A global picture of the Epoch of Reionisation

Adélie Gorce

AstroParticle Symposium

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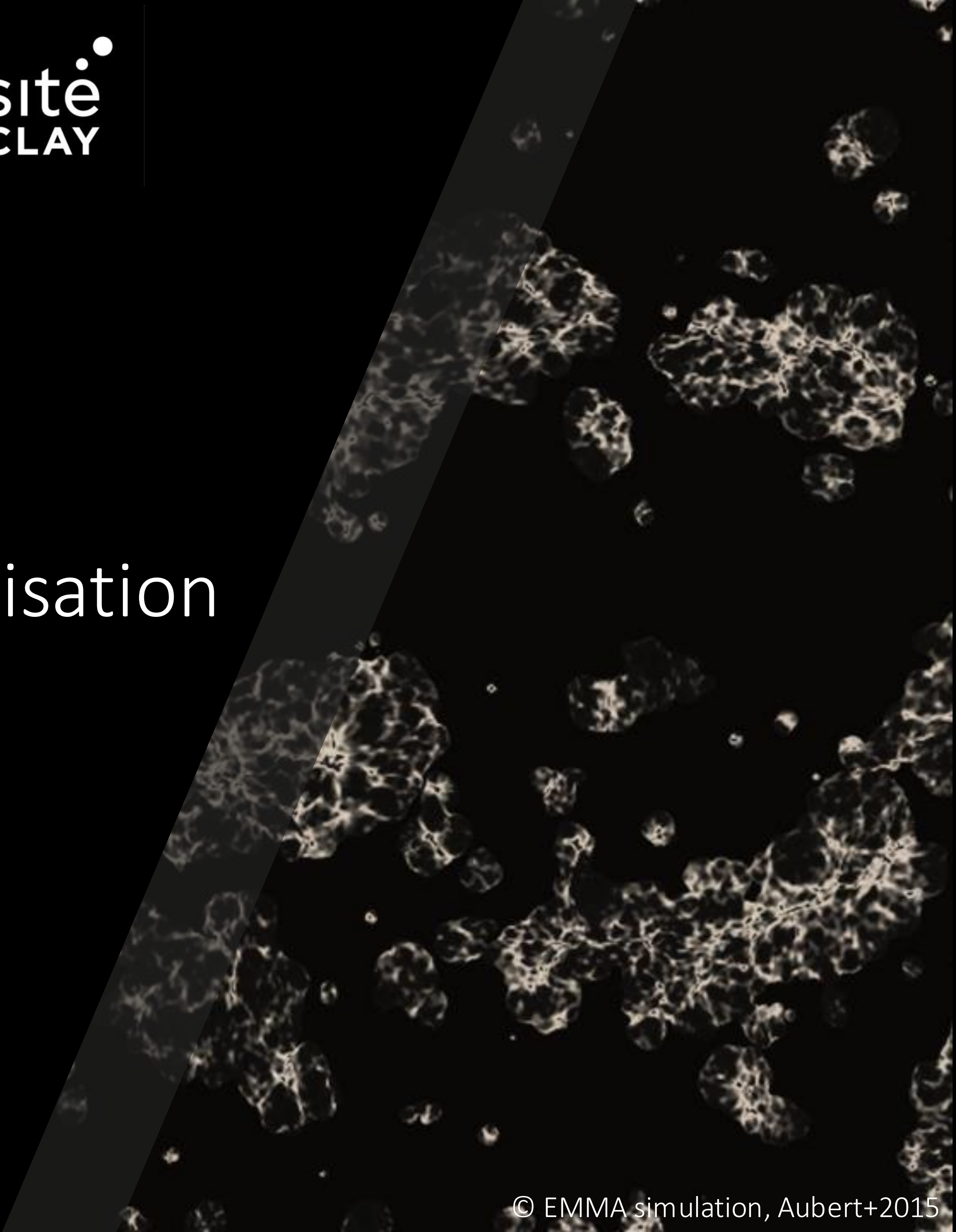
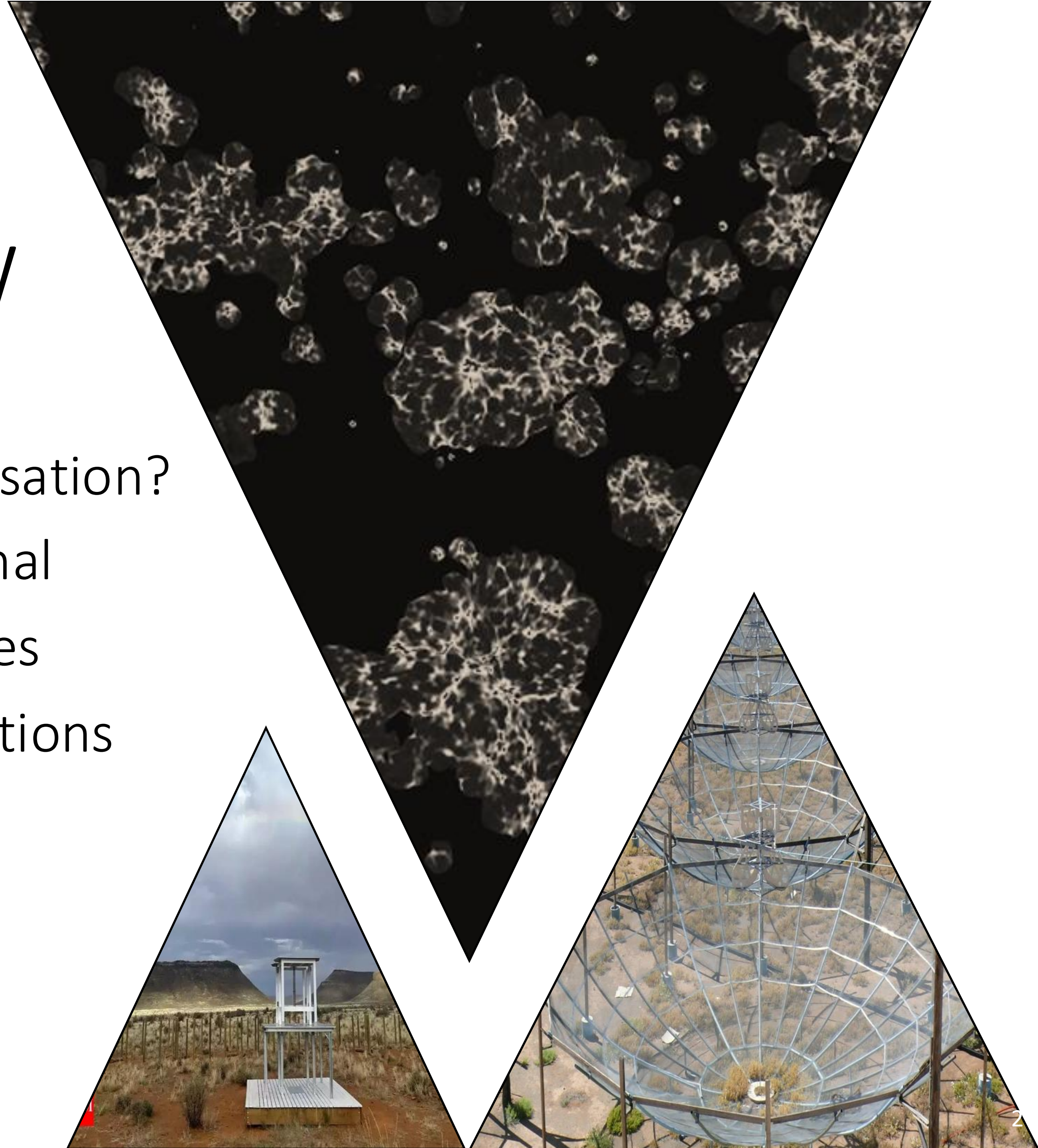
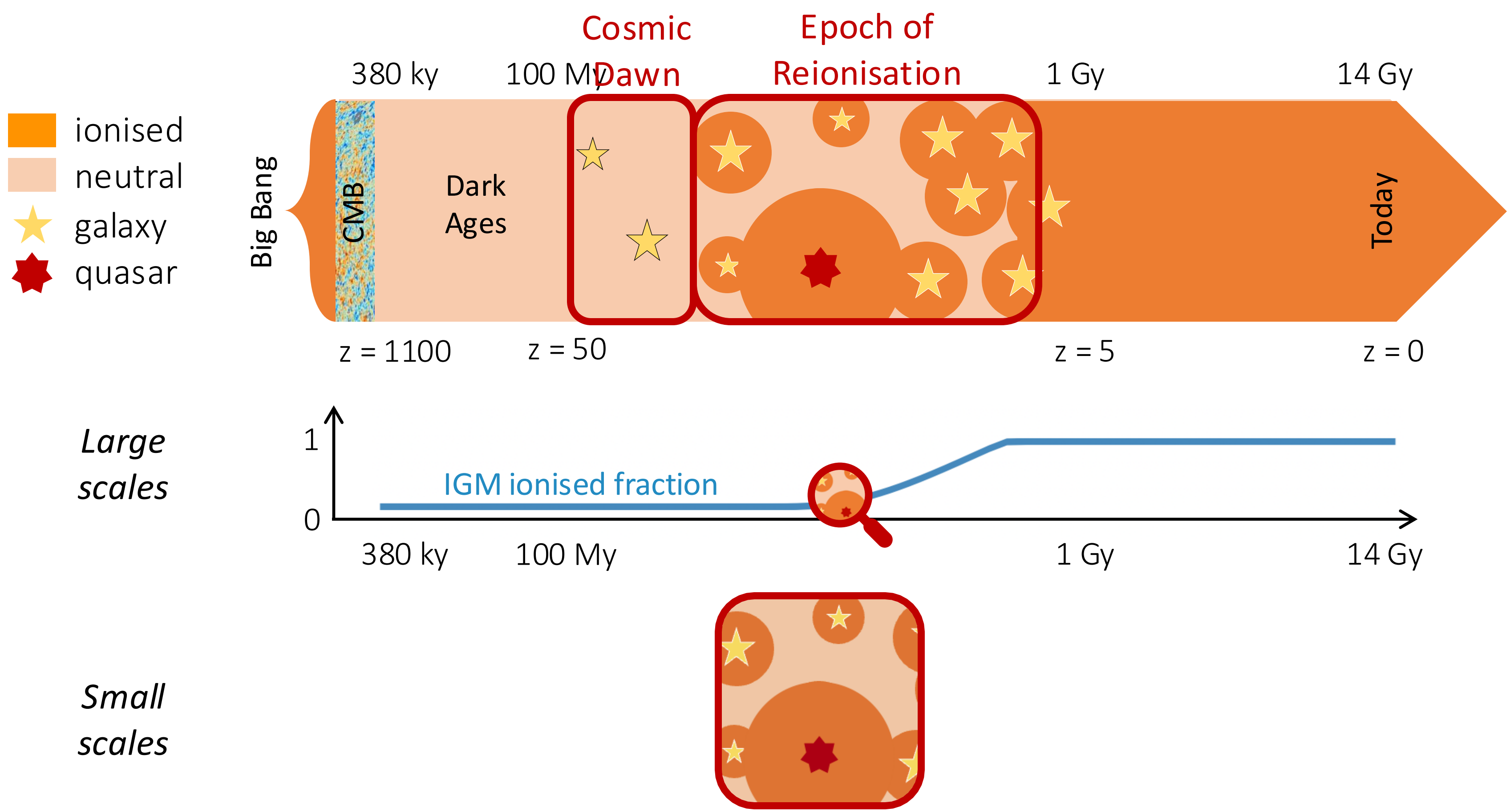


OVERVIEW

I. Introduction:
   What is reionisation?
II. The 21cm signal
III. CMB signatures
IV. Data combinations



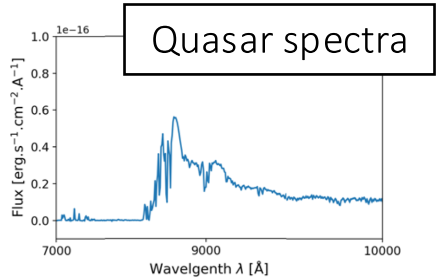
Reionisation & Cosmic Dawn



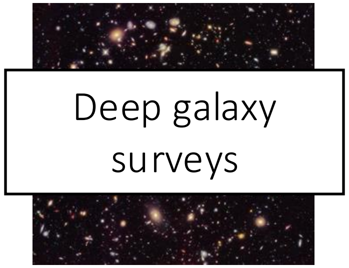
The chronology & topology of reionisation can shed light on the nature of the first stars, the formation of galaxies, the density of the IGM…

Understanding reionisation

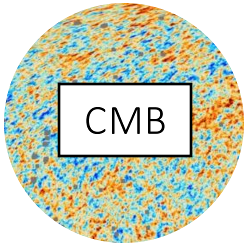
Available data



HI absorption troughs

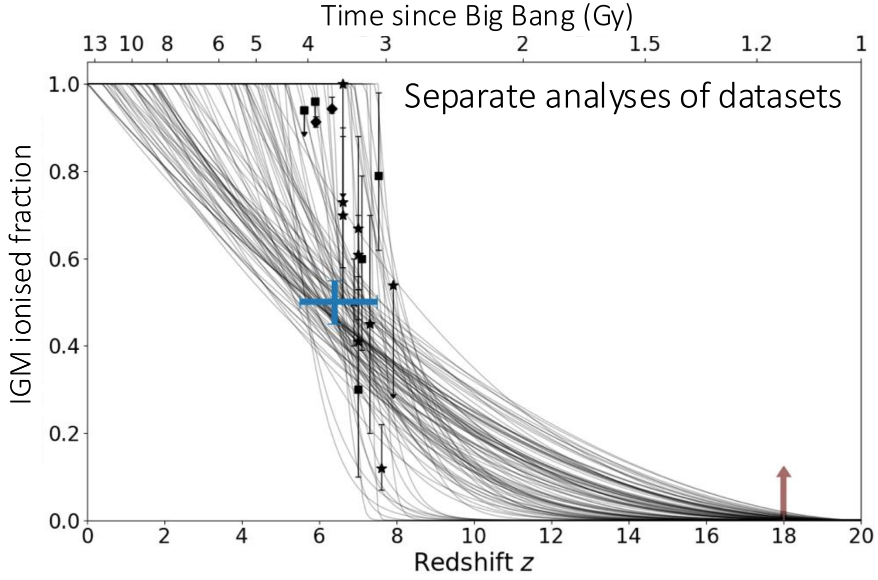


Ionising photons budget



Scattering from free electrons

Current constraints on reionisation history

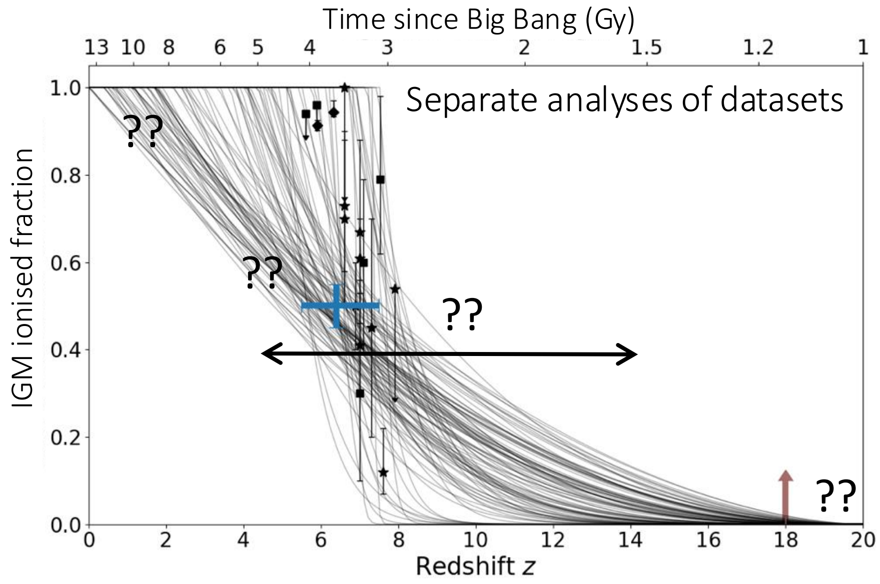


Understanding reionisation

So what do (we think) we know so far?

- Starts slowly around redshift 15-20?
- Reaches 50% ionisation around z = 7?
- Ends z < 6?
- Lasts for 0.5-1Gy?

Current constraints on reionisation history



Understanding reionisation

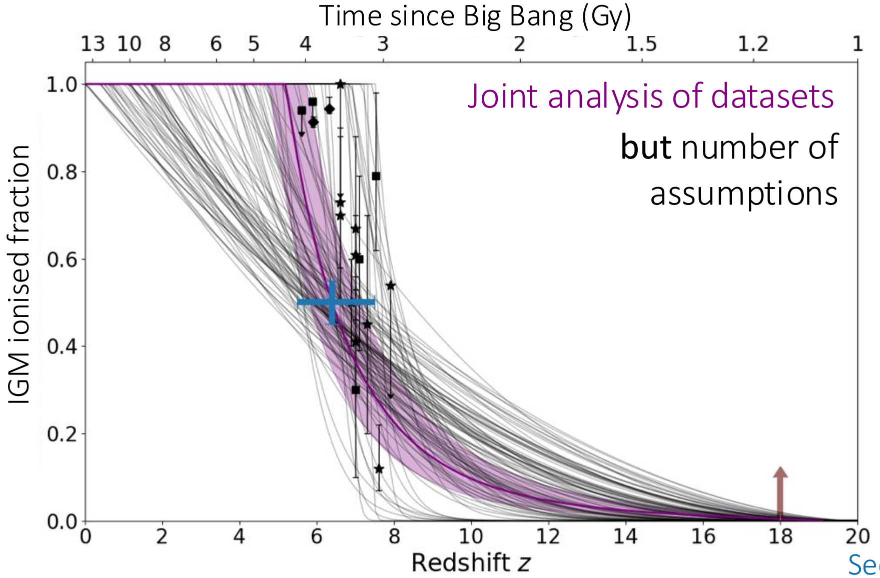
So what do (we think) we know so far?

Not that much…

How can we do better?

1. By combining data sets

Current constraints on reionisation history



See, e.g., Gorce+2018, Muñoz+2024

Understanding reionisation

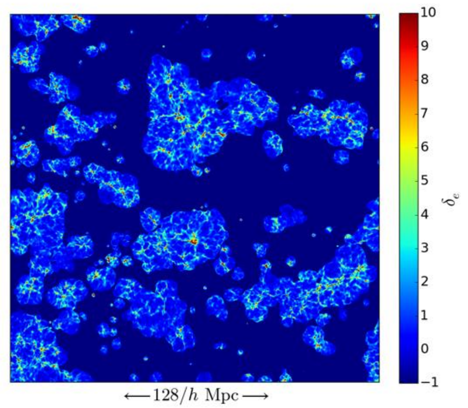
So what do (we think) we know so far?

Not that much…

How can we do better?

1. By combining data sets
2. By working on our theoretical understanding of reionisation

With simulations…



21CMFAST, BEoRN, LICORICE, EMMA, CODA, C2-ray …

Or analytical models…

See, e.g., Furlanetto+2004, Gorce+2020, Schneider+2020, Mirocha+2022, Muñoz 2023, Georgiev+2024…

Understanding reionisation

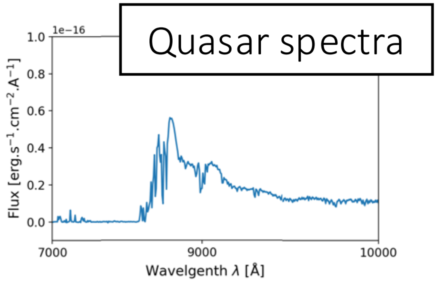
So what do we know so far?

Not that much…

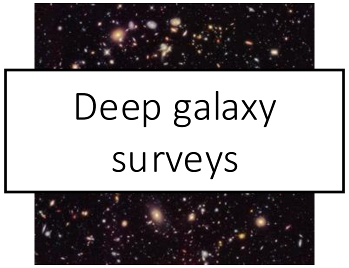
How can we do better?

1. By combining data sets
2. By working on our theoretical understanding of reionisation
3. By finding direct observables

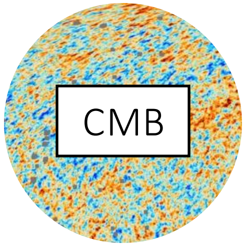
Available data



HI absorption troughs

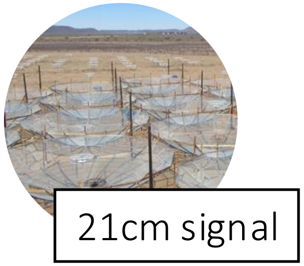


Ionising photons budget



Scattering off free electrons

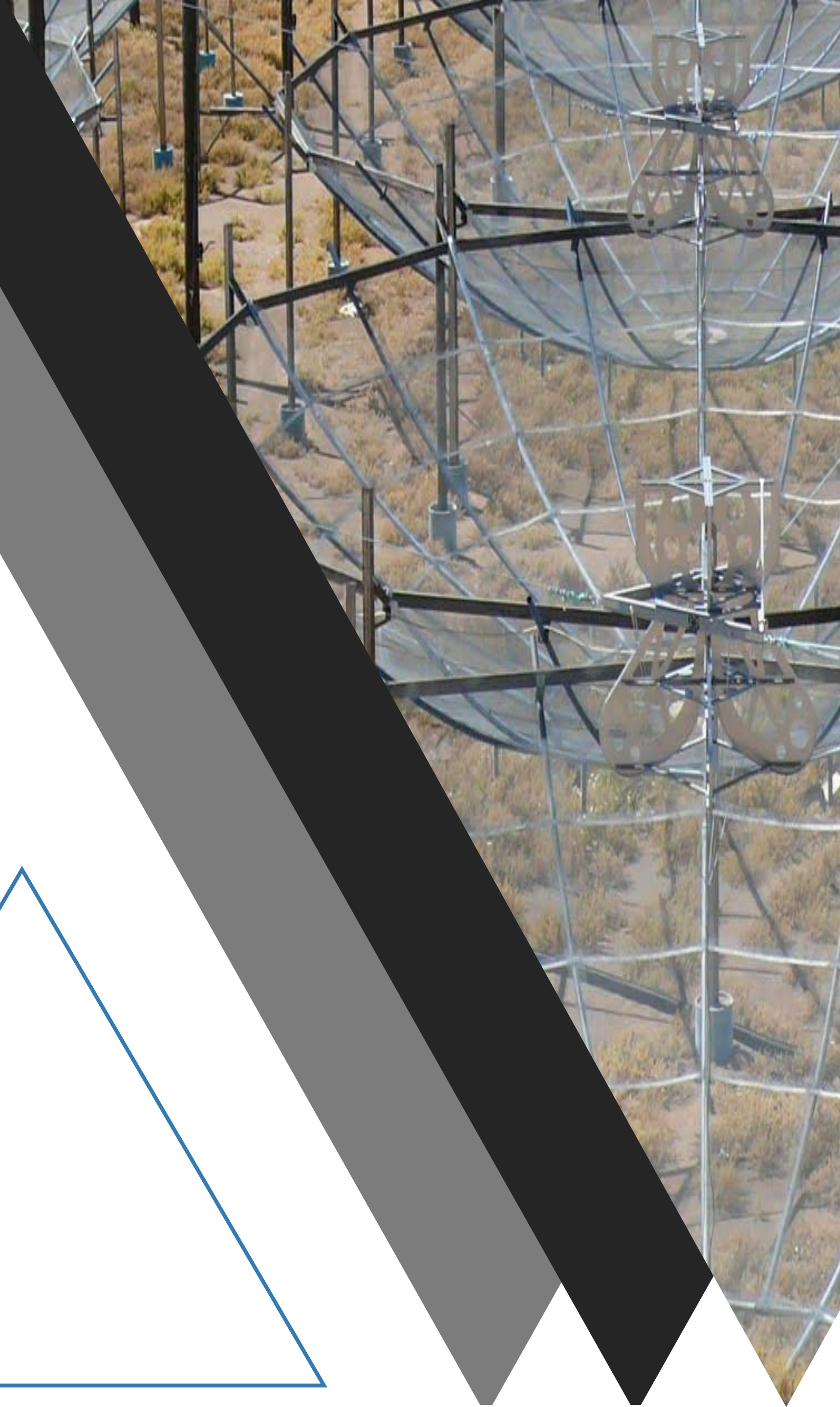
Not observed yet



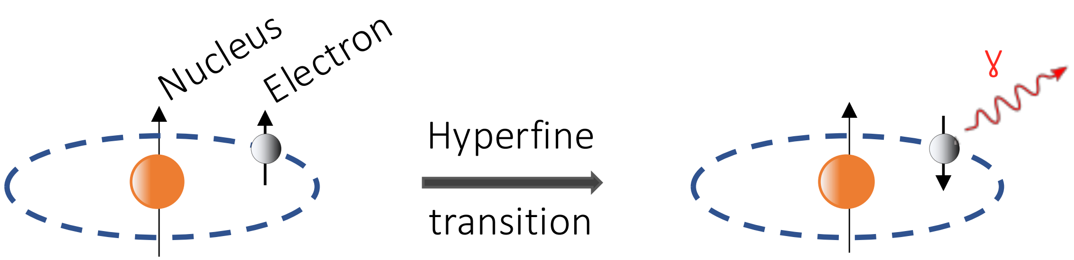
Neutral hydrogen emission

The 21cm signal

Following reionisation
redshift by redshift



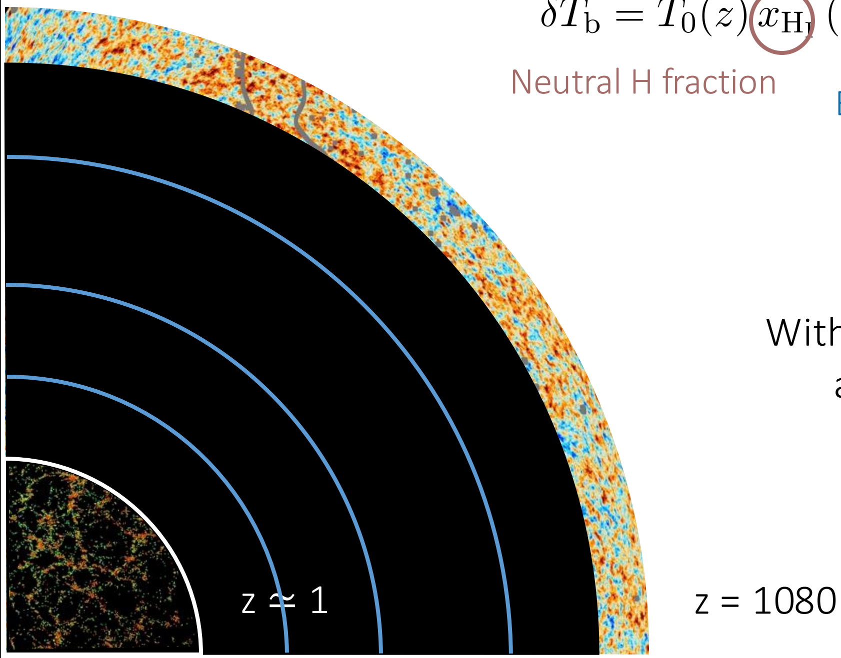
The 21cm signal



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

Neutral H fraction

Baryon density



With the 21cm signal, we can map the Universe at any redshift and follow the growth of ionisation bubbles.

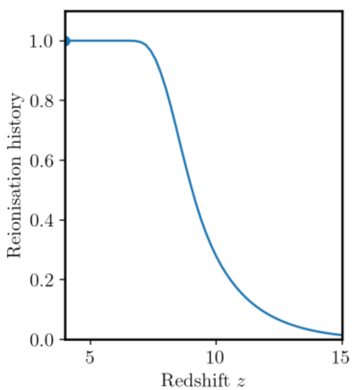
Picture adapted from C. Chiang

The 21cm signal

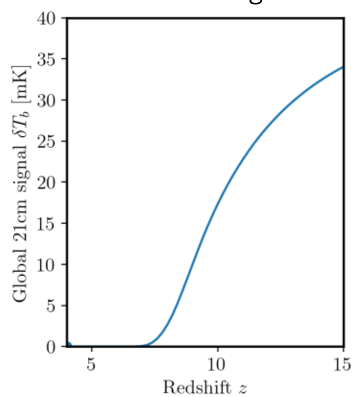
The 21cm signal contains information about

- the global history of reionisation

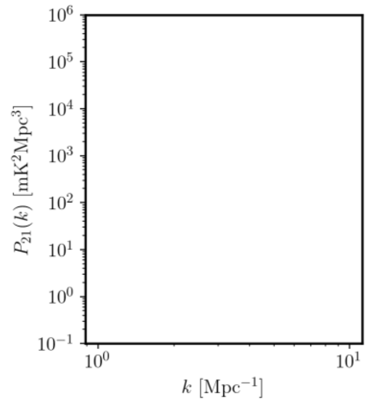
Reionisation history



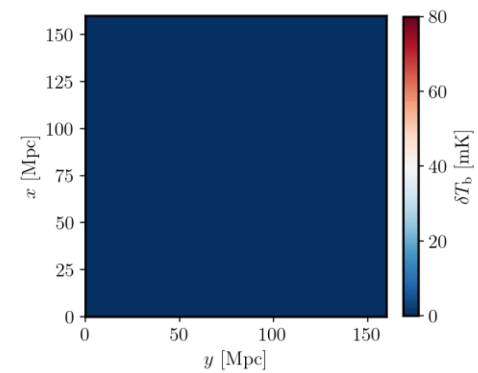
Global 21cm brightness



21cm power spectrum



Intensity map



HERA

SKAO

21CMFAST, Mesinger+2016

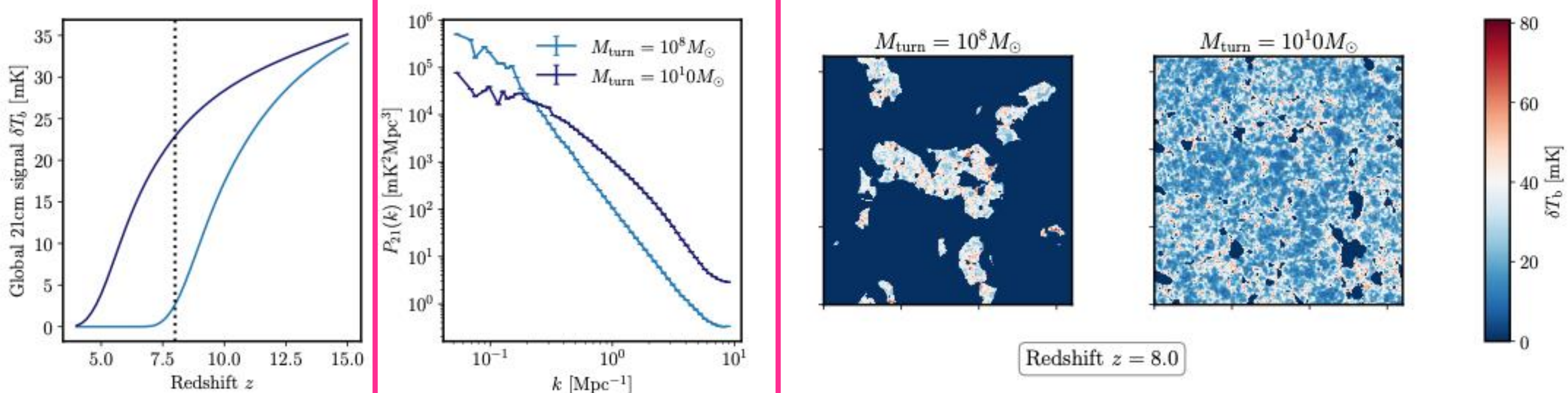
The 21cm signal

The 21cm signal contains information about

- the global history of reionisation
- the properties of the early Universe and galaxies

For different minimal halo mass required for the hosted galaxy to produce ionising photons:

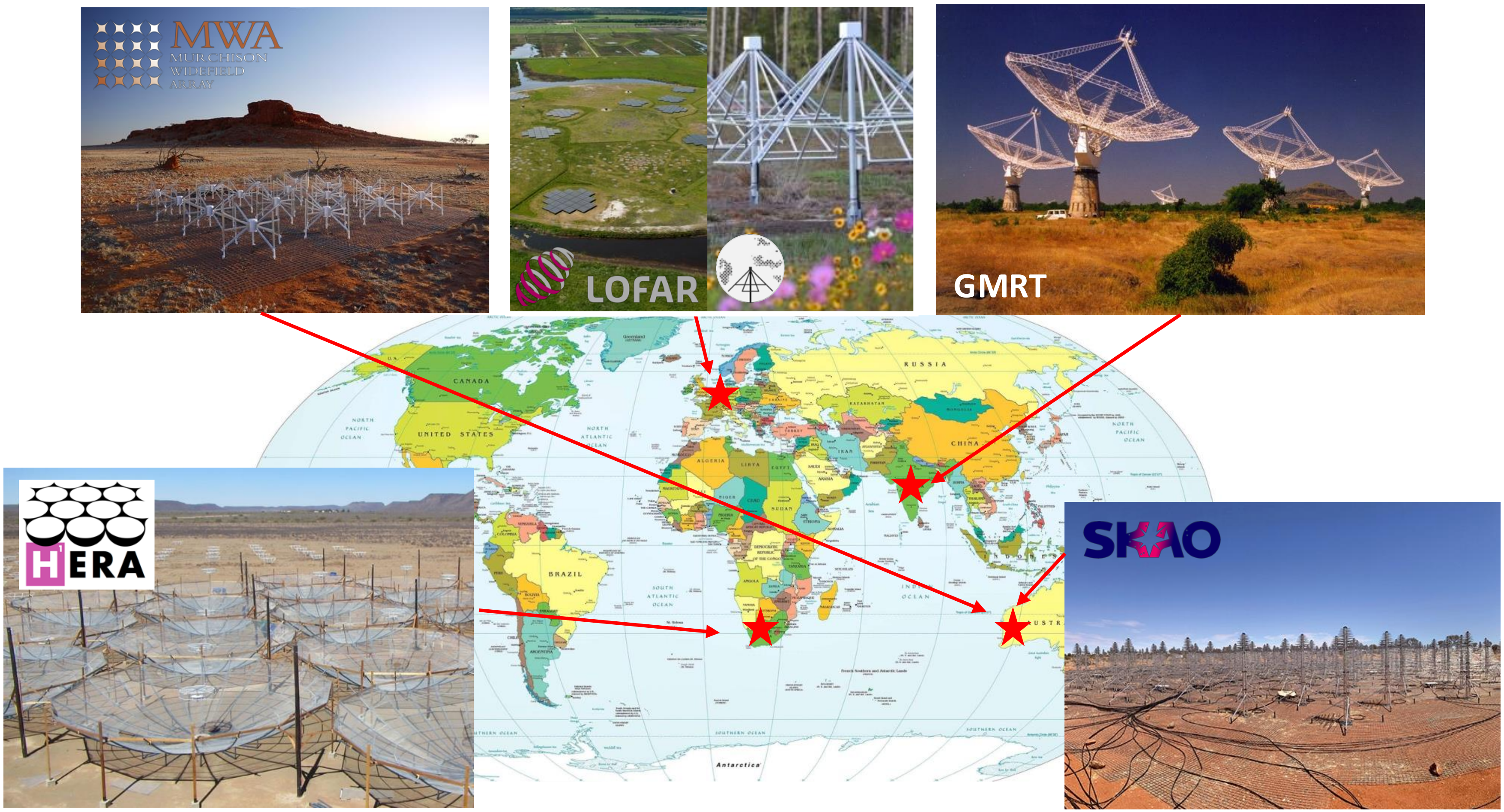
Global 21cm brightness | 21cm power spectrum | Intensity maps



21CMFAST, Mesinger+2016

Radio interferometers around the world

A world-wide effort…

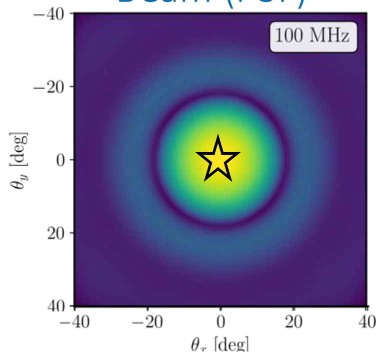


Interferometry 101

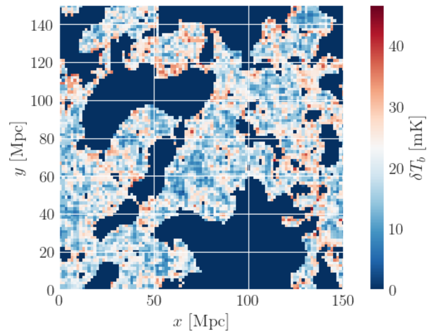
Interferometers measure *visibilities* i.e. Fourier modes on the sky

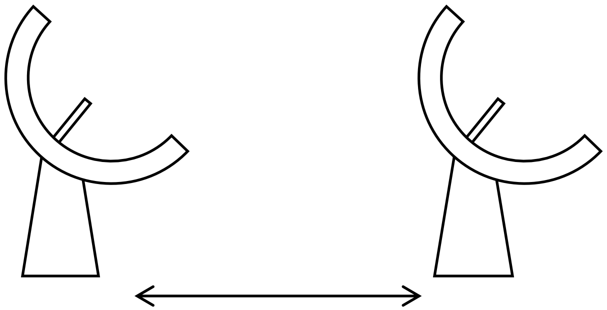
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

Beam (PSF)



Signal intensity





Baseline length b_{ij}
is the Fourier dual of the sky angle
($k_\perp$)

An estimator of the power spectrum is built directly from the visibilities: $\widehat{P}(\boldsymbol{k}) \propto \left\langle \left| \widetilde{V}_{ij}(\nu) \right|^2 \right\rangle$

Interferometry 101

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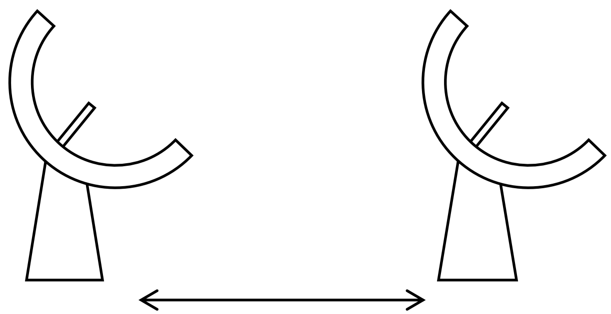
HERA



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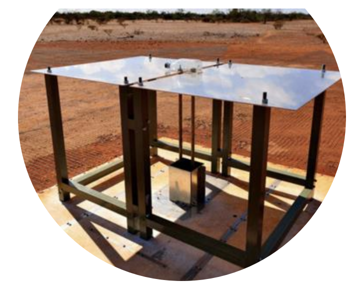
EDGES

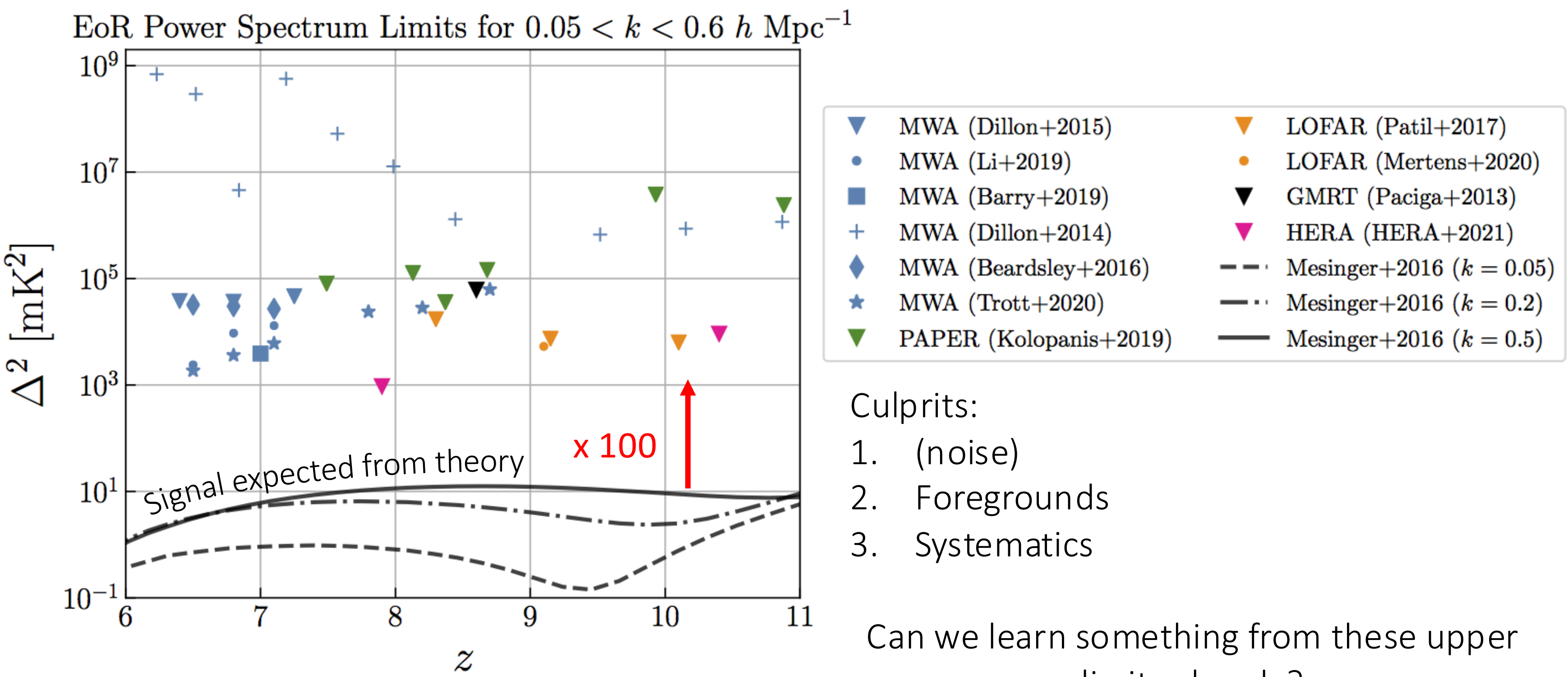


An estimator of the power spectrum is built directly from the visibilities: $\widehat{P}(\boldsymbol{k}) \propto \left\langle \left| \widetilde{V}_{ij}(\nu) \right|^2 \right\rangle$

- Dense arrays measure large-scale fluctuations (e.g. EDGES' "table")
- Wide arrays measure small-scale fluctuations (e.g. HERA)

Upper limits on the high-z power spectrum

… which has only led to upper limits so far.



Culprits:

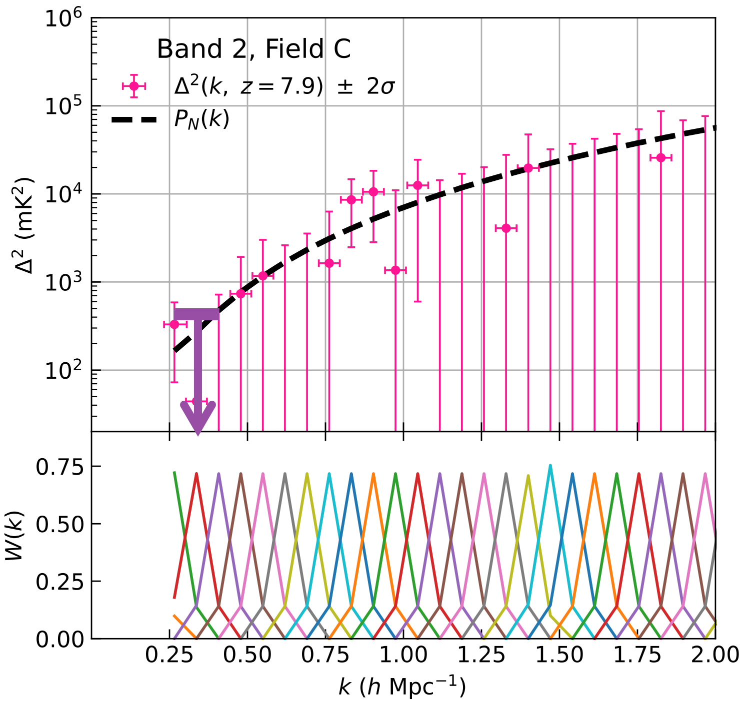
1. (noise)
2. Foregrounds
3. Systematics

Can we learn something from these upper limits already?

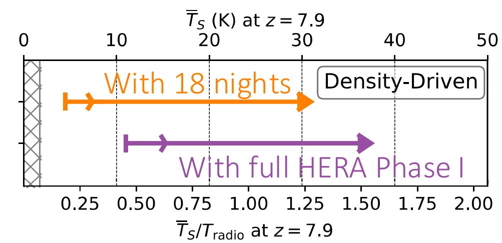
Barry+2022

Upper limits on the high-z power spectrum

- Lowest upper limits on the 21cm power spectrum from HERA
- Measurements at z = 7.9 and z = 10.4
- Results consistent with noise



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



The IGM was heated by z = 10.4, likely by high-mass X-ray binaries

HERA collab et al. 2023

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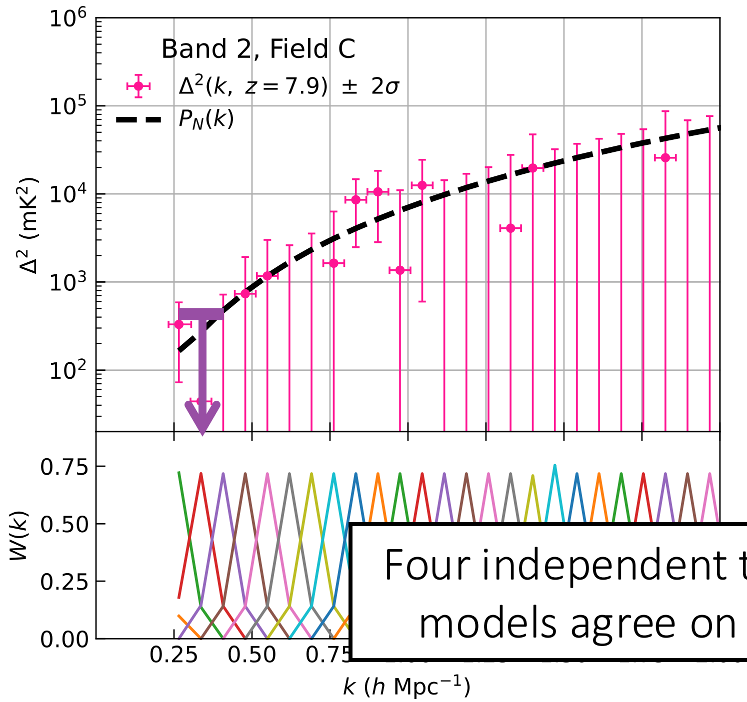
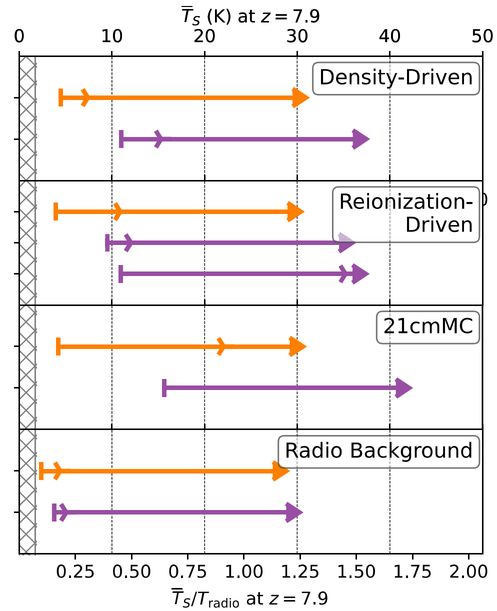


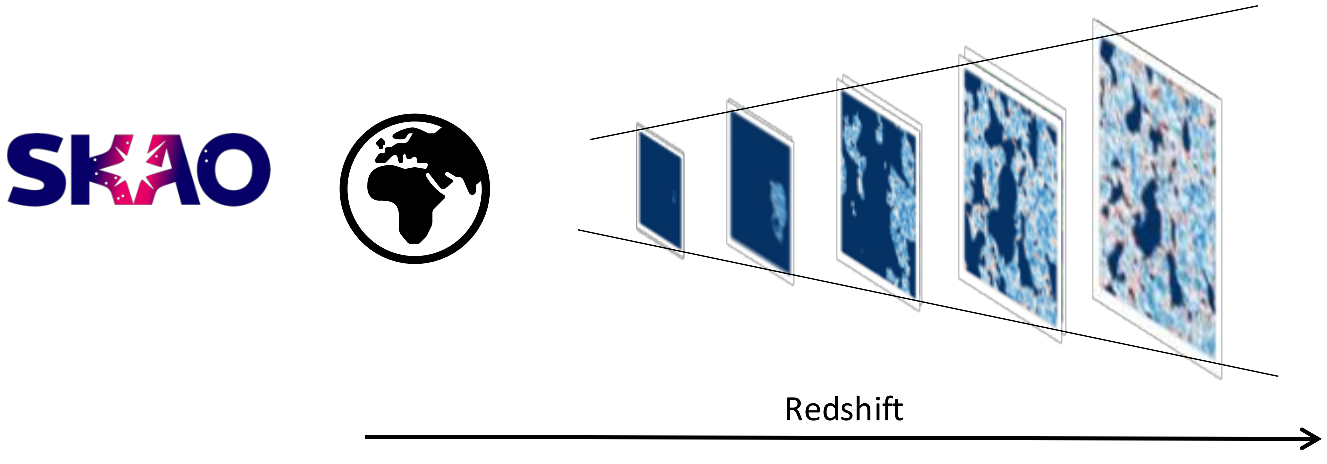
Four independent theory models agree on this.

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



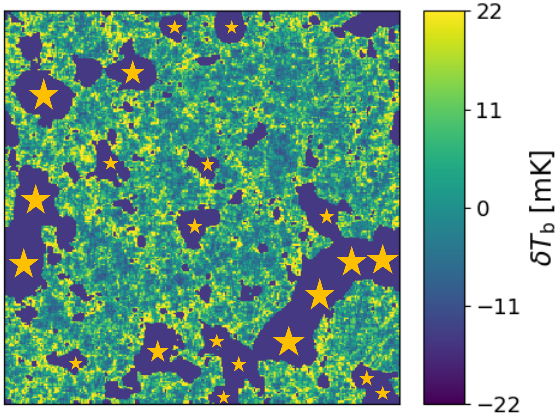
HERA collab et al. 2023

21cm intensity mapping

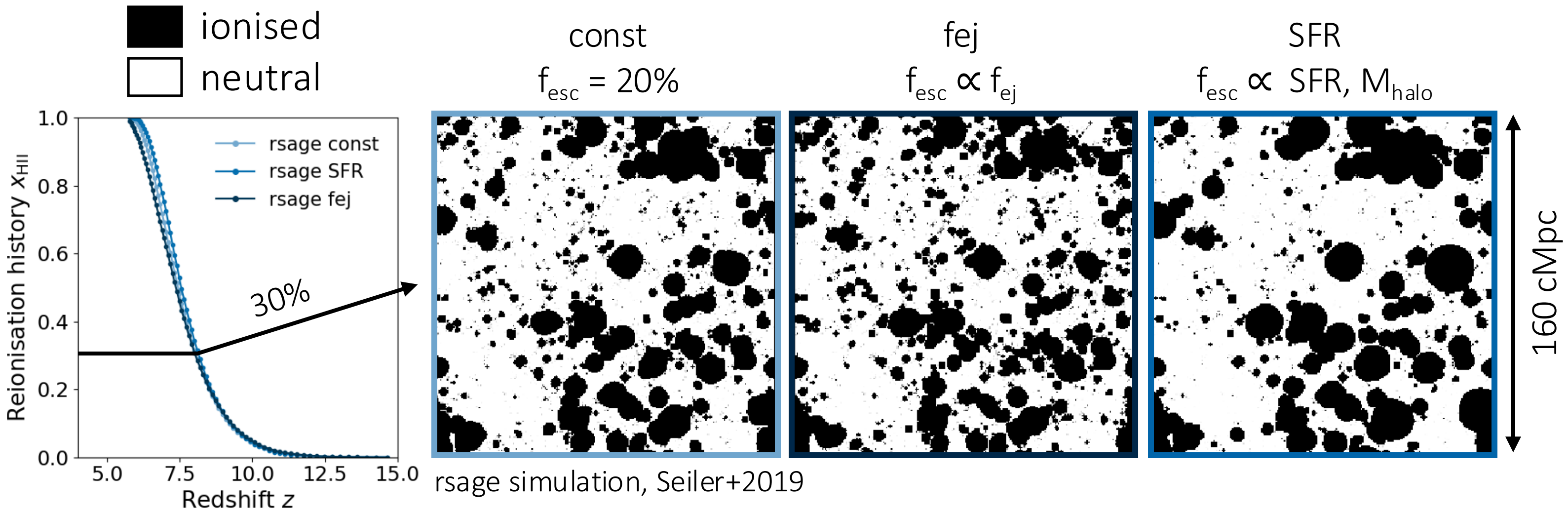


Why intensity mapping?

- SKA will measure maps of the brightness temperature of the 21cm in the IGM
- These maps give access to information about galaxies washed out in large-scale observations:



21cm intensity map
(21CMFAST simulation)



rsage simulation, Seiler+2019

Why intensity mapping?

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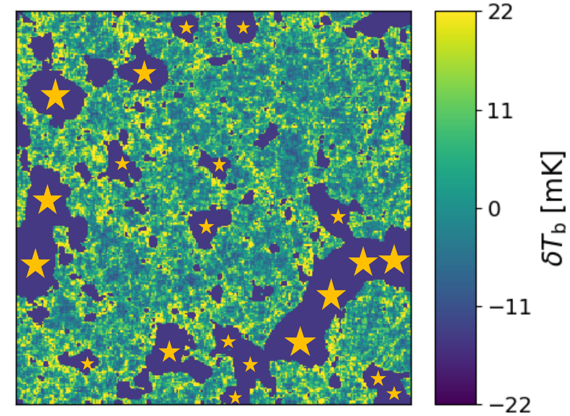
- Effort in developing efficient tools to analyse these datasets to
  - Constrain reionisation and galaxy properties
  - Tackle huge data volumes
  - Complement PS analyses (ex: non-Gaussianity)



21cm intensity map
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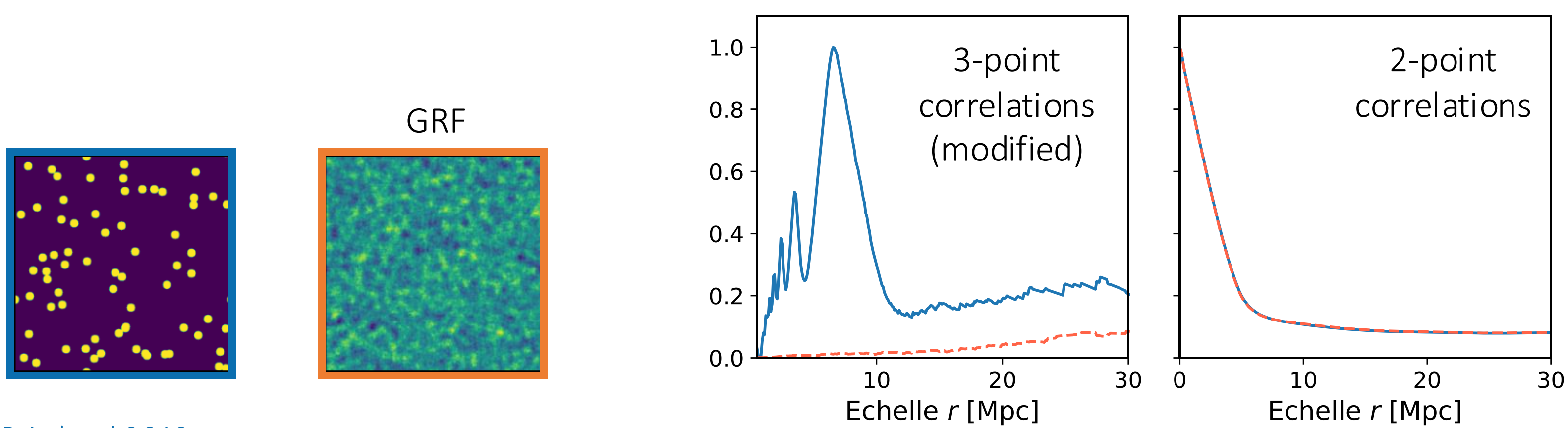

Gorce & Pritchard 2019

Why intensity mapping?

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SKAO

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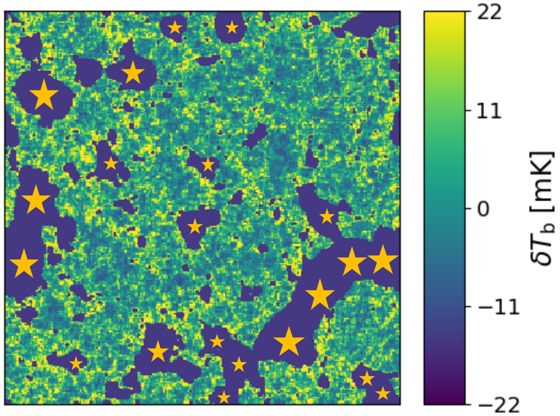
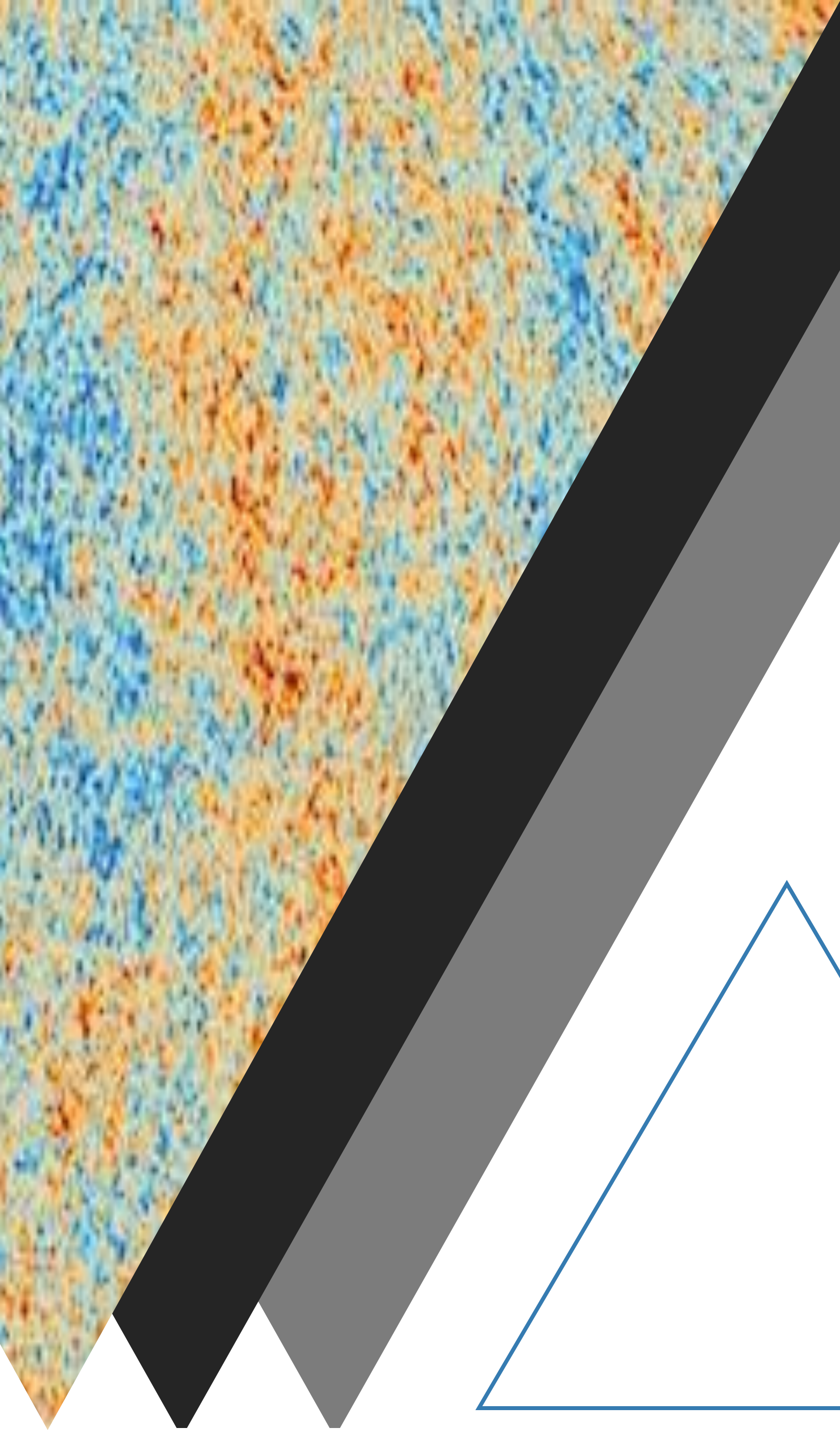


21cm intensity map
(21CMFAST simulation)

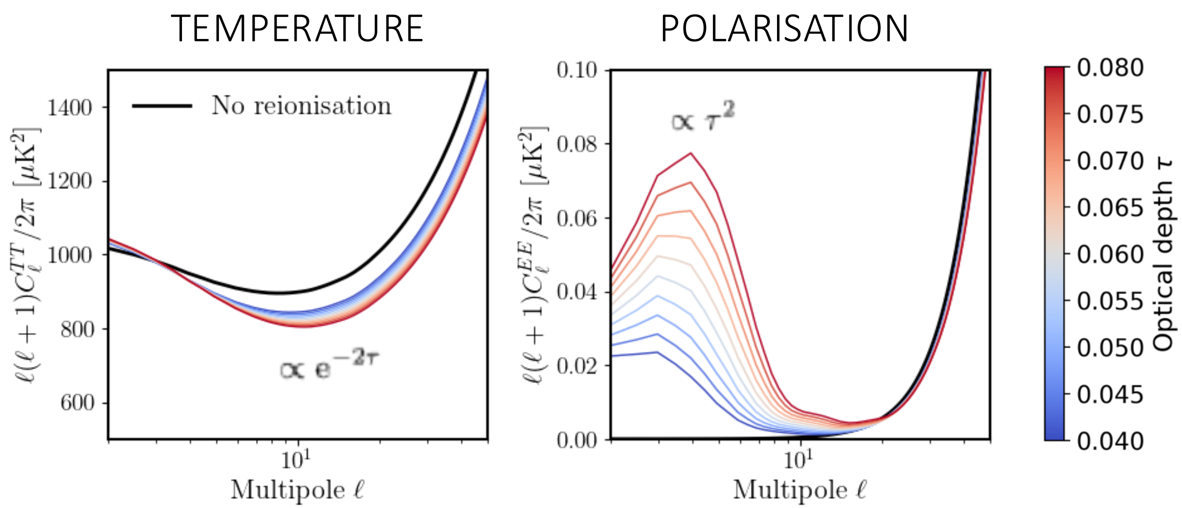
- Solutions *(non-exhaustive list)*:
  - ★ Minkowski functionals & topology (Yoshiura+2016; Elbers & v.d. Weygaert 2017; Chen+2018; Giri+2020; Thélie+2022)
  - ★ Higher order statistics & bispectrum (e.g., Watkinson+2019; Gorce & Pritchard 2019, Majumdar+2020, Hutter+2020)
  - ★ AI techniques (e.g., Chardin+2019, Bianco+2021, Neutsch+2022)
  - ★ Scattering transforms (Greig+2022, Hothi+2023, Prelogović+2024)
  - ★ One-point statistics (Mellema+2006; Gorce+2020; Kittiwisit+2018, 2022)

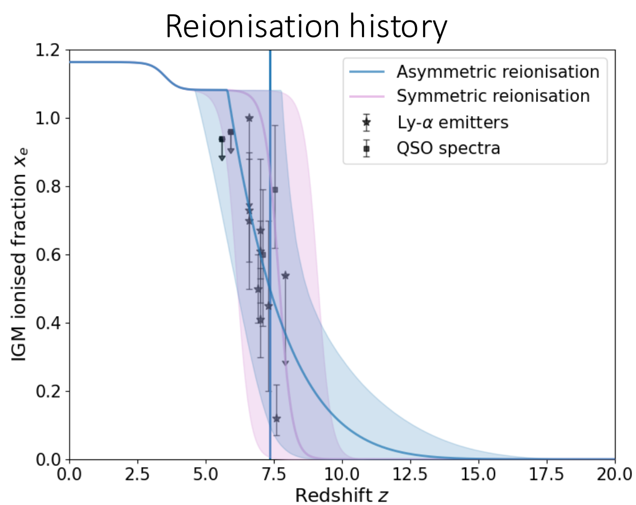


The CMB

Unearthing the imprints of reionisation

CMB scattering during reionisation





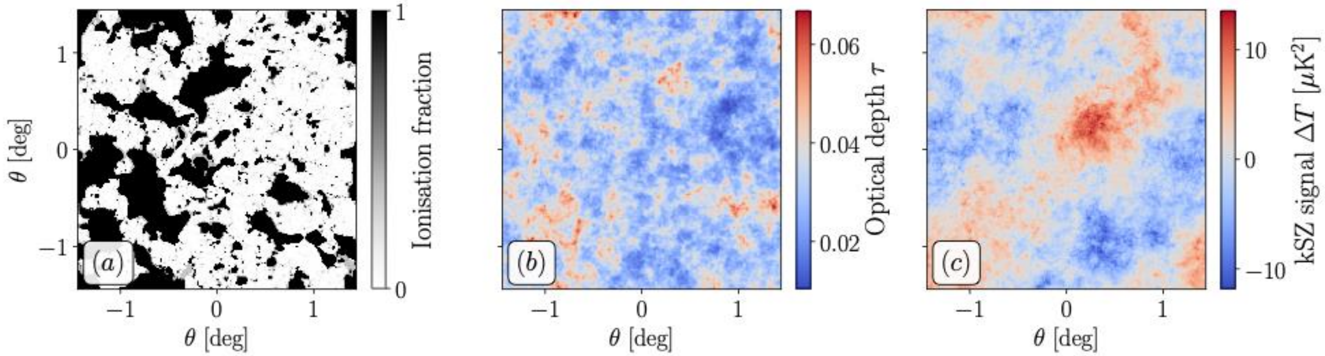
$$\tau(z) = c\,\langle n_\mathrm{H}\rangle\,\sigma_\mathrm{T} f_\mathrm{e} \int_0^z x_e(z')/H(z')\,(1+z')^2\,\mathrm{d}z'$$

τ = 0.054 ± 0.007
(Planck+2018)

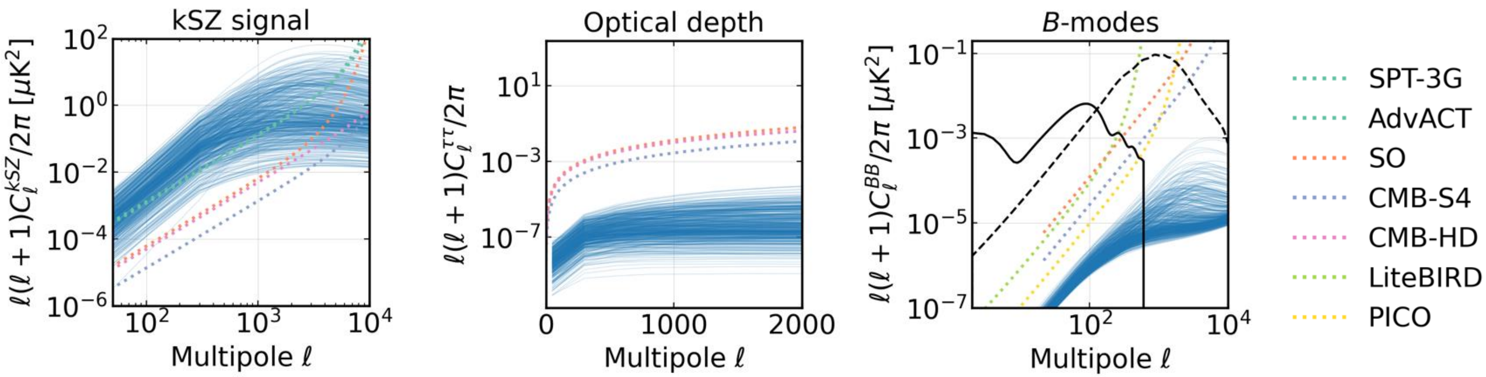
See, e.g., Gorce+2022, Qin+2020, Ilic+ in prep

CMB scattering during reionisation

Reionisation is a patchy process...



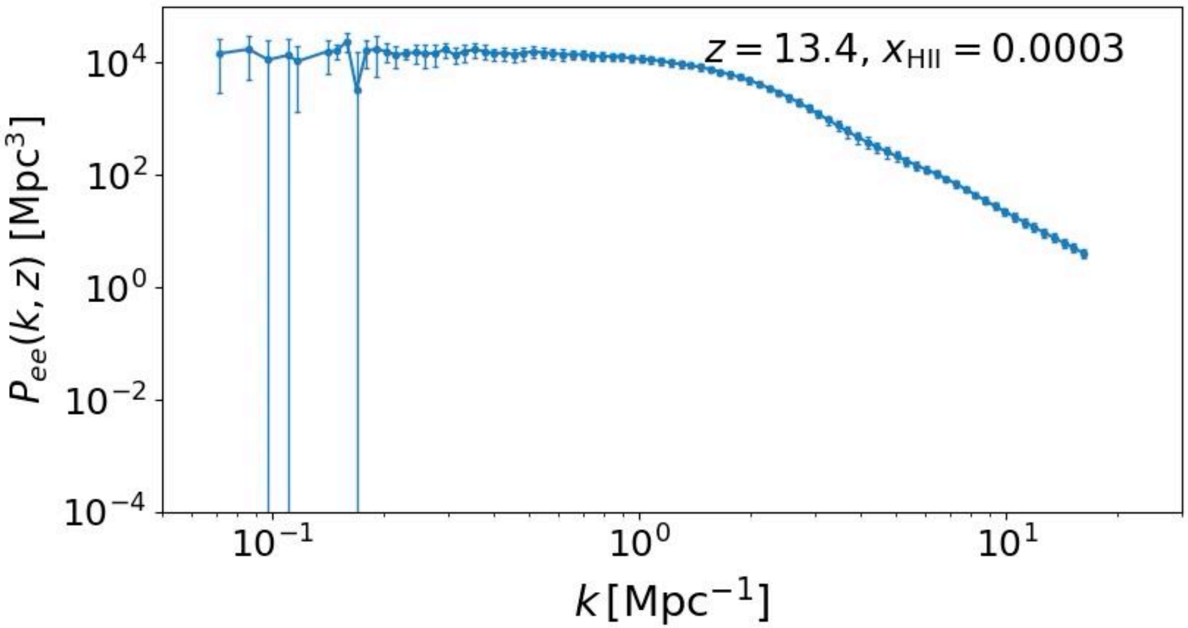
TEMPERATURE POLARISATION

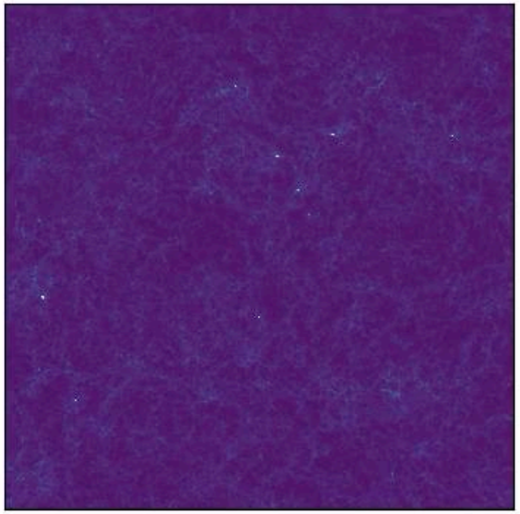


+ y-distortions...

see, e.g., Aghanim+1996, Dvorkin & Smith 2009, Roy+2018, 2020, Gorce+2020

The power spectrum of free electrons $P_{ee}(k,z)$

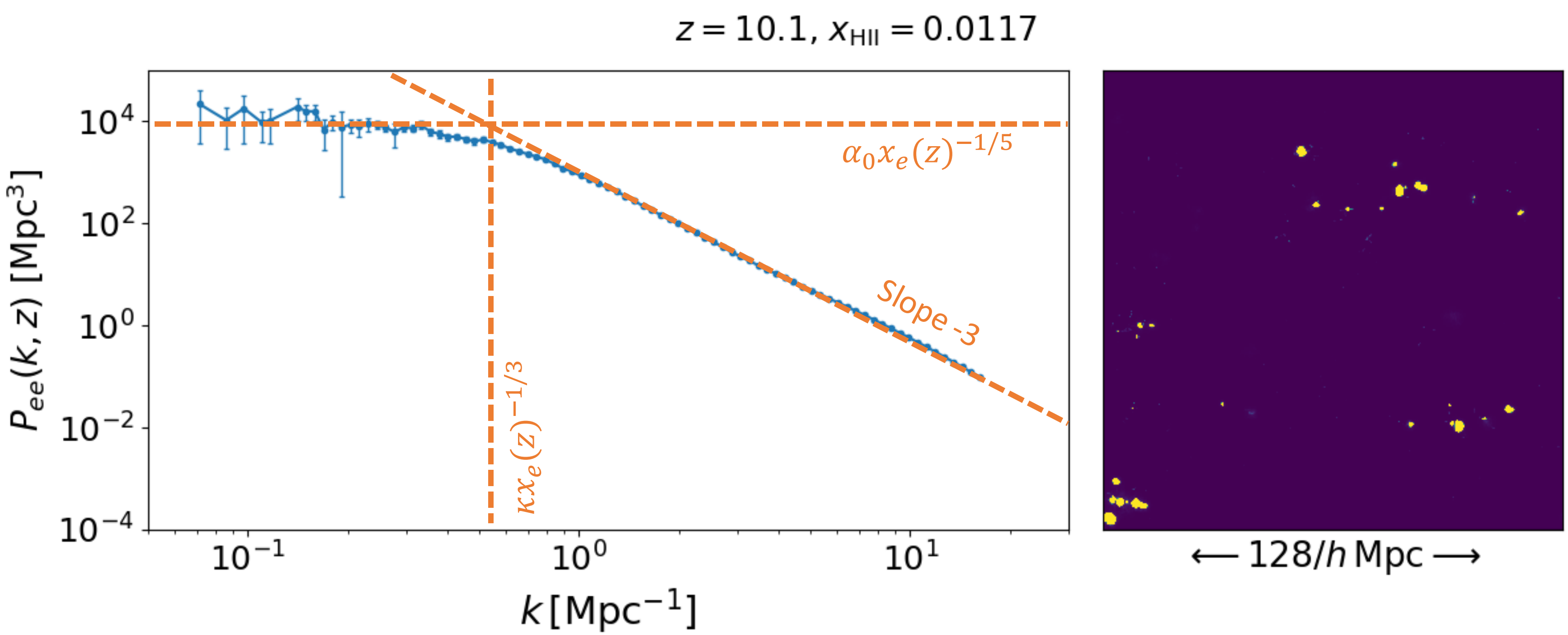




EMMA simulation, Aubert+2008, Gillet+2015

The power spectrum of free electrons $P_{ee}(k,z)$

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



- α_0 : constant amplitude on large scales ⟷ variance of the field
- κ: drop-off frequency ⟷ minimal size of ionised regions

Gorce+2020

The power spectrum of free electrons

Depends on cosmology and a few reionisation parameters (z_{re}, $z_{end,}$, α_0, κ)…

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

High-redshift
(power-law)
Gorce+2020

Low-redshift
(biased matter PS)
Shaw+2012

ONGOING

But… model parameters have no clear physical meaning:

- Recalibrate parameterisation on LoReLi simulations: 10 000 simulations of reionisation varying astrophysics, e.g., minimum halo mass to form stars, X-ray luminosity, ionising escape fraction… (Meriot & Semelin 2023)
- Include a physical dependence, e.g., with symbolic regression

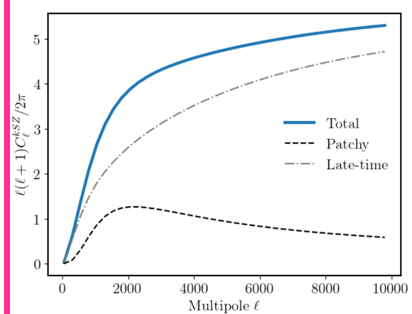
The power spectrum of free electrons

Depends on cosmology and a few reionisation parameters (z_{re}, $z_{end,}$, α_0, κ)…

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

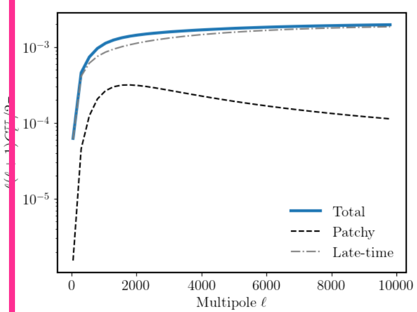
Patchy kSZ spectrum

Gorce+2022



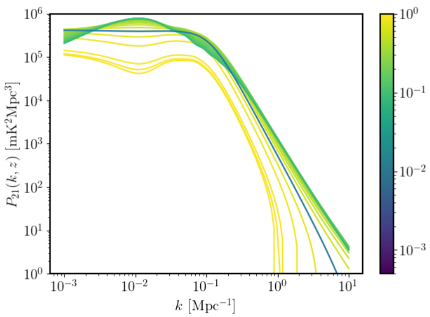
ττ spectrum

Molinier & Gorce, in prep



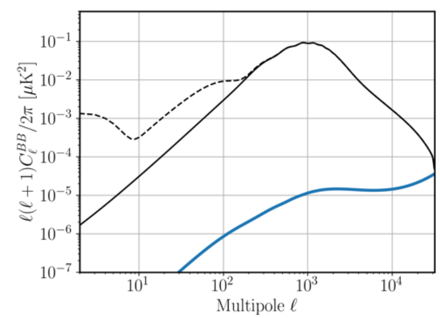
21cm power spectrum

Georgiev, Gorce & Mellema 2024



EoR-induced B-modes

Gorce+, in prep

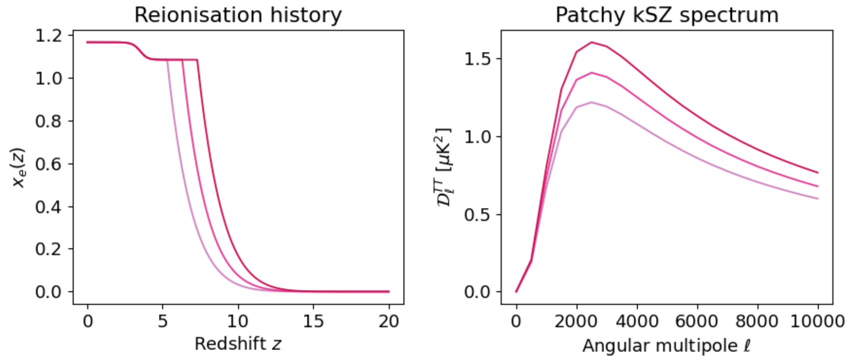


One model that allows joint and cross-analyses between datasets…

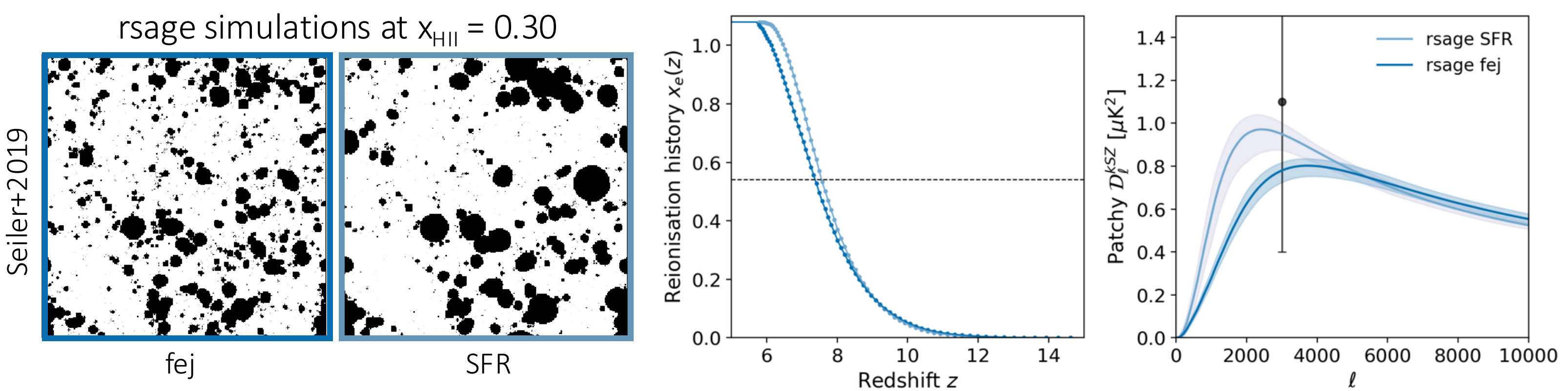
The kinetic Sunyaev Zel'dovich effect

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…

Current high-l analyses: the kSZ as a nuisance

There is information about reionisation in the kSZ spectrum…

… but it is not used in current analyses, resulting in imprecise constraints.

1. Measure kSZ by fitting the amplitude of a template

   Use of templates although amplitude *and* shape depend on reionisation

2. And propagate to reionisation with scalings: $A^{patchy} \propto z_{re} * \Delta z^{0.51}$ (Battaglia+2013)

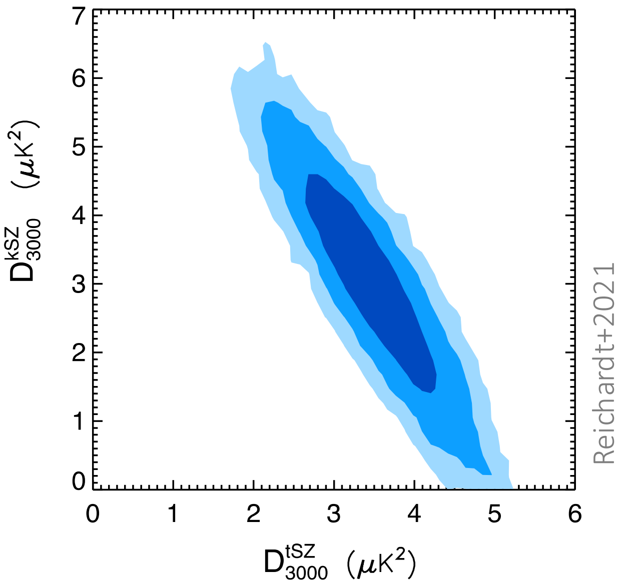
   Scaling relations are largely dependent on the simulations used

<u>Most recent constraints:</u> SPT (Reichardt+2021)

D^{p}_{3000} = 1.1 +1.0/-0.7 μK^2

Δz = 1.1 +1.6/-0.7

Amplitude parameters are correlated:



Current high-l analyses: the kSZ as a nuisance

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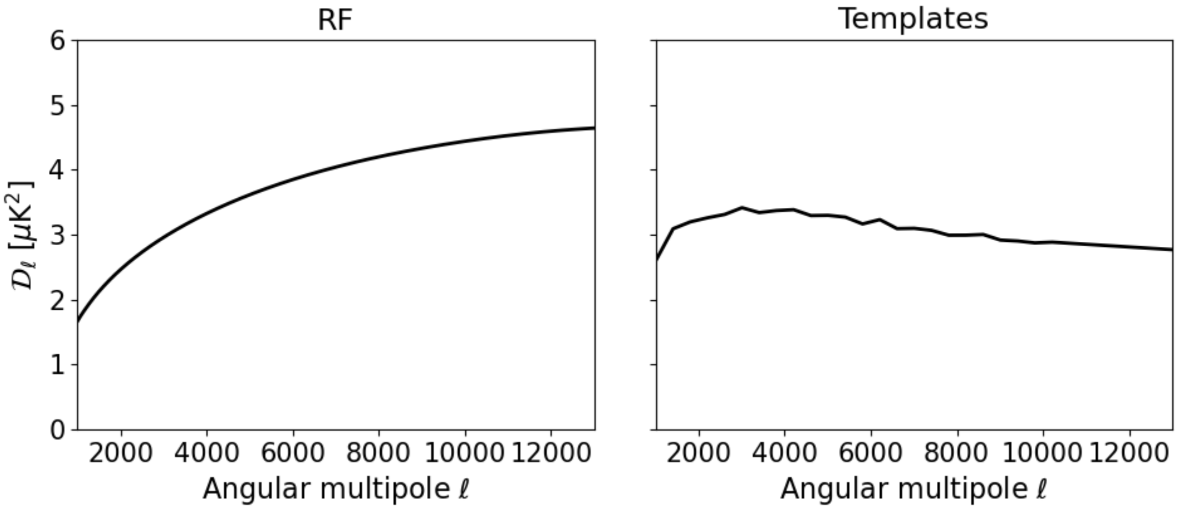
… but it is not used in current analyses, resulting in imprecise constraints.

Proposed solution:

Replace templates by analytic derivations of the SZ spectra
to retrieve the cosmological information enclosed in the foregrounds

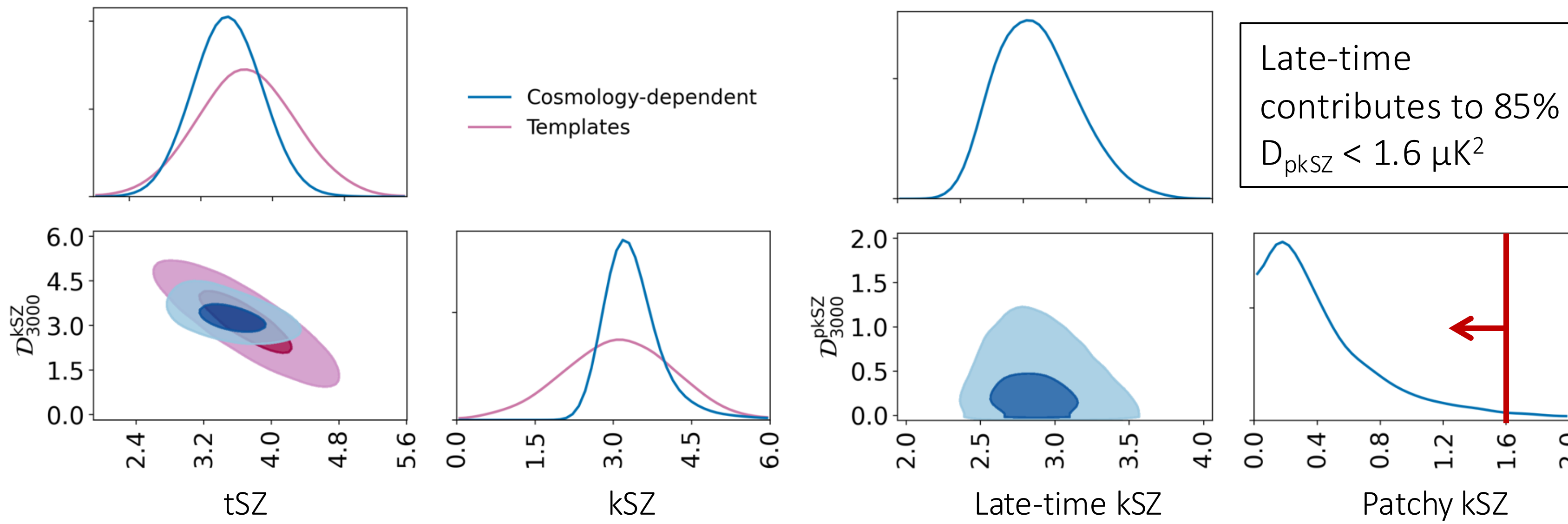


+ joint analysis with large-scale data

Results on SPT data: Free cosmology

Free cosmological parameters compared to initial analysis (Reichardt+2021)

- Planck 2018 Gaussian priors on $\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, n_s
- Flat priors on other parameters (A_s, reion)

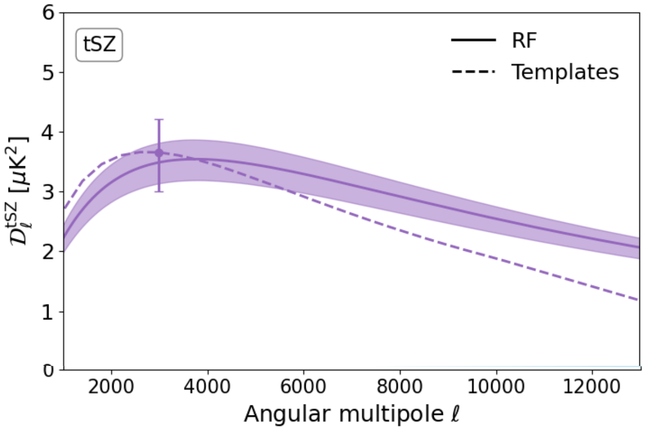


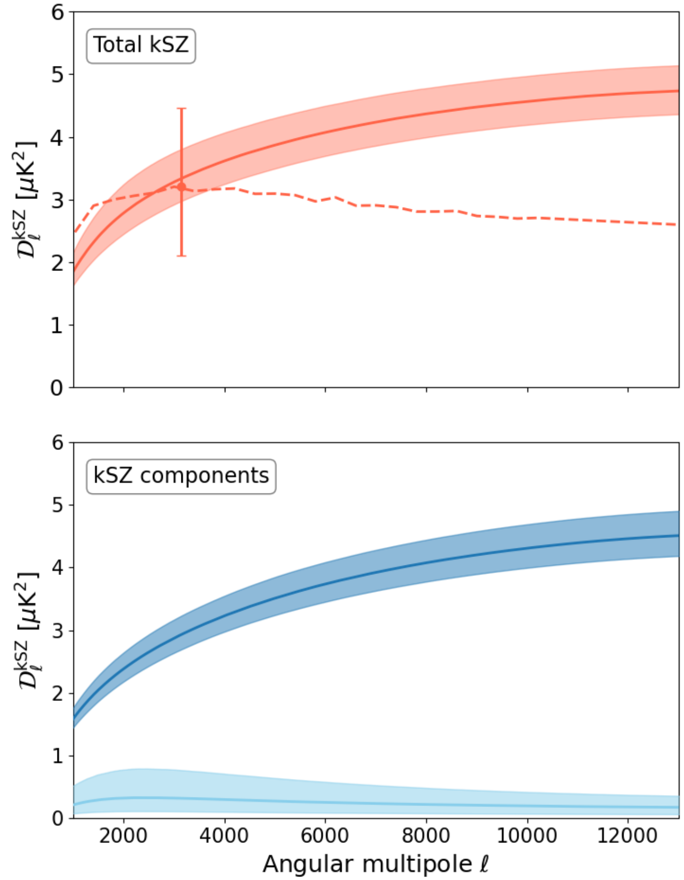
Late-time contributes to 85%
$D_{pkSZ} < 1.6\ \mu K^2$

9 and 5σ measurements of tSZ and kSZ, resp.

Gorce, Douspis, Salvati 2022

Results on SPT data: Free cosmology





Can see the shape of the spectra favoured by the data

Gorce, Douspis, Salvati 2022

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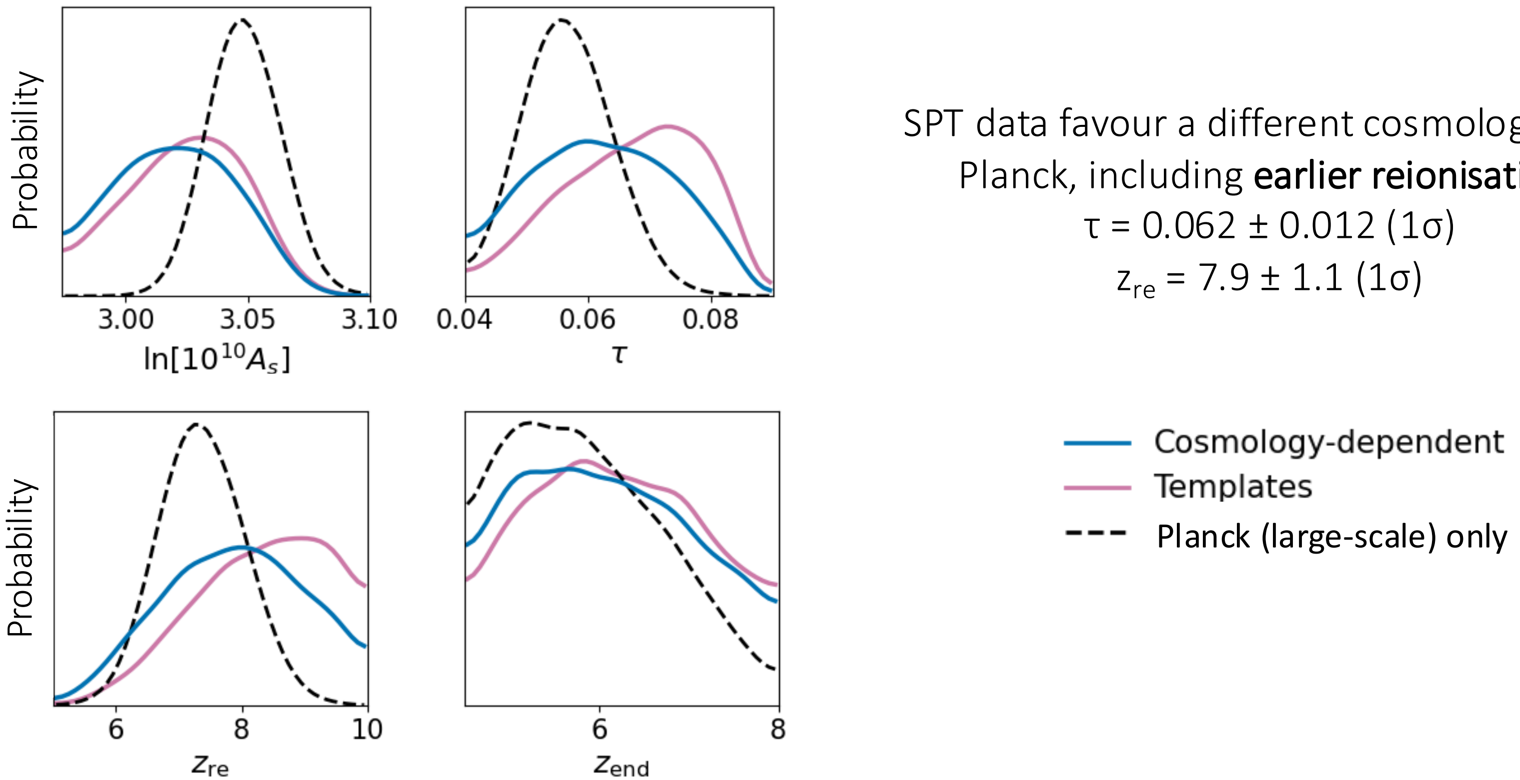

SPT data favour a different cosmology than Planck, including **earlier reionisation**:

$\tau = 0.062 \pm 0.012$ (1σ)

$z_{re} = 7.9 \pm 1.1$ (1σ)

Gorce, Douspis, Salvati 2022

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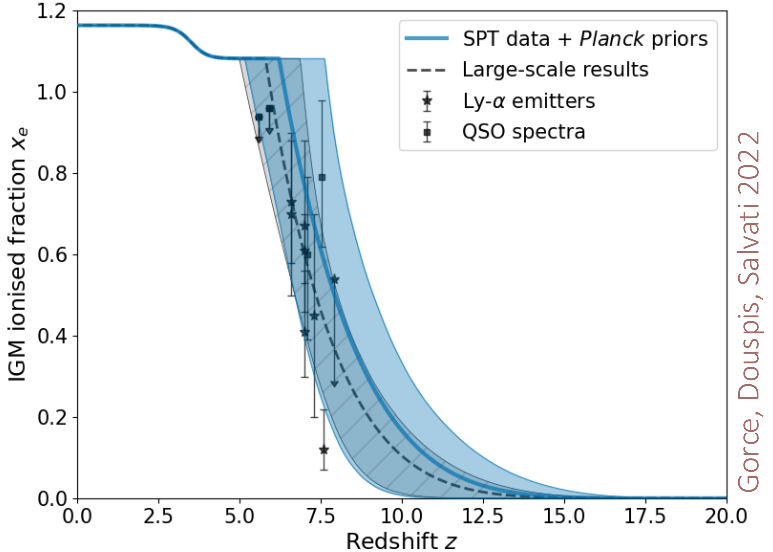

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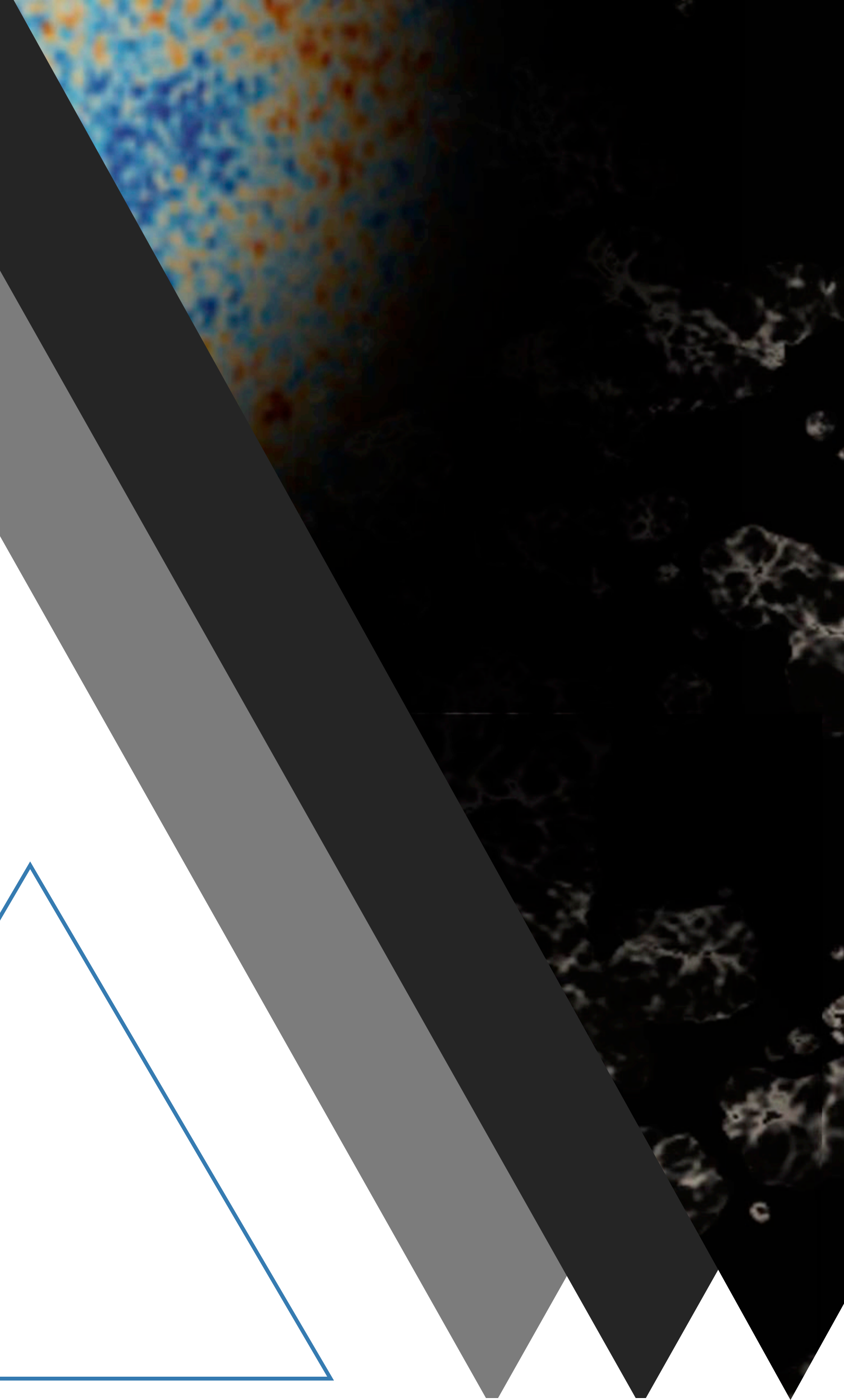
Next steps (ongoing):

- ➢ Use large simulation datasets to improve Pee model (LoReLi, Meriot & Semelin 2023)
- ➢ Improve modelling of other foregrounds (CIB)
- ➢ Consistent analysis with large-scale data →

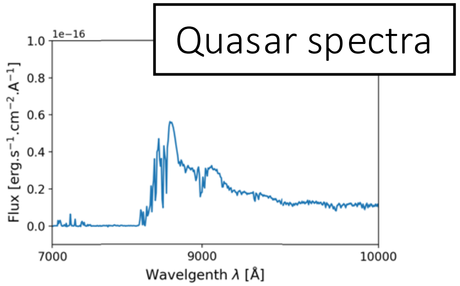
tSZ & kSZ emulators are available at https://szdb.osups.universite-paris-saclay.fr

Combining data sets

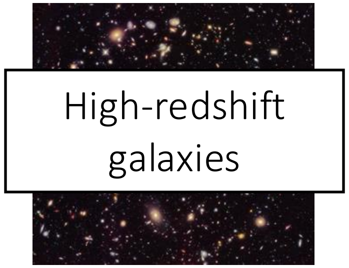
Minimising systematics and uncertainties with independent measurements



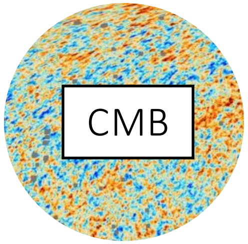
Combining observables



HI absorption troughs

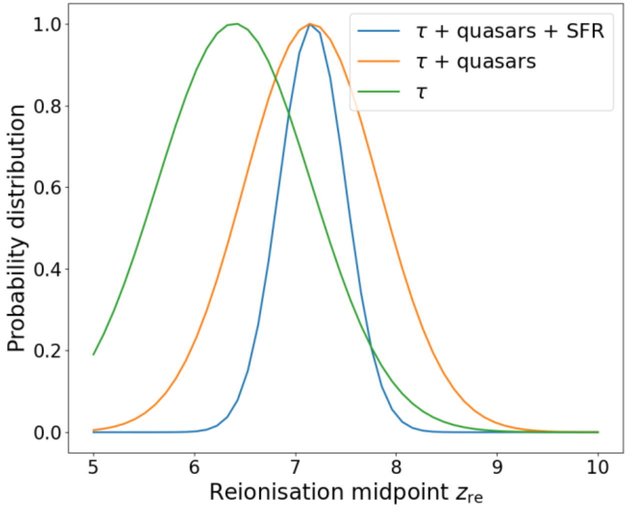


Ionising photon budget



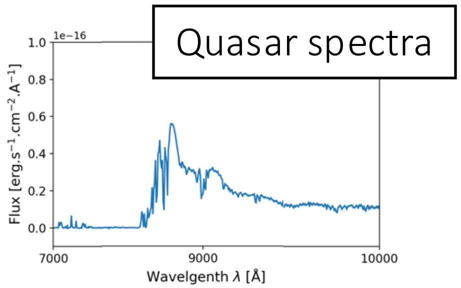
CMB photons scatter off free electrons

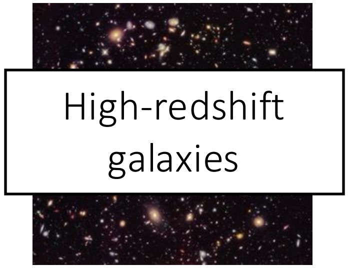
Combining observables reduces uncertainties and removes biases

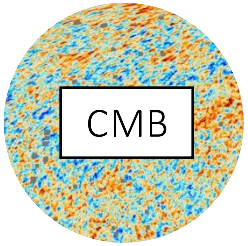


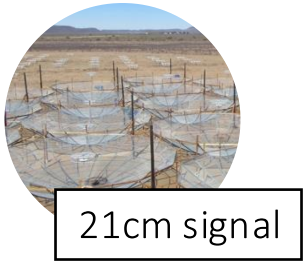
See, e.g., Gorce+2018

Combining observables









To combine observables in a consistent way, we need a common *theoretical model*

- ★ Simulations
  e.g., Su+2011; Greig+2017; La Plante + 2021, 2023; Hutter+2023
- ★ Analytical model
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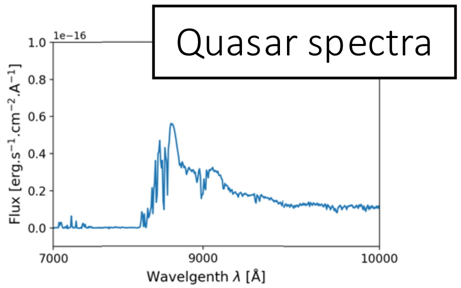
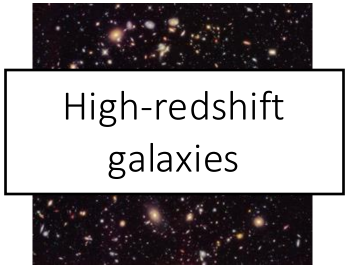
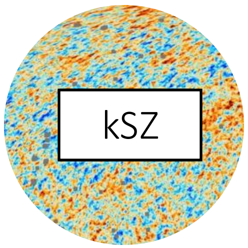
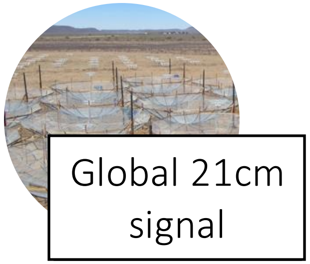
Combining observables









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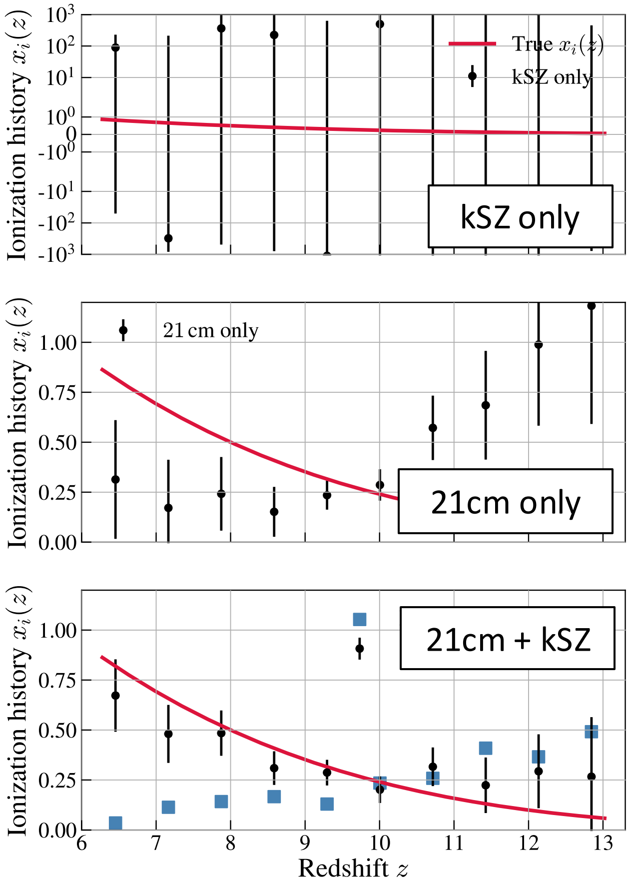
1. kSZ x global 21cm signal
   Bégin, Liu, & **Gorce** 2022

Complementarity kSZ / global 21cm

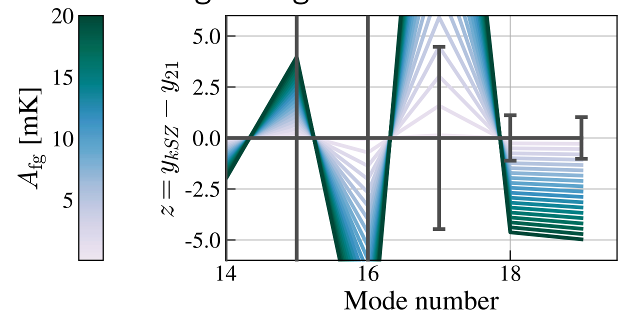
The complementarity can be leveraged to

1. Better constrain the reionisation history

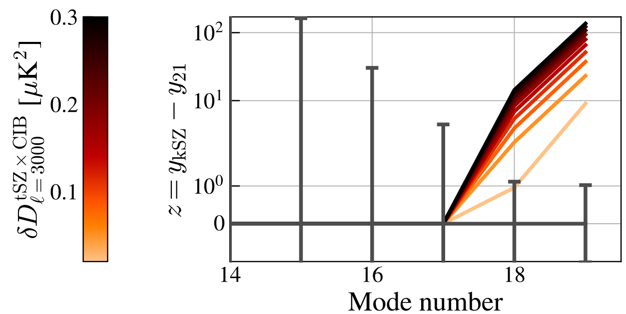


2. Identify and remove systematics

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

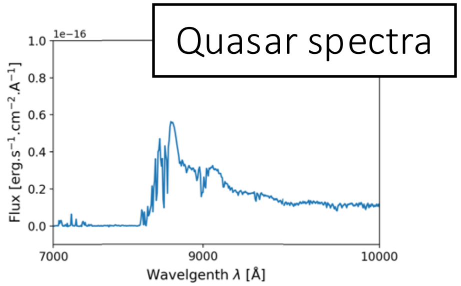


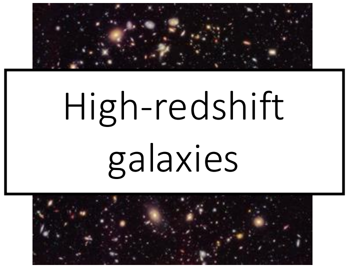
- 0.05 μK² tSZxCIB residual picked up at 100σ

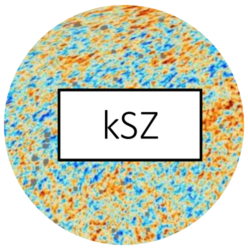


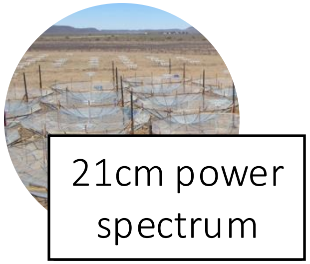
Bégin, Liu & Gorce 2022

Combining observables









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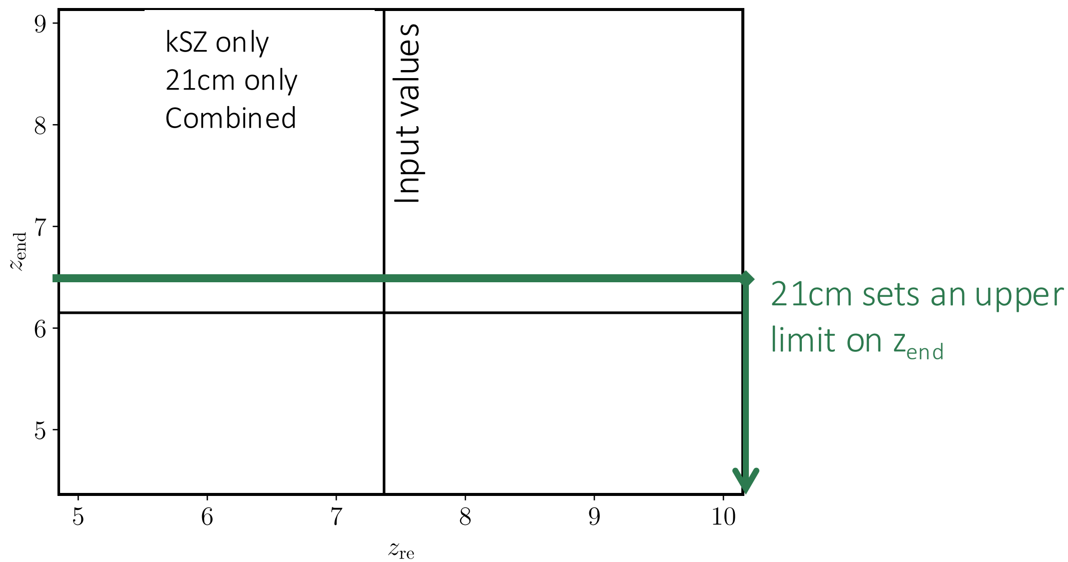
Joint analysis of kSZ and 21cm power spectrum

- Relate the 21cm signal and the kSZ 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 analytical model of P_{ee} to generate both observables in a forecast
  → constrain reionisation end- and midpoint



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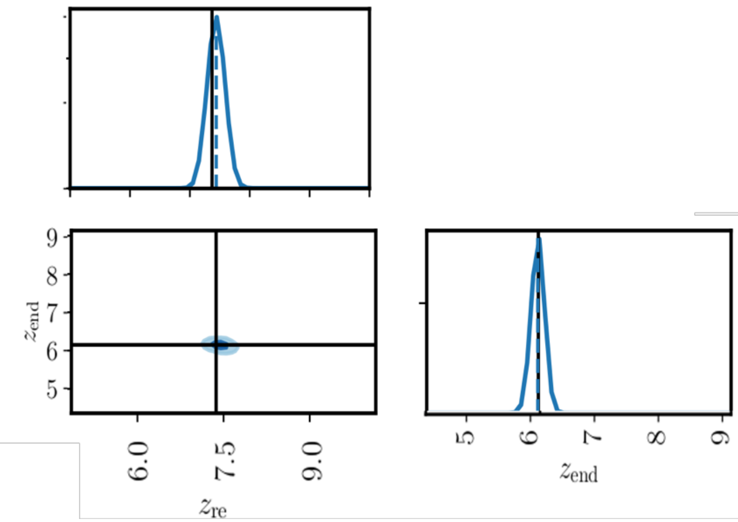
  → constrain reionisation end- and midpoint
- With only three data points, one can recover the reionisation mid- and endpoint with very good accuracy

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.



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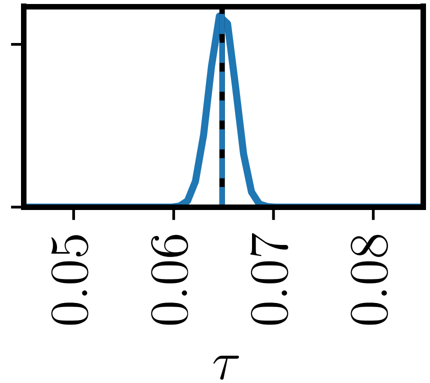
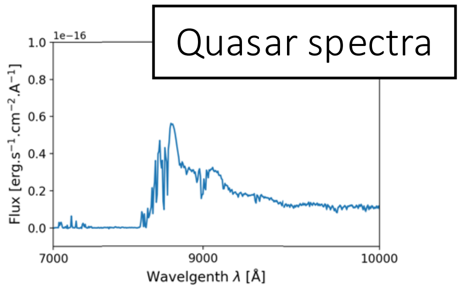
- Use analytical model of P_{ee} to generate both observables in a forecast → constrain reionisation end- and midpoint
- With only three data points, one can recover the reionisation mid- and endpoint with very good accuracy
- And break the tau/As or tau/sum_nu degeneracy!

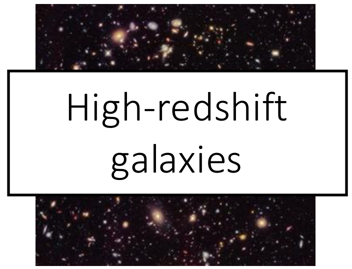


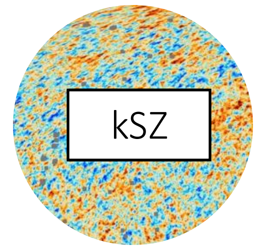
τ = 0.065 +/- 0.001

Georgiev, **Gorce**, & Mellema 2024

Combining observables







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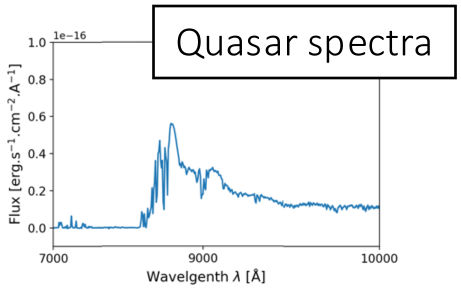

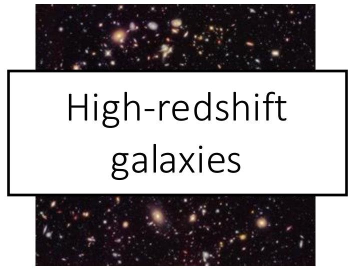

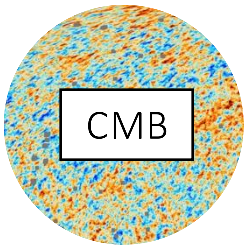

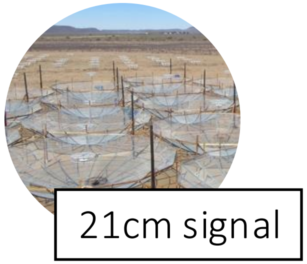

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3. kSZ x galaxies: SPT data favour late & rapid reionisation histories
   Nikolic, Mesinger, Qin, & **Gorce** 2023
4. 21cm power spectrum x galaxies: HERA x Roman, need spectroscopic redshifts
   La Plante, Mirocha, **Gorce**+ 2023

Conclusions

To understand reionisation, data cross-correlations are necessary to overcome systematics and uncertainties.

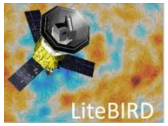
Things to look forward to:

CMB

- Cosmic-variance limited τ
- Small-scale CMB data: kSZ, τ fluctuations

CMB-S4
Next Generation CMB Experiment

SIMONS OBSERVATORY



21cm

- Global signal & power spectrum
- Intensity mapping?

HERA

SKAO

GALAXIES & QUASARS

- Statistical samples of quasar spectra
- Faint end of luminosity functions

Rubin Observatory

Euclid consortium

James Webb Space Telescope JWST NASA • ESA • CSA

The future of EoR study is bright!!

Thank you!