Relating the kinetic Sunyaev-Zel’dovich effect and the 21 cm signal

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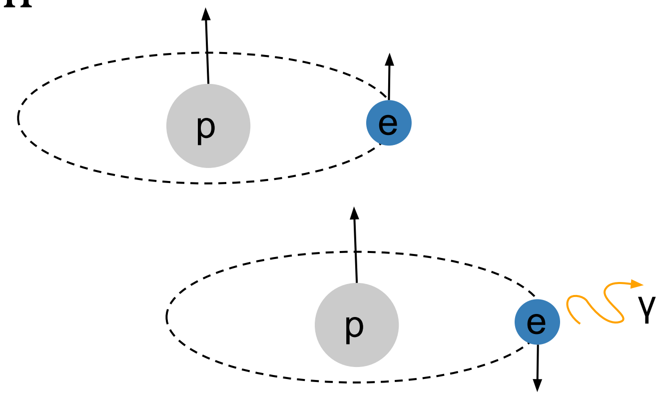
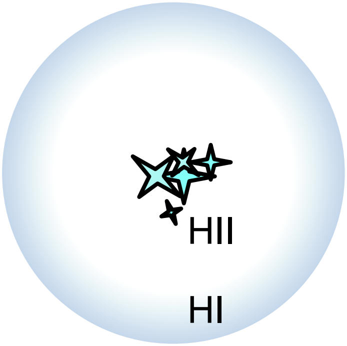
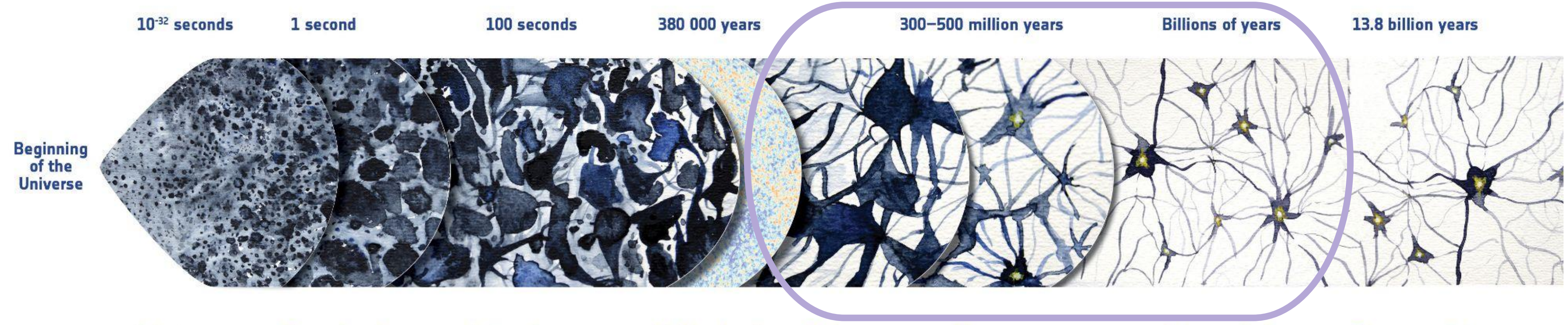
The Epoch of Reionisation

The Epoch of Reionisation (EoR) spans **astrophysical** & **cosmological scales.**
The 21-cm signal contains **ionisation** and **density** information.







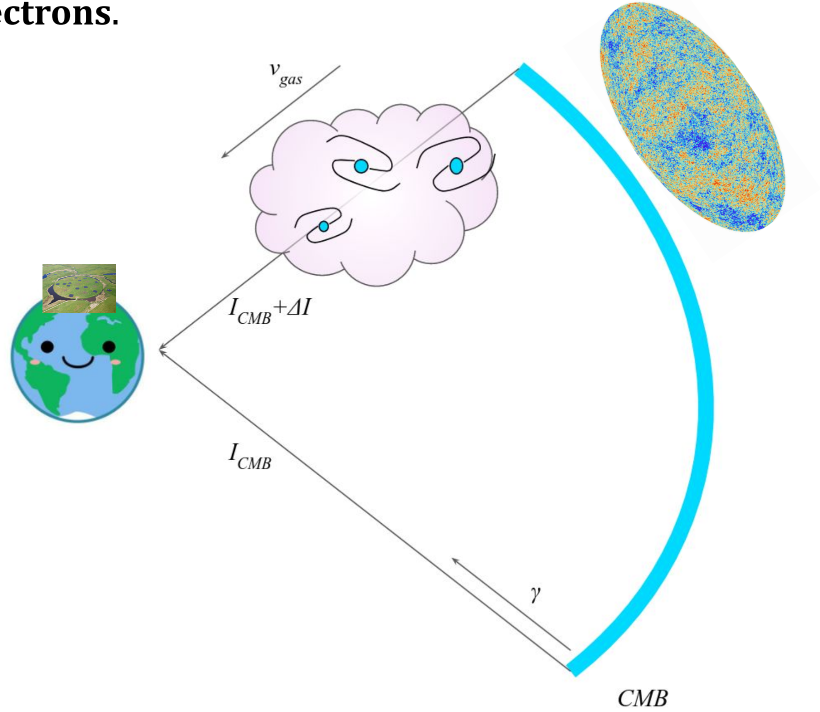
European Space Agency

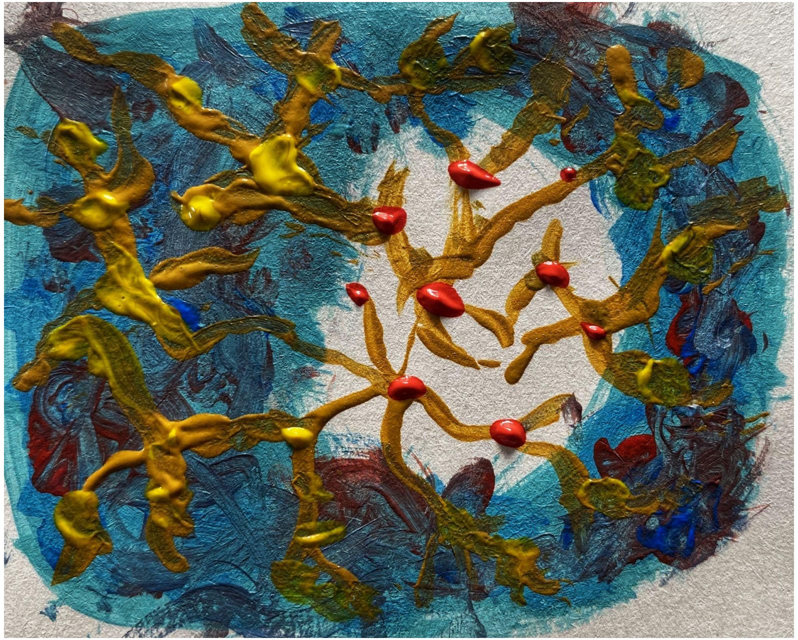
The Sunyaev-Zel’dovich effect

The Sunyaev-Zel'dovich effect results from the **scattering of CMB photons by free electrons**.

During EoR CMB photons **scatter off ionised bubbles** along the LOS.

The patchy kSZ will be **sensitive to the morphology of reionisation.** McQuinn et al. 2005





Decomposing the 21-cm and Electron Density Power Spectra

The 21-cm Power spectrum can be decomposed as:

$$\frac{P_{21}(k,z)}{\overline{x}_{\mathrm{HIv}}(z)^2 T_0(z)^2} = P_{\delta_\rho\delta_\rho}(k,z) + P_{\delta_{xHI}\delta_{xHI}}(k,z) + 2P_{\delta_\rho,\delta_{xHI}}(k,z) + 2P_{\delta_\rho\delta_{xHI},\delta_\rho}(k,z) + P_{\delta_{xHI},\delta_\rho\delta_{xHI}}(k,z) + P_{\delta_\rho\delta_{xHI},\delta_\rho\delta_{xHI}}(k,z)$$

Lidz et al. 2007, Georgiev et al .2022

The above equations can be reconfigured as follows:

$$\frac{P_{21}(k,z)}{T_0(z)^2 \overline{x}_{HIv}(z)^2} = P_{\delta_\rho,\delta_\rho}(k,z) + \overline{x}_{HIIm}(z)^2 P_{ee}(k,z) - 2\overline{x}_{HIIv}(z)\left[P_{\delta_\rho,\delta_\rho}(k,z) + P_{\delta_\rho,\delta_{xHII}}(k,z) + P_{\delta_\rho\delta_{xHII},\delta_\rho}(k,z)\right]$$

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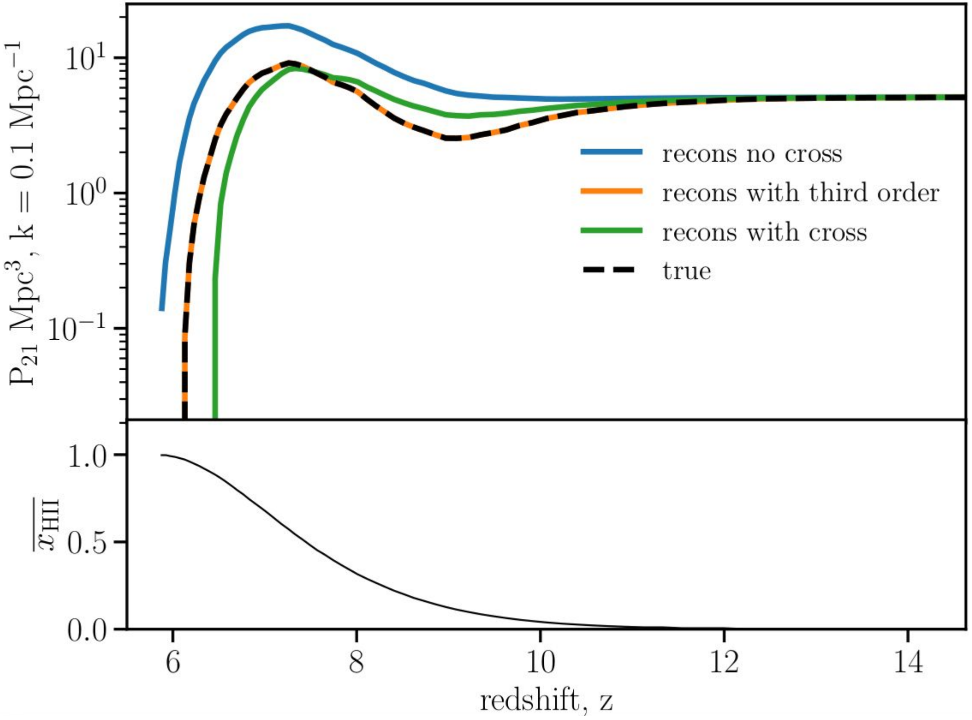
$$\frac{P_{21}(k,z)}{T_0(z)^2\overline{x}_{HIv}(z)^2} = P_{\delta_\rho,\delta_\rho}(k,z) + \overline{x}_{HIIm}(z)^2 P_{ee}(k,z) - 2\overline{x}_{HIIv}(z)\left[P_{\delta_\rho,\delta_\rho}(k,z) + P_{\delta_\rho,\delta_{xHII}}(k,z) + P_{\delta_\rho\delta_{xHII},\delta_\rho}(k,z)\right]$$

Full expression matches $\mathbf{P_{21}}$.

Simplest model overestimates the $\mathbf{P_{21}}$ amplitude and duration of the EoR.



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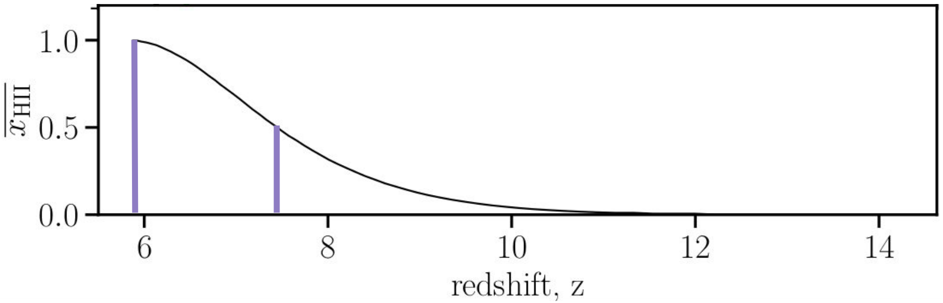
$$\frac{P_{21}(k,z)}{T_0(z)^2\overline{x}_{HIv}(z)^2} = P_{\delta_\rho,\delta_\rho}(k,z) + \boxed{\overline{x}_{HIIm}(z)^2 P_{ee}(k,z)} - 2\overline{x}_{HIIv}(z)\left[P_{\delta_\rho,\delta_\rho}(k,z) + P_{\delta_\rho,\delta_{xHII}}(k,z) + P_{\delta_\rho\delta_{xHII},\delta_\rho}(k,z)\right]$$

$$P_{ee}(k,z) = [f_{\mathrm{H}} - x_e(z)] \times \frac{\boxed{\alpha_0}\, x_e(z)^{-1/5}}{1 + \boxed{[k/\kappa]^3} x_e(z)} + x_e(z) \times b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)$$

Gorce et al. 2020



Sample Parameters:

- z_{re}: EoR mid-point,
- z_{end} : enf of EoR,
- α_0 : constant large-scale amplitude $\mathbf{P_{ee}}$ at high-z,
- κ : minimal size of ionised regions during reionisation.

Forecast Overview

$\mathbf{P_{21}}$ is constructed based on the true (z_{re}, z_{end}, α_0, k)

↓

Input data & uncertainties

↓

Randomly sample parameter space

↓

The EoR history is constructed using the parameterisation from Douspis et al. 2015

↓

$\mathbf{P_{ee}}$ fit from Gorce et al. 2022
$\mathbf{P_{\delta\delta}}$ fit from CAMB

→

$\mathbf{P_{21}}$ is re-constructed, presently without the higher-order terms

↓

χ^2 statistics analysis

↓

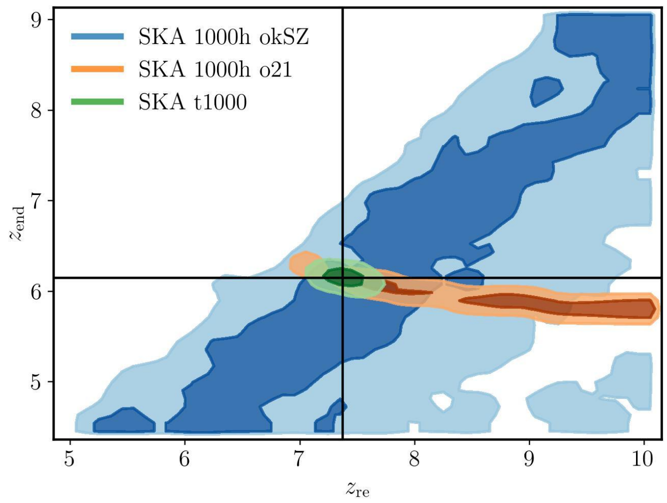
Extract best fit values

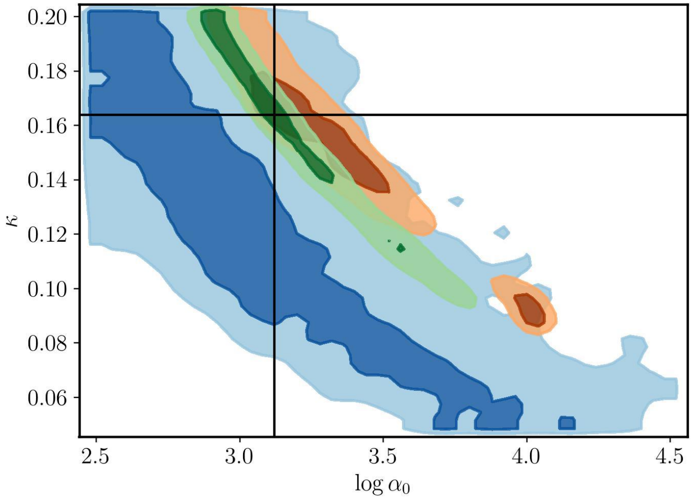
An Intuitive test of the forecast

Two **P_{21}** data points at z = 6.5, 7.8 for k = 0.5 Mpc^{-1} with a noise estimate from Mellema et al. 2013, assuming a 1000 h integration time with SKA.

One **kSZ** data point at l~3000 with 10% uncertainty.

- **kSZ** sensitive to the midpoint (can provide a lower limit on z_{re}).
- **21cm** give us upper limits on z_{end} and lower limits on z_{re}.





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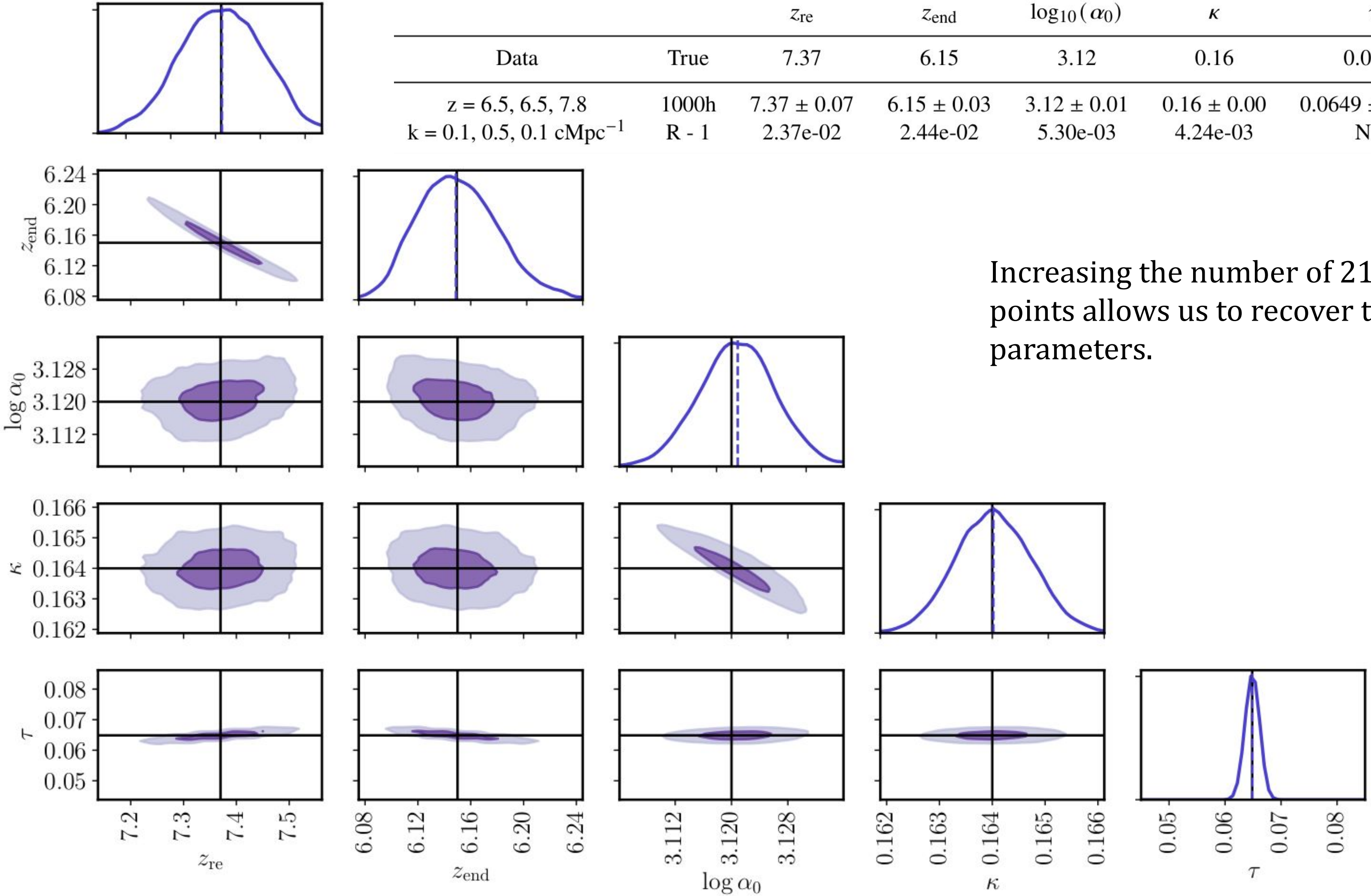
		z_{re}	z_{end}	$\log_{10}(\alpha_0)$	κ	τ	dz
Data	True	7.37	6.15	3.12	0.16	0.0649	1.22
z = 6.5, 6.5, 7.8	1000h	7.37 ± 0.07	6.15 ± 0.03	3.12 ± 0.01	0.16 ± 0.00	0.0649 ± 0.0010	1.22 ± 0.10
k = 0.1, 0.5, 0.1 $cMpc^{-1}$	R - 1	2.37e-02	2.44e-02	5.30e-03	4.24e-03	N/A	N/A



Increasing the number of 21-cm data points allows us to recover the EoR parameters.

Summary & Caveats

The natural connection between $\mathbf{P_{21}}$ and $\mathbf{P_{ee}}$ allows us to relate the patchy kSZ to the 21-cm signal from the EoR.

We build a forecast methodology to extract information on the nature of reionisation, given measurements of each data set.

Caveats:

The larger the $\mathbf{P_{21}}$ error bars the more degenerate (z_{re} , z_{end} , a_0 k).

Method works better for lower redshift or in later periods of EoR as early on $\mathbf{P_{21}} \sim \mathbf{P_{\delta\delta}}$

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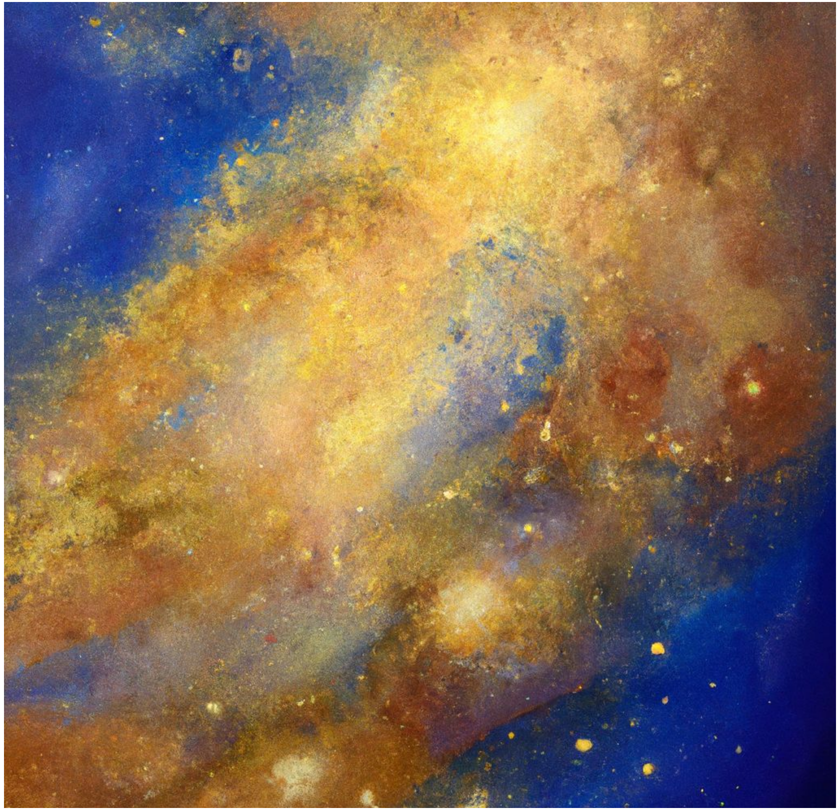


Extra Slides :)

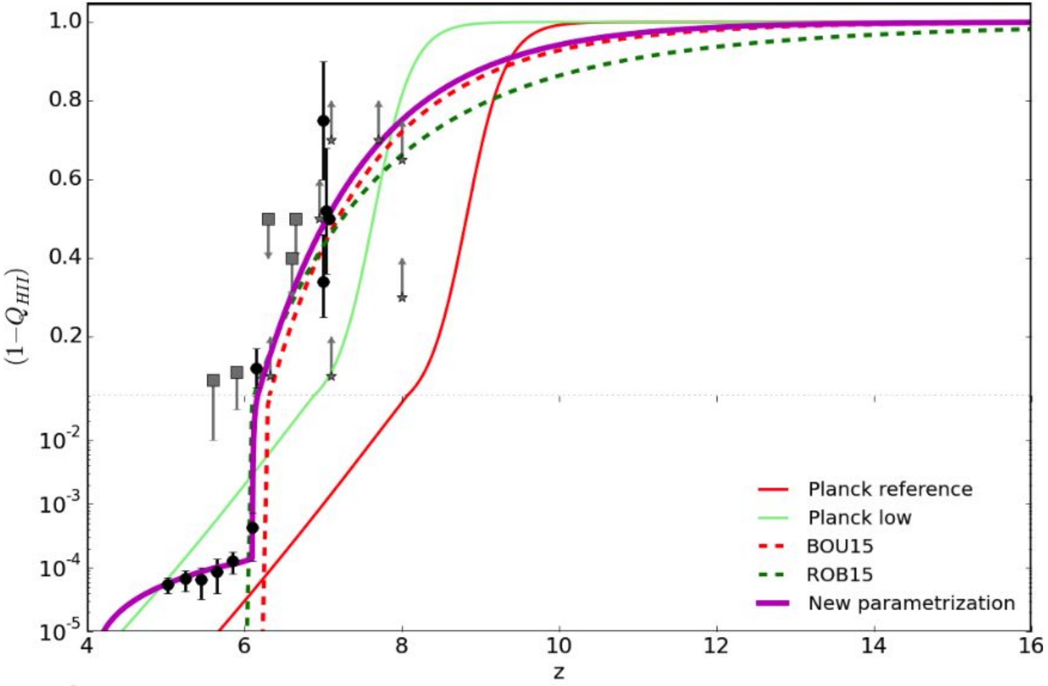
A curious side note

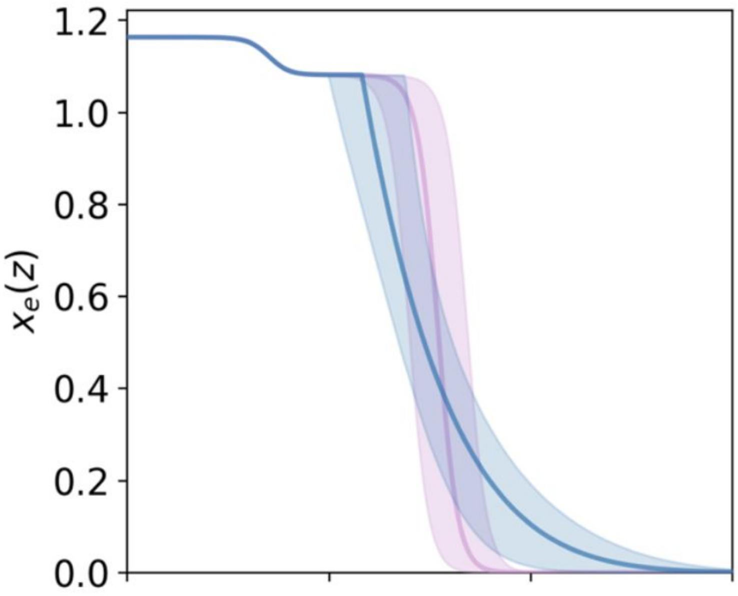
$$\frac{P_{21}(k,z)}{T_0(z)^2\overline{x}_{HIv}(z)^2} = \frac{2P_{21,\delta_\rho}(k,z)}{T_0(z)\overline{x}_{HIv}(z)} - P_{\delta_\rho,\delta_\rho}(k,z) + \overline{x}_{HIIm}(z)^2 P_{ee}(k,z)$$

We can re-express the higher-order terms as the cross correlation between the 21-cm field and the density field

- CO can be used as a proxy $\delta_{gal} \sim b\,\delta_\rho$,
- Interesting connection to the 21-cm bias!

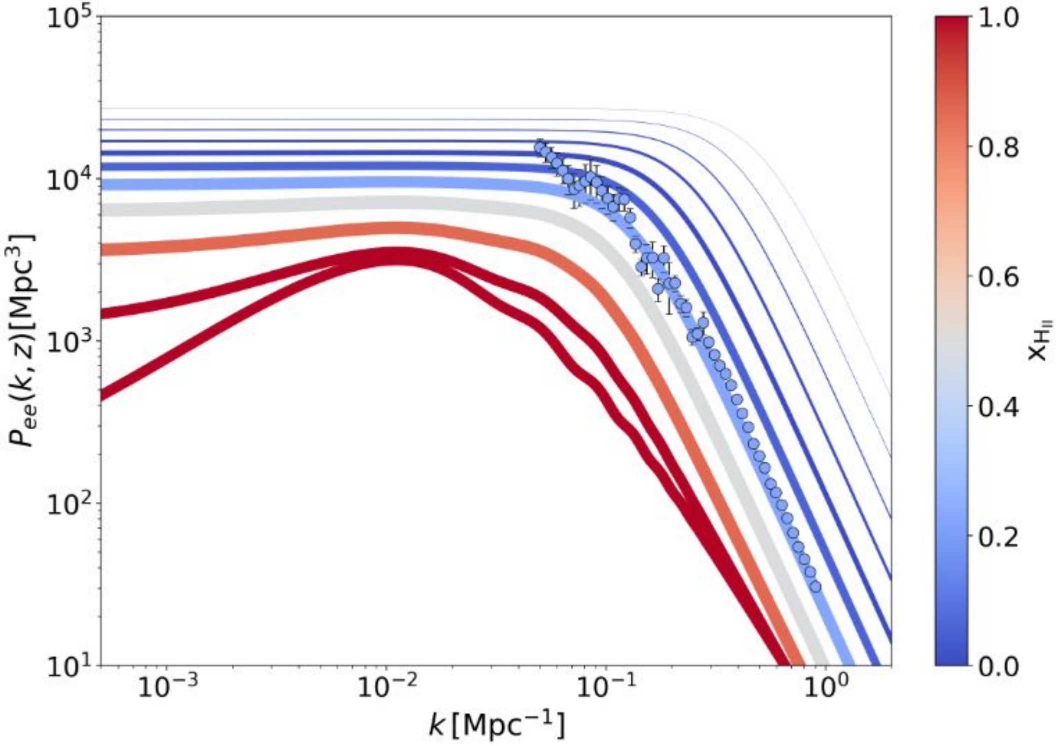
Douspis+2015





$$z < z_p \quad 1 - Q_{\rm HII}(z) \propto (1+z)^3$$

$$z \geq z_p \quad Q_{\rm HII}(z) \propto \exp(-\lambda(1+z))$$



$$\log \alpha_0/\mathrm{Mpc}^3 = 3.93^{+0.05}_{-0.06}$$

$$\kappa = 0.084^{+0.003}_{-0.004}\,\mathrm{Mpc}^{-1}.$$

$$P_{ee}(k,z) = [f_\mathrm{H} - x_e(z)] \times \frac{\alpha_0\, x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)} + x_e(z) \times b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)$$