Probing Cosmic Reionization with Quasar Proximity Zones

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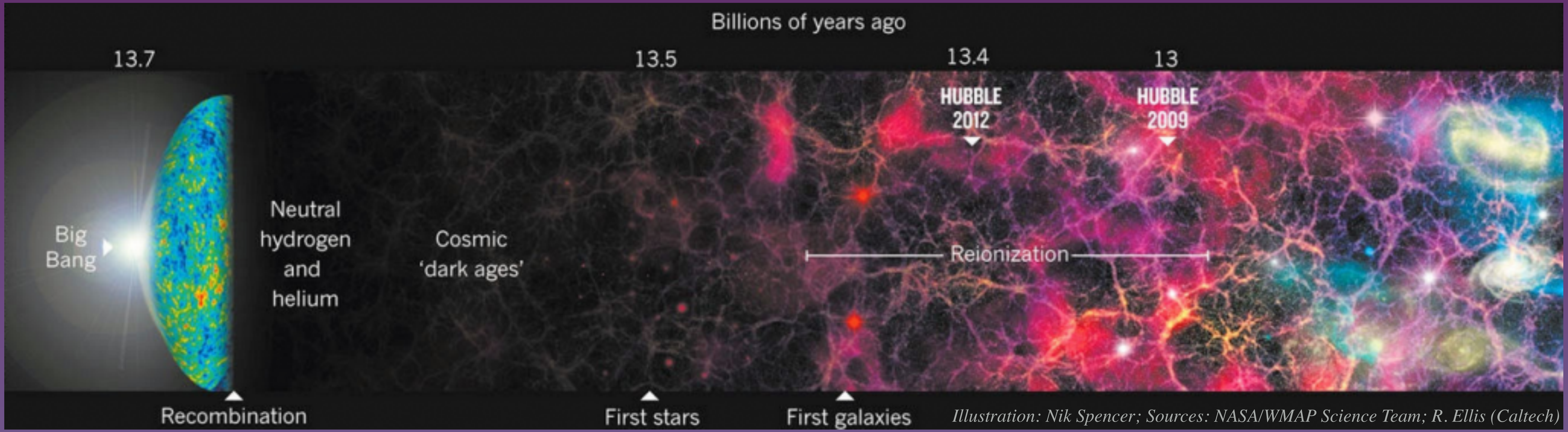
Berkeley, Nov 9, 2021

Outline

- Introduction of cosmic reionization
- Quasar proximity zones as unique probes of reionization
- Study of quasar proximity zones with simulations
    - Recovering the density of the IGM at z~6
    - Galaxy formation in quasar proximity zones
- Future prospect and conclusion

Cosmic Reionization

Beginning

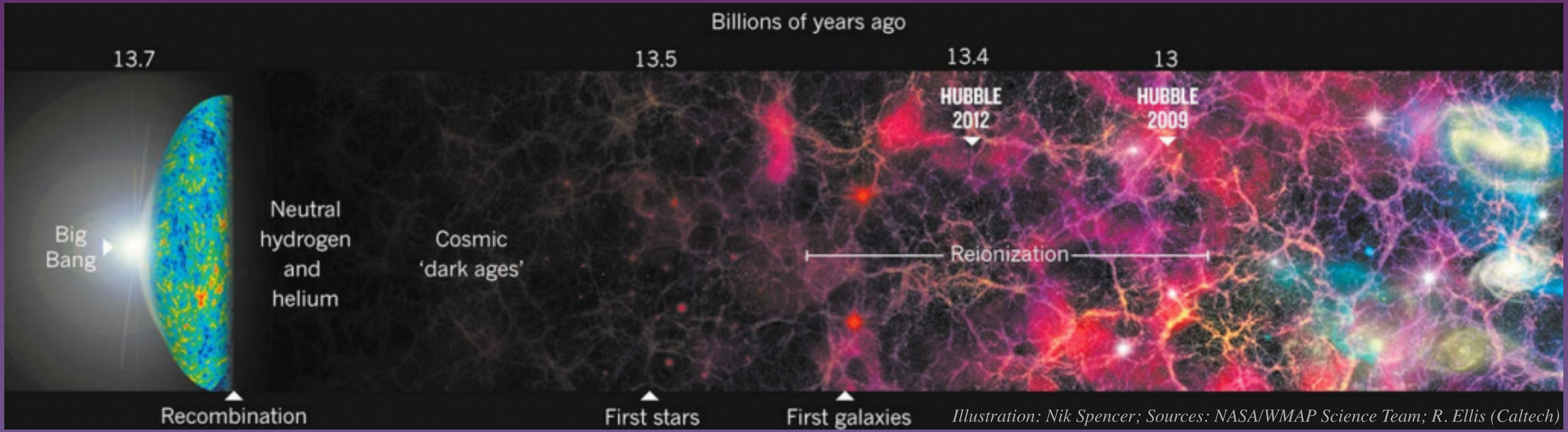


ionized gas

Cosmic Reionization

As time elapses, the Universe expands
and cools down

Beginning



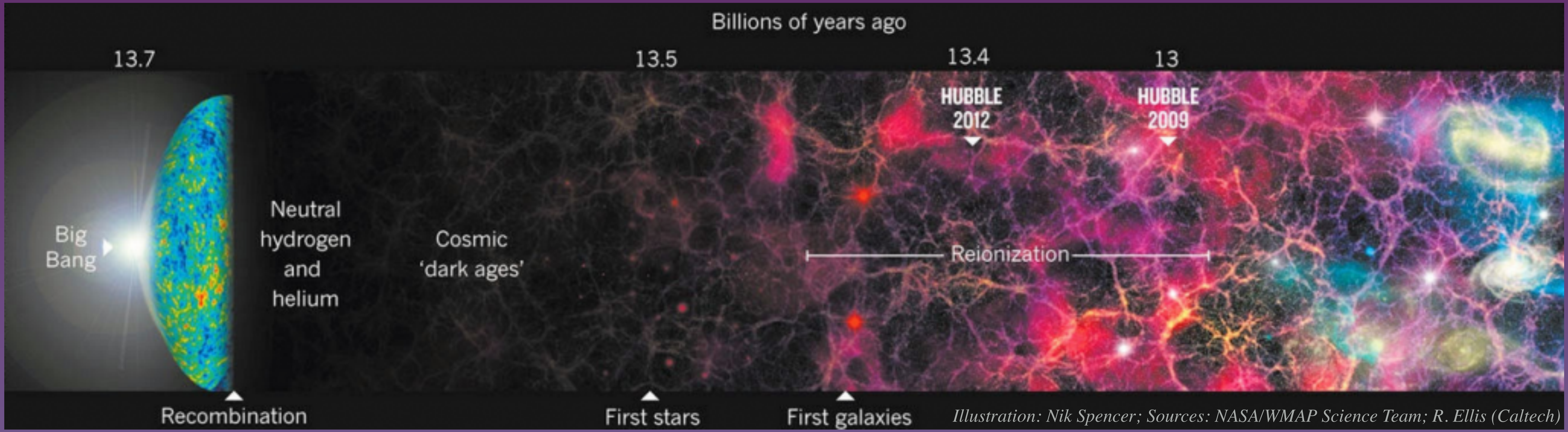
ionized gas

protons and electrons recombines,
forms cold neutral gas (hydrogen)

Cosmic Reionization

Gravity finally pulls matter together
to form stars/galaxies

Beginning



ionized
gas

Stars, quasars, XBs emit
ionizing photons

Cosmic Reionization

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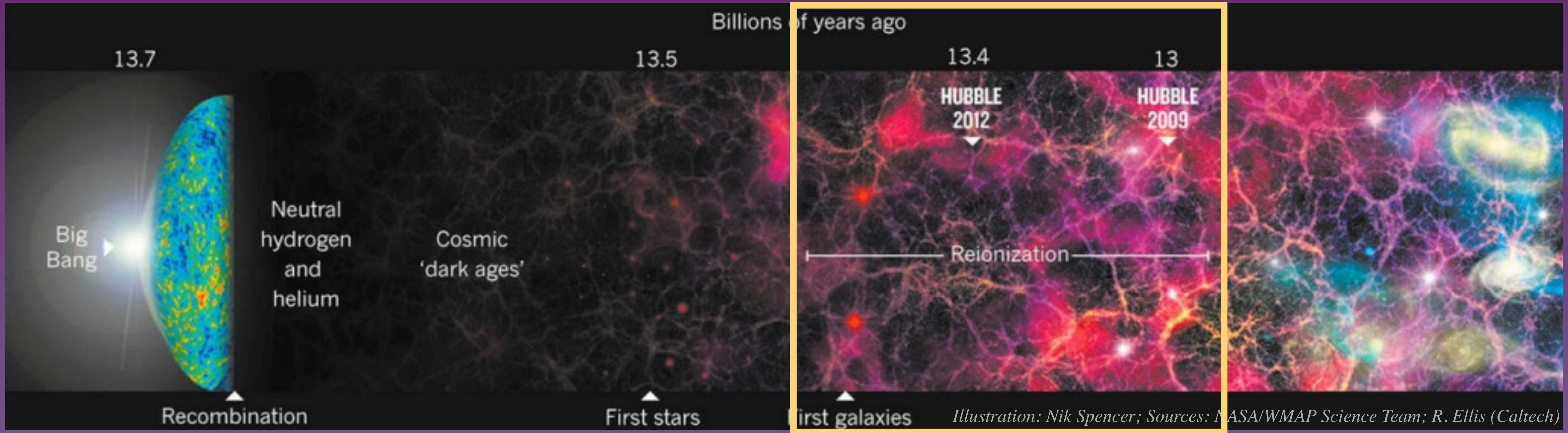

ionized
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Stars, quasars, XBs emit
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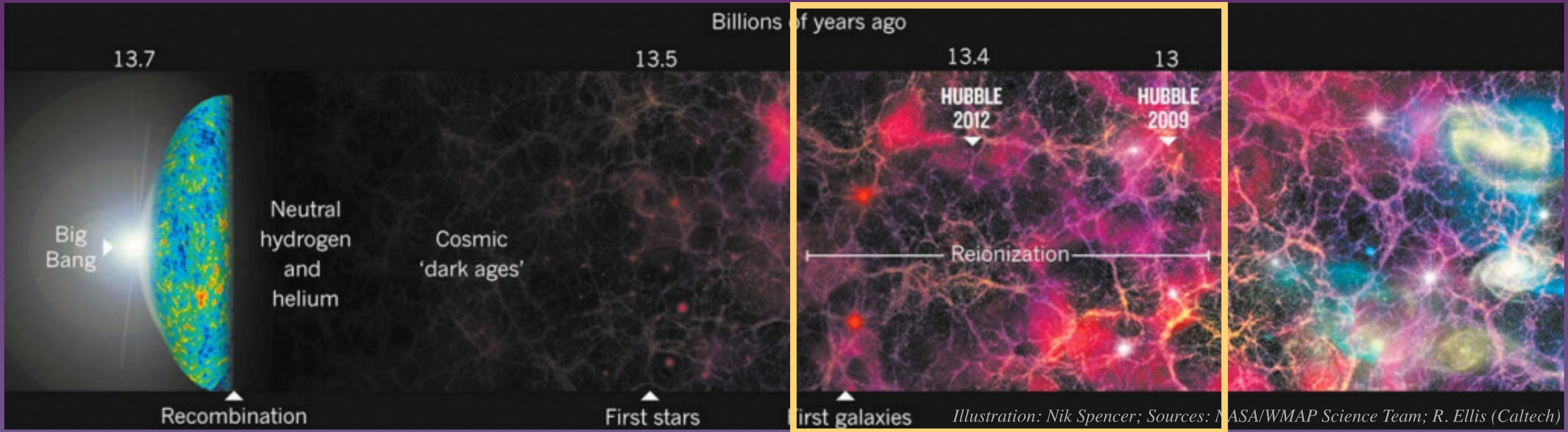
Cosmic Reionization

Starlight ionizes and heats
the intergalactic gas

Beginning



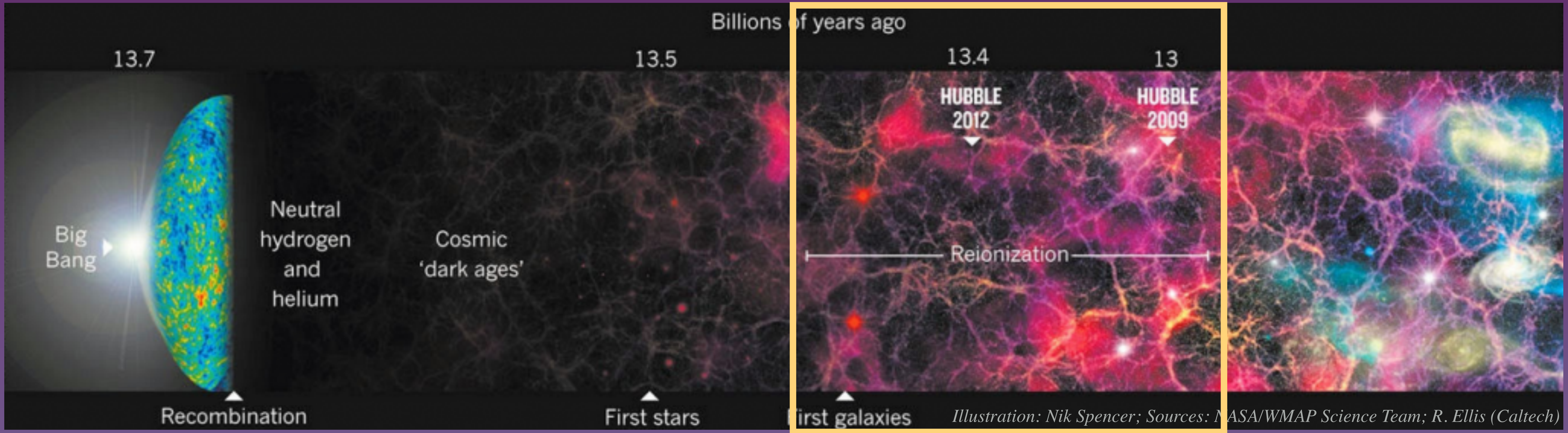
ionized
gas

Reionization process is patchy:
gas around galaxies gets ionized first,
forming ionized bubbles.

Cosmic Reionization

More and more gas gets ionized

Beginning



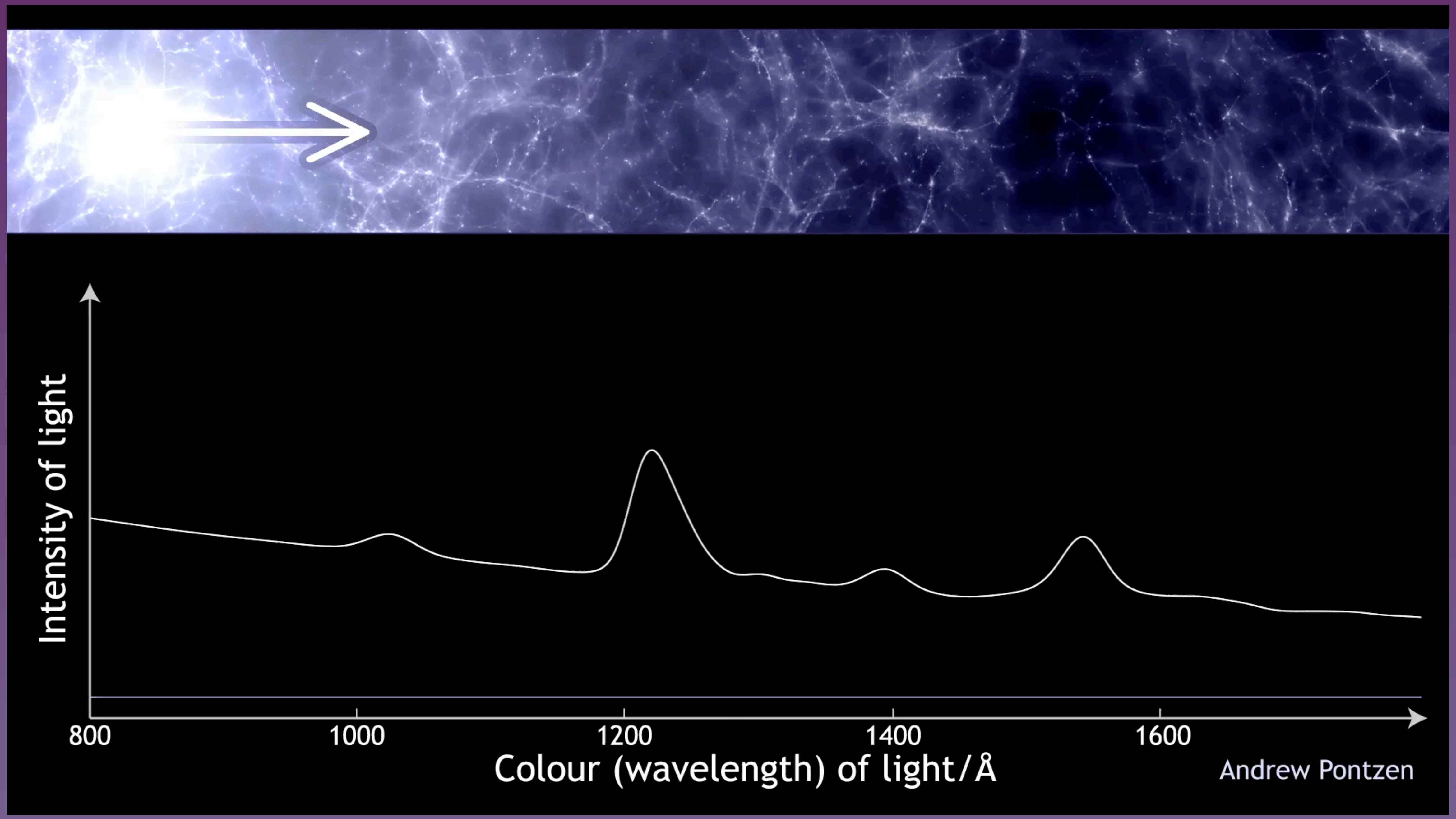
Now

ionized gas

Finally most gas are ionized, with only a little bit of residual neutral gas

Quasar Absorption Spectra

Illustration of Lya Forest at z~3



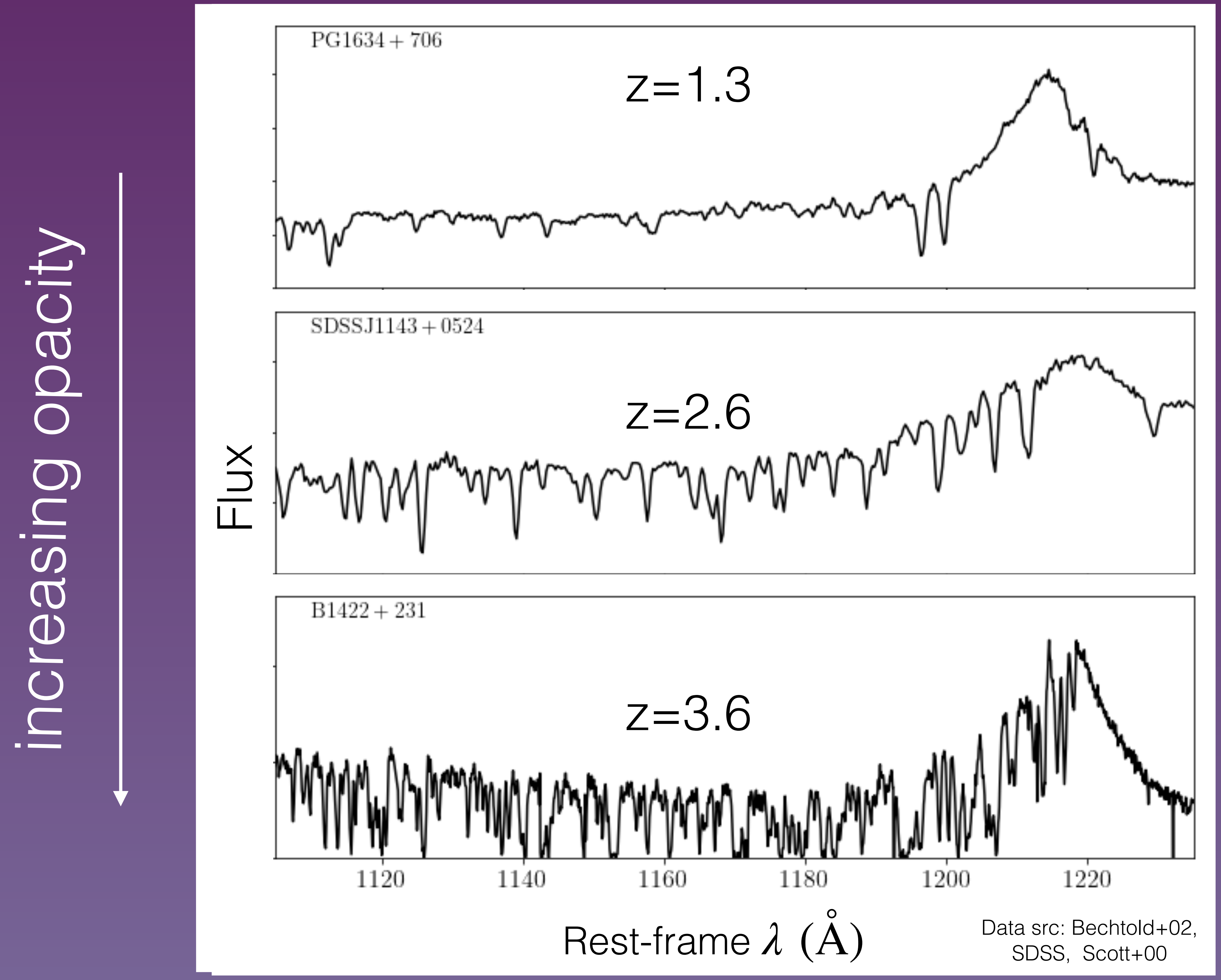
Lya absorption (resonant line):

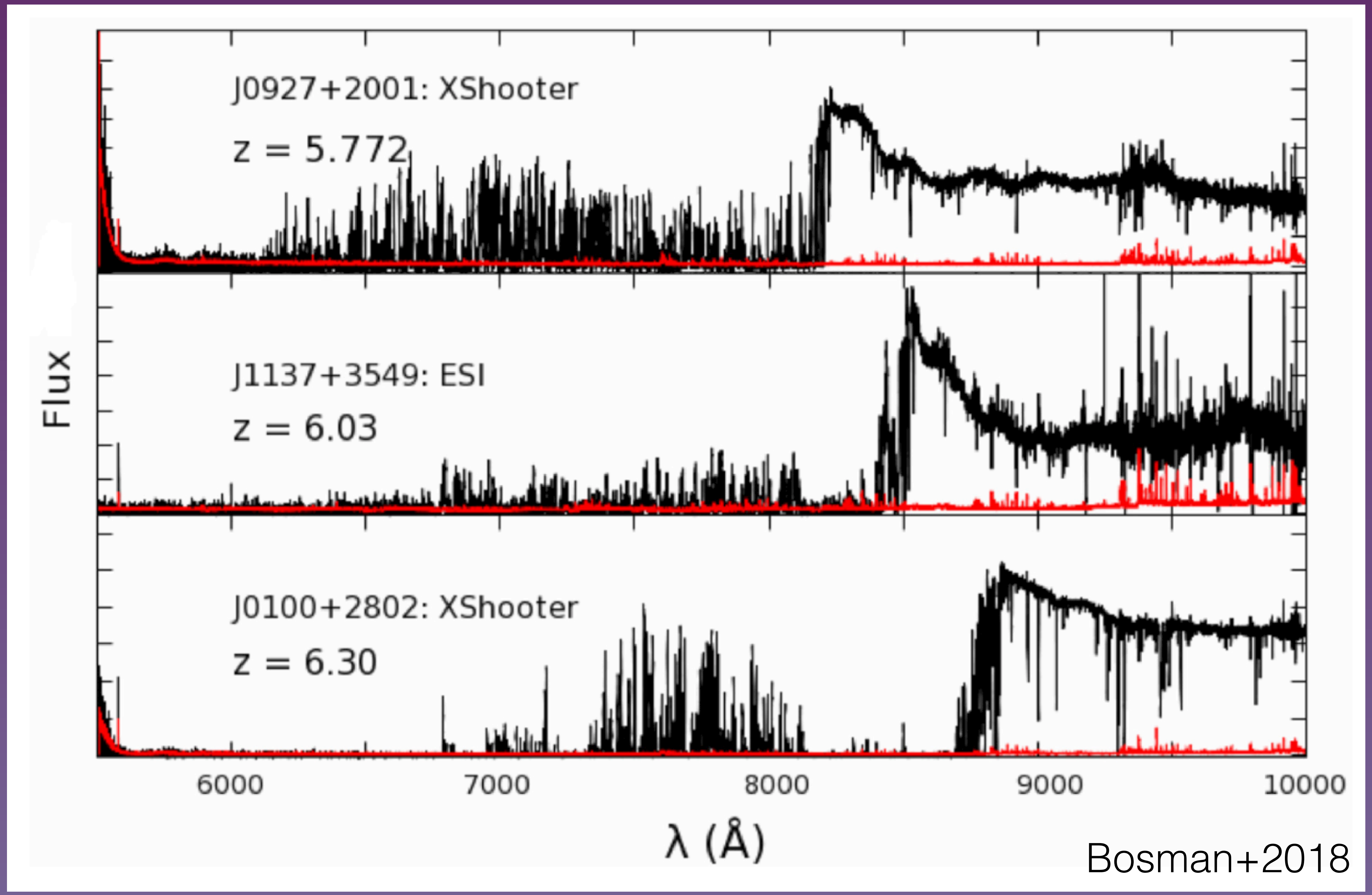
- Large cross-section
- Tiny amount of neutral hydrogen ($x_{\rm HI} \sim 10^{-5}$) can create significant absorption lines
- neutral gas creates saturated absorption
- Lyman alpha forest actually means a very ionized universe

Absorption Forest ⇒ Transmission Spikes

- Lya forests encode important information, e.g., gas density, temperature, ionizing bkg.

- Transmitted flux drops rapidly above z~6 , crucial information lost!





With Current Quasar Spectra

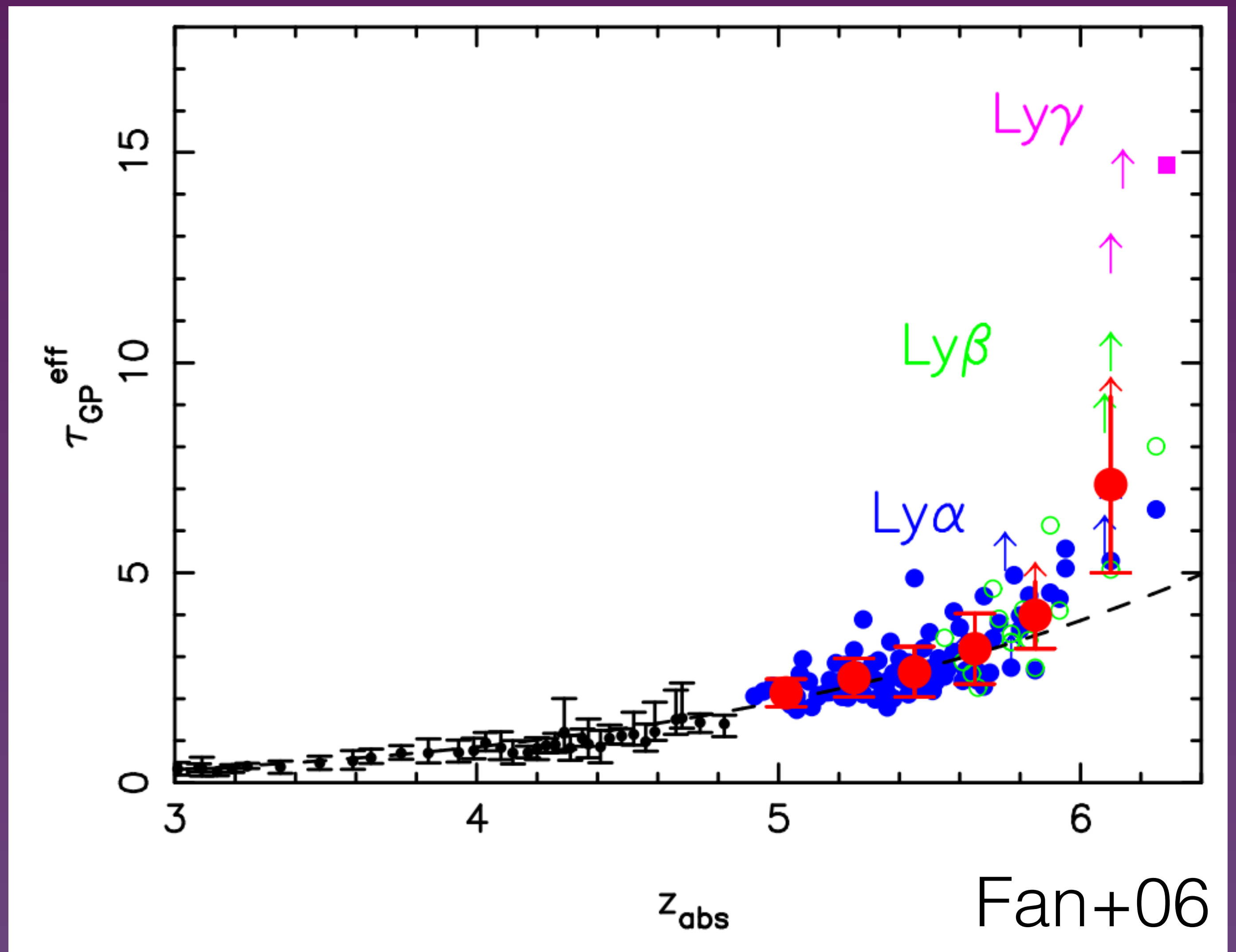
What do we know:

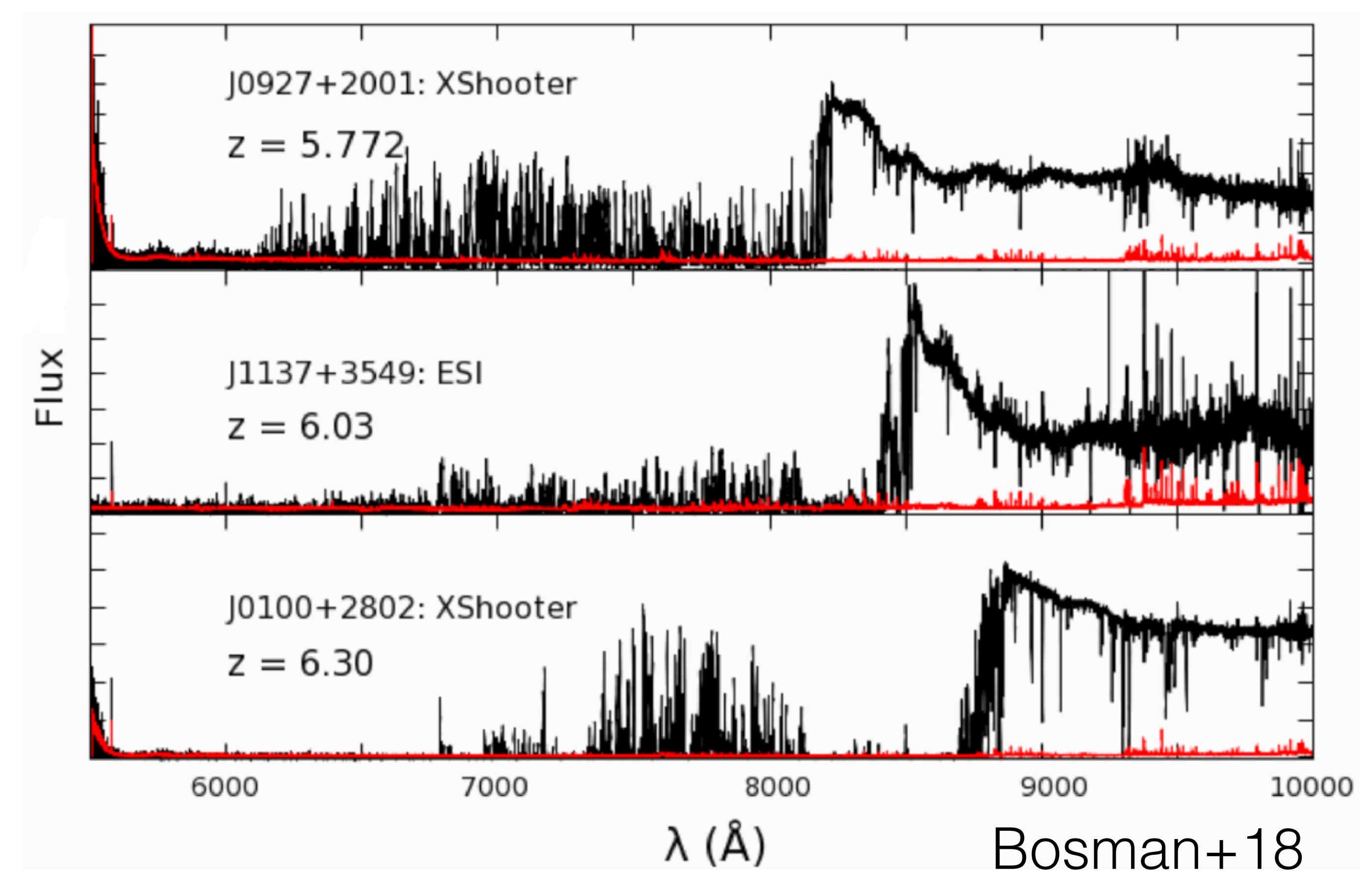
- Optical depth increases dramatically above z~6, indicating the end of reionization (Becker+01, Fan+06 etc.)

But because of the saturation in Lya absorption,

we do not know about the details of the IGM at z>6

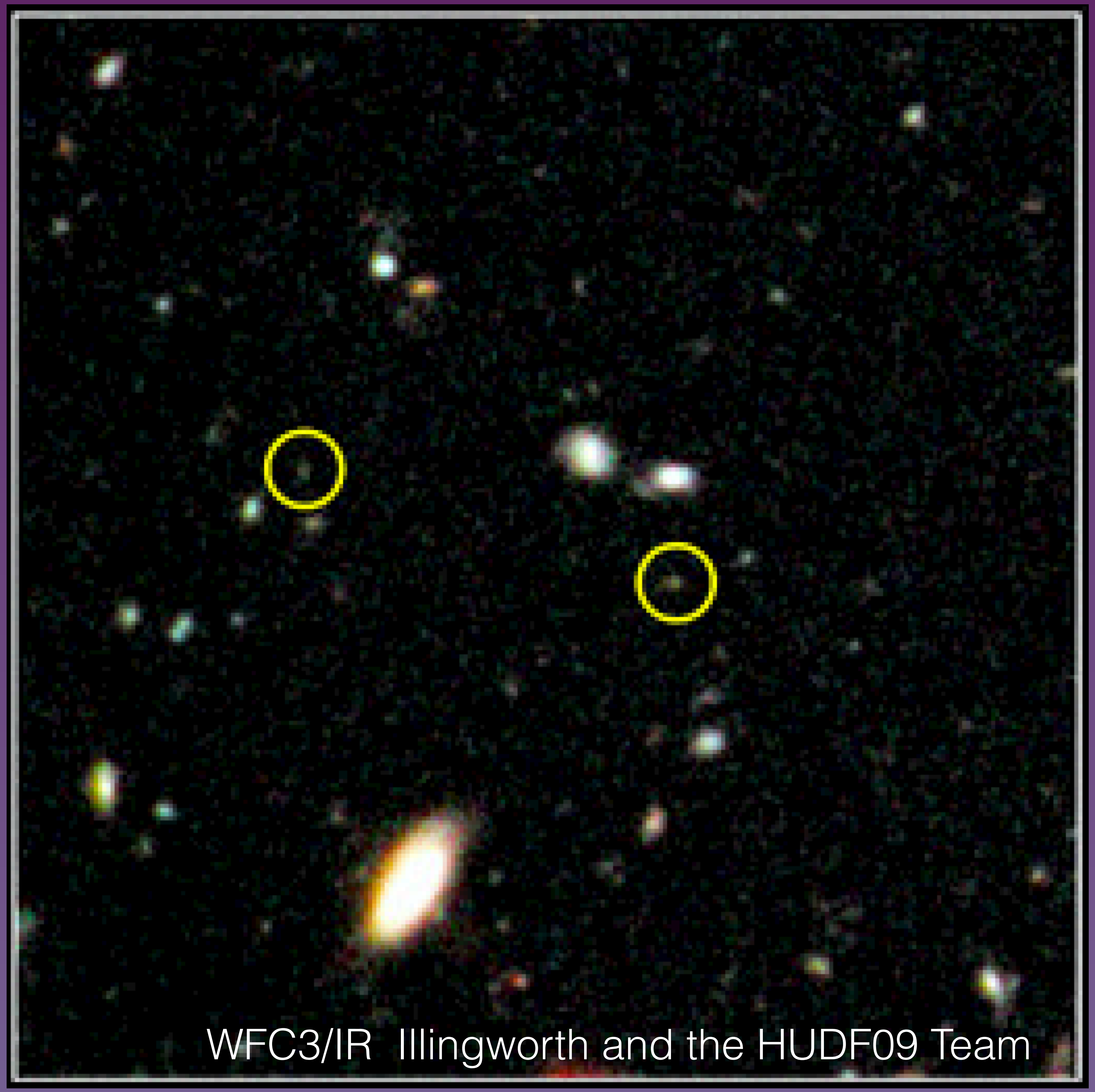
- Density?
- Temperature?
- Neutral fraction?





Observing Reionization Galaxies

More than 1000 z>6 galaxies detected in by HST (Oesch+15, McLeod+16, Bouwens+17, etc.)

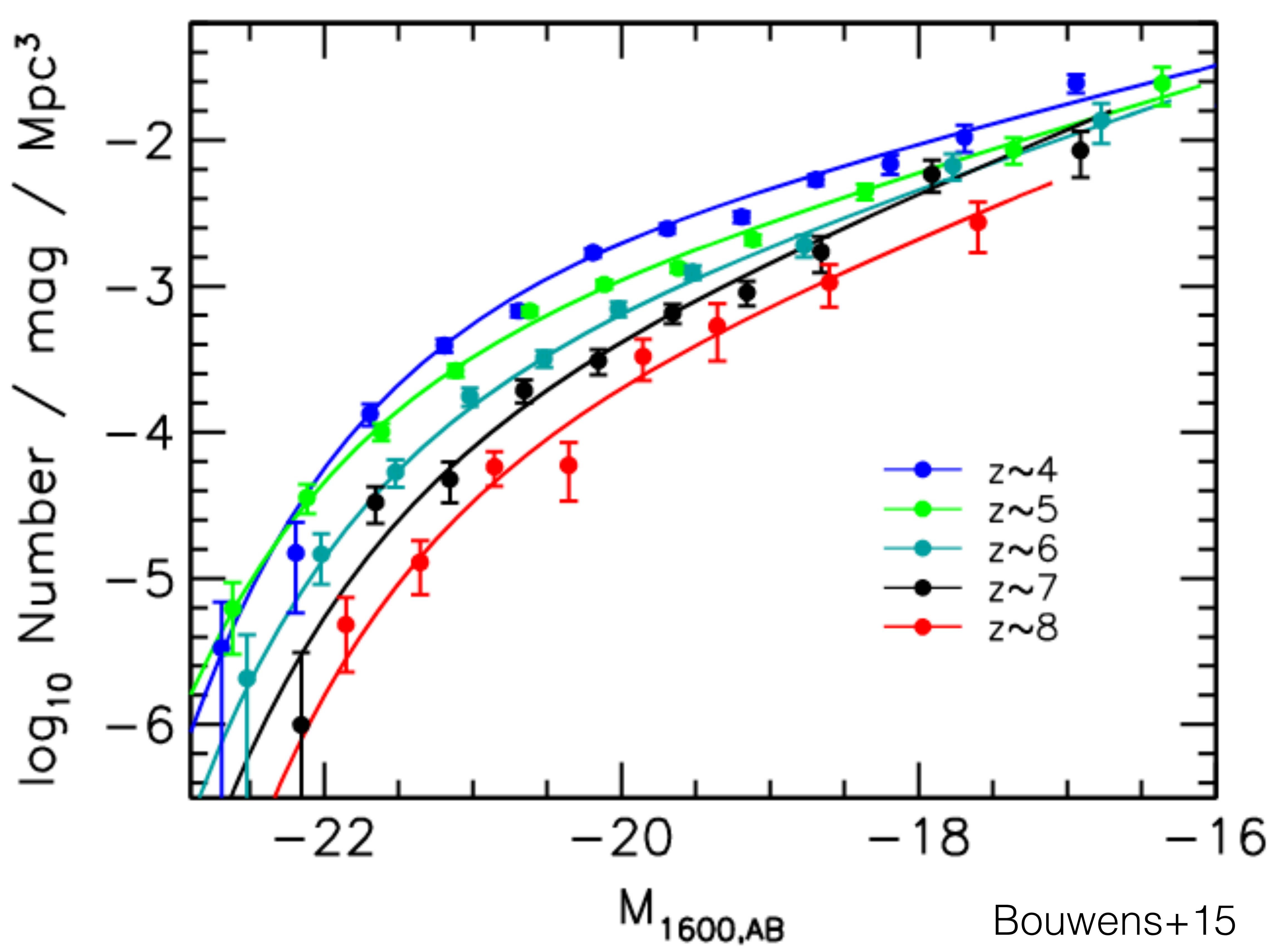


Galaxy Luminosity Function (GLF)

More than 1000 z>6 galaxies detected in by HST (Oesch+15, McLeod+16, Bouwens+17, etc.)

Luminosity functions contain crucial information about:

- structure formation
- Ionizing photon budget



Bouwens+15

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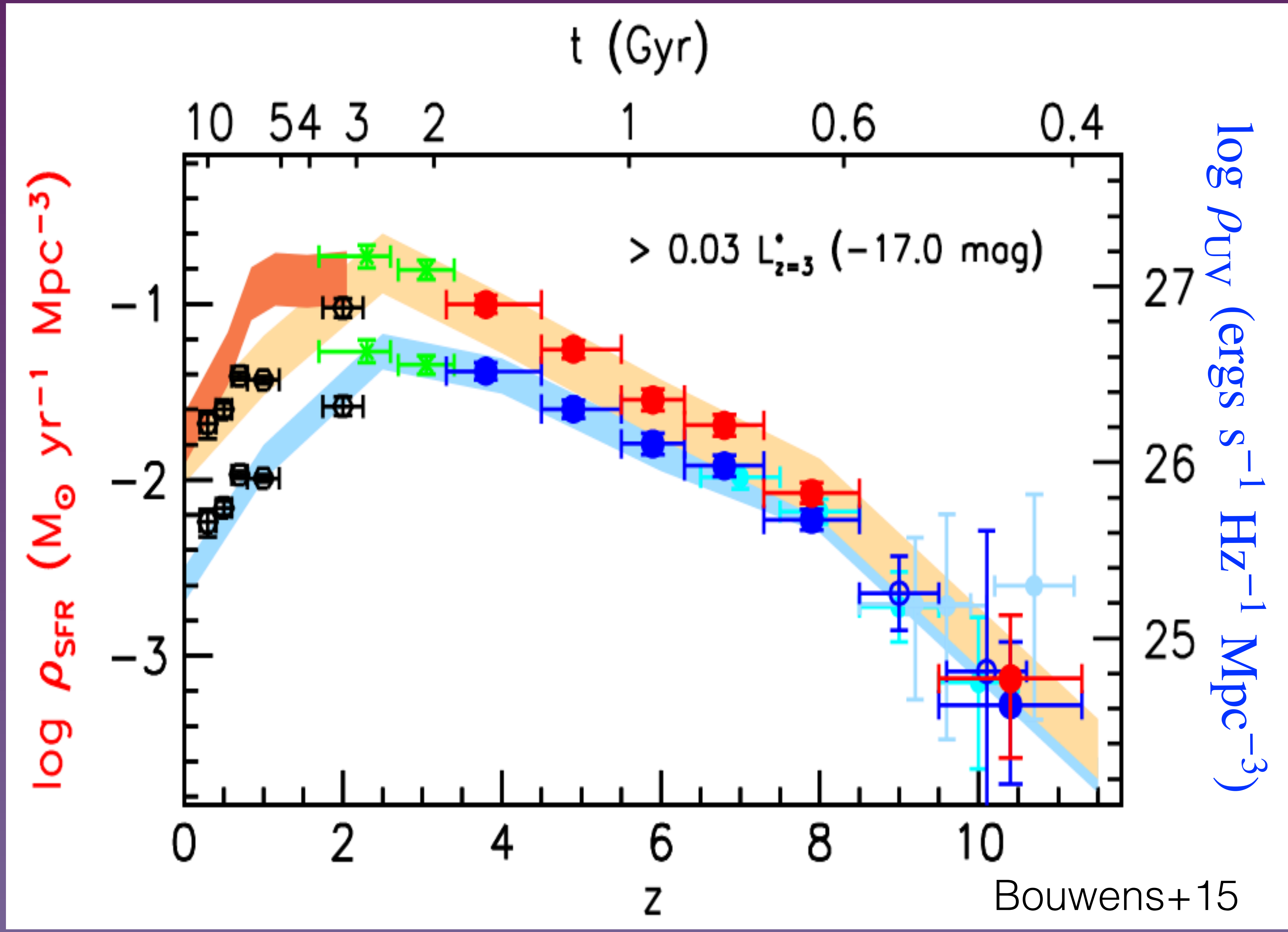
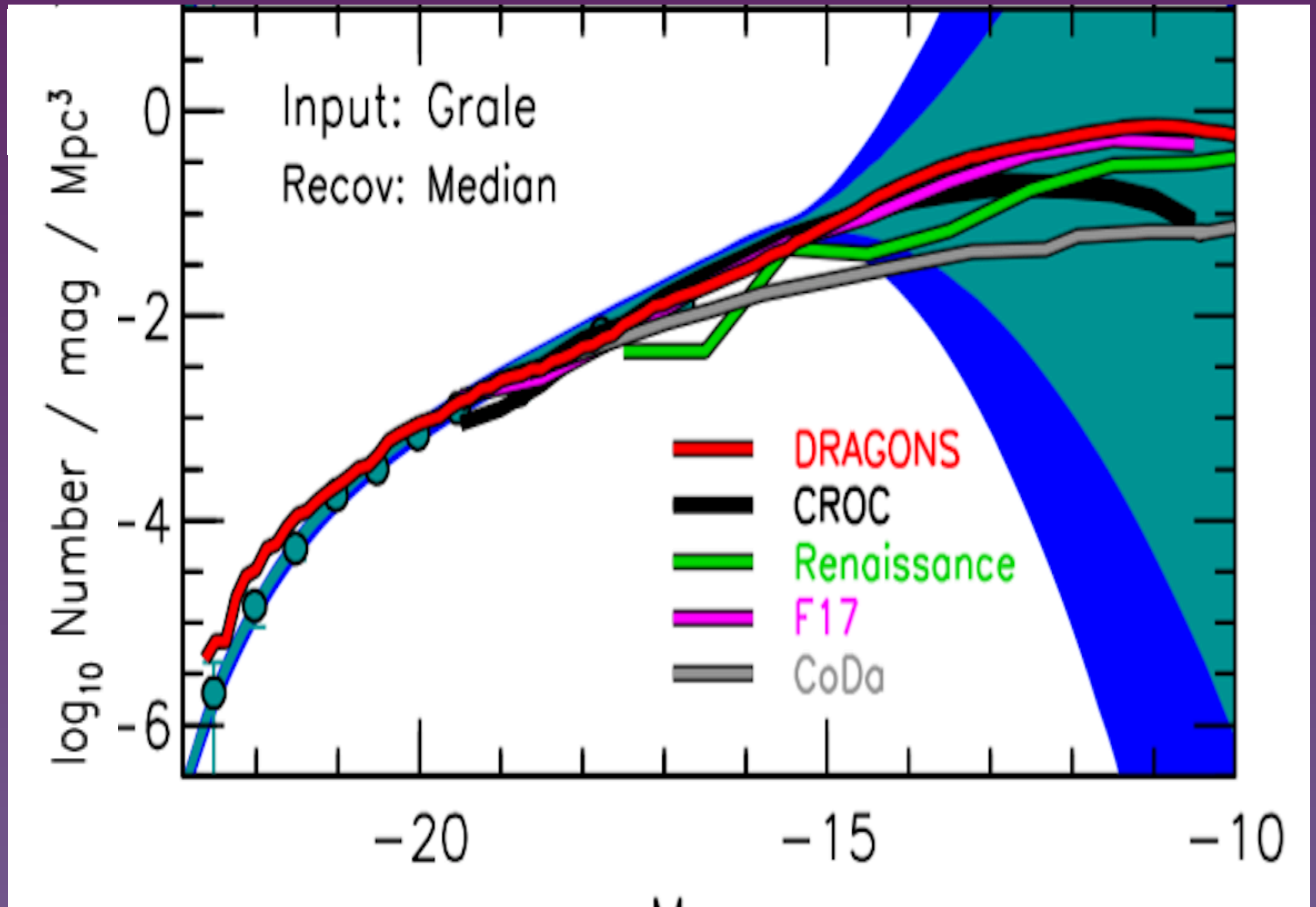


GLF: What We Do Not Know

The faint end of the galaxy luminosity function is uncertain.

- A significant contribution to the ionizing photons budget may come from faint galaxies (Duffy+14 etc.).
- **Radiative Feedback:** small galaxies may be impacted by radiation from other galaxies.
- The effectiveness of radiative feedback is still under debate.



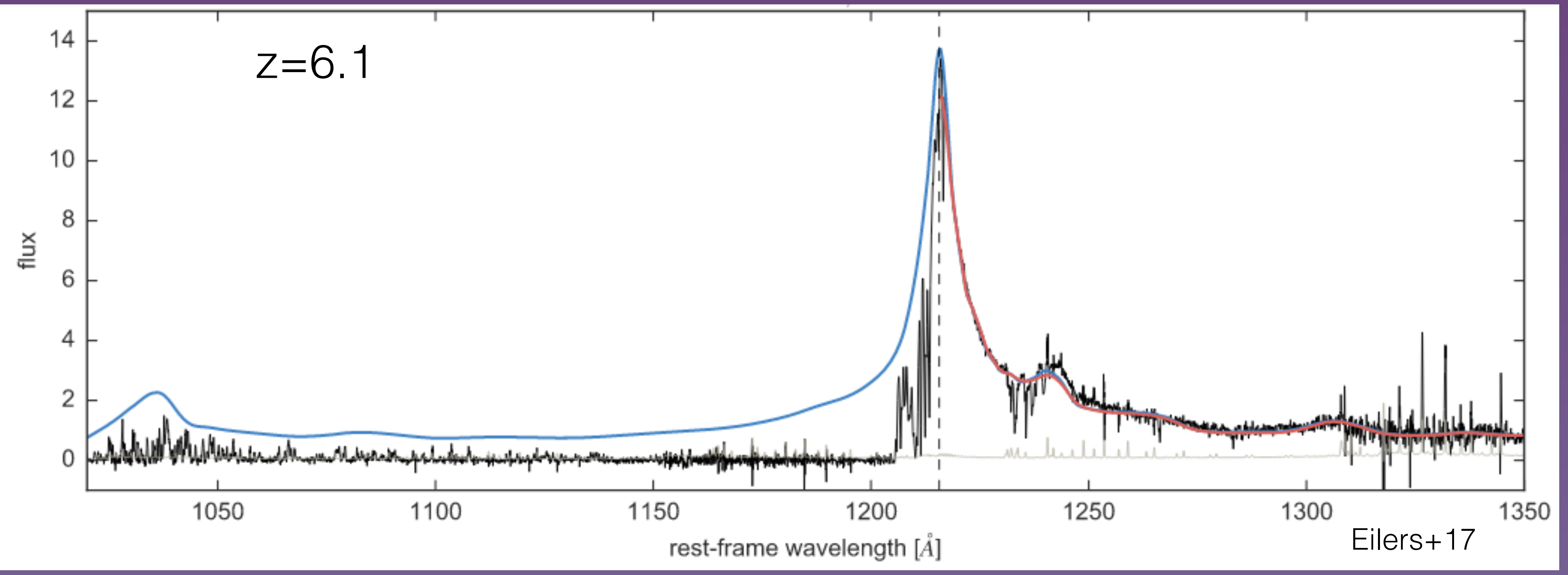
Bouwens+17

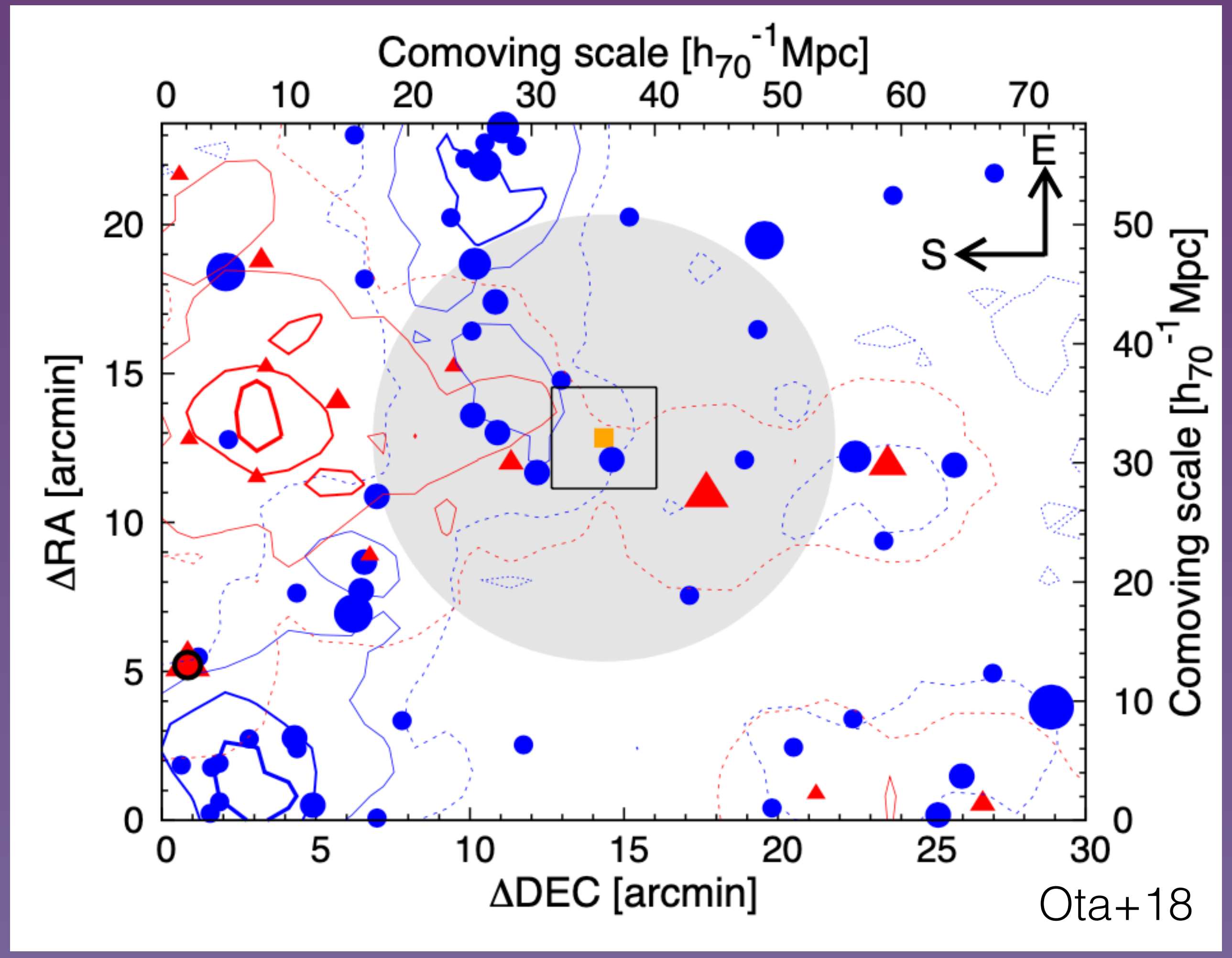
Current Status

- Currently, most constrains of reionization are from quasar spectra and observing individual galaxies.
- Lya spectra: reionization ends at z~6 (Fan+06 etc.)
    - IGM properties is hard to measure at z>6 due to Lya saturation.
- Galaxy Luminosity Function: bright galaxies alone are not likely to provide enough ionization photons (Duffy+14 etc.)
    - The faint end is uncertain due to the radiative feedback from cosmic reionization on faint galaxies.

Quasar Proximity Zone as a Unique Lab

- Luminous! 200+ z>6 quasars identified, with many high-resolution spectra
- Overdense regions? Likely trace "proto-clusters", favorable targets for JWST





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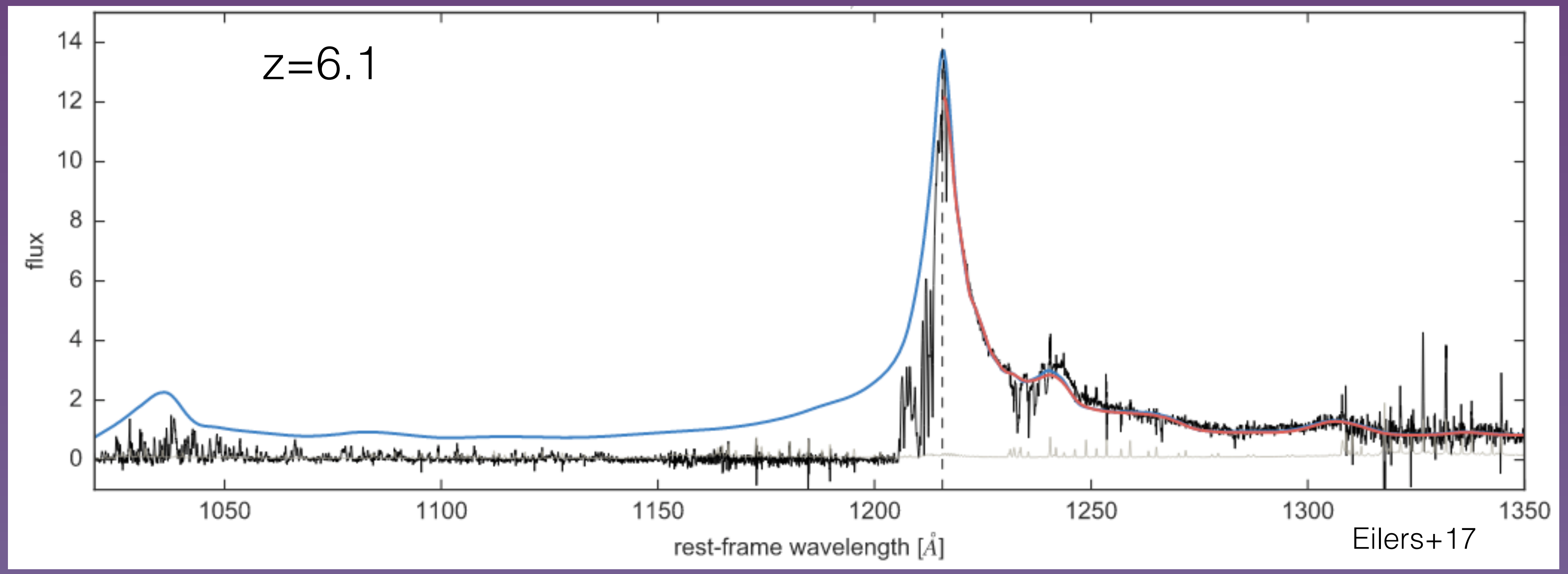
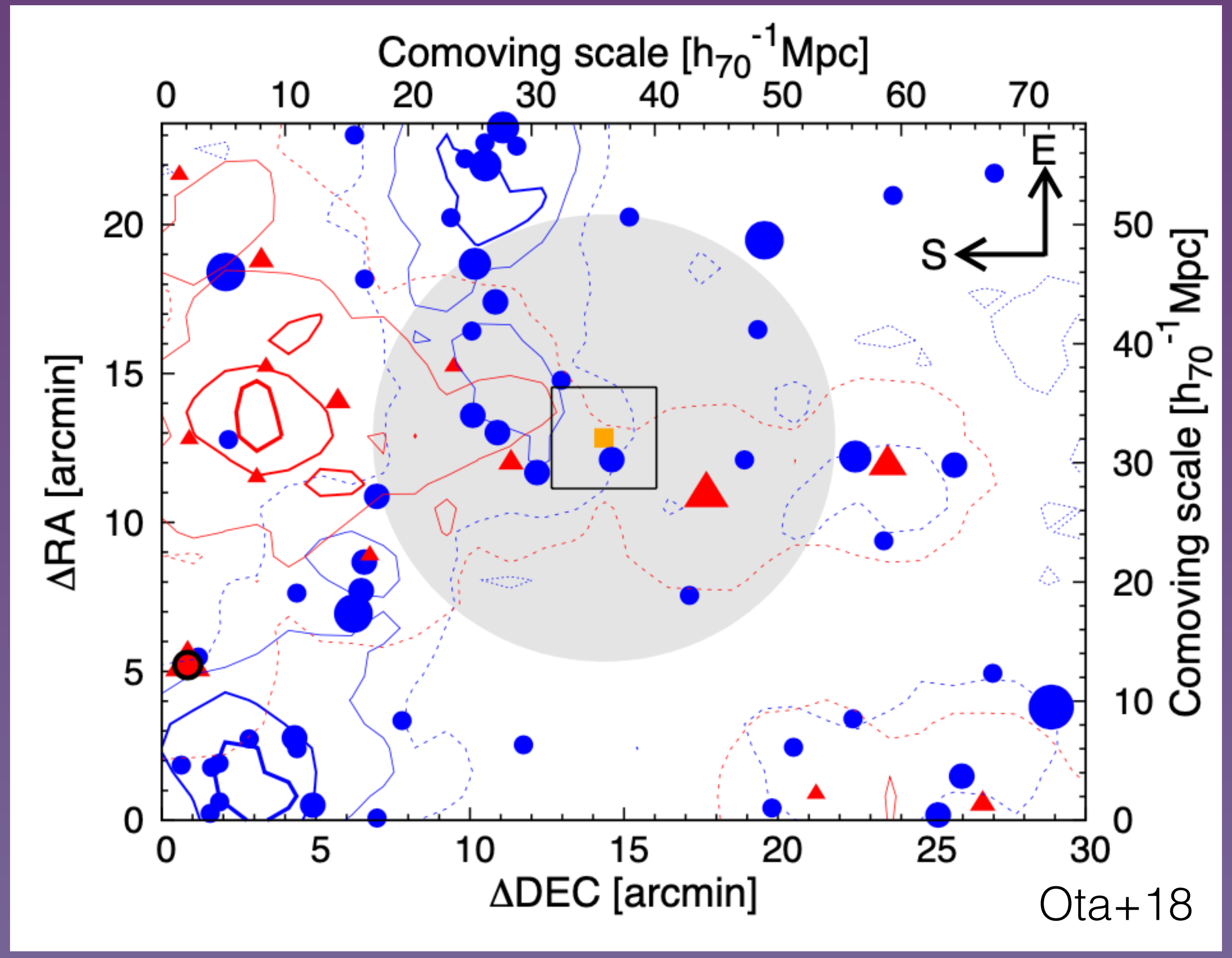
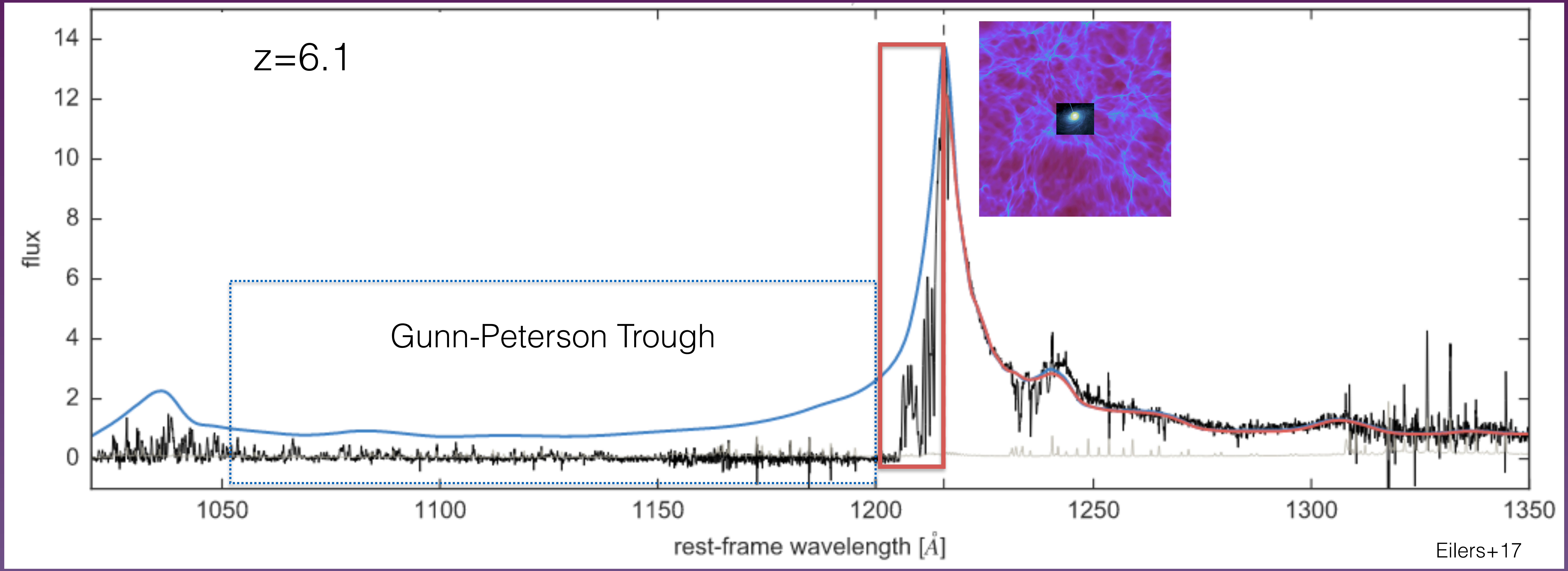
Part 1



Part 2

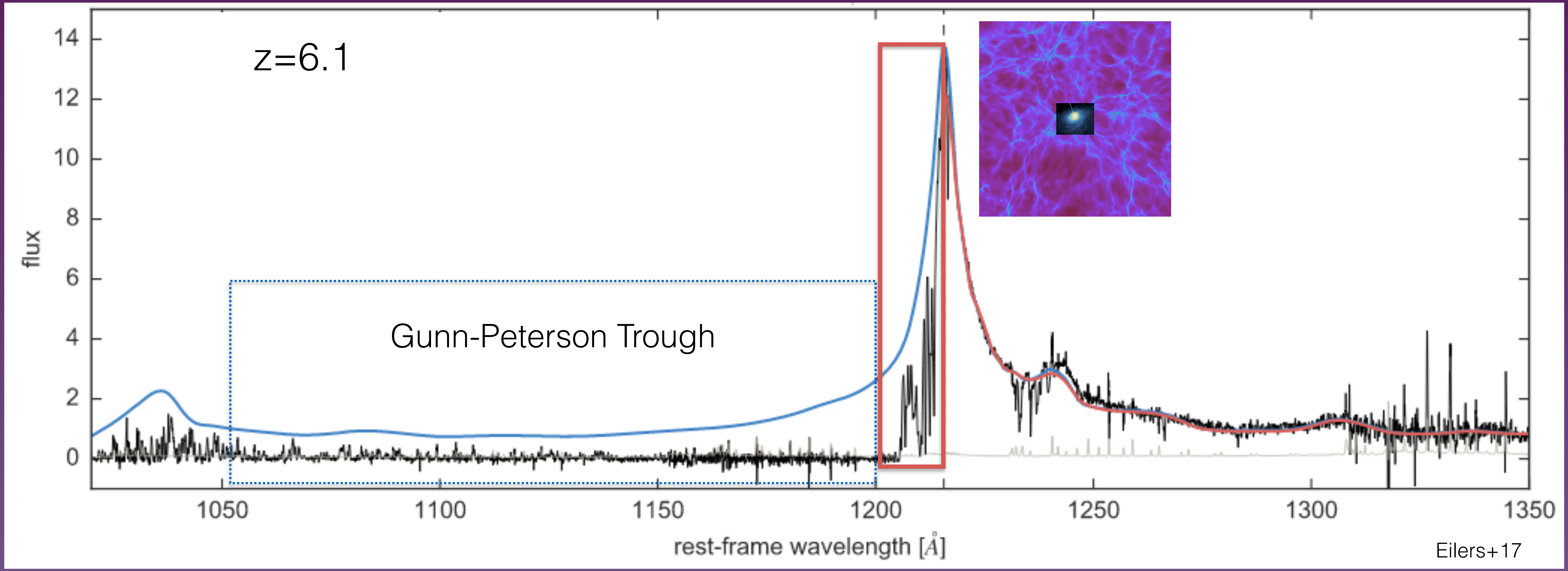


Quasar Proximity Zone Spectra



Lya saturates in most places, **But Not in Quasar Proximity Zones!**

Quasar Proximity Zone Spectra



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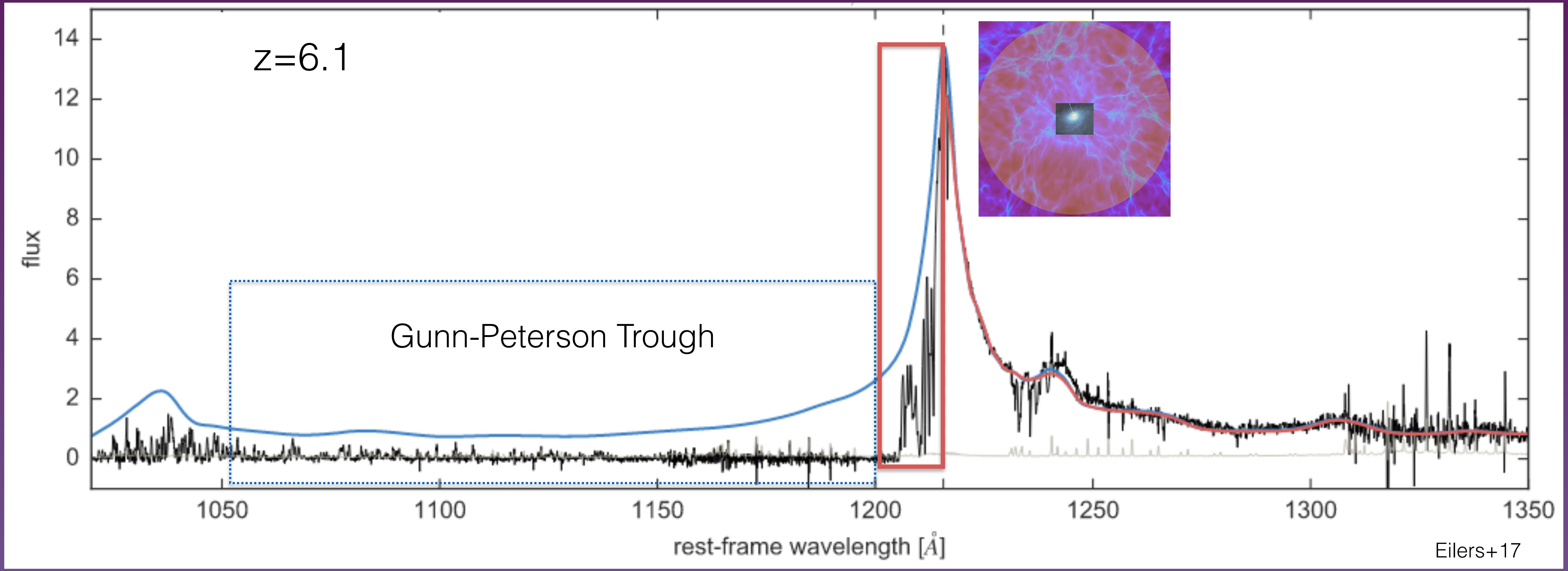

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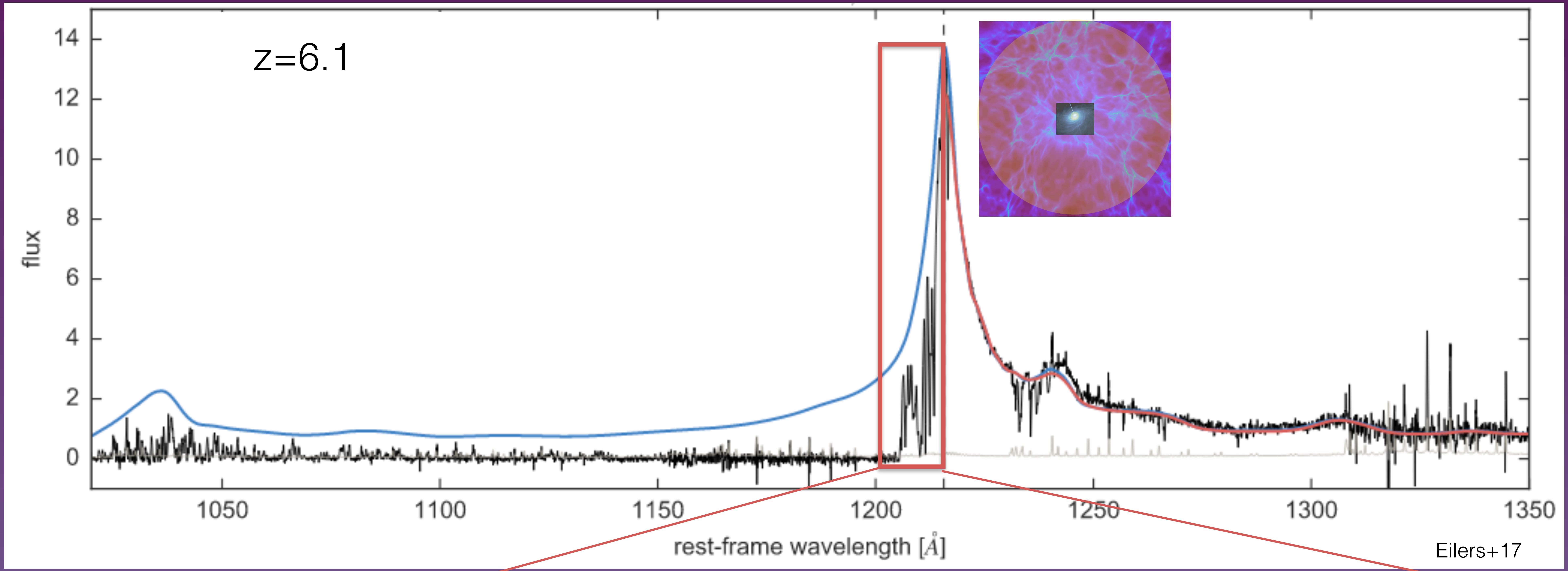
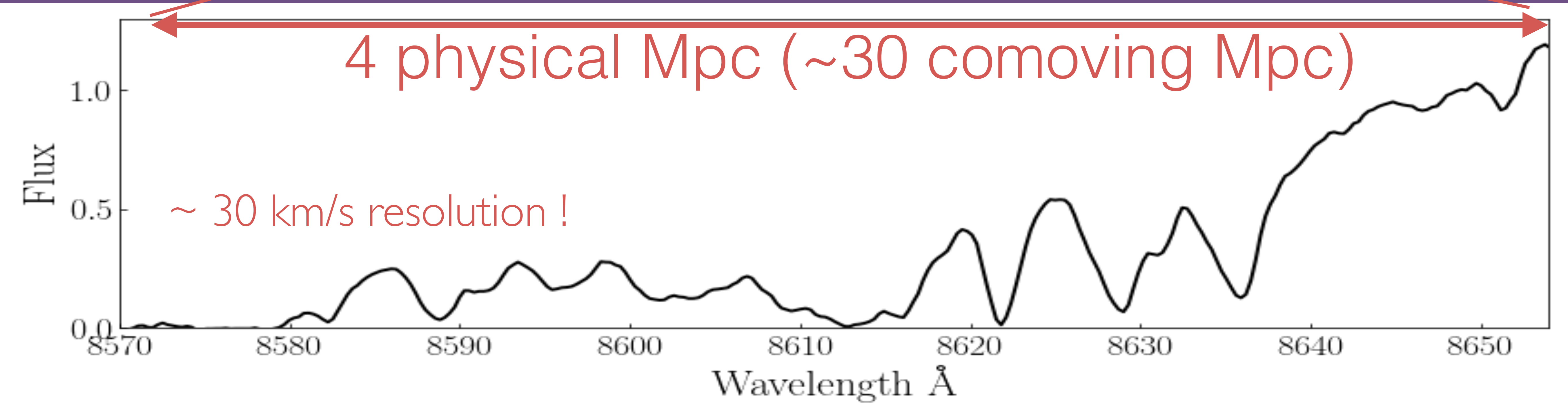


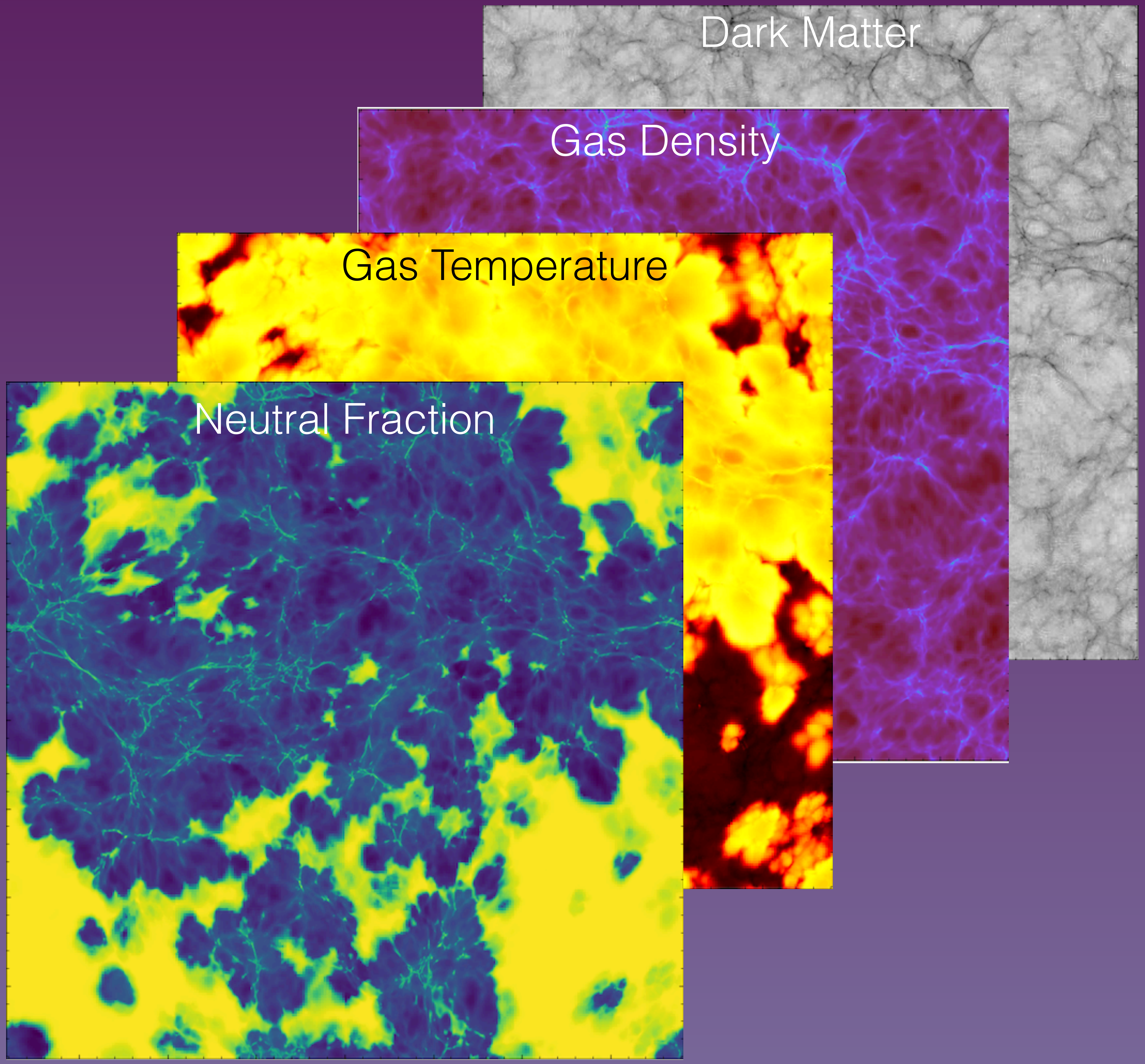


We can potentially do lots of science that we have done at z=2~5 with Lya forest!

CROC Simulations

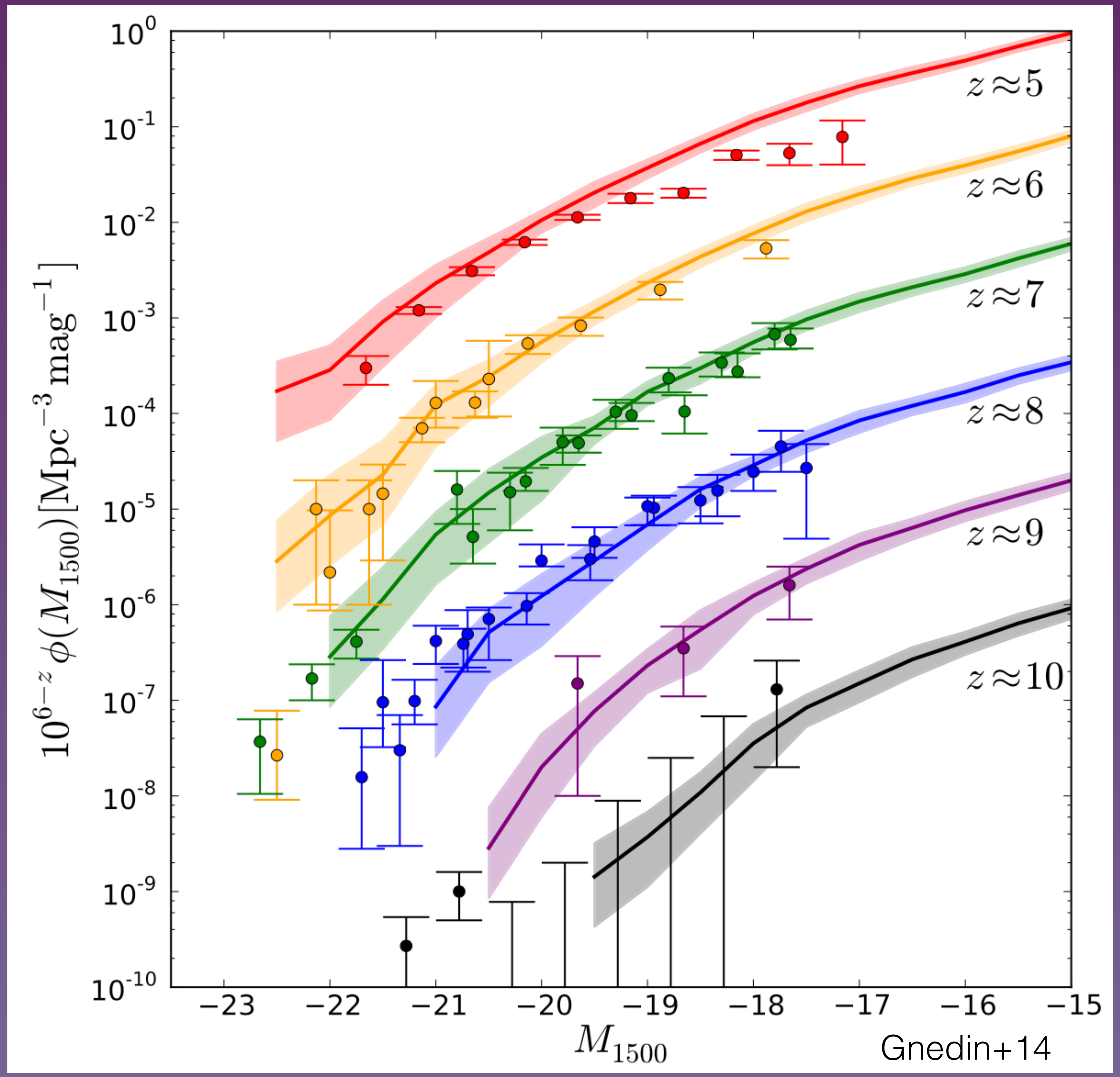
Cosmic Reionization On Computers (CROC) Simulations:

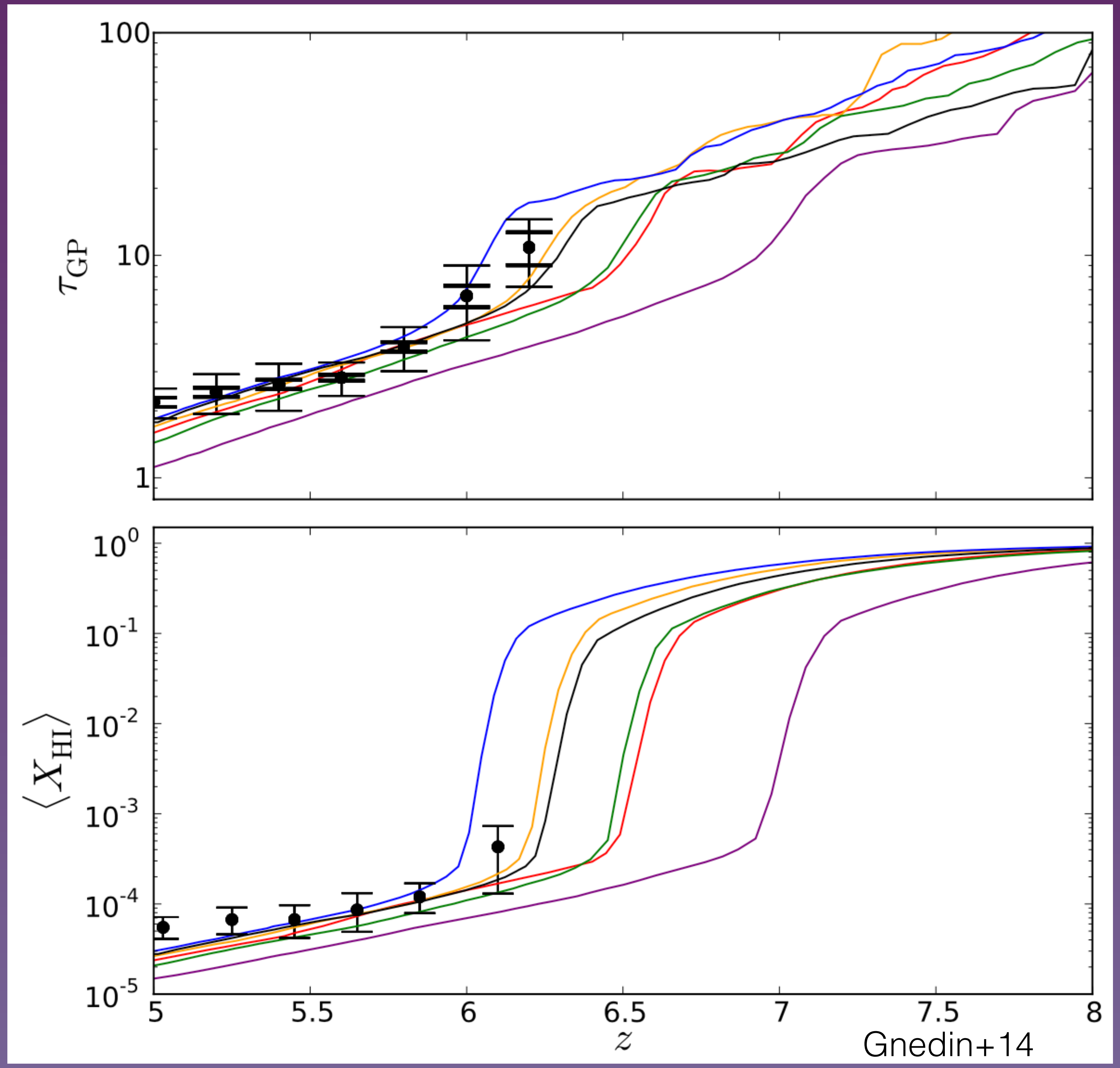
- Box sizes: 30, 60, 120 cMpc
- Adaptive Mesh Refinement ~100 pc peak resolution
- Gas heating/cooling
- Star formation
- Stellar feedback
- Radiative transfer



CROC Simulations

Successfully reproduce luminosity functions and Gunn-Peterson optical depth

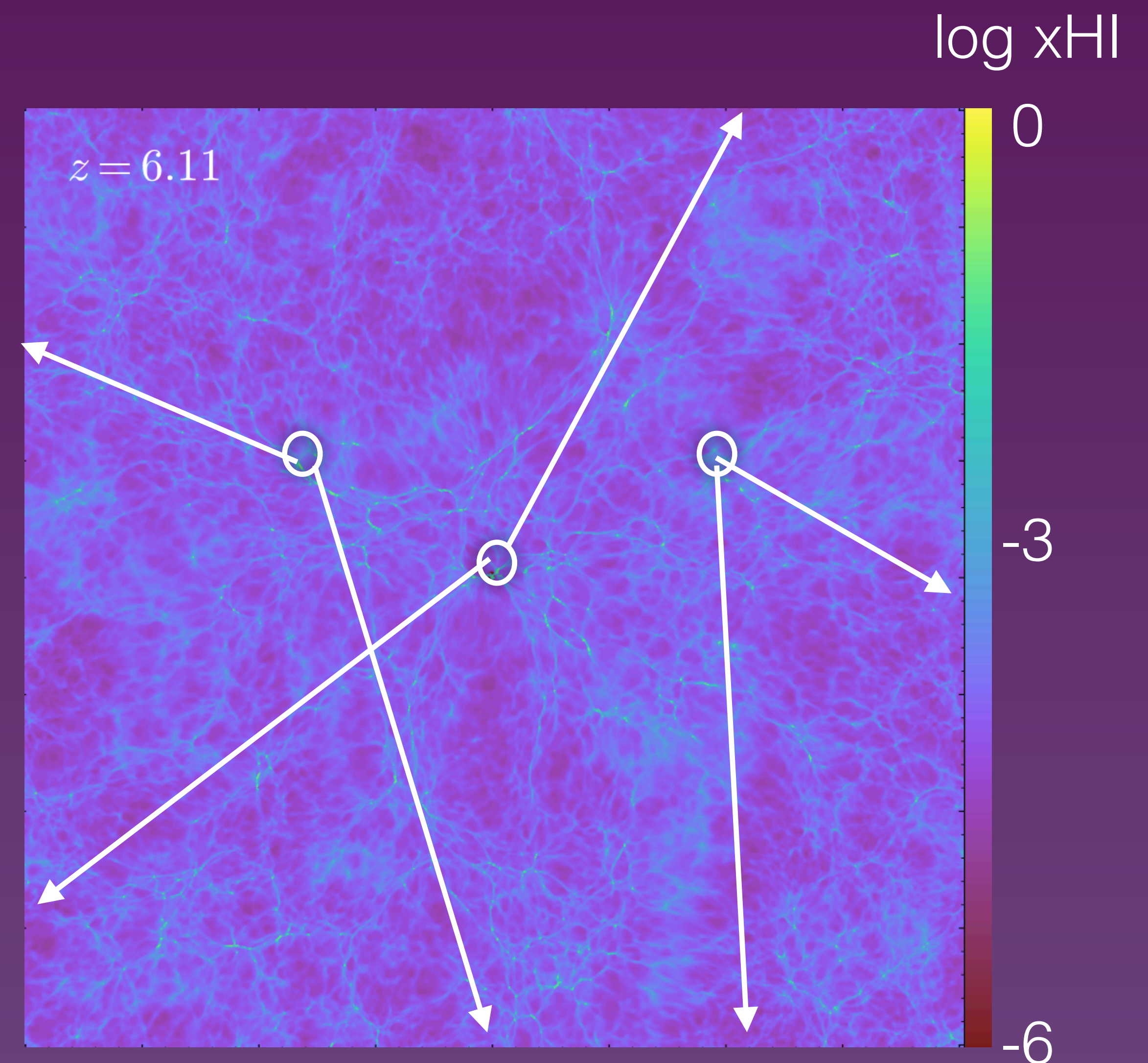




Modeling Quasar Proximity Zones

Make synthetic spectra:

- Identify massive halos as quasar hosts (63 halos with $M_h > 2 \times 10^{11} M_\odot$)
- Randomly draw sightlines (~7000 in total)
- Post-process with quasar radiation for 30 Myr



Chen+2020

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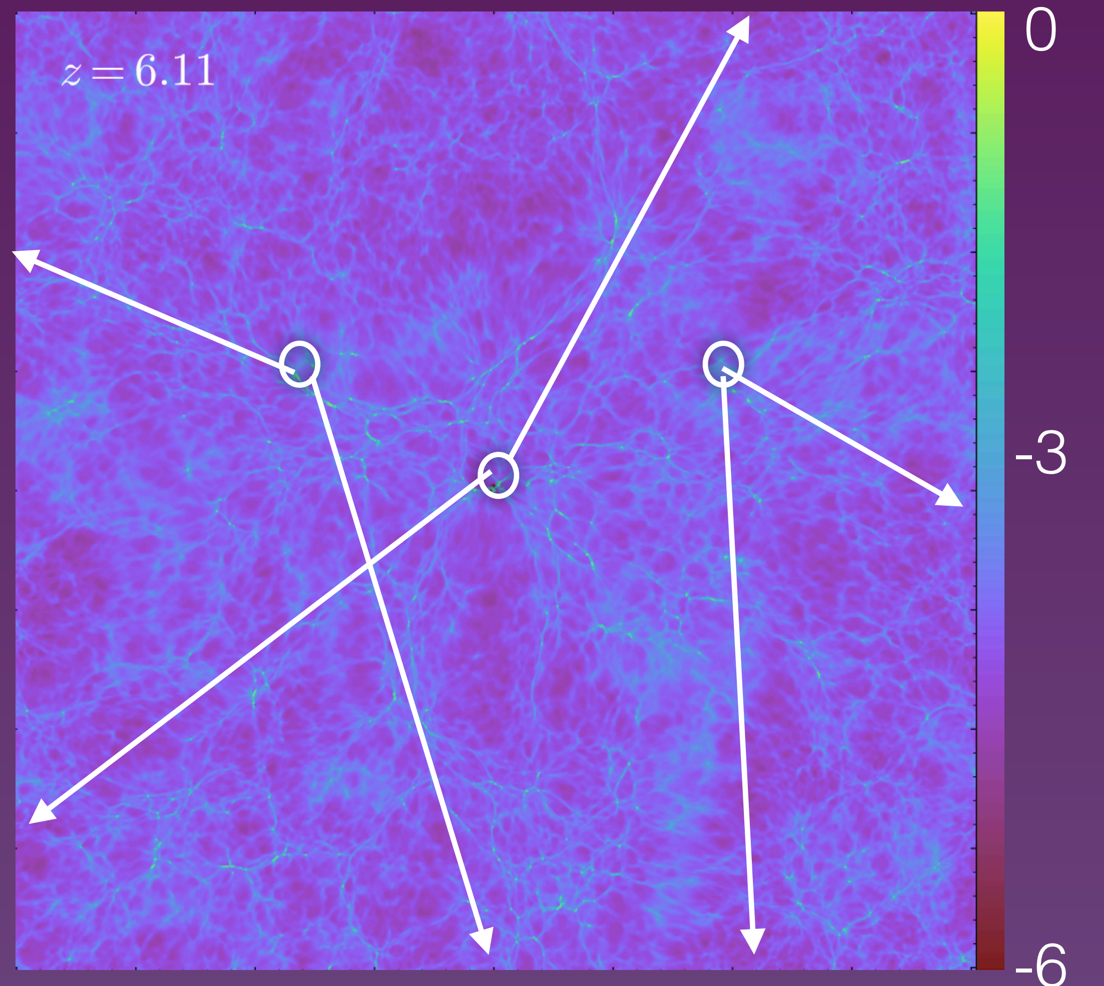
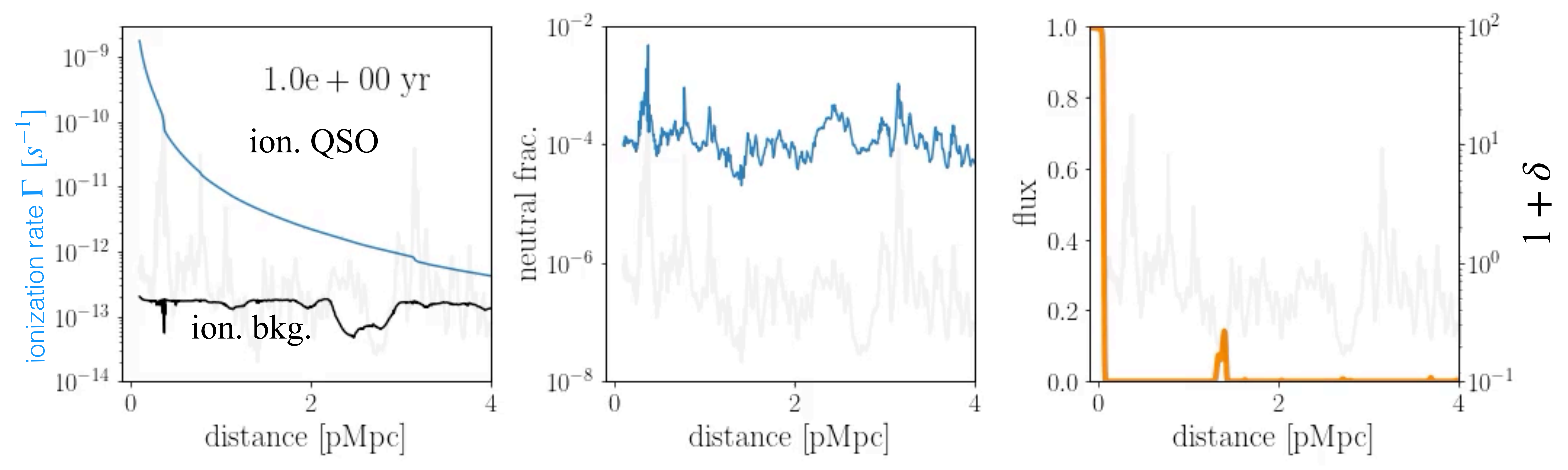


Chen+2020

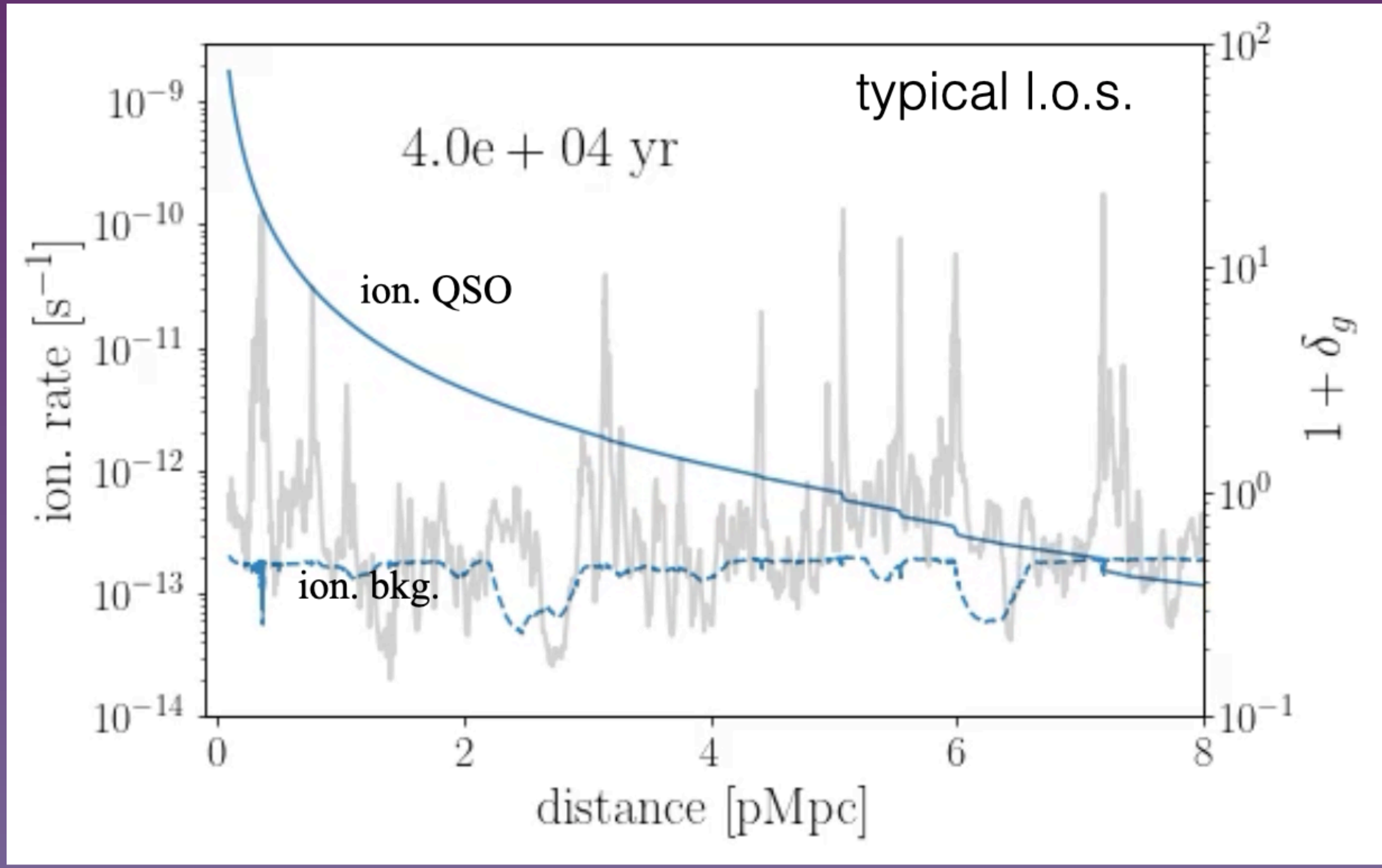
An example sightline at z=6.11:



Recover Density Field

Key insights from simulation:

Radiation profile quickly reaches perfect r^{-2} for most sightlines



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In ionization equilibrium ($t_{\rm ion}$~ $1/\Gamma$, ~ 0.1Myr at 4 pMpc)

$$\Gamma n_{\rm HI} = \alpha n^2$$

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In ionization equilibrium ($t_{\rm ion} \sim 1/\Gamma$, ~ 0.1Myr at 4 pMpc)

$$\boxed{\Gamma} n_{\rm HI} = \boxed{\alpha} n^2$$

ionization rate $\Gamma \propto r^{-2}$

recombination rate α: weak function of temperature,
and $T - \rho$ relation right after reionization is very flat

Recover Density Field

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In ionization equilibrium ($t_{\rm ion}\sim 1/\Gamma$, ~ 0.1Myr at 4 pMpc)

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$n_{\rm HI} \propto \tau$ (observable)

Recover Density Field

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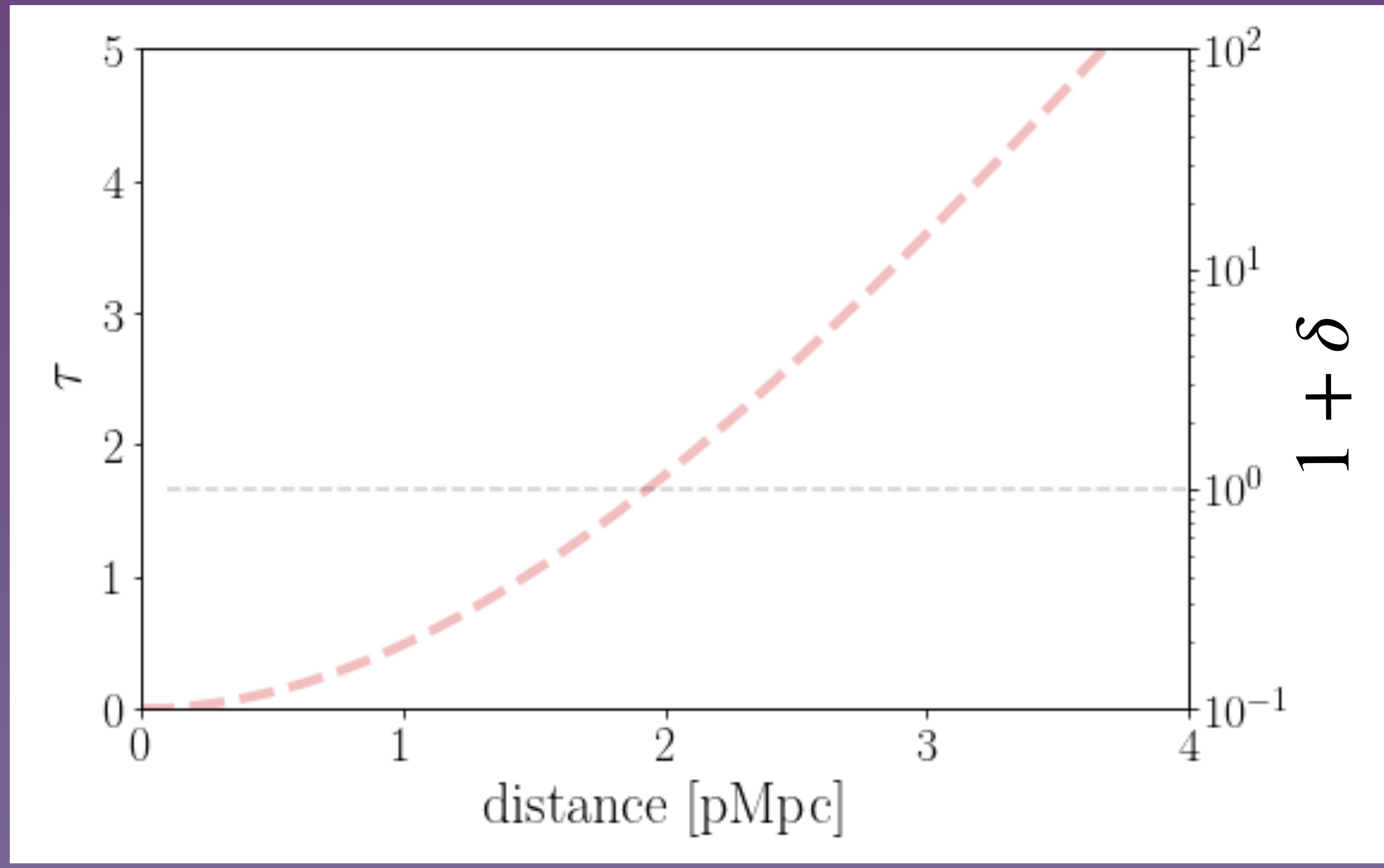

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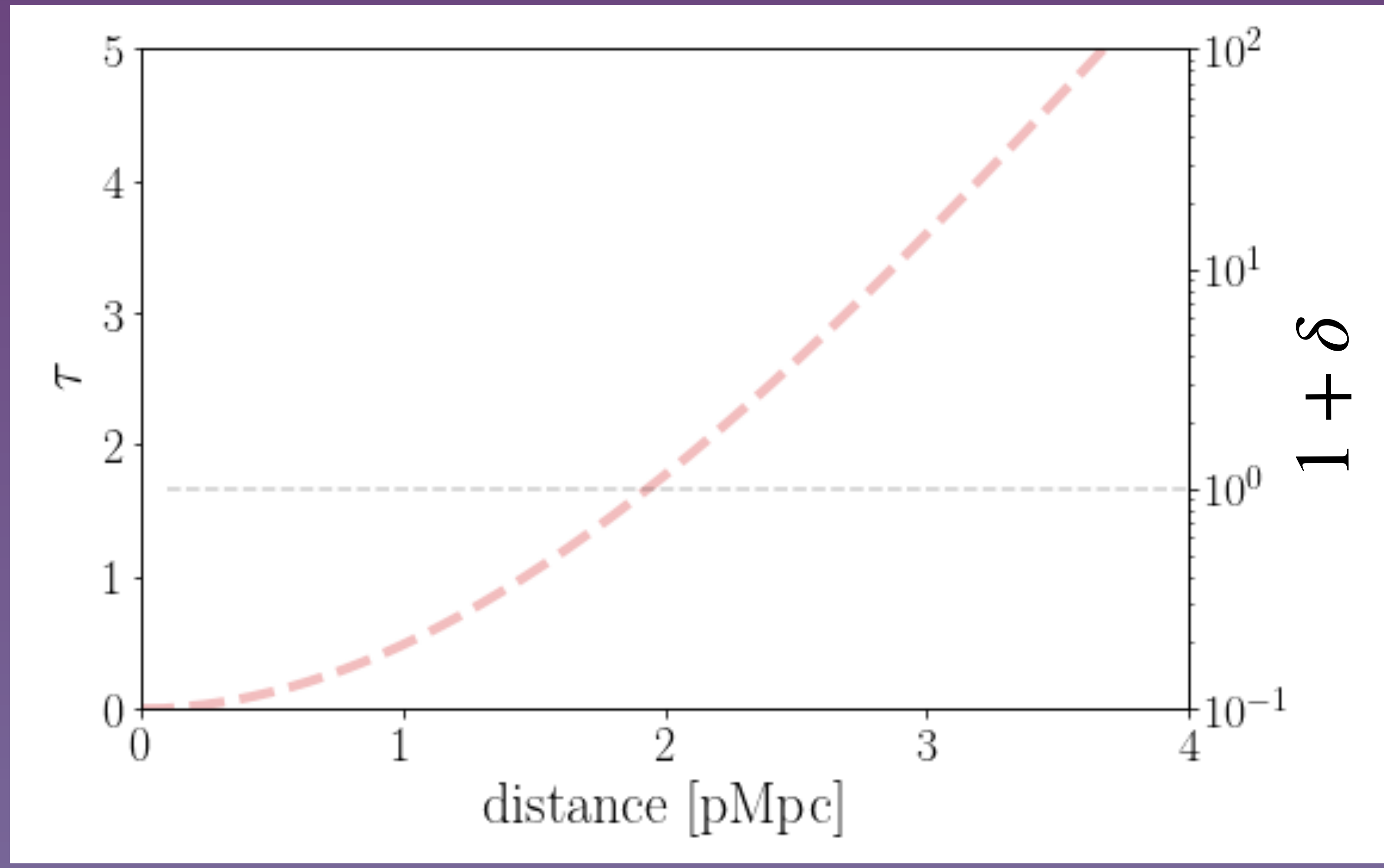

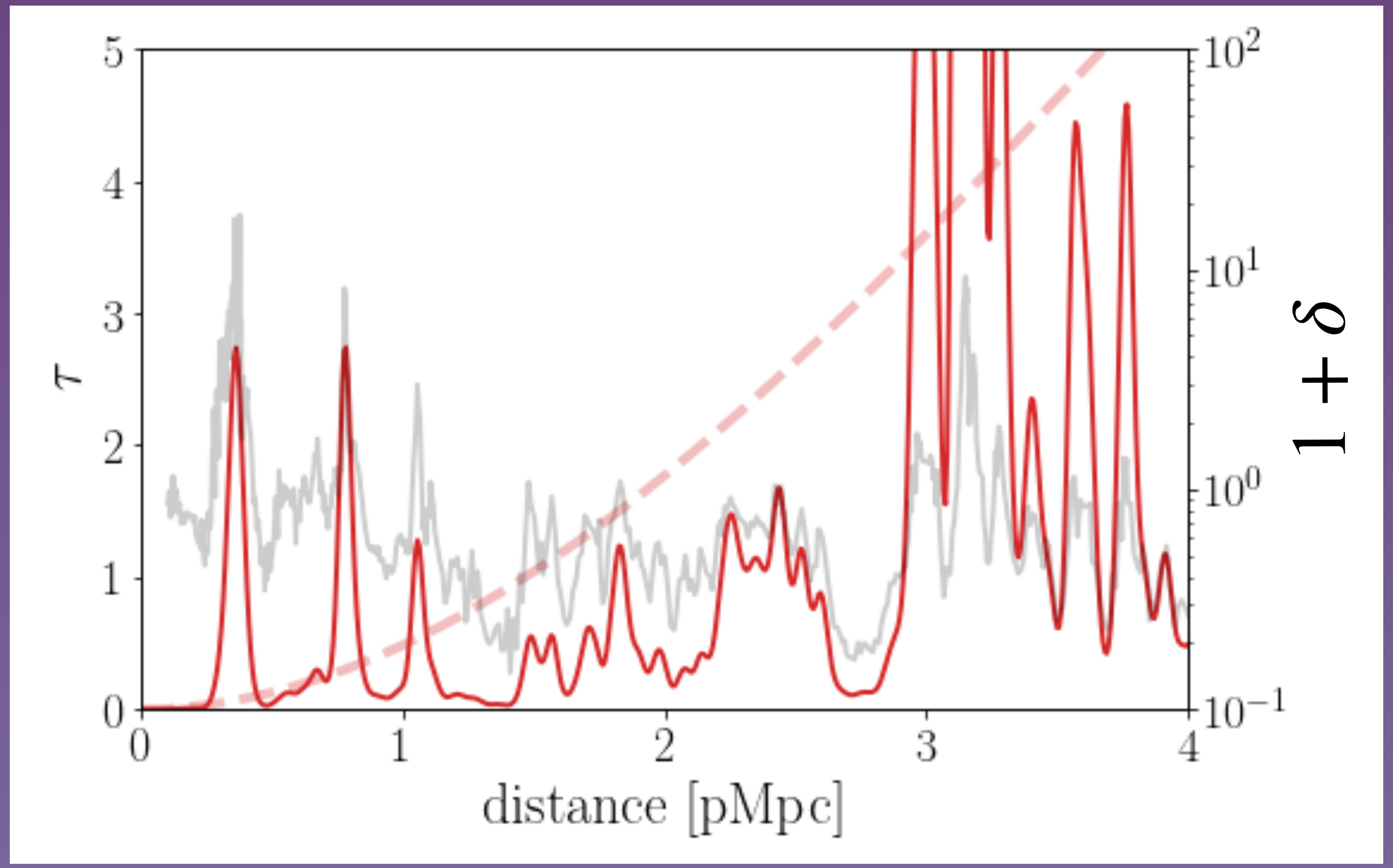

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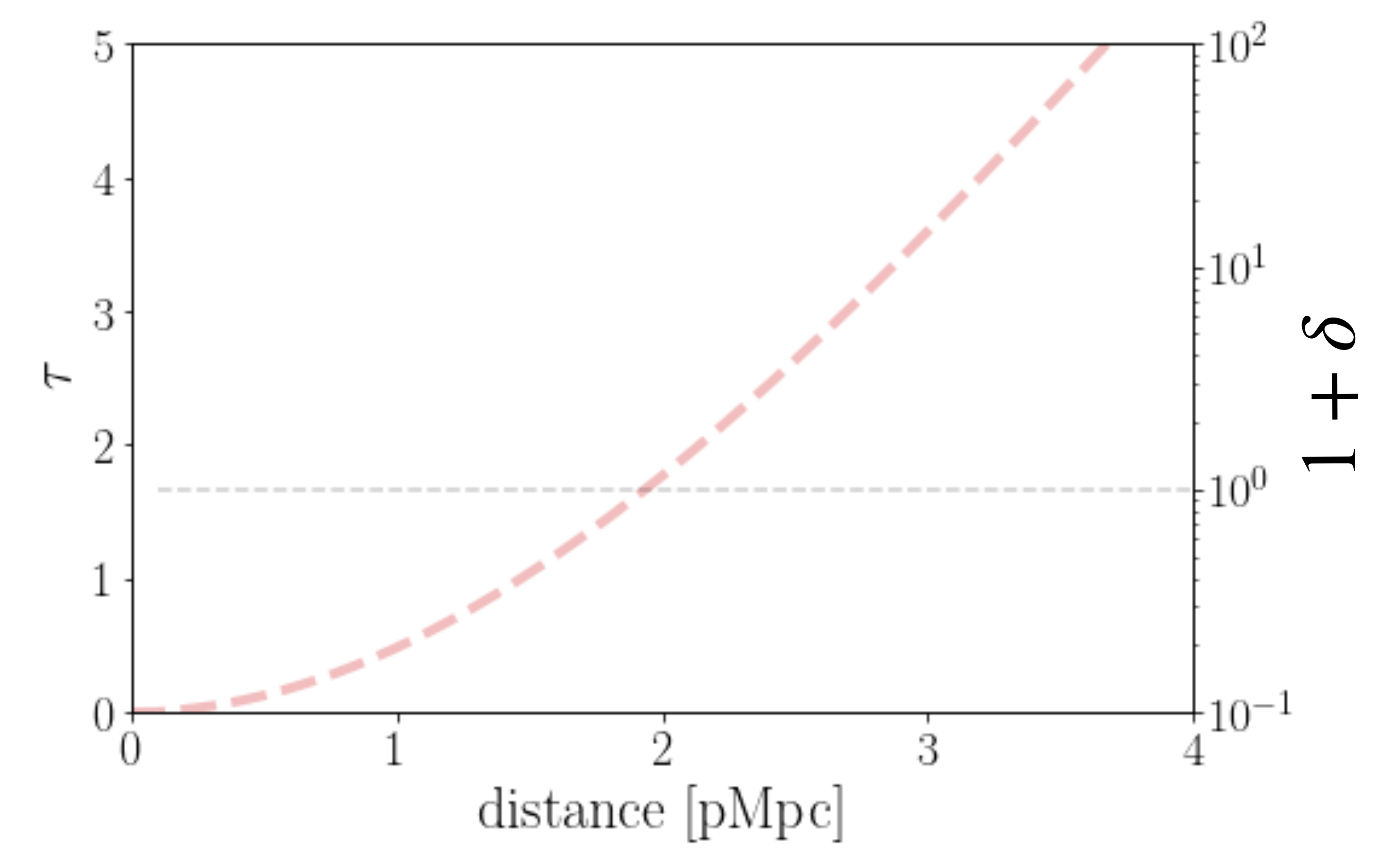
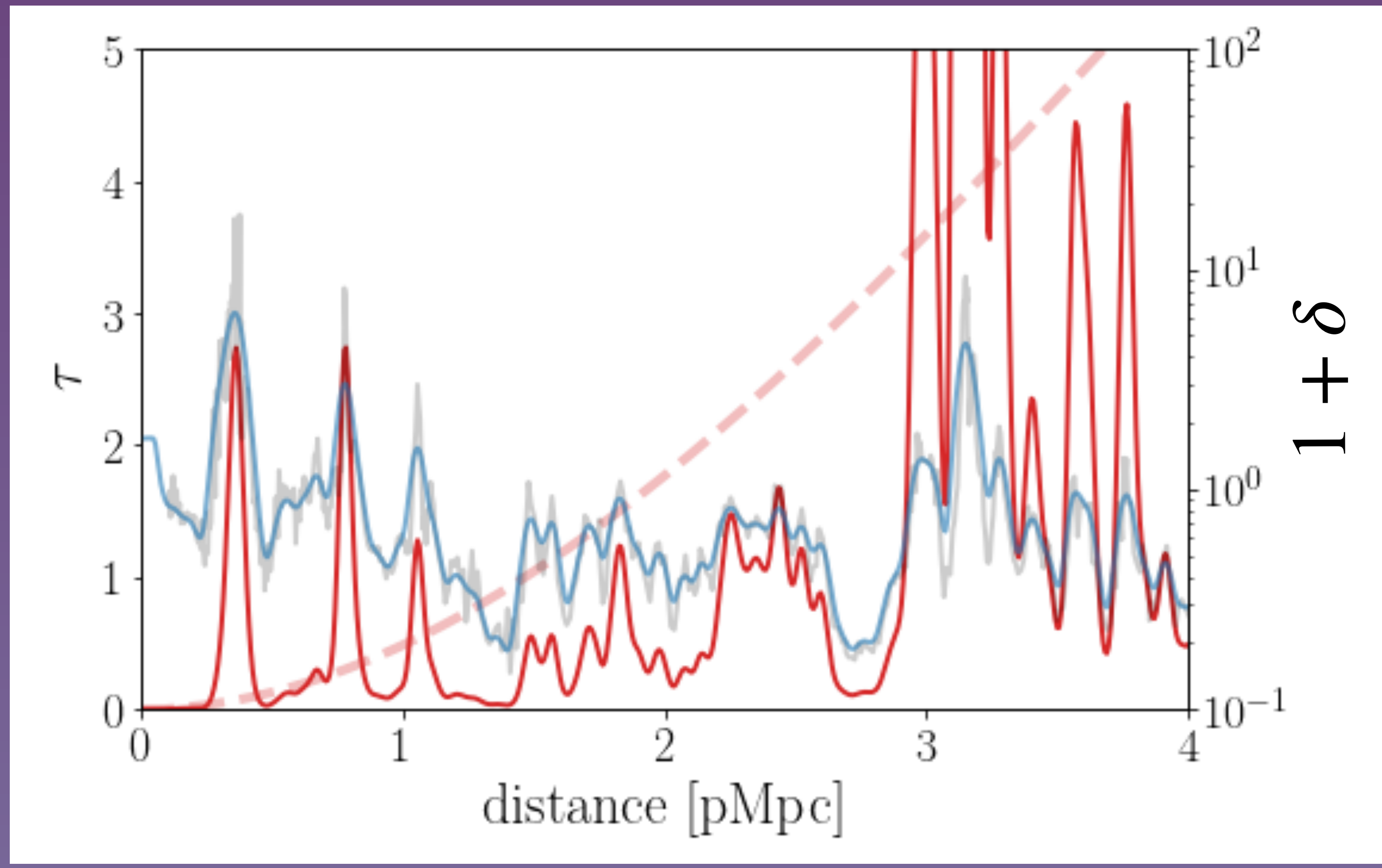
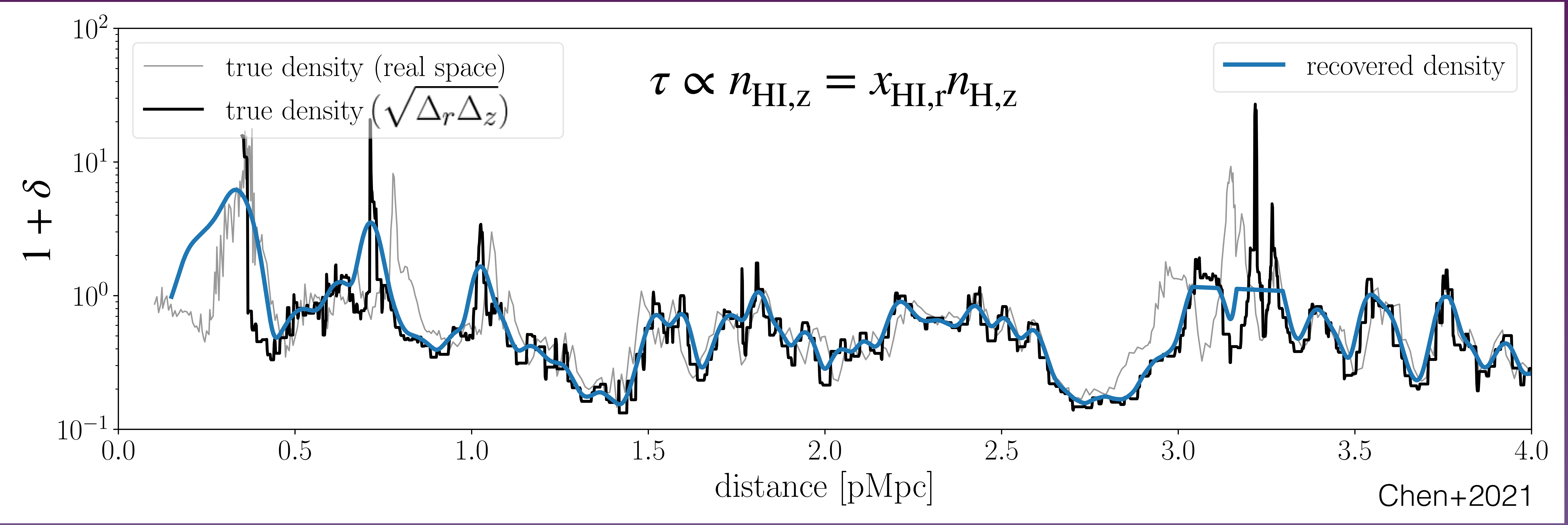




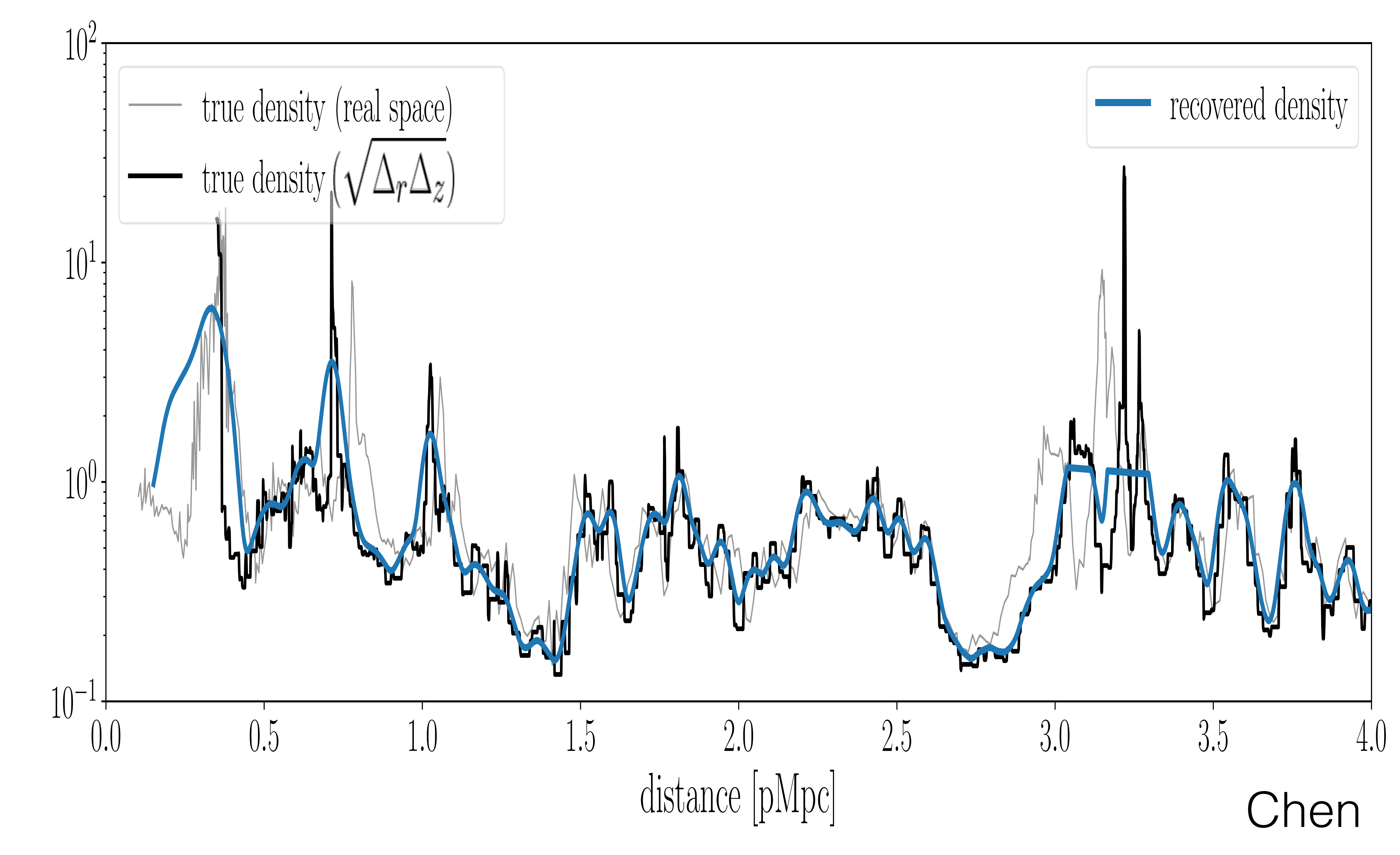
Recovery Result

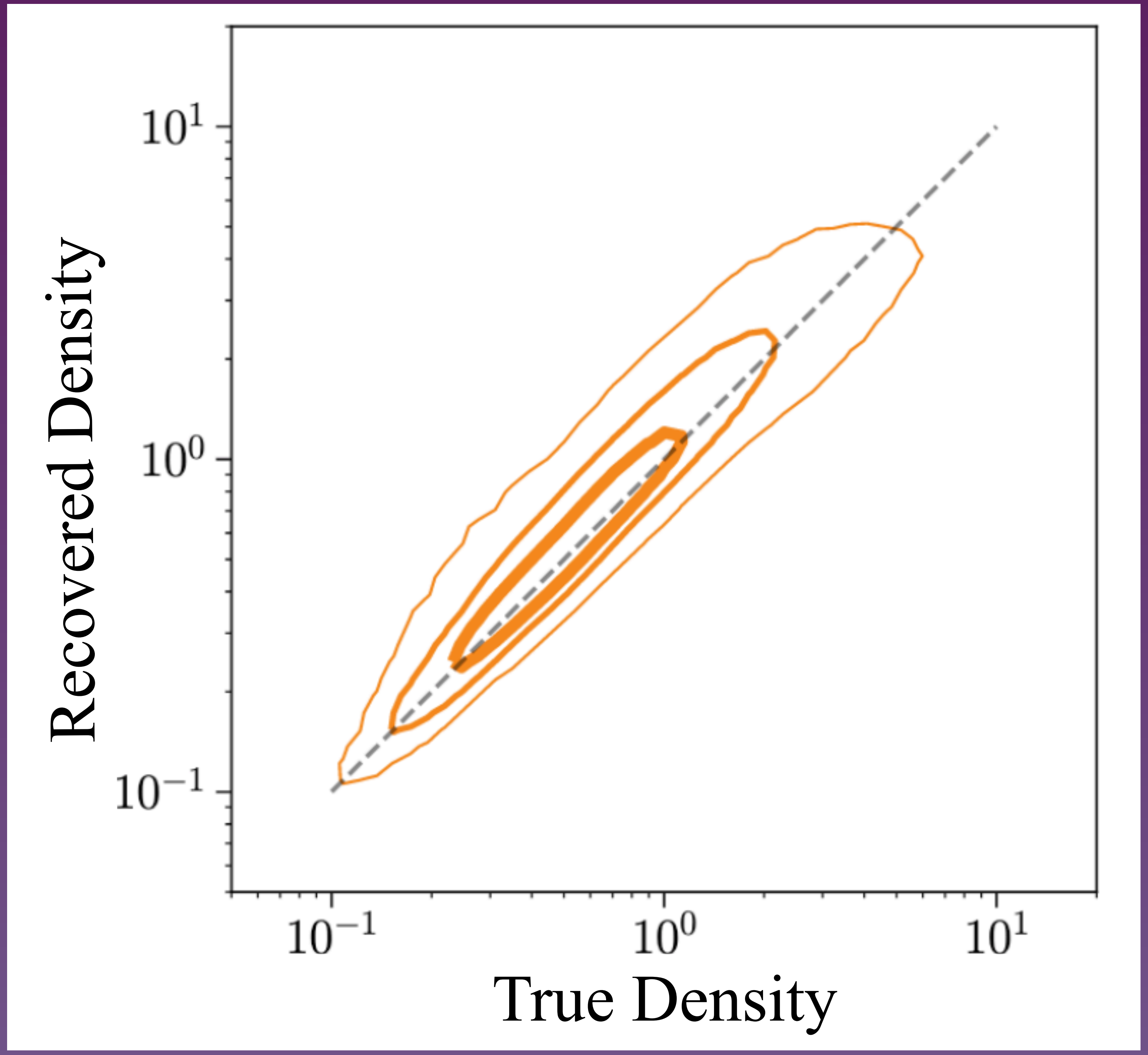


- Recover the smoothed, “redshift-space”-like density $\sqrt{\Delta_r \Delta_z}$
- Sensitive to gas density around the cosmic mean

Check out Chen&Gnedin 2021 ApJ 916,118 for more details!

Recovery Result





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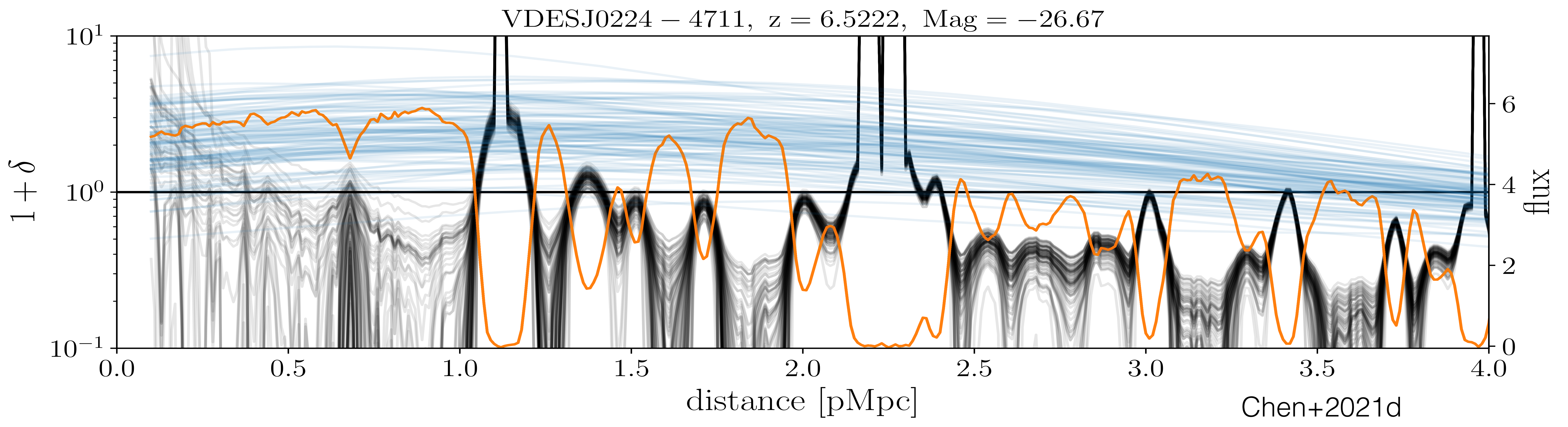
Apply to Observed Spectra

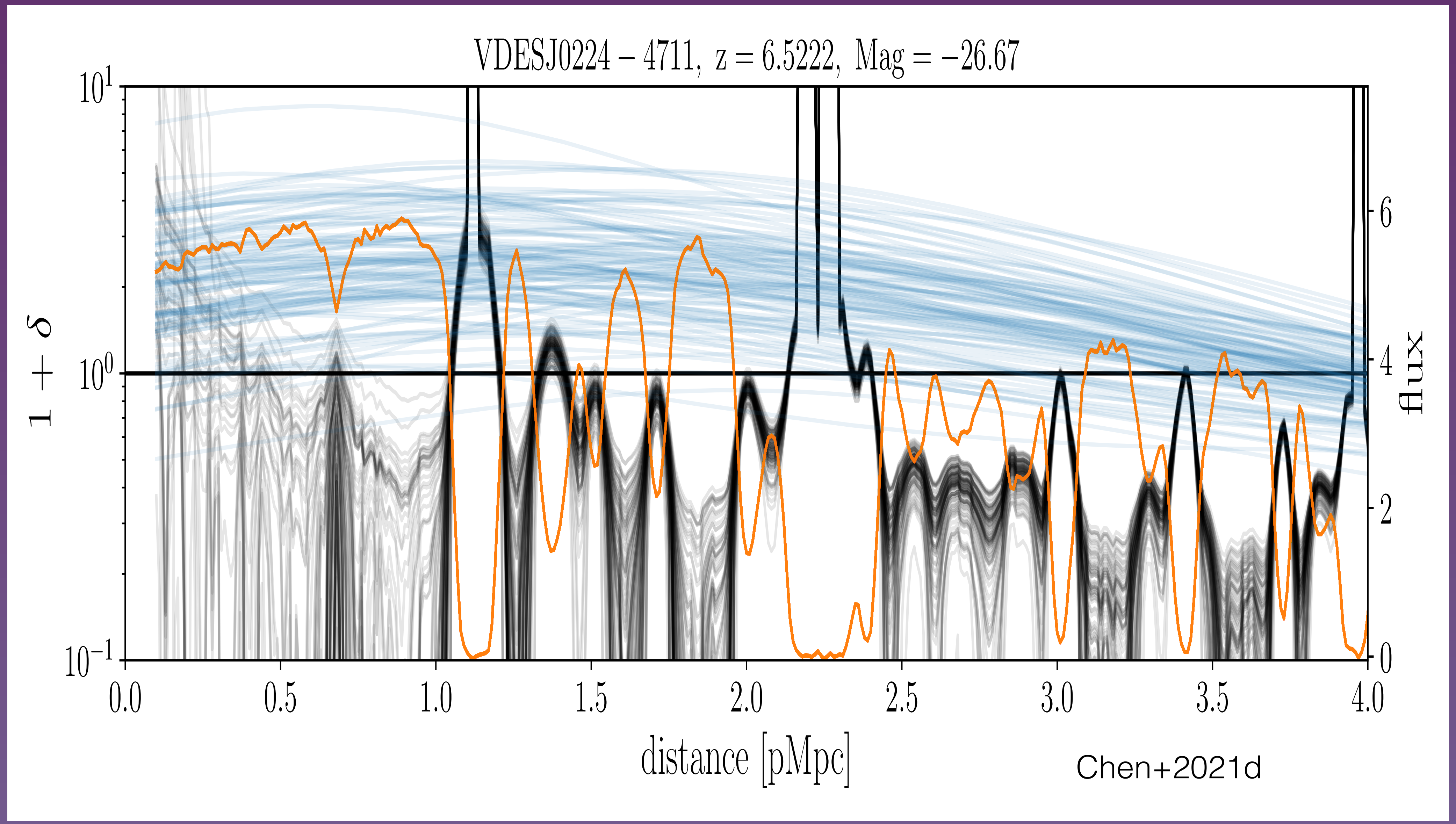
(XSHOOTER/VLT) XQR-30 Survey:

- bright quasars at z~6
- Spectra resolution R> 10,000 (FWHM < 30 km/s)
- SNR>50
- sub-mm QSO redshift measurement

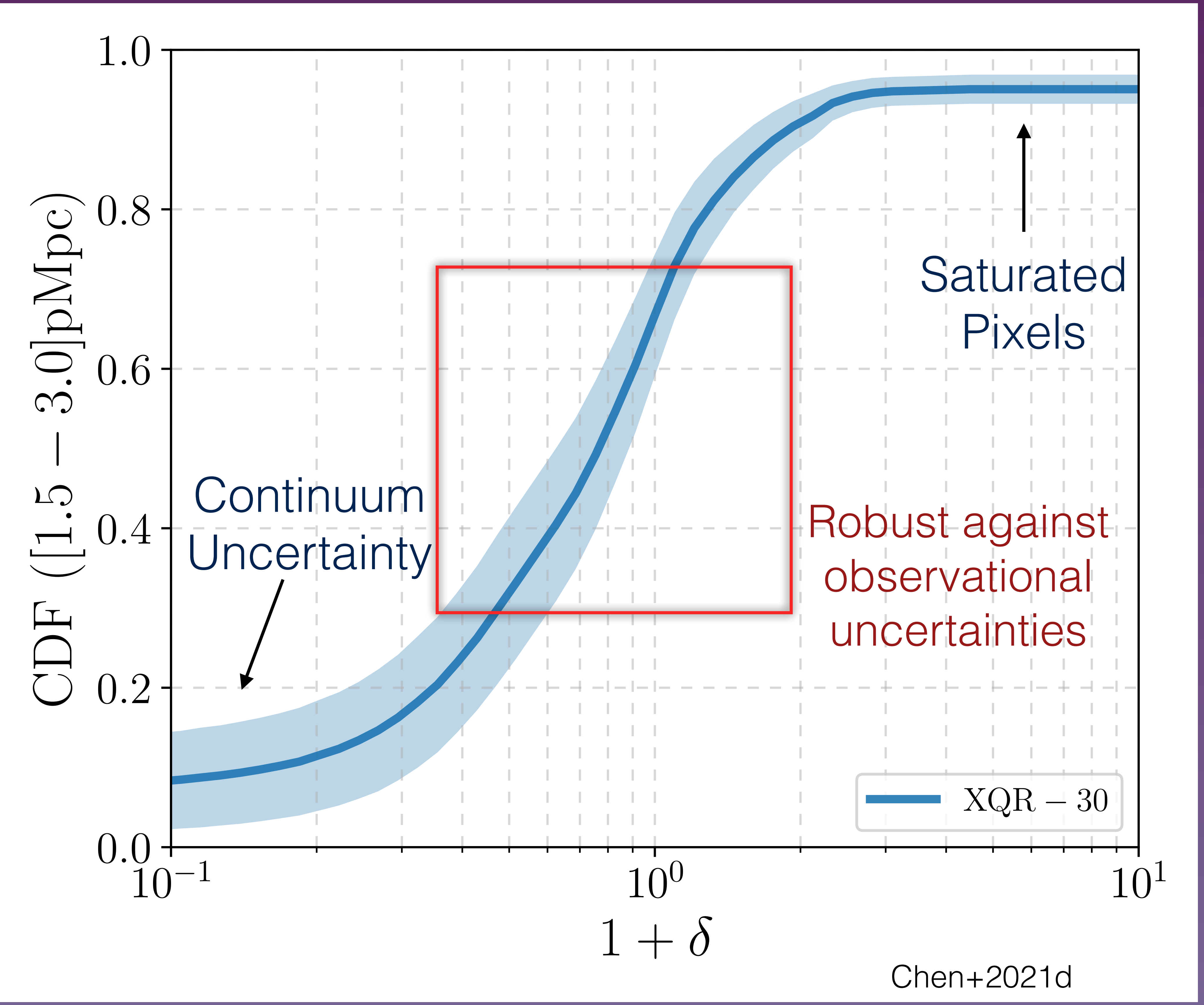


Chen+2021d

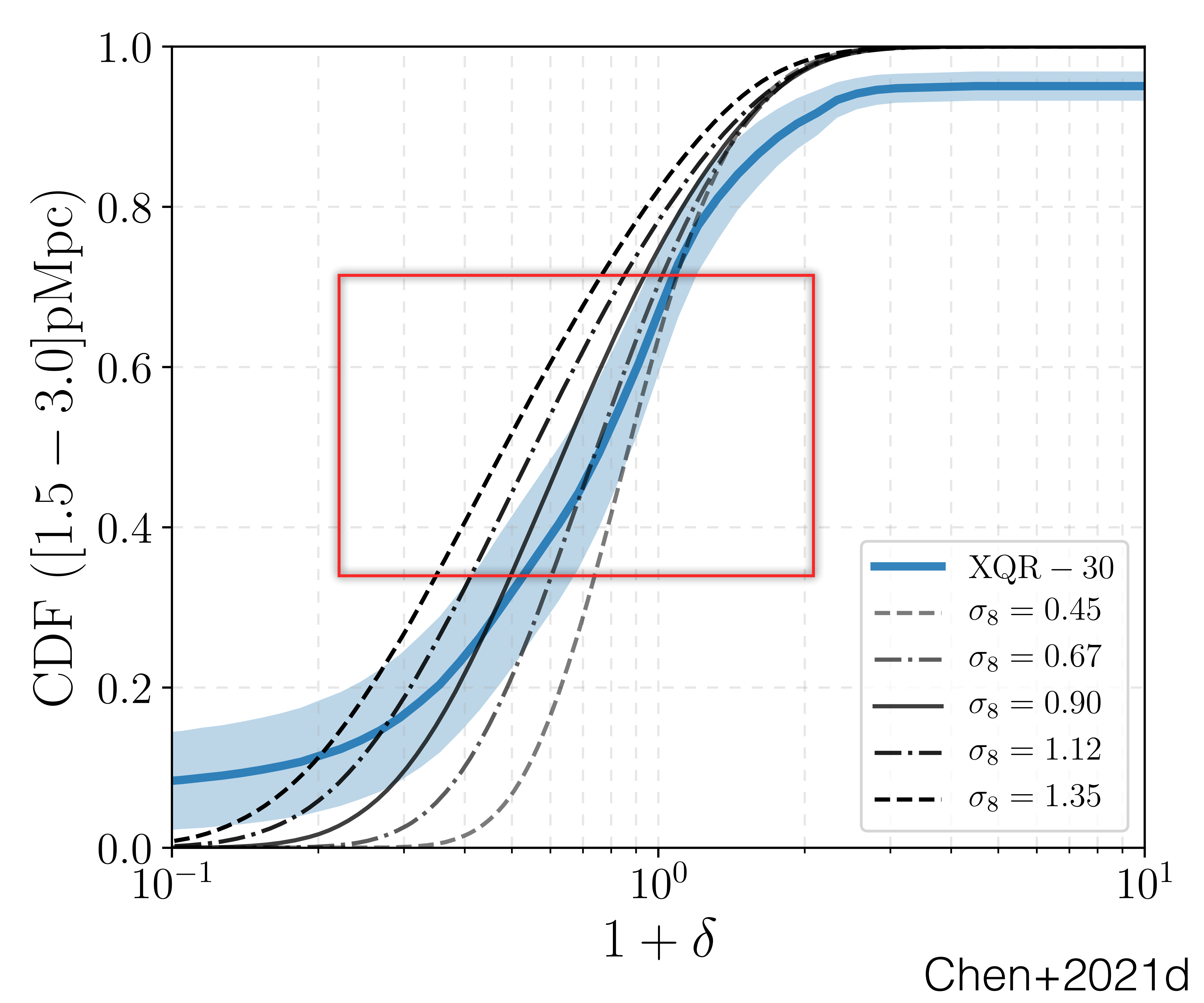
Density Cumulative Distribution Function (CDF)



CDF for 10 sightlines



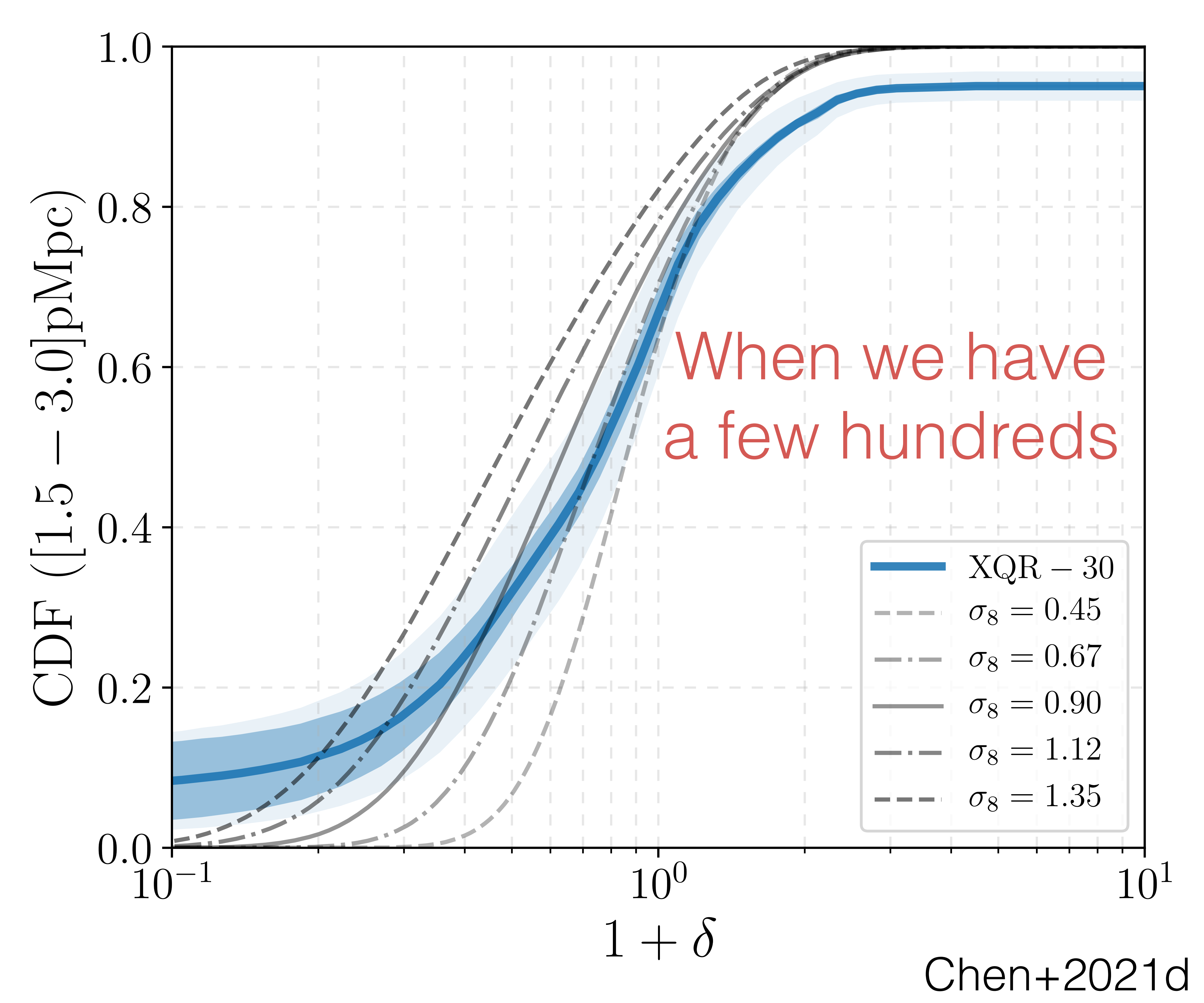
Application to Cosmology



With the current 10 quasars, we obtain a constrain on $\sigma_8 = 0.6 \pm 0.3$

With hundreds of bright quasars at z~6, we can significantly tighten the constraint.

Application to Cosmology



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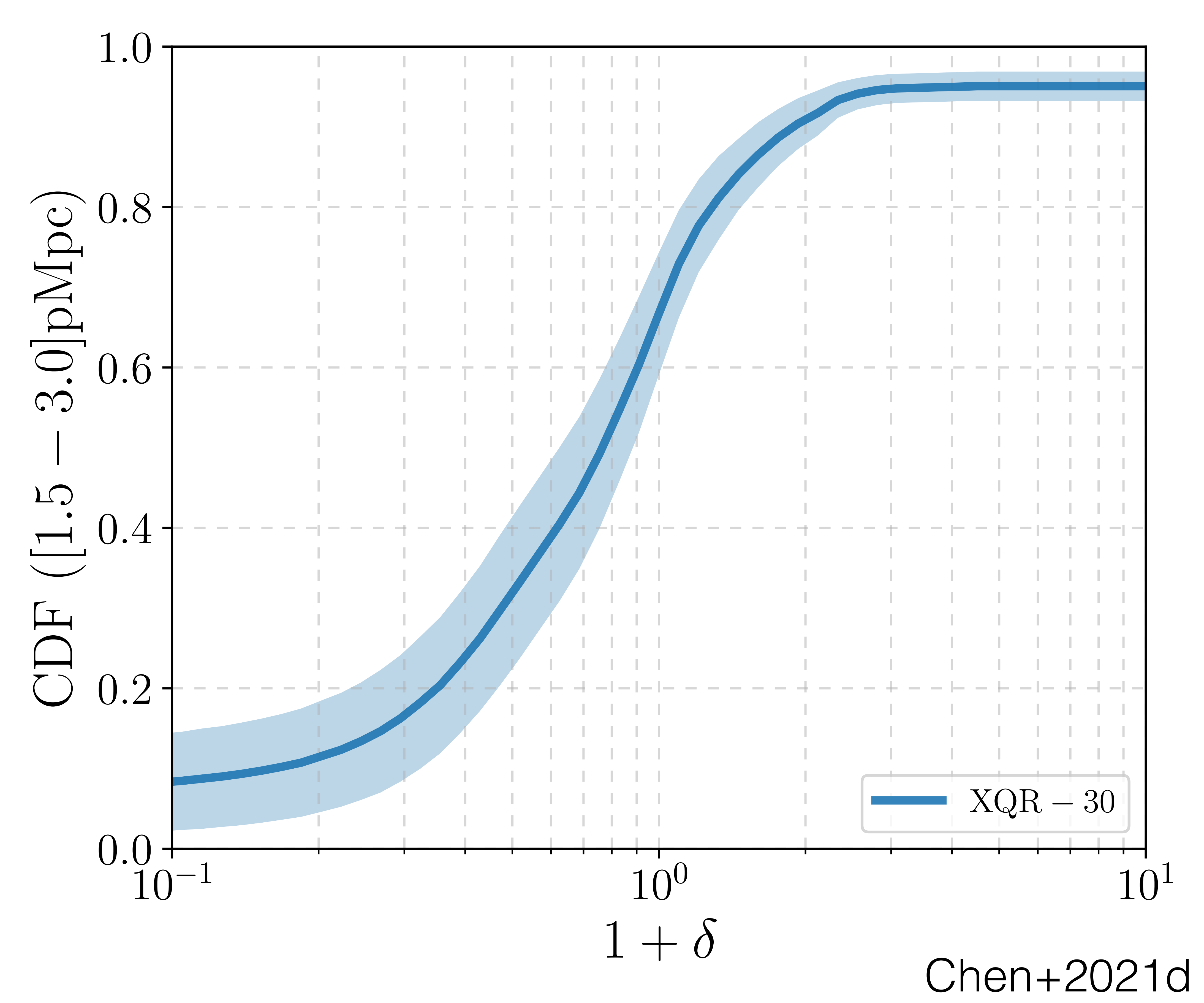
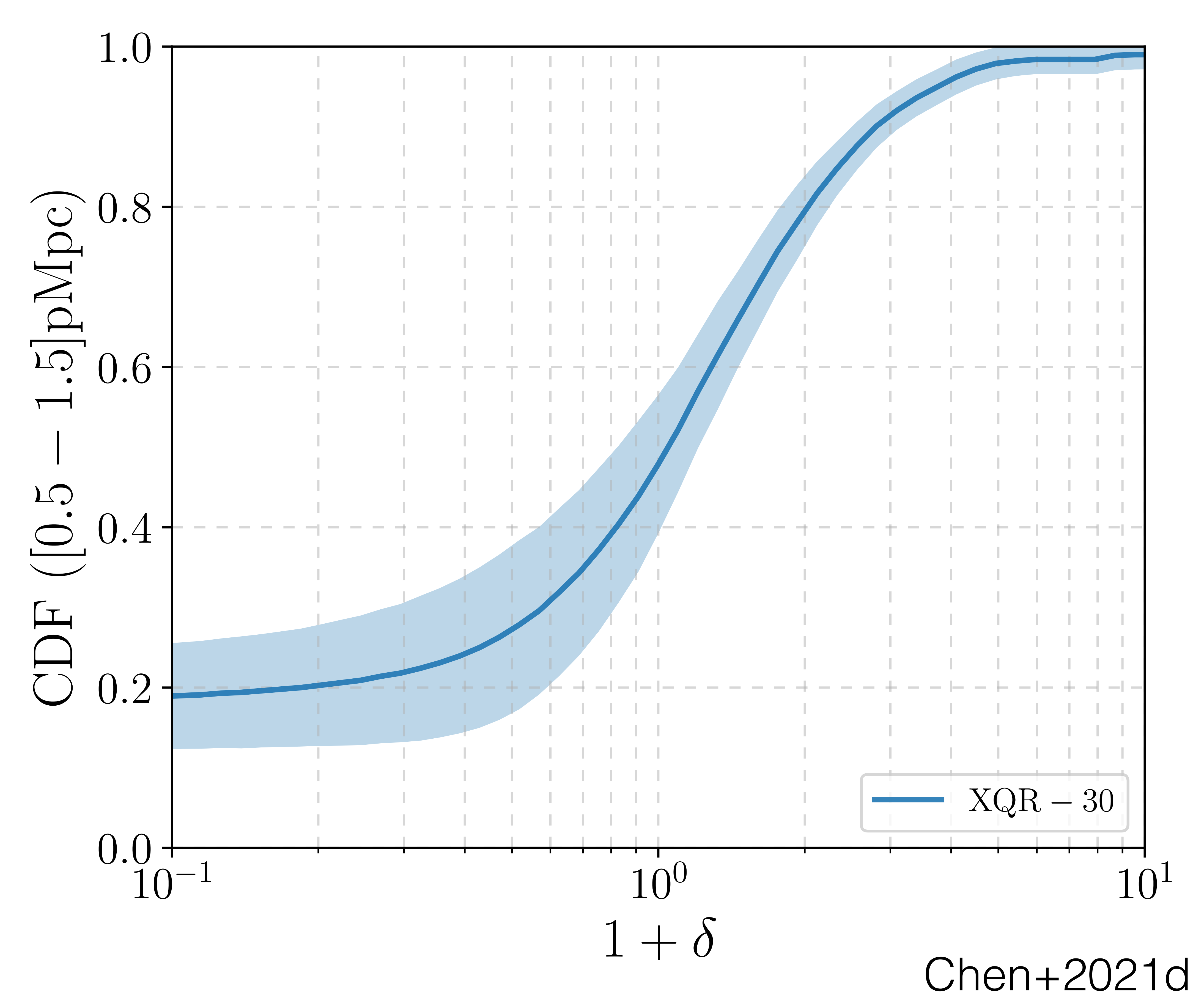
Application to Quasar Formation Model

Outer Region



Application to Quasar Formation Model

Inner Region



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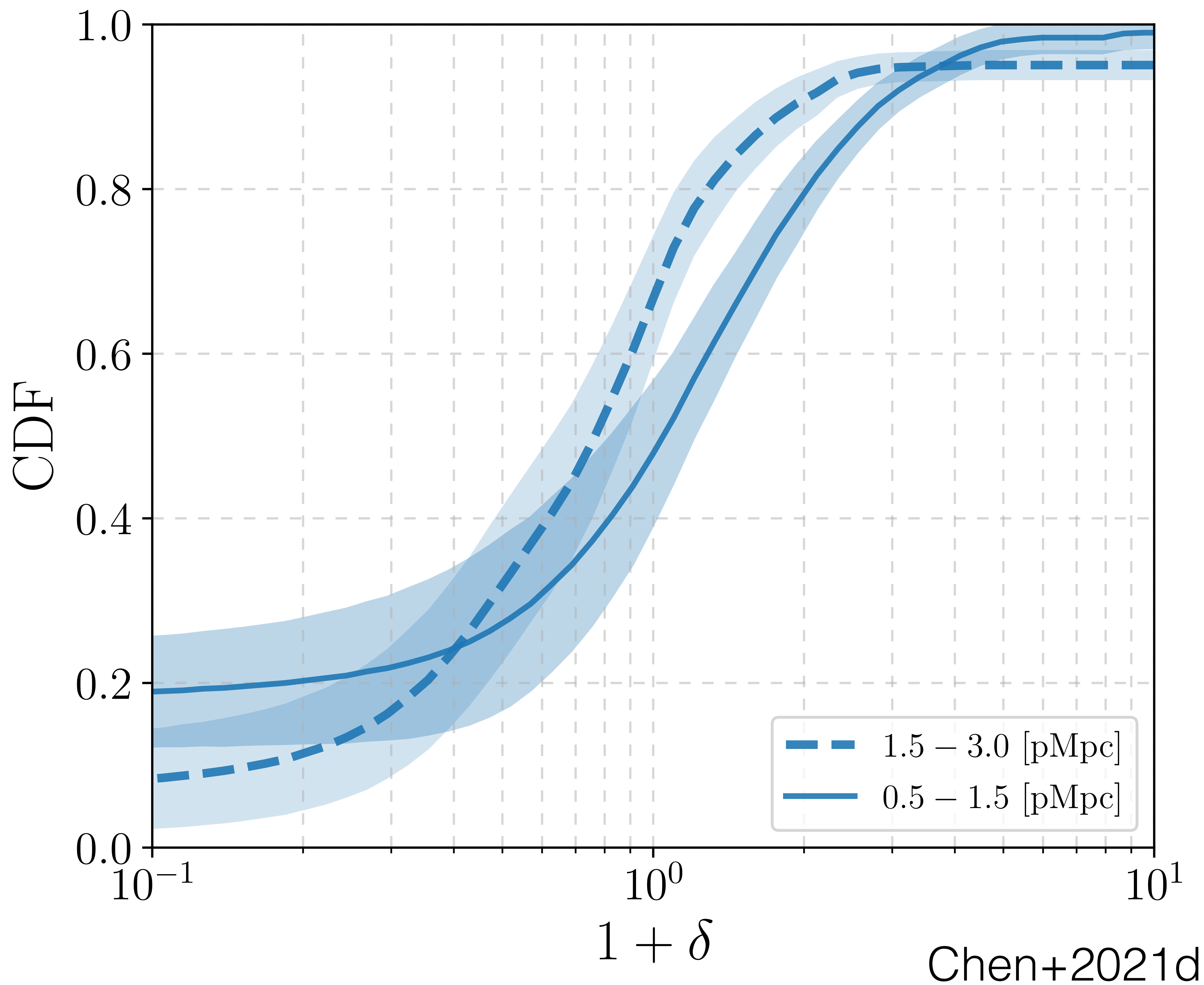

Chen+2021d

Closer to the quasar, the CDF shifts towards higher density.

Using the shift in the CDF, we constrain the typical mass of the quasar host halos $\log_{10} M_h = 12.5^{+0.4}_{-0.7}$.

Check out arXiv:2110.13917 for more details!

Quick Summary 1/2: Recover Density

- We can measure the density field in quasar PZ at z~6
- Sensitive to $\Delta < 10$, scatter of ~ 10%
- We applied this method to observed quasars and obtained the CDF
- The deviation of the recovered density CDF from the "true" one encodes information of quasar (environment, age, etc.)

Quasar Proximity Zone as a Unique Lab

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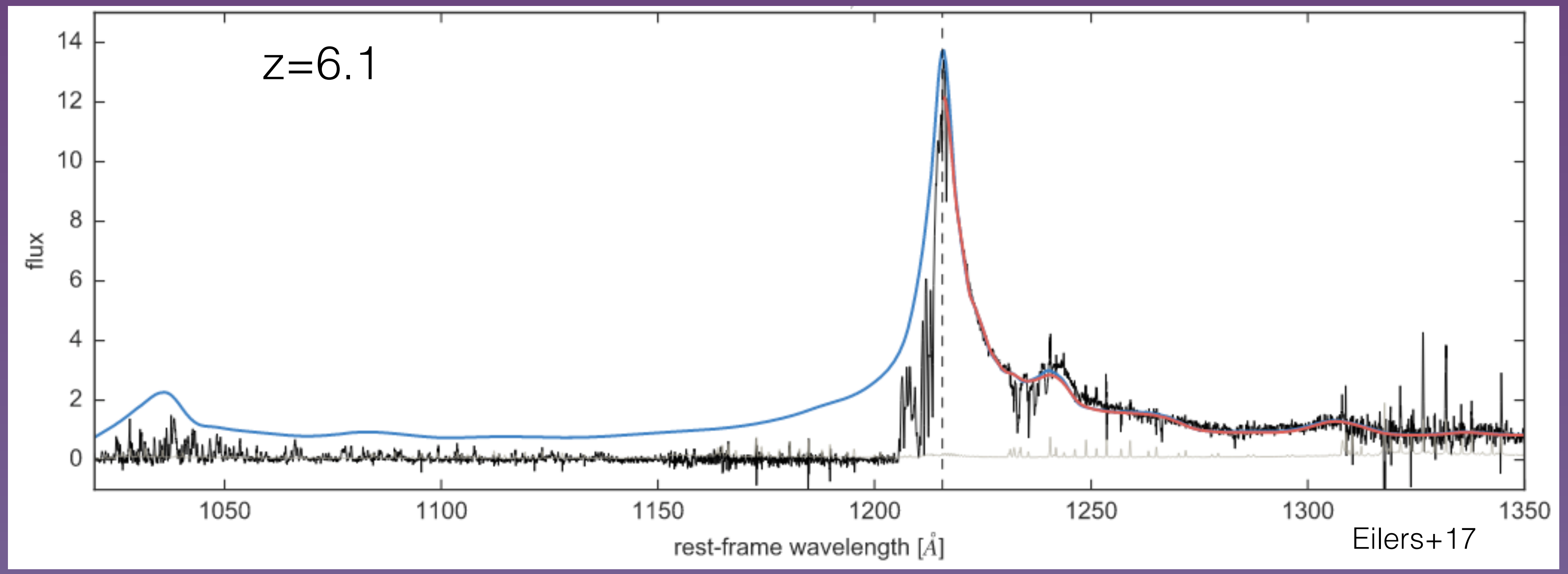
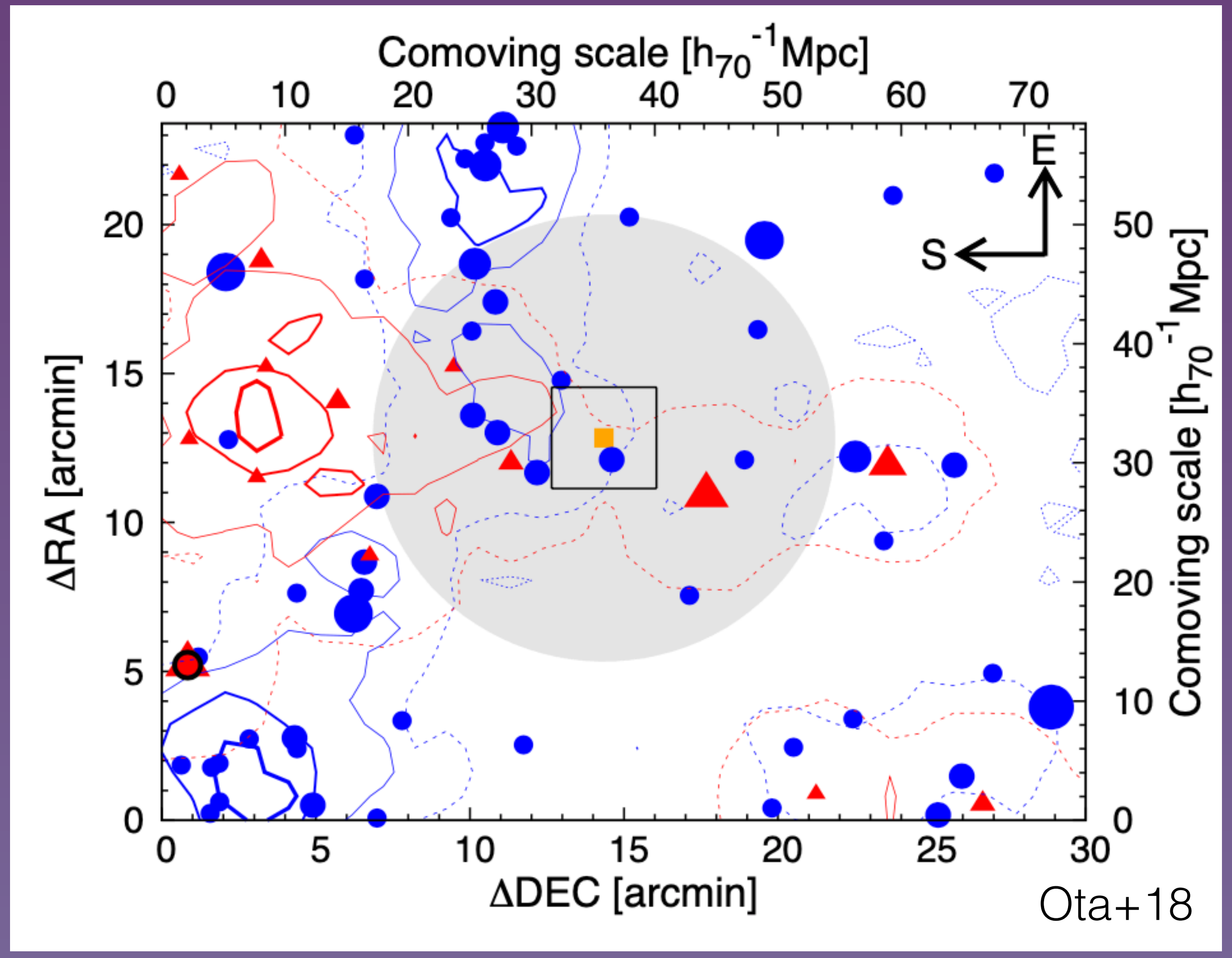
- Overdense region? Likely trace "proto-clusters", favorable target for JWST



Quasar radiative feedback mimics reionization: **Study the quasar field!**

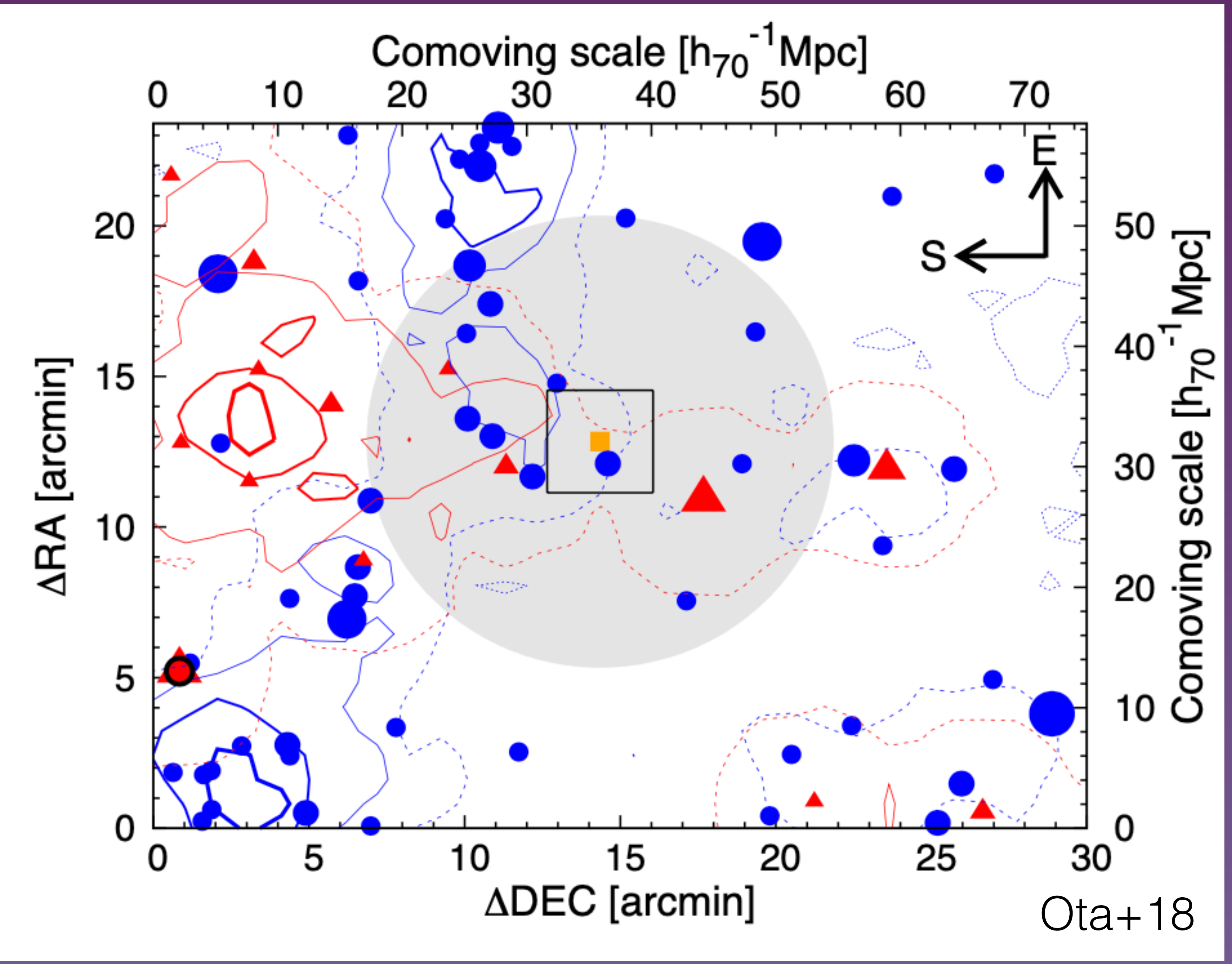


Imaging the Quasar Fields

Motivation to study galaxies in quasar fields:

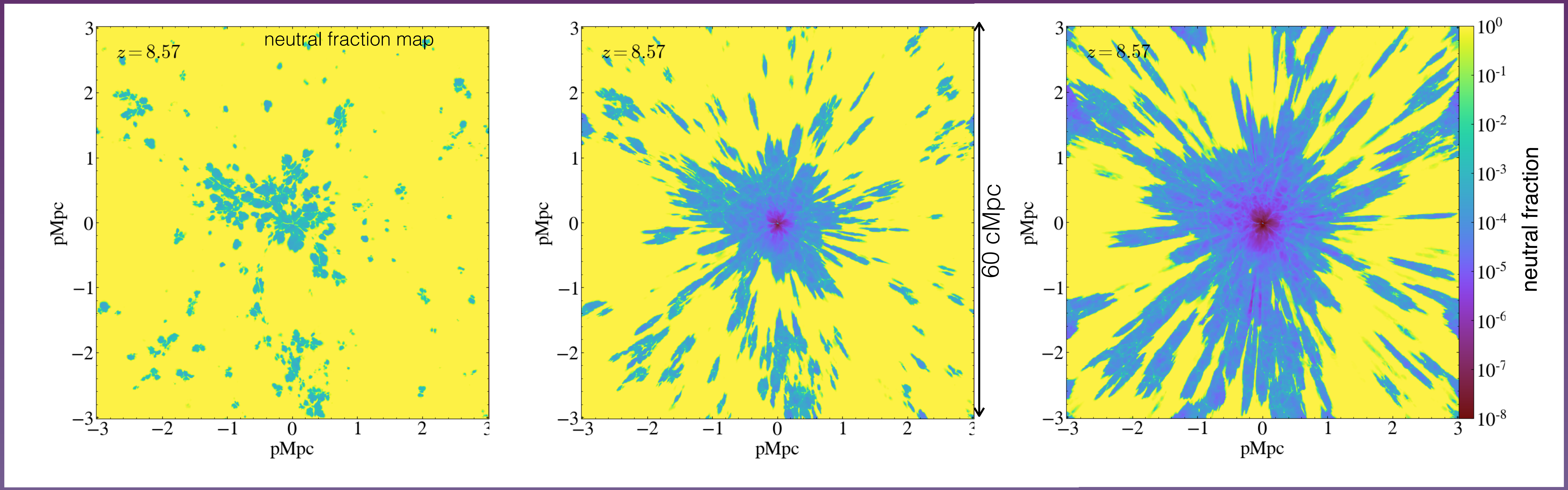
- Galaxies trace matter distribution (another way to construct density field, constrain the environment of first quasars)

- Study how galaxies form in strong radiation field — an alternative way to constrain reionization effect on galaxy formation



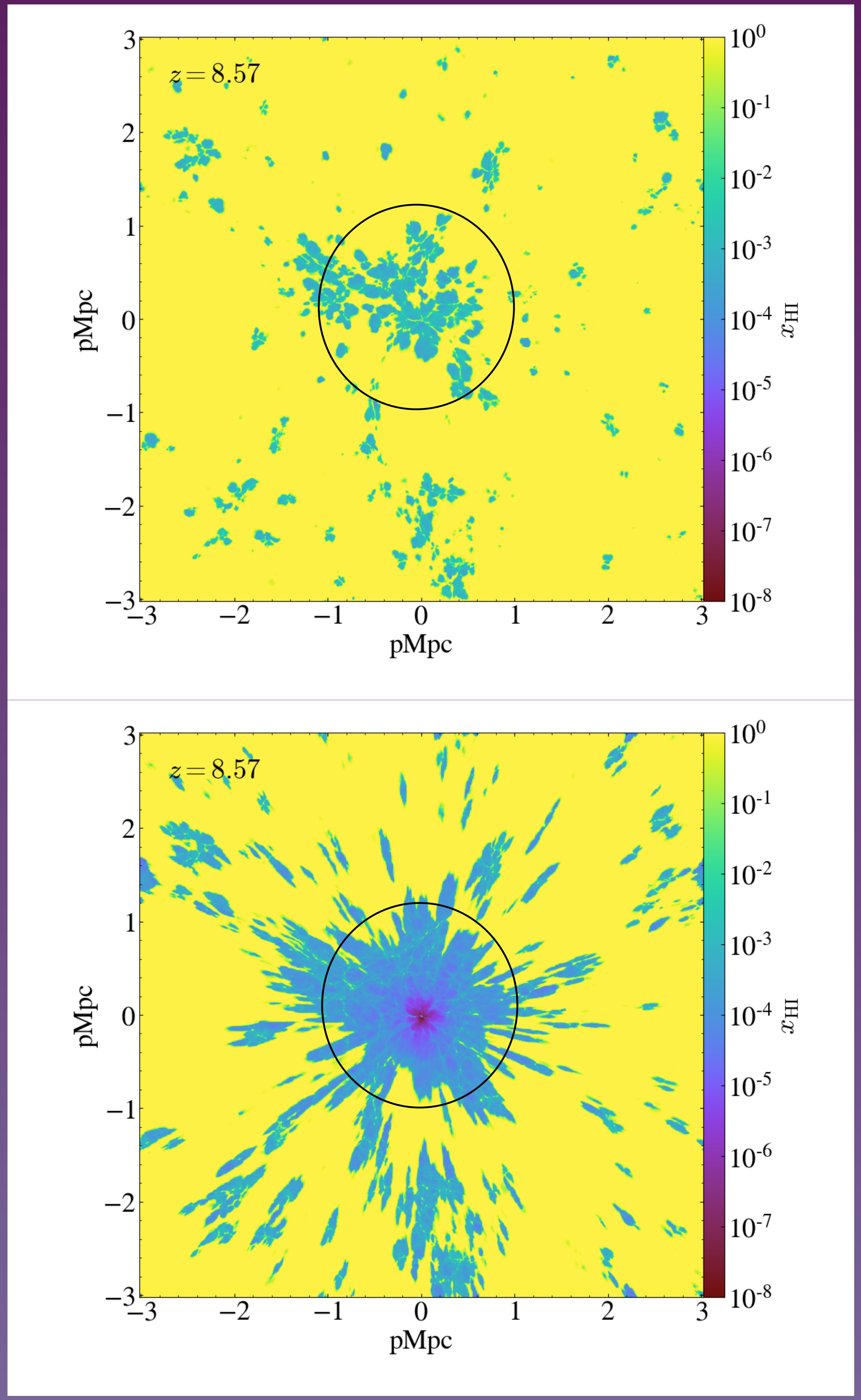
Galaxy Formation in Quasar Fields

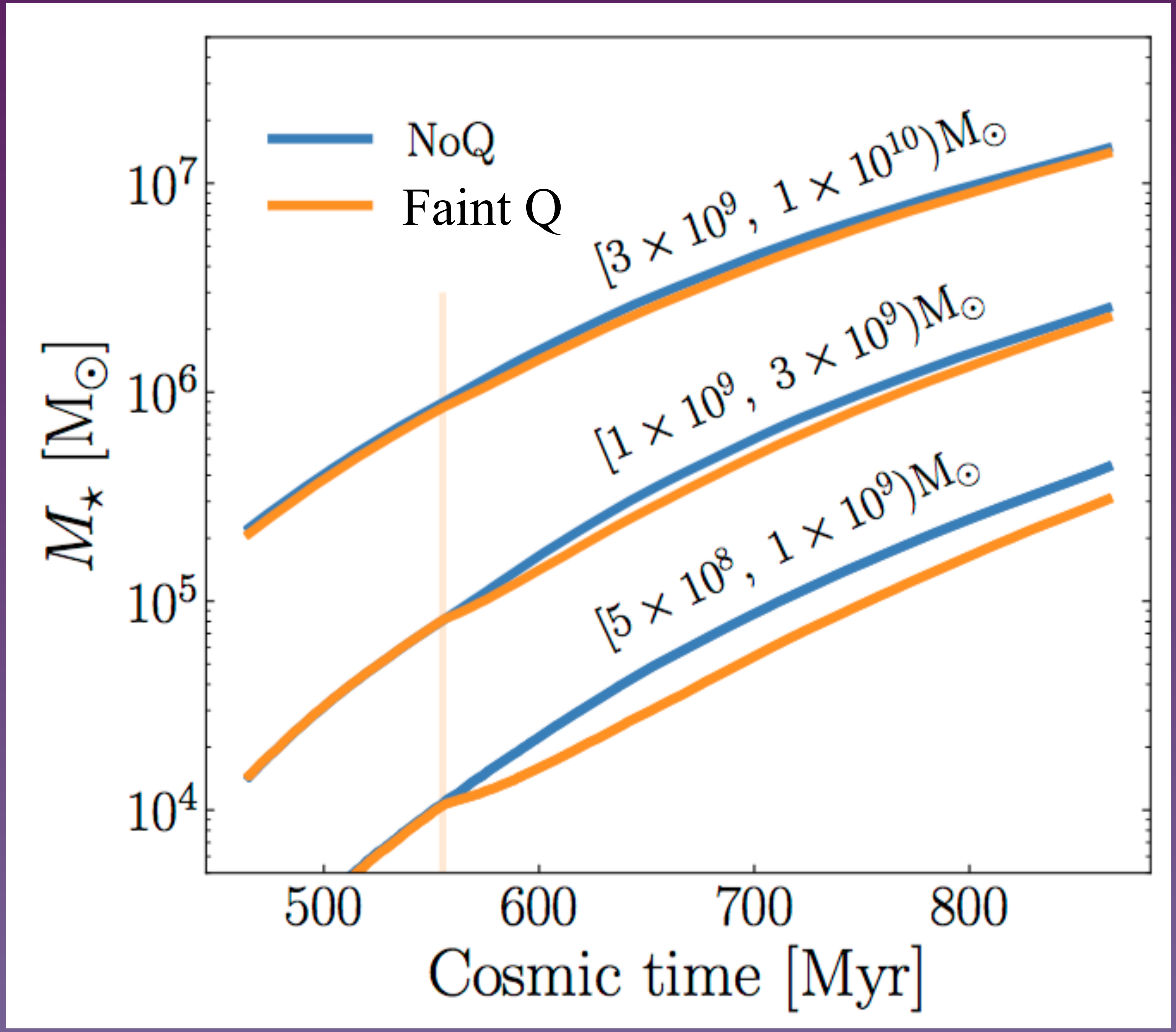
No Quasar sim (NoQ) | Faint Quasar sim | Bright Quasar sim



Chen 2020

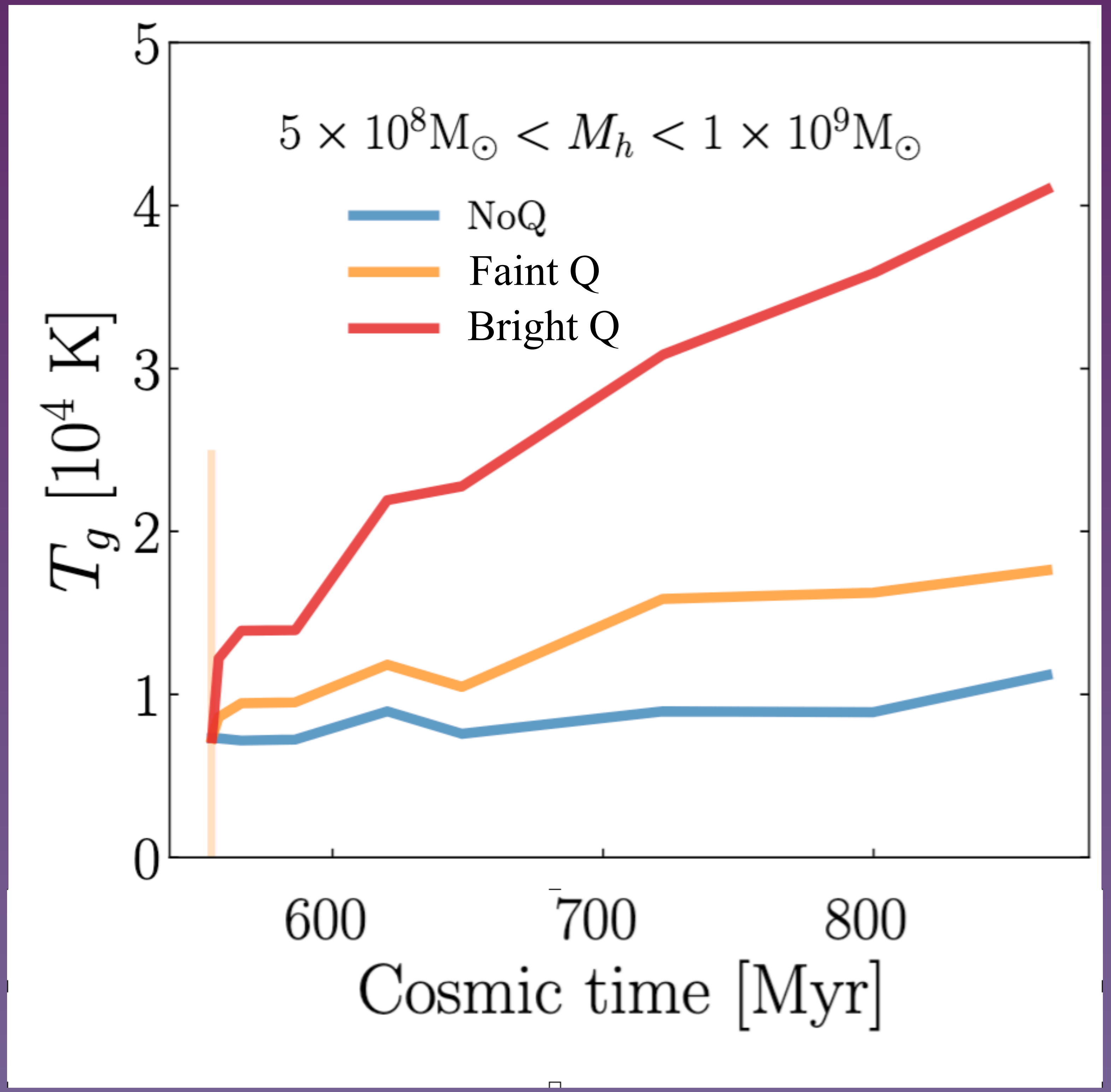
Low Mass Halo Suppressed



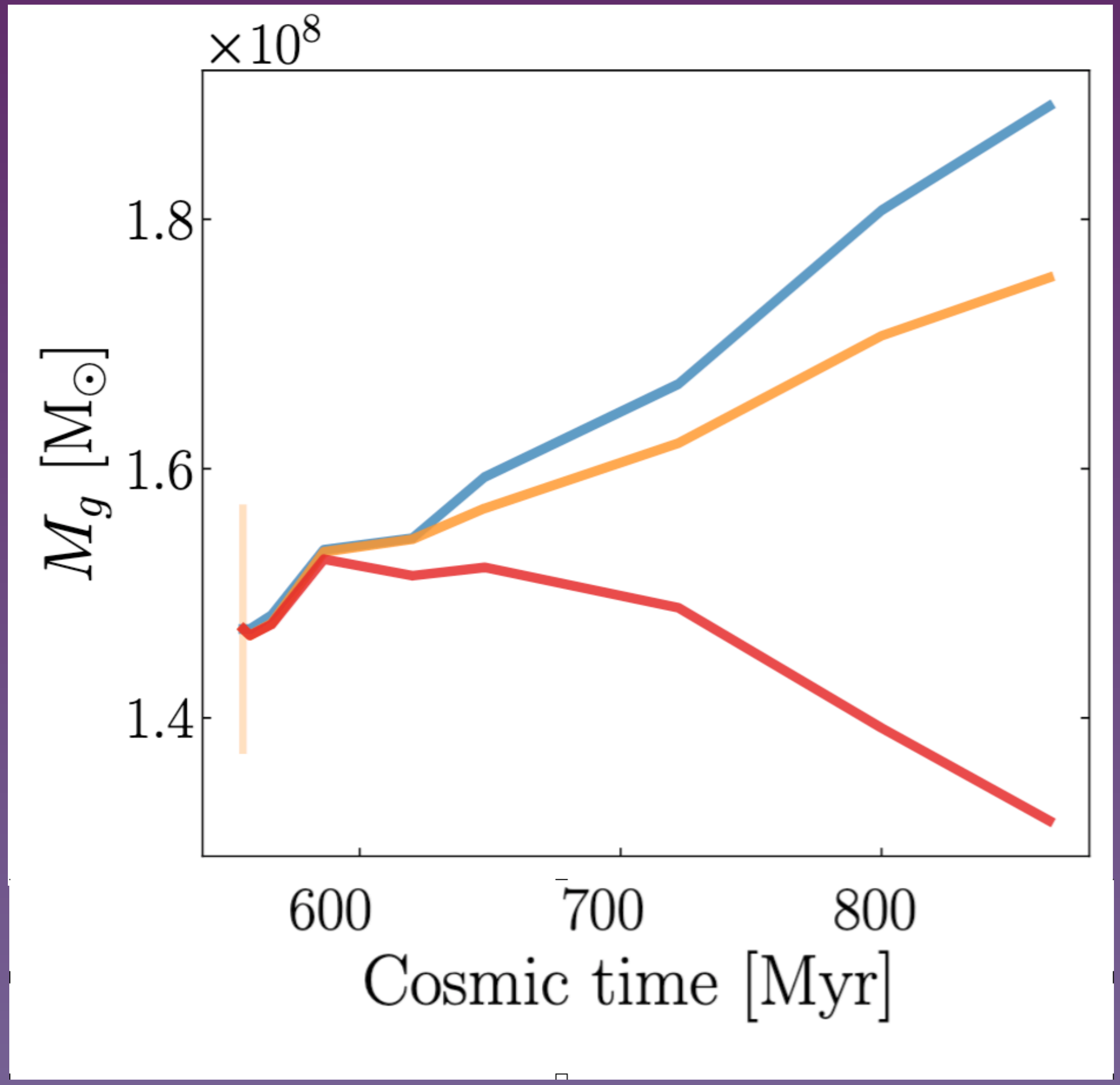


Photoheating reduces gas accreting

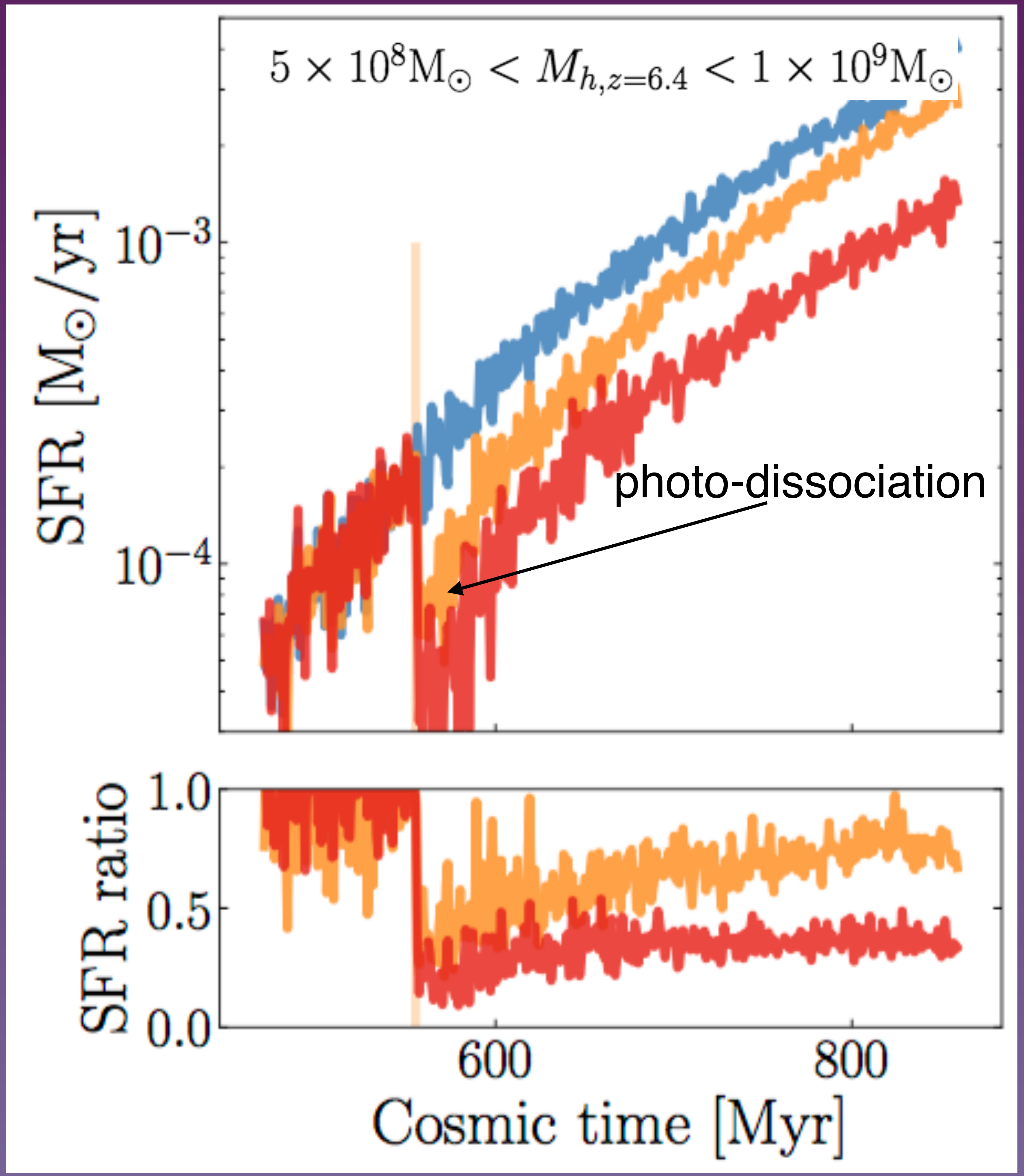
Temperature

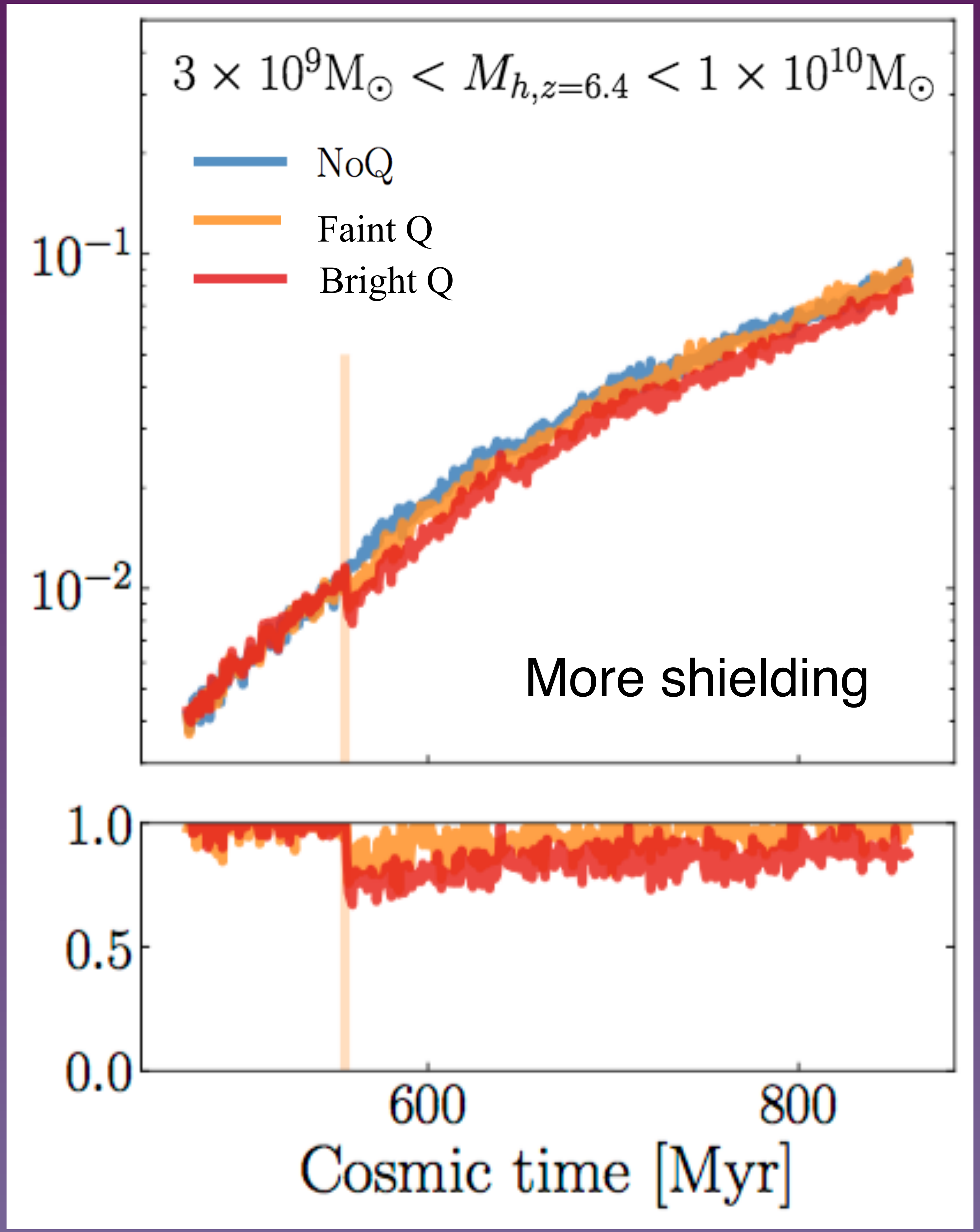


Gas Mass

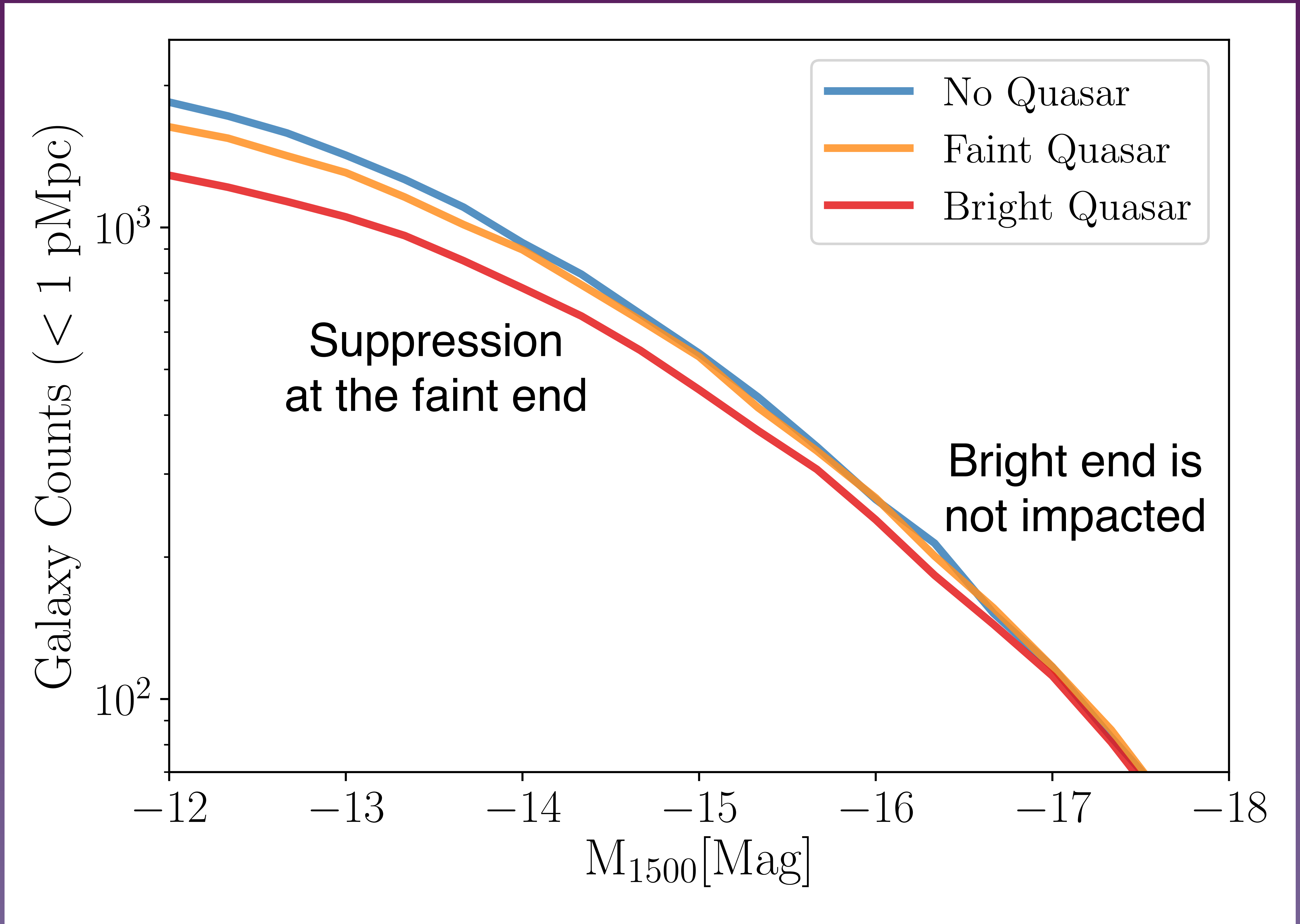


Suppression due to H_2 destruction

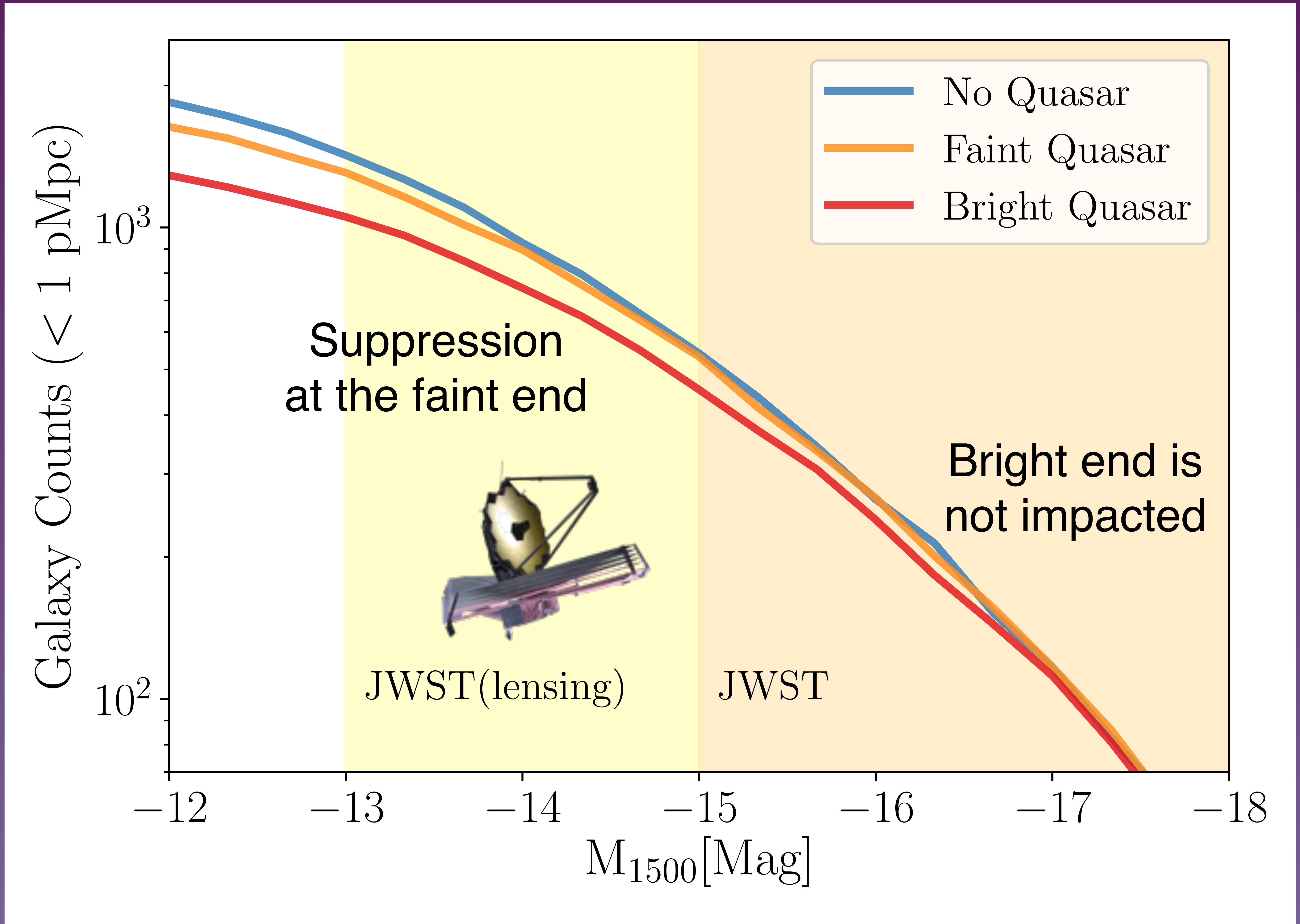




Observable: Luminosity Function



Observable: Luminosity Function



Quick Summary 2/2: Radiative Feedback

- Quasar radiative feedback suppresses star formation in low mass halos
- Photodissociation is the main suppression mechanism, happening on short timescales
- The faint end of luminosity function in quasar fields is suppressed, but the bright end is not impacted
- JWST will play an important role in understanding the quasar-galaxy co-evolution

Check out Chen2020 ApJ 893,165 for more details!

Future Prospect

- James Webb Space Telescope:

  Reionization is one of the primary scientific goals

  GTOs target dozens of $z \gtrsim 6$ quasars !

- Large ground-based telescopes:

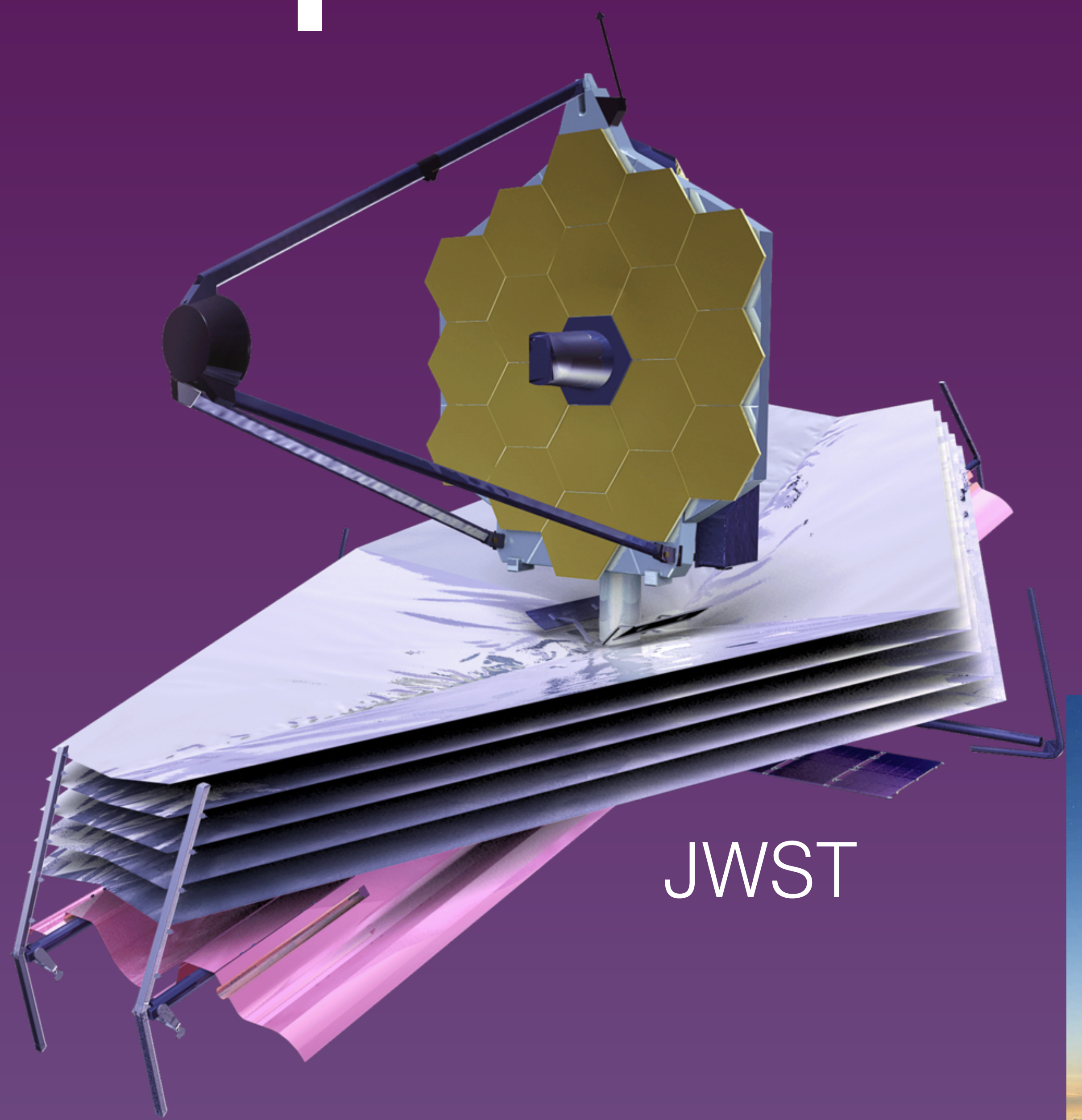
  Current telescopes Keck, VLT etc: R>10,000

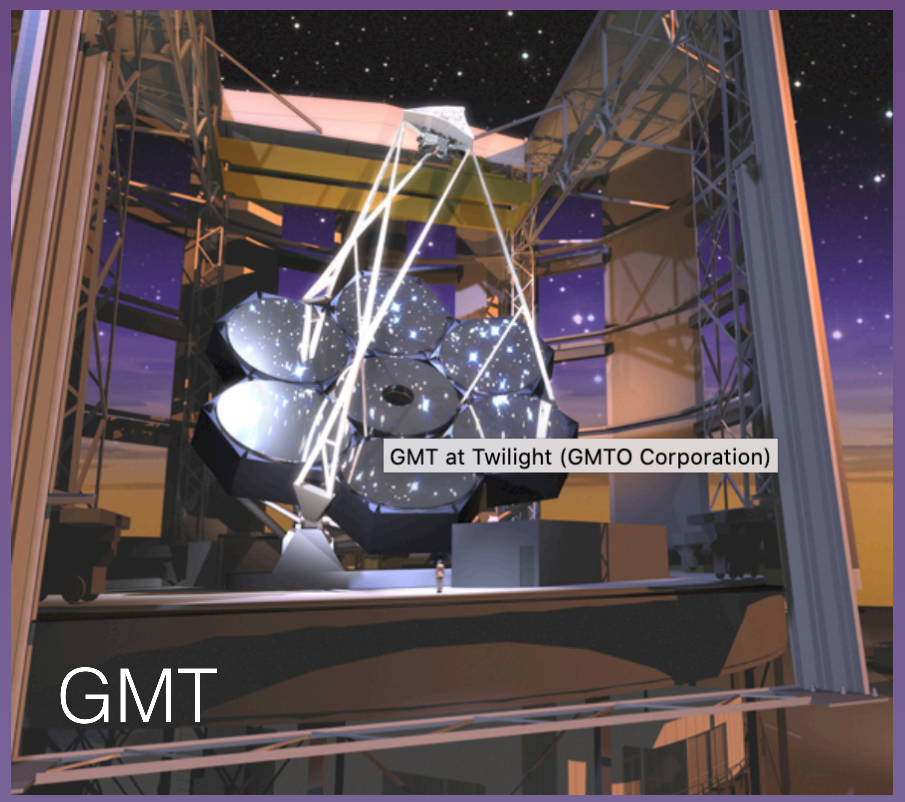
  30-m telescopes: obtain high-res. spectra within 1h!

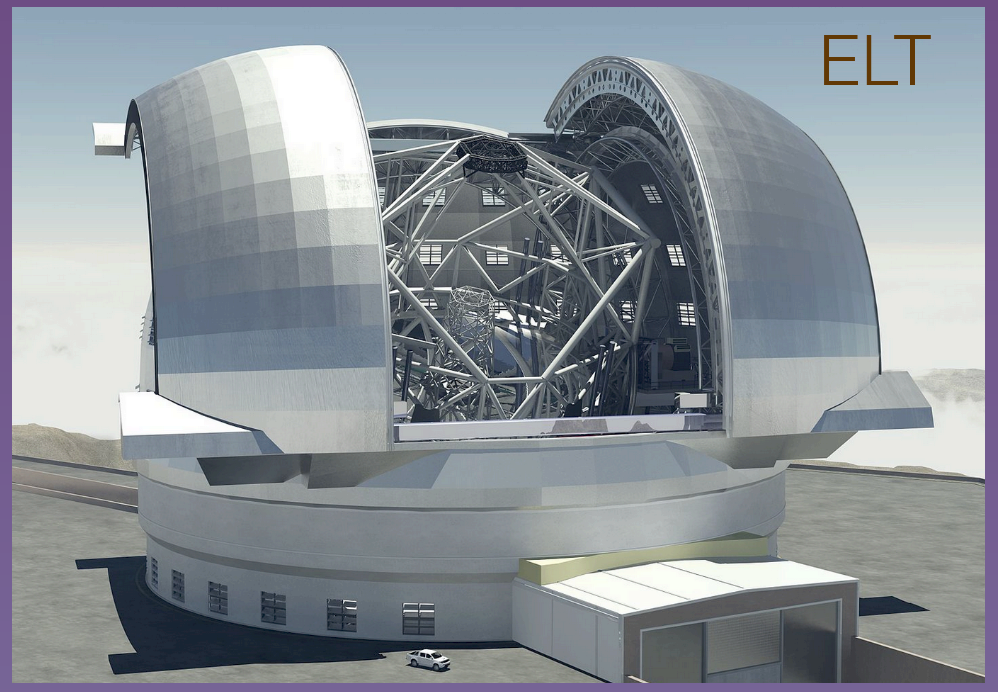
- Interferometers like ALMA:

  Offer accurate redshift measurements

  Measure gas dynamics/SFR in galaxies







Conclusions

- With proximity zone spectra we can recover density fields at z~6
- Recovered density PDFs allow us to learn quasar physics
- Radiative feedback suppresses star formation in low mass halos
- JWST will help us to understand more about radiative feedback
- In the near future we expect a revolution of high quality data, allowing us to do more exciting sciences (cosmology, quasar formation, quasar-galaxy co-evolution etc.)