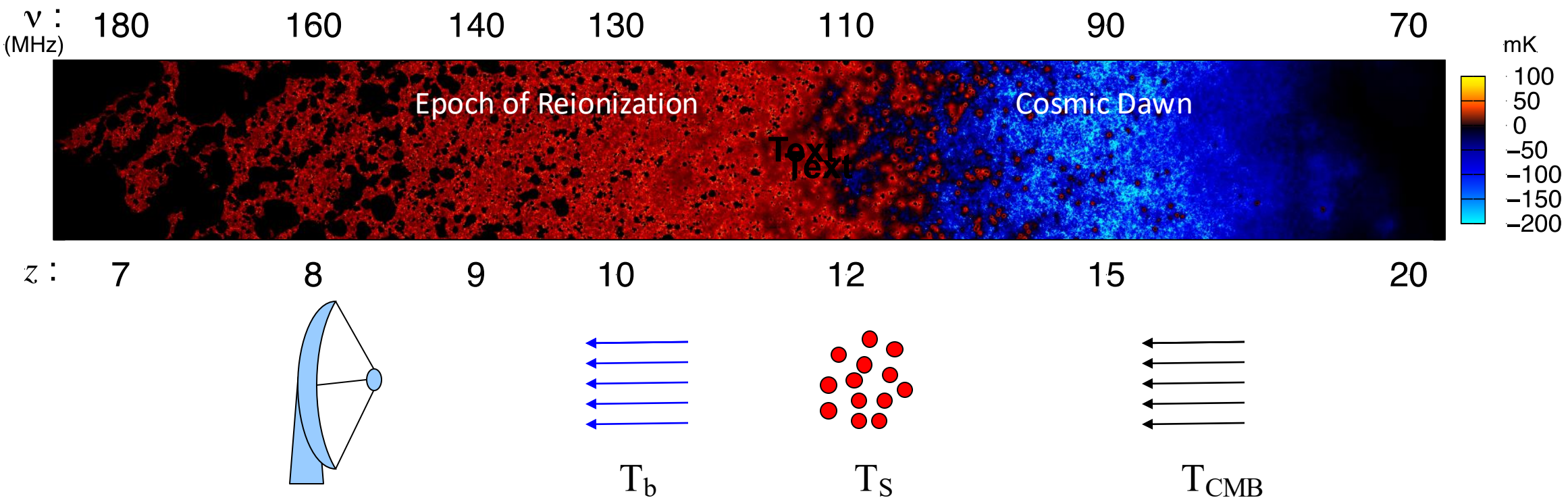
The 21 cm Probe of EoR and Cosmic Dawn

Saleem Zaroubi
Kapteyn, RuG and OUI

dT_b, The Brightness Temperature



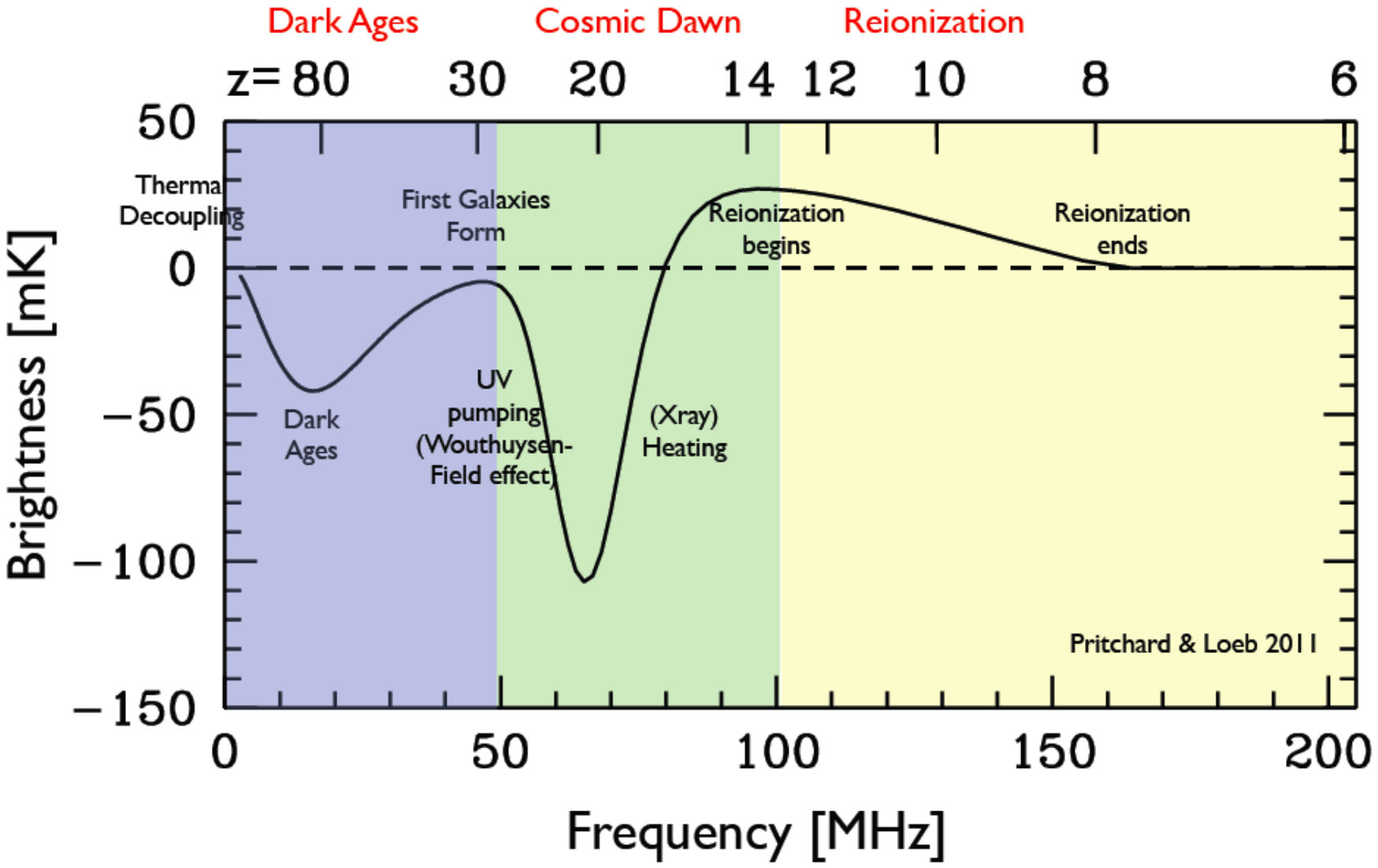
$$\delta T_b = 28\text{mK}\,(1+\delta)\,x_{\rm HI}\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\sqrt{\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)}\left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}}\right],$$

Astrophysics

Cosmology

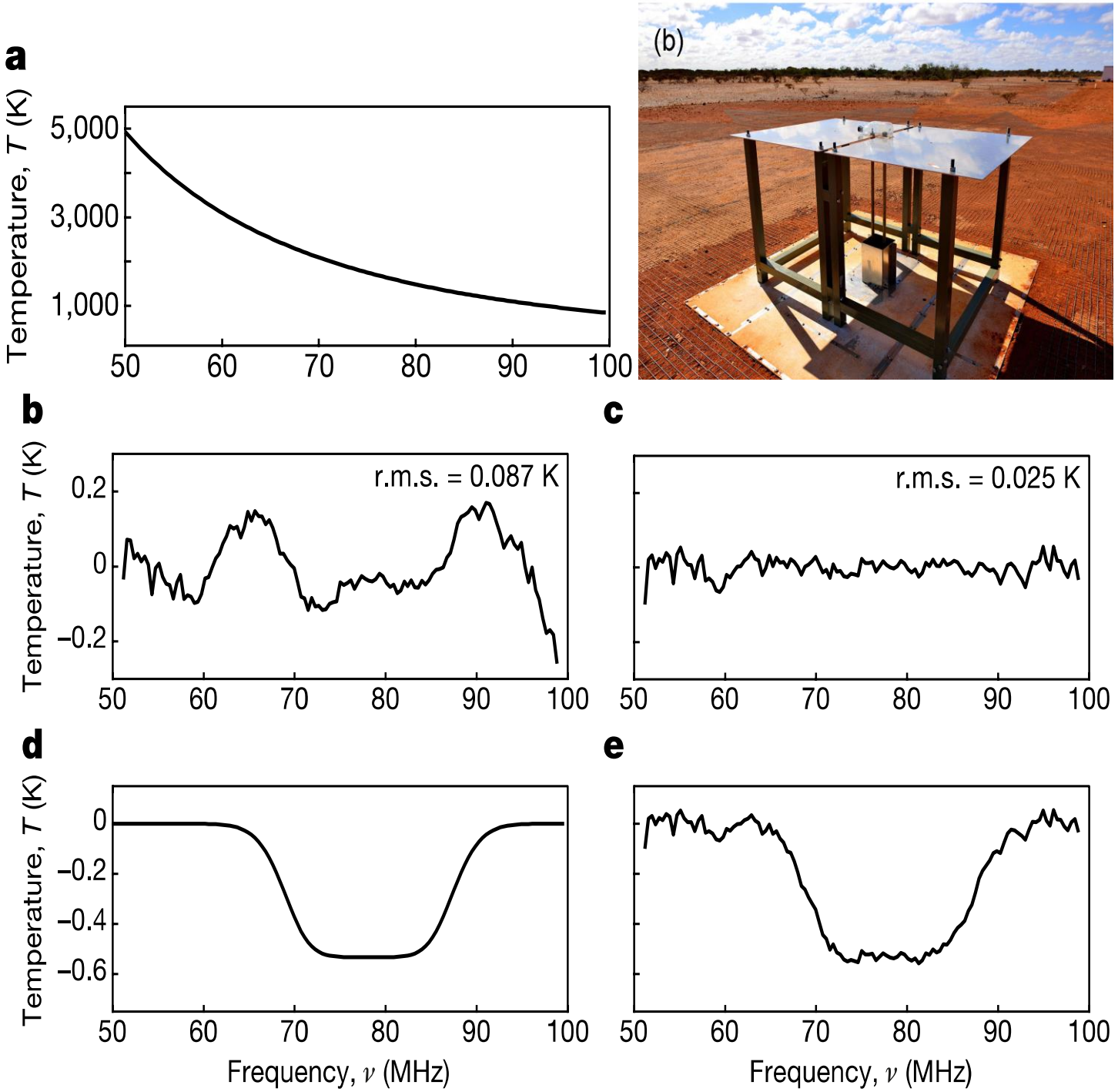
Field 1958, 1959, Madau, Meiksin & Rees 1997, Ciardi & Madau 2003, ….

The Global evolution of T_s

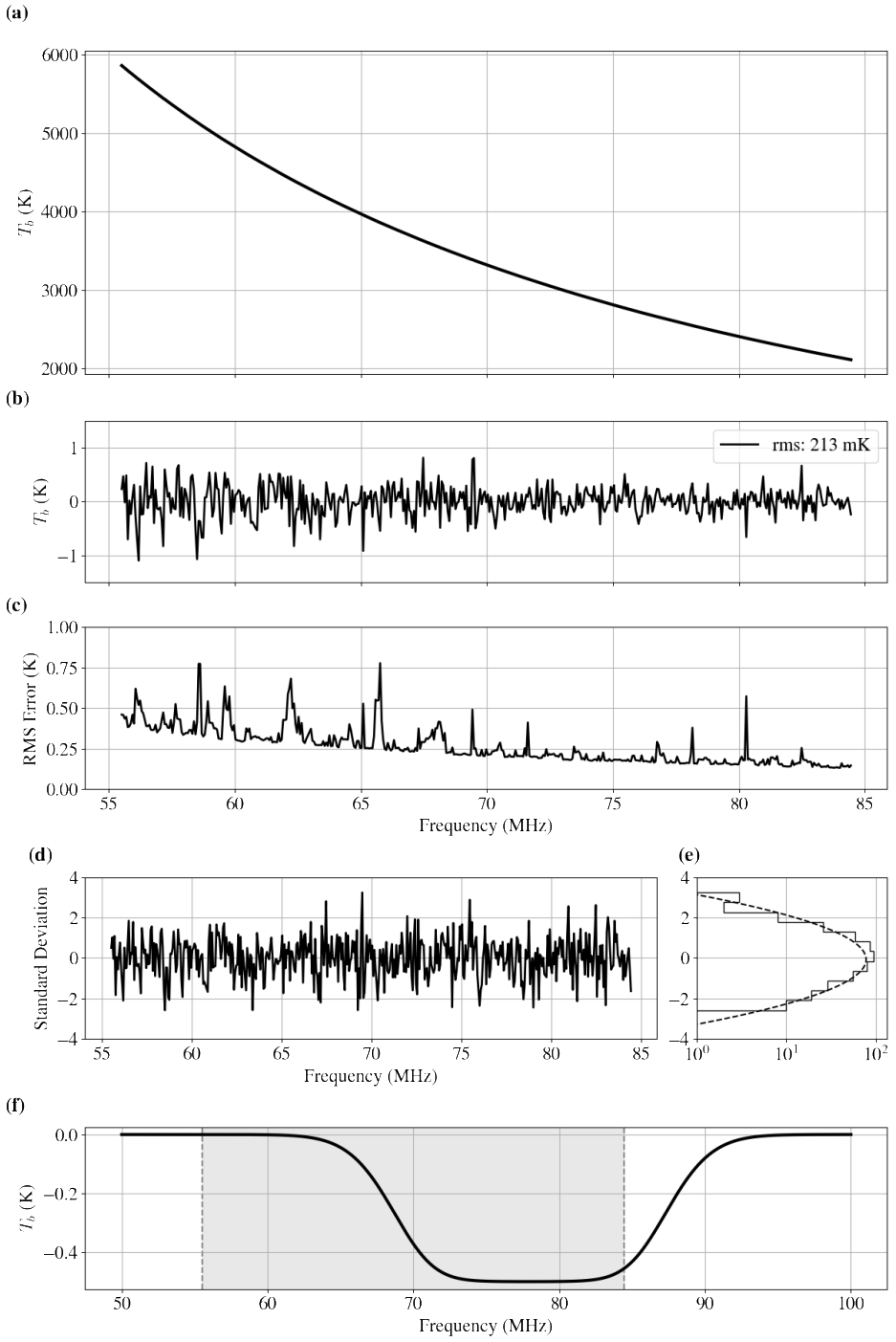


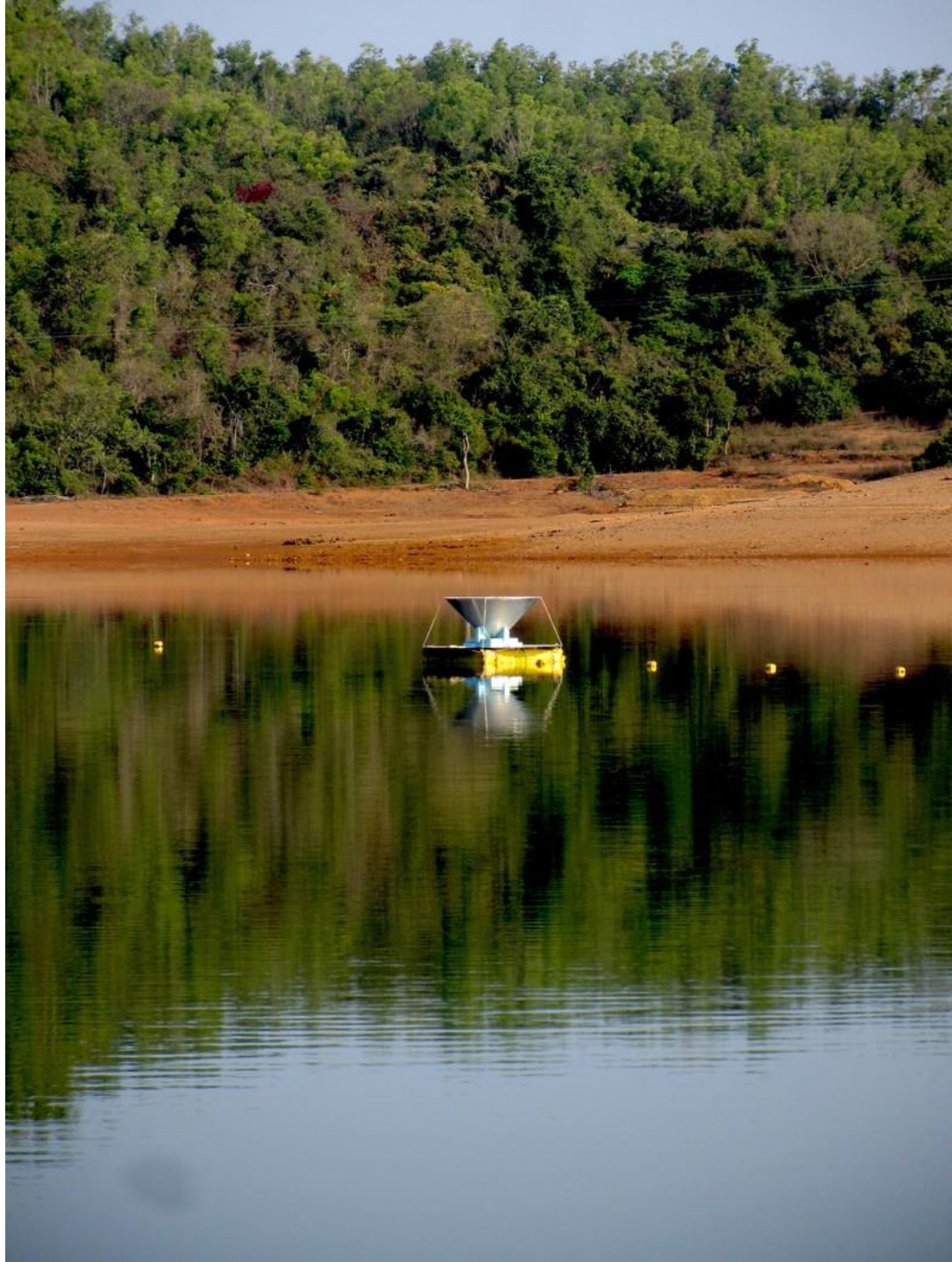
The EDGES result

Bowman+ 2018



SARAS 3 results





Singh et al. 2022

The Observational Effort

MWA
Western Australia

z ~ 6 – 10
~ 32 h published
Beardsley et al. 2016

LEDA
Owen's Valley, California
z~15-30

Greenhill et al. 2012

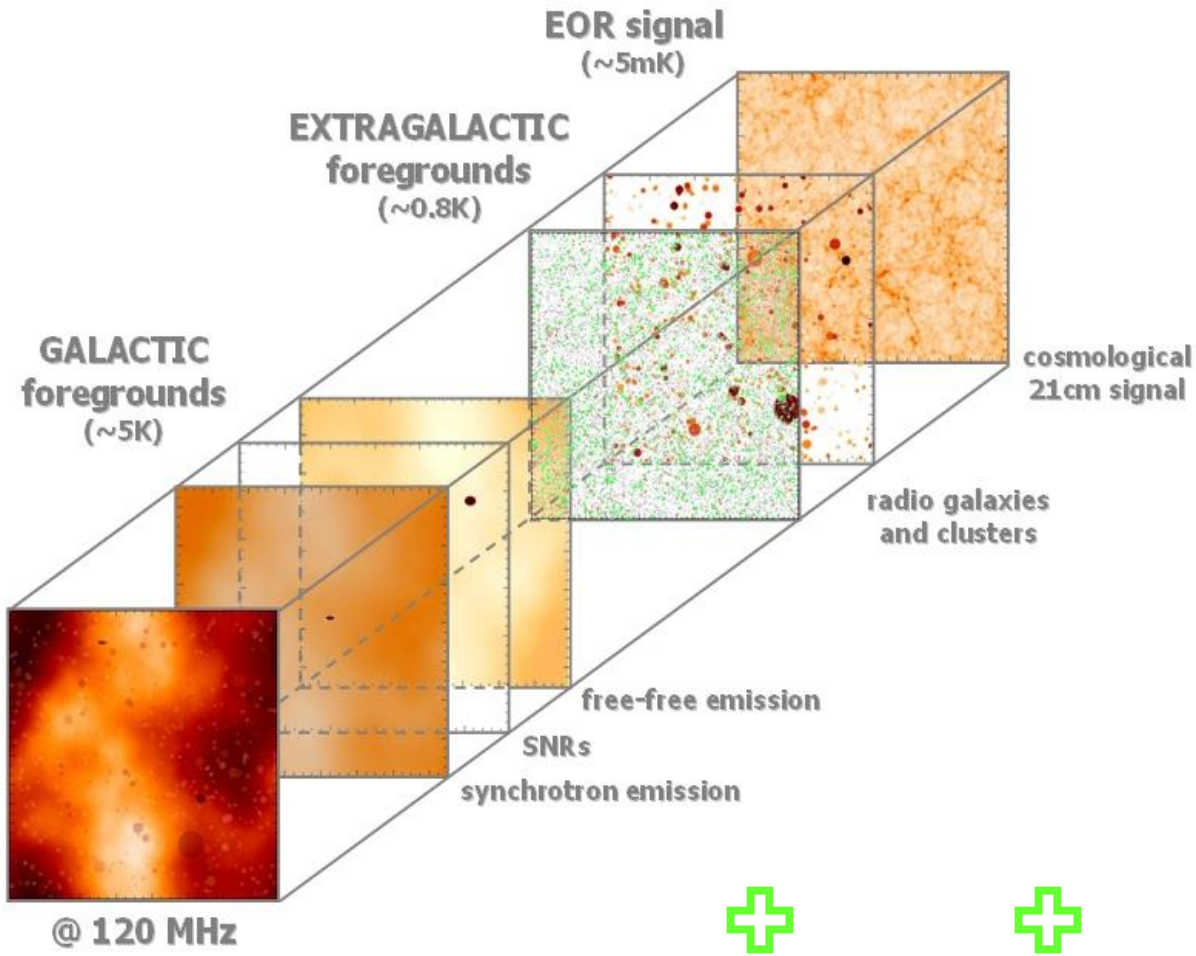
HERA
South Africa
z ~ 6 – 25
240 dishes of 14 m (by ~ 2020)
In (partial) commissioning

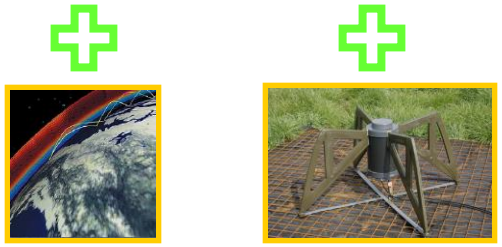
LOFAR
The Netherlands
z ~ 7 – 11
Mertens et al. 2020

NenuFAR
Nançay, France
z ~16 – 23
Munshi et al. 2024

SKA
Western Australia
Low band (z ~ 6 – 25)
Construction 2020-2025

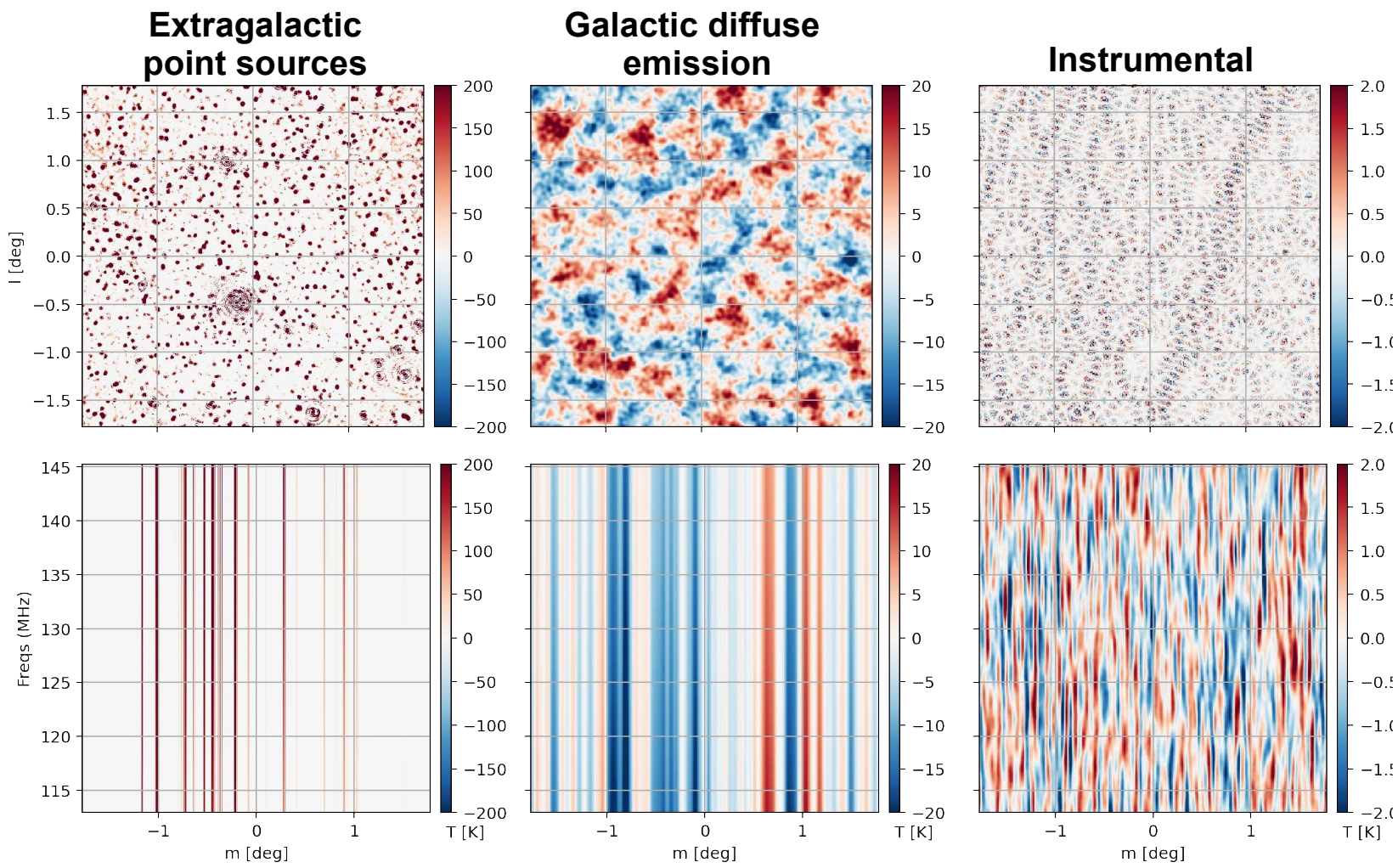
Measuring Redshifted HI: Challenges

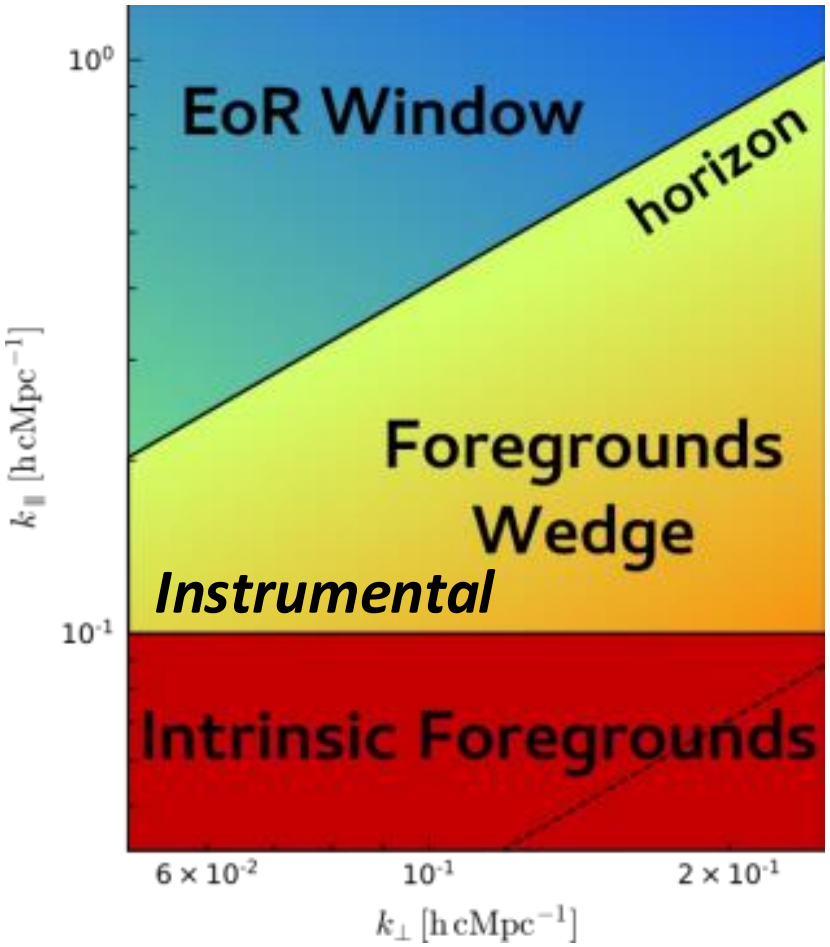




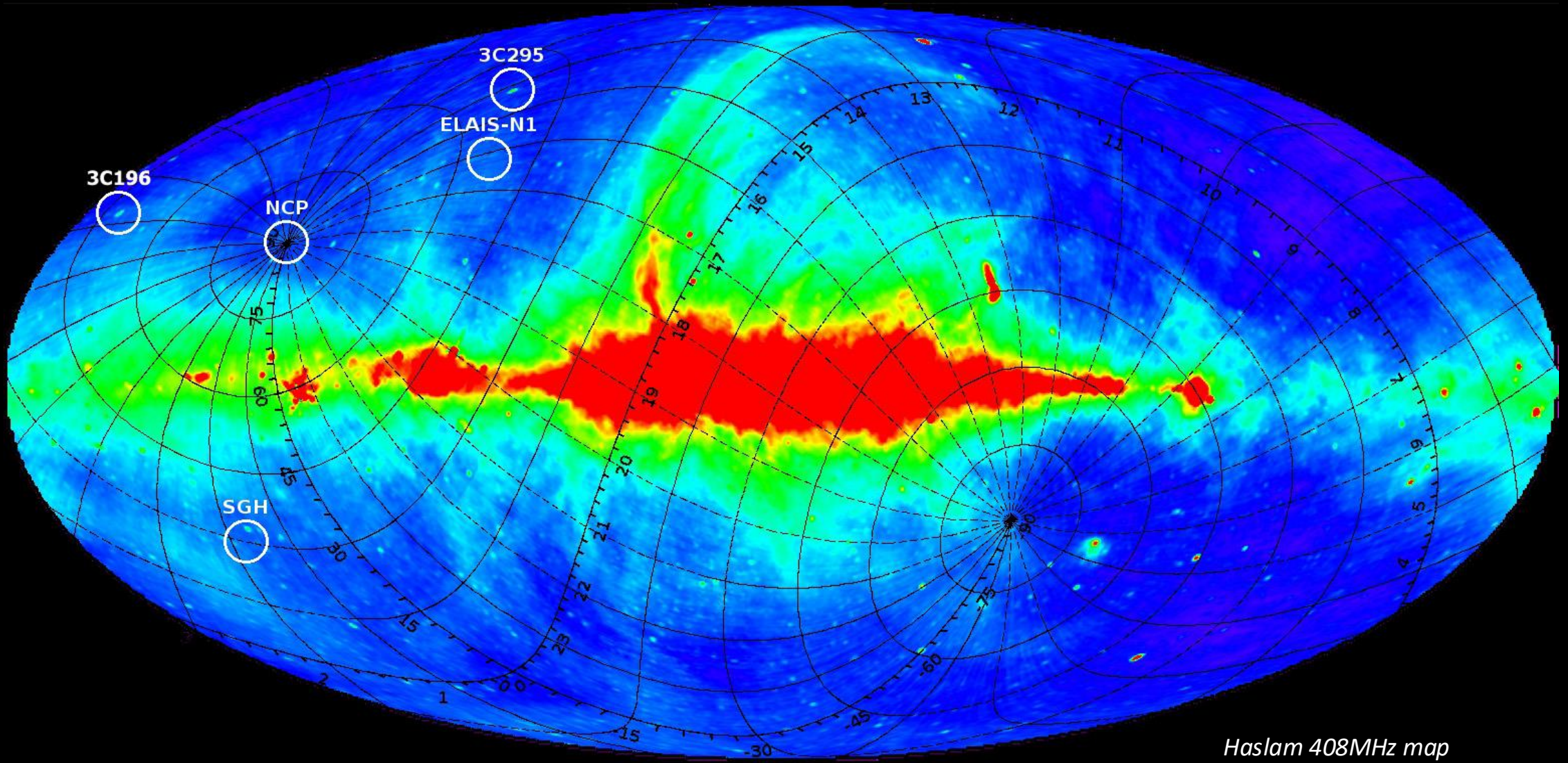
1. Astrophysical Challenges
    1. Foregrounds: total intensity
    2. Foregrounds: polarized
    3. Ionosphere
    4. Etc.
2. Instrumental challenges
    1. Beam stability
    2. Calibration
    3. Resolution
    4. uv coverage
    5. Etc.
3. Computational challenges
    1. Multi petabyte data set
    2. Calibration
    3. inversion

The FG effects on the PS





LOFAR EoR Windows



Haslam 408MHz map

Image of the NCP field at z=9.1

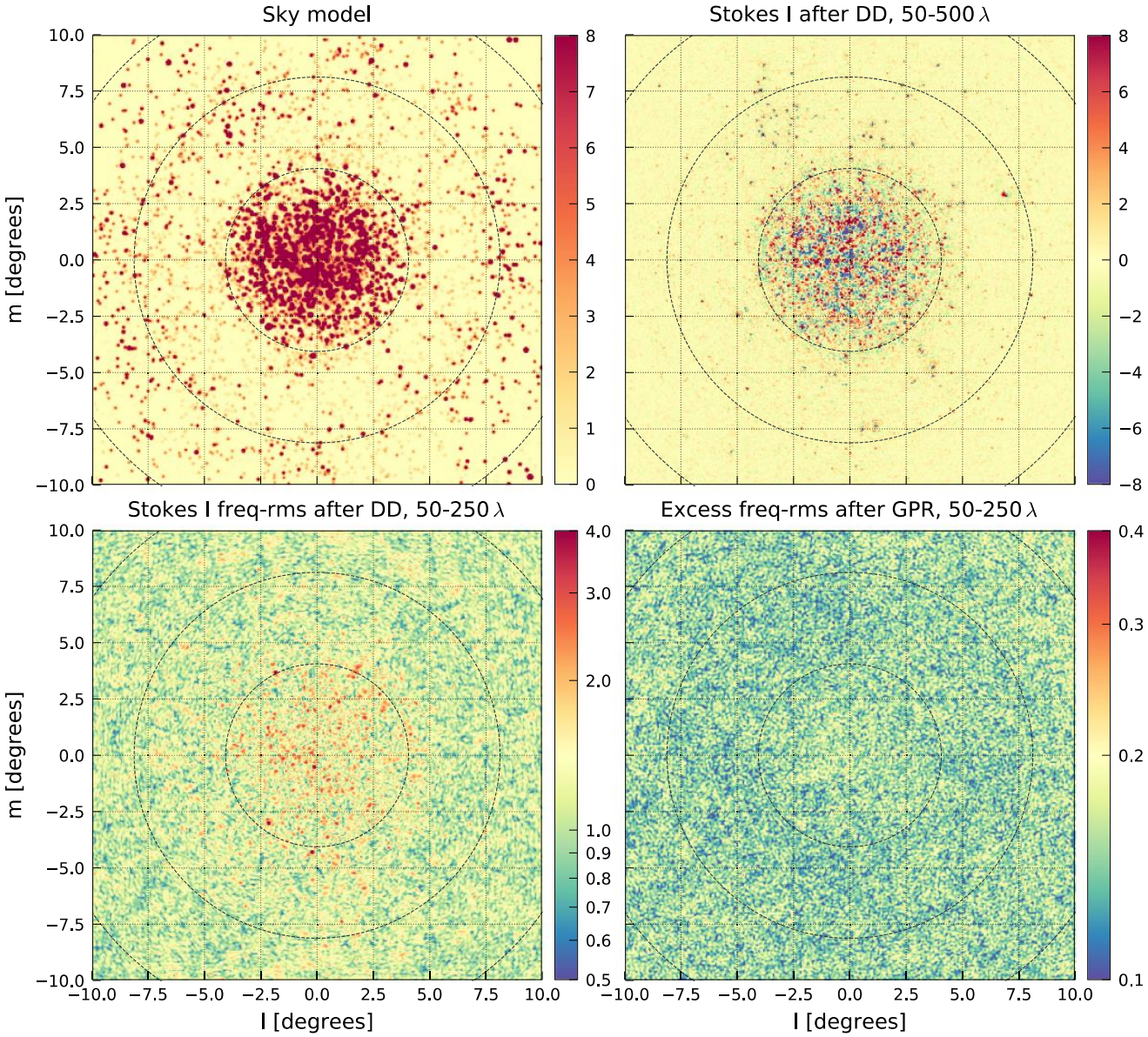
From top-left to bottom-right

1. the sky-model restored with 6.8 arcmin gaussian beam, the mean over frequencies residual.
2. Stokes I after DD
3. Stokes I frequency-rms after DD
4. Stokes I frequency-rms after GPR.

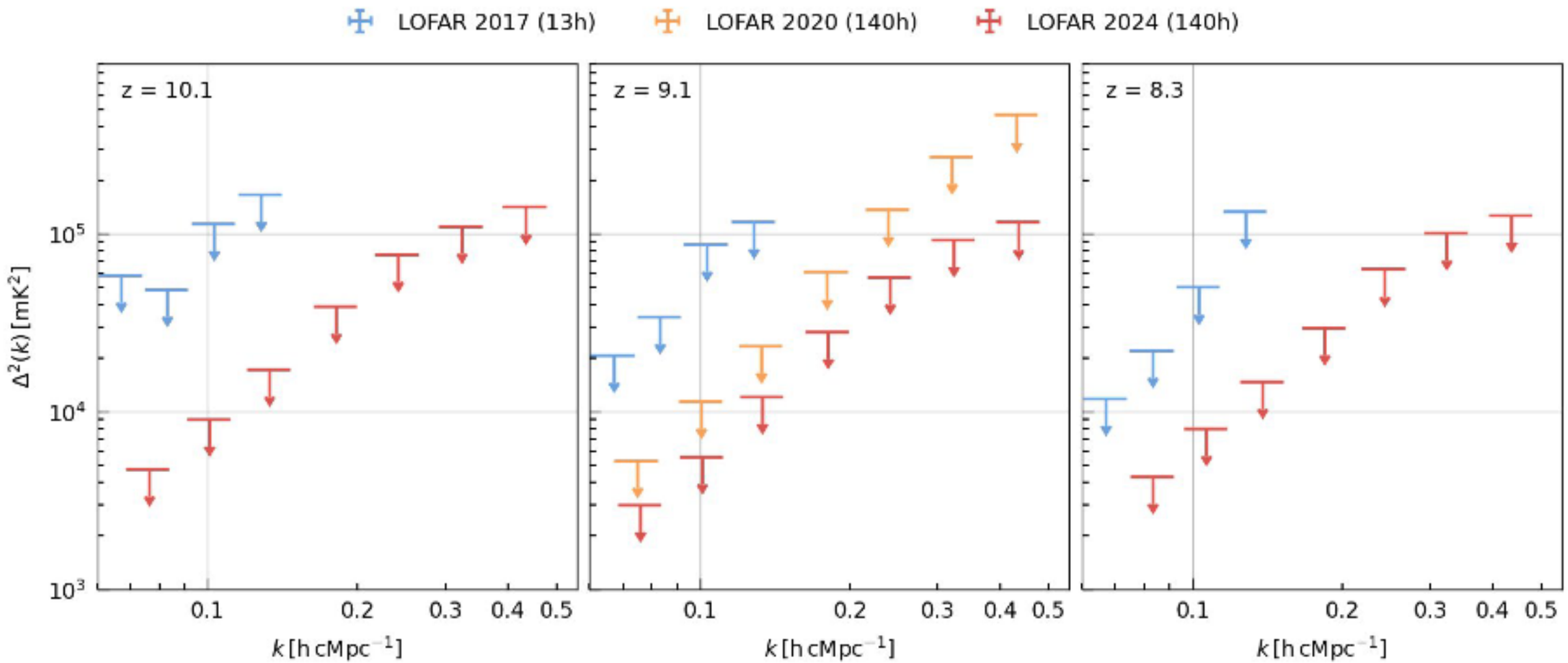
All units are Kelvin

The three circles have diameter of 2, 4 and 8 time the primary beam FWHM (~4 deg)

Mertens et al. 2020

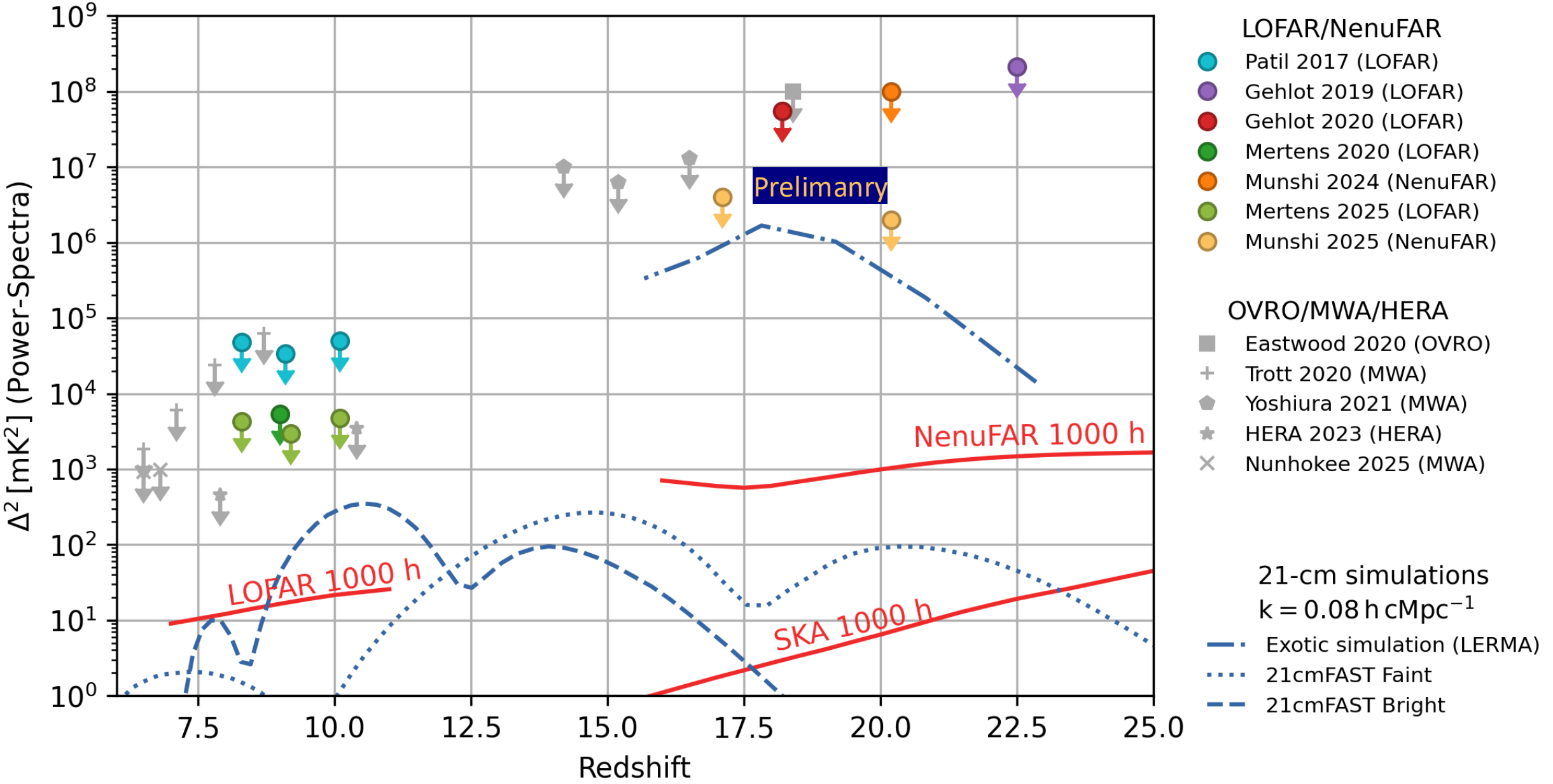


NCP multi-redshift LOFAR upper limits

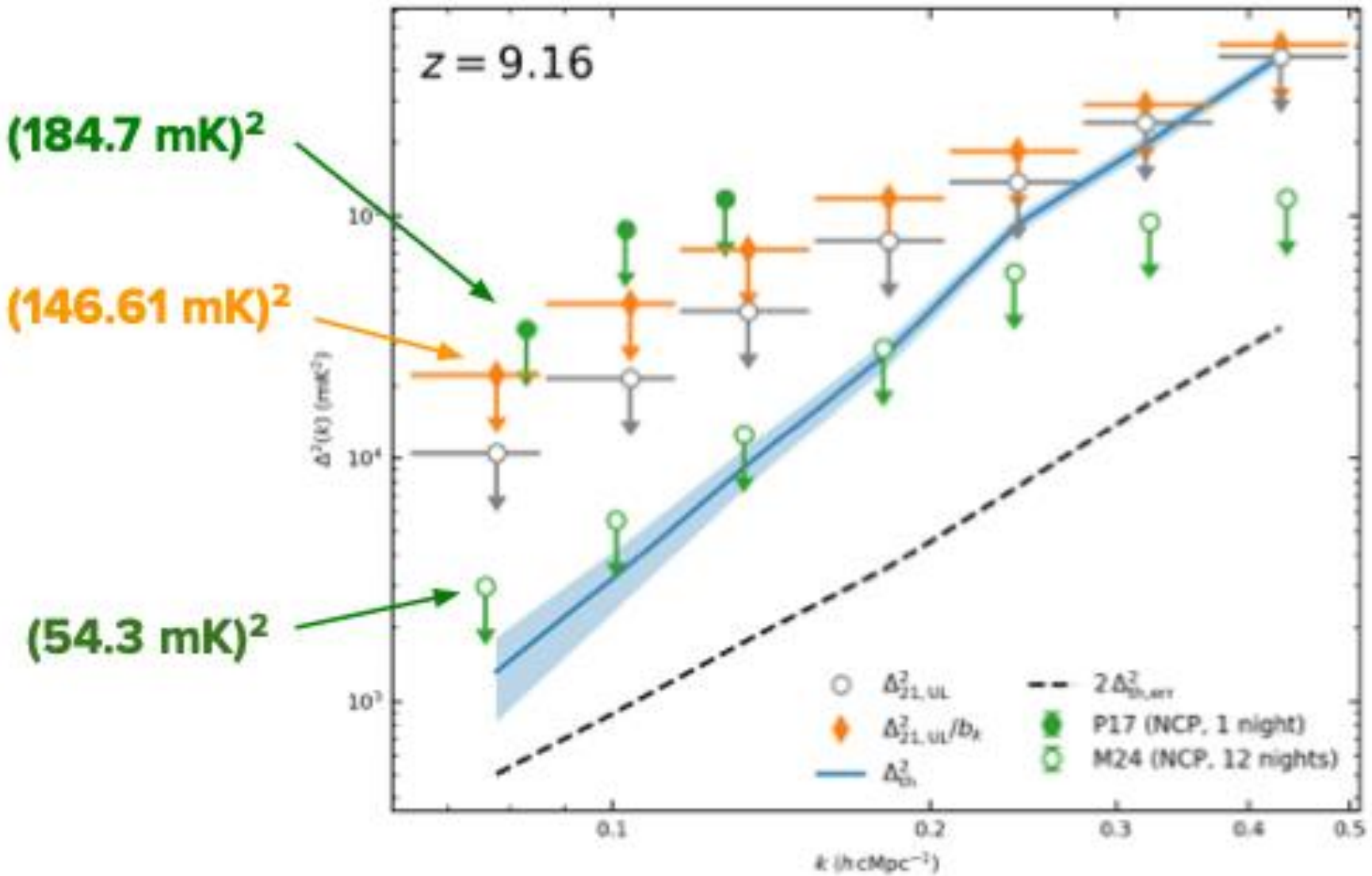


A reduction in upper limits by a factor ~5 to 10 for the three LOFAR redshifts
For z~9, same data as in 2020 → only reduction of excess

Current Status of the field



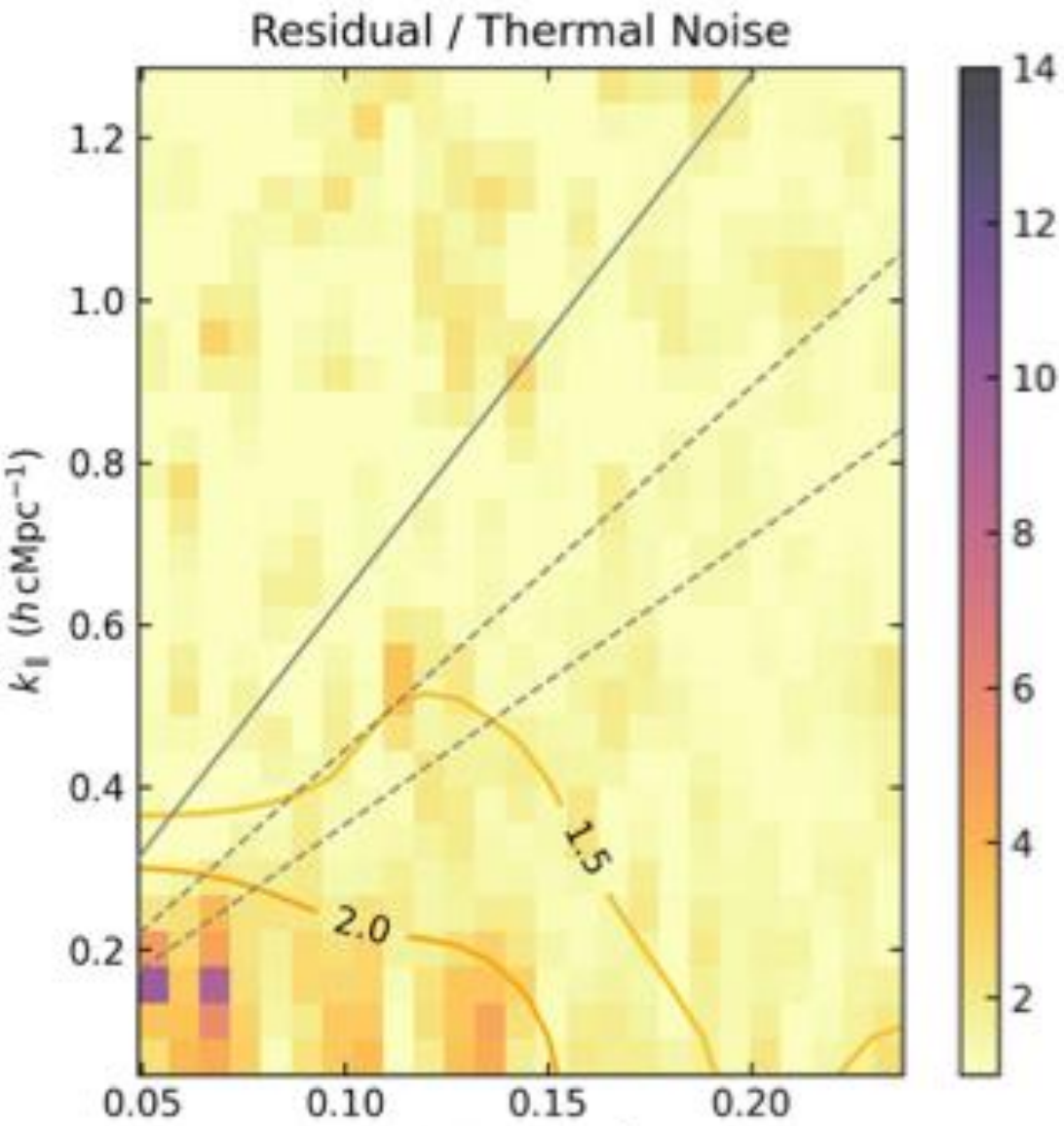
NCP vs 3C196 (after bias correction)

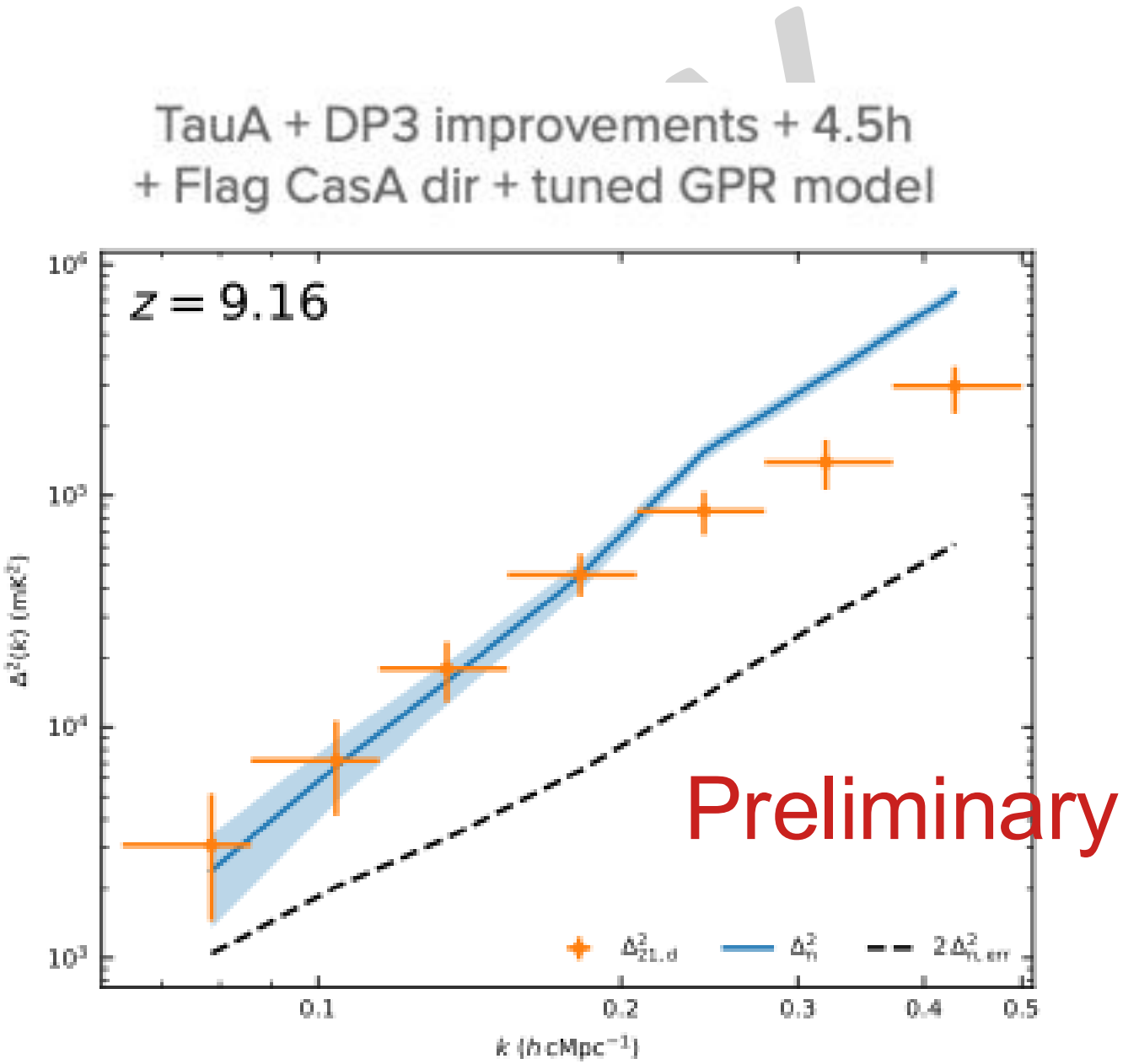


3C196
6 hours

Ceccotti +, 25

3C196 Improvement





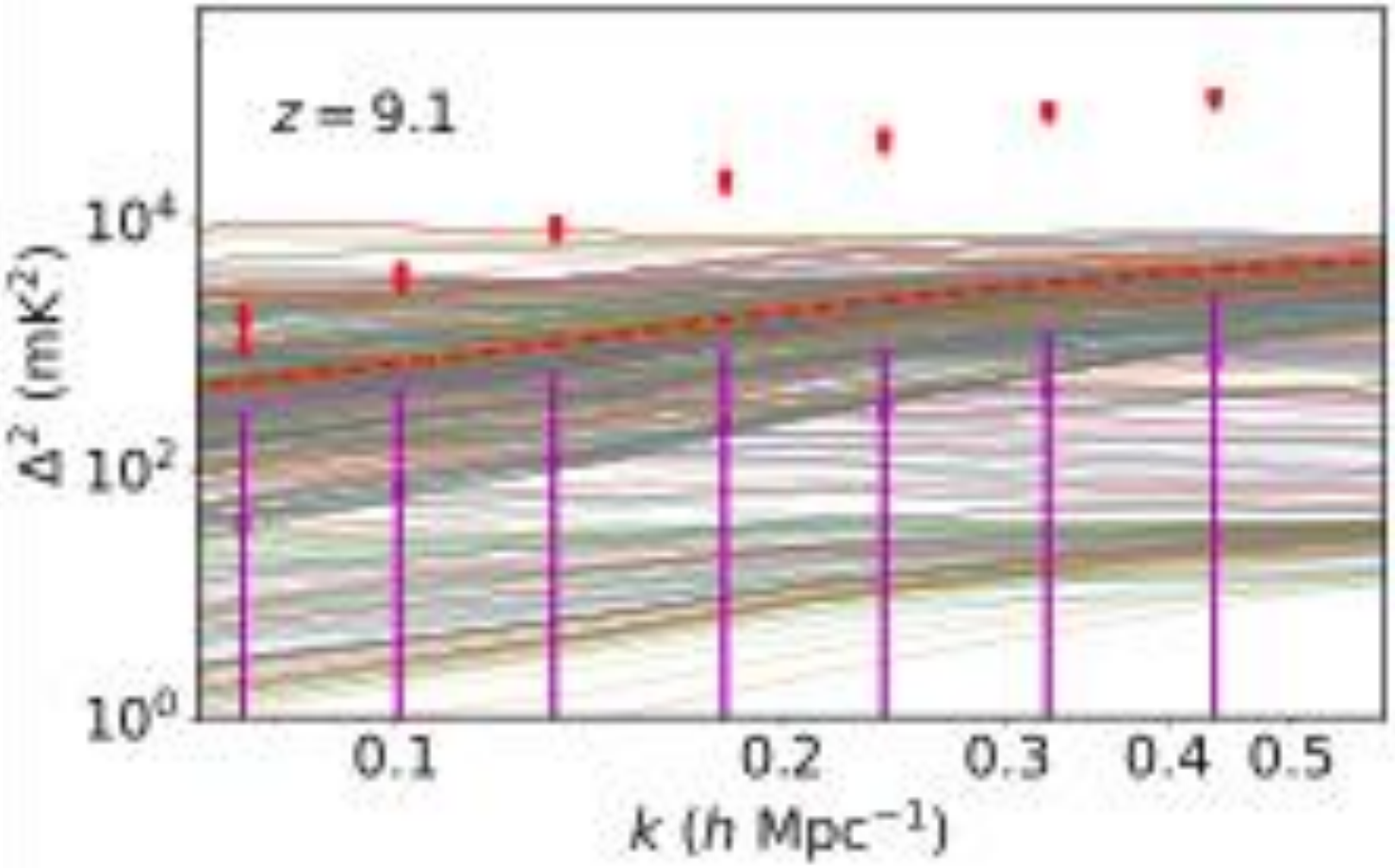
Preliminary

Next steps

- Analyze more data
  - So far, 5% processed for 1 of 2 fields
  - Going to the full data on NCP and 3C196
- Improve our sky models
  - Better modelling of brightest (A-team + 3C 61.1) sources
  - Better Diffuse model
  - Better understanding of the excess power
- Improve calibration
  (spatial & temporal regularization; beam; constraints)

Is modeling the NCP excess noise possible?

Do not trust this completely, yet!!!



Machine Learning based Variational Auto-Encoder (VAE) algorithm.

Requires more careful examination to fully understand its issues.

But very promising.

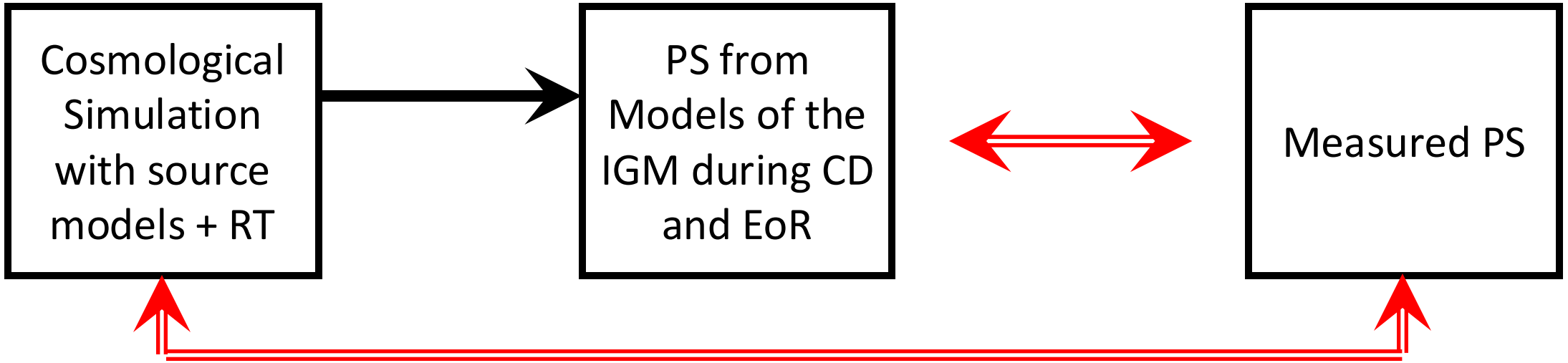
Acharya et al, 2024, MNRAS
Ghara et al., 2025, in prep.

Parameter estimation framework

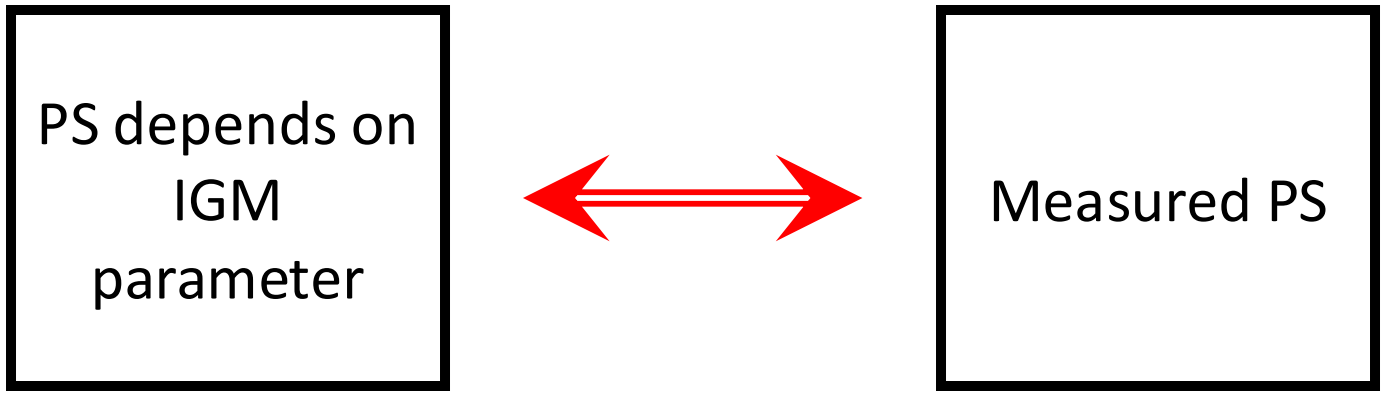
- We analyzed the data in three independent papers, Ghara+20, Mondal+20 and Greig+21
- Here I will focus on the **GRIZZLY** code (Ghara+2015, 2018, based on Thomas+ 2008) results.
- Generate brightness temperature maps at redshift ≈ 9.1 and derive their PS.
- **Combine the GRIZZLY simulations with an MCMC algorithm** to explore the parameter space for different scenarios.
- Scenarios considered:
  - large-scale fluctuations of the signal are mostly driven by fluctuations in x_{HI} (assuming T_S to be uniform)
  - large-scale fluctuations of the signal are mostly driven by fluctuations in T_S

Parameter estimation framework

1.

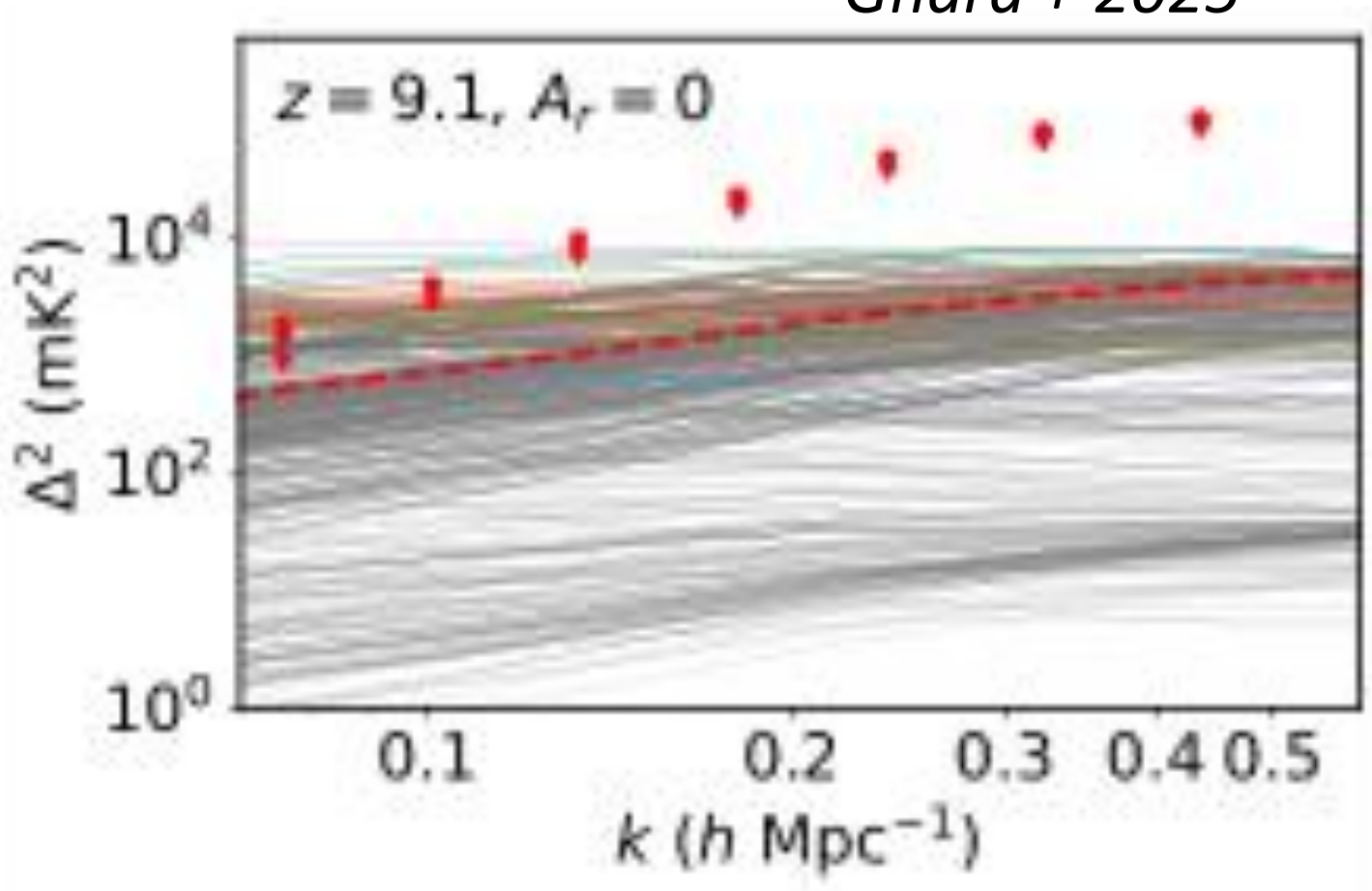


2.



HERA and LOFAR results

Ghara + 2025



HERA finds that the IGM must have been heated above the adiabatic cooling threshold by z ~ 8, independent of uncertainties about IGM ionization and the radio background.

HERA paper 2023

IGM-based analysis framework

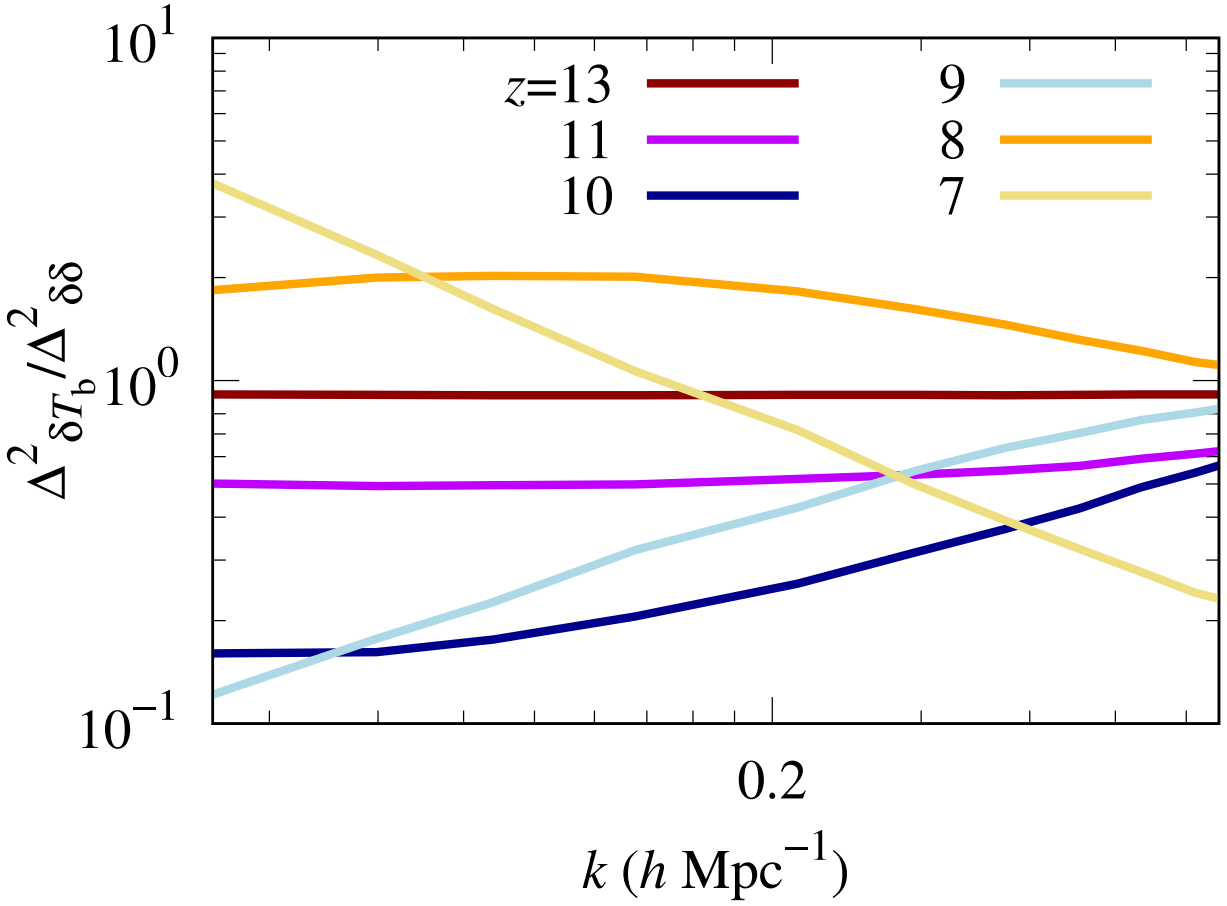
Why this framework?

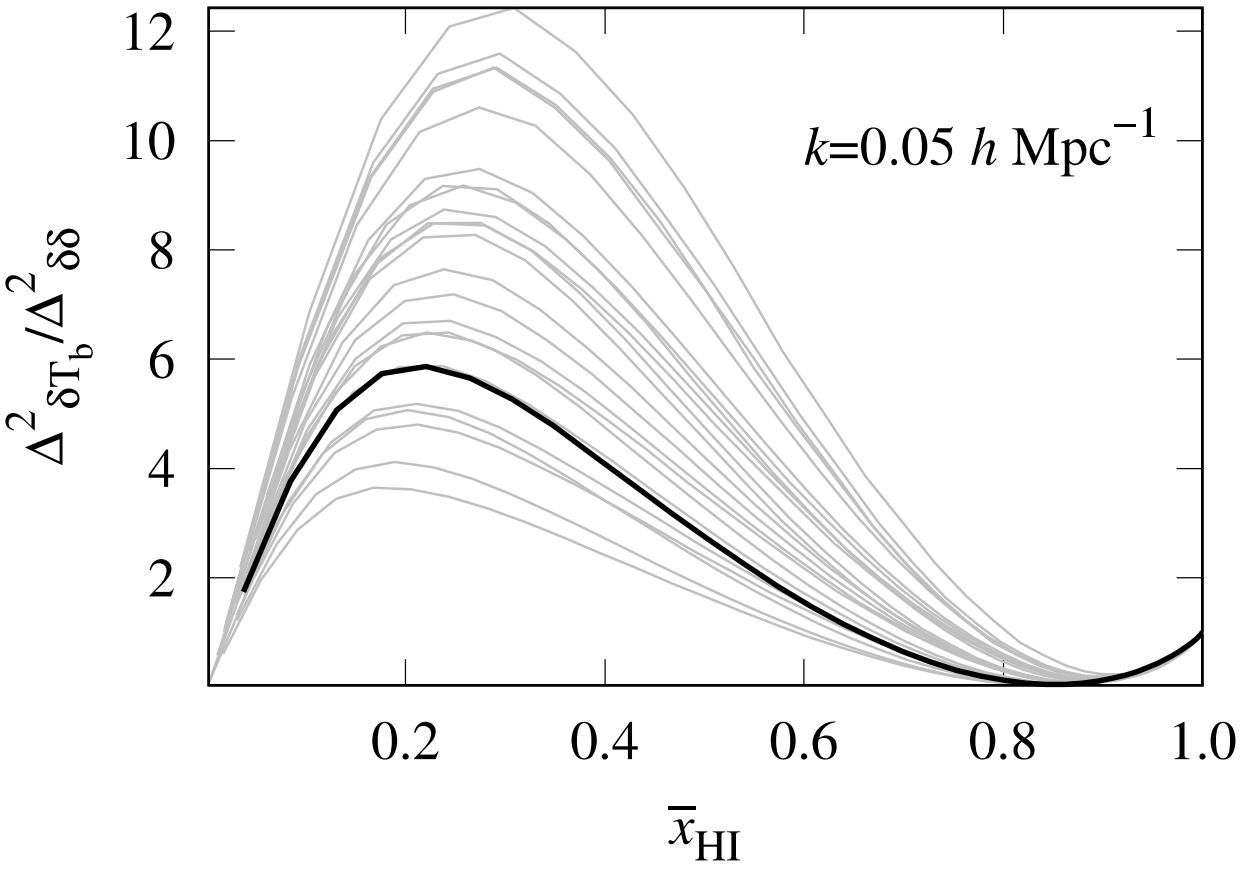
1. The 21 cm PS probes directly the IGM and the sources.
2. The physics of sources and its reioization is uncertain (many free parameter).
3. Degeneracies in the PS due to different sources.

However, one needs to think about what we mean by iGM parameters. For example, Bubble Size Distribution!

Ghara et al. 2024

The PS ratio


10^1
10^0
10^{-1}
$\Delta^2_{\delta T_b}/\Delta^2_{\delta\delta}$
z=13
11
10
9
8
7
0.2
k (h Mpc^{-1})

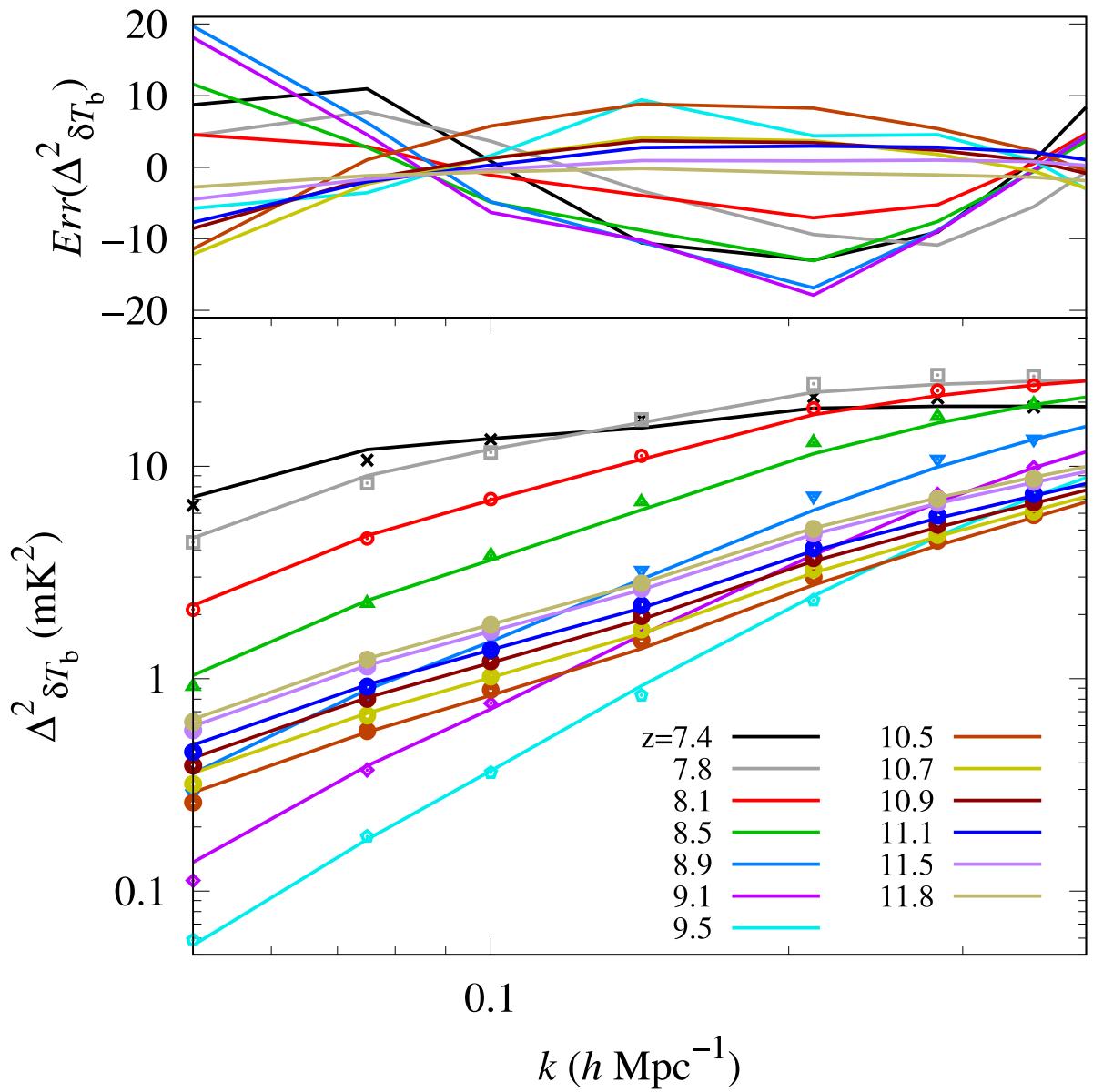

12
10
8
6
4
2
$\Delta^2_{\delta T_b}/\Delta^2_{\delta\delta}$
k=0.05 h Mpc^{-1}
0.2
0.4
0.6
0.8
1.0
$\overline{x}_{\rm HI}$

The Assumptions

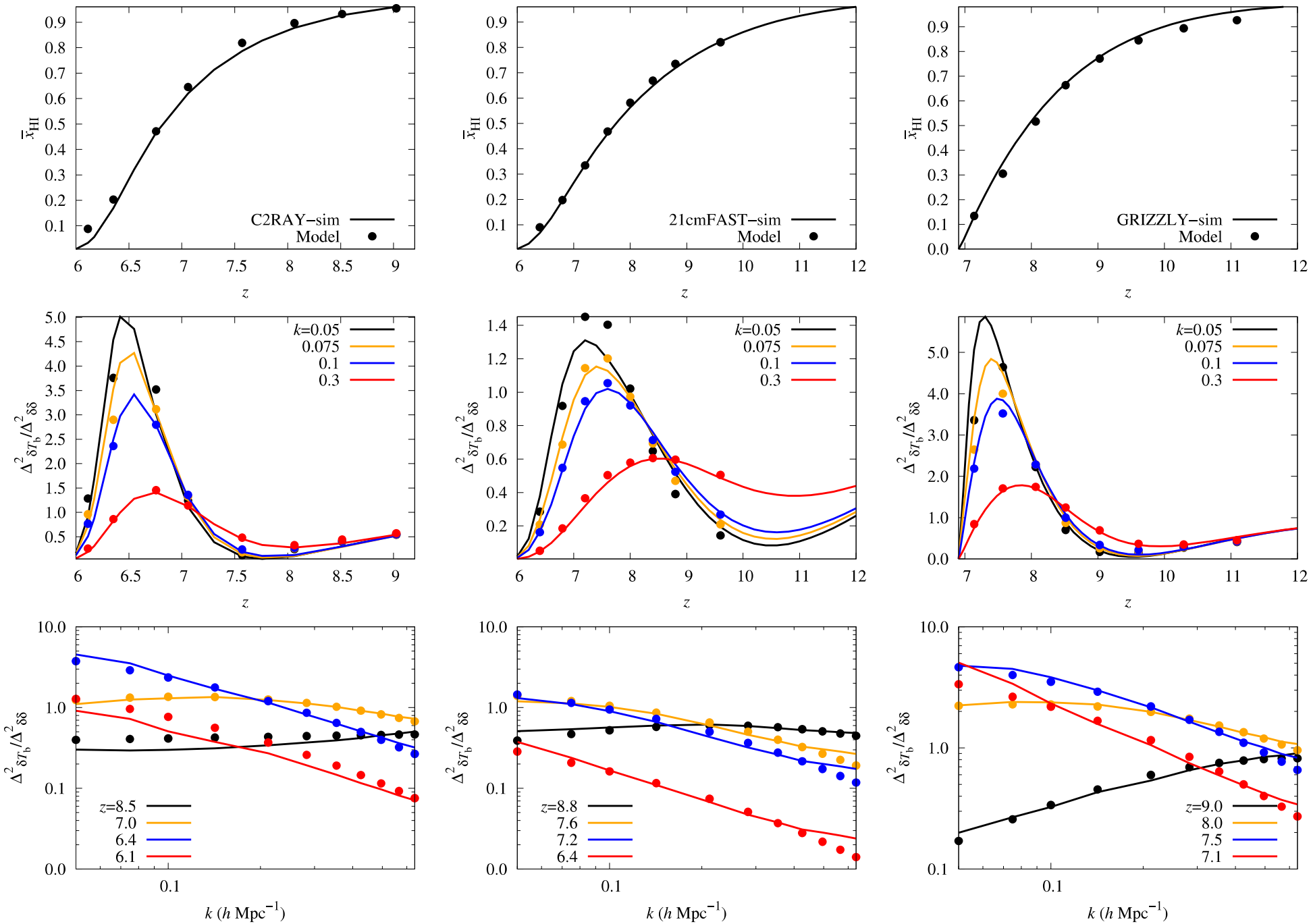
- **The Ansatz:**

$$\Delta^2_{\delta T_\mathrm{b}} = \Delta^2_{\delta\delta} A \frac{\left(\frac{k}{k_c}\right)^\gamma}{1+\left(\frac{k}{k_0}\right)^\eta}$$

- **Finding the redshift dependence of the parameters**



Redshift Evolution



Summary of Results and Nexts steps

- The sensitivity of the 21 cm Experiments is approaching the expected signal level.
- The next decade will deliver many constraints, if not complete detection, of the 21 cm from the EoR and CD.
- SKA is rolling out with initial measurements already taken. It is expected to start delivering on the EoR and CD in the coming 5-10 years.
- Lunar observatories are becoming a serious possibility, promising to probe the Universe's Dark Ages.