Constraining reionization by combining CMB and 21cm observations

A case for joint analyses

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Colloque CMB-France 2023

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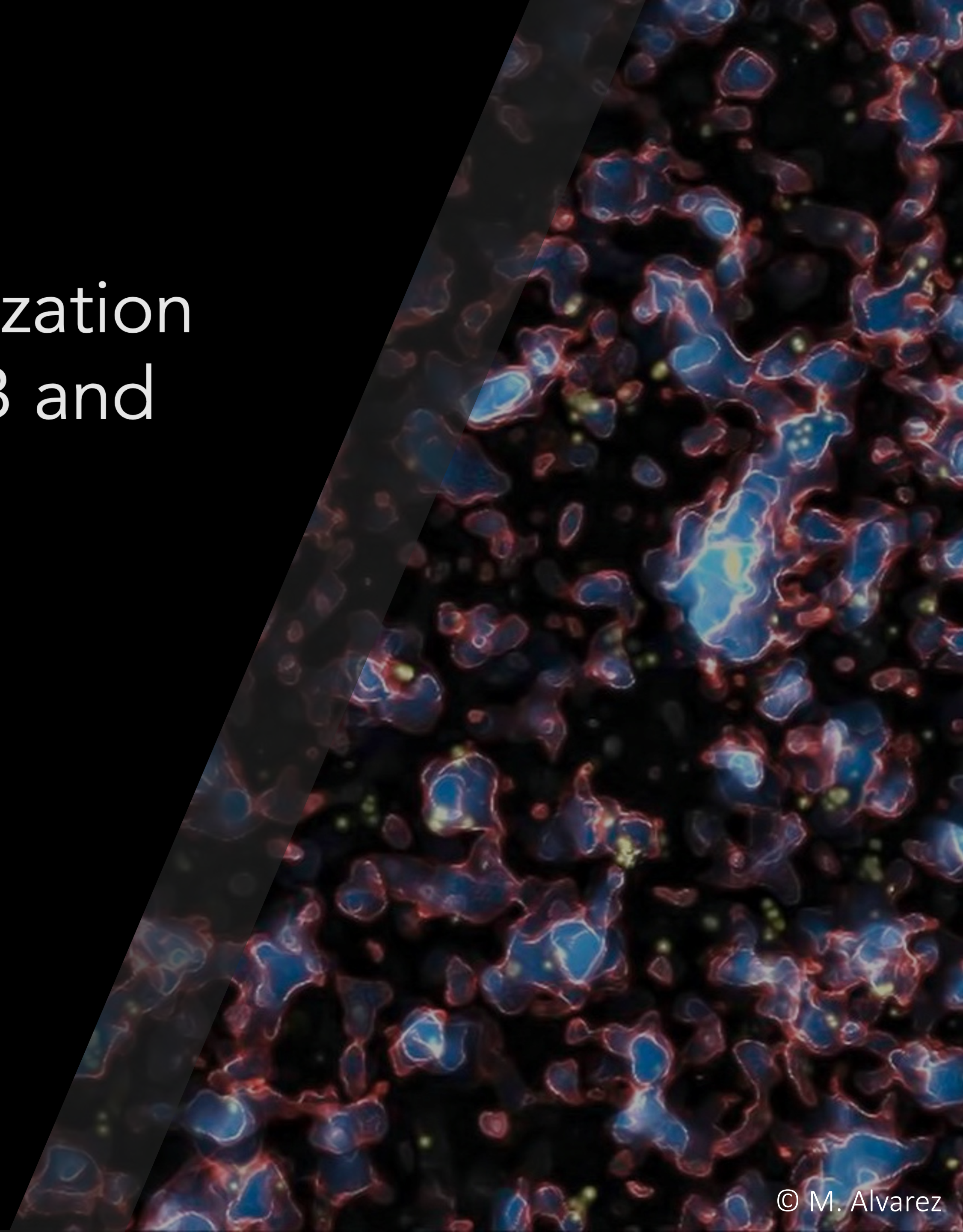

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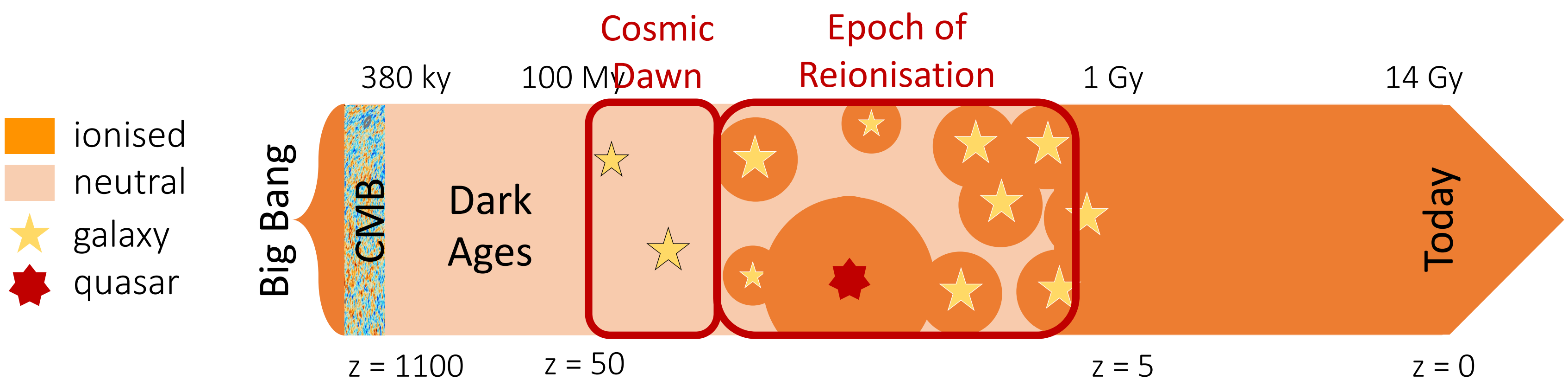
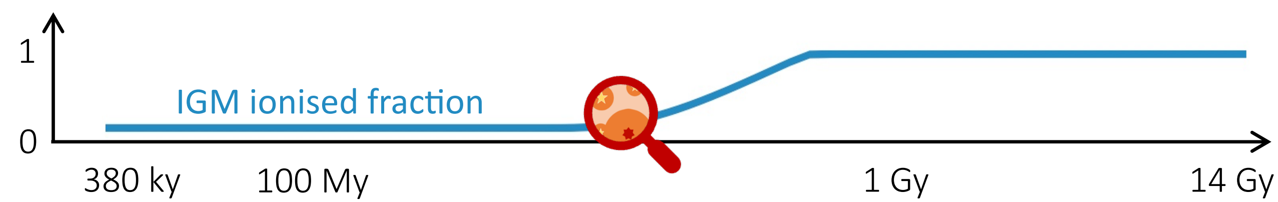
Reionisation & Cosmic Dawn



Large scales



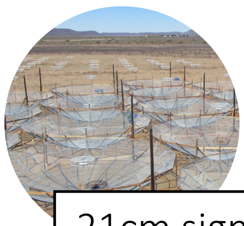
Small scales

The chronology & topology of reionisation can shed light on the nature of the first stars, the formation of galaxies, the density of the IGM…

Imprints of reionisation

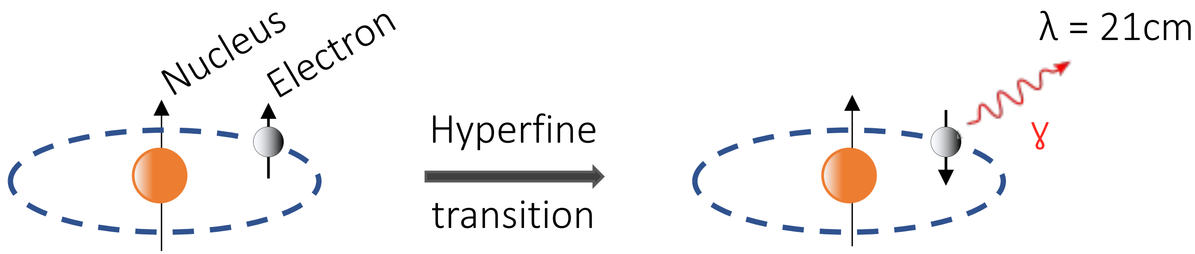
There is a wide range of reionisation observables

Not yet observed



21cm signal

Neutral hydrogen emission



$$\delta T_{\mathrm{b}} = T_0(z)\, x_{\mathrm{H_I}}\, (1 + \delta_{\mathrm{b}}) \left[1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right]$$

Neutral H fraction

Baryon density

With the 21cm signal, we can map the Universe at any redshift
→ 3D power spectrum ≠ CMB

Imprints of reionisation

There is a wide range of reionisation observables (non-exhaustive list…)

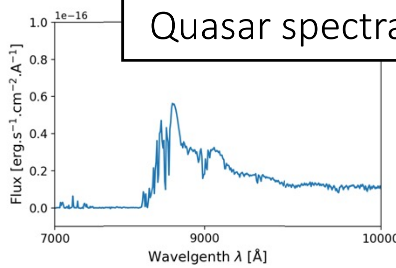
Not yet observed

21cm signal

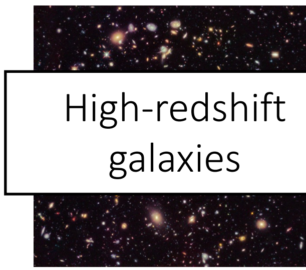
Neutral hydrogen emission

(Some) observations avaialble

Quasar spectra

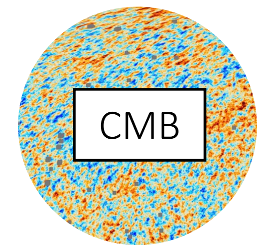


HI absorption troughs



High-redshift galaxies

Ionising photon budget



CMB

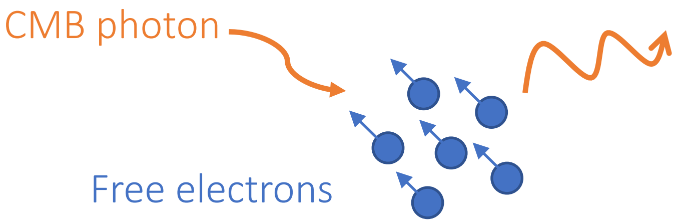
CMB photons scatter off free electrons

- Low signal-to-noise
- Bright foregrounds
- Instrumental systematics
- Modelling uncertainties

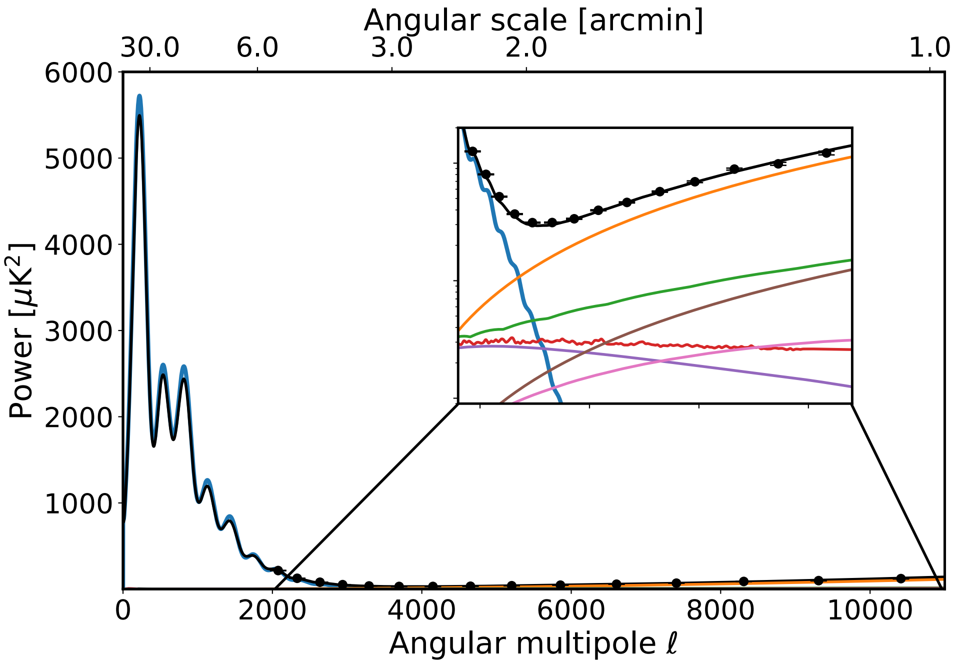
The kinetic Sunyaev-Zel'dovich effect

The kSZ effect corresponds to CMB photons scattering off free electrons with a bulk velocity

Kinetic SZ



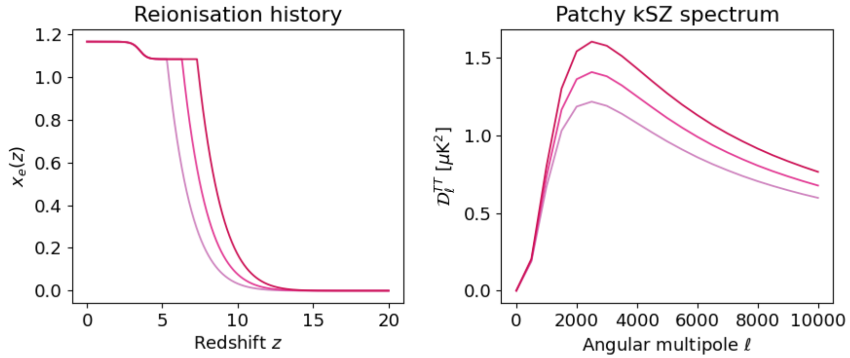
CMB TT power spectrum at 150GHz



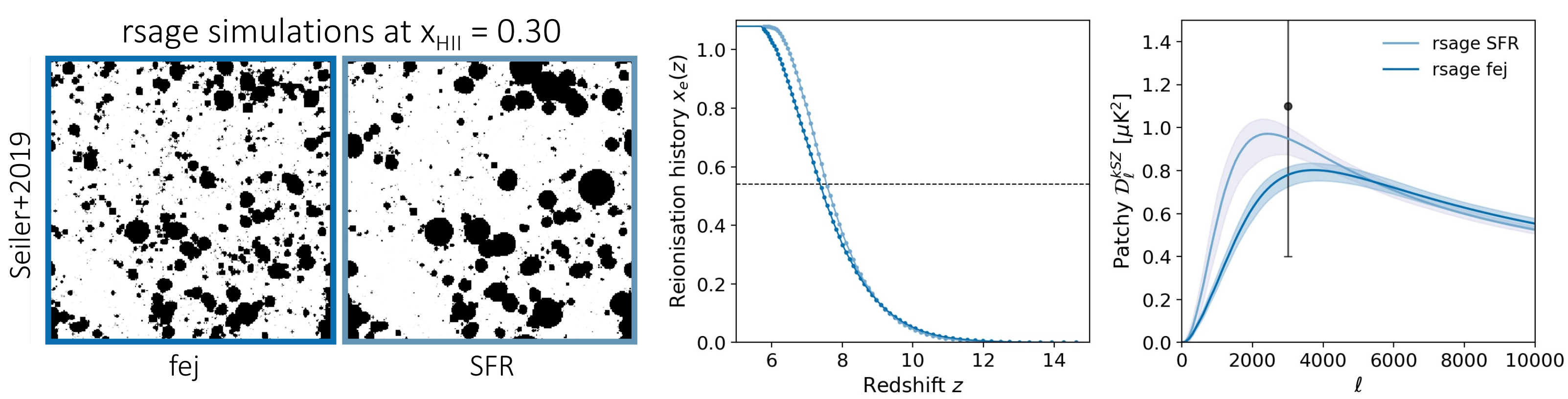
The kinetic Sunyaev-Zel'dovich effect

There is information about reionisation in the kSZ spectrum…

1. About global reionisation history

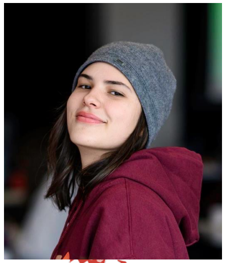


2. About reionisation morphology (and effectively galaxy properties)



Gorce+2020, and, e.g., McQuinn+2005; Iliev+2007; Battaglia+2013; Park+2013…

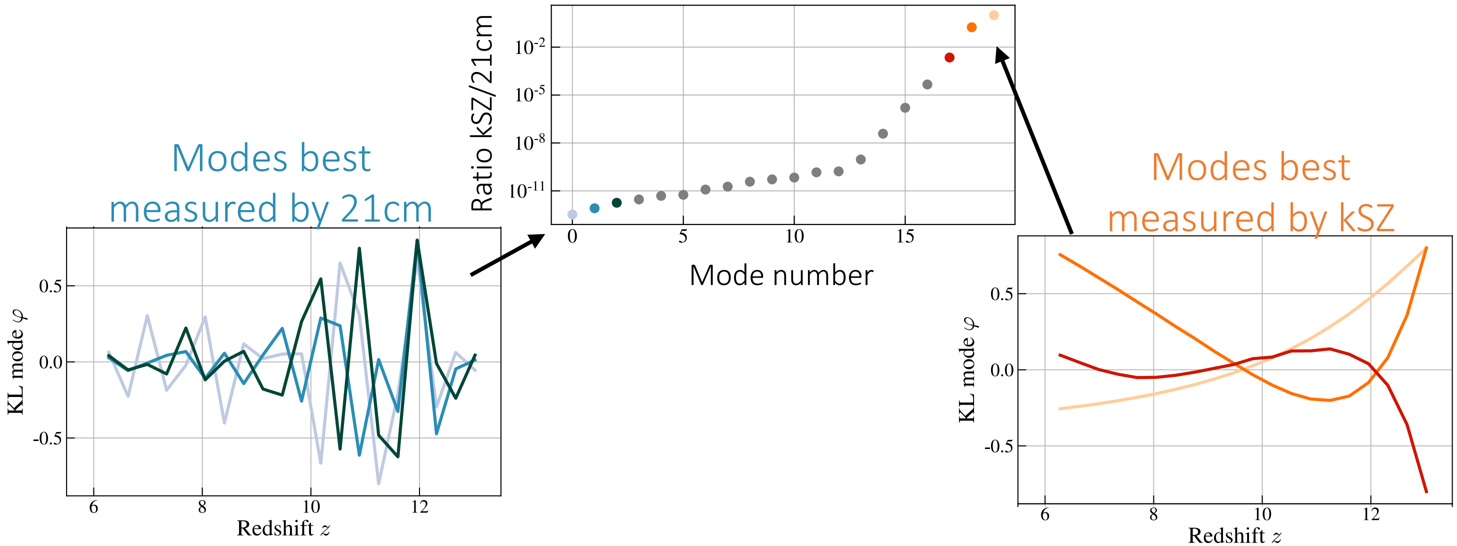
Combining kSZ / global 21cm



21cm global signal	kSZ power spectrum
Averaged over the whole sky	Integrated along line-of-sight
High frequency modes better recovered	Larger for longer EoR
Sensitive to rapid variations of $x_{HI}(z)$	Sensitive to slow variations of $x_{HI}(z)$

Cast Fisher forecast data in Karhunen-Loève basis

→ Eigenvalues describe the relative information content of each probe



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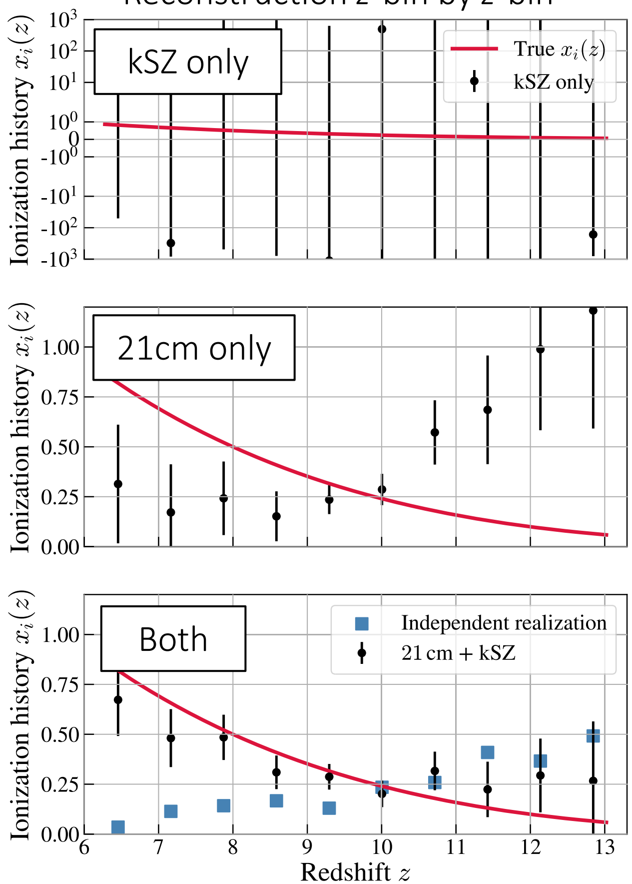
Combining kSZ / global 21cm

The complementarity can be leveraged to

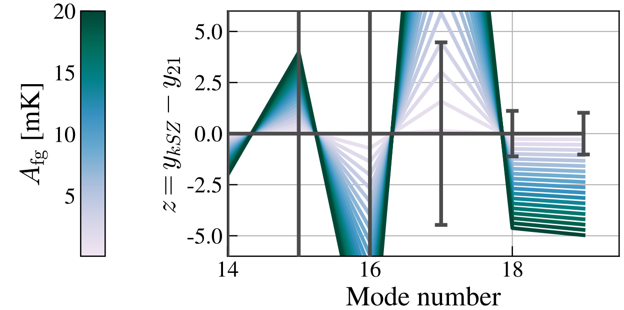
1. Better constrain the reionisation history

Reconstruction z-bin by z-bin

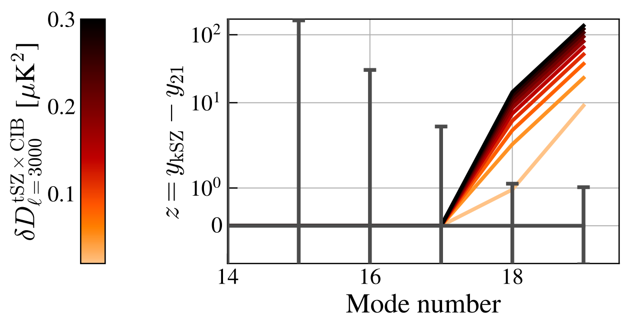


2. Identify and remove systematics

- Foreground residuals 4x smaller than cosmological signal detected at 10σ



- 0.05 μK² tSZxCIB residual picked up at 100σ



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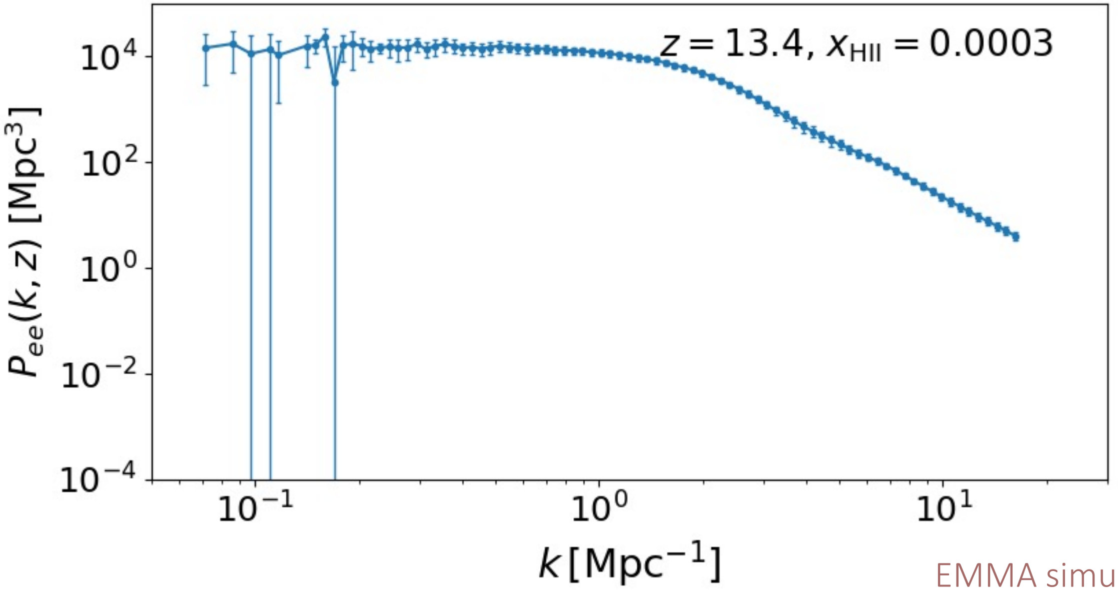
Combining kSZ / 21cm PS

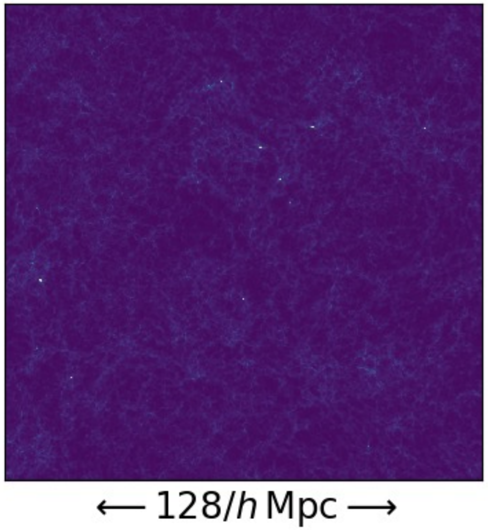
- Relate the 21cm and the kSZ power spectra through their base ingredient: the electron power spectrum

kSZ $$C_\ell^{\mathrm{kSZ}} \propto \int \frac{\mathrm{d}z}{H(z)} \bar{n}_e(z)^2 k^3 v_{\mathrm{rms}}^2(z) \mathrm{e}^{-\tau(z)} d_c(z) \times P_{ee}(k,z)$$

21cm PS $$\frac{P_{21}(k,z)}{T_0(z)^2} = x_e(z)^2 P_{ee}(k,z) + [1-2x_e(z)] P_{bb}(k,z) - 2x_e(z) \left[P_{bi}(k,z) + P_{bi,b}(k,z)\right]$$

- Look at the evolution of $P_{ee}(k,z)$ in high resolution hydrodynamical simulations



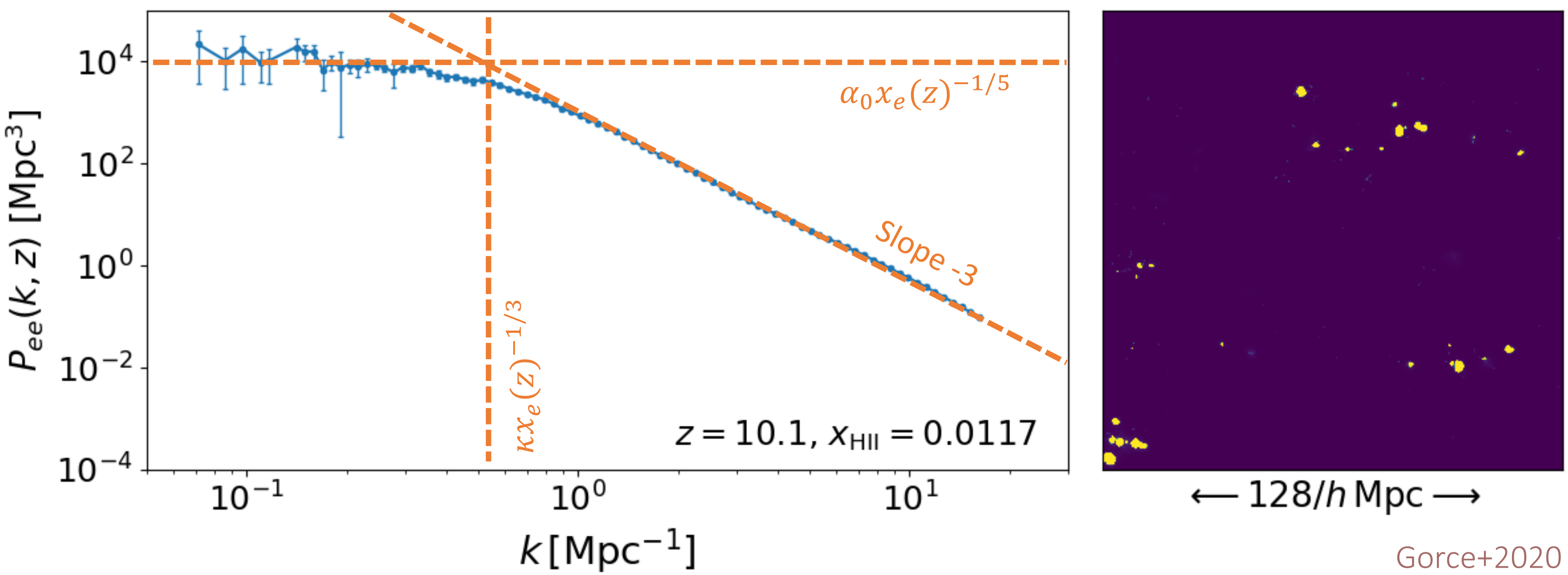


EMMA simulation (see Aubert+2015, Chardin+2019)

Combining kSZ / 21cm PS

- Relate the 21cm and the kSZ <u>power spectra</u> through their base ingredient: the electron power spectrum
- Look at the evolution of $P_{ee}(k,z)$ in high resolution hydrodynamical simulations
- Find a parameterisation of the evolution of $P_{ee}(k,z)$

Early times: power-law $$P_{ee}(k,z) = \frac{\alpha_0 \; x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)}$$



Gorce+2020

Combining kSZ / 21cm PS

- Relate the 21cm and the kSZ power spectra through their base ingredient: the electron power spectrum
- Look at the evolution of $P_{ee}(k,z)$ in high resolution hydrodynamical simulations
- Find a parameterisation of the evolution of $P_{ee}(k,z)$
  Depends on cosmology and a few reionisation parameters (z_{re}, $z_{end,}$, α_0, κ)...

$$P_{ee}(k,z) = \underbrace{[f_{\rm H} - x_e(z)] \times \frac{\alpha_0 \; x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)}}_{\text{High-redshift (power-law)}} + \underbrace{x_e(z) \times b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)}_{\text{Low-redshift (biased matter PS)}}$$

High-redshift (power-law) — Gorce+2020

Low-redshift (biased matter PS) — Shaw+2012

Gorce+2020

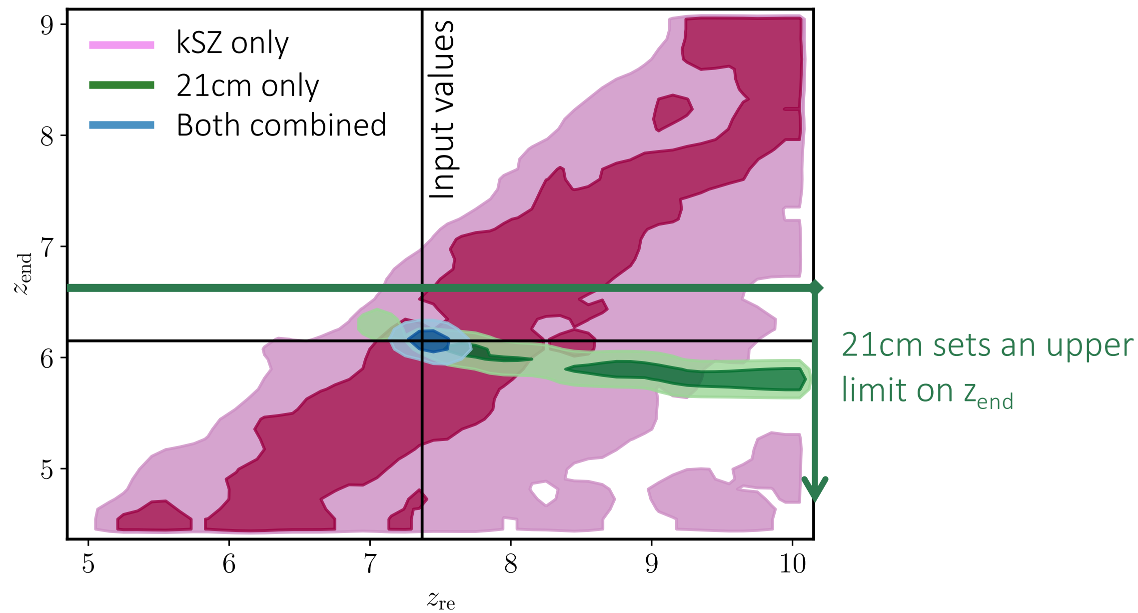
Combining kSZ / 21cm PS

- Relate the 21cm and the kSZ power spectra through their base ingredient: the electron power spectrum

kSZ
$$C_\ell^{\mathrm{kSZ}} \propto \int \frac{\mathrm{d}z}{H(z)} \bar{n}_e(z)^2 k^3 v_{\mathrm{rms}}^2(z) \mathrm{e}^{-\tau(z)} d_c(z) \times P_{ee}(k,z)$$

21cm PS
$$\frac{P_{21}(k,z)}{T_0(z)^2} = x_e(z)^2 P_{ee}(k,z) + [1-2x_e(z)] P_{bb}(k,z)$$

- Use the analytical model of P_{ee} to generate both observable for a given set of reionisation parameters in a forecast → constrain reionisation

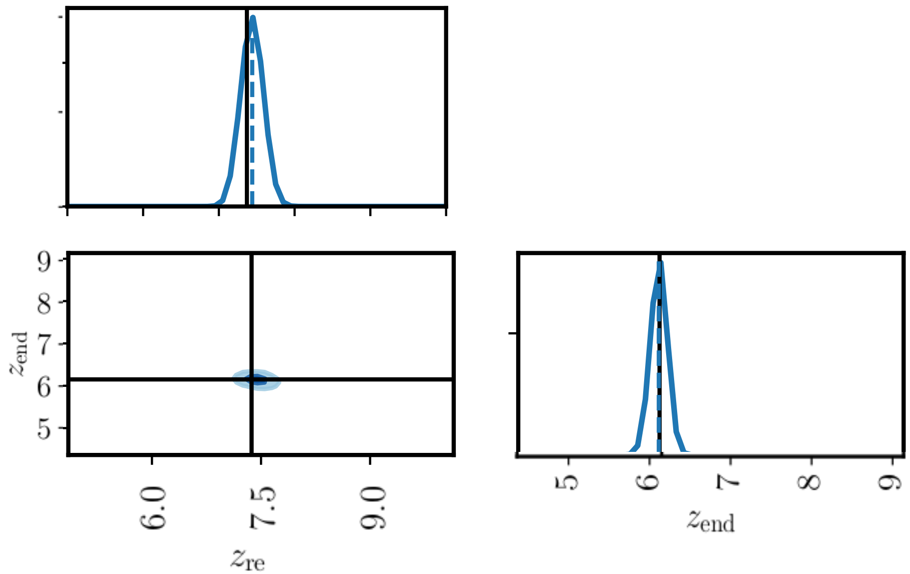


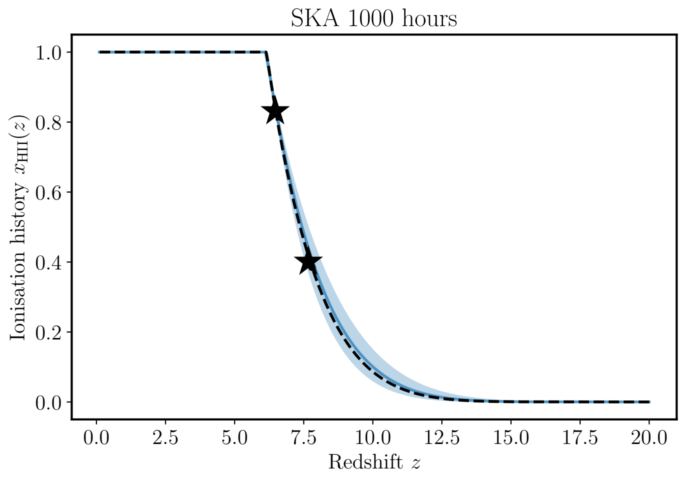
Georgiev, **Gorce** & Mellema in prep

Combining kSZ / 21cm PS

- With only three data points, one can recover the reionisation mid- and endpoint with very good accuracy

21cm: 1000hrs of observation with SKA, 2 data points at k = 0.5 *h*Mpc^{-1} & z = 6.5, 7.8.
pkSZ: 1 data point at l=3000 with 10% error bar.





Georgiev, **Gorce** & Mellema in prep

Combining kSZ / 21cm PS

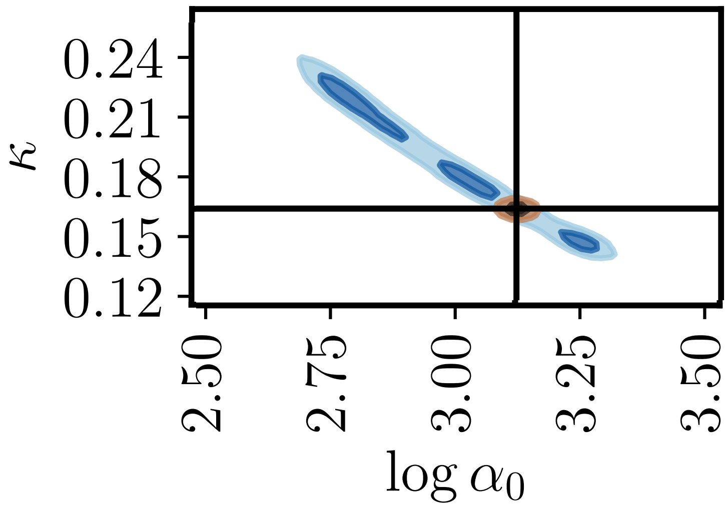
- With only three data points, one can recover the reionisation mid- and endpoint with very good accuracy

  21cm: 1000hrs of observation with SKA, 2 data points at k = 0.5 hMpc^{-1} & z = 6.5, 7.8.
  pkSZ: 1 data point at l=3000 with 10% error bar.

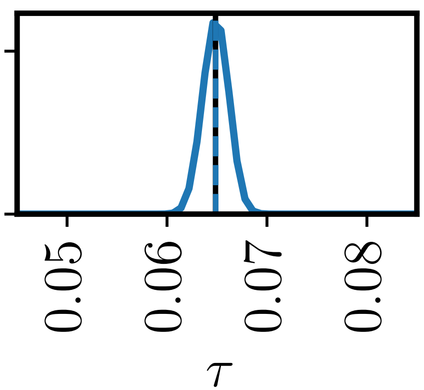
- With one extra 21cm data point at a different scale, we can also constrain the morphology of reionisation

  21cm: Extra data point at k=0.5Mpc^{-1} and z=6.5

Two 21cm data points
Three 21cm data points



We can also make an independent measurement of the Thomson optical depth!



τ = 0.065 +/- 0.001

Georgiev, **Gorce** & Mellema in prep

Conclusions

To understand reionisation, using all the available data is necessary to overcome systematics and uncertainties.

- These works demonstrated the potential of jointly fitting data sets
- Strong constraints possible even with early 21cm data!

A lot of exciting results to expect with forthcoming 21cm and kSZ data!

June 10-14
IAS, Orsay, France
Soon-to-be-announced!