
MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK
BERKELEY CENTER for
COSMOLOGICAL PHYSICS

- **June 2021:** Bachelor's + Master's in Physics (with a minor in Astronomy) at IISER Mohali, Chandigarh/SAS Nagar, India.

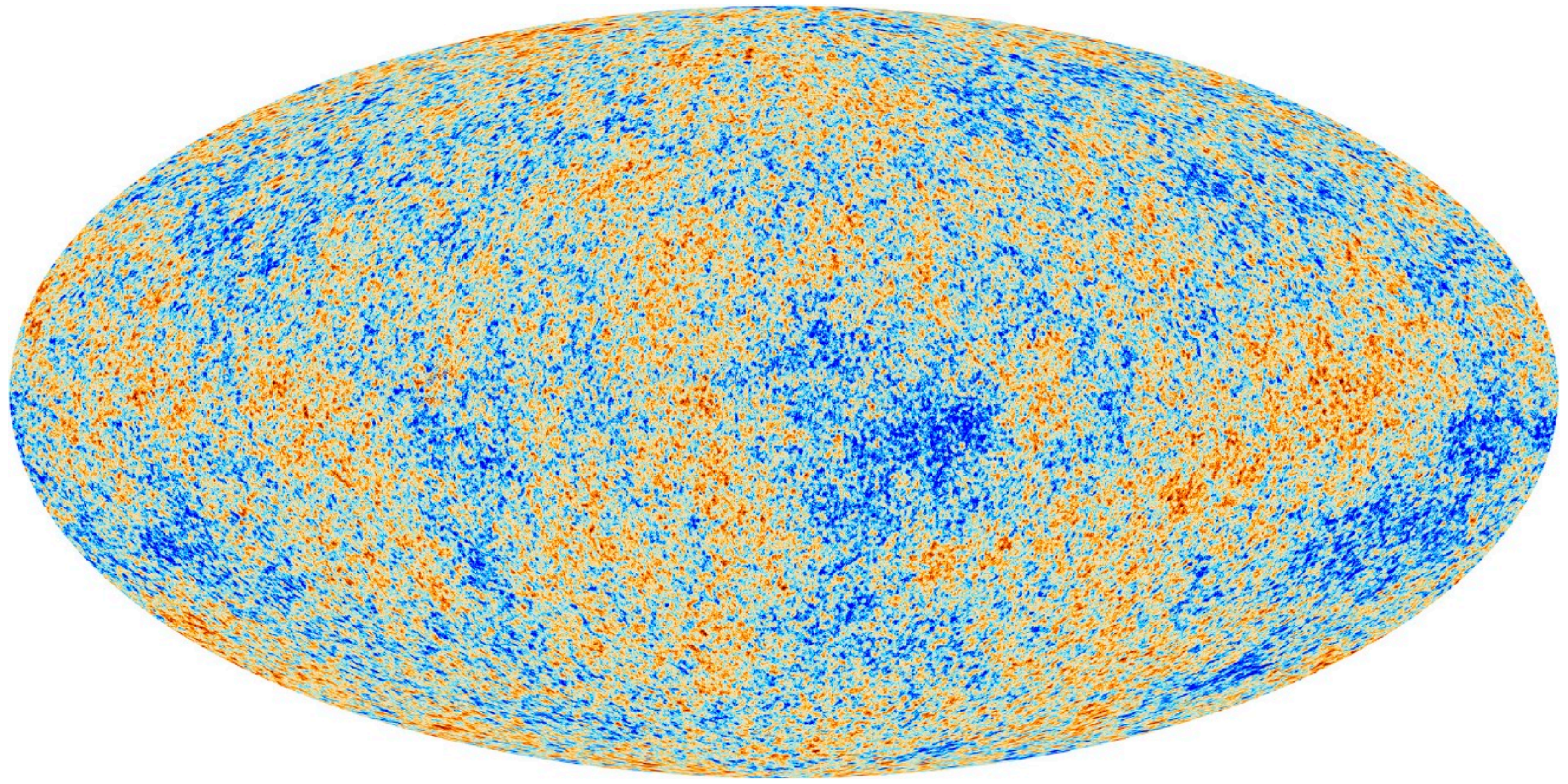
- **July 2025:** PhD in astronomy, at the Max Planck Institute for Astrophysics, Garching, Germany.

- **September 2025 onwards:** at BCCP, working with Simone Ferraro as a part of the *"Learning the Universe"* collaboration.

pictures from my PhD defense!

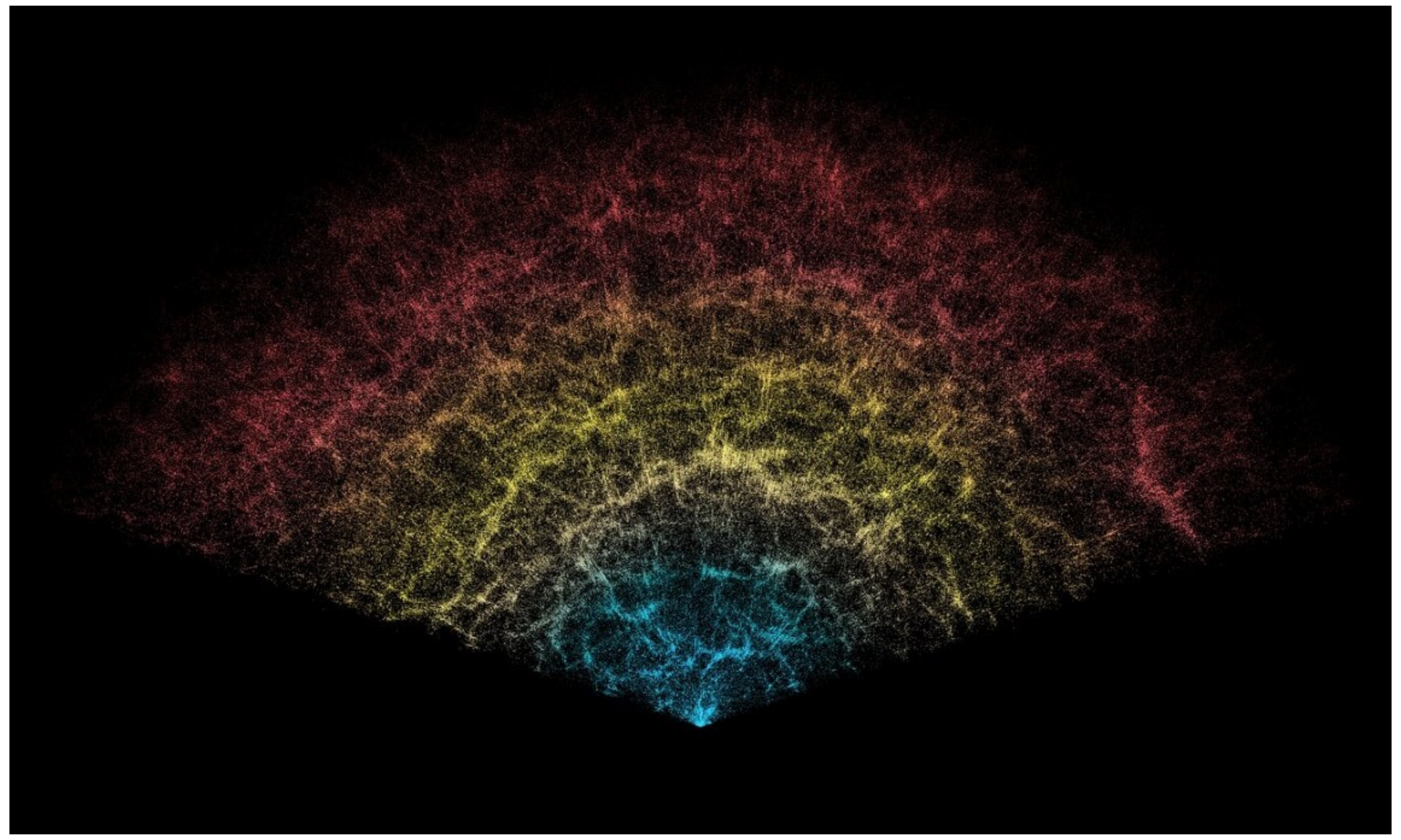
Anshuman Acharya | anshumana@berkeley.edu

t = 400,000 yr



z = 1100

t = 1.5 to 13.8 Gyr



z = ~4 to 0

- CMB + galaxy surveys (BOSS, DESI, etc.) → Λ-CDM model defined with just 6 parameters.
- However, some questions linger.
- In particular, most of these arise from differing measurements of the low and high-redshift Universe!

Hubble tension

S_8 tension

Evolving Dark Energy

SI/fuzzy DM

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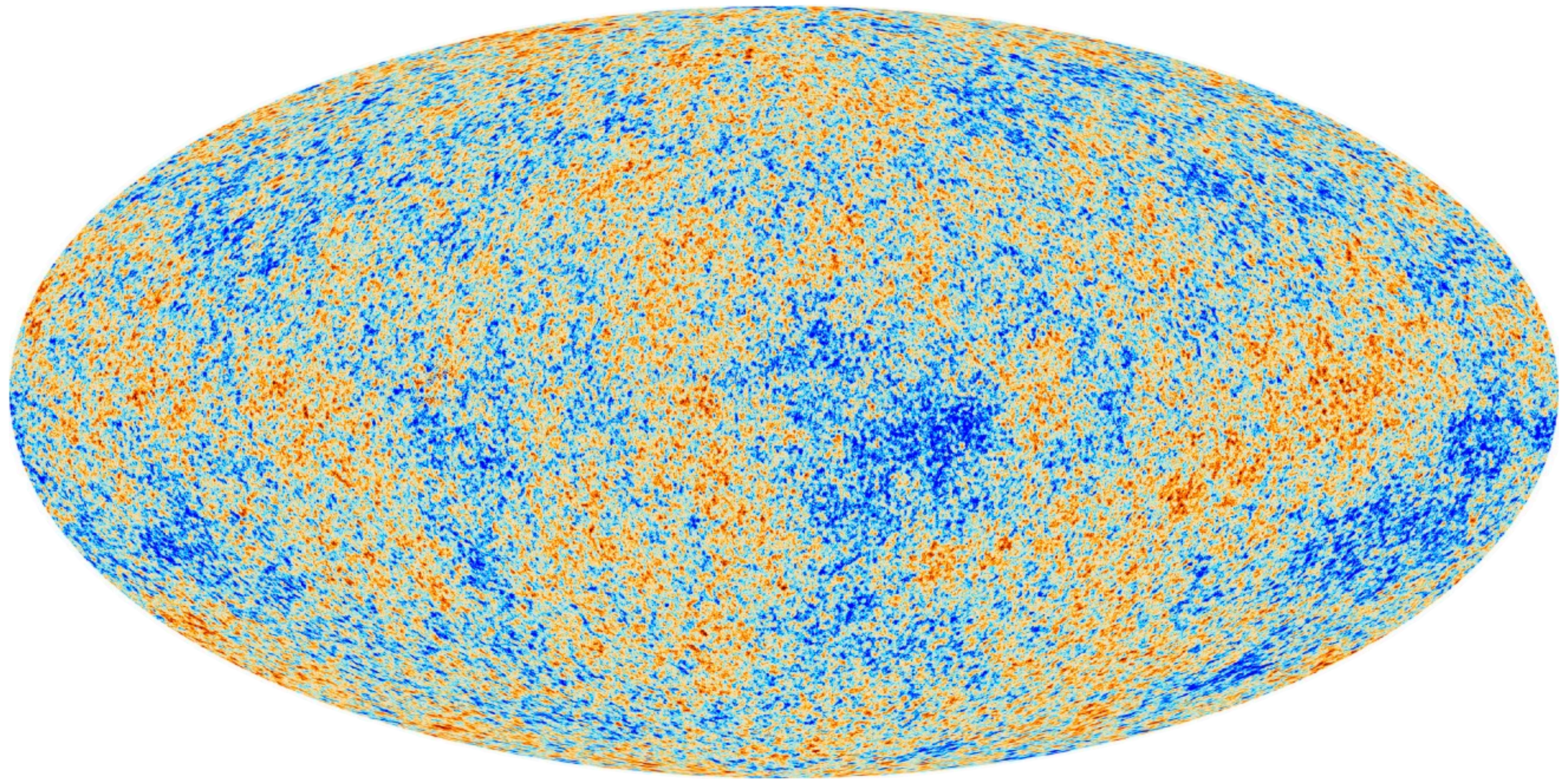

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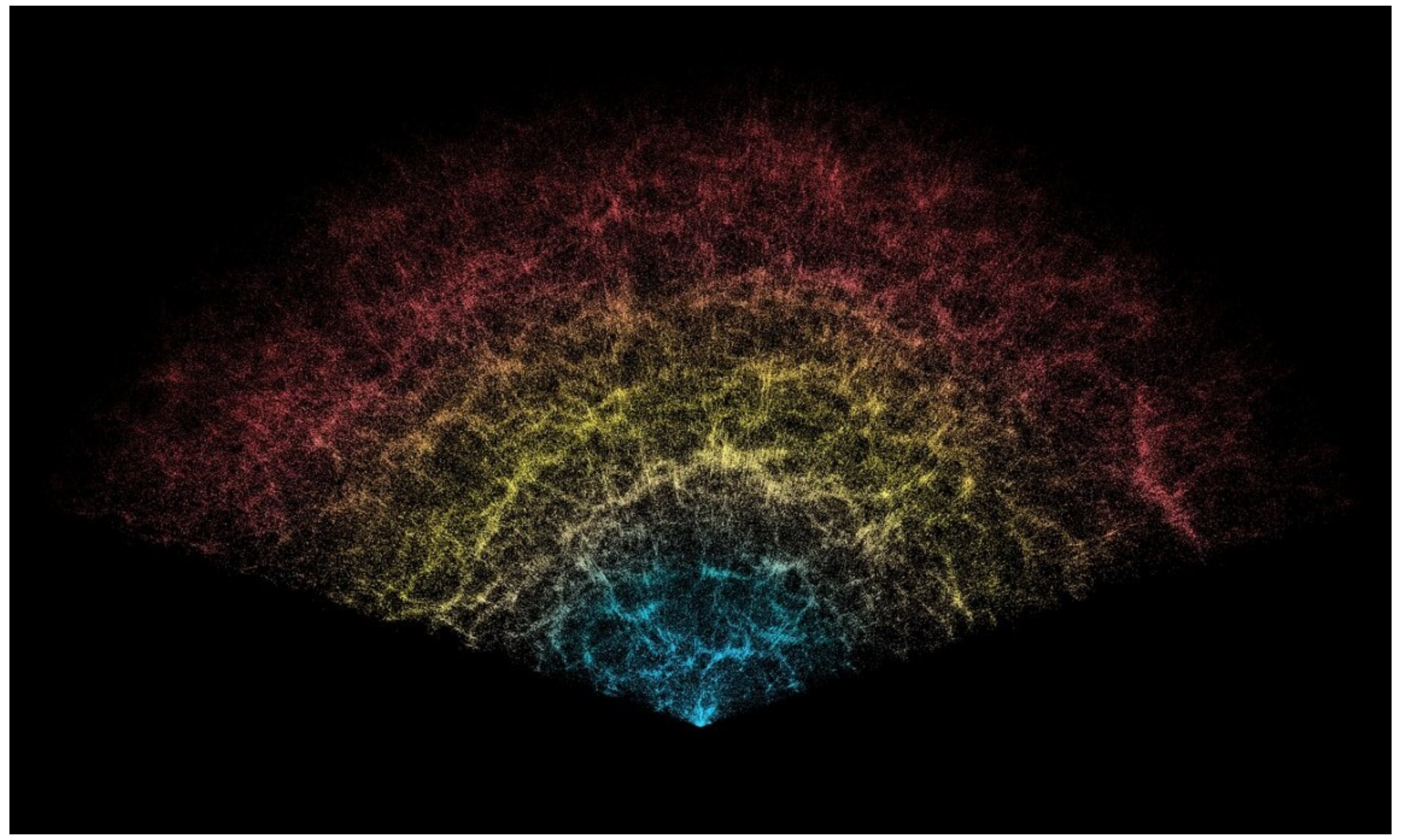

z = ~4 to 0

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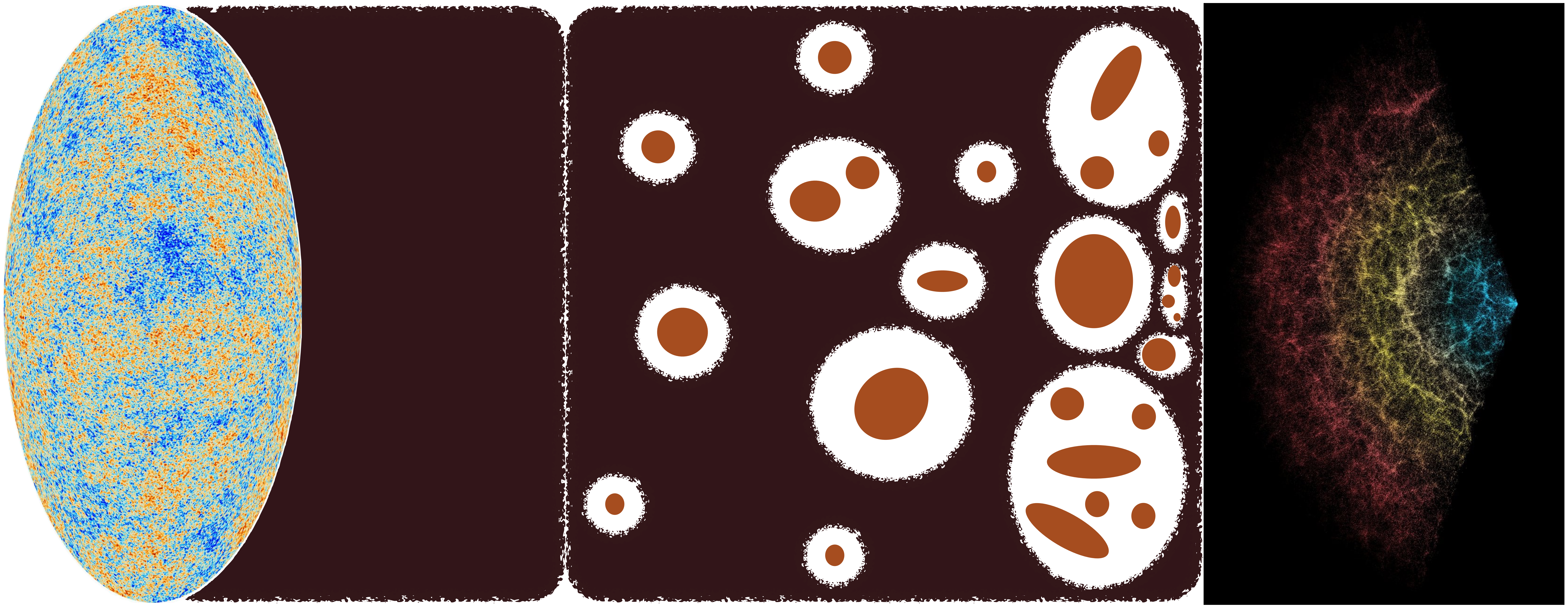
t = 400,000 yr   t = 0.1 Gyr   t = 1.2 Gyr   t = 1.5 to 13.8 Gyr



z = 1100   z = 25   z = 5   z = ~4 to 0

Dark Ages   **Epoch of Reionization**

Anshuman Acharya | anshumana@berkeley.edu

- **Setting the stage with cosmology:** matter clustering, DM properties, etc., decides *where* galaxies form.

- **Writing the script with astrophysics:** astrophysical processes govern *how* galaxies form and evolve, the role of exotic objects (SMBHs, X-ray binaries, etc.), and more.

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- **Clues that EoR provides for cosmology:**

  ➡ **Duration and patchiness of reionization:** affects optical depth measurements from CMB, as well as secondary anisotropies (kSZ).

  ➡ **Drivers of reionization:** the population of dwarf galaxies in mini DM halos can significantly impact the timing of reionization, and is crucially dependent on the nature of DM and matter clustering.

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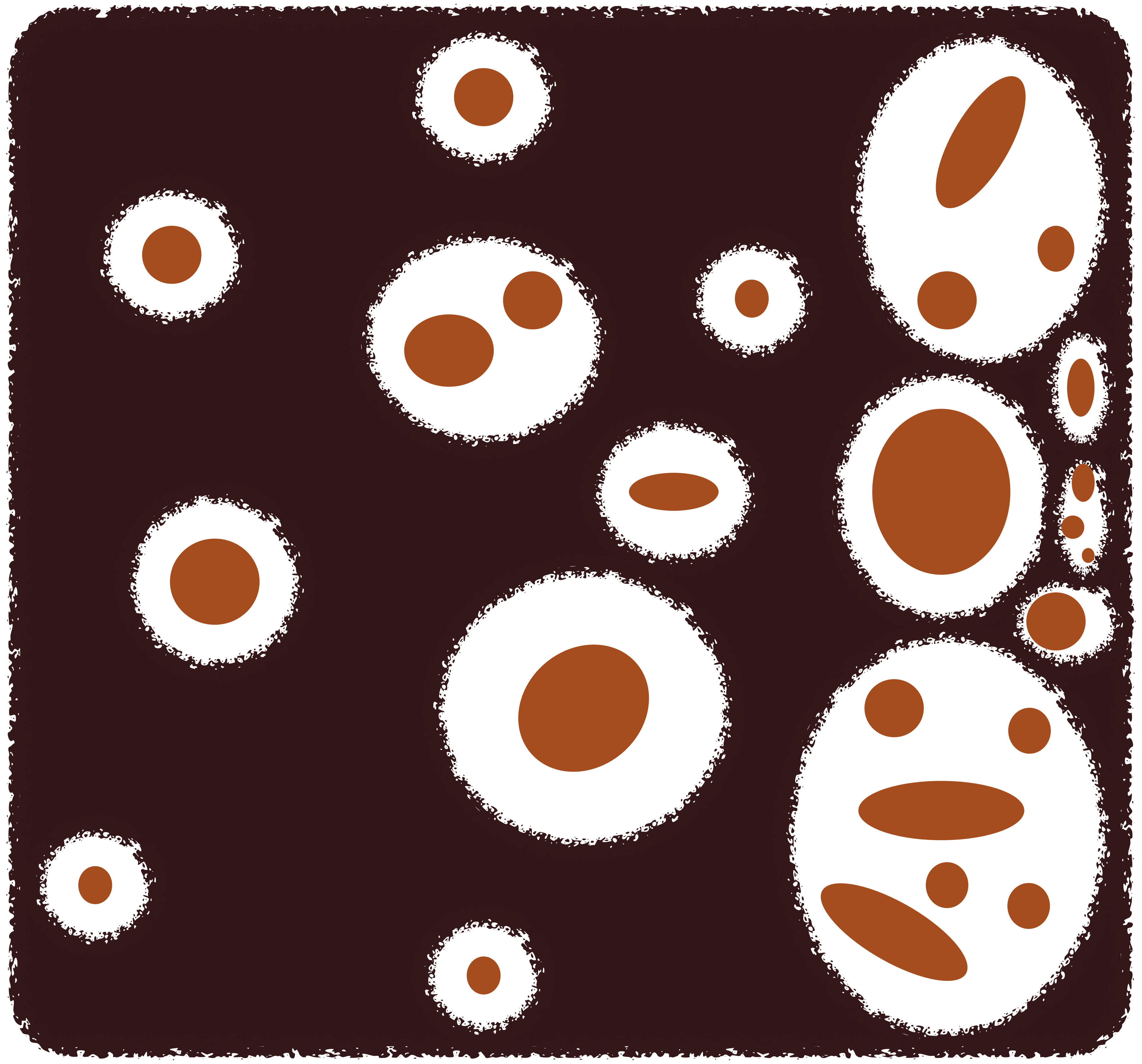
- One way to study the EoR: seek statistical samples of galaxies, AGNs, etc., across EoR redshifts.
- OR, **study the overall Intergalactic Medium!**

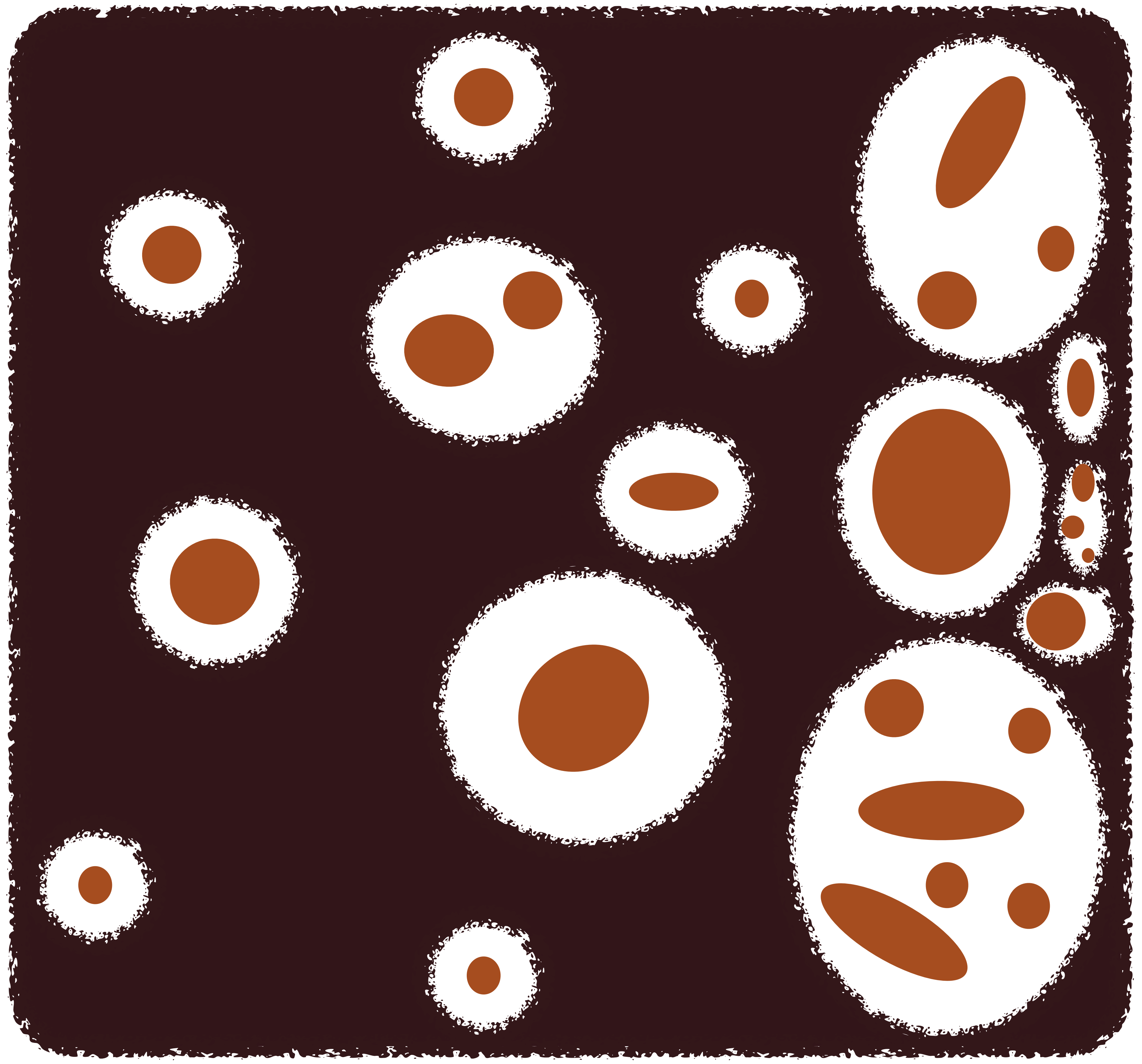


my attempt at showcasing the timeline of reionization.

Anshuman Acharya | anshumana@berkeley.edu

- One way to study the EoR: seek statistical samples of galaxies, AGNs, etc., across EoR redshifts.
- OR, **study the overall Intergalactic Medium!**
- This can be done using the 21-cm signal of neutral Hydrogen.
- A *forbidden spin-flip transition*, as typically, collisional de-excitation dominates.

t = 0.1 Gyr   t = 1.2 Gyr



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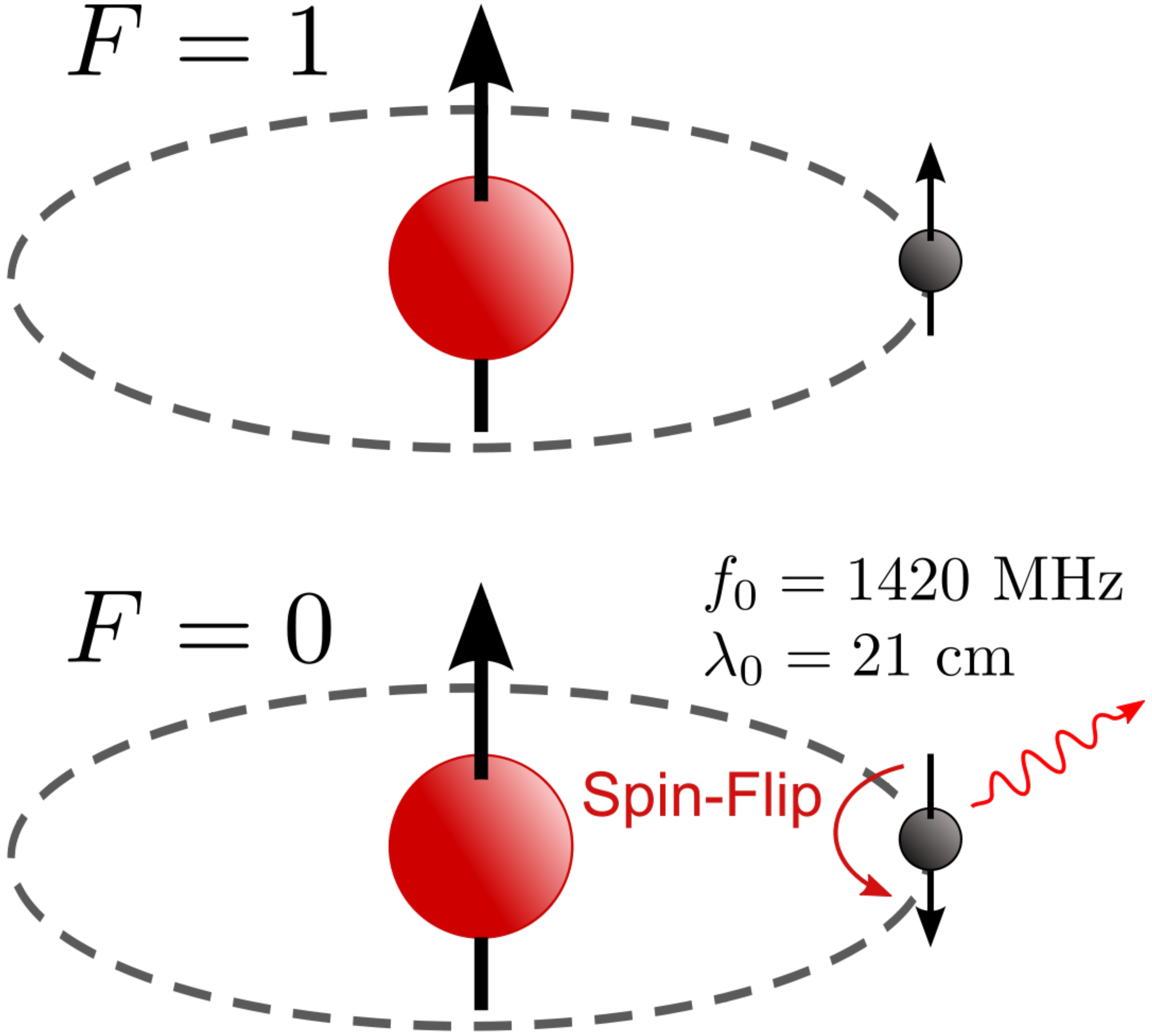

Simplified depiction of the 21-cm photon emission.

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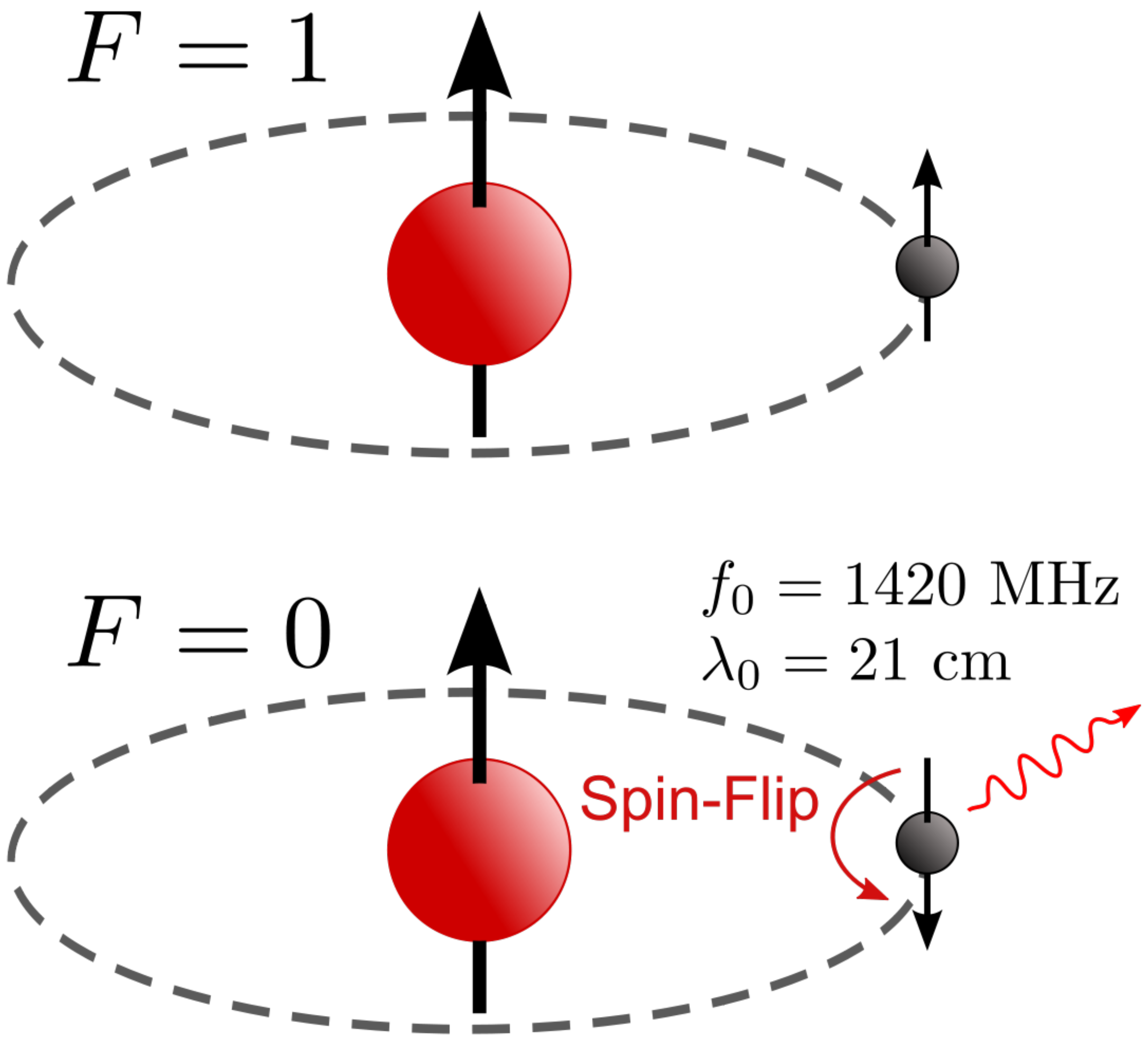
- However, it is possible in the IGM, as it has:

➡**Low density:** just ~1 atom/m^3, so radiative de-excitation is possible.

➡ **H clouds:** lots of Hydrogen, so enough photons can be produced!



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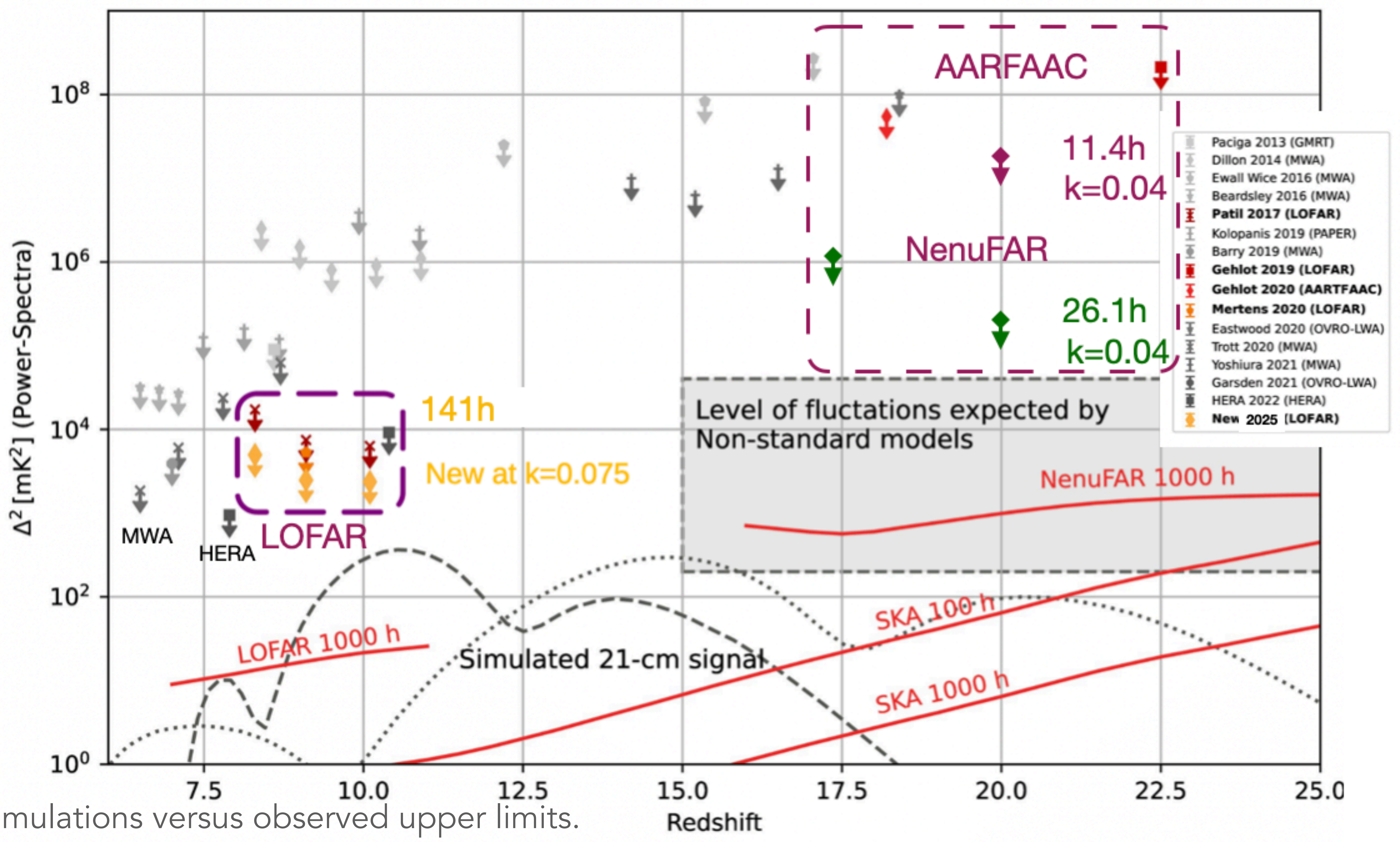
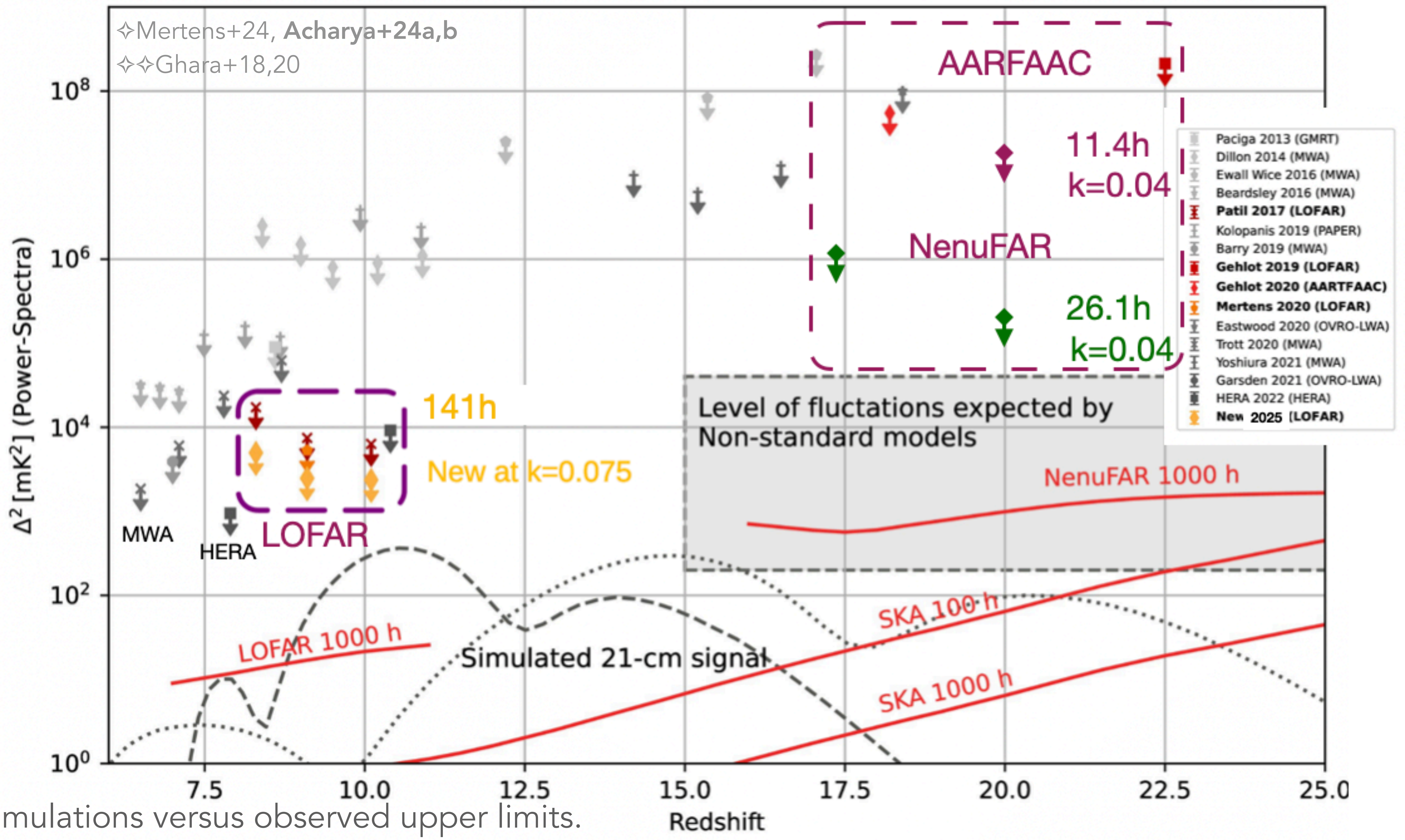


Predicted 21-cm power spectra from simulations versus observed upper limits.

Credits: Florent Mertens.

ML-based✧ foreground subtraction, trained on the *Grizzly*✧✧ simulations: N-body + baryon pasting + 1D radiative transfer.



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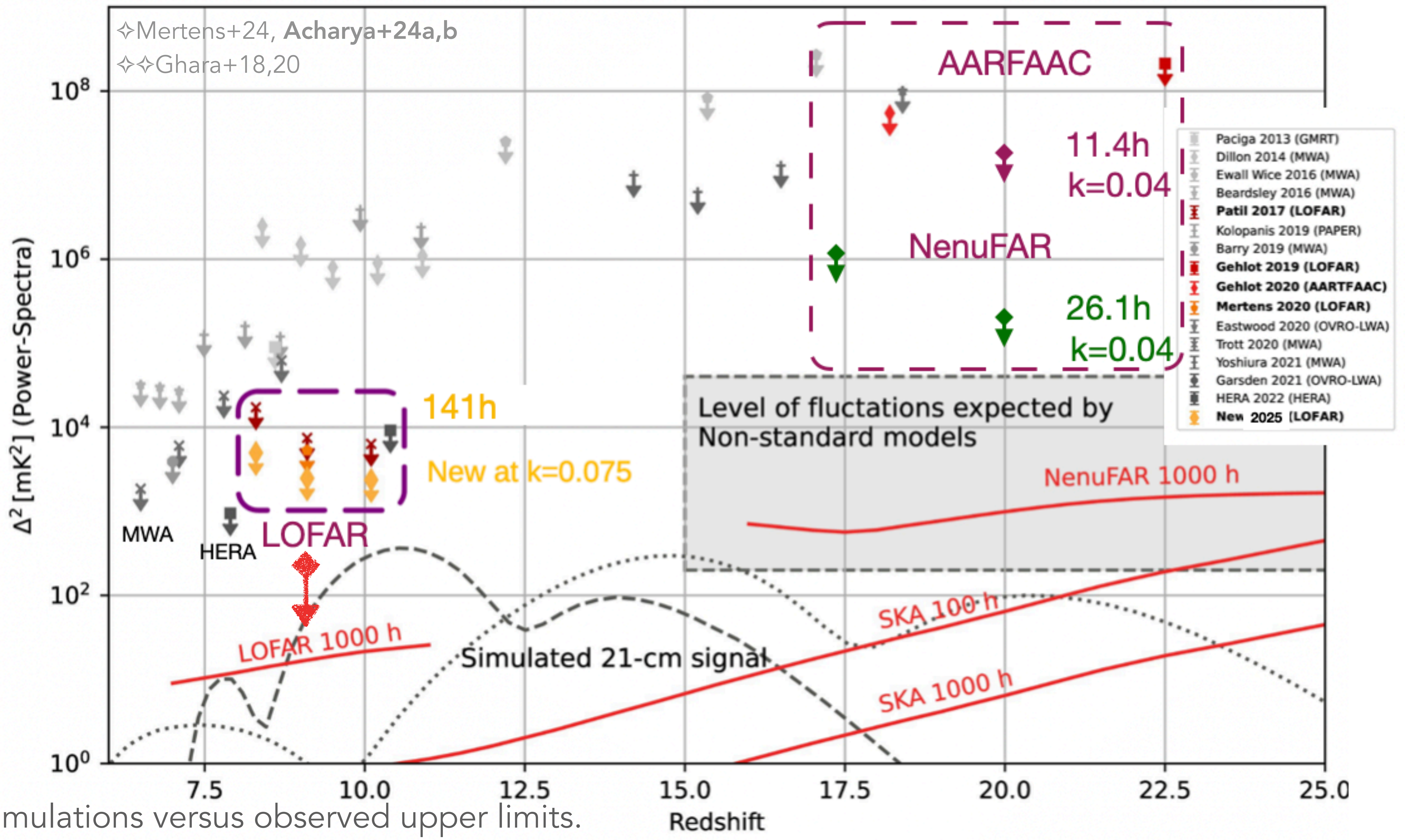
possibly able to separate the systematic excess!



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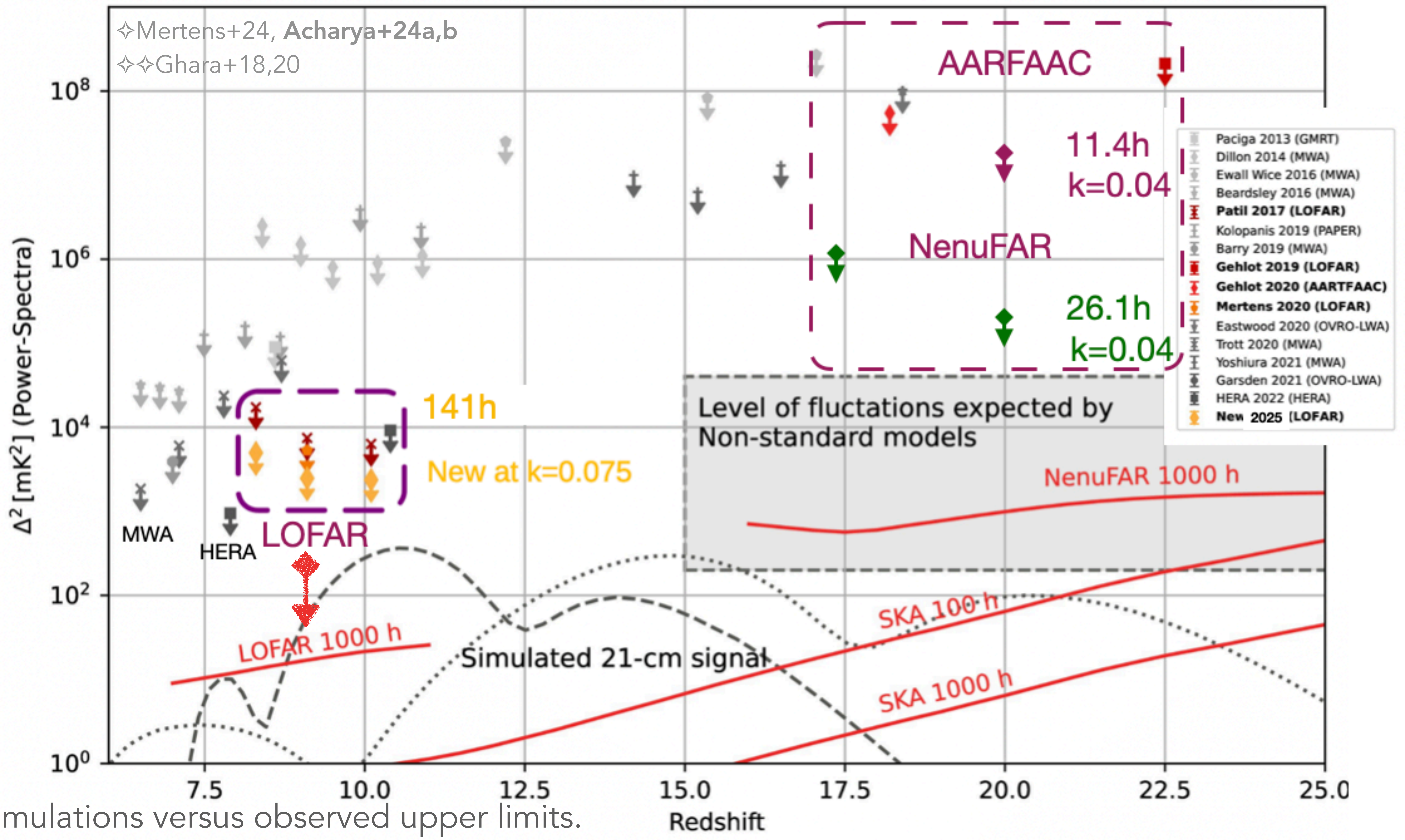
The plan ahead:

- Identify the sources of systematic excess to verify the accuracy of subtraction.



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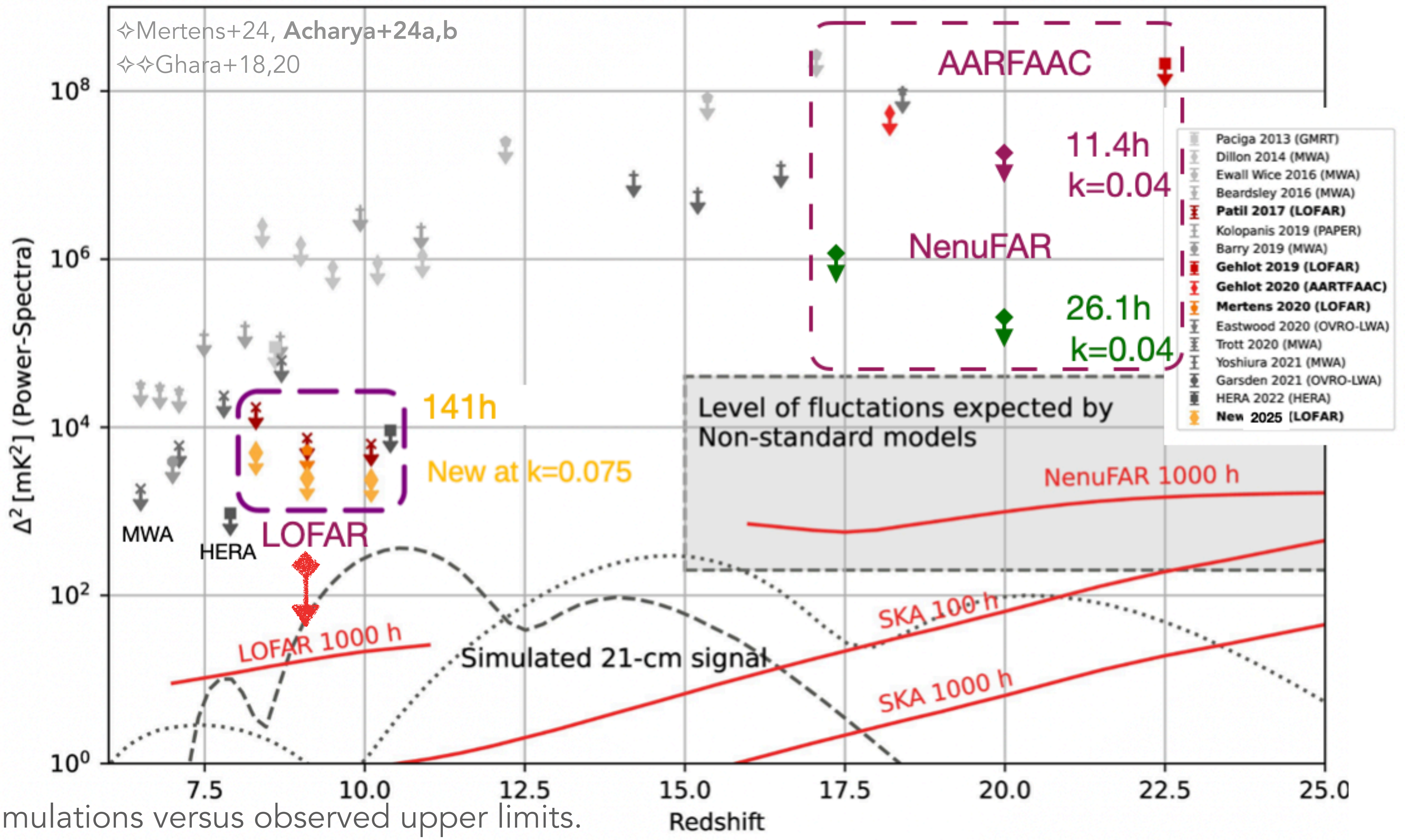
The plan ahead:

- Identify the sources of systematic excess to verify the accuracy of subtraction.
- Cross-correlate this deep field (NCP) with a second deep field (3C196) and results from other telescopes.



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- **Large box size:** we need boxes $> 100h^{-1}$ cMpc ($> 175h^{-1}$ cMpc for X-ray heating) in size to sample the 21-cm power spectrum at $k \leq 1h$ cMpc^{-1}, where radio interferometers are most sensitive.

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- **Fast RT:** simplified radiative transfer that can be run for a large range of models.

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- **Good modelling of galaxy physics:** while full RMHD may be too expensive, modelling galaxy properties with parameters controlling star/AGN/BH formation, supernova feedback, cold/hot gas properties, etc., is necessary.
- **Fast RT:** simplified radiative transfer that can be run for a large range of models.
- **Scalable architecture:** can be increased in resolution to resolve mini halos.
- **Cheap:** can be run by varying cosmological and astrophysical parameters to build SBI datasets.

one simulation to rule them all!

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POLAR


POLAR
Gadget-4 (Dark Matter)
+


POLAR
Gadget-4 (Dark Matter)
+
L-Galaxies (Baryons)
+


POLAR
Gadget-4 (Dark Matter)
+
L-Galaxies (Baryons)
+
Grizzly (RT)

- *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 and then *Grizzly*.

- For starters, we assume that the SEDs have contributions only from stellar sources. Thus, for the 21-cm signal, we assume $T_S \gg T_{CMB}$, thus:

$$\delta T_b = 27 x_{HI}(1 + \delta_B)\left[\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2}\right] \mathrm{mK}\,.$$

✧using the F&P method to suppress cosmic variance, as shown by *Acharya et al. 2024c* and *Giri et al. 2023*

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- There are discrepancies in the measurement of the Hubble parameter H_0 and the matter clustering amplitude σ_8.

- These parameters affect matter clustering, which connects to star formation rates/efficiencies.

- What would happen when we tune all parameters to match a single set of observations?

model	h	σ_8	obs
fiducial	0.6766	0.8102	*Planck*
h **high**	0.7330	0.8102	SN
σ_8 **high**	0.6766	0.8800	eROSITA
σ_8 **low**	0.6766	0.7020	BOSS

Anshuman Acharya | anshumana@berkeley.edu

No tuning, all set to the same values as the fiducial model.

All models tuned to observations!

Anshuman Acharya | anshumana@berkeley.edu

- Parameters impacting star formation efficiency directly.

tuned to low-z observations

Acharya et al. 2024d

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

- Parameters impacting star formation efficiency directly.

tuned to low-z observations

Acharya et al. 2024d

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- Parameters impacting star formation efficiency directly.
- Parameters affecting the amount of cold gas surviving in the galaxy.

Acharya et al. 2024d

tuned to low-z observations

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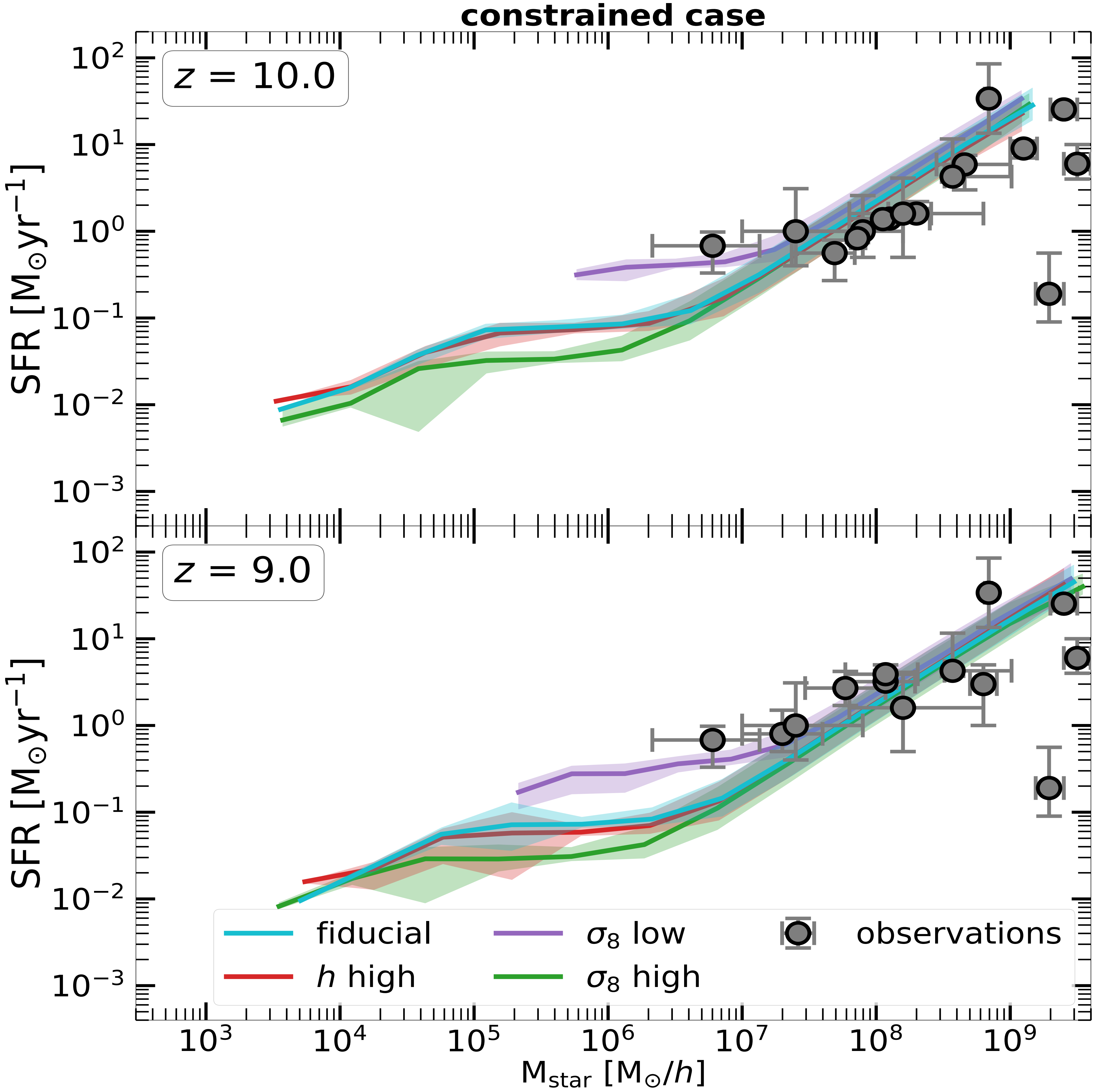
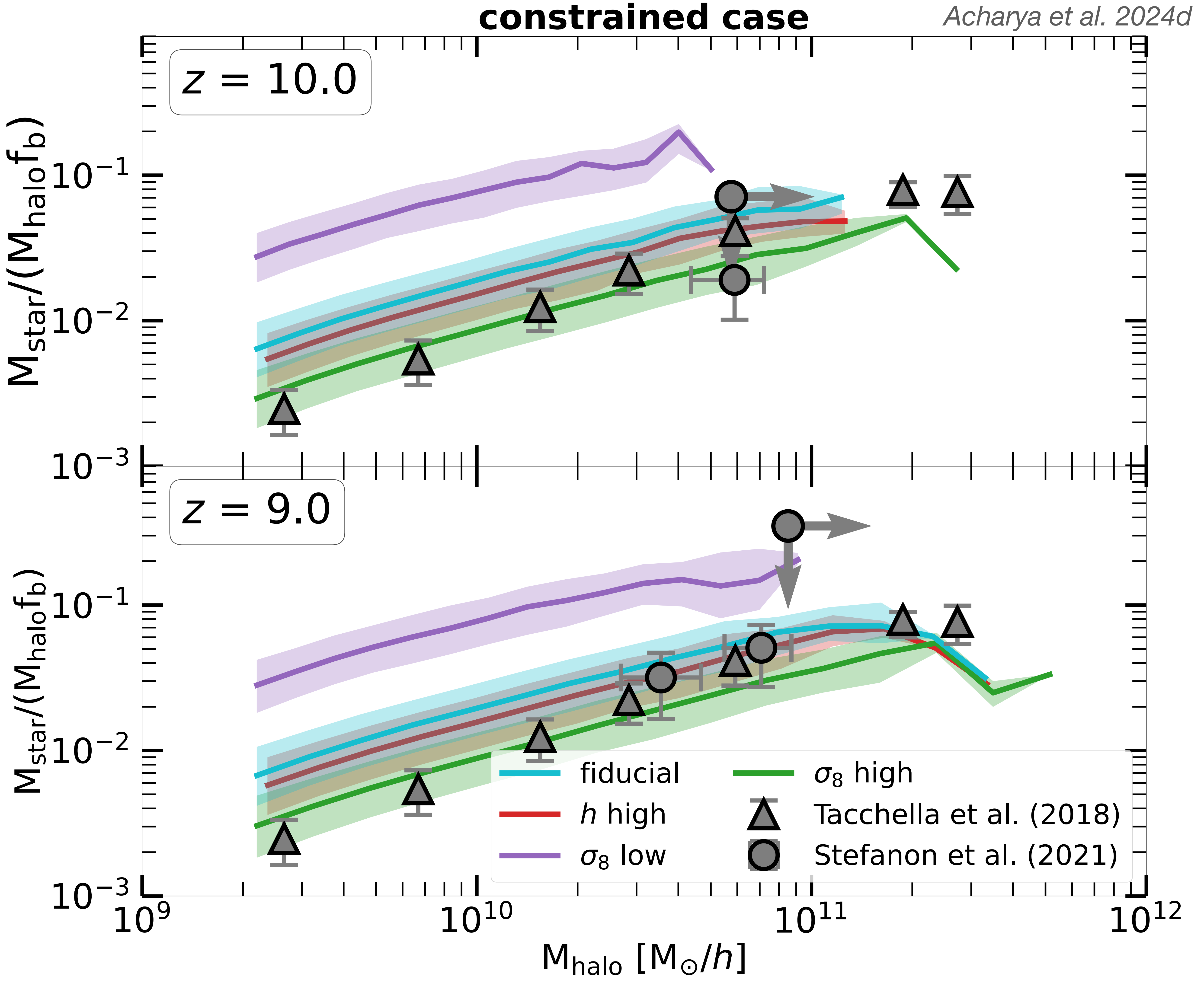


SFR, note the difference at the low-mass end.

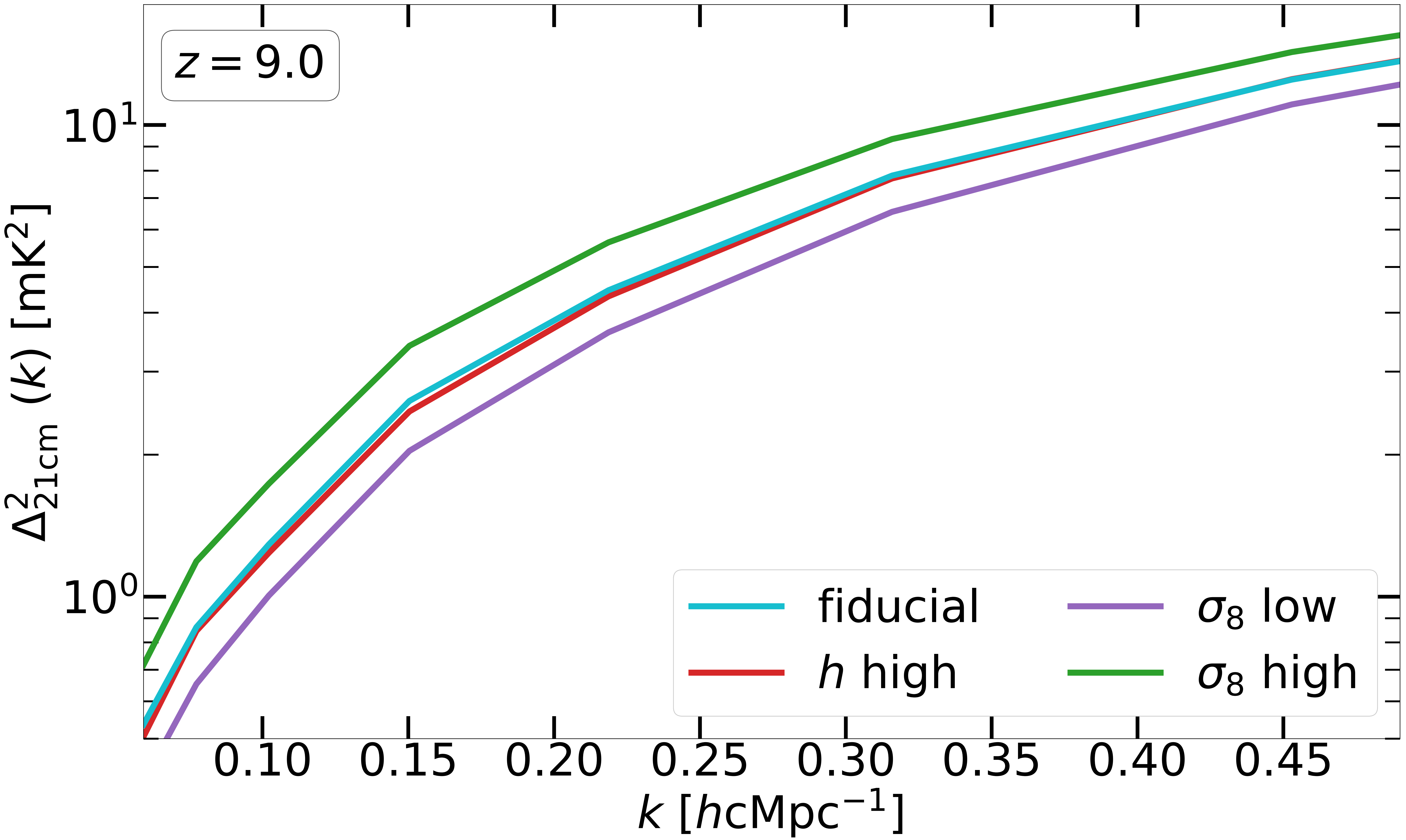


SFE, showing the clear over-efficiency in the σ_8 low model.

Anshuman Acharya | anshumana@berkeley.edu

constrained case

Acharya et al. 2024d

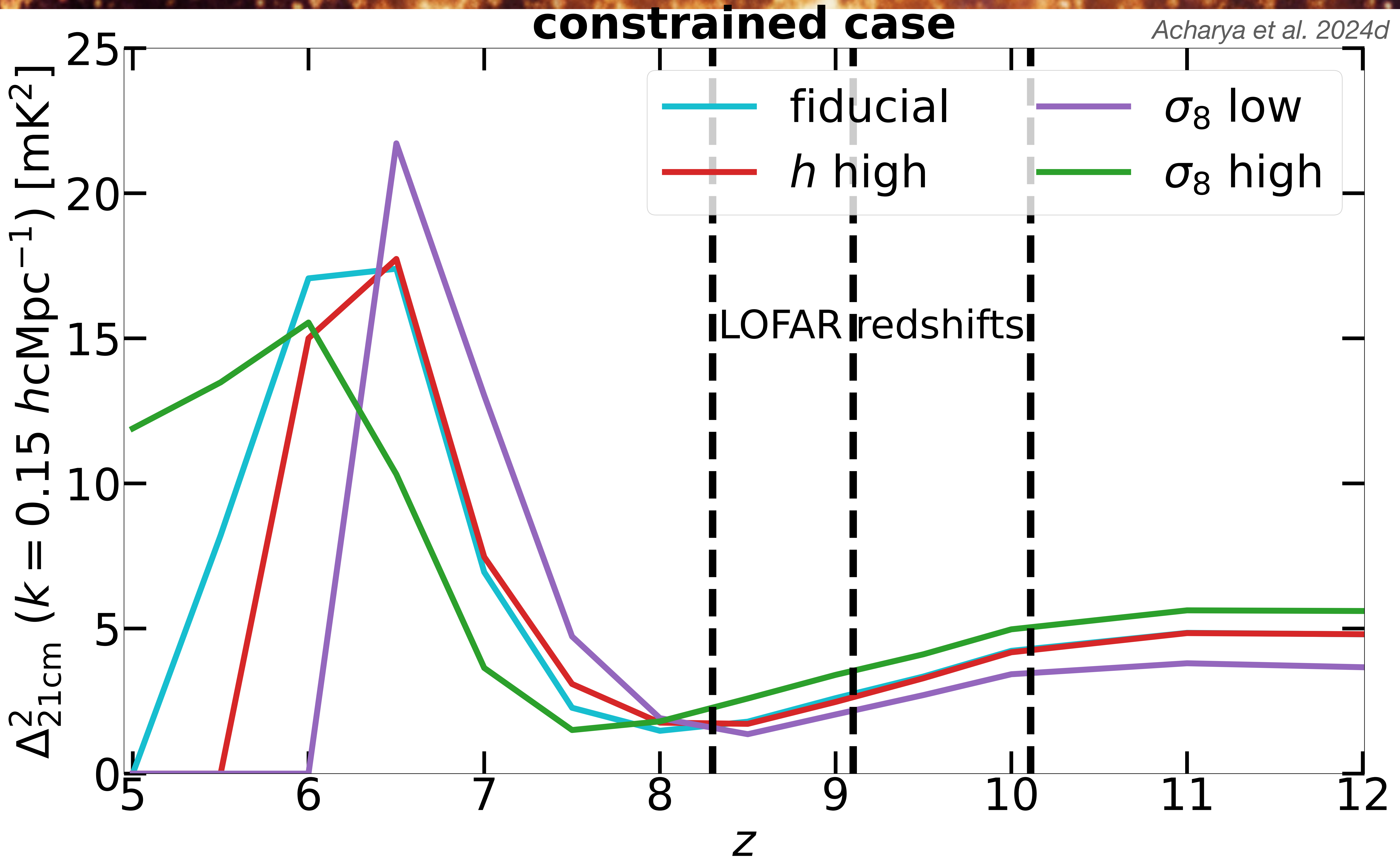


As the difference in the $x_{\rm HI}$ term is reduced, power is primarily governed by the $\delta_{\rm B}$ term.

Anshuman Acharya | anshumana@berkeley.edu

- **Expected signal is weak:** while better modelling is expected to strengthen the signal, the qualitative behaviour is expected to remain consistent.

- **Conclusion:** for parameter inference of the 21-cm signal, cosmological parameters indeed need to vary.



The deepest upper limits (600-800 mK^2, *Acharya et al. 2024c* and *Mertens et al. 2025*) detected by LOFAR would **not** distinguish between the four models.

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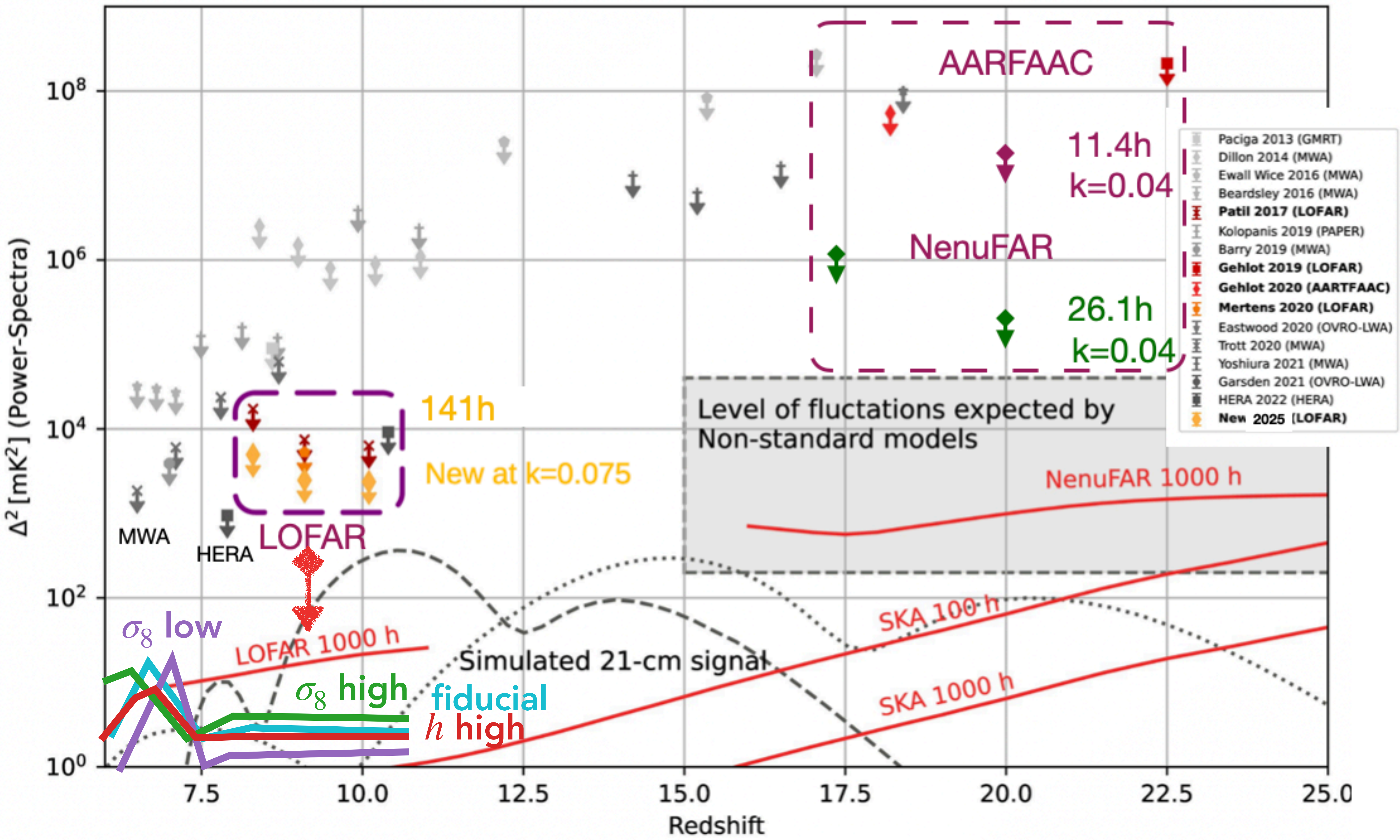

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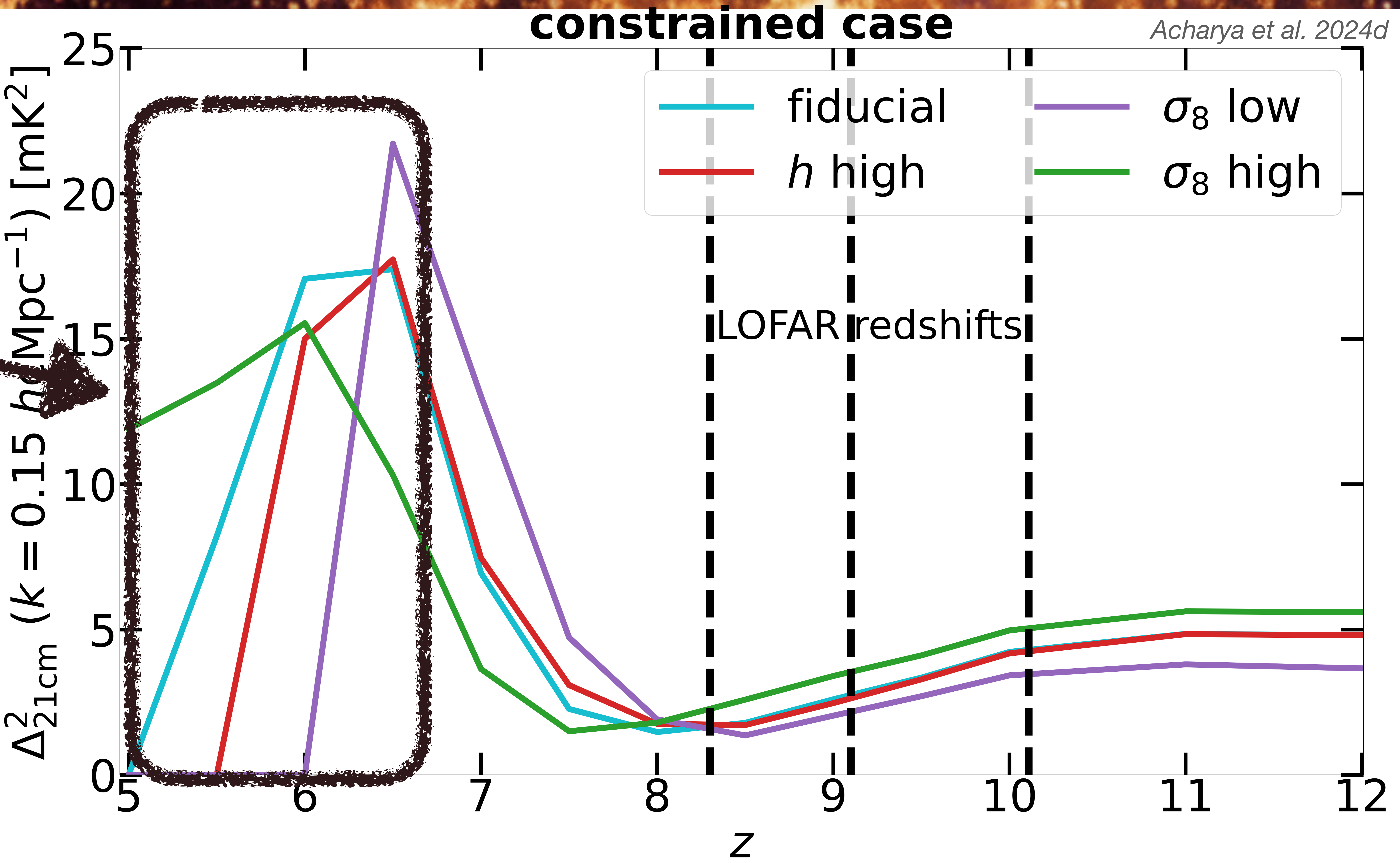

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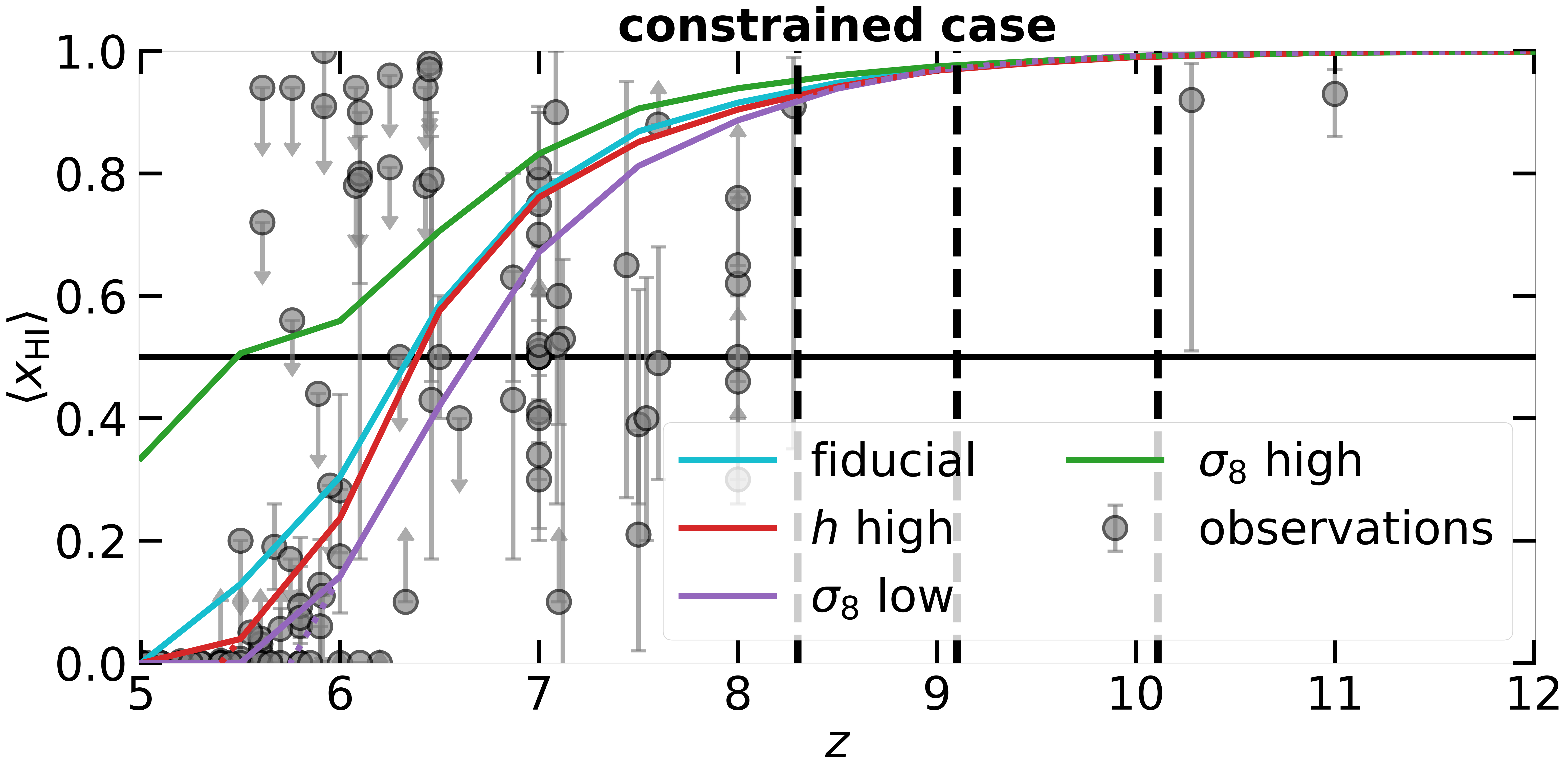
Acharya et al. 2024d

- Better modelling and observations for the end of reionization could provide stronger constraints.
- E.g., volume-averaged neutral H fraction.

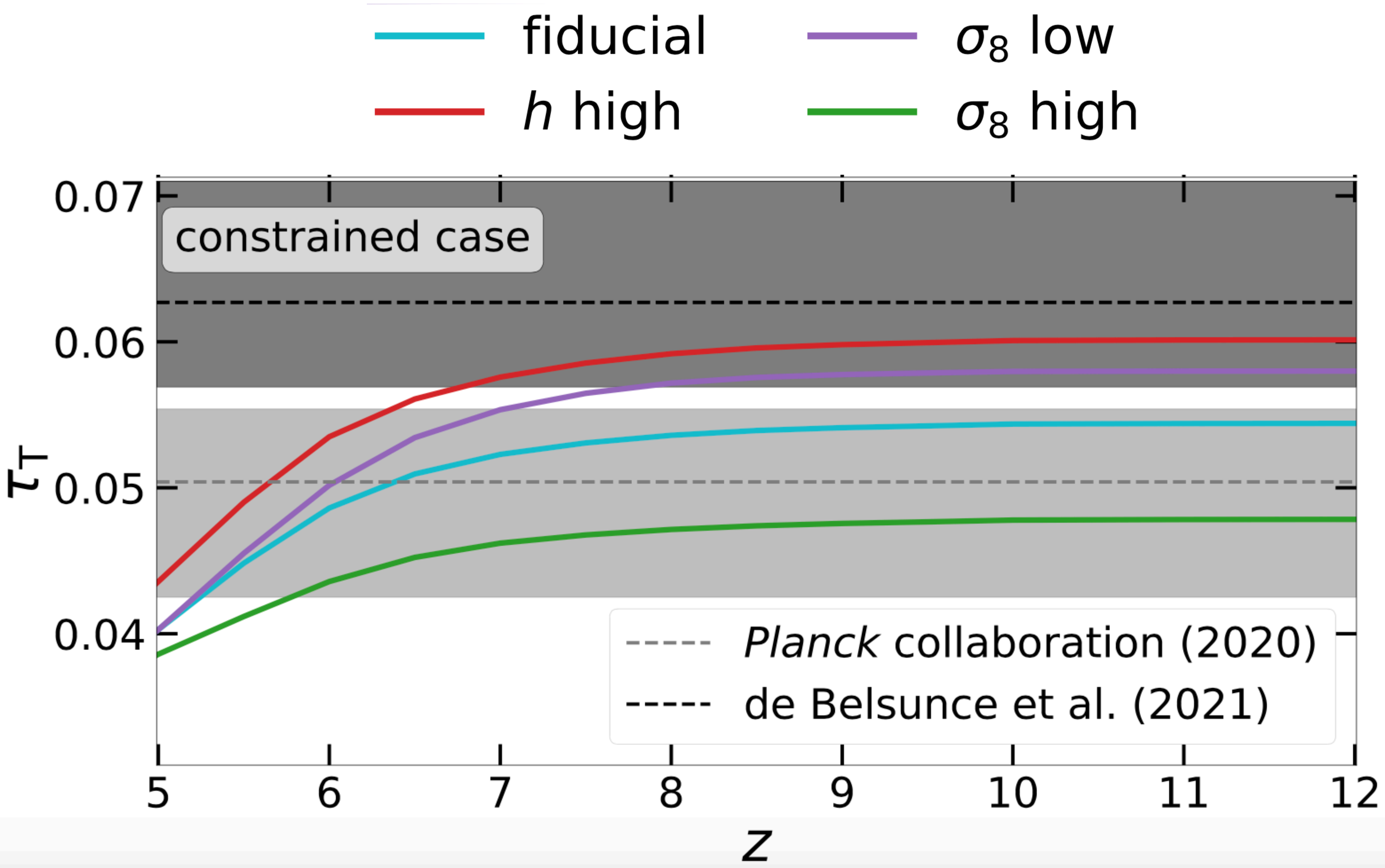


Volume averaged neutral Hydrogen fractions estimated by various observations, shown to be in agreement with all four models.

Acharya et al. 2024d

- Thomson scattering optical depth versus estimates from CMB observations.

- What next?

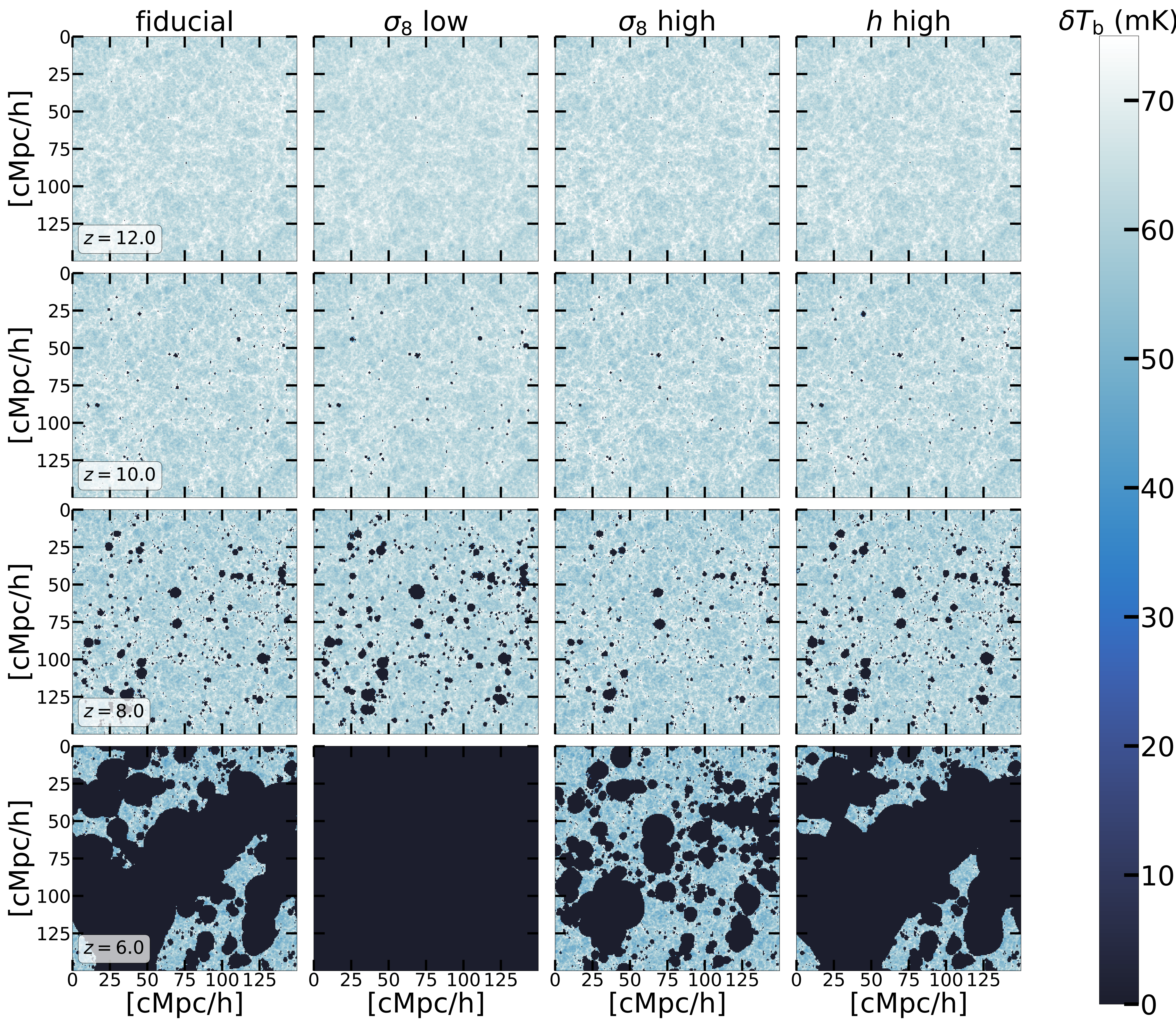


Thomson scattering optical depth estimated from the CMB is dependent on the methods and assumptions, allowing for agreement of all models.

- **IGM tomography with the SKA → cross-correlation with LIM/kSZ maps.**

- Especially crucial once midpoint of reionisation is crossed.

Acharya et al. 2024d

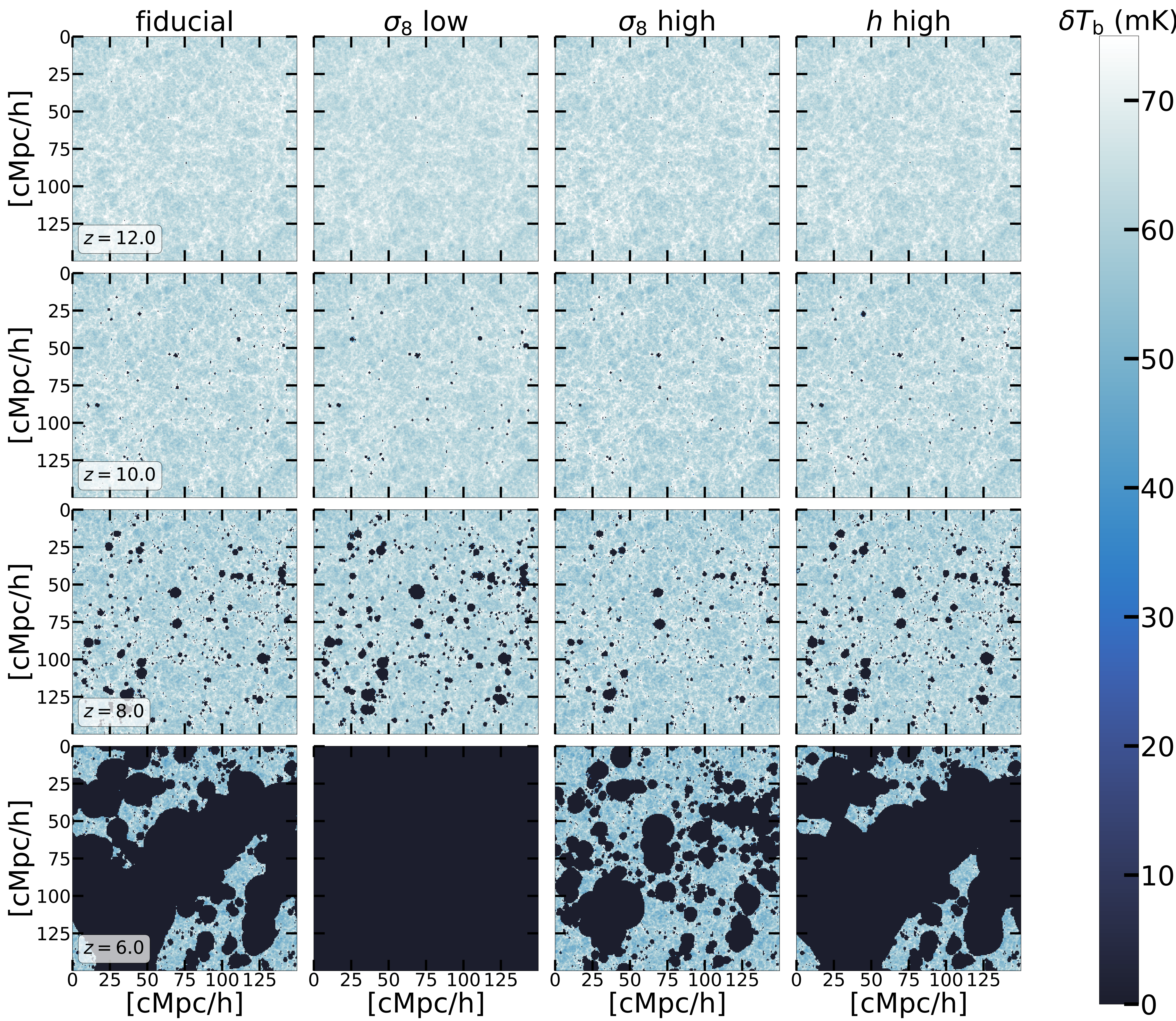


Middle slices of the 4 models across redshifts for the differential brightness temperature. Note the signficant difference at z = 6.

Anshuman Acharya | anshumana@berkeley.edu

- **Modelling the progress of reionisation is crucial:** Pop III star formation in mini halos is missing.

Acharya et al. 2024d



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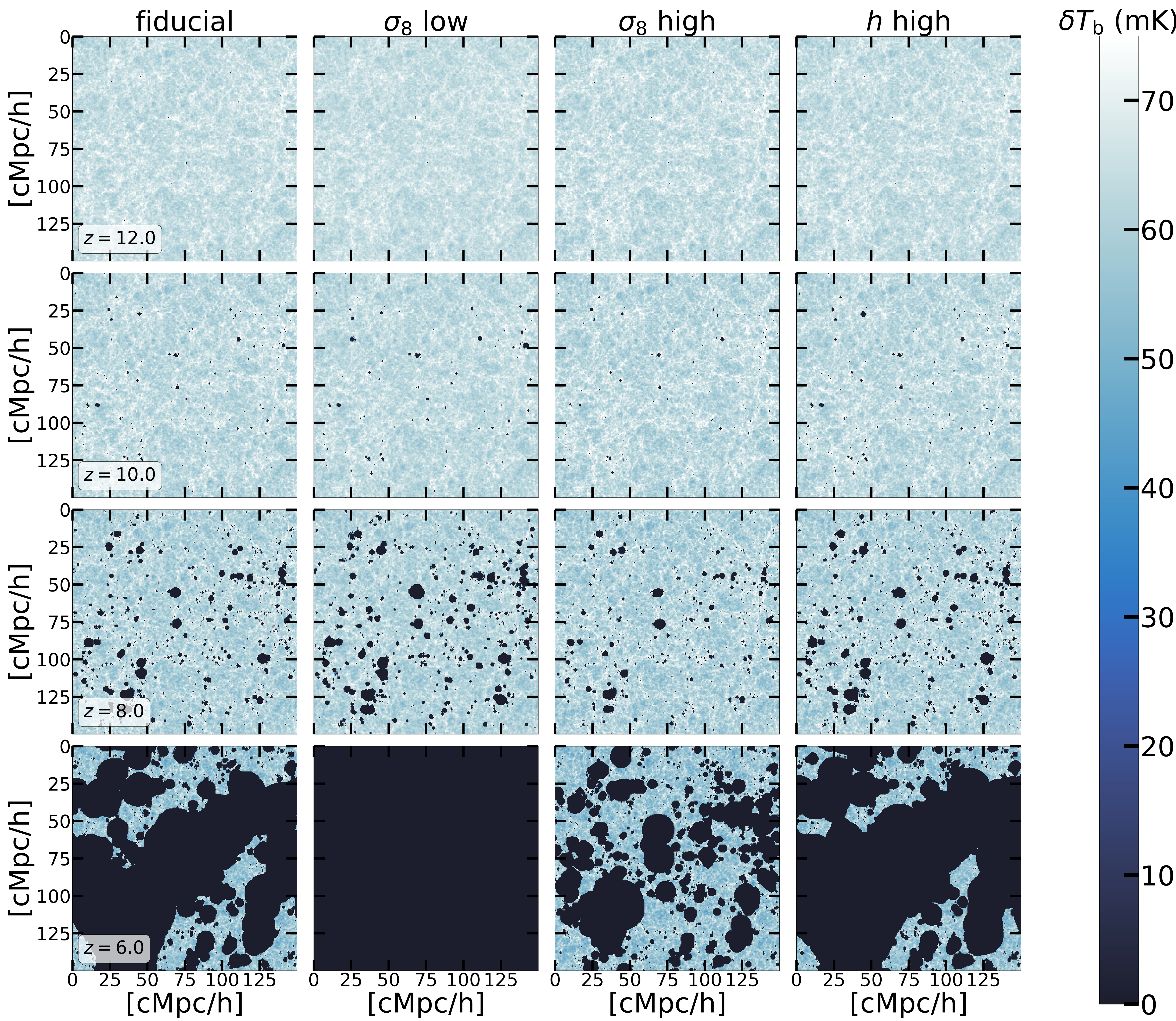
- **Modelling the progress of reionisation is crucial:** Pop III star formation in mini halos is missing.
- Need DM halos of mass $10^{4-5}\ M_{\odot}$.
- Computational costs limits us.

Acharya et al. 2024d



Middle slices of the 4 models across redshifts for the differential brightness temperature. Note the signficant difference at z = 6.

Anshuman Acharya | anshumana@berkeley.edu

- **Large box size:** we need boxes $> 100h^{-1}$ cMpc ($> 175h^{-1}$ cMpc for X-ray heating) in size to sample the 21-cm power spectrum at $k \leq 1h$ cMpc^{-1}, where radio interferometers are most sensitive.

- **Good modelling of galaxy physics:** while full RMHD may be too expensive, modelling galaxy properties with parameters controlling star/AGN/BH formation, supernova feedback, cold/hot gas properties, etc., is necessary.

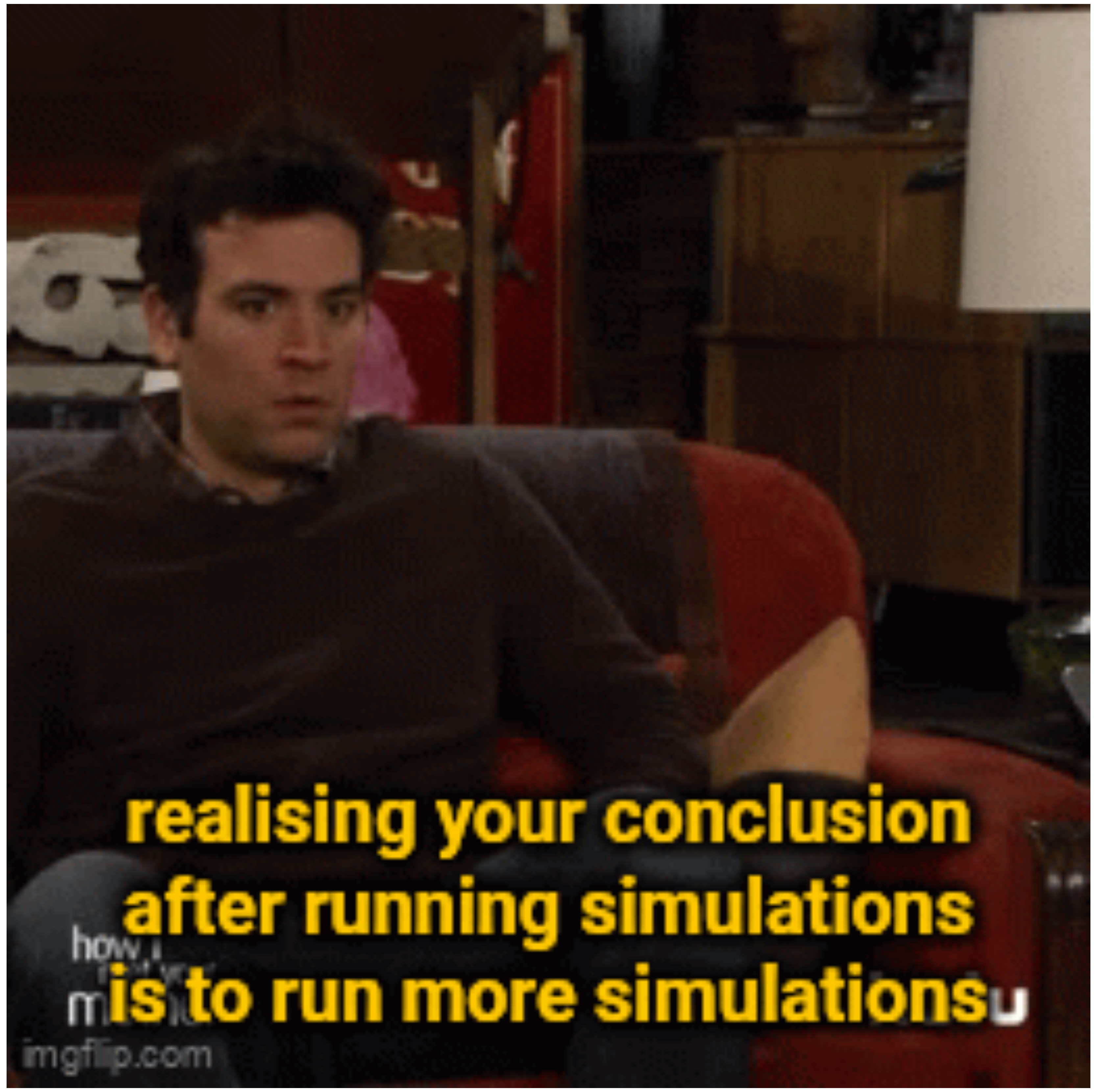
- **Fast RT:** simplified radiative transfer that can be run for a large range of models.

- **Scalable architecture:** can be increased in resolution to resolve mini halos.

- **Cheap:** can be run by varying cosmological and astrophysical parameters to build SBI datasets.

MODELLING

- **Scalable and cheap* architecture → Super-resolution:** using GANs to super-resolve DM halo merger trees✧.



*We still need to run N-body simulations for different cosmologies, or test emulators that translate DM halo positions/merger trees between different cosmologies, DM models, etc.

✧Zhang+24, 25

MODELLING

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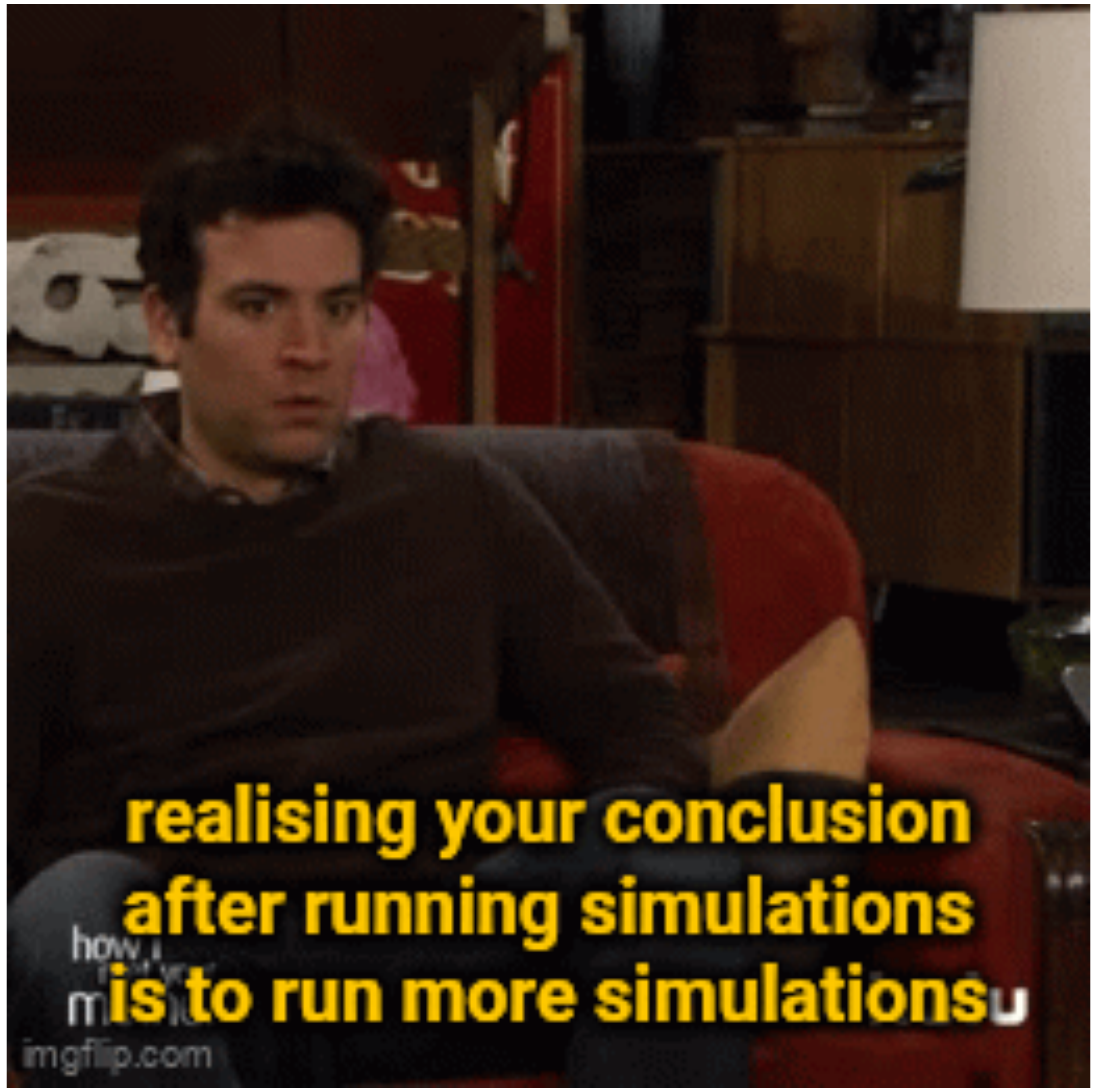
- **Simulation-Based Inference:** use pipelines built by the *Learning the Universe* collaboration for inferring cosmological parameters by cross-correlating kSZ (ACT) and galaxy (SDSS) survey data.



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MODELLING

- **Scalable and cheap* architecture → Super-resolution:** using GANs to super-resolve DM halo merger trees✧.

PARAMETER INFERENCE

- **Simulation-Based Inference:** use pipelines built by the *Learning the Universe* collaboration for inferring cosmological parameters by cross-correlating kSZ (ACT) and galaxy (SDSS) survey data.
- **And at EoR redshifts!:** adapt SBI pipeline for cross-correlating observations (kSZ x 21-cm, [C II]/CO LIM x 21-cm, and more).

Questions?

*We still need to run N-body simulations for different cosmologies, or test emulators that translate DM halo positions/merger trees between different cosmologies, DM models, etc.

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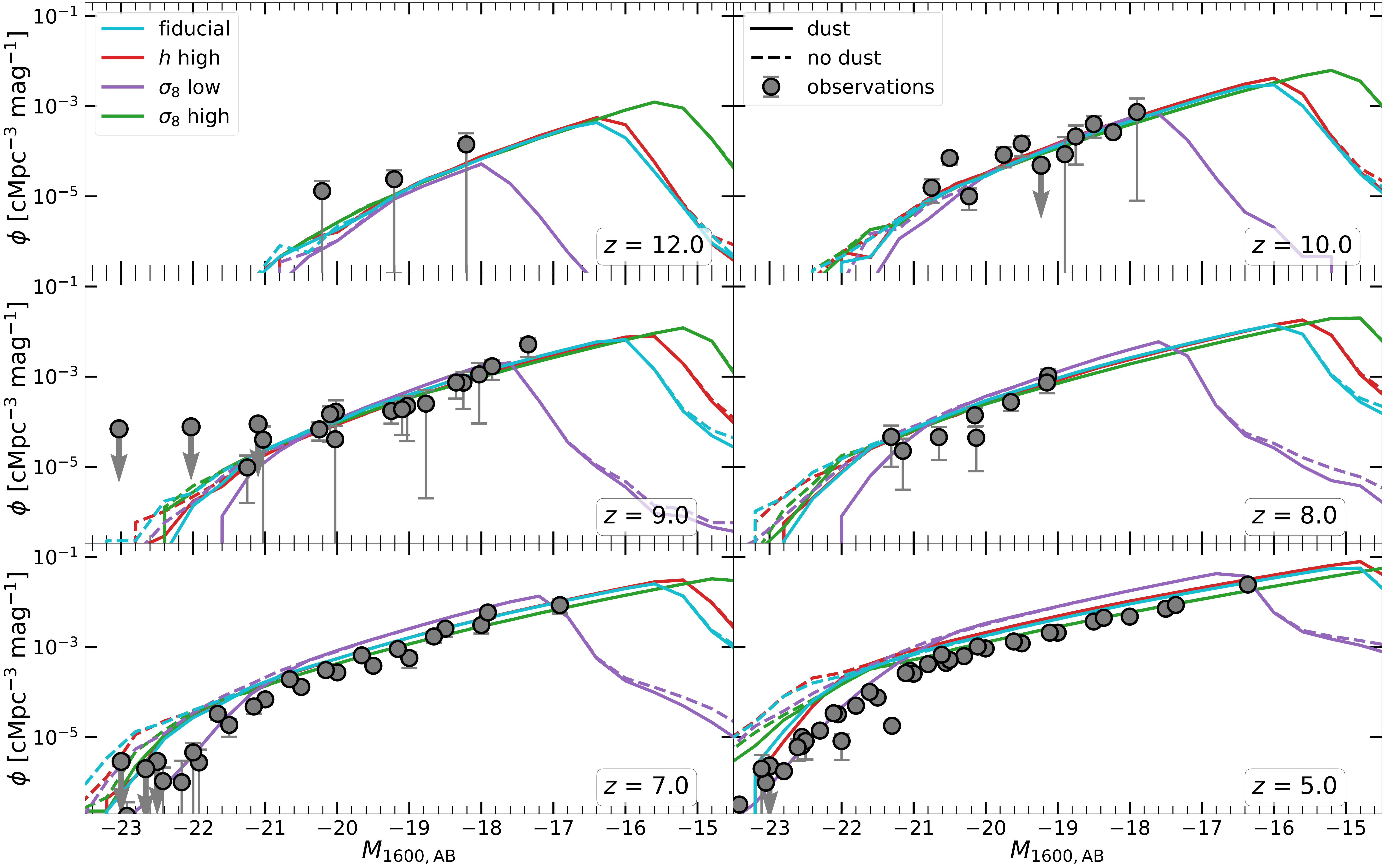
Anshuman Acharya | anshumana@berkeley.edu

UV LFs across redshifts.



Anshuman Acharya | anshumana@berkeley.edu