC) at the request of

- The DOE Office of High Energy Physics (HEP)

- The NSF Divisions of Astronomical Sciences (AST) Physics (PHY) **2017**

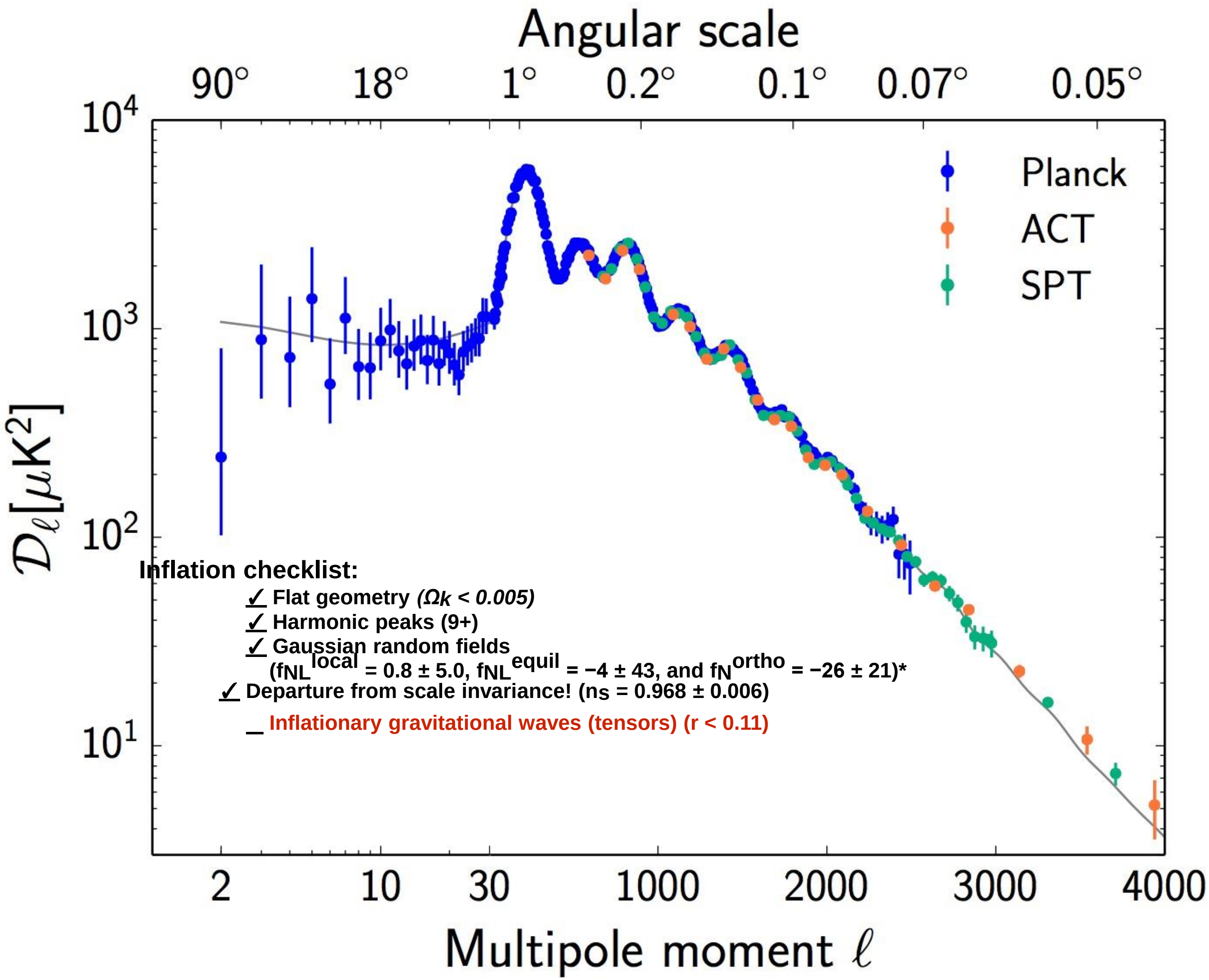
- Polar Programs (PLR)

- to "develop a concept for a CMB-S4 experiment".

Science Requirements - Six areas:

- – Inflation [r or $\sigma(r)$]
- – Neutrinos [(Σ m)]
- – Light relics [$\sigma(N_{eff})$]
- Dark matter [?]
- Dark energy [?]
- Astro [?]

Status of primary CMB TT measurements



Inflation checklist:

- **✓ Flat geometry *($\Omega_K < 0.005$)***
- **✓ Harmonic peaks (9+)**
- **✓ Gaussian random fields ($f_{NL}^{local} = 0.8 \pm 5.0$, $f_{NL}^{equil} = -4 \pm 43$, and $f_N^{ortho} = -26 \pm 21$)***
- **✓ Departure from scale invariance! ($n_S = 0.968 \pm 0.006$)**
- **_ Inflationary gravitational waves (tensors) ($r < 0.11$)**

J. Carlstrom

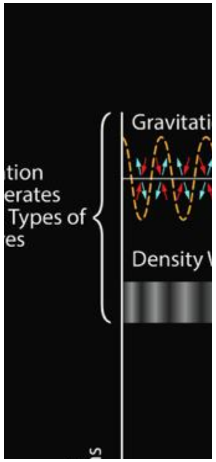
*constraints include CMB polarization data

Glossary

N : the number of e-folds N left to the end of inflation, defined as

$$a = a_f e^{-N}$$

where a is the scale factor and a_f is its value at the end of inflation. The spectrum of fluctuations observed in CMB corresponds to



$$47 < N < 57$$

n_s: Tilt of the spectrum of inflationary perturbations

$$n_s \approx 0.965$$

r : Level of B-modes, r=T/S. Not detected

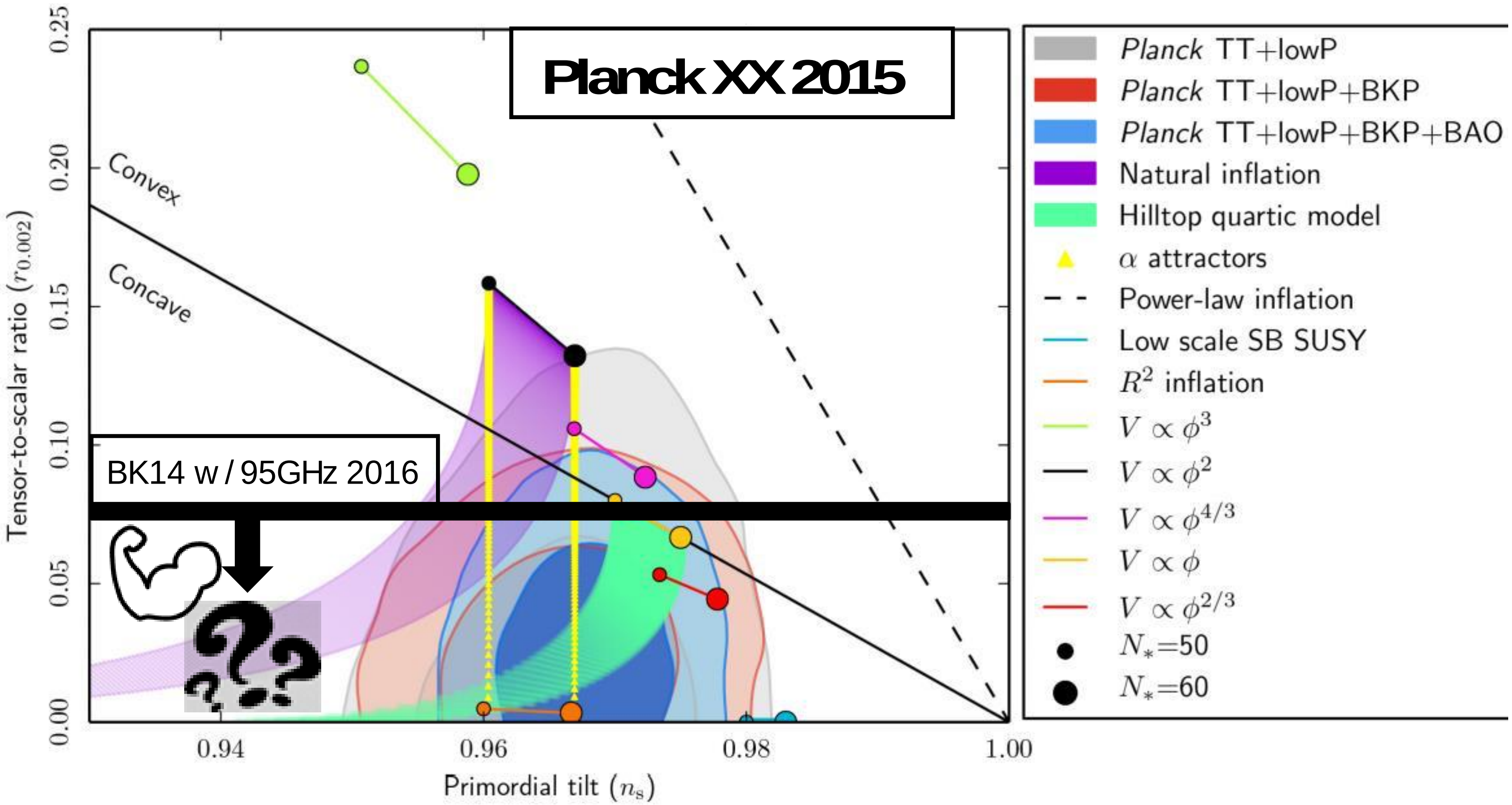
$$r < 0.07$$

N : is the number of supersymmetries, Majorana spinors. The maximal number for theories with highest spin 2 is

$$\mathcal{N} = 8$$

The minimal number which we will consider here is

$$\mathcal{N} = 1$$



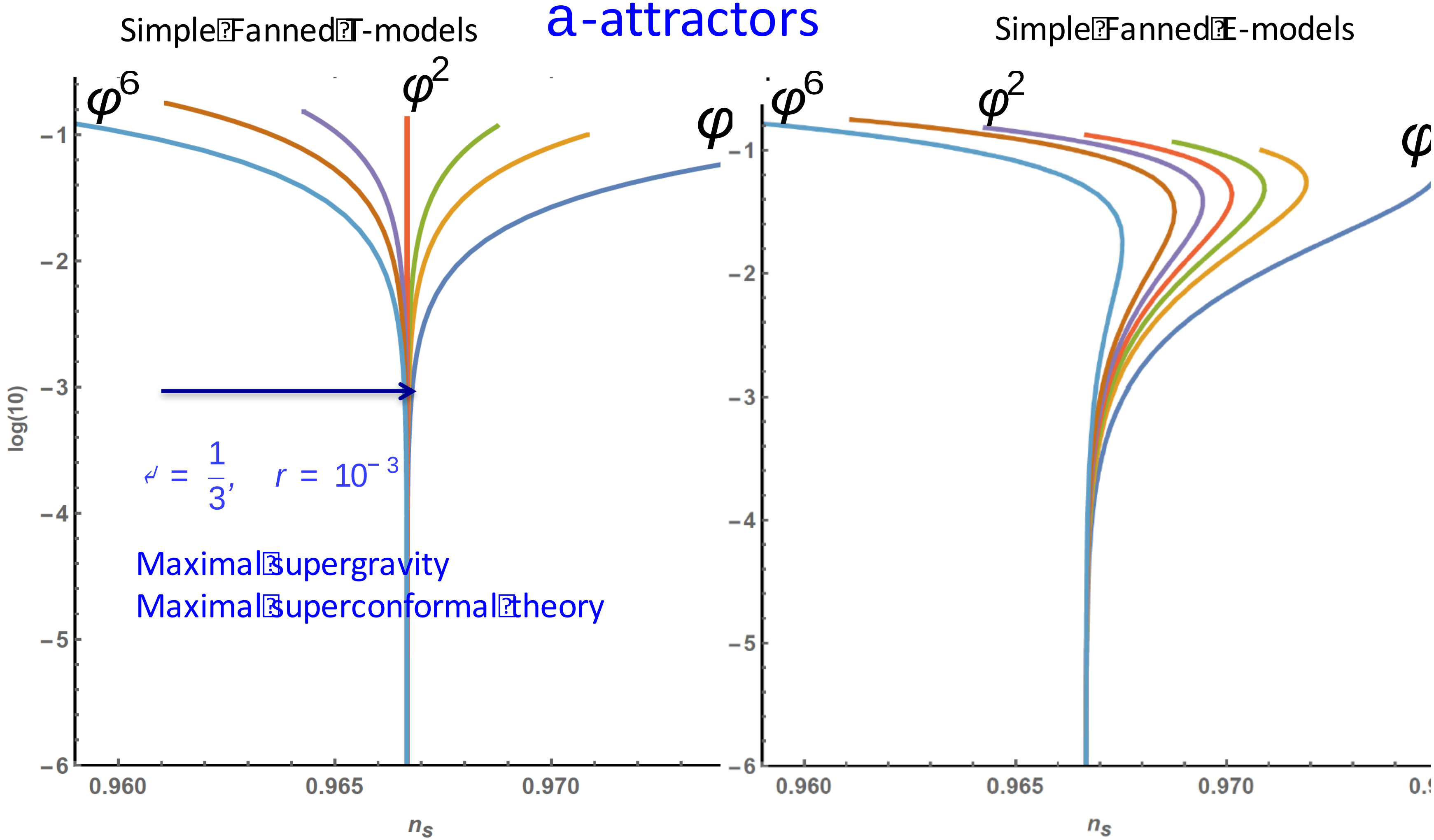
Next in CMB cosmology:

Relentless observation

If B-modes will be discovered soon, $r > 10^{-2}$
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

a-attractors



tanh p ′ / 6↲ σ 2n

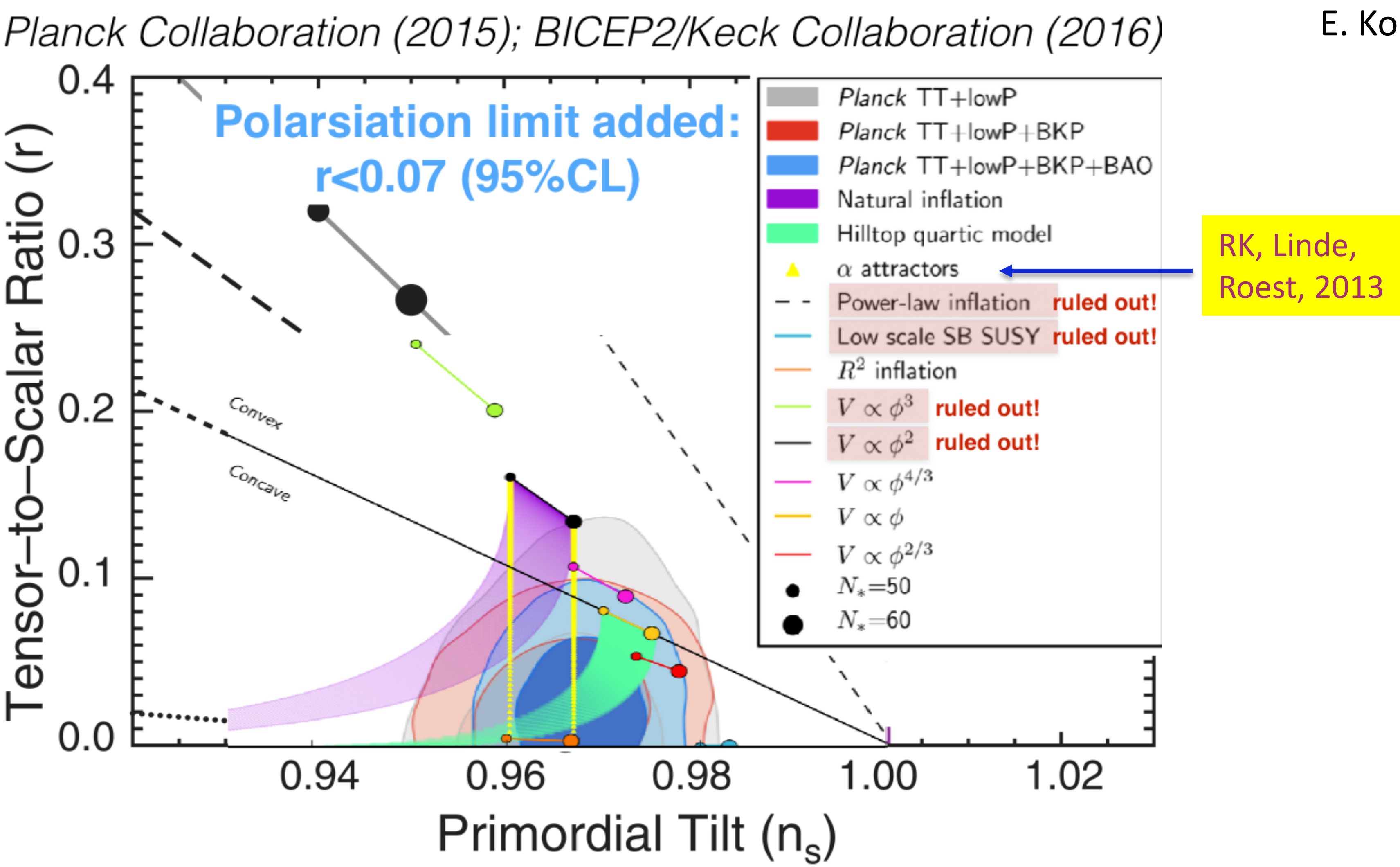
1 − e ^ μ 2/3↲ , σ 2n

If polarization from GW is found…

Then what? The next step is to nail the specific model of inflation

We are closing in on the first 10^{-35} seconds of the universe, using General Relativity and QFT

E. Komatsu



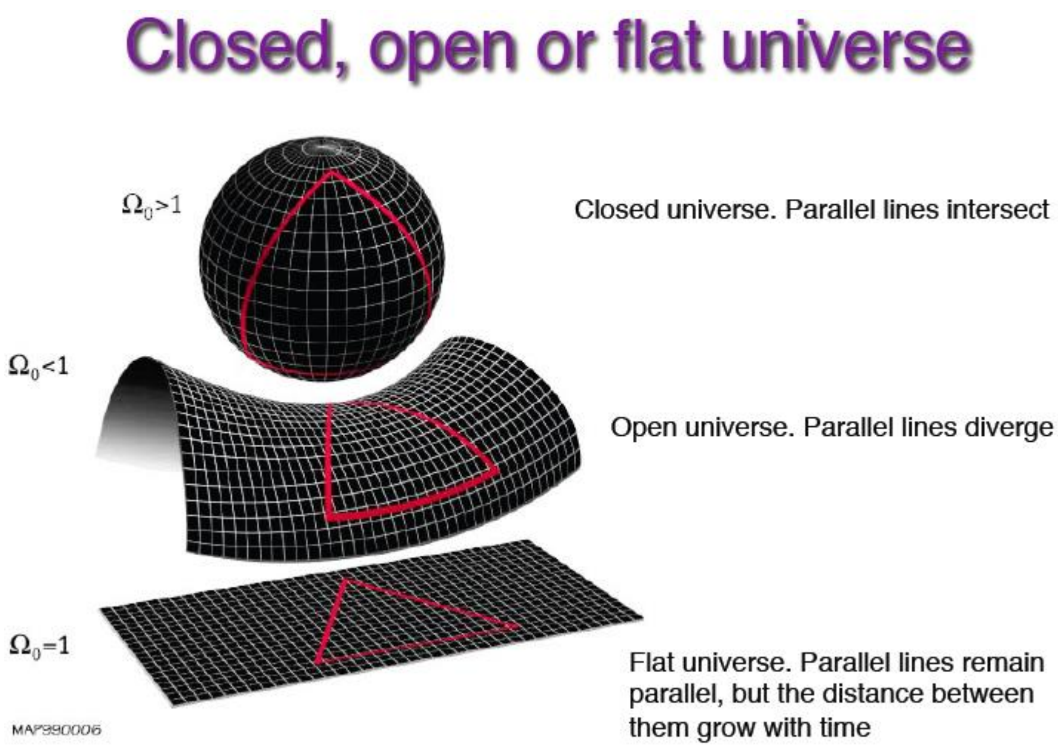
Meaning of the measurement of the curvature of the 3d space

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

Spatial curvature parameter

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

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



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

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

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

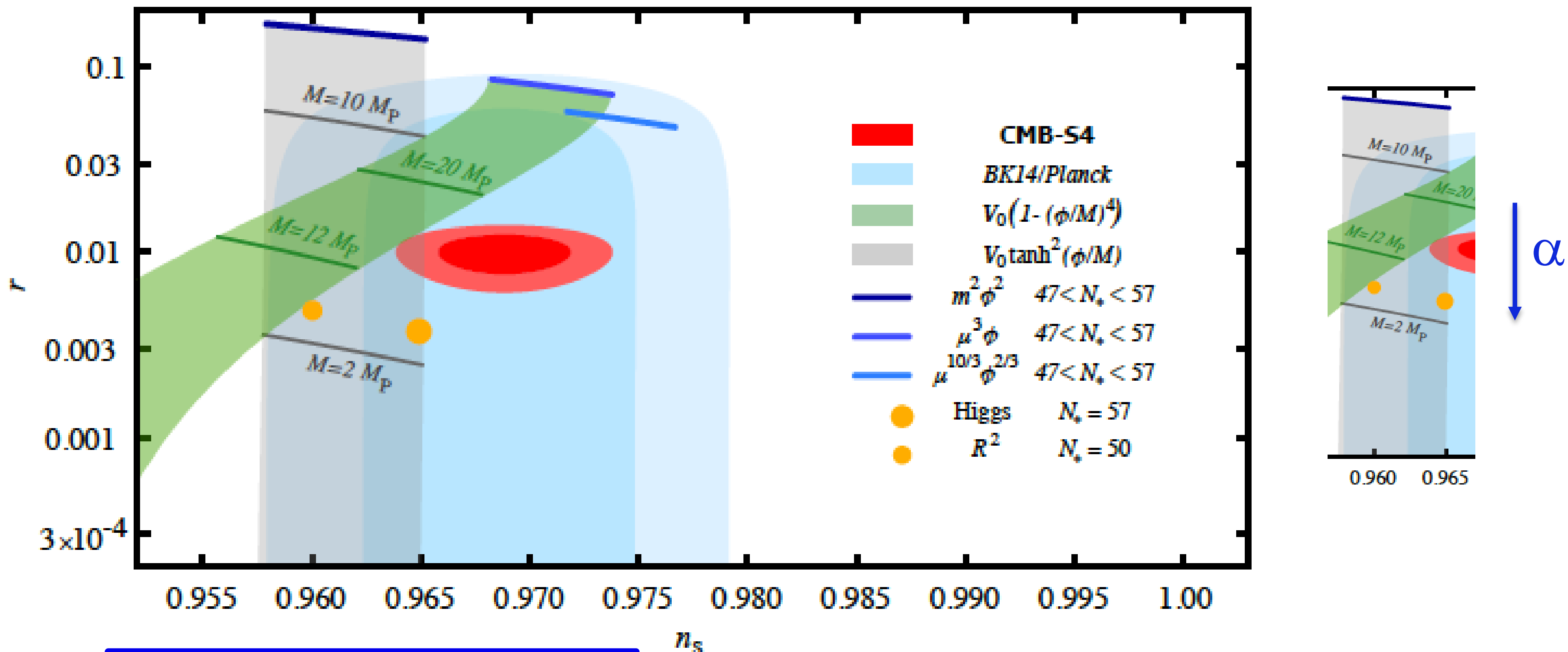
scalar fields are coordinates of the Kahler geometry

Decreasing r, decreasing α, increasing curvature R_K

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

Hyperbolic geometry of a Poincaré disk

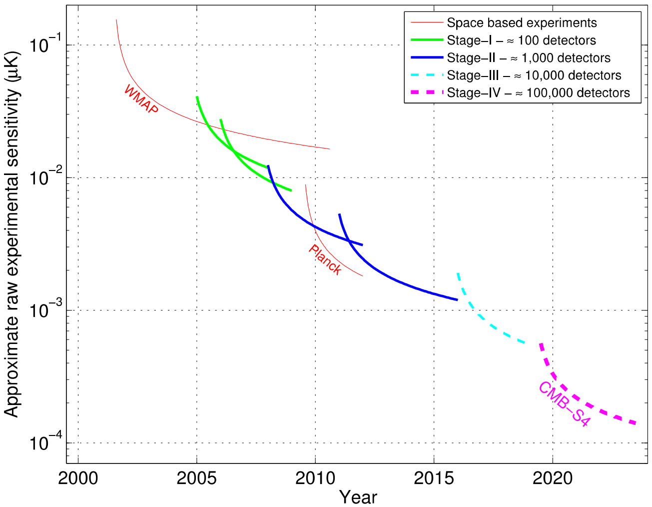
Alpha-Attractors and B-mode Targets



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

CMB-S4 Science Book

October 2016



Primordial Gravity Waves

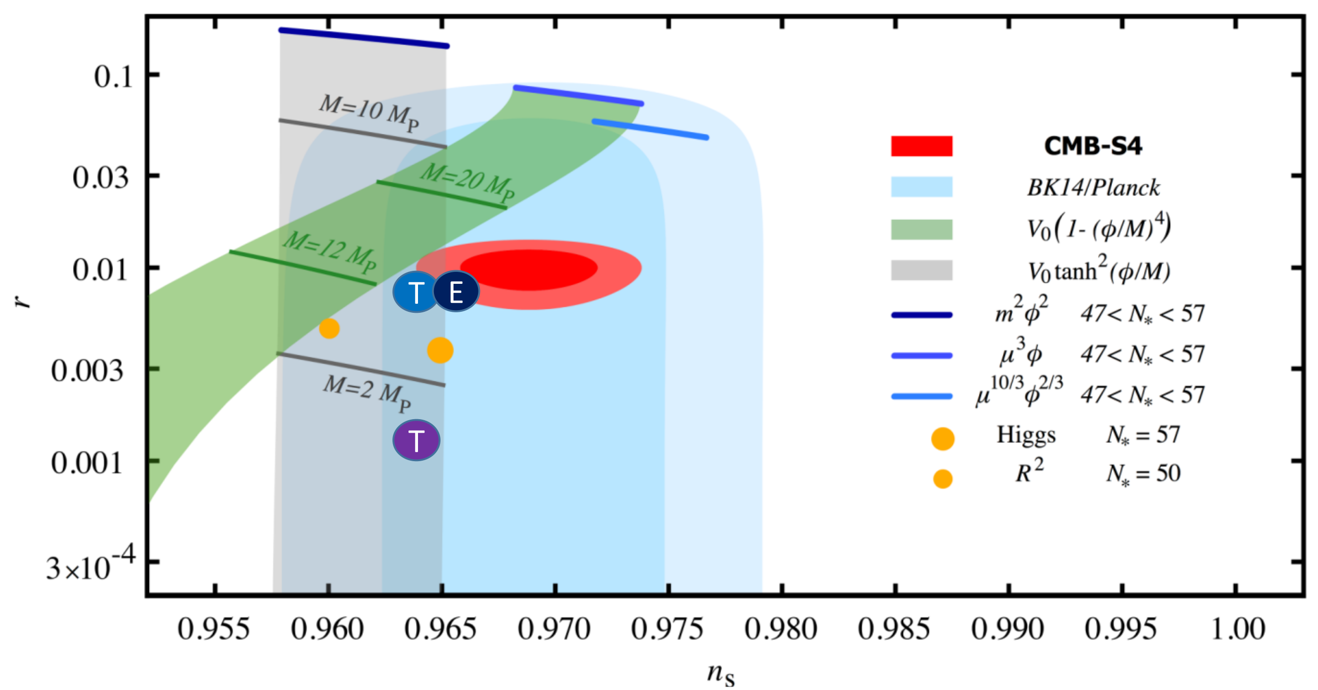
Ferrara, RK, 2016,
RK, Linde, Wrase, Yamada, 2017

α–attractor models

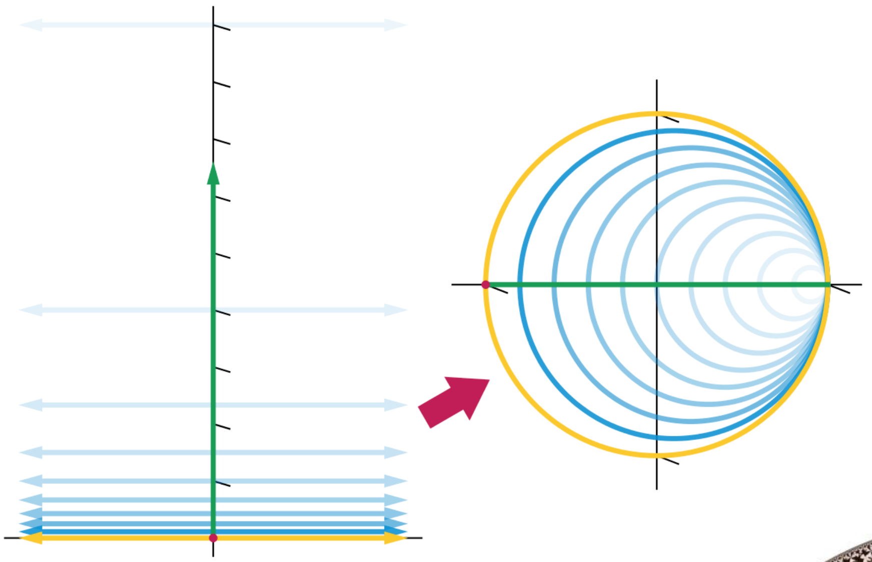
Well motivated new models originating in string theory, M-theory, maximal supergravity

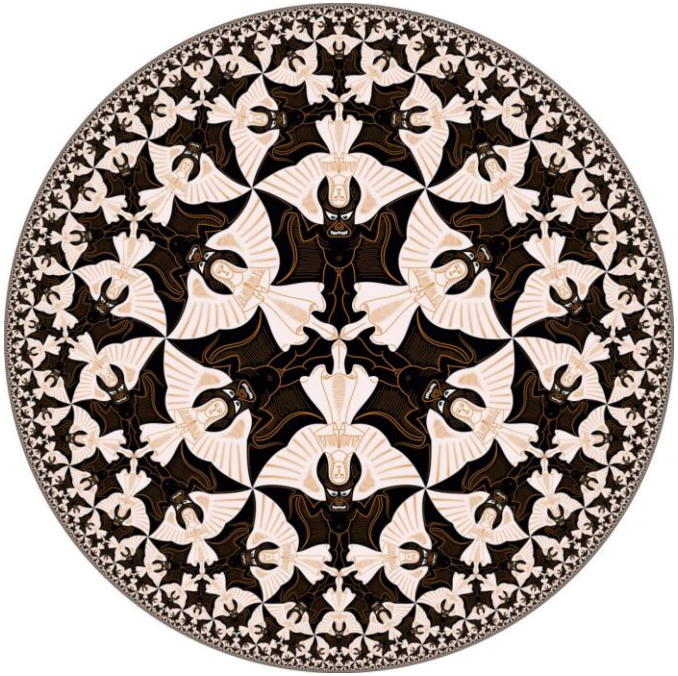
Ground based experiments

Future B-mode satellite missions



From the disk to a half-plane (the Cayley transform)





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

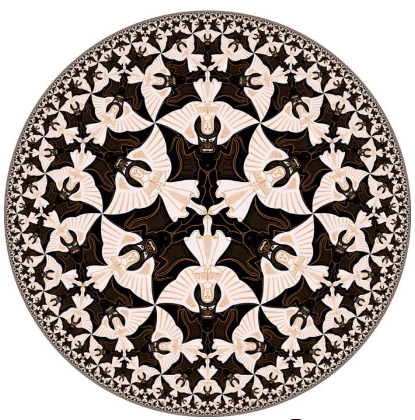
$$Z\bar{Z} < 1$$

Hyperbolic geometry
of a Poincaré disk

Disk or **half-plane**

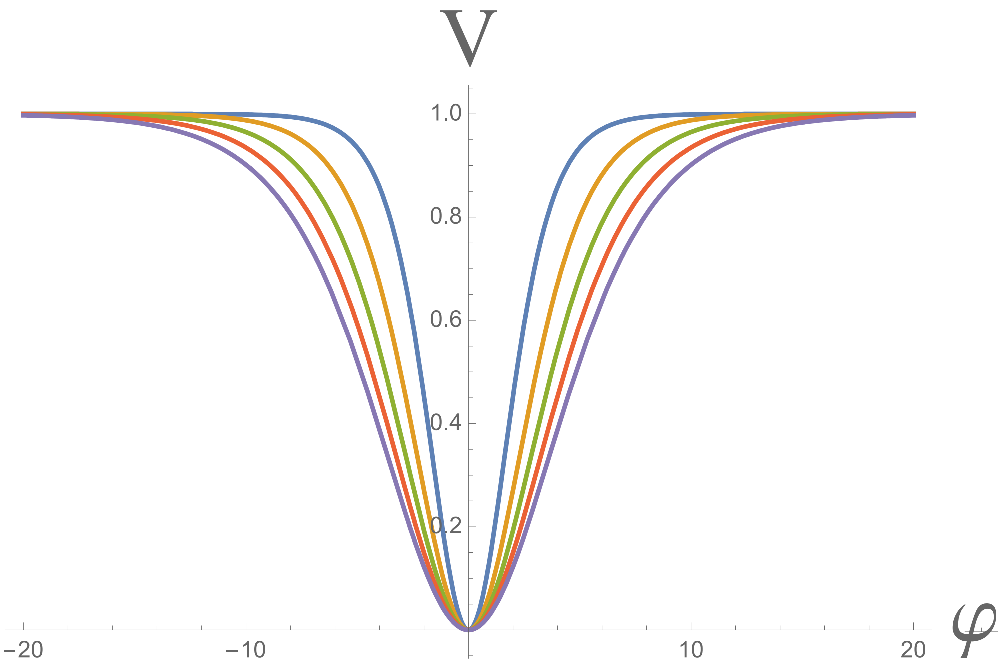
$$T + \bar{T} > 0$$

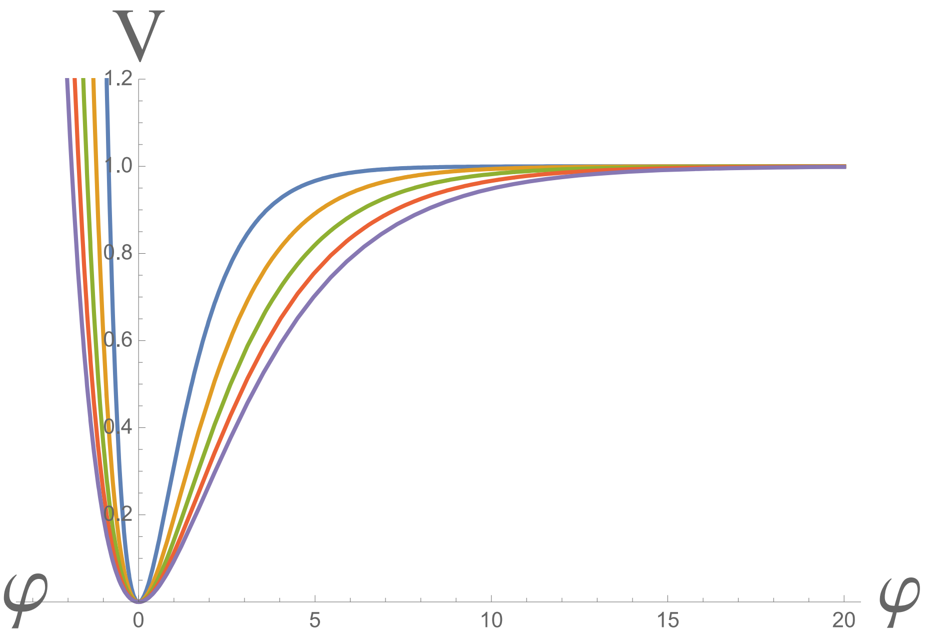
Escher in the Sky, RK, Linde 2015



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

Plateau potentials α-attractors





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

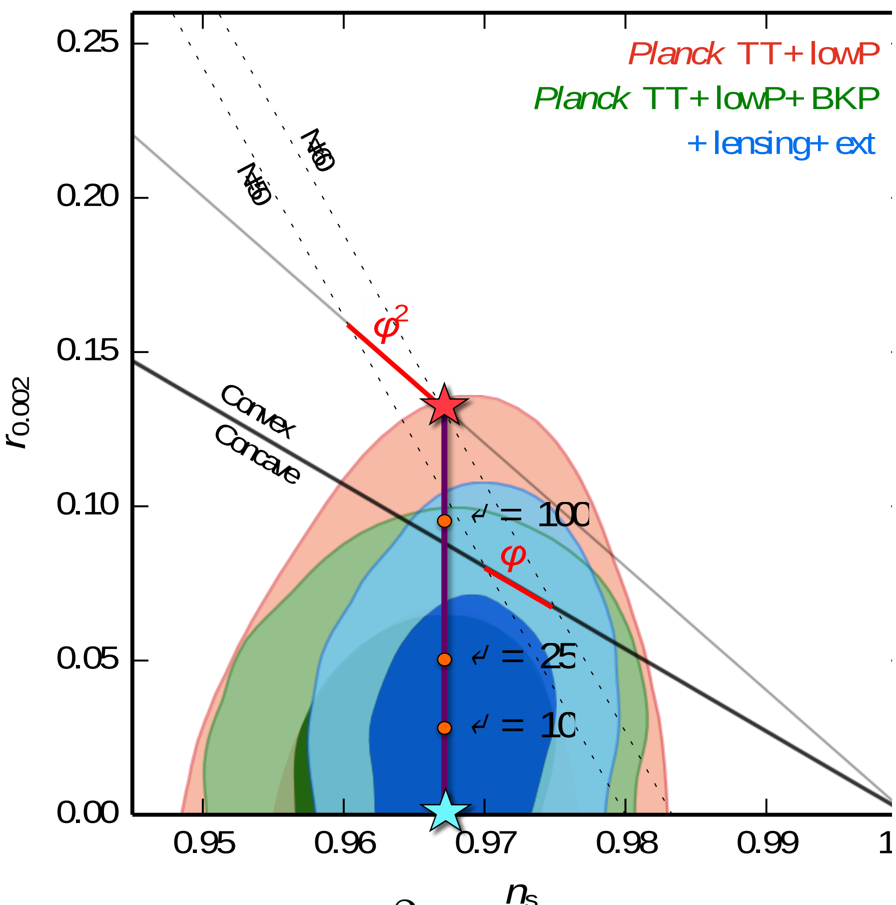
$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \;\; - \alpha\mu^2\Big(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi}\Big)^2$$

Simplest T-model   in canonical variables   Simplest E-model

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

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

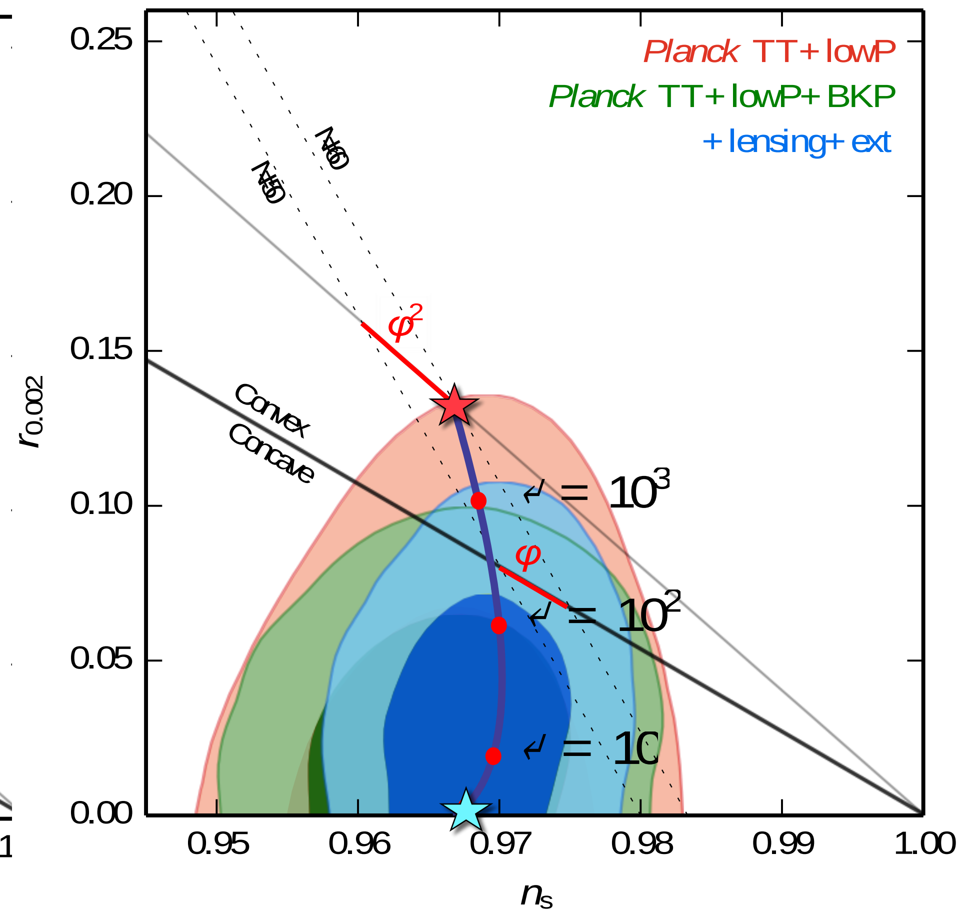
In geometric variables



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

Simplest T-models

RK, Linde, Roest 2013



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

Simplest E-models

Ferrara, RK, Linde, Porrati, 2013

- **Maximal supersymmetry and B-modes**
- M-theory in d=11
- Superstring theory in d=10
- N=8 supergravity in d=4

2016, Ferrara and RK

Scalars are coordinates of the coset space in 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

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

$$n_s \approx 0.963$$

7-disk cosmological model

RK, Linde, Wrase, Yamada, 2017

1. Start with M-theory, or String theory, or N=8 supergravity

2. Perform a consistent truncation to N=1 supergravity in d=4 with a 7-disk manifold

$$K_0 = -\frac{1}{2}\sum_{i=1}^{7} \ln\left(\frac{(\tau_i + \bar{\tau}_i)^2}{4\tau_i\bar{\tau}_i}\right)$$

Tessellation

3. Add a superpotential preserving N=1 supersymmetry with a minimum at

$$W_0 = M\Big(\sum_{1\le i<j\le p} (\tau_i - \tau_j)^2 + \sum_{i=p+1}^{7} (\tau_i - c)^2\Big)$$

$$D_i W_0 = 0$$

4. Add a cosmological part with a nilpotent stabilizer S

$$K_1 = S\bar{S} \qquad W_1 = Sf\big(\sum_i \tau_i\big) + g$$

5. Run Mathematica: the model works beautifully

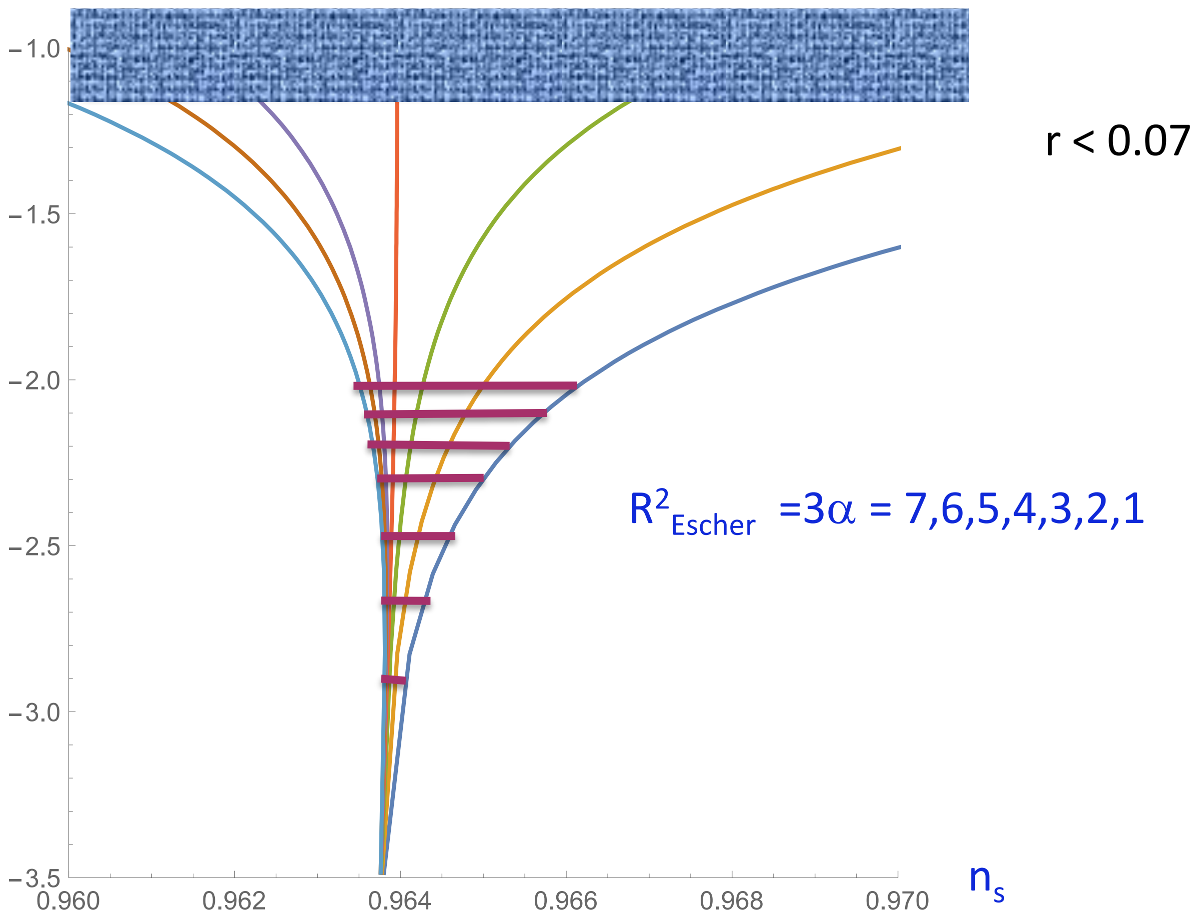
3α= 7,6,5,4,3,2,1

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

Why do we find it useful to talk about the size of the Escher's disks in discussions of the CMB future B-mode targets ?

B-mode targets: from maximal supersymmetry to minimal supersymmetry

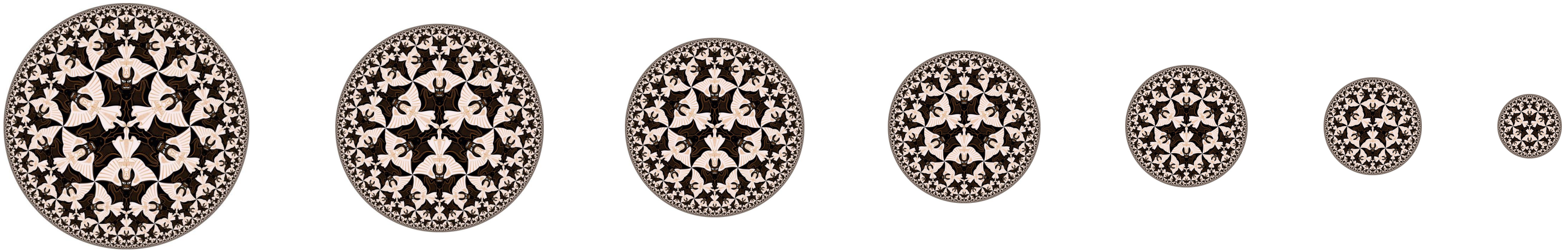
α-attractors $\log_{10} r$- n_s plane



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

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

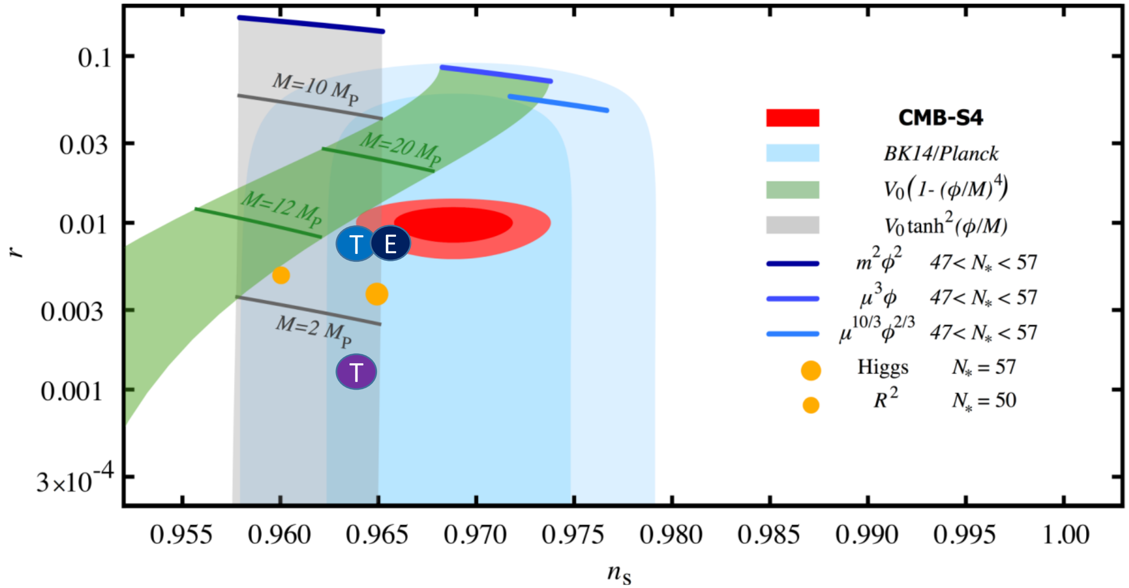
Using a consistent reduction from maximal N=8 supersymmetry theories: M-theory in d=11, String theory in d=10, maximal supergravity in d=4, to the minimal N=1 supersymmetry we have deduced the favorite models with hyperbolic geometry with R^2_{Escher} = 7,6,5,4,3,2,1



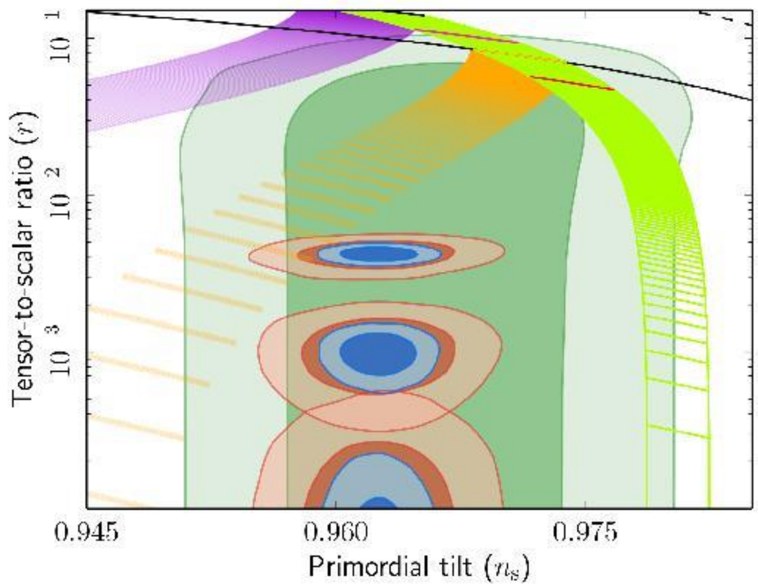
$r \approx 0.9 \times 10^{-2}$ $r \approx 1.3 \times 10^{-3}$

B-mode targets

In contrast with N=1 supersymmetry models where R^2_{Escher} is arbitrary



Ground based detectors



COrE : Cosmic Origin Explorer

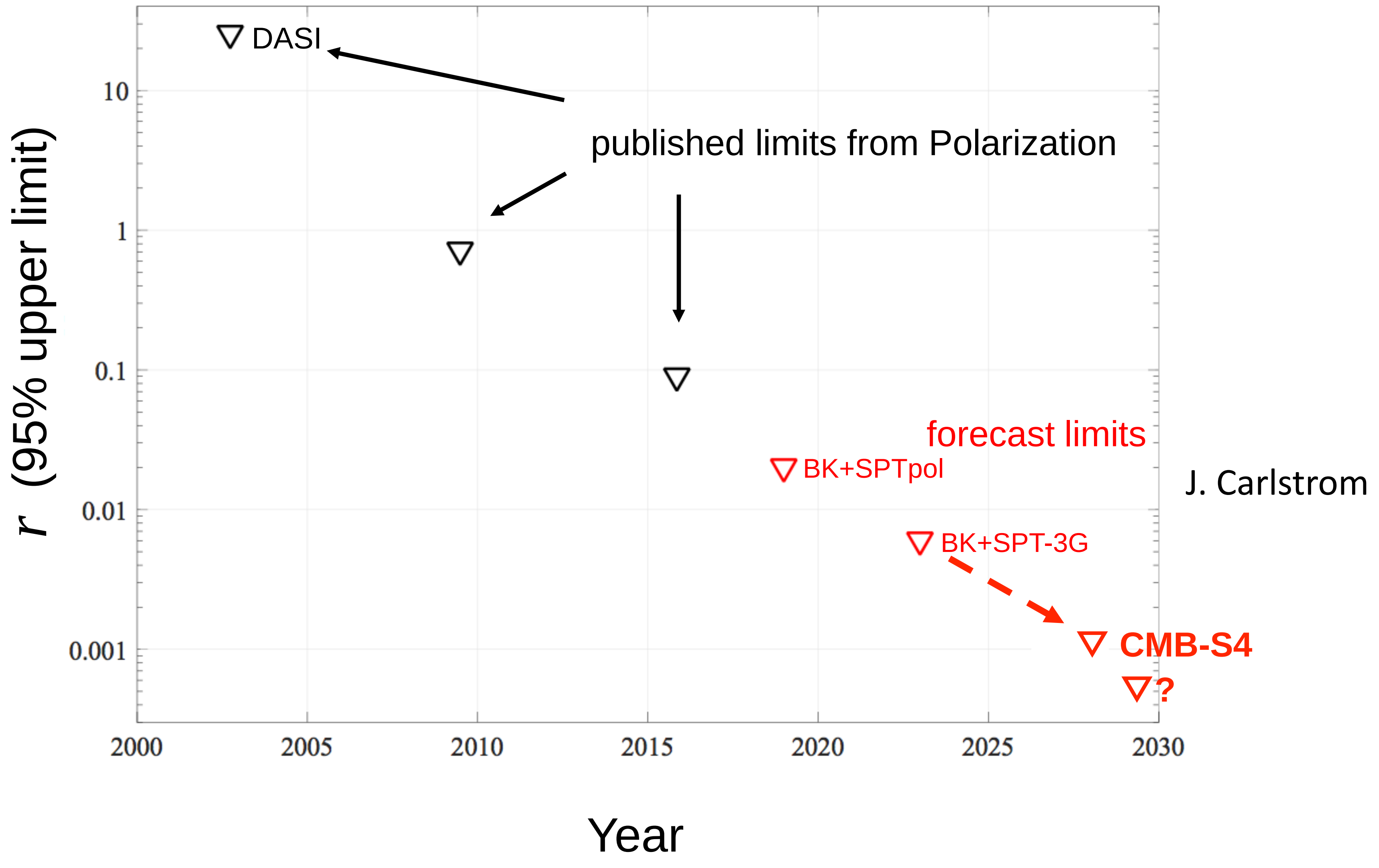
Satellite missions

$\sigma(n_s) = 0.0014$

Improvement factor CORE to Planck 2015 **3.4**

forecast regions for (n_s,r) for CORE
(blue) and LiteBIRD (red)

Published and forecasted r constraints



Keith