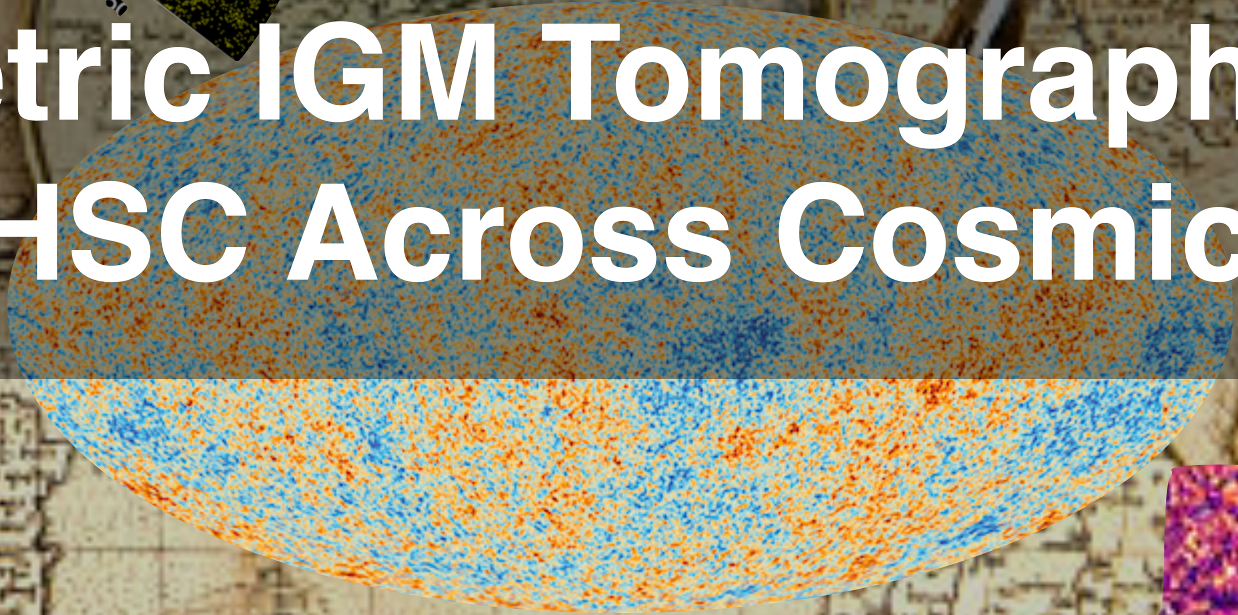
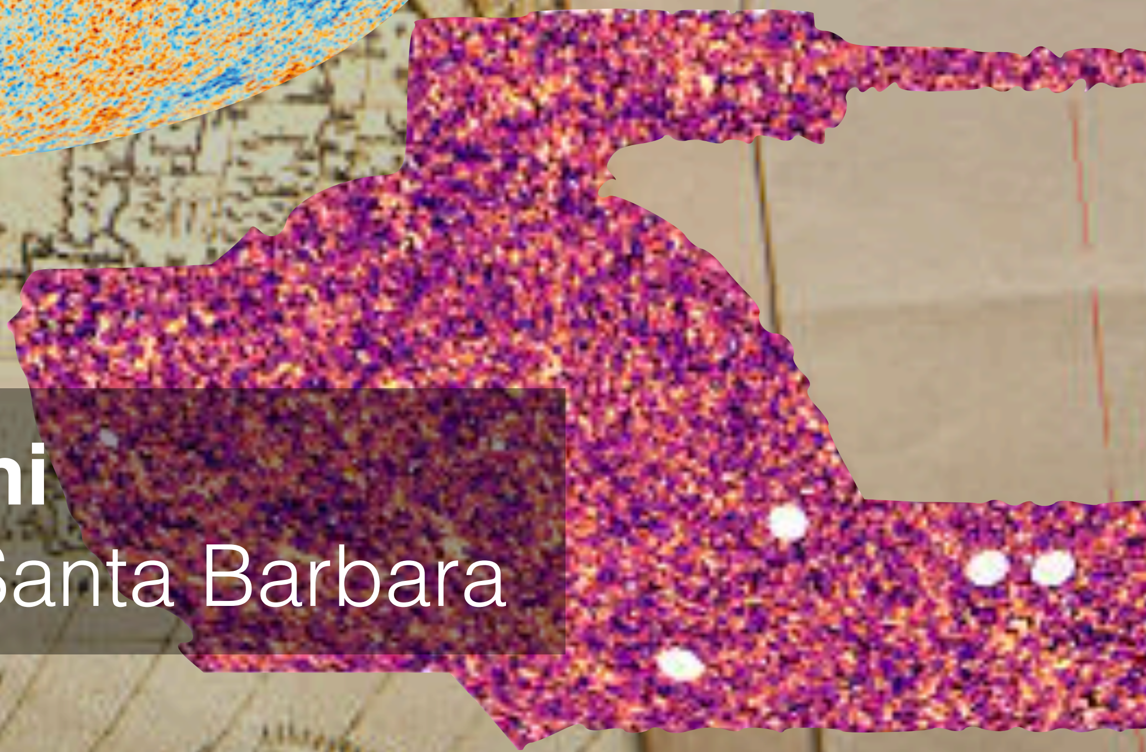
Photometric IGM Tomography with Subaru/HSC Across Cosmic Time



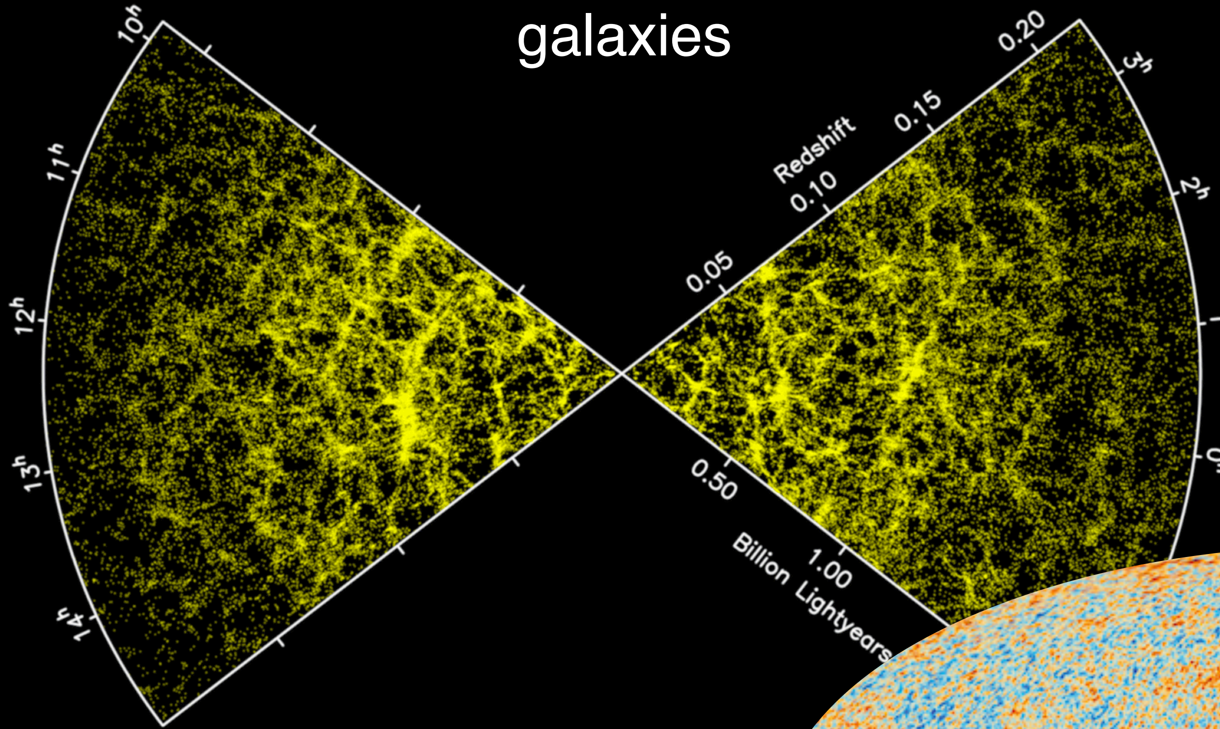


Koki Kakiichi
University of California, Santa Barbara

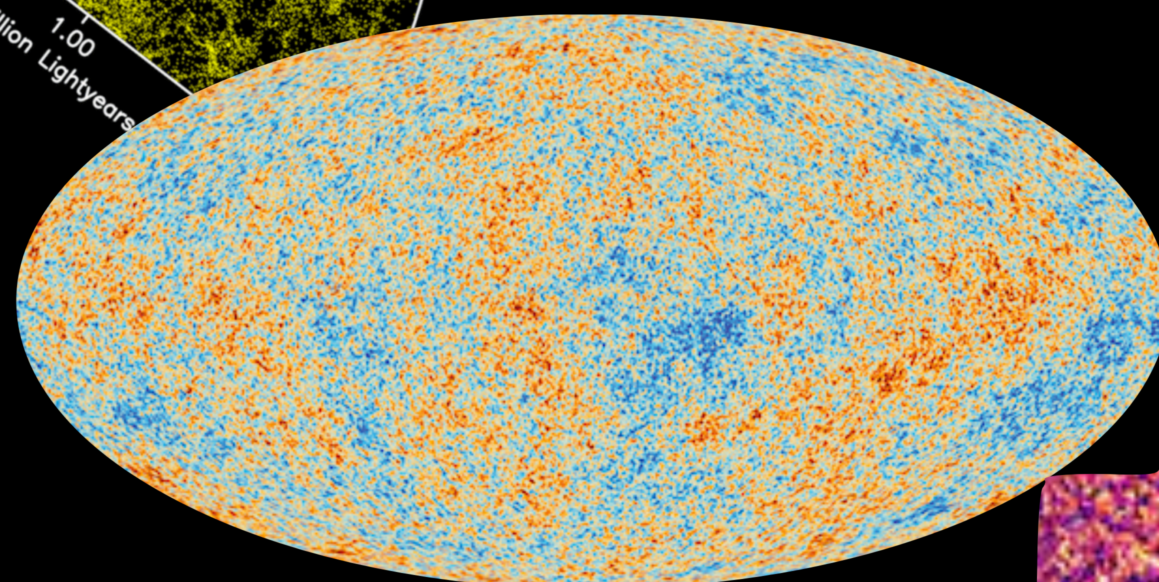
Kakiichi+22 MNRAS in press
Kakiichi+22 in prep

Art of cosmic cartography

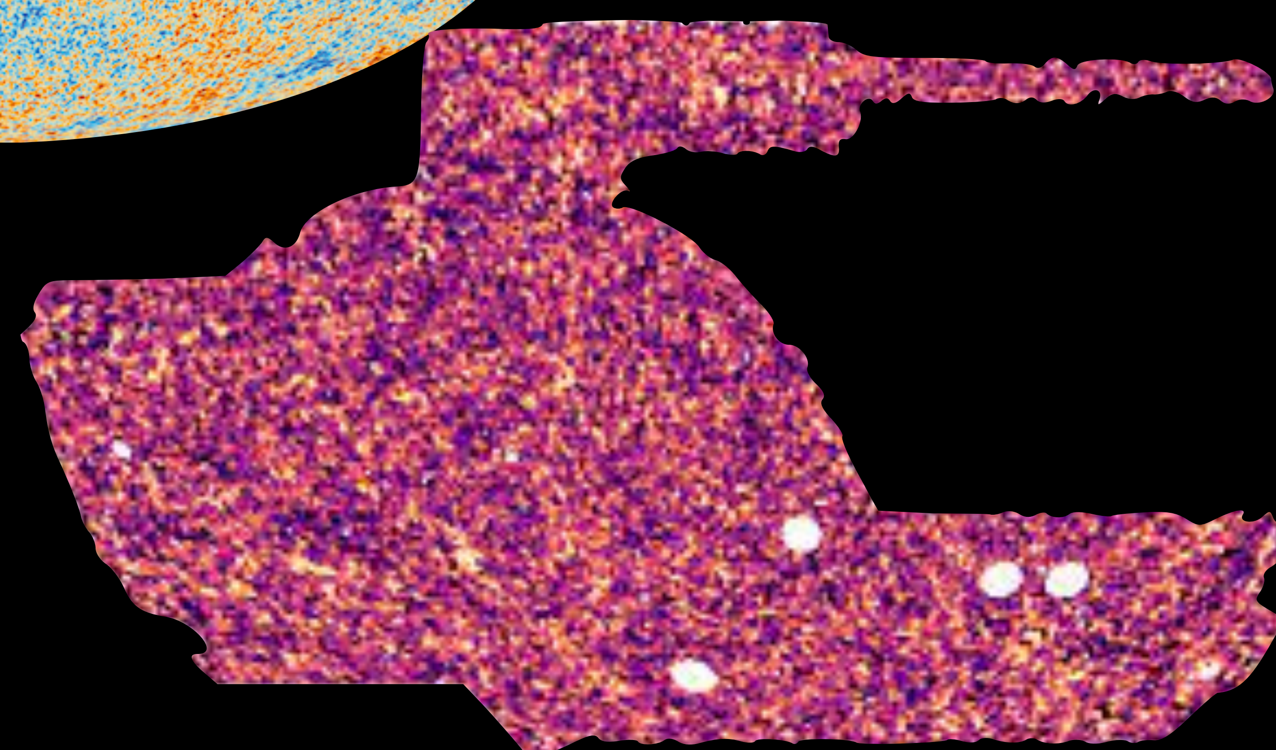
galaxies



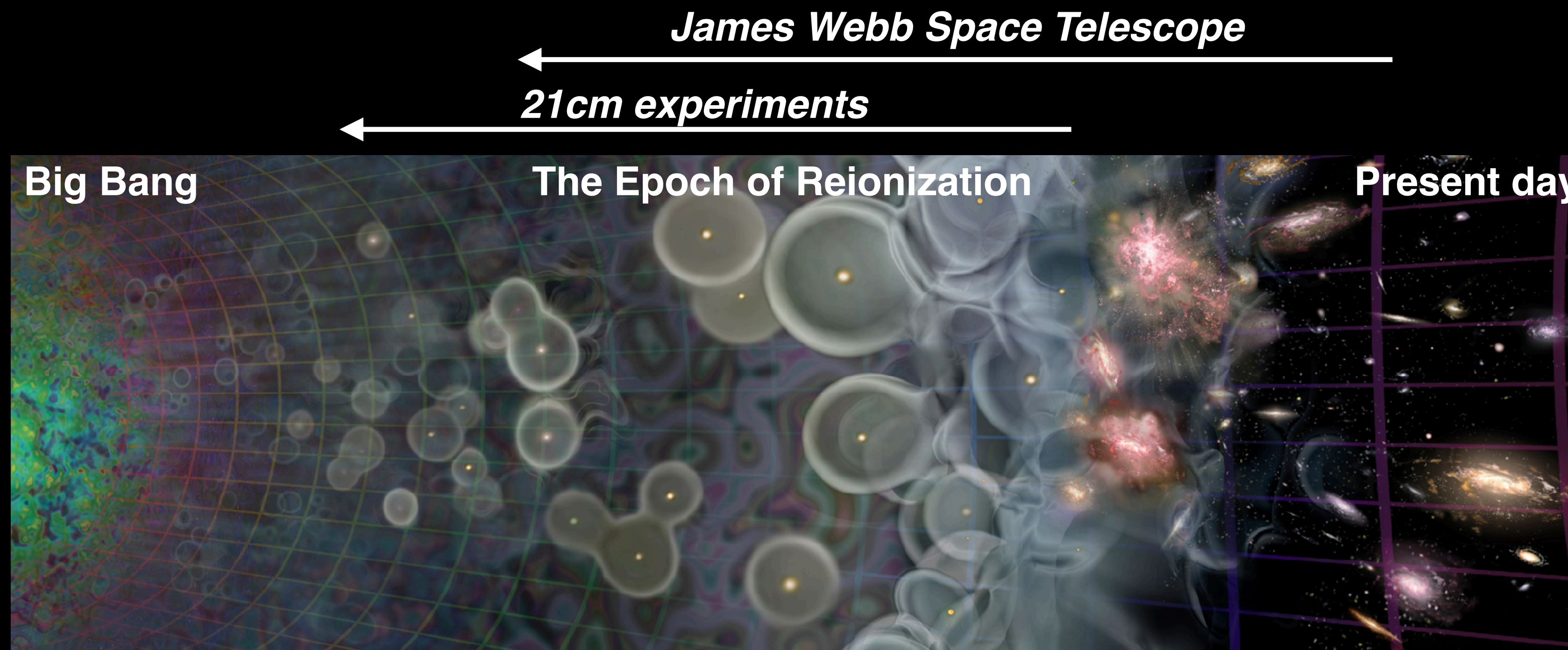
CMB

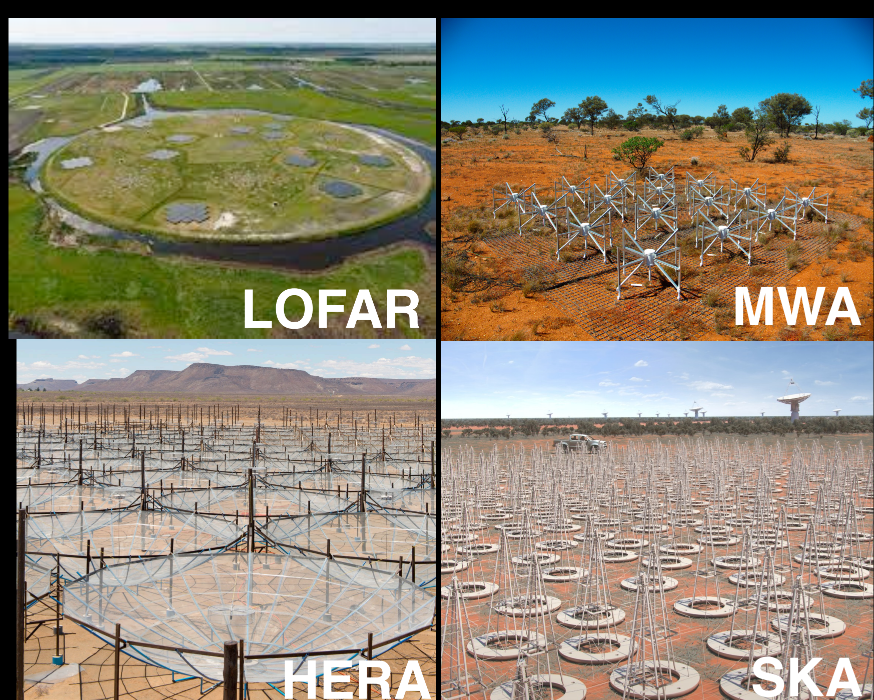


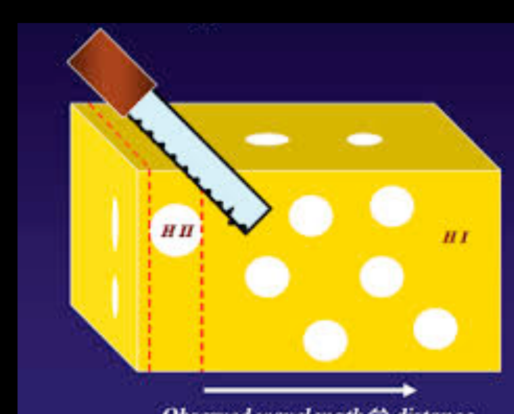
weak lensing



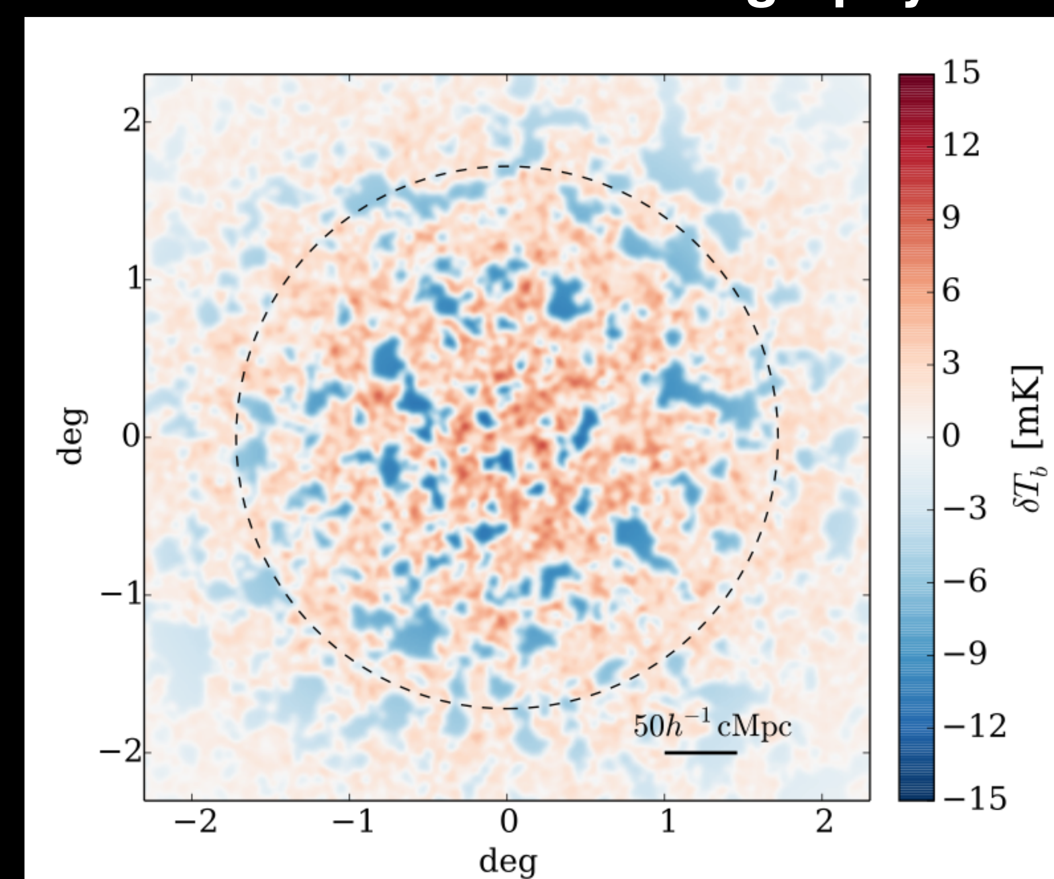
Pushing the redshift frontier of cosmic cartography



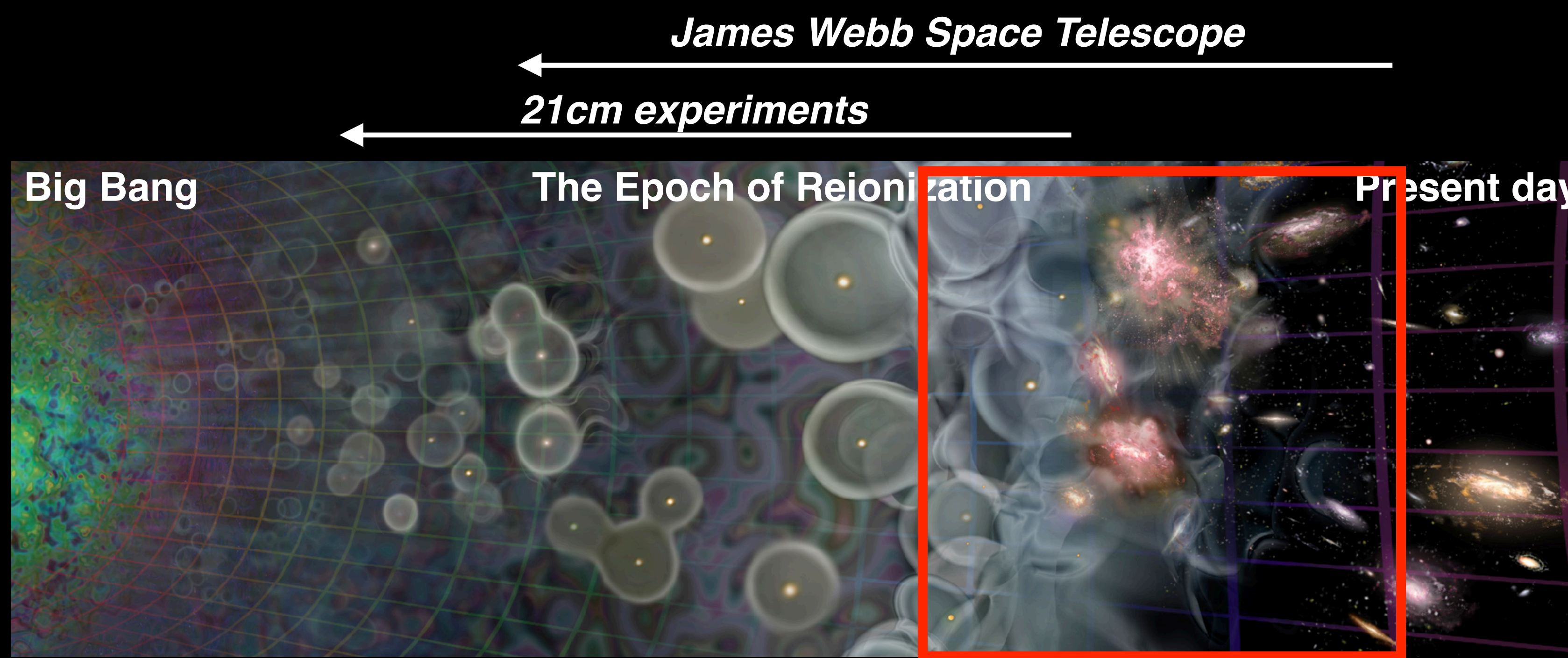




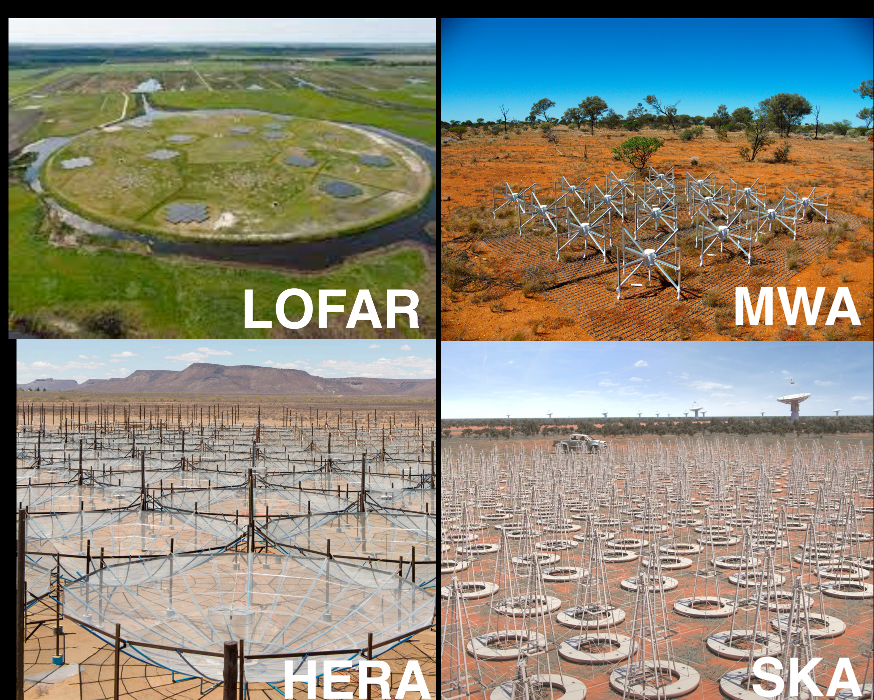
Promise of 21cm tomography

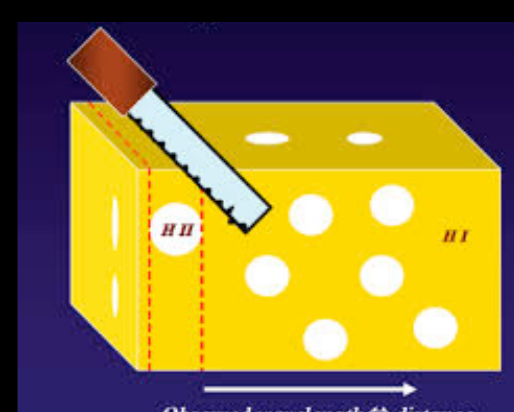


Pushing the redshift frontier of cosmic cartography

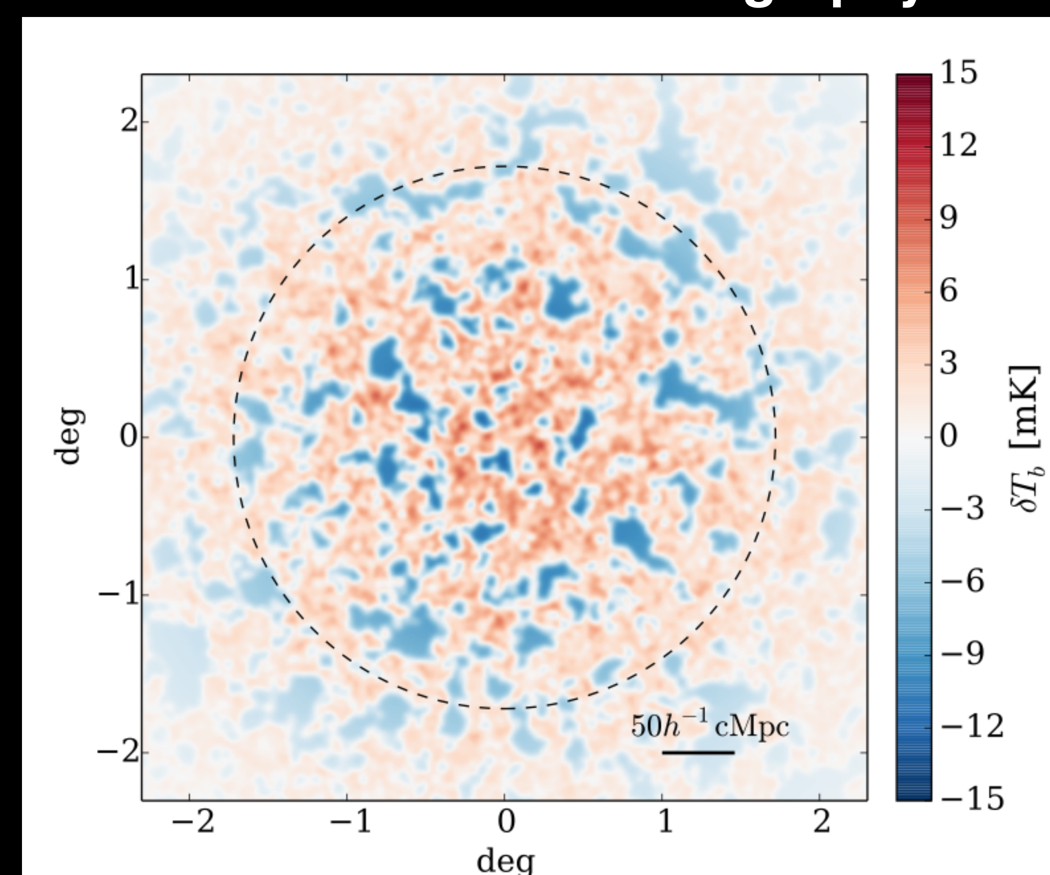


New technique in IGM tomography

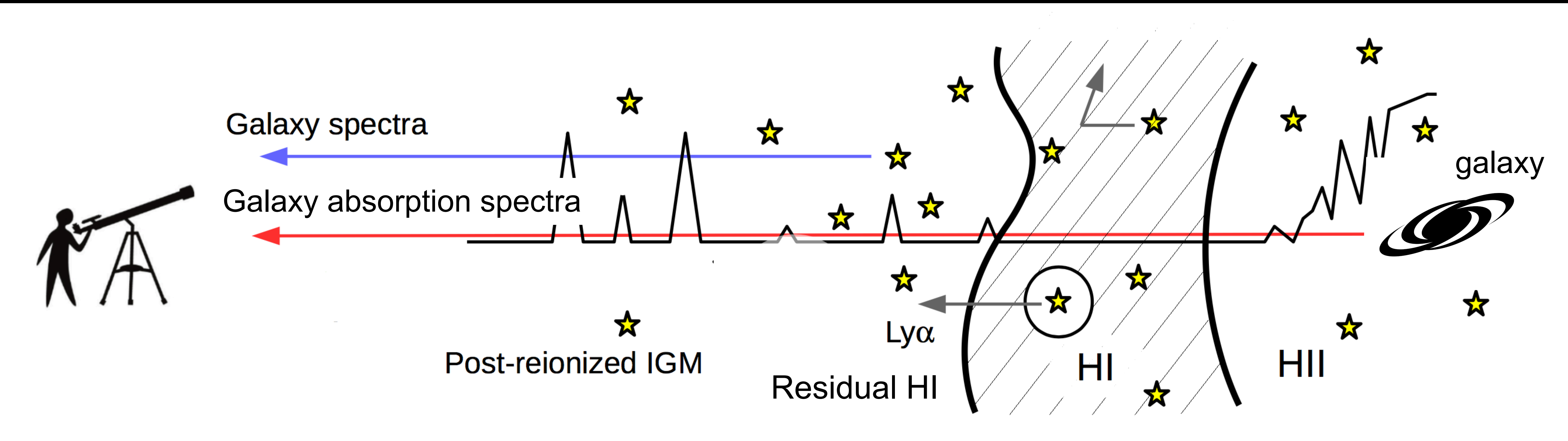


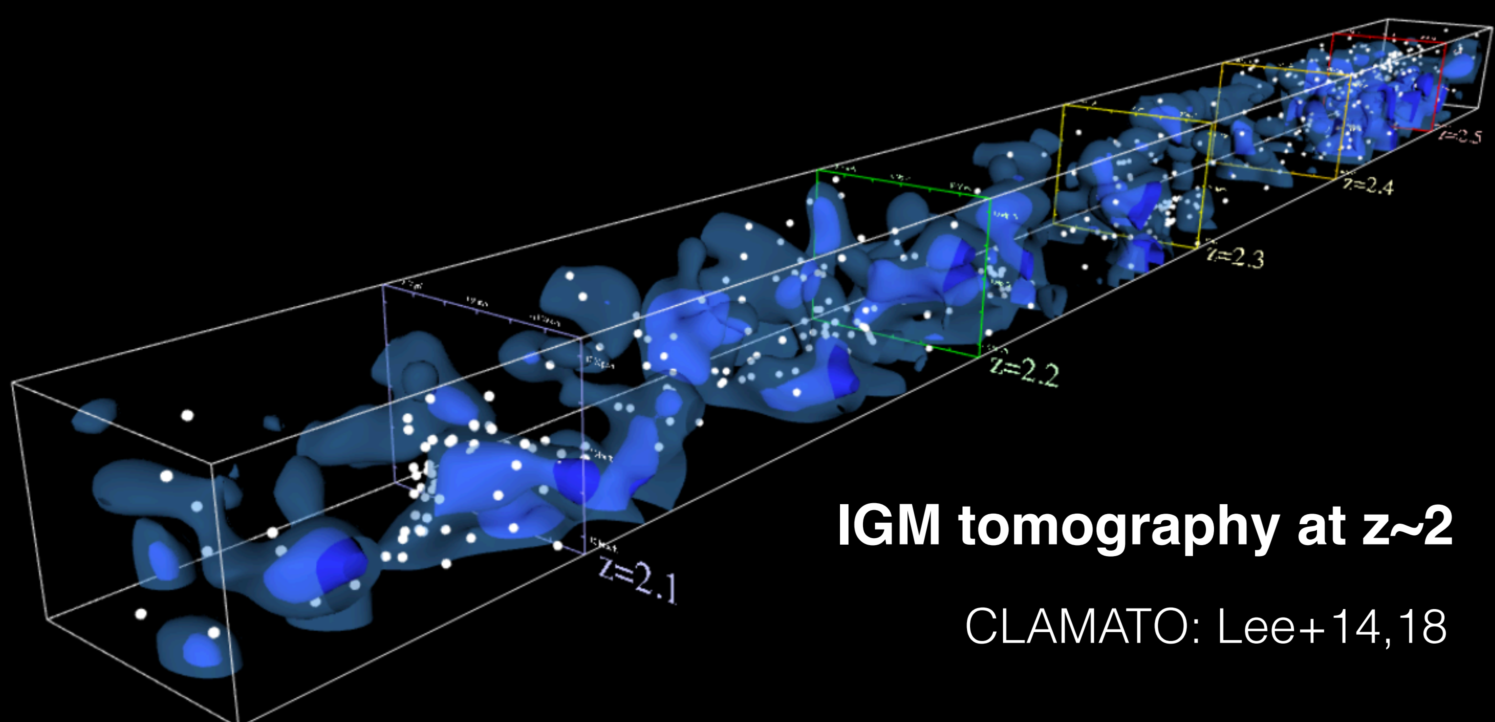


Promise of 21cm tomography



Mapping the galaxy-IGM connection: IGM tomography

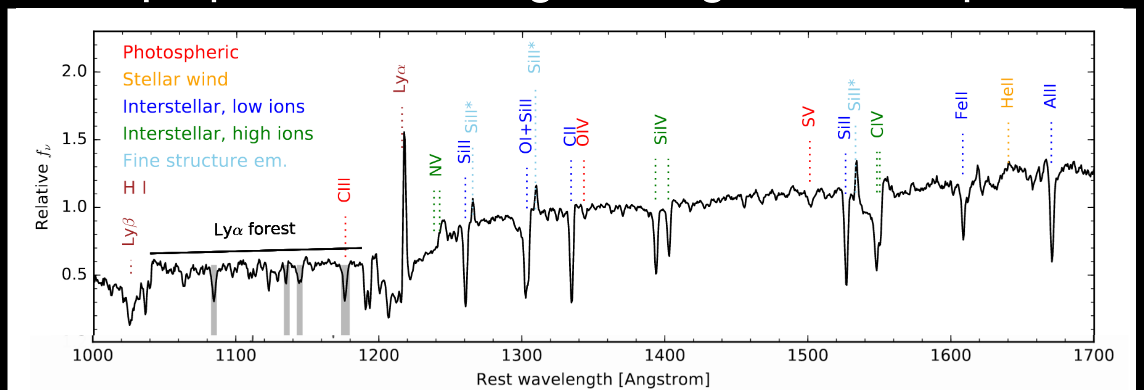




IGM tomography at z~2

CLAMATO: Lee+14,18

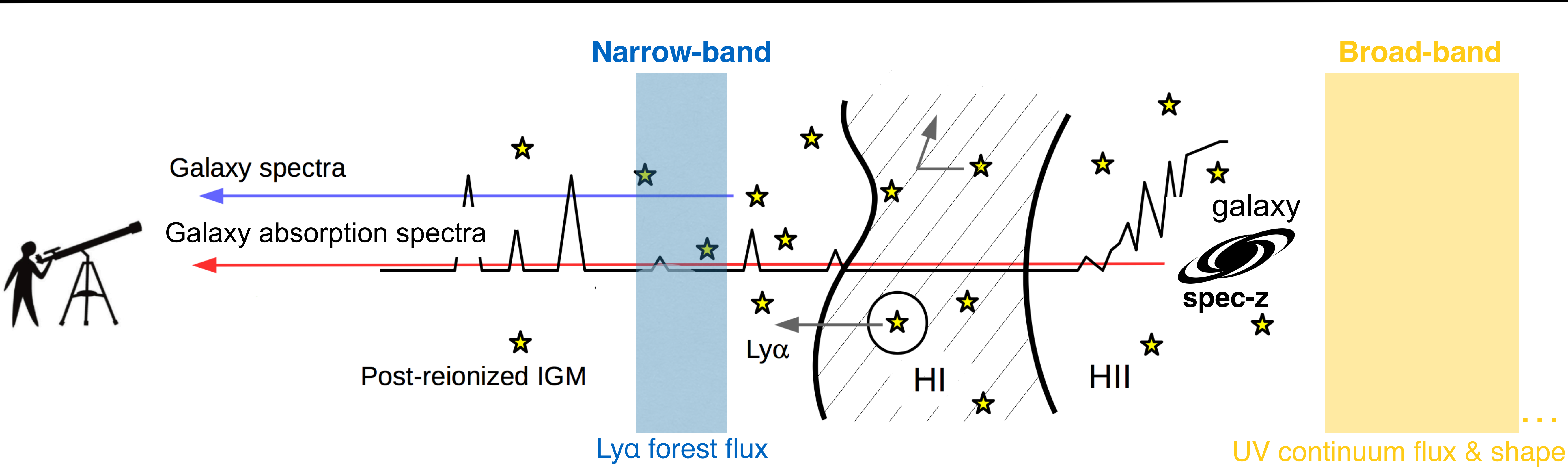
Deep spectra of background galaxies required



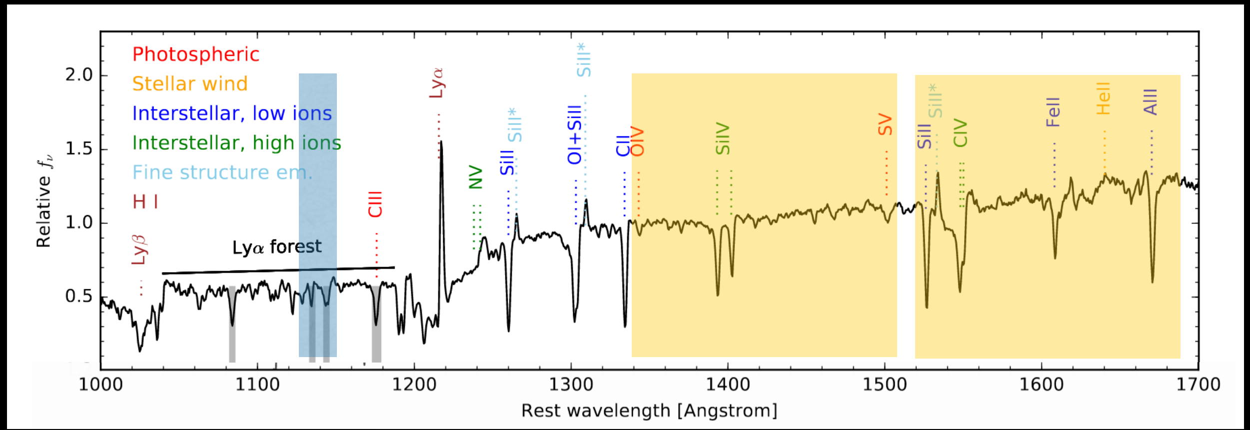
LATIS: Newman+20

But for higher redshifts, we need ELTs…

"Photometric" IGM tomography



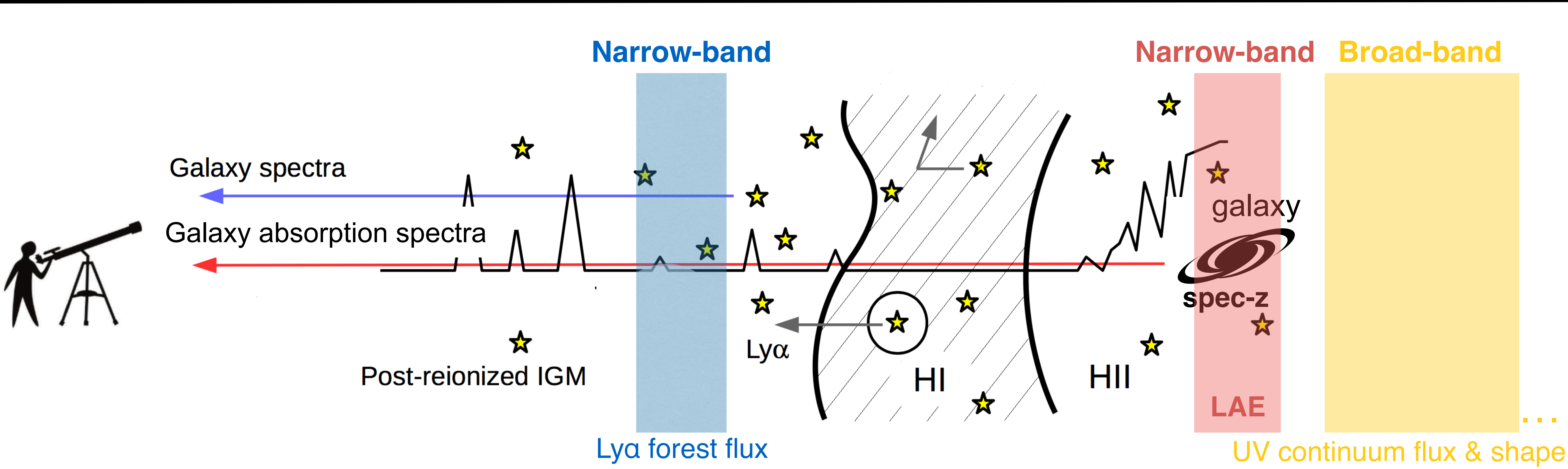
T_{IGM} = exp($-\tau_{\alpha}$) ~ (narrow-band flux) / (broad-band flux)



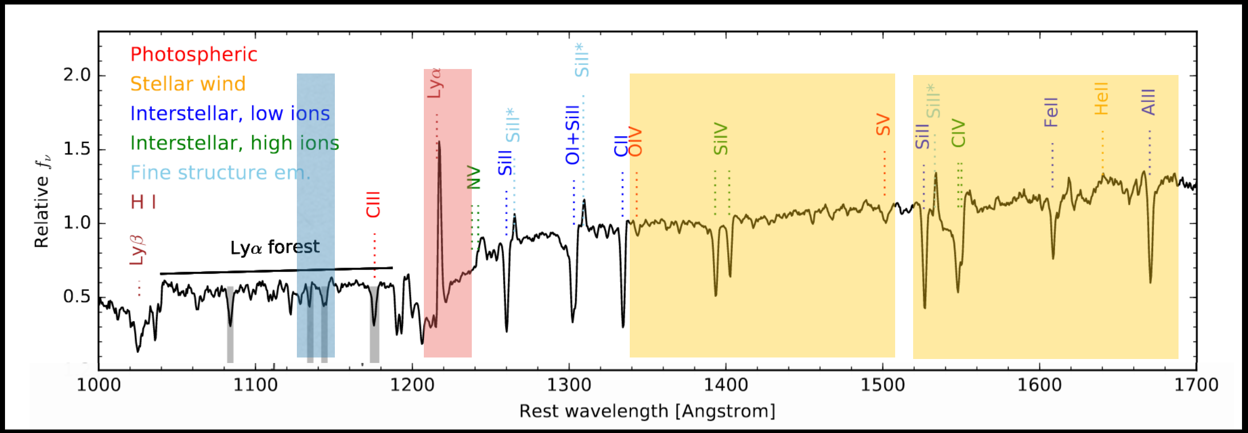
Photometric determination of background galaxy SEDs

cf. Mawatari+2017

"*Photometric*" IGM tomography



$T_{IGM} = \exp(-\tau_\alpha) \sim$ (narrow-band flux) / (broad-band flux)

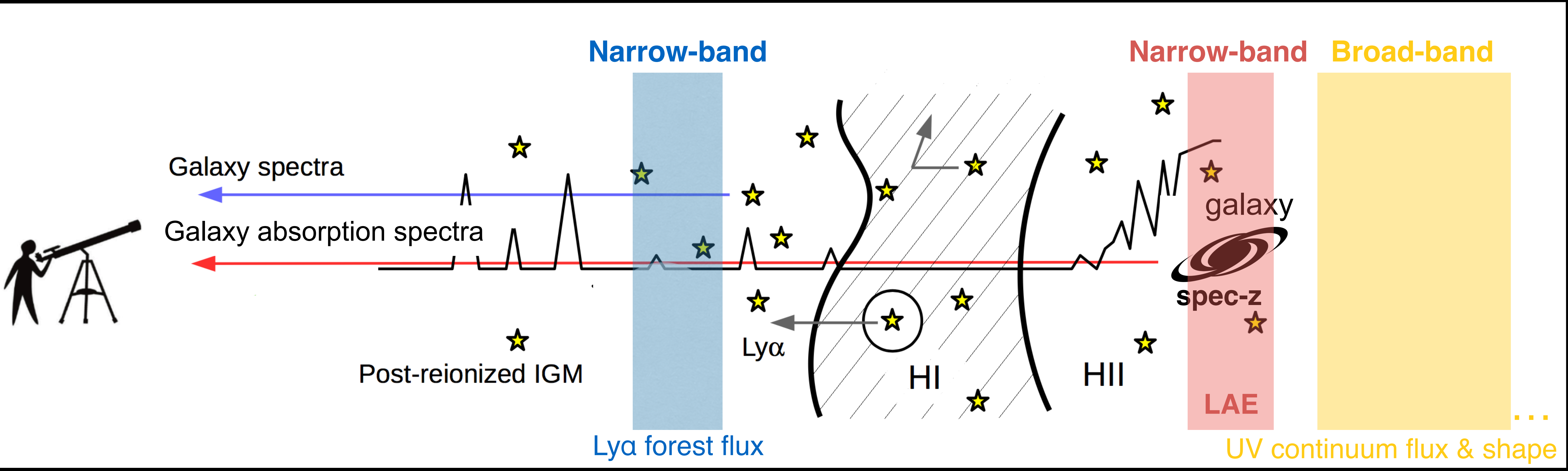


Photometric determination of background galaxy SEDs

Fully photometric.

cf. Kakiichi+22

“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

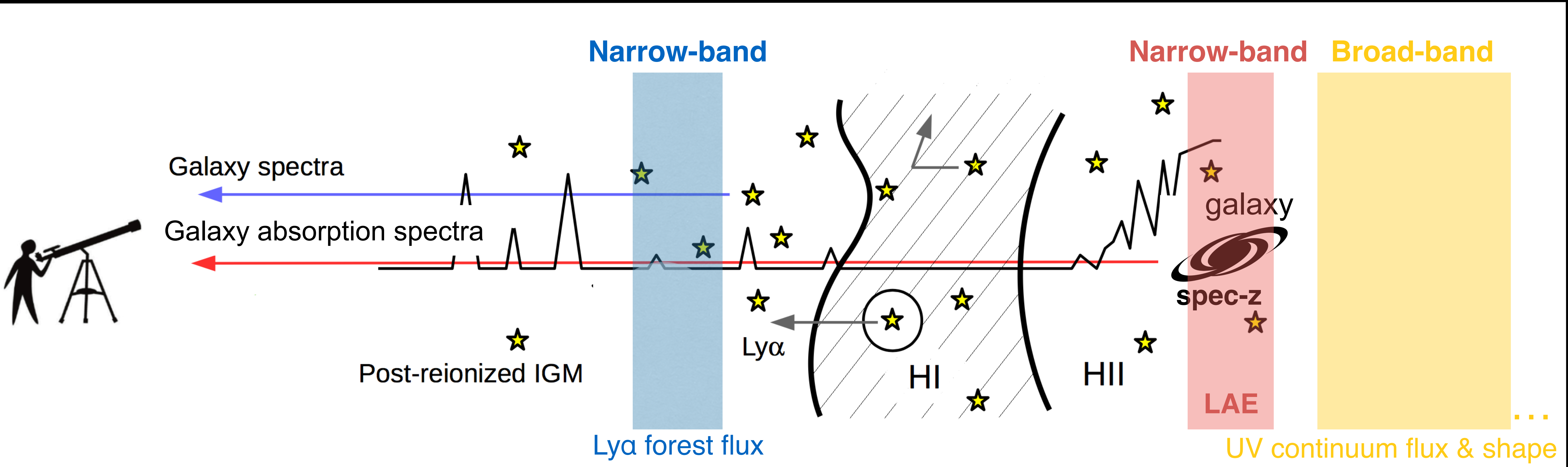
Imager: throughput ~ 60 %
Spectrograph: throughput ~ 10-20 %

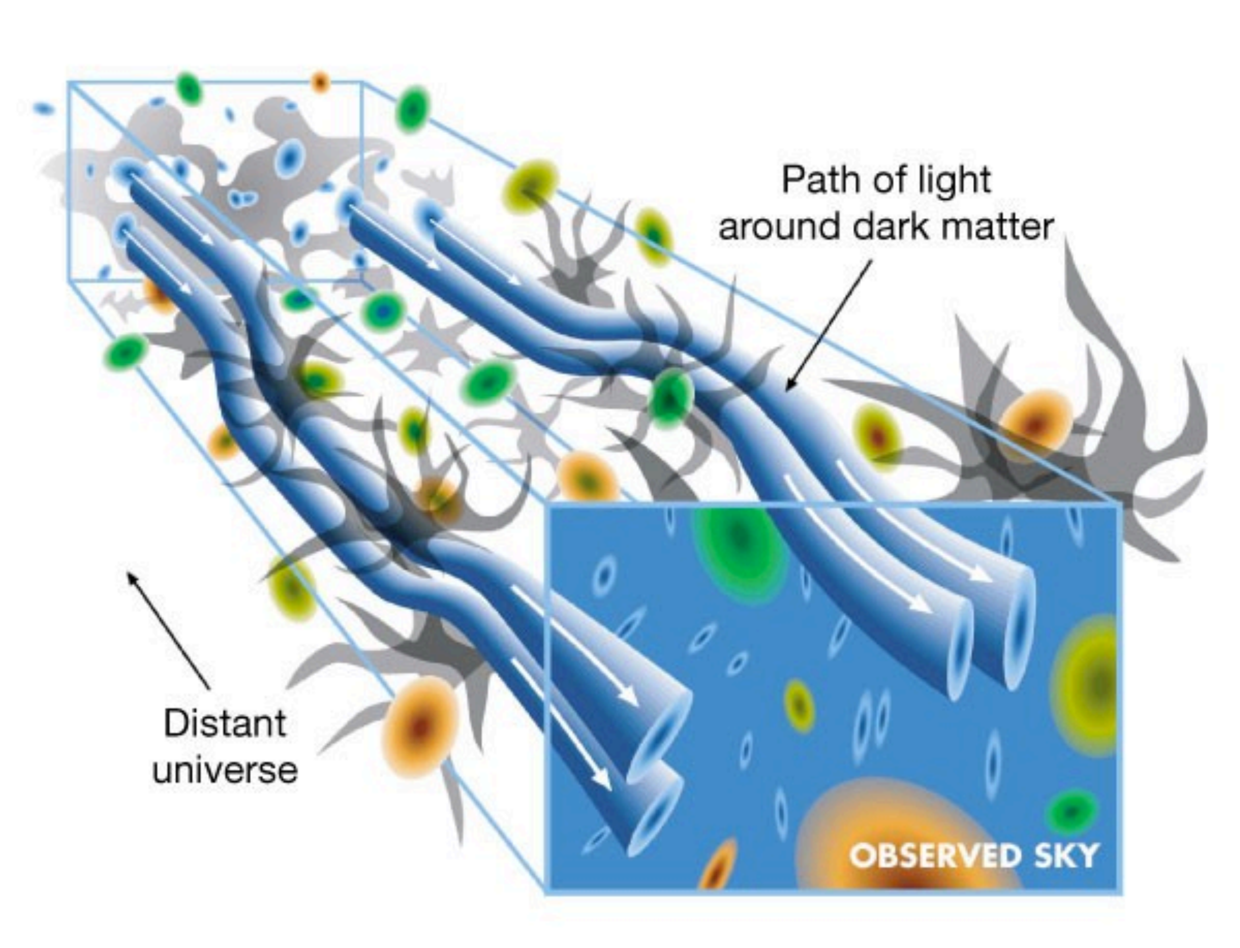
Photometric IGM tomography with 8-10m telescope ≈ Spectroscopic IGM tomography with ELTs.

Advantages

- **Imaging throughput > spectrograph.**
  Applicable at higher redshifts.
- **Can perform in the legacy extragalactic fields.**
  Multi-wavelength dataset already exists.

"Photometric" IGM tomography





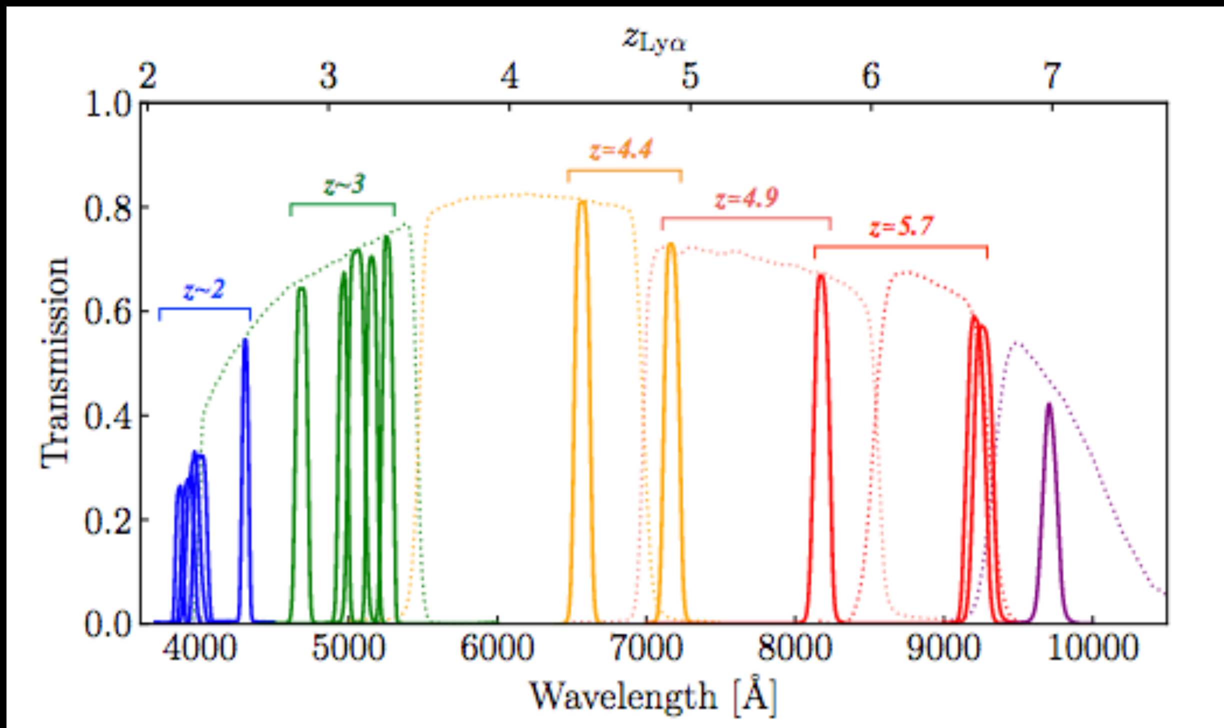
Photometric IGM tomography

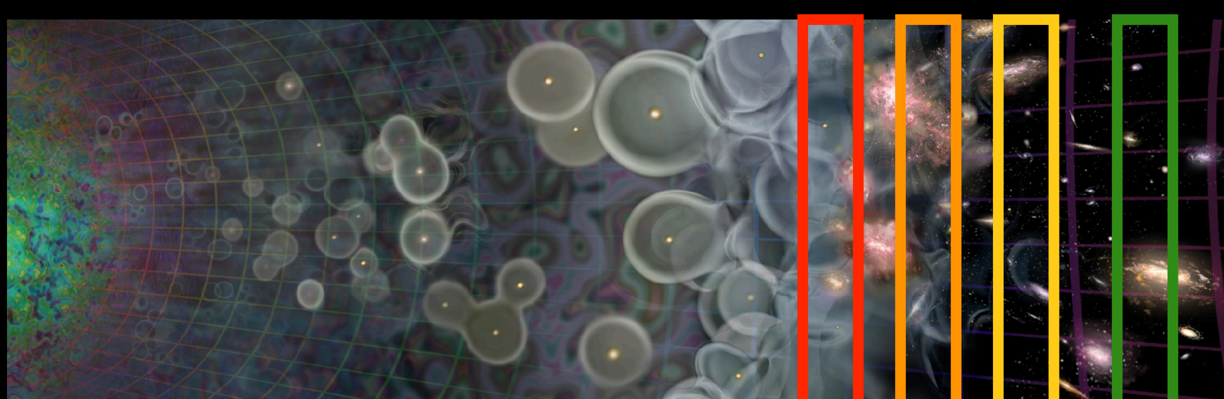
is analogous to weak lensing

Similar technique and methodology can be applied

Photometric IGM tomography with Subaru/HSC

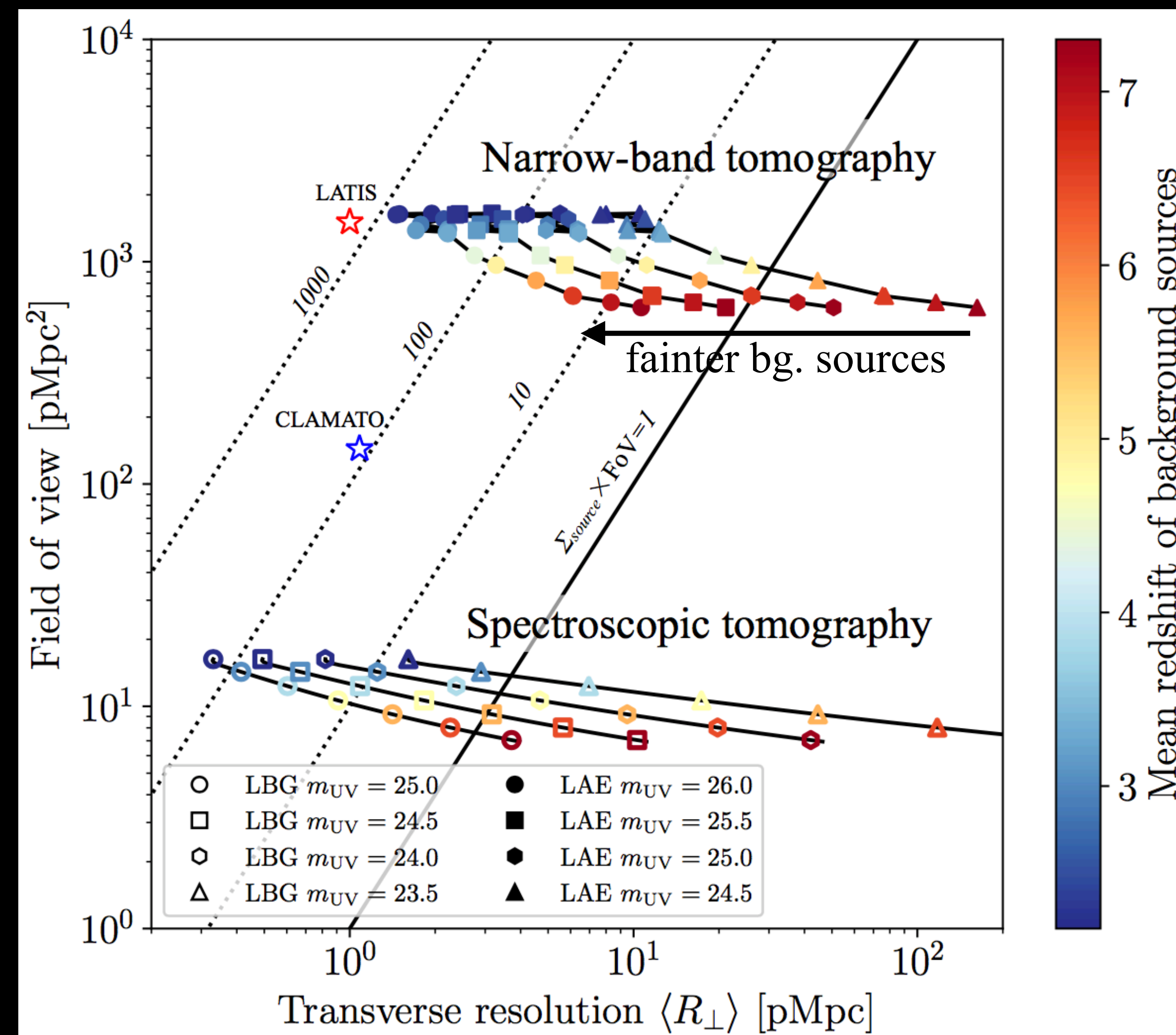
Multiple narrow-band filters





z=5.7 4.9 4.4 3.3

Wide-field of view: 1.7 deg²



Kakiichi+22

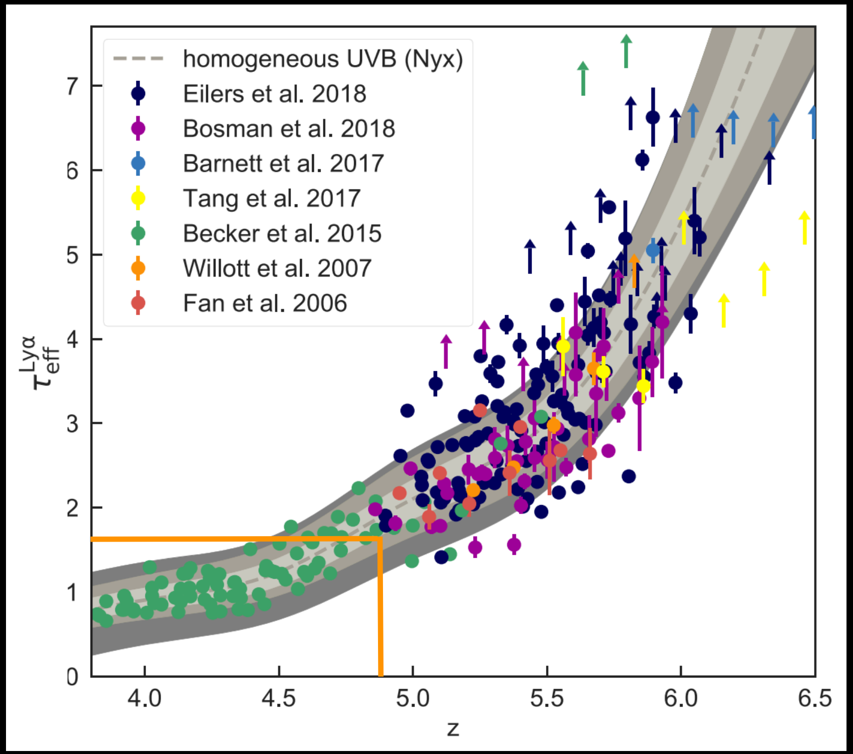
Suitable for making tomographic maps of the IGM at z~3-6
on the scale of ~10 cMpc/h across ~100 cMpc/h field of view

Feasibility: NB IGM tomography with Subaru/HSC

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	
$m_{\rm BB}$=25.0	→	$m_{\rm NB}$=26.7	(>3σ)
$m_{\rm BB}$=26.0	→	$m_{\rm NB}$=27.7	(>1.3σ)



Eilers+18 (Becker+13,Bosman+21)

COSMOS field

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

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 ($3.29 < z_{\rm Ly\alpha} < 3.36$)	$3.39 < z < 4.04$	26.72[a]	27.27	28.47	Inoue et al (2020)
NB718	4.90 ($4.85 < z_{\rm Ly\alpha} < 4.94$)	$4.98 < z < 5.89$	26.29[a]	26.84	28.04	Inoue et al (2020)
NB816	5.72 ($5.68 < z_{\rm Ly\alpha} < 5.77$)	$5.81 < z < 6.86$	26.34[b]	26.89	28.09	Aihara et al (2021)

Broad-band data: HSC SSP DR3

Median 5σ depth (1.5″) [mag]					Reference
g	*r*	*i*	*z*	*y*	
27.85	27.39	27.22	26.86	26.23	Aihara et al (2021)

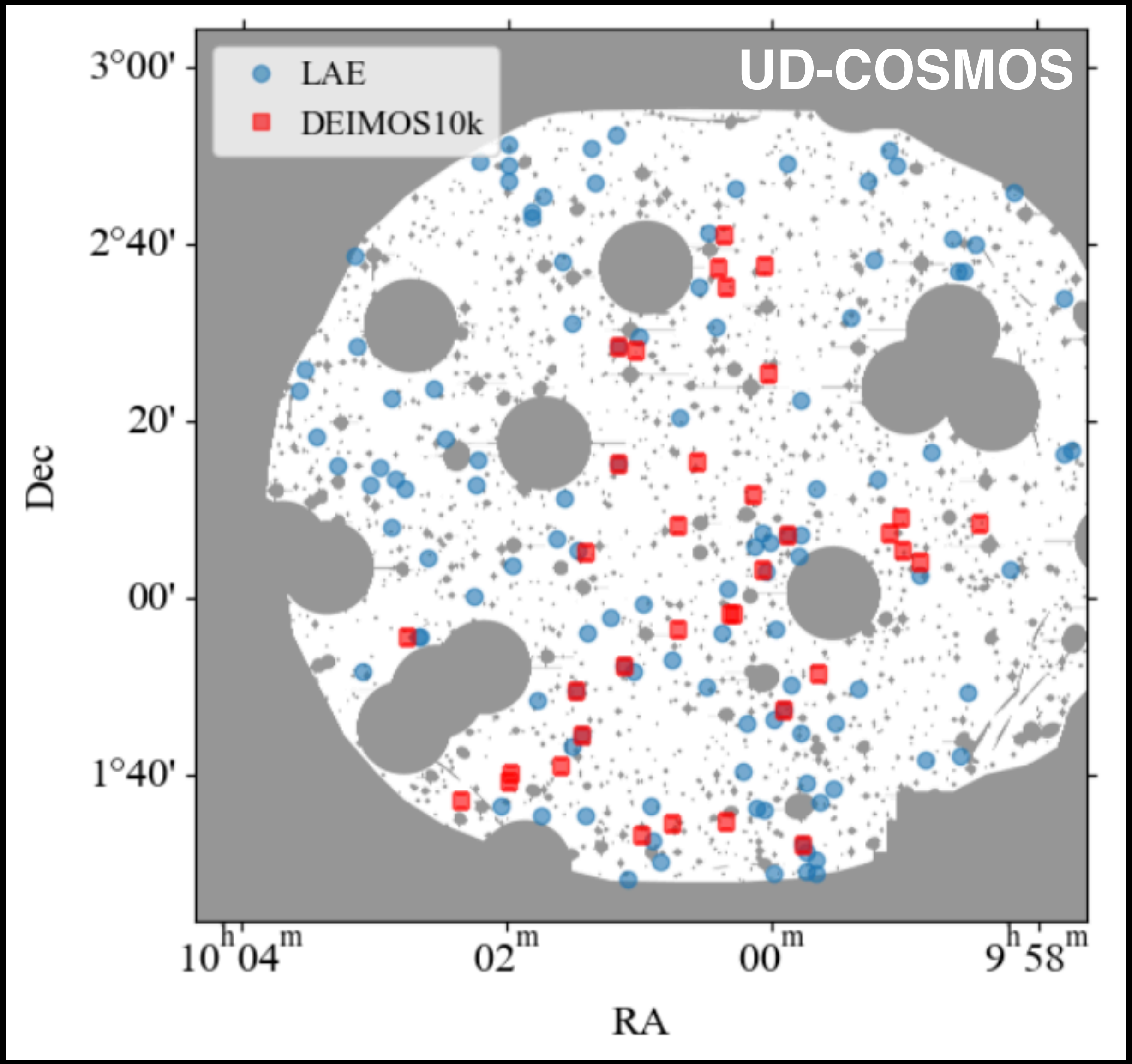
Existing HSC data has enough sensitivity for z=4.9 IGM tomography!!

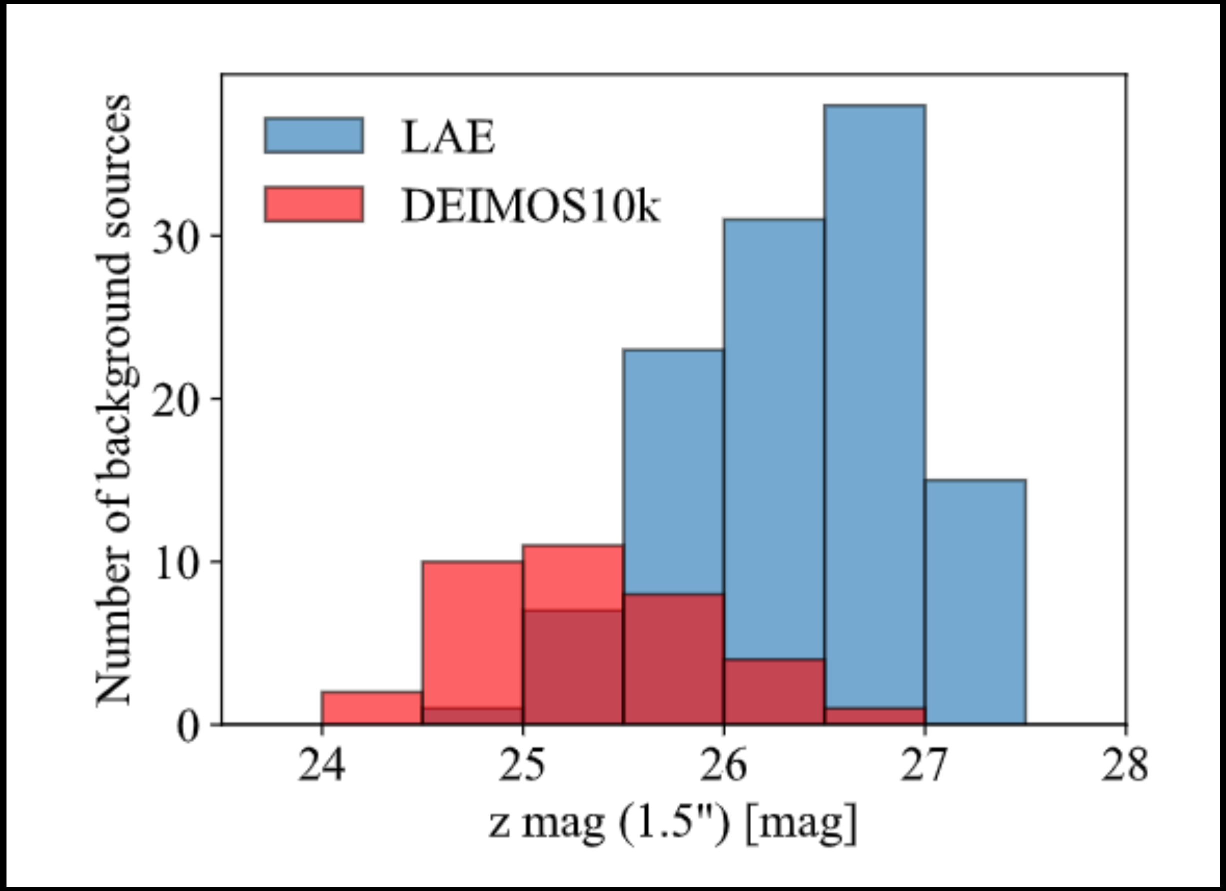
Background sources 4.98 < z < 5.89

Catalogues

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

+ Additional selection criteria: bright background source
  (>5σ UV continuum detection in z-band & non-detection in g-band)





151 background sources
(115 LAEs + 36 DEIMOS10k)

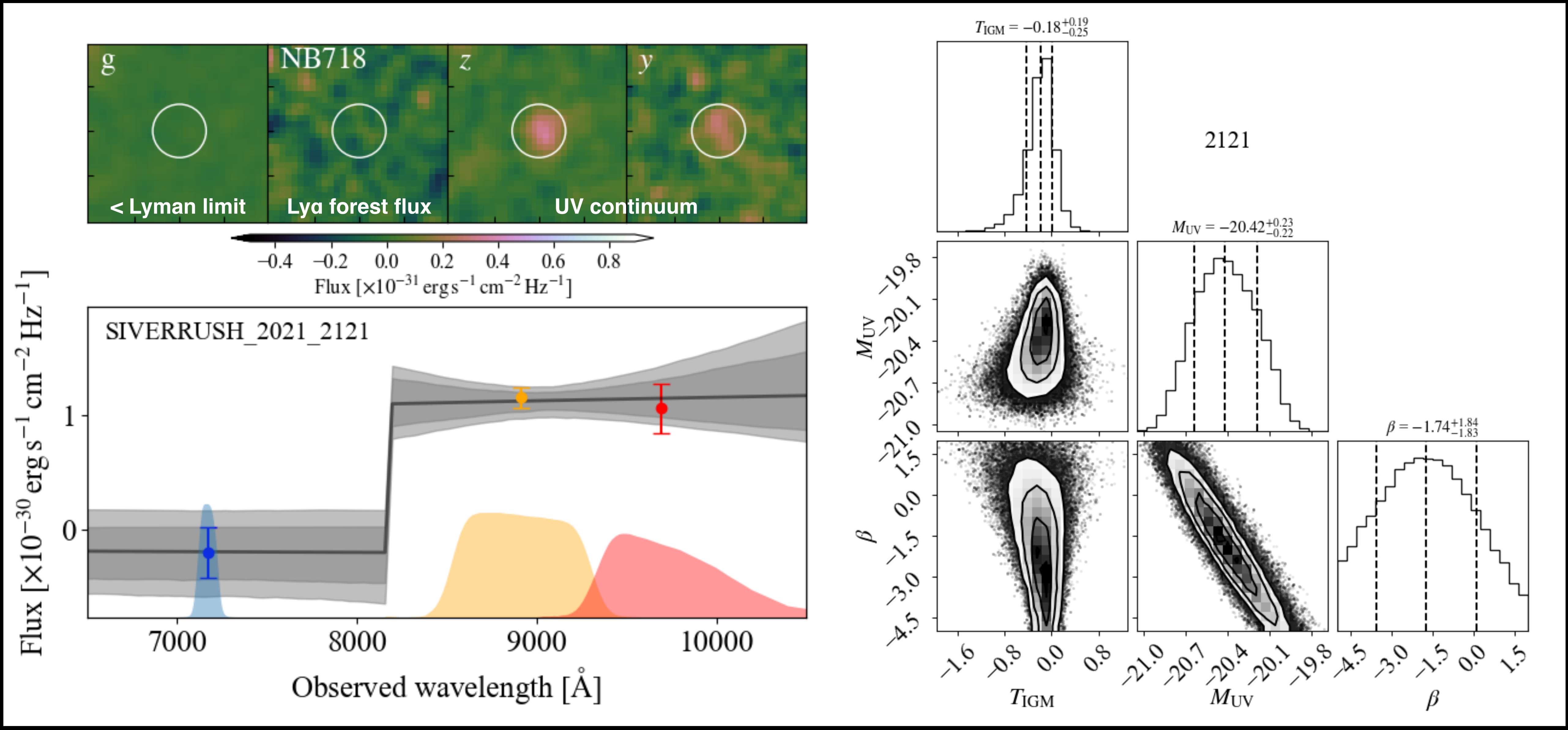
Measurement: IGM transmissions along individual background galaxies

Bayesian SED fitting framework

Data: NB718, z, y flux

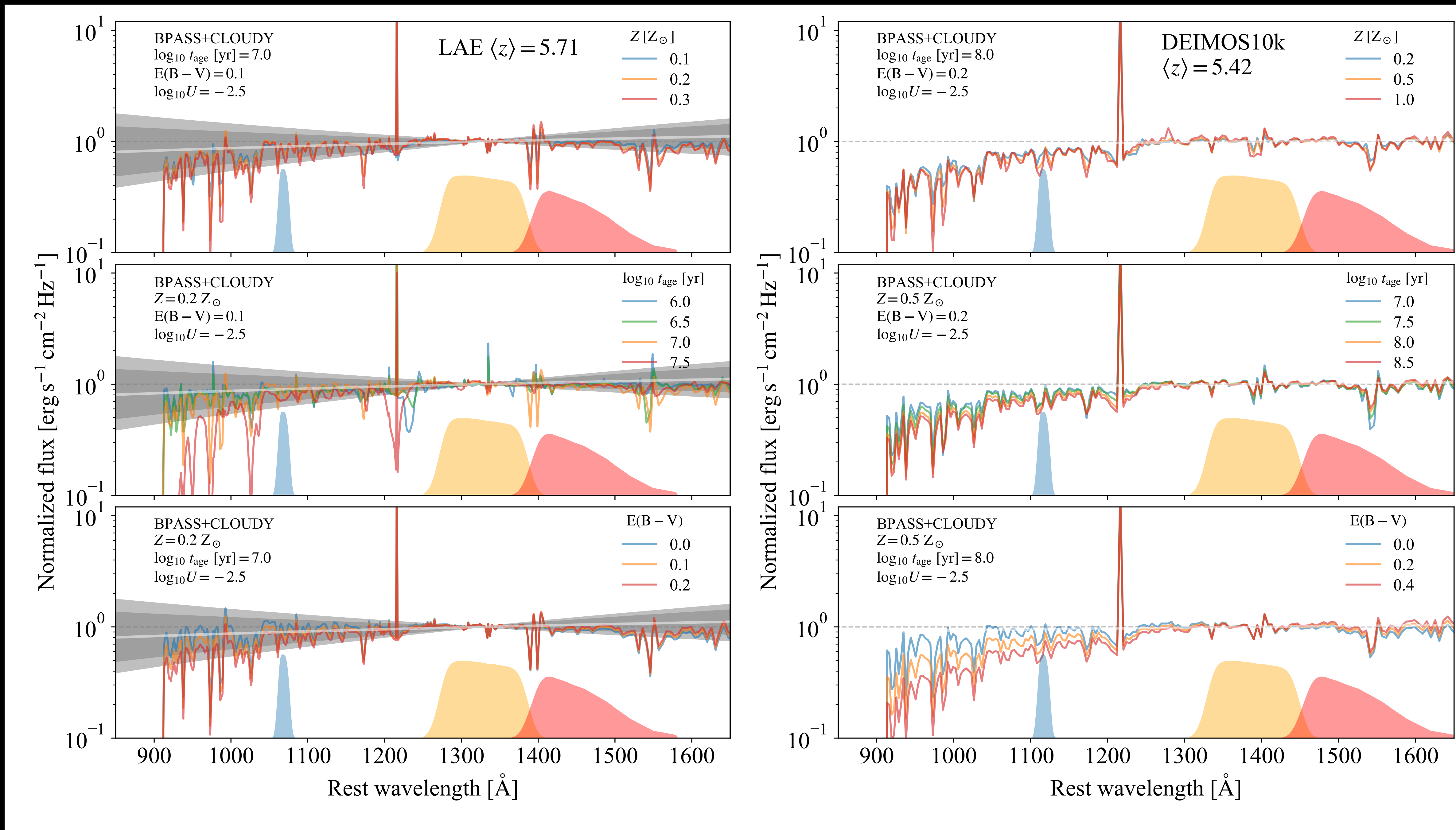
Model: power-law galaxy spectrum (M_{UV}, β) + Lya forest transmission T_{IGM}

Error: Photometric noise



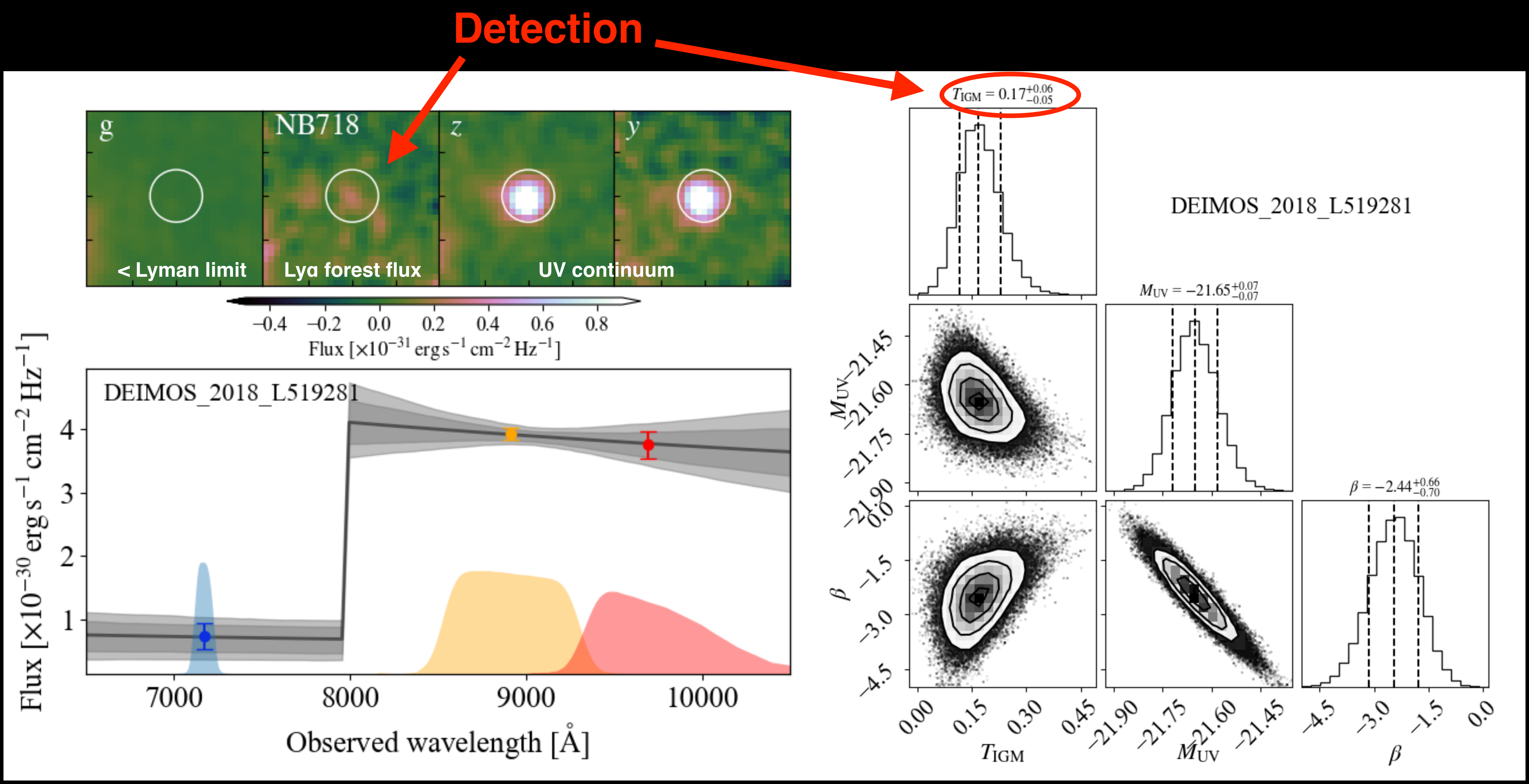
Kakiichi+ in prep

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

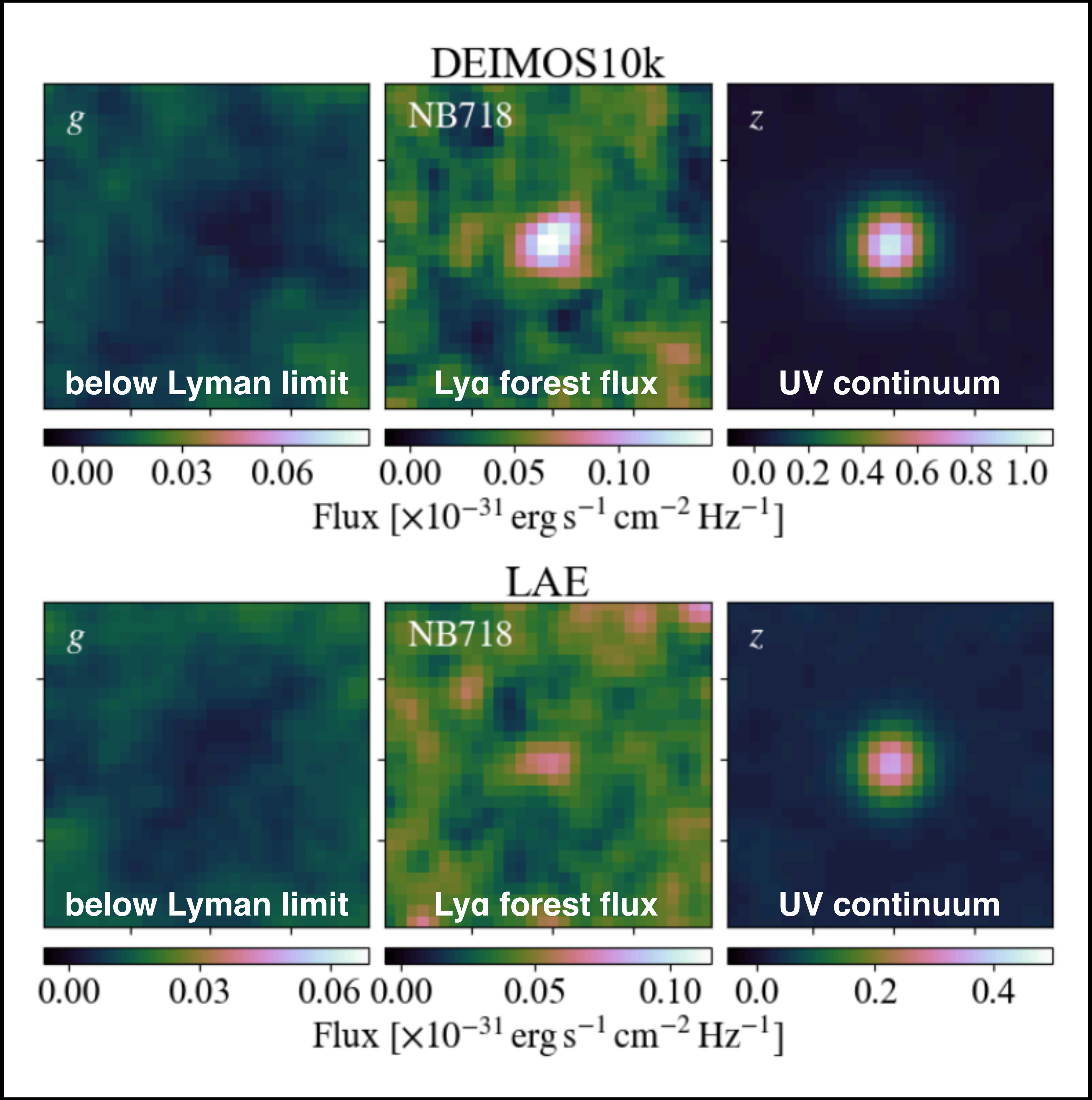


SED template uncertainty ~ 6-27% (i.e. < photometric error ~ 46-80%)
in the individual measurement of the Lyα forest transmission T_{IGM}

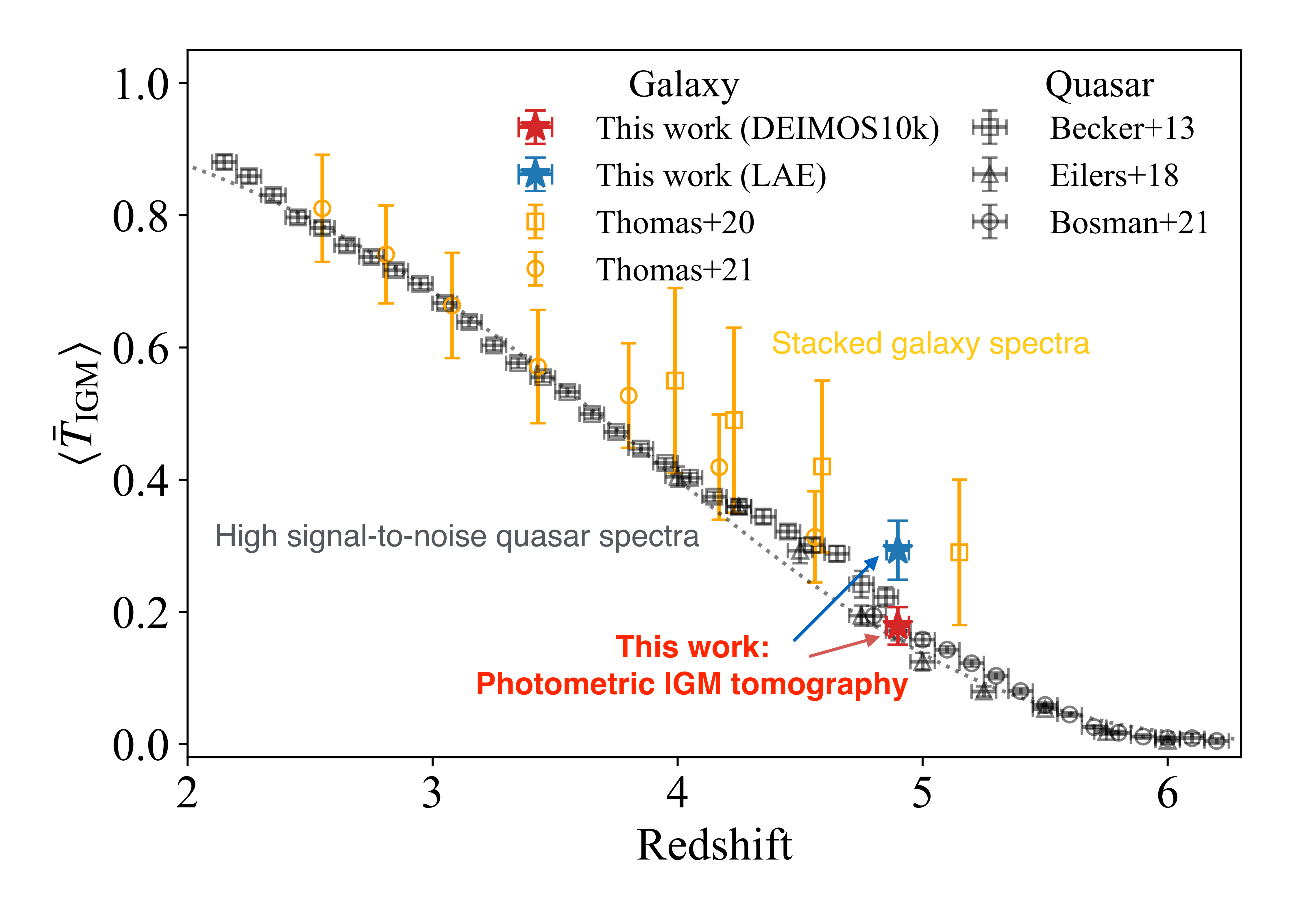
Detection: IGM transmissions along individual background galaxies



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

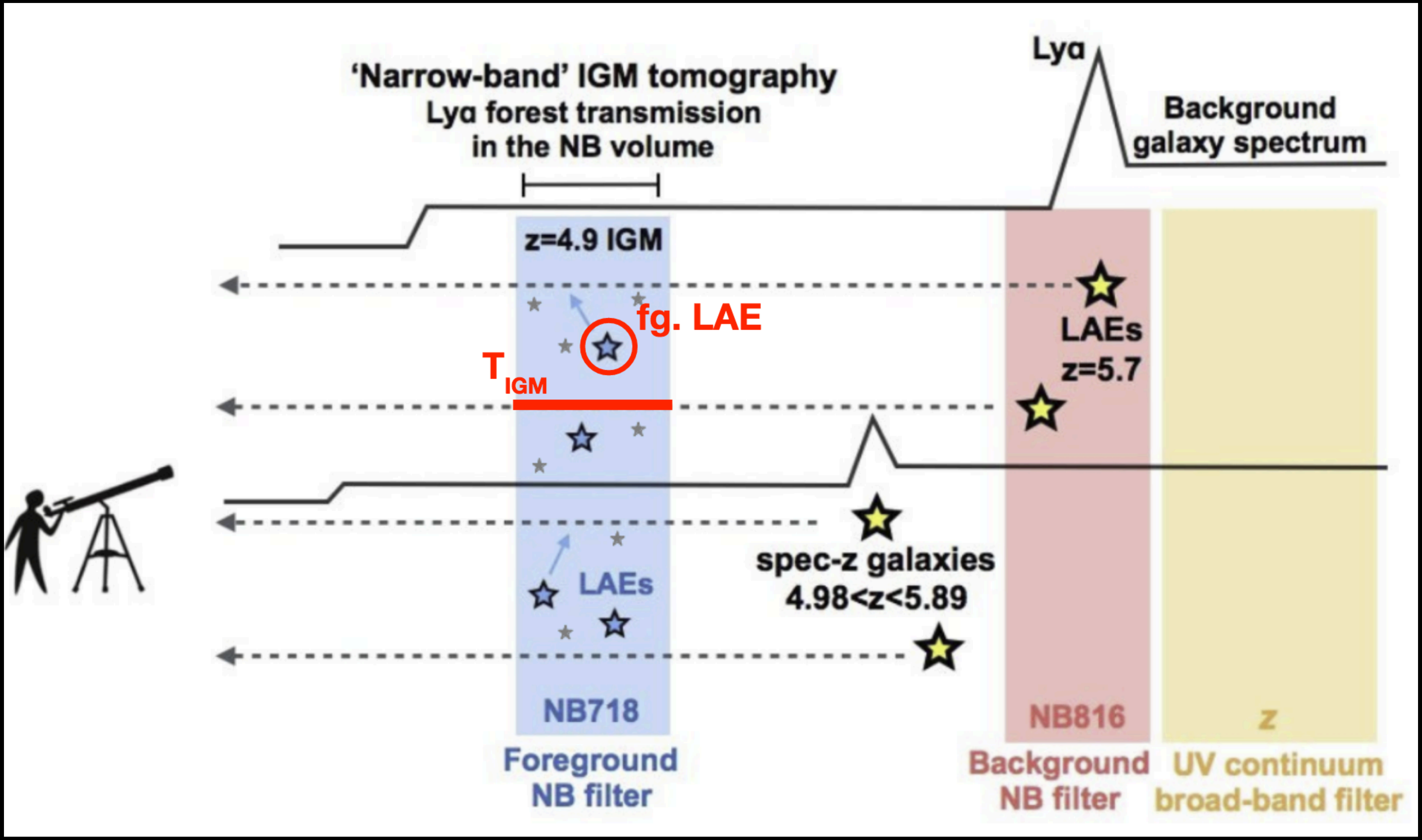


Mean IGM transmission: background galaxies vs quasars



IGM Lyα forest transmission can be measured photometrically.

Galaxy-Lyα forest Cross-Correlation
z=4.9 foreground LAEs × IGM transmission

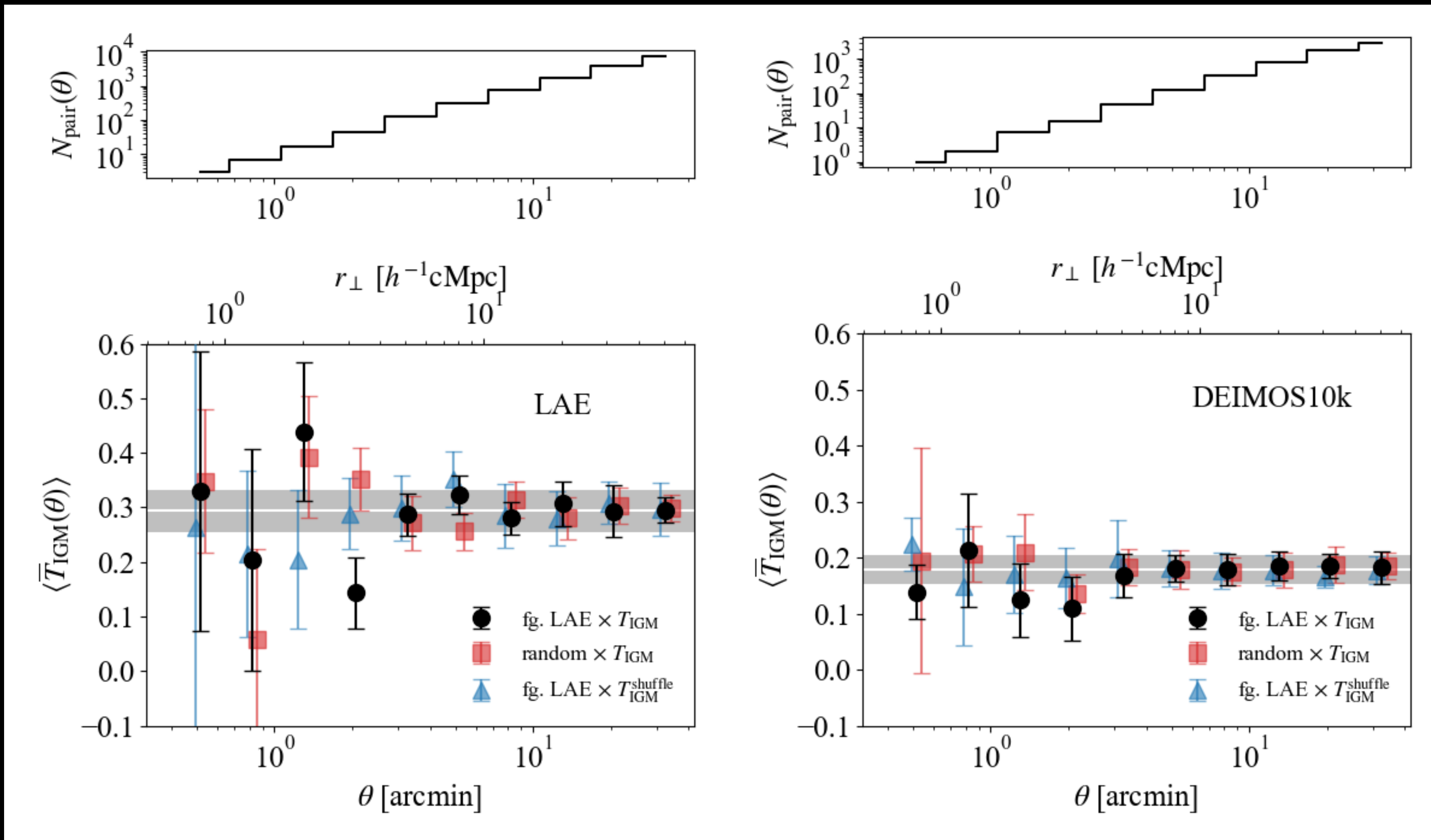


Photometric IGM tomography:
galaxy-Lyα forest cross-correlation → hydrogen gas around foreground galaxies

à la weak gravitational lensing:
galaxy-galaxy lensing → dark matter around foreground galaxies

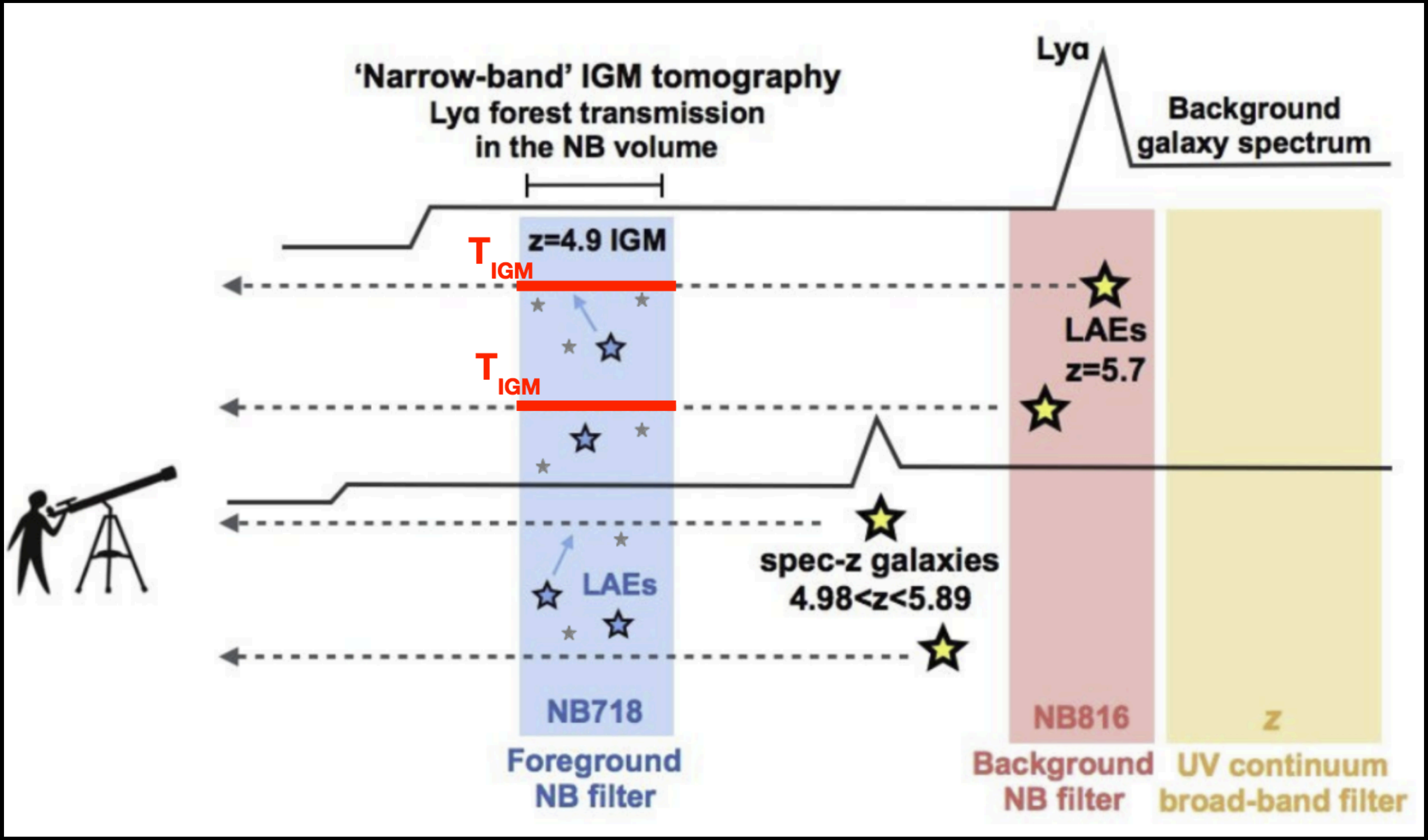
Galaxy-Lyα forest Cross-Correlation

z=4.9 foreground LAEs × IGM transmission



Non-detection. consistent with the mean IGM transmission,
i.e. no extreme IGM fluctuation around z=4.9 galaxies (LAEs) with halo mass of $M_{\rm h}$~10^{11} $M_\odot$

Lyα forest Auto-Correlation
z=4.9 IGM transmission

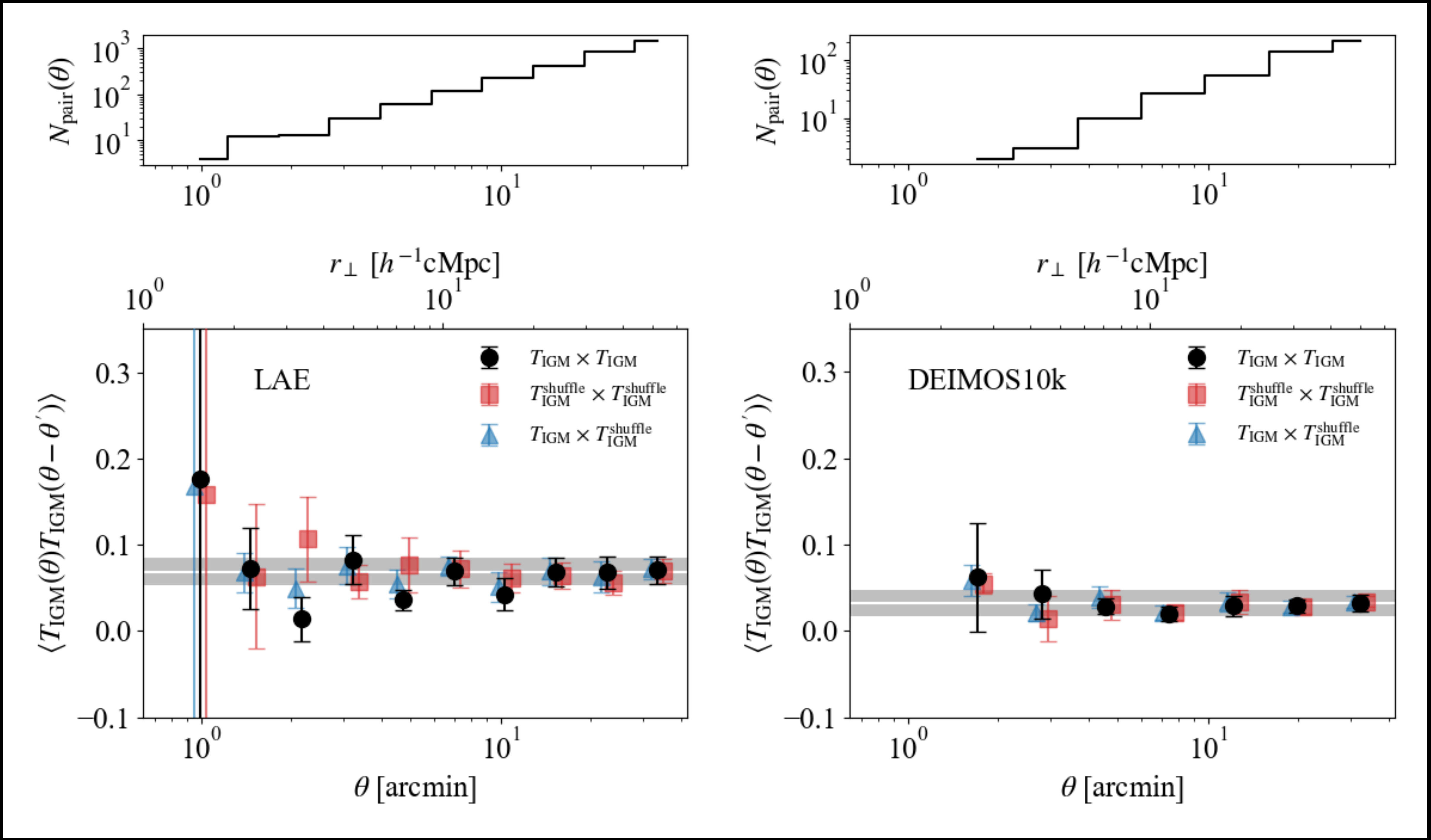


Photometric IGM tomography:
Lyα forest auto-correlation → hydrogen gas fluctuations

à la weak gravitational lensing:
cosmic shear → dark matter fluctuations

Lyα forest Auto-Correlation

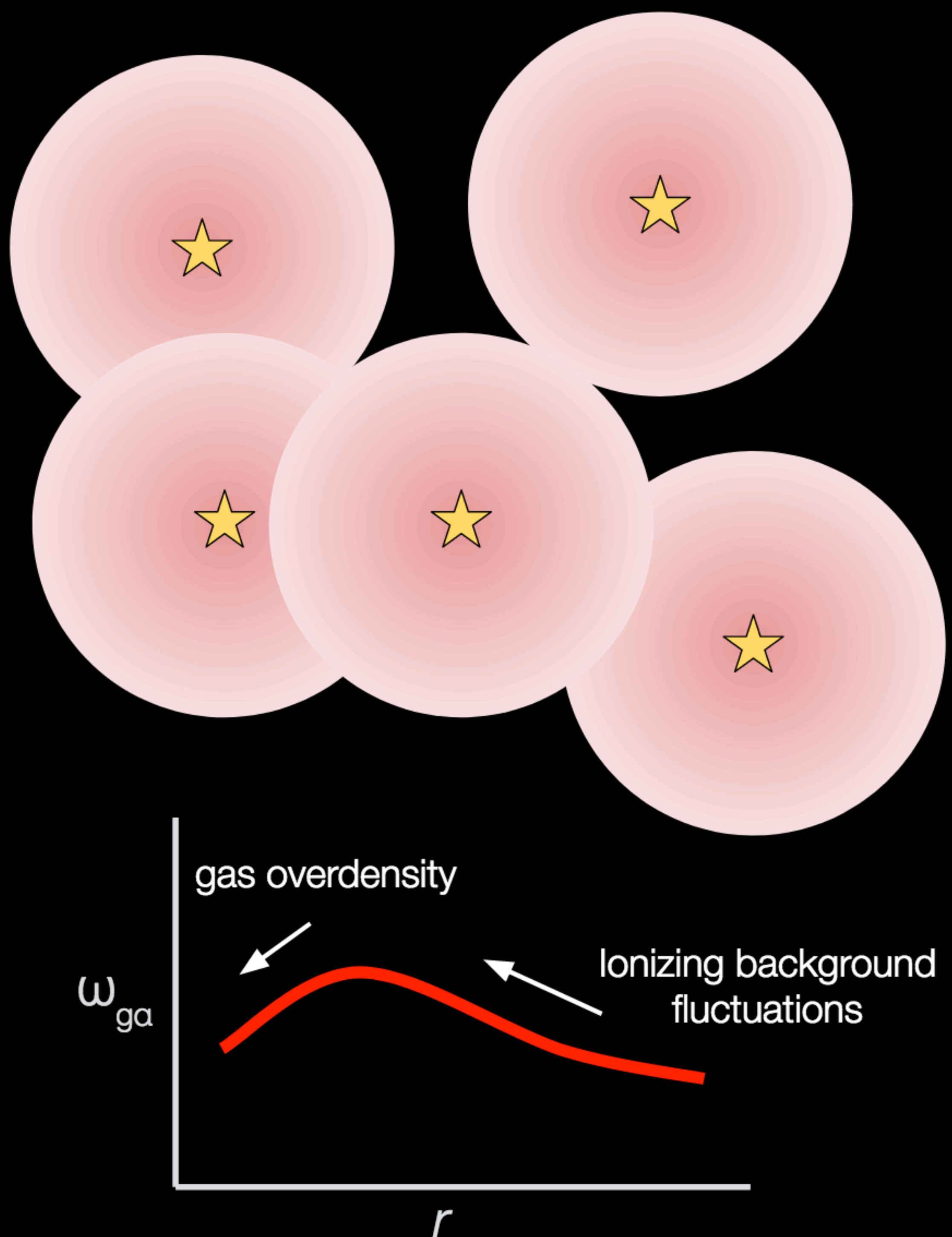
z=4.9 IGM transmission



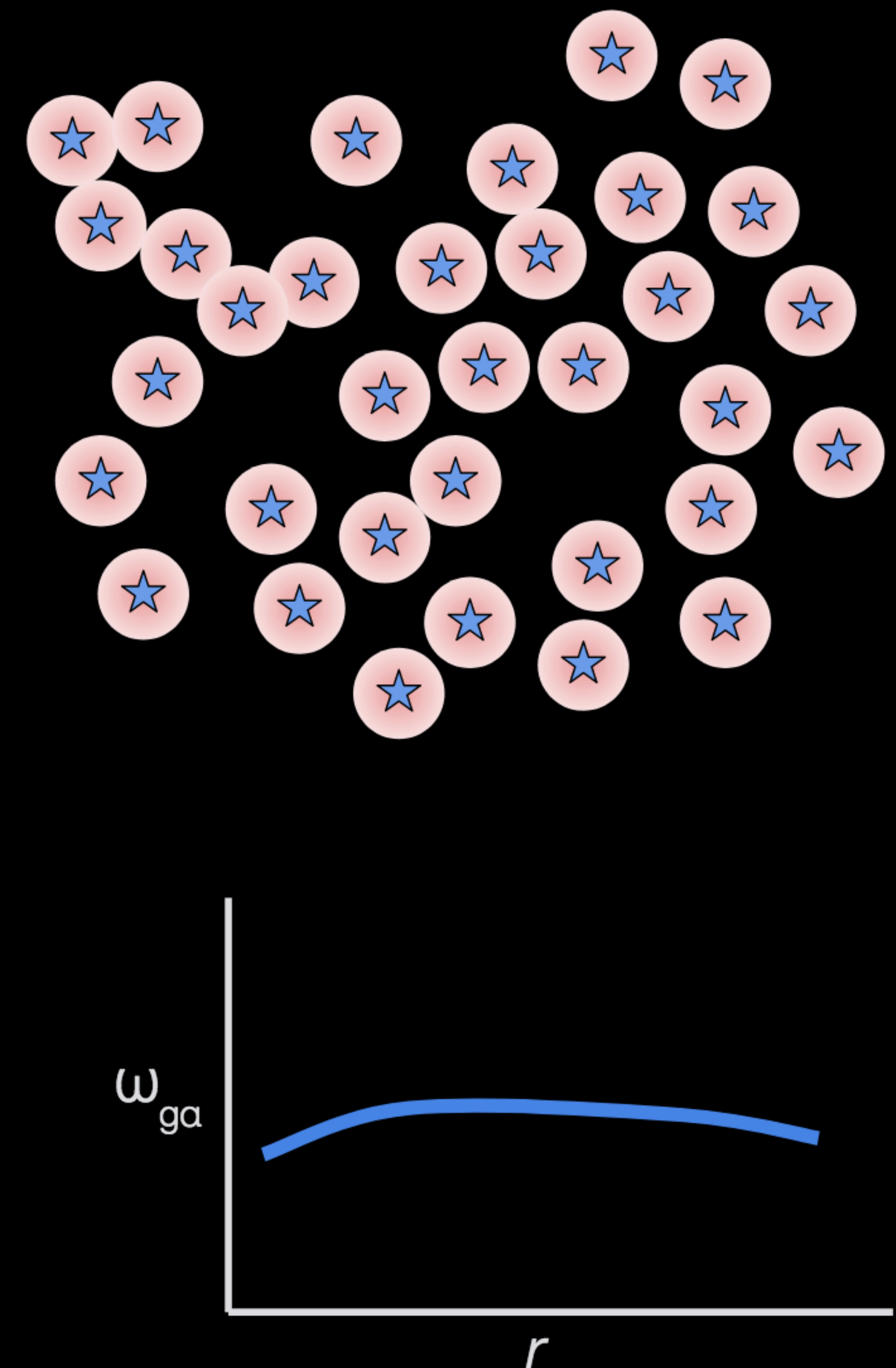
Non-detection.

Implication of non-detection: reionization

Bright galaxy dominated-driven ionizing background



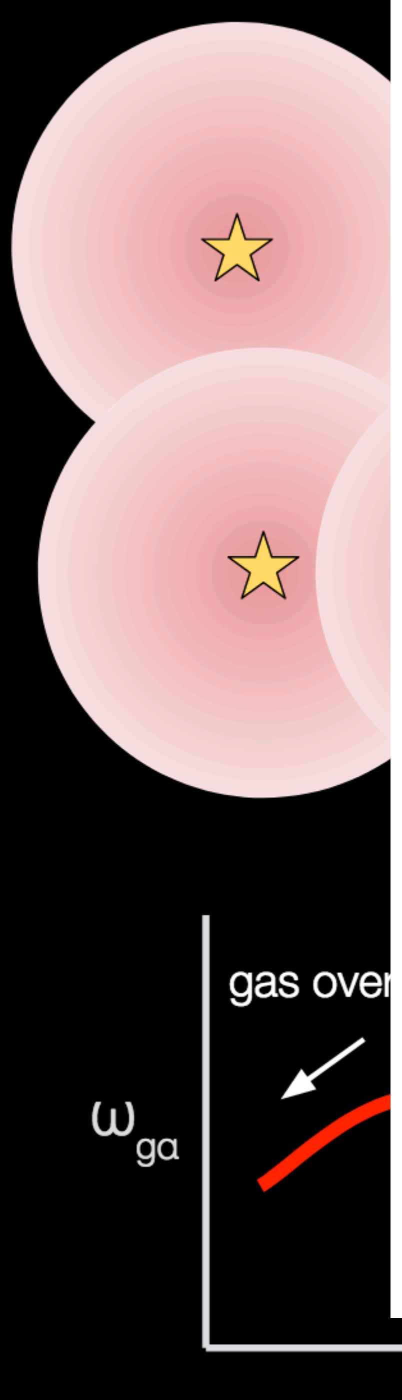
Faint galaxy dominated-driven ionizing background

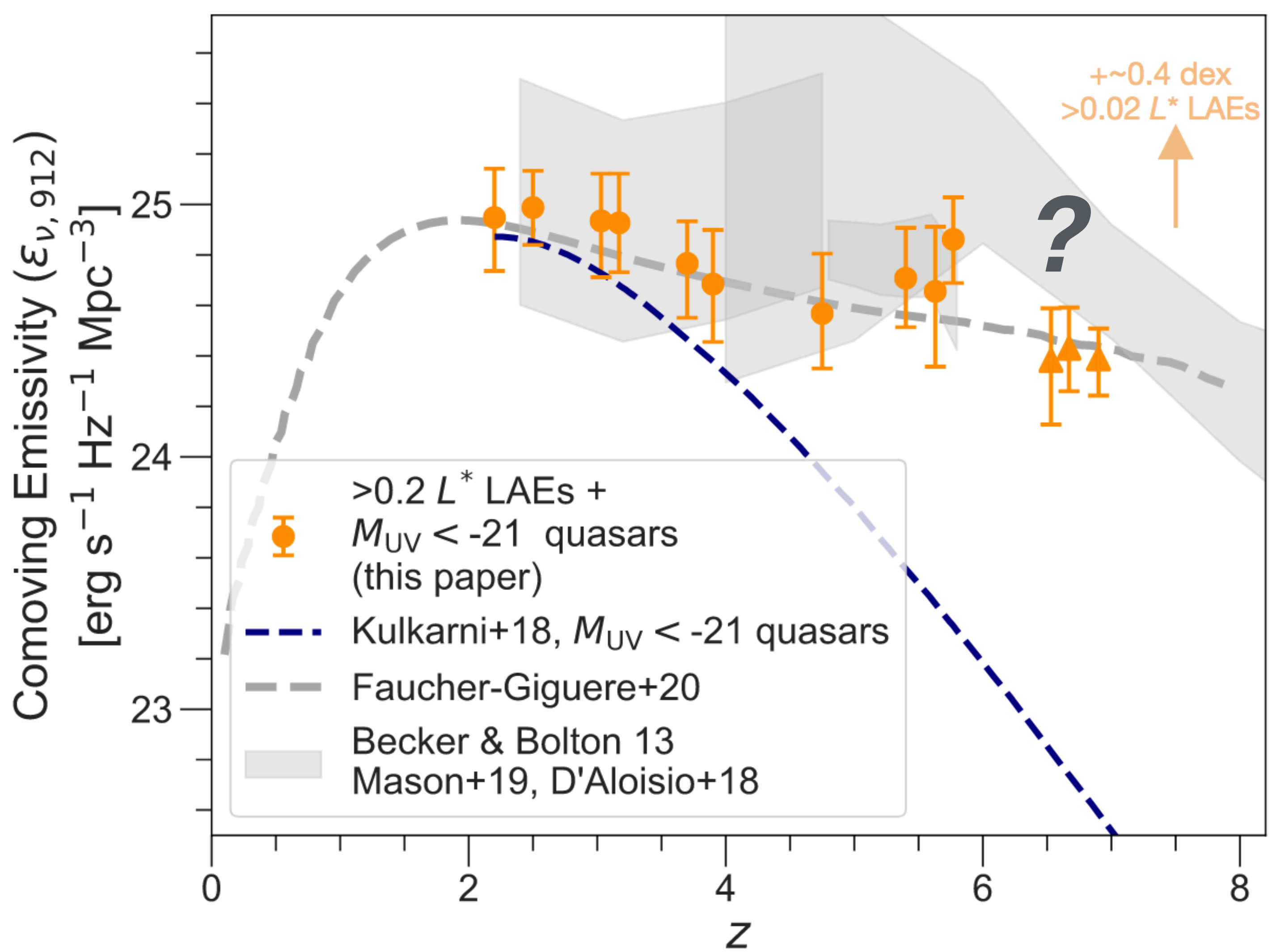


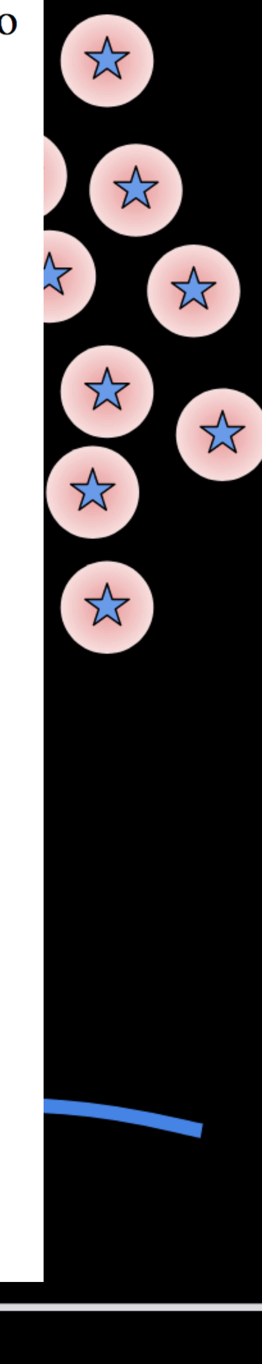
Implication of non-detection: reionization

(Re)Solving Reionization with Lyα: How Bright Lyα Emitters account for the $z \approx 2-8$ Cosmic Ionizing Background

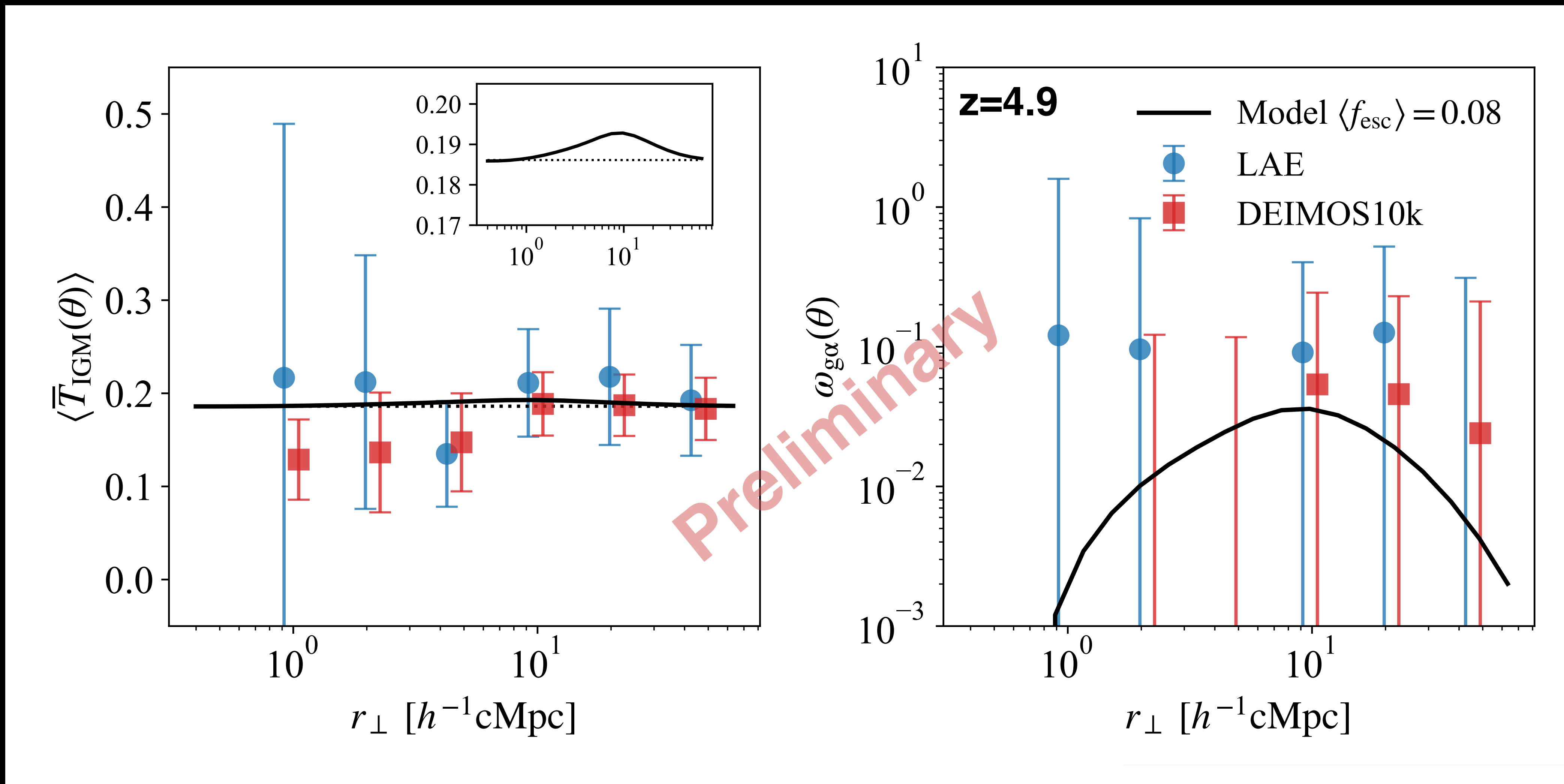
Jorryt Matthee[1⋆†‡], Rohan P. Naidu[2⋆†], Gabriele Pezzulli[3], Max Gronke[4,5,6], David Sobral[7], Pascal A. Oesch[8,9], Matthew Hayes[10], Dawn Erb[11], Daniel Schaerer[8], Ricardo Amorín[12,13], Sandro Tacchella[14], Ana Paulino-Afonso[15], Mario Llerena[12,13], João Calhau[16,17] and Huub Röttgering[18]

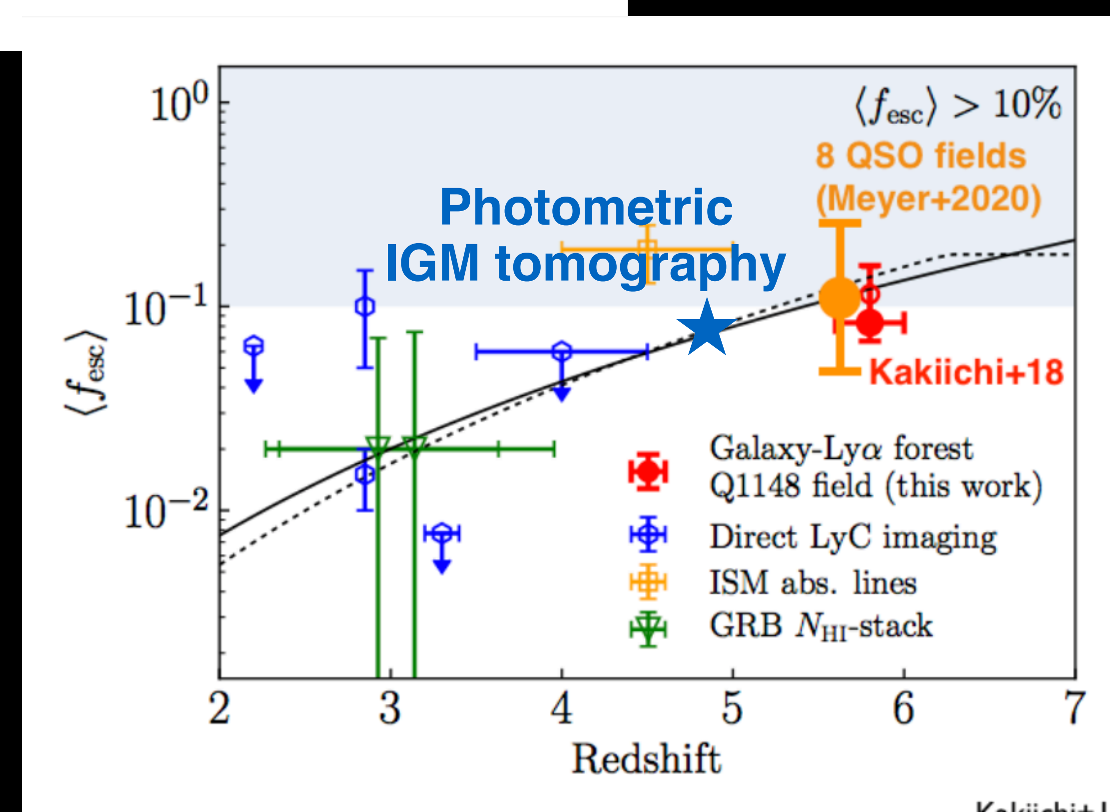






Implication of non-detection: reionization





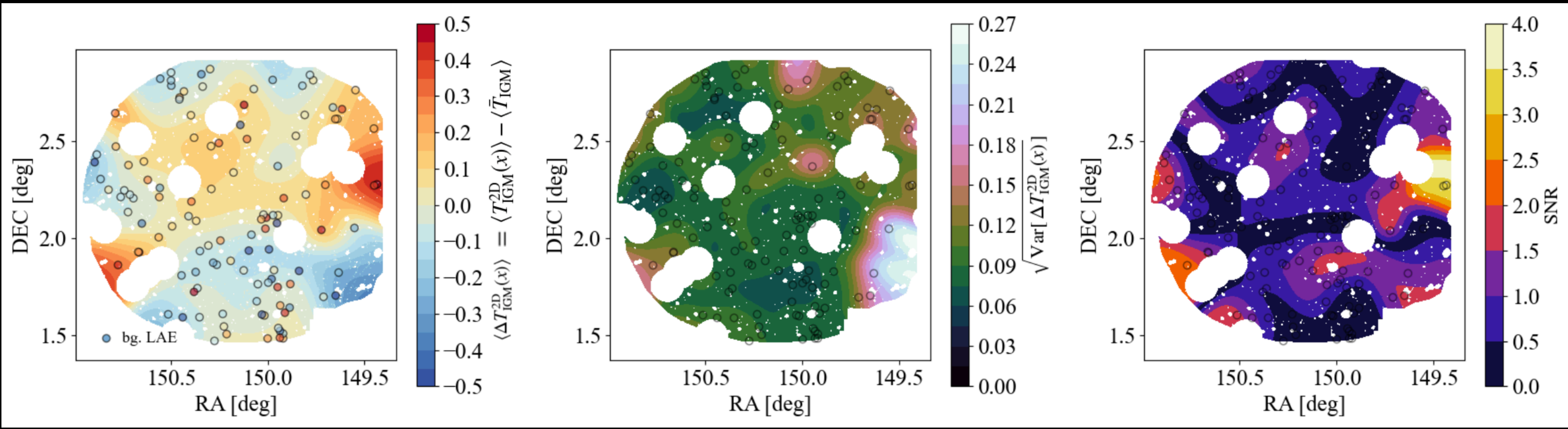
The observed galaxy-Lyα forest cross-correlation seems consistent with a 'standard' model that galaxies with M_{UV}<-15 (re)ionize the IGM with const. f_{esc}~8% & ξ_{ion}~$10^{25.5}$ erg/s/Hz

Map making

Reconstructed 2D IGM tomographic map

Reconstruction method:
Gaussian kernel density-based estimator + posterior

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

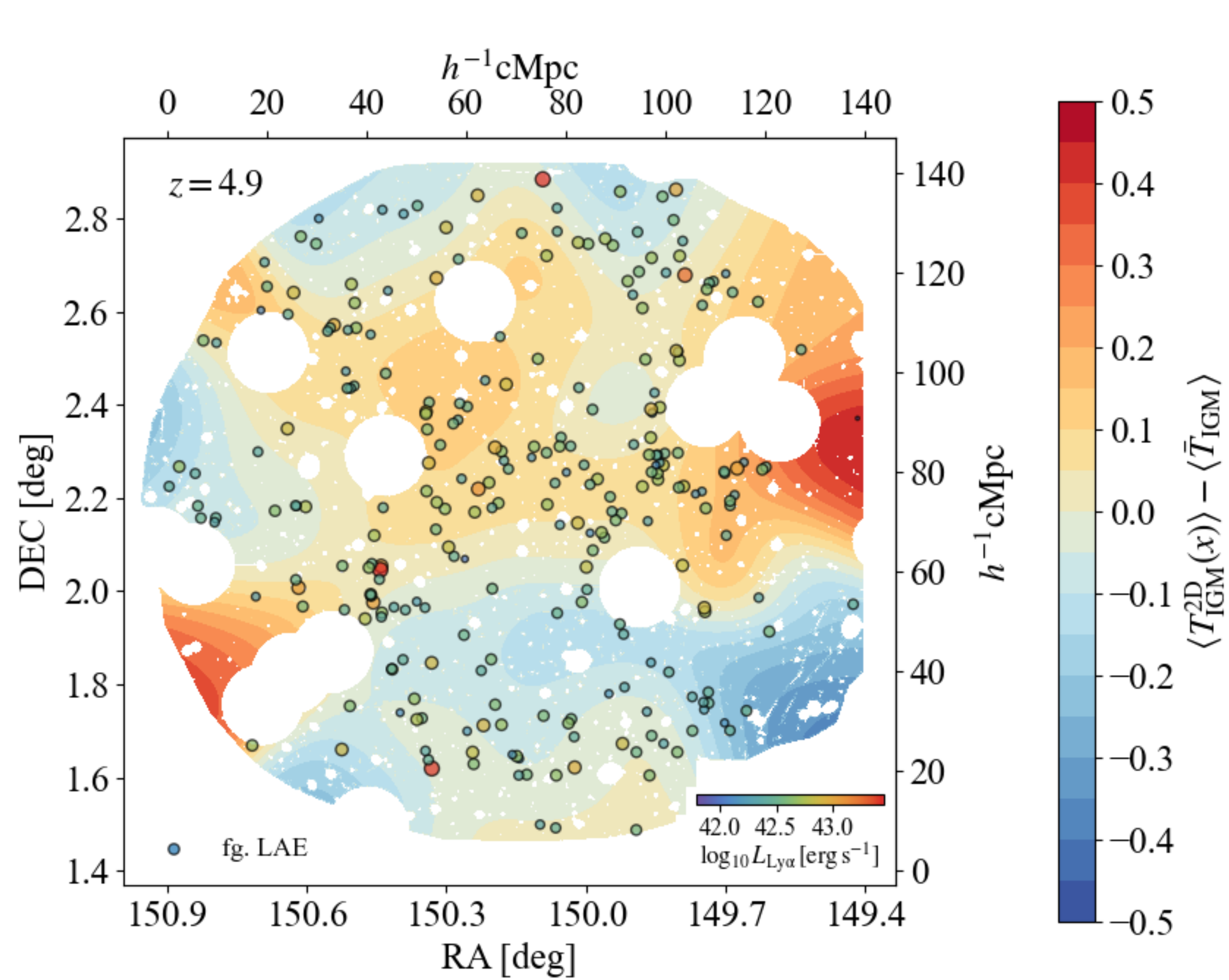


Average SNR of the reconstructed map ~ 0.86
i.e. currently still photometric noise dominated

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

Final product

Large-scale map of LAEs x IGM tomography

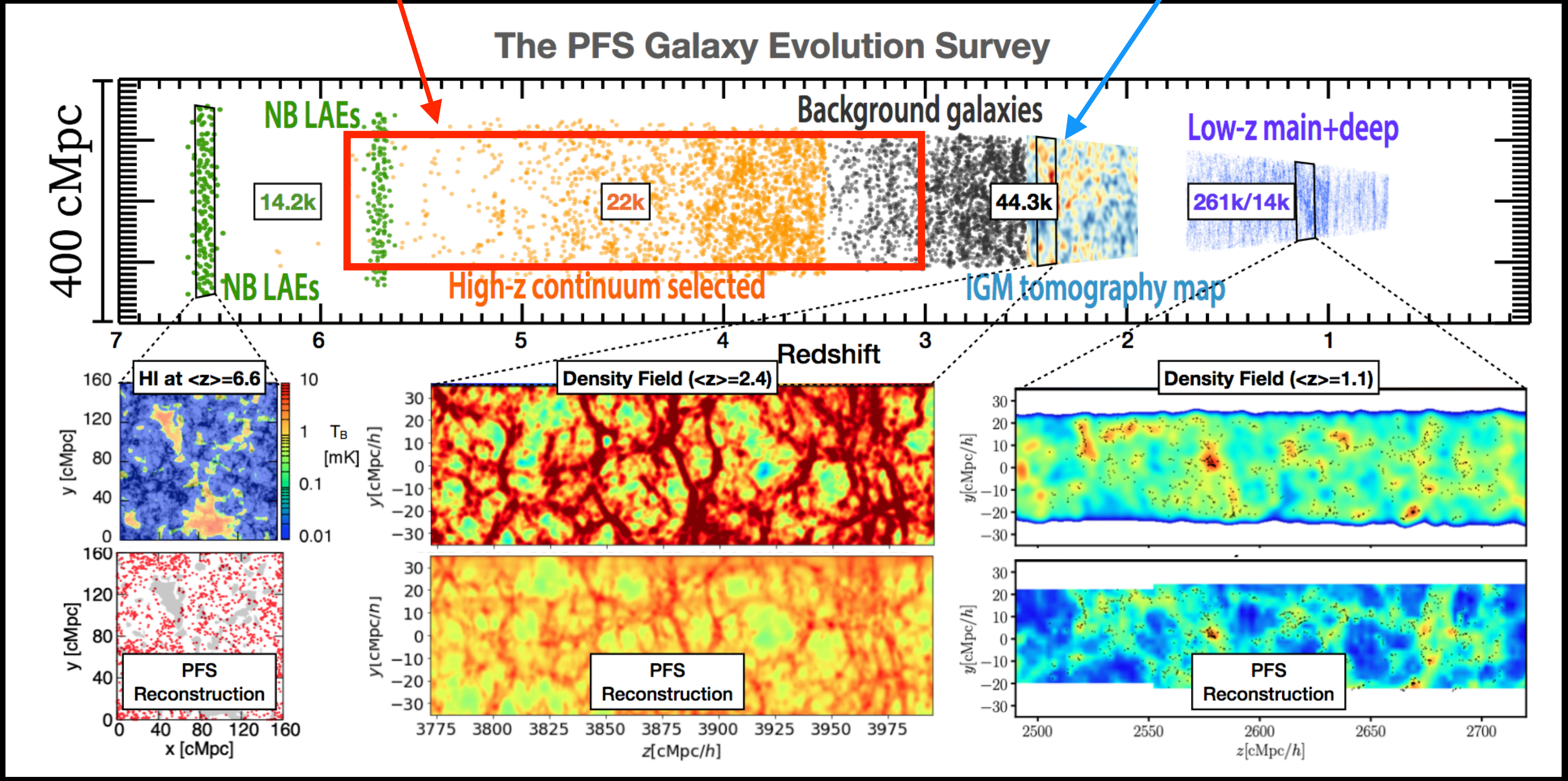


Towards a better (photometric) IGM tomography

"New"

Photometric IGM tomography

Spectroscopic IGM tomography



Greene+22

Subaru/PFS

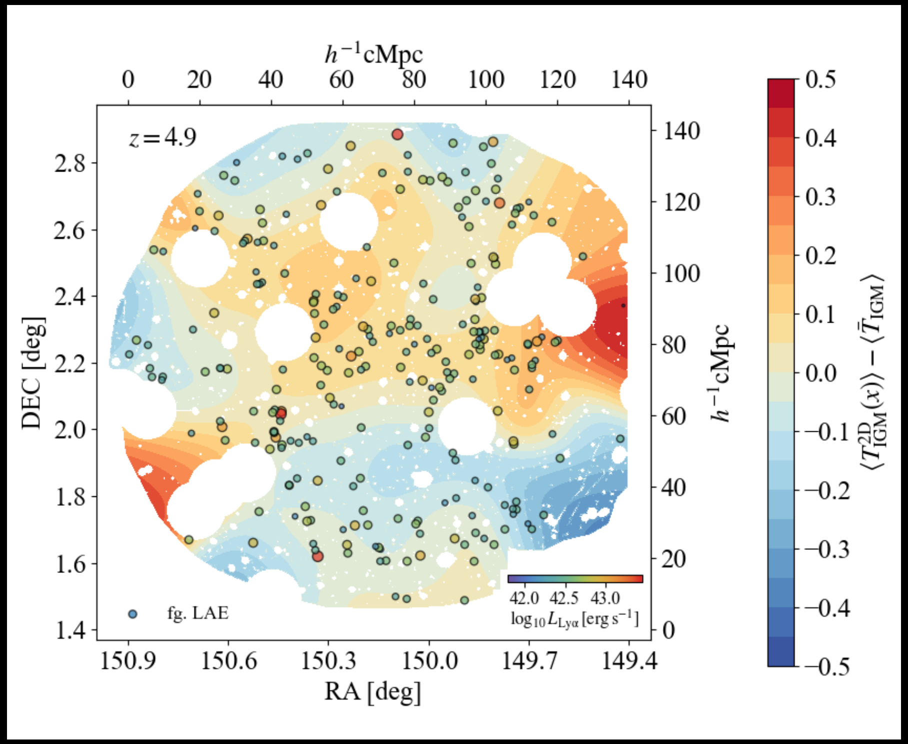
1. Boost the number of spectroscopically-confirmed bright LBGs
2. Correct for the low-redshift interloper effect in LAE sample

UltraVISTA+*Spizter*/SPLASH → *JWST* COSMOS-Webb & PRIMER

3. Better determination of background galaxy SED template

→ break dust-age-T_{IGM} degeneracy

Science applications



Tomography → Science?

Statistical analysis

1. Ionizing escape fraction and UV background: sources of reionization

2. (Fossil) quasar light-echo search:

   growth history of SMBHs & quenching of massive galaxies

Bosman&KK+20, Kakiichi+22

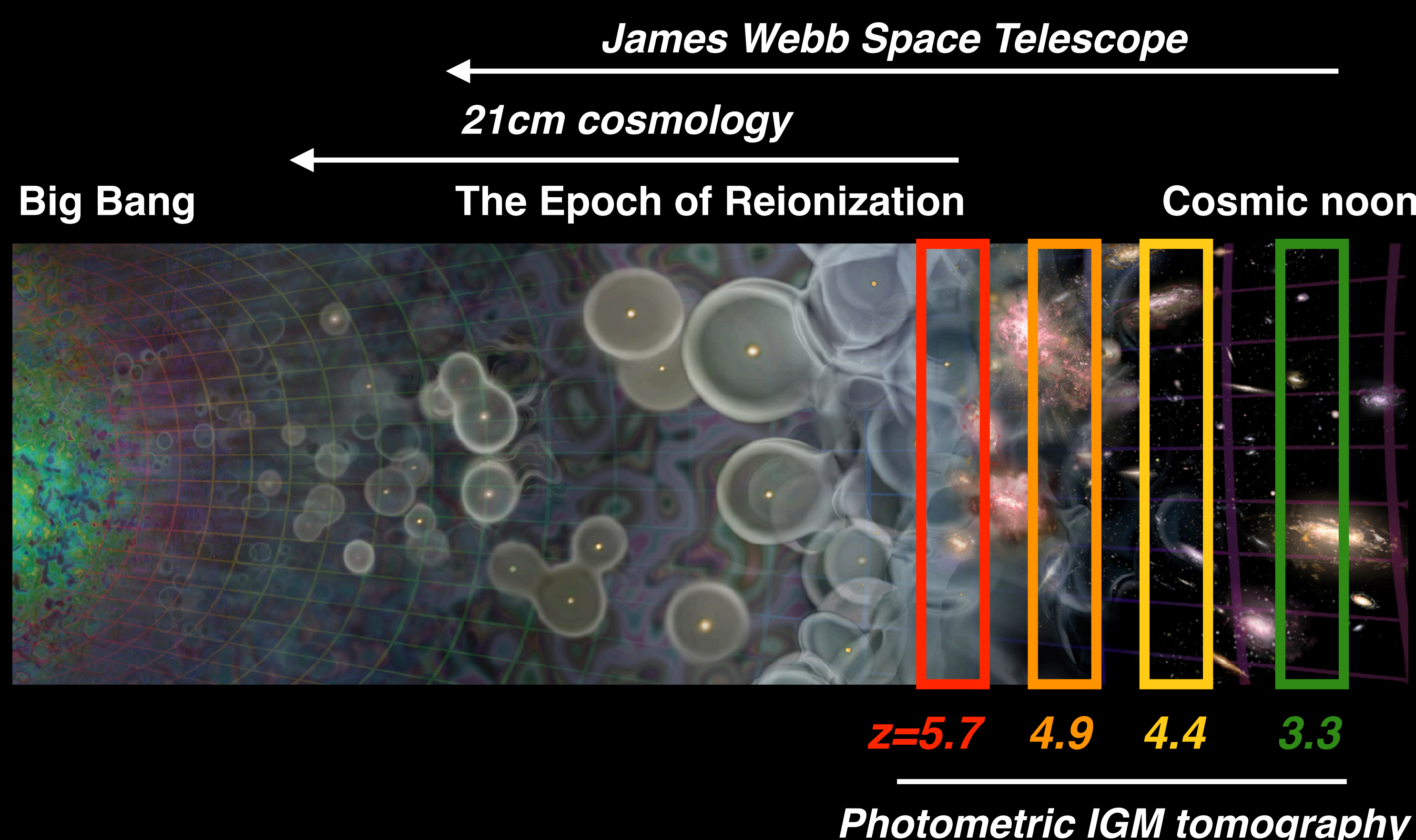
Map-level analysis

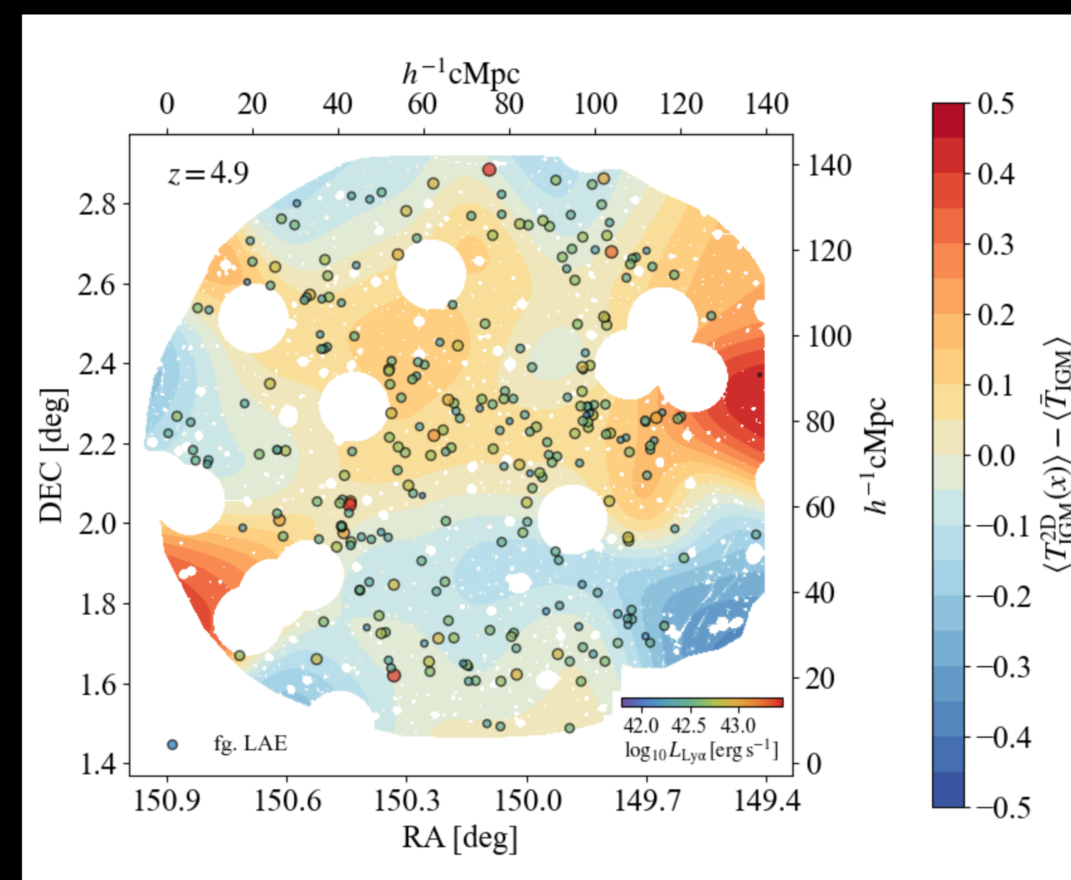
3. Spatial correlation of galaxies with their large-scale IGM environments

A baseline for galaxies × IGM tomography science

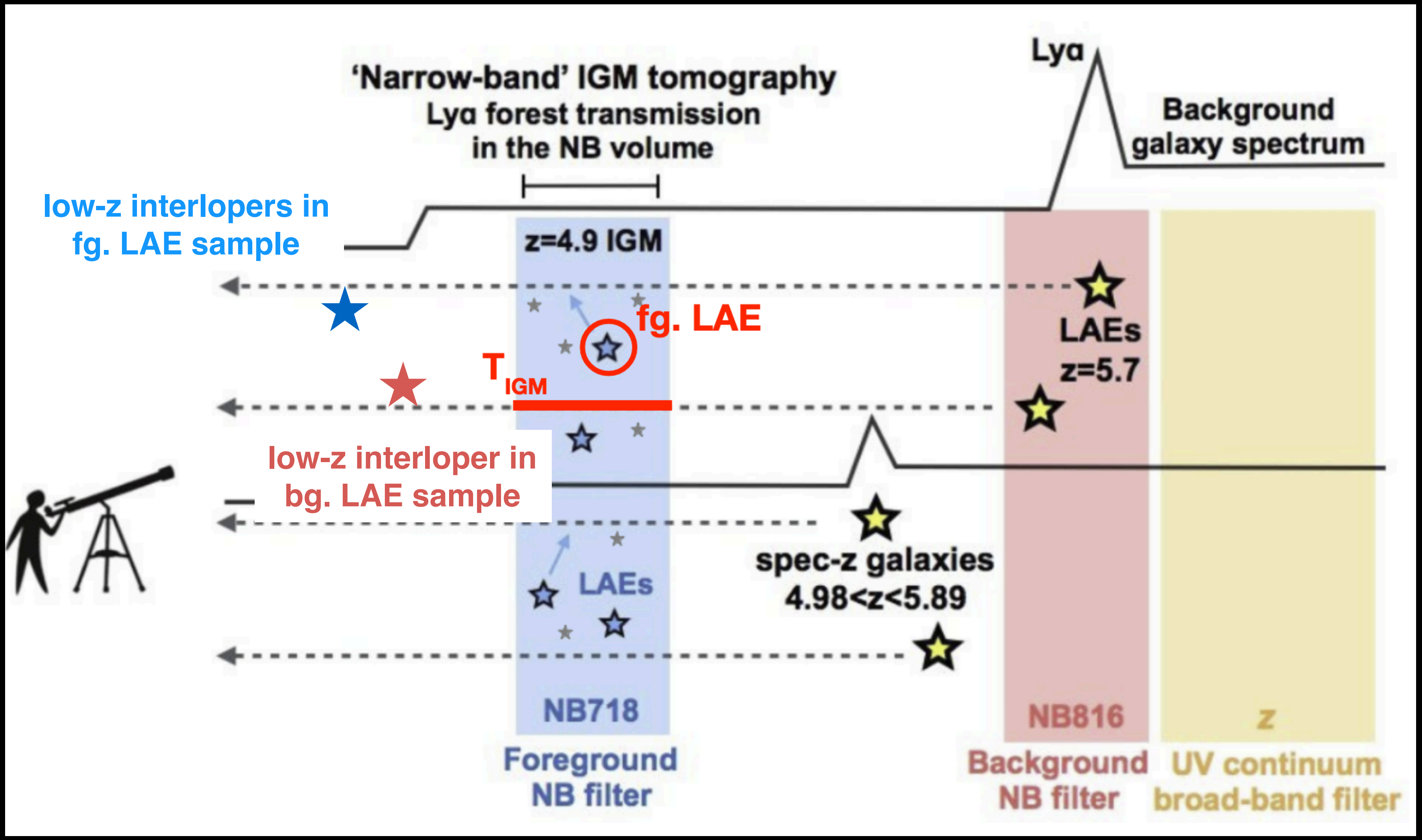
Conclusions

"Photometric IGM tomography" opens a new way forward to study the galaxy-IGM connection across z~3-6 bridging the epoch of reionization to cosmic noon





Correcting for the effect of lower-redshift interlopers



$$\langle \overline{T}_{\rm IGM}(\theta)\rangle = (1-f_{\rm fg.int})(1-f_{\rm bg.int})\langle \overline{T}_{\rm IGM}(\theta)\rangle^{\rm true} + f_{\rm fg.int}(1-f_{\rm bg.int})\langle \overline{T}_{\rm IGM}\rangle^{\rm true} + f_{\rm bg.int}\langle \overline{T}_{\rm IGM}\rangle^{\rm bg.int}$$