Thomson optical depth
–
constraints on Reionization from the CMB
(as seen by *Planck*)

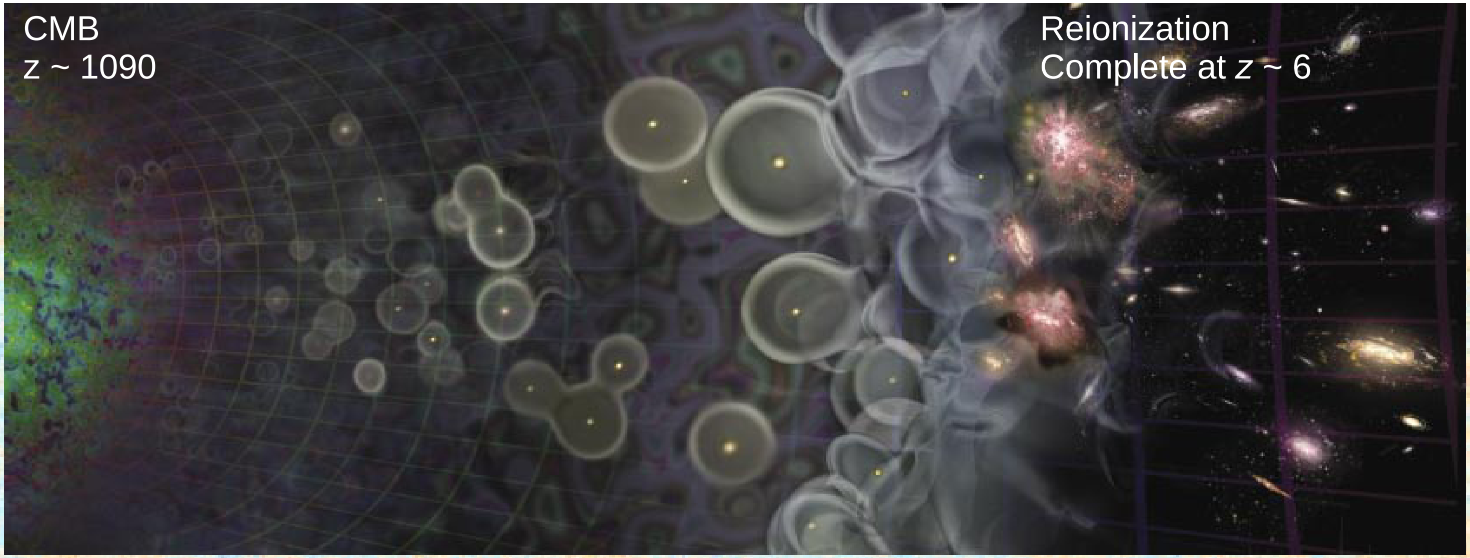
Mathieu Langer

Institut d'Astrophysique Spatiale
Université Paris-Sud – Université Paris-Saclay

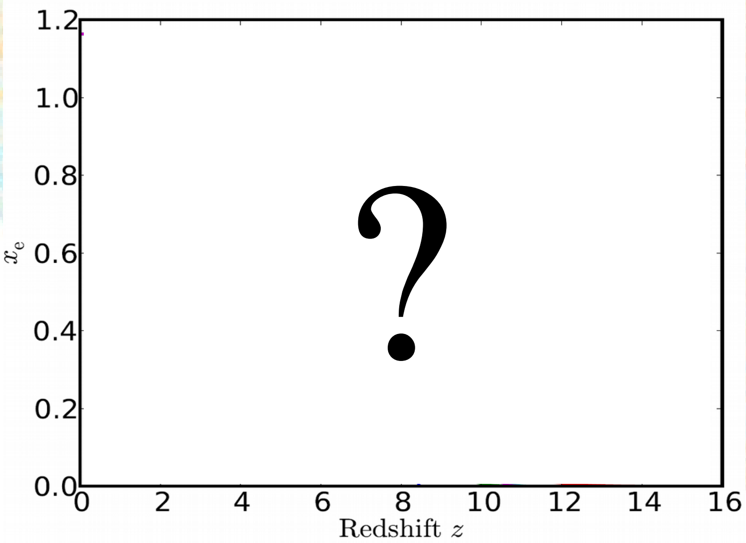
This talk has received funding from the European Union's
Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]

IAU Symposium 333, "Peering towards Cosmic Dawn"
2-6.10.2017 – Dubrovnik

Reducing Reionization



Credits :Sci. Am. & A. Loeb, 2006



- Complex history of Reionization in one function:

  Ionised fraction

$$x_{\rm e}(z) = \bar{n}_{\rm e}(z)/\bar{n}_{\rm H}(z)$$

- Thomson optical depth

$$\tau(z) = \sigma_{\rm T}\bar{n}_{\rm e,0}\int_0^z {\rm d}z'\frac{{\rm d}l}{{\rm d}z'}x_{\rm e}(z')(1+z')^3$$

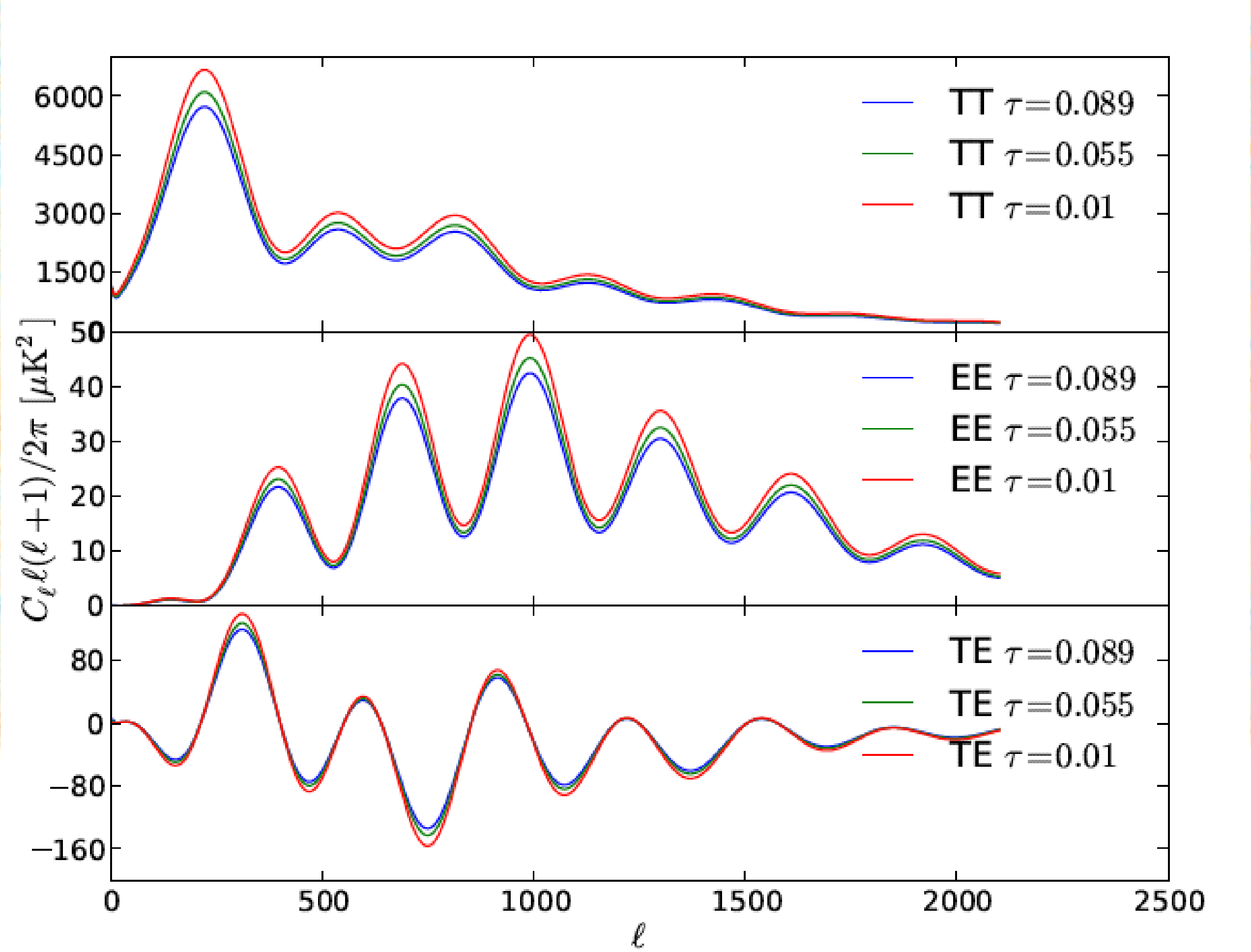
Reionization & the CMB

CMB provides information on Reionization through:

- Temperature anisotropies
  - suppression of TT power at large multipoles
    (very degenerate with other cosmological parameters and foregrounds)
- Polarisation anisotropies
  - suppression of EE power at large multipoles
  - new polarisation anisotropy at large angular scales because the horizon has grown to a much larger size by that epoch
- Kinetic Sunyaev-Zel'dovich effect
  - re-scattering of CMB photons off newly freed electrons (Sunyaev & Zel'dovich 1980)

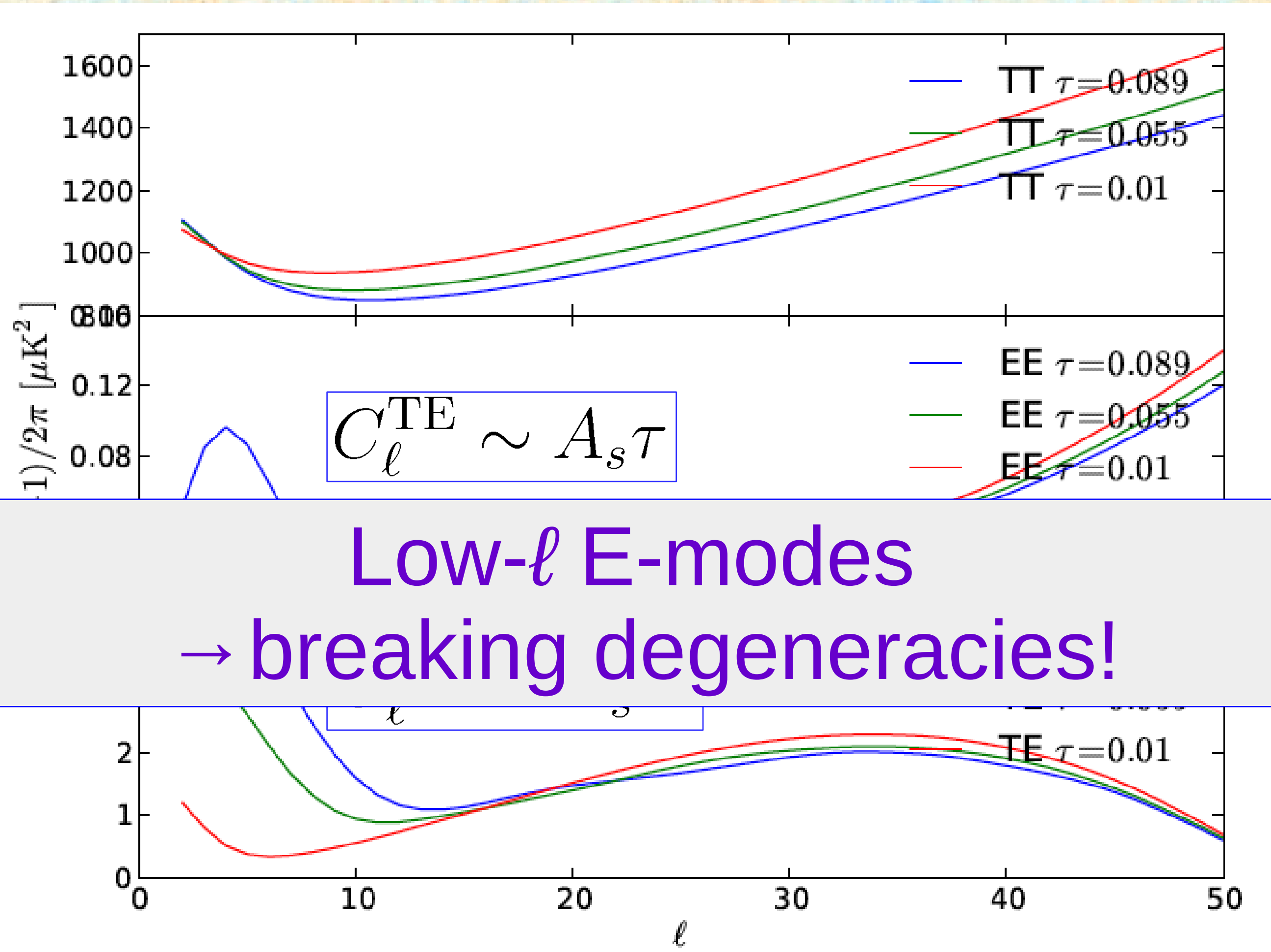
Reionization & CMB: high-ℓ effect

Damping of the power spectra $\sim A_s e^{-2\tau}$



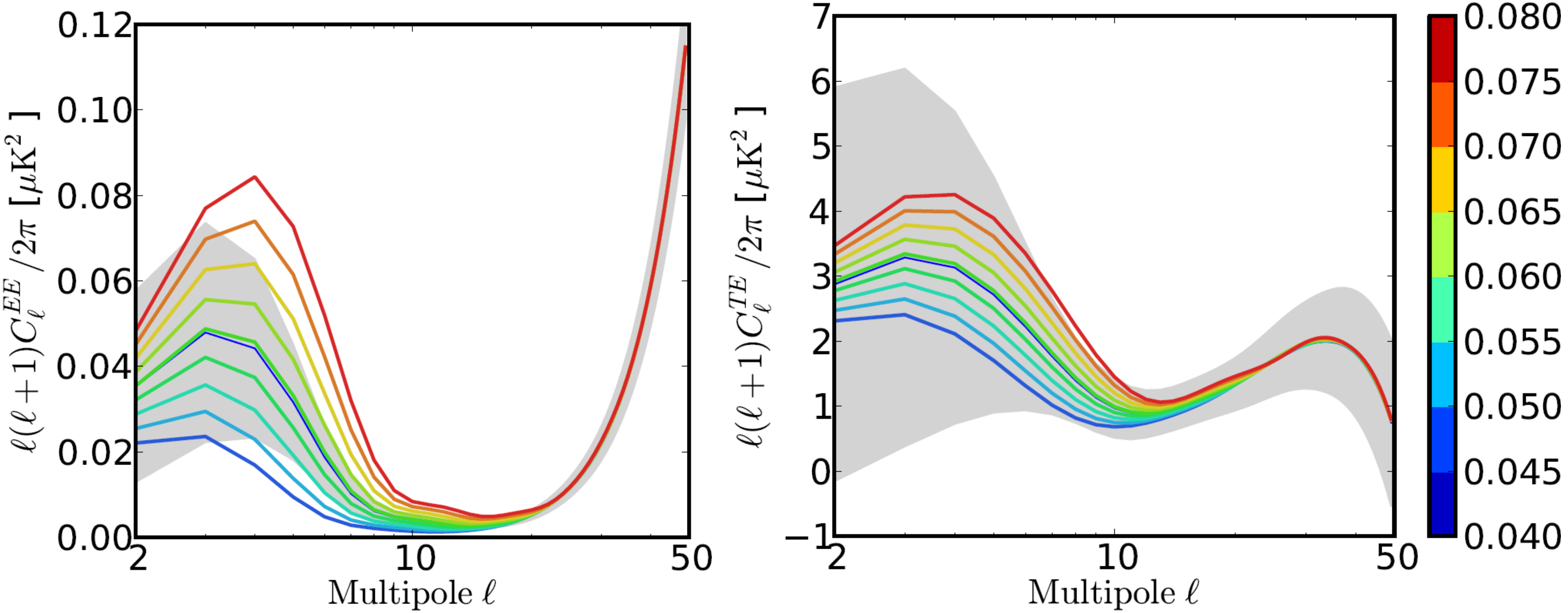
Reionization & CMB: low-ℓ effect

- Additional power on large scales



Low-ℓ E-modes
$\rightarrow$ breaking degeneracies!

Reionization & CMB polar: low-ℓ effect

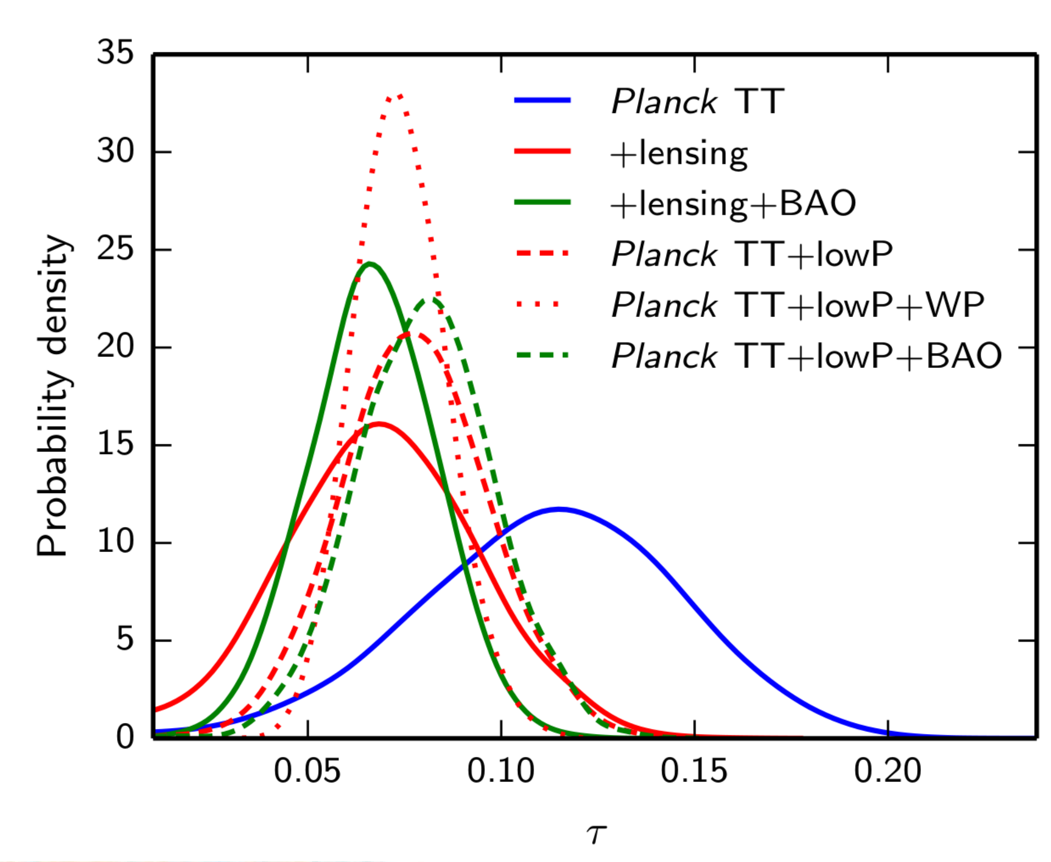


The CMB: a good probe of the optical depth τ

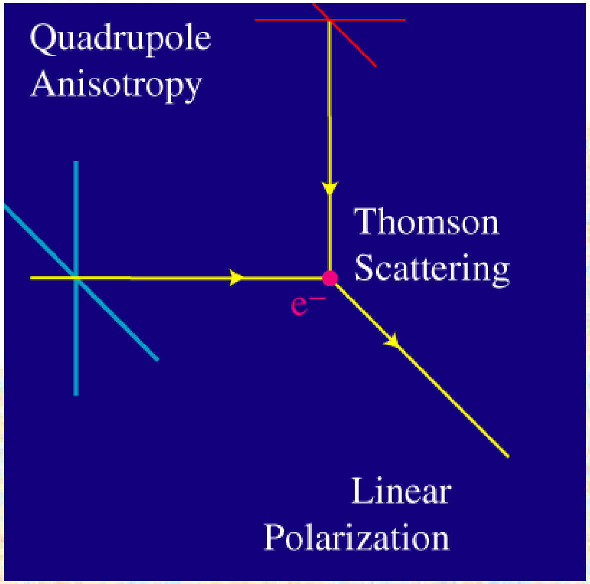
History of the reionization optical depth

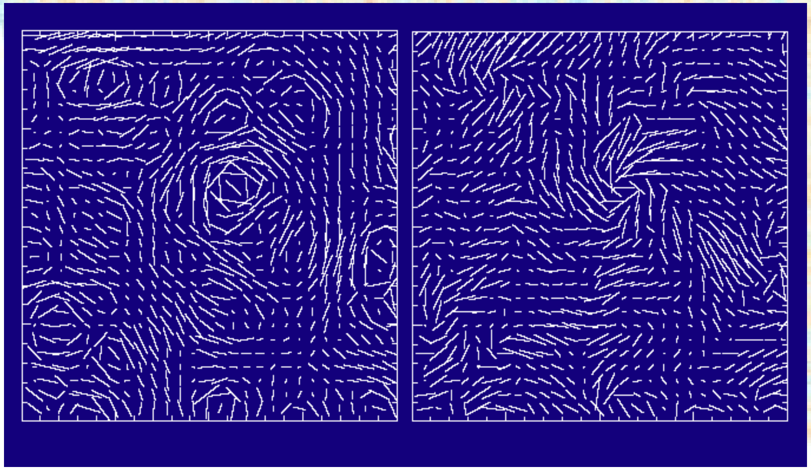
- **WMAP**
  - $\tau = 0.089 \pm 0.014$
- ***Planck* 2013**
  - $\tau = 0.089 \pm 0.014$ (TT with WP)
  - $\tau = 0.075 \pm 0.013$ (TT with *Planck* dust)
- ***Planck* 2015**
  - $\tau = 0.078 \pm 0.019$ (TT + lowP)
  - $\tau = 0.066 \pm 0.016$ (TT + lowP + lensing)
  - $\tau = 0.067 \pm 0.016$ (TT + lensing + BAO)
- ***Planck* HFI EE low-ℓ**
  - Decreasing trend goes on…

Planck 2015 results.
XIII. Cosmological parameters (2016)

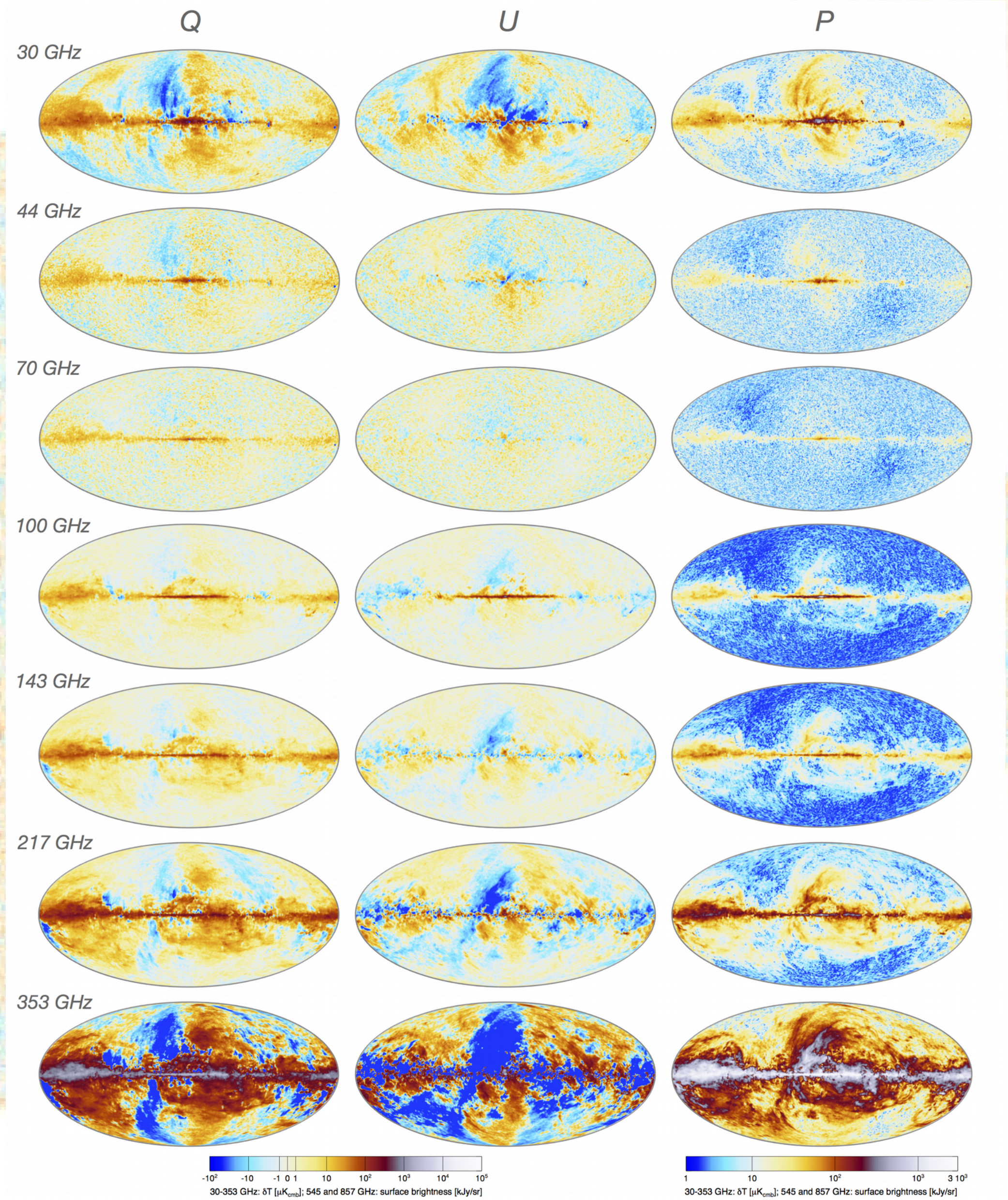


CMB: polarization anisotropies

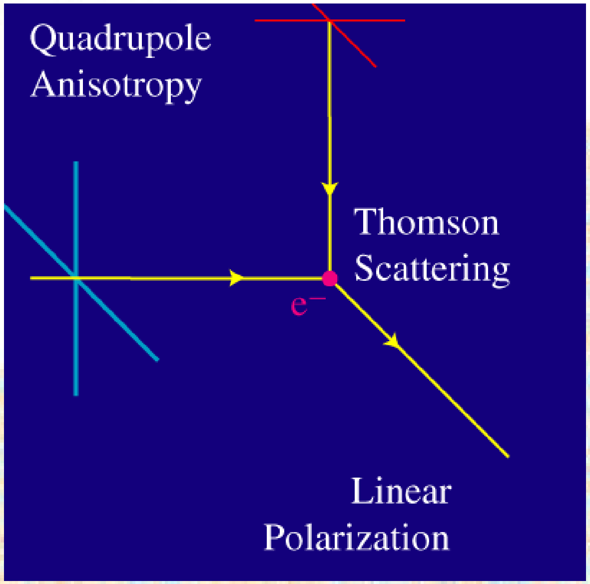


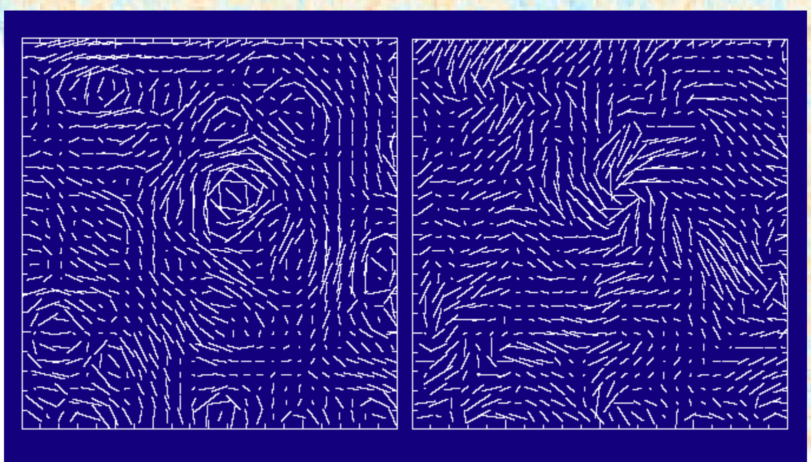


E-mode (curl free) B-mode (curl)

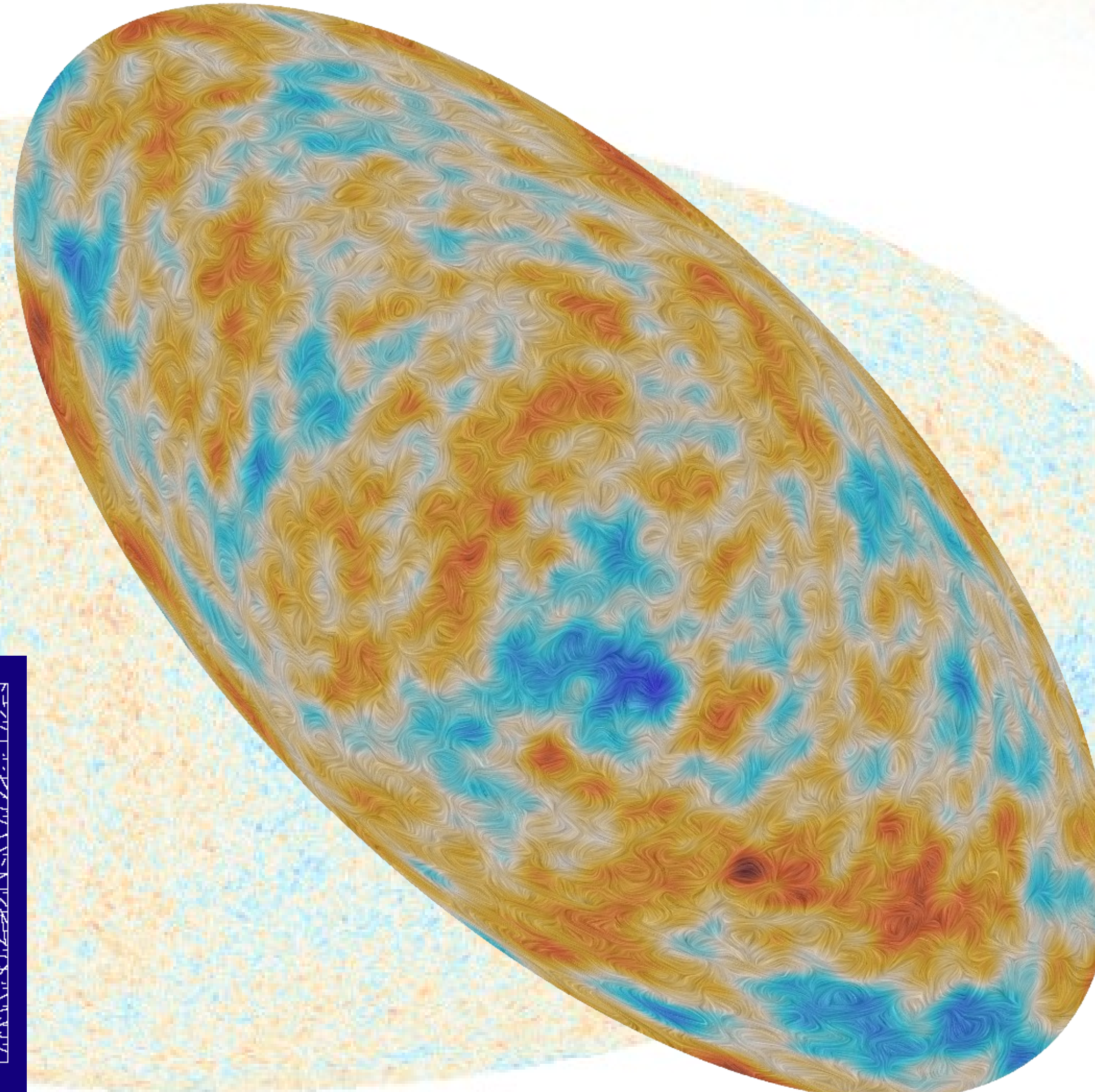


CMB: polarization anisotropies





E-mode (curl free) B-mode (curl)



Planck HFI low-ℓ

- **Pre-2016 *Planck* data: strongest systematics = ADC-NL**
  - reduced by a factor ~ 10 but still not negligible on frequency maps

- **Sources of residual systematics** that matter for low-ℓ data analysis:

Identified, tested & under control!

(detector noise, zodi, far sidelobes, ADC-NL, T-Pol leakage, gain correction, interdetector calibration, bandpass mismatch,…)

→ **Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth** (A&A 596, A107, 2016)

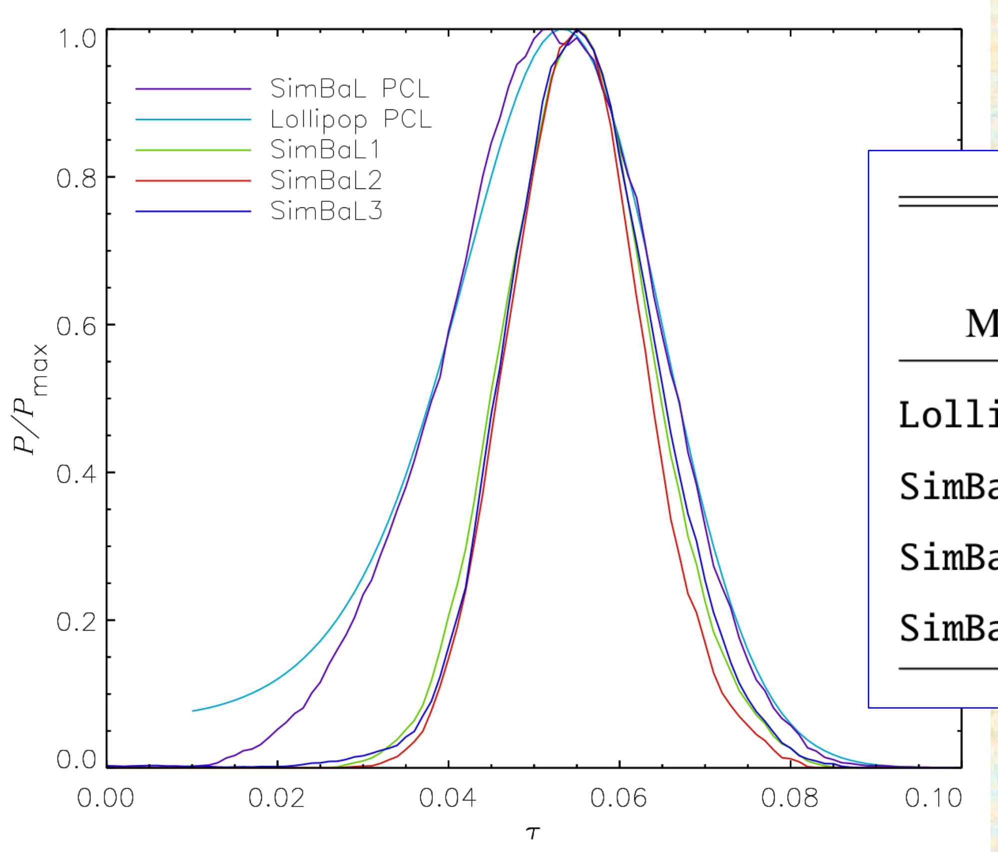
- **Results on E2E Monte-Carlo simulations including ADC-NL**
  - no bias on cross-spectra

Results: two versions of *Planck* analysis based on

- **Two different estimators of cross-power spectra** (esp. 100x150 GHz)
  - Pseudo-C_ℓ → PCL
  - Quadratic Maximum Likelihood → QML

- **Two different likelihoods**
  - Simulation-based likelihood → *SimBaL*
  - LOw-ℓ LIkelihood on Polarized Power spectra → *Lollipop*

Reionization optical depth from *Planck*-HFI EE low-ℓ only



Planck intermediate results. **XLVI**.
A&A 596, A107 (2016)

	PCL		QML	
Method	peak $\pm1\sigma$	peak $+2\sigma$	peak $\pm1\sigma$	peak $+2\sigma$
`Lollipop` . . .	$0.053^{+0.011}_{-0.016}$	0.075	. . .	. . .
`SimBaL1`	$0.052^{+0.011}_{-0.014}$	0.076	$0.055^{+0.009}_{-0.009}$	0.073
`SimBaL2`	. . .	. . .	$0.055^{+0.008}_{-0.008}$	0.071
`SimBaL3`	. . .	. . .	$0.055^{+0.009}_{-0.008}$	0.073

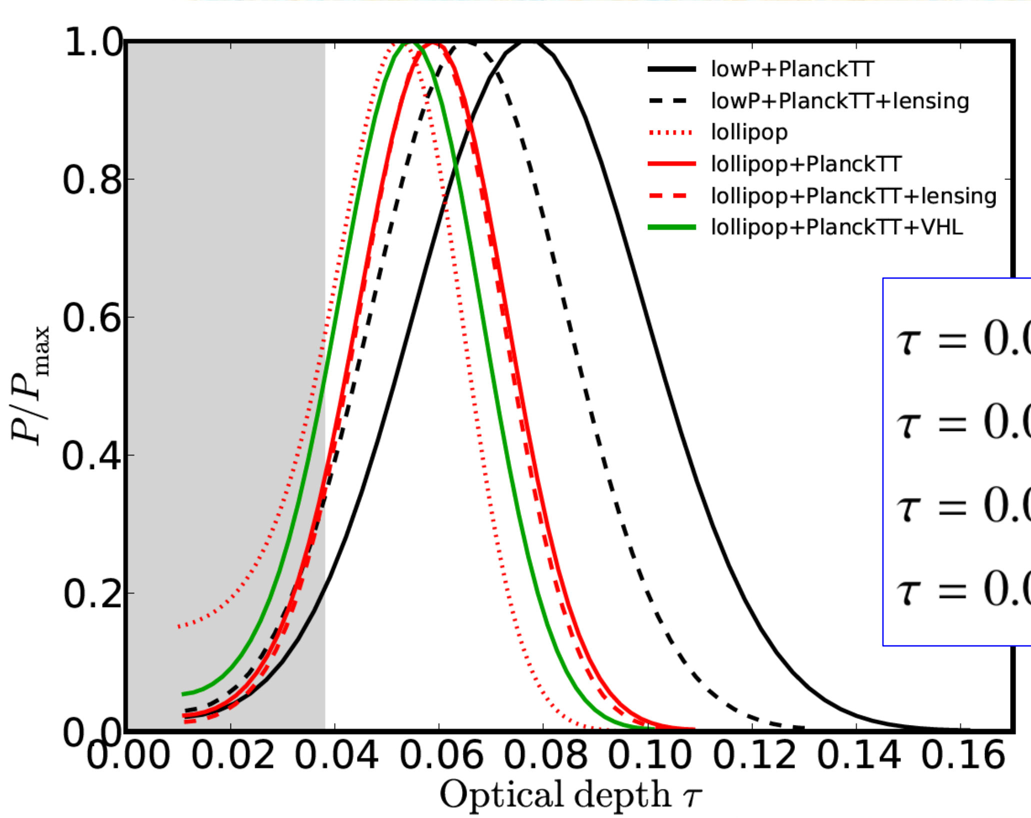
HFIxLFI consistency :

$\tau = 0.049^{+0.015}_{-0.019}$ for the 70×100 cross-spectra,

$\tau = 0.053^{+0.012}_{-0.016}$ for the 70×143 cross-spectra.

Reionization optical depth from *Planck*-HFI EE low-ℓ + **others**

- *Planck* TT CMB spectrum (2015)
- Very High-ℓ ground-based experiments (ACT & SPT)



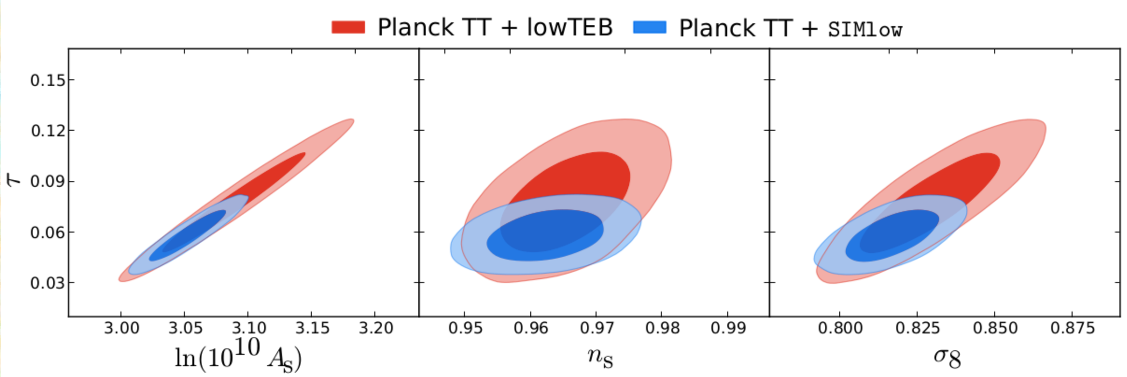
Planck intermediate results. **XLVII.**
A&A 596, A108 (2016)

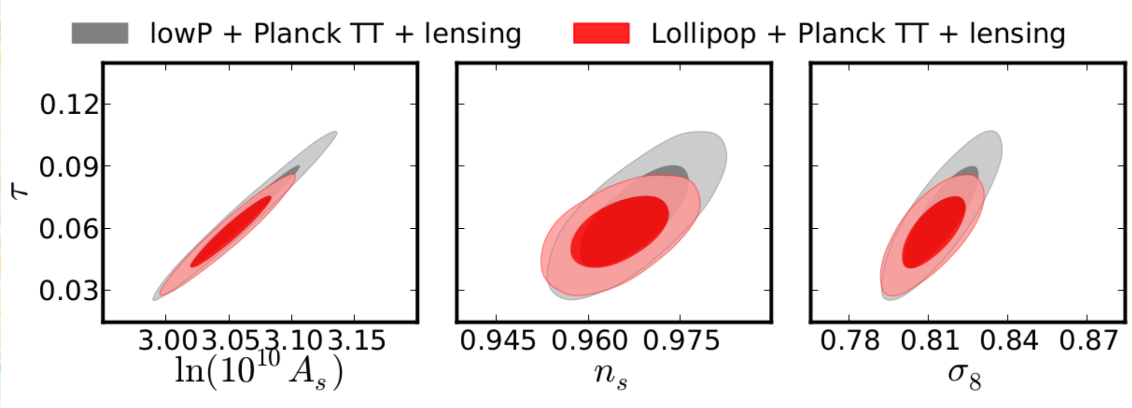
$$\tau = 0.053^{+0.014}_{-0.016}, \quad \texttt{lollipop};$$
$$\tau = 0.058^{+0.012}_{-0.012}, \quad \texttt{lollipop+PlanckTT};$$
$$\tau = 0.058^{+0.011}_{-0.012}, \quad \texttt{lollipop+PlanckTT+lensing};$$
$$\tau = 0.054^{+0.012}_{-0.013}, \quad \texttt{lollipop+PlanckTT+VHL}.$$

τ and degeneracies

- Better τ reduces strongly degeneracy with
  - A_s
  - n_s
  - σ_8
- Adding lensing does not help much

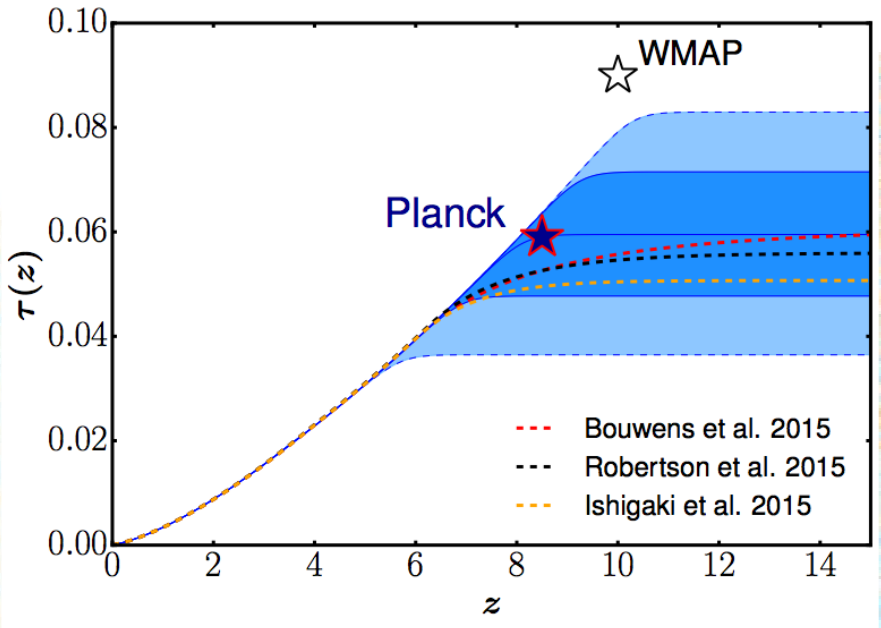
Planck intermediate results. **XLVI**.





Planck intermediate results. **XLVII**.

Optical depth: summary

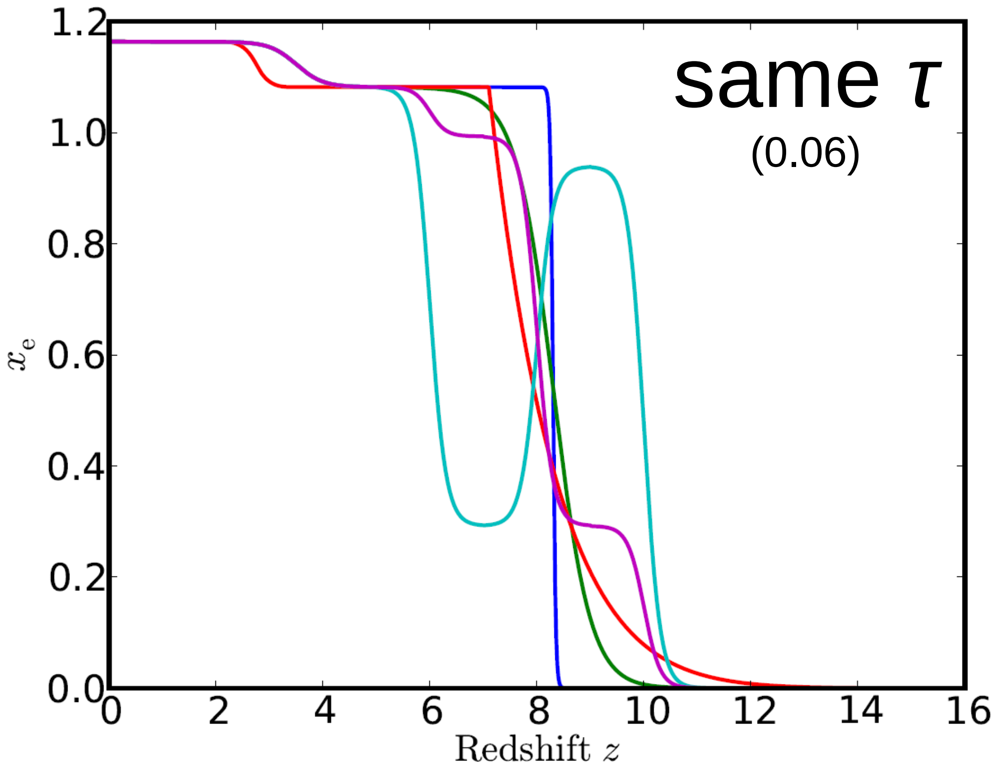


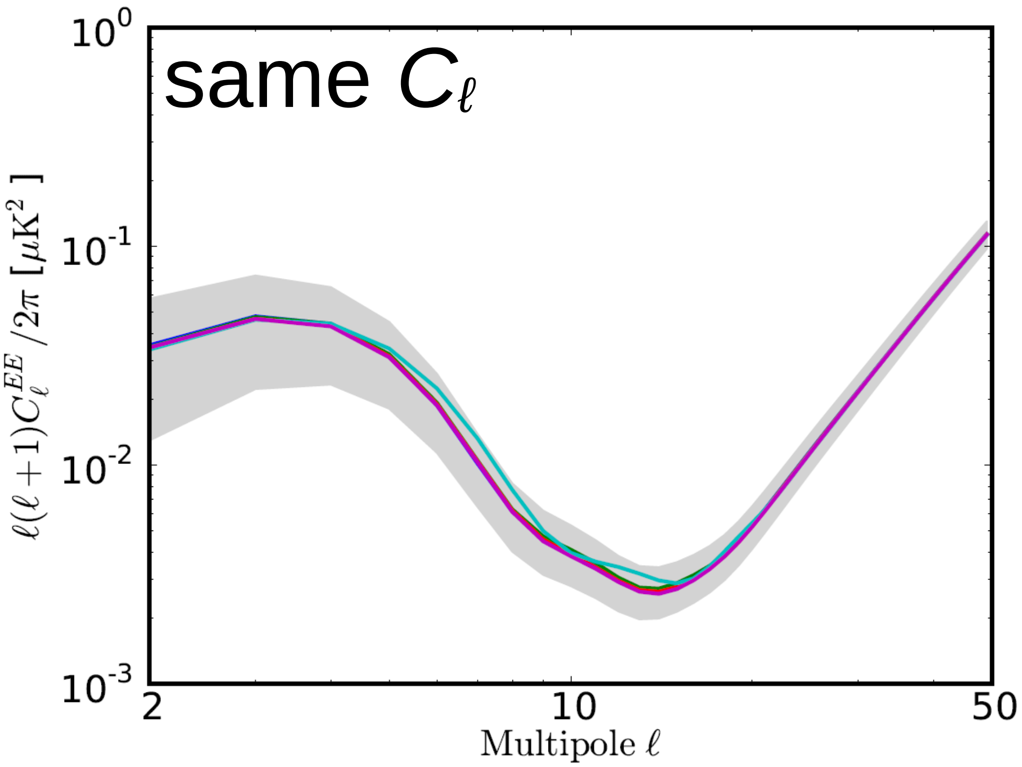
Planck intermediate results. **XLVII**.
Planck constraints on reionization history

Planck:
CMB & galaxies
in agreement

- integrated optical depth for the standard model
- models from Bouwens et al. (2015), Robertson et al. (2015), Ishigaki et al. (2015), using high redshift galaxy UV and IR flux and/or "direct" measurements

Reionization history and the CMB





CMB anisotropy spectra:

not the best probe of the **full** Reionization history

(esp. for small τ...)

Global Reionization: models

Standard model ("instantaneous")

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

f : He_{II} contribution

δz : transition

"Asymmetric" model

$$x_e(z) = \begin{cases} f & \text{for } z < z_{\rm end} \\ f\left(\frac{z_{\rm early} - z}{z_{\rm early} - z_{\rm end}}\right)^{\alpha} & \text{for } z_{\rm end} < z < z_{\rm early} \end{cases}$$

z_{end}: constrained by QSOs (≈ 6)

z_{early}: suggested by structure formation (≤ 20 – 30)

α : rise of ionised fraction

From parameters to physical quantities

- A note on Reionization redshift and duration!
  - Reionization redshift:

$$z_{\rm re} \Longleftrightarrow x_e\left(z_{\rm re}\right) = 50\% f$$

  - Reionization duration:

$$\Delta z = z_{\rm beg} - z_{\rm end} \neq \delta z!$$

In Planck intermediate results. **XLVII**. :

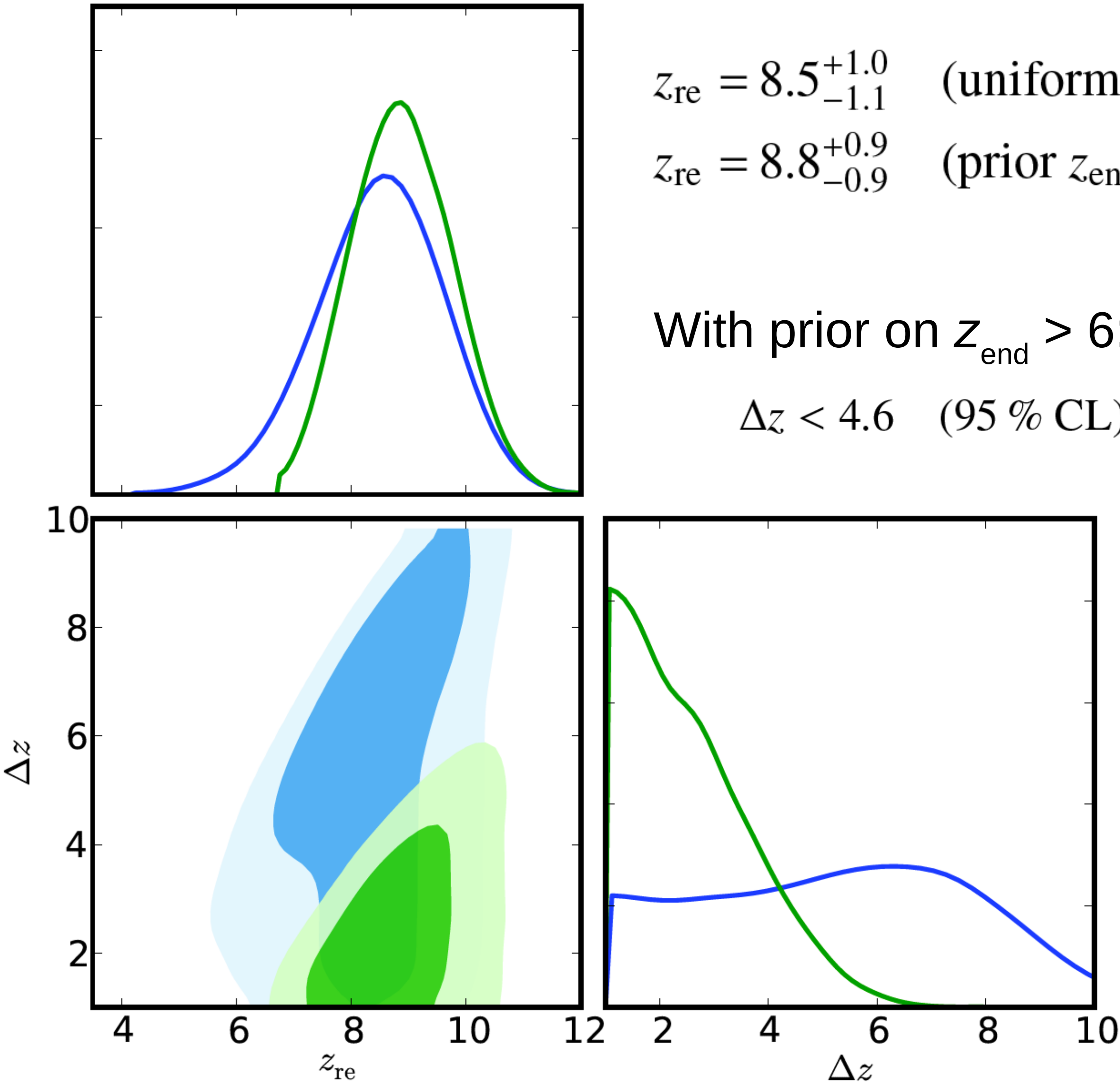
$$\Delta z = z_{10\%} - z_{99\%}$$

Remark:

$$\delta z = 0.5 \Longleftrightarrow \Delta z = 1.73$$

Reionization history in standard model

Planck intermediate results. **XLVII**. Planck constraints on reionization history



$$z_{re} = 8.5^{+1.0}_{-1.1} \quad \text{(uniform prior)}$$

$$z_{re} = 8.8^{+0.9}_{-0.9} \quad \text{(prior } z_{end} > 6\text{)}$$

With prior on $z_{end} > 6$:

$$\Delta z < 4.6 \quad (95\ \%\ \text{CL})$$

Reionization history in asymmetric model

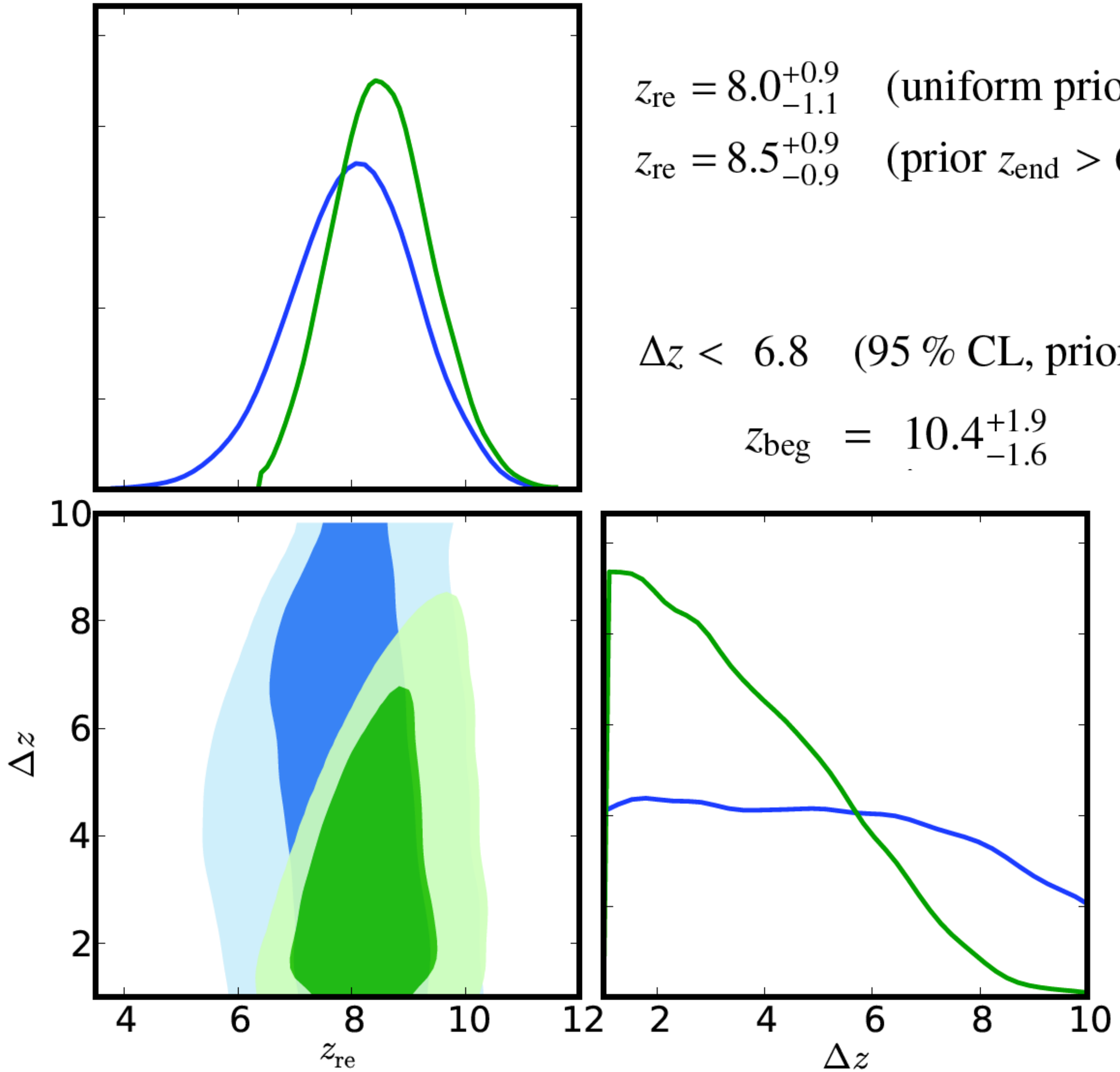
Planck intermediate results. **XLVII**. Planck constraints on reionization history

$z_{\mathrm{re}} = 8.0^{+0.9}_{-1.1}$ (uniform prior)

$z_{\mathrm{re}} = 8.5^{+0.9}_{-0.9}$ (prior $z_{\mathrm{end}} > 6$)

$\Delta z < 6.8$ (95 % CL, prior $z_{\mathrm{end}} > 6$)

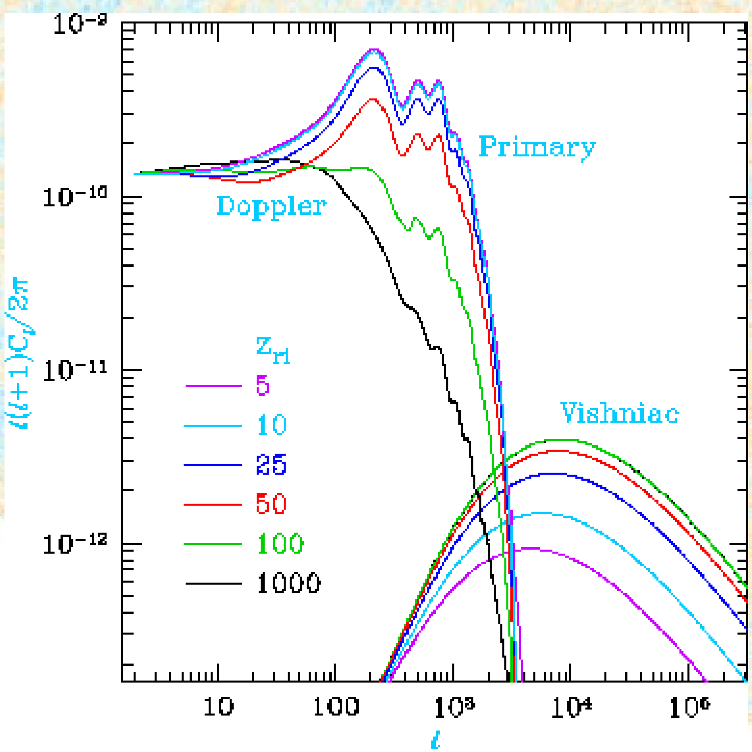
$z_{\mathrm{beg}} = 10.4^{+1.9}_{-1.6}$

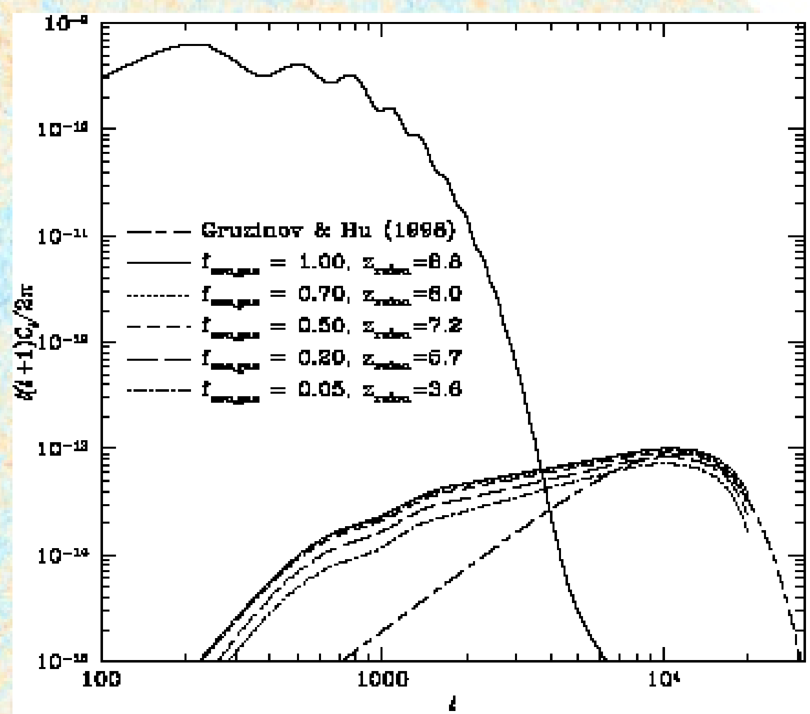


Kinetic SZ effect from Reionization

$$\left(\frac{\delta T}{T}\right)_{\rm kSZ} = -\sigma_{\rm T}\bar{n}_{\rm H,0}\int \frac{(1+z)^2}{H} e^{-\tau}\bar{x}_e(z)\left(1+\delta+\delta_{x_e}+\delta\delta_{x_e}\right)v\,{\rm d}z$$

Modulation by contrasts : density ionisation Doppler





(Benson et al., 2001)

Kinetic SZ effect from Reionization

- Second-order effect, photons scattering off electrons that are moving with a bulk velocity (Sunyaev & Zel'dovich, 1980)
- Homogeneous kSZ (Ostriker & Vishniac, 1986)
  - arising when Reionization is complete

$$D_{\ell=3000}^{\mathrm{h-kSZ}} \propto \left(\frac{\tau}{0.076}\right)^{0.44}$$

Shaw et al. (2012)

- Patchy (or inhomogeneous) Reionization (Aghanim et al. 1996)
  - before Reionization is complete: proper motion of ionised bubbles

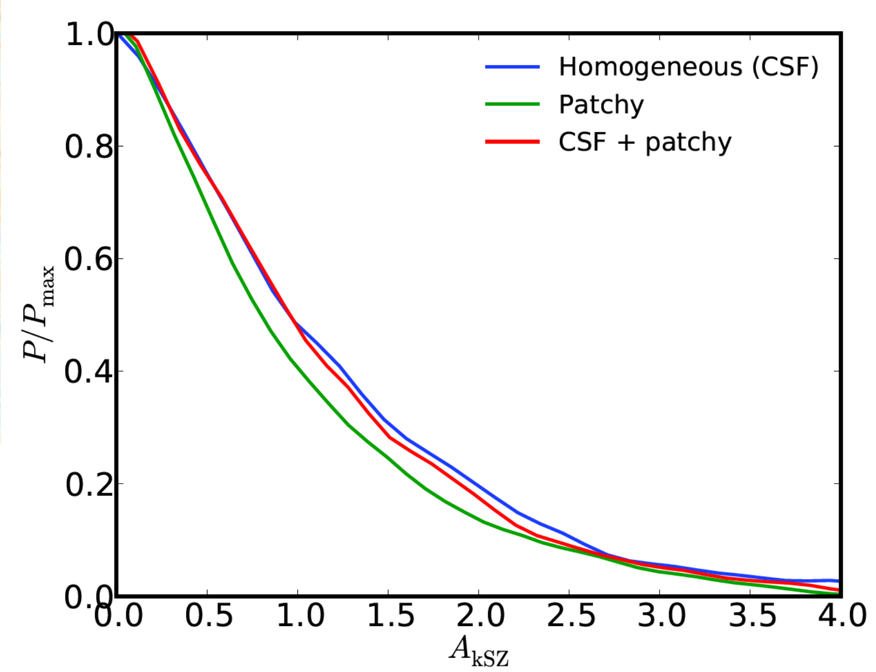
$$D_{\ell=3000}^{\mathrm{p-kSZ}} \propto \left[\left(\frac{1+z_{\mathrm{re}}}{11}\right) - 0.12\right] \left(\frac{z_{25\%} - z_{75\%}}{1.05}\right)^{0.51}$$

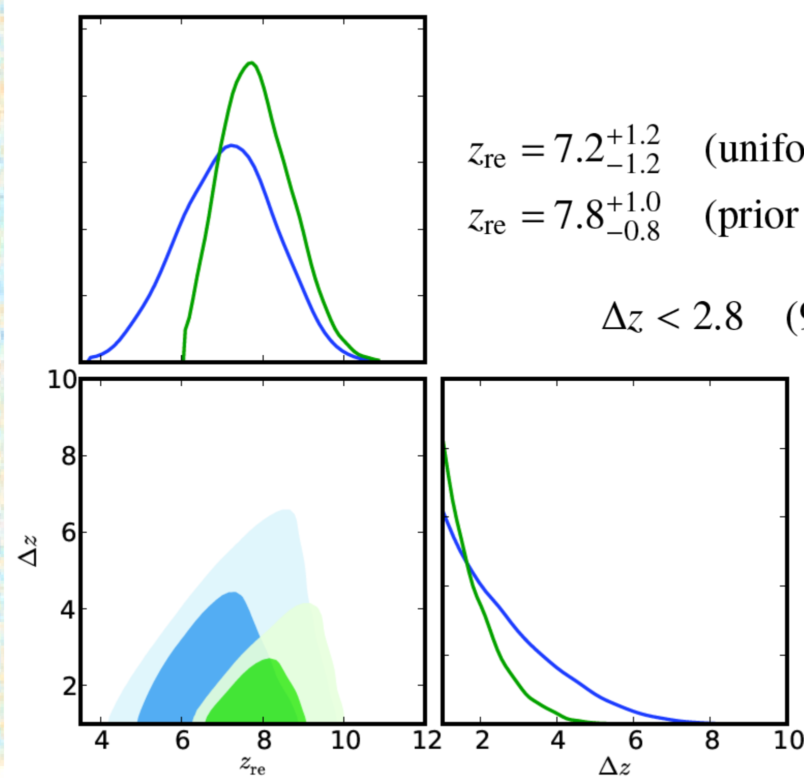
Battaglia et al. (2013)

CMB constraints on kSZ

Planck: not able to measure kSZ independently
⇨ requires high resolution CMB data: ACT & SPT

Planck + ACT + SPT & symmetric model





$z_{\mathrm{re}} = 7.2^{+1.2}_{-1.2}$ (uniform prior)

$z_{\mathrm{re}} = 7.8^{+1.0}_{-0.8}$ (prior $z_{\mathrm{end}} > 6$)

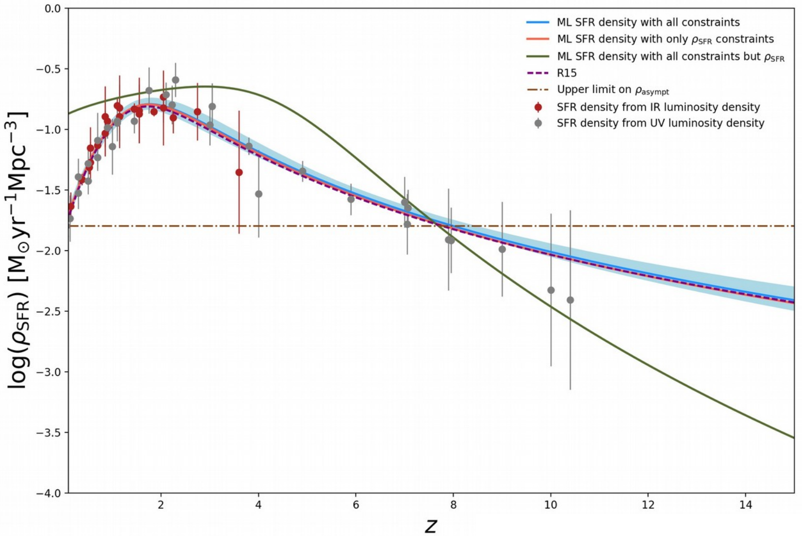
$\Delta z < 2.8$ (95 % CL)

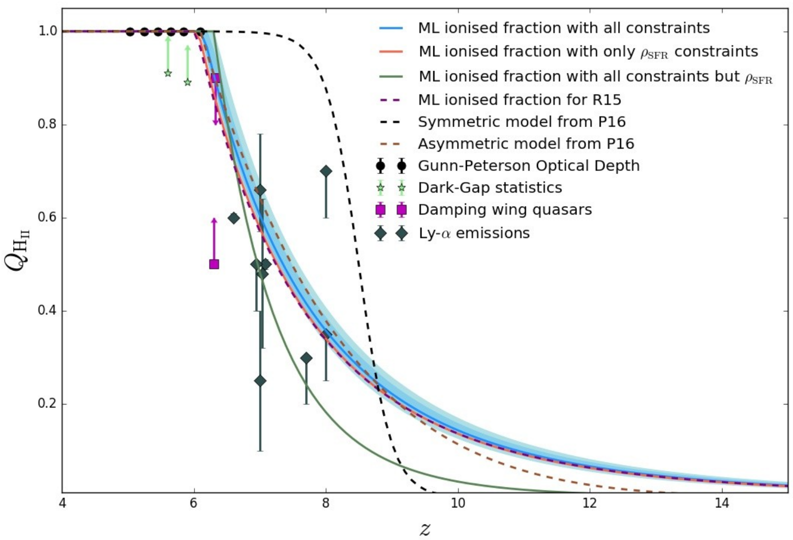
Planck intermediate results. **XLVII**. Planck constraints on reionization history

Agreement with SFR density & neutral fraction measurements

Gorce, Douspis, Aghanim, Langer, A&A submitted (2017)

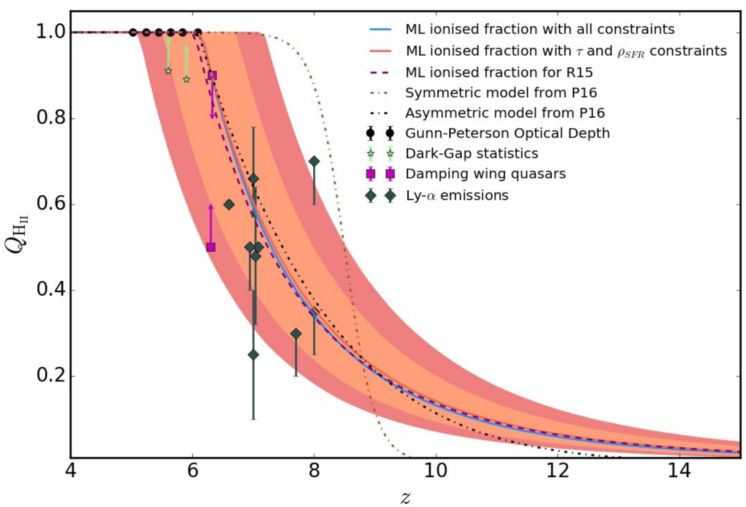
(See also *Planck* intermediate results. **XLVII.** 2016 & Douspis, Aghanim, Ilić, Langer, A&A, 2015)





$$\dot{N}_{ion} \propto \rho_{SFR}$$

$$\frac{dQ_{HII}}{dt} = \dot{N}_{ion} - \frac{Q_{HII}}{t_{rec}}$$



Fan et al. (2006)
McGreer et al. (2015)
Schroeder et al. (2013)
Totani et al. (2006)
McQuinn et al. (2008)
Ouchi et al. (2010)
Ota et al. (2008)
Caruana et al. (2014)
Ono et al. (2012)
Mortlock et al. (2011)
Bolton et al. (2011)
Tilvi et al. (2014)
Schenker et al. (2013)
Pentericci et al. (2014)
Robertson et al. (2013)
Becker & Bolton (2013)
Faisst et al. (2014)
Chornock et al. (2014)
Atek et al. (2015)
McLeod et al. (2015)
Bouwens et al. (2015)

Summary

- The low value of τ as obtained from *Planck* data is
  - consistent with a fully reionized Universe at $z \sim 6$
    Gunn-Peterson effect showing Universe is mostly ionized up to z ~ 6 (Fan et al.)
  - in good agreement with recent constraints on Reionization in the direction of particular sources (in particular distant GRB and Ly-α emitters)
- Reionization history:

  large amount of star-forming galaxies or PopIII stars beyond $z = 15$ **not required**

  but seizable contribution is <u>not excluded</u>
- Maintaining a UV-luminosity density at the maximum level allowed by the constraints at redshifts $z < 10$ and considering only the currently observed galaxy population at $M_{UV} < -17$ seems to be sufficient to comply with all observational constraints
- The CMB: is all Reionization information extracted?

  See final *Planck* release

  → next: spectral distortions of Black Body radiation… ?!

The scientific results presented 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.