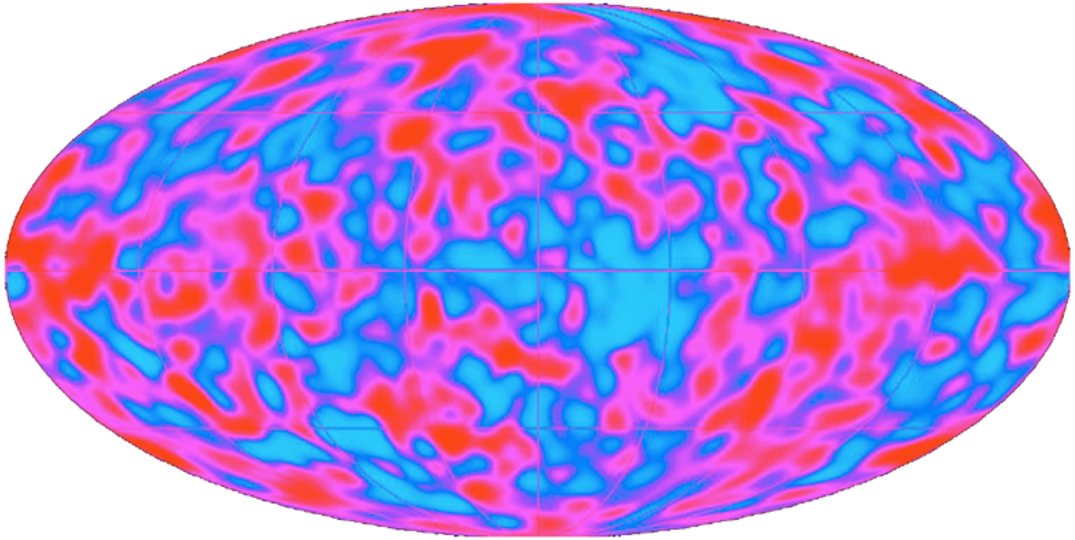
The Microwave Background



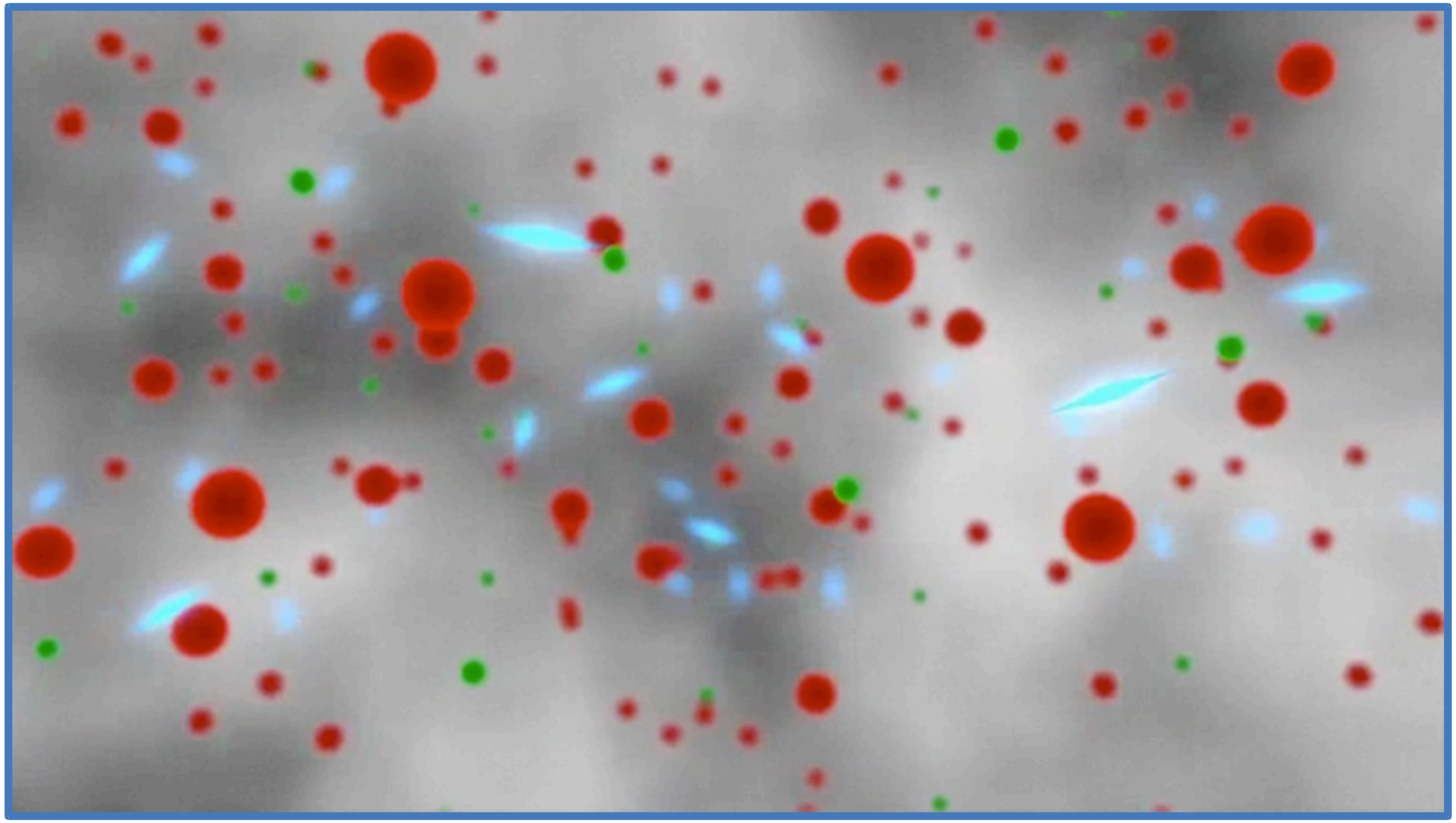
Ken Ganga

- Basics & History
- As of 2013
- B-Modes
- Future

KEN.GANGA@APC.UNIV-PARIS-DIDEROT.FR

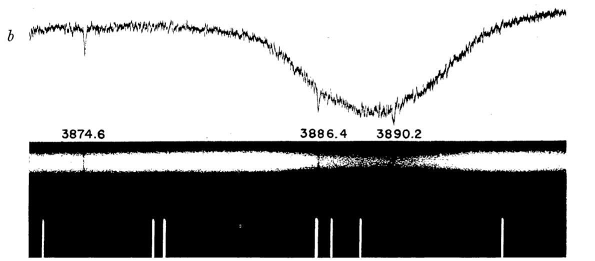
A Photon's Odyssey

In the early Universe, photons are tightly coupled to the hot, charged, plasma and thus provide an image of the Universe at the moment when it cools to the point where electrons and protons combine.



What we see is this image after processing by stuff between us and its creation, mixed with emission from other astrophysical sources.

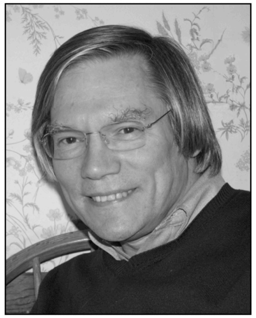
A History of the CMB in One Slide



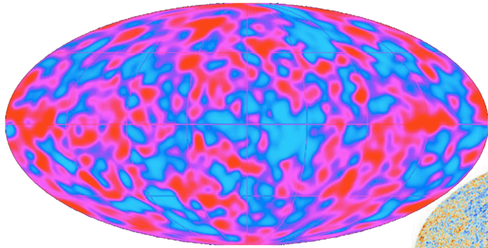
INTERSTELLAR LINES

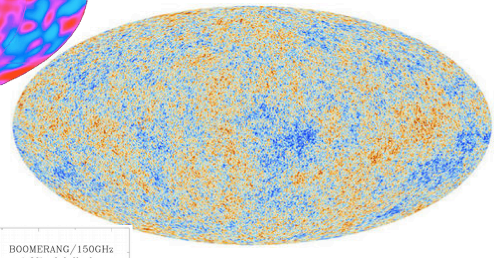
a) α Cygni showing interstellar H and K superposed upon stellar lines; b) ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of *CH* are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably *CN*.

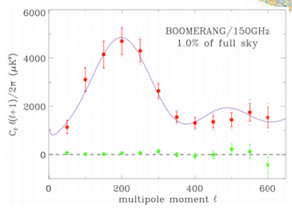
Alexei Starobinsky
b. 1948

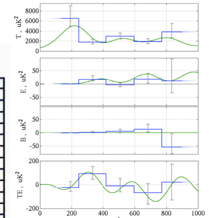


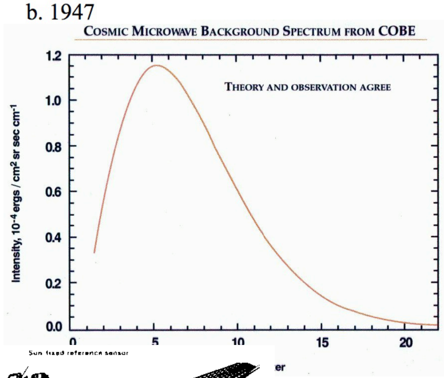
Alan Guth
b. 1947

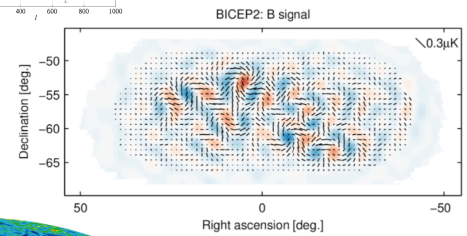




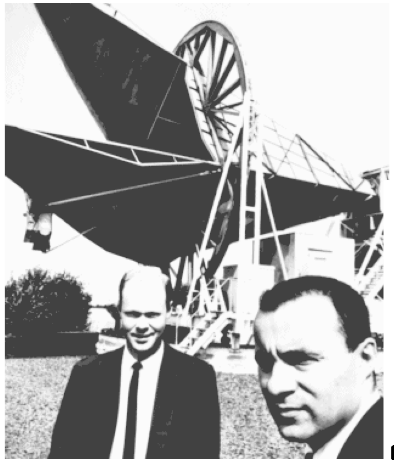


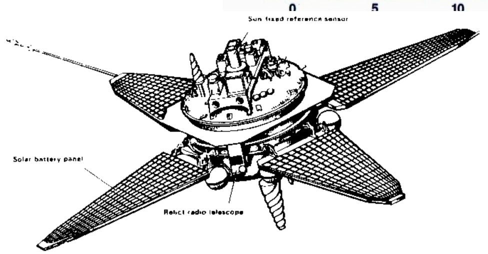




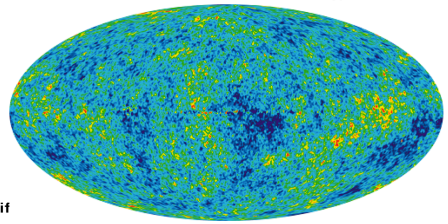


With apologies to most of the field for omissions...



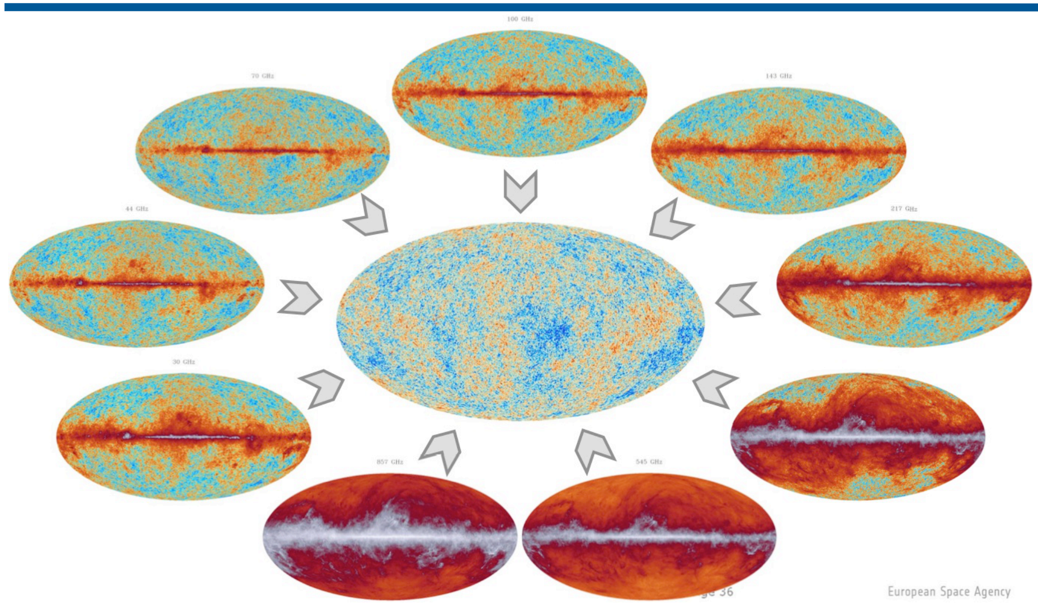


http://rammb.cira.colostate.edu/dev/hillger/Prognoz-9_sketch.gif
Prognoz 9's Relikt 37GHz radiometer



1940 1950 1960 1970 1980 1990 2000 2010 2020

Planck and Cosmological Parameters



Planck collaboration: CMB power spectra & likelihood

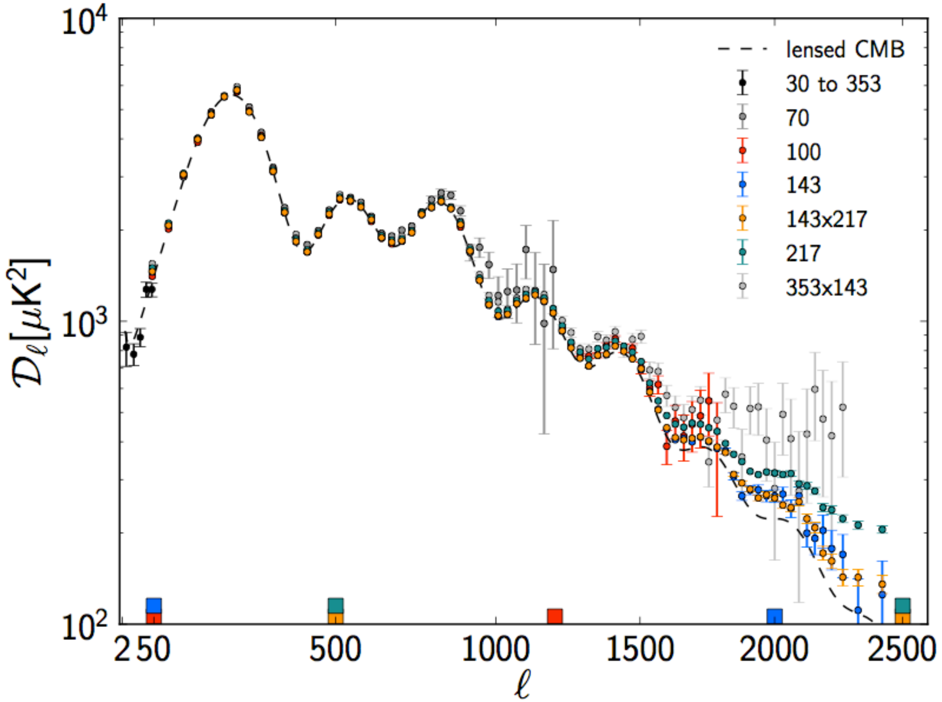


Figure 11. *Planck* power spectra and data selection. The coloured tick marks indicate the ℓ-range of the four cross-spectra included in CamSpec (and computed with the same mask, see Table 4). Although not used, the 70 GHz and 143 x 353 GHz spectra demonstrate the consistency of the data. The dashed line indicates the best-fit *Planck* spectrum.

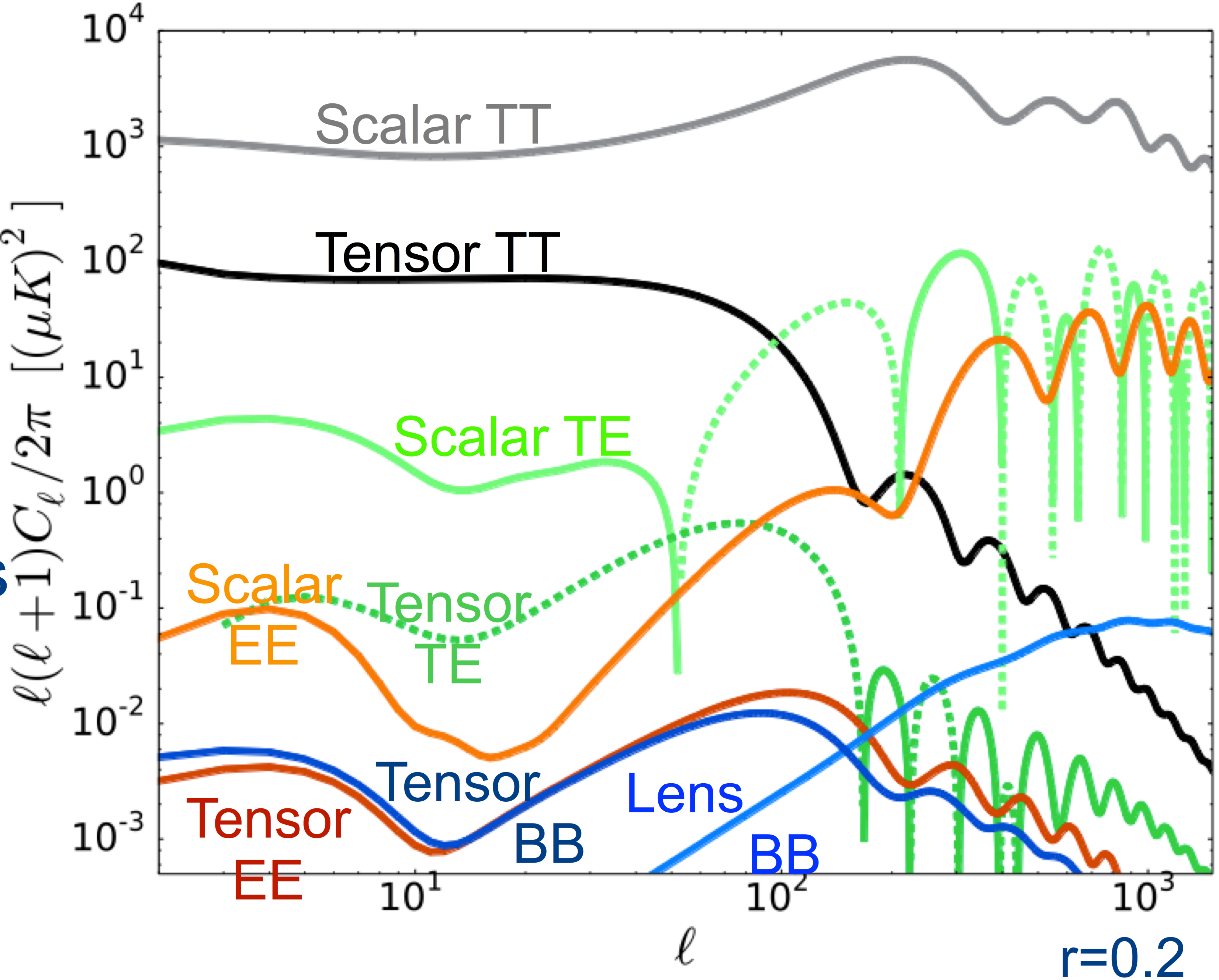
	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8347	0.829 ± 0.012
z_{re}	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09591	0.09589 ± 0.00057
Y_P	0.247695	0.24770 ± 0.00012
Age/Gyr	13.8242	13.817 ± 0.048
z_*	1090.48	1090.43 ± 0.54
r_*	144.58	144.71 ± 0.60
$100\theta_*$	1.04136	1.04147 ± 0.00062

And more!

The CMB Spectra Zoo

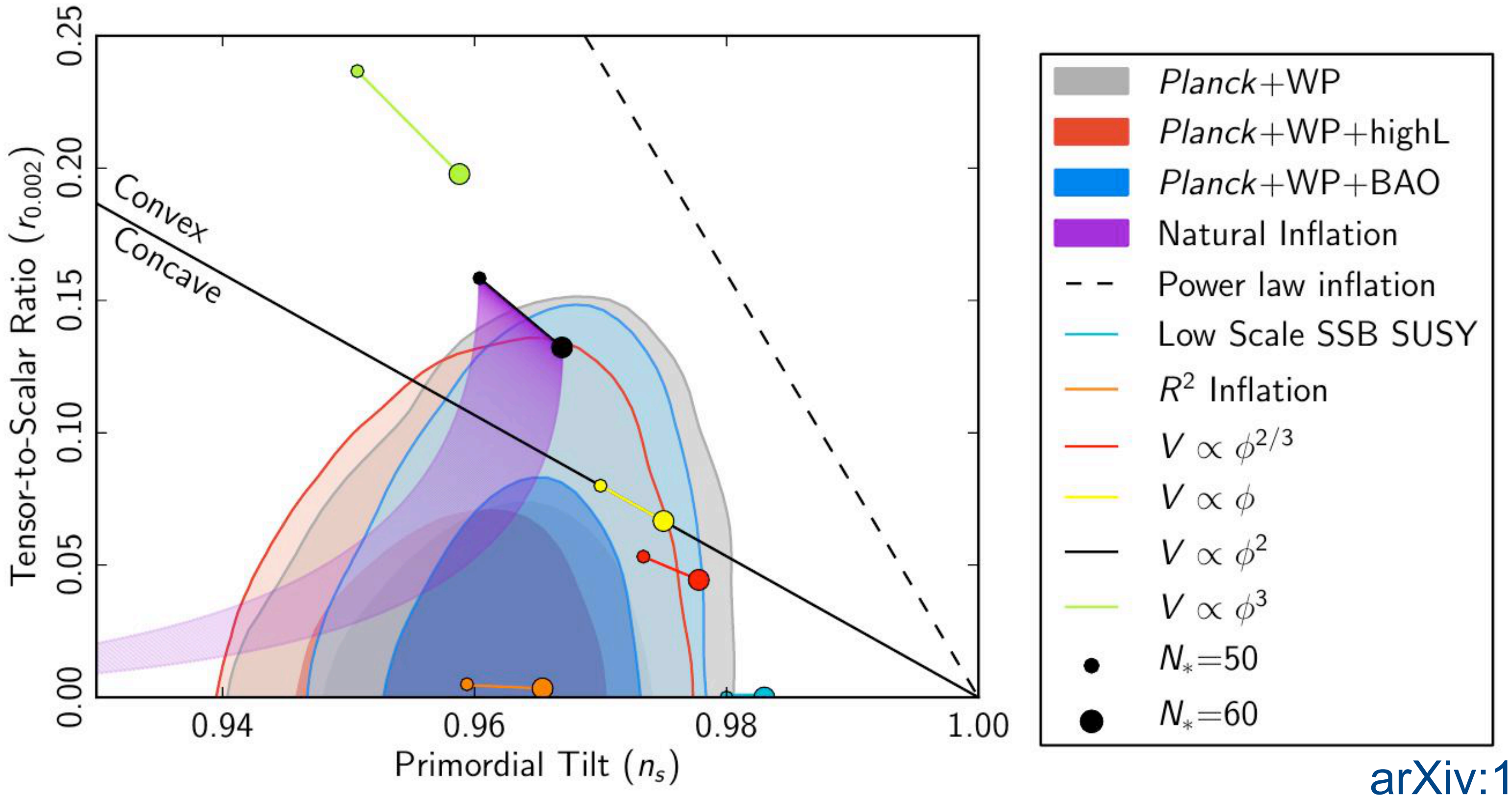
Scalar & Tensor TT, TE, EE & BB Spectra

'r' quantifies the fraction of scalar power in tensors



Inflation

- n_s = 0.9603 ± 0.0073 (Note: n_s<1 at >5σ)
- Tensor-to-scalar ratio: r<0.11
  - In the future, with polarization, we hope to be able to reduce this to ~0.05
- B-Mode Polarization will allow us to improve limits on "r"



arXiv:1303.5082

Differences with Others'

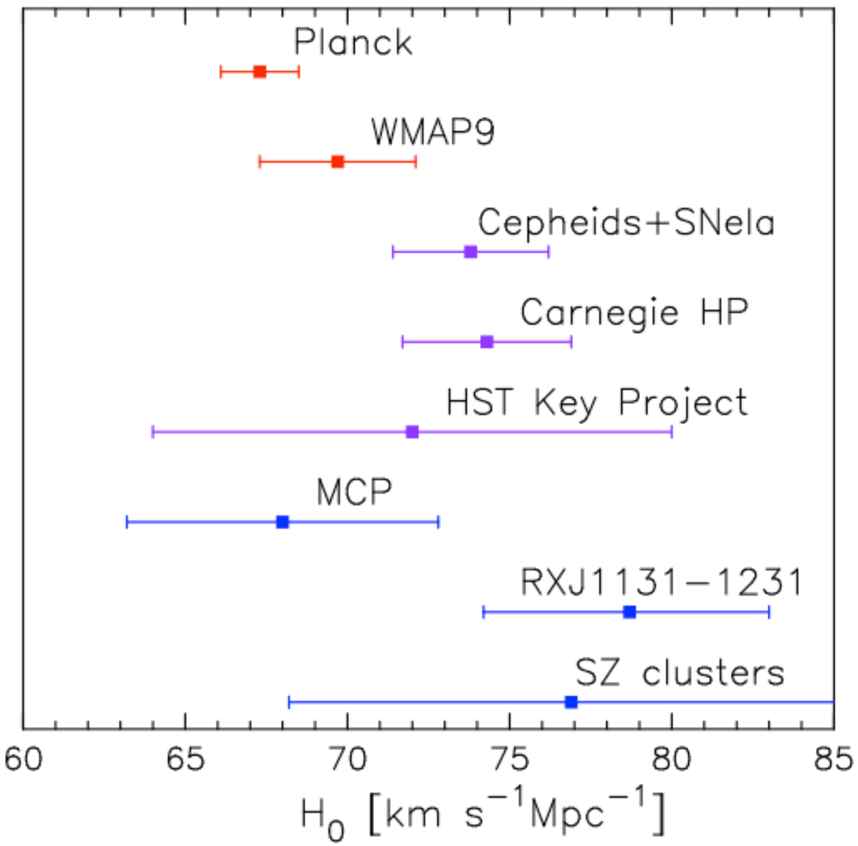


Fig. 16. Comparison of H_0 measurements, with estimates of $\pm1\,\sigma$ errors, from a number of techniques (see text for details). These are compared with the spatially-flat ΛCDM model constraints from *Planck* and *WMAP*-9.

Significant differences between local and distant measures might point towards new physics – but evidence for this is limited.

Ω_m and H_0 are degenerate so a deviation in one will be accompanied by a deviation in the other.

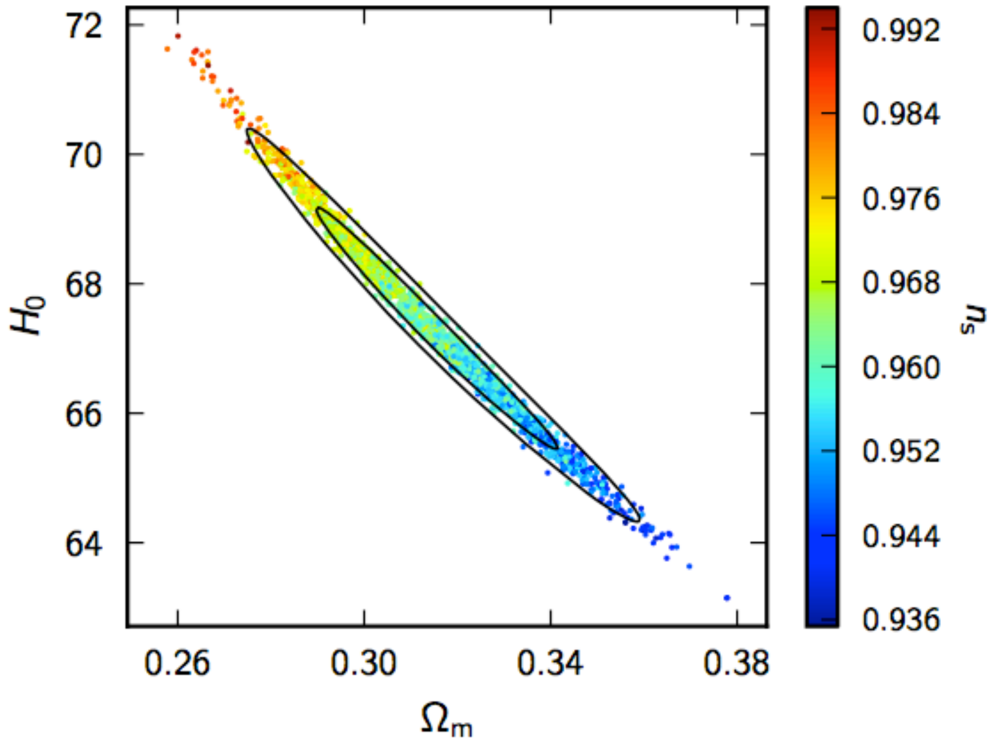
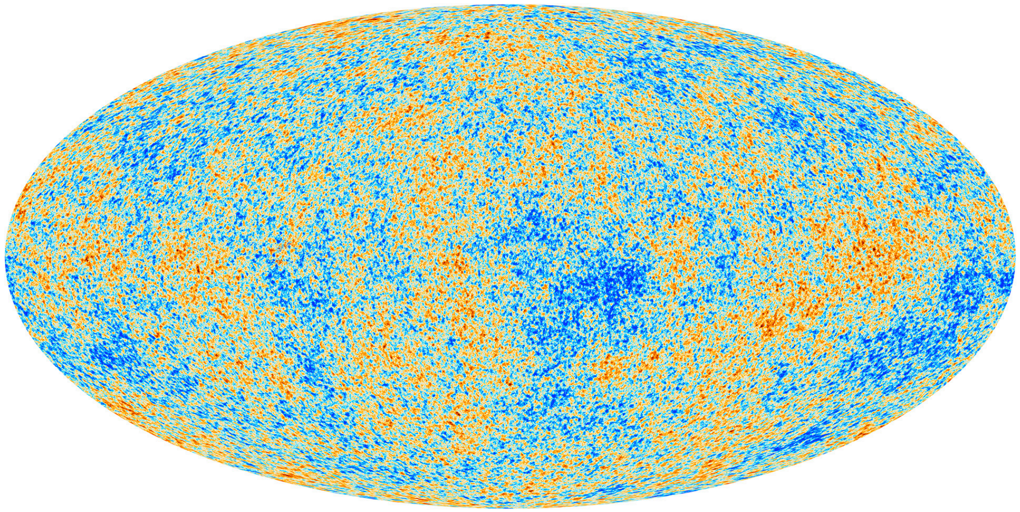


Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including WP, but the well-constrained direction of constant $\Omega_m h^3$ (set by the acoustic scale), is determined almost equally accurately from *Planck* alone.

“Anomalies”



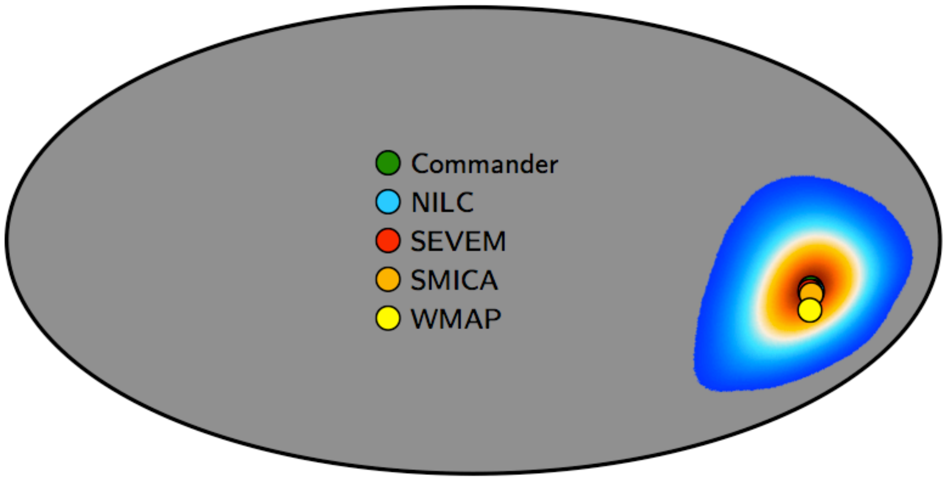
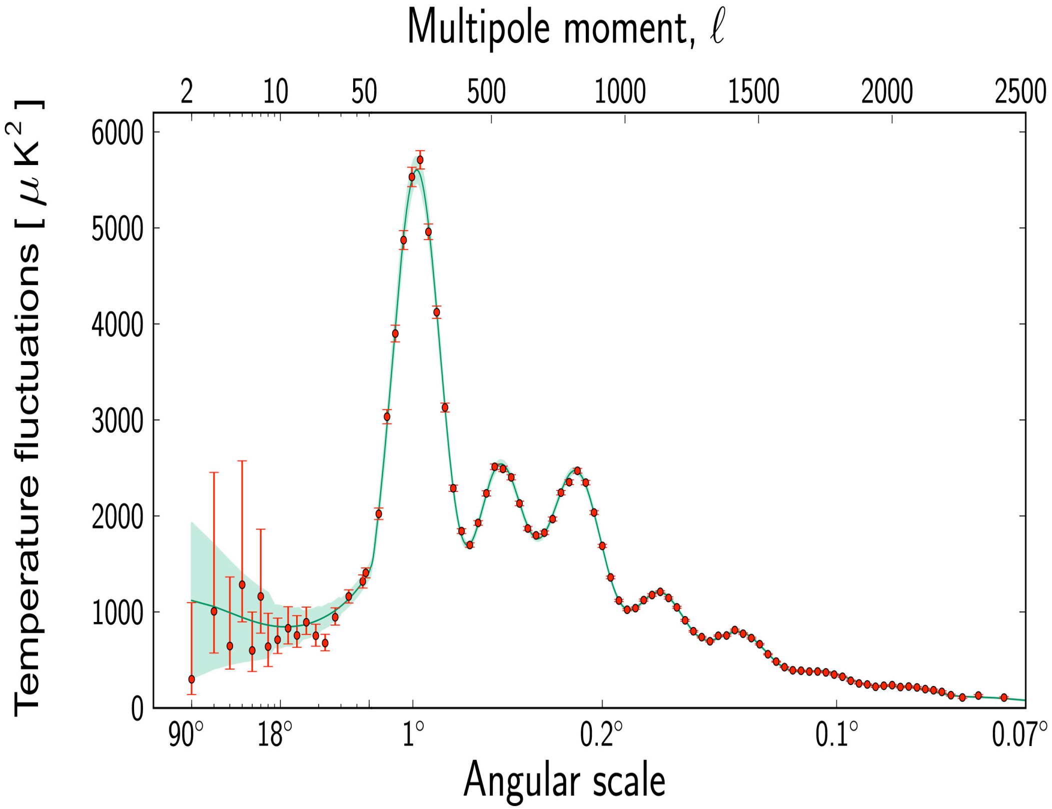


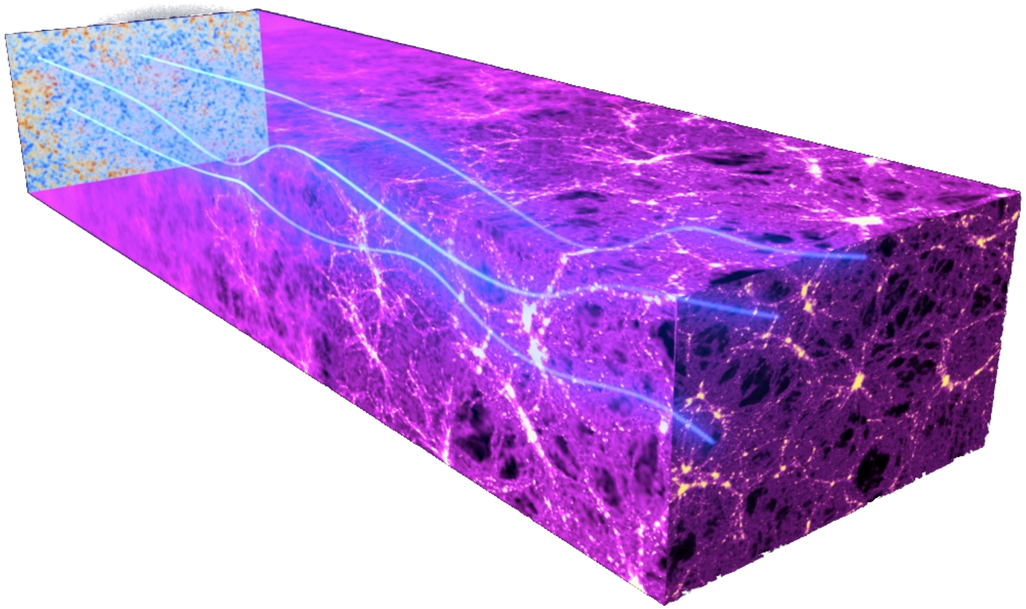
Fig. 32. Consistency between component separation algorithms as measured by the dipole modulation likelihood. The top panel shows the marginal power spectrum amplitude for the 5° smoothing scale, the middle panel shows the dipole modulation amplitude, and the bottom panel shows the preferred dipole directions. The coloured area indicates the 95% confidence region for the `Commander` solution, while the dots shows the maximum-posterior directions for the other maps.

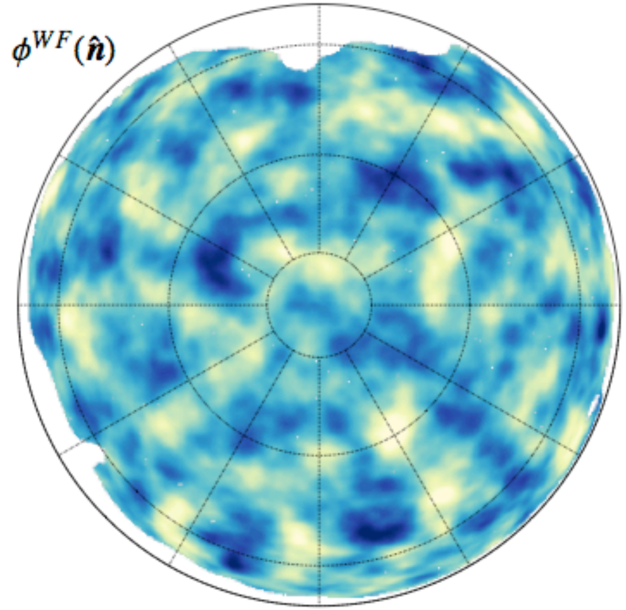


- There are a few ~2-sigma “features” in the CMB maps from COBE, WMAP and now Planck that have intrigued people

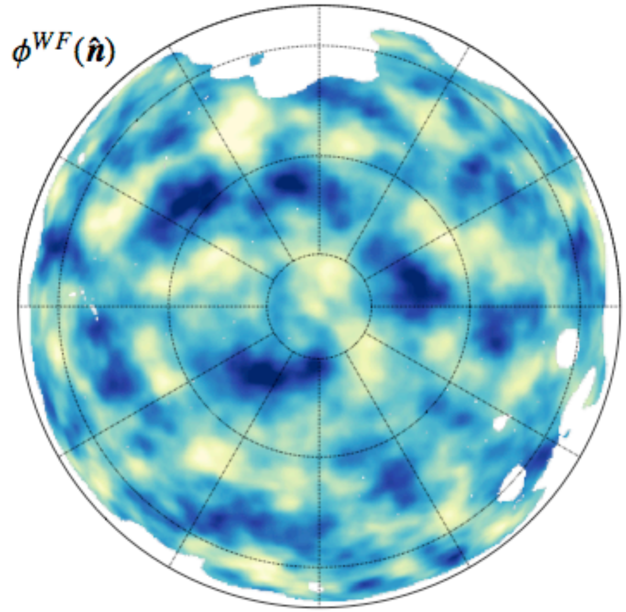
Lensing

- Planck has taken a census of all the material in the Universe
- Note that these maps are noise dominated – they are similar to early *COBE*/DMR maps.
- arXiv:1303.5077





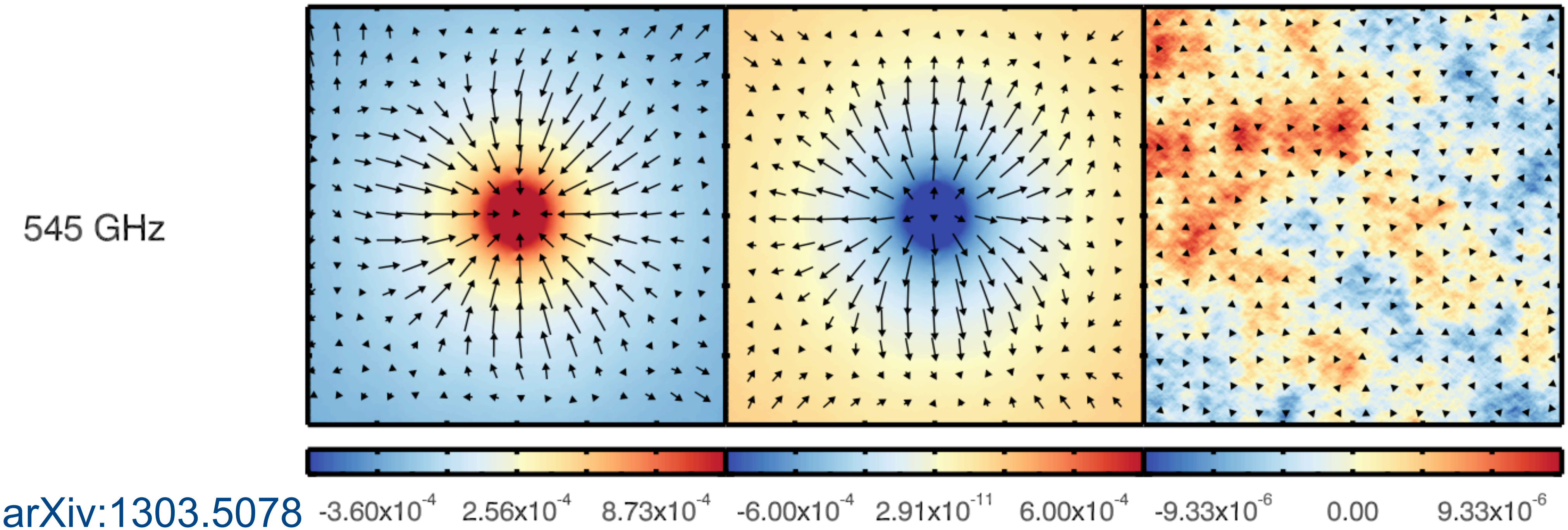
Galactic North



Galactic South

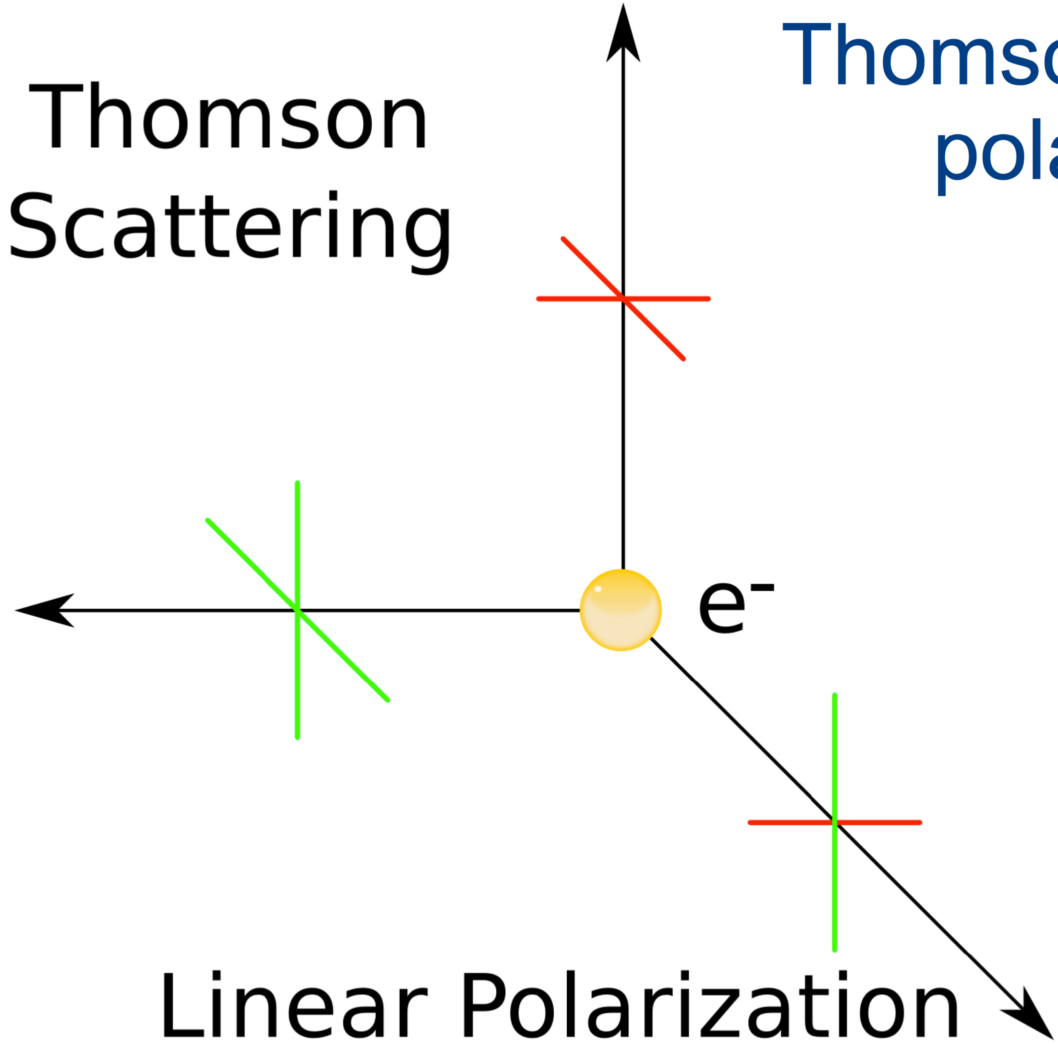
CIB-Lensing Correlations

- The Cosmic Infrared Background (CIB) is the remnant of star formation, much of it around z~2.
  - Here, think of it as a tracer of dark matter.
- This material lenses the CMB
- A lensing/CIB cross-correlation shows this:

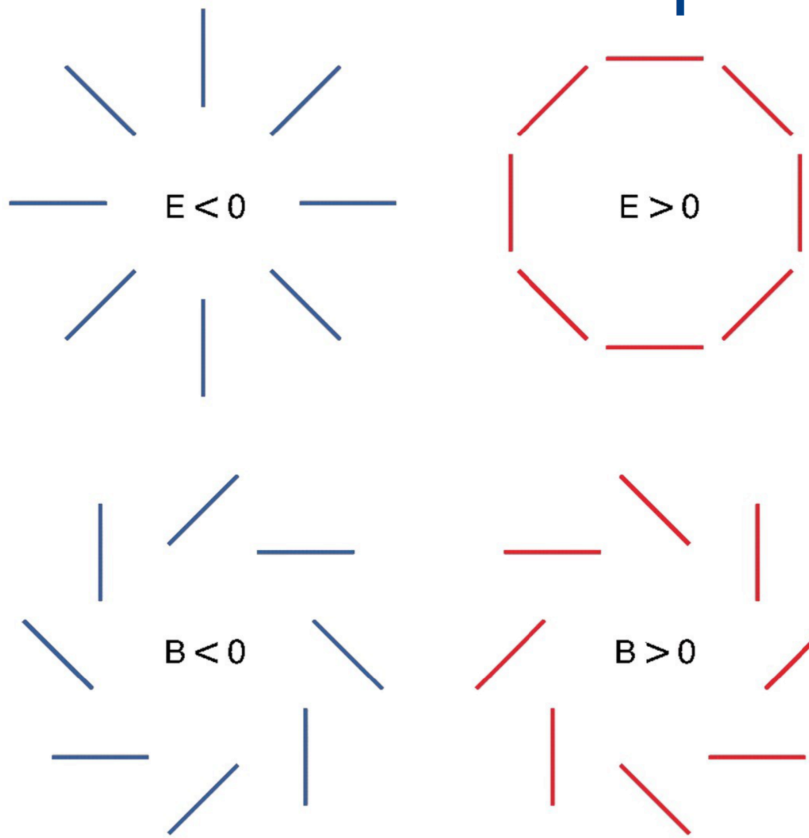


arXiv:1303.5078

“E” and “B” Mode Polarization



Thomson scattering leads to some polarization with a “symmetric” pattern.



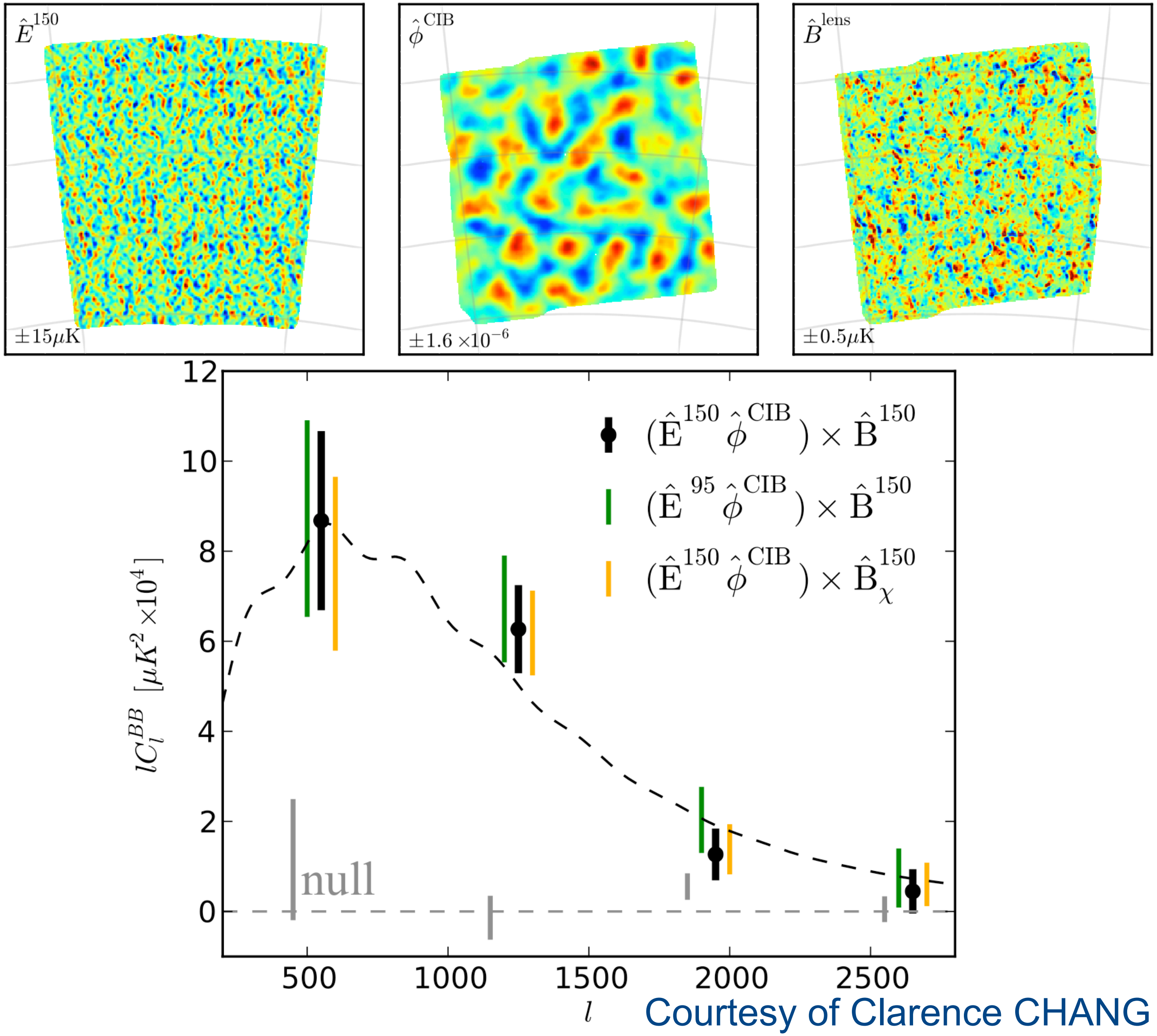
http://www.sciencemag.org/content/328/5981/989/F3.large.jpg

Gravitational waves and lensing break the symmetry to create the asymmetric pattern – B-modes

SPT Lensing B-Mode Detection

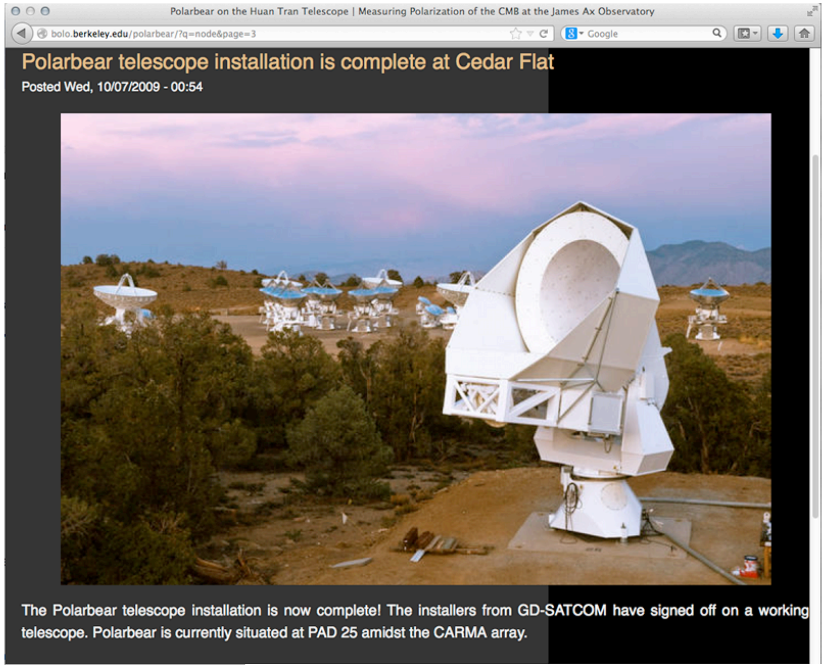
The first B-mode detection was through a cross-correlation between a noisy Bmode map the expected signal from the "infrared background" and measured E-modes.

SPTpol: Hanson et. al., PRL, 111 (2013)



Courtesy of Clarence CHANG

Polarbear, Polarbear2, Simons Array



- First “mega” (kilo, actually) polarization experiment proposed.
- Led by UCBerkeley
- Fielded in Chile
- Taking data now...

POLARBEAR CMB *B*-Mode Power Spectrum 11

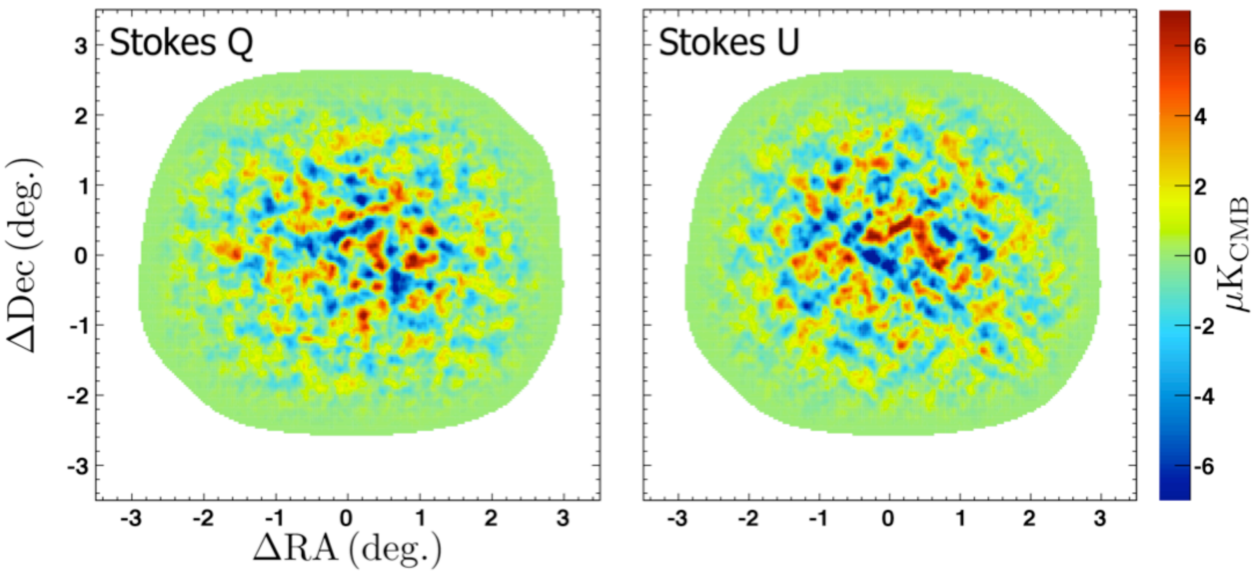
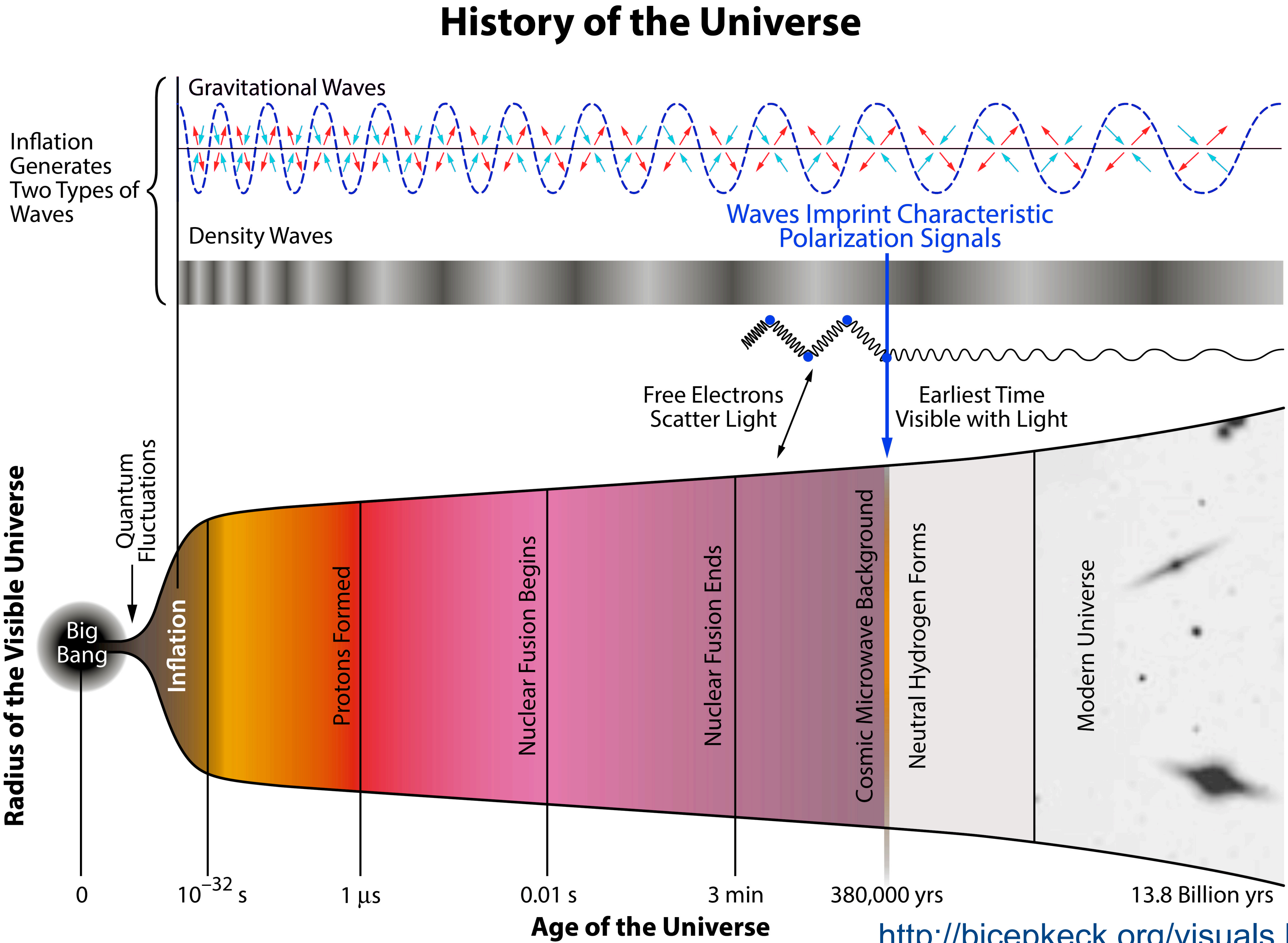


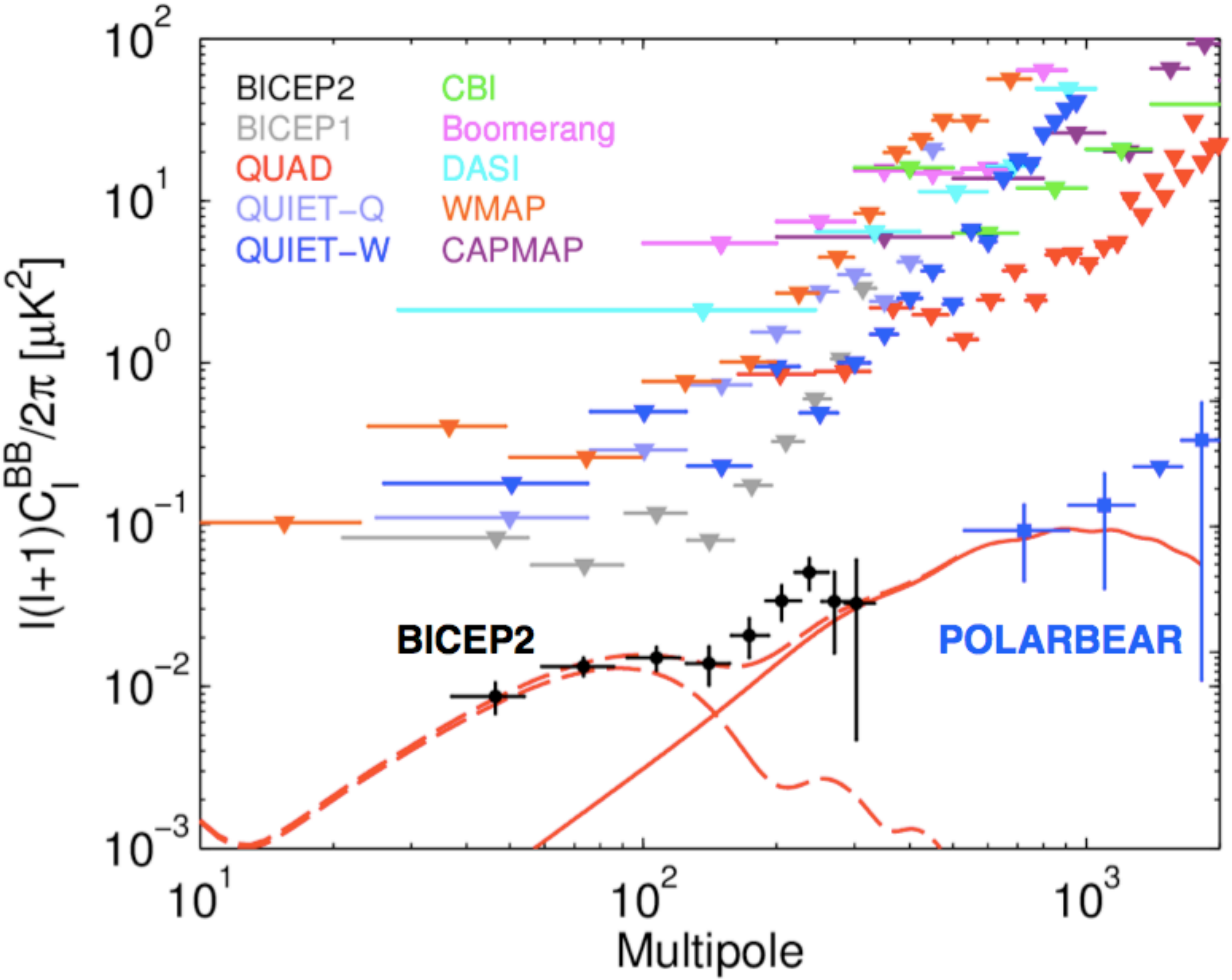
FIG. 6.— POLARBEAR CMB polarization maps of RA23 in equatorial coordinates. The left (right) panel shows Stokes Q (U), where the polarization angle is defined with respect to the North Celestial Pole. These filtered maps are smoothed to 3.5′ FWHM. The clearly visible coherent vertical and horizontal patterns in the Q map and diagonal patterns in the U map are the expected signature of an E-mode signal.

Relic Gravitational Waves – B-Modes



http://bicepkeck.org/visuals.html

BICEP2 Results



BICEP Sees r = 0.2 ?!?!

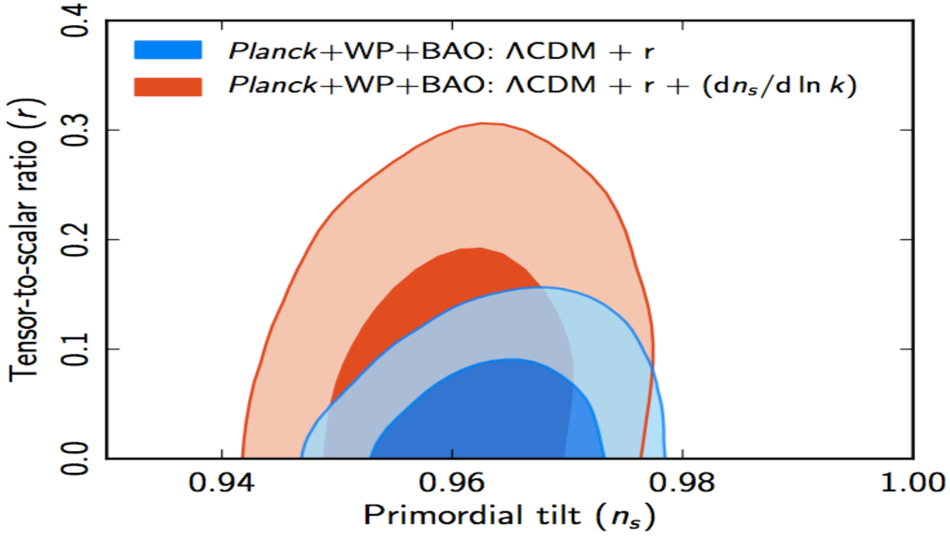
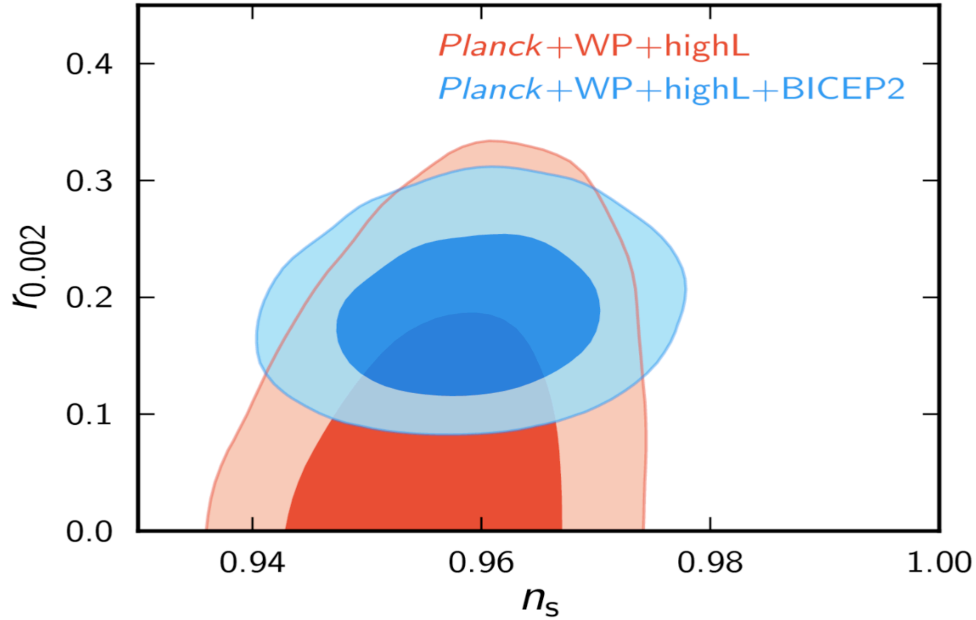


Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.



- "... the fractional contribution of tensor modes is limited to r < 0.13 (95% CL)" -- *Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results (2012)*
- "Planck establishes an upper bound on the tensor-to-scalar ratio of r < 0.11 (95% CL)." -- *Planck 2013 results. XXII. Constraints on inflation*.
- "The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio $r=0.20^{+0.07}_{-0.05}$." -- *BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales (2014)*
- We were looking for a needle in a haystack, but instead we found a crowbar. -- *Clem Pryke*

Exacerbated 'r' Deficit

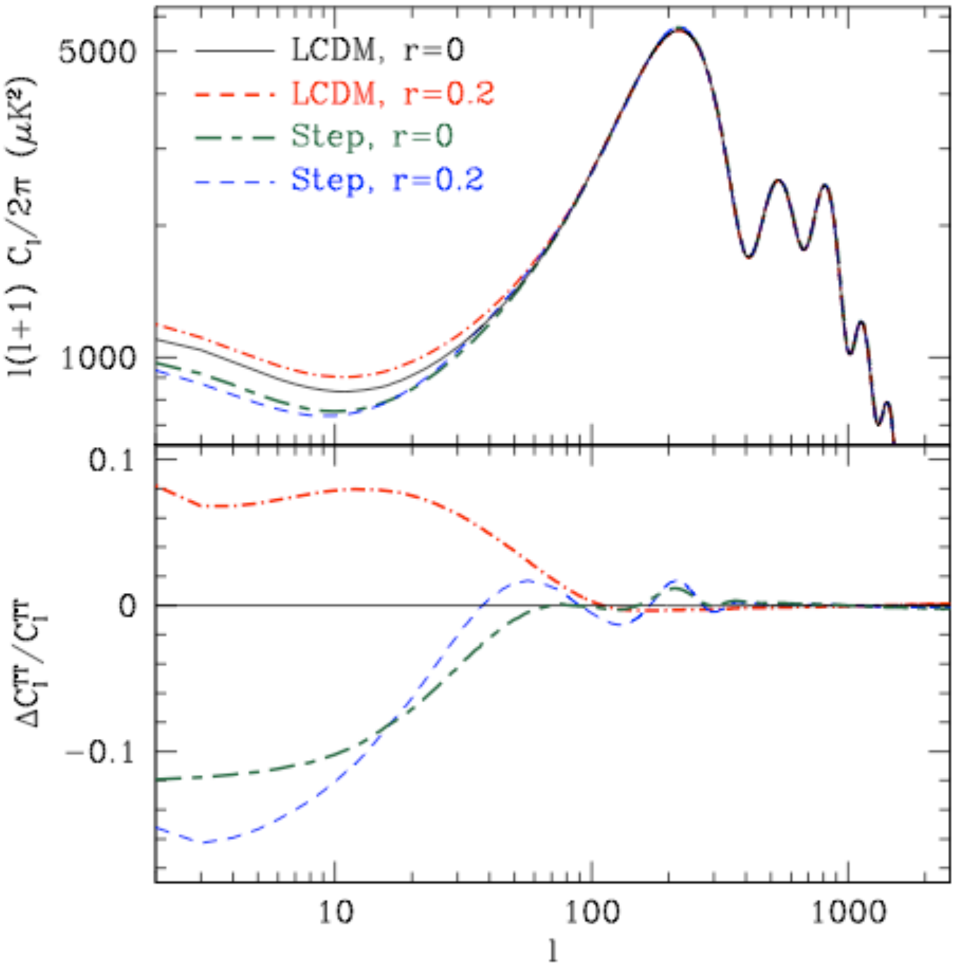
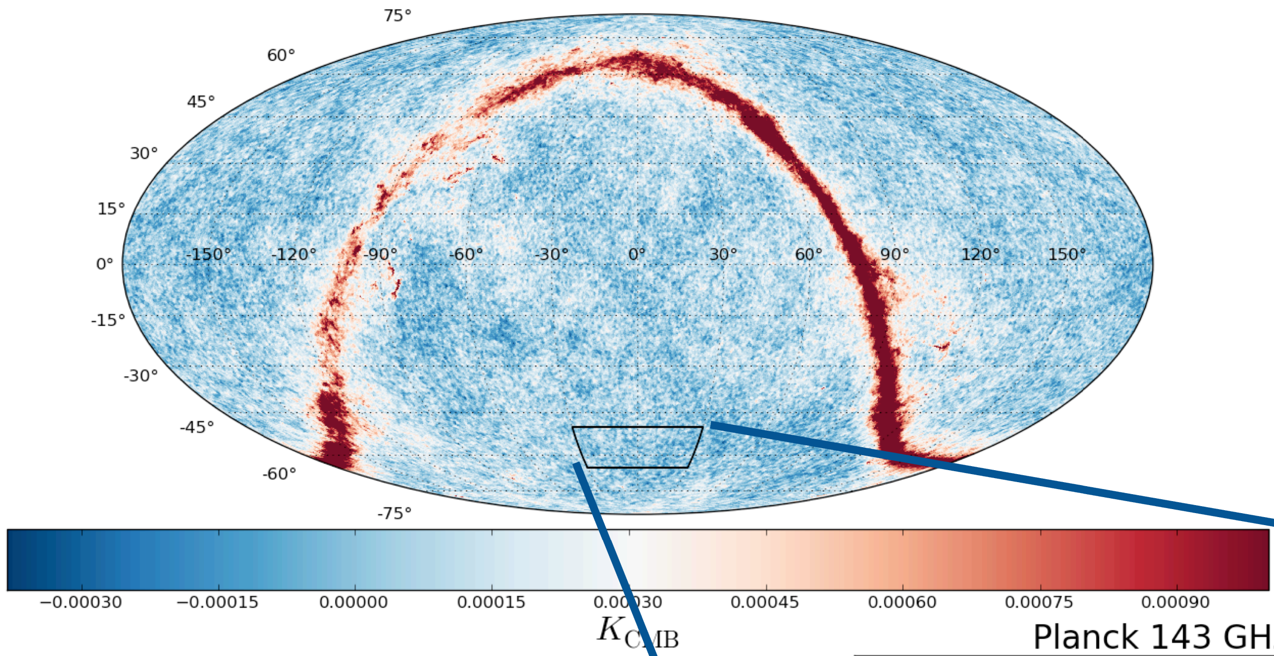


FIG. 1. Total temperature power spectra showing the unobserved excess produced by adding tensors of $r = 0.2$ to the best fit 6 parameter ΛCDM model and its removal by adding a step in the tensor-scalar parameter $\epsilon_H c_s$. Planck data in fact favor removing more power than the tensor excess, preferring a step even if $r = 0$. Step model parameters are given in Tab. I.

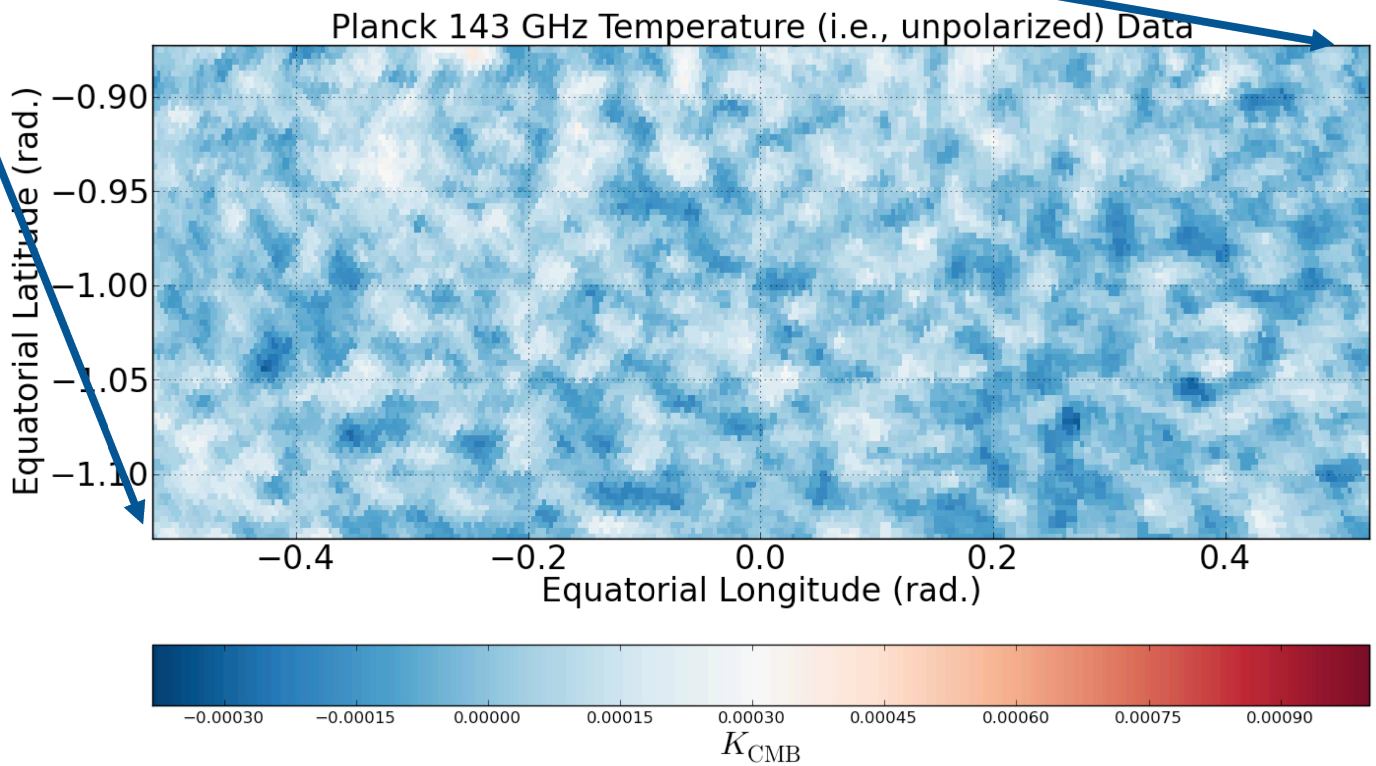
- Spectra fits are usually dominated by the smaller angular scales
- This has led to a small “deficit” at smaller angular scales
- The BICEP2 “r” detection exacerbates this.

Miranda *et al.*; arXiv:1403.5231v2 [astro-ph.CO] 9 May 2014

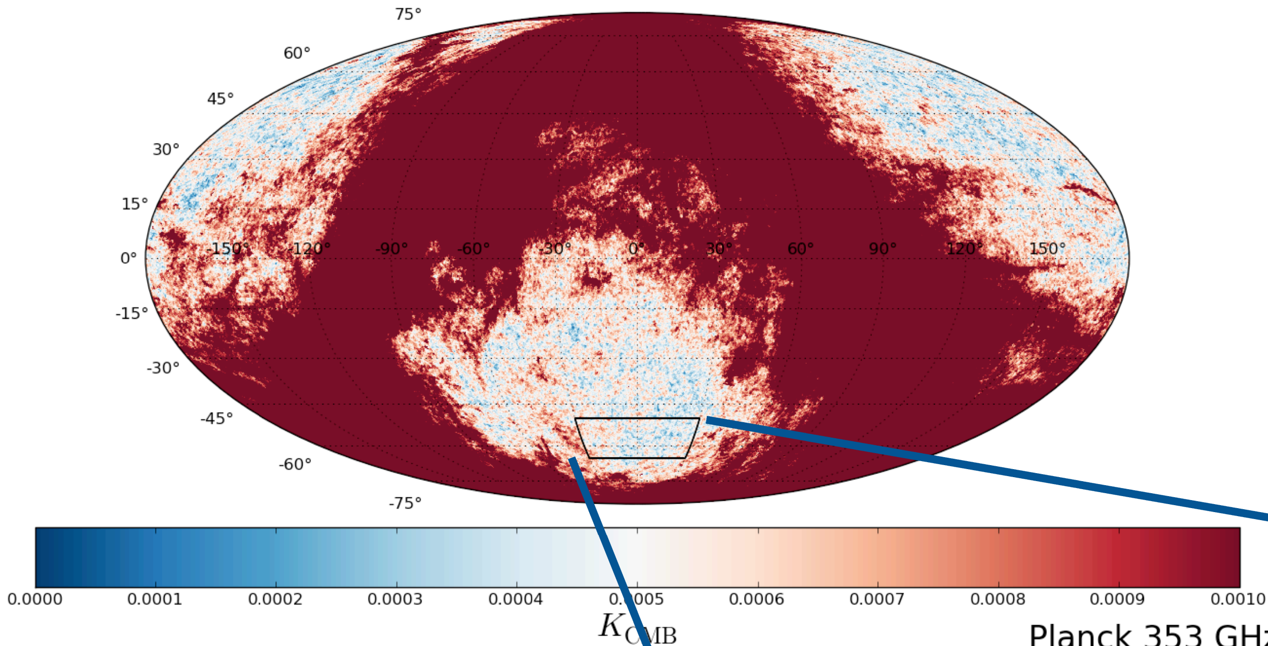
Planck 143 GHz Temperature Map

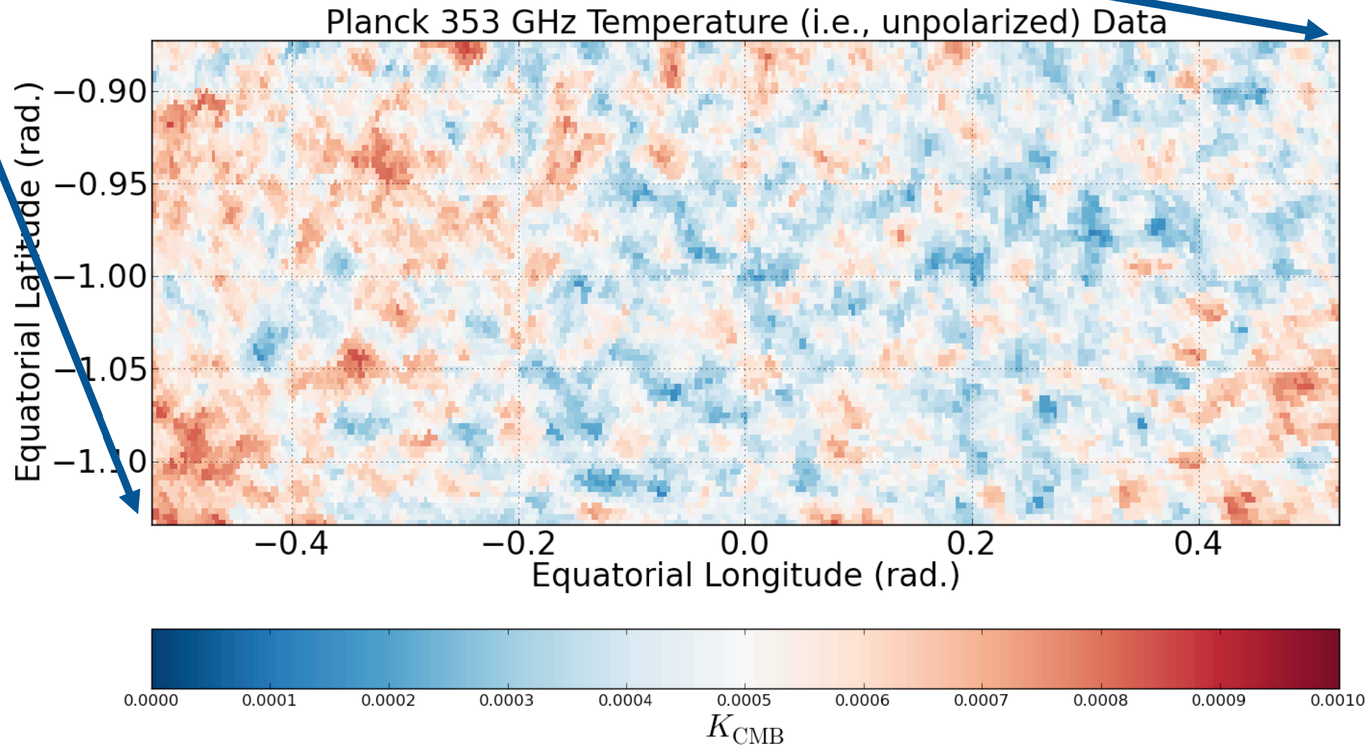


This is a *temperature* map. The analysis for *polarization* is ongoing.



Planck 353 GHz Temperature Map





This is a *temperature* map. The analysis for *polarization* is ongoing.

What Planck is Working on Now

Stokes Q & U at 353 GHz from Planck

Planck collaboration: The *Planck* dust polarization sky

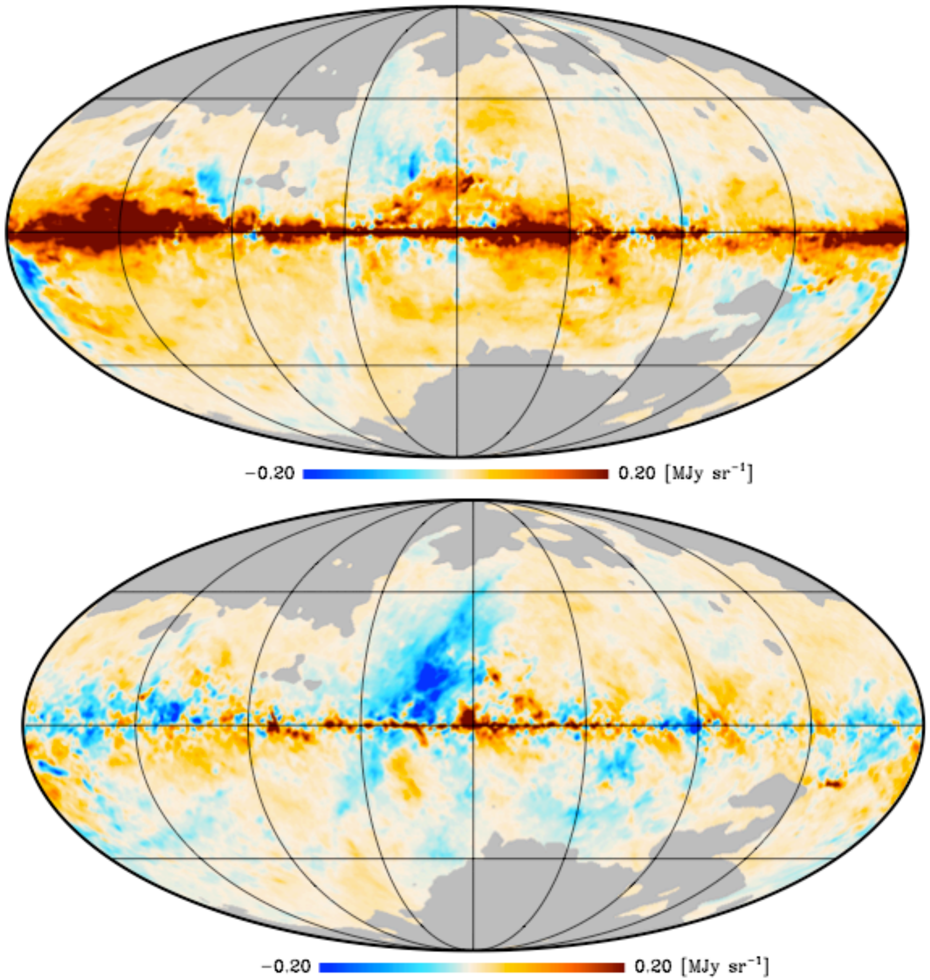


Fig. 1. *Planck* 353 GHz polarization maps at 1° resolution. *Upper*: *Q* Stokes parameter map. *Lower*: *U* Stokes parameter map. The maps are shown with the same colour scale. High values are saturated to enhance mid-latitude structures. The values shown have been bias corrected as described in Sect. 2.3. These maps, as well as those in following figures, are shown in Galactic coordinates with the galactic center in the middle and longitude increasing to the left. The data is masked as described in Sect. 2.4.

arXiv:1405.0871v1 [astro-ph.GA] 5 May 2014

- BICEP has more sensitivity than Planck in their field at 150 GHz
- BUT, Galactic dust is MUCH brighter at 353 GHz than at 150 GHz
- Planck should be able to say much about polarized dust contamination over the full sky, and over the BICEP2 field

PILOT Advertisement

- Balloon to measure linear polarization of Galactic dust emission at 240 & 550 microns (<Planck;10-50 times more sensitive than for dust)
- Initially Galactic Plane observations, but coverage of CMB fields possible.
- Flight readiness review in autumn; 1st flight in 2015.

J.P. Bernard

Can Planck Confirm BICEP2 Directly?

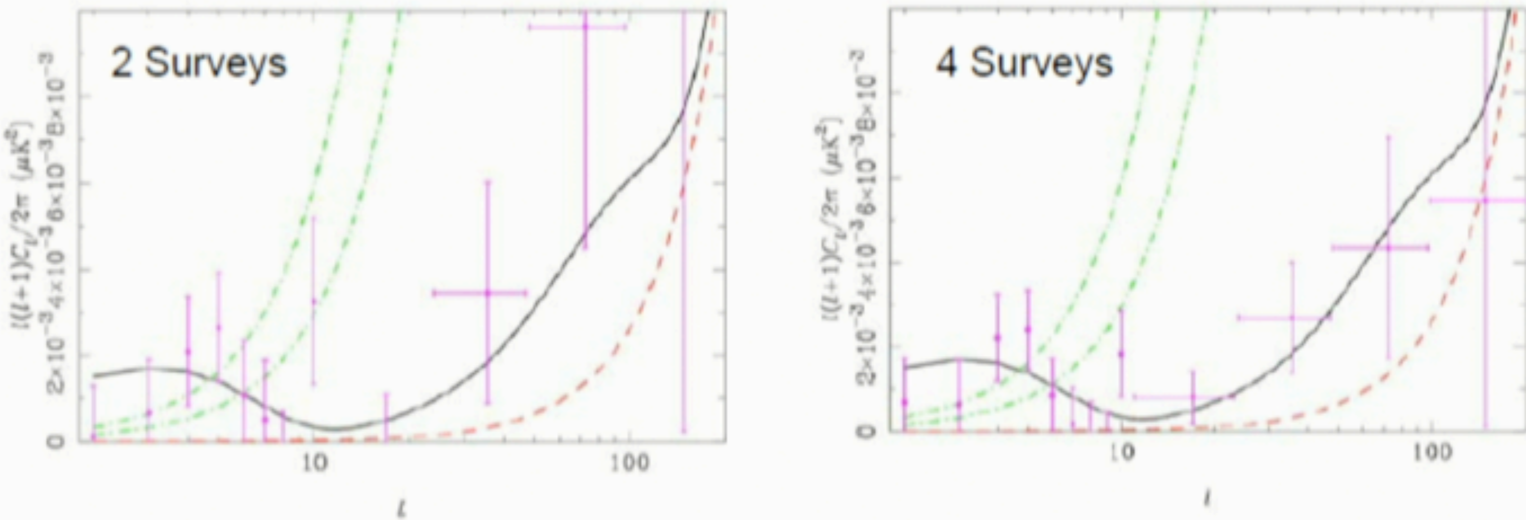


***Figure 2**: The purple points show the results of B-mode recovery from Planck with two sky surveys (left) and four sky surveys (right). An input value of r = 0.05 has been assumed in these simulations. The black lines show the theoretical B-mode spectrum. The dot-dashed green lines show the instrumental noise spectra for two and four surveys. The dashed red lines show the B-mode signal from lensing of E-modes by intervening large-scale structure. A detection of a B-mode with r ~ 0.05 is marginal with two sky surveys but statistically highly significant with four sky surveys.*

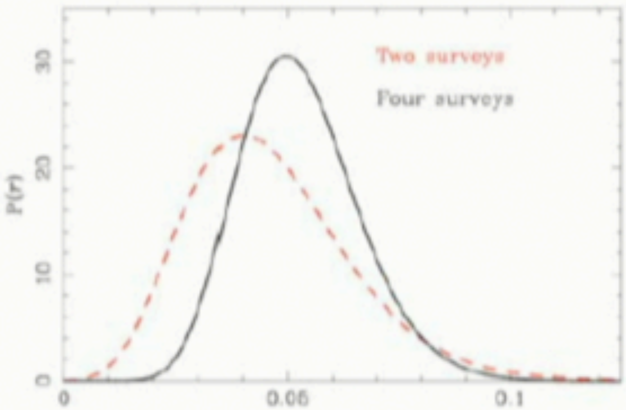


***Figure 3**: Marginalised likelihoods for the tensor-scalar ratio, r, for two Planck sky surveys (red dashed line) and four Planck sky surveys (black solid line). The theoretical 1σ sensitivity limit is r ~ 0.01 for Planck with 4 sky surveys (see Table 1) making Planck competitive with the most sensitive ground based and sub-orbital experiments.*

From Planck Extension Proposal; Presented at Perimeter Institute: Implications of BICEP2
http://pirsa.org/pdf/loadpdf.php?pirsa_number=14040122

Planck's Schedule

- October: Second (Polarization) Public Release
  - HOWEVER: Planck has reserved the right to publish “something” earlier if the team has solid results to contribute ahead of time.
  - Note that it takes of order weeks for Planck to submit a paper even after the primary authors think it's perfect
- December: PLANCK 2014 - The microwave sky in temperature and polarization
  - http://www.consorziofermove rararicerche.it/Eventi/eventi-in-programmazione-nel-2014/planck-2014-the-microwave-sky-in-temperature-and-polarization/planck-2014-the-microwave-sky-in-temperature-and-polarization
- 2015: An additional release

Near-Term Experiments

B-Mode Search Projects Underway

GroundBird MuSE

Ground-Based (Chile):

POLARBEAR: Polarization of Background Radiation

ACTPOL: Atacama Cosmology Telescope – Polarization

ABS: Atacama B-mode Search

CLASS: Cosmology Large Angular Scale Surveyor

Ground-Based (Antarctica):

SPTPOL: South Pole Telescope's polarization-sensitive camera

BICEP2: Background Imaging of Cosmic Extragalactic Polarization (and Keck Array)

QUBIC: Q&U Bolometric Interferometer for Cosmology

Ground-Based (Canary Islands):

QUIJOTE: Q-U-I JOint TEnerife

Balloon Experiments:

EBEX: E and B Experiment

SPIDER: Suborbital Polarimeter for Inflation

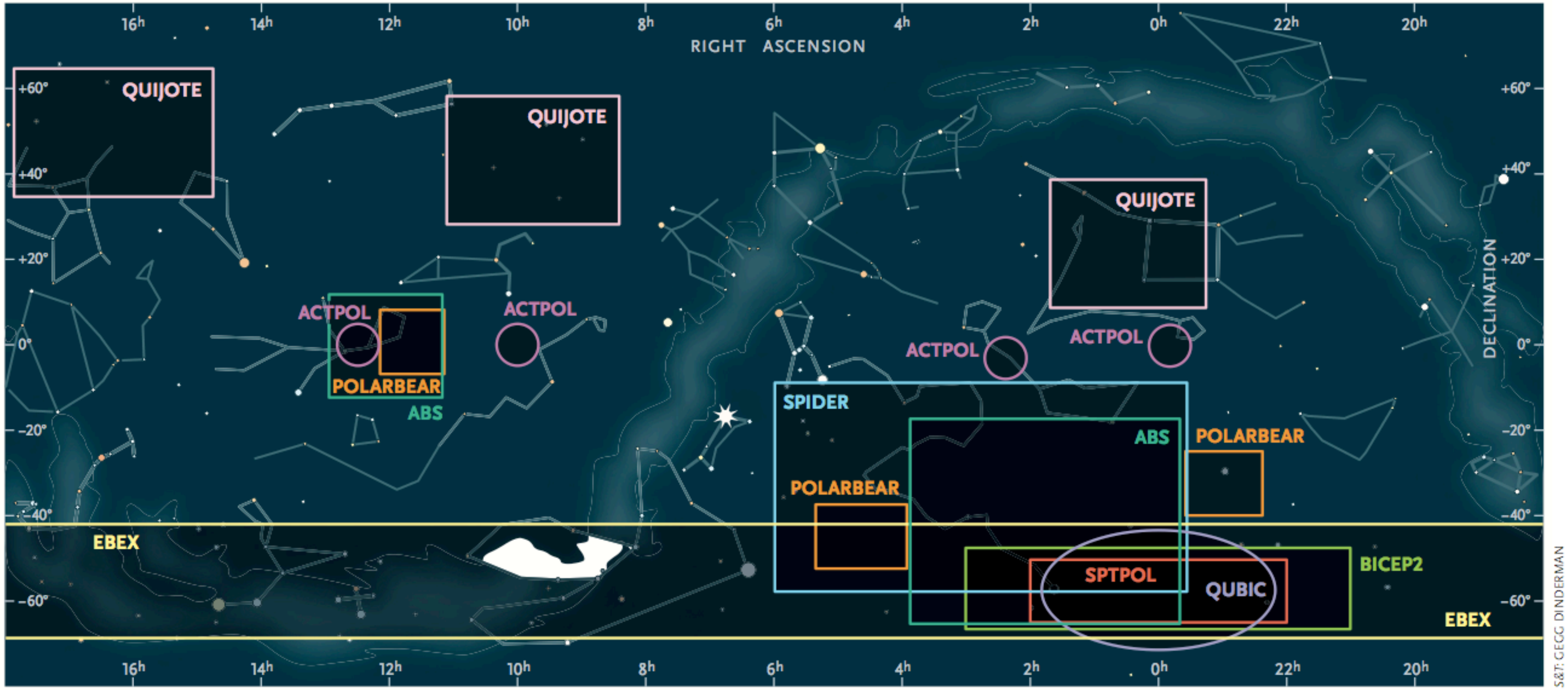
LSPE: Large-Scale Polarization Explorer

PIPER: Primordial Inflation Polarization Explorer

ESA Satellite Mission:

PLANCK

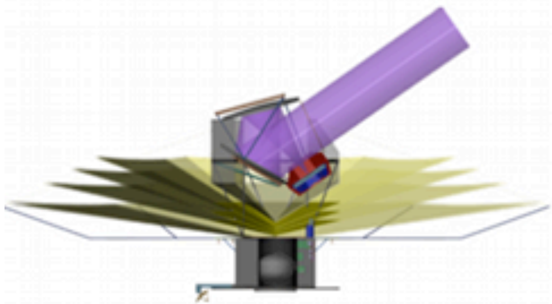
RACE TOWARD THE BIG BANG Several projects are currently hunting for the polarization signature of inflation. Shown below are the fields of view for active projects (except for Planck, which is all-sky). Fields are approximate and distorted by projection at high declinations.



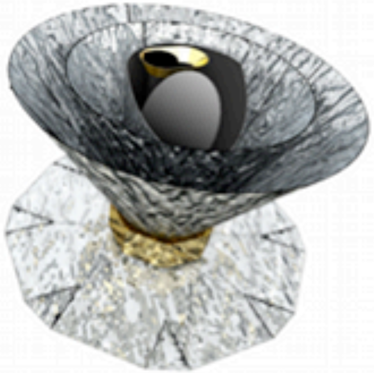
SkyandTelescope.com *October 2013* 27

CMB Mission Concepts in the Current Environment

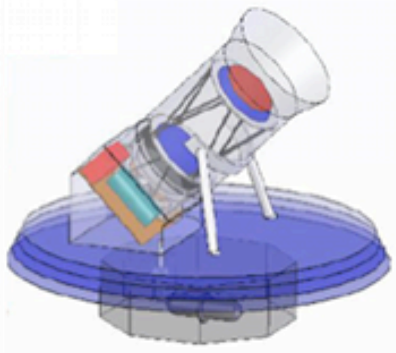
EPIC-IM



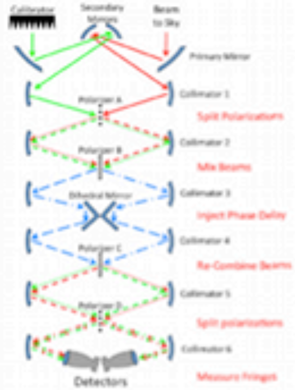
PRISM



LITEBIRD



PIXIE



Can we fit a CMB concept into a ~$220M Explorer cost cap?

Any concept seems very cost challenged at this cap

L2 concepts have a high launch cost

Will the science community accept a single-purpose satellite designed to discover inflationary B-modes?

In the US, the answer from Decadal planning exercise is clearly “No”

We need a detection from the ground first to justify a satellite for full characterization

What about an absolute spectrum instrument?

Absolute spectrum science is interesting and should be considered in its own right

No heritage for polarization measurements is worrisome

Is there a window for a large CMB mission?

Not in the US this decade. We’ll see how PRISM fares in Europe.

Stolen from J. Bock; see: http://www-conf.kek.jp/cmb/2013/

Thank You!

Lensed polarization B-Modes were detected at the end of 2013 by the South Pole Telescope, and confirmed by the Polarbear experiment.

BICEP2 has claimed a detection of primordial gravitational waves, which if confirmed would indicate that cosmological Inflation actually happened.

Planck and other experiments will confirm (or not!) these results soon.

These are exciting times for the Microwave Background

The CMB and Neutrinos

- Neutrinos are becoming a focus for future CMB experiments
- Now:
  - Σm_ν <~ 0.8 eV from the CMB
  - Σm_ν < 0.23 eV from the CMB+BAO
  - N_{eff} ~ 3.3±0.6
    - This goes up to ~3.6 using local H_0 priors.

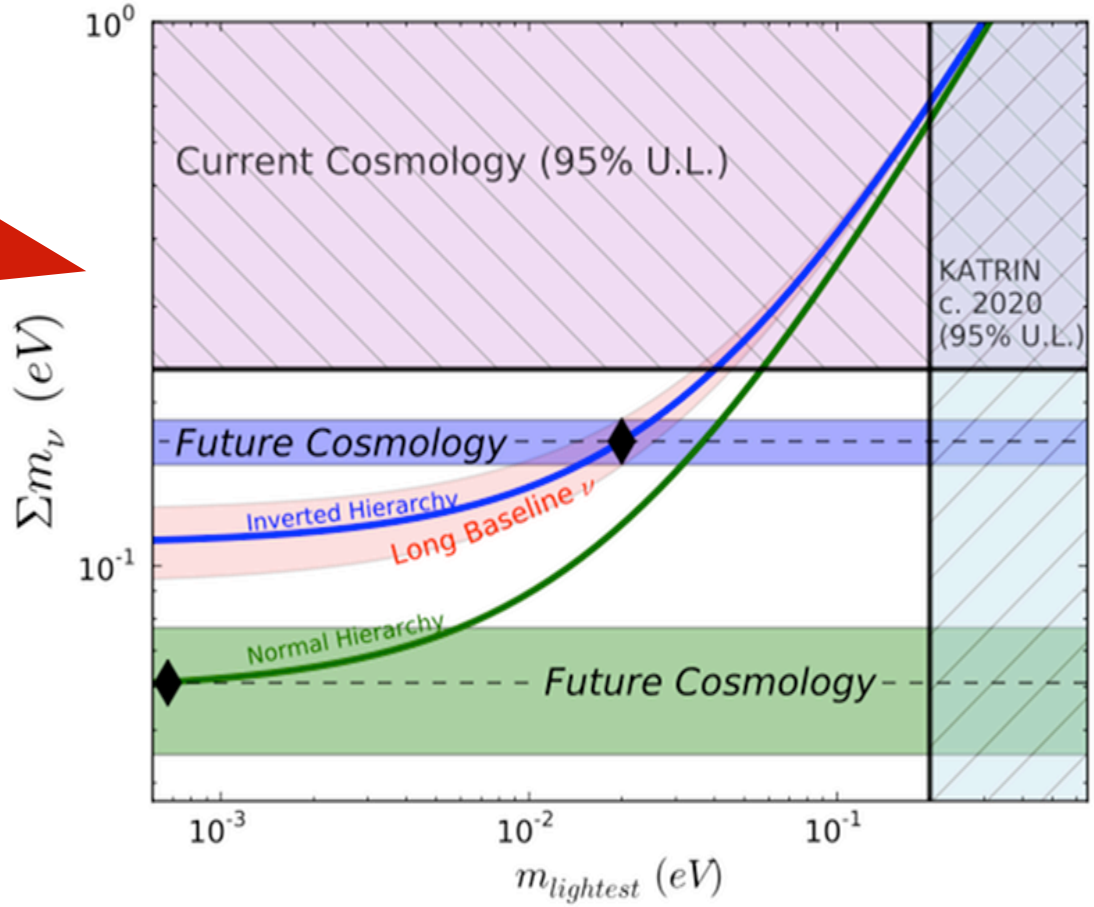


Figure 7. *Current constraints and forecast sensitivity of cosmology to the sum of neutrino masses. In the case of an "inverted hierarchy," with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with 1-σ error shown as a blue band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would still detect the lowest $\sum m_\nu$ at greater than 3-σ.*

arXiv:1309.5386v2 [astro-ph.CO] 24 Sep 2013

Planck and Cosmological Parameters

$\Omega_b h^2 = 0.02197 \pm 0.00027$
$\Omega_c h^2 = 0.1169 \pm 0.0025$

$\tau = 0.089 \pm 0.013$
$N_s = 0.9671 \pm 0.0069$
$\ln(10^{10} A_s) = 3.080 \pm 0.025$

$H_0 = 68.0 \pm 1.1\ \mathrm{kms^{-1}Mpc^{-1}}$

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8347	0.829 ± 0.012
z_{re}	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09591	0.09589 ± 0.00057
Y_P	0.247695	0.24770 ± 0.00012
Age/Gyr	13.8242	13.817 ± 0.048
z_*	1090.48	1090.43 ± 0.54
r_*	144.58	144.71 ± 0.60
$100\theta_*$	1.04136	1.04147 ± 0.00062

And more!