Lessons from the primordial gravitational waves

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Outline

Why inflation?

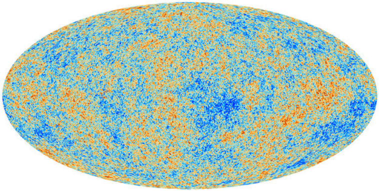
Hot big bang	Inflation
Horizon problem	Single causal patch
Flatness problem	Locally flat
Monopole problem	Diluted away
Initial perturbations	Quantum fluctuations

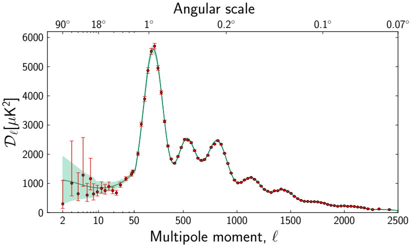
1. Initial conditions for hot big bang
2. A certain amount of expansion is required:

$$\text{Number of } e\text{-folds} : N = \log\left(\frac{a_e}{a_i}\right) \sim 60 \text{ is necessary}$$

3. Typically driven by inflaton with a specific potential $V(\phi)$

2013 Planck results





Good constraints on scalar perturbation, but poor in tensor

… and 17 March, 2014, BICEP2

BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

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to be submitted to a journal TBD

ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the *B*-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu\mathrm{K}_{\mathrm{CMB}}\sqrt{\mathrm{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of *B*-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed *B*-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization

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What all these mean?

- CMB polarization
- BICEP2: experiment, strategy, results
- Anomalies?

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Scalar and tensor perturbations

Distance between 2 points in space

$$dl^2 = a^2(t)\left\{[1+2\mathscr{R}(t,\boldsymbol{x})]\delta_{ij} + h_{ij}(t,\boldsymbol{x}) + \cdots\right]dx^i dx^j$$
$$= a^2(t)e^{2\mathscr{R}}\left[e^h\right]_{ij}dx^i dx^j$$

- $\mathscr{R}(t,\boldsymbol{x})$: curvature perturbation (scalar pert)
  1. Isotropic scaling of space
  2. Relevant to large scale $\delta T/T$
- $h_{ij}(t,\boldsymbol{x})$: gravitational waves (tensor pert)
  1. Anisotropic stretching of space (but area-conserv.: $\det\left[e^h\right]=1$)
  2. 2 physical d.o.f. = 2 pol modes: h_+ and $h_\times$

Status of scalar perturbation

- Nearly scale-invariant power spectrum

$$P_{\mathcal{R}}(k) = \left\langle |\mathcal{R}(k)|^2 \right\rangle \propto k^{n_{\mathcal{R}}-4} \text{ with } n_{\mathcal{R}} \approx 1$$

- Nearly Gaussian fluctuations

$$f_{\rm NL} = \frac{5}{12} \lim_{k_3 \to 0} \frac{\langle \mathcal{R}(k_1)\mathcal{R}(k_2)\mathcal{R}(k_3)\rangle}{P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2) + 2 \text{ perm}} \ll 1$$

CMB Observations including Planck confirmed:

1. $n_{\mathcal{R}} = 0.960 \pm 0.007$ at 1σ ($n_{\mathcal{R}} < 1$ more than 5σ)
2. $f_{\rm NL} = 2.7 \pm 5.8$ at 1σ
3. Perfect agreement with simplest single field inflation

Gravitational waves

- Propagation of graviton quanta
- Assuming the quantization of tensor perturbations $h_s(k)$

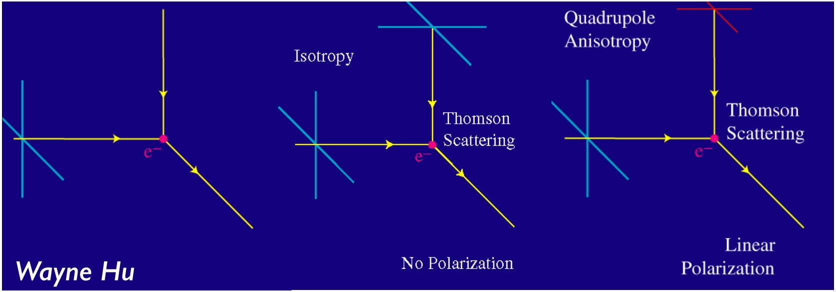
$$\sum_{s=+,\times} \left\langle |h_s(k)|^2 \right\rangle = \frac{2\pi^2}{k^3} \frac{8}{m_{\text{Pl}}^2} \left(\frac{H}{2\pi} \right)^2 \propto k^{n_T-3}$$

- Nearly scale invariant: $n_T = 2\dot{H}/H^2 \equiv -2\epsilon < 0$ (slightly red tilt)
- Directly proportional to total energy: $P_T \propto \rho_{\text{inf}}/m_{\text{Pl}}^4$
- Tensor-to-scalar ratio

$$r \equiv \frac{P_T}{P_{\mathcal{R}}} = 16\epsilon \text{ for canonical single field case}$$

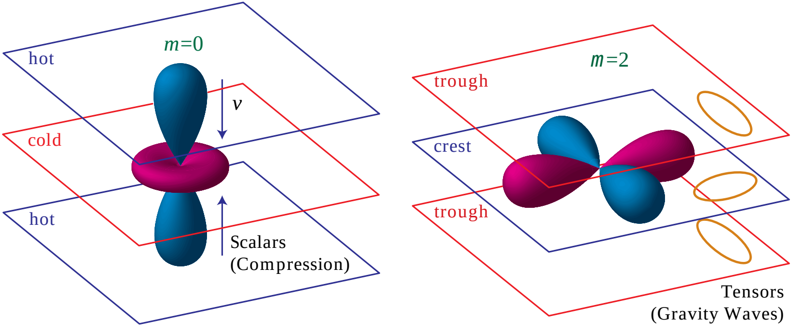
- Distinctive polarization pattern in the CMB: *B*-mode

Physics of CMB polarization



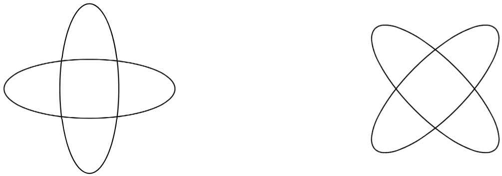
- By a local temp anisotropy different by 90°: quadrapole
- Scalar: motion of electrons w.r.t. photons
- Tensor: anisotropic stretching of space, gravitational waves

Shape of quadrapoles



Temperature polarizations induced by gravitational waves

2 polarization modes of gravitational waves



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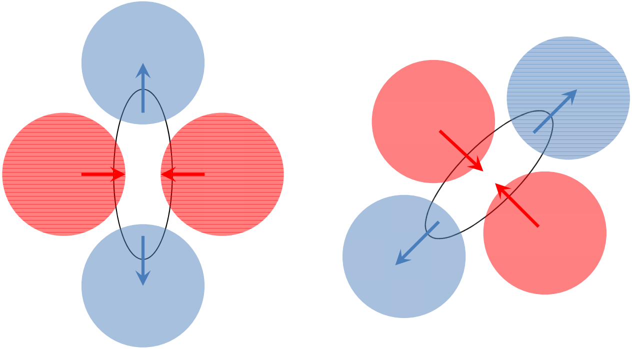

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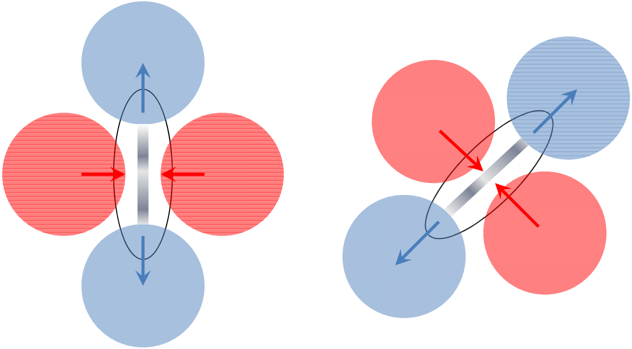
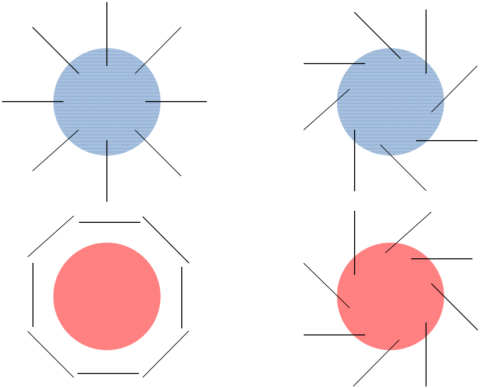


2 polarization states are induced by anisotropic stretching of space

Patterns of polarizations

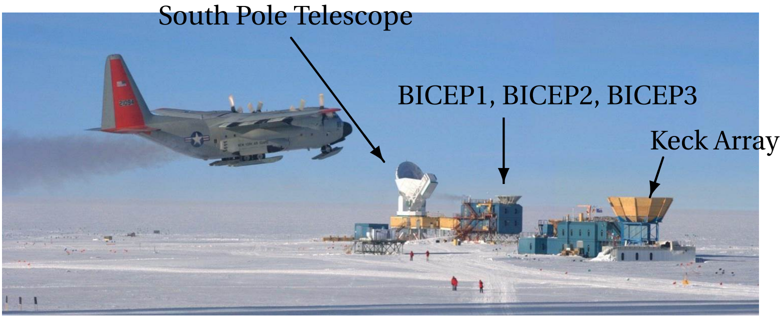
Patterns of polarizations around hot and cold spots



E-mode (grad) *B*-mode (curl)

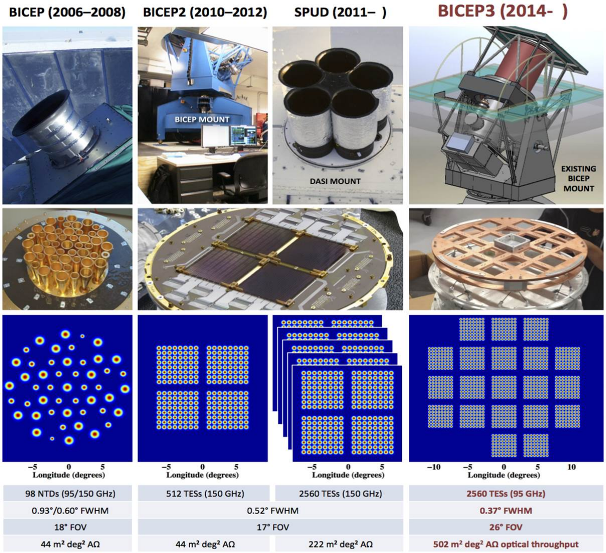
Note: polarization is always parallel to hot spots

BICEP2

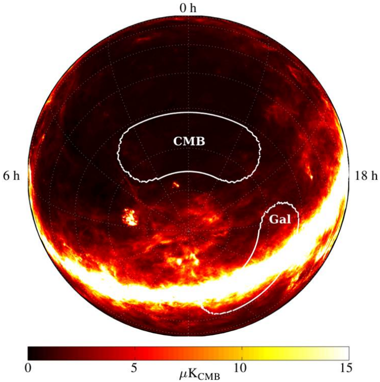


- Backgound Image of Cosmic Extragalactic Polarization
- Small (26cm) refractive telescope at South Pole
- 512 bolometers working at 150 GHz
- 380 square degrees for 3 years (2010-2012)

BICEP2 families

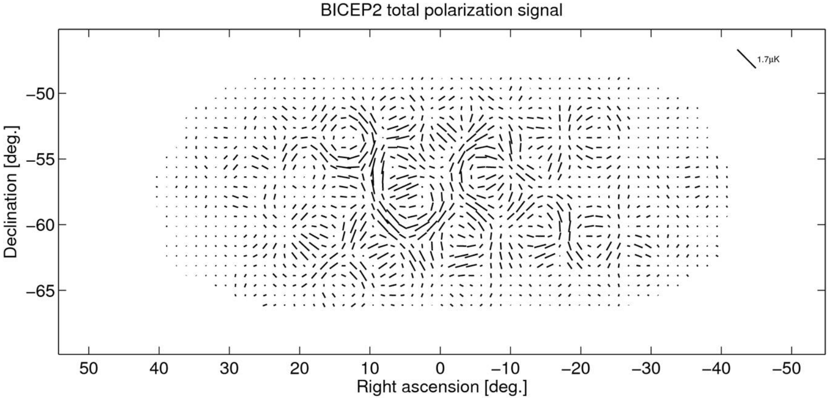


Observational strategy



- “Southern Hole”: exceptionally free of contaminations
- 150 GHz ≈ near the peak of the CMB blackbody spectrum
- Least contaminations

BICEP2 *B*-mode maps



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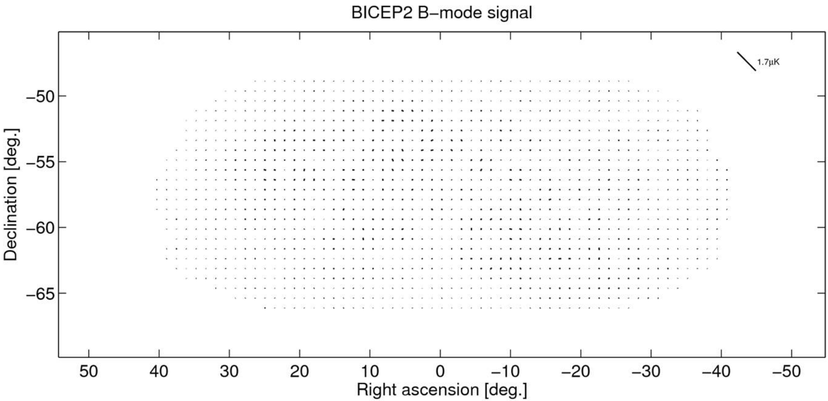

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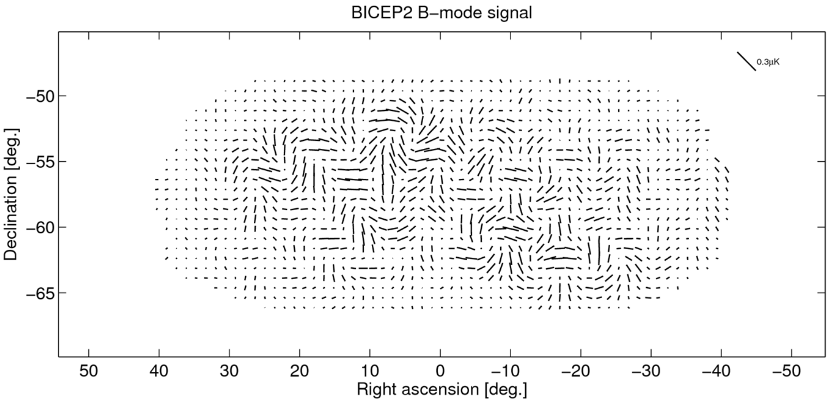
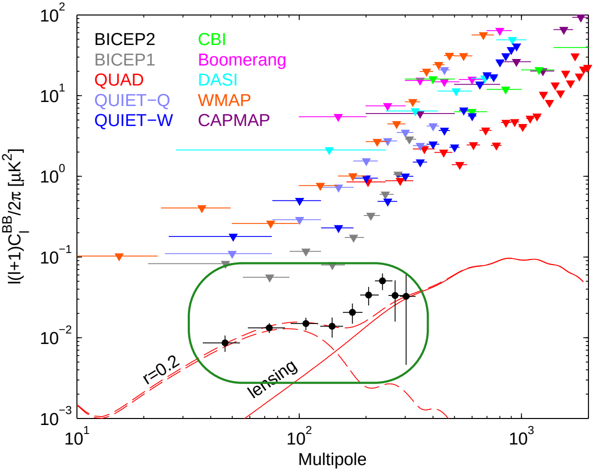


B-mode bounds and detection



$$r = 0.20^{+0.07}_{-0.05} \text{ at } 1\sigma, \text{ with } r = 0 \text{ disfavoured by } 7.0\sigma!$$

What looks sick in $\mathscr{C}_\ell^{BB}$

There seem a few "anomalies" in the current $\mathscr{C}_\ell$ maps:

- Tension w/ Planck?
  ($r = 0.20^{+0.07}_{-0.05}$ vs $r < 0.11$)

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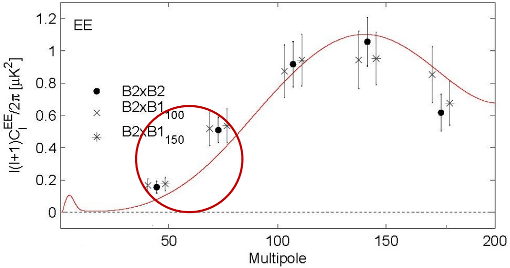

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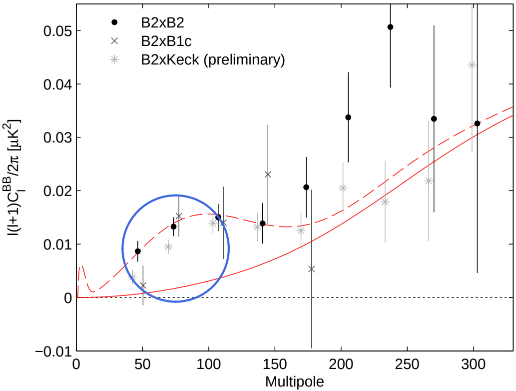

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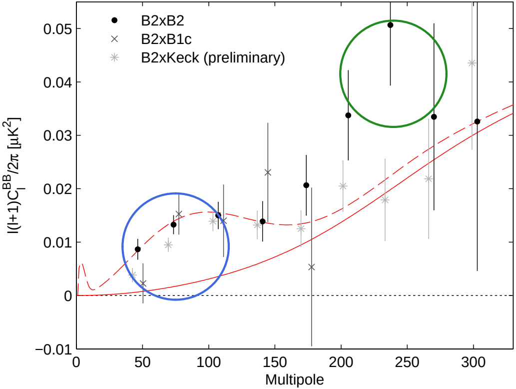

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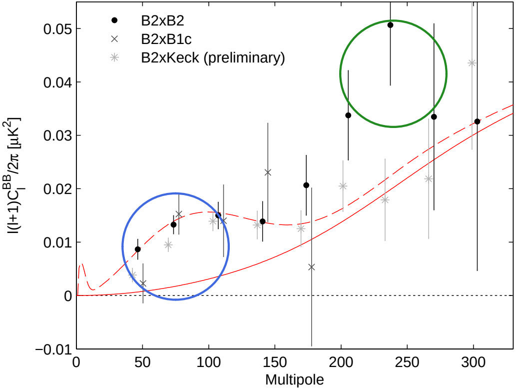

These may be illusive, but if real, what these could mean?

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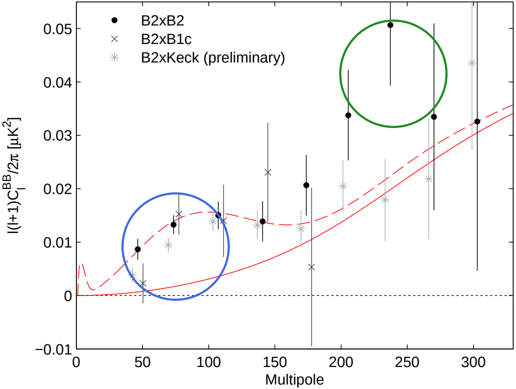

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Blue tensor spectrum in inflation

Tensor spectral index

$$
\begin{aligned}
n_T &= -2\epsilon - 2\epsilon^2 + (2\alpha - 2)\epsilon\eta \\
\eta &\equiv \frac{\dot{\epsilon}}{H\epsilon} \\
\alpha &\equiv 2 - \log 2 - \gamma \approx 0.729637
\end{aligned}
$$

To have positive n_T,

$$\eta \lesssim -1 \longleftrightarrow \epsilon \sim a^{-1}$$

ϵ rapidly decays proportional to $1/a$ or even faster

Working examples

1. Ultra slow-roll inflation

$$V = V_0 \longrightarrow \eta = -6 \ \left(\epsilon \propto a^{-6}\right)$$

Note: $f_{\rm NL} = 5/2$ (consistency relation is broken)

2. Punctuated inflation

$$V(\phi) = \frac{1}{2}m^2\phi^2 - \frac{\sqrt{2\lambda(n-1)}}{n} m m_{\rm Pl}^3 \left(\frac{\phi}{m_{\rm Pl}}\right)^n + \frac{1}{4}\lambda m_{\rm Pl}^4 \left(\frac{\phi}{m_{\rm Pl}}\right)^{2(n-1)}$$

Brief non-inflation phase sandwiched bet 2 slow-roll stages

Running of r

An easy way to disentangle different contributions (especially ϵ)

$$\frac{d\log r}{d\log k} = 1 - n_{\mathscr{R}} + n_T$$

$$= \begin{cases} \eta & \text{for canonical single field} \\ \eta + s & \text{for general single field} \\ \eta_{\text{multi}} + 2\dfrac{N_{,i}N_{,j}}{G^{kl}N_{,k}N_{,l}}\dfrac{R^i{}_{ab}{}^j}{3m_{\text{Pl}}^2}\dfrac{\dot\phi^a\dot\phi^b}{H^2} & \text{for multi-field} \end{cases}$$

$$s \equiv \frac{\dot c_s}{Hc_s}, \quad \eta_{\text{multi}} \equiv \frac{r}{4} - 2m_{\text{Pl}}^2\frac{N_{,i}N_{,j}}{G^{kl}N_{,k}N_{,l}}\frac{V^{;ij}}{V}$$

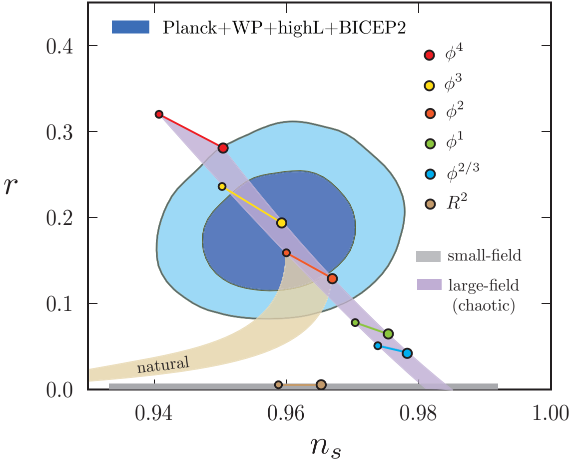
We can build a web of consistency checks
(e.g. with f_{NL} of 2 tensor & 1 scalar)

What we may now be convinced

From the BICEP2 result $r = 0.20^{+0.07}_{-0.05}$

1. $\rho_{\rm inf} \sim 10^{16}$ GeV (any connection to GUT?)
2. Validity of GR and QFT up to such energy scale
3. Quantum gravity signal
4. Lyth bound: field excursion $\gtrsim m_{\rm Pl}$ (some way out?)
5. Proof of inflation?

Model killer



Chaotic $m^2\phi^2$ inflation is back?

Summary

- BICEP2 seems to have detected primordial gravitational waves
- Theoretically
  - Our theories are predictable
  - Large field inflation model?
  - Tension with Planck: interpretation before more data comes...
- Observationally...
  - Testing consistency relation: $r = 16\epsilon$?
  - Multi-frequencies, cross correlations...
  - Tensor tilt

STAY TUNED!