The BICEP2 results and its implications for the physics of the early universe

L. Sriramkumar

Department of Physics, Indian Institute of Technology Madras, Chennai

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Plan of the talk

A few words on the conventions and notations

- We shall work in units such that $c = \hbar = 1$, and define the Planck mass to be $\mathrm{M}_{_{\mathrm{Pl}}} = (8\,\pi\,G)^{-1/2}$.
- As is often done, particularly in the context of inflation, we shall assume the background universe to be described by the spatially flat, Friedmann line-element.
- We shall denote differentiation with respect to the cosmic and the conformal times t and η by an overdot and an overprime, respectively.
- Moreover, N shall denote the number of e-folds.
- Further, as usual, a and $H = \dot{a}/a$ shall denote the scale factor and the Hubble parameter associated with the Friedmann universe.
- Lastly, note that $\mathrm{M}_{_{\mathrm{Pl}}} \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$.

The character of the perturbations

In a Friedmann universe, the perturbations in the metric and the matter can be classified according to their behavior with respect to local rotations of the spatial coordinates on hypersurfaces of constant time as follows[1]:

- Scalar perturbations – Density and pressure perturbations
- Vector perturbations – Rotational velocity fields
- Tensor perturbations – Gravitational waves

The metric perturbations are related to the matter perturbations through the first order Einstein's equations.

The scalar perturbations leave the largest imprints on the CMB, and are primarily responsible for the inhomogeneities in the distribution of matter in the universe.

In the absence of sources, vector perturbations decay rapidly in an expanding universe.

Whereas, the tensor perturbations, *i.e.* the gravitational waves, can be generated even in the absence of sources.

[1] See, for instance, L. Sriramkumar, Curr. Sci. **97**, 868 (2009).

The primordial perturbation spectra[2]

When comparing with the observations, for simplicity, one often uses the following power law, template scalar and tensor spectra:

$$\mathcal{P}_{_{\rm S}}(k) = \mathcal{A}_{_{\rm S}}\, \left(\frac{k}{k_\ast}\right)^{n_{_{\rm S}}-1} \quad \text{and} \quad \mathcal{P}_{_{\rm T}}(k) = \mathcal{A}_{_{\rm T}}\, \left(\frac{k}{k_\ast}\right)^{n_{_{\rm T}}},$$

where $\mathcal{A}_{_{\rm S}}$ and $\mathcal{A}_{_{\rm T}}$ denote the scalar and tensor amplitudes, $k_\ast$ represents the so-called pivot scale at which the amplitudes are quoted, while the spectral indices $n_{_{\rm S}}$ and $n_{_{\rm T}}$ are assumed to be constant.

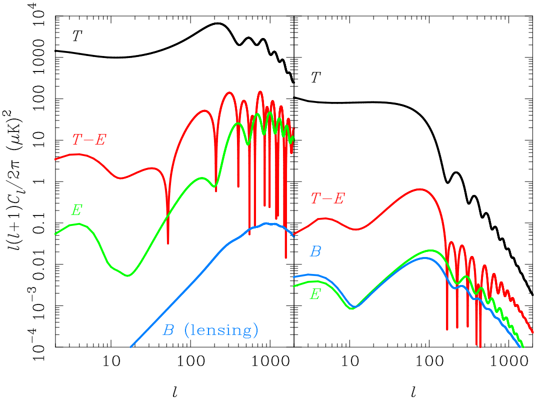
The tensor-to-scalar ratio r is defined as

$$r(k) \equiv \frac{\mathcal{P}_{_{\rm T}}(k)}{\mathcal{P}_{_{\rm S}}(k)}$$

and, often, the dependence of r on the wavenumber of k is assumed to be very weak.

[2]See, for instance, L. Sriramkumar, Curr. Sci. **97**, 868 (2009).

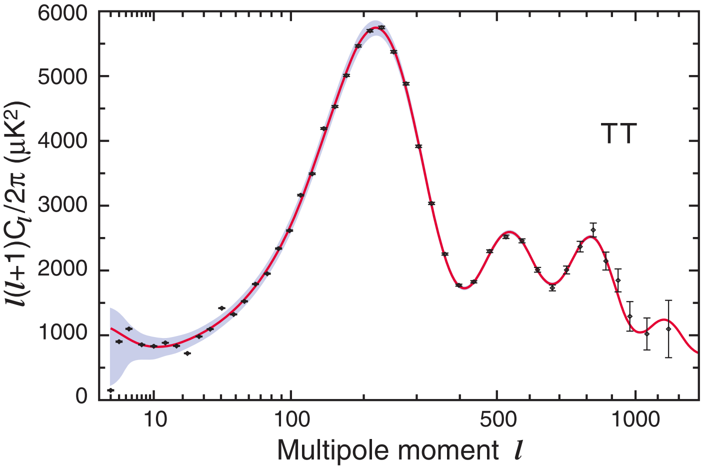
Theoretical angular power spectra[3]



The different *theoretically* computed, CMB angular power and cross-correlation spectra – temperature (T, in black), E (in green), B (in blue), and T-E (in red) – arising due to scalars (on the left) and tensors (on the right) corresponding to a tensor-to-scalar ratio of $r = 0.24$. The B-mode spectrum induced by weak gravitational lensing has also been shown (in blue) in the panel on the left.

[3] Figure from, A. Challinor, arXiv:1210.6008 [astro-ph.CO].

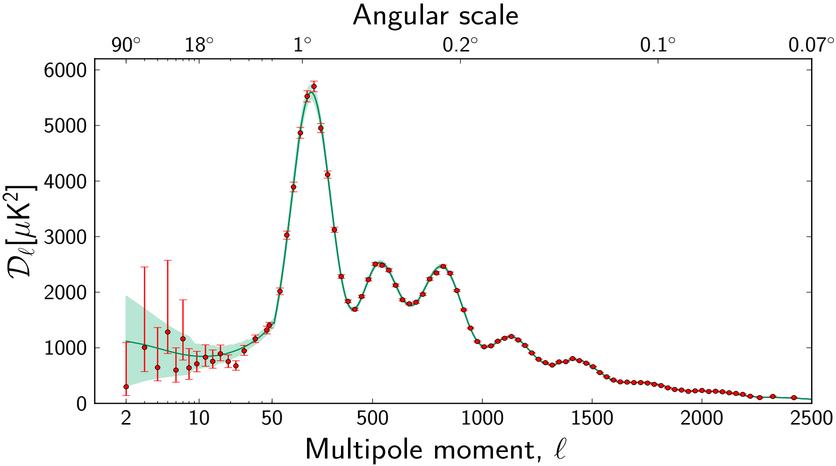
TT angular power spectrum from the WMAP data[4]



The WMAP 9-year data for the CMB TT angular power spectrum (the black dots with error bars) and the theoretical, best fit ΛCDM model with a power law primordial spectrum (the solid red curve).

[4] C. L. Bennett *et al.*, Astrophys. J. Suppl. **208**, 20 (2013).

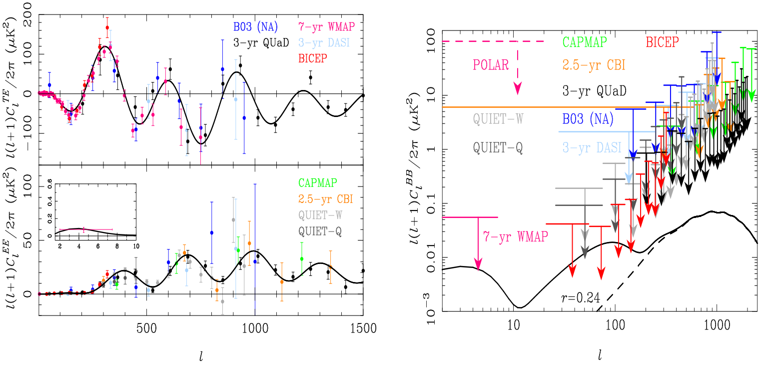
TT angular power spectrum from the Planck data[5]



The CMB TT angular power spectrum from the Planck data (the red dots with error bars) and the best fit ΛCDM model with a power law primordial spectrum (the solid green curve).

[5] P. A. R. Ade *et al.*, arXiv:1303.5075 [astro-ph.CO].

The observed polarization angular power spectra[6]



Measurements and upper bounds on the CMB polarization angular power and cross-correlation spectra by different CMB missions, prior to BICEP2.

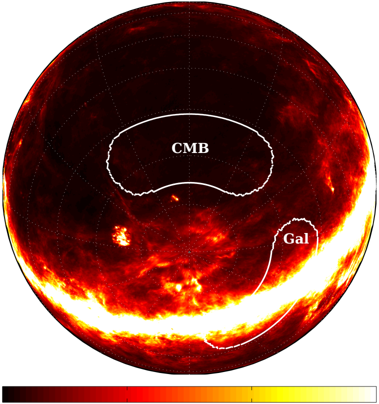
[6]Figure from, A. Challinor, arXiv:1210.6008 [astro-ph.CO].

The BICEP2 instrument at the south pole

The BICEP2[7] instrument that had operated at the south pole from January 2010 through December 2012.

[7] Image from http://www.cfa.harvard.edu/CMB/bicep2/.

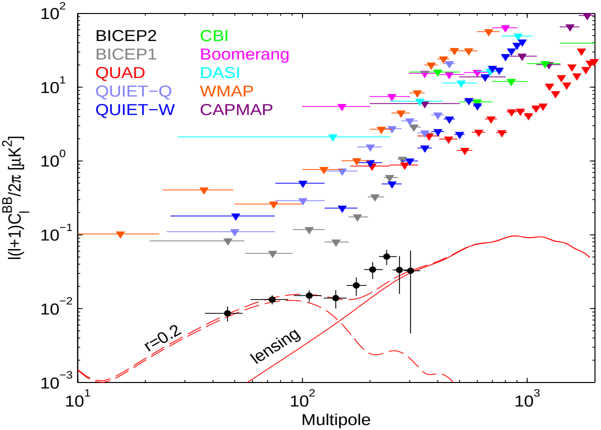
The observing fields of BICEP2[8]



BICEP2 observes the CMB at the frequency of $150\,\mathrm{GHz}$ mostly in a field of about $1000\,\mathrm{deg}^2$ (*i.e.* about 2.4% of the sky) in the so-called 'southern hole'. The southern hole lies away from the galactic plane, where polarized foregrounds (as shown above) are expected to be especially low.

[8] P. A. R. Ade *et al.*, arXiv:1403.4302 [astro-ph.CO].

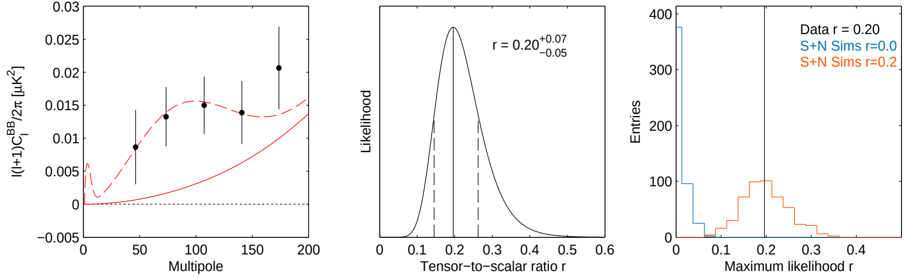
The detection of the B-mode polarization by BICEP2



The detection of the angular power spectrum of the B-mode polarization of the CMB by BICEP2 as well as the limits that have been arrived at by the earlier efforts[9]. The BICEP2 observations, *viz.* the black dots with error bars, seem to be consistent with a tensor-to-scalar ratio of $r \simeq 0.2$.

[9] P. A. R. Ade *et al.*, arXiv:1403.3985 [astro-ph.CO].

The constraints on the tensor-to-scalar ratio r



Left: The theoretical CMB B-mode angular power spectrum and the BICEP2 data on large scales that are not influenced considerably by weak gravitational lensing.
Middle: The constraint on the tensor-to-scalar ratio r arrived at from the BICEP2 data[10]. The maximum likelihood value and the $\pm 1\,\sigma$ interval is $r = 0.20^{+0.07}_{-0.05}$, as indicated by the vertical lines. A vanishing r is ruled out at 7-σ.
Right: Histograms of the maximum likelihood values of r derived from lensed-ΛCDM+noise simulations with $r = 0$ (in blue) and adding $r = 0.2$ (in red). The maximum likelihood value of r for the real data is shown by the vertical line.

[10] P. A. R. Ade *et al.*, arXiv:1403.3985 [astro-ph.CO].

The inflationary perturbation spectra

The curvature and the tensor perturbations, say, $\mathcal{R}_k$ and $\mathcal{U}_k$, satisfy the differential equations

$$\mathcal{R}_k'' + 2\,(z'/z)\,\mathcal{R}_k' + k^2\,\mathcal{R}_k = 0 \quad \text{and} \quad \mathcal{U}_k'' + 2\,\mathcal{H}\,\mathcal{U}_k' + k^2\,\mathcal{U}_k = 0,$$

where $z = a\,\phi'/\mathcal{H}$, with ϕ denoting the background, canonical, inflaton, and $\mathcal{H} = a'/a$ is the conformal Hubble parameter[11].

The inflationary scalar and tensor power spectra, *viz.* $\mathcal{P}_{_{\rm S}}(k)$ and $\mathcal{P}_{_{\rm T}}(k)$, are defined as

$$\mathcal{P}_{_{\rm S}}(k) = \frac{k^3}{2\,\pi^2}\,|\mathcal{R}_k|^2 \quad \text{and} \quad \mathcal{P}_{_{\rm T}}(k) = 4\,\frac{k^3}{2\pi^2}\,|\mathcal{U}_k|^2,$$

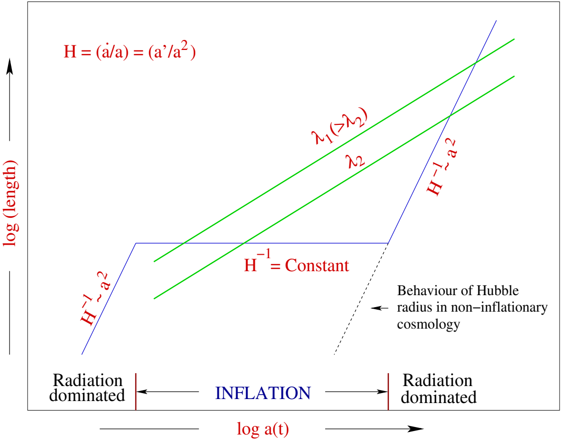
with the amplitudes $\mathcal{R}_k$ and $\mathcal{U}_k$ evaluated, in general, in the super-Hubble limit.

As we have already seen, the tensor-to-scalar ratio r is given by

$$r(k) \equiv \frac{\mathcal{P}_{_{\rm T}}(k)}{\mathcal{P}_{_{\rm S}}(k)}.$$

[11] See, for instance, B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

Behavior of modes during inflation



A schematic diagram illustrating the behavior of the physical wavelength $\lambda_{\rm P} \propto a$ (the green lines) and the Hubble radius $d_{\rm H} = H^{-1}$ (the blue line) during inflation and the radiation dominated epochs[12].

[12] See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.

The spectral indices and their running

The scalar spectral index and its running are defined as[13]

$$n_{\mathrm{S}} \equiv 1 + \frac{\mathrm{d}\ln\mathcal{P}_{\mathrm{S}}}{\mathrm{d}\ln k} \quad \text{and} \quad \alpha_{\mathrm{S}} \equiv \frac{\mathrm{d}\,n_{\mathrm{S}}}{\mathrm{d}\ln k}.$$

Whereas, the tensor spectral index and its running are given by

$$n_{\mathrm{T}} \equiv \frac{\mathrm{d}\ln\mathcal{P}_{\mathrm{T}}}{\mathrm{d}\ln k} \quad \text{and} \quad \alpha_{\mathrm{T}} \equiv \frac{\mathrm{d}\,n_{\mathrm{T}}}{\mathrm{d}\ln k}.$$

[13] See B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

The slow roll approximation

Given a potential $V(\phi)$, the slow roll approximation requires that the following *potential* slow roll parameters be small when compared to unity[14]:

$$\epsilon_{\rm V} = \frac{{\rm M}_{\rm Pl}^2}{2}\left(\frac{V_\phi}{V}\right)^2, \quad \eta_{\rm V} = {\rm M}_{\rm Pl}^2\left(\frac{V_{\phi\phi}}{V}\right) \quad \text{and} \quad \xi^2 = {\rm M}_{\rm Pl}^4\left(\frac{V_\phi\, V_{\phi\phi\phi}}{V^2}\right),$$

where $V_\phi \equiv {\rm d}V/{\rm d}\phi$, $V_{\phi\phi} \equiv {\rm d}^2V/{\rm d}\phi^2$ and $V_{\phi\phi\phi} \equiv {\rm d}^3V/{\rm d}\phi^3$. Note that the smallness of the parameters $\epsilon_{\rm V}$ and $\eta_{\rm V}$ is a *sufficient* condition for inflation to occur, and inflation ends when $\epsilon_{\rm V} \simeq 1$.

Nowadays, it is more common to use the following hierarchy of Hubble flow functions[15]:

$$\epsilon_1 \equiv -\frac{\dot{H}}{H^2} \quad \text{and} \quad \epsilon_{i+1} \equiv \frac{{\rm d}\ln|\epsilon_i|}{{\rm d}N} \quad \text{for} \quad i \geq 1.$$

[14] See, for instance, A. R. Liddle, P. Parsons and J. D. Barrow, Phys. Rev. D **50**, 7222 (1994).

[15] D. J. Schwarz, C. A. Terrero-Escalante, A. A. Garcia, Phys. Lett. B **517**, 243 (2001); S. M. Leach, A. R. Liddle, J. Martin and D. J. Schwarz, Phys. Rev. D **66**, 023515 (2002).

The slow roll scalar amplitude, index and running[16]

At the leading order in the slow roll approximation, the spectral amplitude of the curvature perturbation can be expressed in terms of the potential $V(\phi)$ as follows:

$$\mathcal{P}_{\rm s}(k) \simeq \frac{1}{12\,\pi^2\,{\rm M}_{_{\rm Pl}}^6}\,\left(\frac{V^3}{V_\phi^2}\right)_{k=a\,H},$$

with the subscript on the right hand side indicating that the quantity has to be evaluated when the modes leave the Hubble radius.

At the same order of the approximation, the scalar spectral index is given by

$$n_{_{\rm S}} \equiv 1 + \left(\frac{{\rm d}\ln\mathcal{P}_{_{\rm S}}}{{\rm d}\ln k}\right)_{k=a\,H} = 1 - 2\,\epsilon_1 - \epsilon_2\,,$$

while the running of the scalar spectral index can be evaluated to be

$$\alpha_{_{\rm S}} \equiv \left(\frac{{\rm d}\,n_{_{\rm S}}}{{\rm d}\ln k}\right)_{k=a\,H} = -\left(2\,\epsilon_1\,\epsilon_2 + \epsilon_2\,\epsilon_3\right)\,.$$

[16]See, for instance, B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

The tensor amplitude, spectral index and running

At the leading order in the slow roll approximation, the tensor amplitude is given by

$$\mathcal{P}_{\mathrm{T}}(k) \simeq \frac{2}{3\,\pi^2}\,\left(\frac{V}{\mathrm{M}_{\mathrm{Pl}}^4}\right)_{k=a\,H},$$

while the spectral index and the running can be estimated to be[17]

$$n_{\mathrm{T}} \equiv \left(\frac{\mathrm{d}\ln\mathcal{P}_{\mathrm{T}}}{\mathrm{d}\ln k}\right)_{k=a\,H} = -2\,\epsilon_1 \quad \text{and} \quad \alpha_{\mathrm{T}} \equiv \left(\frac{\mathrm{d}\,n_{\mathrm{T}}}{\mathrm{d}\ln k}\right)_{k=a\,H} = -2\,\epsilon_1\,\epsilon_2.$$

The tensor-to-scalar ratio is then given by

$$r \equiv \frac{\mathcal{P}_{\mathrm{T}}(k)}{\mathcal{P}_{\mathrm{S}}(k)} \simeq 16\,\epsilon_1 = -8\,n_{\mathrm{T}},$$

with the last equality often referred to as the consistency relation[18].

[17] See, B. A. Bassett, S. Tsujikawa and D. Wands, Rev. Mod. Phys. **78**, 537 (2006).

[18] J. E. Lidsey, A. R. Liddle, E. W. Kolb and E. J. Copeland, Rev. Mod. Phys. **69**, 373 (1997).

Amazing prescience!

VOLUME 78, NUMBER 10 PHYSICAL REVIEW LETTERS 10 MARCH 1997

What Would We Learn by Detecting a Gravitational Wave Signal in the Cosmic Microwave Background Anisotropy?

David H. Lyth
School of Physics and Chemistry, Lancaster University, Lancaster LA1 4YB, United Kingdom
(Received 20 June 1996)

Inflation generates gravitational waves, which may be observable in the low multipoles of the cosmic microwave background anisotropy but only if the inflaton field variation is at least of order the Planck scale. Such a large variation would imply that the model of inflation cannot be part of an ordinary extension of the standard model, and combined with the detection of the waves it would also suggest that the inflaton field cannot be one of the superstring moduli. Another implication of observable gravitational waves would be a potential $V^{1/4} = 2$ to 4×10^{16} GeV , which is orders of magnitude bigger than the prediction of most models. [S0031-9007(97)02506-4]

PACS numbers: 98.80.Cq, 04.30.Db, 98.70.Vc

A paper by David Lyth from 1997 with a title that seems amazingly apt in the light of BICEP2 observations.

The scale of inflation

During slow roll, if we ignore the weak scale dependence, we can write

$$r \simeq \frac{2\,V}{3\,\pi^2\,\mathrm{M}_{_{\mathrm{Pl}}}^4}\,\frac{1}{\mathcal{A}_{_{\mathrm{S}}}},$$

where, recall that, $\mathcal{A}_{_{\mathrm{S}}}$ denotes the amplitude of the scalar perturbations.

The amplitude of the primordial scalar perturbations is usually quoted at the pivot scales of either 0.05 or $0.02\,\mathrm{Mpc}^{-1}$, which correspond to multipoles that lie in the Sachs-Wolfe plateau. This value for the scalar amplitude is often referred to as COBE normalization[19].

According to COBE normalization, $\mathcal{A}_{_{\mathrm{S}}} \simeq 2.14 \times 10^{-9}$, which implies that we can write

$$V^{1/4} \simeq 3.2 \times 10^{16}\, r^{1/4}\,\mathrm{GeV} \simeq 2.1 \times 10^{16}\,\mathrm{GeV},$$

with the final value being for the case wherein $r \simeq 0.2$.

Note that, if $H_{_{\mathrm{I}}}$ represents the Hubble scale during the inflationary epoch, as $H_{_{\mathrm{I}}}^2 \simeq V/(3\,\mathrm{M}_{_{\mathrm{Pl}}}^2)$ during slow roll, the above relation also leads to

$$\frac{H_{_{\mathrm{I}}}}{\mathrm{M}_{_{\mathrm{Pl}}}} \simeq 4.6 \times 10^{-5}.$$

[19] E. F. Bunn, A. R. Liddle and M. J. White, Phys. Rev. D **54**, R5917 (1996).

The Lyth bound

Gravitational waves are expected to decay once they enter the Hubble radius during the radiation or the matter dominated epochs.

As a result, the contributions of the primordial gravitational waves to the B-mode of the CMB polarization angular power spectrum drops sharply after multipoles of $\ell \simeq 100$, roughly around the same multipoles where the TT angular power spectrum exhibits its first peak.

The CMB quadrupole, *i.e.* $\ell = 2$, corresponds to the largest cosmological scale of interest, *viz.* the Hubble radius H_0^{-1} today. Hence, we can relate the wavenumbers to the multipoles as $k \simeq H_0\, \ell/2$. Therefore, a Δl corresponds to the width $\Delta k \simeq H_0\, \Delta\ell/2$ in terms of wavenumbers.

As $a \propto \mathrm{e}^N$, the modes over a domain Δk corresponding to $\Delta l \simeq 100$ will leave the Hubble radius during inflation over the time period $\Delta N \simeq \log 10 \simeq 3.9$.

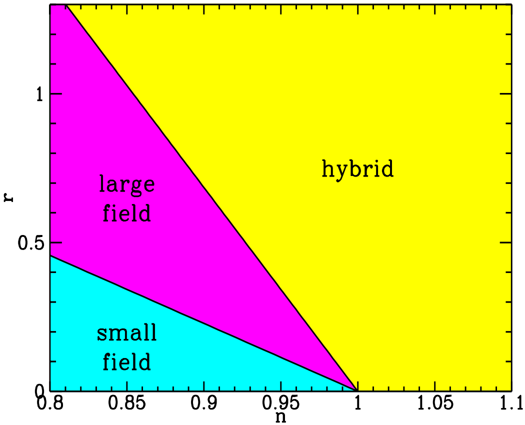
During slow roll, we have $H^2 = V/(3\, \mathrm{M}_{_{\mathrm{Pl}}}^2)$ and $3\, H\, \dot{\phi} \simeq V_\phi$, so that[20]

$$\Delta\phi \simeq (r/8)^{1/2}\, \Delta N\, \mathrm{M}_{_{\mathrm{Pl}}} \simeq 0.6\, \mathrm{M}_{_{\mathrm{Pl}}},$$

with the final value corresponding to $r \simeq 0.2$.

[20] D. H. Lyth, Phys. Rev. Letts. **78**, 1861 (1997).

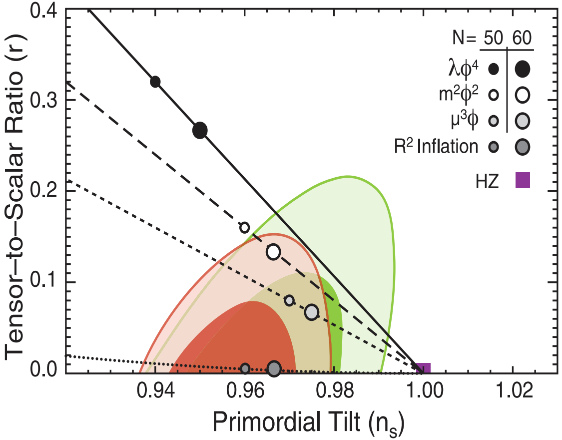
Classification of inflation models in the n_{s}-r plane[21]



The potential $V(\phi) \propto \phi$ separates the small field ($\eta_{\mathrm{V}} < 0$) and large field models ($0 < \eta_{\mathrm{V}} \leq 2\,\epsilon_{\mathrm{V}}$), while the exponential potential $V(\phi) \propto \exp -[\sqrt{2/\alpha}\,(\phi/\mathrm{M}_{\mathrm{Pl}})]$ divides the large field models from the hybrid ones ($\eta_{\mathrm{V}} > 2\,\epsilon_{\mathrm{V}}$).

[21] Figure from W. H. Kinney, A. Melchiorri and A. Riotto, Phys. Rev. D **63**, 023505 (2001).

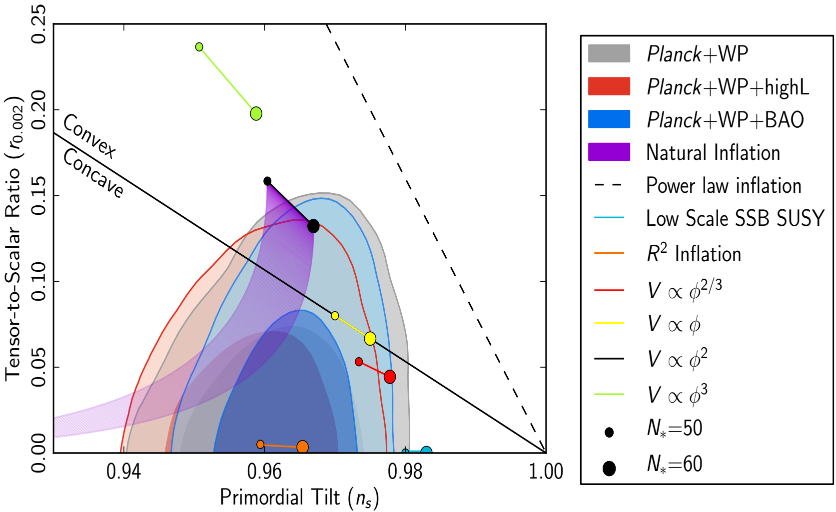
Constraints from the WMAP data[22]



Joint constraints from the WMAP nine-year and other cosmological data on the inflationary parameters n_{s} and r for large field models with potentials of the form $V(\phi) \propto \phi^n$.

[22] G. Hinshaw *et al.*, Astrophys. J. Suppl. **208**, 19 (2103).

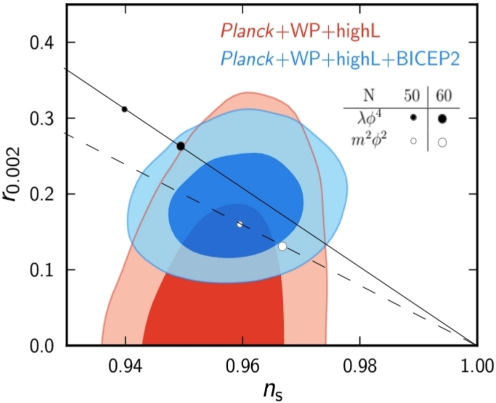
Constraints from Planck[23]



The corresponding constraints from the Planck data for various models.

[23] P. A. R. Ade *et al.*, arXiv:1303.5082 [astro-ph.CO].

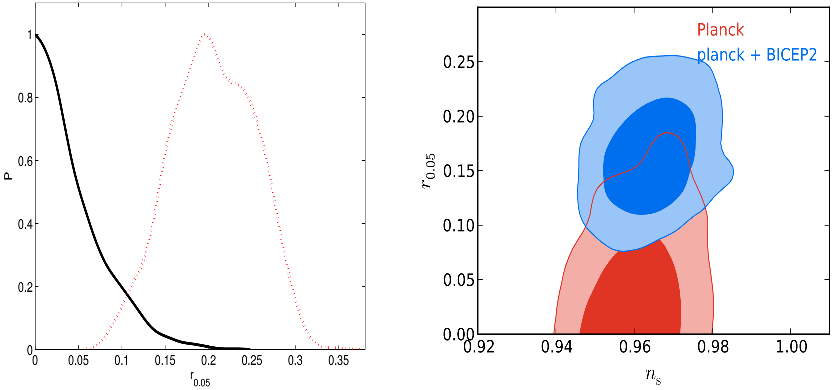
Constraints from the BICEP2 data[24]



Joint constraints from the BICEP2 observations, the Planck data, the polarization data from WMAP as well as data for the high multipoles from SPT and ACT, on the inflationary parameters $n_{\rm s}$ and r.

[24] P. A. R. Ade *et al.*, arXiv:1403.3985 [astro-ph.CO].

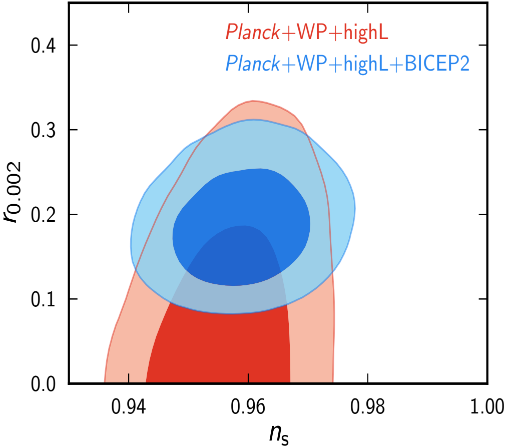
Is there tension between Planck and BICEP2 data?



Left: The one-dimensional marginalized likelihood corresponding to the Planck data (in black), and when the BICEP2 data is included (in red).
Right: Joint constraints in the n_s-r plane[25].

[25] H. Li, J.-Q. Xia and X. Zhang, arXiv:1404.0238 [astro-ph.CO].

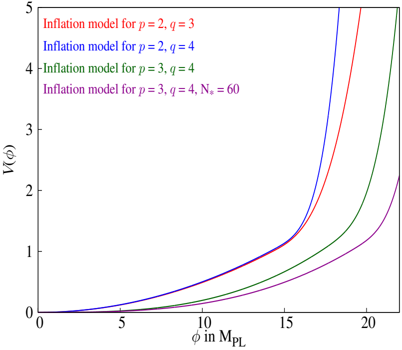
Alleviating the tension with running

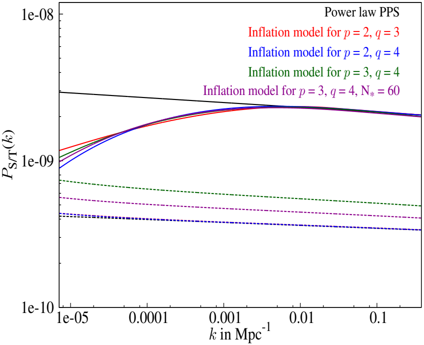


The ‘tension’ is alleviated when the scalar spectral index is allowed to run[26].

[26] P. A. R. Ade *et al.*, arXiv:1403.3985 [astro-ph.CO].

Do the inflationary spectra contain features?



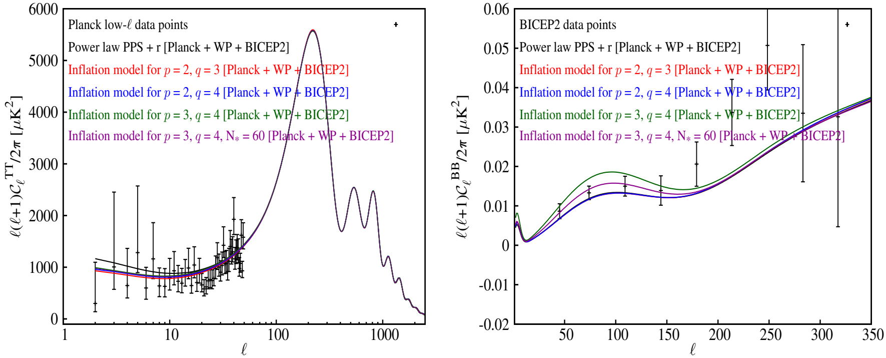


It seems, when the BICEP2 data is combined with the Planck data, the power law primordial spectrum is ruled out at 3-σ[27]. A class of potentials (illustrated on the left), which lead to a drop in scalar power at large scales (as shown on the right), while at the same time result in a tensor-to-scalar ratio as suggested by BICEP2[28].

[27] D. K. Hazra, A. Shafieloo, G. F. Smoot and A. A. Starobinsky, arXiv:1403.7786 [astro-ph.CO].

[28] D. K. Hazra, A. Shafieloo and G. F. Smoot, arXiv:1404.0360 [astro-ph.CO].

The corresponding CMB angular power spectra



The CMB temperature (on the left) and the B-mode (on the right) angular power spectra arising in the 'whipped inflation' models discussed in the previous slide[29]. It should be added that calculations using the BI-spectrum and Non-Gaussianity Operator (BINGO) code[30] suggests that the $f_{\rm NL}$ generated in these classes of models is at the acceptable level of 0.1-0.2.

[29] D. K. Hazra, A. Shafieloo and G. F. Smoot, arXiv:1404.0360 [astro-ph.CO].

[30] D. K. Hazra, L. Sriramkumar and J. Martin, JCAP **1305**, 026 (2013).

Do the results point to non-vacuum initial states?

It is well-known that there exists a degeneracy between inflationary dynamics and non-vacuum initial states[31], in the sense that they provide alternative means of producing similar features in the scalar and tensor perturbation spectra.

One can envisage situations involving squeezed initial states above the conventional Bunch-Davies vacuum that lead to small deviations from scale invariance that are required to improve the fit to the Planck data, while at the same time ensuring that the tensor-to-scalar ratio is sufficiently high (say, by working with the popular quadratic potential) as suggested by the BICEP2 data[32].

[31] L. Sriramkumar and T. Padmanabhan, Phys. Rev. D 71, 103512 (2005).

[32] A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari and G. Shiu, arXiv:1403.6099 [hep-th].

Higgs inflation: Is it alive or dead?

Higgs inflation still alive

Yuta Hamda,* Hikaru Kawai,† Kin-ya Oda,‡ and Seong Chan Park§

*† Department of Physics, Kyoto University, Kyoto 606-8502, Japan
‡ Department of Physics, Osaka University, Osaka 560-0043, Japan
§ Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea

March 21, 2014

Abstract

The observed value of the Higgs mass indicates that the Higgs potential becomes small and flat at the scale around 10^{17} GeV. Having this fact in mind, we reconsider the Higgs inflation scenario proposed by Bezrukov and Shaposhnikov. It turns out that the non-minimal coupling ξ of the Higgs-squared to the Ricci scalar can be smaller than ten. For example, $\xi = 7$ corresponds to the tensor-to-scalar ratio $r \simeq 0.2$, which is consistent with the recent observation by BICEP2.

Is Higgs Inflation Dead?

Jessica L. Cook,[1] Lawrence M. Krauss,[1,2,*] Andrew J. Long,[1,†] and Subir Sabharwal[1]

[1] Department of Physics and School of Earth and Space Exploration Arizona State University, Tempe, AZ 85827-1404
[2] Research School of Astronomy and Astrophysics, Mt. Stromlo Observatory, Australian National University, Canberra, Australia 2611

(Dated: March 21, 2014)

We consider the status of Higgs Inflation in light of the recently announced detection of B-modes in the polarization of the cosmic microwave background radiation by the BICEP2 collaboration. In order for the primordial B-mode signal to be observable by BICEP2, the energy scale of inflation must be high, $V_{\rm inf} \approx 2 \times 10^{16}$ GeV. Higgs Inflation generally predicts a small amplitude of tensor perturbations, and therefore it is natural to ask if Higgs Inflation might accommodate this new measurement. We find the answer is essentially no, unless one considers either extreme fine tuning, or possibly adding new beyond the standard model fields, which remove some of the more attractive features of the original idea. We also explore the possible importance of a factor that has not previously been explicitly incorporated, namely the gauge dependence of the effective potential used in calculating inflationary observables, e.g. n_S and r, to see if this might provide additional wiggle room. Such gauge effects are comparable to effects of Higgs mass uncertainties and other observables already considered in the analysis, and therefore they are relevant for constraining models. But, they are therefore too small to remove the apparent incompatibility between the BICEP2 observation and the predictions of Higgs Inflation.

The Higgs potential $V(\Phi) = \lambda\,\left(\Phi^\dagger\,\Phi\right)$, with $\lambda \simeq \mathcal{O}(1)$ and Φ denoting the Higgs doublet, is found to be inconsistent with the CMB data, unless it is non-minimally coupled to gravity[33]. The issue that requires to be addressed seems to be range for the value of the dimensionless, non-minimal coupling parameter ξ that can be allowed by the theory[34].

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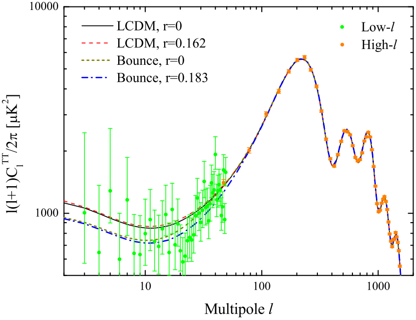
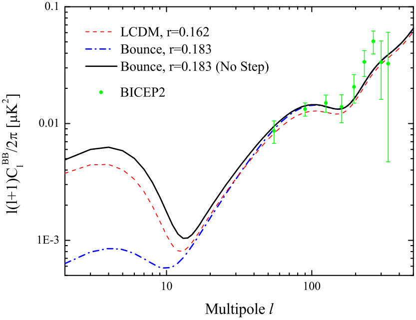
[33] See, P. A. R. Ade *et al.*, arXiv:1303.5082 [astro-ph.CO].

[34] J. L. Cook, L. M. Krauss, A. J. Long and S. Sabharwal,arXiv:1403.4971 [astro-ph.CO]; Y. Hamda, H. Kawai, K.-Y. Oda and S. C. Park, arXiv:1403.5043 [hep-ph].

How do alternatives to inflation perform?

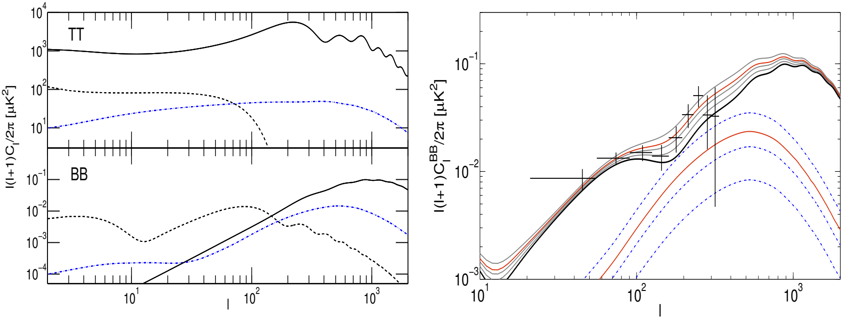




The CMB temperature (on the left) and the B-mode (on the right) angular power spectra in bouncing models, with a matter dominated contracting phase, followed by a bounce and an epoch of inflation. Such a scenario seems to lead to a step-like feature in the scalar and tensor power spectra[35]. The spectra in bouncing-inflation models lead to an improved fit to the Planck and BICEP2 data than the conventional, nearly scale invariant spectra.

[35] J.-Q. Xia, Y.-F. Cai, H. Li and X. Zhang, arXiv:1403.7623 [astro-ph.CO].

Contributions due to topological defects

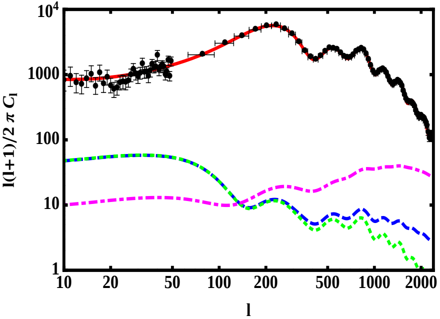


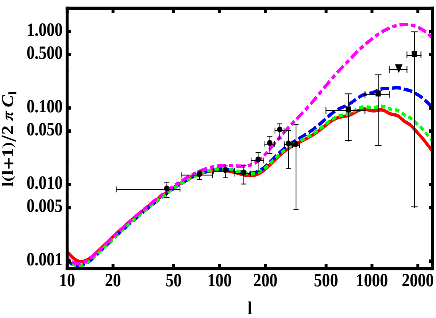
Left: The contributions to the CMB temperature and B-mode angular power spectra from inflationary scalar (black solid) and tensor (black dashed) modes with $r = 0.2$, as well as cosmic strings (blue dot-dashed) with the string contribution $f_{10} = 0.03$.

Right: A contribution from strings (blue dashed) corresponding to $f_{10} = 0.04$ upon adding to the prediction from $r = 0.15$ plus scalar lensing (solid black) to yield the total CMB B-mode angular power spectrum (in grey), leads to a marginal improvement in the fit to the BICEP2 data[36].

[36] J. Lizarraga, J. Urrestilla, D. Daverio, M. Hindmarsh, M. Kunz and A. R. Liddle, arXiv:1403.4924 [astro-ph.CO].

Contributions from primordial magnetic fields





Left: The contributions to the CMB temperature angular power spectrum from inflation (in red) and from three different types of magnetic modes (in green, blue and magenta). The data points are from Planck[37].

Right: The corresponding CMB B-mode angular power spectrum arising as a result of the contributions due to weak lensing and the inflationary tensor mode with $r = 0.2$, and the contributions due to the magnetic modes. Note that the data points are from BICEP2 (circles) and POLARBEAR (squares).

[37] C. Bonvin, R. Durrer and R. Maartens, arXiv:1403.6768 [astro-ph.CO].

Summary

- BICEP2 has detected the B-mode polarization of the CMB angular power spectrum at large angular scales corresponding to the multipoles of $30 \lesssim \ell \lesssim 150$.
- These multipoles correspond to cosmological scales and, hence, the observations are signatures of primordial gravitational waves.
- The observations of BICEP2 correspond to a rather high tensor-to-scalar ratio of $r \simeq 0.2$. Importantly, the BICEP2 team concludes that a vanishing tensor-to-scalar ratio is ruled out at 7-σ.
- If inflation is indeed the mechanism that had generated these primordial gravitational waves, it implies that inflation had occurred at an energy scale of $V^{1/4} \simeq 2.1 \times 10^{16}\,\mathrm{GeV}$. Also, the inflaton would have rolled over $\Delta\phi \simeq 0.6\ \mathrm{M_{Pl}}$ in order to generate the observed amplitude of the tensor modes.
- However, there seems to exist some tension between the BICEP2 observations and the Planck data, which may require to be resolved (say, by BICEP3), before the last word can possibly be said.

Thank you for your attention