Cosmological results from Planck 2015

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On behalf of the Planck collaboration

ICGC, 17 December 2015

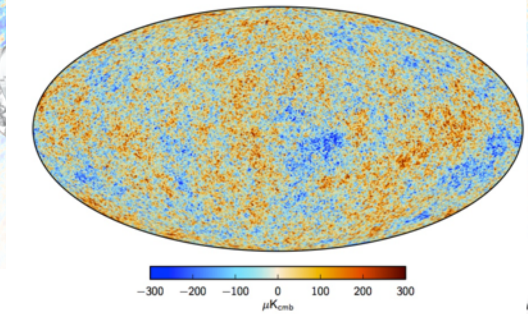
Title	Authors	Publication
Planck 2015 results. I. Overview of products and results	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. II. Low Frequency Instrument data processing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. III. LFI systematic uncertainties	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. IV. LFI beams and window functions	Planck Collaboration	2015 Accepted by 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 Accepted by A&A
Planck 2015 results. VIII. High Frequency Instrument data processing: Calibration and maps	Planck Collaboration	2015 Accepted by 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, likelihoods, and robustness of cosmological parameters	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. XII. Full Focal Plane Simulations	Planck Collaboration	2015 Submitted to A&A
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 Accepted by 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 Submitted to A&A
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 Submitted to A&A
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 Accepted by A&A

2015 Release

- 28 papers
- Disclaimer: this talk will cover only a very small part of all these results!
  - Cosmological parameters (February 2015)
  - Likelihood (July 2015)

CMB in 2 slides

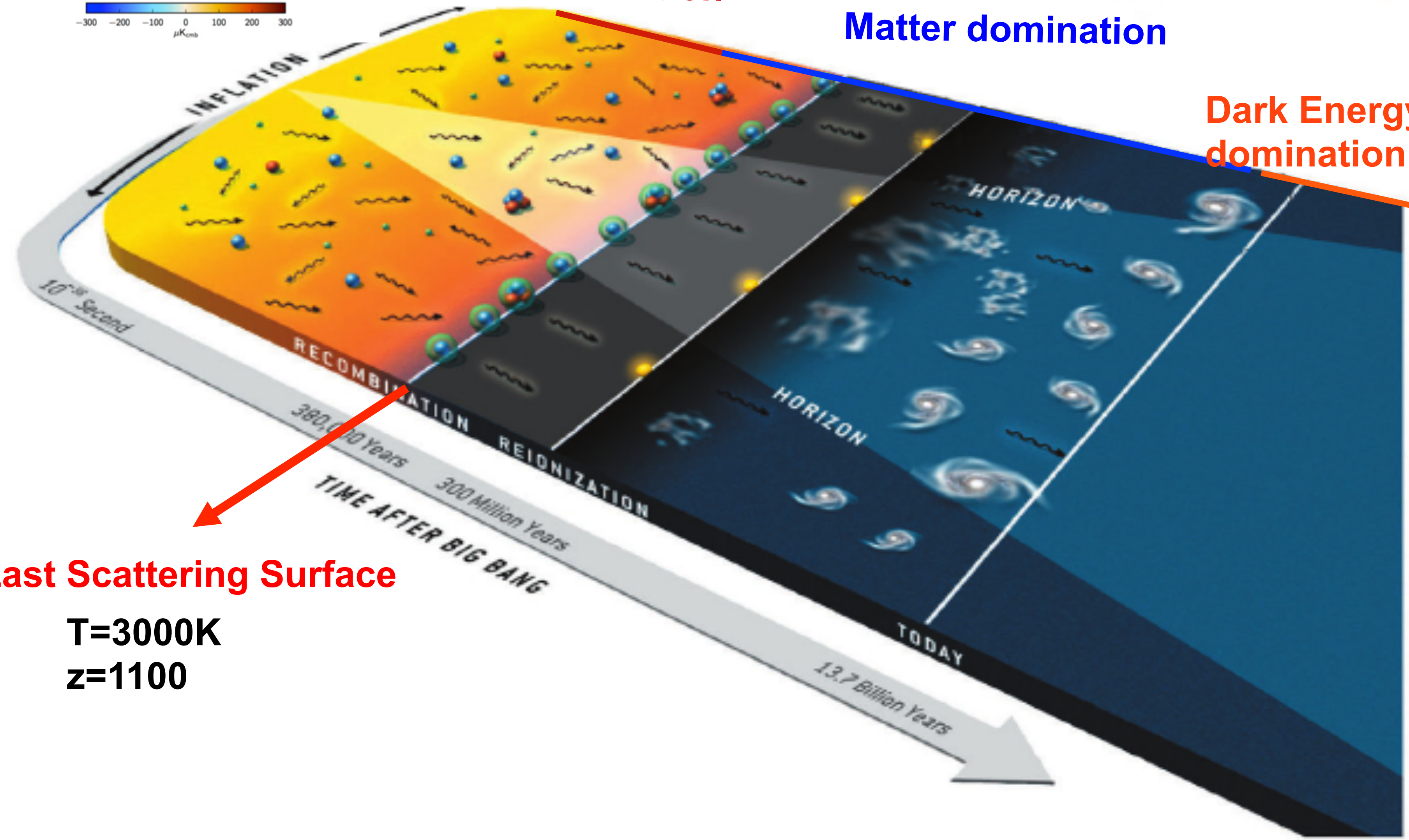
Cosmic History



Radiation domination

Matter domination

Dark Energy domination

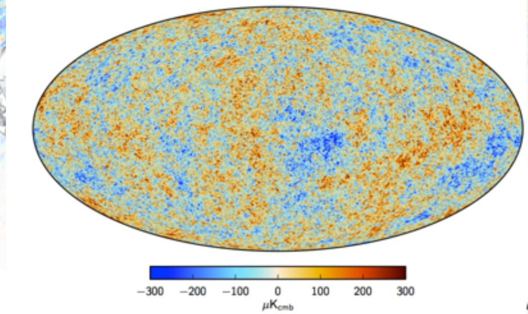


Last Scattering Surface

T=3000K
z=1100

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

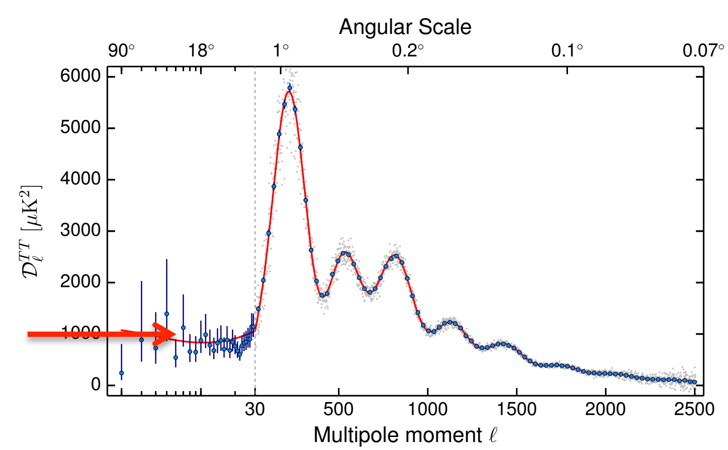
Cosmic History



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

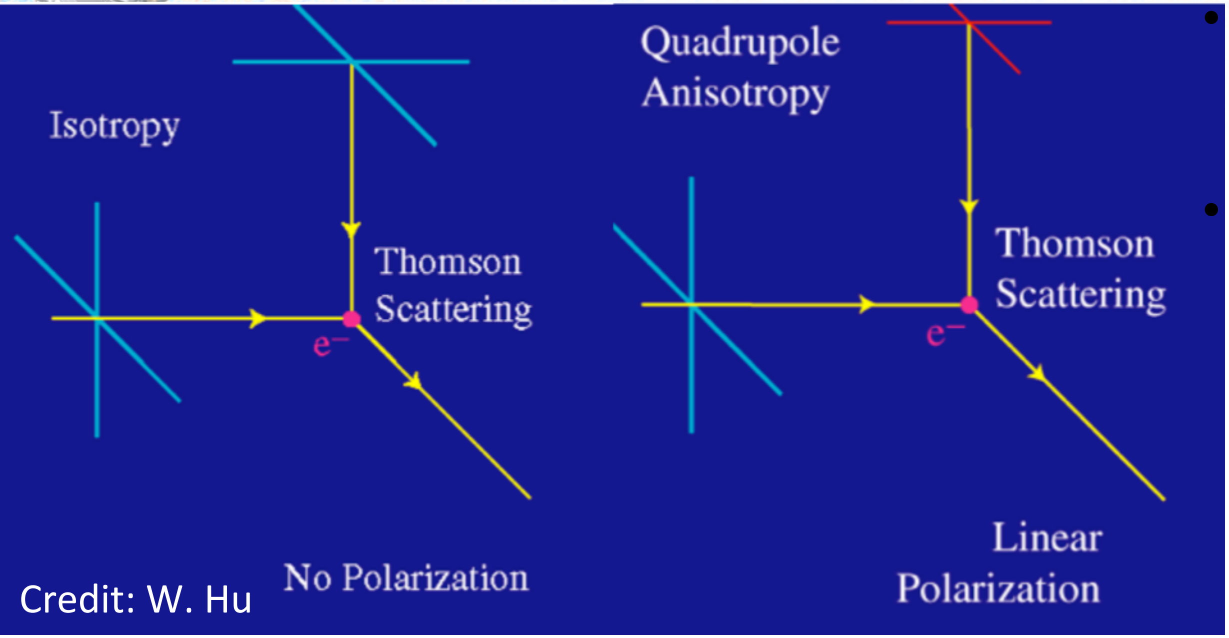
$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

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



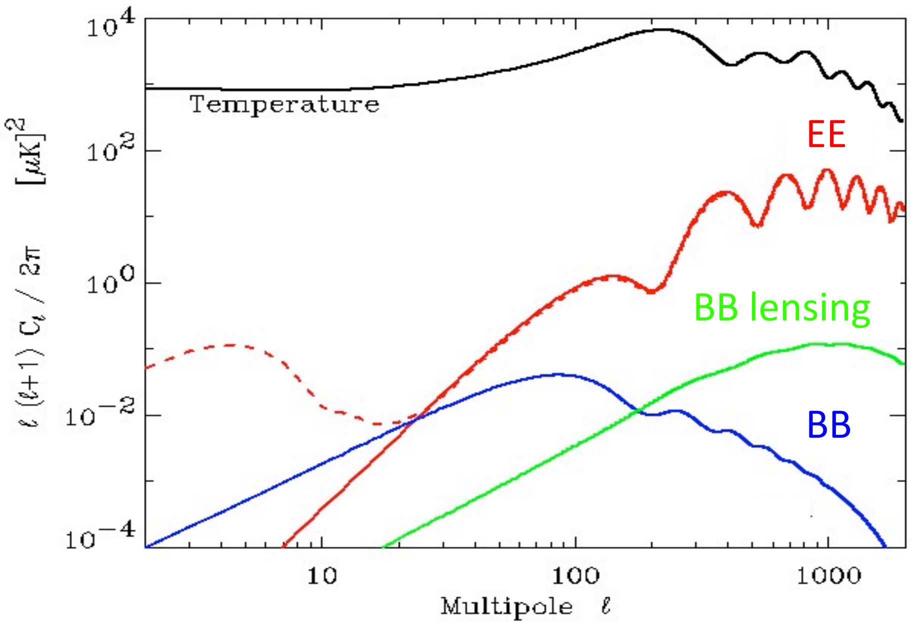
Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu

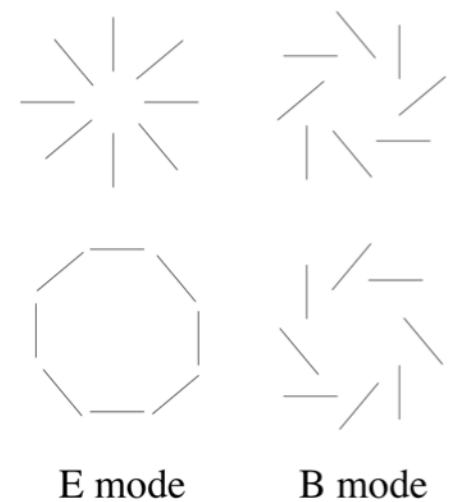
CMB Polarization



Credit: W. Hu

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

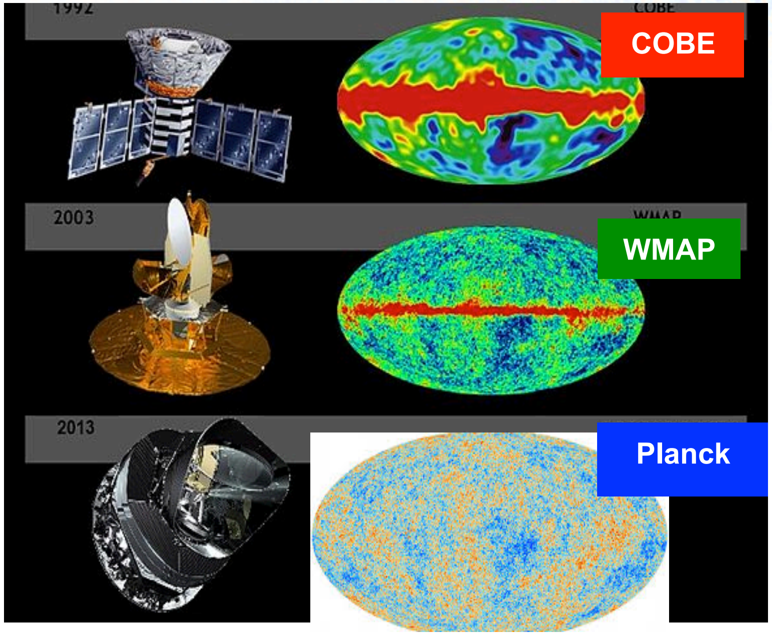


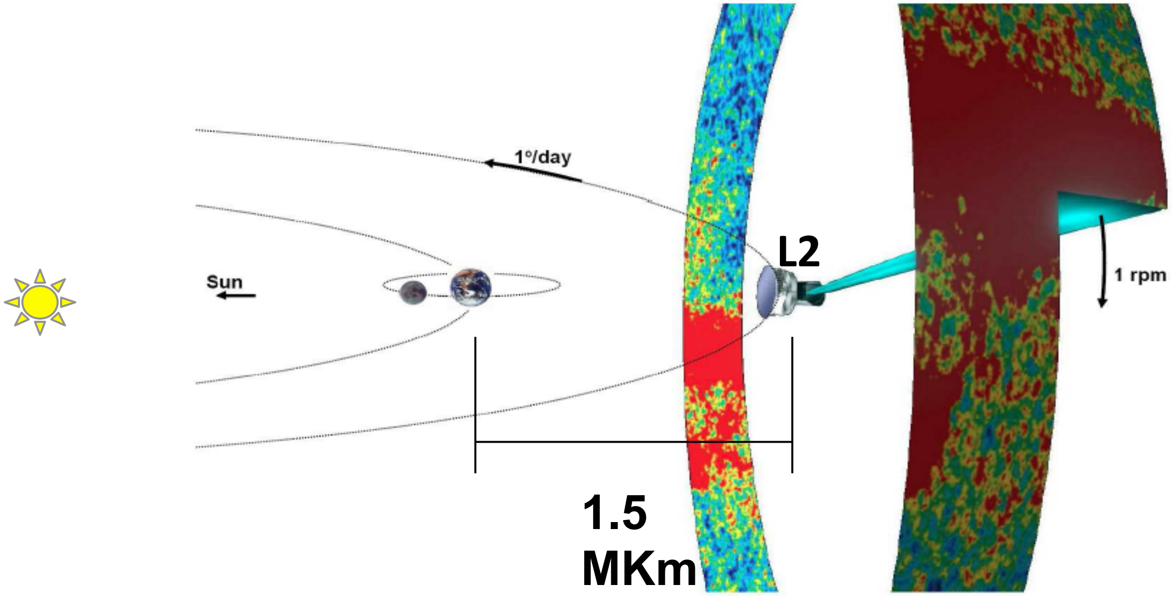


The Planck satellite

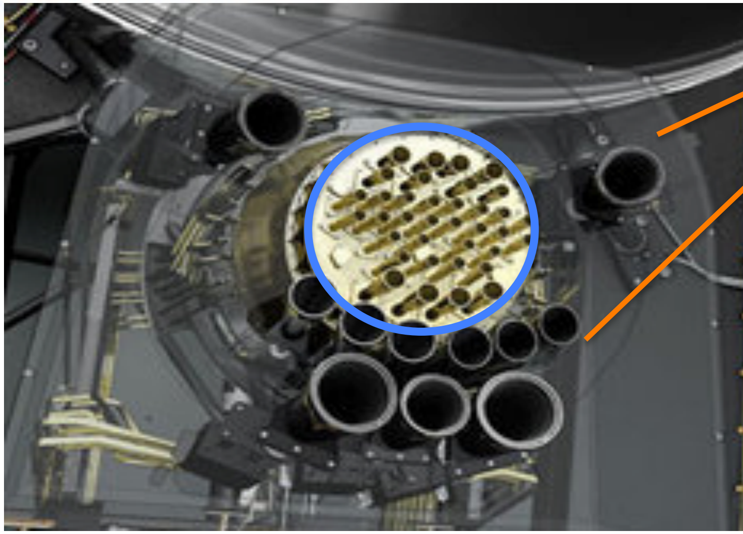
The Planck mission

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



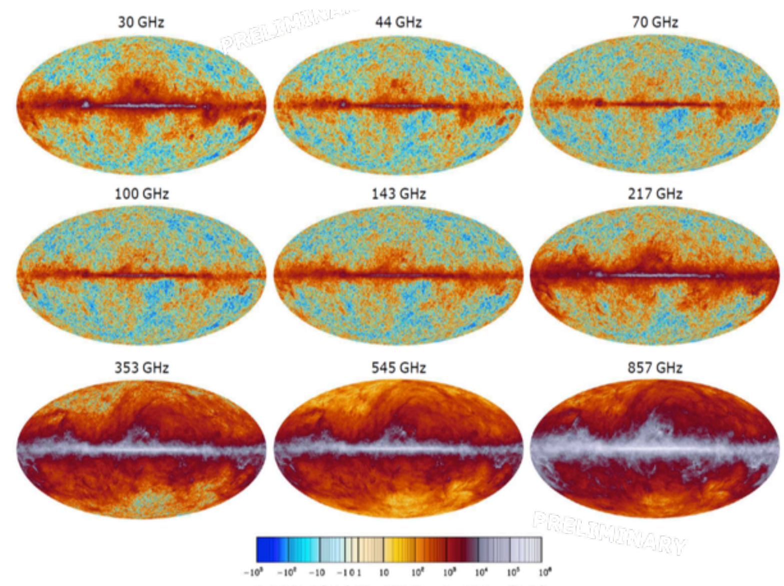


9 Frequencies, 2 instruments



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

HFI:
- 50 bolometers (32 polarized) at **100, 143, 217, 353, 545, 857 Ghz.**
- **30-353 Ghz polarized.**

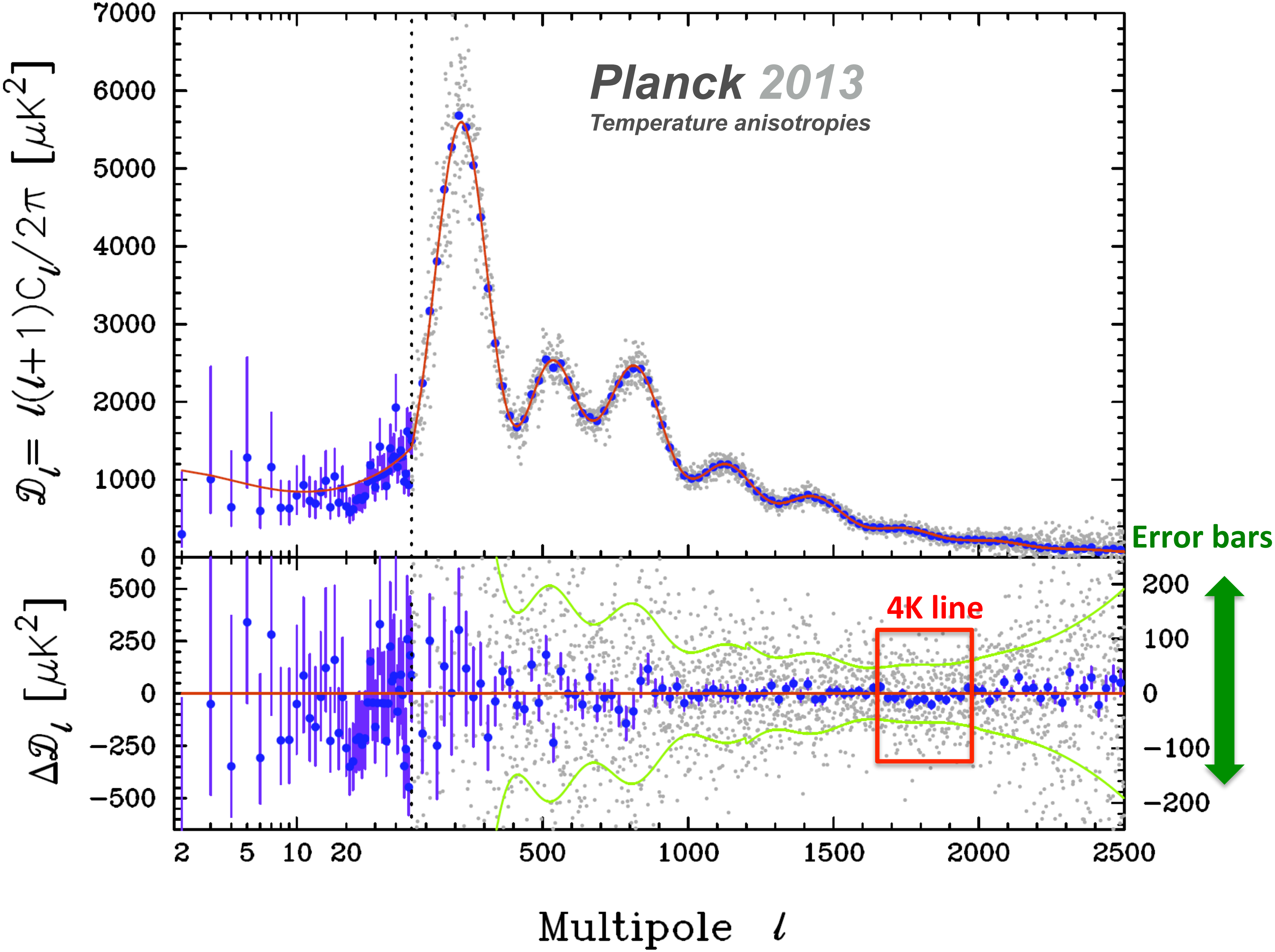


- **1st release 2013: Nominal mission**, 15.5 months, Temperature only.
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization

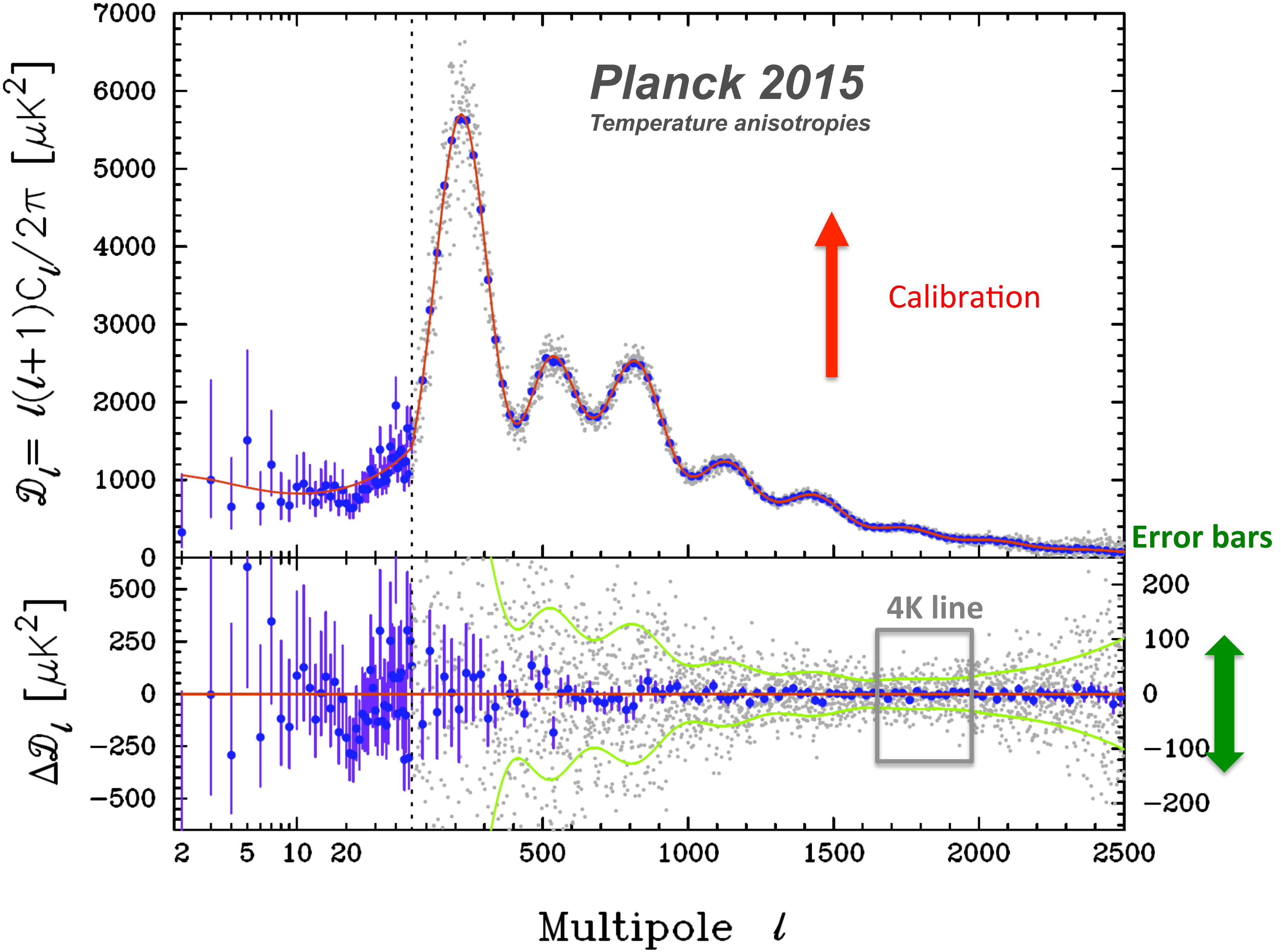
What changed since 2013?

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

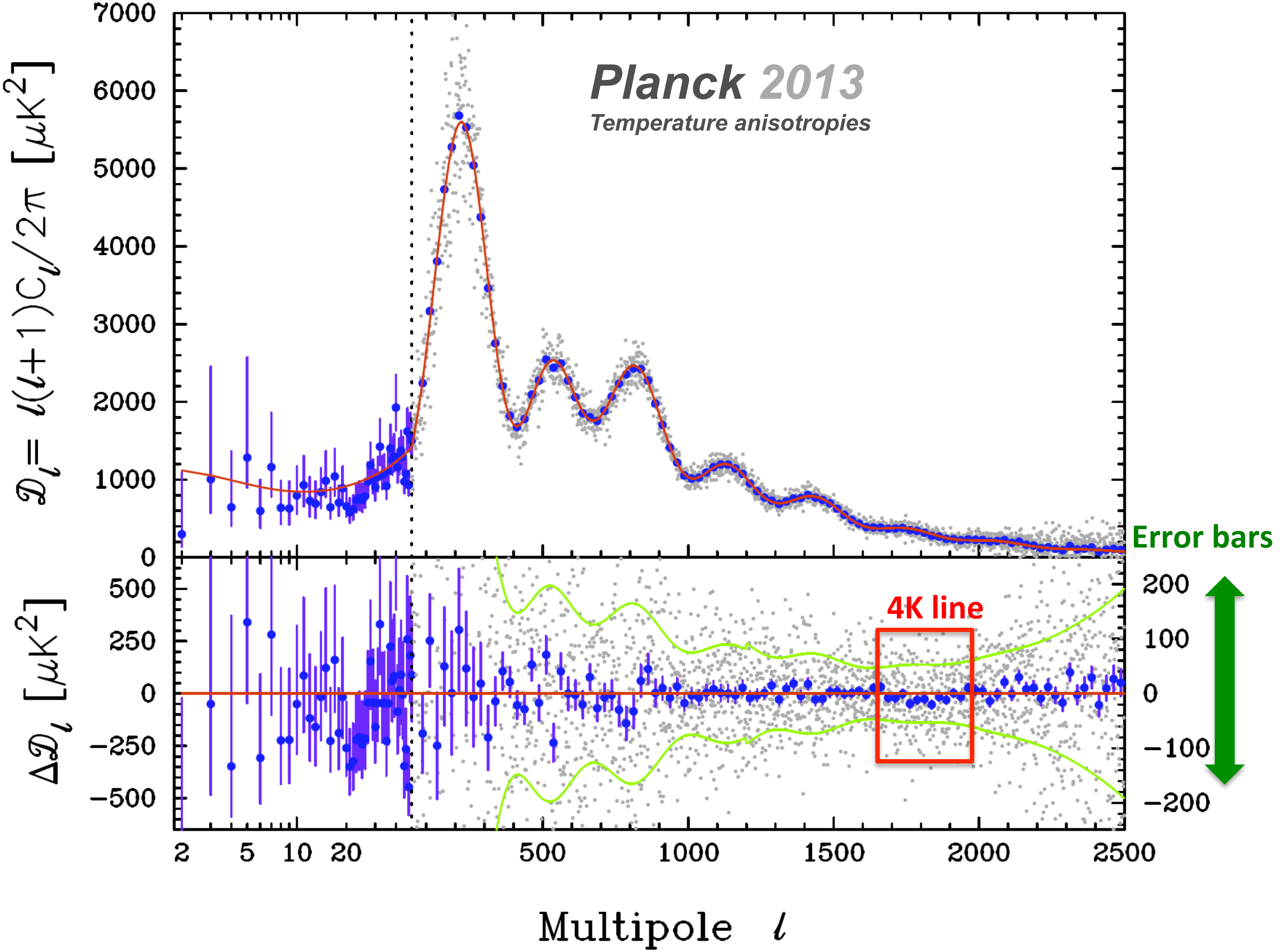
1. **Full** mission data (more than double w.r.t. 2013). Also use smaller galactic masks.
2. **Calibration** -> +2%. Planck 2015 and WMAP now perfectly agree
3. **Systematics** better handled (e.g. $l \sim 1800$ dip due to the 4K line).
4. **Polarization**.
   1. **Low-l** (large scales, $l<30$) polarization 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
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
2
5
10
20
500
1000
1500
2000
2500
Error bars
200
100
0
−100
−200
4K line



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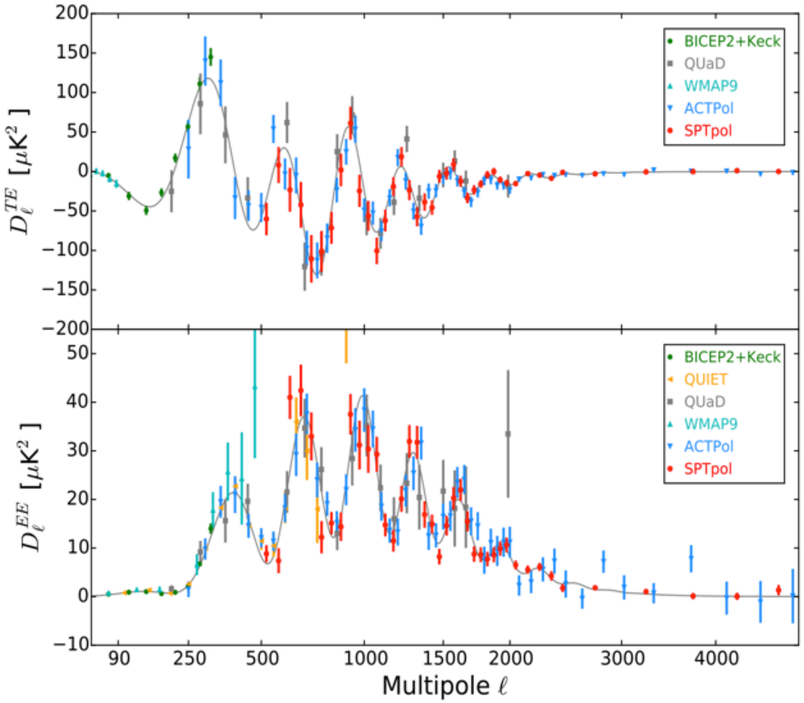
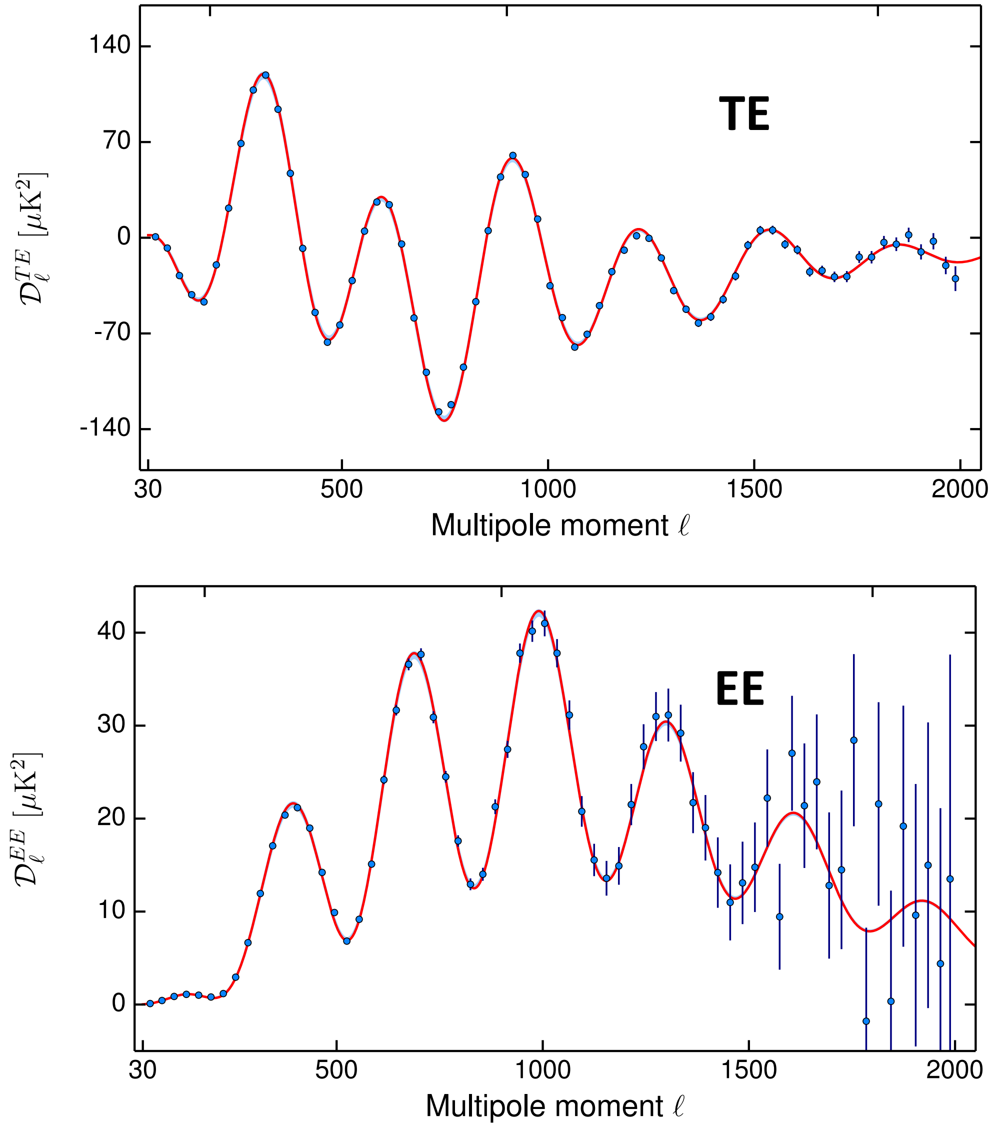
250
0
−250
−500
2
5
10
20
500
1000
1500
2000
2500
Error bars
200
100
0
−100
−200
4K line

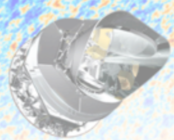
2015 Polarization power spectra

Pre-Planck measurements

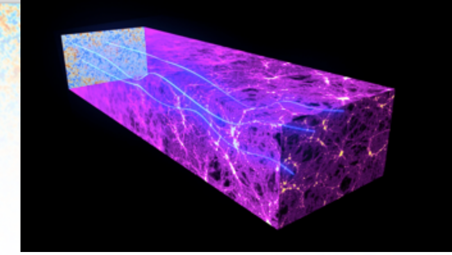


Planck 2015



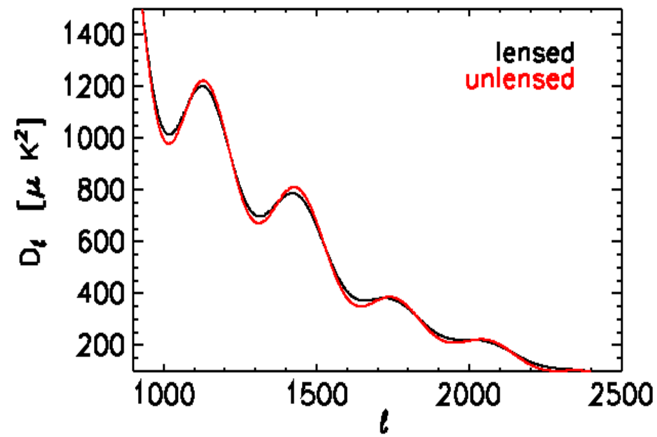


CMB lensing



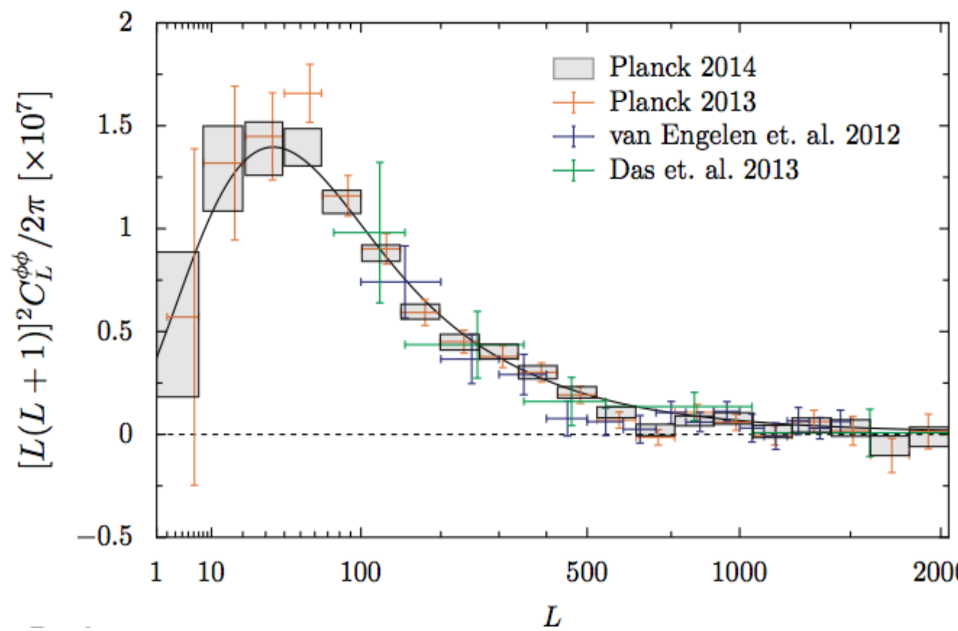
1) Modifies the angular power spectrum at high-l (e.g.smooths the peaks/throughs)

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

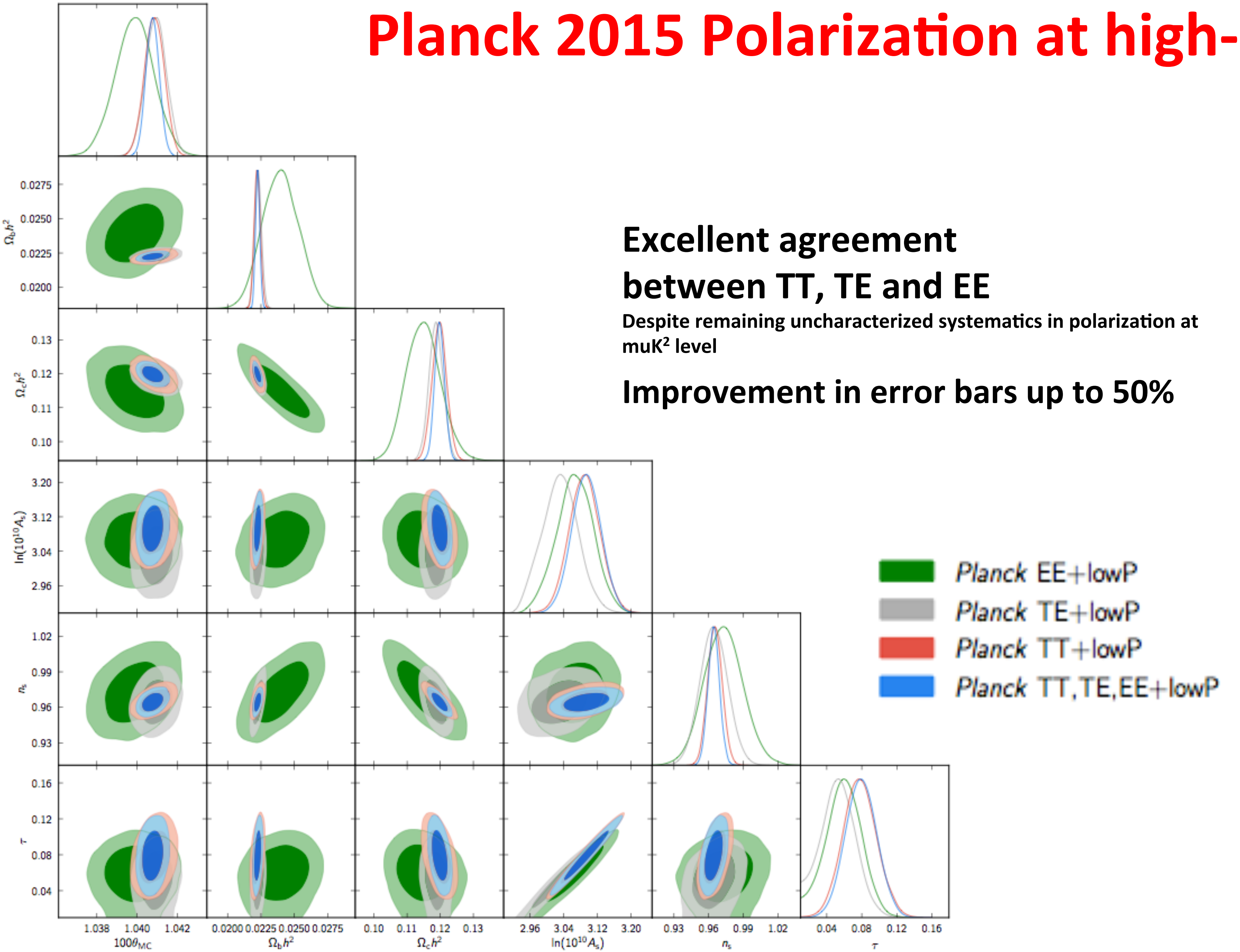
-1 sigma shift
30% weaker constraint

+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 constraint on optical depth weaker and lower than 2013. We use large scale polarization from Planck LFI !

Planck 2015 Polarization at high-l

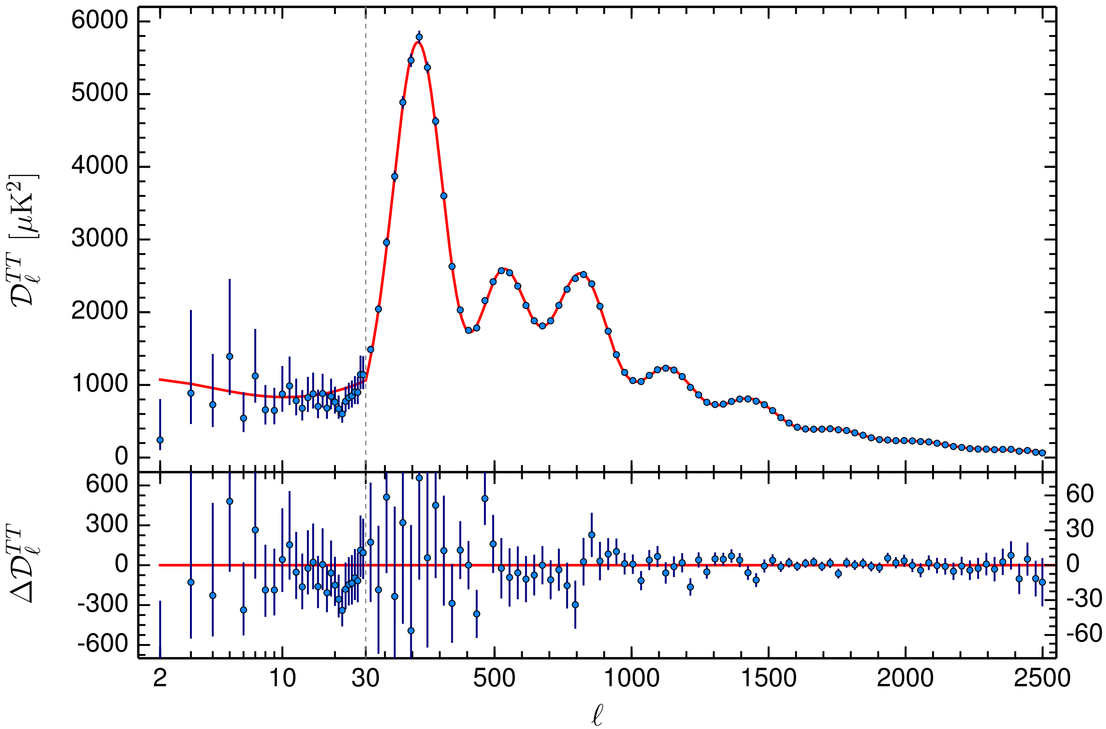


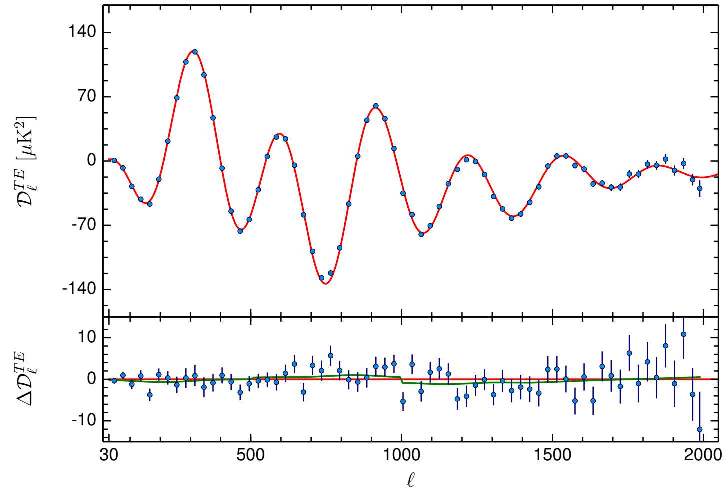
Excellent agreement between TT, TE and EE

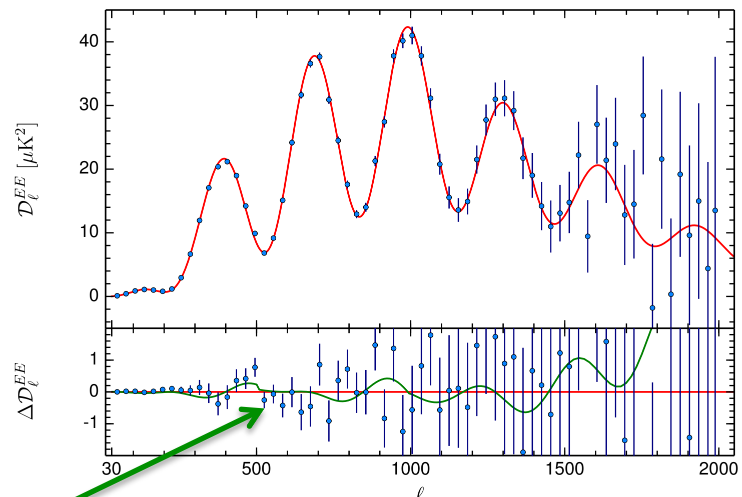
Despite remaining uncharacterized systematics in polarization at muK² level

Improvement in error bars up to 50%

ΛCDM best fit



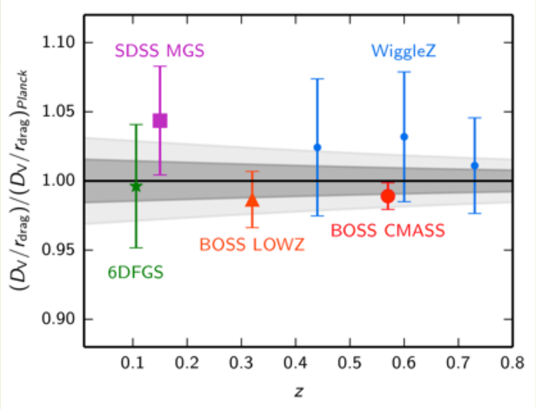




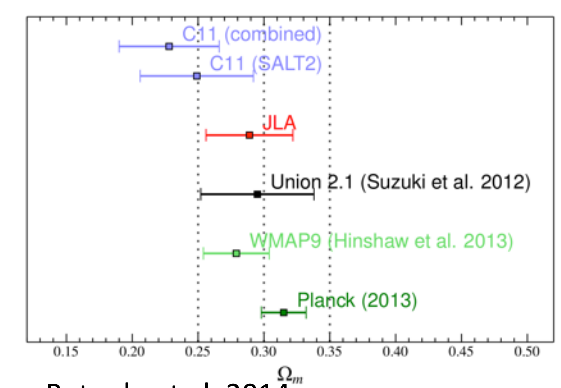
- ΛCDM is very good fit to the data
- Remaining systematics present in polarization spectra, possibly due to unaccounted beam missmatch.

Comparison with other datasets:

BAO

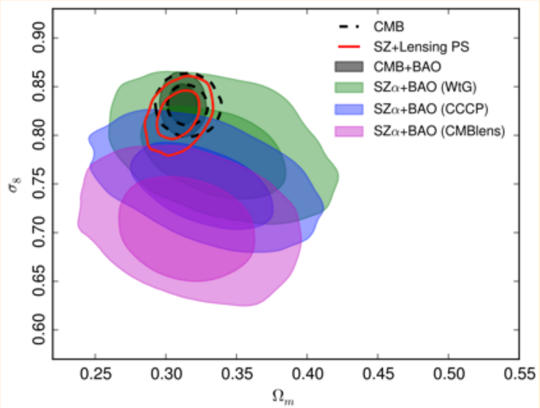


Supernovae (Ω_m)



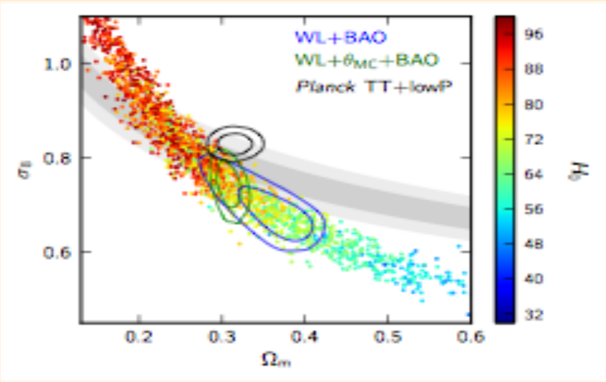
Betoule et al. 2014

Cluster counts (σ_8-Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8-Ω_m)



Direct measurements H_0

H_0=67.8±0.92
(PlanckTT+lowP+lensing)

VS

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

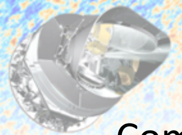
H_0=70.6 ± 3.3 **[1σ tension]**
(Efstathiou+14)

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

[in Km/s/Mpc]

Extensions of ΛCDM

Excellent agreement with ΛCDM!



Curvature:

Compatible with flatness at the level of 10^{-3}

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

(PlanckTT+lowP+Lensing+BAO)

Sum of neutrino masses:

Bound already stronger than what achievable by Katrin (tritium beta decay)

$$\sum m_\nu < 0.23 \text{ eV}$$

(PlanckTT+lowP+Lensing+ext)

Number of relativistic species:

Compatible with standard predition N_{eff}=3.046 with 3 active neutrinos

$$N_{\rm eff} = 3.13 \pm 0.32$$

(PlanckTT+lowP)

Helium abundance

Good agreement with measurements of primordial abundances and BBN predictions

$$Y_{\rm P}^{\rm BBN} = 0.253 \pm 0.021$$

(PlanckTT+lowP)

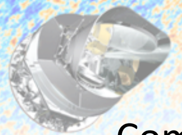
Running of the scalar spectral index

Compatible with no running

$$\frac{dn_s}{d\ln k} = -0.0084 \pm 0.0082$$

(PlanckTT+lowP)

High-l Polarization further improves constraints!



Curvature:

Compatible with flatness at the level of 10^{-3}

$$\Omega_K = 0.000 \pm 0.004 \; (95\%)$$

(PlanckTT+lowP+Lensing+BAO +TE+EE)

Sum of neutrino masses:

Bound already stronger than what achievable by Katrin (tritium beta decay)

$$\sum m_\nu < 0.19 \text{ eV}$$

(PlanckTT+lowP+Lensing+ext+TE+EE)

Number of relativistic species:

Compatible with standard predition N_{eff}=3.046 with 3 active neutrinos

$$N_{\rm eff} = 3.04 \pm 0.17$$

(PlanckTT+lowP+TE+EE)

Helium abundance

Good agreement with measurements of primordial abundances and BBN predictions

$$Y_{\rm P}^{\rm BBN} = 0.251 \pm 0.014$$

(PlanckTT+lowP+TE+EE)

Running of the scalar spectral index

Compatible with no running

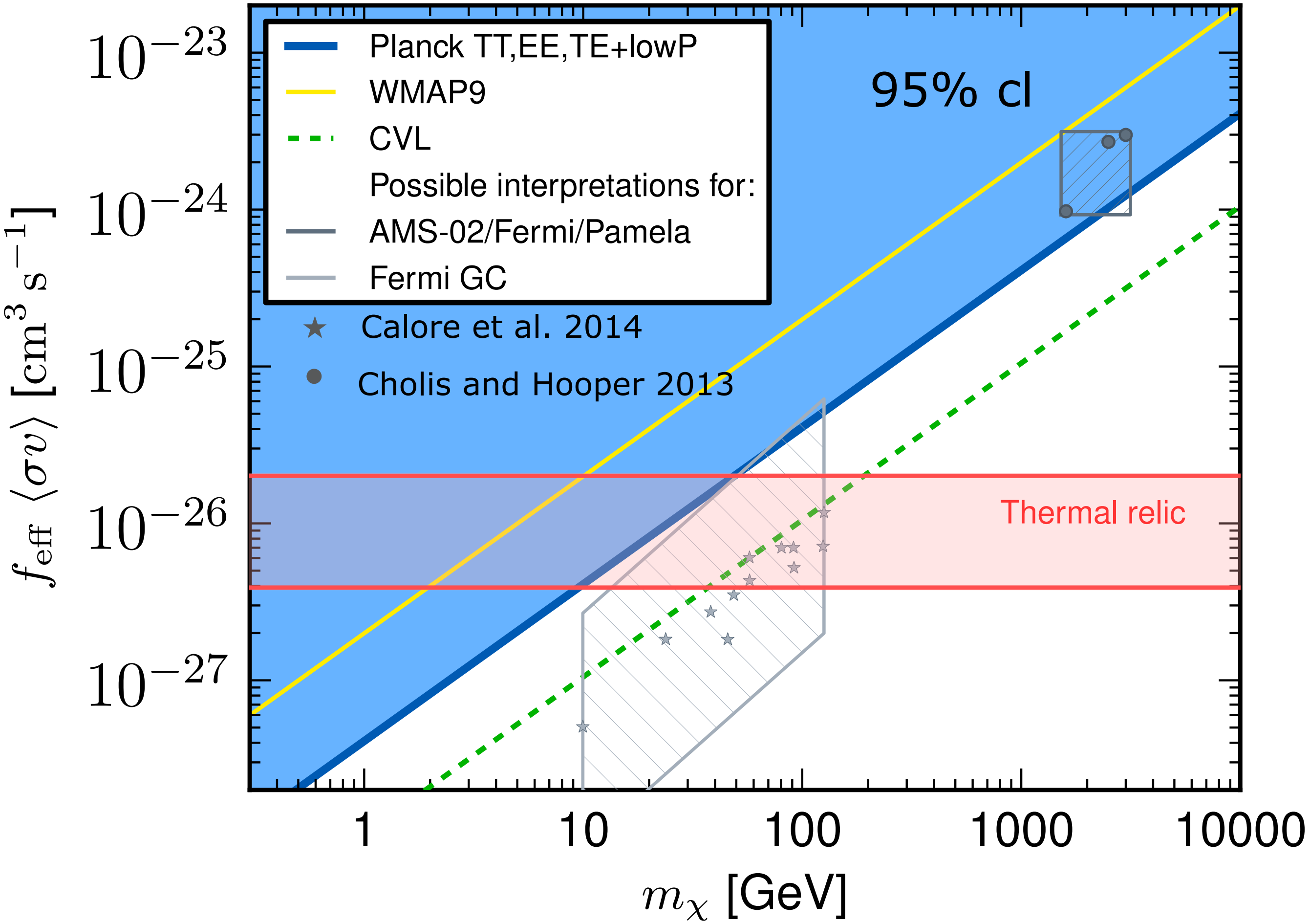
$$\frac{dn_s}{d\ln k} = -0.0057 \pm 0.0071$$

(PlanckTT+lowP+TE+EE)

Polarization is powerful: Dark Matter Annihilation

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

p_{ann}



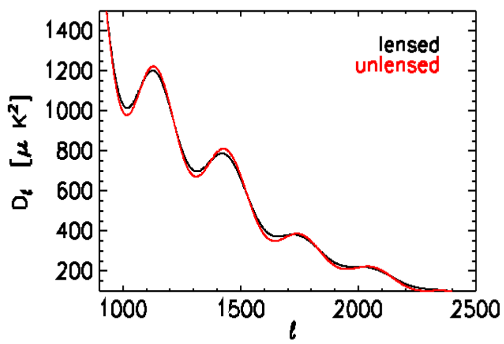
Most of parameter space preferred by AMS-02/Pamela/Fermi ruled out at 95%, under the assumption $<\sigma v>(z=1000)=<\sigma v>(z=0)$

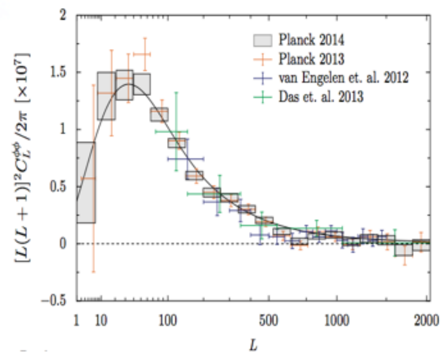
Thermal Relic cross sections at z~1000 ruled out for:

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

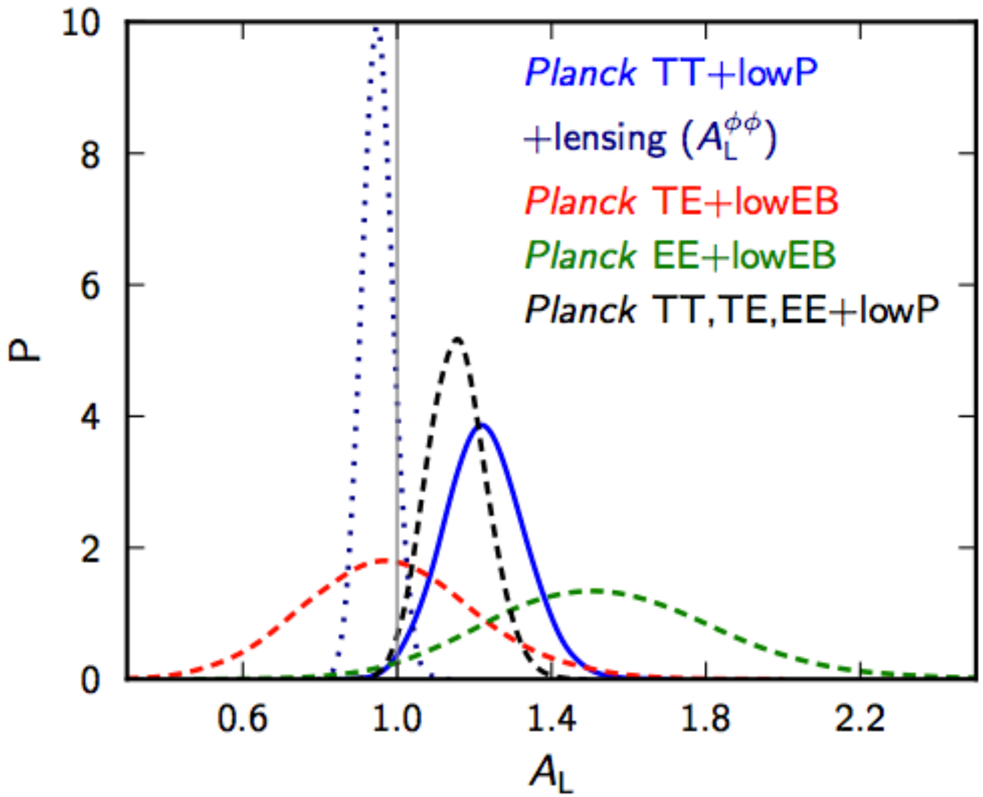
Only a small part of the parameter space preferred by Fermi GC is excluded

A slight preference for high lensing in the power spectrum

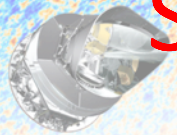




- A_L parametrizes amplitude of lensing power spectrum.
- In LCDM+A_L model, TT power spectrum prefers a ~2-sigma larger lensing amplitude than LCDM prediction.



- We do not think this is physical, because the lensing reconstruction does not share this preference for high amplitude.
- **This could still just be an unlucky statistical fluctuation of the data. It has an impact on extensions of LCDM whichcan provide a larger lensing amplitude in the power spectrum.**

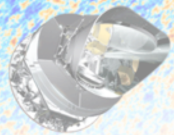


Small deviations of LCDM due to the preference of lensing

- To obtain more lensing in the power spectrum, one can have:
  - Negative Ω_k (positive curvature)
  - Negative dark energy equation of state
  - Modified gravity models that modify perturbations

Parameter	TT	TT+lensing	TT+lensing+ext	
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	**95% c.l.**
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	

- BUT! Statistically not very significant. Additionally, lensing reconstruction does not share this preference for higher amplitude amplitude, it drives back the constraints closer to LCDM.



The BICEP story

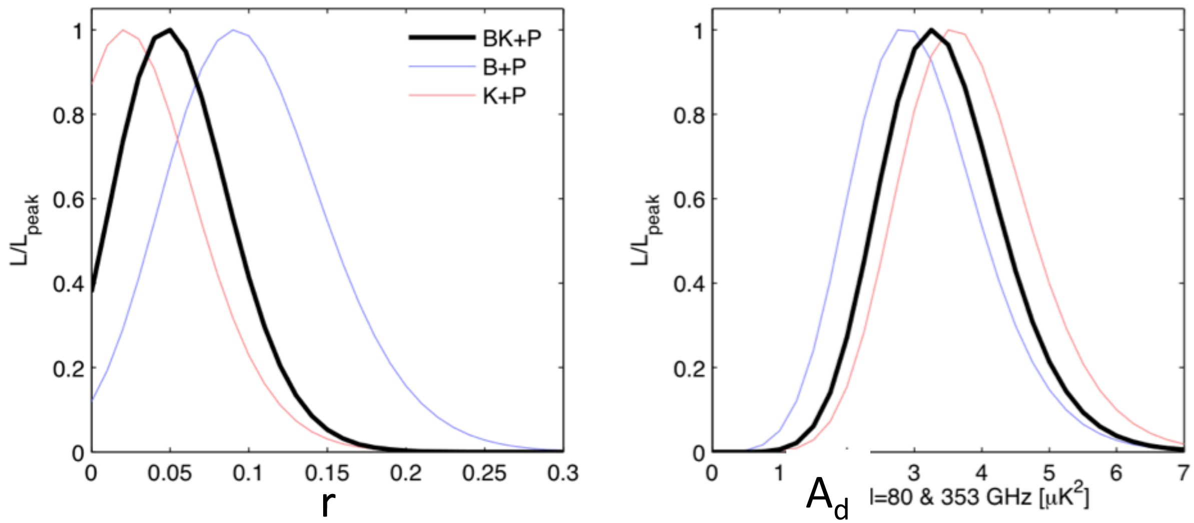
- *March 2014:* BICEP2 claims detection of $r = 0.16^{+0.06}_{-0.05}$ in tension with Planck constraints from TT alone, r<0.11, unless open extensions of LCDM.

- *May 2014:* Flauger+ 2014, Mortonson & Seljak 2014 notice high contamination of dust, Planck collaboration (PIP XIX) publishes at intermediate latitudes higher dust polarization fraction then assumed in BICEP foregrounds models.

- *September 2014:* Planck collaboration publishes results on dust polarization at high latitudes. Dust can account for all the signal observed by BICEP2.

The Bicep2/Keck+Planck analysis

- February 2015: Joint analysis Bicep2/Keck+Planck collaborations
- Used all auto and cross-spectra BB of BICEP2/Keck at 150 and Planck at 217, 353 (detsets) at l=20-200.
- Dust: power law with $D_l \sim l^{-0.4}$ and modified black body frequency spectrum (Fixed T_d, prior on β) $I_d(\nu) \propto \nu^{\beta_d} B_\nu(T_d)$ $T_d = 19.6\,\mathrm{K}$ $\beta_d = 1.59 \pm 0.11$
- Sta



- r =0.048±0.035, r < 0.12 at 95% C.L.
- 5.1 sigma detection of dust power
- Adding Planck TT, r<0.08.

Planck, Bicep & Keck collaborations 2015

Current constraints

- BICEP2/Keck data at 150GHz and 95GHz
- Planck polarized (30–353 GHz) +WMAP 23 & 33GHz
- ΛCDM + r + A_d+A_s

$$r_{0.05} < 0.09$$

BK+Planck+WMAP, BB alone

$$r_{0.05} < 0.12$$

PlanckTT+lowP+lensing+BSH

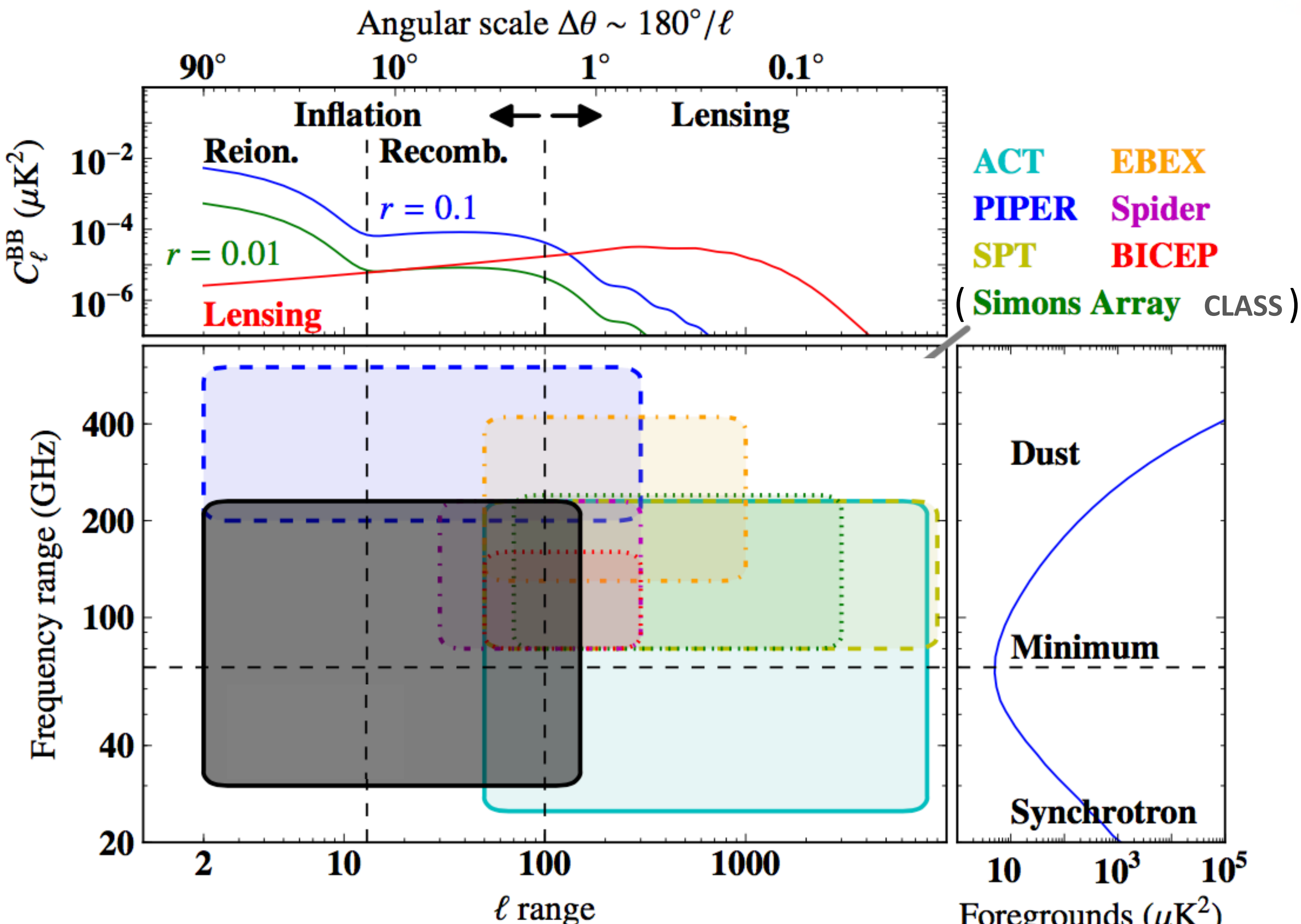
$$r_{0.05} < 0.07$$

BK+Planck+WMAP, BB + PlanckTT+lowP+lensing+BSH

BICEP2&KECK 2015 (1510.09217)

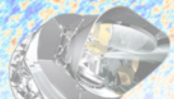
- For the first time, constraints from BB alone are stronger than the ones from TT .
- Combination of Planck TT+BB data and BICEP/KECK BB provides strongest constraints on tensor to scalar ratio to date.

What's next? upcoming



r<~10^{-2}

Modified from Watts 2015



What’s next? <2020

Table 5. Pre-2020 instruments

Advanced ACTpol (ground)

Advanced ACTPol specifications, http://arxiv.org/abs/1406.4794						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
90.0	30.0	11.0	50.0	2.2	20	4000
150.0		9.8		1.3		
230.0		35.4		0.9		

BICEP3+KECK (ground)

BICEP3 + Keck specifications						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
95.0	30.0	1.7	1.0	25.0	20	1300
150.0		3.4		30.0		

CLASS (ground)

CLASS specifications, http://arxiv.org/abs/1408.4788						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
38.0	30.0	39.0	70.0	90.0	20	1100
93.0		10.0		40.0		
148.0		15.0		24.0		
217.0		43.0		18.0		

$r<\sim10^{-3}$

(when combined with Planck)

EBEX 10K (balloon)

EBEX10K specifications, proposal to NASA in 2015						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
150.0	30.0	5.5	2.5	6.6	20	4000
220.0		11.0		4.7		
280.0		25.4		3.9		
350.0		53.0		3.3		

PIPER (balloon)

PIPER specifications, http://arxiv.org/abs/1407.2584						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
200.0	30.0	31.4	85.0	21.0	20	1000
270.0	30.0	45.9		21.0		
350.0	16.0	162.0		21.0		
600.0	10.0	2659.2		21.0		

SIMONS Array (ground)

Simons Array specifications, Ref. [74]						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
90.0	30.0	14.4	65.0	5.2	20	4000
150.0		11.8		3.5		
220.0		40.3		2.7		

Spider (balloon)

SPIDER specifications, http://arxiv.org/abs/0807.1548						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
90.0	24.0	21.2	8.0	45.0	20	800
150.0	24.0	17.7		30.0		

SPT 3G (ground)

SPT-3G specifications, http://arxiv.org/abs/1407.2973						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	$f_{\rm sky}$ [%]	FWHM [arcmin]	$\ell_{\rm min}$	$\ell_{\rm max}$
95.0	27.0	7.0	6.0	1.6	20	4000
148.0	26.0	4.5		1.1		
223.0	23.0	7.5		1.0		

Errard+ 2015

What's next? >2020

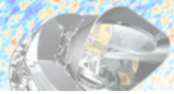


Table 6. Post-2020 instruments

COrE+ specifications, http://conservancy.umn.edu/handle/11299/169642						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
60.0		16.0		14.0		
70.0		14.9		12.0		
80.0		12.9		10.5		
90.0		9.2		9.3		
100.0		8.5		8.4		
115.0		7.0		7.3		
130.0		5.9		6.5		
145.0	30.0	5.0	70.0	5.8	2	
160.0		5.4		5.3		
175.0		5.3		4.8		4000
195.0		5.3		4.3		
220.0		8.1		3.8		
255.0		12.6		3.3		
295.0		27.4		2.9		
340.0		43.7		2.5		
390.0		77.8		2.2		
450.0		164.8		1.9		
520.0		418.2		1.6		
600.0		1272.4		1.4		

LiteBIRD-ext specifications http://ltd16.grenoble.cnrs.fr/IMG/UserFiles/Images/09_TMatsumura_20150720_LTD_v18.pdf						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
40.0		42.5		108		
50.0		26.0		86		
60.0		20.0		72		
68.4		15.5		63		
78.0		12.5		55		
88.5		10.0		49		
100.0		12.0		43		
118.9	30.0	9.5	70.0	36	2	1350
140.0		7.5		31		
166.0		7.0		26		
195.0		5.0		22		
234.9		6.5		18		
280.0		10.0		37		
337.4		10.0		31		
402.1		19.0		26		

Stage-IV specifications, derived so that the noise after component separation, σ_{CMB}, is ~ 1 μK-arcmin, Refs. [64, 77]						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
40.0		3.0		11.0		
90.0		1.5		5.0		
150.0	30.0	1.5	50.0	3.0	20	4000
220.0		5.0		2.0		
280.0		9.0		1.5		

PIXIE specifications, Ref. [78]						
frequencies [GHz]	fractional bandpass [%]	sensitivities [μK-arcmin]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
see Fig. 14			70.0	96.0	2	500

COrE (satellite)

$r <\sim 10^{-4}$

LiteBIRD-ext (satellite)

Stage-IV (ground)

Pixie (satellite)

Errard+ 2015

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.

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