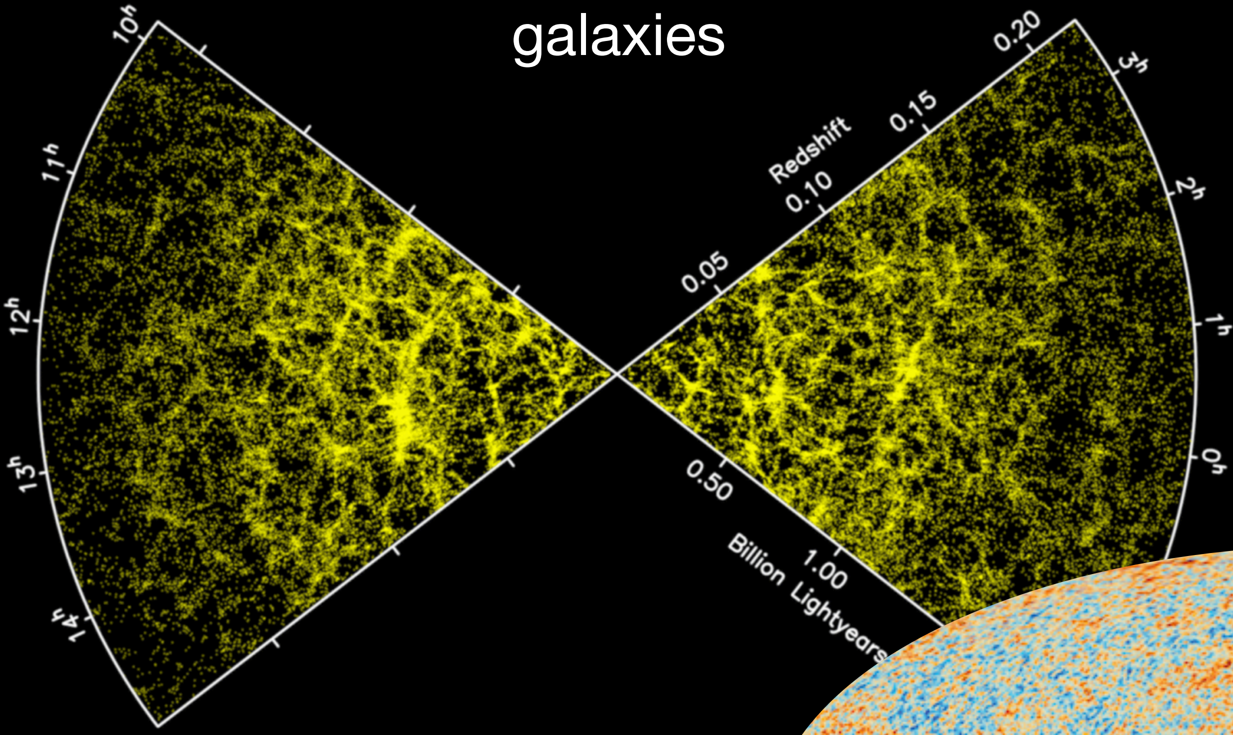
Photometric IGM Tomography Across Cosmic Time

Koki Kakiichi
University of California, Santa Barbara

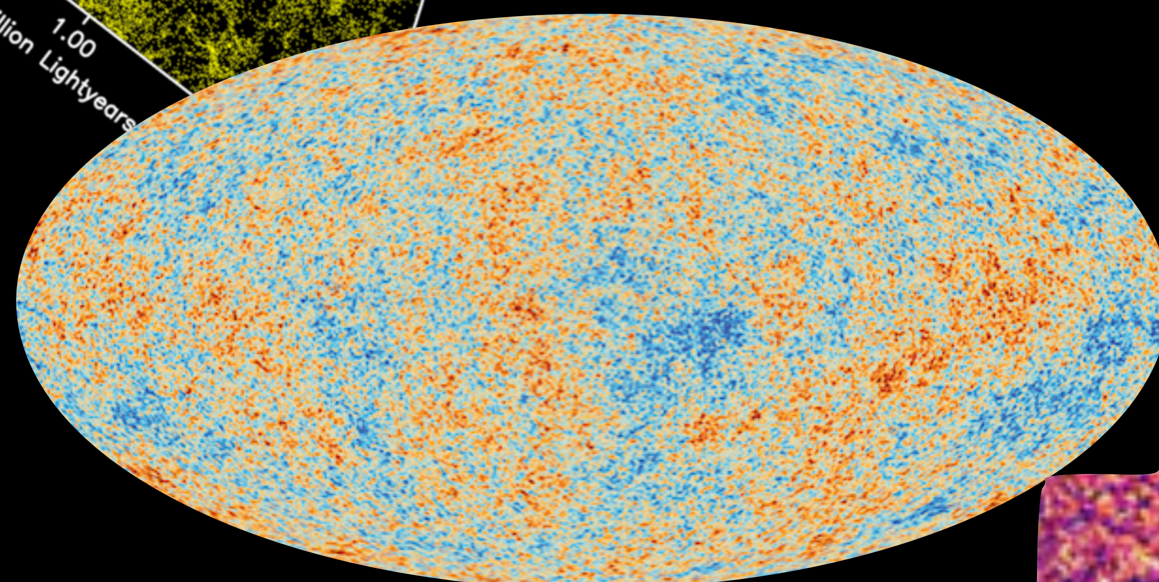
Kakiichi+22 arXiv:2207.08202
Kakiichi+23 arXiv:2301.00373
Kakiichi+ in prep

Art of cosmic cartography

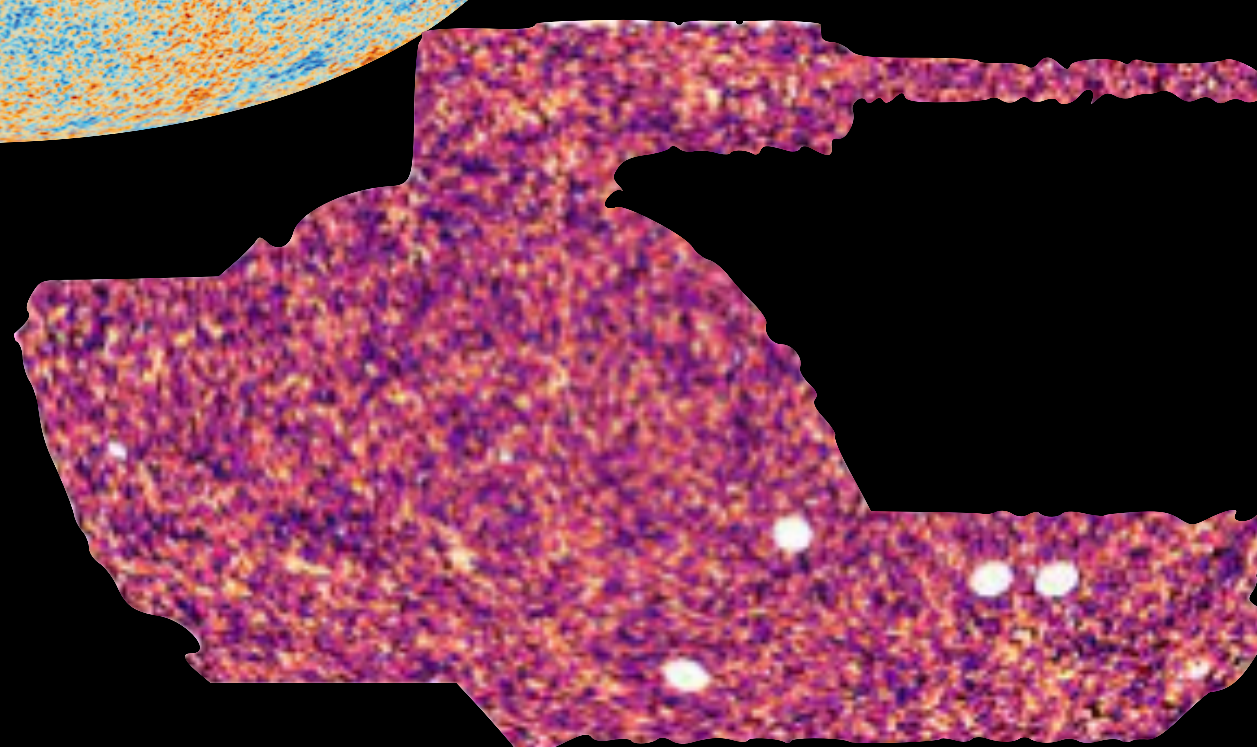
galaxies



CMB

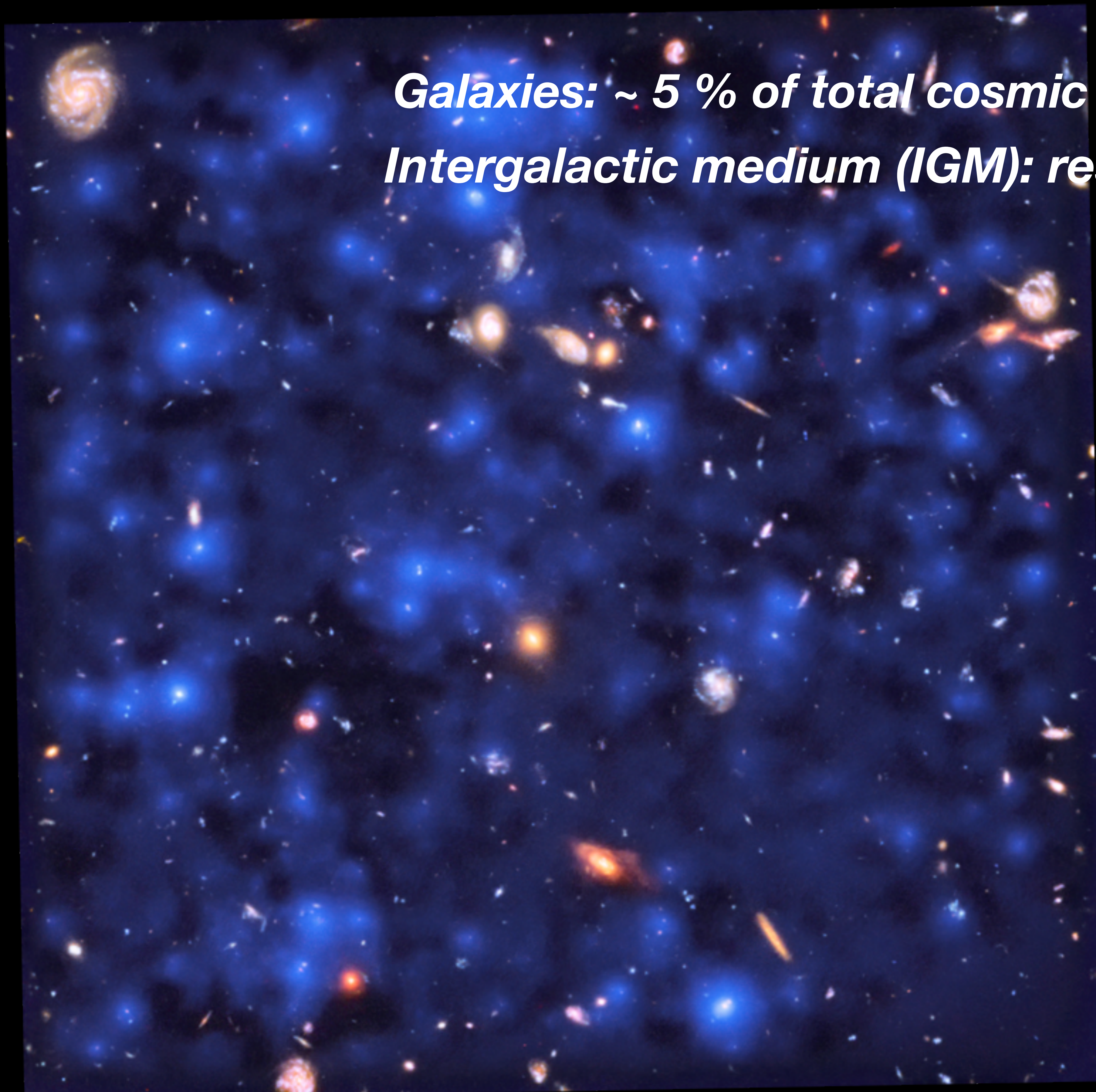


weak lensing

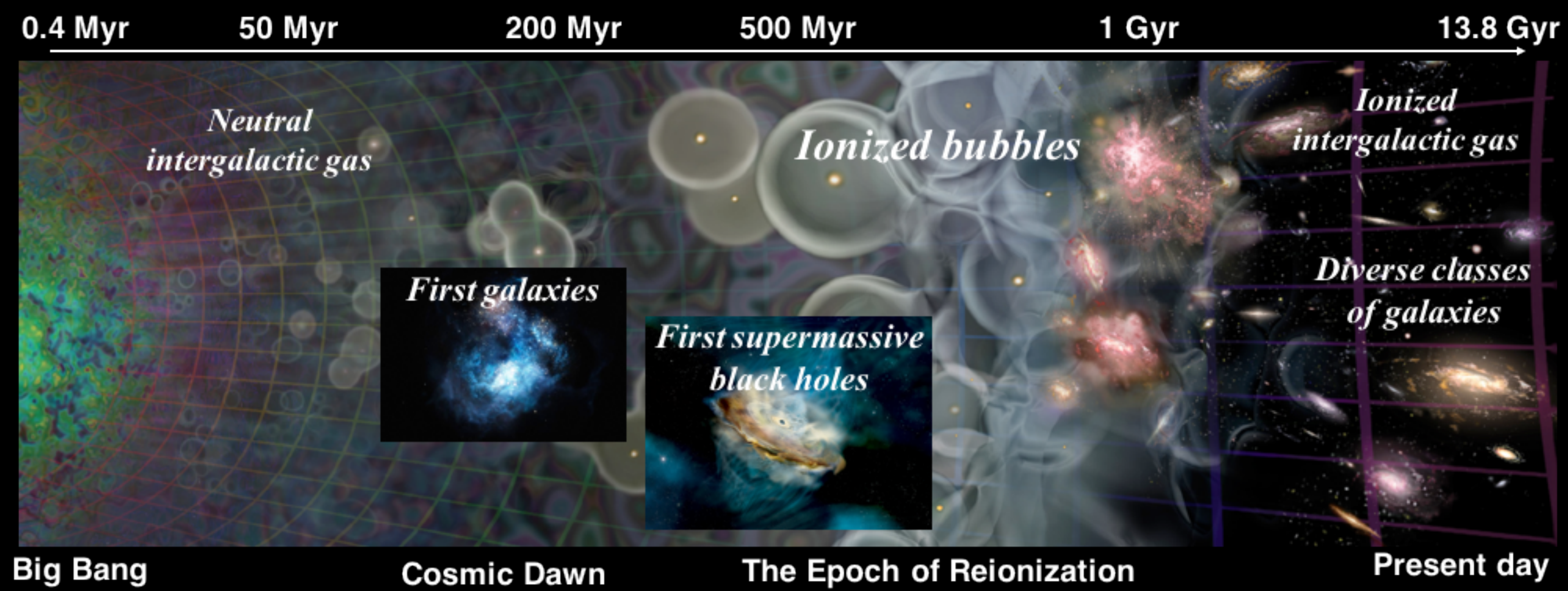


Galaxies: ~ 5 % of total cosmic atoms

Intergalactic medium (IGM): rest ~ 95 %



Pushing the redshift frontier of cosmic cartography



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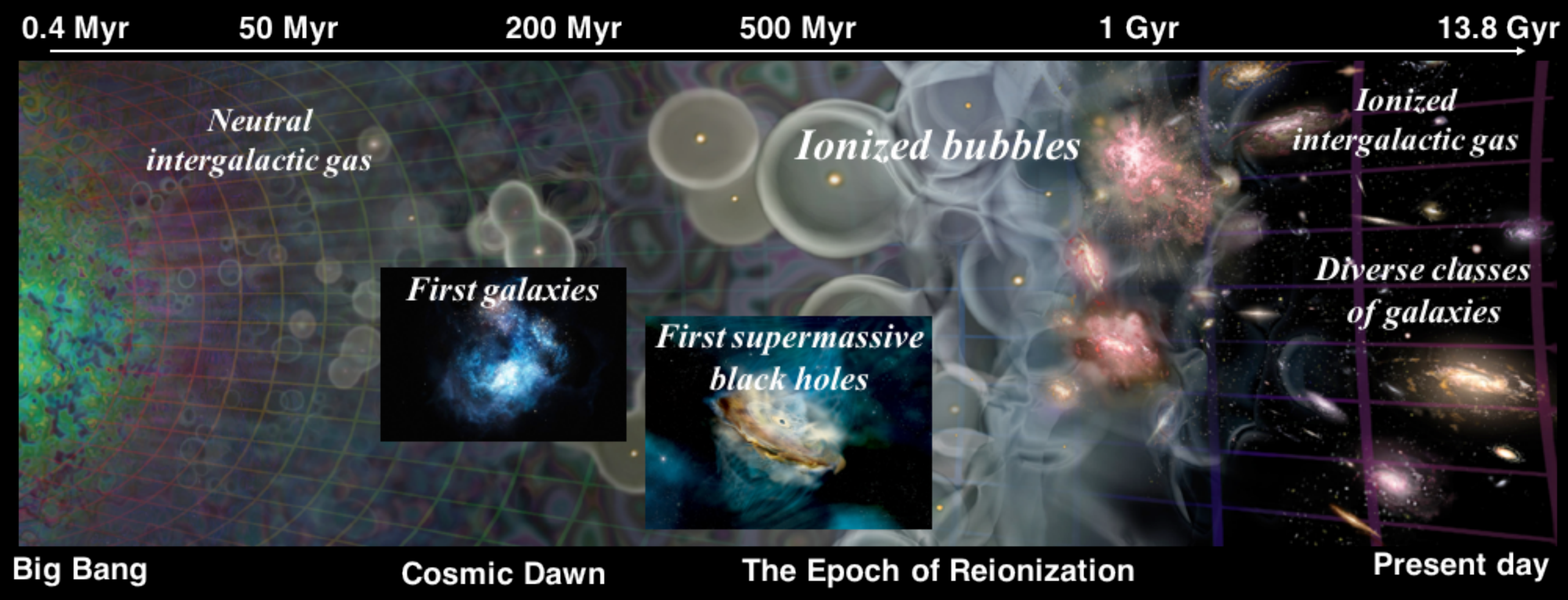


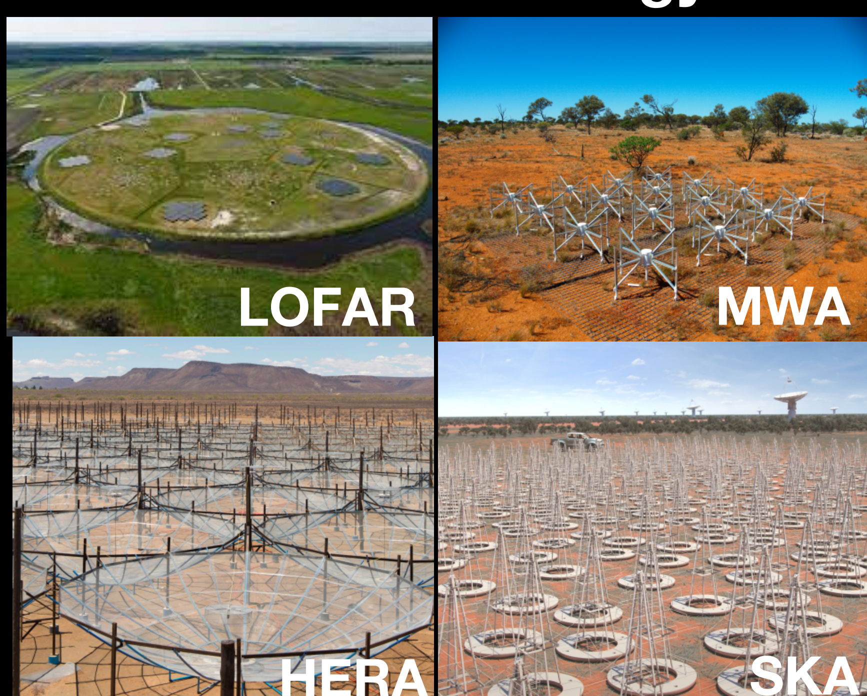
Key questions:

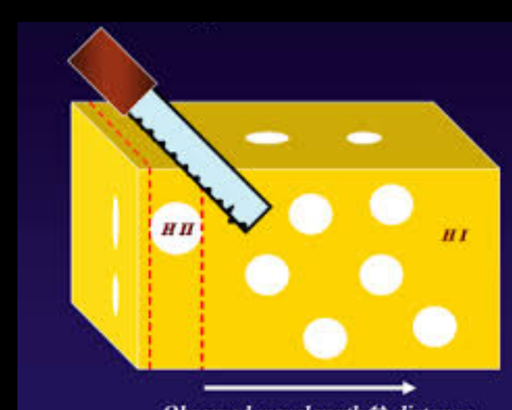
- **What is the origin and astrophysics of the first galaxies & supermassive black holes?**
- **How did they drive the reionization of the Universe?**

Pushing the redshift frontier of cosmic cartography

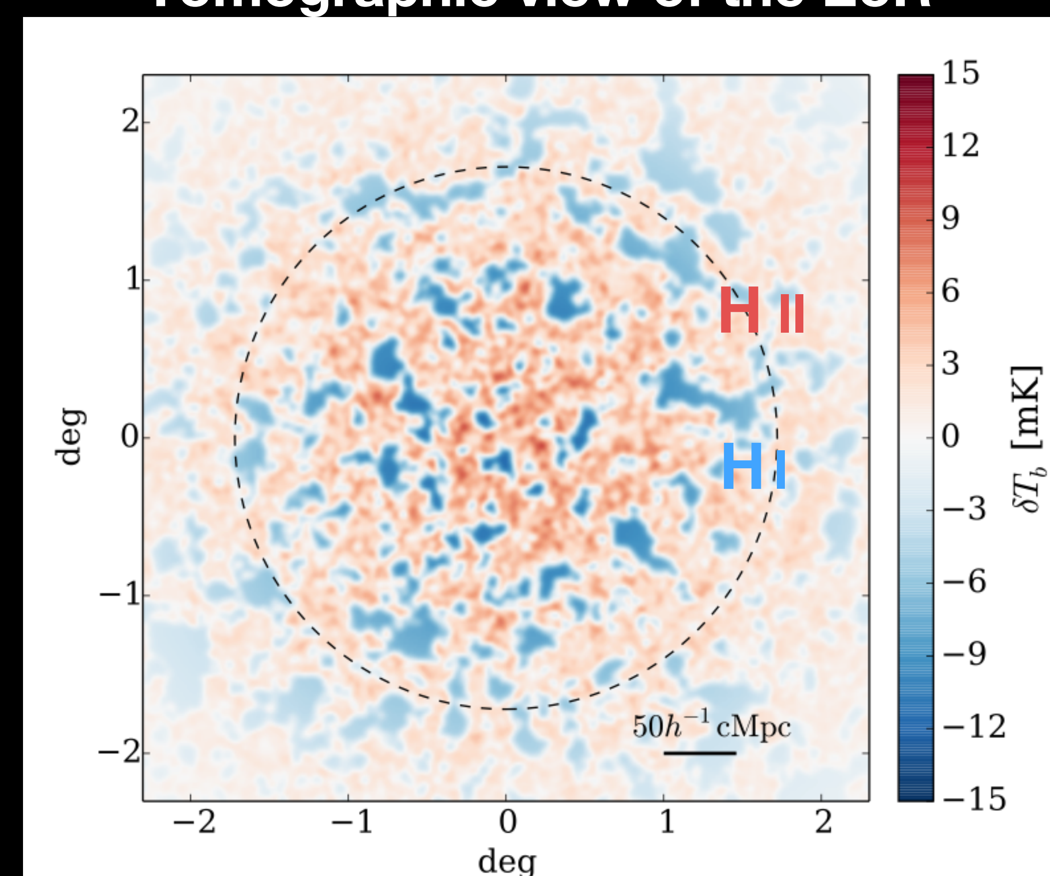
New technique in IGM tomography

21cm cosmology





Tomographic view of the EoR



e.g. Furlanetto et al 06, Prichard & Loeb 12

Kakiichi+18b

Outline

Technique

- Mapping the large-scale cosmic web with "Photometric IGM tomography"

Applications

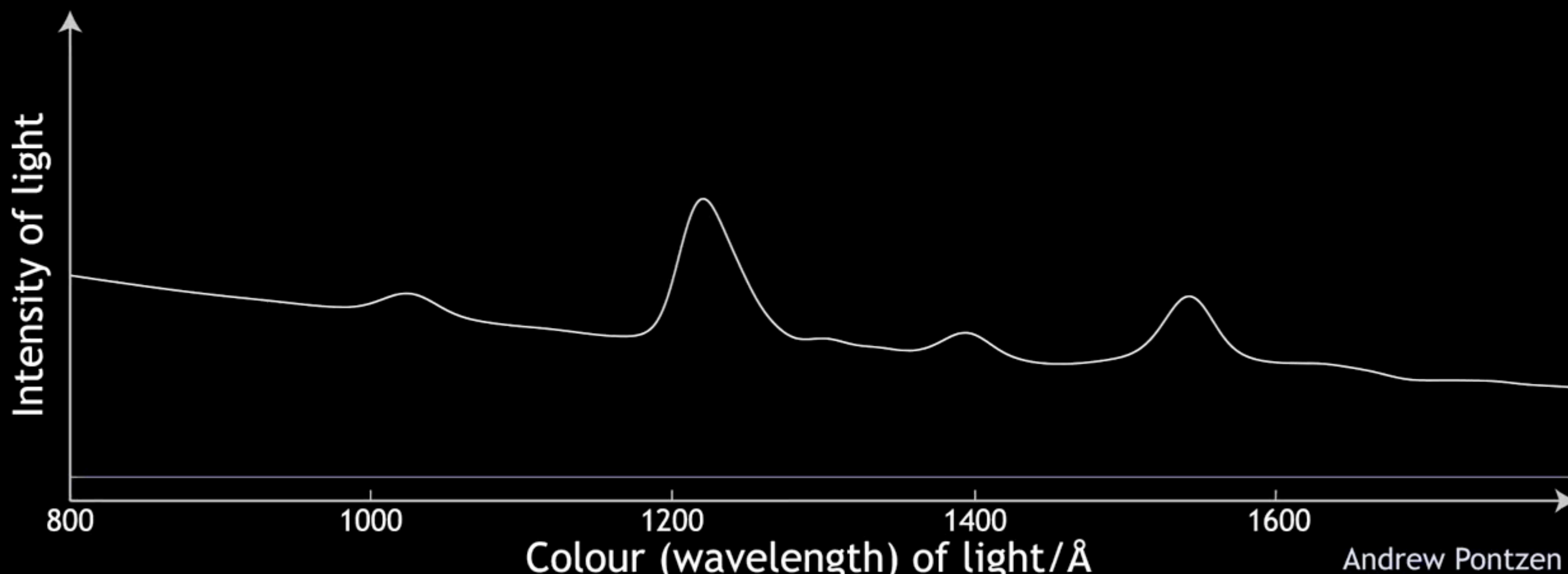
1. Sources of reionization & Ionizing capability of galaxies
2. Growth history of supermassive black holes

Future

- with Subaru/Prime Focus Spectrograph (PFS)
- with James Webb Space Telescope (JWST)
- with 30-m class telescopes e.g. TMT, ELT

Photometric IGM Tomography Technique

Tracing the large-scale structure of the IGM with Lyα forest



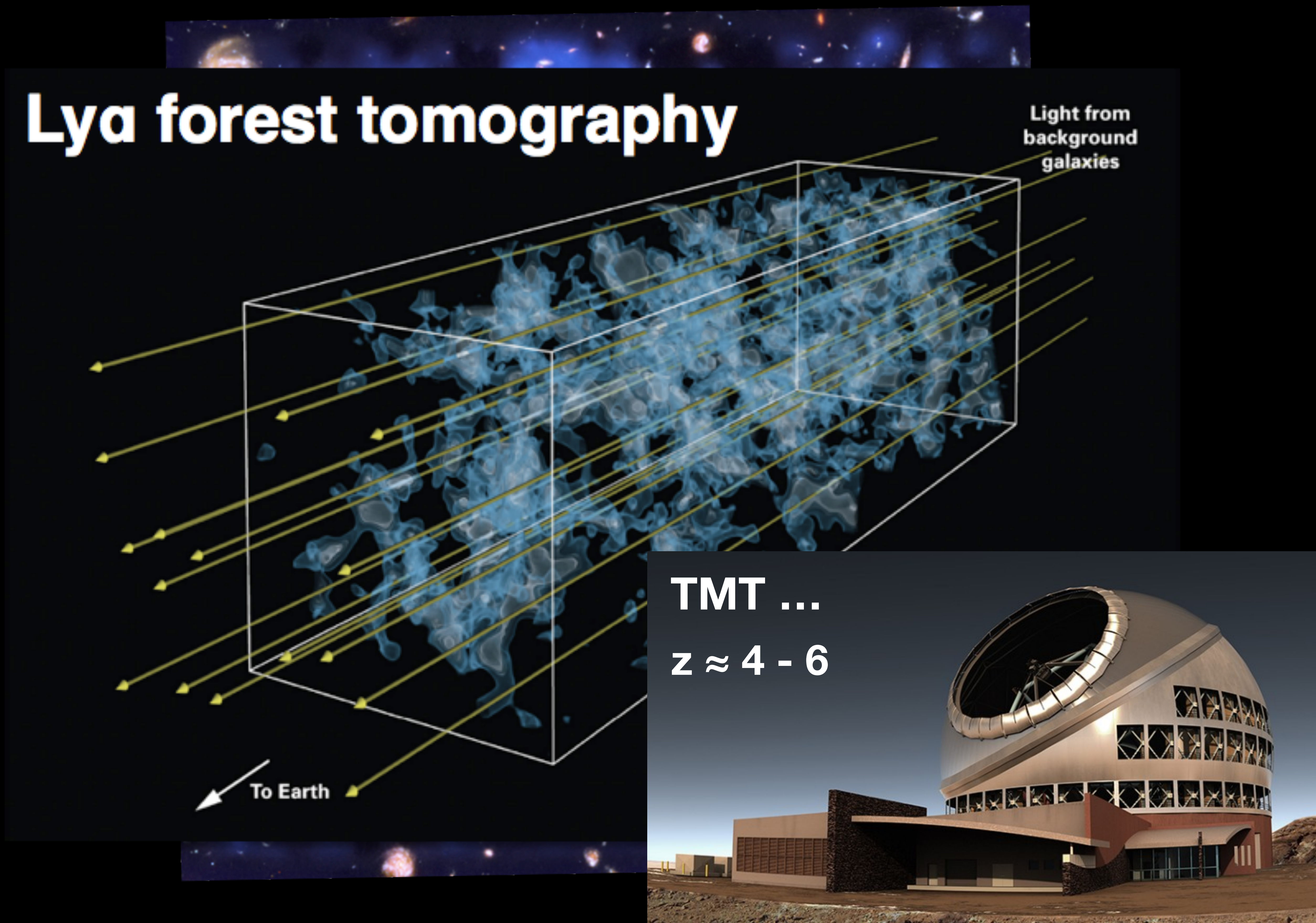
Lyα optical depth $\tau_\alpha \propto \rho^2\, \Gamma_{ion}^{-1}\, T^{-0.72}$

Density

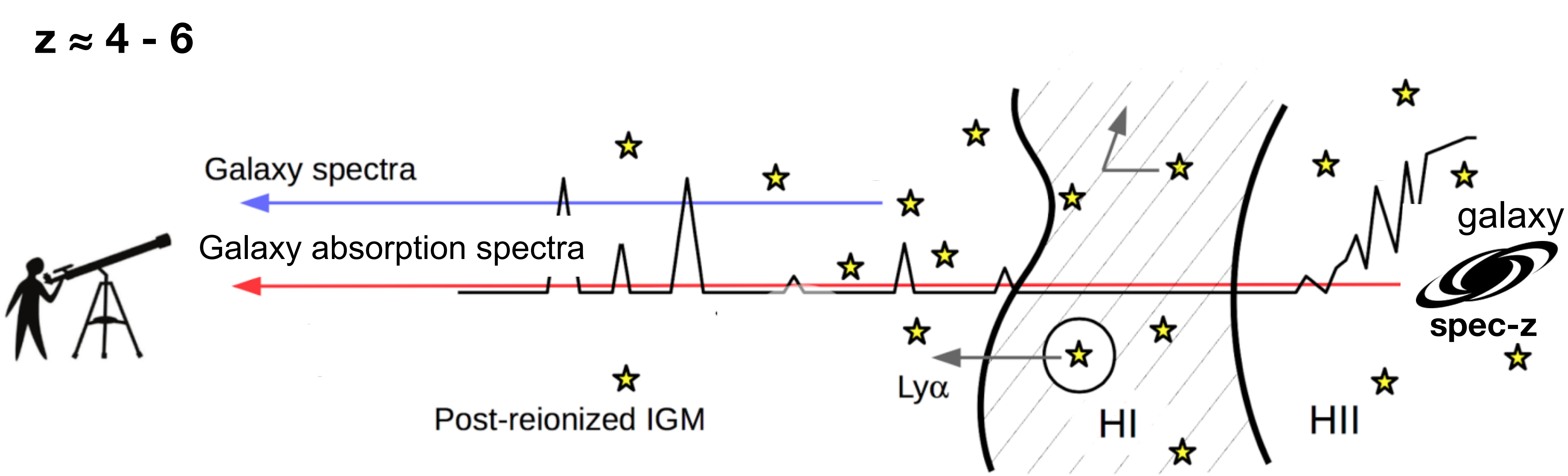
Ionizing background

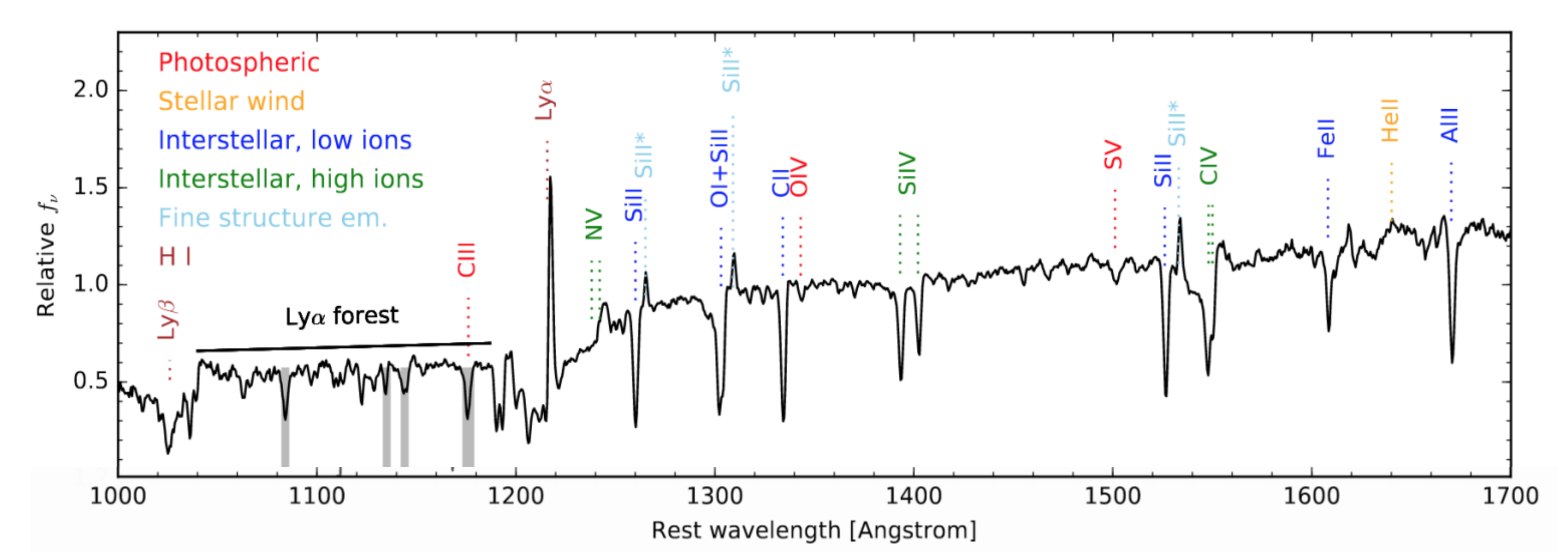
Temperature

Probing the IGM using Lyα forest along Background Galaxies



Spectroscopic IGM tomography

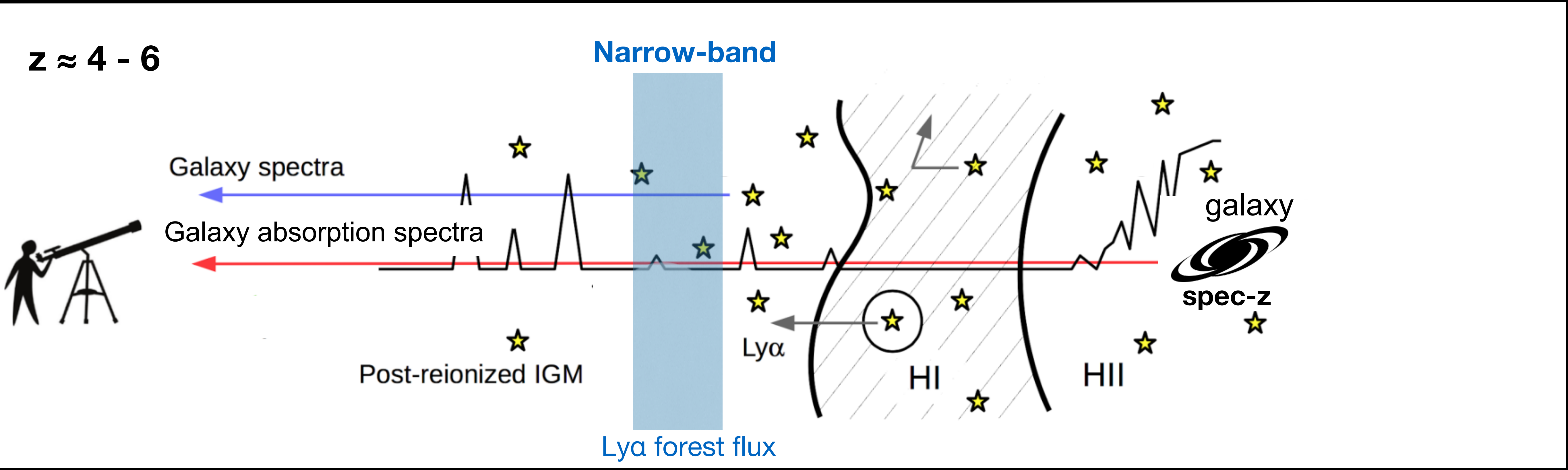


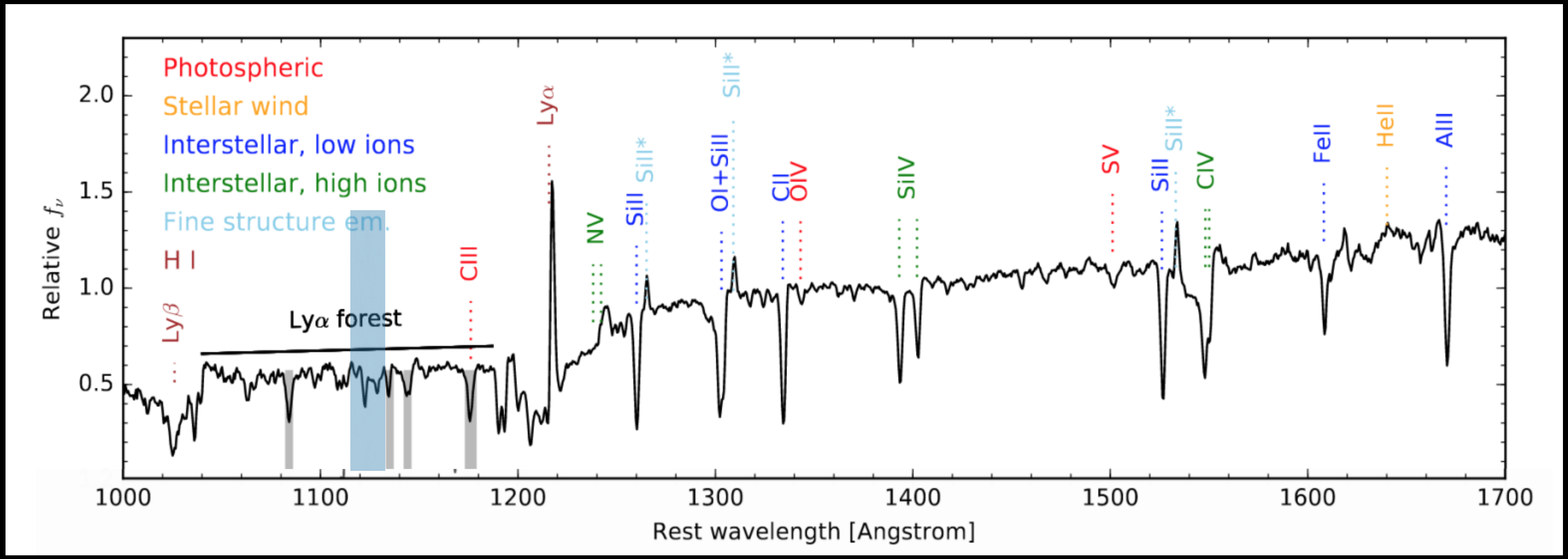


We need … deep spectra of background galaxies

Lee+14,18, Newman+20, Horowitz+22

“*Photometric*” IGM tomography

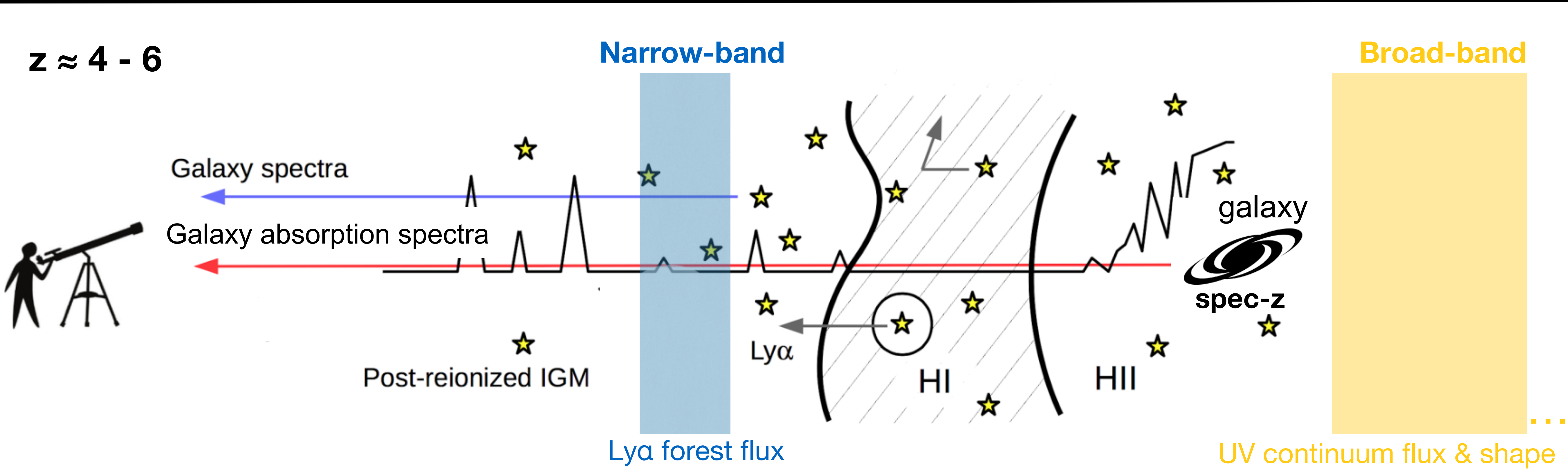


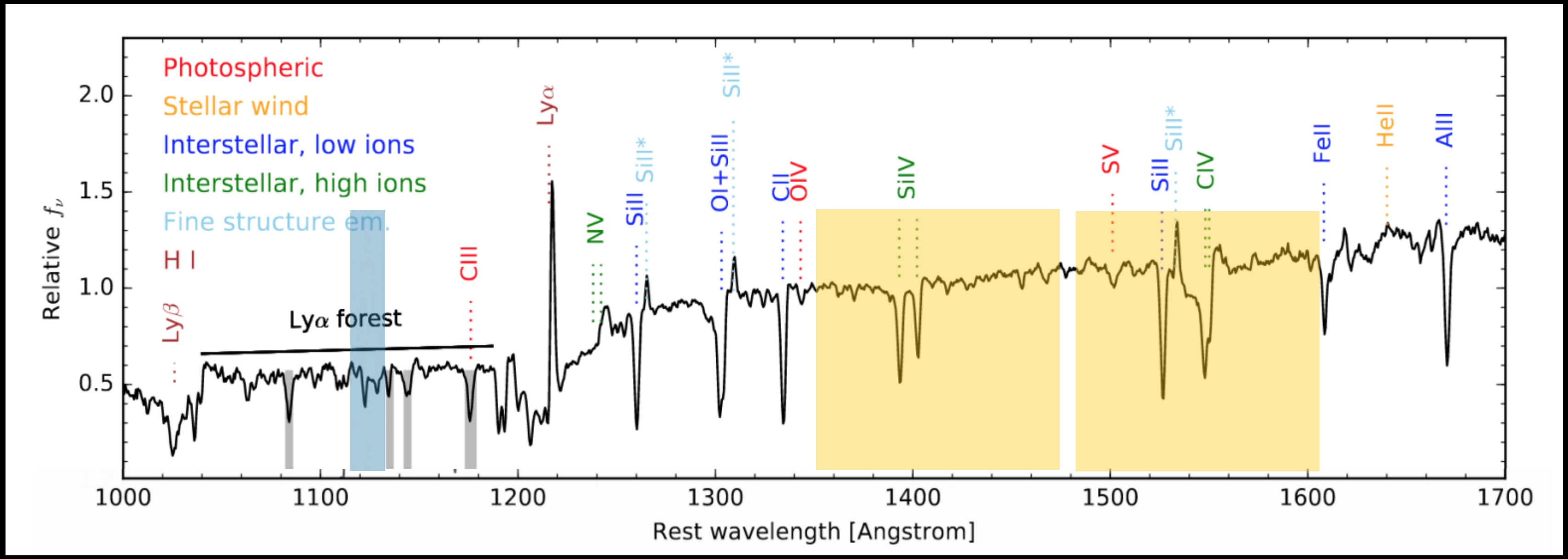


Photometric search for faint Lyα forest flux with a “narrow-band filter”

Mawatari+17, Kakiichi+22,23

“*Photometric*” IGM tomography



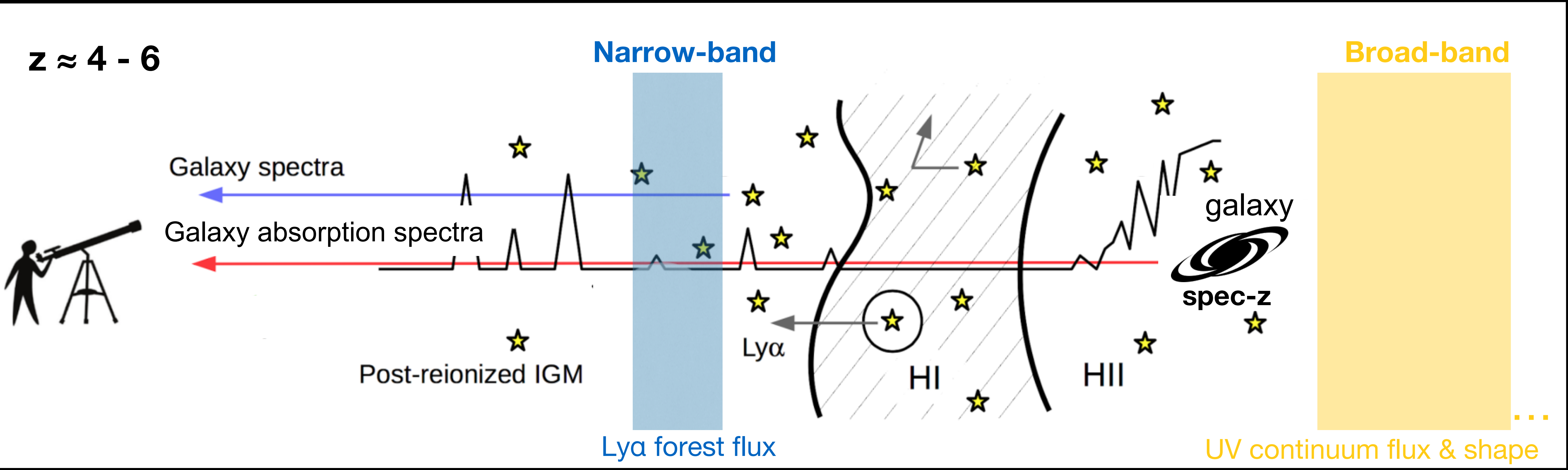


Photometric characterisation of background galaxy’s SEDs

Lyα optical depth

$$\exp(-\tau_\alpha) \approx \frac{\text{Narrow-band flux}}{\text{Broad-band flux}}$$

"Photometric" IGM tomography



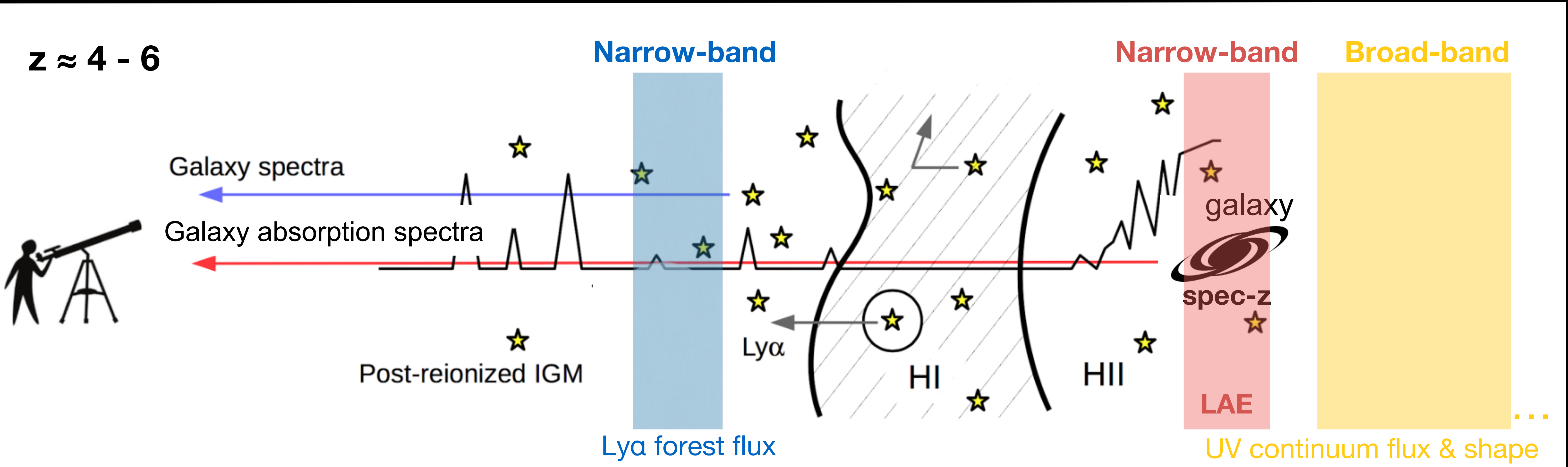
Observed flux ∝ (instrument throughput) x (mirror diameter)^2 x (Lyα forest flux)

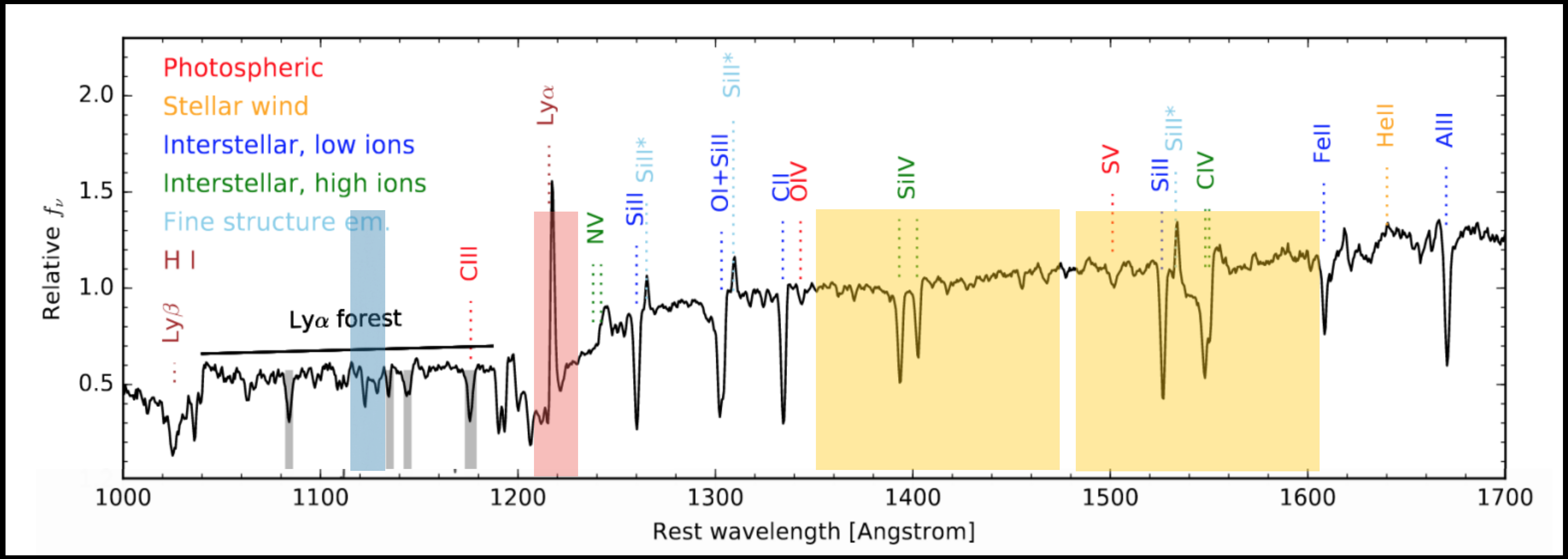
(60% / 10-20%)$^{1/2}$ x (8.2 m Subaru mirror) = 14-20 m mirror

Imager: throughput ~ 60 %
Spectrograph: throughput ~ 10-20 %

≈

"Photometric" IGM tomography

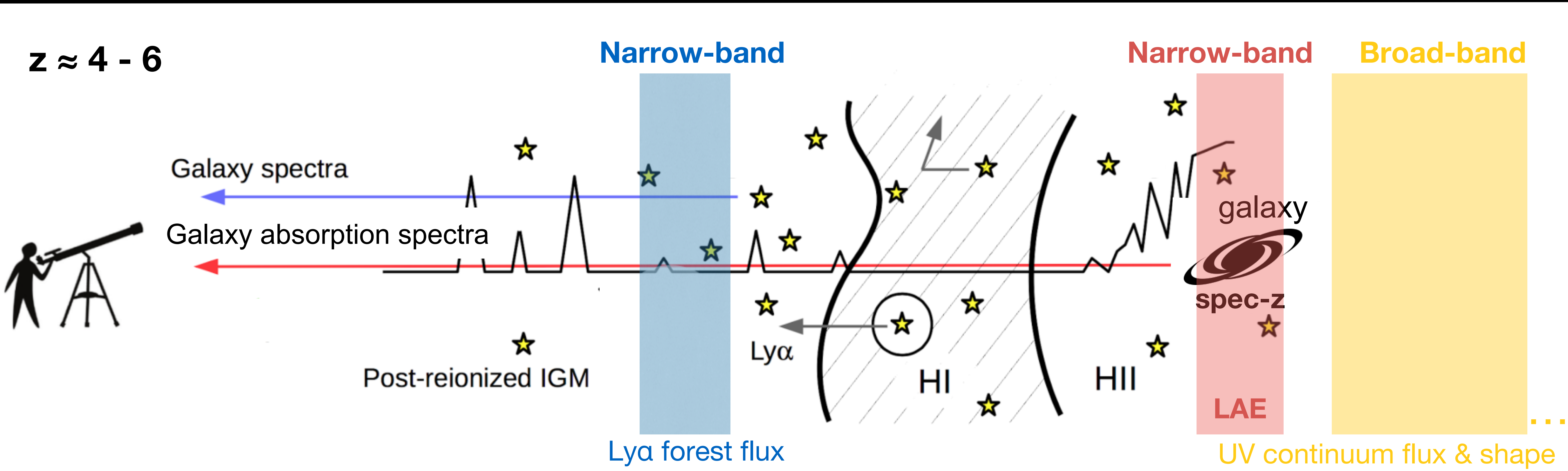


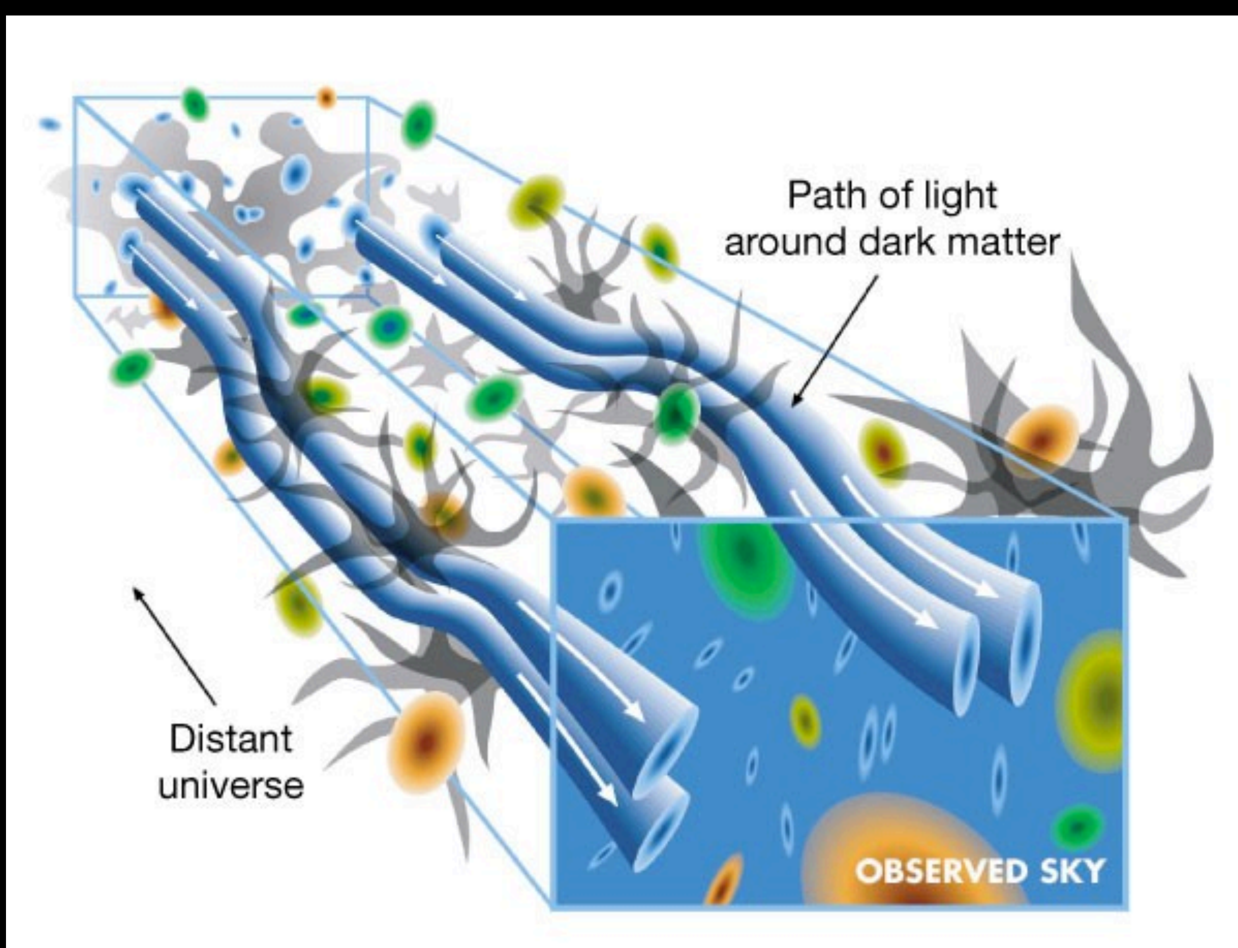


Using LAEs from another narrow-band filter as background galaxies *"double narrow-band technique"*

Fully photometric.

"Photometric" IGM tomography

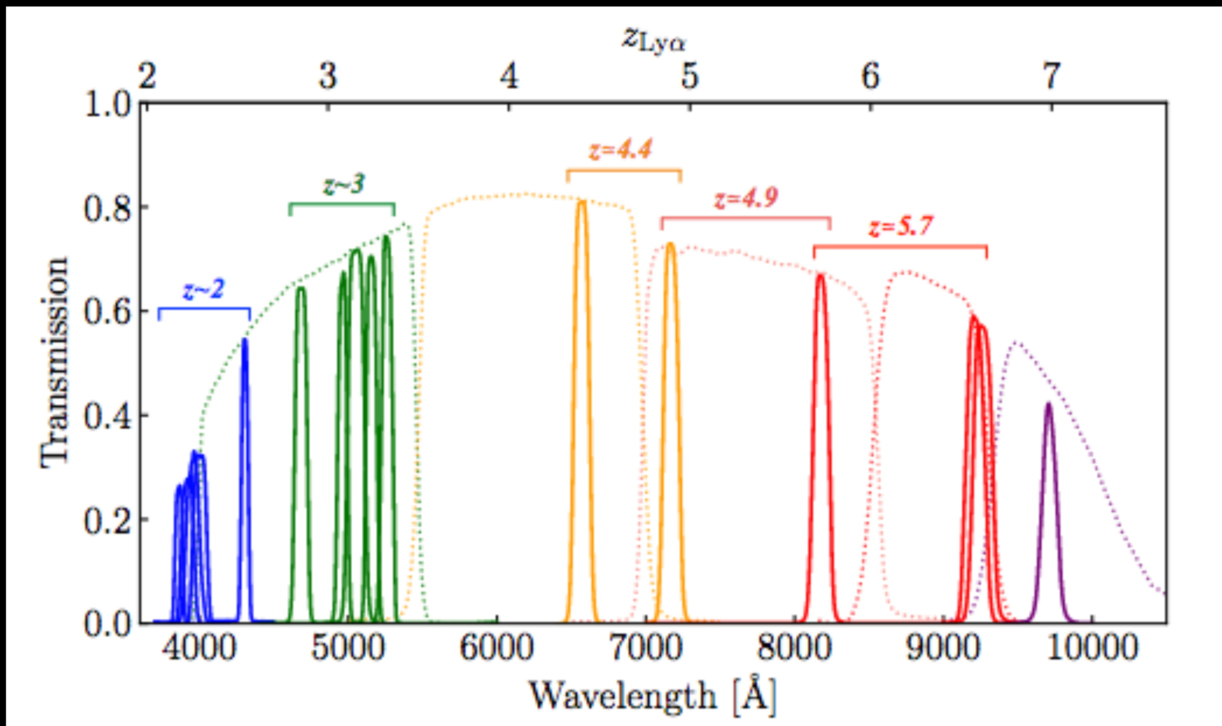


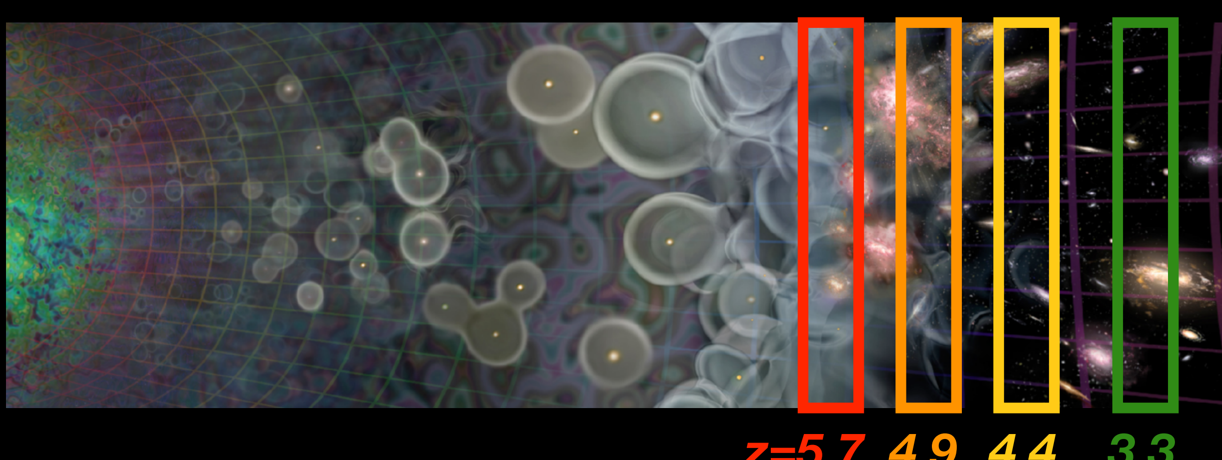


Photometric IGM tomography is analogous to weak lensing tomography

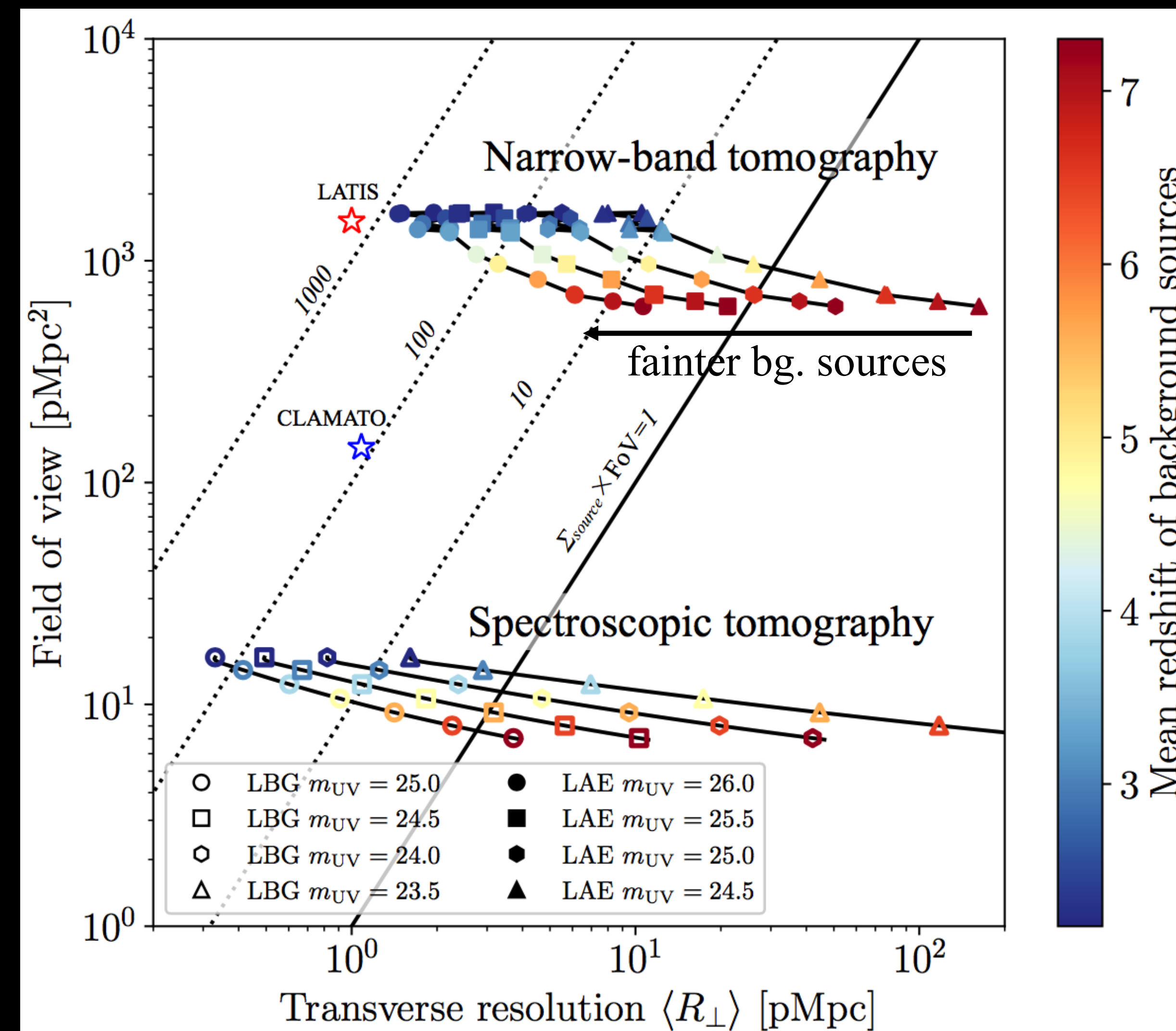
Photometric IGM tomography with Subaru/Hyper-Suprime Cam (HSC)

Multiple narrow-band filters





Wide-field of view: 1.7 deg^2



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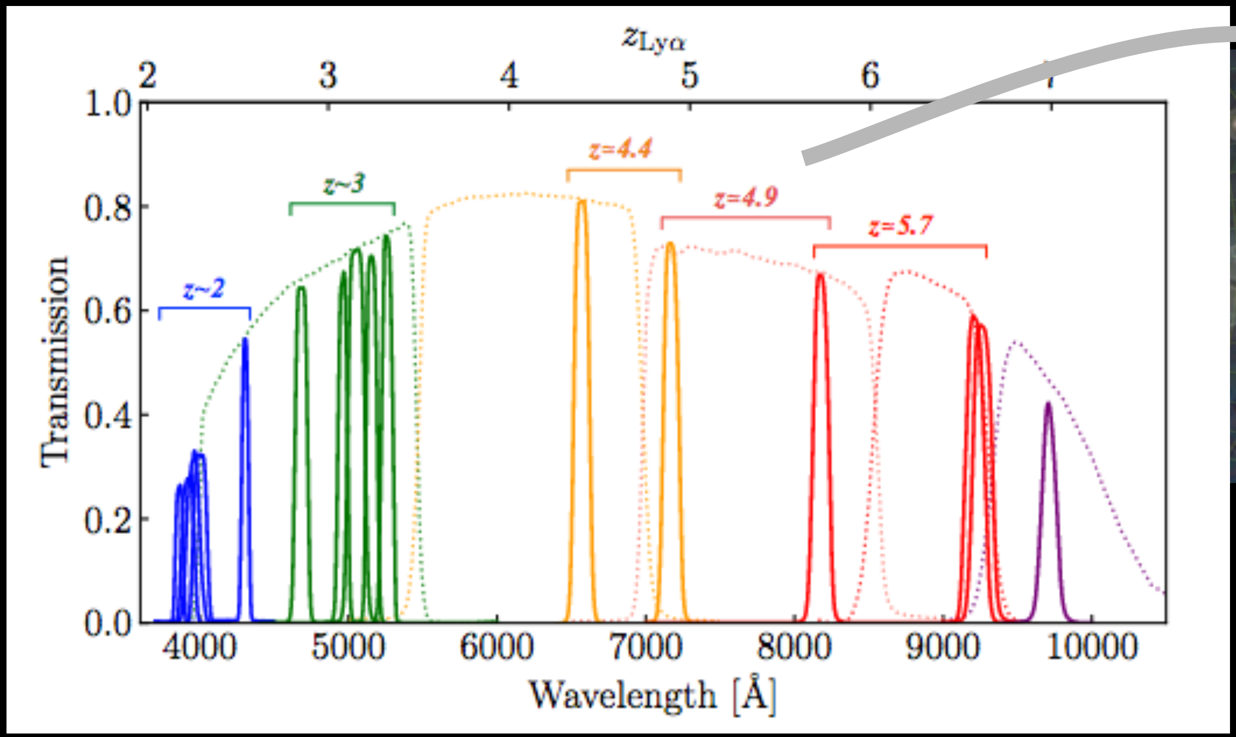
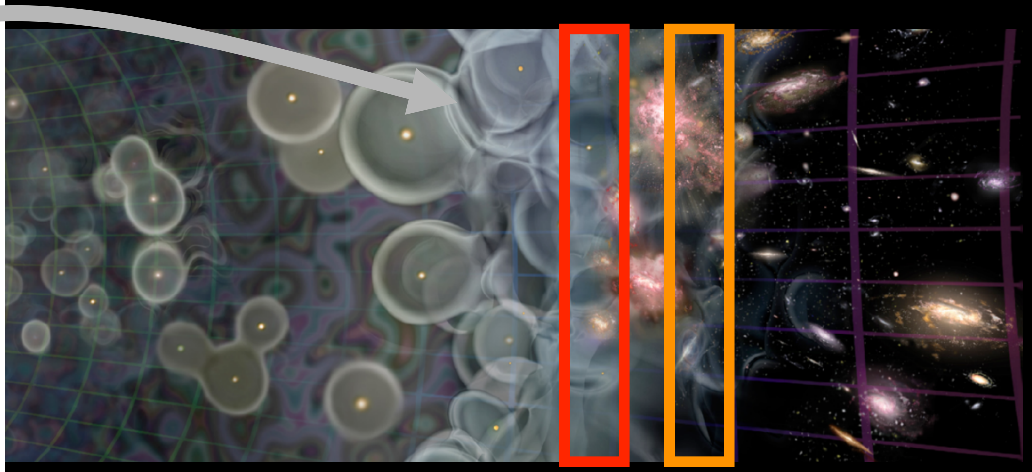
Ideal for making the tomographic maps of the IGM across z~4-6 on the scale of ~10 cMpc/h with ~100 cMpc/h field of view

Pathfinder experiment: COSMOS field
HSC-SSP DR3 public data release

A pair of narrow-band filters for z~5 photometric IGM tomography





z=5.7 | 4.9
NB816 | NB718
Background LAEs | IGM tomography

A rule-of-thumb requirement: differential photometry

$$m_{\rm NB} = m_{\rm BB} - 2.5\log_{10} e^{-\tau_{\rm eff}(z)} \approx m_{\rm BB} + \tau_{\rm eff}(z)$$

background galaxies → expected Lyα forest transmitted flux

$m_{\rm BB}$=25-26 → $m_{\rm NB}$=26.7-27.7 (>3-1.3σ)

Filter	Lyα redshift	bkg. source redshift	5σ depth (1.5″) [AB mag]	3σ depth (1.5″) [AB mag]	1σ depth (1.5″) [AB mag]	Ref Ref
NB527	3.31 ($3.29 < z_{Ly\alpha} < 3.36$)	$3.39 < z < 4.04$	26.72[a]	27.27	28.47	Inoue et al (2020)
NB718	4.90 ($4.85 < z_{Ly\alpha} < 4.94$)	$4.98 < z < 5.89$	26.29[a]	26.84	28.04	Inoue et al (2020)
NB816	5.72 ($5.68 < z_{Ly\alpha} < 5.77$)	$5.81 < z < 6.86$	26.34[b]	26.89	28.09	Aihara et al (2021)

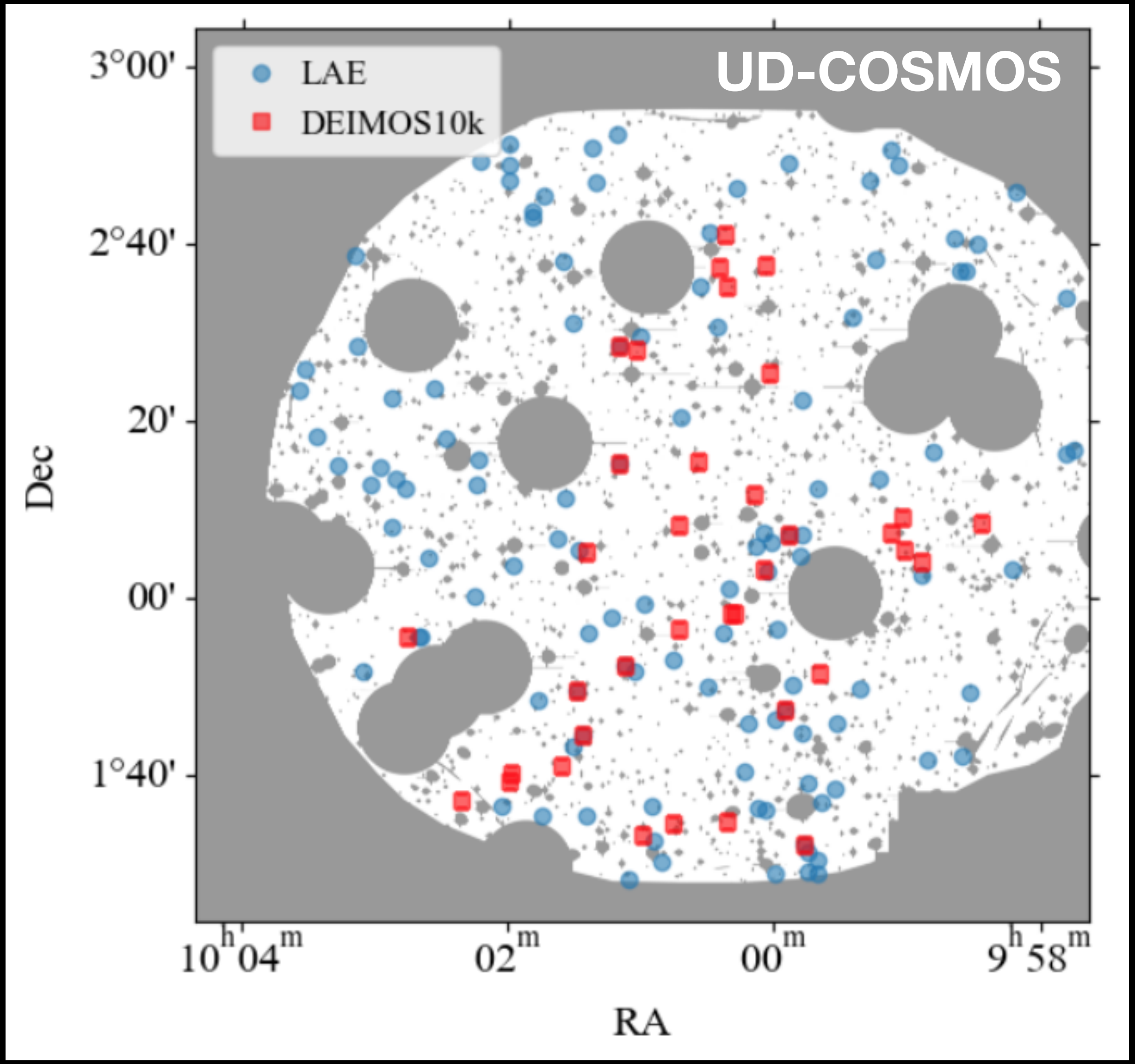
Narrow-band data: HSC SSP DR3 + CHORUS NB survey (part of DR2) in the COSMOS field

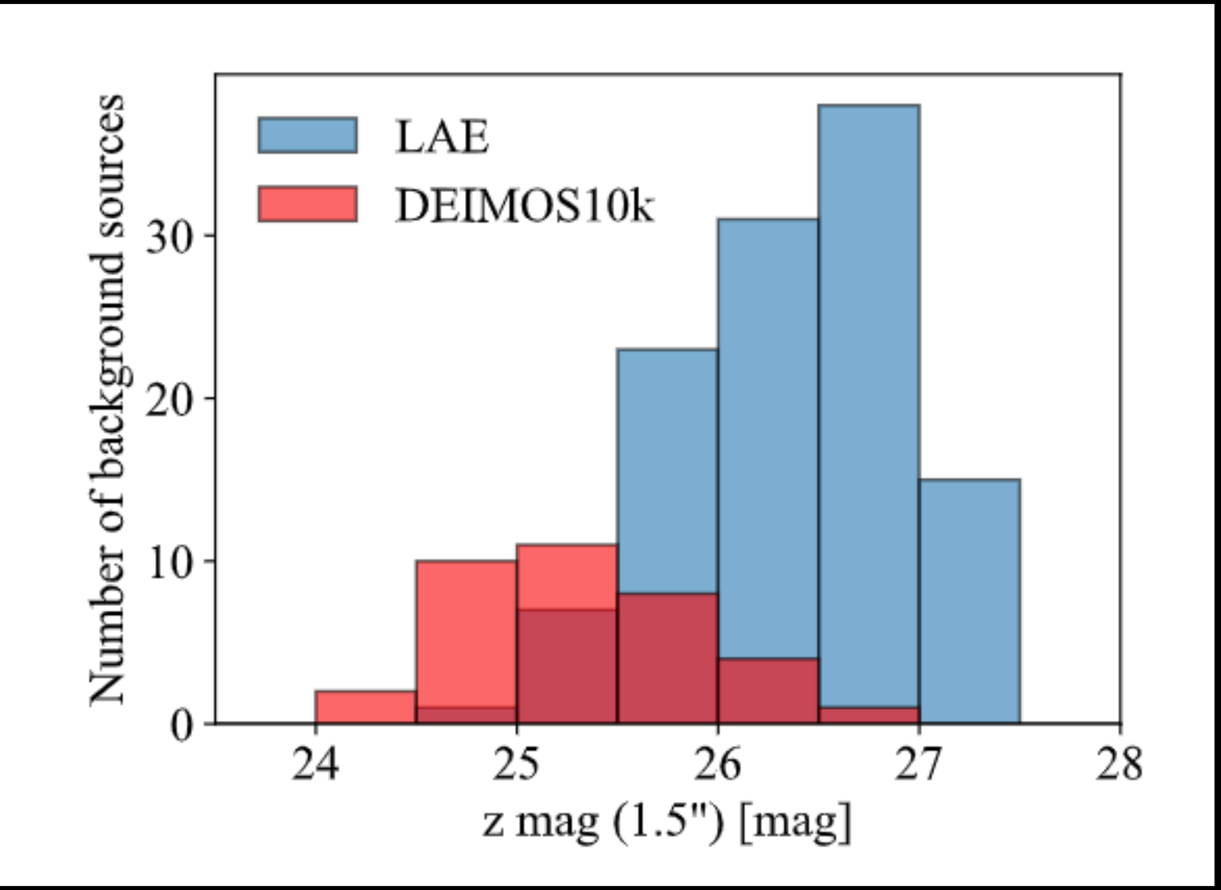
Pathfinder experiment: COSMOS field
Background sources

Catalogues

1. **LAE catalogue (SILVERRUSH, Ono+21)**
2. **Spec-z catalogue (DEIMOS10k, Hasinger+18)**

+ Selection criteria: bright background source & 4.98<z<5.89
  (>5σ UV continuum detection in z-band & non-detection in g-band)





151 background sources
(115 z=5.7 LAEs + 36 DEIMOS10k)

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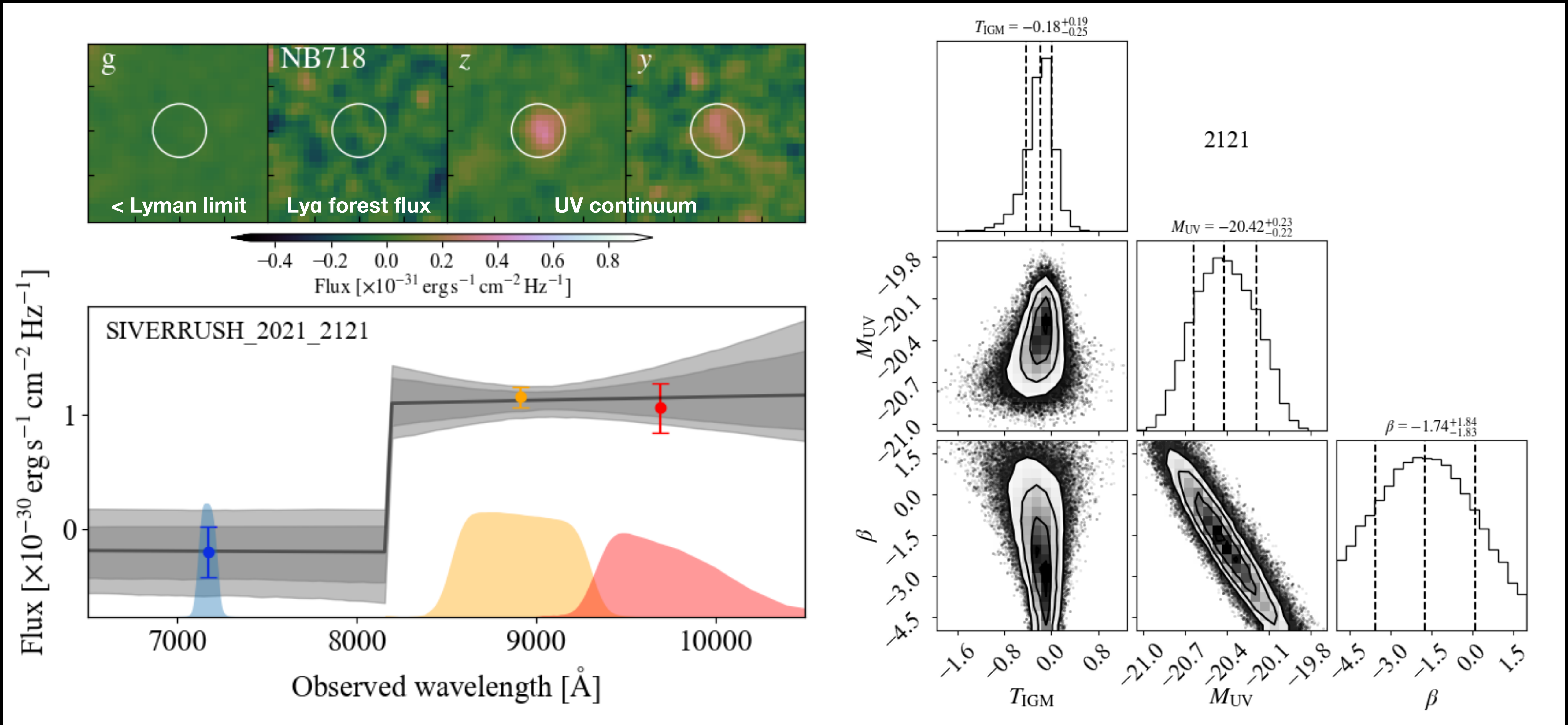
Measurement: IGM transmissions along individual background galaxies

Bayesian SED fitting framework

Data: NB718, z, y flux
Model: power-law galaxy spectrum (M_{UV}, β) + Lya forest transmission T_{IGM}
Error: Photometric noise



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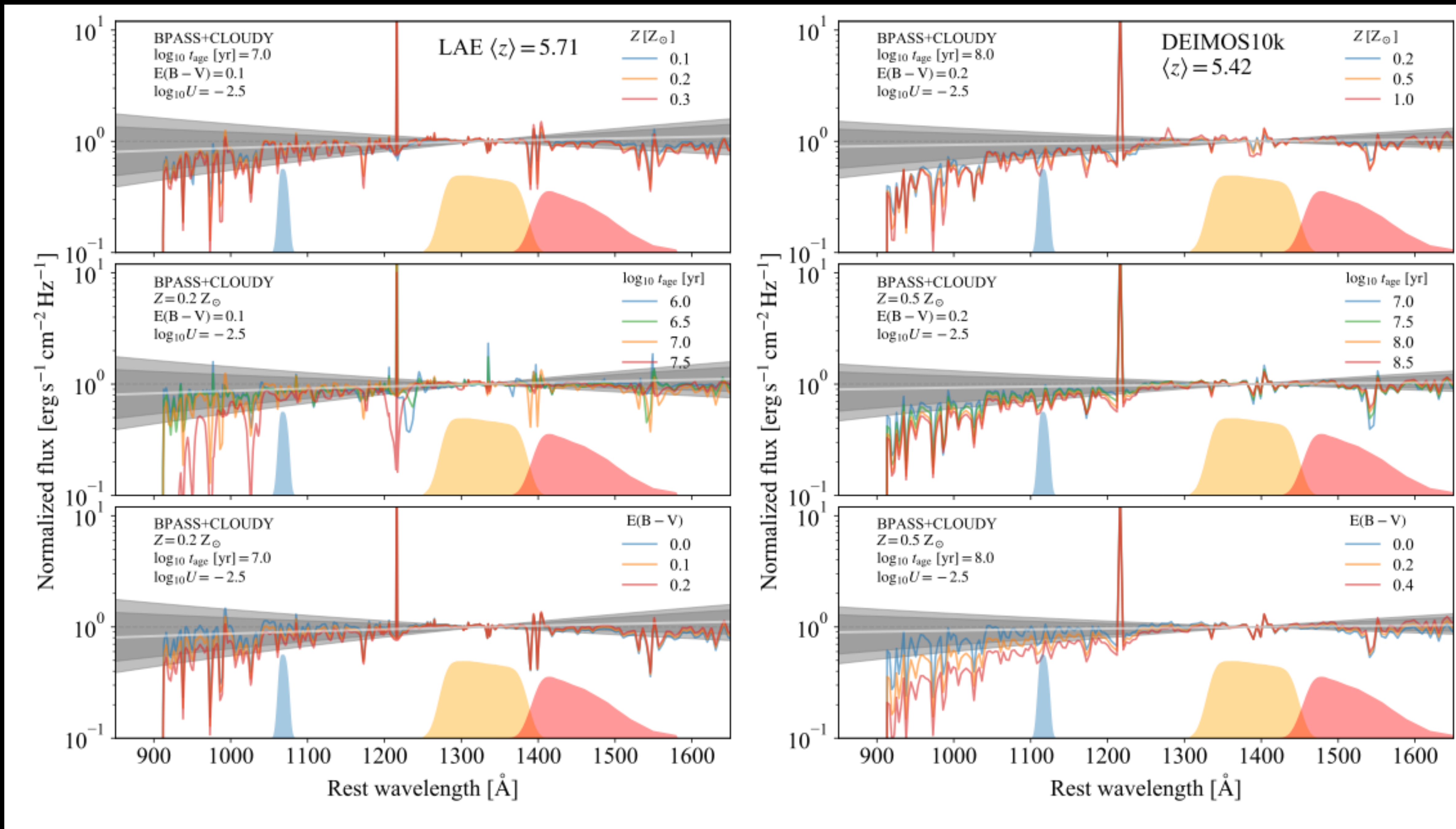
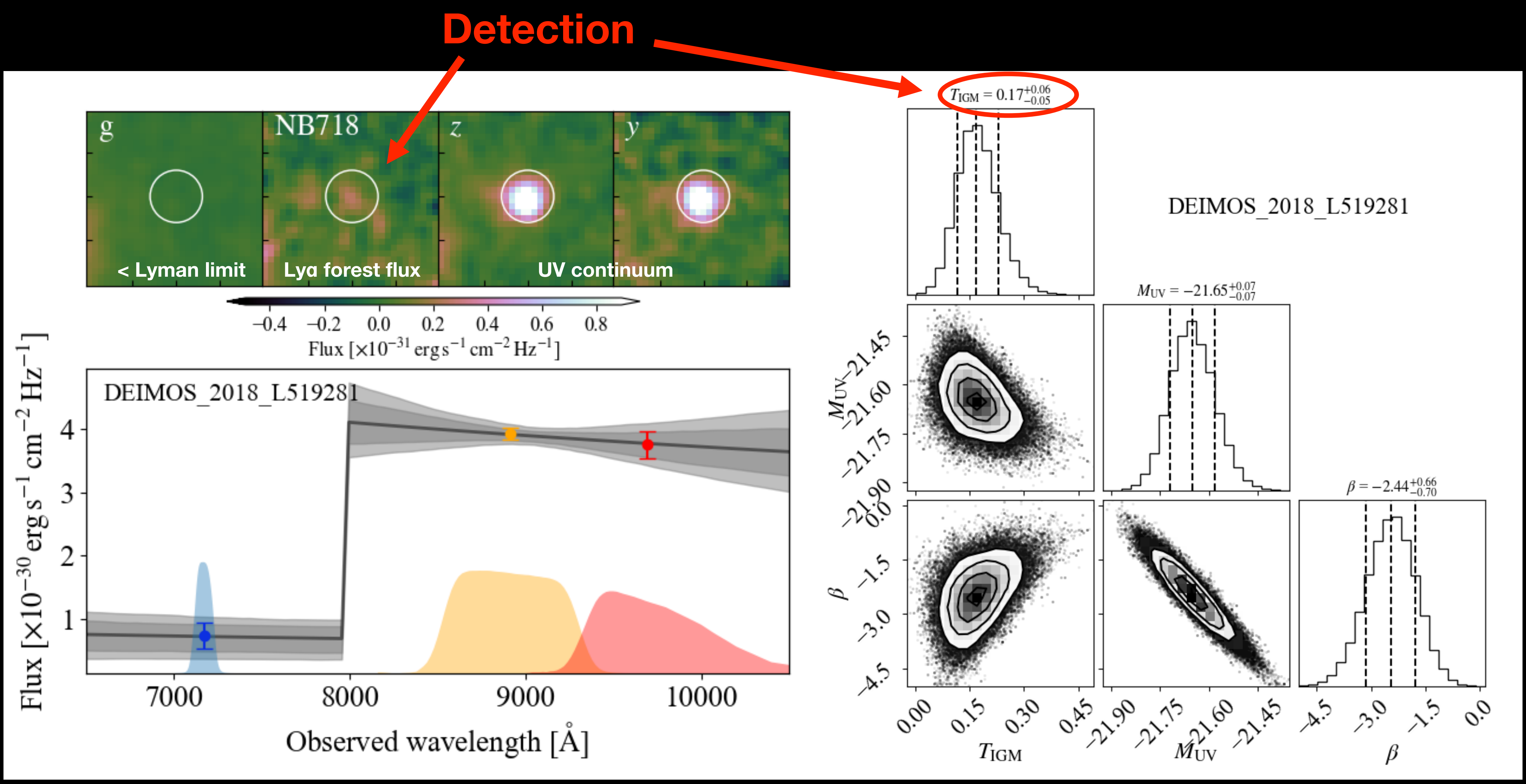
The galaxy SED template uncertainty is a subdominant source of error for photometric IGM tomography (at the current NB depth)



SED template uncertainty ~ 6-27% (i.e. < photometric error ~ 46-80%) in the individual measurement of the Lyα forest transmission T_{IGM}

Detection:
IGM transmissions along individual background galaxies



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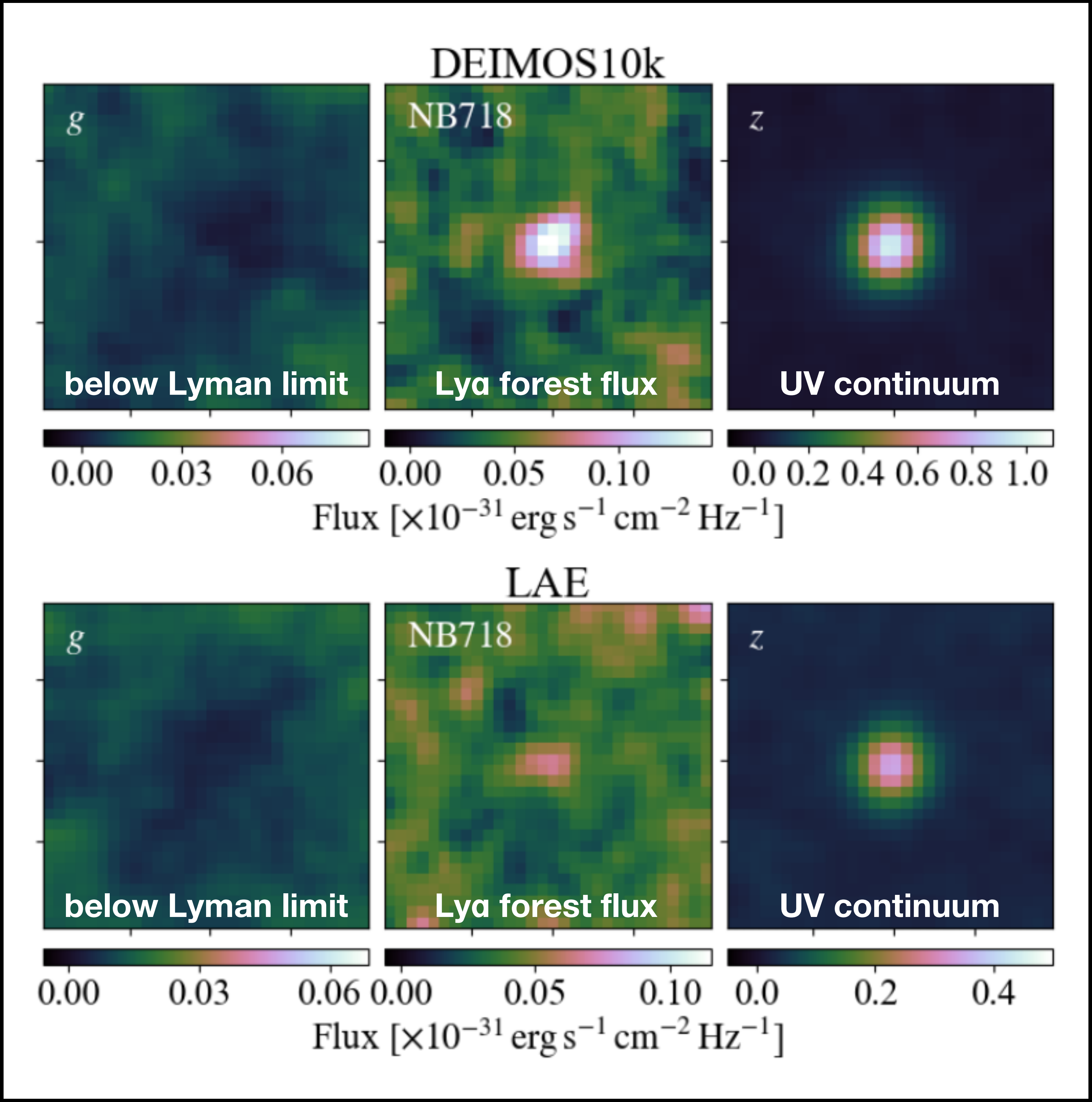
Visual confirmation of the photometric IGM transmission detection
- Stacked images -



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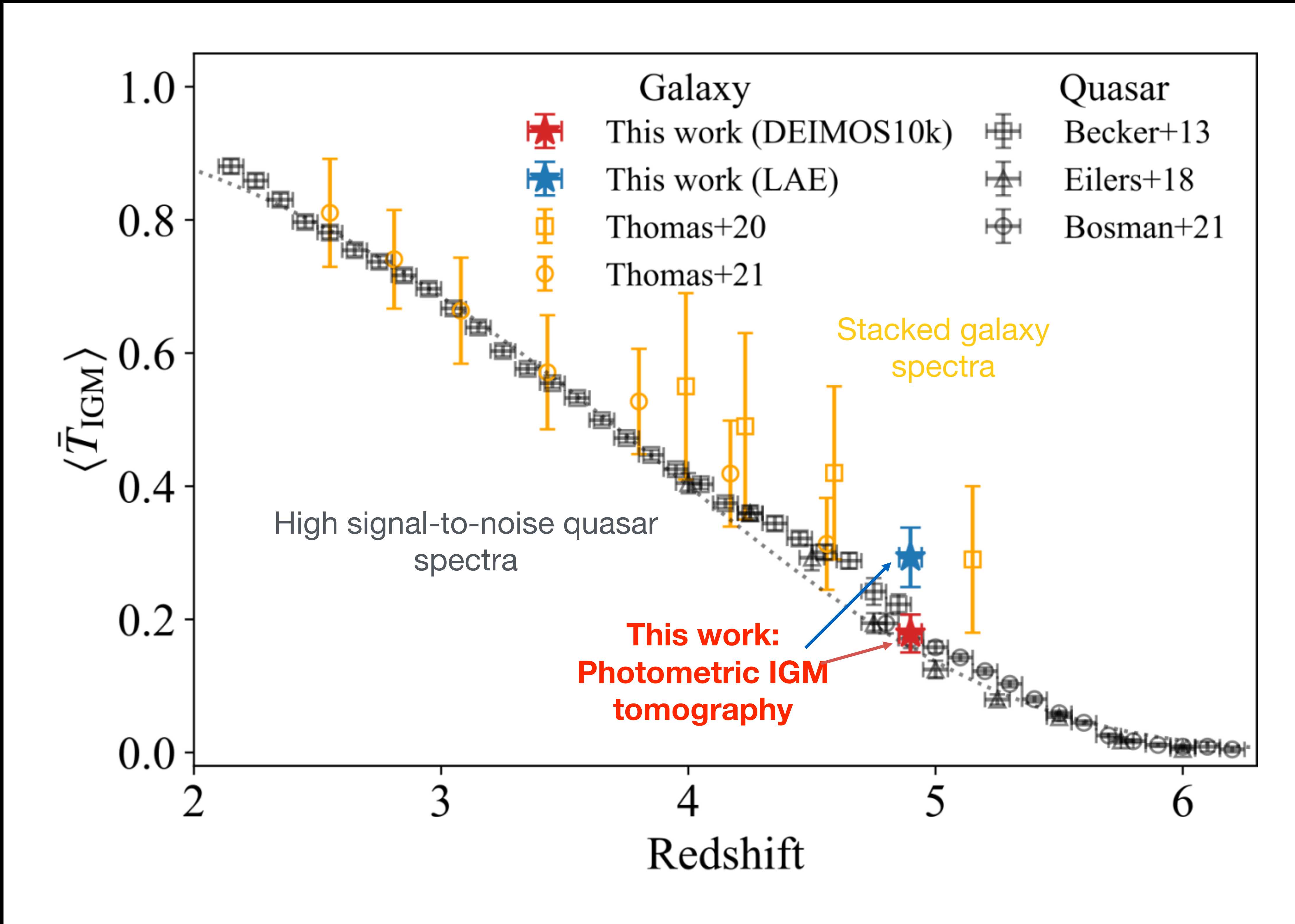
Mean IGM transmission: background galaxies vs quasars



IGM Lyα forest transmission can be measured photometrically.

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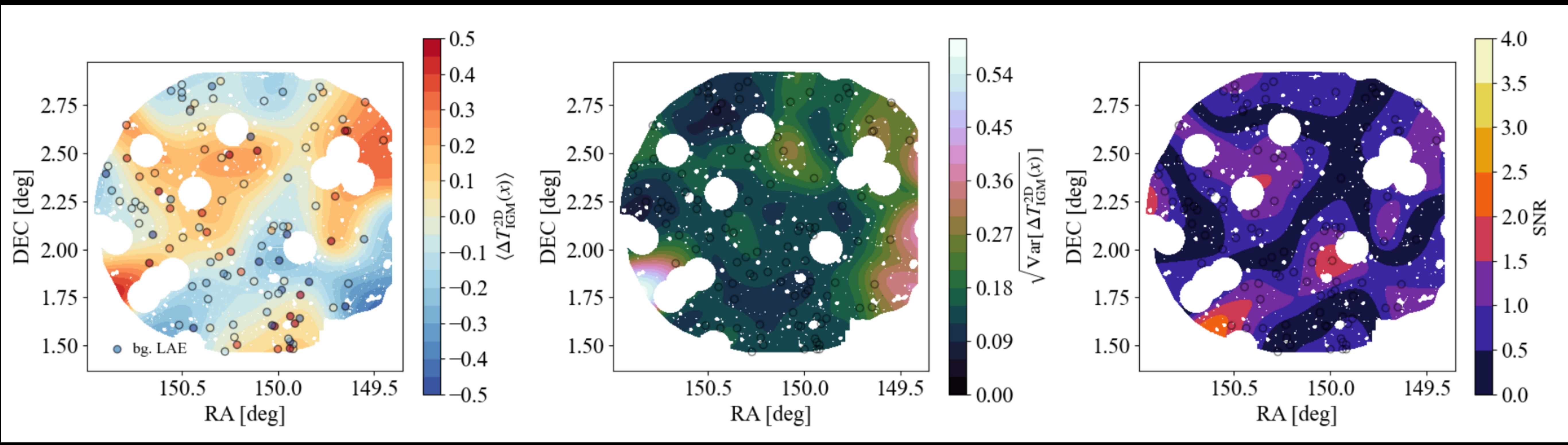
Map making

Reconstructed 2D IGM tomographic map

Reconstruction method:
Gaussian kernel density-based estimator + posterior

$$\langle T_{\rm IGM}^{\rm 2D}(\boldsymbol{x})\rangle = \frac{\sum_{i=1}^{N_{\rm bg}} K_R(\boldsymbol{x}-\boldsymbol{x}_i)\int T_{{\rm IGM},i} P(T_{{\rm IGM},i}|f_{{\rm NB},i}^{\rm obs}, f_{{\rm BB},i}^{\rm obs}) dT_{{\rm IGM},i}}{\sum_{\rm i=1}^{N_{\rm bg}} K_R(\boldsymbol{x}-\boldsymbol{x}_i)}$$



Average SNR of the reconstructed map ~ 0.86
i.e. currently still photometric noise dominated

The first proof-of-concept of photometric IGM tomographic map at z~5

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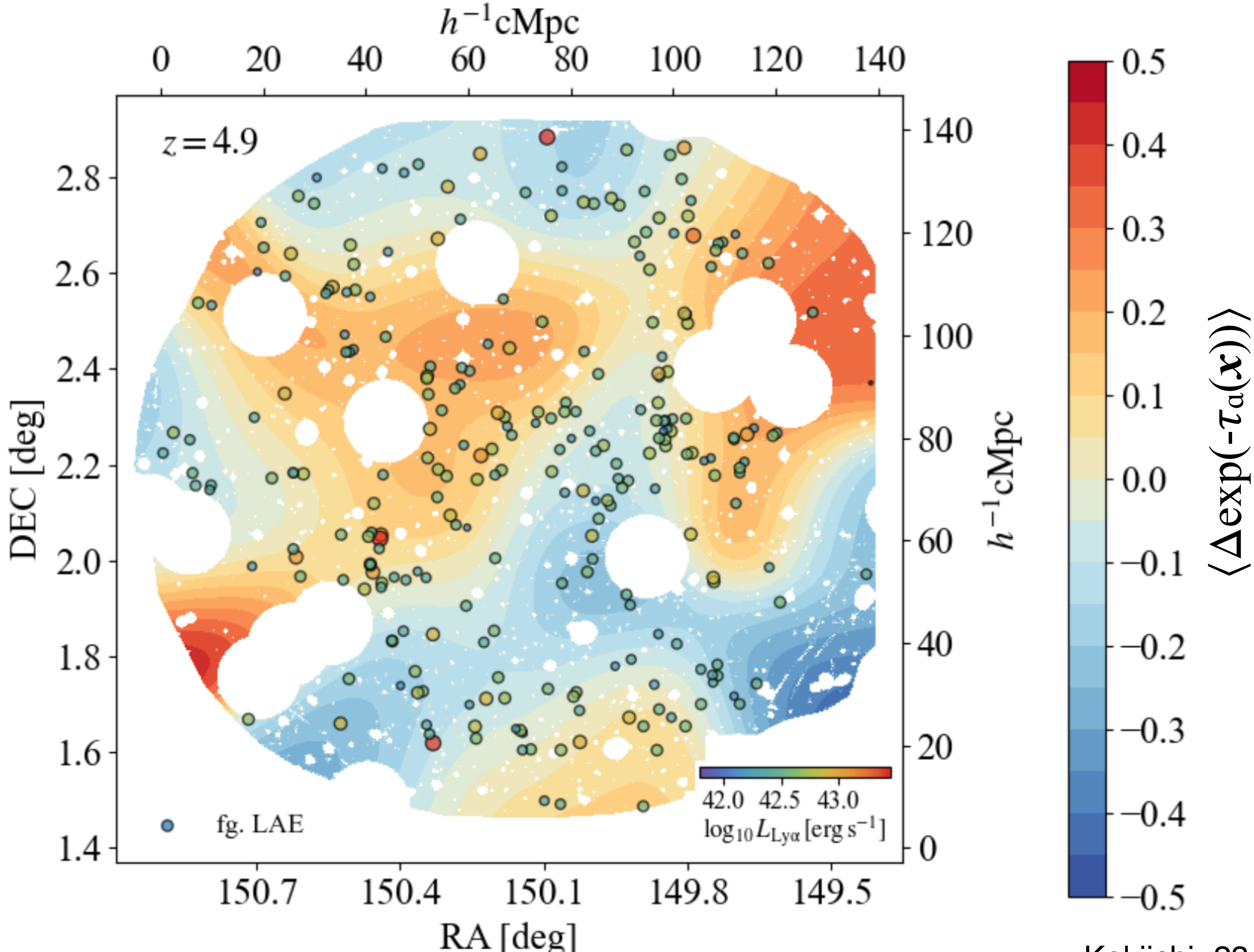
Large-scale map of galaxies & IGM

Photometric Lyα forest tomography



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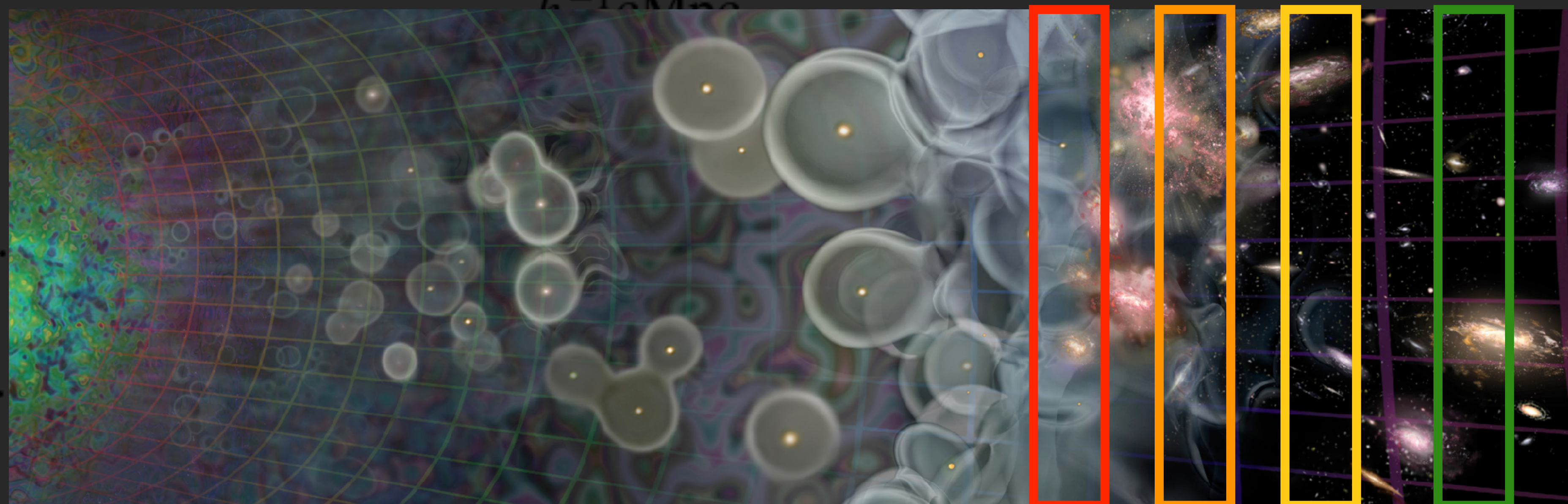
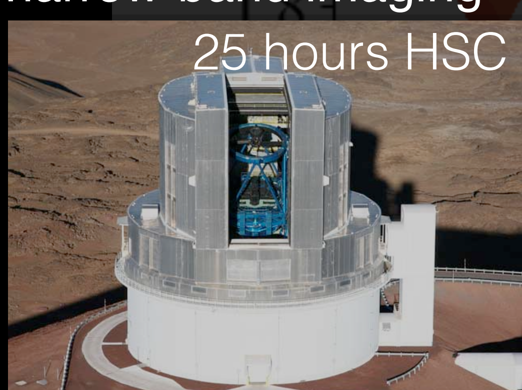
Large-scale map of galaxies & IGM
Photometric Lyα forest tomography

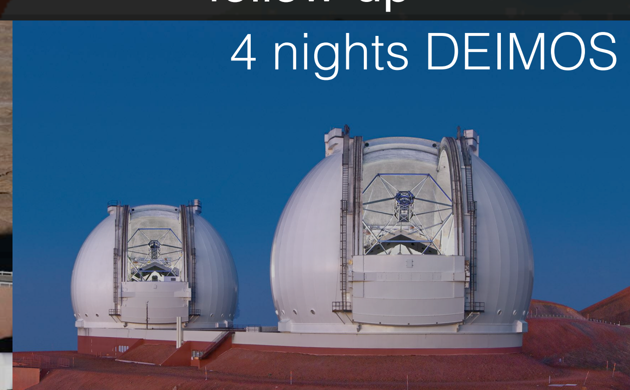
Big Bang | The Epoch of Reionization | Cosmic noon



The tomographic evolutionary view of galaxy assembly & their environments across cosmic history

Extremely-deep narrow-band imaging + Keck spectroscopic follow-up





COSMOGRAPHY survey (PI: Kakiichi)

Subaru Telescope
National Astronomical Observatory of Japan

Semester	S22B
Proposal ID	S22B0077QN
Received	03/08/2022

Application Form for Telescope Time
(Queue Normal+Intensive Programs)

1. Title of Proposal
Narrow-band IGM tomography with Subaru/HSC at z∼5 in the COSMOS field

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COSMOGRAPHY: COSMOS Tomographic Evolution Survey Across $z \sim 3-6$

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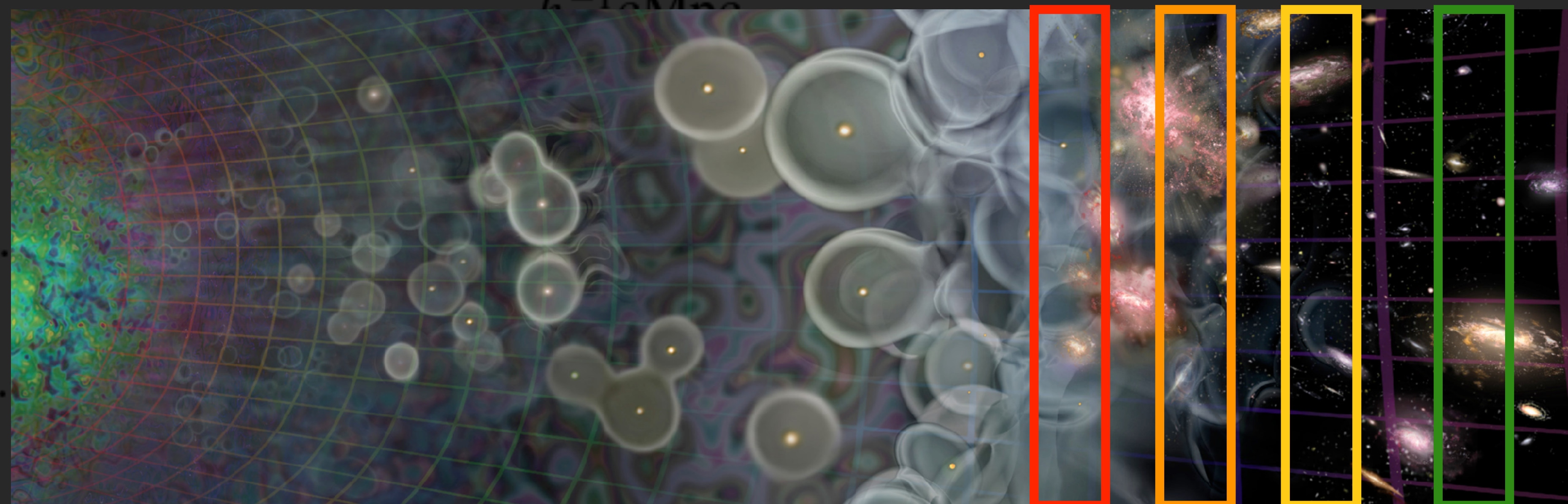

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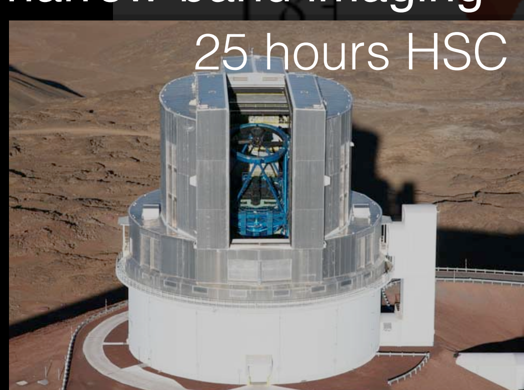

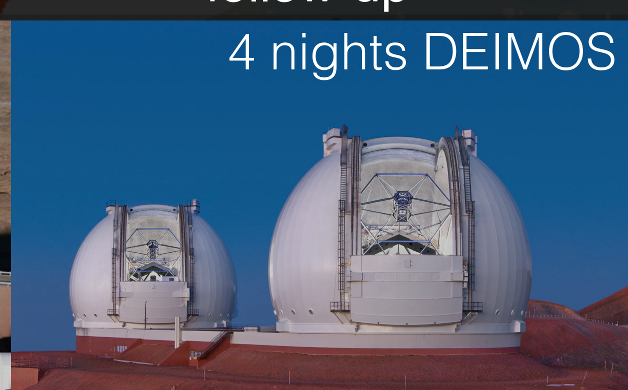

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COSMOGRAPHY: COSMOS Tomographic Evolution Survey Across z ∼ 3 − 6

COSMOGRAPHY survey (PI: Kakiichi)

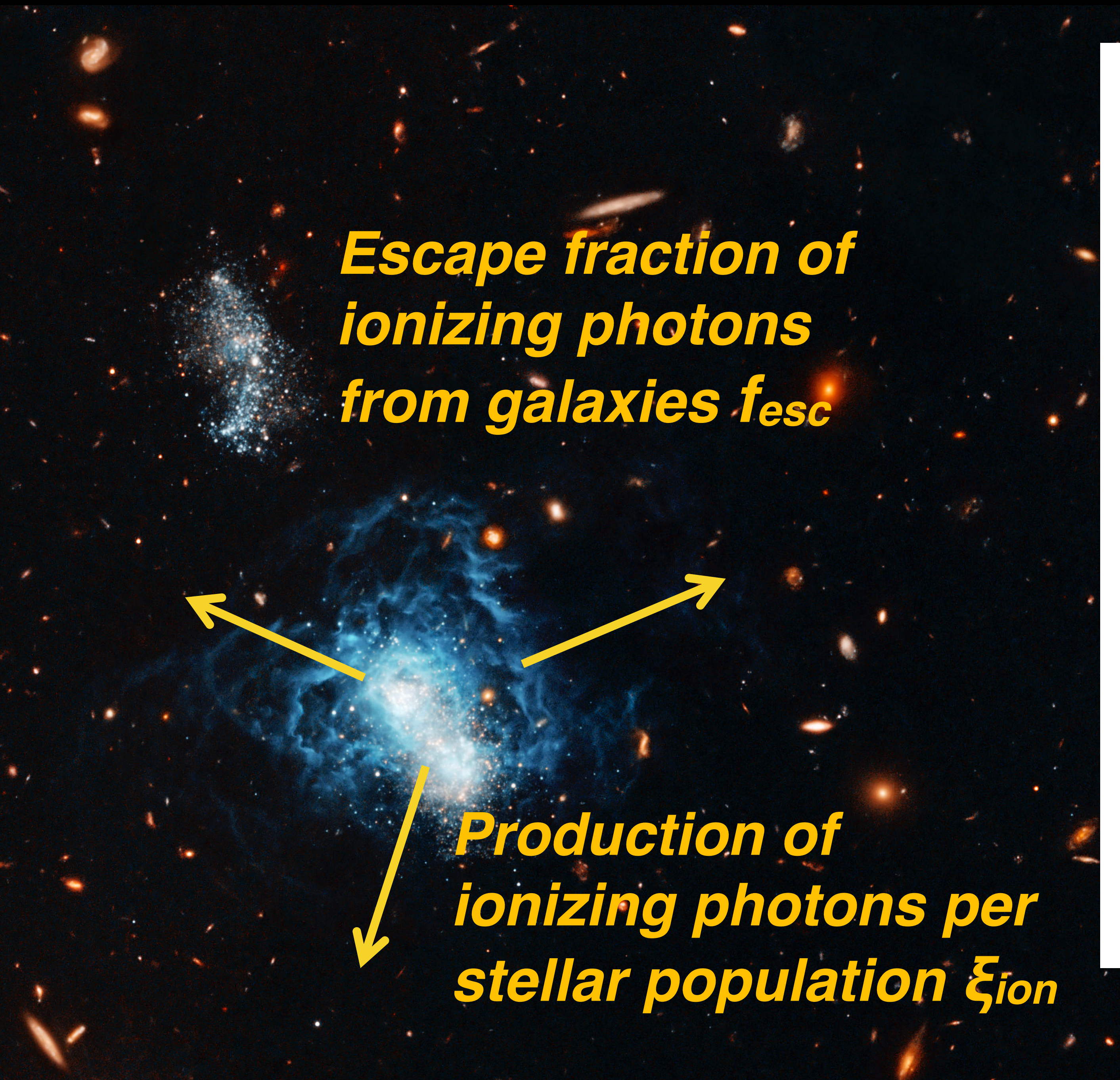
What can we learn from photometric IGM tomography?

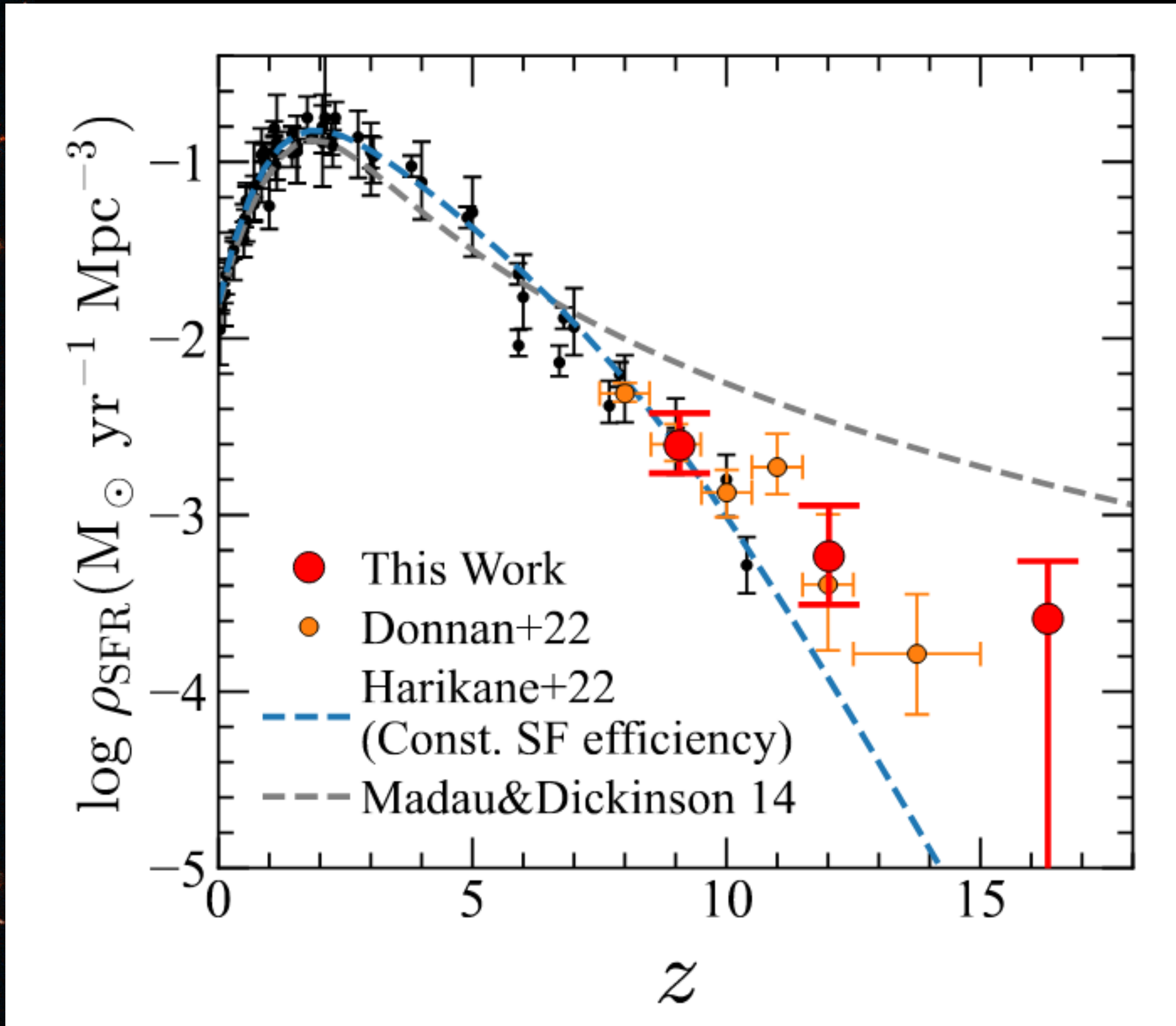
1. *Sources of Reionization & Ionizing capability of galaxies*

What reionized the Universe?

Cosmic ionizing photon budget

$$\dot{n}_{ion} = f_{esc}\, \xi_{ion}\, \rho_{SFR}$$





Harikane+22

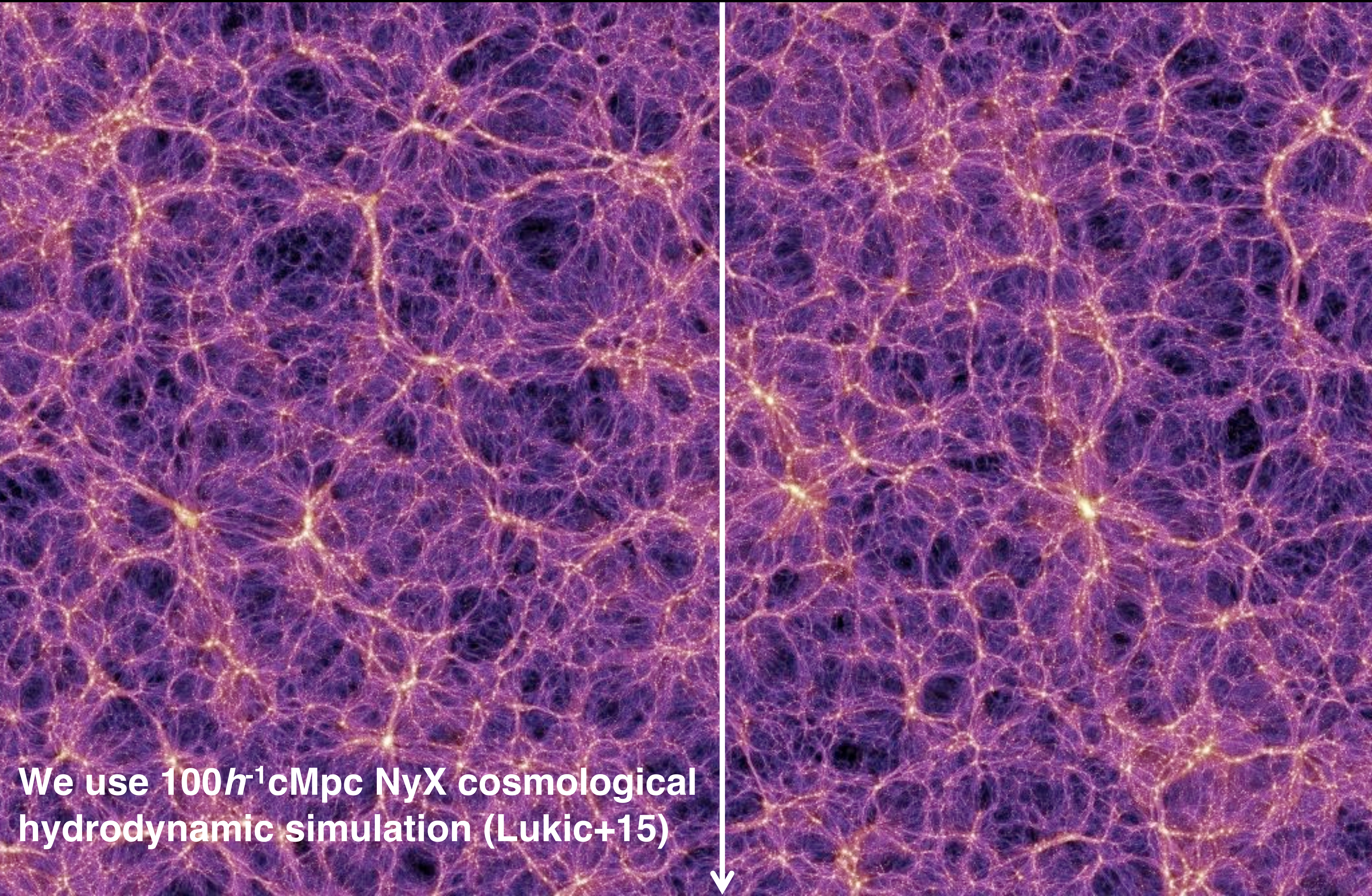
Donnan+22, Bouwens+22, Finkelstein+22

Missing link

f_{esc} ξ_{ion}

The amount of ionizing radiation released from galaxies into the intergalactic gas

Galaxy-Lyα Forest Cross-Correlation
Modelling the impact of leaking ionizing radiation



We use $100h^{-1}$cMpc NyX cosmological hydrodynamic simulation (Lukic+15)

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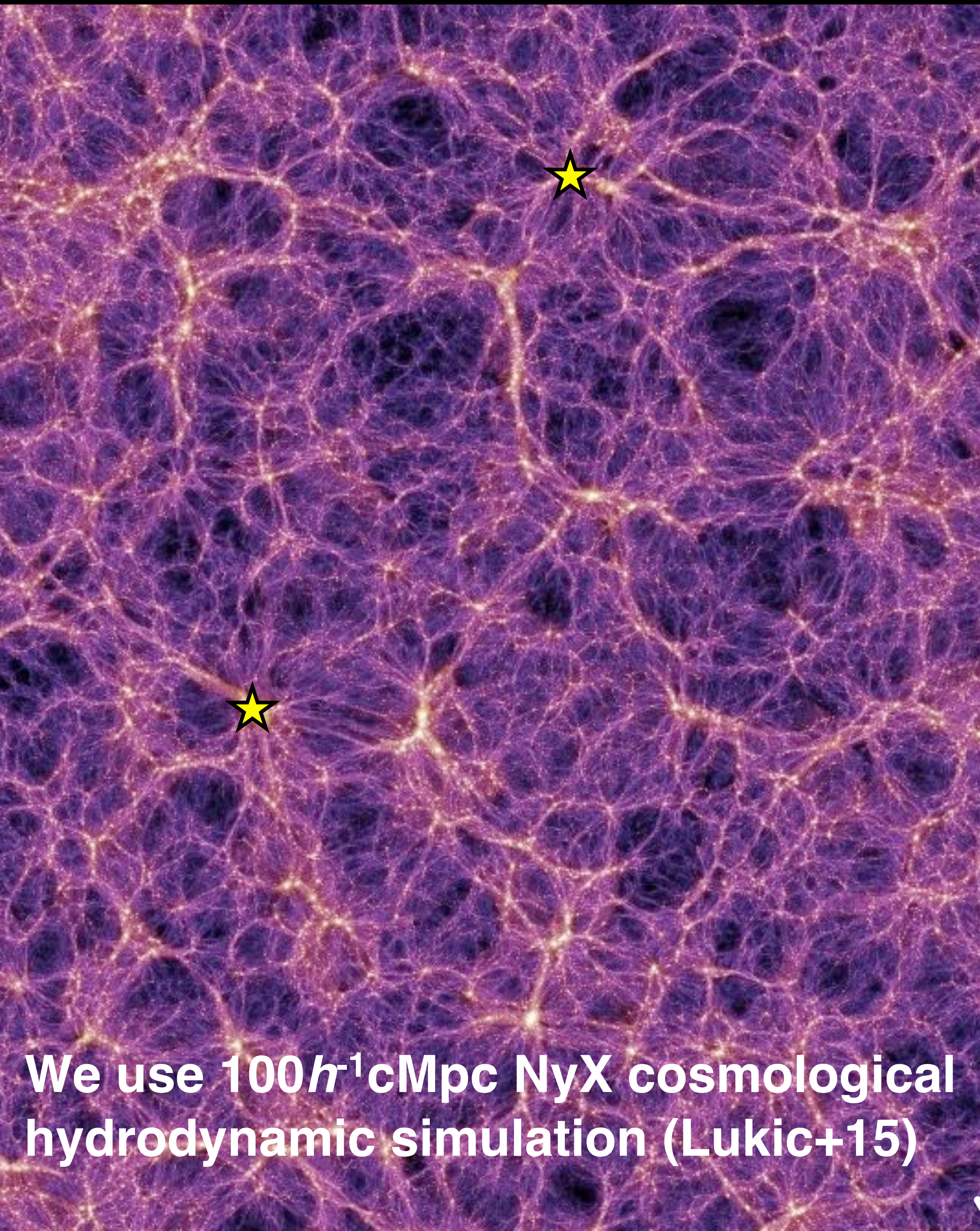

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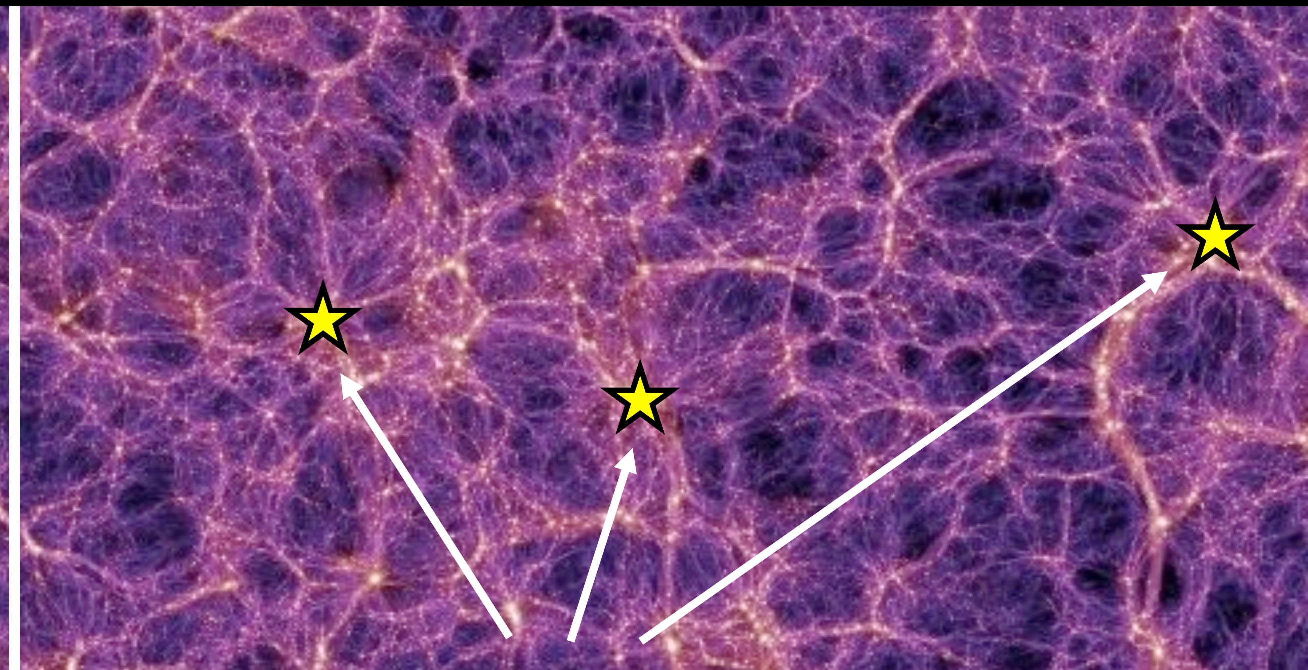
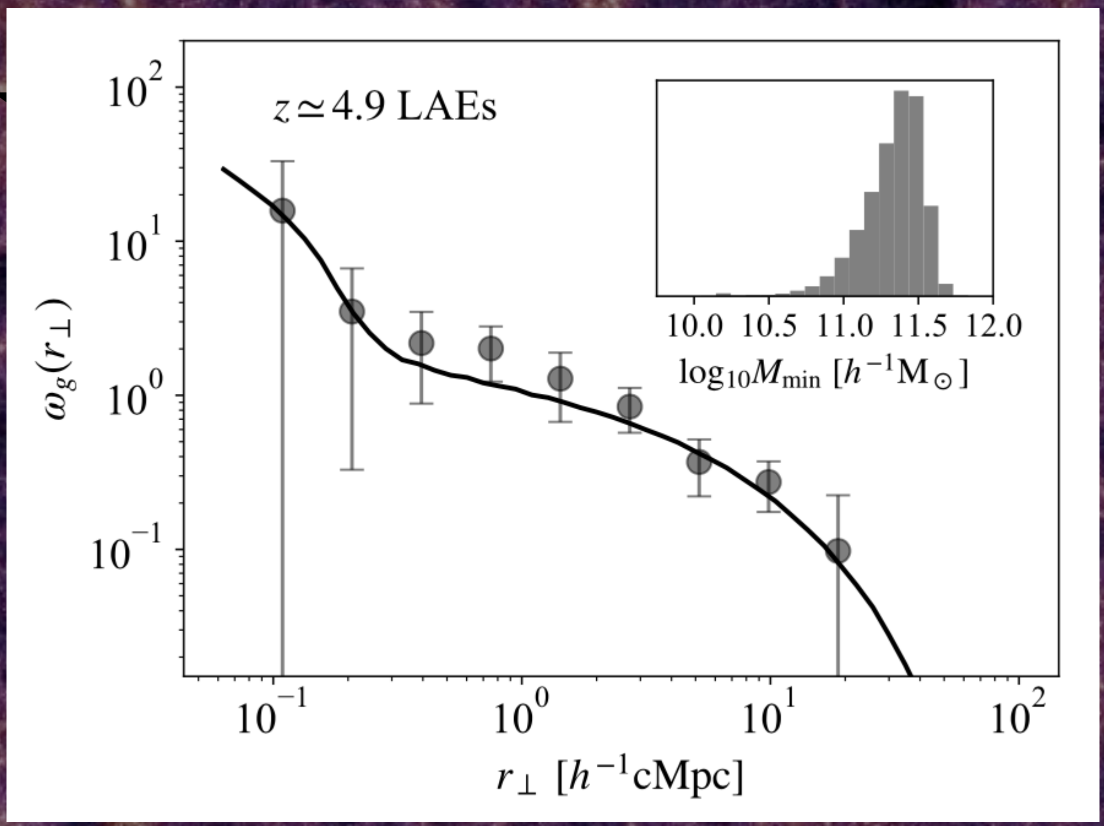


Halo Occupation Distribution model

Observed LAE auto-correlation function



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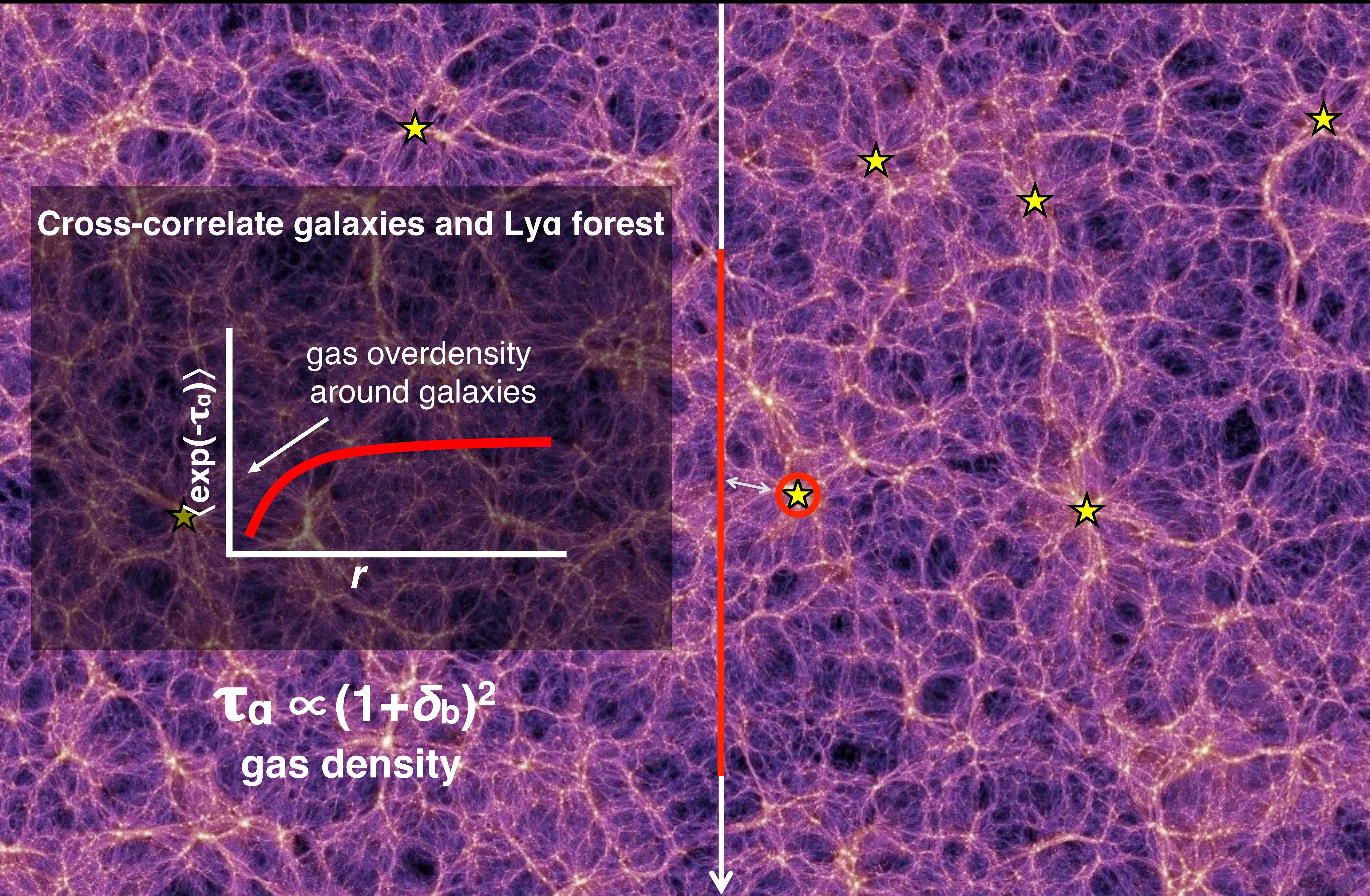

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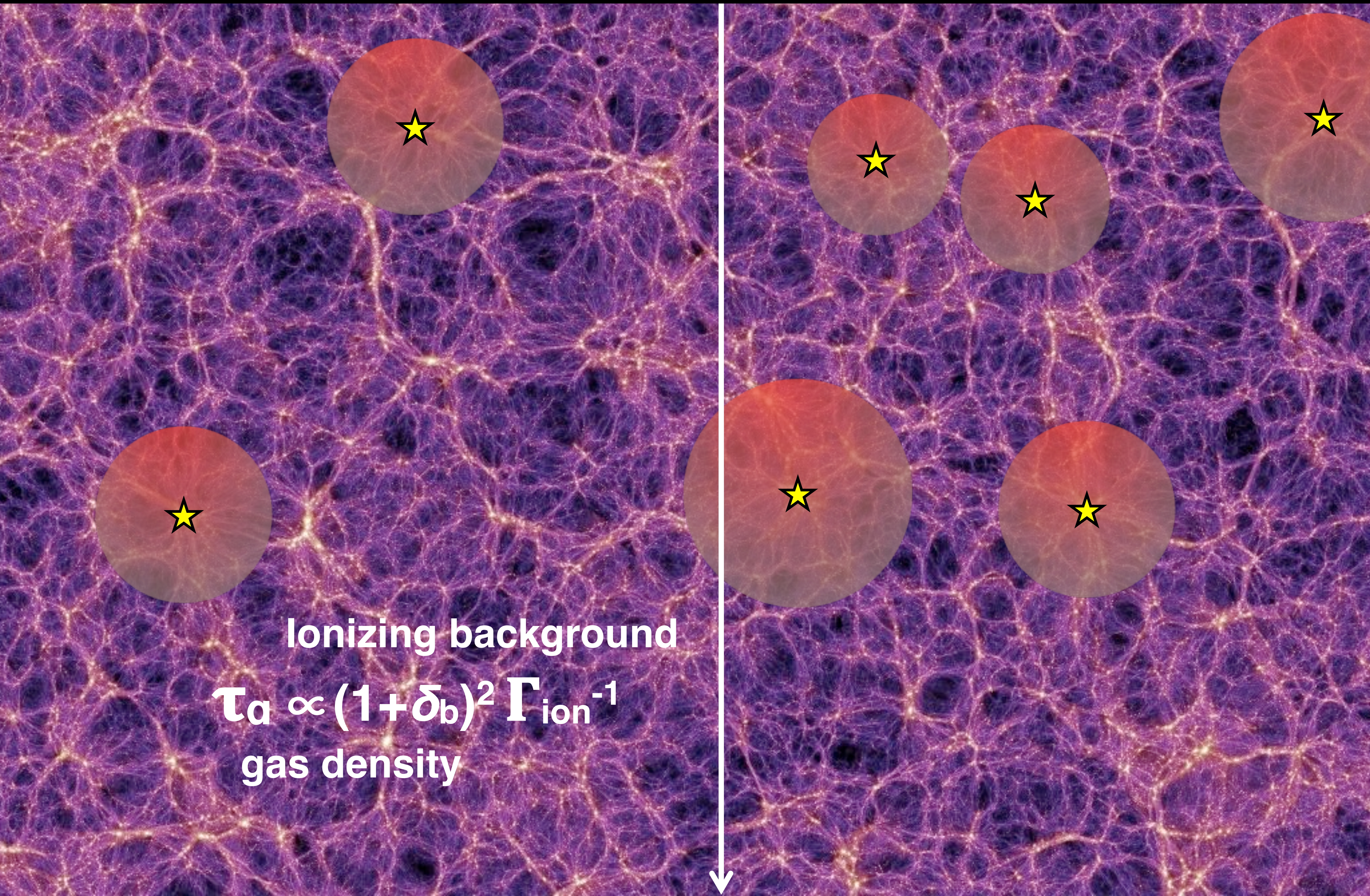

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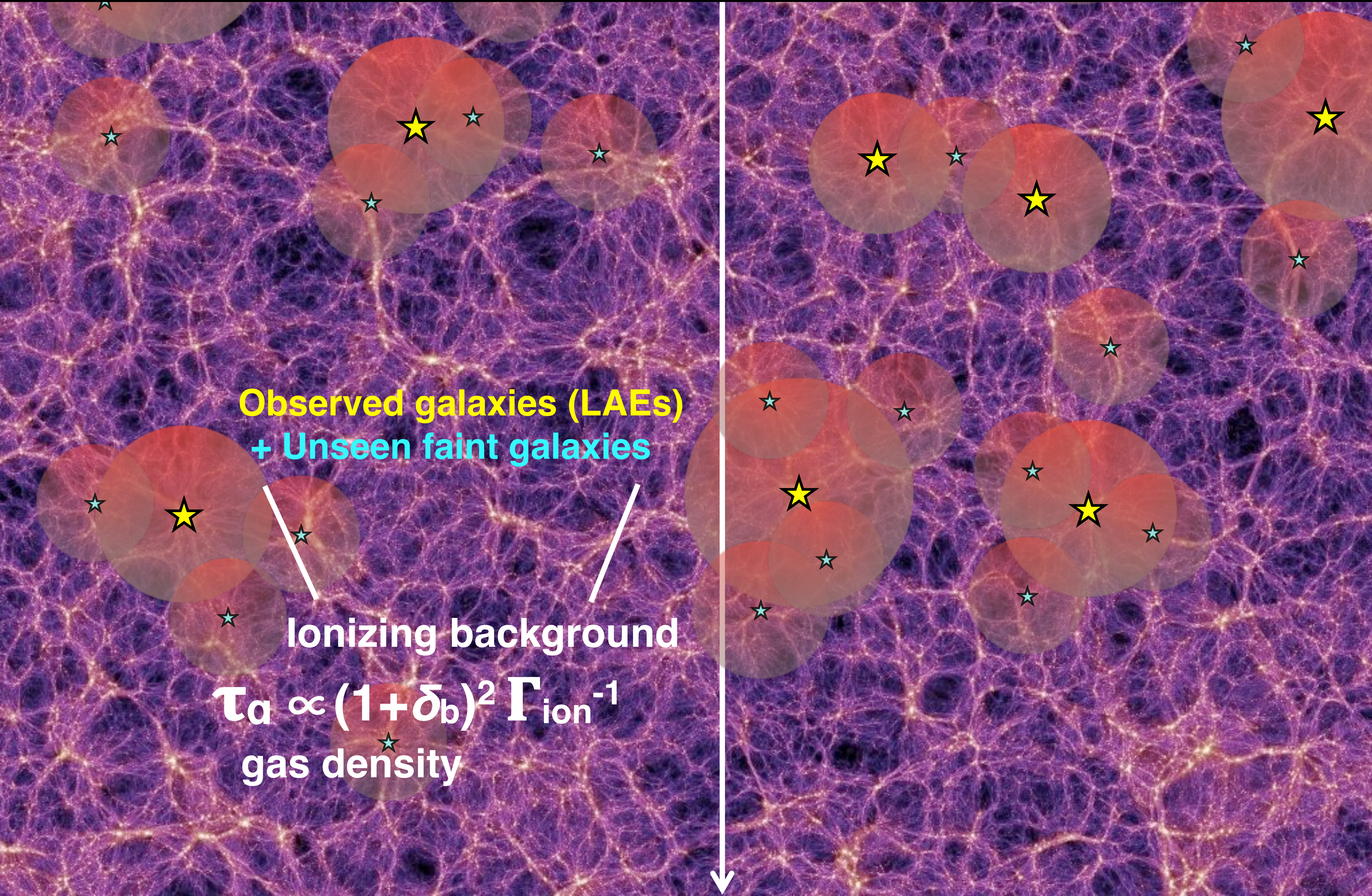

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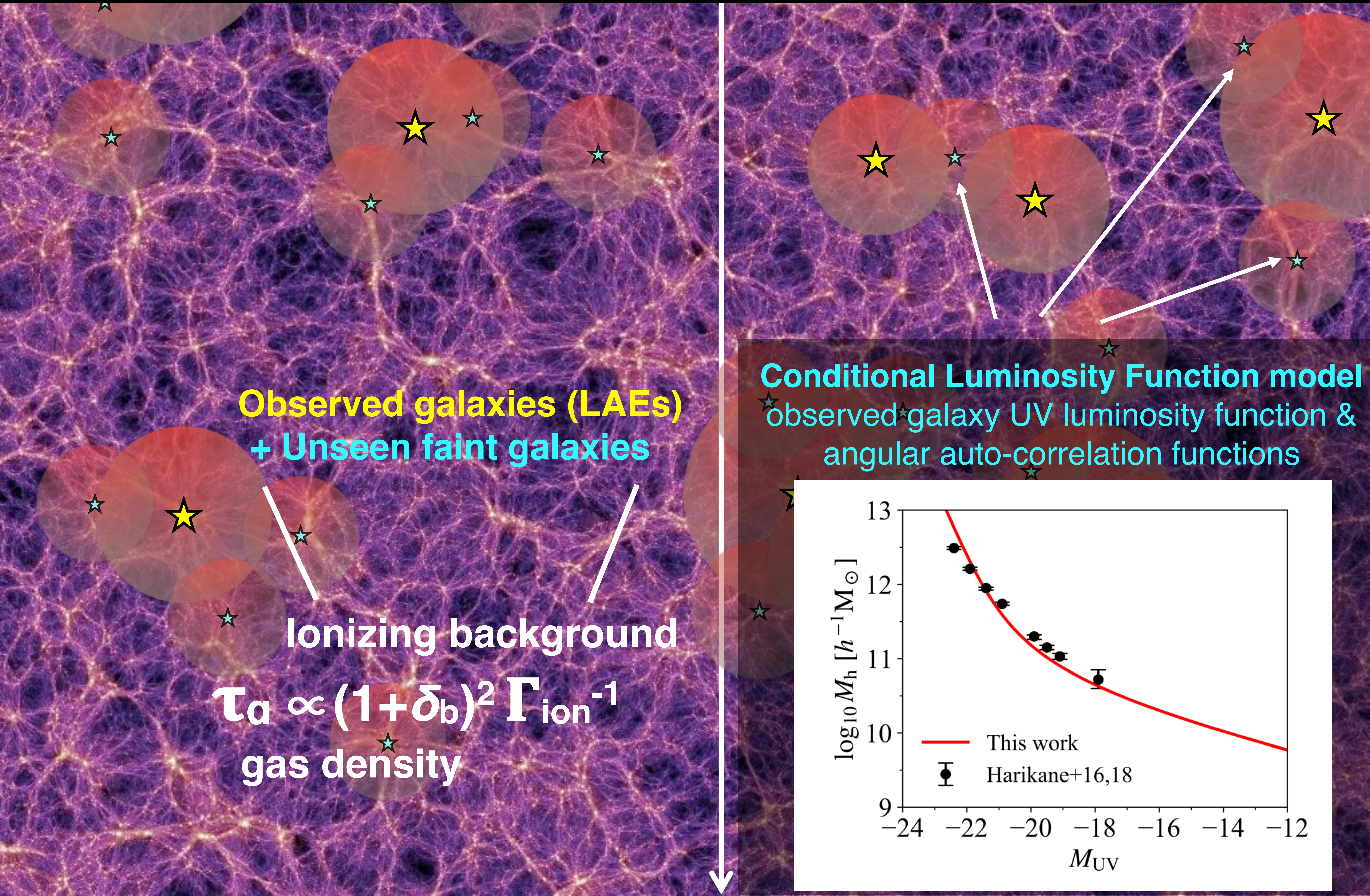
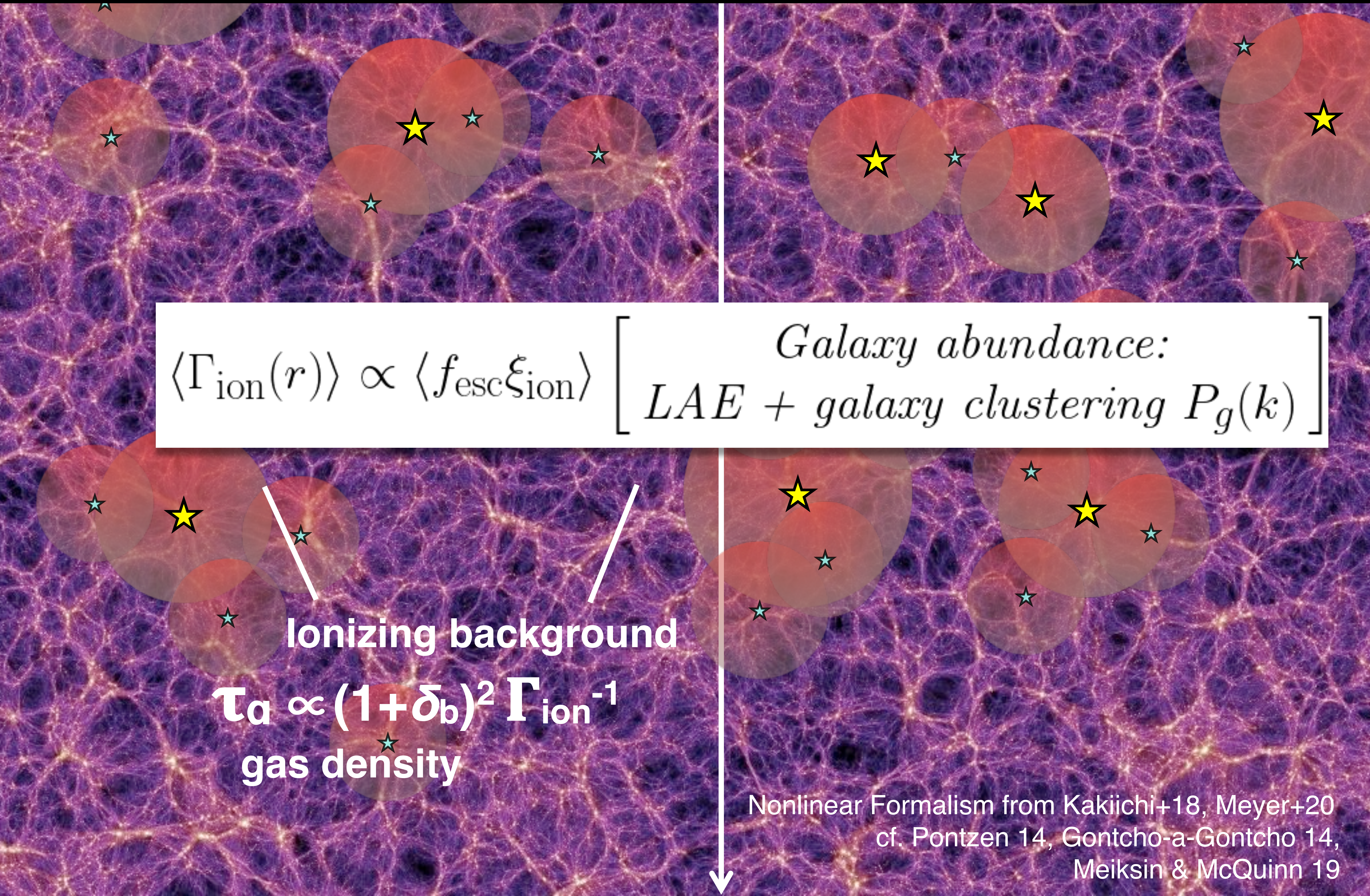


Galaxy-Lyα Forest Cross-Correlation
Modelling the impact of leaking ionizing radiation

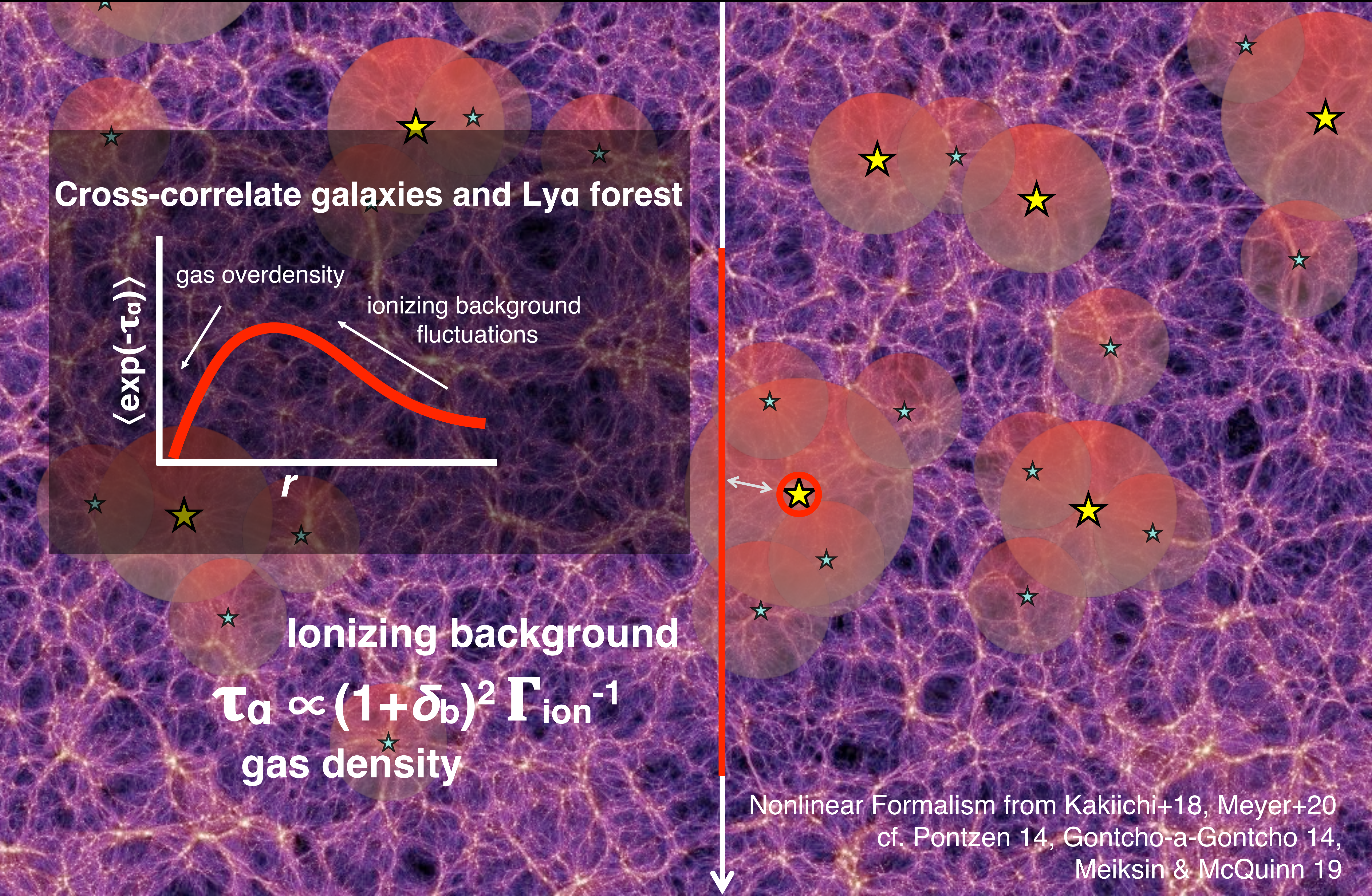


$$\langle \Gamma_{\rm ion}(r) \rangle \propto \langle f_{\rm esc} \xi_{\rm ion} \rangle \left[\begin{array}{c} \textit{Galaxy abundance:} \\ \textit{LAE + galaxy clustering } P_g(k) \end{array} \right]$$

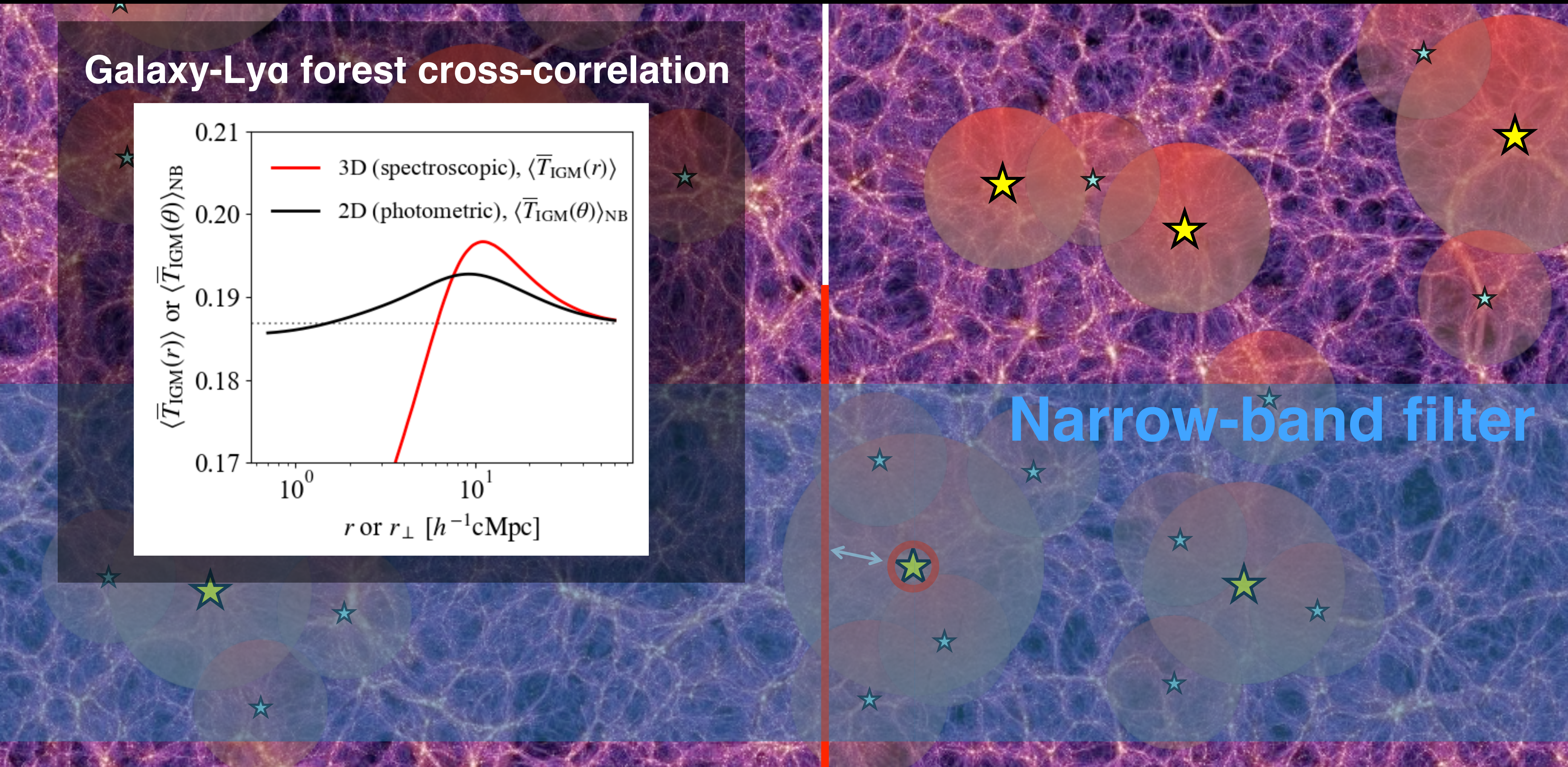
$$\tau_\alpha \propto (1+\delta_b)^2 \, \Gamma_{\rm ion}^{-1}$$

Nonlinear Formalism from Kakiichi+18, Meyer+20
cf. Pontzen 14, Gontcho-a-Gontcho 14,
Meiksin & McQuinn 19

Galaxy-Lyα Forest Cross-Correlation
Modelling the impact of leaking ionizing radiation



3D Galaxy-Lyα Forest Cross-Correlation to 2D Photometric IGM Tomography

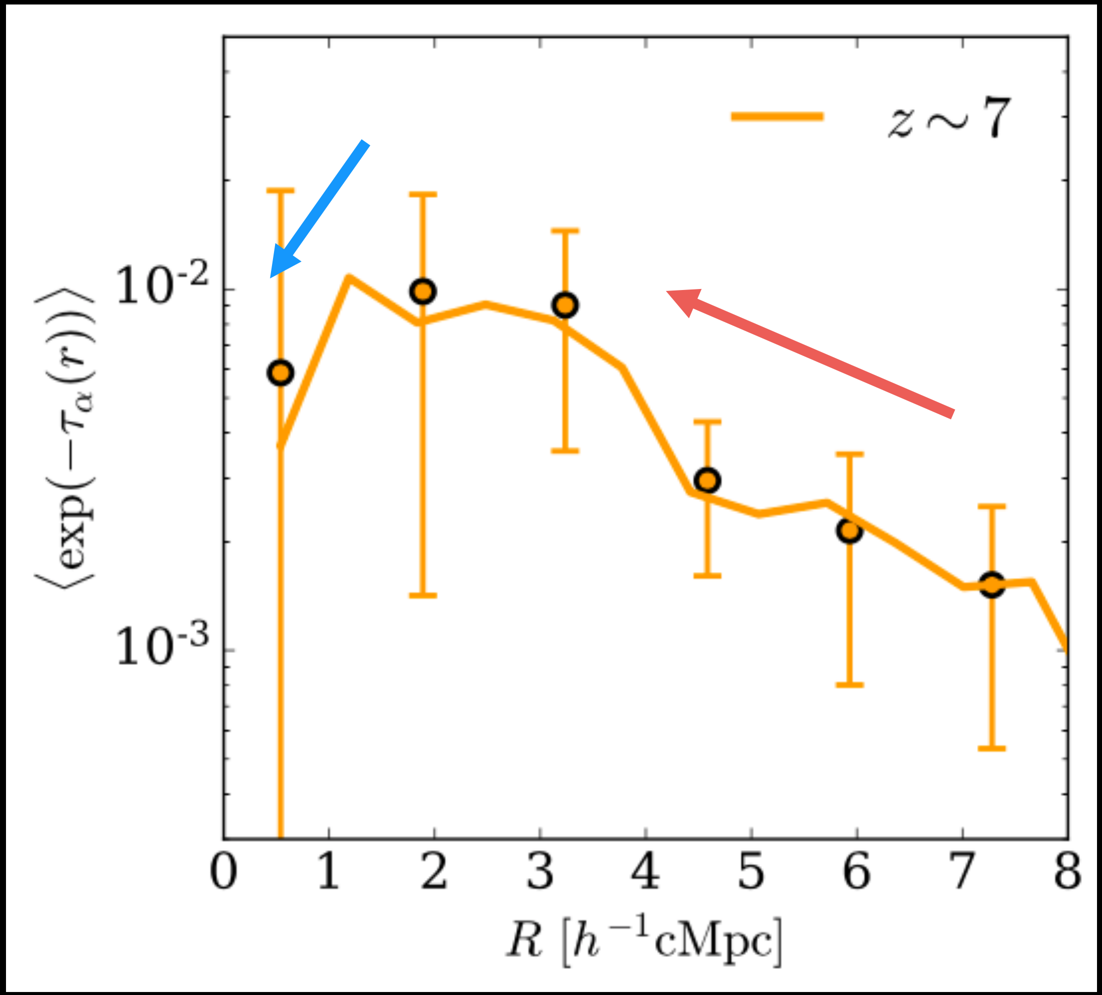


$$\langle \overline{T}_{\rm IGM}(\theta)\rangle_{\rm NB} = \int dz_1 W_{\rm NB}(z_1) \int dz_2 W_{\rm NB}(z_2) \langle \overline{T}_{\rm IGM}\rangle \left[1 + \xi_{{\rm g}\alpha}(r_\parallel, r_\perp)\right]$$

Kakiichi+ in prep

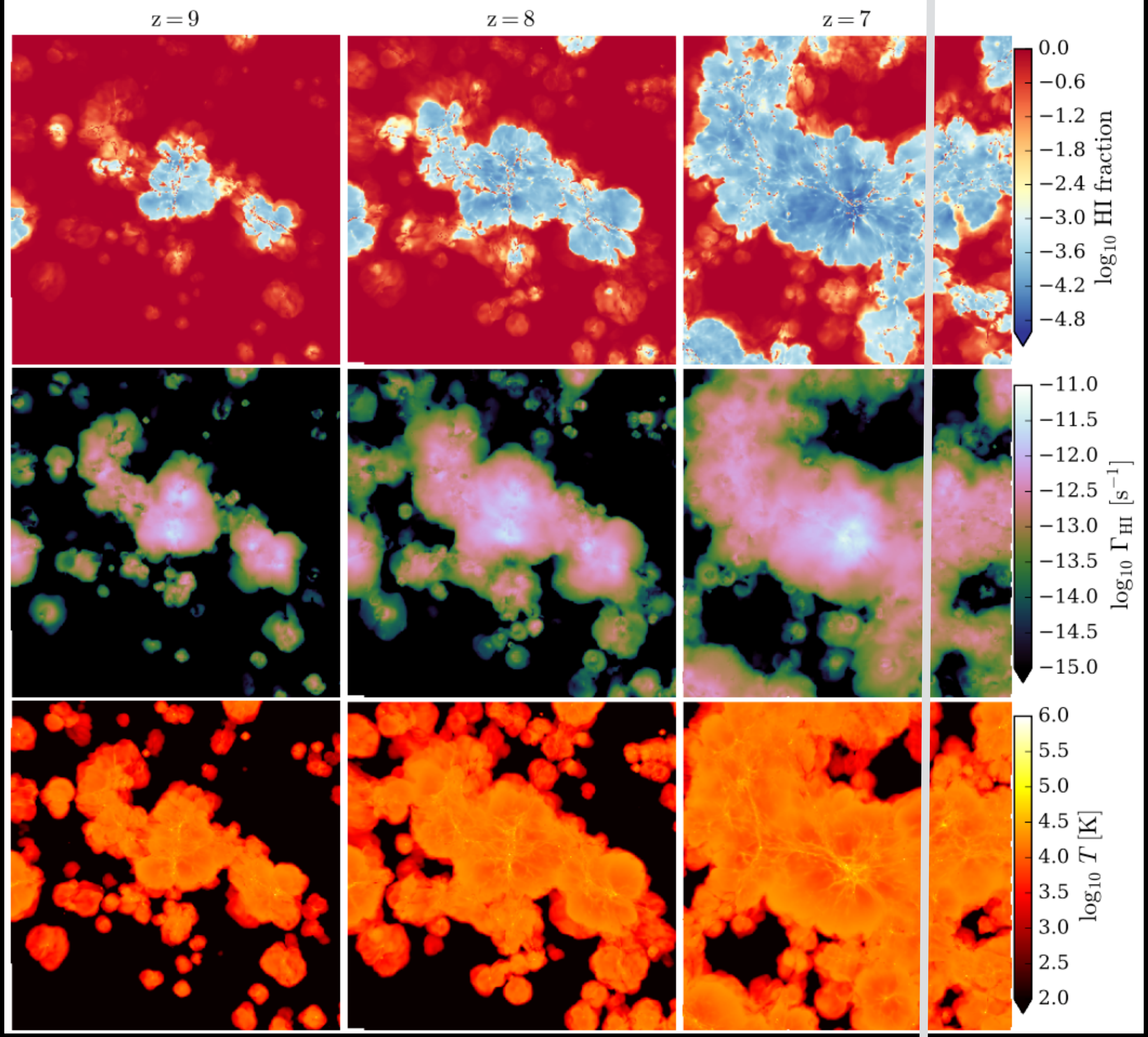
Confirming theoretical galaxy-Lyα forest cross-correlation
with Cosmological Radiation Hydrodynamic Simulation

Gas overdensity



Ionizing background ∝ ⟨$f_{esc}\,\xi_{ion}$⟩

Intuition consistent with theory ✔

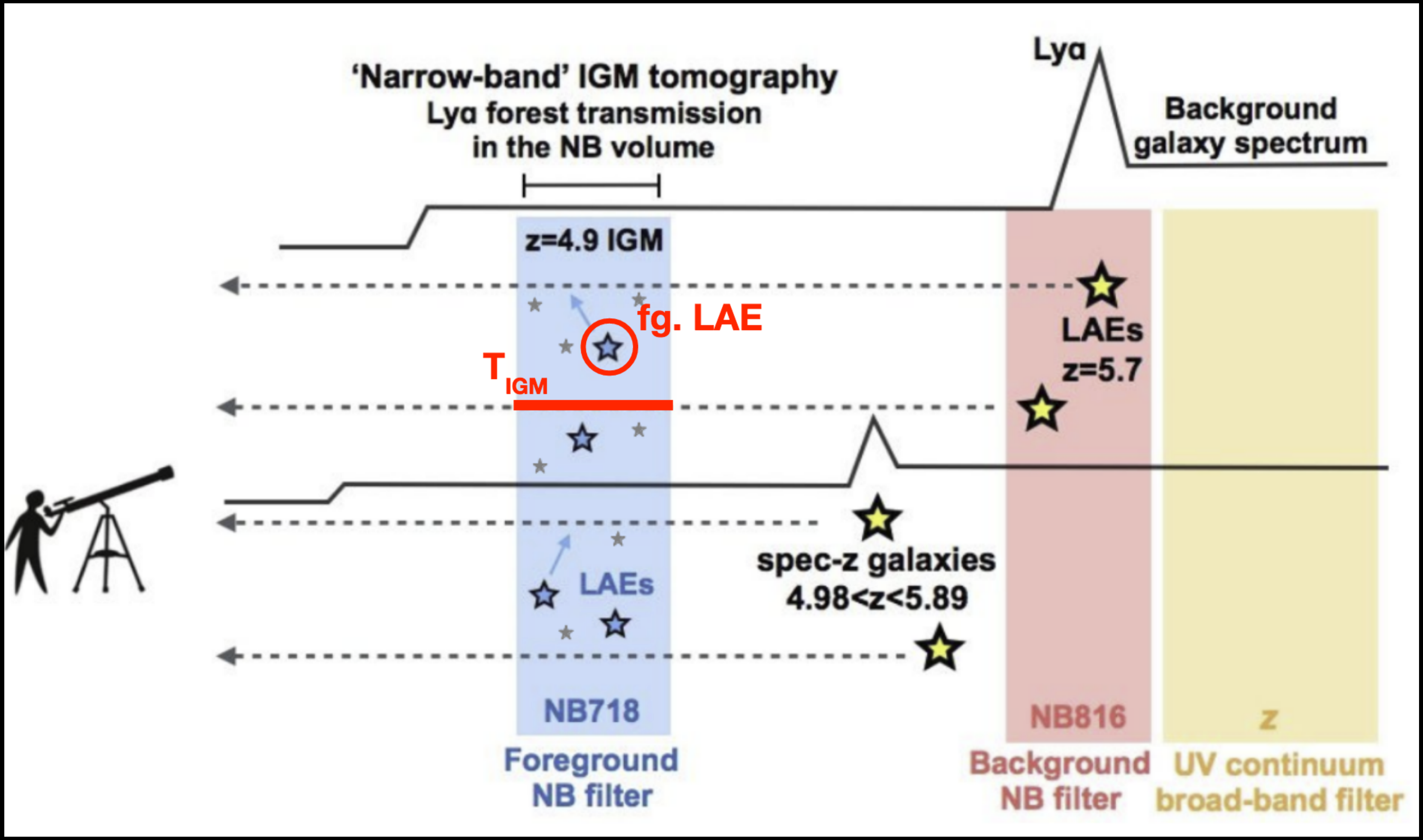


30 Mpc/h zoom-in full RAMSES-RT radiation hydrodynamic simulation around $10^{12}M_\odot$ halo in a 100 Mpc/h box

Kakiichi+in prep

Measuring Galaxy-Lyα forest Cross-Correlation

z=4.9 foreground LAEs × IGM transmission



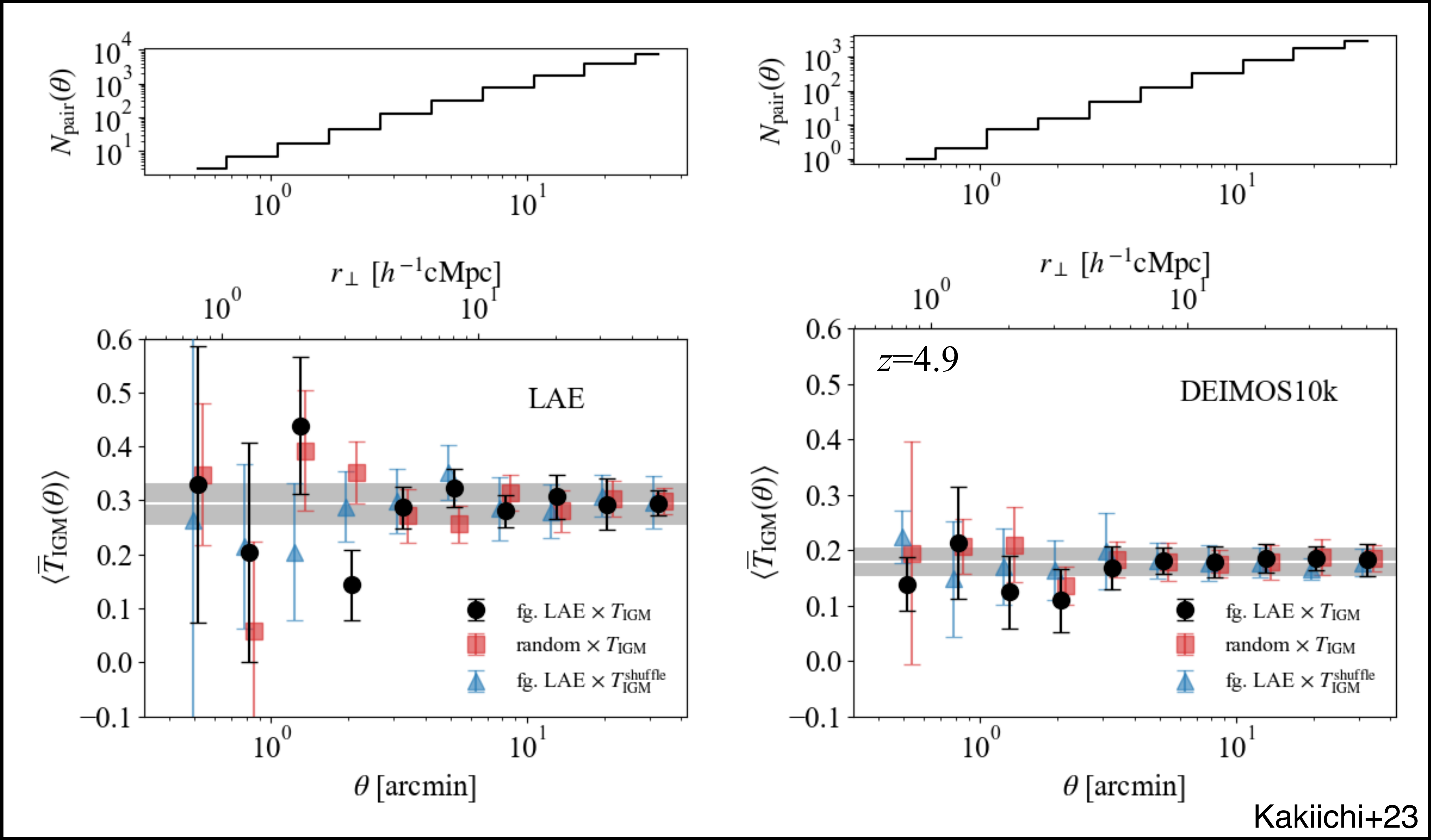
Photometric IGM tomography:

galaxy-Lyα forest cross-correlation → hydrogen gas around foreground galaxies

à la weak gravitational lensing:

galaxy-galaxy lensing → dark matter around foreground galaxies

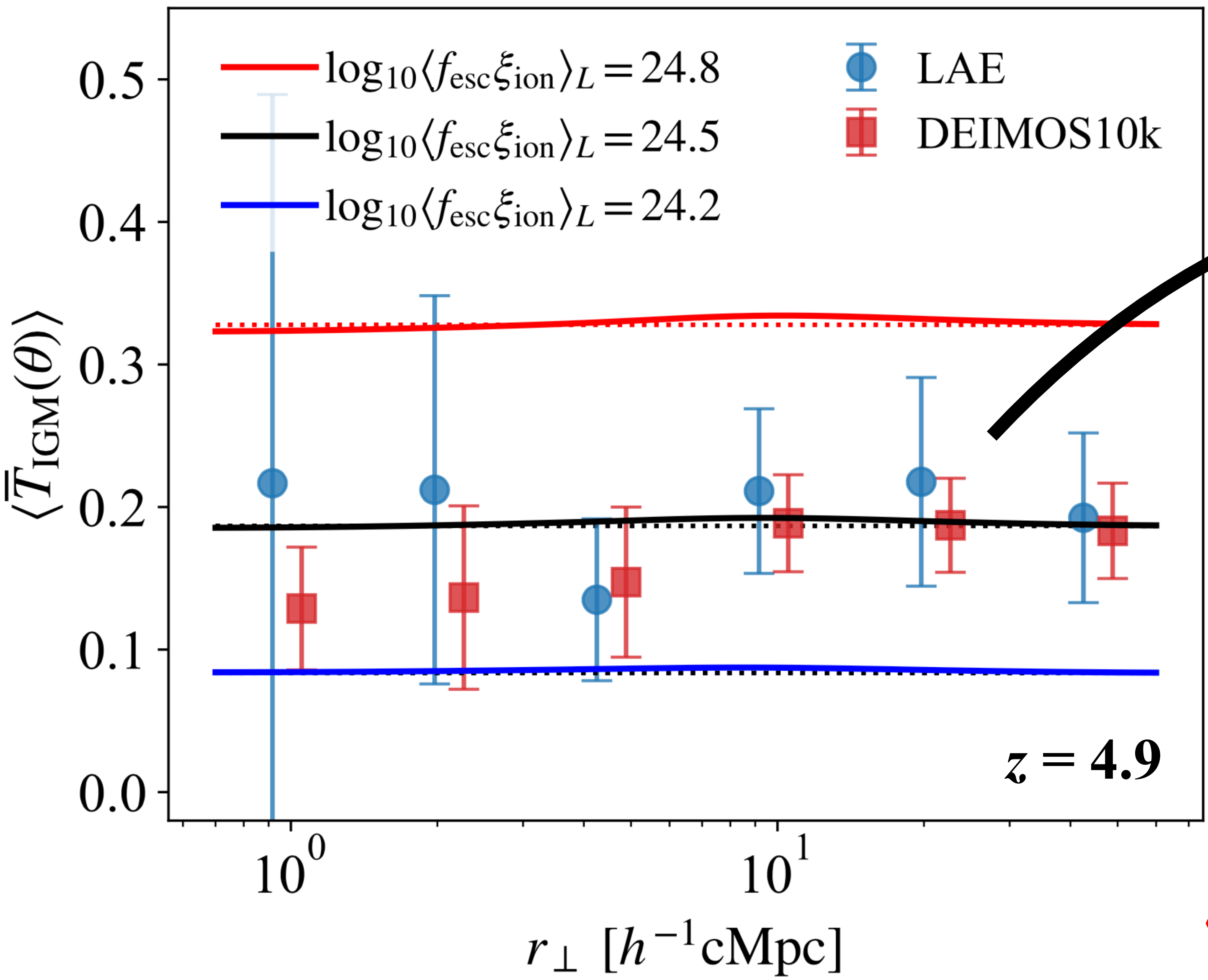
Measurement from photometric IGM tomography
Angular Galaxy-Lyα Forest Cross-Correlation

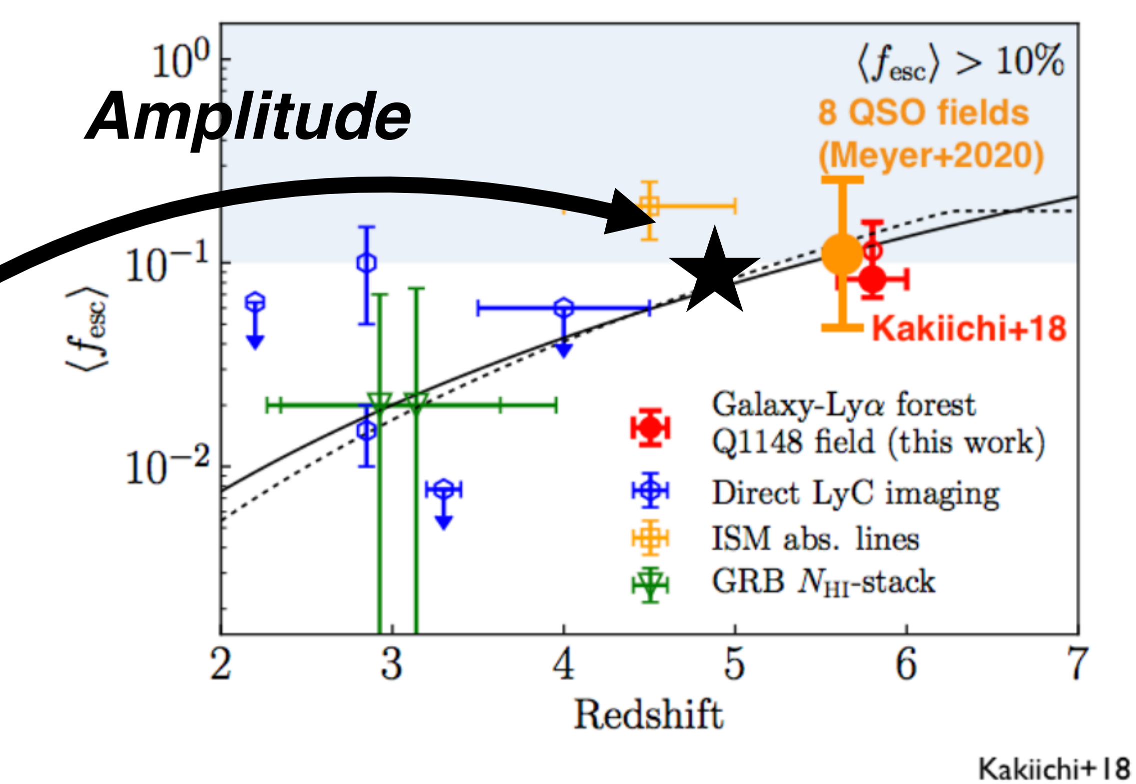


Non-detection. consistent with the mean IGM transmission,

Upper limit on the IGM fluctuation around galaxies at z~5

On sources of reionization – I : Ionizing power of galaxies



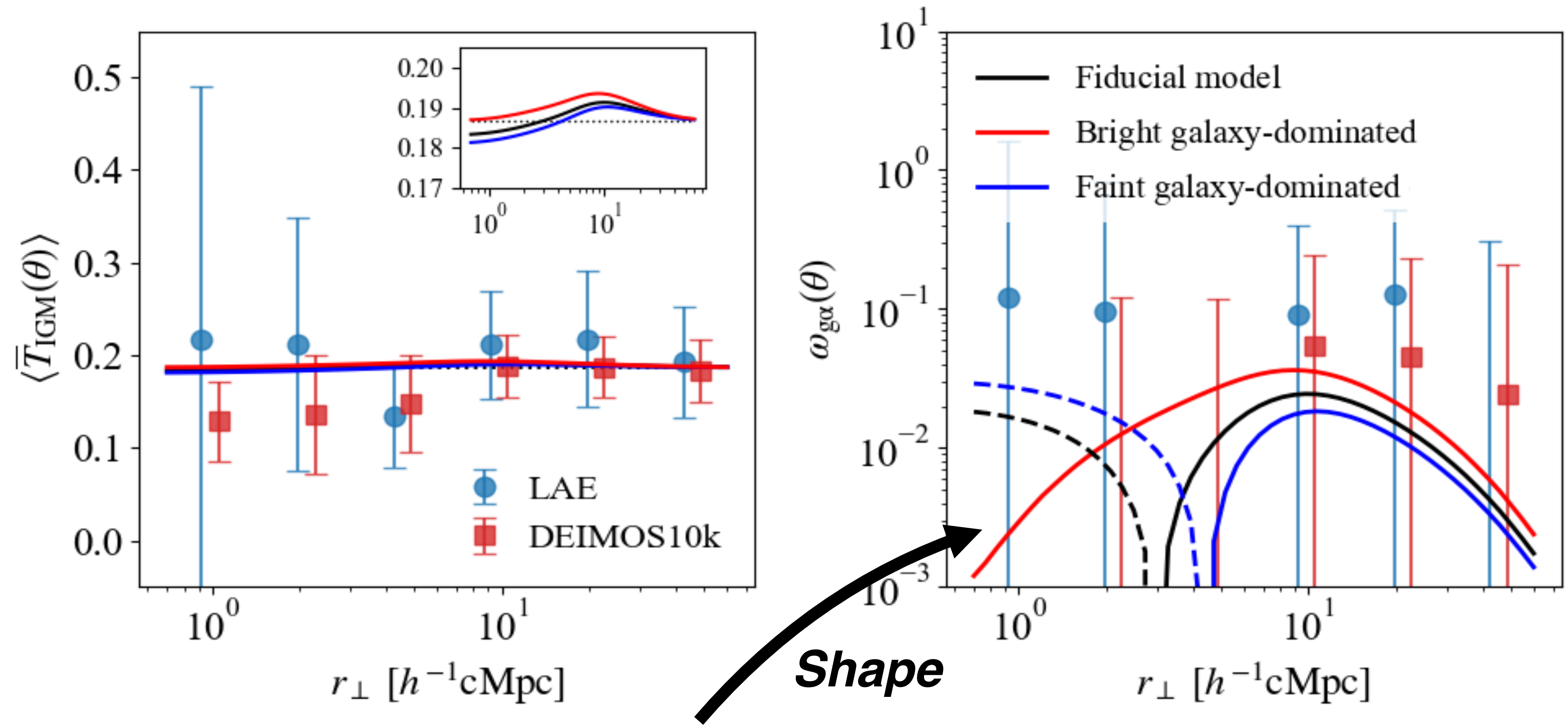


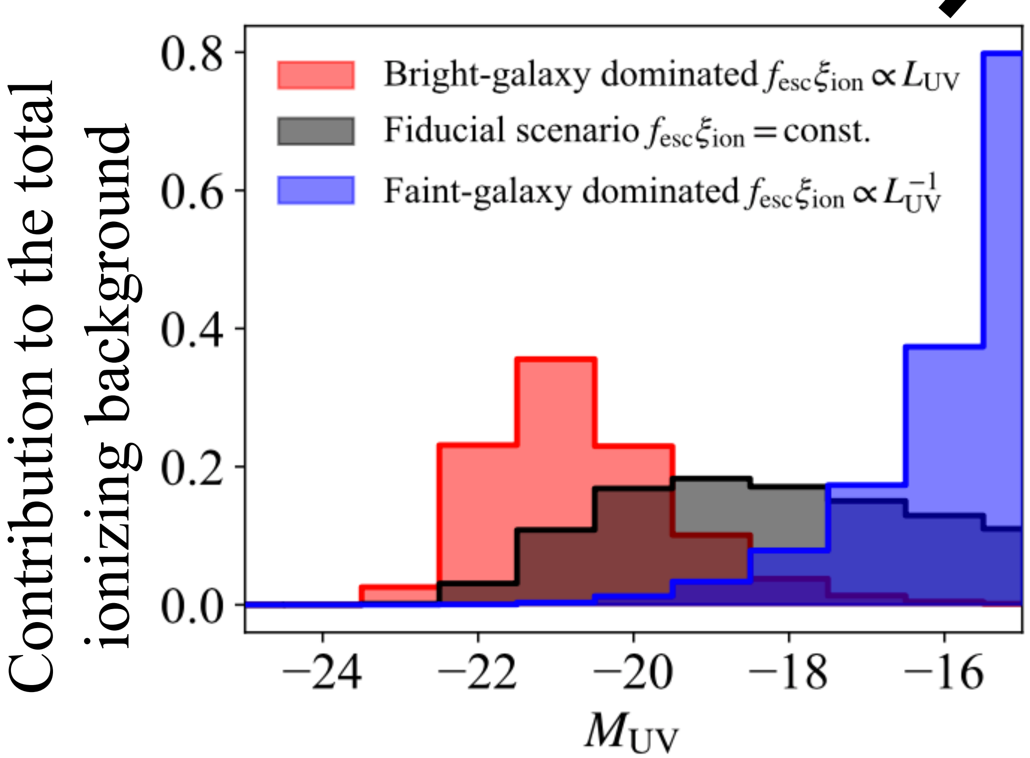
Ionizing power of galaxies

Reionization by galaxies with
$\langle f_{esc}\,\xi_{ion}\rangle \approx 10\% \times 10^{25.5}$ erg^{-1}Hz

Kakiichi+in prep

On sources of reionization – II : Bright vs faint galaxy-dominated reionization





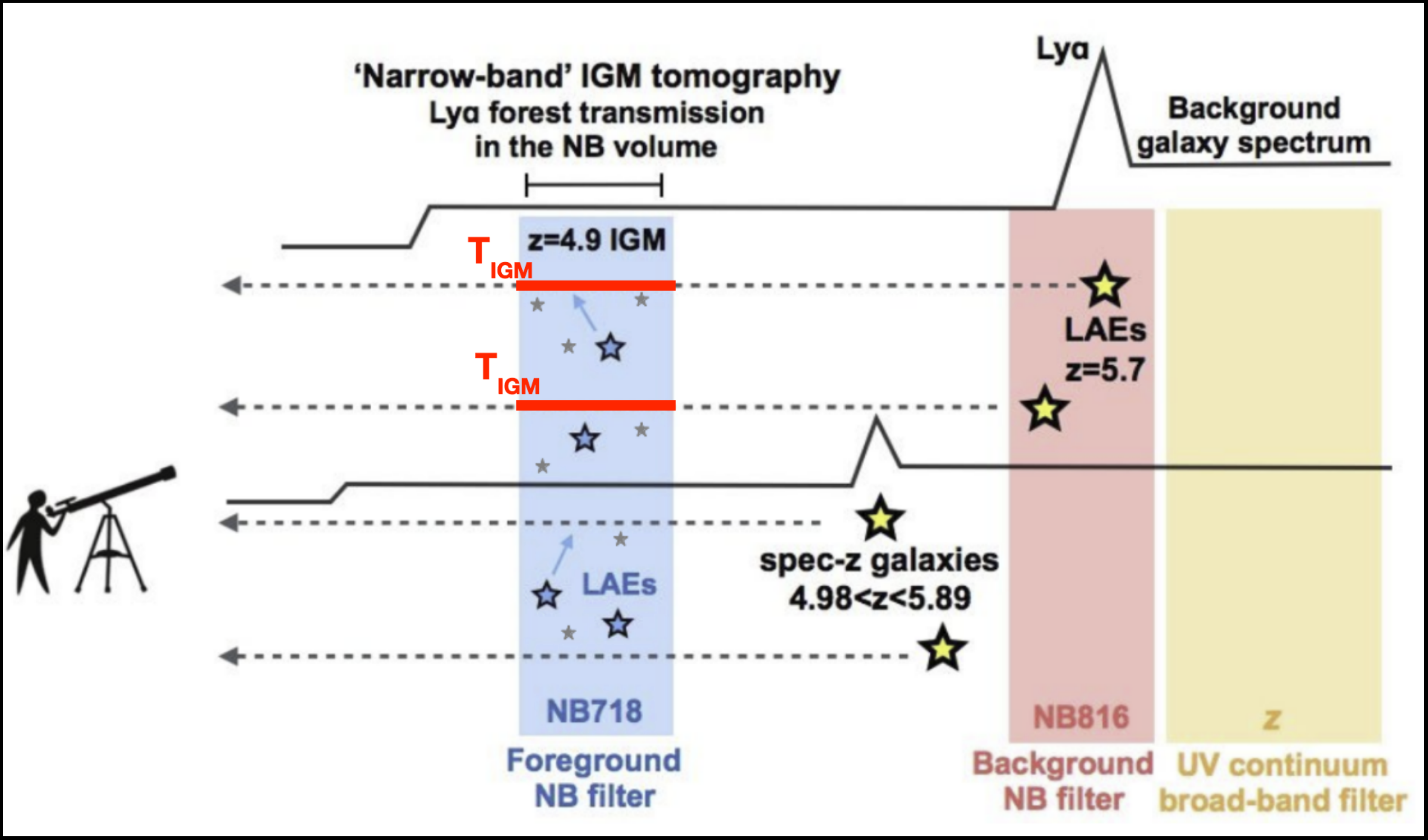
The nature of ionizing sources

Relative contribution of bright vs faint galaxies to reionization

Kakiichi+in prep

Measuring Lyα forest Auto-Correlation

z=4.9 IGM transmission



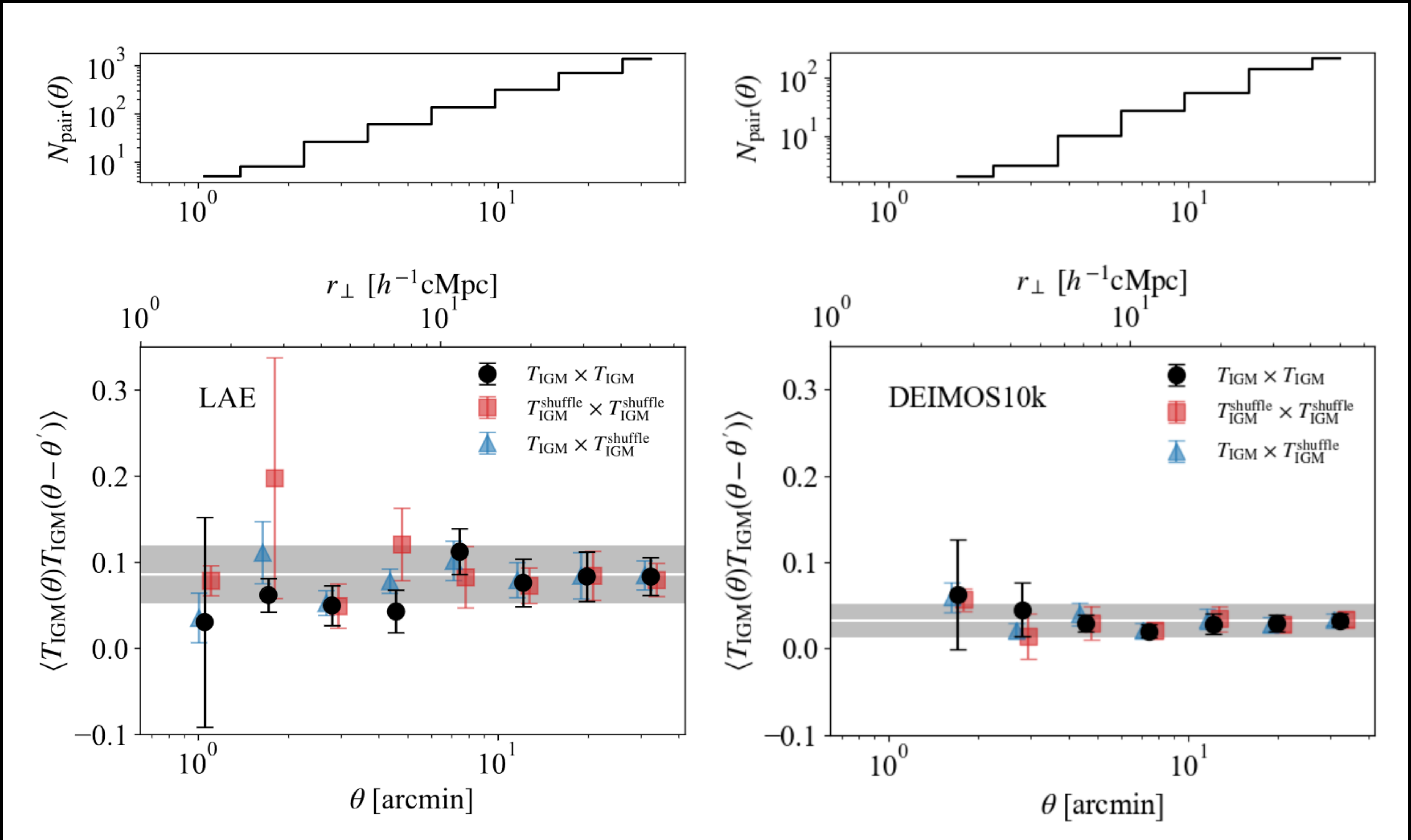
Photometric IGM tomography:

Lyα forest auto-correlation → hydrogen gas fluctuations

à la weak gravitational lensing:

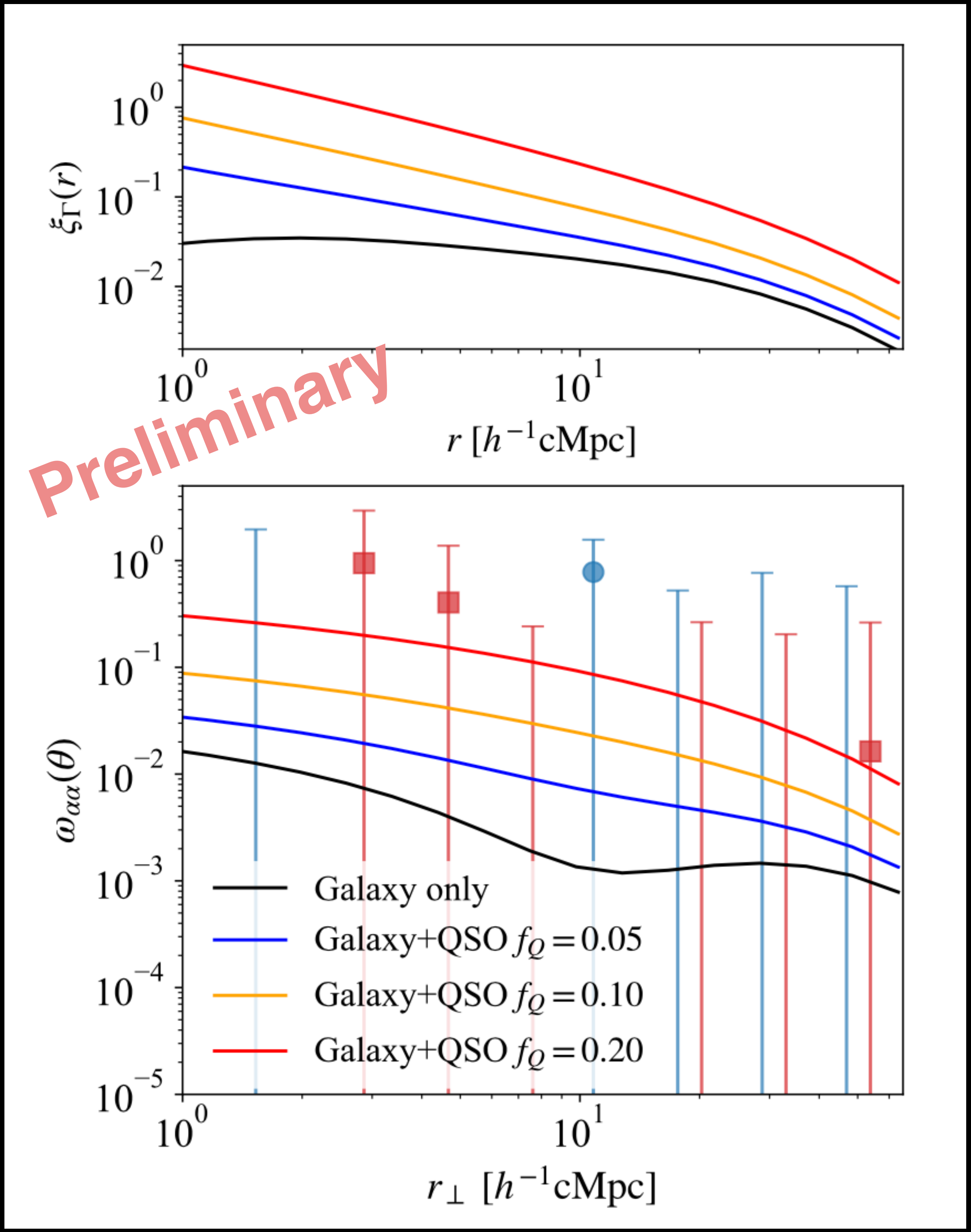
cosmic shear → dark matter fluctuations

Measurement from photometric IGM tomography
Angular Lyα Forest Auto-Correlation



Non-detection.

Limit on the contribution from quasars to reionization
Angular Lyα Forest Auto-Correlation

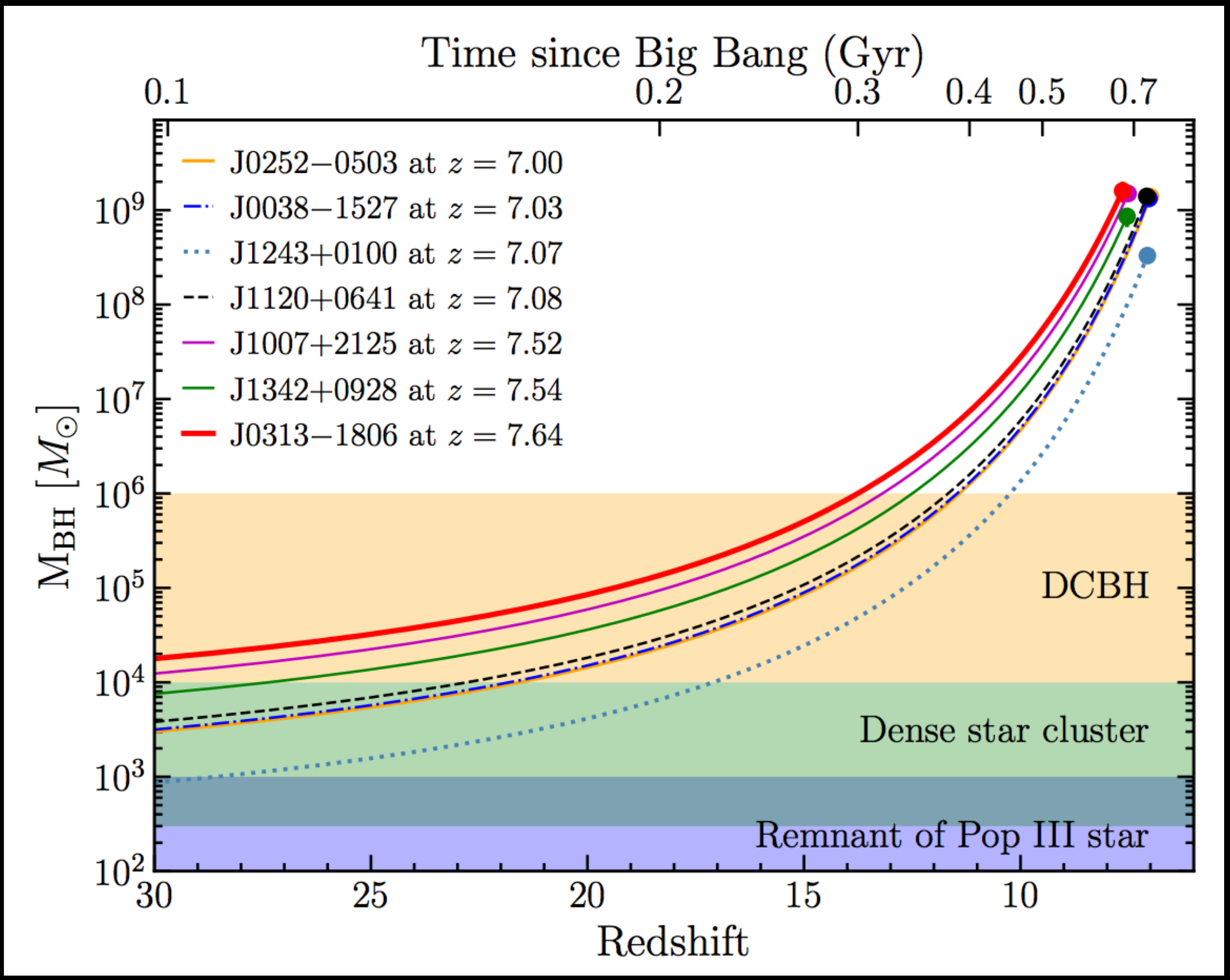


Quasars boosts the shot-noise contribution to angular Lyα forest auto-correlation function

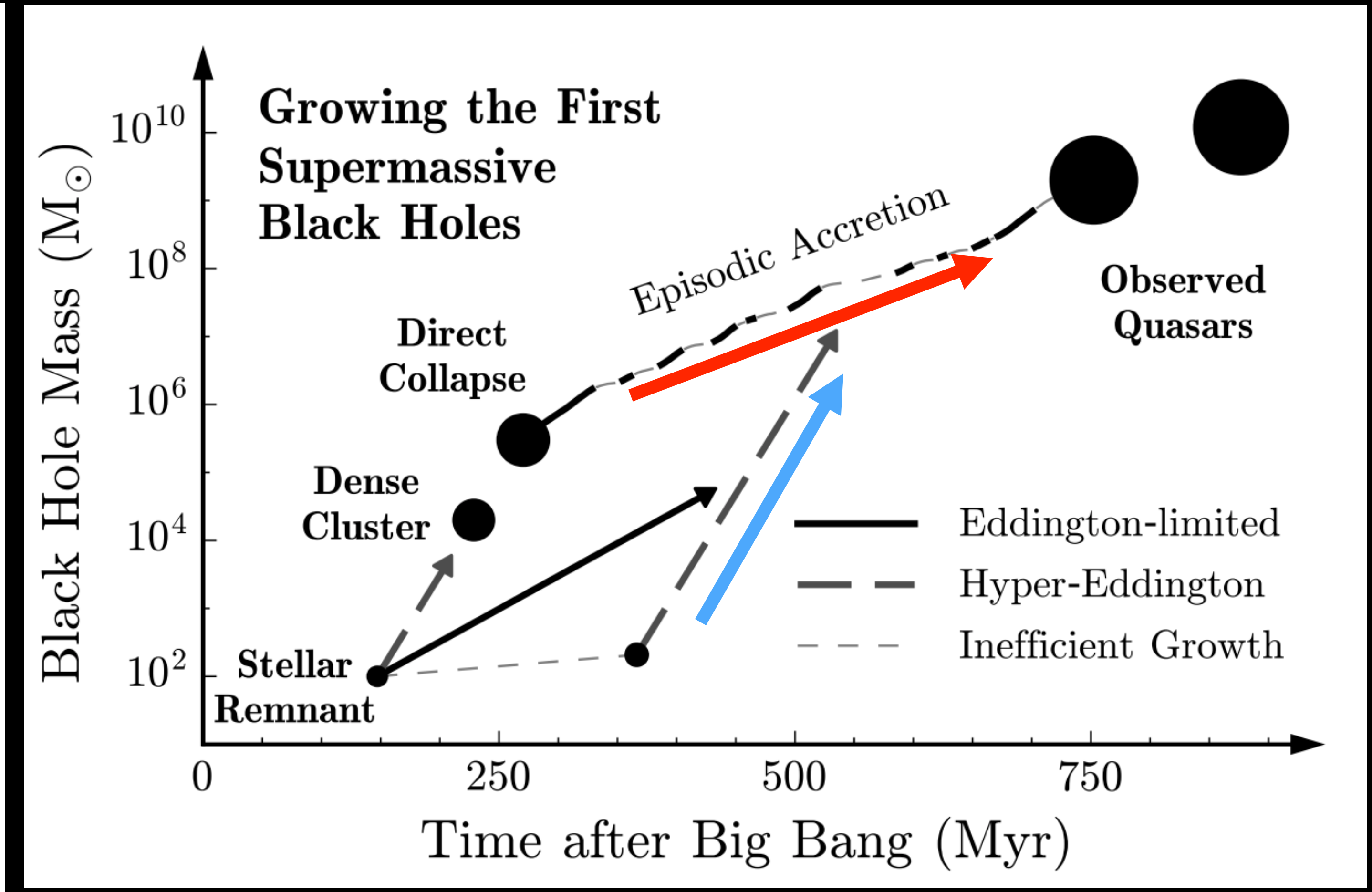
What can we learn from photometric IGM tomography?

2. Recovering the radiative growth history of supermassive black holes

The origin of supermassive black holes at z>6-7?



Wang et al 2021



How did a SMBH acquire its mass?

- ***Kick start from a massive seed >10^4 $M_\odot$? (seed formation)***

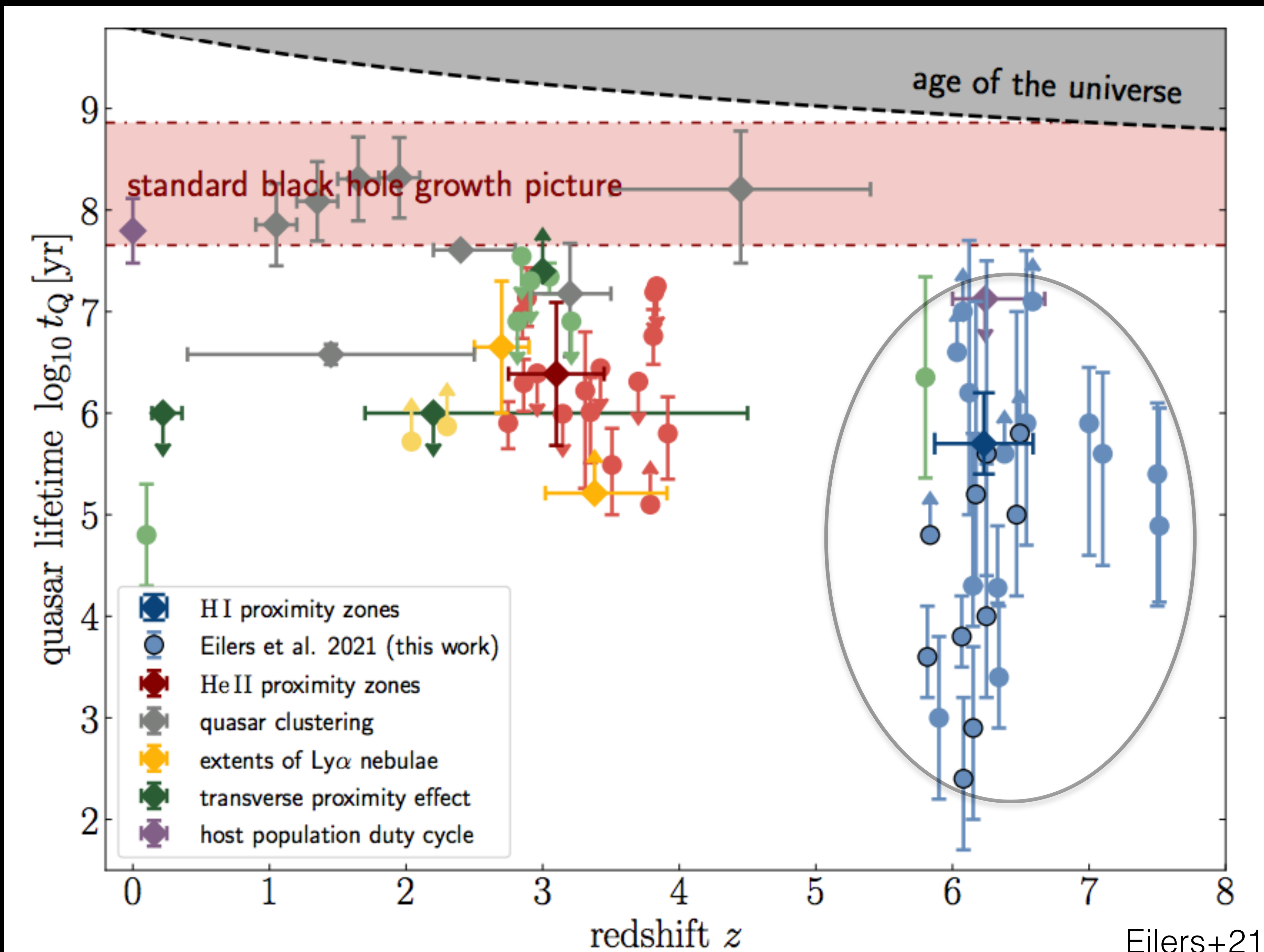
  e.g. Woods et al 2018, Inayoshi et al 2020

- ***Rapid accretion via super-Eddington growth? (growth mechanism)***

  e.g. Madau et al 2014

Growth history of a SMBH is related to the QSO's radiative history

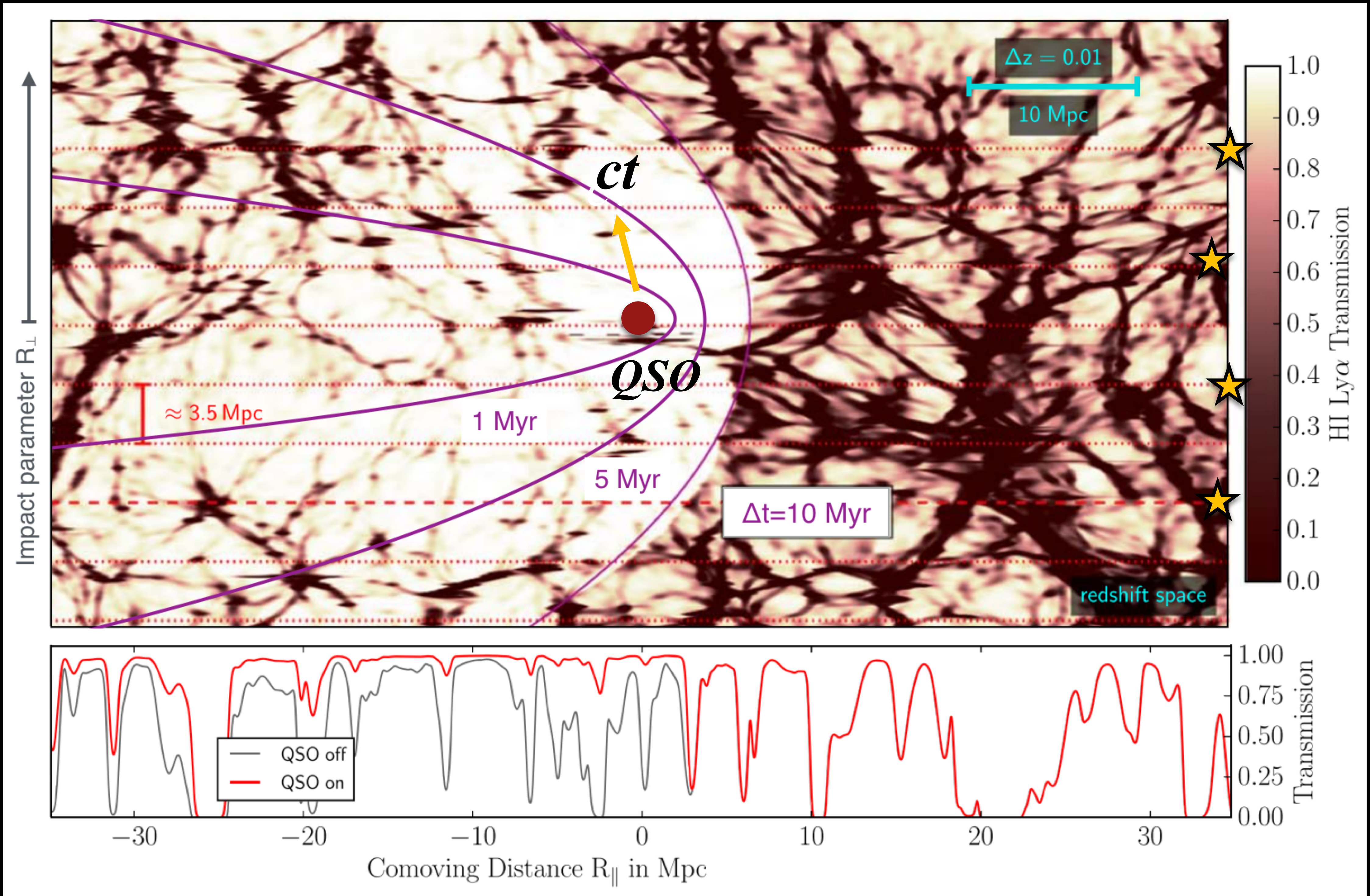
$$L_{\rm QSO} \approx 0.1 \dot{M}_{\rm gas} c^2$$



For High-z QSOs, too short time to grow ~$10^9 M_\odot$ SMBHs via the QSO luminous phases?

Need a new observing strategy to probe the SMBH growth history

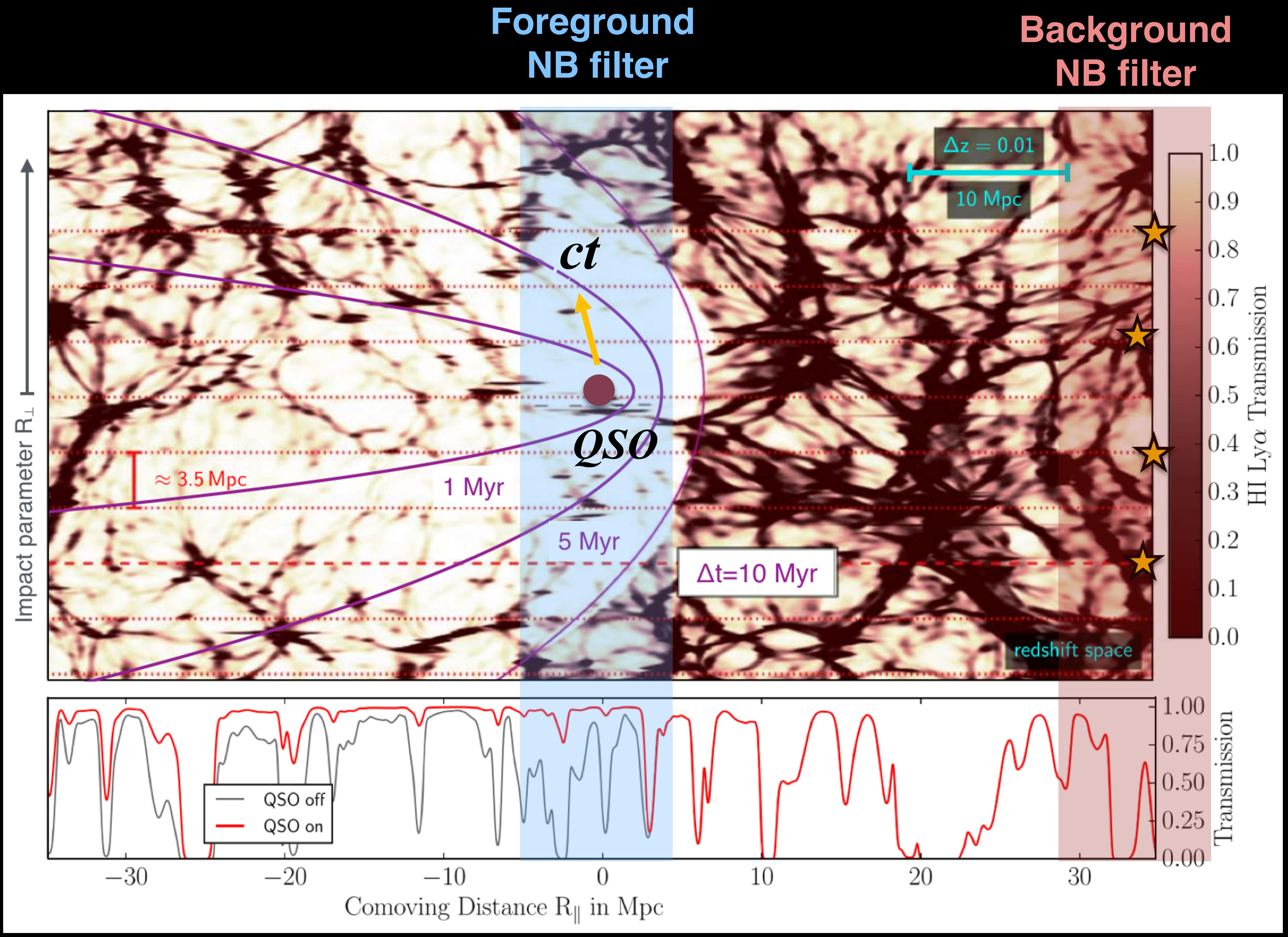
Constraining the QSO-active growth history from "IGM Light-Echo Tomography"



Schmidt et al 2018

See also Adelberger 2004, Visbal & Croft 2008

Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"

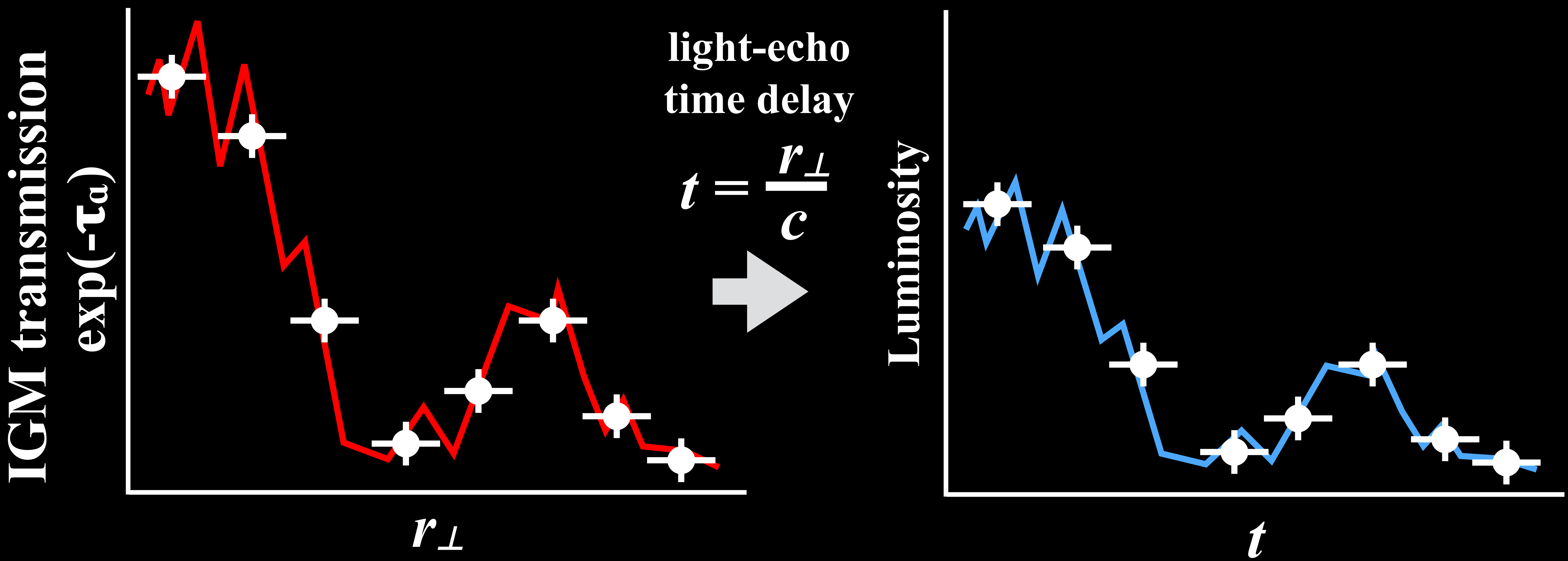


Kakiichi+2022

See also Adelberger 2004, Visbal & Croft 2008

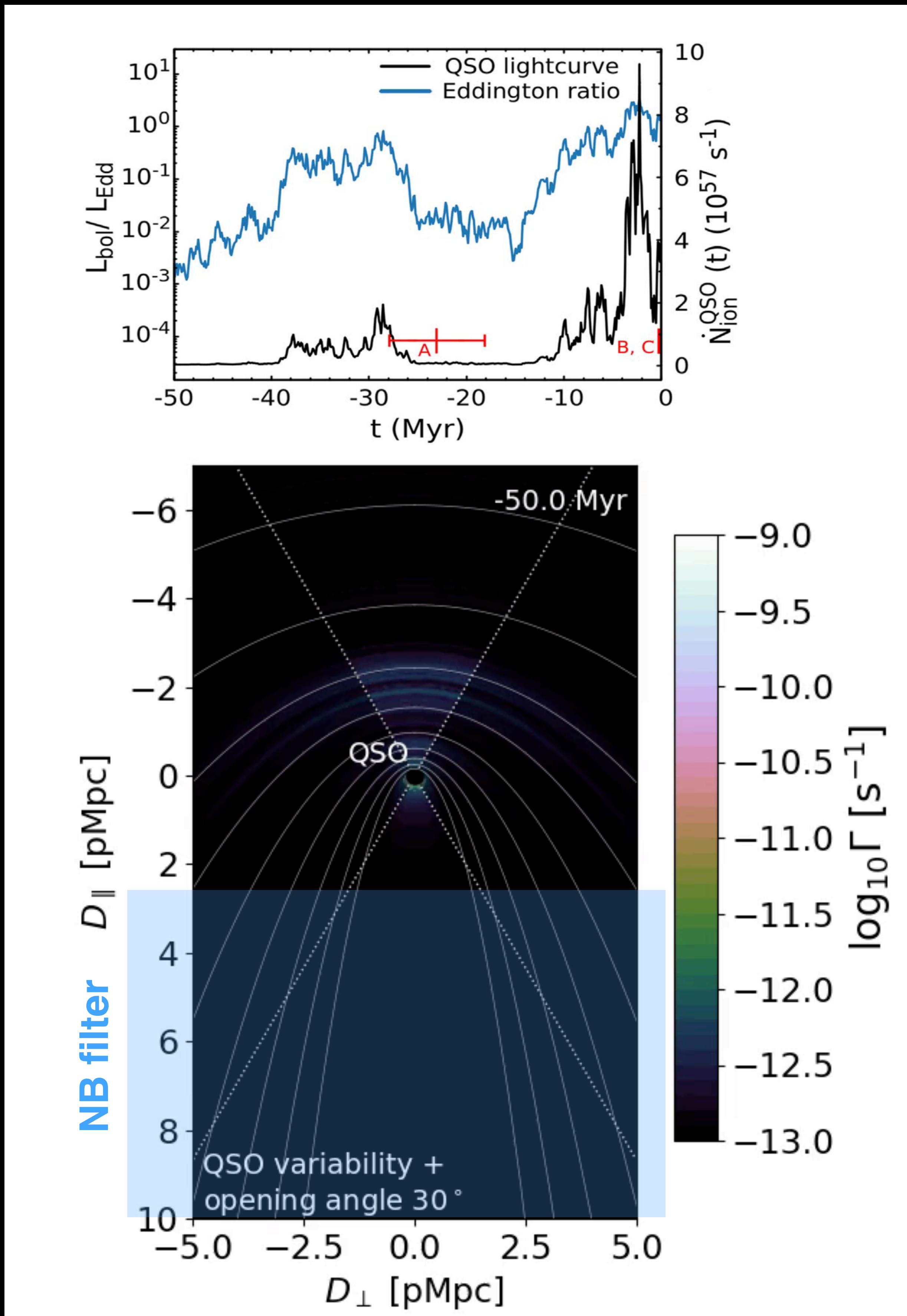
Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"

QSO transverse proximity effect → *Radiative growth history constraint*

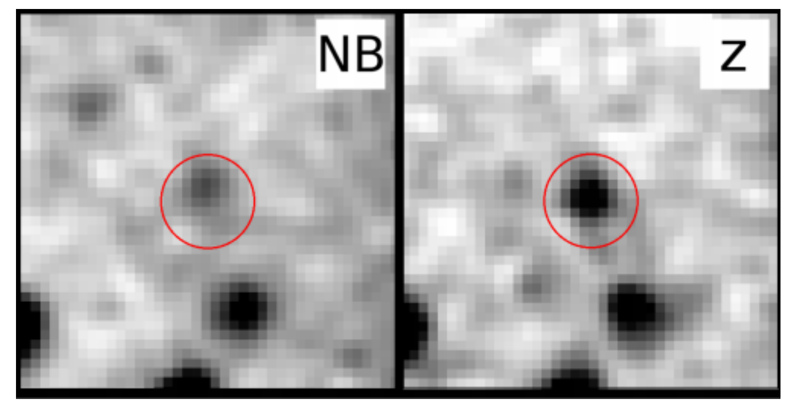


Photometric IGM tomography of QSO light-echo at Mpc-scale translates into a Myr-scale time-domain constraint on the QSO's radiative history of an individual SMBH over the baseline of ~100 Myr

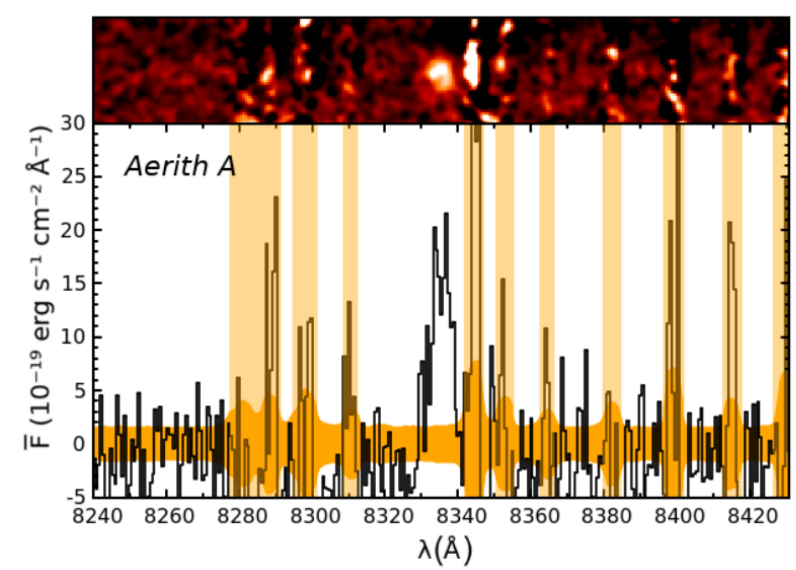
Serendipitous detection: Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"



Photometric detection of the transverse proximity effect around z=5.8 QSO along a background galaxy

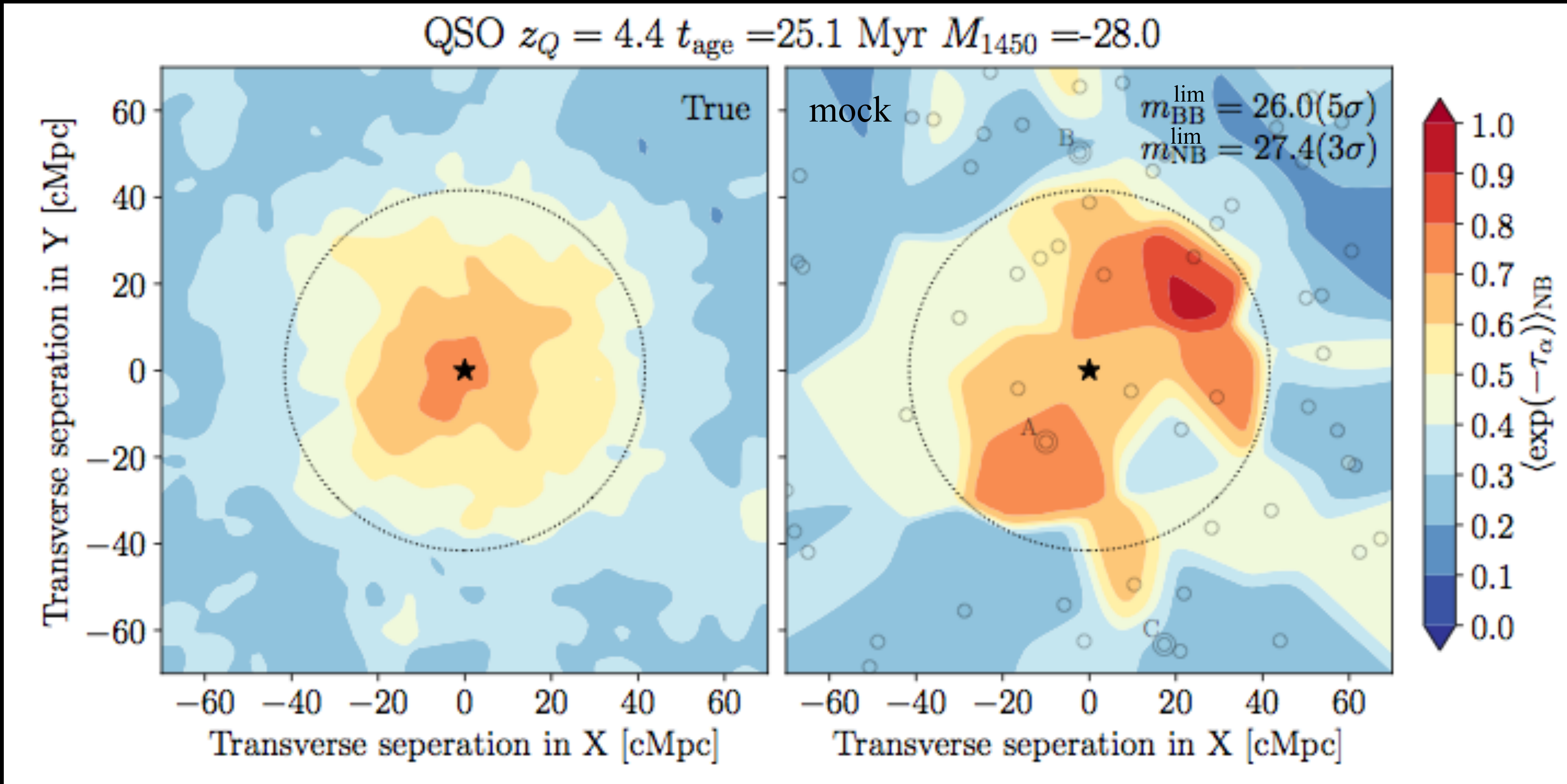


Depth
NB816=27.2(3σ)
z=26.4(3σ)



Bosman, Kakiichi+2020

Simulation Mock:
Photometric IGM Tomography around QSO Light Echoes



Kakiichi+22

<u>Simulations:</u>

1: Cosmological hydrodynamic simulations (>$10^{12}M_\odot$) + RT around QSO
NyX code, $100h^{-1}$cMpc 4096^3 fixed grid (Lukić et al. 2015)

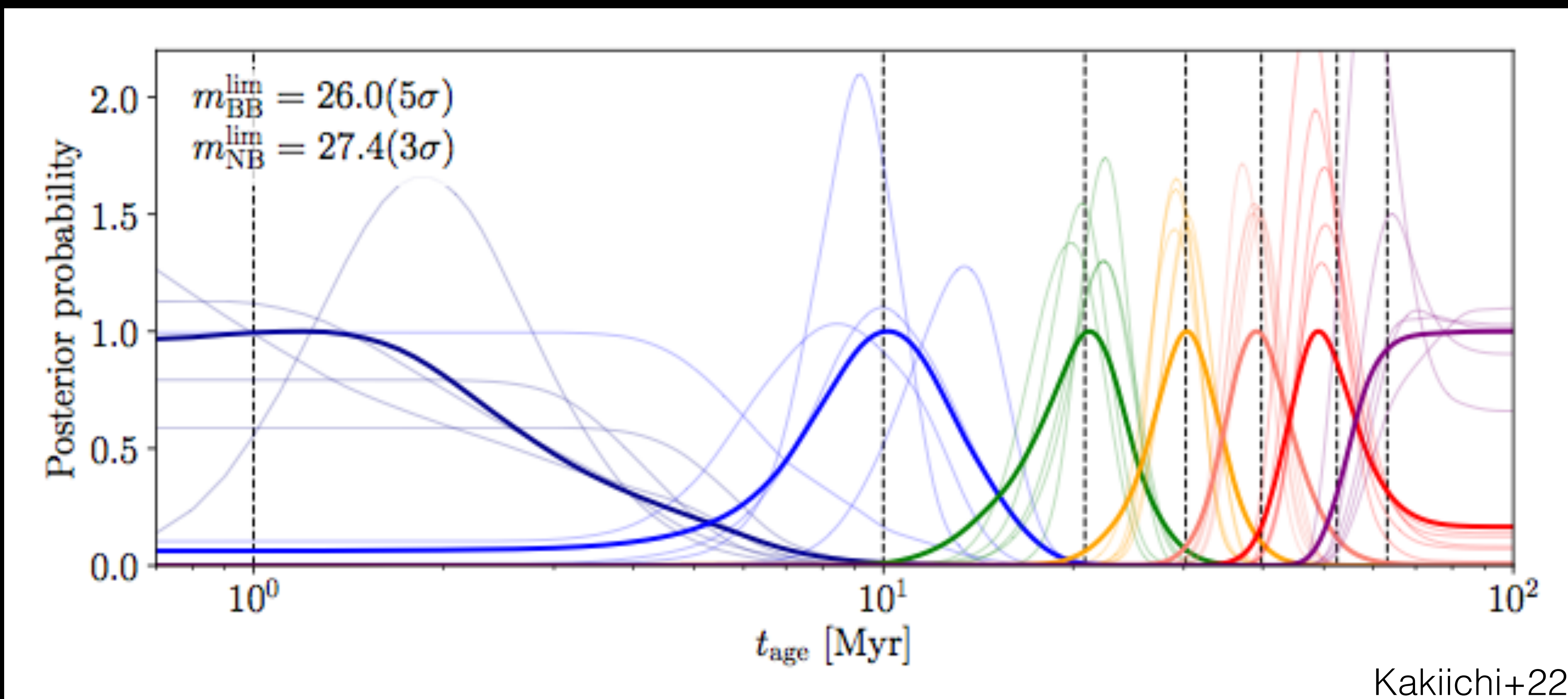
2: Forward modelling of observational systematics

Forecast: constraint on the QSO lifetime t_{age}
Full Bayesian inference framework

NB flux, BB flux — Noise, continuum slope, etc

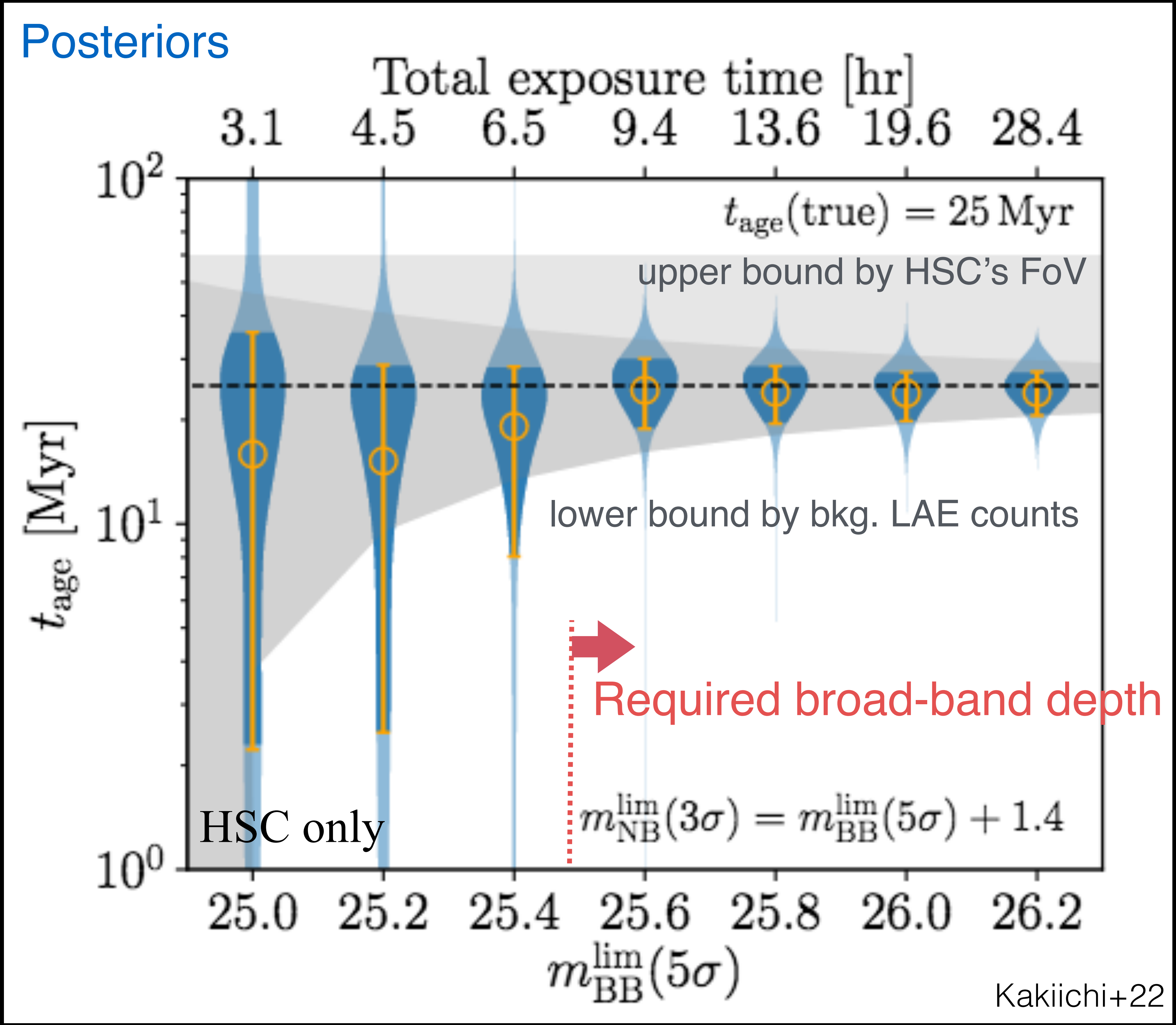
$$P(t_{\rm age}|{\rm obs.,\ systematics}) \propto P(t_{\rm age})\mathcal{L}({\rm obs.}|t_{\rm age},\ {\rm systematics})$$

posterior — **prior** — **Likelihood** ⟵ Forward modelled using many realisations from cosmo. simulation + RT

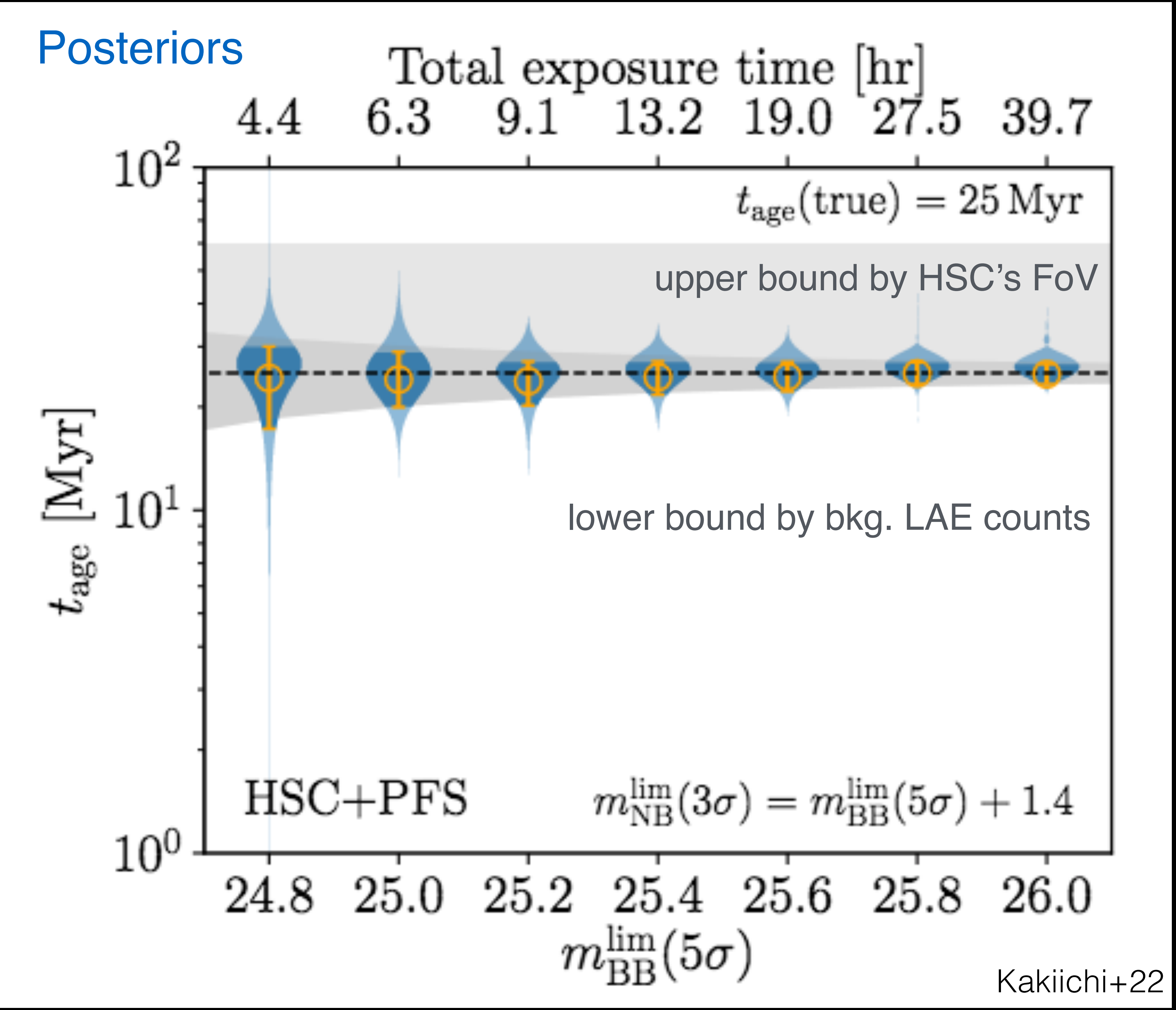


Accuracy of quasar lifetime constraint is limited by the background LAE density

Forecast: constraint on the QSO lifetime
Observational requirement: HSC only

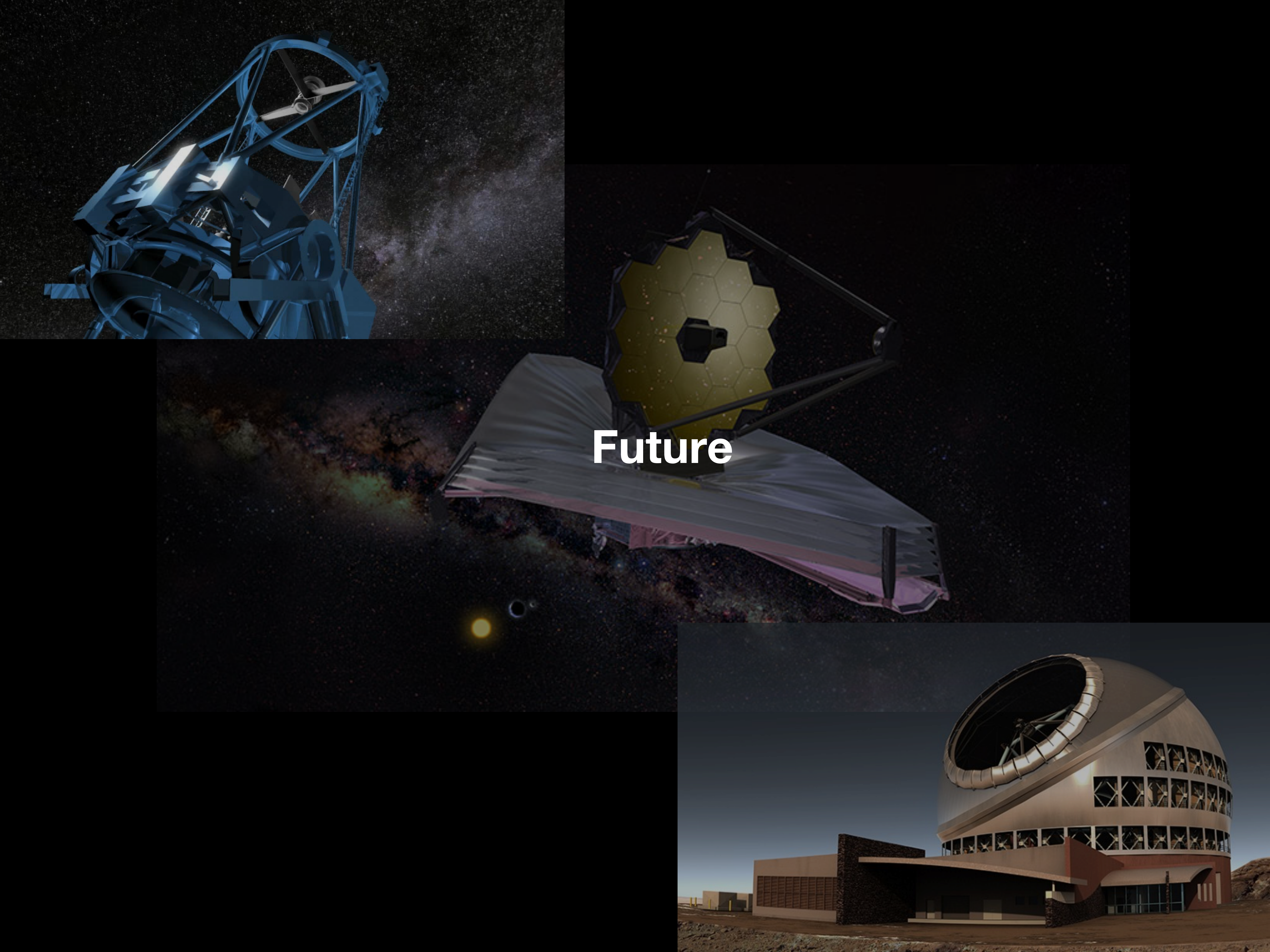


Forecast: constraint on the QSO lifetime
Observational requirement: HSC+PFS



Kakiichi+22

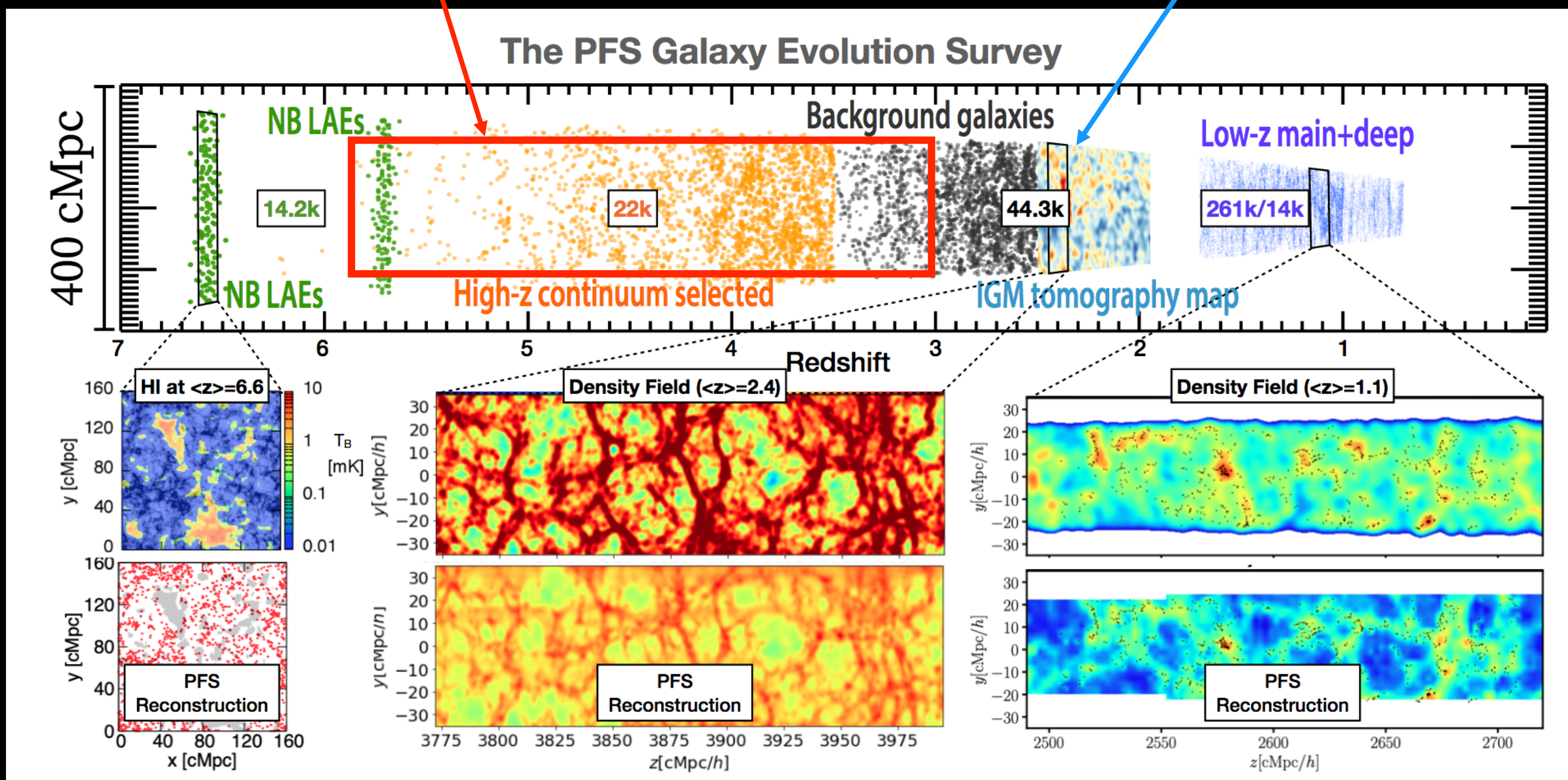
Future



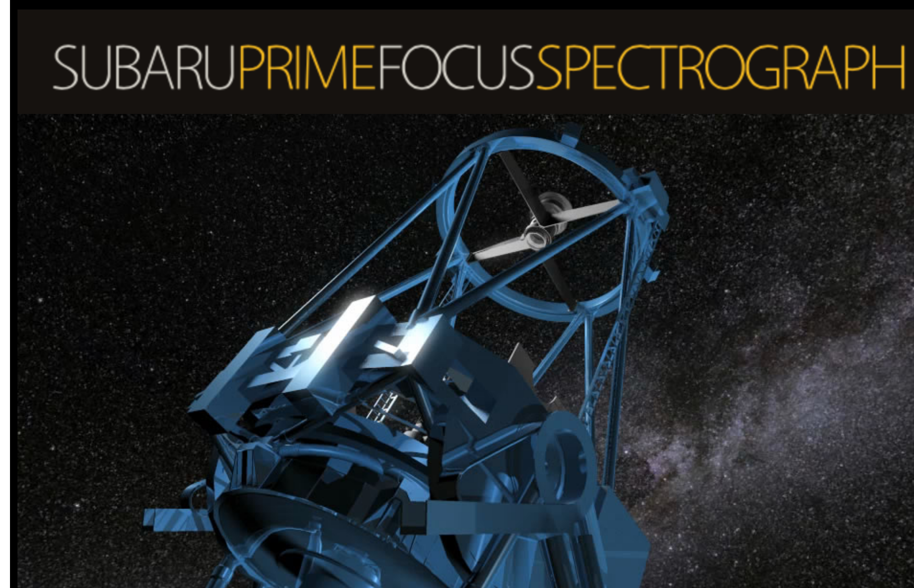
Towards a better photometric IGM tomography – I : with Subaru/PFS

Photometric IGM tomography

Spectroscopic IGM tomography



Greene+22



Subaru/PFS 360-night spectroscopic survey

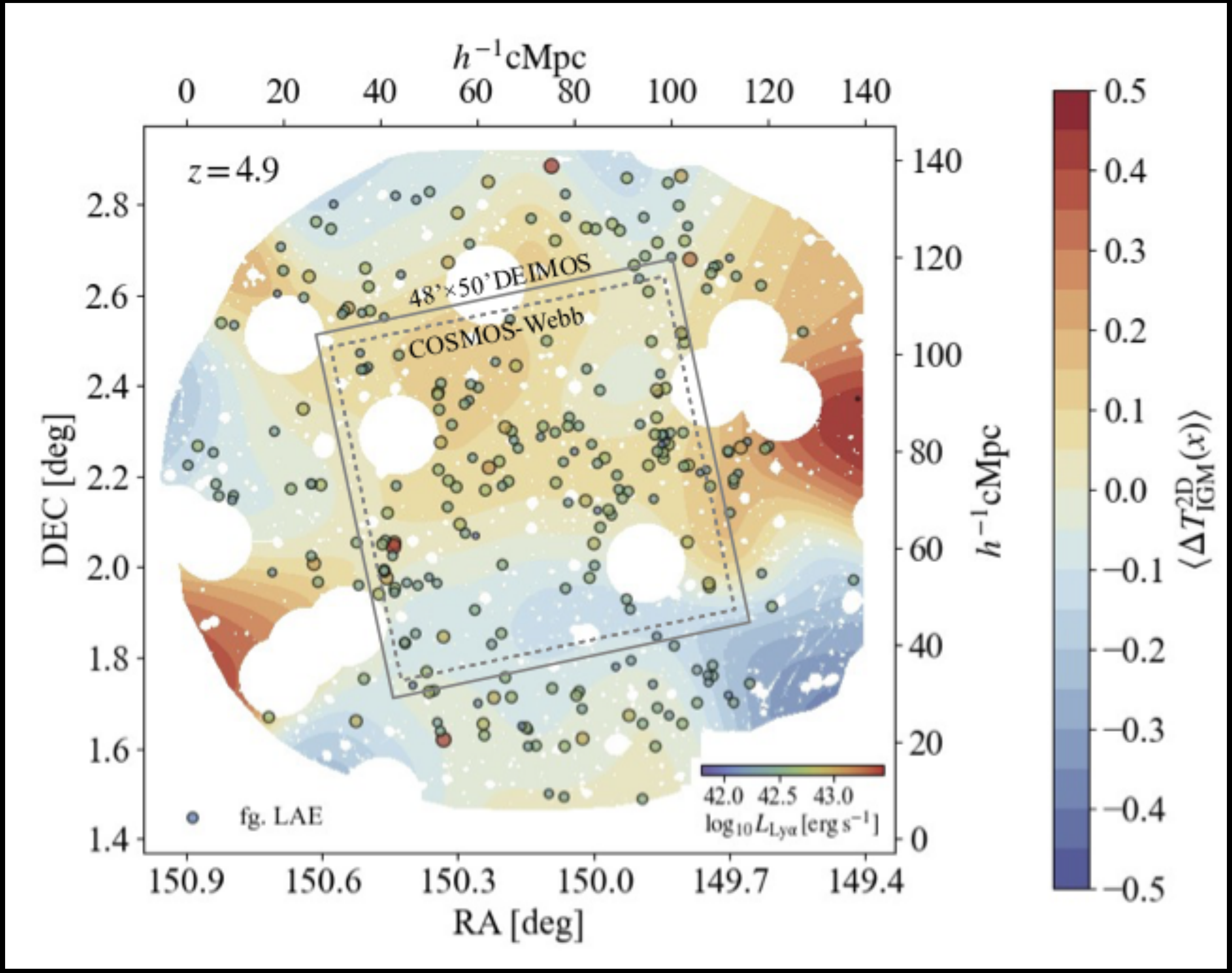
Photometric IGM tomography + traditional wide-field spectroscopic survey

1. Boost the number of spectroscopically-confirmed bright galaxies
2. Correct for the low-redshift interloper effect in background galaxy sample

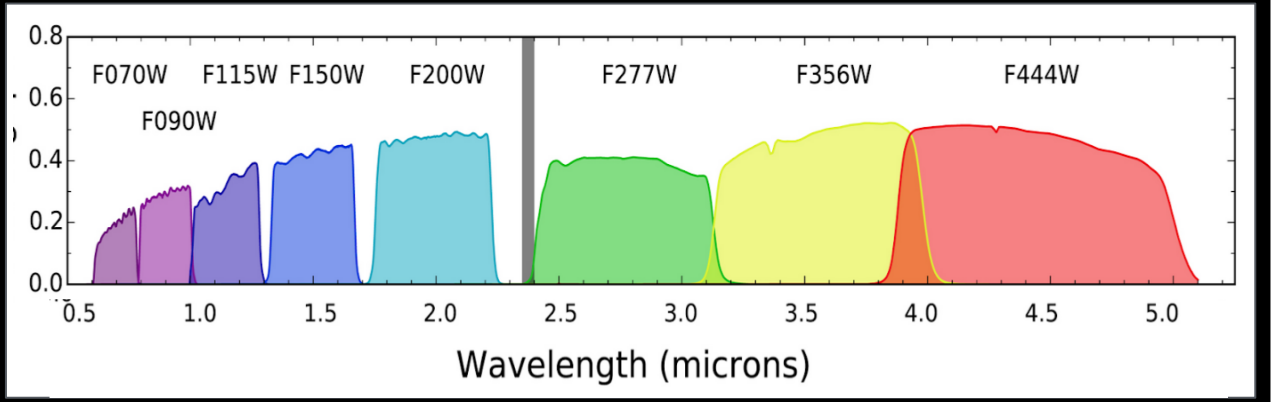
Towards a better photometric IGM tomography – II : with JWST

Photometric IGM tomography

Tomographic slices	
	NB718 z=4.9
	NB816 z=5.7
	NB921 z=6.6



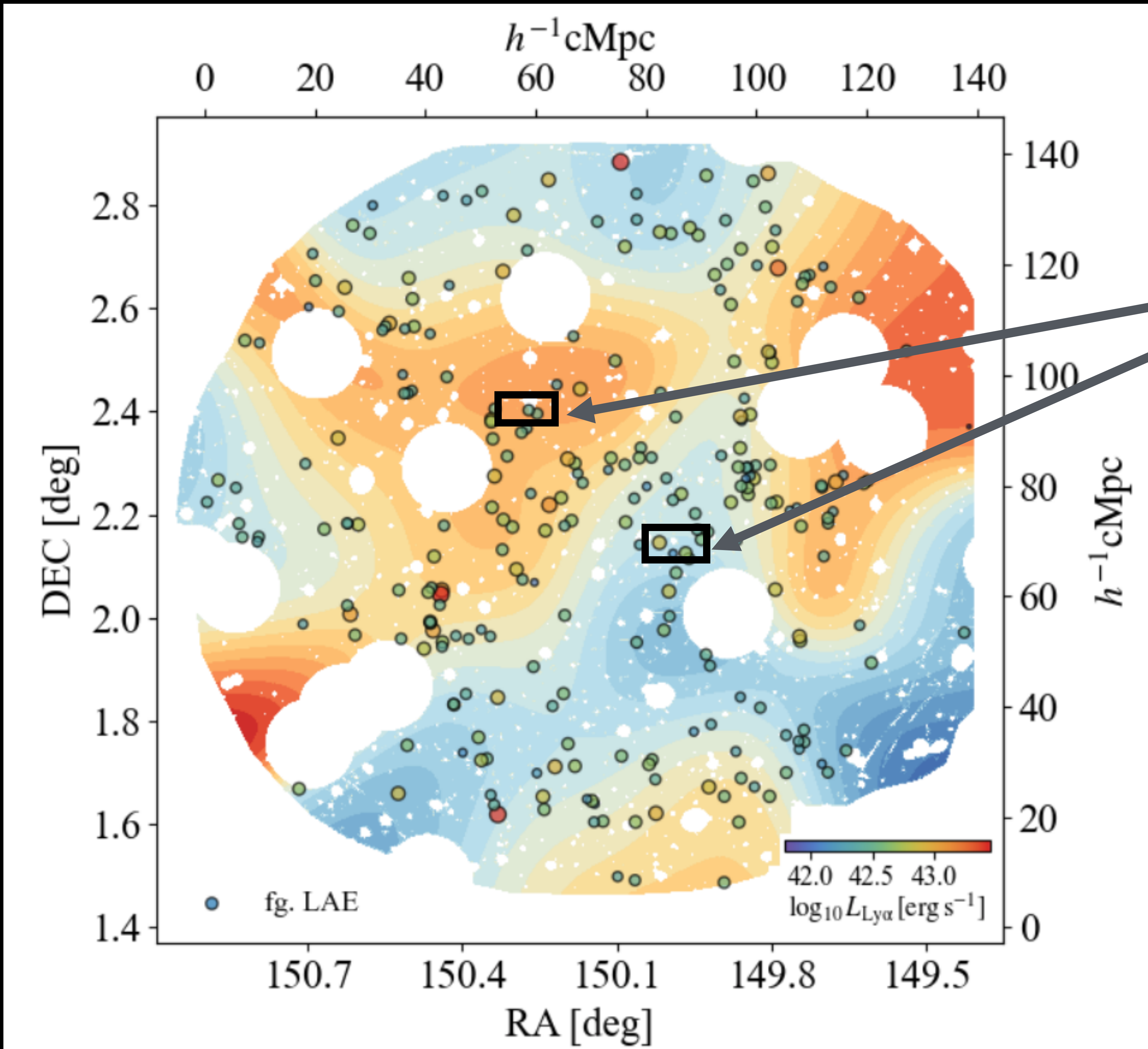
NIRCam near-infrared imaging



Prerequisite: Extremely deep Subaru/HSC imaging (~27.5 mag)

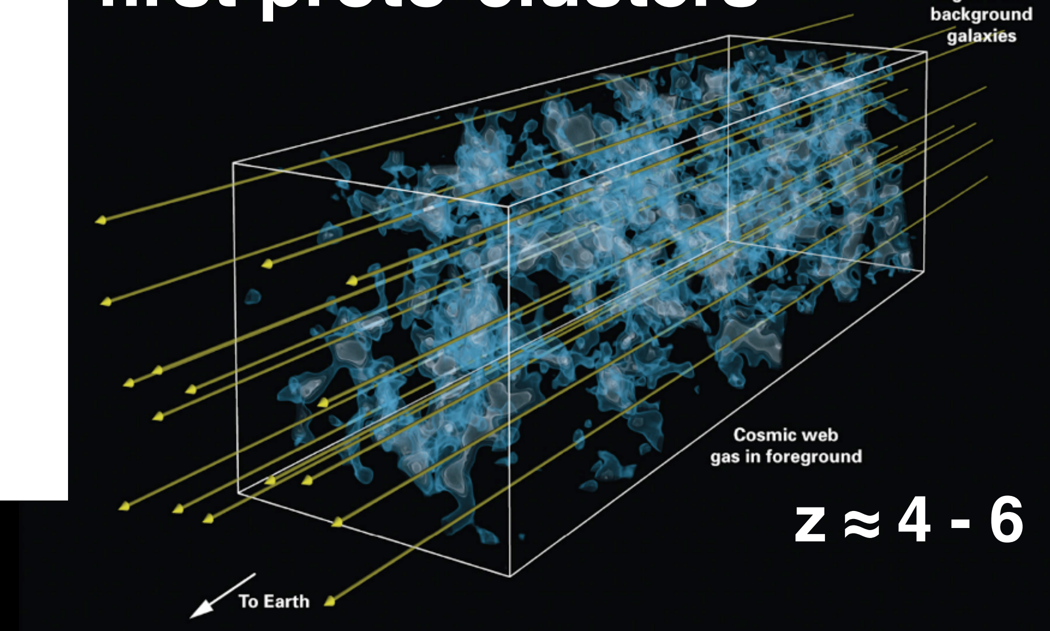
NIRCam imaging: Precise characterization of background galaxy SEDs
NIRCam/WFSS: Unbiased sample of fg. & bg. galaxies at z>5-6

Synergy with 30-m class Telescopes:
Need for wide-field photometric IGM tomography



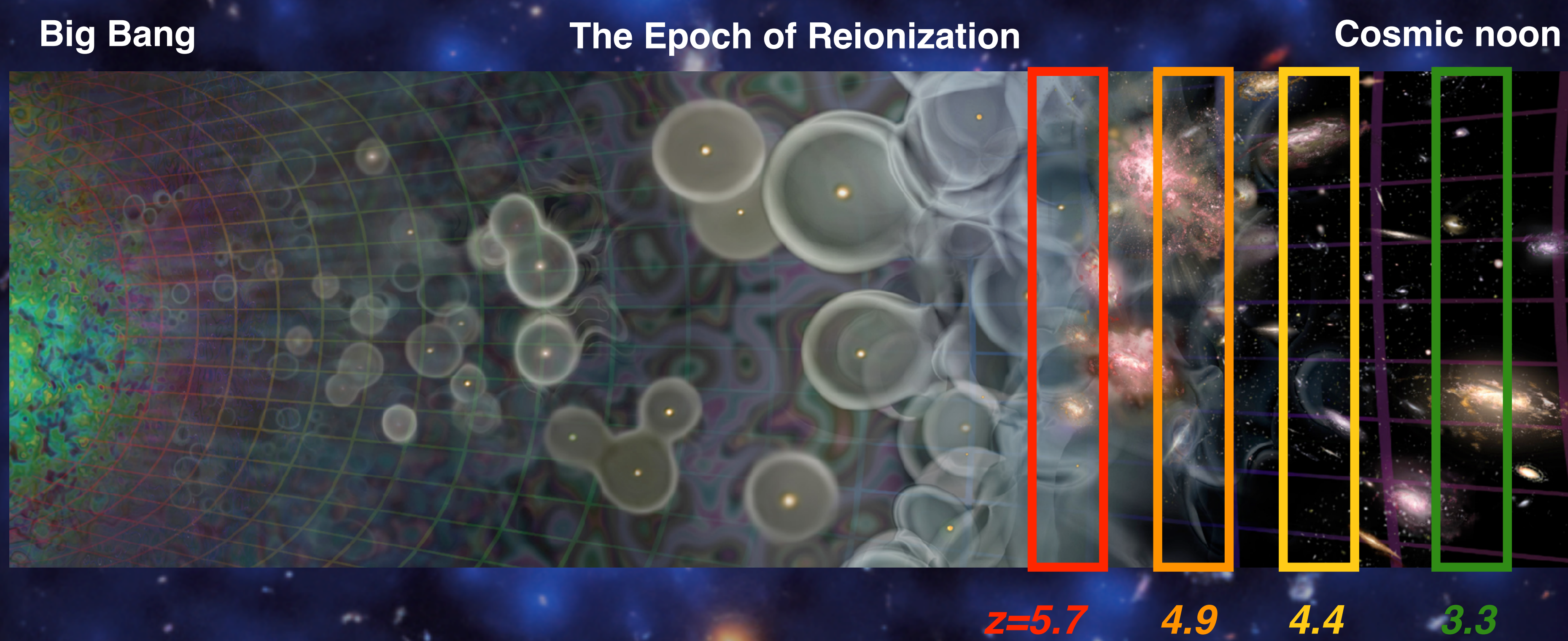
TMT/WFOS

3D IGM tomography of Ionized bubbles & first proto-clusters

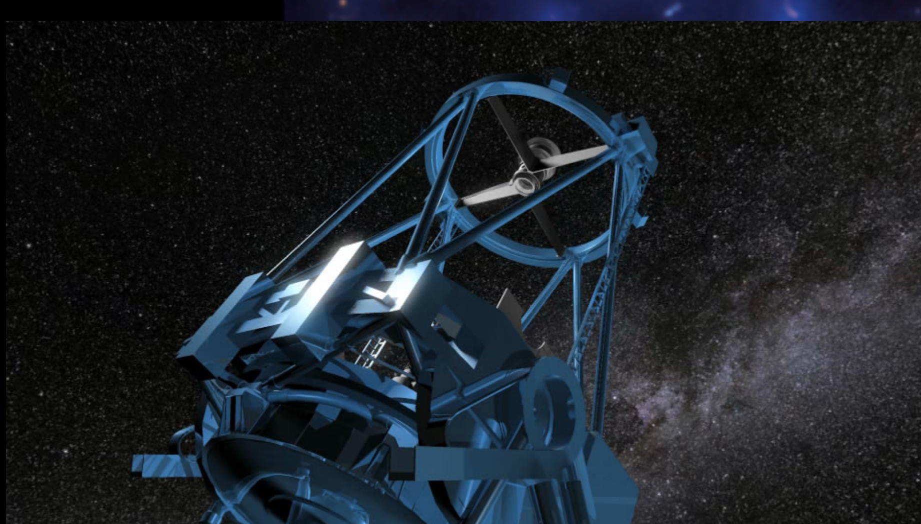
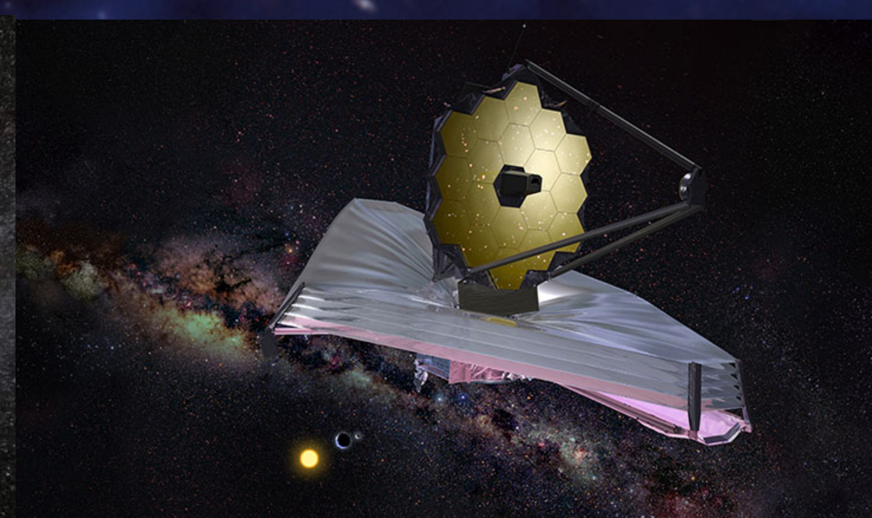


z ≈ 4 - 6

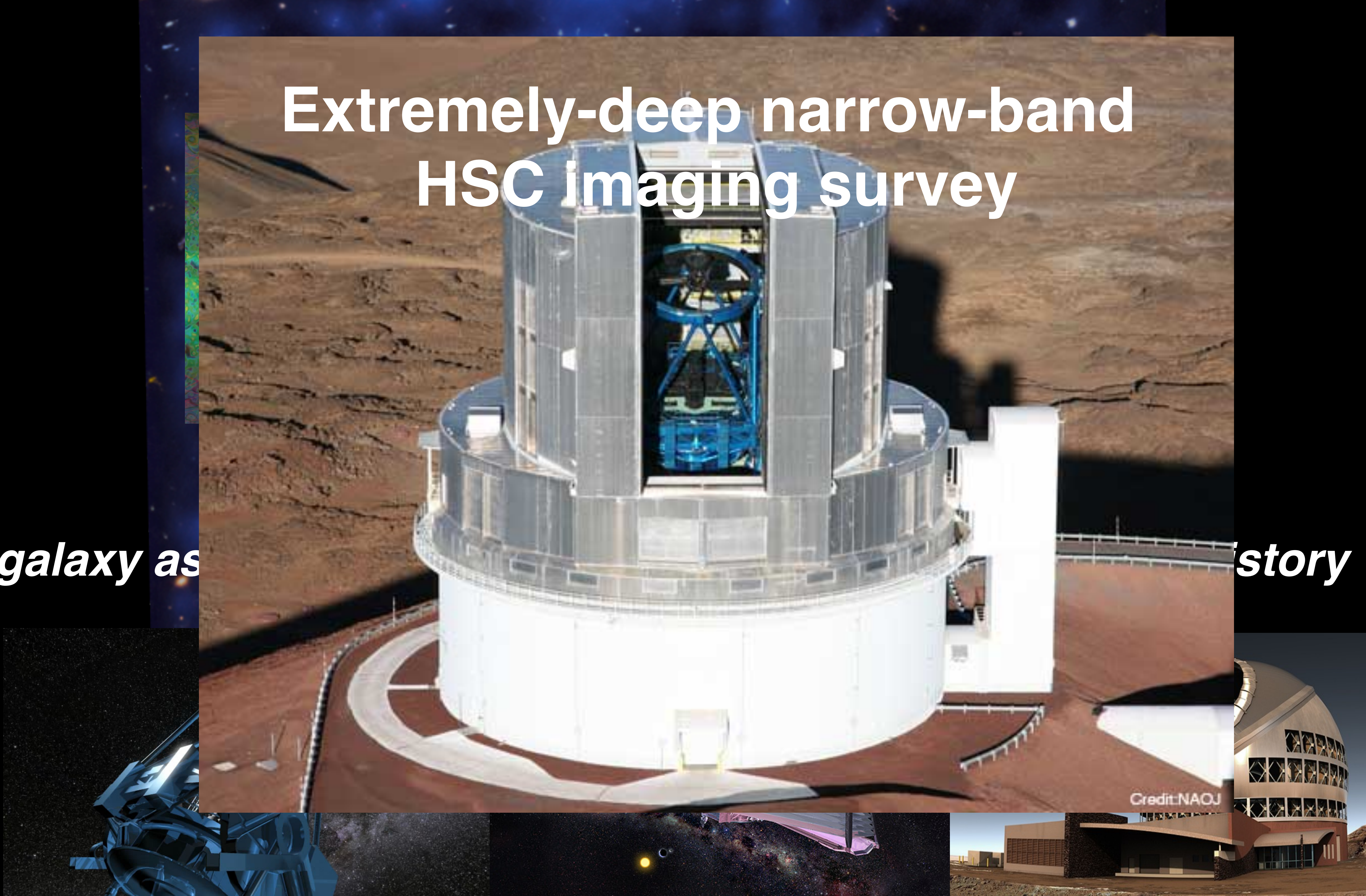
Road map towards full 3D mapping of the cosmic web galaxies and the IGM



The tomographic evolutionary view of galaxy assembly & their environments across cosmic history


Road map towards full 3D mapping of the cosmic web galaxies and the IGM



Summary

“Photometric IGM tomography” opens a new way forward to reveal the entire Cosmic Web of both Galaxies and the IGM from the EoR to Comic Noon

Useful to understand …

- ***How the Universe is reionized***
- ***Origin of supermassive black holes***
- ***Formation of early galaxy assembly within the large-scale cosmic web environment***
- ***Cosmology?***