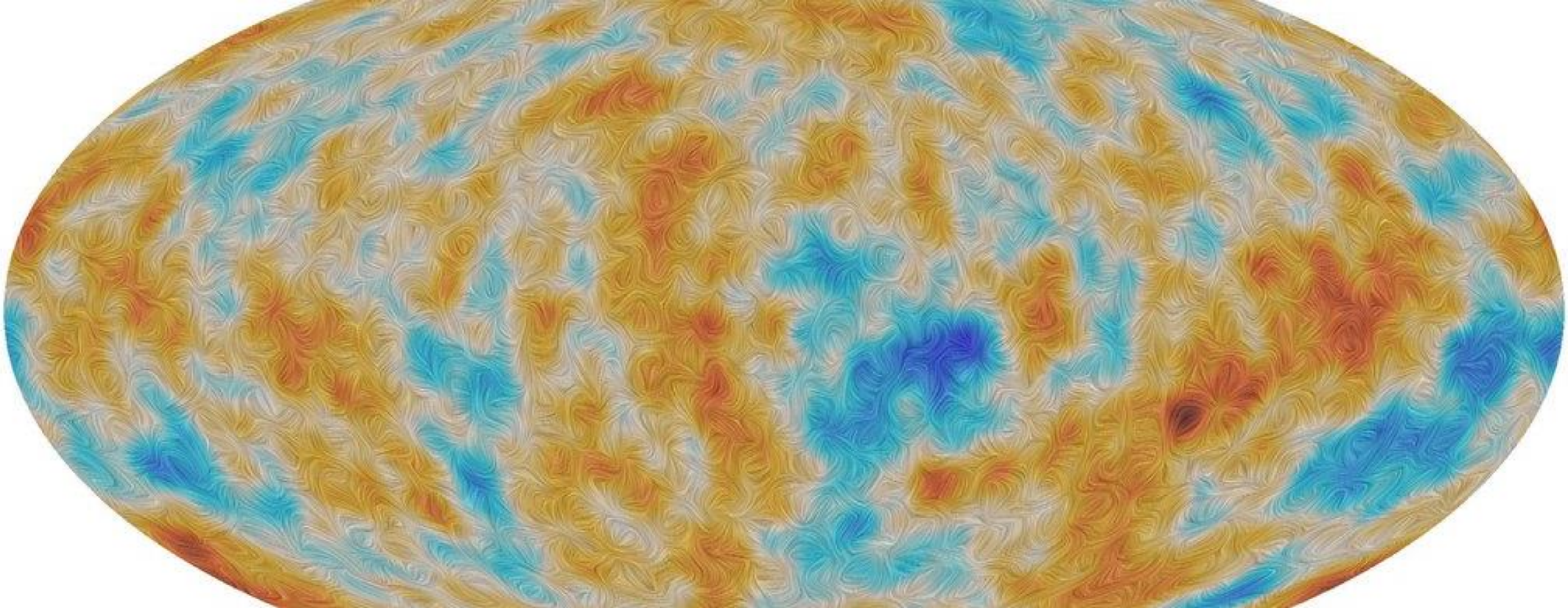

The CMB as a probe of reionization

CMB@60 - 29 May 2025

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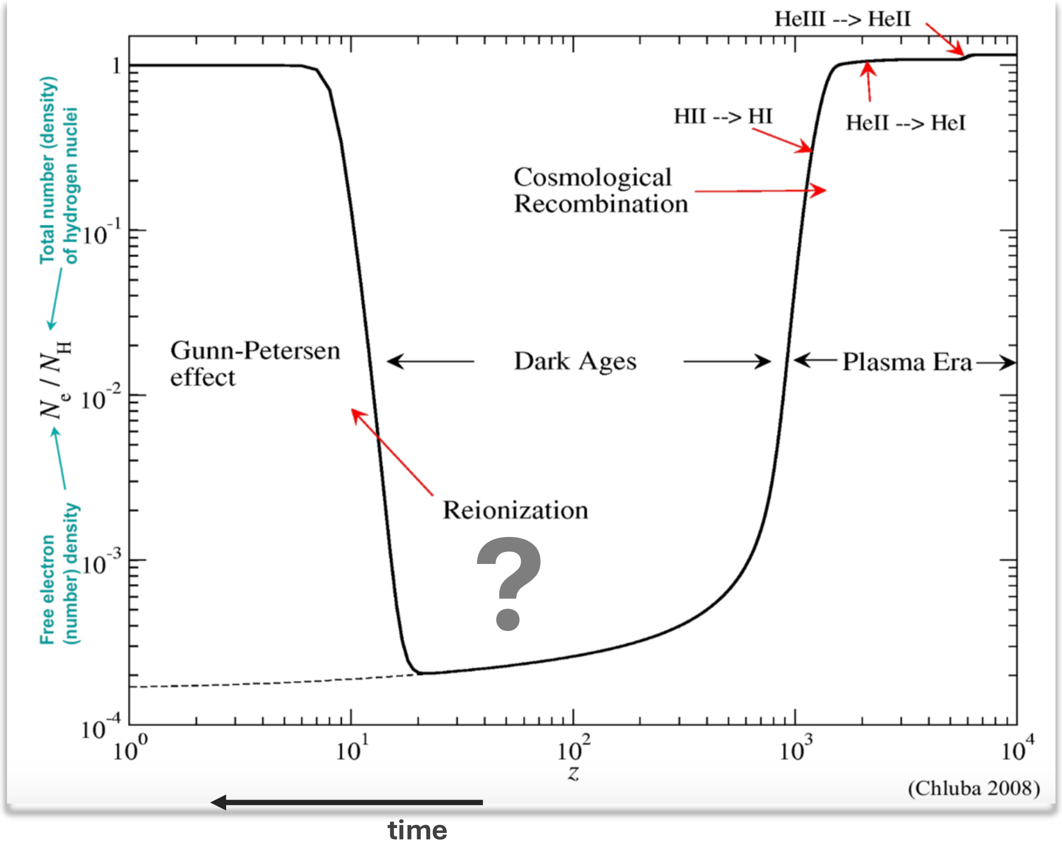
Reionization: imprint on the CMB

- Intergalactic gas transitioned from being cold and neutral, before the first cosmic structures formed, to hot and ionized.
- Exact mechanisms still uncertain: complex interactions between physics of structure formation, thermodynamics of diffuse matter, and emergence of astrophysical sources of radiation and heating.

Cosmic Ionization History



Reionization → newly freed electrons

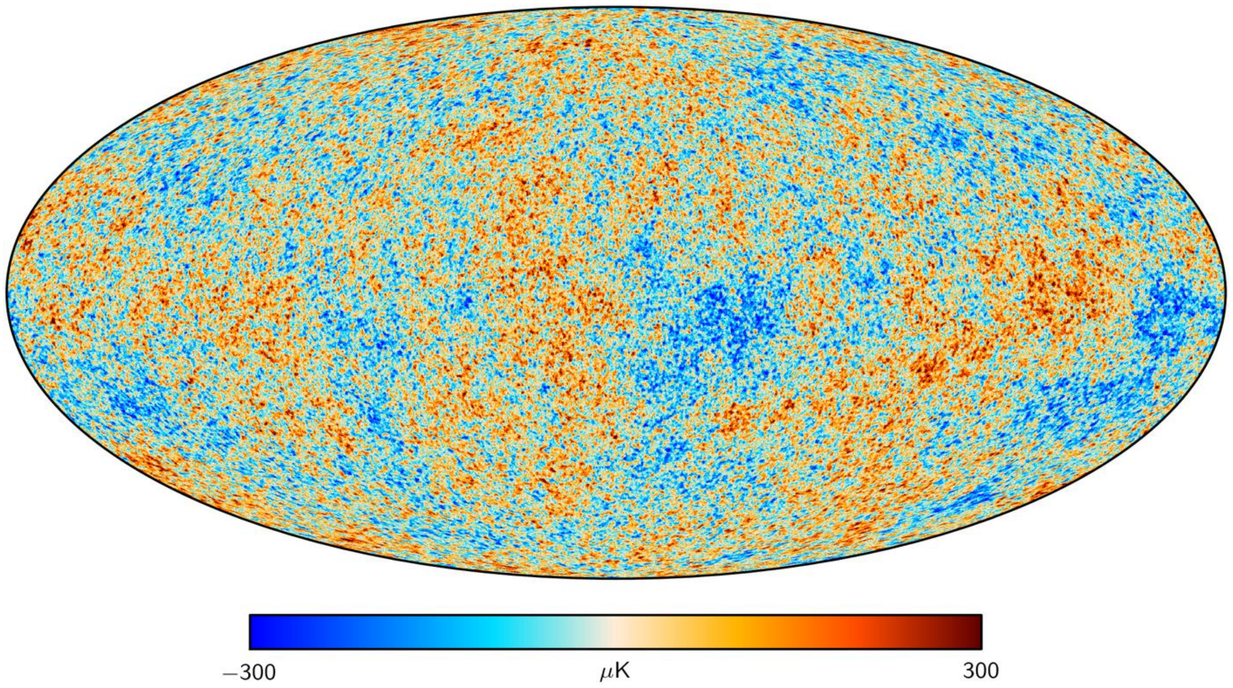
1. **Temperature Anisotropies**
2. **Polarization**
3. **Kinetic Sunyaev-Zel'dovich Effect (kSZ)**

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

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

Currently the optical depth to reionization τ is the ΛCDM parameter with the largest uncertainty (~ 10%).

Temperature Anisotropies

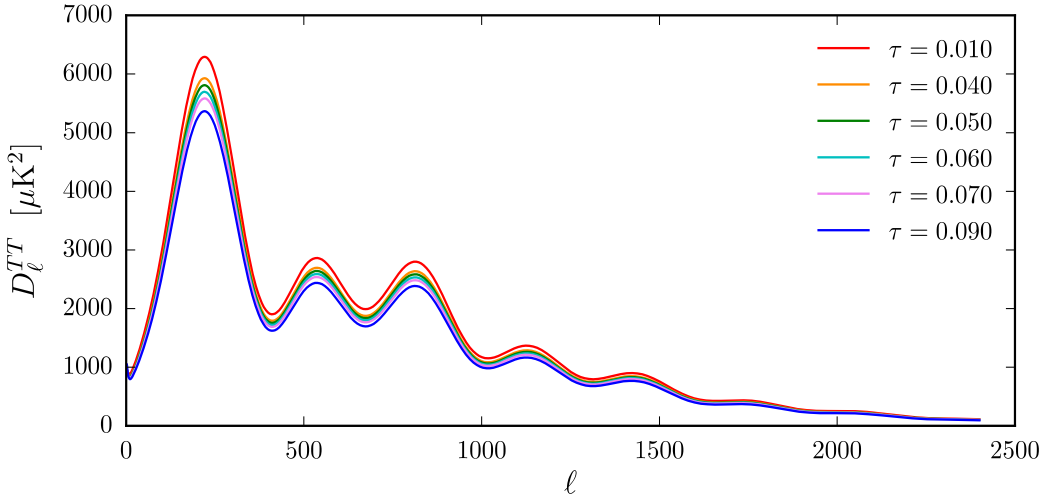


Planck Collaboration 2018

Newly freed electrons during reionization suppress fluctuations at small angular scales

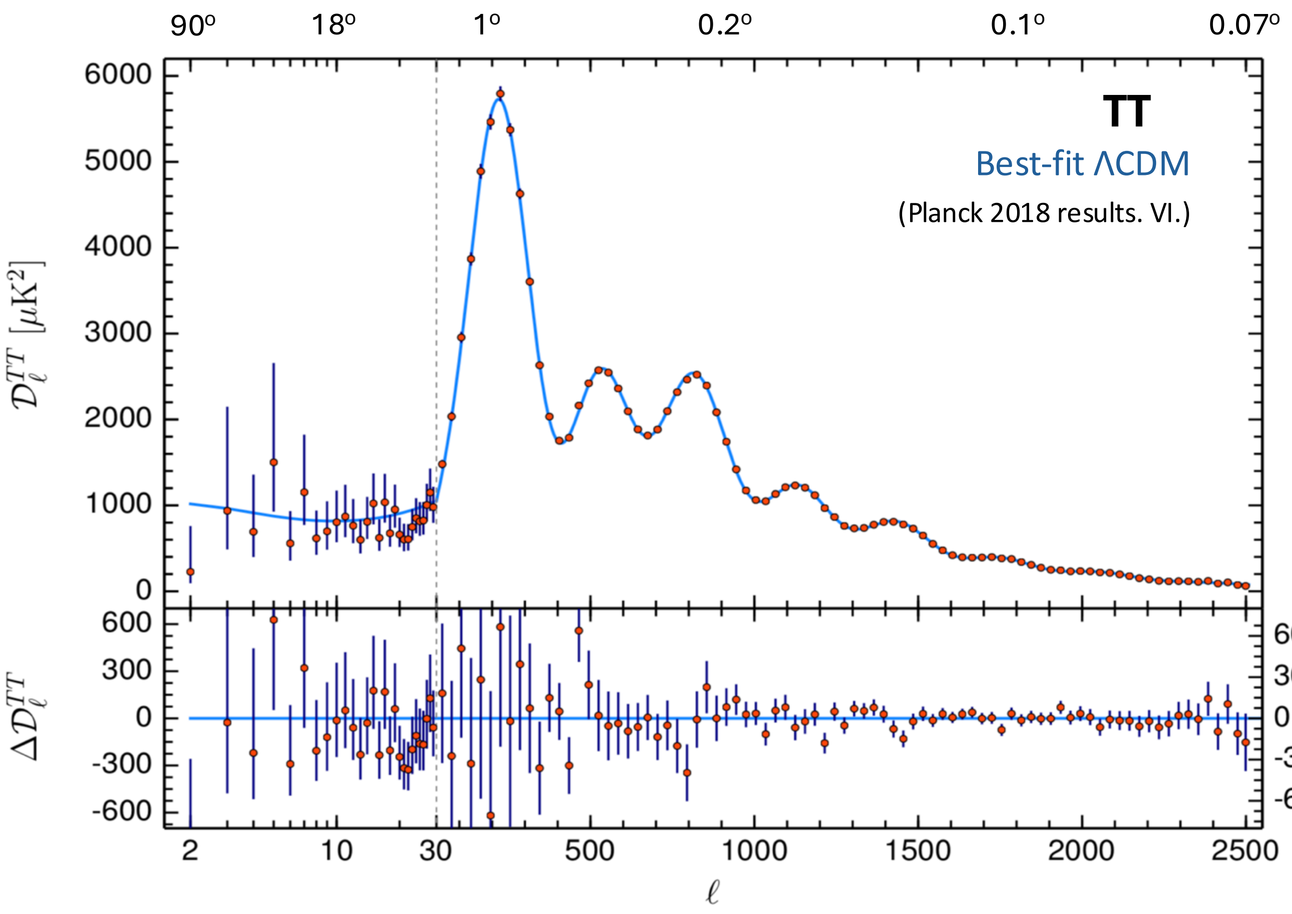
$$\Delta_T \rightarrow \Delta_T e^{-\tau}$$

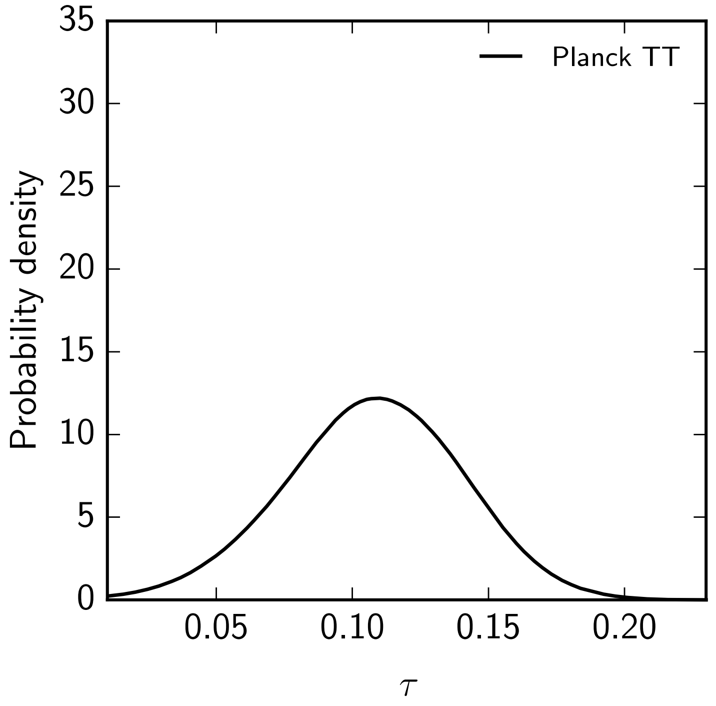
$$C_\ell^{TT} \propto A_s e^{-2\tau}$$



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

Temperature Anisotropies



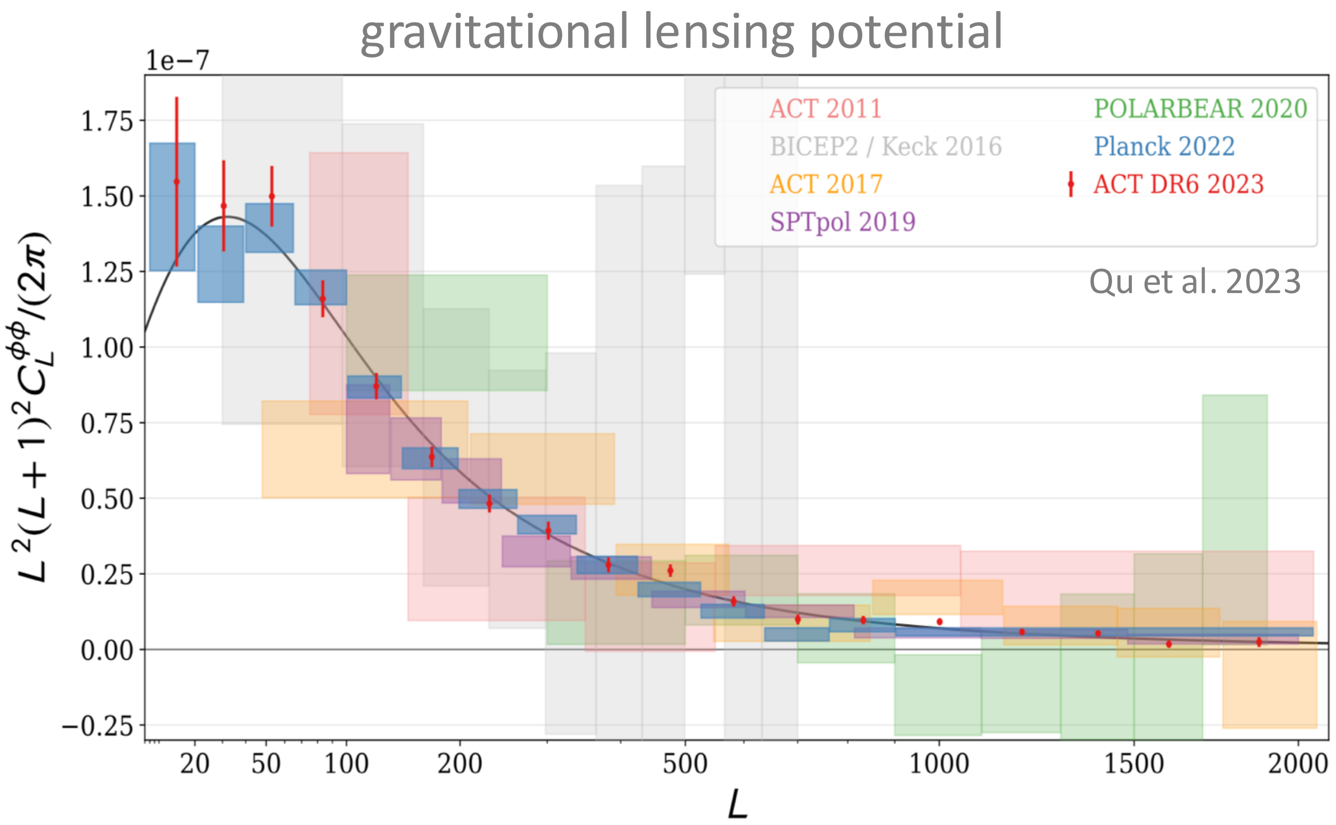


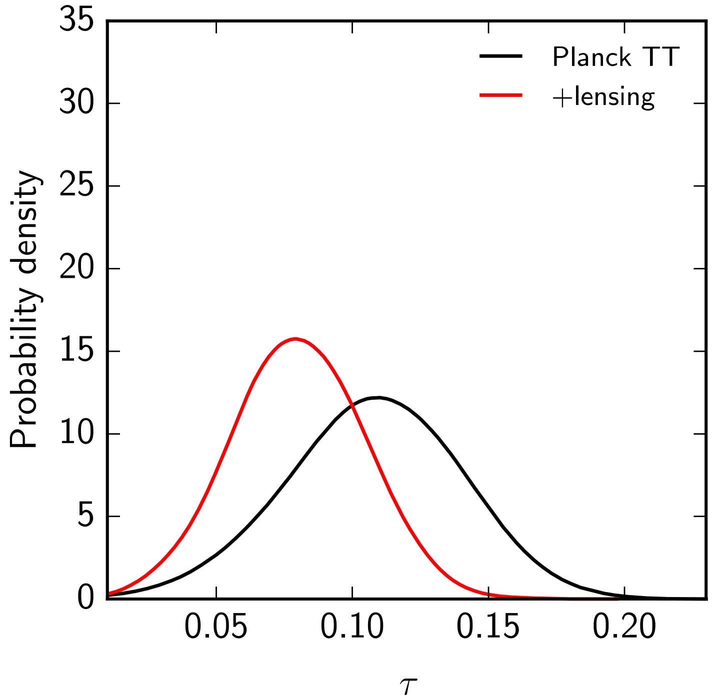
TT power spectrum constrains the combination $A_s\, e^{-2\tau}$ at sub-% level !

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

- Angular power spectrum Cosmic Variance limited up to $\ell \simeq 1600$
- Sky fractions ranging from 86% to 40%
- Seven peaks measured with high signal-to-noise

Adding CMB lensing





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

Planck, ACT provide > 40σ detections

Breaks degeneracy with A_s

τ = 0.080 ± 0.025 (68% CL)

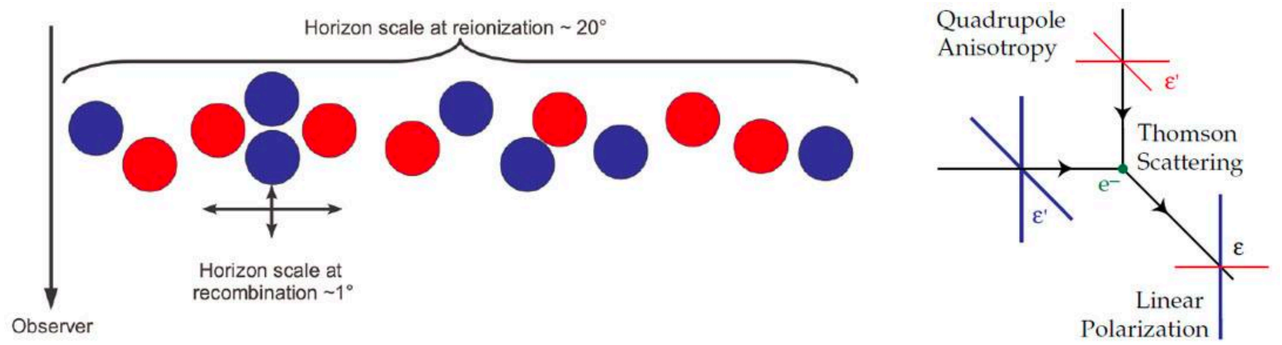
Polarization

(Credit: S. Zaroubi)

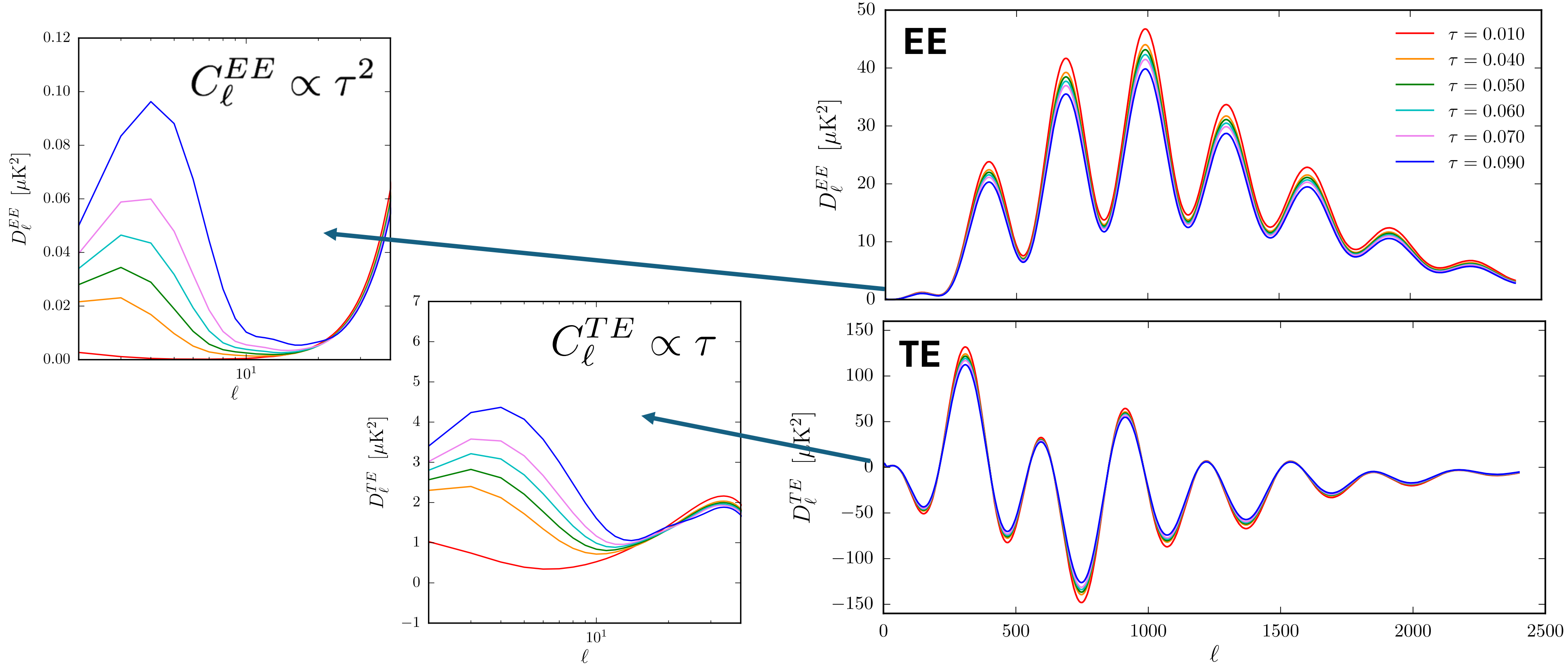
Thomson scattering of local quadrupolar anisotropies off free electrons generates CMB linear polarization.

At reionization → **Bump at low-ℓ in angular power spectra**

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

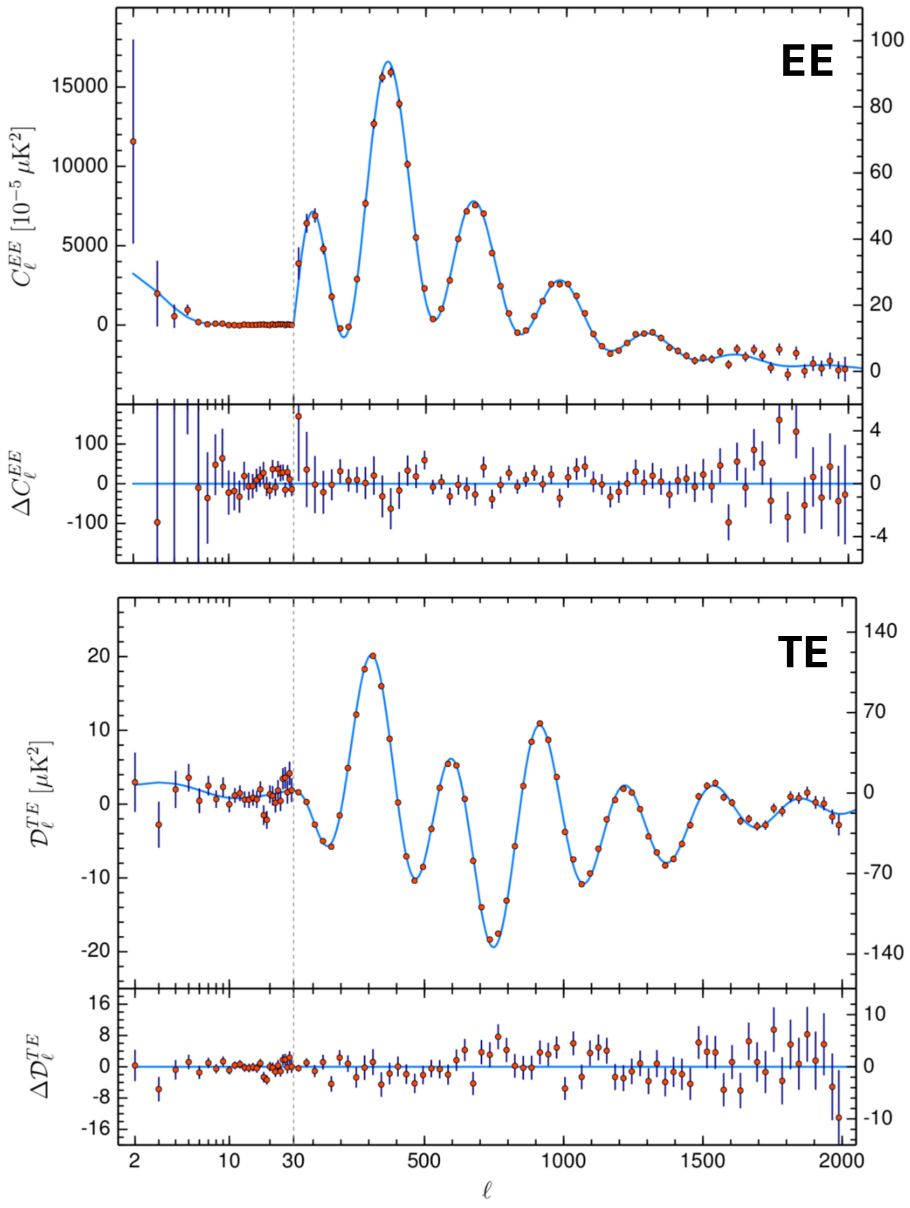


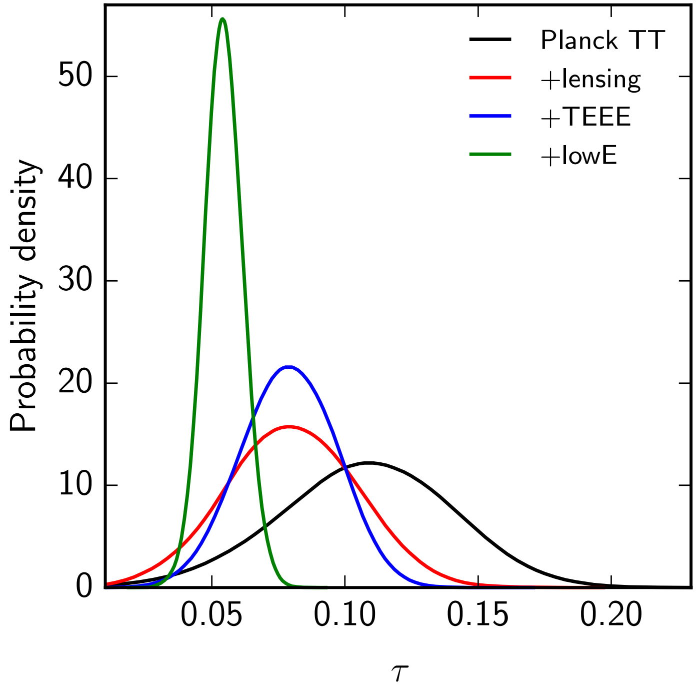
Damping of fluctuations at small angular scales



Polarization

(Planck 2018 results. VI.)





$\boldsymbol{\tau} = 0.079 \pm 0.018$ $\boldsymbol{\tau} = 0.0544 \pm 0.0073$

- Polarization at small angular scales tightens overall the constraints on the cosmological parameters.
- Large-scale EE gives the strongest constraints on τ.

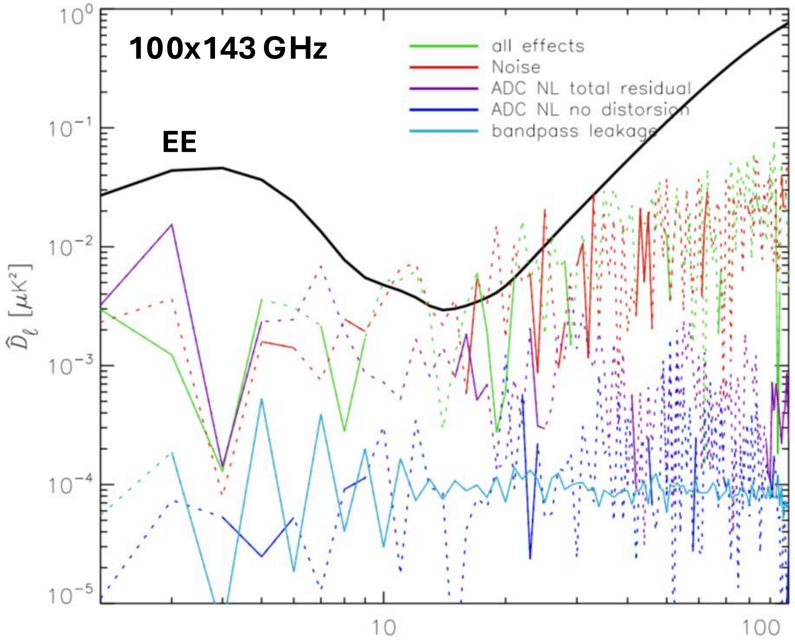
Large Scale Polarization: Challenges

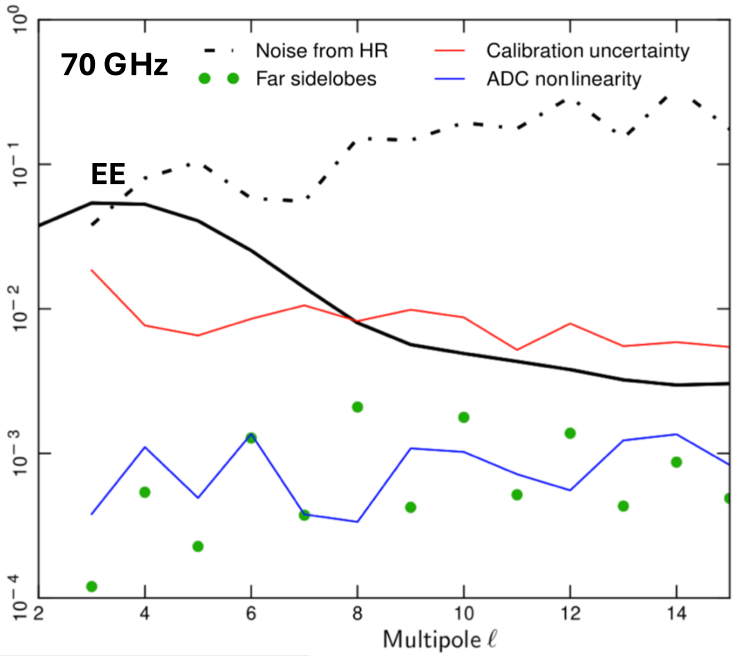
Large scale polarization has little dependence on other cosmological parameters and currently gives the tightest constraints on τ

Measuring large-scale polarization is challenging

- ~ 100 times **weaker signal** than temperature
- Differential measurement
- Large angular scales are **better measured from space**
- **Systematic effects, noise and foregrounds** are important, need:
  - Broad frequency range to model foregrounds
  - Complementarity between instruments
  - E2E realistic simulations to assess interplay of various effects
  - Different data analysis techniques for robustness

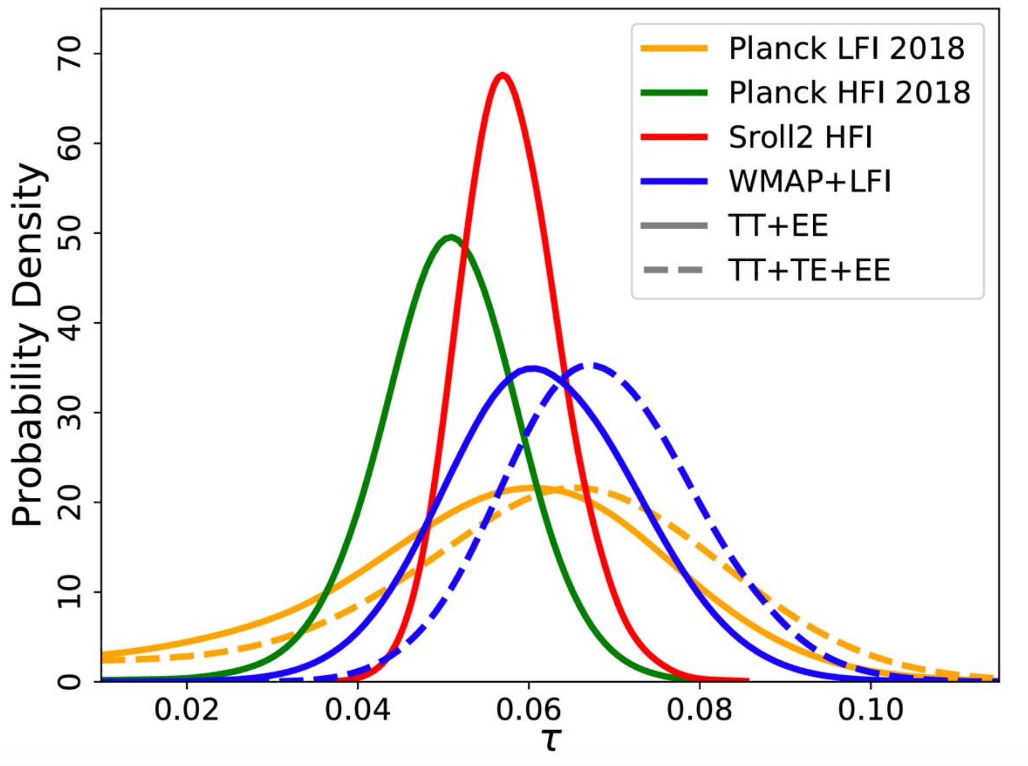
Planck intermediate results 2016. XLVI.

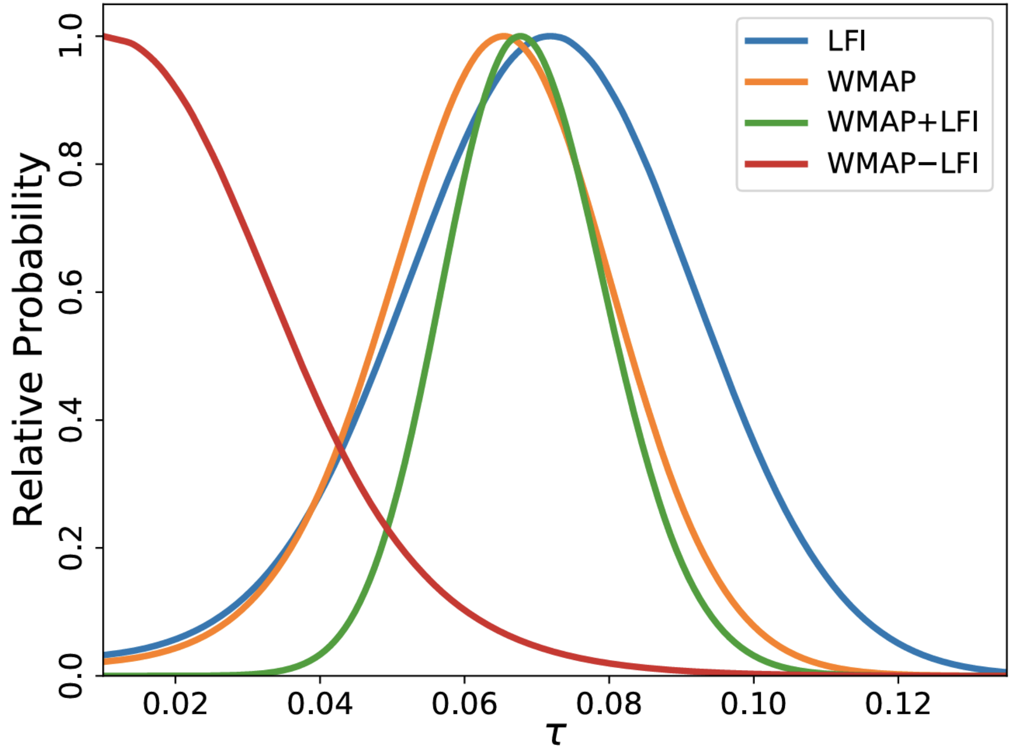




Large Scale Polarization: Consistency of Datasets

Natale et al. 2023, Planck 2018 results V.



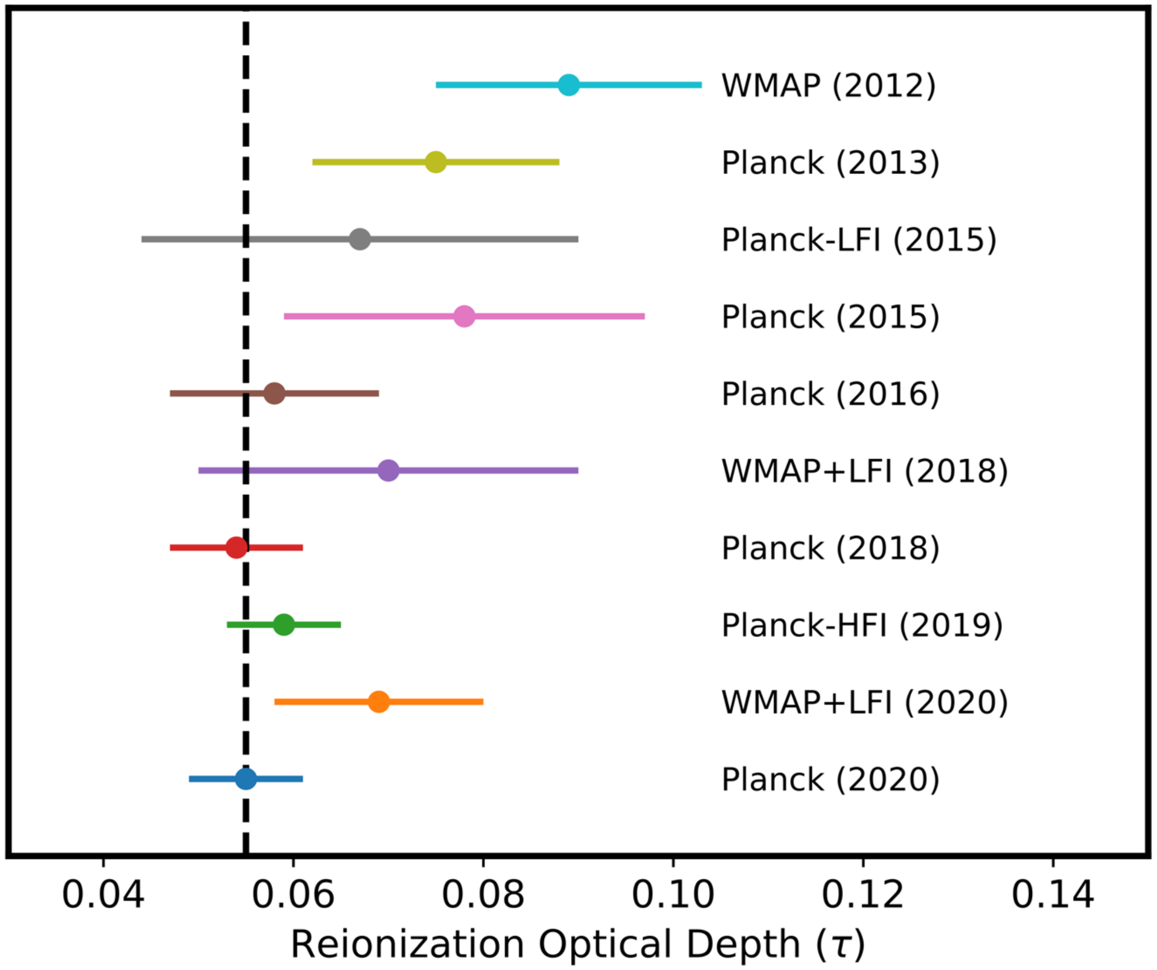


… lots of consistency tests on the datasets

Characterization of the impact of single multipoles, fraction of the sky, …

Large Scale Polarization: “Recent” history of τ measurements

LiteBIRD Coll. PTEP 2023



Improved measurements, together with increased systematics and foreground control
→ **trend towards lower τ values**

$\tau = 0.17 \pm 0.04$ WMAP (2003)

…

…

$\tau = 0.0580 \pm 0.0064$ (Roger+21, Planck-HFI)

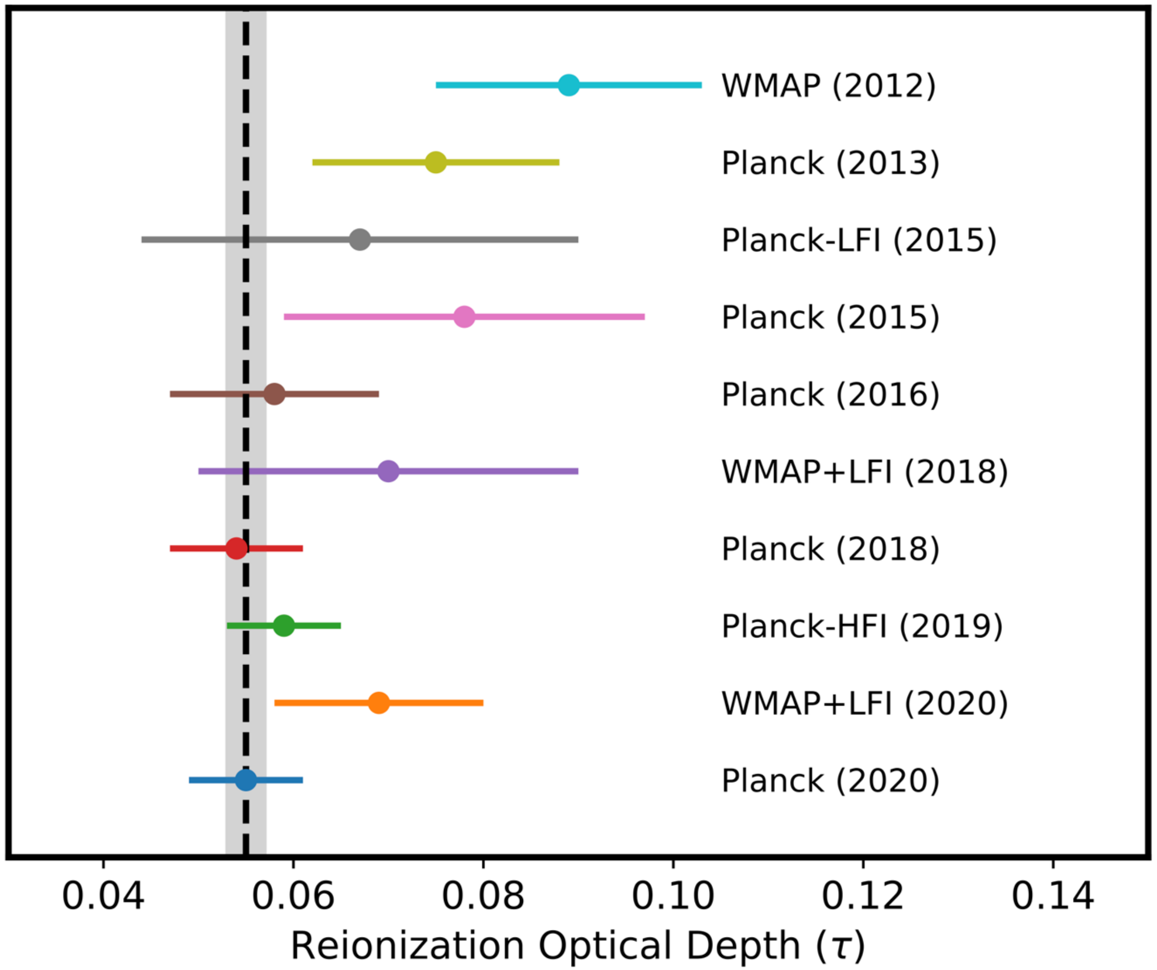
$\tau = 0.066 \pm 0.013$ (BeyondPlanck, WMAP+LFI)

$\tau = 0.0579 \pm 0.0082$ (Wolz+23, Planck-HFI)

$\tau = 0.053 \pm 0.018$ (Li+2025, CLASS x Planck)

Large Scale Polarization: Future prospects

LiteBIRD Coll. PTEP 2023



LiteBIRD will provide a cosmic-variance limited measurement of the ***E*-mode** power spectrum at large scales ($2 < \ell < 200$)

This will lead to

- Signal-dominated measurement of the **optical depth** to reionization ($f_{sky} \sim 70\%$)

  $\sigma(\tau) \approx 0.002 \Rightarrow \times 3$ improvement with respect to current bounds from Planck

- Sensitivity to the **reionization history** is under investigation

Reionization History

- Shown optical depth estimates are obtained assuming an *instantaneous* reionization model for the ionization fraction.
- **Generalizing the ionization fraction model**, allowing for the reconstruction of any arbitrary history using non-parametric models.

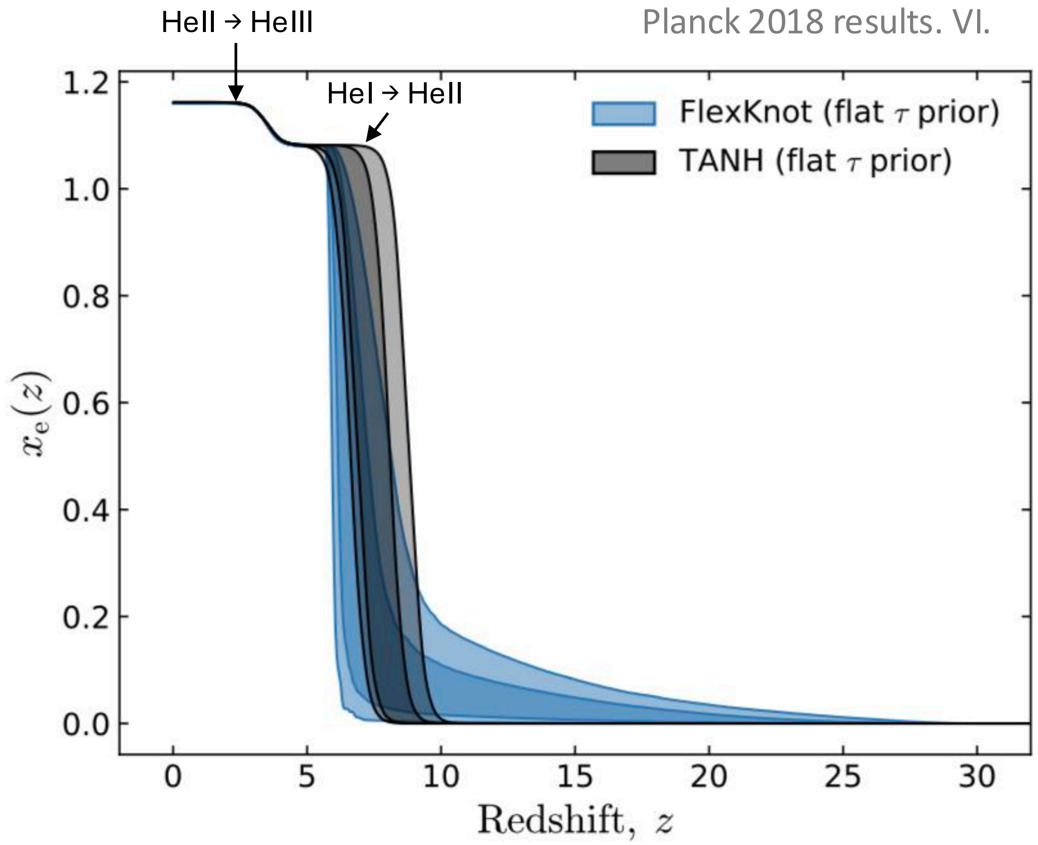
With Planck data:

- τ estimate has **little sensitivity to details of reionization** history modelling
- Consistent with a **universe fully reionized by $z = 6$**
- **Reionization happened late and fast**
- **No significant high-redshift contribution** to the optical depth

$$\tau(15, 30) < 0.018 \quad \text{at} \quad 95\% \text{ CL}$$

- Several analyses come to similar conclusions (Millea & Bouchet 2018, Hazra+2019, Qin+2020, Heinrich & Hu 2021, Paoletti+2025, Ilić+2025, …)

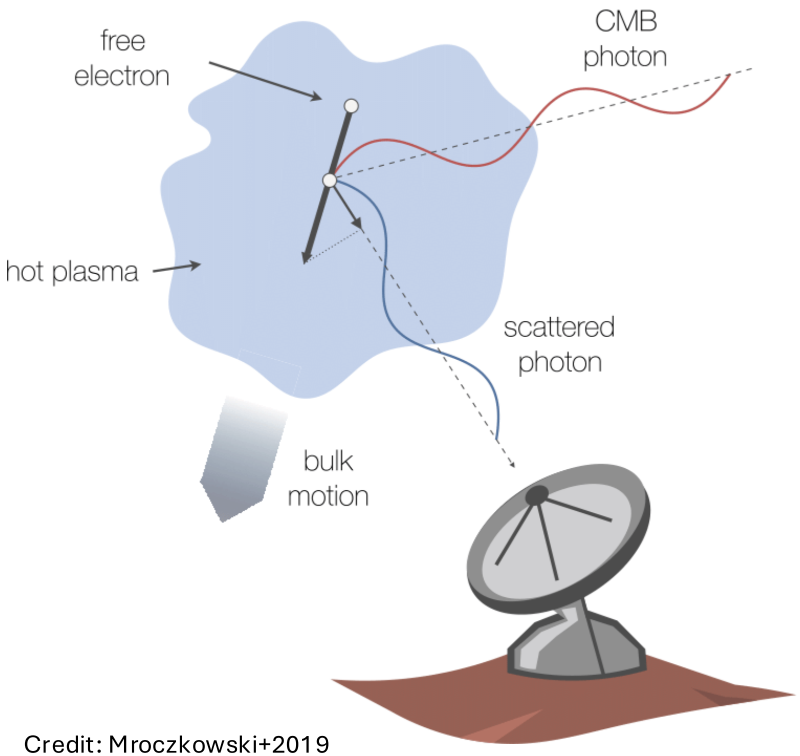
Planck 2018 results. VI.



Reionization History with kSZ

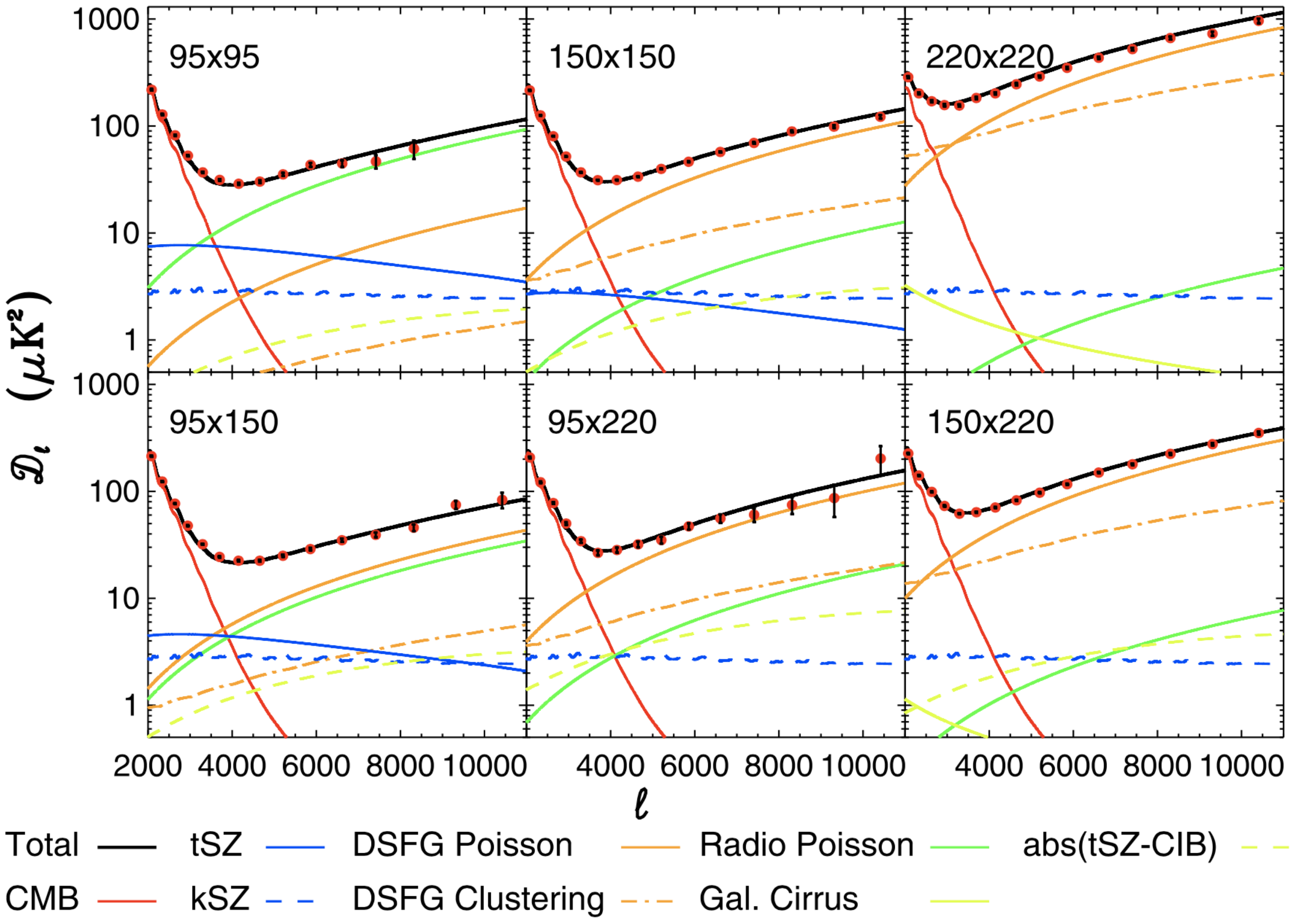
Kinetic Sunyaev-Zel'dovich Effect: secondary temperature anisotropy on small angular scales due to Doppler-shift of CMB photons scattering off electrons moving in bulk flows.

Two components: **homogeneous** = fully ionized IGM, and **patchy** = ionized bubbles around the first sources.



Credit: Mroczkowski+2019

Reichardt et. al 2021 (SPT-SZ + SPTpol)



Reionization History with kSZ

- **kSZ detection** from spectra at ~ 3σ level

  $$D_{3000}^{kSZ} = 3.0 \pm 1.0\ \mu K^2$$

- Some dependence on CIB and SZ models

- Homogeneous and patchy components are highly degenerate in current data.

- Using simulations to model the amplitude of the homogeneous part of the signal

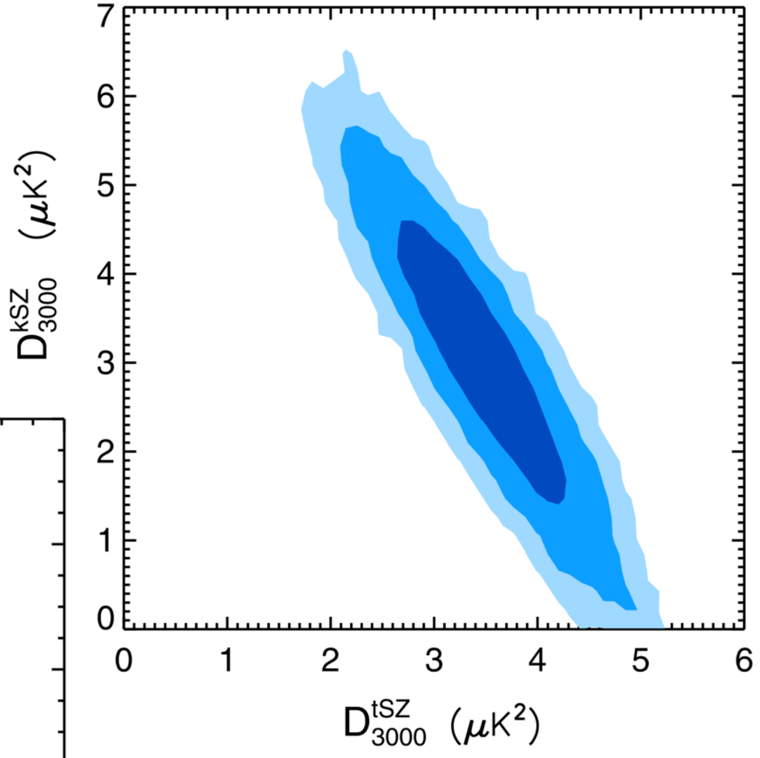
→ **Upper bound on the patchy component**

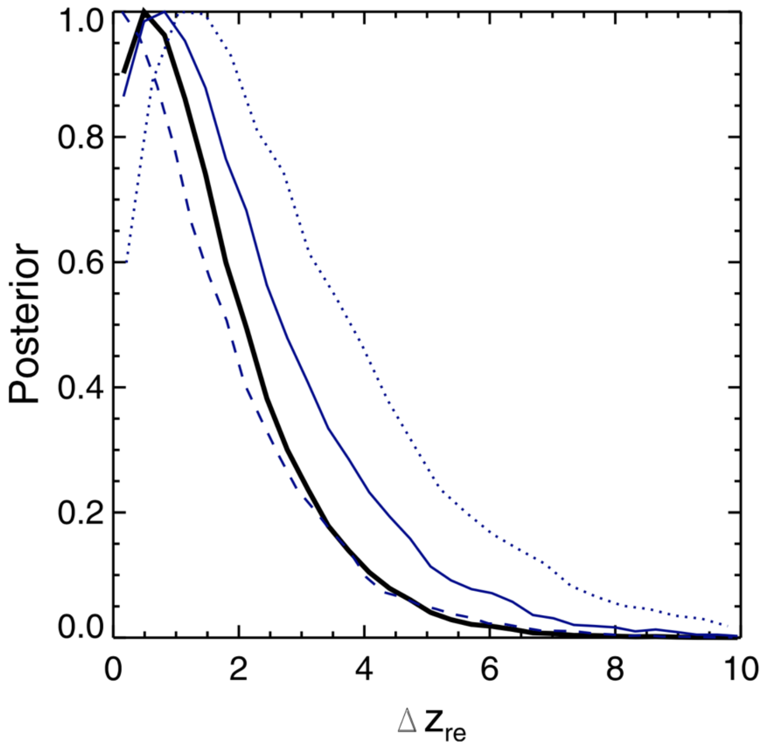
$$D_{3000}^{p-kSZ} < 2.9\ \mu K^2 \quad \text{at} \quad 95\%\ \text{CL}$$

→ **Upper bound on the duration of EoR**

$$\Delta z_{re}^{25\%-75\%} < 5.4 \quad \text{at} \quad 95\%\ \text{CL}$$

Reichardt et. al 2021 (SPT-SZ + SPTpol)





Optical depth and neutrino masses

Massive neutrinos are expected to slow down structure formation.

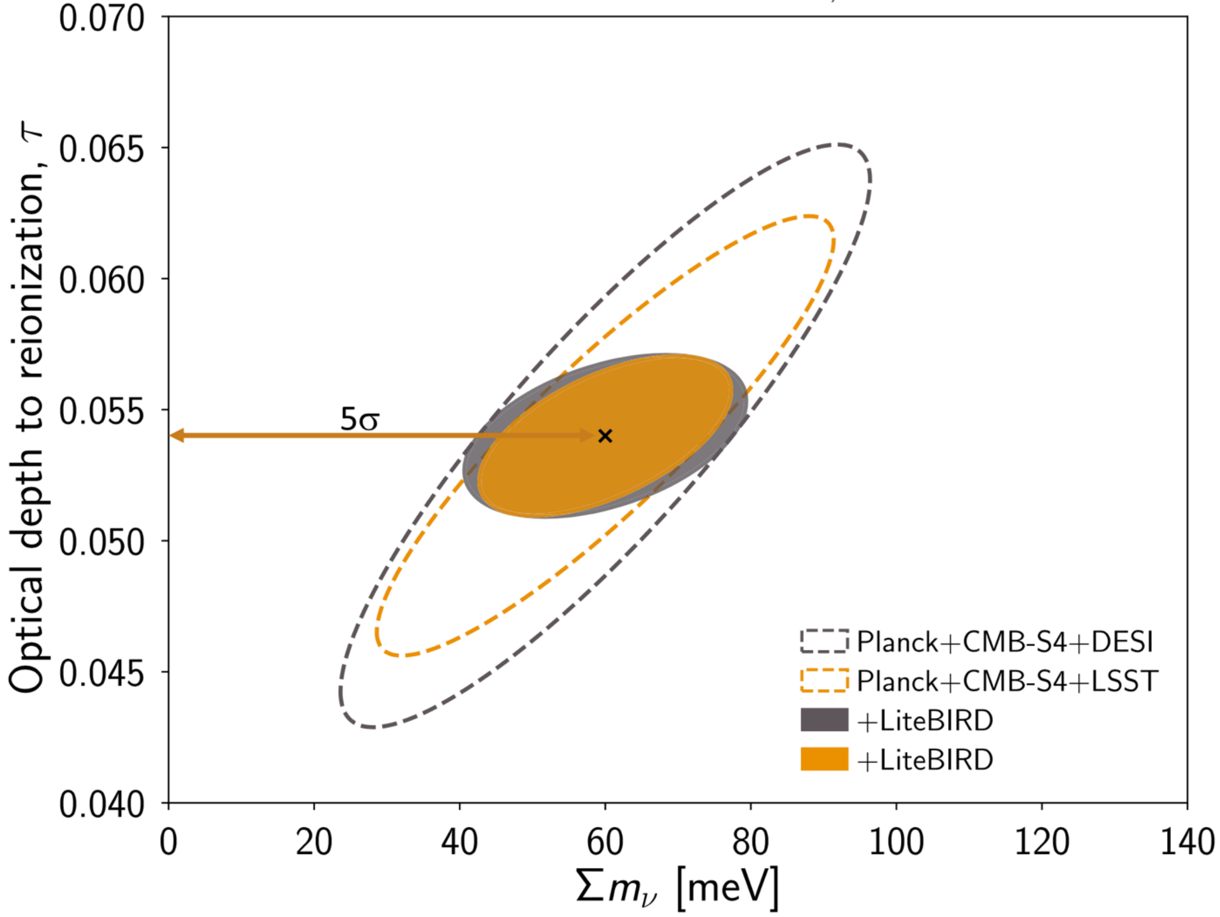
→ $\sum m_\nu$ can be estimated by comparing low redshift vs primordial amplitude of fluctuations.

Due to the degeneracy with A_s, improving τ determination is crucial to measure the sum of neutrino masses.

Improvement in the τ constraint with LiteBIRD full-sky polarization measurements will allow:

- × **3 - 4 improvement** on $\sigma(\sum m_\nu)$ with respect to current bounds
- **$\sigma(\sum m_\nu) \approx$ 12 meV** ⇒ 5σ detection for $\sum m_\nu$ = 60 meV (minimum value in normal ordering)
- Potentially distinguishing between inverted neutrino mass ordering and normal ordering

Calabrese+2017, LiteBIRD Coll. PTEP 2023



For the next 60 years? Among other things …

- Planck estimate of electron scattering optical depth is going to be the best we can have for several years.
- LiteBIRD **large-scale polarization** measurements can allow the most accurate measurement of τ from the CMB.

- Improved **kSZ constraints** from future experiments covering larger sky areas with lower noise and more frequency bands (Simons Observatory, CCAT→FYST, CMB-S4…)
- **Cross-correlations** of kSZ with LSS at the EoR (21cm, Ly-α, …)

- Energy output from structure formation generates **CMB spectral distortions**

- Synergy and combination with **astrophysical predictions and constraints** (JWST, Euclid, Radio, …) will be key for robust inference and to tighten constraints on τ

LiteBIRD Coll. PTEP 2023