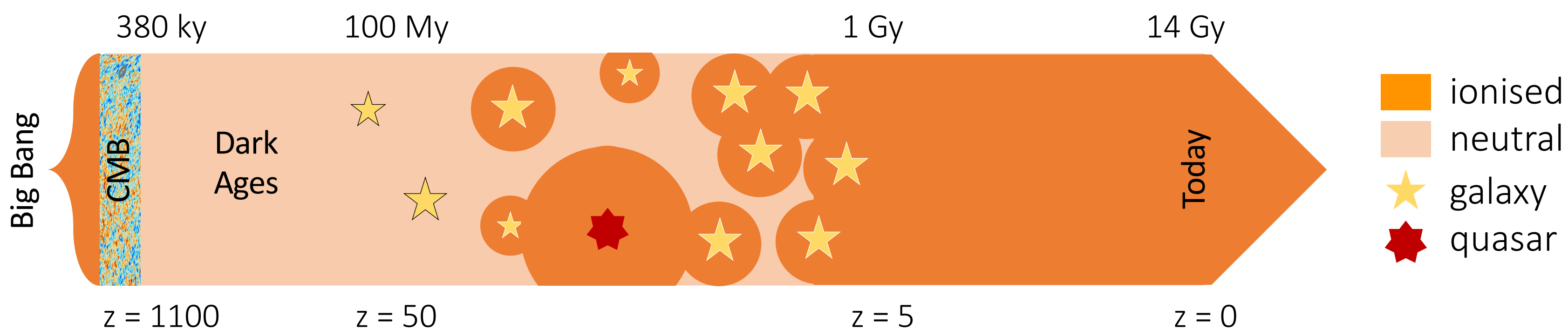
Exploring Cosmic Dawn with the Hydrogen Epoch of Reionization Array

Adélie Gorce,
on behalf of the HERA collaboration

5th global 21cm workshop

October 26, 2022

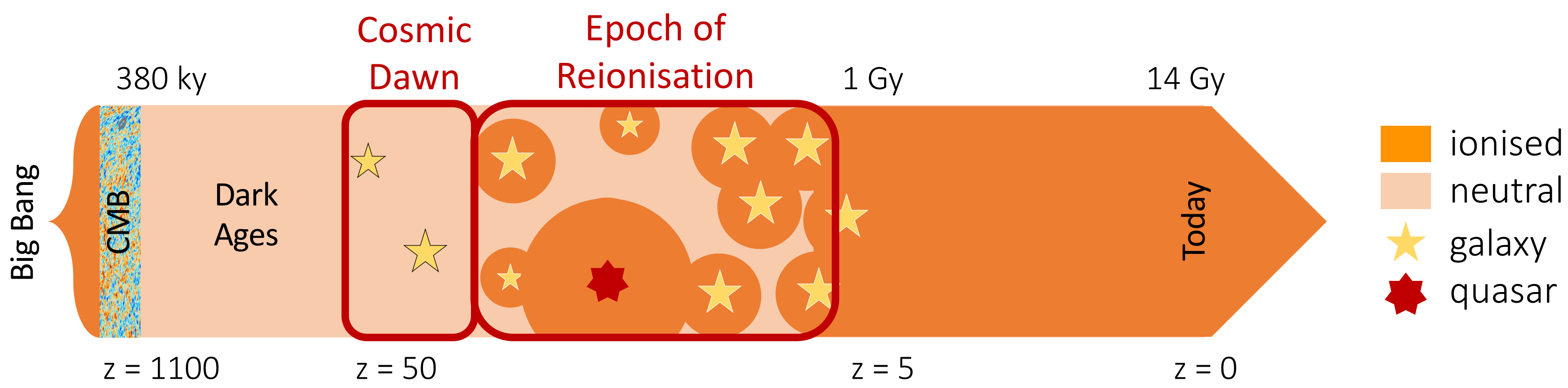
Reionisation & Cosmic Dawn



Chronology & topology of reionisation to unveil

- the birth of first stars
- the density of galaxies
- the nature of the IGM

Reionisation & Cosmic Dawn

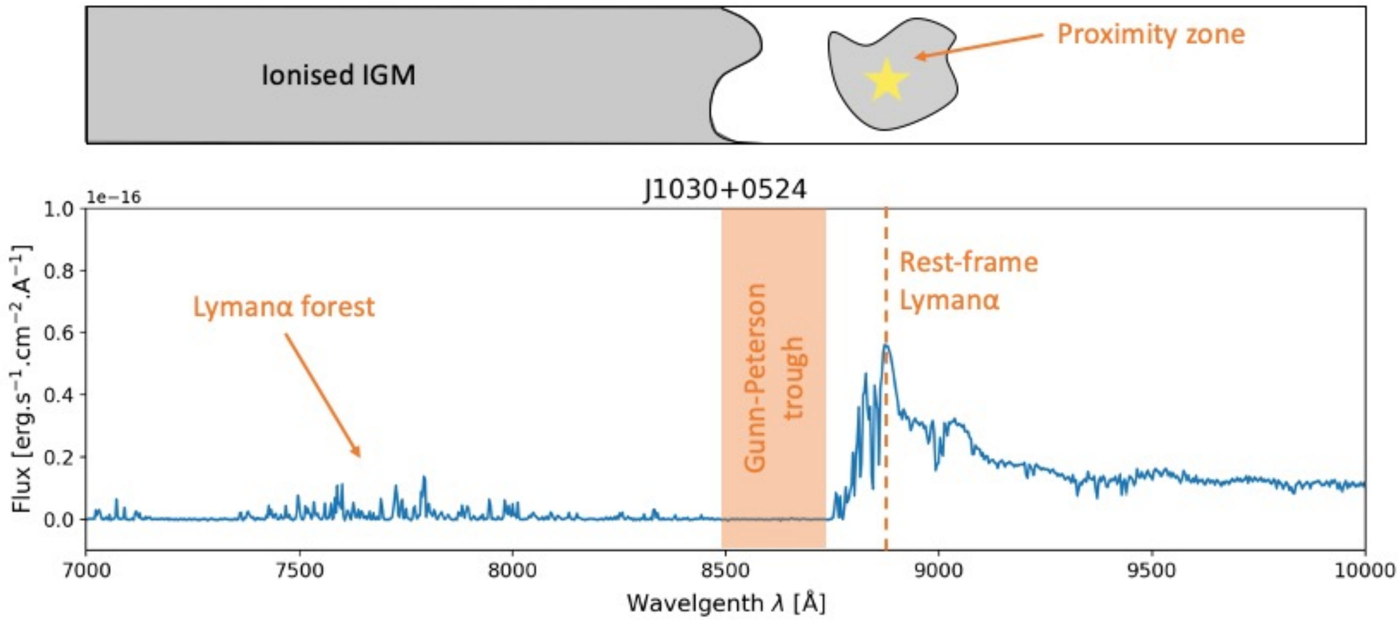


The chronology & topology of reionisation can shed light on

- the birth of first stars
- the density of galaxies
- the nature of the IGM

We already have some clues about reionisation

1. Spectra of quasars and galaxies: Lyman-α forest vs. Gunn-Peterson trough



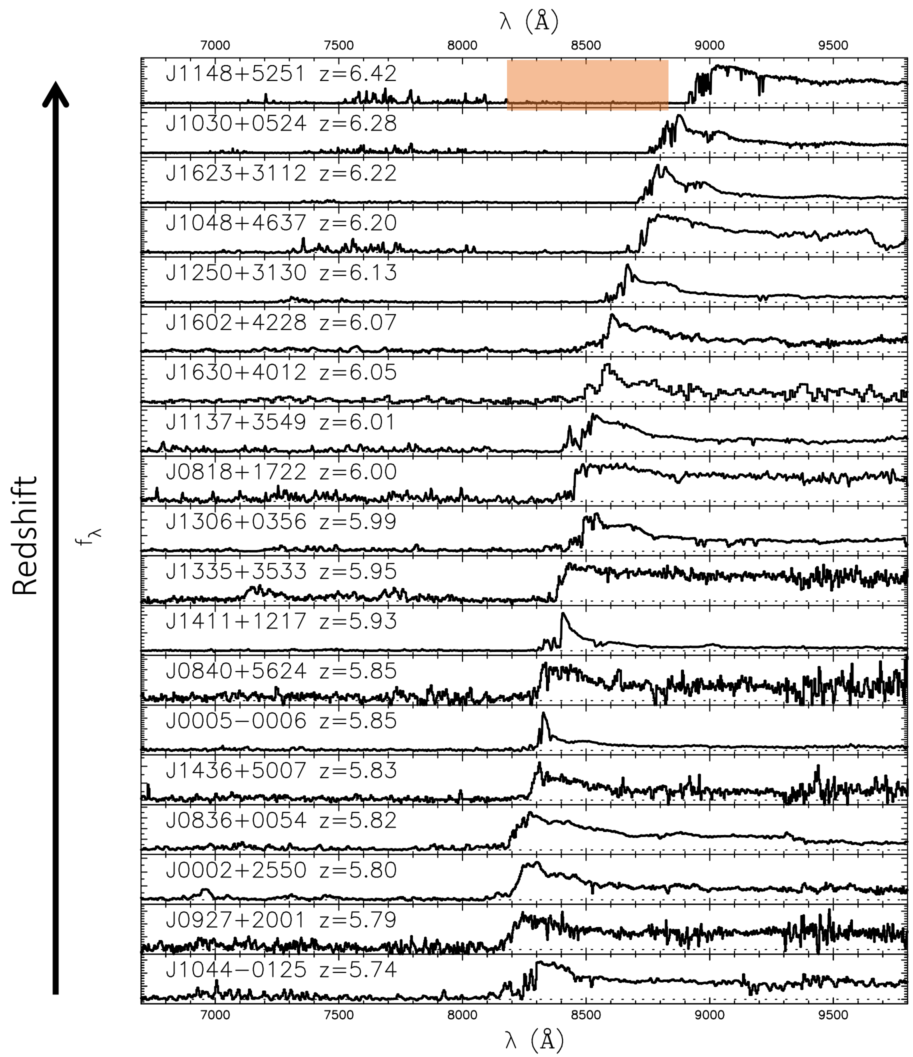
The forest shows as soon as 0.1% of atoms are neutral

Gunn & Peterson 1965

We already have some clues about reionisation

1. Spectra of quasars and galaxies

The SDSS quasars tell us reionisation should be over by redshift 6



Fan+2001, 2006

We already have some clues about reionisation

1. Spectra of quasars and galaxies: reionisation is over by z=6
2. Luminosity of high-redshift galaxies: amount of radiation available to ionise the IGM

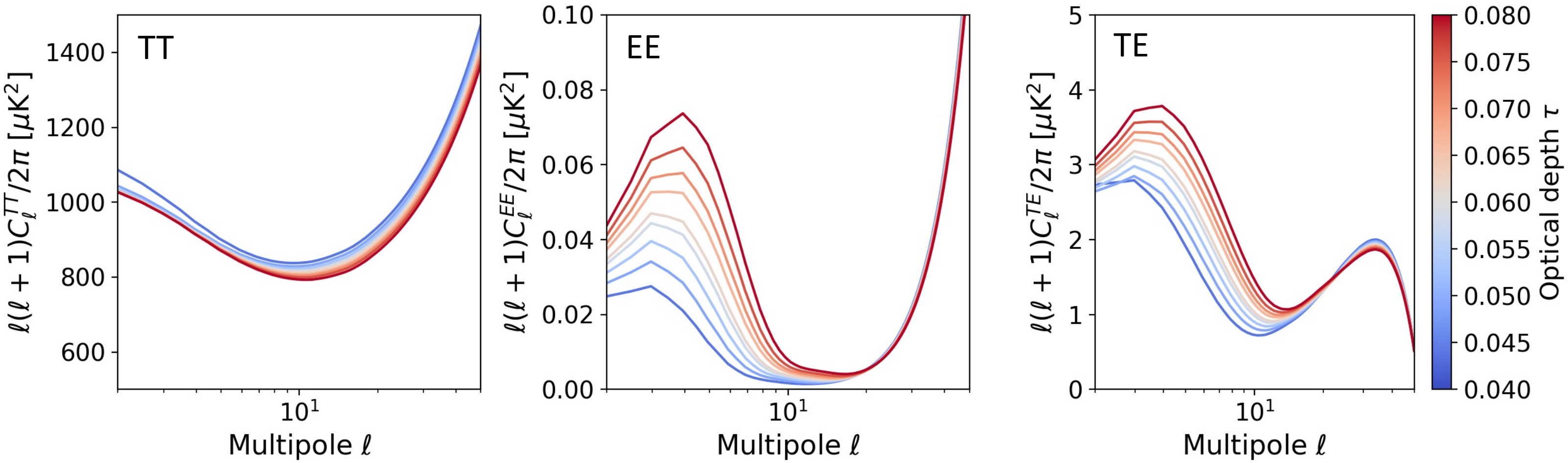
Bouwens+2015, Robertson+2016, Ishigaki+2015, 2018…

We already have some clues about reionisation

1. Spectra of quasars and galaxies: reionisation is over by z=6
2. Luminosity of high-redshift galaxies: amount of radiation available to ionise the IGM
3. CMB optical depth

Mean density of electrons

$$\tau \propto \int_{\mathrm{LSS}}^{a=0} \mathrm{d}\eta \; \bar{n}_e(\eta)$$



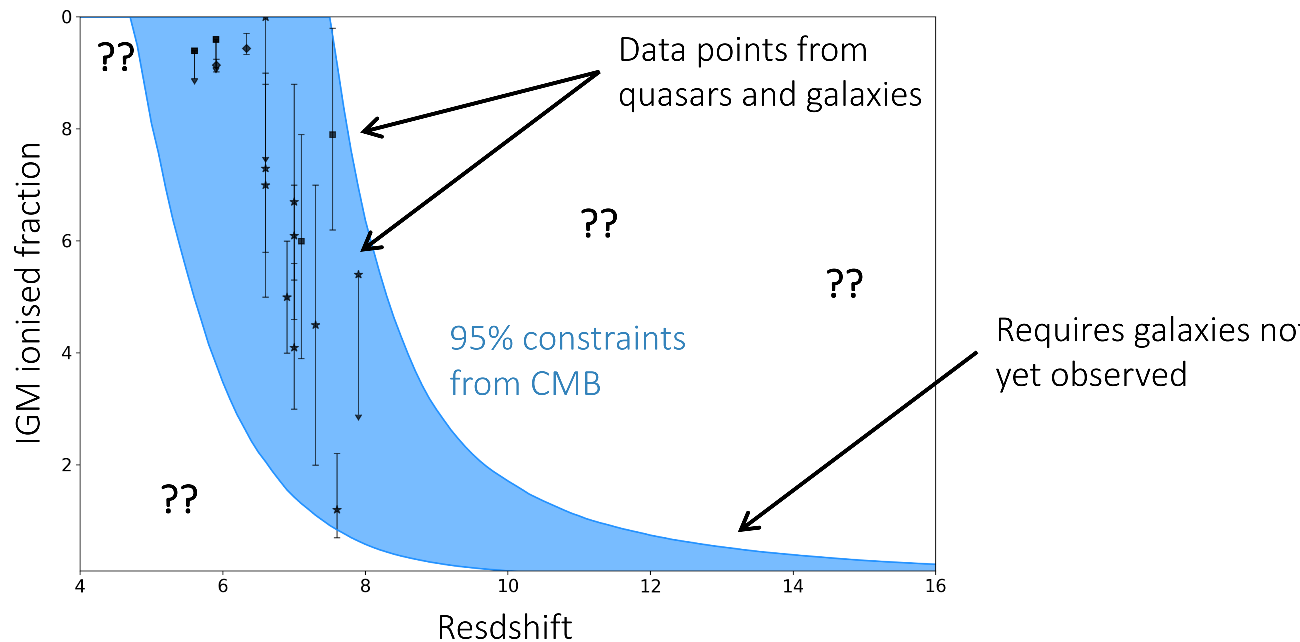
$$\tau = 0.054 \pm 0.07 \longrightarrow z_{\mathrm{re}} = 6.4 \pm 0.8$$

Planck collaboration 2016 XLVII, 2018 I, Gorce 2020

We already have some clues about reionisation

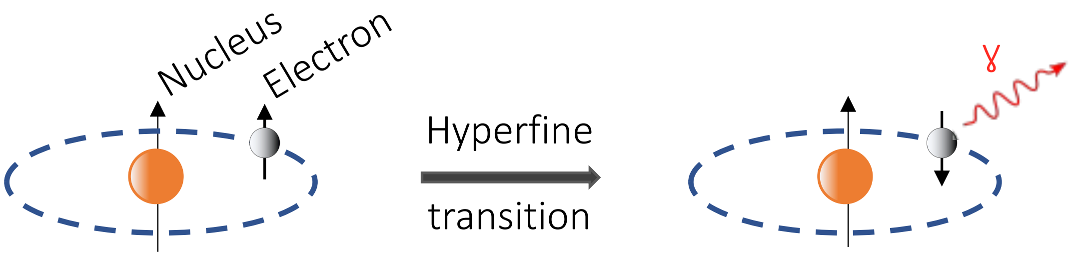
1. Spectra of quasars and galaxies: reionisation is over by z = 6
2. Luminosity of high-redshift galaxies: amount of radiation available to ionise the IGM
3. CMB optical depth: reionisation halfway through at z = 6.5

Does it mean we know everything already?!



Gorce+2018, Ishigaki+2018, Mason+2019, Greig+2017…

The 21cm signal



λ = 21 cm
Redshifted to radio frequencies

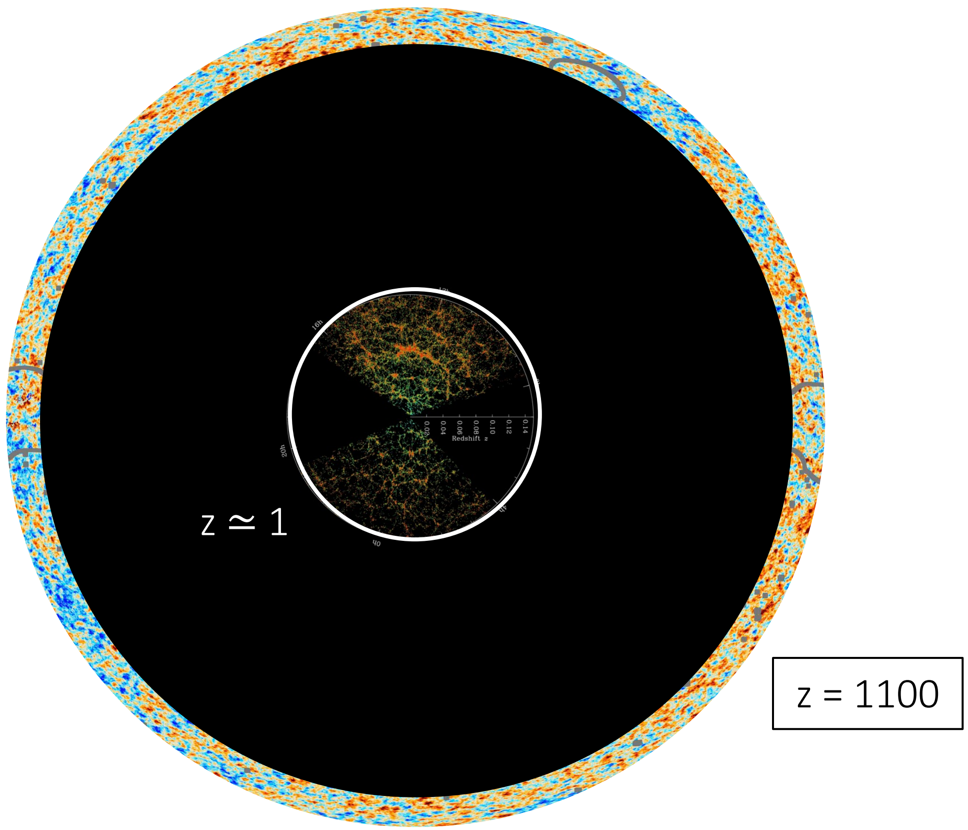
$$\delta T_{\rm b} = T_0(z)\, x_{\rm H_I}\, (1+\delta_{\rm b}) \left[1 - \frac{T_{\rm CMB}}{T_{\rm S}}\right]$$

Neutral H fraction

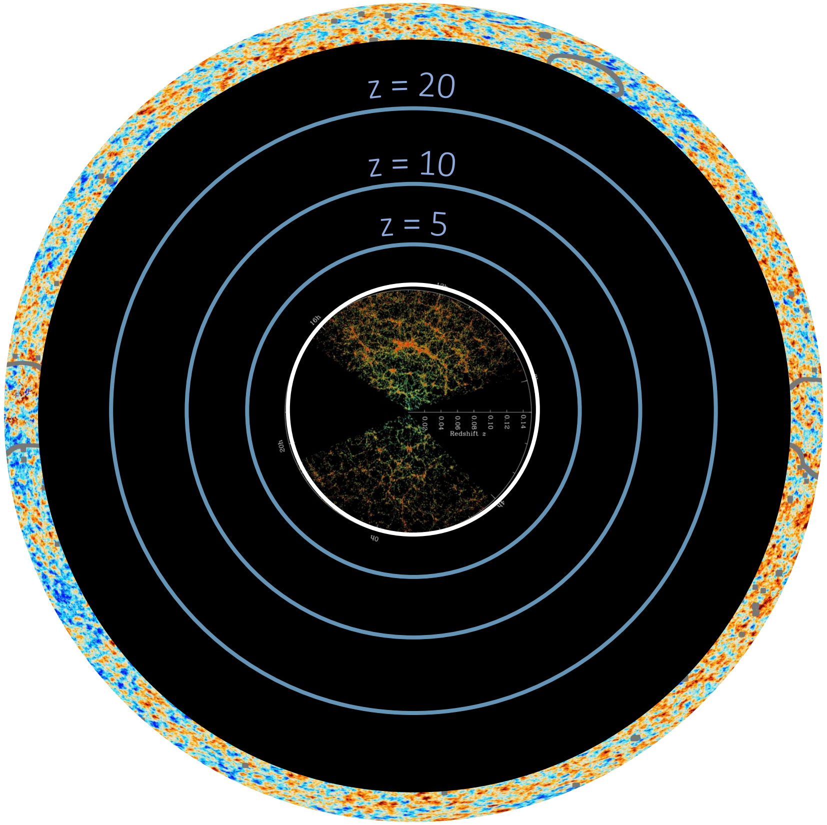
Baryon density

Pritchard & Loeb 2012

The 21cm signal

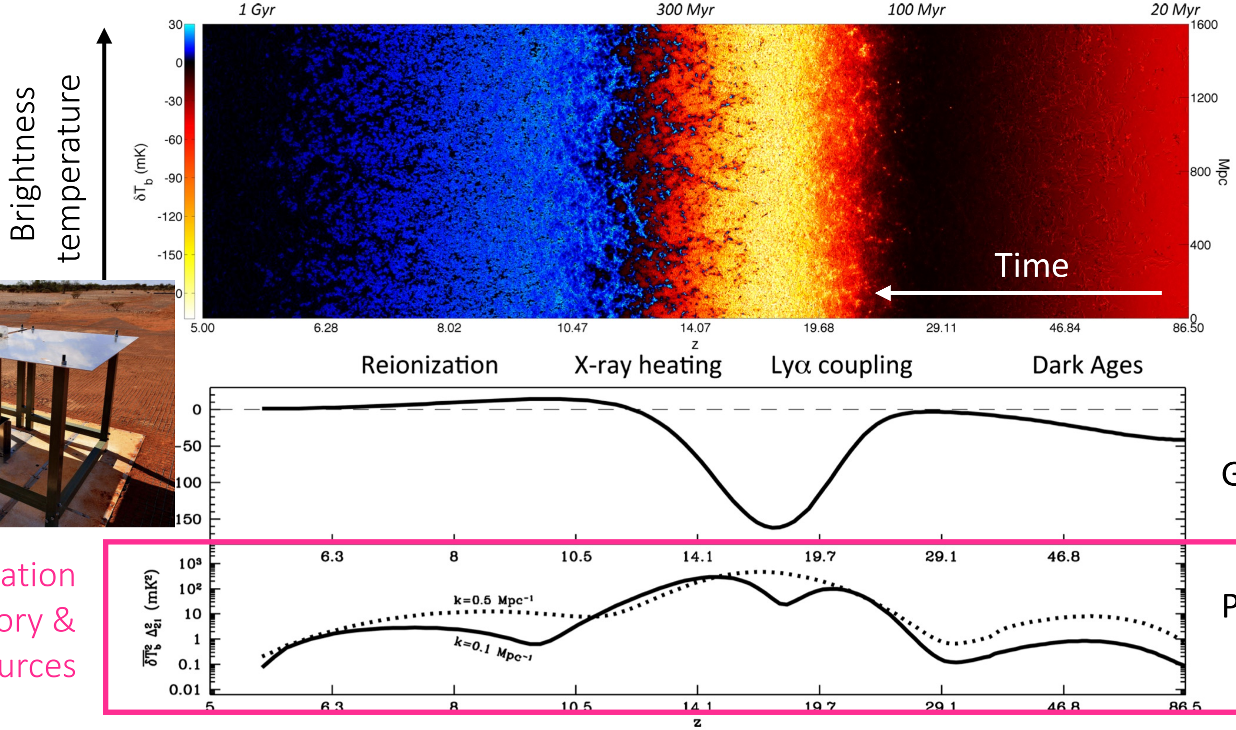


The 21cm signal



With the 21cm signal, we can map the Universe at any redshift

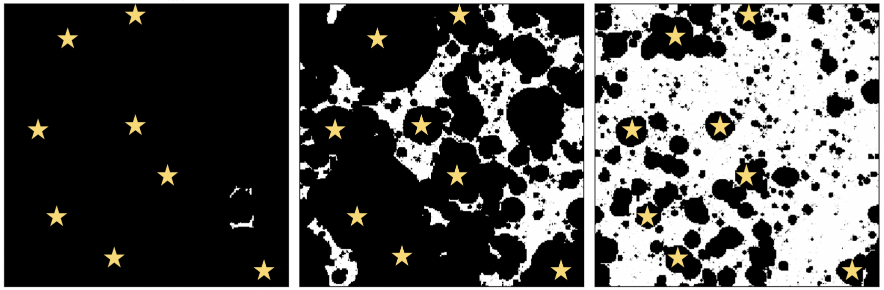
The 21cm signal



Global signal

Power spectrum

Reionisation history & sources



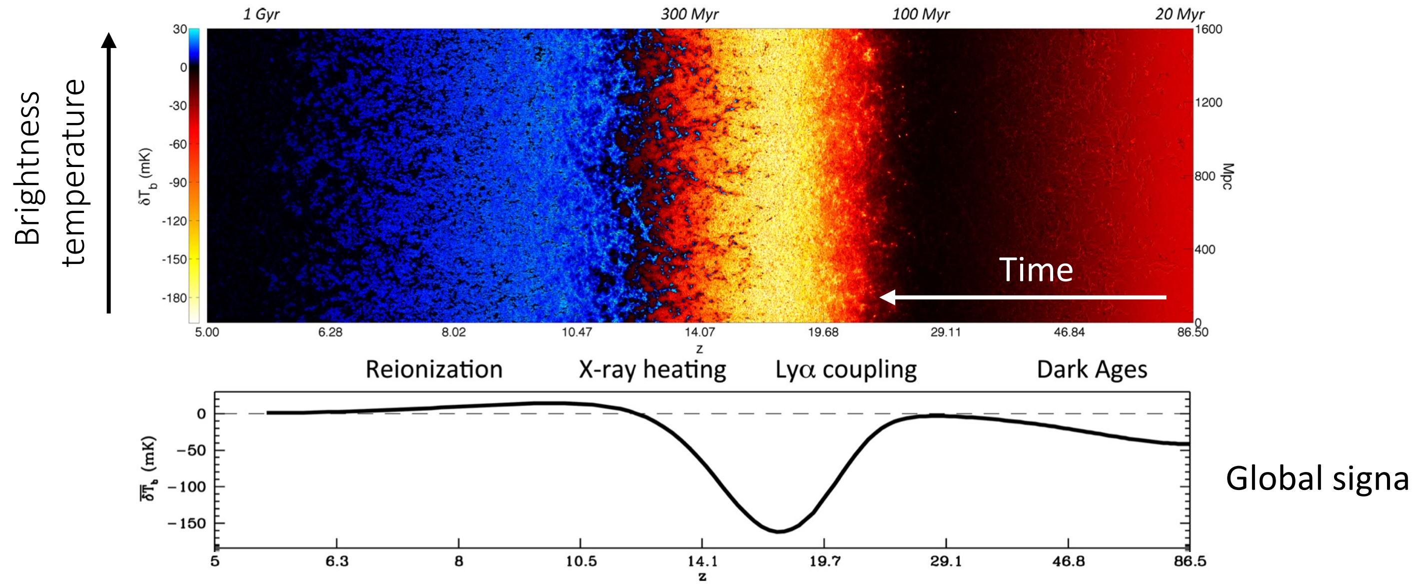
Intensity mapping

ionised

neutral

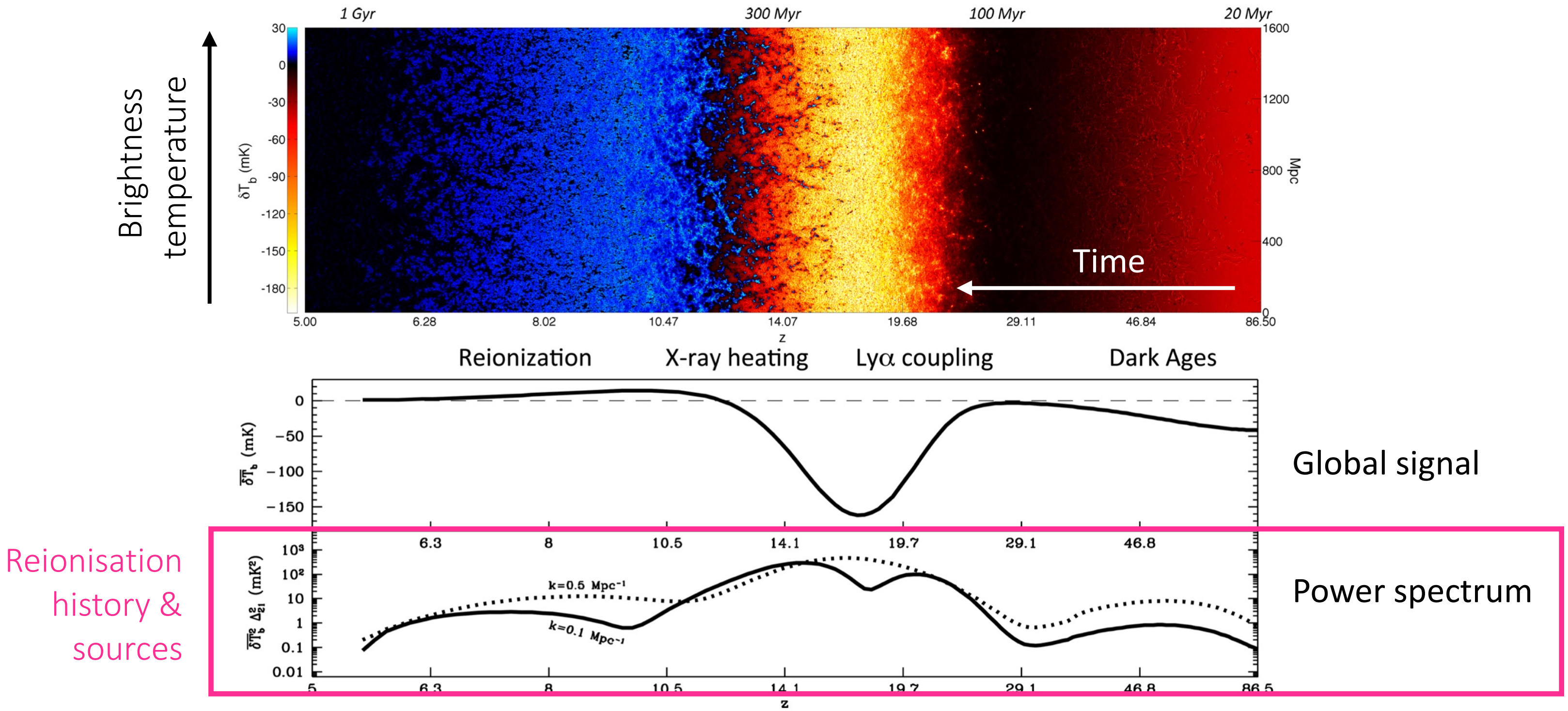
21CMFAST, Mesinger+2016

The 21cm signal



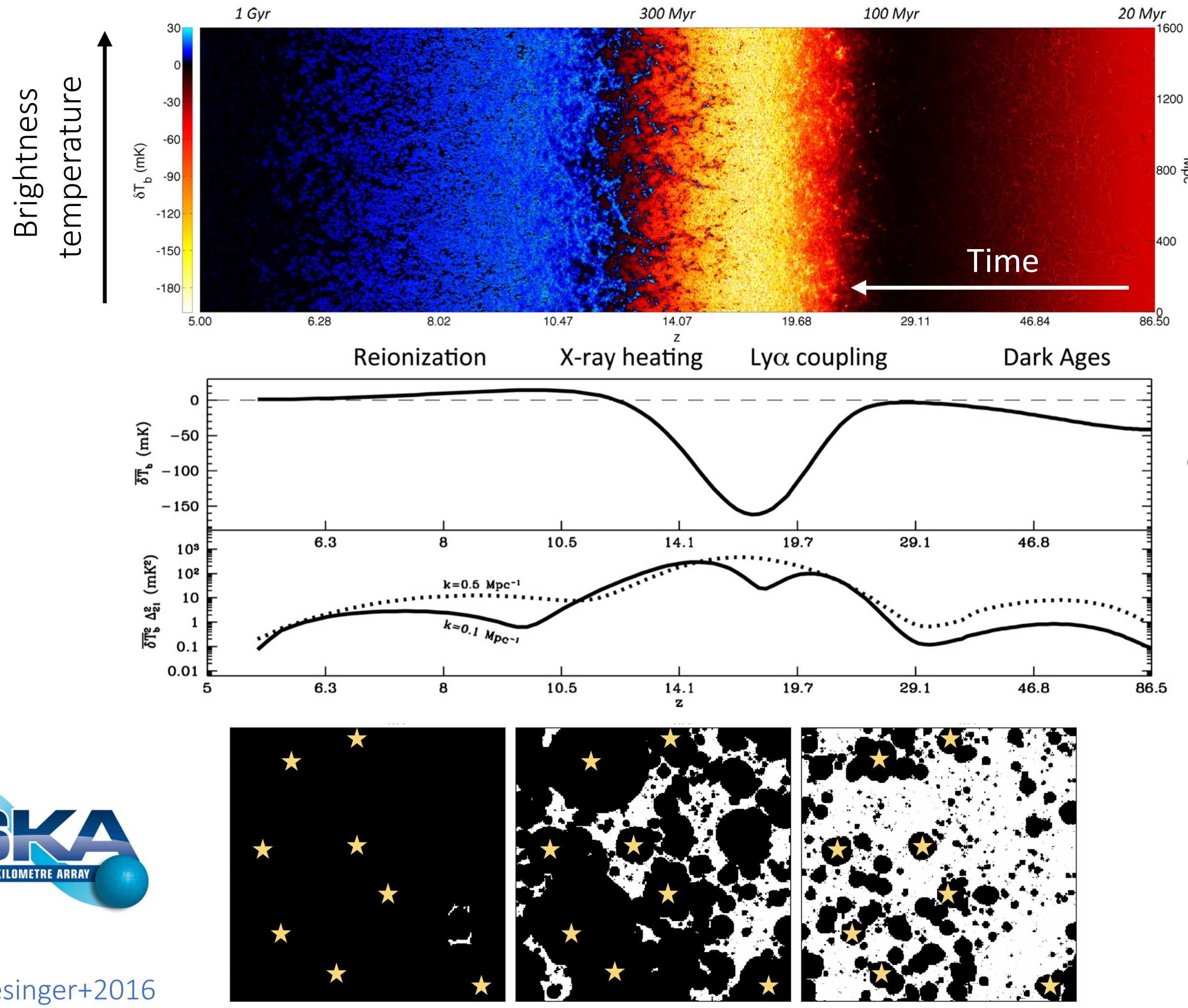
21CMFAST, Mesinger+2016

The 21cm signal



21CMFAST, Mesinger+2016

The 21cm signal



Global signal

Power spectrum

Intensity mapping

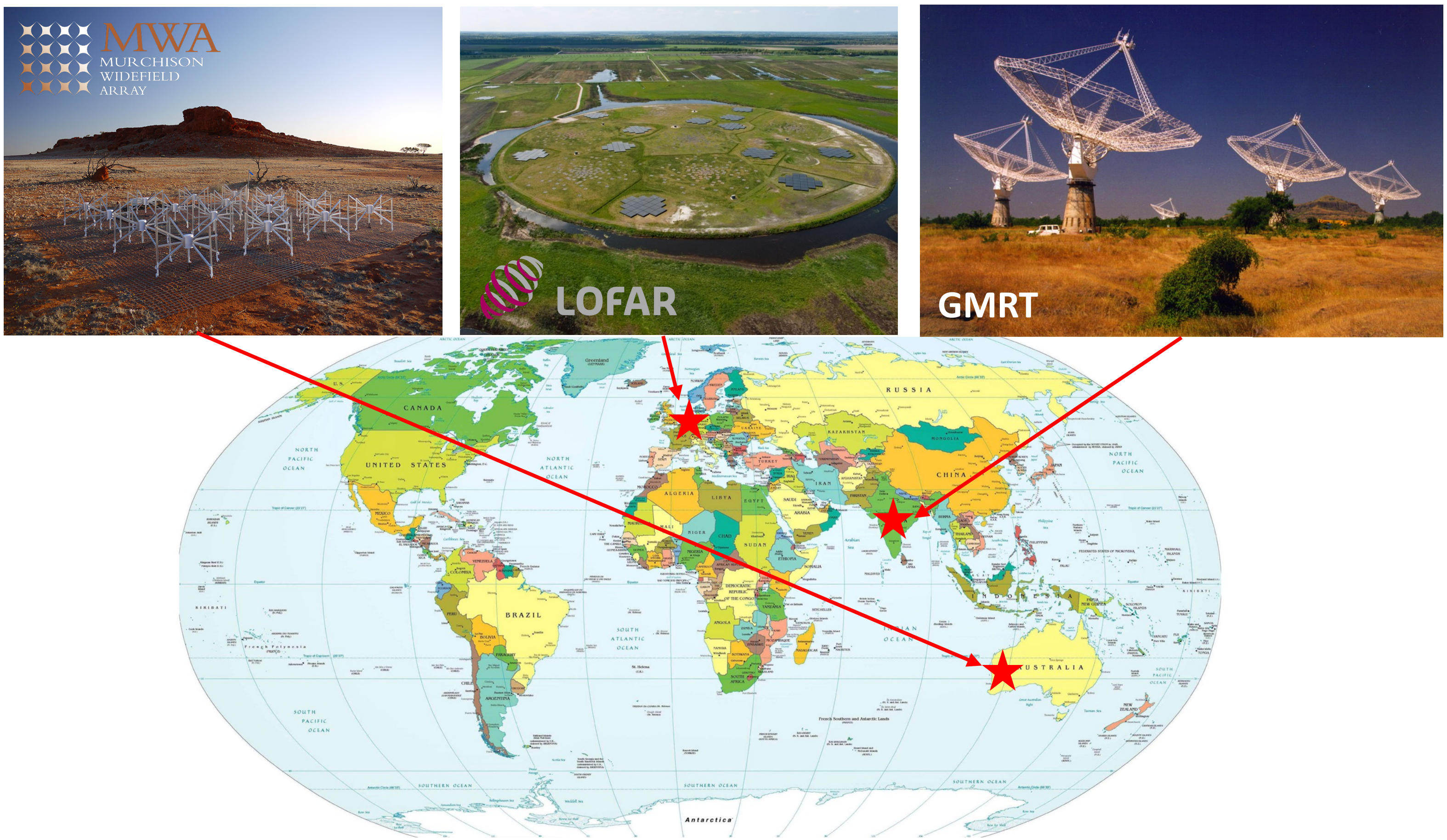
ionised

neutral

21CMFAST, Mesinger+2016

Radio interferometers around the world

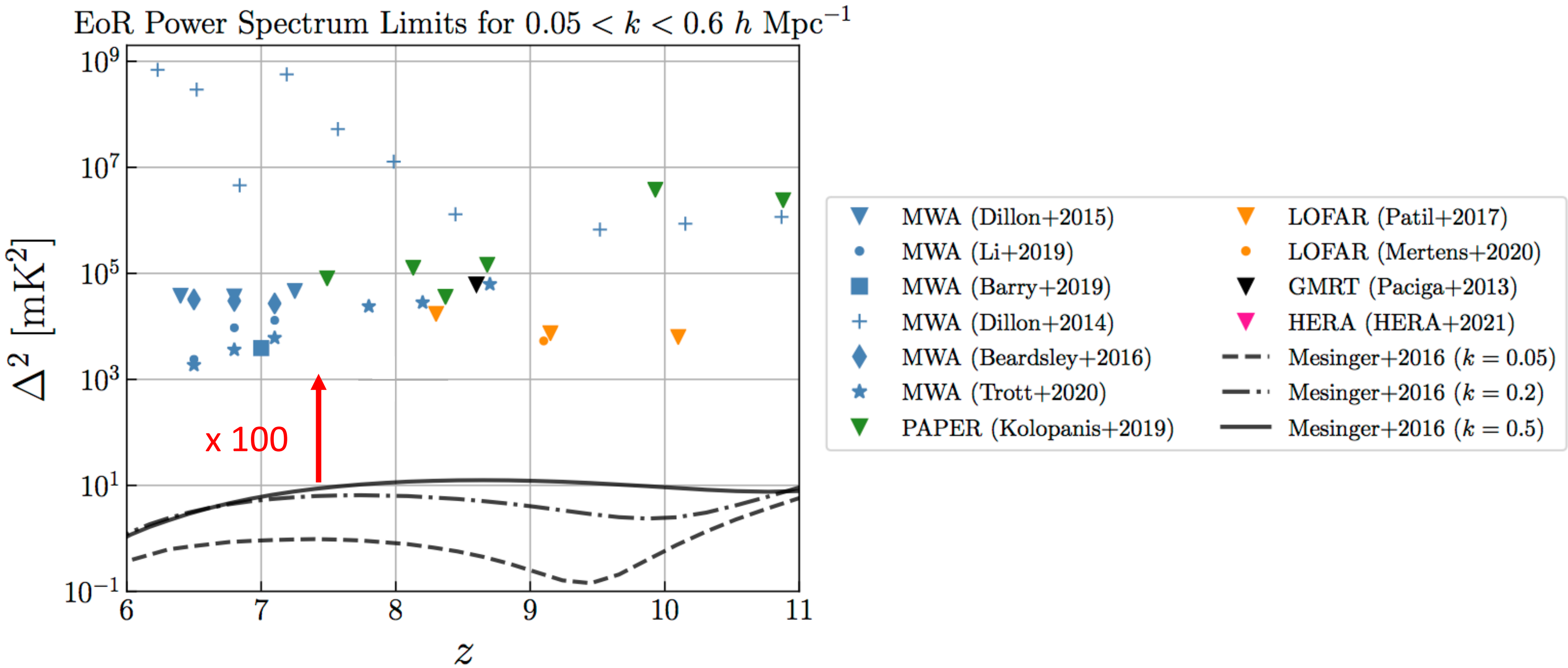
A world-wide effort…



Current upper limits

- The 21cm power spectrum

… which has only led to upper limits so far.



HERA collab et al. 2022a

Radio interferometers around the world

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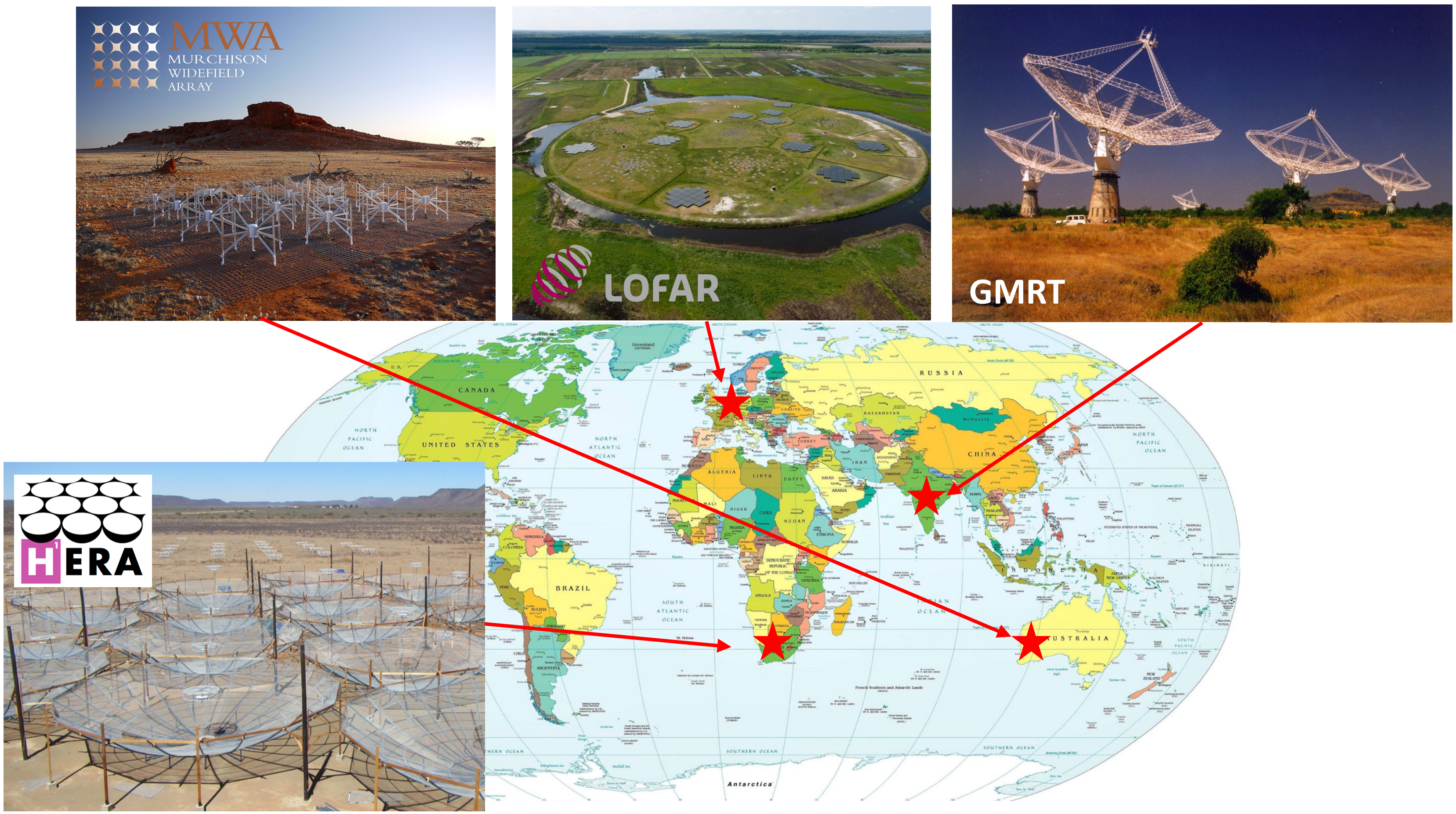
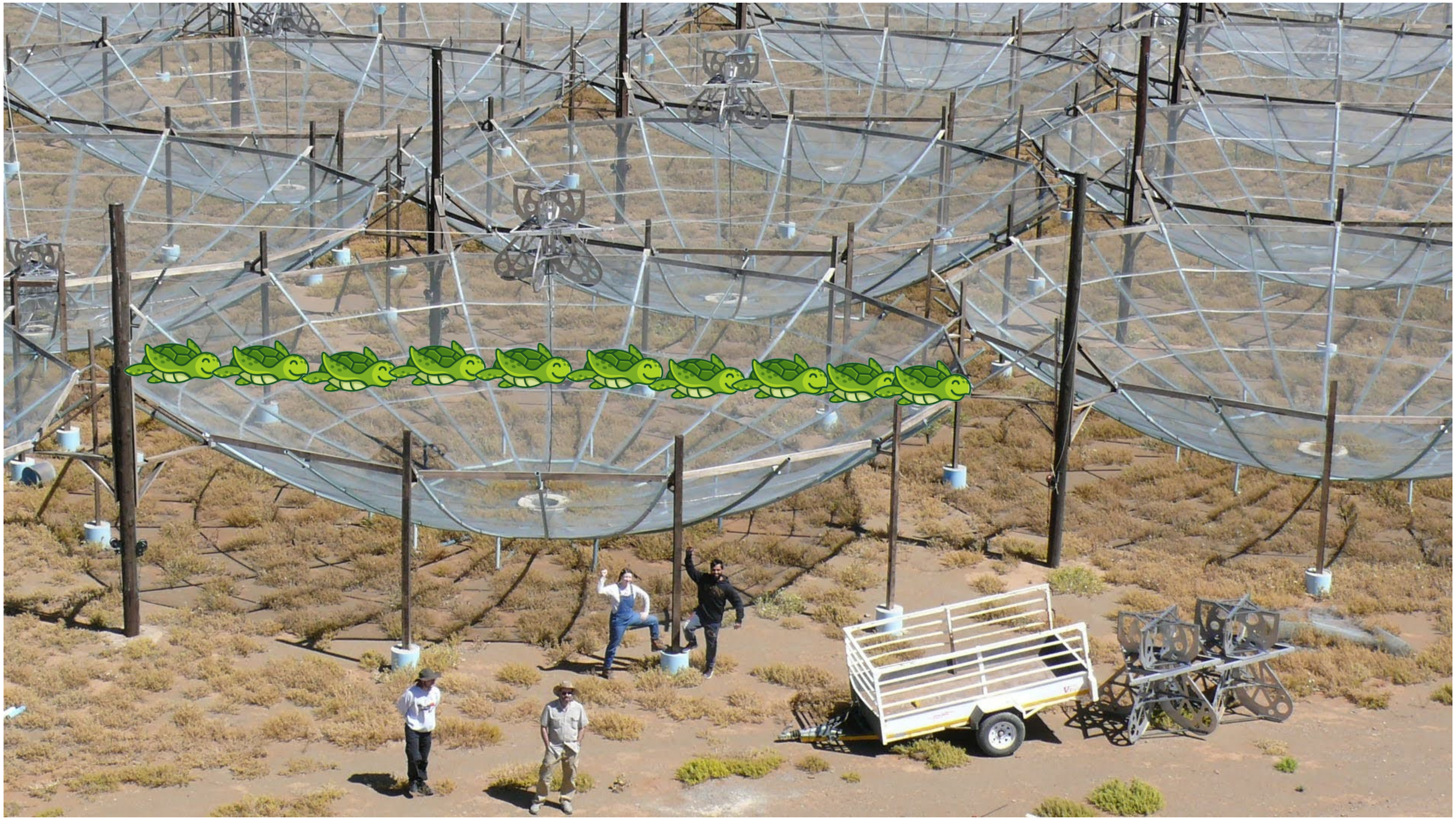



HERA
The Hydrogen Epoch of Reionization Array
CAL POLY POMONA
UNIVERSITY OF WASHINGTON 1861
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868
HARVARD
THE UNIVERSITY OF CALIFORNIA UCLA
SCUOLA NORMALE SUPERIORE
UNIVERSITY OF CAMBRIDGE
ARIZONA STATE UNIVERSITY 1885
UNIVERSITY OF KWAZULU-NATAL
SKA
SKA AFRICA
SQUARE KILOMETRE ARRAY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY of the WESTERN CAPE
NRAO
Penn
UNIVERSITY of PENNSYLVANIA
BROWN
GORDON AND BETTY MOORE FOUNDATION
NSF

The Hydrogen Epoch of Reionization Array

The signal is faint so HERA is huge!

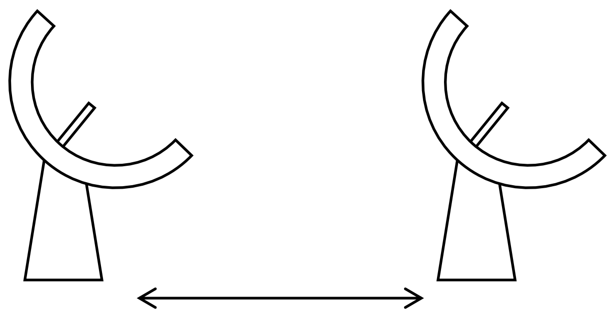


Why an array of antennae?

Interferometers measure “visbilities” 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

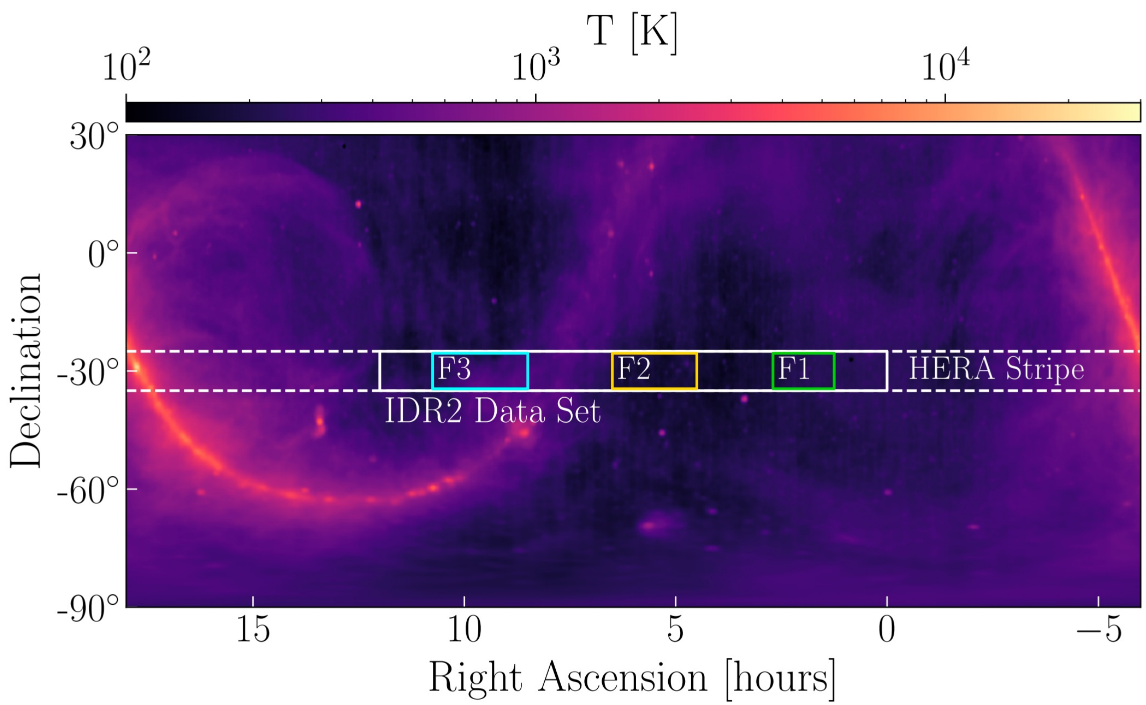


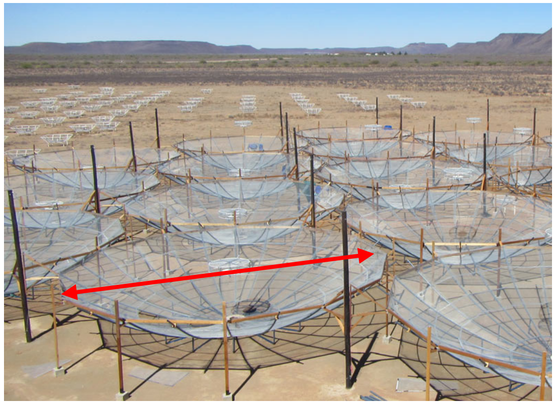
Baseline length b_{ij}
is the Fourier dual of the sky angle
($k_{\perp}$)

- Dense arrays measure large-scale fluctuations (e.g. EDGES’ “table”)
- Wide arrays measure small-scale fluctuations (e.g. HERA & foreground avoidance)

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

The Hydrogen Epoch of Reionization Array





52 14m dishes (→ 350)

- 10° stripe (beam) at fixed declination
- Bandwidth: 100 < ν/MHz < 200 (6 < z < 13)

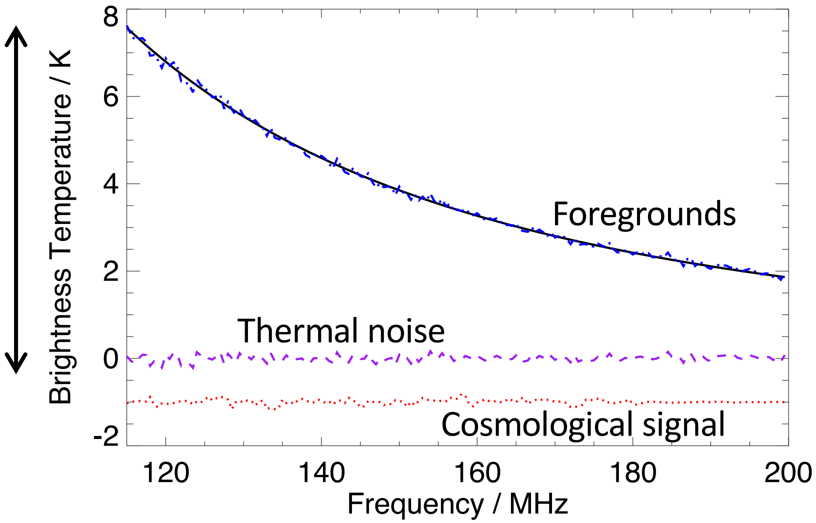
Foregrounds vs. HERA: Round 1

Foregrounds 1 – HERA 0

Extremely bright foregrounds lie between the first stars and us

- Galactic (synchrotron): 73%
- Extra galactic (point sources): 27%

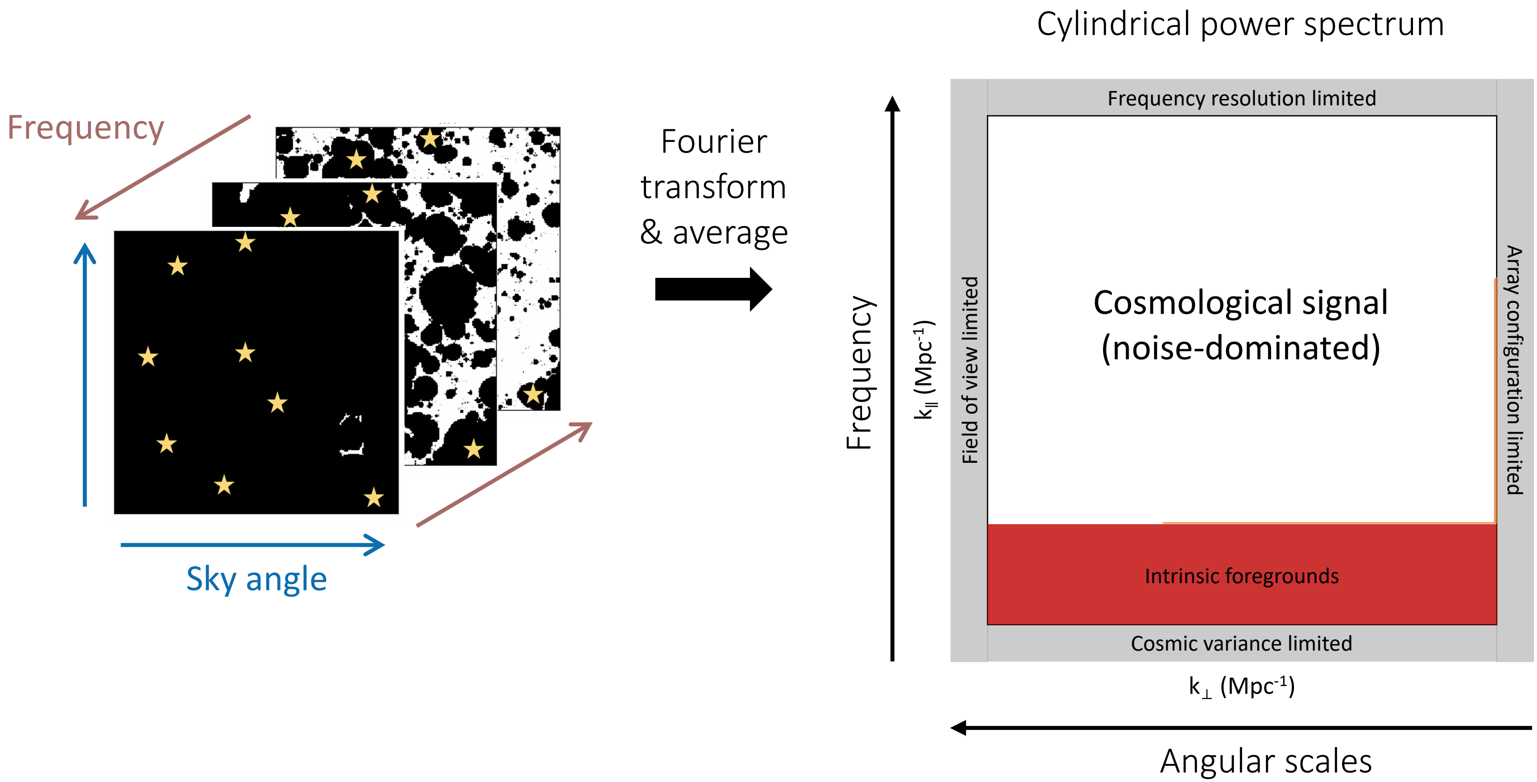
4-5 orders of magnitude



But luckily they are spectrally smooth,
so we can separate them from the cosmological signal in Fourier space…

Chapman+2013

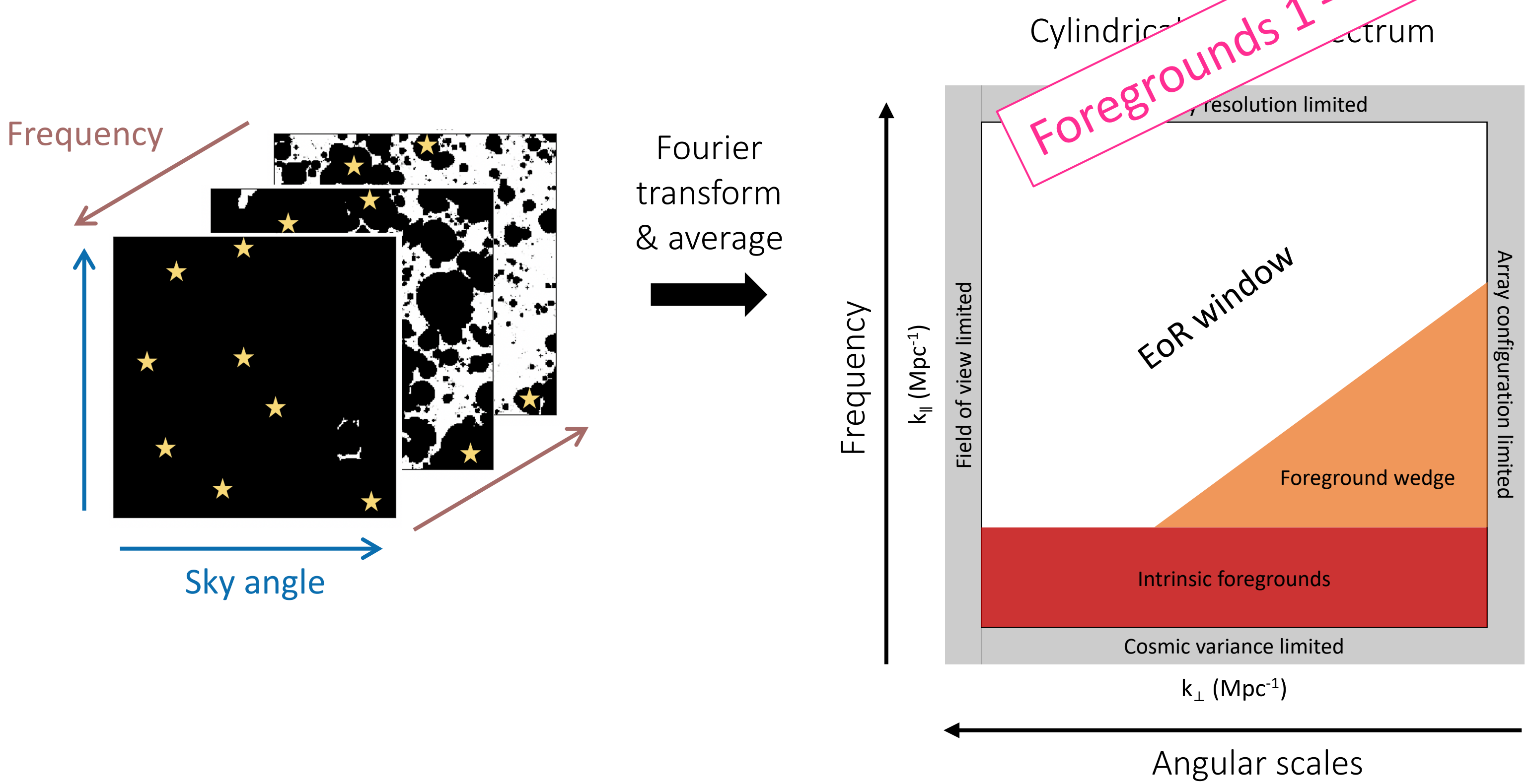
Foregrounds vs. HERA: the power of the wedge



Because the foregrounds are spectrally smooth, they are limited to a specific region of the cylindrical power spectrum.

Parsons+2013, Liu+2015a,b

Foregrounds vs. HERA: the power of the wedge



But the chromaticity of the instrument introduces spectral structure, creating the *foreground wedge* which we do our best to *avoid*

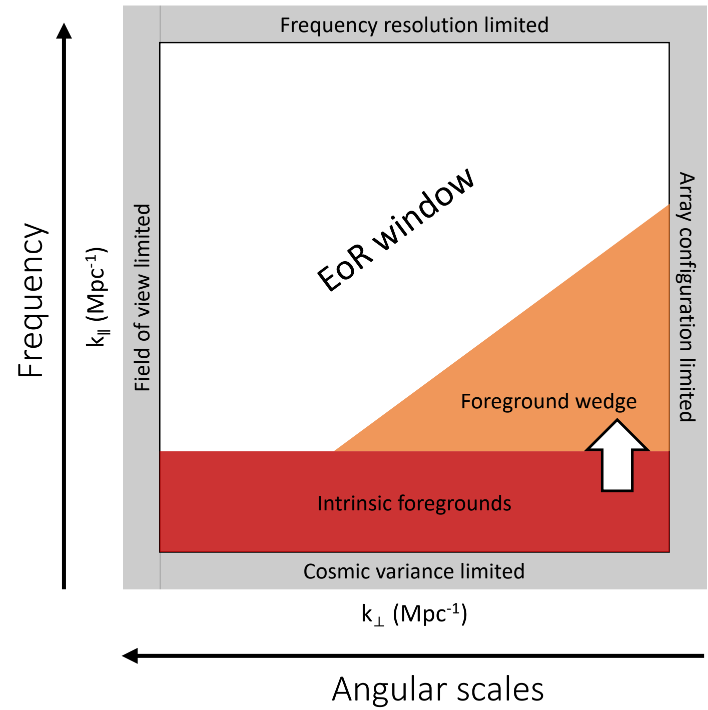
Parsons+2013, Liu+2015a,b

Other strategy: foreground removal (LOFAR)

Foregrounds vs. HERA: the power of the wedge

Foregrounds 1 – HERA 1

Cylindrical power spectrum

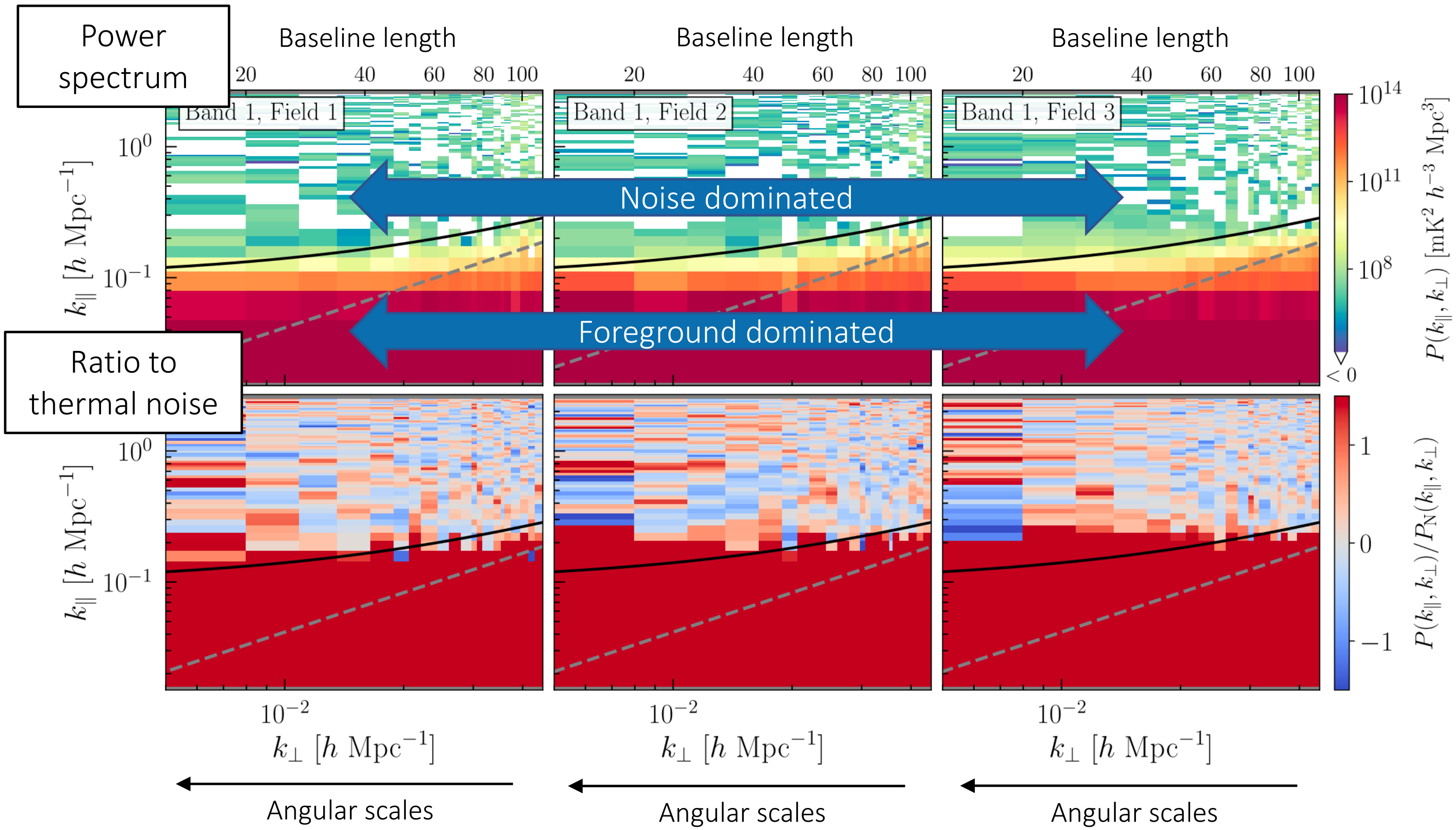


HERA is designed to maximise sensitivity on short baselines (small $k_{\perp}$)

Parsons+2013, Liu+2015a,b

Other strategy: foreground removal (LOFAR)

Results: Cylindrical power spectra

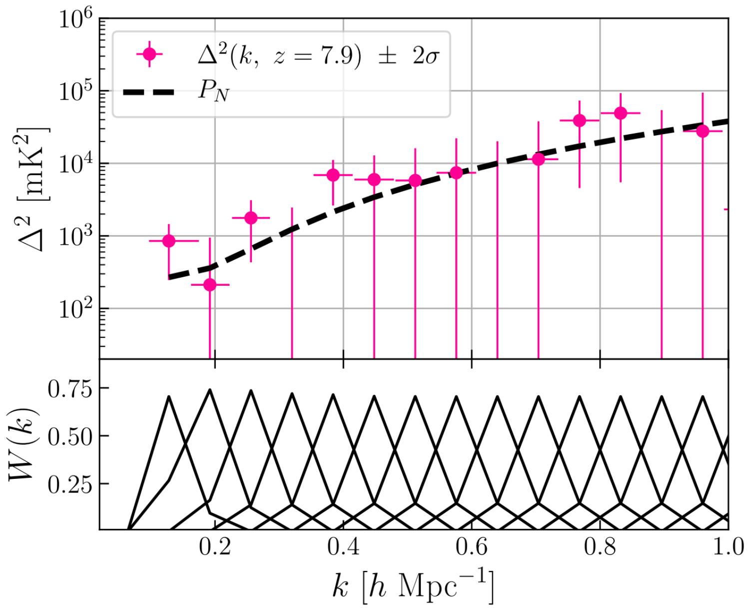


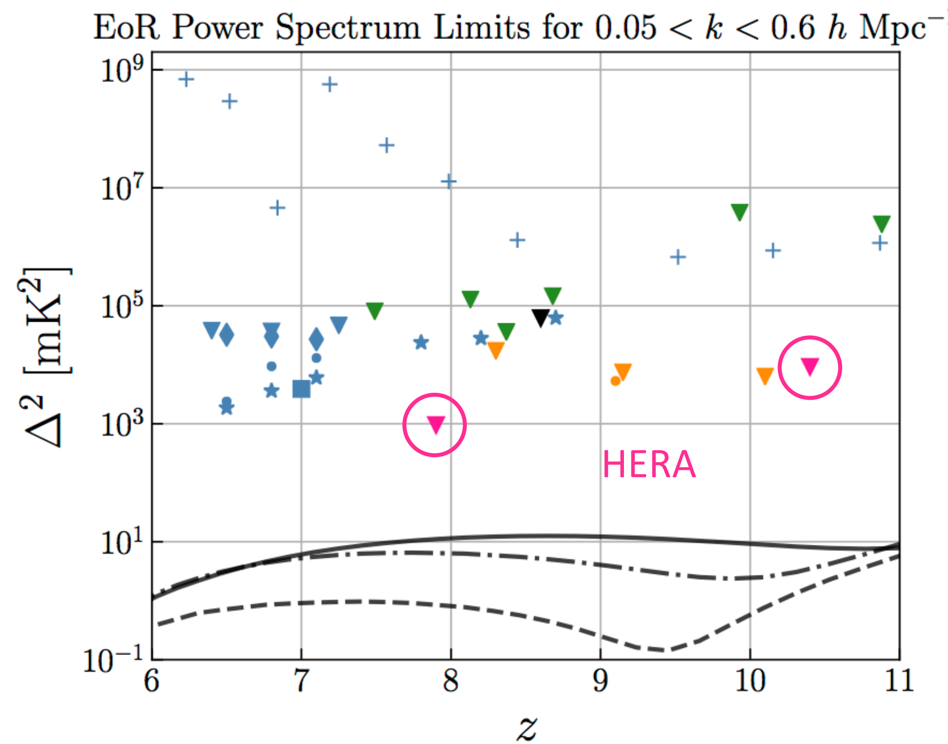
HERA collab et al. 2022a

Results: Spherical power spectra

Foregrounds 2 – HERA 1?

- Lowest upper limits to date
- With *only* 18 nights of data, 39 antennae and foreground avoidance





<u>Constraints on theory?</u>

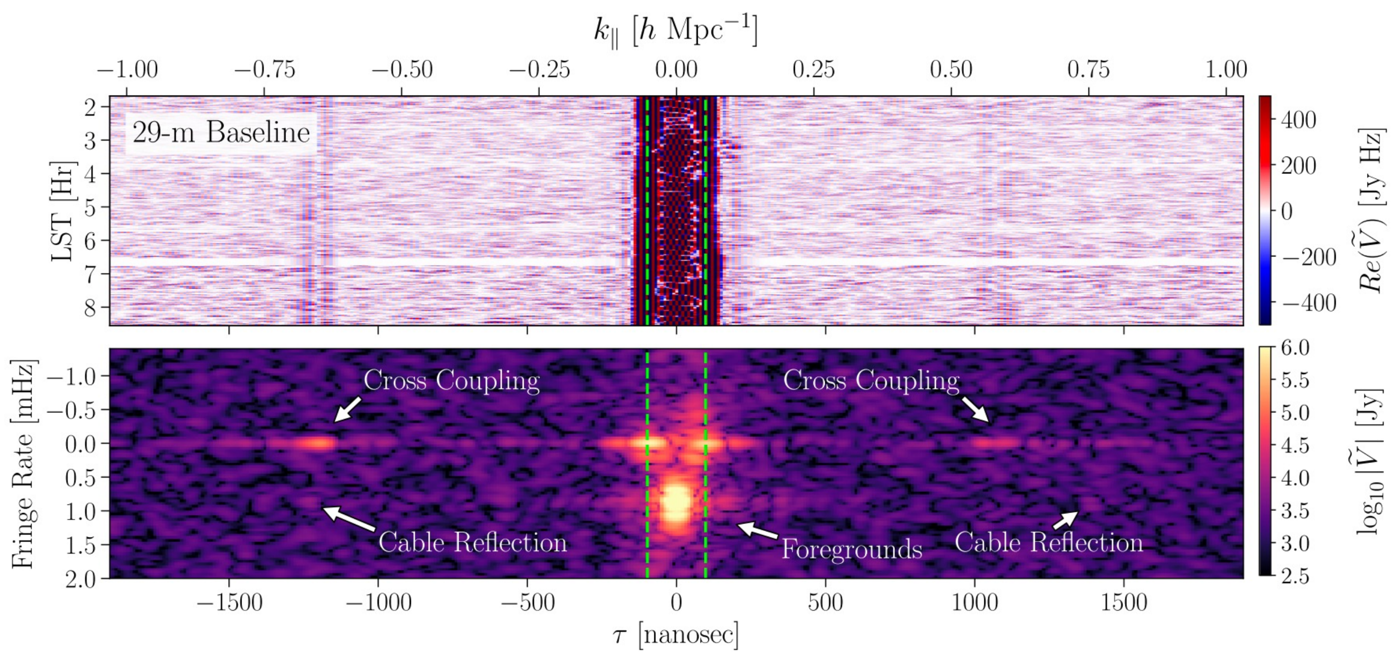
- Rule out an IGM unheated by X-rays at $z = 7.9$
- Difficult to say more at this point

HERA collab et al. 2022a

Another big issue: Systematics

- Understand temporal and spectral structure of systematics to identify them:
  → Cross-coupling systematics have a slow time variability

Systematics chromatography



Kern+2019

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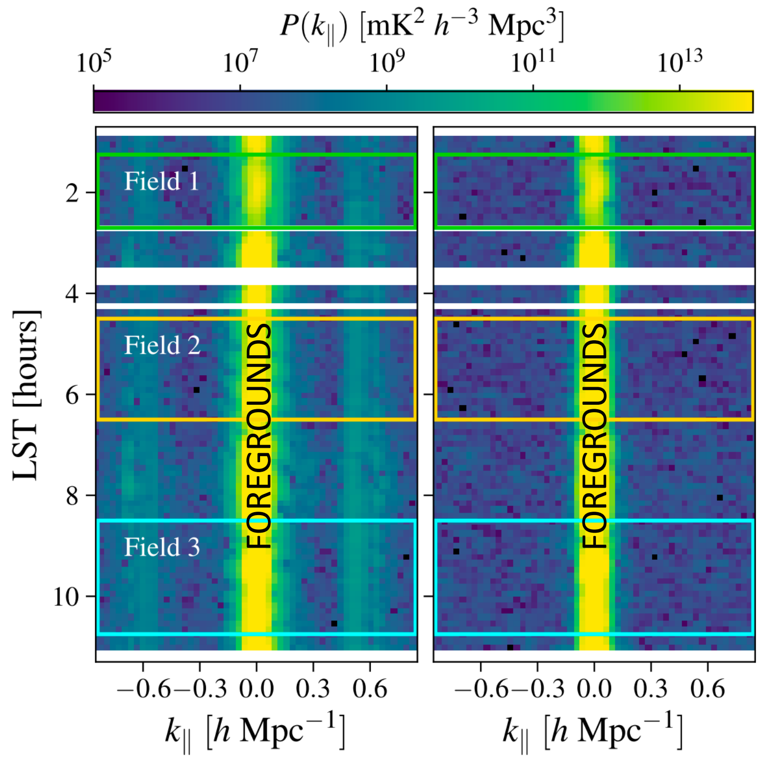


- We are approaching the thermal noise limit!

Kern+2019

Building confidence in the HERA results

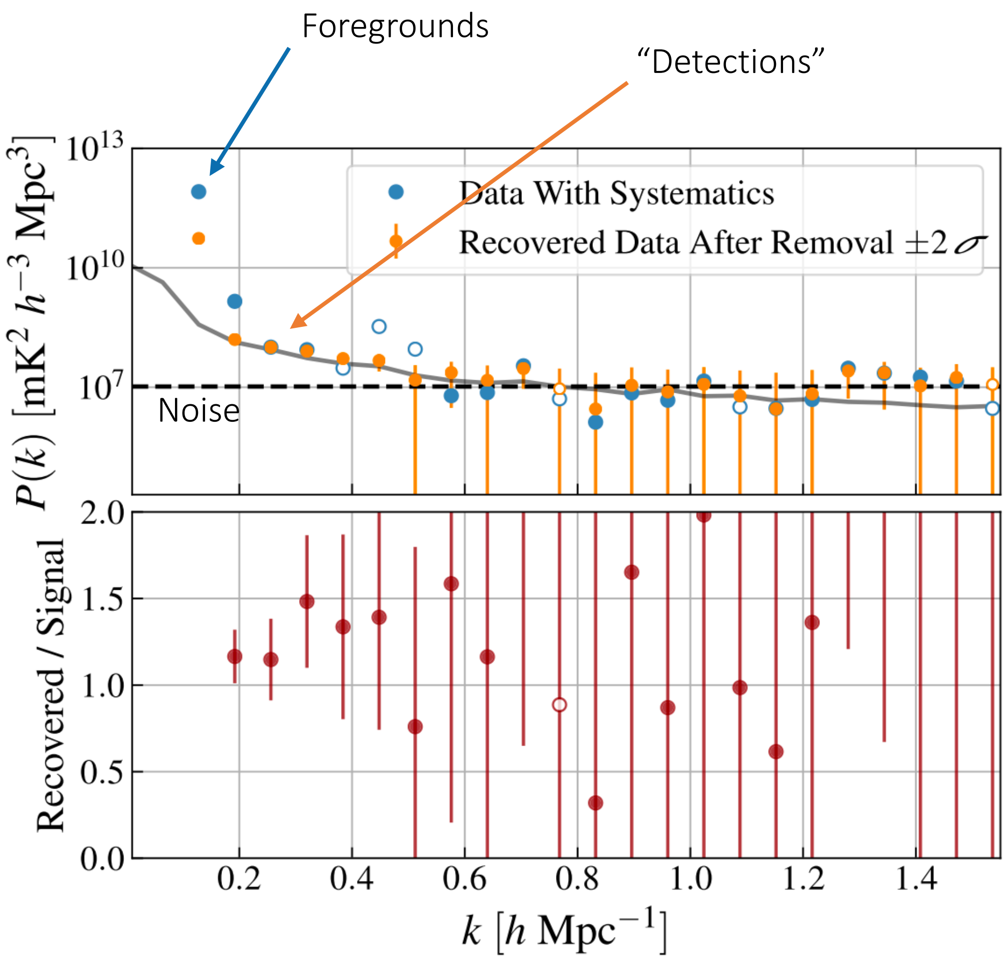
End-to-end simulation pipeline with

- ✓ Cosmological signal
- ✓ Foregrounds
- ✓ Systematics

→ Extract a simulated signal

→ Quantify biases

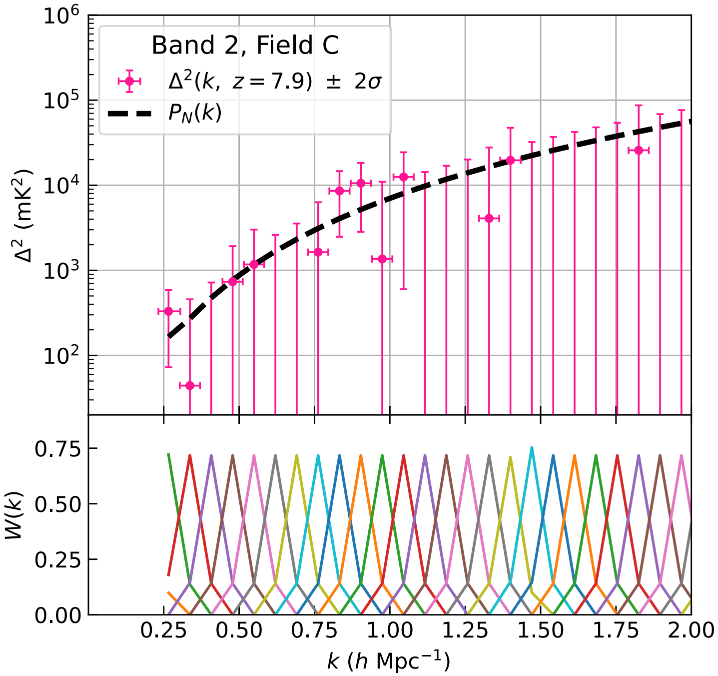
(raised our limits by ≃ 10%)



Aguirre+2022

Understanding how measurements

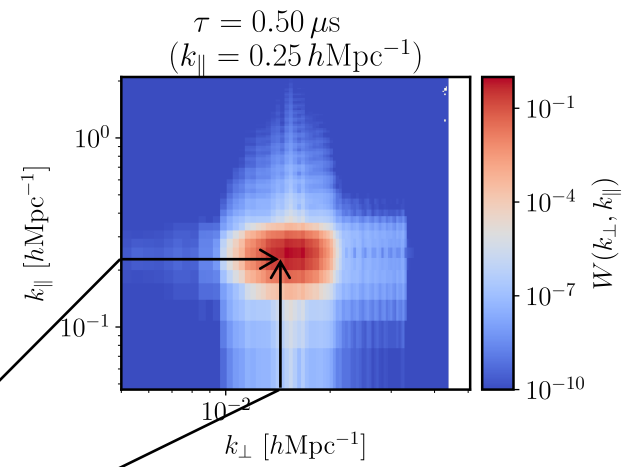
The power spectrum measured by an interferometer is different from the intrinsic cosmological power spectrum.



The window functions are centred on

$$k_\parallel = \frac{2\pi|\tau|}{\alpha(z)}$$

$$k_\perp = \frac{2\pi}{d_c(z)}\frac{\nu b}{c}$$



Power from neighbouring cylindrical k-modes will leak into the measurement of the power spectrum at a given ($k_\perp$, $k_\parallel$).

HERA collaboration 2022c, Gorce+2022

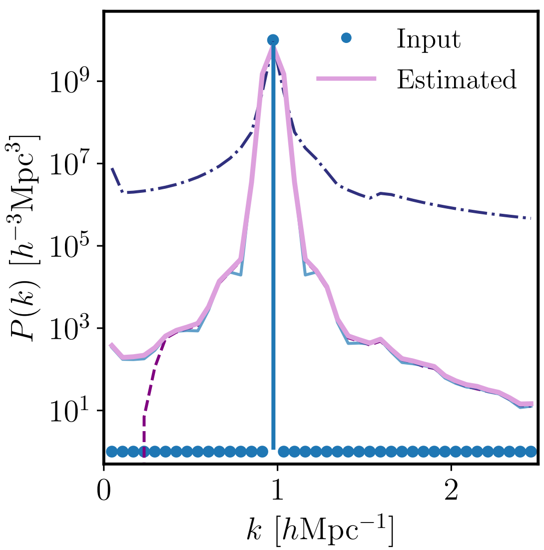
An illustration of mode mixing: Test cases

Consider a model input power and derive the power reconstructed by the instrument:

$$\hat{P}_{\rm out}(b,\tau) = \int \mathrm{d}k_\perp \mathrm{d}k_\parallel \, P_{\rm in}(k_\perp, k_\parallel)\, W(k_\perp, k_\parallel; b, \tau)$$

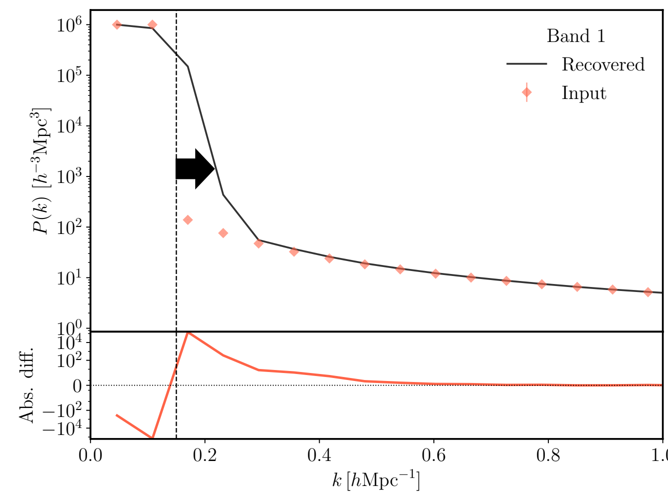
<u>Impulse response</u>

$$P_{\rm in}(k) = \begin{cases} 10^{10} & \text{if } k = k_0, \\ 1 & \text{else,} \end{cases}$$



<u>Simple foreground model</u>

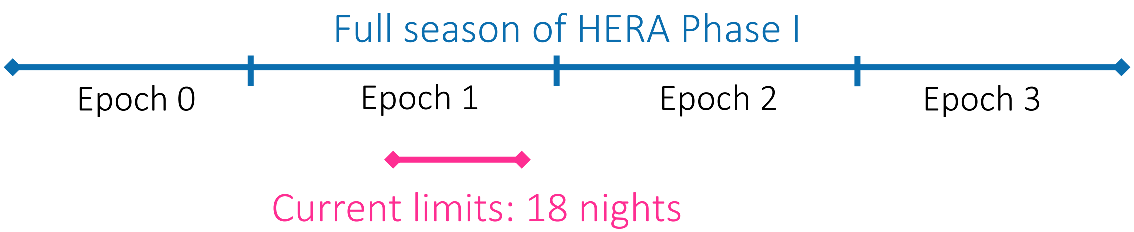
$$P_{\rm fg}(k_\perp, k_\parallel) = \begin{cases} 10^{6} & \text{if } k_\parallel < k_{\rm lim}, \\ 1 & \text{else,} \end{cases} \quad \& \quad P_{\rm cosmo}(k) \propto k^{-2},$$



Power clearly leaking around impulse / outside of wedge

Conclusions: What is next for HERA?

- Use more date to decrease noise: new results coming with full data set



→ From a pure sensitivity perspective, the next limit could be as much as ≃ **3 times deeper**.

- Build all 350 antennae (first results with only 52) and upgrade existing ones

→ Longer bandwidth (4.7 < z < 29)

- With full season (100 nights), should easily conclude on EDGES and **constrain the reionisation history at z +/- 0.1**