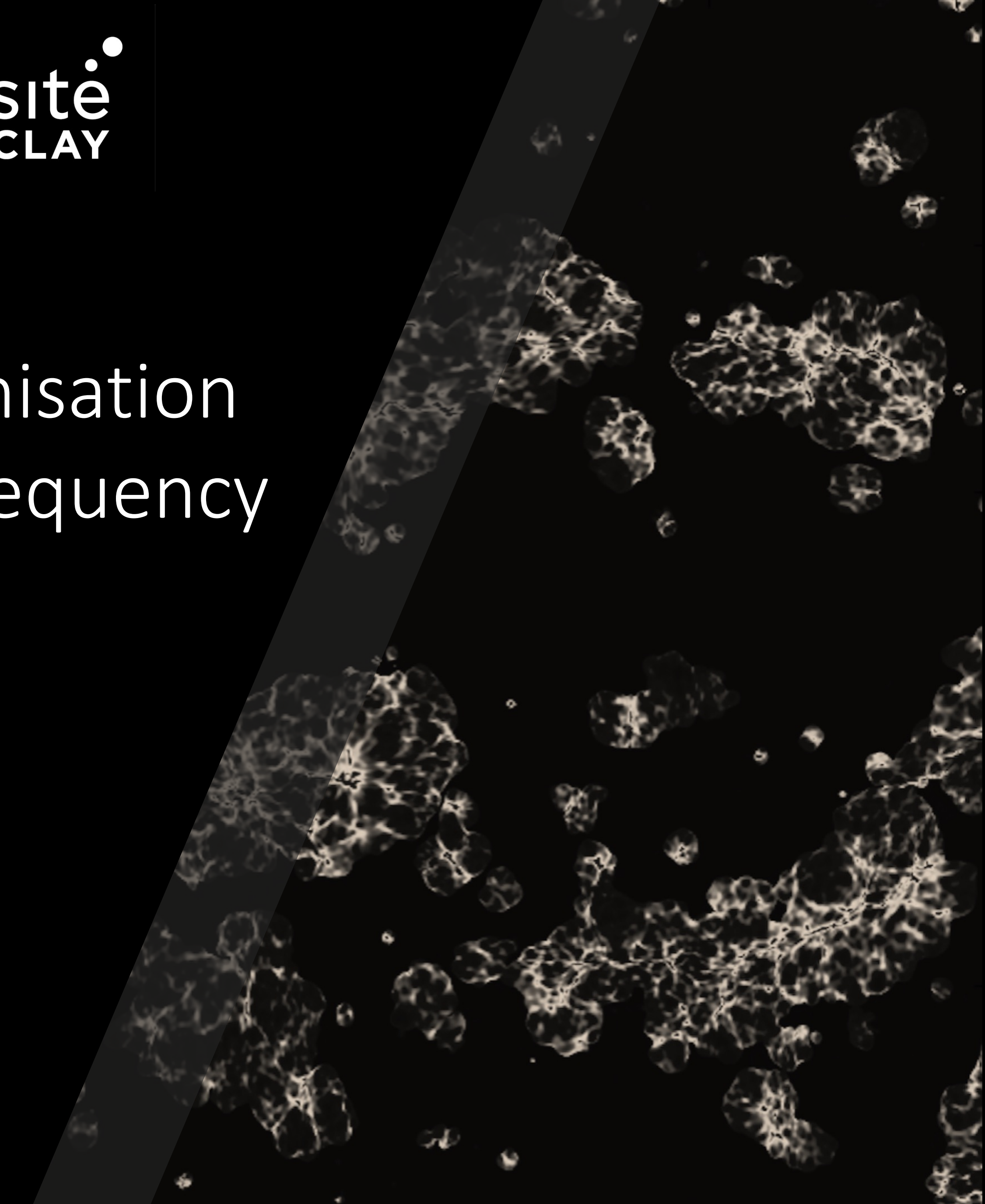
The Epoch of Reionisation through the low-frequency radio lens

Adélie Gorce

17th Marcel Grossmann meeting

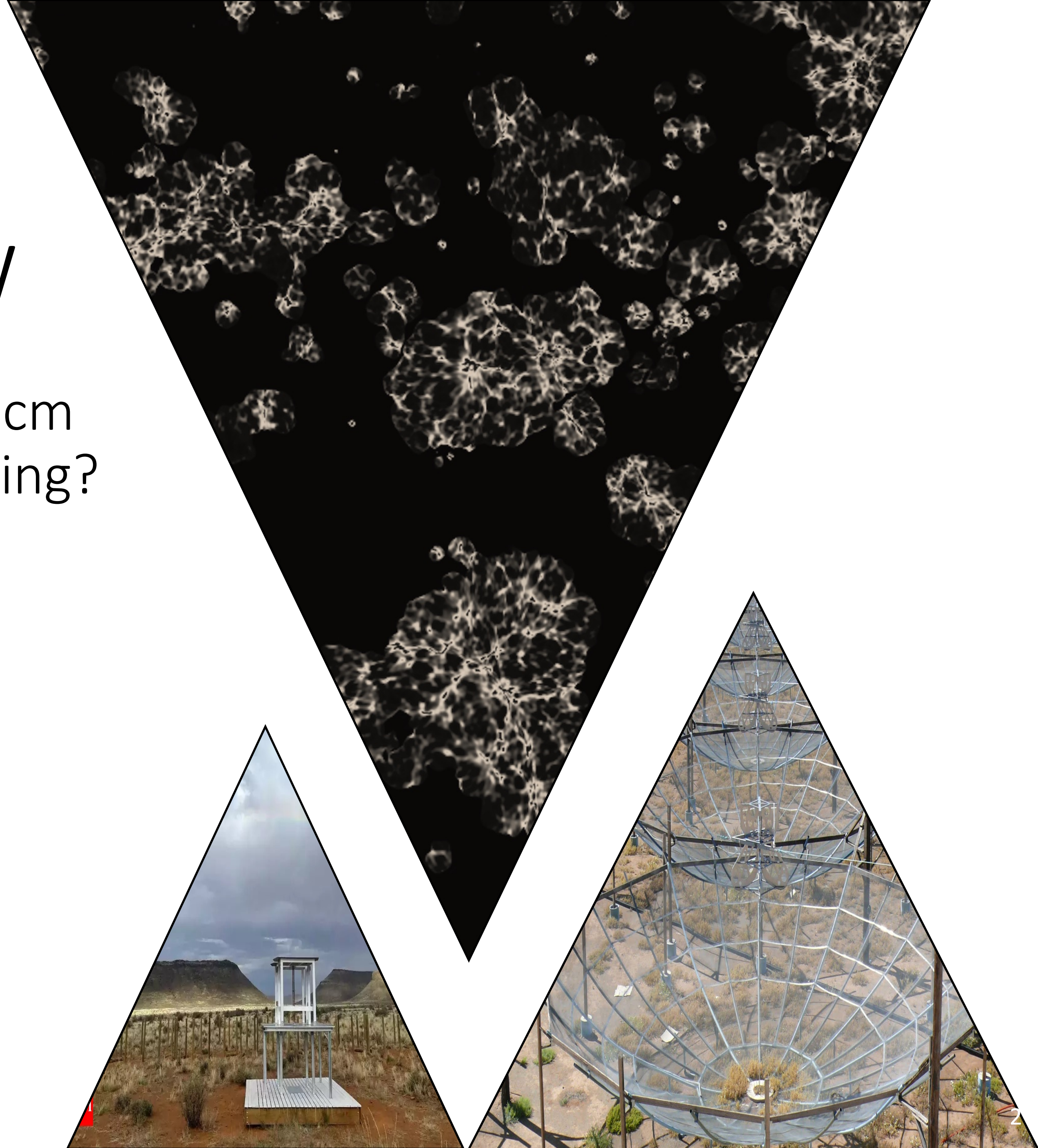
08/07/2024



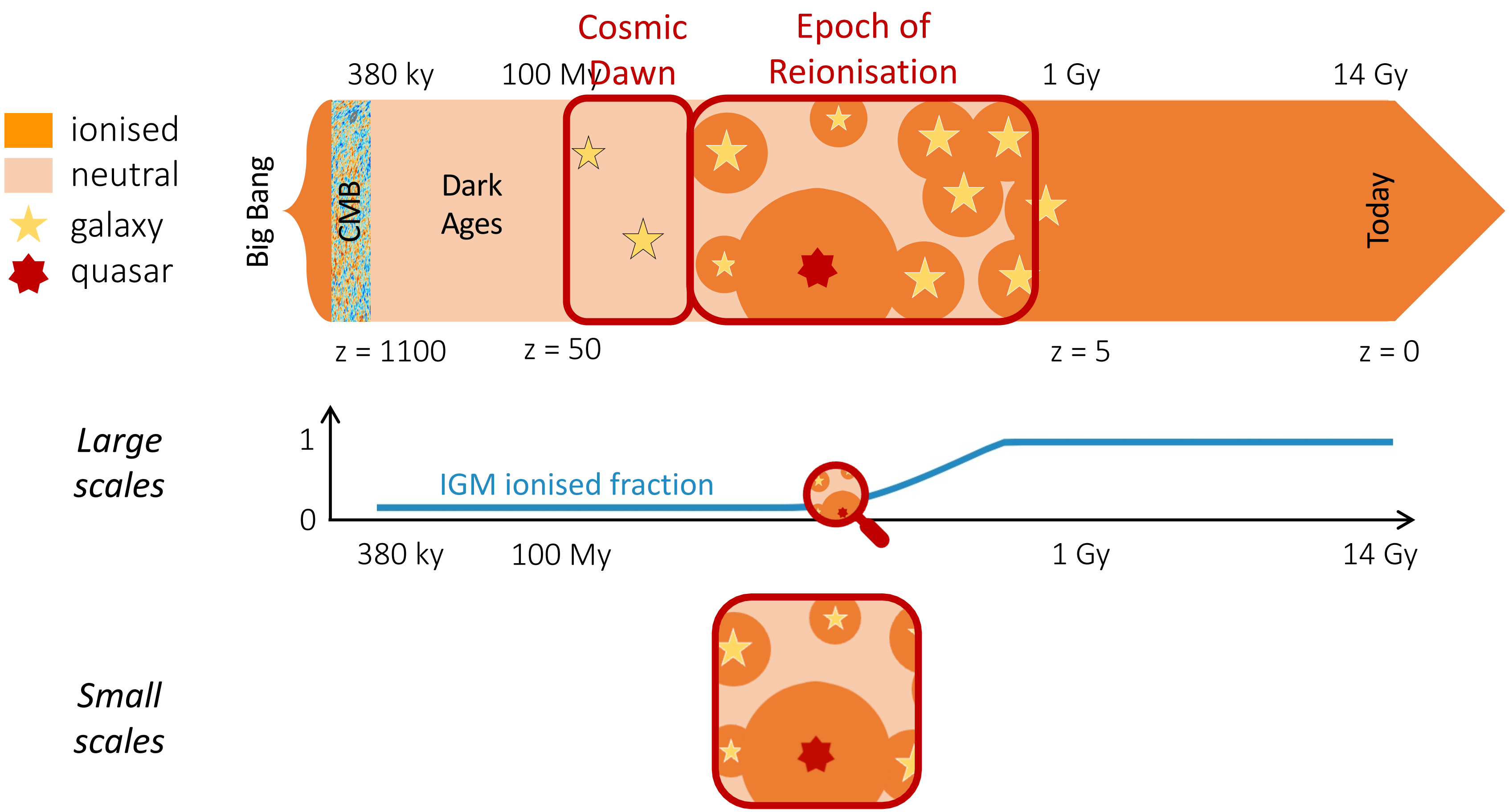
© EMMA simulation, Aubert+2015

OVERVIEW

I. WHY is the 21cm signal interesting?
II. HOW do we measure it?
III. WHEN will we observe it?



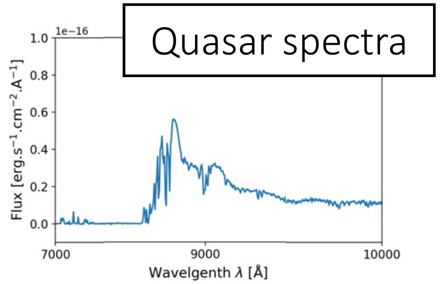
Reionisation & Cosmic Dawn



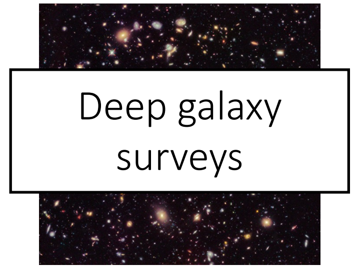
The chronology & topology of reionisation can shed light on the nature of the first stars, the formation of galaxies, the density of the IGM…

Understanding reionisation

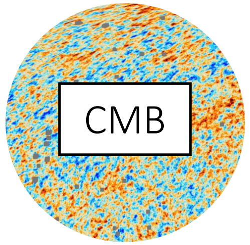
Available data



HI absorption troughs

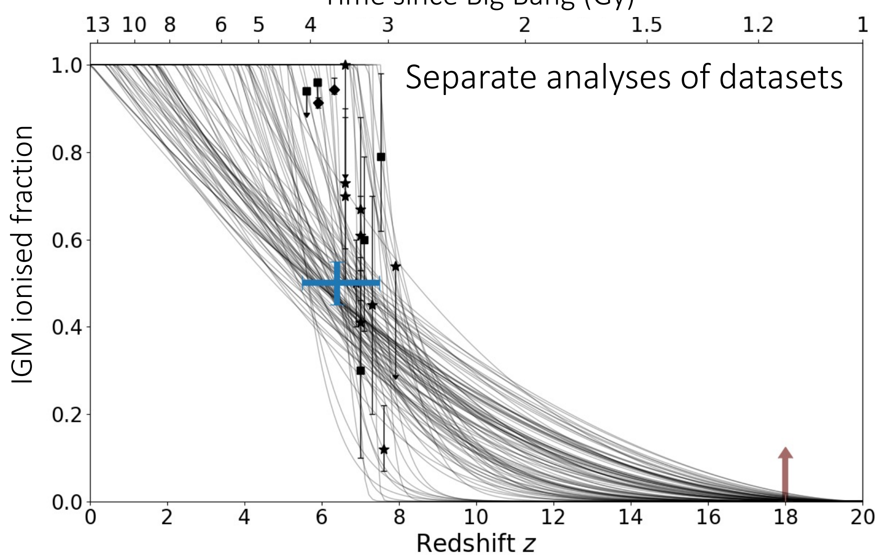


Ionising photons budget



Scattering from free electrons

Current constraints on reionisation history

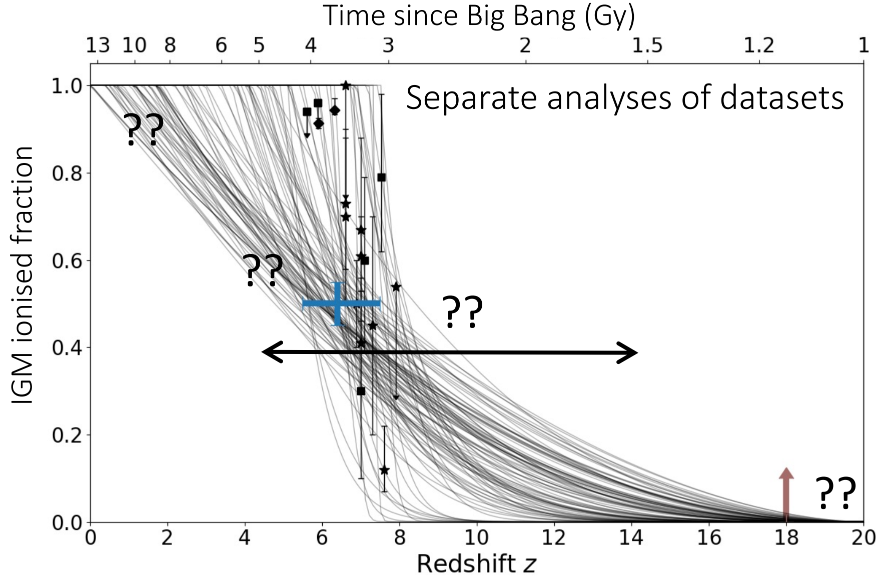


Understanding reionisation

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

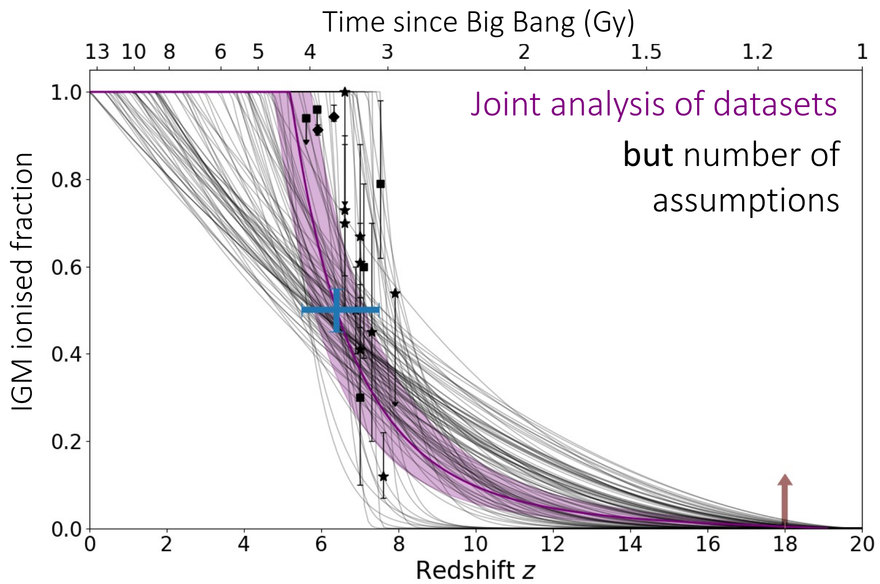
So what do (we think) we know so far?

Not that much…

How can we do better?

1. By combining data sets

Current constraints on reionisation history



See, e.g., Muñoz+2024

Understanding reionisation

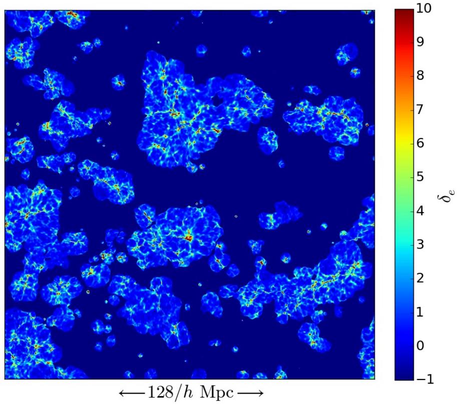
So what do (we think) we know so far?

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

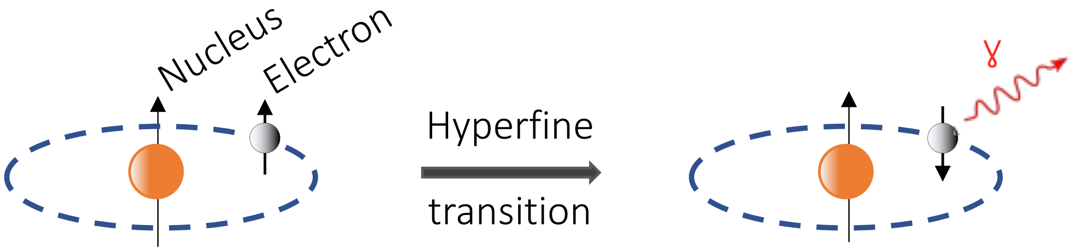
So what do (we think) we know so far?

Not that much…

How can we do better?

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

The 21cm signal



λ = 21 cm
Redshifted to radio frequencies

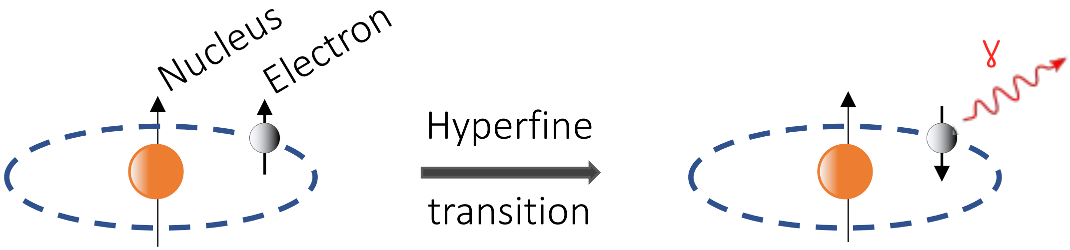
$$\delta T_{\rm b} = T_0(z)\, x_{\rm H_I}\, (1+\delta_{\rm b}) \left[1 - \frac{T_{\rm CMB}}{T_{\rm S}}\right]$$

Neutral H fraction

Baryon density

Pritchard & Loeb 2012

The 21cm signal



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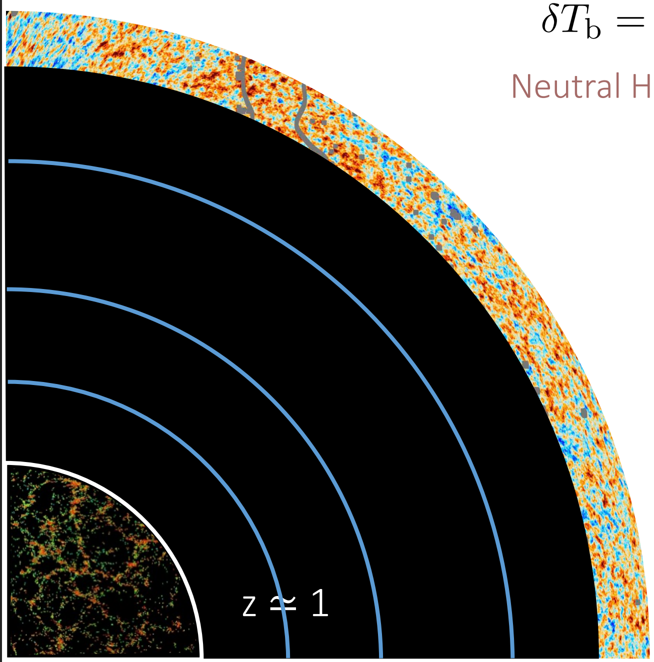


z = 1080

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

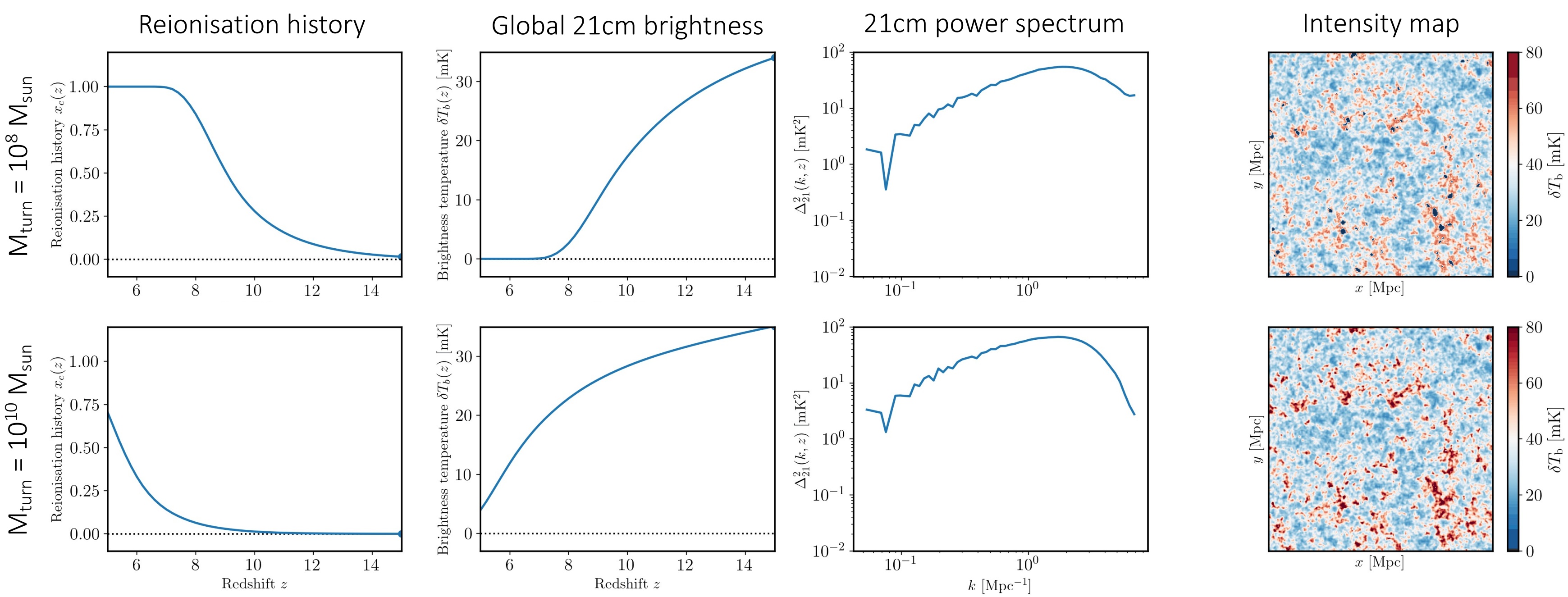
Picture adapted from C. Chiang

The 21cm signal

Why is the 21cm signal interesting?

- It could be measured at any redshift
- It contains information about
  - the global history of reionisation
  - the properties of the early Universe and galaxies

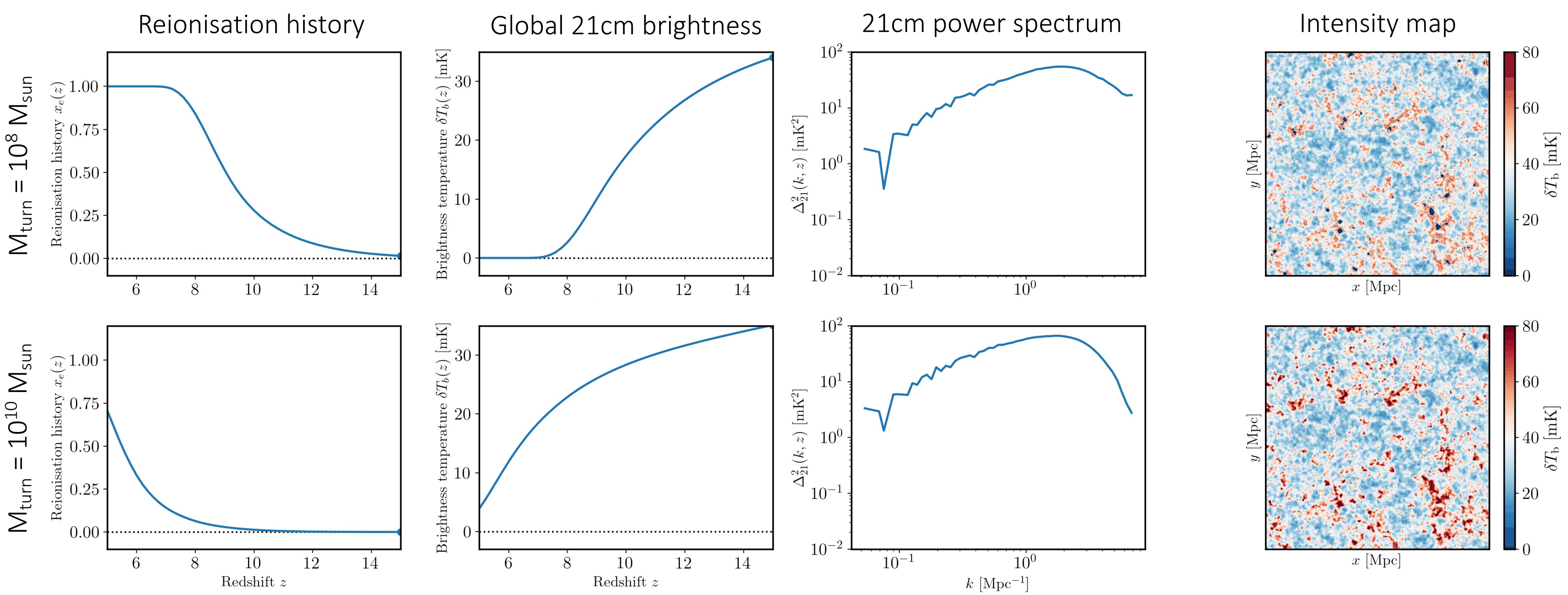
For different minimal halo mass required for the hosted galaxy to produce ionising photons:



The 21cm signal

Why is the 21cm signal interesting?

- ➢ It could be measured at any redshift
- ➢ It contains information about
  - the global history of reionisation
  - the properties of the early Universe and galaxies
- ➢ Its different observables are complementary



The 21cm signal

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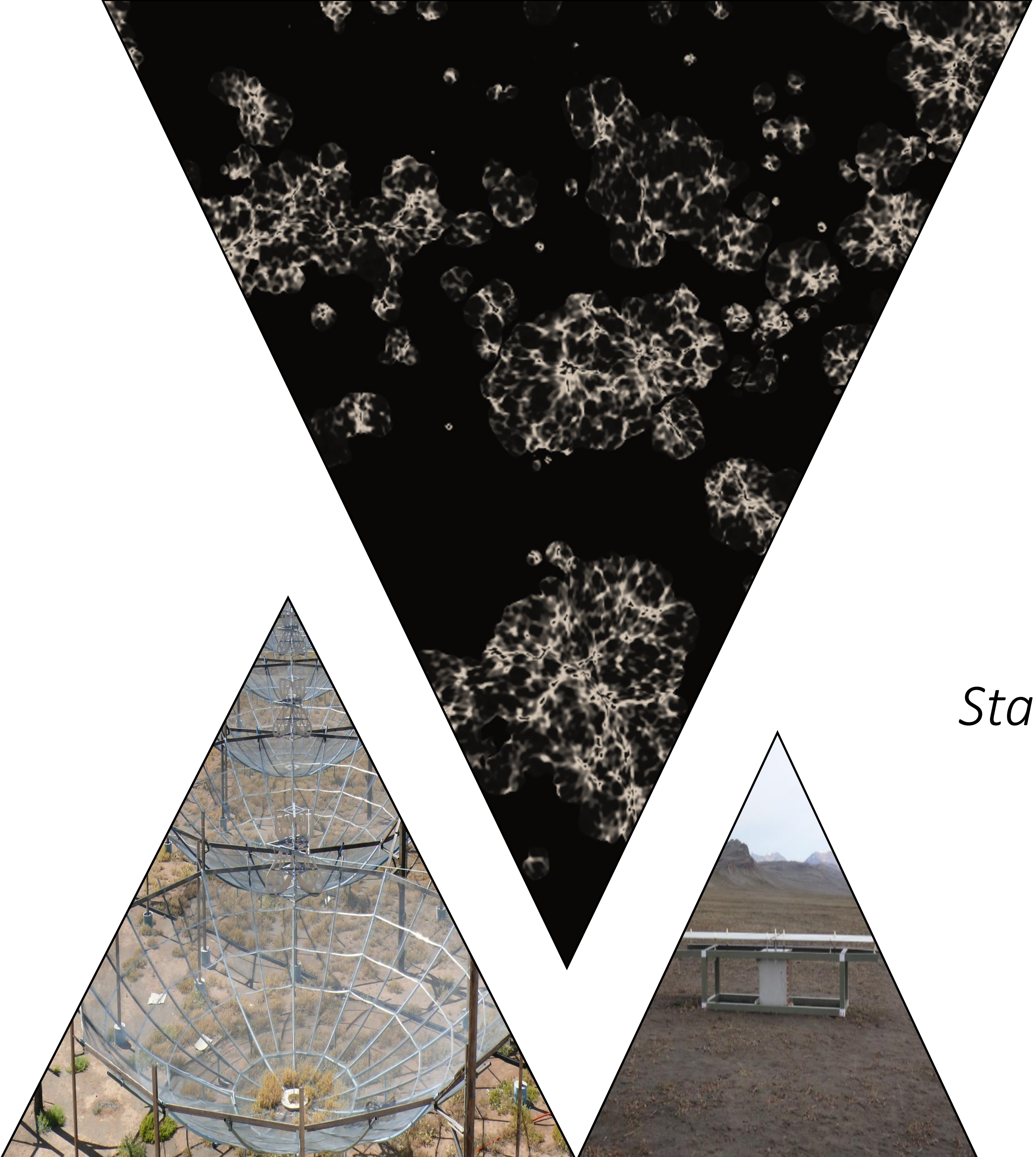
And a lot more

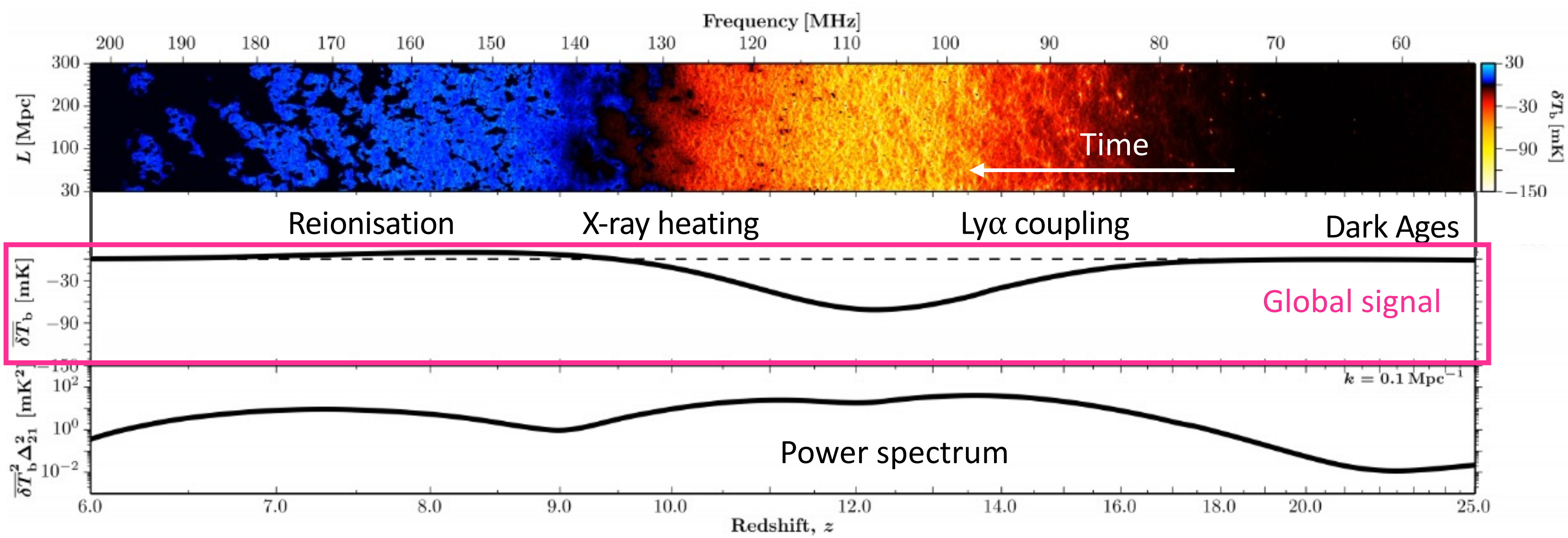
- Cosmology
- Cosmic strings
- Beyond the standard model
- Cosmic heating
- …

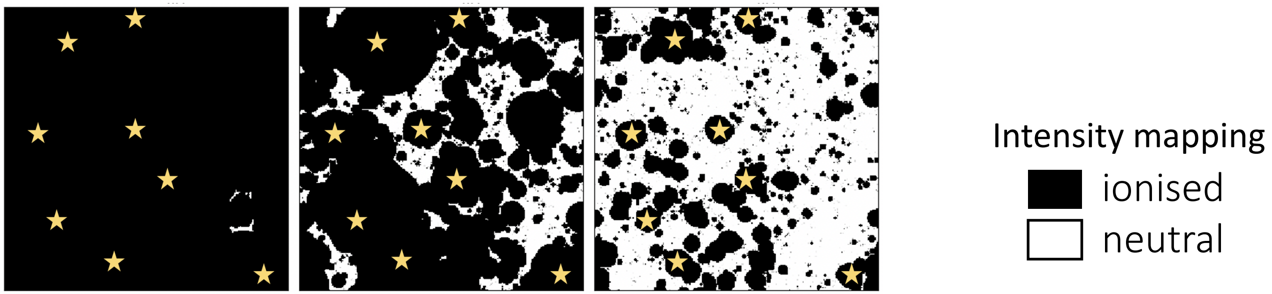


HOW?

Status of high-redshift 21cm observations

The 21cm signal

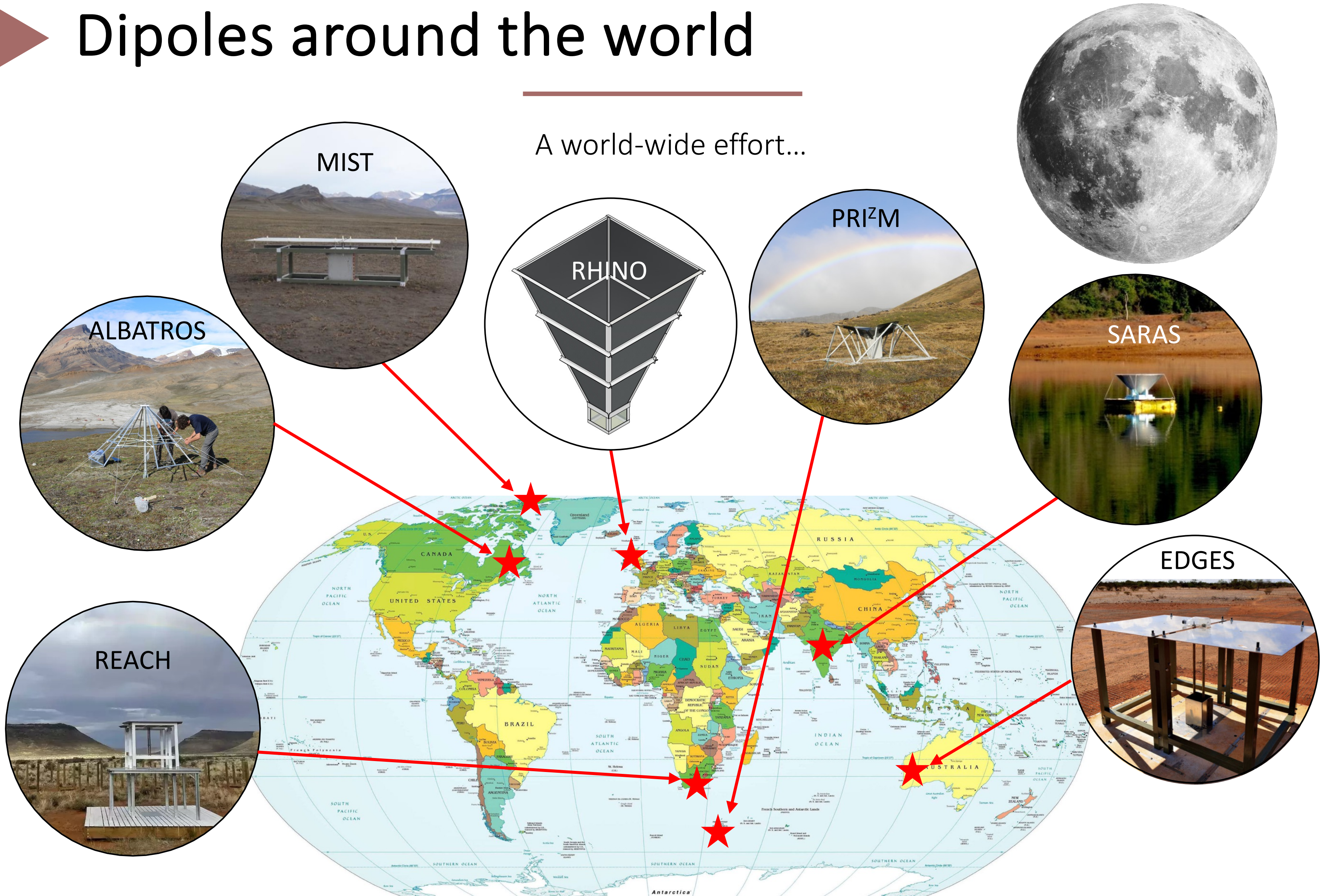




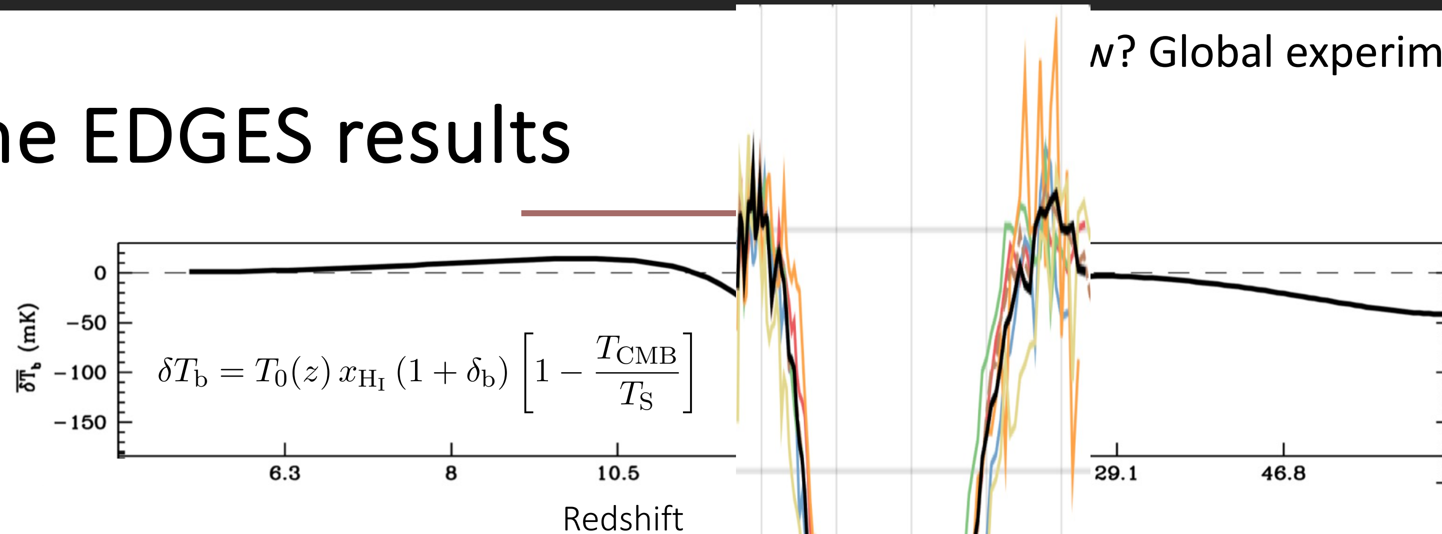
21CMFAST, Mesinger+2016

Dipoles around the world

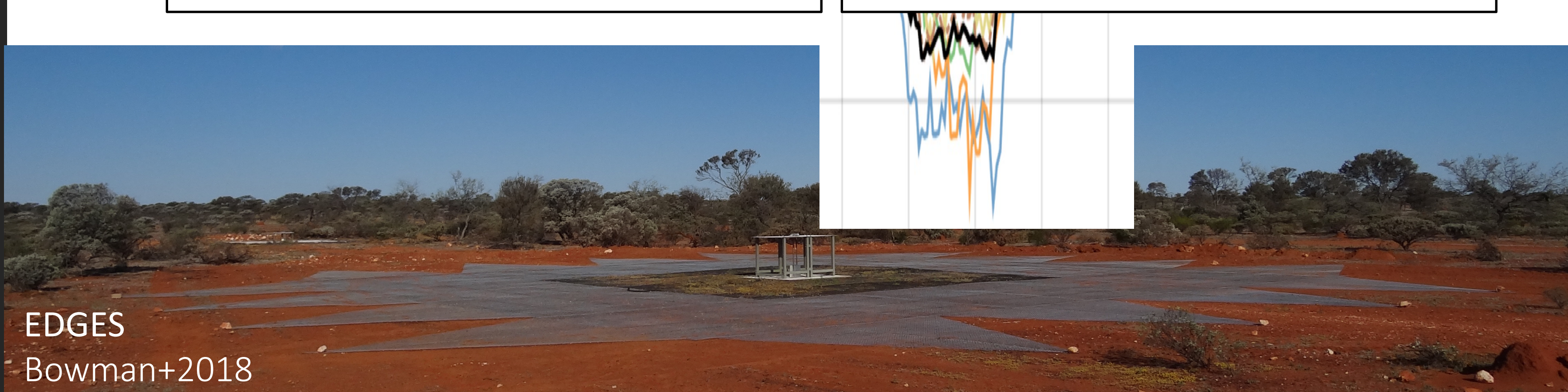
A world-wide effort…



The EDGES results



Amplitude	Shape
○ IGM cooled down by dark matter (e.g., Barkana+2018) ○ Very early radio-loud quasars (e.g., Ewall-Wice+2018) ○ Systematics (e.g., Singh+2019)	○ Extremely efficient star formation (e.g., Mirocha & Furlanetto 2019)

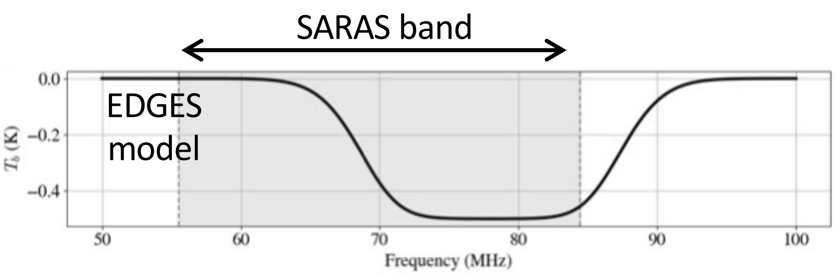


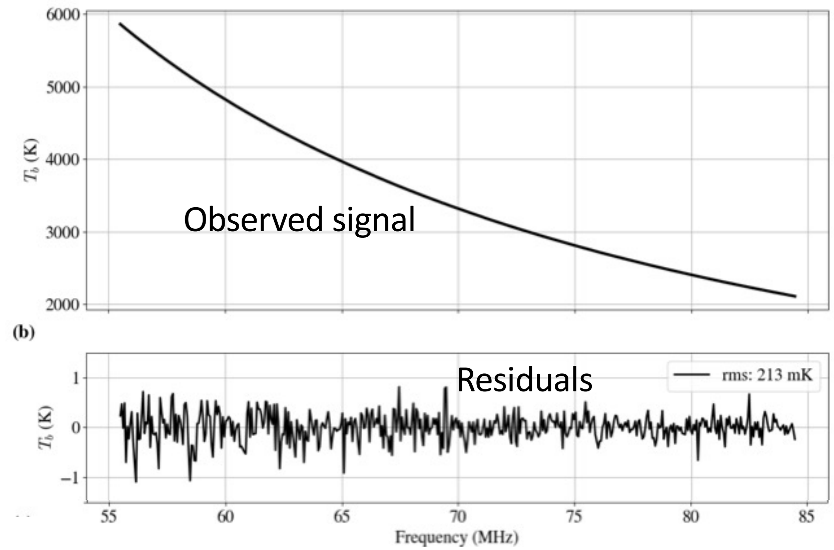
SARAS results

No evidence of the signal in the SARAS data

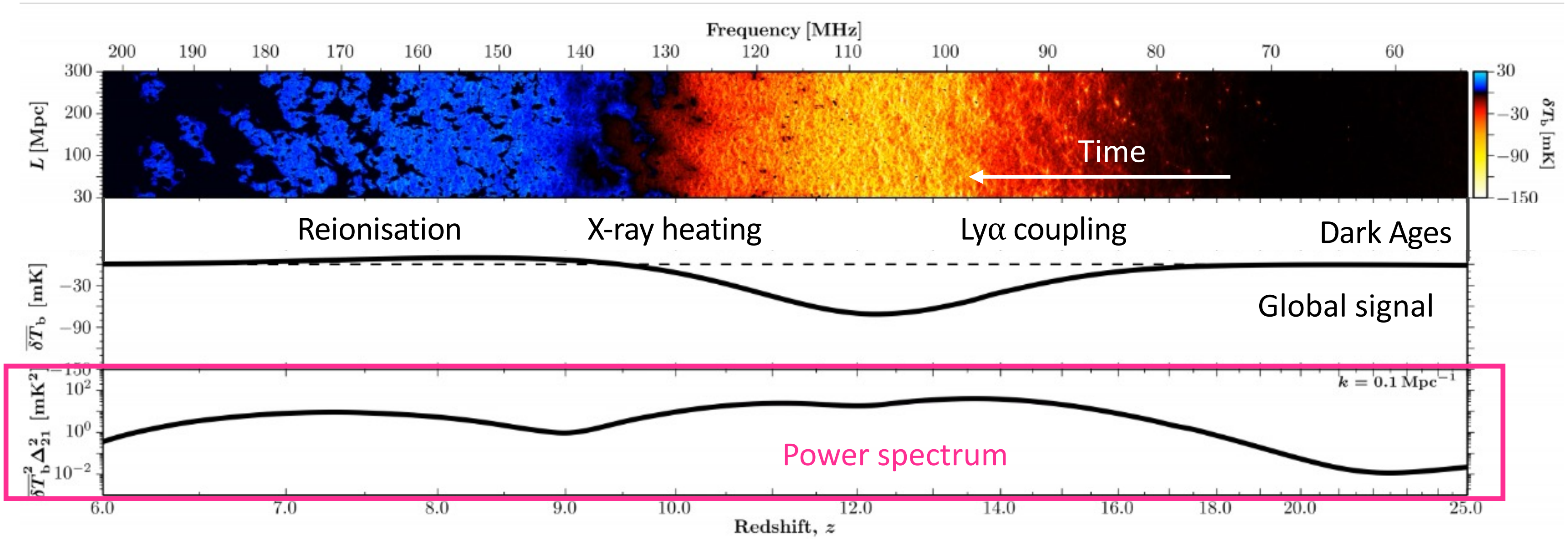
Systematic-related origin of the EDGES signal: rules out best-fit at 95%

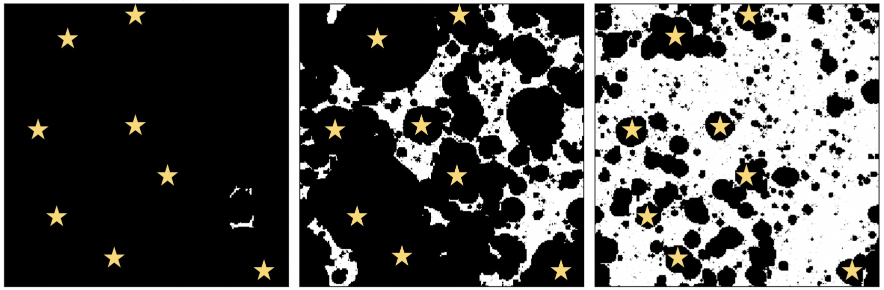
⚠ Smaller bandwidth





The 21cm signal



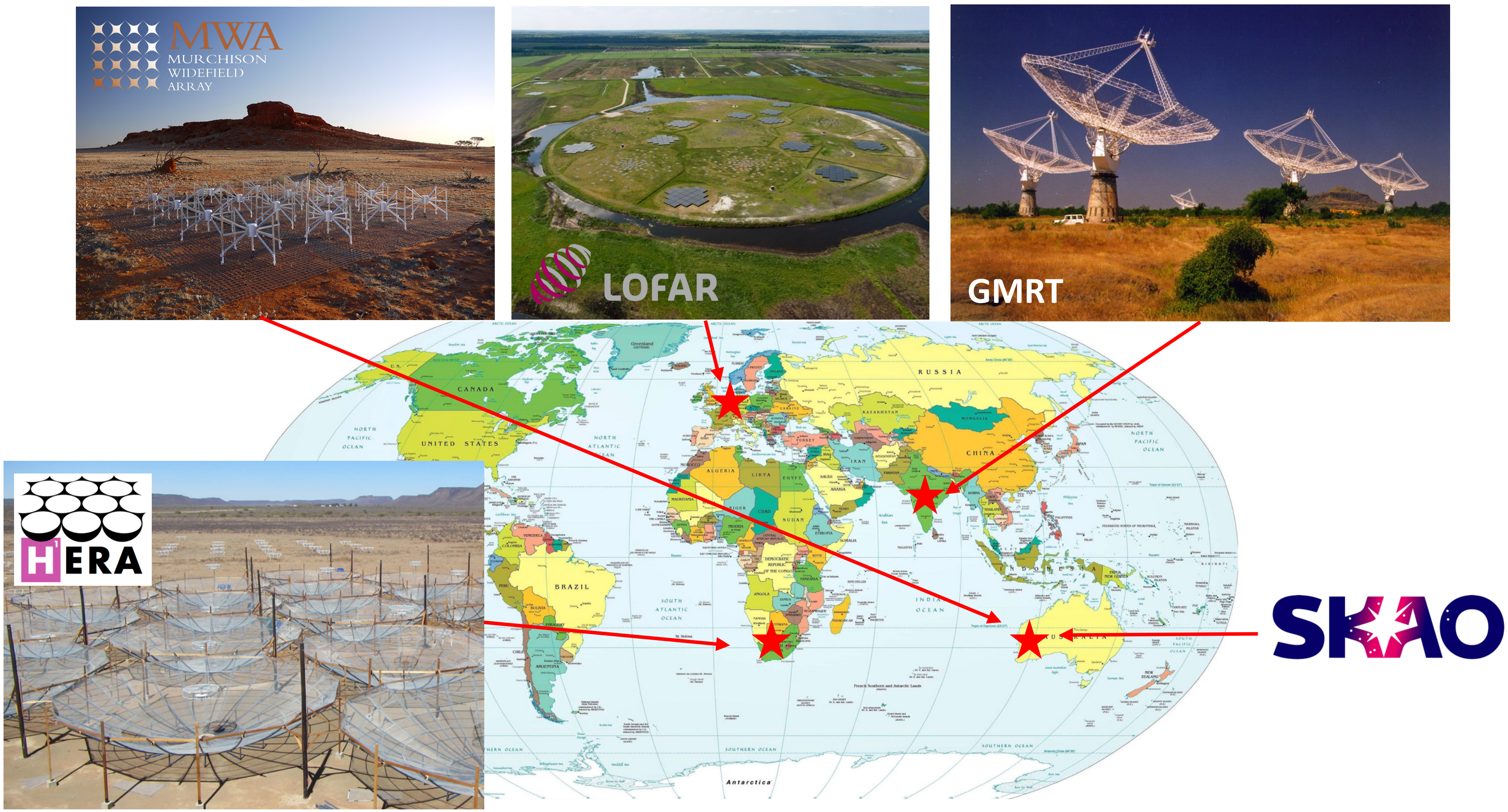


Intensity mapping
- ionised
- neutral

21CMFAST, Mesinger+2016

Radio interferometers around the world

A world-wide effort…

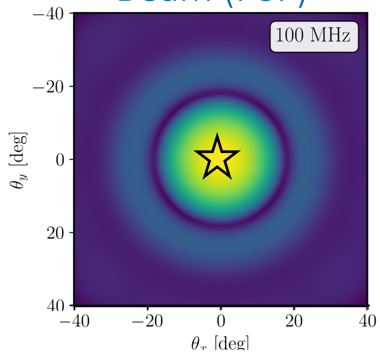


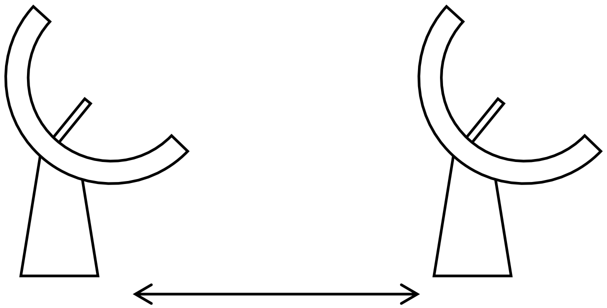
Interferometry 101

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

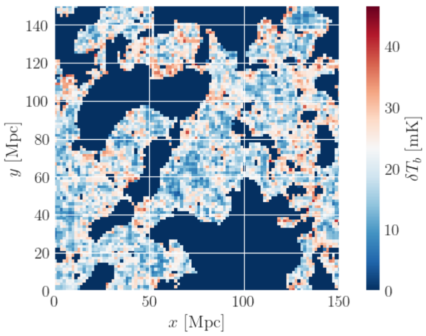
$$V_{ij}(\nu) = \int B_{ij}(\hat{\mathbf{r}}, \nu) I(\hat{\mathbf{r}}, \nu) \exp\left[-2\pi i \frac{\nu}{c} \mathbf{b}_{ij} \cdot \hat{\mathbf{r}}\right] d\Omega$$

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: $\widehat{P}(\boldsymbol{k}) \propto \left\langle \left| \widetilde{V}_{ij}(\nu) \right|^2 \right\rangle$

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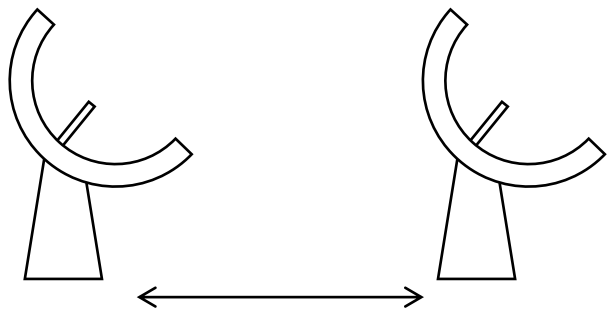
HERA



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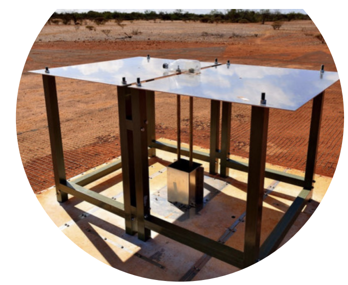
EDGES



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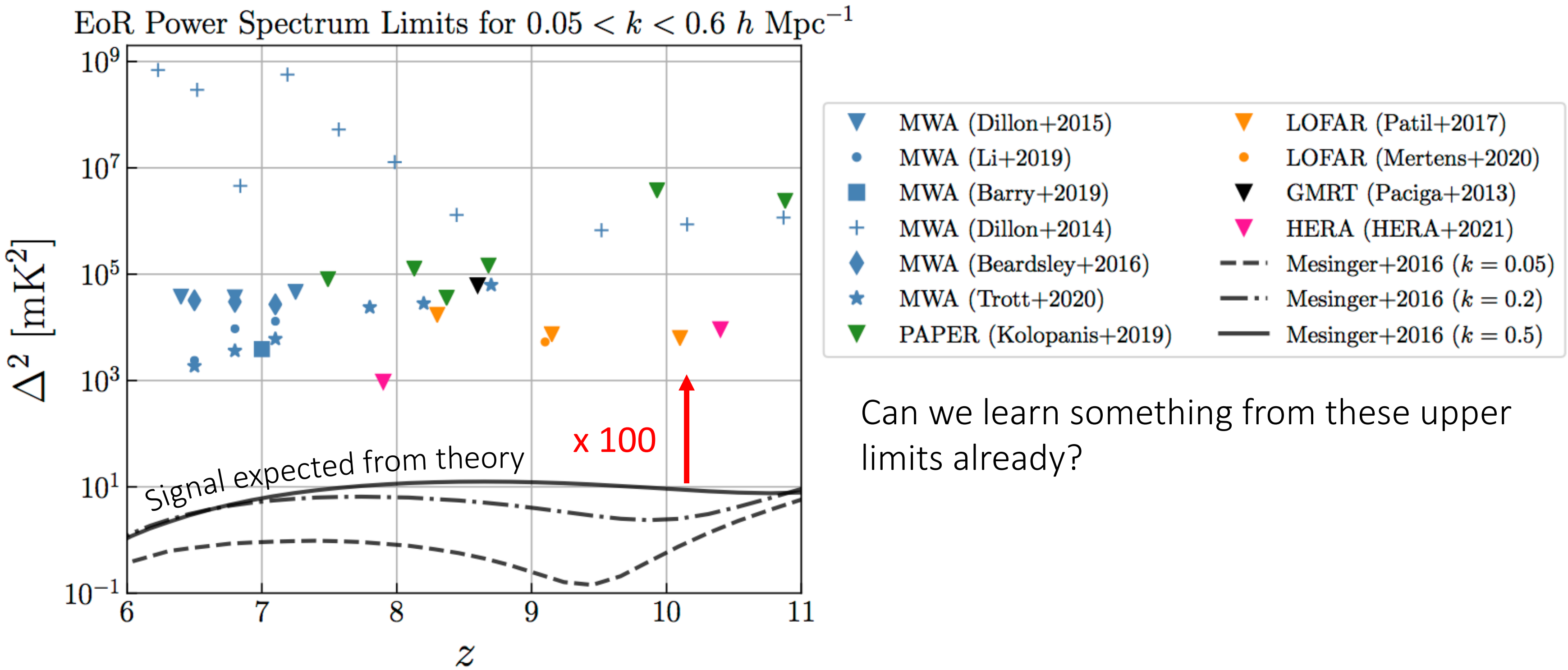
- Dense arrays measure large-scale fluctuations (e.g. EDGES' "table")
- Wide arrays measure small-scale fluctuations (e.g. HERA)

Current upper limits on the power spectrum

… which has only led to upper limits so far.



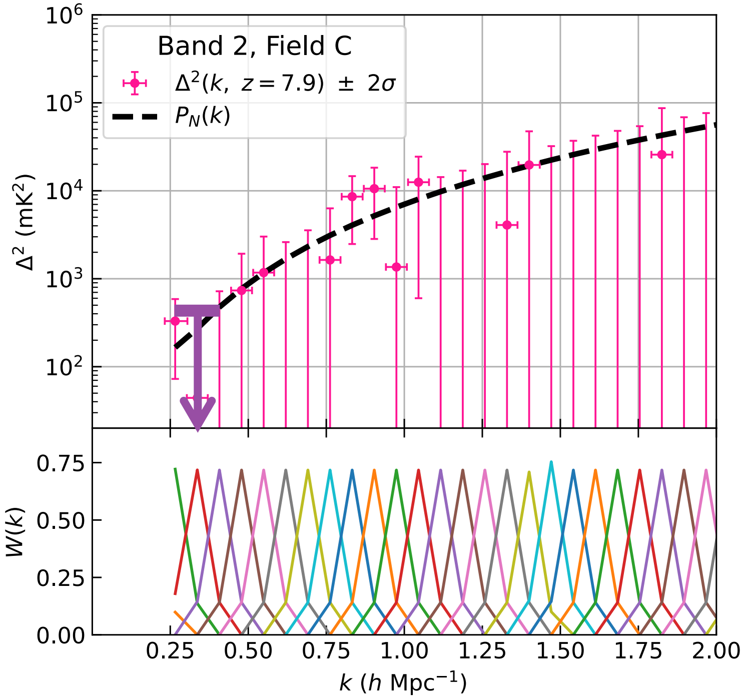
Can we learn something from these upper limits already?

Barry+2022

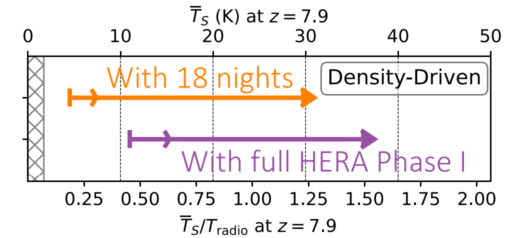
Current upper limits on the power spectrum

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

HERA



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



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

HERA collab et al. 2023

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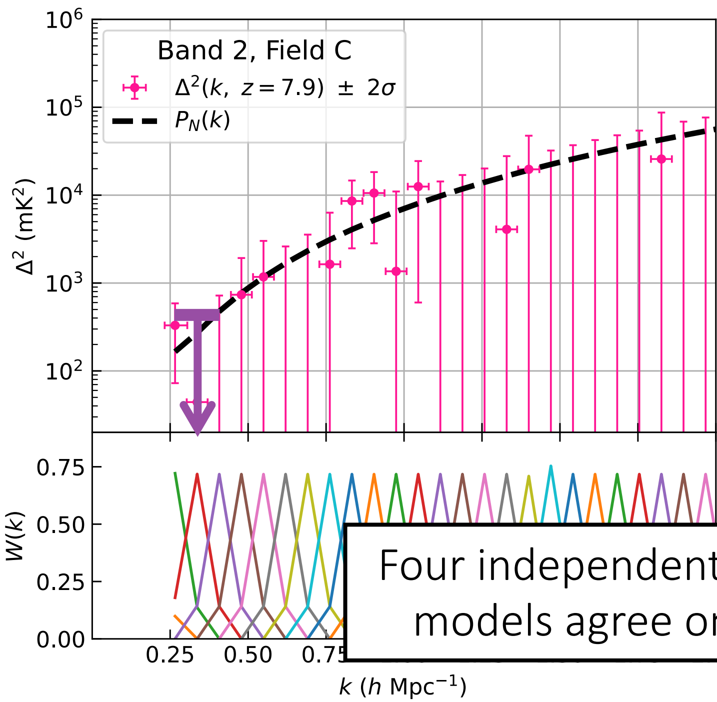
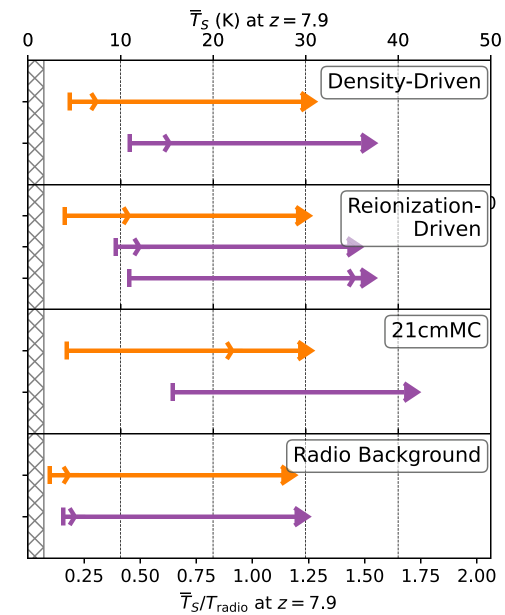
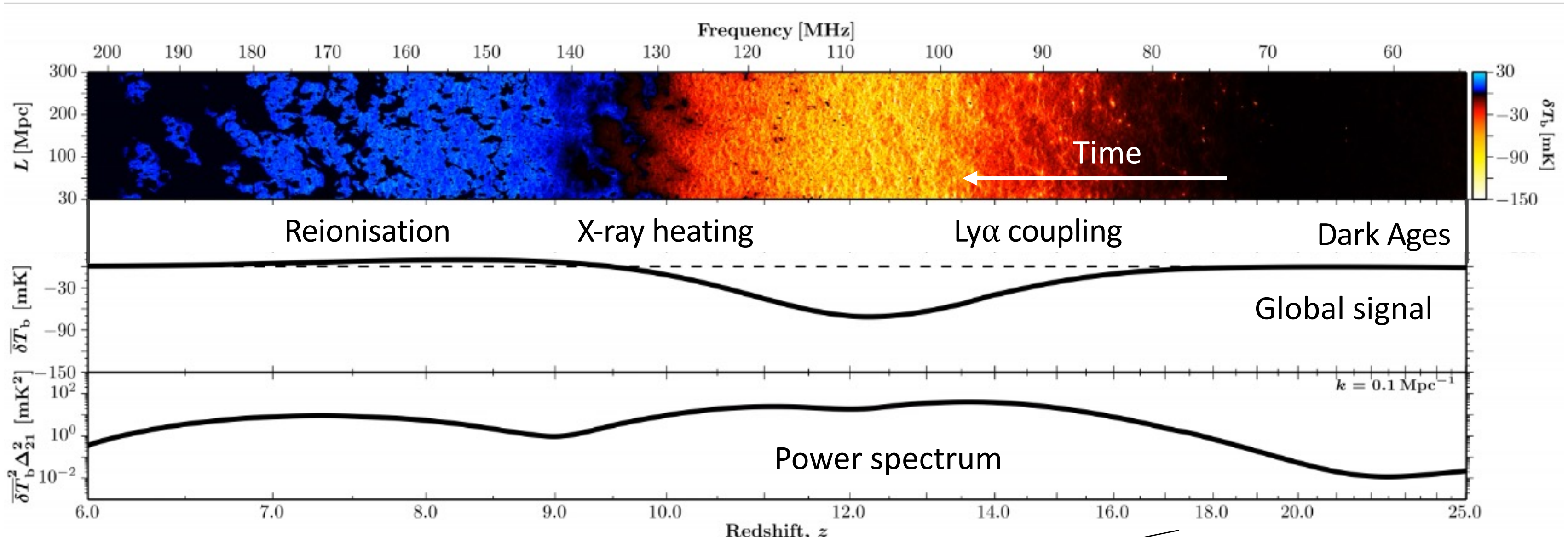


Four independent theory models agree on this.

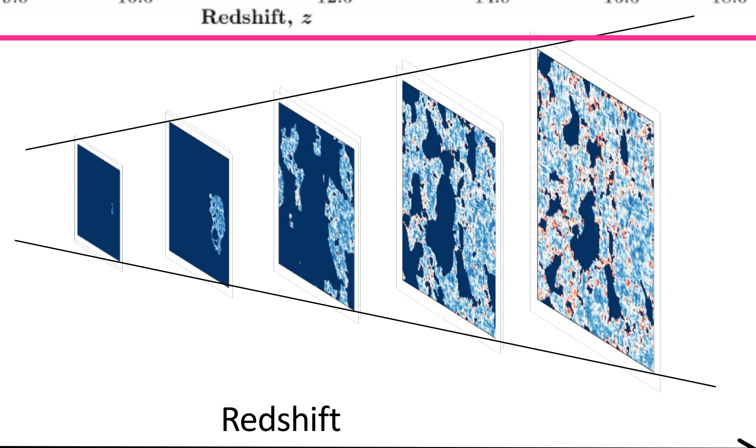


HERA collab et al. 2023

The 21cm signal

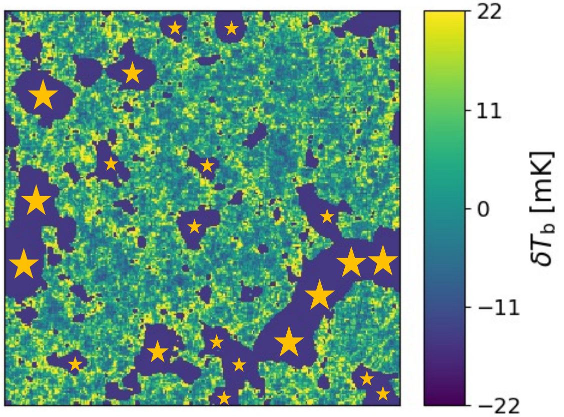


Intensity mapping

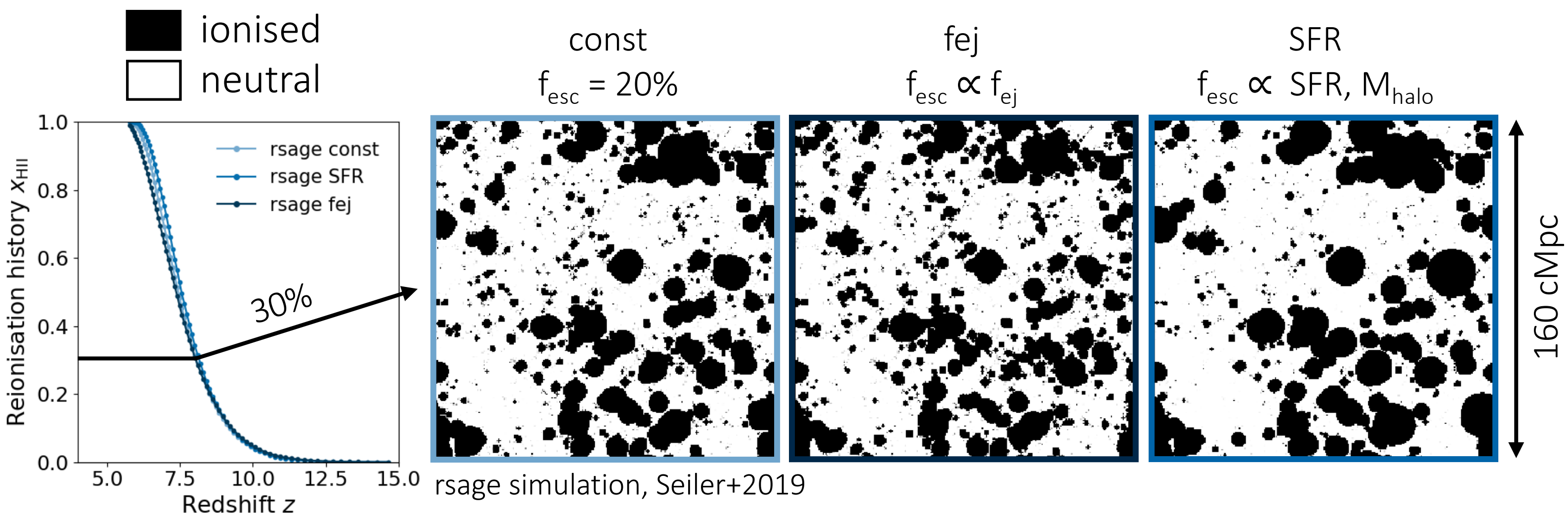


Why intensity mapping?

- 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

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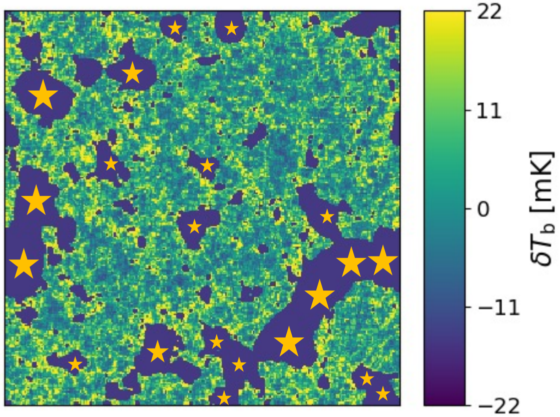
- Effort in developing efficient tools to analyse these datasets to
  - Constrain reionisation and galaxy properties
  - Tackle huge data volumes
  - Complement PS analyses (ex: non-Gaussianity)



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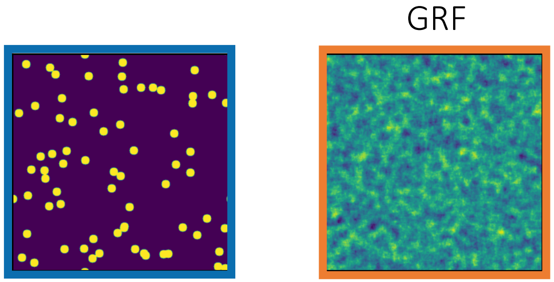

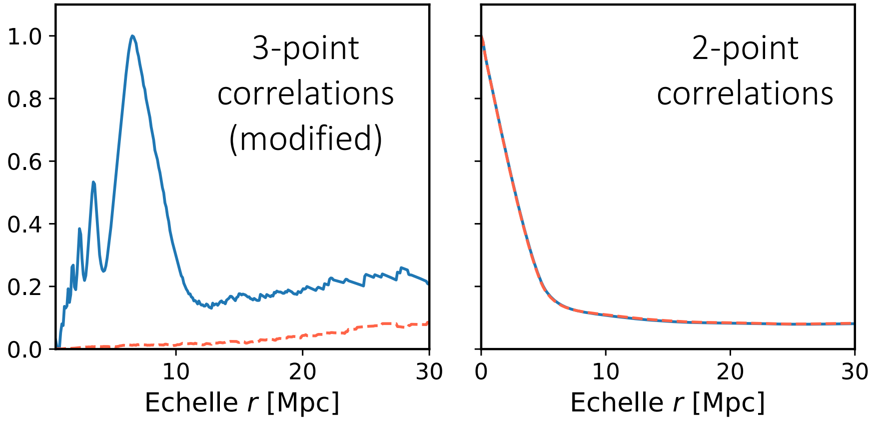

Gorce & Pritchard 2019

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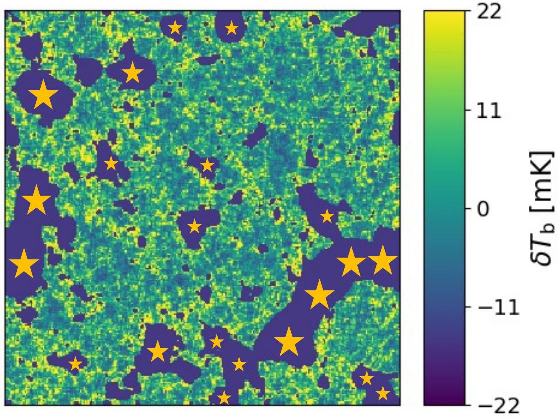
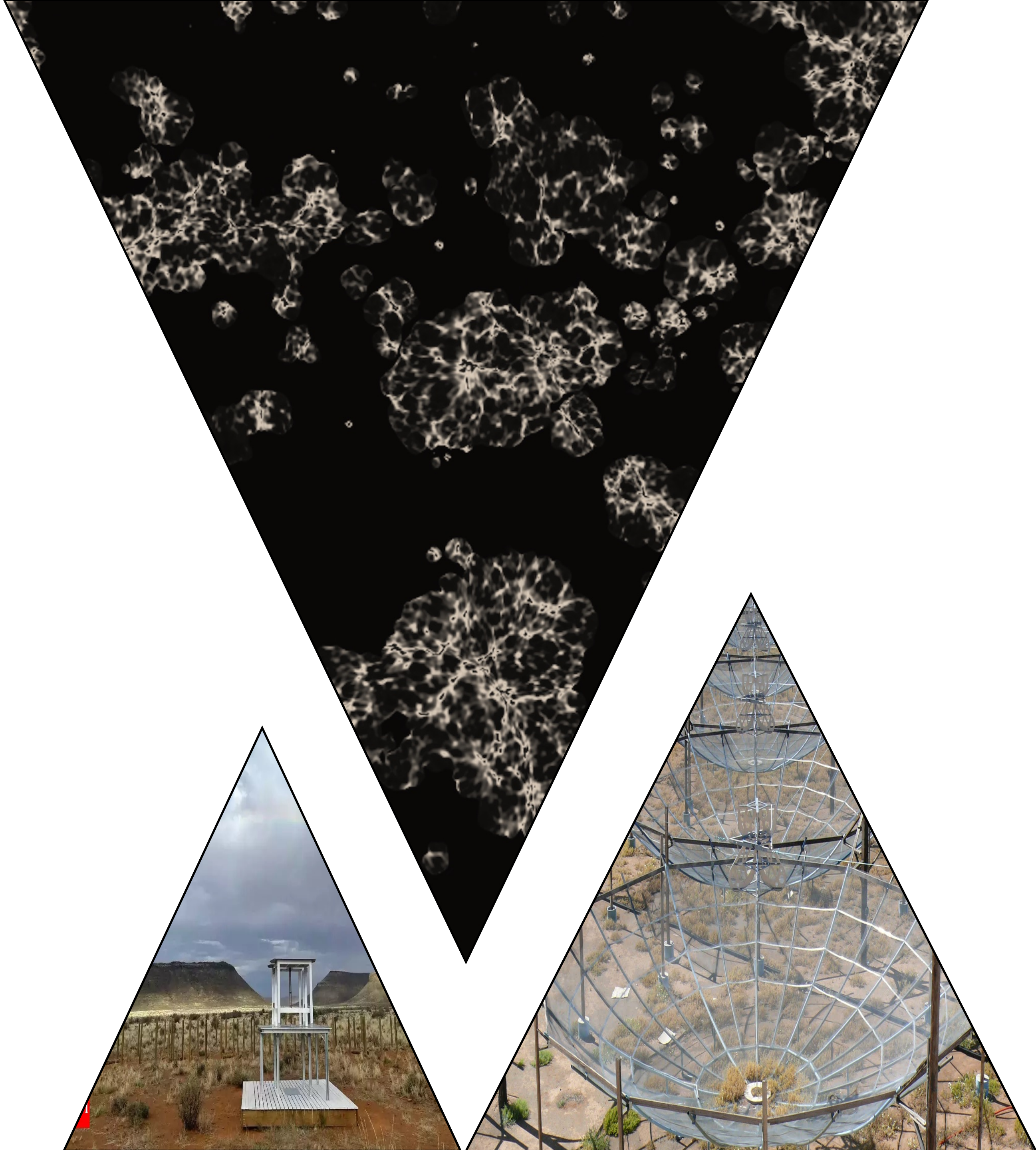


21cm intensity map
(21CMFAST simulation)

- 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)

WHEN?

What is standing between us and detection



Observing the 21cm signal

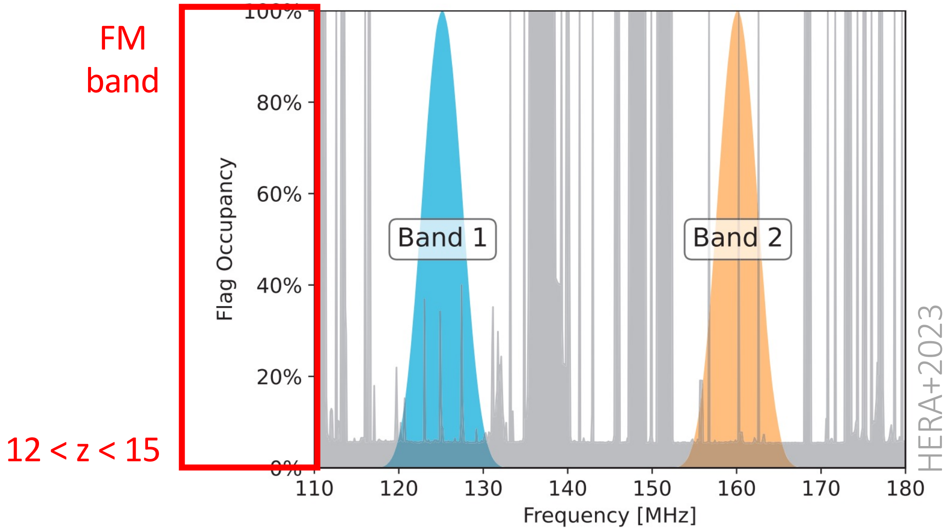
What we're doing:
Looking for the signal emitted by neutral hydrogen over 13by ago.

Why is it difficult?

Slide adapted from Lisa McBride's

Problem: RFI

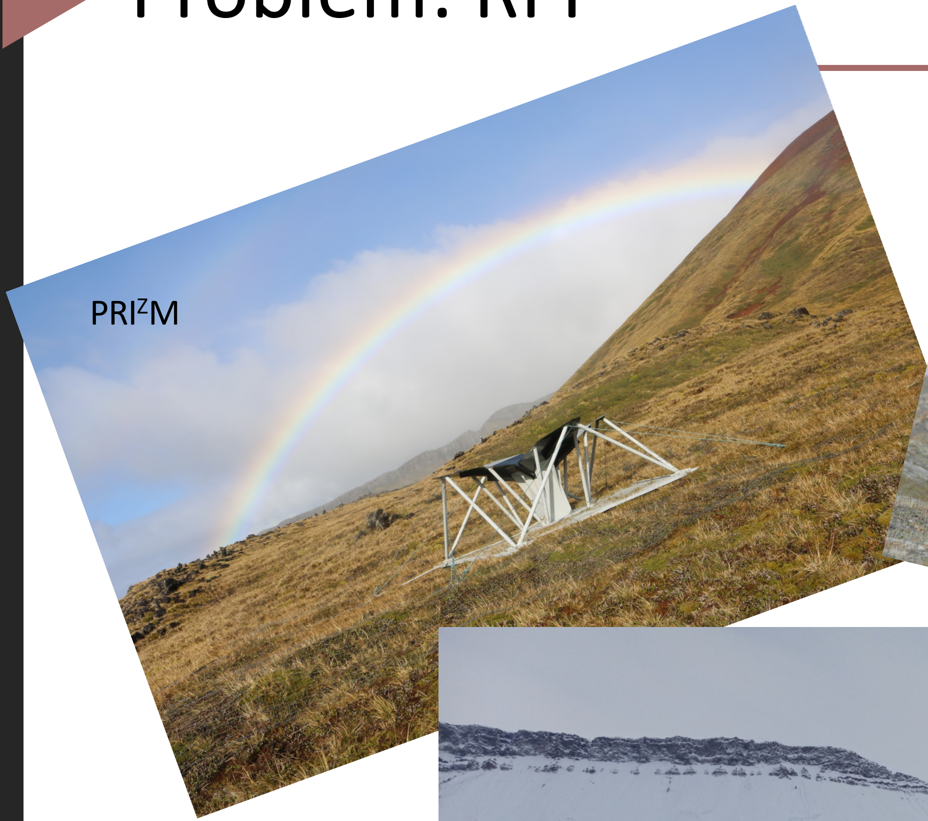
Most of the target frequency band is polluted by human emission: aviation communications, FM radio, radars, … these are called **radio frequency interference (RFI)**

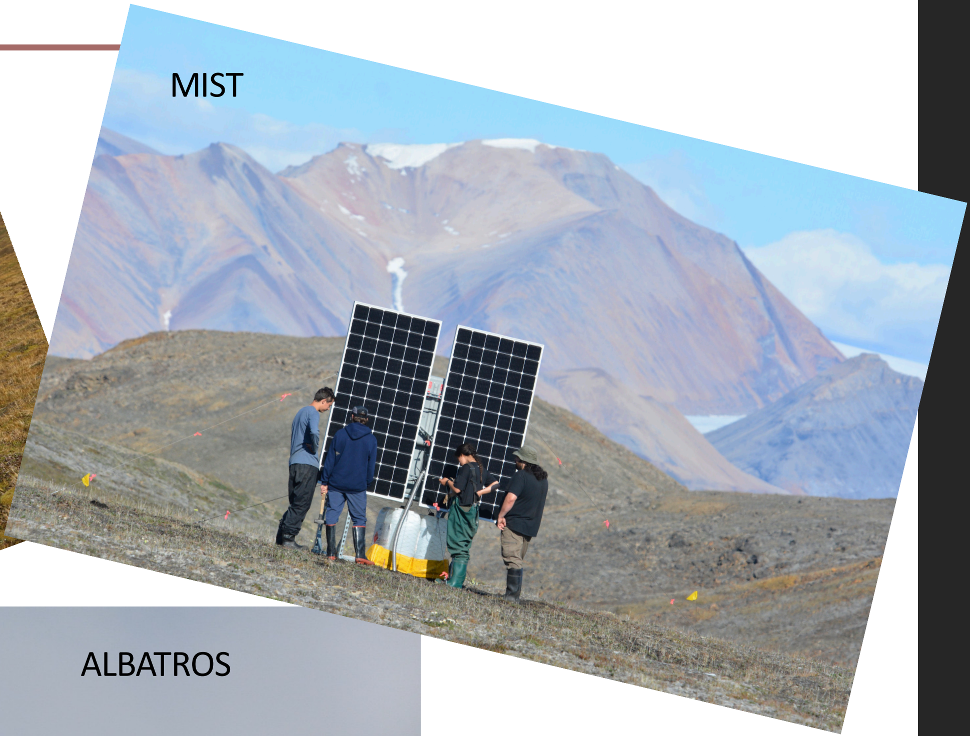


Even the faintest outside signal is measured by our extremely sensitive telescopes
→ limits the amount of data we can analyse

HERA collab+2023

Problem: RFI





Problem: Data volumes

Interferometers gather huge data volumes.

For one season of HERA:

- 160 nights
- 8hr night
- 1536 channels (frequencies)
- Every 10.7 s
- 2 antenna polarisations
- 350 antennas = 122 150 baselines

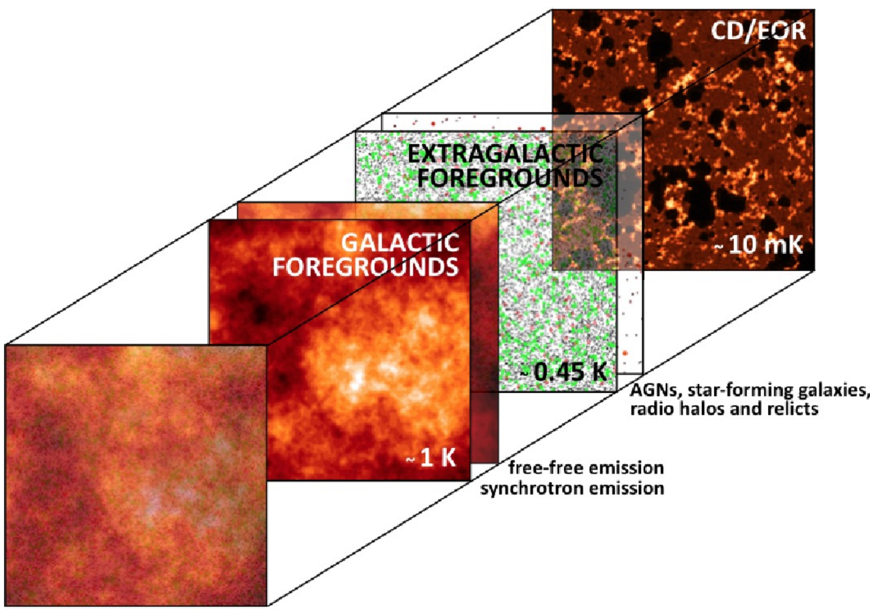
= 926 078 803 738 measurements (or **170TB of data**)

Some of this raw data must be processed *on-site* but without producing RFI.

Problem: Foregrounds

Extremely bright foregrounds lie between the first stars and us and dominate the observed sky

- Amplitude of the cosmological signal = 10 mK
- Amplitude of the foregrounds = 1 000 to 10 000 mK



All foreground treatment methods rely on the assumption that ***foregrounds are spectrally smooth***

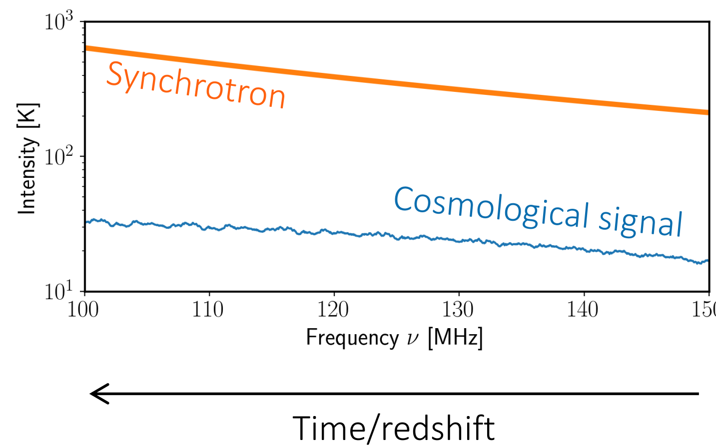


Figure by Vibor Jelic

Problem: Foregrounds

Extremely bright foregrounds lie between the first stars and us and dominate the observed sky. All foreground treatment methods rely on the assumption that ***foregrounds are spectrally smooth***

- Foreground removal (e.g., Chapman+2013, Mertens+2020)
- Foreground avoidance (e.g., Parsons+2012, Liu+2014)

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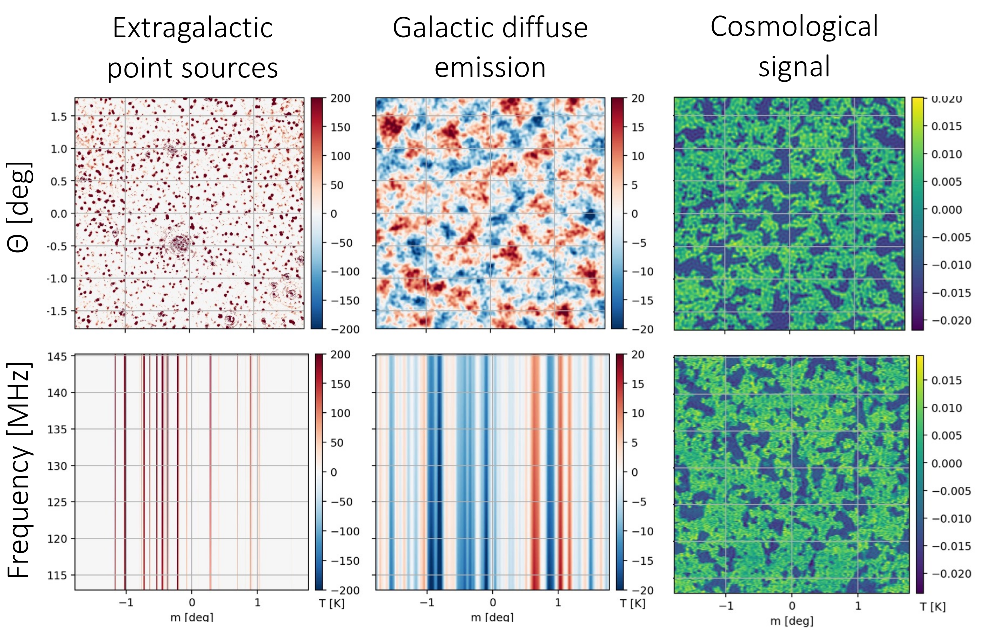
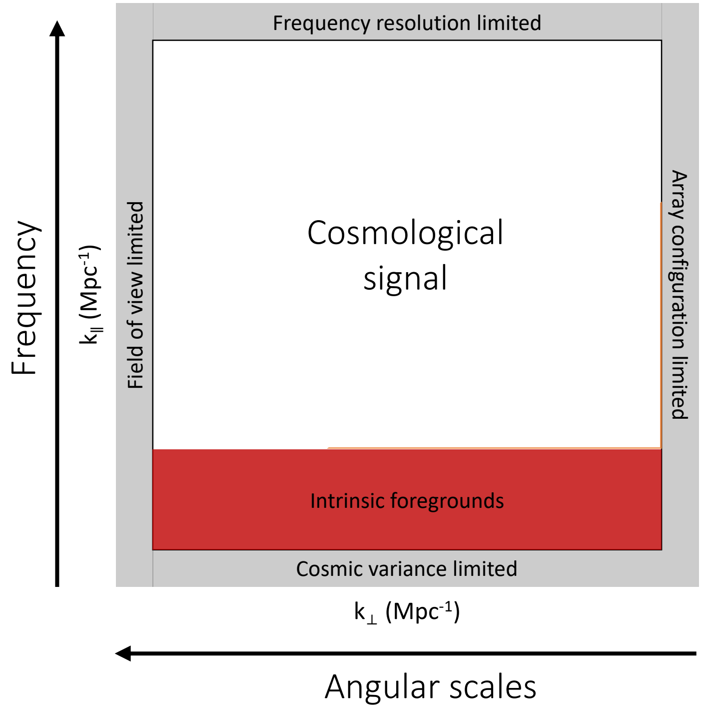


Figure by Florent Mertens

Cylindrical power spectrum



Problem: Foregrounds

Extremely bright foregrounds lie between the first stars and us and dominate the observed sky. All foreground treatment methods rely on the assumption that ***foregrounds are spectrally smooth***

- Foreground removal (e.g., Chapman+2013, Mertens+2020)
- Foreground avoidance (e.g., Parsons+2012, Liu+2014)

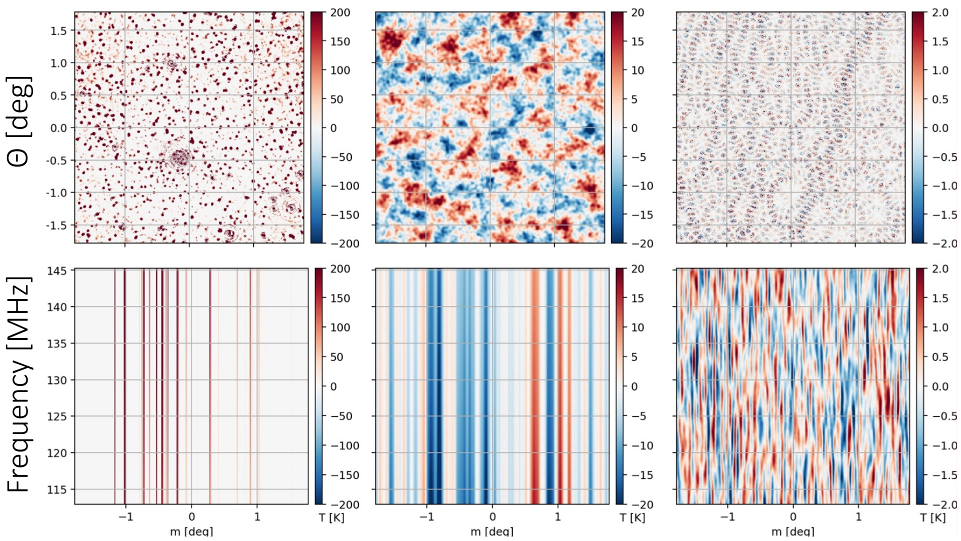
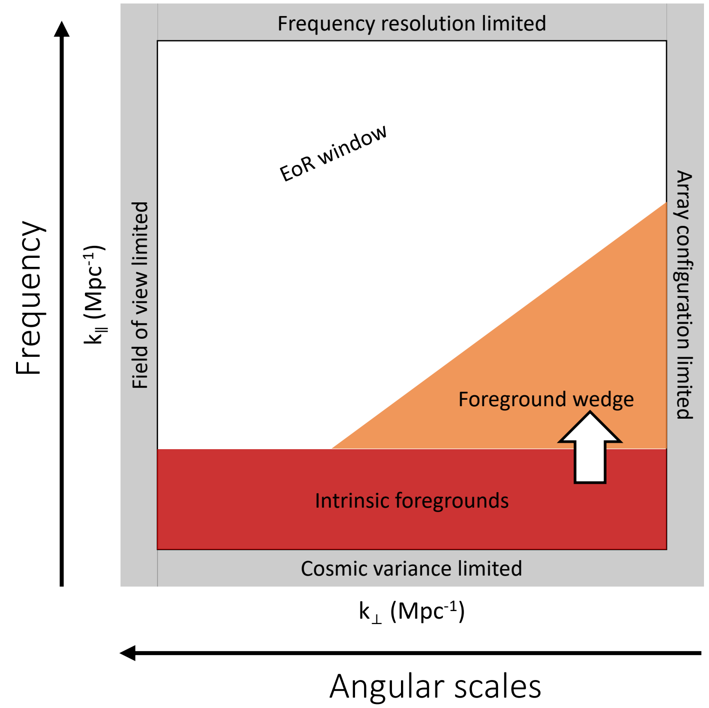


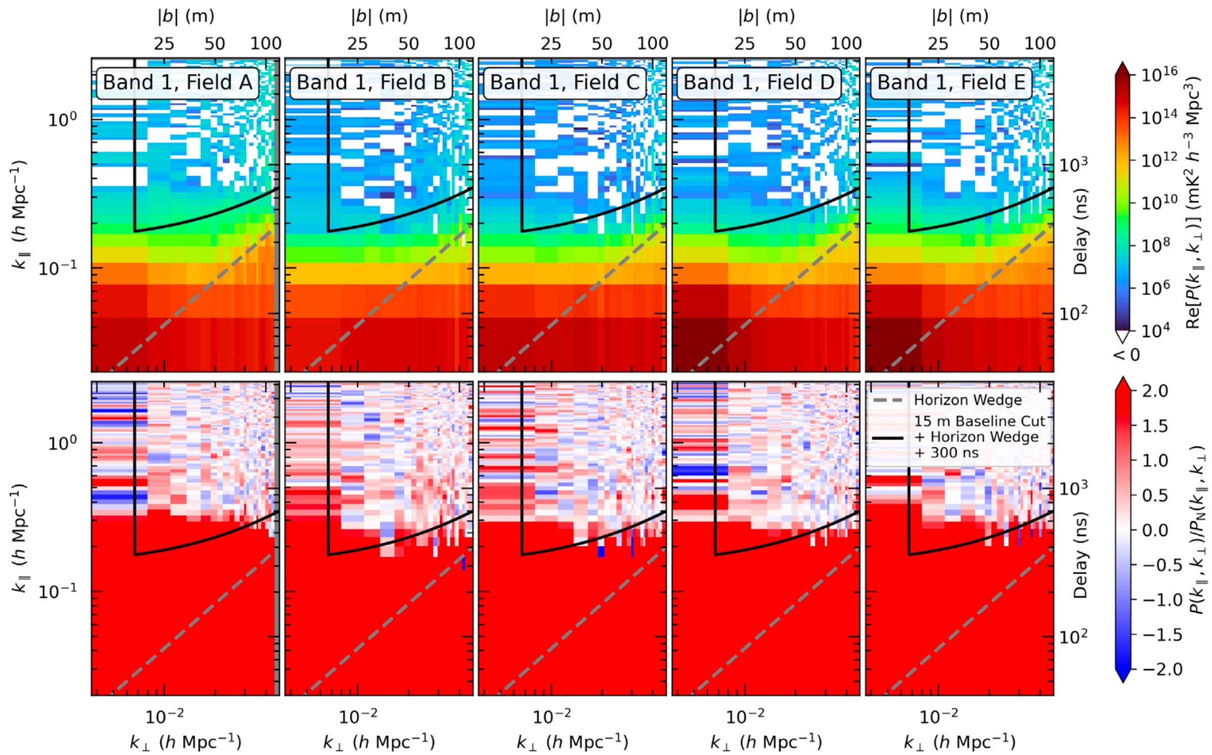
Figure by Florent Mertens

Cylindrical power spectrum



Problem: Foregrounds

Extremely bright foregrounds lie between the first stars and us and dominate the observed sky. All foreground treatment methods rely on the assumption that ***foregrounds are spectrally smooth*** but the chromaticity of the instrument introduces spectral structure and biases.



- - Foreground wedge (horizon)

— Buffer + short baselines

z = 10.4

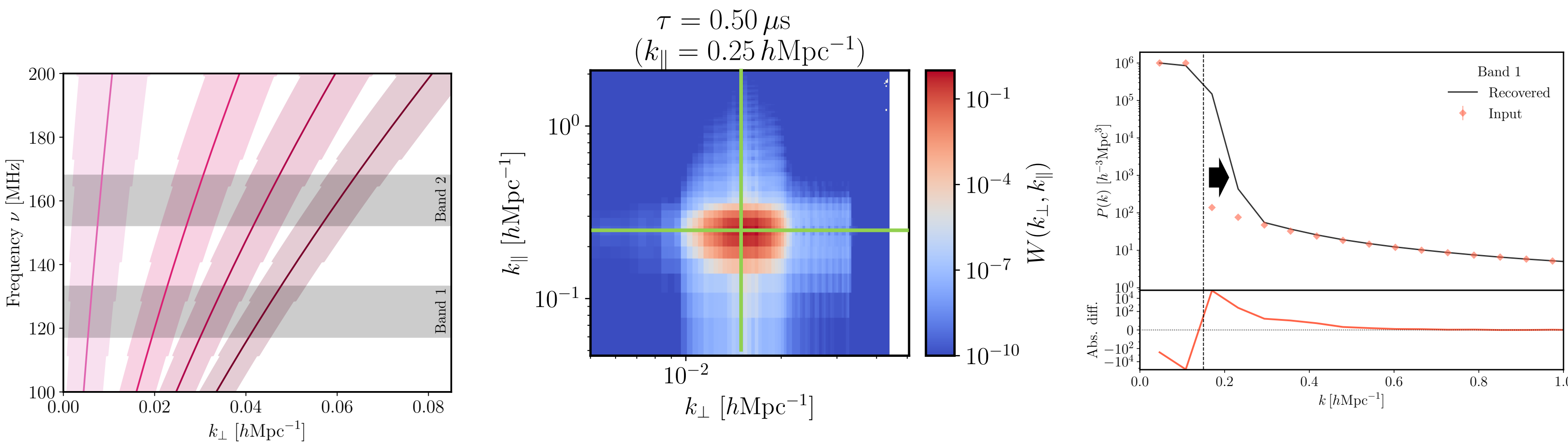
HERA collab et al. 2023

Problem: (Instrumental) systematics

Many unknown systematics need to be understood and characterised:

- Cross-coupling between antennas
- Cable reflections
- Ionosphere
- …

Ex: Chromaticity & window functions in Fourier space



Gorce & the HERA collab+2023

Problem: Mice!!!

Conclusions

Why? Observing the high-redshift 21cm signal will tell us about the timing and morphology of reionisation and, in turn, about the physical properties of the first galaxies and the early Universe.

How? Collaborating and sharing our experience with different experiments around the world.

When?

- 2018: Claimed detection of the global 21cm signal at $z = 17$
- Up to now: Upper limits on the 21cm power spectrum
- Detection when the major challenges (foregrounds and instrumental systematics) have been overcome.

Keep an eye out, we will get there!

Thank you!