COSMIC MICROWAVE BACKGROUND FROM GROUND-BASED AND SPACE EXPERIMENTS

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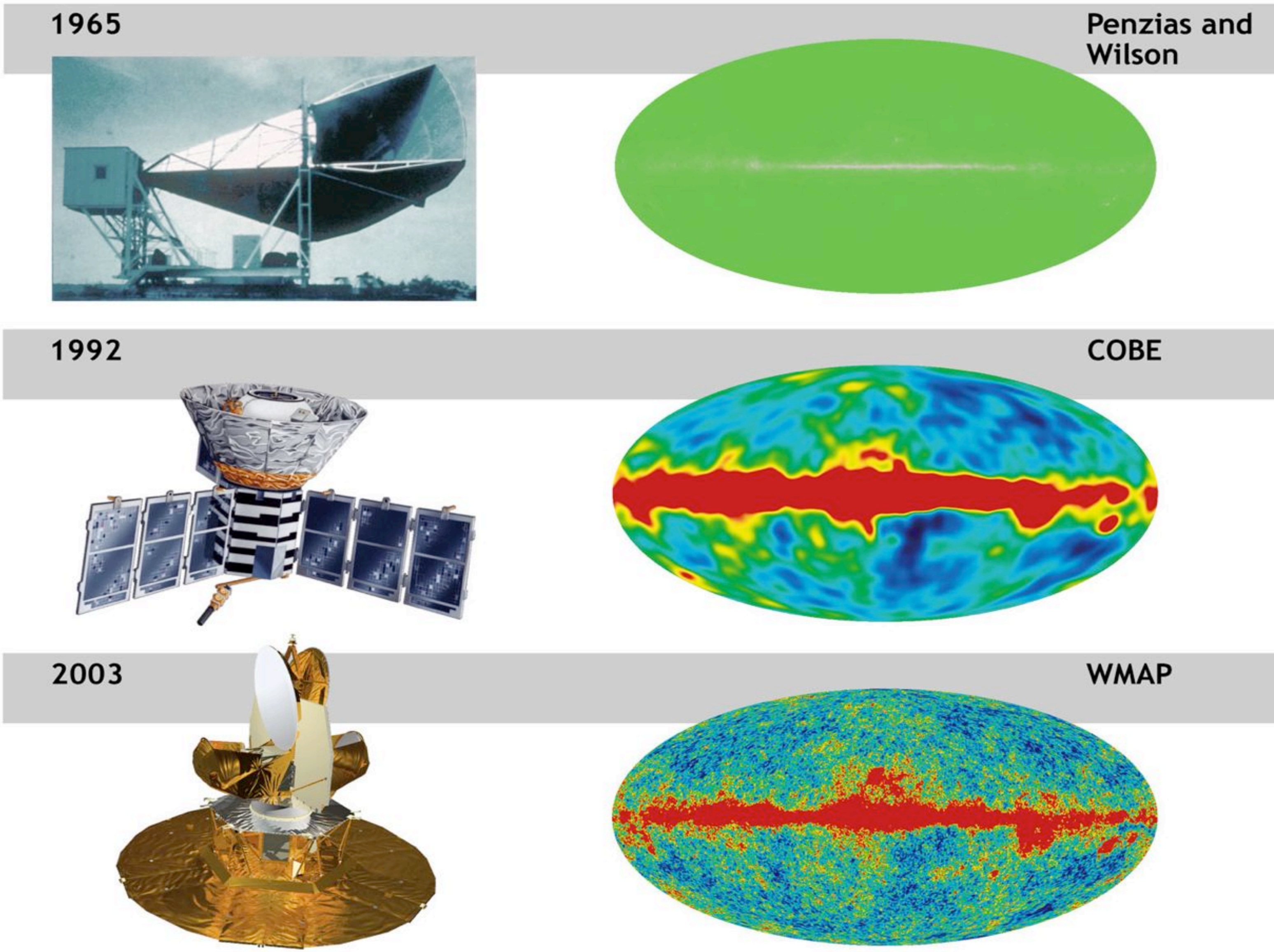
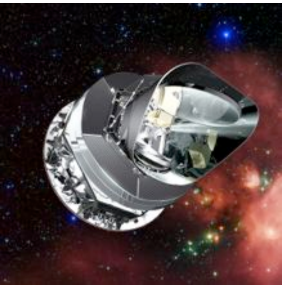
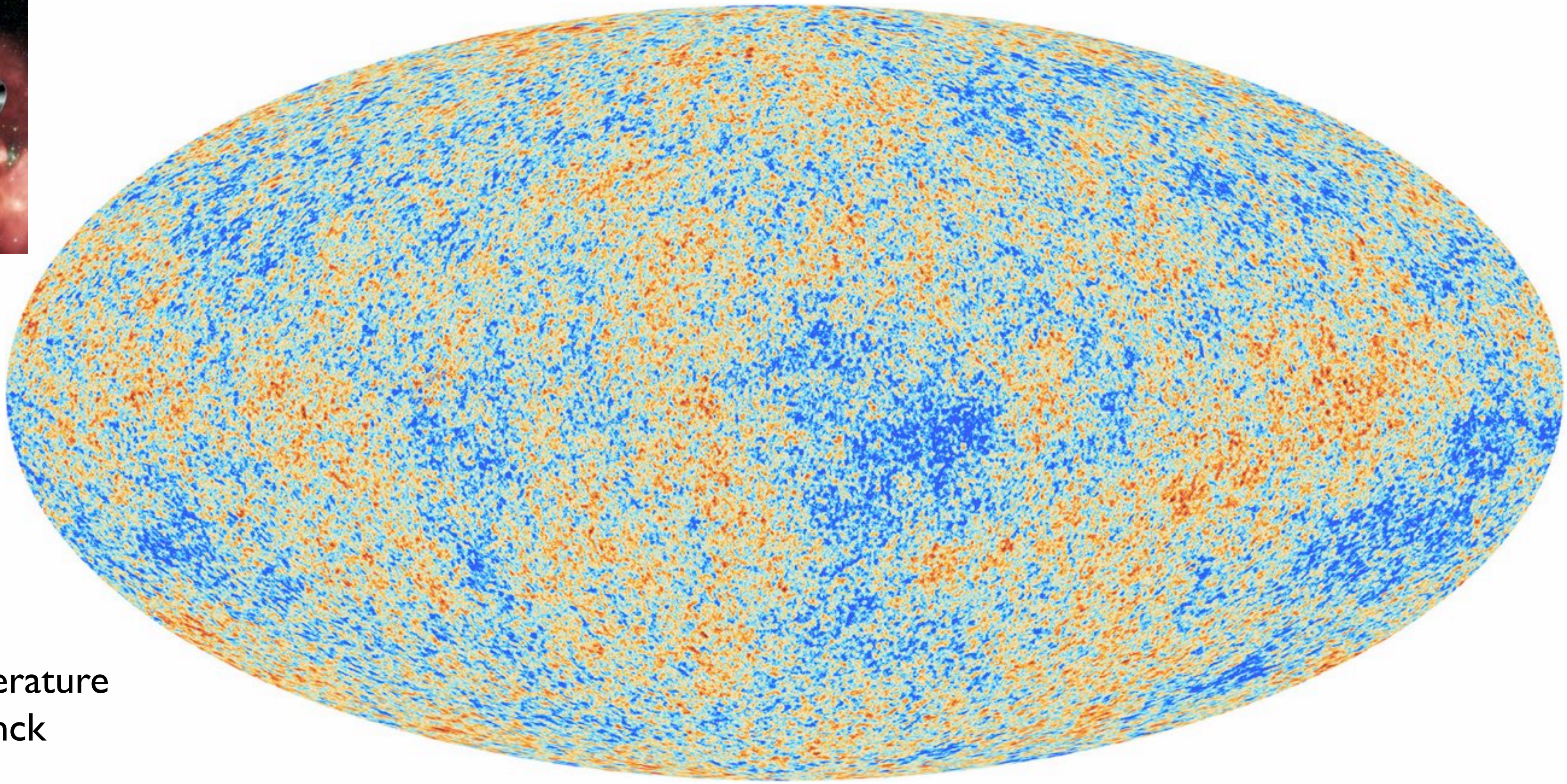


The cosmic microwave background (CMB) radiation is one of the fundamental observables of cosmology, ever since its serendipitous discovery in 1965

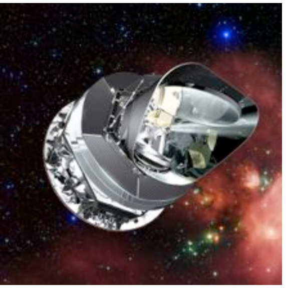


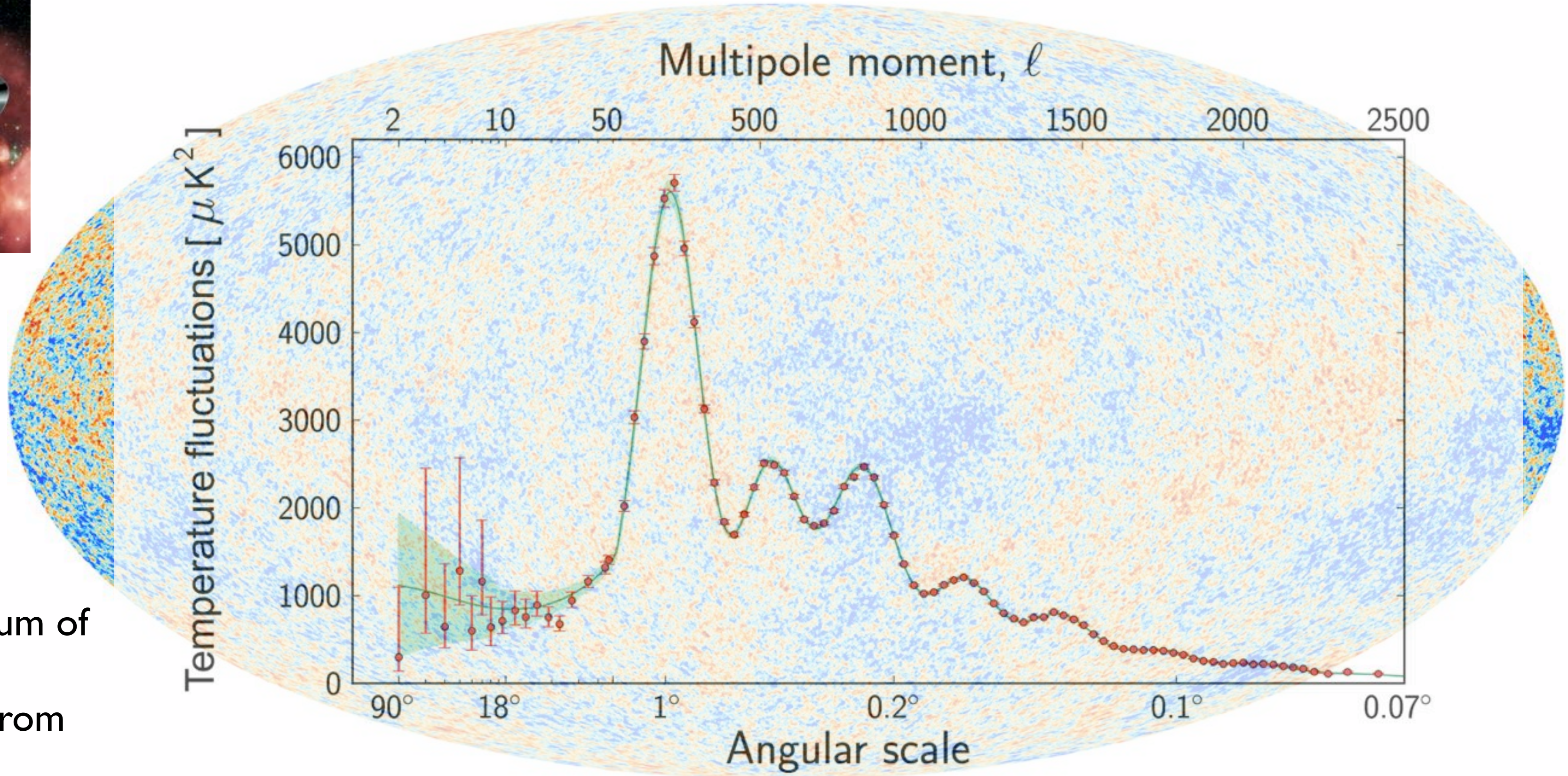


Full sky temperature map from Planck (2013)

The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old.

Its tiny (~ 10^{-5}) temperature and polarization anisotropies encode a wealth of cosmological information.



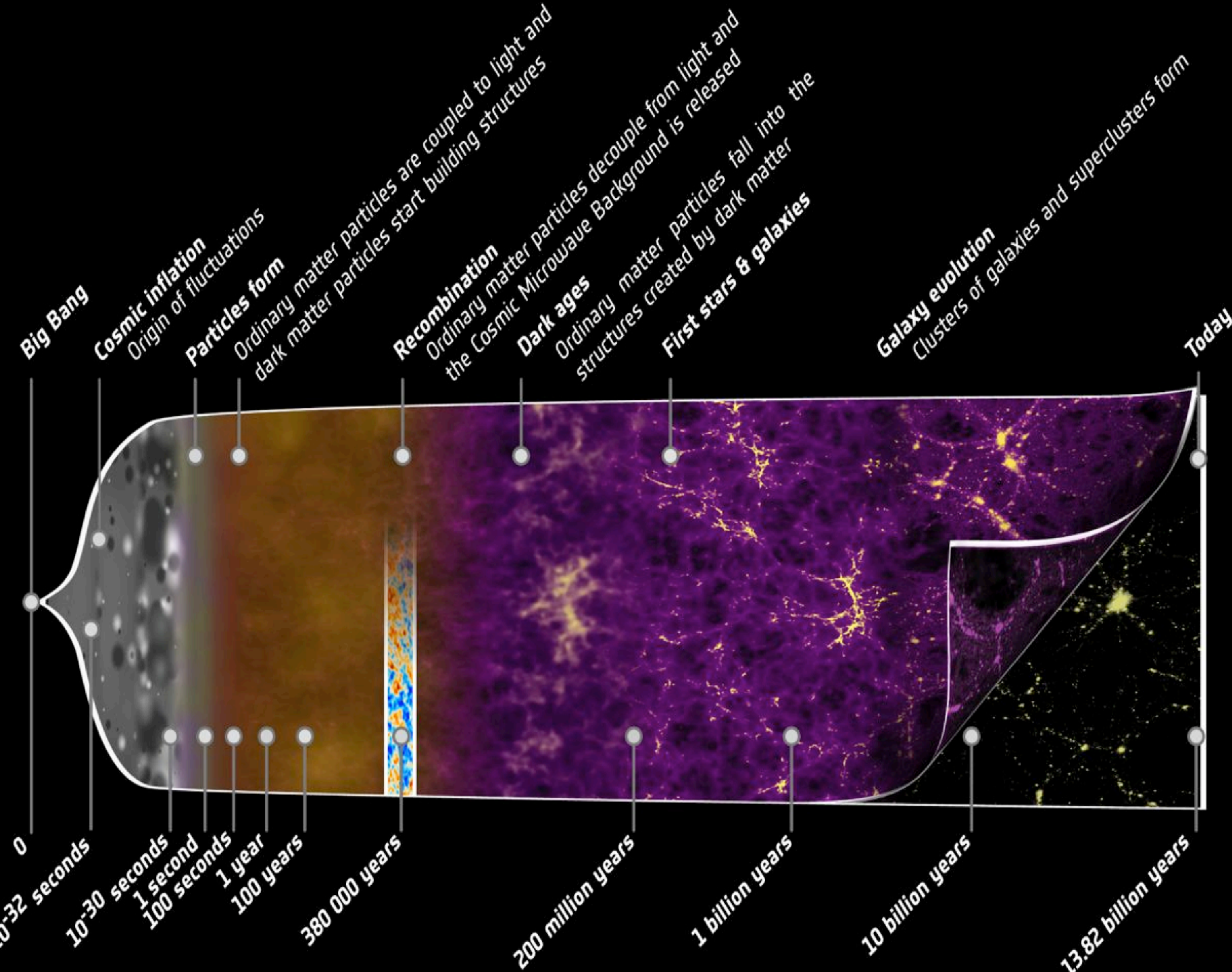


Power spectrum of temperature fluctuations from Planck (2013)

If the fluctuations are gaussian, all the statistical information in the map is encoded in the two point correlation function or in its harmonic transform, the angular power spectrum:

$$\Theta(\hat{n}) = \sum_{\ell=0}^{\ell=\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$\left\langle a_{\ell m} a^*_{\ell' m'} \right\rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

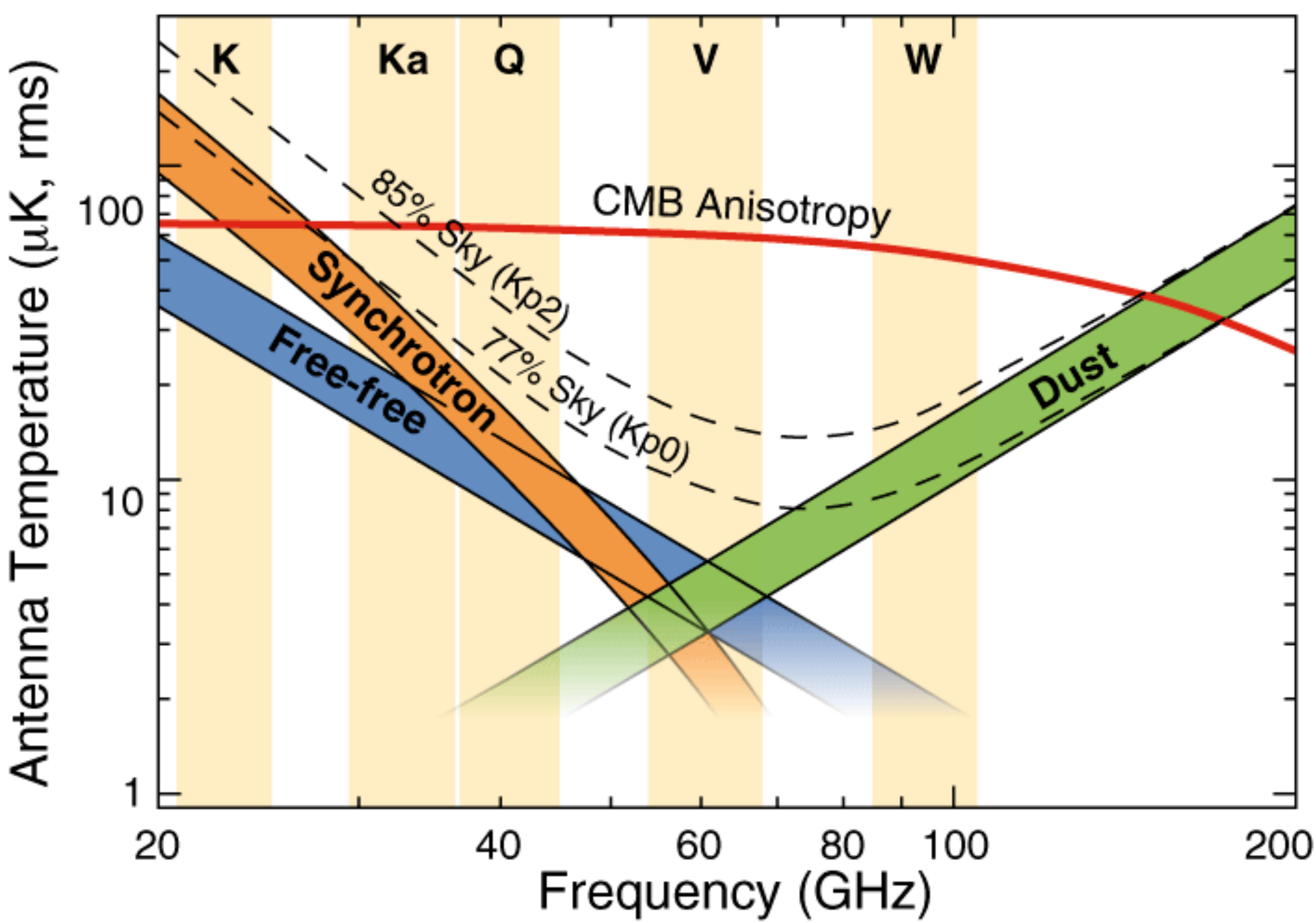
Sources of uncertainty in CMB observations:

- Cosmic variance (i.e., sample variance due to the fact that we have only a single Universe to observe)

- Instrumental noise

- Instrumental systematics (calibration, optical response of the telescope, scanning strategy ….)

- Astrophysical foregrounds (synchrotron, dust, free-free ….)



K
Ka
Q
V
W
85% Sky (Kp2)
77% Sky (Kp0)
CMB Anisotropy
Synchrotron
Free-free
Dust
Antenna Temperature (μK, rms)
100
10
1
20
40
60
80
100
200
Frequency (GHz)

Ground-based experiments

Pros

- cheaper than space-based
- more freedom in experimental design
- can reach high raw sensitivity by deploying very large focal planes of thousands (or more) detectors
- shorter timescale

Cons

- Limited by atmospheric emission and noise; needs to go to sites with excellent observing conditions (Antarctica, Atacama desert) or above the atmosphere (balloon-borne experiments)
- Even there, the available windows are too few to allow foreground removal (you need at least as many maps as the components to separate)
- The presence of the sun (and of the moon) makes difficult to cover a large fraction of the sky. Also, polarized diffraction from the ground.

Space-based experiments

Pros

- wide frequency coverage
- full sky coverage
- environmental stability

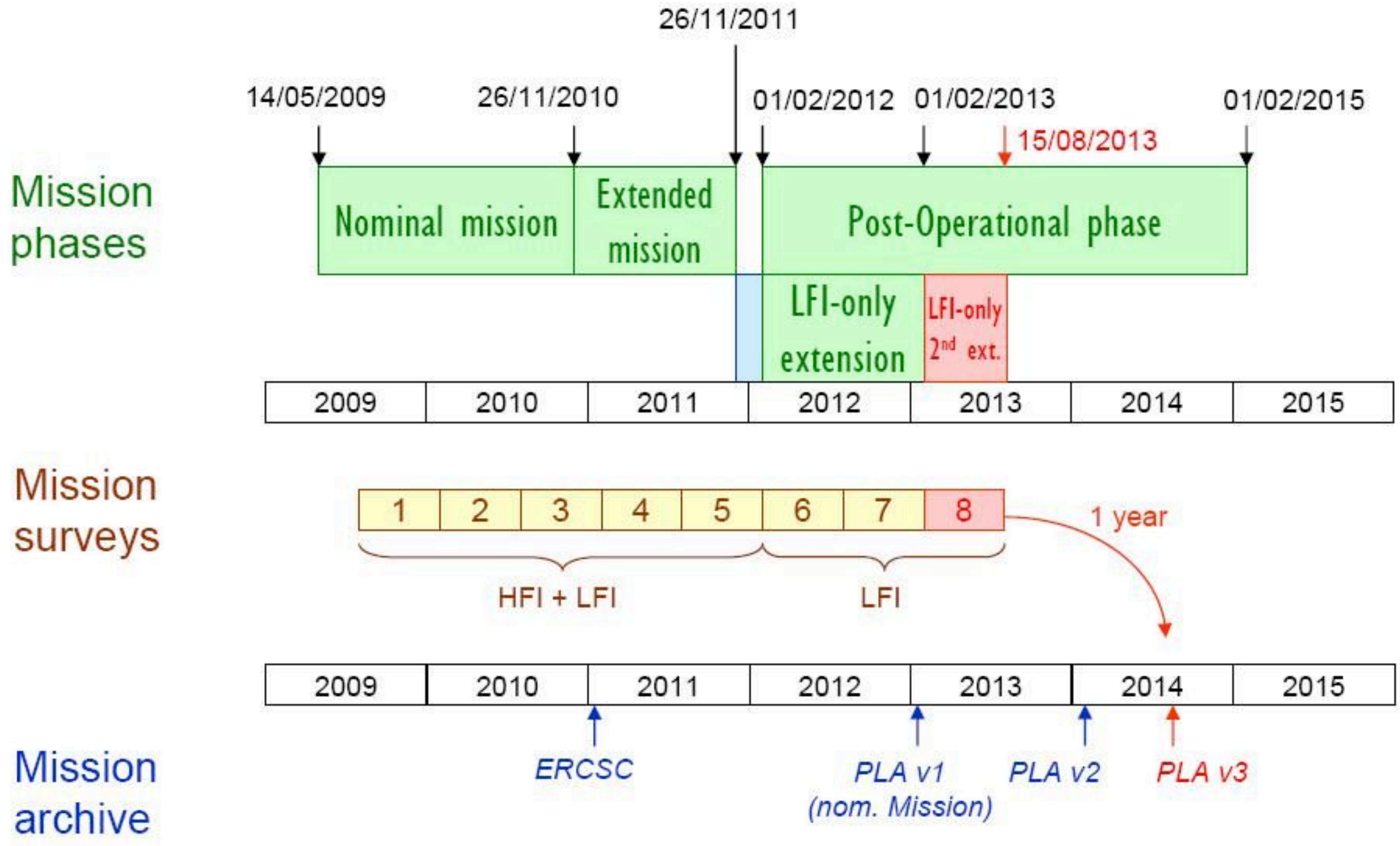
Cons

- expensive
- more constraints on the experimental design
- longer time to develop

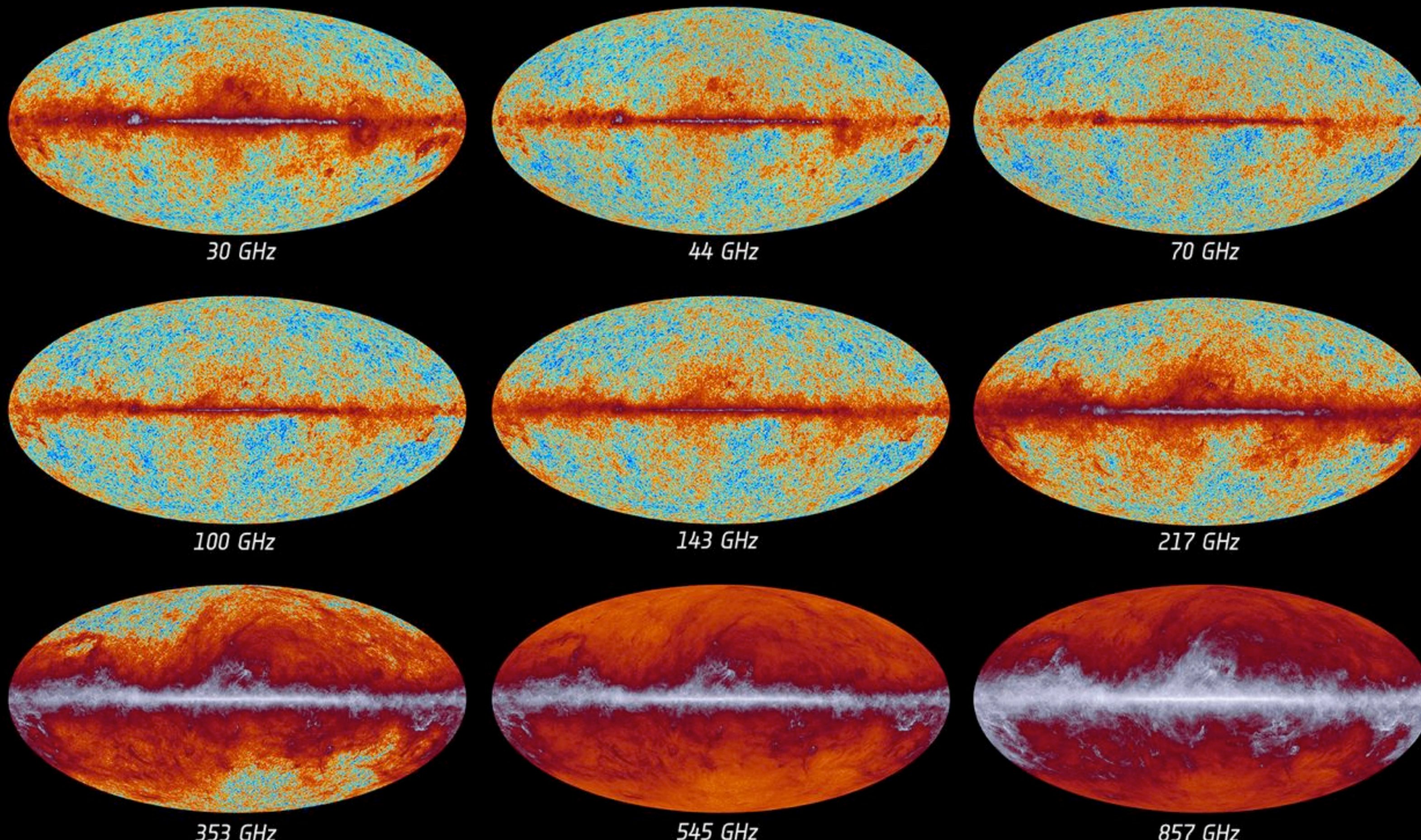
Planck Surveyor

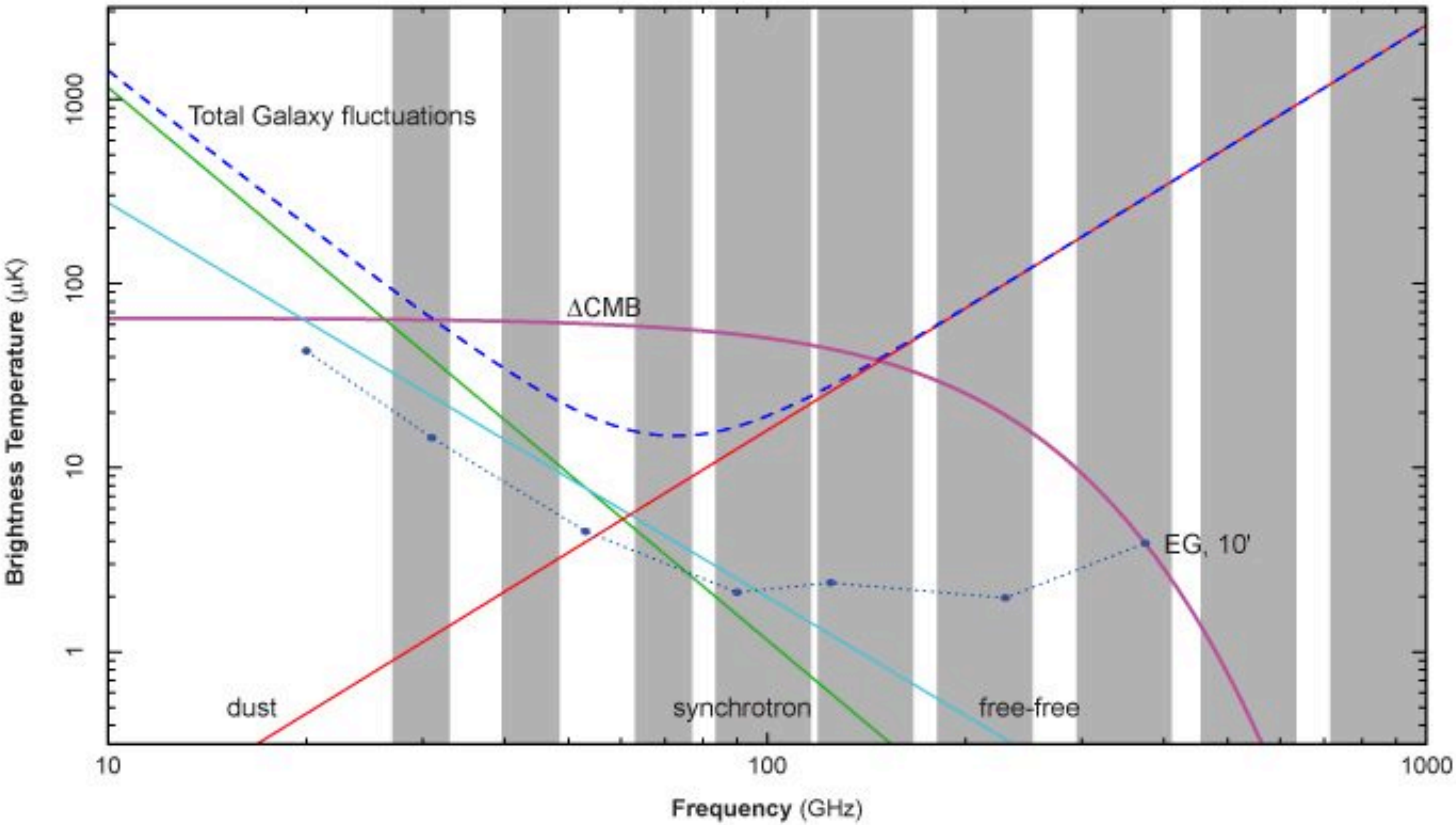
- Third-generation ESA satellite dedicated to the CMB
- Two instruments, LFI (radiometers 30 - 70 GHz) and HFI (bolometers 100 – 867 Ghz)…
- … that observed the mw sky for ~ 29 (HFI) and 48 (LFI) months
- 74 detectors
- angular resolution between 30′ and 5′, $\Delta T/T \sim 2 \times 10^{-6}$
- first cosmological release in May 2013, using the "nominal mission" temperature data (15.5 months of observations)
- second cosmological release in late 2014: full mission temperature and polarization
- third and final release in 2015

Planck's operational timeline

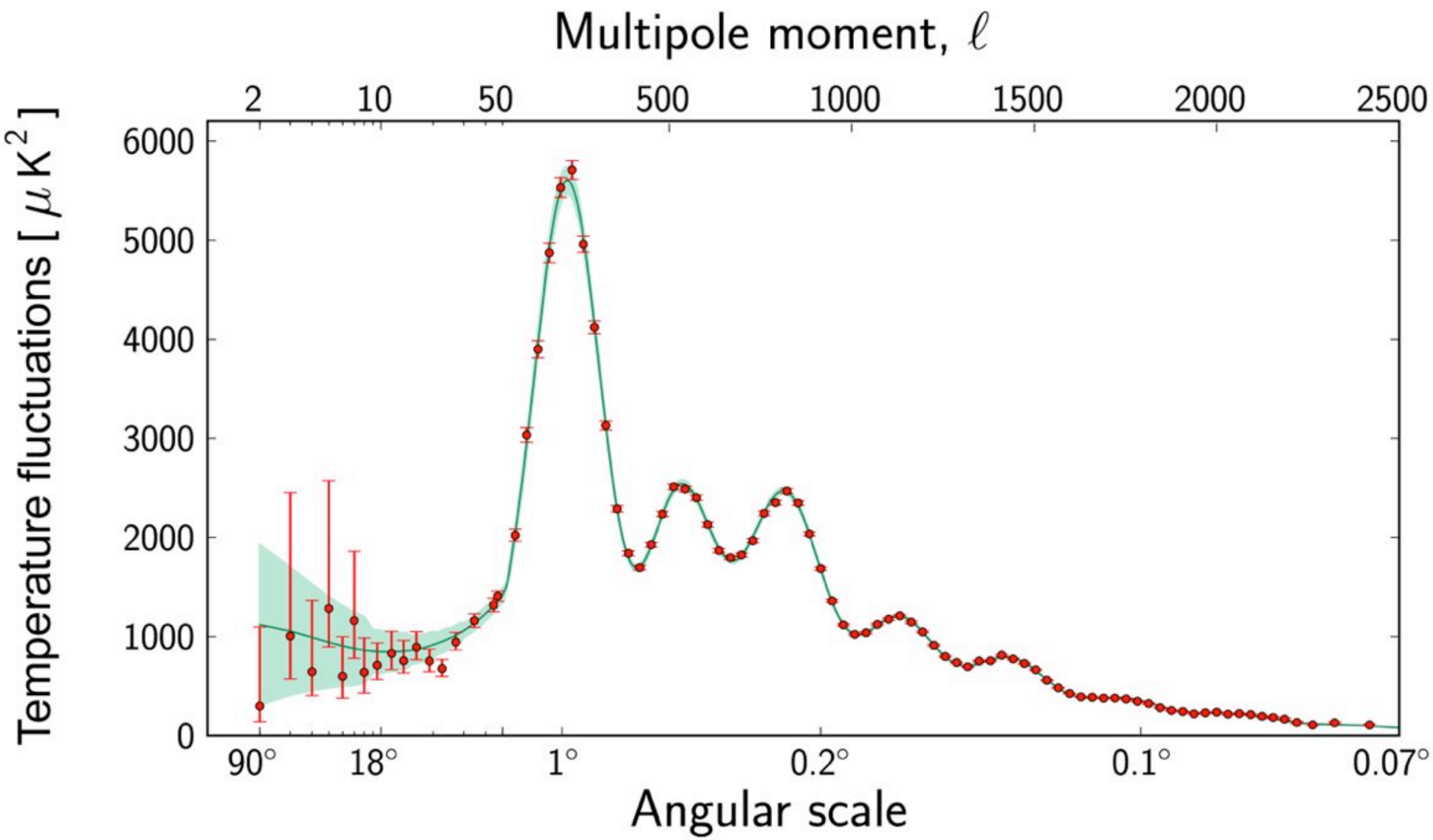


The sky as seen by Planck





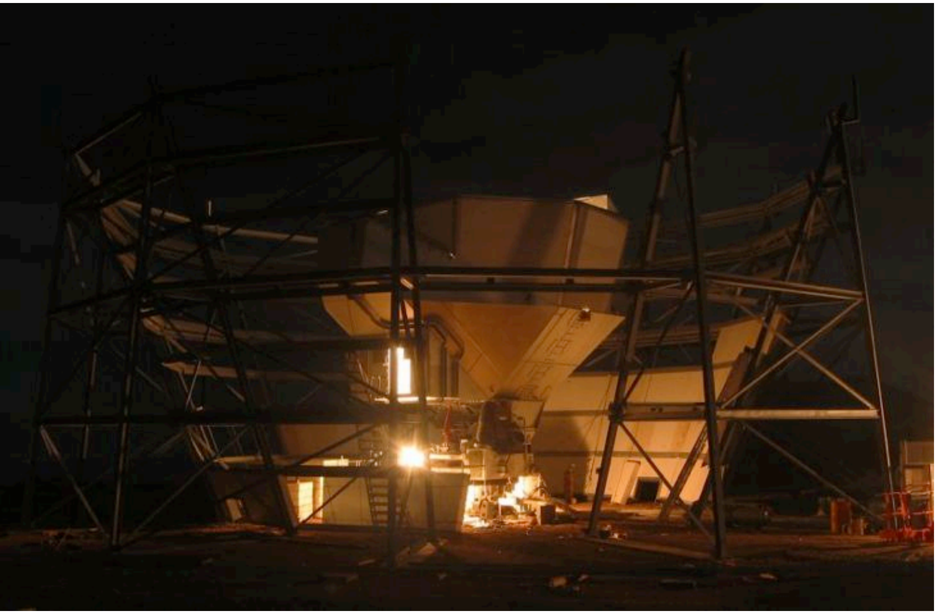
Total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free-free
1000
100
10
1
Brightness Temperature (μK)
10
100
1000
Frequency (GHz)



The temperature power spectrum measured by Planck is extremely consistent with the standard flat LCDM cosmology with a nearly scale-invariant spectrum of primordial adiabatic scalar fluctuations

Small-scale experiments

Atacama Cosmology Telescope (ACT)



6-meter telescope

~1000 TES bolometers @145, 215, 280 GHz each

~ 300x2 deg^2 with 1.5′ resolution

Observed from 2008 to 2010

probes 600 < ell < 3000

South Pole Telescope (SPT)

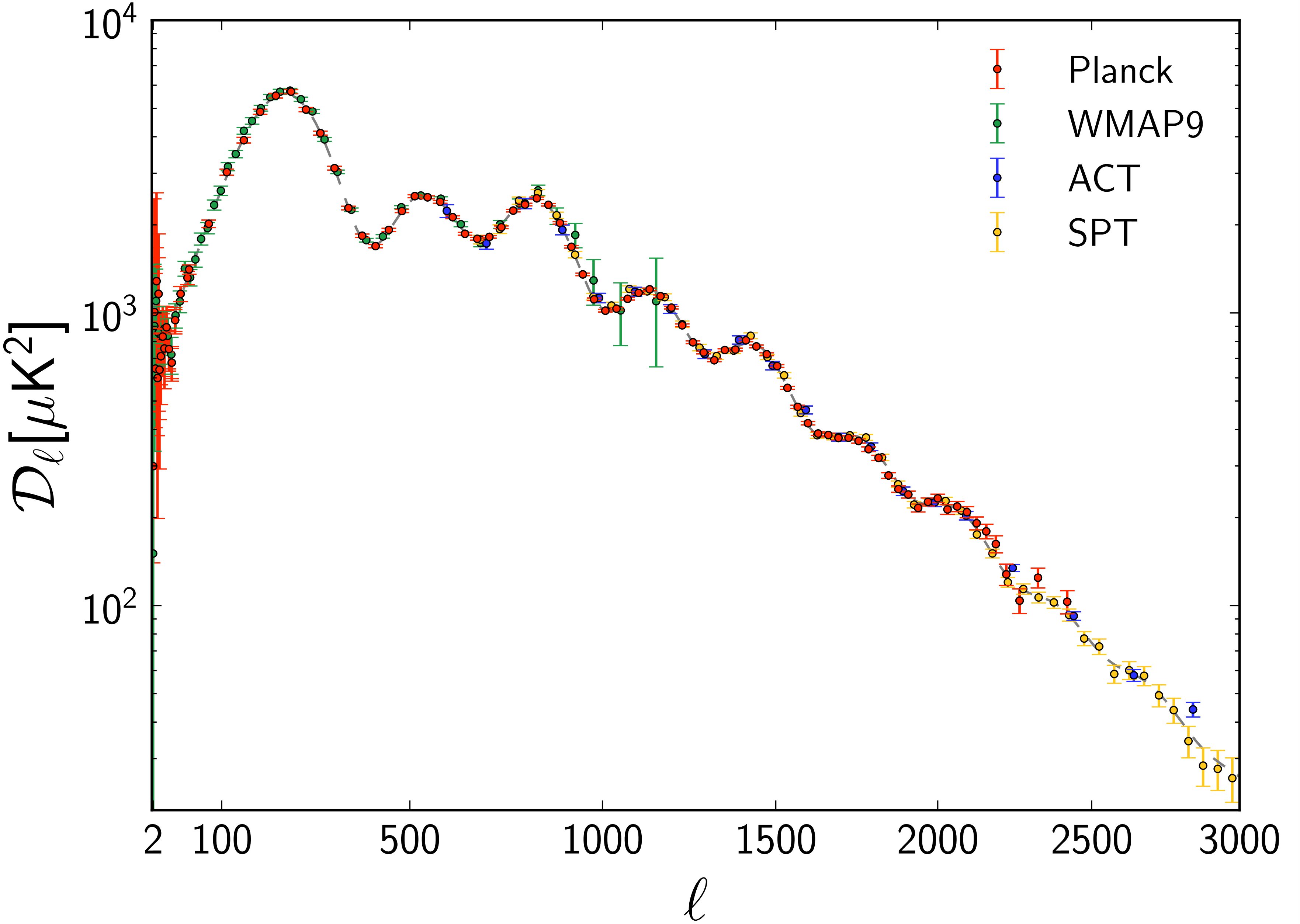
10-meter telescope

960 TES bolometers @100, 150, 220 GHz

~ 2500 deg^2 with 1′ resolution

Observed from 2008 to 2011

probes 600 < ell < 3000



Excellent agreement between the TT spectra

Base LCDM model (Planck + WP + HighEll)

Parameter		Value +/- 68% uncertainty
$\Omega_b h^2$	Baryon density	0.02207 +/- 0.00027
$\Omega_c h^2$	DM density	0.1198 +/- 0.0026
100θ	Acoustic scale at recombination	1.04132 +/- 0.00063
τ	Optical depth to reionization	0.091 +/- 0.014
$\ln(10^{10} A_s)$	Amplitude of scalar perturbations	3.090 +/- 0.025
n_s	Spectral index of scalar pertubations	0.9585 +/- 0.0070
H_0	Hubble constant	67.3 +/- 1.2
Ω_Λ	Dark energy density	0.685 +/- 0.017
σ_8	Variance of density fluctuations at the $8h^{-1}$ Mpc scale	0.828 +/- 0.012
z_{re}	Reionization redshift	11.1+/- 1.1

Further tests of the standard model

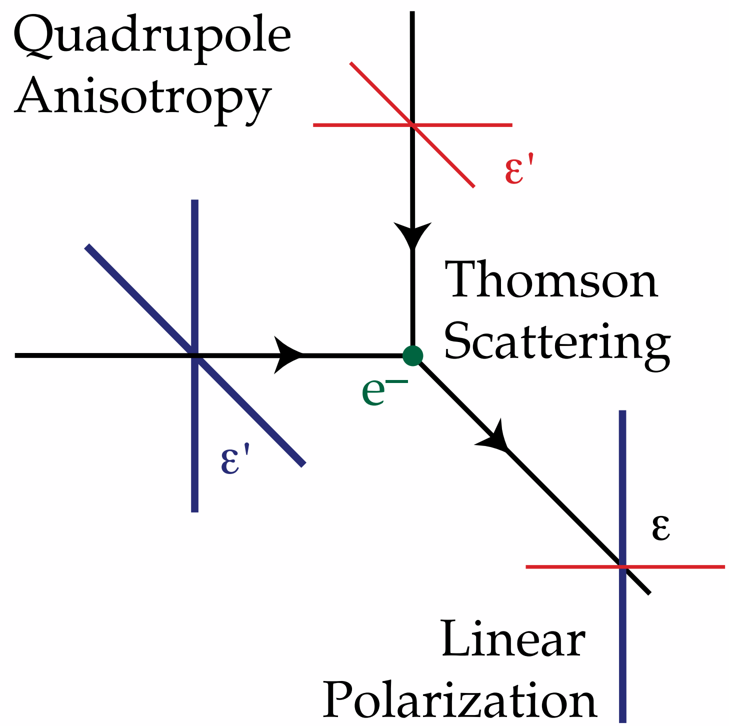
- Sum of neutrino masses:
  - We know that neutrinos are massive (oscillations)
  - Minimum possible sum mass is around 0.07 eV
  - Planck: **no detection**, limit from all data is 0.23 eV
- Extra particles? **N_{eff} consistent with 3 neutrinos only, $N_{eff} < 4$ at 95%**
- Is 'Λ' really a cosmological constant ? **Consistent with p=-ρ**
- Topology of the universe: **limits close to horizon size**
- decaying dark matter, varying constants: **no detections**
- tests of assumptions (isotropy, Gaussianity): **strong limits**, **some anomalies**
- Tensor fluctuations**: $r < 0.11$** (from temperature, model dependent, no B mode polarization so far).
- Tests of initial conditions for perturbations: **no surprises**
- Further constraints on inflation (running spectra index, etc) …

EXTENDED ΛCDM MODELS (Planck +BAO)

Parameter	Value (95%)
Ω_K	-0.0005±0.0066
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040
$dn_s/d\ln k$	-0.014±0.017
$r_{0.002}$	<0.11
w	-1.13±0.24

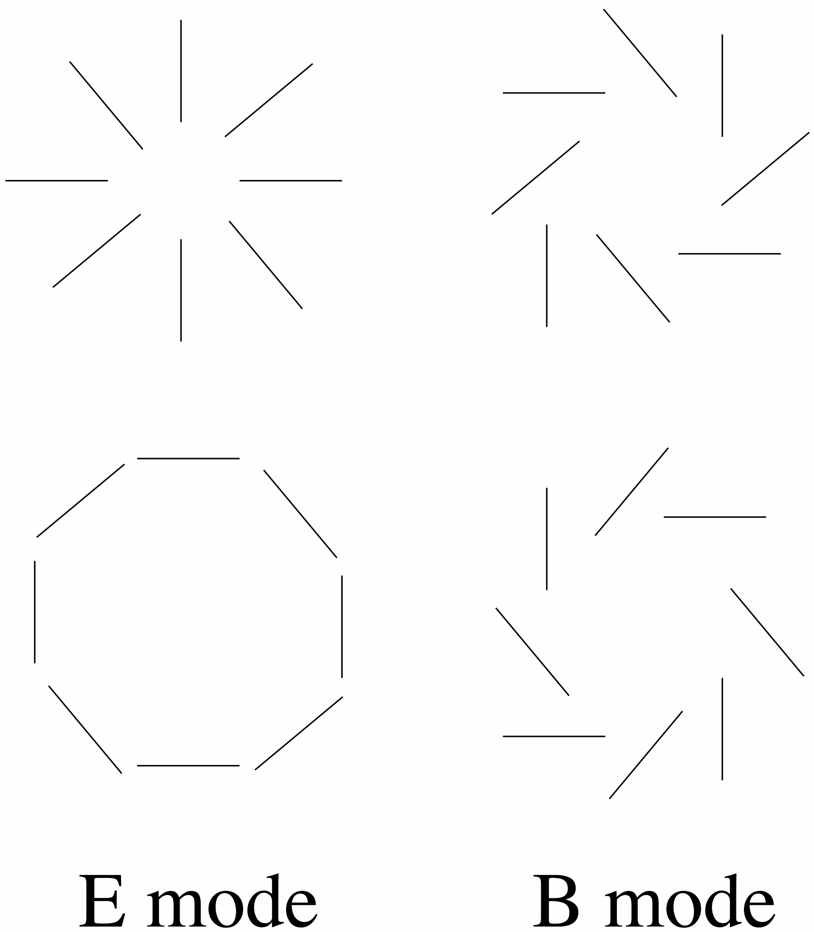
Beyond temperature: the CMB polarization

- The CMB radiation is polarized with an amplitude of a few μK, due the local radiation quadrupole at last scattering
- Most of this polarization pattern is generated by density (scalar) perturbations at the time of last scattering….
- …. but a small part of it (peaking at ~ degree scales) could have been be generated by primordial gravitational waves (tensor modes)
- Two polarization components: grad-like, parity-even ("E modes") and curl like, parity-odd ("B modes")
- Scalar perturbations generate E polarization only, while tensor perturbations generate both B and E



- Spurious B-modes generated by gravitational lensing at small scales

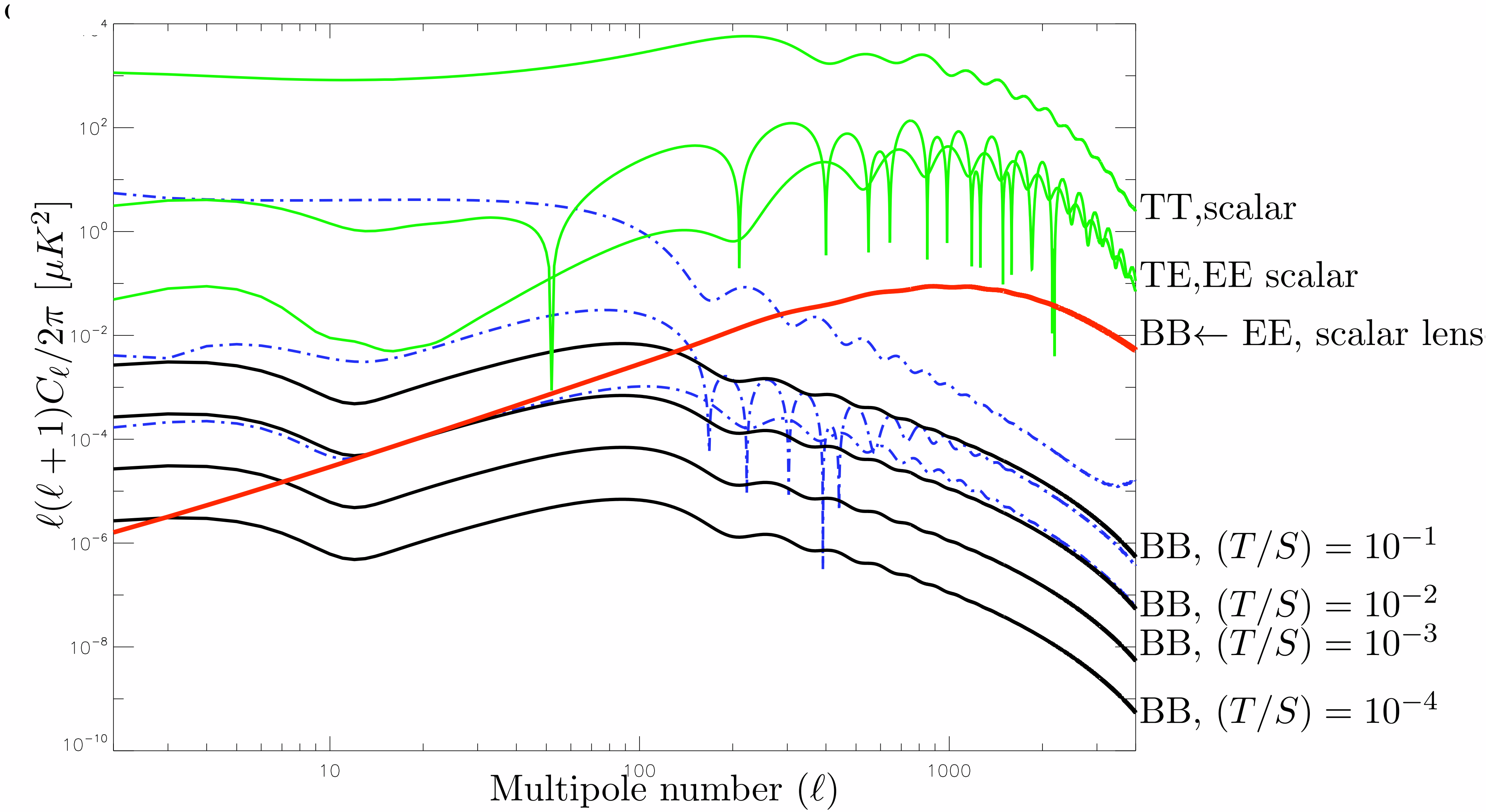
E-mode and B-mode



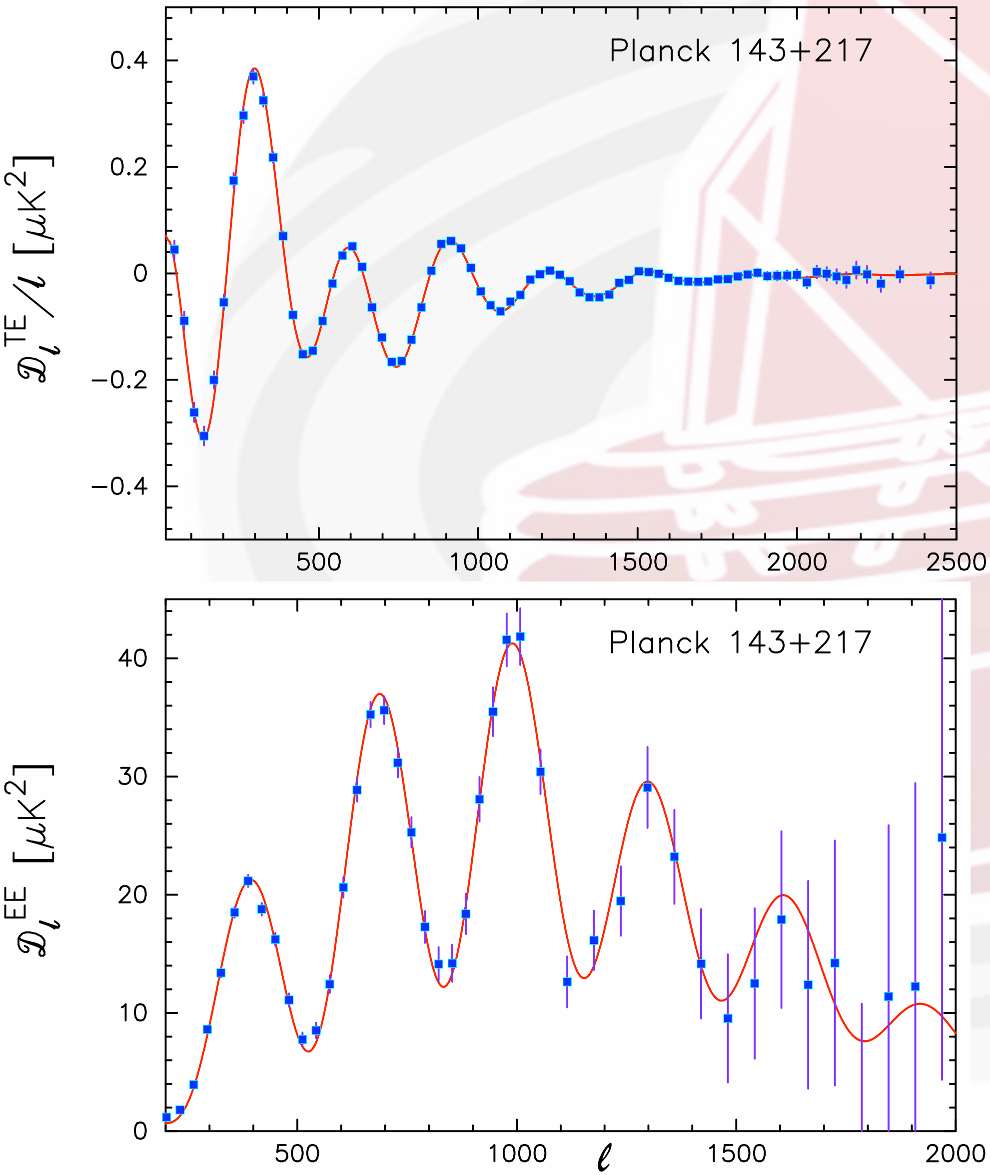
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Tensor modes are expected to be produced during inflation by the same mechanism of amplification of vacuum fluctuations that produces B-modes

→ B-modes are a smoking gun for inflation



CMP polarization with Planck



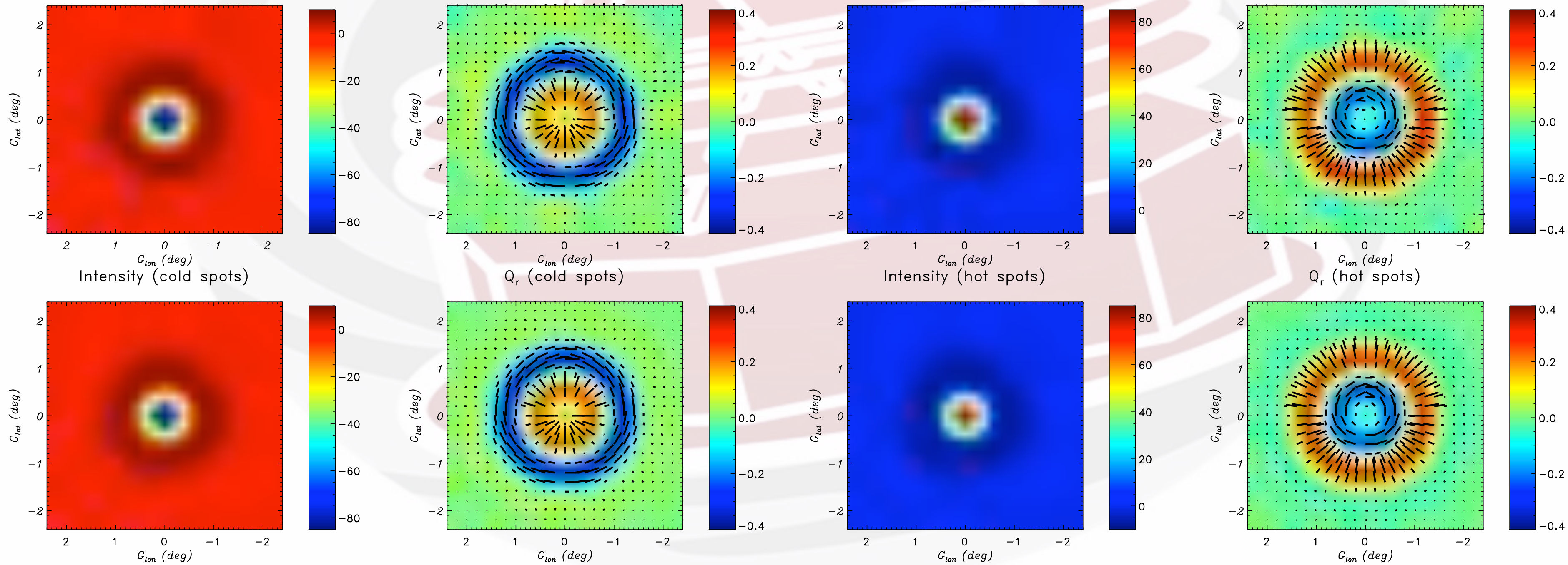
Polarization not delivered in 2013. Large angular scales need better cleaning. Small angular scale are already in good shape as shown.

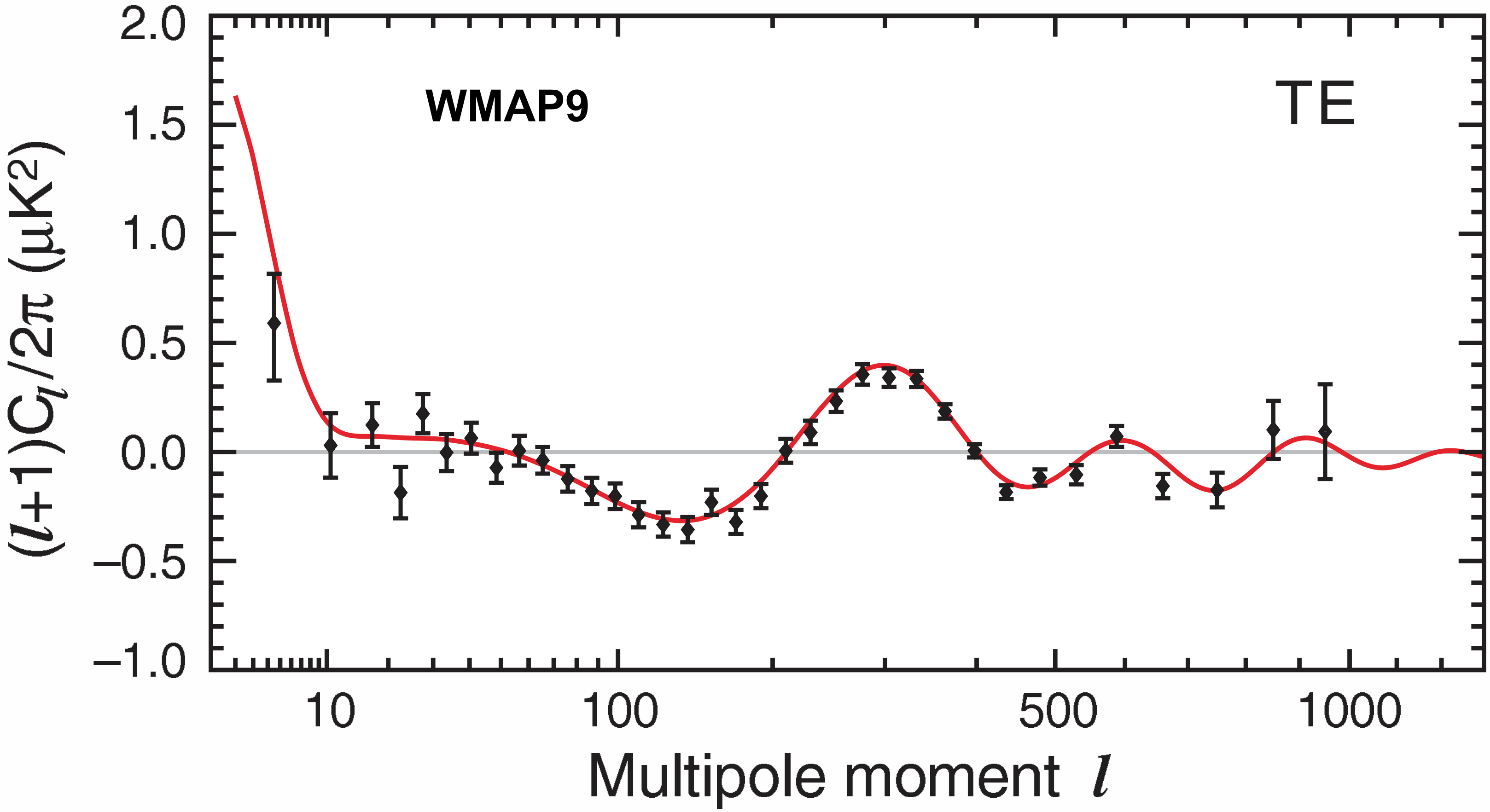
The red line is not a fit to the polarization data, but the predicted curve from the ΛCDM model assuming the temperature data!

Polarization and hot spots

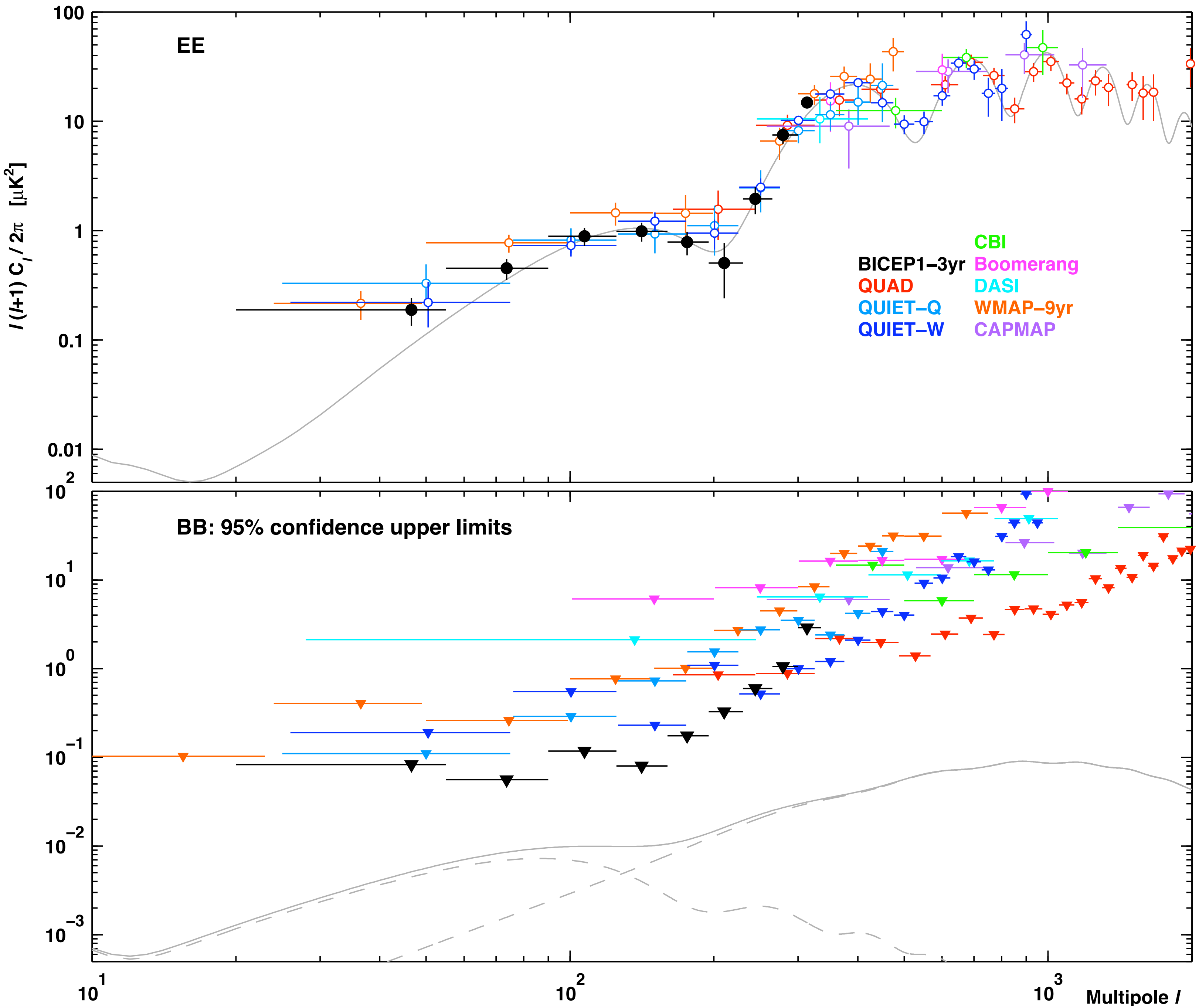
Stack hot/cold spots in the CMB. See the TE correlation in real space!

Remarkable proof of inflation: existence of super-horizon fluctuations



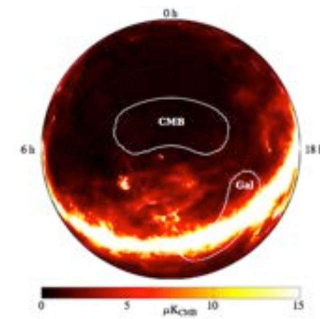


WMAP9
TE
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
(l+1)C_l/2π (μK²)
10
100
500
1000
Multipole moment l

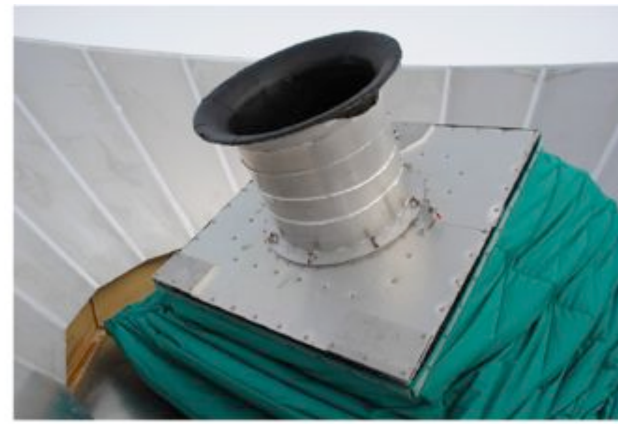


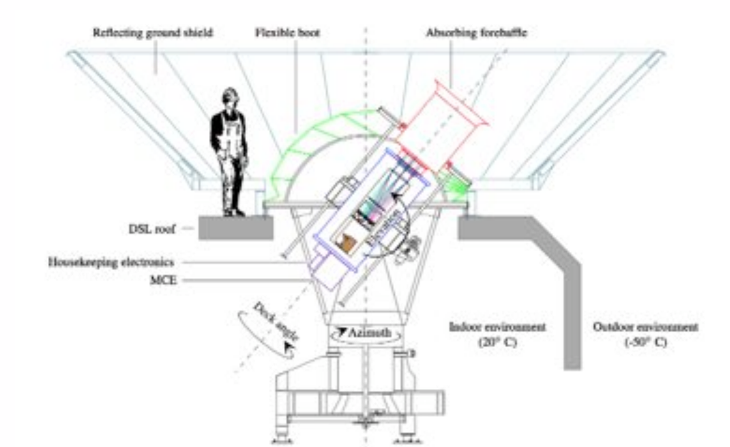
EE
BB: 95% confidence upper limits
BICEP1–3yr
QUAD
QUIET–Q
QUIET–W
CBI
Boomerang
DASI
WMAP–9yr
CAPMAP
l (l+1) C_l / 2π [μK²]
Multipole l

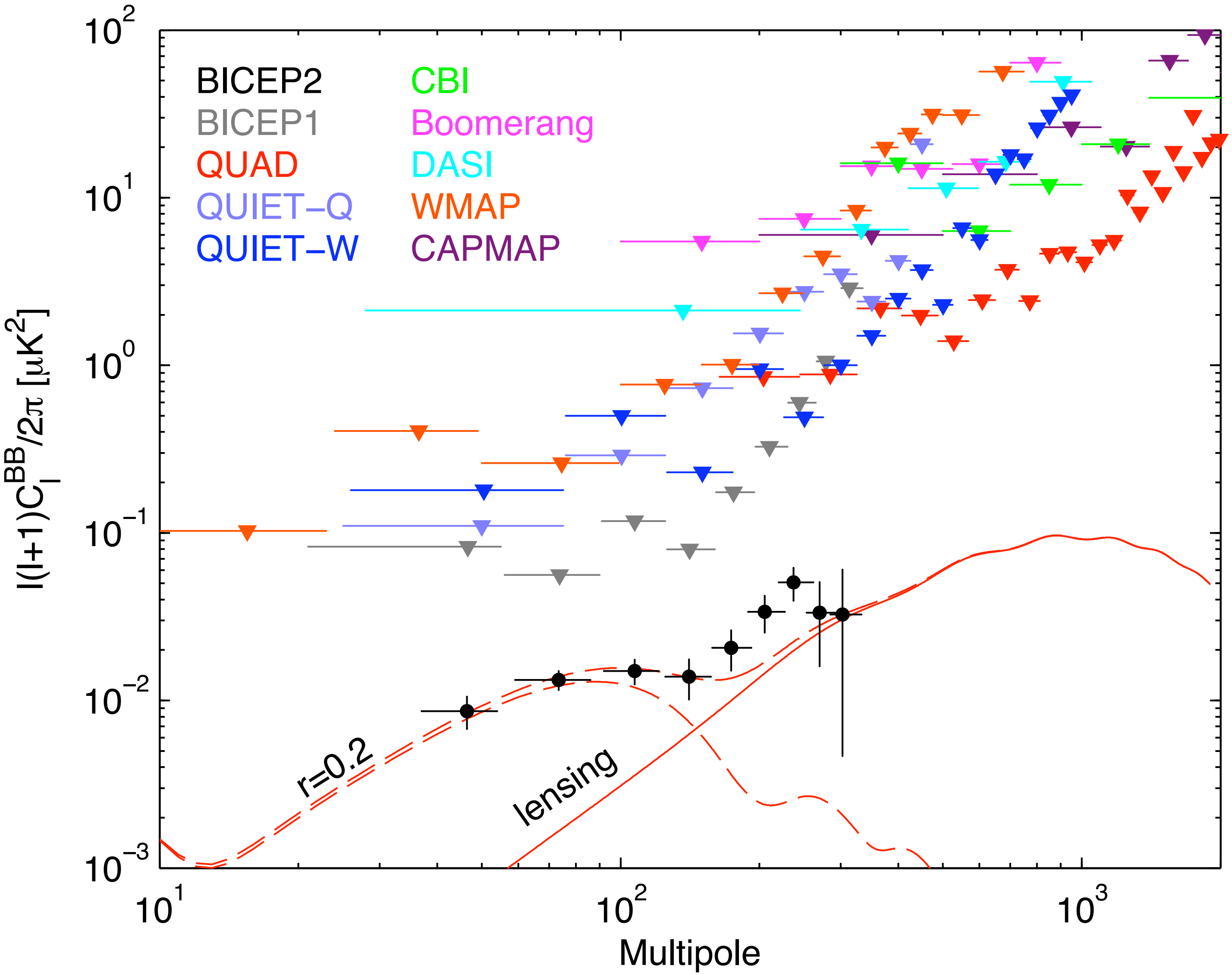
Meet BICEP2



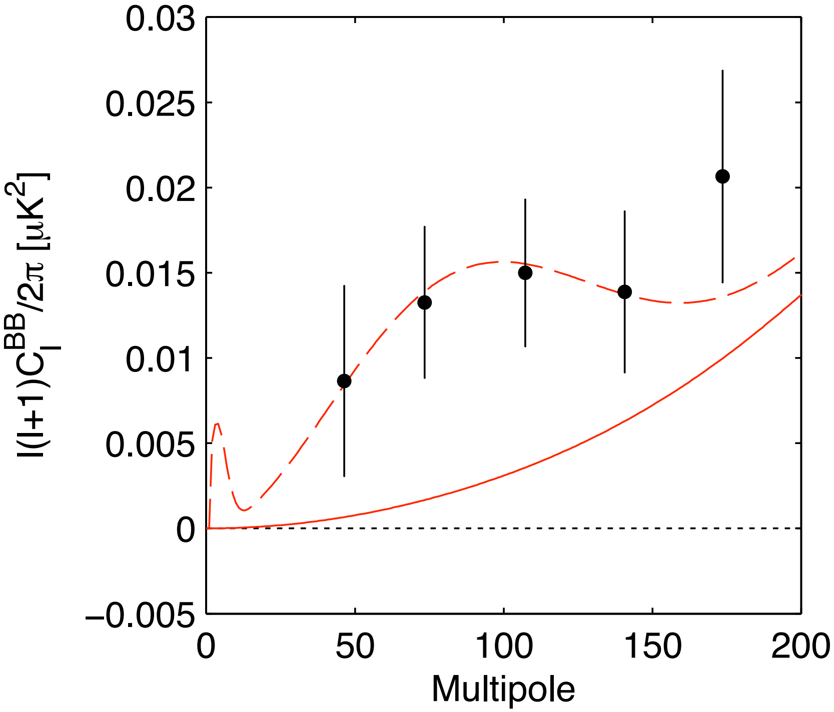
- Small (26 cm) refractive microwave telescope operating at South Pole, specifically designed to do B-mode science
- Deep integration on low Galactic emission small patch (380 deg^2 or 0.9% of the sky, 87 nK per 1 deg pixel in polarization)
- Array of 512 TES Bolometers (one order of magnitude *more* than Planck)
- Single frequency at 150 GHZ, operated from to 2010 to 2012. Predecessor BICEP1 (also 100 GHz), follower BICEP3. Keck array (5 x BICEP2, with also 100 and 220 GHz in operation within same facility from 2014.

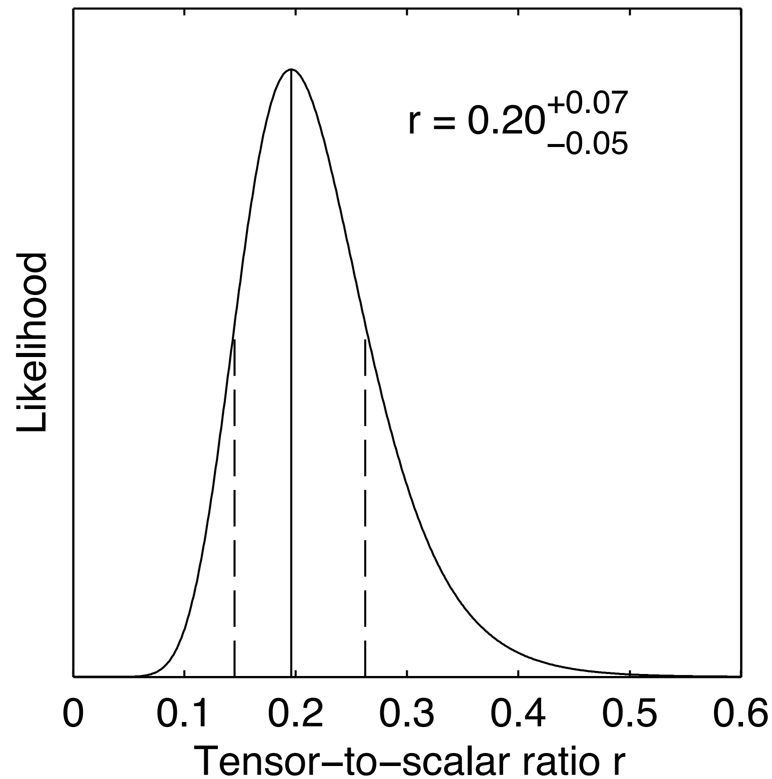






BICEP2 has detected a substantial B-mode excess at degree angular scales, where the inflationary signal is expected to peak



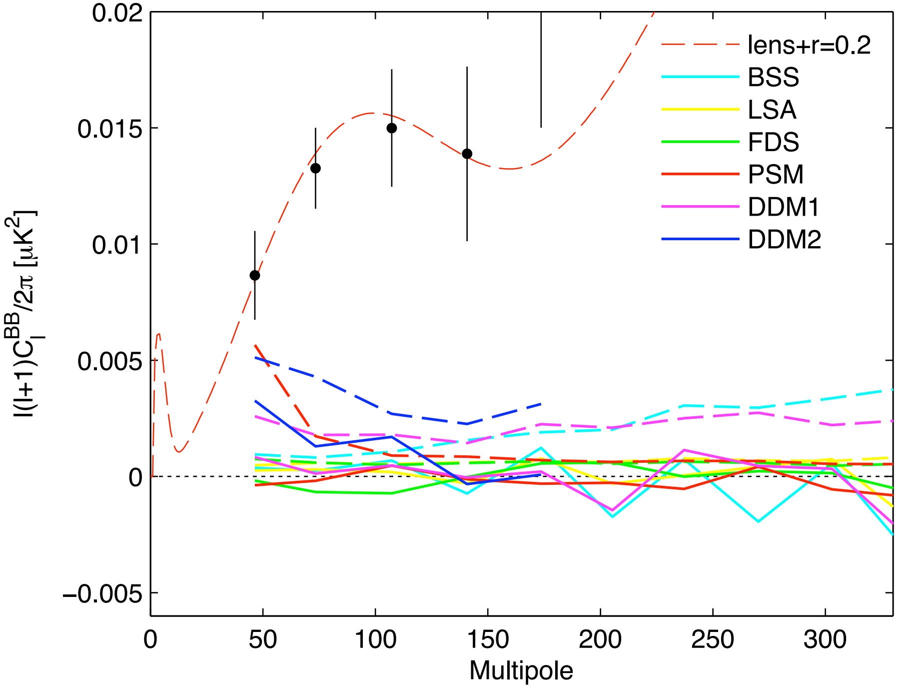


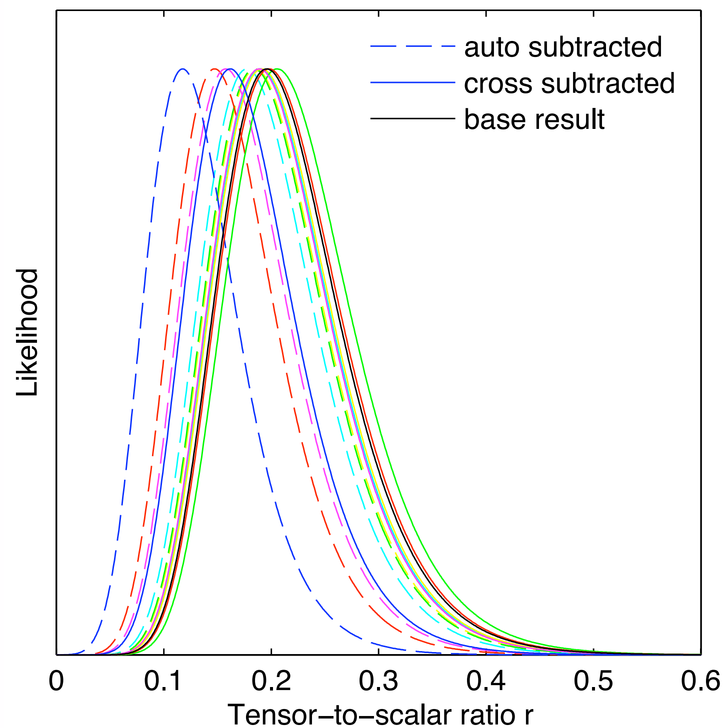
r = 0.20 +/– 0.05

Implies inflation @ ~ 2x10^{16} GeV

r=0 ruled out at high significance

Tension with Planck and other CMB (r < 0.11)?





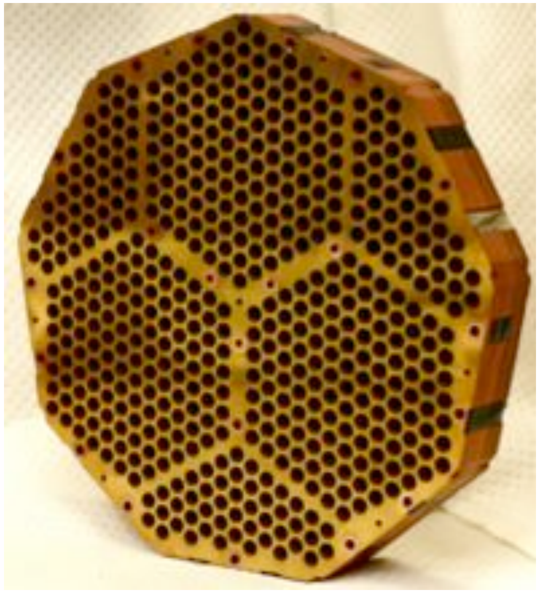
Different foreground modeling can bring r down to 0.16

Also, the tension can be reconciled in extended models (all limits are model dependent)

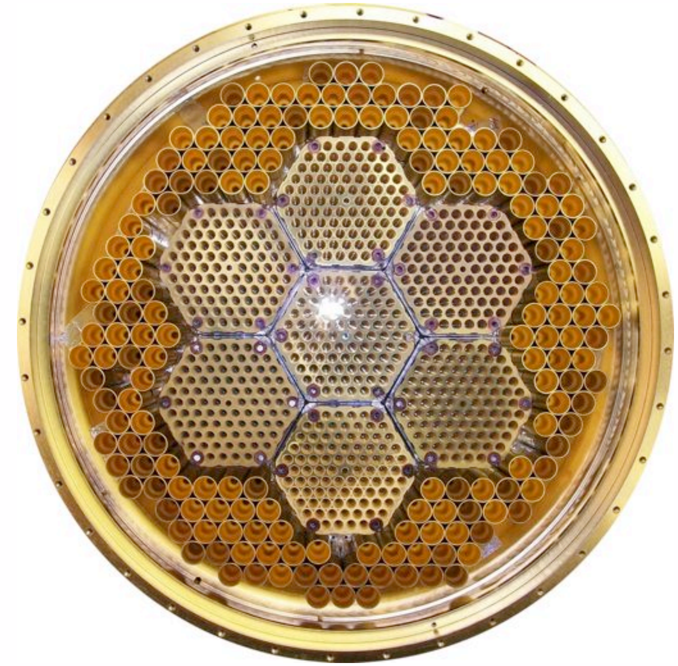
ACTPol

Polarization sensitive updgrade to ACT

~3000 TES detectors @90, 150 GHz. First light Jul 2013
Observed four regions for a total ~ 280deg2 for three months in 2013
EE spectrum should be coming (very?) soon

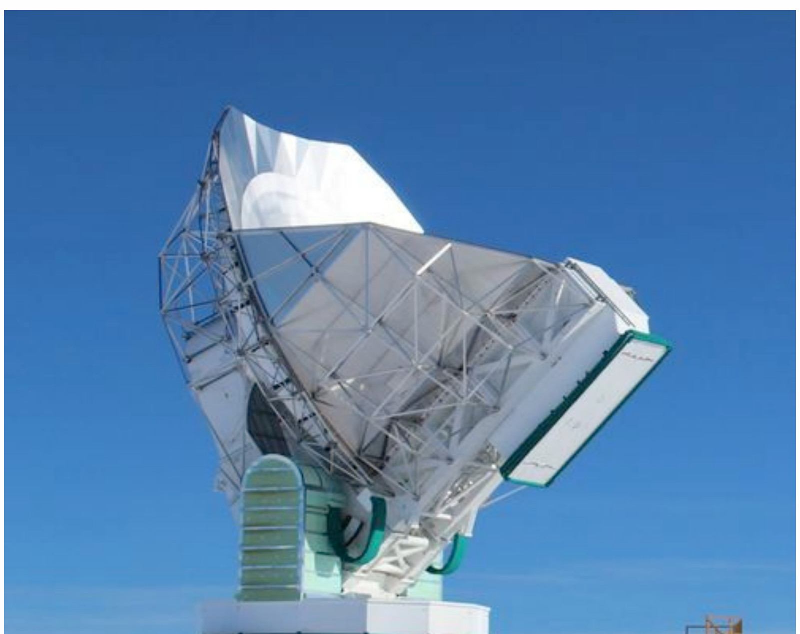


SPTPol

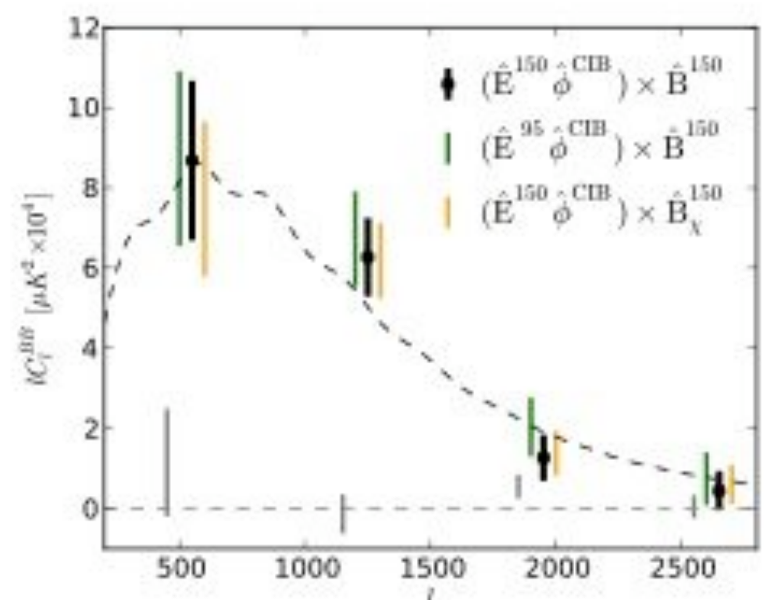


Polarization-sensitive upgrade to SPT

- 1600 TES detectors @90, 150 GHz. First light Jan 2012
- observed 100deg^2 field in 2012, observing 500deg^2 in 2013-2015
- EE spectrum should be coming soon



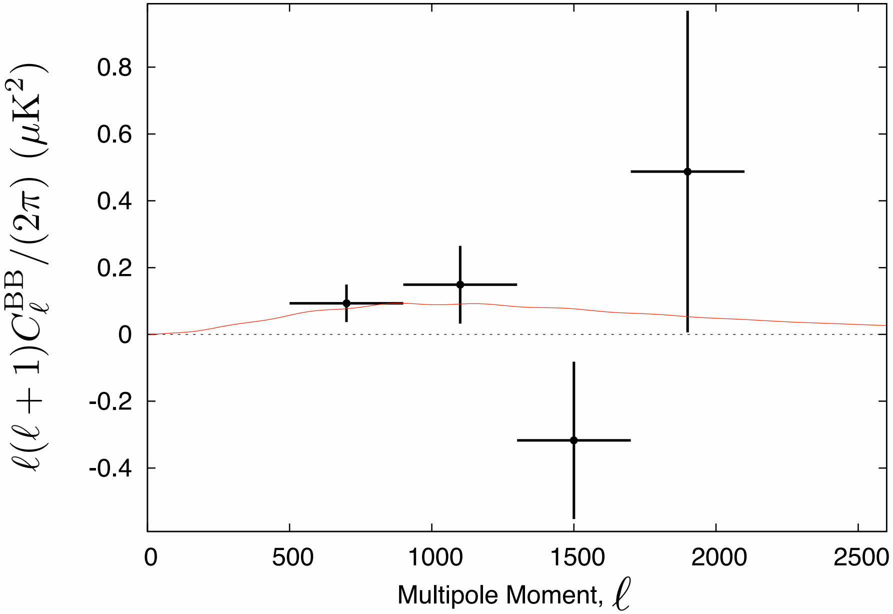
Detection of the lensing B-modes



POLARBEAR

CMB polarization dedicated experiment in Atacama desert
4m telescope
~ 1200 TES detectors @ 150 GHz
3.5' resolution
Targets both large and small scales
Upgrade in 2014: 7588 detectors @90, 150 GHz

Detection of the lensing B-modes



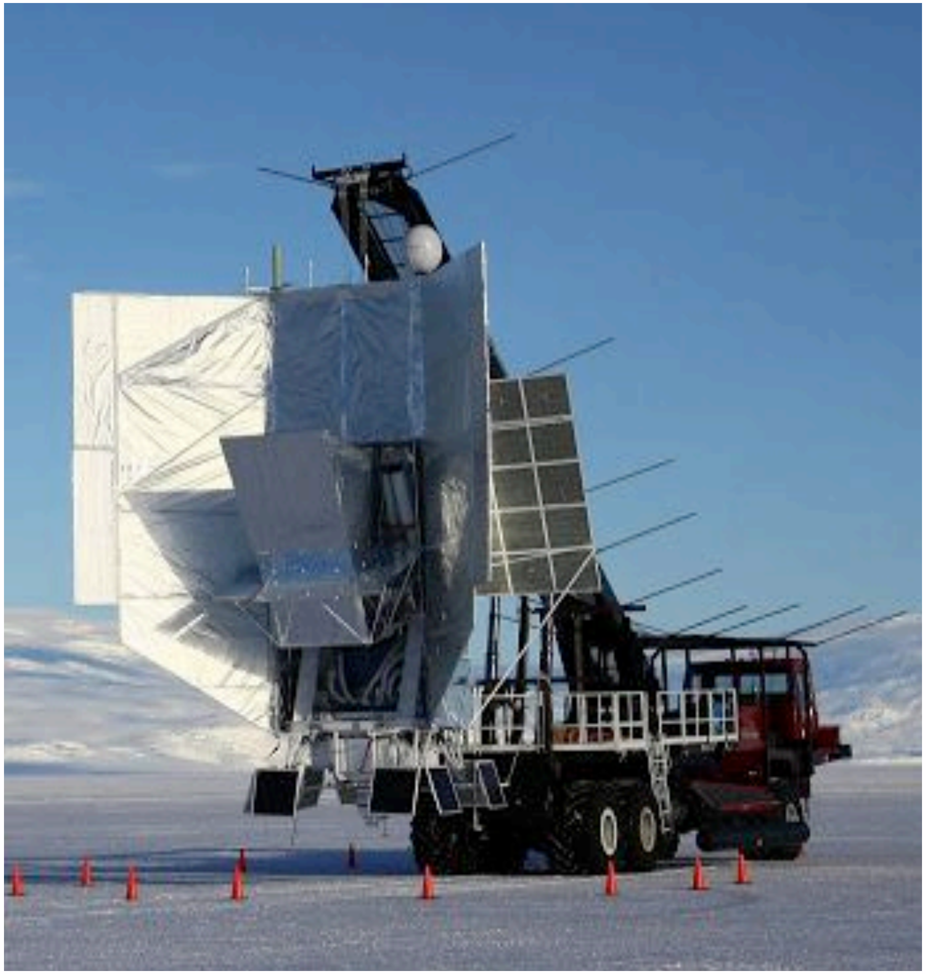
EBEX

Balloon-borne CMB polarization dedicated experiment

~ 1000 TES detectors @ 150, 250, 410 GHz

8’ resolution

Analysis of the data collected from the observation of ~6000 deg^2 during the first science flight is ongoing

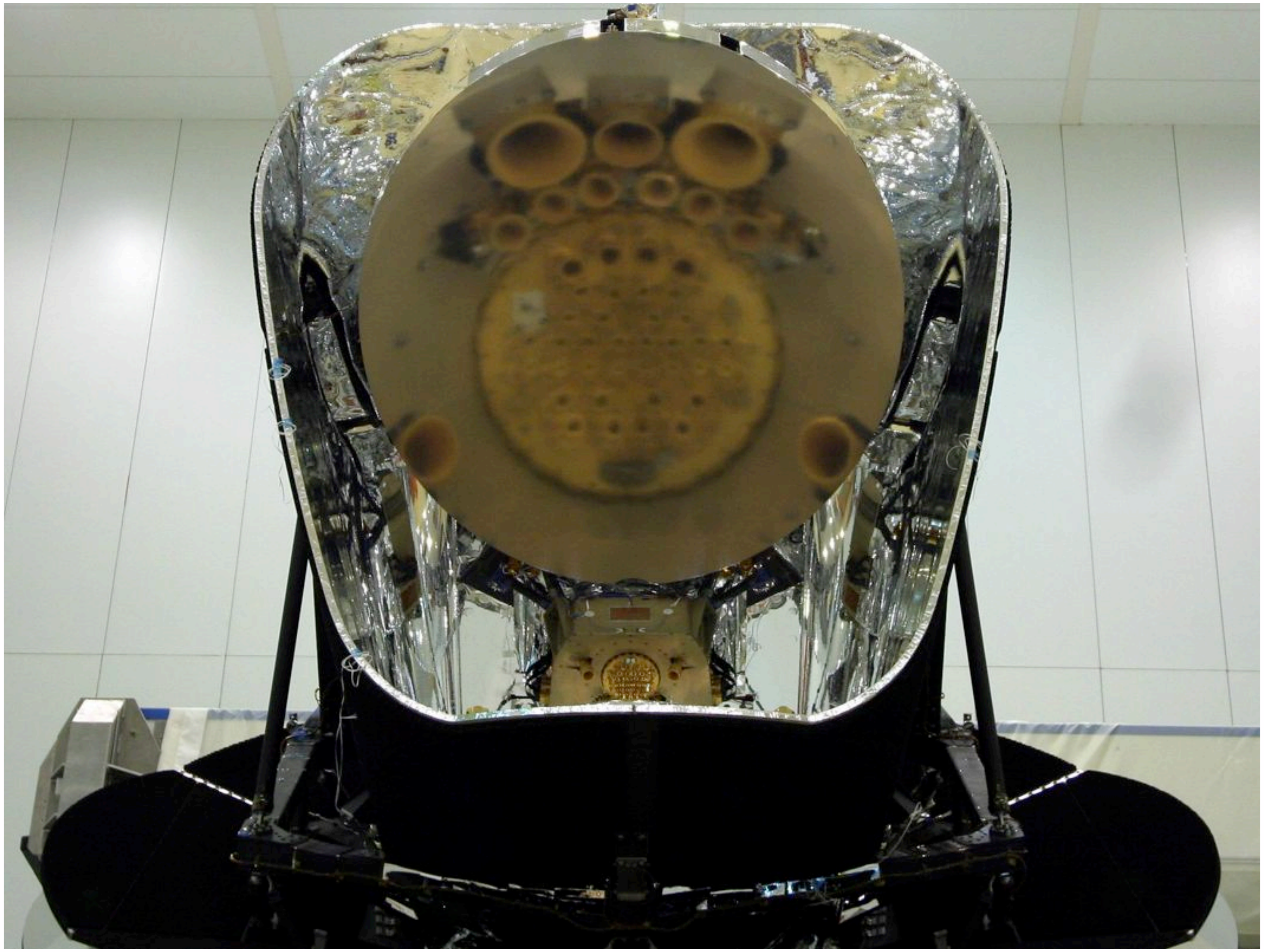


KECK ARRAY

5 polarimeters, each very similar to BICEP2
~ 2500 TES detectors @ 100, 150 GHz
Analysys is ongoing

PLANCK

is going to release polarization data (including maps at high frequencies, crucial for fg removal) with the second release, later this year



Cosmological parameters

6-parameters model

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Baryon density today	$\Omega_b h^2$	0.00028	0.00013
Cold dark matter density today	$\Omega_c h^2$	0.0027	0.0010
Thomson scattering optical depth	τ	0.013	0.0042
Hubble constant [km/s/Mpc]	H_0	1.2	0.53
Scalar spectrum power-law index	n_S	0.007	0.0031

Constraints on other parameters

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Effective number of neutrino species	N_{eff}	0.42	0.18
Fraction of baryonic mass in helium	Y_p	0.035	0.010
Dark energy equation of state	w	0.32	0.20
Varying fine-structure constant	α/α_0	0.0043	0.0018

→ Expected reduction in error bars by factors of 2 or more

THE FUTURE

- Upgrades already planned for many of these experiments: SPT-3G (2016), ABS (operative), AdvACT (?), Simons Array (2018), EBEX6K (?)

- SPTPol, ACTPol, EBEX, Keck Array results should come soon

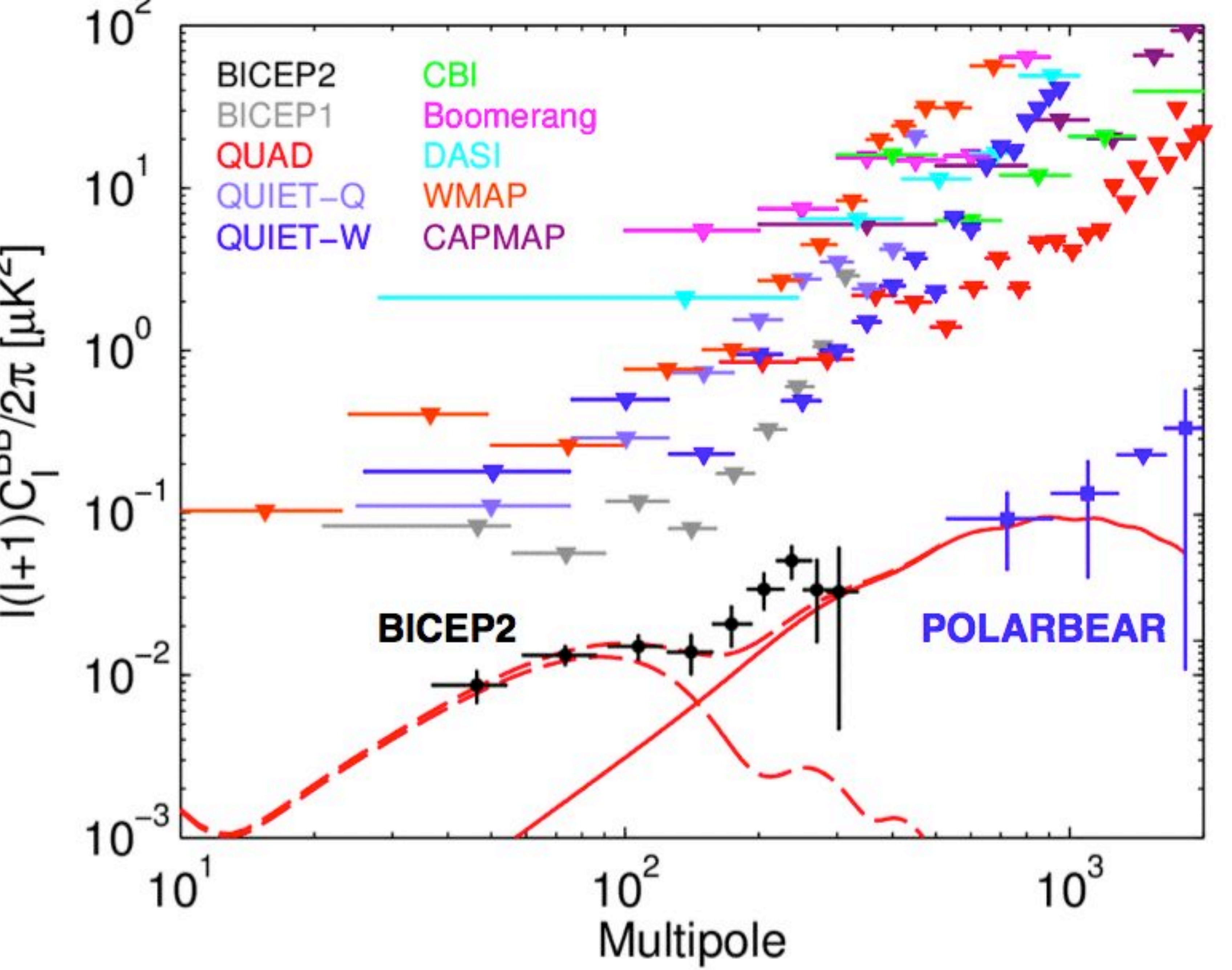
- Spider will fly later this year

- Proposed space missions: CORE/PRISM (see white paper astro-ph/1306.2259), PIXIE, LITEBIRD

SUMMARY

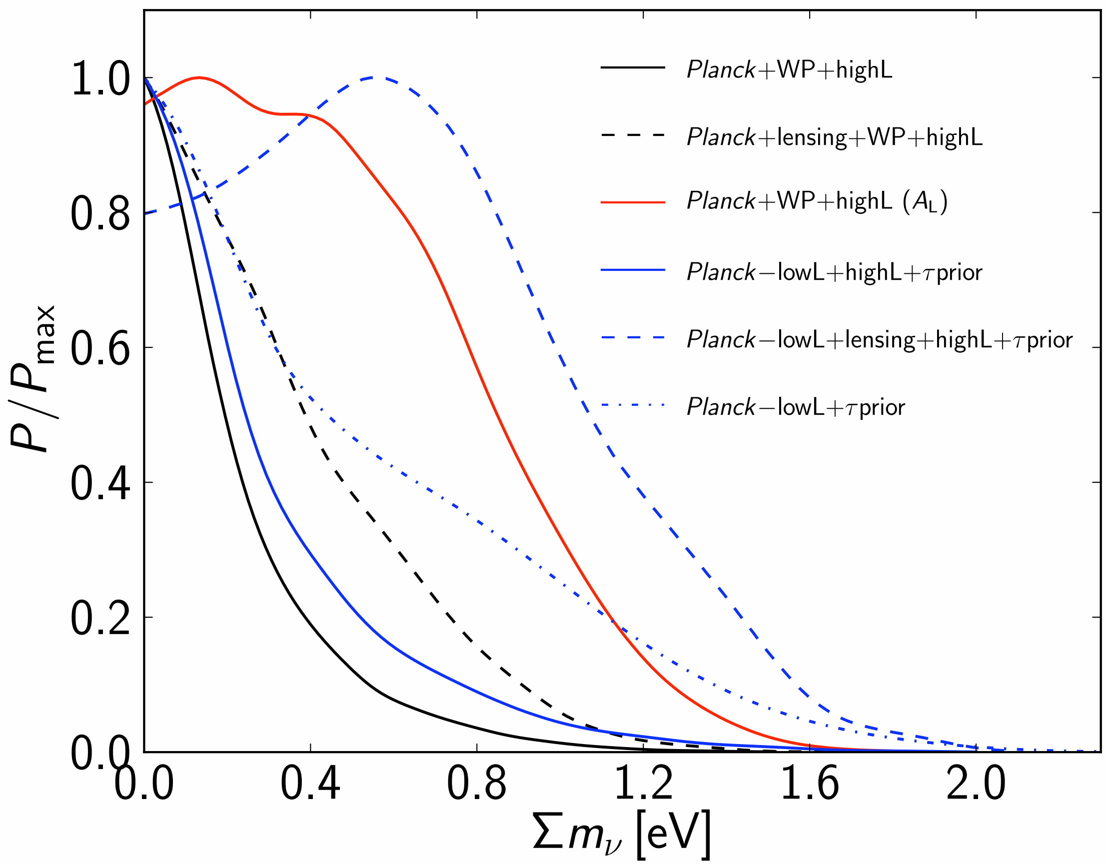
- Precision observations of the CMB are at the basis of our current understanding of the Universe
- The next Planck data release will yield the definitive characterization of the temperature anisotropies over a wide range of scales
- The future is called polarization.
- Several ground-based experiments are currently targeting the CMB polarization. Some of them are expected to release their results in next months.
- Planck polarization also is coming later this year.
- The BICEP2 detection is a breakthrough – but needs independent confirmation!
- The different experiments are complementary
- A polarization-dedicated space mission, in the long run, is necessary

BACKUP SLIDES



BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
BICEP2
POLARBEAR
$l(l+1)C_l^{BB}/2\pi$ [μK²]
Multipole
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3

Constraints on neutrino mass



Σm_ν < 0.93 eV (Planck+WP)

Σm_ν < 0.66 eV (Planck+WP+highL)

Σm_ν < 0.25 eV (Planck+WP+BAO)

Σm_ν < 0.23 eV (Planck+WP+highL +BAO)

Σm_ν < 1.08 eV [Planck+WP+highL (A_L)]

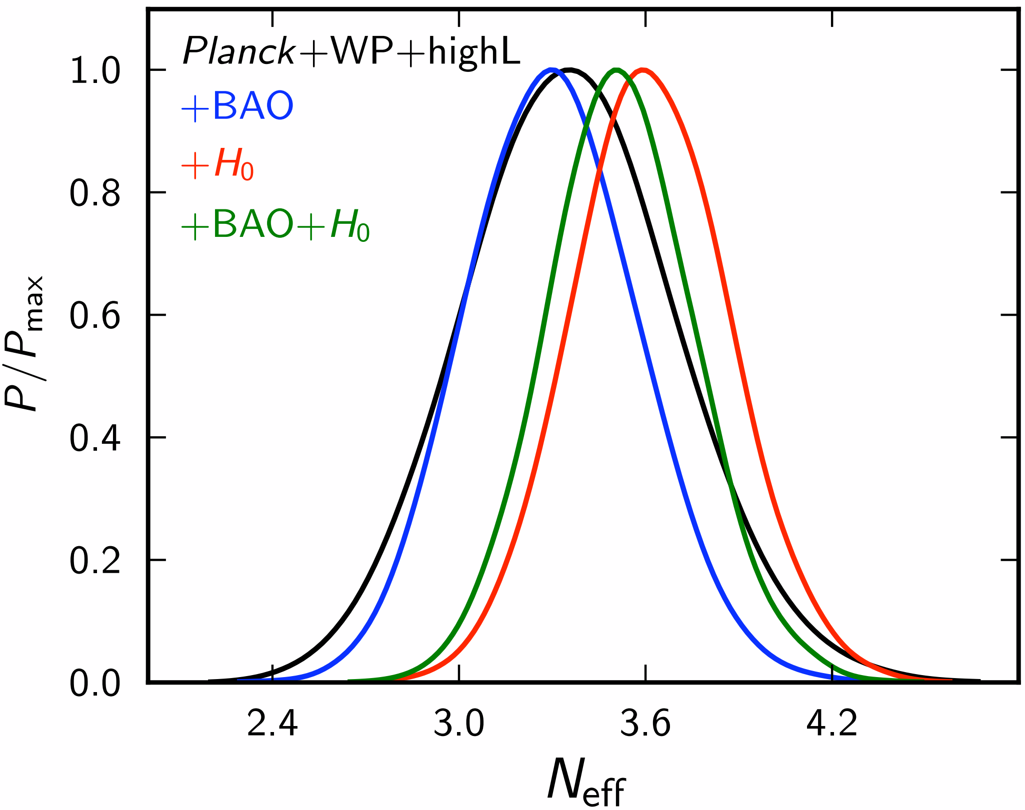
Σm_ν < 0.85 eV (Planck+lensing +WP+highL)

(all limits are 95% CL)

- the posterior broadens when the lensing information is removed from the TT spectrum
- the constraint is also degraded when we add the information on the lensing spectrum itself (as estimated from the temperature trispectrum TTTT)
- this is because the 4-point function has a mild preference for larger masses wrt the 2-point function

Probing N_{eff} with CMB data

For Planck + other CMB datasets:



$N_{eff} = 3.51^{+0.80}_{-0.74}$ (Planck+WP)

$N_{eff} = 3.36^{+0.68}_{-0.64}$ (Planck+WP+ highL)

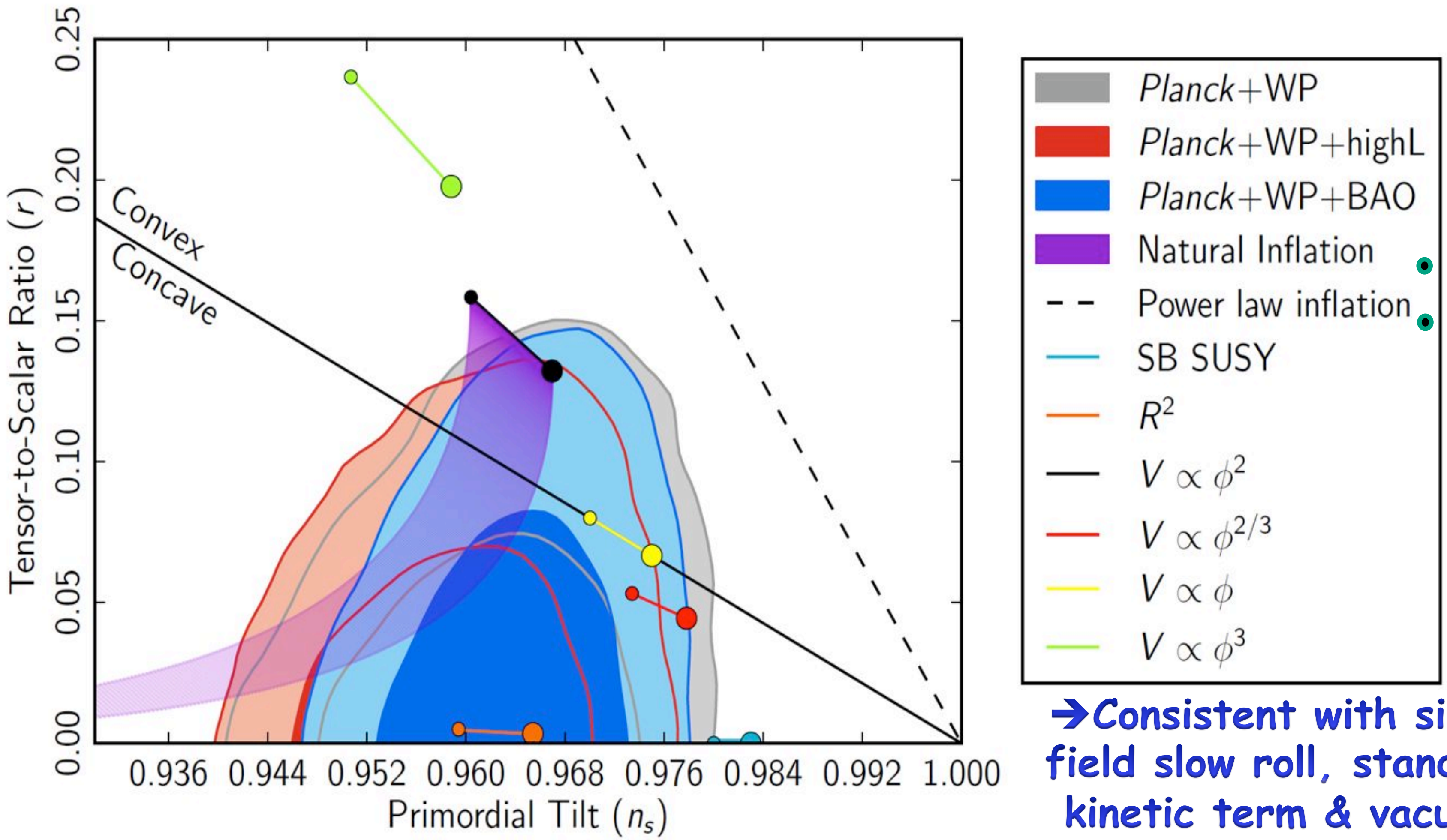
$N_{eff} = 3.39^{+0.77}_{-0.70}$ (Planck+WP+lensing)

$N_{eff} = 3.28^{+0.67}_{-0.64}$ (Planck+WP+highL+ lensing)

(all limits are 95% CL)

- $N_{eff} = 0$ is excluded at ~ 10 sigma
- both $N_{eff} = 3$ and $N_{eff} = 4$ are always within 2σ

Main constraint on Inflation physics



➔Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits).

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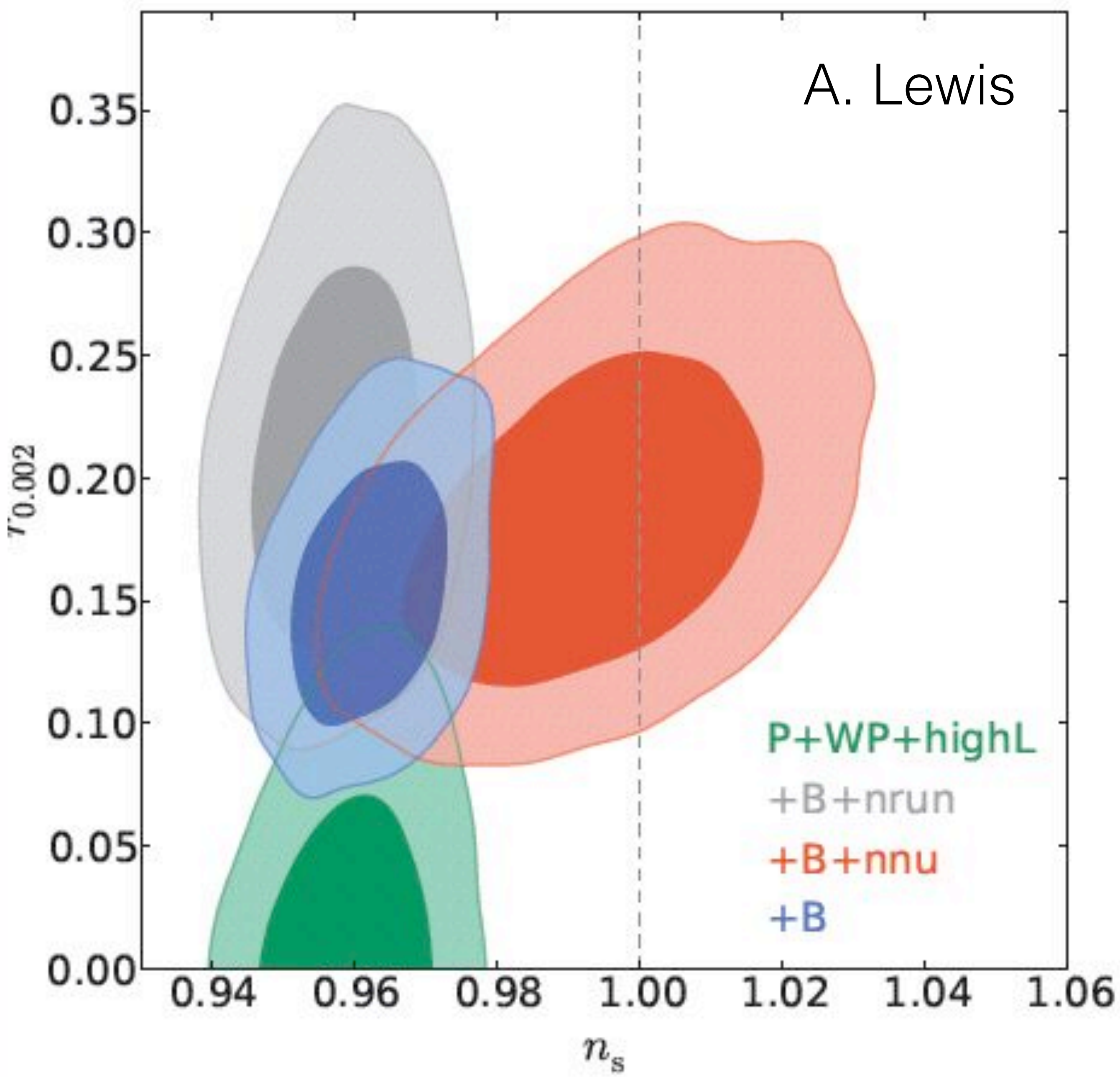
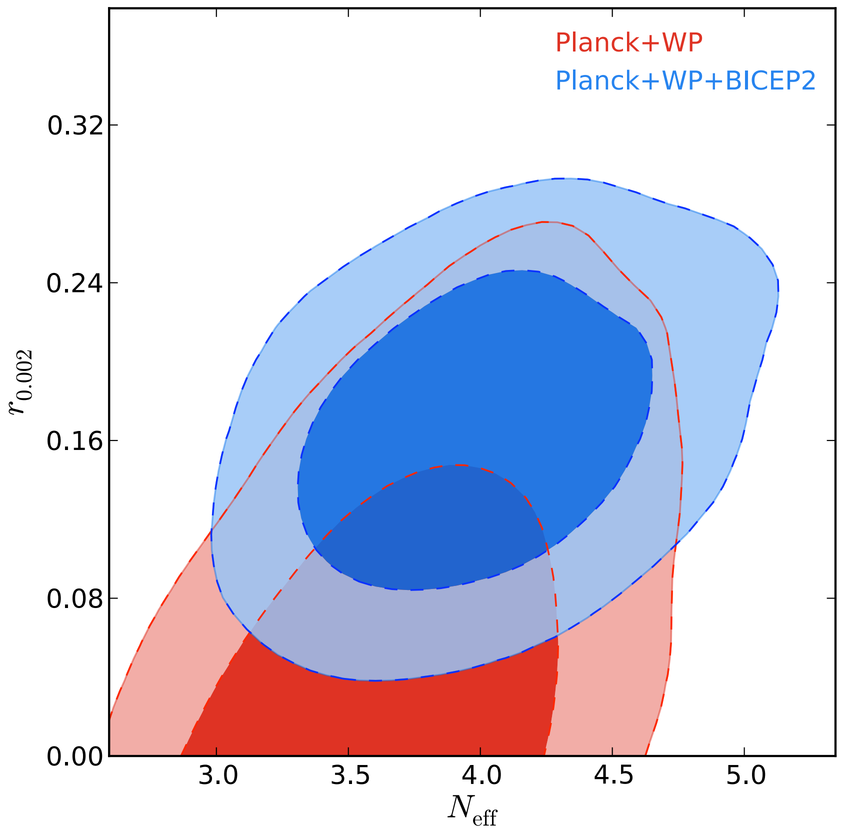
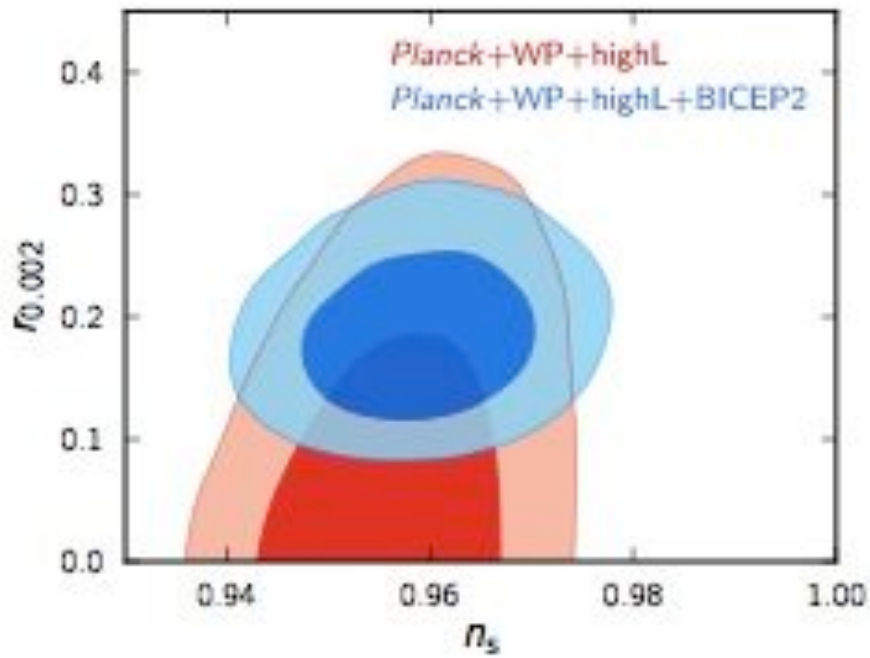
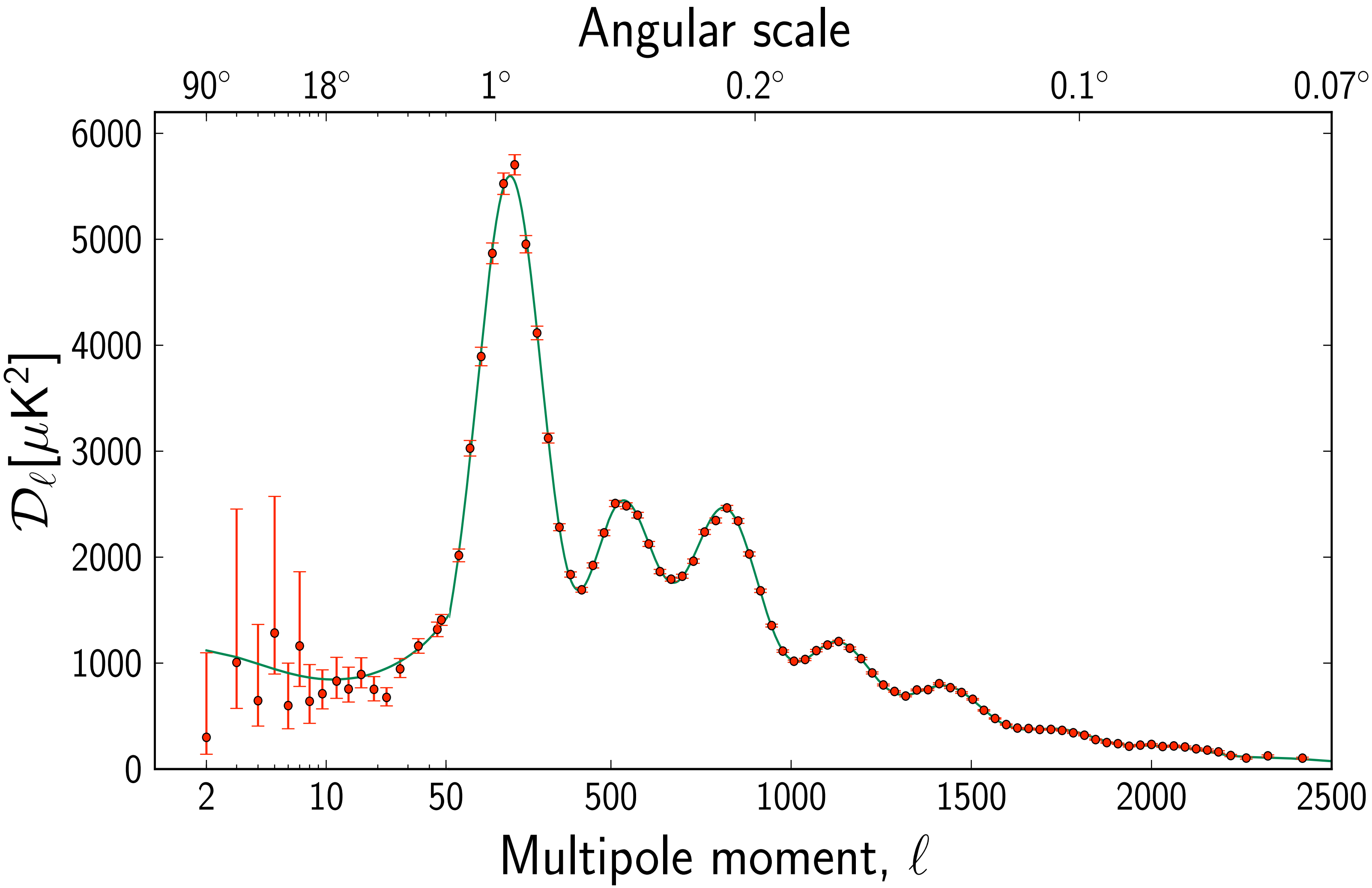

A. Lewis
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
1.02
1.04
1.06
$r_{0.002}$
n_s
P+WP+highL
+B+nrun
+B+nnu
+B

Additional relativistic species (Giusarma et al., 2014)



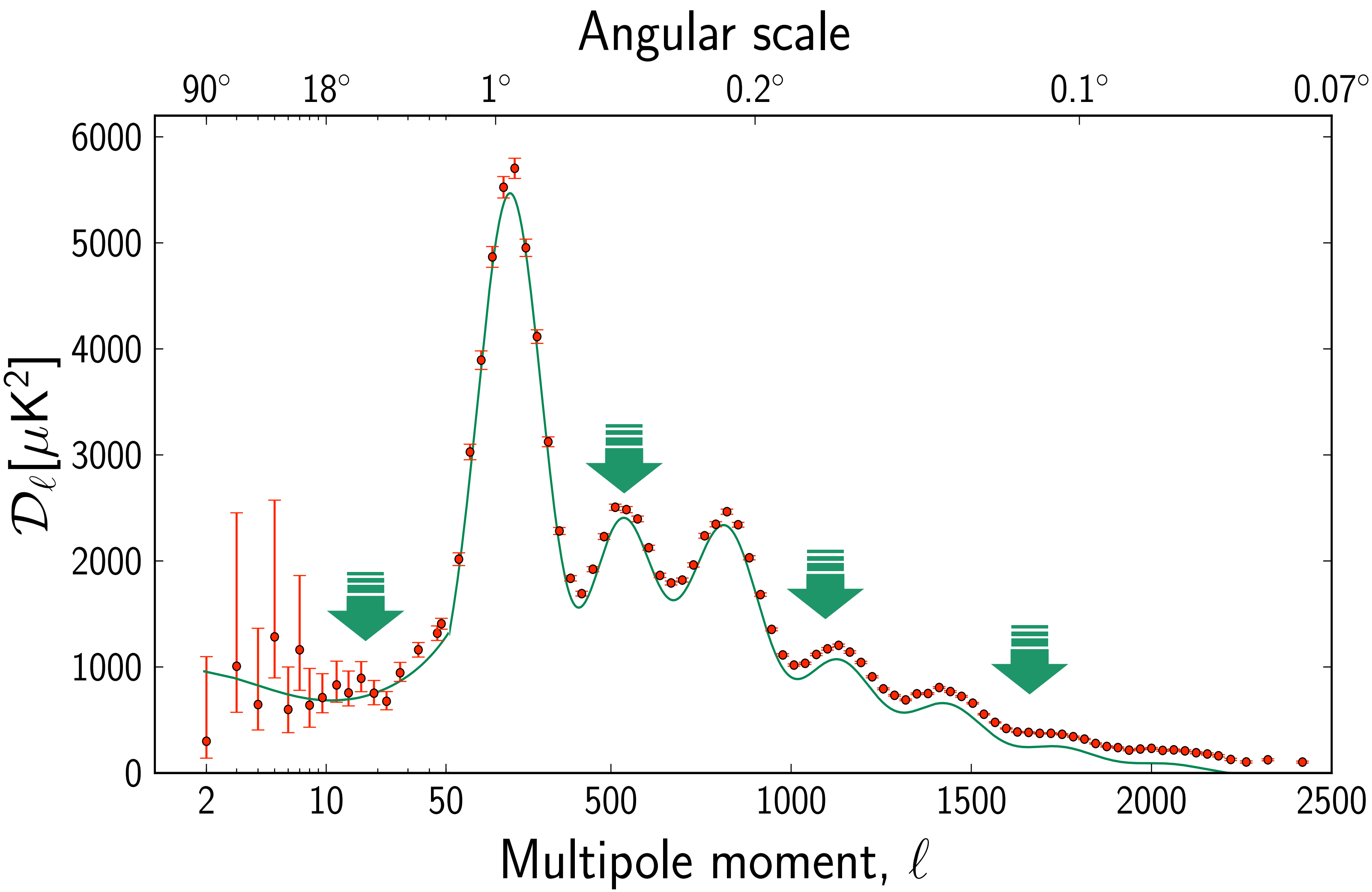
Running of the spectral index (BICEP2 paper)



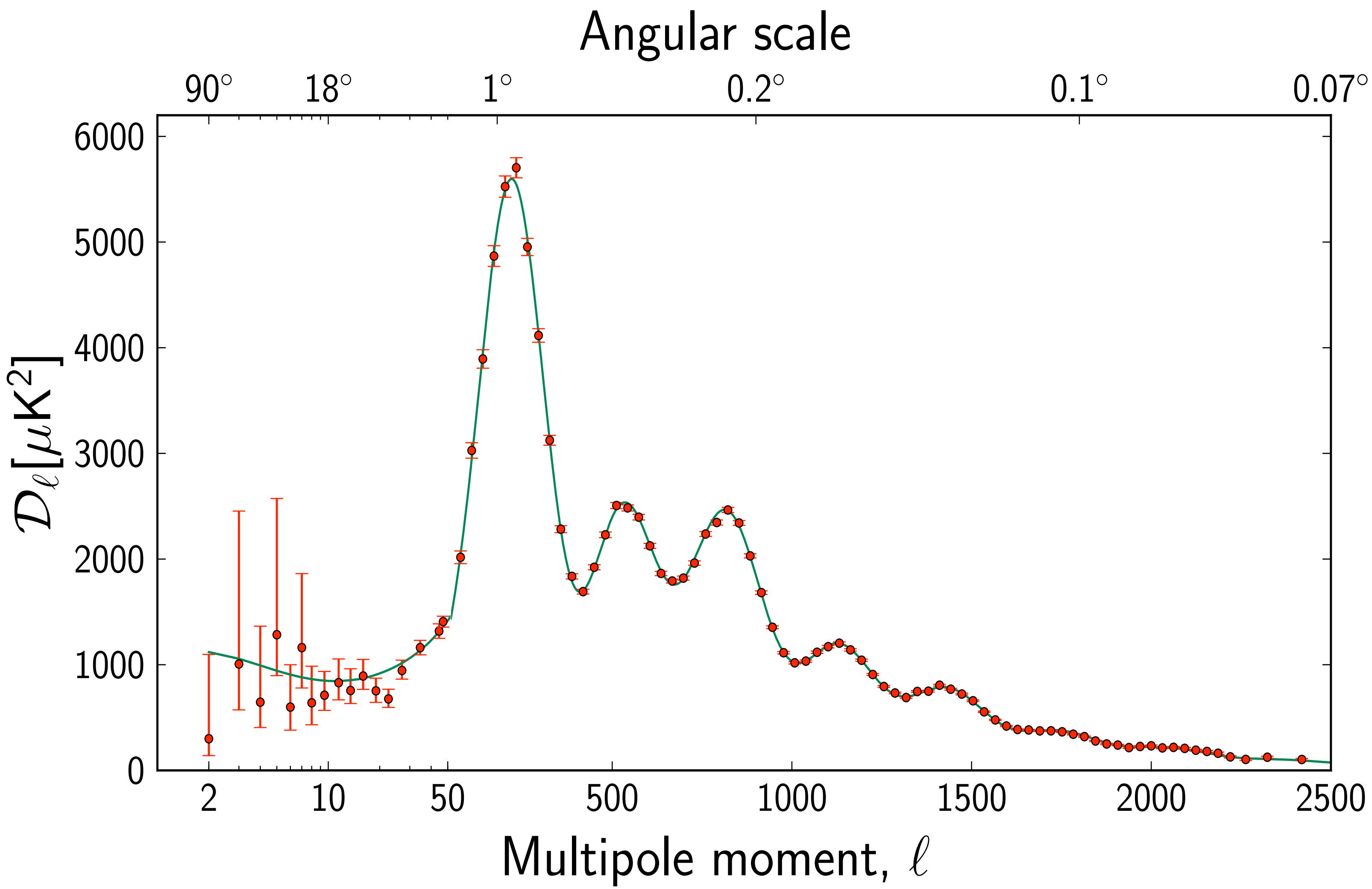


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

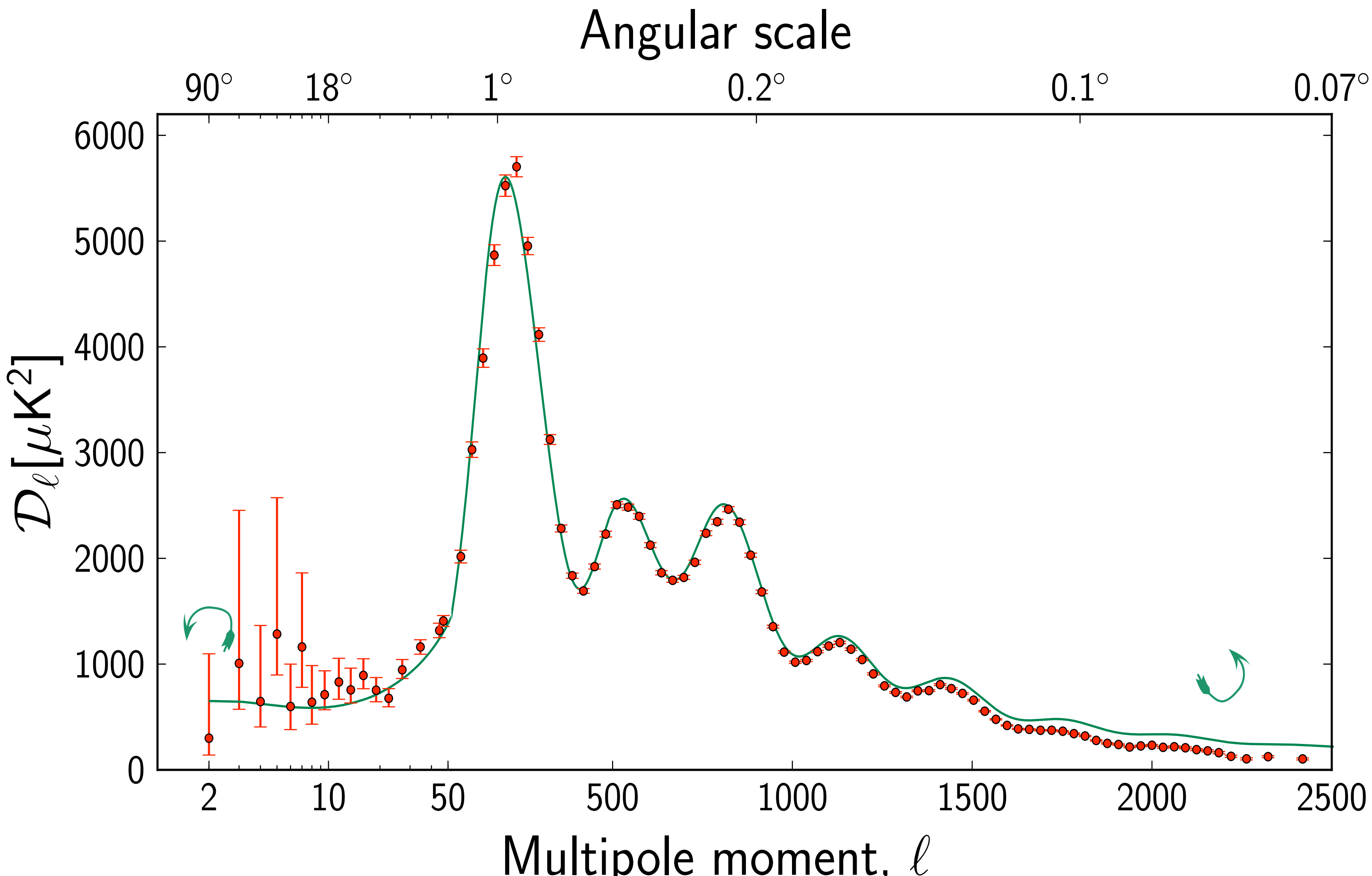
The low-l anomaly



The low-l anomaly



The low-l anomaly



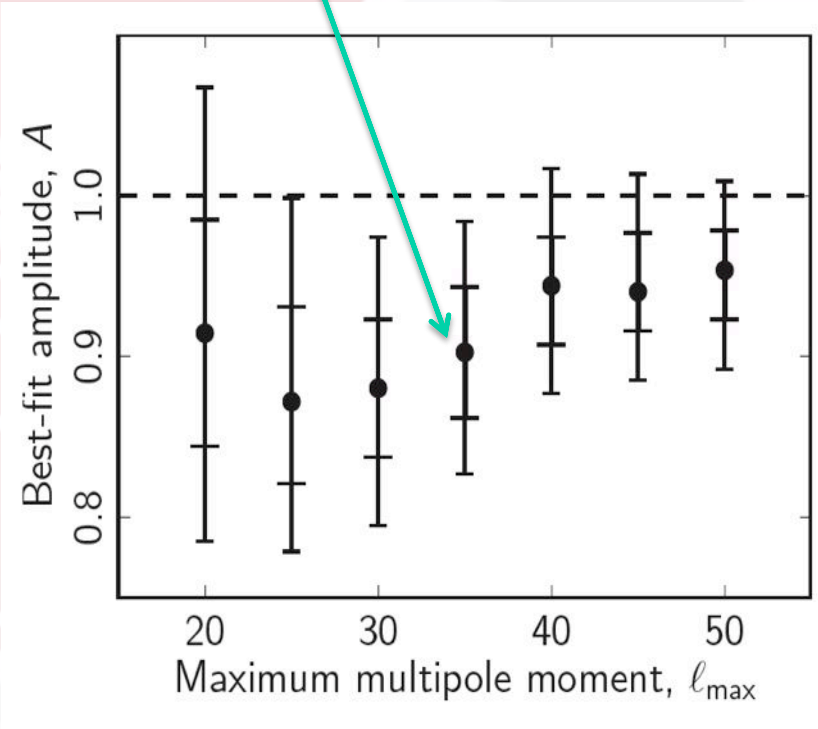
A simple amplitude test

- Rescale the power spectrum in amplitude:

$$C_\ell(A) = A\ C_\ell^{\Lambda CDM}$$

- Find the best-fit A as a function of maximum multipole l.
- There is a 99% “anomaly” for l_{max}=30.
- The anomaly fades away at higher multipoles → where theory and data agree remarkably well.

< 1 at more then two σ



Checking consistency by SFH

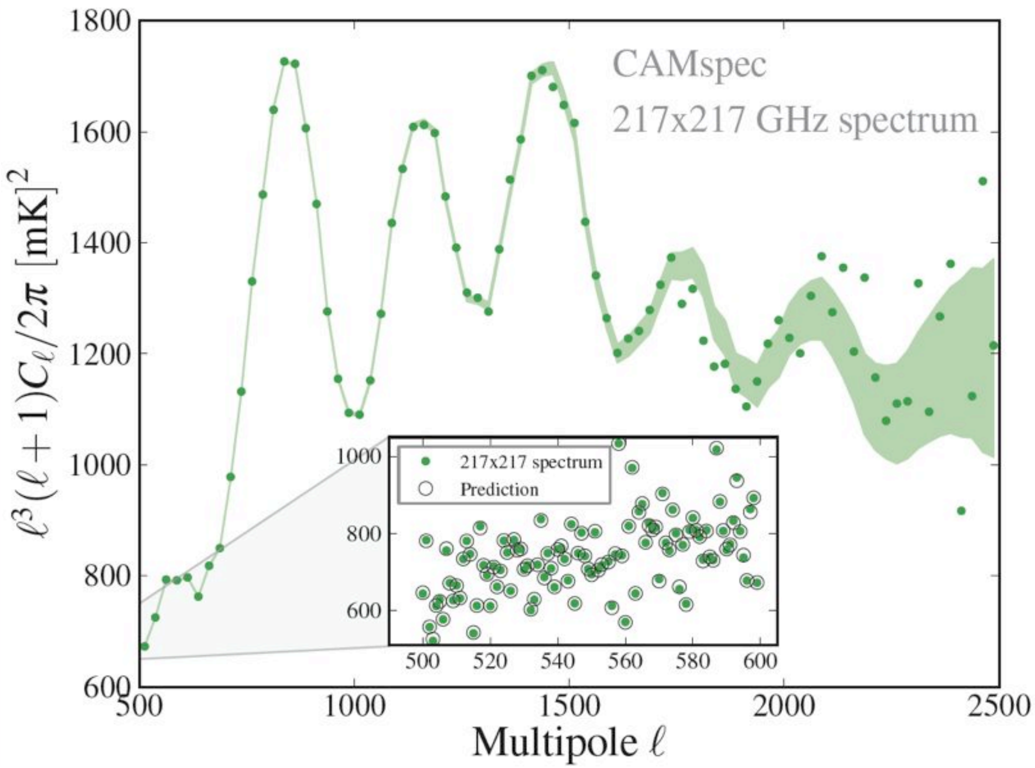
SFH draw 500 samples of the 217x217 spectrum from the CamSpec covariance, *conditioning* on the observed 100x100, 143x143, and 143x217 spectra, assuming no beam uncertainty.

They then compare with our 217 X 217 GHz spectrum (below); they also replace the observed 217x217 spectrum in the likelihood by their sampled spectra and run to parameters (next).

The 217GHz Planck points appear:

- low at l ~ 1800, on the downside of the 6th peak
- High at l ≳ 2100, after the 7th peak

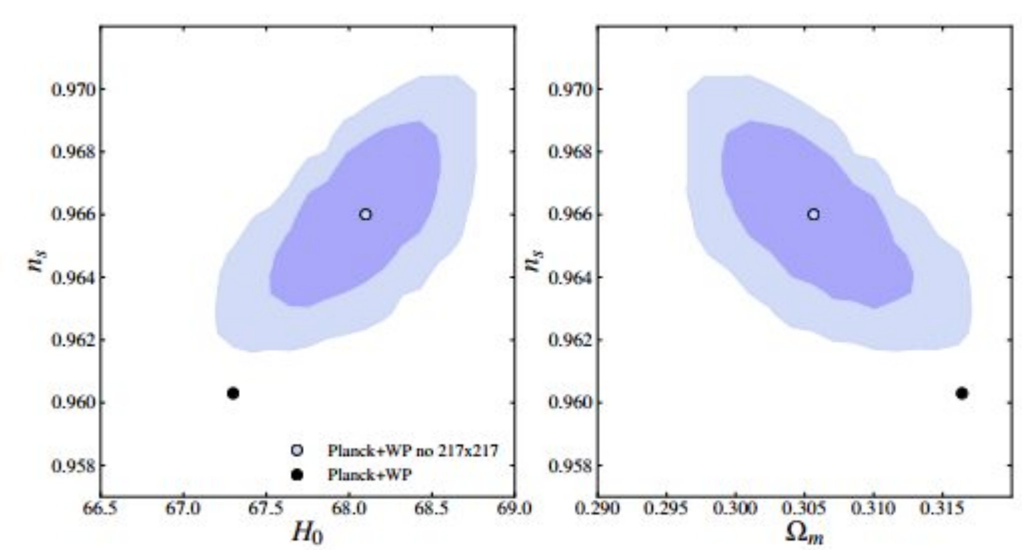
as compared to the expectation from the other cross-spectra



Claim 1

The parameter shift is larger than expected.

Fig 1 reproduced below shows the (Planck+ WP - 217x217) best fit value, surrounded by contours of the expected difference between when adding the 217x217 samples. Our actual Planck+WP values is the black point, suggesting it is moving by more than anticipated



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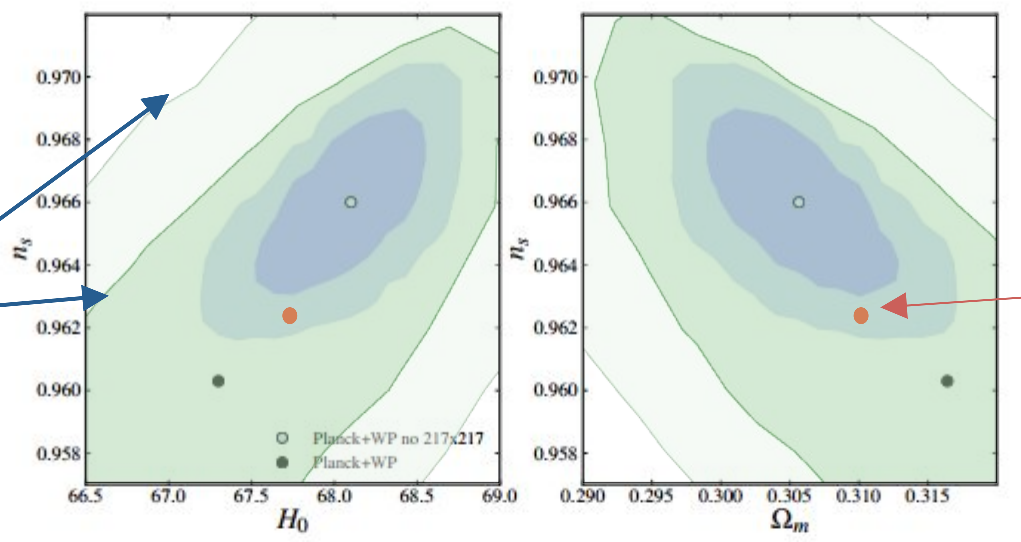
Planck+WP parameter posteriors @ 68 & 95% CL



Planck+WP with 1800 bite marginalized over

- The shift is quite small as compared to the final parameter uncertainty (green bands)
- We acknowledged ourselves the effect of the l~1800 bite – red point
- *SFH agree with us that this has very little impact on cosmological parameters*