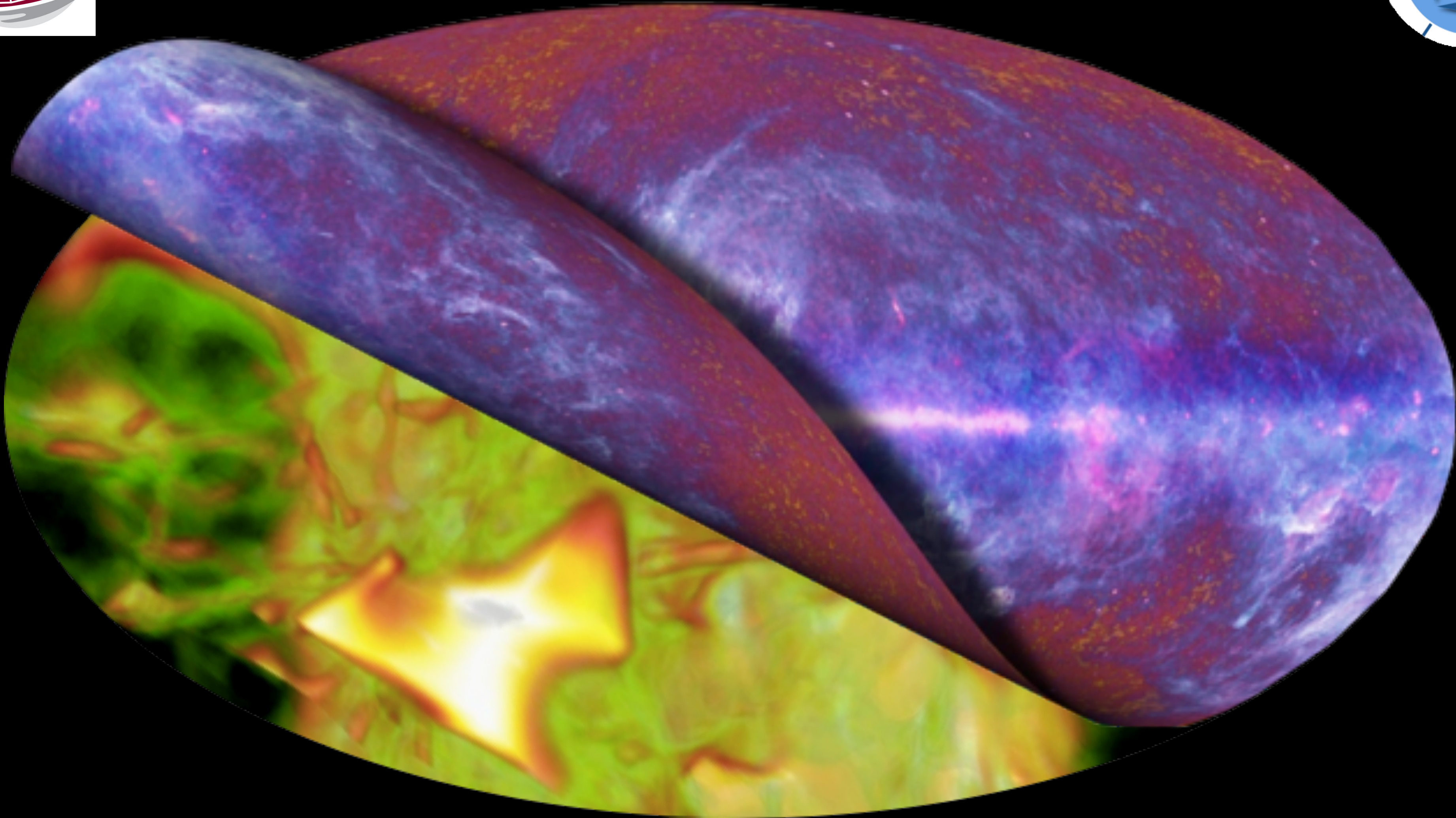
Reionisation at Planck era



Reionisation picture: simulation, courtesy D.Aubert et al.

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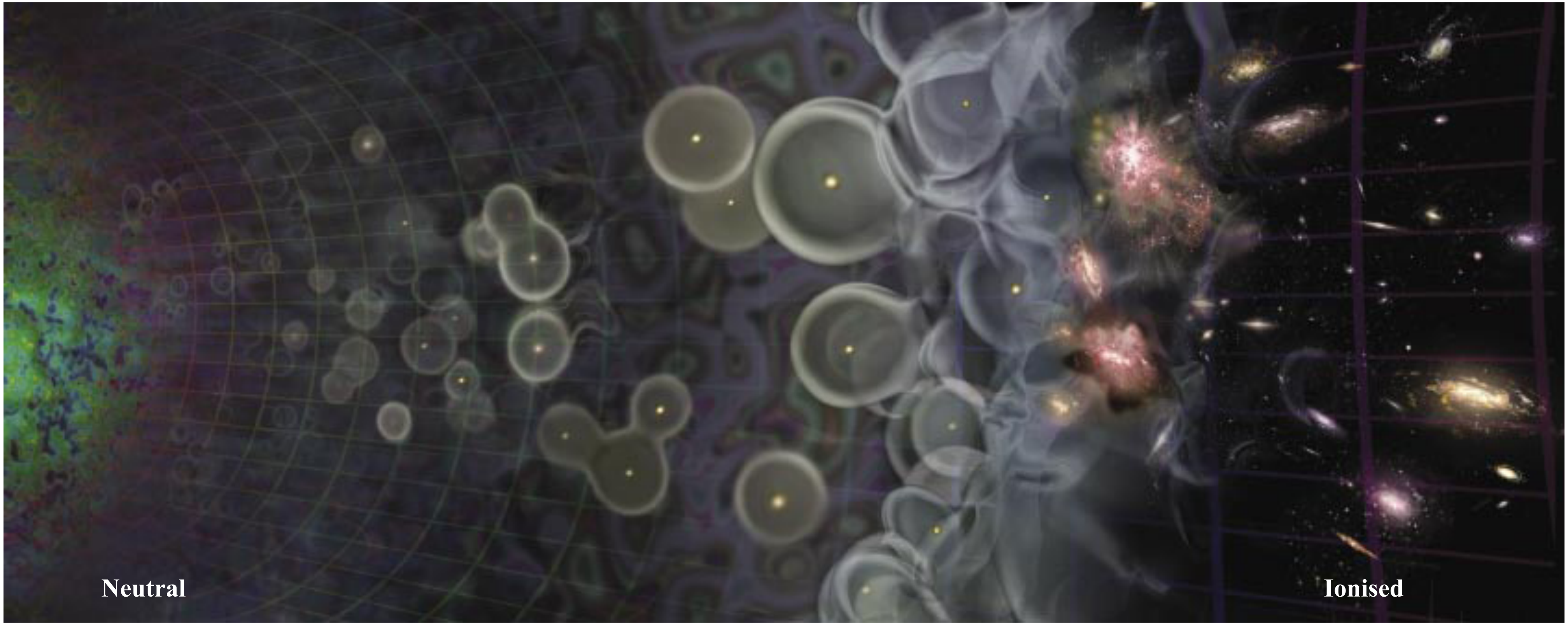
How and when did Reionisation occur?

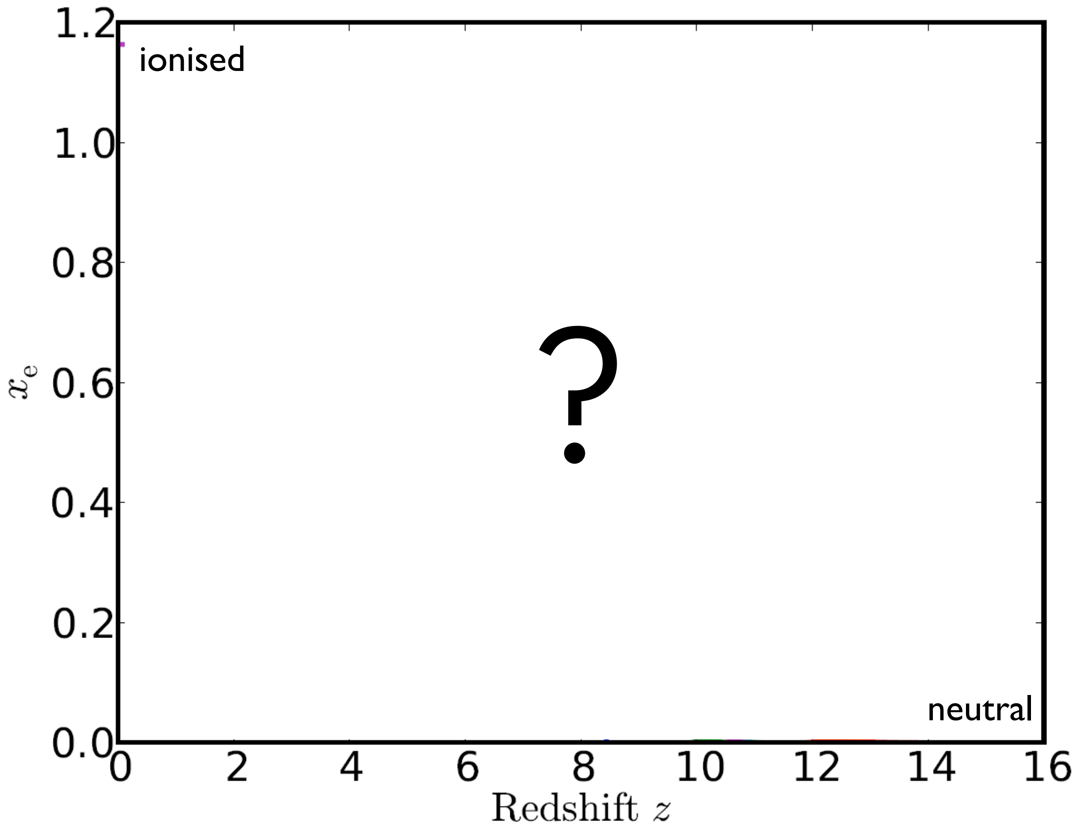


Credits :Sci. Am. & A. Loeb, 2006

CMB	**First stars**	**First galaxies?**	**First quasars?**	Reionisation	Today
372 000 years	100 Myrs ?			Complete at 1Gyr (?)	13.8 Gyrs

Reionisation

Epoch of Reionisation (EoR): period during which the cosmic gas went **from neutral to ionised** through the action of the **first luminous, ionising sources**.



Reionisation optical depth:

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

Parametrize the complex history of Reionisation in one function:

$x_e(z)$: ionised fraction ($\Leftrightarrow Q_{HII}$)

$$x_e(z) = \bar{n}_e(z)/\bar{n}_H(z)$$

Reionisation & the CMB

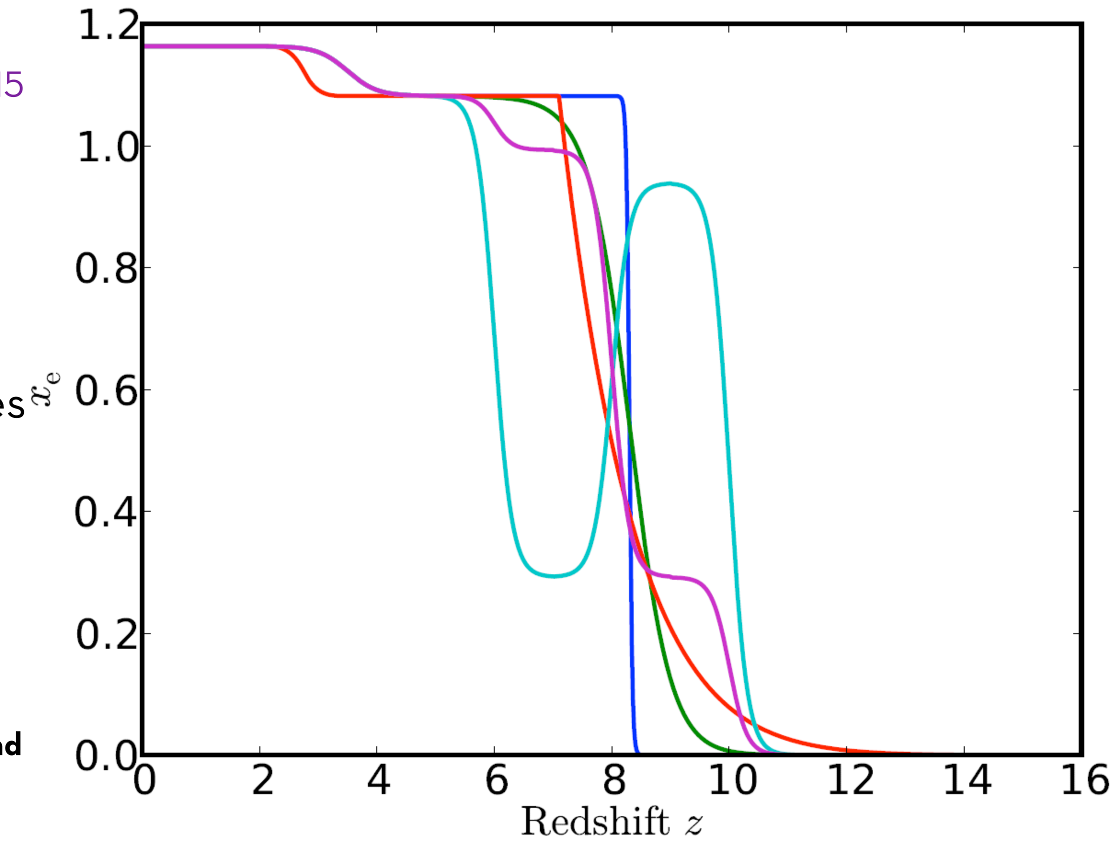
- **“Symmetric”** (standard tanh)
  - 2 parameters: z_{re}, Δz
- **“Asymmetric”** Douspis et al. 2015

motivated: data & simulations

- Two types of sources:
  - “gentle”: stars & galaxies
  - “abrupt”: QSOs finish

phenomenological description:

$$z_{start}, z_{end}, z_{trans} \leftrightarrow z_{re}, \Delta z_{begin}, \Delta z_{end}$$



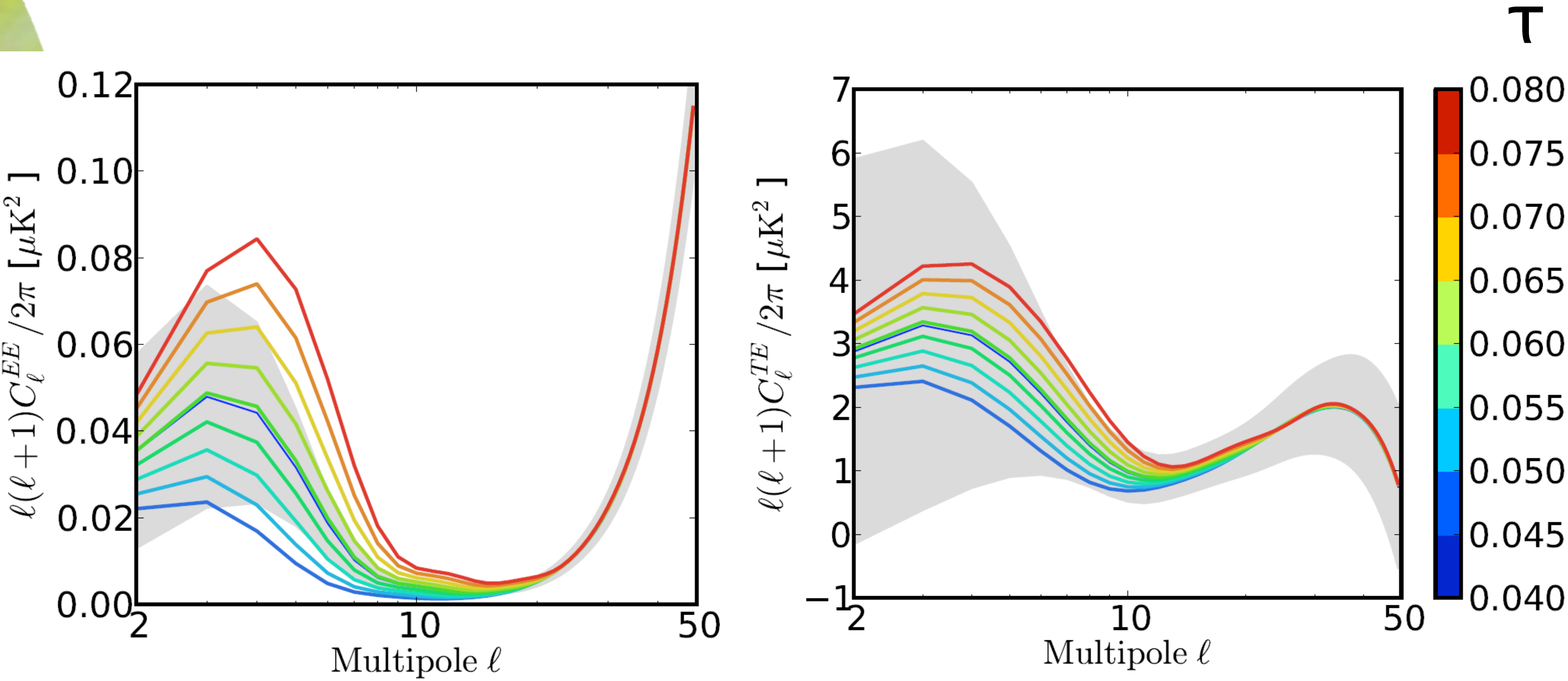
- **Model independent**
  - $x_e(z)$ in redshift bins
  - Principal Component Analysis

Reionisation & the CMB

CMB provides information on Reionisation through:

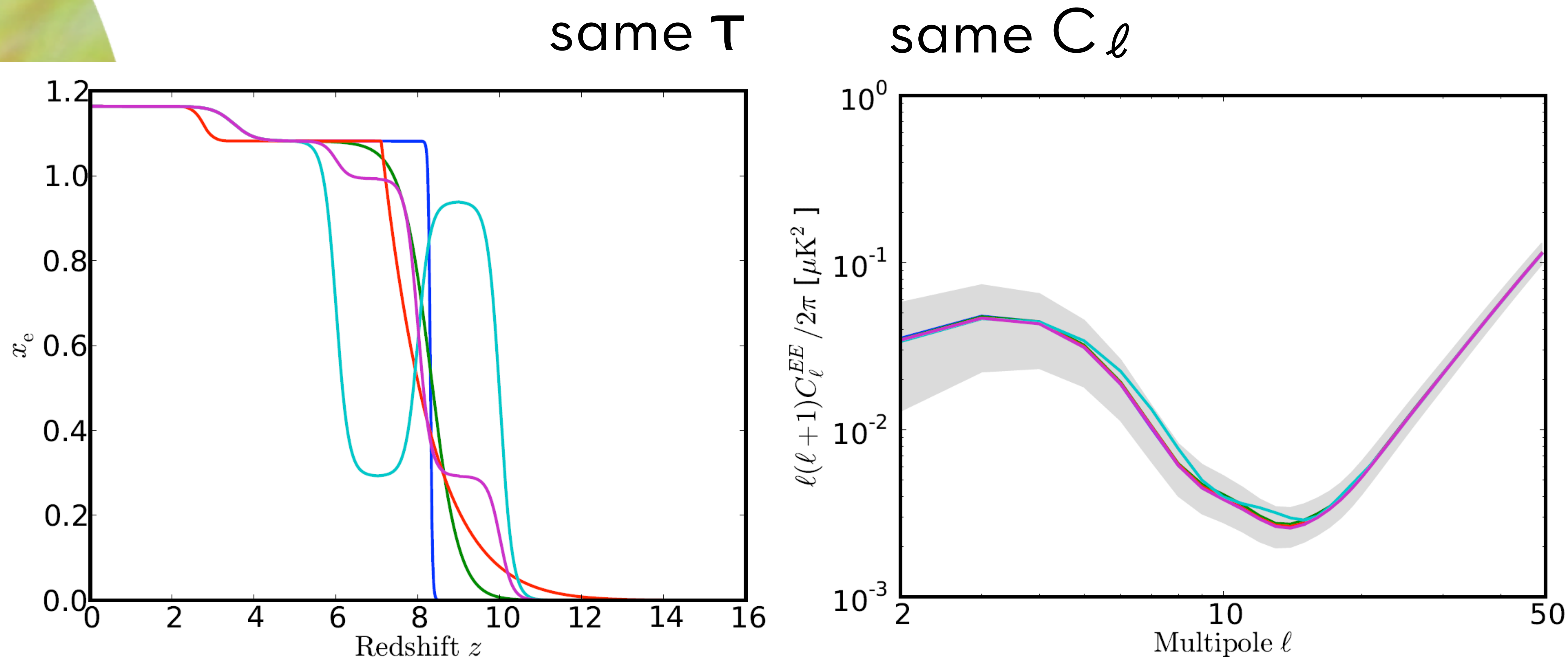
- **Temperature anisotropies**
  - suppression of TT power at large multipoles
    (very degenerate with other cosmological parameters and foregrounds)
- **Polarisation anisotropies**
  - suppression of EE power at large multipoles
  - new polarisation anisotropy at large angular scale because the horizon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

Reionisation & CMB polar: low-ℓ



CMB is a good probe of the optical depth τ

Reionisation, the CMB & degeneracies

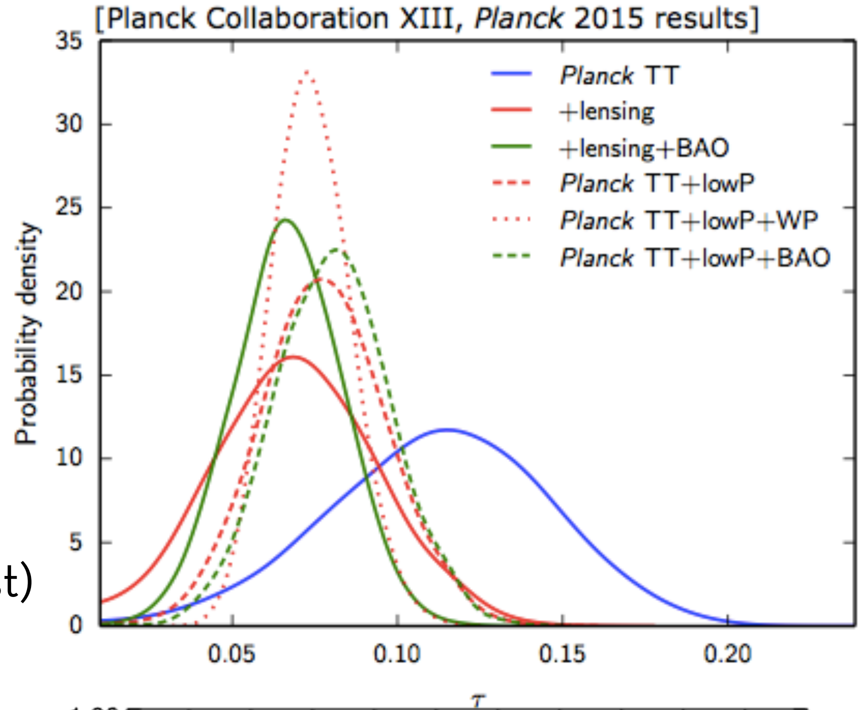


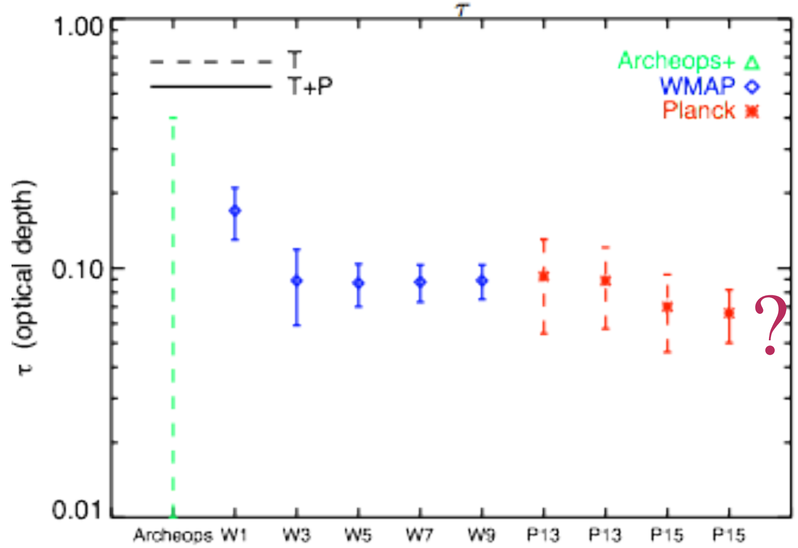
CMB is **not** a good probe of the Reionisation history...

Reionisation optical depth

CMB data

- **WMAP**
  - τ = 0.089 ± 0.014
- **Planck 2013**
  - τ = 0.089 ± 0.014 (TT with WP)
  - τ = 0.075 ± 0.013 (TT with WP-HFI dust)
- **Planck 2015**
  - τ = 0.078 ± 0.019 (TT + lowP)
  - τ = 0.066 ± 0.016 (TT + lowP + lensing)
  - τ = 0.067 ± 0.016 (TT + lensing + BAO)
- **Planck HFI EE low-ℓ**
  - decreasing trend continues … ?





Planck HFI low-ℓ

- **Previous Planck data: strongest systematics = ADC-NL**
  - has been reduced by a factor almost 10 but still not negligible on frequency maps
- **Identified: all dominant sources of residual systematics that matter for low-ℓ data analysis**
- **Results on E2E Monte-Carlo simulations including ADC-NL**
  - no bias on cross-spectra

Results: two versions of *Planck* analysis based on two different noise/system statistics

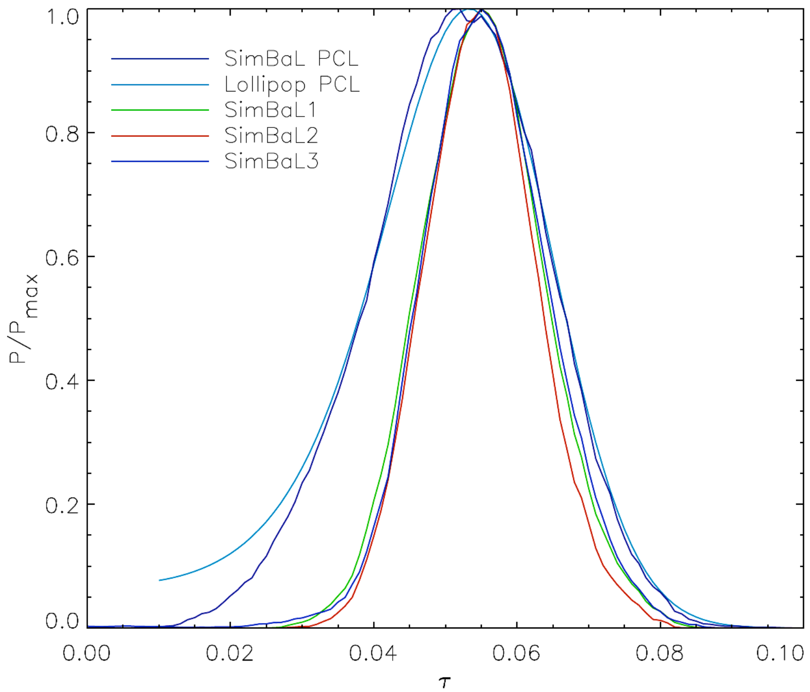
- **Likelihood based on cross-spectra between Planck frequency maps**
  - Lollipop likelihood: Hamimeche & Lewis (2008) approximation modified for cross-spectra, Mangilli, Tristram et al. (2015) → Planck intermediate results. XLVII. Planck constraints on reionization history (arXiv:1605.03507)
  - SimBaL ("simulation-based likelihood") → Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth (arXiv:1605.02985)

Reionisation optical depth

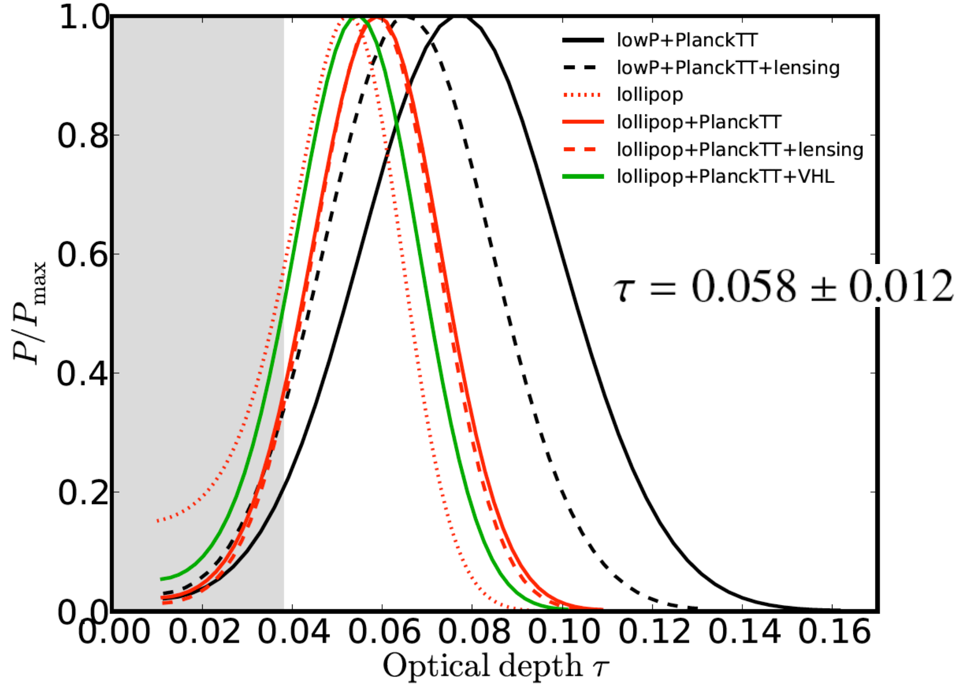
Results: from a combination of

1. Planck TT CMB spectrum (2015)
2. two versions of Planck EE low-ℓ
3. Very High-ℓ ground-based experiments (ACT & SPT)

Optimistic
(arXiv:1605.02985)

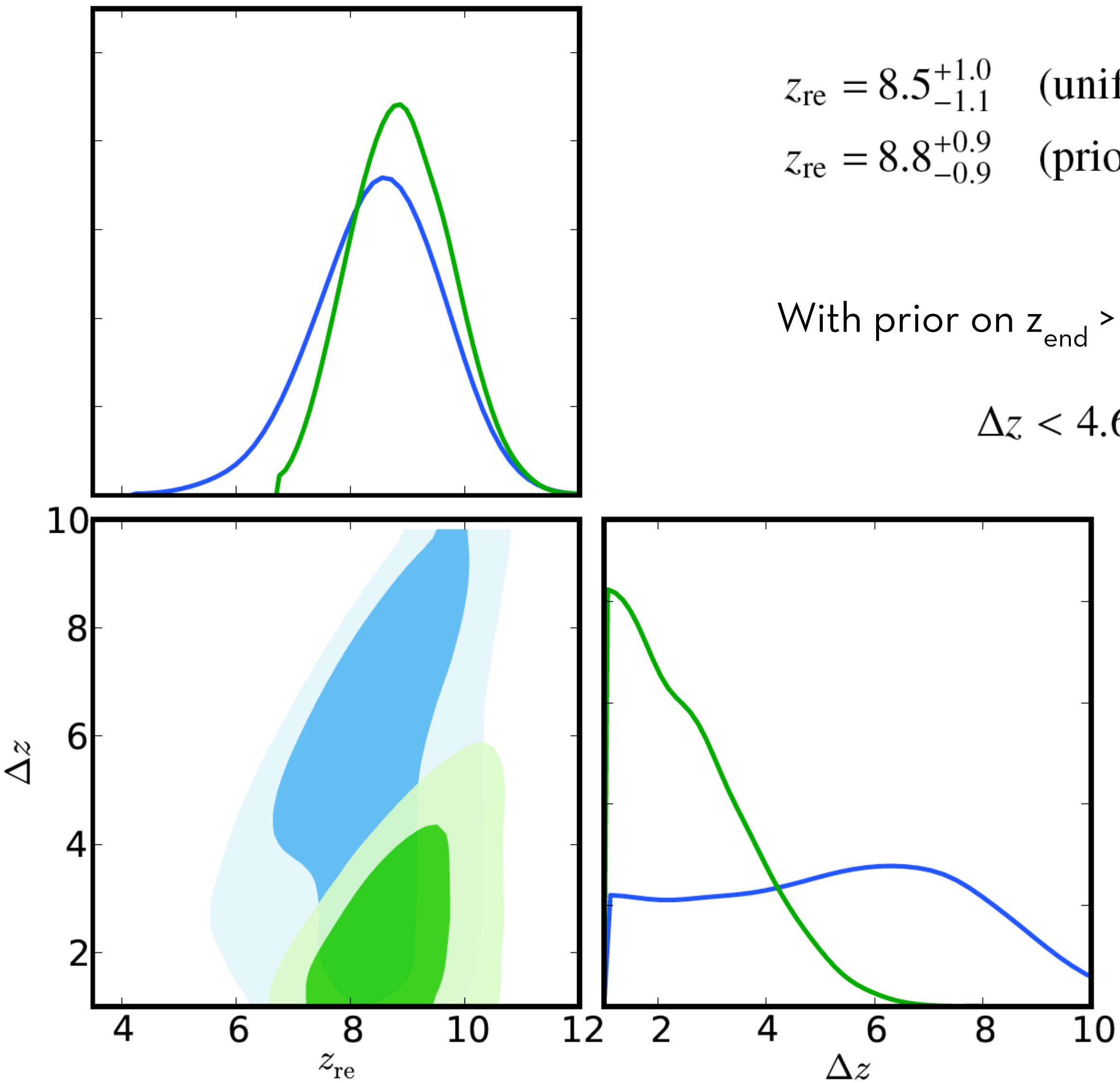


Conservative
(arXiv:1605.03507)



Symmetric model

Planck constraints on reionization history (arXiv:1605.03507)



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

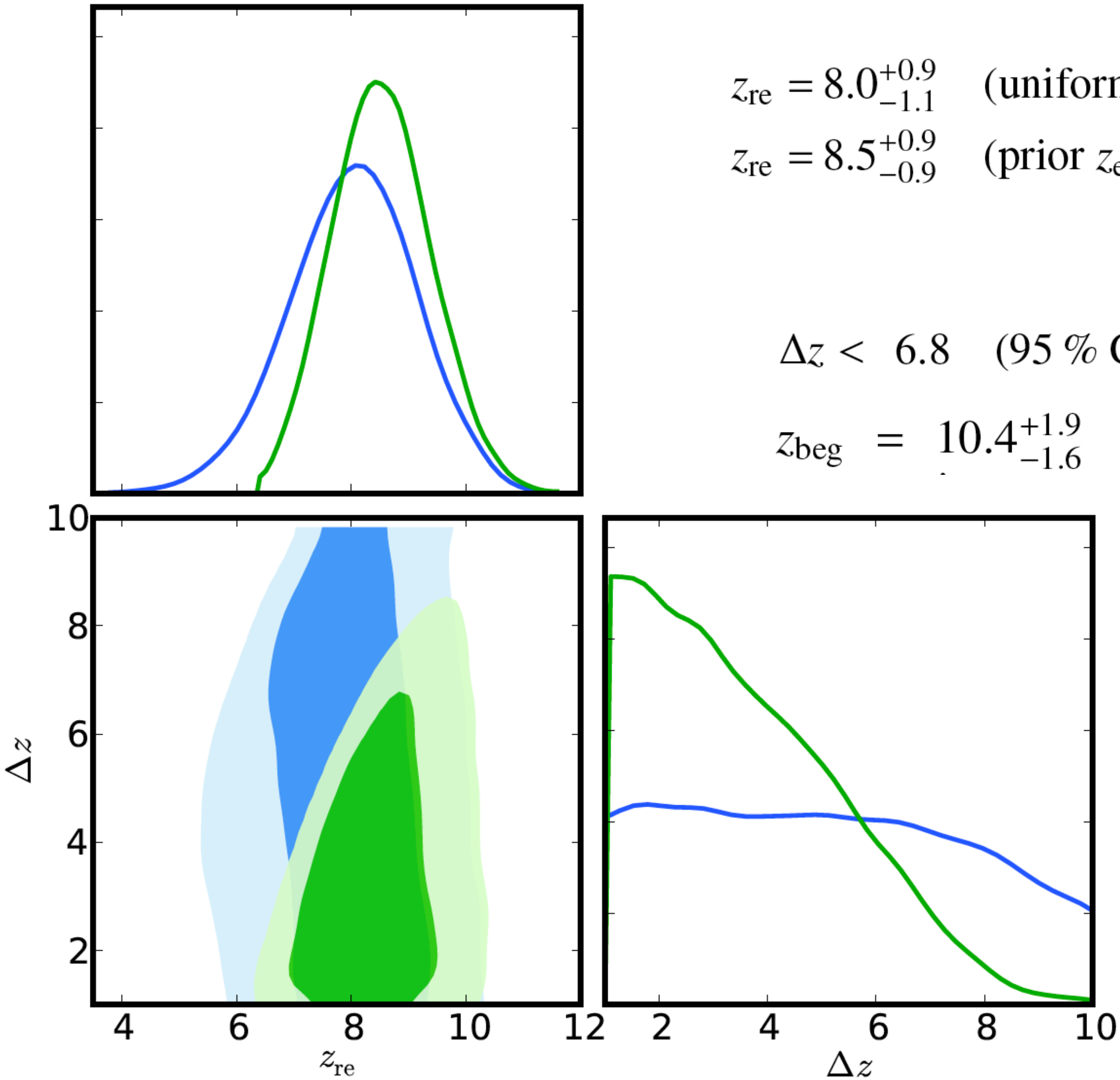
$$z_{re} = 8.8^{+0.9}_{-0.9} \quad \text{(prior } z_{end} > 6)$$

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

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

Asymmetric model

Planck constraints on reionization history (arXiv:1605.03507)



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

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

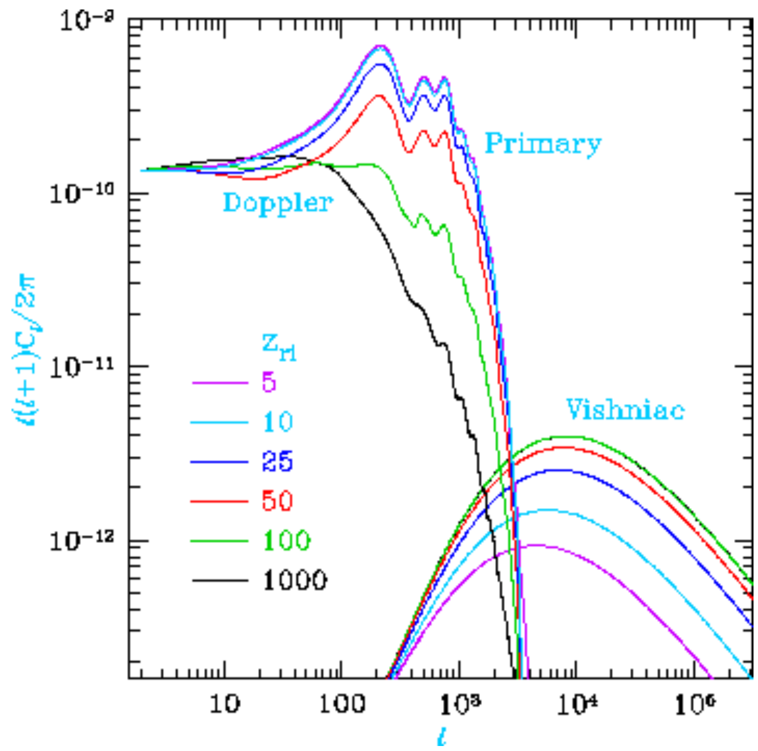
$$\Delta z < 6.8 \quad (95\,\%\ \text{CL, prior } z_{\rm end} > 6)$$

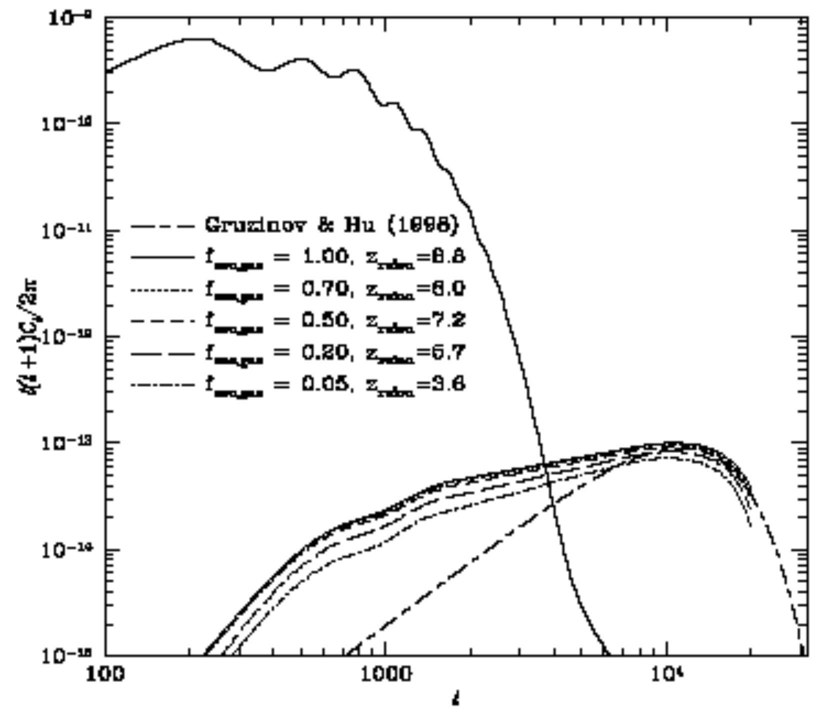
$$z_{\rm beg} = 10.4^{+1.9}_{-1.6}$$

Kinetic SZ effect from Reionisation

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

Modulation by contrasts : density, ionisation, Doppler





(Benson et al., 2001)

Kinetic SZ effect from Reionisation

- 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 Reionisation is complete

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

Shaw et al. 2012

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

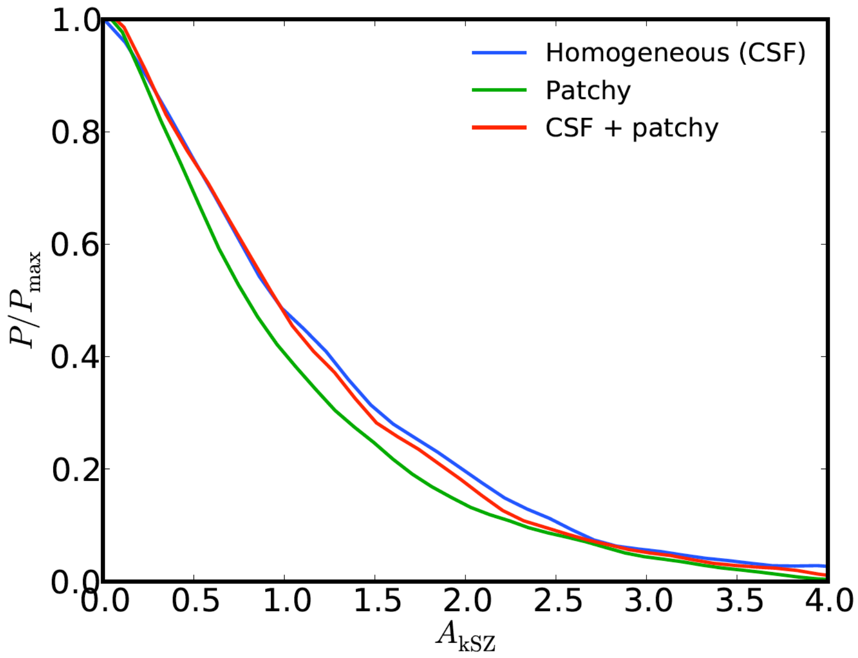
$$D_{\ell=3000}^{\mathrm{p-kSZ}} \propto \left[\left(\frac{1+z_{\mathrm{re}}}{11}\right) - 0.12\right]\left(\frac{\Delta_z}{1.05}\right)^{0.51}$$

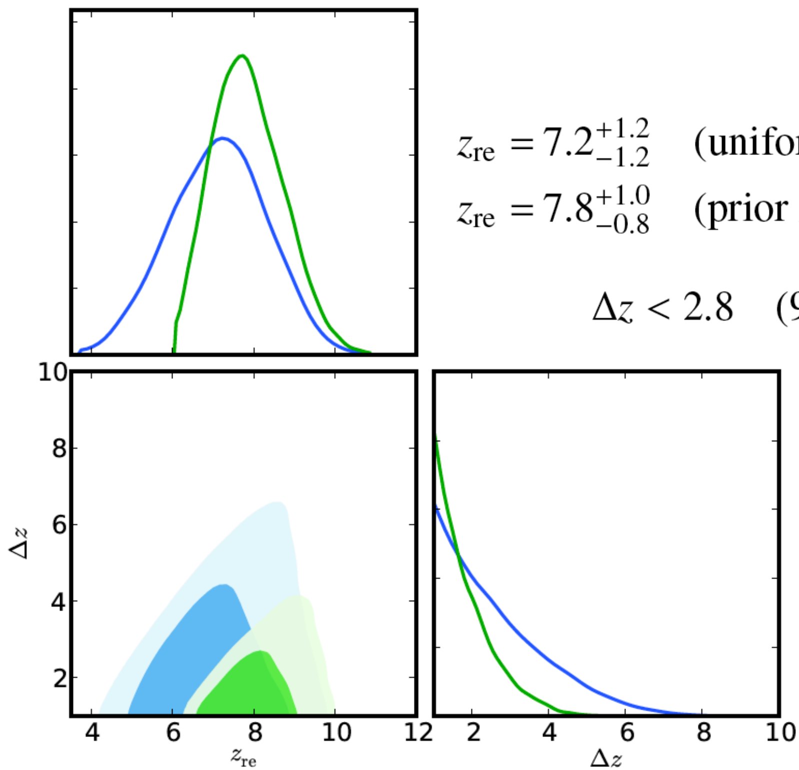
Battaglia et al. 2013

CMB constraints on kSZ

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

Planck + ACT + SPT & symmetric model





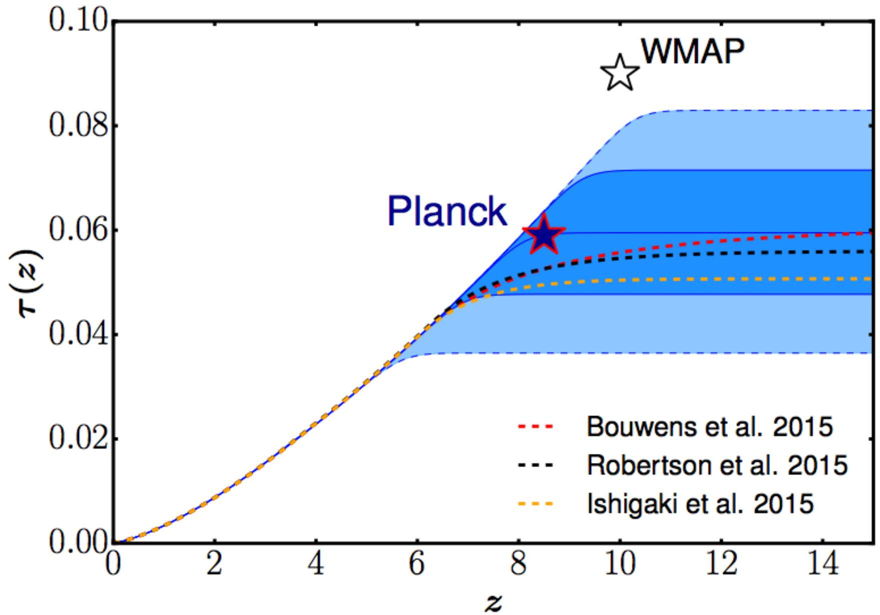
$z_{re} = 7.2^{+1.2}_{-1.2}$ (uniform prior)

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

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

Planck constraints on reionization history (arXiv:1605.03507)

Optical depth: summary



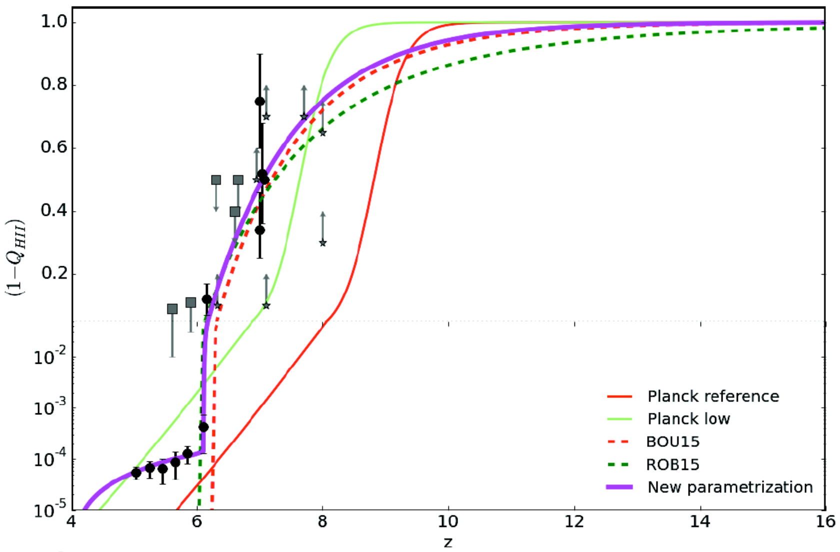
Planck intermediate results. XLVII. Planck constraints on reionization history (arXiv:1605.03507)

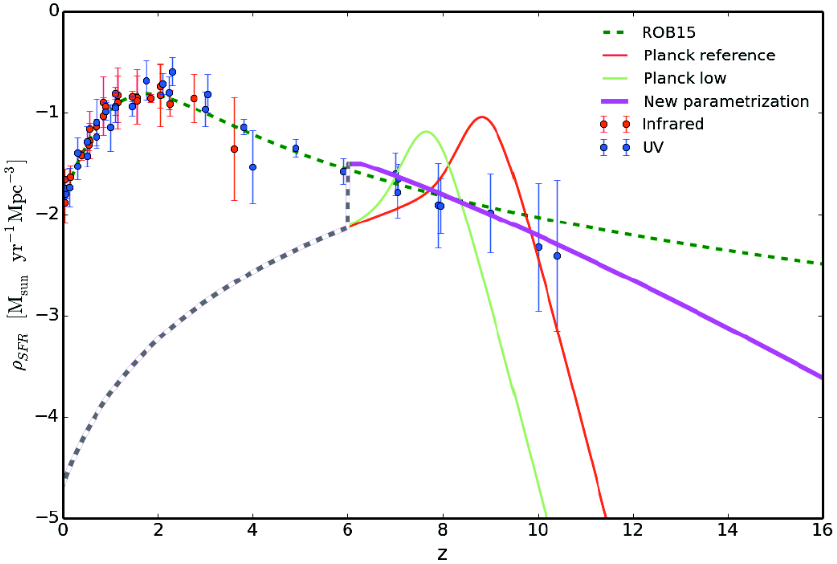
Planck:
CMB & structures
in agreement

- integrated optical depth for the symmetric model (tanh, $\Delta z = 0.5$)
- 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

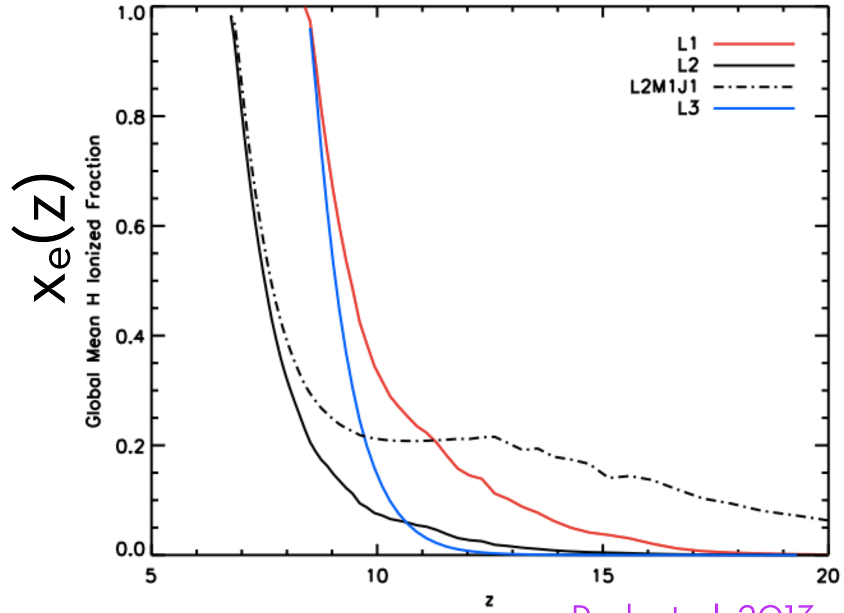
Low redshift probes

Fan et al. (2006a)
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. (2014)
Pentericci et al. (2014)
Robertson et al. (2013)
Becker & Bolton (2013)
Faisst et al. (2014)
Chornock et al. (2014)





$$\frac{dQ_{HII}}{dt} = \dot{N}_{ion} - \frac{Q_{HII}}{t_{rec}} \qquad \dot{N}_{ion} \propto \rho_{SFR} \times f_{esc}$$



Park et al, 2013

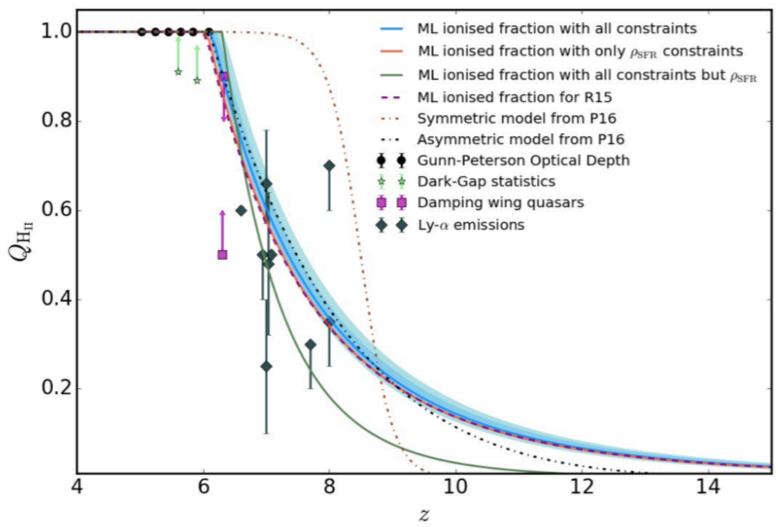
New parameterization

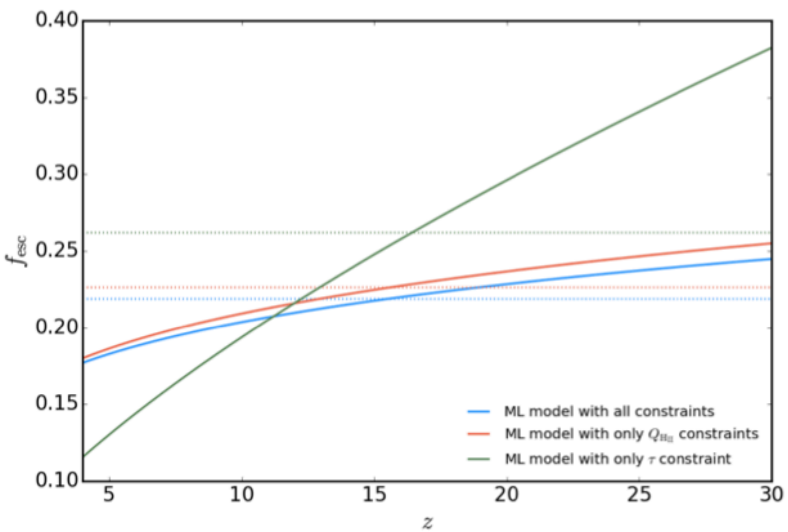
$$1 - Q_{\mathrm{H_{II}}} \propto (1+z)^3 \qquad z < z_{\mathrm{p}}$$

$$Q_{\mathrm{H_{II}}} \propto \exp\left(-\lambda(1+z)\right) \qquad z \geq z_{\mathrm{p}}$$

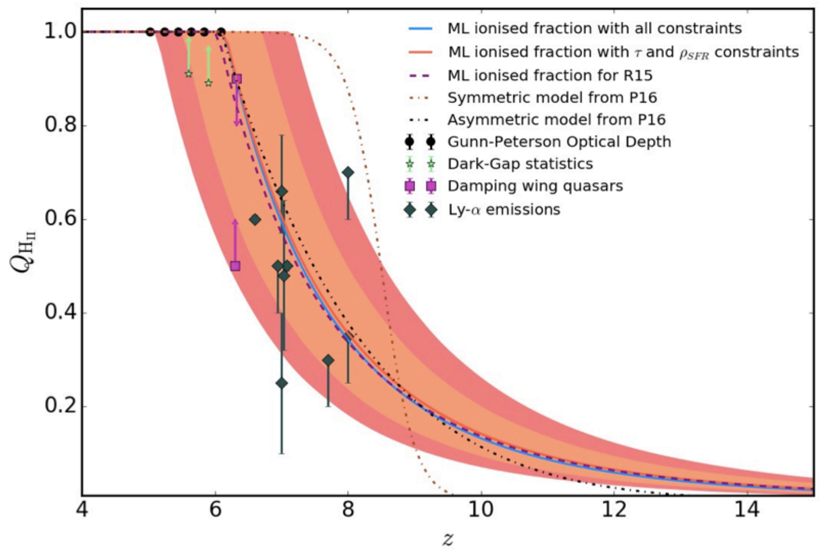
Douspis, Aghanim, Ilić, Langer, A&A, 2015

Combining probes





f_{esc} free



f_{esc}~0.2

Observational constraints on key-parameters of cosmic reionisation history, Gorce, Douspis, Aghanim, Langer (A&A sub.)

Discussion

- A lower value for τ as suggested by Planck data is
  - consistent with a fully reionised Universe at $z \sim 6$
    Gunn-Peterson effect showing Universe is mostly ionized up to $z \sim 6$ (Fan et al.)
  - in good agreement with recent constraints on Reionisation in the direction of particular objects (in particular distant GRB and Ly-α emitters)

- Reionisation history: large amount of star-forming galaxies beyond $z = 15$ not required

- Maintaining a UV-luminosity density at the maximum level allowed by the luminosity density constraints at redshifts $z < 9$ and considering only the currently observed galaxy population at $M_{UV} < -17$ seems to be sufficient to comply with all observational constraints without the need for high redshift ($z = 10$ to 15) galaxies

- CMB: all Reionisation information extracted? → next: spectral distortions of Black Body?!