The CMB as a probe of reionization

Results from Planck

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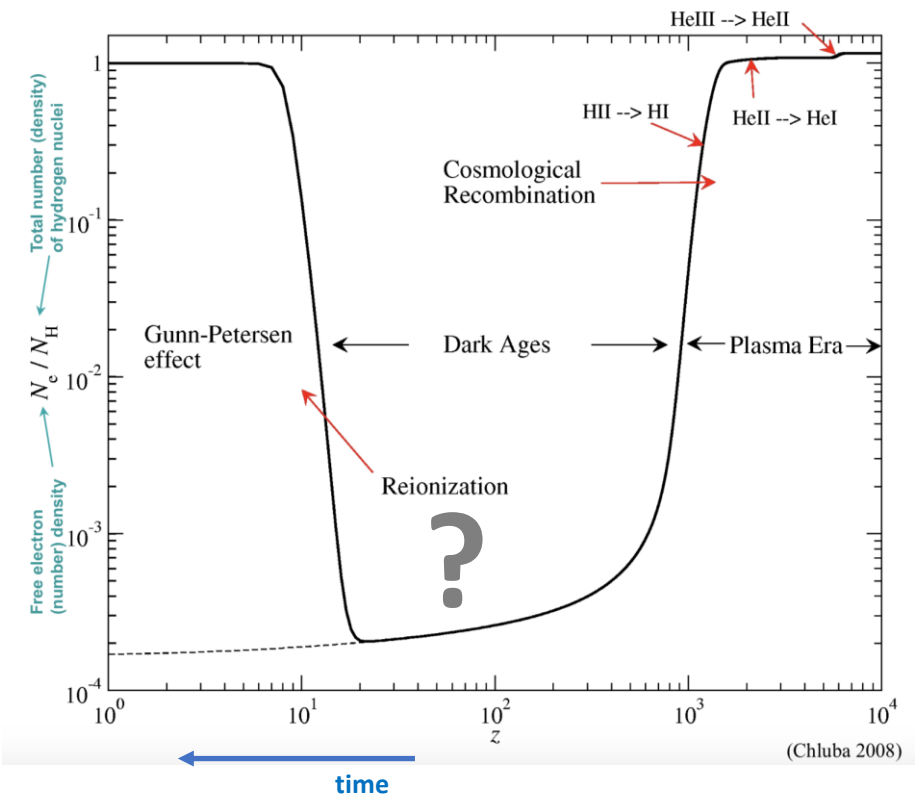
Cosmic Ionization History

Reionization is the second major change in the ionization state of hydrogen in the universe



Impact on the CMB

Reionization -> newly freed electrons

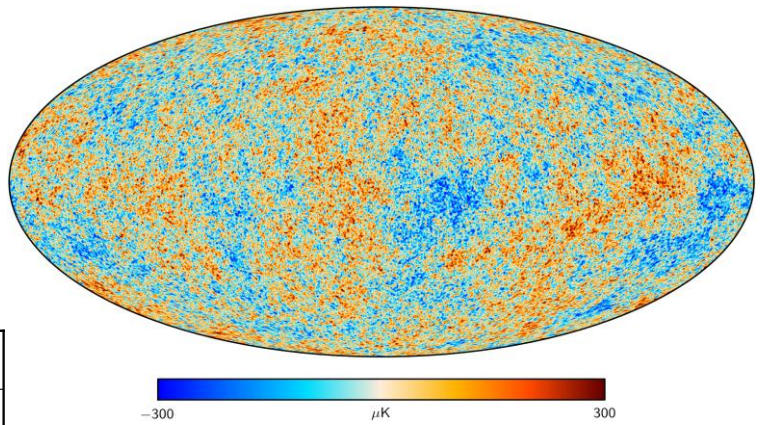
1. **Temperature Anisotropies**: damping of fluctuations at small angular scales
2. Polarization: damping of fluctuations at small angular scales plus generation of new polarization anisotropy on large angular scales
3. Kinetic Sunyaev-Zel'dovich (kSZ) Effect: secondary temperature anisotropy on small 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 Thomson scattering optical depth

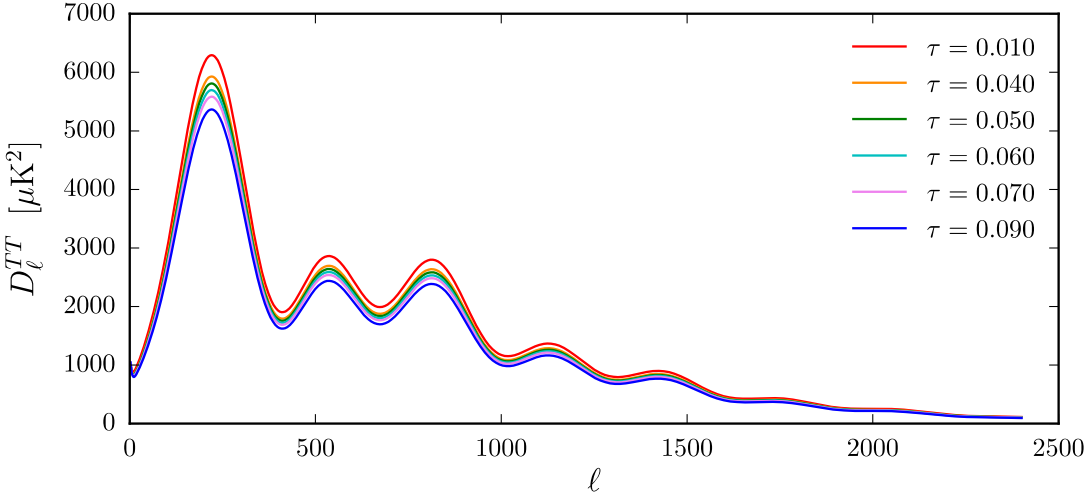
$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T c dt'$$

Temperature Anisotropies

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

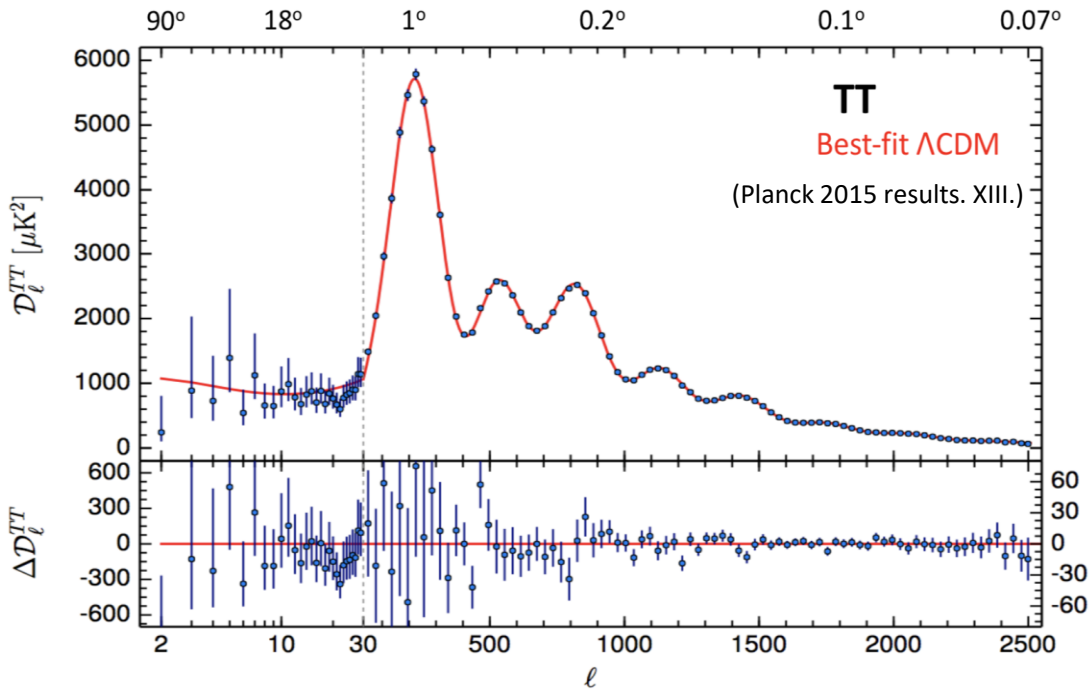


$$C_\ell^{TT} \propto A_s e^{-2\tau}$$

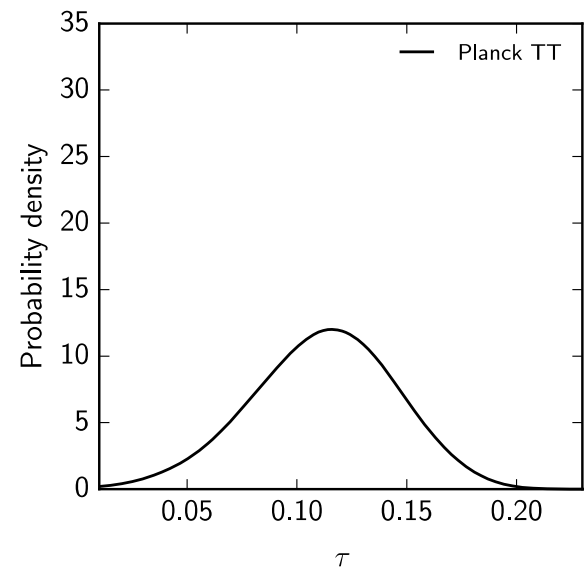


τ degenerate with other cosmological parameters, especially A_s and related parameters n_s , σ_8, … and foregrounds.

Temperature Anisotropies



Cosmic Variance Limited up to l =1600, sky fraction =75-40%

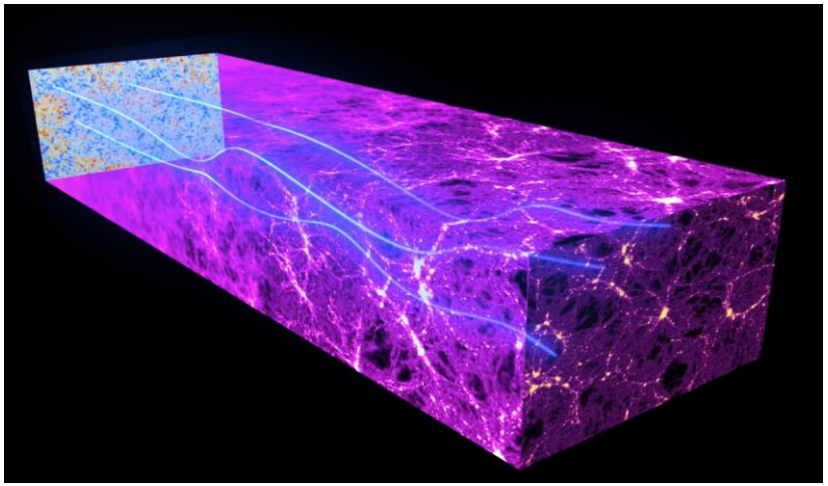


TT power spectrum constrains the combination $A_s\, e^{-2\tau}$ at sub-% level !

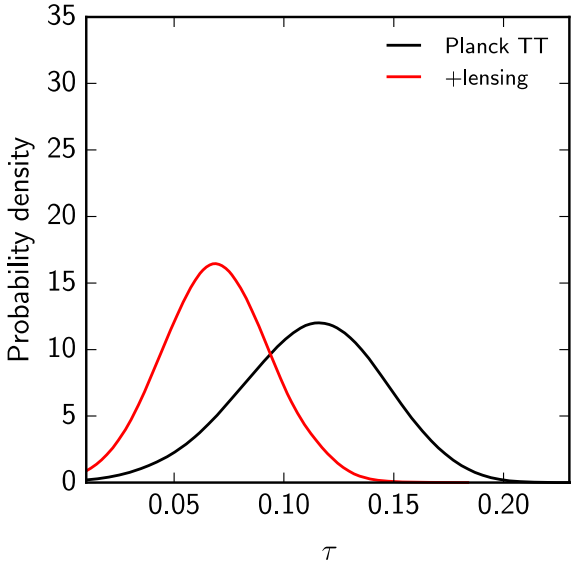
$10^9\, A_s\, e^{-2\tau} = 1.875\ \pm 0.014$

Temperature Anisotropies

Gravitational Lensing



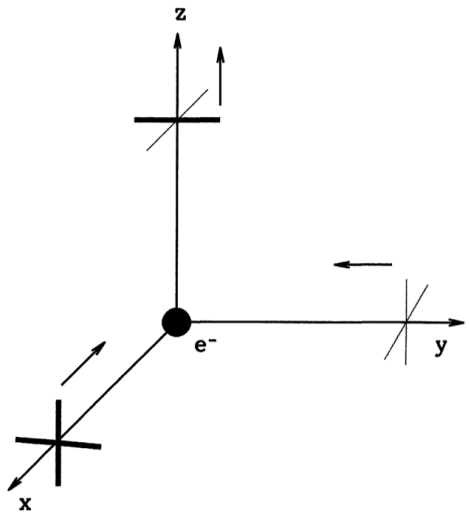
When CMB photons propagate across the universe their paths get deflected by the gravitational tug of intervening matter: this effect is known as gravitational lensing and it provides a **clean probe of the clustering of matter** integrated across a wide range of redshifts along the line of sight. Deflections ~ 2 arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.

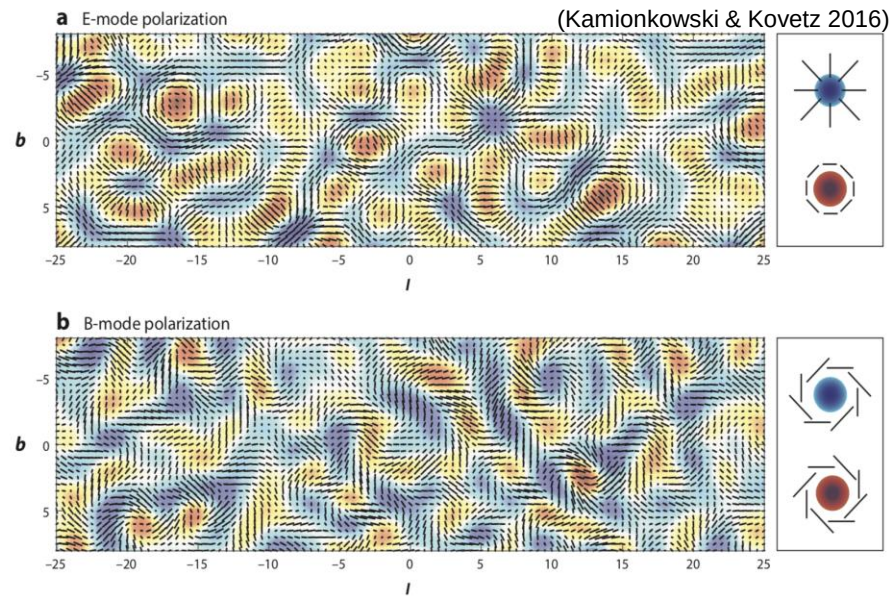


Breaks degeneracy with A_s

Polarization

CMB linear polarization generated by Thomson scattering of local quadrupolar anisotropies off free electrons





(Kamionkowski & Kovetz 2016)

Maps of the Stokes Parameters

$$I = \left\langle |E_x|^2 + |E_y|^2 \right\rangle \qquad Q = \left\langle |E_x|^2 - |E_y|^2 \right\rangle \qquad U = \left\langle 2\,Re\left(E_x E_y^*\right)\right\rangle$$

Polarization

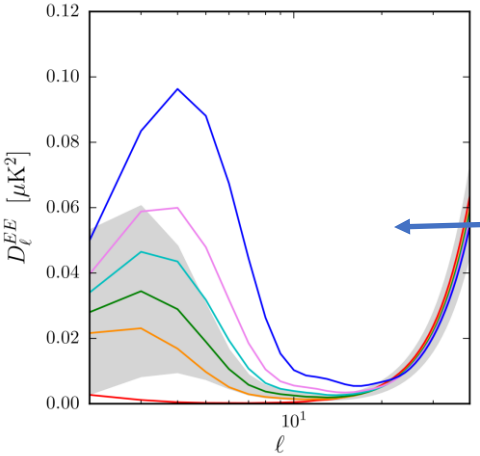
Bump in low-ℓ spectra

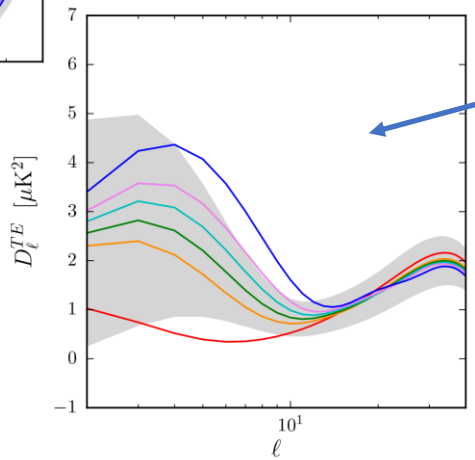
Height $\Delta_E \to \Delta_E \tau \quad C_\ell^{EE} \propto \tau^2 \quad C_\ell^{TE} \propto \tau$

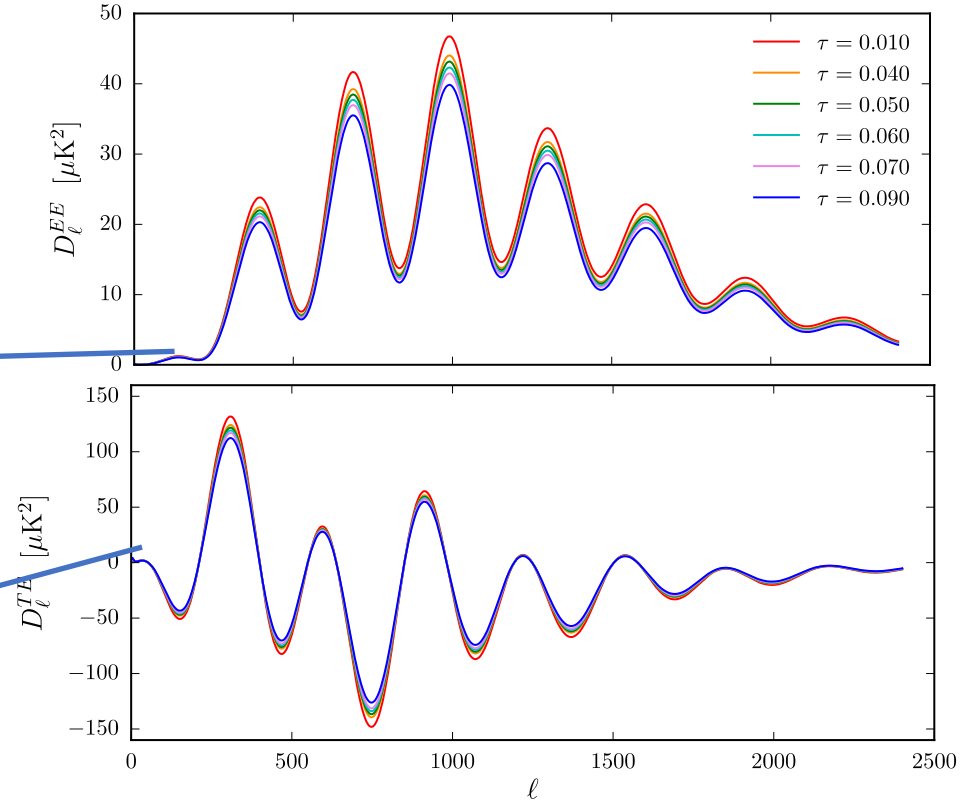
Low values of tau are difficult to measure !

Location tells you when

Little dependence on the other parameters

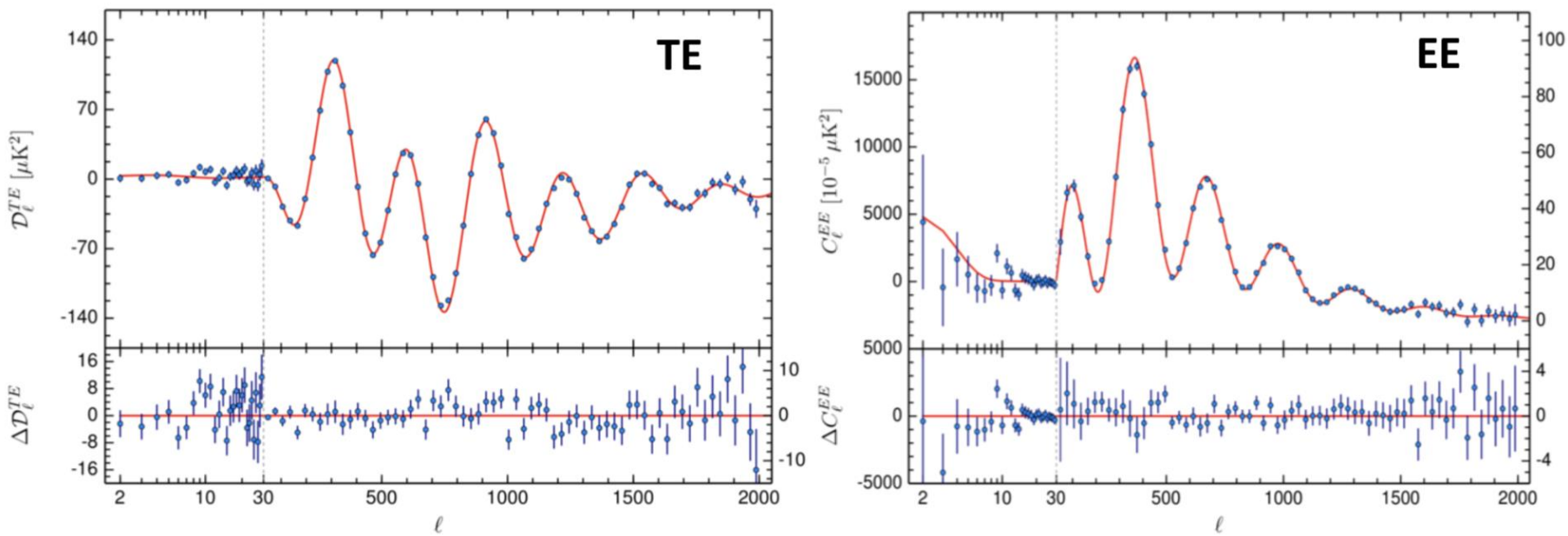






Polarization

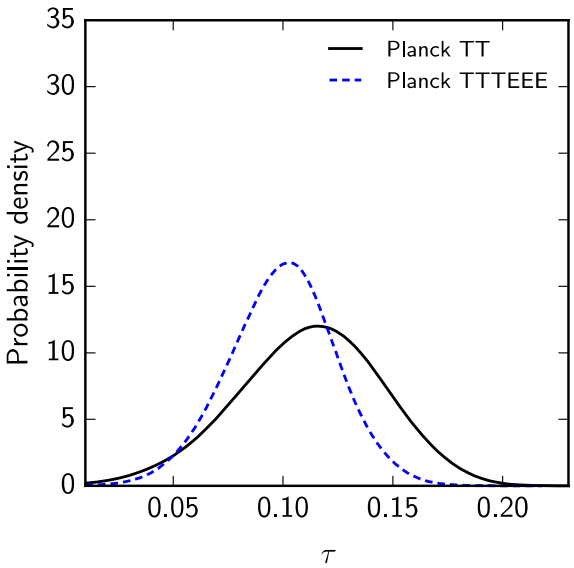
(Planck 2015 results. XI.)

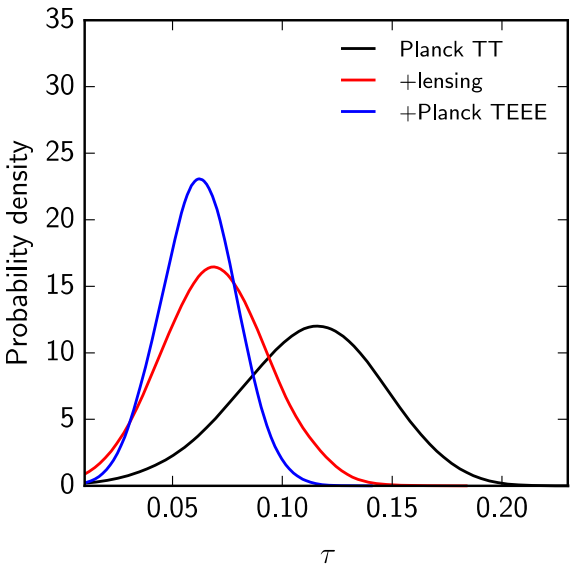


Red line is the best-fit cosmology from temperature data

Polarization

Adding polarization at small angular scales





Consistency check as small scale foregrounds are less important than in TT.

Residual low level systematics are still unaccounted for O(1 μK^2) (e.g., T → P leakage,…)

improvements expected with the upcoming 2018 data release

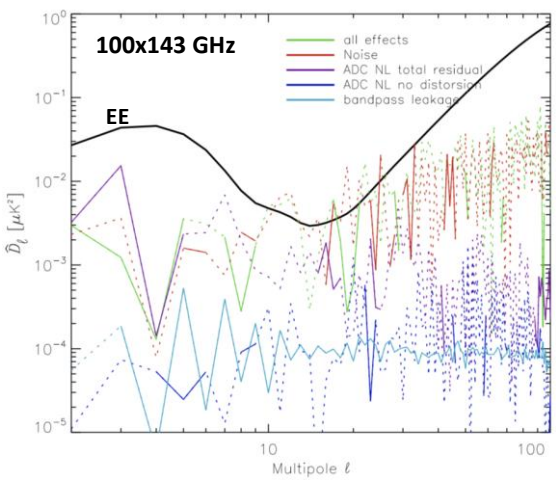
Large Scale Polarization

Measuring Polarization is challenging

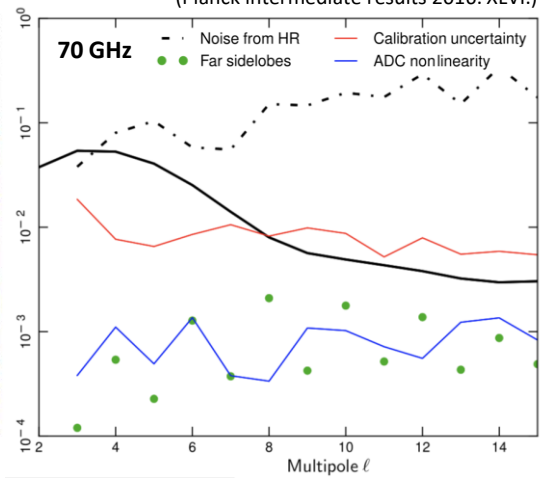
- Differential measurement
- Large angular scales are better measured from space
- Signal ~ 100 times weaker than temperature
- Systematic effects, noise and foregrounds are important

Tackling this challenge with Planck

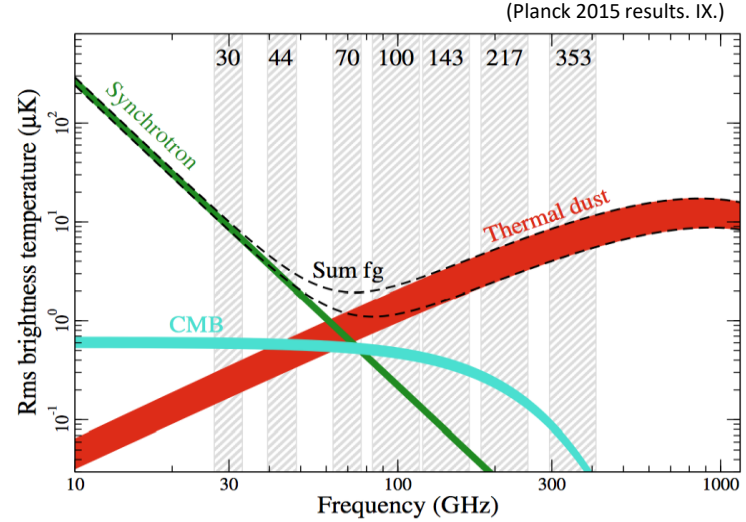
- Full sky coverage
- Broad frequency range to model foregrounds
- Complementarity between LFI and HFI
- E2E simulations to model noise and systematics
- Application of different data analysis techniques



(Planck intermediate results 2016. XLVI.)



(Planck 2015 results. IX.)



Large Scale Polarization

Planck Low Frequency Instrument

(Planck 2015 results. XI.)

Template cleaning of 70 GHz maps $\boldsymbol{m}$ = [Q, U]

$$\boldsymbol{m} = \frac{1}{1-\alpha-\beta}(\boldsymbol{m}_{70} - \alpha\boldsymbol{m}_{30} - \beta\boldsymbol{m}_{353}),$$

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

Foreground coefficients by minimising

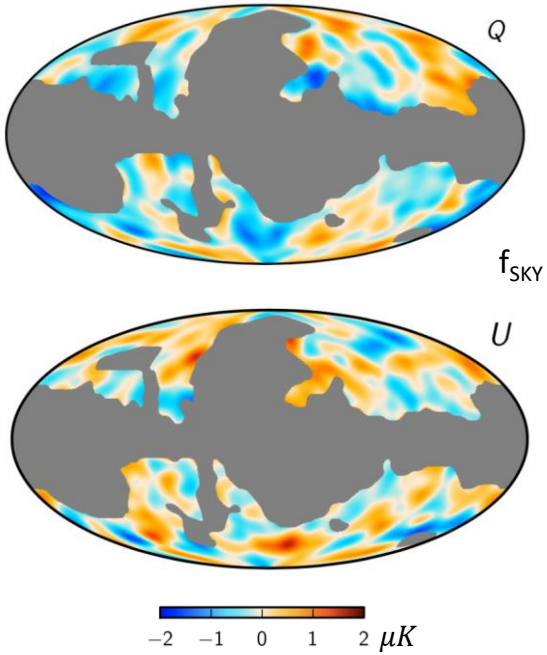
$$\chi^2 = (1-\alpha-\beta)^2 \boldsymbol{m}^{\mathsf{T}} \mathsf{C}_{\mathsf{S+N}}^{-1} \boldsymbol{m},$$

Noise covariance of the cleaned polarized maps

$$\mathsf{N} = \frac{1}{(1-\alpha-\beta)^2}\left(\mathsf{N}_{70} + \delta_\alpha^2 \boldsymbol{m}_{30}\boldsymbol{m}_{30}^{\mathsf{T}} + \delta_\beta^2 \boldsymbol{m}_{353}\boldsymbol{m}_{353}^{\mathsf{T}}\right)$$

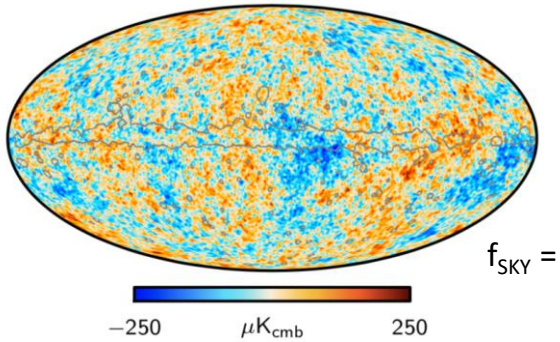
Pixel-based likelihood

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



f_{SKY} = 46%

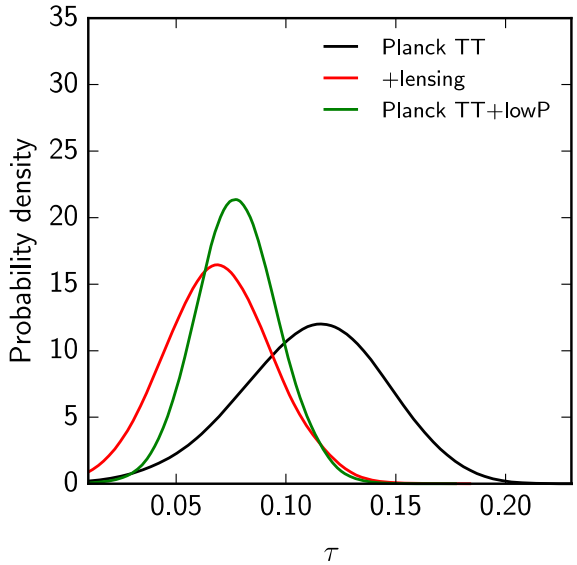
Commander Temperature Solution

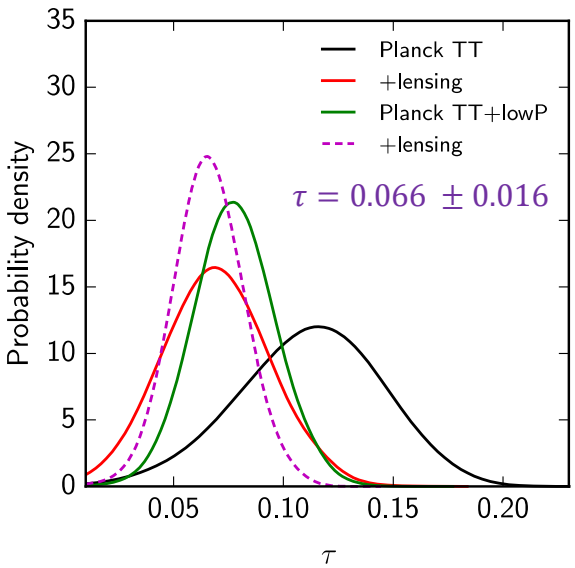


f_{SKY} = 93%

Large Scale Polarization

Adding measurements from LFI





Consistency between large scale polarization and lensing
Different measurements, very different systematics and foregrounds -> important robustness test

Large Scale Polarization

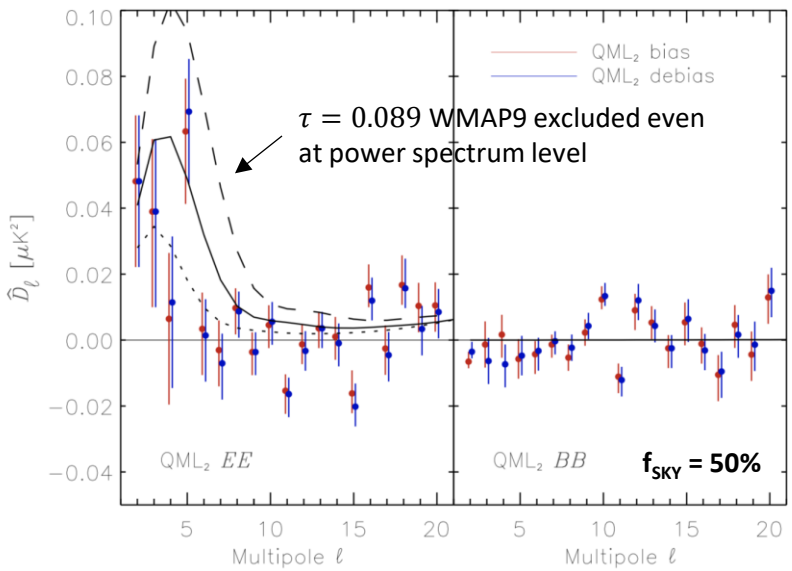
Planck High Frequency Instrument

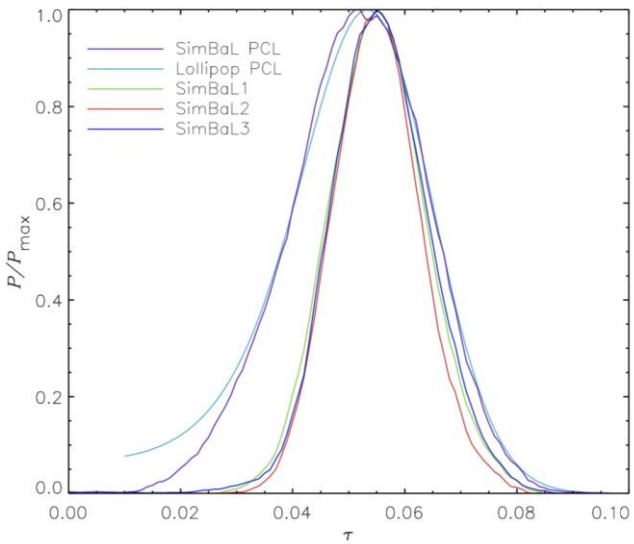
Analysis based on 100 GHz and 143 GHz maps: most *clean* and sensitive channels.

Maps are foreground cleaned using ILC method with 30 GHz and 353 GHz as tracers of synchrotron and dust emissions.

Noise difficult to model to high accuracy → Analysis uses **E-mode 100 x 143 GHz cross-power spectrum** estimate and the associated **likelihood is modelled from full end-to-end simulations**.

(Planck intermediate results 2016. XLVI.)

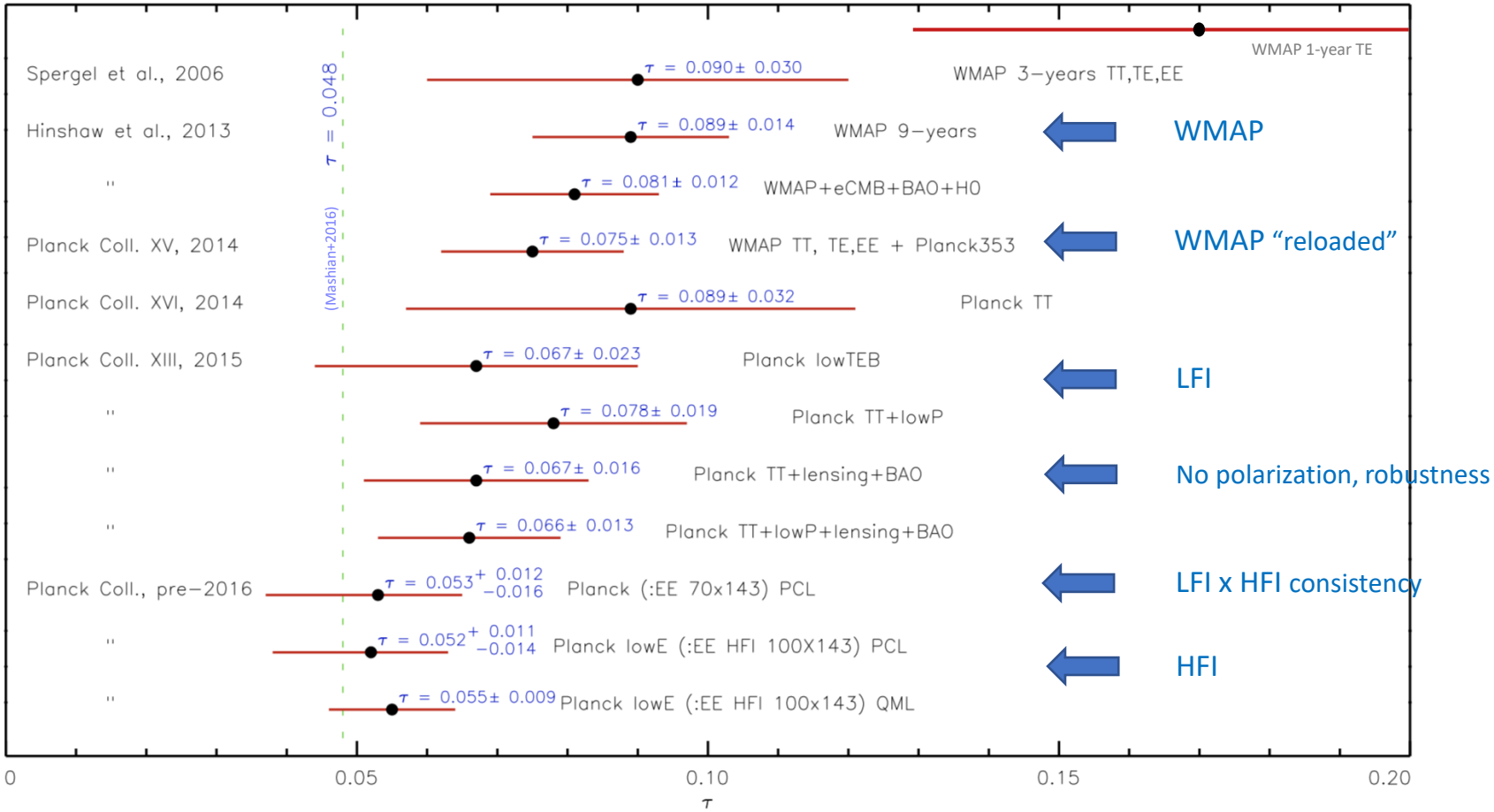




Improved measurements
Increased systematics and foreground control
Trend towards lower values

Cosmic variance limit
$\sigma(\tau) \simeq 0.002$

HISTORY OF THOMSON OPTICAL DEPTH DETERMINATION



Polarization

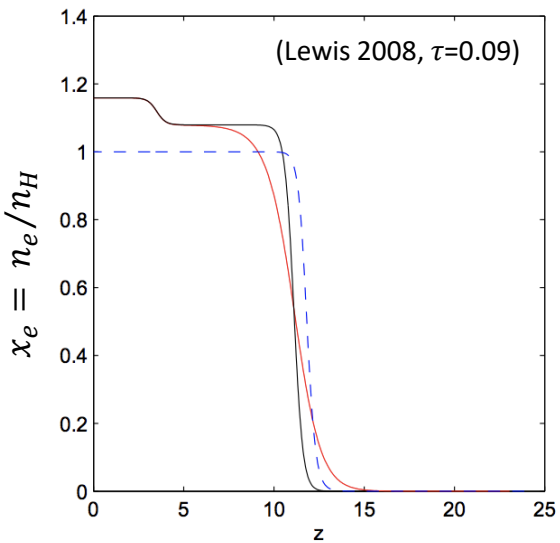
Reionization History

Results shown so far were obtained under the assumption of *instantaneous* reionization:

$$x_e(z) = \frac{f}{2}\left[1 + \tanh\left(\frac{y - y_{re}}{\delta y}\right)\right] \qquad y = (1+z)^{3/2} \qquad \delta y = \tfrac{3}{2}(1+z)^{1/2}\delta z$$

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

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



Planck TT + lowP (LFI) (2015)

$\tau = 0.078 \pm 0.019 \qquad z_{re} = 9.89^{+1.8}_{-1.6}$

Planck TT + lowP (LFI) + lensing (2015)

$\tau = 0.066 \pm 0.016 \qquad z_{re} = 8.8 \pm 1.5$

Planck TT + lowE (HFI) (2016)

$\tau = 0.0581 \pm 0.0094 \qquad z_{re} = 8.11 \pm 0.93$

Good internal consistency in Planck

Significantly lower values than WMAP

Better agreement with present astrophysical predictions from high-z luminosity functions (Robertons+2015, Bouwens+2015, Ishigaki+2015)

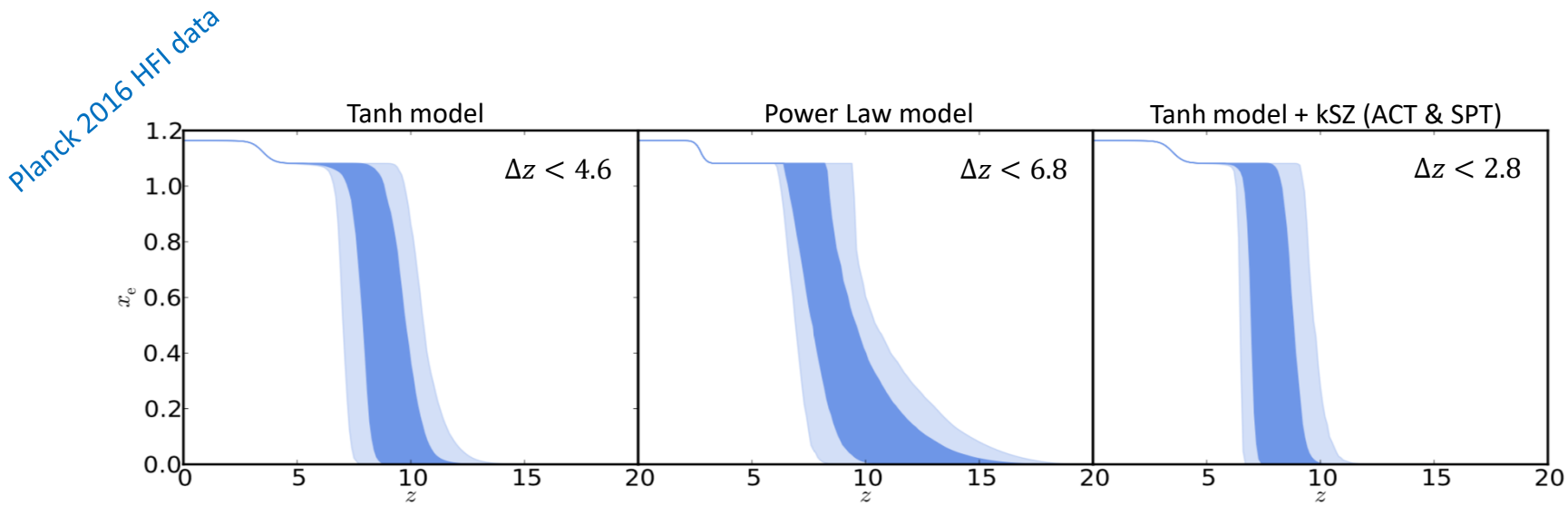
Polarization

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 $\Delta z - z_{re}$



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

Polarization

Reionization History

Generalizing the ionization fraction model

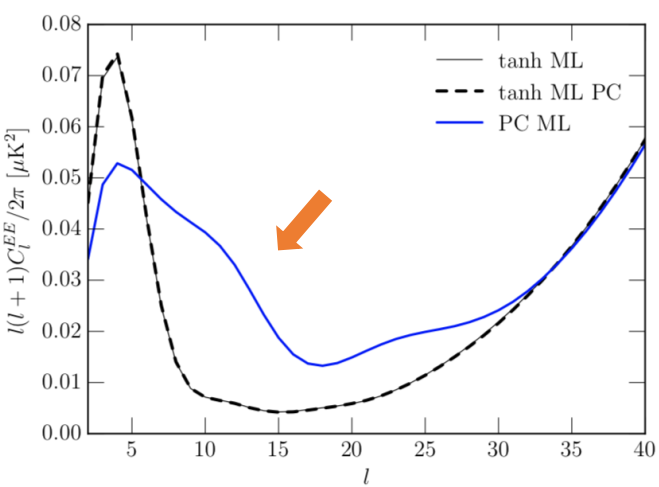
- Non parametric models trying to fit the *shape* of the reionization *bump* in the E-mode spectrum, e.g. Principal Components Analysis

  (Heinrich+2017, Heinrich & Hu 2018) find that Planck 2015 LFI polarization likelihood constrains 5 PC to describe C_ℓ^{EE} for $6 < z < 30$.

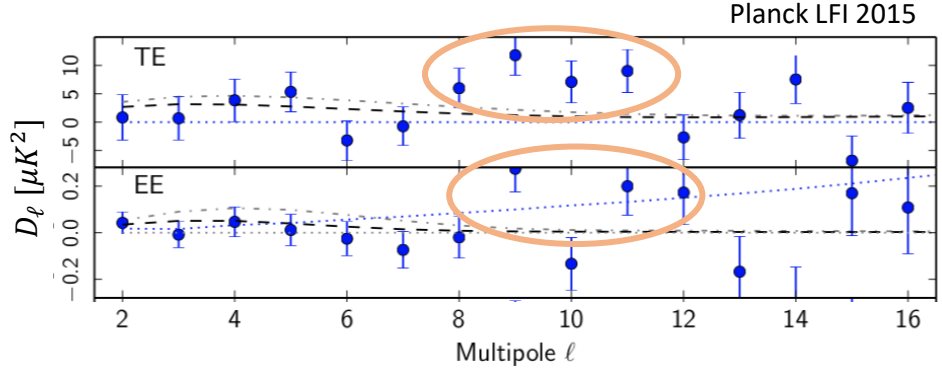
  This modelling results in a non-negligible contribution from high-redshifts

  $\tau(15, 30) = 0.033 \pm 0.016 \quad (\sim 2\sigma)$

  Tentatively interpreted as a signature of the first stars (Miranda+2017).



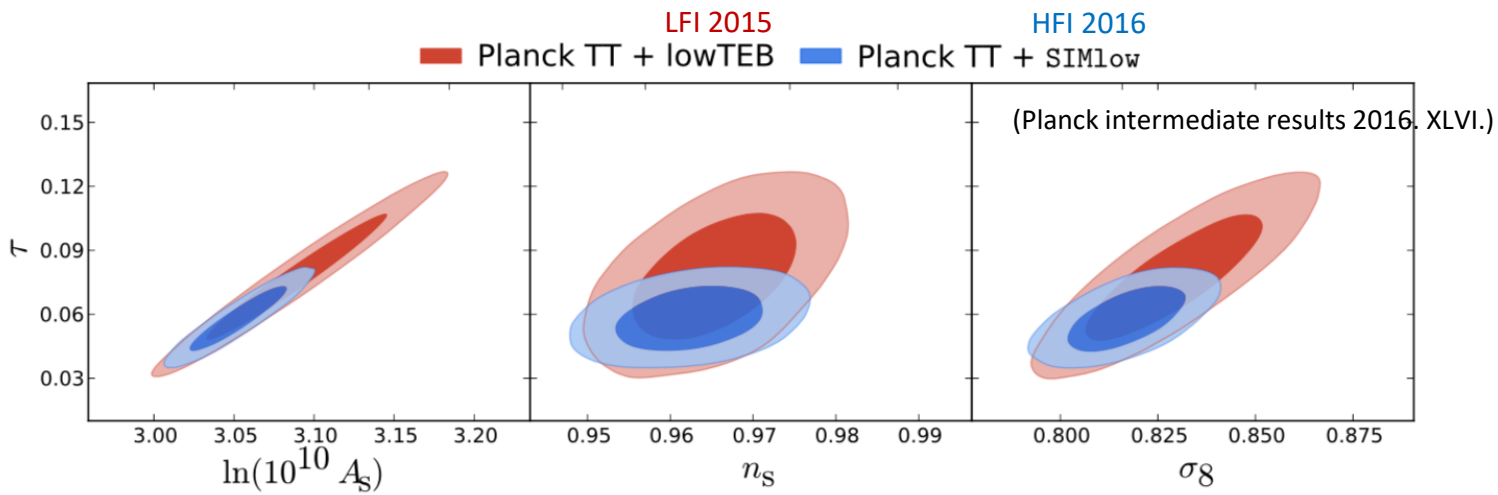
Planck LFI 2015



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

Large Scale Polarization

Impact on other cosmological parameters



Improved constraint on σ_8 is lower by 1σ. Better agreement with estimates from low redshift probes (e.g. galaxy clusters abundance, galaxy weak lensing), but *tensions* not completely removed.

Other cosmological parameters shifts by at most $0.5\ \sigma$ (see also Lattanzi+2017).

Hubble constant H_0 lowers by $0.4\ \sigma$ -> *tension* with direct measurements at $3.8\ \sigma$ level (Riess+2018)

Improved upper limit on sum of neutrino masses $\Sigma m_\nu < 0.72$ eV → $\Sigma m_\nu < 0.59$ eV → $\Sigma m_\nu < 0.17$ eV (+lensing+BAO)

An accurate measurement of τ is fundamental to enable a possible 4σ detection of the sum of the neutrino masses with Stage-4 experiments (Addison+2015, Calabrese+2016, Liu+2016)

Final remarks

Relevance to both Astrophysics & Cosmology

Cosmic reionization holds the key to understand structure formation in the Universe, and can inform us about the properties of the first sources (star formation efficiency, escape fraction of ionizing photons, …)

Accurate determination of cosmological parameters and precise tests of fundamental physics with the CMB (will) depend on the ability of constraining the optical depth, and the reionization history, to high precision.

Although Planck was not originally designed for polarization studies, its full sky observations of the CMB linear polarization represent already a significant improvement over previous measurements.

Current results from Planck $\tau = 0.055 \pm 0.009$ in *agreement* with astrophysical constraints, supporting the basic picture according to which reionization is powered by emission from early galaxies between $z \sim 10$ and $z \sim 6$, with AGNs taking over at $z < 6$.

What to look forward to

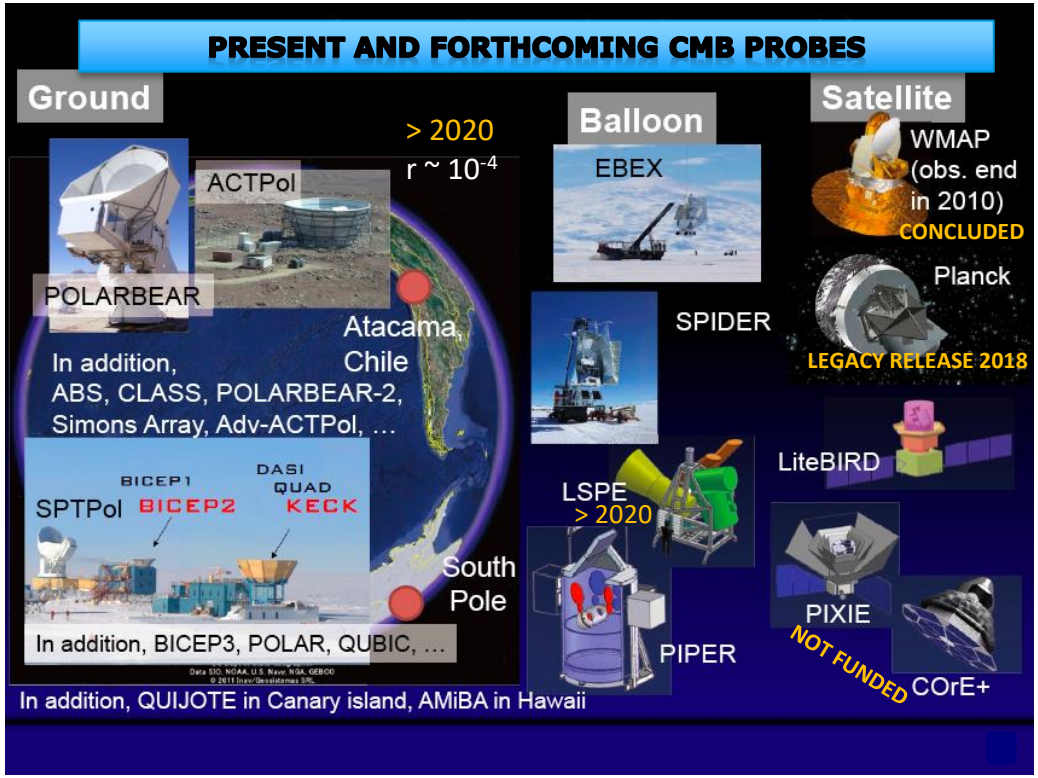
Planck legacy release in 2018, featuring improved polarization characterization and analyses

kSZ measurements from ground-based experiments (CMB-S4, Calabrese+2014, Smith & Ferraro 2017)

Future CMB missions for measuring polarization on large angular scales (e.g. LSPE, LiteBIRD)

Spectral Distortions (?)

Complementary Probes
JWST, Euclid, 21cm data (see Carlo's talk on SKA)



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THANK YOU