Interpreting 21-cm Upper Limits from LOFAR EoR

Garrelt Mellema
Department of Astronomy / Oskar Klein Centre
Stockholm University

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Raghu Ghara, Sambit Giri, Rajesh Mondal, Ivelin Georgiev, Ilian Iliev, Saleem Zaroubi, Benedetta Ciardi

Content

- Digging for the 21-cm power spectrum
- Simple cases
- Interpretation in terms of astrophysics: sources vs. IGM
- Multi-redshift IGM constraints
- Summary & conclusions

Low frequency interferometers

Google Maps

HERA
(SA/USA)

LOFAR
(NL/Europe)

MWA
(Australia)

Hard work!

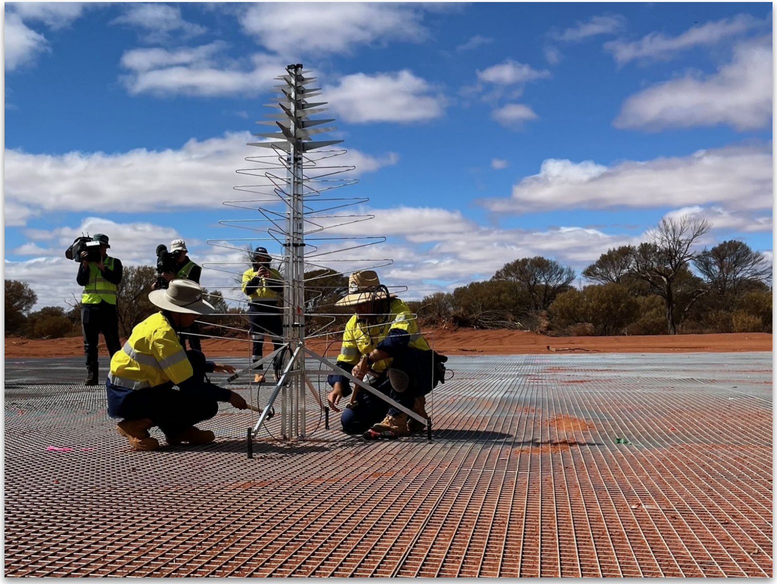
What we are hoping for…

Hard work!

What we are fearful of..

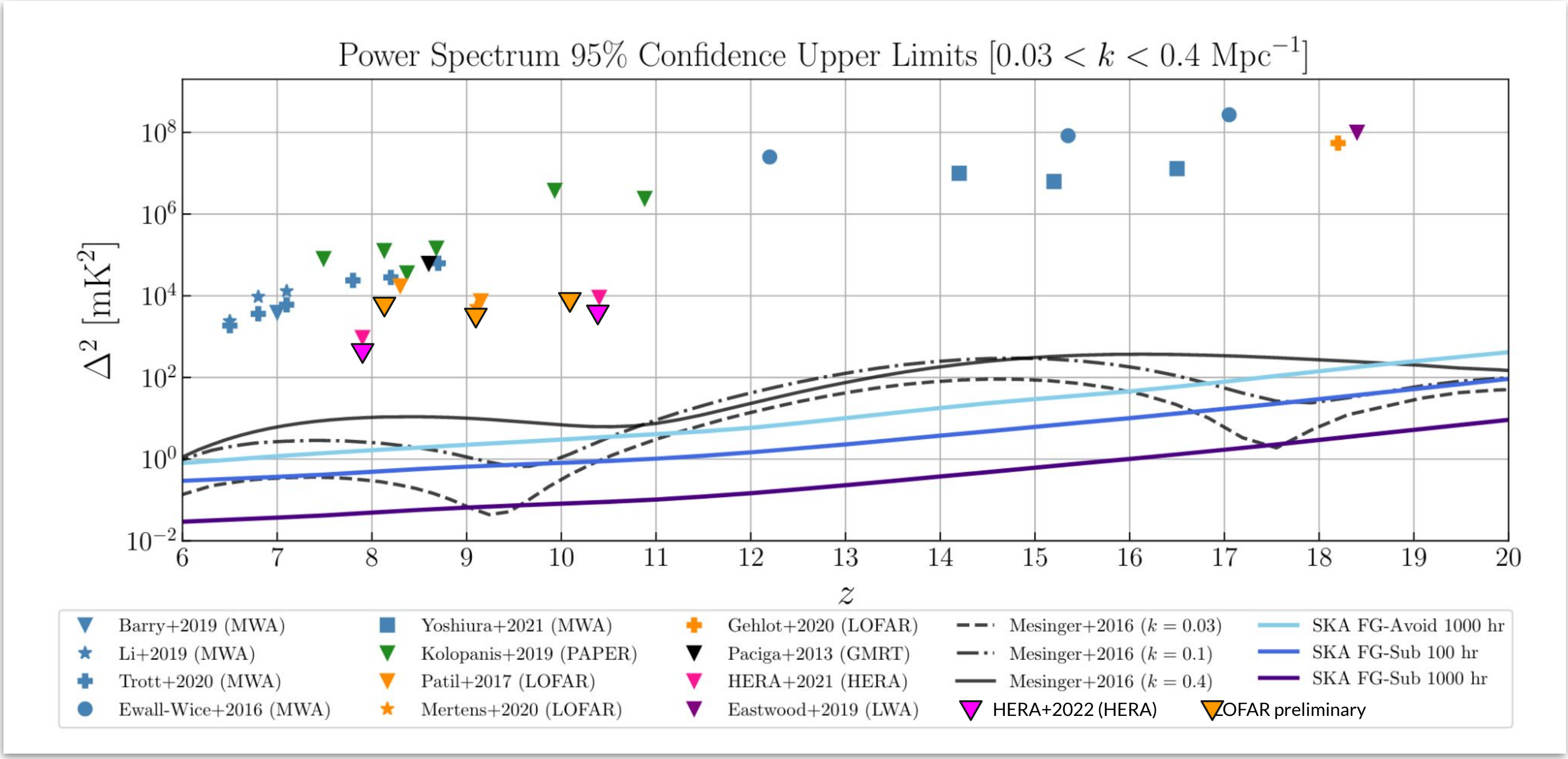
Future with SKA-Low

SKA-Low Aperture Array Verification System (Australia)



7 March 2024: first of the 131,072 SKA-Low antennas deployed

Current power spectra upper limits



Barry et al. (2022)

Redshifted 21-cm signal

- Observed with the CMB as background signal:

$$\delta T_{\mathrm{b}} = 27 x_{\mathrm{HI}} (1 + \delta) \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right) \left(\frac{1+z}{10}\right)^{1/2} \quad \mathrm{mK}$$

- Depends on:
  - HI density: $\mathbf{x_{HI}\ (1+\delta)}$
  - Spin (excitation) temperature: $\mathbf{T_S}$

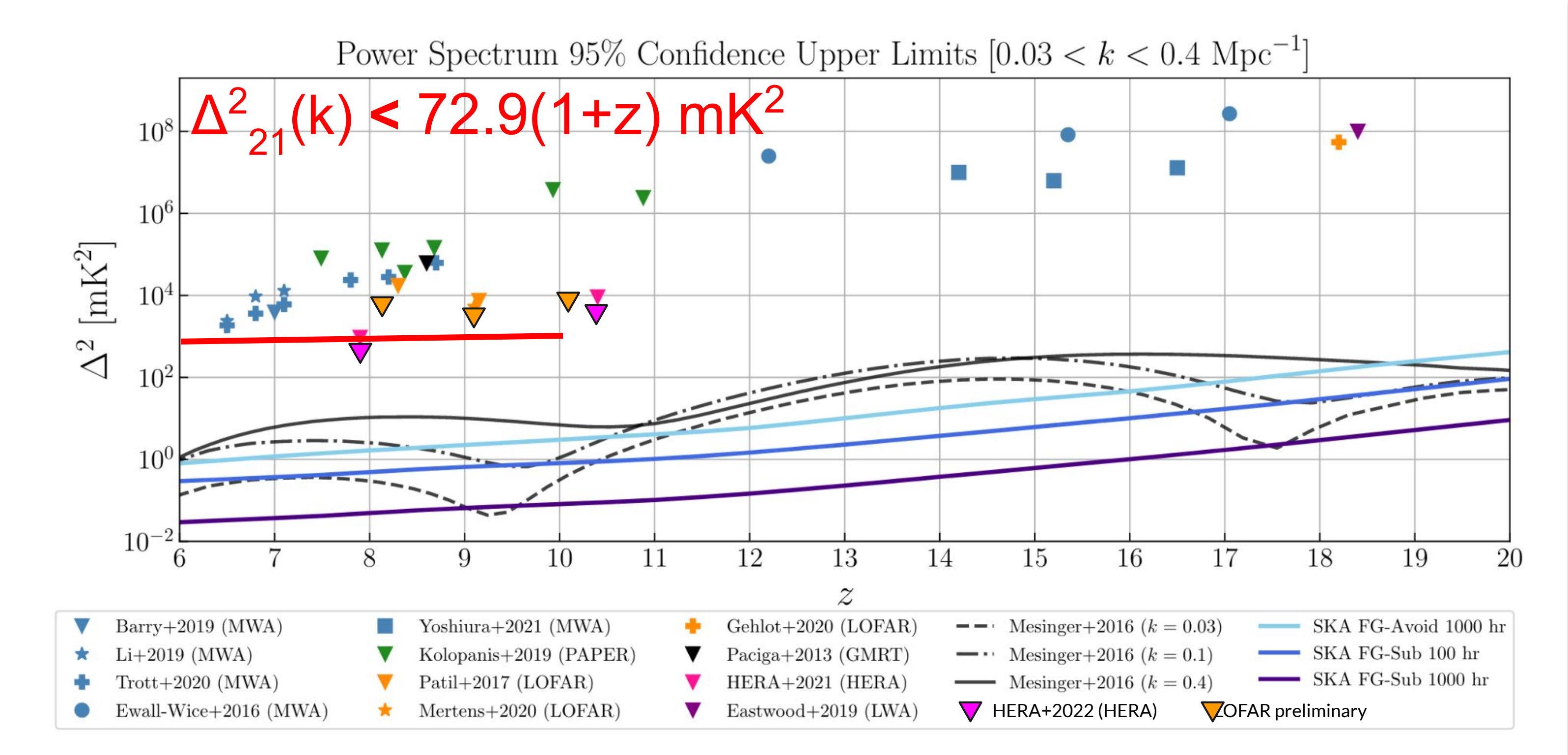
Simple case 1: only x_{HI} fluctuations

$$\delta T_b = 27 x_{\rm HI}(1+\delta)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)\left(\frac{1+z}{10}\right)^{1/2} \quad \rm mK$$

- If $T_S \gg T_{CMB}$: $\Delta^2_{21}(k) < 72.9(1+z)\,\rm mK^2$
  largest when k-scale fully matches sizes of HII regions.

- For arbitrary, homogeneous T_S: $\Delta^2_{21}(k) < 72.9(1+z)\left(1-\frac{T_{\rm CMB}}{T_{\rm S}}\right)^2 \rm mK^2$

Simple case 1



Barry et al. (2022)

Simple case 2: Unheated neutral IGM

Adiabatic, homogeneous T_S and x_{HI}=1, only density fluctuations:

T_S= 0.02(1+z)^2 K (unheated IGM), T_{CMB}= 2.7(1+z) K

$$\Delta^2_{21}(k) = 72.9\Delta^2_{\mathrm{m}}(k)(1+z)^{-1}\left(1 - \frac{135}{1+z}\right)^2 \mathrm{mK}^2$$

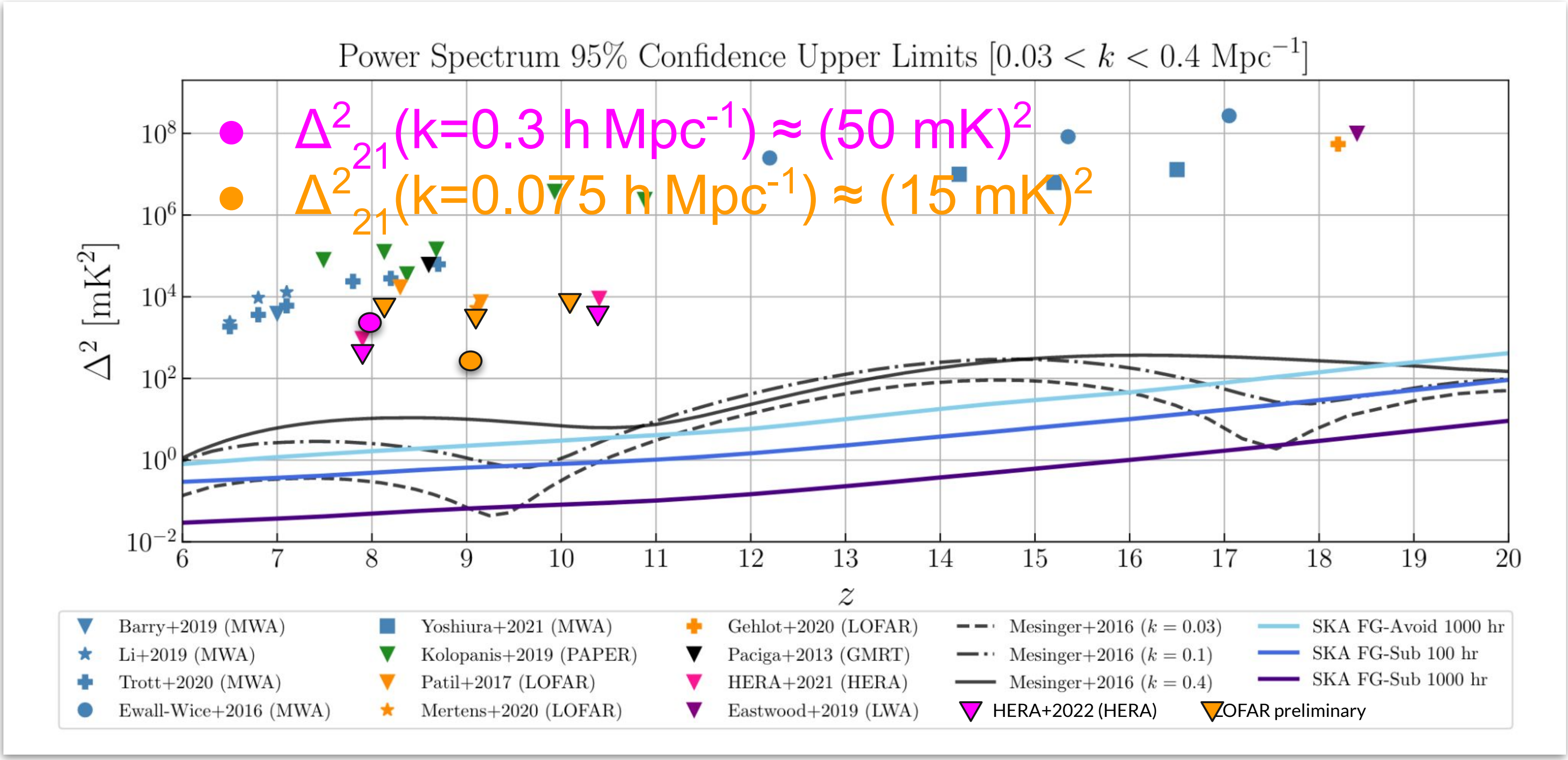
(linear bias model)

Abdurashidova et al. (2022)

At z~8: Δ^2_{21}(k=0.3 h Mpc^{-1}) ≈ (50 mK)^2 Above HERA UL!

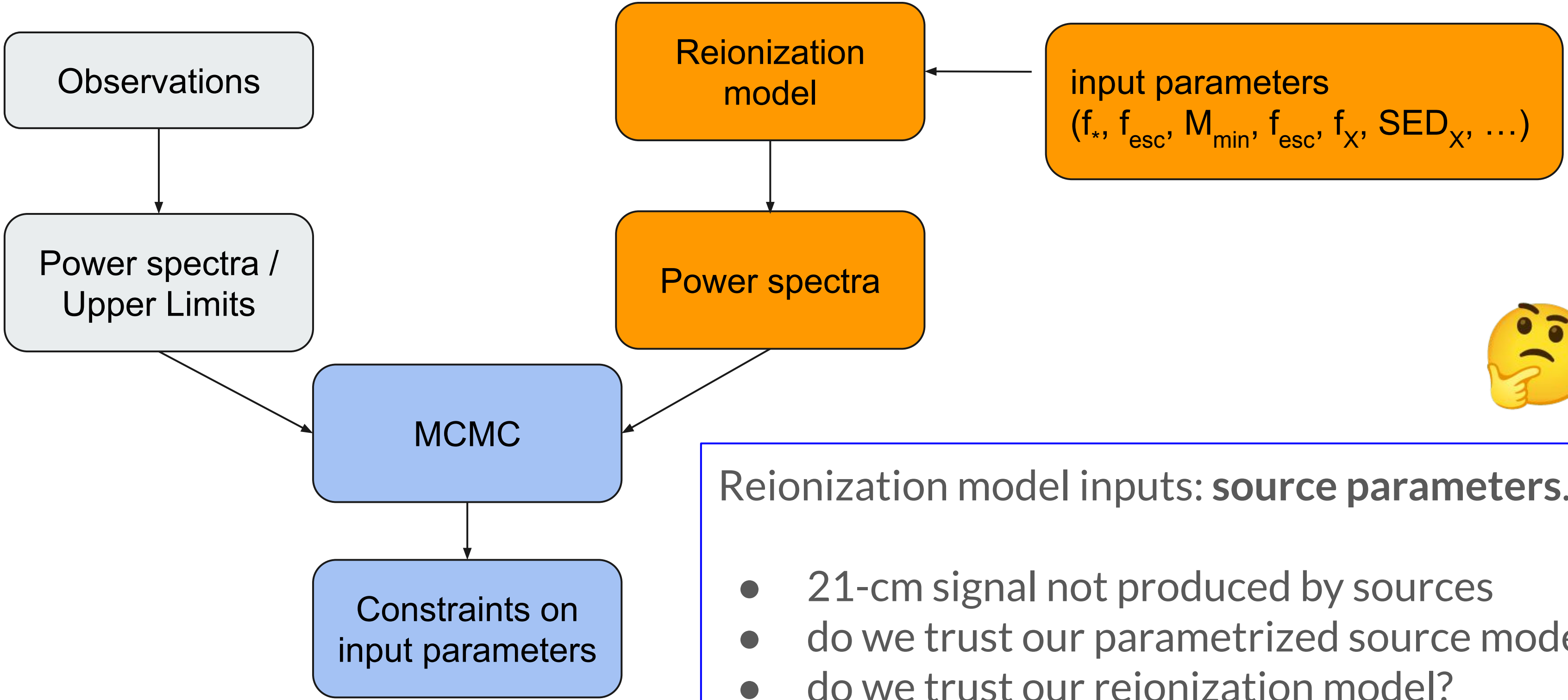
At z~9: Δ^2_{21}(k=0.075 h Mpc^{-1}) ≈ (15 mK)^2 Below LOFAR UL!

Simple case 2



Barry et al. (2022)

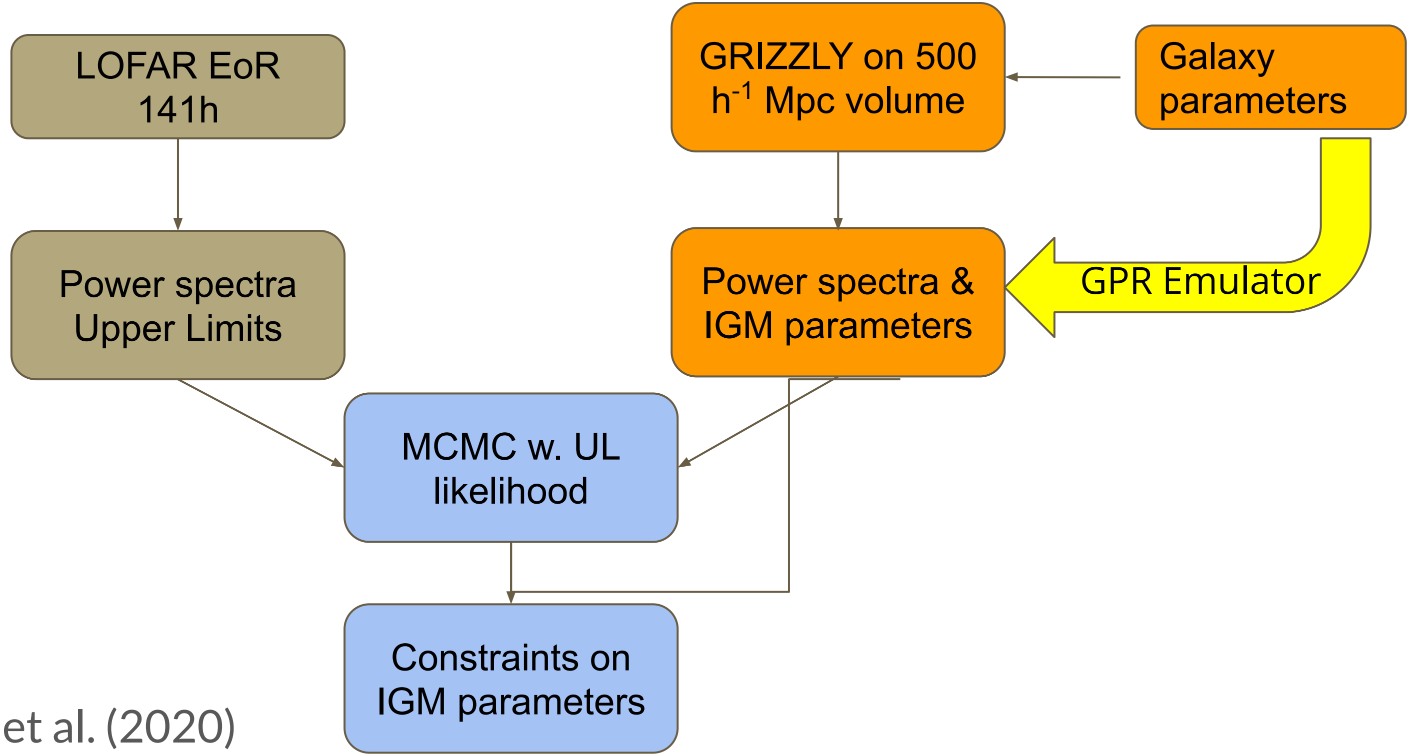
General inference



Reionization model inputs: **source parameters.**

- 21-cm signal not produced by sources
- do we trust our parametrized source model?
- do we trust our reionization model?

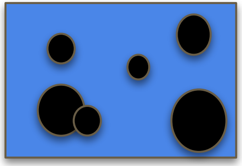
IGM inference for LOFAR ULs



Ghara, Giri, GM et al. (2020)

Inference on IGM parameters

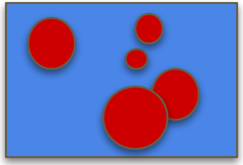
Ionized regions in IGM with uniform low $\mathbf{T_S}$:



Parameters:

- $\langle x_{HII} \rangle$
- T_S
- $(R_{peak}, \Delta R)$ sizes ionized regions
- $\langle \delta T_b \rangle$

High $\mathbf{T_s}$ regions embedded in low $\mathbf{T_s}$ environment (non-uniform $\mathbf{T_s}$):



Parameters:

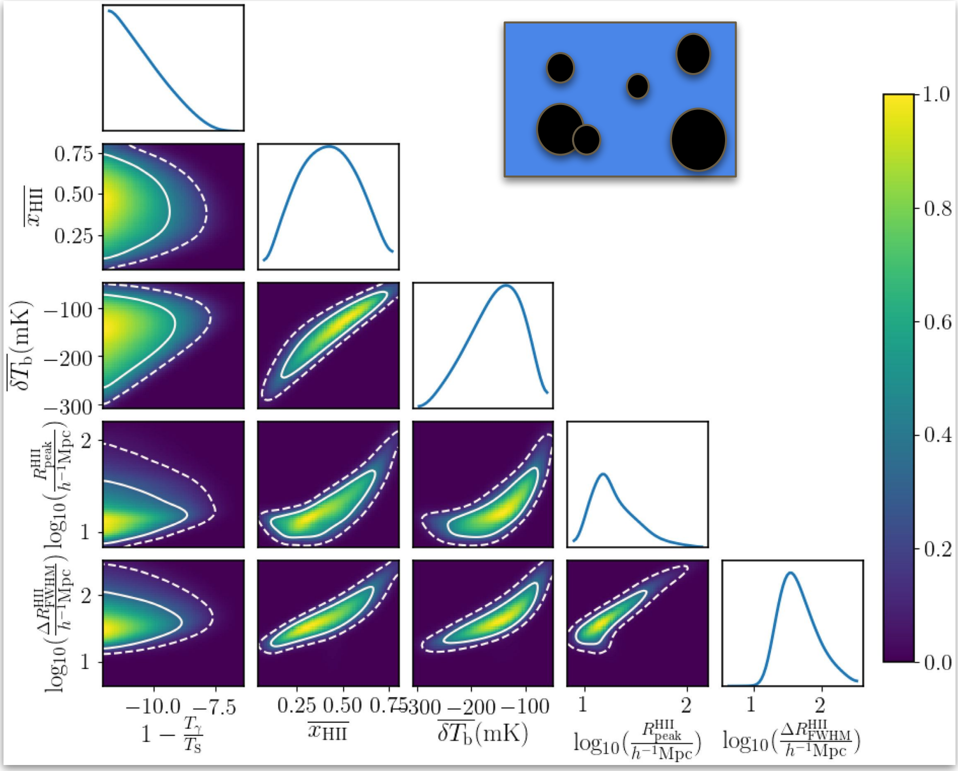
- f_{heat}
- $\langle T_S \rangle$
- $(R_{peak}, \Delta R)$ sizes heated regions
- $\langle x_{HII} \rangle$
- $\langle \delta T_b \rangle$

Ghara, Giri, GM et al. (2020)

LOFAR UL Implications for IGM

Ruled out (2σ) models must have:

- $T_S < 3$ K
- $\langle x_{HII} \rangle \in [0.13, 0.74]$
- $R_{peak} \in [8, 58]$ Mpc
- $\Delta R \in [16, 185]$ Mpc
- $\langle \delta T_b \rangle \in [-251, -57]$ mK



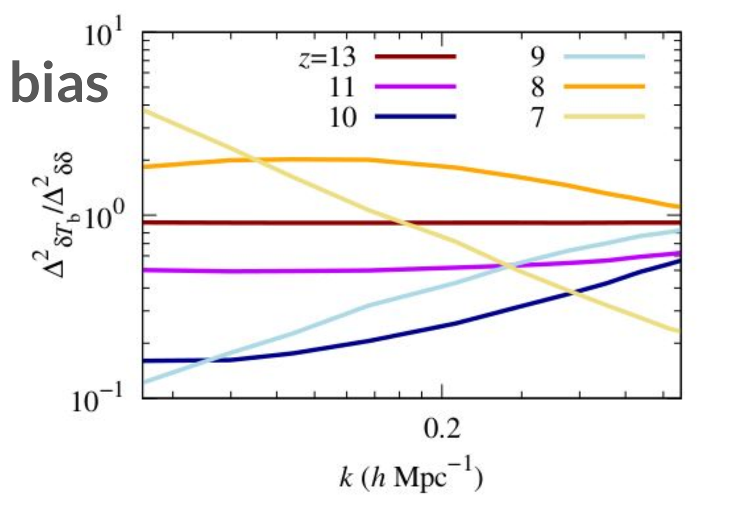
Ghara, Giri, GM et al. (2020)

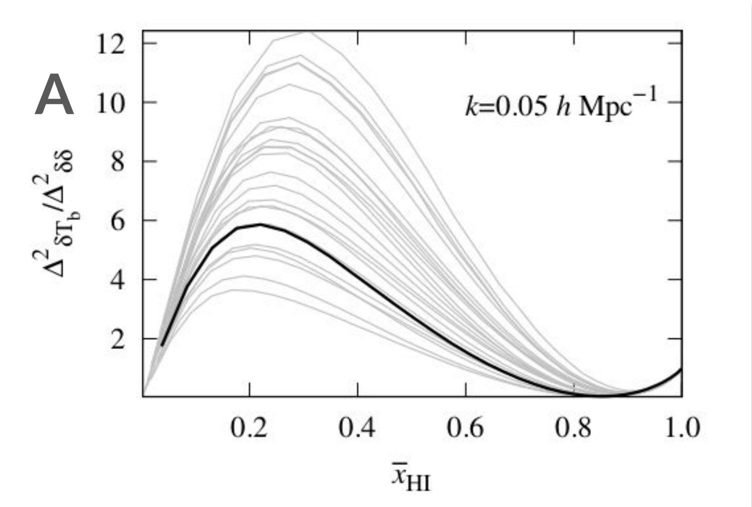
Multi-redshift Upper Limits?

- Next LOFAR EoR ULs will be for three redshifts (10.4, 9.1, 8.1); joint interpretation preferable.
- But: IGM parameters by construction constrain a single redshift.
- Do IGM parameters evolve in a predictable / parameterizable way?
- Ghara et al. (2024): 21-cm scale-dependent bias $b_{21}^2 = \frac{\Delta_{21}^2(k)}{\Delta_{\rm m}^2(k)}$

21-cm Bias Evolution

Ghara et al. (2024)





$$\Delta^2_{\delta T_b} = \begin{cases} \Delta^2_{\delta\delta} A \dfrac{\left(\frac{k}{0.05}\right)^{\gamma}}{1+\left(\frac{k}{0.3}\right)^{1.5}}, & \text{if } \bar{x}_{HI} \lesssim \bar{x}_{HI,min}. \\ \Delta^2_{\delta\delta} A \left(\dfrac{k}{0.05}\right)^{\gamma}, & \text{otherwise.} \end{cases}$$

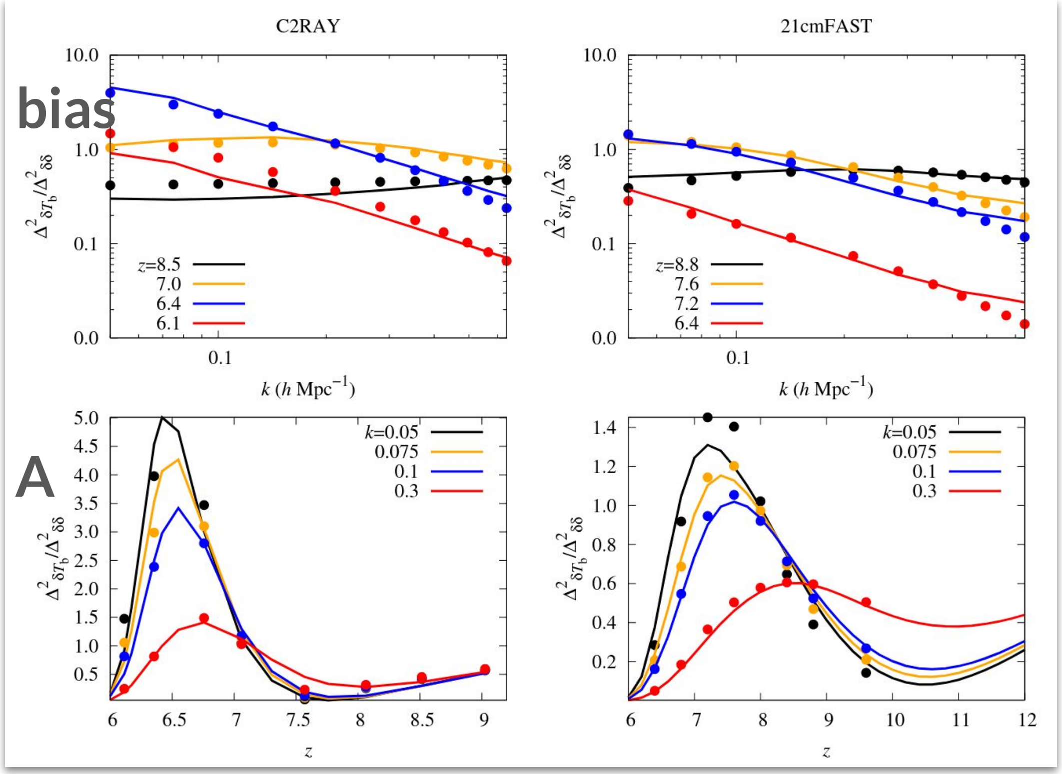
Evolution of A and γ: 5 parameters

Reionization history: 3 parameters

Testing the Bias Evolution Model

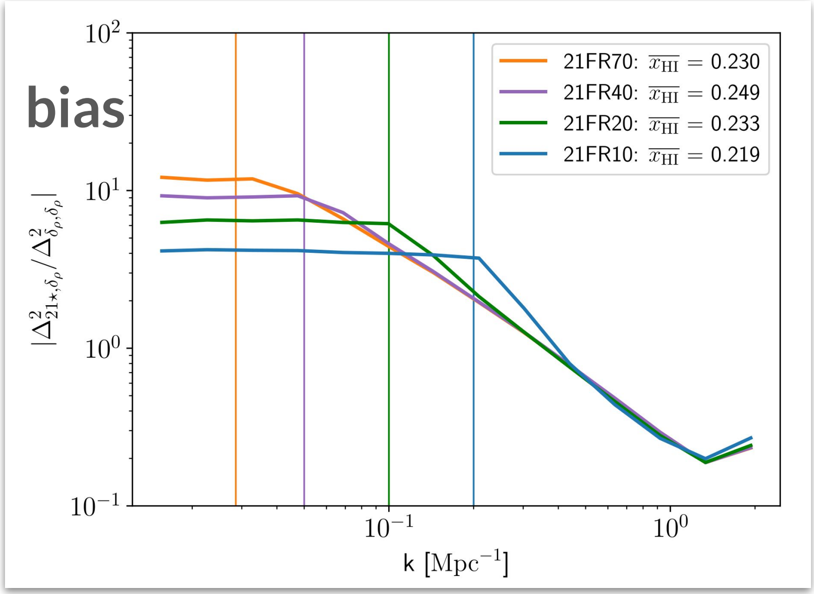
- Developed from large sample of GRIZZLY models.
- Tests on C^2Ray and 21cmFAST results show that the model is robust.

Ghara et al. (2024)



Understanding the 21-cm Bias

- Do these parameters have any physical meaning?
- Under investigation; some connections already known:
  - Break⇔mean free path for ionizing photons (Georgiev et al. 2022)
  - Amplitude at large scales ⇔ source bias & ionization fraction (e.g. McQuinn & D'Aloisio 2018)



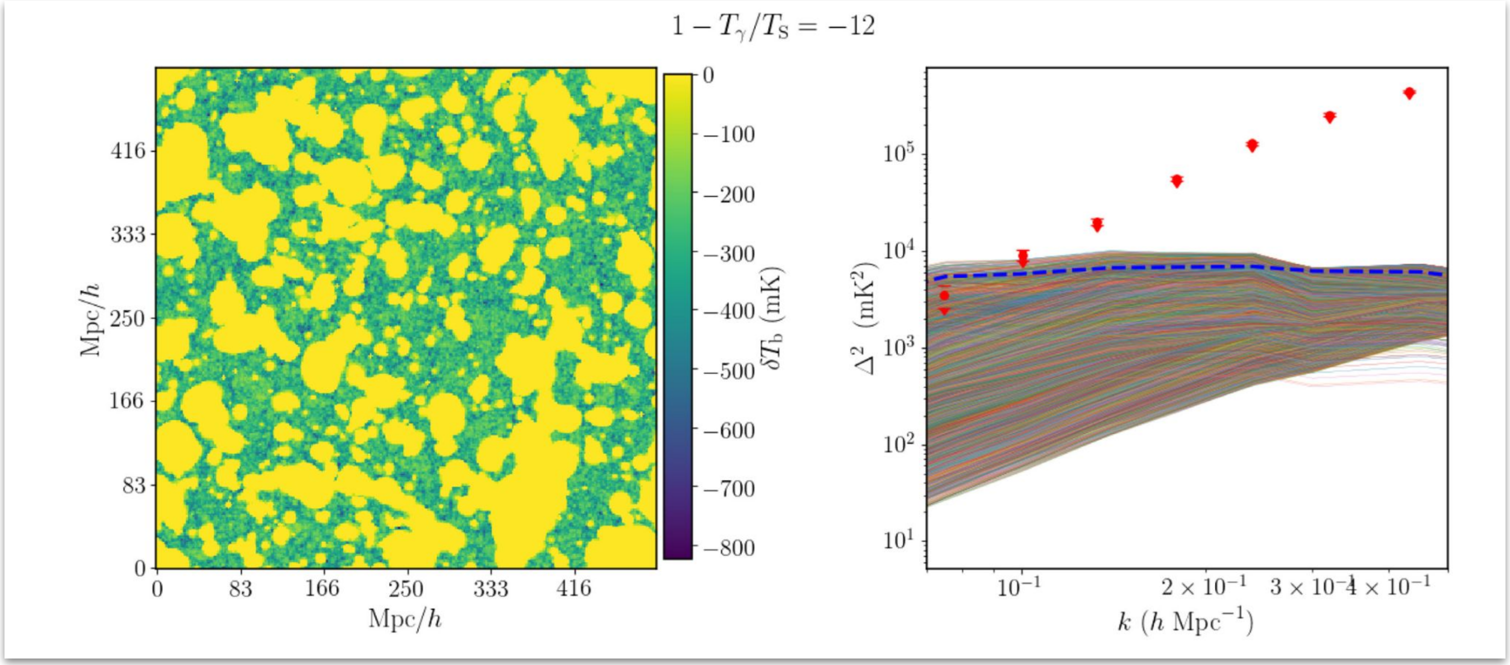
Georgiev, GM et al. (2022)

Summary

- Current upper limits are on the edge of yielding hard constraints.
- Parameter inference can be done on source parameters or IGM parameters.
- Constraints on IGM parameters should be model-independent but are for a single redshift.
- The 21-cm bias appears to yield a parameterizable evolution which can be used for IGM inference.
- The shape of the 21-cm bias curves connect to key physics but needs further investigation.

Upper limits exclude scenarios

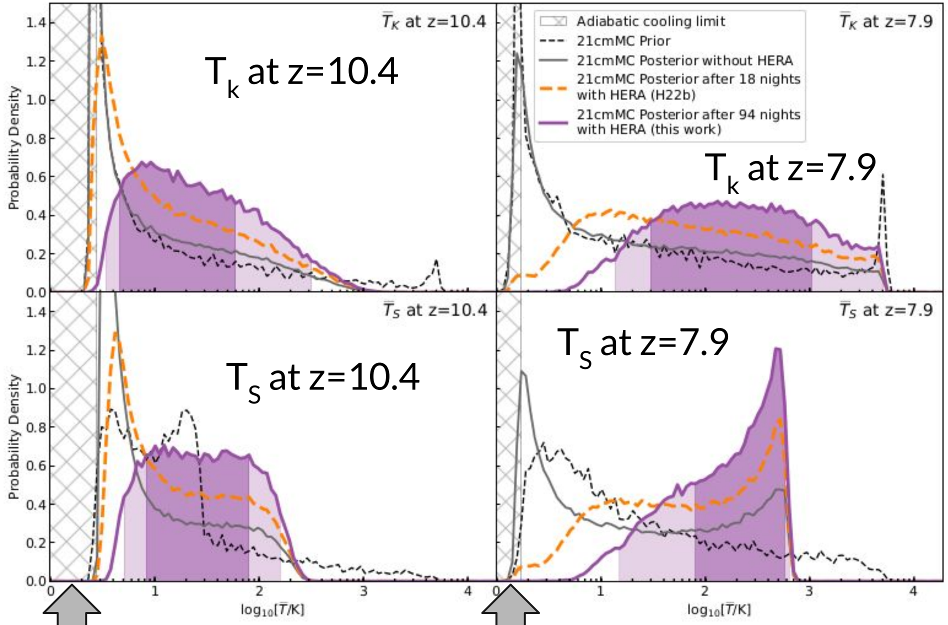
Ghara, Giri, GM et al. (2021)



LOFAR 141 hrs
$\Delta^2 < (73\ \text{mK})^2$
for
k=0.075 h Mpc^{-1}
at z=9.1

Upper limits exclude scenarios

Marginalised 1D PDFs



adiabatic values

HERA collaboration et al. (2022)
effectively 150 hrs, k=0.25 Mpc^{-1}

$\Delta^2 < (21\ mK)^2$ at z=7.9
$\Delta^2 < (59\ mK)^2$ at z=10.4

Analysis: At both z=10.4 and 7.9, the neutral IGM has been heated above the adiabatic value!