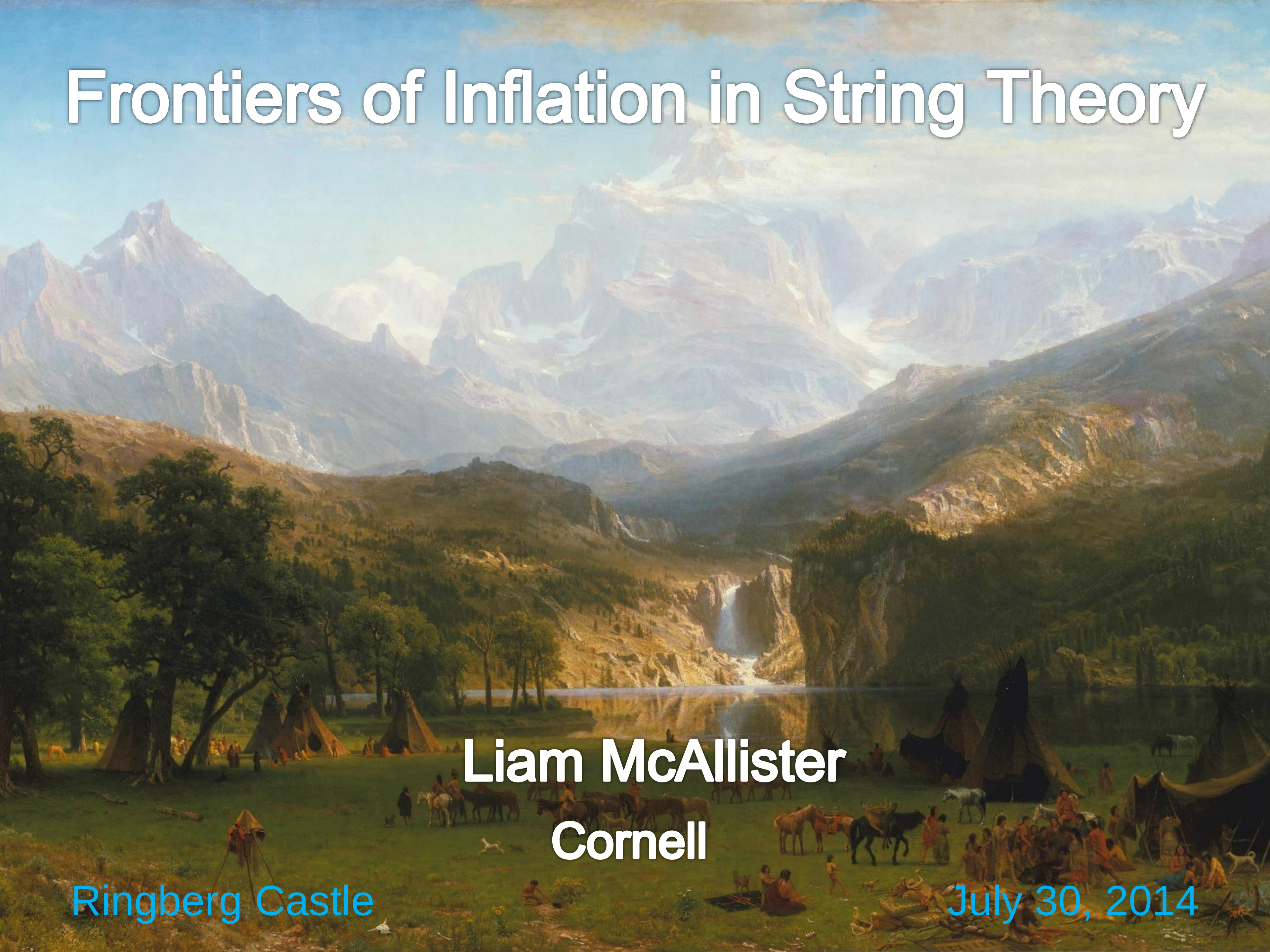
Frontiers of Inflation in String Theory



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Inflation and String Theory

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Abstract

We review cosmological inflation and its realization in quantum field theory and in string theory. This material is a portion of a book, also entitled *Inflation and String Theory*, to be published by Cambridge University Press.

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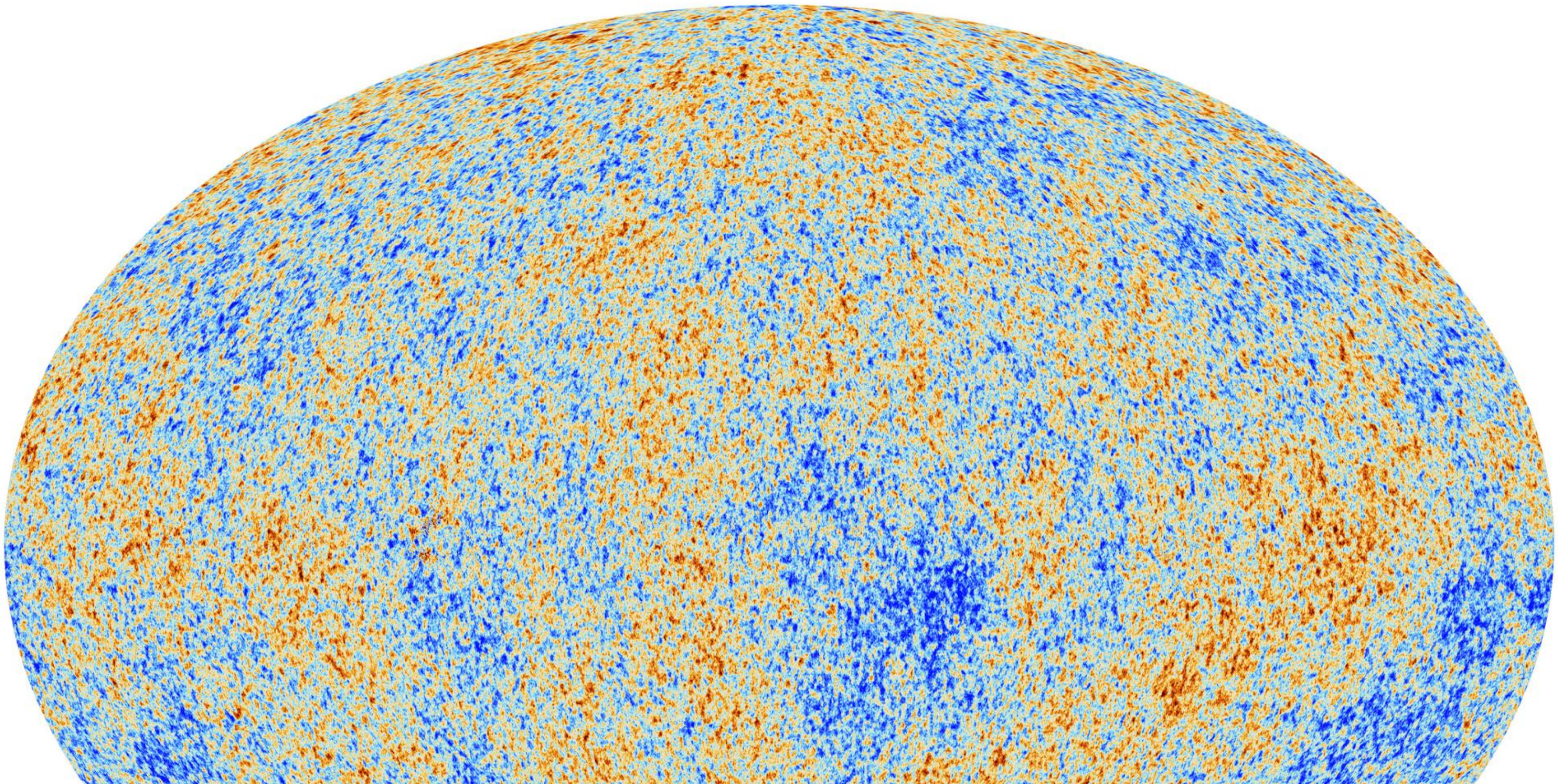
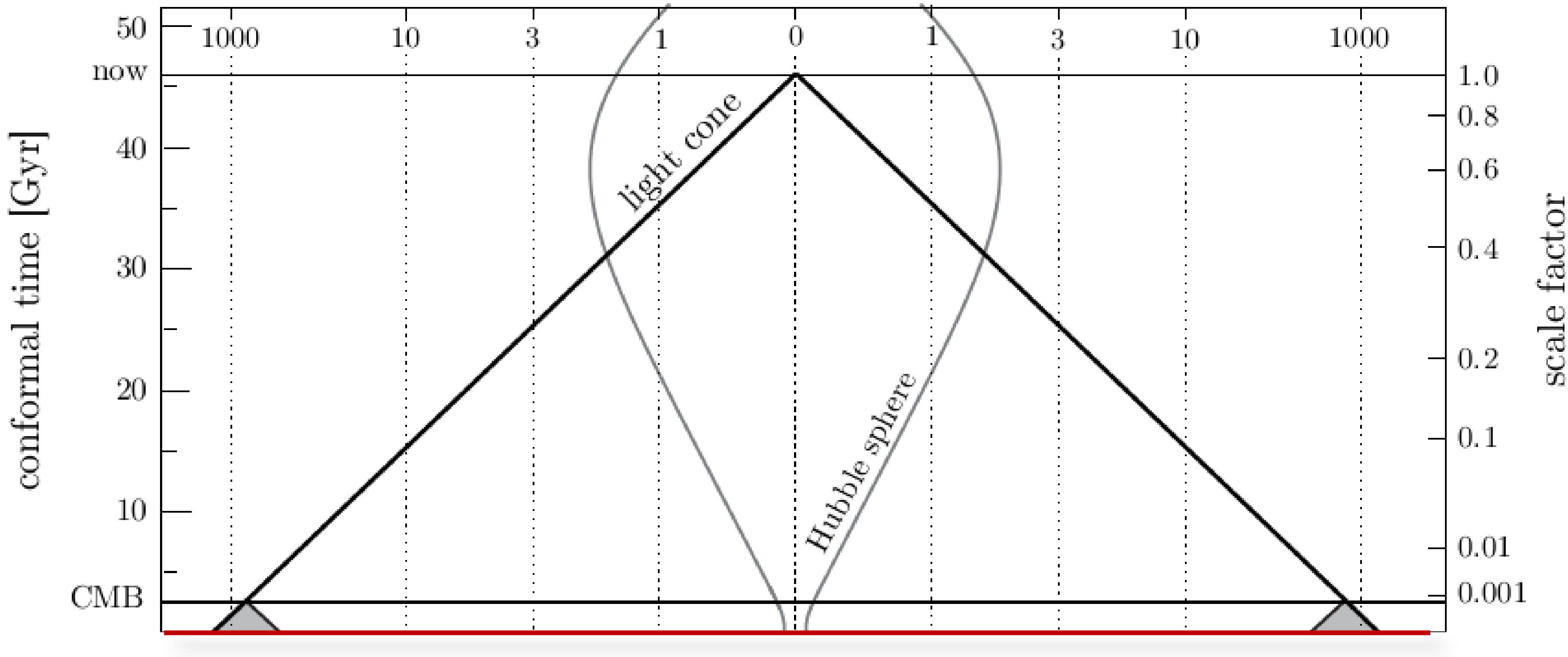
hep-th/1404.2601

Plan

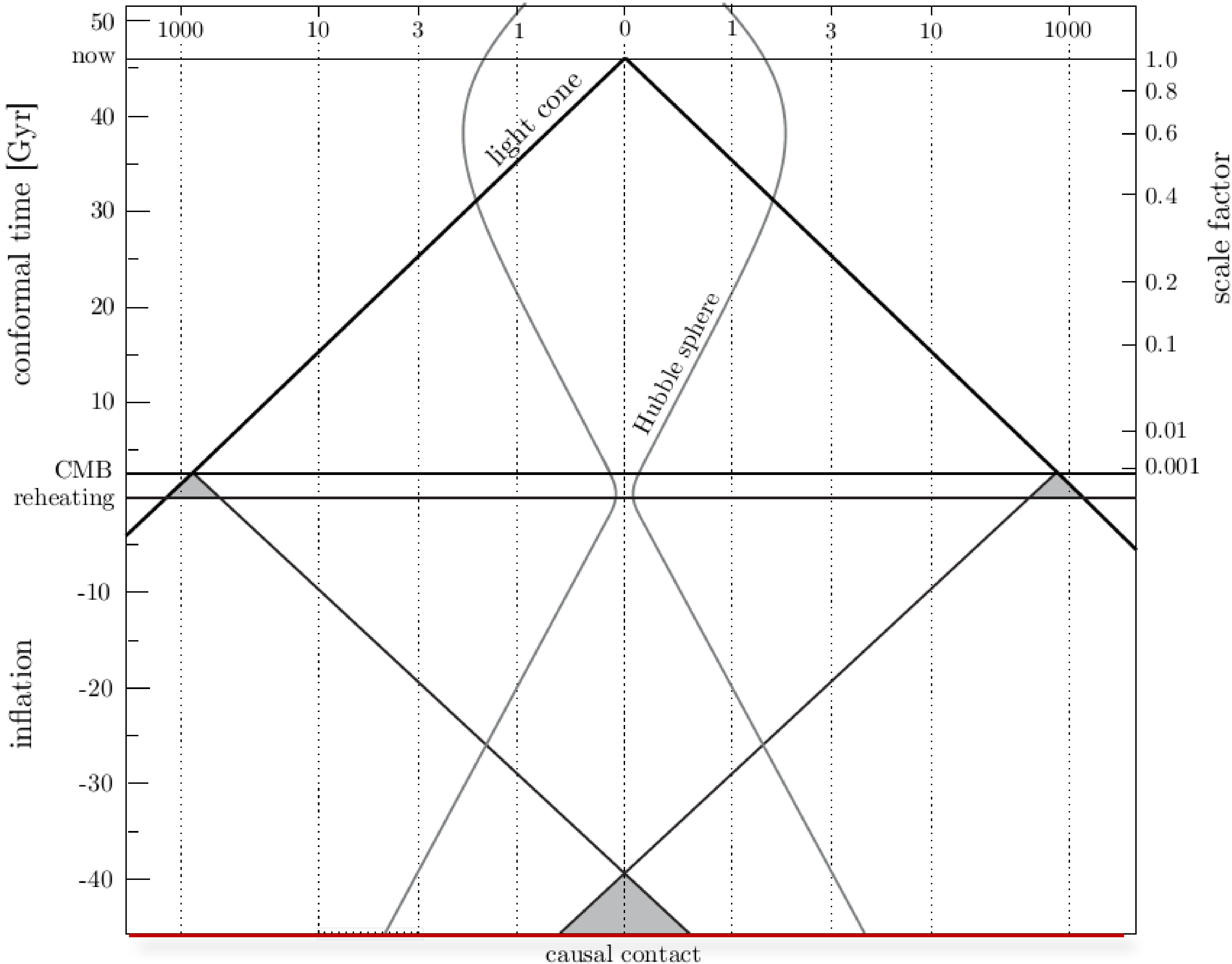
I. Background: inflation and the CMB
II. Inflation in string theory: the task
III. Inflation in string theory: examples
IV. Outlook

I. Inflation and the CMB





The Horizon Problem



50
now
40
30
20
10
CMB
reheating
-10
-20
-30
-40
conformal time [Gyr]
inflation
1000
10
3
1
0
1
3
10
1000
1.0
0.8
0.6
0.4
0.2
0.1
0.01
0.001
scale factor
light cone
Hubble sphere
causal contact

Inflation

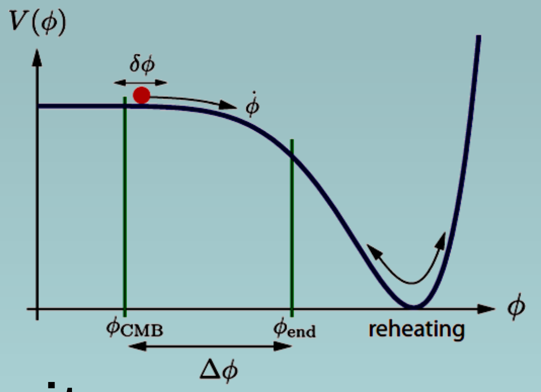
Guth 81; Linde 82; Albrecht, Steinhardt 82

- An epoch of quasi-exponential expansion

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2 \qquad a(t) = a(0)e^{Ht}, \quad H \approx const.$$

- Simplest example: single scalar field with a potential,

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

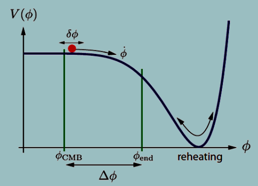


- Acceleration is prolonged if curvature of V is small in Planck units,

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv M_p^2 \frac{V''}{V} \ll 1$$

Perturbations in Inflation

- Quantum fluctuations of the inflaton are stretched to superhorizon scales, forming primordial density perturbations, then CMB temperature anisotropies and the seeds of large-scale structures.



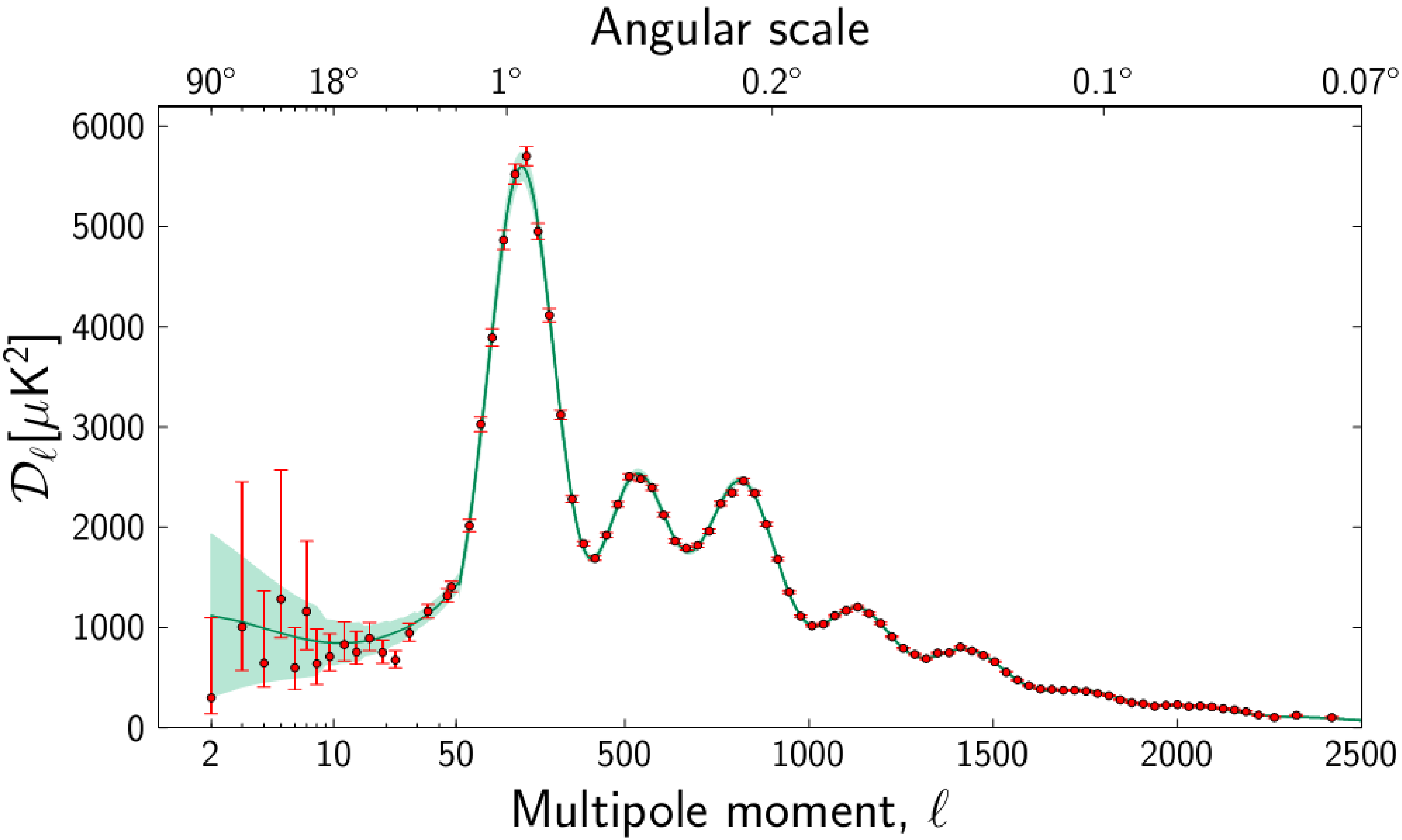
- Quantum fluctuations of the graviton are stretched to superhorizon scales, forming primordial gravitational waves.

$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2}\frac{1}{\epsilon}\frac{V}{M_{\rm pl}^4} \quad , \quad \Delta_h^2 = \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4} \, .$$

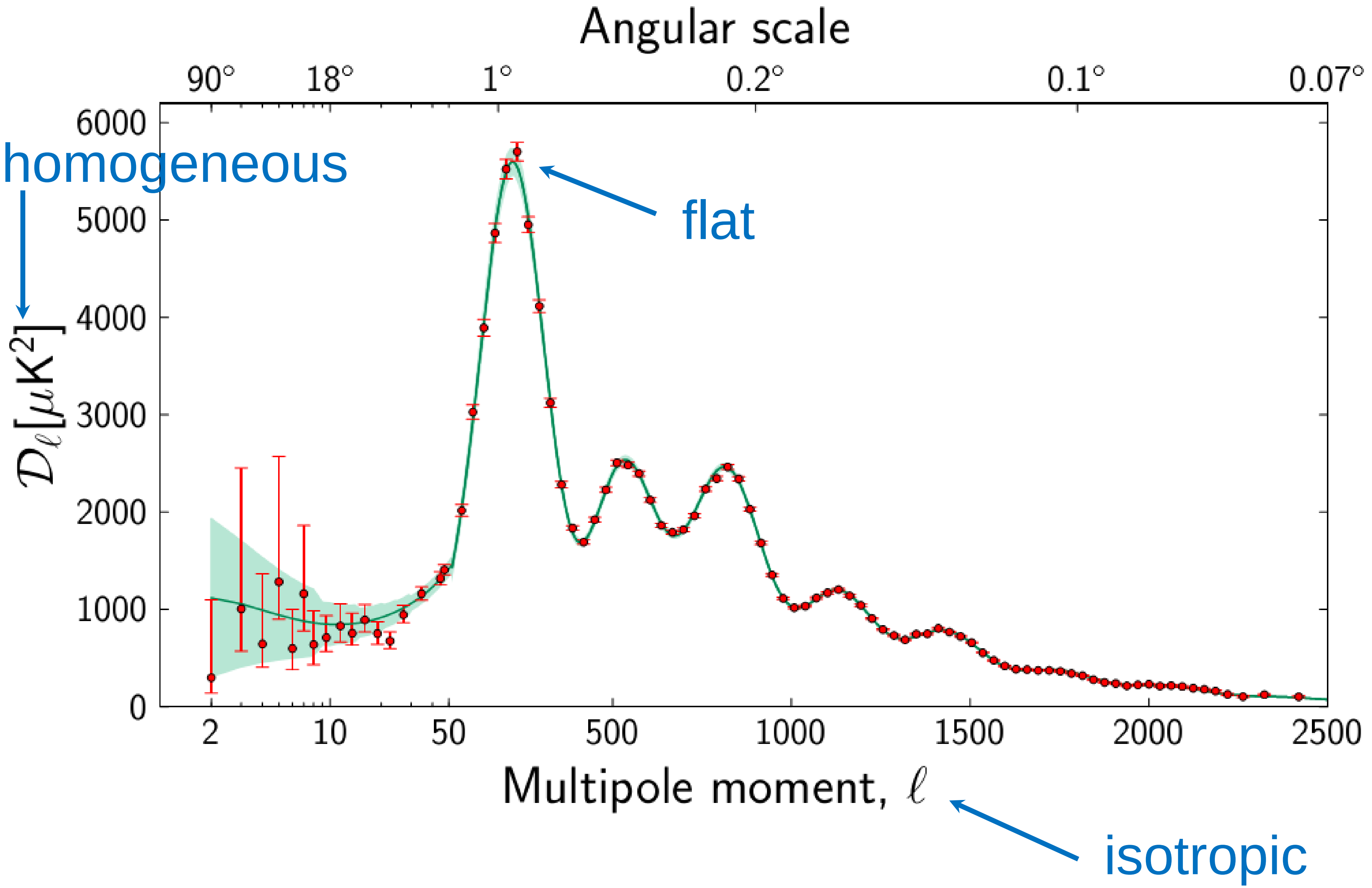
Successes of inflation

- By design, inflation provides a causal explanation for the approximate homogeneity and isotropy of the universe.
- In particular, inflation addresses the horizon problem, providing classical dynamics explaining the constancy across the sky of the mean CMB temperature.
- Inflation made additional predictions:
  - Approximate flatness
  - Scalar perturbations that are
    - Approximately Gaussian
    - Approximately adiabatic
    - Approximately, but not exactly, scale invariant
    - Phase-correlated across superhorizon distances, leading to
      - acoustic peaks
      - TE anti-correlation on large angular scales
  - Tensor perturbations that are
    - Approximately Gaussian
    - Approximately, but not exactly, scale invariant
    - Phase-correlated across superhorizon distances

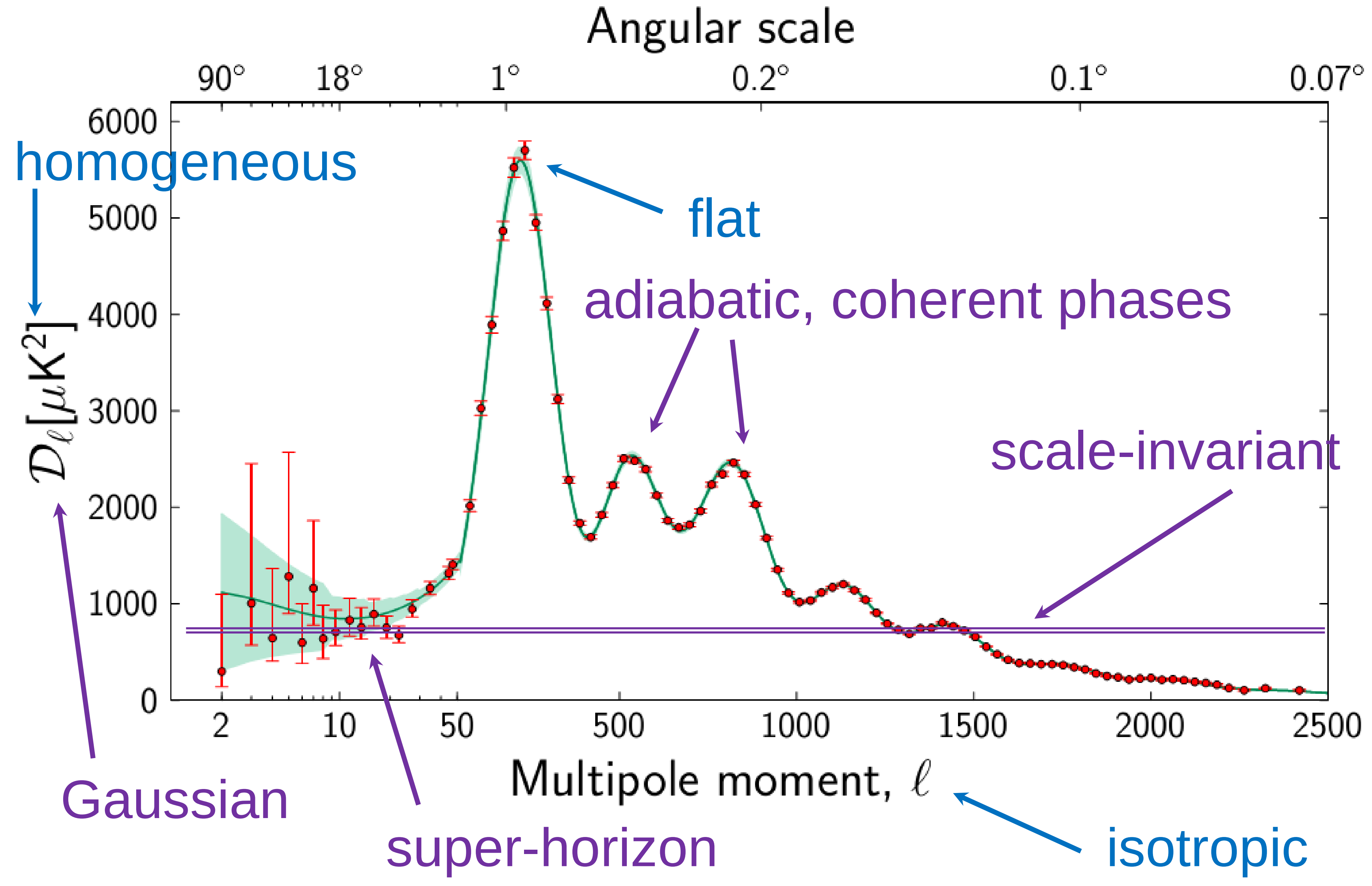
Planck 2013 CMB power spectrum



Planck 2013 CMB power spectrum



Planck 2013 CMB power spectrum

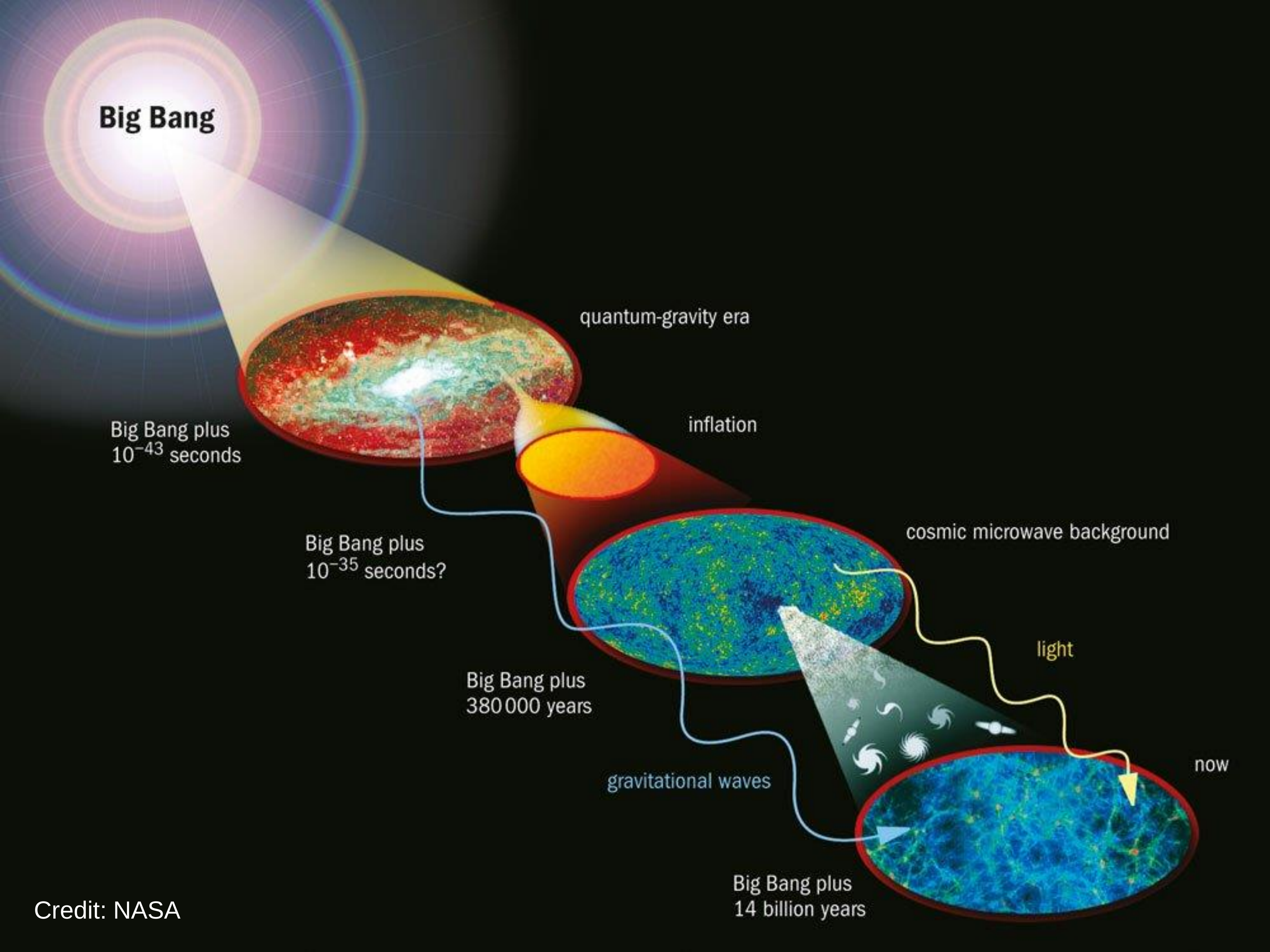


Concordance cosmology

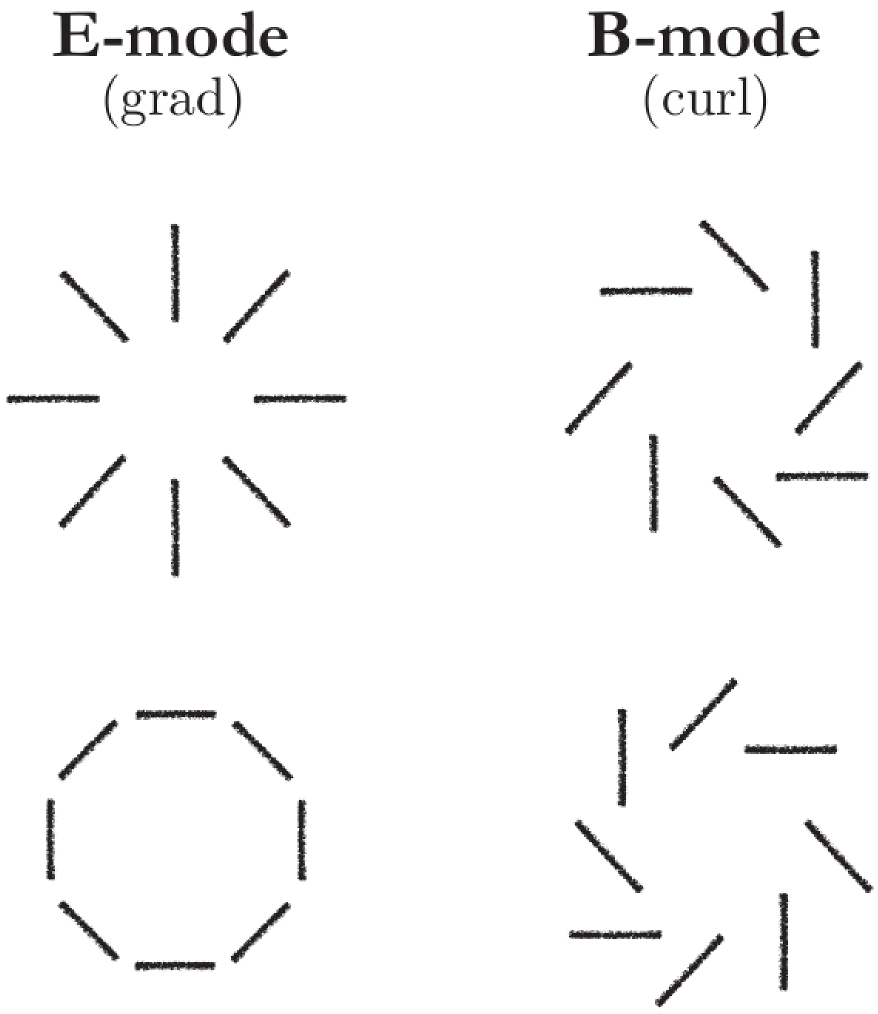
Parameter	Planck	$\cdots + \text{WMAP}$	$\cdots + \text{ACT} + \text{SPT}$	$\cdots + \text{BAO}$
$\Omega_b h^2$	0.02207 ± 0.00067	0.02205 ± 0.00056	0.02207 ± 0.00054	0.02214 ± 0.00048
$\Omega_c h^2$	0.1196 ± 0.0061	0.1199 ± 0.0053	0.1198 ± 0.0052	0.1187 ± 0.0034
Ω_Λ	0.683 ± 0.040	0.685 ± 0.034	0.685 ± 0.033	0.692 ± 0.021
τ	0.097 ± 0.080	0.089 ± 0.027	0.091 ± 0.027	0.092 ± 0.026
$10^9 A_s$	2.23 ± 0.32	2.20 ± 0.11	2.20 ± 0.11	2.20 ± 0.11
n_s	0.962 ± 0.019	0.960 ± 0.014	0.959 ± 0.014	0.961 ± 0.011
Ω_K	-0.072 ± 0.081	-0.037 ± 0.049	-0.042 ± 0.048	-0.0005 ± 0.0066
n_s	0.963 ± 0.019	0.962 ± 0.015	0.960 ± 0.014	0.962 ± 0.011
r	< 0.115	< 0.127	< 0.117	< 0.119
n_s	0.974 ± 0.030	0.956 ± 0.016	0.955 ± 0.015	0.960 ± 0.012
α_s	-0.034 ± 0.035	-0.013 ± 0.018	-0.015 ± 0.017	-0.013 ± 0.018

Primordial gravitational waves and CMB polarization

Primordial gravitational waves leave an imprint in the CMB polarization, by inducing a quadrupole anisotropy at the time of decoupling.


Big Bang
quantum-gravity era
Big Bang plus
10^−43 seconds
inflation
Big Bang plus
10^−35 seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

Credit: NASA



Scalar perturbations source E-modes. DASI, 2002
Lensing of E-modes sources B-modes. SPTPol, 2013
Tensor perturbations source primordial B-modes. BICEP2, 2014?

Primordial gravitational waves and CMB polarization

- Amplitude of signal depends only on the energy scale of inflation,

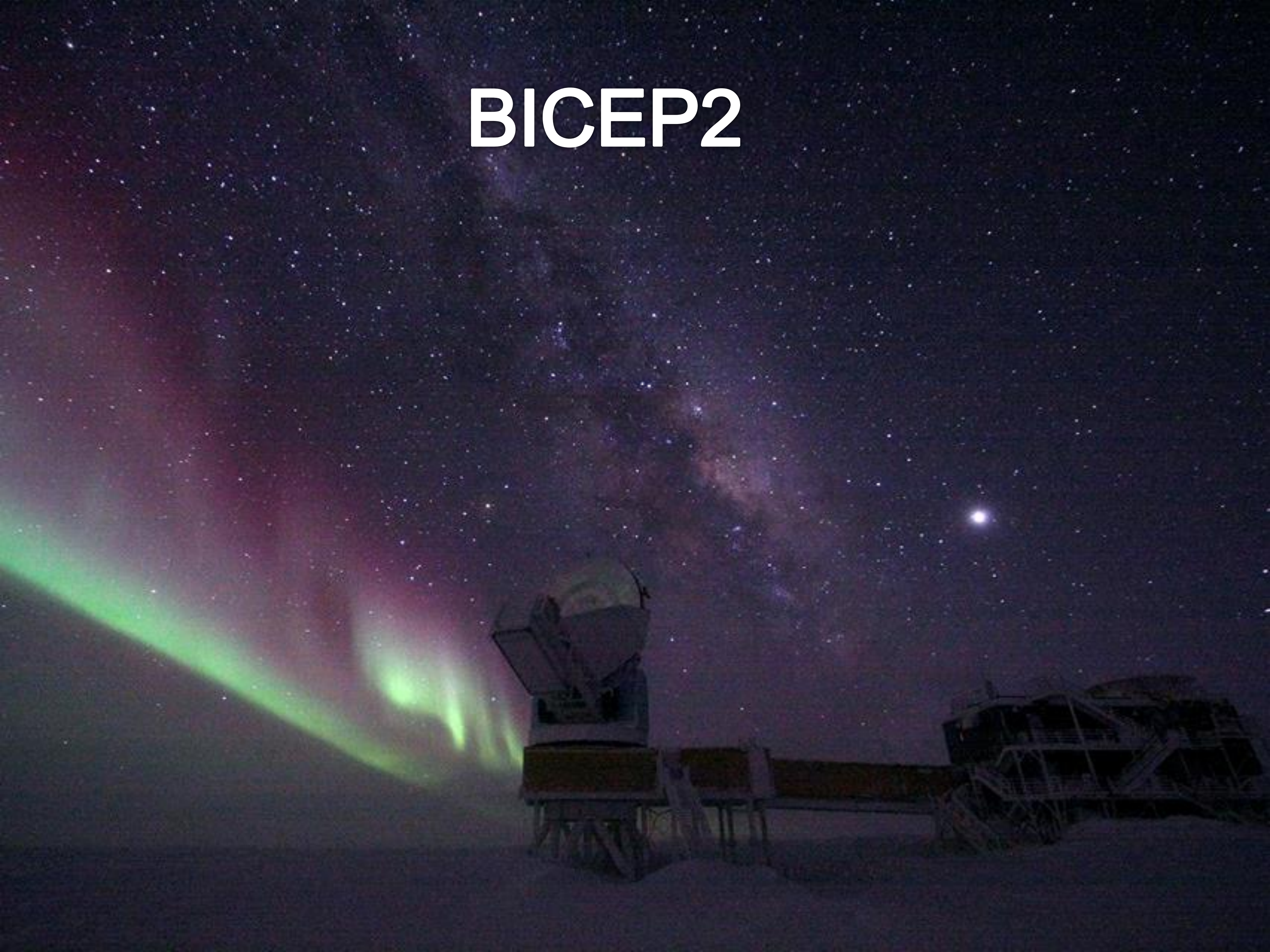
$$\Delta_h^2 = \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}$$

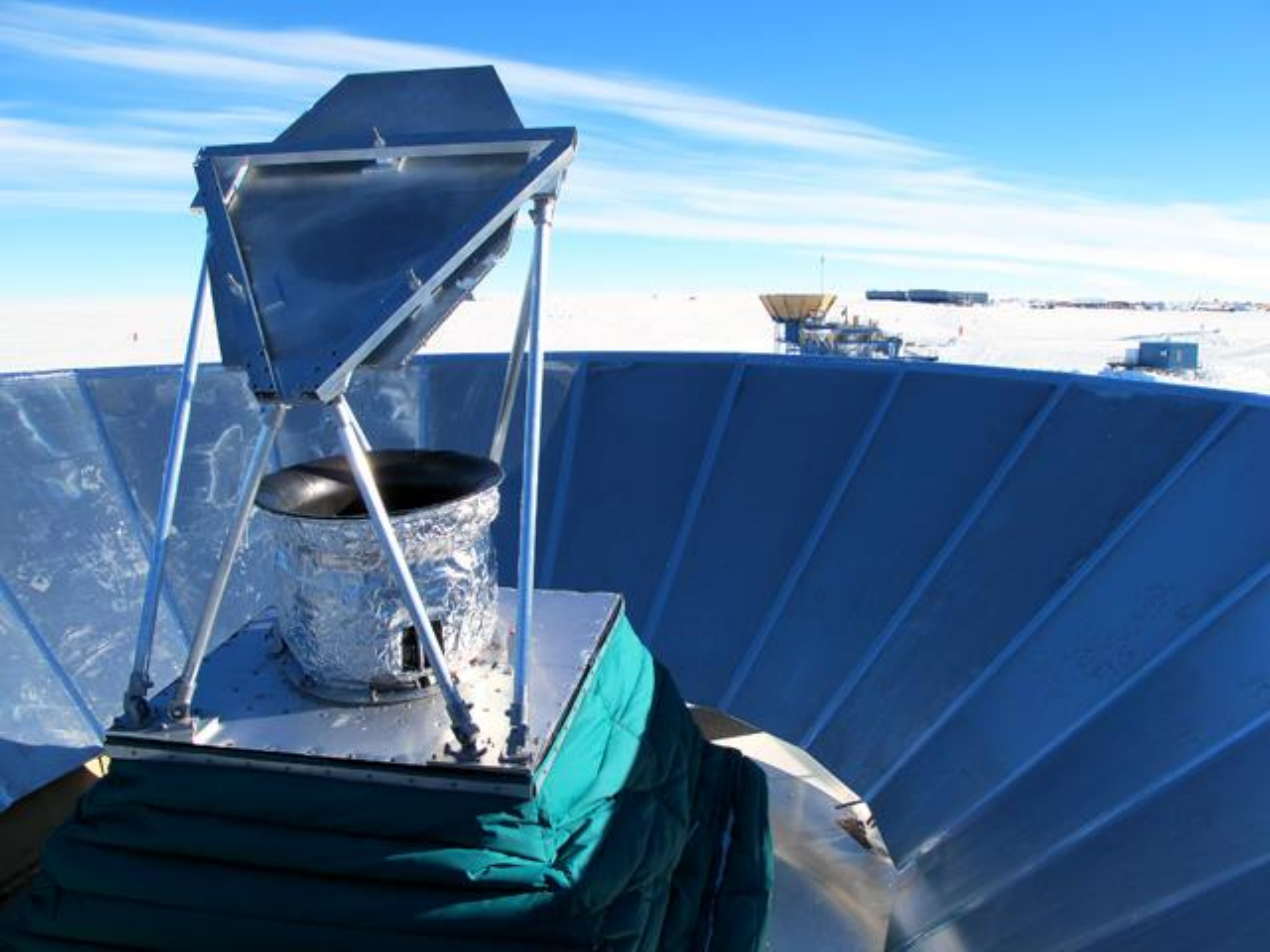
- Parametrized in terms of tensor-to- scalar ratio,

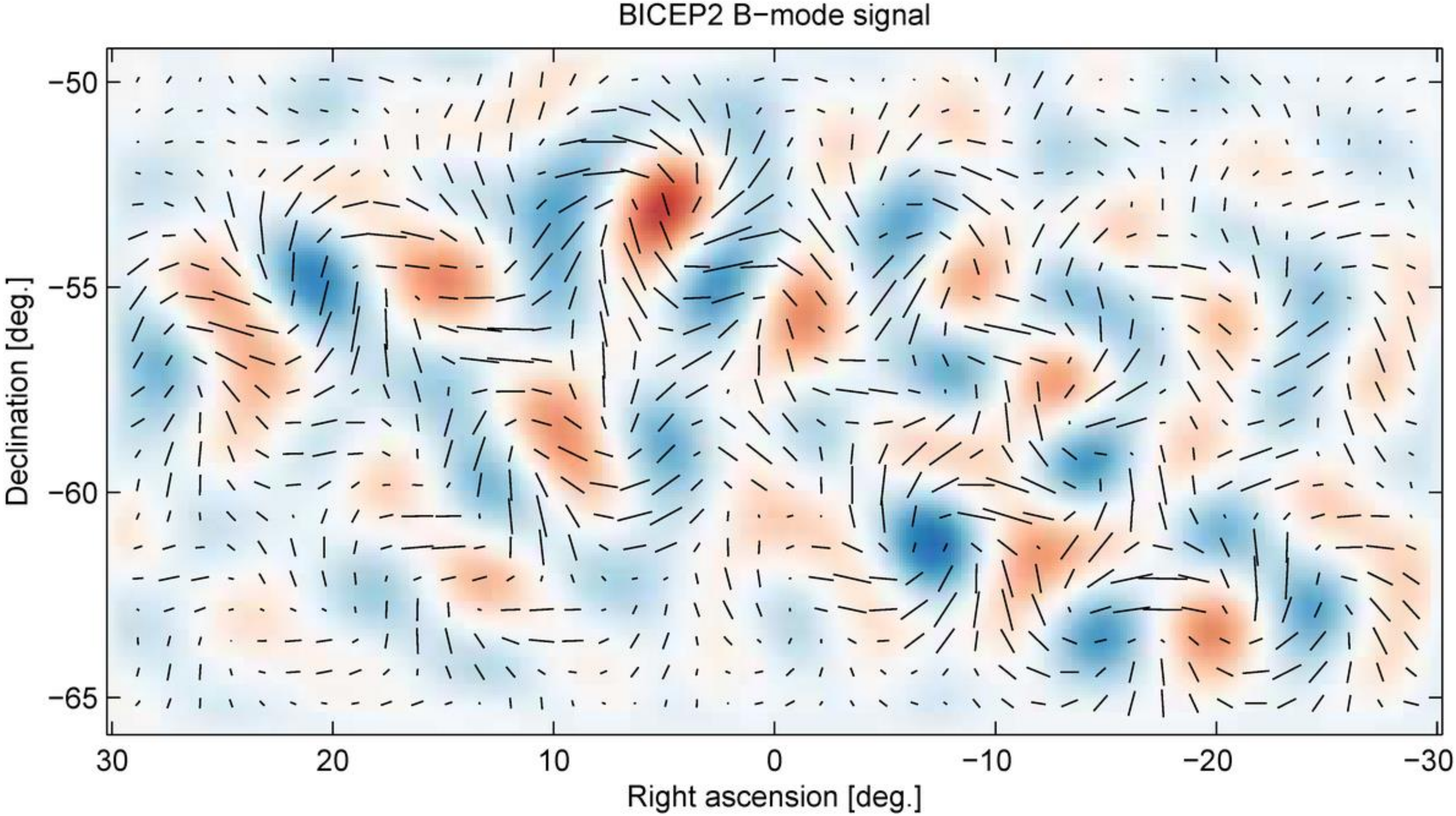
$$r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} \,.$$

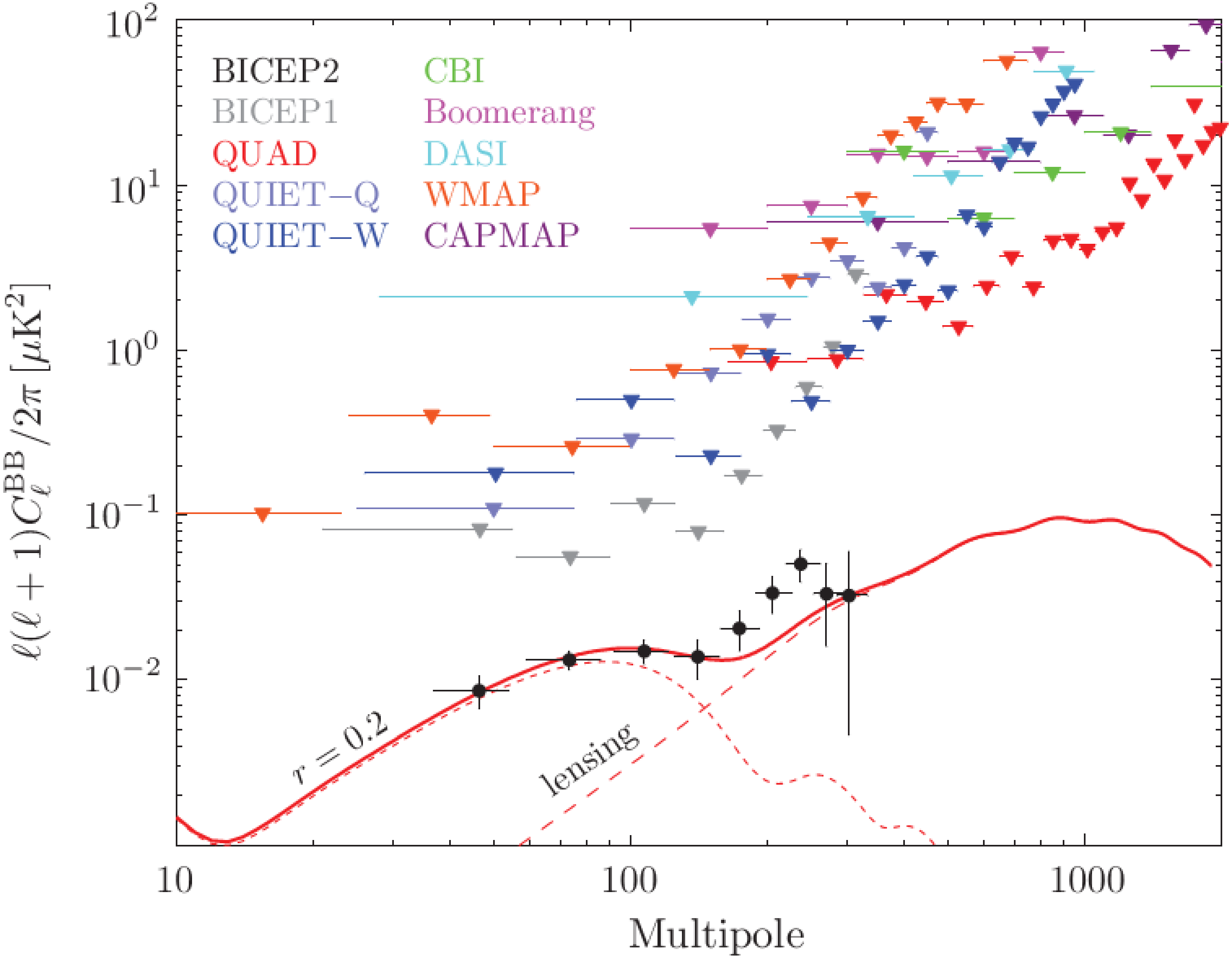
$$V^{1/4} = 2.0 \times 10^{16}\ \mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4} = 8 \times 10^{-3} \left(\frac{r}{0.1}\right)^{1/4} M_{\rm pl} \,.$$

BICEP2



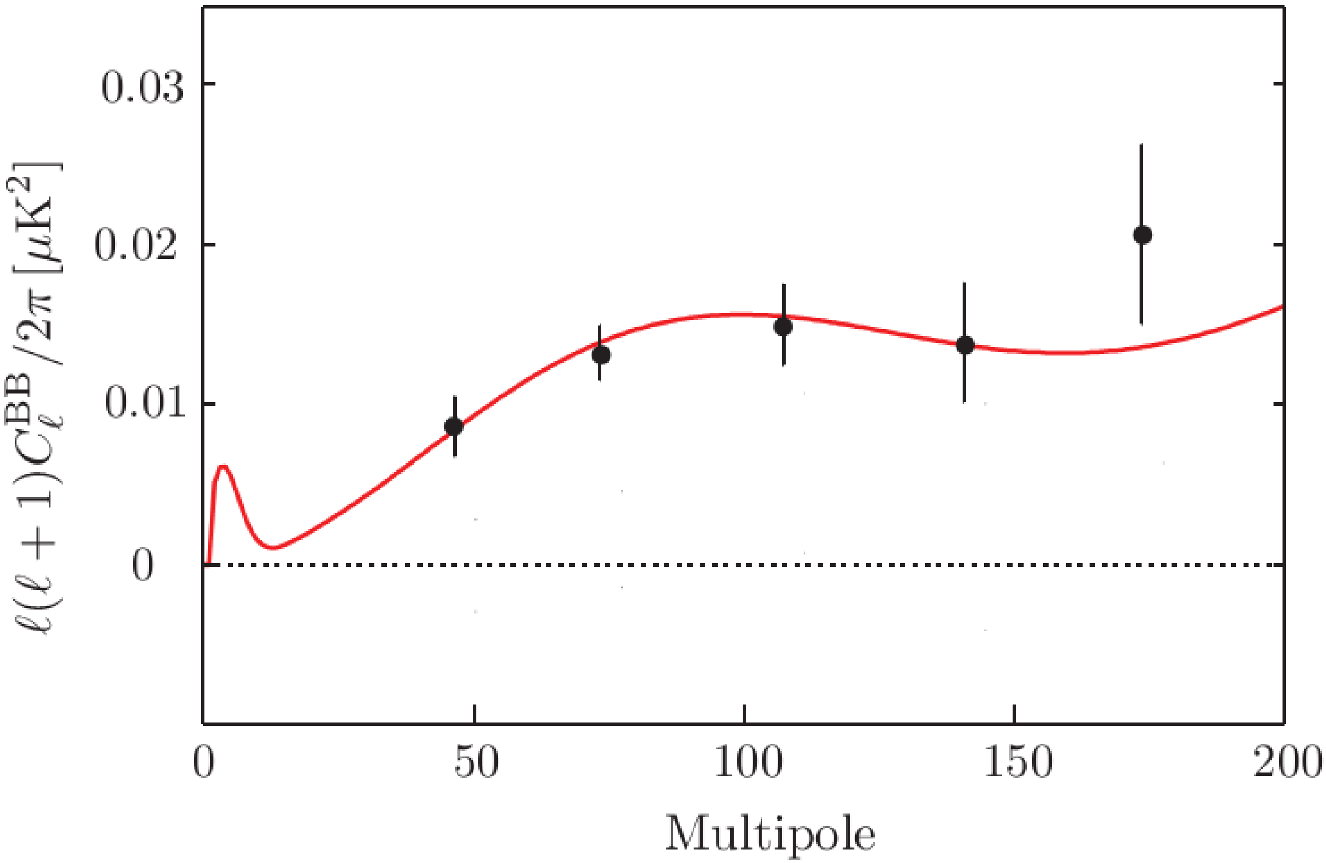



BICEP2 B−mode signal
−50
−55
−60
−65
Declination [deg.]
30
20
10
0
−10
−20
−30
Right ascension [deg.]



BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
$r = 0.2$
lensing
10^2
10^1
10^0
10^{-1}
10^{-2}
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/2\pi\ [\mu\mathrm{K}^2]$
10
100
1000
Multipole

$$r = 0.2^{+0.07}_{-0.05}$$



0.03
0.02
0.01
0
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/2\pi\,[\mu\mathrm{K}^2]$
0
50
100
150
200
Multipole

Is this real?

Is BICEP2 really seeing B-modes on the sky?

Appears very plausible: extensive checks for instrument systematics.

If yes, are they primordial?

Foregrounds:

i. Polarized dust

ii. Synchrotron radiation

Dust contribution, and its uncertainty, were underestimated.

Flauger, Hill, Spergel 14. (cf. Mortonson and Seljak 14)

Must wait for clarification via experiment.

Ideally, by another instrument, at another frequency, from another part of the sky.

In “a few months”: BICEP2+Planck
BICEP2+KeckArray

A new dawn for quantum gravity?

If BICEP2 has detected the imprint of inflationary gravitational waves, we learn that:

1. Inflation took place at extremely high energy, 10^{16} GeV~$10^{-2}M_p$.
2. The gravitational field is quantized.
3. The inflaton displacement was super-Planckian.

Any *one* of these would be a historic discovery, and an unprecedented window on quantum gravity.

Photo credit: Steffen Richter

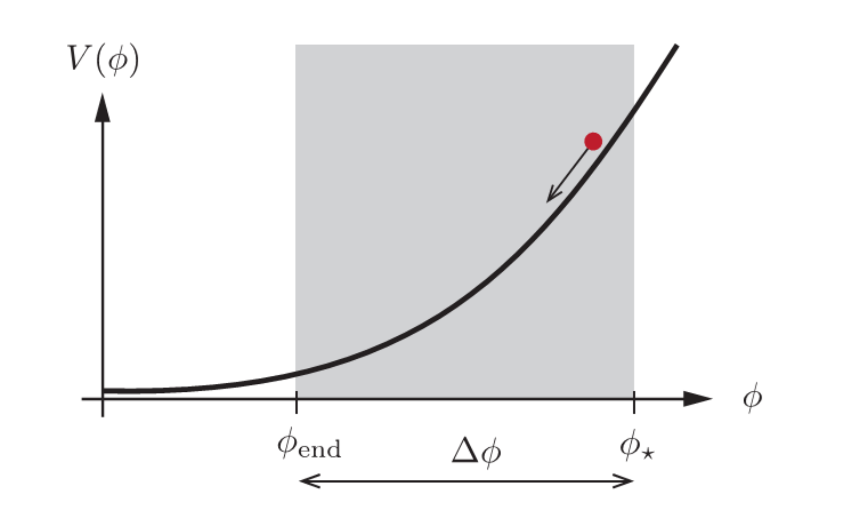
The Lyth bound

- Relates *r* to the displacement of the inflaton in field space.

$$\Delta^2_{\mathcal{R}} = \frac{1}{24\pi^2}\frac{1}{\epsilon}\frac{V}{M_{\rm pl}^4} \quad , \quad \Delta^2_h = \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4} \, . \qquad r = 8\left(\frac{1}{M_{\rm pl}}\frac{{\rm d}\phi}{{\rm d}N}\right)^2$$

$$\frac{\Delta\phi}{M_{\rm pl}} = \int_0^{N_\star} {\rm d}N \sqrt{\frac{r(N)}{8}} \, .$$

$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$



The Lyth bound

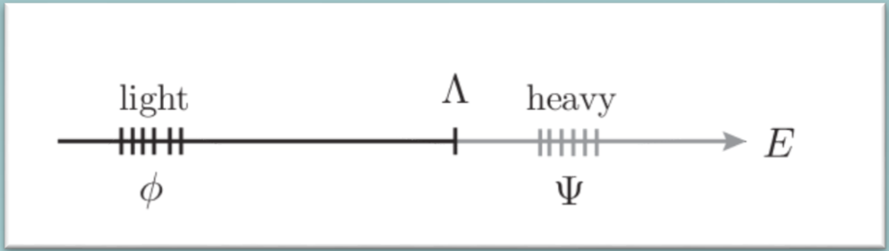
- Derivation quoted was for single-field slow roll inflation, canonical kinetic term.
- Violations of slow roll *slightly* relax the bound.
- Nontrivial kinetic terms strengthen the bound. **Baumann and Green 11**
- Multiple fields:
  - $\Delta\phi$ = arc length in field space.
  - Arc length ≠ displacement. **Berg, Pajer, Sjörs 09**
  - If slow roll holds, multi-field perturbations strengthen the bound.
  - Violations of slow roll can *slightly* relax the bound. **L.M., Renaux-Petel, Xu 12**

$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$

Scalar Lagrangian in EFT

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{pl}}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$$S_{\mathrm{eff}}[\phi] = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{pl}}^2}{2}R + \mathcal{L}_l[\phi] + \sum_i c_i\,\frac{\mathcal{O}_i[\phi]}{\Lambda^{\delta_i-4}}\right]$$



$$\mathcal{L}[\phi,\Psi] = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda\phi^4 - \frac{1}{2}(\partial\Psi)^2 - \frac{1}{2}M^2\Psi^2 - \frac{1}{4}g\phi^2\Psi^2$$

Symmetries in large-field inflation

$$\mathcal{L}_{\text{eff}}[\phi] = \mathcal{L}_l[\phi] + \sum_i c_i \frac{\mathcal{O}_i[\phi]}{\Lambda^{\delta_i - 4}} \qquad \mathcal{L}_l[\phi] = -\frac{1}{2}(\partial\phi)^2 - \mu^{4-p}\phi^p$$

Linde 83

Approximate shift symmetry: $\phi \mapsto \phi + const.$

Radiatively stable: safe from loops of light fields, i.e. inflaton and graviton. $\frac{\Delta V}{V} = c_1 \frac{V''}{M_{\text{pl}}^2} + c_2 \frac{V}{M_{\text{pl}}^4}$ **Smolin 80**

Consistent as a low-energy theory.

Symmetries in large-field inflation

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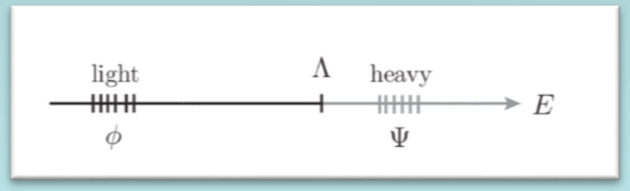
Consistent as a low-energy theory.
Question: does it admit a UV completion? What are the effects of 'loops' of heavy fields (d.o.f. of the UV completion)?

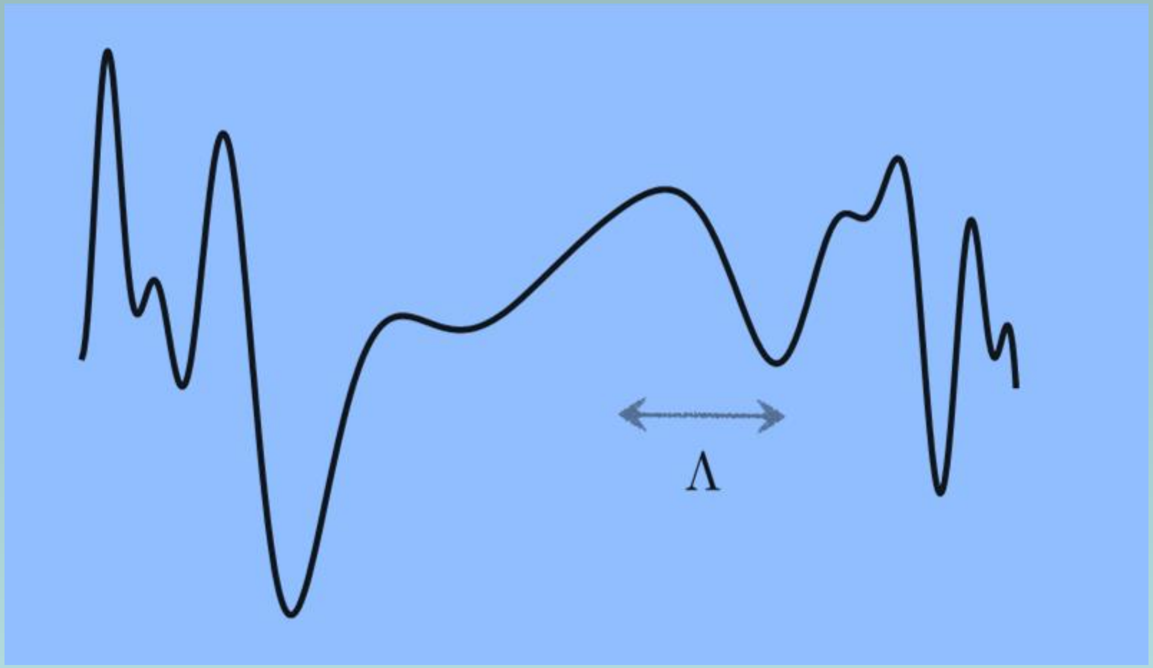
$$\mathcal{L}[\phi,\Psi] = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda\phi^4 - \frac{1}{2}(\partial\Psi)^2 - \frac{1}{2}M^2\Psi^2 - \frac{1}{4}g\phi^2\Psi^2 \qquad \lim_{g\to 0} c_i(g) = 0\ .$$

That is: does the UV completion approximately respect the shift symmetry?



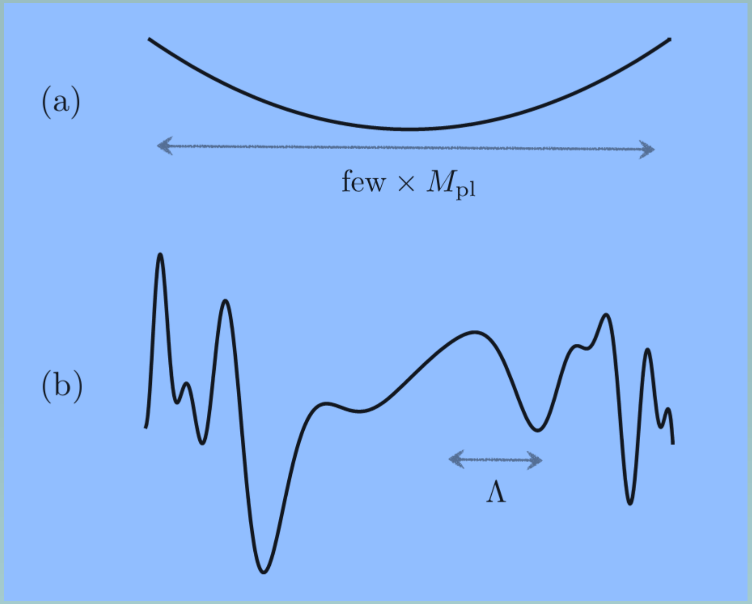
Scalar Lagrangian in EFT

$$\mathcal{L}_{\text{eff}}[\phi] = \mathcal{L}_l[\phi] + \sum_{i=1}^{\infty}\left(\frac{c_i}{\Lambda^{2i}}\phi^{4+2i} + \frac{d_i}{\Lambda^{2i}}(\partial\phi)^2\phi^{2i} + \frac{e_i}{\Lambda^{4i}}(\partial\phi)^{2(i+1)} + \cdots\right)$$



Super-Planckian displacements

- In an effective field theory with UV cutoff Λ, if the inflaton has order-one couplings to the UV d.o.f. then we expect 'structure' on scales ~ Λ.
- Detectable tensors are possible only if V varies smoothly over super-Planckian distances.
- But GR breaks down at $\Lambda \leq M_p$. Parametrically less, in some computable UV completions, e.g. weakly coupled string theory.



- We must grapple directly with quantum gravity.
- A primordial interpretation of BICEP2 tells us that the inflaton is weakly coupled to the d.o.f. that UV complete gravity: the QG theory enjoys an approximate symmetry.

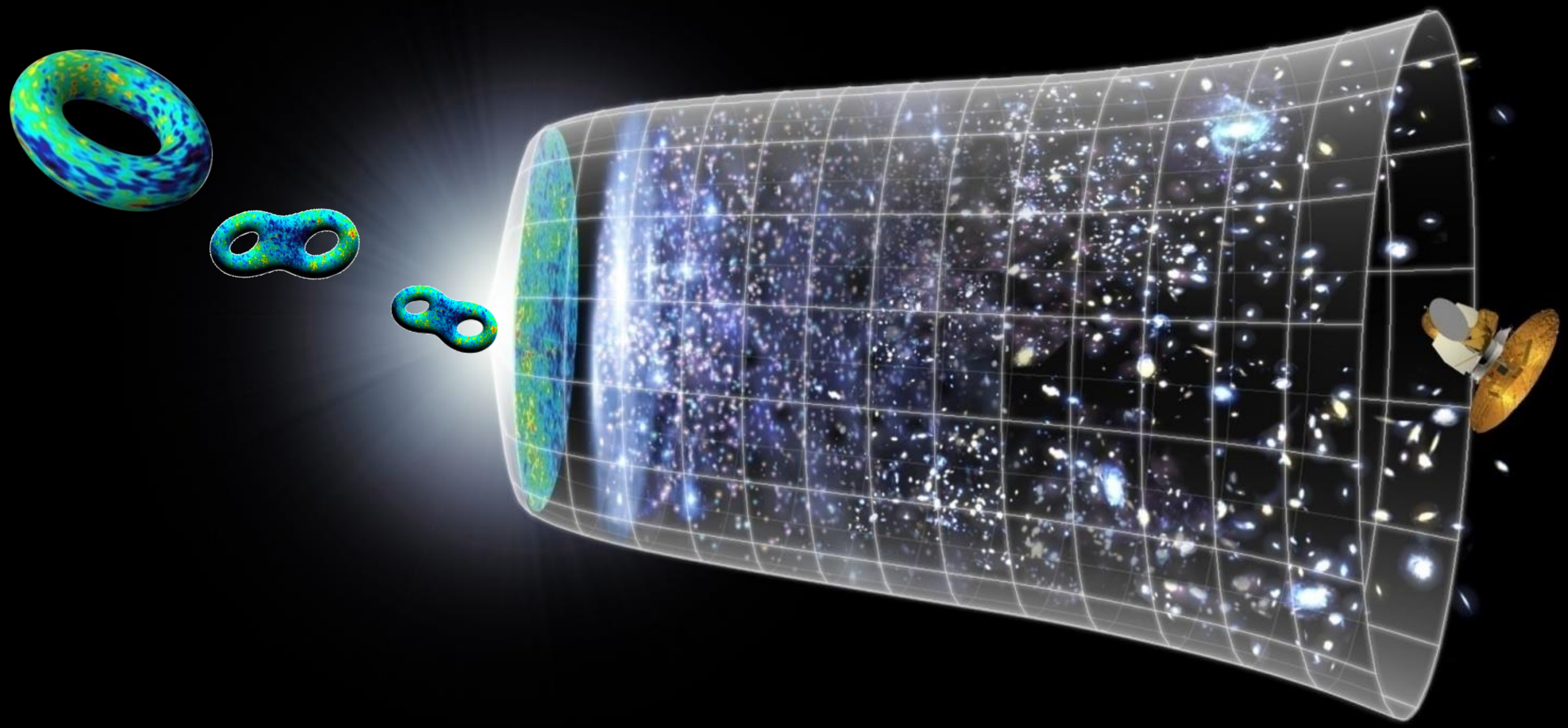
Stages of acceptance

- Didn't the Lyth bound build in assumptions about symmetries? Effective field theory? An invalid Taylor expansion of the potential?
  - No. It is a purely kinematic statement.
- Can't we evade the bound by violating single field slow roll?
  - No, not by enough to remove the problem.
- "The energies are sub-Planckian, so quantum gravity is safely irrelevant: all corrections scale as V/M_p^4."
  - Energies are indeed 'small': $E \sim 10^{-2}$ Mp. But in string theory there are definitely corrections $\sim(\phi/M_p)^p$: quantum gravity can see vevs, not just energies.
- "I wrote down a monomial potential. It looks so simple!"
  - Yes, but writing it down implicitly assumes the absence of UV corrections from couplings to QG.
- Can't I use a global symmetry to protect the potential?
  - Exact continuous global internal symmetries are (thought to be) violated by QG. Not every low energy symmetry can be UV completed. Asserting that the violation is smaller than Planckian is a strong assertion about QG.
- How about a global symmetry in N=1 or N=2 supergravity?
  - That does not help. Those theories are not UV finite and require QG completions.

Symmetries in quantum gravity

- Given an EFT that supports large-field inflation, why not just assume there is a UV completion that respects the symmetry? (Do we really have to work out the details?)
- Exact continuous global symmetries are thought to be absent in quantum gravity. The general expectation is that the scale of breaking is the Planck scale. If so, these symmetries (in unmodified form) are inadequate for large-field inflation.
- Moreover, we won't learn about QG through cosmological experiment if we assume away the constraints!
- A detection of IGW would give an unprecedented opportunity to quantify symmetry properties of QG, provided that we actually embed inflation in QG.

II. Inflation in string theory: the task



NASA/WMAP Science Team

Status summary

- Many mechanisms for inflation in string theory have been identified.
- A number of these have been shown to be compatible with moduli stabilization.
- Totally explicit moduli stabilization, with a first principles end-to-end computation of the inflaton potential from topological data (including computing next-order corrections to show they are small) has not been achieved, but:
  - solid progress is being made.
  - indirect determination of the action has grown quite sophisticated
- There are string theory constructions both of large-field inflation and of small field inflation. The technical challenges are rather different. Far too early to try to judge which is more natural in string theory.

Task: Compactification

Ideally: specify discrete data (compactification topology, quantized fluxes, wrapped branes), and derive, order by order in α' and g_s, a 4d EFT that supports inflation. Planck-suppressed contributions should be *computed*.

Task: Compactification

- In practice:
  - The problem is difficult! Compactness and broken supersymmetry spoil many methods applicable in cleaner systems.
  - Many analytic data unavailable (e.g., metric on a compact CY3)
  - Perturbative corrections past one loop are rarely known, but frequently important.
  - Perturbative and nonperturbative quantum effects often control the vacuum structure and potential.
  - A huge arsenal of approximation schemes is used. But these are not always convergent parametric expansions.
- Extensive use of approximations, estimates, and assumptions creates ambiguity.
  - Reasonable people may well disagree over whether a given model ‘exists’ or ‘works’.

Approximations

- Classical
- Large radius
- Leading instanton
- Noncompact
- SUSY
- Minkowski
- Decoupled
- Probe
- Dilute flux
- Large charge
- Smeared
- Adiabatic

The state of the art

(for type IIB string theory on an orientifold of a CY3: all other cases are strictly harder/less developed for this purpose)

- Specify compactification, at the level of Hodge numbers, orientifold actions, D-brane configurations.
- Assume that generic 3-form flux stabilizes the complex structure moduli and axiodilaton.
- Compute potential for Kähler moduli and D-brane positions, with contributions from (some of)
  - Euclidean D-branes, or gaugino condensation on seven-branes. Arithmetic genus condition occasionally checked; Pfaffian prefactor rarely computed, assumed ~O(1).
  - The $(\alpha')^3$ Riemann^4 correction.
  - Other less-characterized α' corrections
  - String loop corrections at one loop. Often one takes a form conjectured based on toroidal orientifolds. **Berg, Haack, + Kors 05, + Pajer 07**

The state of the art

(for type IIB string theory on an orientifold of a CY3: all other cases are strictly harder/less developed for this purpose)

With this approximation to the effective action:

- Establish existence of a local minimum of the moduli potential. Typically AdS_4, either SUSY or non-SUSY.
  - In few-moduli cases, this is clean.
  - In many-moduli cases, potential instabilities are often underestimated.
- Argue for the possibility of 'uplifting' to de Sitter.
  - Simplest module for uplifting: anti-D3-brane in Klebanov-Strassler (or similar).
    - Metastable?

    KPV, DeWolfe, Kachru, Mulligan, Bena, Grana, Halmagyi, Giecold, Massai, Dymarsky, Kuperstein, McGuirk, Shiu, Sumitomo, Wrase, Van Riet, Danielsson
  - This module is reasonable in compactifications admitting highly warped regions
  - Instabilities arising on uplifting are often underestimated.

The state of the art

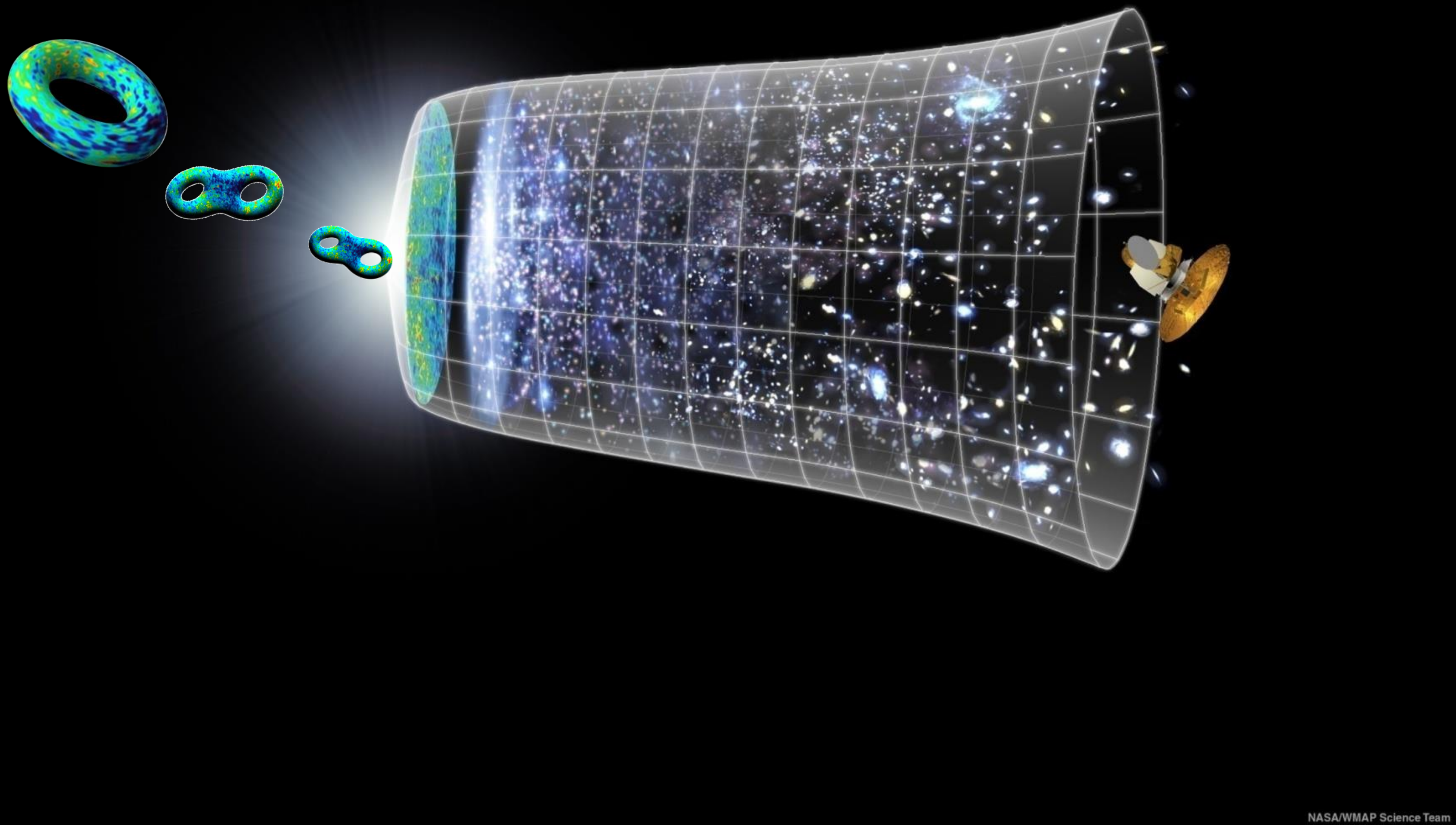
(for type IIB string theory on an orientifold of a CY3: all other cases are strictly harder/less developed for this purpose)

In this setting, identify an inflaton candidate and compute its potential.

Many challenges:

- Physical effects that give mass to the moduli also give an undesirably large mass to the inflaton.
- So if the moduli potential comes from quantum effects at order N, we must compute V_{inf} to the same order.
- ‘Stabilized’ moduli shift or fluctuate during inflation.
- Inflationary energy breaks supersymmetry.
- Inflationary energy backreacts on the compactification.

III. Inflation in string theory: examples



Natural inflation

Goal: identify a robust symmetry in a UV completion that protects the inflaton over a super-Planckian range.

In the EFT scenario known as natural inflation, **Freese, Frieman, Olinto 90** a PQ symmetry $\phi \mapsto \phi + const.$ of an axion is invoked to protect the inflaton potential.

$$\mathcal{L}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \Lambda^4\left[1 - \cos\left(\frac{\phi}{f}\right)\right] + \cdots$$

To address questions of the UV completion of this symmetry, we should embed natural inflation models in string theory.

Axions in string theory

- Axions are numerous, descending from $\int_{\Sigma_p} C_p$ and $\int_{\Sigma_2} B_2$
- For example, one finds hundreds of axions in typical Calabi-Yau compactifications.
- In the absence of fluxes and branes, axions enjoy a shift symmetry to all perturbative orders in the string loop expansion and the α' expansion. **Wen, Witten 86; Dine, Seiberg 86**
- Nonperturbative effects break the continuous shift symmetry, generating a periodic potential:

$$\mathcal{L} = \frac{1}{2} f^2 (\partial\theta)^2 - \Lambda^4 \left[1 - \cos(\theta)\right] = \frac{1}{2} (\partial\phi)^2 - \Lambda^4 \left[1 - \cos(\phi/f)\right]$$

- Periodicity: $2\pi f$

Axion decay constants

- The quantity of interest is the periodicity of a canonically-normalized field. So we must examine the kinetic term for the axion field.
- When axions arise from dimensional reduction of p-forms ω_p threading p-cycles, the kinetic term is determined by $\omega_p \wedge \star_6 \omega_p$
- In N=1 supergravity theories, this information is packaged in the Kähler potential.
- The simplest case is a single axion: after a field redefinition, the Lagrangian takes the canonical form:

$$\mathcal{L} = \frac{1}{2} f^2 (\partial\theta)^2 - \Lambda^4 \left[1 - \cos(\theta)\right] = \frac{1}{2}(\partial\phi)^2 - \Lambda^4 \left[1 - \cos(\phi/f)\right]$$

Natural Inflation in string theory?

Q: Can we use $V = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$ to drive large-field inflation?

Freese, Frieman, Olinto 90

This requires $f \gg M_p$.

A: Super-Planckian single-axion decay constants not possible in presently computable limits of string theory.

Banks, Dine, Fox, Gorbatov 03

$$\frac{f}{M_P} \propto \frac{g_s^\alpha}{\mathcal{V}^\beta} \ll 1$$

$$\alpha, \beta \geq 0$$

Natural Inflation in string theory?

To realize natural inflation in string theory, we will need to relax one or more implicit assumptions.

A. Explore new regimes of strong coupling or small volume where decay constants can be large. **Grimm 14**

B. Incorporate monodromy of an axion: repeatedly traverse the fundamental sub-Planckian period of an axion. **Silverstein, Westphal 08; L.M., Silverstein, Westphal 08** **Flauger, L.M., Pajer, Westphal, Xu 09**

C. Consider more than one axion.
   - With two axions one can fine-tune the decay constants to achieve "decay constant alignment", and a super-Planckian effective period. **Kim, Nilles, Peloso 04**
   - With N >> 1 axions without-fine-tuned decay constants, the collective displacement can be super-Planckian. (N-flation, a realization of assisted inflation) **Dimopoulos, Kachru, McGreevy, Wacker 05**

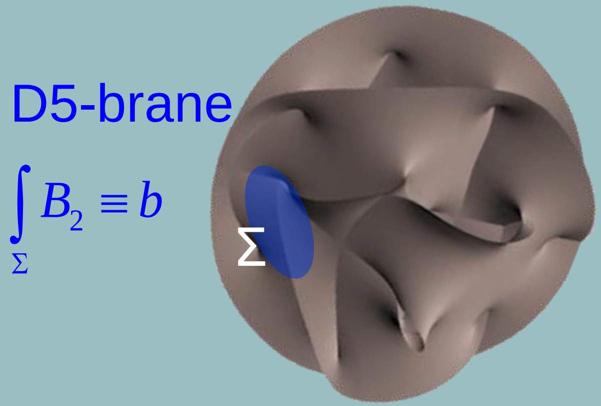
Recent progress on all these fronts.

Axion monodromy inflation

Periodic axion field ‘unwound’ to give monotonic potential over an enlarged range, with residual symmetry protection.

Silverstein, Westphal 08
L.M., Silverstein, Westphal 08
Flauger, L.M., Pajer, Westphal, Xu 09
Berg, Pajer, Sjörs 09
Franco, Galloni, Retolaza, Uranga 14
Palti, Weigand 14
Marchesano, Shiu, Uranga 14
Blumenhagen, Plauschinn 14
Hebecker, Kraus, Witkowski 14
Arends, Hebecker, Heimpel, Kraus, Lüst, Mayrhofer, Schick, Weigand 14
Hassler, Lüst, Massai 14
Kaloper, Lawrence 14
L.M., Silverstein, Westphal, Wrase 14
+…

Axion monodromy from wrapped fivebranes



$$V_{DBI} = \int_{\Sigma_2} \frac{d^2\xi \, e^{2A-\Phi}}{(2\pi)^5 \alpha'^3} \sqrt{\det(G+B)}$$

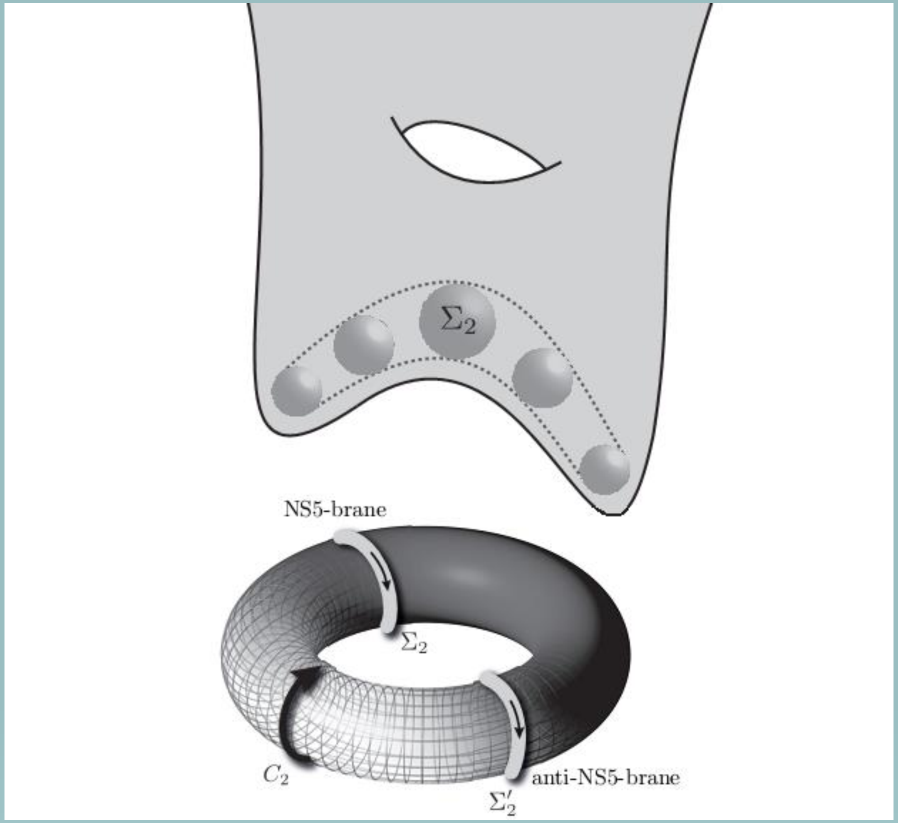
For large b, $V_{DBI} \propto \int_{\Sigma_2} B_2 \equiv b$

so we can define $V_{DBI} \approx \mu^3 b f \equiv \mu^3 \phi$

Fivebrane contribution not periodic: as axion shifts by a period, potential undergoes a monodromy that unwraps the axion circle.
Result: asymptotically linear potential over an *a priori* unlimited field range.

L.M., Silverstein, Westphal 08

For $\mathcal{O}(10^2)$ circuits one can obtain $\Delta\phi = 11 M_p$



For tadpole cancellation, take fivebrane and anti-fivebrane wrapped on homologous curves, metastabilized by a larger representative in between.

cf. Aganagic, Beem, Seo,Vafa

Similar structures could be used for (p,q) 7-branes **Palti, Weigand**

Holographic description, NS5 replaced by flux: **Franco, Galloni, Retolaza, Uranga**

Compactification and stabilization

Attach to KKLT compactification. Does the mechanism survive?

- Moduli potential gives a fatal contribution to the potential for b, but not for c, which has shift-symmetric K.
- Thus, take NS5-brane pair, and take c to be the inflaton. The leading c-dependence in the effective action comes from the NS5-brane tension.
- Kähler moduli stabilization by ED3-branes is problematic: magnetized ED3s intersecting inflationary cycle give $\eta \sim 1$.
  - Topological choice: ensure that all four-cycles with dangerous intersections are stabilized by gaugino condensation on seven-branes.
  - Then inflaton potential arises at two-instanton level, while moduli potential arises at one-instanton level.

Backreaction and stability

- Inflationary order parameter is induced D3-brane charge on NS5-branes. Q_{D3}=# of axion cycles remaining.
- D3-brane charge and tension backreact, warping the geometry. This changes the ED3 action (resp. D7-brane gauge coupling), so the moduli potential is exponentially sensitive to the inflaton vev.
- Model-building solution: isolate the fivebrane pair in a warped region, suppressing the effect on the remainder.
  - But this suppresses the decay constant, requiring more axion cycles.
- If the inflaton is a combination of two axions, the backreaction problem is much diminished. **Berg, Pajer, Sjörs 09**

Axion monodromy inflation

Issues for all models (not just NS5 example!):

Realization including (& unspoiled by) moduli stabilization.

Backreaction of inflationary energy.

- worse for smaller f
- obvious in some cases (e.g. NS5 pair), but very generally present: this is a feature of chaotic inflation.

All these models are complicated once completed. Local/probe/unstabilized analyses can easily overlook some of the issues.

Chaotic inflation vs. moduli stabilization

V changes by a factor ~ 100 during chaotic inflation.

In any extradimensional model of chaotic inflation with localized sources (for inflation or stabilization), it is challenging to avoid shifting of vevs as inflation proceeds.

Result: large corrections to V from backreaction.

e.g. D3 charge on NS5-brane pair

D3 or D7 position

These affect ED3 action, leading to inflaton-dependence in moduli potential.

Berg, Haack, Körs 04; Baumann, Dymarsky, Klebanov, Maldacena, L.M., Murugan 06
L.M., Silverstein, Westphal 08; Flauger, L.M., Pajer, Westphal, Xu 09.

Decay constant alignment

- With two axions one can fine-tune the decay constants to achieve a super-Planckian effective period

$$V(\phi) = \Lambda_A^4 \left[1 - \cos\left(\frac{\phi^1}{f_{A1}} + \frac{\phi^2}{f_{A2}}\right)\right] + \Lambda_B^2 \left[1 - \cos\left(\frac{\phi^1}{f_{B1}} + \frac{\phi^2}{f_{B2}}\right)\right]$$

$$\frac{f_{A1}}{f_{A2}} = \frac{f_{B1}}{f_{B2}}.$$

Mechanism: **Kim, Nilles, Peloso 04**
(cf. also **Kappl, Krippendorf, Nilles 14**)

String embeddings:

Long, L.M., McGuirk 14
Ben-Dayan, Pedro, Westphal 14
Gao, Li, Shukla 14

Flux potentials

Inflaton potential from classical flux W can be fine-tuned, in principle.

Marchesano, Shiu, Uranga
Blumenhagen, Plauschinn
Hebecker, Kraus, Witkowski
Arends, Hebecker, Heimpel, Kraus, Lüst, Mayrhofer, Schick, Weigand

Risk: terms beyond classical W less-controlled.

- loop corrections to K
- Nonperturbative W
  - Pfaffian
  - Fluxed instantons

Berg, Haack, Körs; Berg, Haack, Pajer; Hebecker, von Gersdorff

Conclusions

- Evidence for primordial gravitational waves allows us to probe the symmetry structure of quantum gravity through explicit ultraviolet completions of inflation.
- We understand string theory mechanisms for large-field inflation and for small-field inflation.
- Axion inflation is a promising route to large-field inflation in string theory.
- Inflation in string theory has advanced to a stage where theory errors can be quantified and models can be falsified.
- But painstaking work is required to characterize any given model well enough to see QG constraints, if any.
- Much work remains to map out the space of models that can exist even in known compactifications.

Outlook

- If the BICEP2 signal is primordial, this is a result of truly exceptional significance, comparable to the discovery of the CMB itself.
  - Quantum gravity becomes indispensable for the interpretation of cosmological data;
  - The task of embedding inflation in string theory becomes sharper, technically harder, and more urgent;
  - The reverberations for theorists and observers will last a very long time.
- If instead BICEP2 has seen dust,
  - The evidence for inflation remains extremely strong;
  - Small-field inflation models in string theory should be the target of truly systematic exploration;
  - Future experimental clues may be scarce and slow to emerge.