

# The Role of Galaxies and AGN during Reionization

— Insights from JWST ASPIRE QSO fields and IGM Tomography —

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**DAWN**

COSMIC DAWN CENTER

Nordita, Cosmic Dawn at High Latitudes, 24 June 2024



UNIVERSITY OF  
COPENHAGEN

# JWST pushes the frontier of distant galaxies & reionization ...



**Credit: NIRCам GOODS-South field**

NASA, ESA, CSA, B. Robertson, B. Johnson, S. Tacchella, M. Rieke, D. Eisenstein, A. Pagan

**JWST pushes the frontier of distant galaxies & reionization ...**

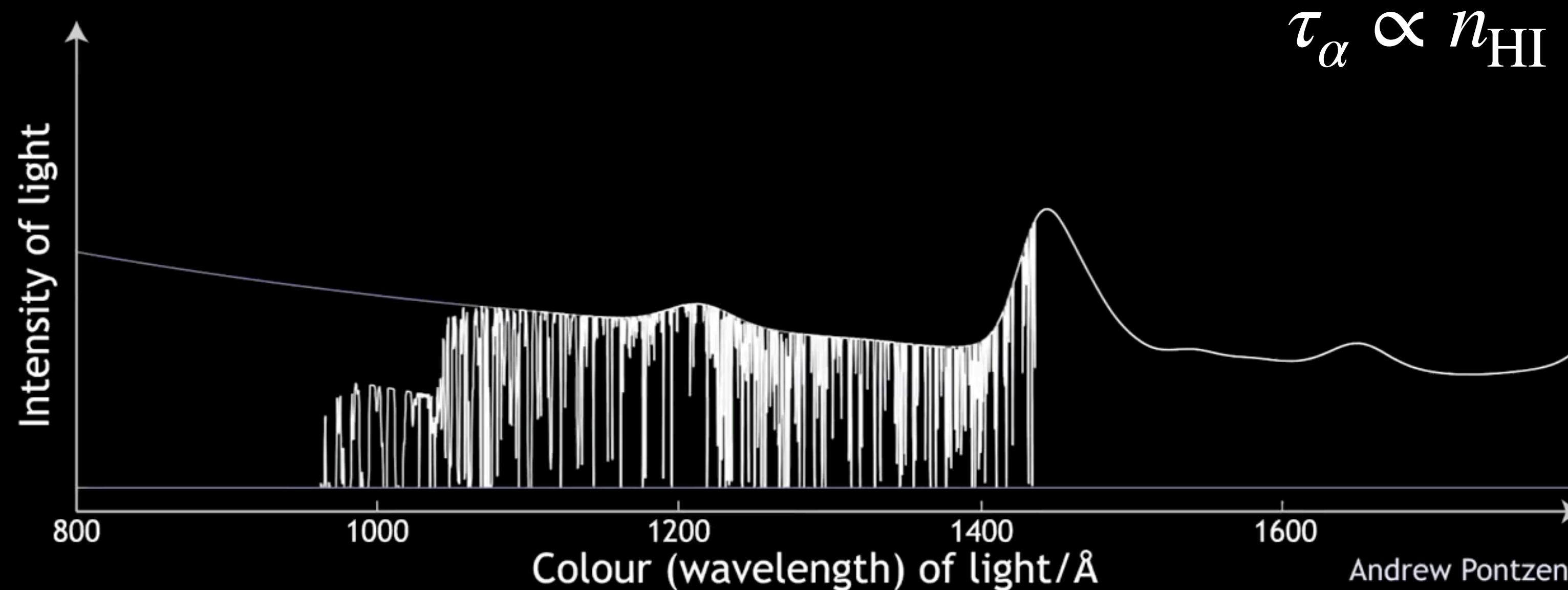
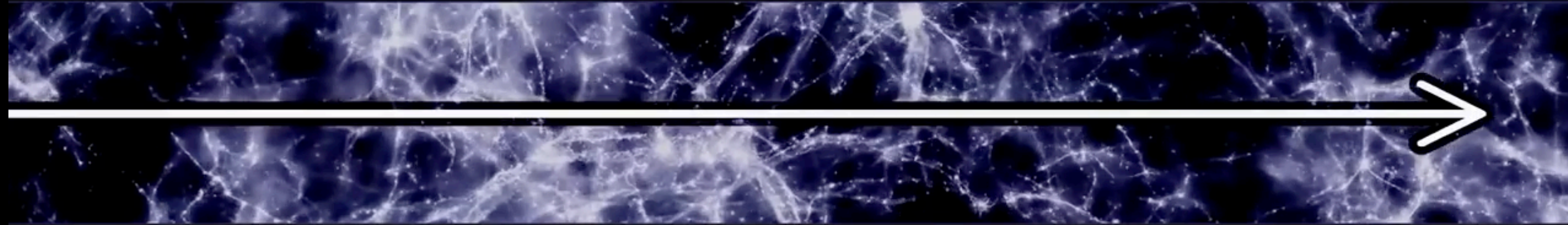
**When do we think that we have 'solved' cosmic reionization?**



**Credit: NIRCam GOODS-South field**

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# Ly $\alpha$ forest is the cleanest probe of the Intergalactic Medium (IGM)



**Ly $\alpha$  optical depth**

$$\tau_\alpha \simeq 11(1+\delta_m)^2 \left( \frac{\Gamma_{\text{HI}}}{10^{-12} \text{ s}^{-1}} \right)^{-1} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.72} \left( \frac{1+z}{7} \right)^{9/2}$$

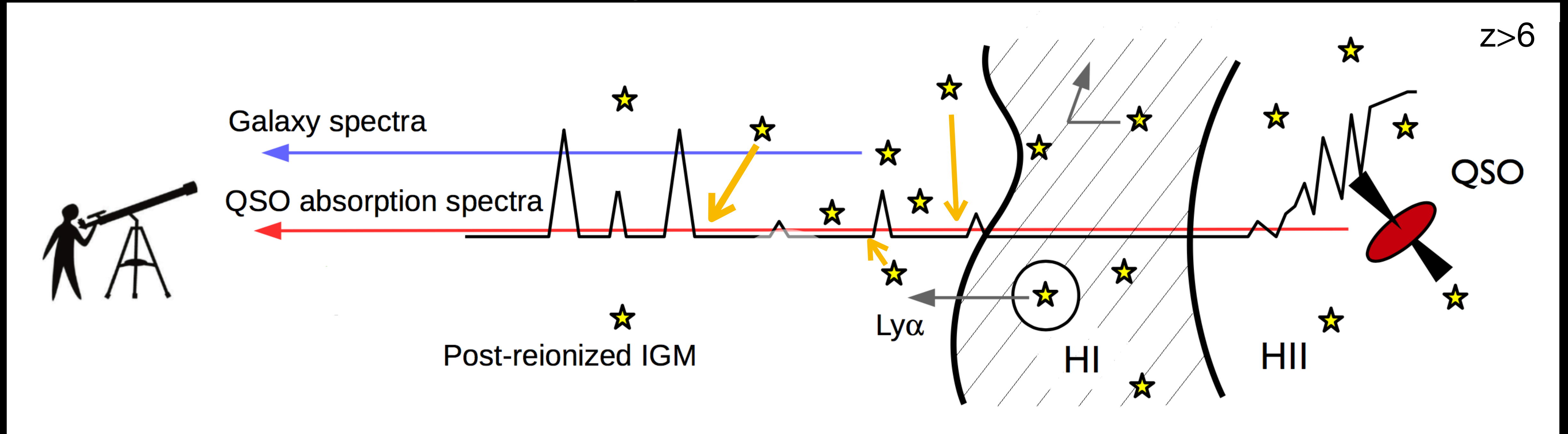
Density fluctuations
Ionising background
Temperature

**Physics of the IGM**

Meiksin+09, Becker+15,  
McQuinn+16 for reviews

# Probing the role of galaxies and AGN during the final stages of reionization

## JWST spectroscopic survey of galaxies in QSO fields



*The spatial correlation between galaxies and Ly $\alpha$  forest tests directly how galaxies reionized the IGM*

Pre-JWST ground-based galaxy survey in QSO fields (Kakiichi+18, Meyer+19,20, Bosman+20) & scope of JWST EIGER (Kashino+23) and ASPIRE (Wang+23) surveys with NIRCcam/WFSS

# JWST ASPIRE Cycle 1 (PI: Wang)

## NIRCam/F356W Grism Spectroscopic Galaxy Survey of 25 QSO Fields at $z > 6$

Wang et al incl. KK 2023



“JWST as Redshift Machine”

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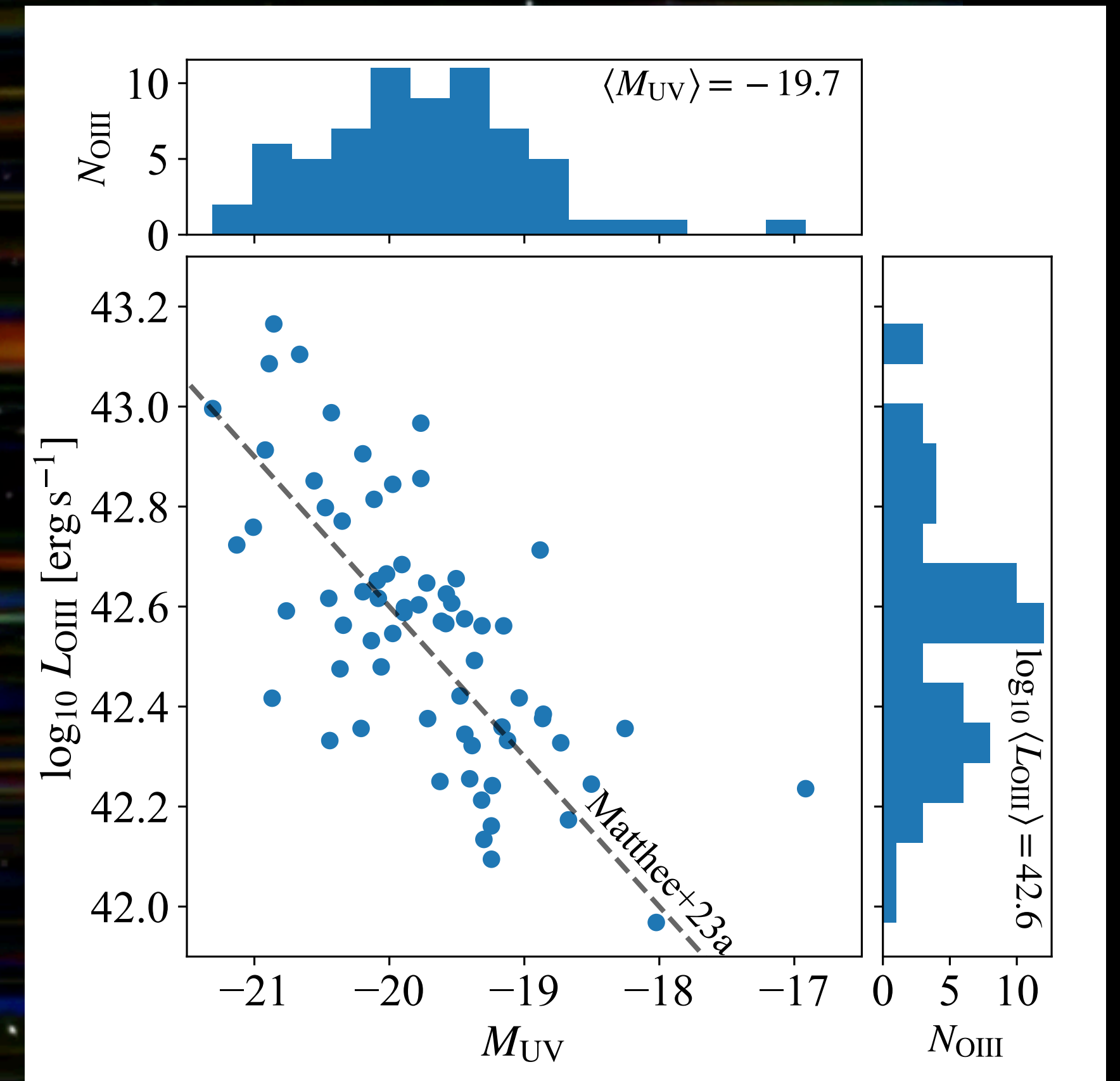
Wang et al incl. KK 2023

‘Shallow & wide’ survey to reveals  $\sim 300$   $5.3 < z < 7$  galaxies with [OIII] lines in the Ly $\alpha$  forest regions of 25 background QSOs

cf. EIGER survey targets 6 QSO fields with deep exposure

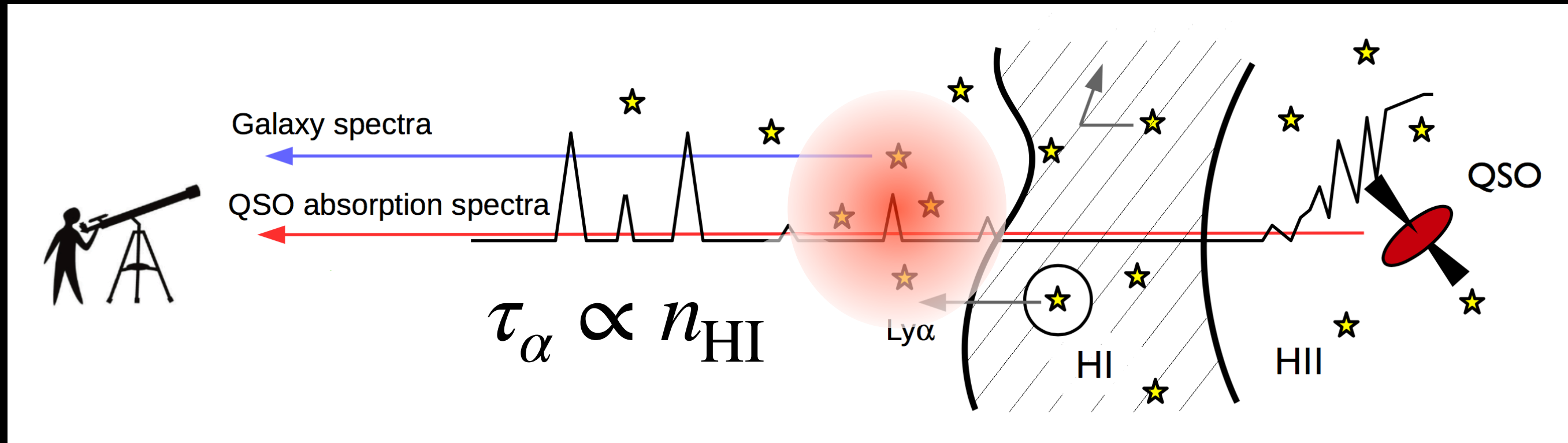
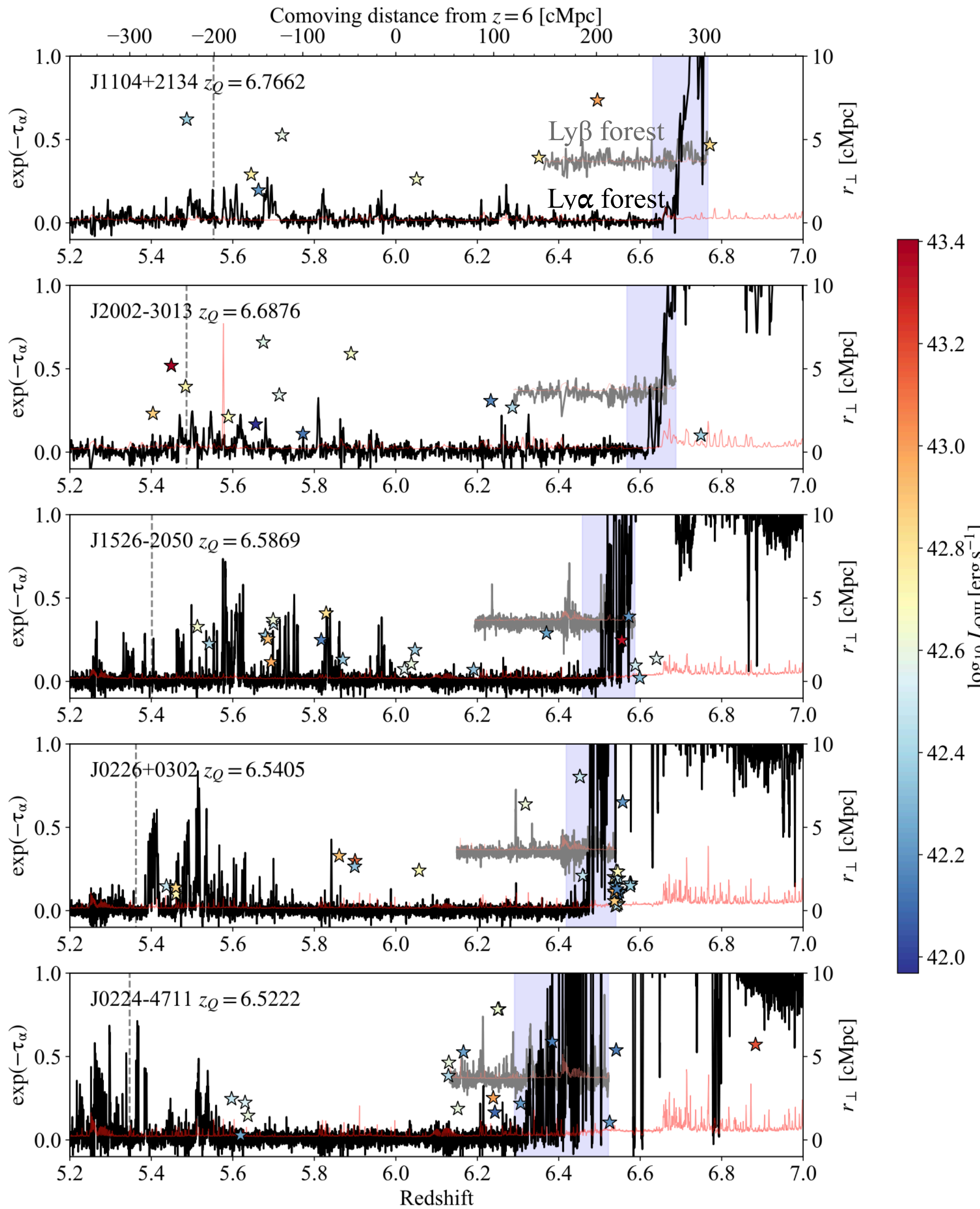
See also Daichi Kashino’s Talk

$z > 6$  QSO



“JWST as Redshift Machine”

# JWST map of galaxy-IGM spatial correlations at $z \sim 6$

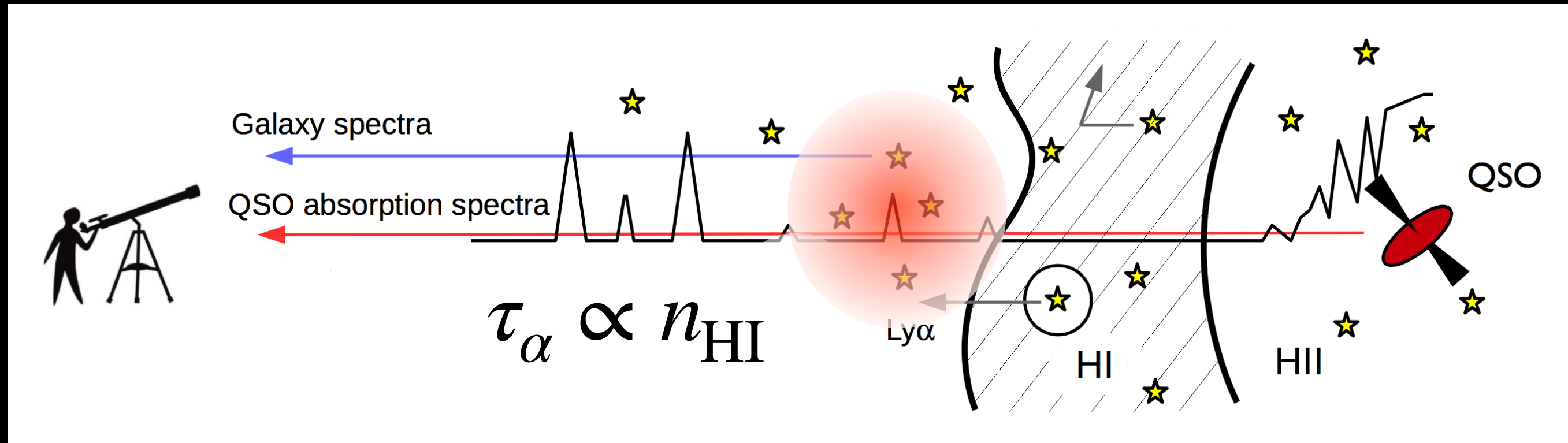
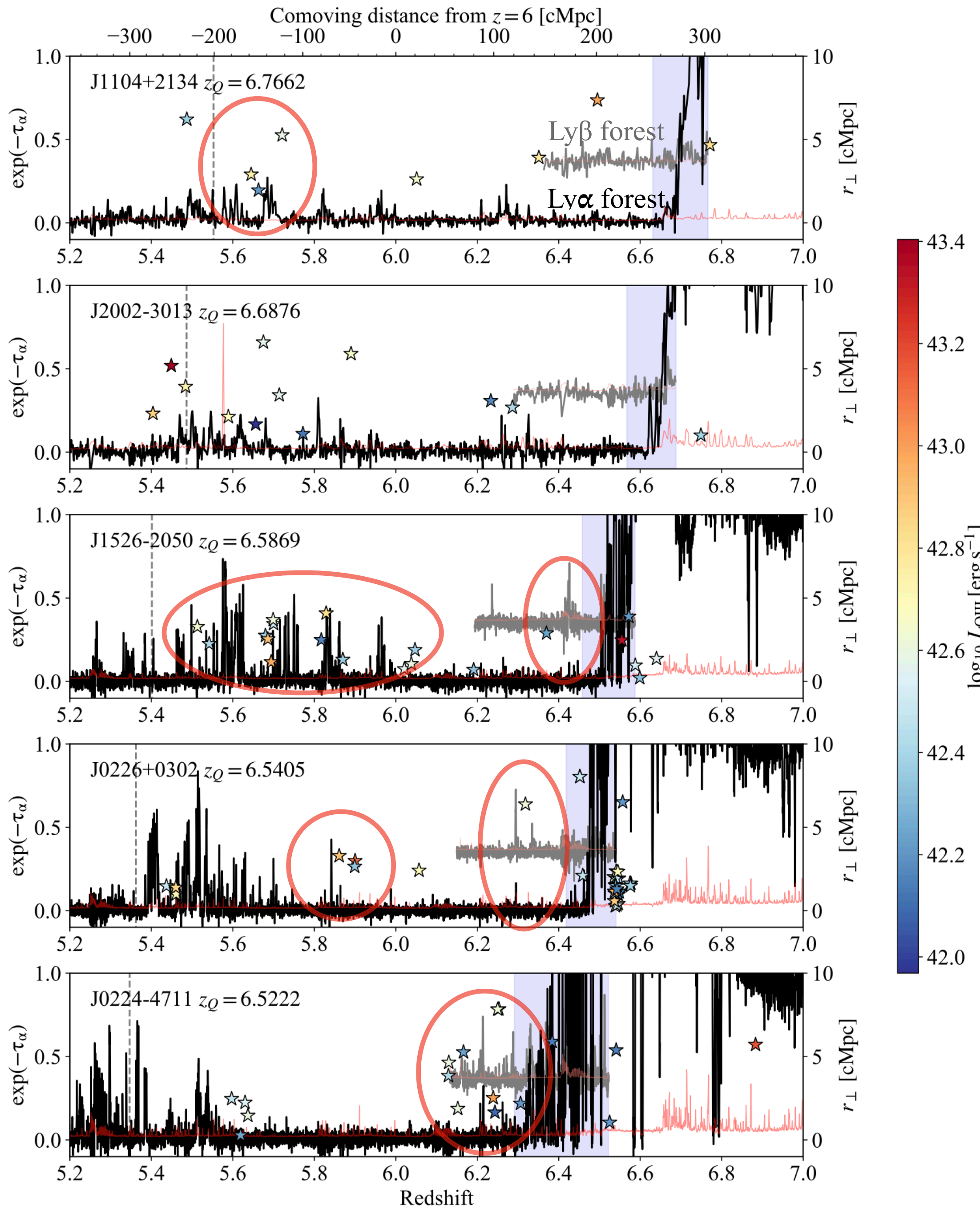


**[OIII] emitters reside in the highly ionized IGM at  $z \sim 6$**

See also Xiangyu Jin's Talk



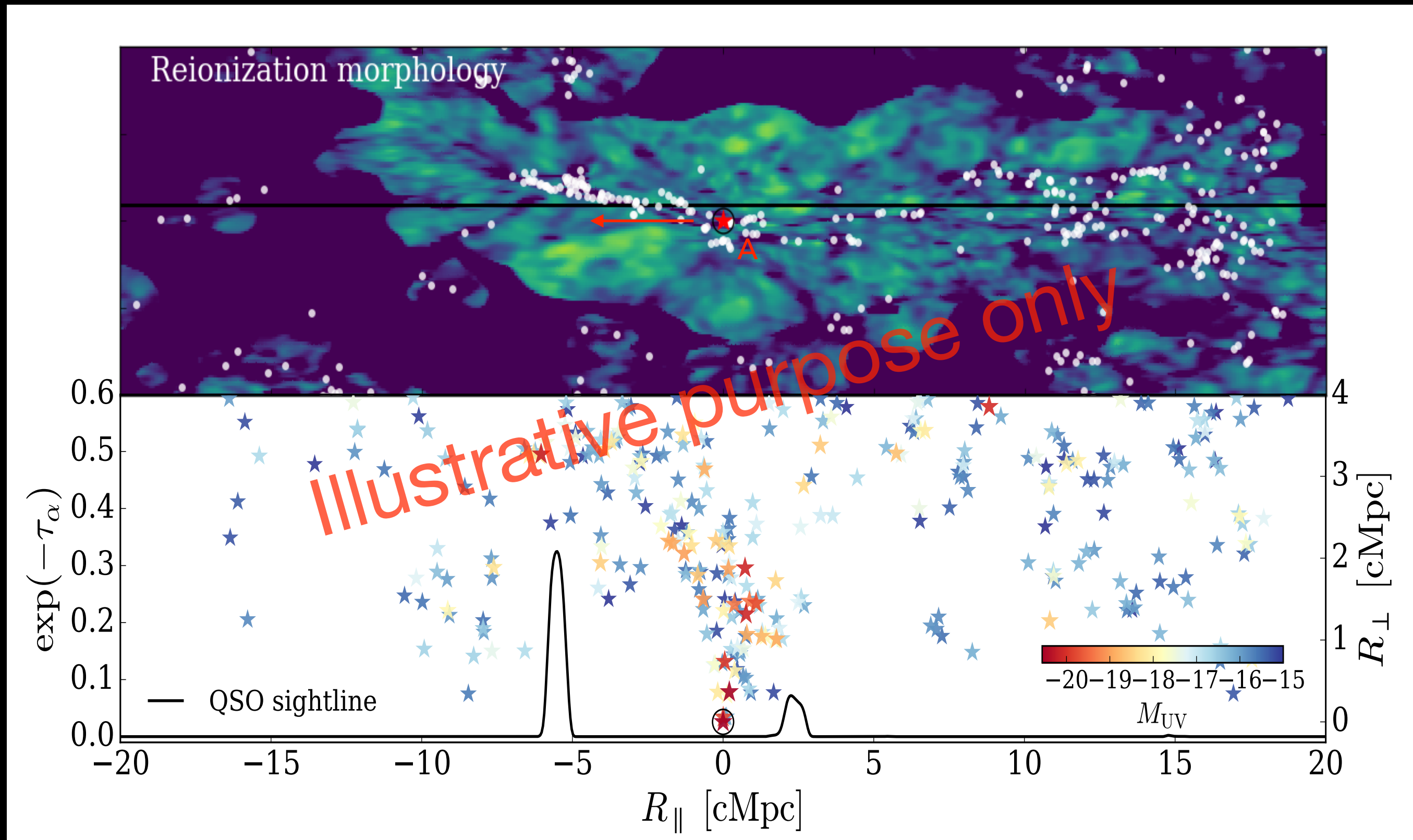
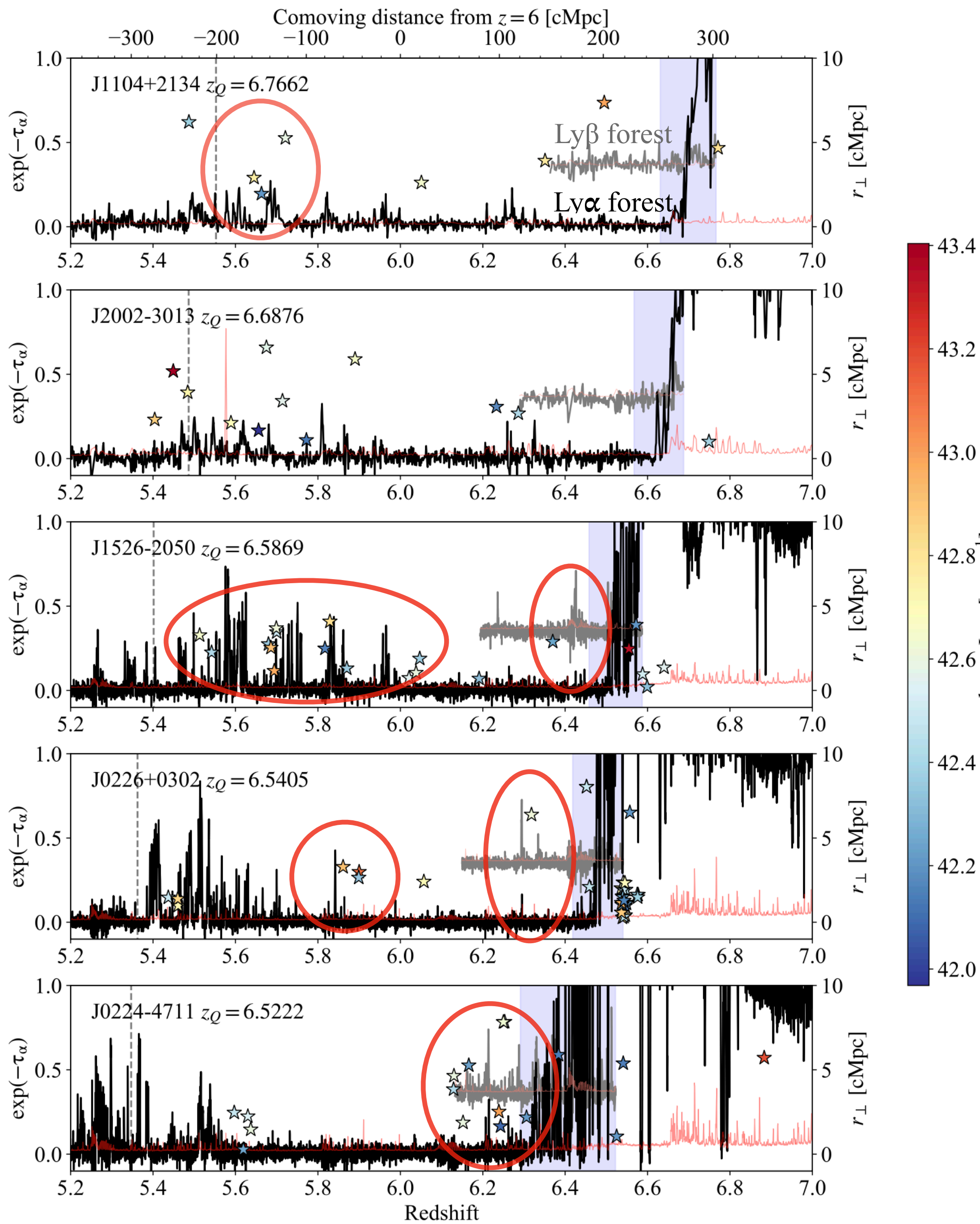
# JWST map of galaxy-IGM spatial correlations at $z \sim 6$



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# JWST map of galaxy-IGM spatial correlations at $z \sim 6$

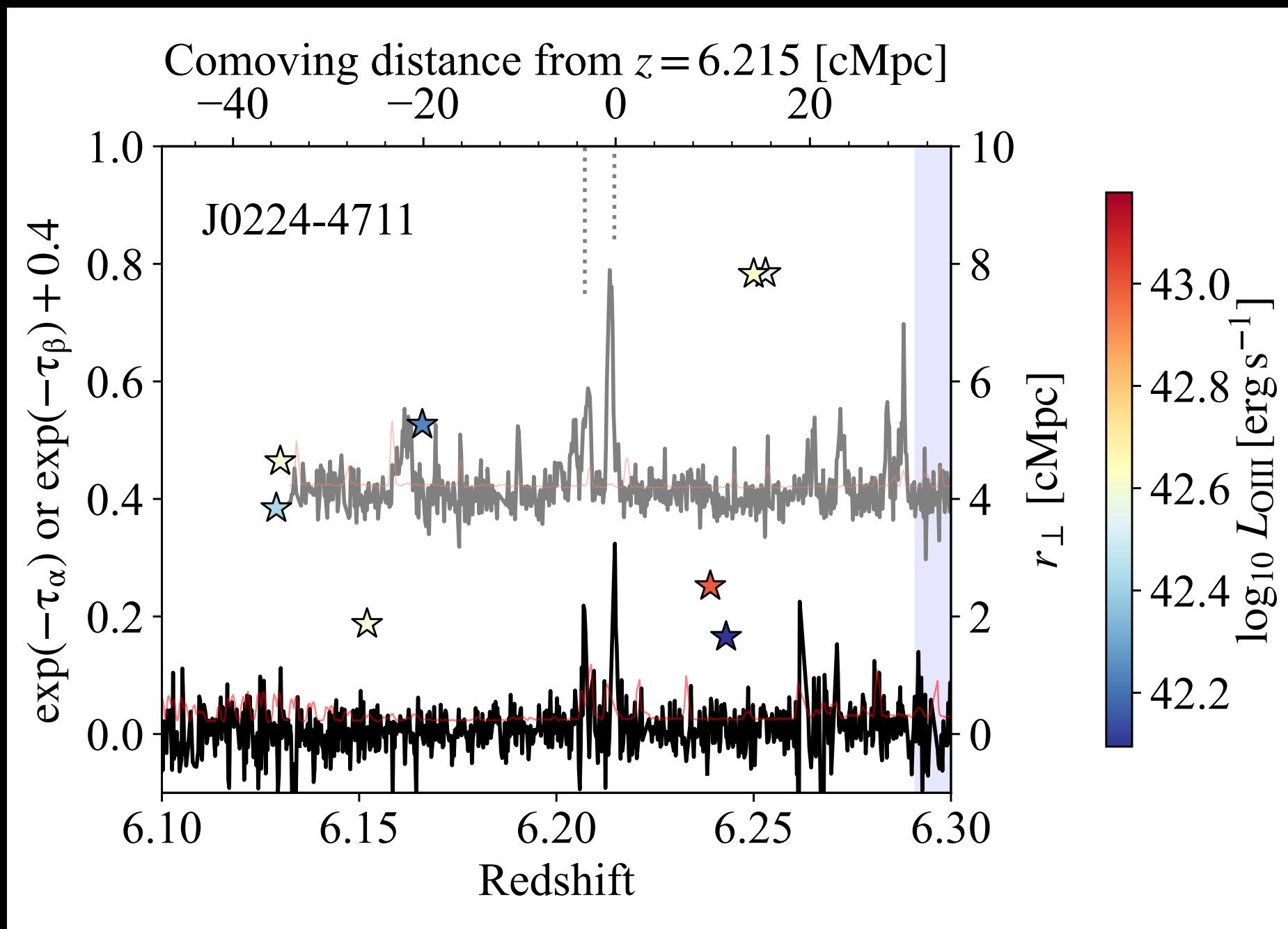


Maybe, it could be like this?



# Reionization by oligarchs or peasants?

Evidence for faint unseen galaxies completing reionization

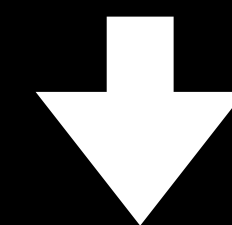


- **Observed [OIII] emitters ( $M_{UV} \approx -20$ ) are sub-dominant contributor to the ionising background in this ionised region of the IGM**

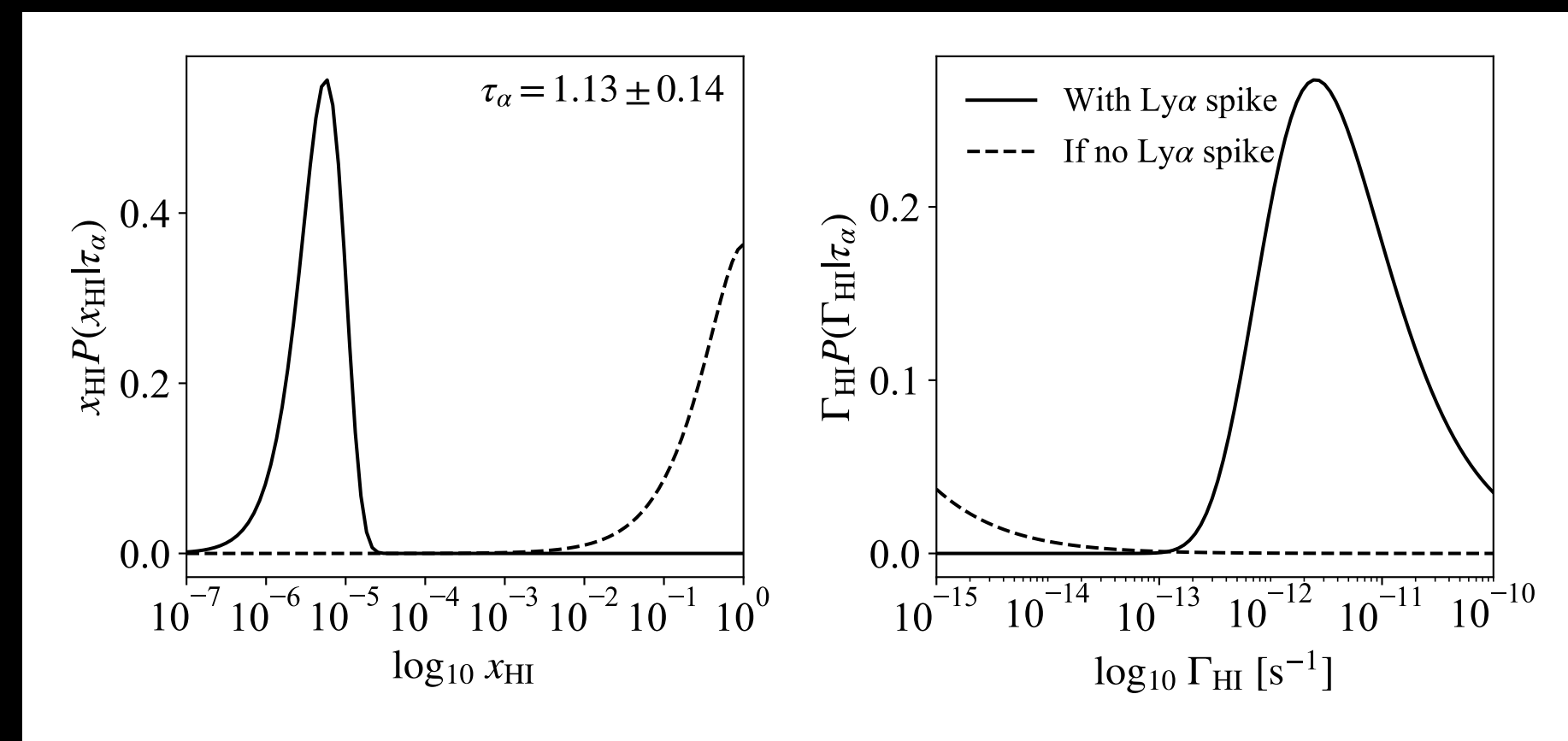
$$\frac{\Gamma_{\text{HI}}^{\text{OIII}}}{\Gamma_{\text{HI}}} < 0.003 \left( \frac{f_{\text{esc}}^{\text{OIII}}}{0.10} \right) \left( \frac{\xi_{\text{ion}}^{\text{OIII}}}{10^{25.5} \text{ erg}^{-1} \text{ Hz}} \right)$$

- **Faint AGN?**

$$\frac{\Gamma_{\text{HI}}^{\text{AGN}}}{\Gamma_{\text{HI}}} < 0.07 \left( \frac{f_{\text{esc}}^{\text{AGN}}}{1.0} \right) \left( \frac{\xi_{\text{ion}}^{\text{AGN}}}{10^{25.84} \text{ erg}^{-1} \text{ Hz}} \right)$$

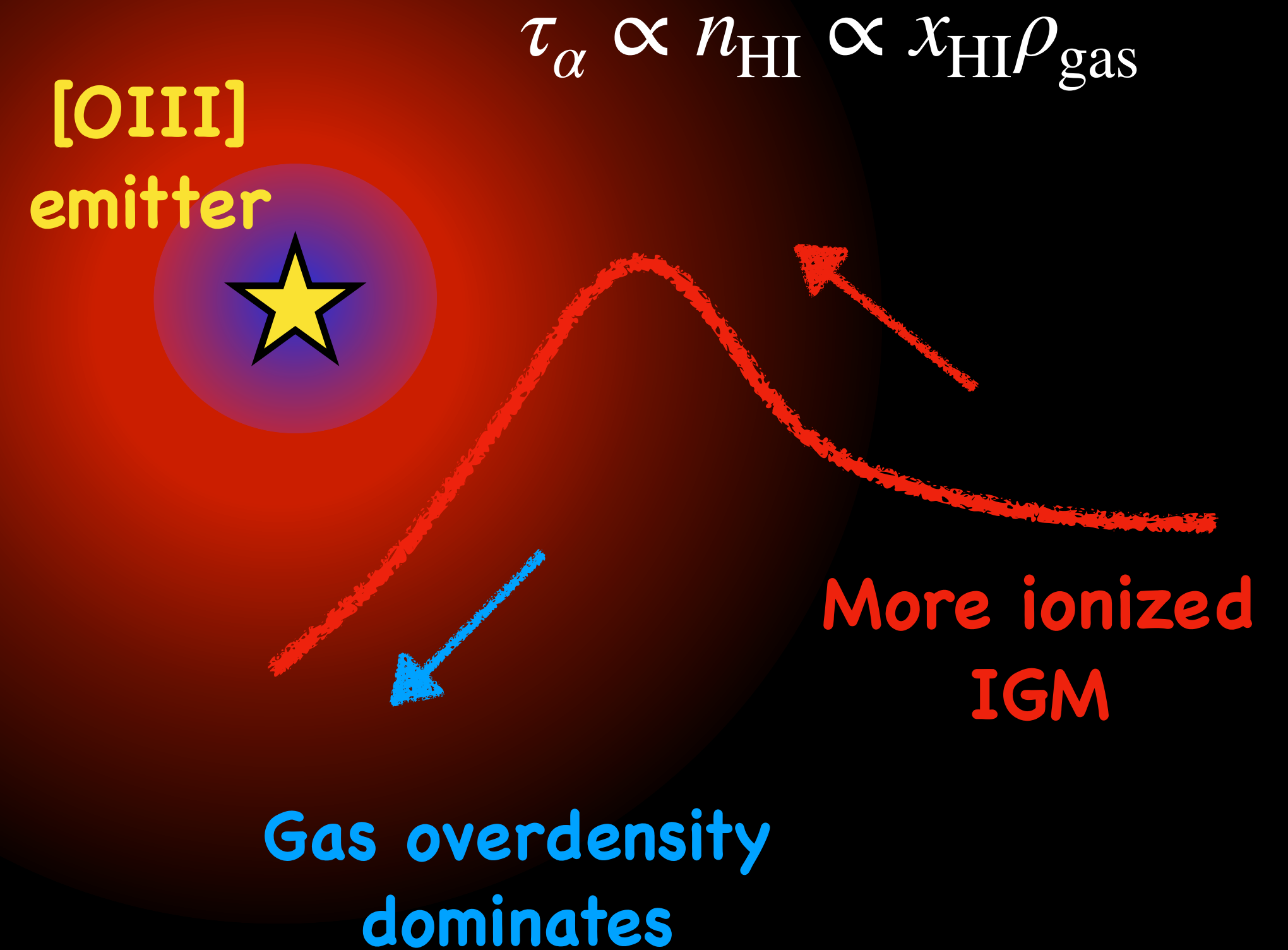
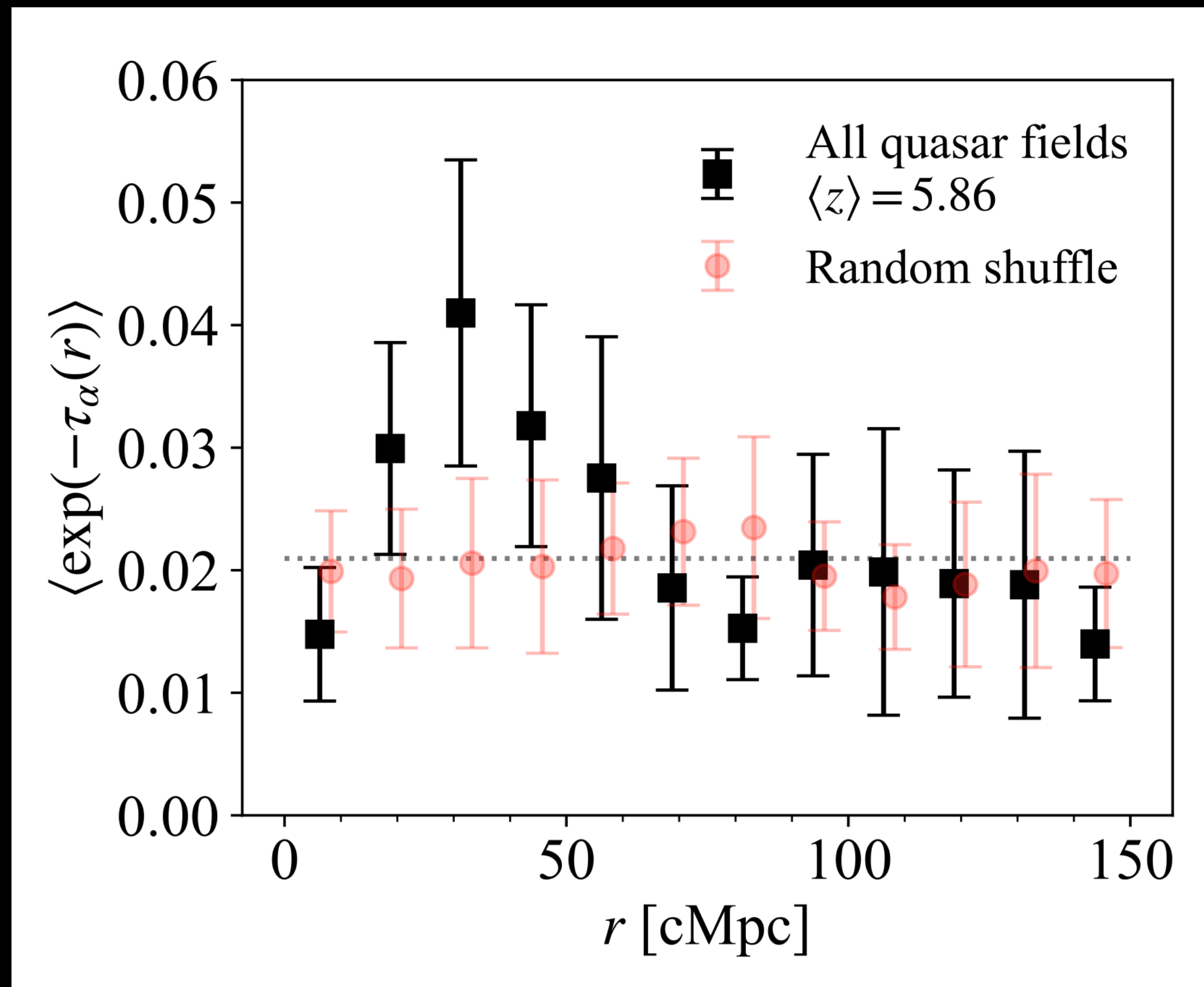


**Fainter or unseen galaxies are likely the main source of reionization during its final stage**



# Galaxy-Ly $\alpha$ forest cross-correlation

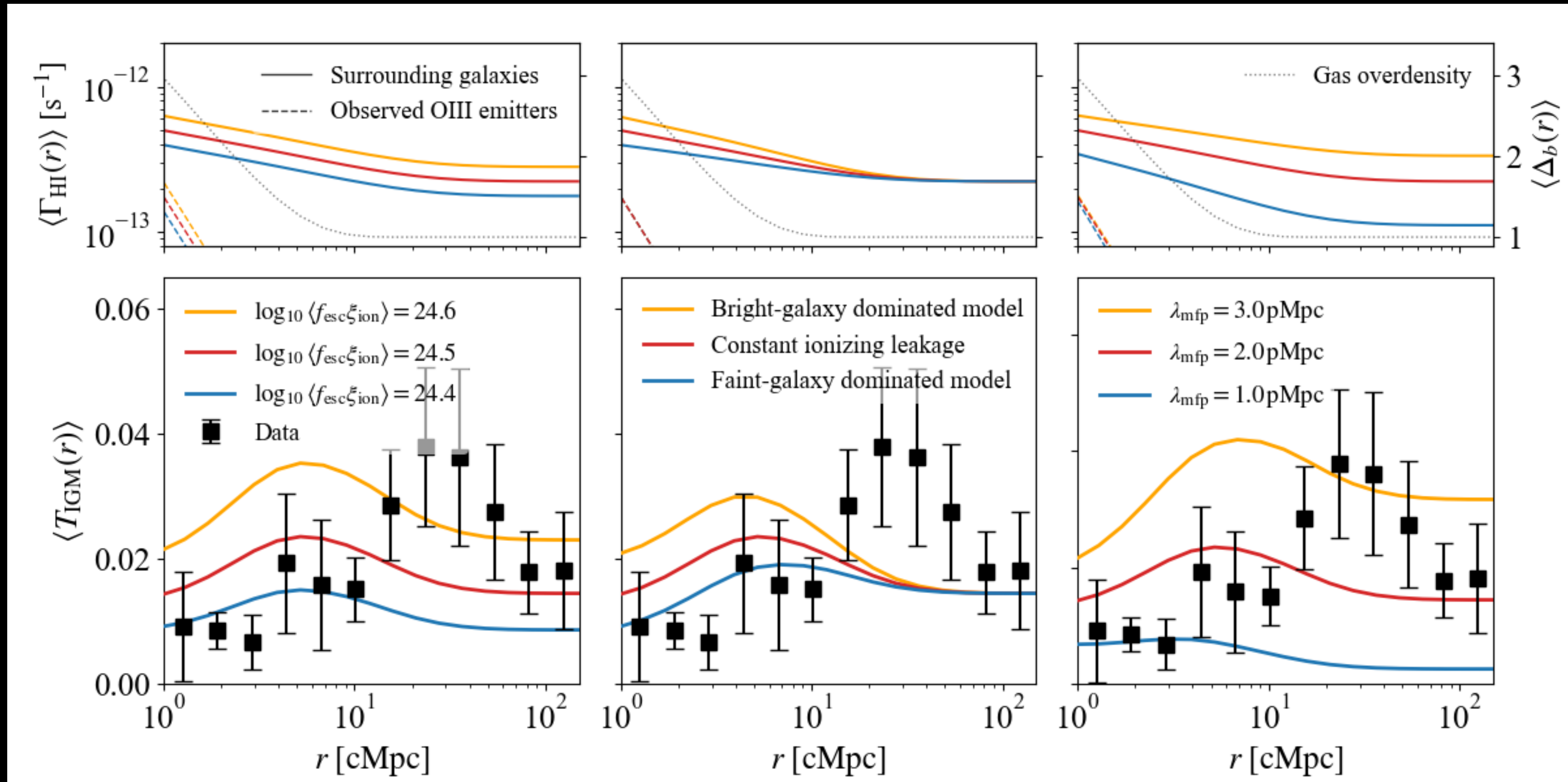
Evidence for galaxies residing in the highly ionized IGM environment at  $z \sim 5.8$



Evidence for large-scale excess IGM transmission around galaxies

# Galaxy-Ly $\alpha$ forest cross-correlation

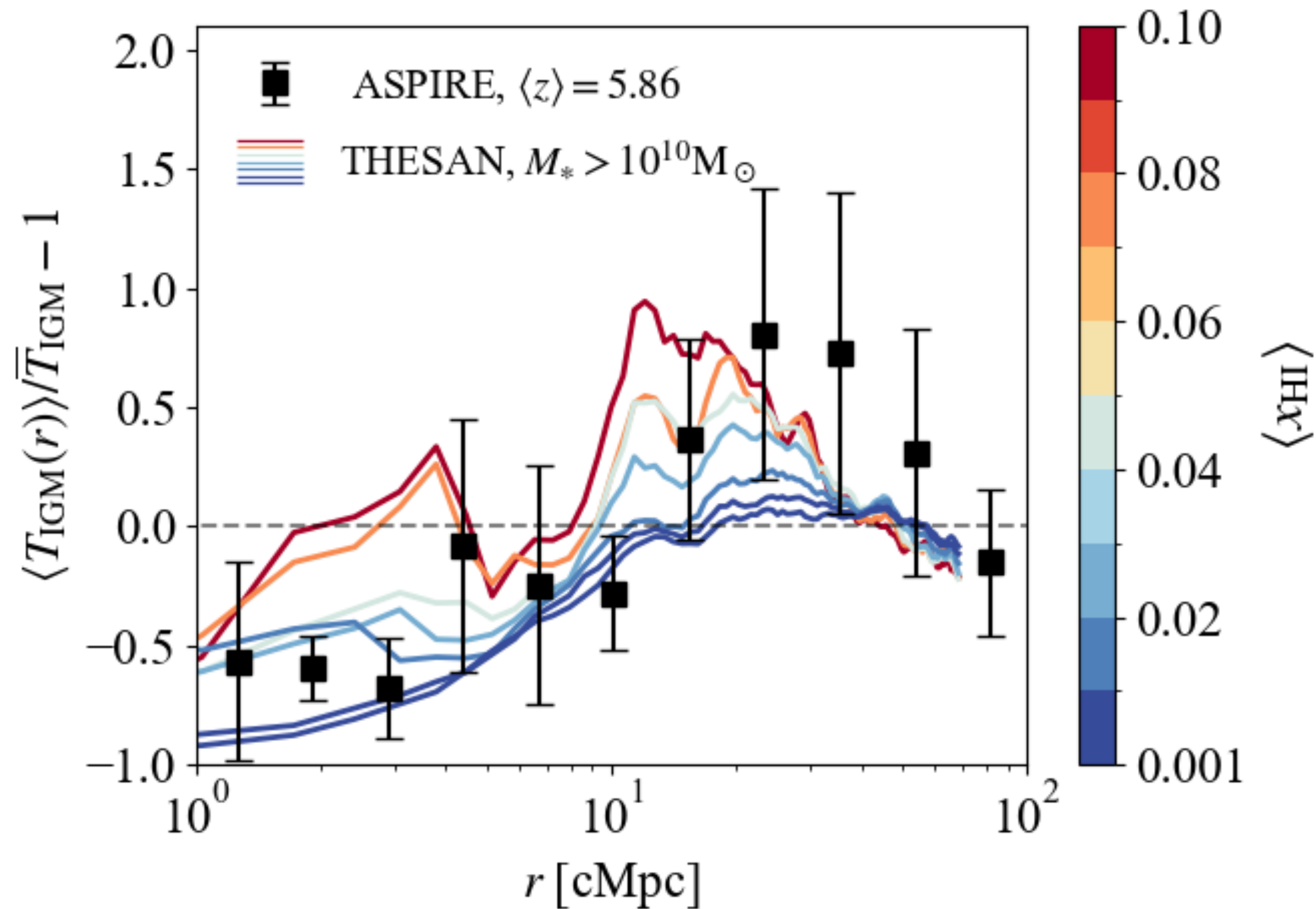
Comparison with halo model + fluctuating UV background



Based on Kakiichi+18 & Meyer+20 conditional luminosity function + RT model framework  
Source model matched to Bouwens+21 luminosity function & Harikane+22 galaxy clustering

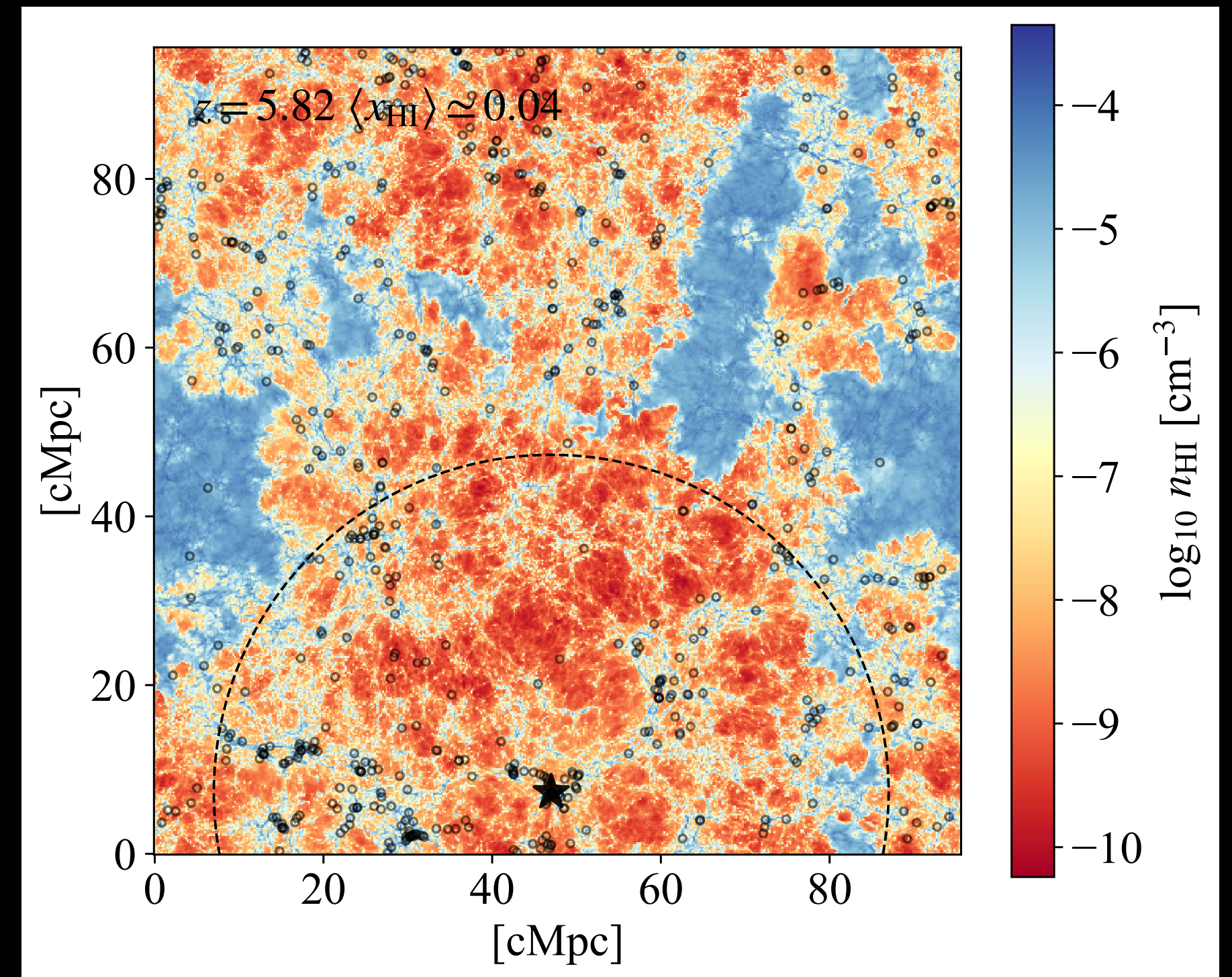
# Galaxy-Ly $\alpha$ forest cross-correlation

THESAN full cosmological radiation hydrodynamic simulations



Neutral islands at  $z < 6$ ?

Underlying spatial distribution of galaxies & reionization morphology

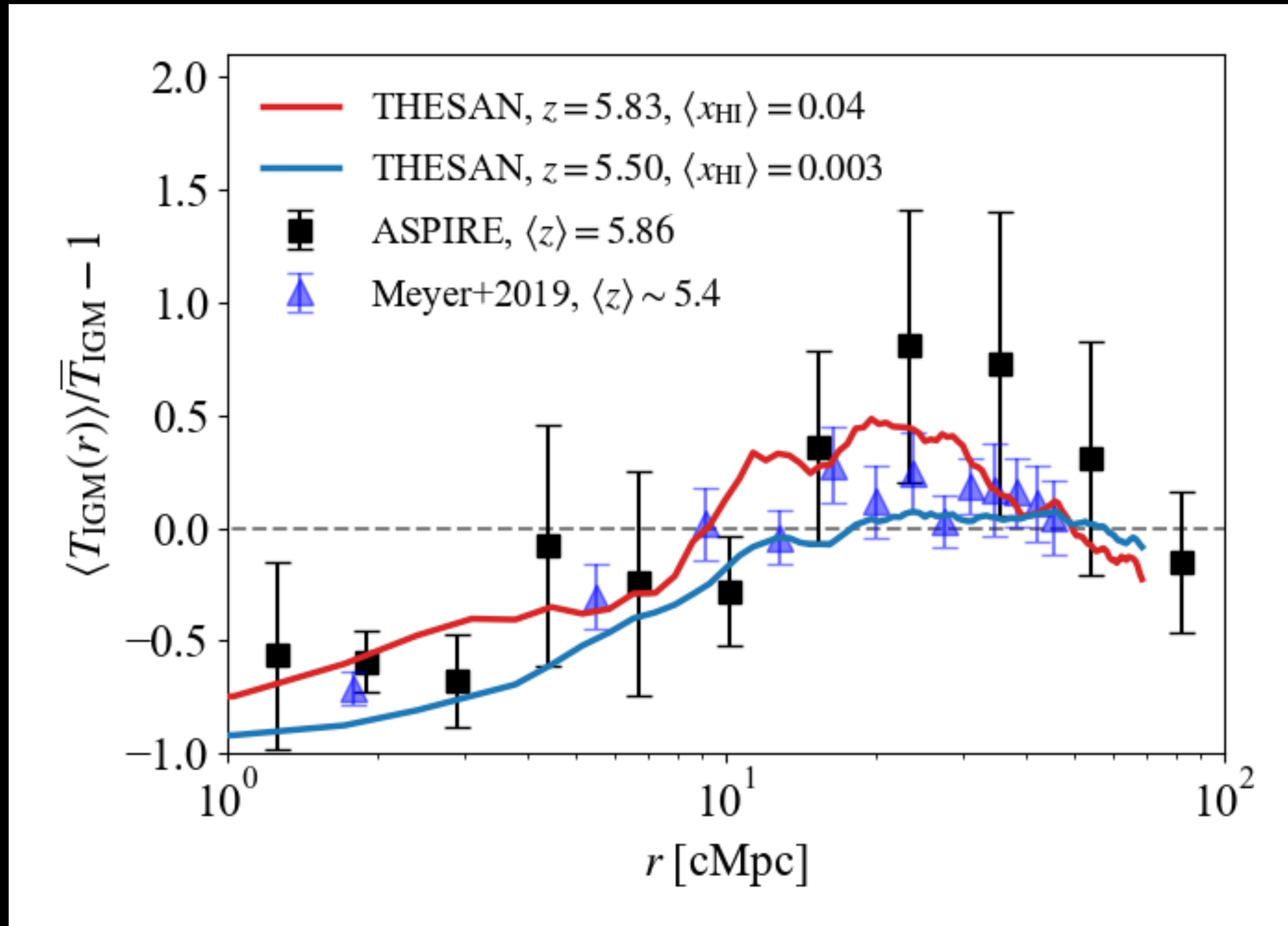


THESAN public release (Garaldi+23)

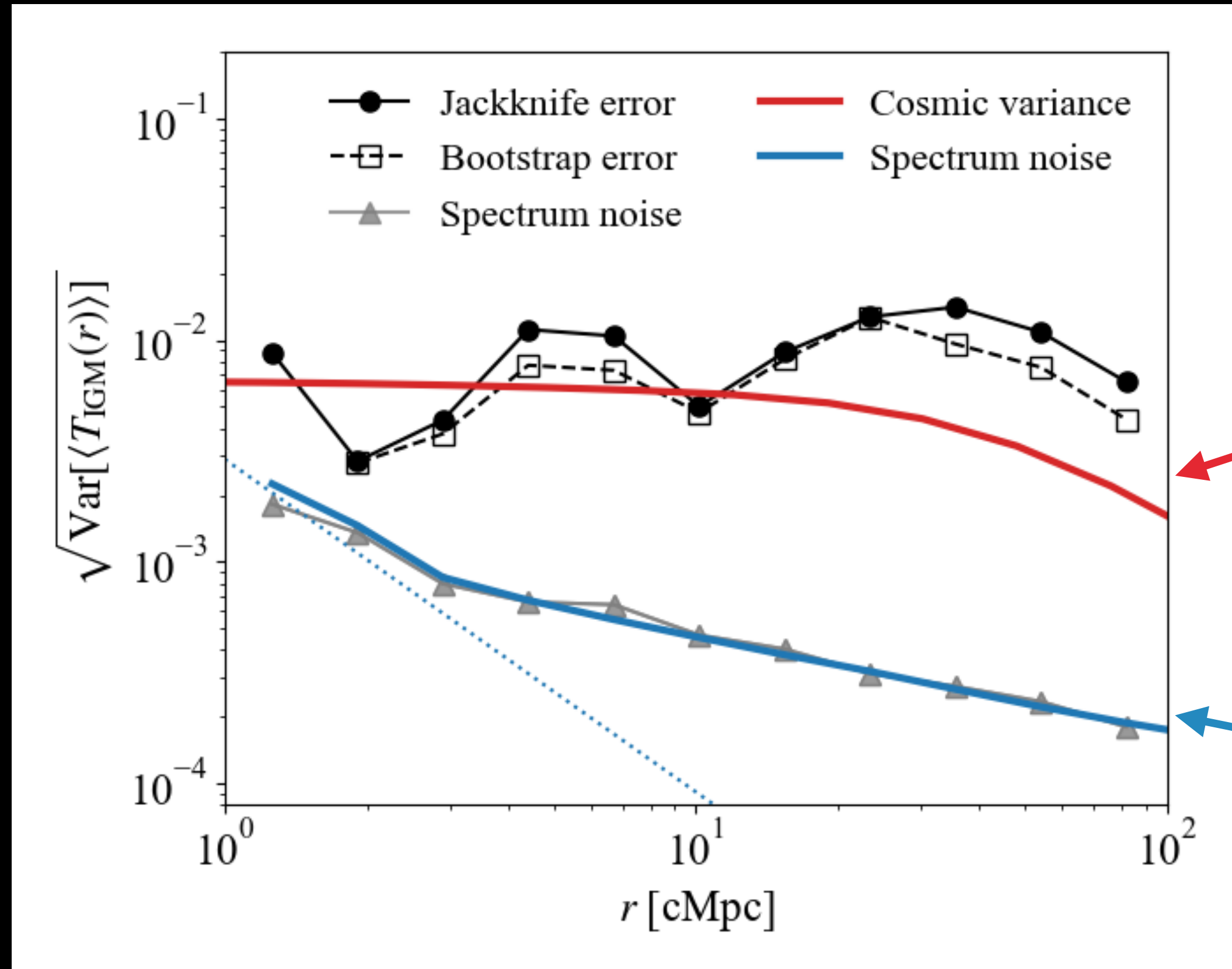
See Enrico Garaldi's Talk

**Universal prediction of all reionization theories  
= Galaxies in the ionized IGM / bubbles.**

# Rapid redshift evolution of galaxy-Ly $\alpha$ forest cross-correlation at the final stages of reionization



# Do we understand the error? Yes, sort of.



**Cosmic variance**

$\sim 1/(\text{Survey Volume}) \sim 1/(\# \text{ of quasar fields})$

**Noise in Ly $\alpha$  forest.**

$\sim 1/(\text{signal-to-noise of quasar spectra})$

## Theory

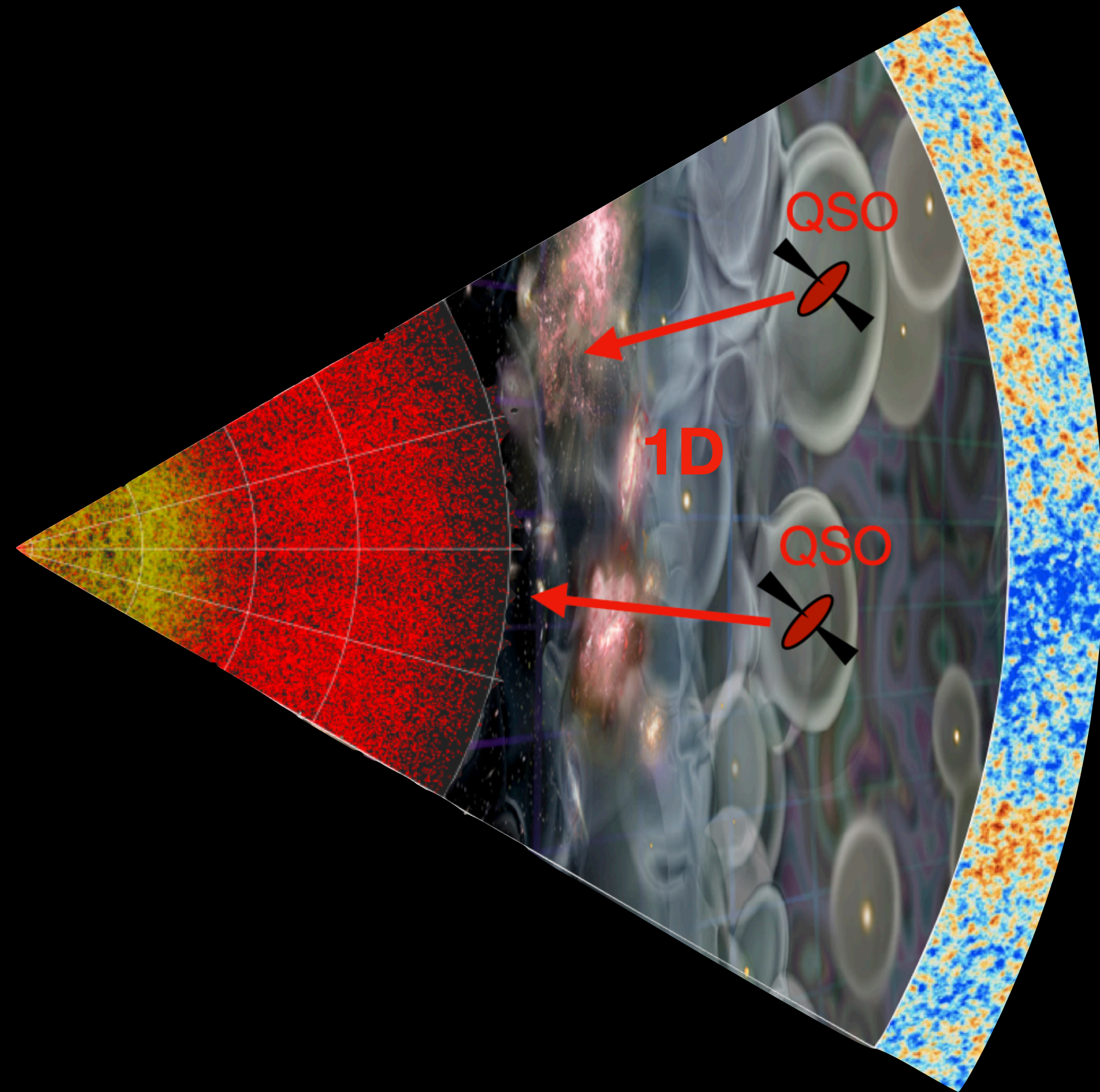
$$\text{Cov}[\langle \hat{T}_{\text{IGM}}(r_i) \rangle, \langle \hat{T}_{\text{IGM}}(r_j) \rangle] = \frac{\bar{T}_{\text{IGM}}^2}{V_s} \int_0^\infty \frac{k^2 dk}{2\pi^2} \bar{j}_0(k | r_i) \bar{j}_0(k | r_j) \text{Var}[\hat{P}_{g\alpha}(k)]$$

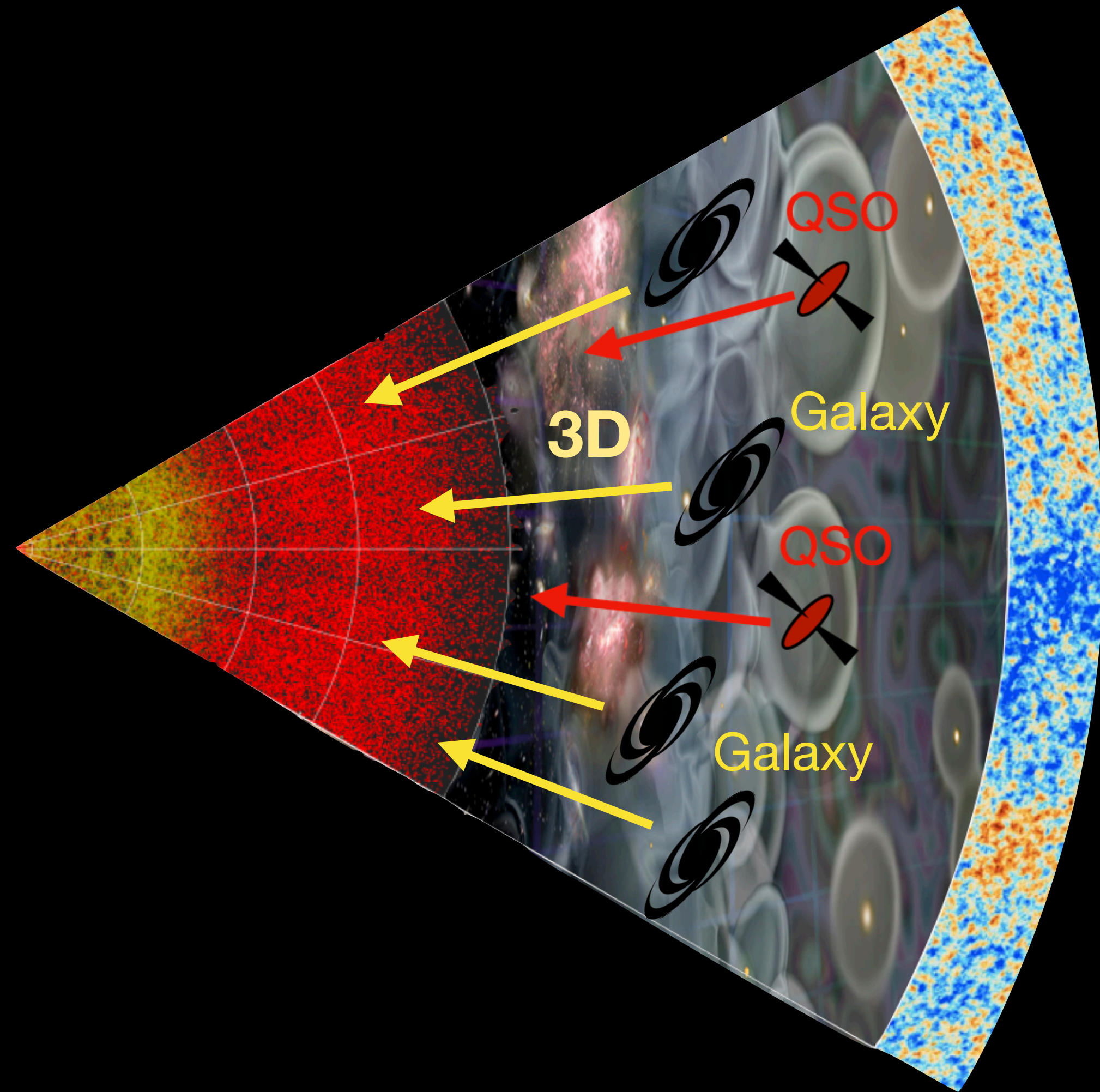
$$\text{Var}[\hat{P}_{g\alpha}(k)] = \underbrace{P_{g\alpha}(k)^2}_{\text{red}} + \left( \underbrace{P_g(k)}_{\text{red}} + \underbrace{n_{g,3D}^{-1}}_{\text{blue}} \right) \left( \underbrace{P_\alpha(k)}_{\text{red}} + \underbrace{P_\alpha^{1D}(k_{\parallel})}_{\text{red}} \underbrace{n_{\text{eff},2D}^{-1}}_{\text{blue}} \right)$$

McQuinn & White 2011

Linear power spectra with UV background fluctuations (Pontzen 2014, Gontcho-a-Gontcho+2014)



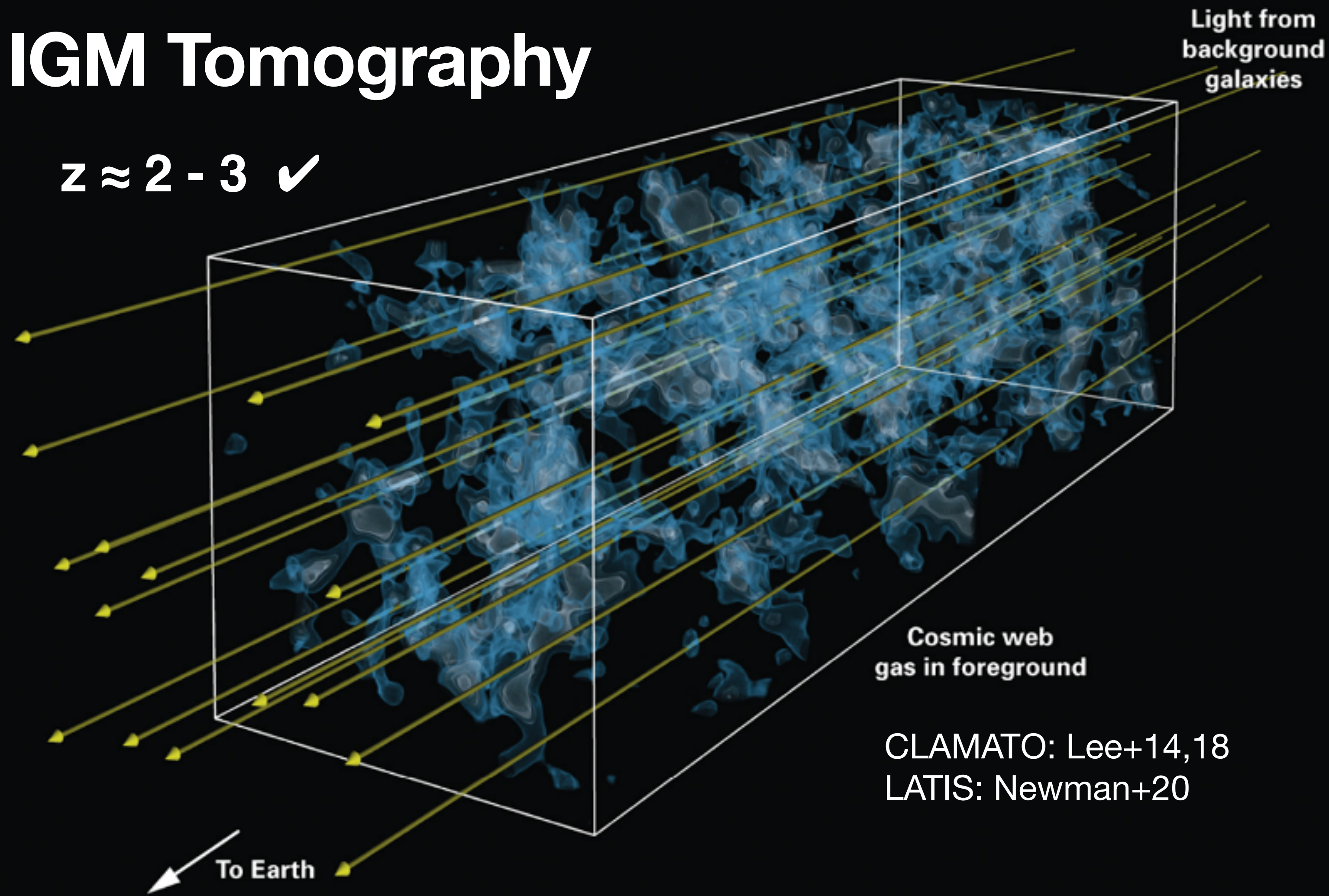




# Towards Mapping the Cosmic Frontier in “3D”

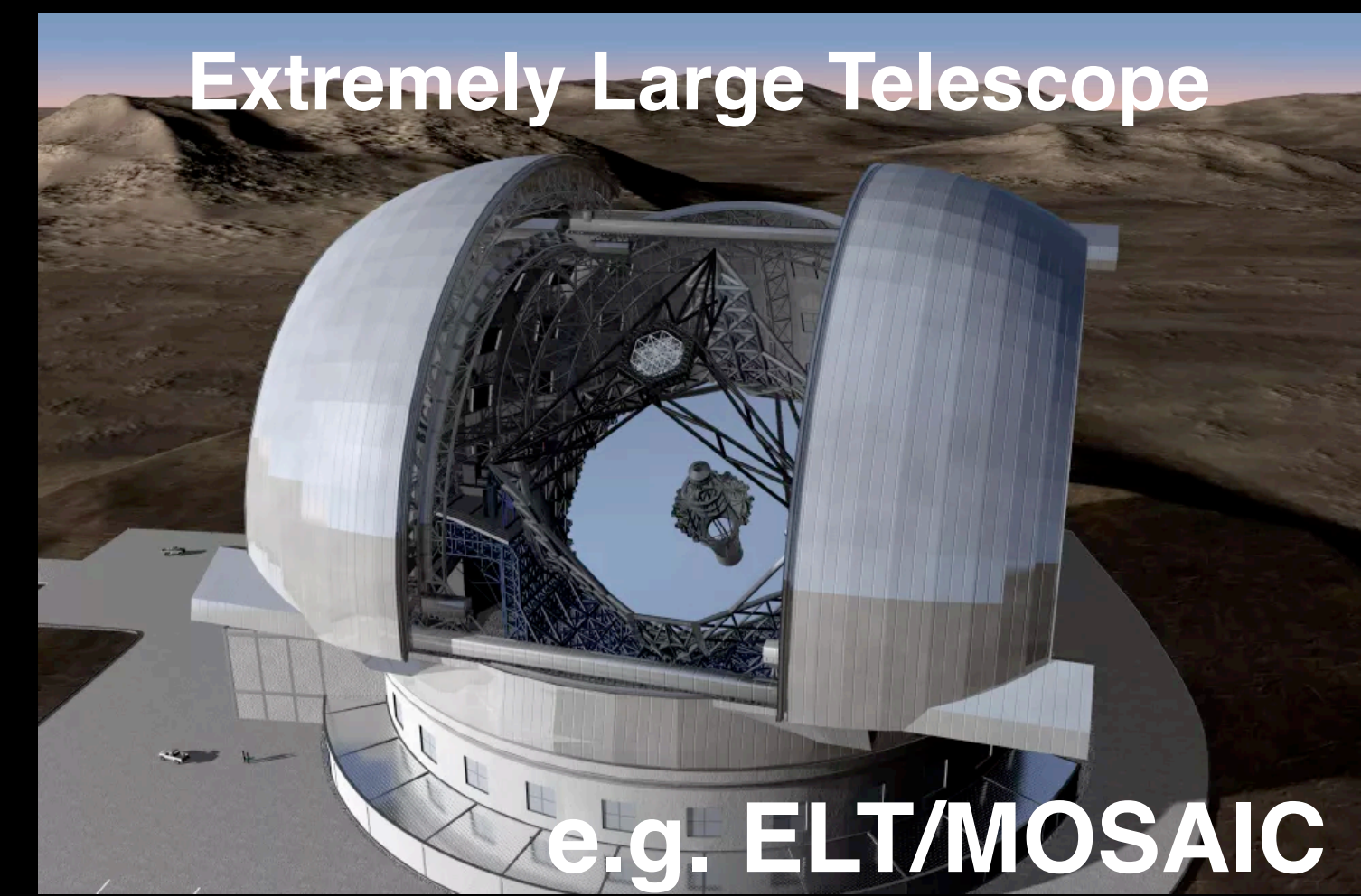
## IGM Tomography

$z \approx 2 - 3$  ✓



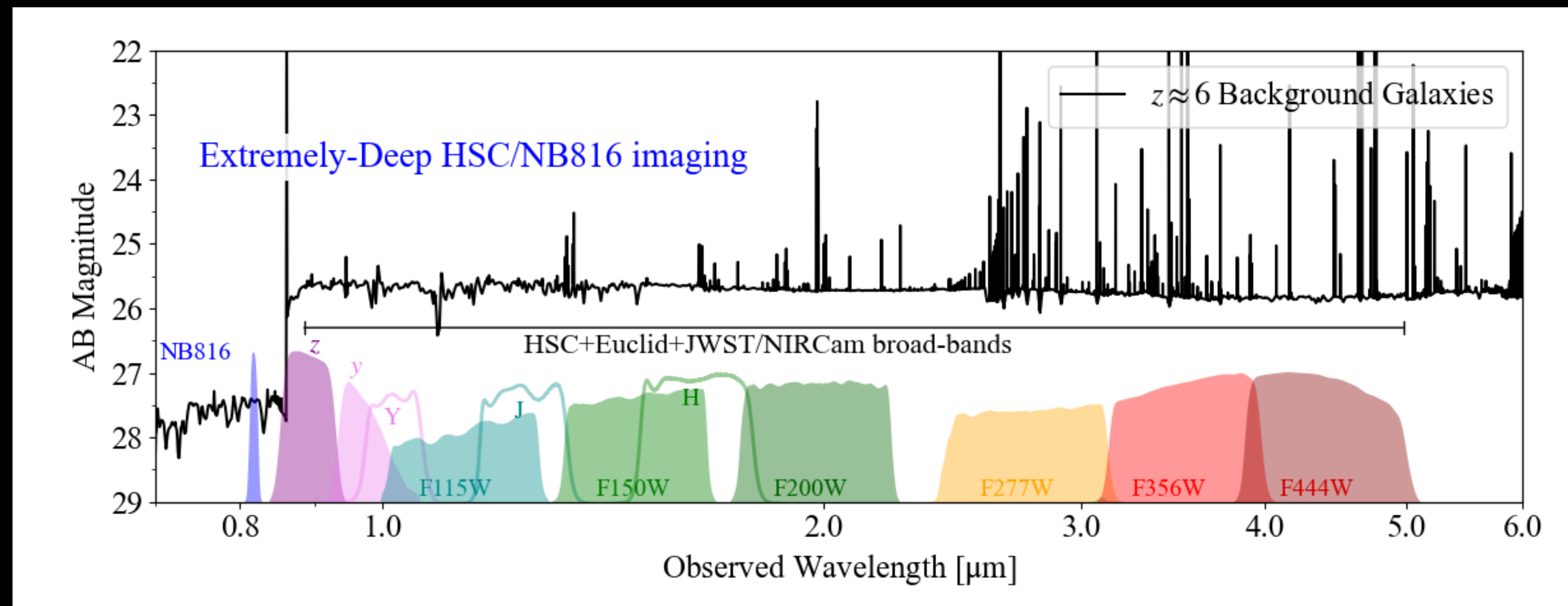
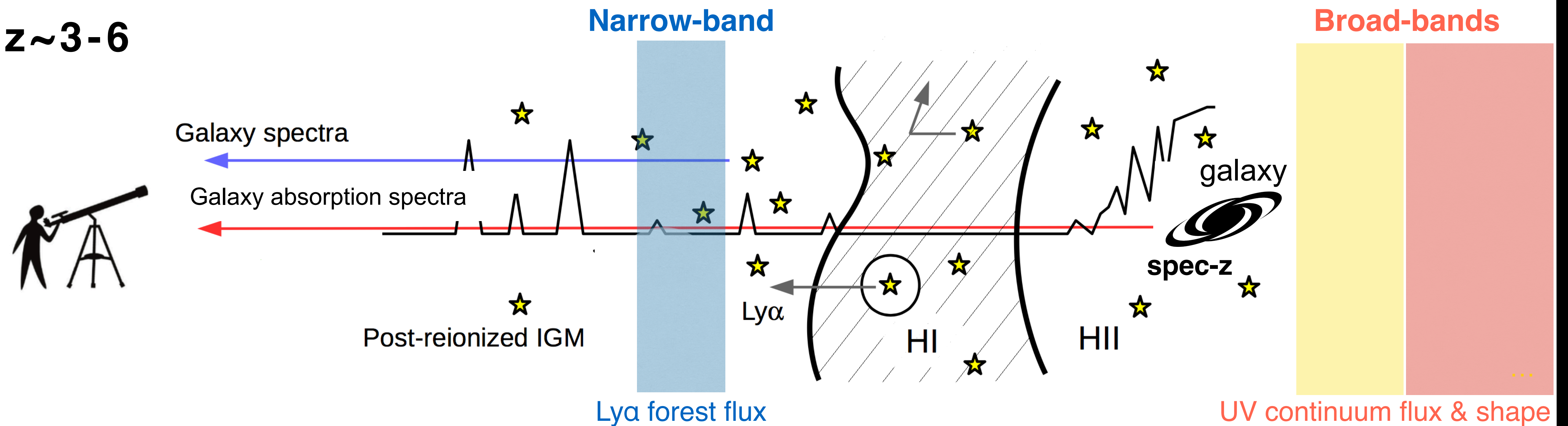
For  $z \approx 3 - 6$ , we need 30-m class telescopes...

Japeli+19



# Mapping the Cosmic Web: “Photometric” IGM Tomography

$z \sim 3-6$



Photometric measurement of the IGM transmission along background galaxies

# Mapping the Cosmic Web: “Photometric” IGM Tomography

$z \sim 3-6$

Narrow-band

Broad-bands

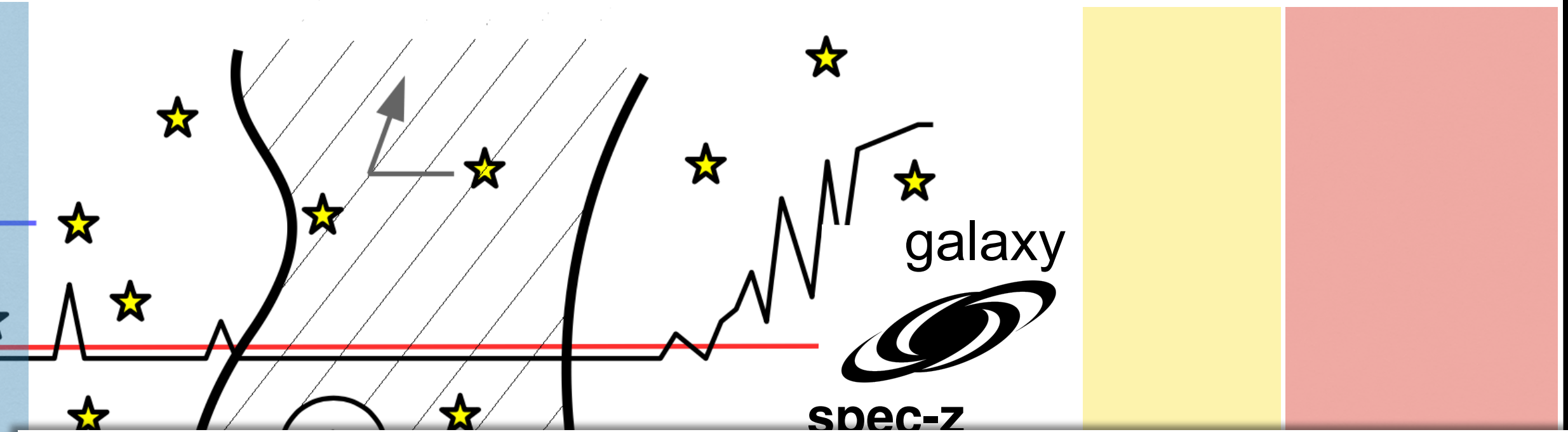


Galaxy spectra

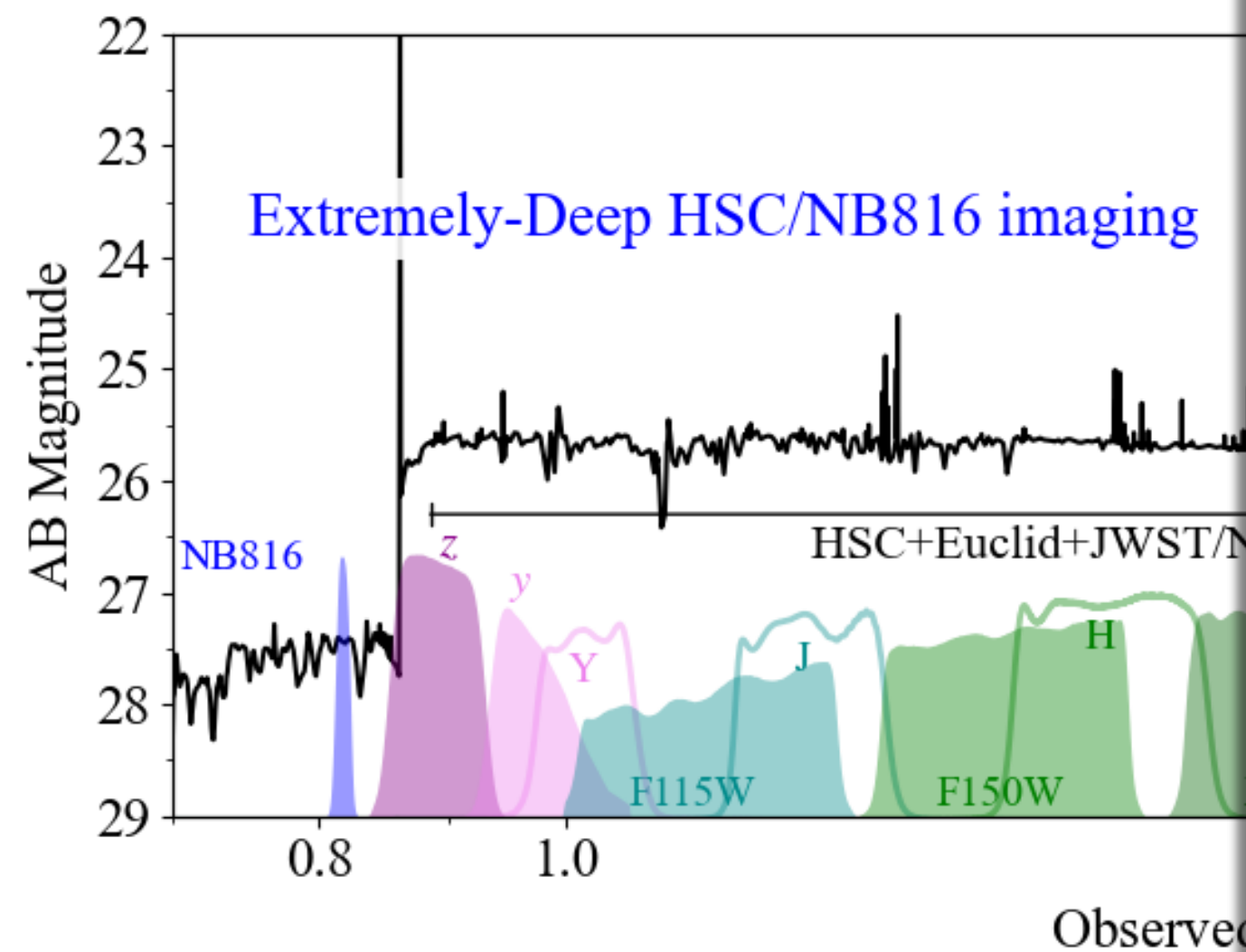
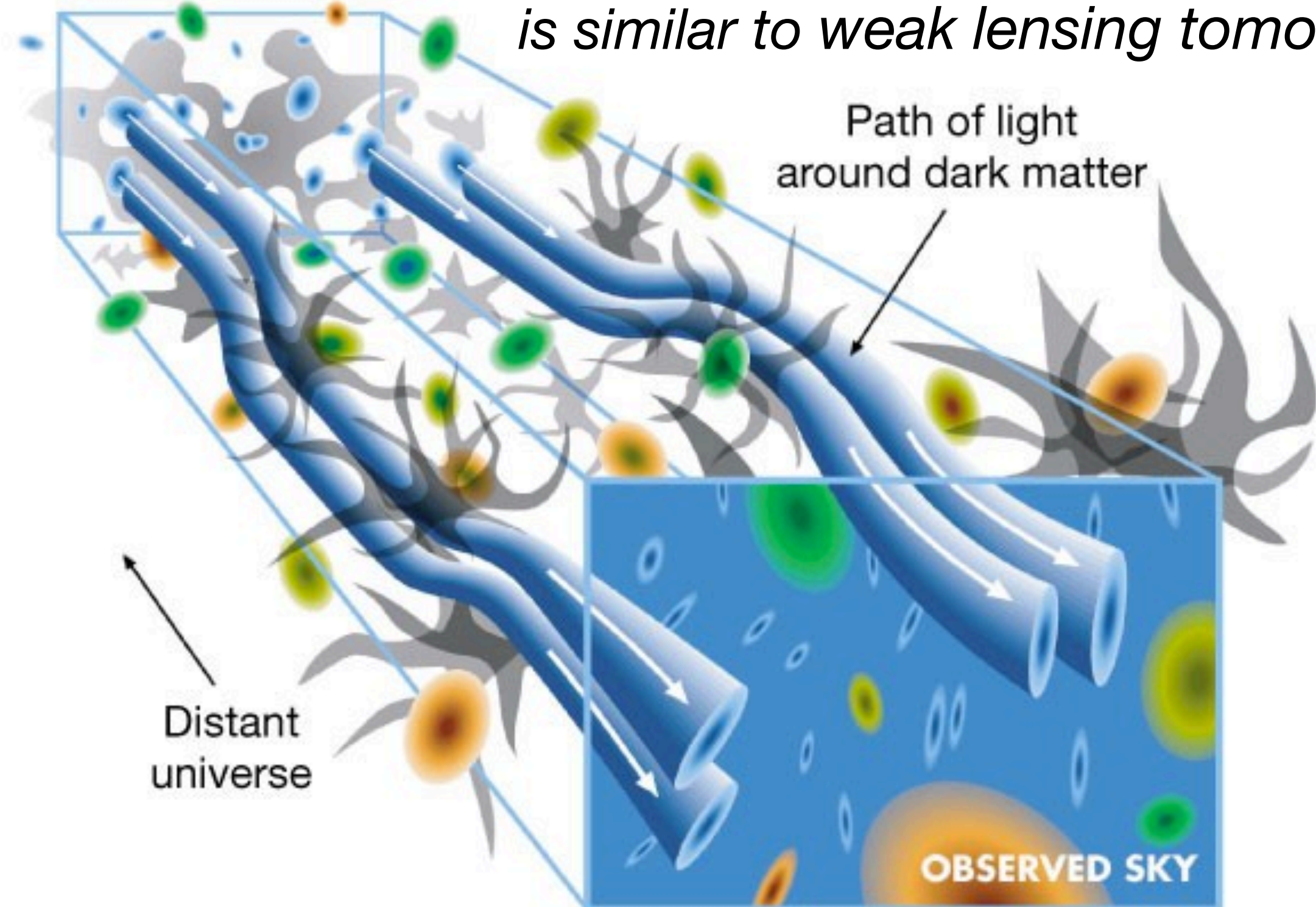
Galaxy absorption spectra

Post-reionized IGM

$\text{Ly}\alpha$  forest

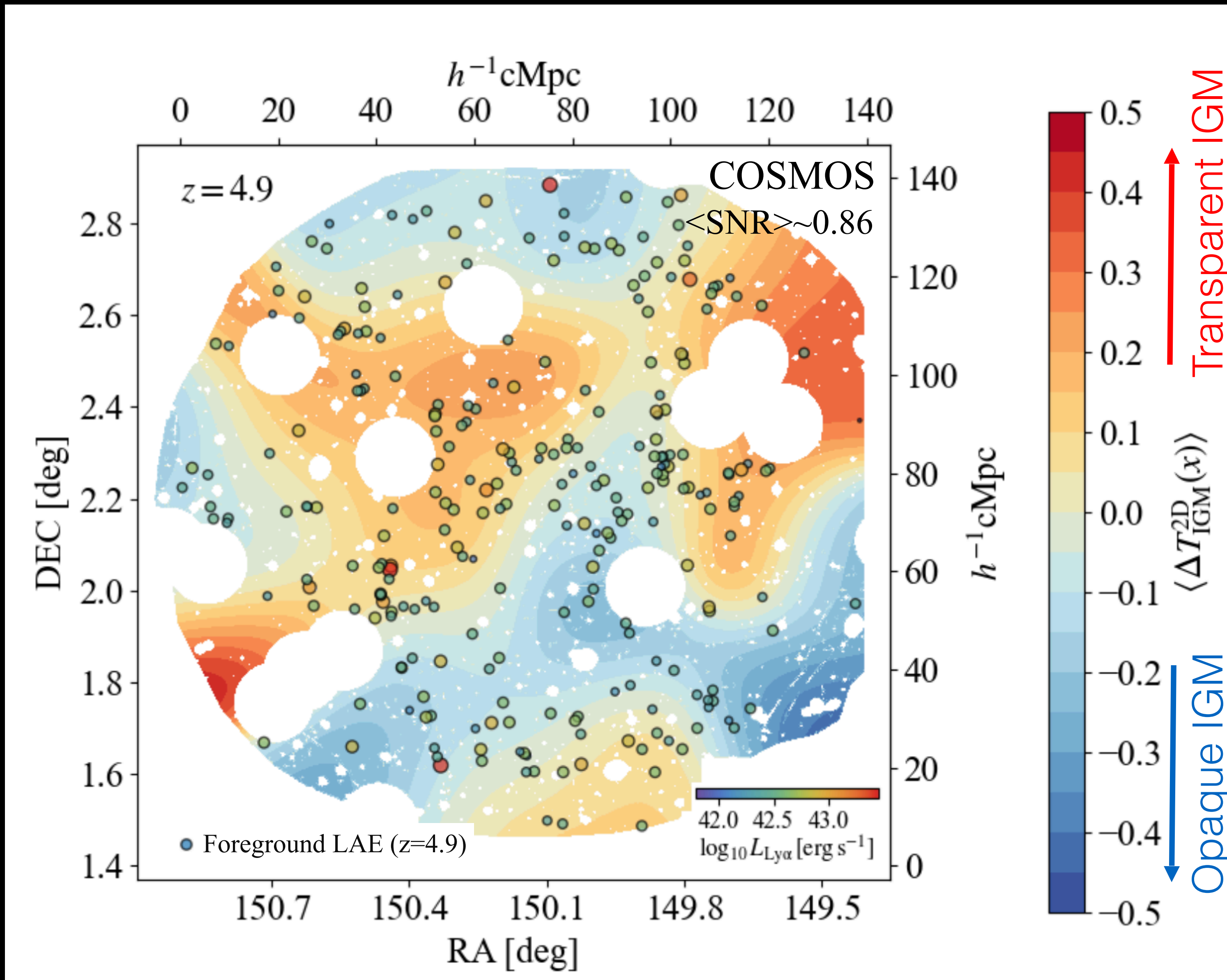


The method of photometric IGM tomography is similar to weak lensing tomography

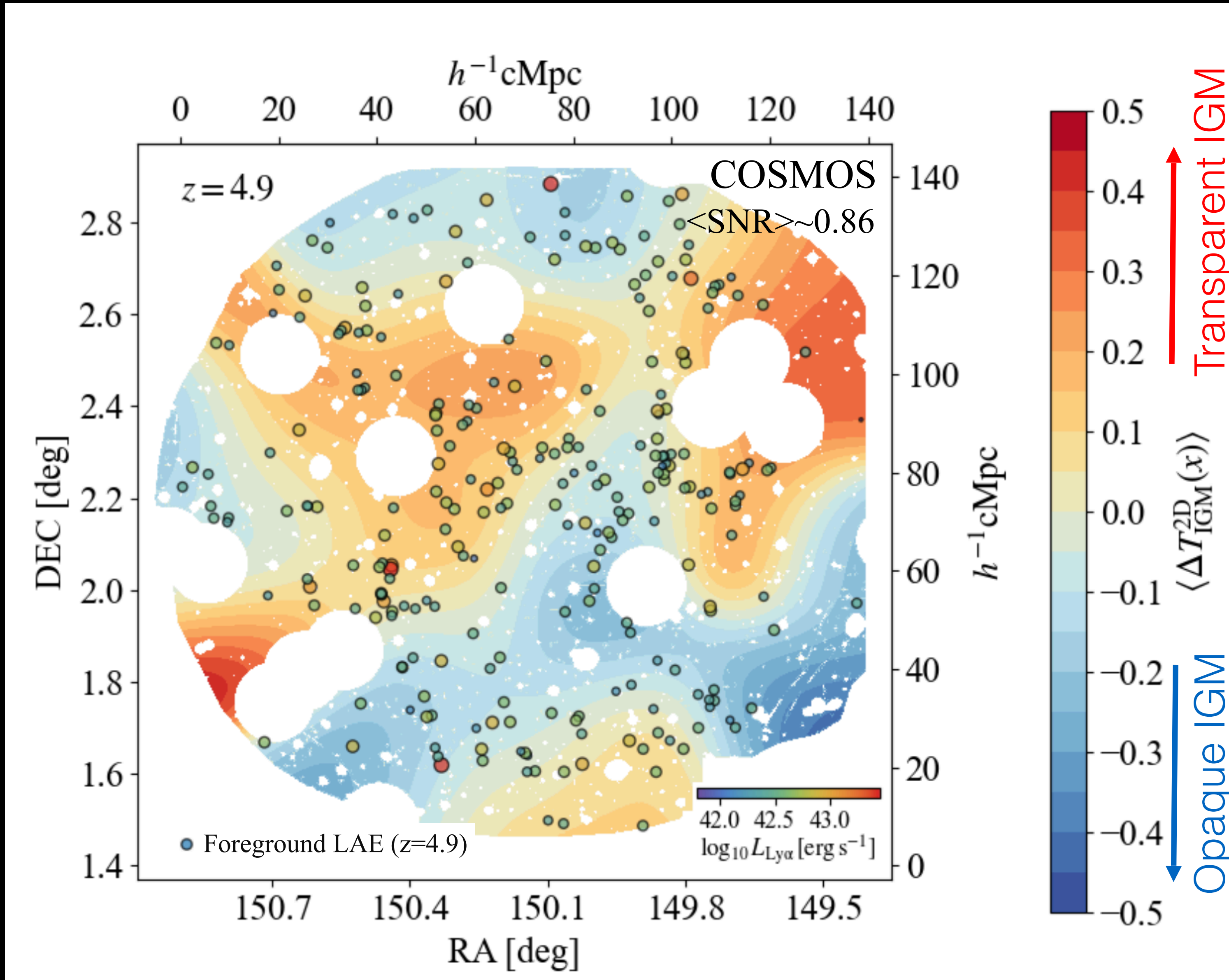


Photometric measurement of the IGM

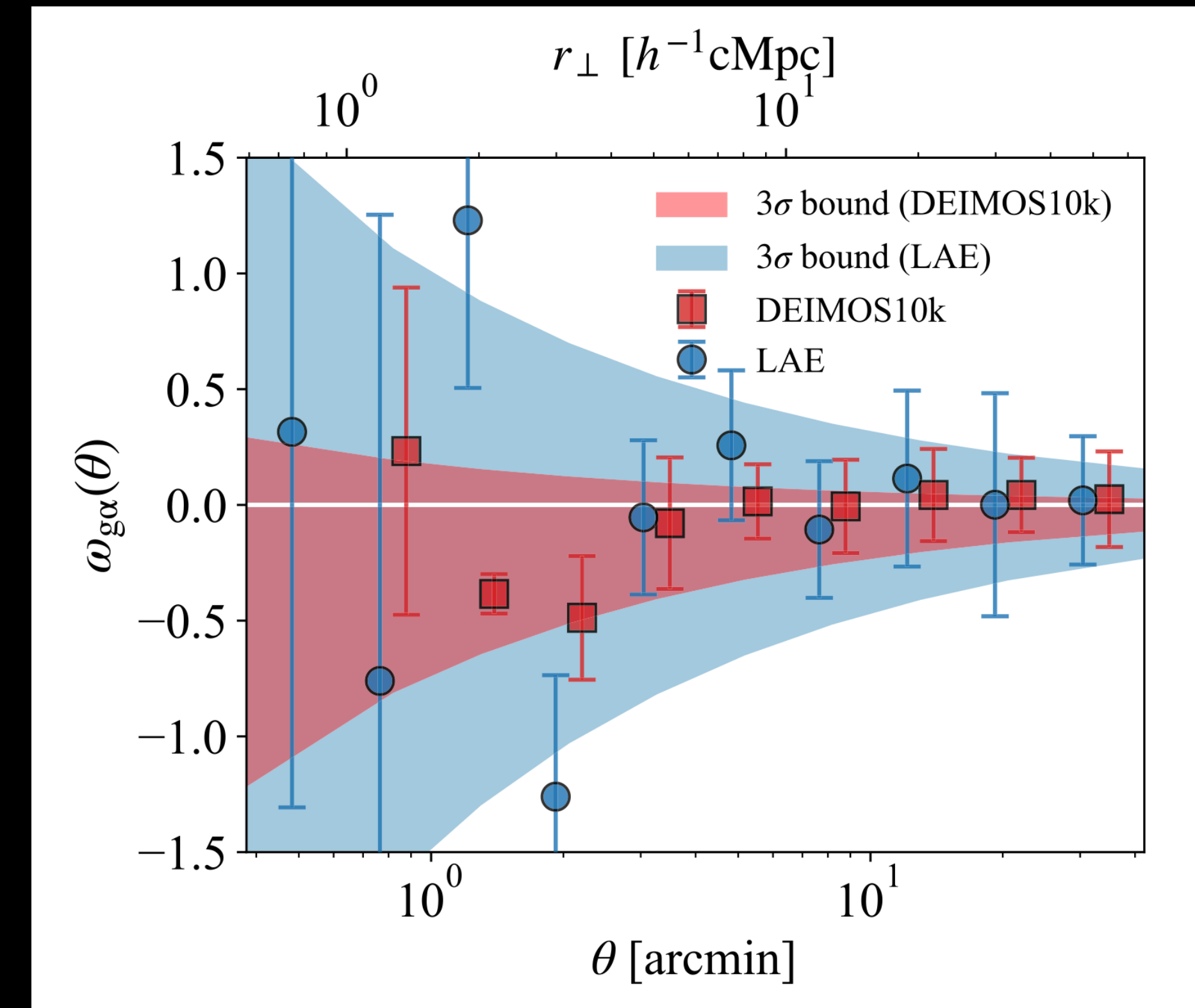
# Pilot Subaru/HSC study of Photometric IGM Tomography at $z \sim 5$



# Pilot Subaru/HSC study of Photometric IGM Tomography at $z \sim 5$



## Galaxy-Lya forest cross-correlation



**Null detection.**  
**Consistent with the rapid evolution**  
**at the tail end of reionization.**

# JWST: Mapping the Universe in 3D

JWST Wide-Field Grism Spectroscopic Survey of the COSMOS-Web Field

## “COSMOS-3D”

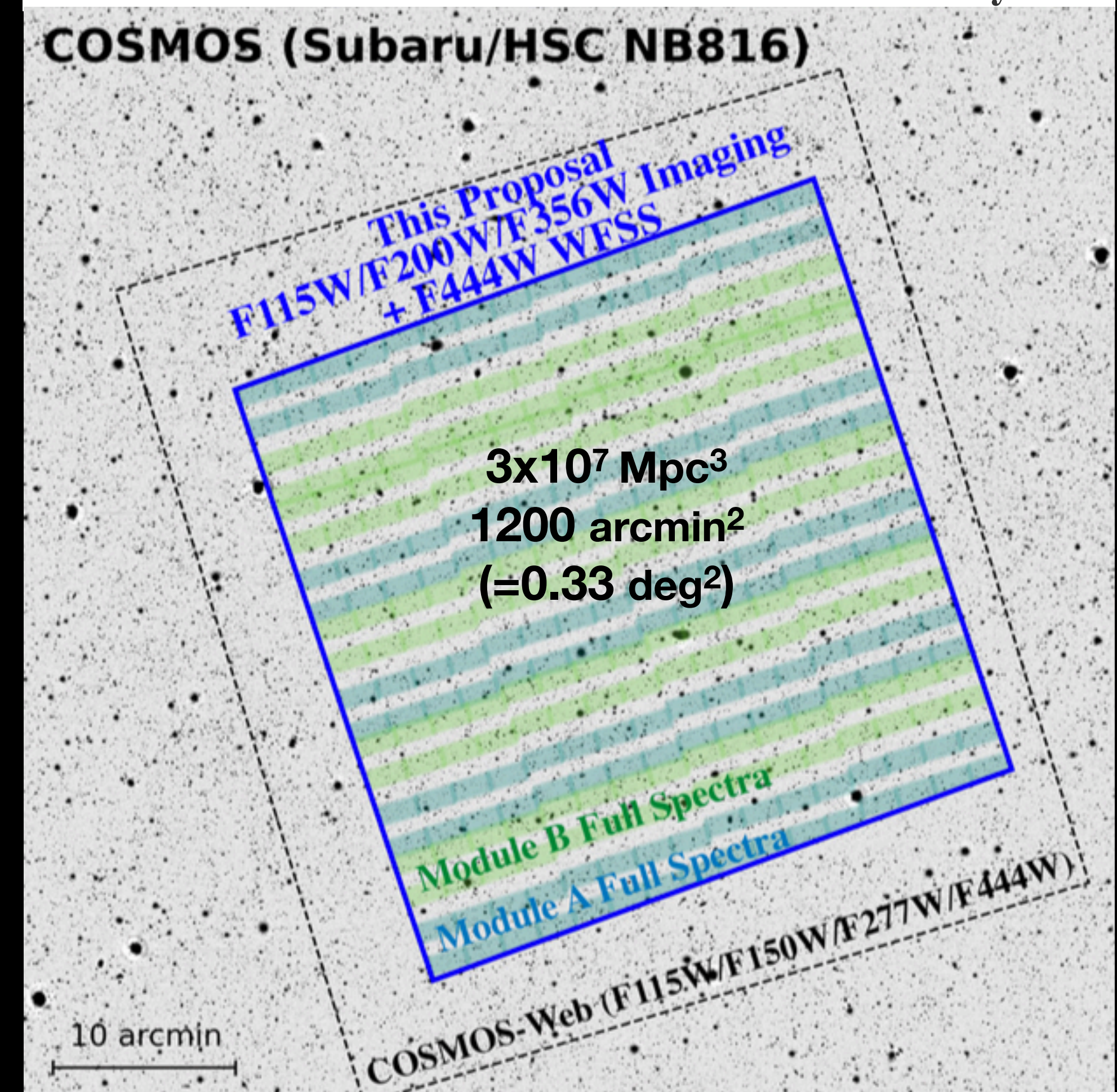
Large 265 hour public treasury program

- $z \sim 0-9$  spectroscopic survey  
NIRCam/F444W WFSS
- Complete full NIRCam imaging  
F115W (2nd epoch), F200W & F356W
- Parallel MIRI imaging  
F1000W & F2100W

This is built on legacy of FRESCO (Oesch+23) & 3D-HST (Brammer+12) & many years of the community effort on the COSMOS field, e.g. COSMOS-Web (Casey & Kartaltepe+23), COSMOS2020 (Weaver+21) ... Scoville+07

COSMOS-3D: A Legacy Spectroscopic/Imaging Survey of the Early Universe  
GO Cycle-3

COSMOS (Subaru/HSC NB816)

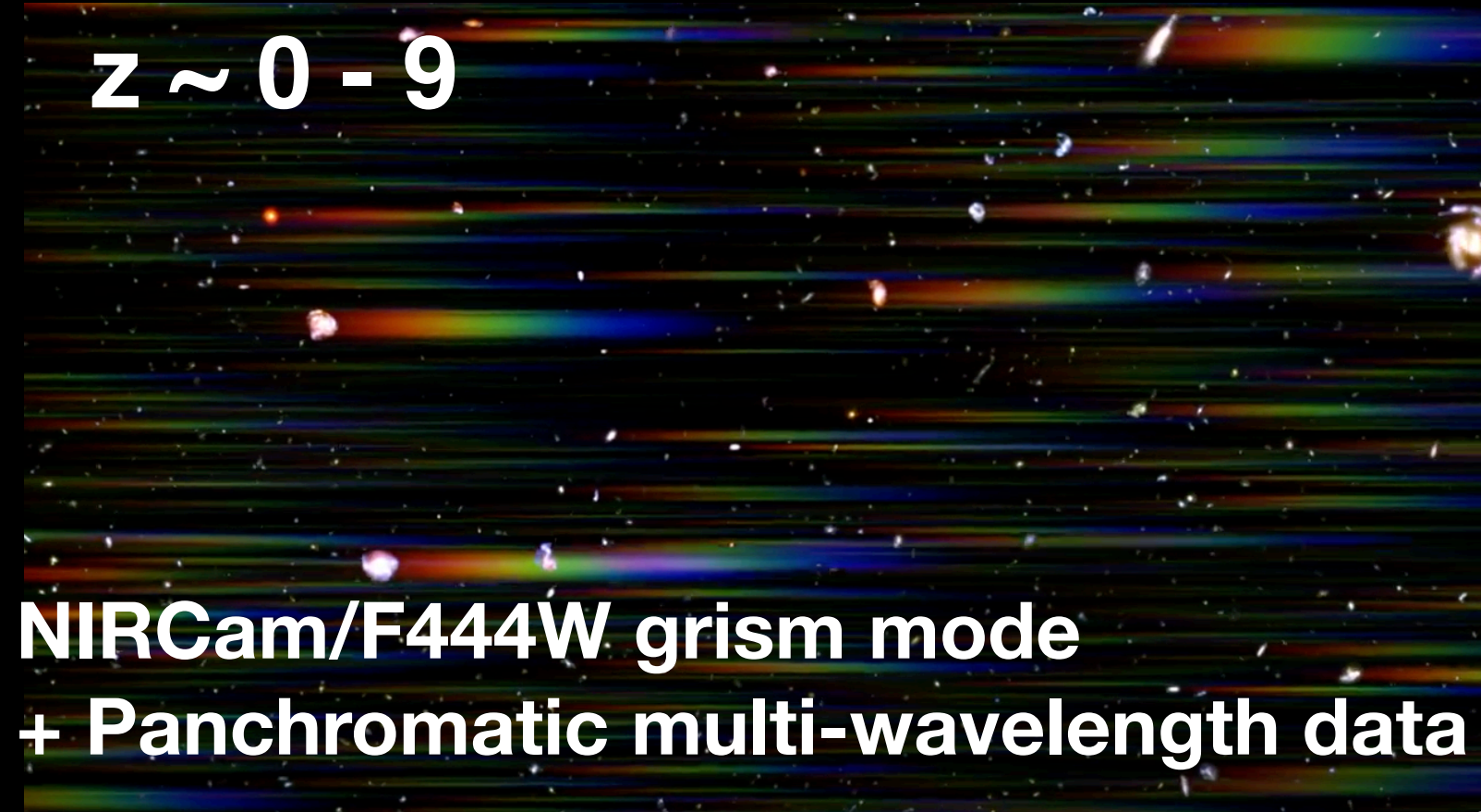


PI: Kakiichi, Co-PIs: Wang, Fan, Liu, Yang, Egami



# JWST: Mapping the Universe in 3D

3D Pano-Chromatic View of the Universe from sub-kpc to tens of Mpc over  $z \sim 0-9$



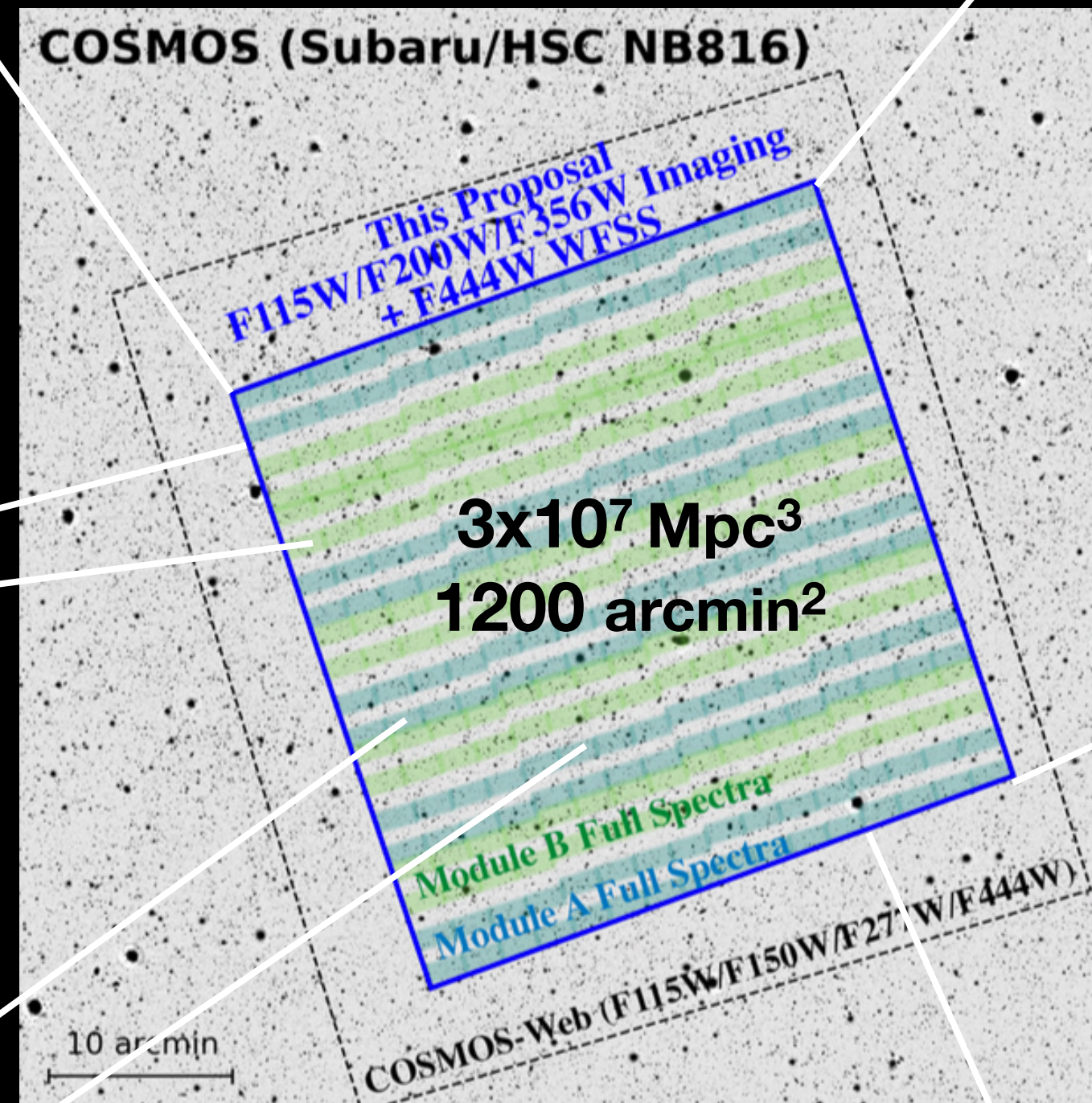
- **Large-scale clustering and formation of early galaxies**

Crisis of  $\Lambda$ CDM? or

Efficient build-up of stellar mass?

i.e. *Galaxy formation vs Cosmological interpretations*

## COSMOS-3D



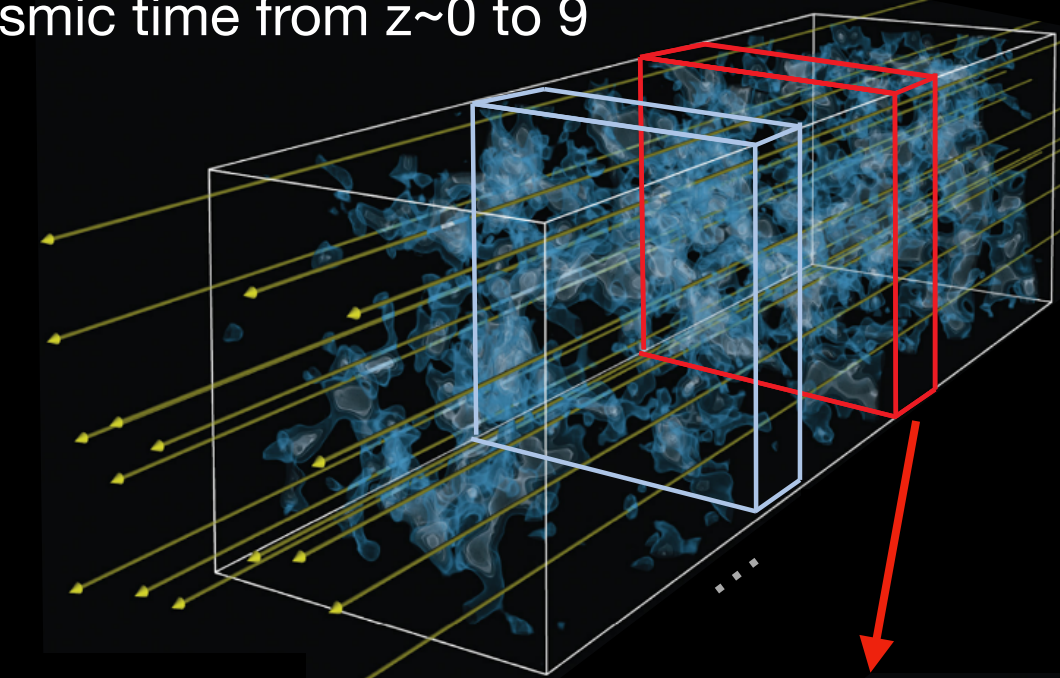
- **Large-scale clustering and demographics of SMBHs**

Mysteries surrounding

Little Red Dots &

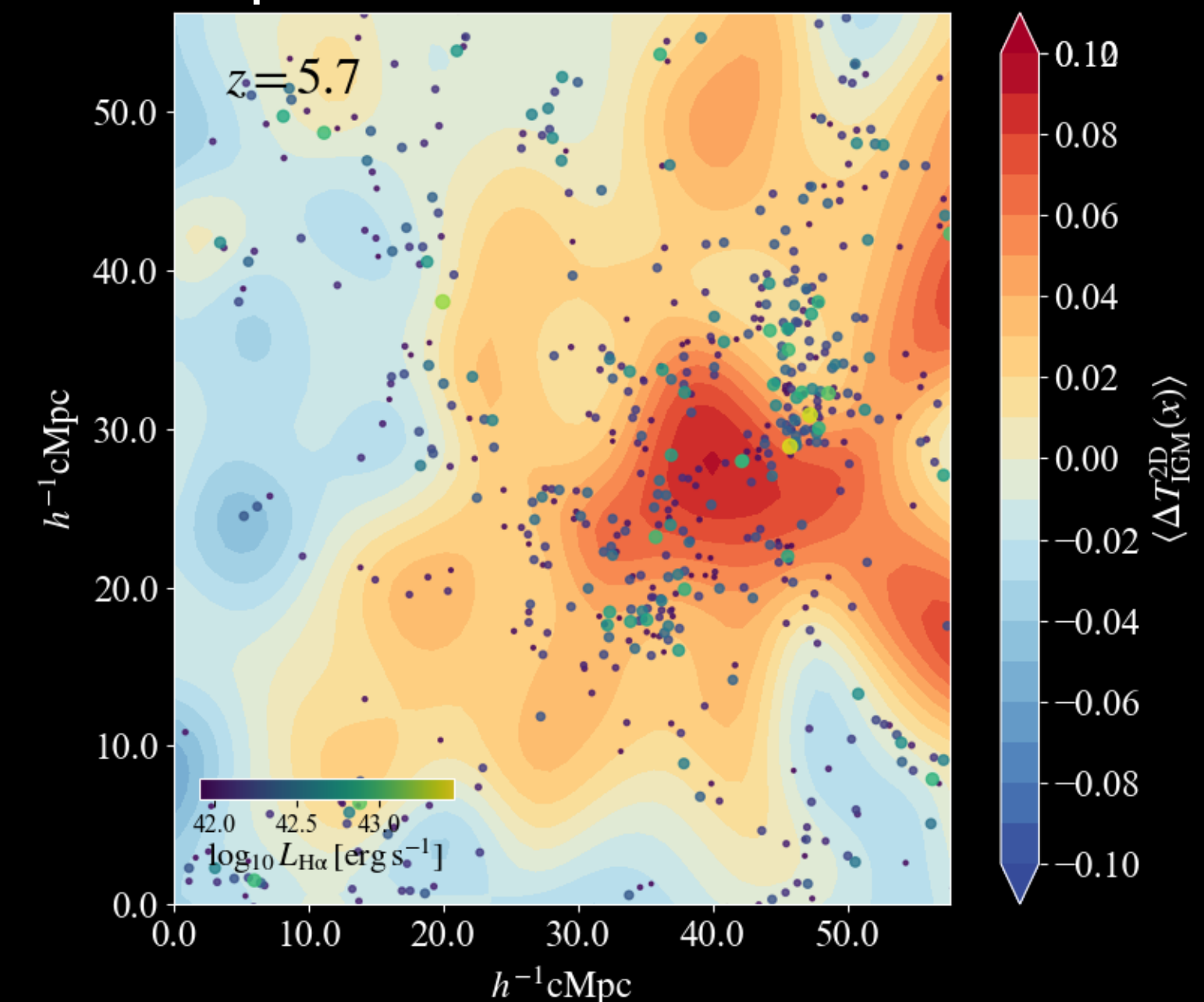
Formation of early SMBHs

Map all foreground & background galaxies across cosmic time from  $z \sim 0$  to 9



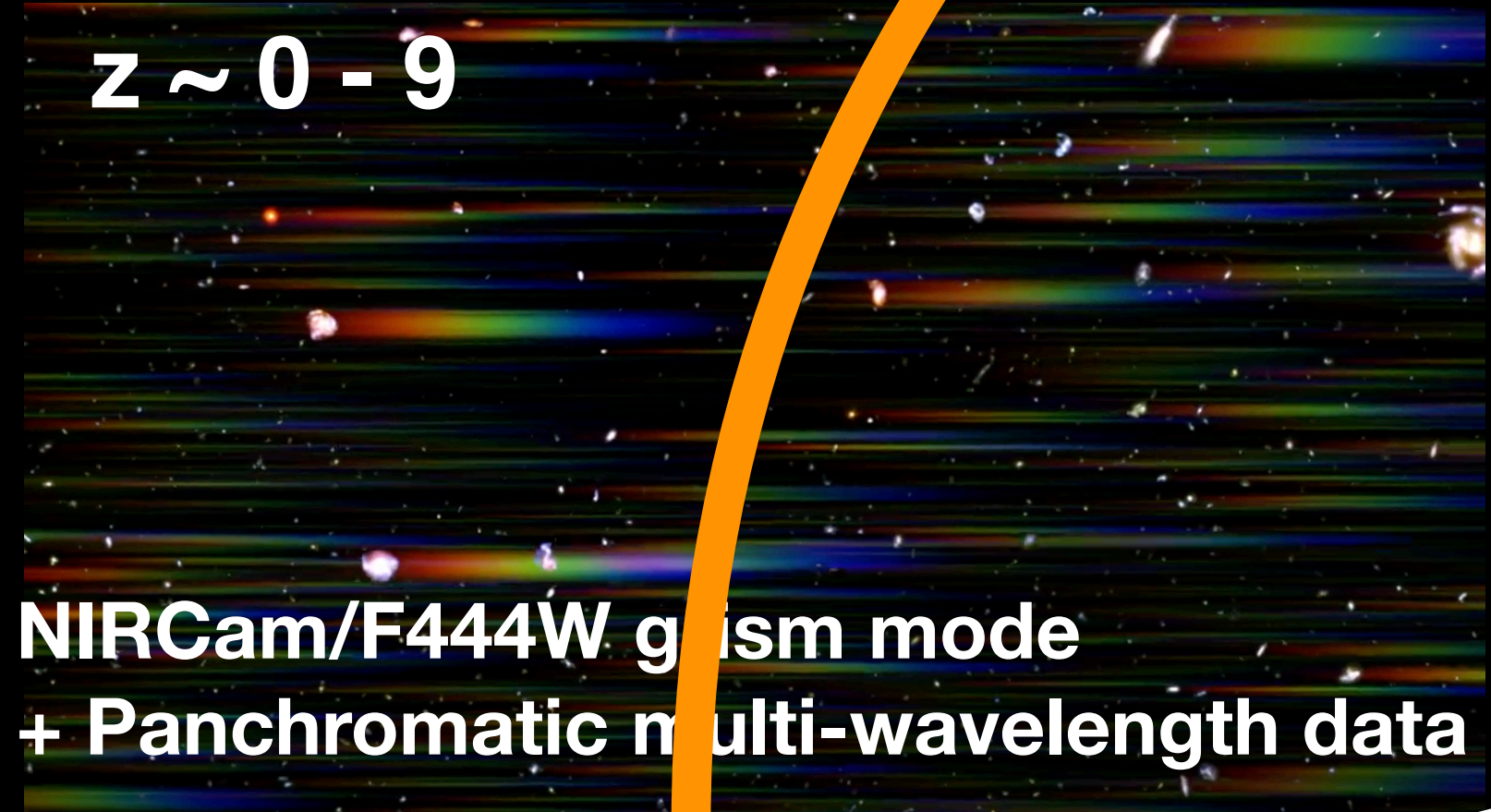
- **Galaxies in the Cosmic Web**  
JWST galaxies  $\times$  IGM tomography

Epoch of Reionization



# JWST: Mapping the Universe in 3D

3D Pano-Chromatic View of the Universe from sub-kpc to tens of Mpc over  $z \sim 0-9$



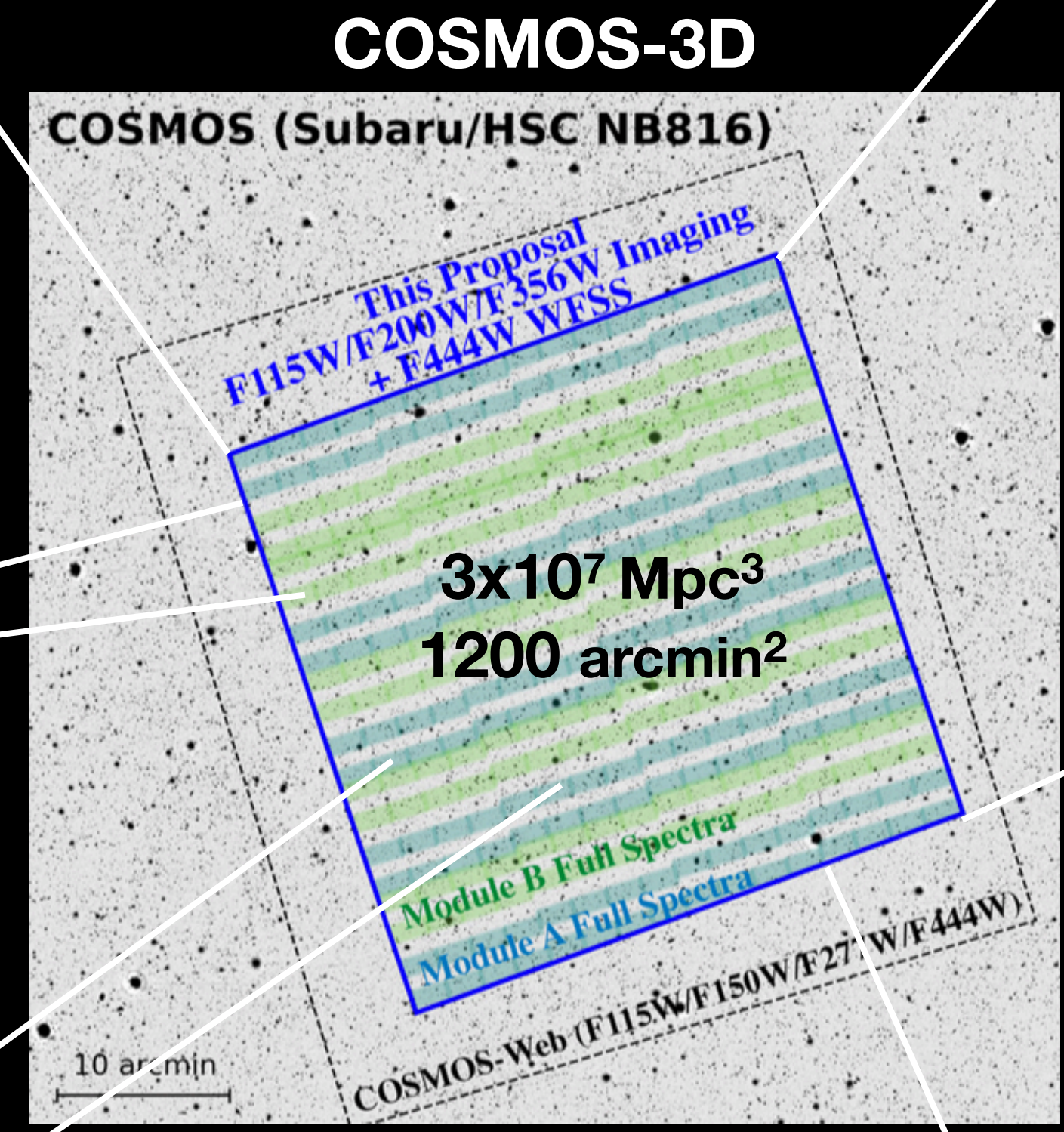
NIRCam/F444W grism mode  
+ Panchromatic multi-wavelength data

• **Large-scale clustering and formation of early galaxies**

Crisis of  $\Lambda$ CDM? or  
Efficient build-up of stellar mass?

i.e. *Galaxy formation vs Cosmological interpretations*

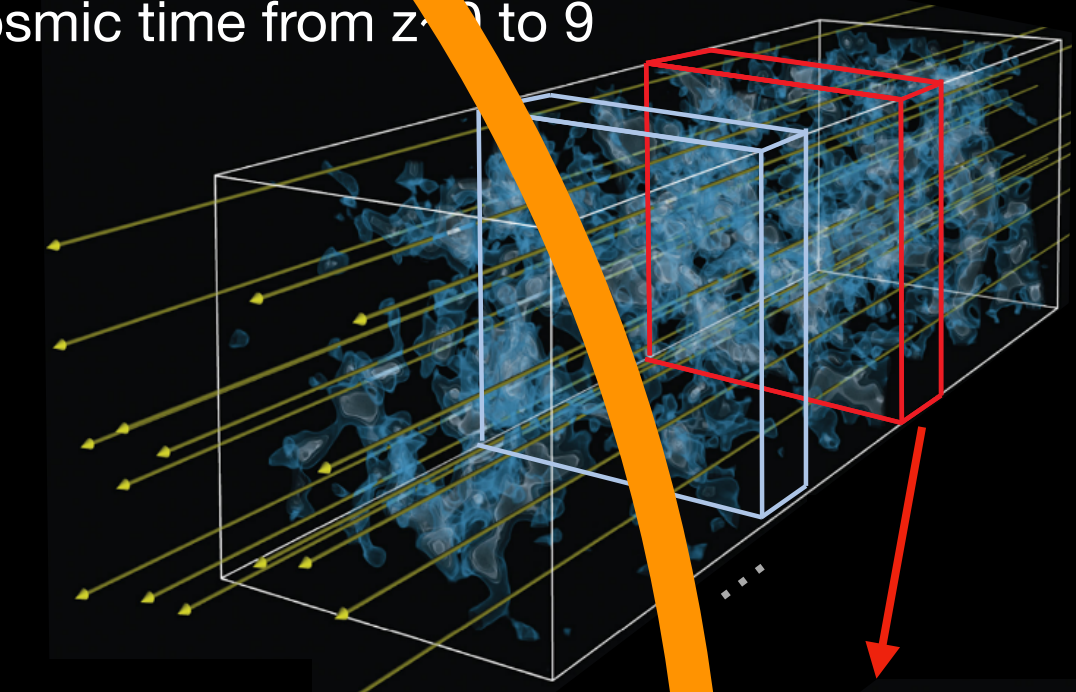
**Subaru**  
HSC & PFS  
& **Euclid**



• **Large-scale clustering and demographics of SMBHs**

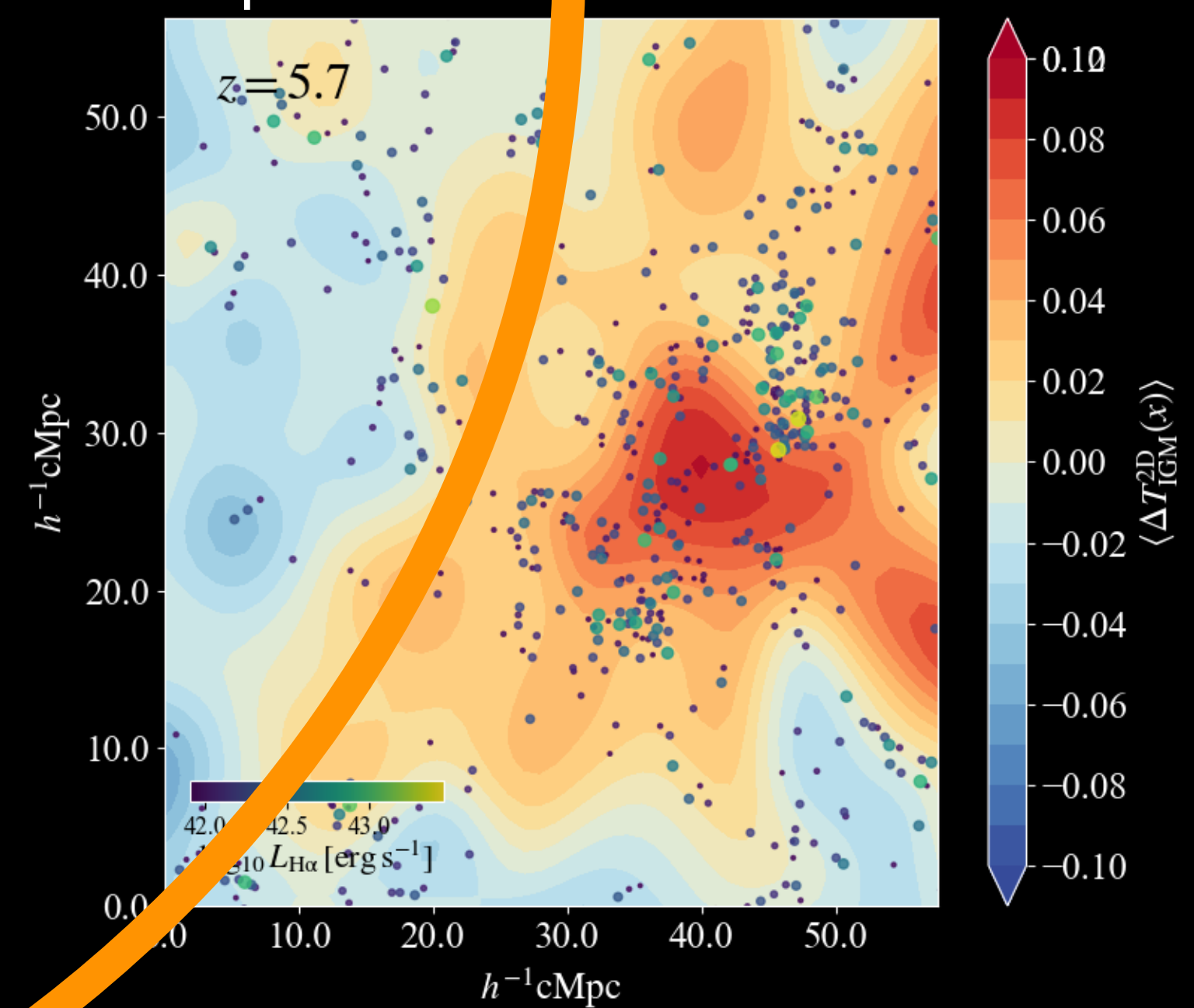
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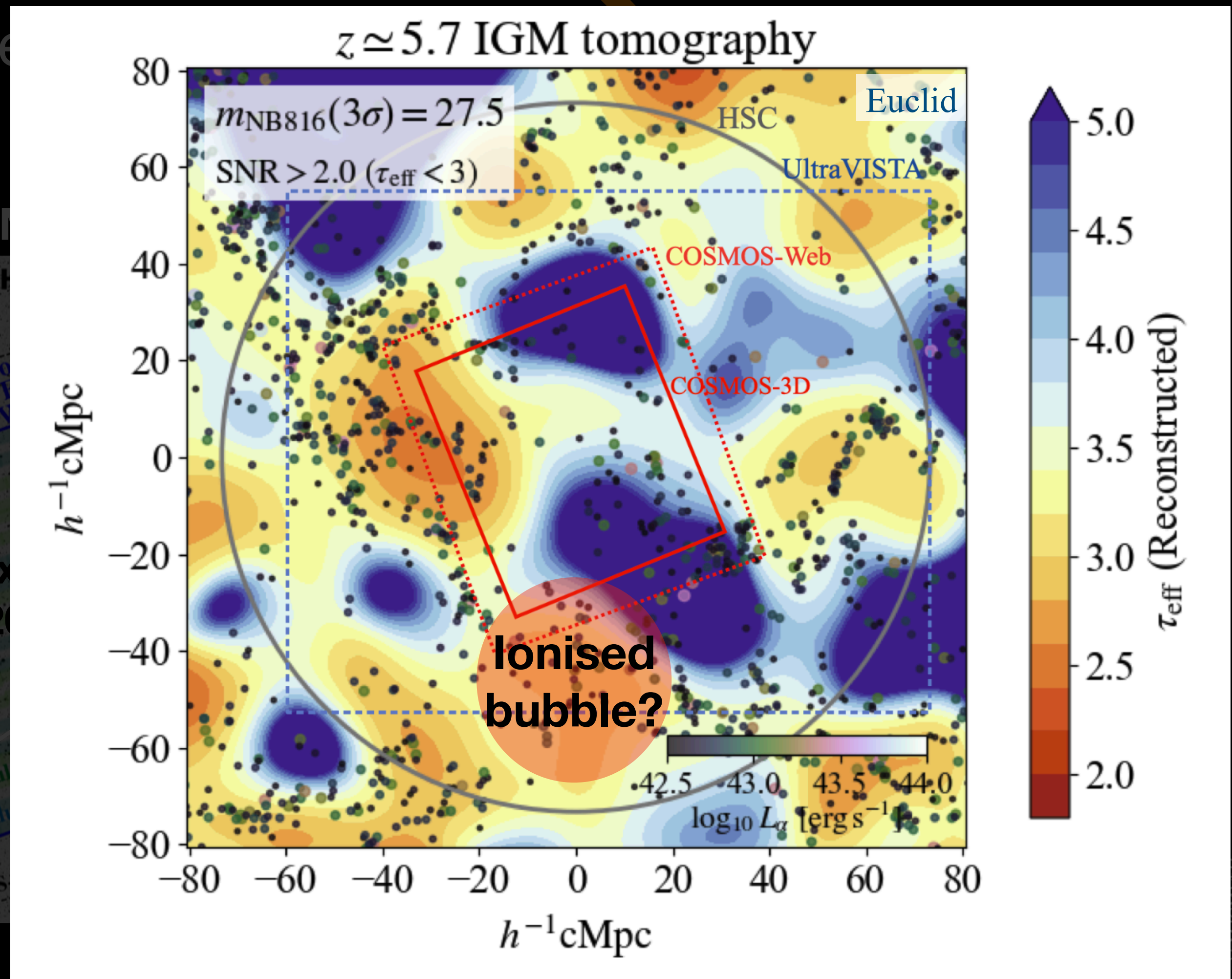
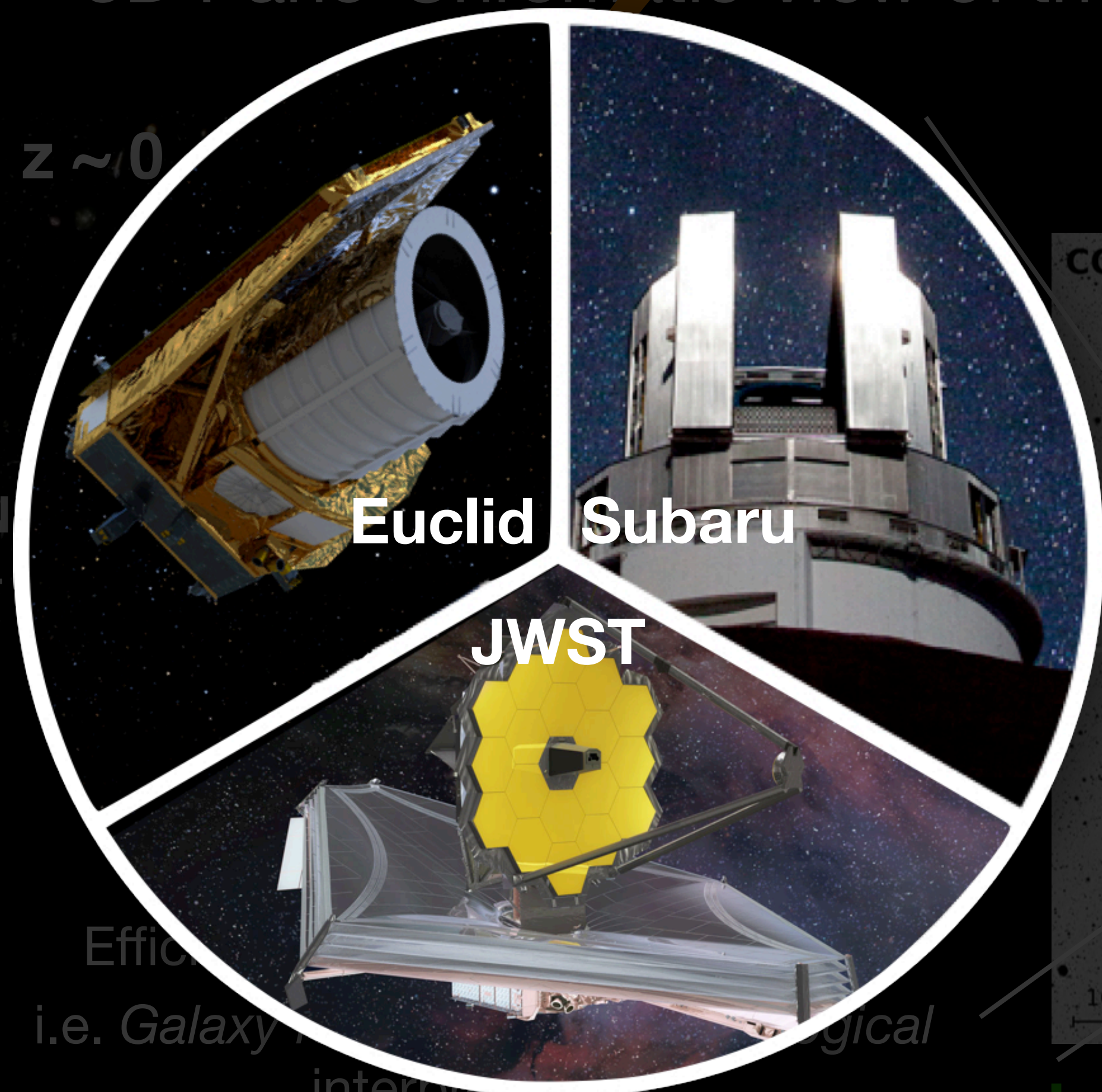
• **Galaxies in the Cosmic Web**  
JWST galaxies  $\times$  IGM tomography

Epoch of Reionization



# JWST: Mapping the Universe in 3D

## Synergy



**Dream of galaxy  $\times$  21cm tomography may come true?**

**Morphological analysis of ionised bubbles and the spatial correlation with galaxies**

Kakiichi+17, Busch et al 20, Giri & Mellema 21, Elbers & van de Weygaert 19,23

e.g. Kakiichi+22,23

# Summary

- **Spatial correlation between galaxy and Ly $\alpha$  forest**  
from JWST ASPIRE QSO field survey
  1. Evidence for [OIII] emitters residing in highly ionized IGM at the final stage of reionization from statistical [OIII] emitter-Ly $\alpha$  forest cross-correlation
  2. Evidence for faint or unseen galaxies completing reionization from individual [OIII] emitter - transmission spike associations
- **Photometric IGM tomography** is one of the key driver of  
a Cycle-3 *public treasury program* “**COSMOS-3D**”

JWST Wide-Field Grism Spectroscopic Survey of the COSMOS-Web Field with NIRCam/F444W + parallel MIRI imaging (F1000W & F2100W) + time-domain F115W

Back-up

