L'inflation après BICEP2 (partie 1)

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Astrophysics

BICEP flexes its muscles

A telescope at the South Pole has made the biggest cosmological discovery so far this century

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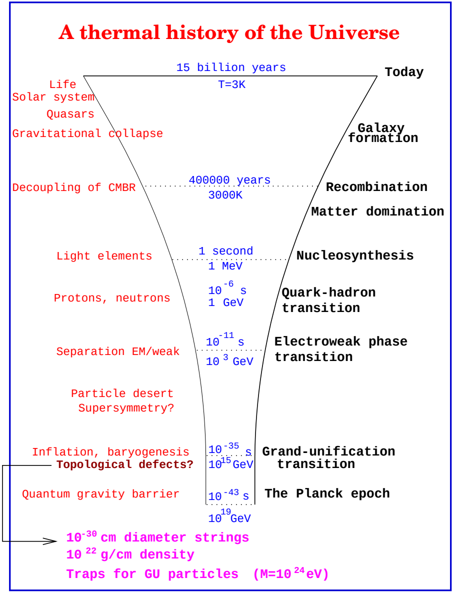
ONE useful feature of a scientific theory is that it makes testable predictions. Such predictions, though, do not have to be testable straight away. Physics is replete with prophecies that could be confirmed or denied only decades later, once the technology to examine them had caught up. The Higgs boson, for example, was 50 years in the confirming.

Incredibly exciting and important but definitive confirmation still lacking

CMB community still in process of digesting this result

Thermal history of the universe



Why inflation ? What's wrong with a radiation dominated universe all the way back to the big bang ? The horizon problem.

Line element for homogeneous, isotropic expanding universe :

$$ds^2 = -dt^2 + a^2(t)\left[dx^2 + dy^2 + dz^2\right], \quad H^2 \equiv \frac{\dot{a}^2(t)}{a^2(t)} = \frac{8\pi G}{3}\rho(t)$$

$w = (p/\rho)$, $\rho \sim a^{-3(1+w)}$, $\frac{da}{dt} \sim a^{(-1/2+3w/2)} \implies a(t) \sim t^{\alpha}, \alpha = \frac{2}{3w+3}$.

Transformation to conformal coordinates

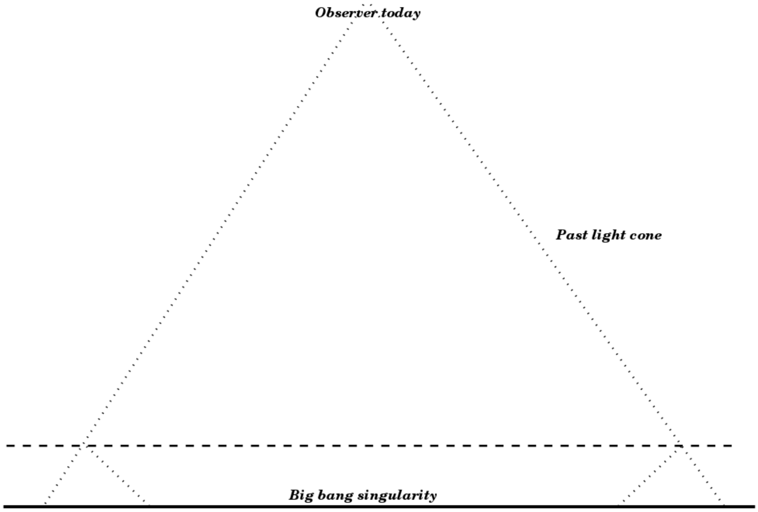
$$ds^2 = a^2(\eta)\left[-d\eta^2 + dx^2 + dy^2 + dz^2\right]$$

requires

$$\eta(t) = \int \frac{dt}{a(t)},$$

We want integral to require at $t \to 0+$.

What goes wrong when the integral does not diverge ? The horizon problem.



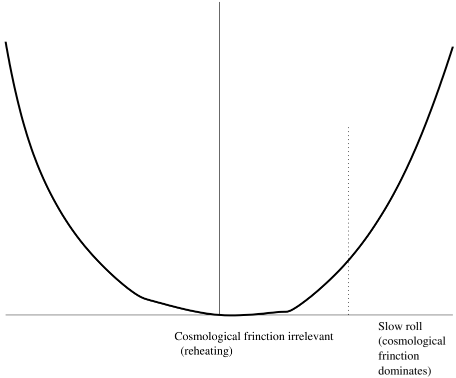
Initial conditions must be put in by hand.

The deadly sins of a non-inflationary universe.

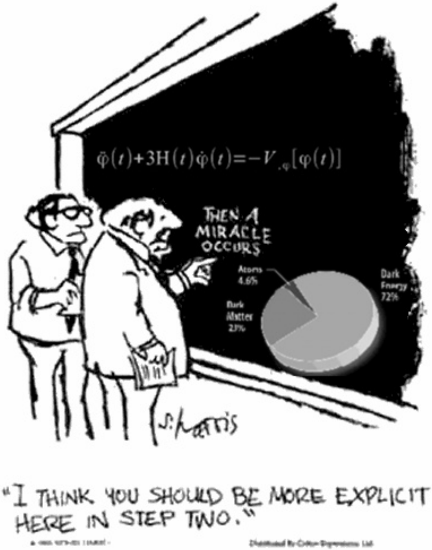
1. Monopole problem
2. Horizon problem
3. Flatness problem
4. Smoothness problem

Single-Field Inflation

At the beginning there was a scalar field that dominated the universe. Everything came from this scalar field and there was nothing without the scalar field. The quantum fluctuations of this field (that is, those of the vacuum) generated small fluctuations that advanced or retarded the instant of re-heating. These were the seeds of the large-scale structure.



Inflation at zeroth order



Courtesy of The New Yorker

Massless scalar field in de Sitter space

$H_{phys} = \text{(constant)}$.

$$ds^2 = -\frac{1}{\eta^2}(-d\eta^2 + d\mathbf{x}^2), \qquad -\infty < \eta < 0.$$

$$S = \int \sqrt{-g} g^{\mu\nu}(\partial_\mu \phi)(\partial_\nu \phi) = \int d^4x \; a^2(\eta) \left[\left(\frac{\partial \phi}{\partial \eta} \right)^2 - (\nabla \phi)^2 \right]$$

$$\frac{\partial^2 \phi}{\partial \eta^2} - \frac{2}{\eta} \frac{\partial \phi}{\partial \eta} + k^2 \phi = 0$$

Bessel equation

$$\phi(\eta) = \eta^{3/2} H^{(1)}_{3/2}(-k\eta)$$

$(k\eta) \approx 1$ horizon crossing.

Important points :

- Both the inflaton/scalar gravity degrees of freedom and the tensor metric perturbations exhbit the same qualitative behavior as the above idealized example.
- Modes fluctuation on subhorizon scales but become frozen in on superhorizon scales and stay frozen in until after the end of inflation.

Perturbations generated during inflation

$$\boxed{\hbar = c = 1, M_{pl}^{-2}} \qquad \delta\phi \approx H \qquad \frac{\delta\rho}{\bar{\rho}} \approx H \cdot \delta t, \quad \delta t \approx \frac{\delta\phi}{\dot{\phi}}$$

$$H\dot{\phi} \approx V_{,\phi}, \quad \dot{\phi} \approx V_{,\phi}/H, \quad H^2 \approx \frac{1}{M_{pl}^2} V, \frac{\delta\rho}{\bar{\rho}} \approx \frac{V^{3/2}[\phi(k)]}{M_{pl}^3 \ V_{,\phi}}$$

Scalar perturbations : $\boxed{\mathcal{P}_S^{1/2}(k) \approx O(1) \cdot \frac{V^{3/2}[\phi(k)]}{M_{pl}^3 \ V_{,\phi}[\phi(k)]}.}$

Tensor perturbations : $\boxed{\mathcal{P}_T^{1/2}(k) \approx O(1) \cdot \frac{H}{M_{pl}} \approx O(1) \cdot \frac{V^{1/2}}{M_{pl}^2}}$

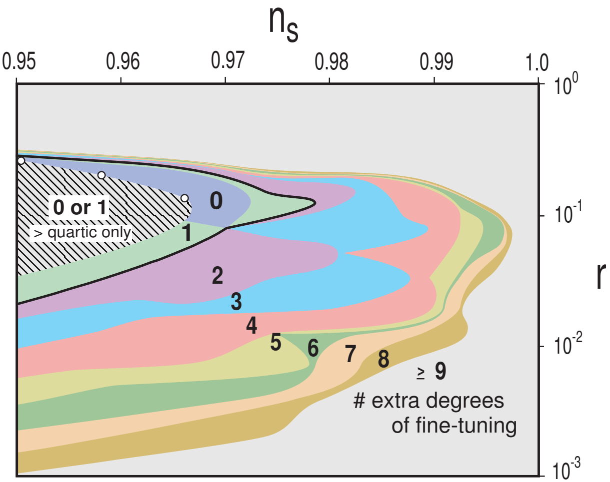
$\phi(k) \equiv$ value of ϕ at horizon crossing of the mode k

Reconstruction of the inflationary potential : the tensors measure the height of the potential, the scalars the slope.

Tests of inflation

- Order zero tests
  - Flatness, homogeneity, isotropy, no monopoles, entropy of observable universe
- Scalar perturbations
  - Scale invariance (approximate) (Harrison, Zeldovich, Peebles)
  - Gaussianity
  - Primordial character of comsological perturbations. No decaying modes observed.
- Tensor perturbations
  - Direct measure of the Hubble constant in the **very** early universe when a given mode left the horizon
  - New unique prediction of inflation

Expected (T/S) From Inflation ? (I)



From Boyle, Steinhardt and Turok.

Expected (T/S) From Inflation ? (II)

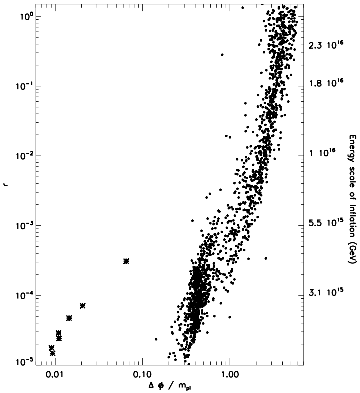
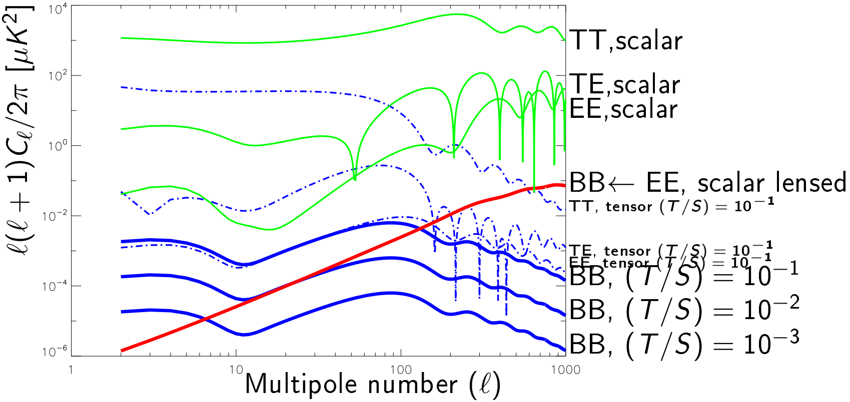
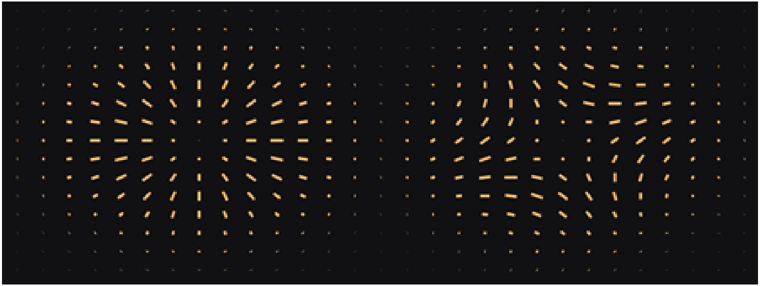


Figure produced by L. Verde, following closely the method of W. Kinney et al., Phys. Rev. D74, 023502 (2006) (astro-ph/0605338).

Inflationary Prediction for Scalar & Tensor Anisotropies



E and B Mode Polarization



E mode B mode

$$\mathbf{Y}^{(E)}_{\ell m,ab} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}}\left[\nabla_a\nabla_b - \frac{1}{2}\delta_{ab}\right] Y_{\ell m}(\hat{\Omega})$$

$$\mathbf{Y}^{(B)}_{\ell m,ab} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}}\frac{1}{2}\left[\epsilon_{ac}\nabla_c\nabla_b + \nabla_a\epsilon_{bc}\nabla_c\right] Y_{\ell m}(\hat{\Omega})$$

Projection of « scalars, » « vectors » and « tensors » onto the celestial sphere

Under projection onto the celestial sphere :

$$(scalar)_3 \rightarrow (scalar)_2,$$

$$(vector)_3 \rightarrow (scalar)_2 + (vector)_2,$$

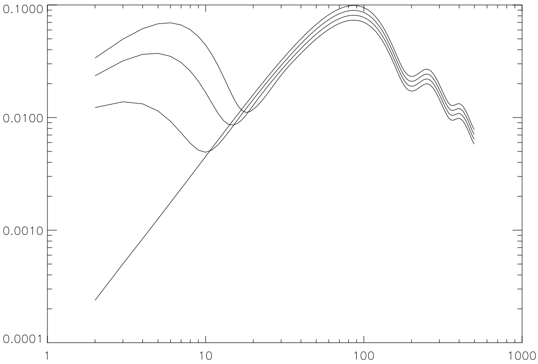
$$(tensor)_3 \rightarrow (scalar)_2 + (vector)_2.$$

There is no $(tensor)_2$ component. The E mode polarization is scalar ; the B mode is vector.

It follows that at linear order the scalar modes cannot generate any B mode polarization.

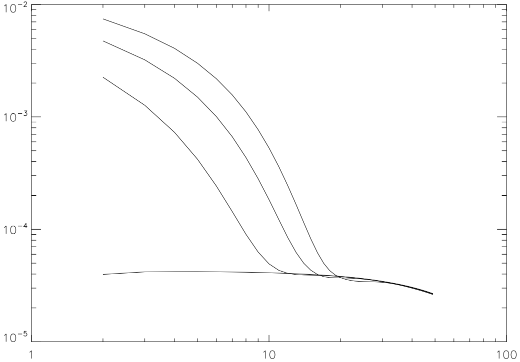
Note crucial role of linearity assumption.

The Reionization Bump (I)



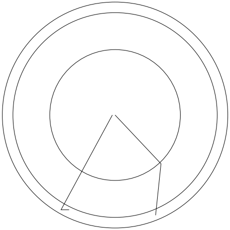
$\tau = 0.0, 0.5, 0.10, 0.15$ (bottom $\rightarrow$ top)

The Reionization Bump (II)



Amplification of the B mode signal relative to the non reionized case by a factor of about 50,100, and 150 at $\tau = 0.05$, $\tau = 0.10$, and $\tau = 0.15$, respectively.

The Reionization Bump (III)



It turns out that

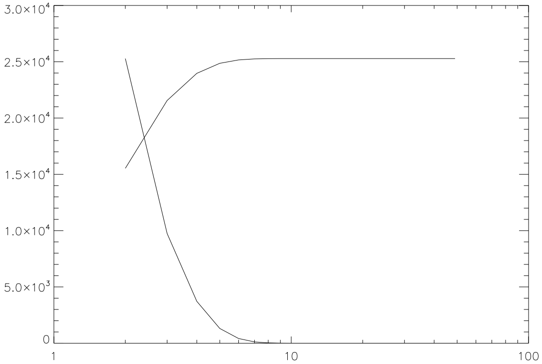
$$P \propto (1-\tau) d^2_{lastscatter} \frac{\partial^2 T}{\partial x^2}$$

is small compared to

$$P \propto \tau d^2_{reion} \frac{\partial^2 T}{\partial x^2}$$

even when τ is small.

The Reionization Bump (IV)



Information is concentrated at the very lowest multipoles.

Pro : There is comparatively a very large signal.

Drawback : It may be very hard to rule out a galactic explanation given the large role of the lowest ℓ. No way to jacknife the data. (Cf. Controversy regarding the significance of the WMAP low quadrapole.)

Lensing of the E mode into the B mode — $(E^{scalar} + \Phi \to B^{scalar})$

(Flat sky approximation : $(\ell m) \to \boldsymbol{\ell}, \quad \boldsymbol{\theta}, \boldsymbol{\ell} \in \mathcal{R}^2$.)

$$\delta\boldsymbol{\theta} = (\boldsymbol{\nabla}\Phi), \qquad\qquad \delta T(\boldsymbol{\theta}) = (\boldsymbol{\nabla}\Phi)\cdot(\boldsymbol{\nabla}T).$$

$$\delta T(\boldsymbol{\ell}_F) = \int \frac{d^2\boldsymbol{\ell}_L}{(2\pi)^2}\ (-\boldsymbol{\ell}_L)\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)\ \Phi(\boldsymbol{\ell}_L)\ T(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L).$$

$$\langle T(\boldsymbol{\ell})\ T(\boldsymbol{\ell}')\rangle = (2\pi)^2\ \delta^2(\boldsymbol{\ell} + \boldsymbol{\ell}')\ C^{TT}(\ell)$$

$$C^{TT}(\boldsymbol{\ell}_F) = \int \frac{d^2\ell_L}{(2\pi)^2}\ [\boldsymbol{\ell}_L\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)]^2\ C^{\Phi\Phi}(\boldsymbol{\ell}_L)\ C^{TT}(\boldsymbol{\ell}_I = |\boldsymbol{\ell}_F - \boldsymbol{\ell}_L|)$$

$$C^{BB}(\boldsymbol{\ell}_B) = \int \frac{d^2\ell_L}{(2\pi)^2}\ [\boldsymbol{\ell}_L\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)]^2\ \sin^2[2\Theta(\boldsymbol{\ell}_B, \boldsymbol{\ell}_E)]C^{\Phi\Phi}(\boldsymbol{\ell}_L)\ C^{EE}(\boldsymbol{\ell}_E = |\boldsymbol{\ell}_B - \boldsymbol{\ell}_L|)$$

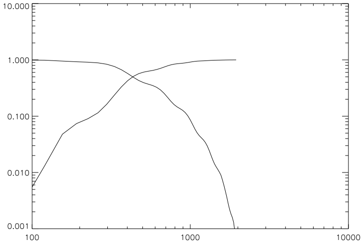
Lensing of the E mode into the B mode (II)

For small values of ℓ_B,

$$C^{BB}(\ell_B \approx 0) \sim \int_0^{\infty} \frac{d\ell}{\ell}\ \ell^6 C^{\Phi\Phi}(\ell)\ C^{EE}(\ell)$$

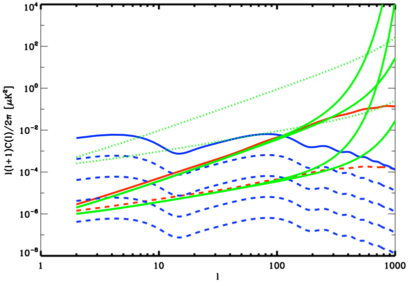
The bulk of the integral is concentrated around $\ell \approx 300$.
White noise spectrum up to $\ell \lesssim 300$

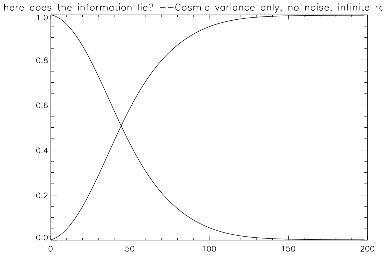
$$F(\ell_{max}) = \frac{\int_0^{\ell_{max}} \frac{d\ell}{\ell}\ \ell^6 C^{\Phi\Phi}(\ell)\ C^{EE}(\ell)}{\int_0^{\infty} \frac{d\ell}{\ell}\ \ell^6 C^{\Phi\Phi}(\ell)\ C^{EE}(\ell)}$$



Where does the information on (T/S) lie ?

$$\delta c_{\ell,measurable} \sim \frac{c_{\ell,parasite} + n_\ell}{\ell}$$

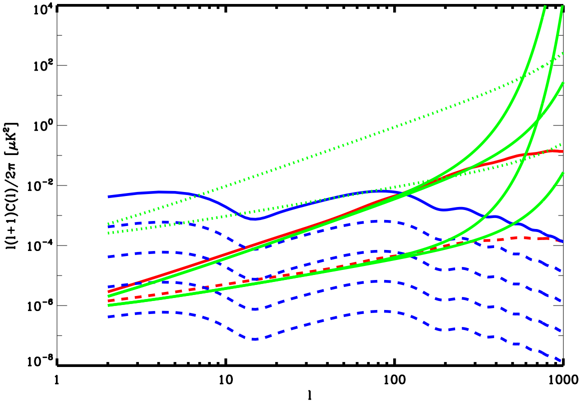




Conclusion : Approx. 80 % of the information (excluding the reionization bump) lies between $\ell = 20$ and $\ell = 80$.

The detection of B modes

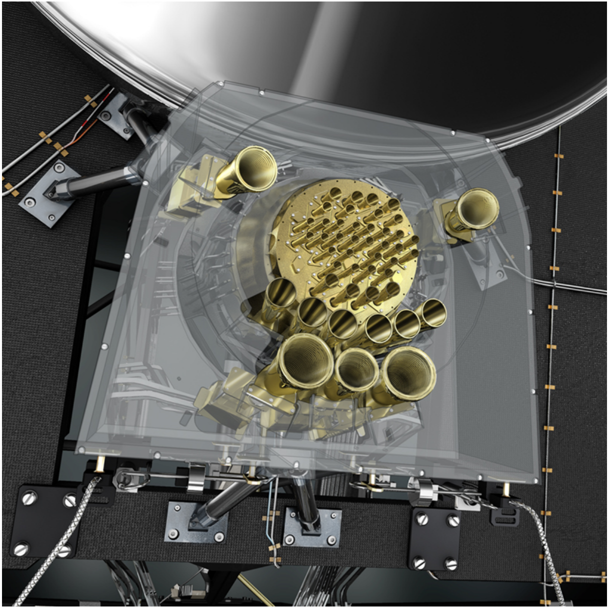
The B mode is that component that cannot be represented as a double gradient on the celestial sphere. In the linear approximation there is no B mode component arising from scalar degrees of freedom. The presence of the B mode would unambiguously signal the presence of primordial gravitational waves.



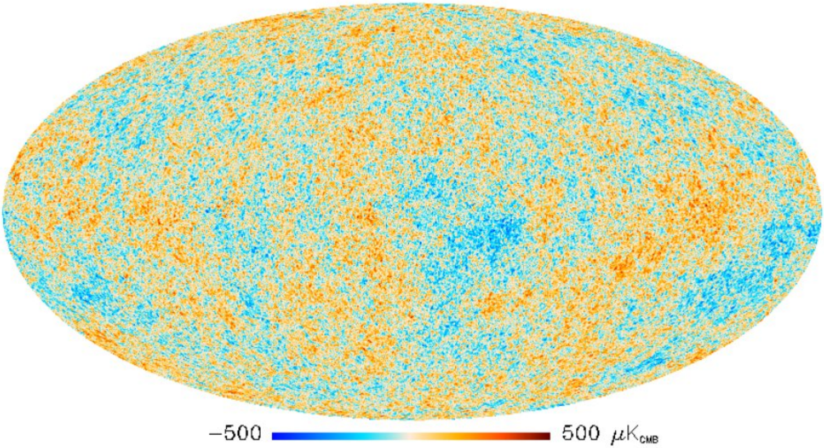
The Planck legacy and other experiments

The ESA *Planck* mission

PLANCK focal plane



Planck ILC (internal linear combination) full-sky CMB temperature map



Planck gravitational lensing power spectrum

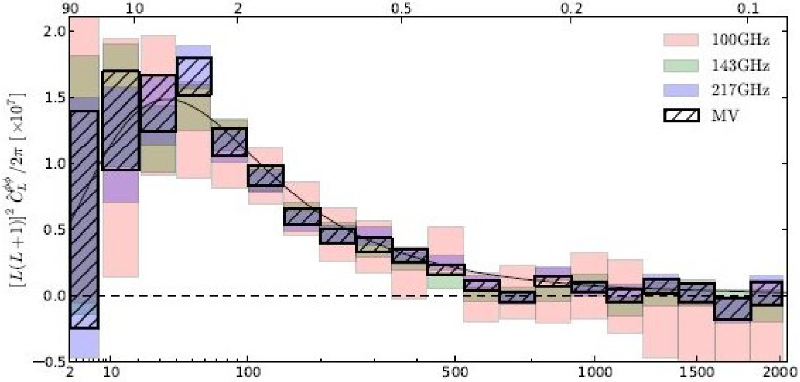
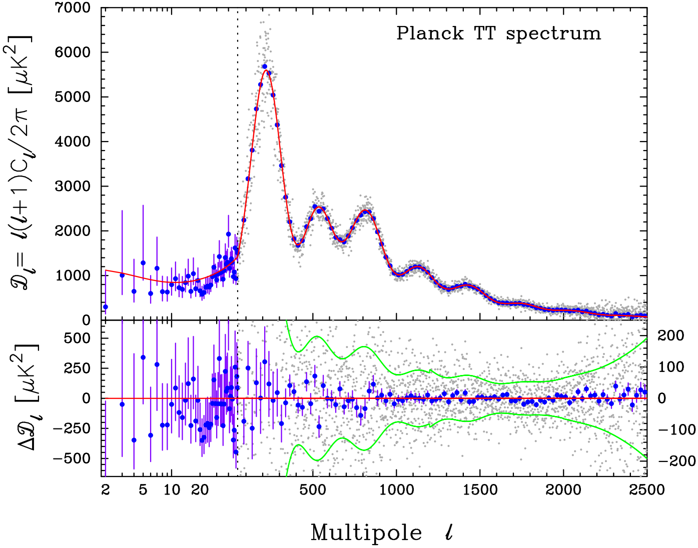
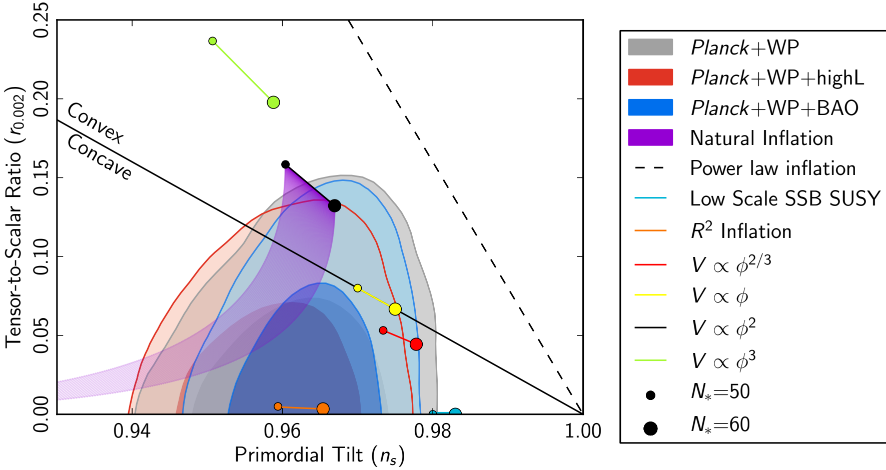


Fig. 18. Fiducial lensing power spectrum estimates based on the 100, 143, and 217 GHz frequency reconstructions, as well as the minimum-variance reconstruction that forms the basis for the *Planck* lensing likelihood.

Planck 2013 temperature power spectrum



Implications for inflation—summary plot



Searching for primordial gravitational waves from inflation using B modes of the CMB polarization anisotropy

Predictions of cosmic inflation

(Albrecht, Brout, Englert, Guth, Kazanas, Linde, Sato, Starobinsky, Steinhardt)

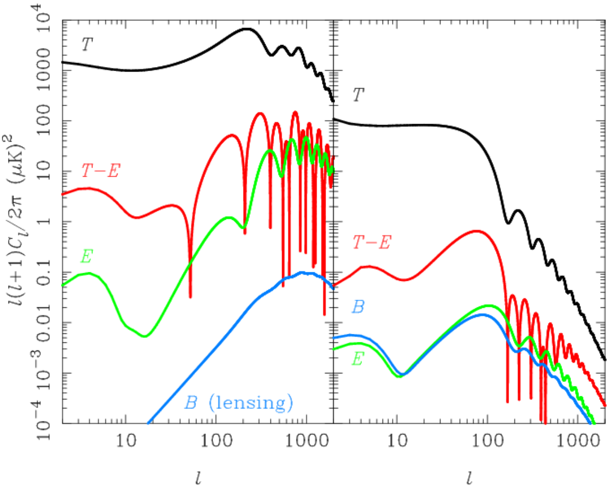
Cosmic inflation predicts two types of perturbations from a perfectly homogeneous and isotropic universe :

1. Scalar perturbations
2. Tensor perturbations

The first were first detected in the CMB by COBE in 1992 and have been characterized precisely over a wide range of scales by numerous CMB experiments, including especially WMAP and Planck space missions, augmented at small angular scales by ground based observations data from SPT and ACT.

The second constitute a highly unique and nontrivial prediction of inflationary theory. If we accept the BICEP2 claim, these have been dectected at $\approx 5.9\sigma$, although open questions remain (e.g., impact of foregrounds, high data points at large ℓ for which a plausible explanation is lacking). In any case, a precise characterization of the tensor spectrum remains to be carried out and promises to greatly enhance our understanding of cosmic inflation and test the consistency between the scalar and tensor perturbations.

Detecting tensor modes with the CMB (I)



r=0.24

Taken from : Challinor, astro-ph/1210.6008

How do we detect tensor modes with the CMB ? (II)

- The shape of the temperature spectrum at low-ℓ provide limited means for detecting tensor r based on the differing shape of the scalar and tensor TT templates.
- Using the TT spectrum, however, is runs into two complications :
  - Cosmic variance. $\delta c_l / c_\ell \approx \ell^{-1}$, so even if we had the perfect theoretical template, for an $r \approx 0.2$ the differences between a nontensor and tensor spectrum are measurable only for $\ell \lesssim 100$.
  - The main message from Planck 2013 has been that the six-parameter model provides a good fit to the temperature data and that Planck finds no statistically significant evidence favoring extensions to this model. Most notably, a power law power spectrum is assumed **and extrapolated to scales where it is not constrained**. " There can be features in the spectrum and other new physics.
- One must read the fine print in the contract and resist the temptation to overinterpret and claim that "inflation generically predicts...". "Speaking from the framework of effective field theory,...."

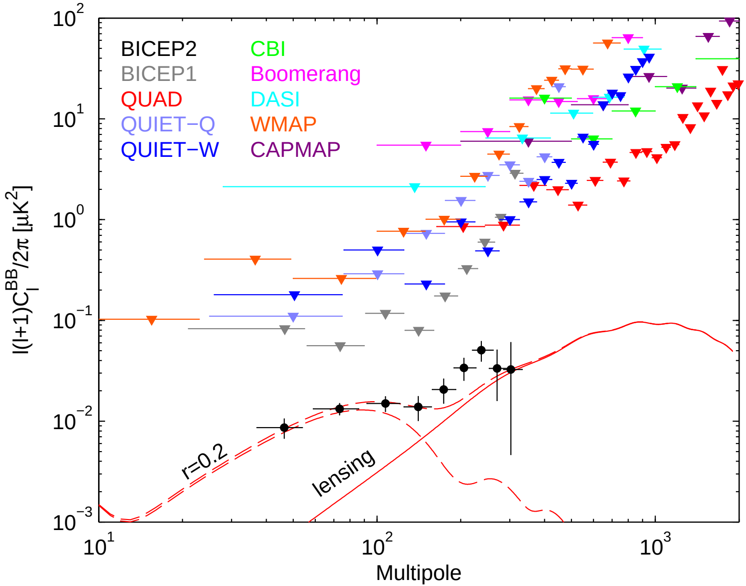
Update on BICEP2

Overview of lineage of BICEP experiments

1. BICEP 1
   - Past round.
     1/10 mapping speed of BICEP II. Used 2-lens refracting telescope with corrugated feed horen having 49 detector pairs at two frequencies (100 GHz and 150 GHz) with 0.93° and 0.60° resolution, respectively. Mapped 2% of sky from the South Pole during 2006-2008 . Outcome : $r = 0.02^{+0.31}_{-0.26}$. (Chiang et al., 0906.1181)
2. BICEP 2
   - Similar to BICEP but with 512 detectors coupled to phase array slotted antennas observing only at one frequency 150 GHz [Basic philosophy : detect first and ask questions later. Don't worry endlessly about foregrounds.]
3. Keck array
   - Five Bicep2-like two-lens refractive telescopes with a total of 2560 detectors (data partially analyzed).

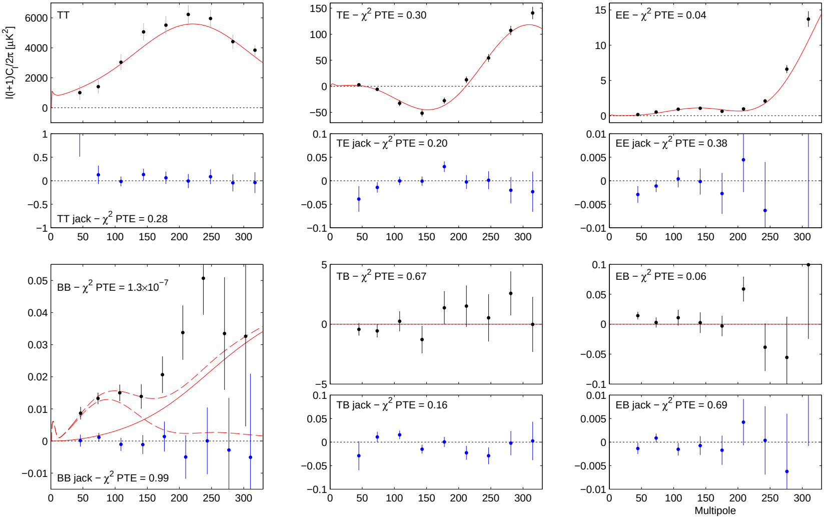
BICEP2 summary plot :

"Smoking gun" of gravitational waves from inflation ?

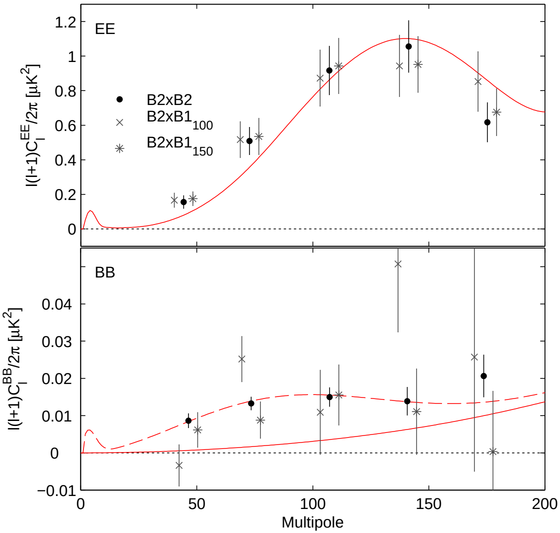


BICEP2 results on linear scale

(to represent errors more realistically)



Cross-correlation with BICEP I at 100GHz and 150 GHz



High-ℓ gravitational lensing points too high by factor of almost 2.

Plausible explanation lacking.