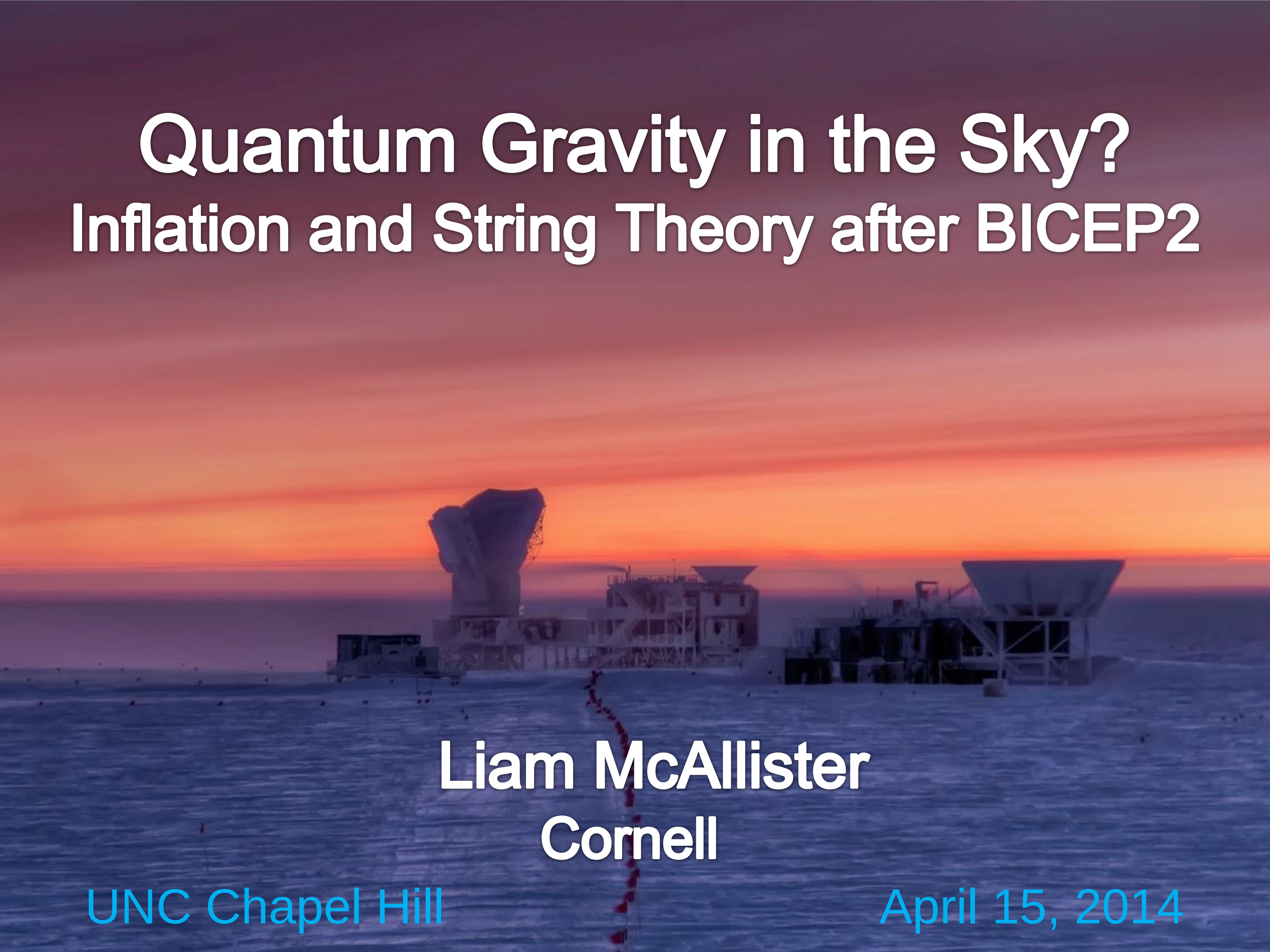


Quantum Gravity in the Sky?

Inflation and String Theory after BICEP2

Liam McAllister

Cornell

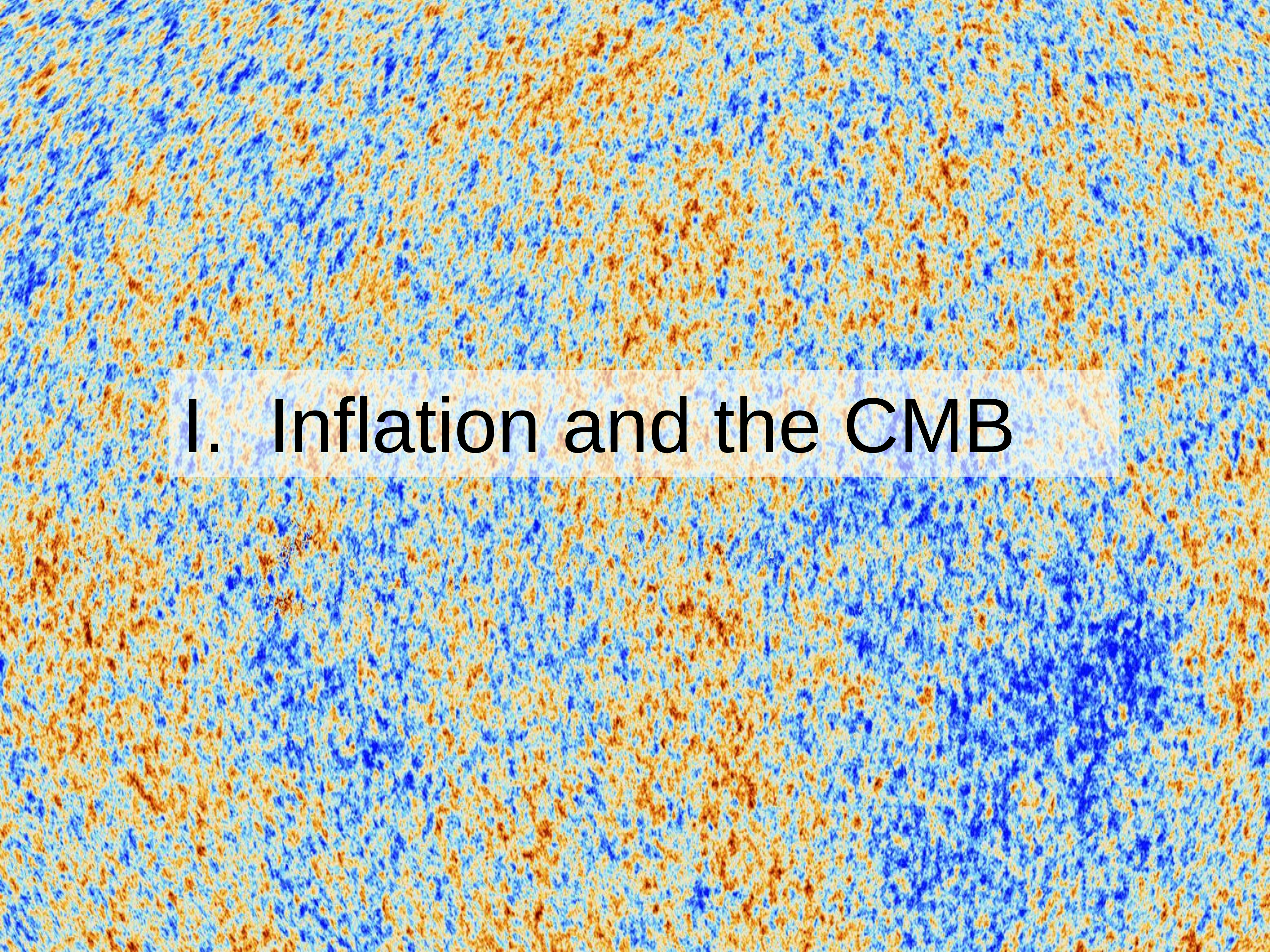
UNC Chapel Hill

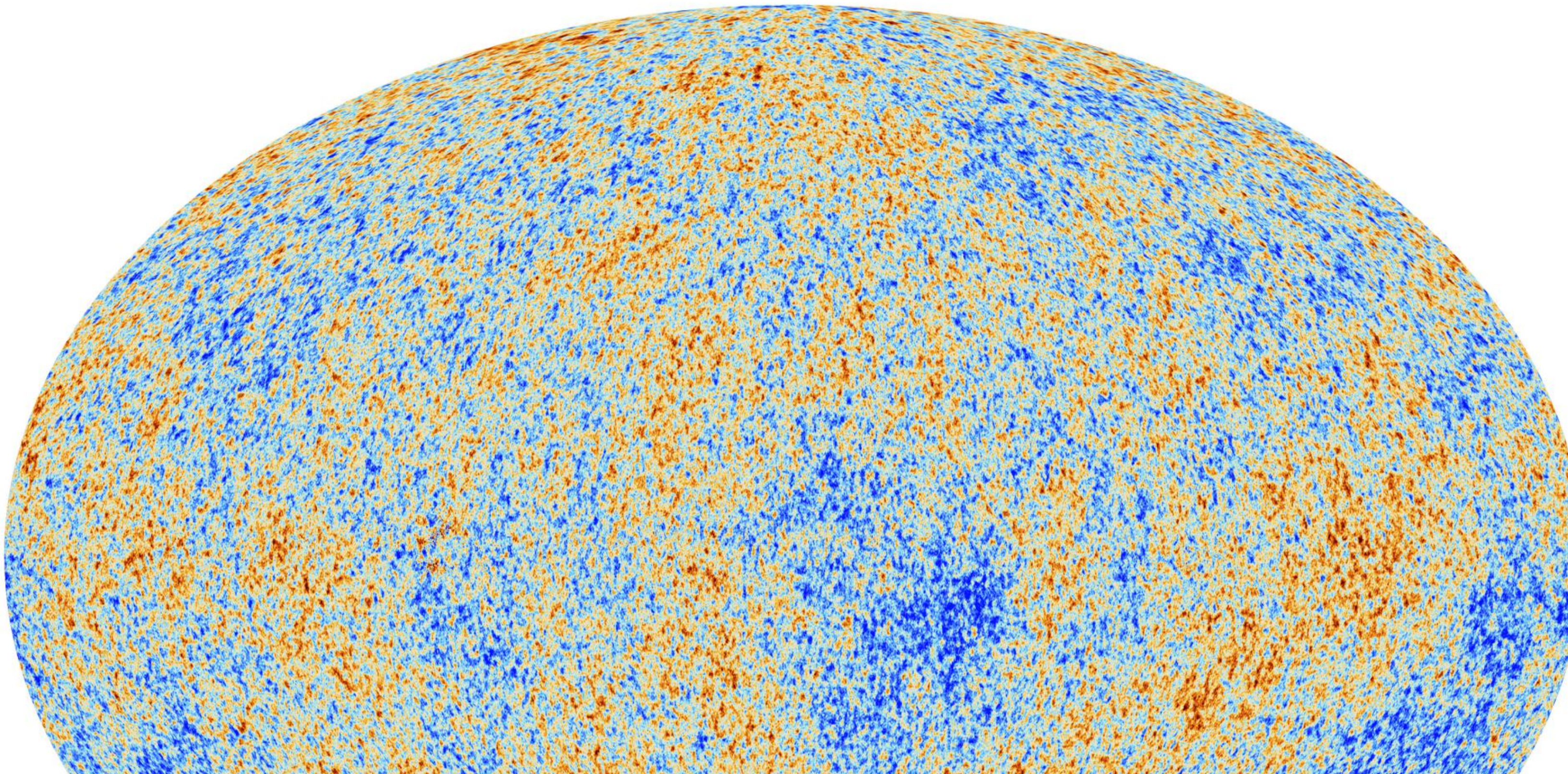
April 15, 2014

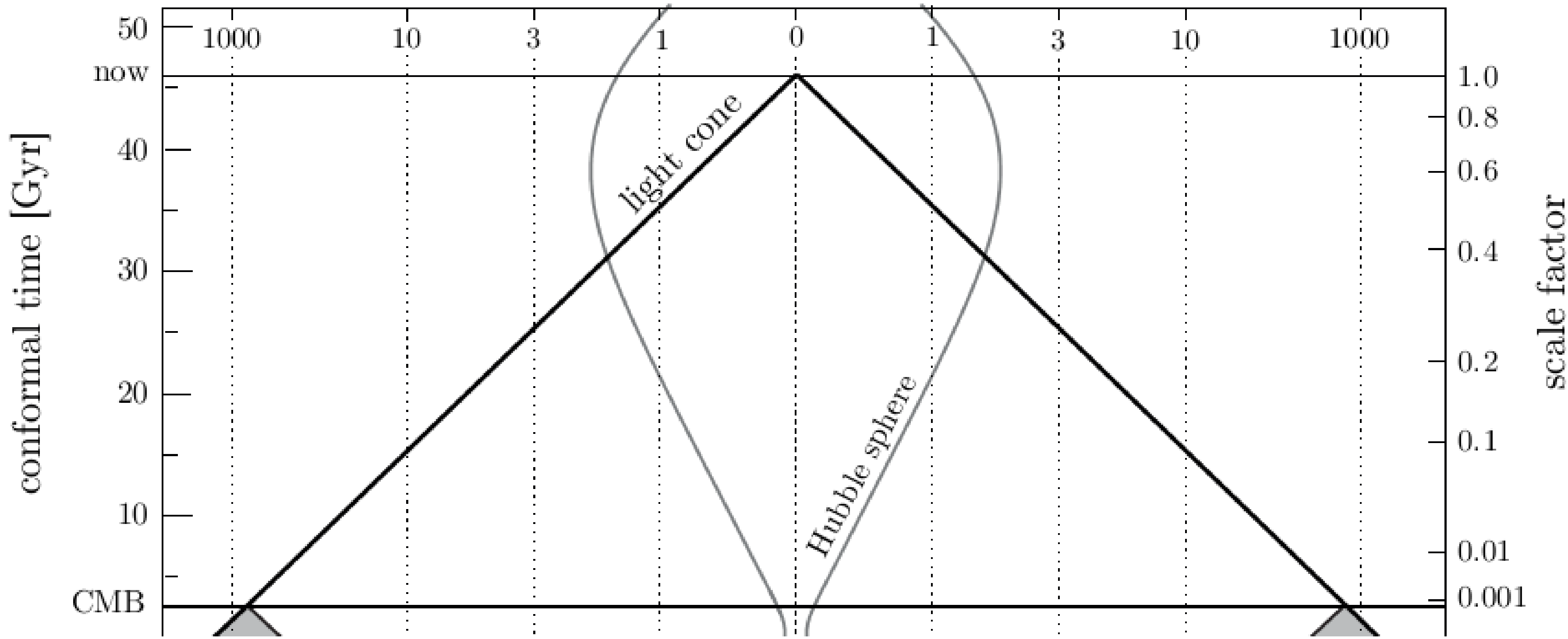
Plan

I. Background: inflation and the CMB
II. The BICEP2 result
III. Consequences for inflation
IV. Inflation in string theory
V. Outlook

I. Inflation and the CMB







The Horizon Problem

Inflation

Guth 81; Linde 82; Albrecht, Steinhardt 82

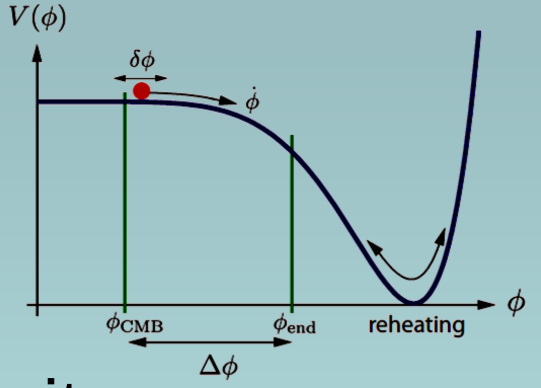
- An epoch of quasi-exponential expansion

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$a(t) = a(0)e^{Ht}$$
$$H \approx const.$$

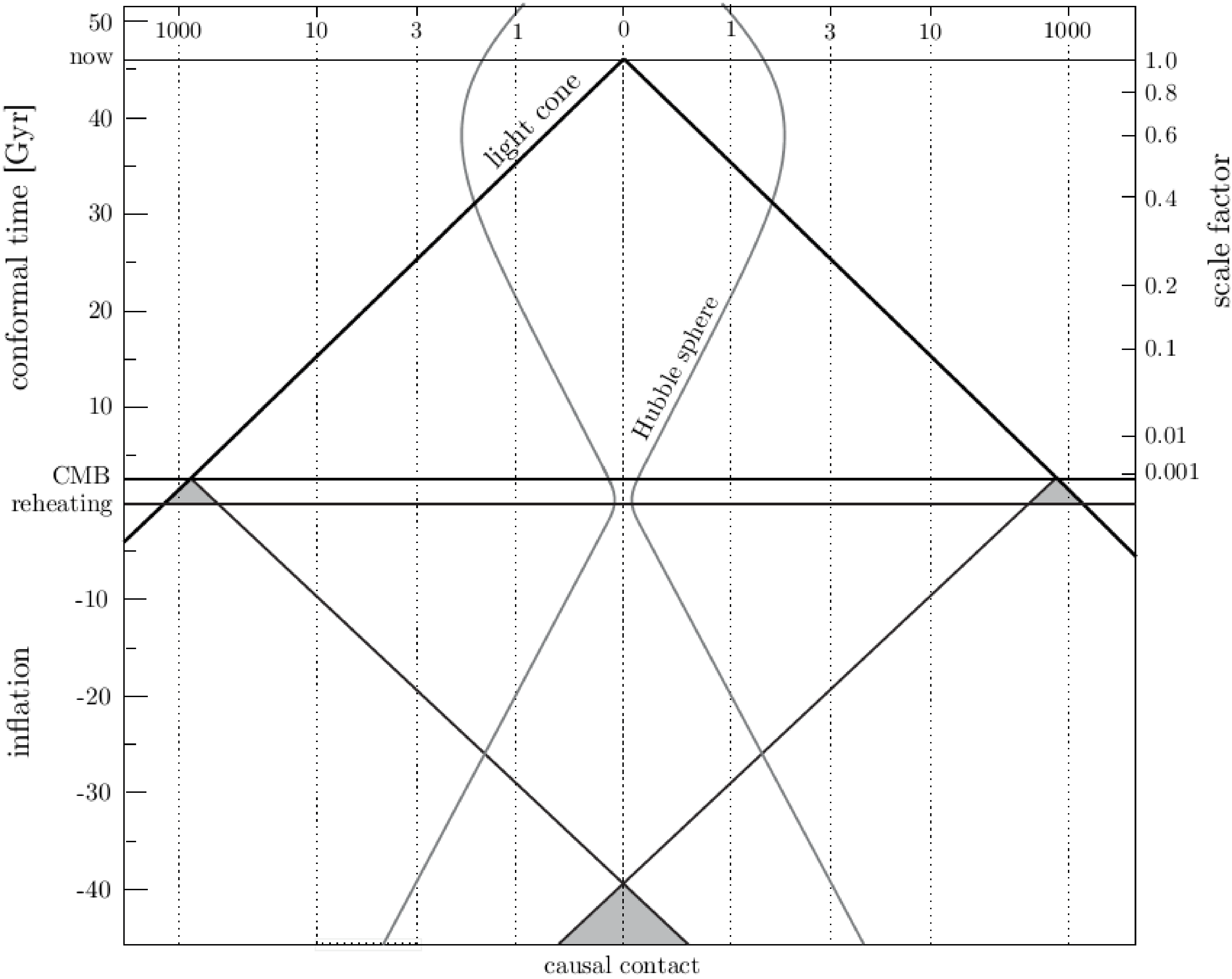
- Simplest example: single scalar field with a potential,

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



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

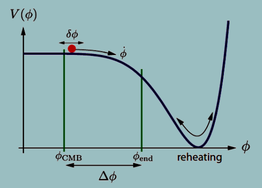
$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv M_p^2\frac{V''}{V} \ll 1$$



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

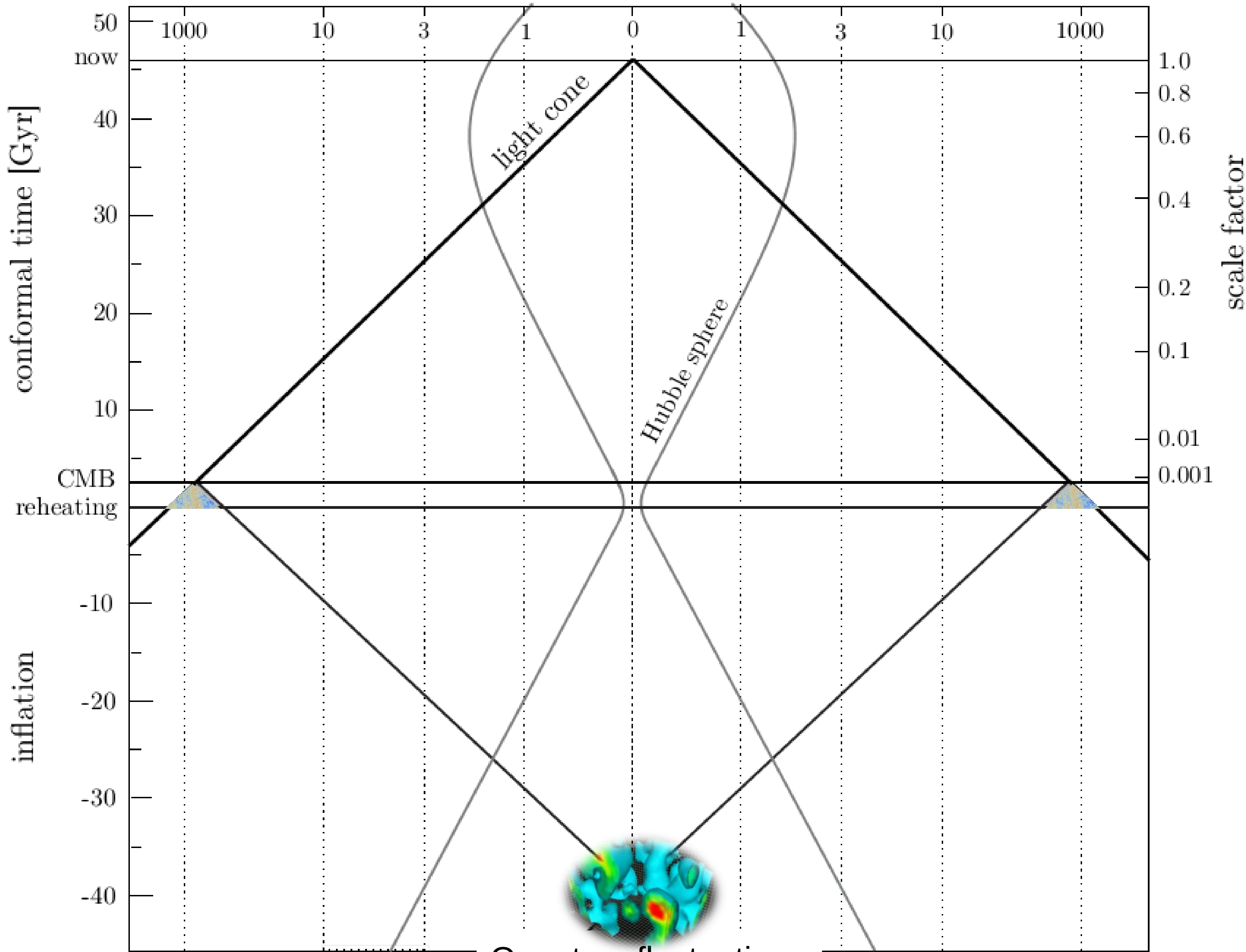
Perturbations in Inflation

- 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.

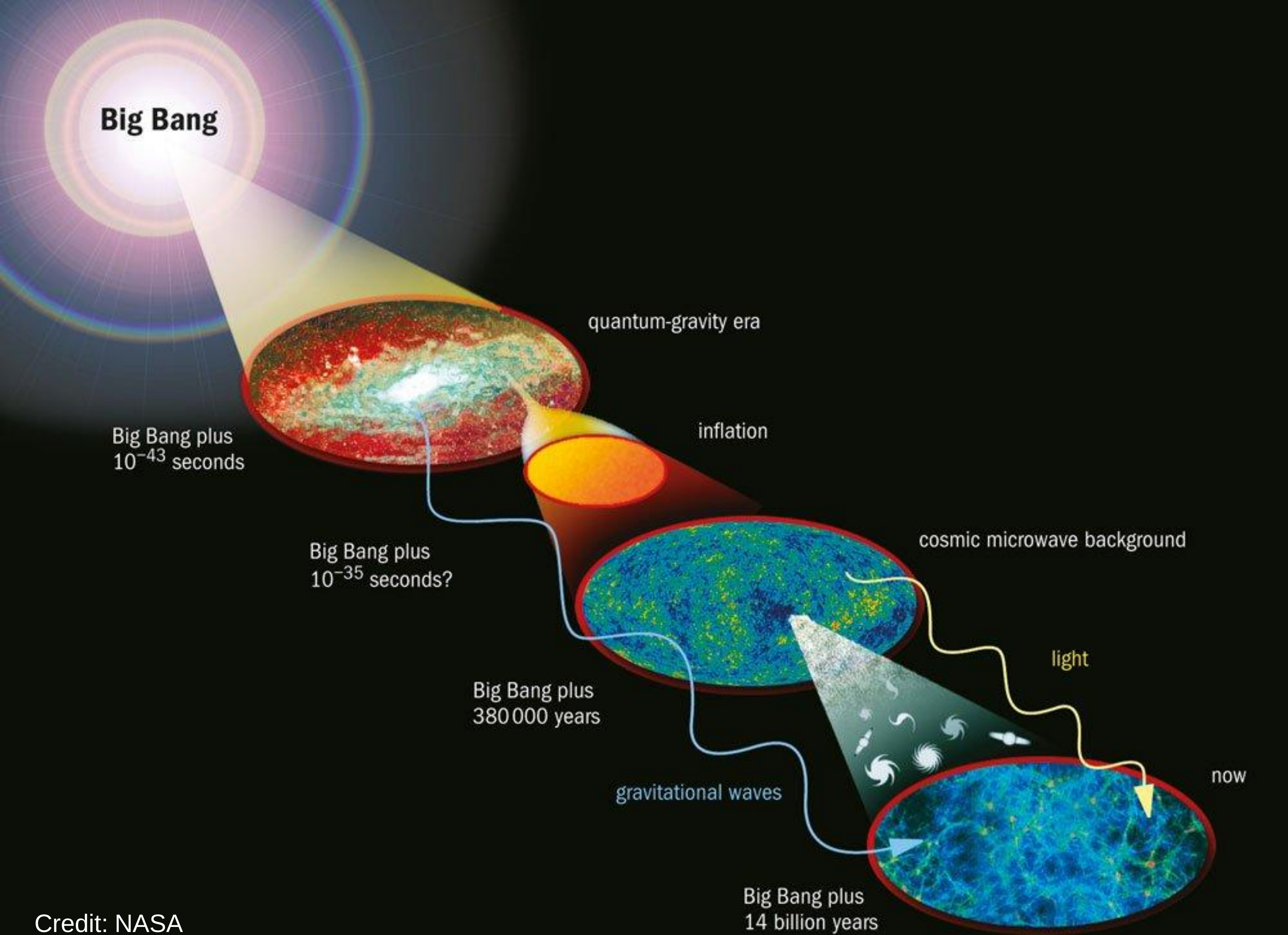


- Quantum fluctuations of the graviton are stretched to superhorizon scales, forming primordial gravitational waves.

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

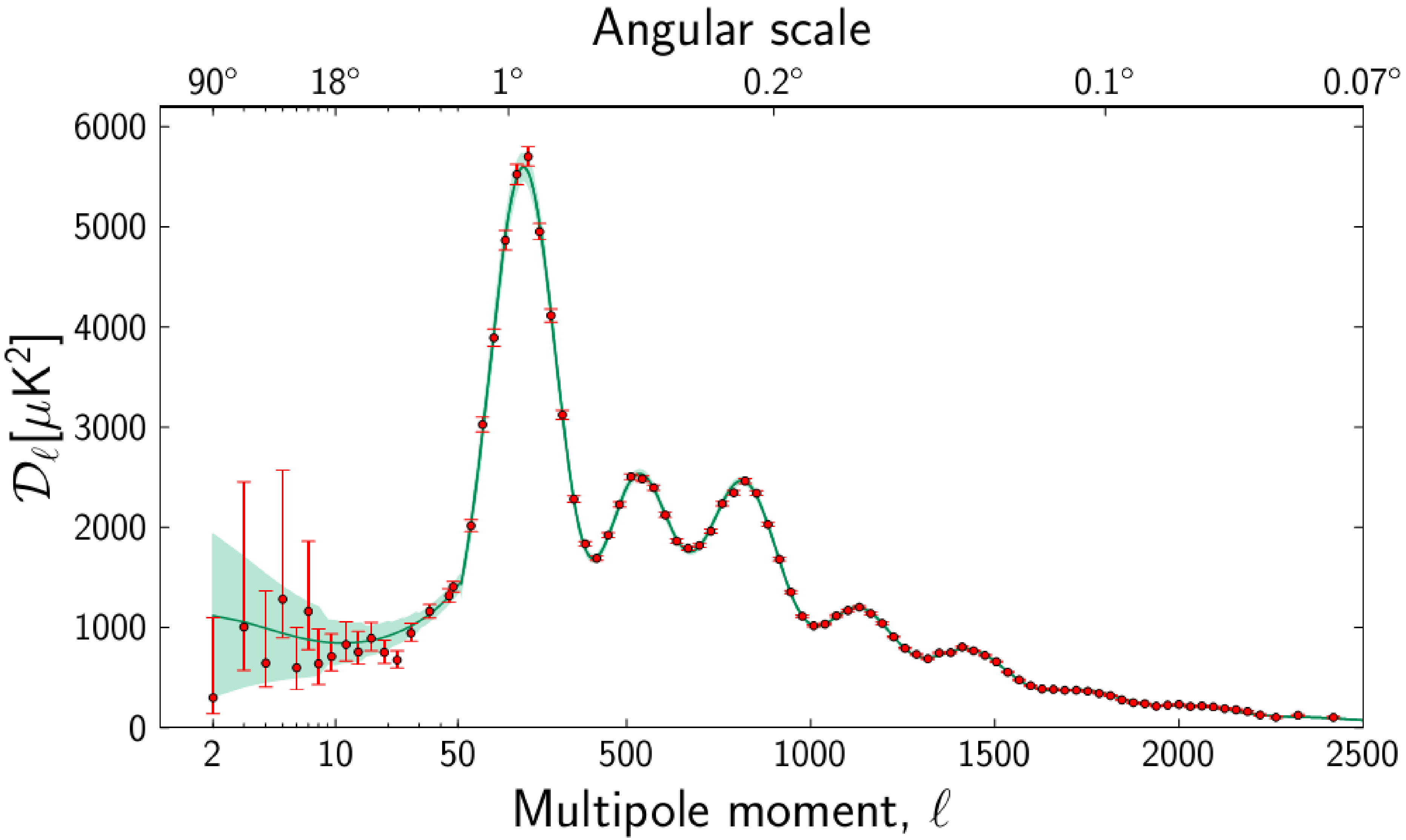


Quantum fluctuations

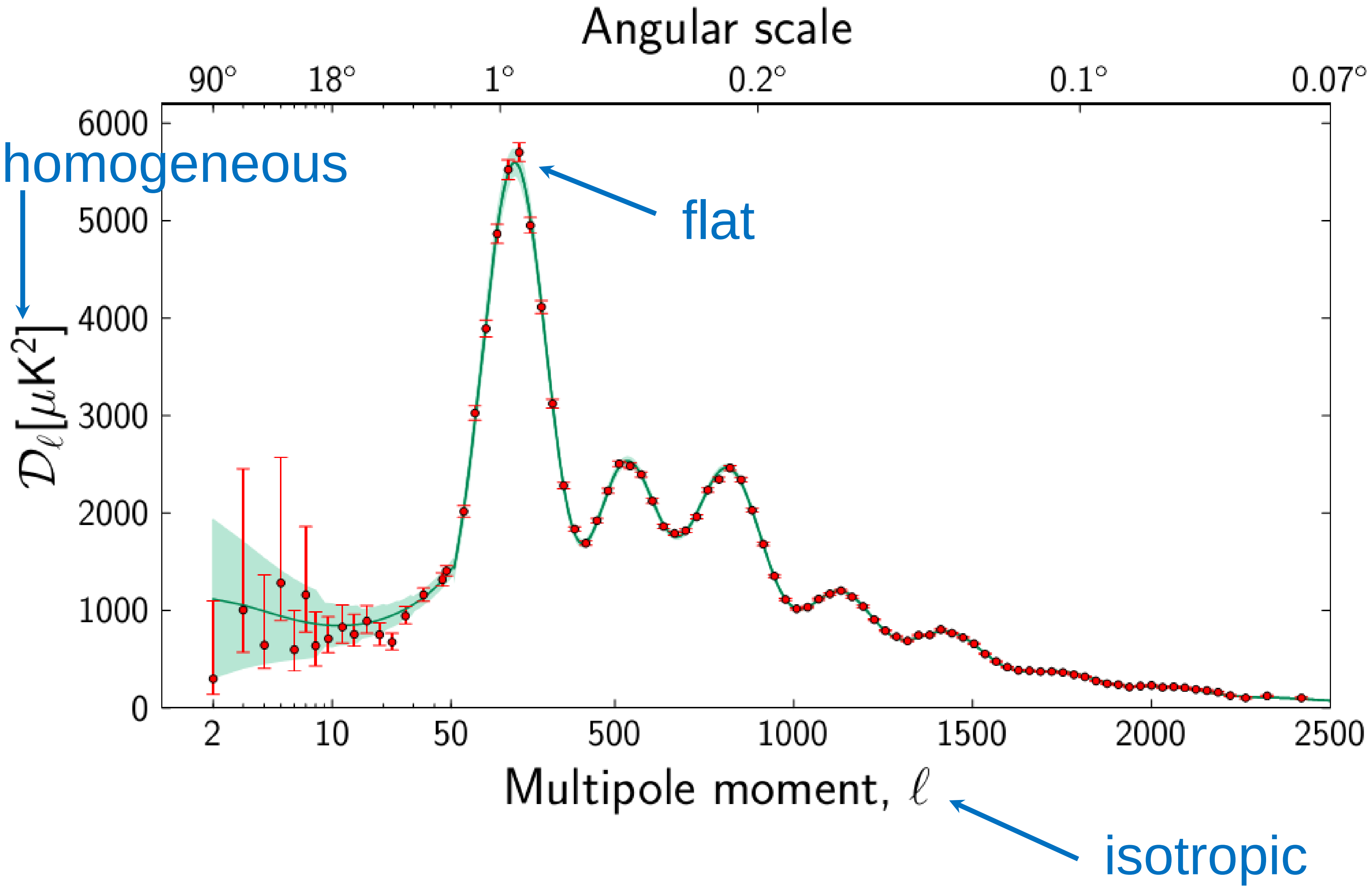

Big Bang
quantum-gravity era
Big Bang plus
10^{-43} seconds
inflation
Big Bang plus
10^{-35} seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

Credit: NASA

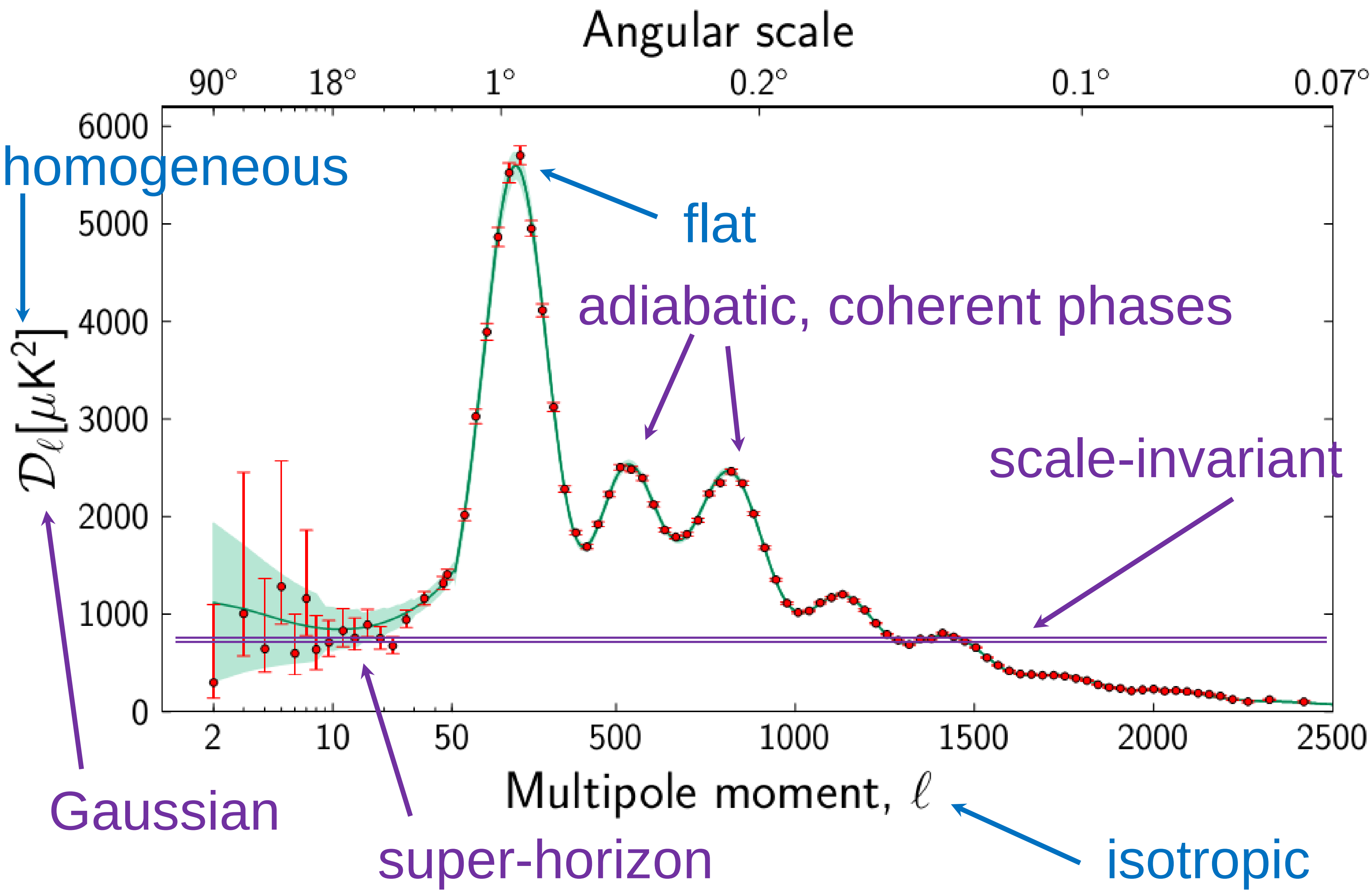
Planck 2013 CMB power spectrum

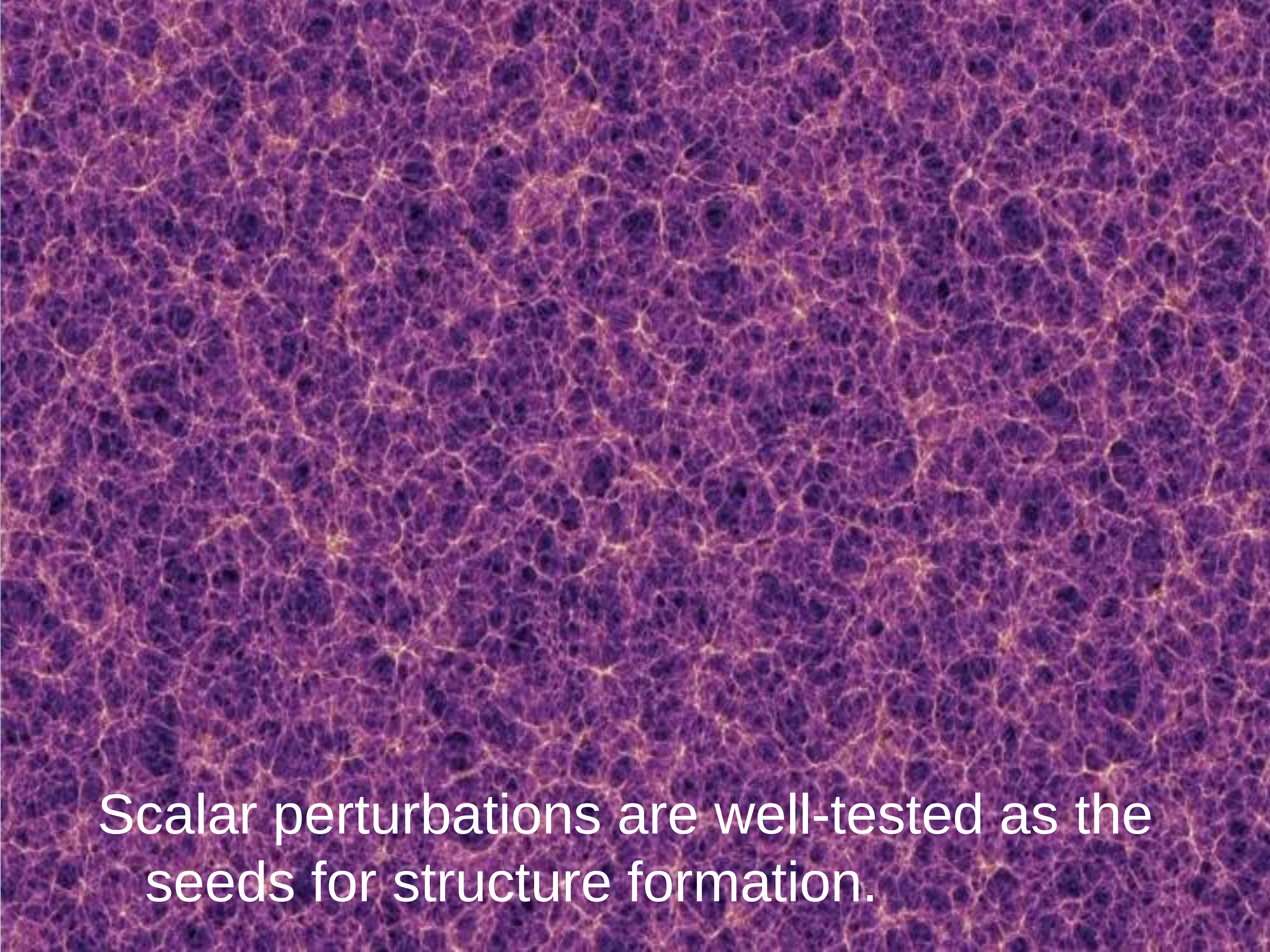


Planck 2013 CMB power spectrum



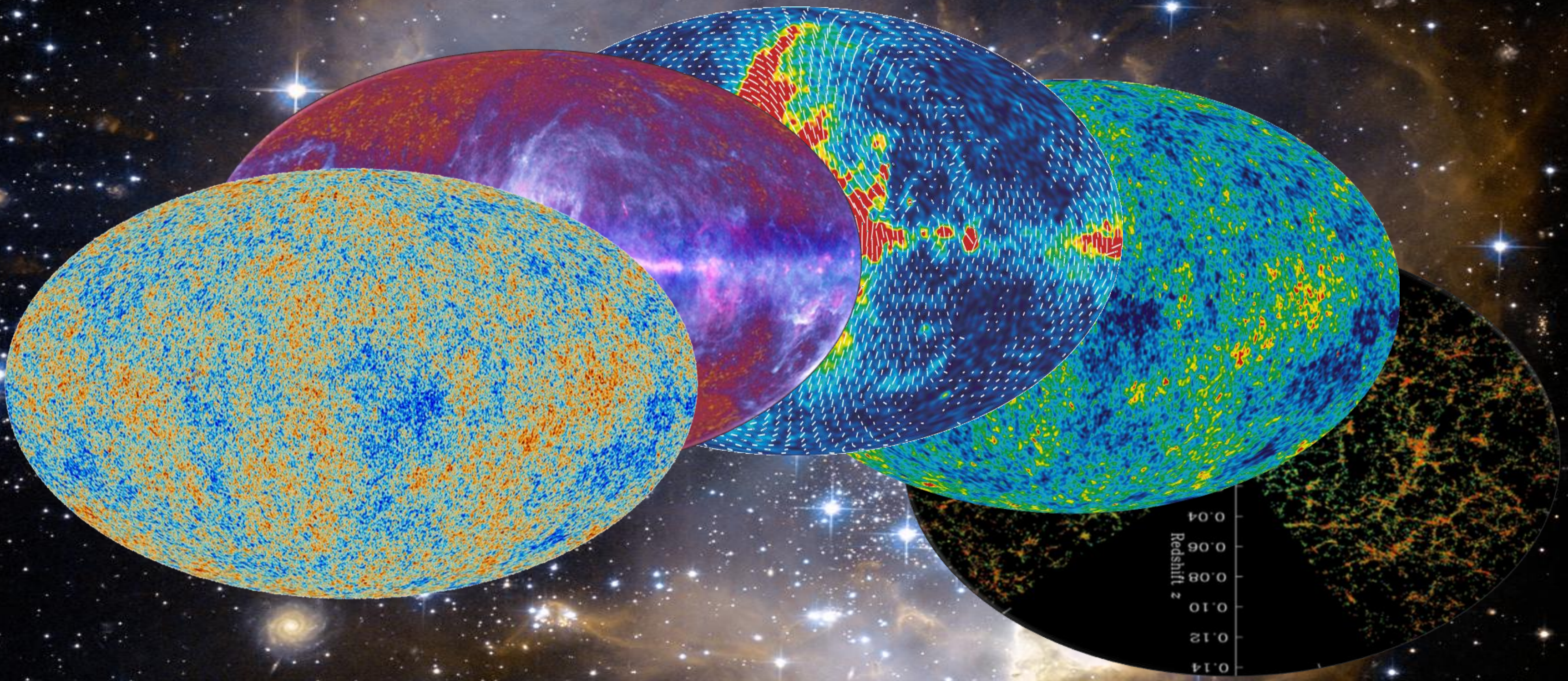
Planck 2013 CMB power spectrum



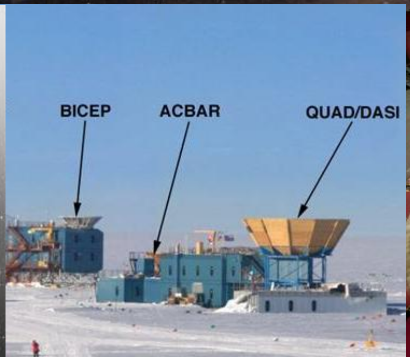


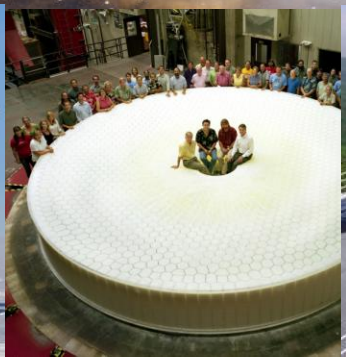
Scalar perturbations are well-tested as the seeds for structure formation.

A golden age of cosmology



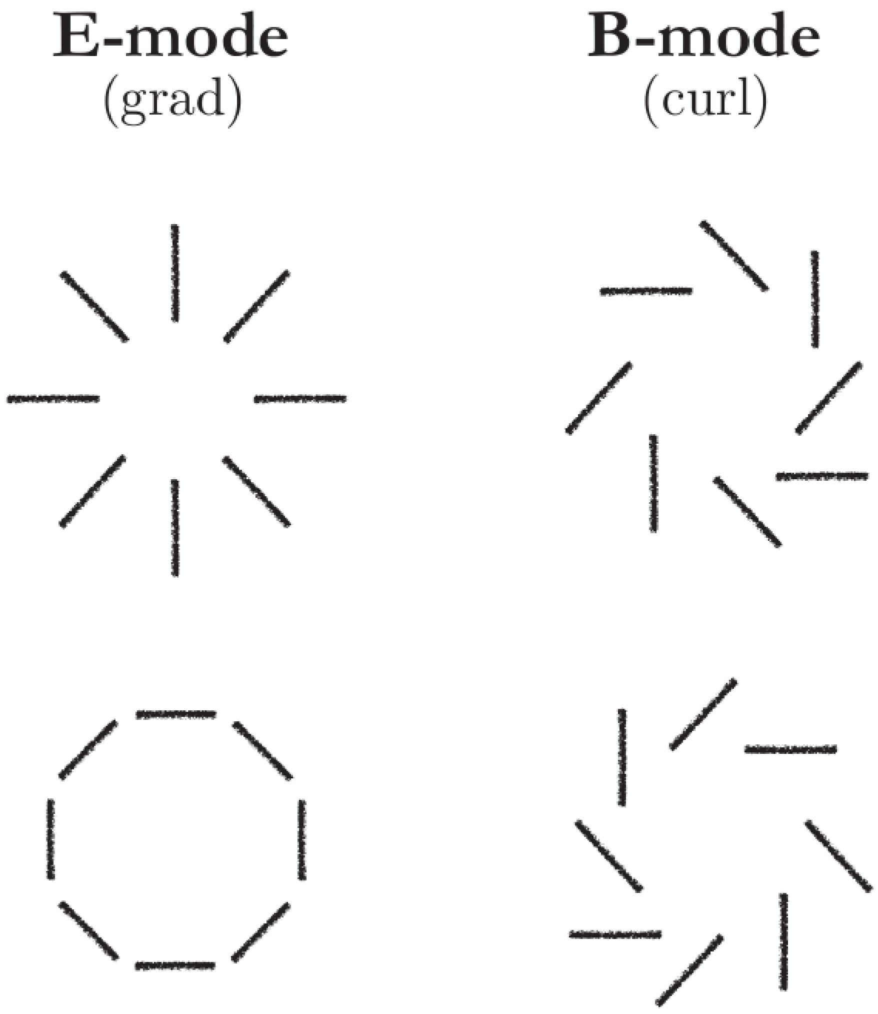
Planck; WMAP; SDSS





Primordial gravitational waves and CMB polarization

- Quantum fluctuations of the graviton are stretched to superhorizon scales to form primordial gravitational waves.
- Tensors leave an imprint in the CMB polarization, by inducing a quadrupole anisotropy at the time of decoupling.



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,

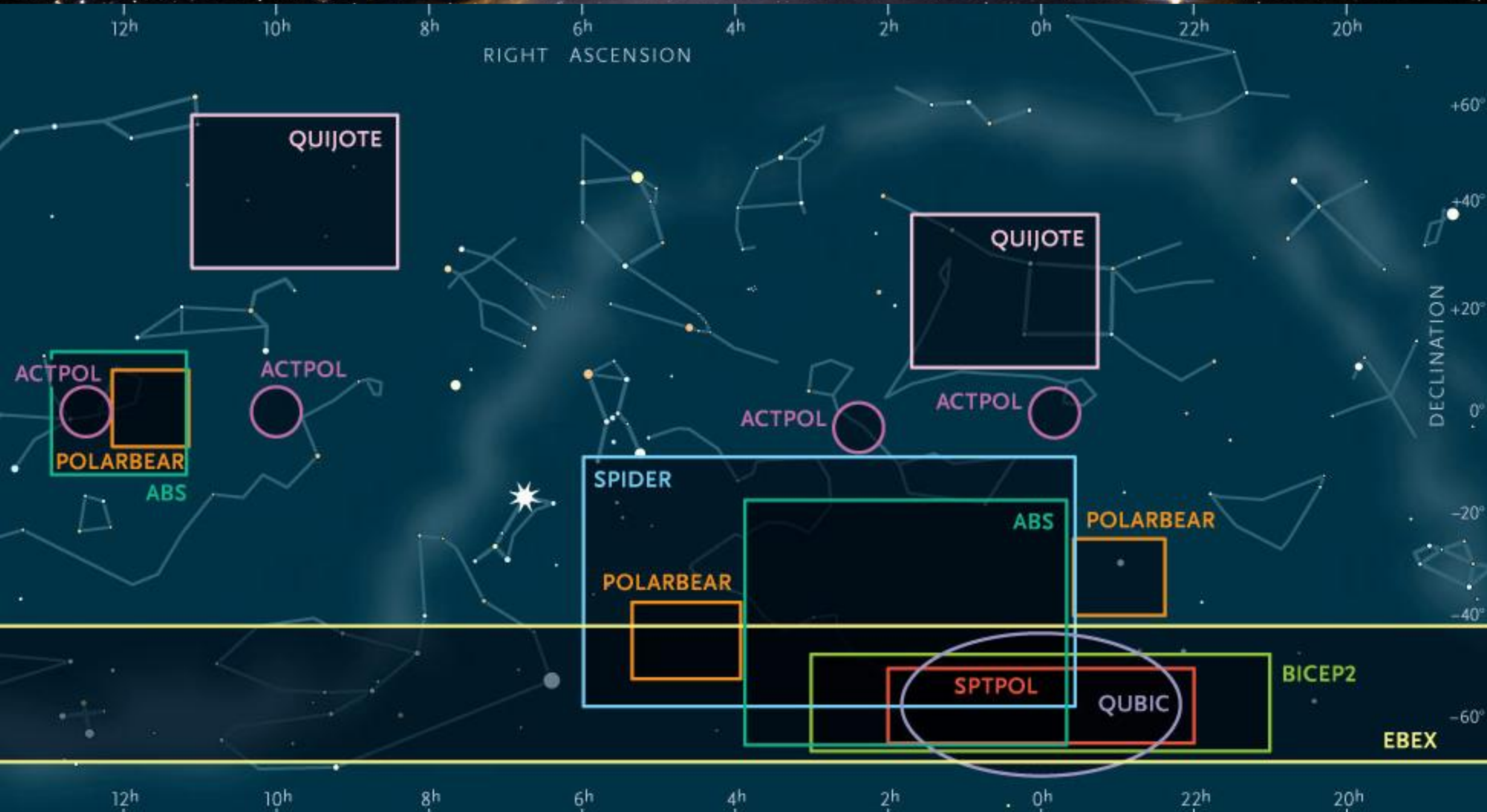
$$\Delta_h^2 = \frac{2}{3\pi^2} \frac{V}{M_{\rm pl}^4}$$

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

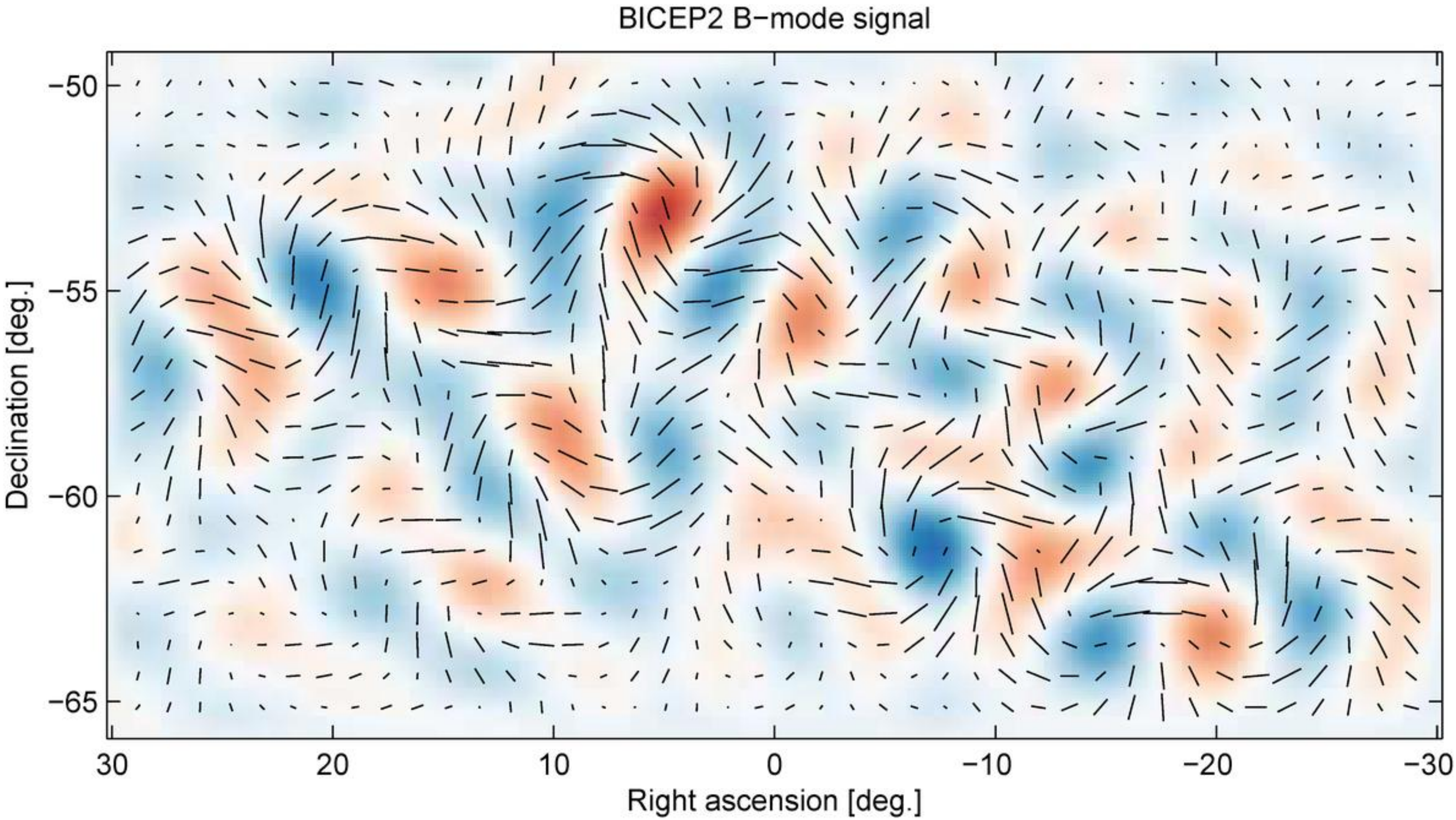
$$r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} \, .$$

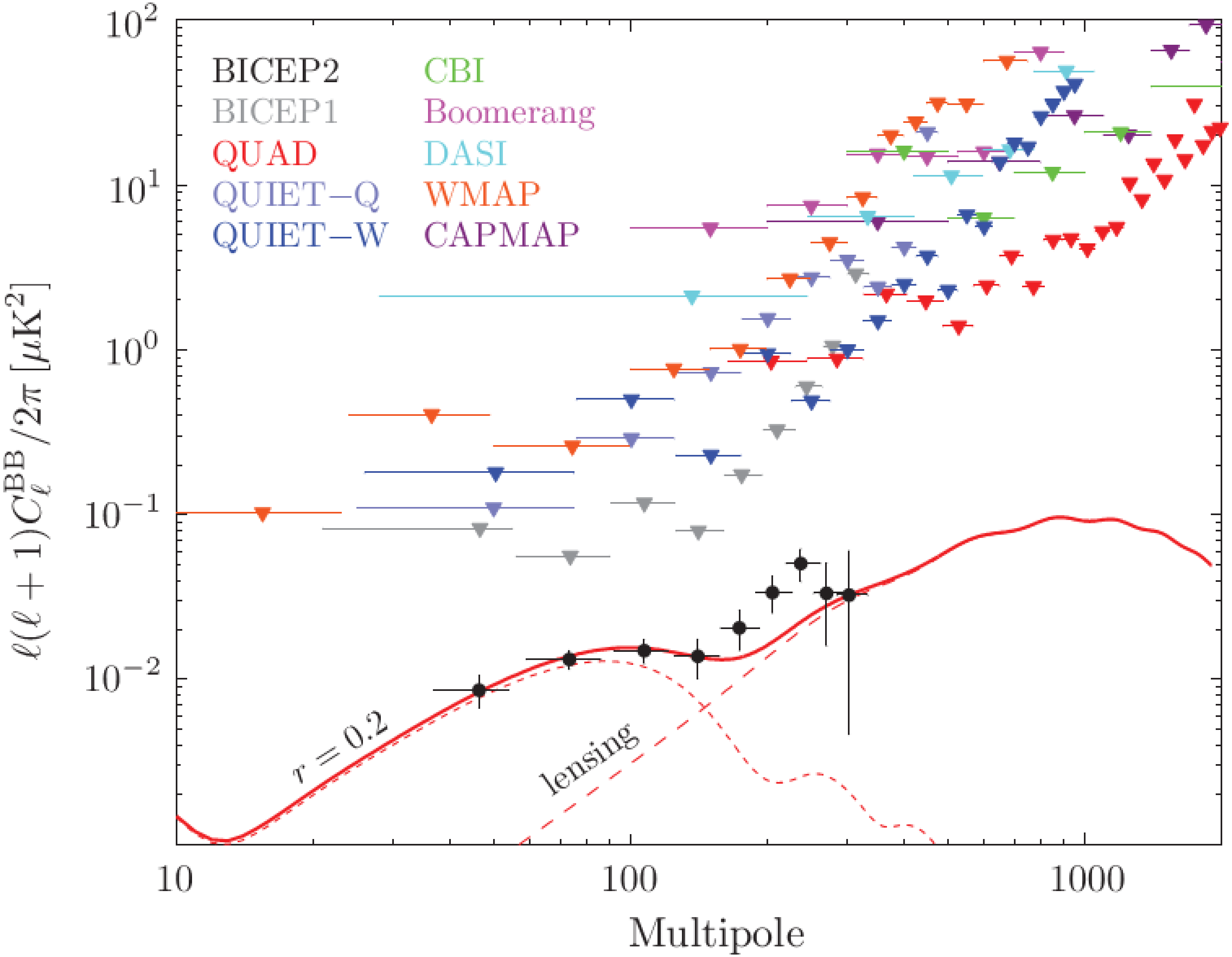
$$V^{1/4} = 2.0 \times 10^{16} \text{ GeV} \left(\frac{r}{0.1}\right)^{1/4} = 8 \times 10^{-3} \left(\frac{r}{0.1}\right)^{1/4} M_{\rm pl} \, .$$

II. The BICEP2 result



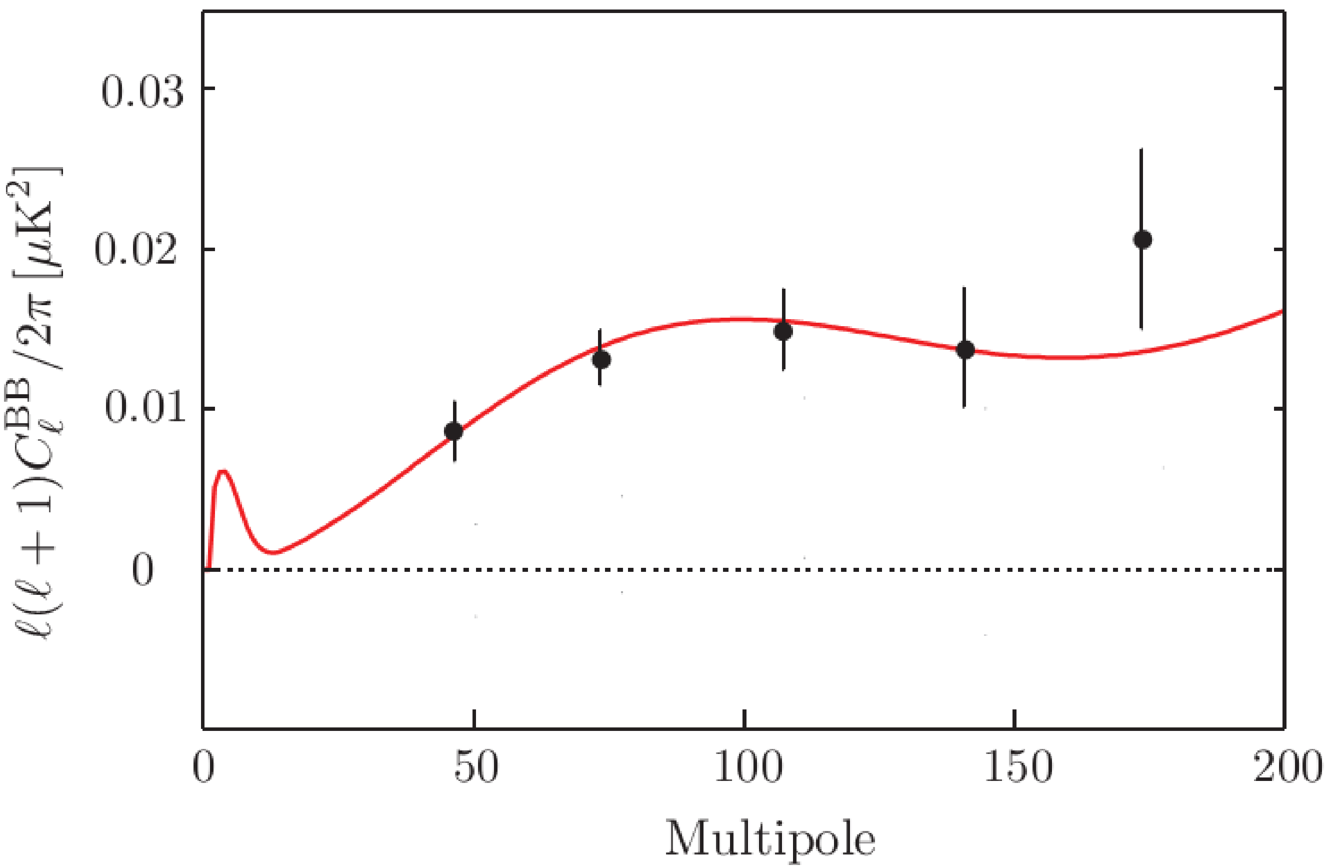
Credit: Sky and Telescope


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



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}
$\ell(\ell+1)C_\ell^{\rm BB}/2\pi\ [\mu{\rm K}^2]$
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?

Instrumental effects?

BB power is orders of magnitude below TT power; could there be leakage?

If yes, are they primordial?

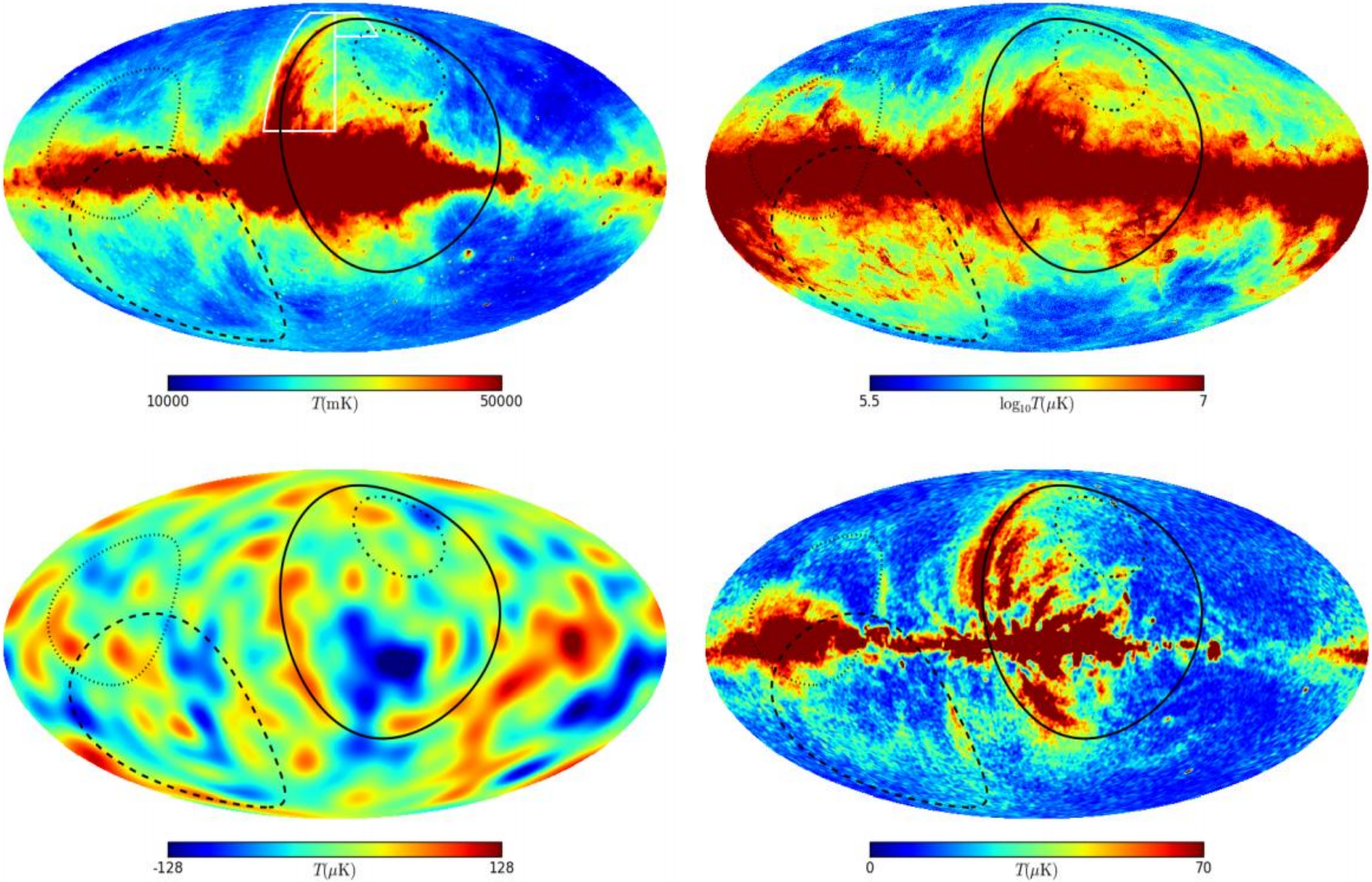
Foregrounds:

i. Polarized dust

ii. Synchrotron radiation

iii. Radio loops? Liu, Mertsch, Sarkar 1404.1899

Estimates of (i), (ii) are far below signal. (iii)?


10000
T(mK)
50000
5.5
log10T(μK)
7
-128
T(μK)
128
0
T(μK)
70

Is this real?

Is BICEP2 really seeing B-modes on the sky?

Instrumental effects?

BB power is orders of magnitude below TT power; could there be leakage?

If yes, are they primordial?

Foregrounds:

i. Polarized dust

ii. Synchrotron radiation

iii. Radio loops? Liu, Mertsch, Sarkar 1404.1899

Estimates of (i), (ii) are far below signal. (iii)?

By all accounts the team is superb and the experiment and analysis were performed with great care.

But the implications are truly extraordinary.

Prudent to await confirmation by another experiment, at another frequency, from another part of the sky.

I would hesitate to read too much into the central value.

III.
Implications for inflation


"Can you say it again?"

A new dawn for quantum gravity

If the signal is real, and if we adopt the most straightforward interpretation (inflationary gravity waves), we conclude that

1. Inflation happened.

A new dawn for quantum gravity

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1. Inflation happened.
2. At extremely high energy, 10^{16} GeV~$10^{-2}M_p$.

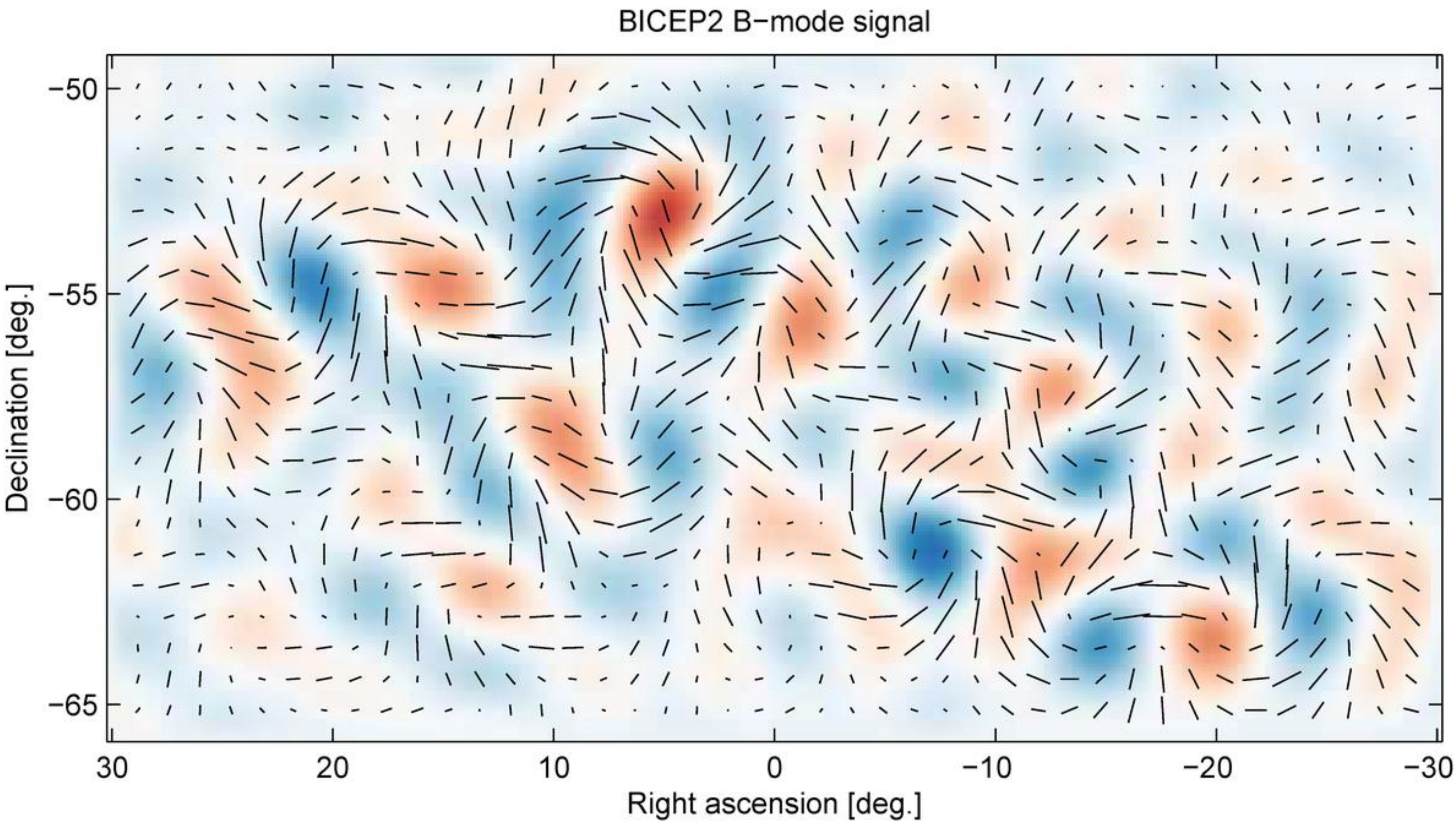
$$V^{1/4} = 2.0 \times 10^{16}\ \mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4} = 8 \times 10^{-3} \left(\frac{r}{0.1}\right)^{1/4} M_{\mathrm{pl}}\ .$$

The highest energy scale for which we have positive experimental evidence just jumped by 12 orders of magnitude.

A new dawn for quantum gravity

If the signal is real, and if we adopt the most straightforward interpretation (inflationary gravity waves), we conclude that

1. Inflation happened.
2. At extremely high energy, 10^{16} GeV~$10^{-2}M_p$.
3. Gravity is quantized.



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

A new dawn for quantum gravity

If the signal is real, and if we adopt the most straightforward interpretation (inflationary gravity waves), we conclude that

1. Inflation happened.
2. At extremely high energy, 10^{16} GeV~$10^{-2}M_p$.
3. Gravity is quantized.
4. The inflaton displacement was super-Planckian.

Any *one* of 1-4 would be a historic discovery.

A new dawn for quantum gravity

If the signal is real, and if we adopt the most straightforward interpretation (inflationary gravity waves), we conclude that

1. Inflation happened.
2. At extremely high energy, 10^{16} GeV~$10^{-2}M_p$.
3. Gravity is quantized.
4. The inflaton displacement was super-Planckian.

From (2),(3),(4): quantum gravity is required to interpret the observations. Remainder of this talk: explain this in effective field theory and in string theory.

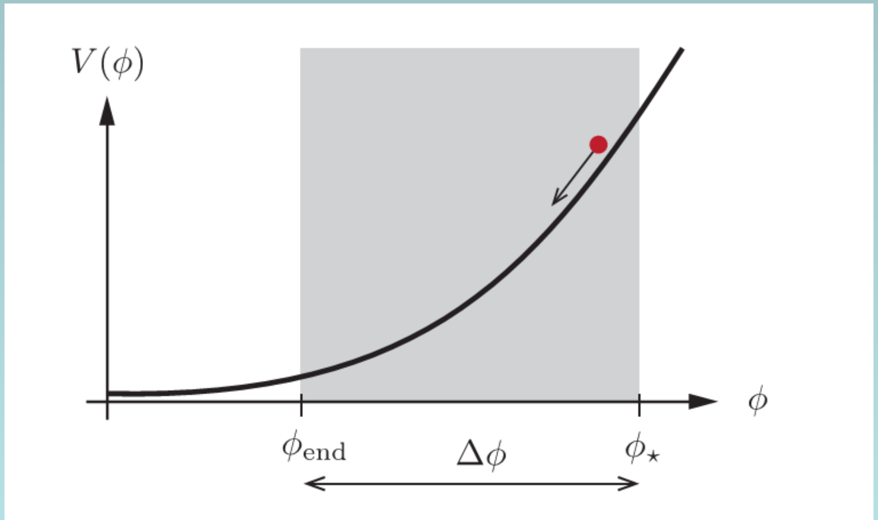
The Lyth bound

- Idea: relate *r* to the displacement of the inflaton in field space.

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

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

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



The Lyth bound

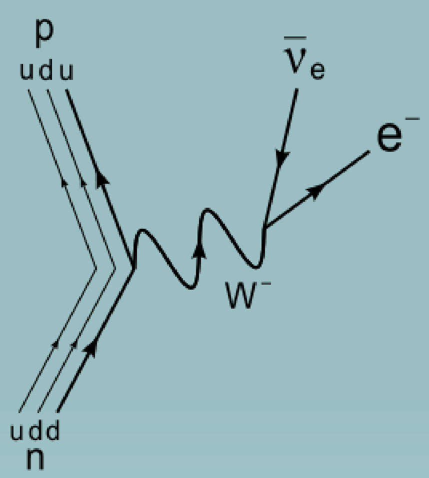
- Derivation quoted was for single-field slow roll inflation, canonical kinetic term.
- Violations of slow roll *slightly* relax the bound.
- Nontrivial kinetic terms strengthen the bound. Baumann and Green
- Multiple fields:
  - $\Delta\phi$ = arc length in field space.
  - Arc length ≠ displacement. Berg, Pajer, Sjörs 2009
  - If slow roll holds, multi-field perturbations strengthen the bound.
  - Violations of slow roll can *slightly* relax the bound. L.M., Renaux-Petel, Xu 2012

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

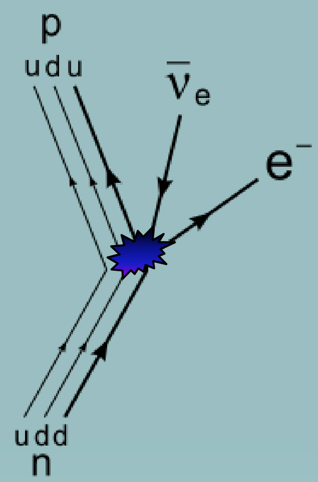
Significance of the Lyth bound

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

Effective field theory warmup



‘integrate out’ W

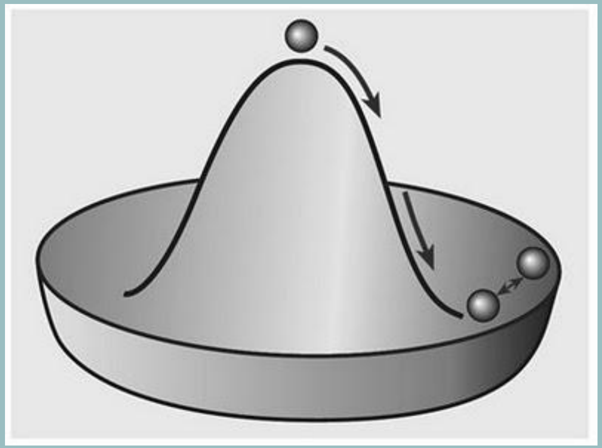


Effective theory has a 4-fermion interaction, but no W.

$$\propto \frac{1}{M_W^2} \bar{p}\, n\, \bar{e}\, \nu_e$$

Low-energy phenomena, e.g. beta decay, depend on high-energy physics, e.g. existence of W bosons.

Cutoff-scale distances?



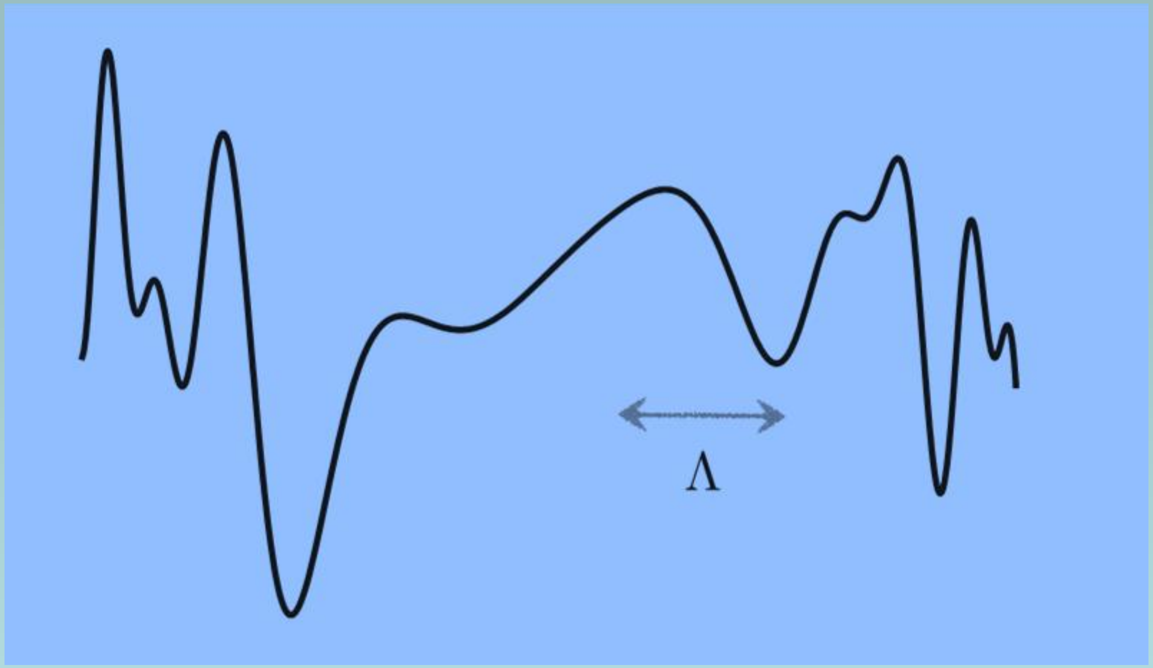
Higgs vev: v = 246 GeV.

Changes in Higgs vev of order v change the low-energy physics, e.g. restore electroweak symmetry.

Higgs potential has ‘structure’ on scales ~ v.

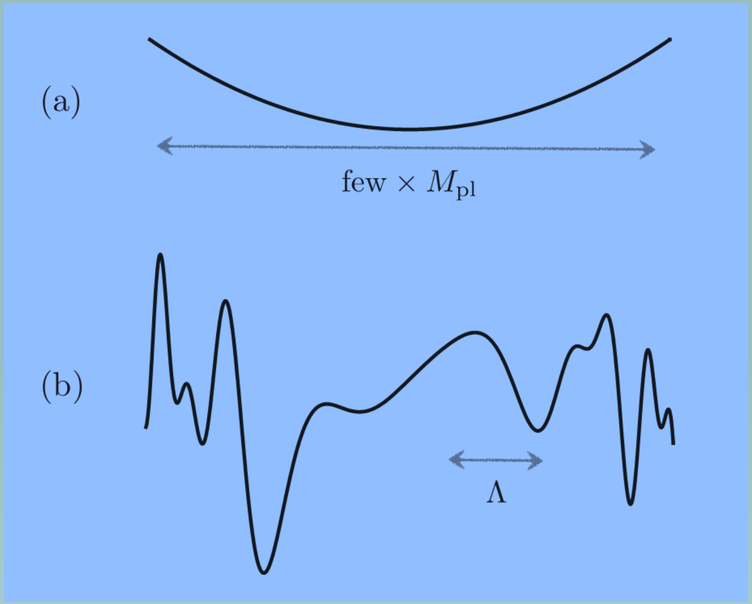
Scalar Lagrangian in EFT

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



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.
- BICEP2 tells us that the inflaton is weakly coupled to the d.o.f. that UV complete gravity: the quantum gravity theory enjoys an approximate symmetry.

Planck-sensitivity of inflation

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0(\phi)$$

$$\eta \equiv M_p^2 \frac{V''}{V} \ll 1$$

$$\Delta V \equiv \mathcal{O}_\Delta = V_0 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4} \Longrightarrow \delta\eta \sim \left(\frac{M_p}{\phi}\right)^2 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4}$$

$$\Delta = 6: \quad \delta\eta \sim \left(\frac{M_p}{\Lambda}\right)^2 \gtrsim 1$$

For small inflaton displacements, $\Delta\phi \lesssim M_{pl}$, one must control corrections $\mathcal{O}_\Delta$ with $\Delta \lesssim 6$.

For large inflaton displacements, $\Delta\phi \gg M_{pl}$, one must control an infinite series of corrections, with arbitrarily large Δ.

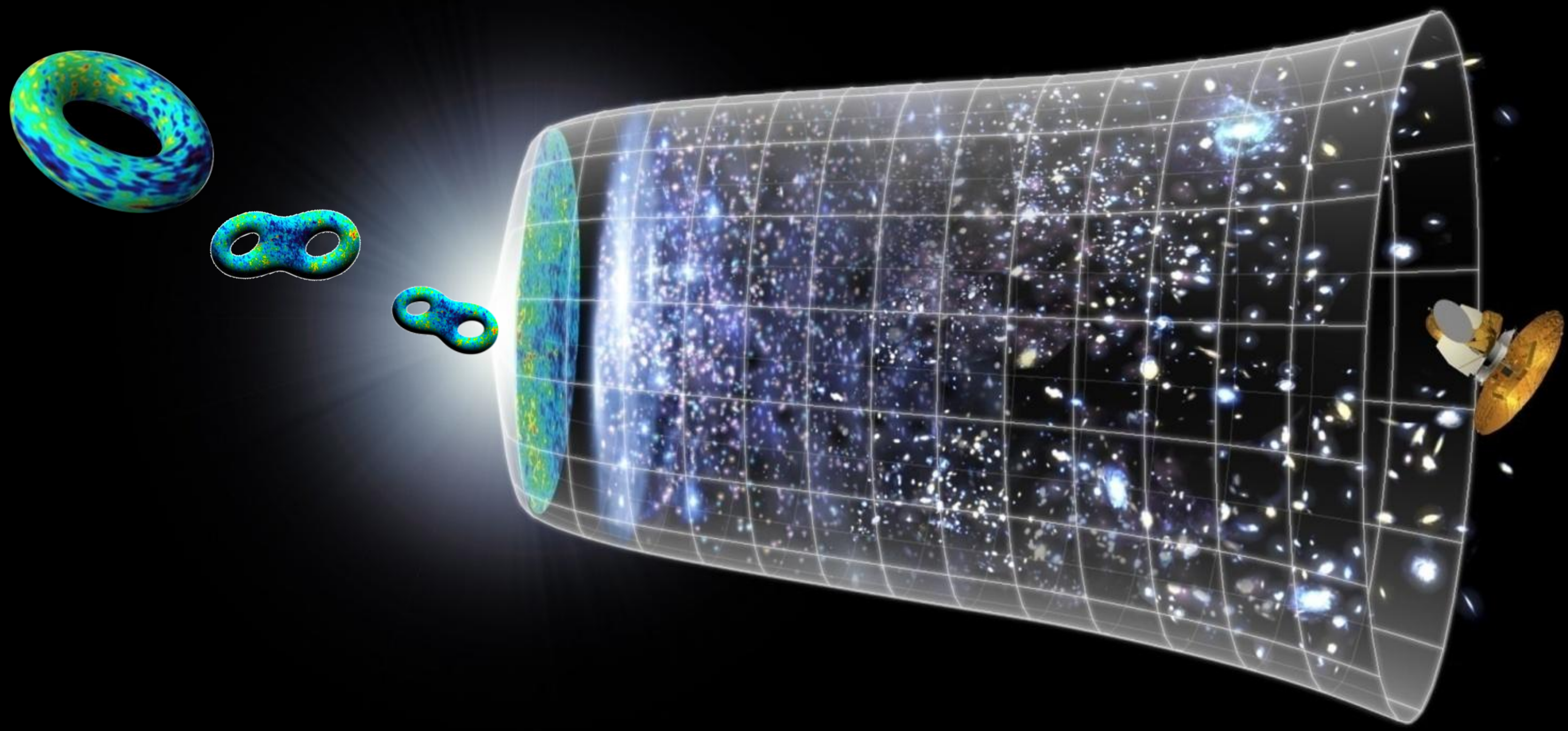
Stages of acceptance, I

- 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 generally 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.

Stages of acceptance, II

- So any adequate low-energy symmetries require assumptions about QG that have already been shown not to hold universally?
  - Yes.
- Does that mean that given a candidate symmetry, I need to check that it admits an ultraviolet completion in a QG theory?
  - Yes.
- Would it then be advisable to check this directly in string theory?
  - Yes.
- Do we know how to build any models of inflation in string theory?
  - Yes, at least to the level that we can construct de Sitter space in string theory.
- Are there models of large-field inflation in string theory?
  - There are several scenarios.
  - The kinematic requirement of a large field space can be met.
  - The dynamic requirement of a smoothly varying potential is more delicate.
  - Stabilizing the moduli during high-scale inflation appears possible.
  - Considerable work is required to produce explicit calculable models, but the core problem is simply strong coupling, not an ‘obstruction’ or ‘no-go’.

IV. Inflation in string theory



NASA/WMAP Science Team

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. e.g. ‘smearing’, probe approximation, noncompact approximation, truncation.
- Extensive use of approximations, estimates, and assumptions creates ambiguity.
  - Reasonable people may well disagree over whether a given model ‘exists’ or ‘works’.

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 Kahler 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). Controversial, but in my view the problems are overstated.
  - This module is reasonable in compactifications admitting highly warped regions. In small compactifications with mild warping, controllable uplifting is much more challenging.
  - 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.

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.

hep-th/1404.2601

Axion monodromy inflation

L.M., Silverstein, Westphal 08

See also:

Kim, Nilles, Peloso 04
Dimopoulos, Kachru, McGreevy, Wacker 05
Grimm 07
Silverstein, Westphal 08
Flauger, L.M., Pajer, Westphal, Xu 09
Berg, Pajer, Sjörs 09

Symmetries and large field inflation

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

In axion inflation models, a PQ symmetry is invoked to protect the inflaton potential over super-Planckian distances.

Freese, Frieman, Olinto 90

To address questions of the UV completion, we will try to embed these models in string theory. Will the moduli potential respect the candidate shift symmetry?

Promising candidate: an axion

- Axions are numerous, descending from $\int_{\Sigma_p} C_p$ and $\int_{\Sigma_2} B_2$
- Typically enjoy all-orders shift symmetry

Wen, Witten 86
Dine, Seiberg 86

- Nonperturbative effects break the continuous shift symmetry, generating a periodic potential:

$$V = \Lambda^4 \cos(a) = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

$$\frac{1}{2} f^2 (\partial a)^2 \equiv \frac{1}{2}(\partial \phi)^2$$

- The field range, i.e. the periodicity, is 2πf.

Idea: "Natural Inflation"

Q: Can we use $V = \Lambda^4 \cos(a) = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$ to drive inflation? This requires $f \gg M_p$.

Freese, Frieman, Olinto 90

A: Not possible in presently computable limits of string theory.

Banks, Dine, Fox, Gorbatov 03

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Since the individual decay constants are too small, we can:

- Take the inflaton to be a collective excitation of many axions (N-flation)

Dimopoulos, Kachru, McGreevy, Wacker 05; Easther, L.M 05; Grimm 07

- Traverse many periods of one axion (axion monodromy)

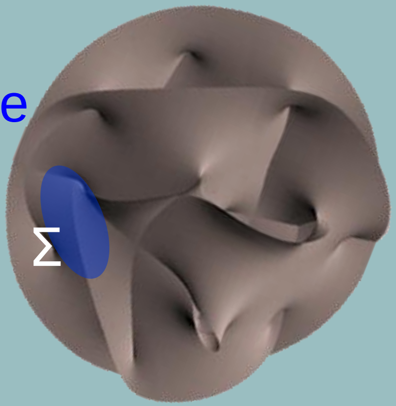
L.M., Silverstein, Westphal 08

cf. first monodromy model (D-brane monodromy) Silverstein, Westphal 08

Axion monodromy from wrapped fivebranes

D5-brane

$$\int_{\Sigma} B_2 \equiv b$$



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

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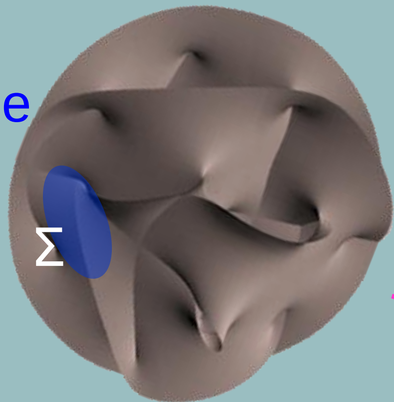

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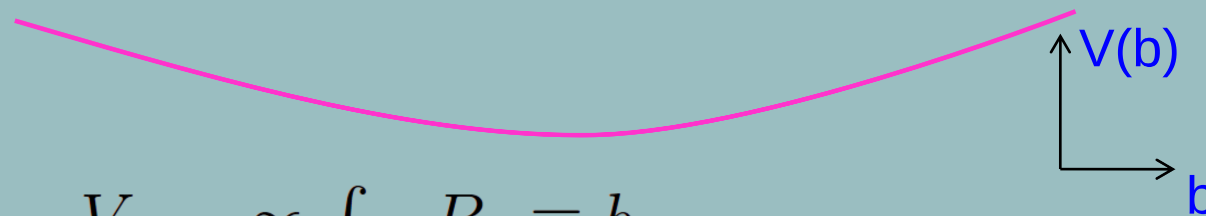


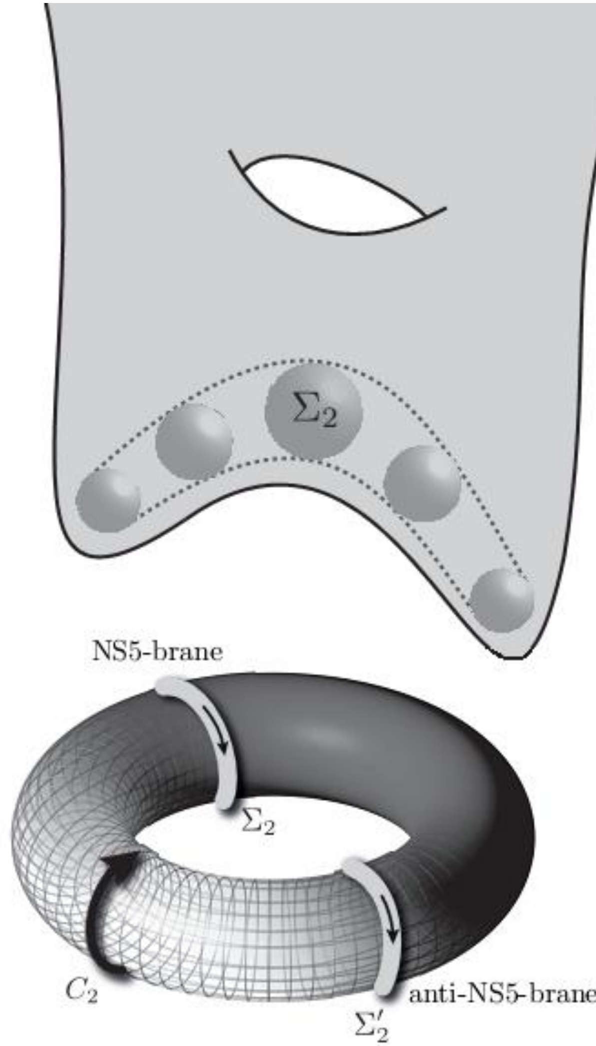
For large b, $$V_{DBI} \propto \int_{\Sigma_2} B_2 \equiv b$$

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

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 $$\boxed{\Delta\phi = 11 M_p}$$



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

cf. Aganagic, Beem, Seo,Vafa

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.
- 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.
- Kahler moduli stabilization by ED3-branes is problematic: magnetized ED3s intersecting inflationary cycle give η~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. Parametric control.

Backreaction and stability

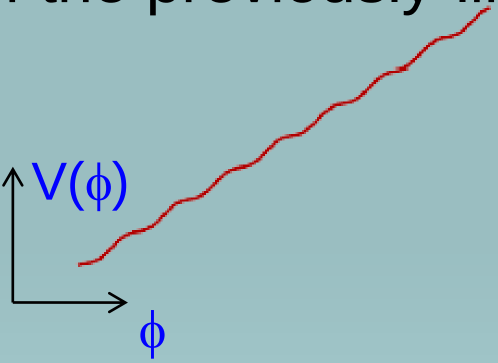
- Inflationary order parameter is induced D3-brane charge on NS5-branes. Q_{D3}=# of axion cycles remaining.
- D3-brane charge and tension backreact, warping the geometry. This changes the ED3 action (resp. D7-brane gauge coupling), so the moduli potential is exponentially sensitive to the inflaton vev.
- 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**

Nonperturbative corrections

Continuous shift symmetry is also broken by nonperturbative effects (e.g., Euclidean D1-branes).

This introduces periodic modulations of the previously-linear inflaton potential.

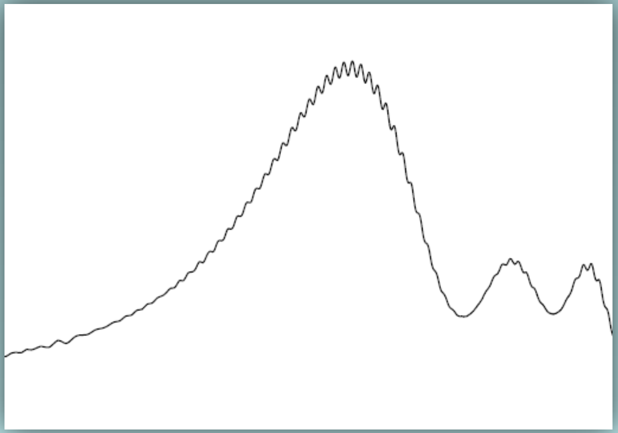
$$V(\phi) = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$



This produces a driving force that resonates with oscillations of the modes inside the horizon.

Result: resonant perturbations of the spectrum and bispectrum.

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left[1 + \delta n_s \cos\left(\frac{\phi_k}{f}\right)\right]$$



Flauger, L.M., Pajer, Westphal, Xu 09

Axion monodromy recap

- A scenario for large-field inflation in string theory.
- Fiducial model: NS5-brane pair in a warped region of a KKLT compactification of type IIB string theory.
- Mechanism is compatible with nonperturbative stabilization of Kahler moduli.
  - Certain cycles must be stabilized by D7-brane gaugino condensation, not by ED3s.
  - Backreaction by D3-brane charge is problematic, but can be contained by isolating the fivebranes.
- Predictions:
  - $r = 0.07$
  - Ripples in scalar power spectrum and bispectrum, with model-dependent frequency and amplitude. Detectable in some cases.

Axion monodromy outlook

- In my own very biased view, axion monodromy is the most promising mechanism yet proposed for realizing large field inflation in string theory.
  - Rooted in symmetry. Axion shift symmetry good to all orders in perturbation theory.
  - Multiple circuits of axion circle provide the required large range.
- The best-understood realization of axion monodromy is not worked out at the level that small-field inflation in string theory has been (e.g., D3-brane inflation).
- In part, large field inflation is just hard: near-Planckian energies mean little parametric control.
- But even for a small-field model, proper characterization can take years of work. Corresponding effort not yet applied to any one large field scenario.

Conclusions

If the BICEP2 detection is confirmed, the simplest interpretation is that:

1. Inflation occurred near the GUT scale.
2. The B-modes are the imprint of quantum fluctuations of the graviton, stretched to superhorizon scales.
3. The inflaton underwent a super-Planckian displacement, protected by an approximate symmetry of the quantum gravity theory.

Constraining alternative interpretations is now very important!

What now?

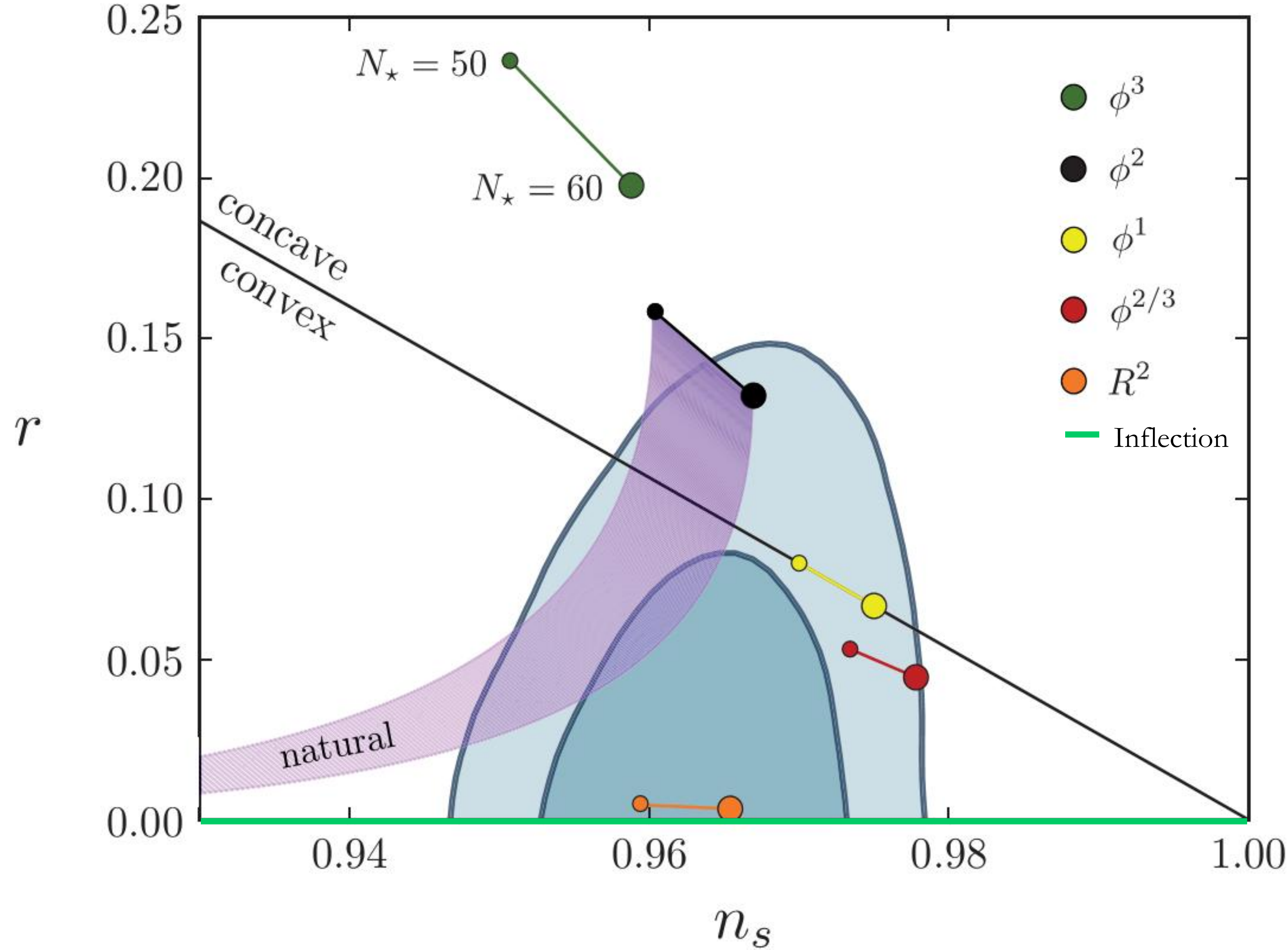
- Be sure the signal is primordial
- Understand whether alternative sources for tensors (rescattering, phase transitions) are compatible with the data.
- Understand/resolve the tension with Planck
- Develop more robust, explicit scenarios for large-field inflation in string theory.

Outlook

- The BICEP2 result has truly exceptional significance, comparable to the discovery of the CMB itself.
- If the result is confirmed, and alternative interpretations are excluded, we will have experimental evidence for the quantization of the gravitational field!
- For string theorists, and for all who are curious about the nature of gravity, what better news could one possibly imagine?
  - Quantum gravity becomes indispensable for the interpretation of cosmological data;
  - CMB observations give us a direct window on the physics of the Planck scale, to test and refine our ideas about fundamental physics.
- If this holds up, its reverberations for theorists and observers will last a very long time.


Congratulations to the BICEP2 team;
may your result be confirmed!

Backup



$N_\star = 50$
$N_\star = 60$
concave
convex
natural
ϕ^3
ϕ^2
ϕ^1
$\phi^{2/3}$
R^2
Inflection
r
n_s
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00

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	$\boxed{< 0.119}$
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