B mode observations from space

Martin Bucher
Laboratoire APC
Université Paris 7

5 juin 2014, Fuerteventura conference

Breaking news 22 March 2014

The Economist | World politics | Business & finance | Economics | Science & technology | Culture

Astrophysics

BICEP flexes its muscles

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

Mar 22nd 2014 | From the print edition

Timekeeper | Like 204 | Tweet 39

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.

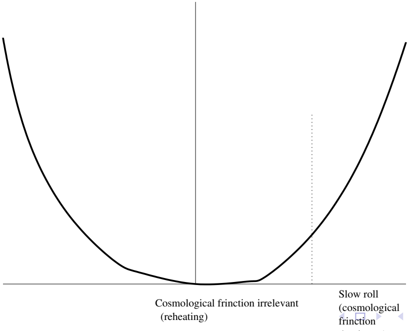
Incredibly exciting and important but definitive confirmation still lacking

CMB community still in process of digesting this result

Single-Field Inflation

In 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.

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi}$$



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

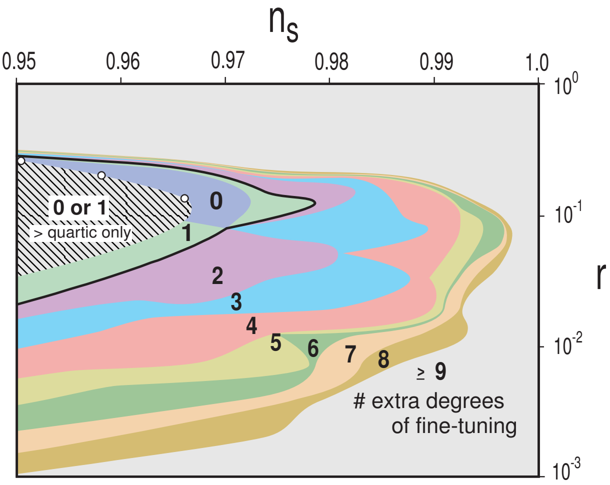
$\phi(k) \equiv$ value of ϕ at horizon crossing of the mode k

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)

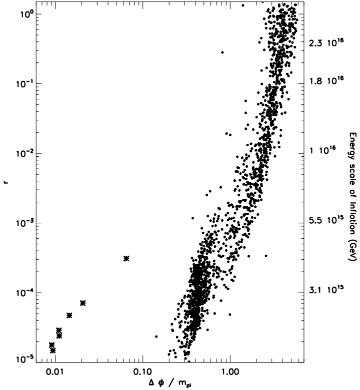
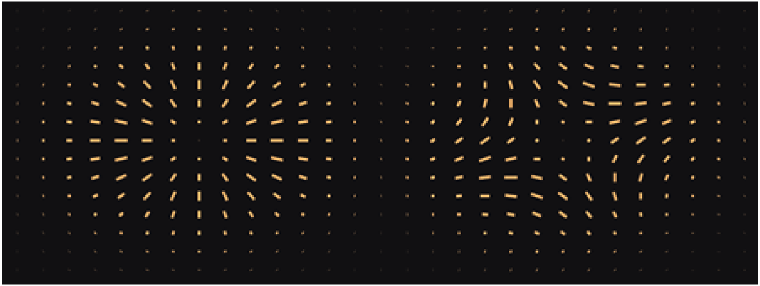


Figure produced by L. Verde, following closely the method of W. Kinney et al., Phys. Rev. D74, 023502 (2006) (astro-ph/0605338).

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 :

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

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

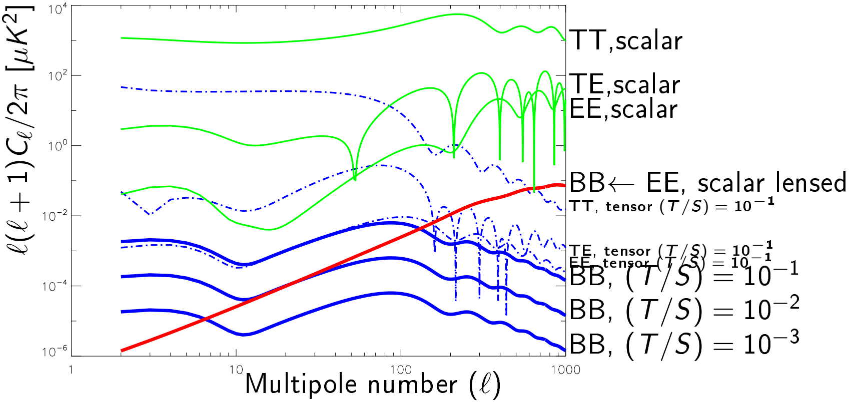
$$(tensor)_3 \to (scalar)_2 + (vector)_2.$$

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

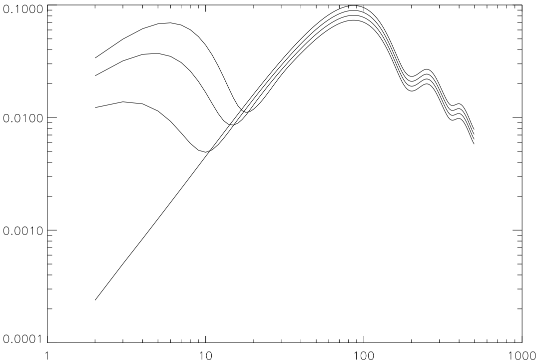
It follows that at linear order the scalar modes cannot generate any B mode polarization.

Note crucial role of linearity assumption.

Inflationary Prediction for Scalar & Tensor Anisotropies

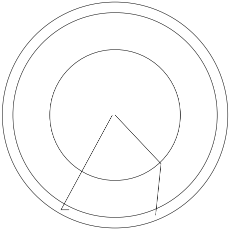


The Reionization Bump (I)



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

The Reionization Bump (III)



It turns out that

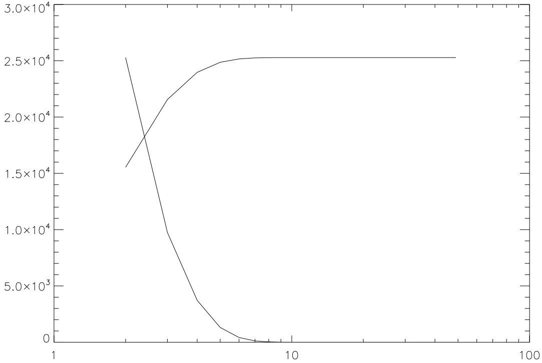
$$P \propto (1-\tau) d^2_{lastscatter} \frac{\partial^2 T}{\partial x^2}$$

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)



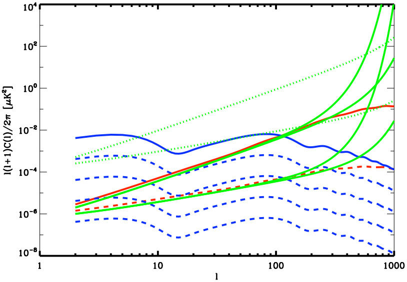
Information is concentrated at the very lowest multipoles.

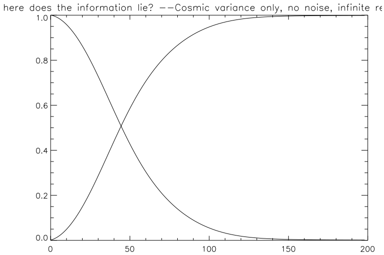
Pro : There is comparatively a very large signal.

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.)

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

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

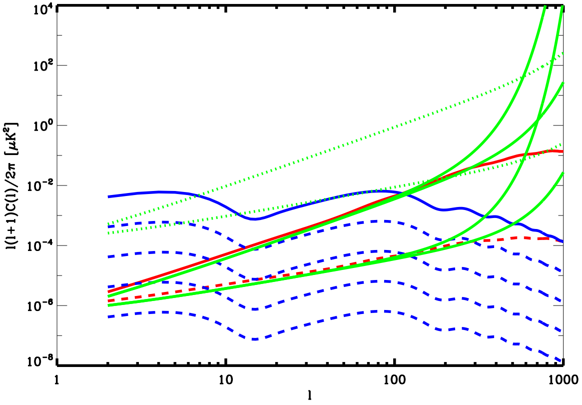




Conclusion : Approx. 80 % of the information (excluding the reionization bump) lies between $\ell = 20$ and $\ell = 80$.

The detection of B modes

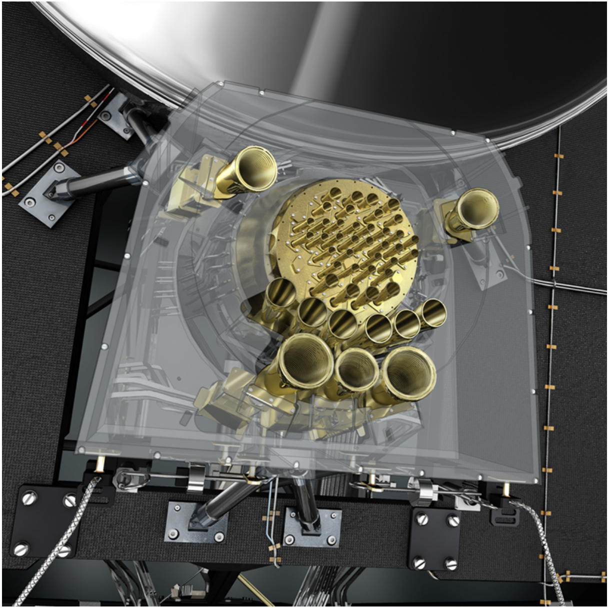
The B mode is that component that cannot be represented as a double gradient on the celestial sphere. In the linear approximation there is no B mode component arising from scalar degrees of freedom. The presence of the B mode would unambiguously signal the presence of primordial gravitational waves.



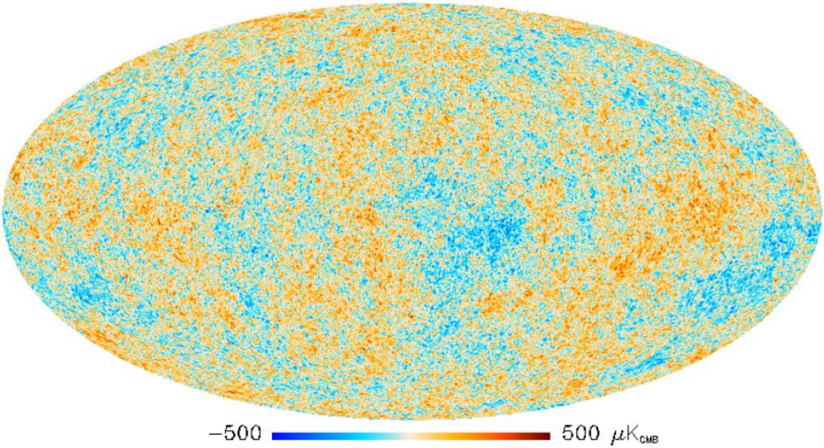
The Planck legacy and other experiments

The ESA *Planck* mission

PLANCK focal plane



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



Planck gravitational lensing power spectrum

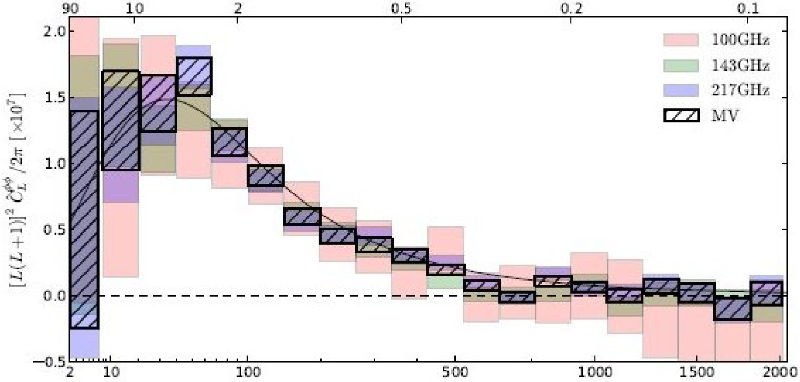
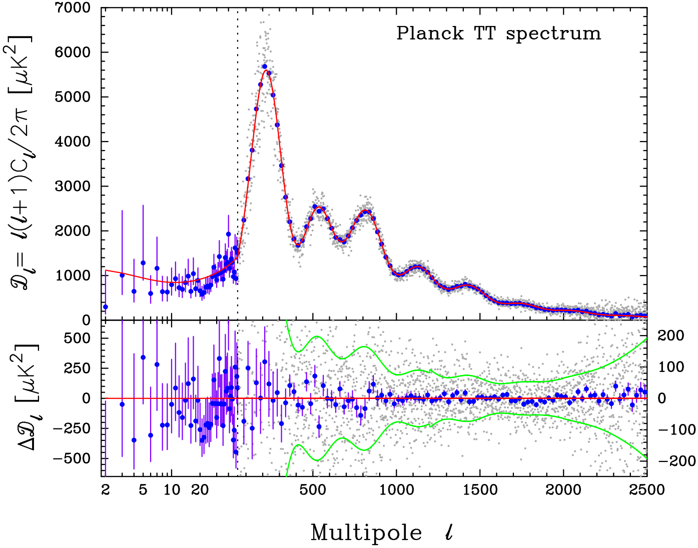
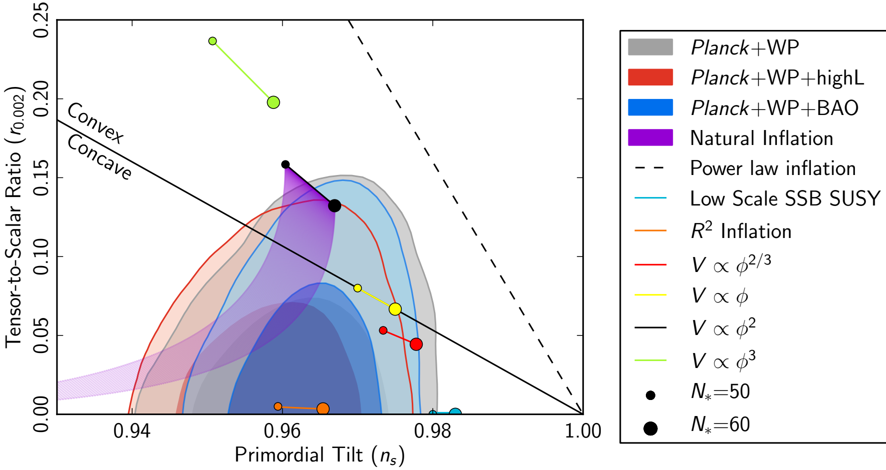


Fig. 18. Fiducial lensing power spectrum estimates based on the 100, 143, and 217 GHz frequency reconstructions, as well as the minimum-variance reconstruction that forms the basis for the *Planck* lensing likelihood.

Planck 2013 temperature power spectrum

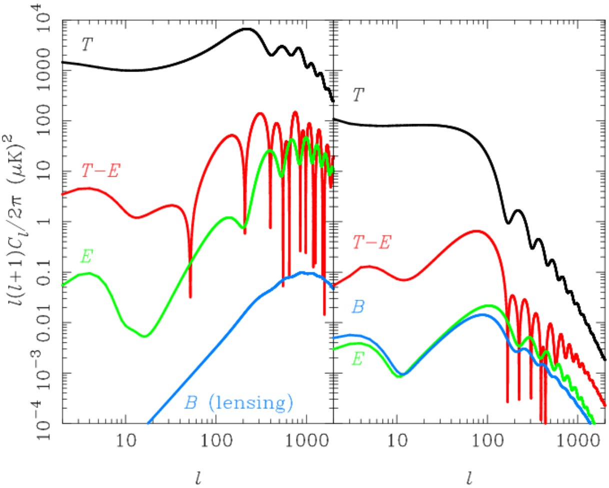


Implications for inflation—summary plot



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

Detecting tensor modes with the CMB (I)



r=0.24

Taken from : Challinor, astro-ph/1210.6008

How do we constrain tensor modes with the temperature data ?

- 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,...."

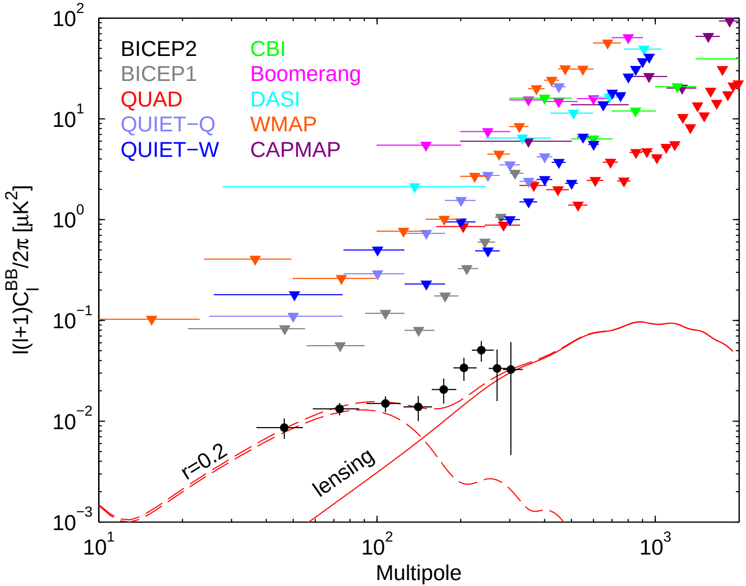
Update on BICEP2

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).

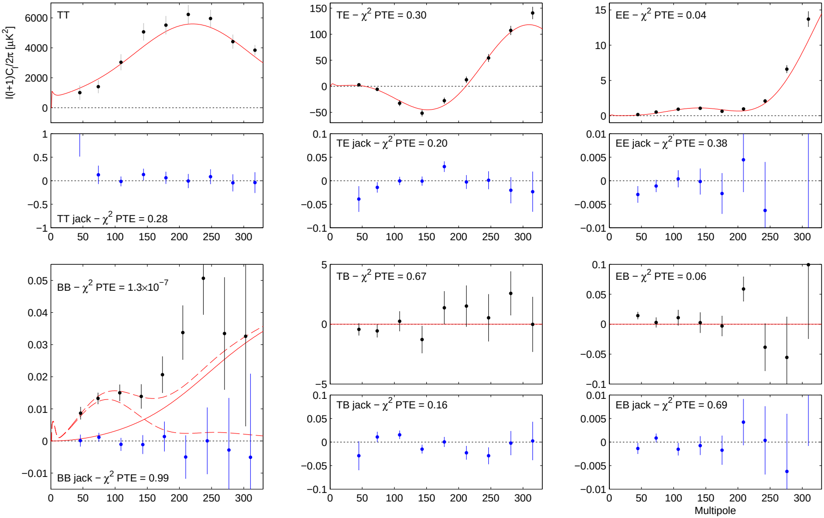
BICEP2 summary plot :

"Smoking gun" of gravitational waves from inflation ?

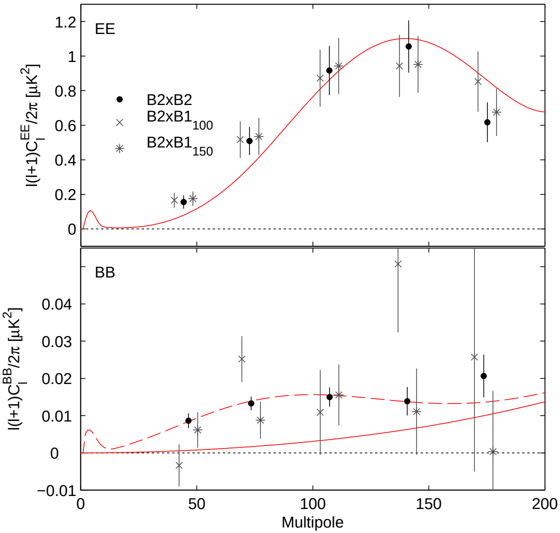


BICEP2 results on linear scale

(to represent errors more realistically)



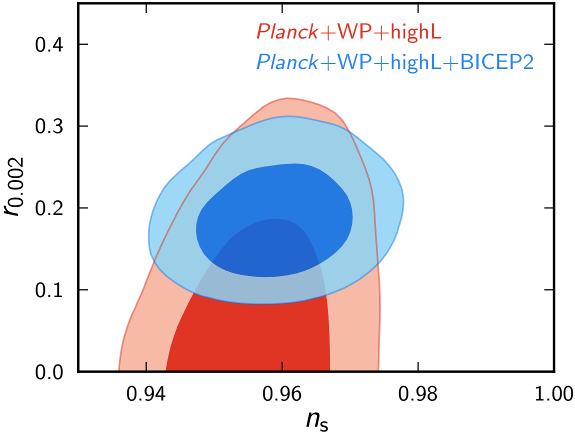
Cross-correlation with BICEP I at 100GHz and 150 GHz



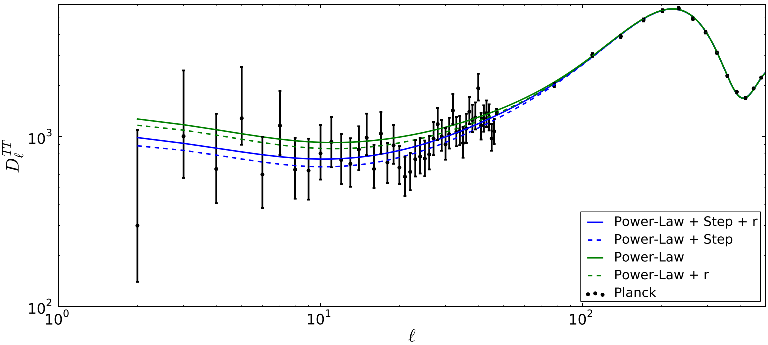
High-ℓ gravitational lensing points too high by factor of almost 2.

Plausible explanation lacking.

BICEP2 claim on Planck-like plot

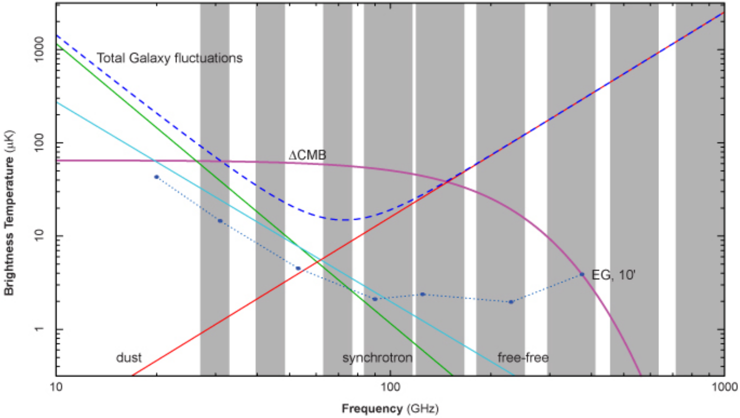


Hard art of power spectrum bending



Many ways to bend low-ℓ power spectrum without messing up high-ℓ multipoles, but all seem to require extending the six-parameter concordance model of cosmology.

Planck frequency bands



Anonymous said...

Pierre Ramond once quipped that "rumors can travel faster than the speed of light because they carry no information." Perhaps this blog lends support to Ramond's theory, which incidentally was formulated before the advent of the blogosphere. It is disappointing to see the author of this blog appropriate for himself the role of shadow spokesperson for the Planck Collaboration, to which he is in no way connected. I found it hard to understand how someone with no expertise in CMB foregrounds should find it legitimate to be interviewed by Science magazine based on the "rumors that have been coming in." Let us wait till Planck is ready to present findings that have been carefully checked and abstain from speaking on behalf of the Planck collaboration based on the claim of being a clearinghouse for Planck rumors. Martin Bucher (bucher@apc.univ-paris7.fr)

13 May 2014 09:07

nature International weekly journal of science

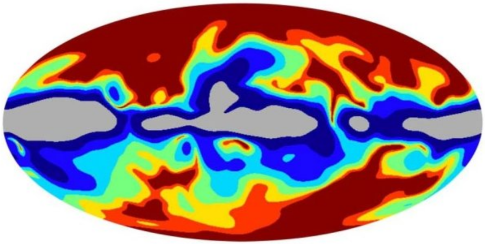
NATURE | NEWS

'No evidence for or against gravitational waves'

Two analyses suggest signal of Big Bang ripples announced in March was too weak to be significant.

Ron Cowen

29 May 2014



Planck Collaboration (ESLAB2013)

Preliminary data from the Planck probe on how galactic dust scatters microwave radiation, presented at an April 2013 meeting, are now being used to evaluate the strength of signals from the primordial Universe.

Results from an independent (non-Planck) analysis

Toward an Understanding of Foreground Emission in the BICEP2 Region

Raphael Flauger, J. Colin Hill, David N. Spergel

(Submitted on 28 May 2014)

astro-ph/1405.7351

BICEP2 has reported the detection of a degree-scale B-mode polarization pattern in the Cosmic Microwave Background (CMB) and has interpreted the measurement as evidence for primordial gravitational waves. Motivated by the profound importance of the discovery of gravitational waves from the early Universe, we examine to what extent a combination of Galactic foregrounds and lensed E-modes could be responsible for the signal. We reanalyze the BICEP2 results and show that the 100x150 GHz and 150x150 GHz data are consistent with a cosmology with r=0.2 and negligible foregrounds, but also with a cosmology with r=0 and a significant dust polarization signal. We give independent estimates of the dust polarization signal in the BICEP2 region using four different approaches. While these approaches are consistent with each other, the expected amplitude of the dust polarization power spectrum remains uncertain by about a factor of three. The lower end of the prediction leaves room for a primordial contribution, but at the higher end the dust in combination with the standard CMB lensing signal could account for the BICEP2 observations, without requiring the existence of primordial gravitational waves. By measuring the cross-correlations between the pre-Planck templates used in the BICEP2 analysis and between different versions of a data-based template, we emphasize that cross-correlations between models are very sensitive to noise in the polarization angles and that measured cross-correlations are likely underestimates of the contribution of foregrounds to the map. These results suggest that BICEP1 and BICEP2 data alone cannot distinguish between foregrounds and a primordial gravitational wave signal, and that future Keck Array observations at 100 GHz and Planck observations at higher frequencies will be crucial to determine whether the signal is of primordial origin. (abridged)

Reaction from BICEP2 :

"We certainly stand by our results."
—John Kovac (quoted in Scientific American)

Lecciones del experimento BICEP2

EL PECADO CAPITAL DE LA SOBERBIA

Cuando te vas apartando de Dios y vas perdiendo tu inocencia, te vas volviendo más desconfiado, y cuando una persona se vuelve más desconfiada, empieza la soberbia a salir, el odio, la rabia y la furia, la envidia, los celos, toda esa serie de cosas que son las que encierran a una persona en una prisión.

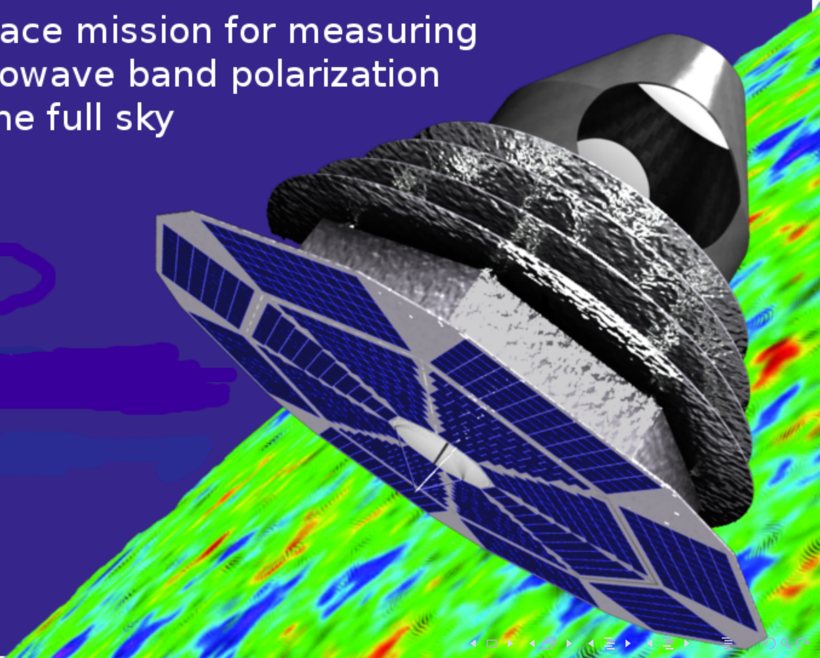
¿Se puede subir al Cielo teniendo algún pecado capital sin superar? No, no puede subir nadie si tiene los pecados. No he conocido a nadie que tenga pecados y haiga subido. ¿Aunque los tenga casi superados? Para eso está el purgatorio, para pulgar esos pecados, pero no se puede subir teniendo pecados, es imposible.

El pecado más grave es la soberbia, puesto que es el tronco del árbol donde salen todas las ramas. La soberbia es el tronco donde se asienta el Demonio, y a través de la soberbia uno se cree que lo sabe todo, que no le hace falta nadie, que no necesita a nadie, que lo puede hacer todo y que puede comprarlo todo. Esas son algunas de las cosas que la soberbia encierra. La soberbia se contrarresta con la humildad. ¿Hasta qué punto llega la humildad? Hasta el punto más fuerte, cuanto más humilde seas… El trono del Demonio será destruido.

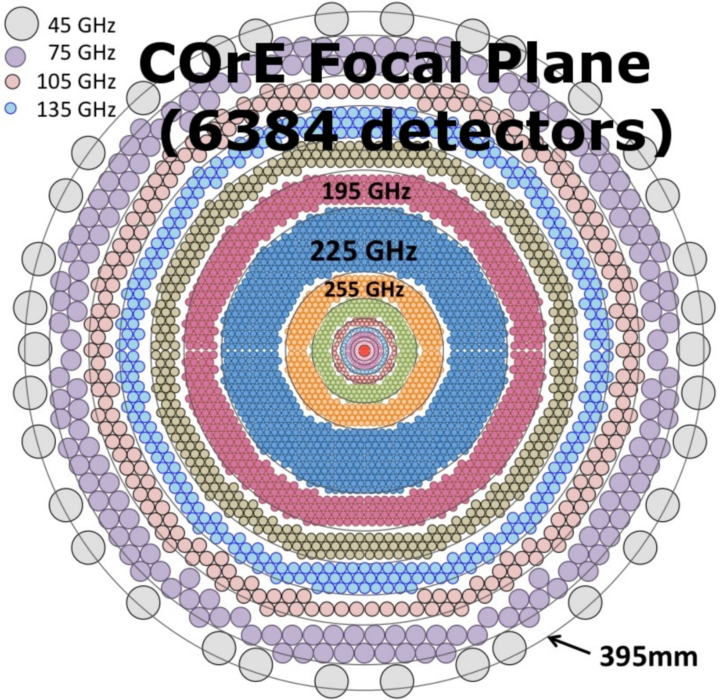
http ://mensajesdelcielo.net/leyes/los-pecados-capitales/la-soberbia/index.html

COrE : Cosmic Origins Explorer

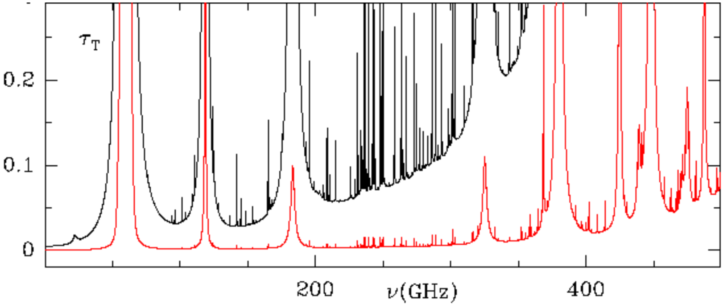
A space mission for measuring microwave band polarization on the full sky



COrE Focal Plane (6384 detectors)



Observations from the ground

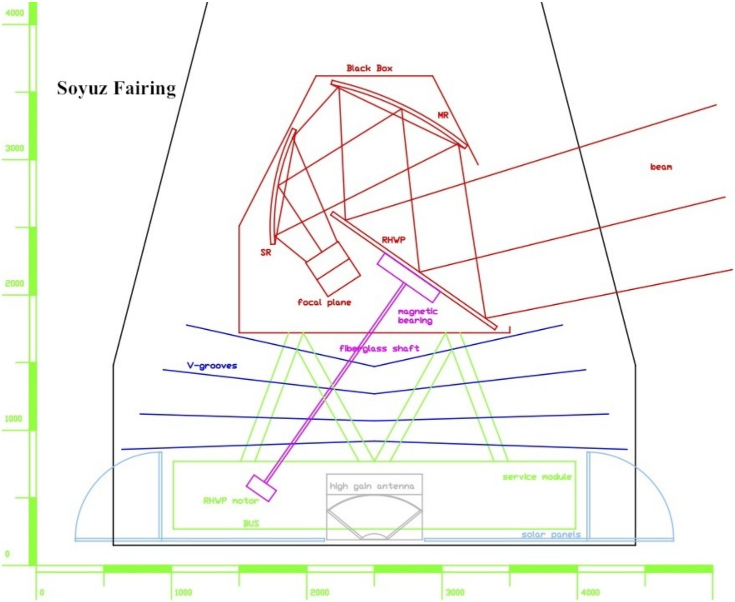


Atmospheric interference. Calculated optical depth through the atmosphere for a good ground-based site like the South Pole or Dome-C in Winter (black) and at balloon altitude (red). Frequency bands for sub-orbital experiments must be carefully chosen to avoid the emission by molecular lines. Moreover, emission from oxygen lines is circularly polarized and care must be taken to avoid a significant polarized signal from the tails of these lines.

History–European polarization satellites

- (circa 2006) CNES SAMPAN study - a refracting telescope - Conclusion : too expensive for France to do it alone, should explore mission in a European context
- (2006 - 2007) B-Pol defined (main partners : France, Germany, Italy, Spain, United Kingdom with a expression of interest from several US groups) proposal submitted in 2007 to ESA as a class M mission. Judged not technologically not ready, bets too much on a single and uncertain scientific objective, (i.e., B modes). Design : several telescopes for the various frequencies)
- (Jun 2010) Announcement of an M3 slot in the framework of ESA Cosmic Vision, remobilization of European collaboration, attempt to improve performance within the budget, to expand the science case, documents available at (www.core-mission.net). COrE was not selected but ranked 4th by the AWG, 3 projects were forwarded by the AWG to the SSAC. Disappointing but not bad ! !
- (2013) PRISM proposal. ESA Call for large mission (L3/L4) (2026/2034). European community submitted proposal mainly targetting non-CMB science (eg ultimate SZ survey) with 3m cooled telescope and FFT (pixie like instrument). Made final round, but in the end A
- ESA M4 slot announcement rumored (around 2024). Initial meeting for COrE+ held in Paris. Possible delays in ESA call and uncertainty in BICEP2 has somewhat slowed down planning process.

COrE schematic



Photon shot noise

For a single mode :

$$\langle N \rangle = \left(\exp(x) - 1\right)^{-1}, \qquad x = \left(\frac{h\nu}{k_B T_{CMB}}\right) = \left(\frac{\nu}{57\ GHz}\right)$$

$$\langle N^2 \rangle = 2\langle N \rangle^2 + \langle N \rangle, \qquad \langle (\delta N)^2 \rangle = \langle N \rangle^2 + \langle N \rangle = N^2 + N$$

$$\left(\frac{\delta N}{N}\right) = \sqrt{1 + N^{-1}}$$

For $x \gg 1$, pure Poissonian noise, almost. For $x \ll 1$, photon bunching (Hanbury Brown and Twiss) photons arrive roughly in bunches of N, these correlations augment noise relative to Poisson distribution.
Radio astronomers' formula (quantum corrected)

$$\left(\frac{\delta I}{I}\right) = \frac{1}{\sqrt{N_{det}}} \left(\frac{T_{sky} + \epsilon_{tel} T_{tel}}{T_{sky}}\right) \frac{1}{\sqrt{(\Delta\nu) t_{obs}}} \sqrt{e^{-1} + n_{occ}^{-1}}$$

$e = (\text{quantum efficiency}) = (\text{prob. } \gamma \text{ is absorbed}), \qquad T_{sky} \approx T_{CMB}$
$\epsilon_{tel} = (\text{telescope emissivity})$

Polarization modulation with a rotating half-wave plate

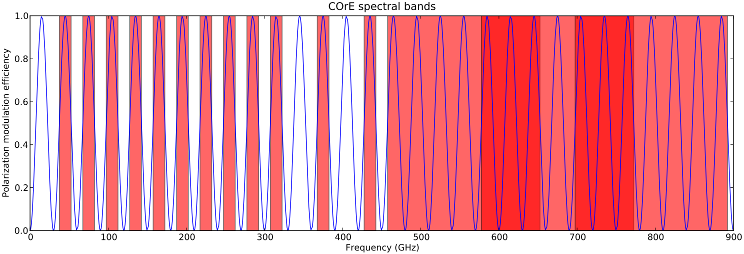
$$\begin{pmatrix} E_x^{(tel)} \\ E_y^{(tel)} \end{pmatrix} = \begin{pmatrix} \cos\Omega t & \sin\Omega t \\ -\sin\Omega t & \cos\Omega t \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \cos\Omega t & -\sin\Omega t \\ \sin\Omega t & \cos\Omega t \end{pmatrix} \begin{pmatrix} E_x^{(sky)} \\ E_y^{(sky)} \end{pmatrix}$$

$$\left\langle (E_x^{tel})^2 \right\rangle = I + Q\cos 4\Omega + U\sin 4\Omega t$$

$$\left\langle (E_x^{tel})^2 \right\rangle = I - Q\cos 4\Omega - U\sin 4\Omega t$$

- For measuring polarization, all harmonics —in particular those at $0\Omega t$, $2\Omega t$—are rejected except those at $4\Omega t$ are rejected.
- Stray light that becomes polarized from within telescope is thus rejected. $T_{tel} \to B\ mode$
- One is not subtracting two measurements with different beamsizes, aliasing T anisotropy into B mode
- Still has to know detector and telescope geometry very accurate ; otherwise, E mode masquerades as B mode

COrE's 15 Spectral Bands



Note that 3 highest bands overlap

- In order to carry out foreground subtraction and provide redundancy for cross-checks 15 bands are required, minus a few. [3 synchrotron-amp.+spect-ind+running, 1 CMB, 2 free-free, 6 dust (2 BBs A+temp+emmis. index)+1 th.sz=13+2(safety)]

ν GHz	n_{unpol}	n_{pol}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

PLANCK (30 month mission)

ν *GHz*	$(\Delta\nu)$ *GHz*	n_{det}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

Table: **COrE performance compared to WMAP and PLANCK.**

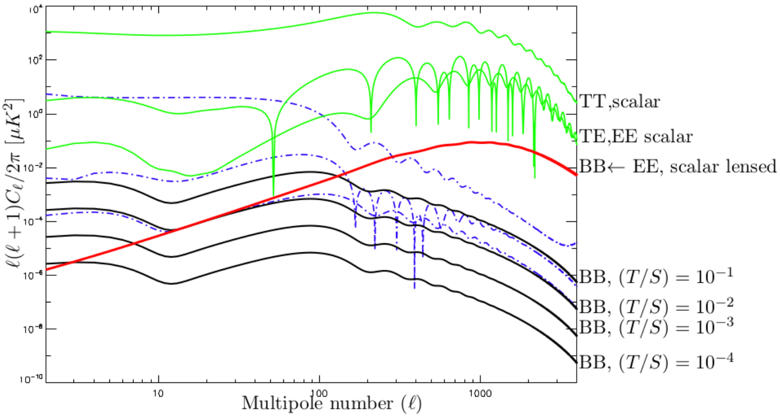
Foregrounds and component separation

- **Synchrotron emission** (cosmic rays spiralling in galactic magnetic field) $T_{sync,RJ} \propto \nu^{\alpha}$ where $\alpha \approx 3$ but varies spatially. Spectrum smooth in ν. Observed by WMAP to be highly polarized.
- **Free-free emission** bremsstrahlung of electrons in HI regions, For I H_{α} maps serve as faithful tracer. At most slightly polarized.
- **Spinning dust** (aka anomalous dust emission) regions of low frequency emission correlated with dust emission at high-frequencies. Attributed to rapidly (supra-thermally) spinning dust grains. Polarization properties uncertain.
- **Thermal dust emission.** At present best model has two components with separate amplitudes, emissivity indices, and temperatures. Model could become more complicated as data improves.
- **Zodiacal light.** Hotter dust from our solar system. Thermal emission and scattering. Most visible in 25μ maps, does not lend itself well to traditional component separation methods.
- **Sunyaev-Zeldovich (thermal and kinetic).**
- **Radio and infrared point sources.** Each have a different spectrum. Mask brightest and model unresolved.

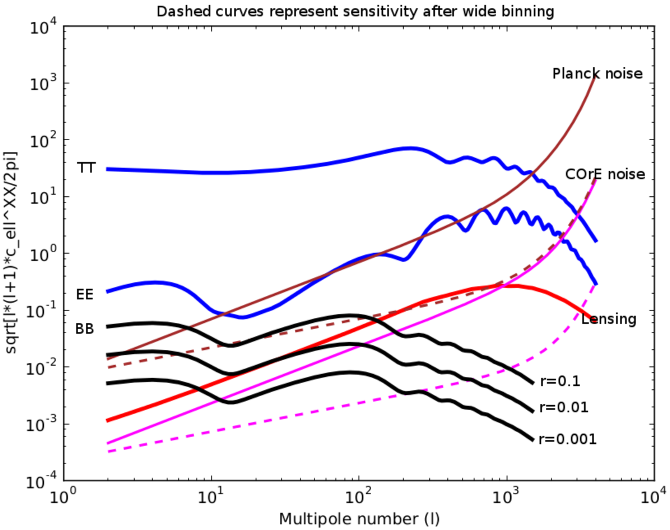
Linear component separation model.
$T_f^{sky}(\Omega) = M_{fc} X_c(\Omega)$
Simulations and forecasts for COrE : Basak, Bonaldi, Delabrouille, Peiris, Ricciardi, Verde

Scenario I : Targetting detection of $r \approx 10^{-3}$

B-mode predictions



Planck and COrE sensitivities



Planck and COrE sensitivities

ν	θ_{fwhm}	n_{det}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz	arcmin		RJ	CMB	RJ	CMB
23	52.8	2	413	418	584	592
33	39.6	2	413	424	584	600
41	30.6	4	365	381	516	539
61	21.0	4	438	481	619	681
94	13.2	8	413	516	584	729

WMAP (9 year mission)

ν	n_{unpol}	n_{pol}	θ_{fwhm}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz			arcmin	RJ	CMB	RJ	CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

PLANCK (30 month mission)

ν	$(\Delta\nu)$	n_{det}	θ_{fwhm}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz	GHz		arcmin	RJ	CMB	RJ	CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

COrE component separation

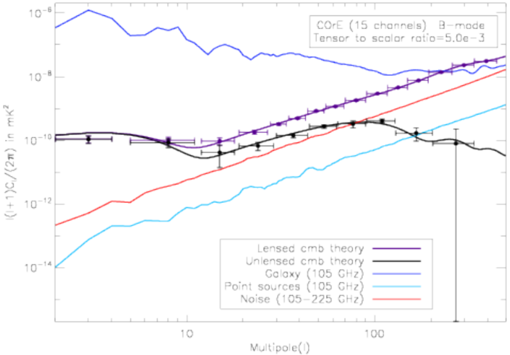


Figure 17: Component separation exercise for B mode detection assuming $(T/S) = 5 \times 10^{-3}$. The solid black curve shows the predicted blackbody B mode power spectrum, which is a combination of the tensor B modes (black curve) and a gravitational lensing background (not shown) making primordial E modes appear partially as B modes. The upper solid blue curve shows the contribution of diffuse galactic emission in one of the 'cleaner' channels (here 105 GHz) after masking. The red curve indicates the instrument noise that would be obtained by combining five CMB channels, and the light blue curve indicates contamination by point sources after the brightest ones ($S > 100$ mJy at 20 GHz and $S > 500$ mJy at 100 microns) have been cut out. The purple data points indicate the recovered raw primordial spectrum measurements, as compared to the theoretical spectrum (purple line). The black points result after the gravitational lensing contribution has been removed, leaving only the recovered tensor contribution. Here mask 2 (an apodised, galactic cut with $f_{sky} \simeq 0.70$) has been used.

Inflationary models

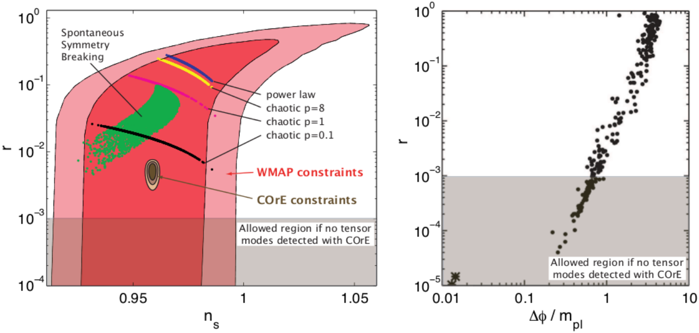


Figure 3: **Constraints on inflation from COrE.** For a broad range of inflationary models COrE can be expected to detect primordial gravitational waves from inflation. The large contours on the left panel show the present constraints from WMAP seven-year data in the r-n_S plane. A few parameterized families of inflationary models give an idea of representative model predictions. The small contours illustrate what a COrE detection would look like if $r > 5 \times 10^{-3}$. The part of parameter space still allowed at 2σ in the case of a non-detection is shown in grey. The right panel shows the 'main sequence' of inflationary models generated using a model independent approach.

Summary of low-r option : disovery of B modes from inflation

- This option assumes that the BICEP2 claimed detection is explaned by an underestimated contribution from galactic foregrounds or unaccounted systematic errors. Until a confirmation from another experiment is in hand, this option cannot be excluded.
- Under this option the mission design objective is to maximize the discovery potential. This means having exquisite raw sensitivity accompanied by corresponding control over systematic errors and observing over mutiple channels to allow accurate removal galactic and other foreground contaminants.

Scenario II : Precision characterization of $c_{BB,tensor}$ with $r \approx 0.1 - 0.2$

Probing consistency of inflationary paradigm

$$\epsilon \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}\left(\frac{d\ln V(\phi)}{d(\phi/M_{\rm Pl})}\right)^2, \qquad \eta \equiv M_{\rm Pl}^2 \frac{V''}{V} = \frac{d^2 \ln V(\phi)}{d(\phi/M_{\rm Pl})^2} - 2\epsilon$$

$M_{\rm Pl} = (8\pi G)^{-1/2} = 2.4 \times 10^{18}$ GeV

Scalar perturbations cannot measure the height of the potential

$$A_S(k) = \frac{2}{5}\mathcal{P}_R^{1/2}(k) \approx \frac{\epsilon^{-1/2}}{5\pi\sqrt{3}} \left.\frac{V^{1/2}(\phi)}{M_{\rm Pl}^2}\right|_{k=a(\phi)H(\phi)}, \qquad n_S \equiv 1 + \frac{d\ln A_S^2(k)}{d\ln k} \approx 1 + 2\eta - 6\epsilon.$$

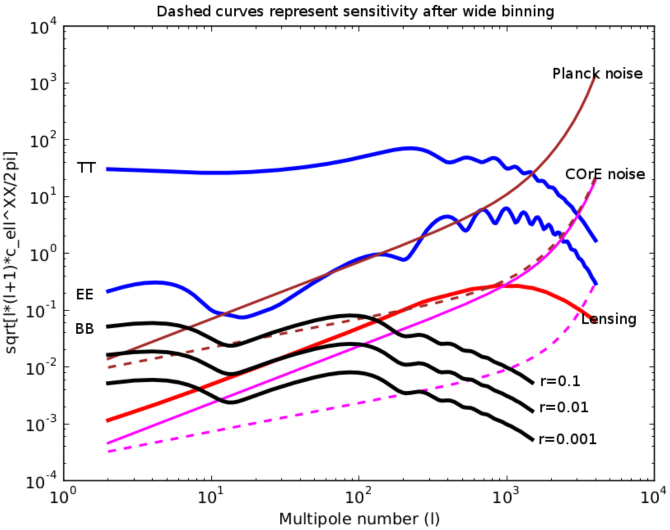
Tensor perturbations (i.e., gravitational wavesi generated during inflation) measure the height of the potential

$$A_T(k) \equiv \frac{1}{5\sqrt{2}}\mathcal{P}_{gw}^{1/2} \approx \frac{1}{5\pi\sqrt{3}} \left.\frac{V^{1/2}(\phi)}{M_{\rm Pl}^2}\right|_{k=a(\phi)H(\phi)}, \qquad n_T \equiv \frac{d\ln A_T^2(k)}{d\ln k} \approx -2\epsilon$$

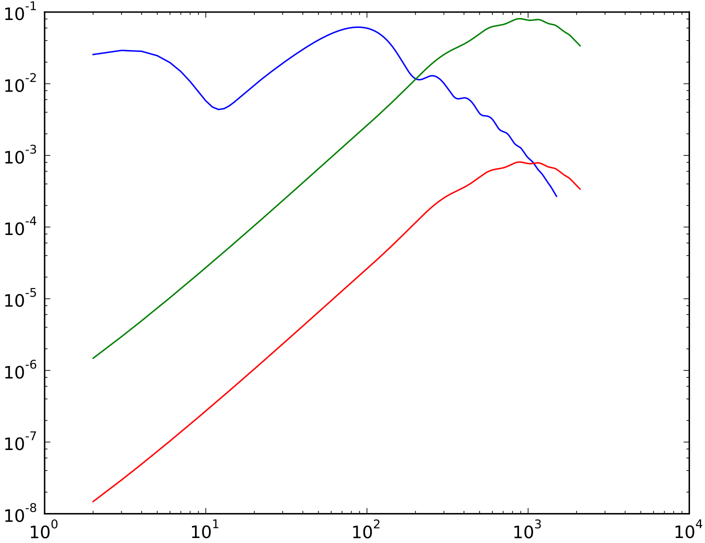
Consistency condition

$$r = T/S \equiv \frac{\mathcal{P}_{gw}}{\mathcal{P}_R} = 16\frac{A_T^2}{A_S^2} \approx 16\,\epsilon = -8\,n_T\,,$$

Planck and COrE sensitivities



What if we could clean 90% of the lensing noise?



Conclusions :

- CMB observations has an exciting future and the best is likely still ahead, regardless of the outcome of the BICEP2 debate
- The BICEP2 foreground debate highlights the need to complement a vigorous ground and balloon based observing program with observations from space, where many more frequency bands can be accessed and the stable conditions needed for the control of systematic errors are present.
- COrE+ is an exciting European medium-class space mission to search for B modes and do an host of other interesting science.
- Here COrE+ and its European predecessors have been emphasized. But there exist a number of exciting competing/complementary initiatives in the US and Japan (LiteBIRD, Pixie, EPIC, CMB Stage 4)

Lensing science and delensing

Gravitational lensing spectrum : COrE vs Planck

From COrE White Paper (astro-ph/1102.2181

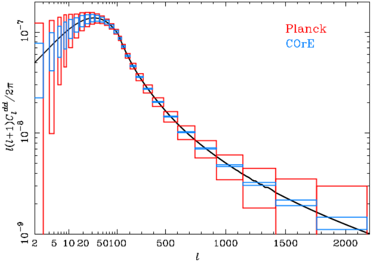


Figure 6: **COrE vs PLANCK for measuring the lensing power spectrum**. Bandpower errors are plotted (including cosmic variance) on the deflection power spectrum from PLANCK (24 months; red) and COrE (blue) using lens reconstruction with temperature and polarization (no iteration). With COrE, the power spectrum is cosmic-variance limited to $l \approx 500$.

Lensing reconstruction noise

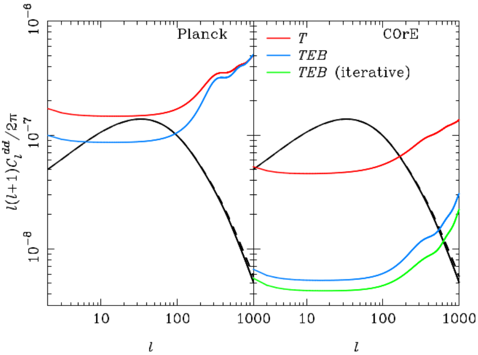


Figure 5: **Lensing reconstruction noise** on the deflection power spectrum for an extended PLANCK mission (24 months; left) and COrE (right) using temperature alone (red) and temperature and polarization (blue). For COrE, we also show the approximate noise level (green) for an improved iterative version of the reconstruction estimator following Ref. [30]. The deflection power spectrum is also plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). The maximum multipole used in the reconstruction is $l_{\max} = 2500$.

Measuring absolute neutrino masses with COrE

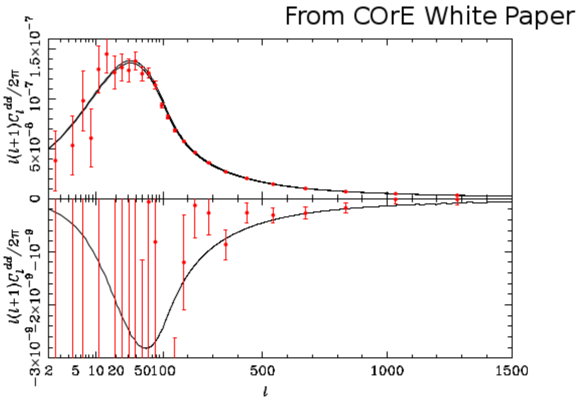


Figure 7: **Gravitational lensing deflection power spectrum.** The simulated deflection power spectrum from COrE is shown assuming an inverted hierarchy of neutrino masses with the minimum total mass allowed by oscillation data ($m_1 \approx m_2 = 0.05\,\mathrm{eV}$ and $m_3 = 0\,\mathrm{eV}$). In the upper panel, the solid lines are the theory power spectrum for this scenario (lower) and for three massless neutrinos (upper). The difference between these spectra is plotted in the lower panel illustrating how COrE can distinguish these scenarios from C_l^{dd} in the range $l > 200$. We have assumed 70% sky coverage after Galactic masking.

What it takes to measure neutrino masses

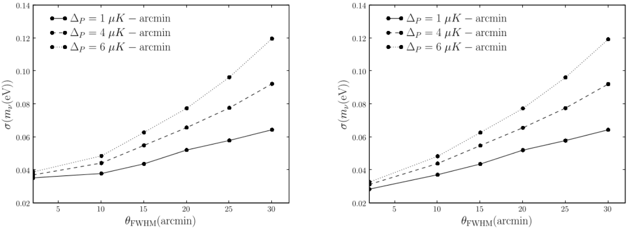


Figure 5: Uncertainty $\sigma(m_\nu)$ on the neutrino mass as a function of beam size and noise level for $\ell_{\max} = 2000$ (left panel) or $\ell_{\max} = 4000$ (right panel) using CMB lens reconstruction, assuming fixed w, Ω_K.

From: CMBPol Mission Concept Study: Gravitational Lensing