POLAR

Radio2024, Erlangen
13 Nov 2025

POLAR: Simulations of the Epoch of Reionization for studying the Intergalactic Medium 21-cm signal

ANSHUMAN ACHARYA
MAX PLANCK INSTITUTE FOR ASTROPHYSICS, GARCHING

Collaborators:
Qing-Bo Ma (Guizhou Normal University), Sambit K. Giri (NORDITA),
Benedetta Ciardi (Max Planck Institute for Astrophysics), Raghunath Ghara (IISER Kolkata),
Garrelt Mellema (Stockholm University), Saleem Zaroubi (University of Groningen) and the LOFAR EoR team.

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LOFAR

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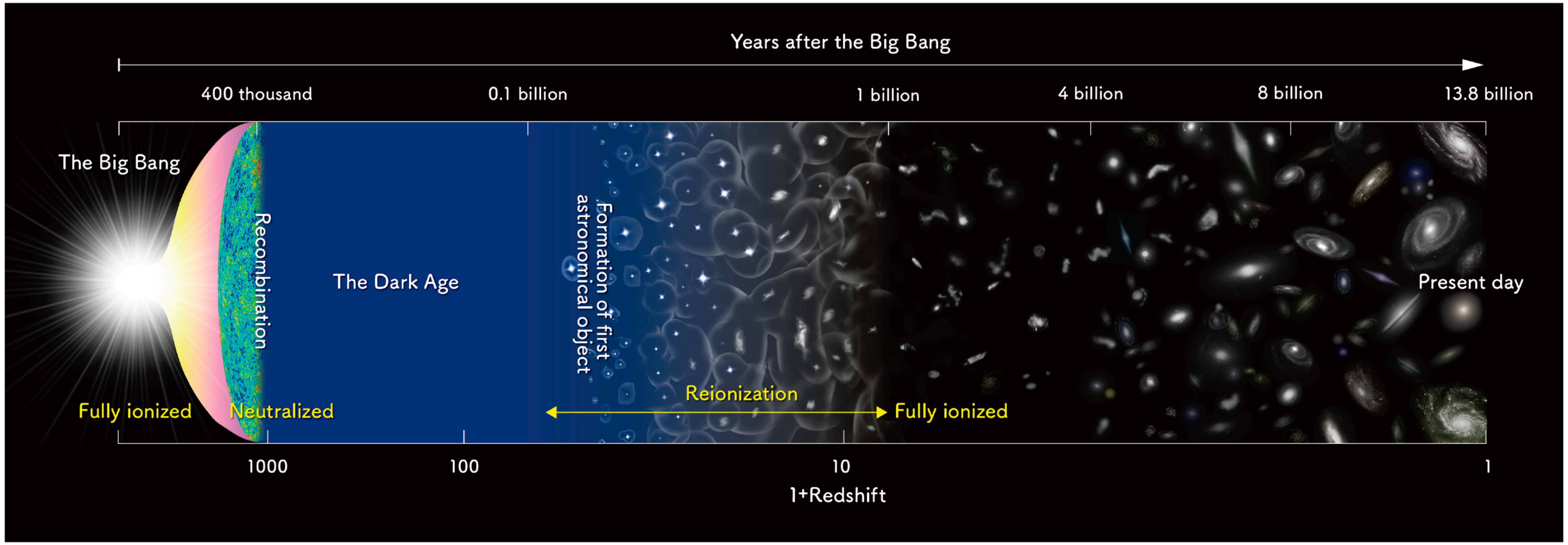
What is the Epoch of Reionization?



History of the Universe.

Anshuman Acharya | anshuman@mpa-garching.mpg.de

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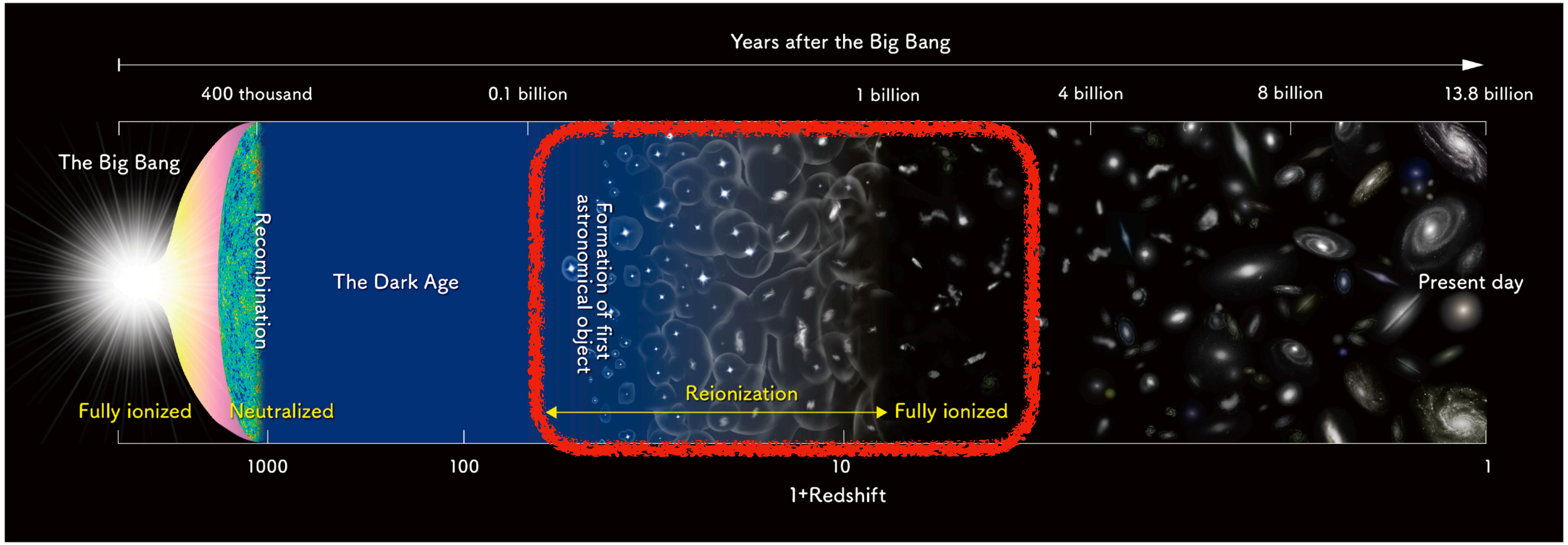
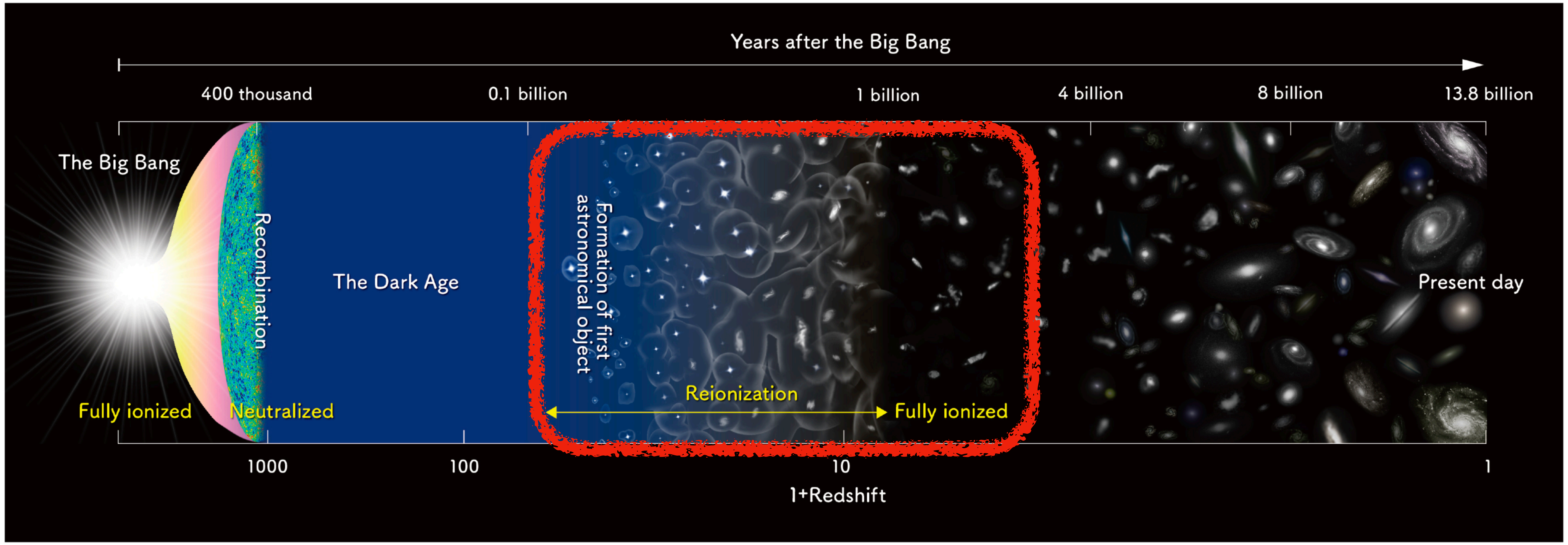


History of the Universe.

What is the Epoch of Reionization?

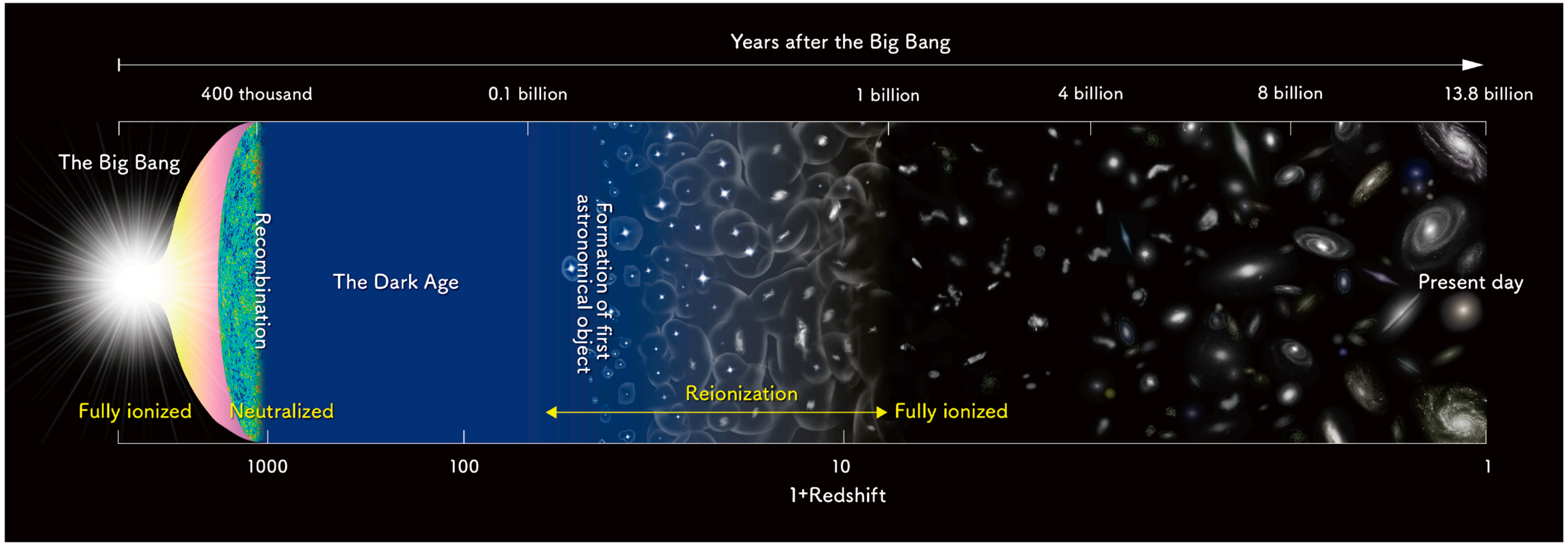
- Period when clouds of neutral H reionised by:
  - the first stars and thus…
  - the first galaxies
  - black holes,
  - and more!



History of the Universe.

Why is the Epoch of Reionization important?

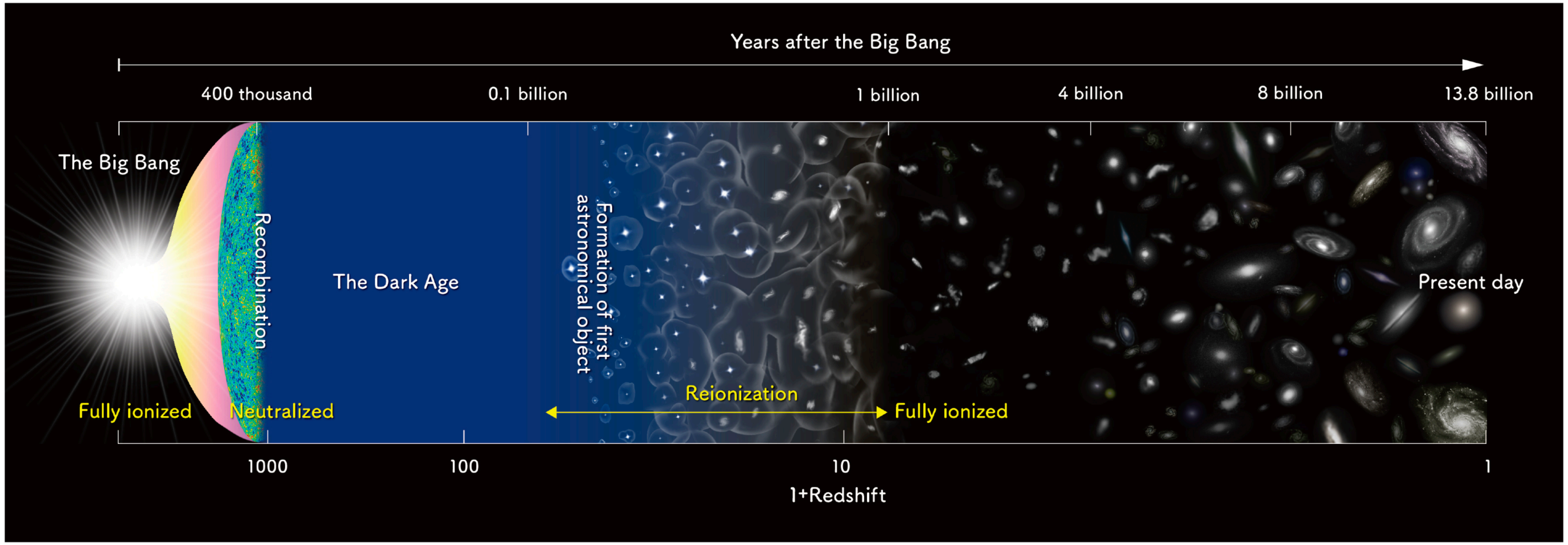
- Understanding the EoR helps in: understanding the formation and evolution of **all** astronomical objects.
- Timelines, processes, rates, etc.



History of the Universe.

How to study the Epoch of Reionization?

- Using the…



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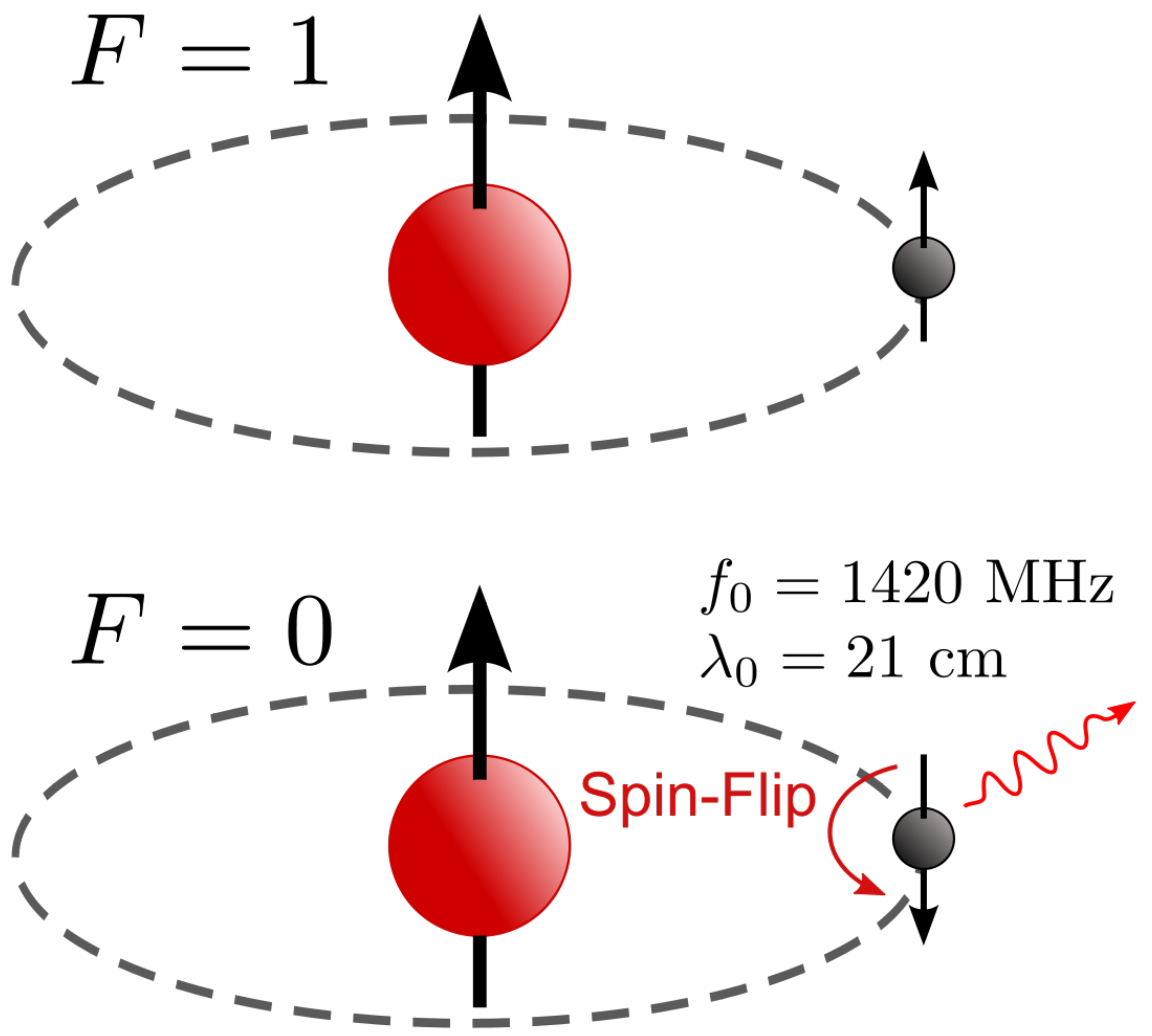
The IGM 21-cm signal

Credits: Wikimedia Commons

- **Forbidden** transition from parallel magnetic dipole moments of proton and electron spins to antiparallel.

- Usually collisional de-excitation and not radiative.



Simplified depiction of the 21-cm photon emission.

The IGM 21-cm signal

- **Forbidden** transition from parallel magnetic dipole moments of proton and electron spins to antiparallel.

- Usually collisional de-excitation and not radiative.

- But **IF**, gas clouds have really low densities (~1 atom/m^3!)…

- And **IF** we have large amounts of low-density neutral H gas clouds, there are enough photons for detection!

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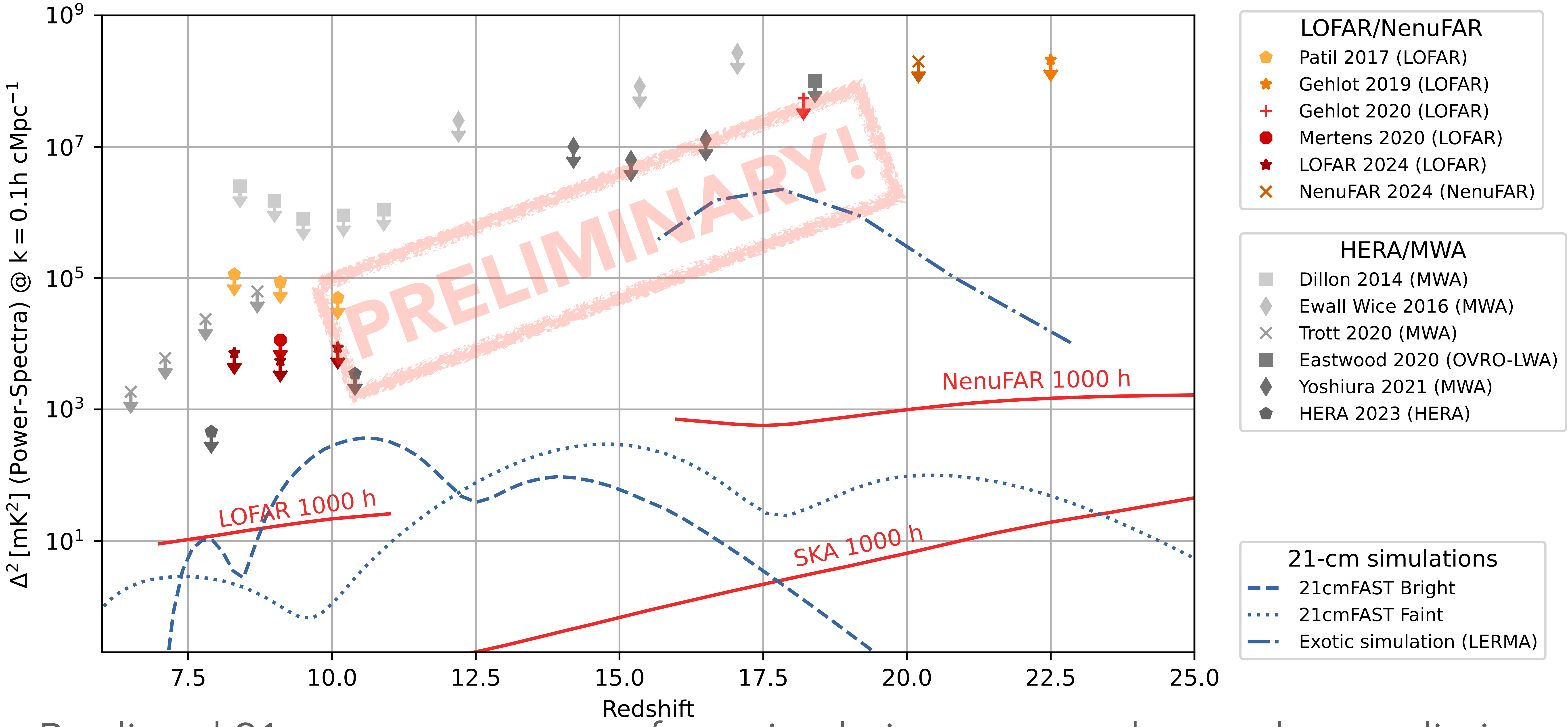
Where are we currently?

LOFAR's efforts with ML-GPR

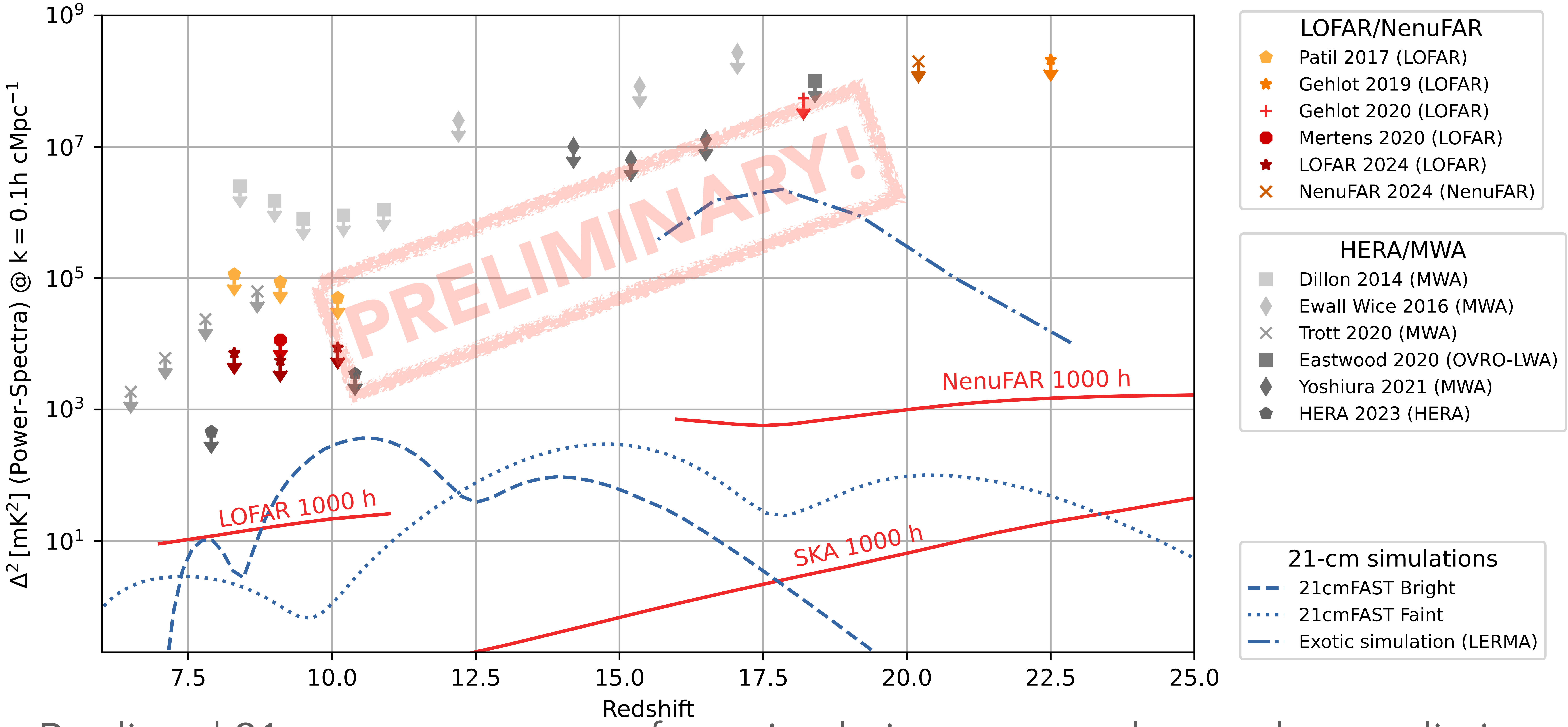


Predicted 21-cm power spectra from simulations versus observed upper limits.

Credits: Florent Mertens.

LOFAR's efforts with ML-GPR

- **ML-GPR✧:** 21-cm signal power spectrum template, used in Gaussian Process Regression.



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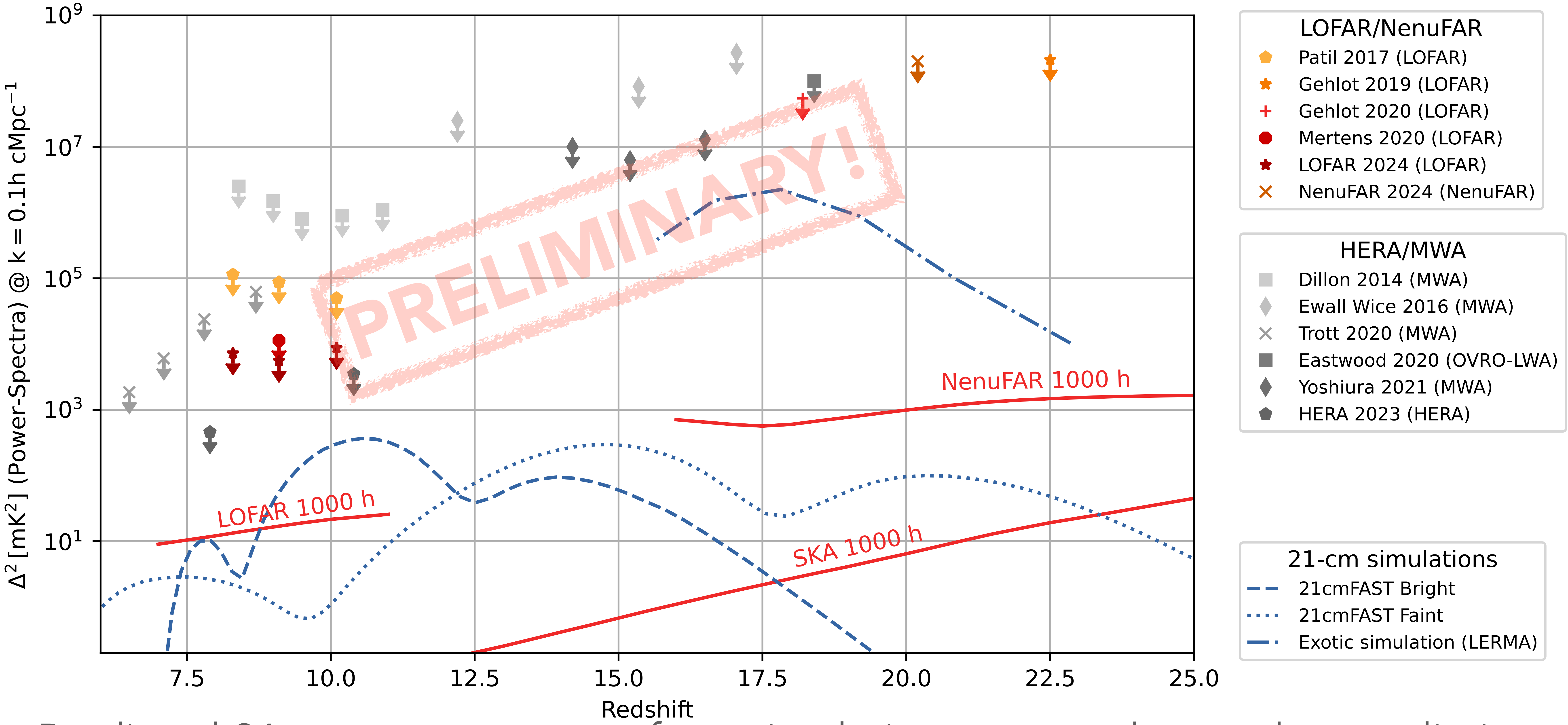
✧Mertens+24, **Acharya+24a,b**

LOFAR's efforts with ML-GPR

- **ML-GPR✧:** 21-cm signal power spectrum template, used in Gaussian Process Regression.
- Template built by training on the GRIZZLY✧✧ simulations: N-body + Radiative Transfer.
- More robust, better separation from systematics.



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✧✧Ghara+18,20

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Need for new simulations

- GRIZZLY assumed properties of baryons in a simplified manner, thus not taking into account complexities of star formation, supernova feedback, AGN, etc.

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- A bias in the training set could decide the possibility of detection, even with more data.

- **Solution:** using a semi-analytic model, to factor in baryonic processes.

- This is achieved by using L-Galaxies along with Radiative Transfer.

- Faster than full RHD simulations, especially for IGM scales (> 150 Mpc/h).

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The POLAR simulations

- The model✧:
  - N-body (GADGET-4), L = 150 Mpc/h, N = 2048^3 particles, $m_p = 5 \times 10^7 M_\odot$, with 156 snapshots between z = 25 to 5.
  - Post-processed with L-Galaxies to factor in galaxy evolution.
  - And with 1D radiative transfer from GRIZZLY.

✧Ma+23, **Acharya+24c submitted**

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for first tests

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  - Post-processed with L-Galaxies to factor in galaxy evolution.
  - And with 1D radiative transfer from GRIZZLY.
  - If we can vary the astrophysics, how much does it need to vary to make different cosmologies viable?

✧Ma+*2023*, ***Acharya+2024c submitted***

Alternative cosmologies

Fiducial cosmology:

$$\Omega_{\rm m} = 0.3111,\ \Omega_\Lambda = 0.6889,\ \Omega_{\rm b} = 0.04897,\ h = 0.6766,\ \sigma_8 = 0.8102$$

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***h* high cosmology (from SH0ES+HST, 2022):**

$\Omega_m = 0.3111,\ \Omega_\Lambda = 0.6889,\ \Omega_b = 0.04897,\ h = 0.7330,\ \sigma_8 = 0.8102$

higher h,
higher matter
clustering

Alternative cosmologies

σ_8 high case (from eROSITA, 2024):

$\Omega_m = 0.3111,\ \Omega_\Lambda = 0.6889,\ \Omega_b = 0.04897,\ h = 0.6766,\ \sigma_8 = 0.880$

Fiducial cosmology:

$\Omega_m = 0.3111,\ \Omega_\Lambda = 0.6889,\ \Omega_b = 0.04897,\ h = 0.6766,\ \sigma_8 = 0.8102$

σ_8 low cosmology (from BOSS+KV450, 2020):

$\Omega_m = 0.3111,\ \Omega_\Lambda = 0.6889,\ \Omega_b = 0.04897,\ h = 0.6766,\ \sigma_8 = 0.702$

higher/lower σ_8, higher/lower matter clustering

Astrophysical Parameters

- L-Galaxies: Star formation efficiency, energy released per supernova.
- GRIZZLY: $f_{\rm esc}$ = 12.5%, such that the fiducial model reionizes by z = 5.
- GRIZZLY: ionizing photons only from stars (X-ray binaries, AGN, shock-heated ISM, not included).

Astrophysical Parameters

tuned to low-z observations

Parameter	H15	H20	fiducial	s8low	s8high	hhigh
$\alpha_{\rm SF}$	0.025	0.060	**0.20**	**0.50**	**0.20**	**0.20**
$\alpha_{\rm SF,burst}$	0.60	0.50	**0.80**	**0.90**	**0.80**	**0.80**
$\beta_{\rm SF,burst}$	1.90	0.38	0.38	0.38	0.38	0.38
$k_{\rm AGN}$ $[10^{-3}{\rm M}_\odot\ {\rm yr}^{-1}]$	5.3	2.5	**2.0**	**2.0**	**2.0**	**2.0**
$f_{\rm BH}$	0.041	0.066	0.066	0.066	0.066	0.066
$V_{\rm BH}$ $[{\rm km\ s}^{-1}]$	750	700	700	700	700	700
$M_{\rm r.p.}$ $[10^{14}{\rm M}_\odot]$	1.2	5.1	5.1	5.1	5.1	5.1
$\alpha_{\rm dyn.fric.}$	2.5	1.8	1.8	1.8	1.8	1.8
$\epsilon_{\rm reheat}$	2.6	5.6	**8.0**	**8.0**	**8.0**	**8.0**
$V_{\rm reheat}$ $[{\rm km\ s}^{-1}]$	480	110	**250**	**250**	**250**	**250**
$\beta_{\rm reheat}$	0.72	2.90	2.90	2.90	2.90	2.90
$\eta_{\rm eject}$	0.62	5.50	5.50	5.50	5.50	5.50
$V_{\rm eject}$ $[{\rm km\ s}^{-1}]$	100	220	220	220	220	220
$\beta_{\rm eject}$	0.8	2.0	2.0	2.0	2.0	2.0
$\gamma_{\rm reinc.}$ $[10^{10}\ {\rm yr}^{-1}]$	3.0	1.2	1.2	1.2	1.2	1.2
$E_{\rm SN}$ $[10^{51}\ {\rm erg}]$	1.0	1.0	**0.80**	**0.15**	**2.00**	1.0
$Z_{\rm yield}$	0.030	0.030	0.030	0.030	0.030	0.030

Parameter table of L-Galaxies.

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UV Luminosity Functions

UVLFs at z = 9 and 10. **We also reproduce recently observed bright galaxies at $z \geq 14$**!

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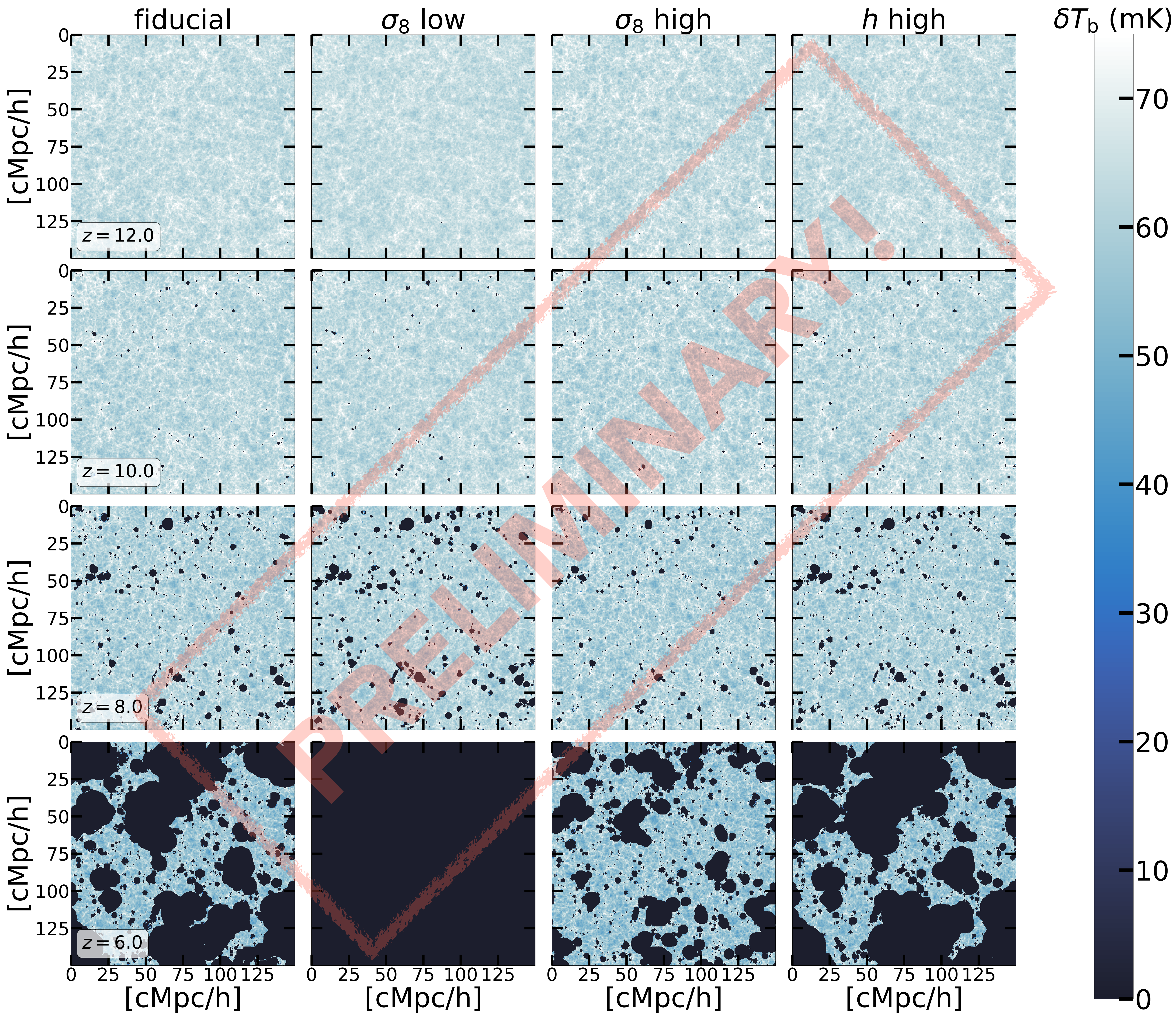
21-cm signal: δT_b

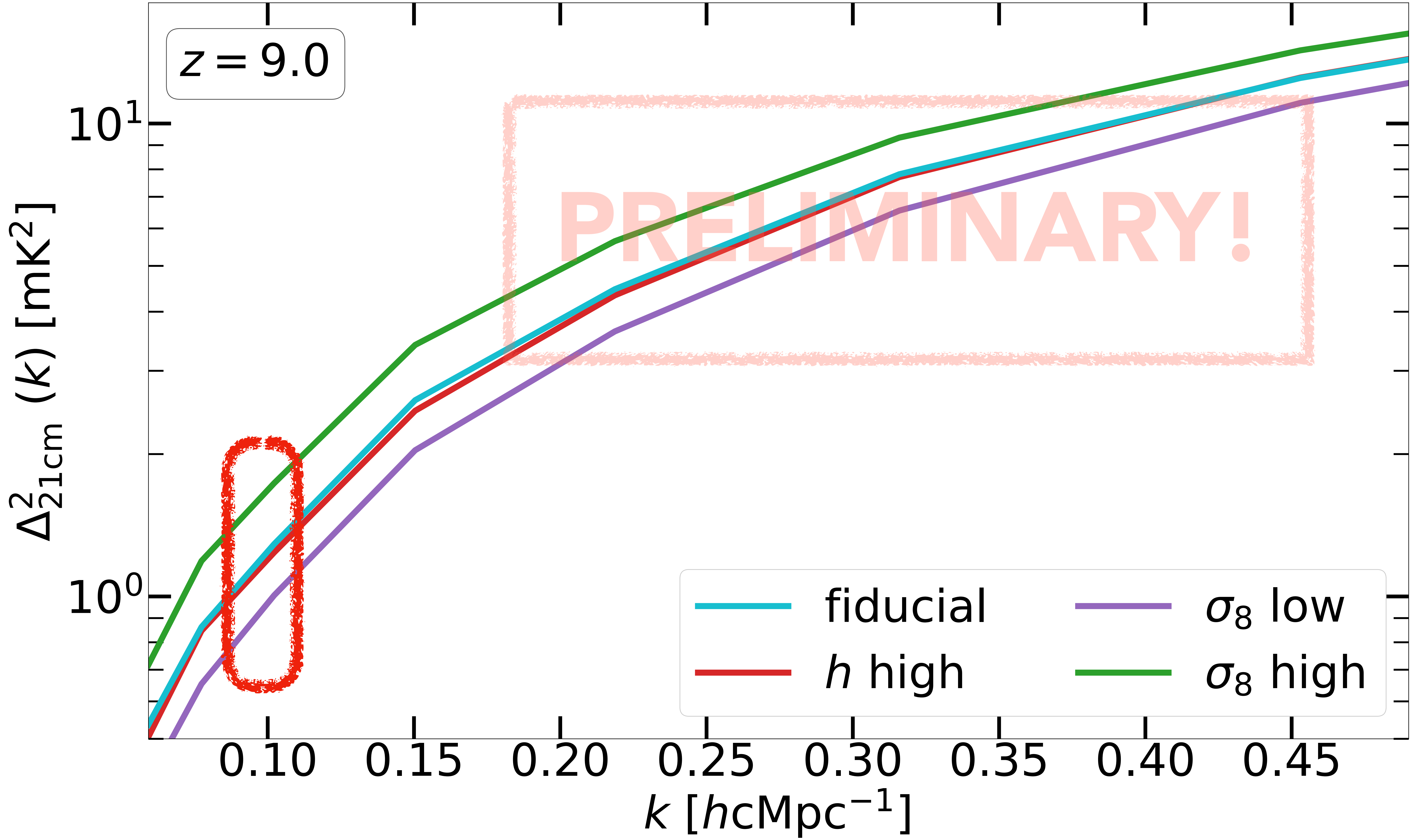
- **Low σ_8:** low $\mathrm{E_{SN}}$ and more star formation after enough clumping → faster reionization!
- **High σ_8:** high $\mathrm{E_{SN}}$ blows away gas leading to slower star formation → slower reionization.
- **High h:** faster reionization.



Differential brightness temperature map slices across redshifts.

Acharya+24c, submitted

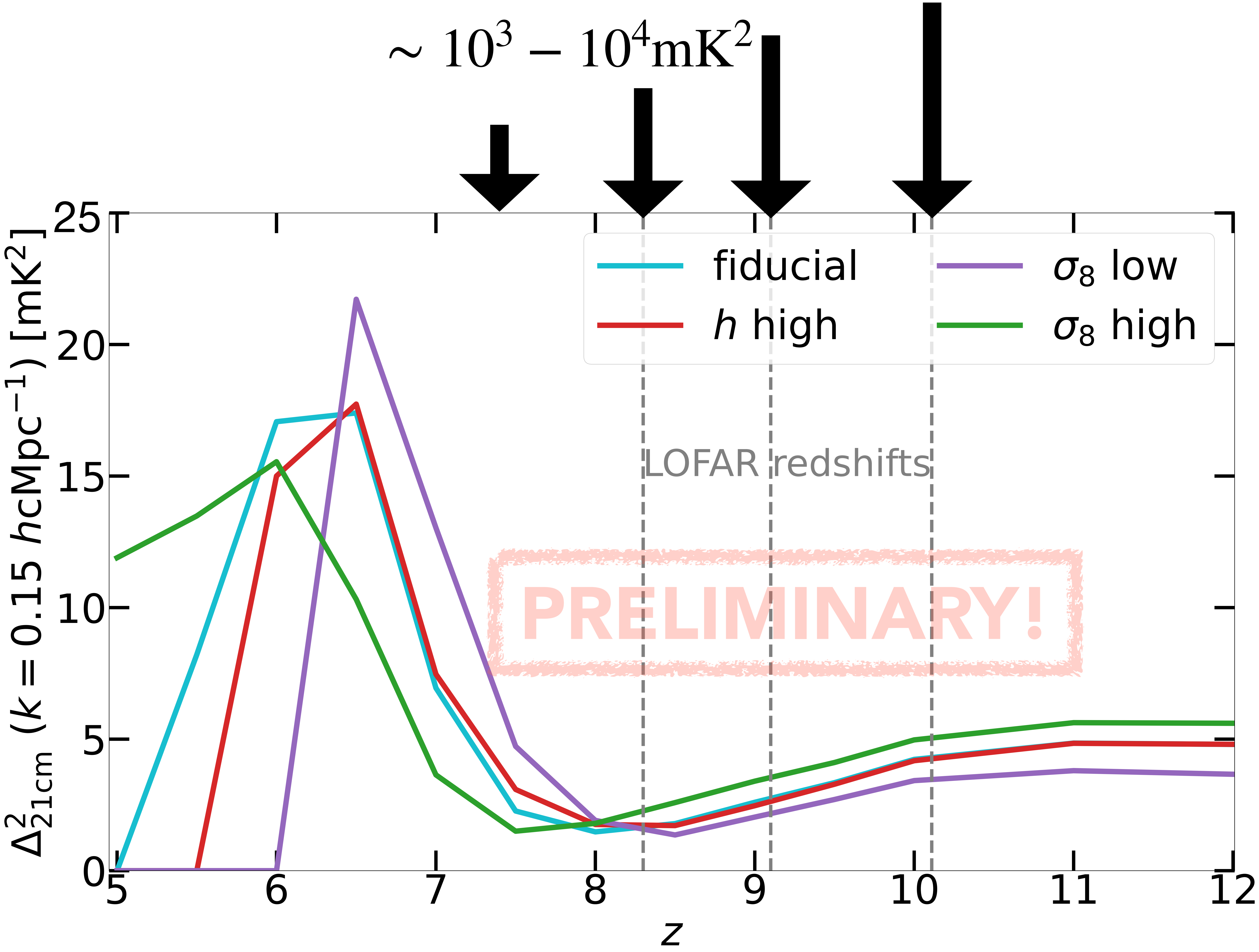
21-cm signal: Power spectrum



Acharya+24c, submitted

21-cm signal: Power spectrum

- **Expected signal is weak:** while better modeling is expected to strengthen the signal, a qualitative agreement between models and deeper upper limits is expected.
- **Conclusion:** despite differing cosmologies and astrophysics, similar observables are possible.



21-cm power spectrum at $k = 0.15\ h\mathrm{cMpc}^{-1} \approx 0.1\ \mathrm{cMpc}^{-1}$ across redshift.

Acharya+24c, submitted

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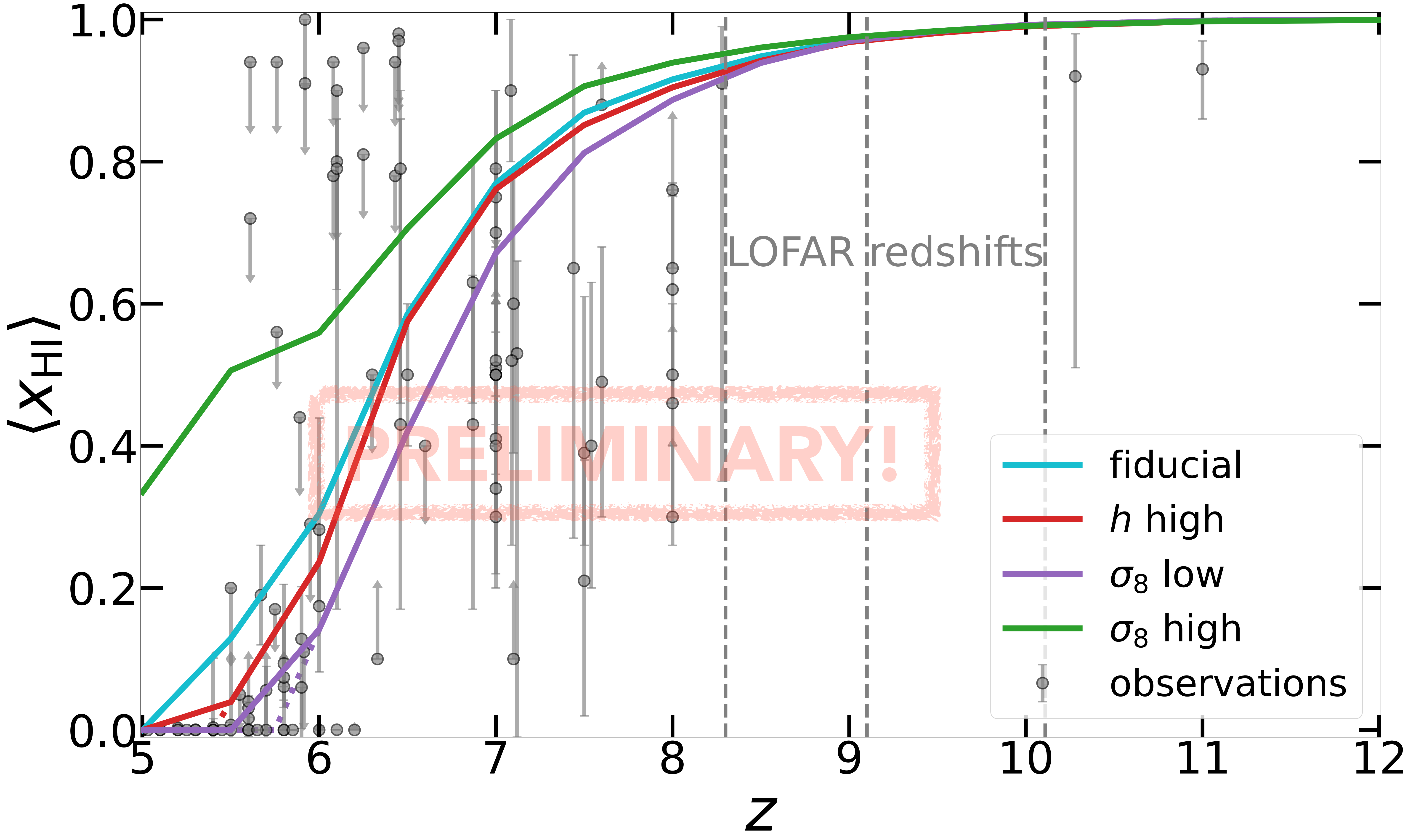
Neutral Hydrogen Fraction: possible probe?

- Stronger constraints on the end of EoR from Lyman-α forest observations can constrain models!
- Multi-wavelength parameter inference is necessary.



Volume averaged neutral H fraction across redshifts.

Acharya+24c, submitted

Plans Ahead

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- Multi-observation constraints: JWST, Euclid, LIM experiments, and more!
- Resolution boosting as multiple high-res simulations is too expensive.
- Diffusion modeling to introduce super-resolved dark matter halos.
- Train ML-GPR on POLAR and apply it to LOFAR data.

On the postdoc job market; suggestions welcome!

Questions?

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