The CMB as a probe of Reionization
Results from Planck

Marina Migliaccio
University of "Tor Vergata" & INFN, Rome, Italy

ASI/COSMOS Workshop on ΛCDM
28 – 29 May 2019, Univ. Rome Tor Vergata, Italy

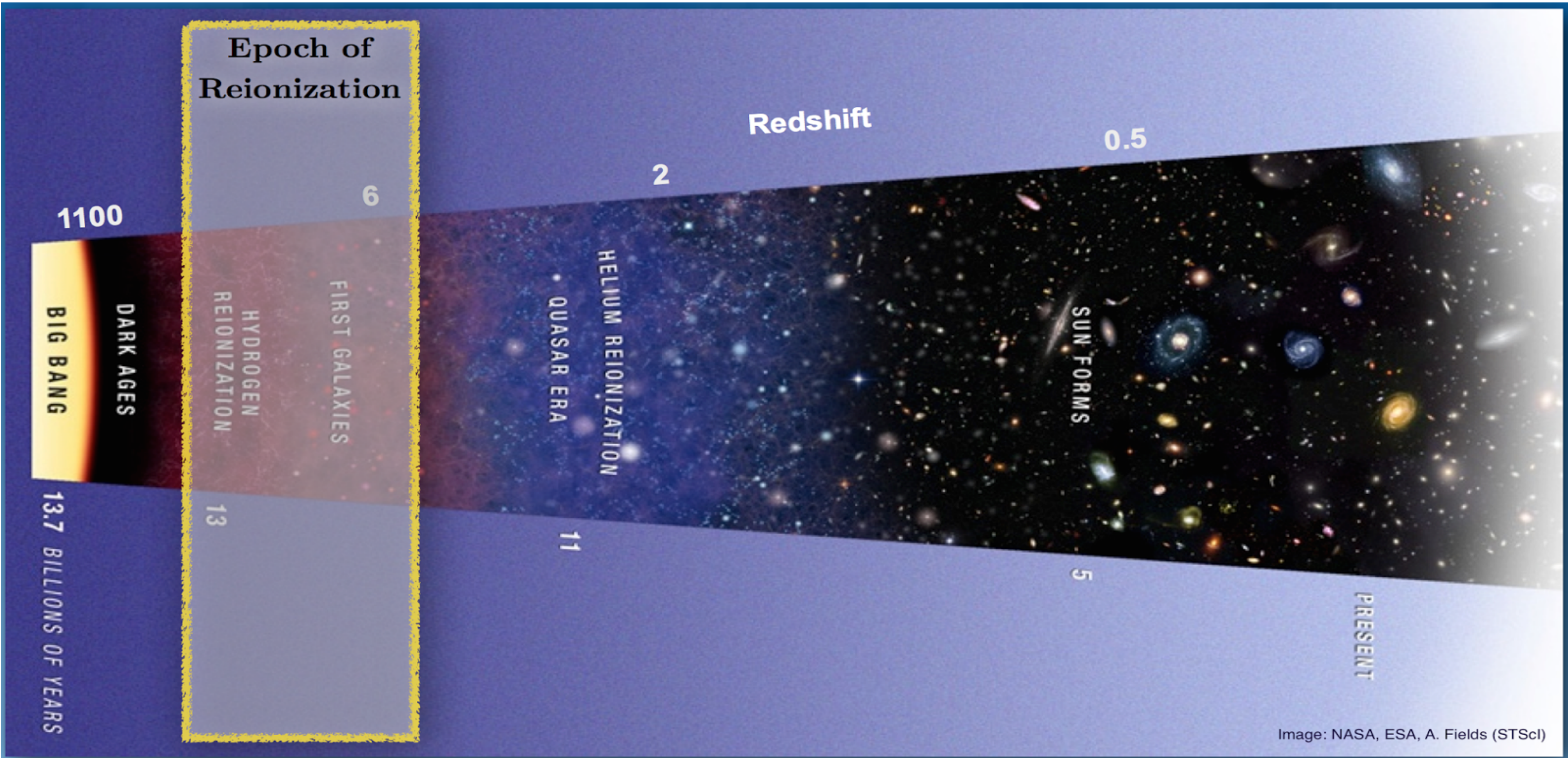
Reionization

The second major change in the ionization state of hydrogen in the universe

Empirical, analytical and numerical models

Increasingly deep astrophysical observations

Cosmic Microwave Background measurements



Imprints in the CMB

Reionization -> newly freed electrons

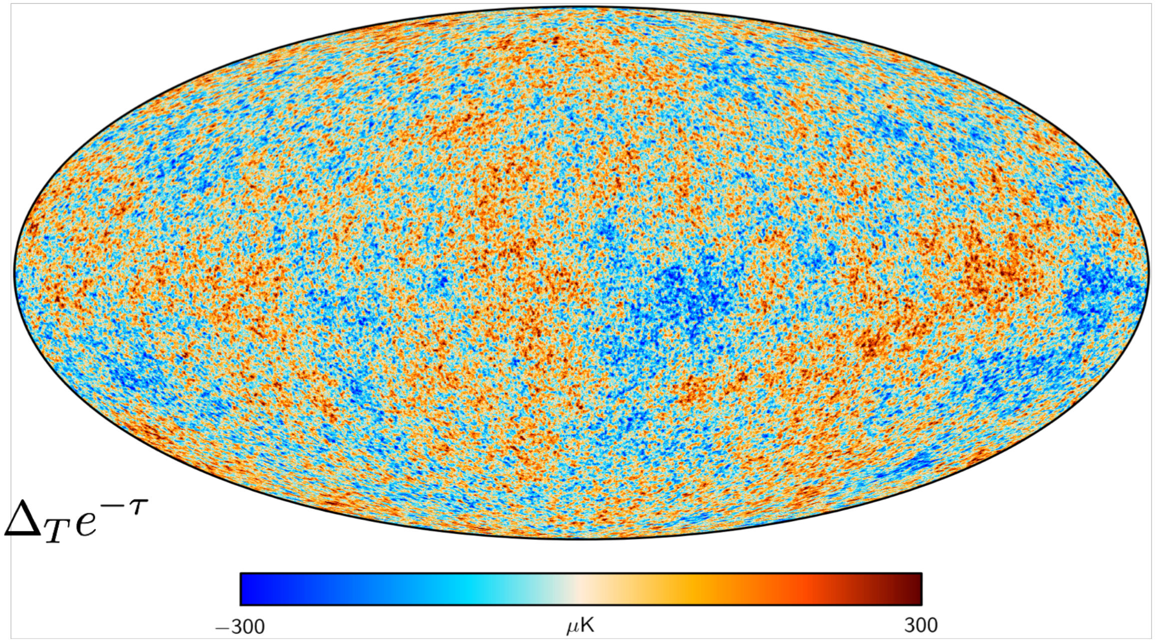
1. Temperature Anisotropies: suppression of fluctuations at small angular scales
2. Polarization: suppression of fluctuations at small angular scales plus generation of new polarization anisotropy on large angular scales
3. Kinetic Sunyaev-Zel'dovich (kSZ) Effect: secondary temperature anisotropy on small angular scales due to Doppler-shift of photons scattering off electrons moving in bulk flows (homogeneous + patchy)

The main physical quantity controlling the impact on the CMB is the Thomson scattering optical depth

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T c\, dt'$$

Currently the ΛCDM parameter with the largest associated uncertainty (~ 15%)

Temperature Anisotropies

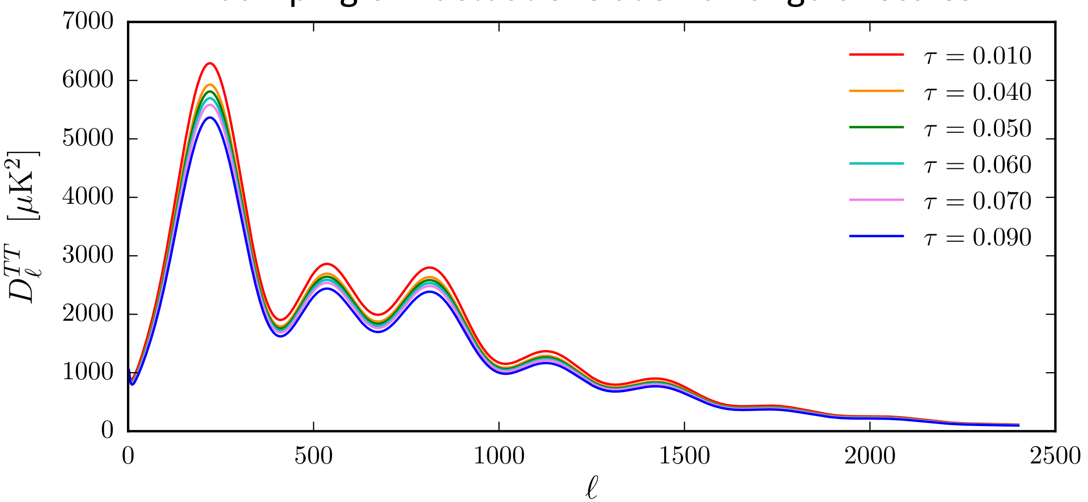


$$\Delta_T \to \Delta_T e^{-\tau}$$

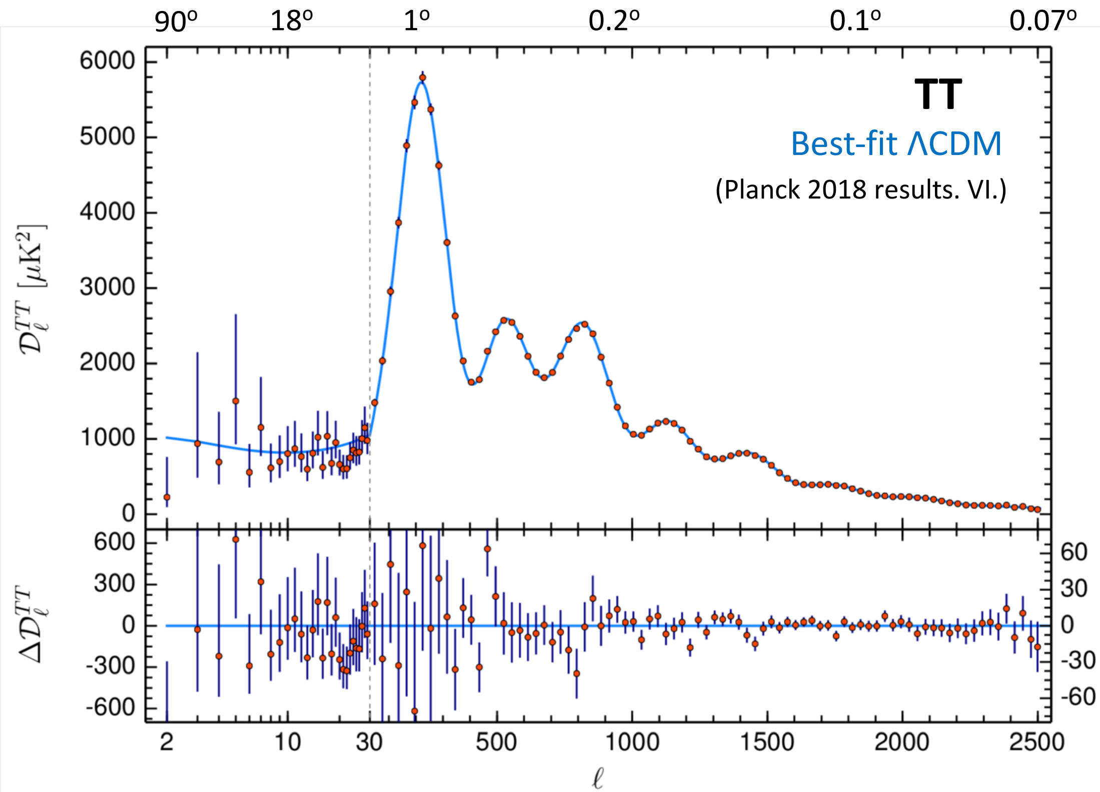
$$C_\ell^{TT} \propto A_s e^{-2\tau}$$

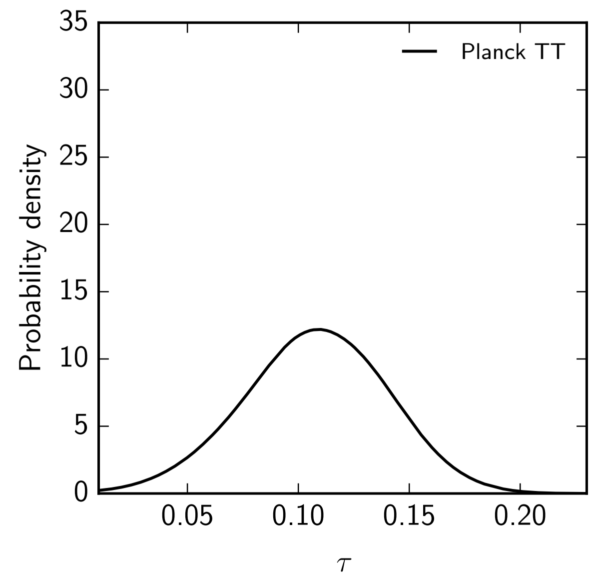
τ degenerate with other cosmological parameters, especially A_s, but also n_s, $\sigma_8, \Sigma m_\nu$, … and foregrounds.

damping of fluctuations at small angular scales



Temperature Anisotropies





TT power spectrum constrains the combination $A_s\, e^{-2\tau}$ at sub-% level !

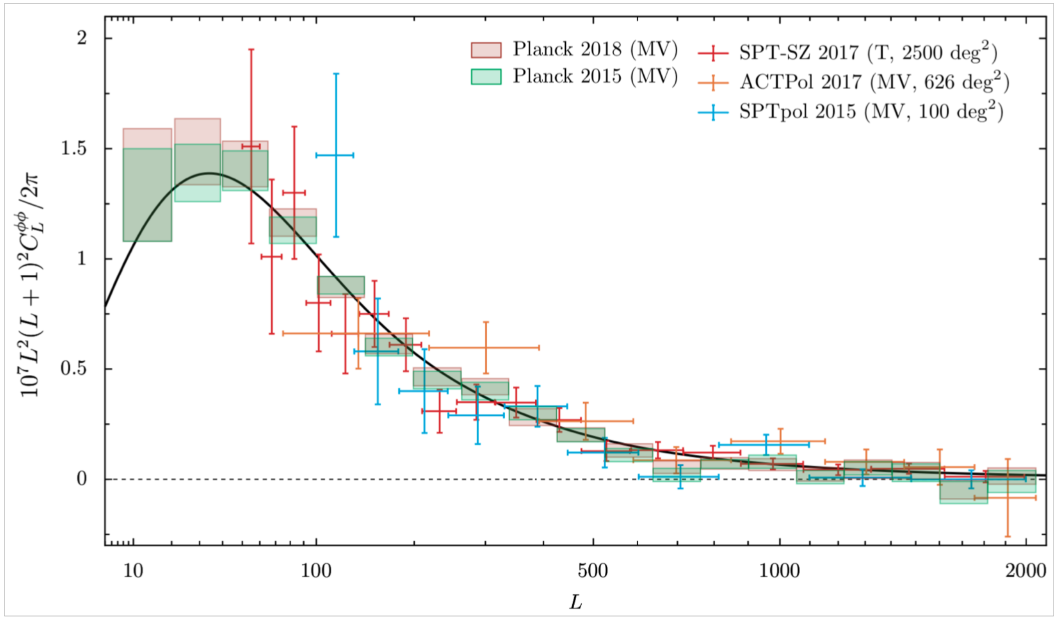
$10^9\, A_s\, e^{-2\tau} = 1.873\ \pm 0.016$

ΛCDM is an excellent fit to Planck data.

Cosmic Variance Limited up to $\ell \simeq 1600$, sky fractions ranging from 86% to 40%. Seven peaks measured with high signal-to-noise.

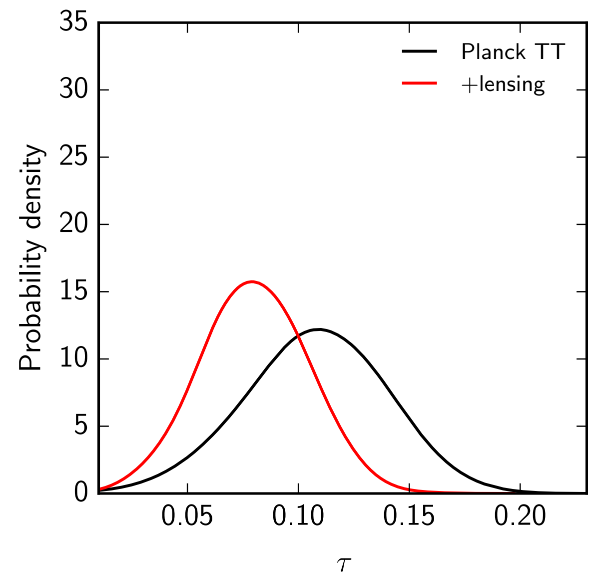
Temperature Anisotropies

CMB Gravitational Lensing



Clean probe of the clustering of matter integrated across a wide range of redshifts along the line of sight.

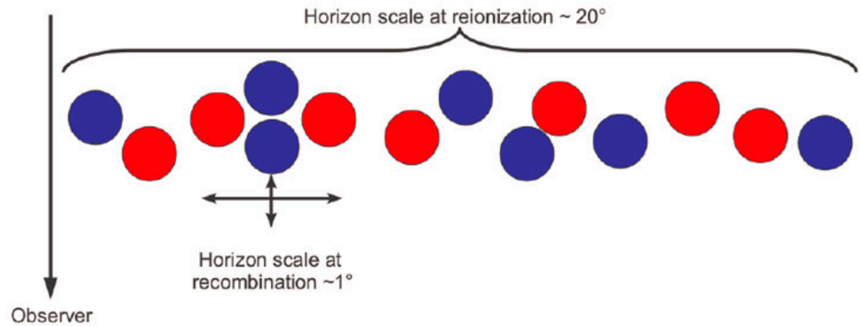
Deflections ~ 2 arcmin, coherent over 2 degree scales. Need **high angular resolution, low-noise observations** of the CMB. **Planck provides a 40-sigma detection!** (Planck 2018 results. VIII.)

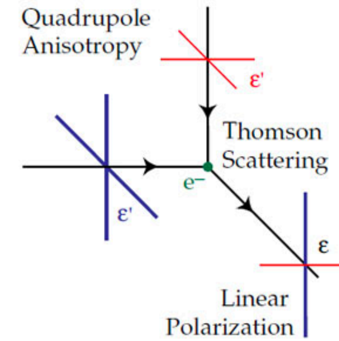


Breaks degeneracy with A_s

τ = 0.080 ± 0.025 (68% CL)

Polarization

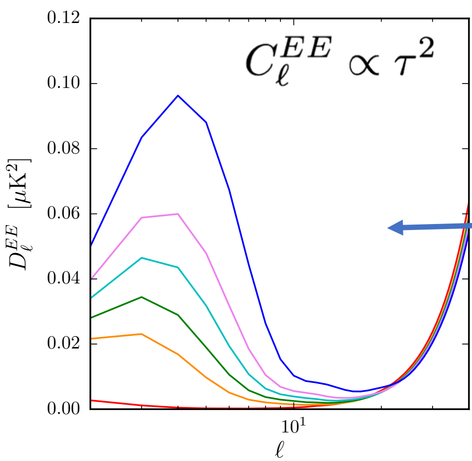


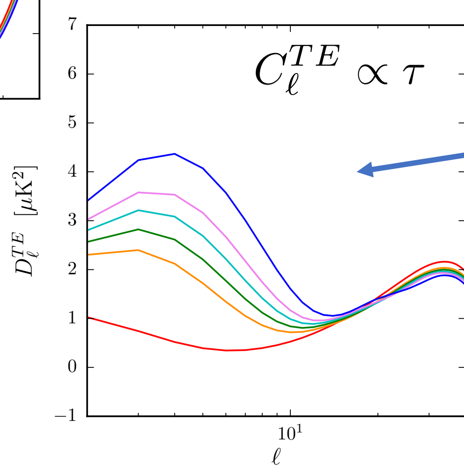


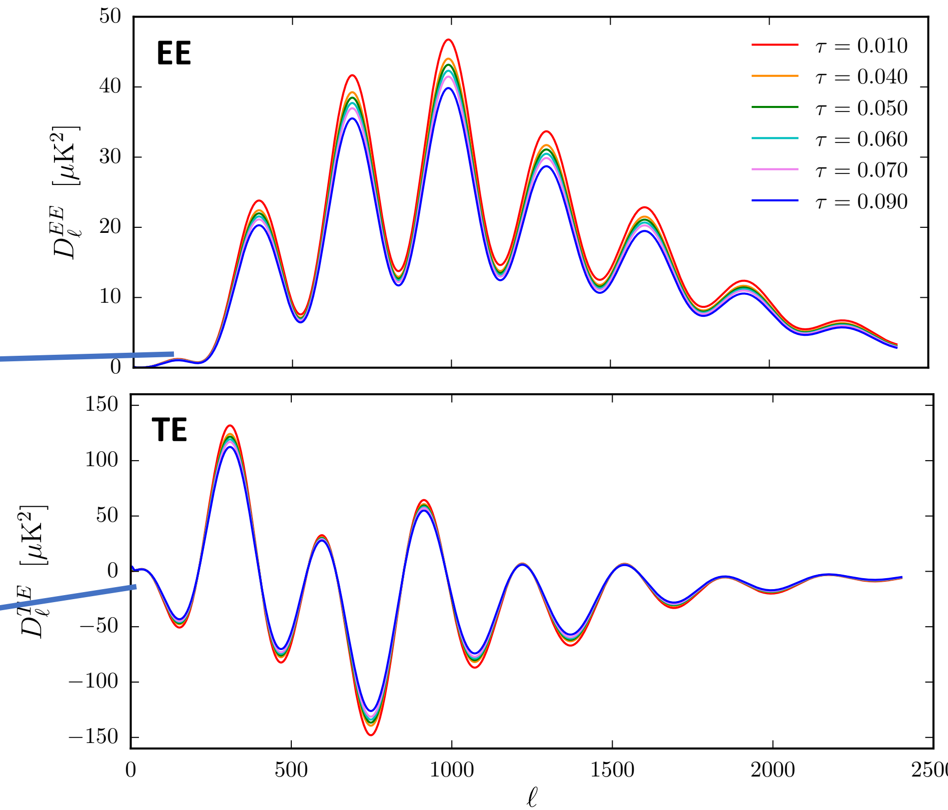
(Credit: S. Zaroubi)

<u>*Bump*</u> at low-ℓ in angular power spectra

Amplitude is a *direct* measure of τ.
Location tells you when.
Shape depends on ionization history.

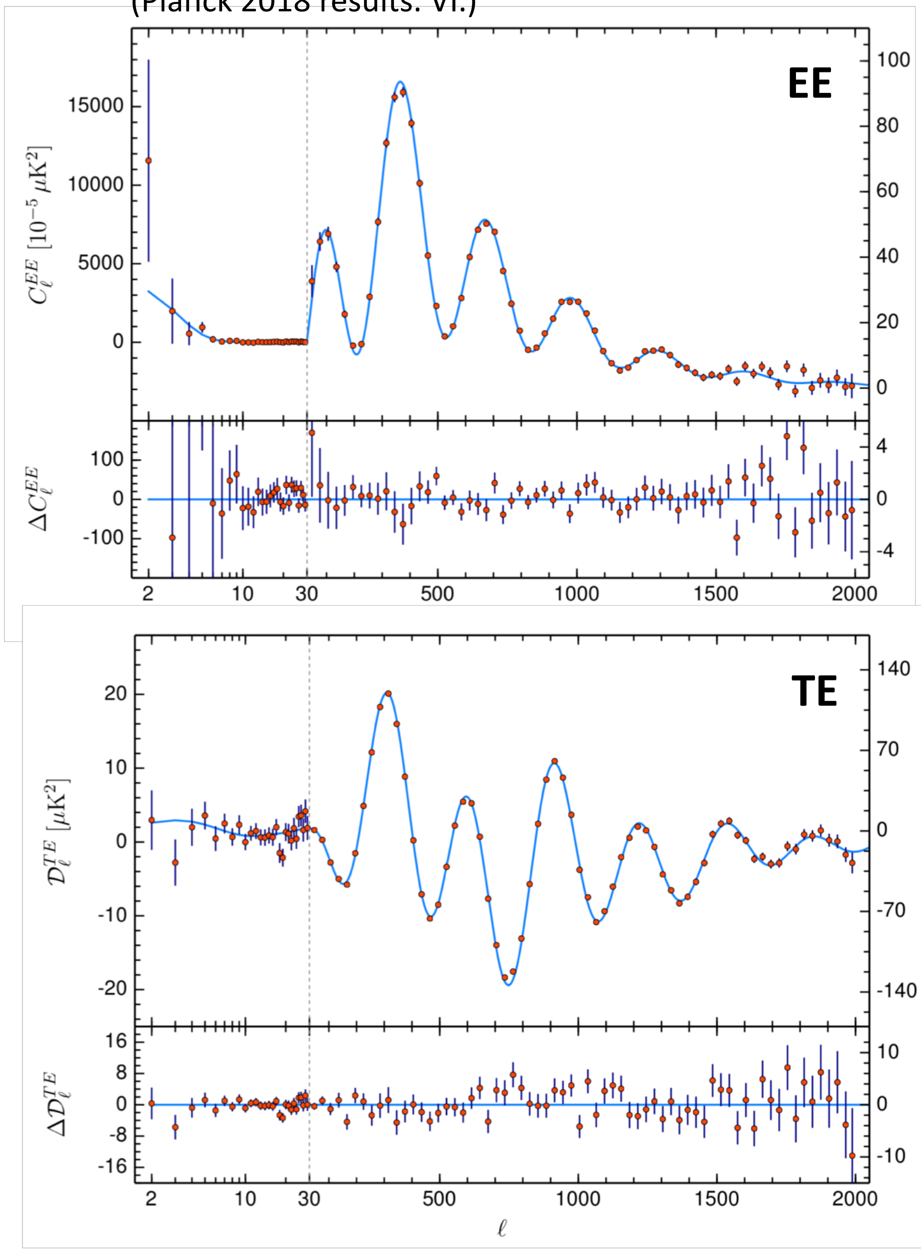






Polarization

(Planck 2018 results. VI.)

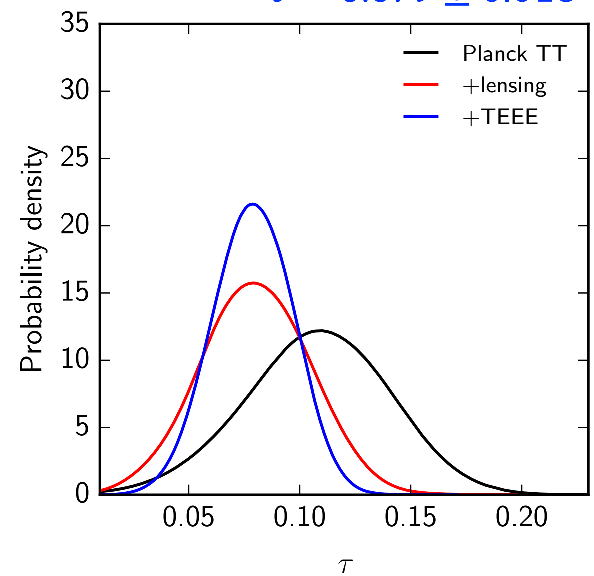


Adding polarization at small angular scales

ΛCDM is an excellent fit to the data.

Improved characterization of temperature-to-polarization leakage and polarization efficiencies w.r.t. 2015 data release.

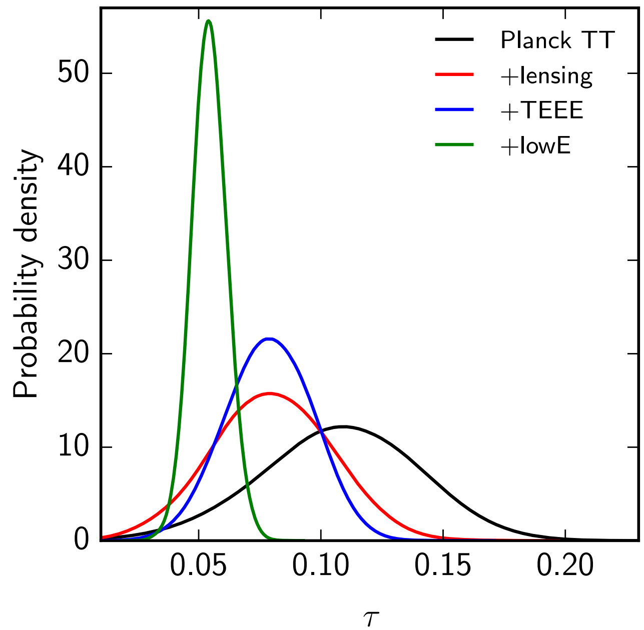
$\boldsymbol{\tau} = 0.079 \pm 0.018$



Overall tighter constraints on the cosmological parameters. Consistency check as small scale foregrounds are less important than in TT.

Large Scale Polarization

$$\tau = 0.0544 \pm 0.0073$$



- Large scale polarization has little dependence on other cosmological parameters and currently gives the tightest constraints on τ

- Consistency with lensing, which however is more model dependent. Different measurements, very different systematics and foregrounds → Important robustness test.

Large Scale Polarization

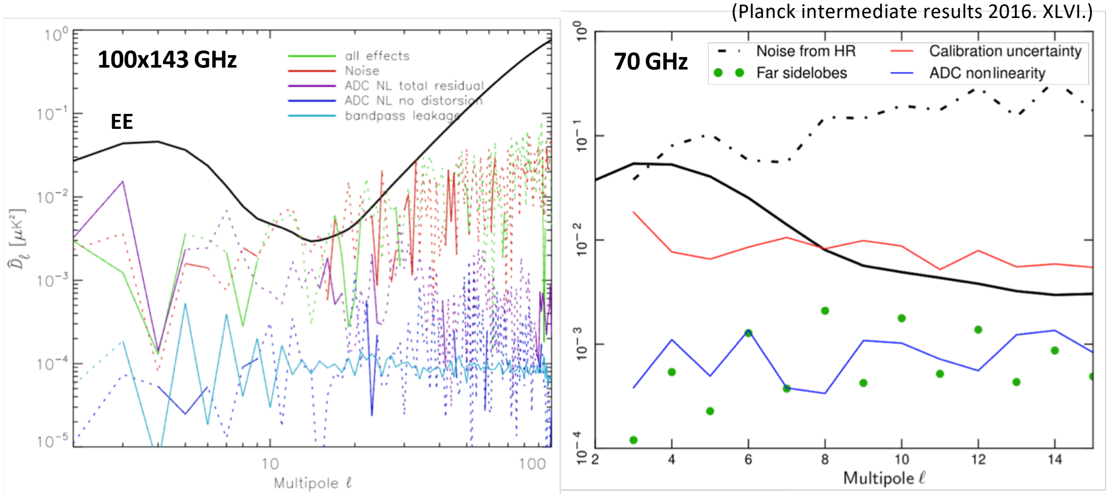
Measuring Polarization is challenging

- Large angular scales are best measured from space
- Signal ~ 100 times weaker than temperature
- Instrumental noise and foregrounds need to be characterized with high accuracy
- Differential measurement
- Requires exquisite control of systematic effects

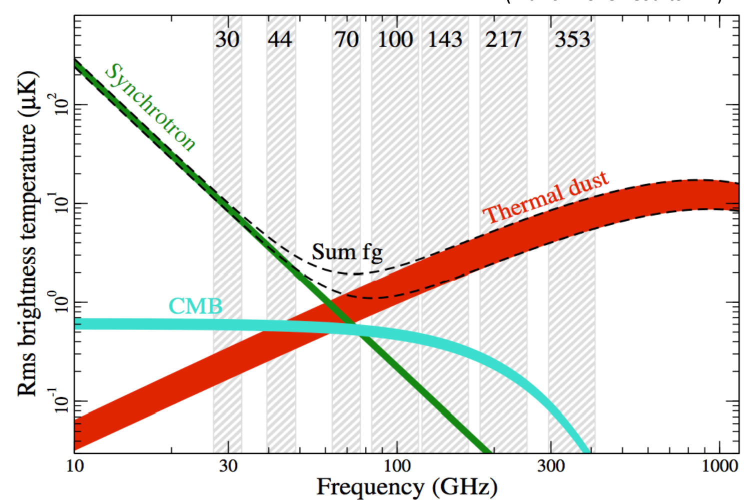
Tackling this challenge with Planck

- Full sky coverage
- Broad frequency range to model foregrounds
- E2E simulations to model noise and systematics
- Application of different data analysis techniques
- Complementarity between the Low Frequency Instrument (LFI) and High Frequency Instrument (HFI)

(Planck intermediate results 2016. XLVI.)



(Planck 2015 results. IX.)



Large Scale Polarization

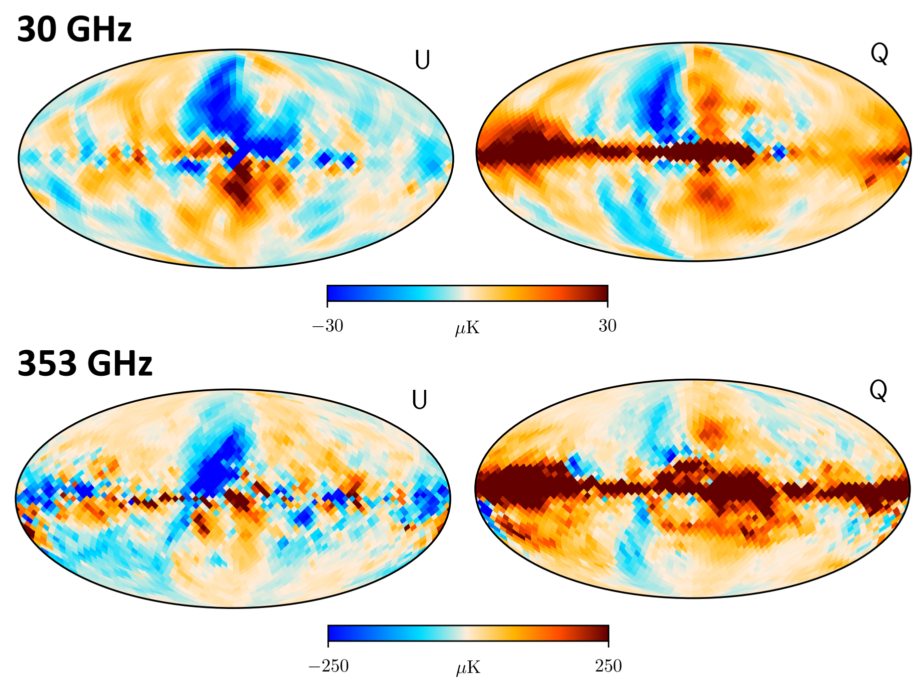
Planck LFI and HFI low-ℓ likelihoods

1) Real-space template fitting procedure to mitigate foreground contamination

Template cleaning of maps ***m*** = [Q, U] for the channels= 70, 100, 143 GHz

$$\mathbf{m} = \frac{1}{1-\alpha-\beta}\left(\mathbf{m}_{ch} - \alpha\mathbf{m}_{30} - \beta\mathbf{m}_{353}\right)$$

30 GHz: tracer of synchrotron emission
353 GHz: tracer of thermal dust emission



Foreground coefficients by minimising, on ~ 70% of the sky:

$$\chi^2 = (1-\alpha-\beta)^2\mathbf{m}^{\mathrm{T}}\mathbf{C}_{\mathrm{S+N}}^{-1}\mathbf{m}$$

$$\mathbf{C}_{\mathrm{S+N}} \equiv (1-\alpha-\beta)^2\langle\mathbf{m}\mathbf{m}^{\mathrm{T}}\rangle$$
$$= (1-\alpha-\beta)^2\mathrm{S}(C_\ell^{\mathrm{th}}) + \mathrm{N}_{ch} + \alpha^2\mathbf{N}_{30} + \beta^2\mathbf{N}_{353}$$

Noise covariance of the cleaned polarized maps

$$\mathbf{N} = \frac{1}{(1-\alpha-\beta)^2}\left(\mathbf{N}_{ch} + \alpha^2\mathbf{N}_{30} + \beta^2\mathbf{N}_{353} + \sigma_\alpha^2\mathbf{m}_{30}\mathbf{m}_{30}^T + \sigma_\beta^2\mathbf{m}_{353}\mathbf{m}_{353}^T\right)$$

Large Scale Polarization

Planck LFI low-ℓ likelihood

2) Pixel-based Gaussian likelihood for *cleaned* 70GHz temperature and polarization maps used to estimate cosmological parameters.

$$\mathcal{L}(C_\ell) = \mathcal{P}(\boldsymbol{m}|C_\ell) = \frac{1}{(2\pi)^{N/2}|\mathsf{M}|^{1/2}} \exp\left(-\frac{1}{2}\boldsymbol{m}^\mathsf{T}\,\mathsf{M}^{-1}\boldsymbol{m}\right)$$

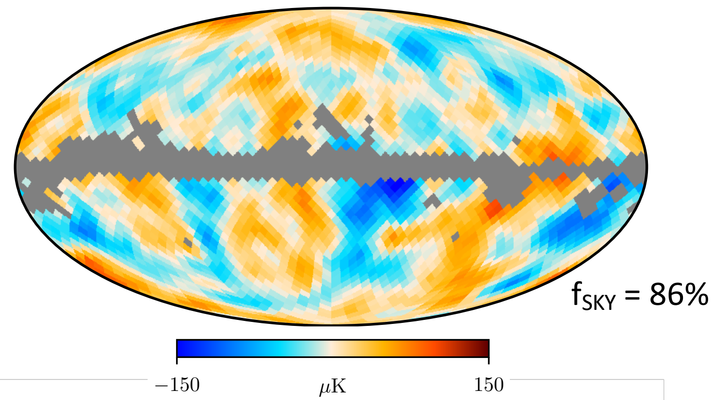
Includes complete information on TEB, but requires accurate determination of the noise covariance matrices.

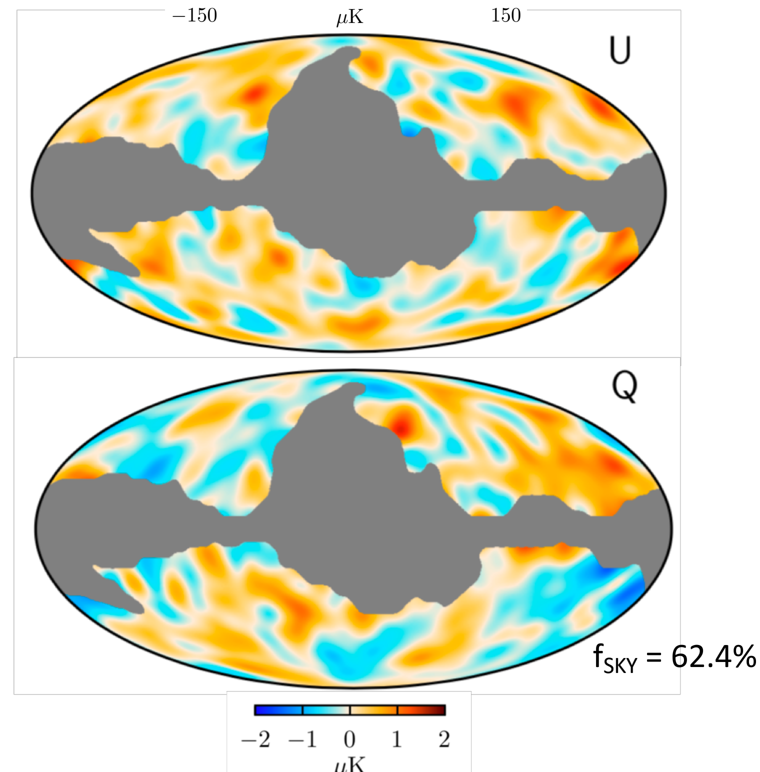
(Planck 2018 results. V. in prep)

Parameter	ΛCDM	ΛCDM + r
$\ln(10^{10}A_s)$	2.965 ± 0.055	$2.70^{+0.23}_{-0.13}$
τ	0.063 ± 0.020	0.064 ± 0.019
$r_{0.002}$	–	≤ 1.7
$A_s e^{-2\tau}$	$0.171^{+0.086}_{-0.087}$	$1.33^{+0.21}_{-0.26}$

Fixing all the other cosmological parameters

Commander Temperature Solution

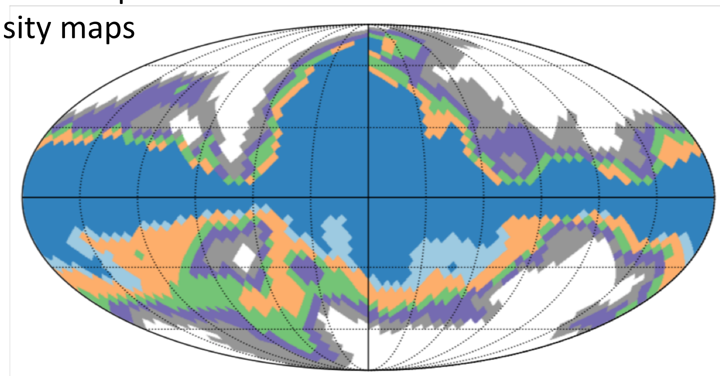


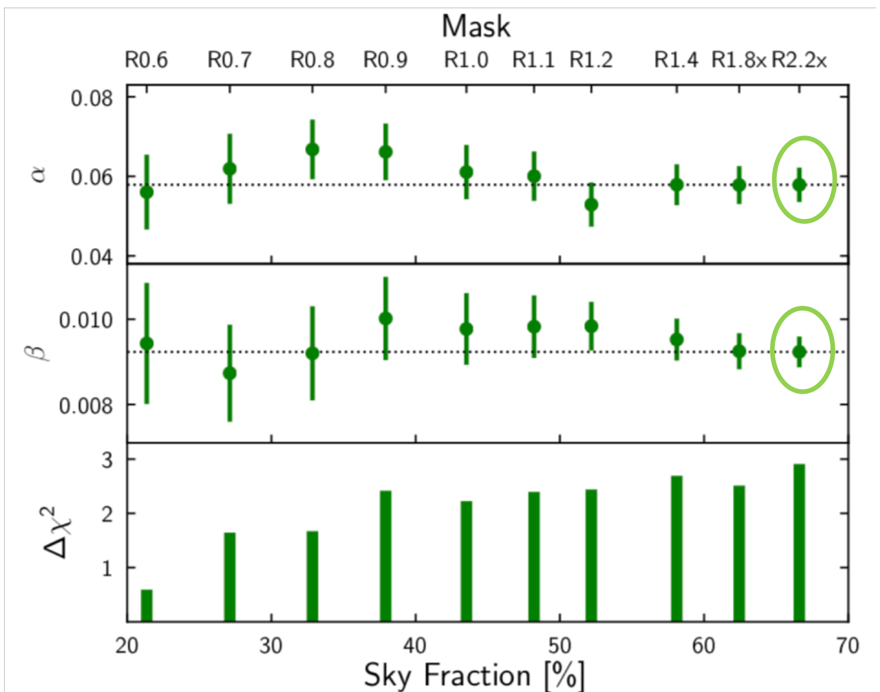


Large Scale Polarization

Planck LFI low-ℓ likelihood

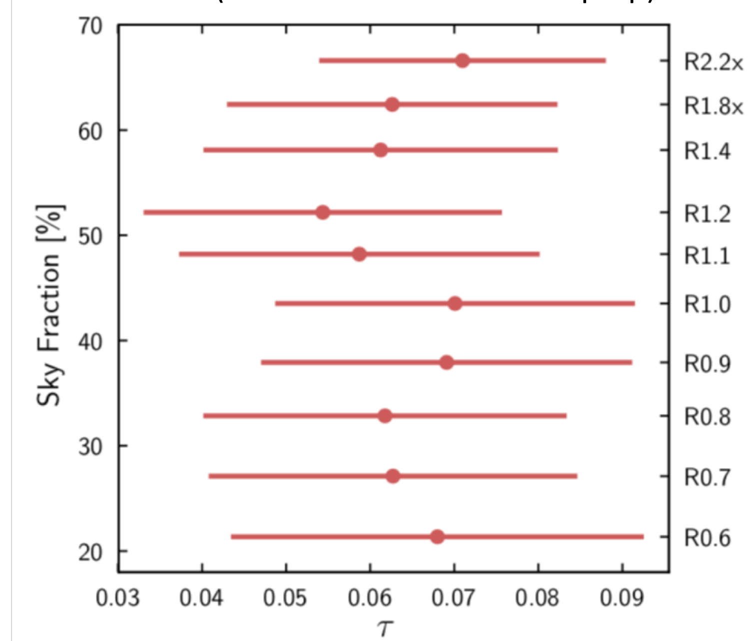
Masks built thresholding 30 GHz and 353 GHz polarization intensity maps





Robustness of results against mask choices

(Planck 2018 results. V. in prep)



Shifts of τ values measured on different masks are consistent with expectations from realistic MC simulations (noise + foregrounds + CMB) analysed with the template fitting and likelihood pipeline.

Large Scale Polarization

Planck HFI low-ℓ likelihood

2) **Baseline Planck 2018 low-ℓ polarization likelihood** based on the lowest HFI frequencies:

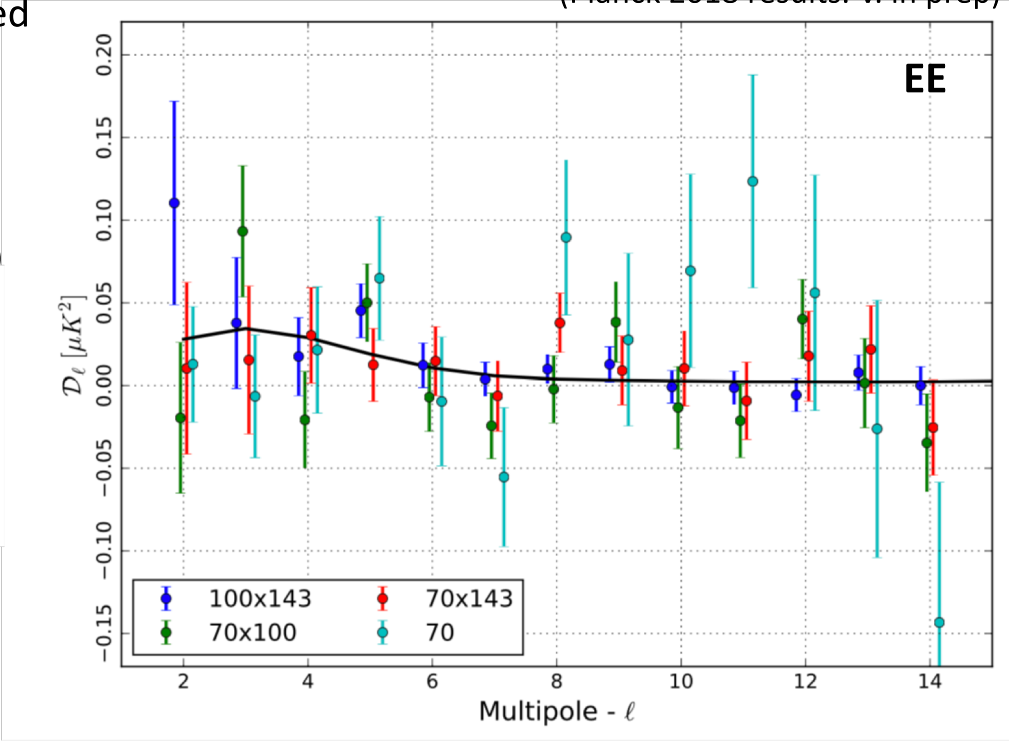
- E-mode QML 100 x 143 GHz cross power spectrum on 50% of the sky.
- Residual systematics at low-ℓ prevent the use of a pixel based likelihood.
- Likelihood modelled from full end-to-end simulations (CMB + noise + systematics).
- TE and TT-EE, TT-TE, TE-EE are not included in the likelihood.

HFI LowE 2018 (Planck 2018 results. V. in prep)

Parameter	ΛCDM	ΛCDM + r
$\ln(10^{10}A_s)$	2.924 ± 0.052	$2.863^{+0.089}_{-0.062}$
τ	0.0506 ± 0.0086	0.0503 ± 0.0087
$r_{0.002}$	–	≤ 0.41
$A_s e^{-2\tau}$	$1.685^{+0.083}_{-0.091}$	$1.59^{+0.11}_{-0.13}$

Fixing all the other cosmological parameters

(Planck 2018 results. V. in prep)

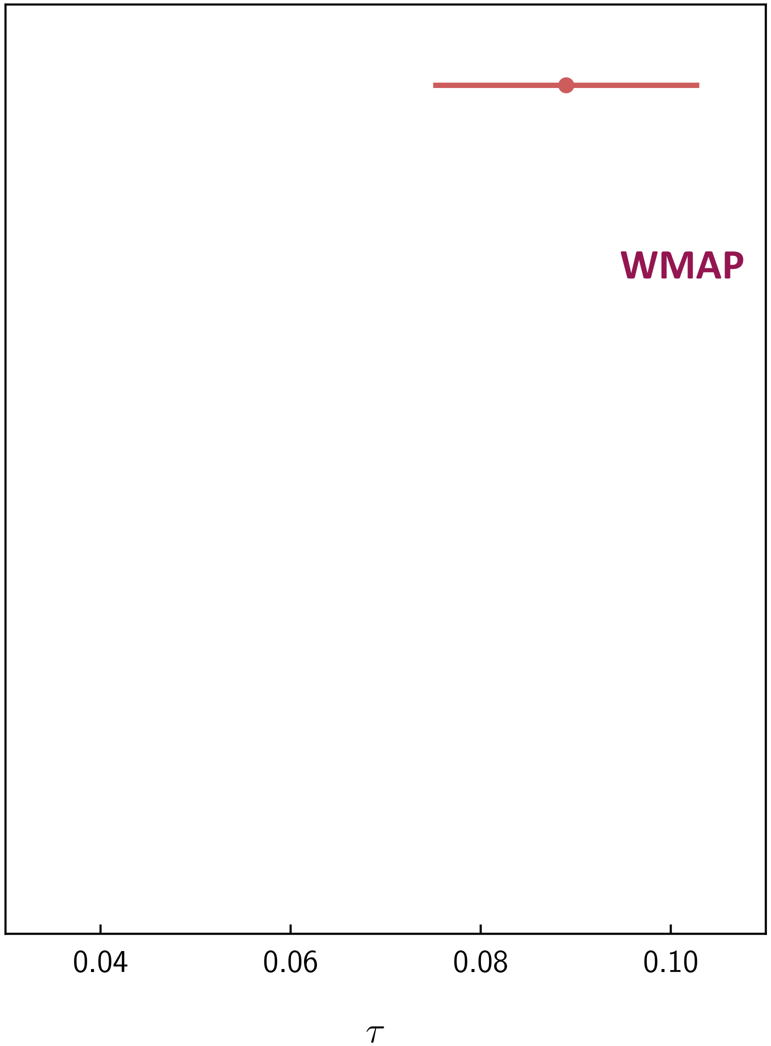


Large Scale Polarization: "Recent" history of τ measurements

Improved measurements, together with increased systematics and foregrounds control, resulted in a trend towards lower τ values.

WMAP 9yrs
(Hinshaw+ 2013)

$\tau = 0.089 \pm 0.014$

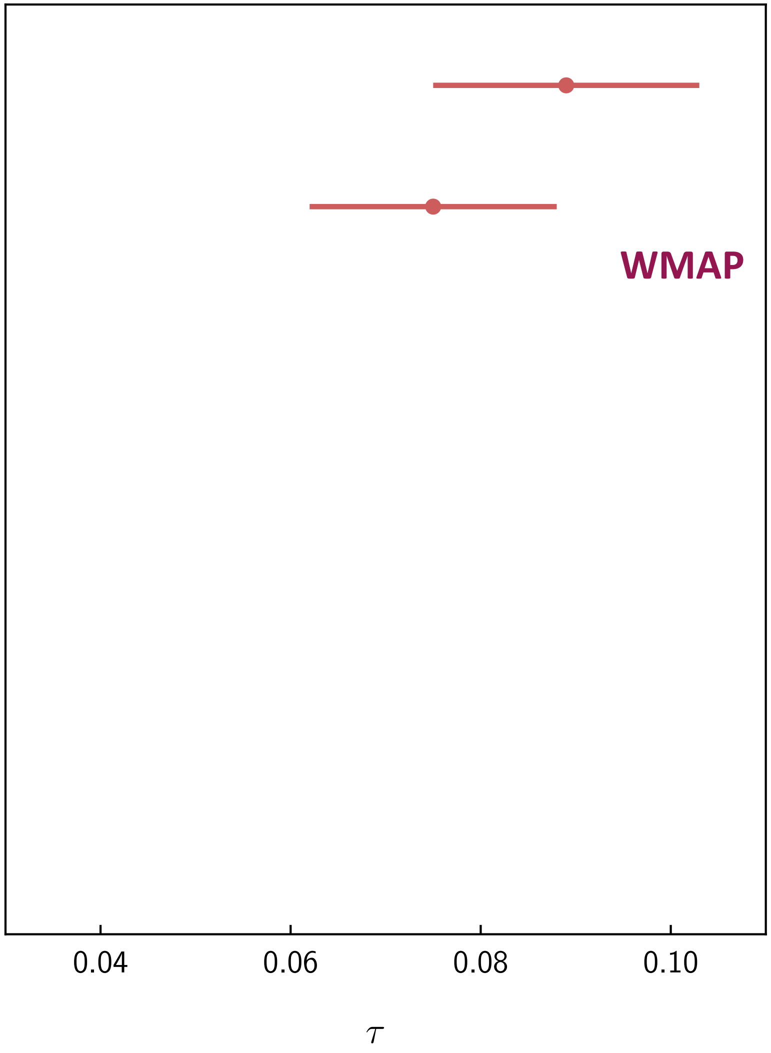


Large Scale Polarization: “Recent” history of τ measurements

Improved measurements, together with increased systematics and foregrounds control,
resulted in a trend towards lower τ values.

WMAP 9yrs
(Hinshaw+ 2013)
$\tau = 0.089 \pm 0.014$

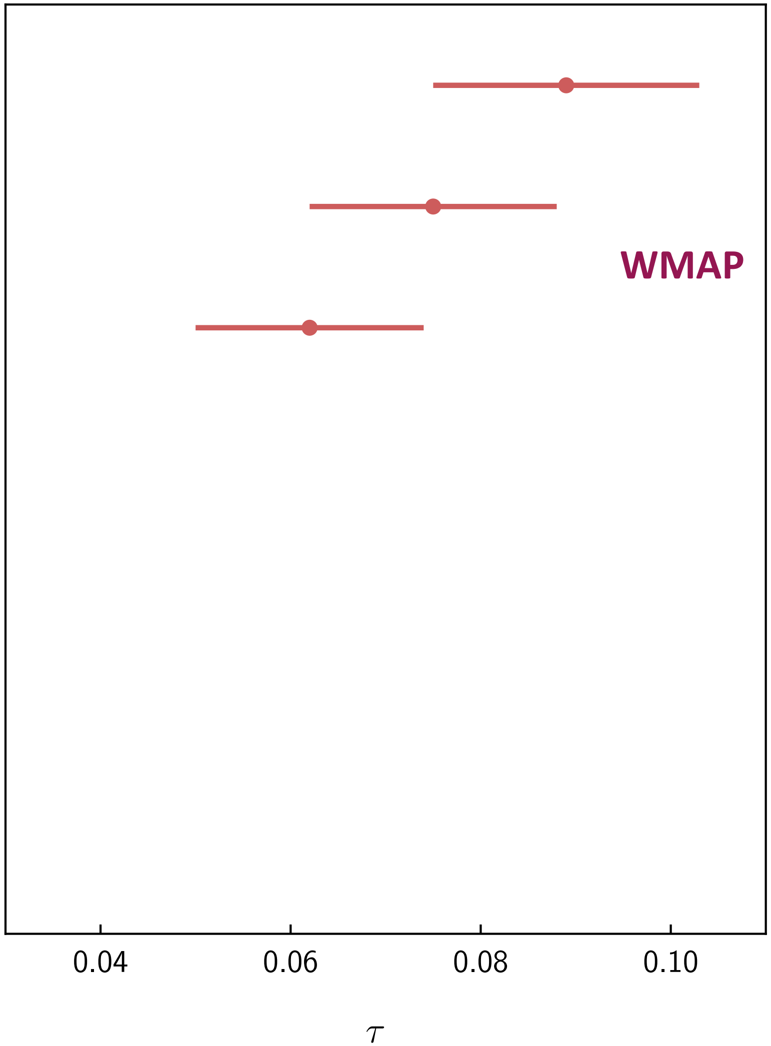
WMAP 9yrs + Planck 353 GHz
(Planck 2013 results XVI)
$\tau = 0.075 \pm 0.013$



Large Scale Polarization: “Recent” history of τ measurements

Improved measurements, together with increased systematics and foregrounds control, resulted in a trend towards lower τ values.

WMAP 9yrs (Hinshaw+ 2013)	$\tau = 0.089 \pm 0.014$
WMAP 9yrs + Planck 353 GHz (Planck 2013 results XVI)	$\tau = 0.075 \pm 0.013$
WMAP 9yrs + Planck 353 GHz (Planck 2018 results V in press)	$\tau = 0.062 \pm 0.012$



Large Scale Polarization: "Recent" history of τ measurements

Improved measurements, together with increased systematics and foregrounds control, resulted in a trend towards lower τ values.

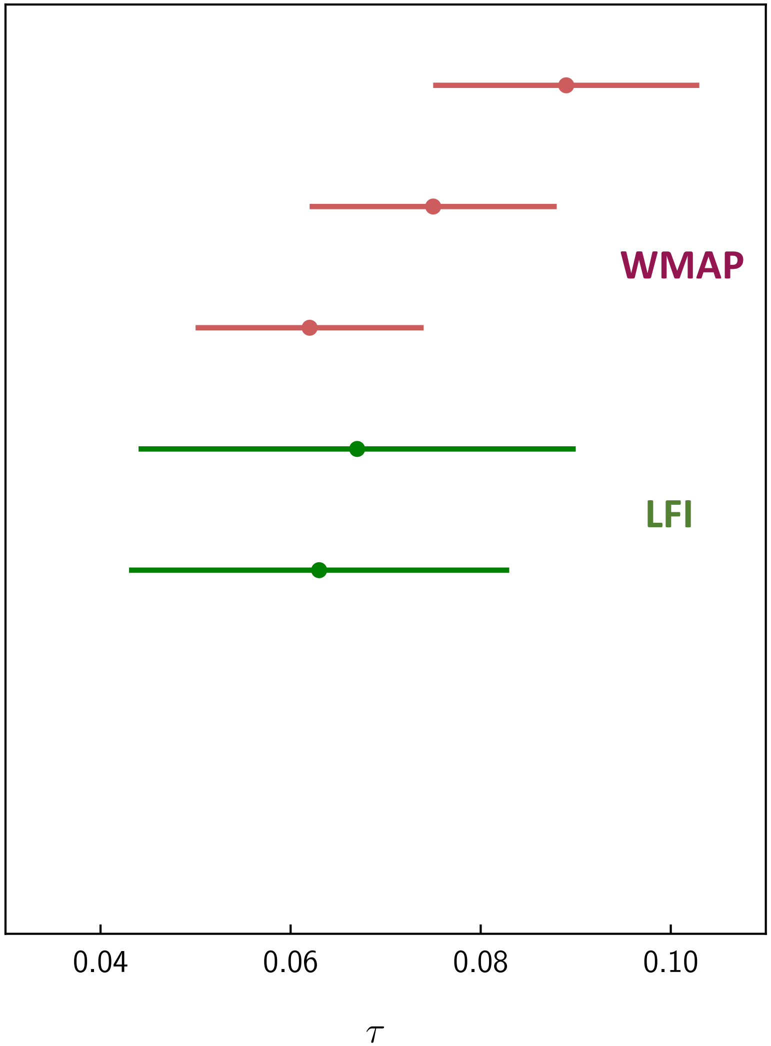
WMAP 9yrs (Hinshaw+ 2013) $\tau = 0.089 \pm 0.014$

WMAP 9yrs + Planck 353 GHz (Planck 2013 results XVI) $\tau = 0.075 \pm 0.013$

WMAP 9yrs + Planck 353 GHz (Planck 2018 results V in press) $\tau = 0.062 \pm 0.012$

Planck lowTEB (LFI 2015) (Planck 2015 results XIII) $\tau = 0.067 \pm 0.023$

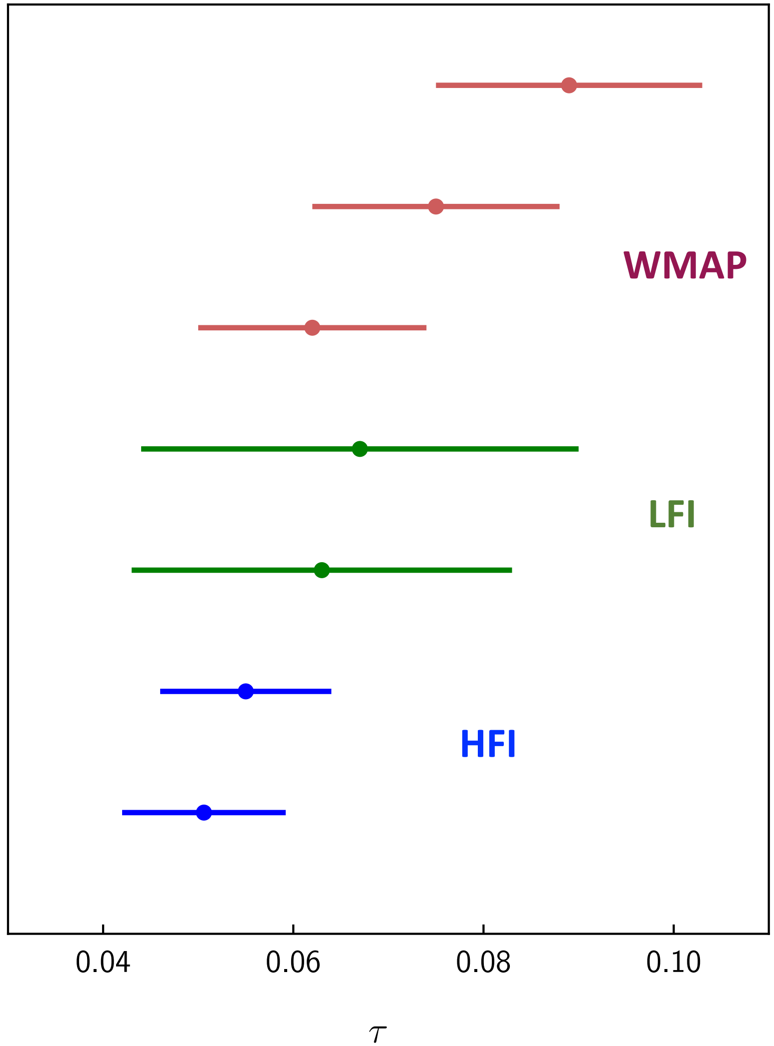
Planck lowTEB (LFI 2018) (Planck 2018 results V in prep) $\tau = 0.063 \pm 0.020$



Large Scale Polarization: "Recent" history of τ measurements

Improved measurements, together with increased systematics and foregrounds control, resulted in a trend towards lower τ values.

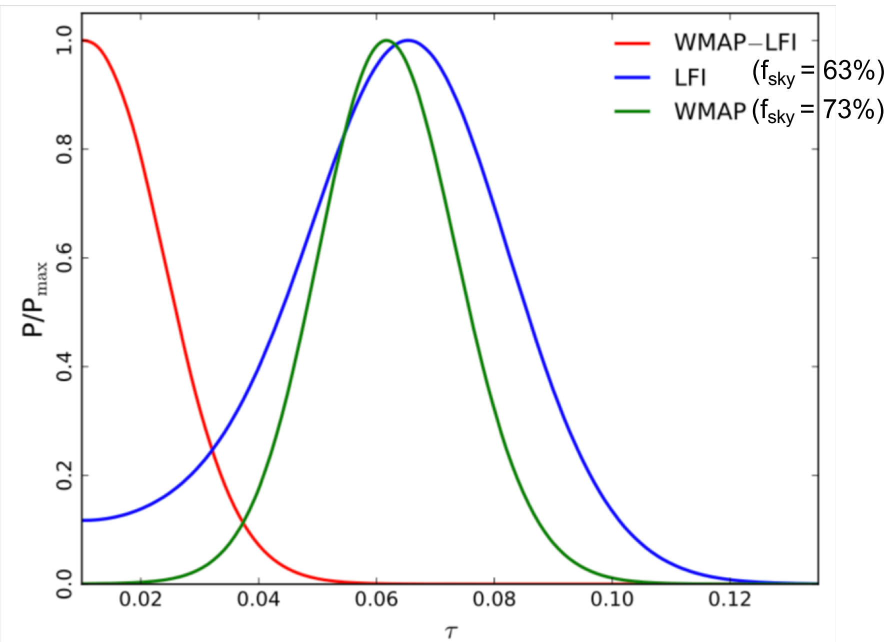
WMAP 9yrs (Hinshaw+ 2013)	τ = 0.089 ± 0.014
WMAP 9yrs + Planck 353 GHz (Planck 2013 results XVI)	τ = 0.075 ± 0.013
WMAP 9yrs + Planck 353 GHz (Planck 2018 results V in press)	τ = 0.062 ± 0.012
Planck lowTEB (LFI 2015) (Planck 2015 results XIII)	τ = 0.067 ± 0.023
Planck lowTEB (LFI 2018) (Planck 2018 results V in press)	τ = 0.063 ± 0.020
Planck lowE (HFI 2016) (Planck int. results 2016. XLVI)	τ = 0.055 ± 0.009
Planck lowE (HFI 2018) (Planck 2018 results V in press)	**τ = 0.0506 ± 0.0086**



Large Scale Polarization

Consistency of datasets

CMB at low frequencies: LFI and WMAP



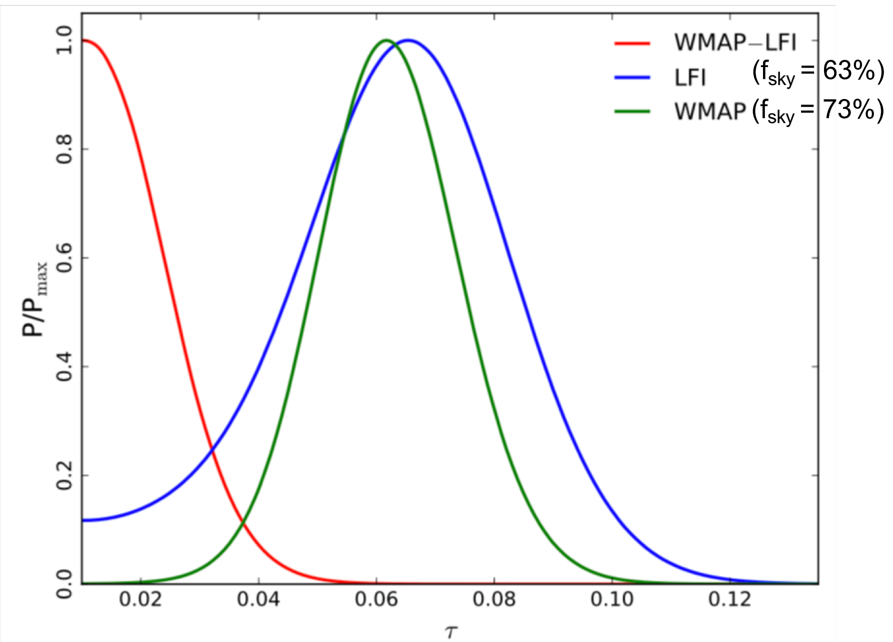
Re-analysis of WMAP: cleaning dust with 353 GHz maps and synchrotron with K-band

(Planck 2018 results V in press)

Large Scale Polarization

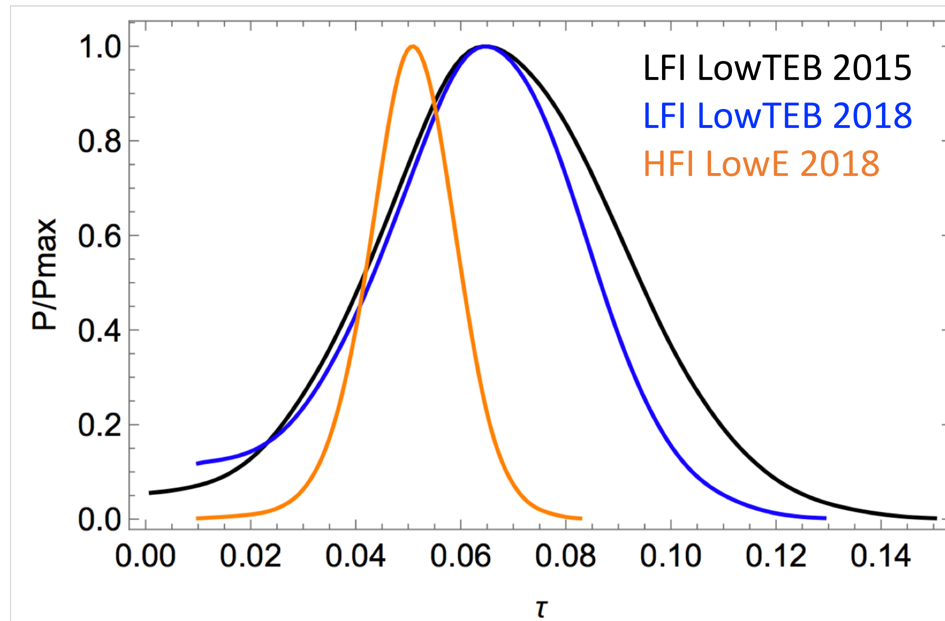
Consistency of datasets

CMB at low frequencies: LFI and WMAP



Re-analysis of WMAP: cleaning dust with 353 GHz maps and synchrotron with K-band

Good internal consistency in Planck



(Planck 2018 results V in press)

Reionization History

Optical depth estimates are obtained assuming *instantaneous* reionization model for the ionization fraction

Planck TTTEEE + lowE: $\tau = 0.0544^{+0.0070}_{-0.0081}$ and $z_{re} = 7.68 \pm 0.79$ (68% CL)

$$\tau = n_H(0)\, c\, \sigma_T \int_0^z dz\, x_e \frac{(1+z)^2}{H(z)}$$

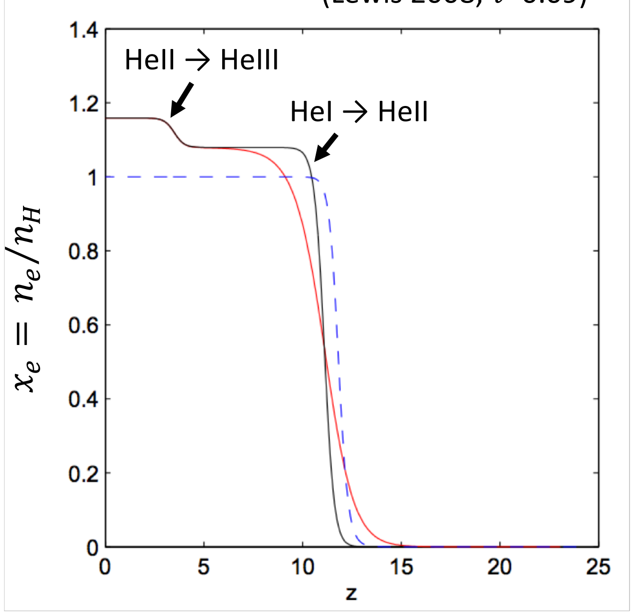
$$x_e(z) = \frac{f}{2}\left[1 + \tanh\left(\frac{y - y_{re}}{\delta y}\right)\right]$$

$$y = (1+z)^{3/2}$$

$$\delta y = \tfrac{3}{2}(1+z)^{1/2}\delta z$$

$\delta z = 0.5$ $\Delta z = z_{10\%} - z_{99\%} = 1.73$

(Lewis 2008, τ=0.09)



$z_{re} \equiv z_{50\%}$ the redshift at which x_e is at half its maximum value f $= (1 + n_{He}/n_H)$

Reionization History

Generalizing the ionization fraction model, thus allowing for the reconstruction of any arbitrary reionization history using non parametric models.

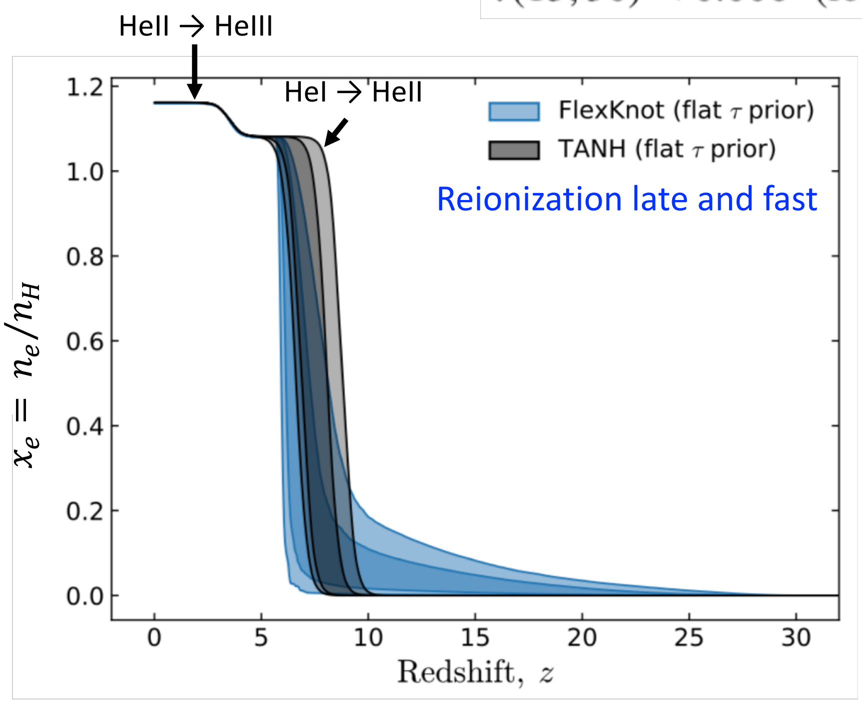
Heinrich+2017, Miranda+2017, Heinrich & Hu 2018

Hazra & Smooth 2017, Villanueva-Domingo+2018, Dai+2018, Millea & Bouchet 2018, Hazra+2019

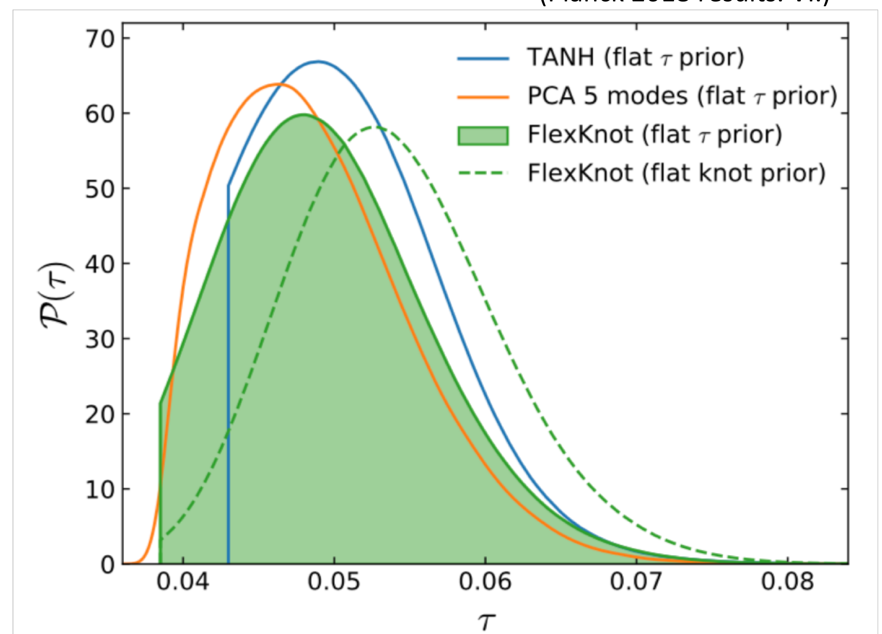
With latest Planck data:

- τ estimate has little sensitivity to details of reionization history modelling
- Consistent with a universe fully reionized by $z = 6$ (Becker+2001, Fan+2006)
- No preference for a significant high-redshift contribution to the optical depth

$$\tau(15, 30) < 0.006 \quad (\text{lowE; flat } \tau(15, 30); \text{FlexKnot})$$

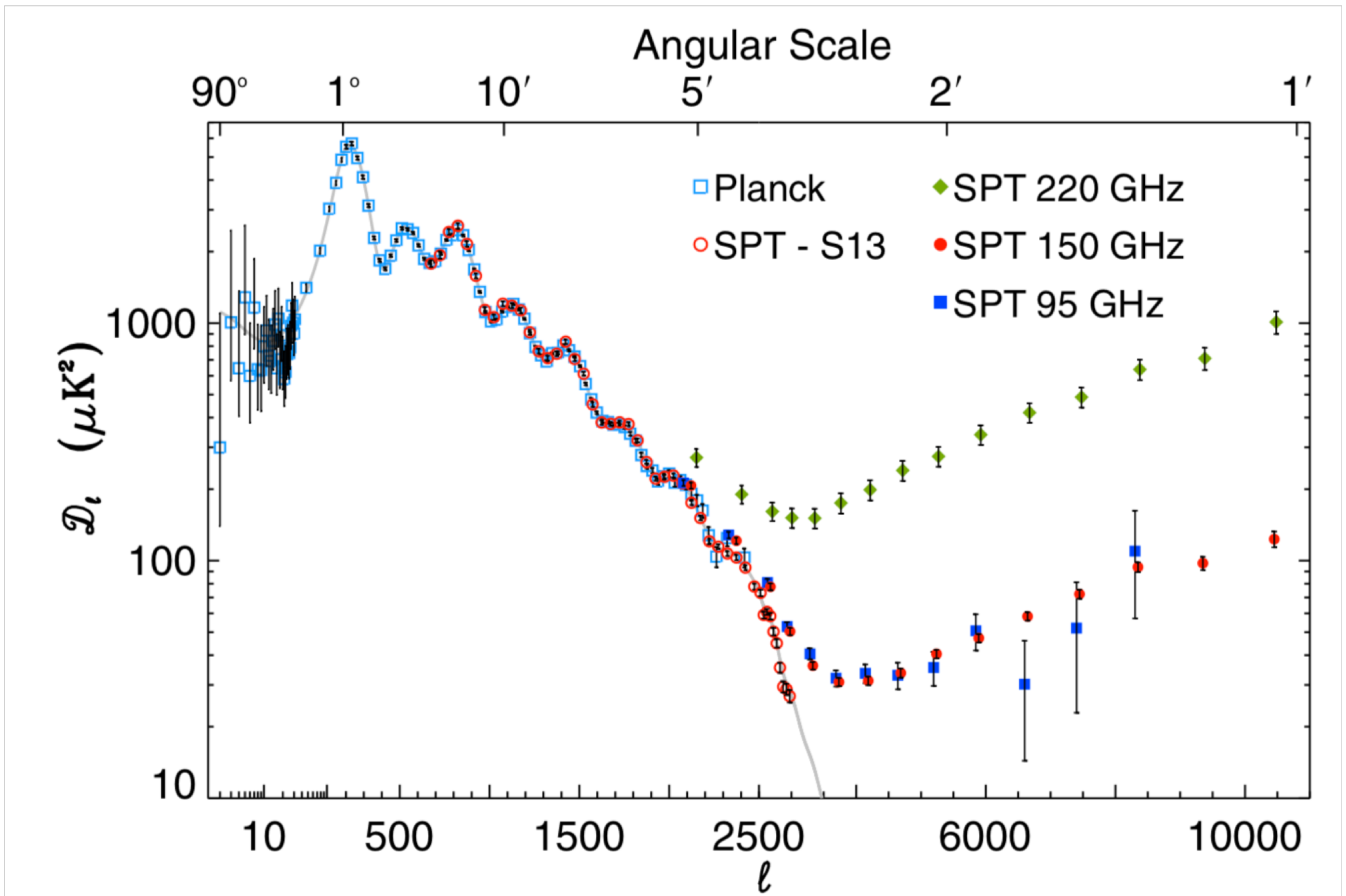


(Planck 2018 results. VI.)



Reionization History

Kinetic Sunyaev-Zel'dovich Effect: secondary temperature anisotropy on small angular scales due to Doppler-shift of photons scattering off electrons moving in bulk flows. Two components: homogeneous, fully ionized IGM, and patchy, ionized bubbles around the first sources. These components are highly degenerate in current data.



George et al. 2015

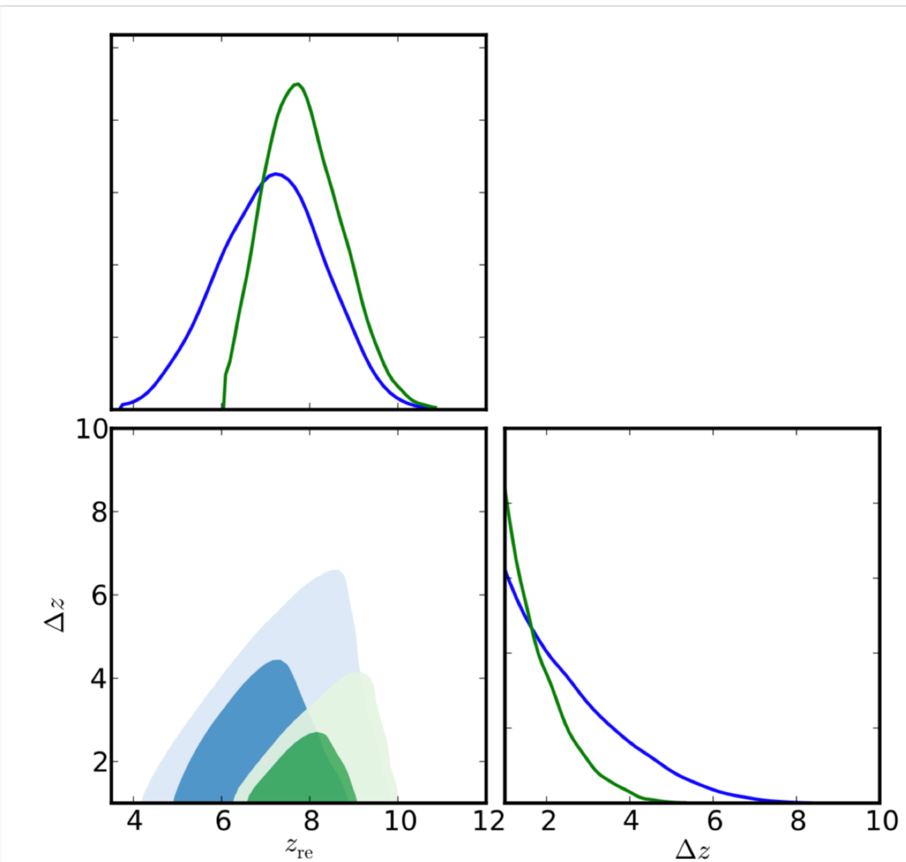
$D_{3000}^{kSZ} = 2.9 \pm 1.3 \; \mu K^2$

Detection at 98.1% CL

Reionization History

Kinetic Sunyaev-Zel'dovich Effect: secondary temperature anisotropy on small angular scales due to Doppler-shift of photons scattering off electrons moving in bulk flows. Two components: homogeneous, fully ionized IGM, and patchy, ionized bubbles around the first sources. These components are highly degenerate in current data.

Planck intermediate results XLVII. 2016



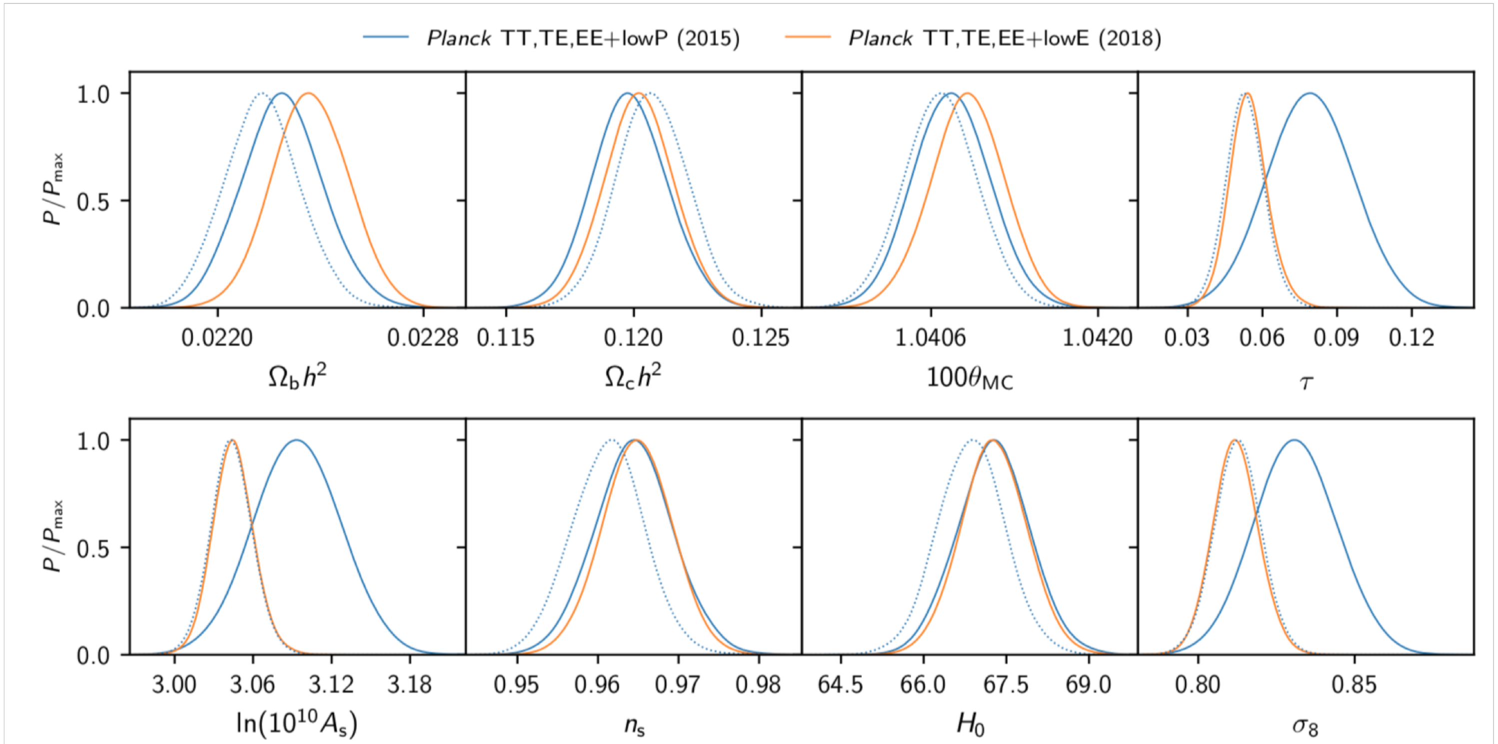
Planck 2016 polarization + kSZ (SPT, ACT)
Fitting separately for a homogeneous and patchy contribution → constraints on the duration

$\Delta z = z_{10\%} - z_{99\%}$

$\Delta z < 4.8$ (95% CL, uniform prior)

$\Delta z < 2.8$ (95% CL, prior $z_{end} > 6$)

Impact of τ on cosmological parameters



Tighter 95% CL upper limit on the sum of neutrino masses: $\Sigma m_\nu < 0.72$ eV (TT+lowP, 2015) → $\Sigma m_\nu < 0.56$ eV (TT+lowE, 2018) → $\Sigma m_\nu < 0.12$ eV (TTTEEE+lowE+lensing+BAO, 2018)

Final remarks

- Planck data support a reionization happing late and fast
- Planck estimate of electron scattering optical depth is going to be the best we can have for several years. Future ground-based CMB experiments (Simons Observatory, S4, …) will rely on this measurement.
- Although the work of the Planck Collaboration is almost completed, the full potential of the legacy data has not been exhausted and it is the subject of ongoing and future work.

What to look forward to

- Future CMB missions measuring polarization on large angular scales (e.g. LSPE, CLASS, JAXA-LiteBIRD)
- kSZ measurements from ground-based experiments
- CMB spectral distortion experiments
- Complementary probes: Radio surveys, in particular SKA, mapping the neutral H across the EoR. High redshift sources by Euclid, JWST, …

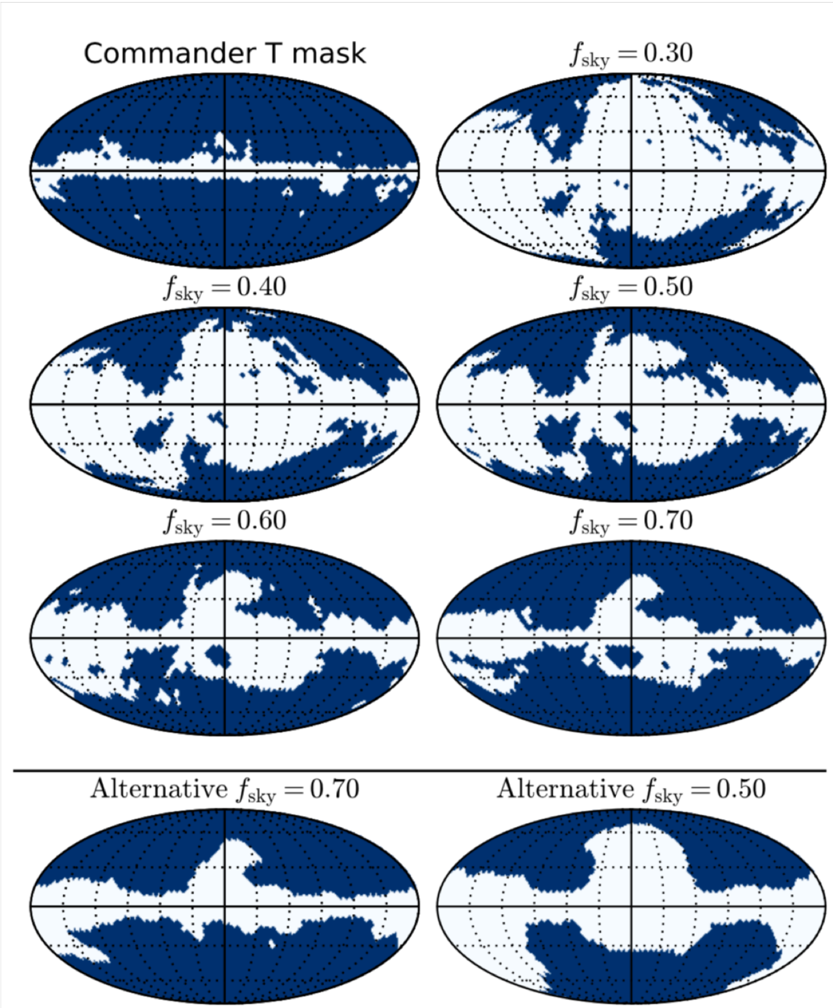
THANK YOU

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

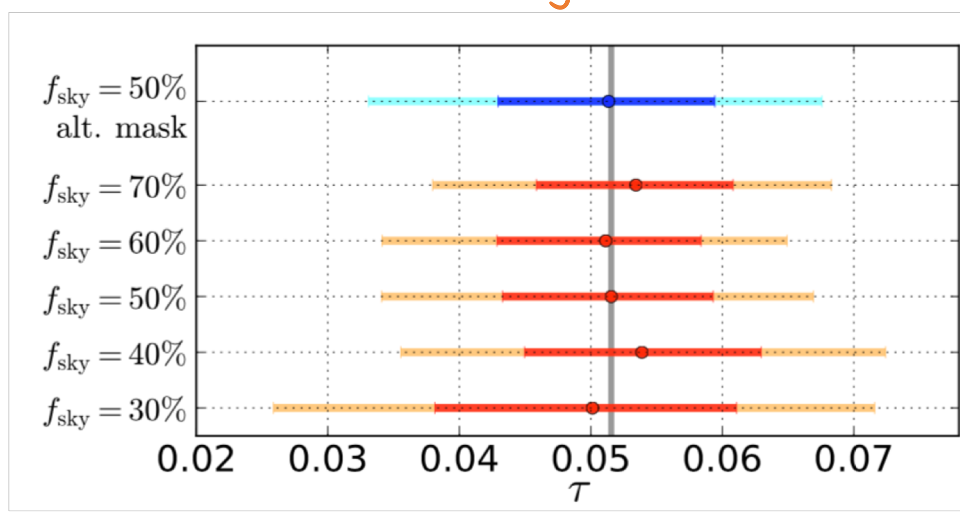
BACKUP SLIDES

Large Scale Polarization

Planck HFI low-ℓ likelihood



Robustness of results against mask choices



Large Scale Polarization

Planck HFI low-ℓ likelihood

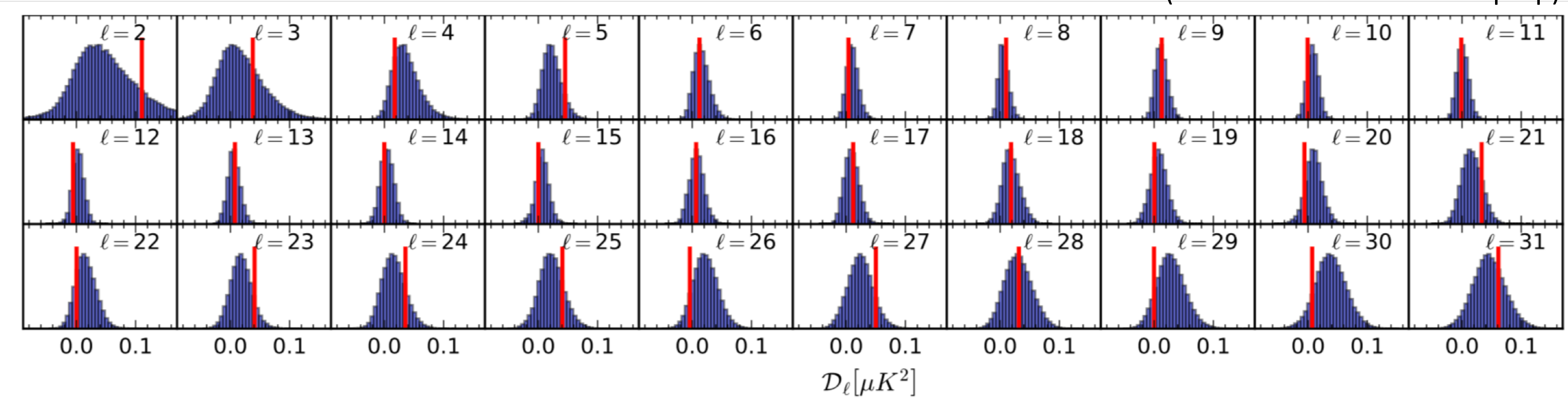
Simulations based Likelihood

Sample Cosmology $10^9 A_s \sim \mathrm{U}(0.6, 3.8)$ $\tau \sim \mathrm{U}(0, 0.14)$ $r \sim \mathrm{U}(0, 1)$

corresponding to $0\,\mu K^2 \leq \mathcal{D}_\ell^{EE} \leq 0.30\,\mu K^2, \quad 0\,\mu K^2 \leq \mathcal{D}_\ell^{BB} \leq 0.20\,\mu K^2$

For each model, characterize instrument and cosmic variance with 300 CMB + (noise + systematics + foreground cleaning residuals) simulated maps.
Estimate the data probability from the distribution of the simulations.

(Planck 2018 results. V. in prep)



For each multipole, interpolate the probabilities of the different models to measure

$g_\ell(C_\ell^{\mathrm{data}}, C_\ell) \approx \log P(C_\ell^{\mathrm{data}}, C_\ell)$ and ignoring ℓ-to-ℓ correlations

The likelihood approximations is: $\log \mathcal{L}\left(C^{\mathrm{theory}} \middle| C^{\mathrm{data}}\right) \approx \sum_{\ell=2}^{29} g_\ell\left(C_\ell^{\mathrm{data}}, C_\ell\right)$

(Planck int. results 2016. XLVI)

Table 5. For each CMB frequency, the amplitude of the power spectrum D_ℓ at $\ell = 4$ that is removed for the dust and synchrotron foregrounds.

Frequency [GHz]	Dust Mean [μK^2]	Dust Uncertainty [μK^2]	Synchrotron Mean [μK^2]	Synchrotron Uncertainty [μK^2]
70	0.0041	0.0010	0.019	0.005
100	0.0227	0.0020	0.0036	0.0011
143	0.106	0.0052	~~0.0007~~	~~0.0004~~

Notes. These are computed from the 353 and 30-GHz power spectra at $\ell = 4$; uncertainties are scaled appropriately by the projection coefficients and relative errors.

$$D_l^{EE}(\tau = 0.05) = 0.0284\ \mu K^2$$

Foreground scaling coefficients

Channel	$\alpha \cdot 10^{-2}$	$\beta \cdot 10^{-2}$
100	1.83 ± 0.12 [0.18]	1.950 ± 0.014 [0.015]
143	–	4.078 ± 0.011 [0.013]

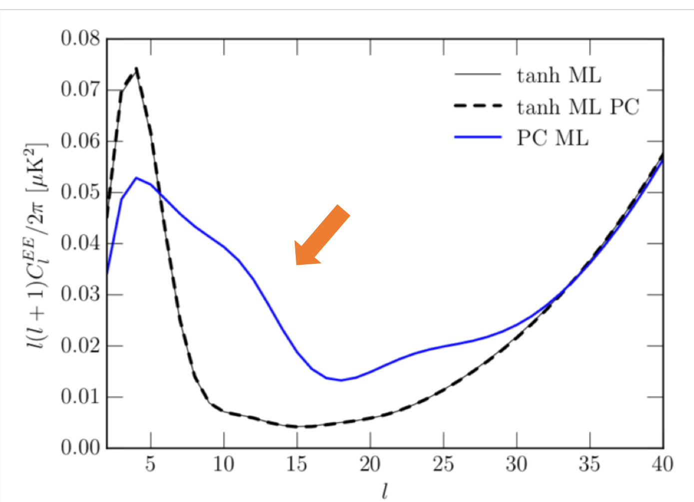
70GHz $\alpha = 0.058 \pm 0.004$ $\beta = 0.0092 \pm 0.0004$

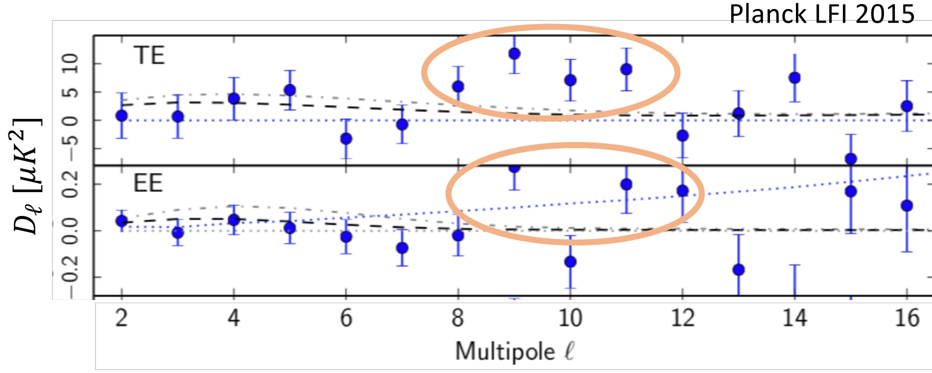
Reionization History

Generalizing the ionization fraction model

- Non parametric models trying to fit the *shape* of the reionization *bump* in the E-mode spectrum, e.g. Principal Components Analysis

  (Heinrich+2017, Heinrich & Hu 2018) find that Planck 2015 LFI polarization likelihood constrains 5 PC to describe C_ℓ^{EE} for $6 < z < 30$.
  This modelling results in a non-negligible contribution from high-redshifts
  $\tau(15,30) = 0.033 \pm 0.016 \quad (\sim 2\sigma)$
  Tentatively interpreted as a signature of the first stars (Miranda+2017).





Alternate analyses find no convincing evidence of early reionization: (Villanueva-Domingo+2018) broad class of possible reionization parameterizations, (Hazra & Smooth 2017) free electron fraction in redshift bins, (Dai+2018) using PCA, (Millea & Bouchet 2018) PCA of HFI 2016

Polarization

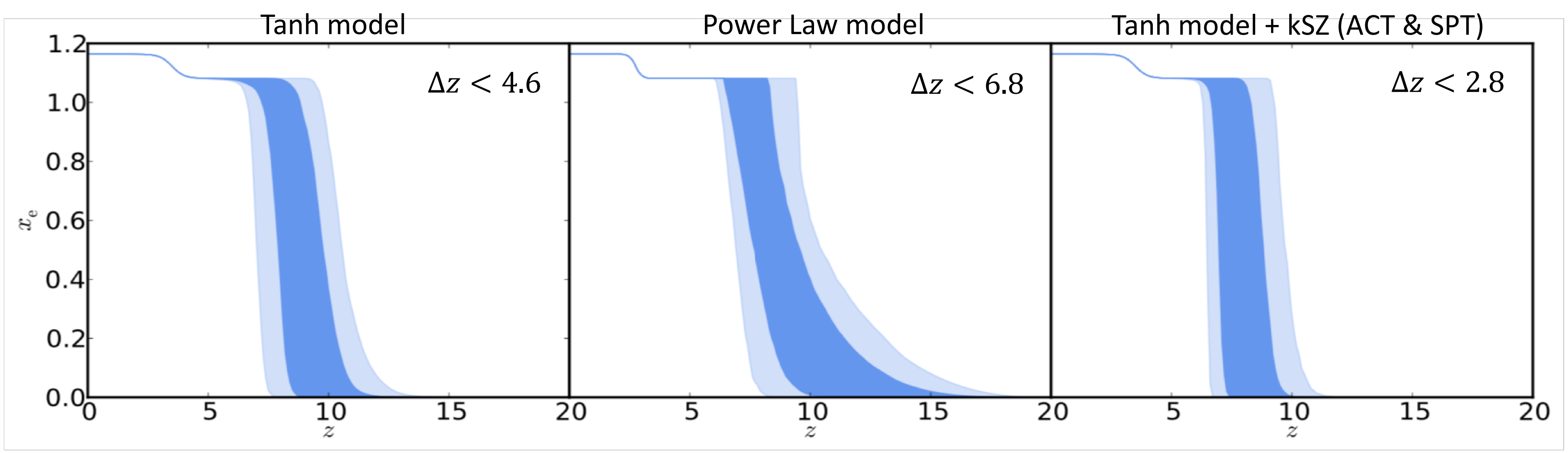
Reionization History

Generalizing the ionization fraction model

- Redshift asymmetric parametrization, more flexible description of numerical simulations of the reionization process, e.g. power law (Planck intermediate results 2016. XLVII.)

Planck data are consistent with a universe fully reionized by $z = 6$ (Becker+2001, Fan+2006).
Set the prior $z_{end} > 6$ to break degeneracy $\Delta z \; - z_{re}$

Planck 2016 HFI data



Constraints still model dependent. **Data disfavour early onset of reionization**.

Reionization

The second major change in the ionization state of hydrogen in the universe

Cosmic Ionization History