Inferring the timing and morphology of cosmic reionization through forward models

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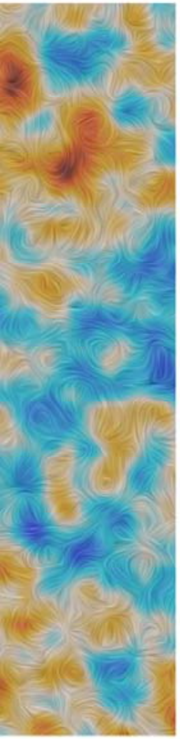
erc
European Research Council

First billion years - birth of structure and Cosmic Dawn

Image: ESA

CMB



$z \approx 10^3$

cosmic time [yr]

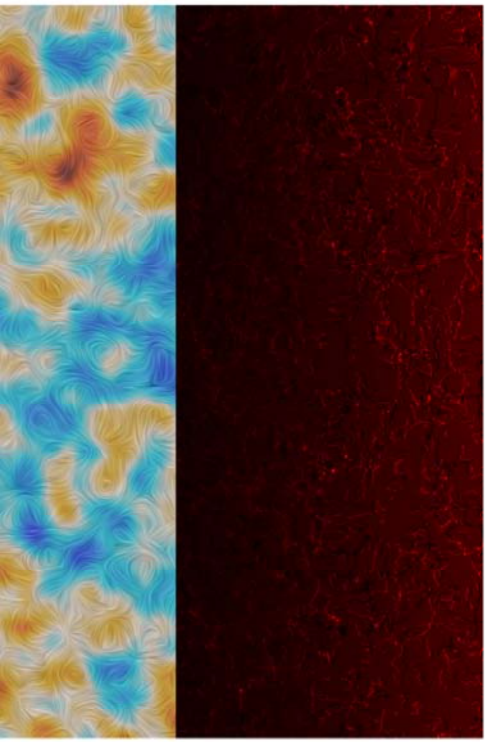
$4 \cdot 10^5$

First billion years - birth of structure and Cosmic Dawn

Image: ESA

AM+2016

CMB **Dark Ages**



$z \approx 10^3$ $z \approx 30$

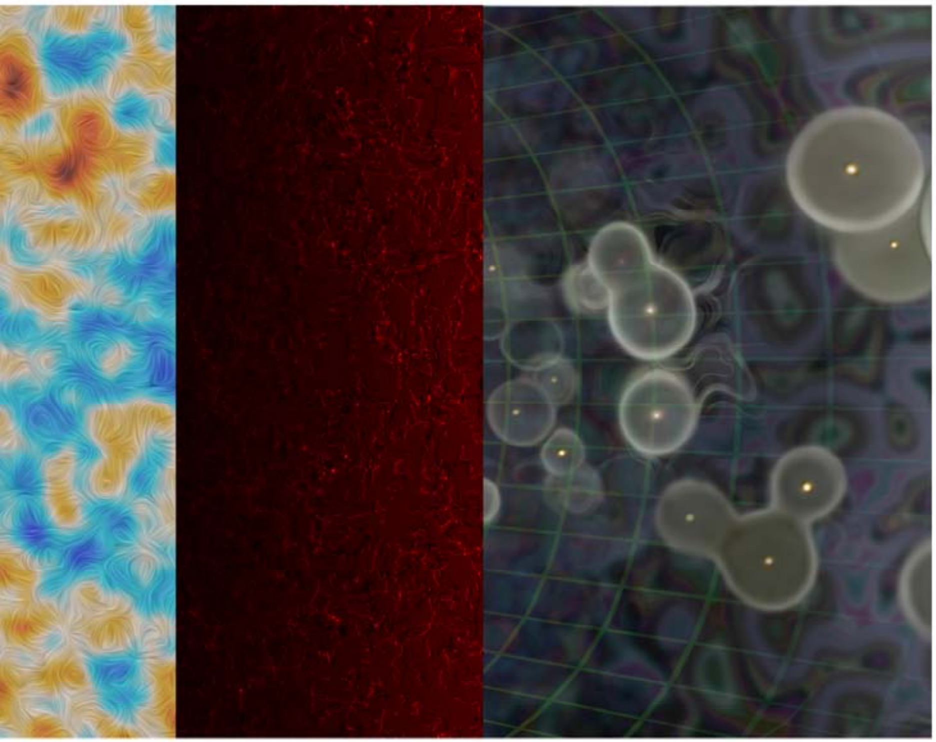
cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz

CMB Dark Ages **Cosmic Dawn**



$z \approx 10^3$ $z \approx 30$

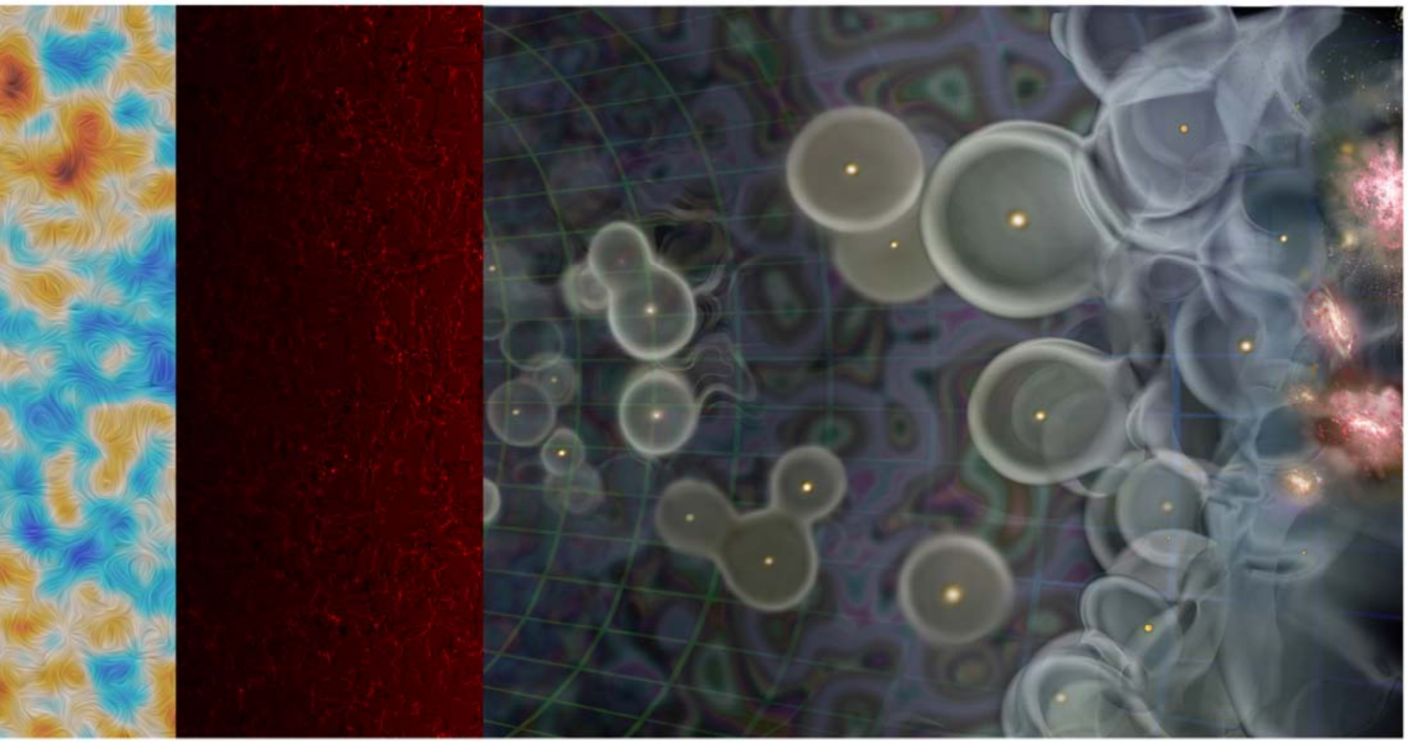
cosmic time [yr]

$4 \cdot 10^5$ 10^8

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz

CMB Dark Ages Cosmic Dawn **Reionization**



$z \approx 10^3$ $z \approx 30$ $z \approx 5$

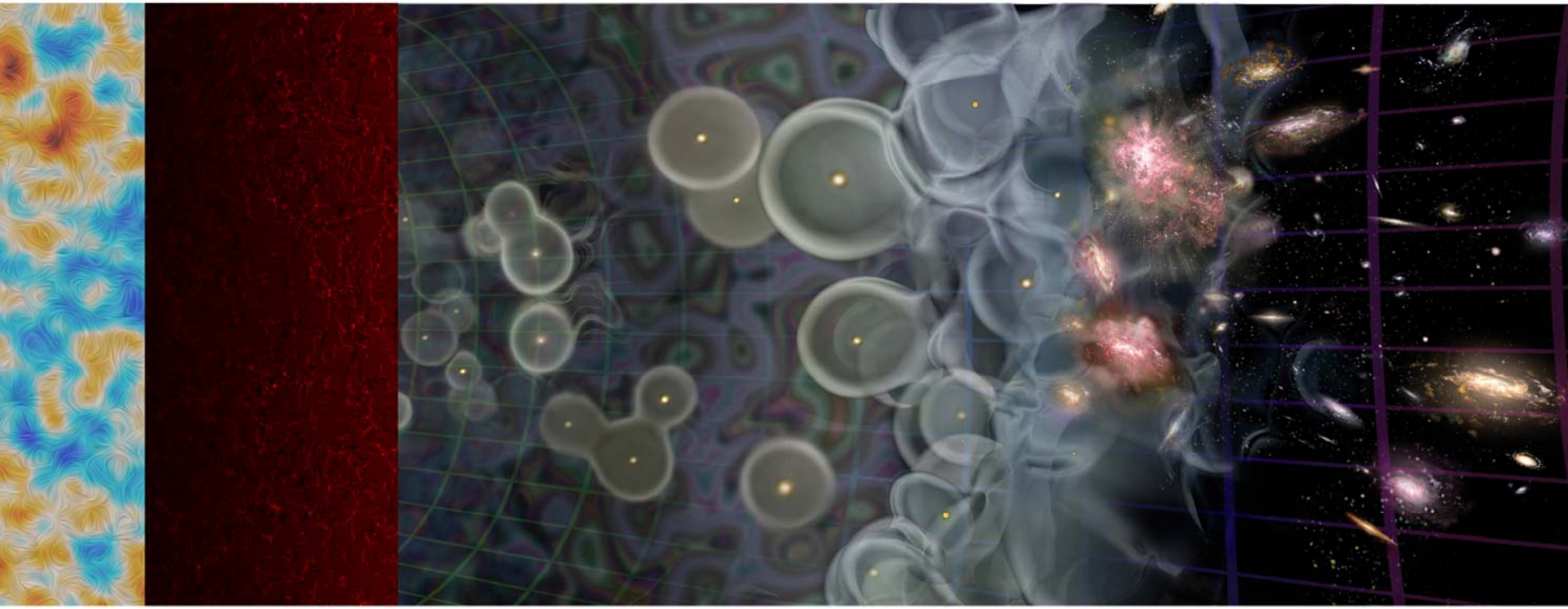
cosmic time [yr]

$4 \cdot 10^5$ 10^8 10^9

First billion years - birth of structure and Cosmic Dawn

Image: NASA/
CXC/M.WEISS
AM+2016; J. Munoz

CMB | Dark Ages | Cosmic Dawn | Reionization | **Late Universe**



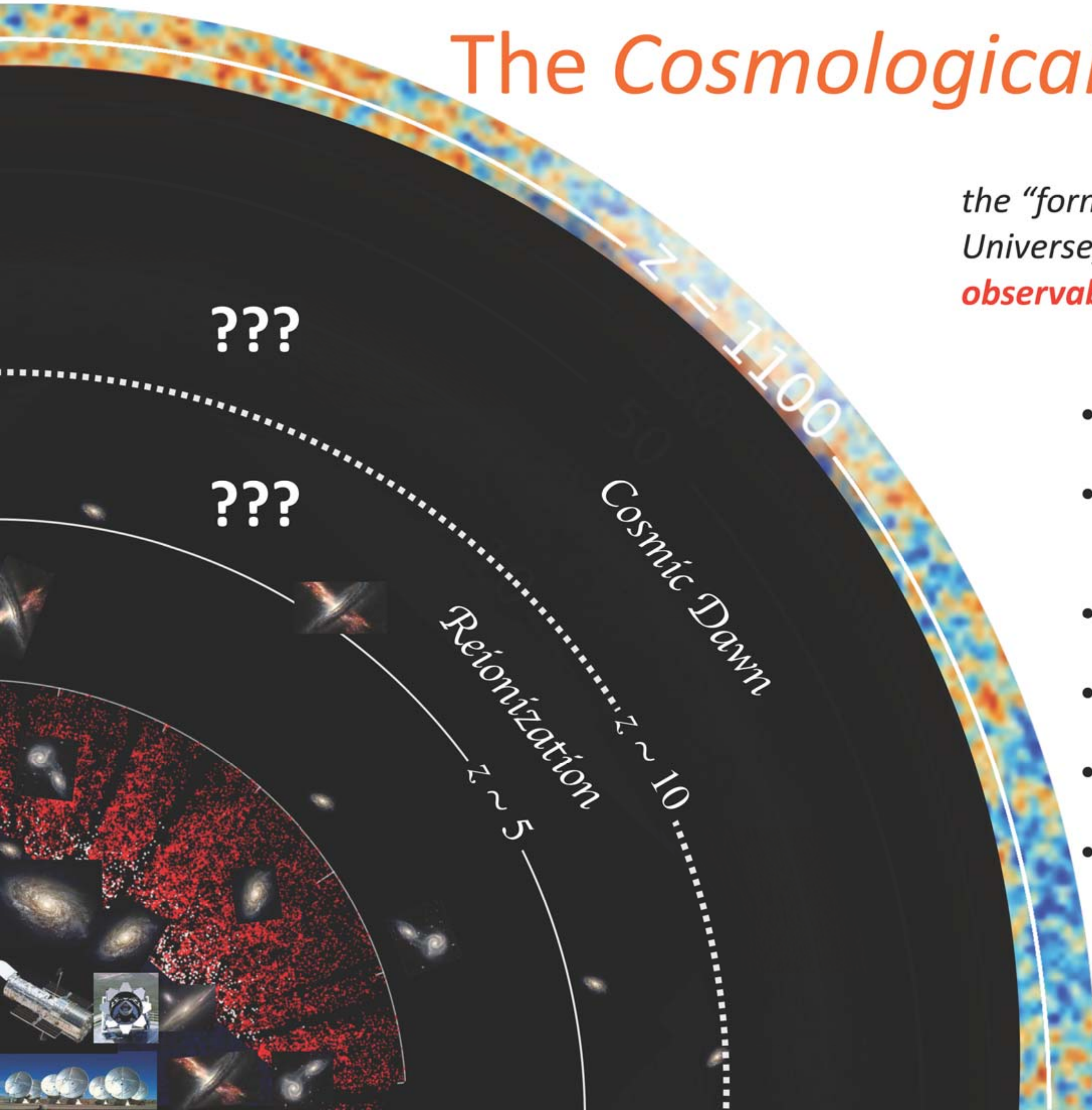
$z \approx 10^3$ | $z \approx 30$ | $z \approx 5$ | $z = 0$

cosmic time [yr]

$4 \cdot 10^5$ | 10^8 | 10^9 | 10^{10}

The Epoch of Reionization: the final phase change of our Universe

The *Cosmological Frontier…*

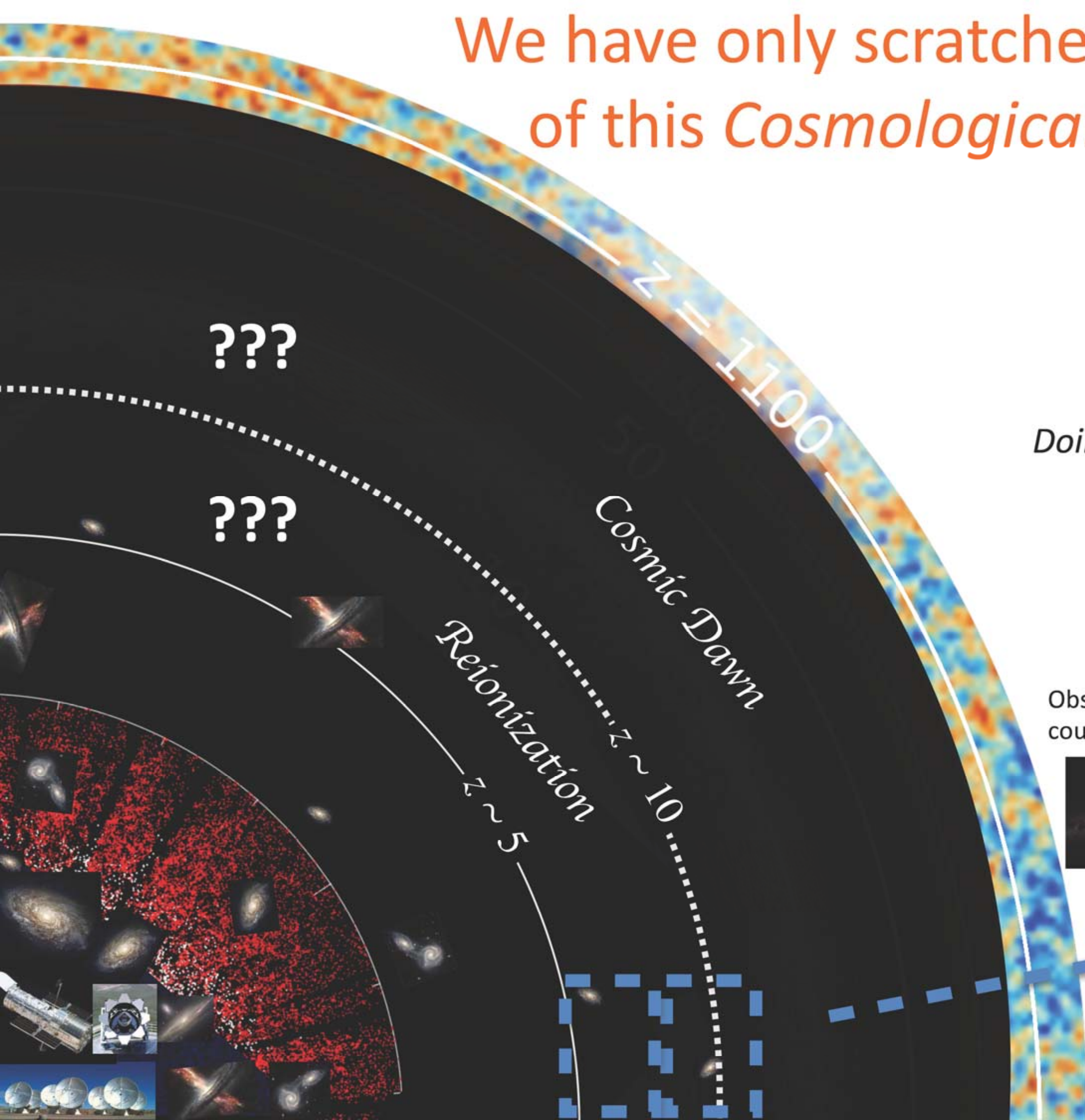


the "formative childhood" of the Universe, yet the ***majority of the observable volume***

- When and how did the first galaxies form?
- How did they impact each other and their surroundings?
- What are the dominant feedback mechanisms?
- Can we learn about Dark Matter properties?
- How does the Hubble parameter evolve?
- What are the properties of the first stars and black holes?

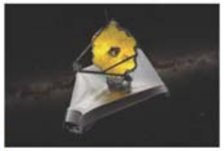
adapted from Cynthia Chiang

We have only scratched the surface of this *Cosmological Frontier*…



Doing a galaxy census….

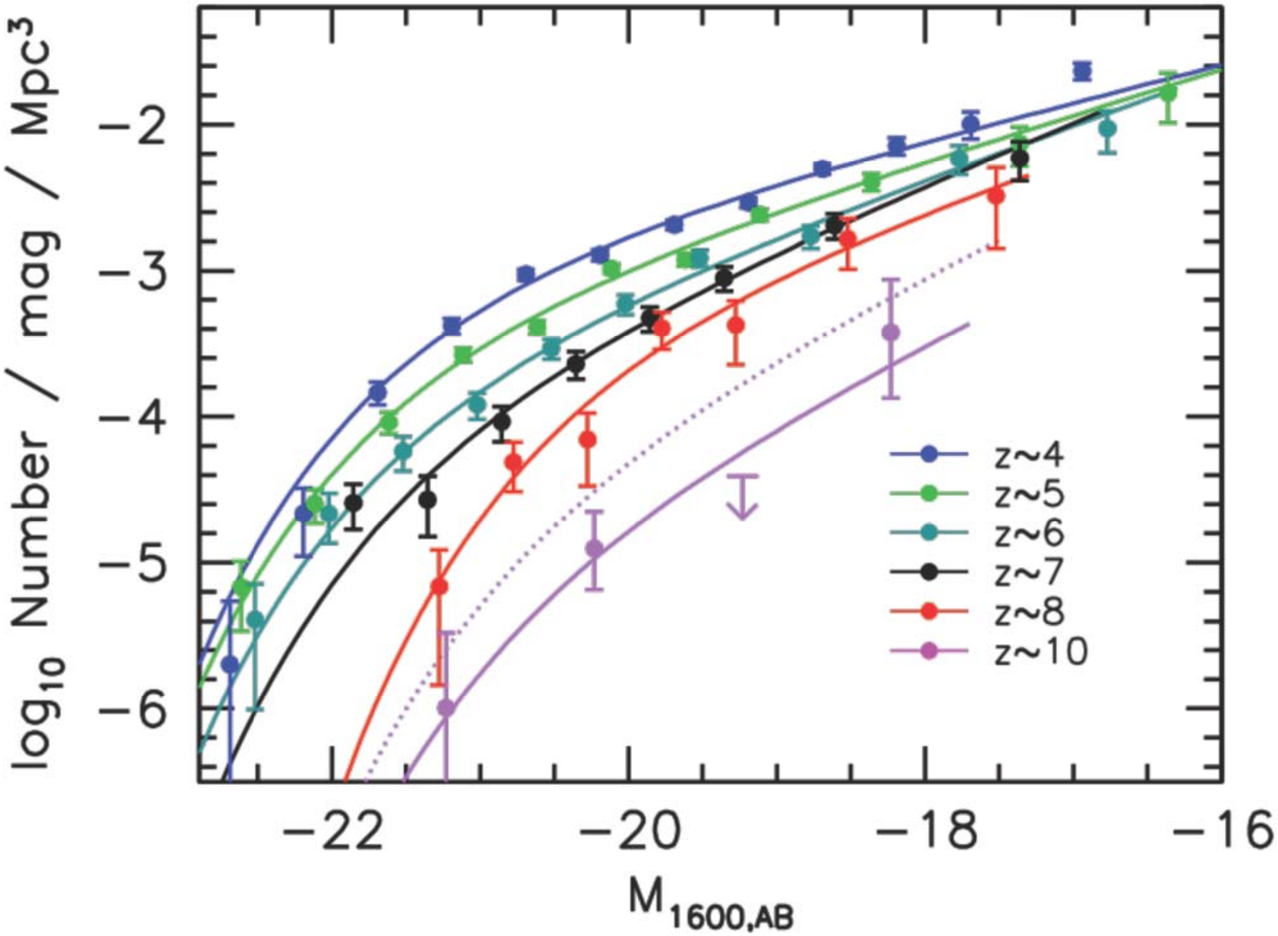
Observe with Hubble / JWST and count galaxies



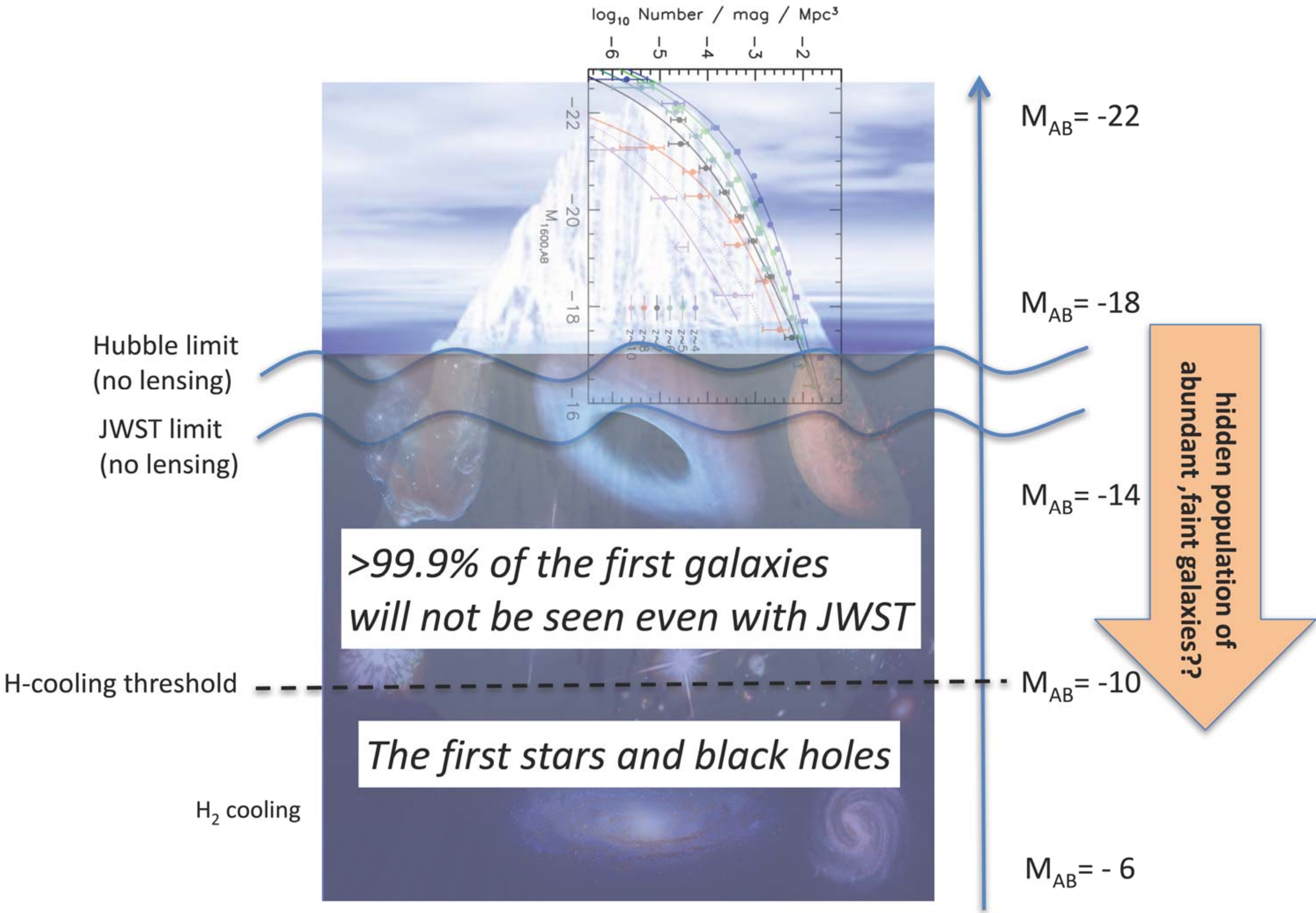
adapted from Cynthia Chiang

Galaxies during the first billion years

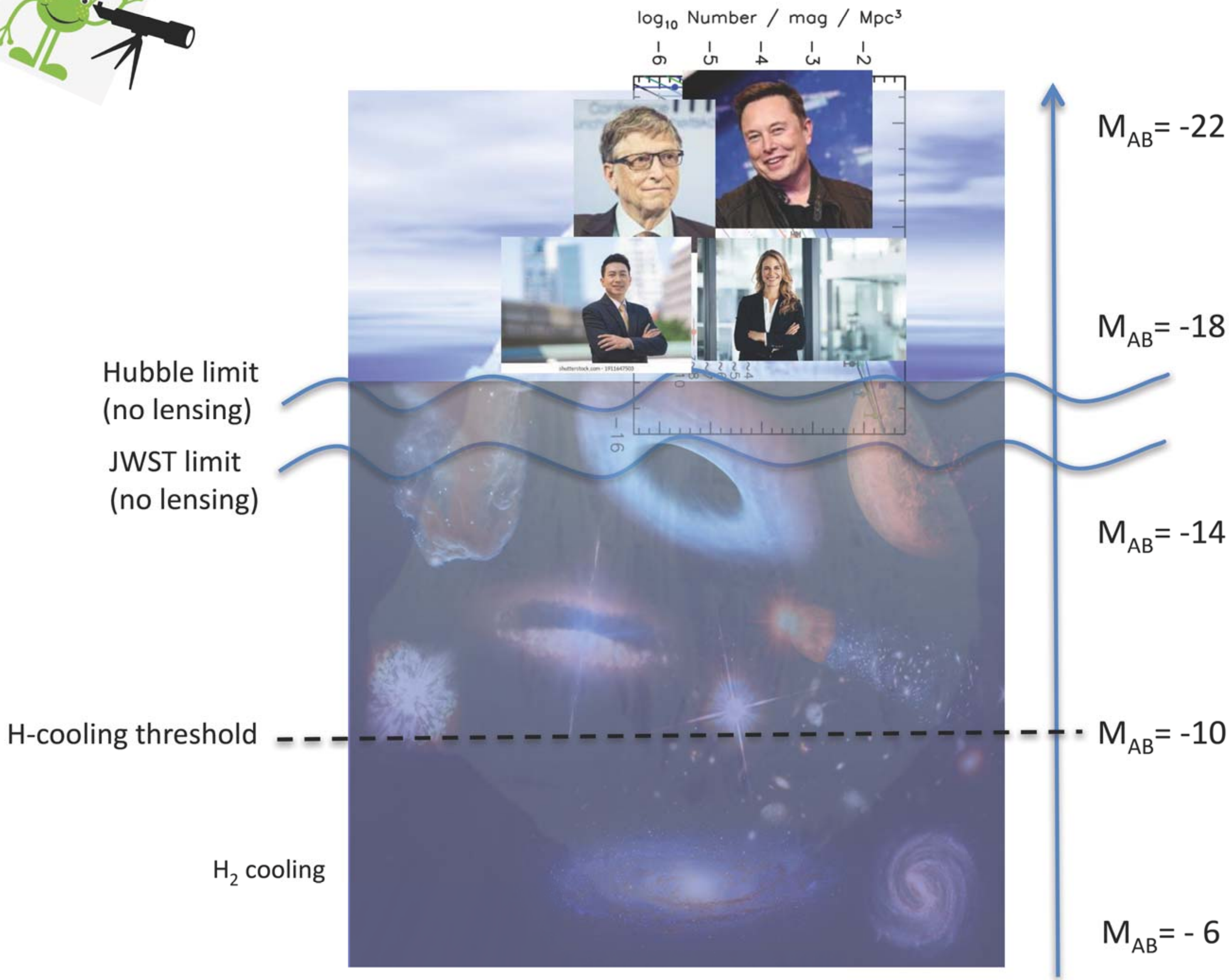
- Telescopes like Hubble and ALMA have enabled detailed studies of *the brightest galaxies*

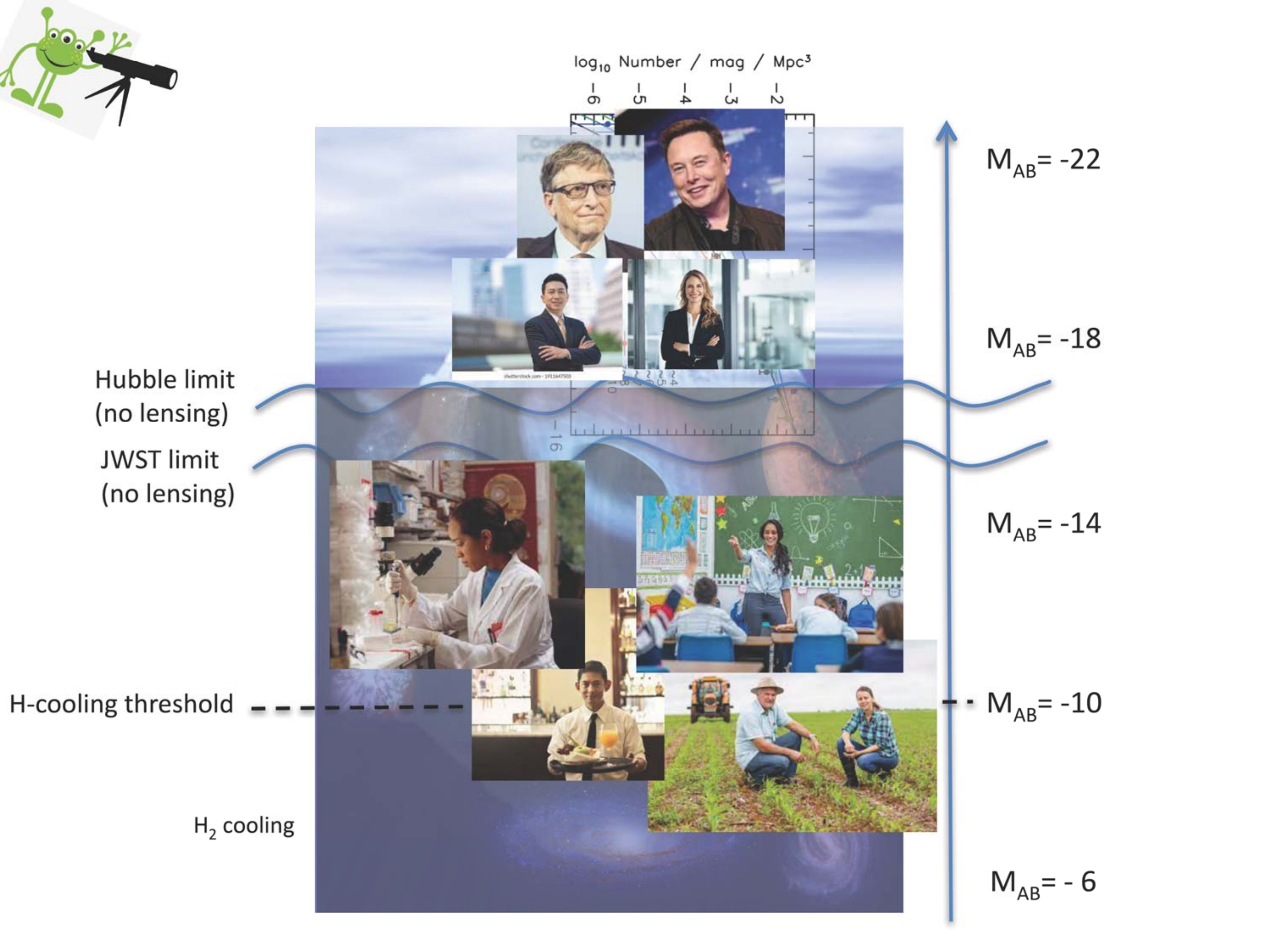


Bouwens+ (2015)

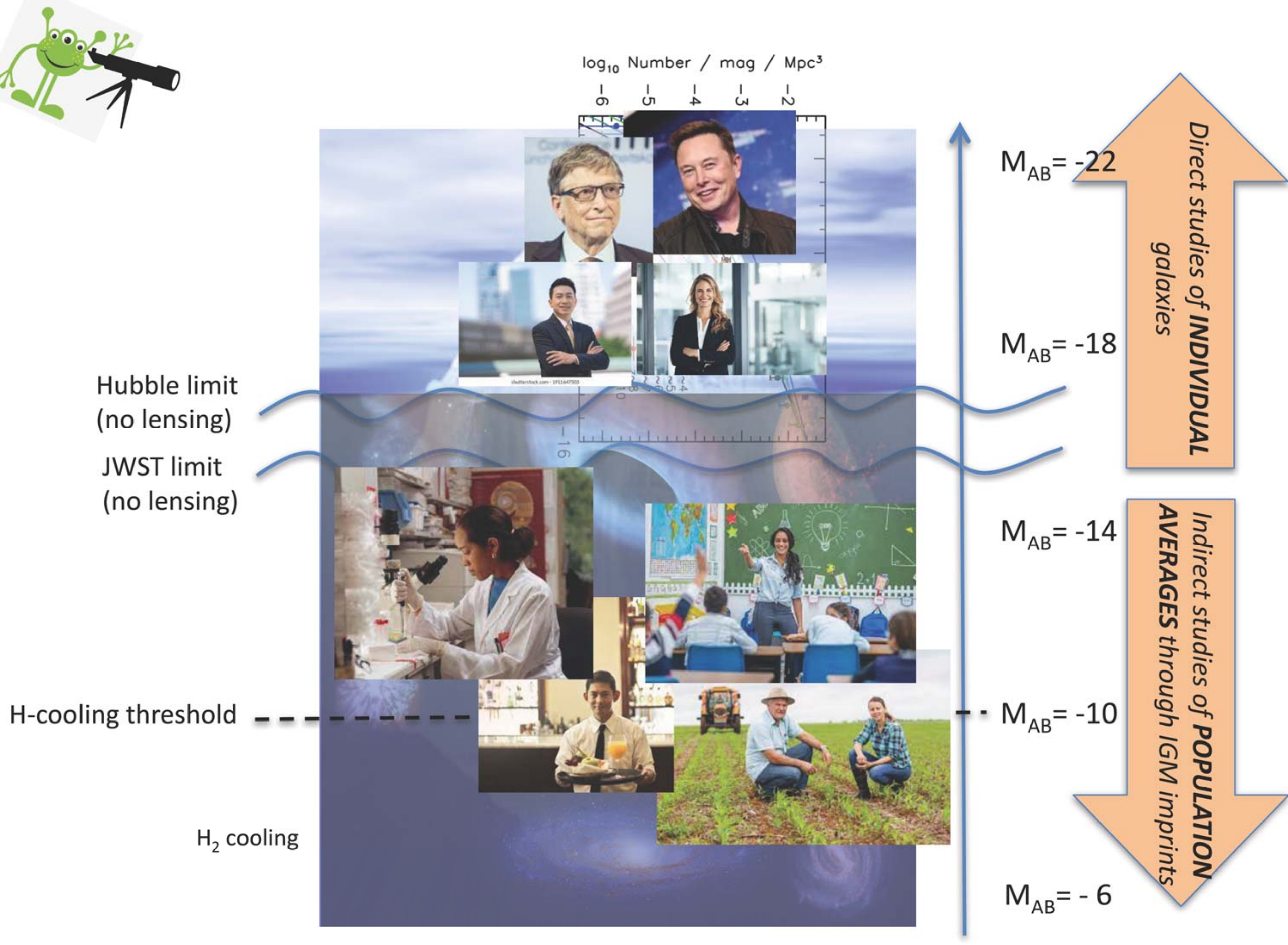


log10 Number / mag / Mpc3
M1600,AB
Hubble limit
(no lensing)
JWST limit
(no lensing)
H-cooling threshold
H2 cooling
>99.9% of the first galaxies
will not be seen even with JWST
The first stars and black holes
MAB= -22
MAB= -18
MAB= -14
MAB= -10
MAB= - 6
hidden population of
abundant ,faint galaxies??


log10 Number / mag / Mpc³
-6
-5
-4
-3
-2
-16
Hubble limit
(no lensing)
JWST limit
(no lensing)
H-cooling threshold
H2 cooling
MAB= -22
MAB= -18
MAB= -14
MAB= -10
MAB= - 6



log10 Number / mag / Mpc³
-6 -5 -4 -3 -2
Hubble limit
(no lensing)
JWST limit
(no lensing)
H-cooling threshold
H_2 cooling
M_{AB}= -22
M_{AB}= -18
M_{AB}= -14
M_{AB}= -10
M_{AB}= - 6


log10 Number / mag / Mpc³
-6 -5 -4 -3 -2
Hubble limit
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JWST limit
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H-cooling threshold
H2 cooling
MAB= -22
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MAB= -10
MAB= - 6
Direct studies of INDIVIDUAL galaxies
Indirect studies of POPULATION AVERAGES through IGM imprints

Why use the IGM to learn about the EoR?

- The IGM temperature and density is shaped by the cumulative radiation from *all* galaxies —> a *democratic* probe of all photons

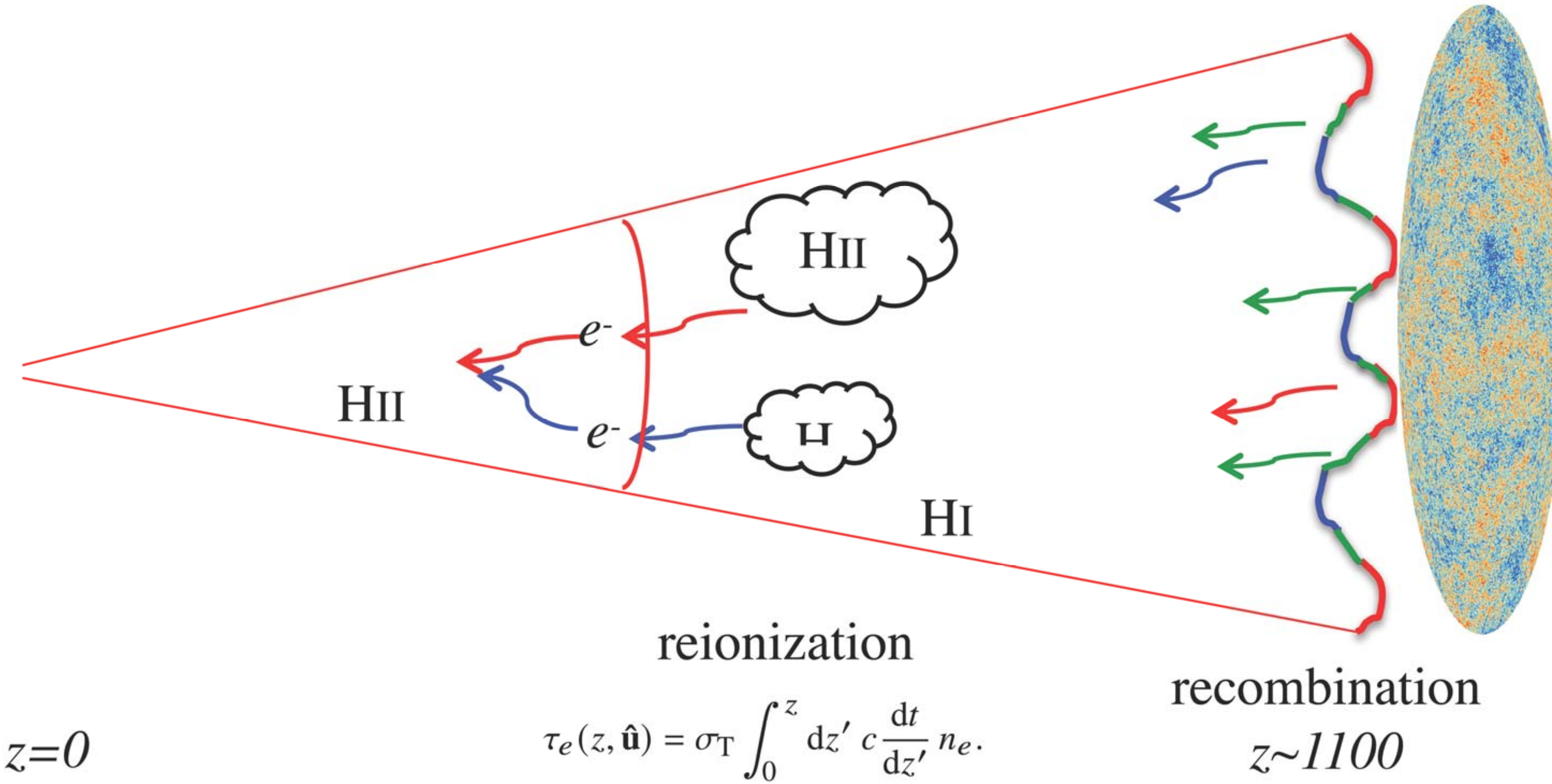
- Lots of statistics

- Not biased by proximity to sources

credit:Millenium simulation

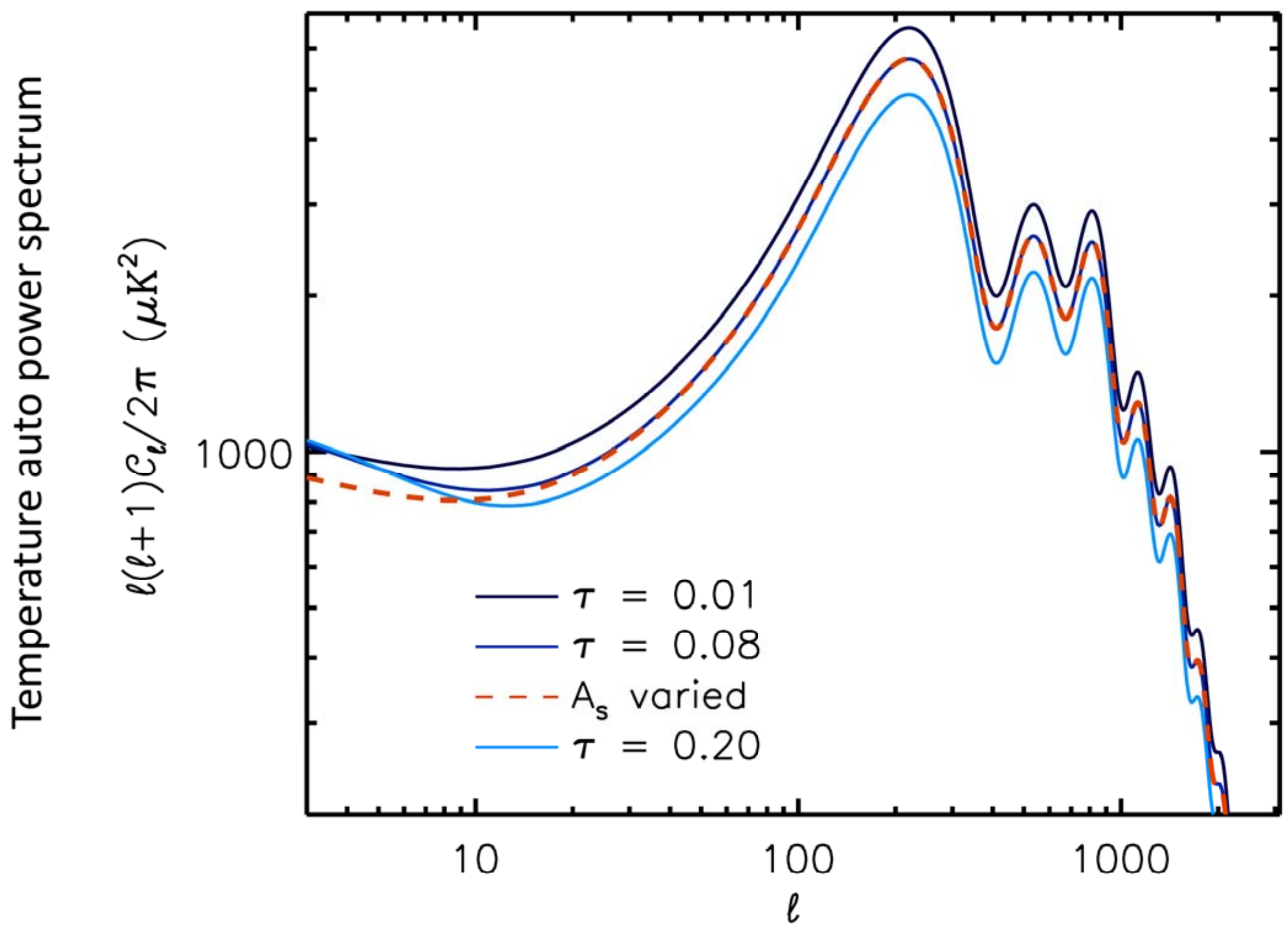
Studying the EoR

- Two main classes of probes
  1. **Integral CMB constraints (e.g. τ_e, kinetic SZ)**



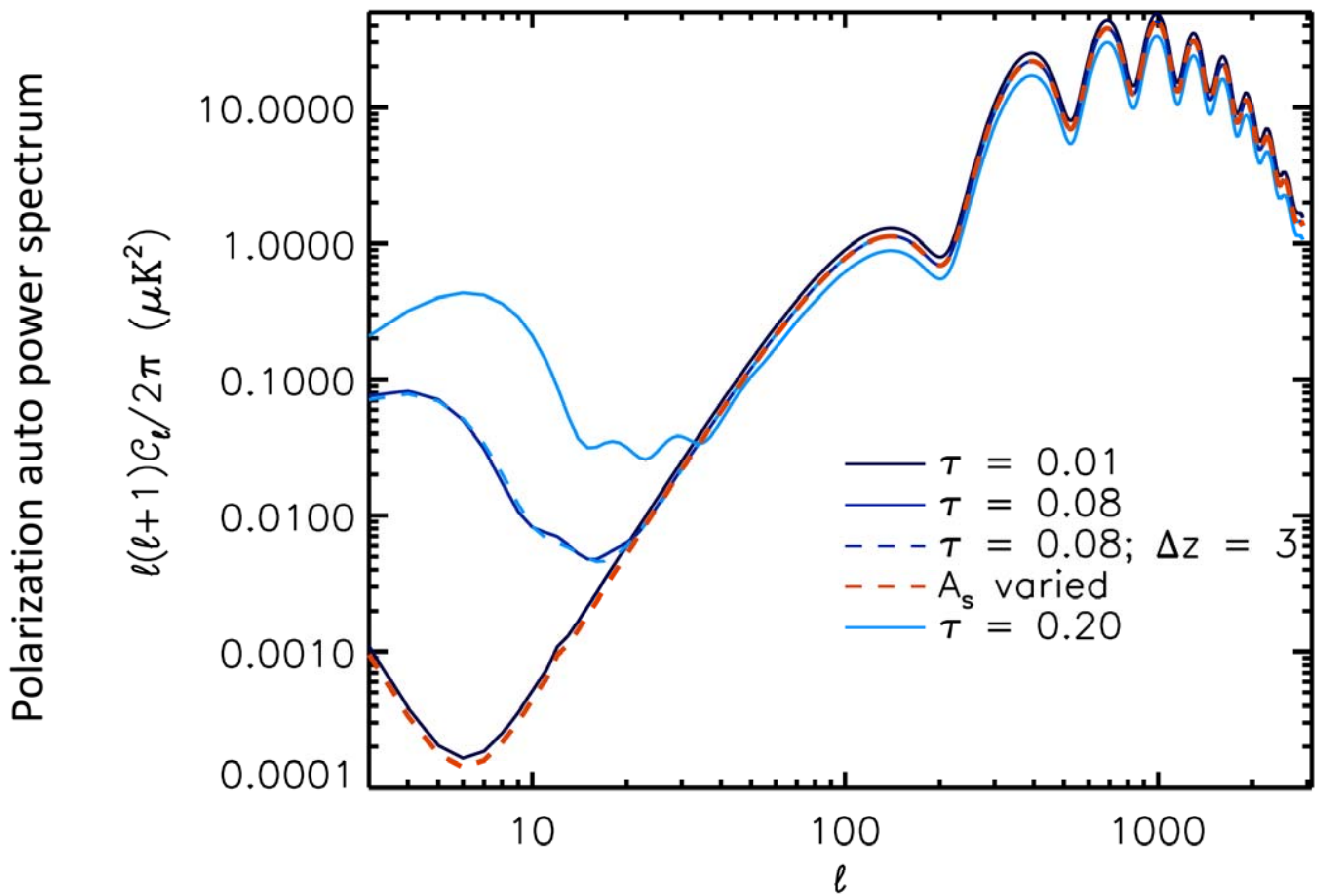
$$\tau_e(z, \hat{\mathbf{u}}) = \sigma_T \int_0^z dz' \, c \frac{dt}{dz'} n_e .$$

Optical depth to the CMB



$$\tau_e(z, \hat{\mathbf{u}}) = \sigma_T \int_0^z \mathrm{d}z' \, c \frac{\mathrm{d}t}{\mathrm{d}z'} n_e .$$

Optical depth to the CMB

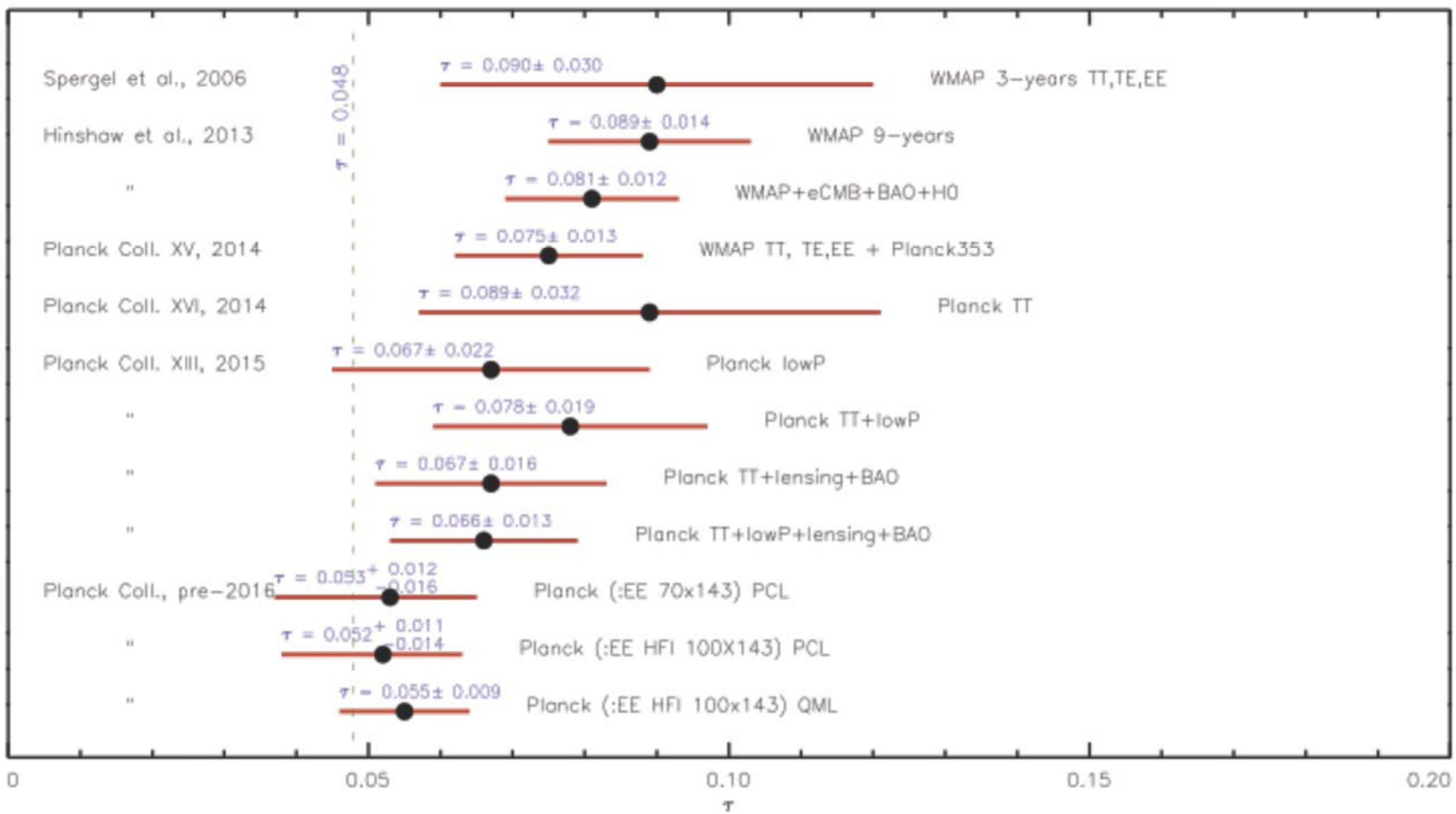


note the size of the signal

$$\tau_e(z, \hat{\mathbf{u}}) = \sigma_T \int_0^z dz'\, c \frac{dt}{dz'} n_e .$$

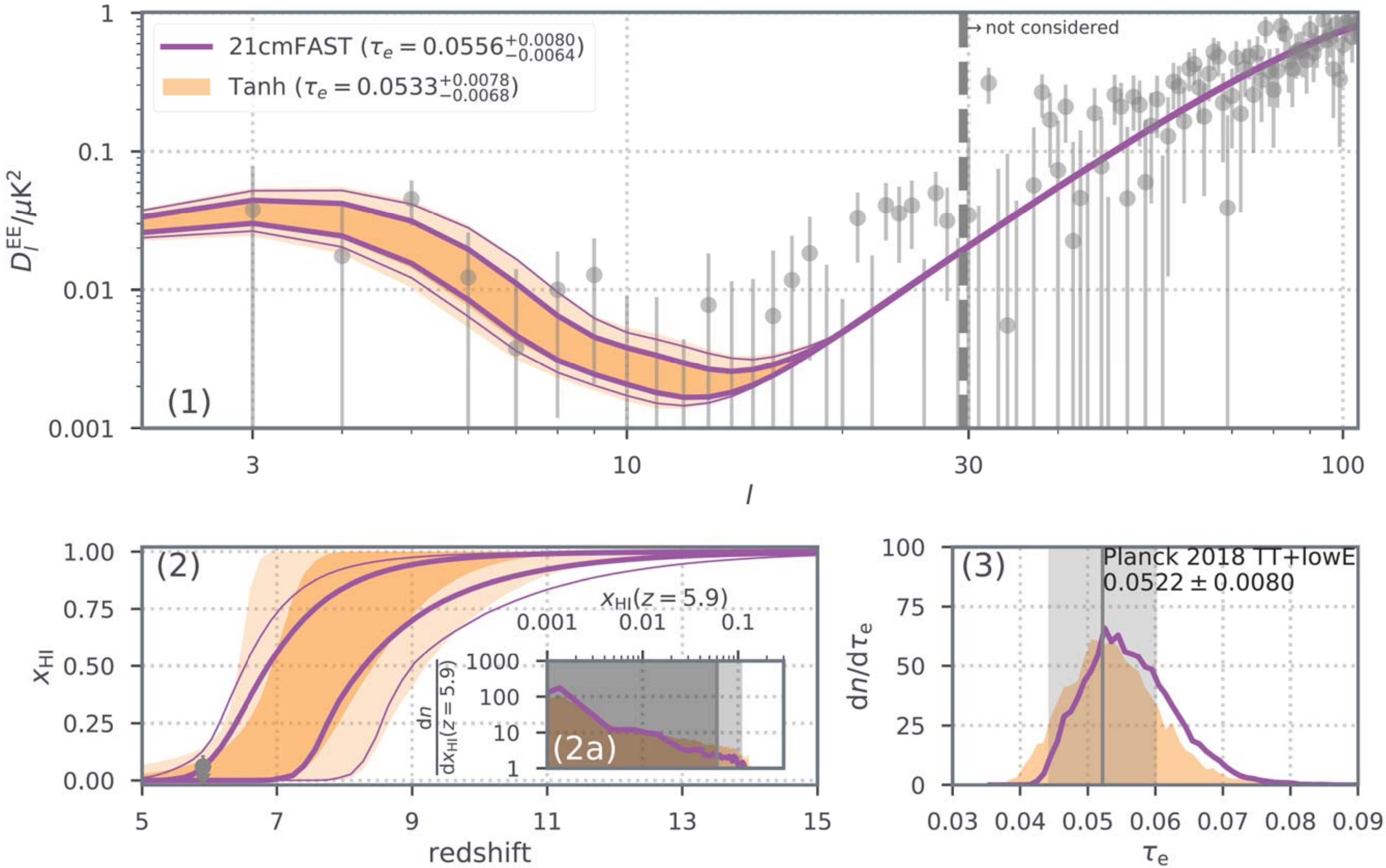
History of Thompson scattering optical depth measurements

WMAP1 2003



Planck 2016

Current EoR constraints from the CMB

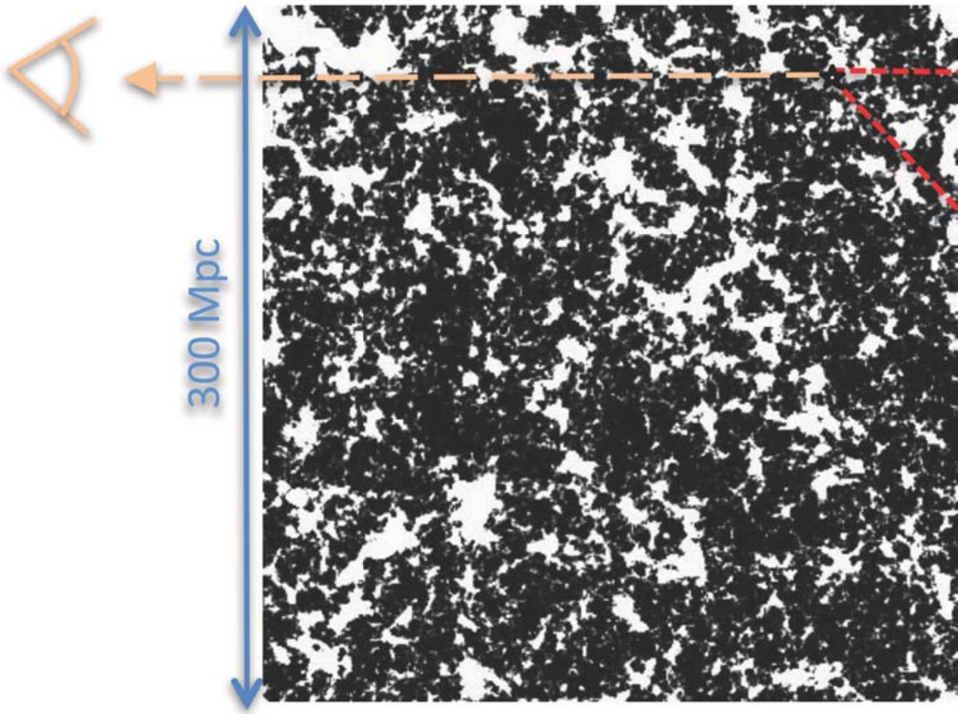


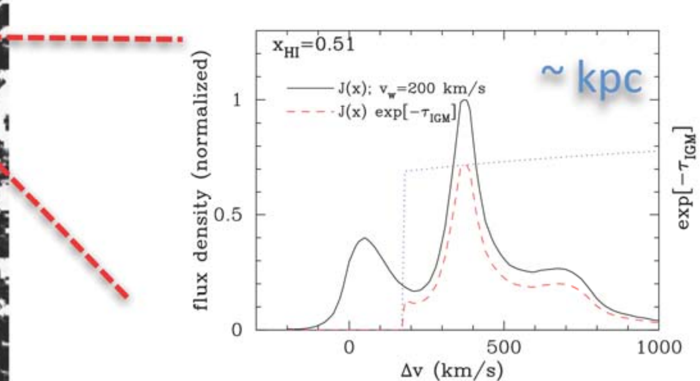
Qin, Poulin, AM+ (2020)

When?

- Two main classes of probes
  1. Integral CMB constraints (e.g. τ_e, kinetic SZ)
  2. **Astrophysical 'flashlights' (e.g. high-z galaxies, QSOs)**

Lyα damping wing absorption as a probe of the EoR



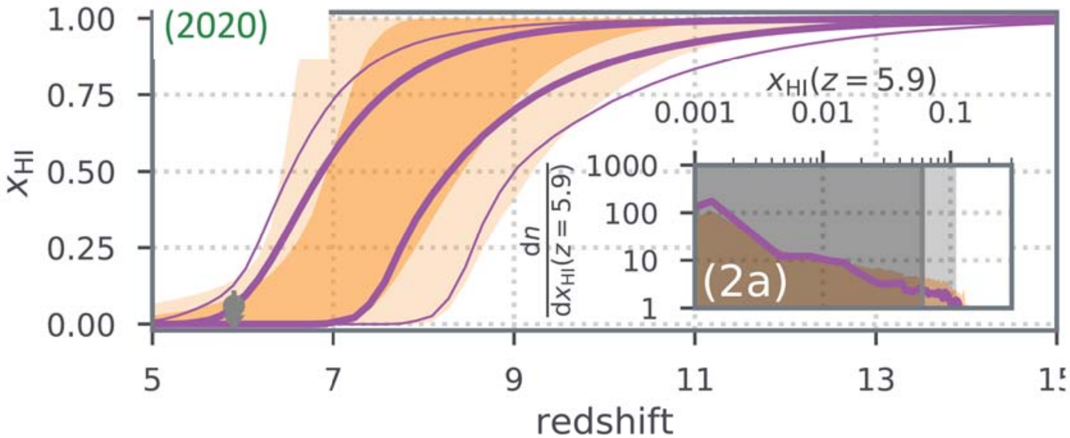


during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

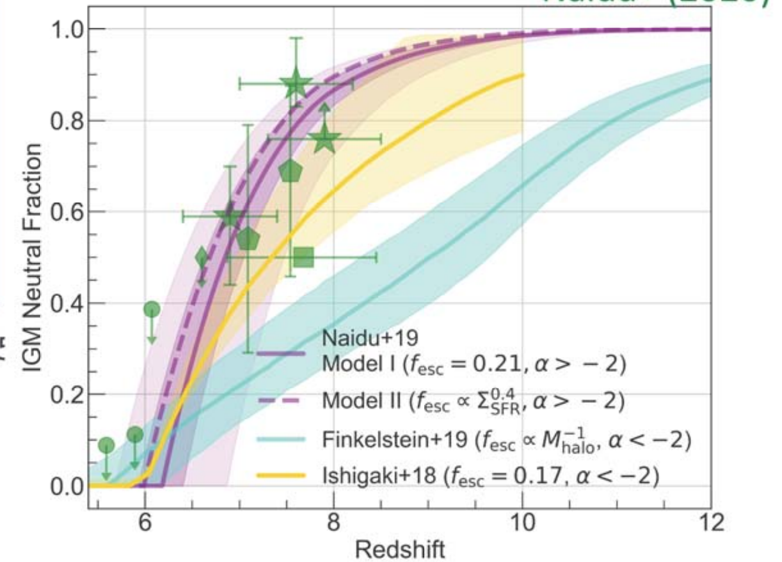
- We have constraints from:
  1. Lyα forest opacity
  2. QSO damping wings
  3. QSO near zones
  4. Redshift evolution of Lyα EW
  5. Redshift evolution of LAE
  6. Clustering of LAEs

Until recently, the timing of the EoR was fairly uncertain...

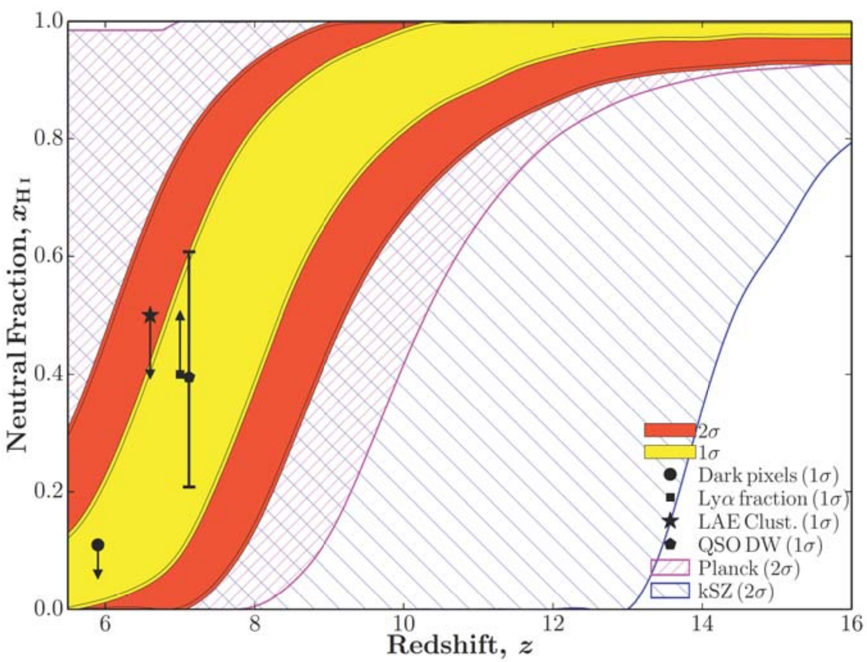
Qin+ (2020)



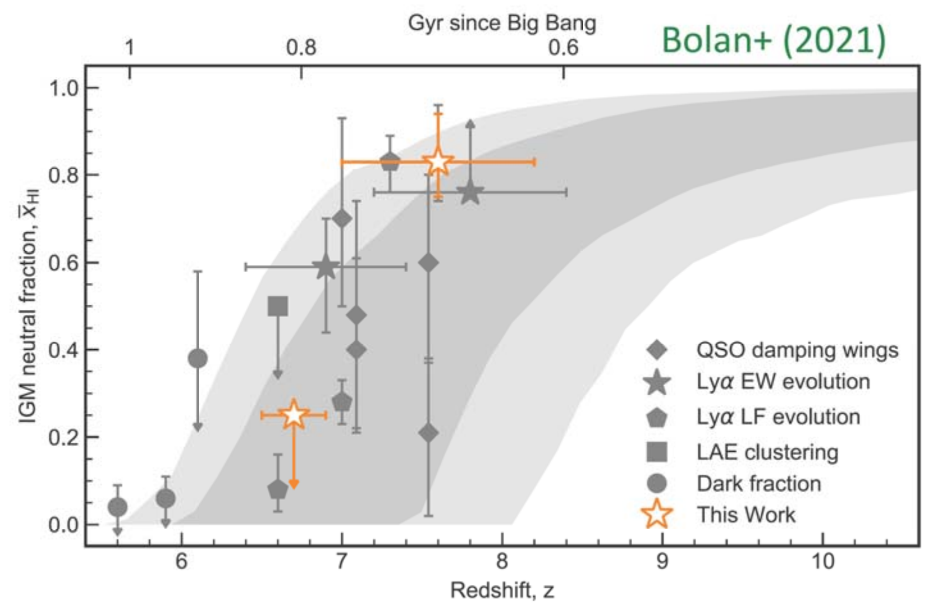
Naidu+ (2020)



Greig & AM (2017)



Bolan+ (2021)



Improved inference from the Lyα forest

- We have constraints from:

1. **Lyα forest opacity**

- **Sensitive to the end stages of the EoR**

- **Probes large volumes of the Universe: (i) amazing statistics; (ii) not biased by local environment of sources**

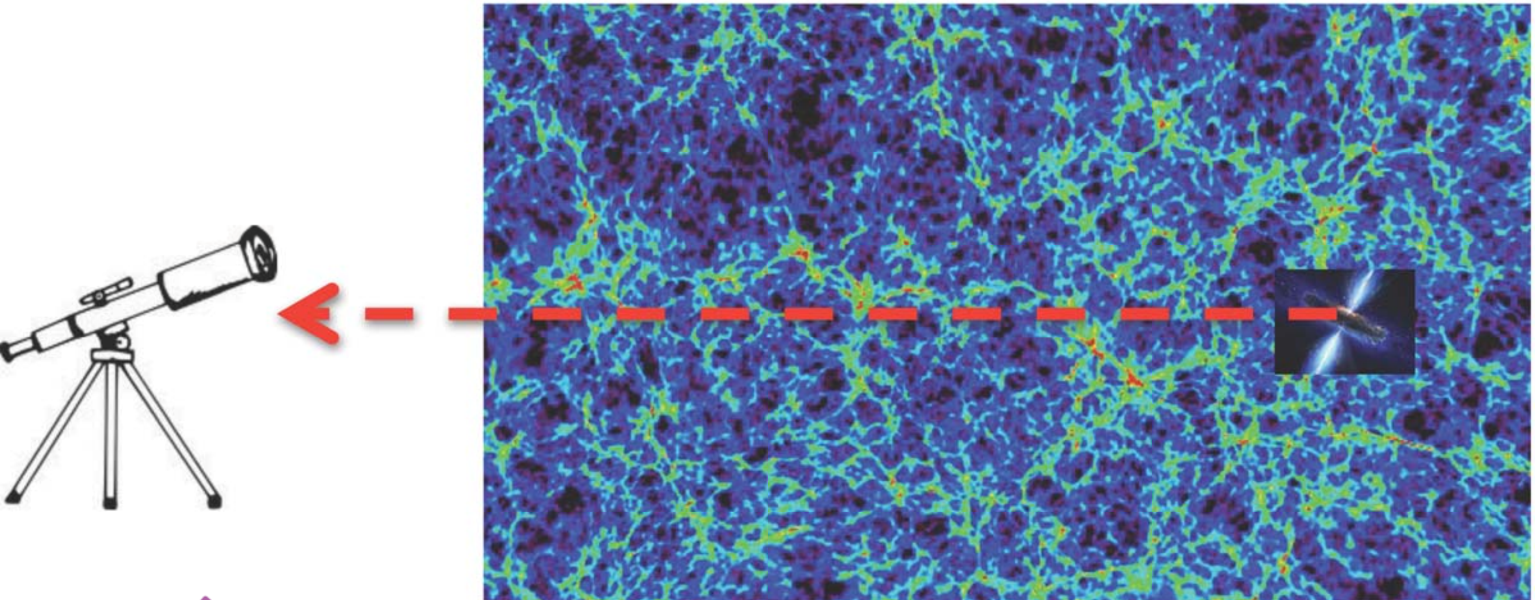
- **Unabsorbed continuum can be predicted to ~1-10% level precision (e.g. Bosman+2021)**

- **Beautiful recent dataset from XQR30**

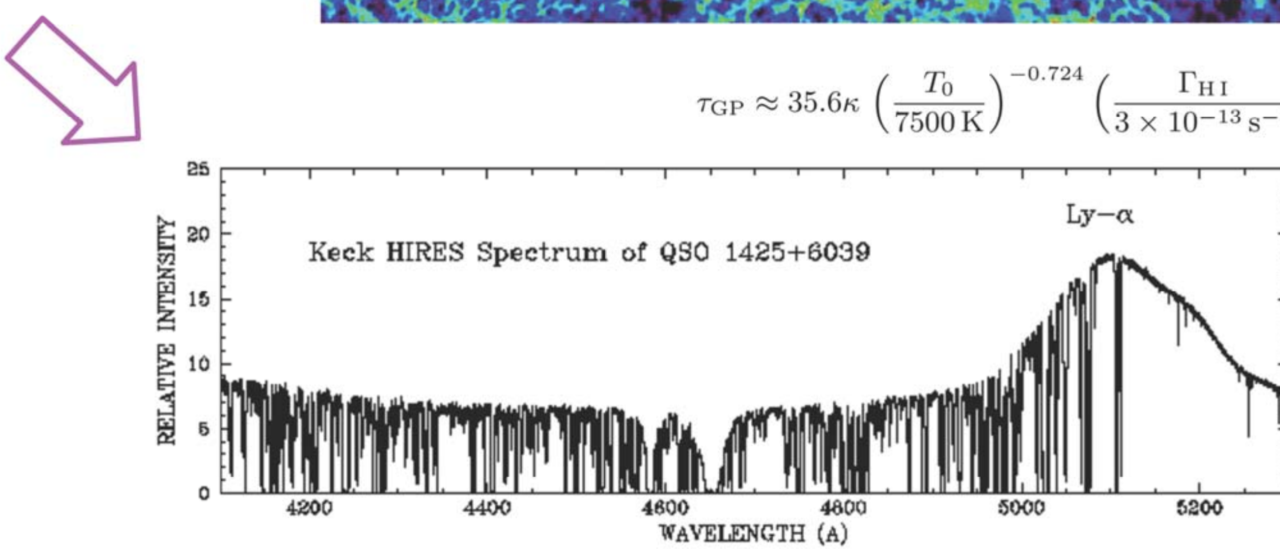
Qin, AM+ in prep

A bit of history…

The Lyα forest is the oldest, most robust probe of the IGM



$$\tau_{\rm GP} \approx 35.6\kappa \left(\frac{T_0}{7500\,{\rm K}}\right)^{-0.724} \left(\frac{\Gamma_{\rm H\,I}}{3\times10^{-13}\,{\rm s}^{-1}}\right)^{-1} \Delta^{2-0.724(\gamma-1)} \left(\frac{1+z}{6.6}\right)^{4.5},$$



The presence of flux in the Lyα forest provided the first solid estimate of the ionization state of the IGM

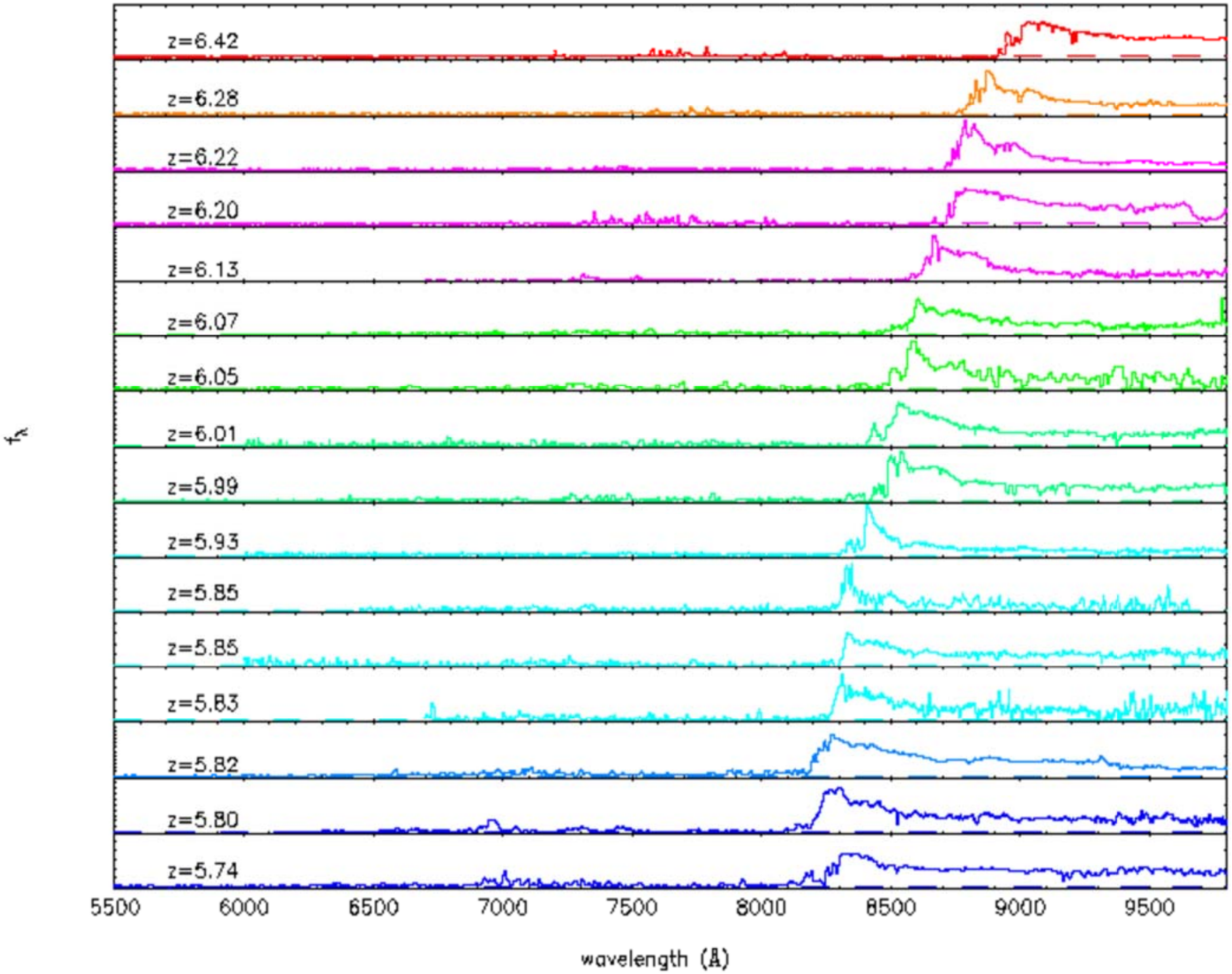
NOTES

ON THE DENSITY OF NEUTRAL HYDROGEN IN INTERGALACTIC SPACE

Recent spectroscopic observations by Schmidt (1965) of the quasi-stellar source 3C 9, which is reported by him to have a redshift of 2.01, and for which Lyman-α is in the visible spectrum, make possible the determination of a new very low value for the density of neutral hydrogen in intergalactic space. It is observed that the continuum of the source continues (though perhaps somewhat weakened) to the blue of Ly-α; the line as seen on the plates has some structure but no obvious asymmetry. Consider, however, the fate of photons emitted to the blue of Ly-α. As we move away from the source along the line of sight, the source becomes redshifted to observers locally at rest in the expansion, and for one such observer, the frequency of any such photon coincides with the rest frequency of Ly-α in his frame and can be scattered by neutral hydrogen in his vicinity. The calculation of the size of the effect is very easily performed as follows:

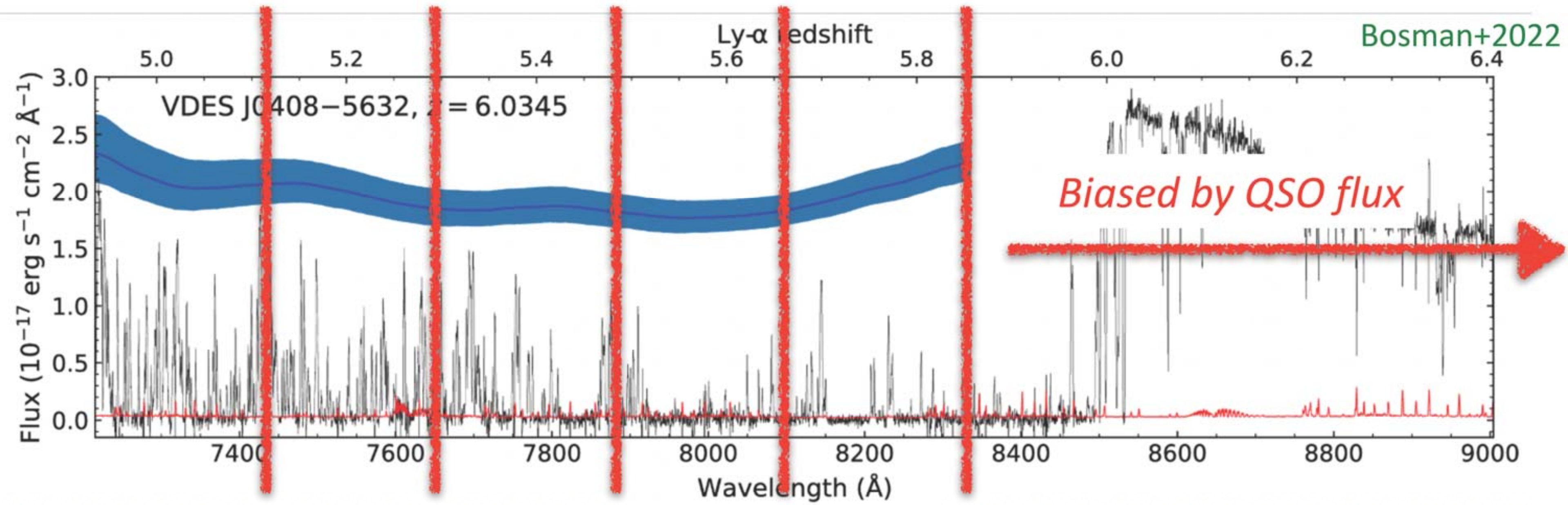
Gunn & Peterson (1965)

But we see less and less flux at higher z



Fan+ (2006)

Usually quantified in terms of an "effective optical depth"

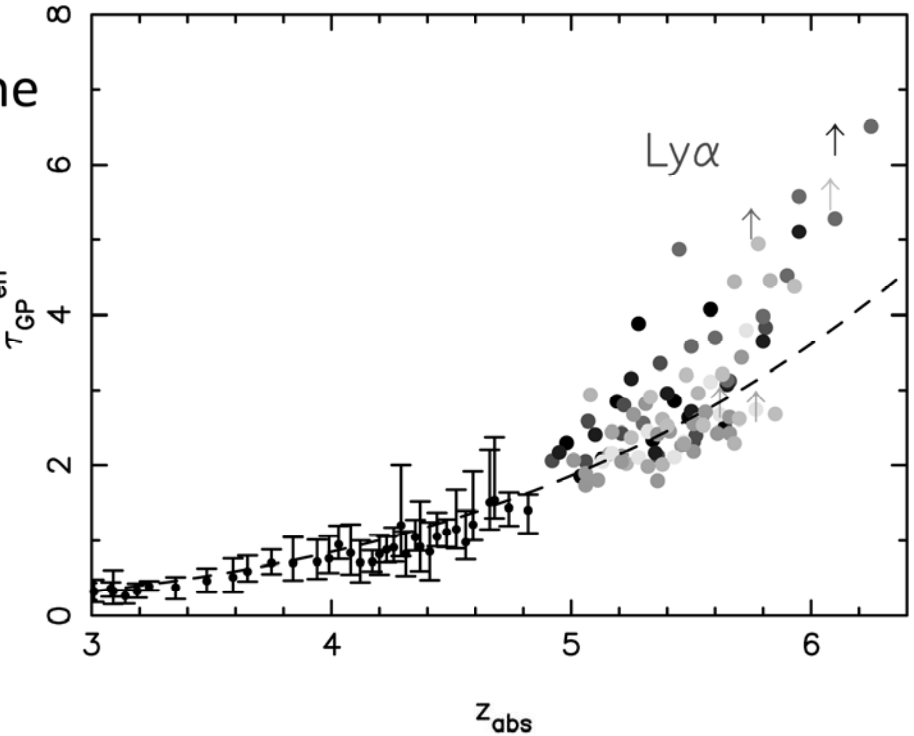


Define "effective optical depth" over each segment:

$$\tau_{\rm eff} \equiv -\ln\langle f \rangle_{\Delta z=0.1}$$

Lya effective optical depth, circa 2006

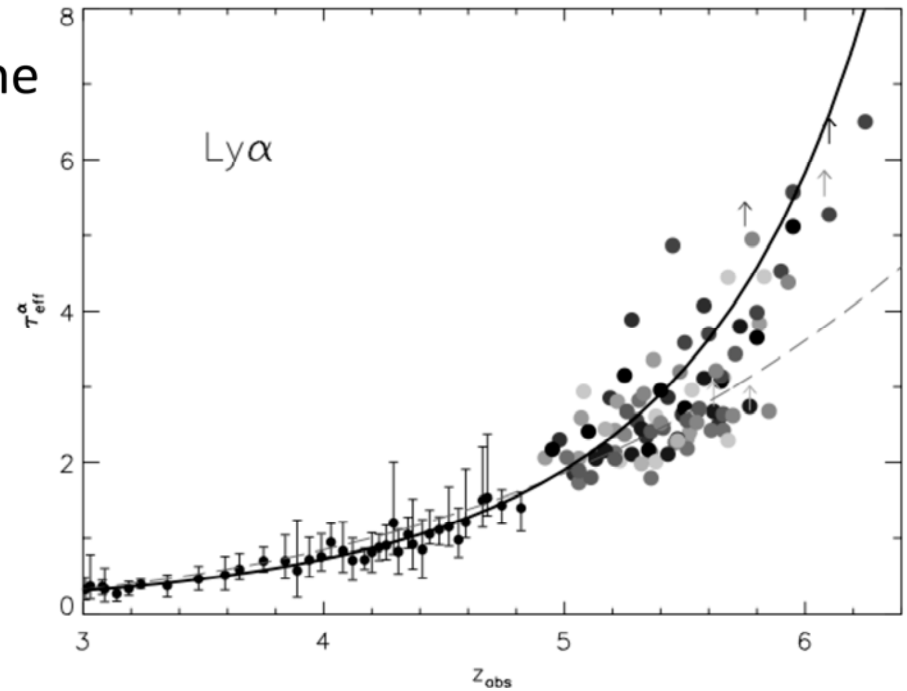
Accelerated **rise** and sightline to sightline **scatter** of effective optical depth was suggestive of reionization at z~6



Fan+ 2006

Lya effective optical depth, circa 2006

Accelerated **rise** and sightline to sightline **scatter** of effective optical depth was suggestive of reionization at z~6



BUT

Becker+ 2007

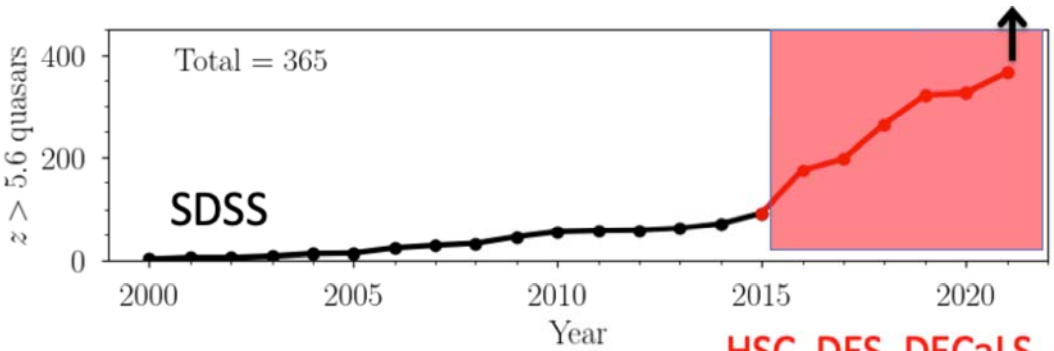
Distributions of τ_{eff} consistent with an ionized Universe at z<6 (e.g. Becker+2007; Lidz+2007; Gallerani+2008)

Only fluctuations in the density field are sufficient to explain the data

So we can't really tell from the forest data…

Until we started getting lots more, high quality QSO data

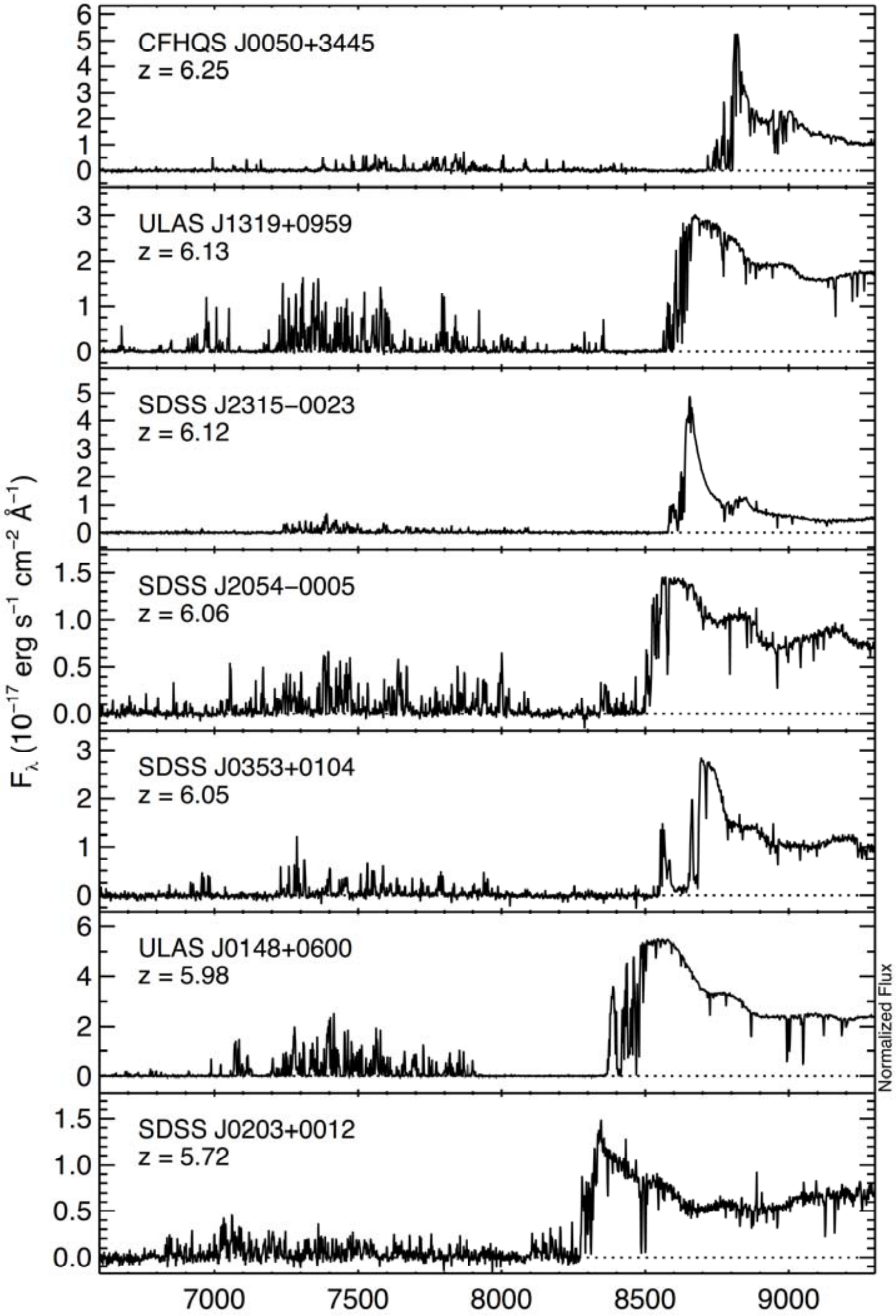
~5x more quasars
in the last 5 years



HSC, DES, DECaLS
Pan-STARRS1, VHS, UHS

Andika+2020
Bañados+2015-2021
Belladitta+2020
Carnall+2015
Fan+2019
Jiang+2015-2016
Matsuoka+2016-2019
Mazzucchelli+2017
Pons+2019
Reed+2015-2019
Tang+2019
Venemans+ 2015ab
Wang+2016-2021
Yang+2017-2020
Wu+2015
...

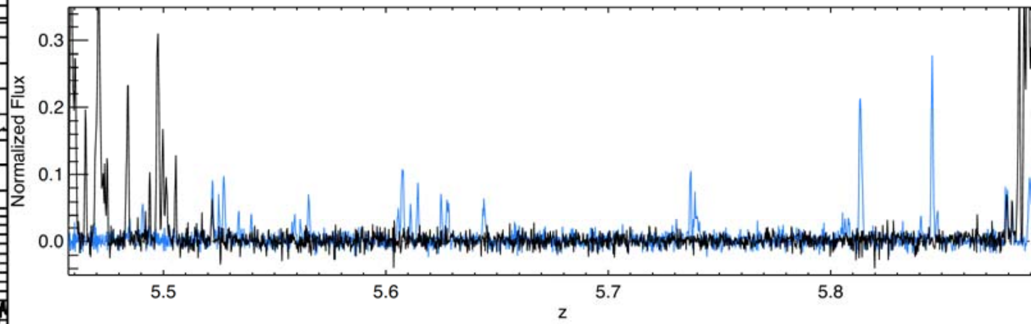
slide courtesy of E. Banados



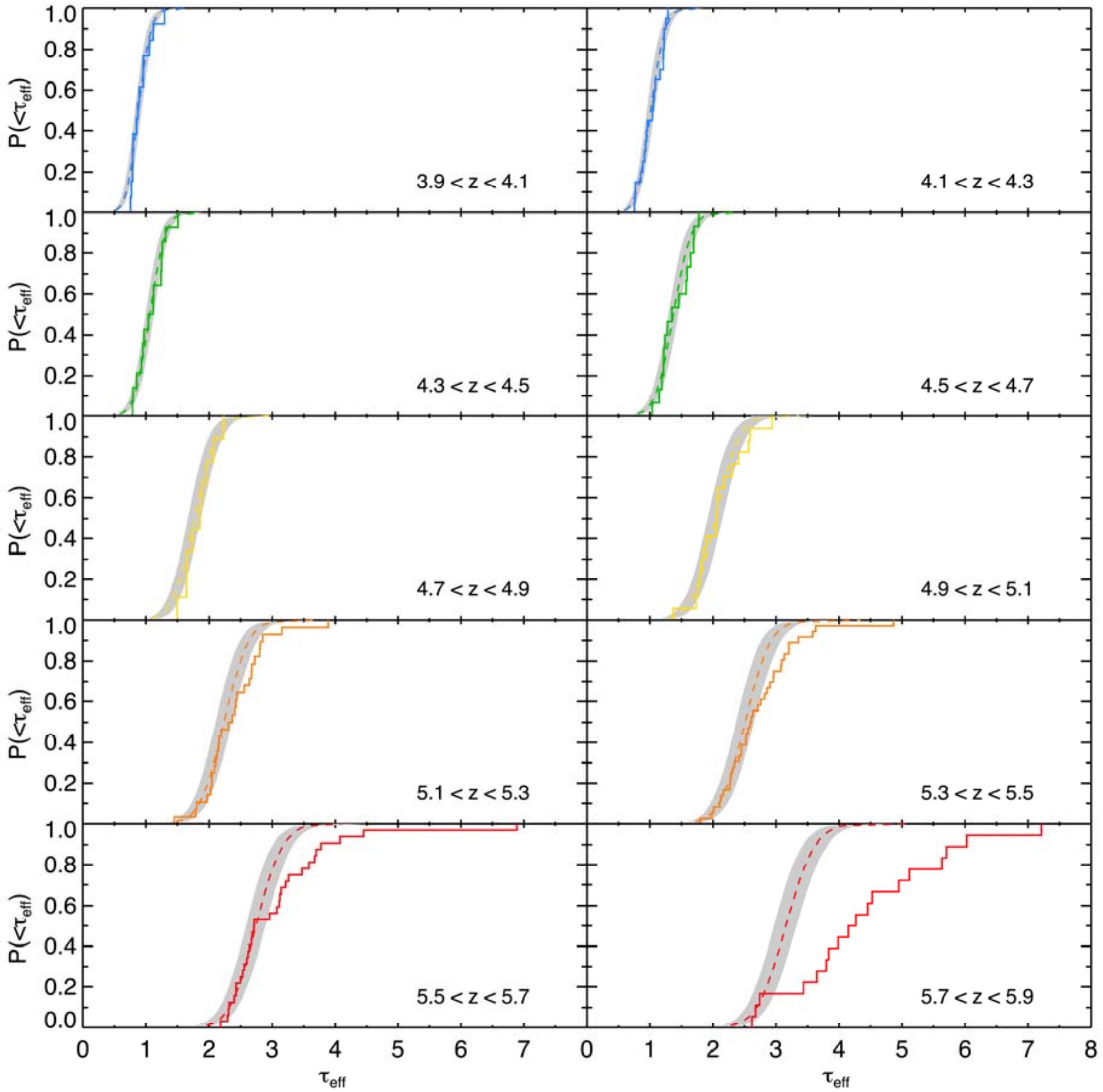
With even larger scatter and longer dark troughs

Becker+ 2015

GP through that is 160Mpc long!!!



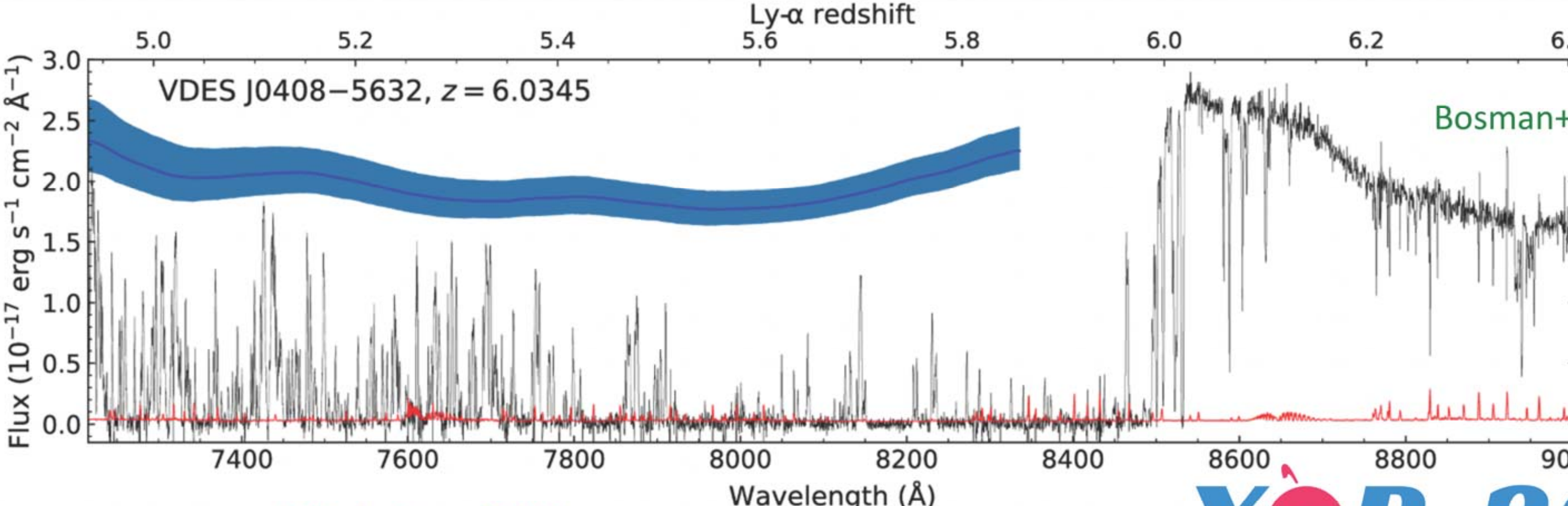
Large scatter



Distributions of τ_{eff} are ***TOO BROAD*** to be consistent with a uniform, pervasive UVB at z>5.2

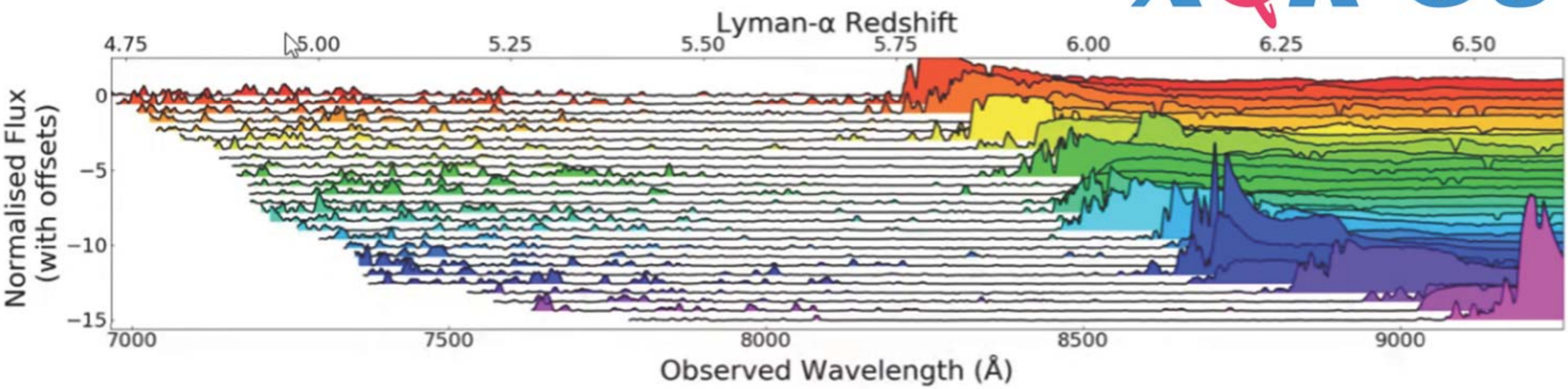
Becker+ 2015

XQR-30: super high-quality QSO spectra at z=5.8-6.6 using X-Shooter on VLT (PI: *V. D'Odorico*)



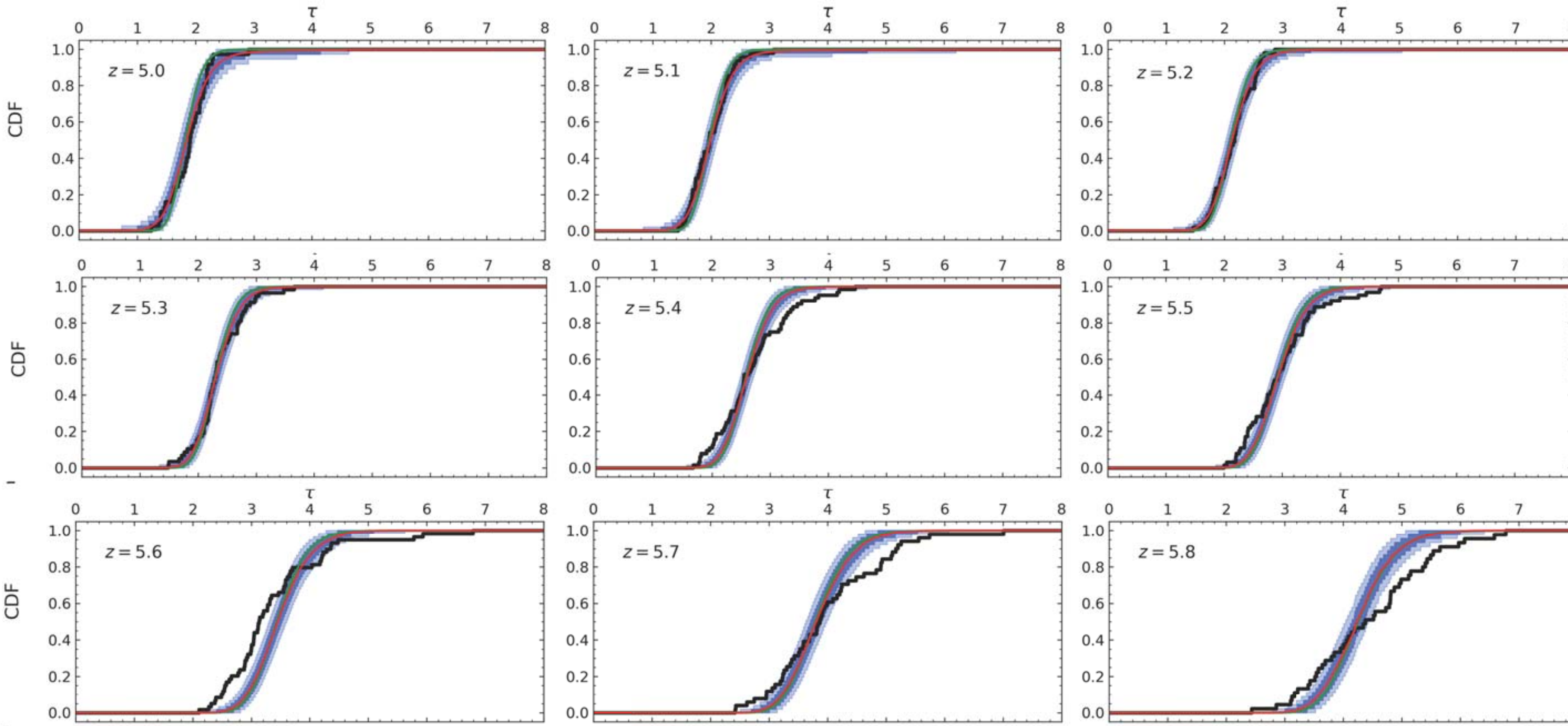
Bosman+2022

D'Odorico+2023



total sample >40 spectra probing forest at 5<z<6.4

We need an additional source of scatter



Distributions of τ_{eff} are ***TOO BROAD*** to be consistent with a uniform, pervasive UVB at z>5.2

Bosman+2021

XQR-30

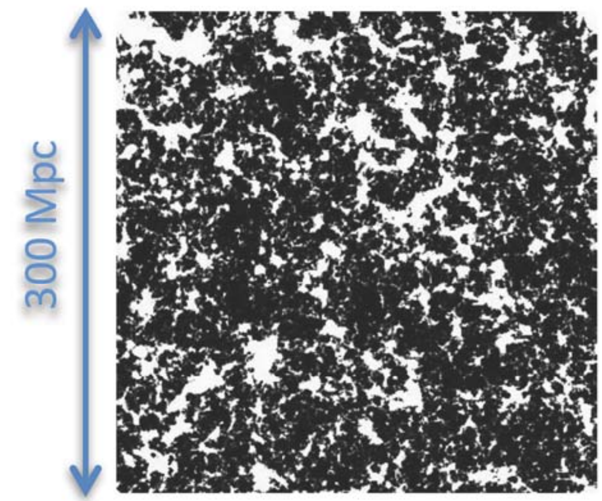
What can increase fluctuations in τ_{eff}?

Ionized component

$$\tau_{HII} \propto \frac{\Delta^2 \alpha_B(T)}{\Gamma_{\rm ion}} \propto \frac{\Delta^2 \alpha_B(T)}{\epsilon_{\rm ion} \lambda_{\rm mfp}}$$

Neutral component

$$\tau_{HI} \sim 10^5 - 10^6$$



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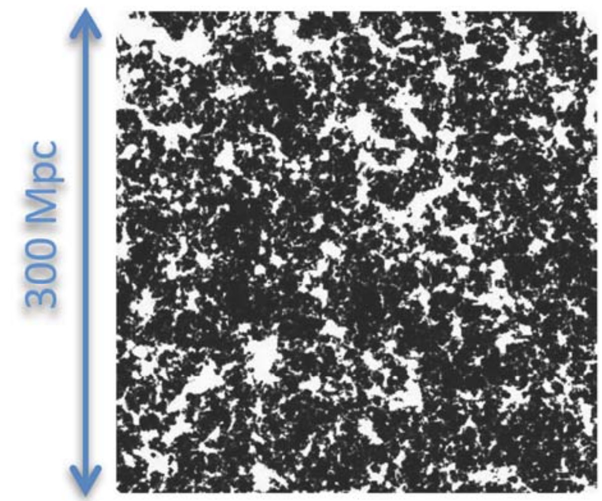
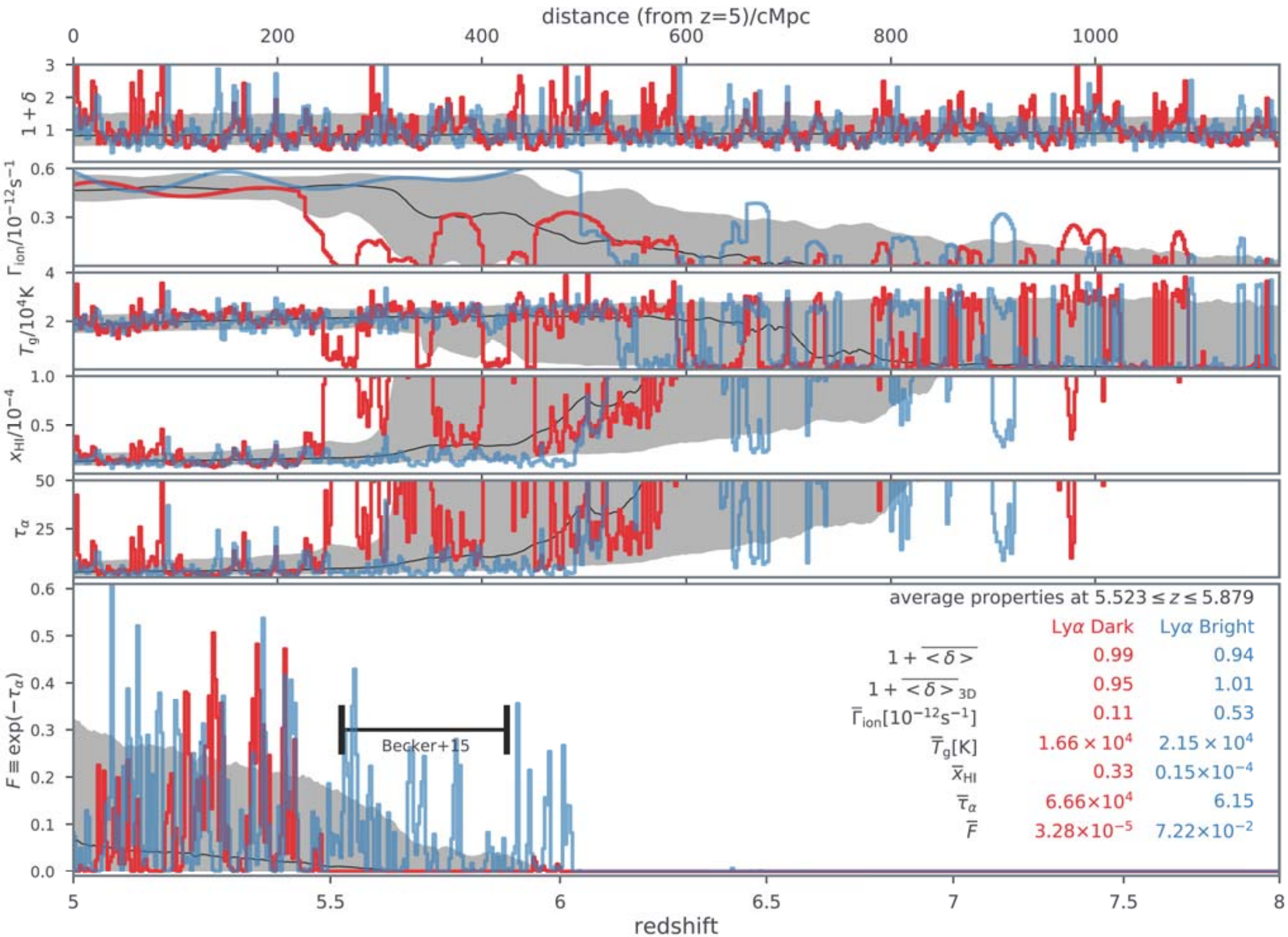


Large-scale fluctuations could be explained by (***tuning***):

- Temperature (e.g. D'Aloisio+2015)
- Rare sources (Chardin+2015,2017; Meiksin+2020)
- Mean free path (Davies+2016; Davies+2023)
- patchy EoR (Kulkarni+2019; Keating+2020; Choudhury+2021; Qin+2021)

Or a combination of effects —

large scale fluctuations from a combination of EoR and UVB

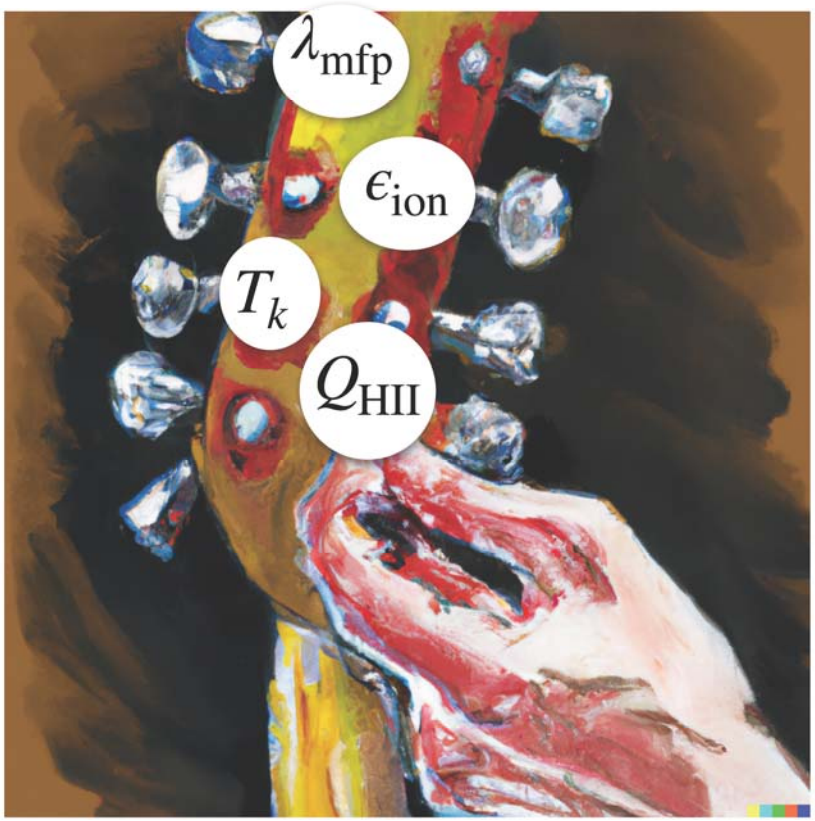


from MAP model

Qin, AM+ 2021

see also Keating+2020

The problem with *tuning*...

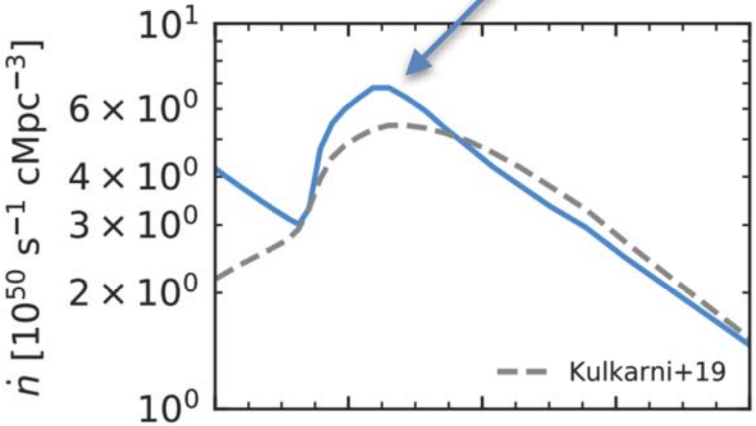


DALL-E 2 OpenAI

What do we learn about galaxies, if we introduce “effective” parameters and “tune”?

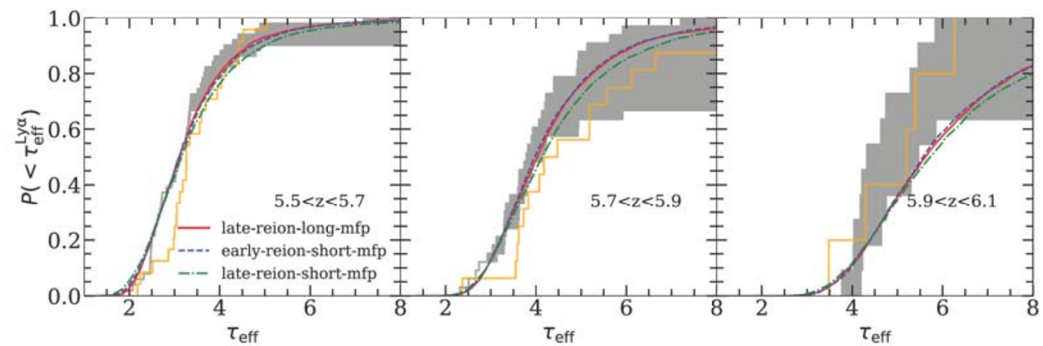
The problem with *tuning*…

unphysical(?) “bump” in emissivity



Kulkarni+19; Keating+20

Degeneracy from ad-hoc mpf and EoR tuning



Nasir&D’Aloisio (2019)

What do we learn about galaxies, if we introduce “effective” parameters and “tune”?

The only *correct* way to learn from data is through **Bayesian inference** from **physical forward models**

- We need efficient **simulations** with a parametric **model** for cosmology + astrophysics + systematics
- We need **observations**!
- We need a quantitative way of **comparing** the model(s) to the observations

$$P(\theta|X) = \frac{P(X|\theta)P(\theta)}{P(X)}$$

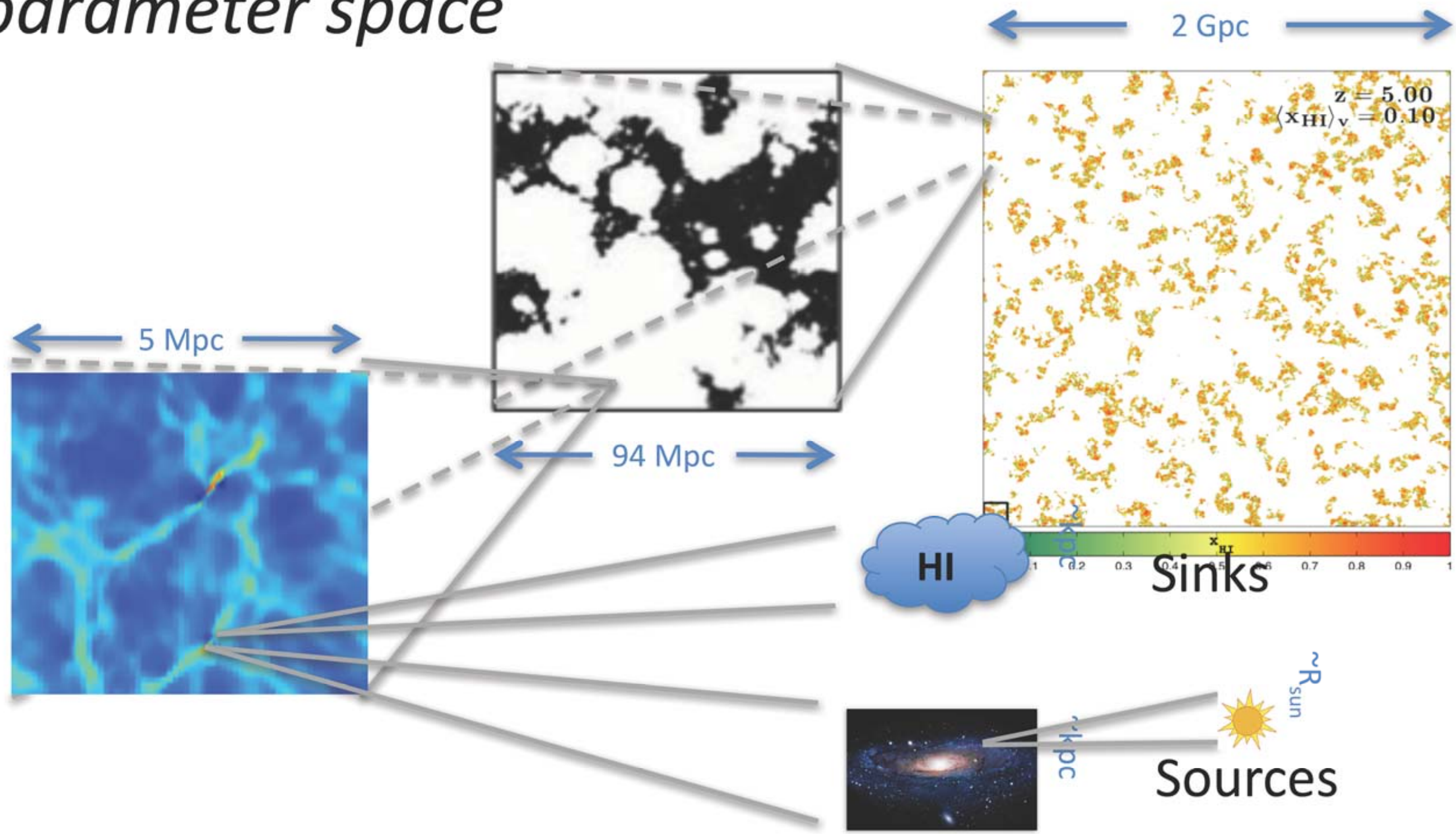
Lots of quality data can really stress-test our models…

Why is it so hard to model?

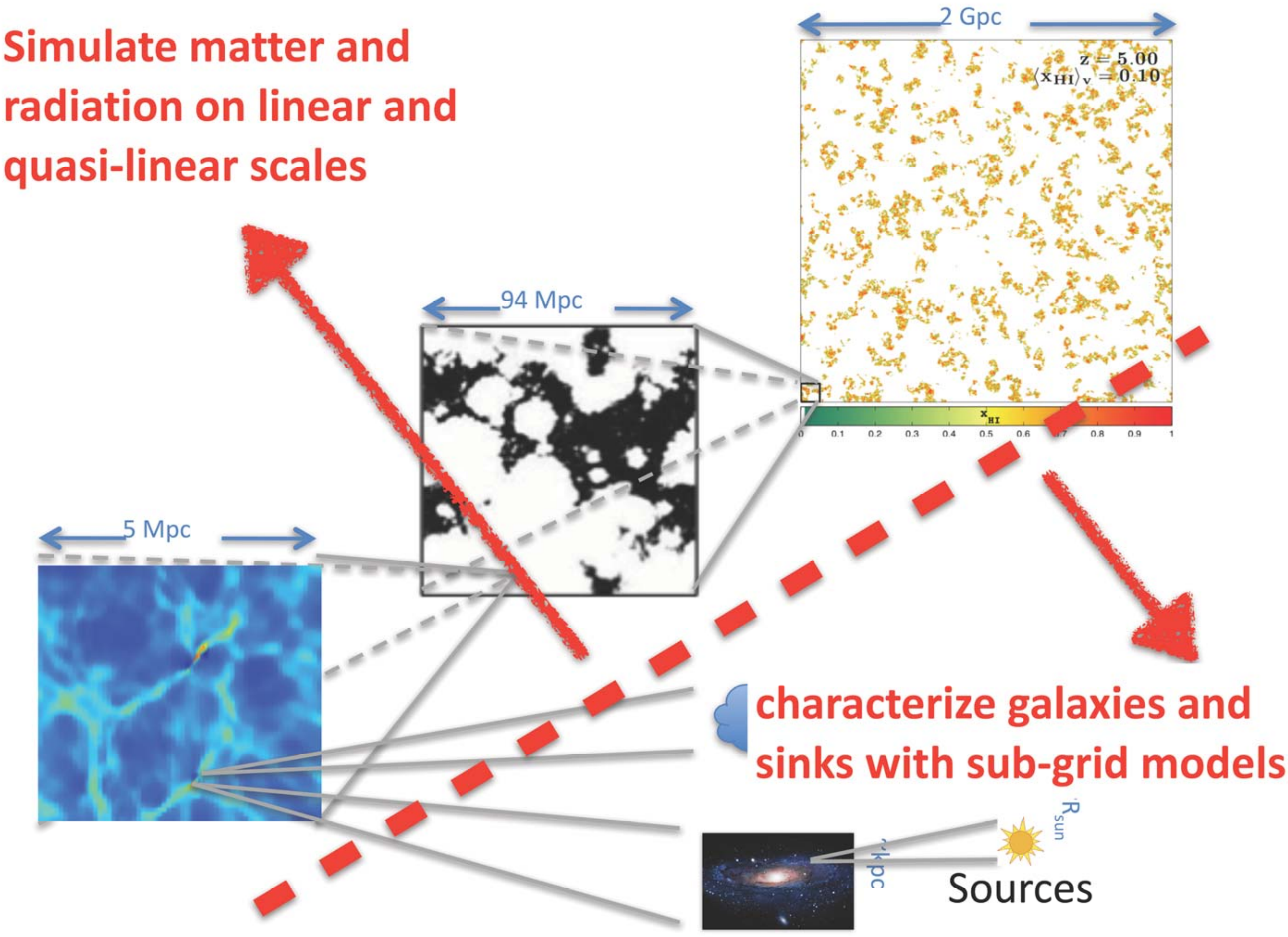
Challenges in IGM modeling

(i) Range of scales - *need multi-scale modeling*

(ii) Complexity - *need efficient sampling of large parameter space*



Forward modeling the Lyα forest and other EoR observables



The method

i) **For a given sample of galaxy parameters, simulate light-cones of Lyα optical depth with 21cmFAST**

$$\frac{M_*}{M_h} = \mathbf{f}_{*,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_*} \frac{\Omega_b}{\Omega_m}$$

$$L_{1500} \propto \frac{M_*}{\mathbf{t}_* t_{\rm dyn}}$$

$$L_{\rm ion} \propto \mathbf{f}_{\rm esc,10} \left(\frac{M_h}{10^{10} M_\odot} \right)^{\alpha_{\rm esc}} \left(\frac{1+z}{7} \right)^{\beta_{\rm esc}} L_{1500}$$

$$f_{\rm duty} = \exp[-\mathbf{M}_{\rm turn}/M_h]$$

Qin, AM+ in prep

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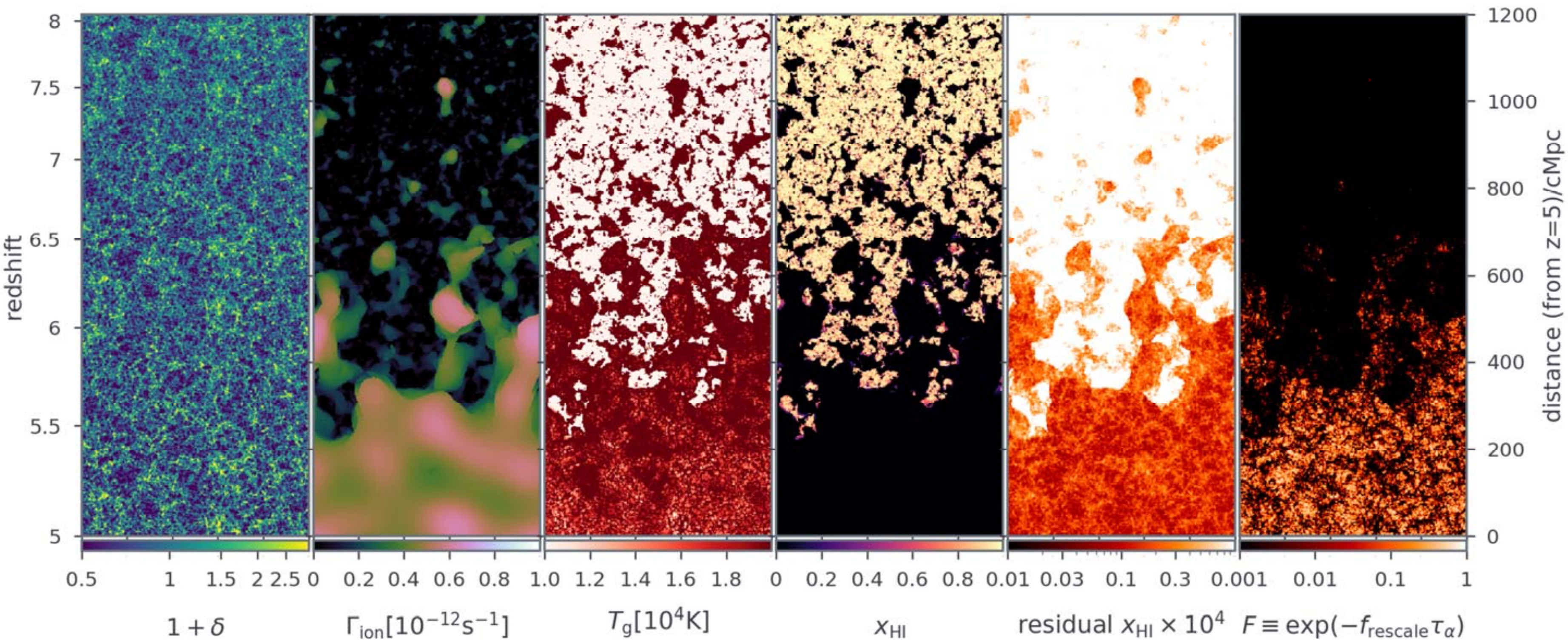

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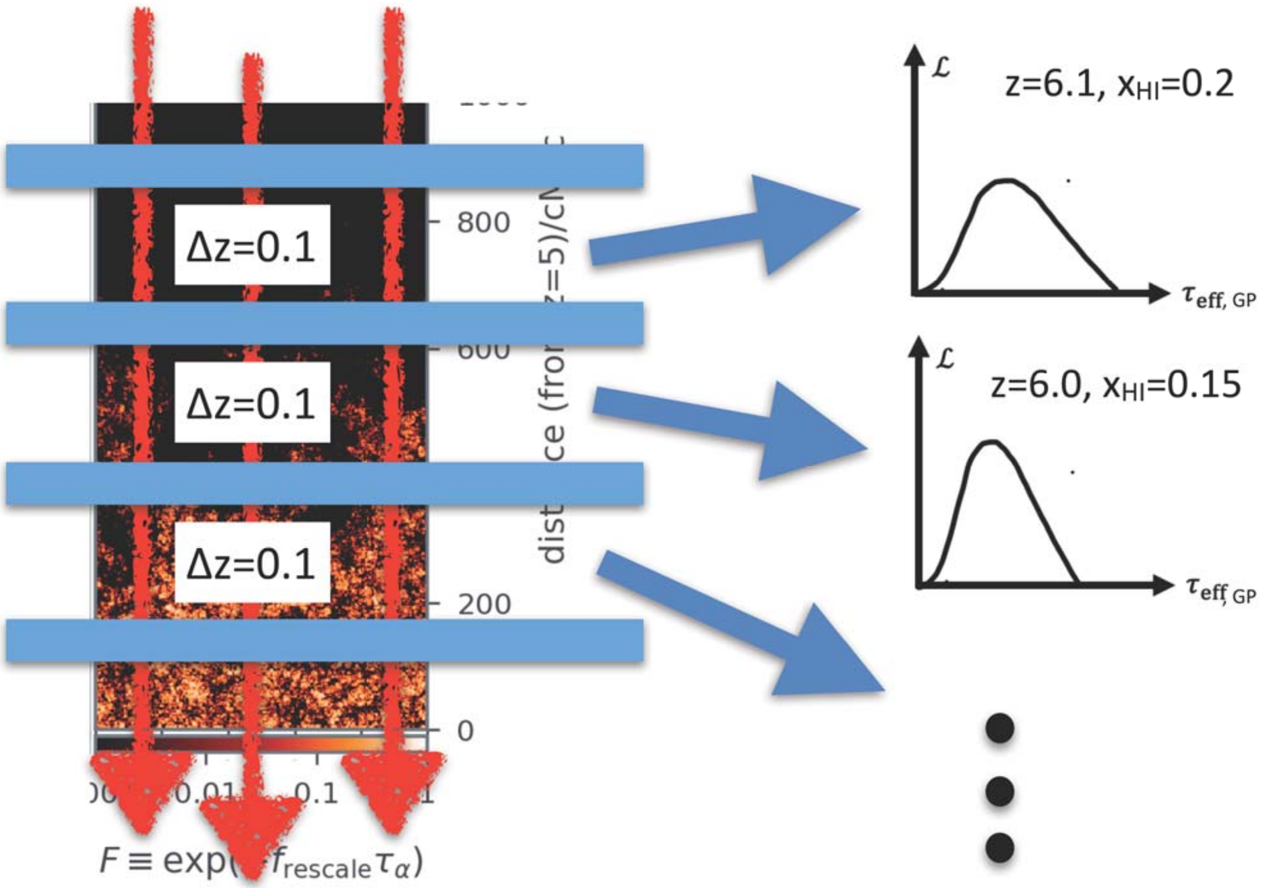

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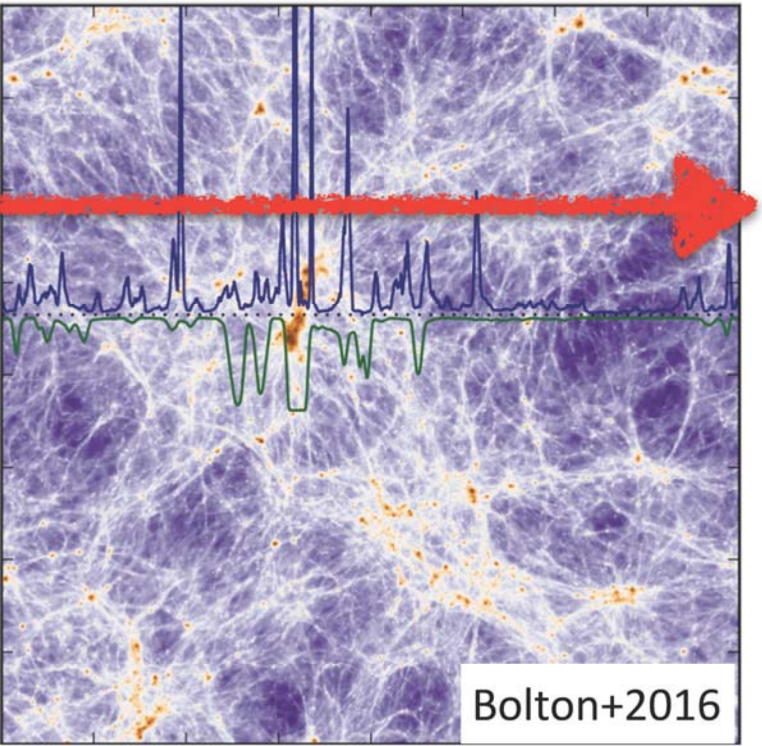

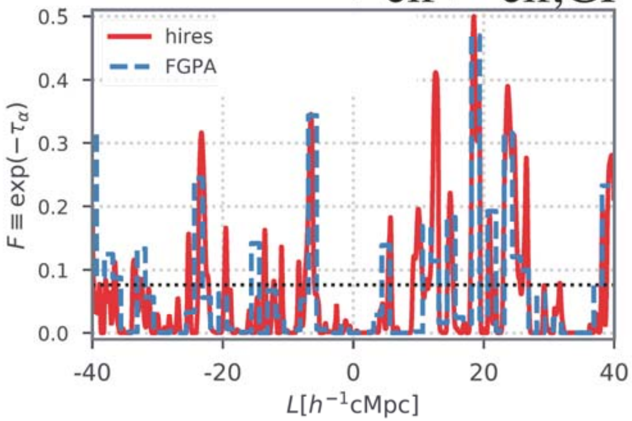

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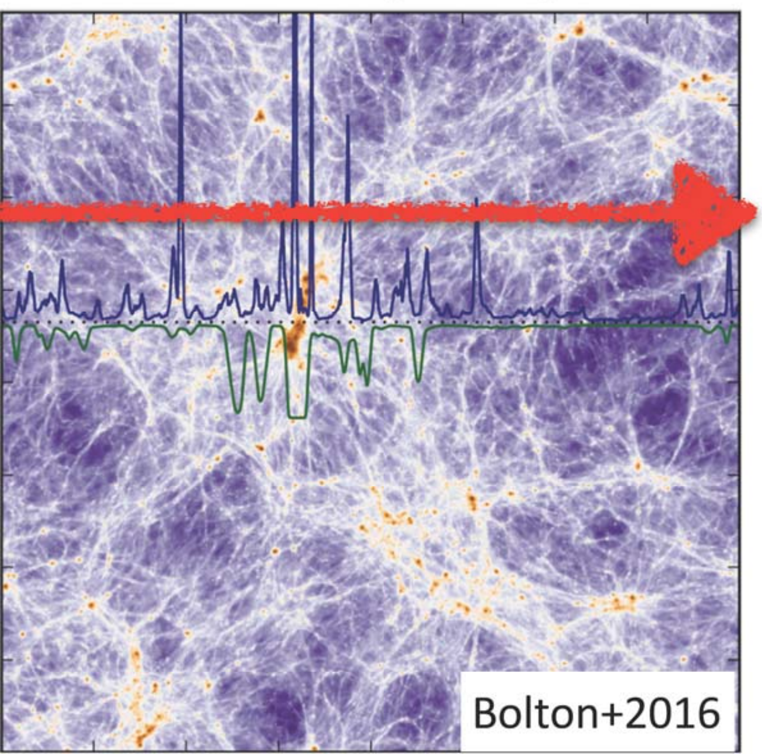

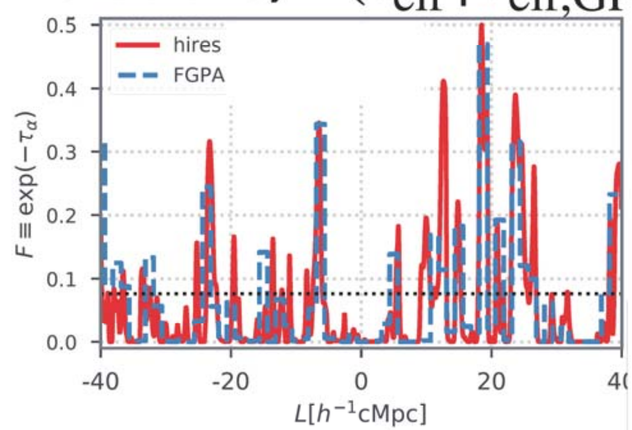

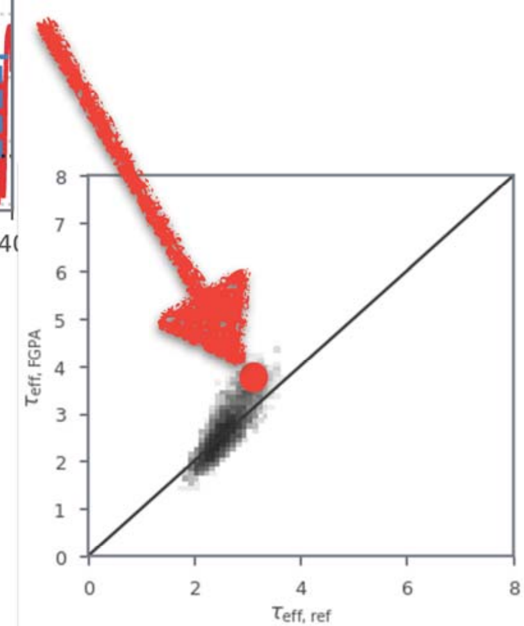

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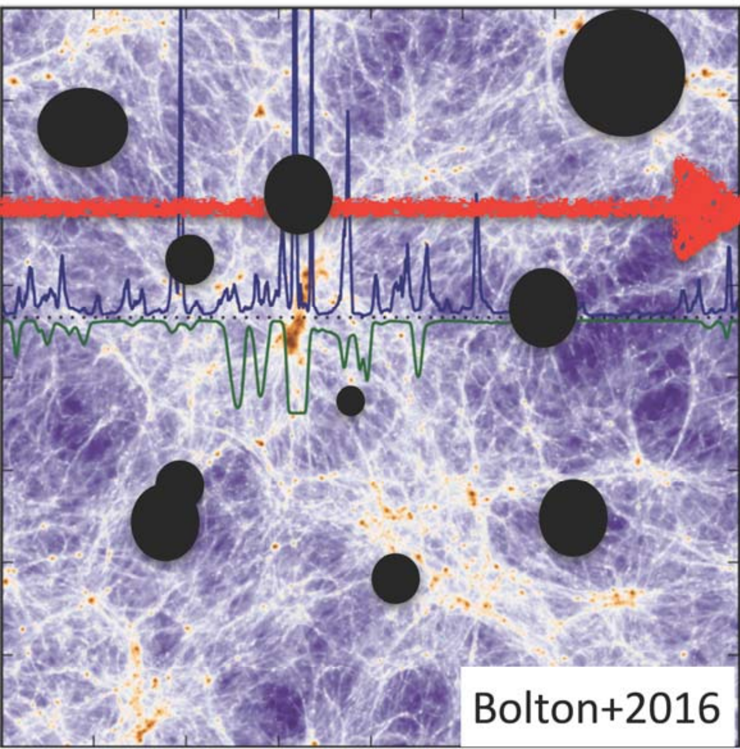

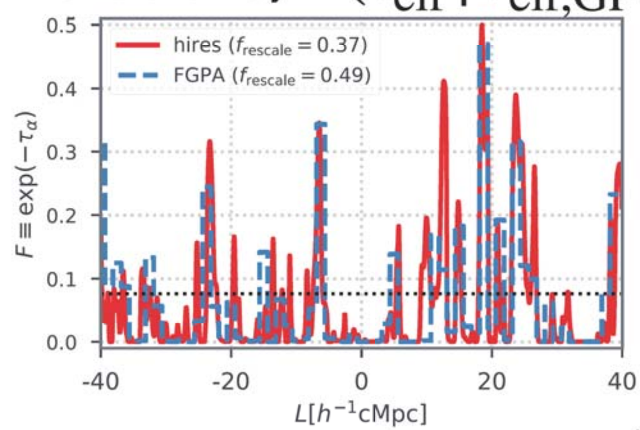

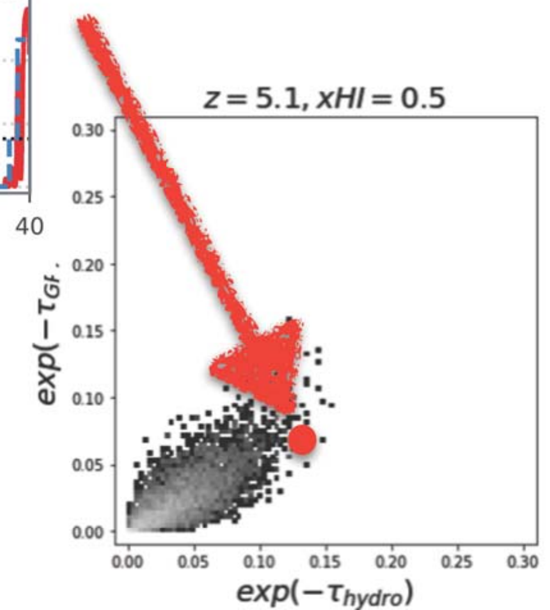

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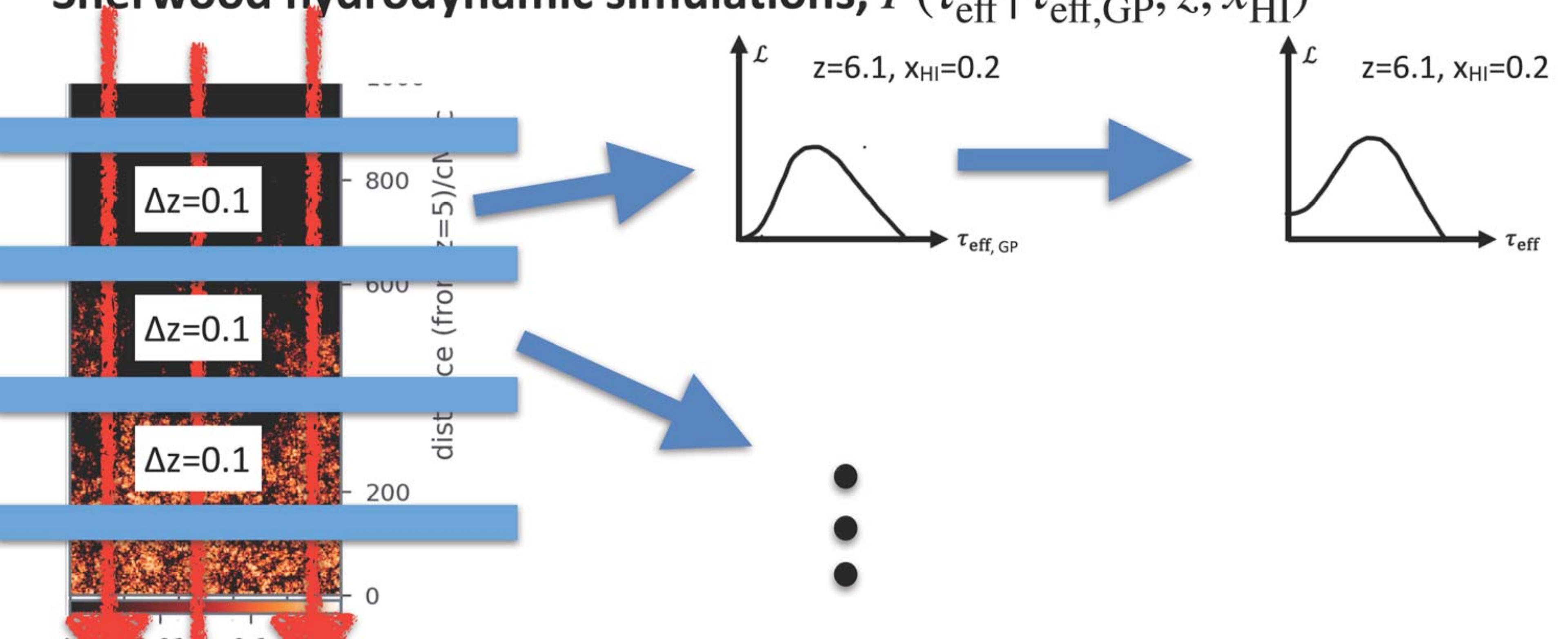

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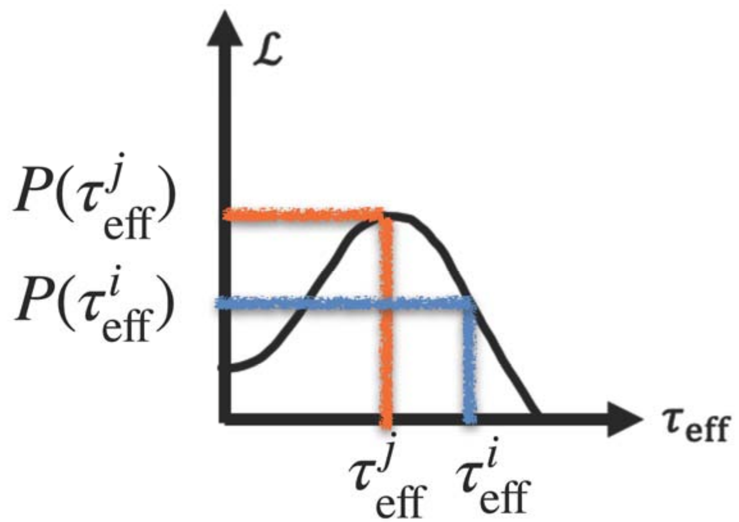
iv) **Evaluate the forest likelihood. For each observed QSO, *i*, the likelihood is just $P(\tau_{\rm eff} = \tau^i_{\rm eff}, z)$. The total forest likelihood is then**

$$\prod_{z=5.3}^{z=6.2} \prod_{i=1}^{N_{los(z)}} \mathcal{L}_z(\tau_{{\rm eff},i})$$



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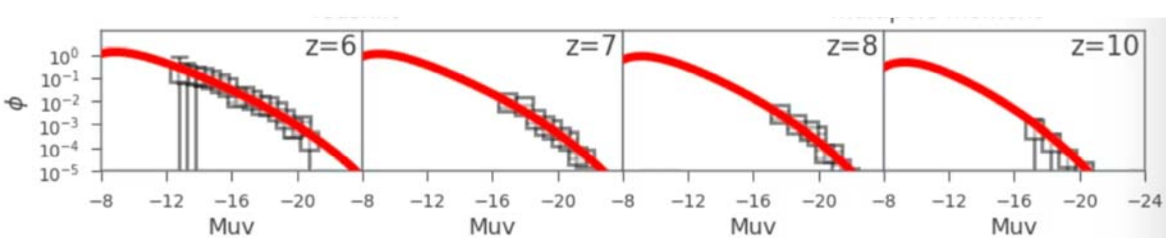
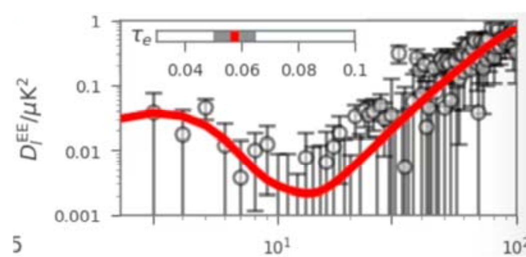
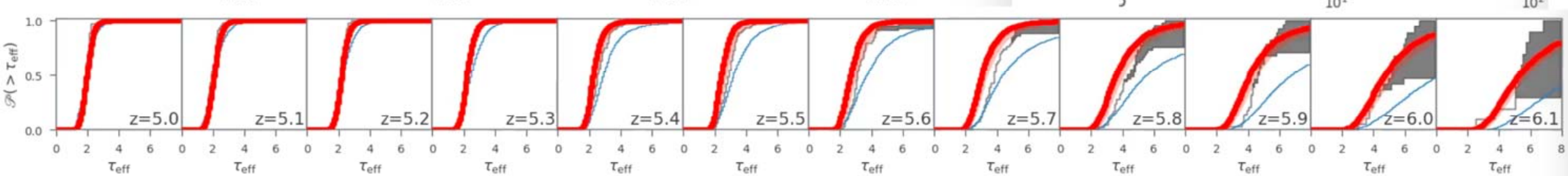
iv) Evaluate the forest likelihood.

v) **Compute the total likelihood, including also: (i) HST UV LFs at z=6,7,8,10; (ii) Planck tau_e**





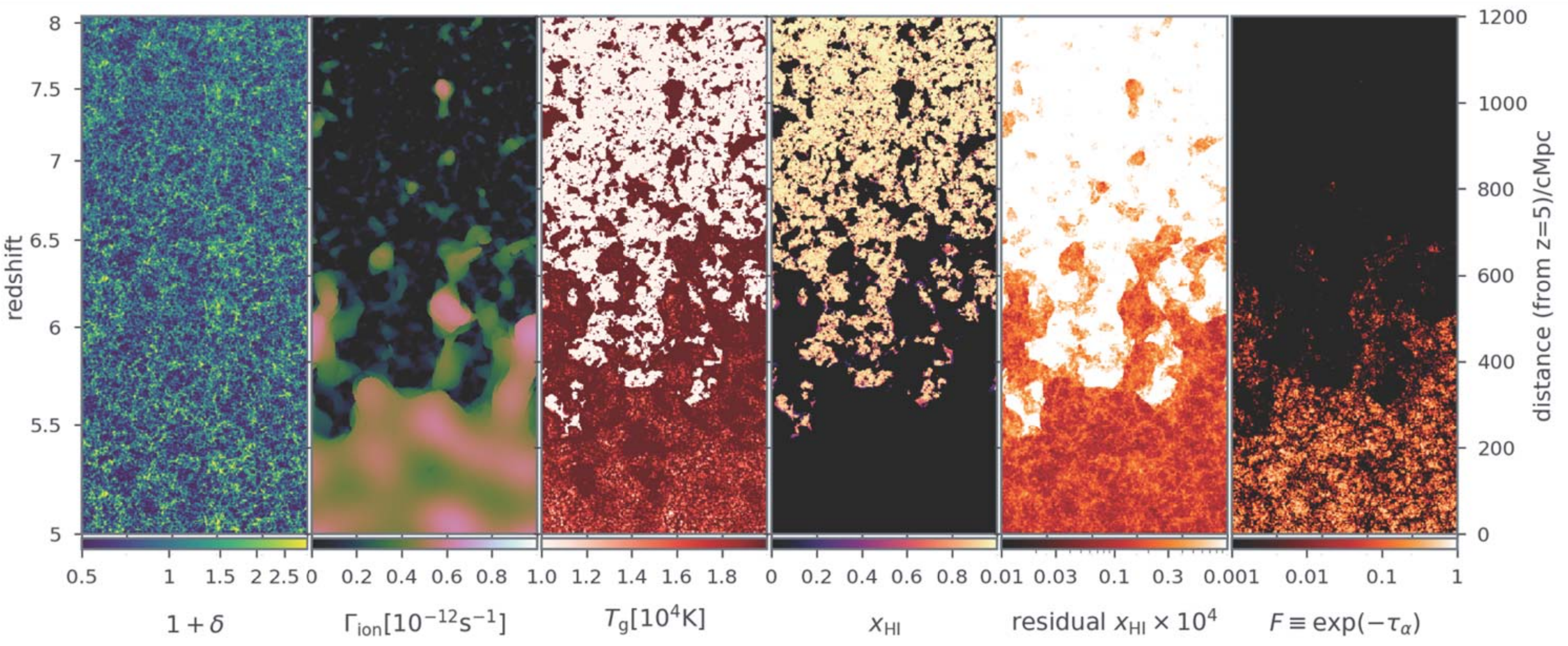


The method

i) For a **NEW** sample of galaxy parameters, simulate light-cones of Lyα optical depth with 21cmFAST

Repeat sampling ~ 100k times with 21cmMC to build a posterior

Lightcone image from Qin, AM+ (2021)



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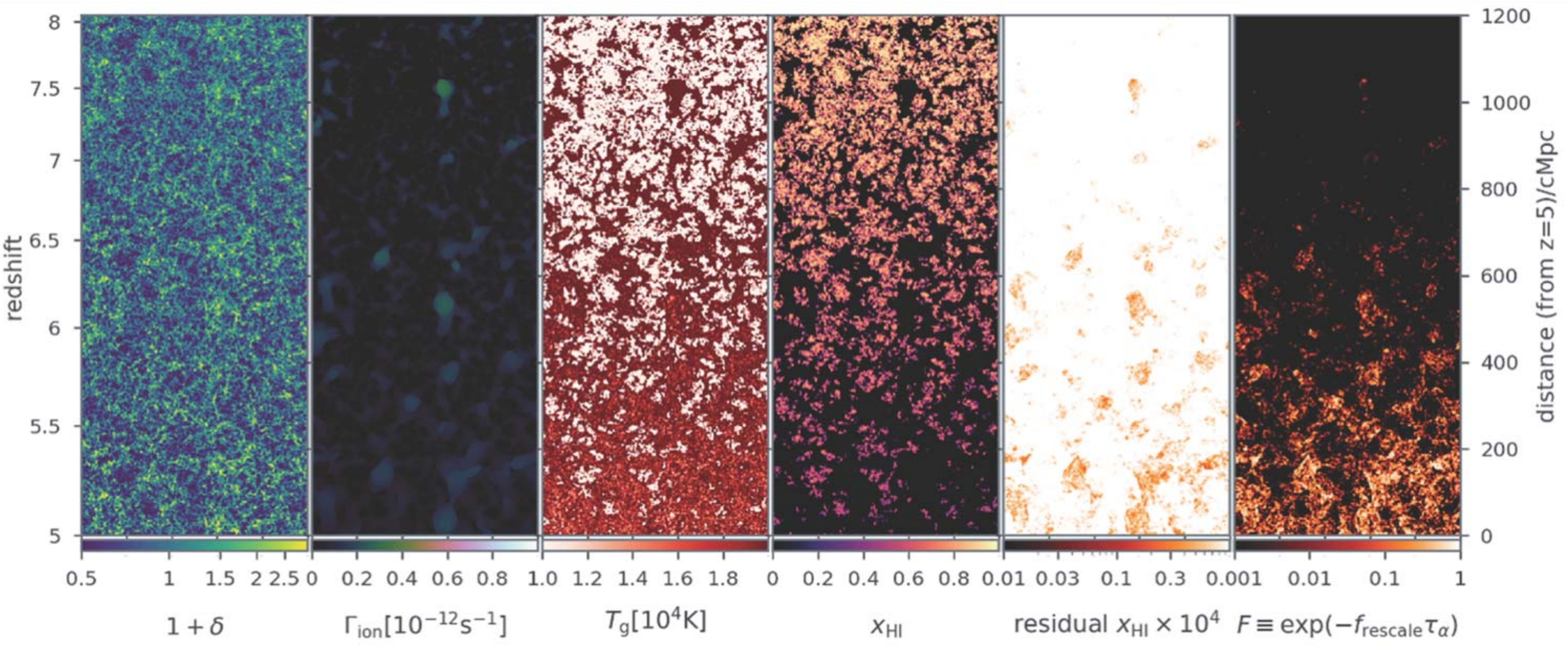

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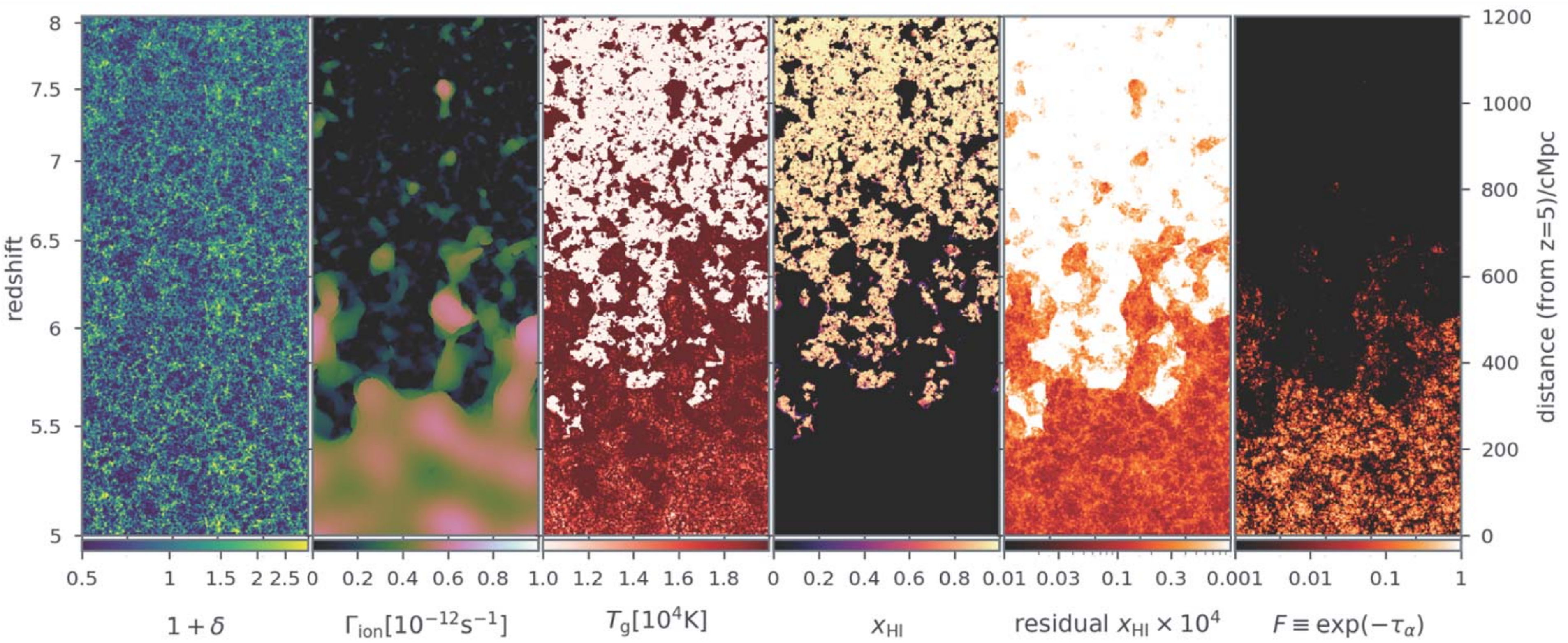

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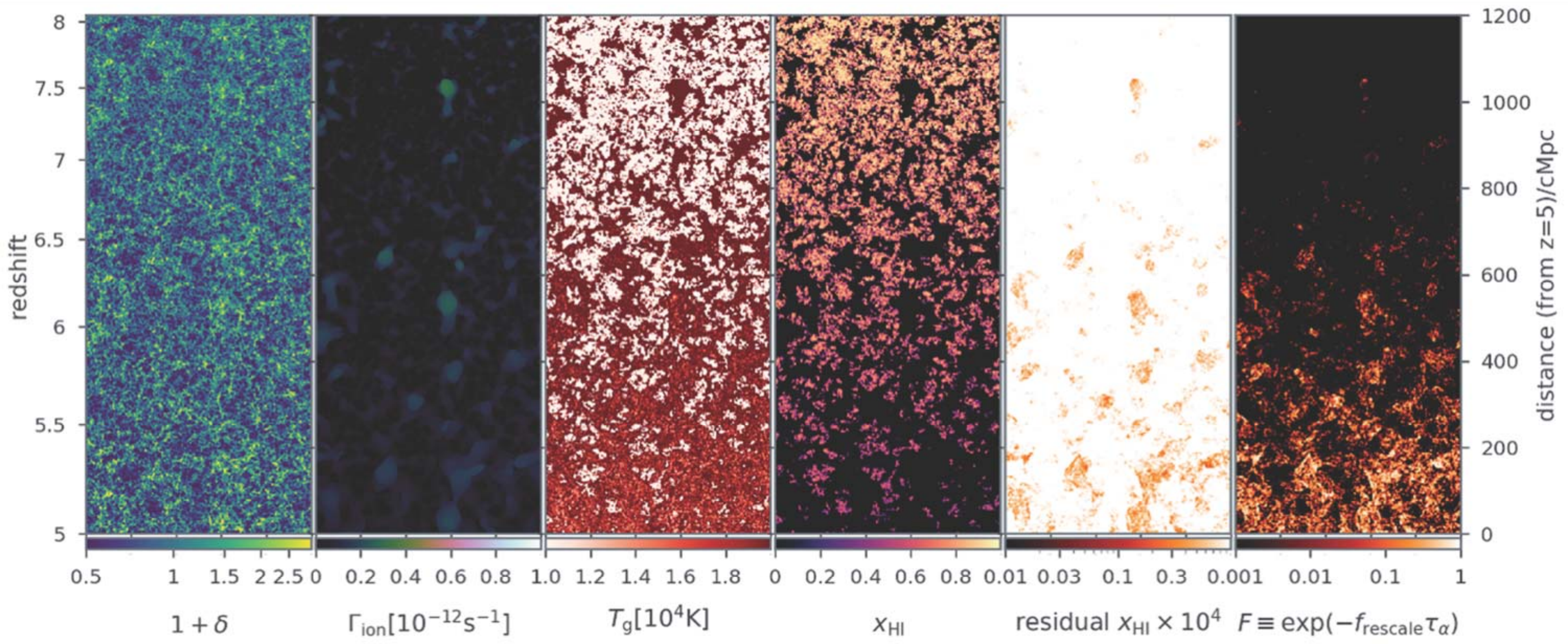
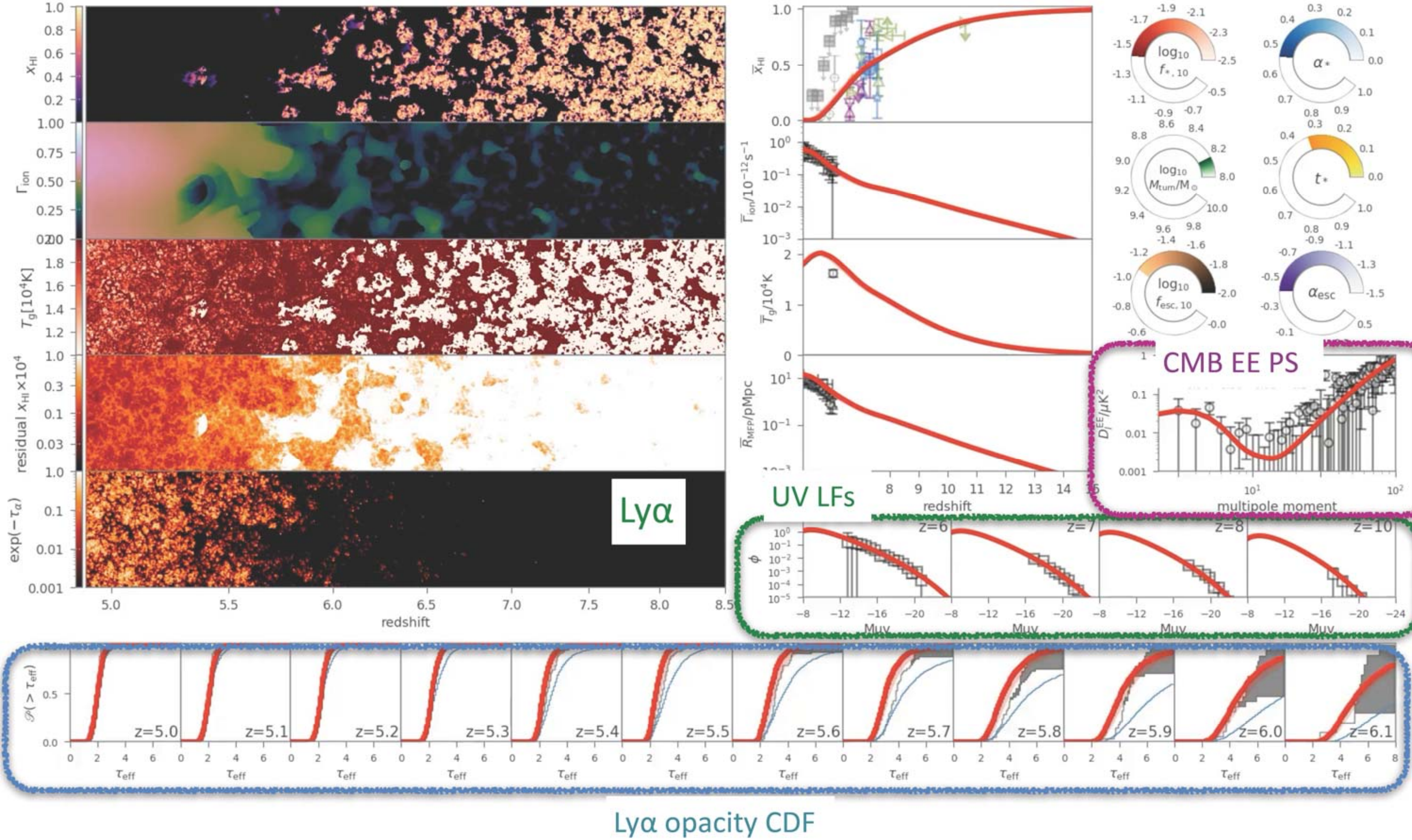


Forward modeling: Lyα forest + UV LFs + CMB τ



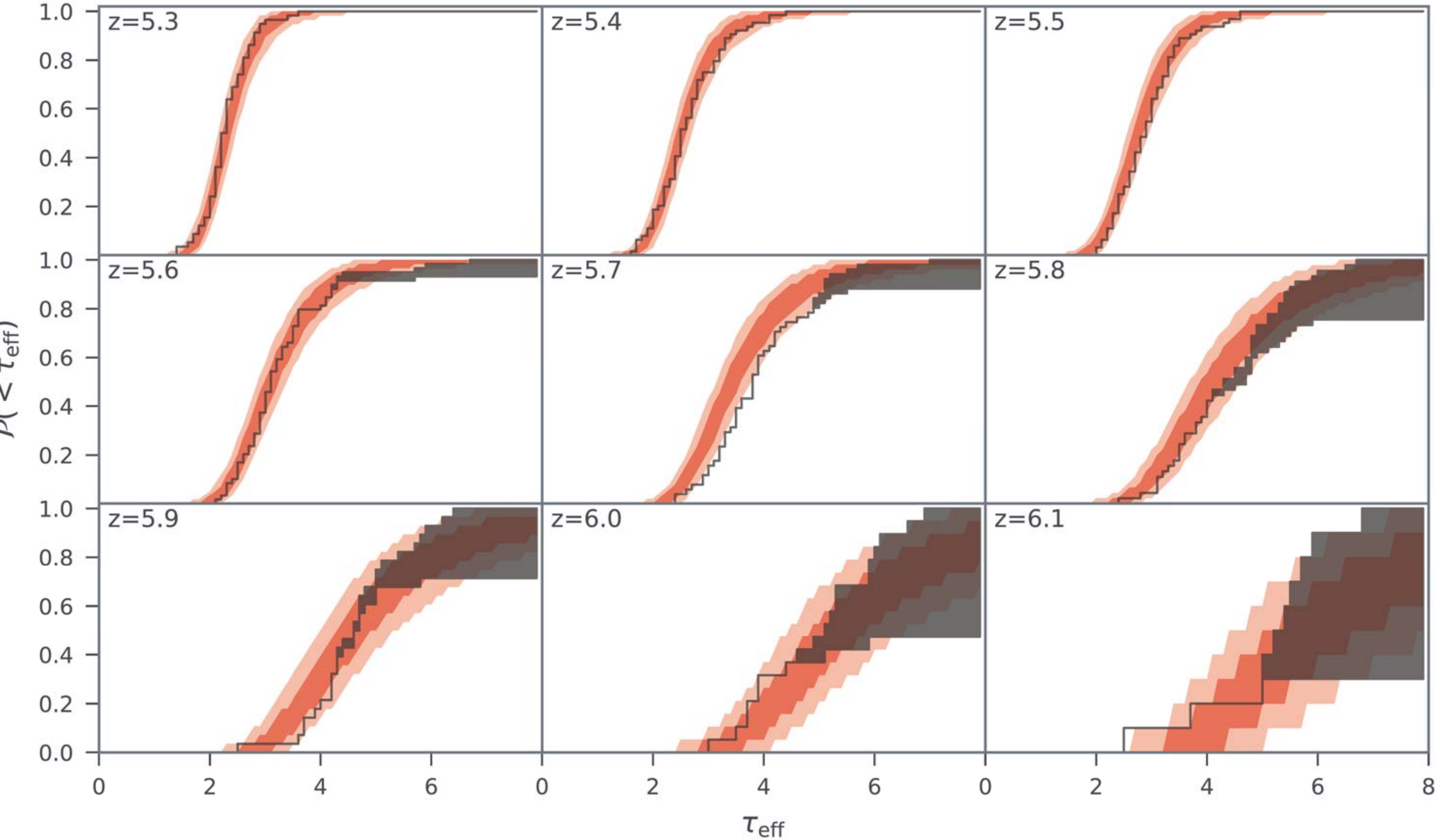
Qin, AM+, in prep

Movie credit: Y. Qin

Results (*preliminary!*)

Qin, AM+ in prep

Forest τ_{eff} distributions

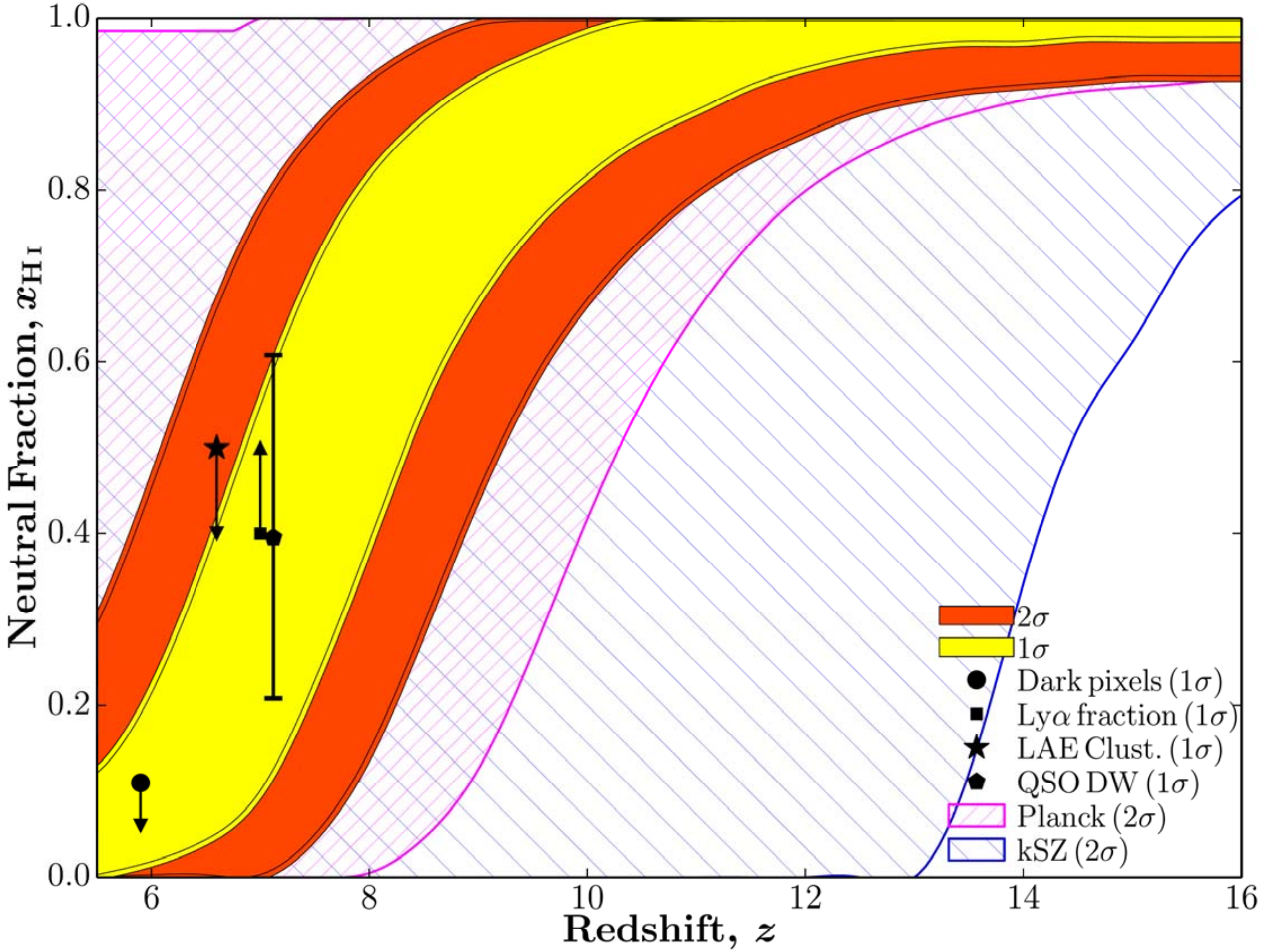


Joint fit over all redshift bins! no recalibration at each redshift, hyperparameters, removing mean flux, ad-hoc tuning / effective parameters, artificially scaling mfp or emissivity vs z, etc.

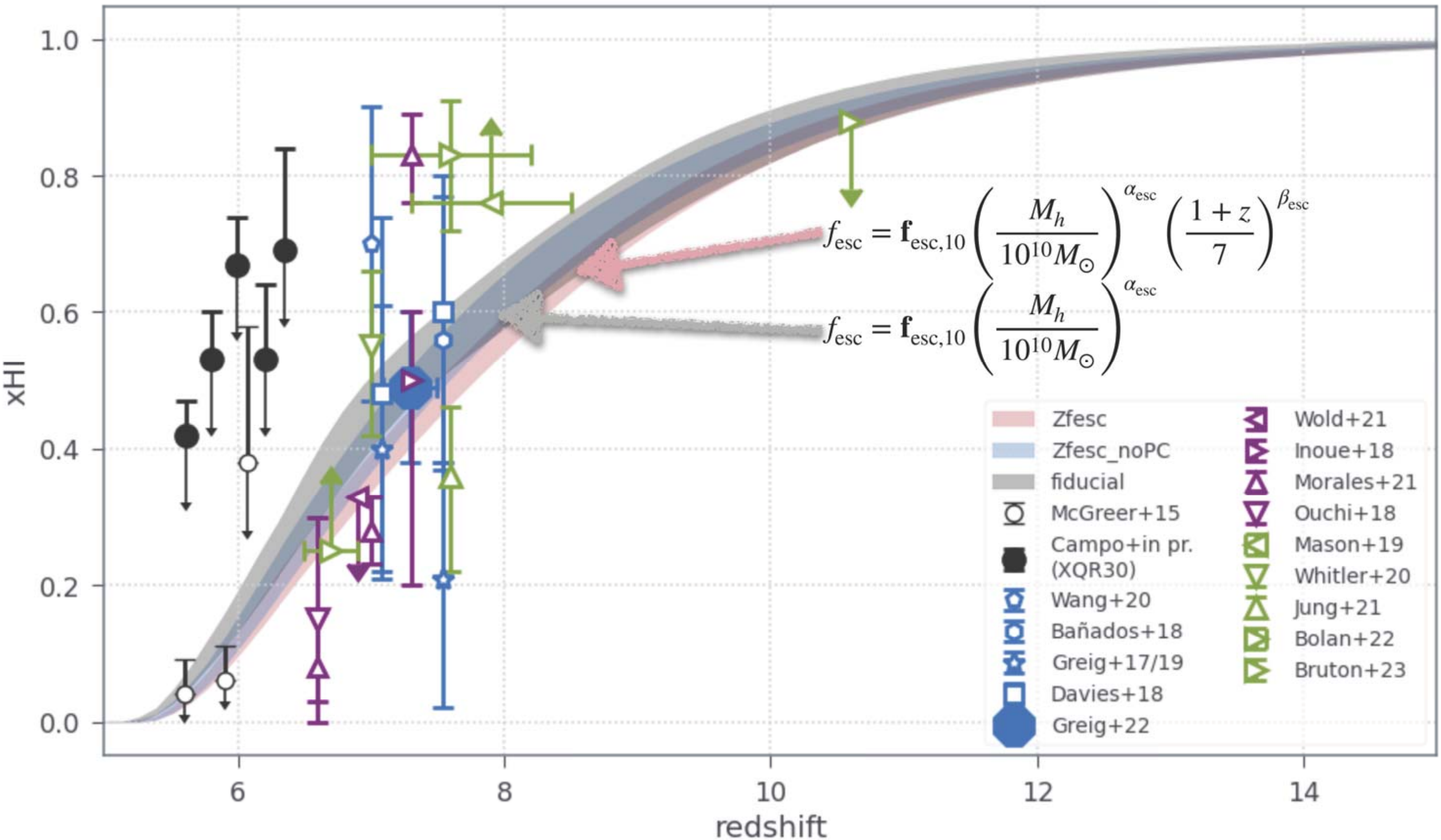
Qin, AM+ in prep

Until recently, the timing of the EoR was fairly uncertain...

Greig & AM (2017)



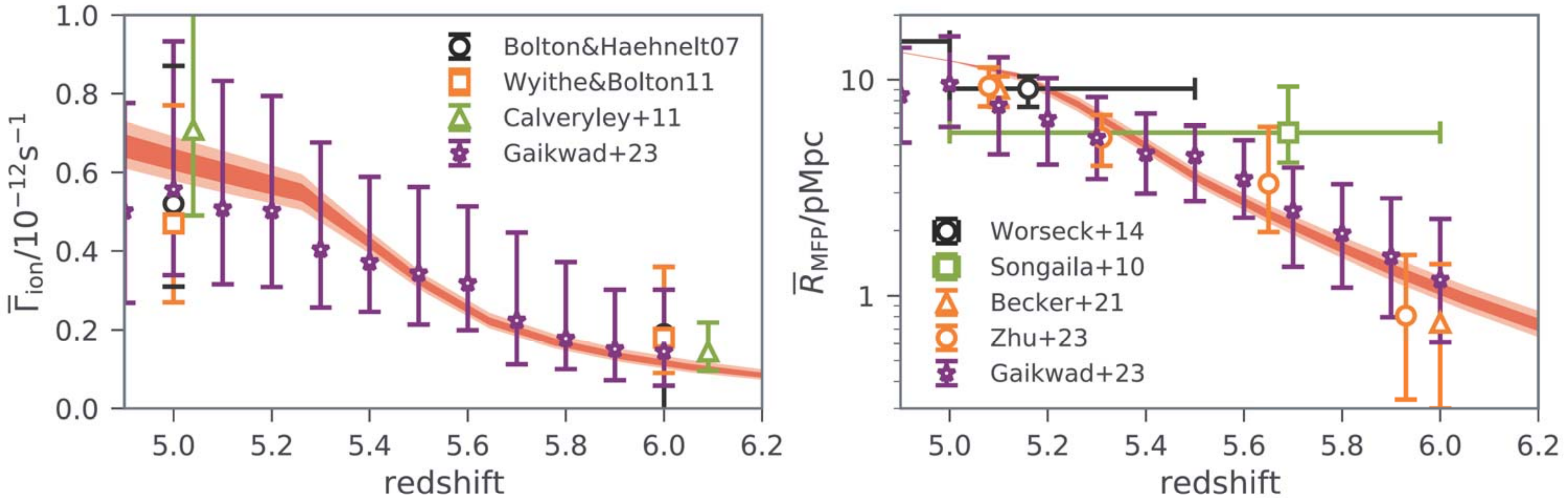
Inferred EoR history



None of these data points are used in the likelihood!

Qin, AM+ in prep

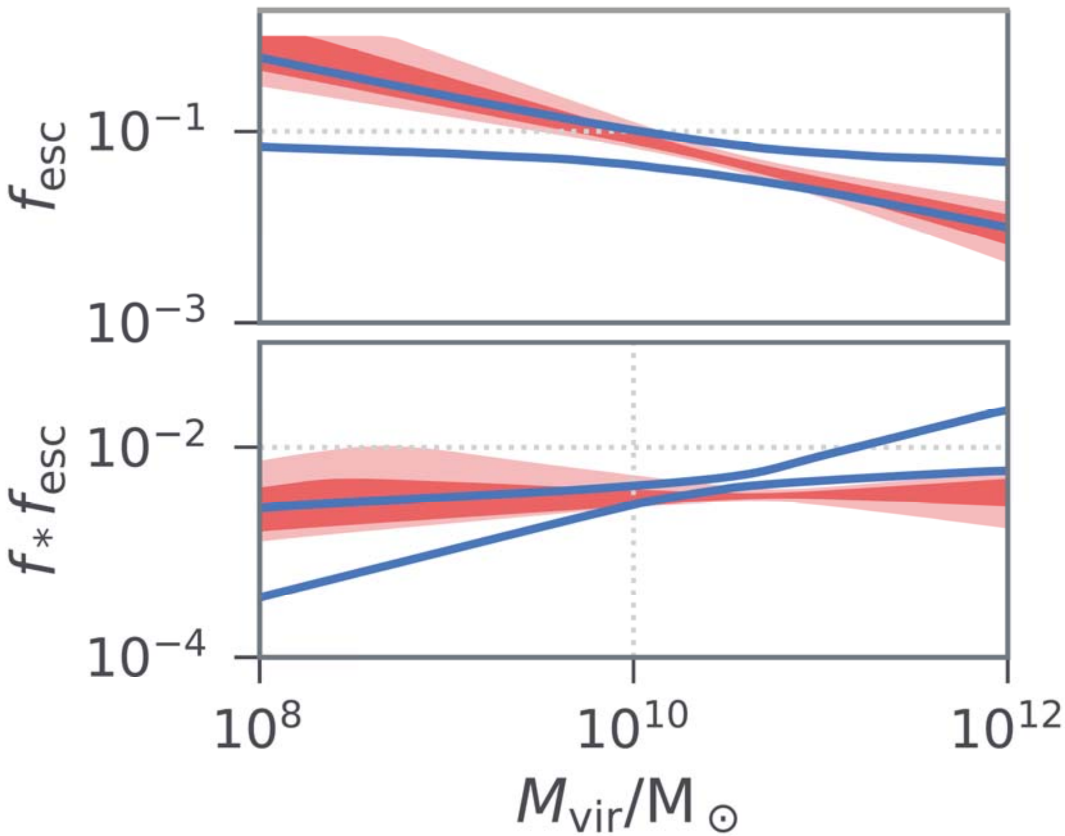
Average IGM properties



Qin, AM+ in prep

None of these data points are used in the likelihood!

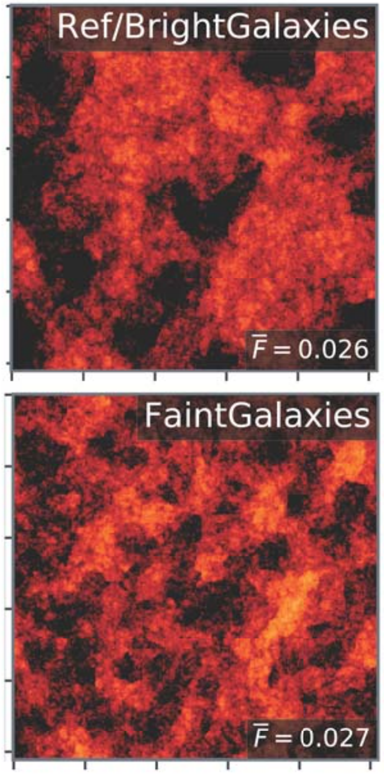
Conclusions about galaxy properties are model dependent however…

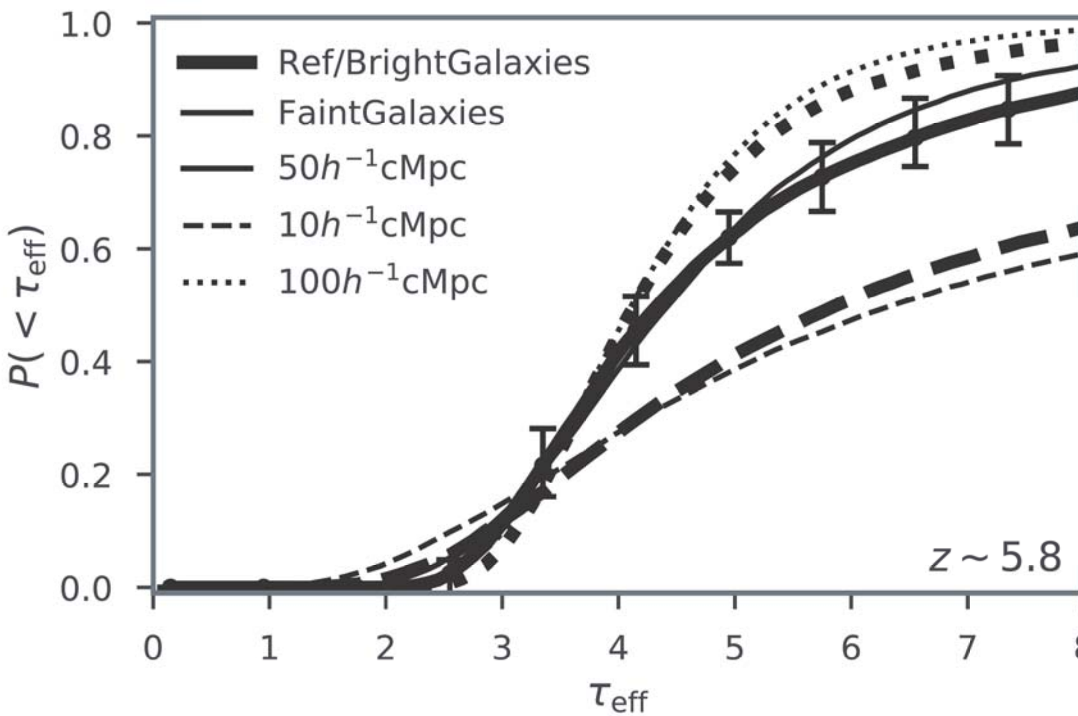


PRELIMINARY

Qin, AM+ in prep

The Lyα forest does not have the dynamic range to probe EoR morphology

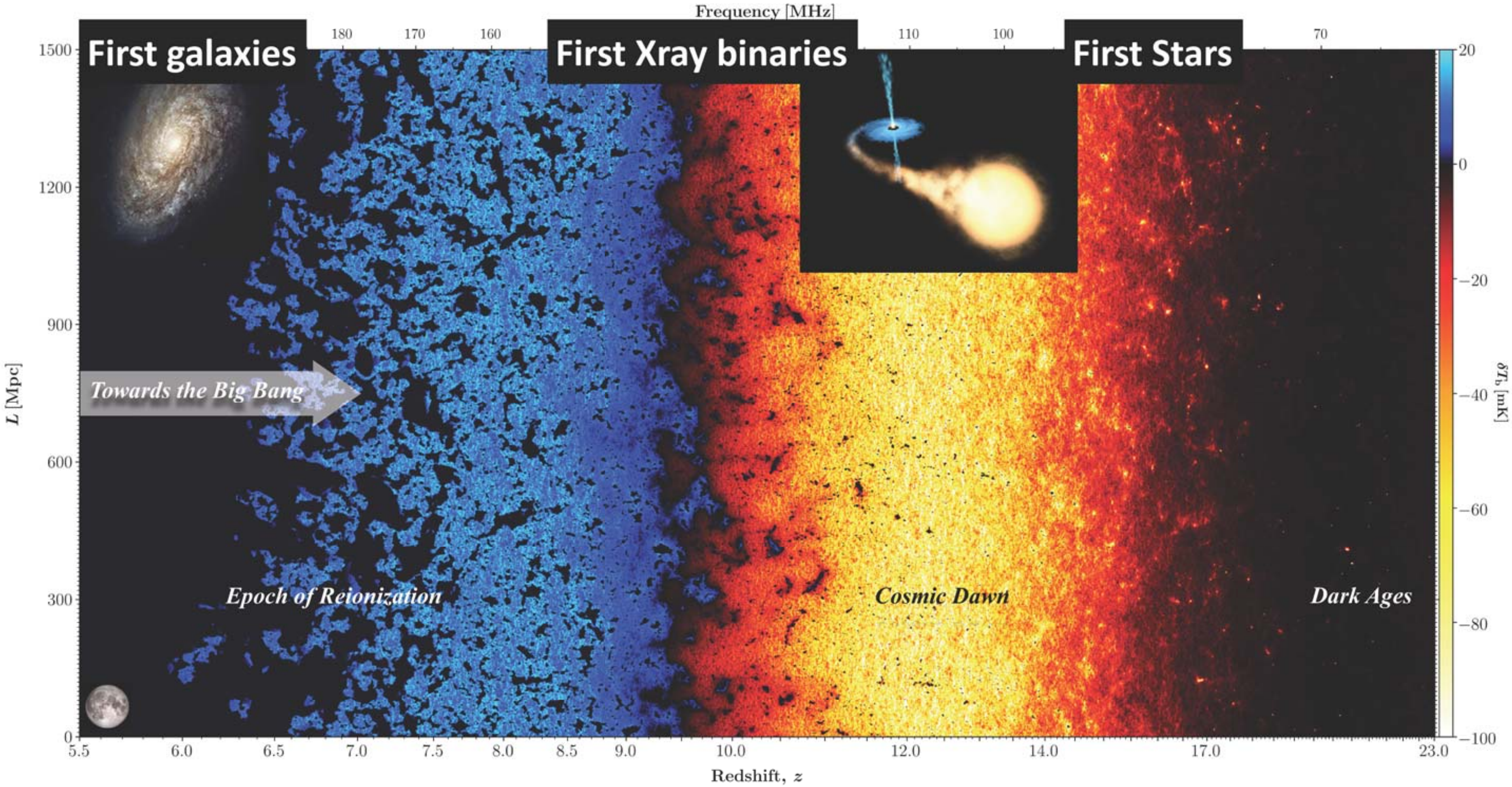




Qin+2021

We need other probes to understand morphology!

We will have reionization topology with the 21cm signal with SKA

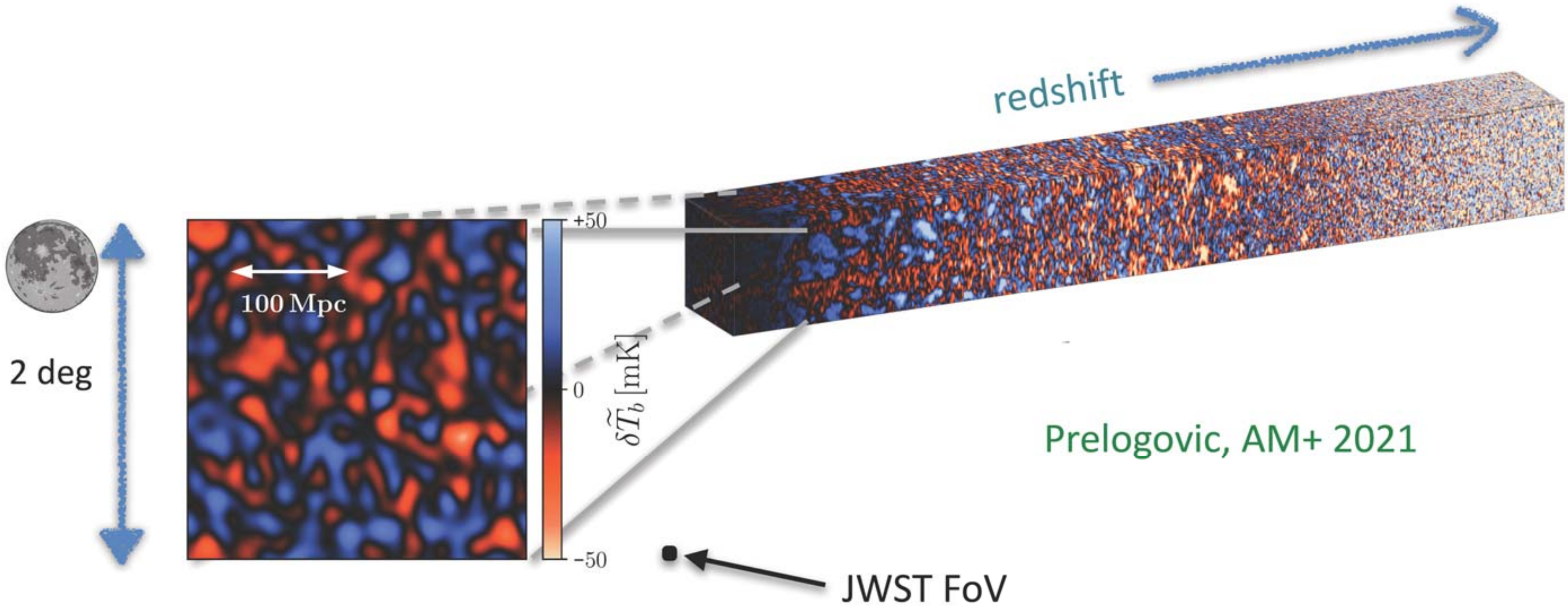


$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\,\mathrm{mK}$$

Figure courtesy of J. Park

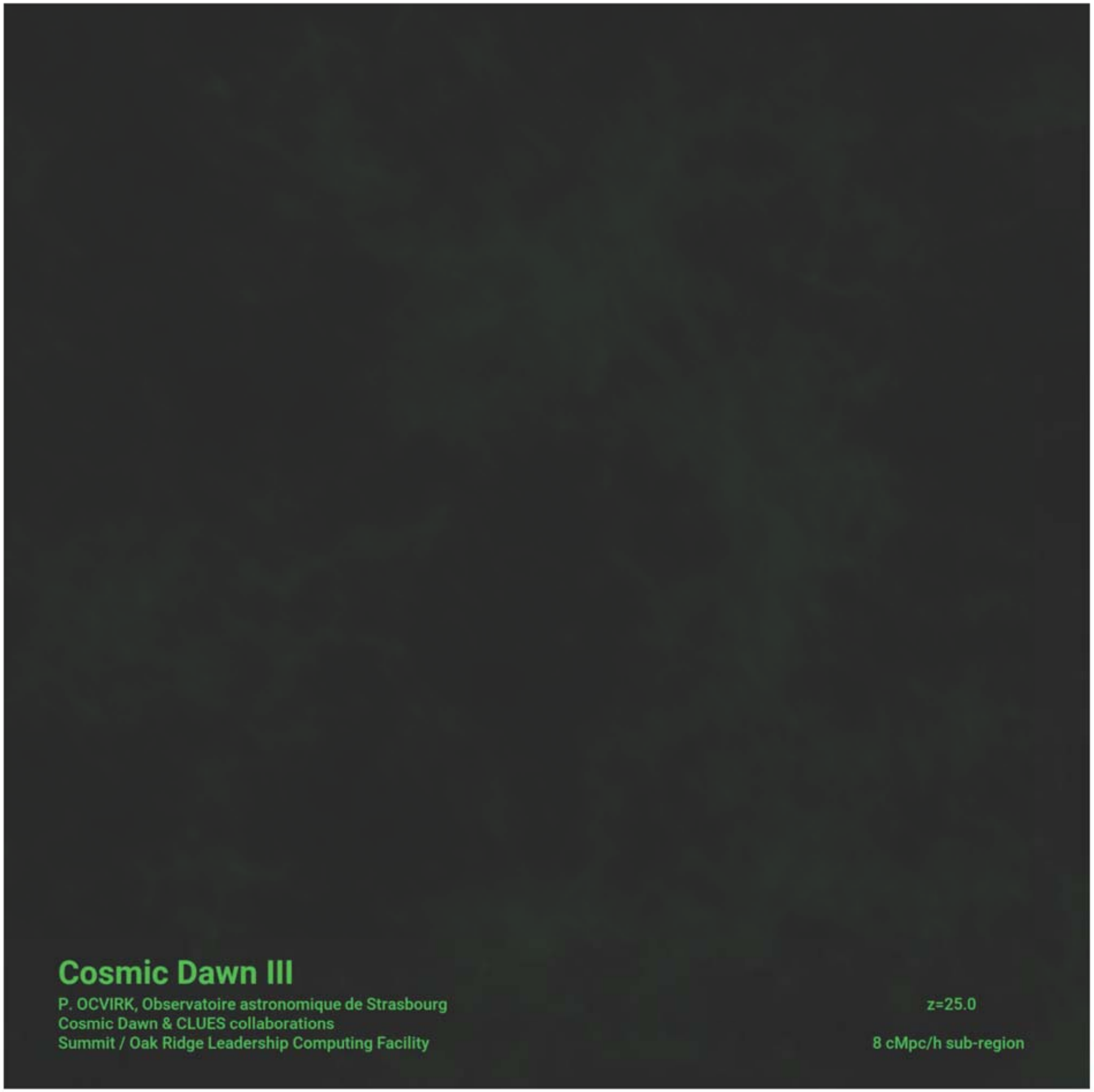
However, this is on large scales…

And is unlikely to come for another ~decade at least…



single frequency slice with
noise and foreground excision

It would be great to study topology sooner and also on smaller scales…



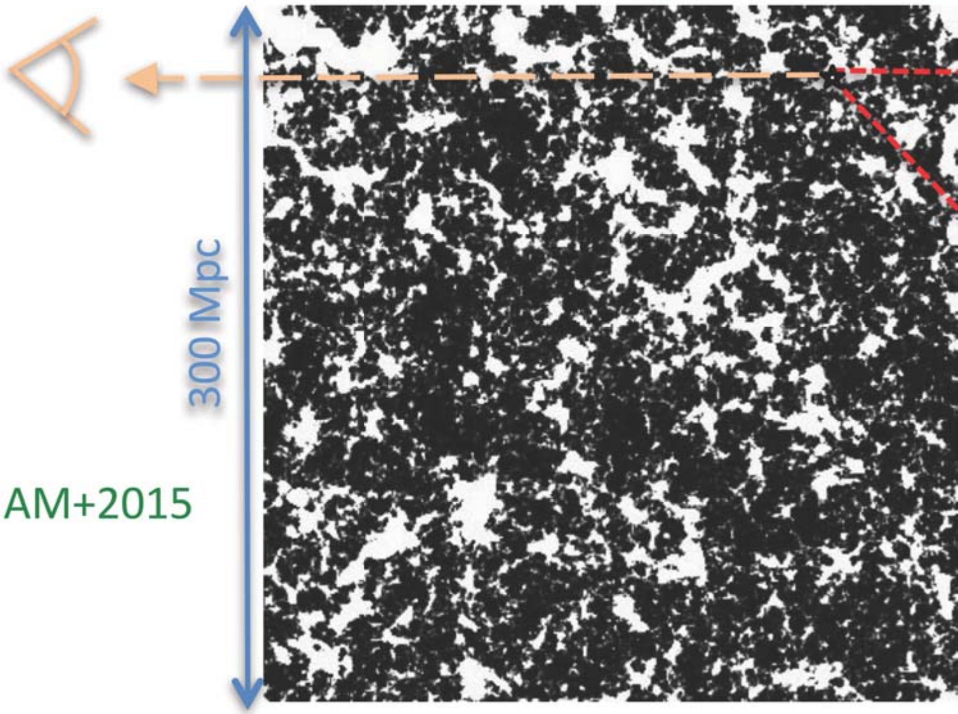
zoom-in comparable to JWST FoV

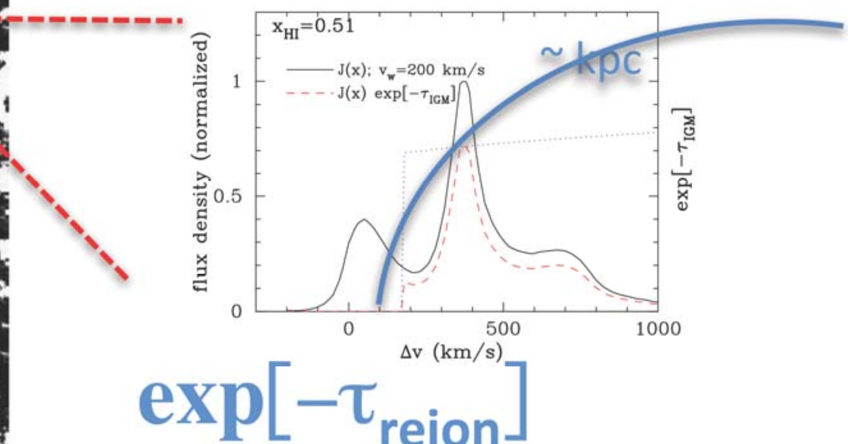
Ionization morphology allows us to:

- determine **which galaxies drive reionization**
- connect the **growth of individual cosmic HII regions to the properties of galaxies** inside them
- connect the JWST-detectable galaxies to the **thousands of surrounding galaxies too faint to detect**

CODAIII, credit: P. Ocvirk

Lyman alpha from galaxies is a great tool to study EoR topology NOW



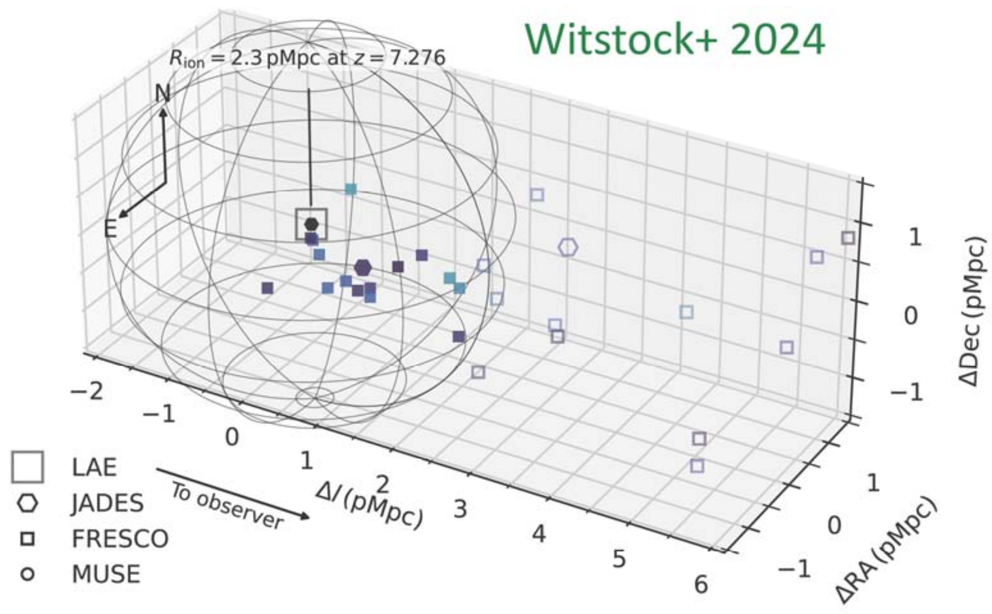


during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

Lyα damping wing absorption is an especially powerful probe of the **EARLY STAGES OF THE EOR**

Exciting recent observations of galaxy groups

e.g. Tilvi+20; Endsley & Stark 22; Jung+22; Saxena+23; Whitler+23; Hayes & Scarlatta 23; Umeda+23; Witstock+24



Exciting recent observations of galaxy groups

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but…

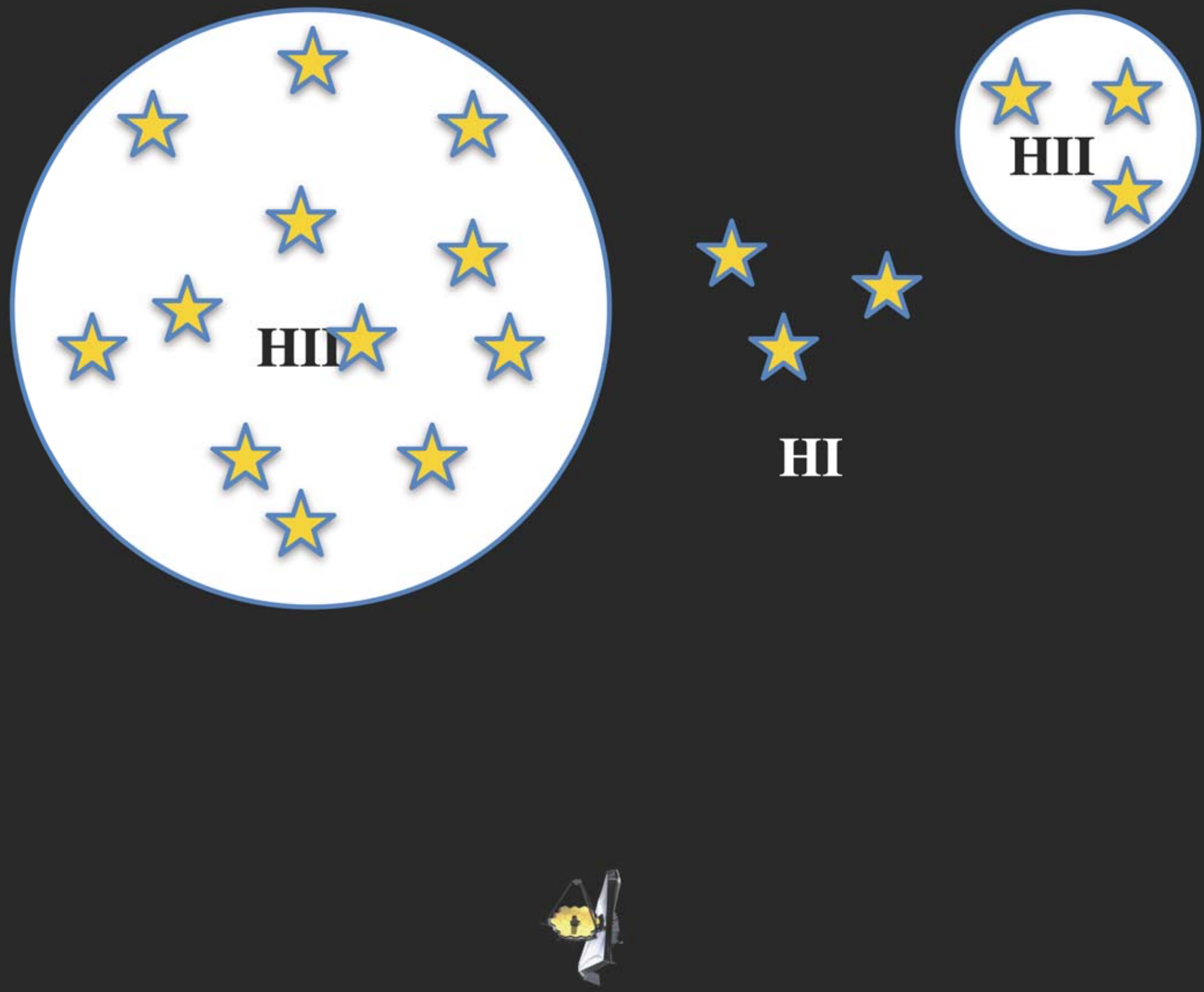
Analysis of surrounding HII topology is very approximate / qualitative…

- typically observed galaxies are treated **individually?!?** (*HII regions come from the cumulative radiation of **thousands of fainter galaxies***)
- assume **uniform reionization?!?** (*reionization is patchy -> **scatter and bias** in estimates* Mesinger & Furlanetto 08)
- ignores or simplifies many sources of **stochasticity** when assuming **intrinsic emission?!?**

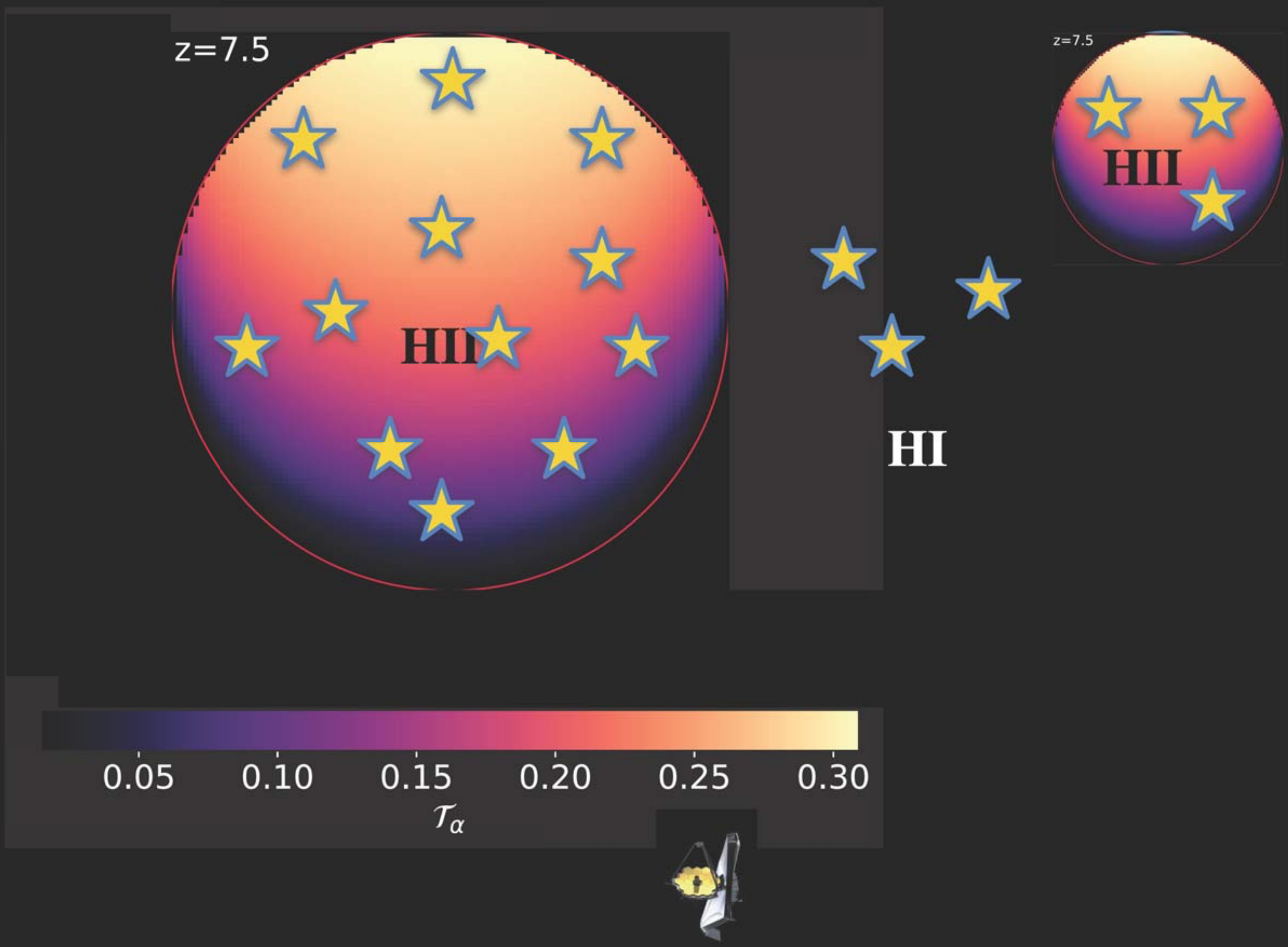
New frameworks for studying EoR topology using galaxy “groups”

in collaboration with **Ivan Nikolić** (SNS), **Ting-Yi Lu** (DAWN), Charlotte Mason (DAWN)

Combining information from individual galaxies



Combining information from individual galaxies



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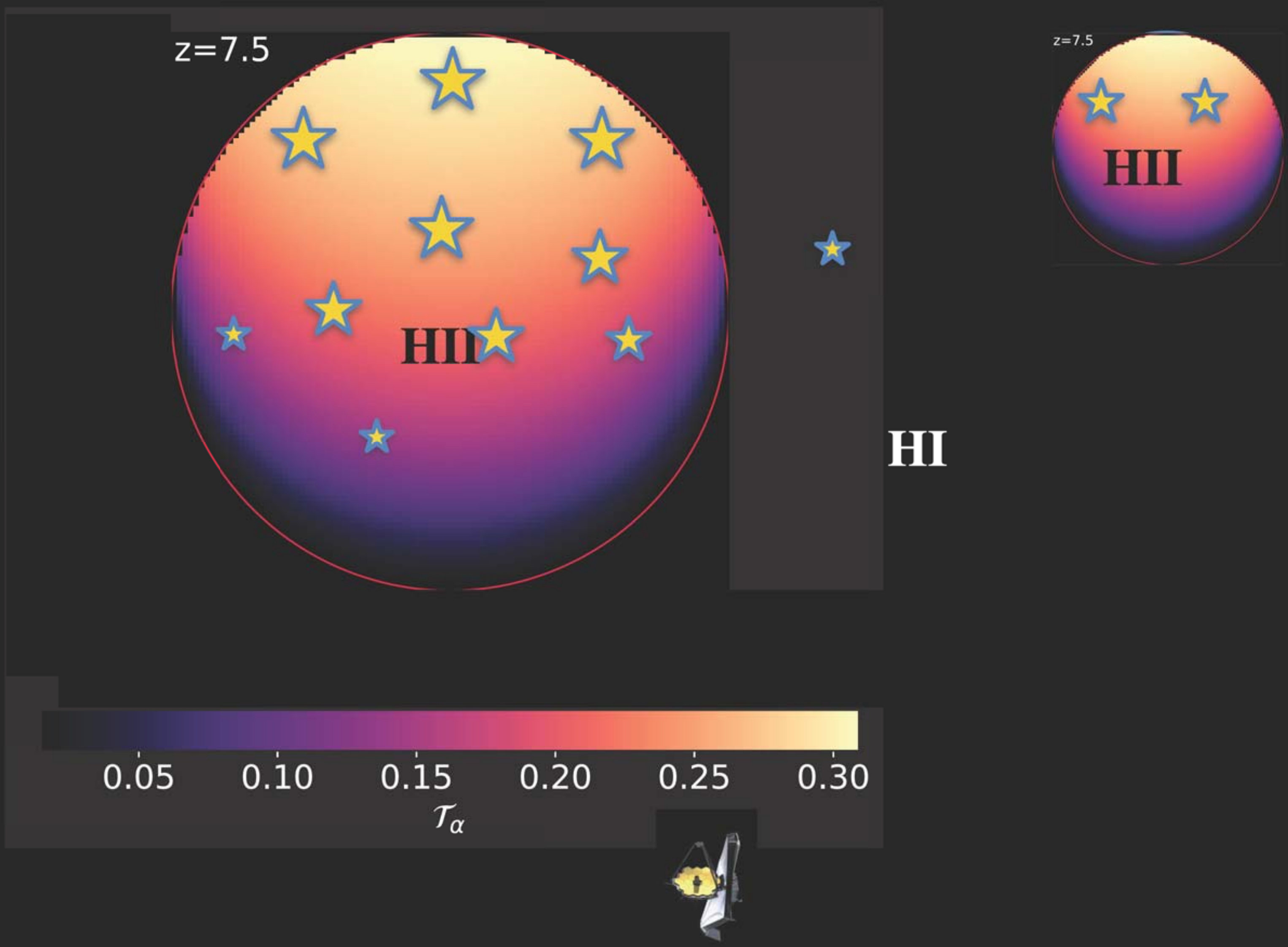

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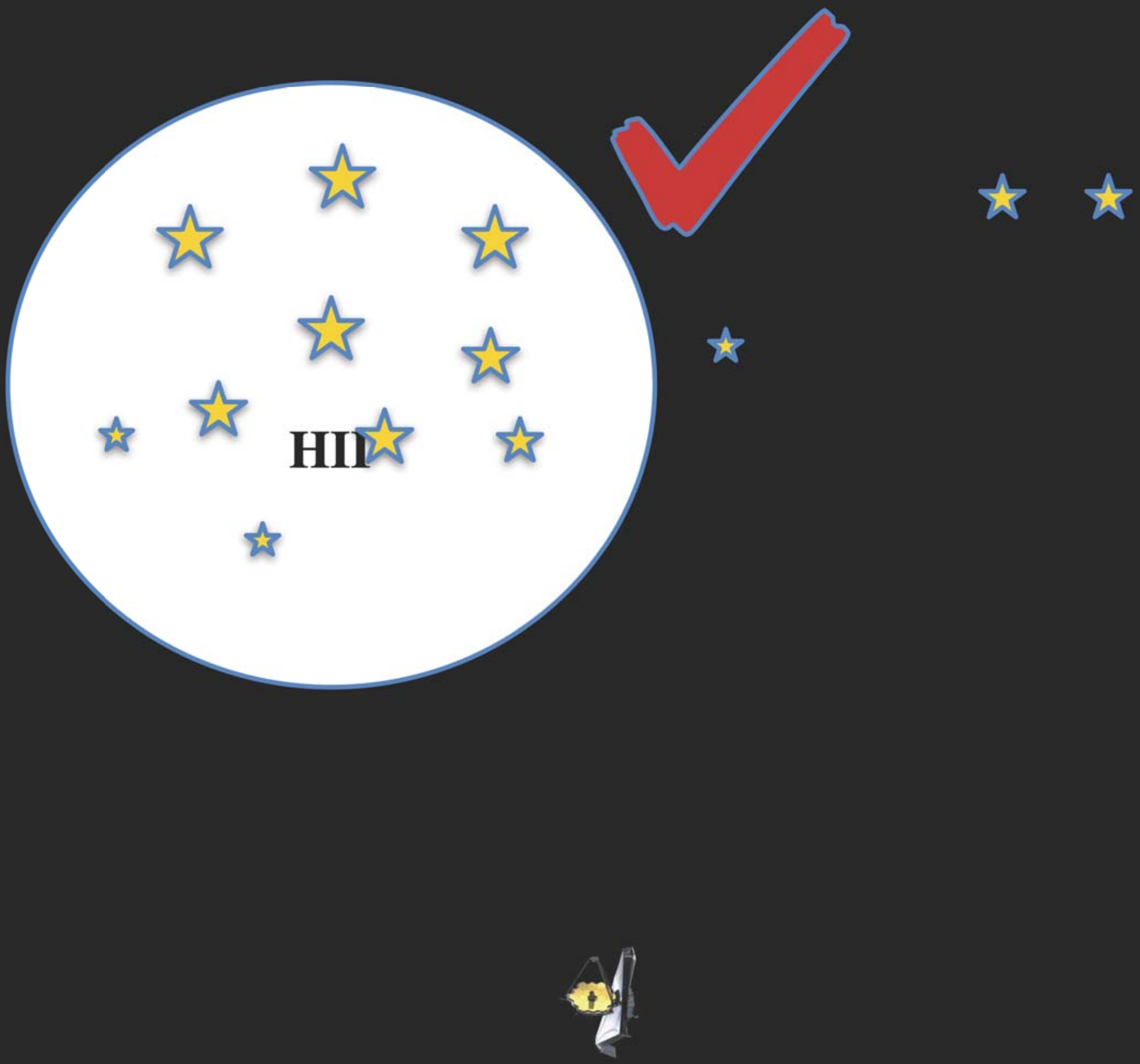


Inferring bubbles around galaxies

GOAL: Infer the position and size of an HII region, given galaxy observations

$$P(\mathcal{O}, R_b \,|\, \mathbf{x}^i, f^i_\alpha(\lambda), M^i_{\rm uv}, z)$$

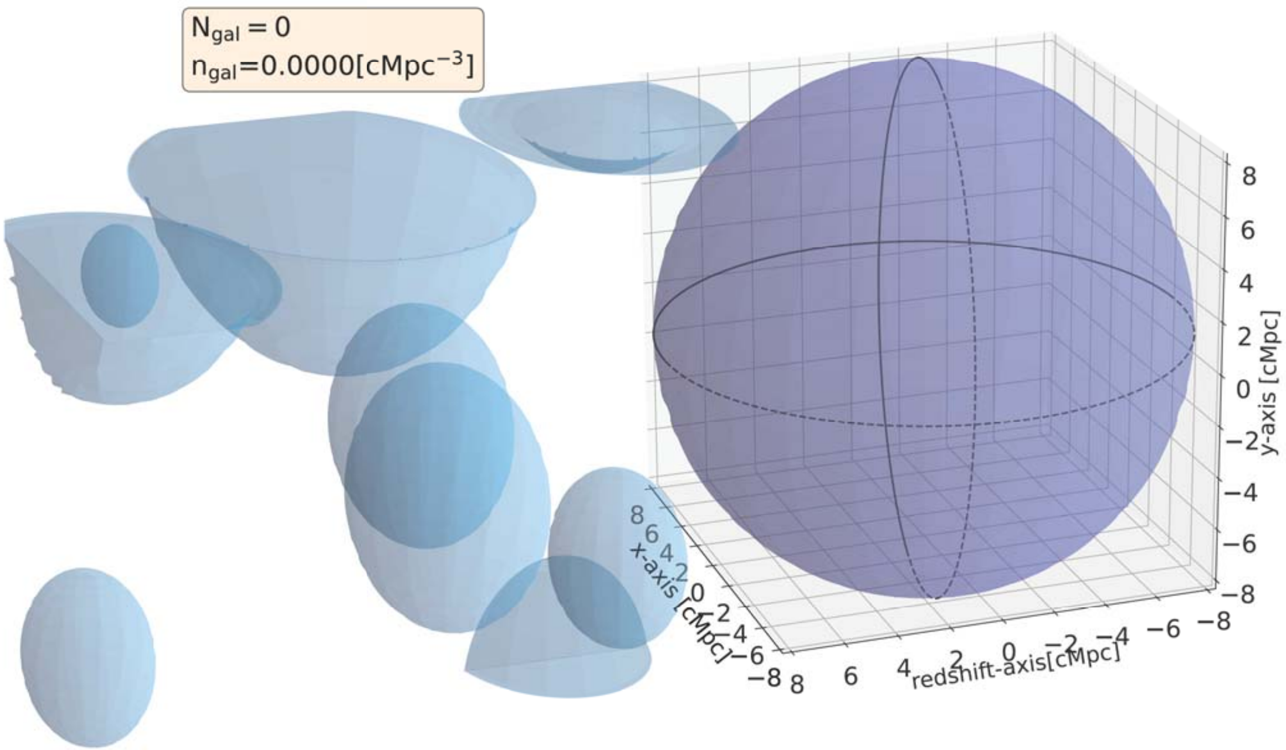
Forward model sources of stochasticity:

- global neutral fraction
- surrounding patchy EoR topology
- galaxy location
- Muv
- Lyα intrinsic flux (Δv, EW)
- NIRSpec noise

Nikolić, AM+ in prep

Inferring individual bubbles around galaxy groups

PRELIMINARY



Nikolić, AM+ in prep

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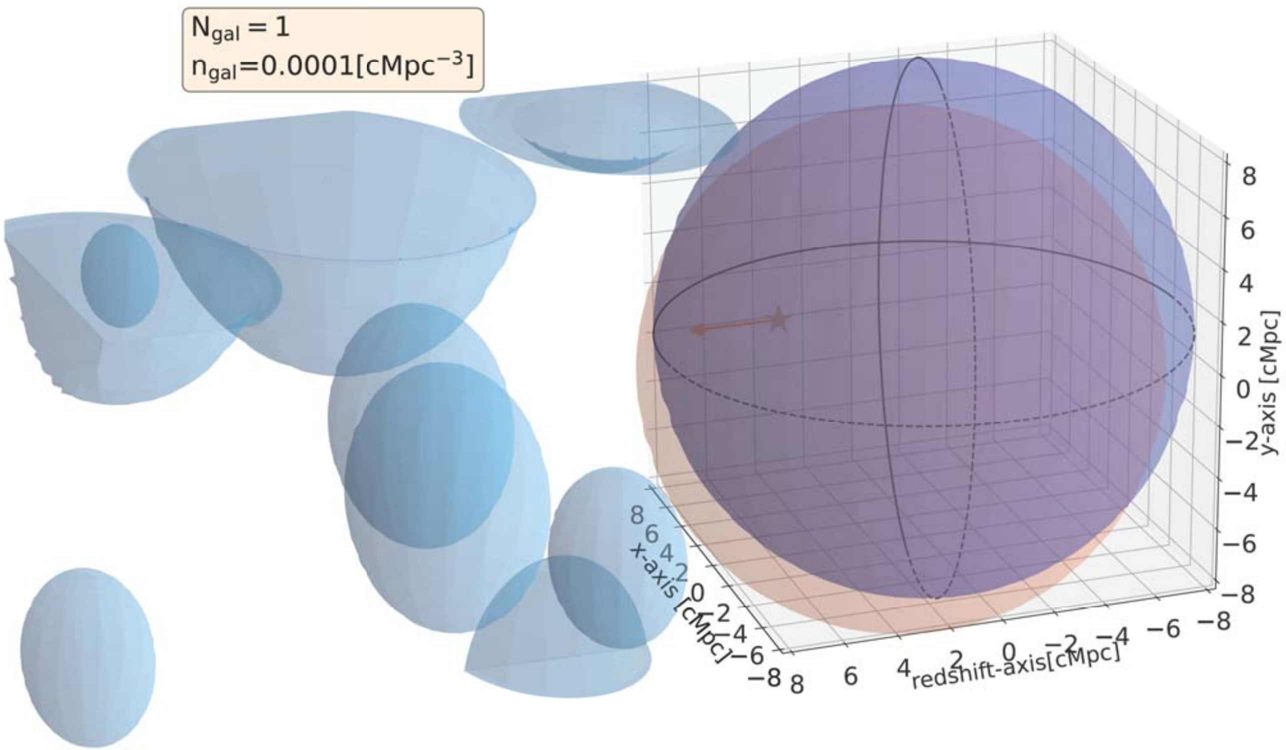

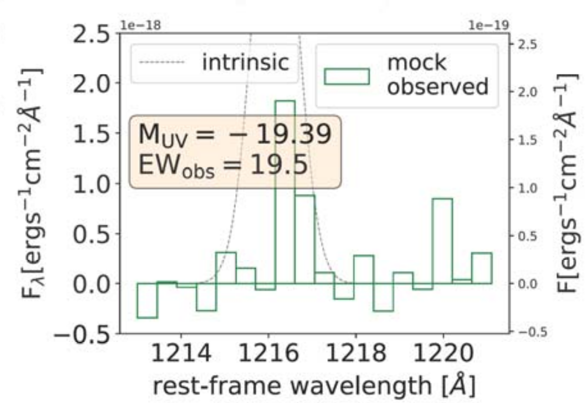

Nikolić, AM+ in prep

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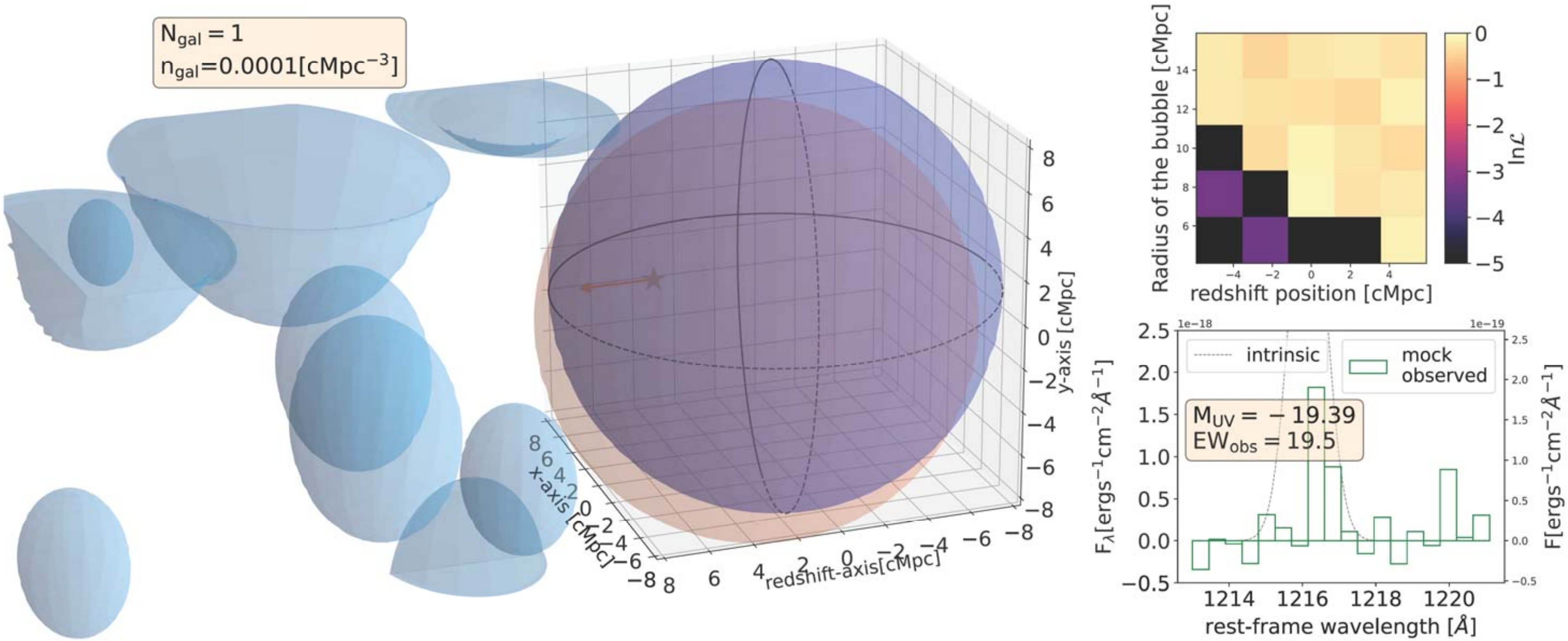

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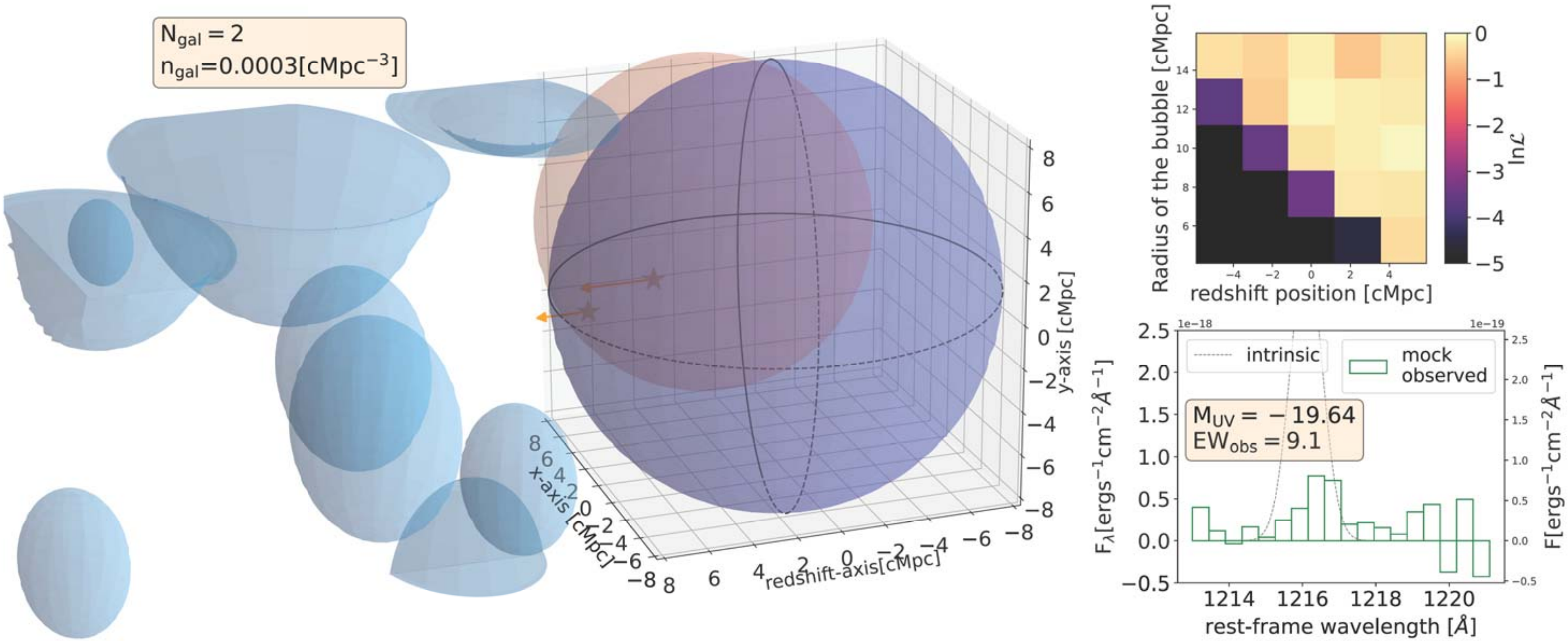

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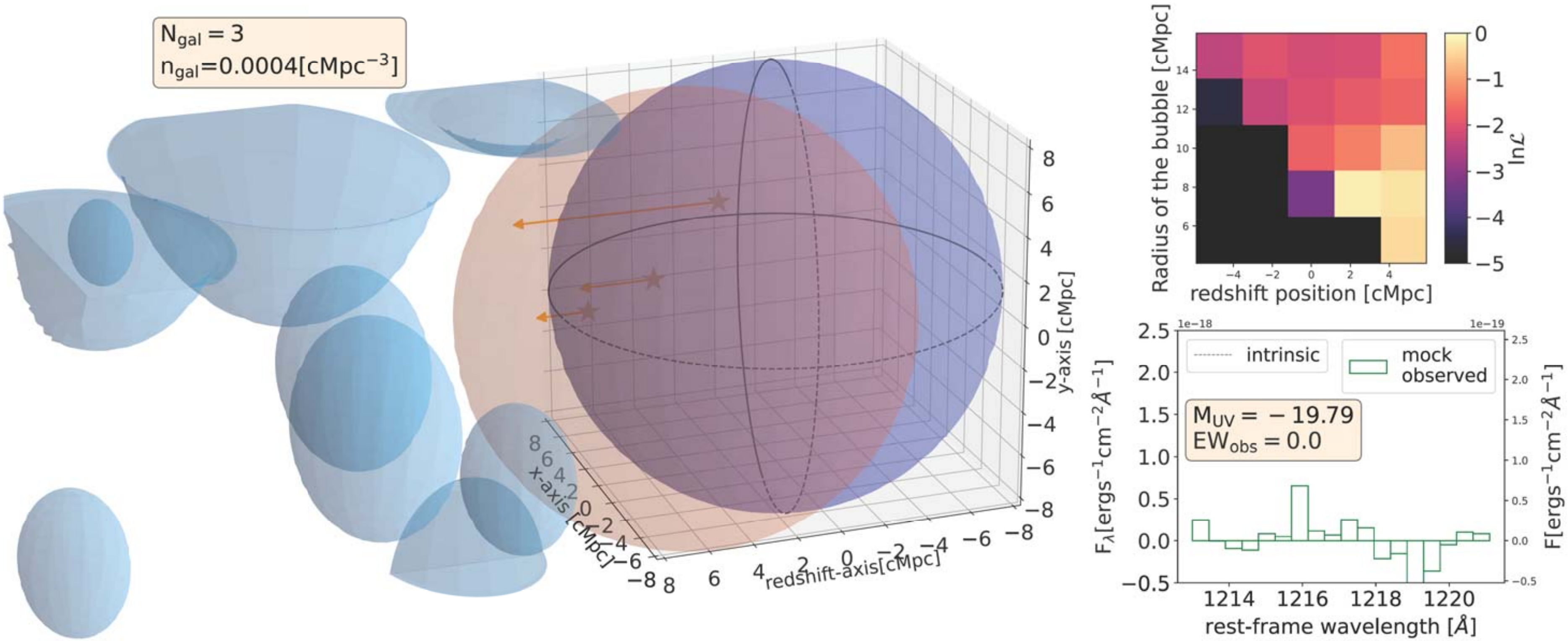

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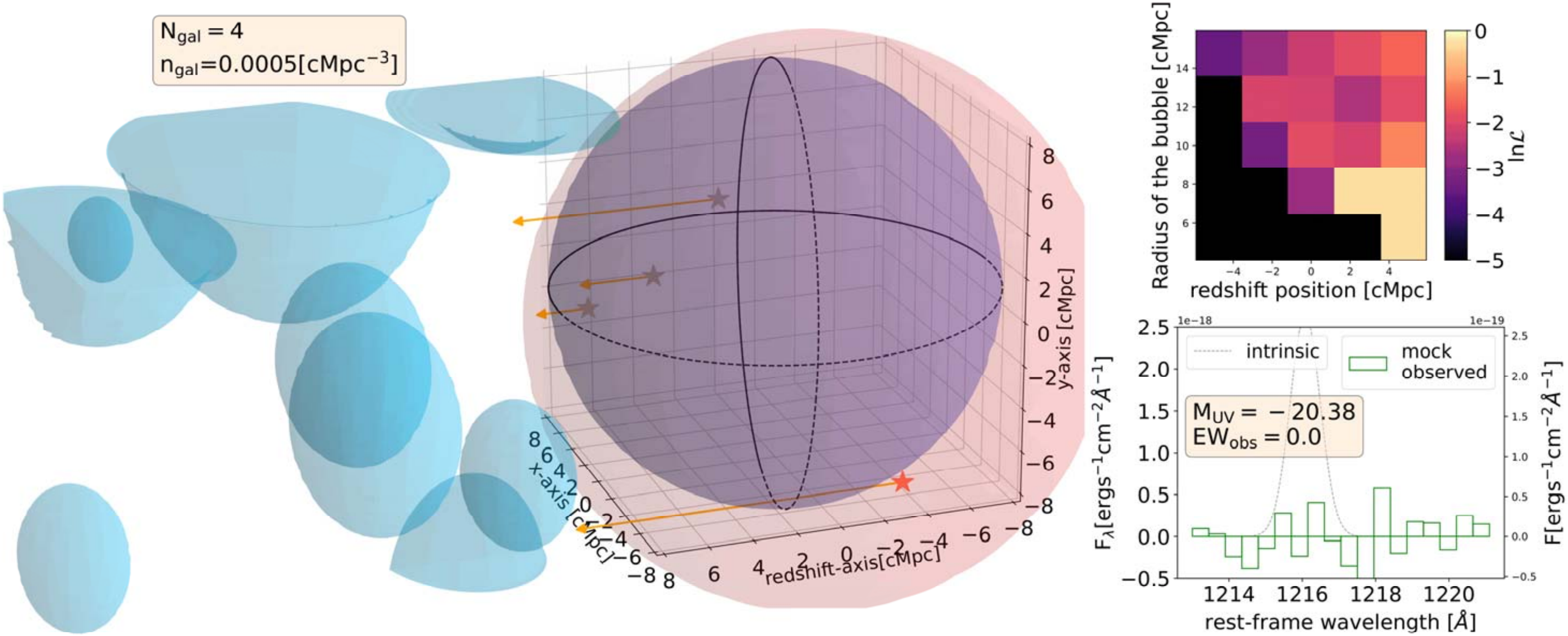
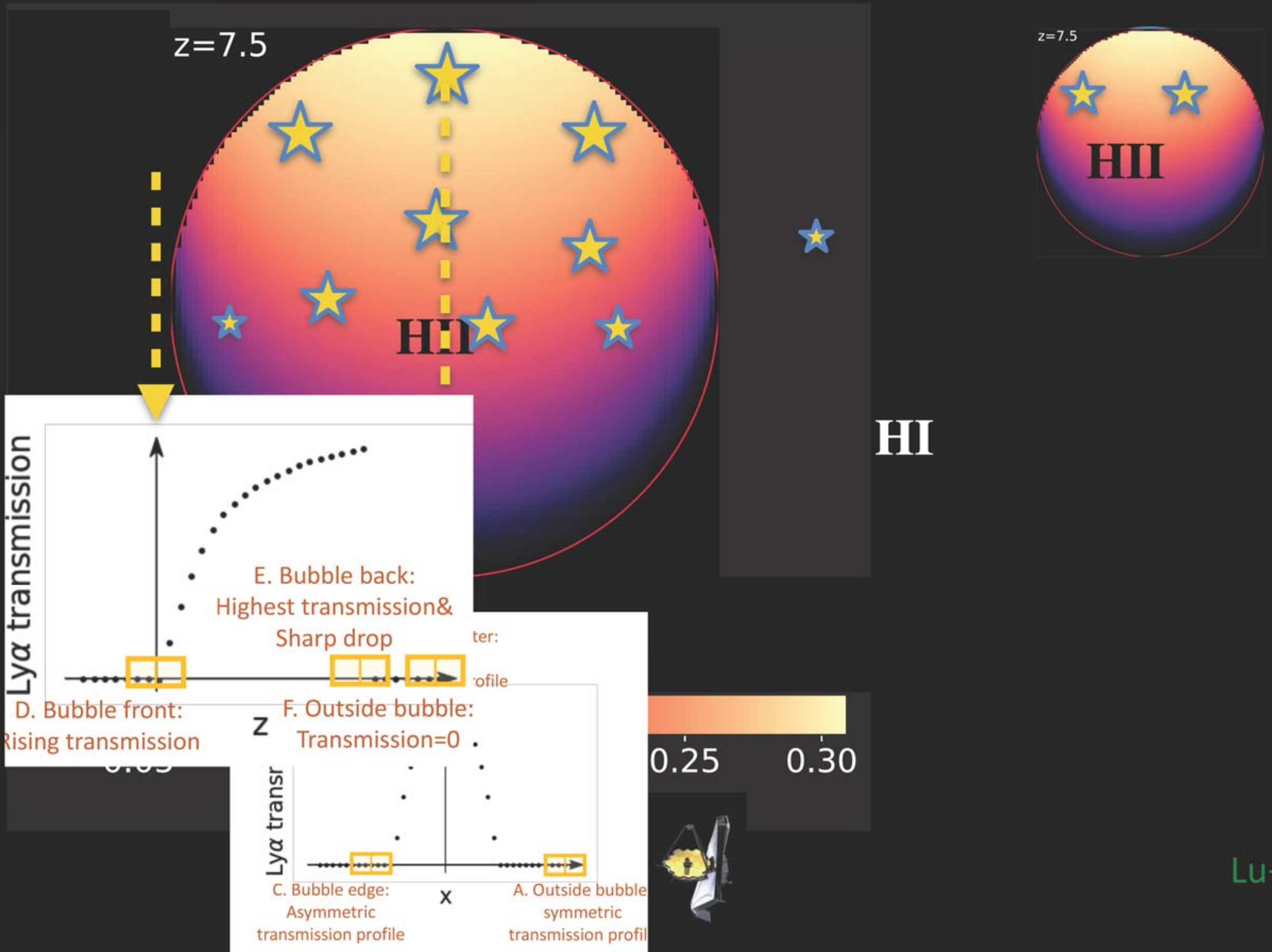


Nikolić, AM+ in prep

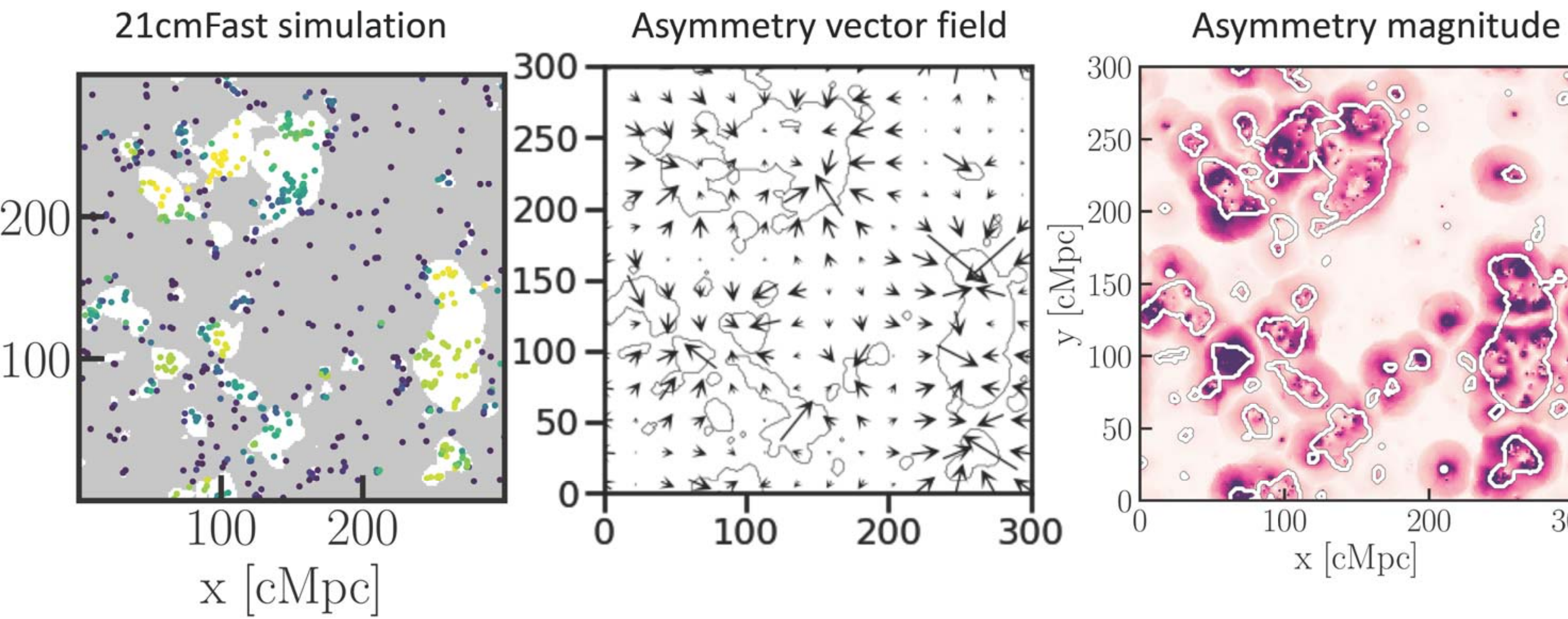
Large-scale topology:
edge detection through asymmetry



Lu+, in prep

Large-scale topology: edge detection through asymmetry

PRELIMINARY



Lu+, in prep

Conclusions

- Our new **multi-scale forward models** recover Lyα forest data, in combination with UV LFs and CMB τ_{eff}, without *ad-hoc tuning* or introducing *effective* parameters

- **Reionization is late: ends at z~5.3 - 5.4 with midpoint at z ~ 7 - 7.5**

- Estimates of IGM mean free path and ionizing background are *converging between different analysis approaches* -> data is very constraining

- We do not know anything about the topology of this inhomogeneous process
  (i) tells us **which galaxies drove the EoR**
  (ii) allows us to connect **galaxy properties to local HII** environment; contribution of **faint galaxies**

- Lyα from galaxies can map local reionization topology during early EoR
  (i) **Bayesian inference of HII bubbles is possible with ~3x10^{-3} galaxies / cMpc^3**
  (ii) **Asymmetry** of large-scale Lyα EW maps can find **edges of bubbles**

Apply for a PhD in Physics and/or Computational Astrophysics at Scuola Normale Superiore in Pisa, Italy

- Scuola Normale Superiore (SNS) is Italy's premier university, consistently ranked top in the country and among the top in the world, when normalized by size
- The Cosmology Group at SNS has won numerous awards, including 3 ERC grants and 3 Marie Curie fellowships