BICEP: Implications for Theory

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BICEP: Implications for Theory

Main assumptions I make in this talk

1. The BICEP2 result is observationally and experimentally correct.
2. The B-modes they see are cosmological and primordial and are not due to foregrounds etc.
3. The B-modes are generated as inflationary tensor modes: quantum fluctuations of a massless graviton during inflation.

Basic Inflationary Scales

Slow roll parameters:

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2, \qquad \eta = M_P^2 \frac{V''}{V}.$$

Tensor-to-scalar ratio:

$$r = 16\epsilon$$

Scale of inflation:

$$V^{1/4} = \epsilon^{1/4}\left(6.6 \times 10^{16}\text{GeV}\right) = \left(\frac{r}{0.2}\right)^{1/4} 2.2 \times 10^{16}\text{GeV}.$$

Observation of $r \neq 0$ tells us the (high) energy scale at which inflation occurred.

Basic Inflationary Scales

$V_{inf} = \left(\frac{r}{0.2}\right)^{1/4} 2.2 \times 10^{16}\text{GeV}$ is a very large scale.

It is a factor 10^{13} larger than the energy scales probed at the LHC and only a factor of 100 lower than the Planck scale.

In string theory/ extra dimensional models, the string scale and Kaluza-Klein scale are lower than the Planck scale, so V_{inf} is even closer to these.

V_{inf} is extremely close to the traditional grand unification scale. No obvious connection, but...

Consequences of $V_{inf} \sim 10^{16}\text{GeV}$

- The QCD axion is essentially ruled out for $f_a \gtrsim 10^{13}\text{GeV}$ without any assumptions on initial misalignment angle.
- QCD axions with high f_a overproduce dark matter for generic initial misalignment angles θ_i.
- Pre-BICEP: avoid this by keeping H small and tune θ_i small.
- BICEP implies

$$\langle(\delta a)^2\rangle \sim \left(\frac{H}{2\pi}\right)^2 \sim \left(10^{13}\text{GeV}\right)^2$$

This gives a minimal contribution to θ_i, generating over-large isocurvature perturbations.

Consequences of $V_{inf} \sim 10^{16}\text{GeV}$

Positive vacuum energy breaks supersymmetry:

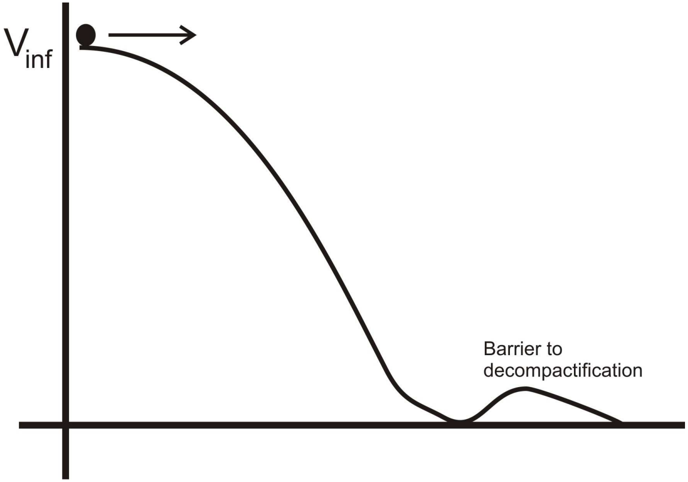
$$V_{inf}^4 \sim m_{3/2}^2 M_P^2 \sim \left(\frac{m_{3/2}}{30\text{TeV}}\right)^2 (10^{11}\text{GeV})^4.$$

$$m_{3/2} \sim 10^{13}\text{GeV} \left(\frac{V_{inf}}{10^{16}\text{GeV}}\right)^2$$

However low-scale supersymmetry requires $m_{3/2} \lesssim 100\text{TeV}$.

This implies either no low-scale supersymmetry or a large change in characteristic scales between the inflationary epoch and the final vacuum.

Consequences of $V_{inf} \sim 10^{16}$GeV



How to reach a stable vacuum and avoid decompactification?

$r \neq 0$ and Inflationary Field Excursions

Slow-roll equations for inflaton ϕ as a function of efoldings N give

$$\frac{d\phi}{dN} = \pm\sqrt{2\epsilon(N)}M_P.$$

While CMB scales leave horizon, $\Delta N \sim 4$, and we have $(r = 16\epsilon)$

$$\Delta\phi \gtrsim \sqrt{\frac{r}{0.20}}0.56M_P.$$

If $\epsilon(N)$ is approximately constant throughout inflation, then

$$\Delta\phi \sim \left(\frac{N_{efold}}{60}\right)\sqrt{\frac{r}{0.2}}9.5M_P$$

$r = 0.2$ implies a transPlanckian excursion of the inflaton field.

$r \neq 0$ and Inflationary Field Excursions

Why is $\Delta\phi > M_P$ important?

New physics at scale Λ implies operators suppressed by a cutoff Λ.

We can expand the inflaton potential in powers of $\frac{\phi}{M_P}$:

$$V(\phi) = V_0 + \sum_n \lambda_n \left(\frac{\phi}{M_P} \right)^n$$

Flatness over transPlanckian distances requires control of all terms λ_n.

Involves physics suppressed by M_P - hard to address outside a theory of quantum gravity.

$r \neq 0$ and Inflationary Field Excursions

$r \neq 0$ implies higher-dimension couplings of inflaton Φ to hidden sector field Σ suppressed by a scale $\Lambda > M_P$, e.g.

$$\partial_\mu \Phi \partial^\mu \Phi \frac{\Sigma}{\Lambda}$$

These higher derivative operator generate non-Gaussianities.

Limits on non-Gaussianities and $r \neq 0$ implies the suppression scale $\Lambda > M_P$.

Another requirement to understand a theory of the Planck scale to understand suppression of these operators.

(1304.5226 Baumann et al)

$r \neq 0$ and Inflationary Field Excursions

Note that 'constants' of Standard Model are expected to arise as vevs of scalar fields.

$$y_e = y_e\left(\frac{\Phi}{M_P}\right), \quad \alpha_{em} = \alpha_{em}\left(\frac{\Phi}{M}\right), \ldots$$

Transplanckian excursions imply the Standard Model couplings will be very different during inflation than now.

Does this imply anything?

Consequences for Inflationary Models

The Bonfire of the Models

Consequences for Inflationary Models

- Assuming simplest BICEP interpretation as inflationary gravitational waves, all small-field inflation models are dead.
- Restricts to class of large field models (chaotic inflation, natural inflation, M-flation, N-flation, (P,Q)-inflation, axion monodromy inflation, fibre inflation, ...)
- However: problem of UV embedding: generally control of approximations/backreaction breaks down at $\Delta\phi \sim M_P$.
- 'Controlled models lack a UV embedding; UV-embedded models lack control'
- Personal view: all proposed large-field models have large problems. Is something missing?

Consequences for Dark Radiation

Pre-BICEP: 'CMB does not favour existence of $\Delta N_{eff} \neq 0$'

$N_{eff} = 3.30 \pm 0.27$ (Planck + eCMB + BAO, Planck XVI)
$N_{eff} = 3.52 \pm 0.24$ (Planck + eCMB + BAO + H0, Planck XVI)

Tension of Planck ΛCDM value of H_0 with that from local measurements - how trustworthy are local measurements and are error bars correct?

This all changes with $r \neq 0$.

Consequences for Dark Radiation

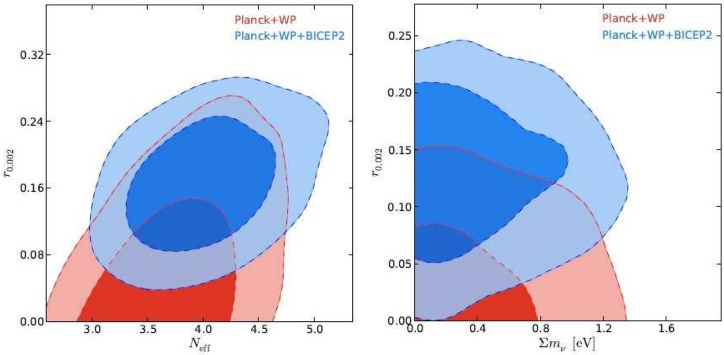


FIG. 5: Left panel: Constraints in the N_{eff} vs r plane from Planck+WP and Planck+WP+BICEP2 data. Notice how the inclusion of the BICEP2 constraint shifts the contours towards $N_{\rm eff} > 3$. Right panel: constraints on the Σm_ν vs r plane from Planck+WP and Planck+WP+BICEP2 data. In this case there is no indication for neutrino masses from the combination of CMB data.

From 1403.4852 Giusarma et al

Consequences for Dark Radiation

Neutrinos help reconcile Planck measurements with both Early and Local Universe

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In light of the recent BICEP2 B-mode polarization detection, which implies a large inflationary tensor-to-scalar ratio $r = 0.2^{+0.07}_{-0.05}$, we re-examine the evidence for an extra sterile massive neutrino, originally invoked to account for the tension between the cosmic microwave background (CMB) temperature power spectrum and local measurements of the expansion rate H_0 and cosmological structure. With only the standard active neutrinos and power-law scalar spectra, this detection is in tension with the upper limit of $r < 0.11$ (95% confidence) from the lack of a corresponding low multipole excess in the temperature anisotropy from gravitational waves. An extra sterile species with the same energy density as is needed to reconcile the CMB data with H_0 measurements can also alleviate this new tension. By combining data from the Planck and ACT/SPT temperature spectra, WMAP9 polarization, H_0, baryon acoustic oscillation and local cluster abundance measurements with BICEP2 data, we find the joint evidence for a sterile massive neutrino increases to $\Delta N_{\rm eff} = 0.81 \pm 0.25$ for the effective number and $m_s = 0.47 \pm 0.13$eV for the effective mass or 3.2σ and 3.6σ evidence respectively.

From 1403.8049

Consequences for Dark Radiation

5.2 base_r_nnu_planck_BICEP_lowl_lowLike_highL

Parameter	Best fit	95% limits	Parameter	Best fit	95% limits	Parameter	Best fit	95% limits
$\Omega_b h^2$	0.02265	$0.02273^{+0.00085}_{-0.00083}$	$A^{PS,ACT}_{148}$	10.64	$10.5^{+1.}_{-1.1}$ [illegible]	H_0	73.5	$74.0^{+6.6}_{-6.5}$
$\Omega_c h^2$	0.1281	$0.1281^{+0.0099}_{-0.0098}$	$A^{PS,ACT}_{218}$	77.2	$76.5^{+8.4}_{-8.7}$	$r_{0.002}$	[illegible]	$0.184^{+0.091}_{-0.085}$
$100\theta_{MC}$	1.04052	$1.0405^{+0.0014}_{-0.0013}$	$A^{PS,SPT}_{95}$	7.05	$7.40^{+2.9}_{-2.7}$	$10^9 A_s$	2.270	$2.29^{+0.16}_{-0.15}$
[illegible]	0.0973	$0.101_{-0.030}$ [illegible]	$A^{PS,SPT}_{150}$	10.05	$9.88^{+1.0}_{-0.98}$	$\Omega_m h^2$	0.1514	$0.151^{+0.010}_{-0.010}$
N_{eff}	3.82	$3.85^{+0.76}_{-0.70}$	$A^{PS,SPT}_{220}$	74.4	74^{+9}_{-9}	$\Omega_m h^3$	0.1112	$0.112^{+0.016}_{-0.015}$
n_s	0.9917	$0.995^{+0.034}_{-0.033}$	$r^{PS}_{95\times150}$	0.838	> 0.682	Y_P	0.2549	$0.2552^{+0.0090}_{-0.0089}$
$\ln(10^{10} A_s)$	3.122	$3.129_{-0.068}$ [illegible]	$r^{PS}_{95\times220}$	0.634	$0.59^{+0.24}_{-0.24}$	$10^9 A_s e^{-2\tau}$	1.8683	$1.867^{+0.041}_{-0.043}$
$r_{0.05}$	0.169	$0.174^{+0.072}_{-0.070}$	$r^{PS}_{150\times220}$	0.9301	$0.939^{+0.047}_{-0.045}$	Age/Gyr	13.07	$13.04^{+0.67}_{-0.66}$
A^{PS}_{100}	226	226^{+100}_{-100}	A^{ACTs}_{dust}	0.431	$0.44^{+0.37}_{-0.39}$	z_*	1090.98	$1090.9^{+1.2}_{-1.2}$
A^{PS}_{143}	80.6	79^{+20}_{-20}	A^{ACTe}_{dust}	0.855	$0.85^{+0.39}_{-0.38}$	r_*	138.6	$138.5^{+5.7}_{-5.6}$
A^{PS}_{217}	66.6	65^{+20}_{-20}	y^{ACTs}_{148}	0.9885	$0.989^{+0.015}_{-0.015}$	$100\theta_*$	1.04022	$1.0402^{+0.0016}_{-0.0016}$
A^{CIB}_{143}	3.09	$3.20^{+1.6}_{-1.5}$	y^{ACTs}_{217}	1.0011	$1.002^{+0.027}_{-0.026}$	z_{drag}	1061.73	$1061.9^{+2.8}_{-2.7}$
A^{CIB}_{217}	47.9	49^{+10}_{-9}	y^{ACTe}_{148}	0.9847	$0.985^{+0.015}_{-0.014}$	r_{drag}	141.1	$141.0^{+5.9}_{-5.8}$
A^{tSZ}_{143}	2.52	< 4.76	y^{ACTe}_{217}	0.9600	$0.960^{+0.021}_{-0.020}$	k_D	0.14474	$0.1449^{+0.0047}_{-0.0044}$
$r^{PS}_{143\times217}$	0.822	$0.83^{+0.13}_{-0.12}$	y^{SPT}_{95}	0.9748	$0.977^{+0.040}_{-0.037}$	$100\theta_D$	0.16286	$0.1629^{+0.0015}_{-0.0015}$
$r^{CIB}_{143\times217}$	1.000	> 0.855	y^{SPT}_{150}	0.9797	$0.981^{+0.020}_{-0.019}$	z_{eq}	3265	3255^{+160}_{-150}
γ^{CIB}	0.602	$0.62^{+0.16}_{-0.16}$	y^{SPT}_{220}	1.0160	$1.019^{+0.047}_{-0.044}$	$100\theta_{eq}$	0.8398	$0.842^{+0.034}_{-0.032}$
c_{100}	1.00056	$1.00058^{+0.00080}_{-0.00078}$	Ω_Λ	0.7194	$0.722^{+0.039}_{-0.043}$	$r_{drag}/D_V(0.57)$	0.07335	$0.0736^{+0.0027}_{-0.0025}$
c_{217}	0.99749	$0.9975^{+0.0027}_{-0.0026}$	Ω_m	0.2806	$0.278^{+0.043}_{-0.039}$	$H(0.57)$	0.0003293	$0.000331^{+0.000020}_{-0.000019}$
$\xi^{tSZ\times CIB}$	0.37	—	σ_8	0.8548	$0.857^{+0.041}_{-0.041}$	$D_A(0.57)$	1292	1287^{+92}_{-91}
A^{kSZ}	6.19	> 2.07	z_{re}	11.87	$12.1^{+2.6}_{-2.5}$			
β^1_1	0.55	$0.5^{+1.1}_{-1.1}$	r_{10}	0.0878	$0.091^{+0.045}_{-0.042}$			

Best-fit $\chi^2_{eff} = 10552.87$; $\bar{\chi}^2_{eff} = 10590.70$; $R - 1 = 0.01434$

χ^2_{eff}: CMB - lowlike_v222: 2013.46 BICEP2: 38.53 commander_v4.1_lm49: -4.89 CAMspec_v6.2TN_2013_02_26_dist: 7810.07 act-spt_2013_01: 695.60

Conclusions

BICEP result has clear implications for

- Need for large-field inflation models
- Need a theory of quantum gravity to control large-field inflation models
- Physics of QCD axion
- Physics of supersymmetry
- Dark radiation
- To be determined....