



planck



Cosmological results from Planck 2015

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On behalf of the Planck collaboration



Outline and a few frequent questions.

- Short intro about CMB and Planck
- **Neutrino constraints.** How model dependent are they?
- **Dark matter annihilation:** can we evade the CMB constraints?
- Constraints on **inflationary gravitational waves:** what's next?

2015 Release

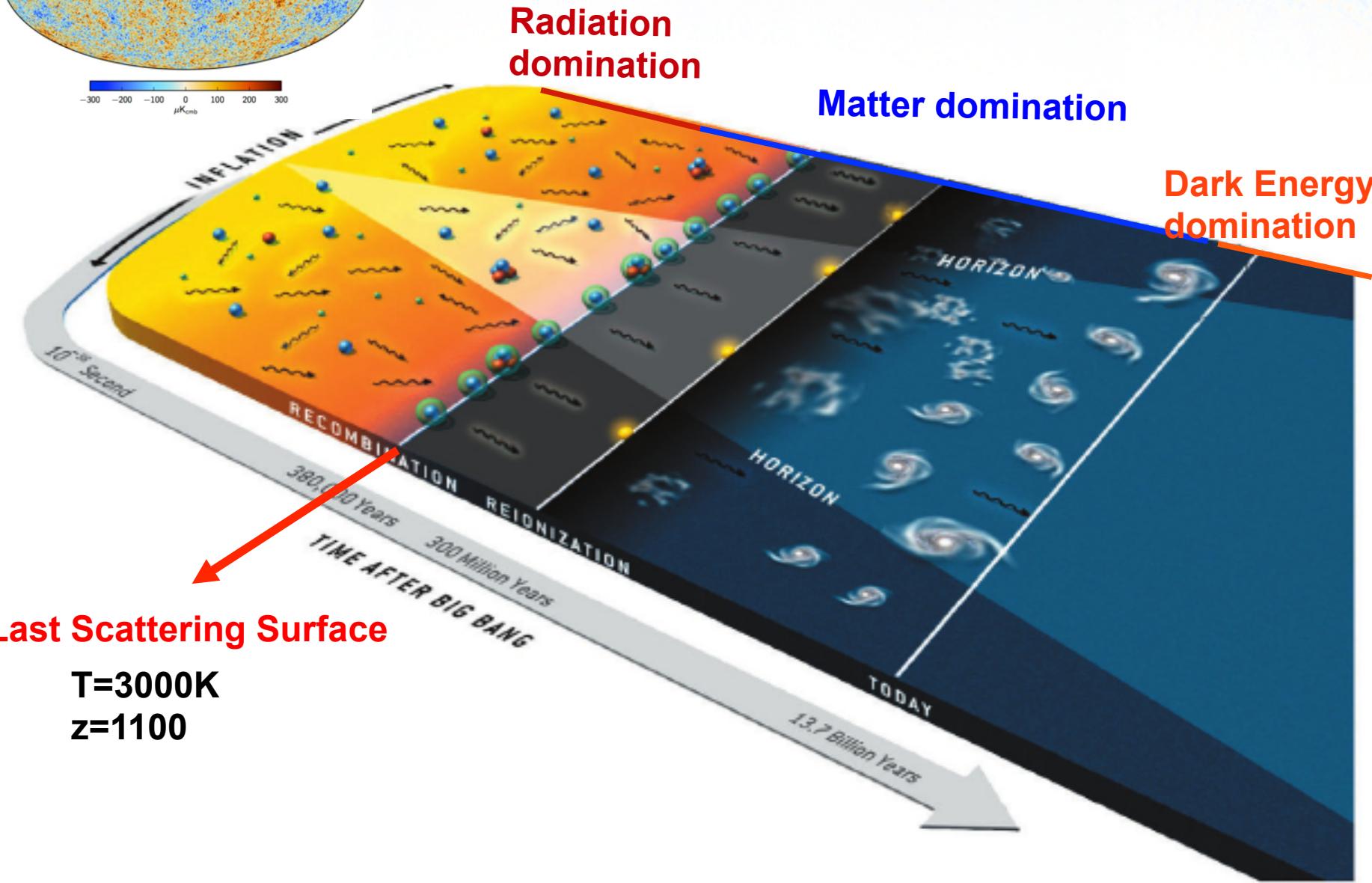
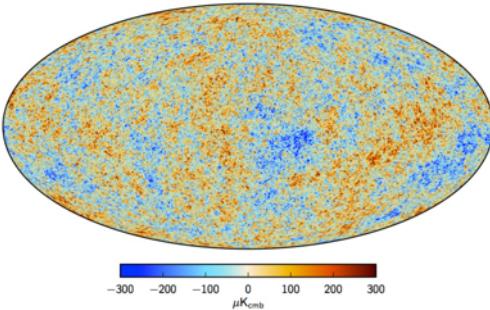
Title	Authors	Publication
Planck 2015 results. I. Overview of products and results	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. II. Low Frequency Instrument data processing	Planck Collaboration	2015 Submitted to A&A
Planck 2015 results. III. LFI systematic uncertainties	Planck Collaboration	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

- 28 papers
- In this talk
 - Cosmological parameters (February 2015)
 - Likelihood (July 2015)

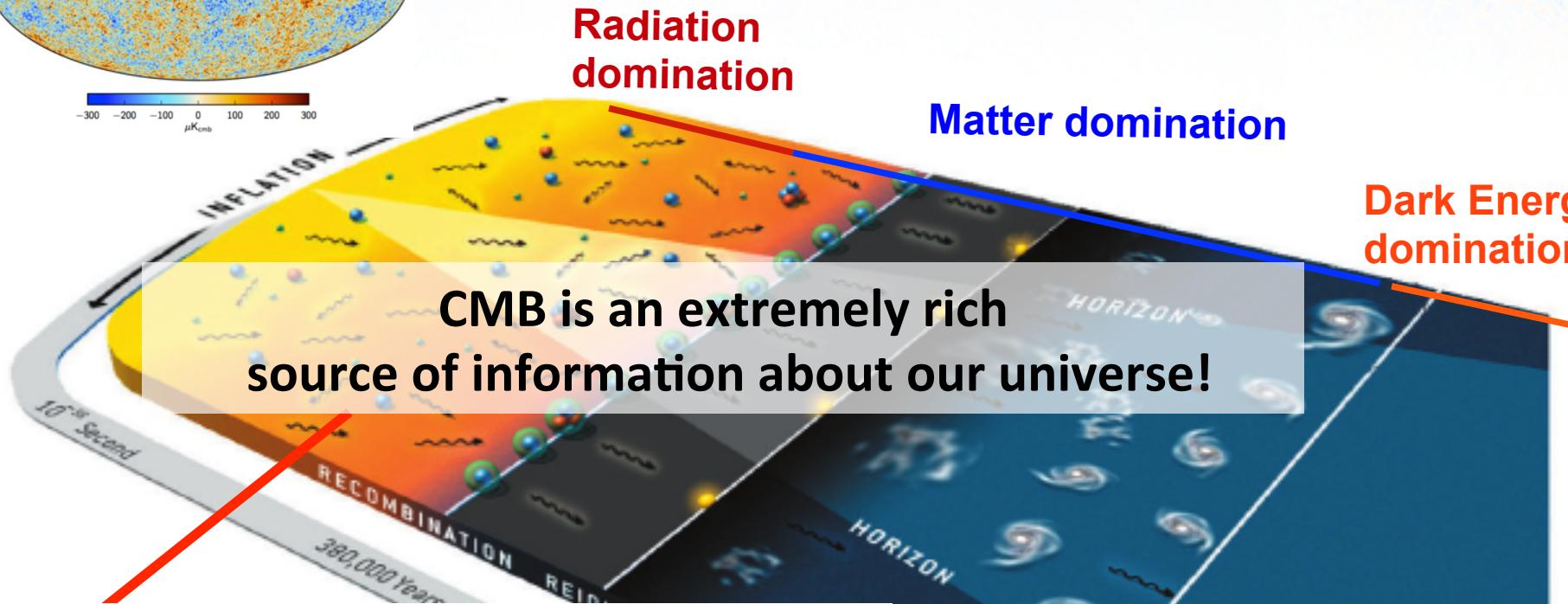
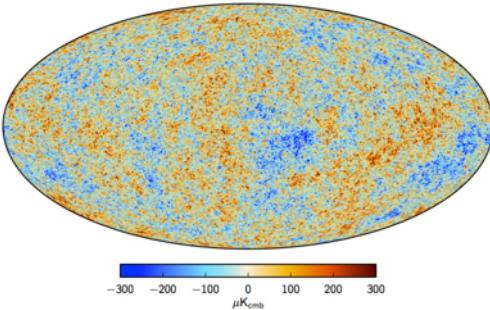


CMB in 2 slides

Cosmic History

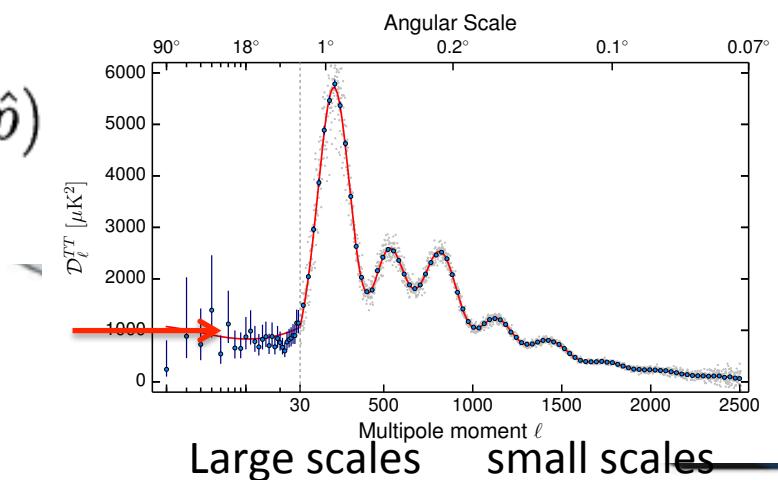


Cosmic History



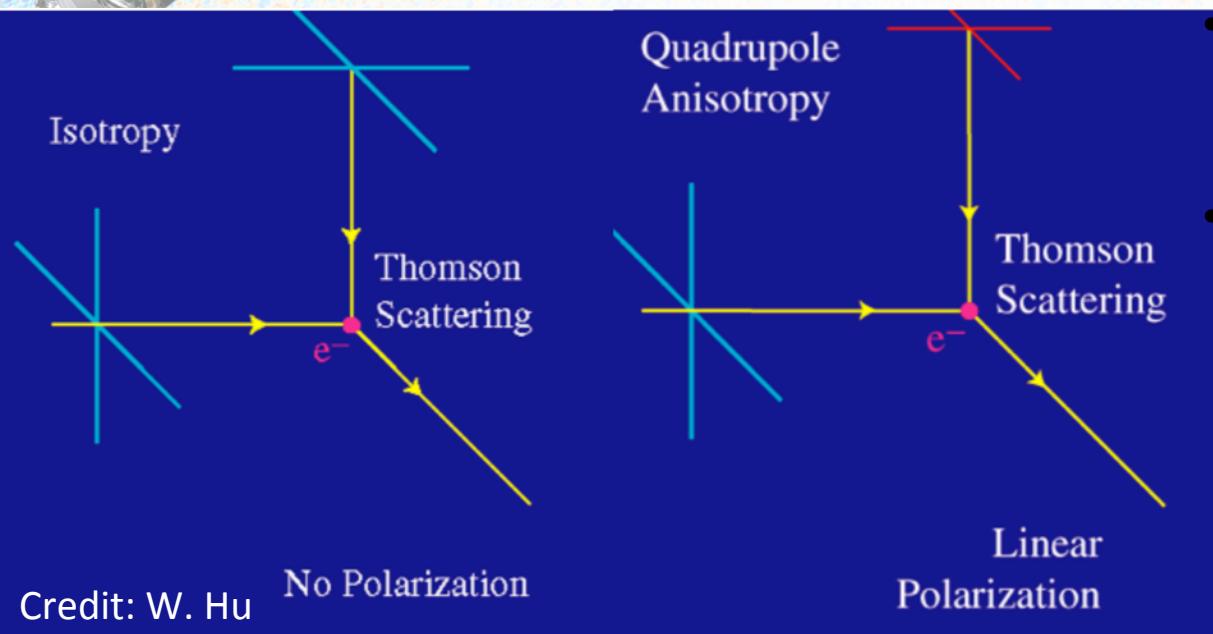
$$\Theta(\vec{x}, \hat{p}, \eta) = \sum_{l=1}^{\infty} \sum_{m=-l}^l a_{lm}(\vec{x}, \eta) Y_{lm}(\hat{p})$$

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

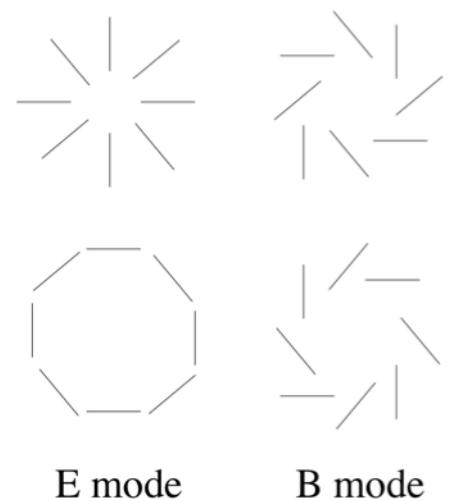
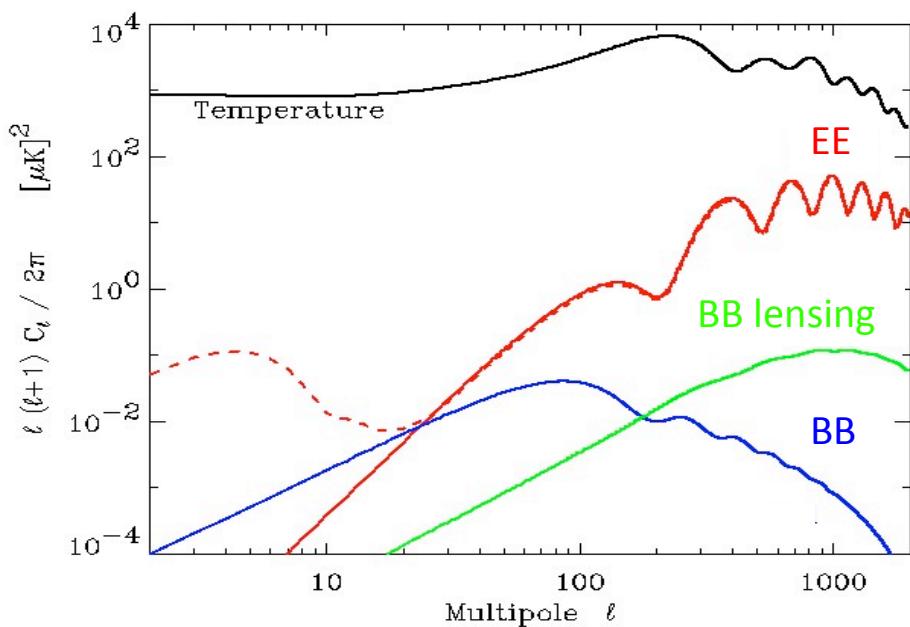




CMB Polarization



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



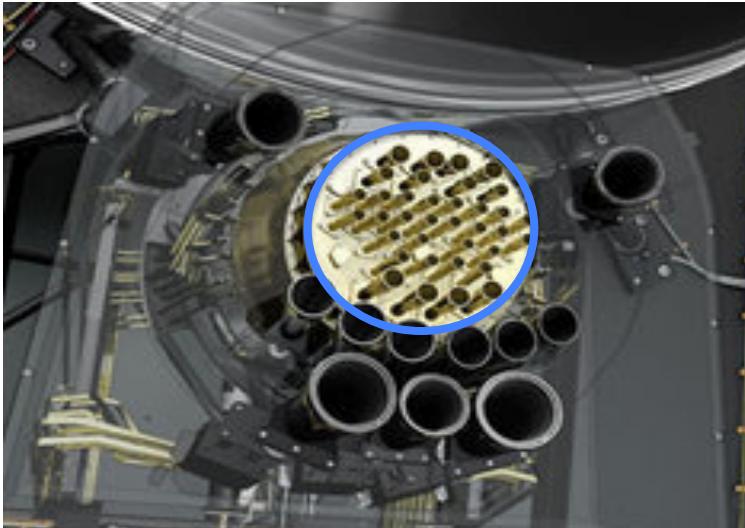
E mode B mode



The Planck satellite



9 Frequencies, 2 instruments



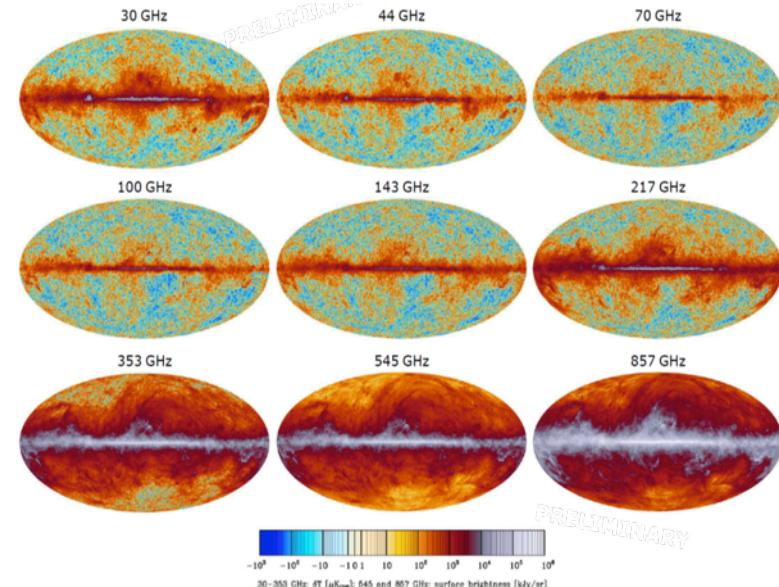
LFI:

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

HFI:

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

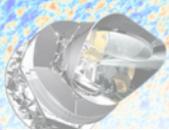
- Third generation CMB satellite missions (after COBE and WMAP).
- Launched in **2009** to L2, operated until **2013**.
- **1st release 2013: Nominal mission**, 15.5 months, Temperature only.
- **2nd release 2015: Full mission**, 29 months for HFI, 48 months for LFI, Temperature + Polarization





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. $\ell \sim 1800$ dip due to the 4K line).
4. **Polarization.**
 1. **Low- ℓ** (large angular scales, $\ell < 30$) polarization from **Planck LFI** instead of **WMAP9 polarization** (used in 2013) to constrain reionization.
 2. **High- ℓ** (small angular scales, $\ell > 30$) polarization from **HFI**.



Λ CDM results from TT

[1] Parameter	2013N(DS)	2015F(CHM) (Plik)
$100\theta_{\text{MC}}$	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

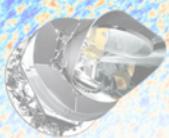
2013=Planck Nominal 2013 TT+low-l WMAP polarization
2015=Planck Full 2015 TT+low-l Planck LFI polarization.

- 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 !



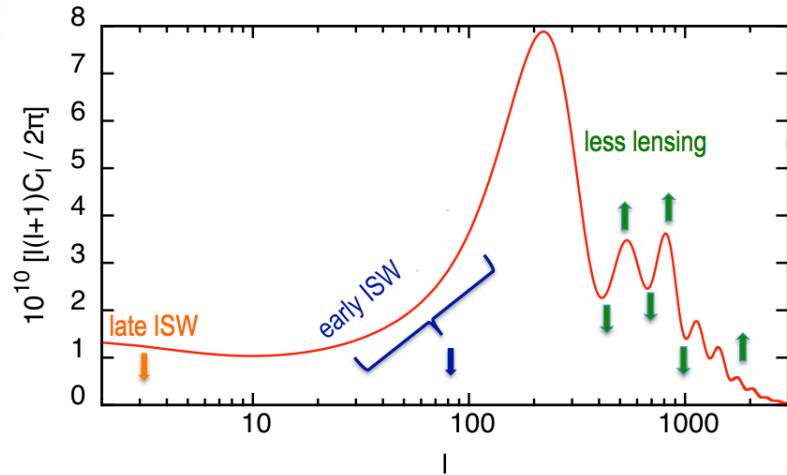
A few frequent questions

- Short intro about CMB and Planck
- **Neutrino constraints.** How model dependent are they?
- **Dark matter annihilation:** can we evade the CMB constraints?
- Constraints on **inflationary gravitational waves:** what's next?



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
Planck TT+lowP	<0.93	<0.72 (23%)	<0.49 (48%)
Planck TT+lowP +lensing	<1.1	<0.68 (38%)	<0.59 (46%)
Planck TT+lowP +lensing+BAO		<0.25	<0.22

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)!



How model dependent are these constraints?

Σm_ν (95% CL) [eV]

PlanckTT+TE+EE +lowP+lensing+BAO	<0.22
+Neff	<0.22
+Neff, w, Alens, running, r, (no lensing)	<0.5

Assumption: 3 degenerate massive neutrinos,
Neff-3.046 massless relativistic species

Planck collaboration XII 2015
Di Valentino et al. 2015



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.

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

	2013	2015	2015 +EE,TE
PlanckTT+lowP	3.51 ± 0.39	3.13 ± 0.32 (18%)	2.99 ± 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.
- $N_{\text{eff}} > 0$ confirmed at ~ 15 -sigma.
- $N_{\text{eff}} = 4$ excluded at 3-5 sigma!

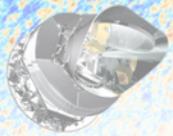


How model dependent are these constraints?

Neff (68% CL)

PlanckTT+TE+EE +lowP+lensing +BAO	$<2.98 \pm 0.18$
+ Σm_ν	2.99 ± 0.18
+ Σm_ν , w, Alens, running, r (no lensing)	3.1 ± 0.5

Assumption: 3 degenerate massive neutrinos,
Neff-3.046 massless relativistic species

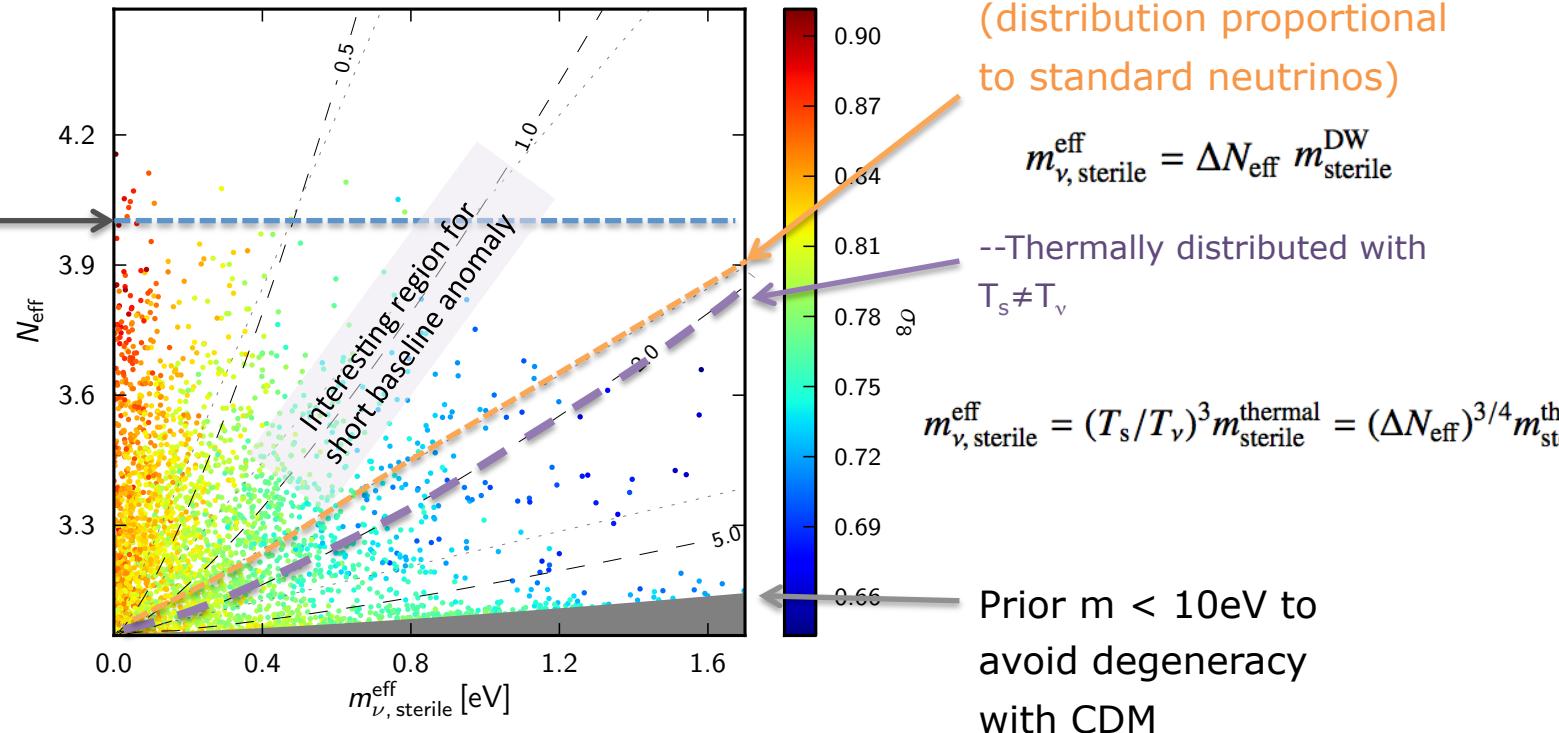


Massive sterile Neutrinos

Assumptions: 3 standard neutrinos

($\Sigma m_\nu = 0.06 \text{ eV}$), $N_{\text{eff}} = 3.046$ massive relativistic species

One thermalised sterile neutrino species (thermally distributed with $T_s = T_\nu$)



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



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- Short intro about CMB and Planck
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- **Dark matter annihilation:** can we evade the CMB constraints?
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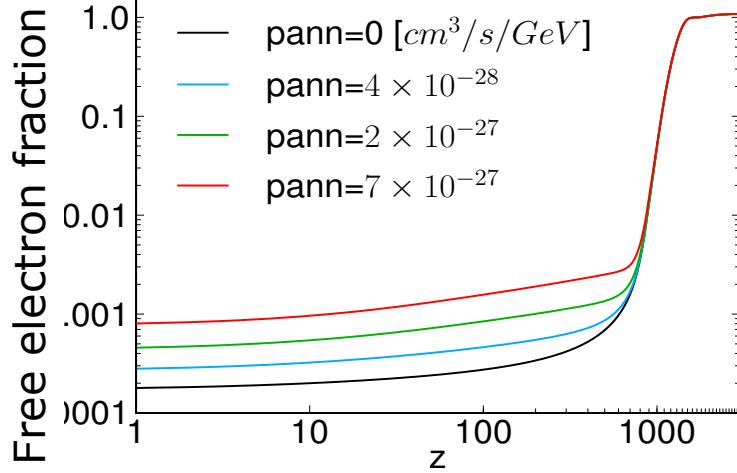


DM annihilation at the epoch of recombination

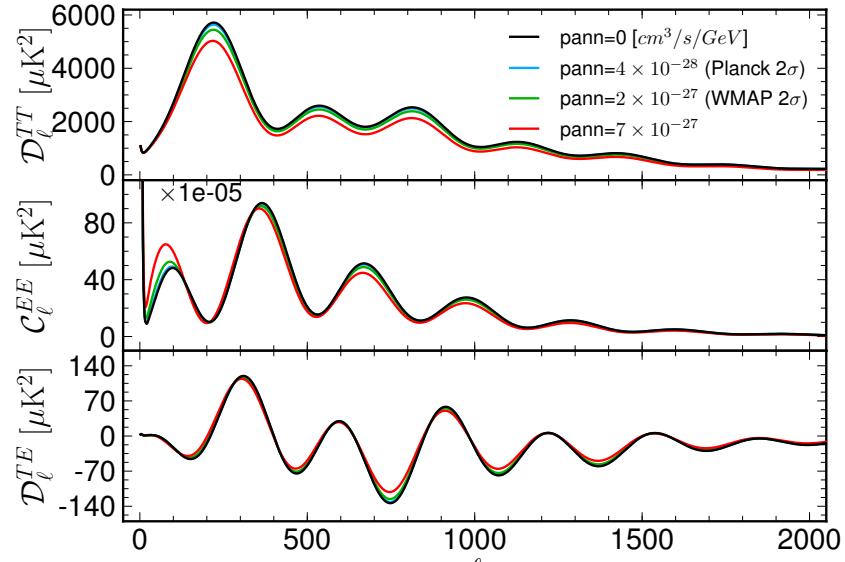
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6$$

$$f_{eff} \frac{\langle \sigma v \rangle}{m_\chi}$$

p_{ann}



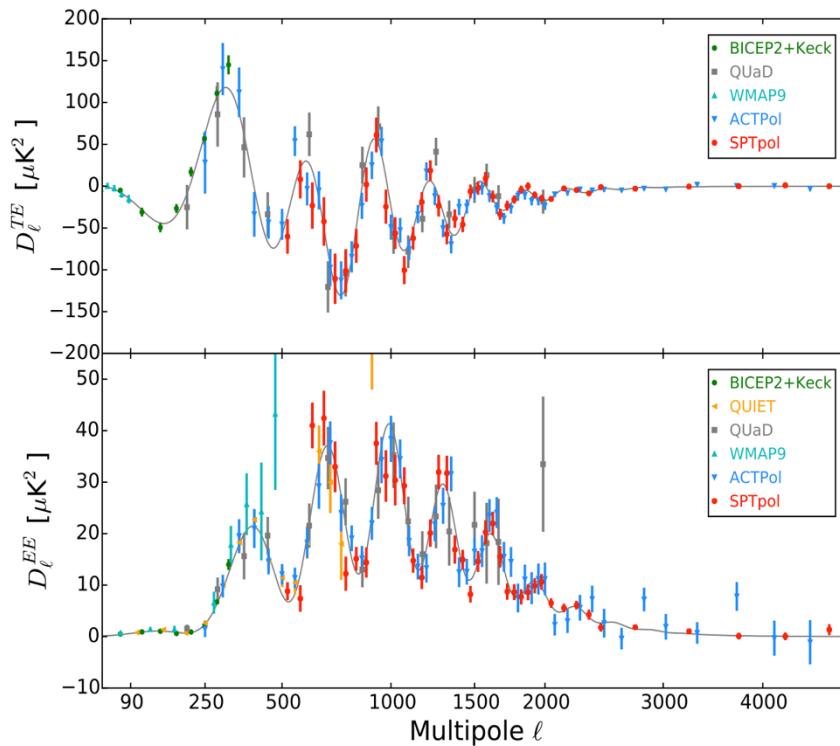
The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.



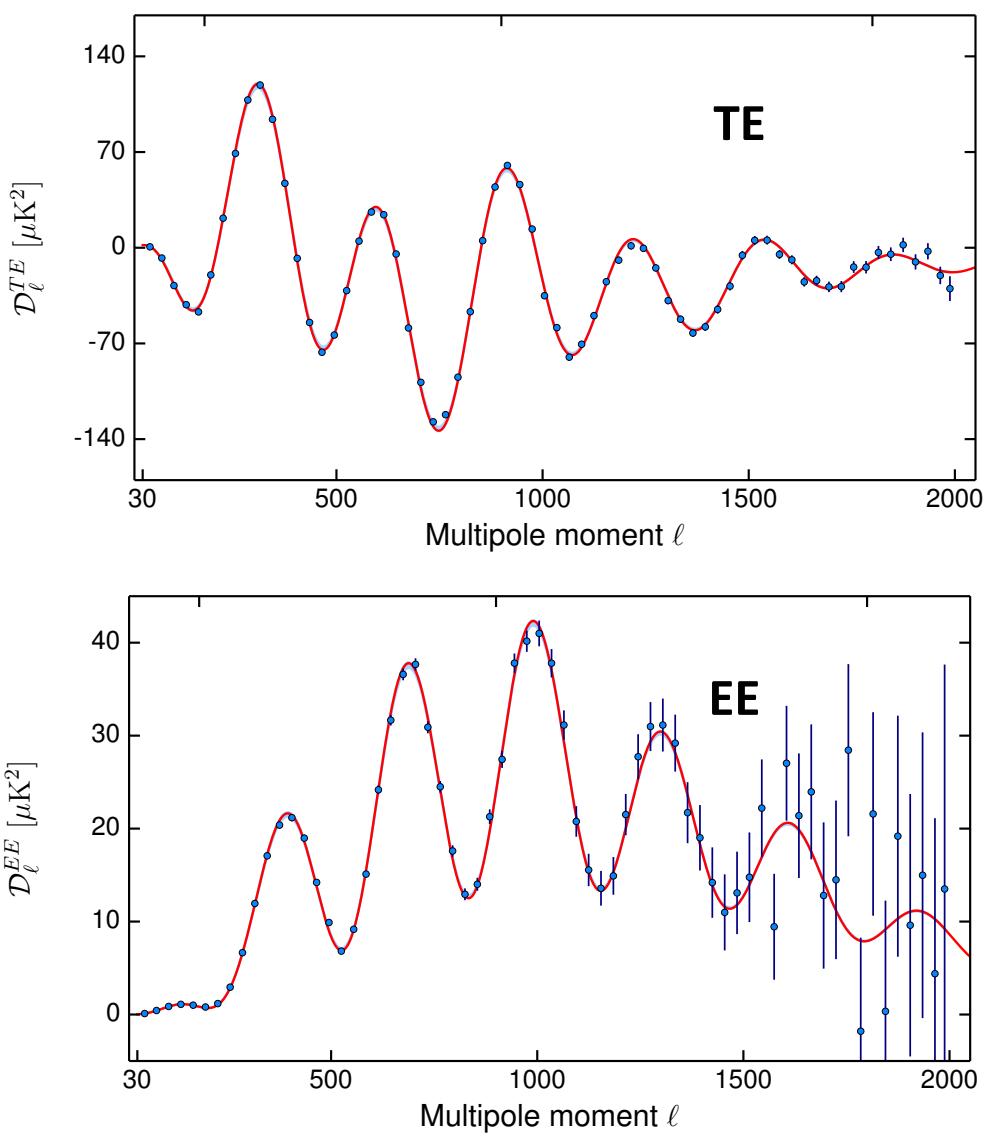
- The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.
- Suppresses the peaks, but enhances polarization at large scales!

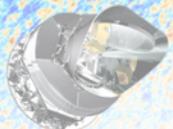
2015 Polarization power spectra

Pre-Planck measurements

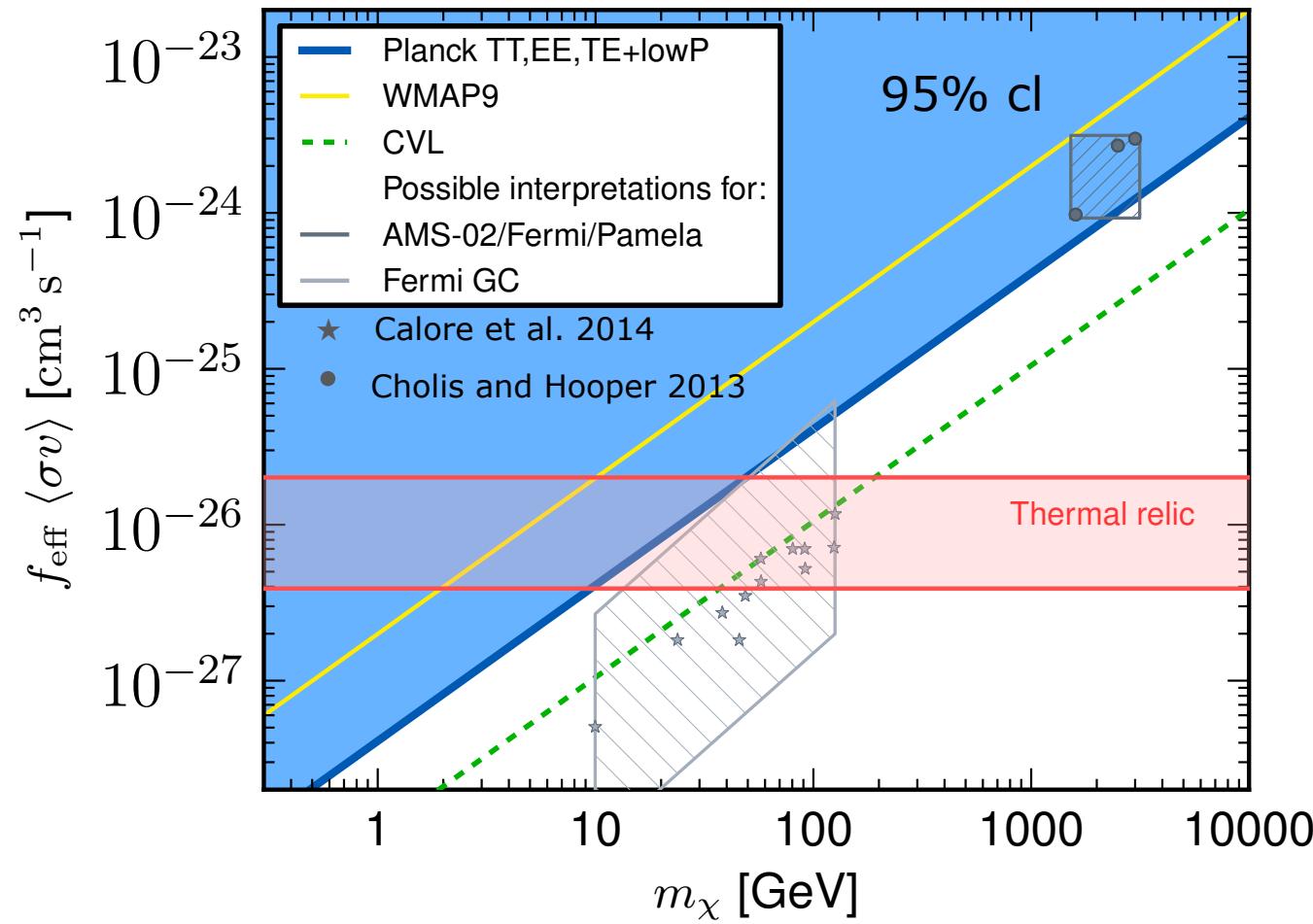


Planck 2015





Constraints on Dark Matter Annihilation



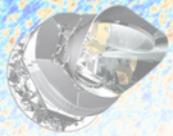
Most of parameter space preferred by AMS-02/Pamela/Fermi ruled out at 95%, under the assumption $\langle \sigma v \rangle(z=1100) = \langle \sigma v \rangle(z=0)$

Thermal Relic cross sections at $z \sim 1000$ ruled out for:

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

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

See also Vivian Poulin's talk



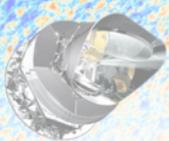
A Few Caveats

- The CMB set constraints on m_χ - $\langle\sigma v\rangle$ plane at the epoch of recombination ($z=1100$). If $\langle\sigma v\rangle$ depends on DM velocity:
 - If $\langle\sigma v\rangle \propto v^n$, $n > 0$ (e.g. p-wave), constraints could be evaded today, since $\langle\sigma v\rangle$ could be small at the epoch of recombination, but large today, ($v/c (z=1100) \sim 10^{-8}$, $v/c (z=0) \sim 10^{-3}$ for $m_\chi \sim O(100\text{GeV})$).
 - If $\langle\sigma v\rangle \propto v^n$, $n < 0$, (e.g. Sommerfeld enhancement) CMB constraints might be stronger.
 - If the high flux of positron/electron fraction in cosmic rays is due to a combination of a high cross section and extra DM clumping, preferred DM parameter space can shift below the Planck constraint.



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Inflation: n_s and r

- From **Planck TT+lowP**:

- Almost a **6 σ departure** from scale invariance (but model dependent! relaxable when opening N_{eff})

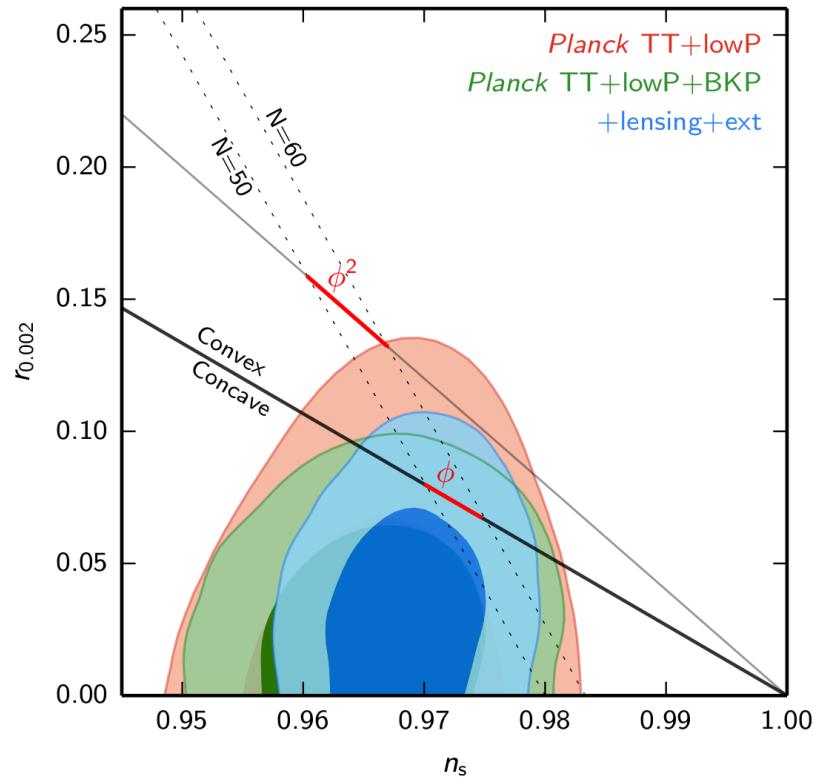
$$n_s = 0.9655 \pm 0.0062$$

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

$$r < 0.10$$

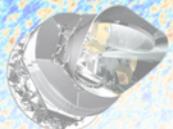
- Adding BB measurements from **BICEP2/KECK**, foreground-cleaned with Planck data (**Planck TT+lowP +BKP**):

$$r < 0.08$$



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

n_s =spectral index of primordial scalar perturbations



Updated constraints on r

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

$$r_{0.05} < 0.09$$

BK+Planck+WMAP, **BB** alone

$$r_{0.05} < 0.12$$

Planck**TT**+lowP+lensing+BSH

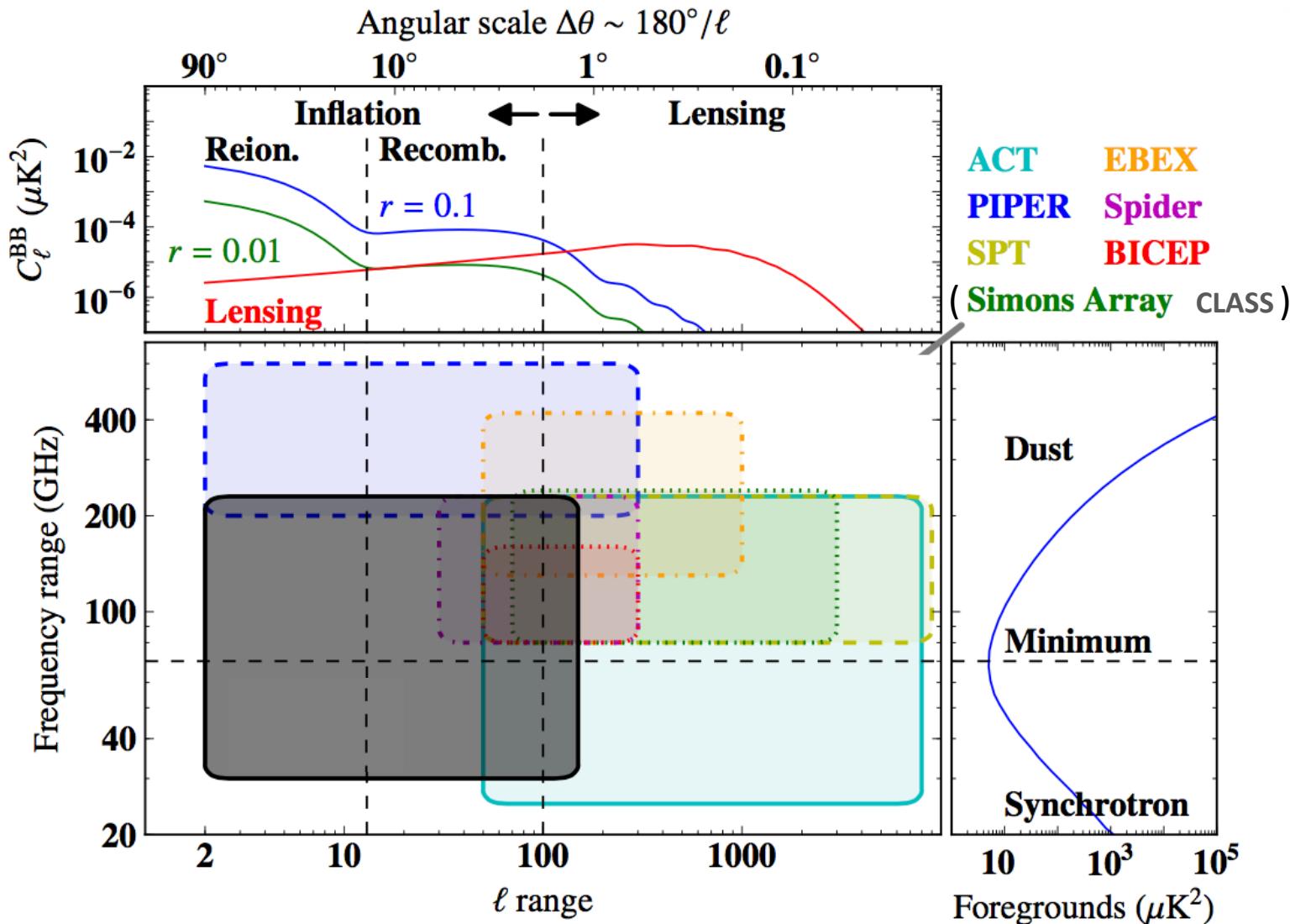
$$r_{0.05} < 0.07$$

BK+Planck+WMAP, **BB** +
Planck**TT**+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



Modified from Watts 2015



What's next? <2020

Table 5. Pre-2020 instruments

Advanced ACTPol specifications, http://arxiv.org/abs/1406.4794						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
90.0		11.0		2.2		
150.0	30.0	9.8	50.0	1.3	20	4000
230.0		35.4		0.9		
BICEP3 + Keck specifications						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
95.0		1.7		25.0		
150.0	30.0	3.4	1.0	30.0	20	1300
CLASS specifications, http://arxiv.org/abs/1408.4788						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
38.0		39.0		90.0		
93.0		10.0		40.0		
148.0	30.0	15.0	70.0	24.0	20	1100
217.0		43.0		18.0		
EBEX10K specifications, proposal to NASA in 2015						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
150.0		5.5		6.6		
220.0		11.0		4.7		
280.0	30.0	25.4	2.5	3.9	20	4000
350.0		53.0		3.3		
PIPER specifications, http://arxiv.org/abs/1407.2584						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
200.0		31.4		21.0		
270.0	30.0	45.9		21.0		
350.0	16.0	162.0	85.0	21.0	20	1000
600.0	10.0	2659.2		21.0		
Simons Array specifications, Ref. [74]						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
90.0		14.4		5.2		
150.0	30.0	11.8	65.0	3.5	20	4000
220.0		40.3		2.7		
SPIDER specifications, http://arxiv.org/abs/0807.1548						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
90.0		21.2		45.0		
150.0	24.0	17.7	8.0	30.0	20	800
SPT-3G specifications, http://arxiv.org/abs/1407.2973						
frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
95.0		7.0		1.6		
148.0	27.0	4.5	6.0	1.1	20	4000
223.0	26.0	7.5		1.0		

Advanced ACTpol (ground)

BICEP3+KECK (ground)

CLASS (ground)

$$r < \sim 10^{-3}$$

(when combined with
Planck)

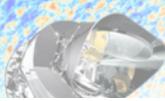
EBEX 10K (balloon)

PIPER (balloon)

SIMONS Array (ground)

Spider (balloon)

SPT 3G (ground)



What's next? >2020

Table 6. Post-2020 instruments

COrE+ specifications, <http://conservancy.umn.edu/handle/11299/169642>

frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	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		5.0		5.8		
160.0	30.0	5.4	70.0	5.3	2	
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		

COrE (satellite)

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

frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	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		

LiteBIRD-ext (satellite)

frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	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		

Stage-IV (ground)

frequencies [GHz]	fractional bandpass [%]	sensitivities [$\mu\text{K}\text{-arcmin}$]	f_{sky} [%]	FWHM [arcmin]	ℓ_{min}	ℓ_{max}
see Fig. 14			70.0	96.0	2	500

Pixie (satellite)

Errard+ 2015

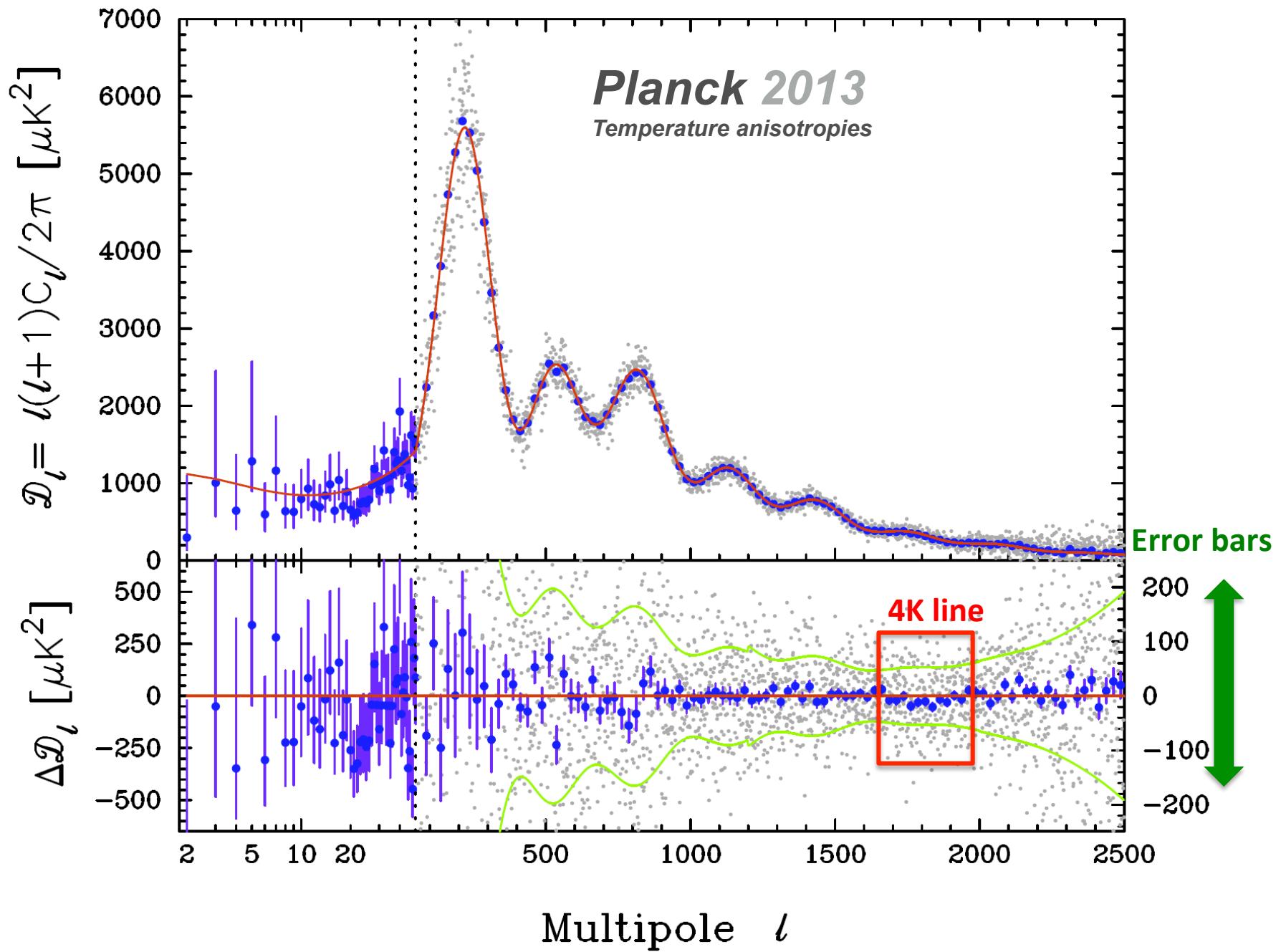
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

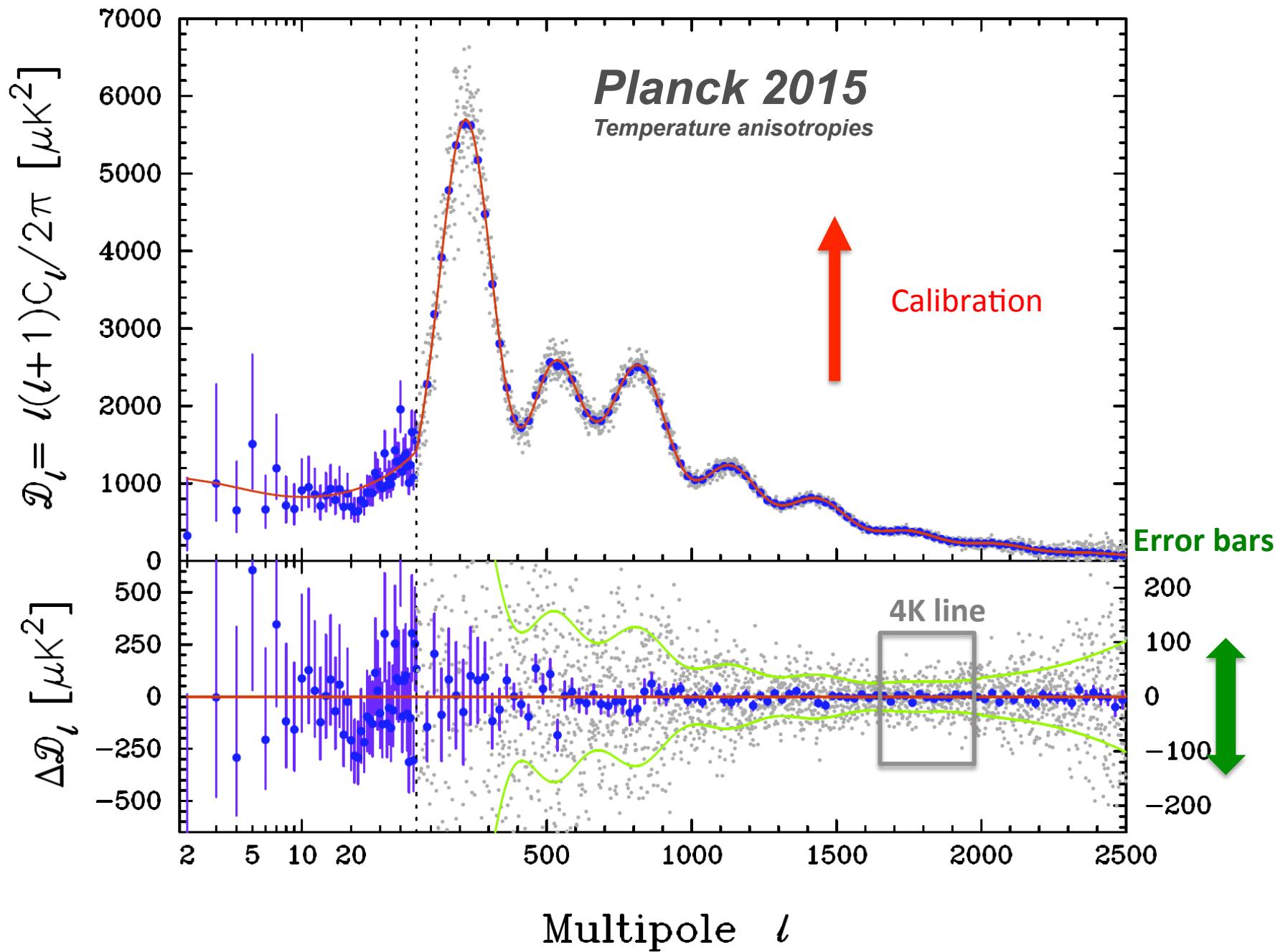


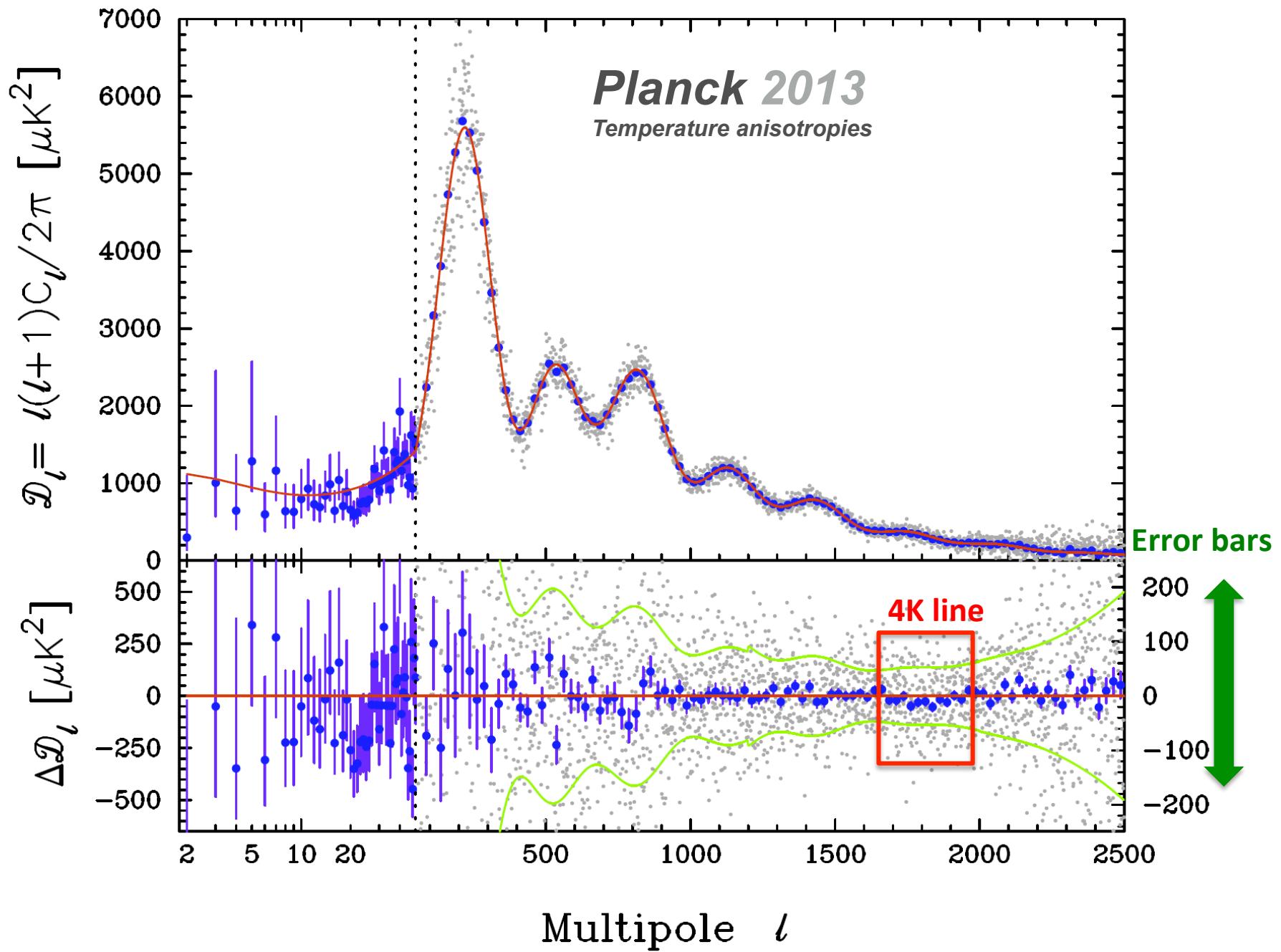
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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



What changed since 2013?

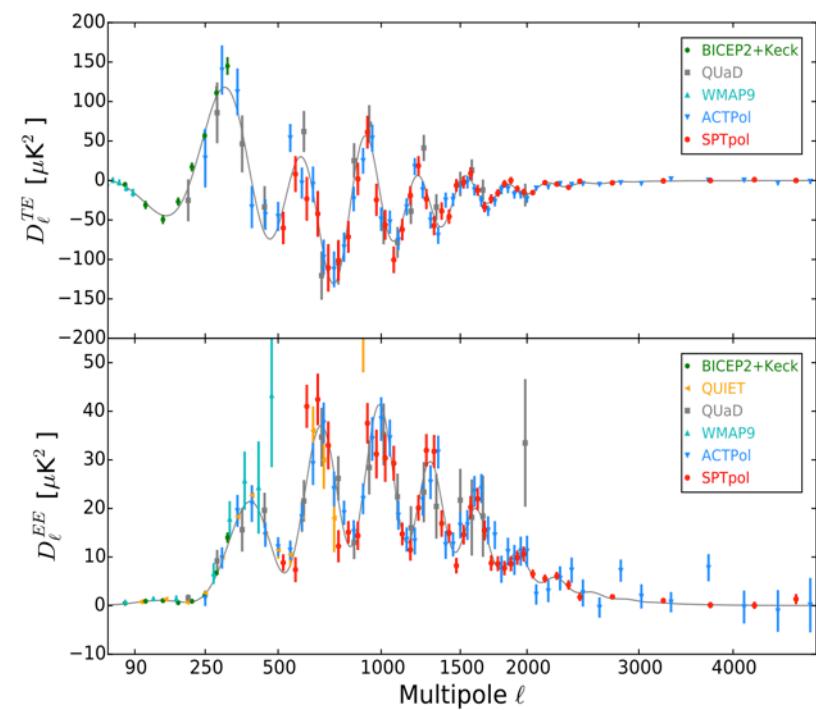




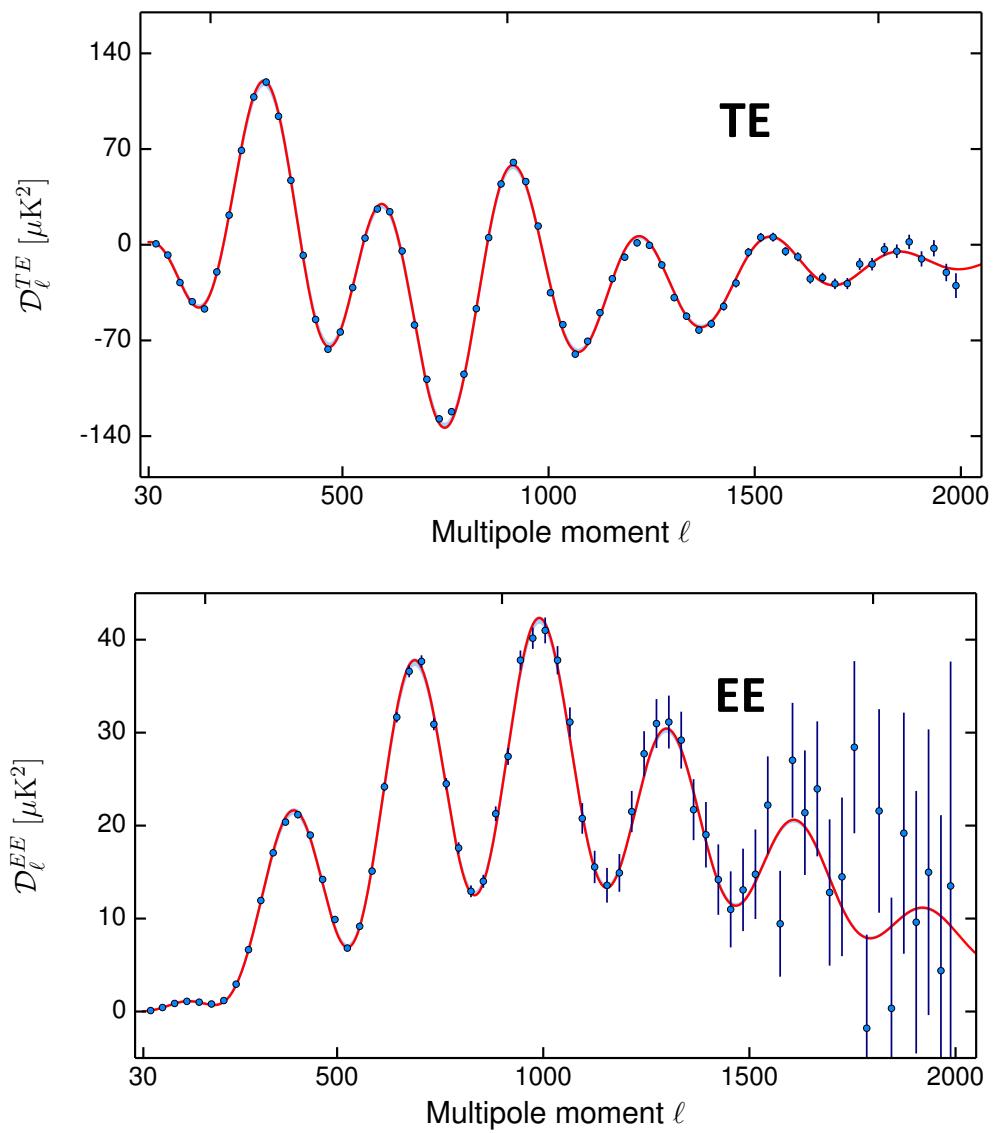


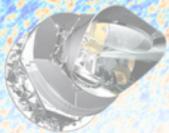
2015 Polarization power spectra

Pre-Planck measurements

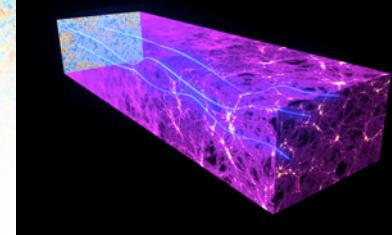


Planck 2015



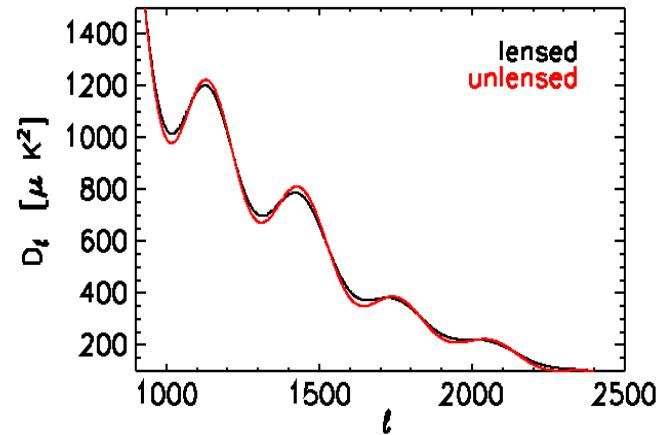


CMB lensing



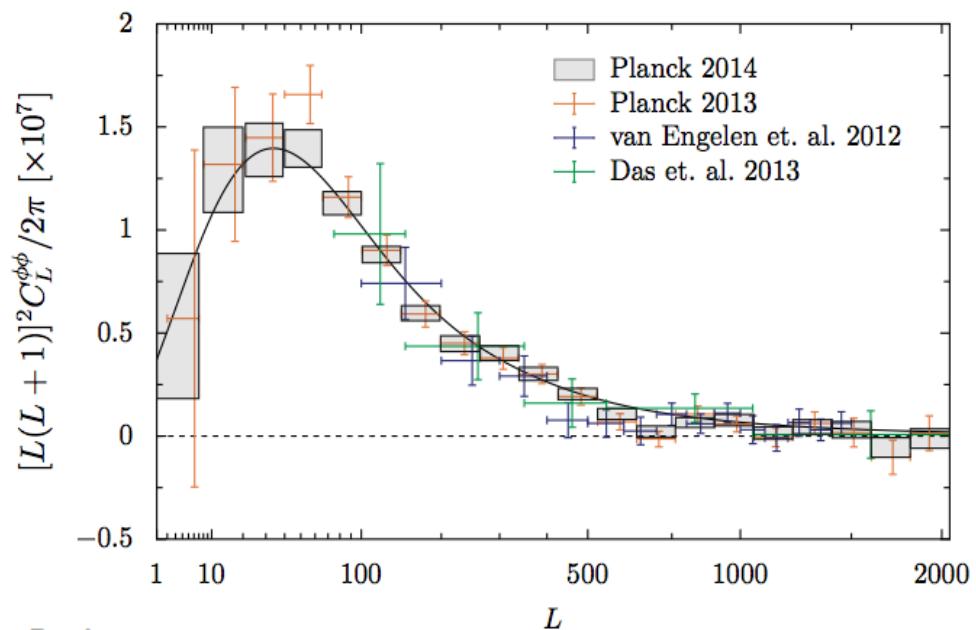
- 1) Modifies the angular power spectrum at high- l
(e.g. smooths the peaks/throughs)

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

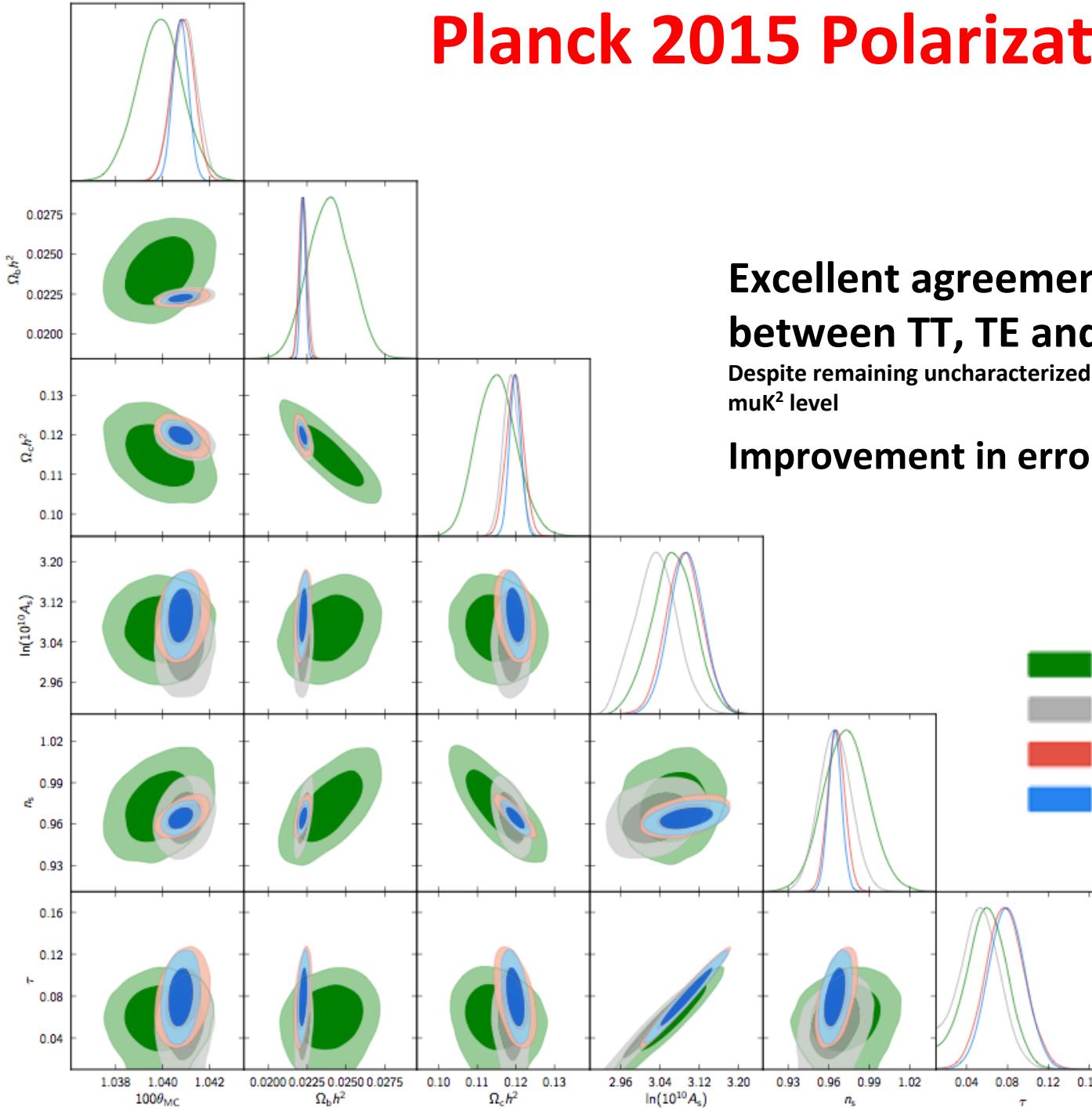


- 2) Breaks isotropy of the CMB.
Lensing potential reconstructed from the non-gaussian 4-point correlation function.

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



Planck 2015 Polarization at high-l



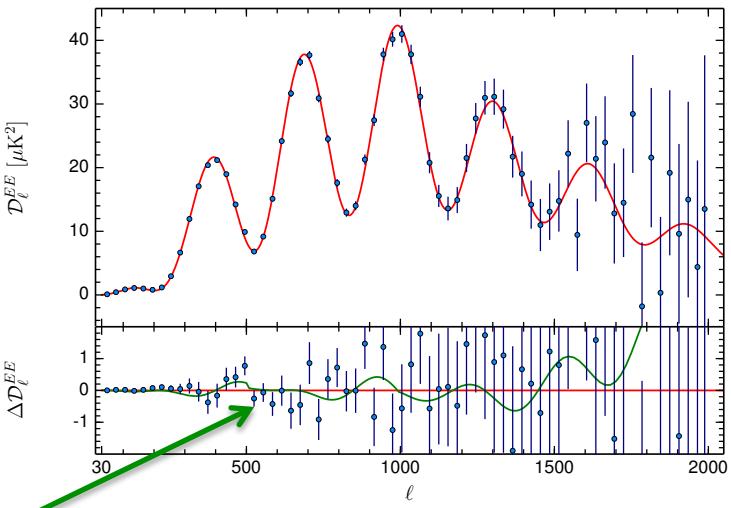
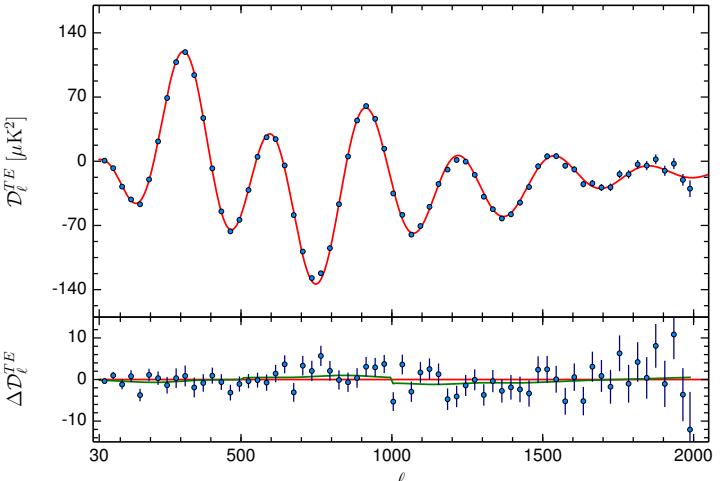
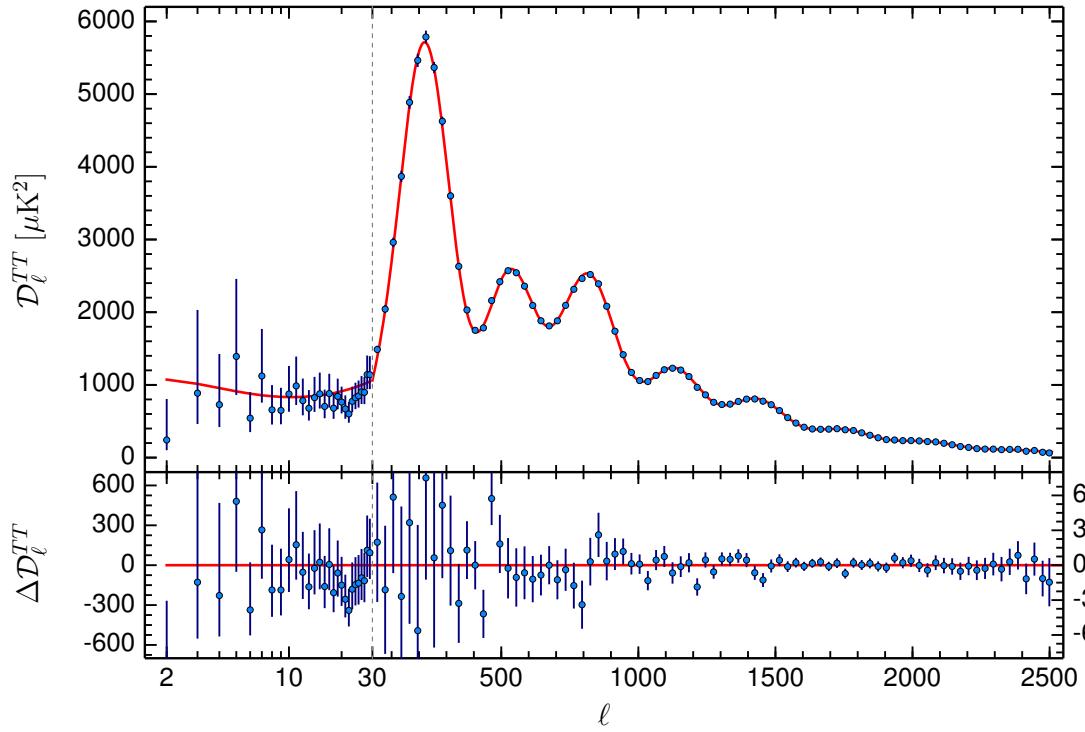
**Excellent agreement
between TT, TE and EE**

Despite remaining uncharacterized systematics in polarization at
 μK^2 level

Improvement in error bars up to 50%

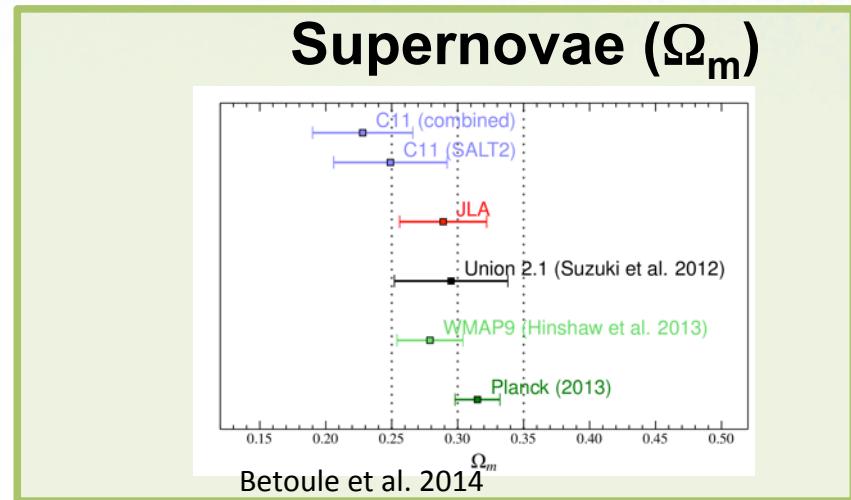
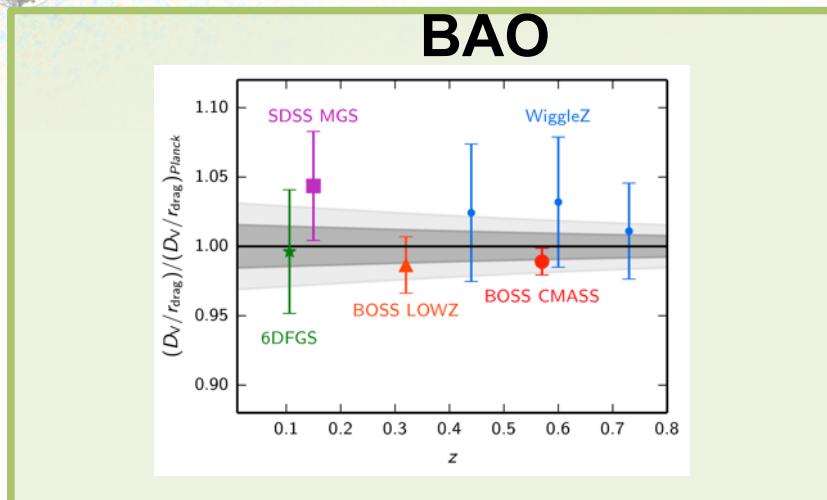
- █ *Planck EE+lowP*
- █ *Planck TE+lowP*
- █ *Planck TT+lowP*
- █ *Planck TT,TE,EE+lowP*

Λ CDM best fit

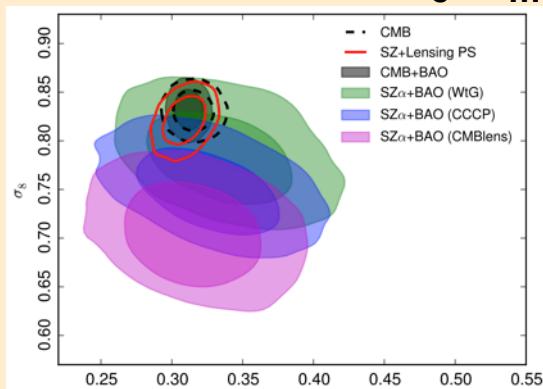


- Λ CDM is very good fit to the data
- Remaining systematics present in polarization spectra, possibly due to unaccounted beam mismatch.

Comparison with other datasets:

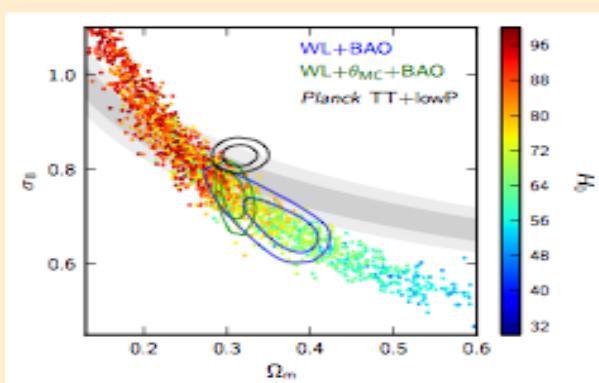


Cluster counts (σ_8 - Ω_m)



Planck collaboration XXIV

Weak Lensing (σ_8 - Ω_m)



Direct measurements H_0

$H_0 = 67.8 \pm 0.92$
(PlanckTT+lowP+lensing)

VS

$H_0 = 72.8 \pm 2.4$ [2 σ tension]
(Riess+11)

$H_0 = 70.6 \pm 3.3$ [1 σ tension]
(Efstathiou+14)

$H_0 = 74.3 \pm 2.6$ [2.5 σ tension]
(Freedman+12)
[in Km/s/Mpc]



Extensions of Λ CDM



Excellent agreement with Λ CDM!

Curvature:

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

$$\Omega_K = 0.000 \pm 0.005 \text{ (95\%)} \\ (\text{PlanckTT+lowP+Lensing+BAO})$$

Sum of neutrino masses:

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

$$\sum m_\nu < 0.23 \text{ eV} \\ (\text{PlanckTT+lowP+Lensing+ext})$$

Number of relativistic species:

Compatible with standard prediction $N_{\text{eff}} = 3.046$ with 3 active neutrinos

$$N_{\text{eff}} = 3.13 \pm 0.32 \\ (\text{PlanckTT+lowP})$$

Helium abundance

Good agreement with measurements of primordial abundances and BBN predictions

$$Y_{\text{P}}^{\text{BBN}} = 0.253 \pm 0.021 \\ (\text{PlanckTT+lowP})$$

Running of the scalar spectral index

Compatible with no running

$$\frac{dn_s}{d \ln k} = -0.0084 \pm 0.0082 \\ (\text{PlanckTT+lowP})$$



High-l Polarization further improves constraints!

Curvature:

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

$$\Omega_K = 0.000 \pm 0.004 \text{ (95\%)}$$

(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 prediction $N_{\text{eff}} = 3.046$ with 3 active neutrinos

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

(PlanckTT+lowP+TE+EE)

Helium abundance

Good agreement with measurements of primordial abundances and BBN predictions

$$Y_p^{\text{BBN}} = 0.251 \pm 0.014$$

(PlanckTT+lowP+TE+EE)

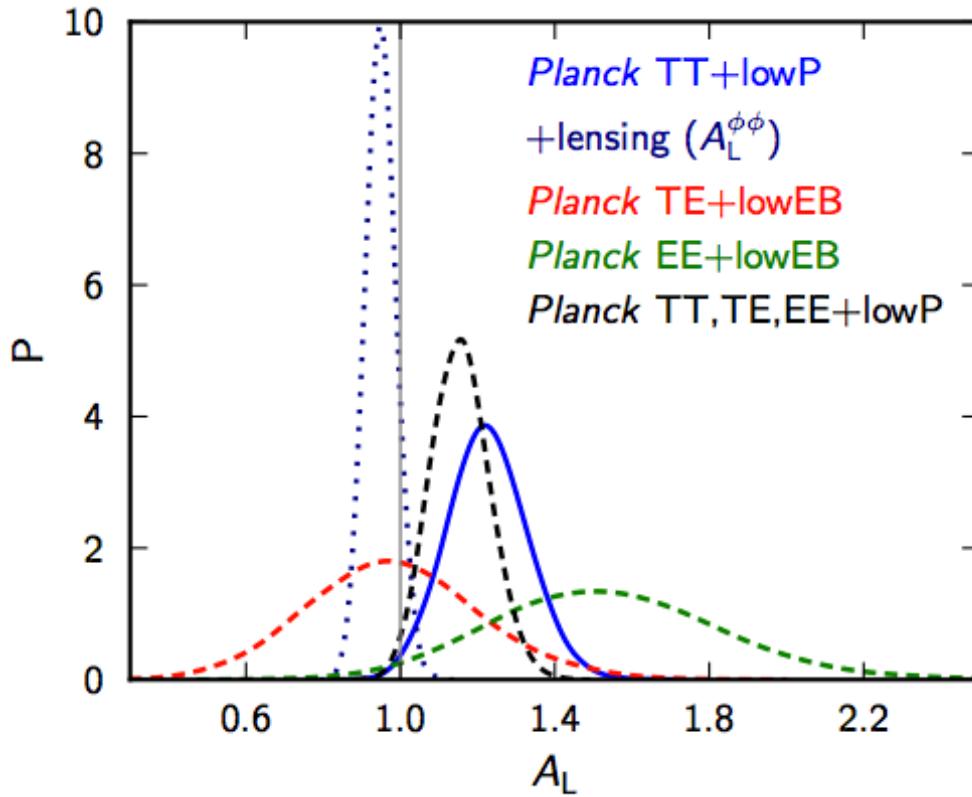
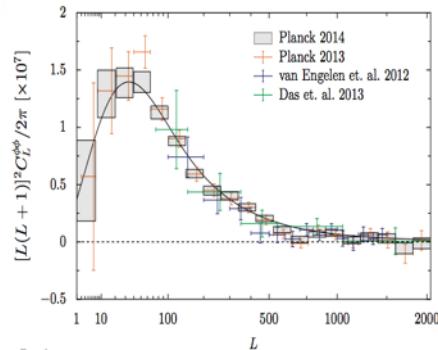
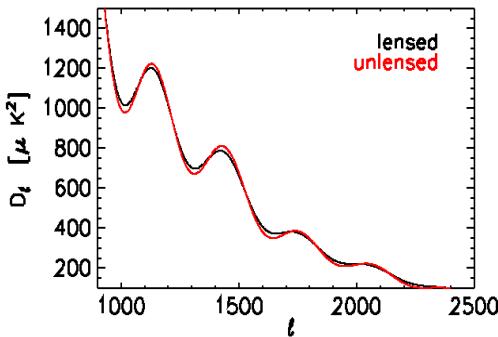
Running of the scalar spectral index

Compatible with no running

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

(PlanckTT+lowP+TE+EE)

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 which can provide a larger lensing amplitude in the power spectrum.**

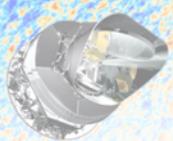


Small deviations of LCDM due to the preference of lensing

- 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

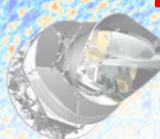
Parameter	TT	TT+lensing	TT+lensing+ext	
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	95% c.l.
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	

- 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.



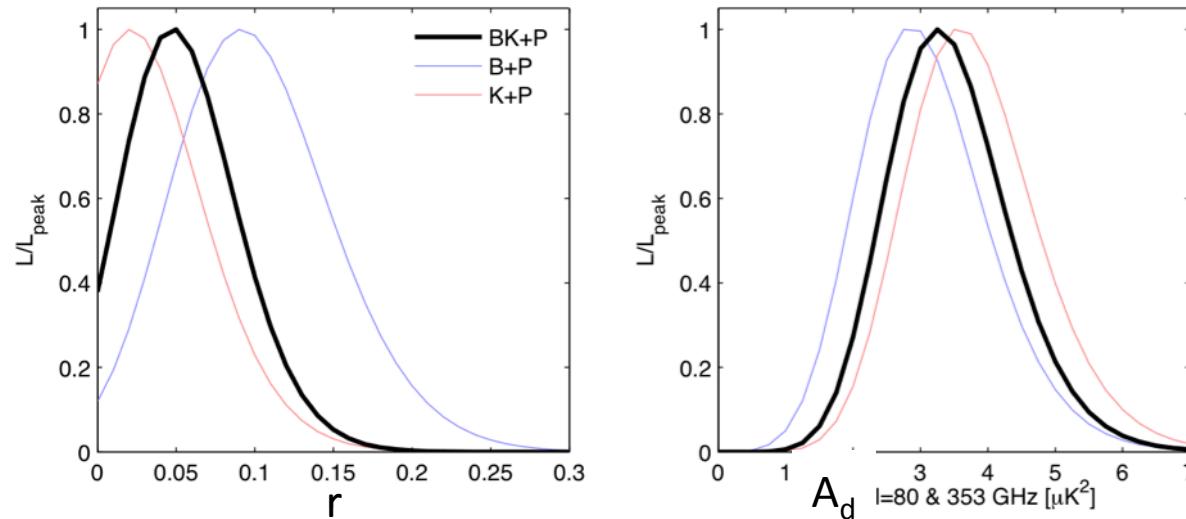
The BICEP story

- *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 than 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.

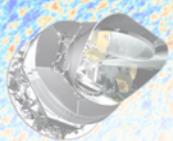


The Bicep2/Keck+Planck analysis

- 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) $I_d(\nu) \propto \nu^{\beta_d} B_\nu(T_d)$ $T_d = 19.6\text{ K}$ $\beta_d = 1.59 \pm 0.11$
- Sta



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



Current constraints

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

$$r_{0.05} < 0.09$$

BK+Planck+WMAP, **BB** alone

$$r_{0.05} < 0.12$$

Planck**TT**+lowP+lensing+BSH

$$r_{0.05} < 0.07$$

BK+Planck+WMAP, **BB** +
Planck**TT**+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.