Planck results 2015

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On behalf of the Planck collaboration

Pheno 2015, Pittsburgh, 04 May 2015

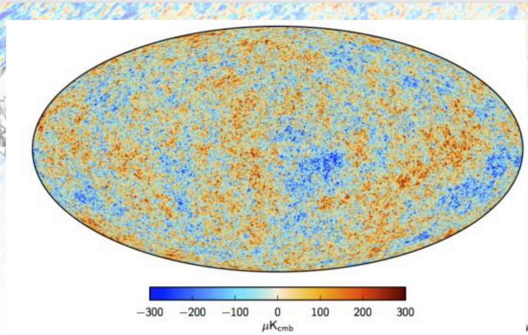
Planck 2015 results. I. Overview of products and results	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. II. Low Frequency Instrument data processing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. III. LFI systematic uncertainties	Planck Collaboration	2015 In prep.
Planck 2015 results. IV. LFI beams and window functions	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. V. LFI calibration	Planck Collaboration	2015 In prep.
Planck 2015 results. VI. LFI maps	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. VII. High Frequency Instrument data processing: Time-ordered information and beam processing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. VIII. High Frequency Instrument data processing: Calibration and maps	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. IX. Diffuse component separation: CMB maps	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. X. Diffuse component separation: Foreground maps	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XI. CMB power spectra, likelihood, and consistency of cosmological parameters	Planck Collaboration	2015 In prep.
Planck 2015 results. XII. Simulations	Planck Collaboration	2015 In prep.
Planck 2015 results. XIII. Cosmological parameters	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XIV. Dark energy and modified gravity	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XV. Gravitational lensing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XVI. Isotropy and statistics of the CMB	Planck Collaboration	2015 In prep.
Planck 2015 results. XVII. Primordial non-Gaussianity	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XVIII. Background geometry and topology of the Universe	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XIX. Constraints on primordial magnetic fields	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XX. Constraints on inflation	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XXI. The integrated Sachs-Wolfe effect	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XXII. A map of the thermal Sunyaev-Zeldovich effect	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XXIII. Thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation	Planck Collaboration	2015 In prep.
Planck 2015 results. XXIV. Cosmology from Sunyaev-Zeldovich cluster counts	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XXV. Diffuse, low-frequency Galactic foregrounds	Planck Collaboration	2015 In prep.
Planck 2015 results. XXVI. The Second Planck Catalogue of Compact Sources	Planck Collaboration	2015 In prep.
Planck 2015 results. XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XXVIII. The Planck Catalogue of Galactic Cold Clumps	Planck Collaboration	2015 Submitted to A&A

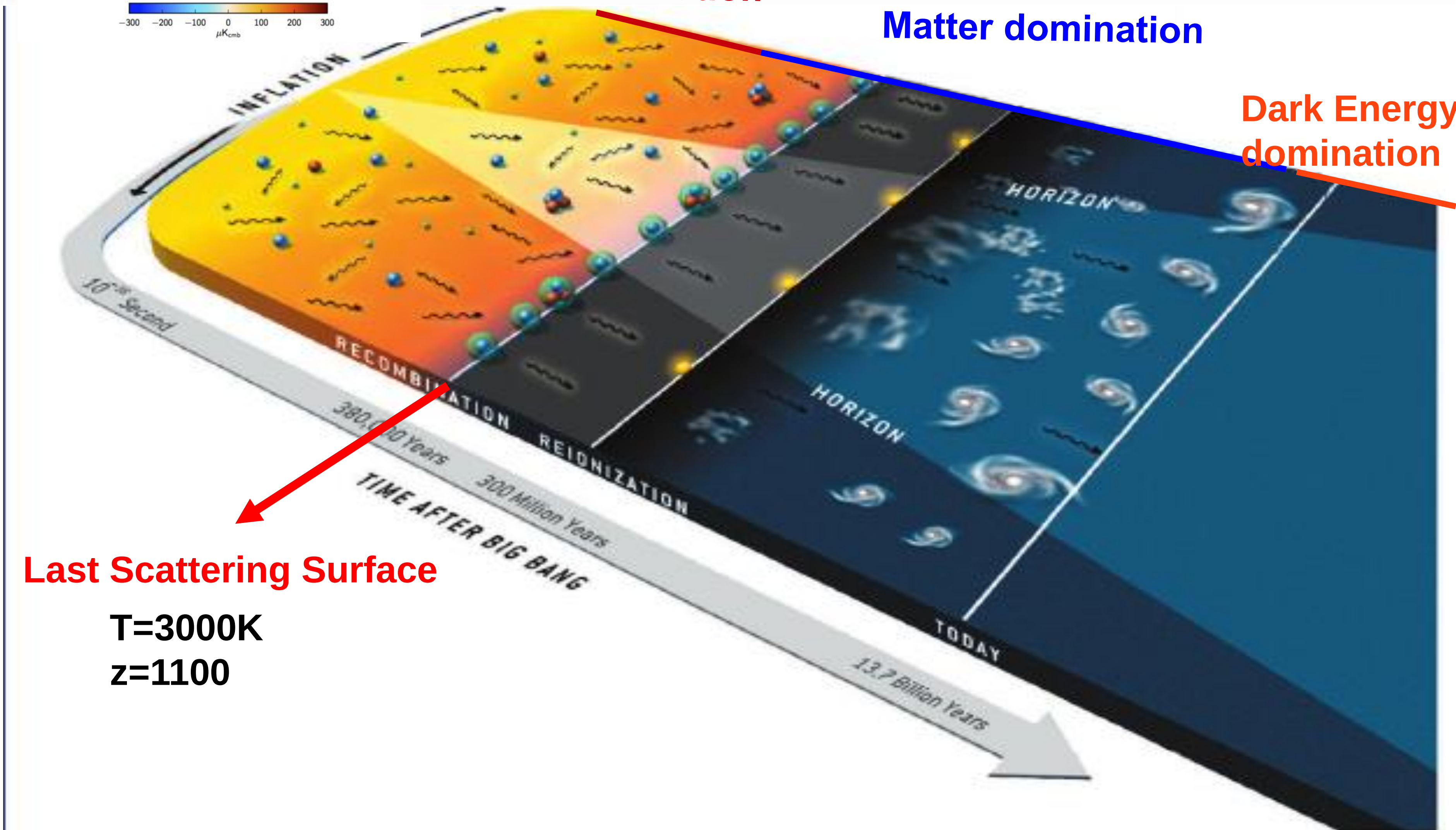
2015 Release

- 28 papers (few of them still in preparation)
- This talk will cover only a very small part of all these results, mostly in the Cosmological Parameters paper.

CMB in 2 slides

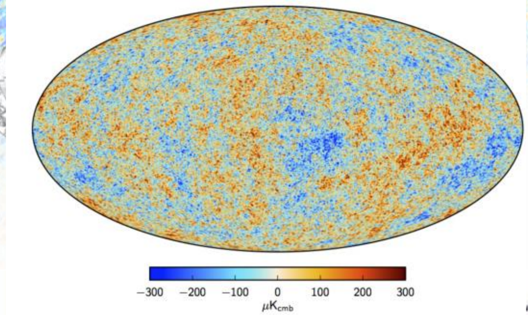
Cosmic History





Hu & White (2004), artist B. Christie/SciAm; available at http://background.uchicago.edu

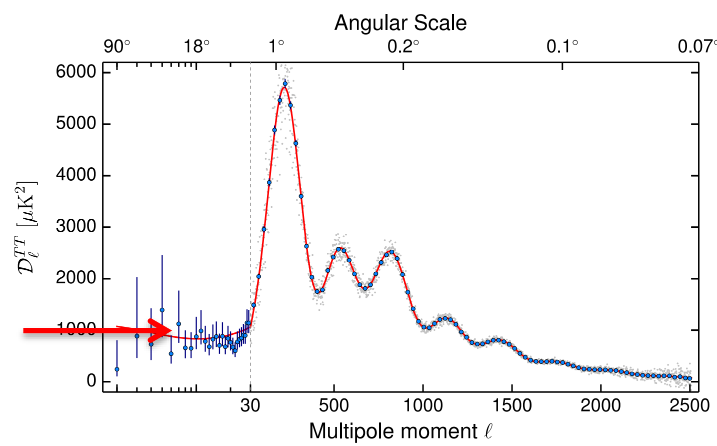
Cosmic History



CMB is an extremely rich source of information about our universe!

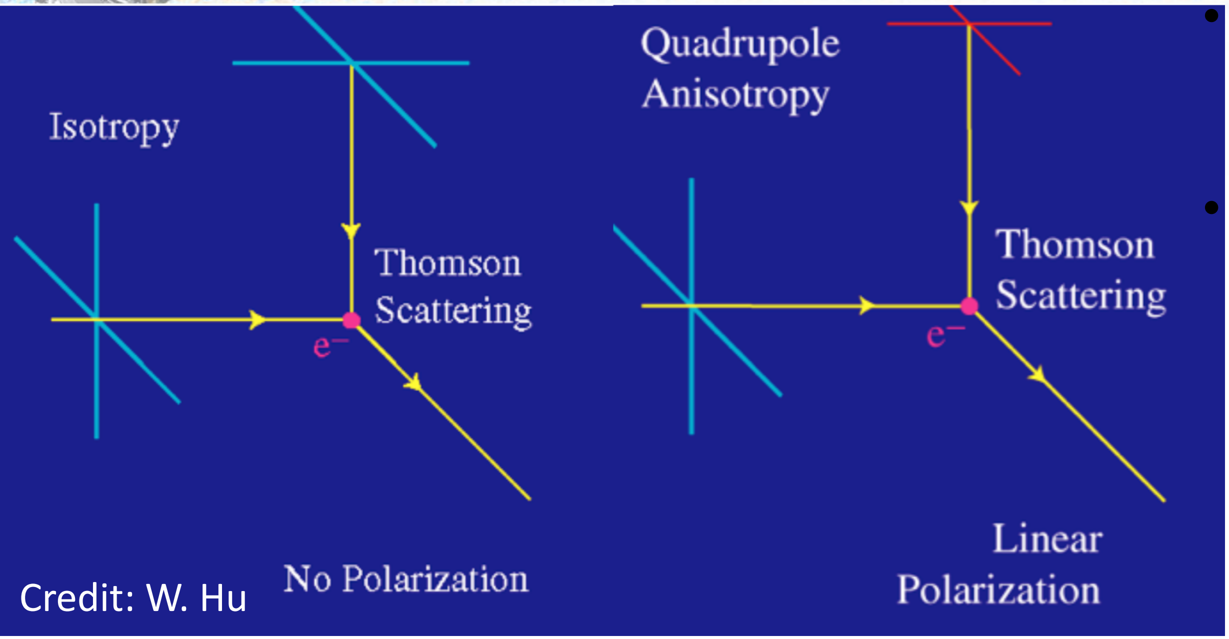
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}a^{*}_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$

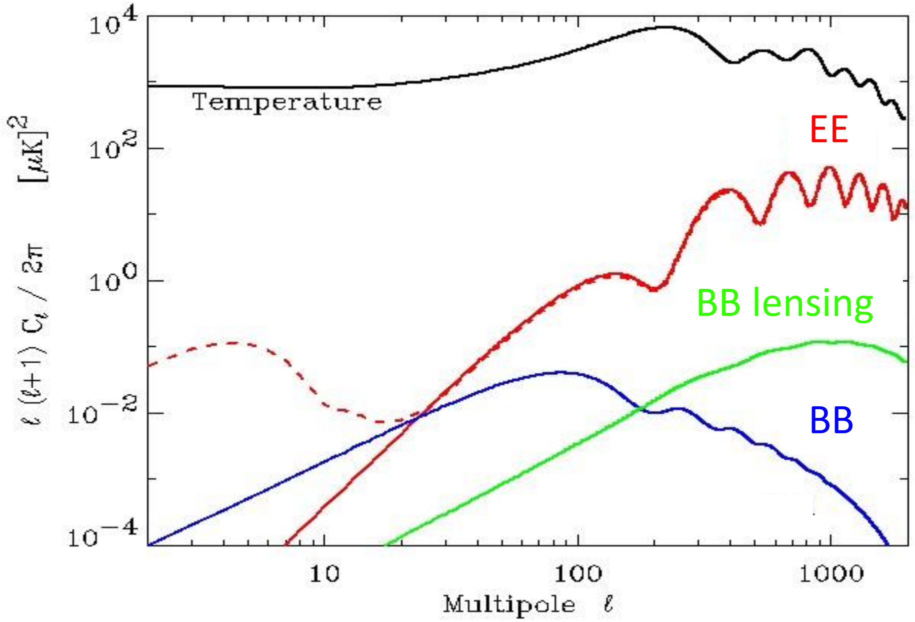


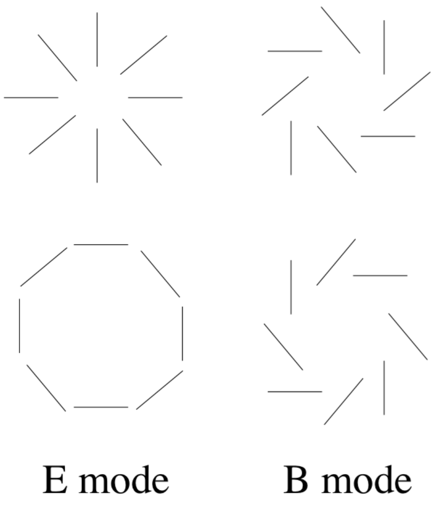
Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu

CMB Polarization



- Polarization generated by local quadrupole in temperature.
- Sources of quadrupole:
  - Scalar: E-mode
  - Tensor: E-mode and B-mode

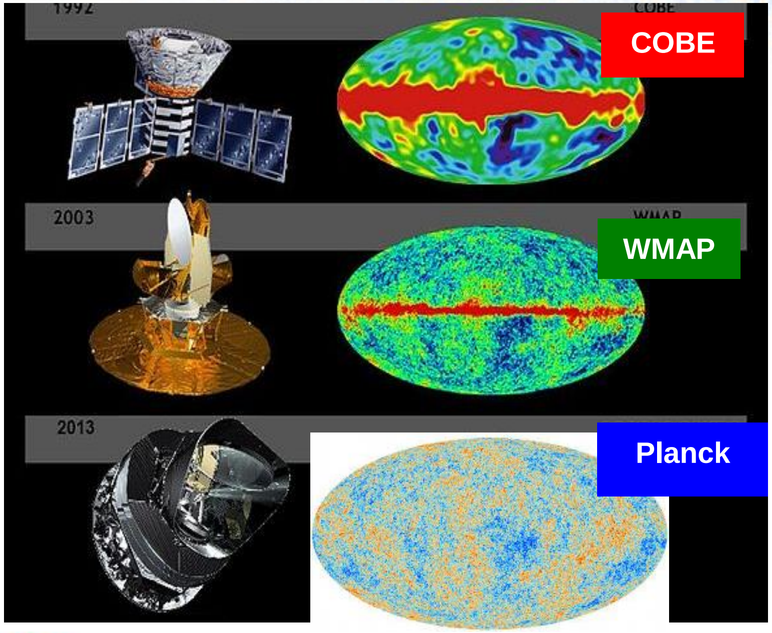


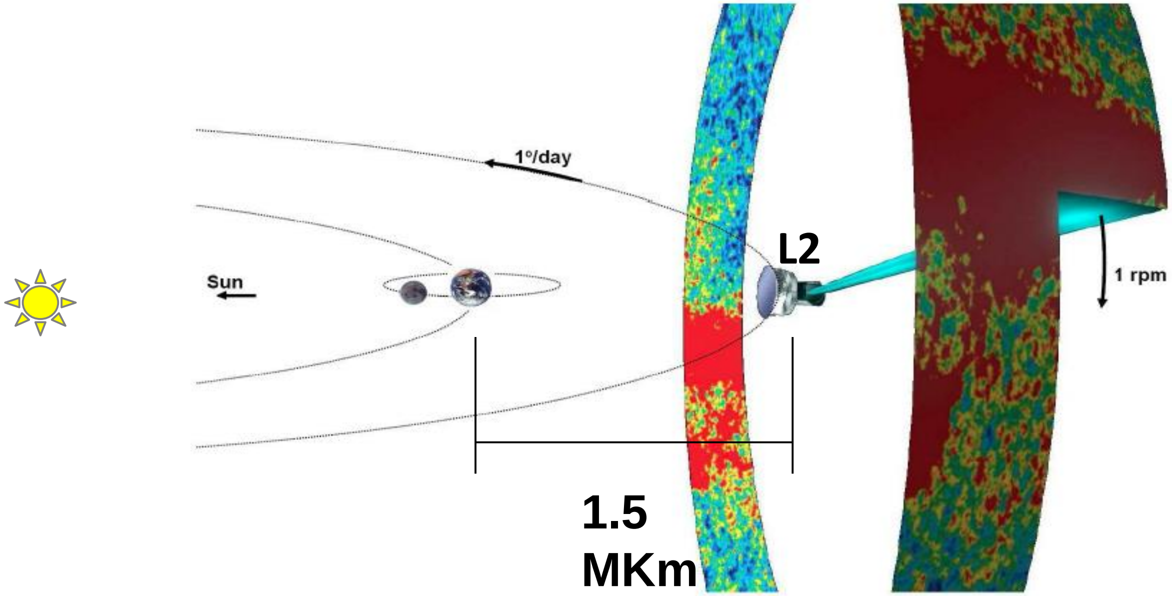


The Planck satellite

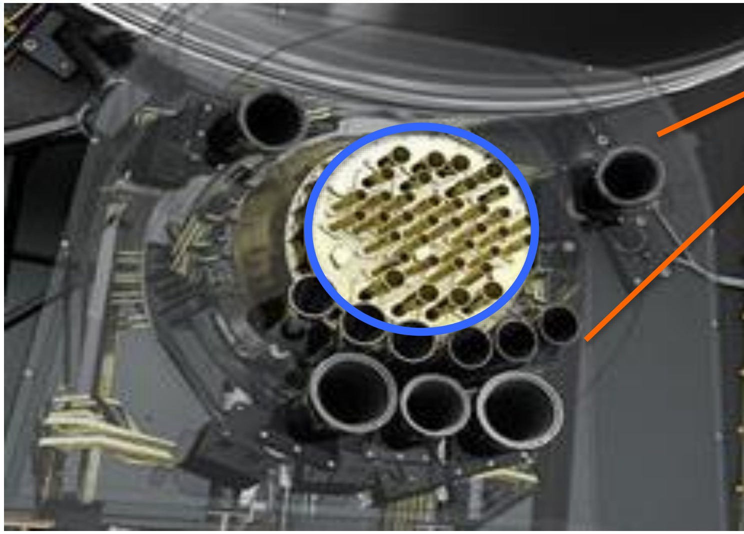
The Planck mission

- Third generation satellite missions.
- Launched in May 2009 to L2 (with Herschel), operated until 2013.
- Two scans of the entire sky every year.





9 Frequencies, 2 instruments



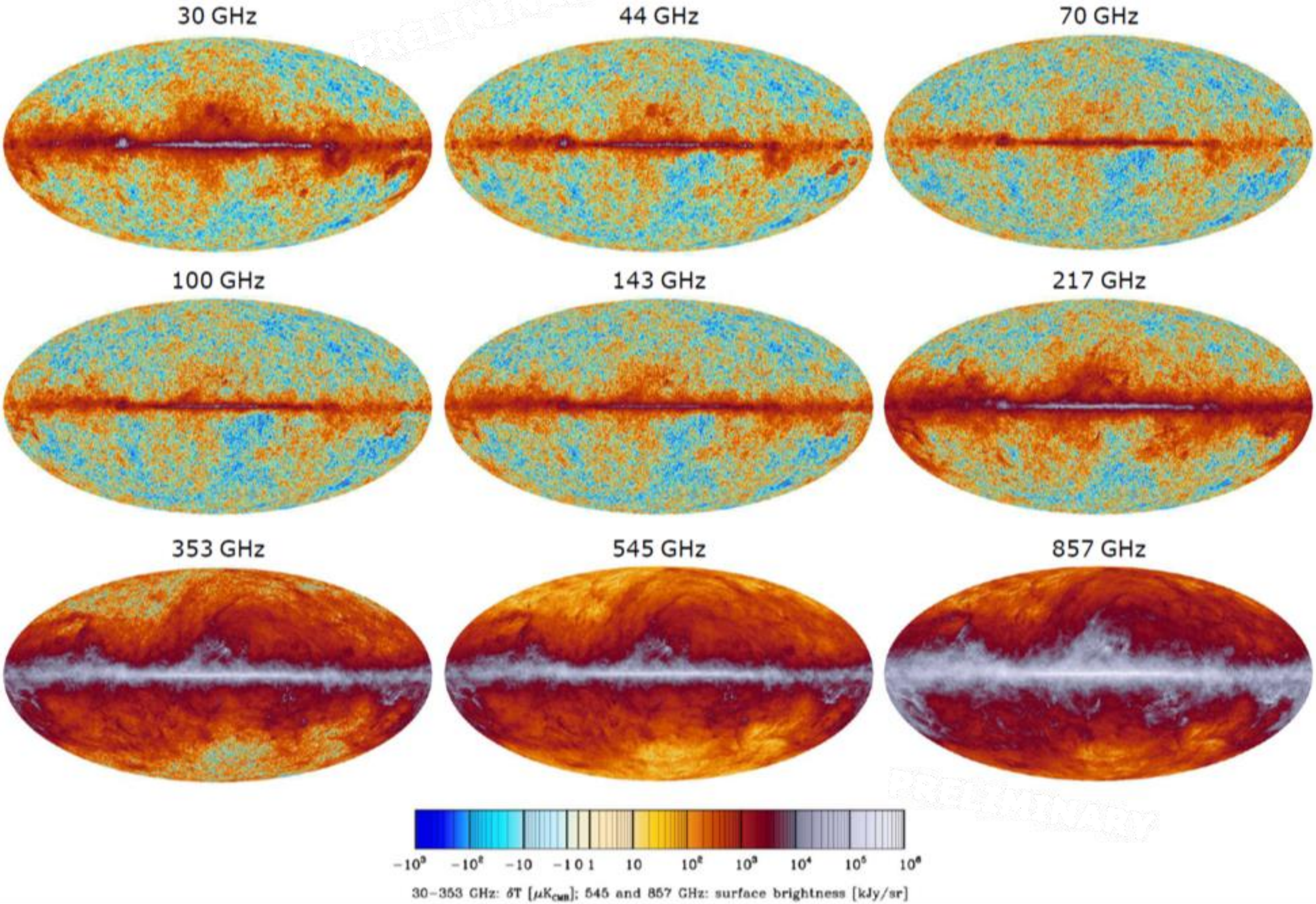
LFI:

- 22 radiometers at **30, 44, 70 Ghz.**
- Cooled at 20K.
- Operative till 2013 (**8** full scans)

HFI:

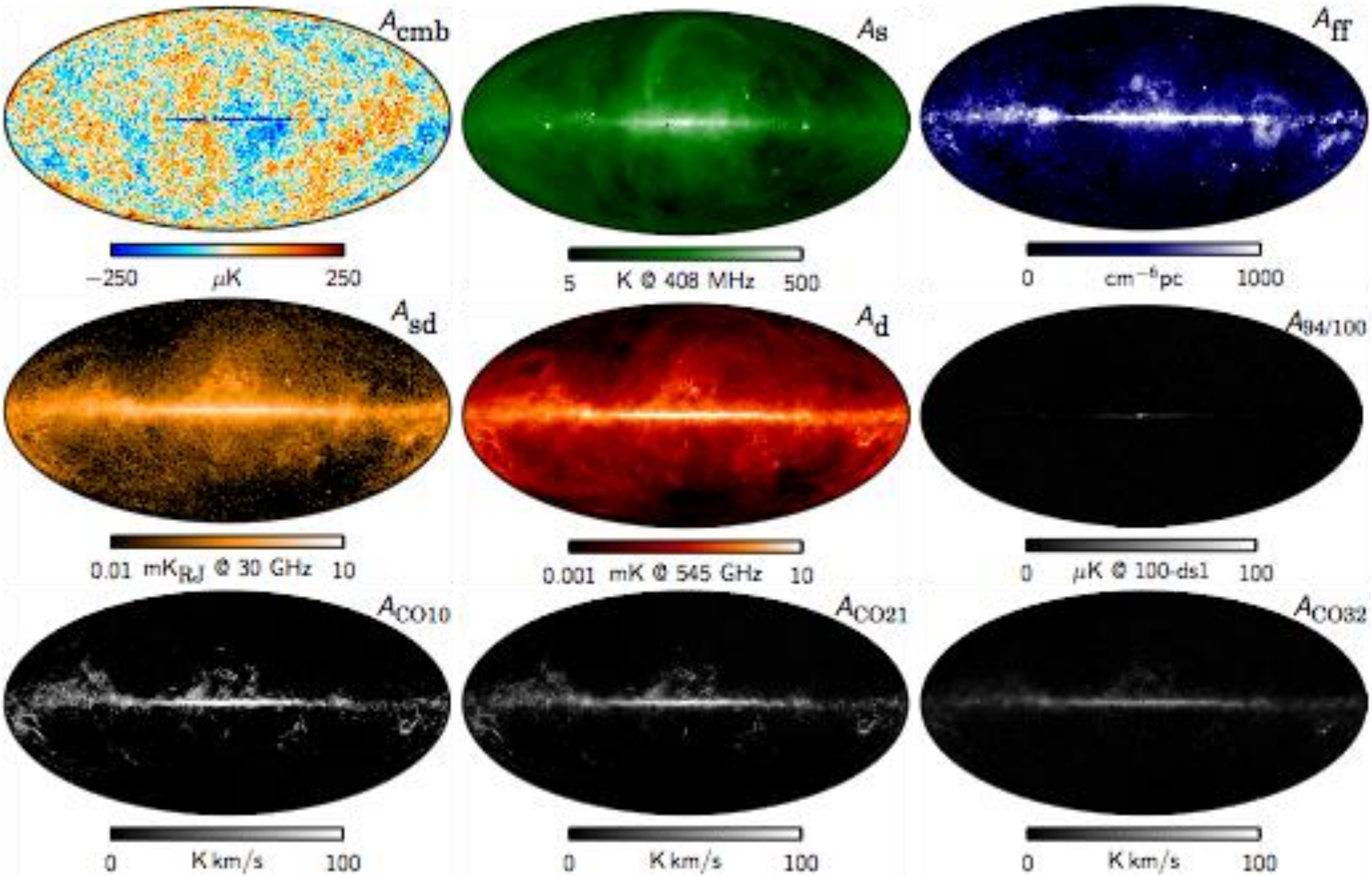
- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**
- Cooled at 0.1K (^{3}He/^{4}He).
- Operative till 2012 (**5** full scans)

- **1st release 2013: Nominal mission**,15.5 months, Temperature only.
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization



Planck 2015

Microwave sky



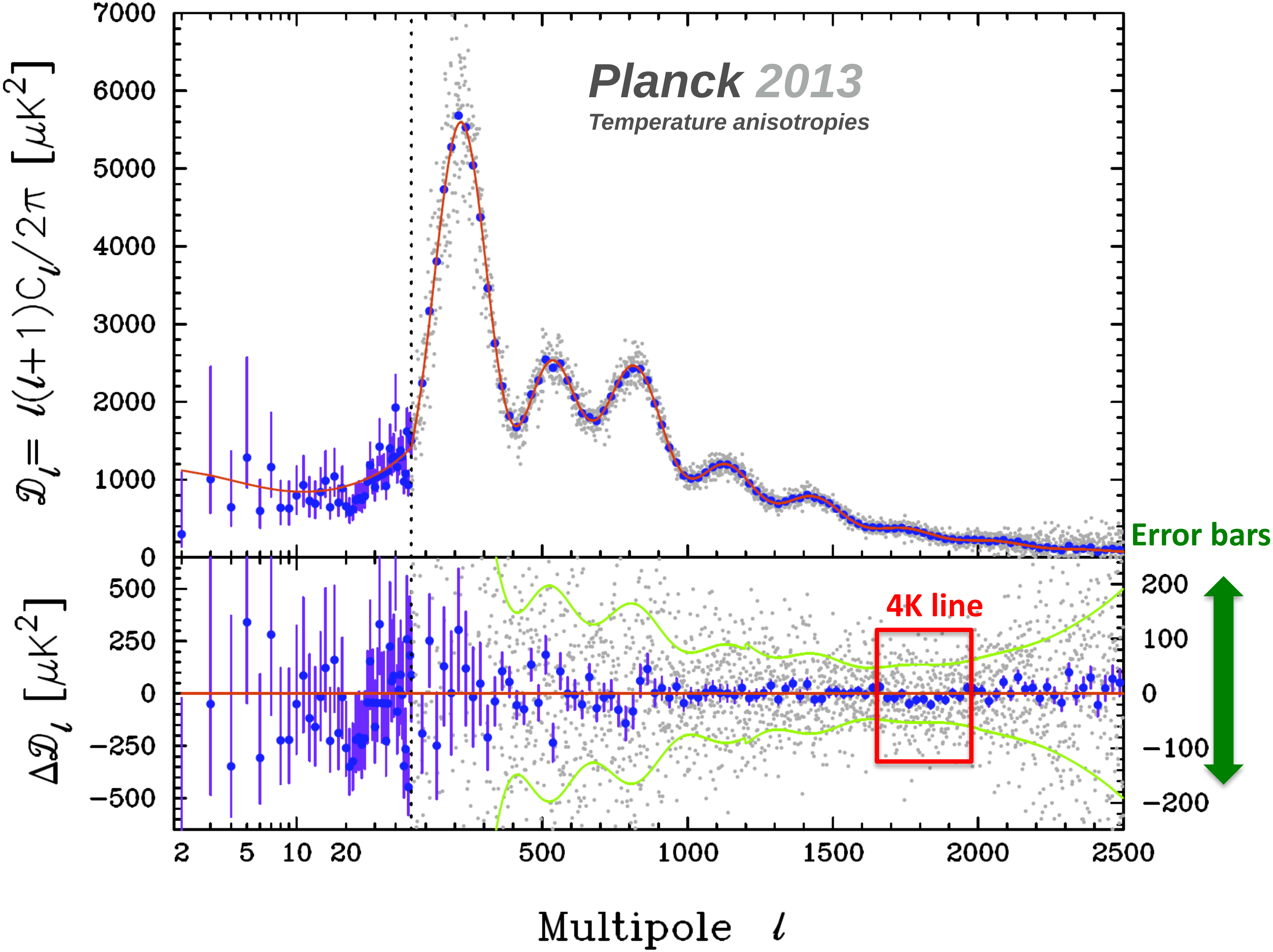
Planck 2015

Components in the microwave sky

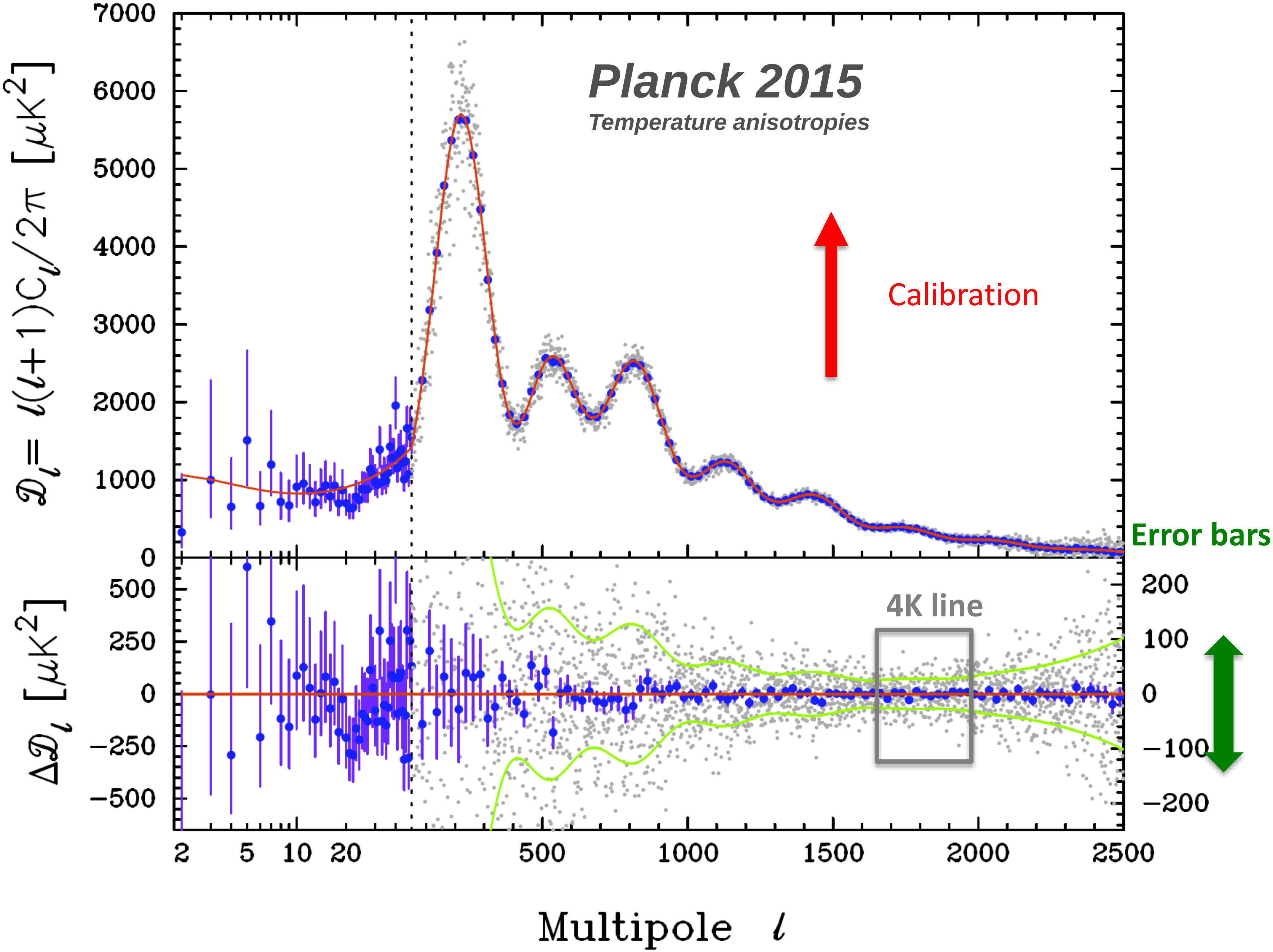
What changed since 2013?

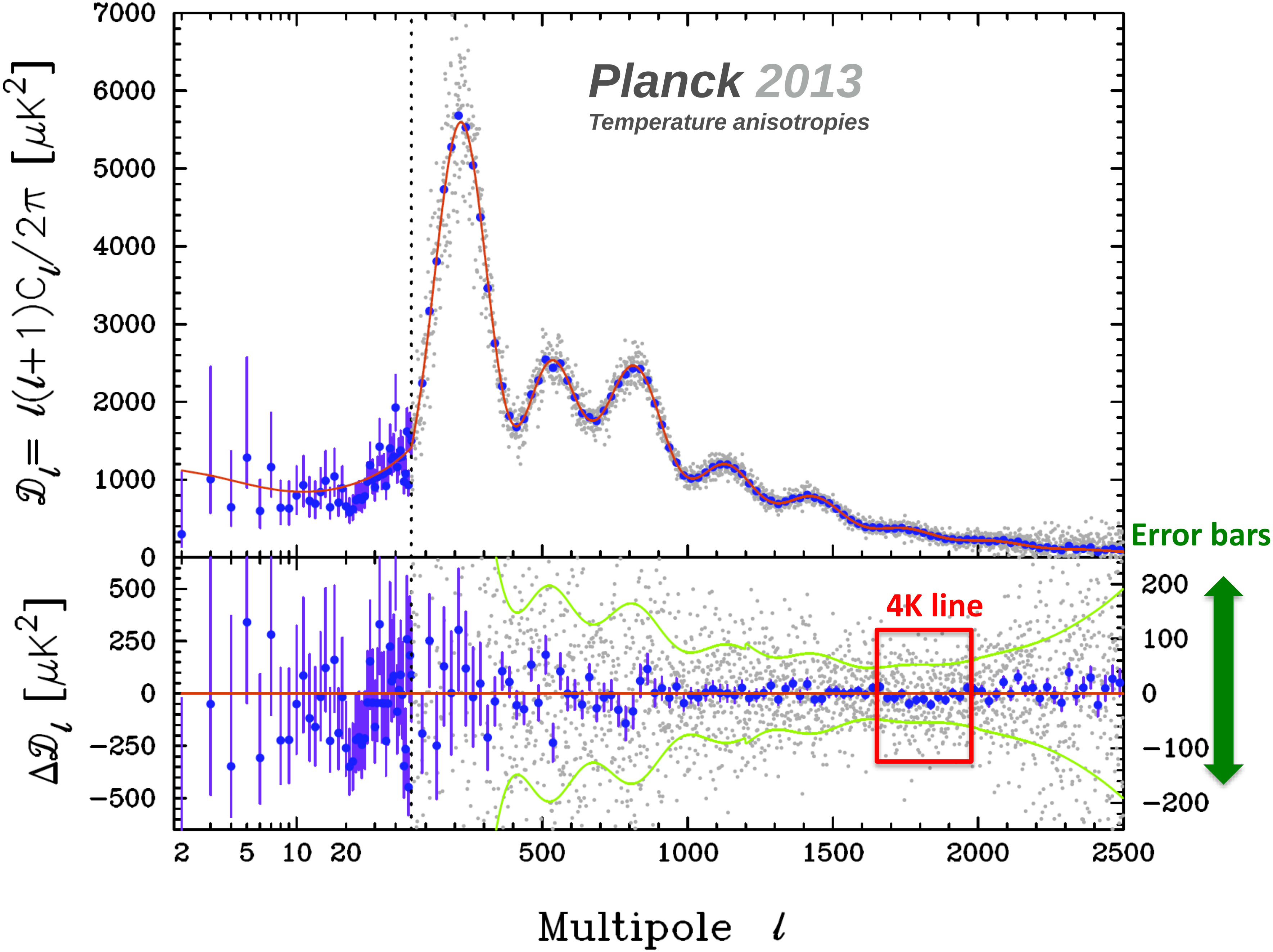
3 things that changed since 2013 and that are relevant for cosmology

1. Calibration -> +2%. Planck 2015 and WMAP now perfectly agree
2. Better handling of systematics (e.g. l~1800 dip due to the 4K line).
3. Planck polarization. Low-l polarization from Planck instead of WMAP9 to constrain reionization.



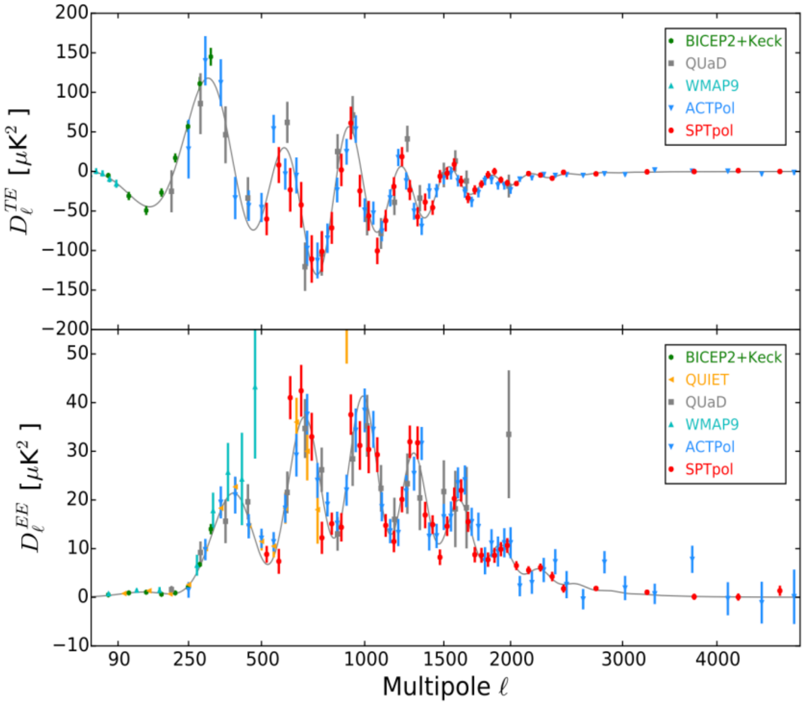
Planck 2013
Temperature anisotropies
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi \; [\mu K^2]$
$\Delta\mathcal{D}_\ell \; [\mu K^2]$
Multipole ℓ
Error bars
4K line
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Planck 2015
Temperature anisotropies
Calibration
Error bars
4K line
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ

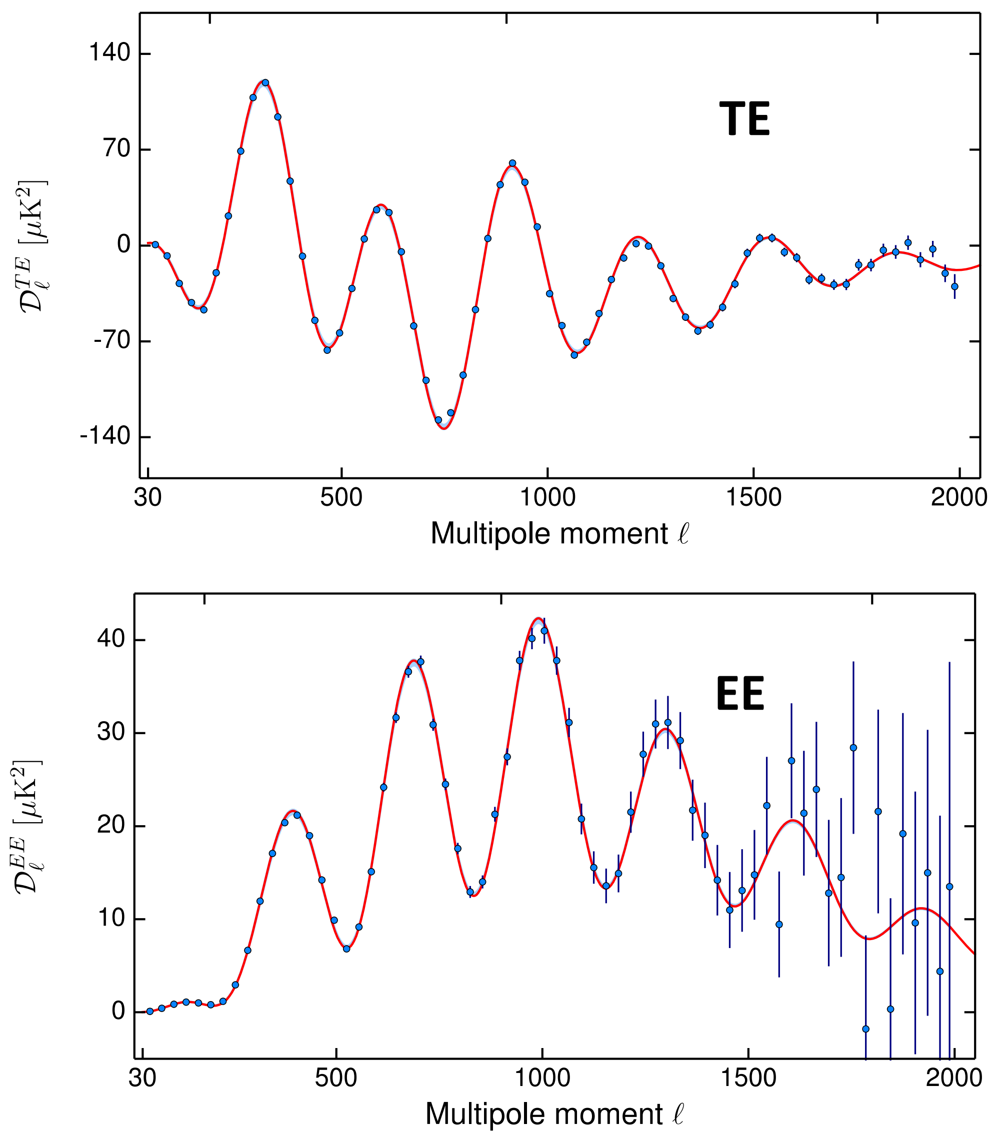

Planck 2013
Temperature anisotropies
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ [μK^2]
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell$ [μK^2]
500
250
0
−250
−500
Error bars
200
100
0
−100
−200
4K line
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ

2015 Polarization power spectra

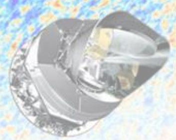
Pre-Planck measurements

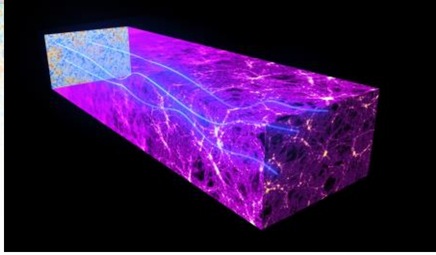


Planck 2015



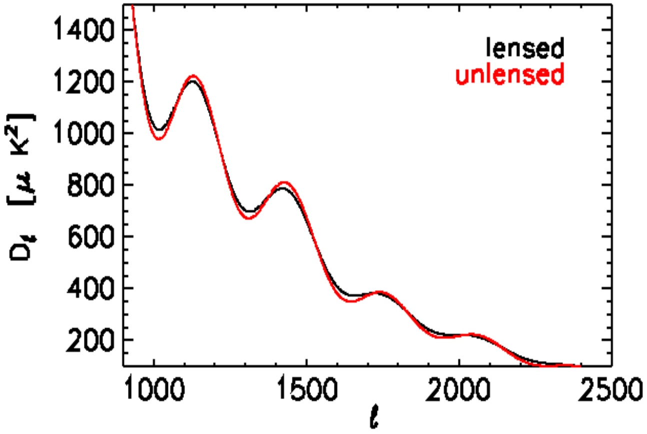
CMB lensing





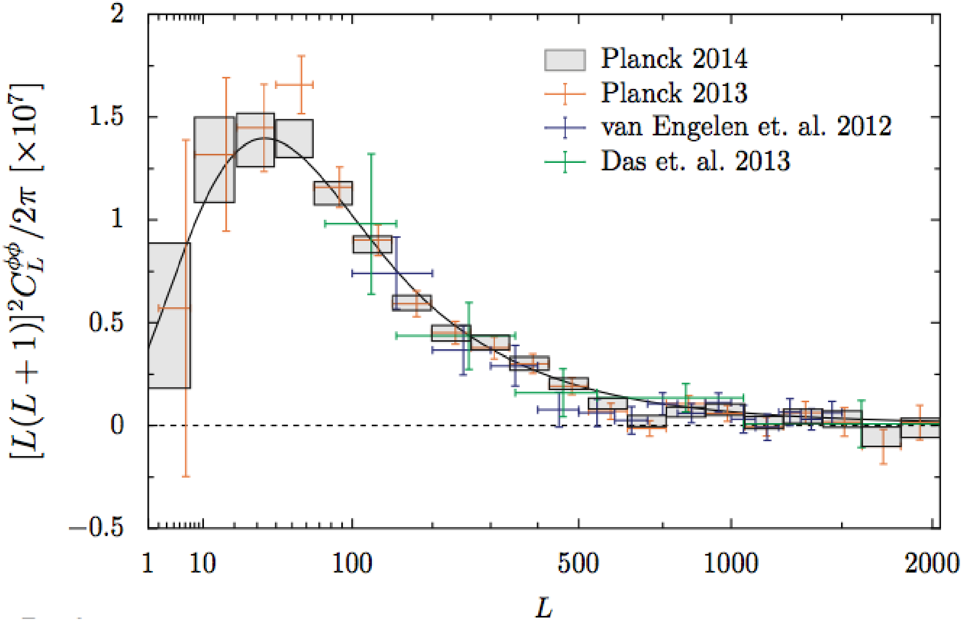
1) Modifies the angular power spectrum at high-l (e.g.smooths the peaks/throughs)

Planck detects lensing in the angular power spectrum at 10σ!



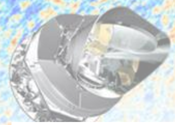
2) Breaks isotropy of the CMB.
Lensing potential reconstructed from the non-gaussian 4-point correlation function.

Planck 2015 detects lensing from 4-p. function at 40σ!
(25σ in 2013)



Results on ΛCDM

ΛCDM results from TT



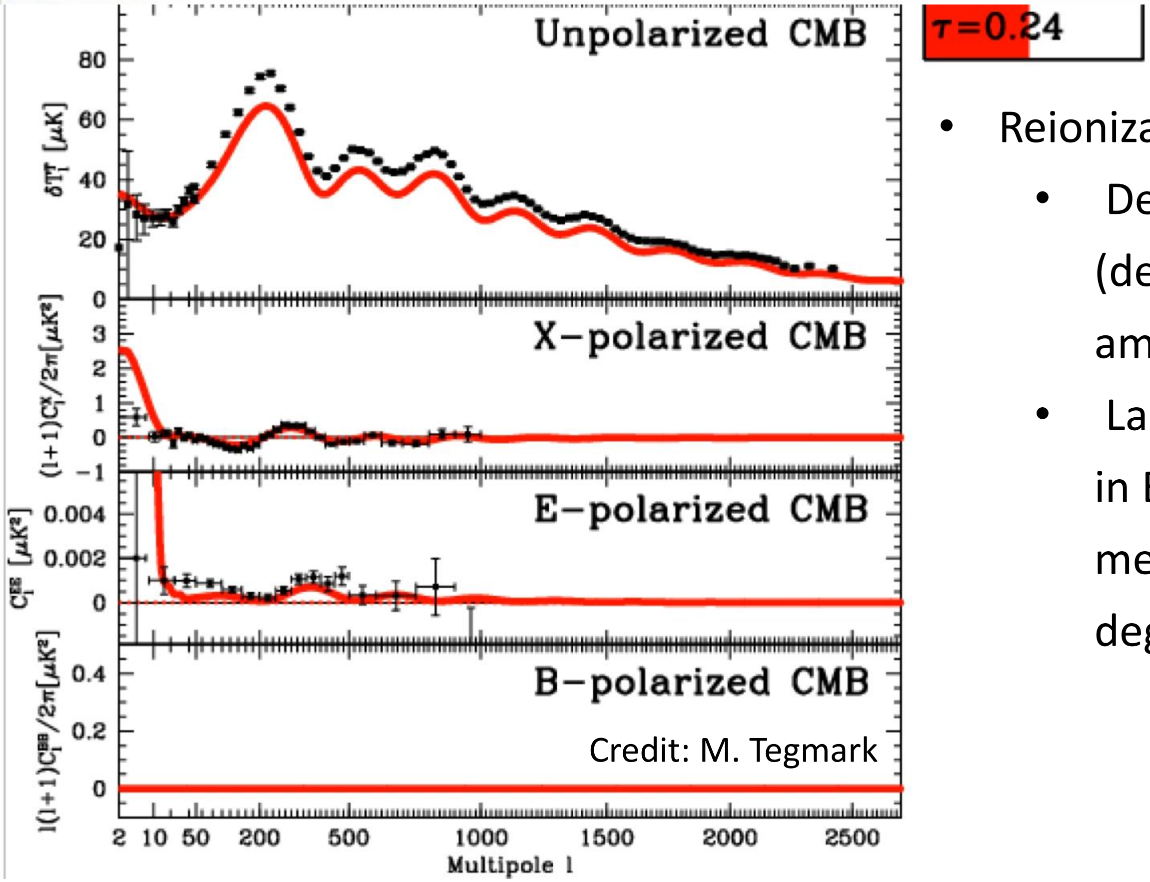
[1] Parameter	2013N(DS)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04086 ± 0.00048
$\Omega_b h^2$	0.02205 ± 0.00028	0.02222 ± 0.00023
$\Omega_c h^2$	0.1199 ± 0.0027	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.26 ± 0.98
n_s	0.9603 ± 0.0073	0.9652 ± 0.0062
Ω_m	0.315 ± 0.017	0.316 ± 0.014
σ_8	0.829 ± 0.012	0.830 ± 0.015
τ	0.089 ± 0.013	0.078 ± 0.019
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.881 ± 0.014

-1 sigma shift
30% weaker
constraint
+3.5 sigma shift

2013=Planck Nominal 2013 TT+low-l WMAP polarization
2015=Planck Full 2015 TT+low-l Planck LFI polarization.

- Very good consistency between 2013-2015.
- Error bars improved by ~30%
- Calibration change shifts $10^9 A_s e^{-2\tau}$.
- 2015 tau constraint weaker and lower value than 2013!

Optical depth to Reionization



- Reionization
  - Decreases amplitude of spectra (degenerate with primordial amplitude As, following $A_s e^{-2\tau}$)
  - Large scale (low-l) reionization bump in E-polarization => allows measurement of τ (breaks tau-As degeneracy).

2013 Planck results: used WMAP-9 EE and TE spectra at l<23.

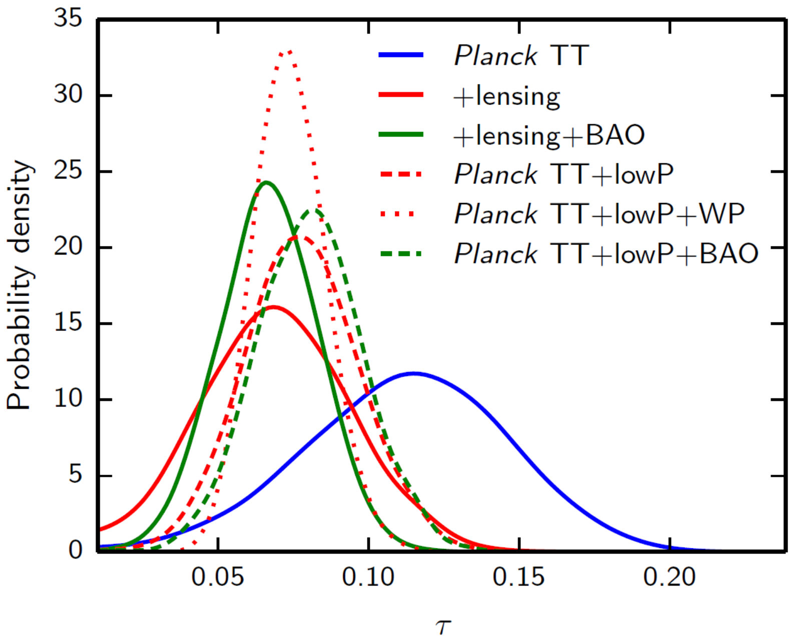
2015 Planck results: uses LFI polarization data at l<30.

Optical depth to Reionization

$\tau = 0.089 \pm 0.013$ $z_{\rm re} = 11.1 \pm 1.1$ *Planck 2013 + Wmap 9 low-l polarization*

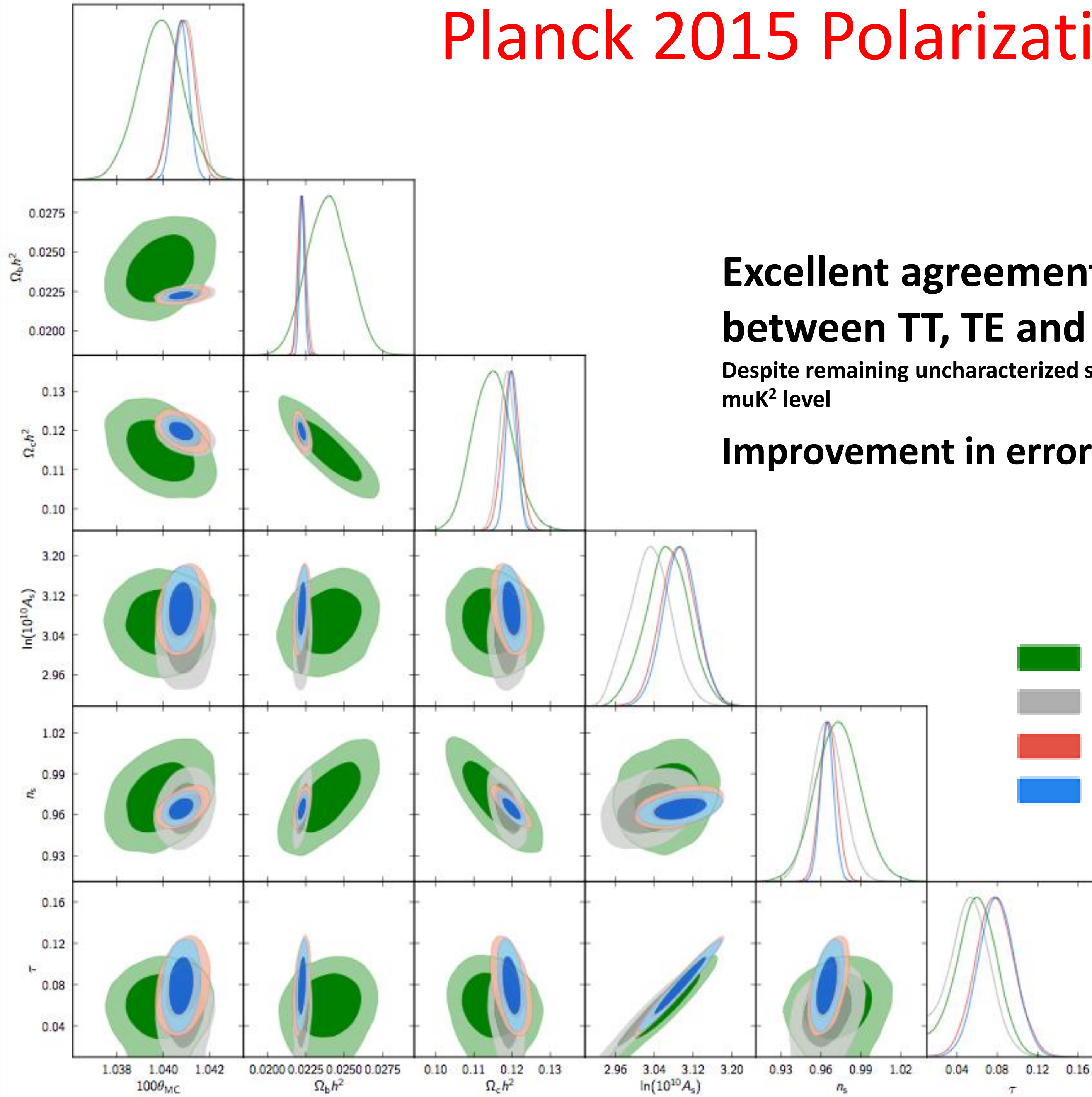
$\tau = 0.078^{+0.019}_{-0.019}$, $z_{\rm re} = 9.9^{+1.8}_{-1.6}$, *Planck* TT+lowP $\sigma_8 = 0.829 \pm 0.014$

$\tau = 0.066^{+0.016}_{-0.016}$, $z_{\rm re} = 8.8^{+1.7}_{-1.4}$, *Planck* TT+lowP+lensing $\sigma_8 = 0.815 \pm 0.009$



- Planck 2013 used WMAP low-l polarization.
- Planck 2015 uses Planck LFI low-l polarization: reionization redshift decreased by ~1 sigma wrt WMAP. Lensing further lowers value of tau.
- Consistent results if WMAP cleaned with Planck 353 dust template.

Planck 2015 Polarization at high-l

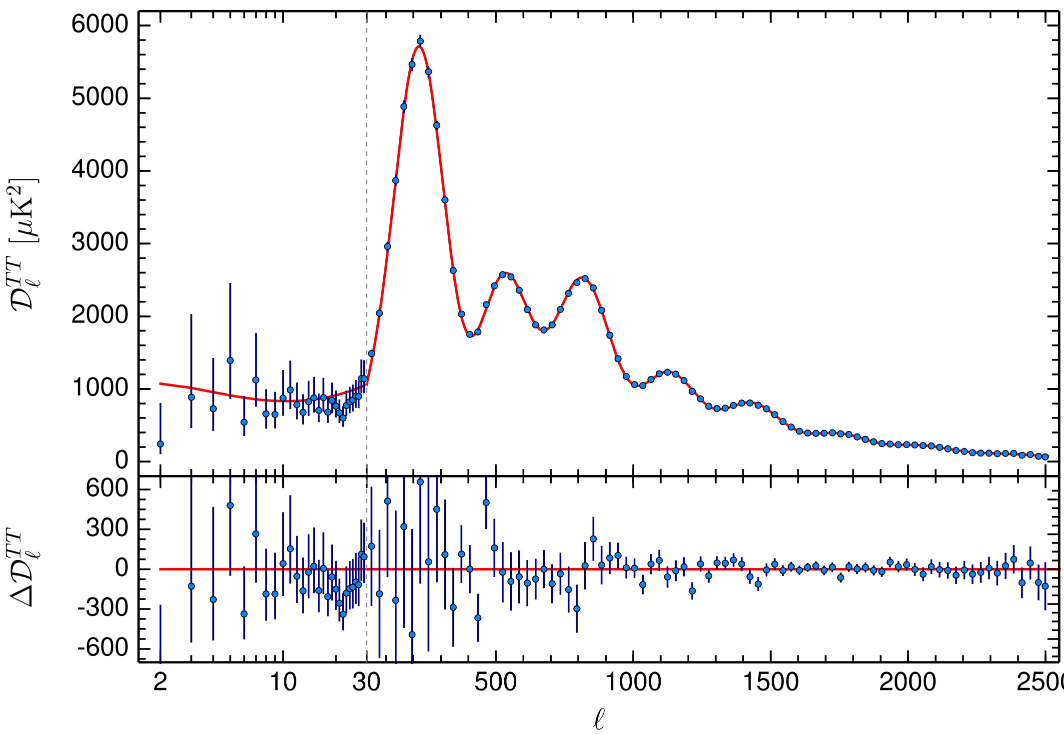


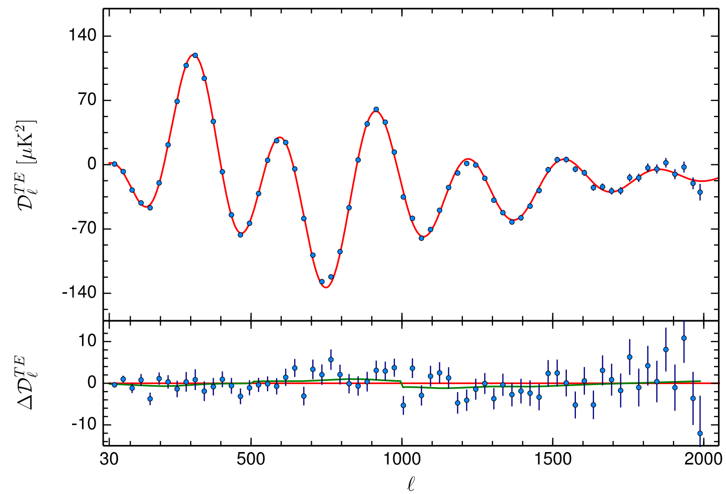
Excellent agreement between TT, TE and EE

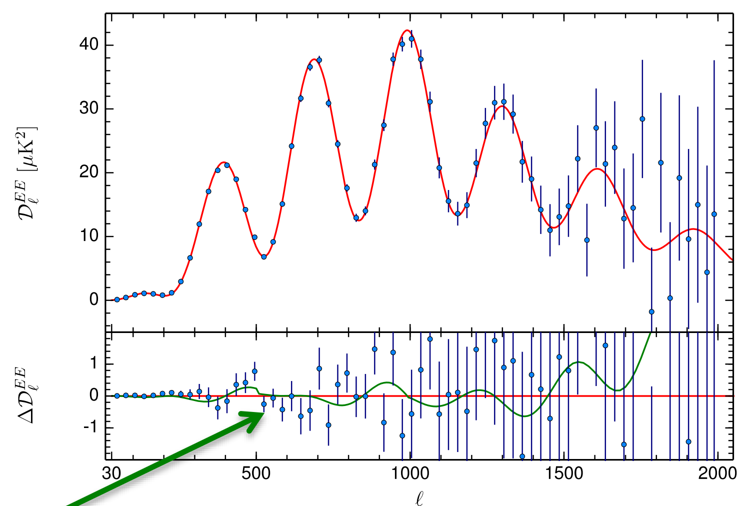
Despite remaining uncharacterized systematics in polarization at muK^2 level

Improvement in error bars up to 50%

ΛCDM best fit



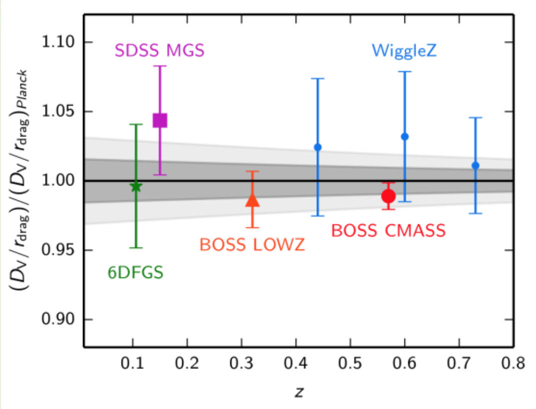




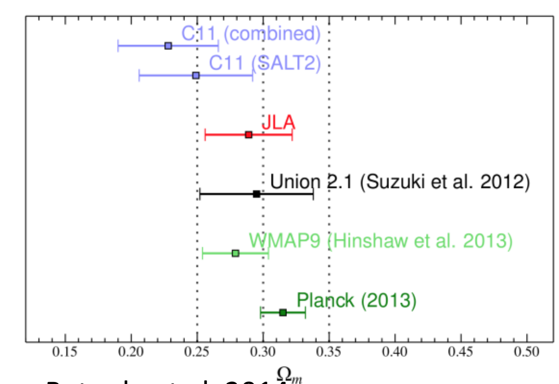
- ΛCDM is very good fit to the data
- Remaining systematics present in polarization spectra, possibly due to unaccounted beam missmatch.

Comparison with other datasets:

BAO

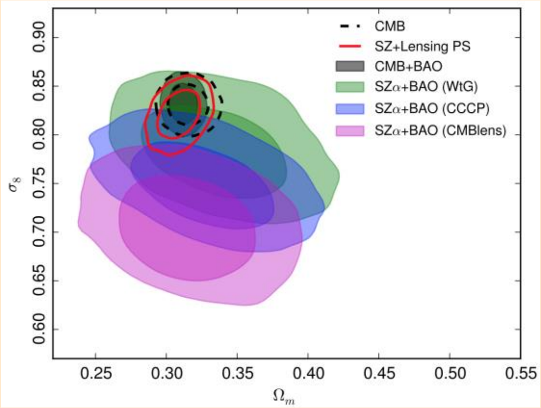


Supernovae (Ω_m)



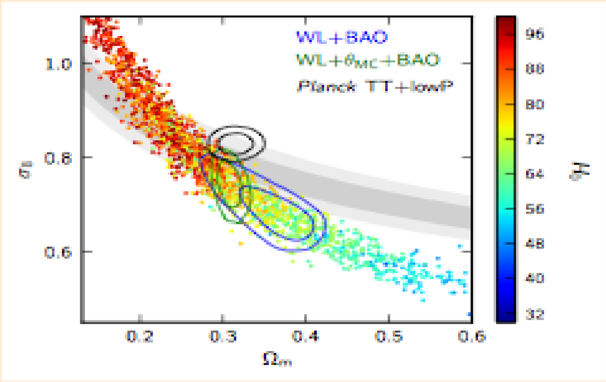
Betoule et al. 2014

Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H_0

H_0=67.8±0.96
(PlanckTT+lowP+lensing)

VS

H_0=72.8±2.4 **[2σ tension]**
(Riess+11)

H_0=70.6 ± 3.3 **[1σ tension]**
(Efstathiou+14)

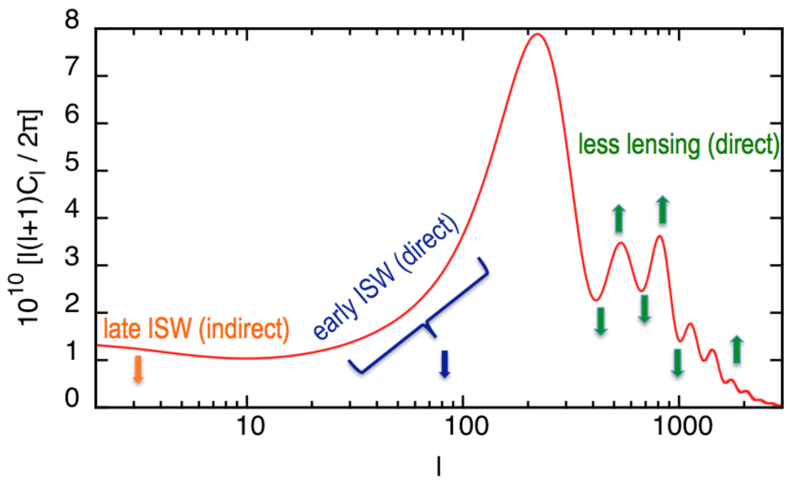
H_0=74.3 ± 2.6 **[2.5σ tension]**
(Freedman+12)

[in Km/s/Mpc]

Extensions of ΛCDM

Sum of neutrino masses

- Relativistic at the epoch of recombination, Non-relativistic at late times
- At large scales (T only): changes early and late ISW through changes of expansion rate.
- At small scales: Less lensing, less smoothing of the peaks.



Σm_ν(95% CL) [eV]	2013	2015	2015 +TE,EE
PlanckTT+lowP	<0.93	<0.72 (23%)	<0.49 (48%)
PlanckTT+lowP+lensing	<1.1	<0.70 (36%)	<0.58 (47%)
PlanckTT+lowP+lensing+ext		<0.23	<0.19

For 2013, lowP is WMAP polarization

Assumption: 3 degenerate massive neutrinos

- Full mission TT data improve constraints by ~20-40%.
- « Best » estimate from TT+lowP+lensing+ext. Already stronger than expected sensitivity from Katrin (tritium beta decay)!

Number of relativistic species

- CMB is sensitive to radiation density.
- Neff parametrizes the radiation density other than photon). Neff=3.046 (standard).
- Non-standard Neff could be due to additional radiation (sterile neutrino, light relics) or non-standard thermal history.

	2013	2015	2015 +EE,TE
PlanckTT+lowP	3.51±0.39	3.13±0.32 (18%)	2.98±0.20 (48%)
PlanckTT+lowP +BAO	3.40±0.30	3.15±0.23 (23%)	3.04±0.18 (40%)

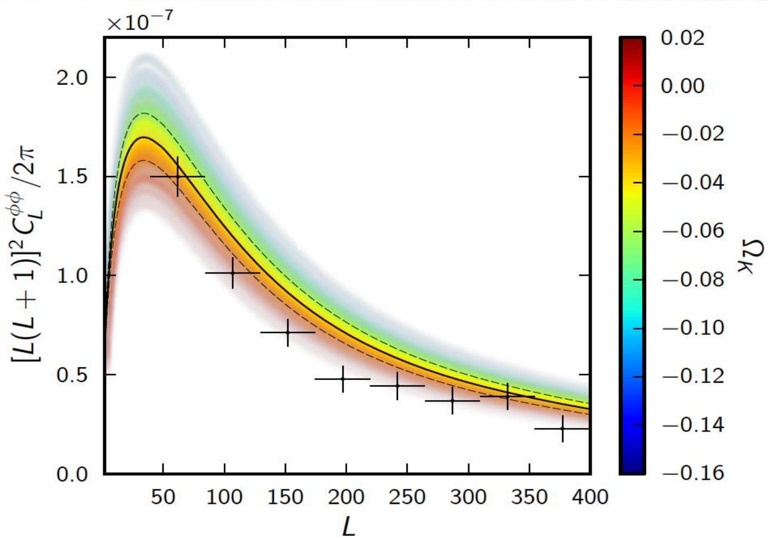
Assumption:
1 massive neutrino at 0.06eV, other massless

(for 2013, lowP is WMAP polarization) (68% C.L.)

- Planck measures N_{eff} in perfect agreement with the standard value, 3.046.
- $N_{eff}>0$ confirmed at ~15-sigma.
- $N_{eff}=4$ excluded at 3-5 sigma!

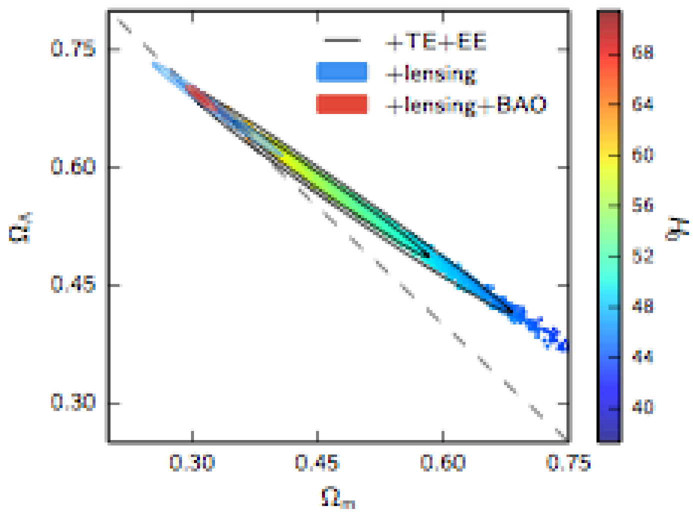
Curvature

- From (simple) inflation, Ω_k expected to be ~10^{-5}.
- Primordial CMB cannot tightly constrain Ω_k because of geometrical degeneracy.
- Planck alone places constraints at ~10^{-2} level thanks to lensing, that breaks geometrical degeneracy.
- Adding BAO, constraint at the level of ~10^{-3}



$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$

(PlanckTT+lowP+Lensing+BAO)



$$\Omega_K \equiv 1 - \Omega_m - \Omega_\Lambda$$

Inflation: n_s and r

- From **Planck TT+lowP:**
  - Almost a **6σ departure** from scale invariance (but model dependent! relaxable when opening Neff)

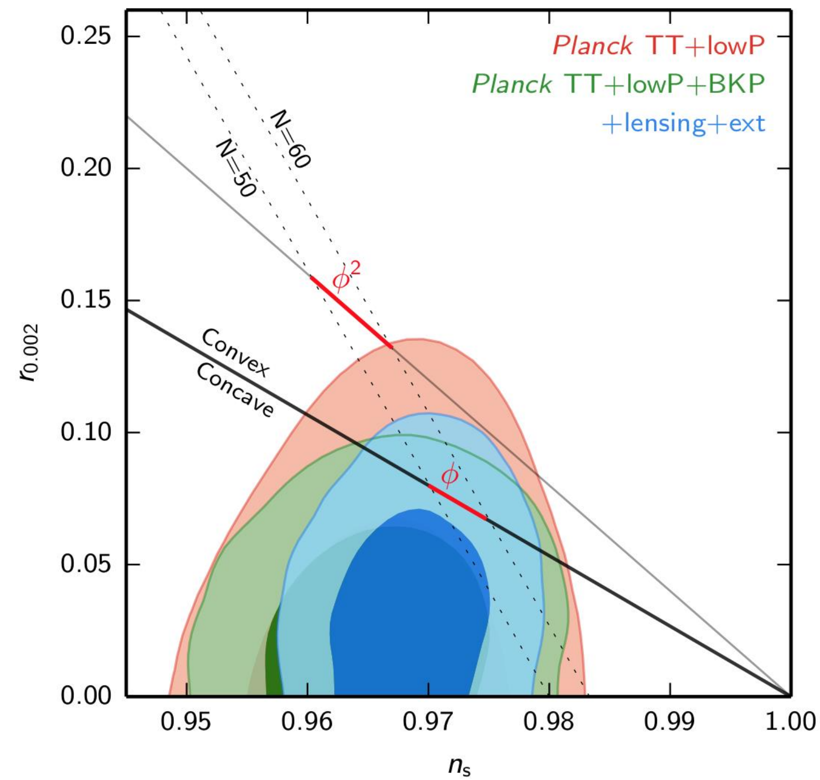
    $n_s = 0.9655 \pm 0.0062$

  - Tensor to scalar ratio constrained at 95%c.l.:

    $r < 0.10$

- Adding BB measurements from BICEP/KECK, foreground-cleaned with Planck data (Planck TT+lowP+BKP):

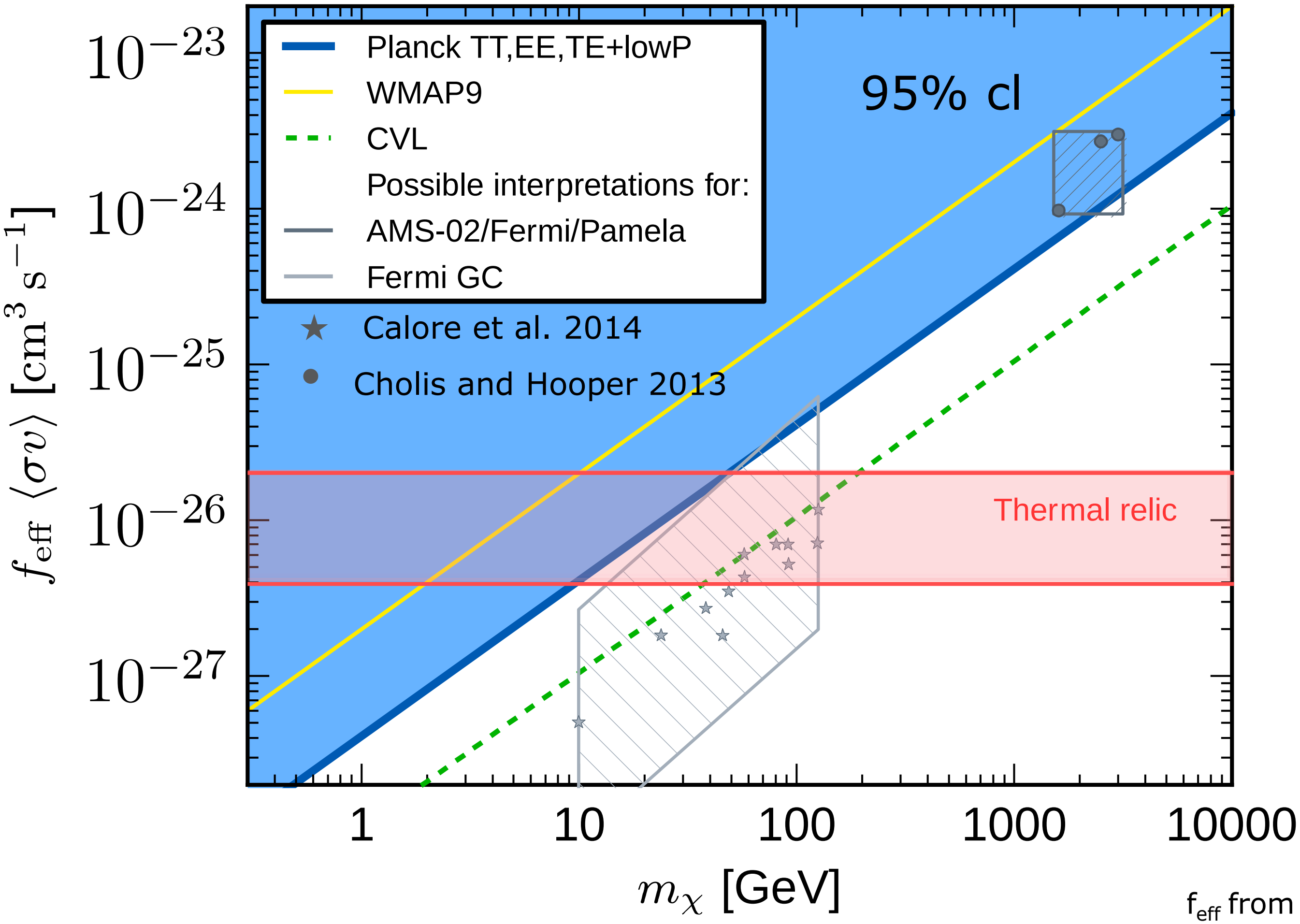
  $r < 0.08$



r=Power in tensor (Grav. Waves)/scalar (density pert.)

ns=spectral index of primordial scalar perturbations

Constraints on Dark Matter Annihilation



Most of parameter space preferred by AMS-02/Pamela/Fermi ruled out at 95%, under the assumption $\langle\sigma v\rangle(z=1000)=\langle\sigma v\rangle(z=0)$

Thermal Relic cross sections at z~1000 ruled out for:

m~<40 GeV (e^-e^+)
m~<16 GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

Only a small part of the parameter space preferred by Fermi GC is excluded

$f_{\rm eff}$ from T. Slatyer (Madhavacheril et al. 2013)

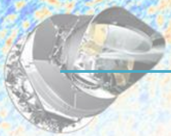
Conclusions

- Great consistency between Planck 2013-2015.
- In agreement with BAO and Supernovae, less so with cluster counts and direct H0 measurements.
- Polarization brings great information. Allows spectacular constraints (e.g. Dark matter annihilation)
- Polarization has remaining systematics. To be understood in 2016 release.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

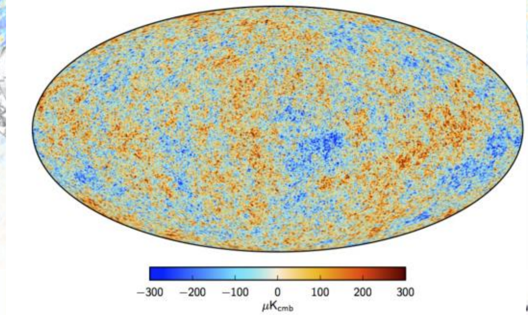
Polarization



	Shift in sigma TTTEEE-TT	Error bar improvement TTTEEE-TT [%]	TTTEEE measurement accuracy [%]
$\Omega_b h^2$ Baryon density	0.13	**44**	0.72
$\Omega_c h^2$ DM density	0.05	**47**	1.25
100θ Acustic scale	-0.17	**47**	**0.03**
τ Reion. Optical depth	0.05	12	21.52
$\ln(10^{10}A_s)$ Power Spectrum amplitude	0.14	6	1.10
n_s Scalar spectral index	-0.16	27	0.51
H_0 Hubble	-0.04	45	0.98
Ω_m Matter density	0.05	43	2.88
σ_8	0.14	8	1.56
$10^9 A_s e^{-2\tau}$ Power Spectrum amplitude	0.14	17	0.64

- Good consistency when adding polarization information wrt TT alone
- Great improvement in error bars!
- Many parameters determined at subpercent level!

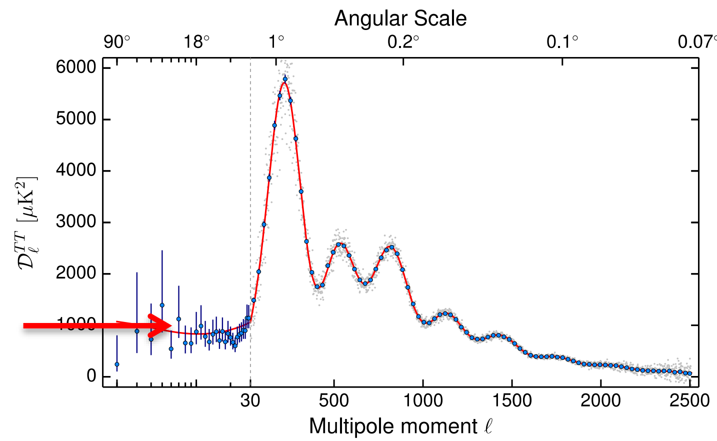
Cosmic History



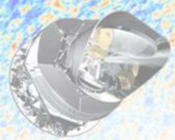
CMB is an extremely rich source of information about our universe!

$$\Theta(\vec{x},\hat{p},\eta)=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}a^*_{l'm'}\rangle=\delta_{ll'}\delta_{mm'}C_l$$



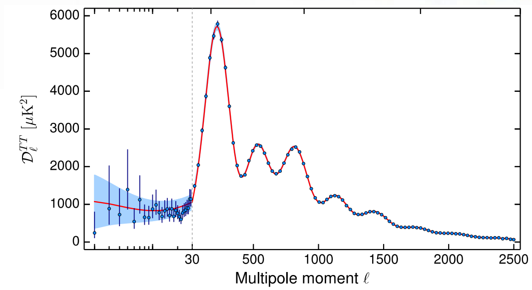
Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu

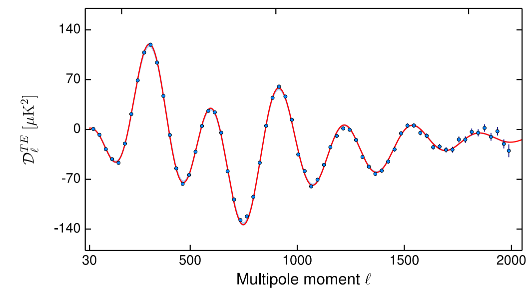


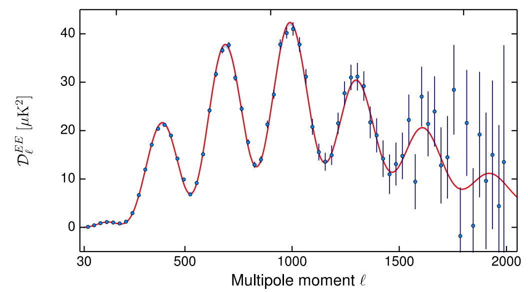
Likelihood

- Low-l (l<30):
  - **TT**: Pixel-based approach based on Commander component separated map, 92% sky, **all Planck frequencies used+WMAP+Haslam**
  - **TE and EE**: Pixel based approach based on **Planck LFI 70Ghz** map, 46% of the sky. 30 Ghz and 353Ghz used for foreground cleaning.

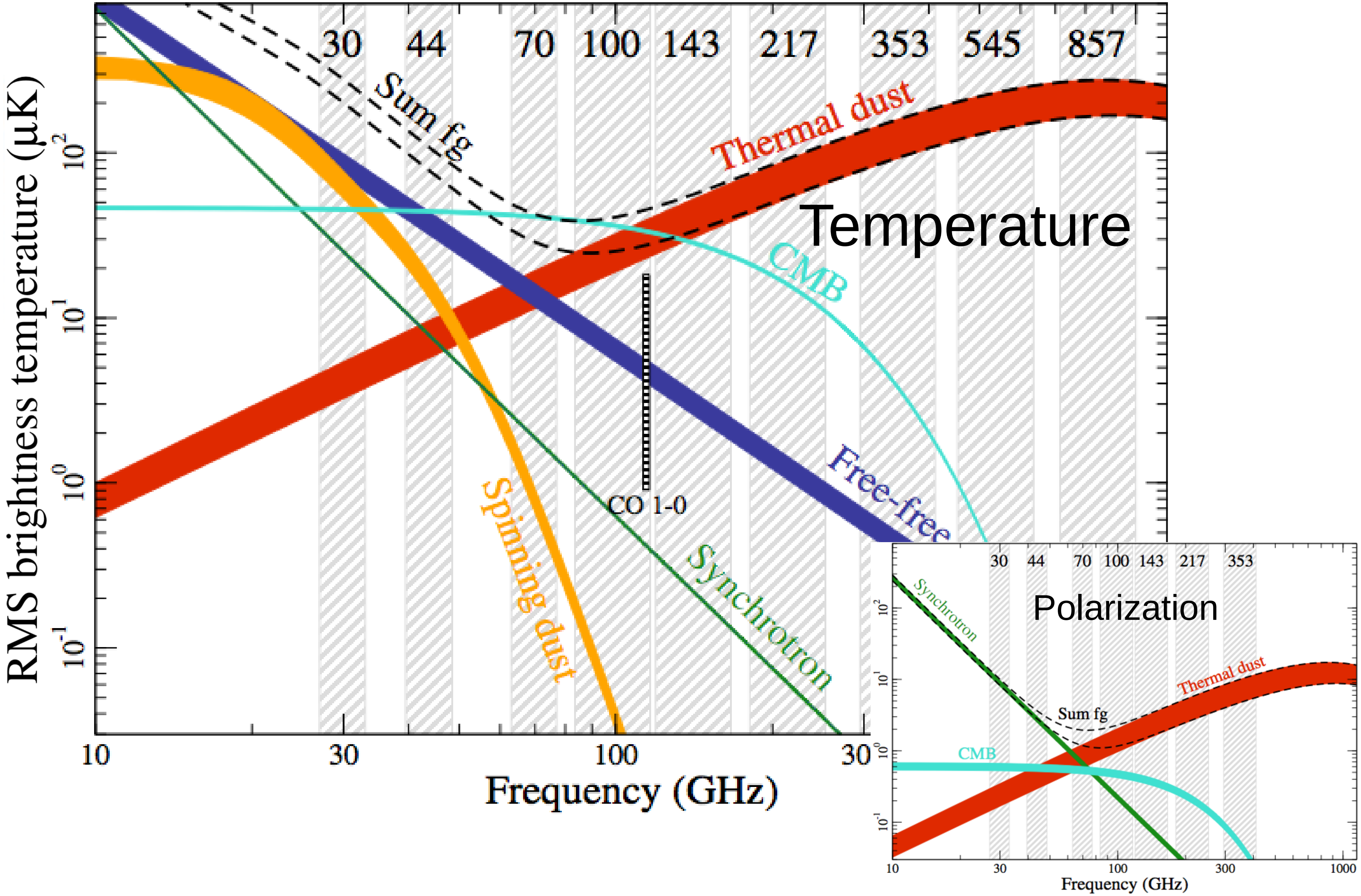
- High-l (l>30):
  - **TT**: Gaussian likelihood based on **HFI 100, 143, 217Ghz** at (70, 60 ,50% sky)
  - **TE,EE**: Gaussian likelihood, **HFI 100, 143, 217Ghz** at (70, 50 ,40% sky).



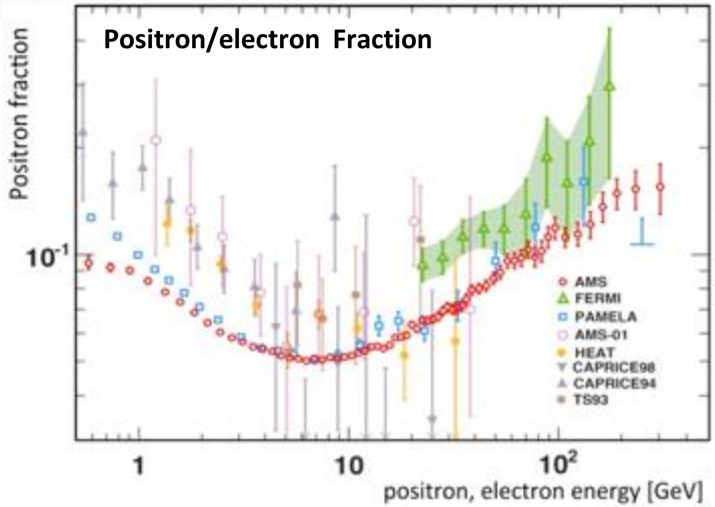


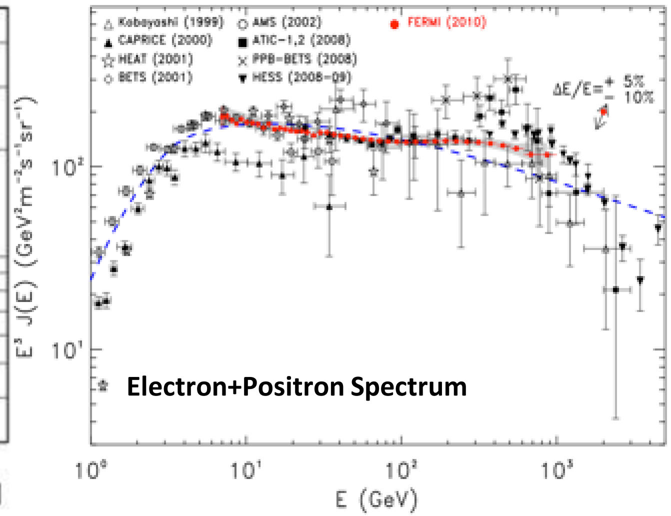


9 Frequencies for foregrounds!



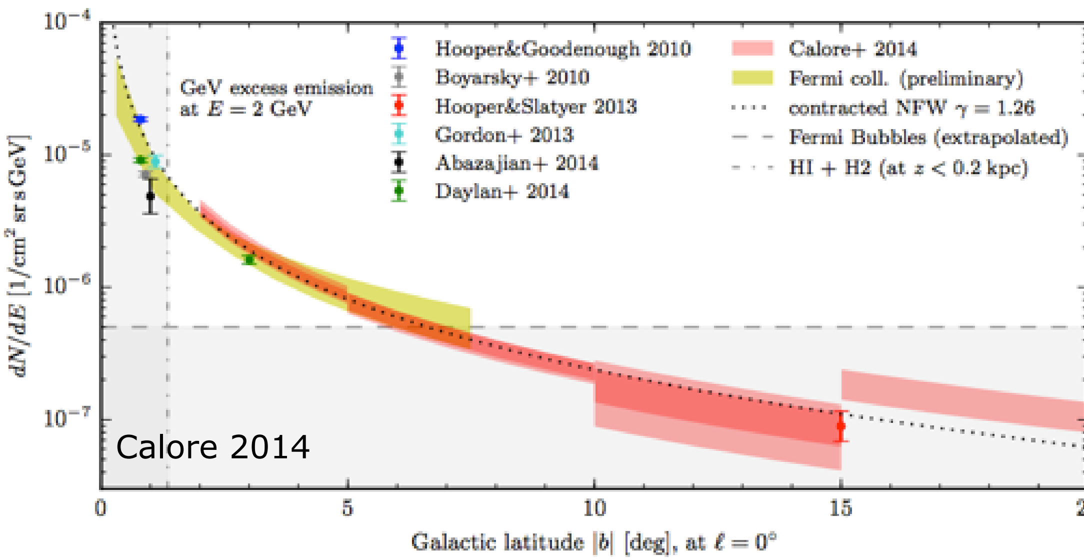
Recent anomalies:
Dark matter annihilation?





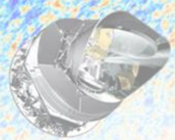
Cosmic rays excesses in PAMELA/FERMI/AMS-02

- Leptonic ann.chan.,
- Mass ~ TeV,
- Large cross-section required ($\sim 10^{-23}$cm^3/s).
- Need broken power law in electrons.



Fermi Galactic Center excess

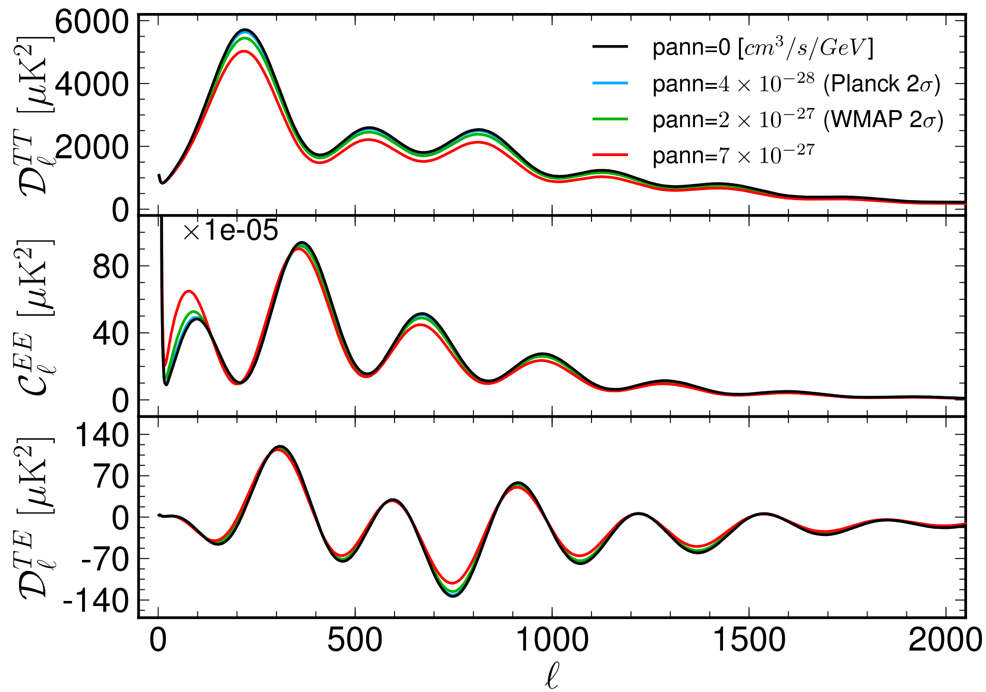
- Many ann. chan. allowed.
- Mass ~ few tens GeV,
- Thermal relic cross section ($\sim 10^{-26}$cm^3/s)



DM annihilation at the epoch of recombination

p_{ann}

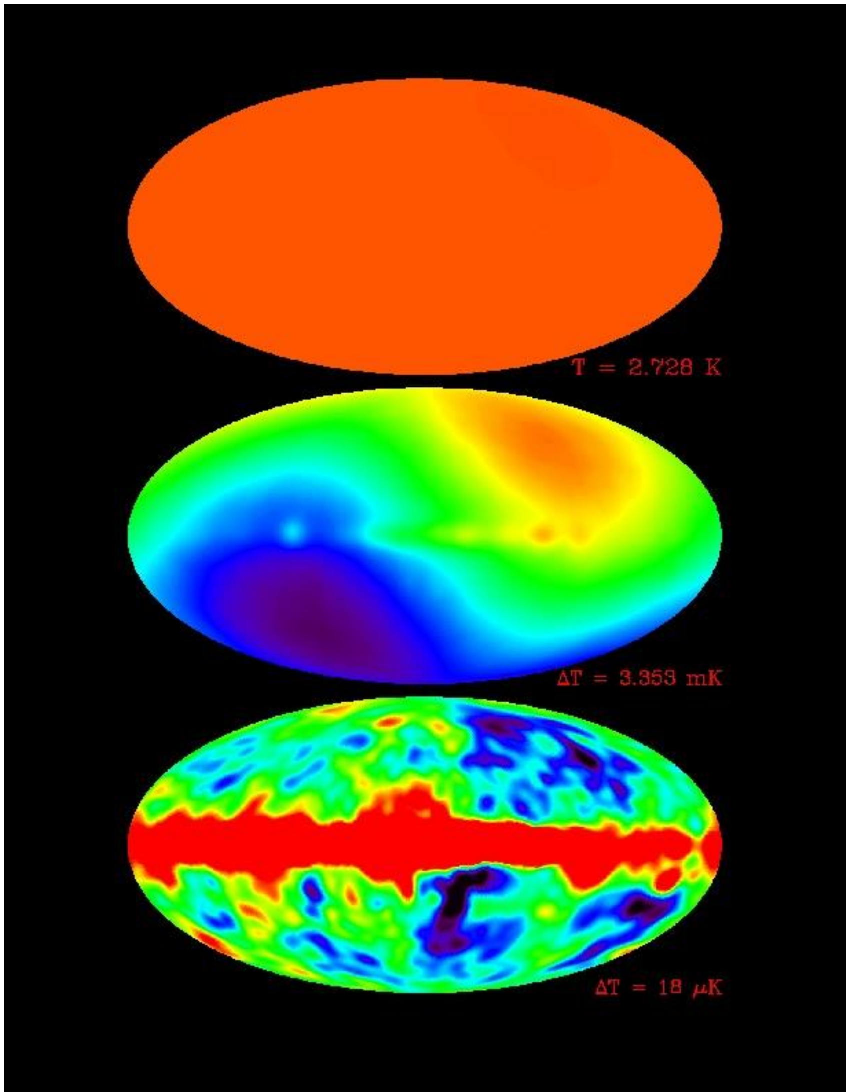
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 f_{eff} \frac{<\sigma v>}{m_\chi}$$



- The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.
- Suppresses the peaks, but enhances polarization at large scales!

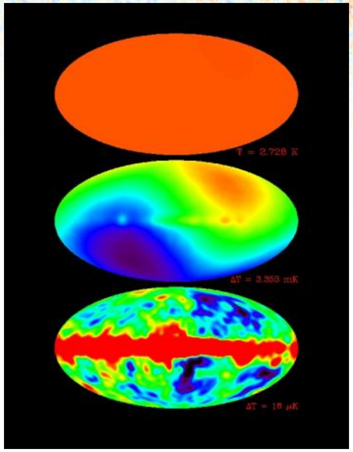
1. Calibration

T_{cmb} known from COBE. Modulated by Solar system motion and satellite motion w.r.t. sun. If the velocity (of the sun or of the satellite w.r.t sun) is known, we can predict the temperature shift it produces, and thus calibrate the instrument.



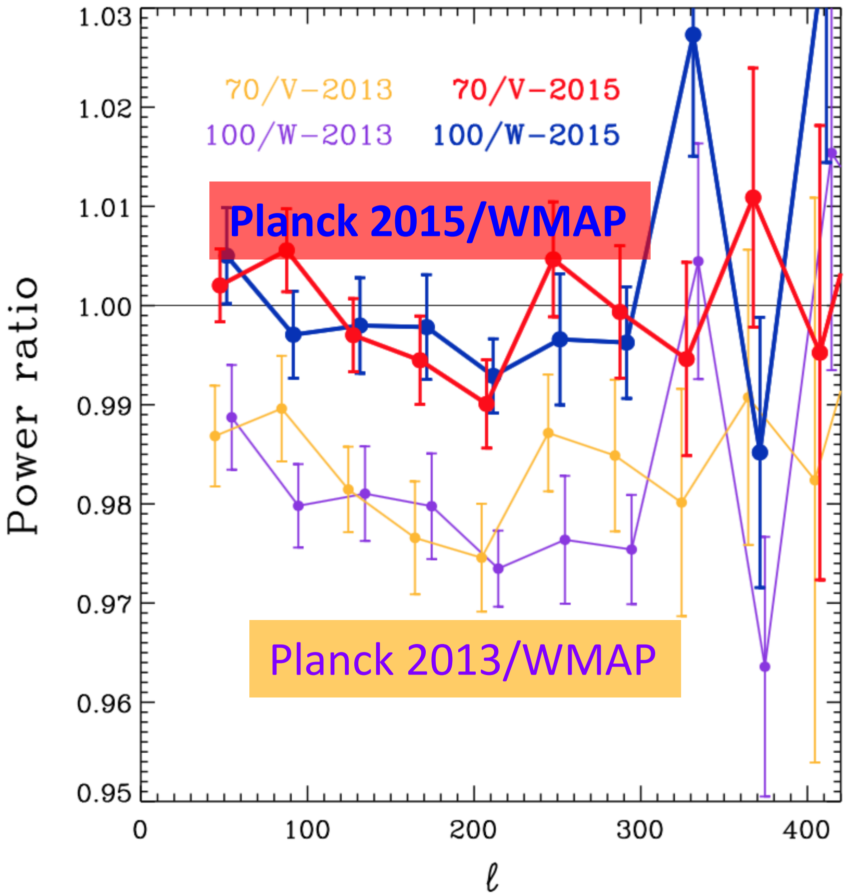
Solar dipole: the sun baryocenter moves w.r.t. the CMB rest frame with v=369 km/s.
Orbital dipole: the satellite moves around the sun with a velocity of ~30 km/s

1. Calibration

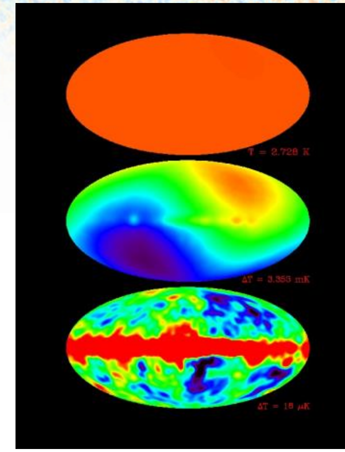


- 2013:
  - **Planck** calibrated on **WMAP solar dipole**. WMAP calibrated on its orbital dipole.
  - BUT! Unexpected ~2% difference in power ratio between WMAP and Planck

- 2015:
  - Planck calibrated on its own **orbital dipole**. Data calibration up-shifted by ~%2 (in power).
  - Reasons of discrepancy understood
    - HFI: near/far sidelobes, very long time constant, better ADC correction
    - LFI: beams, data analysis improvements
    - WMAP: solar dipole was off by ~0.6% (in power)



1. Calibration



- 2013:
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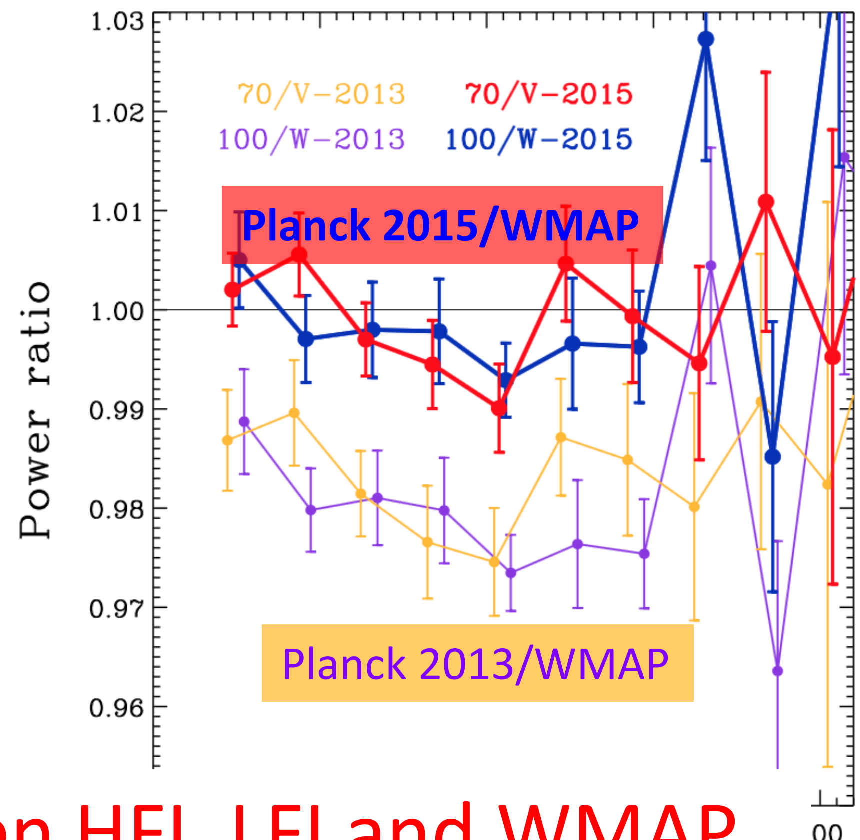
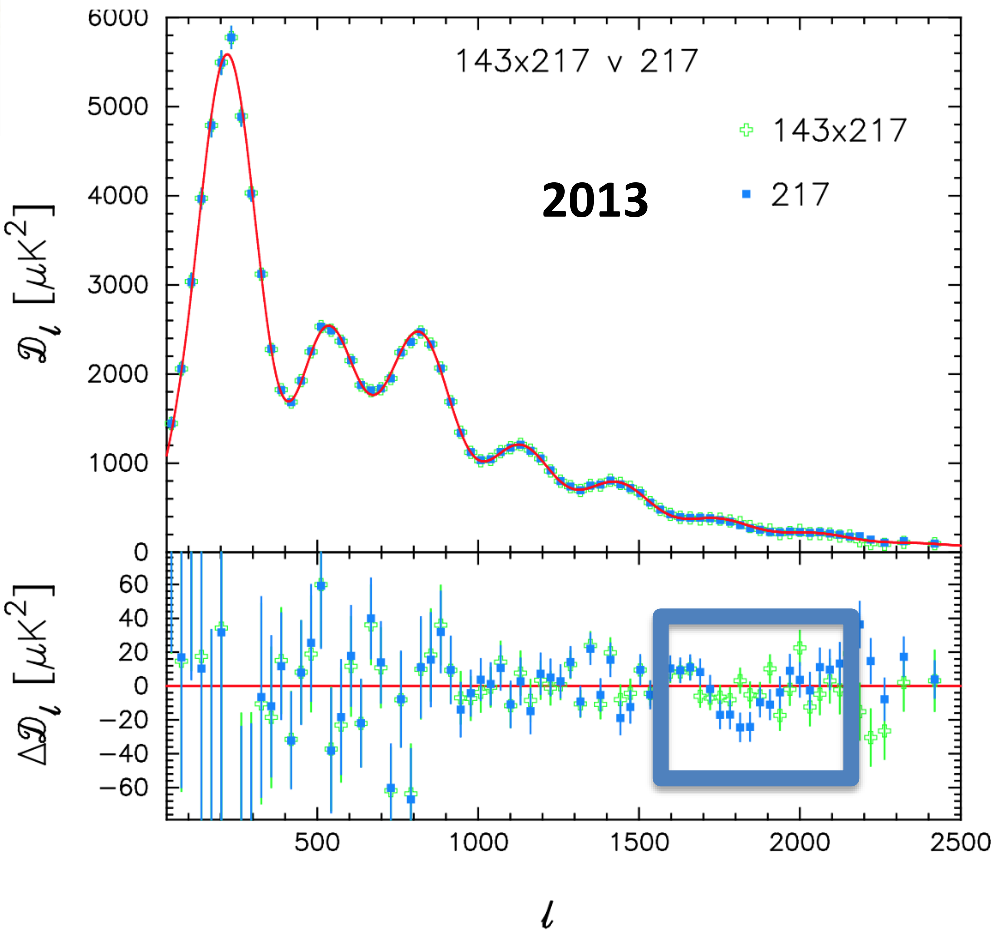


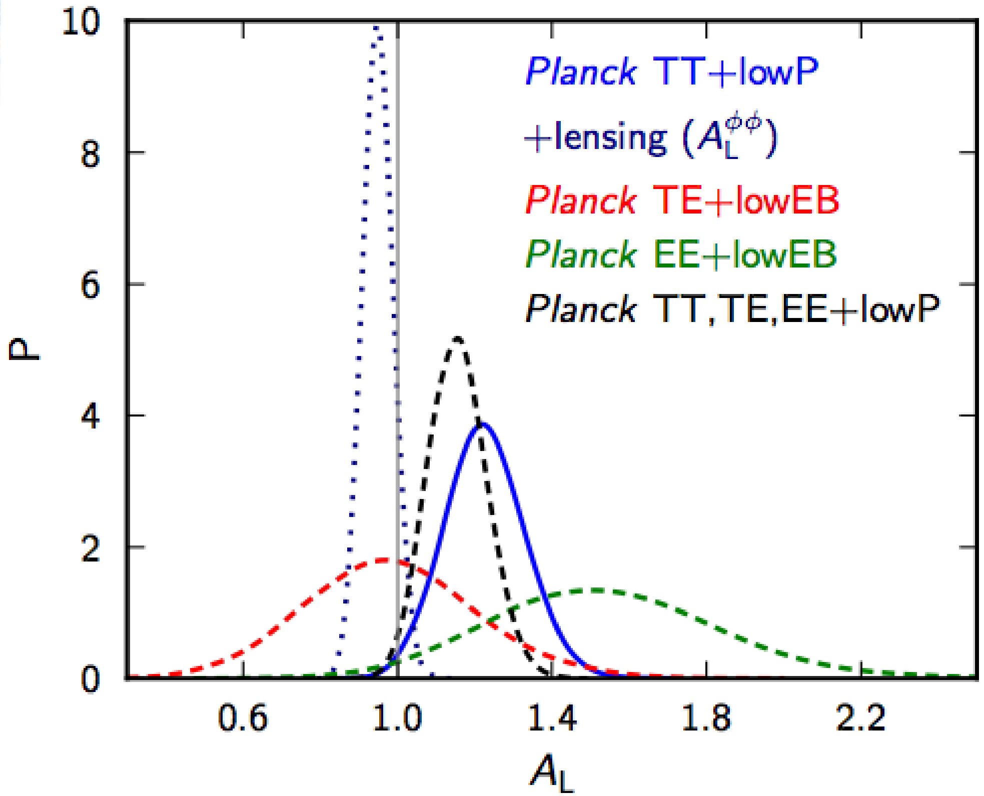
Excellent agreement between HFI, LFI and WMAP

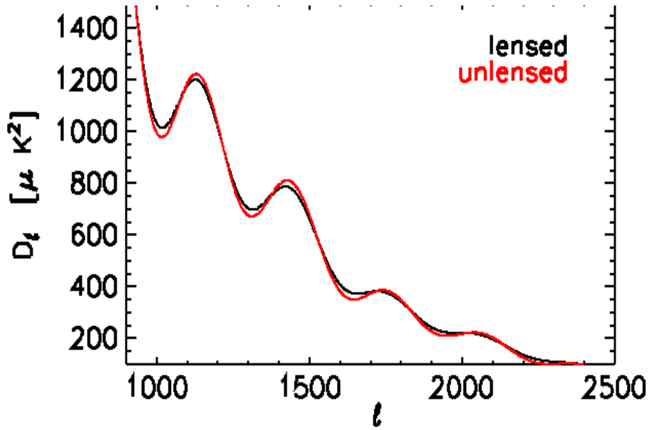
2. 4K line



- Interferance between 4K cooler and data readout=>narrow lines in HFI data, correlated between bolometers. Imperfect correction resulted in feature at l~1800 in cross-detset spectra.
- We now discard the data rings most affected by the 4K lines.

The Alens problem





- A_L parametrizes amplitude of lensing power spectrum.
- In LCDM+A_L model, TT power spectrum prefers a ~2-sigma larger lensing amplitude.
- In LCDM (Alens=1), the preference for high lensing shifts As to larger values.
- In extensions of LCDM, parameters that can increase lensing (e.g. negative Ω_k or w<1) feature small deviations from LCDM values. These deviations disappear when adding CMB lensing reconstruction data and BAO.
- A preference for large lensing provides strong constraints on neutrino mass (that would reduce lensing power).

Optical depth to Reionization

$\tau = 0.089 \pm 0.013$ $z_{re} = 11.1 \pm 1.1$ *Planck 2013 + Wmap 9 low-l polarization*

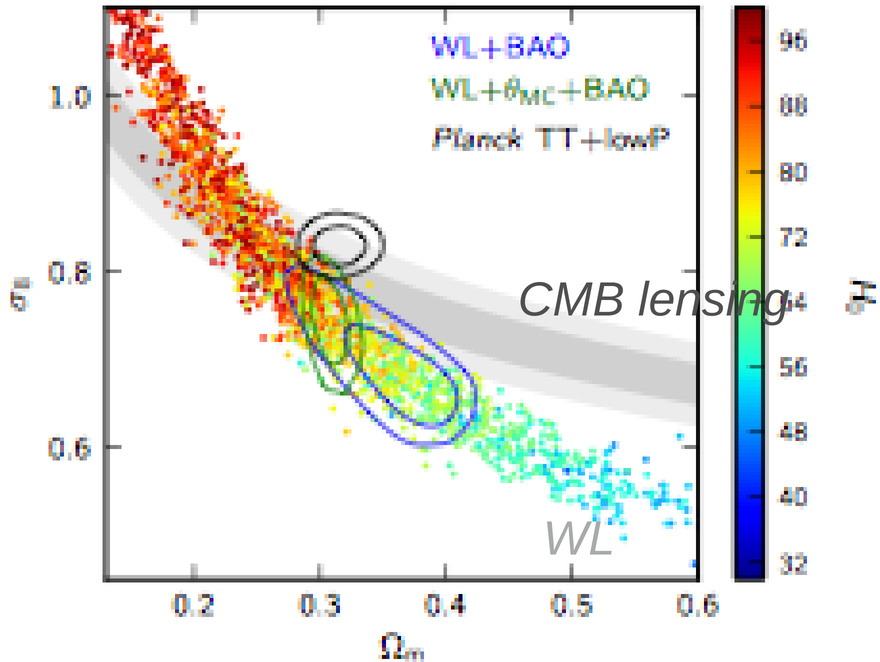
$$\tau = 0.078^{+0.019}_{-0.019}, \; z_{re} = 9.9^{+1.8}_{-1.6}, \; \textit{Planck}\ \text{TT+lowP}$$

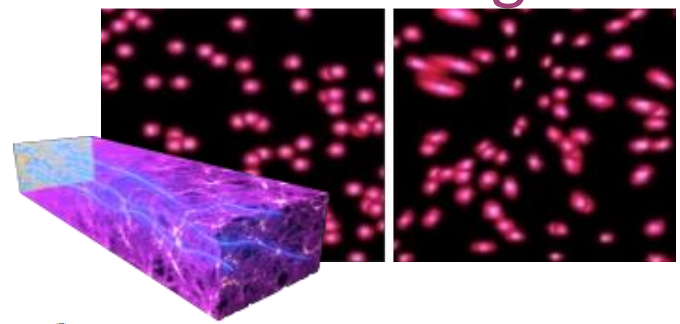
$$\tau = 0.066^{+0.016}_{-0.016}, \; z_{re} = 8.8^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lowP+lensing}$$

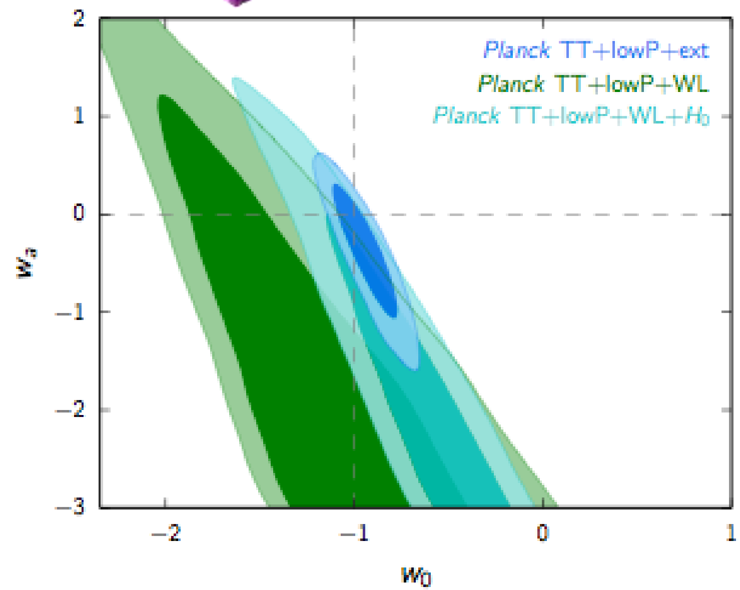
$$\tau = 0.067^{+0.016}_{-0.016}, \; z_{re} = 8.9^{+1.7}_{-1.4}, \; \textit{Planck}\ \text{TT+lensing+BAO}$$

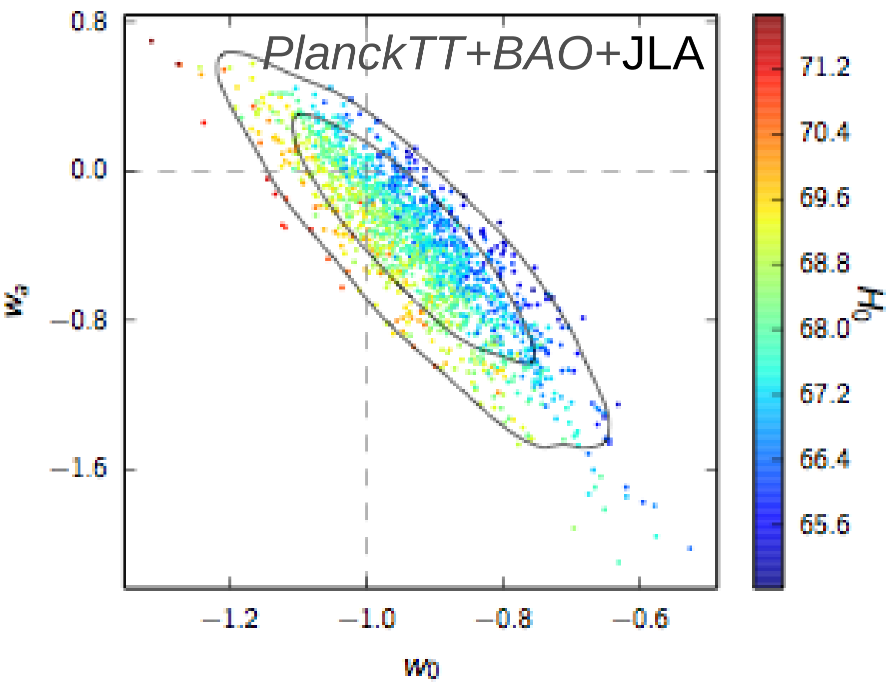
- Lensing reconstruction pushes As to lower values.
  In order to maintain the same normalization of the CMB power spectrum, tau shift at lower values as well, following the $A_s e^{-2\tau}$ degeneracy.

Weak Lensing









Tension with WL on galaxies

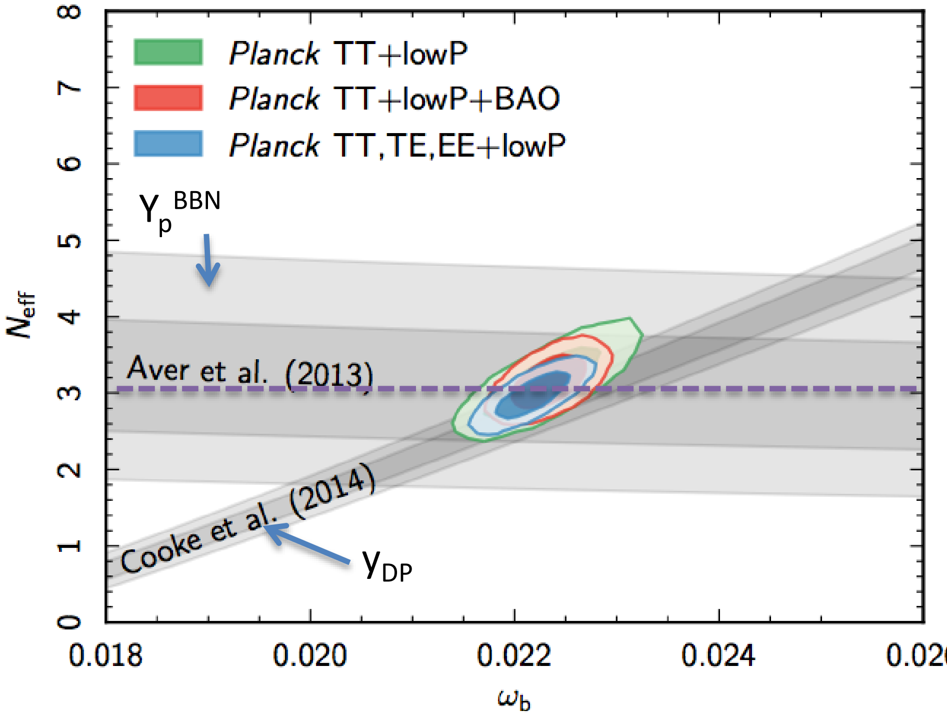
WL wants smaller σ_8

Seems to be driven by the WL small scales

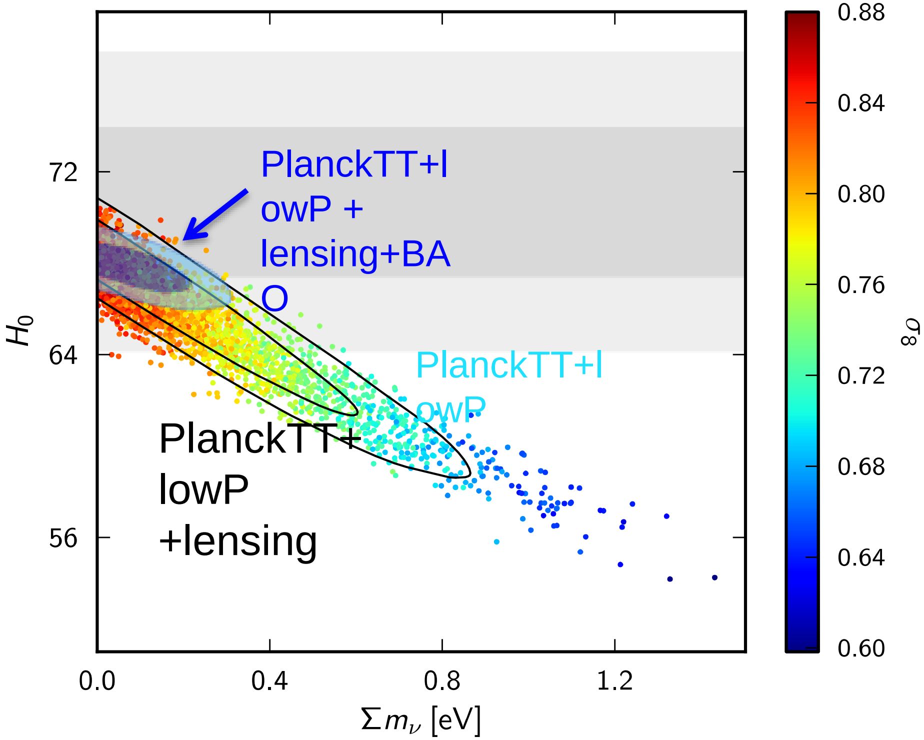
- uncertainty on the non-linear regime+baryonic feedback aT small scales

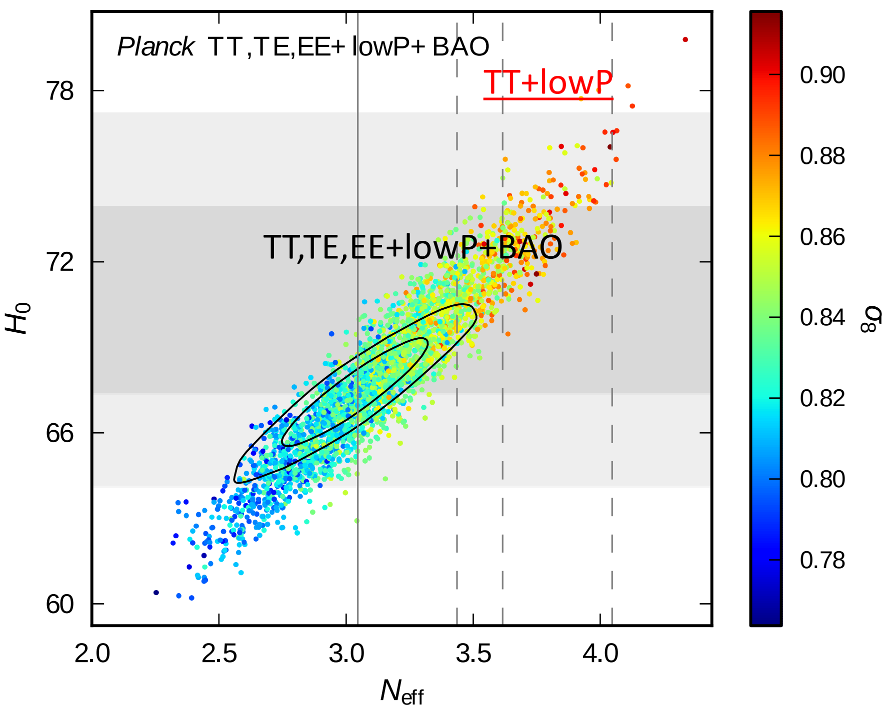
Number of relativistic species: Great agreement with BBN!

- PArthENoPE code for BBN predictions (Pisanti et al. 2008). From primordial Yhe and deuterium measurements, constraints on N_{eff}-$\Omega_b h^2$
- Great agreement between CMB and primordial abundance measurements, assuming standard BBN!



Neutrinos and tensions



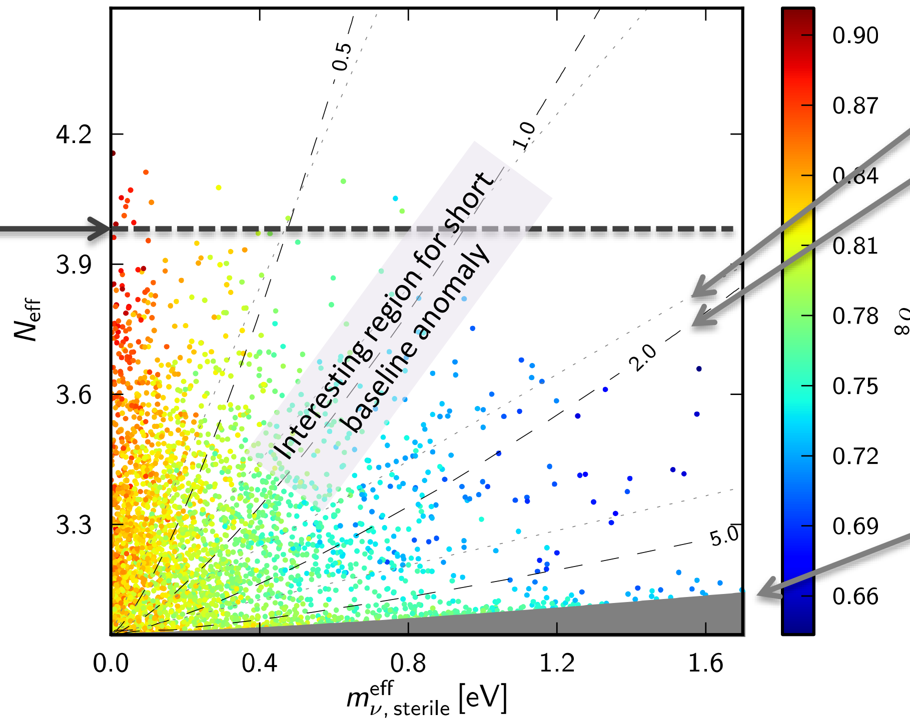


- Neutrino mass alleviates σ_8 tension-> requires low H_0
- Neff alleviates H_0 tension-> requires high σ_8
- Need both to solve tensions(or massive sterile neutrinos).

$$\left.\begin{array}{l} N_{\rm eff} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32\,\mathrm{eV} \end{array}\right\} \quad (95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO}).$$

Massive sterile Neutrinos

One thermalised sterile neutrino species



Physical masses (DW sterile neutrino) (early decoupled thermal particle)

Prior m < 10eV to avoid degeneracy with CDM

$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{\rm eff}_{\nu,\,{\rm sterile}} &< 0.59\,{\rm eV} \end{aligned}\right\} \quad (95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}).$$

Sigma8 values

$\sigma 8 = 0.829 \pm 0.014$ LCDM, Planck TT+lowP

$\sigma 8 = 0.8149 \pm 0.0093$ LCDM, Planck TT+lowP+lensing (1σ lower)

$\sigma 8 = 0.802 \pm 0.018$ LCDM+Alens, Planck TT+lowP (1.5σ lower)

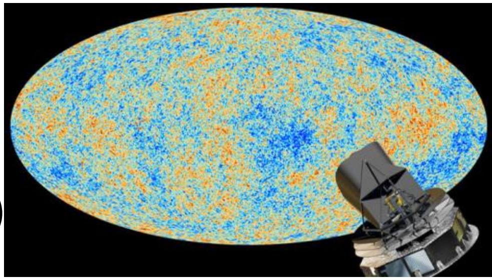
$\sigma 8 = 0.805 \pm 0.018$ LCDM+Alens, Planck TT+lowP+lensing

BICEP-2&KECK at South Pole

- **Goal: primordial B-mode detection. Strategy:Observe a small (clean) patch of the sky, very deep**
- BICEP-2
  - 512 bolometers at **150 GHz**
  - Observed 380 deg^2 **(1% of the sky)** [2010-2012]
- Keck Array
  - 5 times BICEP2 at **150 GHz** [2012-2013]
  - (2/5 detectors switched to **100Ghz** since 2013)

The Planck ESA satellite

- **Many scientific goals. Strategy: full sky, many frequency channels for foreground removal**
- 9 frequency channels (30-850 Ghz), **7 polarized (30-353 Ghz)**
- Data taking: 2009-2013. Data releases:
  2013 (14 months of data, intensity only), 2015 (full mission, with polarization)
- Observations at **353Ghz** => perfect for dust cleaning!

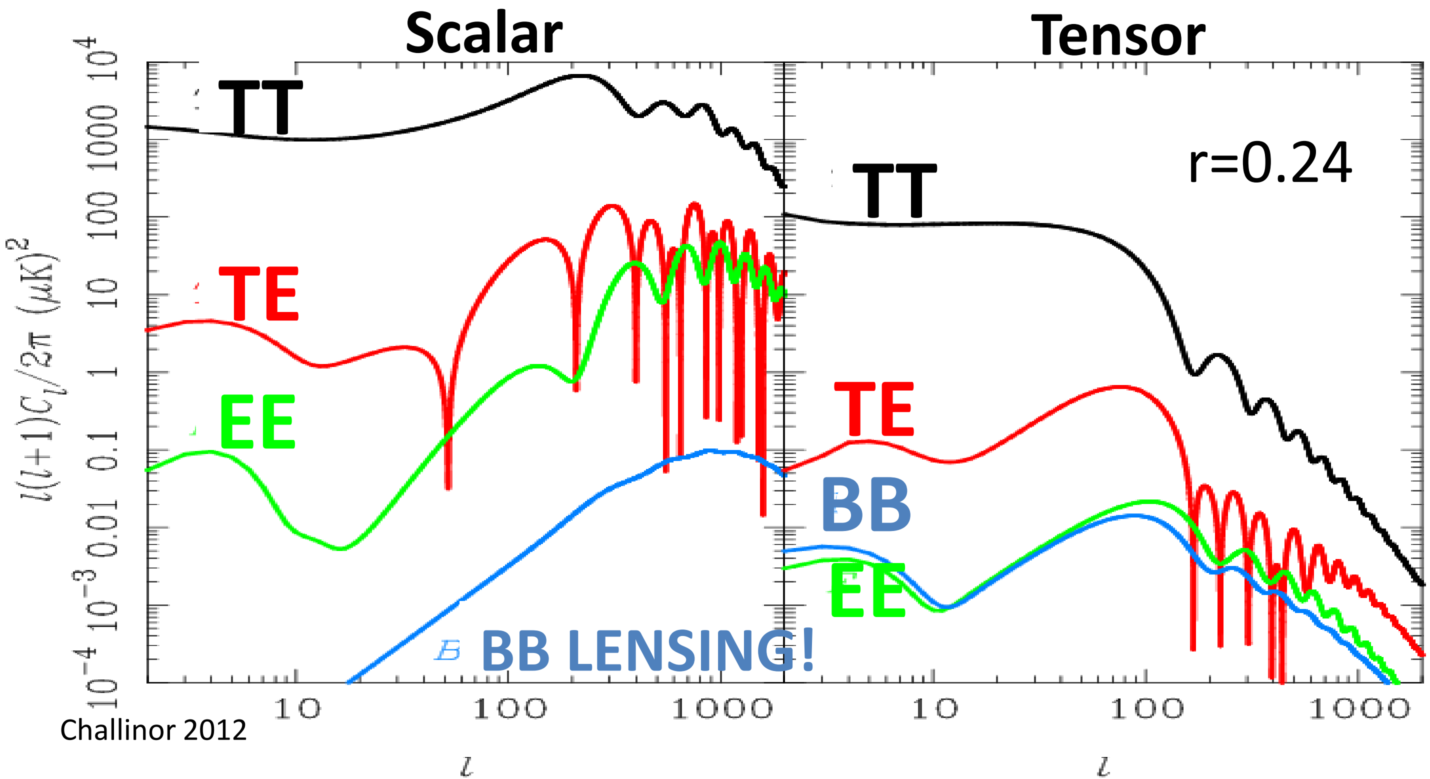


Pre-Bicep r constraints

- Pre-Bicep constraint on r from **TT** constraints from Planck 2013 (indirect measurement, very degenerate with other parameters)

$$r_{0.002} < 0.11 \quad (95\%;\ \text{no running}),$$

Planck collaboration 2013



Challinor 2012

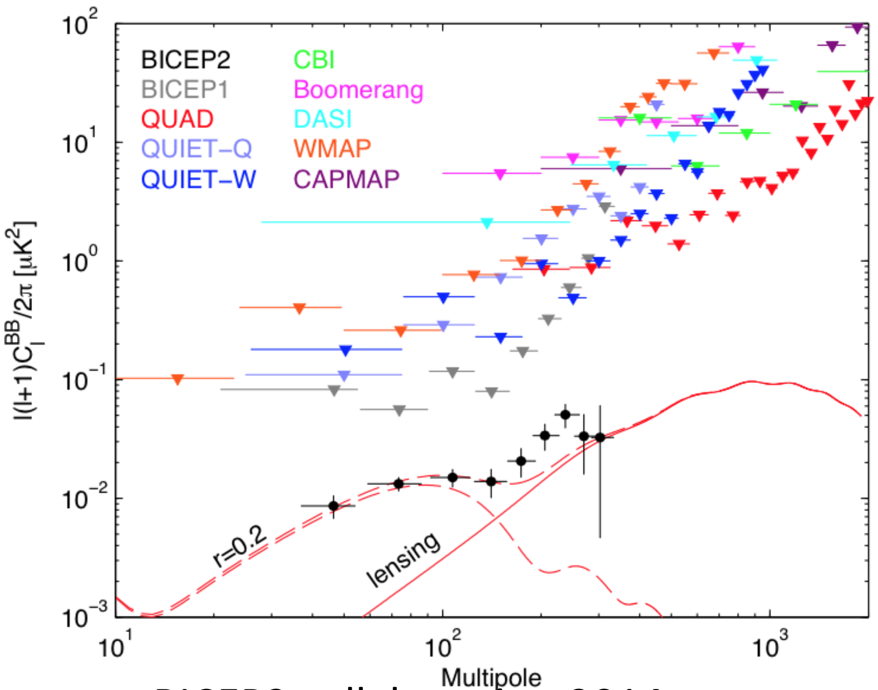
March 2014: the BICEP-2 claim

- BICEP-2 from **BB**

$r = 0.20^{+0.07}_{-0.05}$ No foreground subtraction

$r = 0.16^{+0.06}_{-0.05}$ With foreground subtraction

7/5.9 sigma detection



BICEP2 collaboration 2014

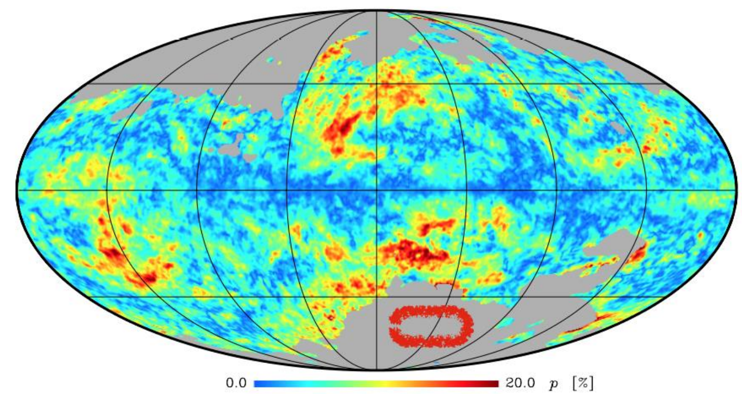
- Compatible with Planck constraints from TT only allowing extensions of LCDM
- Foreground estimation tricky, assumed ~5% dust polarization fraction. No Planck polarization available at the time (only preliminary maps from ESLAB conference presentations).
- Rapidly questioned by Flauger et al. 2014, Mortonson et Seljak 2014

Planck results on polarized dust

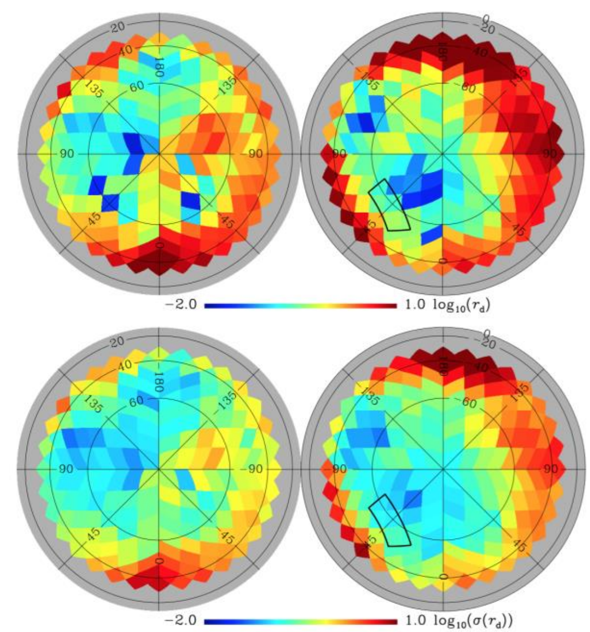
polarisation fraction p

$$p = \frac{\sqrt{Q^2 + U^2}}{I},$$

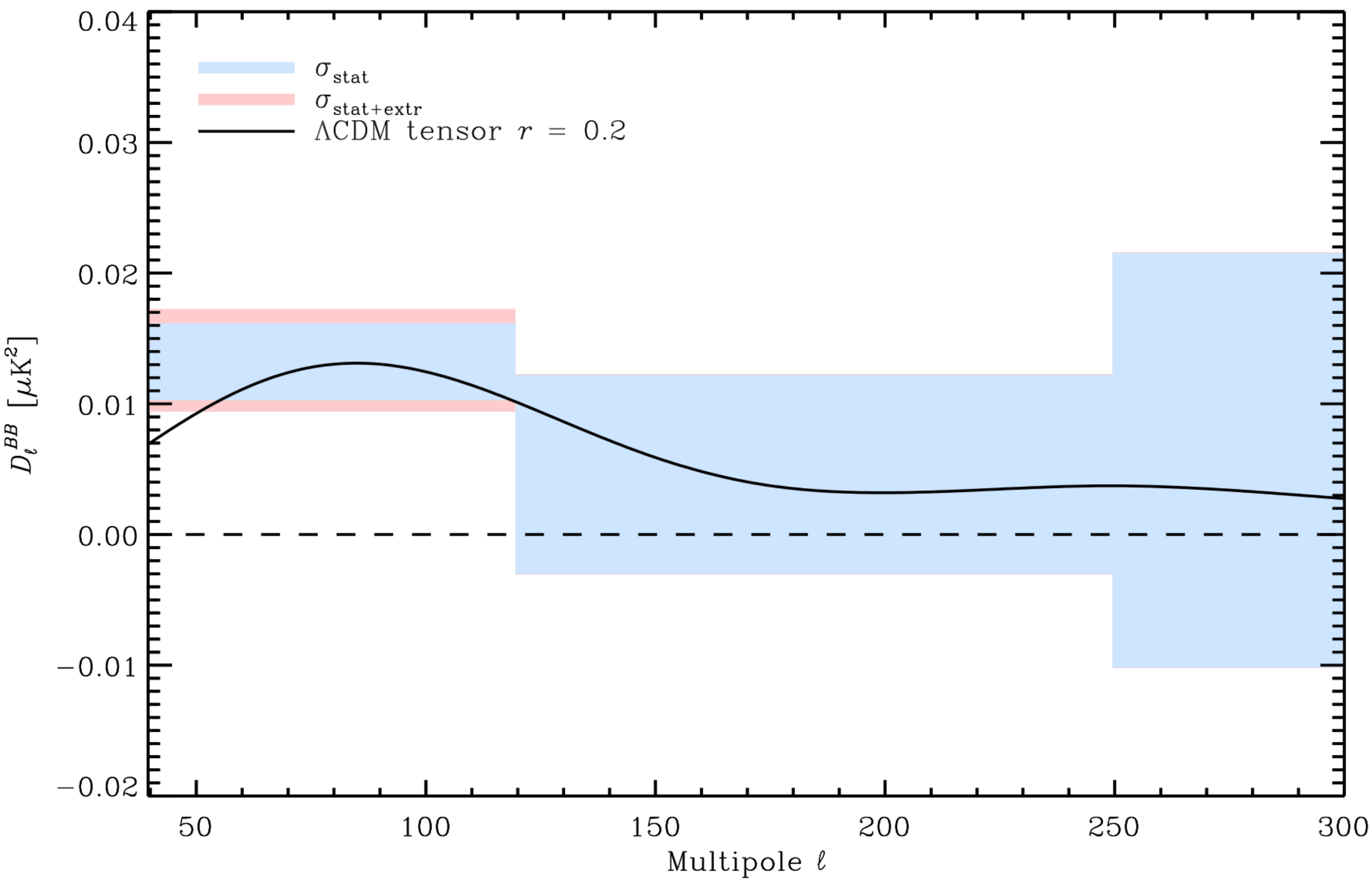
- May 2014, results at intermediate galactic latitudes (Planck collaboration 2014, PIP XIX)



- September 2014: results at high galactic latitudes (Planck collaboration 2014, PIP XXX.



September 2014: Planck results on polarized dust at high latitudes

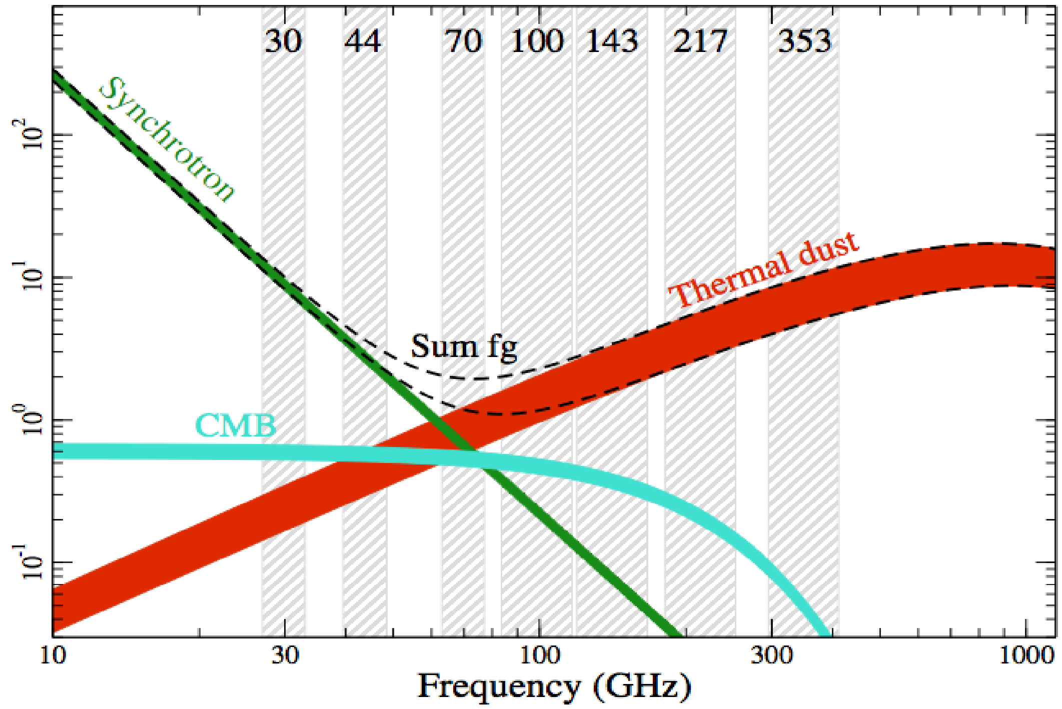


353Ghz **measurement of dust** in the BICEP-2 field extrapolated at 150Ghz

Planck collaboration, PIP XXX, 2014

February 2015: Joint Planck and Bicep2/Keck results

- Joint analysis (Planck and Bicep2/Keck collaborations 2015)
- Bicep-2 and Keck data at 150Ghz
- Planck data at 30-353Ghz



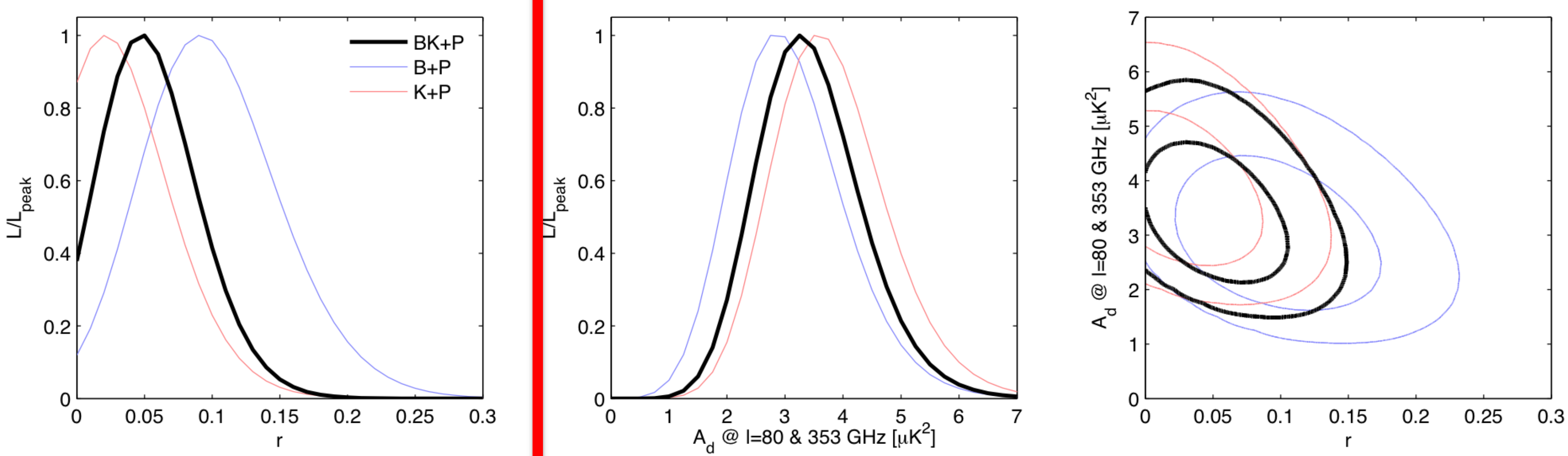
Fiducial analysis

- Standard ΛCDM + r + A_d
- Dust: power law with $D_l \sim l^{-0.4}$ and modified black body frequency spectrum (Fixed T_d, prior on β)

$$I_{\rm d}(\nu) \propto \nu^{\beta_{\rm d}} B_\nu(T_{\rm d}) \quad T_{\rm d} = 19.6\,{\rm K} \quad \beta_{\rm d} = 1.59 \pm 0.11$$

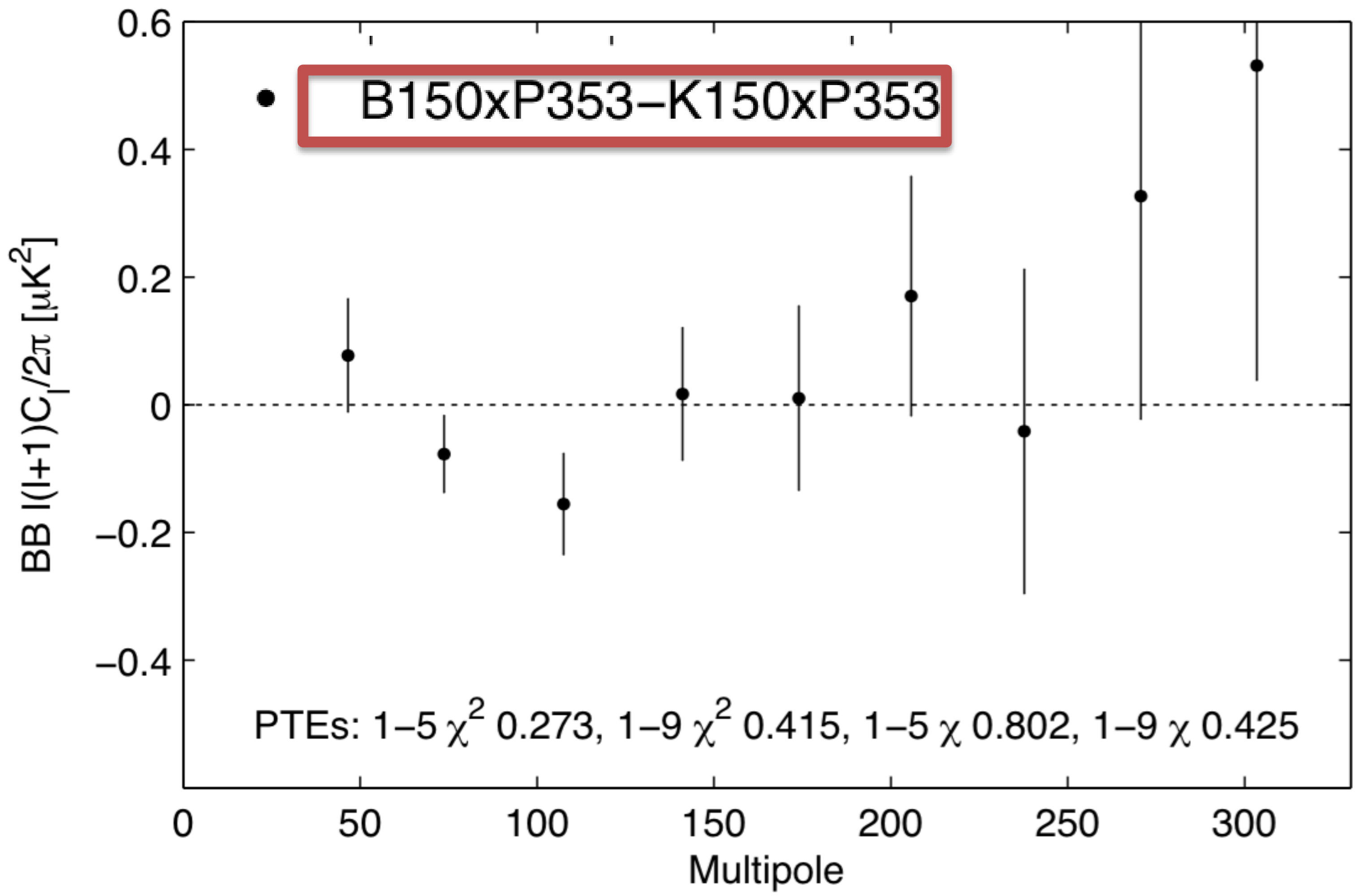
- All auto and cross-spectra of BK150, P217, P353 (for auto Planck, cross-detsets are used) using l=20-200

Fiducial analysis



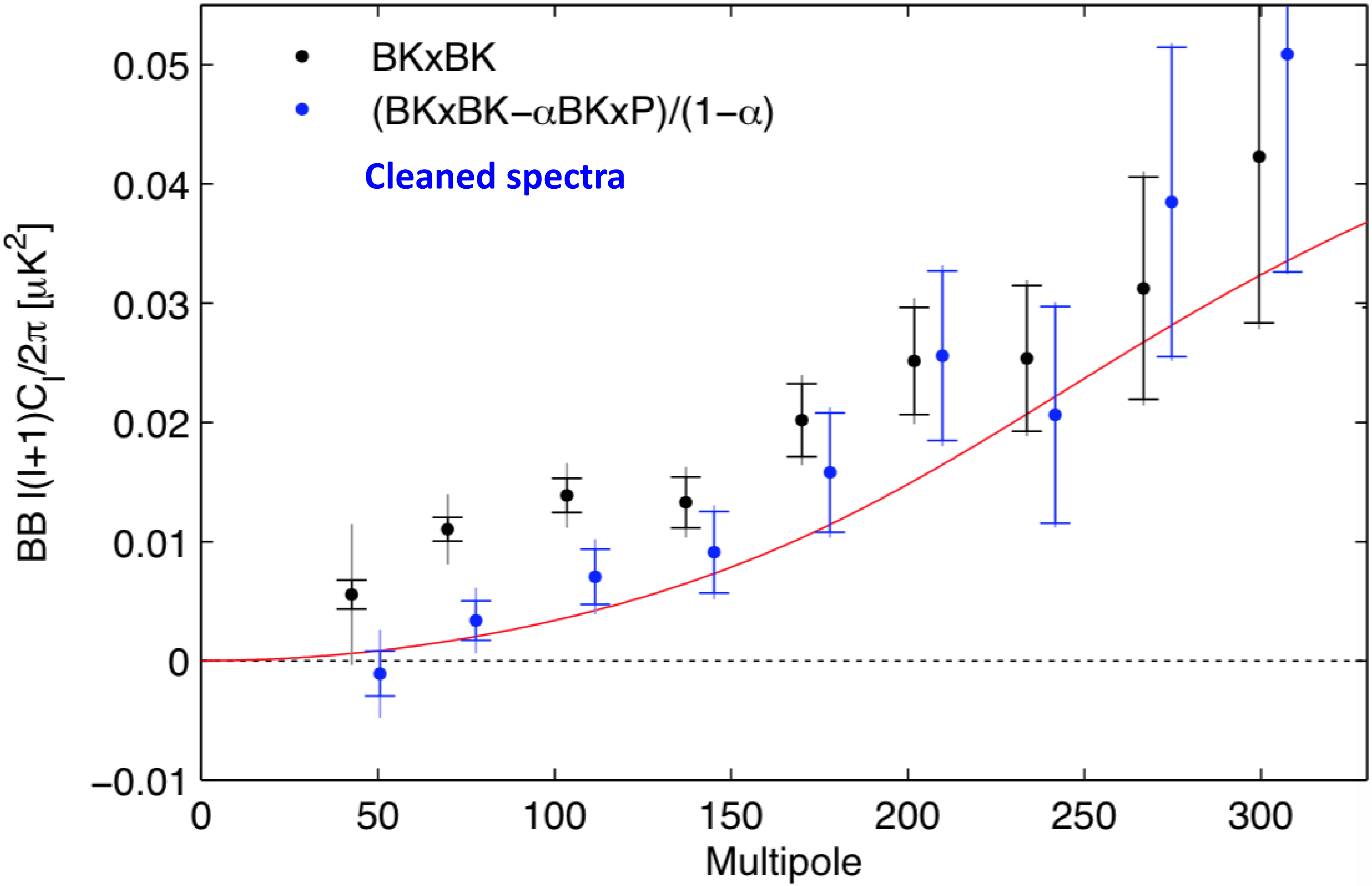
- r =0.048±0.035, r < 0.12 at 95% C.L.
- 5.1 sigma detection of dust power
- Other lines: Bicep alone, Keck alone

Consistency of BICEP2 vs KECK

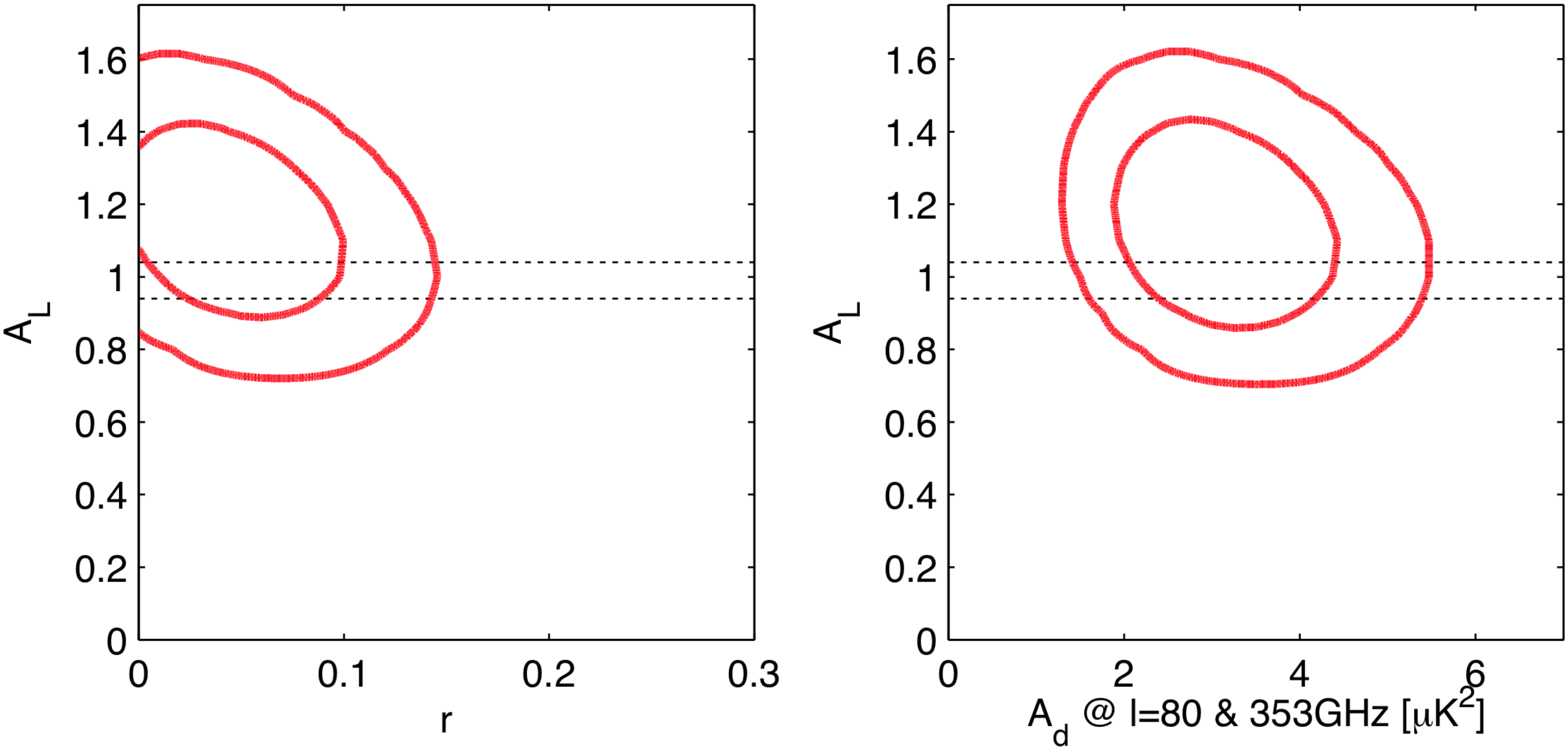


Simulations to assess expected difference between the two experiments. No evidence for discrepancy

Cleaned spectra



A 7-sigma lensing detection



$$A_{\rm L} = 1.13 \pm 0.18$$

What's next?

Ground Based

	Chile	Have data	Current or planned freqs
*	ABS		145 GHz
	ACTPol/AdvACt		30, 40, 90, 150, 230 GHz
	POLARBEAR		90, 150 GHz
*	CLASS		40, 90, 150 GHz
	Antarctica		
*	BICEP/KECK		90, 150, 220 GHz
	SPTPol		90, 150 GHz
	QUBIC-Bolo int.	2016	90, 150, 220 GHz
	Elsewhere (for now)		
	B-Machine –WMRS		40 GHz
*	GroundBIRD, LiteBIRD	2016	150 GHz
*	GLP – Greenland	TBD	150, 210, 270 GHz
*	MuSE-Multimoded	TBD	44, 95, 145, 225, 275 GHz
	QUIJOTE –Canaries, HEM		11-20, 30 GHz

Balloons

		Have data	Current or planned freqs
*	EBEX		150, 250, 210 GHz
	LPSE	TBD	5 chan 40-250 GHz
*	PIPER	2015	200, 270, 350, 600 GHz
*	SPIDER		90, 150, 280 GHz

Credit L. Page, December 2014

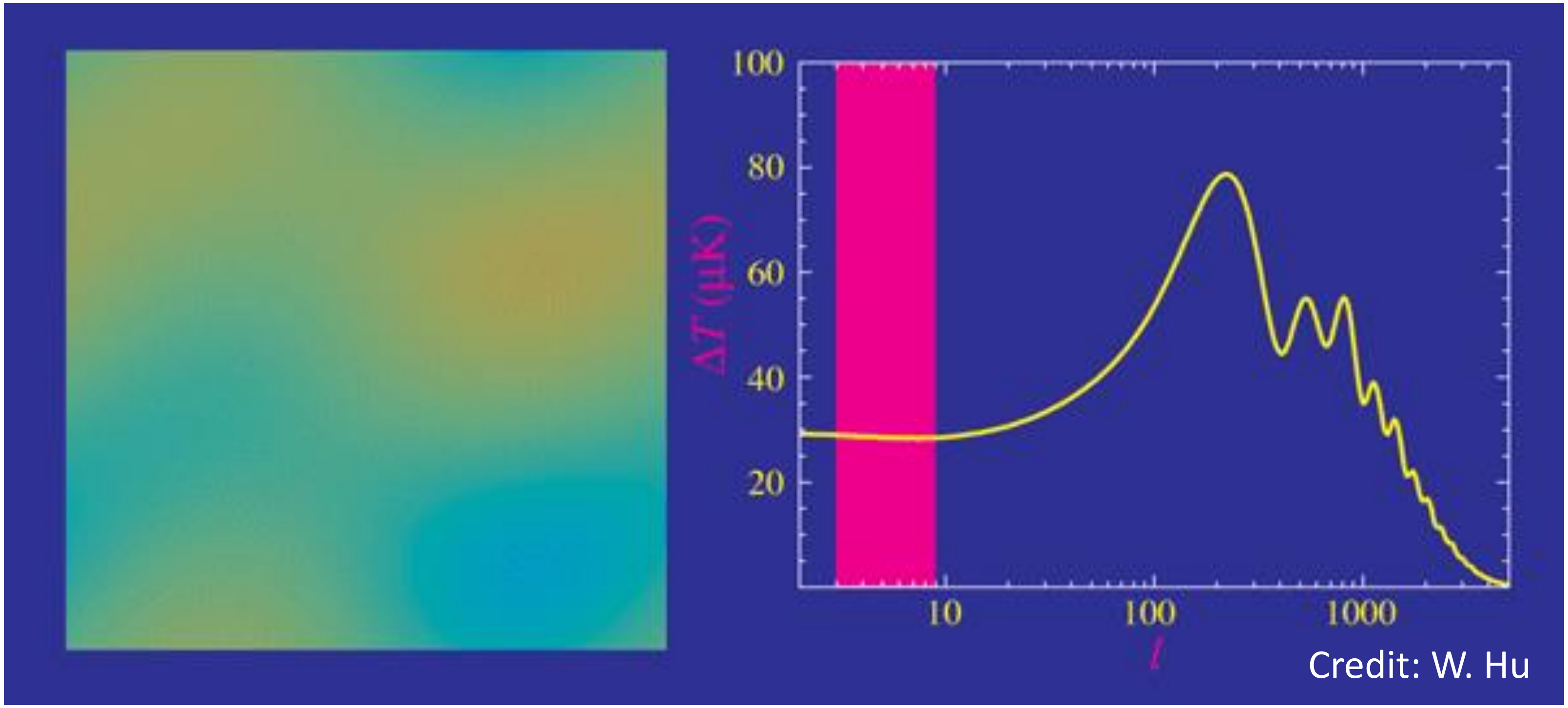
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Angular power spectrum

$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}a^{*}_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$



Angular power spectrum

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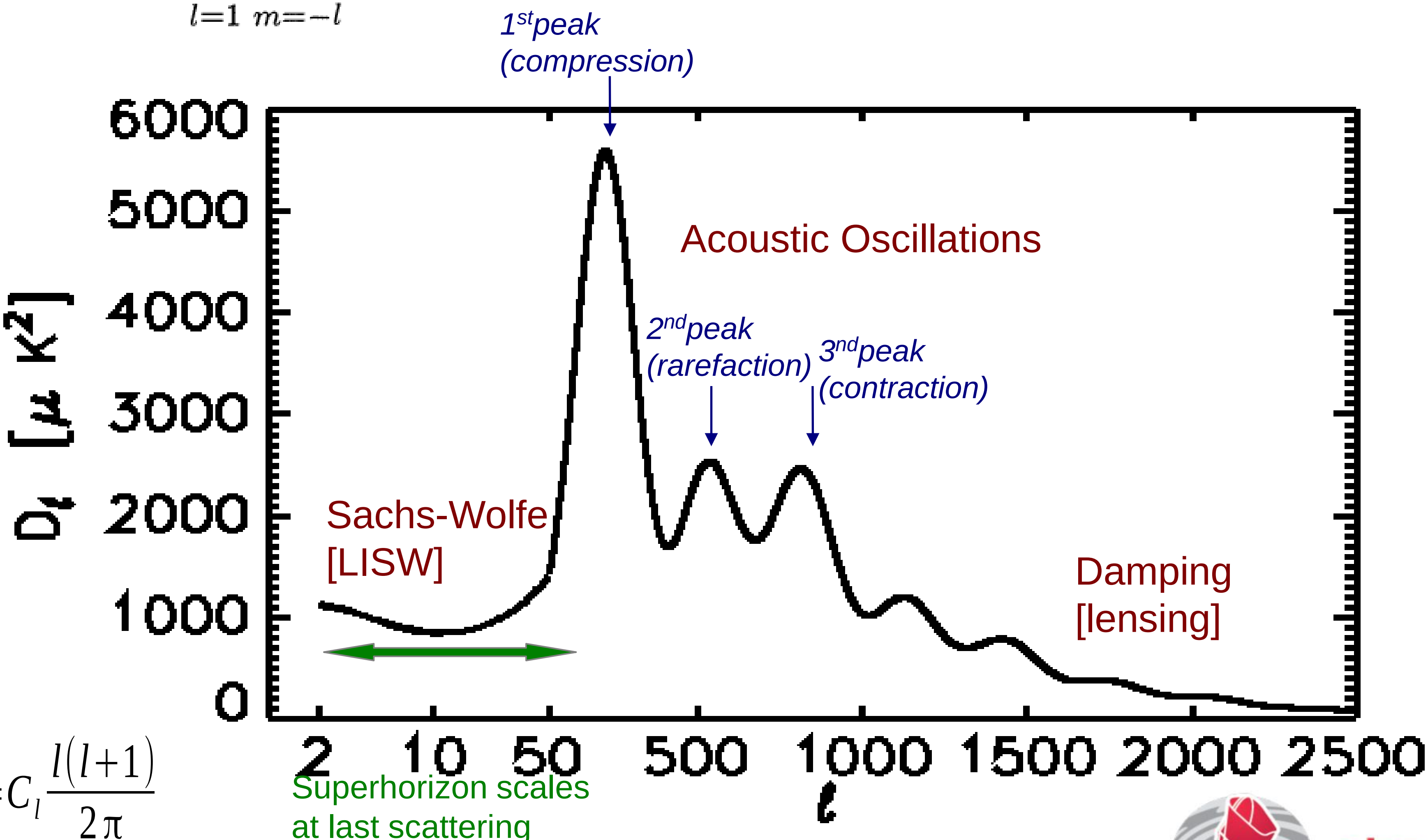


$$D_l=C_l\frac{l(l+1)}{2\pi}$$

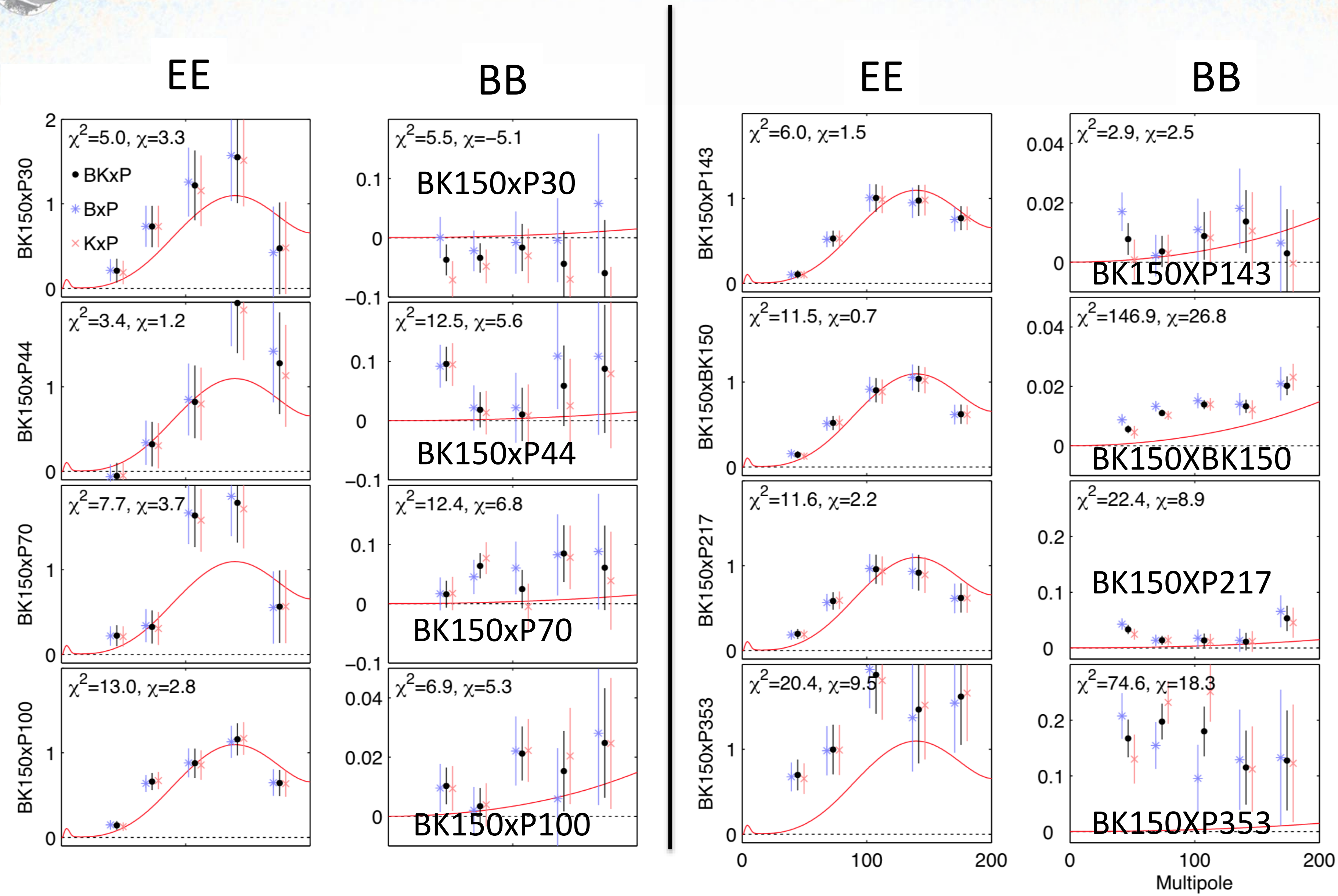
planck

Low-l and High-l likelihood

- **2<l<29**:
  - Pixel based likelihood.
    - Temperature map from component separation (uses all Planck and WMAP-9 maps),
    - Polarization map from 70GHz LFI (syncrotron cleaned with 30GHz, dust cleaned with 353GHz)

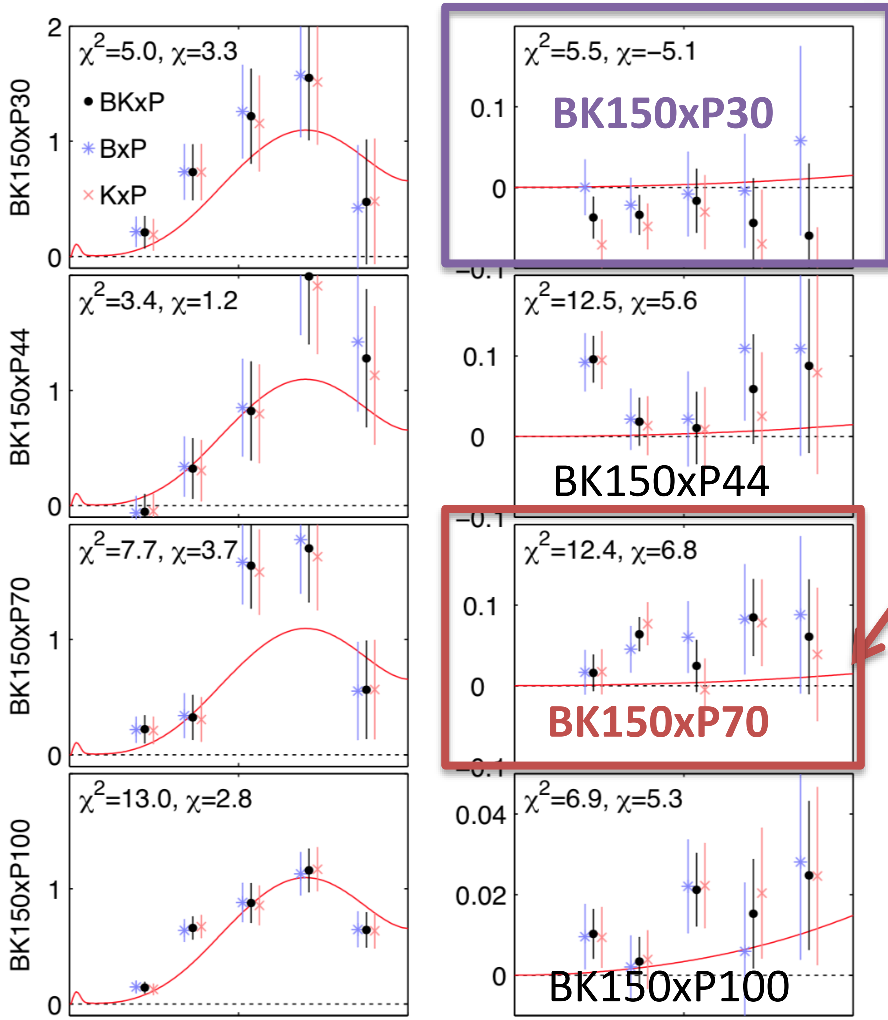
- **30<l<2500**:
  - Uses **100, 143, 217Ghz** Half-Mission cross power-spectra.
  - Masking of galaxy (fsky ~70%,60%, 50% in temperature, 70%,50%, 40% in polarization).
  - Fits unresolved foreground parameters together with cosmological parameters.

BICEP+KECK X Planck



= Lensed LCDM model, r=0

BK X Planck:low frequencies



Small excess in BK150xP70, but no excess in BK150xP30,

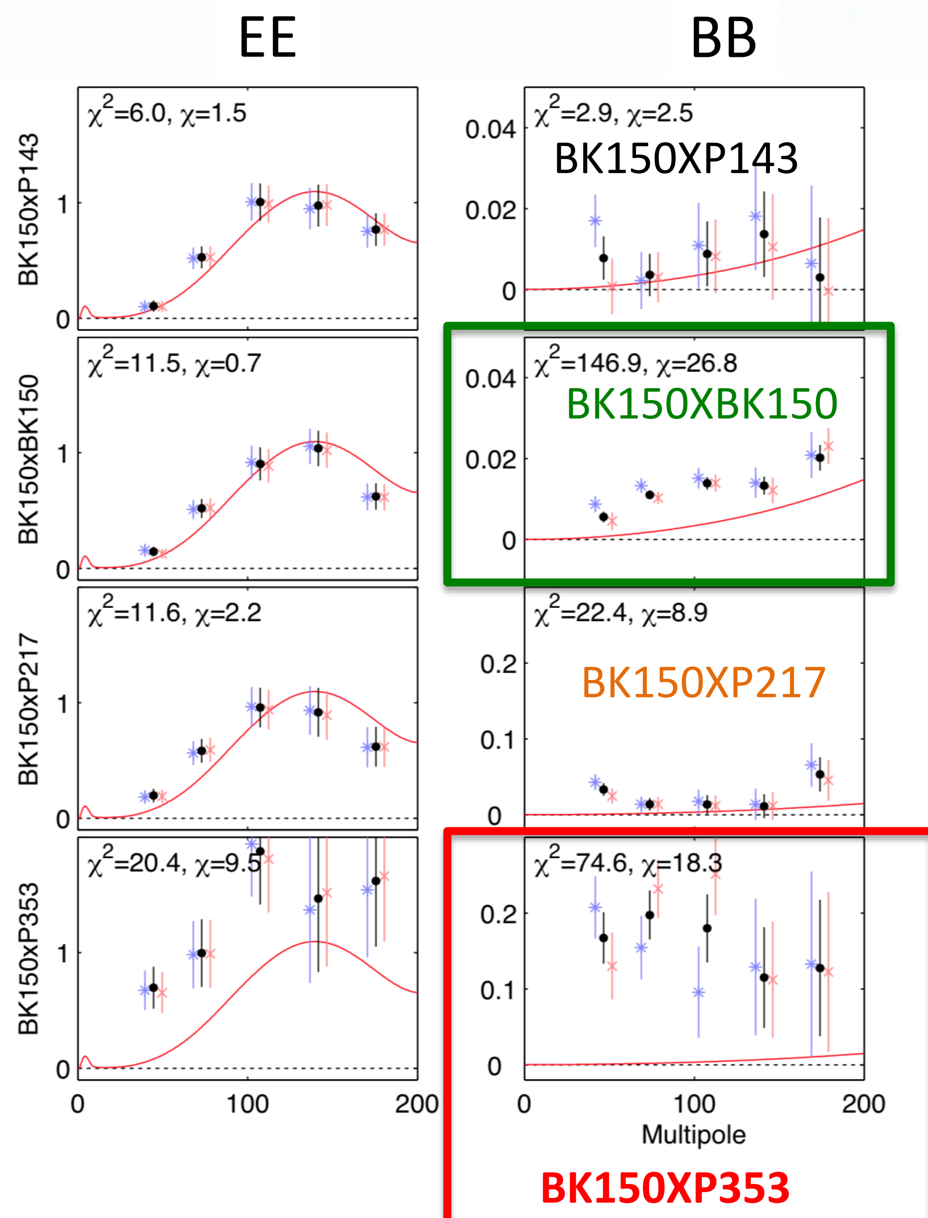
No evidence for syncrotron contamination at 150Ghz (expected to scale as $\sim\nu^{-3.3}$)

BK X Planck

- At 150x353 dust expected to be 25 times larger than at 150x150 (modified black body spectrum)

$$I_{\mathrm{d}}(\nu) \propto \nu^{\beta_{\mathrm{d}}} B_{\nu}(T_{\mathrm{d}})$$

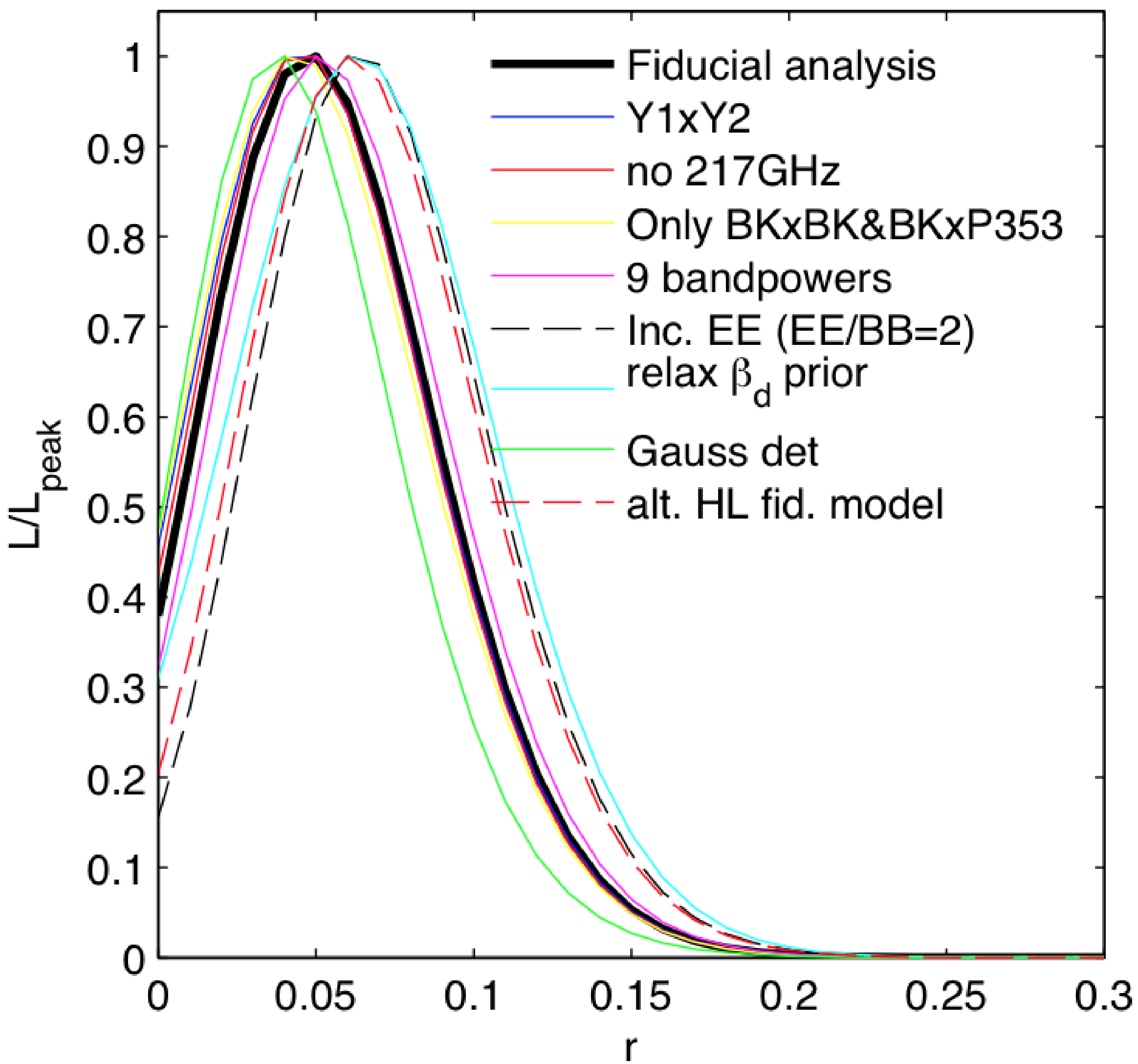
- Large correlation at 150x353 in BB (and at 150x217)



Tests

- Choice of Planck single-frequency spectra: yearly or half- ring instead of detset).
- Using only 150 and 353 GHz
- Using only BK150×BK150 BK150×P353:The statistical weight of the BK150×BK150 and BK150×P353 spectra dominate.
- Extending the bandpower range to $20 < l < 330$
- Including EE spectra, setting EE/BB = 2 from dust. Constraint A_d narrows,small change in r constraint.
- Relaxing the β_d prior: relaxing the prior on the dust spectral index to $\beta_d = 1.59 \pm 0.33$ pushes the peak of the r constraint up (but if frequency spectral index varied significantly across the sky it would invalidate cross-spectral analysis)
- Varying the dust power spectrum shape, marginalizing over spectral indices in the range −0.8 to 0.
- Using Gaussian determinant likelihood
- Varying the HL fiducial model: default, with r=0. Alternative, r=0.2

Tests



Fiducial analysis
Y1xY2
no 217GHz
Only BKxBK&BKxP353
9 bandpowers
Inc. EE (EE/BB=2)
relax β_d prior
Gauss det
alt. HL fid. model
L/L_{peak}
r
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.05
0.15
0.25

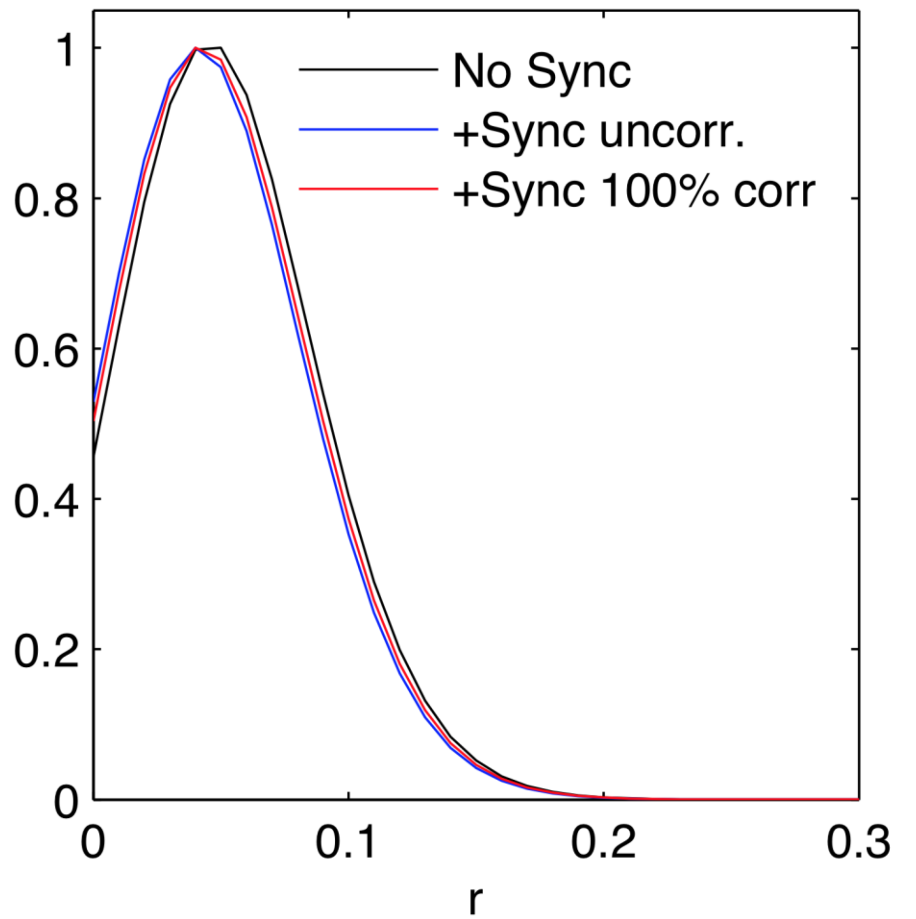
No evidence for syncrotron contamination

- Tested the sensitivity to adding a syncrotron component (Planck 30Ghz channel to constrains it)
- Frequency scaling

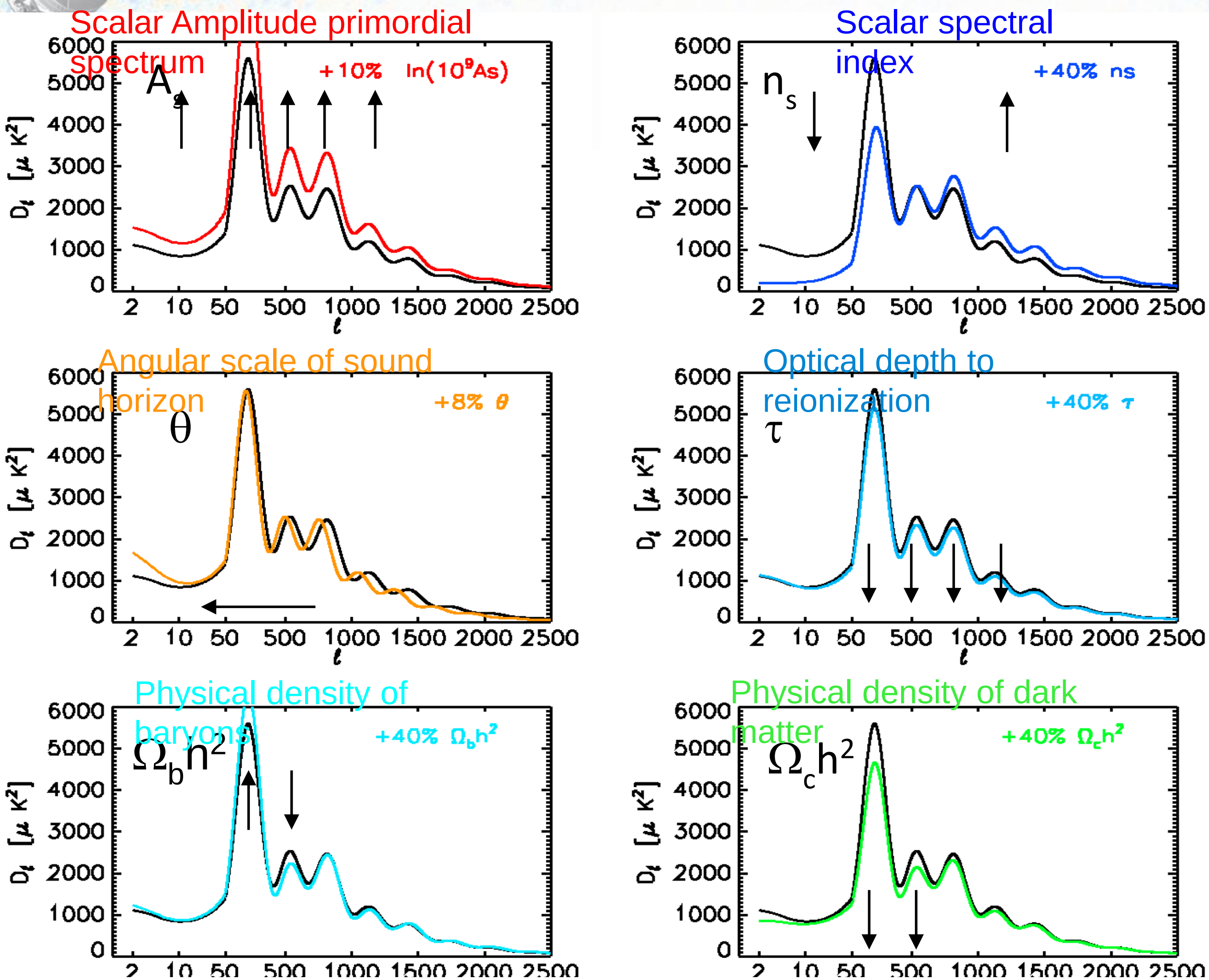
$$\nu^{-3.3}$$

- Power spectrum scaling

$$\mathcal{D}_\ell \propto \ell^{-0.6}$$



6 LCDM parameters



- Initial conditions A_s, n_s:

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0} \right)^{n_s -}$$

- Expansion history q
- Reionization t

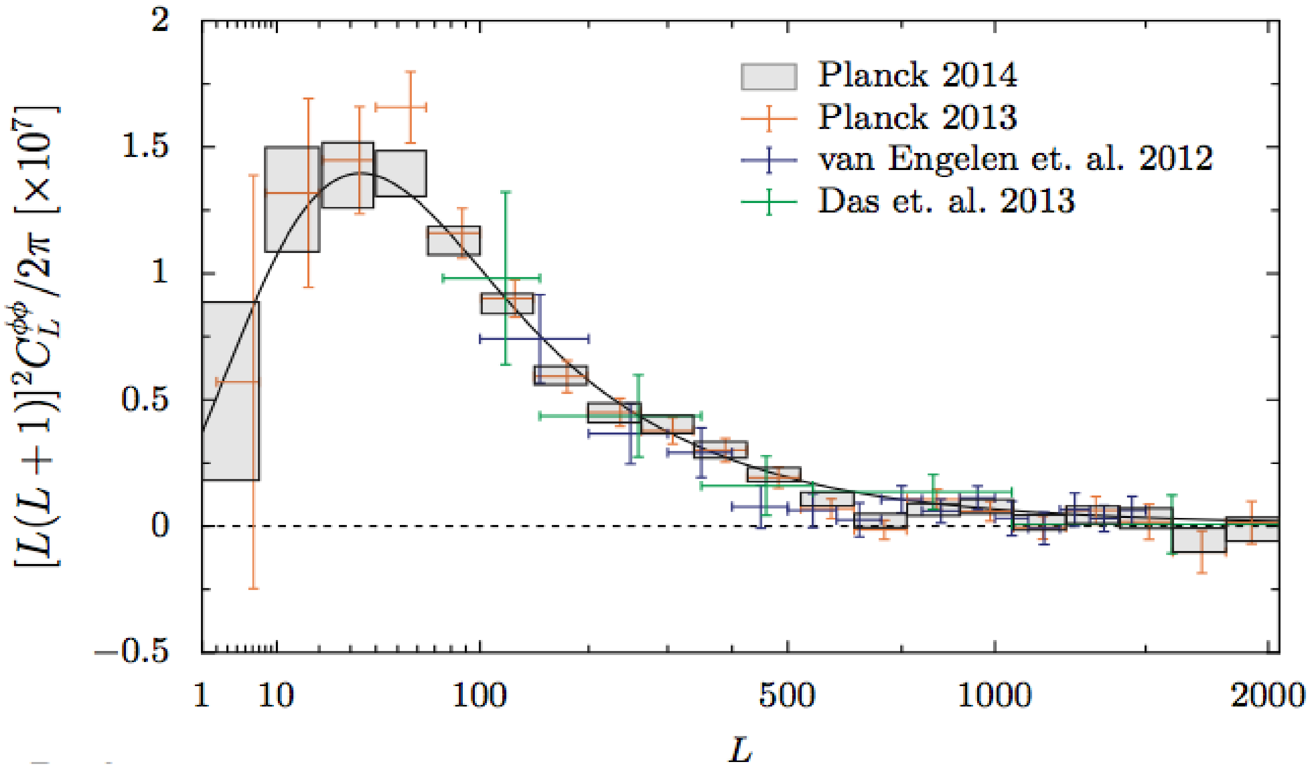
- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:

- Adiabatic initial conditions
- Neff=3.046
- 1 massive neutrino 0.06eV.
- Sudden reionization (Δz=0.5)

planck

Lensing potential power spectrum

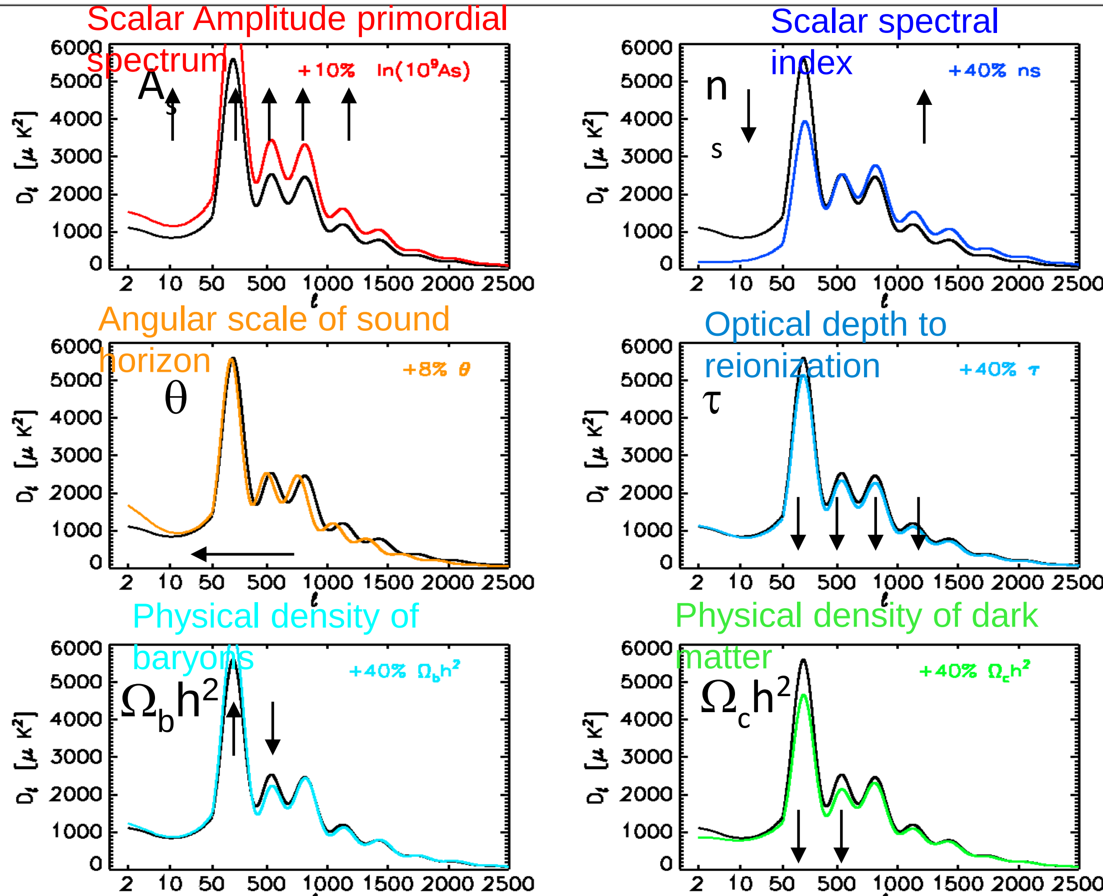


- **2)** It breaks isotropy of the CMB. Lensing potential map can be extracted from the non-gaussian 4-point correlation function.
- Lensing potential power spectrum used in cosmological analysis (40<L<400).

- **Planck 2015 detects lensing at 40σ!**

Results

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1



Neutrino perturbations

- Standard model of cosmology predicts neutrino perturbations, characterized by effective sound speed and viscosity parameter (isotropic and anisotropic pressure perturbations)
- Standard values for free-streaming particles (c_{eff}^2, c_{vis}^2) = (1/3, 1/3); perfect fluid: (1/3,0)…

Parameter	TT	TT,TE,EE	TT,TE,EE+BAO
$c^2_{\rm vis}$	0.57 ± 0.16	0.336 ± 0.039	0.338 ± 0.040
$c^2_{\rm eff}$	0.314 ± 0.012	0.3256 ± 0.0063	0.3257 ± 0.0059

- Standard free-streaming behaviour in perfect agreement with Planck data