

# Constraining reionization by combining CMB and 21cm observations

A case for joint analyses

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Introduction

### Reionisation & Cosmic Dawn



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

Introduction

### Imprints of reionisation

 $T$ here is a wide range of reionisation observables



With the 21cm signal, we can map the Universe at any redshift  $\rightarrow$  3D power spectrum  $\neq$  CMB

### Imprints of reionisation

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



## The kinetic Sunyaev-Zel'dovich effect

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



### 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…



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## Combining kSZ / global 21¢m

The complementarity can be leveraged to





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so, deferring a discussion of potential systematics (and how

One method for combining data into a single ionization history is to employ a least-squares estimator, where we wish to construct an estimator  $\mathbf{r}$ history x, given a collection of measurements y. In our case, we take you coefficients. Relating the measurement to what we want to

where  $\mathcal{A}$ of two R<sup>−</sup><sup>1</sup> matrices), and nconc is the concatenated noise vector, i.e., nconc ¼ ðn21; nkSZÞ. Note that this noise is not the instrumental noise contribution from the original 21 cm or kSZ measurements, but instead, the "noise" in our determination of y<sup>21</sup> and ykSZ. It therefore has a covariance

With these definitions, the least squares estimator for the

yconc ¼ Ax þ nconc; ð25Þ

#### Combining kSZ / 21cm PS *N* r I *x*  $\overline{X}$   $\overline{Y}$   $\overline{Y}$  *<sup>V</sup>* <sup>2</sup> <sup>=</sup> <sup>1</sup>

o Relate the 21cm and the kSZ power spectra through their base ingredient: the electron power spectrum *V* (*s*)  $\overline{1}$ *N*

*k*=1

*x*loc(*k*)

<sup>2</sup> *<sup>x</sup>*¯<sup>2</sup>

 $\overline{\phantom{a}}$ 

$$
\text{KSZ} \qquad C_{\ell}^{\text{kSZ}} \propto \int \frac{\mathrm{d}z}{H(z)} \bar{n}_e(z)^2 k^3 v_{\text{rms}}^2(z) e^{-\tau(z)} d_c(z) \times P_{ee}(k, z) \\ \text{21cm PS} \qquad \frac{P_{21}(k, z)}{T_0(z)^2} = x_e(z) \left[ P_{ee}(k, z) + [1 - 2x_e(z)] P_{bb}(k, z) - 2x_e(z) \right] P_{bi}(k, z) + P_{bi,b}(k, z) \tag{21cm}
$$

ition of p (k<sub>7</sub>  $\circ$  Look at the evolution of P<sub>ee</sub>(k,z) in high resolution hydrodynamical simulations



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### Combining kSZ / 21cm PS matter fields.

- o Relate the 21cm and the kSZ power spectra through their base ingredient: the electron power spectrum early stages of reionisation as can be seen on the right panel Therefore, we choose in this work to use a direct parameterisa-
- o Look at the evolution of  $P_{ee}(k,z)$  in high resolution hydrodynamical simulations  $i$ stion and calibrations. The parameters,  $\frac{1}{2}$
- $\circ$  Find a parameterisation of the evolution of P $_{\rm ee}$ (k,z)

 $P_{ee}(k, z) = \frac{\alpha_0 x_e(z)^{-1/5}}{1 + 5k/13z_0}$  $1 + [k/\kappa]^3 x_e(z)$ Early times: power-law



. (13)

related to the typical bubble size, in the bias between the H i and

electrons density power spectra of our six simulations in the

This behaviour is close to what we observe in the free

#### **ble SC** Combining kSZ / 21cm PS line), hinting at a relation between the cut-o↵ frequency and the relation to the typical bubble size, in the bias between the  $\mathbf{r}_i$  $\frac{1}{2}$  contribution of patchy contribution to the patchy corresponding to the **This behaviour is compining KSZ / ZICM PS** power spectrum, so that a precise knowledge of *be*(*k*,*z*) is not electrons density power spectra of our six simulations in the power spectrum, so that a precise knowledge of *be*(*k*,*z*) is not required. In the future, if we want to apply our results to apply our results to apply our results to apply our

- electrons density power spectra through their base ingredient: early state electron power spectrum of Fig. 2, showing *Pee*(*k*,*z*) for the first of our six simulations. shu the NSZ <u>power spectra</u> through their base ingredier<br>... ... . .tww.  $\mathcal{L}$  be the sum of homogeneous and patchy ks $\mathcal{L}$ a, showing *Peer and the ksz nower* spectra through their hase ingredient: Therefore, we choose in this work to use the use a direct parametering when  $\frac{1}{2}$ tion of the scale and redshift evolution of *Pee*(*k*,*z*) during reion-<u>er spectra</u> through their c
- $\sim$  1000  $\mu$  Look at the evolution of P<sub>ee</sub>(k,z) in high resolution hydrodynamical simulations tion of the scale and redshift evolution of *Pee*(*k*,*z*) during reion-Tor r<sub>ee</sub>(K,Z) in high resolution hydrodynamical simul  $\sim$  1 ook at the evolution of P  $\left(k, \frac{1}{2}\right)$  in high resolution hydrodynamical simulations and  $\overline{a}$  , are defined as i fiigh resolution hydrodynamical simulations

cient for this work since  $\sigma$  this work since  $\sigma$  this work since  $\sigma$ 

to modes 10<sup>3</sup> < *k*/Mpc<sup>1</sup> < 1 where *Pee* follows the matter

spectrum, we will need a better model as the observed signal as the observed signal as the observed signal  $\alpha$ 

required. In the future, if we want to apply our results to apply our results to apply our results to con-

is a biased matter it on our simulation of the evolution of  $P_{ee}(k, z)$  $\frac{1}{2}$   $\frac{1}{2}$  and  $\frac{1}{2}$   $\frac{1}{2}$  and  $\frac{1$ Depends on cosmology and a few reionisation paramete 1/5 1 + [*k*/]3 *xe*(*z*)  $\frac{1}{2}$  fluctuations of  $\frac{1}{2}$  (kg) Depends on cosmology and a few reionisation parameters (z<sub>re</sub>, z<sub>end,</sub>, α<sub>0</sub>, κ)...

$$
P_{ee}(k, z) = [f_{\rm H} - x_e(z)] \times \frac{\alpha_0 x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)} + x_e(z) \times b_{\delta e}(k, z)^2 P_{\delta \delta}(k, z)
$$
  
High-redshift  
(power-law)  
George+2020  
Shaw+2012  

. (13) The contract of the contract of the

related to the typical bubble size, in the bias between the H i and

early stages of reionisation as can be seen on the right panel

lines on the figure corresponds to *k* = 91/<sup>4</sup>/*R* (dashed vertical

This behaviour is close to what we observe in the free

In log-space, on large scales, *Pee* has a constant amplitude which, as mentioned above, depends on the filling fraction and therefore reaches its maximum ↵<sup>0</sup> at the start of the reionisation

*Pee*(*k*,*z*) <sup>=</sup> ↵<sup>0</sup> *xe*(*z*)

<sup>5</sup> The bubble radii actually follow a Gaussian distribution centred on

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15 px with standard deviation 2 px.

#### *<sup>V</sup>* <sup>2</sup> <sup>=</sup> <sup>1</sup> Combining kSZ / 21cm PS *N* r I *<sup>x</sup>*loc(*k*)*x*loc(*<sup>k</sup>* <sup>+</sup> *<sup>i</sup>s*) *<sup>x</sup>*¯<sup>2</sup>

*k*=1 o Relate the 21cm and the kSZ power spectra through their base ingredient: *<sup>x</sup>*loc(*k*)*x*loc(*<sup>k</sup>* <sup>+</sup> *<sup>i</sup>s*) *<sup>x</sup>*¯<sup>2</sup> the electron power spectrum

kSZ

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

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

*k*=1

21cm PS

*C*kSZ ` / *H*(*z*) o Use the analytical model of P<sub>ee</sub> to generate both observable for a given set of *n*¯*e*(*z*) <sup>2</sup>*k*3*v*<sup>2</sup> rms(*z*)e⌧(*z*) reionisation parameters in a forecast → constrain reionisation *dc*(*z*) ⇥ *Pee*(*k, z*) (10)



 $\overline{\phantom{a}}$ 

## Combining kSZ / 21cm PS

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

 $\frac{3.5 \text{ mpc}}{2.5}$  $\mathcal{S}_{\mathcal{A}}$ 21cm: 1000hrs of observation with SKA, 2 data points at  $k = 0.5$  hMpc<sup>-1</sup> &  $z = 6.5$ , 7.8. pkSZ: 1 data point at l=3000 with 10% error bar.



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### Combining kSZ 71cm PS 6*.*08 *<u>\_\_</u>*<br>•  $\overline{\mathsf{c}}$

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

SKA 1000 h 3k2z

- 21cm: 1000hrs of **observation with SKA, 2 data points at k = 0.5** *hM* nc<sup>-1</sup> & z = 6.5, 7.8. point 10% error bar. pkSZ: 1 da
- o With one extra 2 Lcm data point at a different scale, we also constrain the with one extra z<sub>reionisation</sub> **22.25 Property Countries**<br>22.25 Countries Extra data point at k=0.5Mpc-1 and z=6.5  $\overline{\mathbf{A}}$

 $\frac{1}{2}$ wo 21cm data poin hree 21cm data points

3*.*00

 $\log \alpha_0$ 

3*.*25 0*.*8

3*.*50 1*.*6

d*z* = *z*re ° *z*end

0*.*15 0*.*18 0*.*21 0*.*24 ∑

2*.*50

0*.*12

6*.*24

2*.*50 0*.*12

2*.*75 0*.*20

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

> 0*.*18 0*.*05 0*.*21 0*.*24 <sup>∑</sup> <sup>0</sup>*.*<sup>0600</sup> 0*.*06 0*.*07 0*.*08  $\tau$

> > $\tau = 0.065 +/- 0.001$

0*.*0650

6*.*16

4*.*5

*z*end

0*.*0650

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ø

0*.*0625



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

- o These works demonstrated the potential of jointly fitting data sets
- o Strong constraints possible even with early 21cm data!
- A lot of exciting results to expect with forthcoming 21cm and kSZ data!

