Probing Cosmic Reionization with Quasar Proximity Zones

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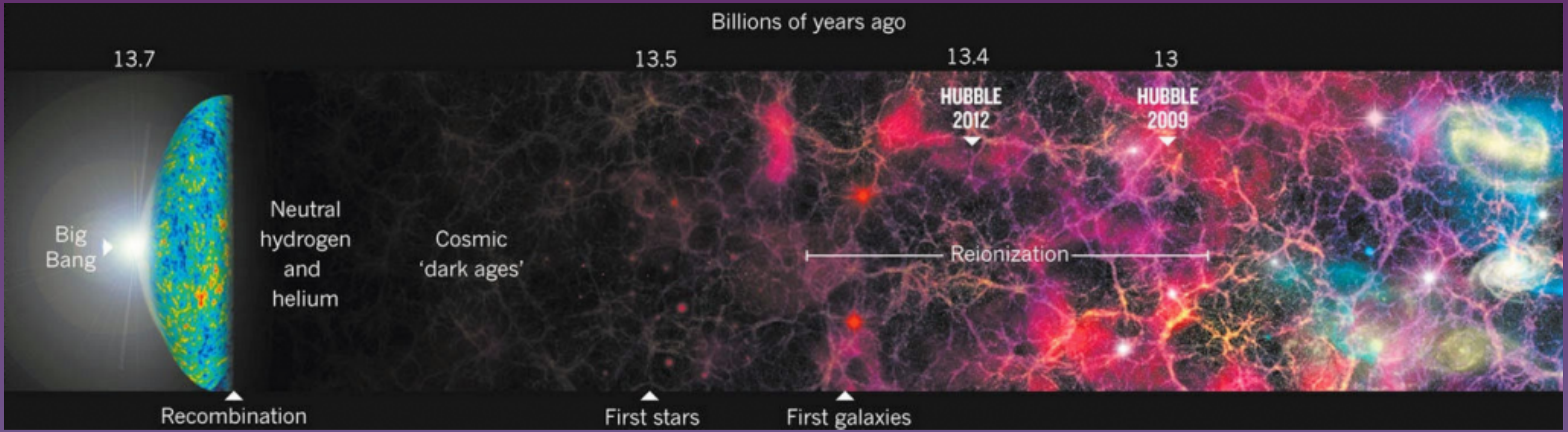
Outline

- 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 (arXiv:2101.11627)
    - Galaxy formation in quasar proximity zones (arXiv:1911.09113)
- Future prospect and conclusion

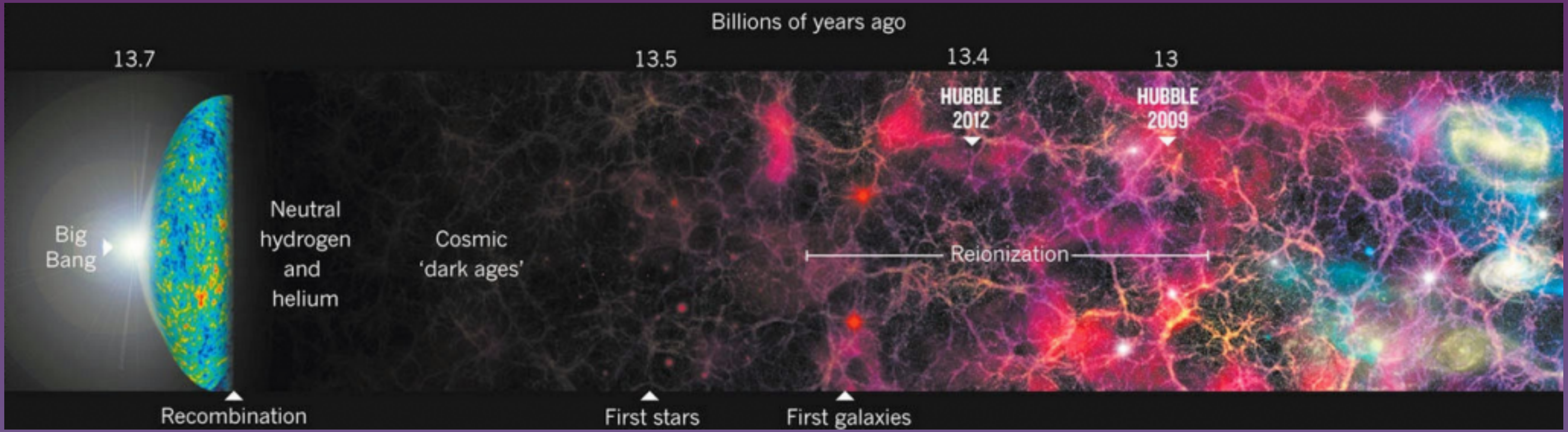
History of the Universe



ionized gas

History of the Universe

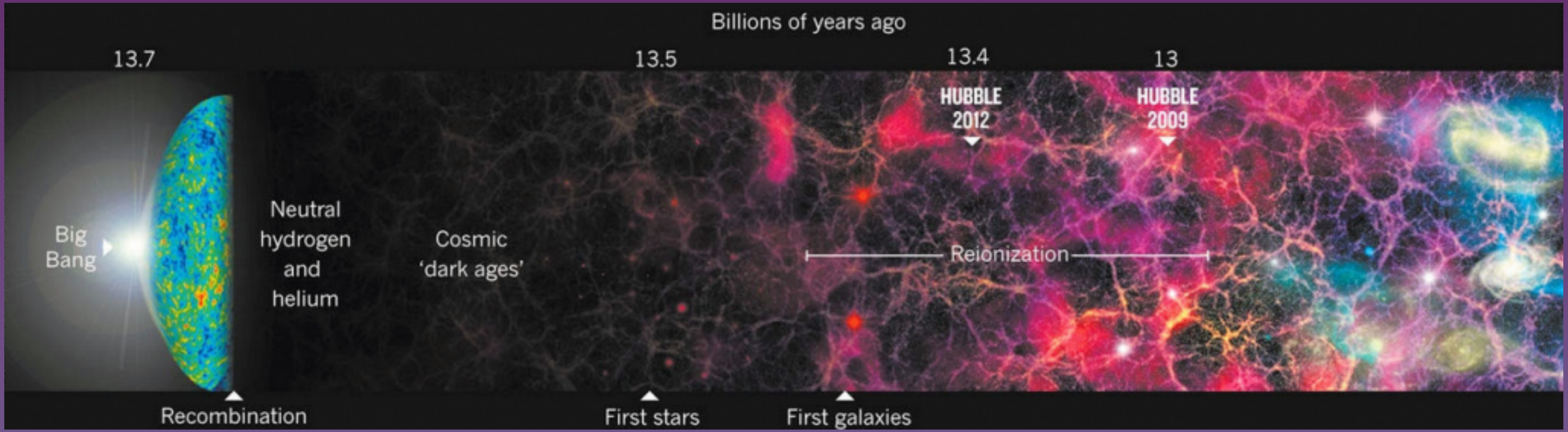
As time elapses, the Universe expands
and cools down



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

History of the Universe

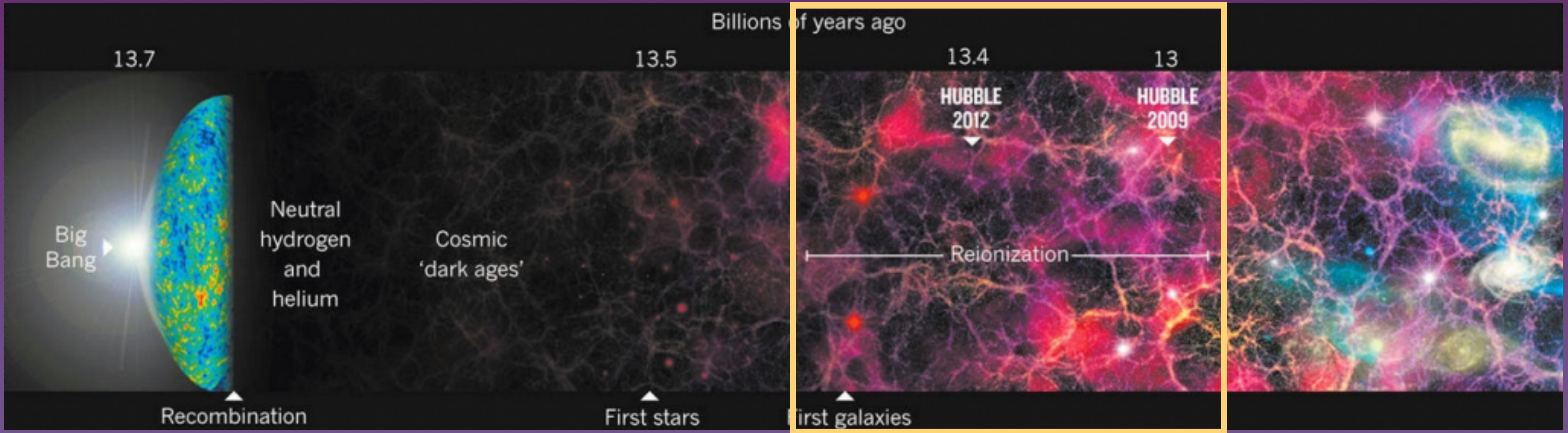
Gravity finally pulls matter together
to form stars/galaxies



Stars, quasars, XBs emit
ionizing photons

History of the Universe

Starlight ionizes and heats
the intergalactic gas



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

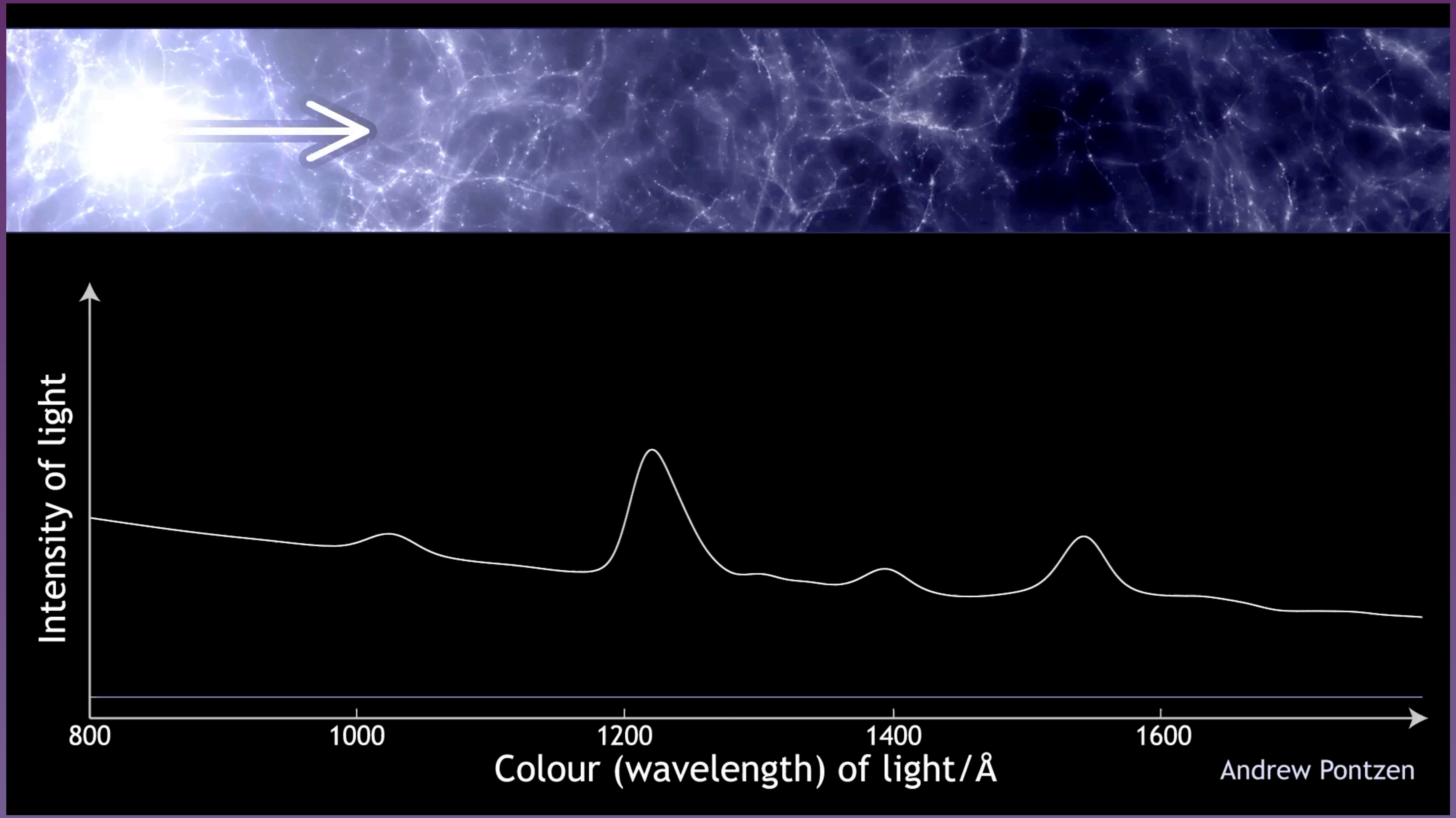
History of the Universe

More and more gas gets ionized

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

Quasar Absorption Spectra

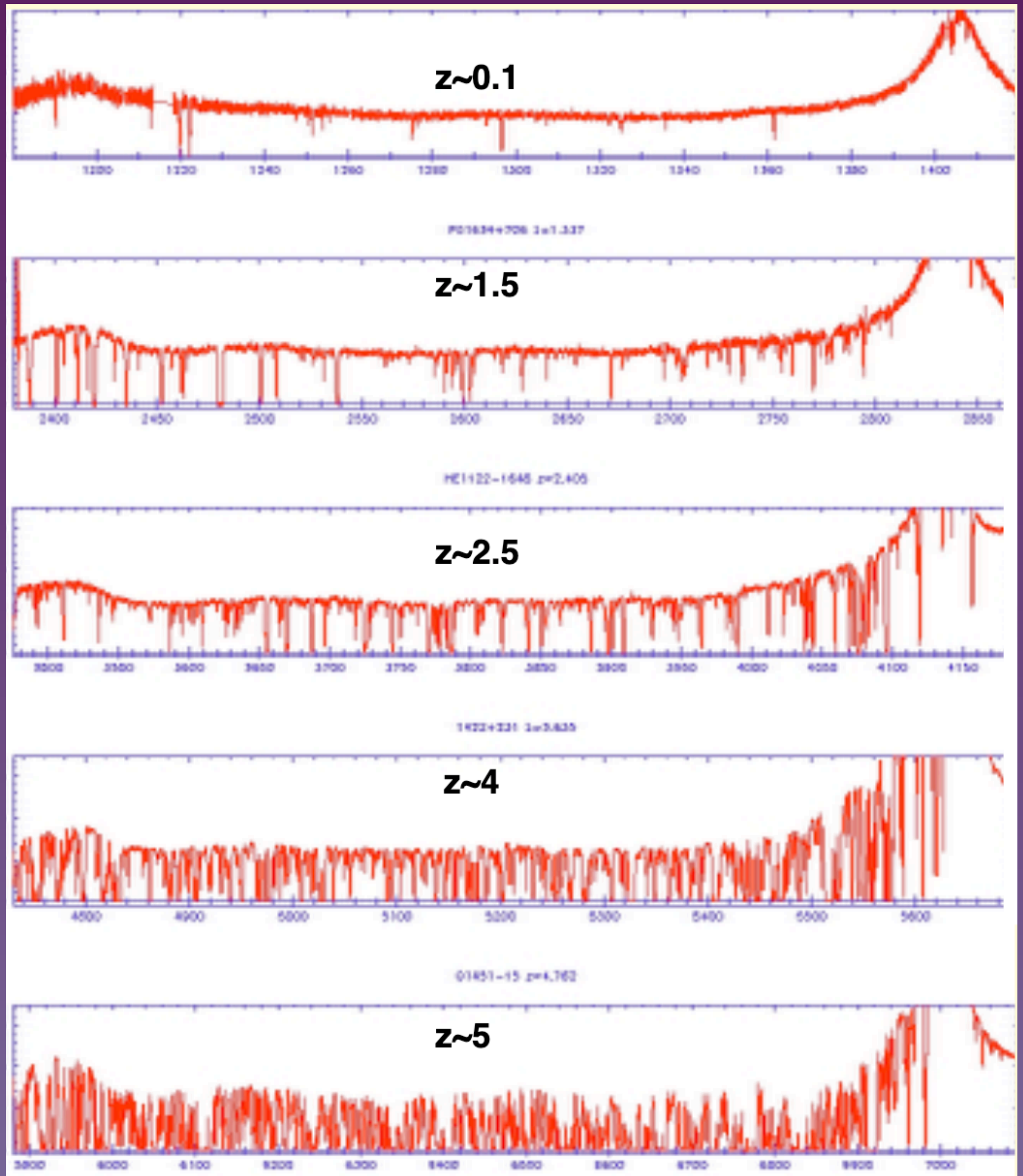
Illustration of Lya Forest at z~3



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

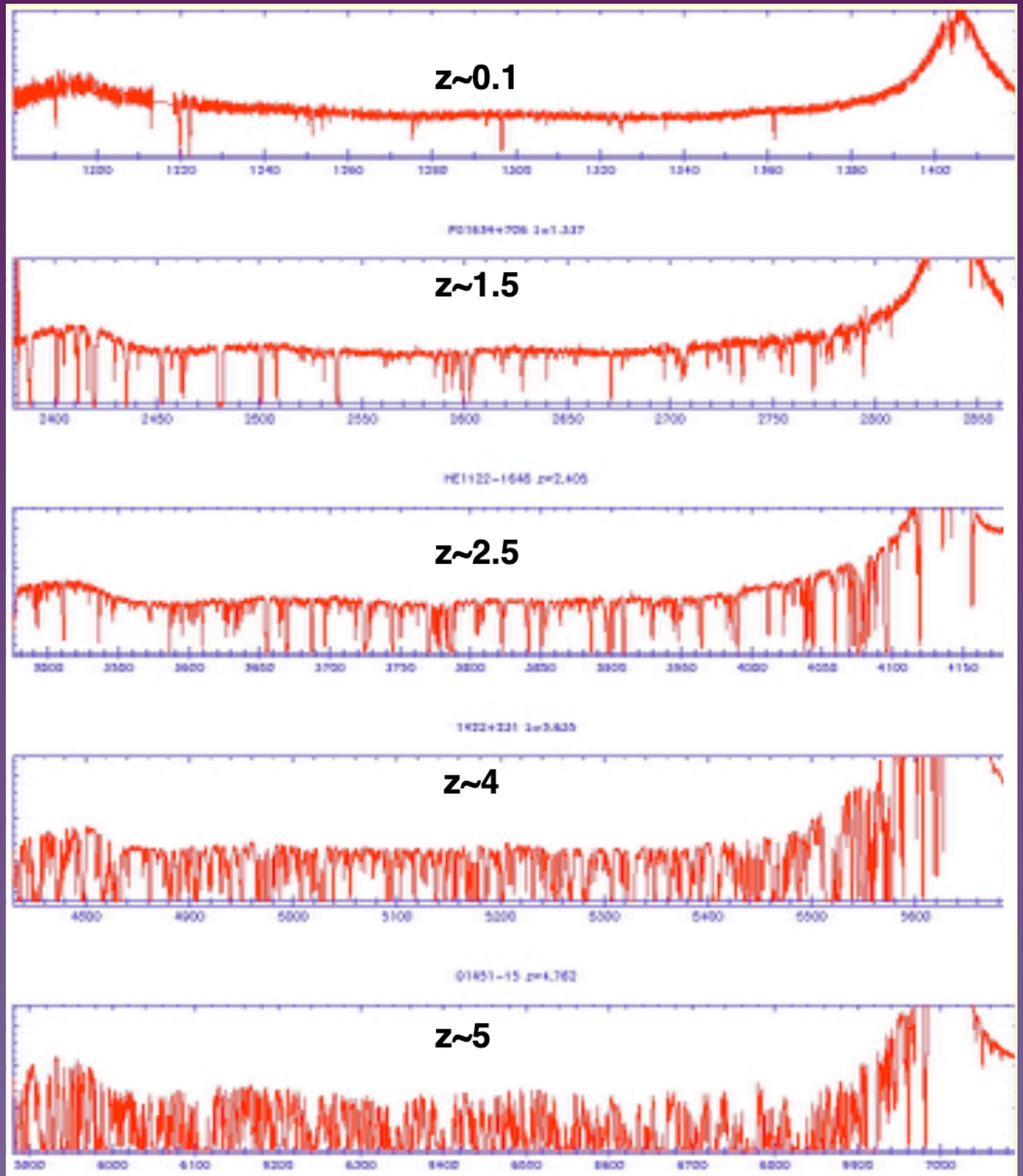
Quasar Absorption Spectra



Credit: Xiaohui Fan

Lya forests contain info about $\rho, T, \Gamma_{\rm bkg}$ etc.

Quasar Absorption Spectra



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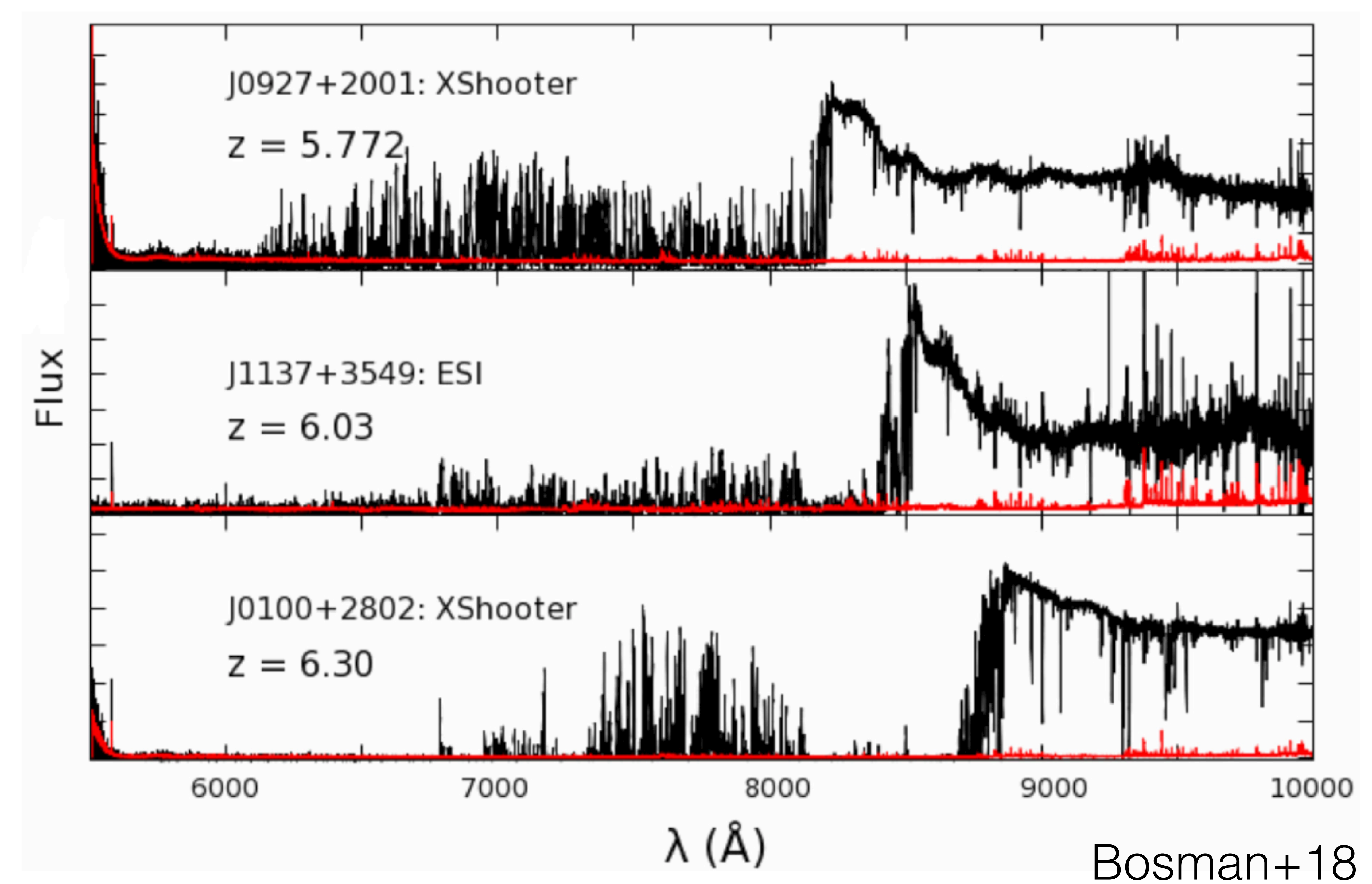


Bosman+18

Transmitted flux drops rapidly above z~6

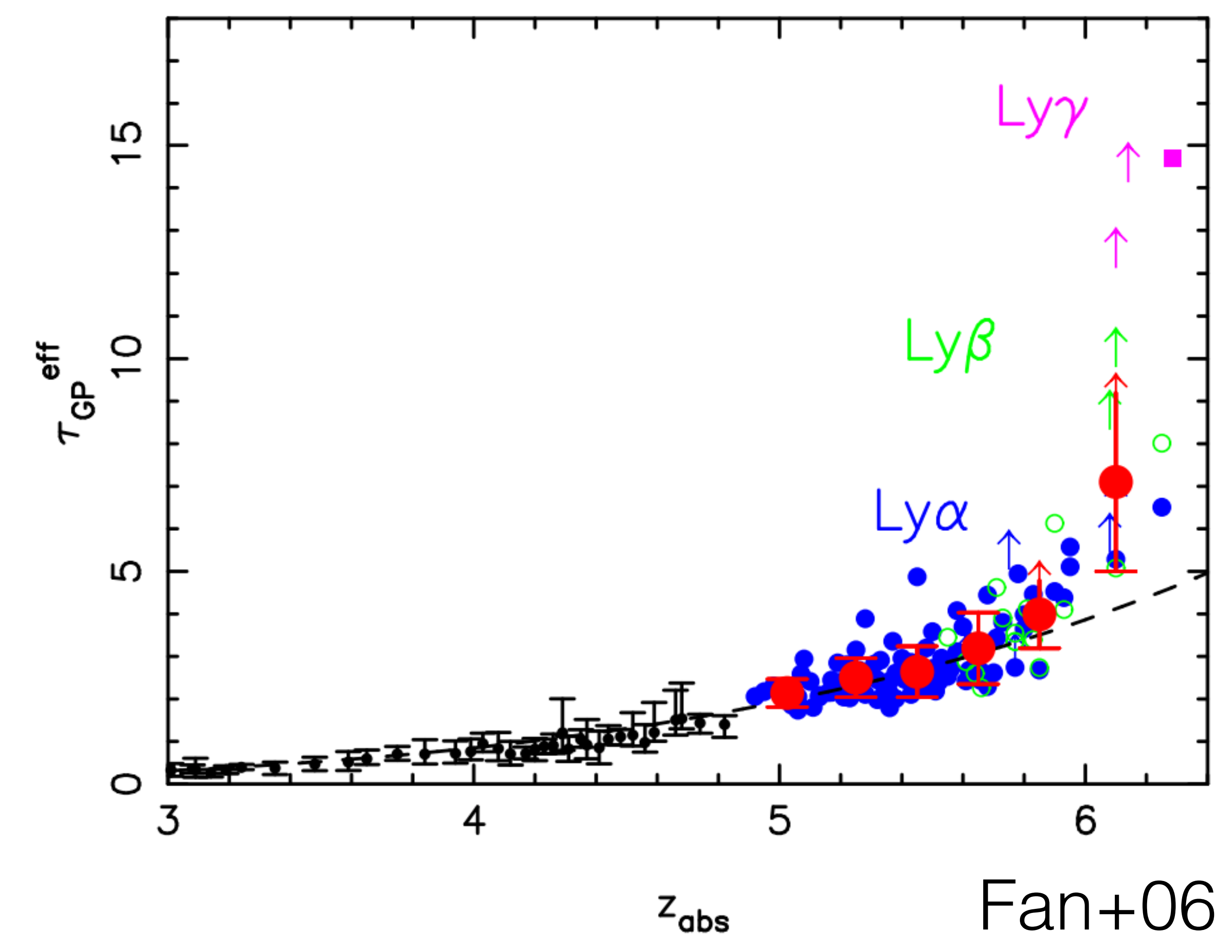
With Current Quasar Spectra

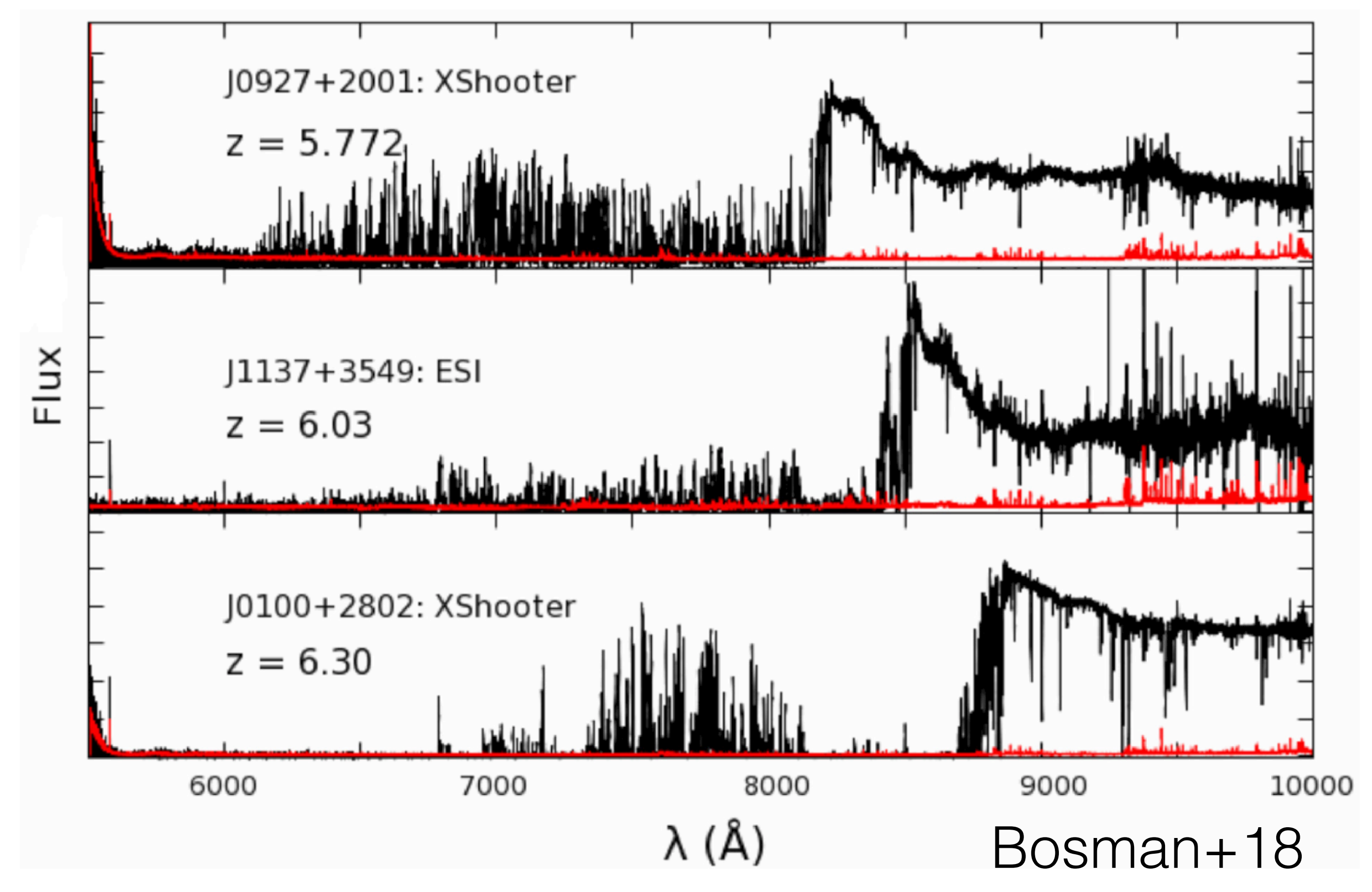
What do we know:

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

What do we not know:

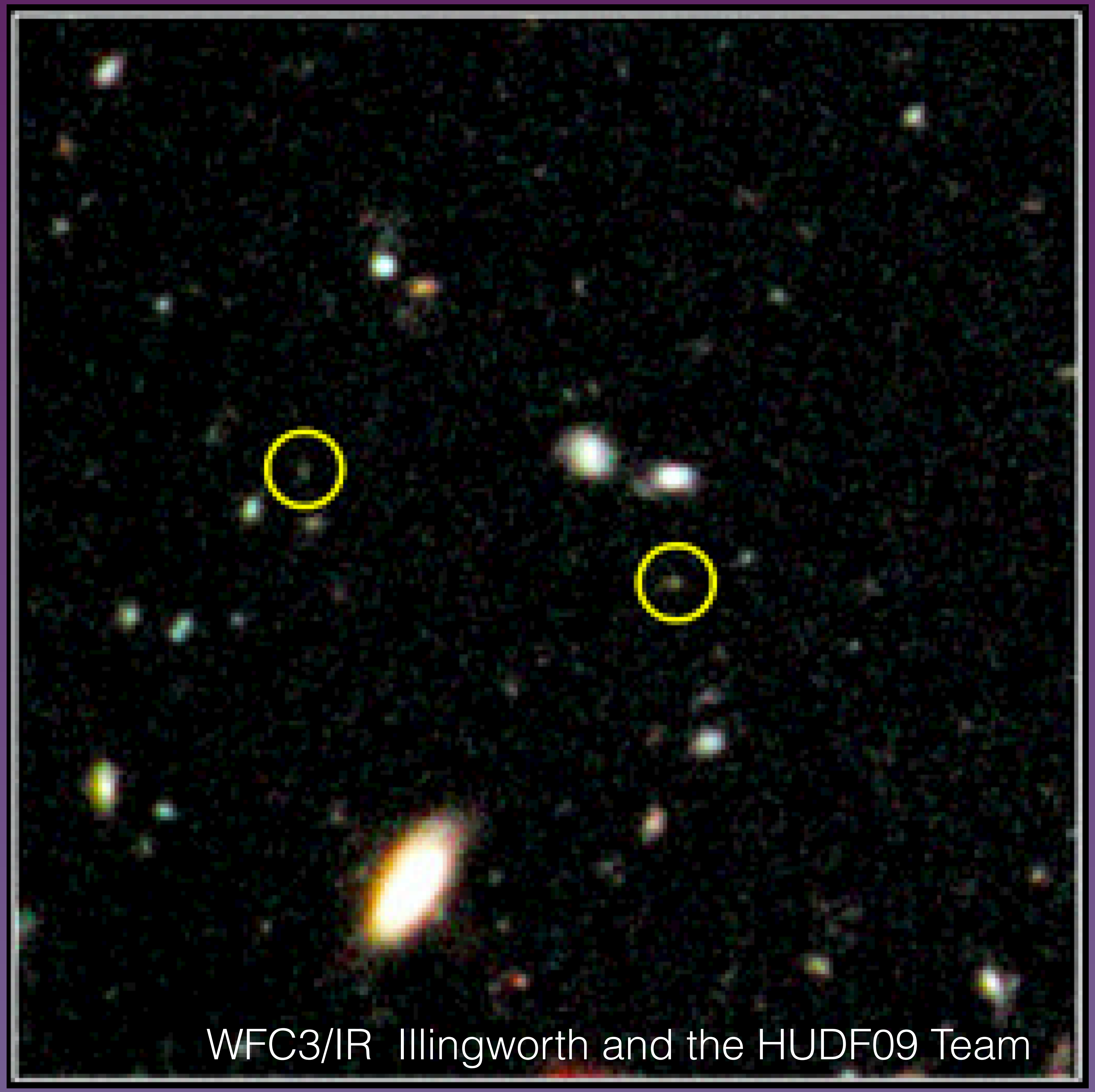
- What is the ionization state at z>6
- What is the density and temperature of the IGM?
- ……





Observing Reionization Galaxies

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

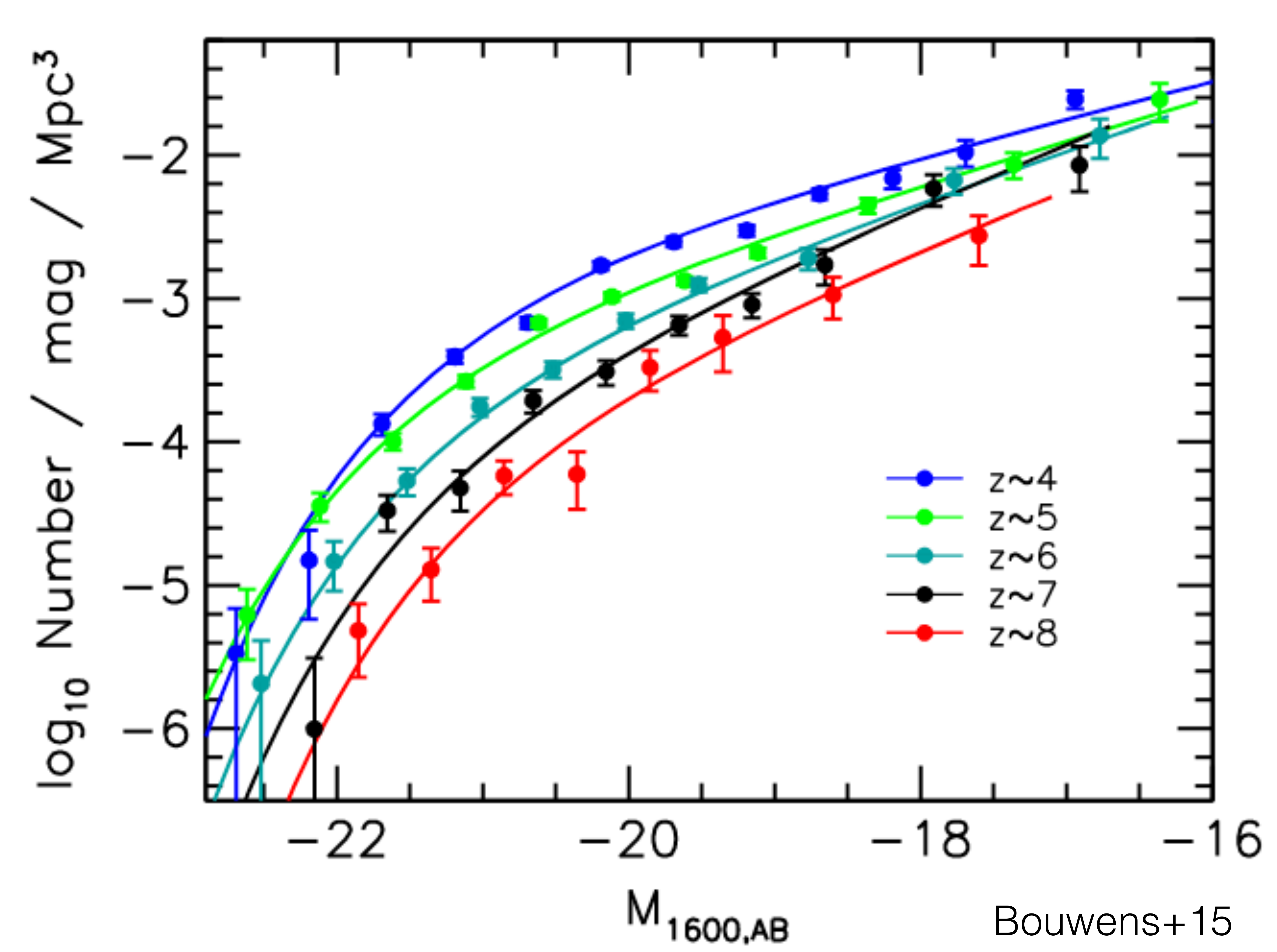


Galaxy Luminosity Function (GLF)

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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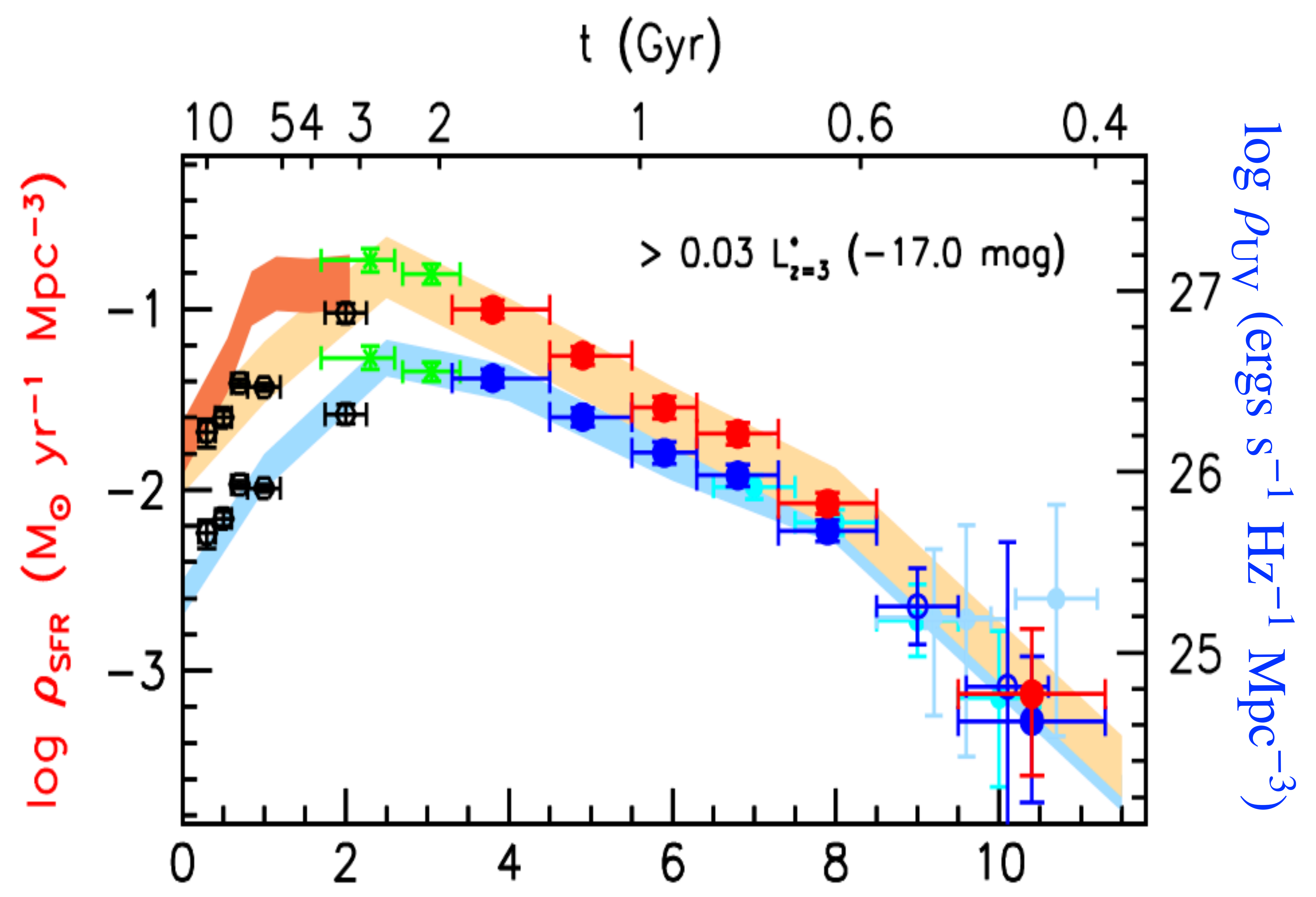


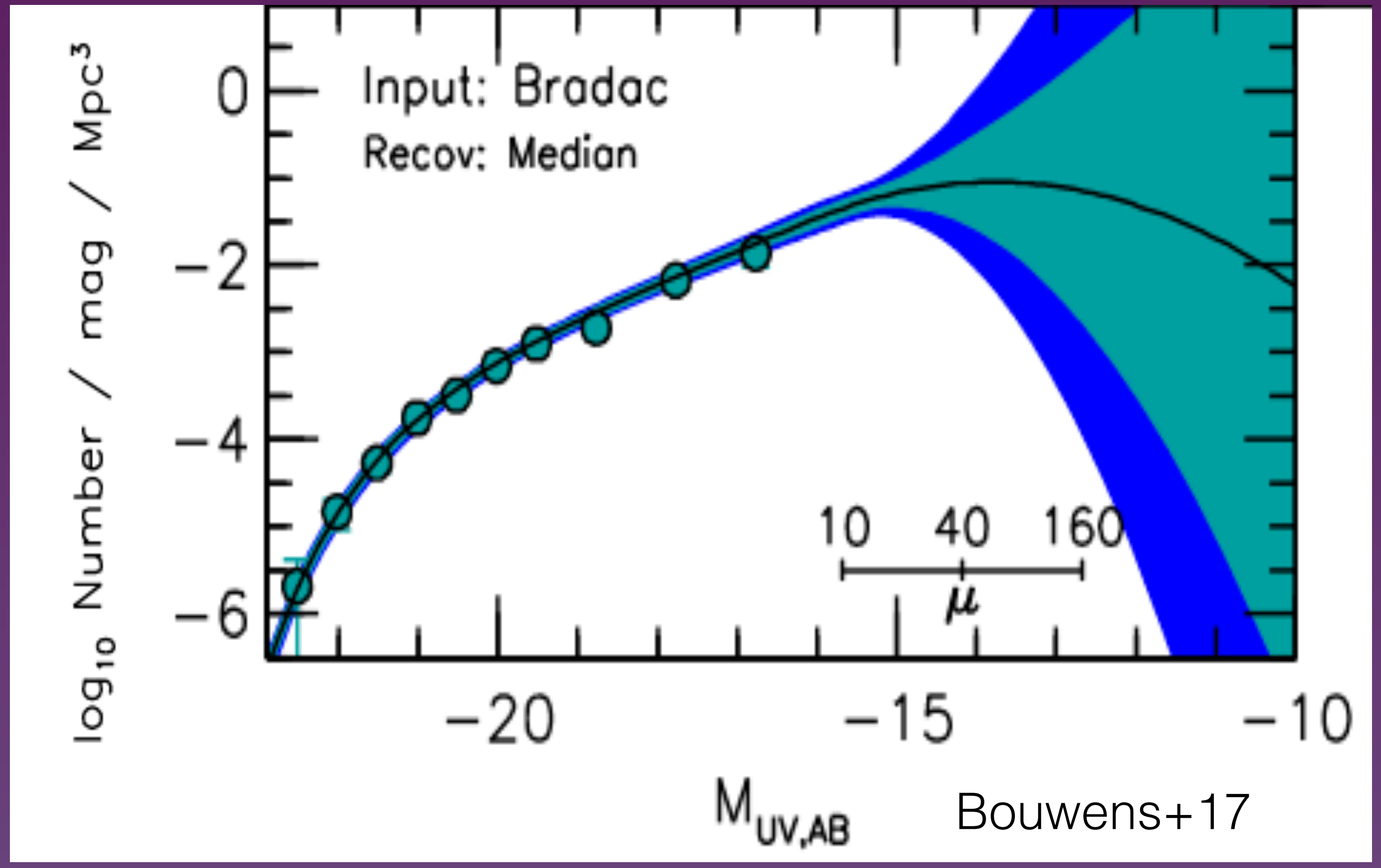
Bouwens+15

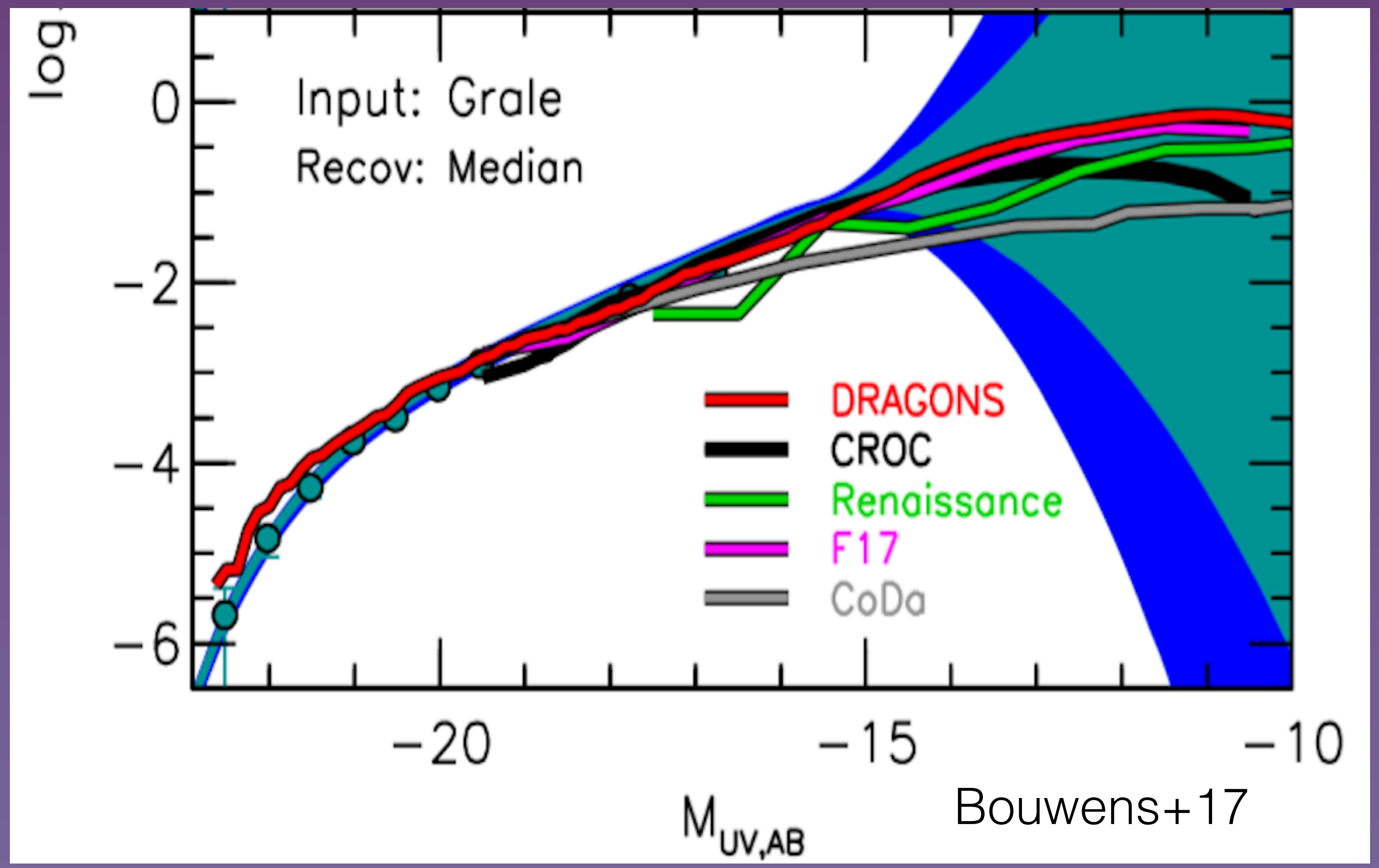
GLF: What do we not know

The Faint End of the Galaxy Luminosity Function:

- Currently, the deepest observation can only go down to Muv ~ -16
- Gravitational lensing model has large uncertainty

- “Back-reaction”: small galaxies may be impacted by radiation from other galaxies
- The effect of back-reaction is in debate: where is the turnover?



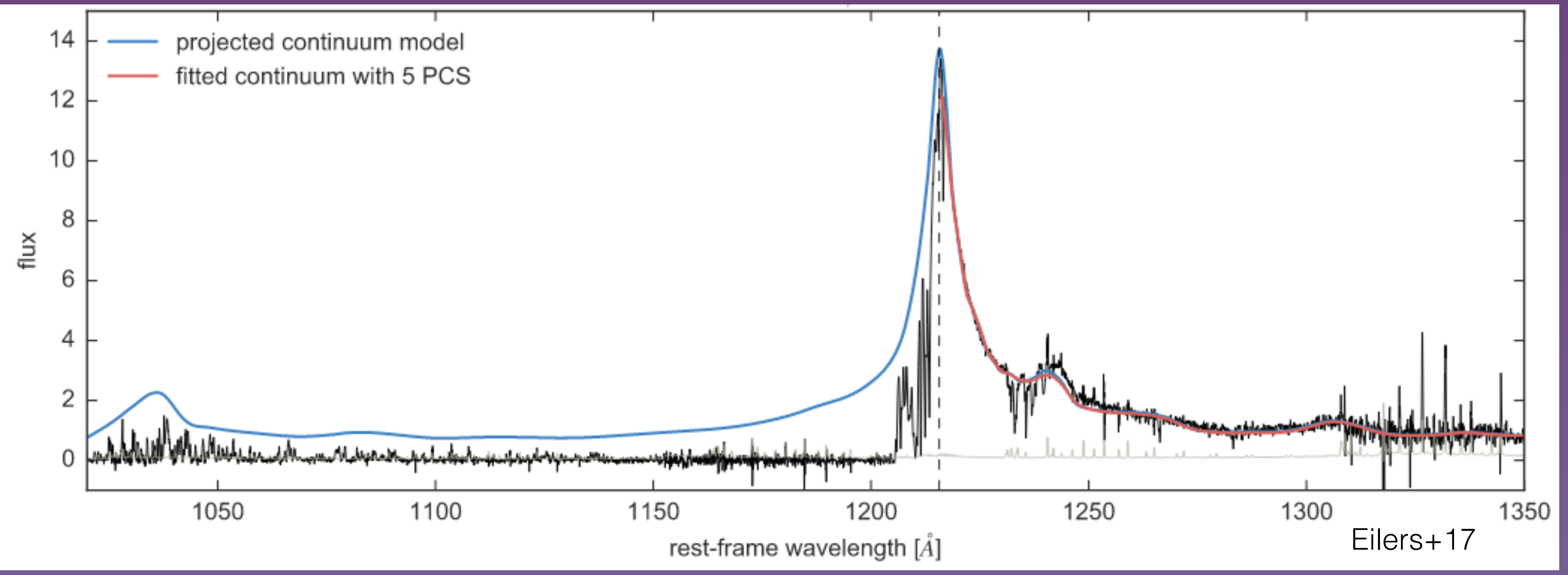


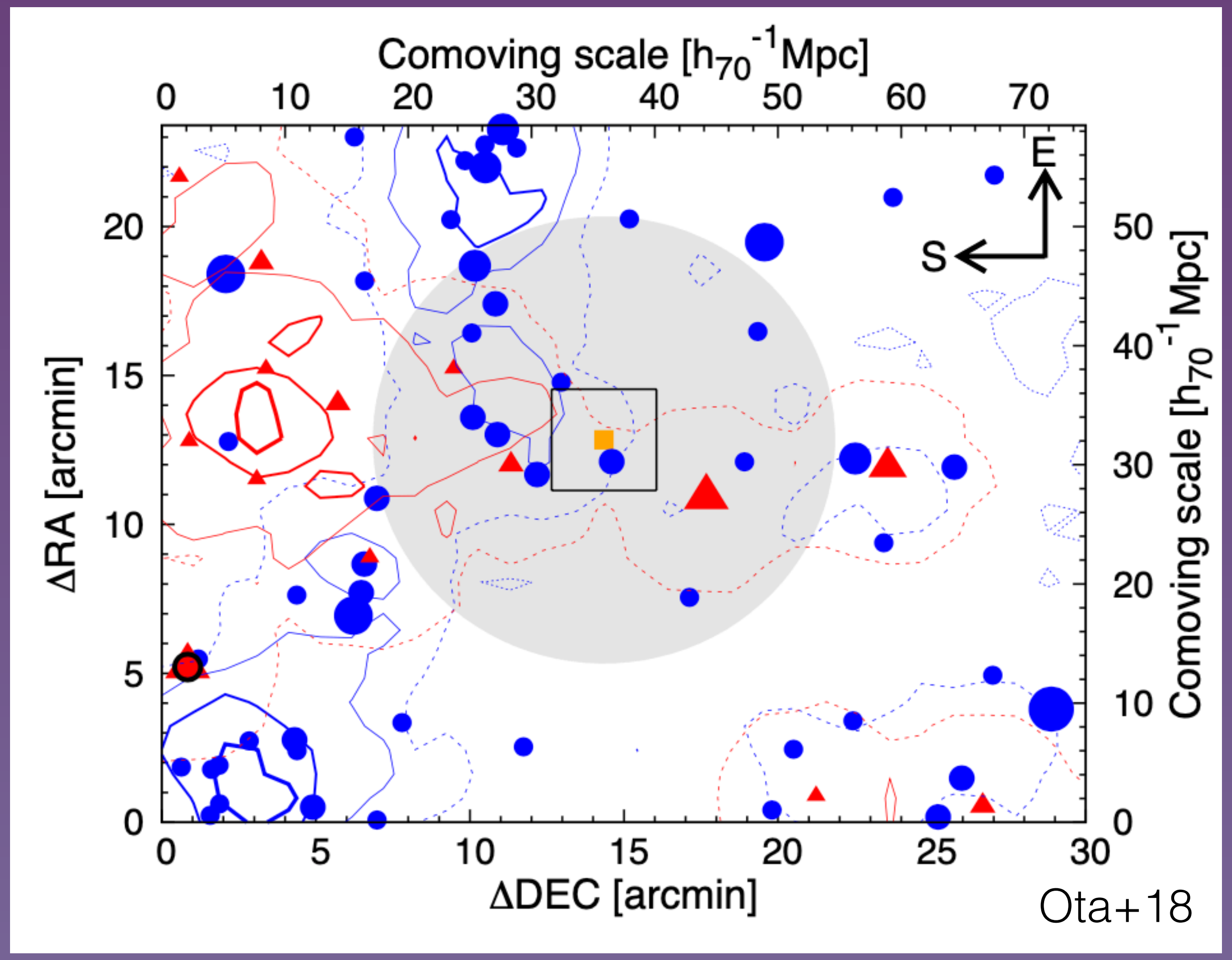
Quick Summary 1: Current Status

- Currently, most constrains of reionization are from quasar spectra and observing individual galaxies.
- Lya spectra: reionization ends at z~6 (Fan+06 etc.)
    - Lya absorption saturates at z>6 in most places.
- 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 reionization back-reaction on faint galaxies.

Quasar Proximity Zone as a Unique Lab

- Luminous! 200+ z>6 quasars detected, with many high-resolution spectra
- Overdense region? Likely trace “proto-clusters”, favorable target for JWST





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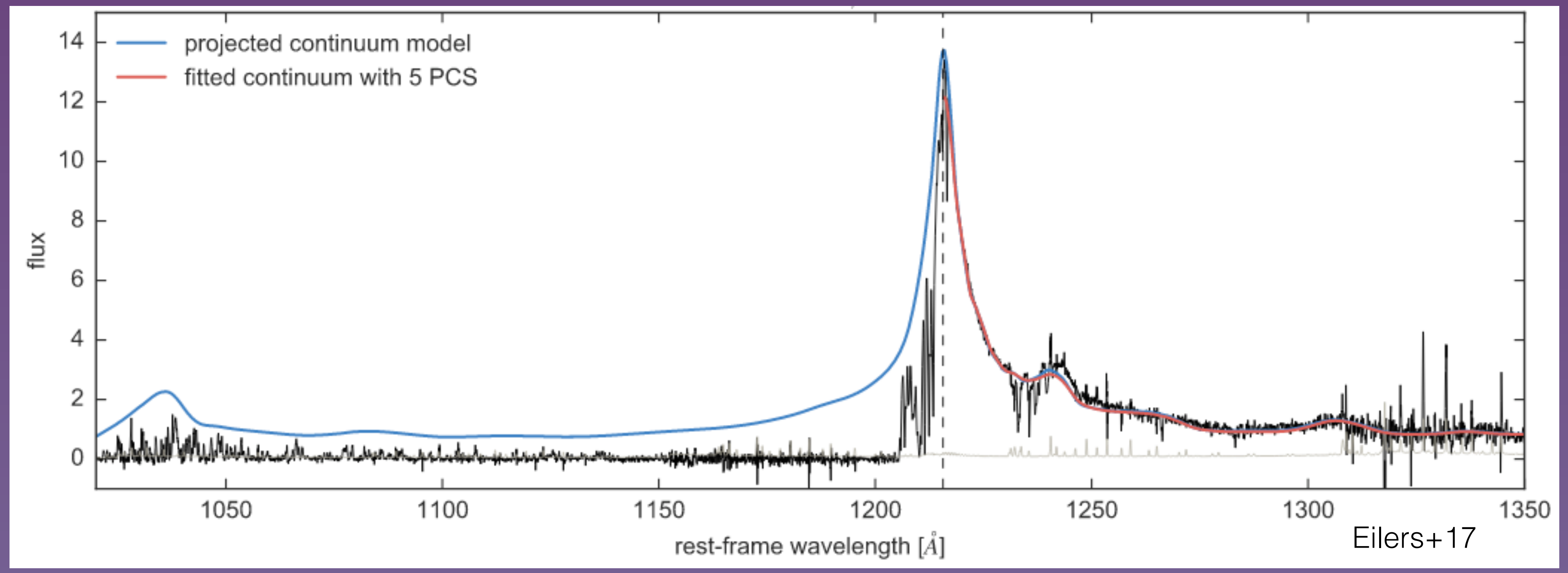
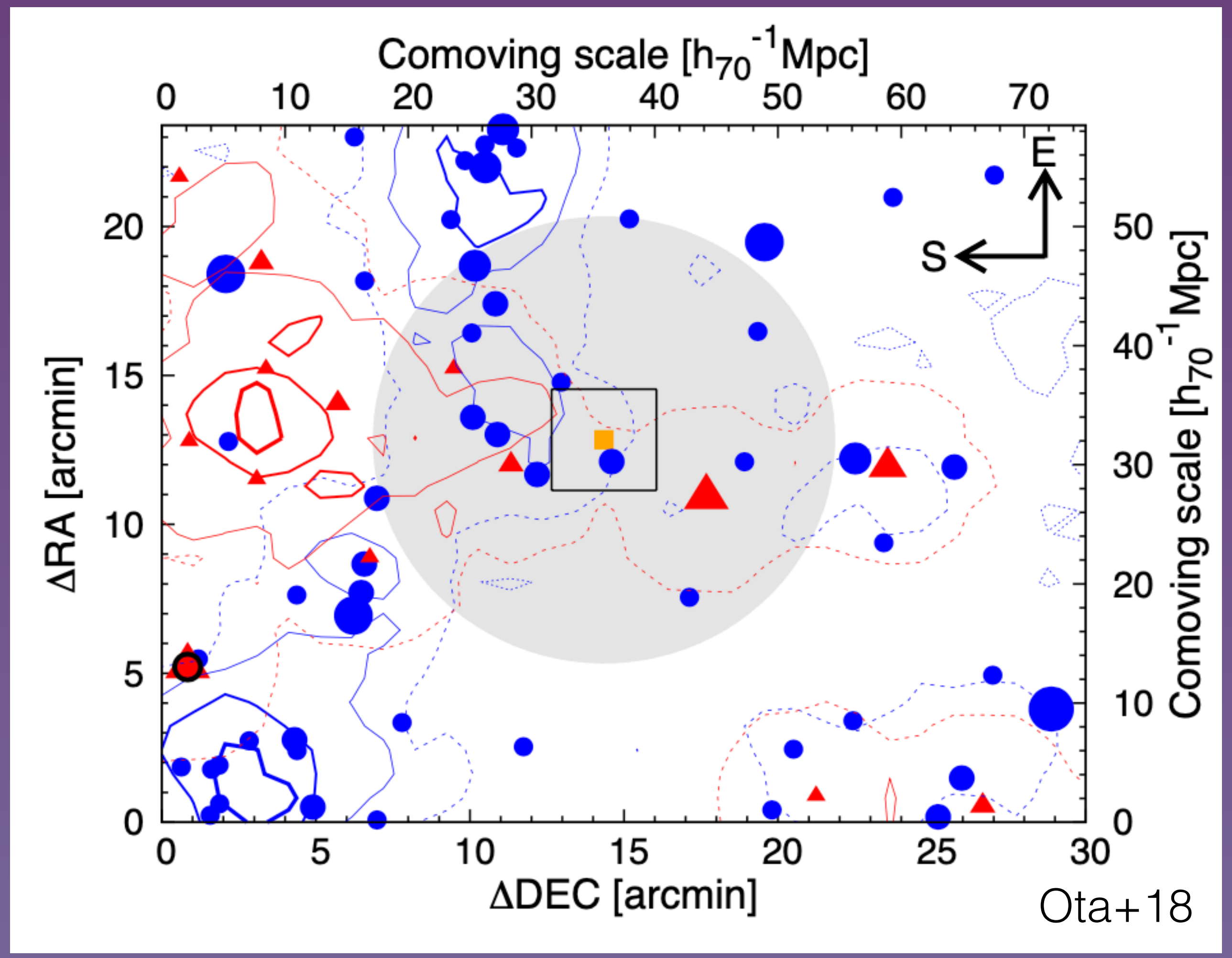
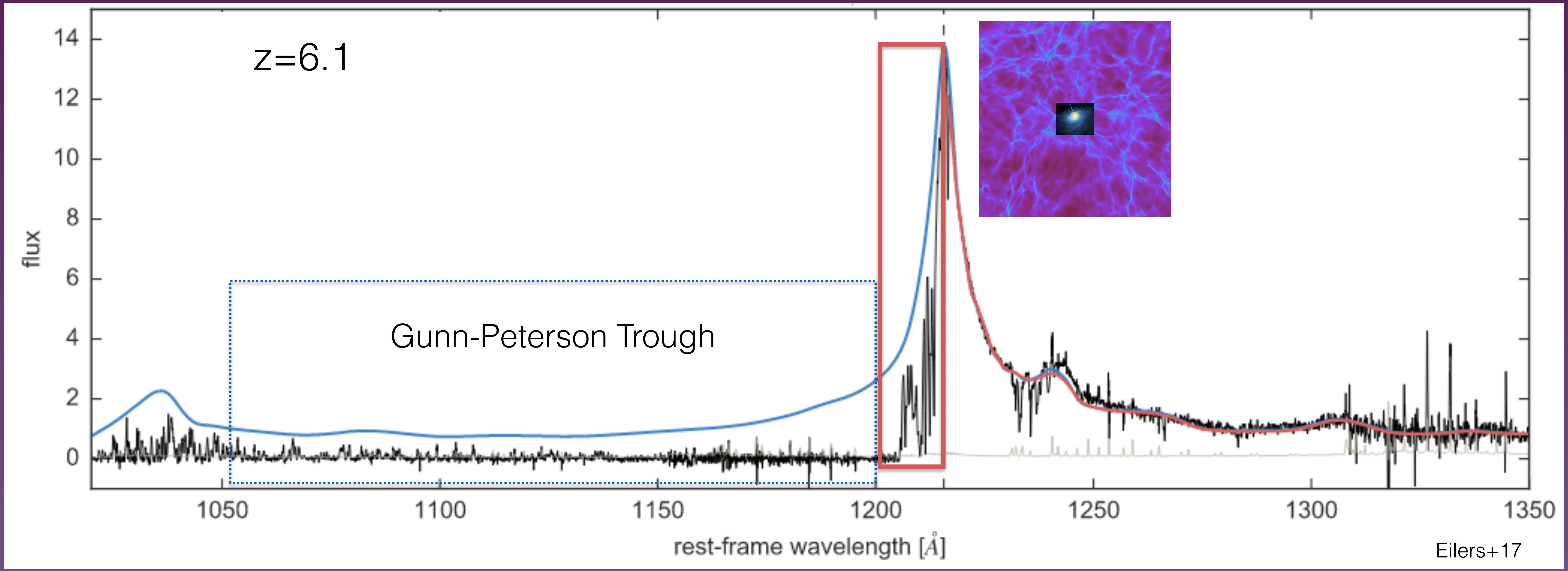
Lya saturates in most places, **But Not Quasar Proximity Zone!**





Quasar Proximity Zone Spectra



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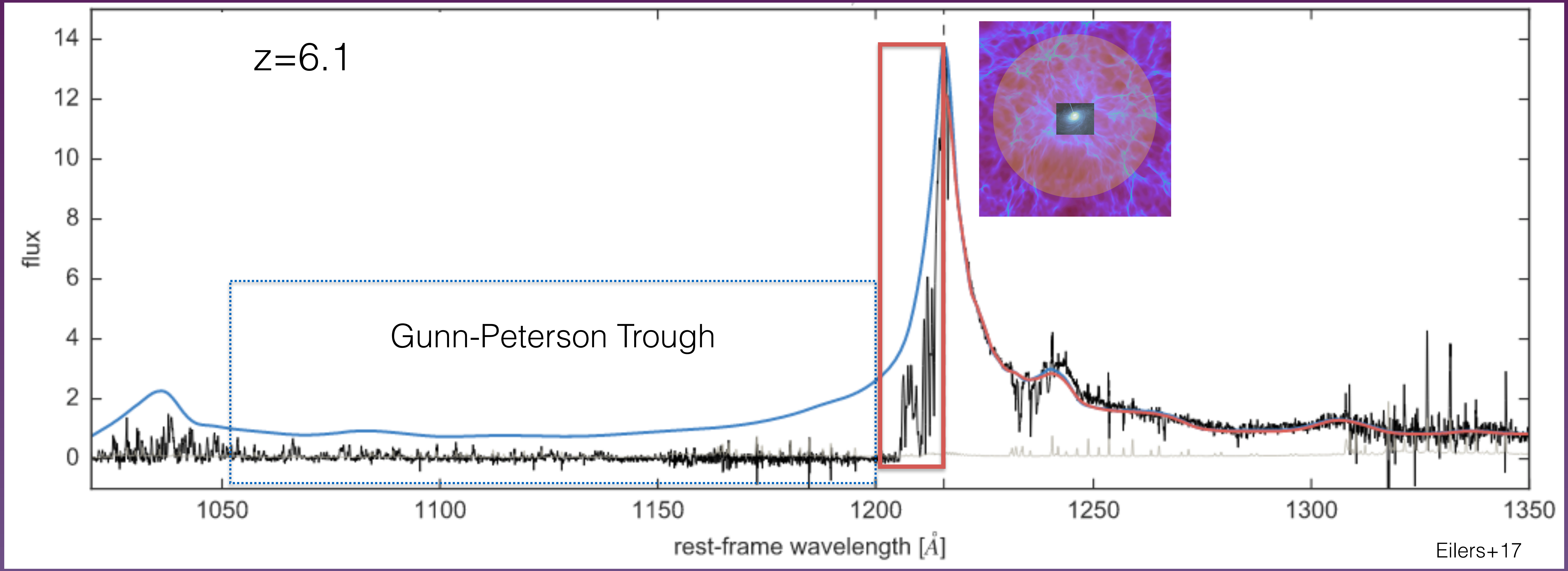

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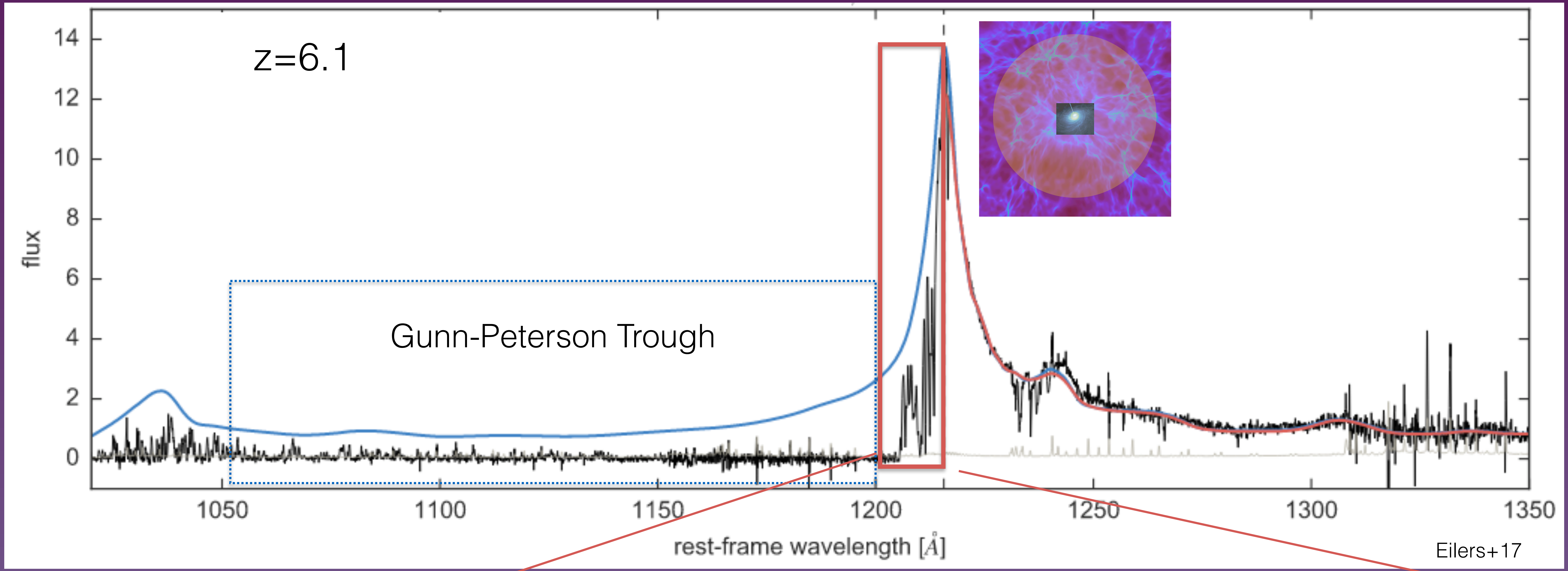
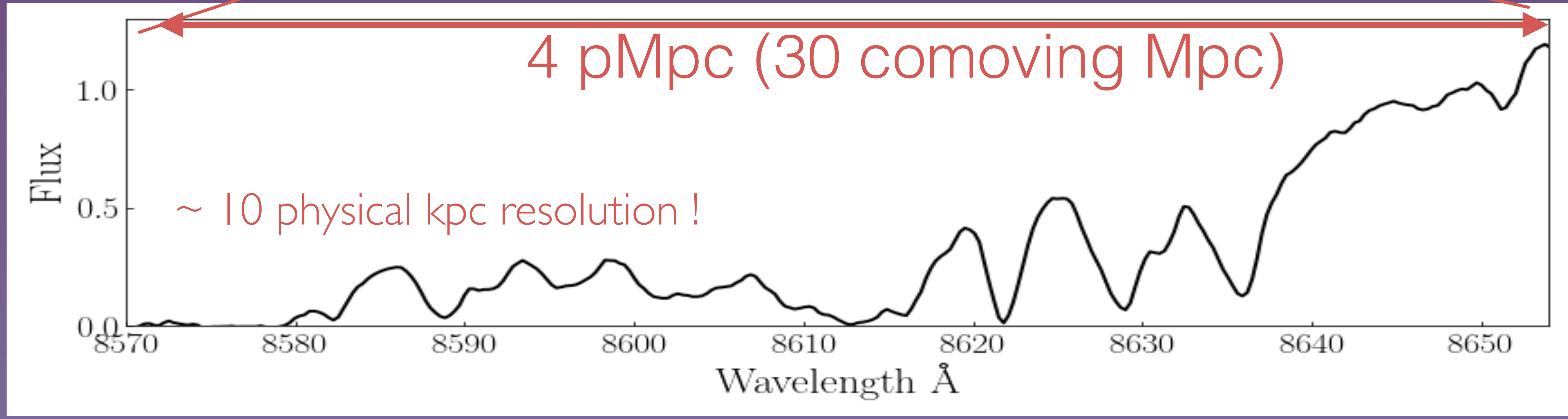


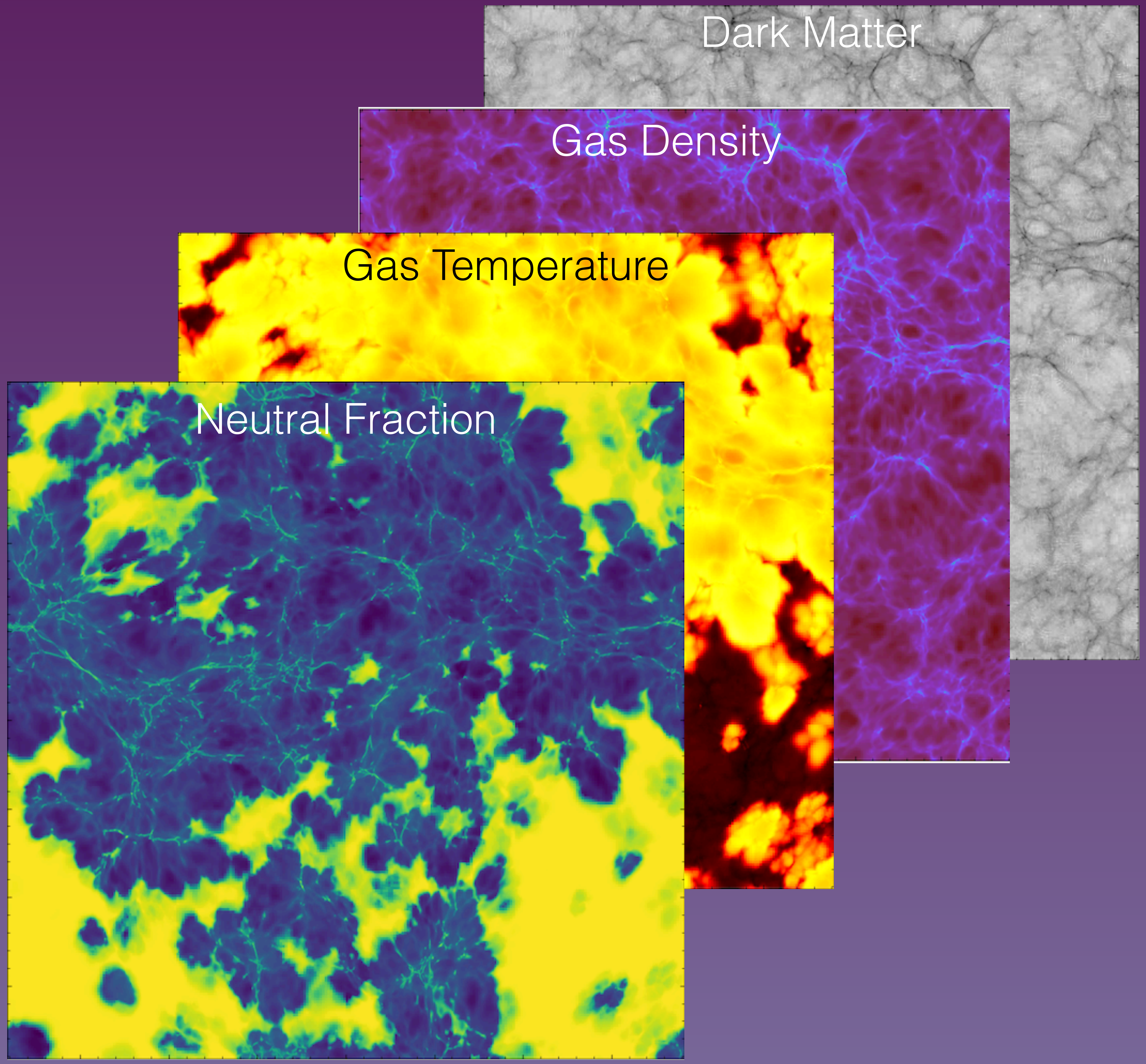


We can potentially do lots of science that we have done at z=2~5 with Lya forest!

CROC Simulations

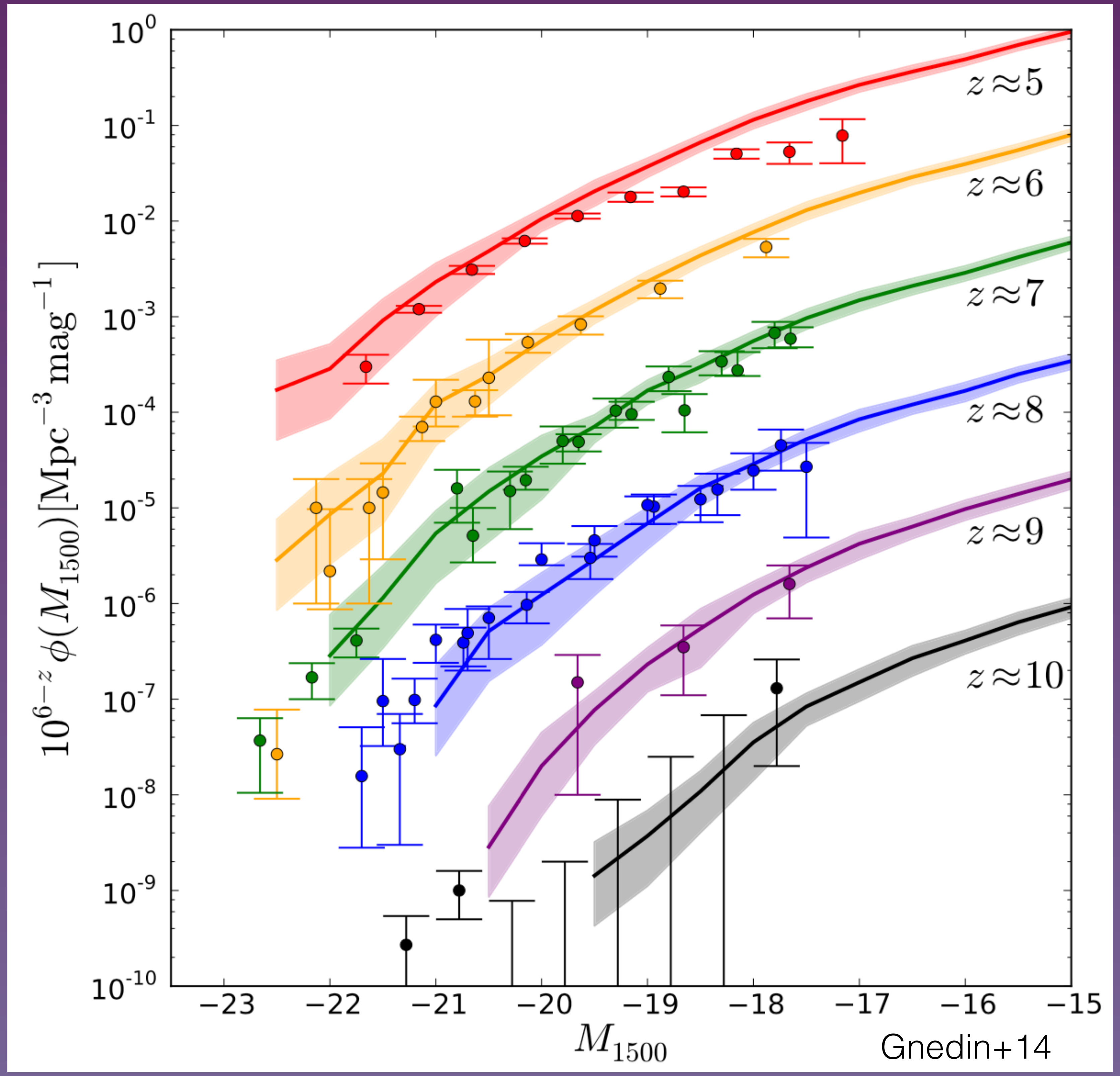
Cosmic Reionization On Computers (CROC) Simulations:

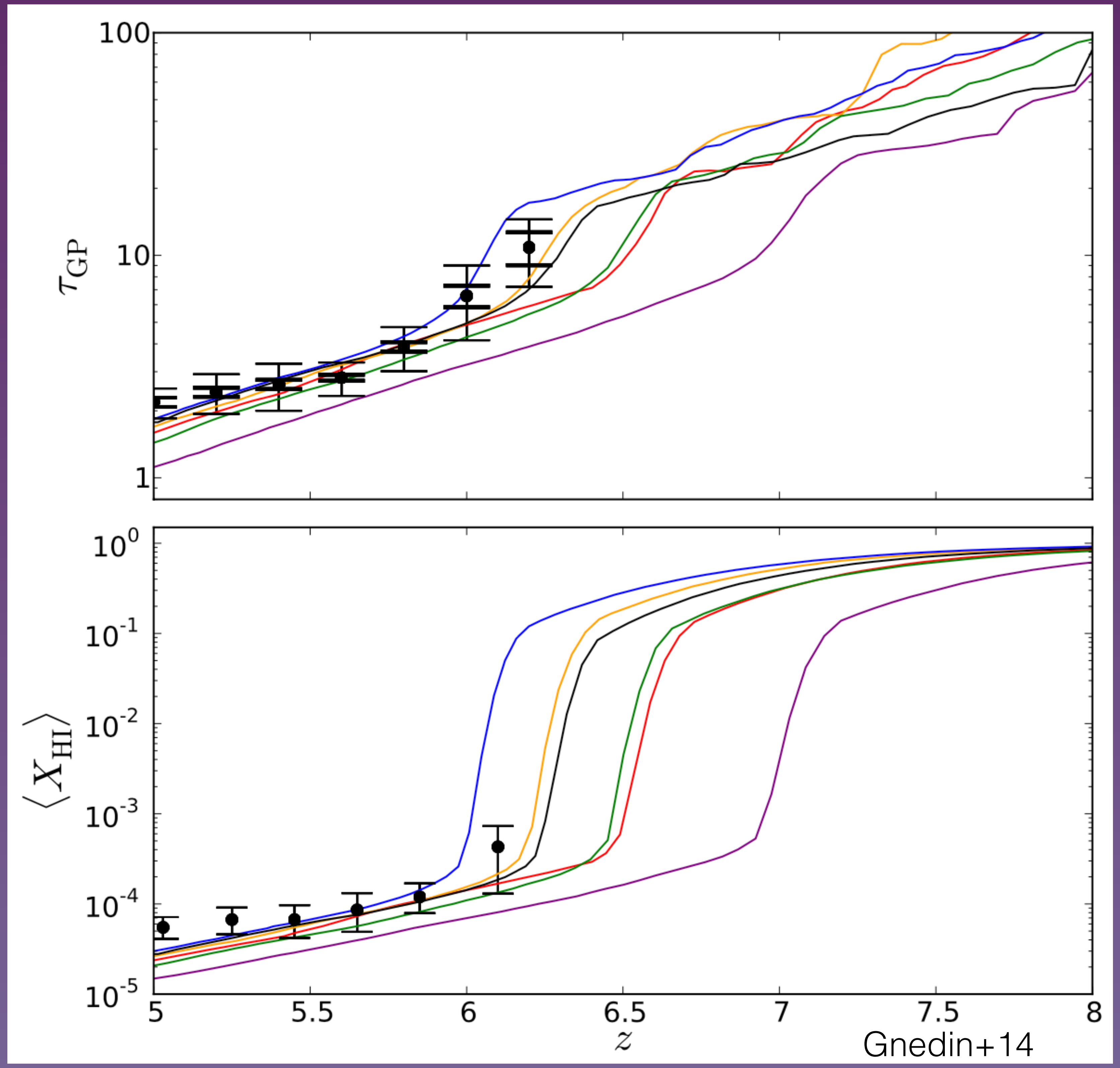
- Box sizes: 30, 60, 120 cMpc
- Adaptive Mesh Refinement ~100 pc peak resolution
- Gas heating/cooling
- Star formation
- Stellar feedback
- Radiative transfer



CROC Simulations

Reproduce luminosity functions and Gunn-Peterson optical depth:

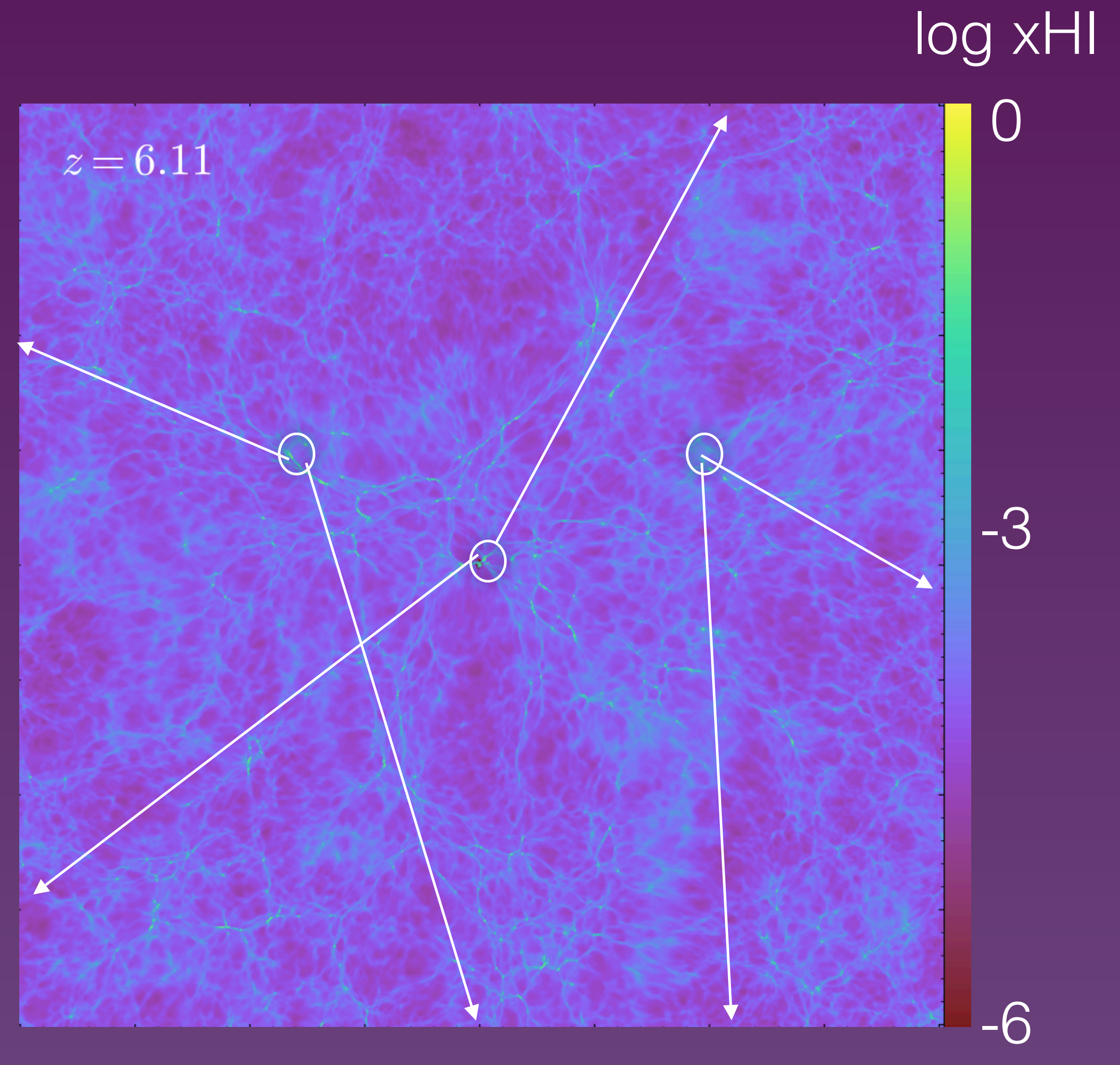




Quasar Proximity Zones

Model proximity zone spectra:

- Identify massive halos as quasar hosts
- Randomly draw sightlines
- Post-process with (Mag=-26.7) quasar spectra



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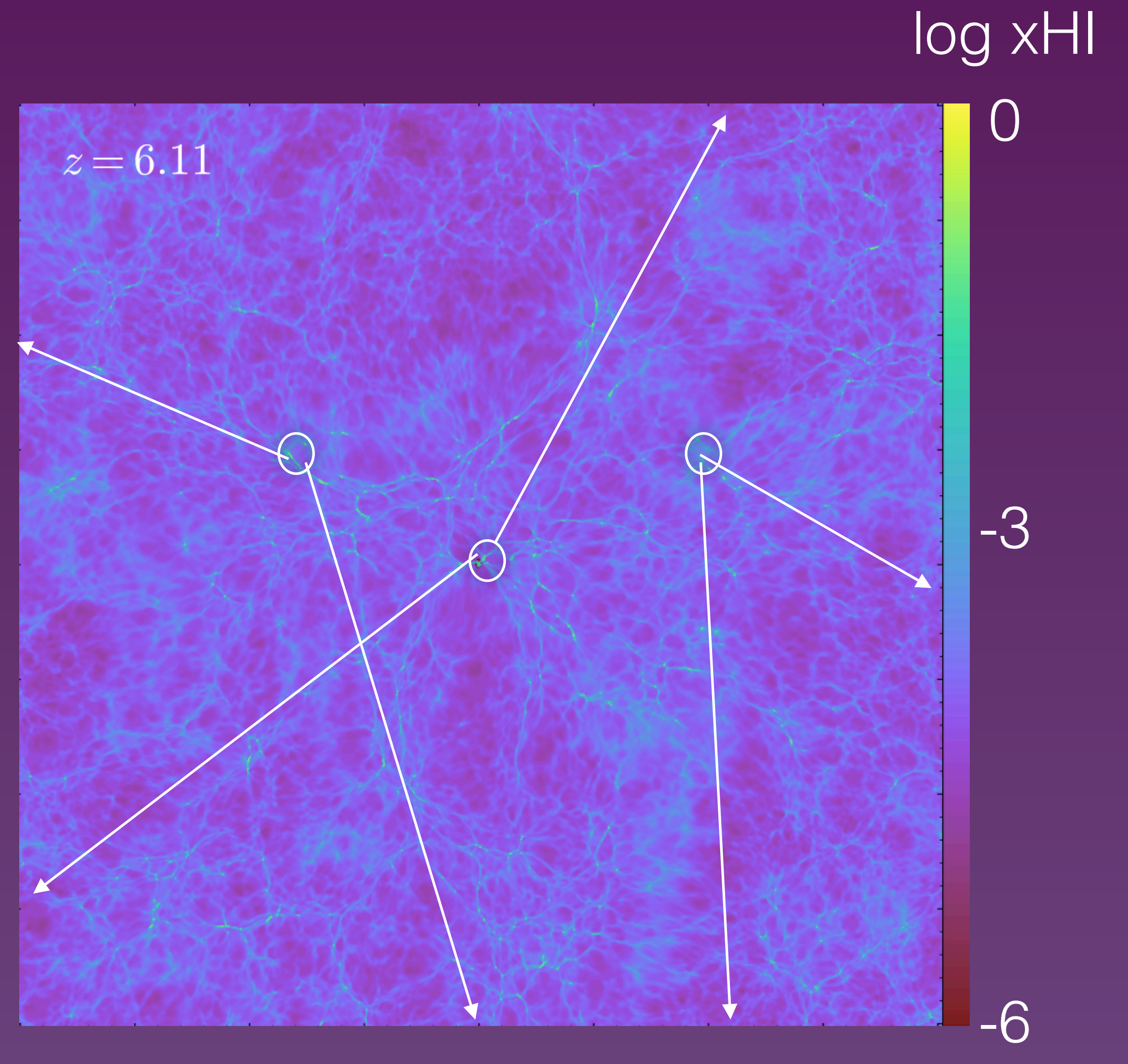

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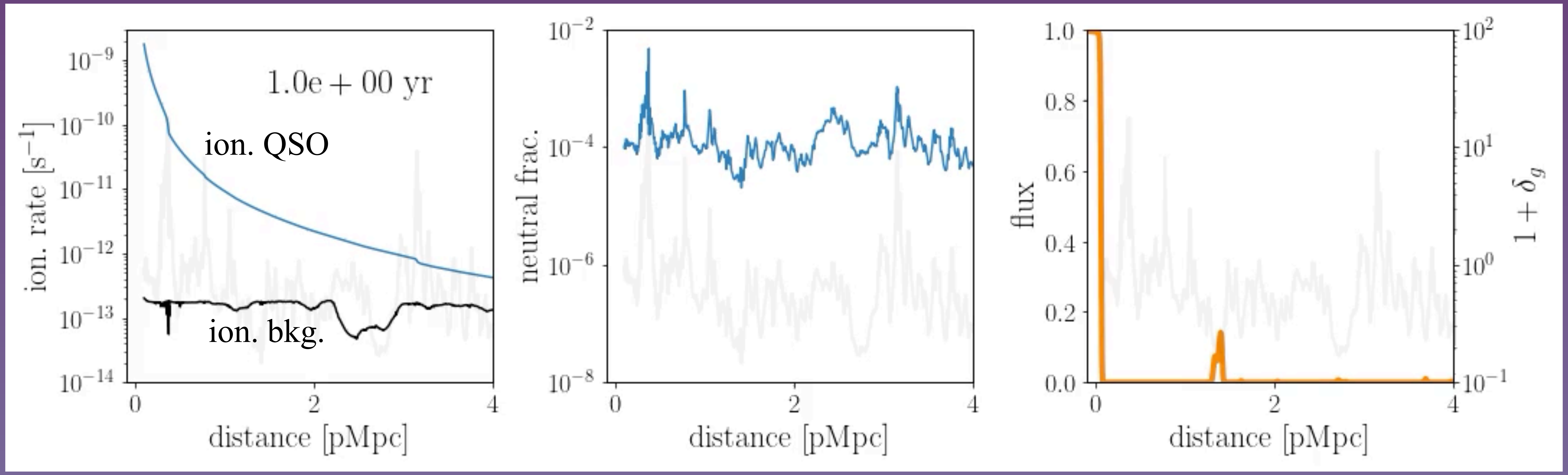
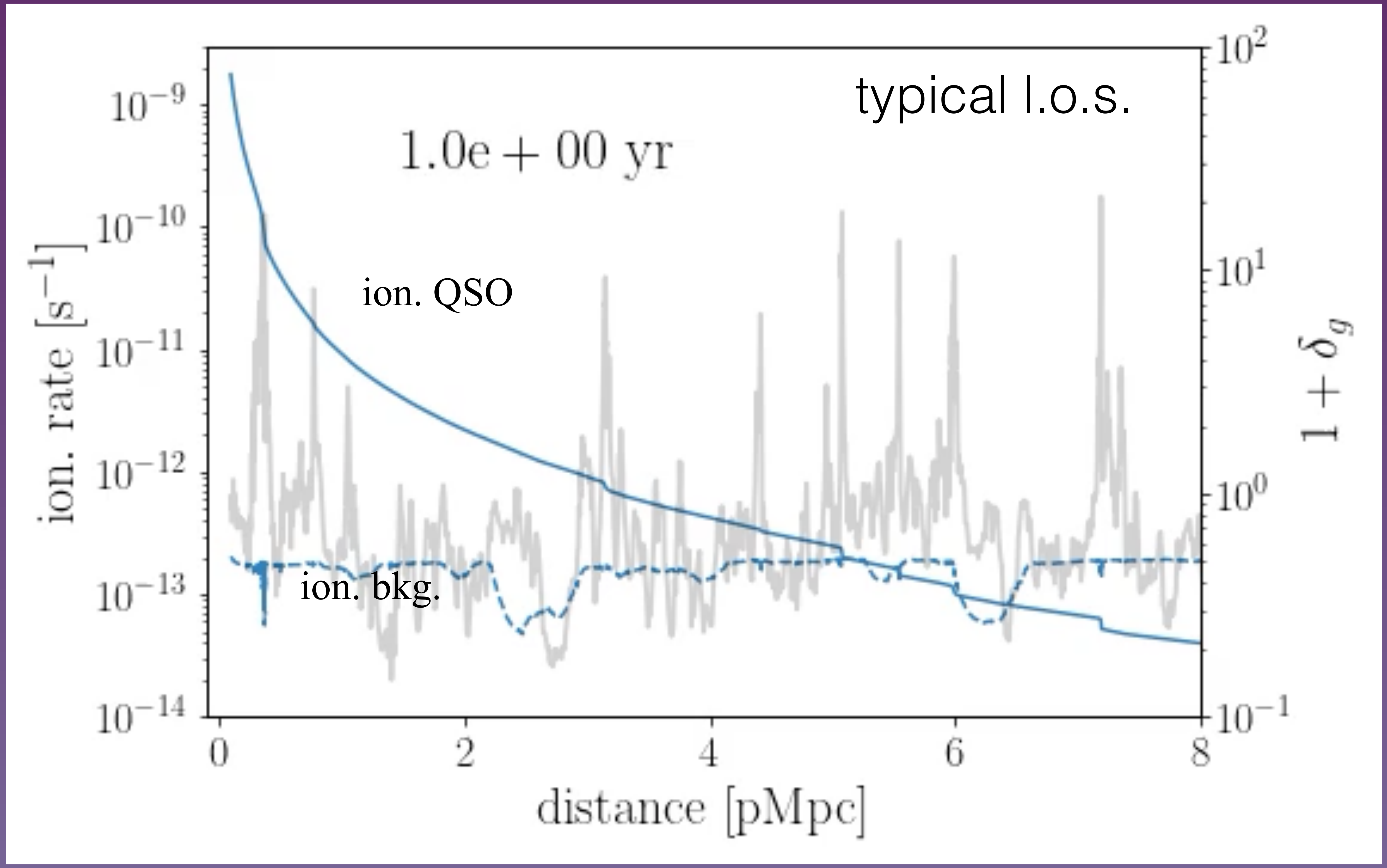
An example sightline at z=6.11:



Recover Density Field

Key insights from simulation:

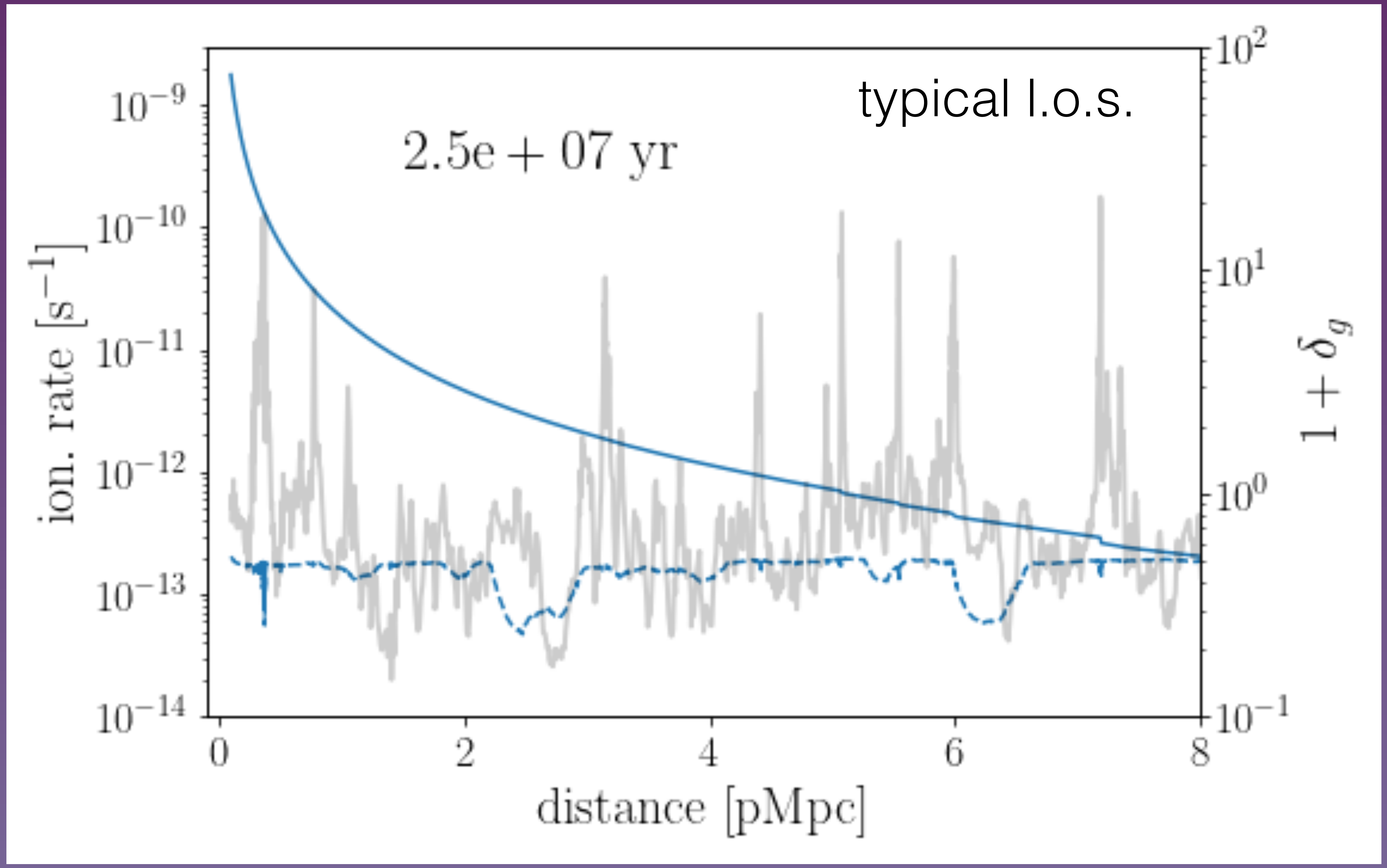
- Pre-LLSs disappear rapidly (radiation profile $\propto r^{-2}$ for most sightlines)

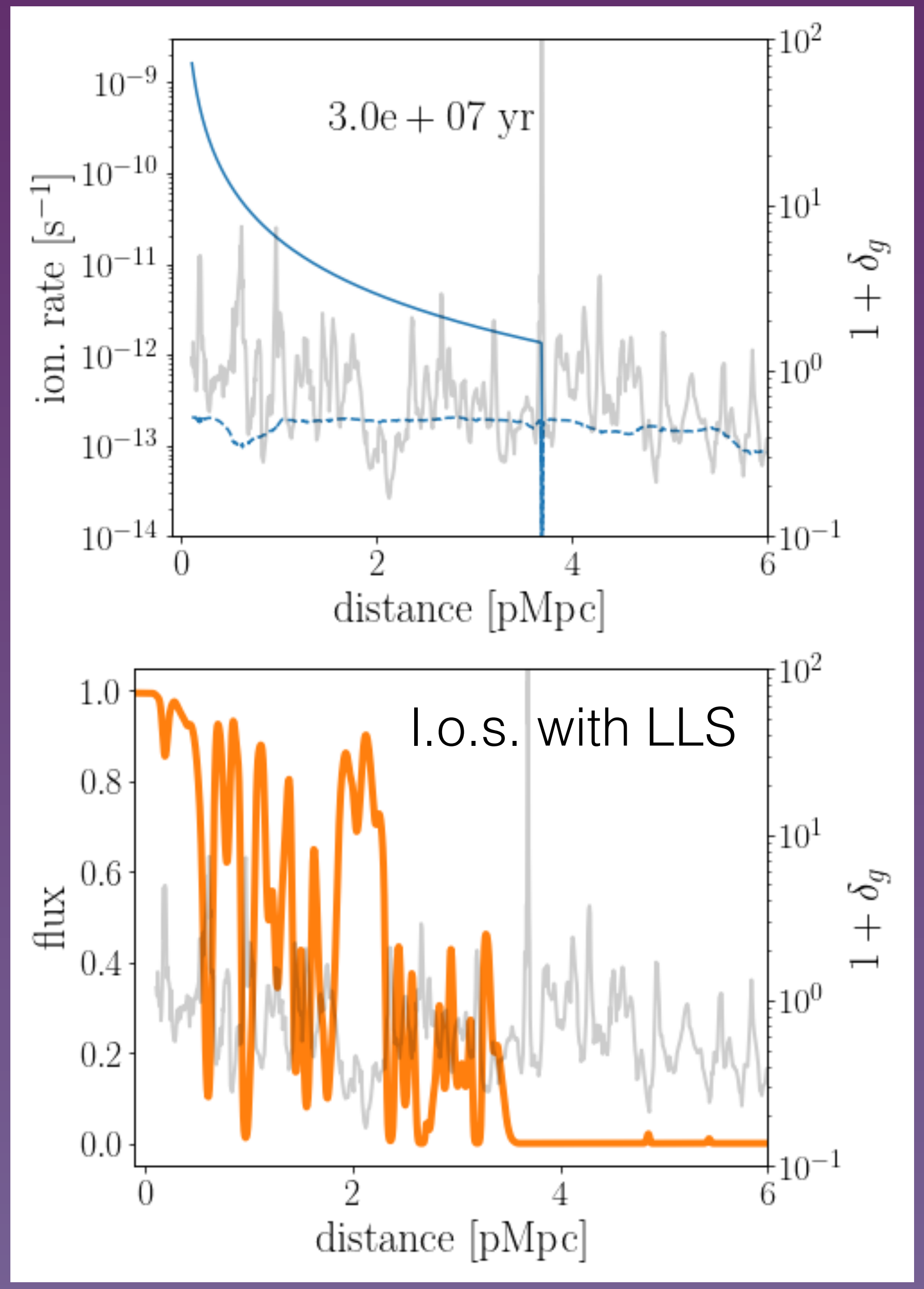


Recover Density Field

Key insights from simulation:

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





Remaing LLSs usually cut off the PZ
Within a PZ, the profile is often a perfect r^{-2}

Recover Density Field

Key insights from simulation:

- Radiation profile reaches perfect r^{-2} for most sightlines
- In ionization equilibrium ($t_{\rm ion}\sim 1/\Gamma$, ~ 0.1Myr at 4 pMpc)

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

$T - \rho$ relation right after reionization is much flatter than that at lower-redshift

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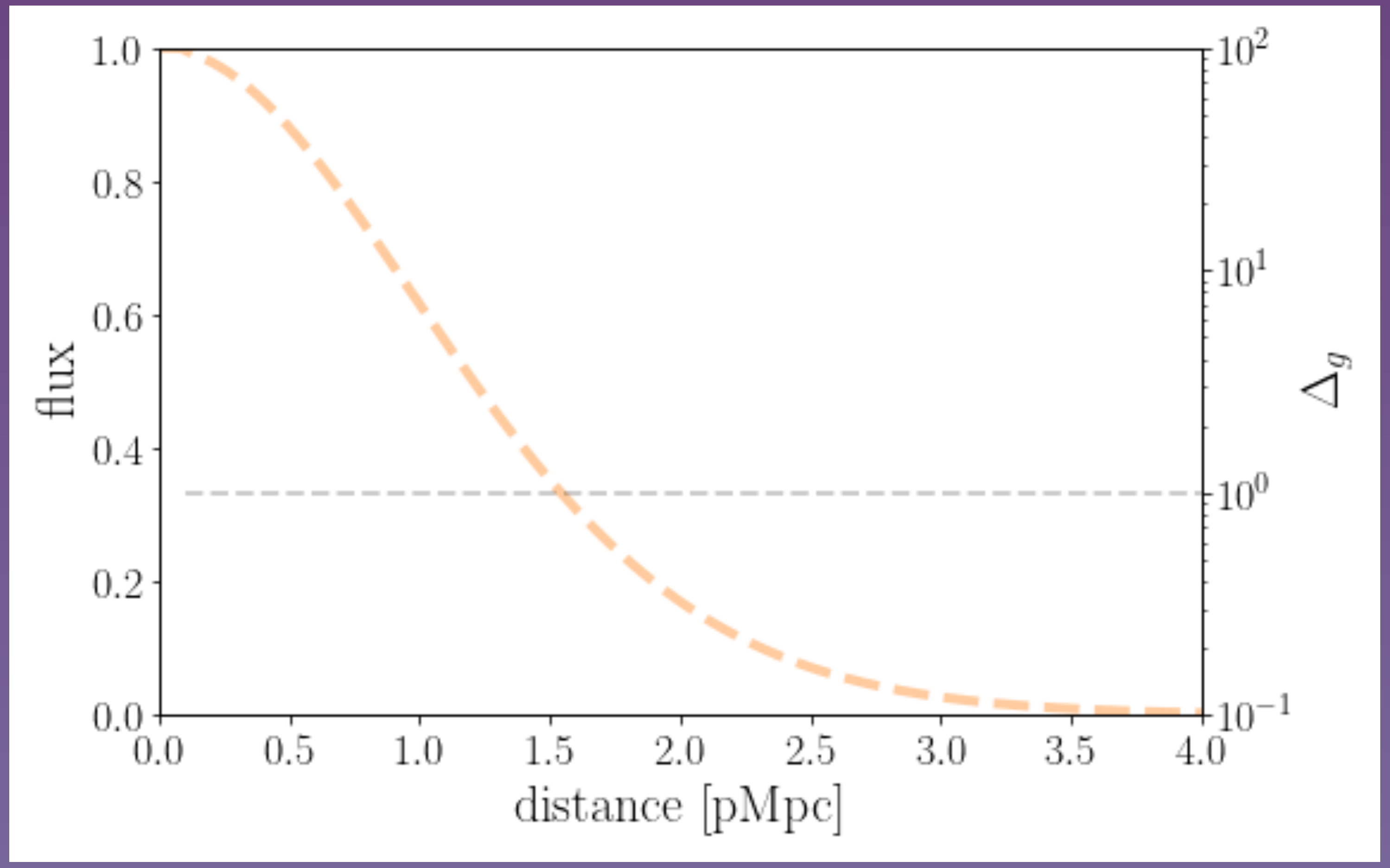

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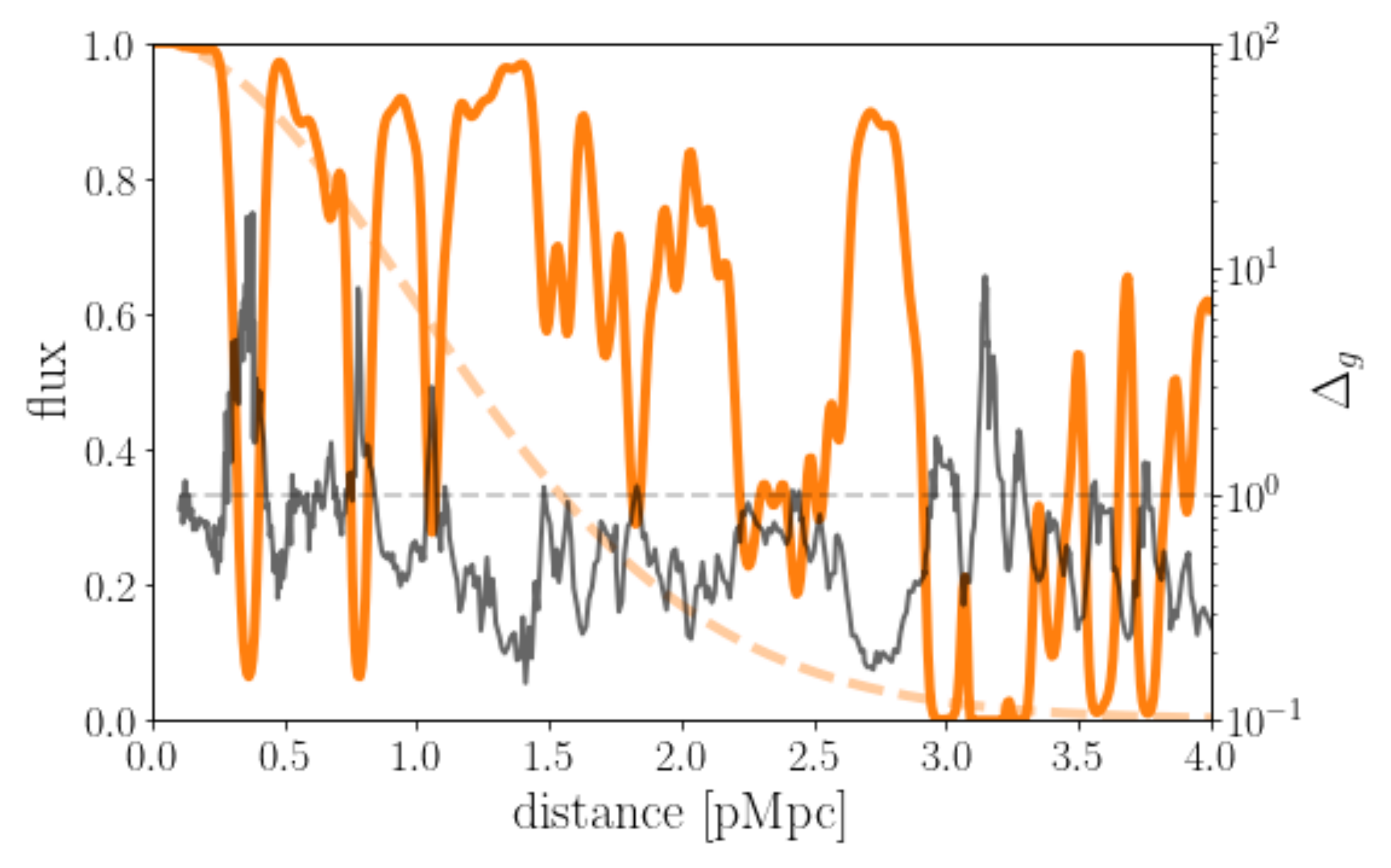

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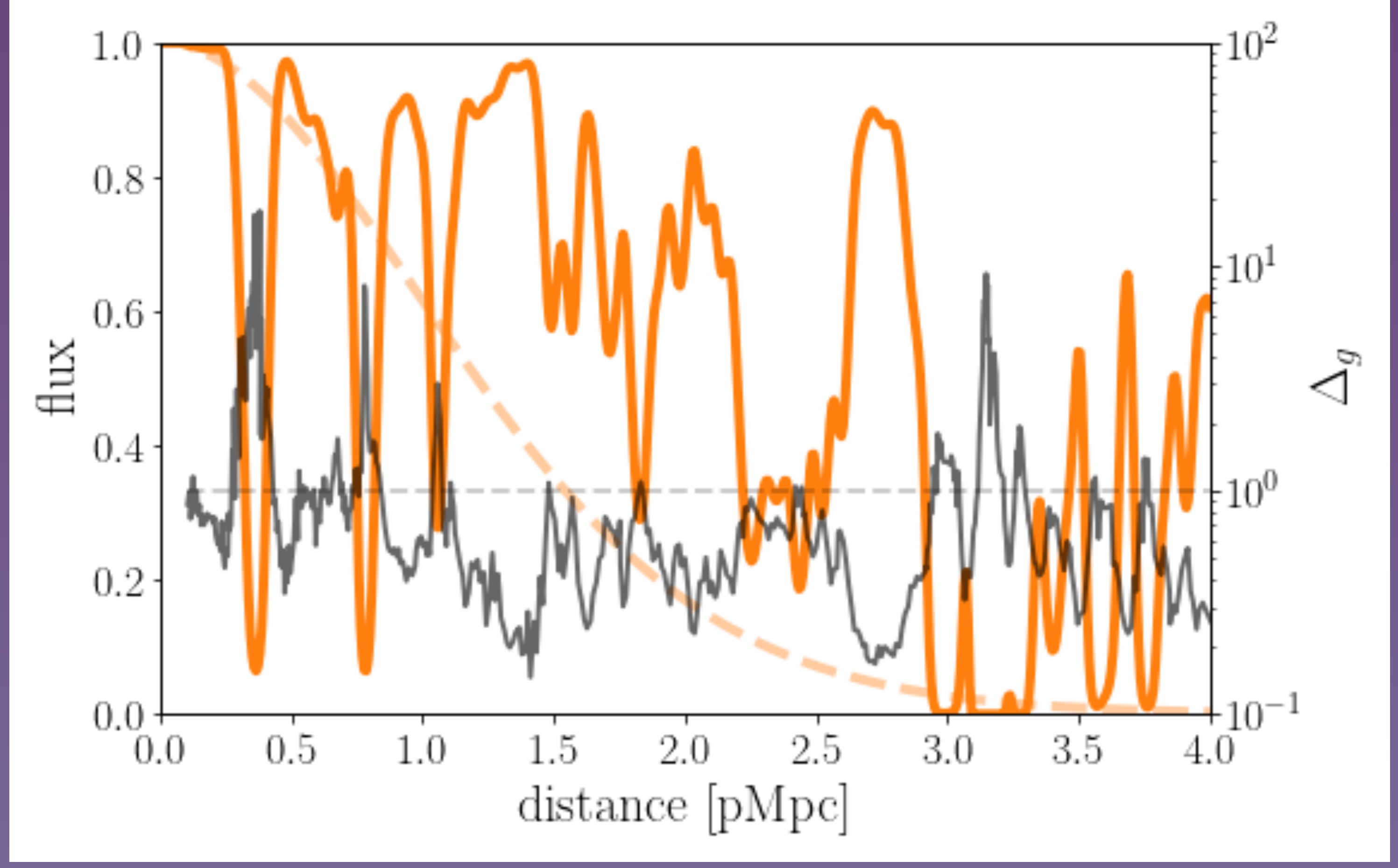

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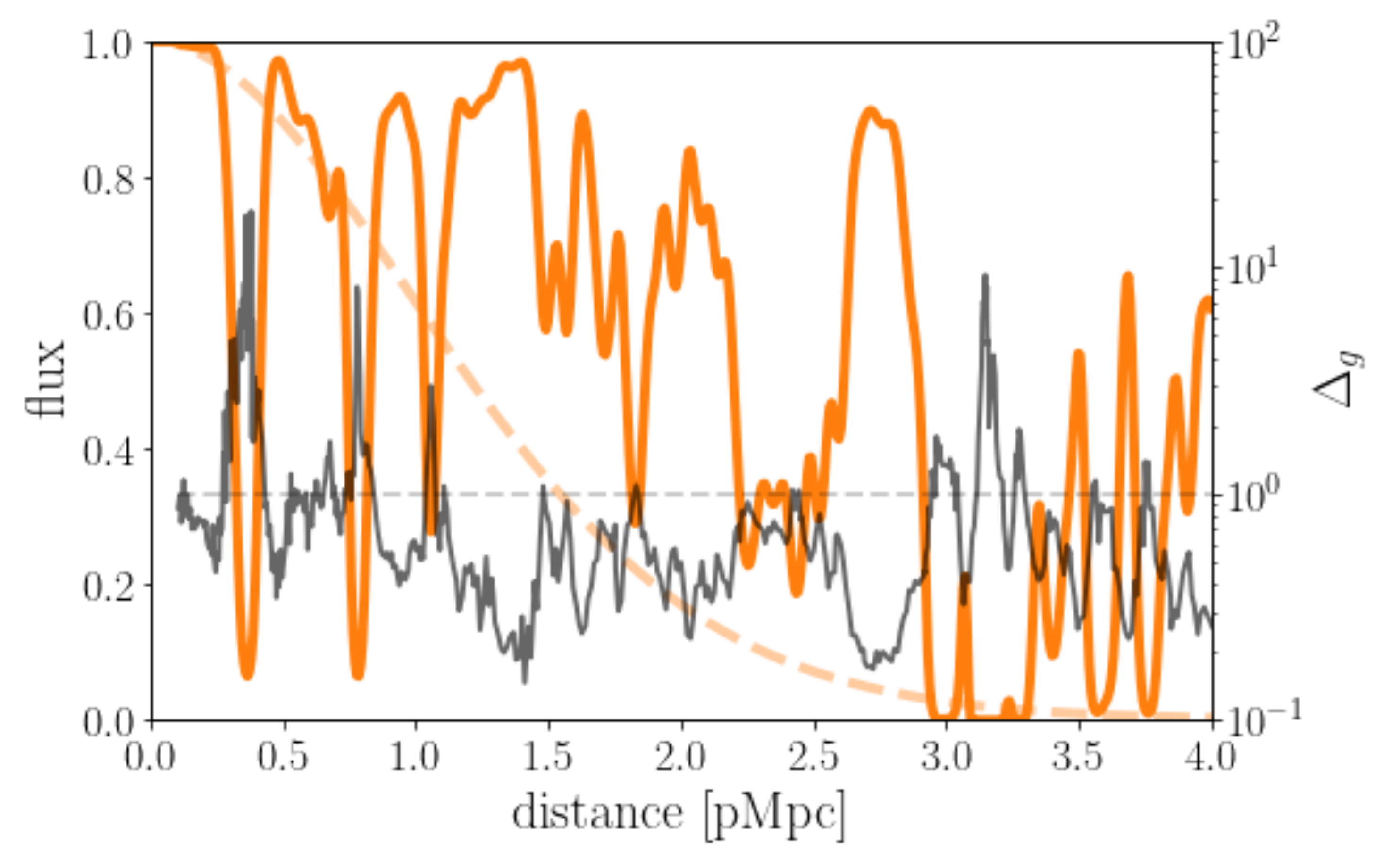

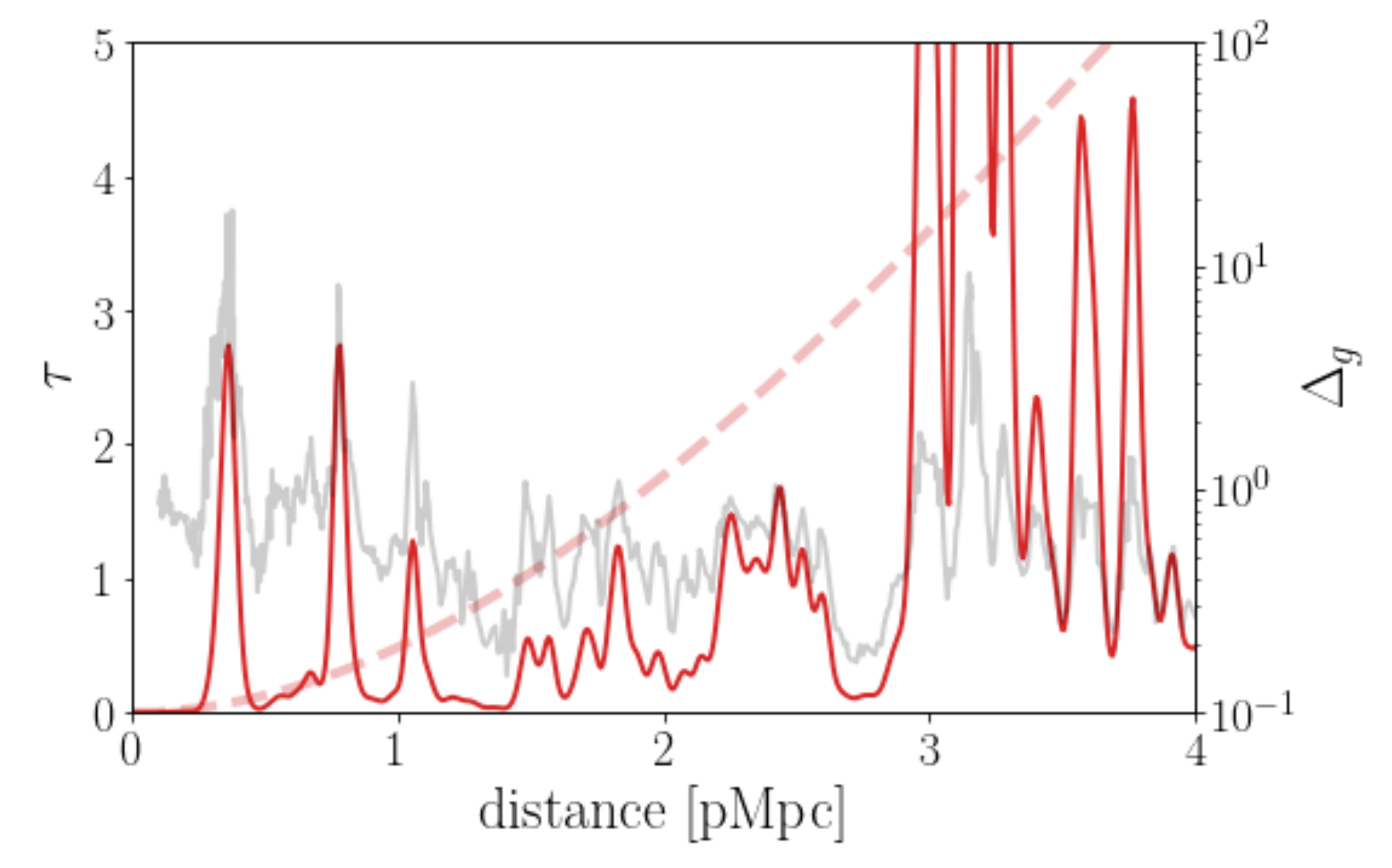

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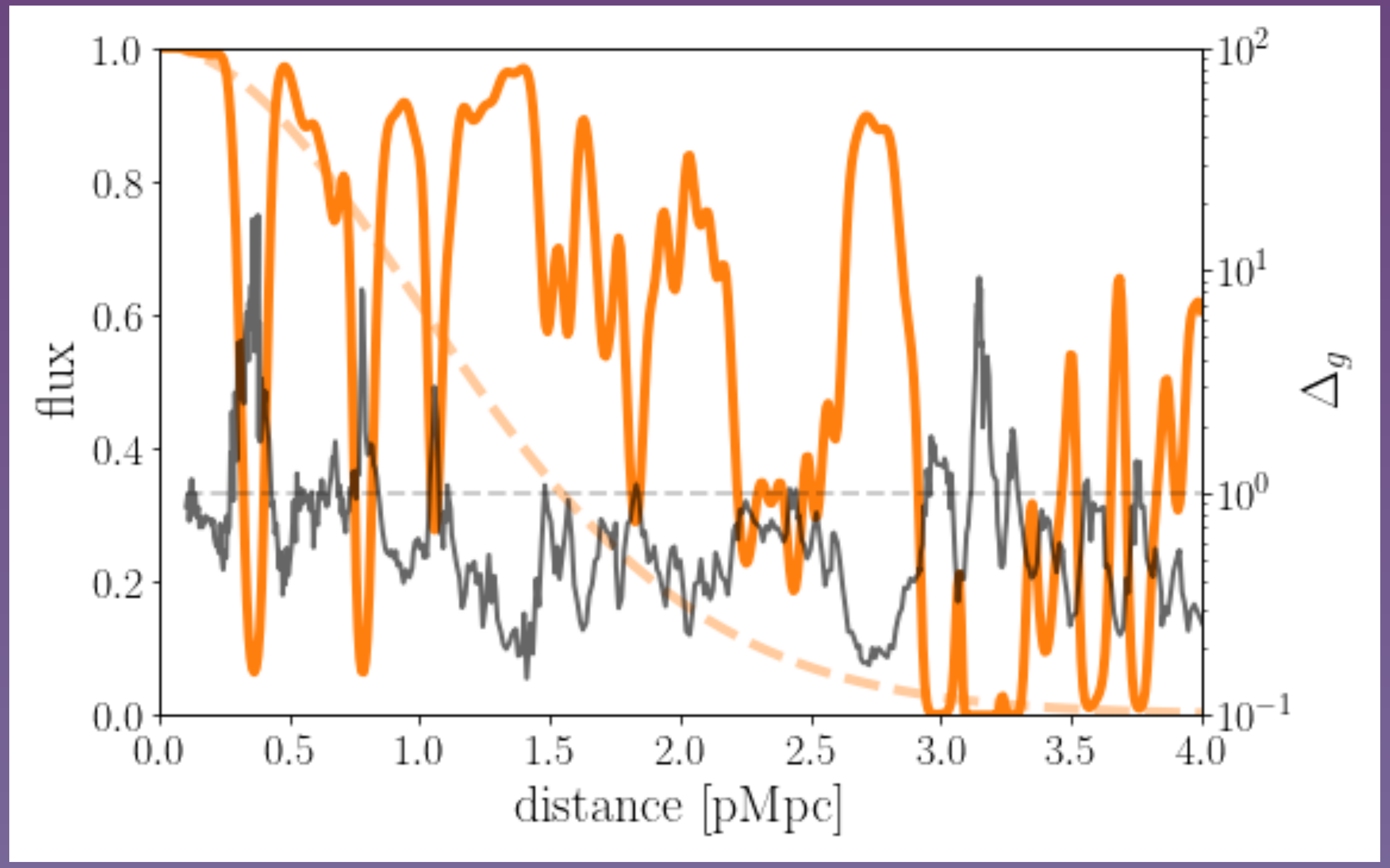
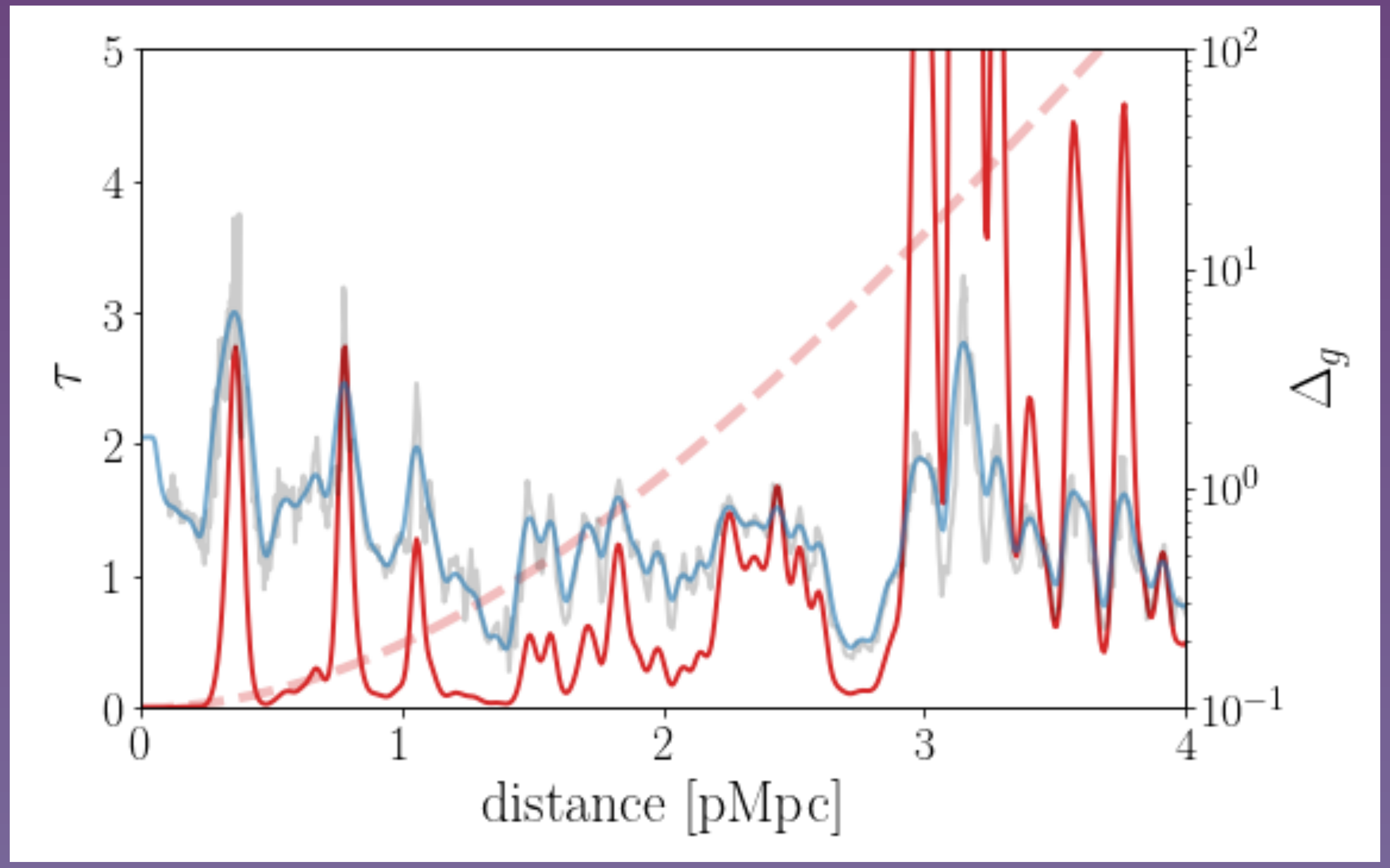
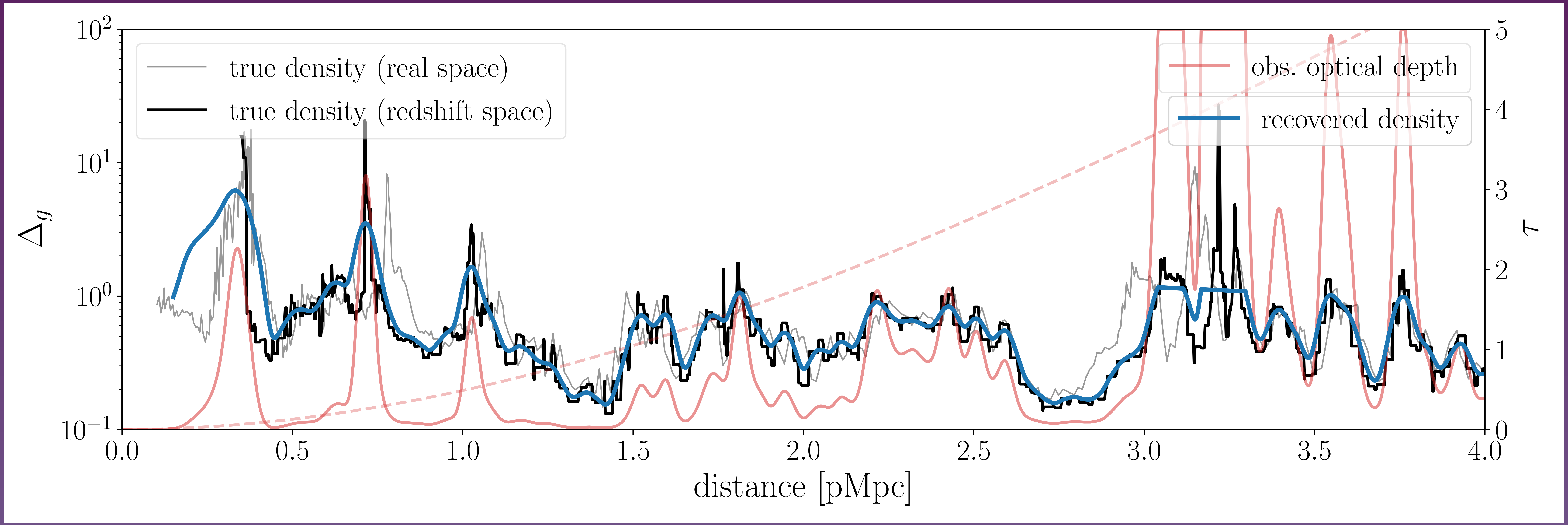


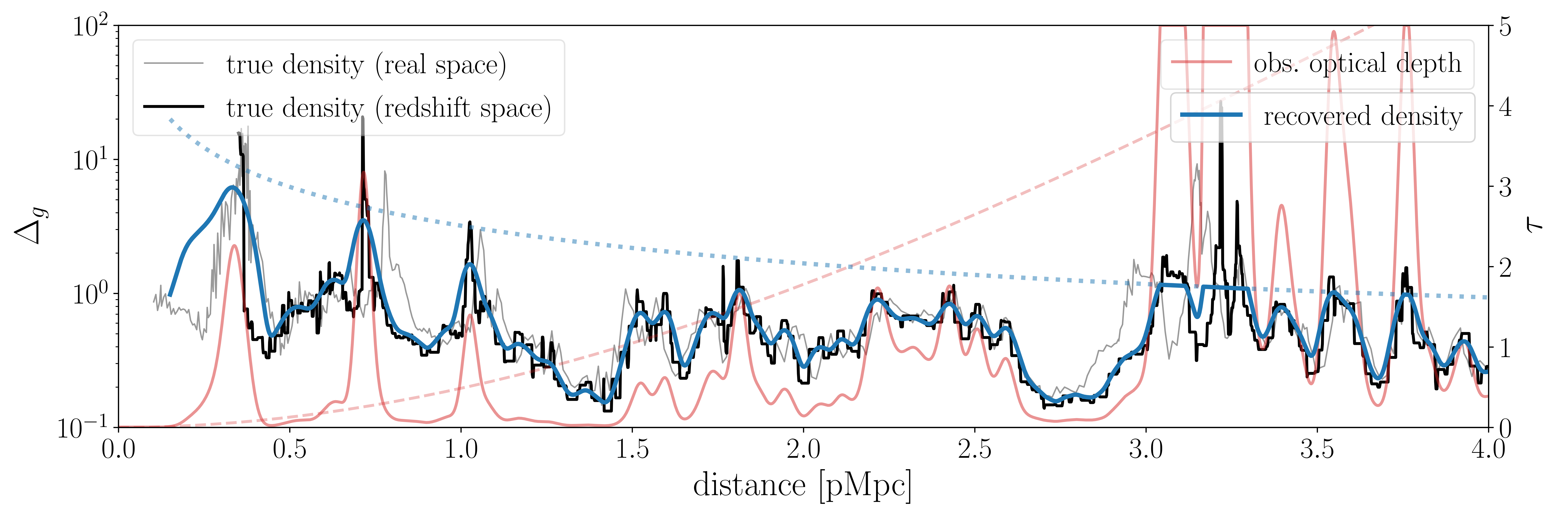


Recovery Result



- Systematic inflow within ~1 pMpc (~7 comoving Mpc)
- We can recover Δ~ 10 at 0.5 pMpc, Δ~ 1 at 4 pMpc (for a M=-26.7 quasar)
- Thermal broadening smooths small scales (~10 pkpc) density fluctuation

Recovery Result



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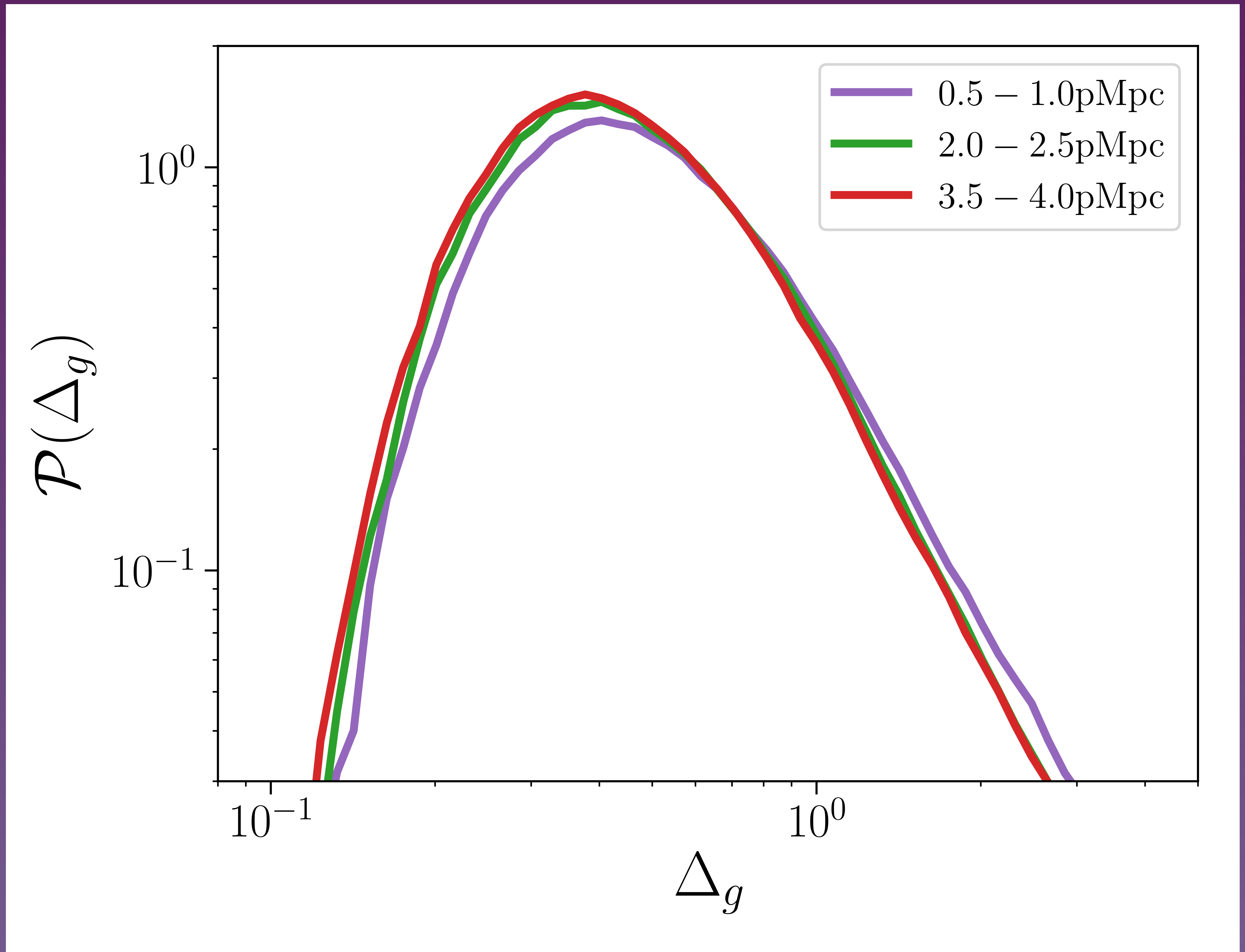
Result: Density PDF



True density field:

$10^{11}\mathrm{M}_\odot$ halos correlate with over density at ~1 pMpc scale

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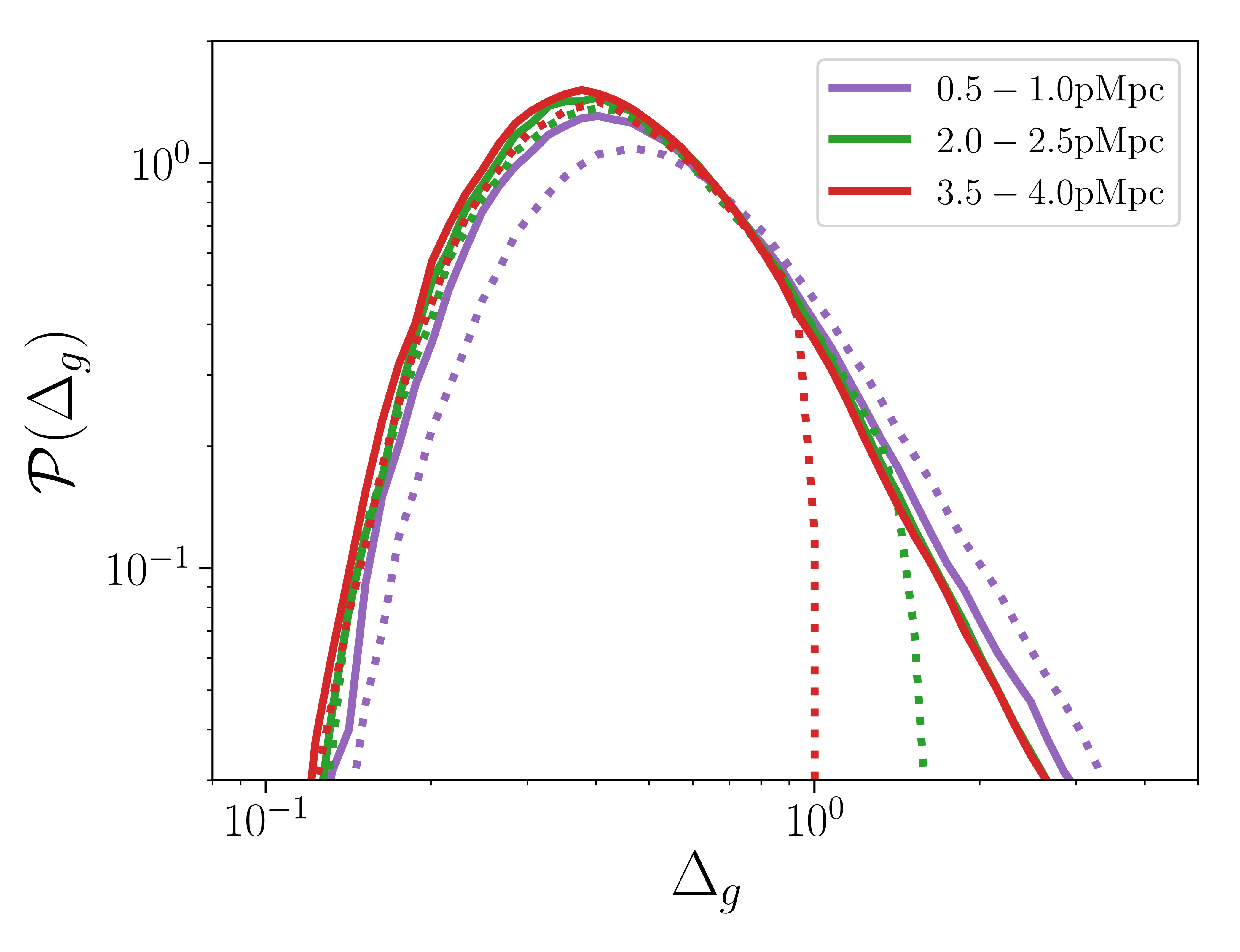


True density field:

$10^{11}M_\odot$ halos correlate with over density at ~1 pMpc scale

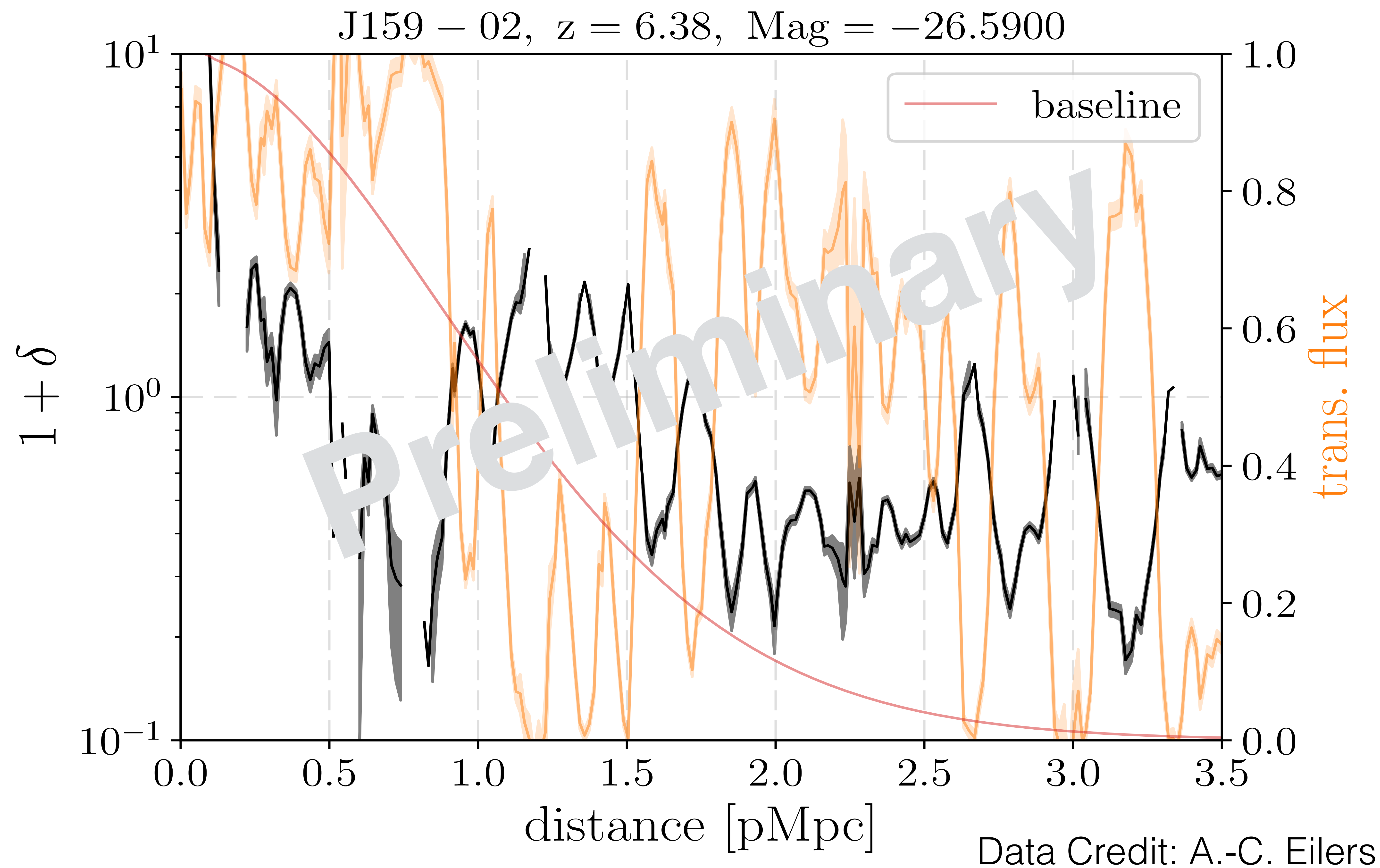
Recovered density field:

within ~1 pMpc, biased high; outside ~1 pMpc, matches well

Quick Summary II: Recover Density

- We can measure the density field in quasar PZ at z~6
- Sensitive to $\Delta < 10$, scatter of ~ 30%
- Recovered density PDFs match true PDFs at > 1 pMpc
- The deviation of the recovered density PDF from the "true" one encodes information of quasar (environment, age, etc.)

Preliminary Results: Apply to Observed Spectra



Data Credit: A.-C. Eilers

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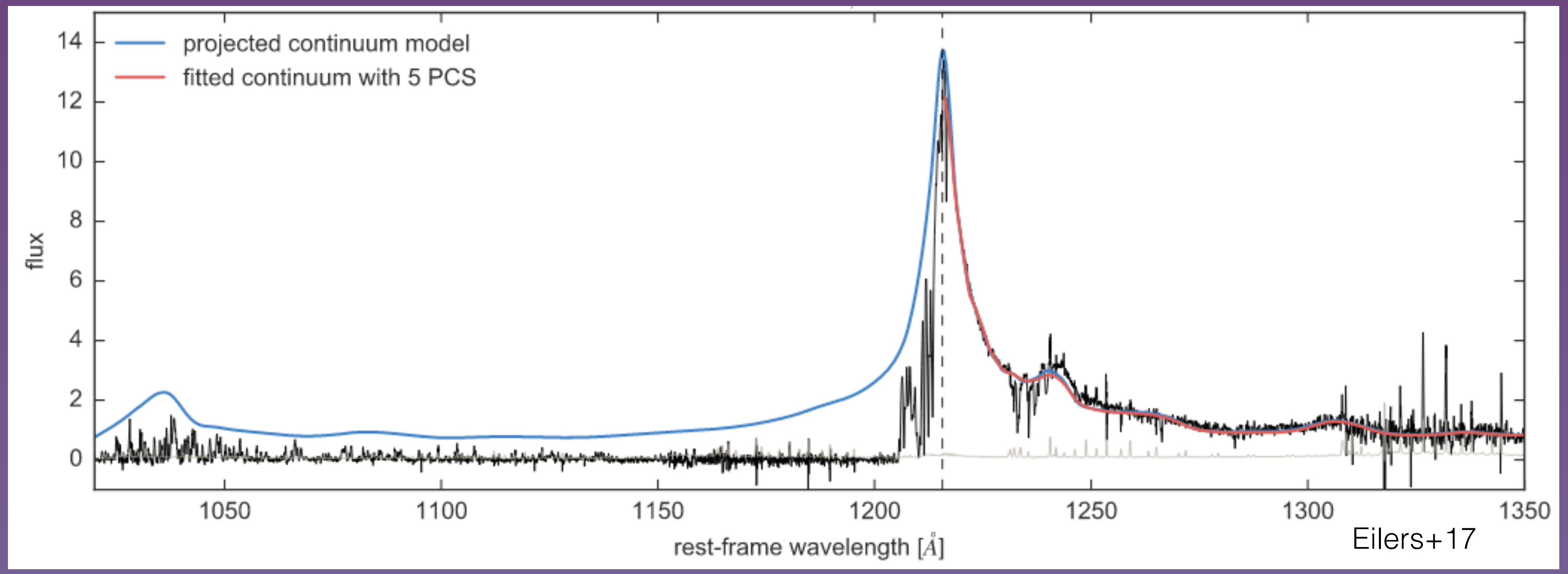
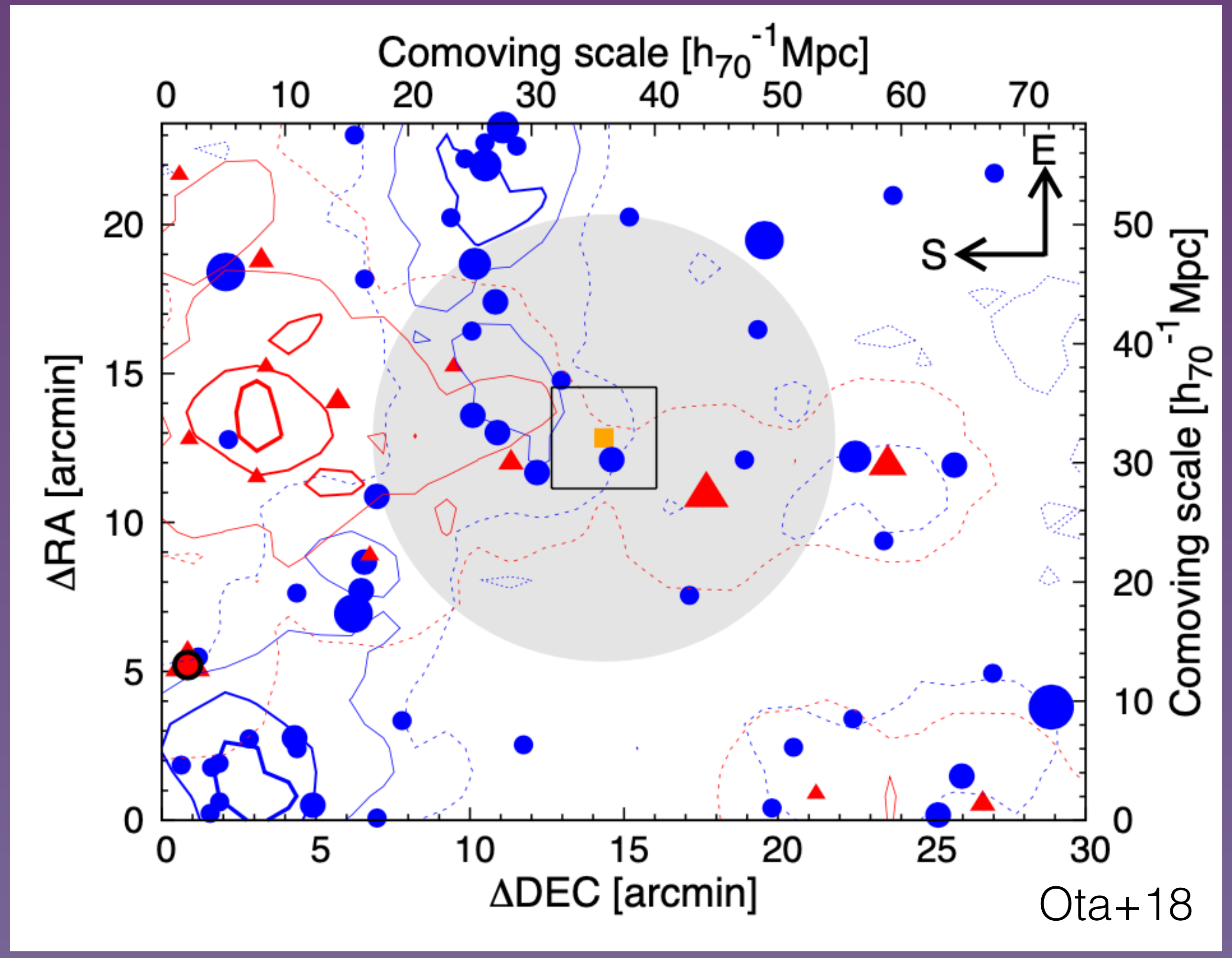


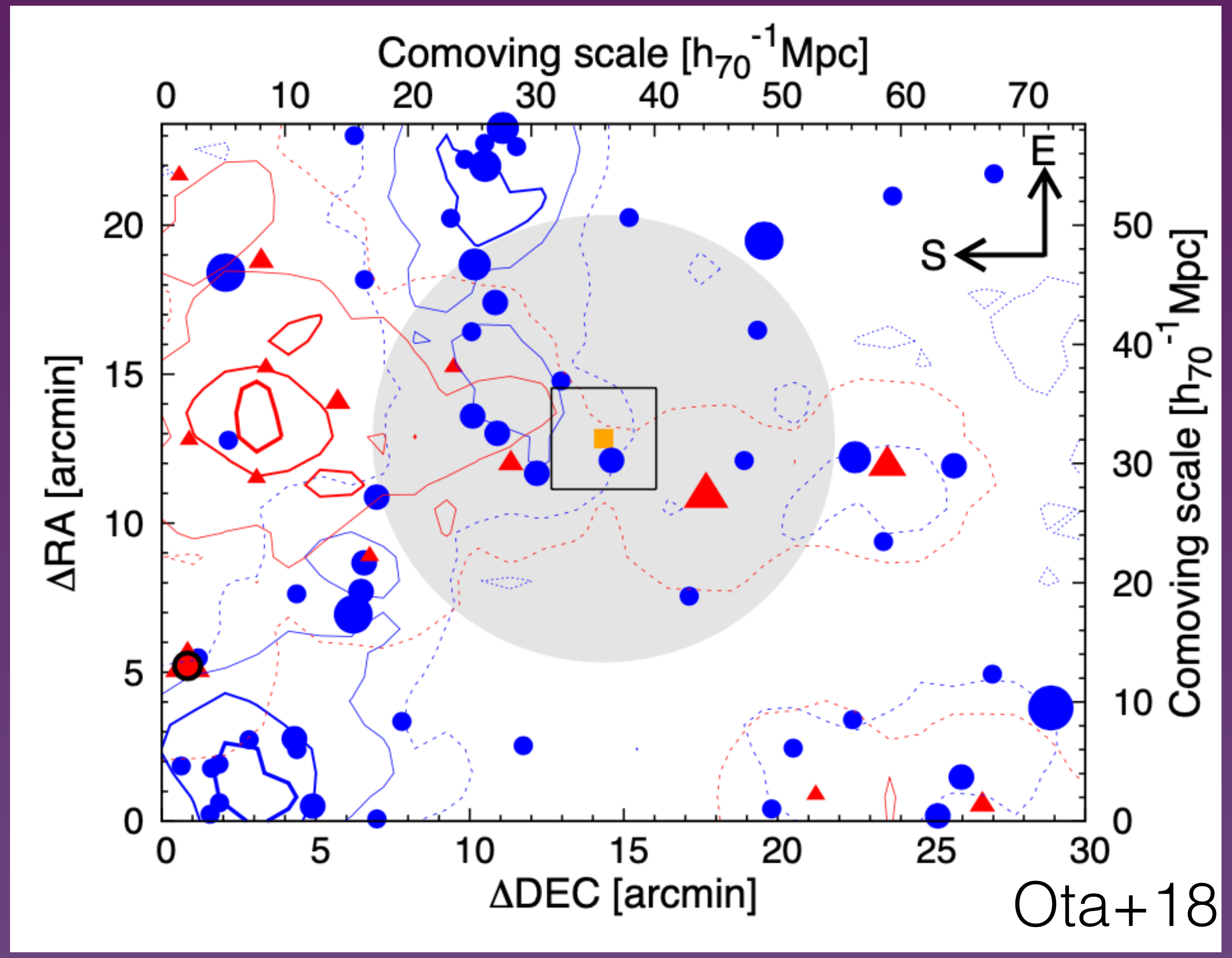
Quasar reionization feedback mimic reionization: **Study the quasar field!**

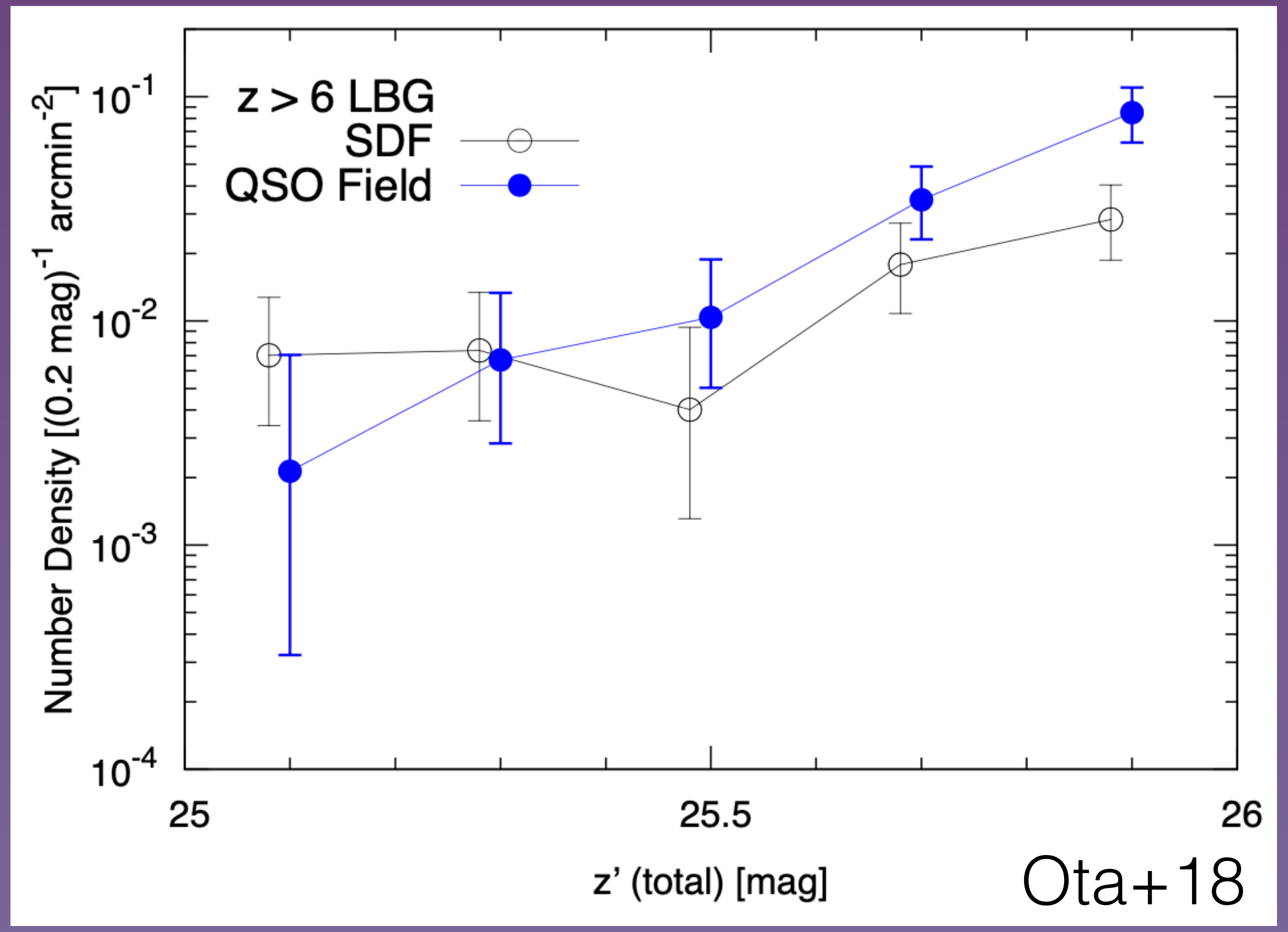


Imaging the Quasar Fields

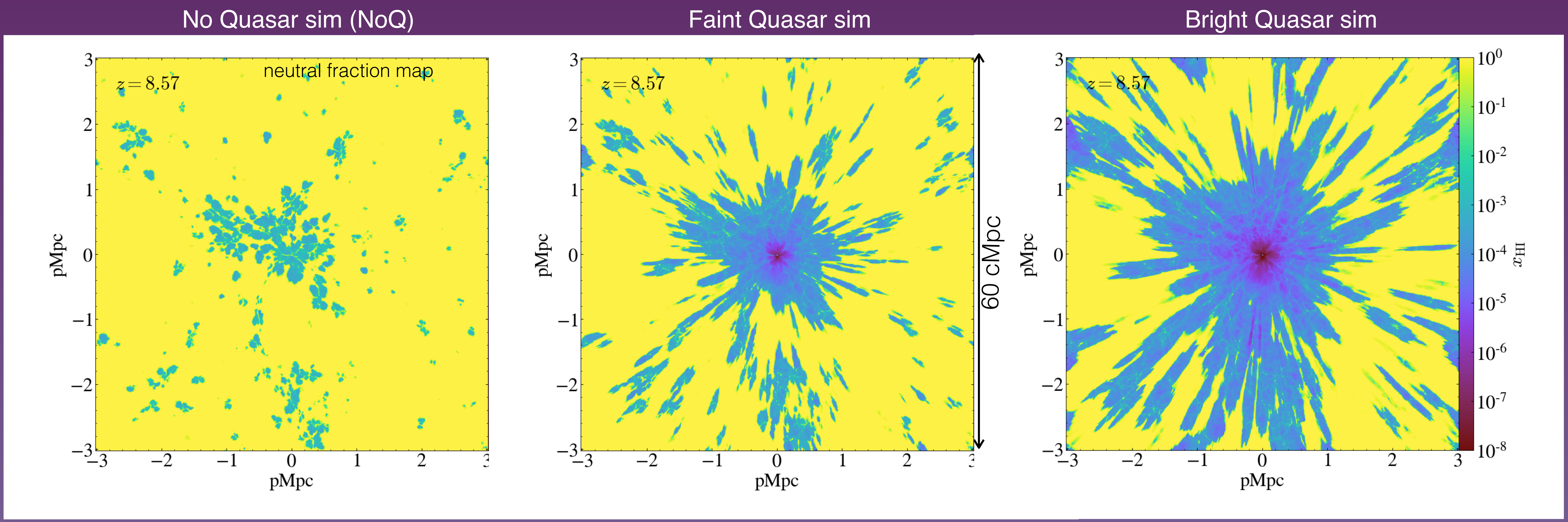
Motivation to study galaxies in quasar fields:

- Galaxies trace matter distribution (another way to construct density field, constrain the environment of first quasars)
- Study how galaxies formation in strong radiation field — an alternative way to constrain reionization effect on galaxy formation

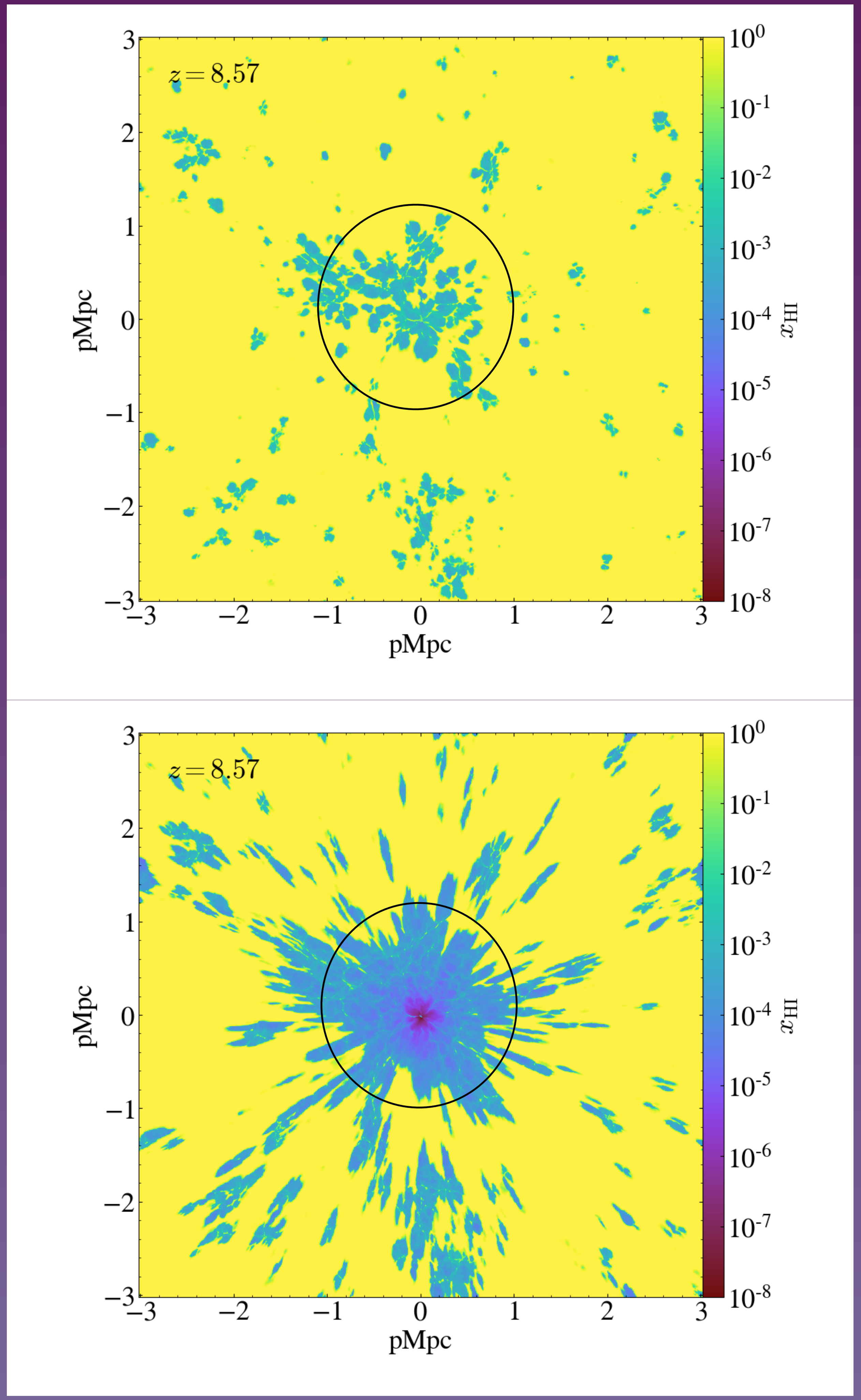


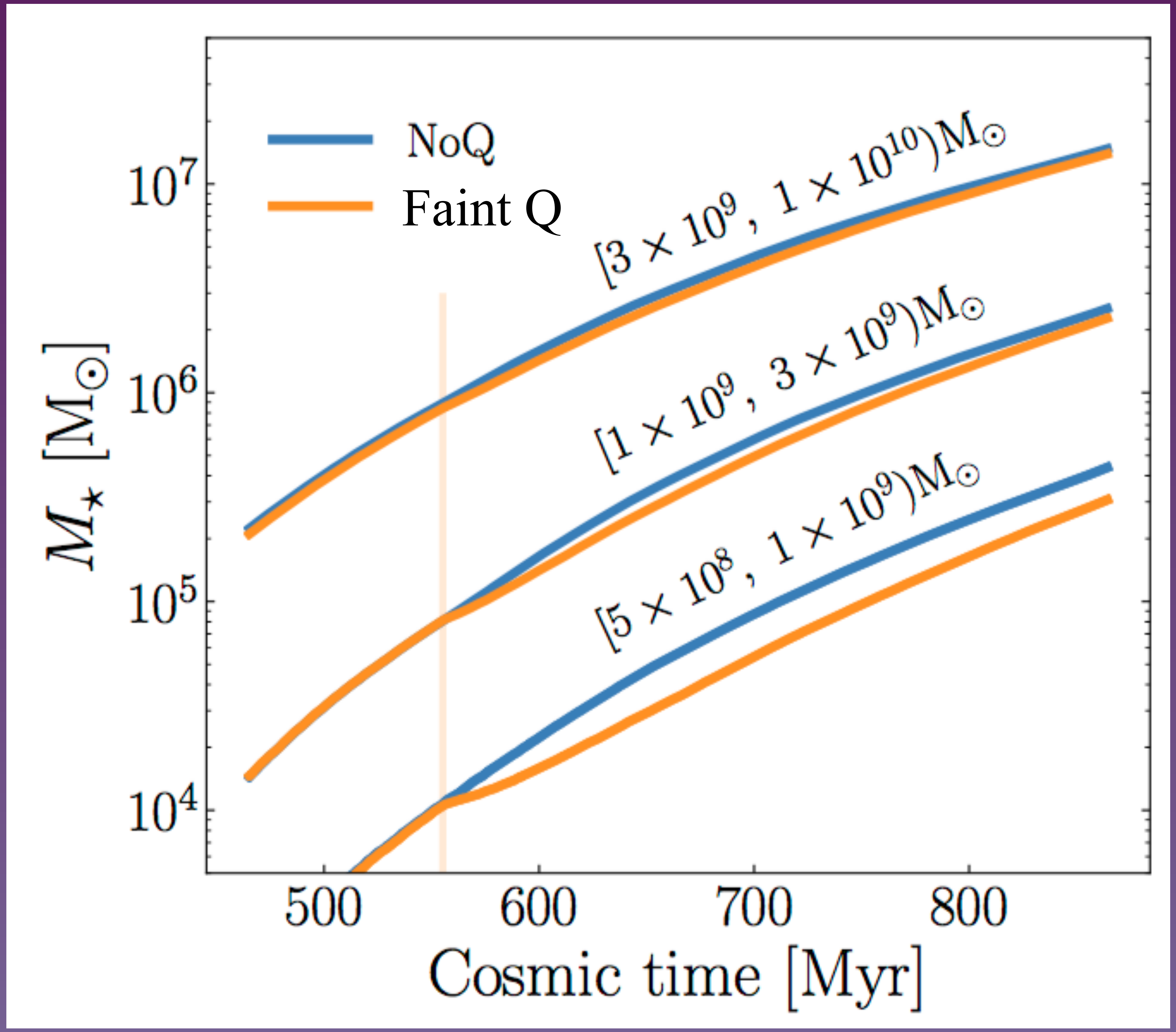


Galaxy Formation in Quasar Fields



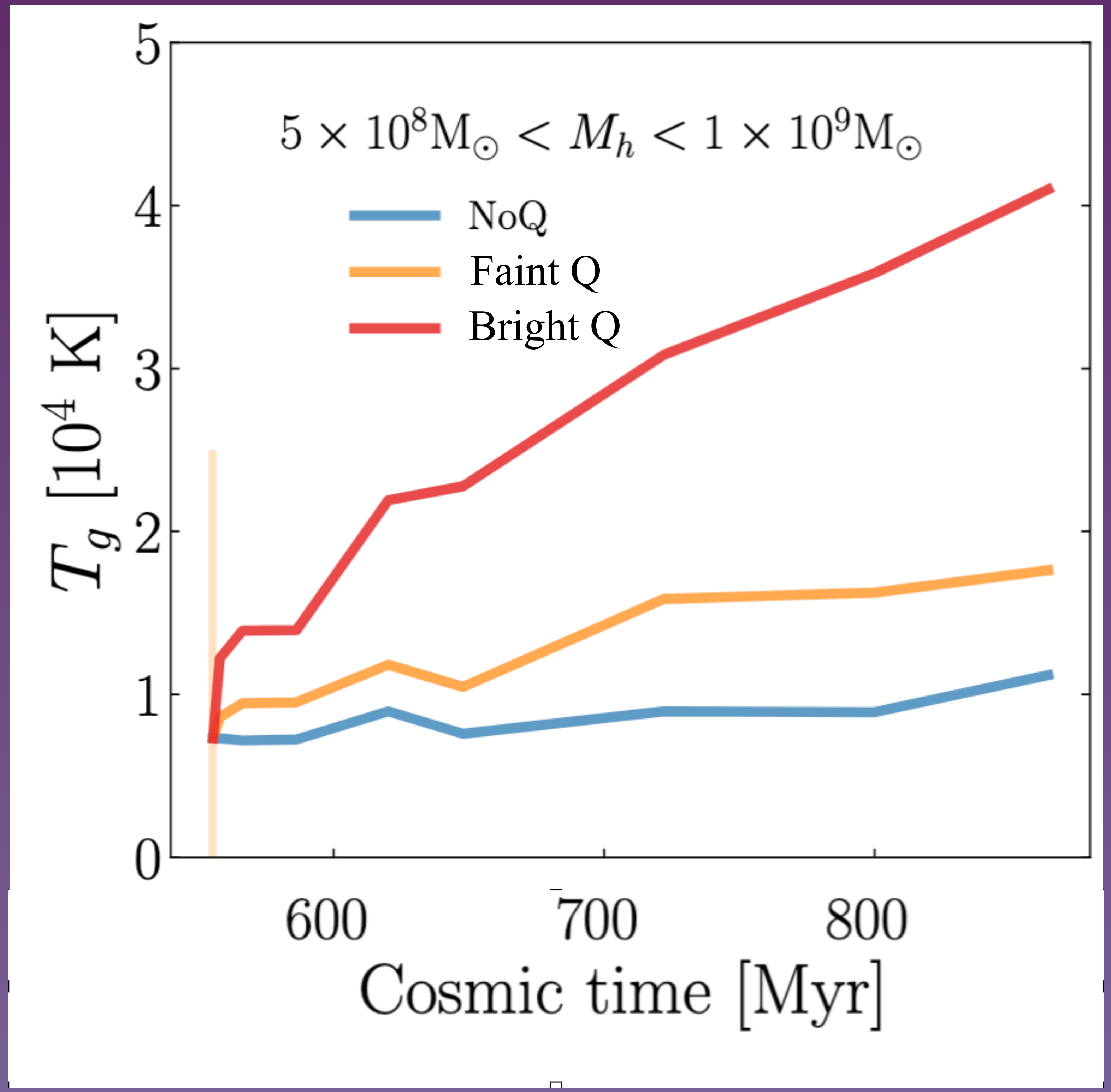
Low Mass Halo Suppressed



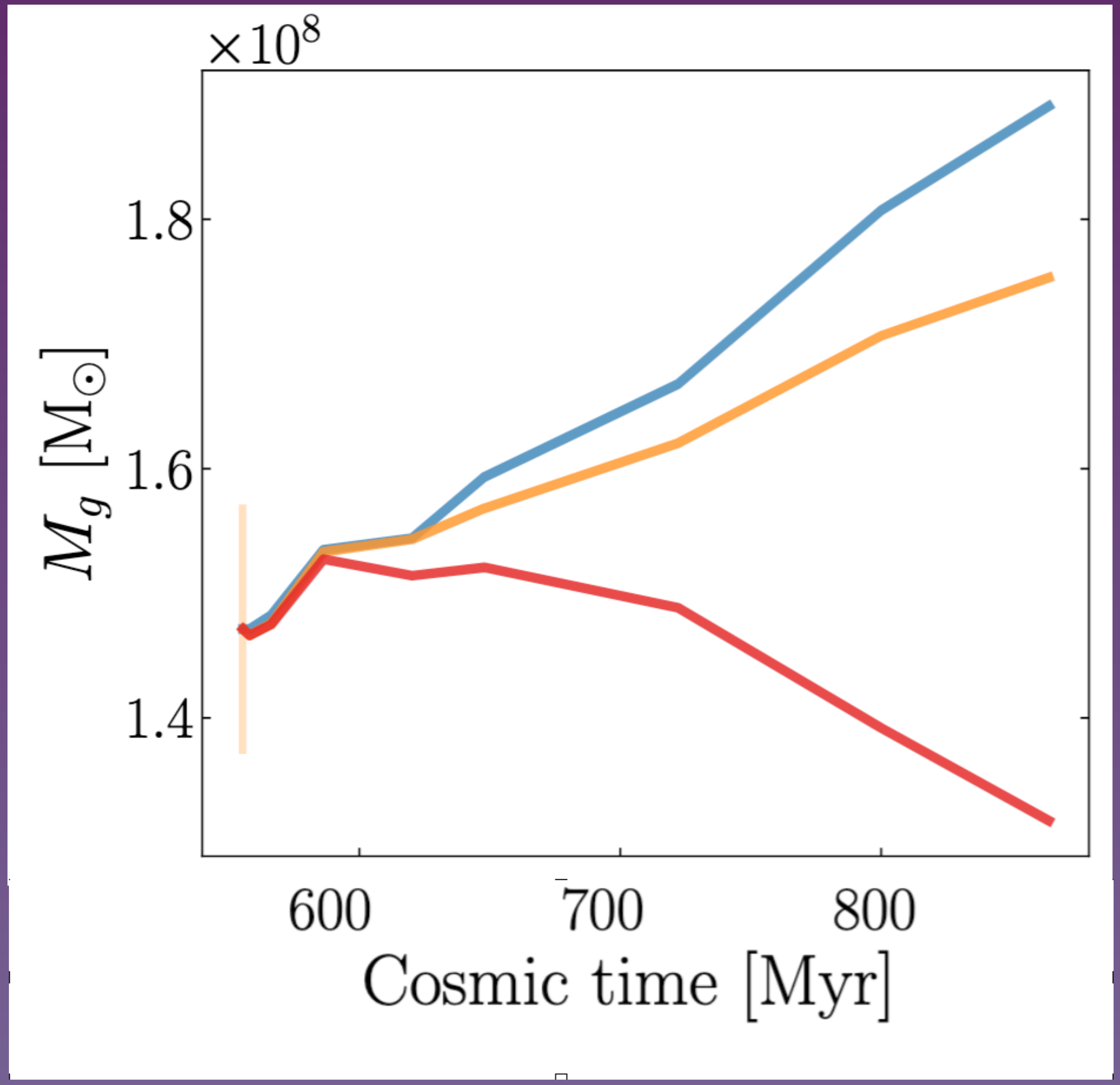


Photoheating reduces gas accreting

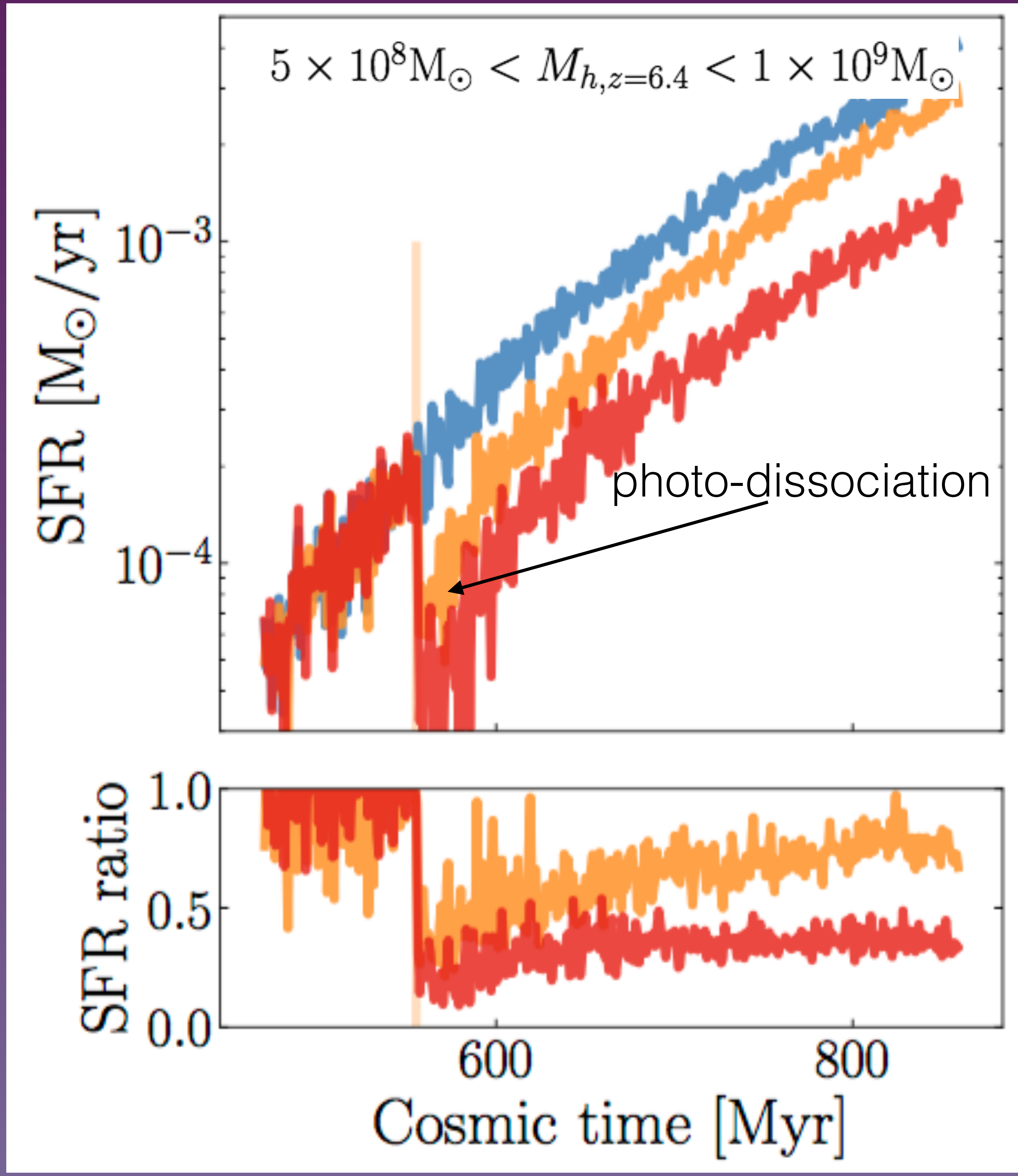
Temperature

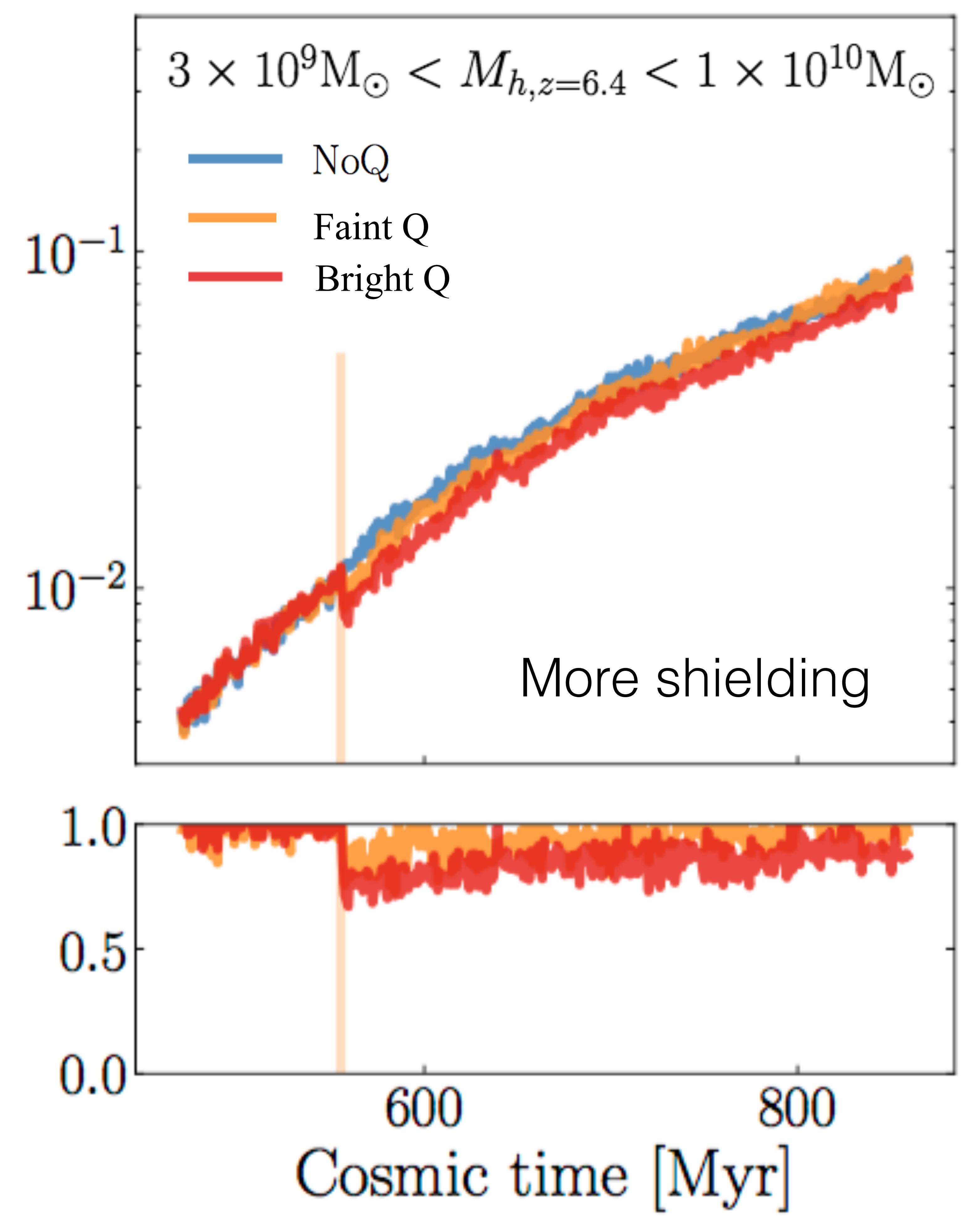


Gas Mass

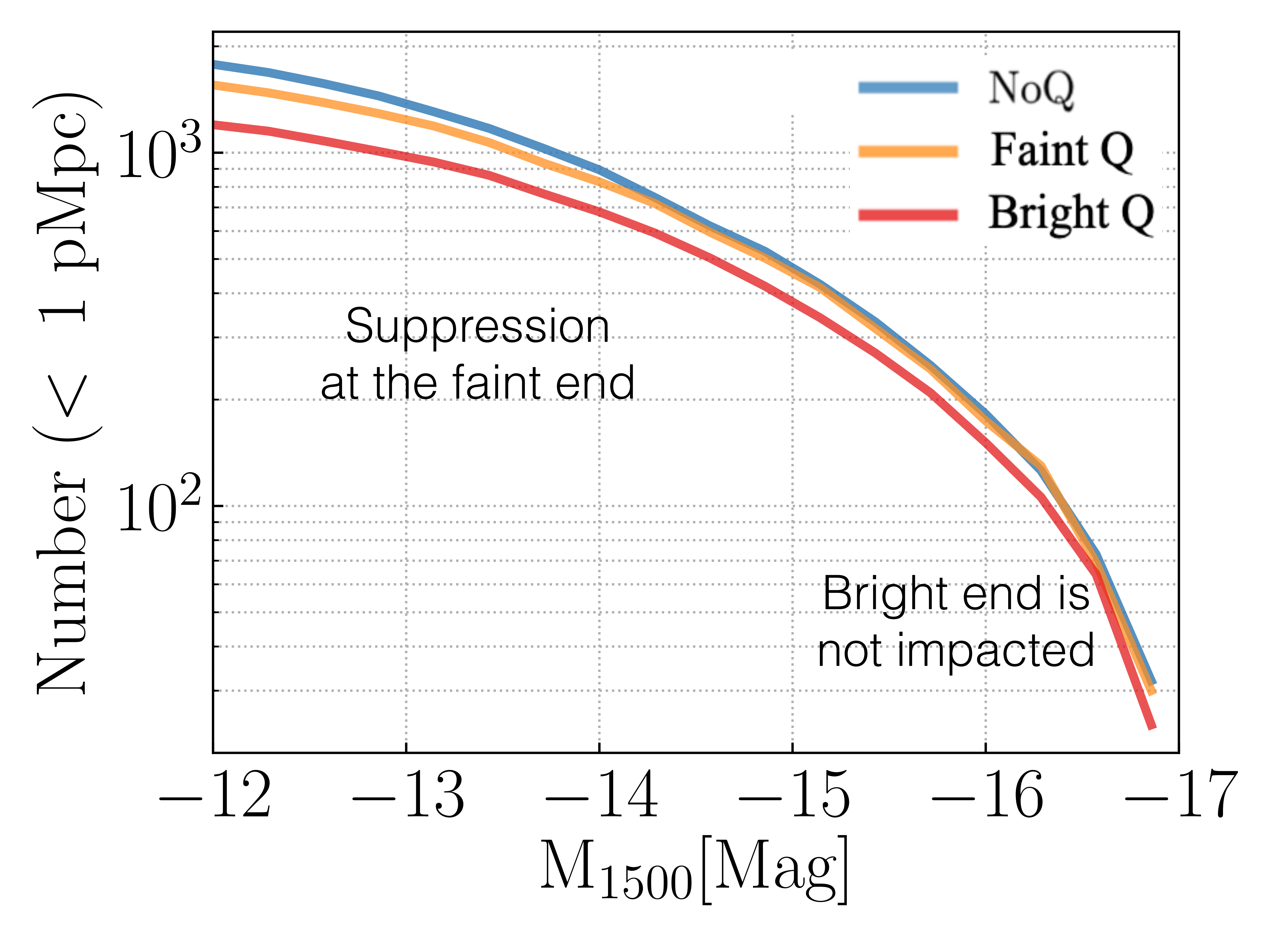


Suppression due to H_2 destruction

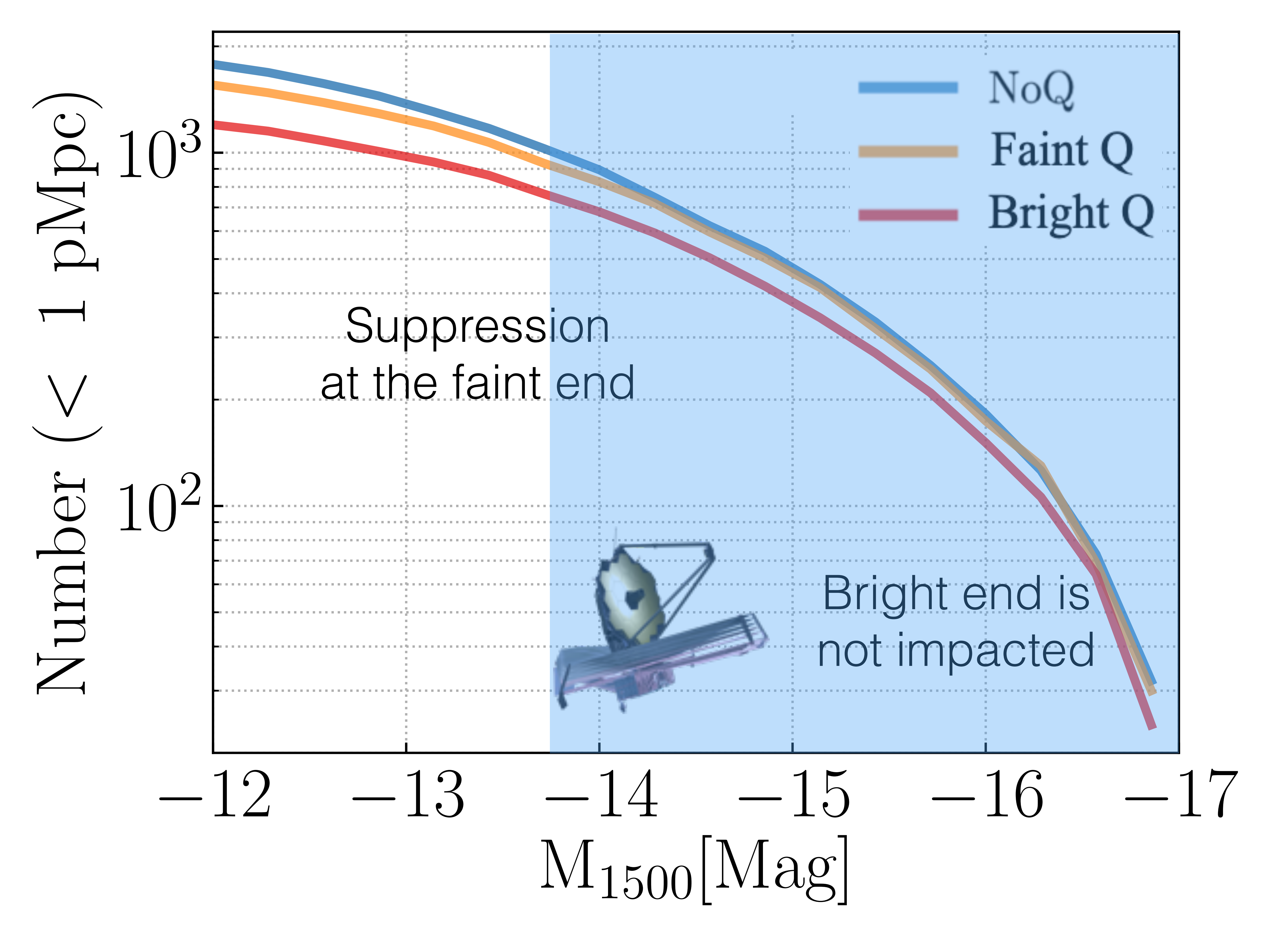




Observable: Luminosity Function



Observable: Luminosity Function



Quick Summary III: Radiative Feedback

- Quasar radiative feedback suppresses star formation in low mass halos
- Photodissociation is the main suppression mechanism, happening in short timescales
- Photoheating contributes to the suppression in long 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 galaxy-quasar co-evolution

Future Prospect

- James Webb Space Telescope:

  Reionization is one of the primary scientific goals

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

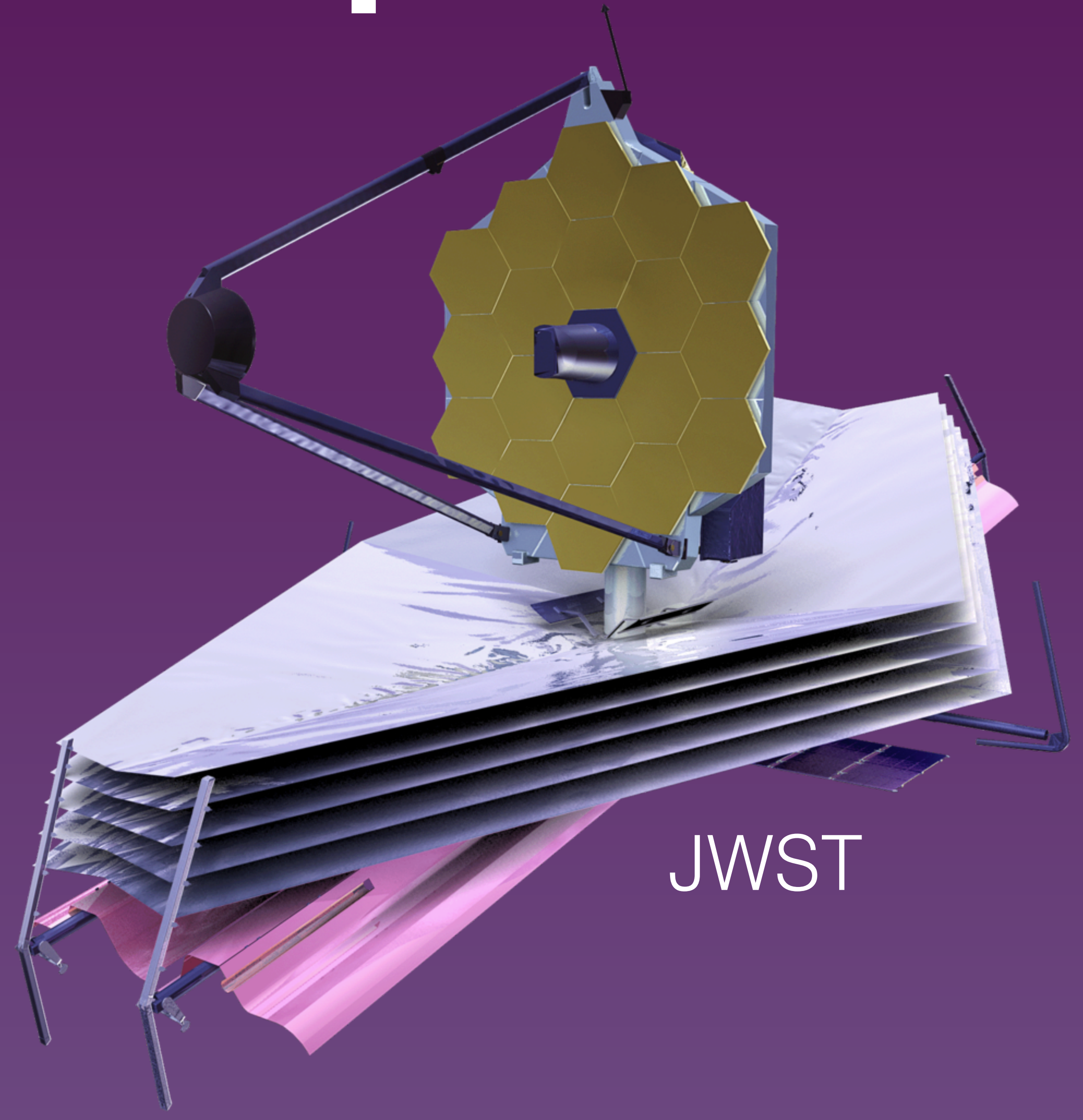
- 30m class telescopes:

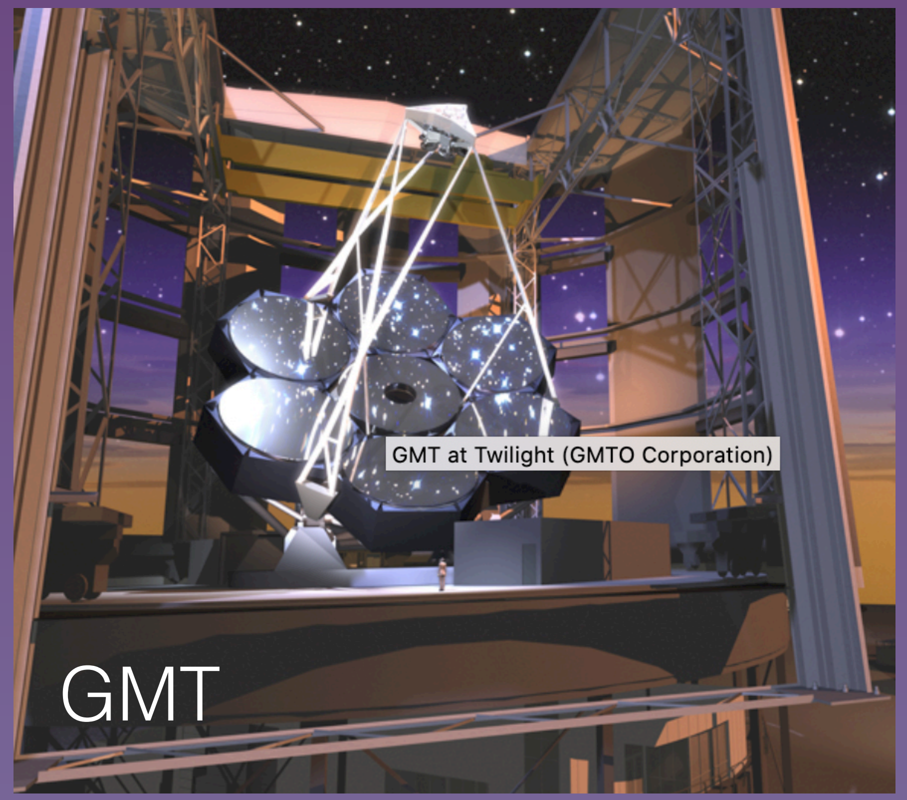
  Obtain high resolution spectra within an hour !

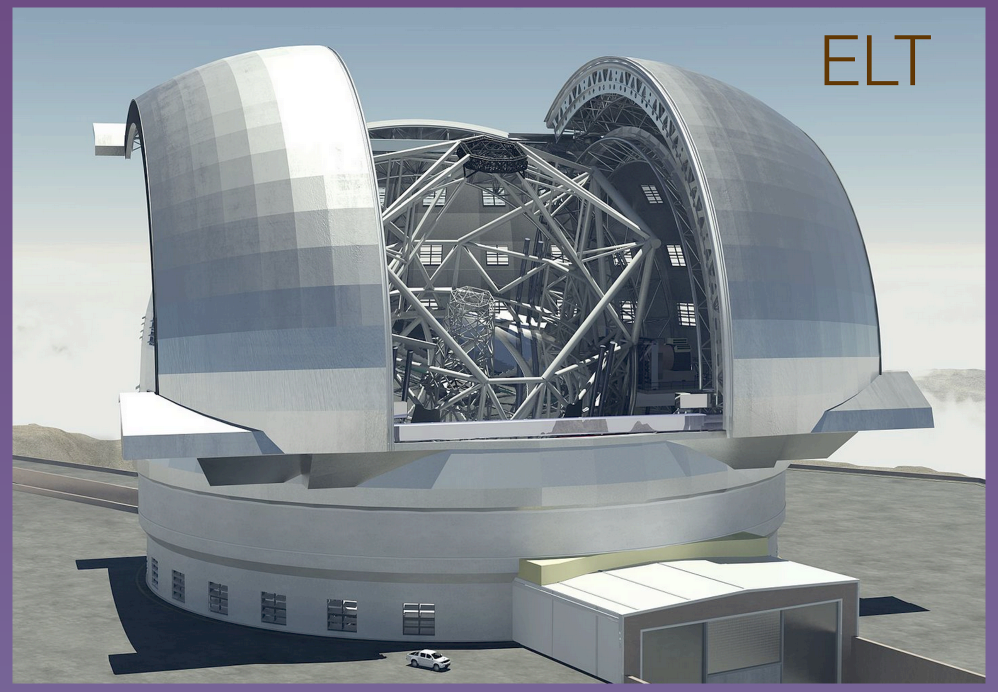
- Existing facilities like ALMA:

  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 radiation 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.)