Cosmological results from Planck 2015

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KICP-UChicago

On behalf of the Planck collaboration

Invisibles 2015, Madrid, 26 June 2015

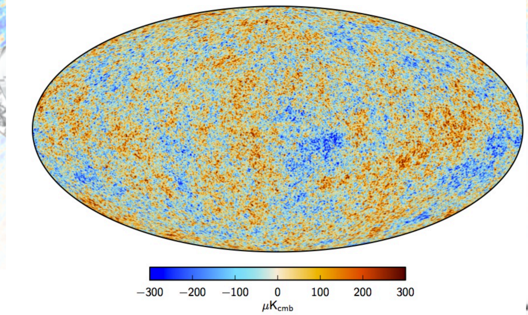
Planck 2015 results. I. Overview of products and results	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. II. Low Frequency Instrument data processing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. III. LFI systematic uncertainties	Planck Collaboration	2015 In prep.
Planck 2015 results. IV. LFI beams and window functions	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. V. LFI calibration	Planck Collaboration	2015 Submitted to A&A
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 Submitted to A&A
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 Submitted to A&A
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 Accepted by A&A
Planck 2015 results. XXVIII. The Planck Catalogue of Galactic Cold Clumps	Planck Collaboration	2015 Submitted to A&A

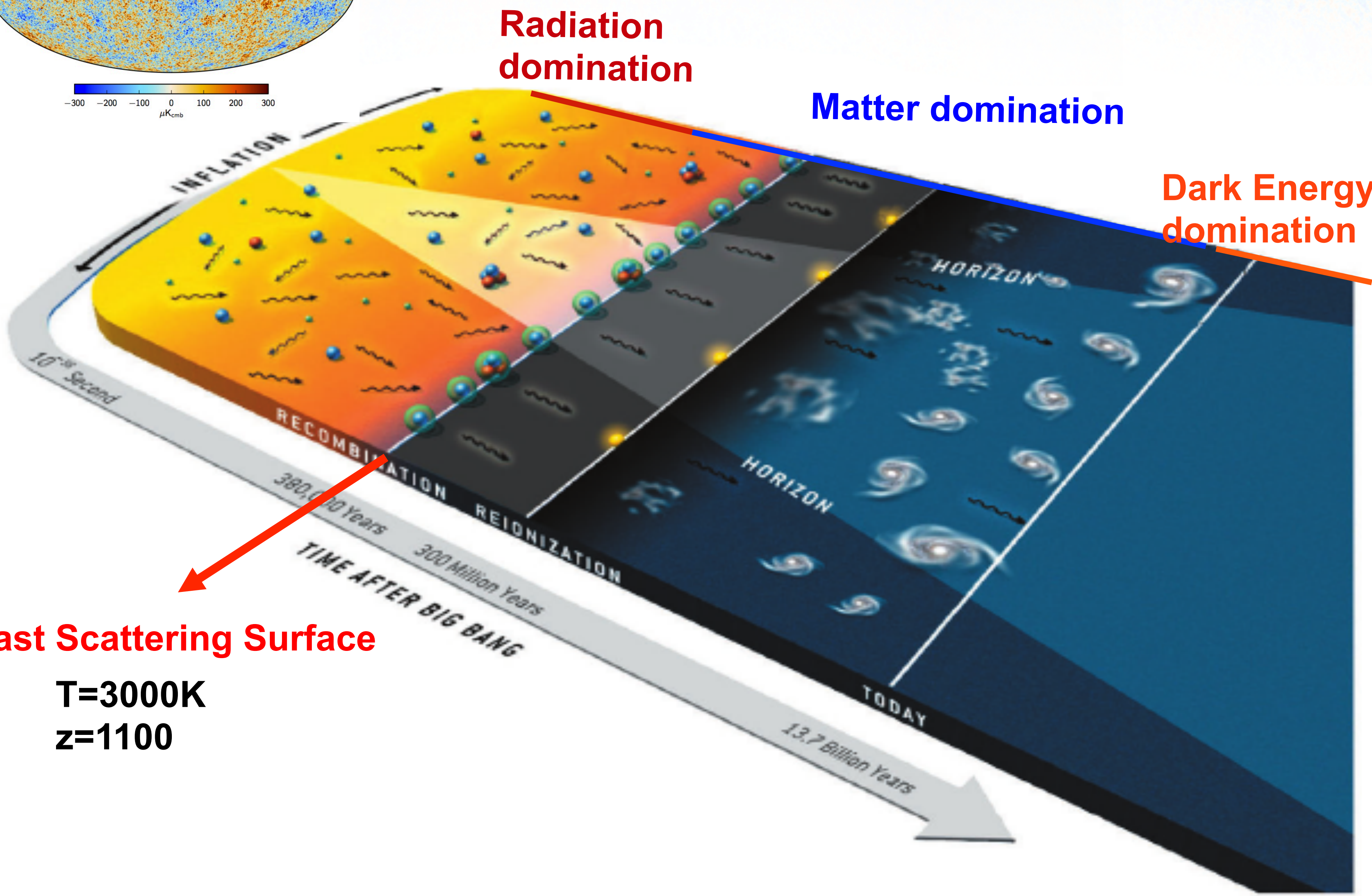
2015 Release

- 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.

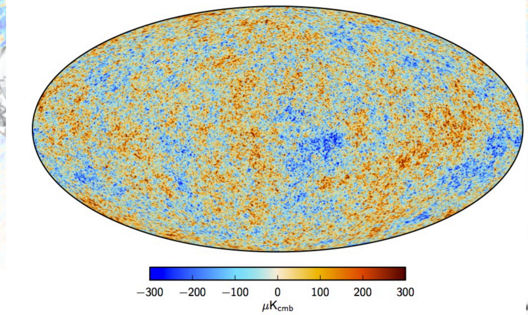
CMB in 2 slides

Cosmic History





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



Cosmic History

Radiation domination

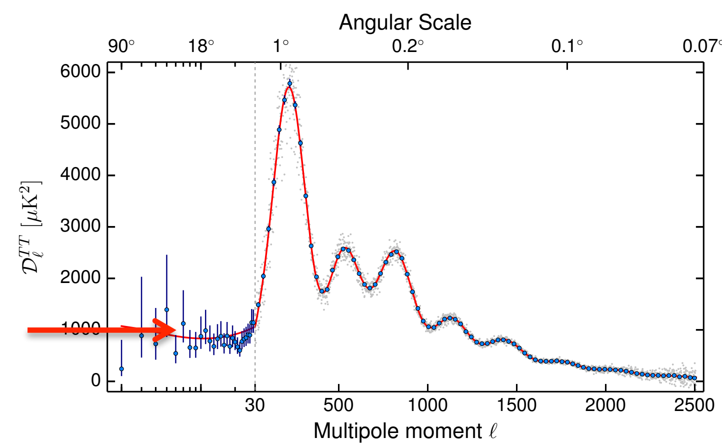
Matter domination

Dark Energy domination

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

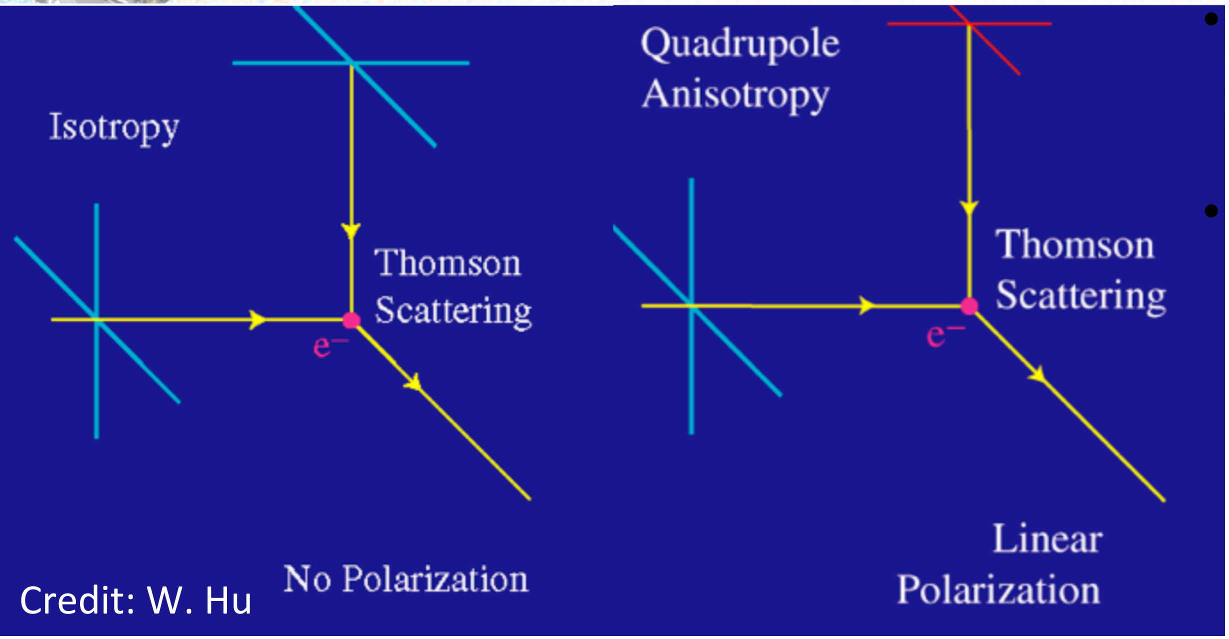
$$\Theta(\vec{x},\hat{p},\eta)=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

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

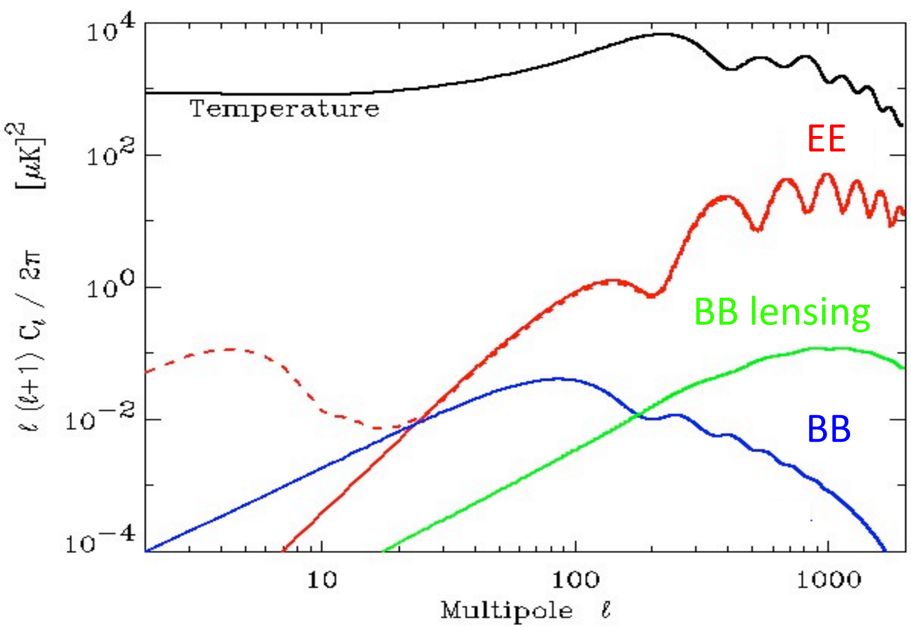


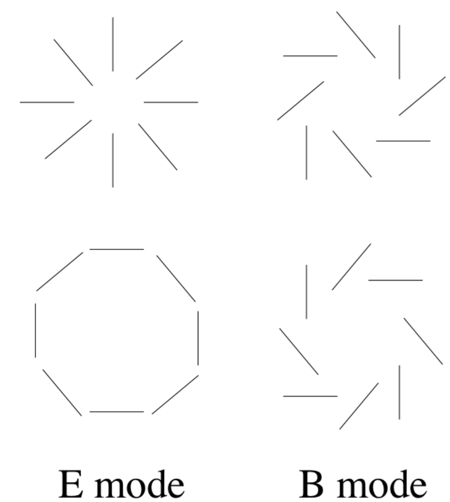
Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

CMB Polarization



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

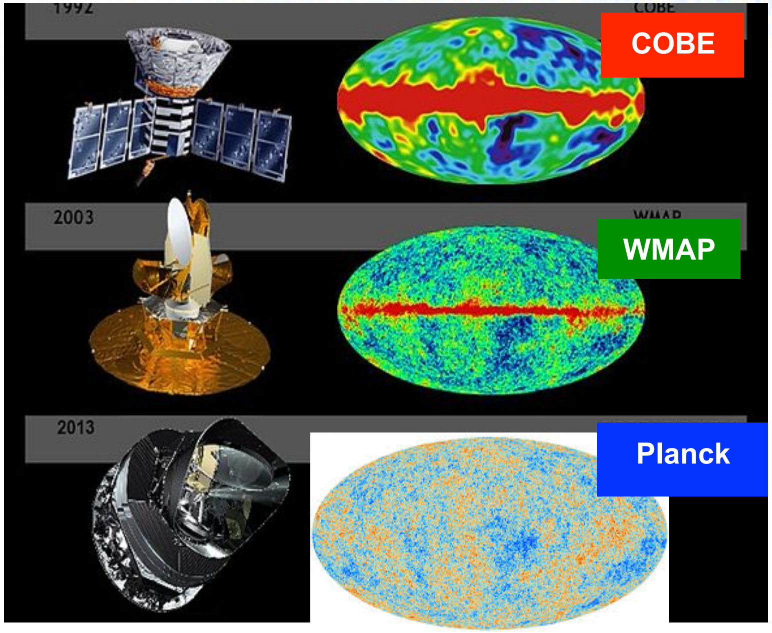


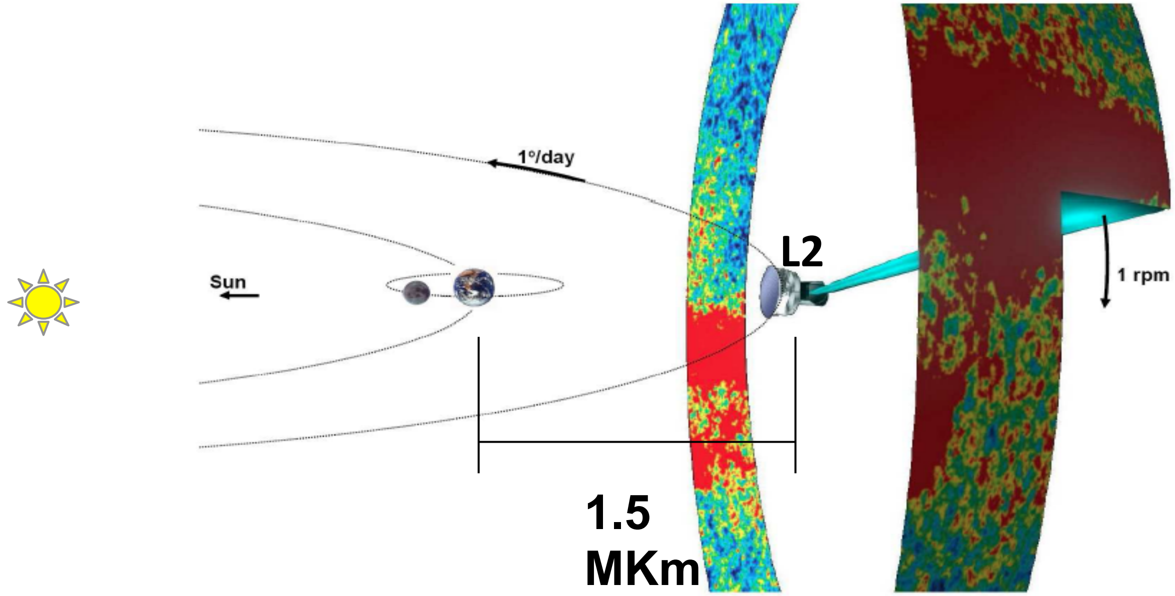


The Planck satellite

The Planck mission

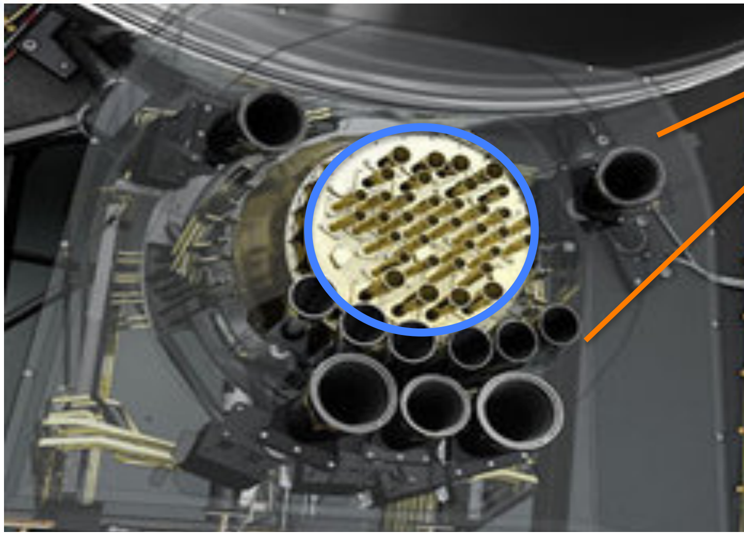
- Third generation satellite missions.
- Launched in **2009** to L2 (with Herschel), operated until **2013**.





planck

9 Frequencies, 2 instruments



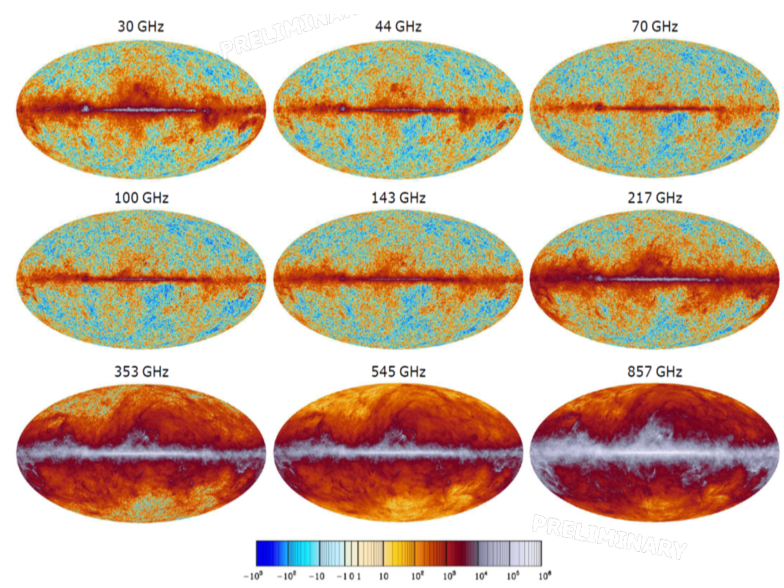
LFI:

- 22 radiometers at **30, 44, 70 Ghz.**

HFI:

- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**

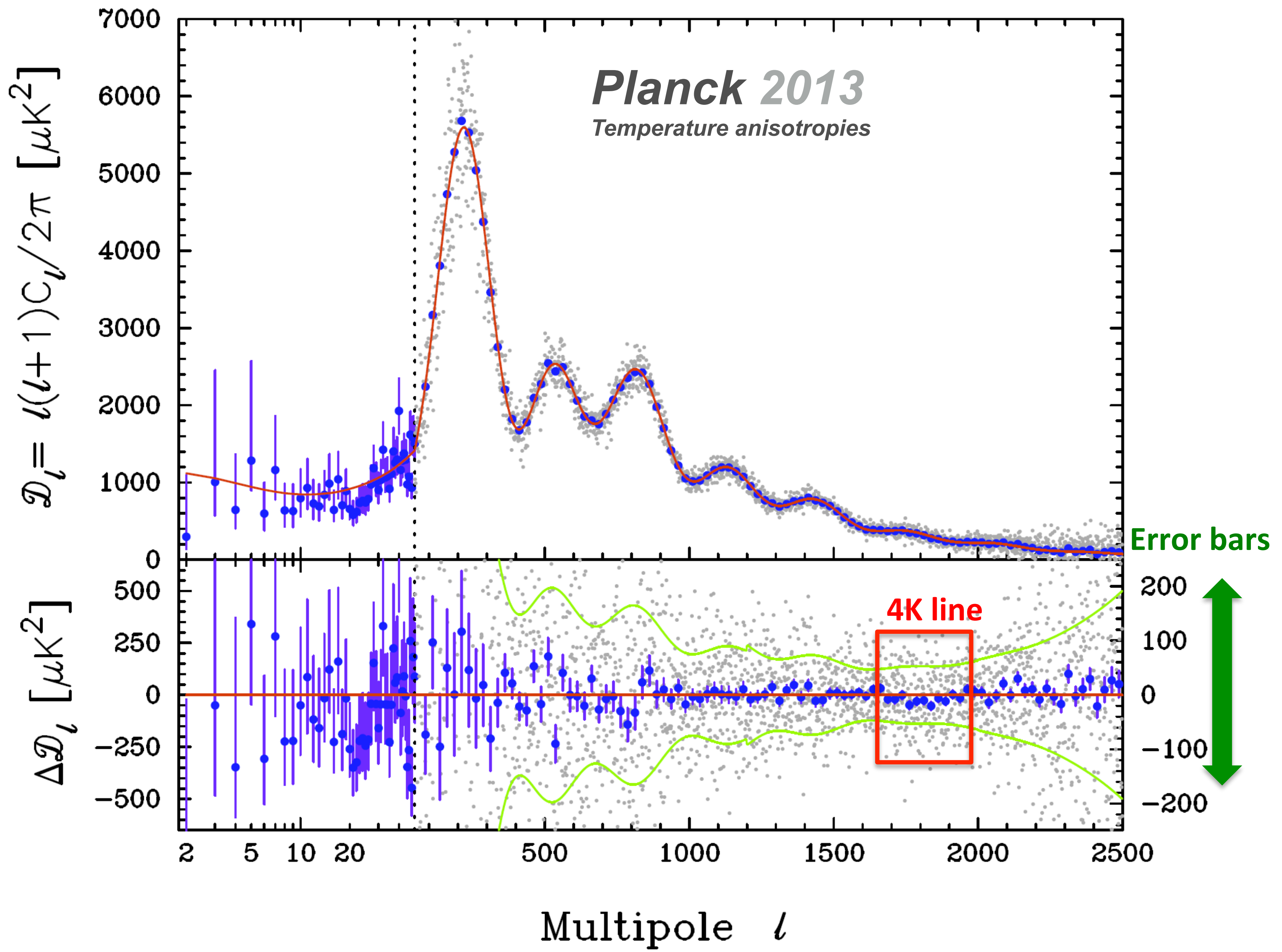
- **1st release 2013: Nominal mission**, 15.5 months, Temperature only.
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization



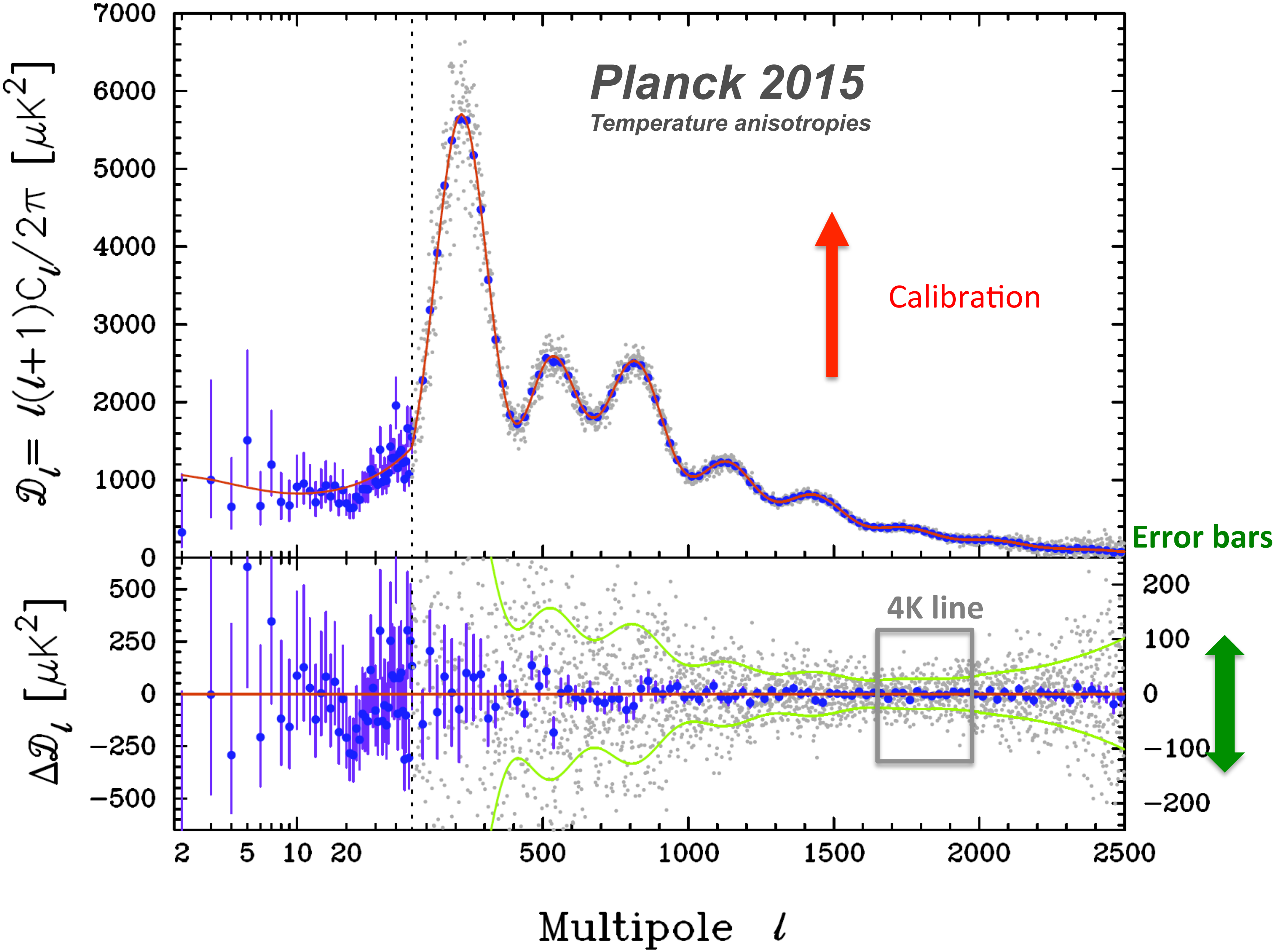
What changed since 2013?

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

1. **Full** mission data (more than double w.r.t. 2013)
2. **Calibration** -> +2%. Planck 2015 and WMAP now perfectly agree
3. **Systematics** better handled (e.g. l~1800 dip due to the 4K line).
4. **Polarization**.
    1. **Low-l** (large scales, l<30) polarization from **Planck LFI** instead of **WMAP9 polarization** (used in 2013) to constrain reionization.
    2. **High-l** (small scales, l>30) polarization from **HFI**.



Planck 2013
Temperature anisotropies
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
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ



Planck 2015
Temperature anisotropies
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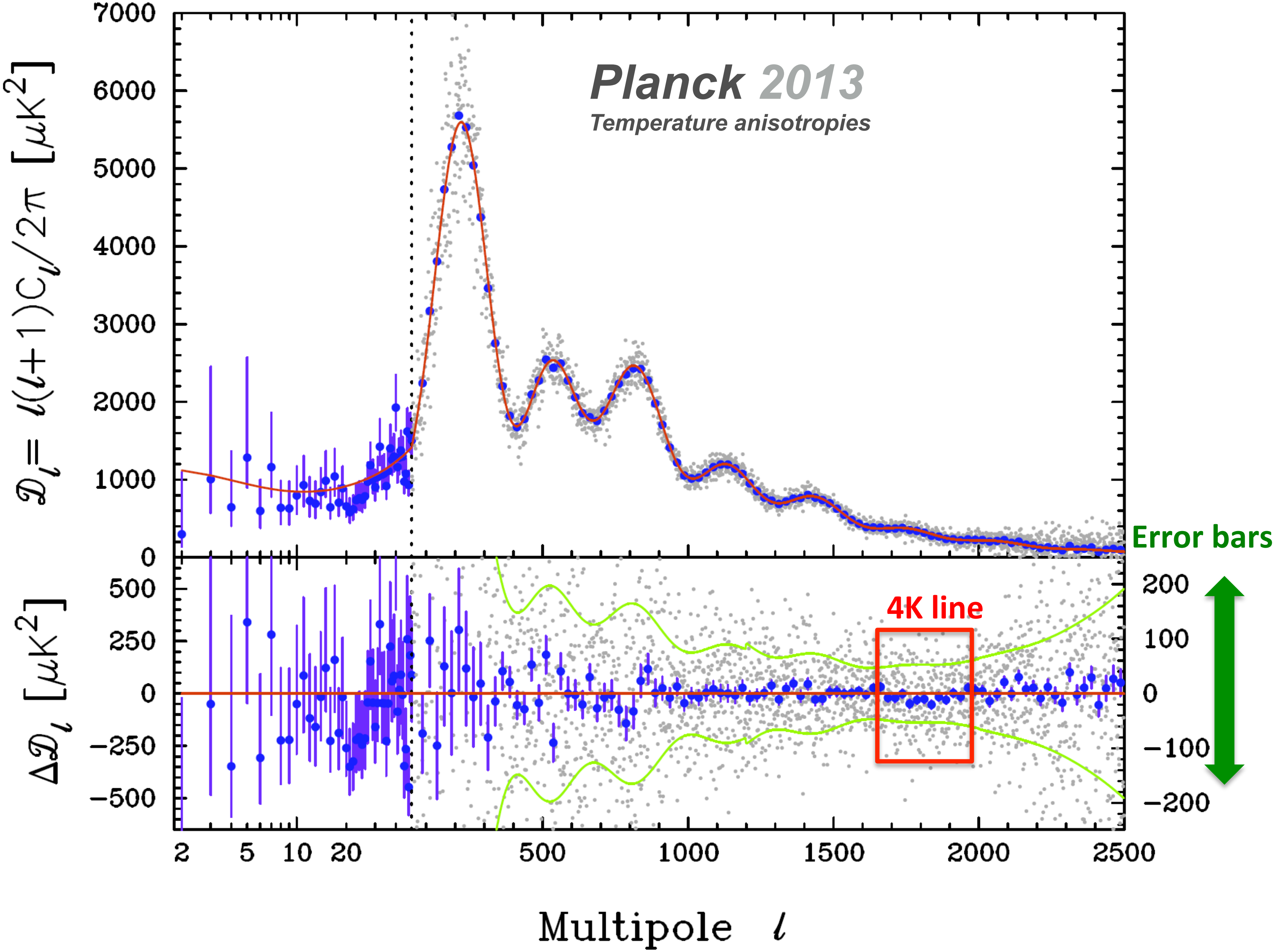

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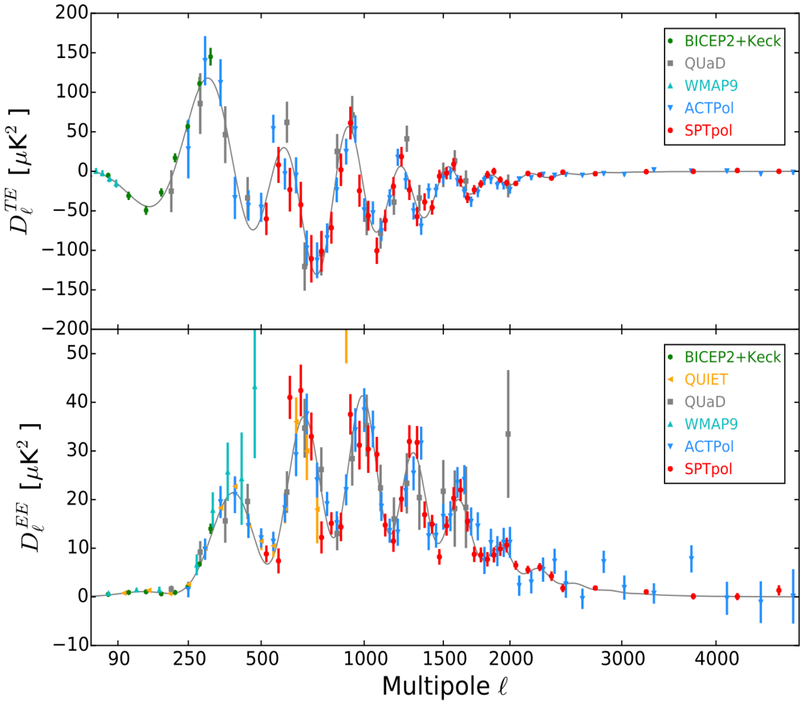
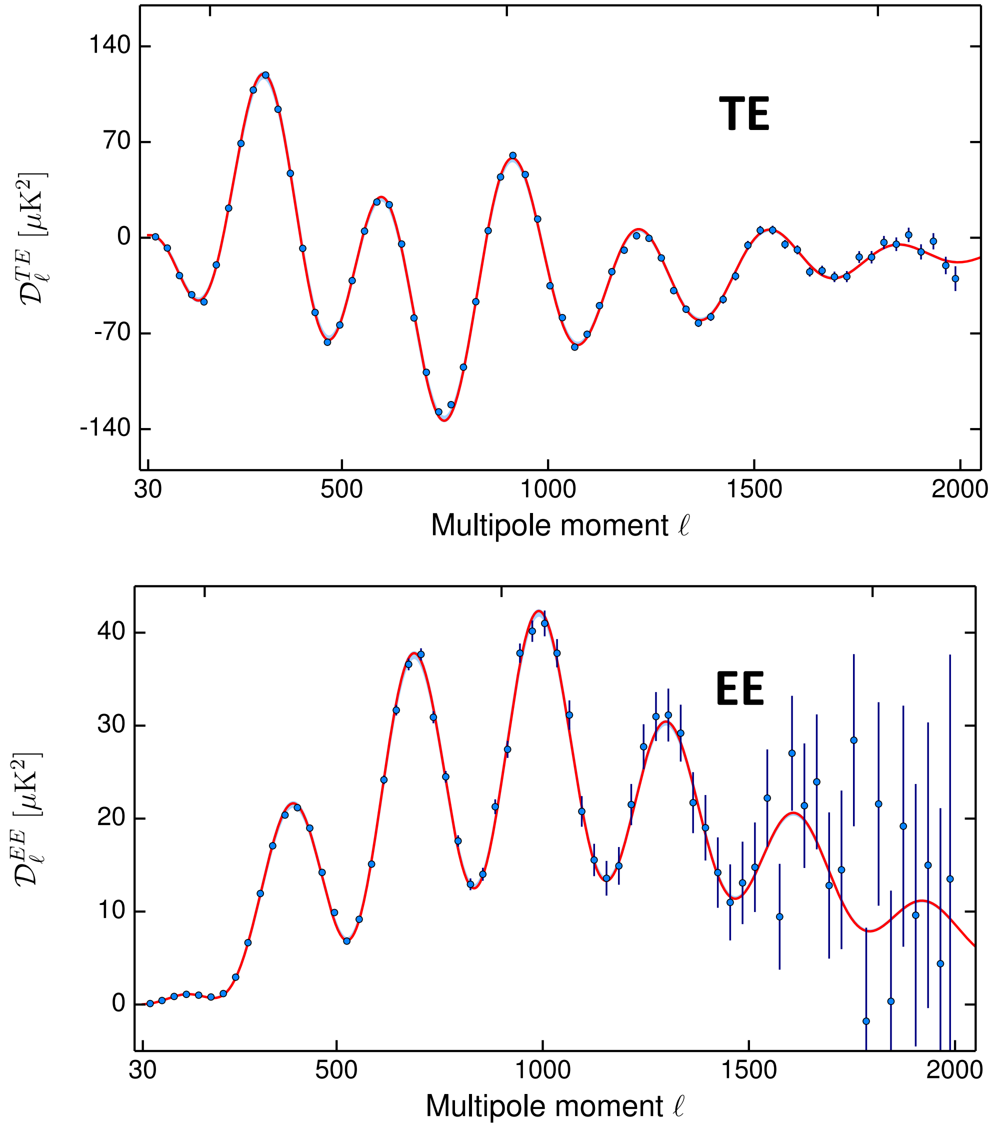
2015 Polarization power spectra

Pre-Planck measurements



Planck 2015



Results on ΛCDM

ΛCDM results from TT

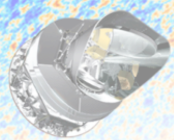
[1] Parameter	2013N(DS)	2015F(CHM) (Plik)
$100\theta_{MC}$	1.04131 ± 0.00063	1.04086 ± 0.00048
$\Omega_b h^2$	0.02205 ± 0.00028	0.02222 ± 0.00023
$\Omega_c h^2$	0.1199 ± 0.0027	0.1199 ± 0.0022
H_0	67.3 ± 1.2	67.26 ± 0.98
n_s	0.9603 ± 0.0073	0.9652 ± 0.0062
Ω_m	0.315 ± 0.017	0.316 ± 0.014
σ_8	0.829 ± 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

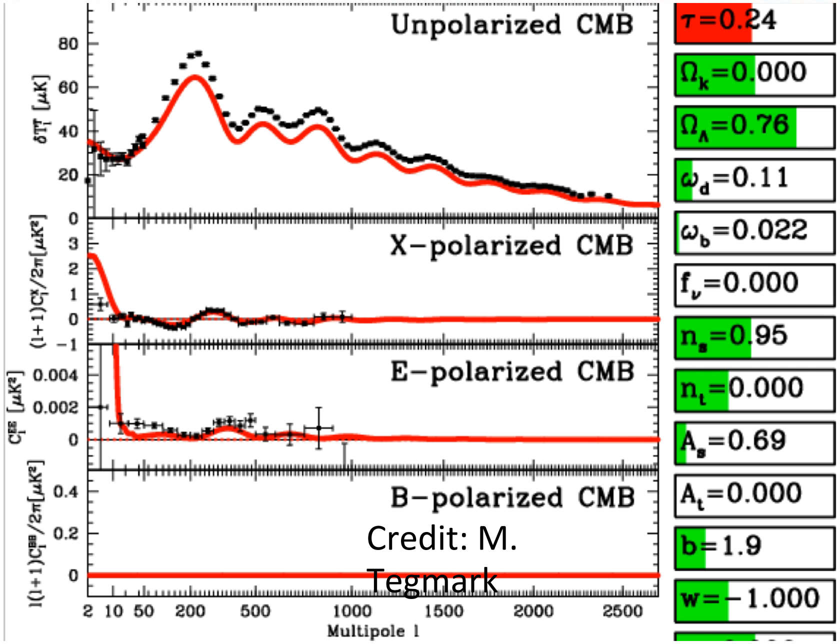
2013=Planck Nominal 2013 TT+low-l WMAP polarization
2015=Planck Full 2015 TT+low-l Planck LFI polarization.

- 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

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

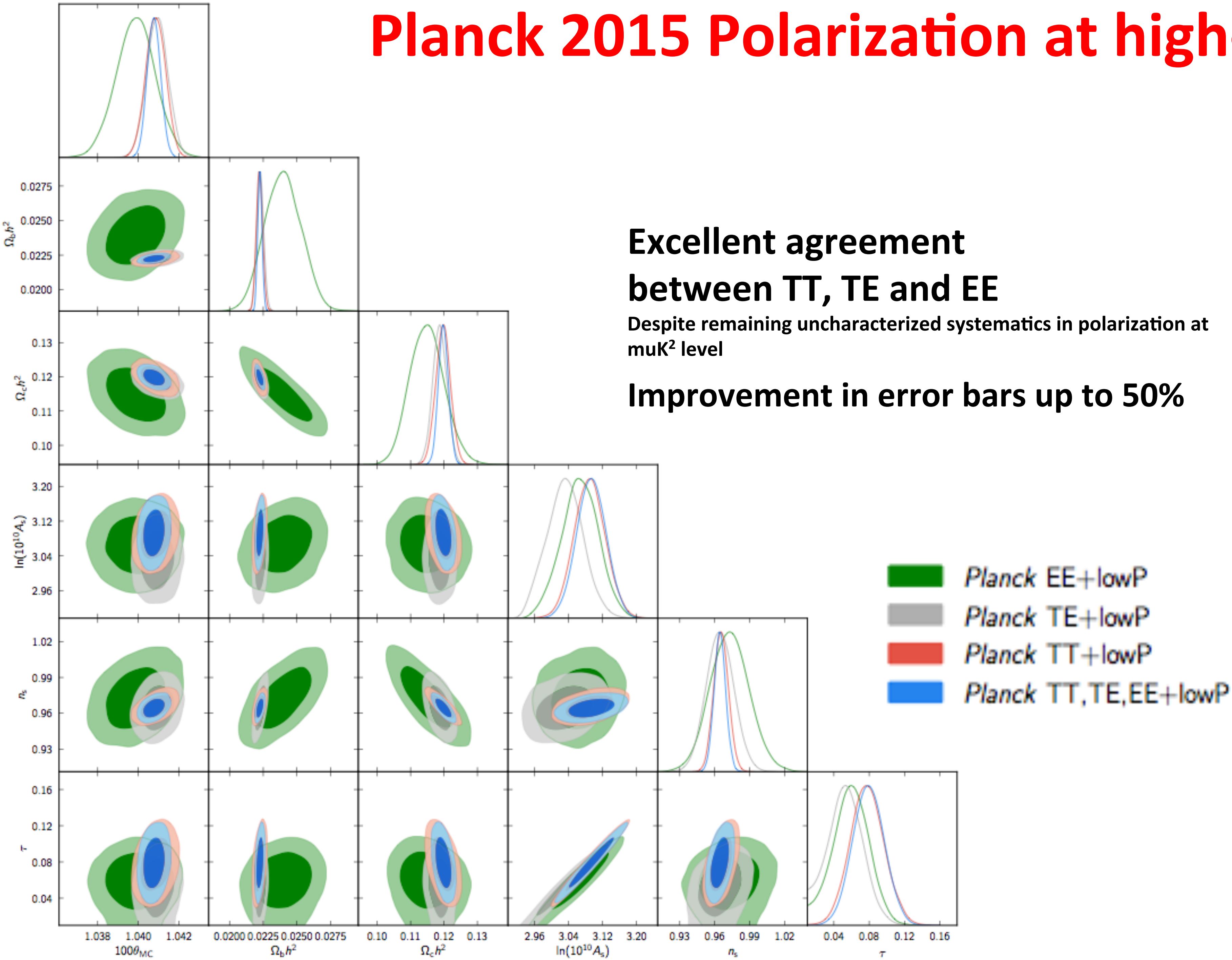


$\tau = 0.089 \pm 0.013 \quad z_{re} = 11.1 \pm 1.1$ *Planck 2013 + Wmap 9 low-l polarization*

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

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

Planck 2015 Polarization at high-l

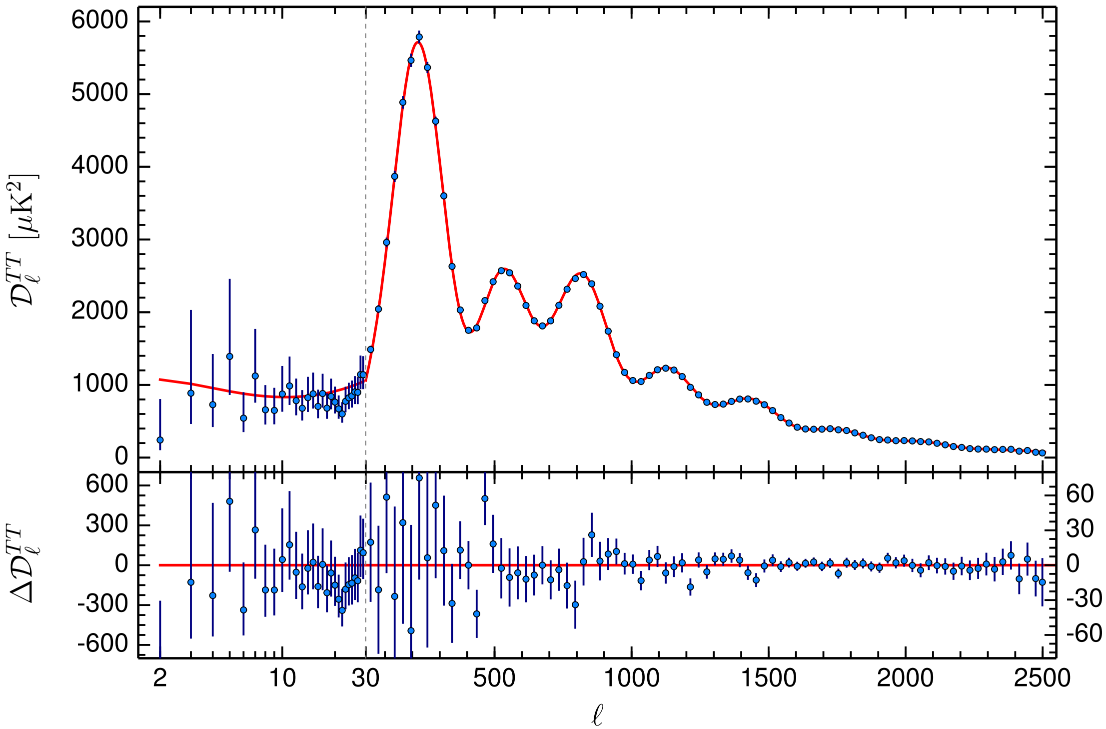


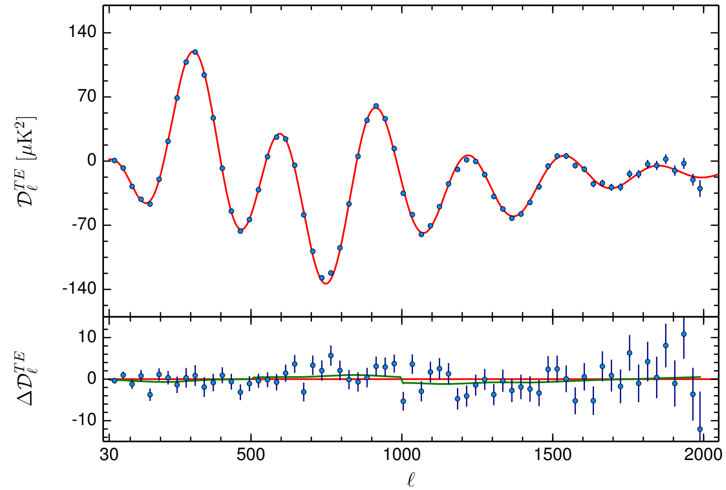
Excellent agreement between TT, TE and EE

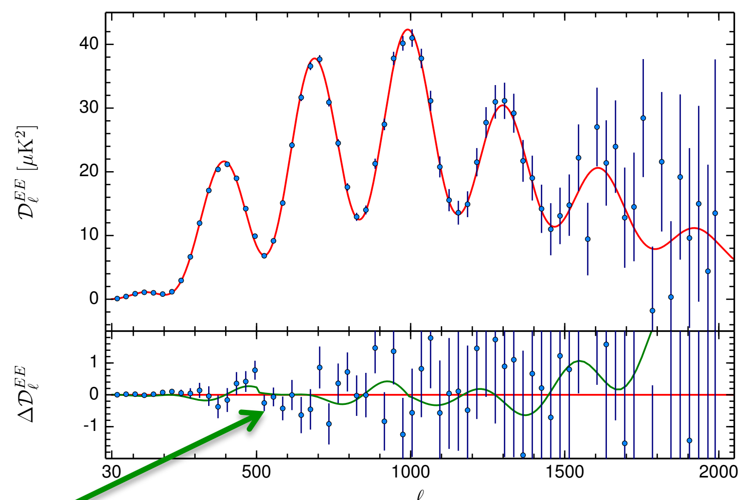
Despite remaining uncharacterized systematics in polarization at muK² level

Improvement in error bars up to 50%

ΛCDM best fit



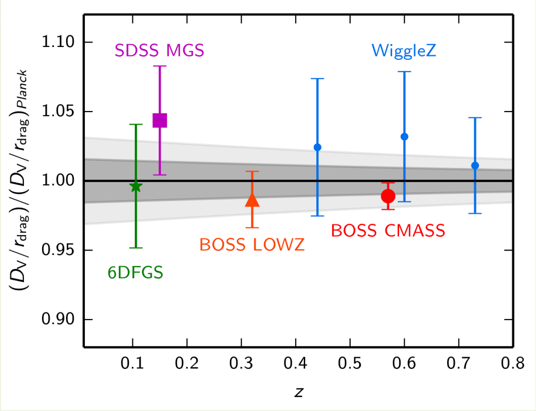




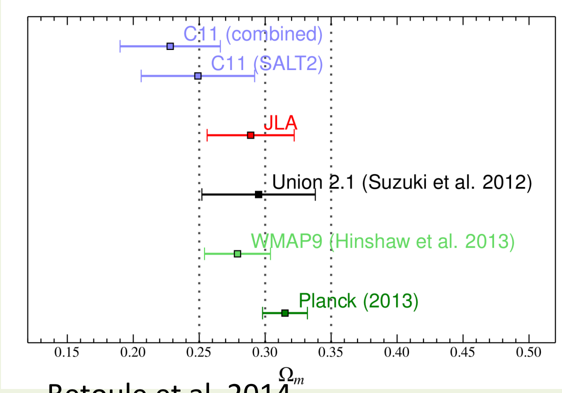
- ΛCDM is very good fit to the data
- Remaining systematics present in polarization spectra, possibly due to unaccounted beam missmatch.

Comparison with other datasets:

BAO

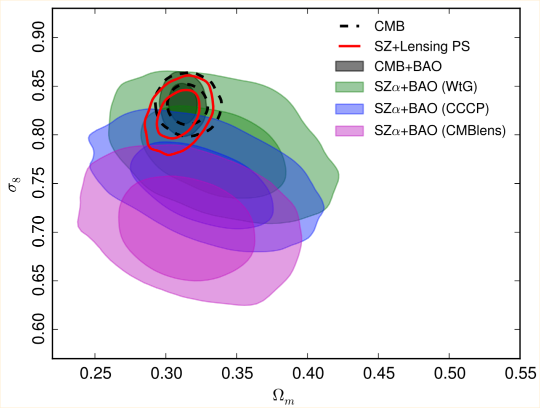


Supernovae (Ω_m)



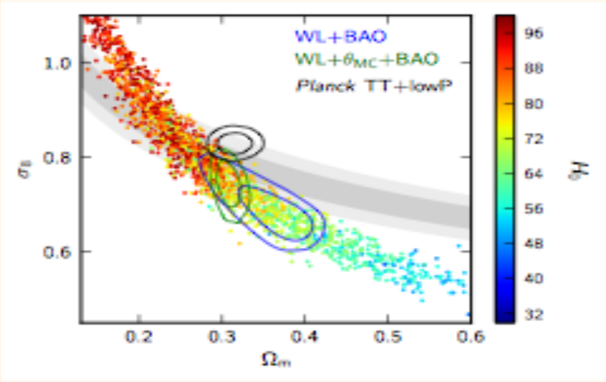
Betoule et al. 2014

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)

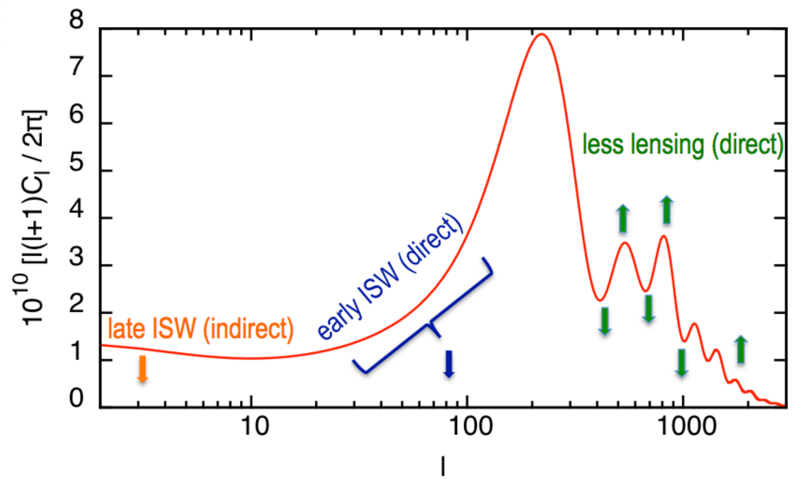
H_0=74.3 ± 2.6 **[2.5σ tension]**
(Freedman+12)

[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+BAO		**<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.

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

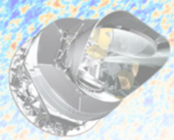
	2013	2015	2015 +EE,TE
PlanckTT+lowP	3.51±0.39	3.13±0.32 (18%)	2.98±0.20 (48%)
PlanckTT+lowP +BAO	3.40±0.30	**3.15±0.23 (23%)**	**3.04±0.18 (40%)**

Assumption:
1 massive neutrino at 0.06eV, other massless

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

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

Inflation: n_s and r



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

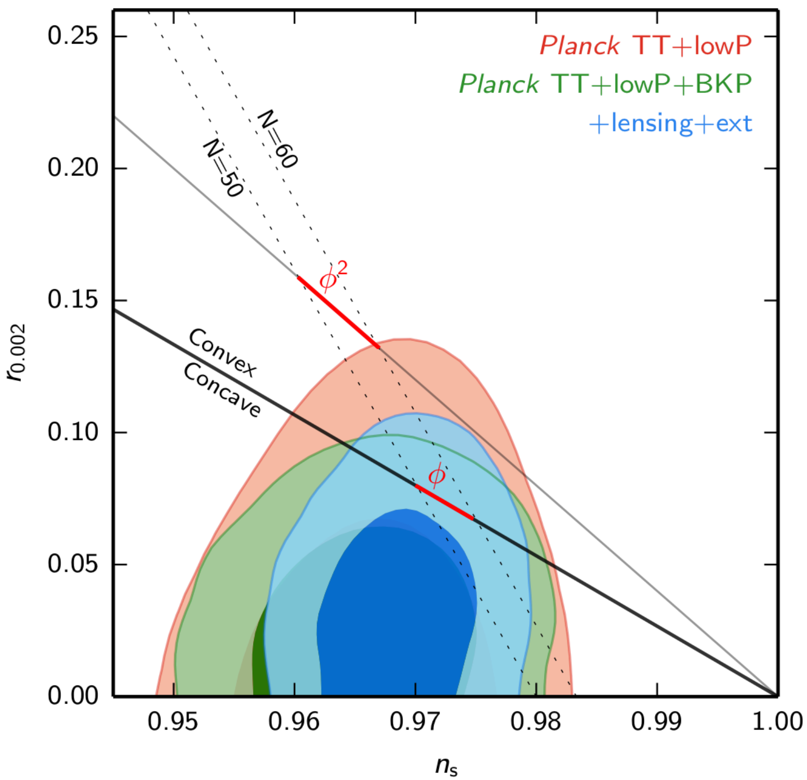
    n_s=0.9655±0.0062

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

    r<0.10

- Adding BB measurements from **BICEP2/KECK**, foreground-cleaned with Planck data (**Planck TT+lowP +BKP**):

    r<0.08



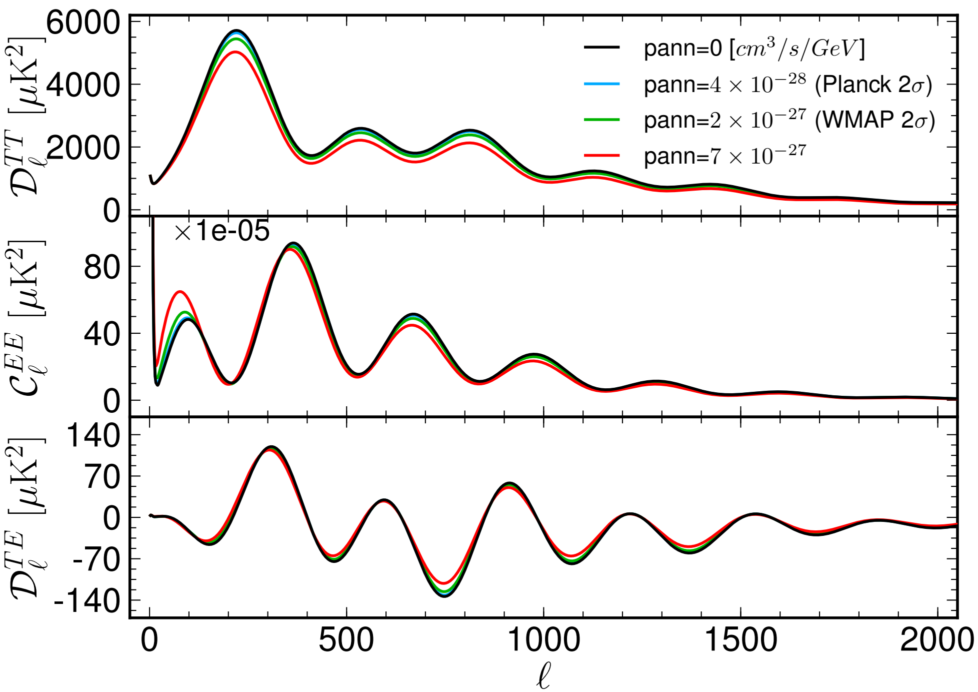
r=Power in tensor (Grav. Waves)/scalar (density pert.)

ns=spectral index of primordial scalar perturbations

DM annihilation at the epoch of recombination

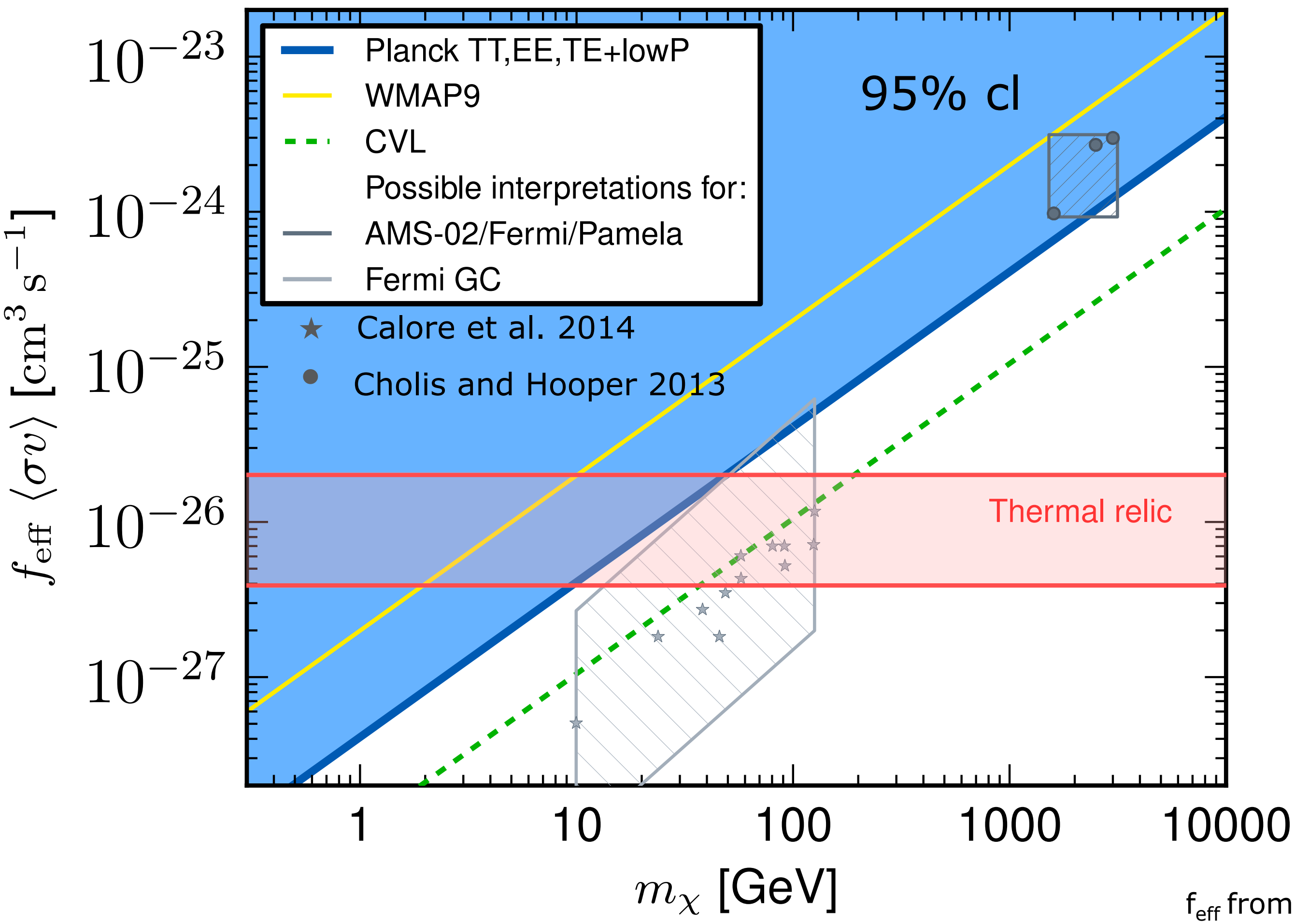
$$p_{ann}$$

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



- 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!

Constraints on Dark Matter Annihilation



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

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 provides 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.

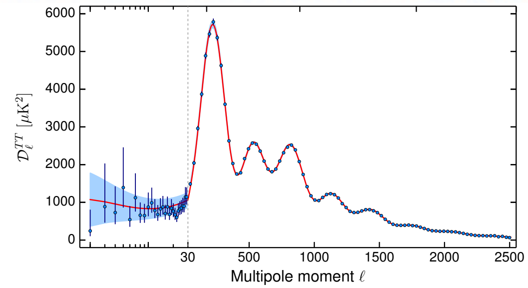
Polarization

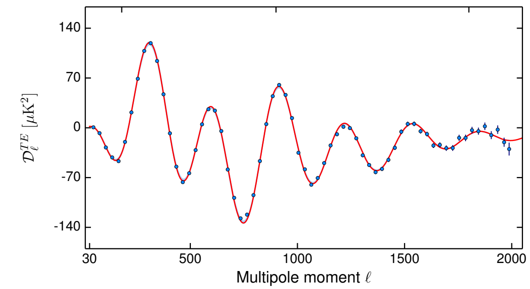
	Shift in sigma TTTEEE-TT	Error bar improvement TTTEEE-TT [%]	TTTEEE measurement accuracy [%]
$\Omega_b h^2$ Baryon density	0.13	**44**	0.72
$\Omega_c h^2$ DM density	0.05	**47**	1.25
100θ Acustic scale	-0.17	**47**	**0.03**
τ Reion. Optical depth	0.05	12	21.52
$\ln(10^{10} A_s)$ Power Spectrum amplitude	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

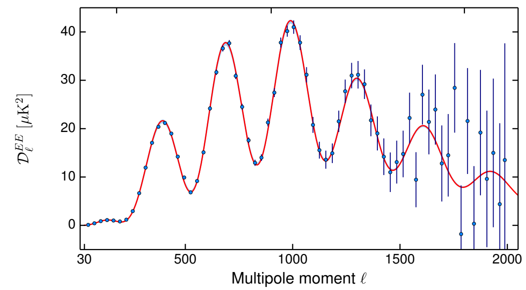
- Good consistency when adding polarization information wrt TT alone
- Great improvement in error bars!
- Many parameters determined at subpercent level!

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).

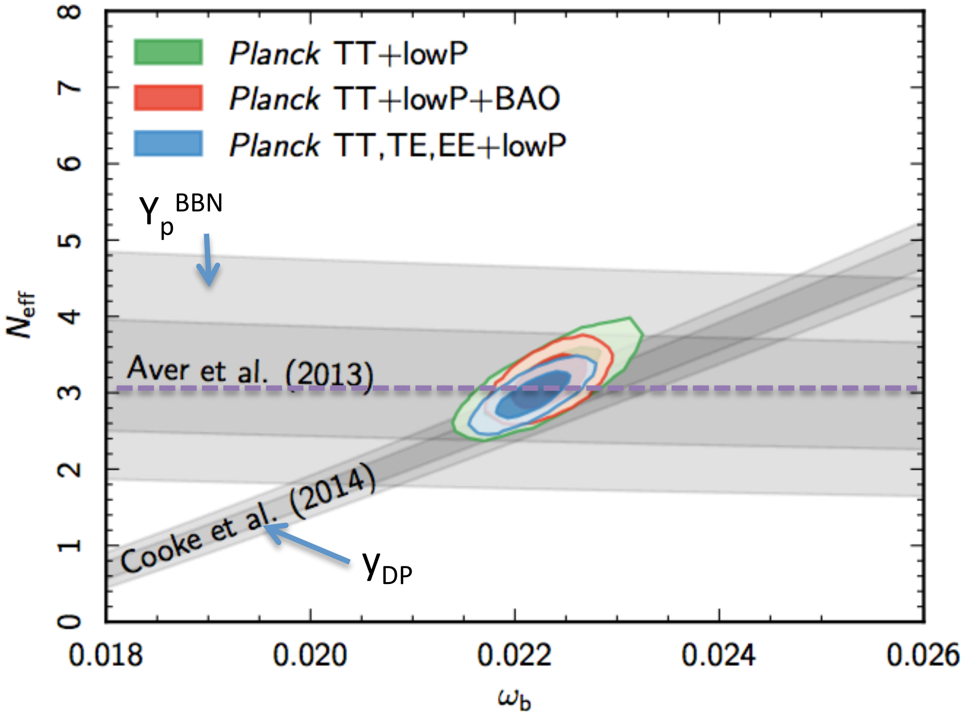






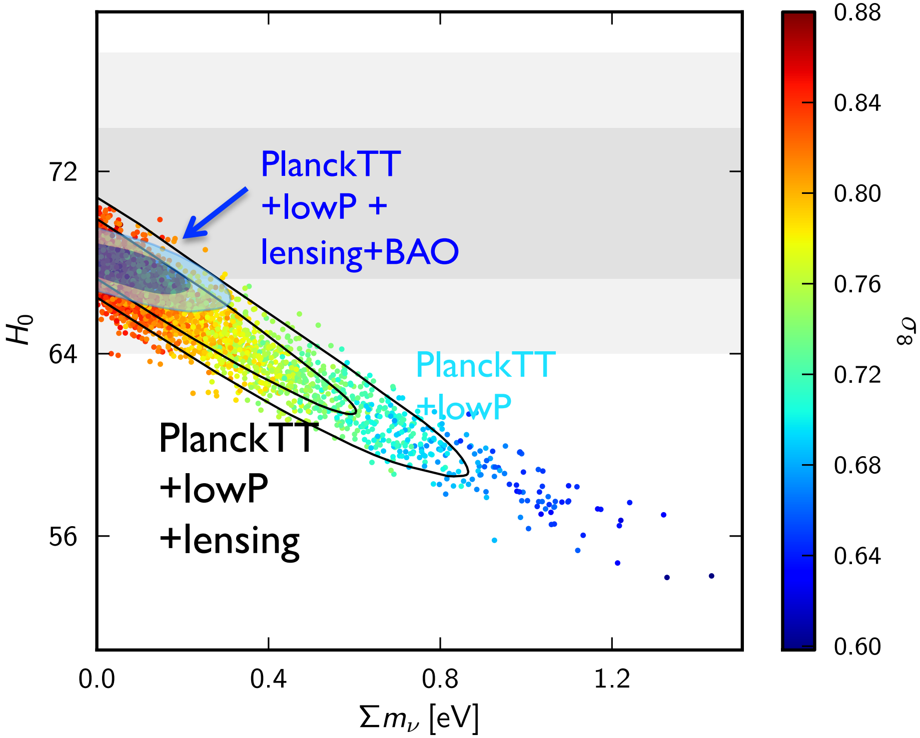
Number of relativistic species: Great agreement with BBN!

- 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!

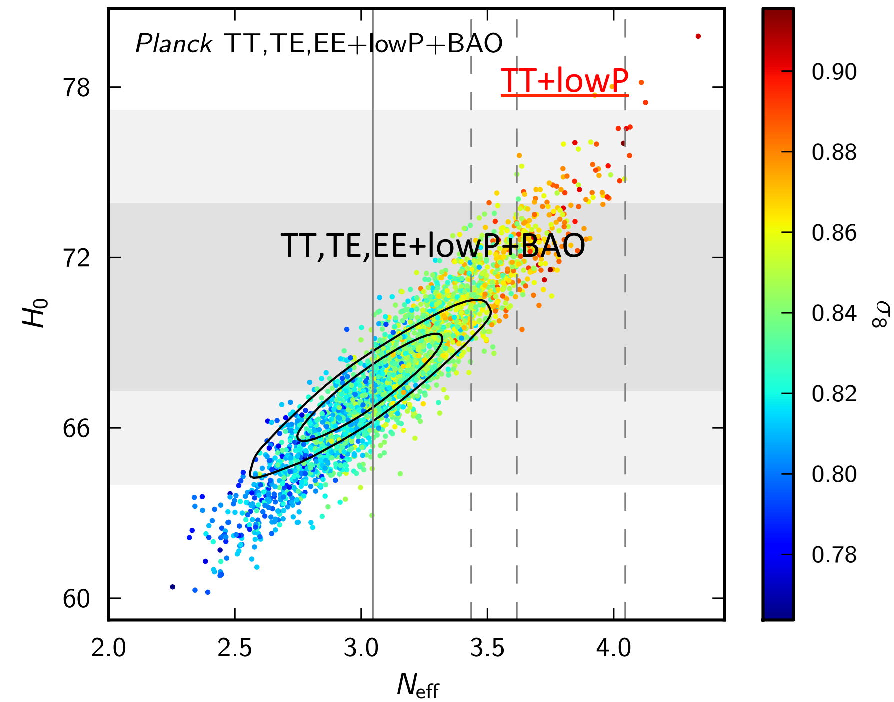


Neutrinos and tensions

σ_8 tension



H_0 tension

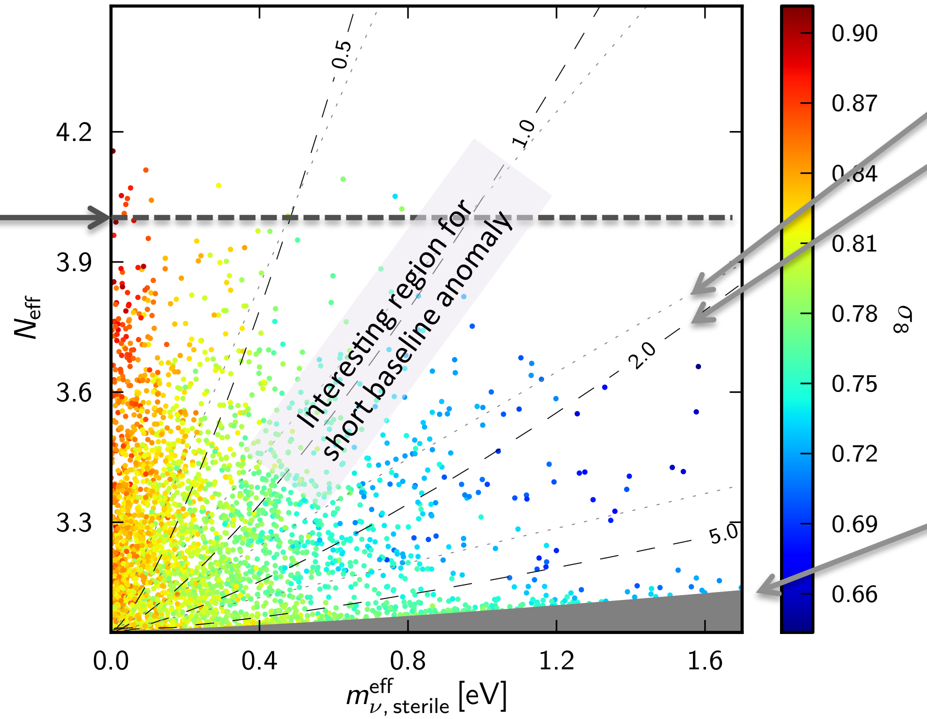


- Neutrino mass alleviates σ_8 tension-> requires low H_0
- Neff alleviates H_0 tension-> requires high σ_8
- Need both to solve tensions(or massive sterile neutrinos).

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

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

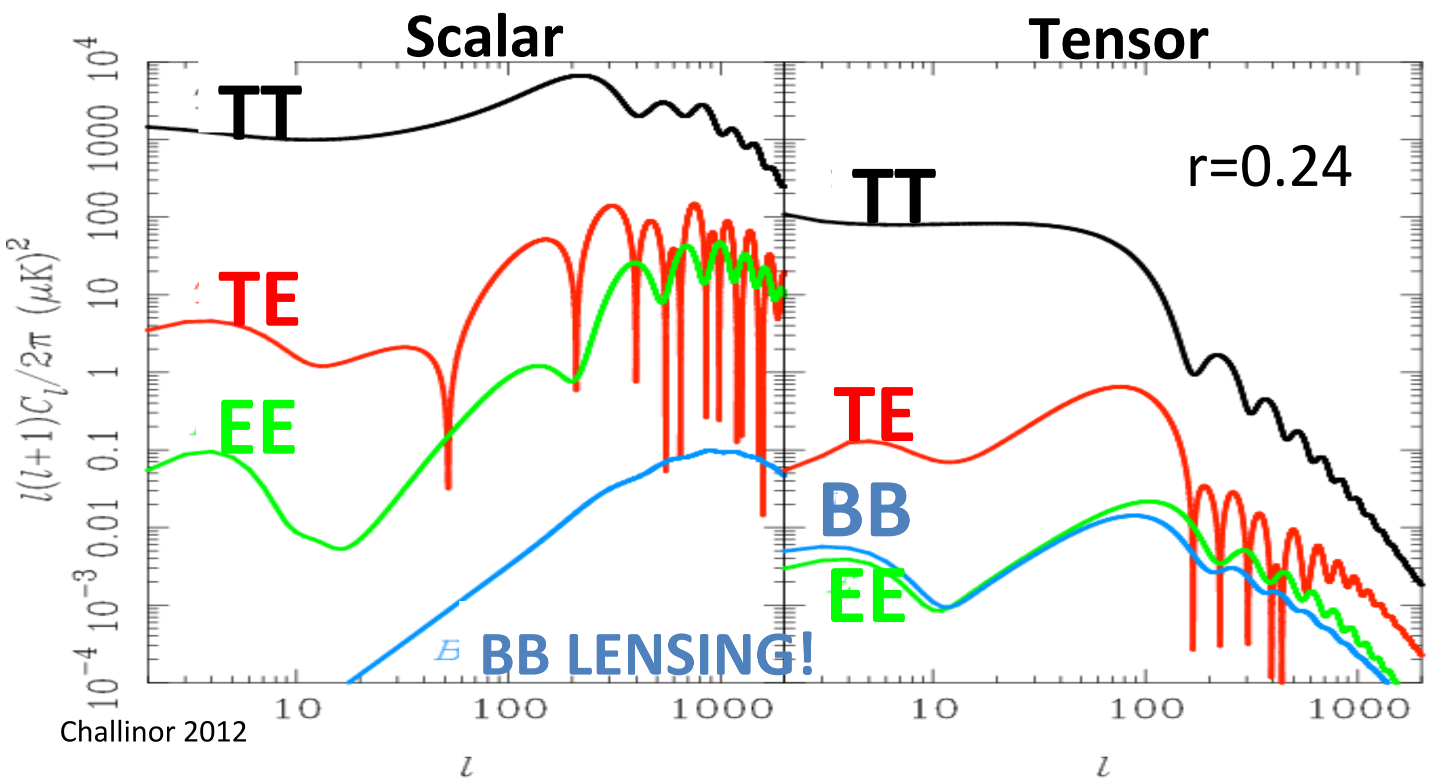
$$\left.\begin{array}{r}N_{eff} < 3.7 \\ m^{eff}_{\nu,\,sterile} < 0.59\,\text{eV}\end{array}\right\}\quad (95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}).$$

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



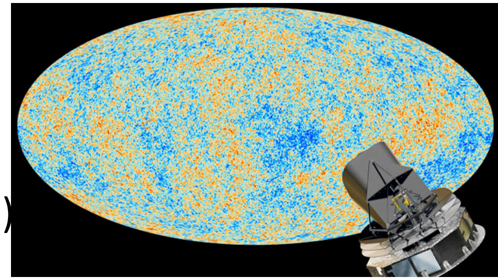
Challinor 2012

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!

March 2014: the BICEP-2 claim

- BICEP-2 from **BB**

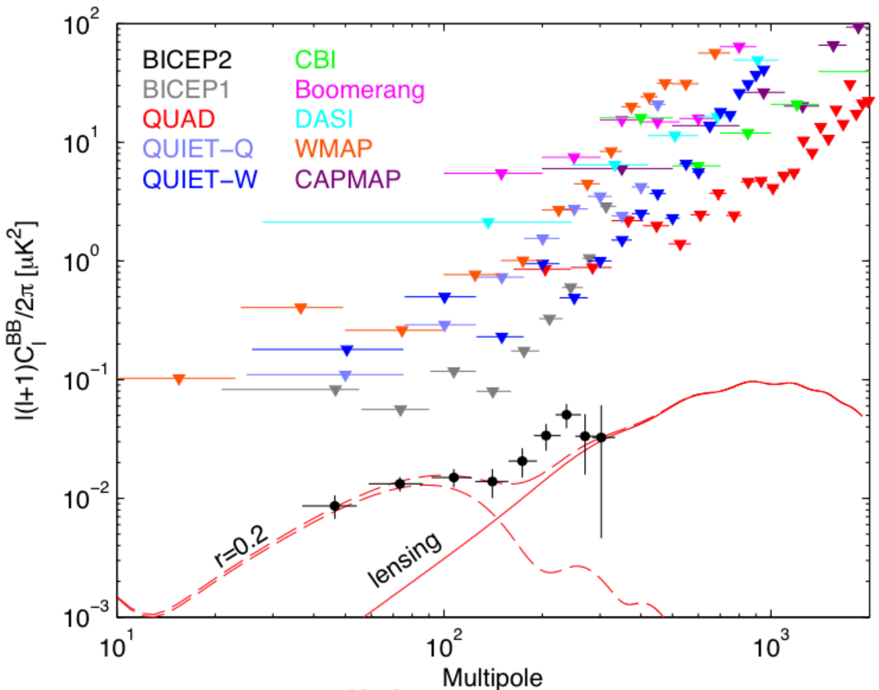
$$r = 0.20^{+0.07}_{-0.05}$$

No foreground subtraction

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

With foreground subtraction

7/5.9 sigma detection



BICEP2 collaboration 2014

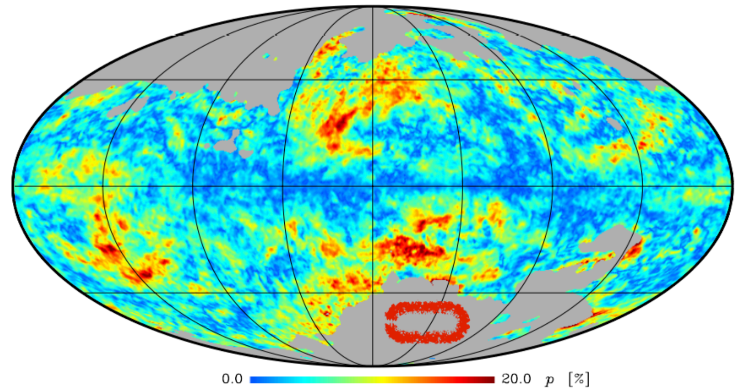
- Compatible with Planck constraints from TT only allowing extensions of LCDM
- Foreground estimation tricky, assumed ~5% dust polarization fraction. No Planck polarization available at the time (only preliminary maps from ESLAB conference presentations).
- Rapidly questioned by Flauger et al. 2014,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

Planck results on polarized dust

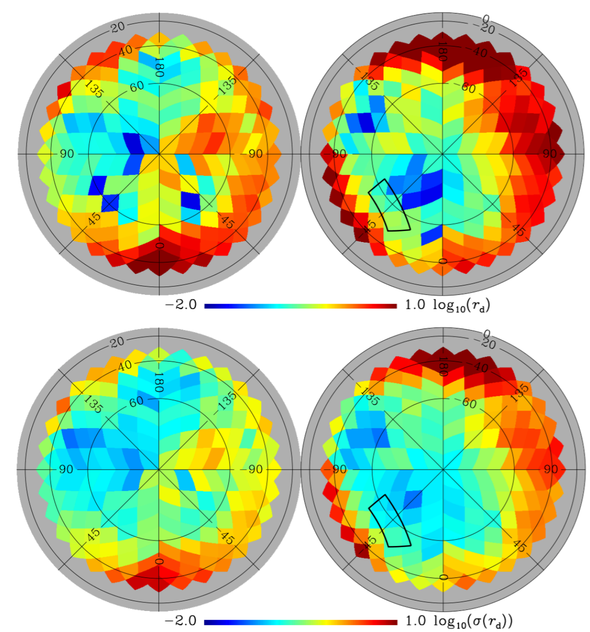
polarisation fraction p

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

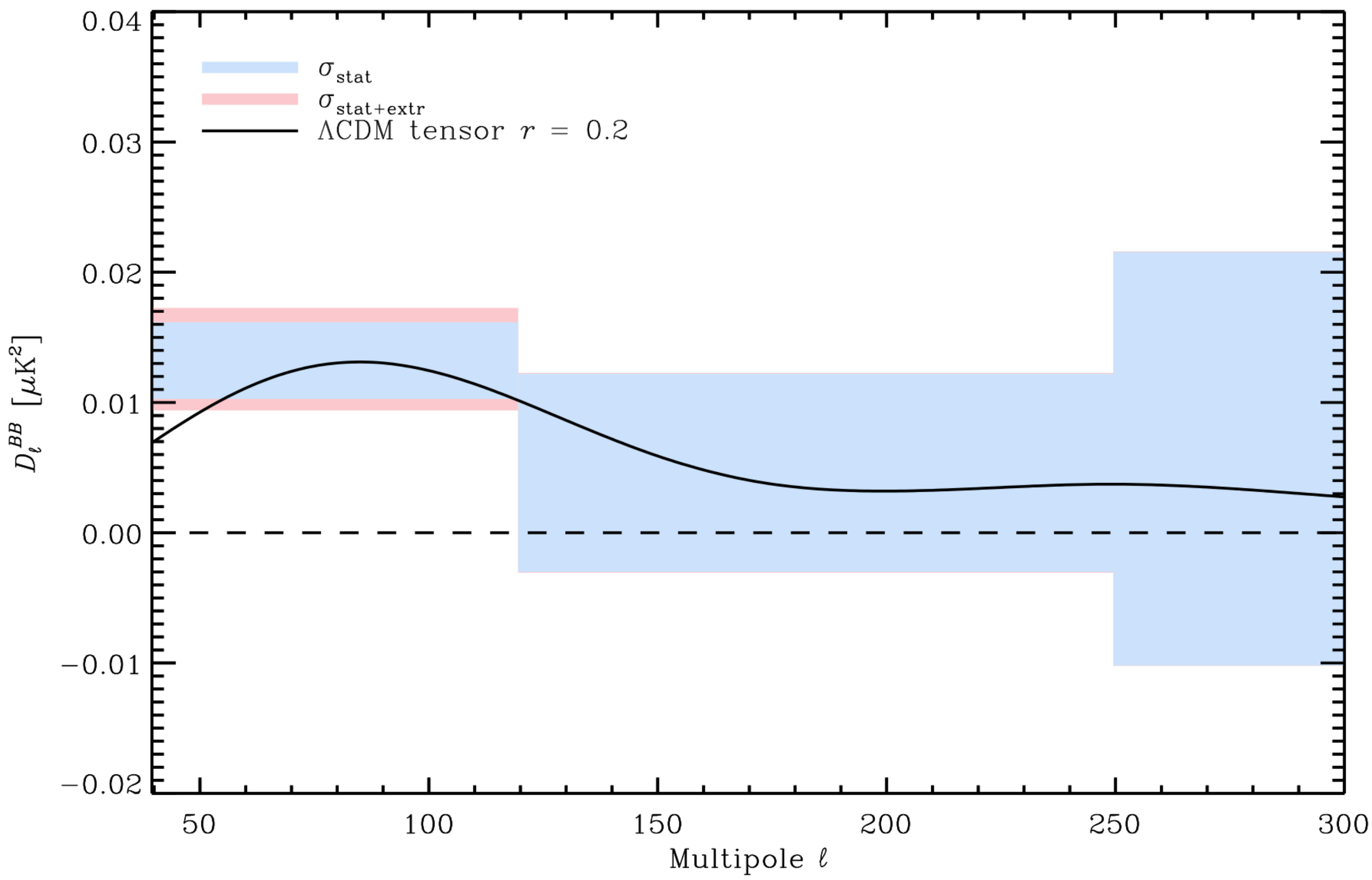
- May 2014, results at intermediate galactic latitudes (Planck collaboration 2014, PIP XIX)



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



September 2014: Planck results on polarized dust at high latitudes

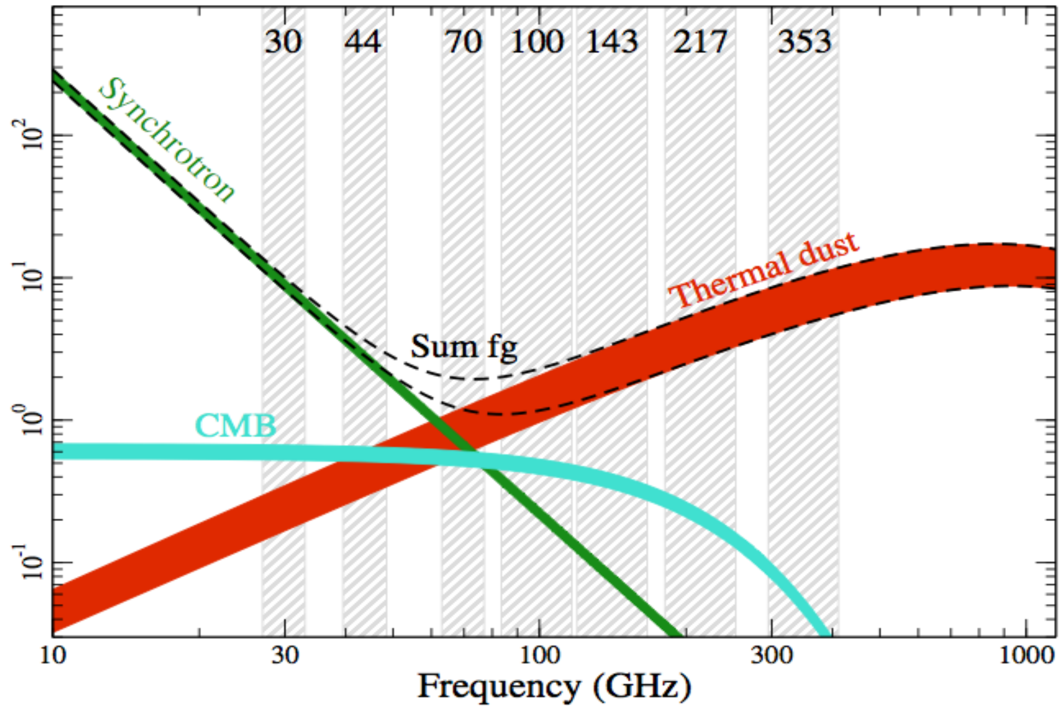


353Ghz **measurement of dust** in the BICEP-2 field extrapolated at 150Ghz

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



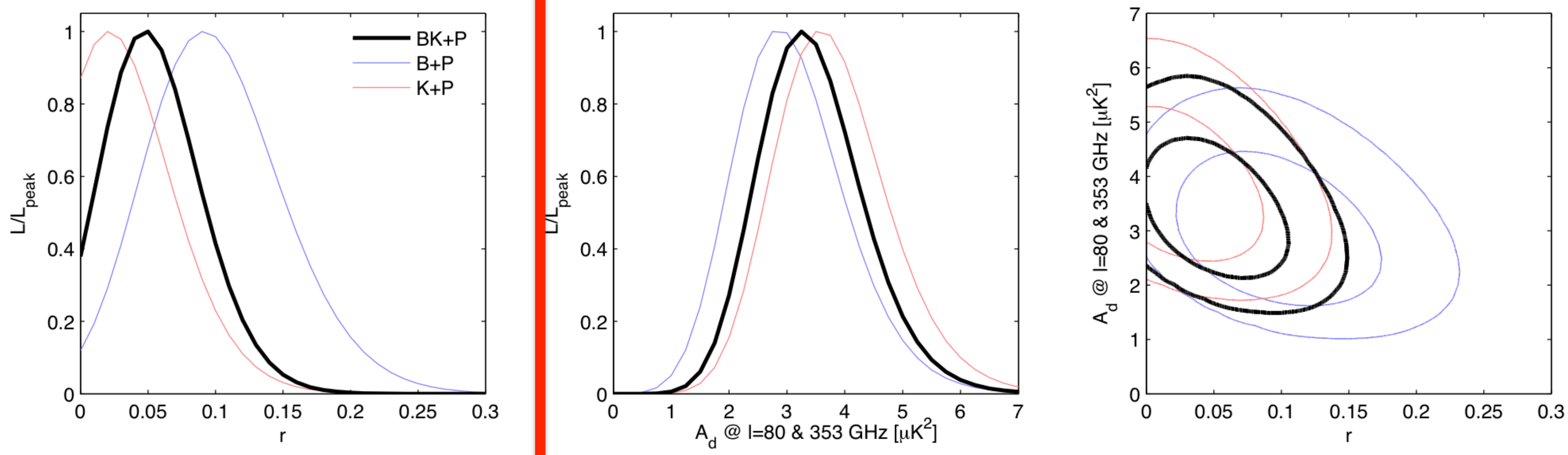
Fiducial analysis

- 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)

$$I_d(\nu) \propto \nu^{\beta_d} B_\nu(T_d) \quad T_d = 19.6\,\mathrm{K} \quad \beta_d = 1.59 \pm 0.11$$

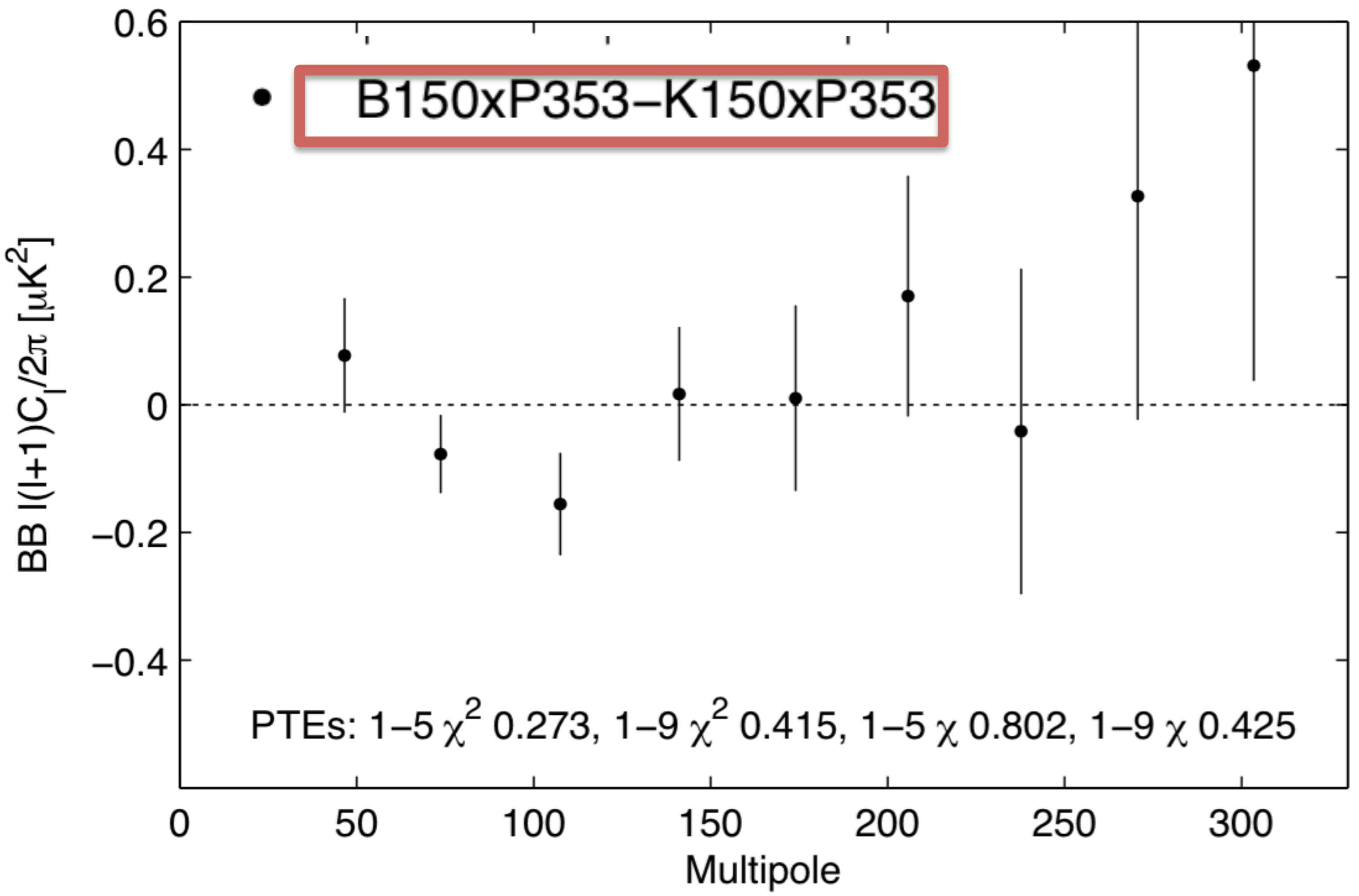
- All auto and cross-spectra of BK150, P217, P353 (for auto Planck, cross-detsets are used) using l=20-200

Fiducial analysis



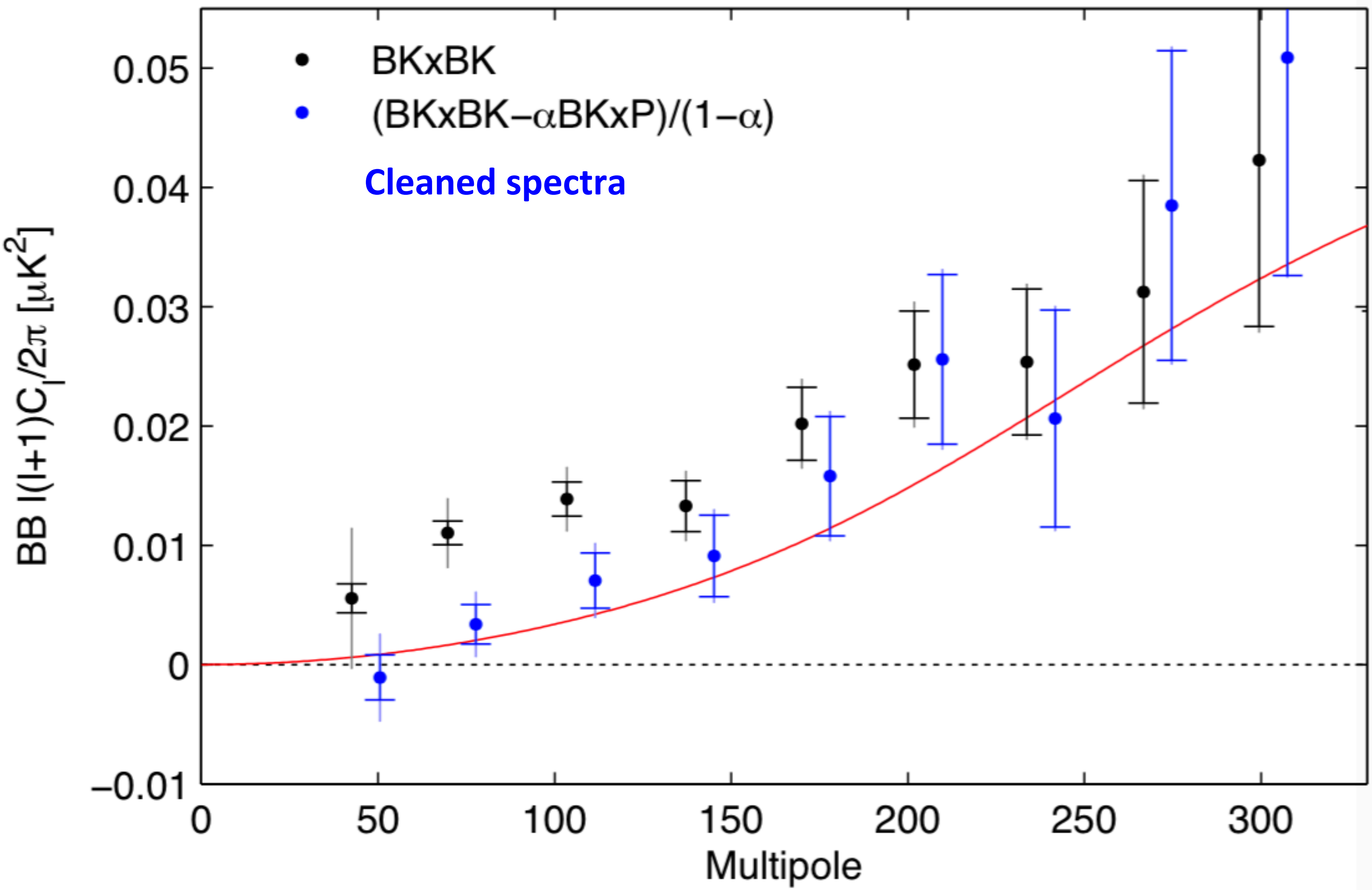
- r =0.048±0.035, r < 0.12 at 95% C.L.
- 5.1 sigma detection of dust power
- Other lines: Bicep alone, Keck alone

Consistency of BICEP2 vs KECK



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

Cleaned spectra



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)

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

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