GALAXIES AS AGENTS OF COSMIC REIONIZATION IN THE JWST ERA

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with Rohan Naidu, Ruari Mackenzie, Daichi Kashino, Simon Lilly, Rob Simcoe, Rongmon Bordoloi, Christina Eilers, David Sobral, Matthew Hayes, Gabriele Pezzulli and the MUSE GTO team

ETH zürich

Institute of Science and Technology Austria

European Research Council
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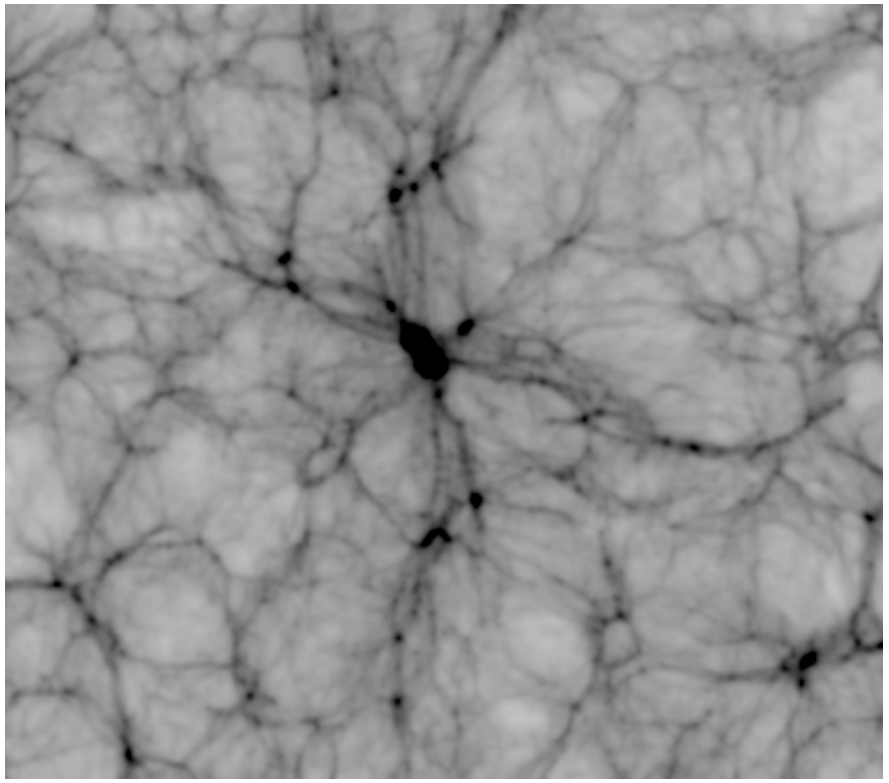
REIONIZATION: A COMPLEX THEME

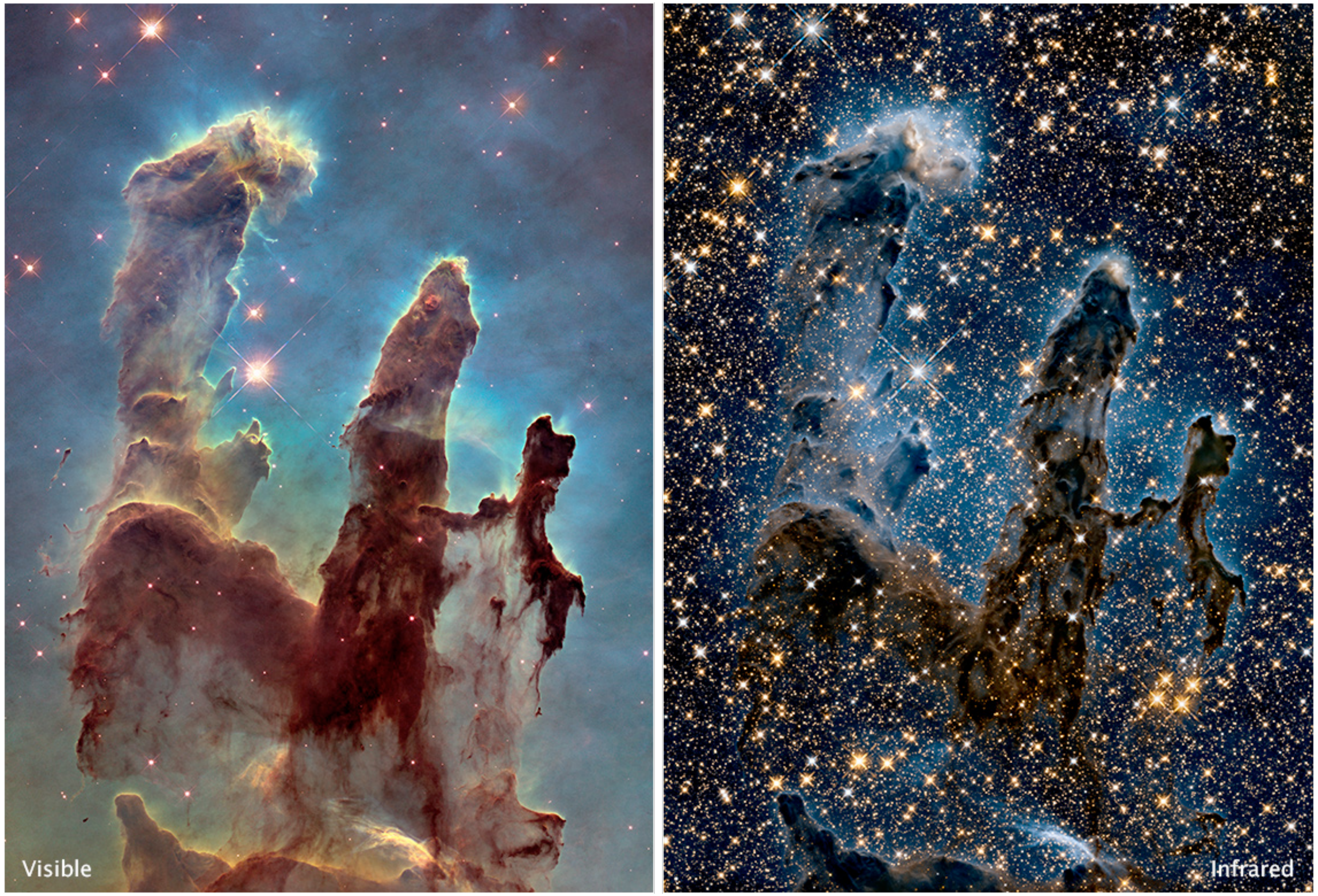


- **the production of the ionizing photons** (stars, accretion disks)
- **the trajectory through the ISM** (dust, feedback, ISM structure)
- **the structure and clustering of intergalactic gas** (structure formation)

THIS TALK

- *Lessons from analogues in the intermediate-age Universe (XLSz2)*
- *First results from the JWST EIGER survey*
- *Future directions*

Fesc: the key challenges



Young stars: born in dense gas clouds where no ionizing photons can escape

Bursty episodes of leakage? (e.g. Trebitsch+2016, Ma+2020, Rosdahl+2022)
Pre-supernova feedback? (e.g. Keller+2022)

FESC: THE KEY CHALLENGES

Stochastic IGM transmission

IGM *stochastically* absorbs LyC photons (average: 60% at z~3, 95% at z=6)

(e.g. Steidel+2018)

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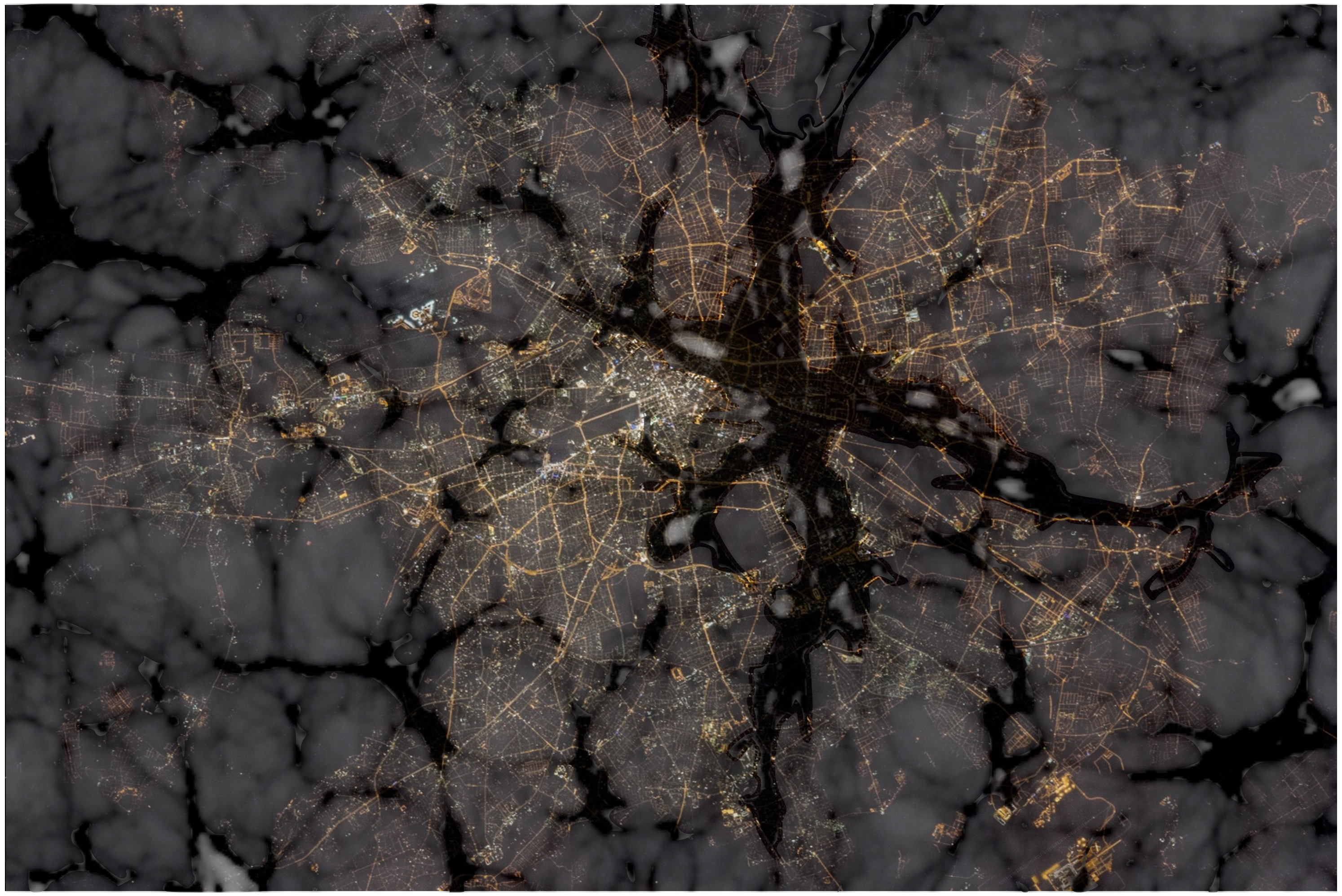
Stochastic IGM transmission



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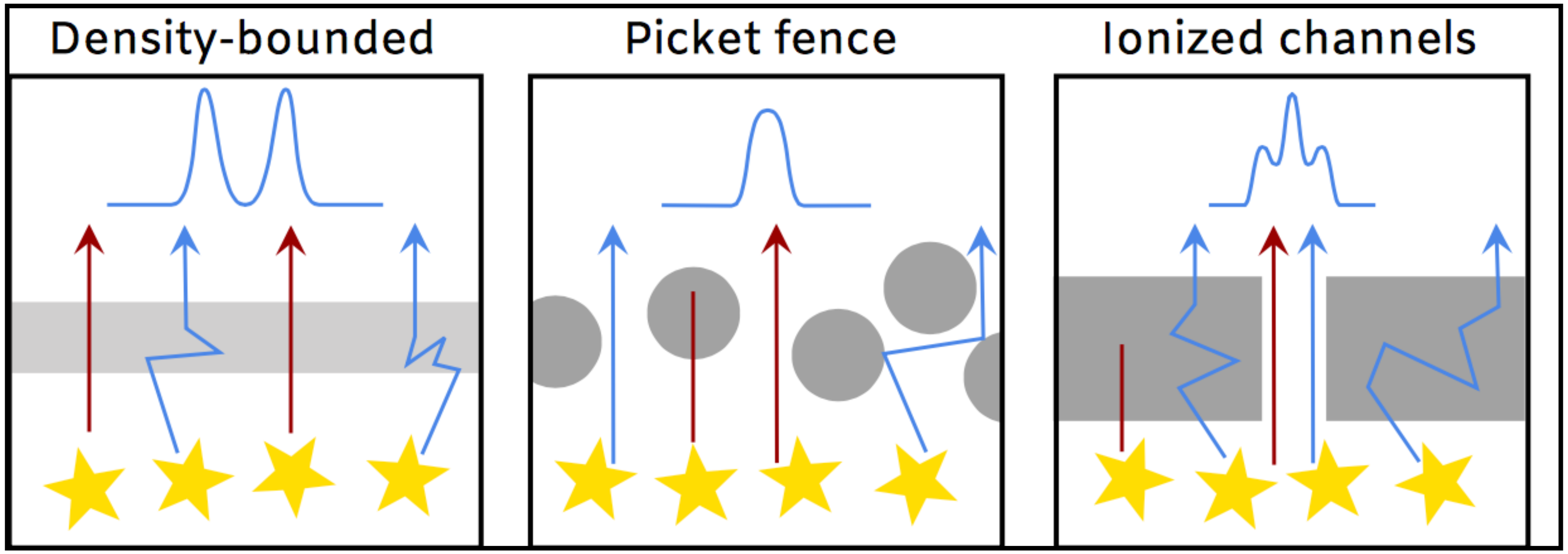
(e.g. Steidel+2018)

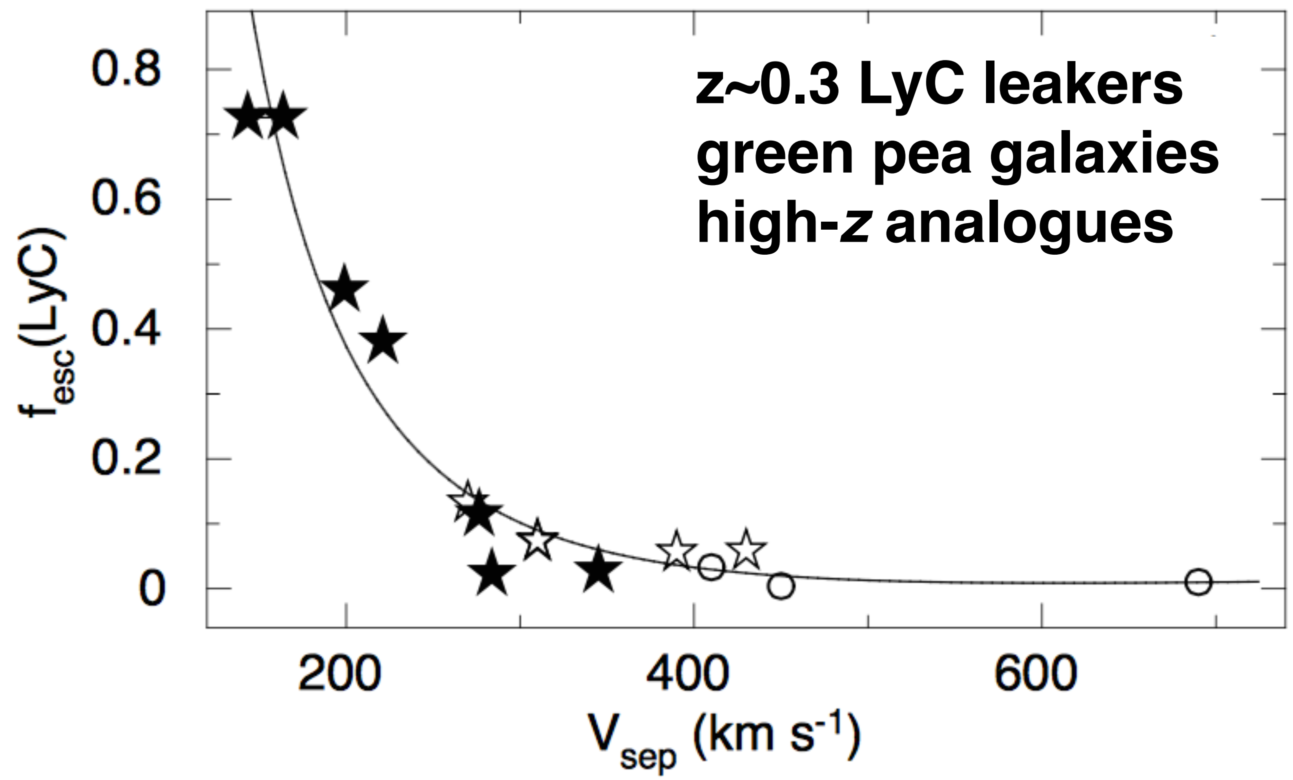
THE LYMAN-ALPHA BYPASS

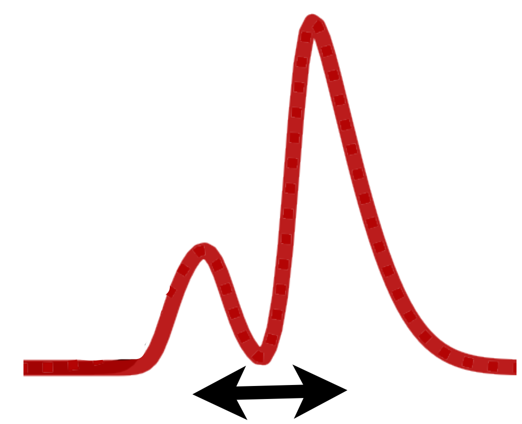


Inset sketches from Rivera-Thorsen+2017

Observed Lyman-alpha emission photons trace the ISM structure between stars & us

THE LYMAN-ALPHA BYPASS



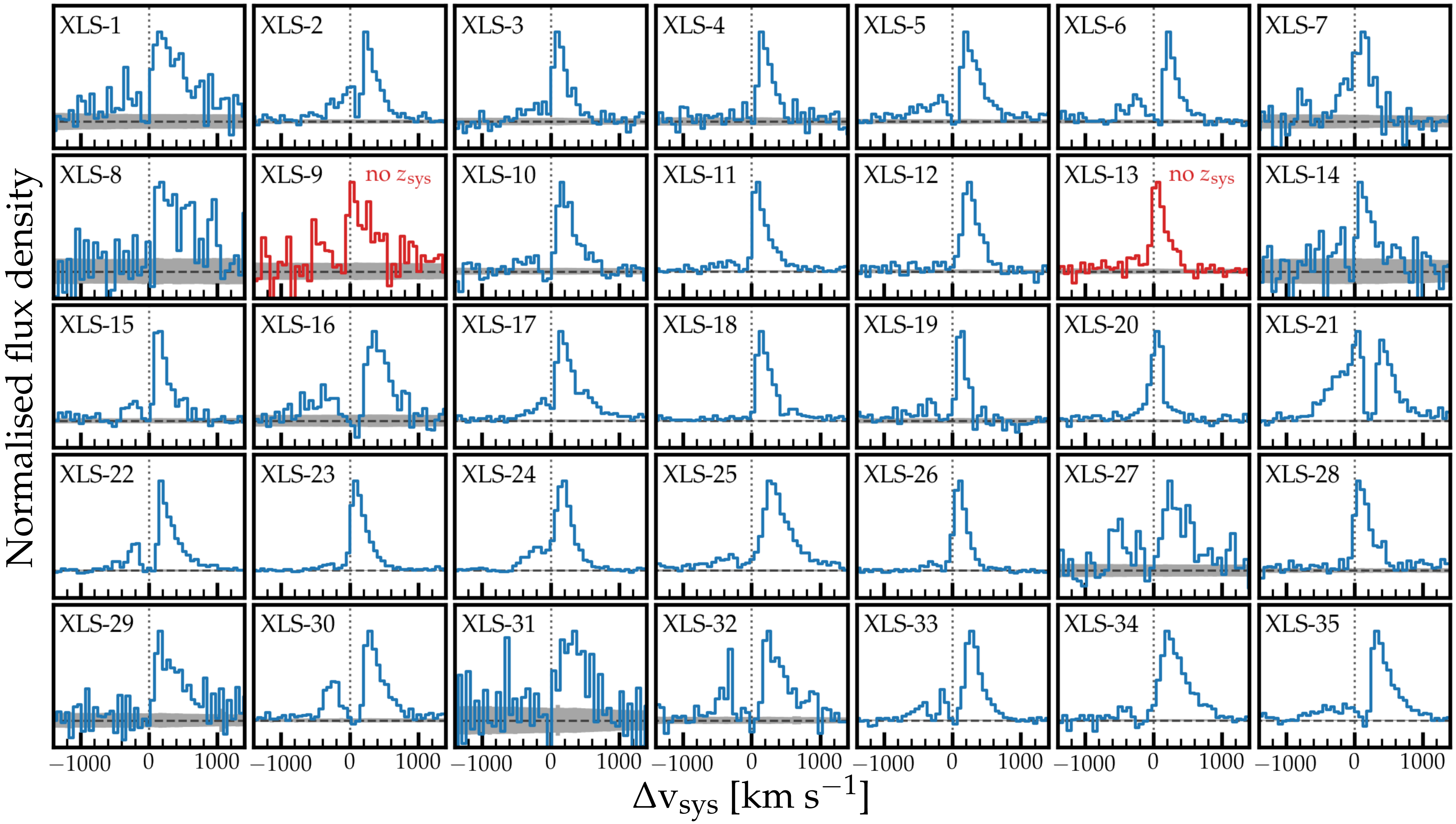


Izotov+2018,2021
see also
Verhamme+2015, Kakiichi & Gronke 2019
Gazagnes+2020

- **The Lyman-α (Lyα) line is the best indirect indicator of ionizing photon (LyC) escape**

e.g. Izotov+2018,Gazagnes+20, Flury+22

HIGH-RESOLUTION LYA PROFILES FROM XLS-z2

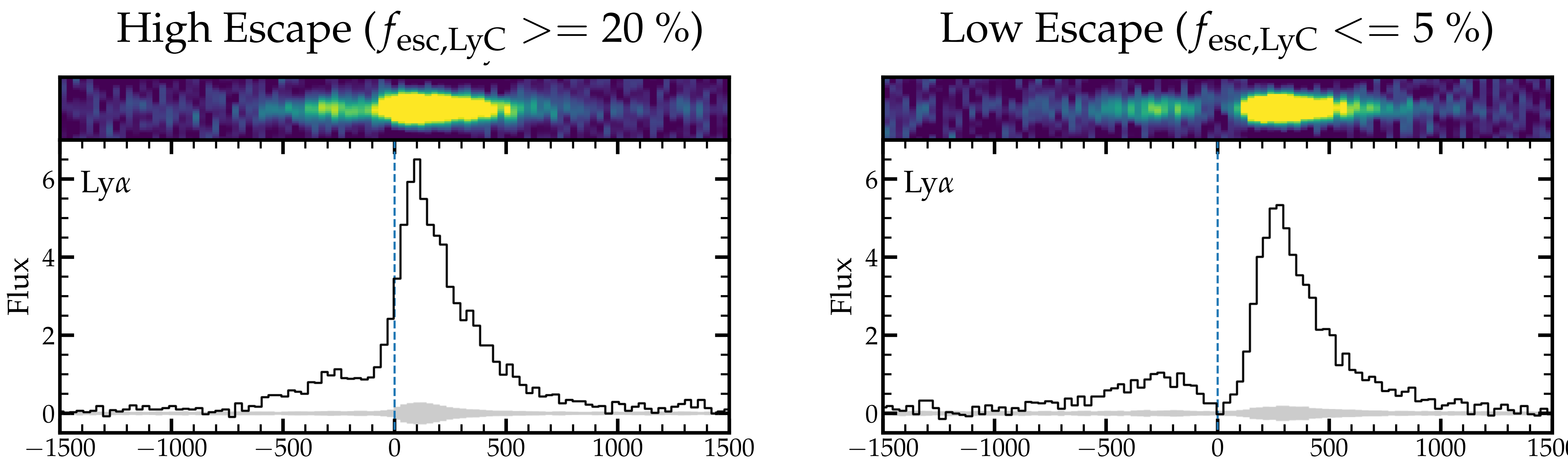


Unprecedented combination of resolution, S/N and available systemic redshifts

N=35, purely selected based on Lya flux & EW (>0.2 L* [“bright”] and EW>25 Å)

Matthee+2021

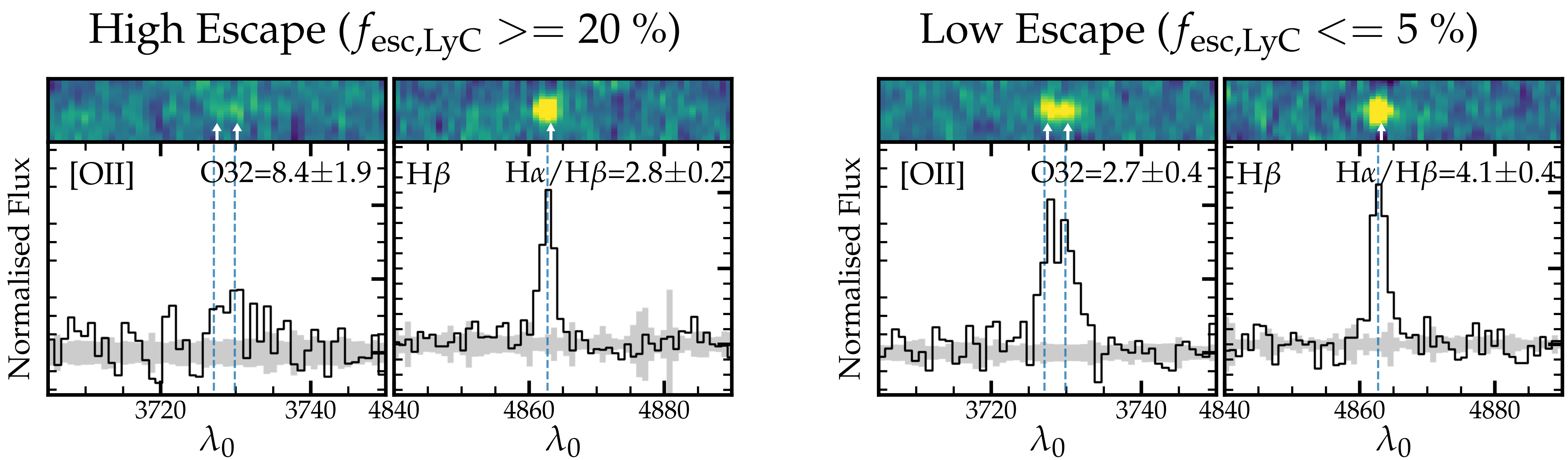
From which of these galaxies do Ionizing photons escape?



- **Roughly half the LAEs seem to be leakers, the others not**
- **Our *fiducial* values for the *Ionizing* f_{esc} of the stacks are 50% (range: 20-50%) and <5%**
- **This implies <f_{esc}> = 25% for bright LAEs,**
  consistent with direct measurements in stacks (Steidel+2018, Pahl+2021)

Naidu & Matthee et al. 2022

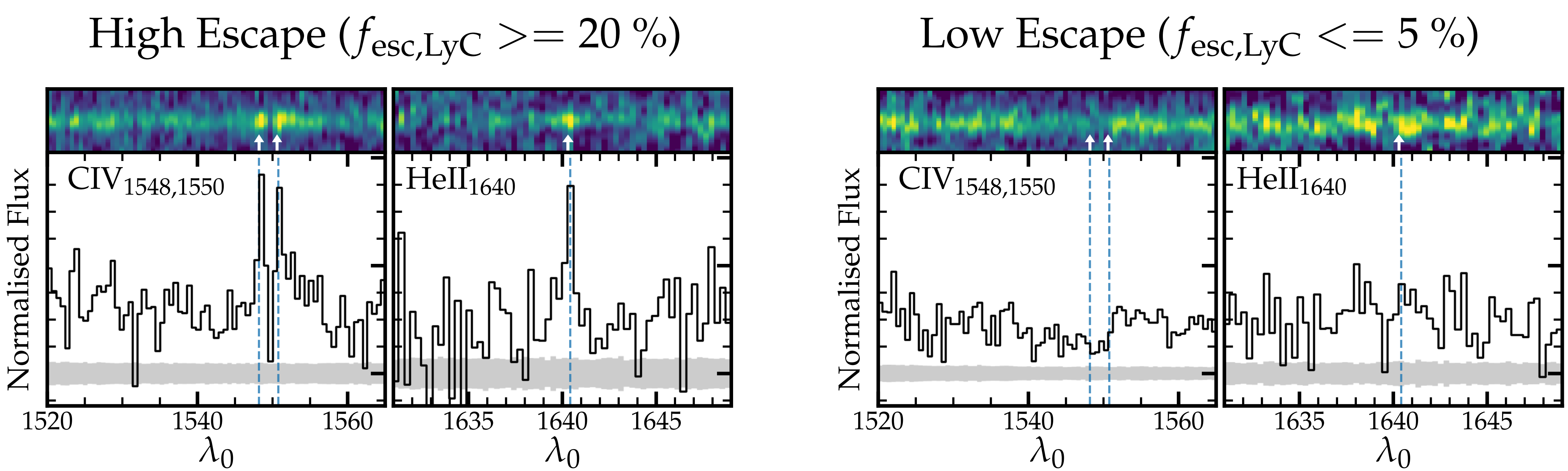
LEAKERS HAVE A HIGHLY IONISED, DUST-FREE ISM AT Z=2



- **Leakers have a higher ionisation parameter (O32=8 vs O32=3)**
- **Leakers have negligible dust attenuation (Ha/Hb=2.8 vs Ha/Hb=4)**

Naidu & Matthee et al. 2022

LEAKERS HAVE MORE YOUNG STARS WITH HARDER SPECTRA AT Z=2



High ionisation lines
High optical line EWs

No high ionisation lines
Moderate optical line EWs

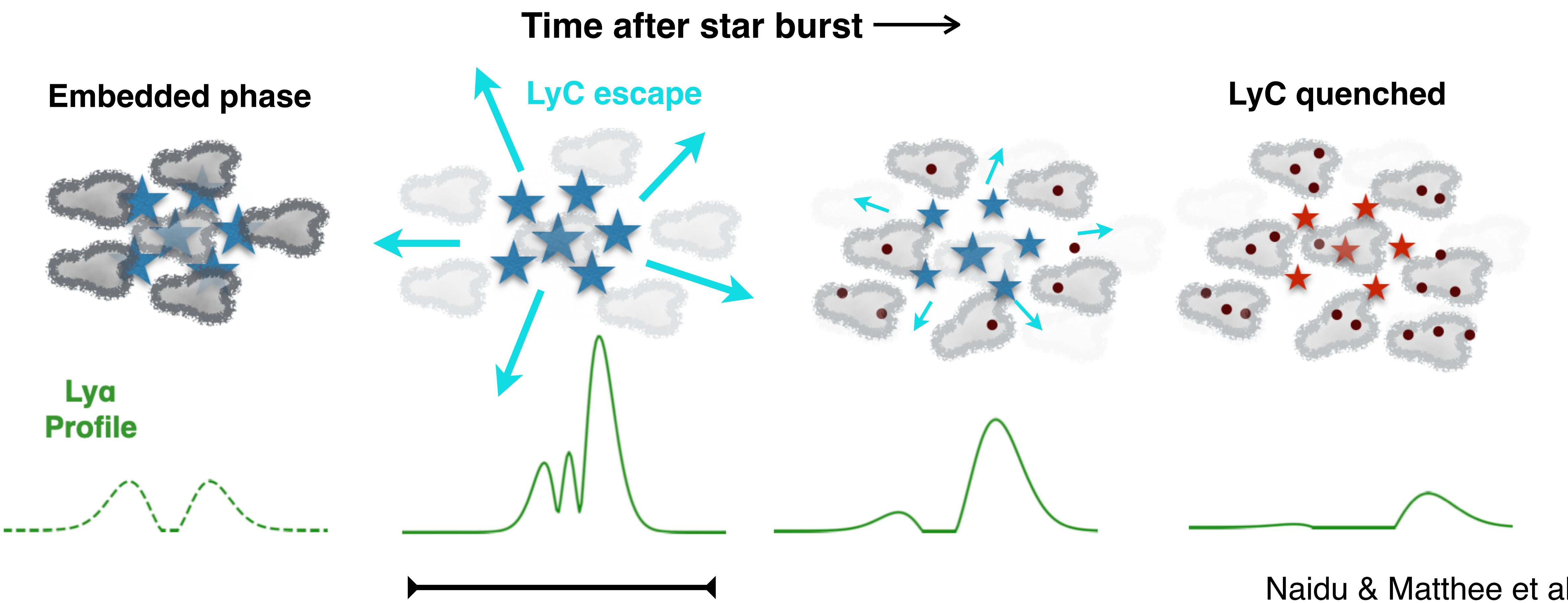
High Production and Escape of LyC occurs in sync, ages ~3-10 Myr

Also seen in simulations (e.g. Ma+2020, Rosdahl+2022)
see also Marques-Chavez+2022b

CIV tracing LyC Fesc: see also Schaerer+22, Saxena+22, Mainali+22, Mascia+23

Naidu & Matthee et al. 2022

THE SYNCHRONY OF PRODUCTION & ESCAPE

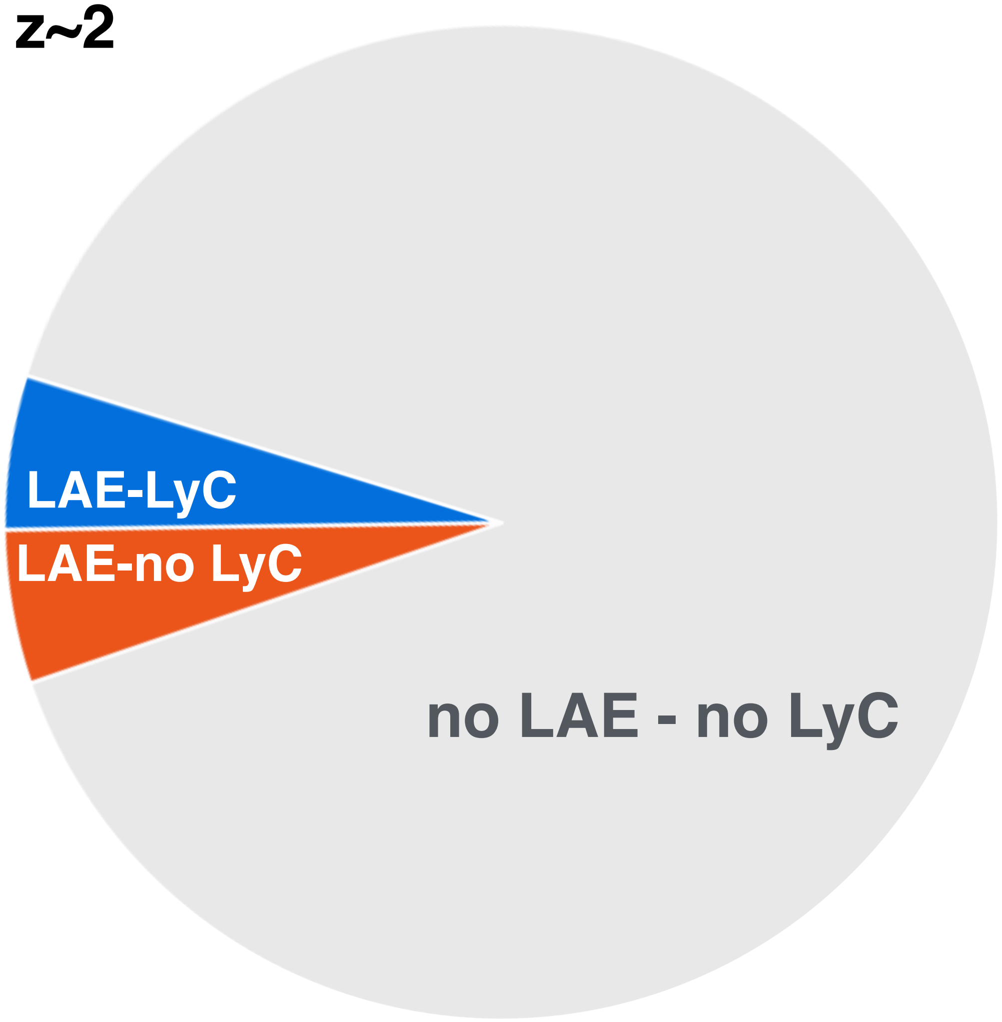


Naidu & Matthee et al. 2022

- **Ionizing photon escape occurs in rare bursty phases, even in *intermediate-mass* galaxies**
  Naidu&Matthee et al. 2022
- **<u>Clear and well-understood selection function allows *cosmic* averages</u>**
  Matthee&Naidu et al. 2022

DEMOGRAPHICS OF F_{ESC} AMONG SFGS (BASED ON LFS)

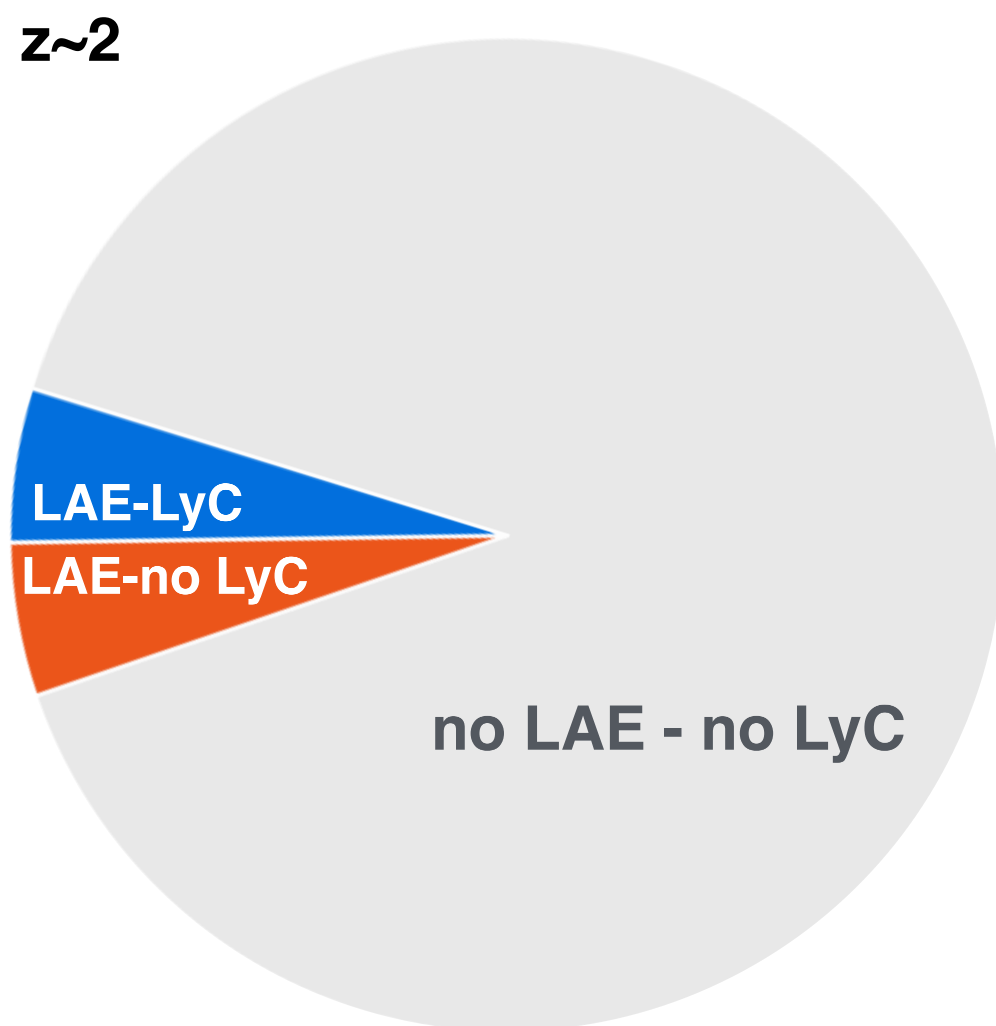
z~2



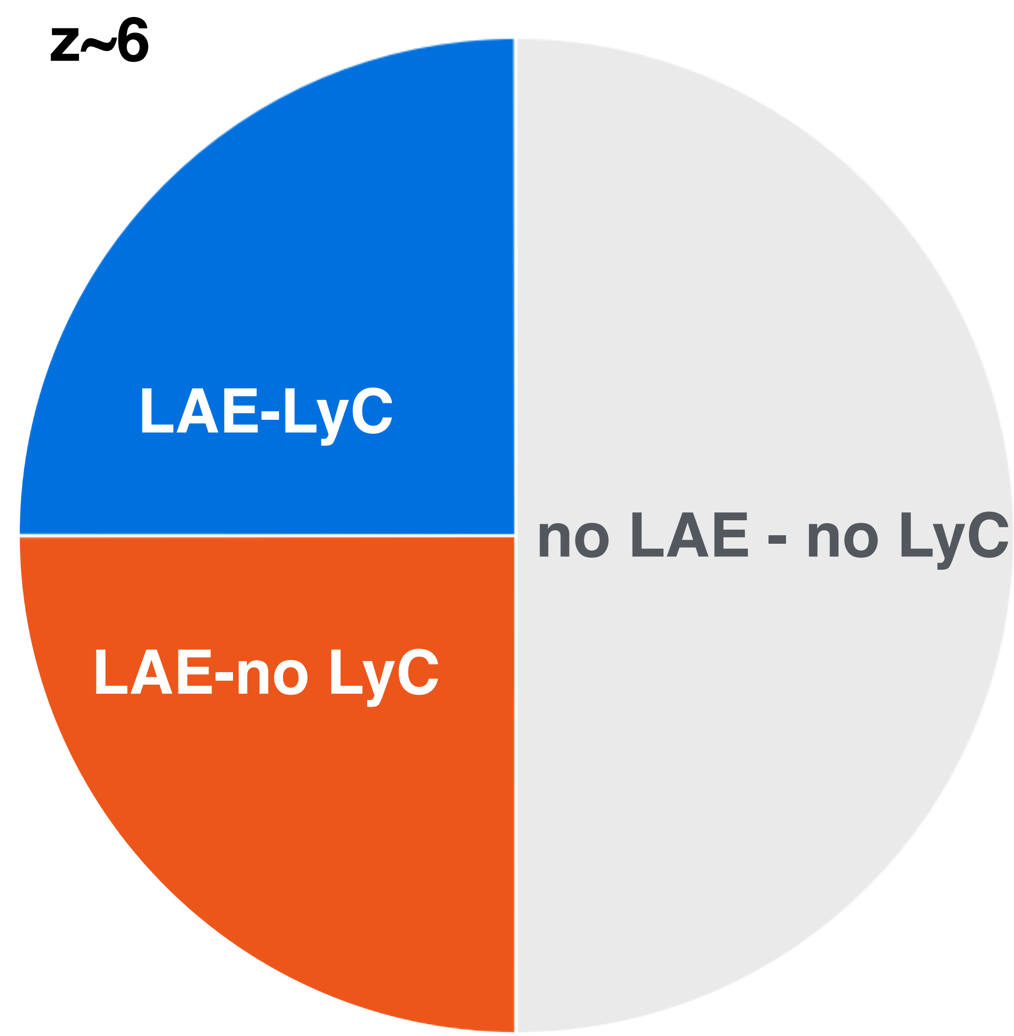
<f_{esc}> ~ 1-2.5%

Matthee & Naidu et al. 2022

Demographics of F_{esc} among SFGs (based on LFs)



$\langle f_{esc} \rangle \sim$ 1-2.5%



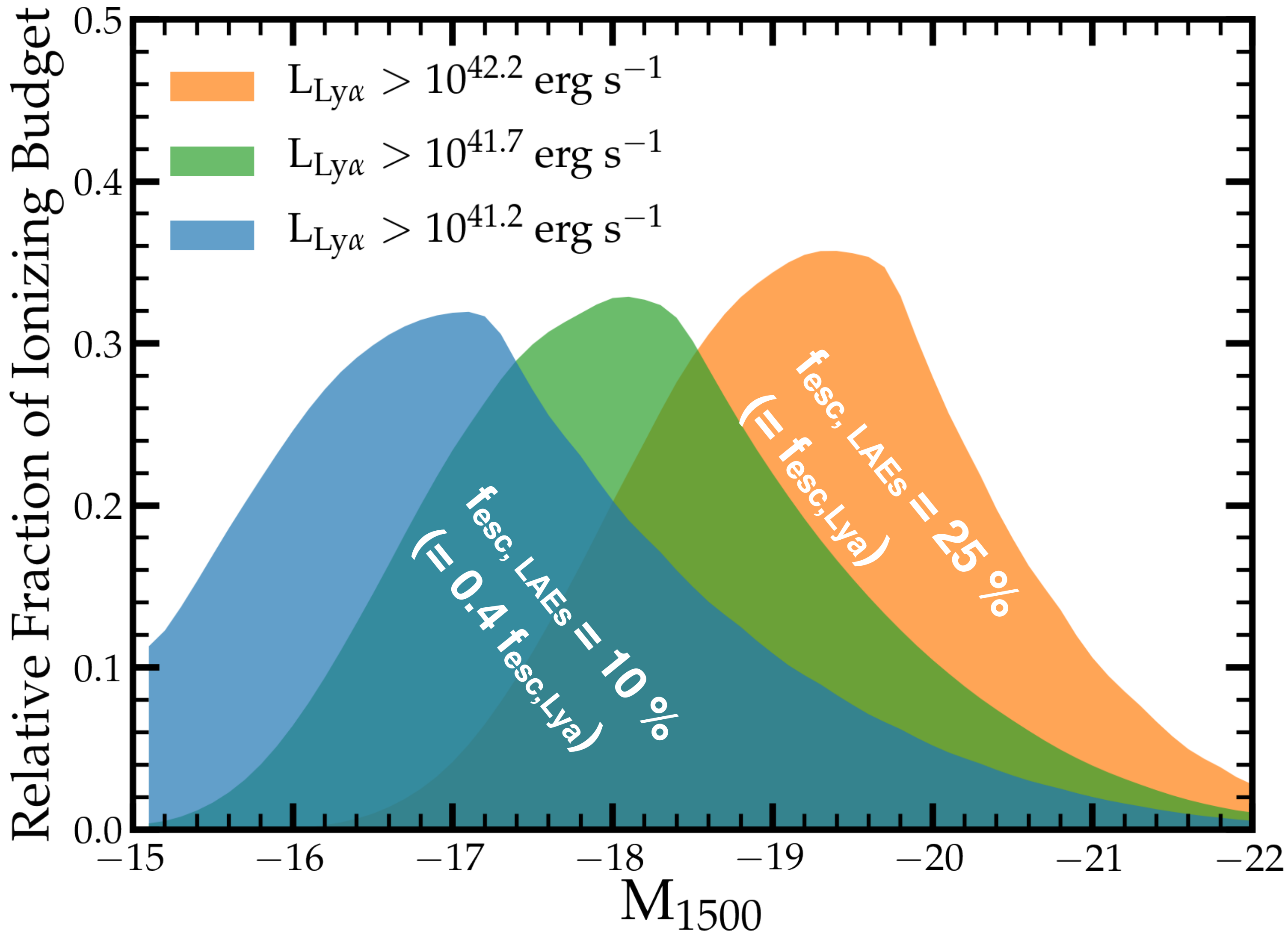
$\langle f_{esc} \rangle \sim$ 5-12.5%

—> The average $\langle f_{esc} \rangle$ of the galaxy population very likely evolves!

LAE fraction increase see also Stark+2010, Hayes+2011, Cassata+2015, Konno+2016

Matthee & Naidu et al. 2022

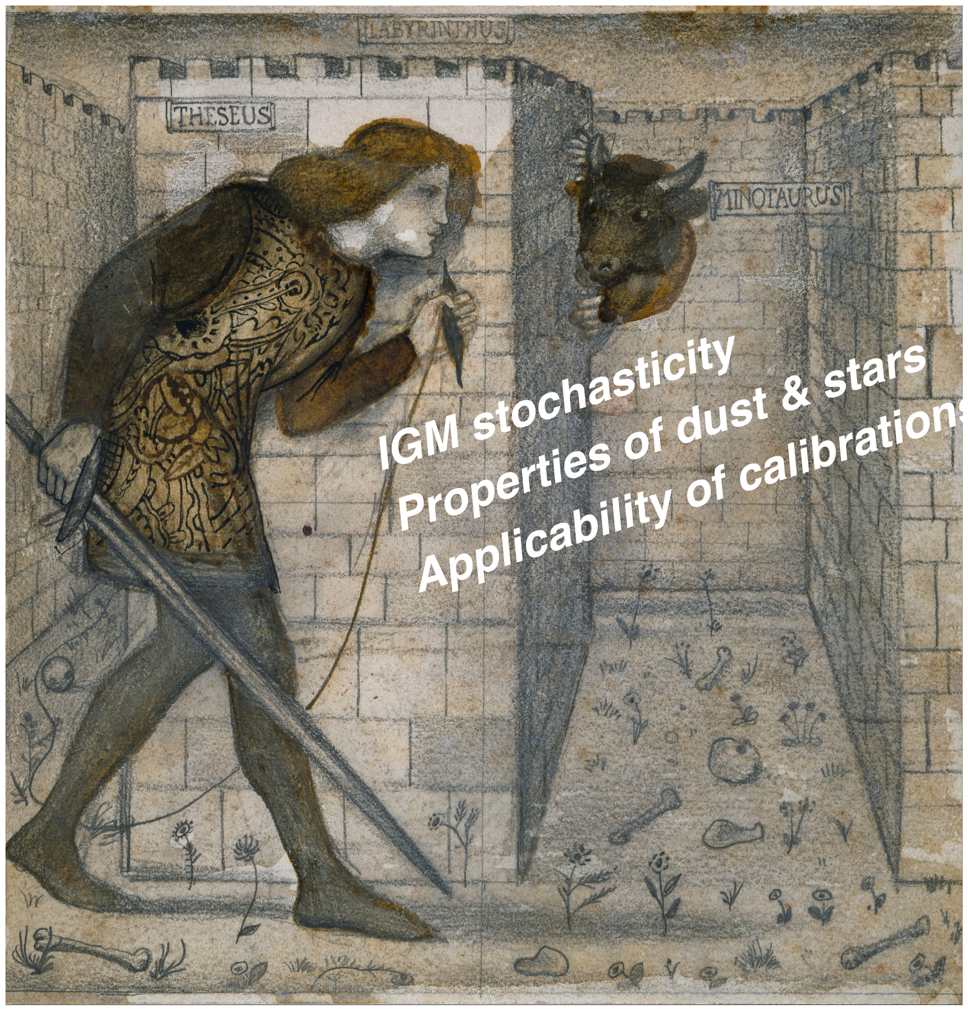
Ongoing question: How is <F_{ESC}> distributed among galaxies?



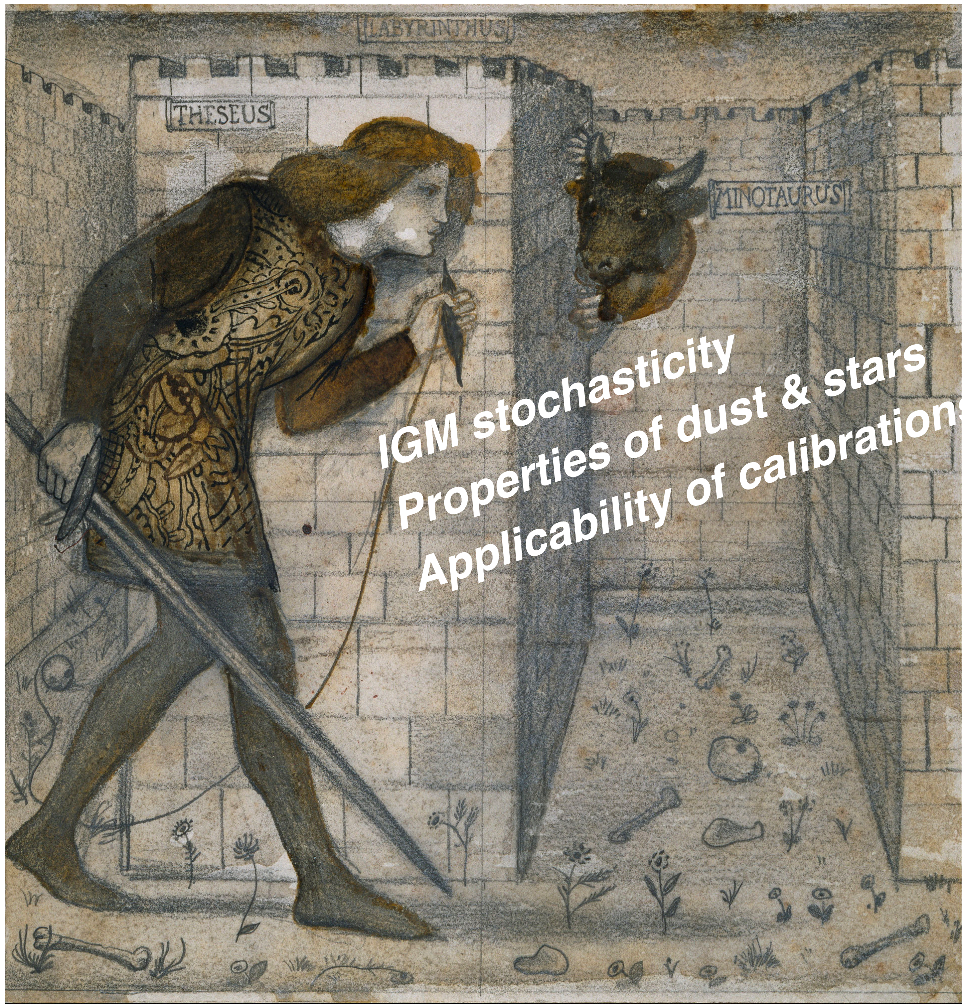
Indirect indicators suggest f_{esc} = 10-25 % for LAEs

But this relatively narrow range has significant impact on the distribution of the ionizing photon budget!

Matthee & Naidu et al. 2022



LABYRINTHUS
THESEUS
MINOTAURUS
IGM stochasticity
Properties of dust & stars
Applicability of calibration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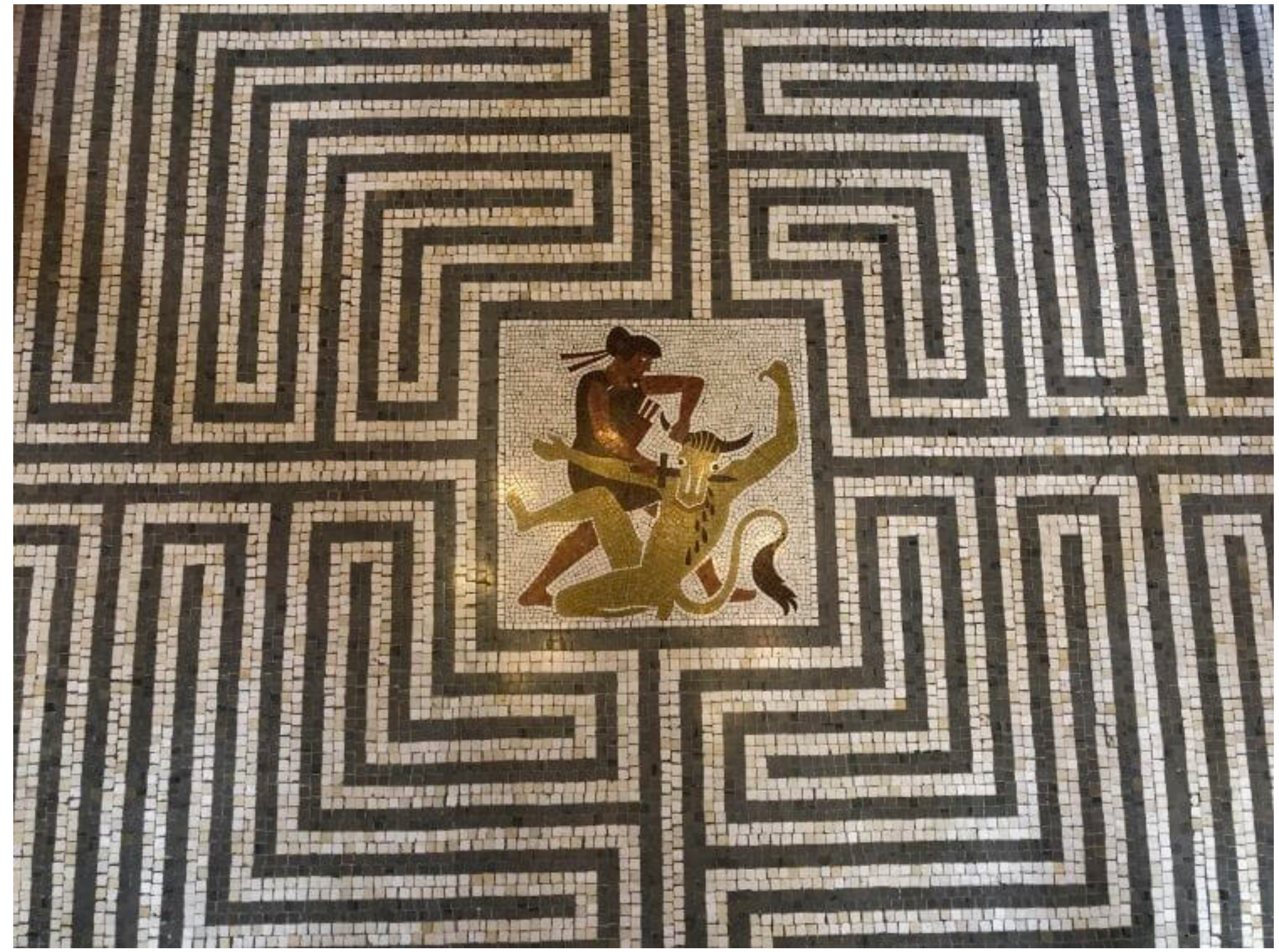


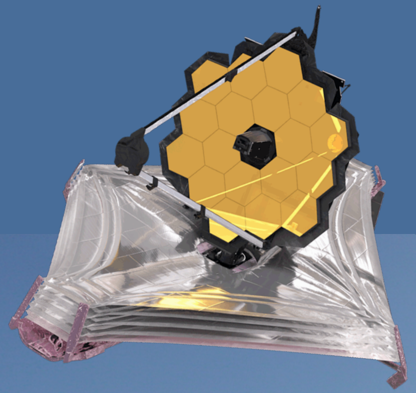
EIGER

Emission-line Galaxies and Intergalactic Gas in the Epoch of Reionization

- **A large 120 hr Cycle 1 JWST GTO program (PI Simon Lilly)**

- **JWST/NIRCam imaging and slitless spectroscopy in 6 quasars at z=6-7**
- 21 arcmin^2 Imaging magnitude ~29, spectroscopy at 3-4 micron 2x10^{-18} erg/s/cm2 (S/N=5)

- **Main science goal: Directly measure the relation between galaxies and IGM at z~5-7**



Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization

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Robert A. Simcoe (MIT)

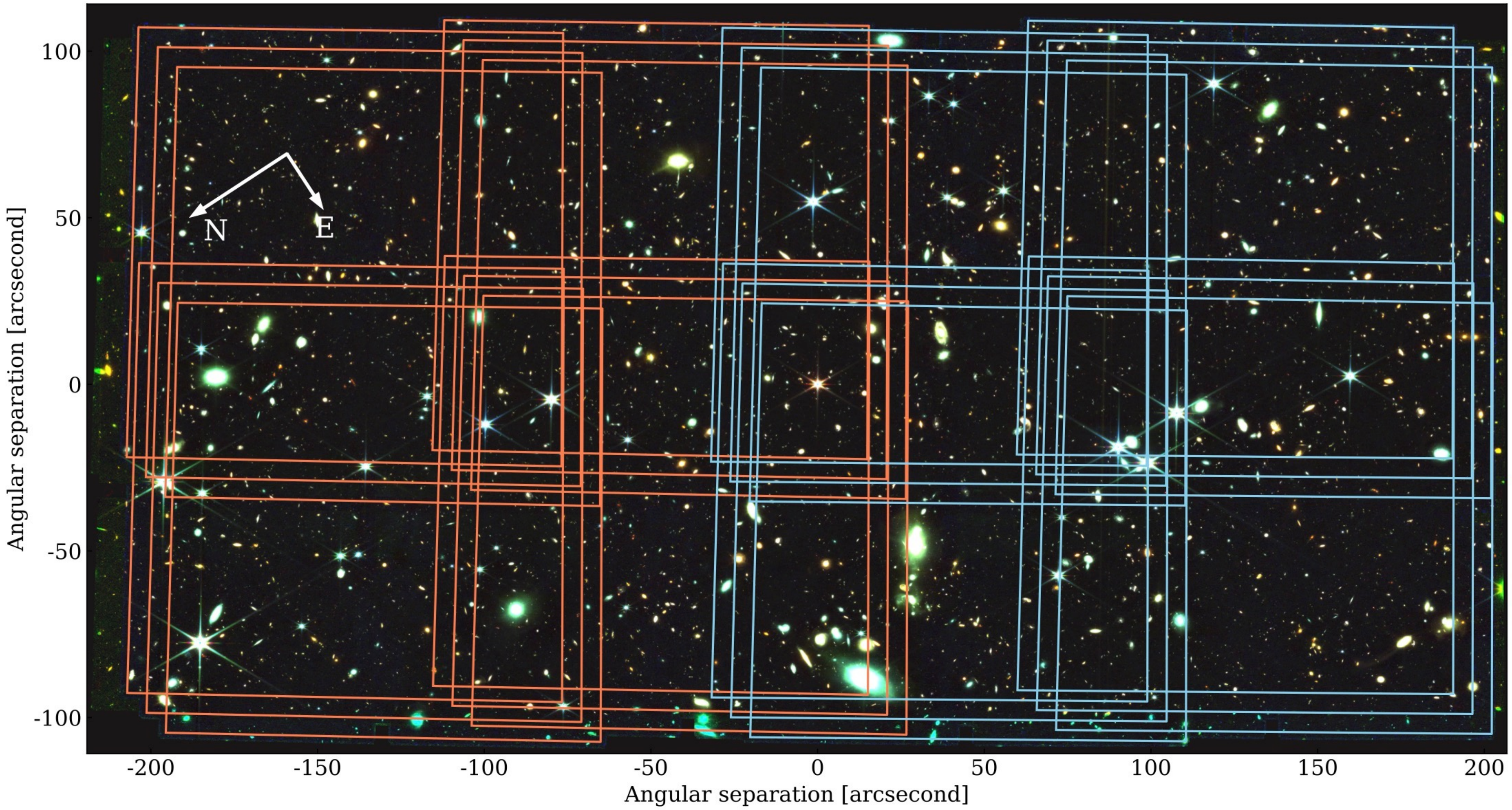
Rongmon Bordoloi (NCSU)

Anna-Christina Eilers (MIT)

Jorryt Matthee (ETH Zurich)

EIGER

EMISSION-LINE GALAXIES AND INTERGALACTIC GAS IN THE EPOCH OF REIONIZATION

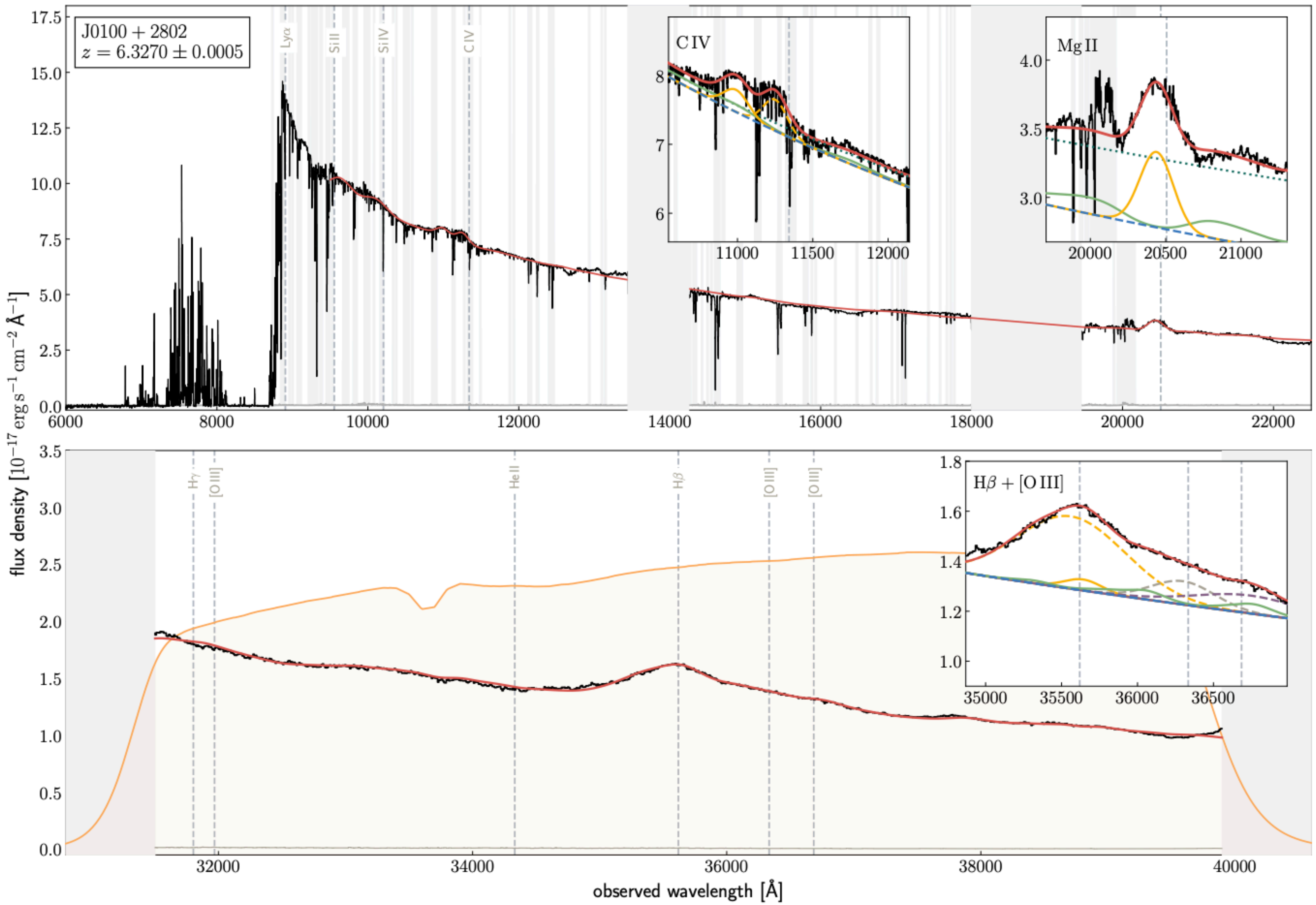


Quasars:

- **J0100+2802 — the most luminous quasar and the most massive BH at z>6**
- **J1148+5251 — the highest number of CIV absorbers at z~4-5**
- **J1120+0641 — first QSO at z>7, record for >6 years**
- **J0148+0600 — the longest Gunn-Peterson trough at z~5.7**
- **J1030+0524 — for long time, the most distant SDSS quasar (ancillary data)**
- **J159-02 — highest number of MgII absorbers at z>6**

Survey paper: Kashino+2023

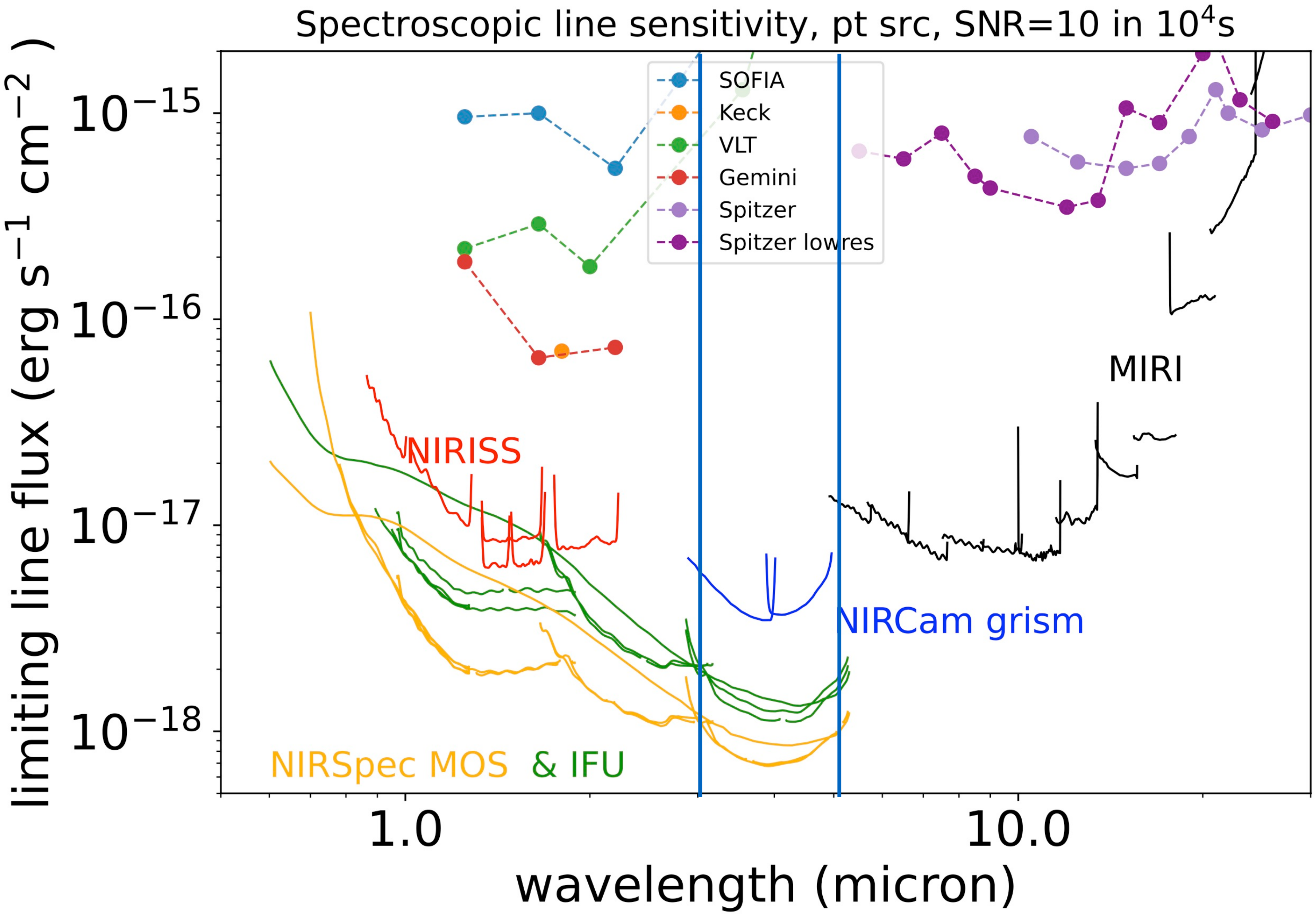
Emission-line galaxies and Intergalactic Gas in the Epoch of Reionization



- **J0100+2802 — the most luminous quasar and the most massive BH at z>6**

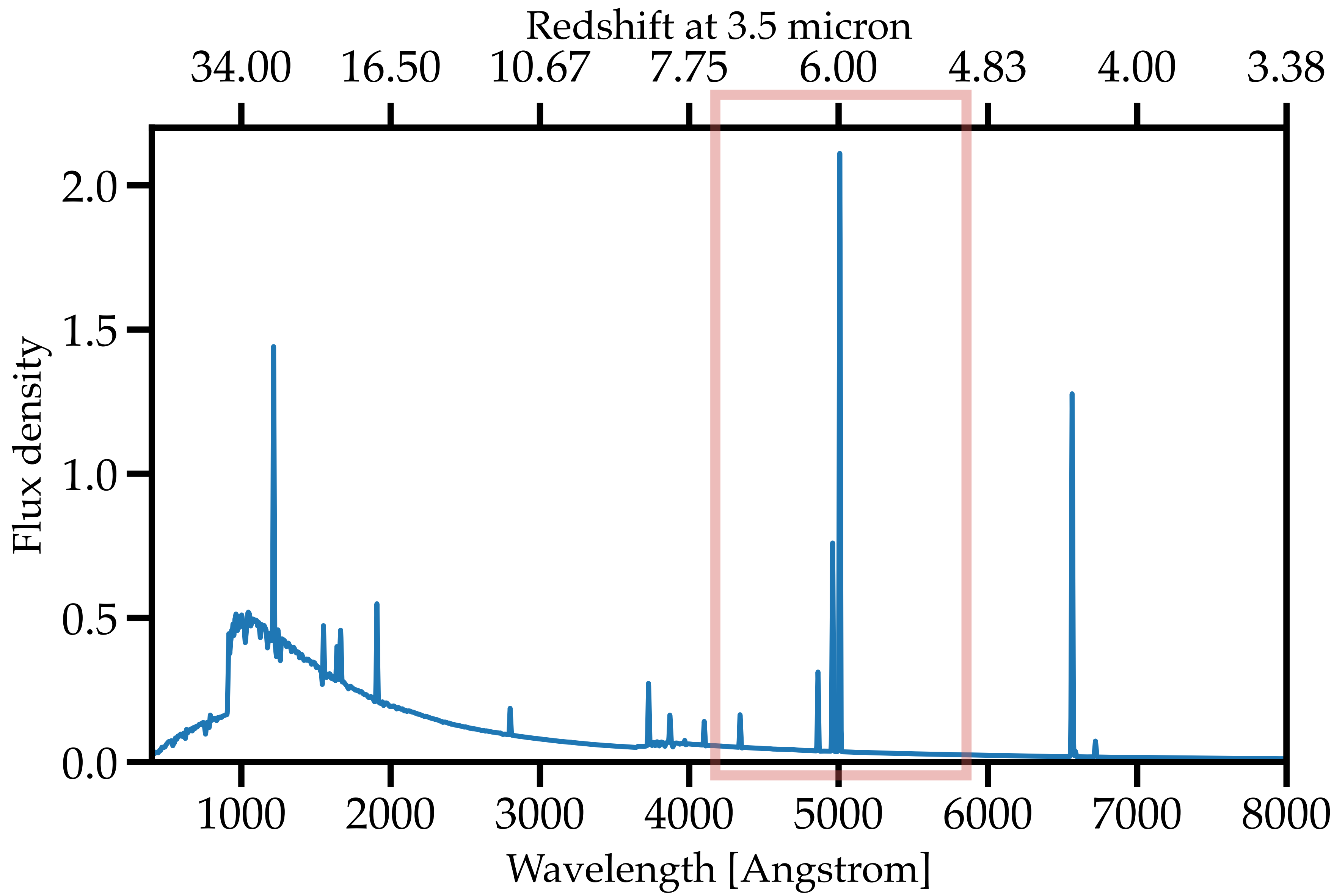
QSO spectrum: Eilers+23

EIGER — PHILOSOPHY *GRISM SPECTROSCOPY WHERE JWST IS BEST*



Rigby+22

EIGER — *Grism spectroscopy where EoR galaxies are brightest*

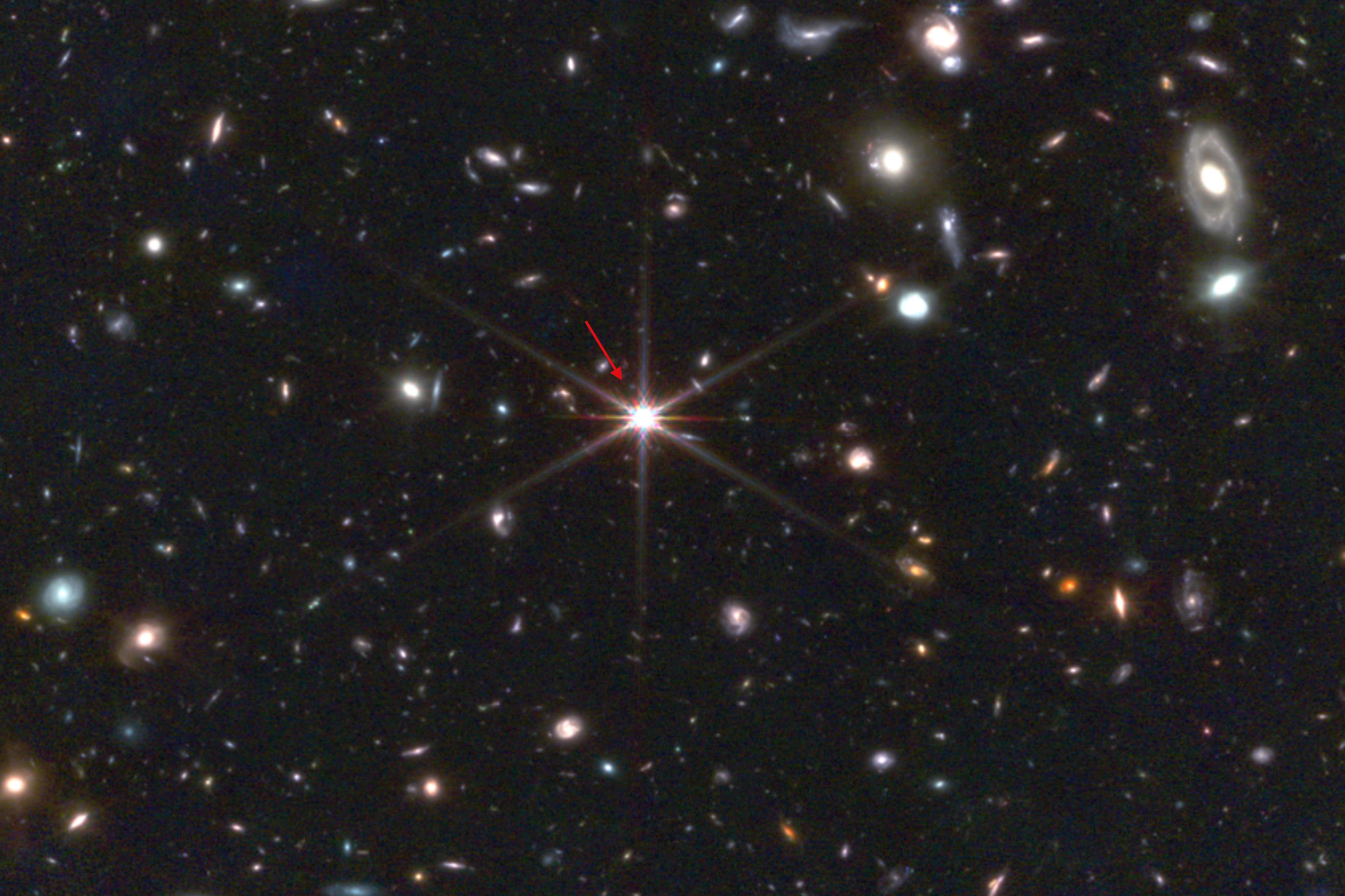


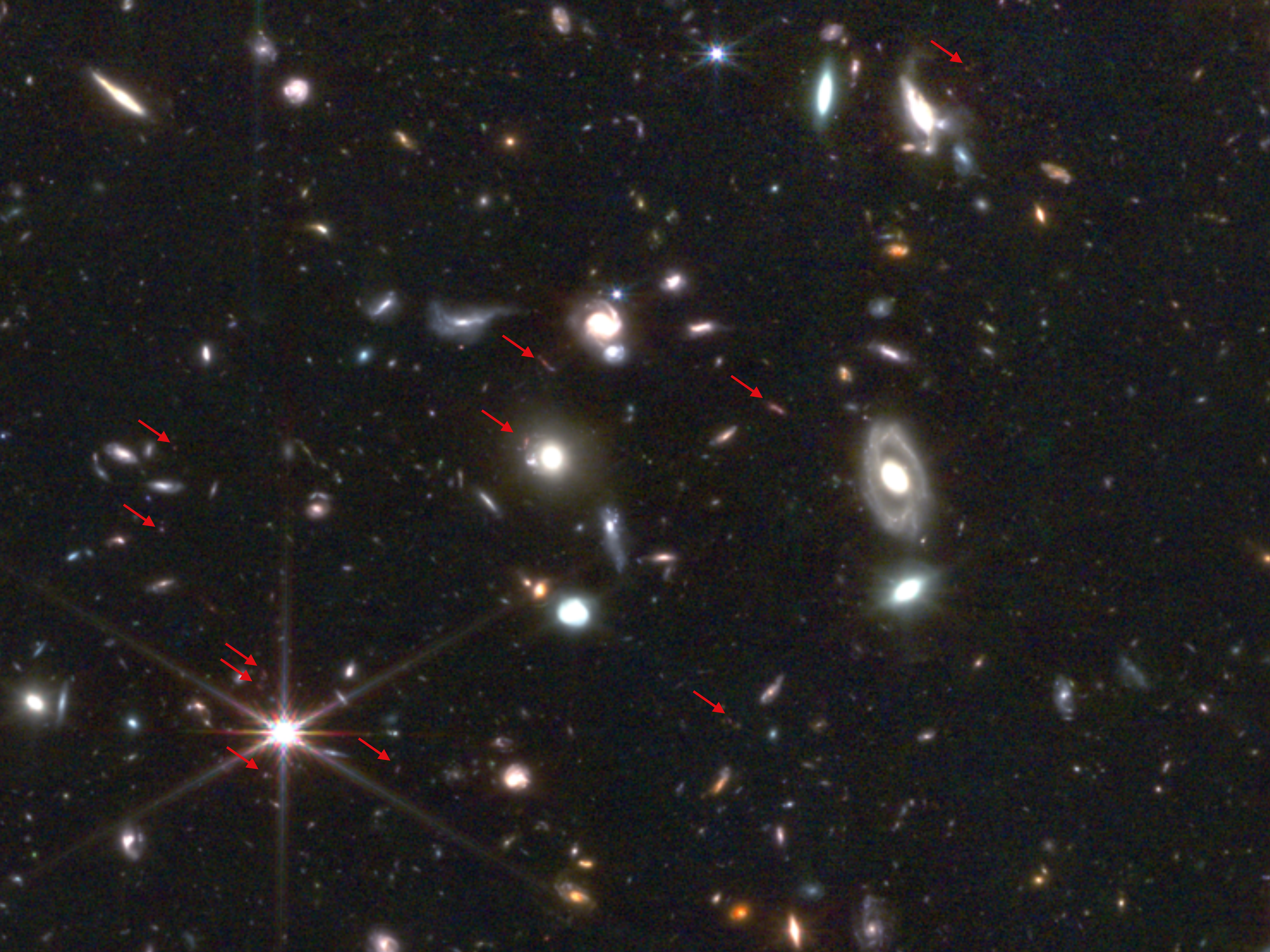
- **Young galaxies have very strong emission-lines in the rest-frame optical**
- **These are observed at z~4-9 at 3-5 micron where *JWST* is most sensitive**

see e.g. analogues studied by Izotov+21, +++


F115W/F200W/F356W *JWST* NIRCam, ~10 hours
The EIGER team

QSO J0100+2802





DATA PROCESSING NIRCAM/WFSS

JWST NIRCam (F115W/F200W/F356W)

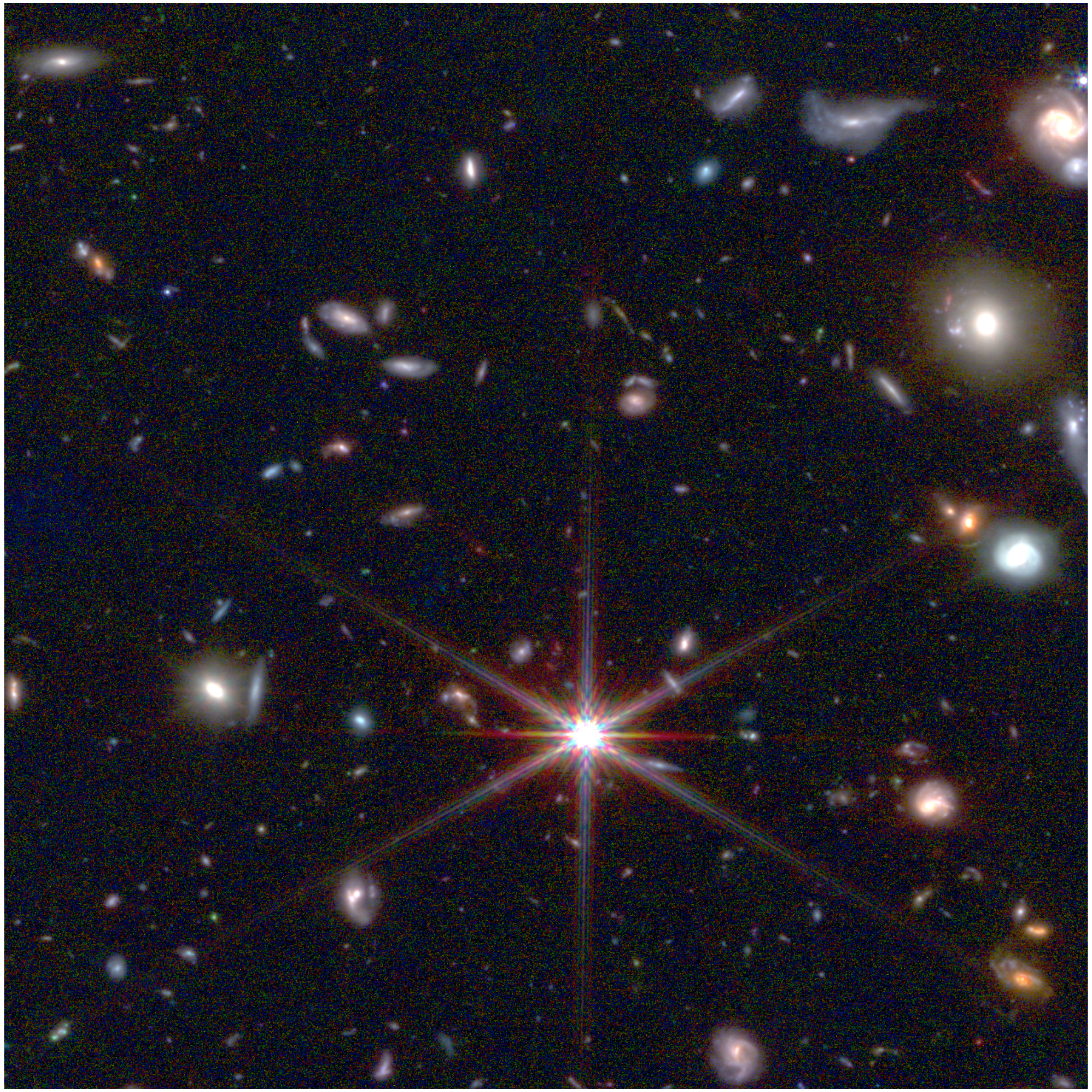


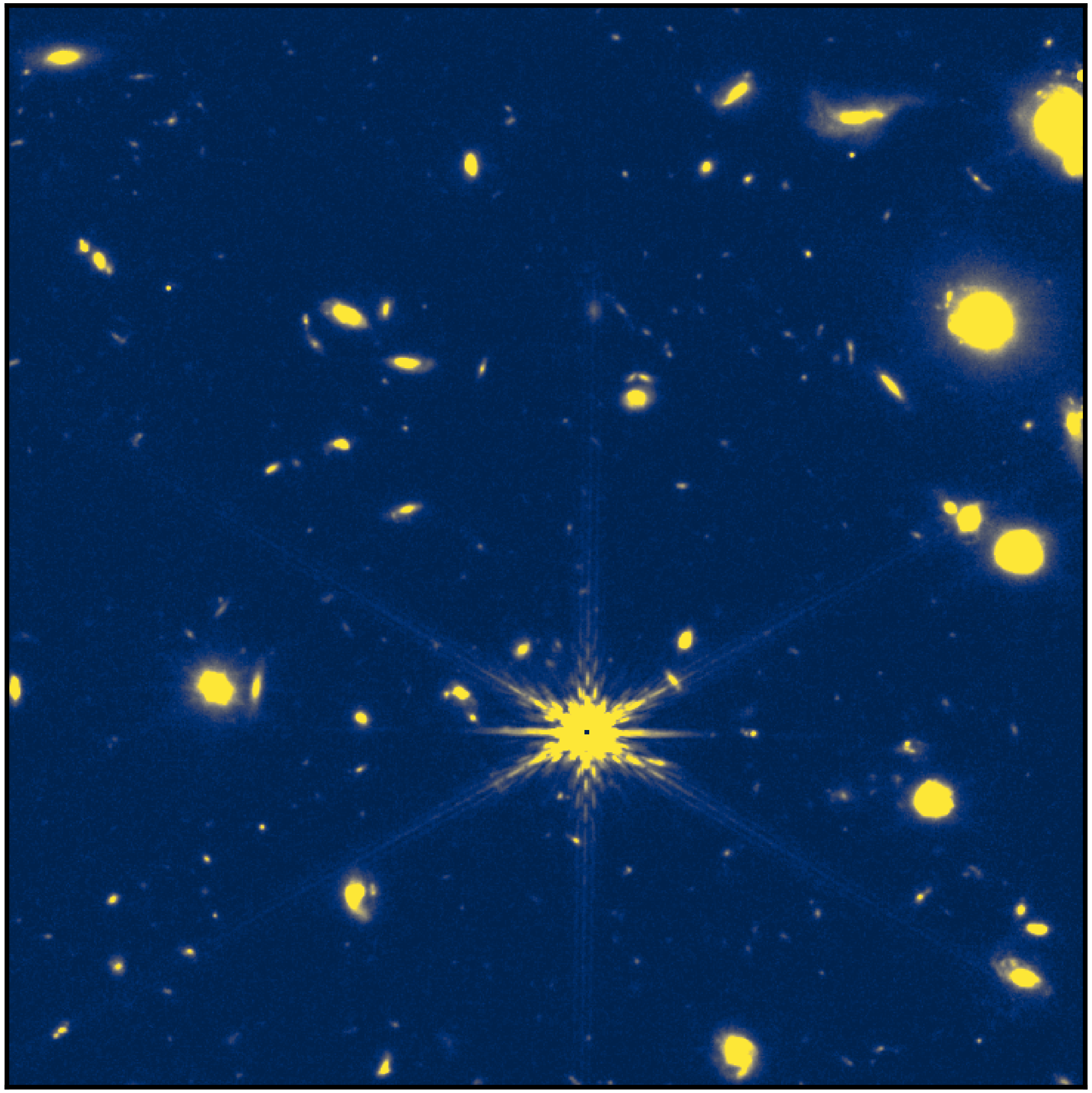
Image credit: Matthee & Mackenzie

QSO J0100+2802, z=6.3, 23 August 2022

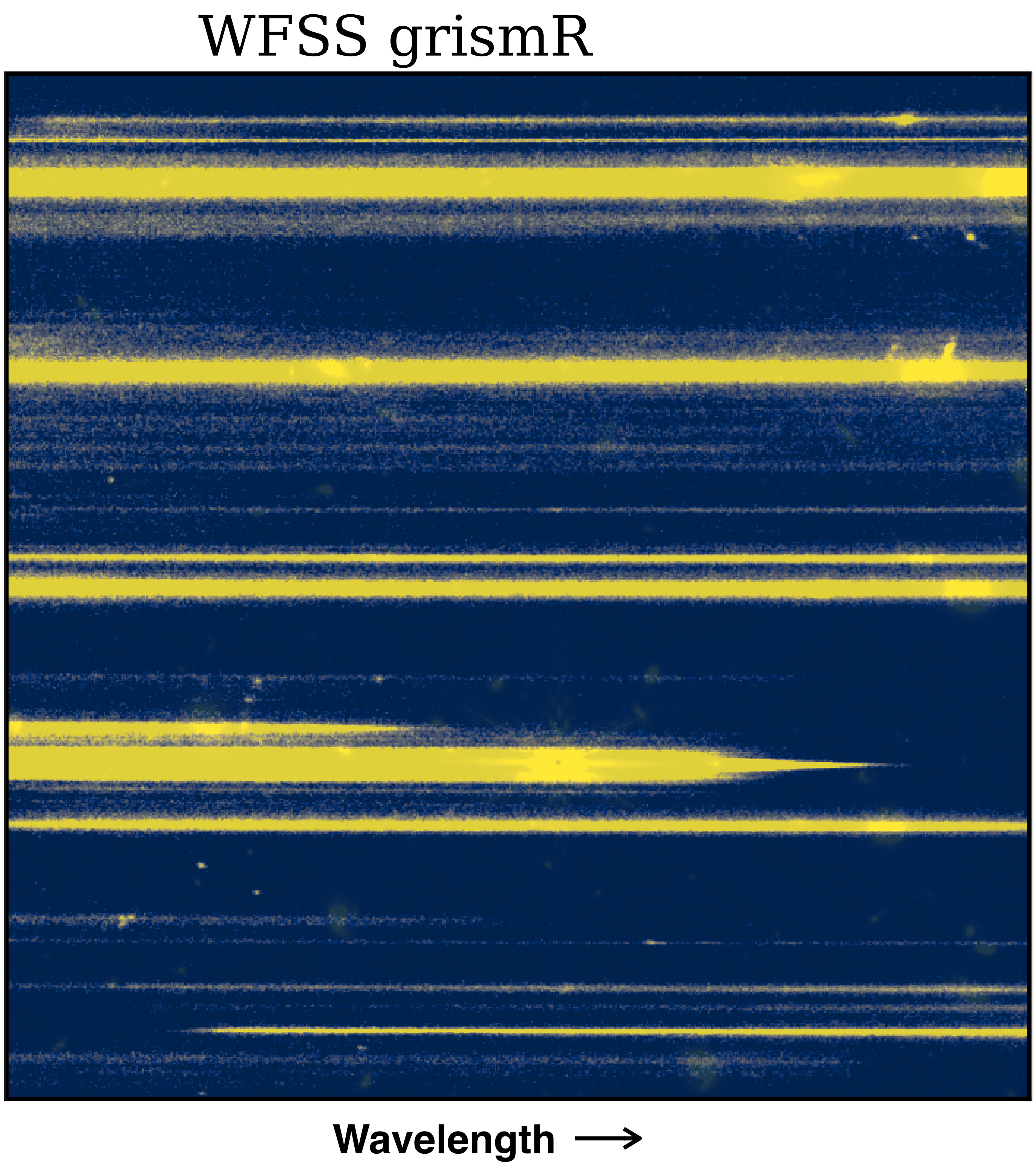
(~1% of total *AGENTS* data)

NIRCAM WFSS EMISSION LINE SELECTION

NIRCam F356W modA

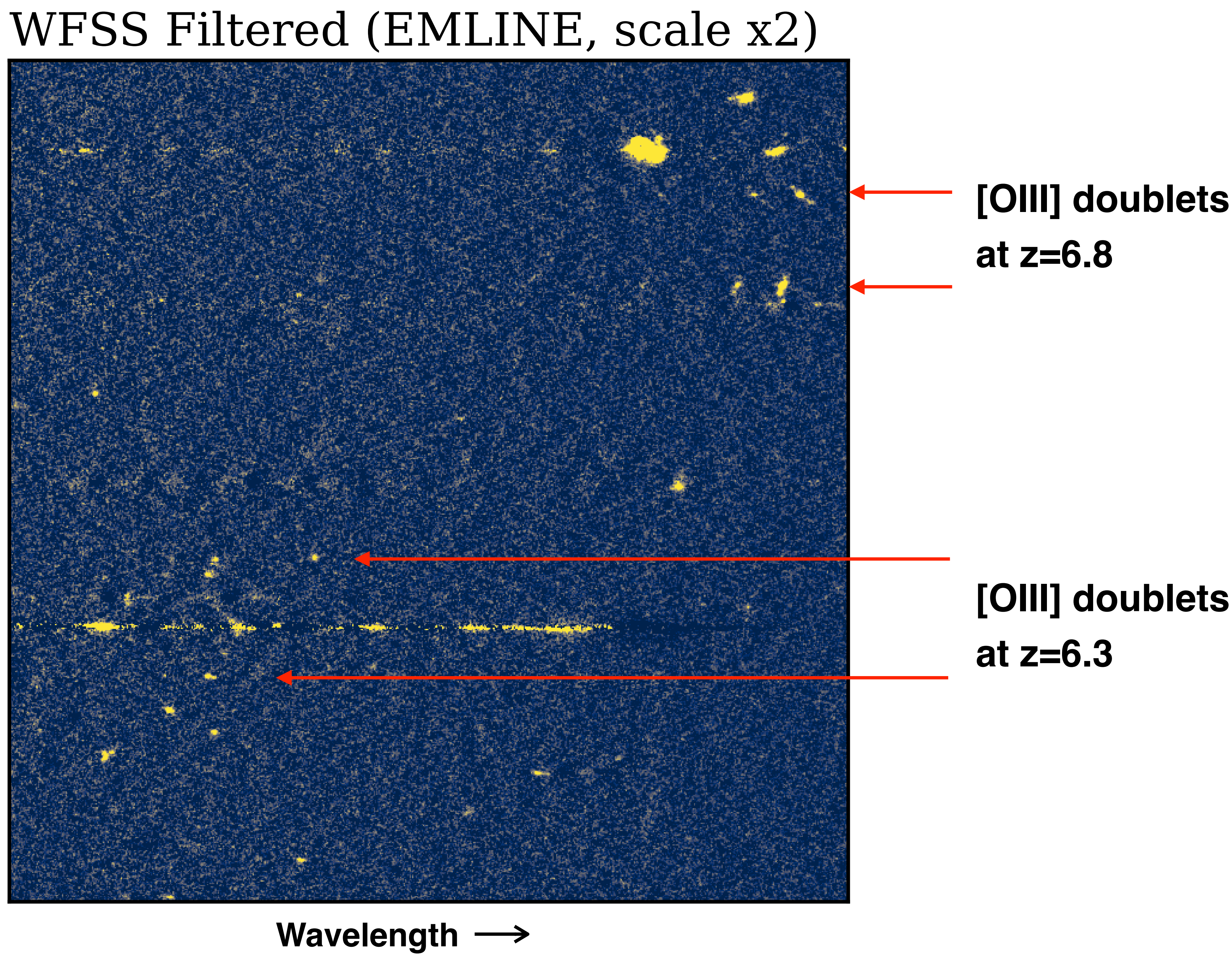


NIRCAM WFSS EMISSION LINE SELECTION



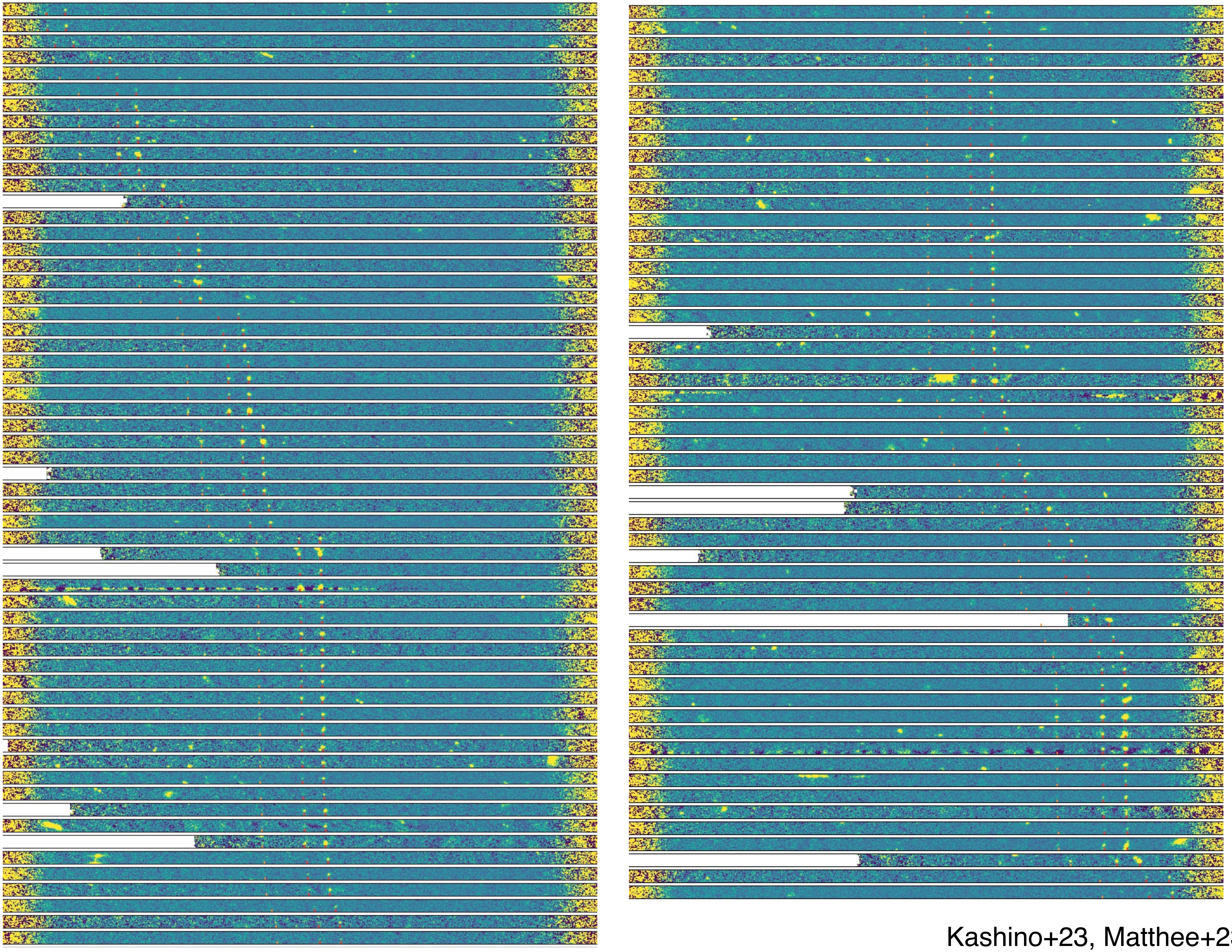
Note the high resolution R~1600 compared to e.g. HST grisms

NIRCAM WFSS EMISSION LINE SELECTION



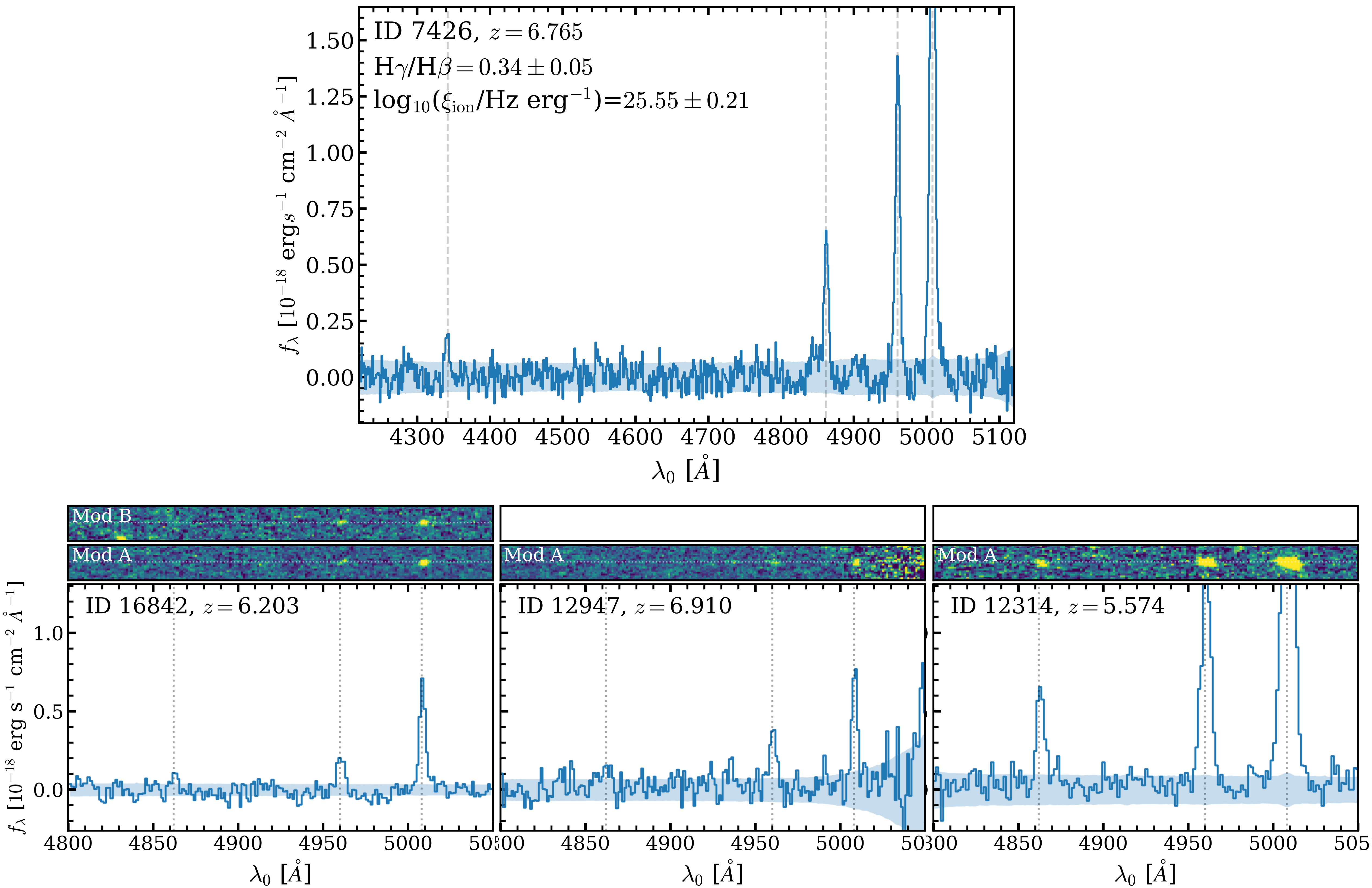
Kashino+23, Matthee+23

First batch of z~5-7 galaxies with [OIII] spectroscopic redshifts



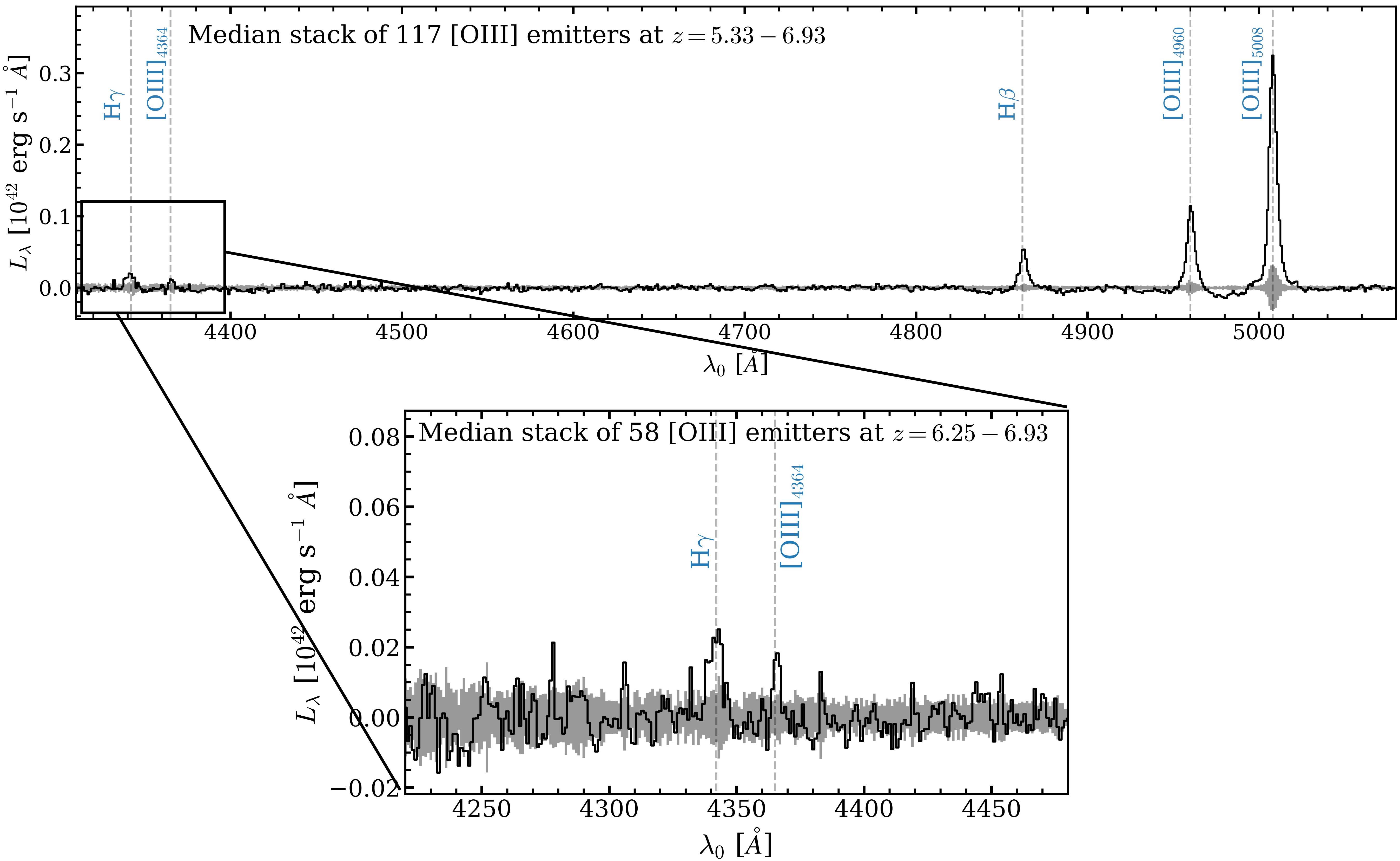
Kashino+23, Matthee+23

EIGER: Some example spectra



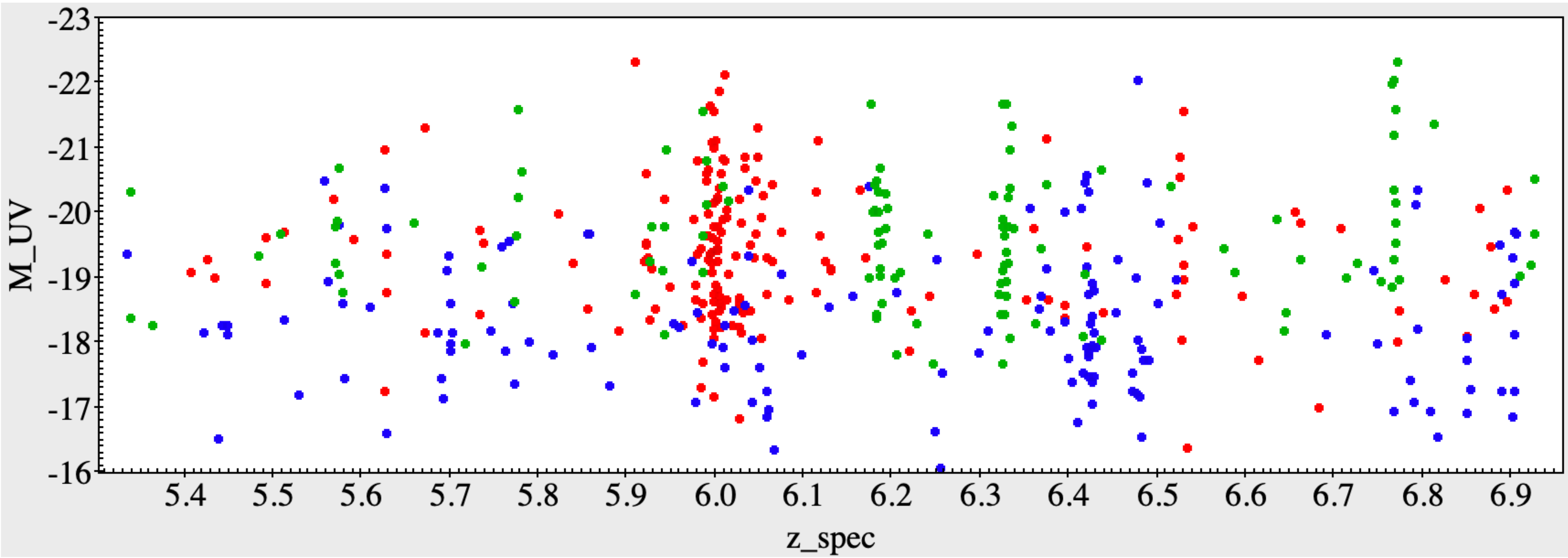
Matthee+23

EIGER: STACKED SPECTRUM REVEALS FAINT LINES AS HGAMMA, [OIII]4363



Matthee+23

EIGER: JWST/NIRCam is a redshift machine

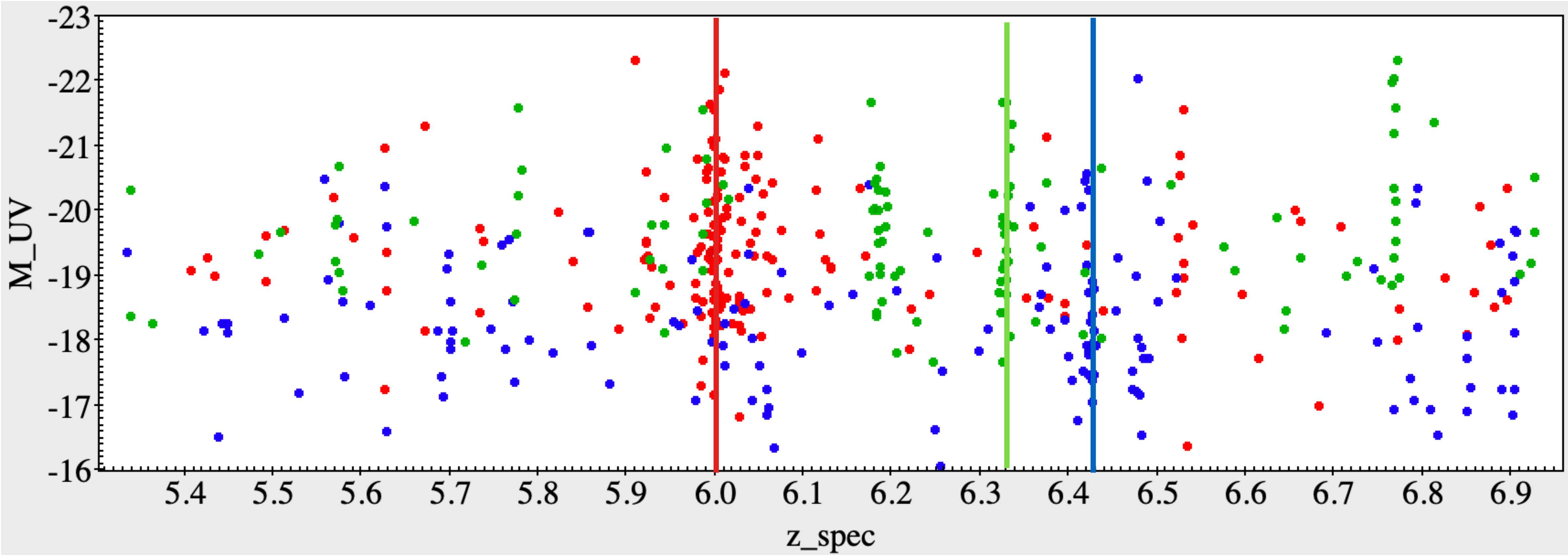


<u>50% of the EIGER data (status 17 April 2023):</u>

440 spectroscopic confirmed redshifts at z=5.3-6.9 with the [OIII] doublet

110 (220) of those also have Hbeta at S/N>5 (3)

EIGER: JWST/NIRCAM IS A REDSHIFT MACHINE



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440 spectroscopic confirmed redshifts at z=5.3-6.9 with the [OIII] doublet

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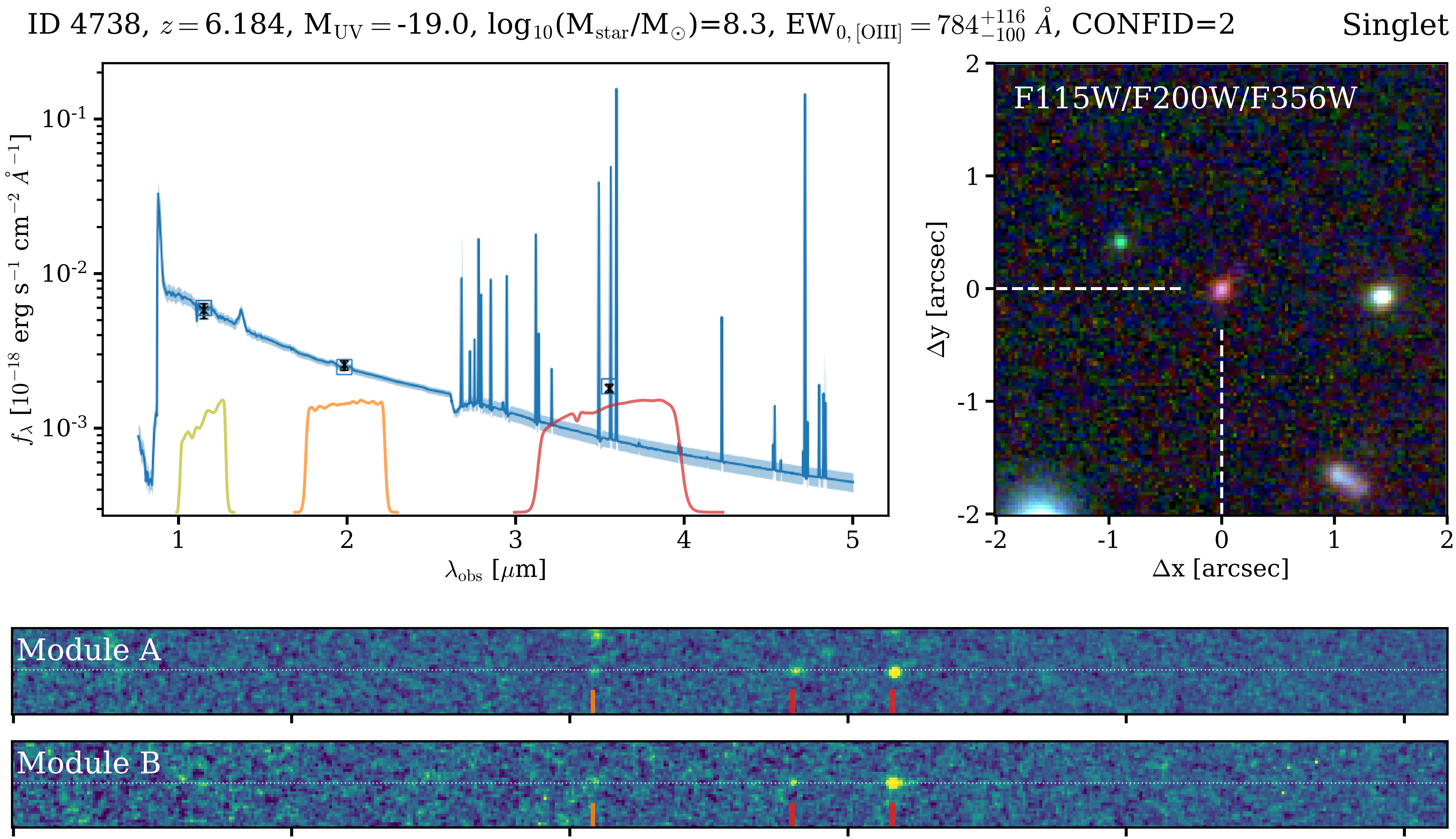
~25% of the objects are at the QSO redshifts

SOME EXAMPLE [OIII] EMITTERS ~800 MYR AFTER BIG BANG



Matthee+23

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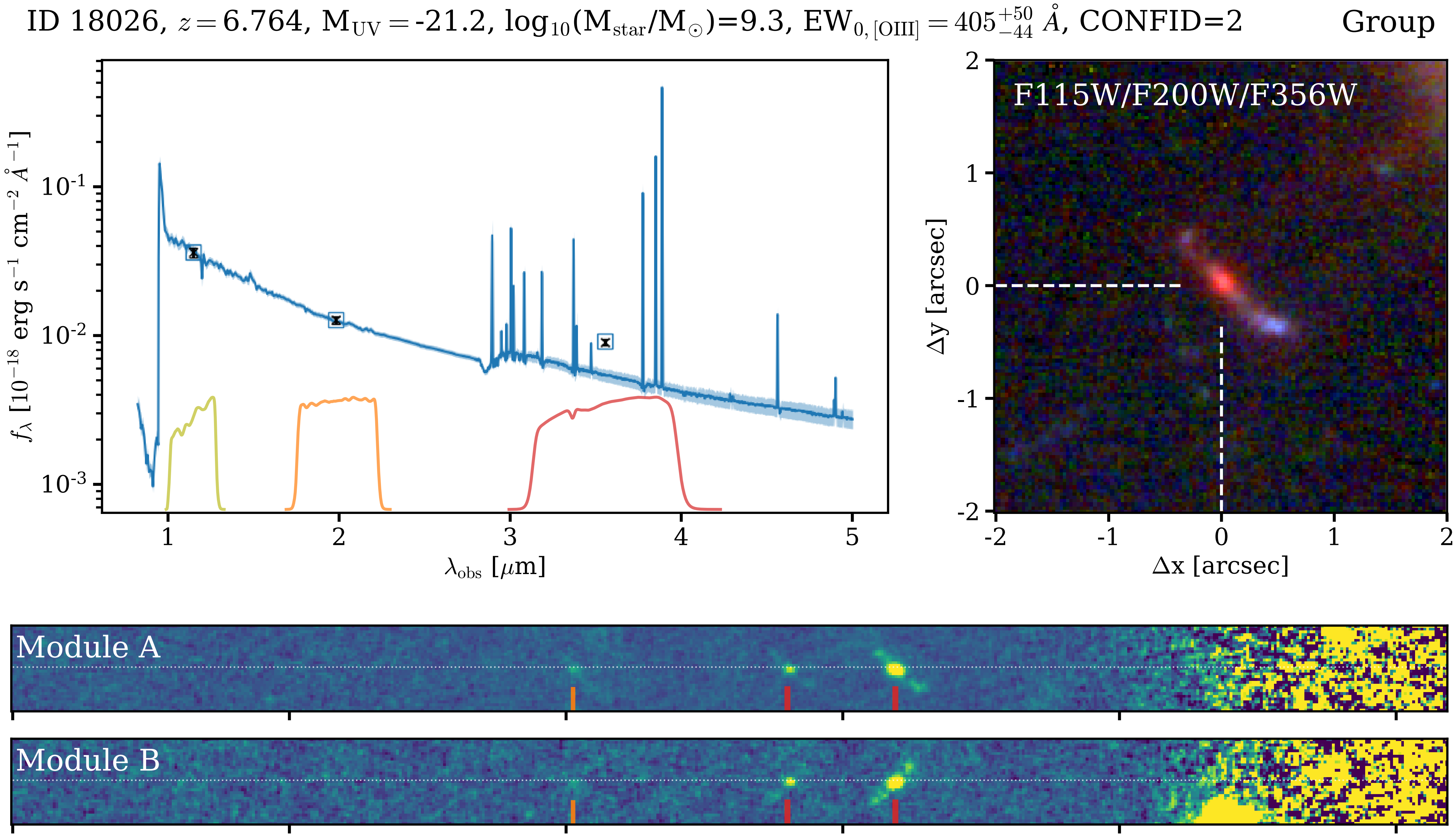

Matthee+23

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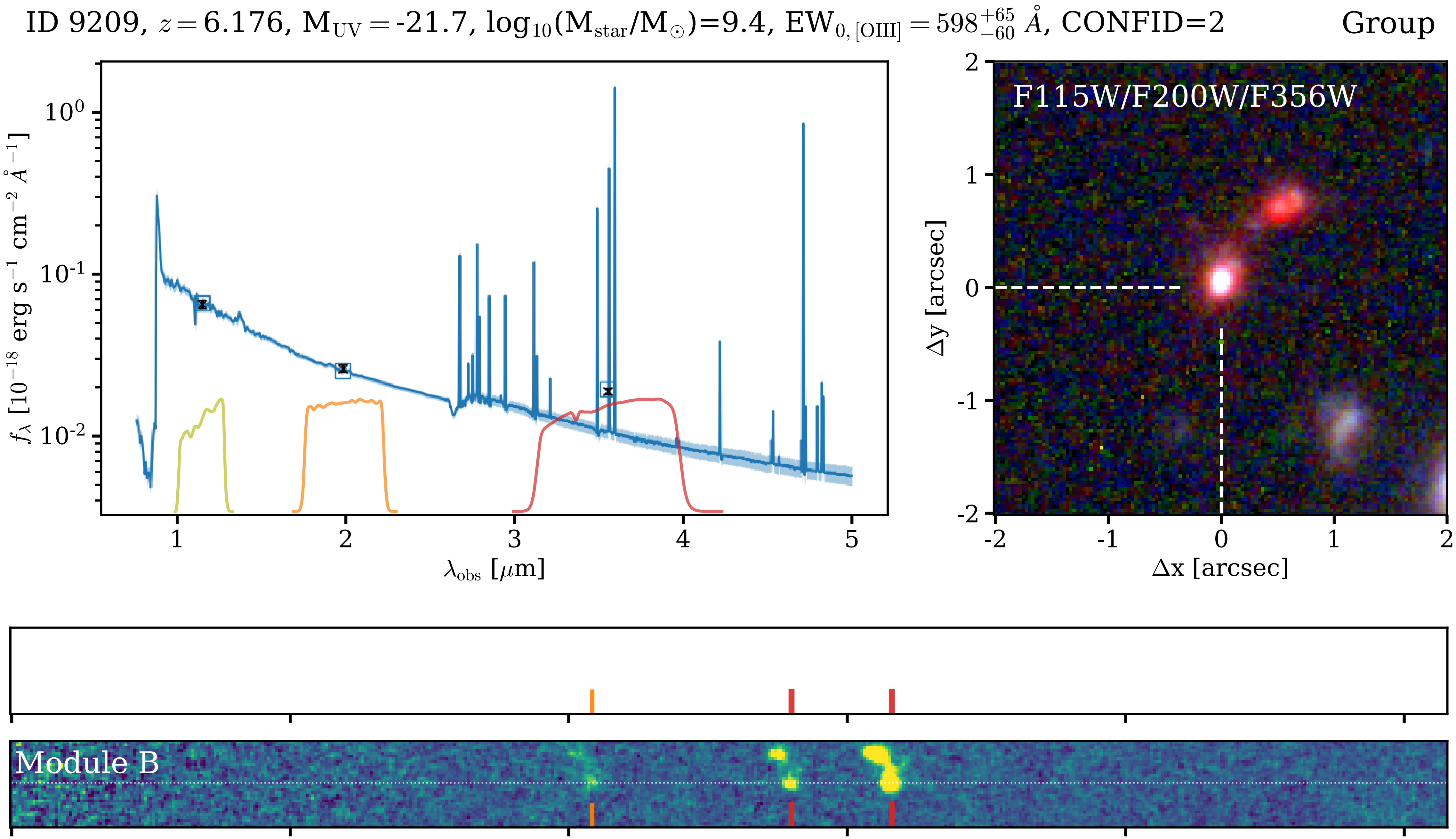
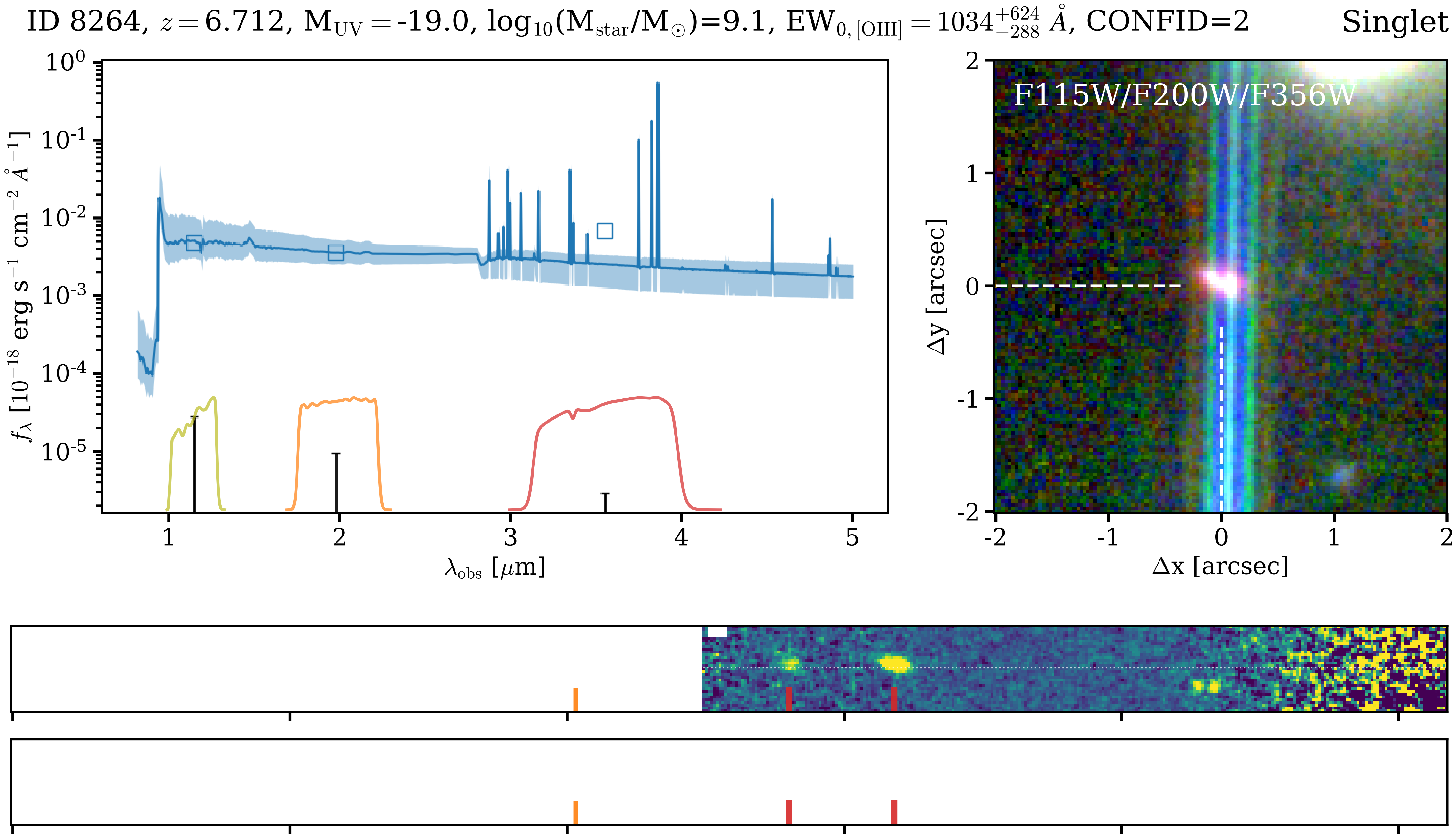


Matthee+23

SOME EXAMPLE [OIII] EMITTERS ~800 MYR AFTER BIG BANG

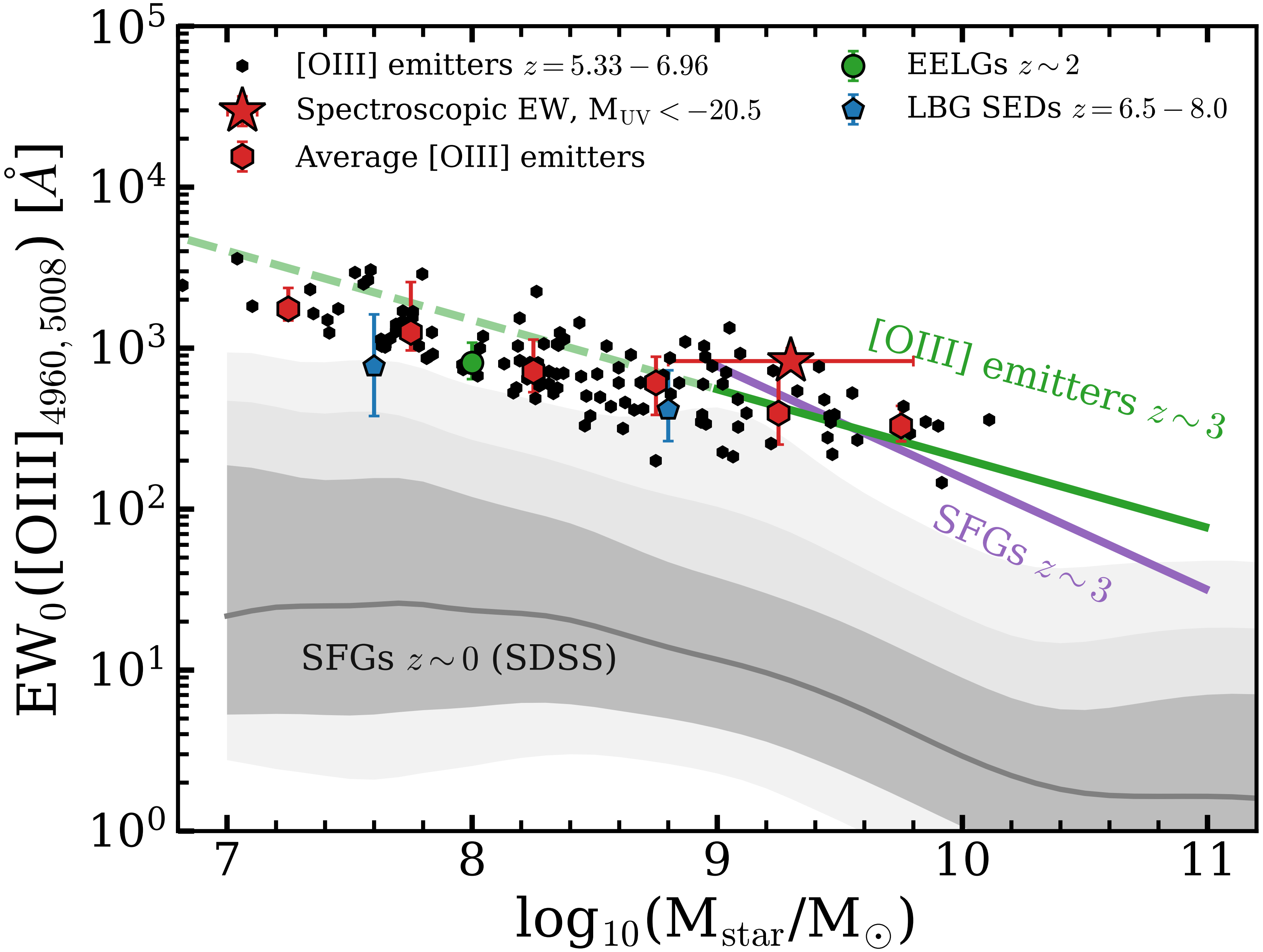


You would never put a slit on this object..

Matthee+23

EIGER:

Confirmation that z~5-7 galaxies have *ubiquitous* strong Hβ+[OIII] lines



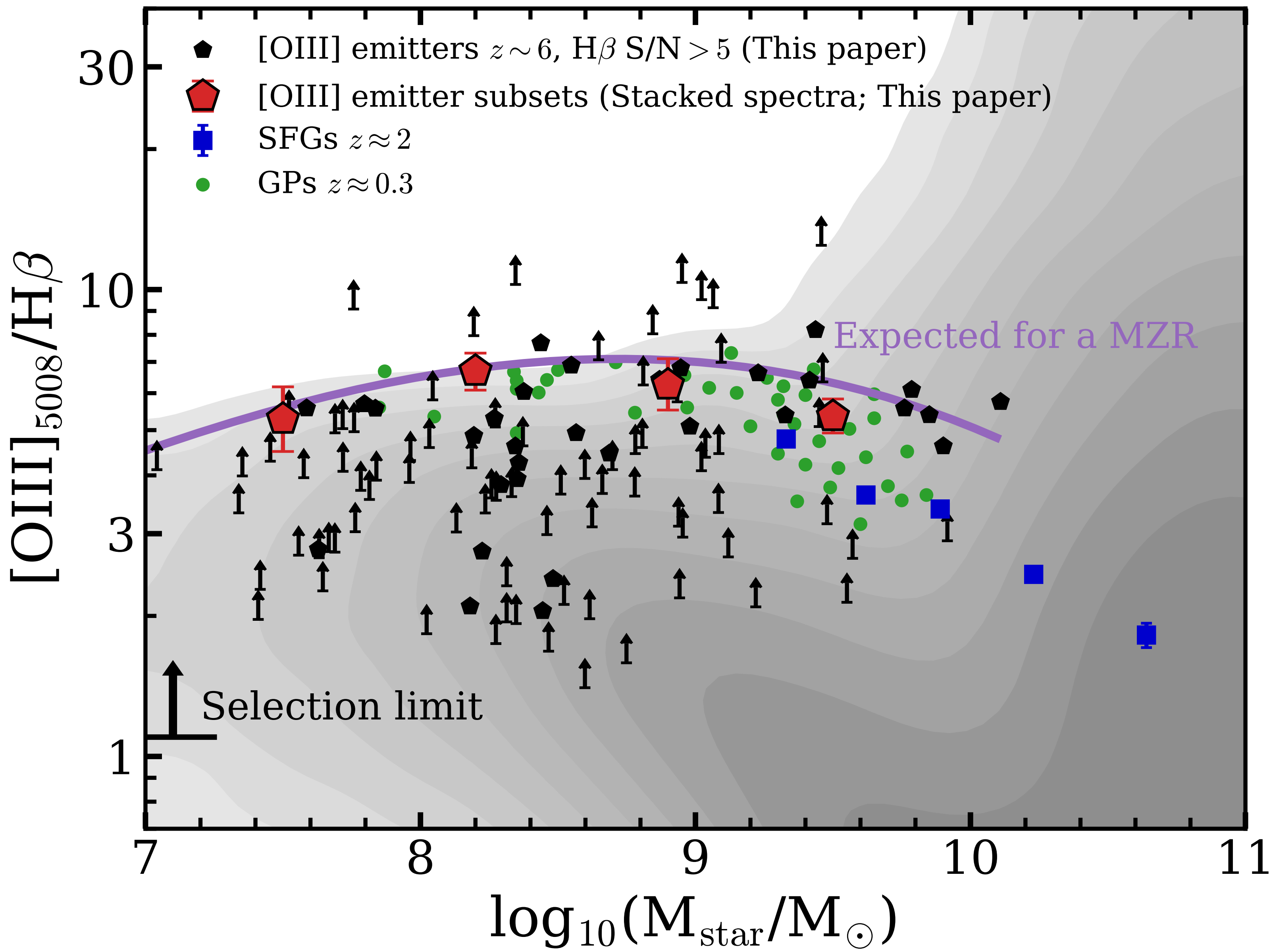
Typical EWs ~1000 A, only found in <1% of SDSS galaxies

EWs are higher for lower mass galaxies, extending z~2-3 results

Matthee+23

EIGER:

Confirmation that z~5-7 galaxies have a highly excited ISM



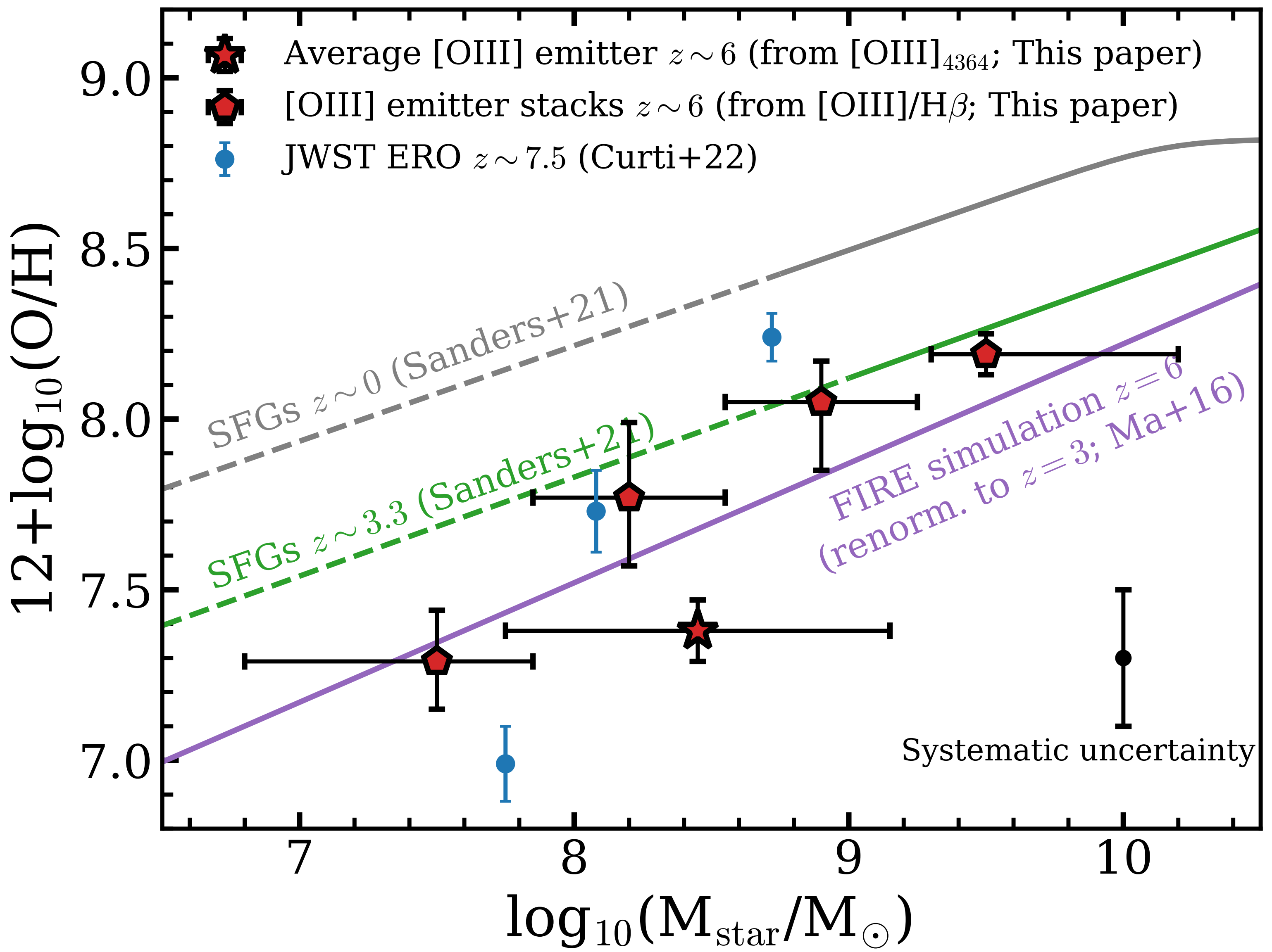
O3/Hb ratios are very high ~5

extending z~2-3 results (e.g. Sanders+21) down to ~50x lower masses

Matthee+23

EIGER:

First indication that z~5-7 galaxies follow a Mass - Metallicity relation



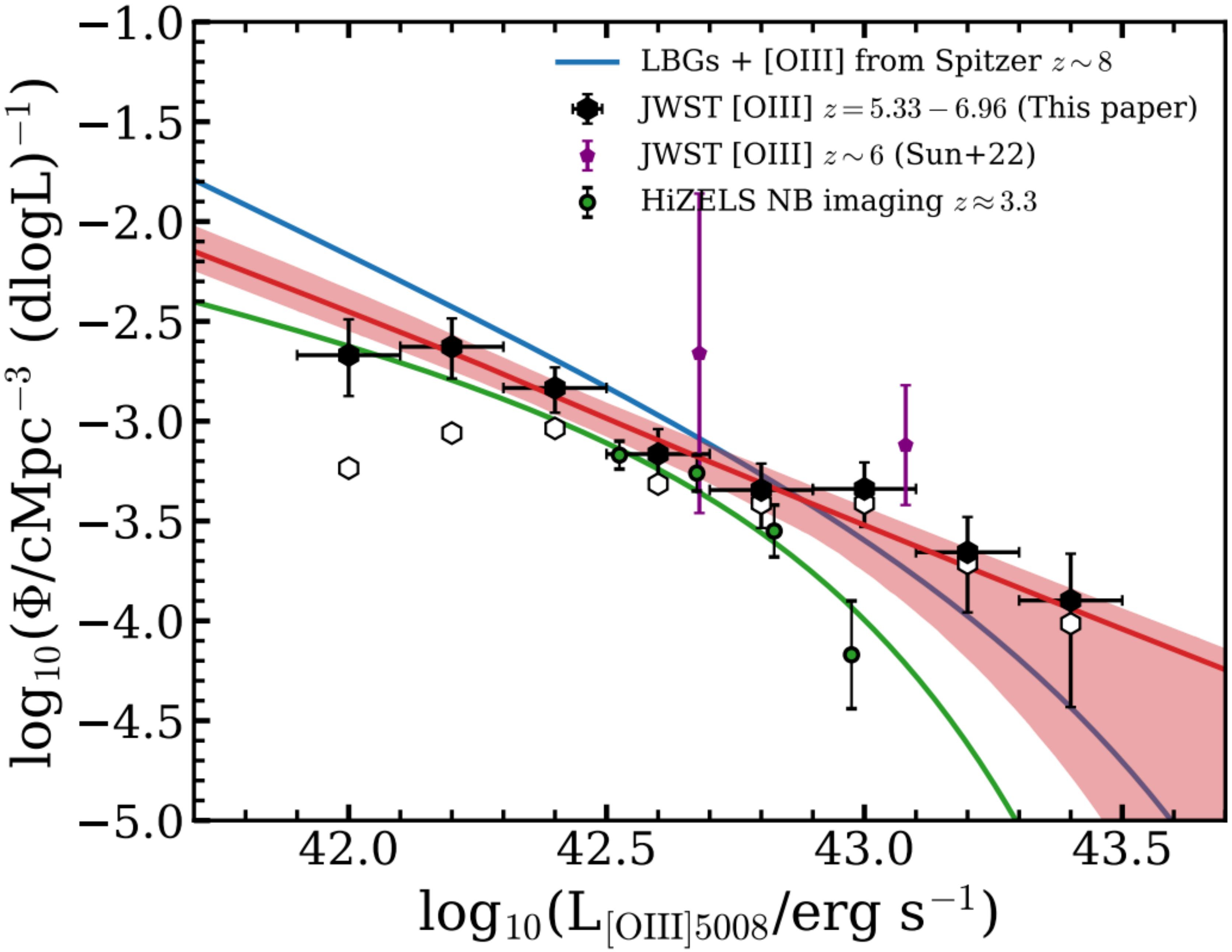
Metallicities ~10% solar (2-30% range)

Based on strong-line indicator (O3/Hb) and Direct Method in stack

Matthee+23

EIGER:

First spectroscopic [OIII] LF at z~6



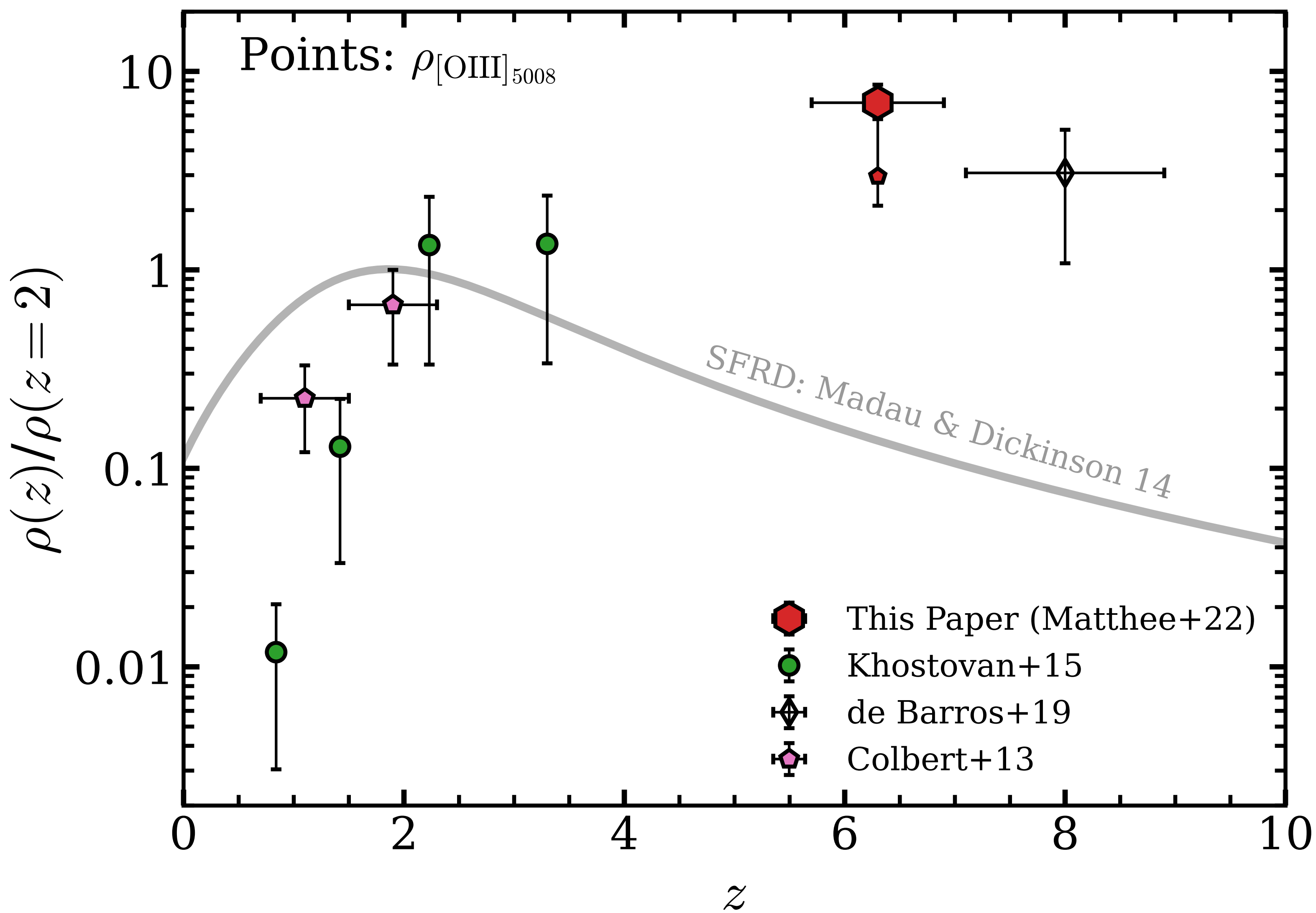
[OIII] LF at z~6 similar to [OIII] LF at z~3

Lower number densities than commissioning data (Sun+22)

Matthee+23

EIGER:

THE [OIII] LUMINOSITY DENSITY EVOLVES DIFFERENTLY FROM SFR DENSITY

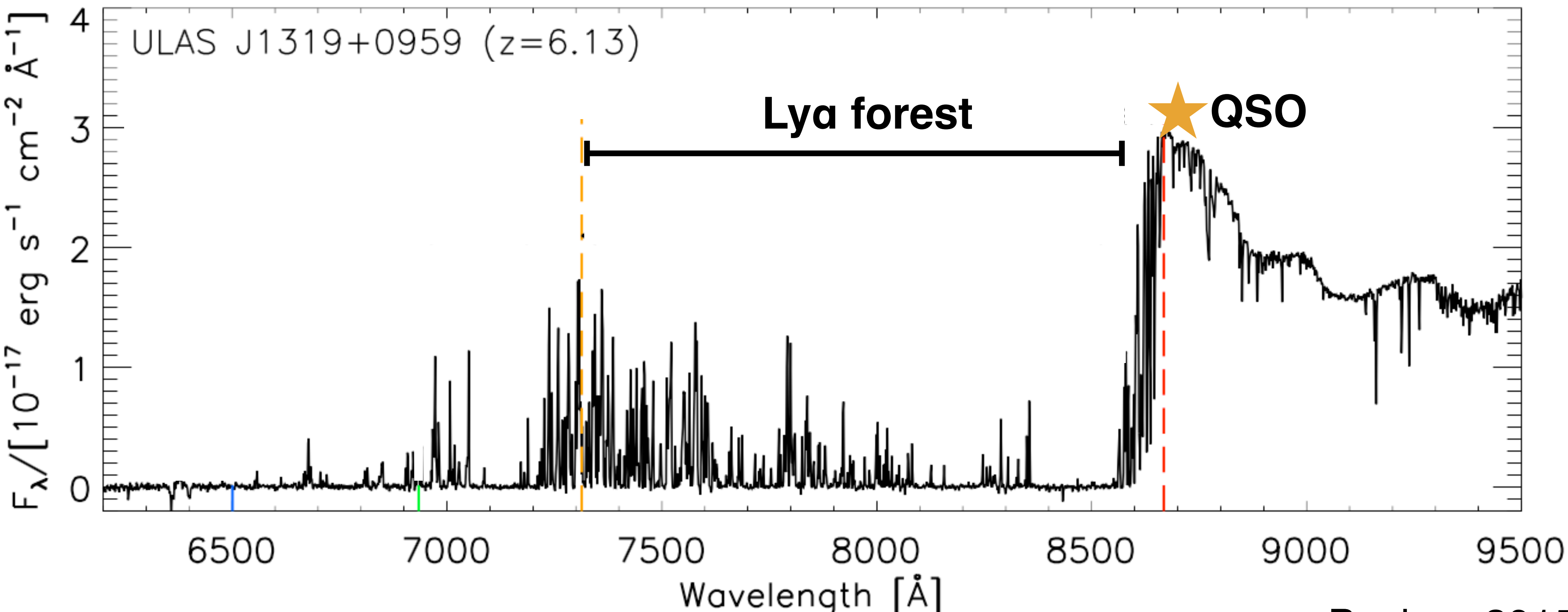


- **Conspiracy of the evolving mass function and the mass - metallicity relation makes the Universe very *green* at z~6**

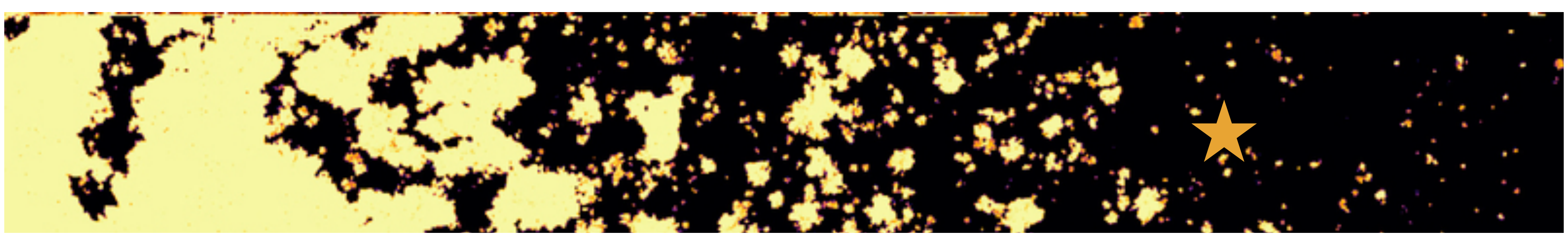
- **An Hb+[OIII] scan very efficiently tells you the galaxy density distribution at z~5-7**

Matthee+23

IGM LYA FOREST - GALAXY CROSS CORRELATION

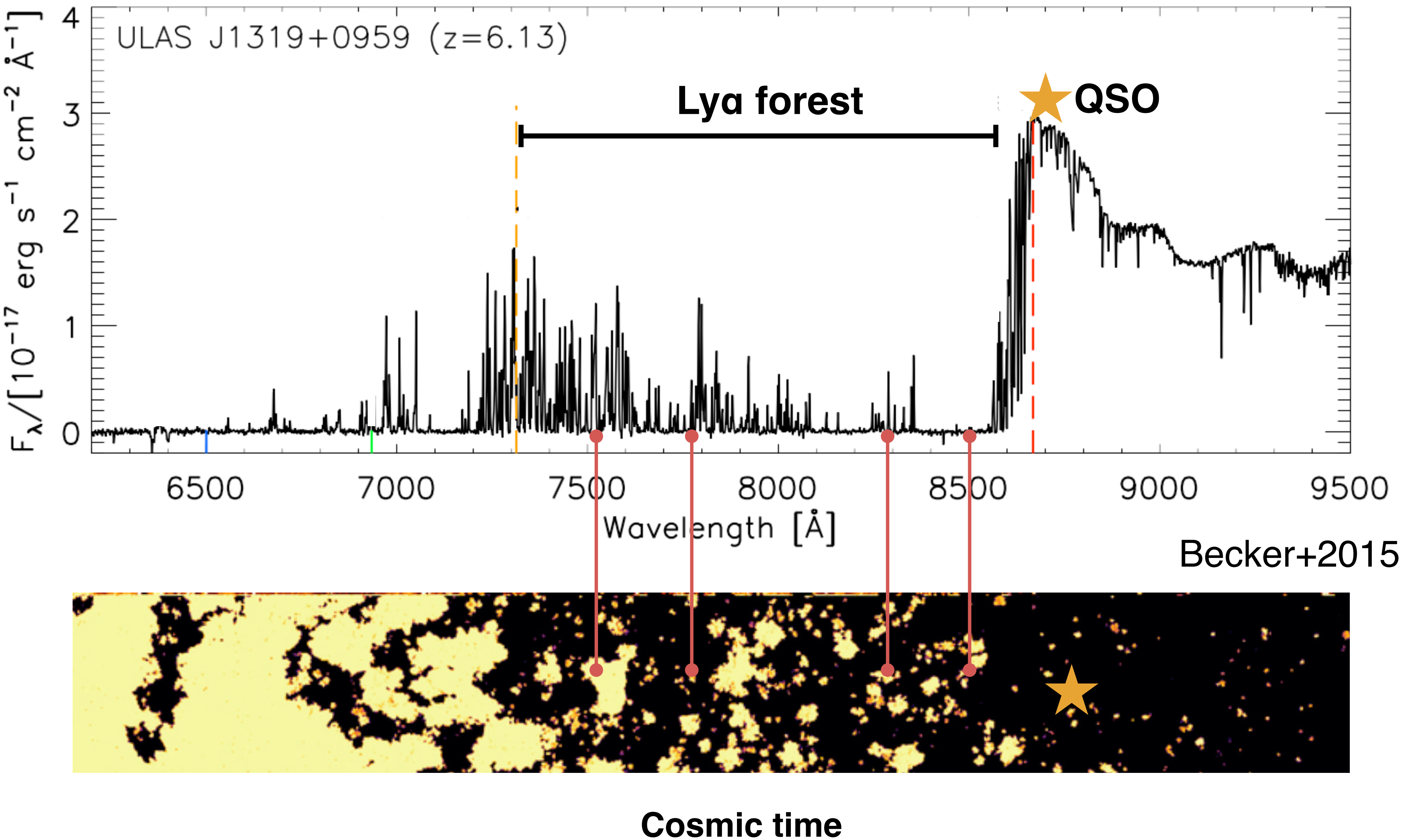


Becker+2015



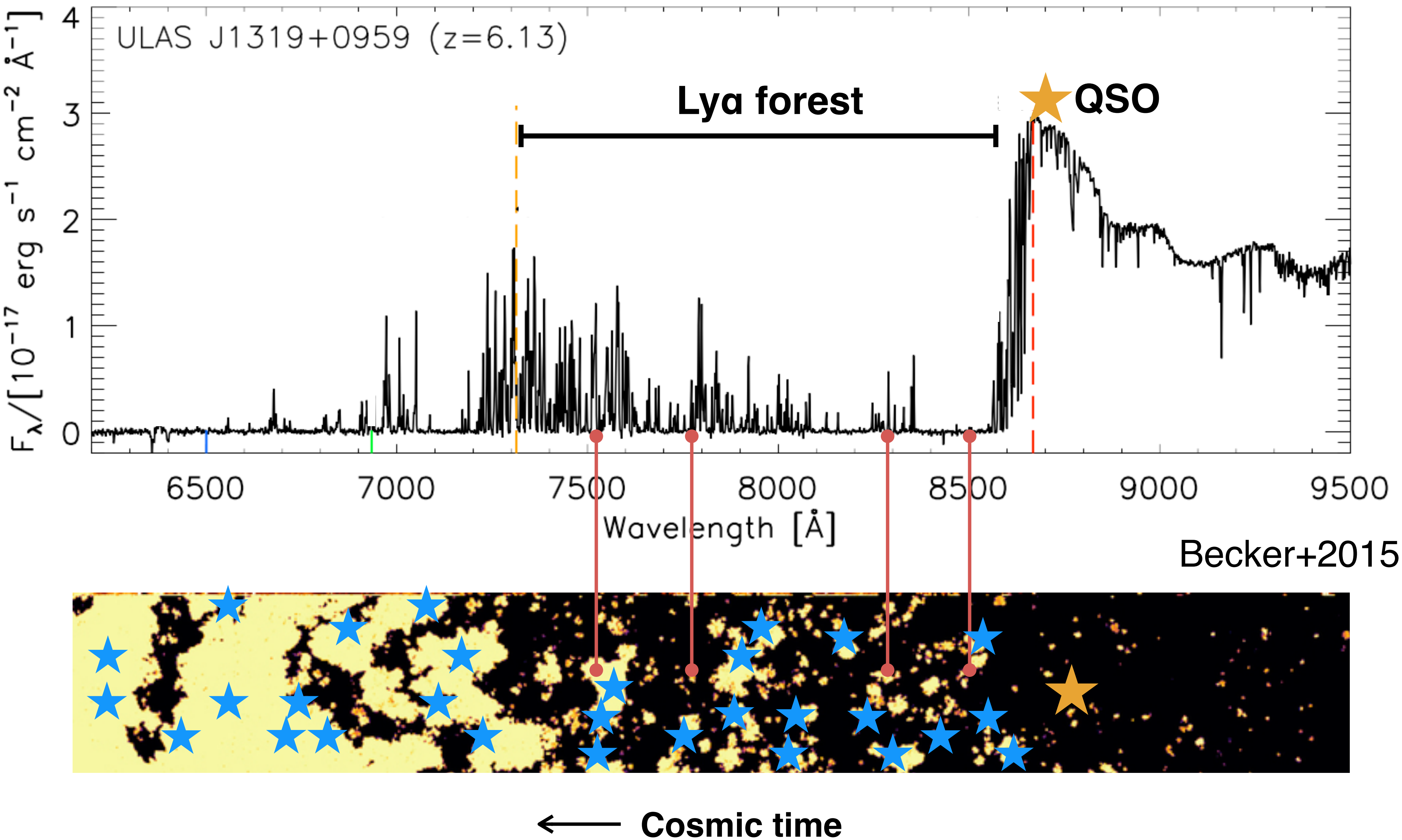
⟵ **Cosmic time**

IGM LYA FOREST - GALAXY CROSS CORRELATION



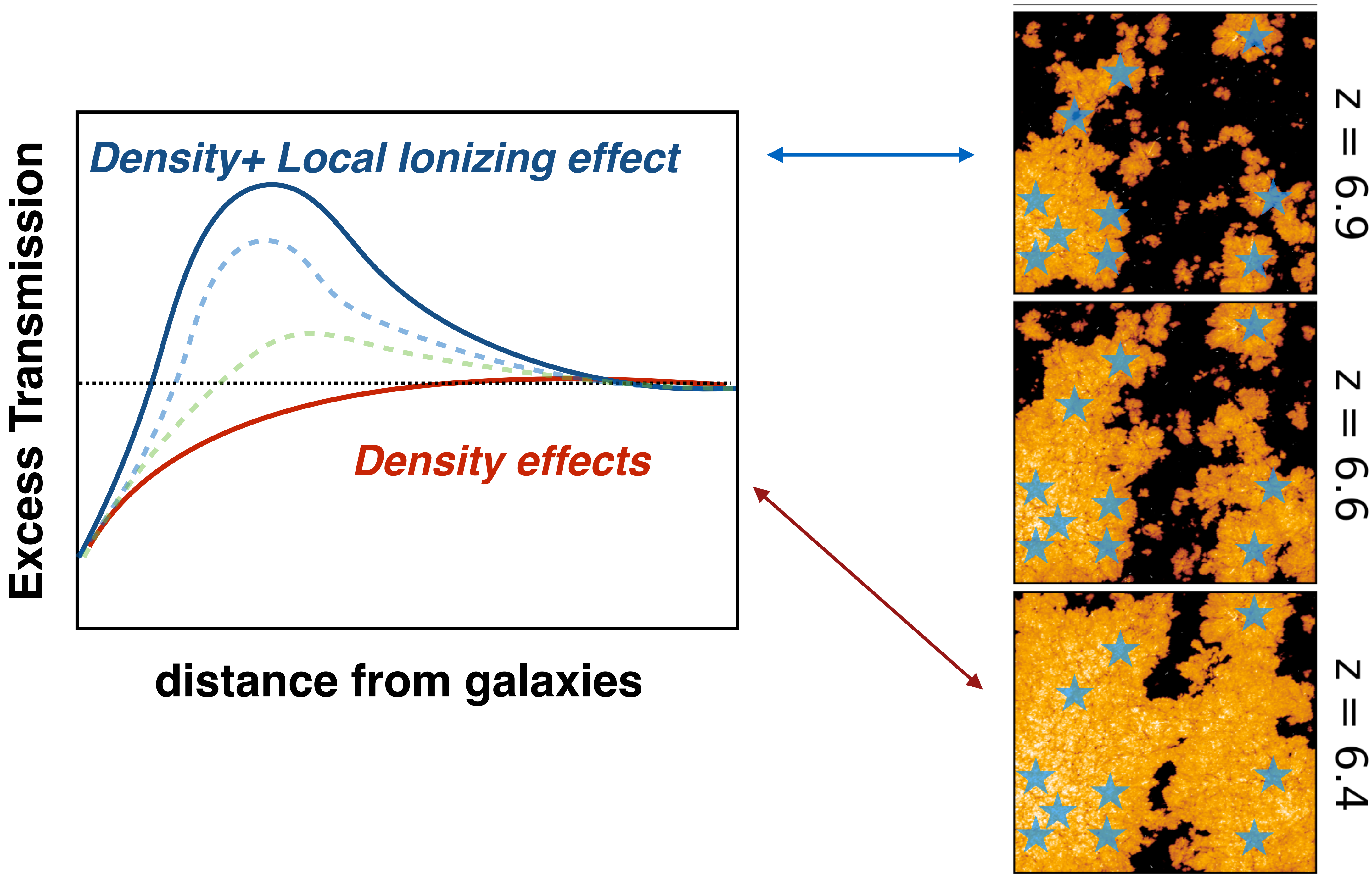
- **Galaxy surveys in quasar fields enable IGM - galaxy (★) cross-correlation**

IGM LYA FOREST - GALAXY CROSS CORRELATION



- **Galaxy surveys in quasar fields enable IGM - galaxy (★) cross-correlation**

Cross-correlation intergalactic gas & galaxies



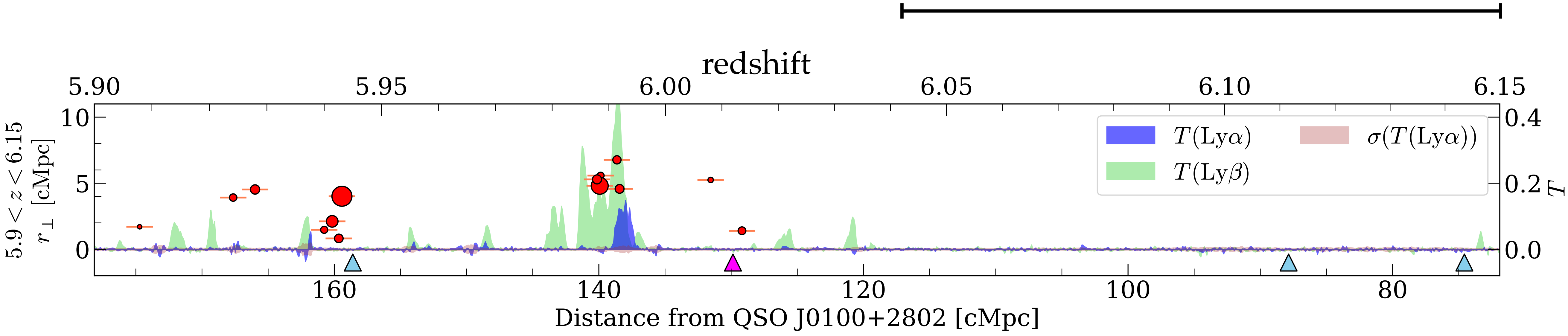
see Kakiichi+18, Garaldi+22

EIGER:

Comparison of galaxies and LyA and LyB transmission spikes

In the J0100 field

Long opaque region at z=6.0-6.15: no galaxies

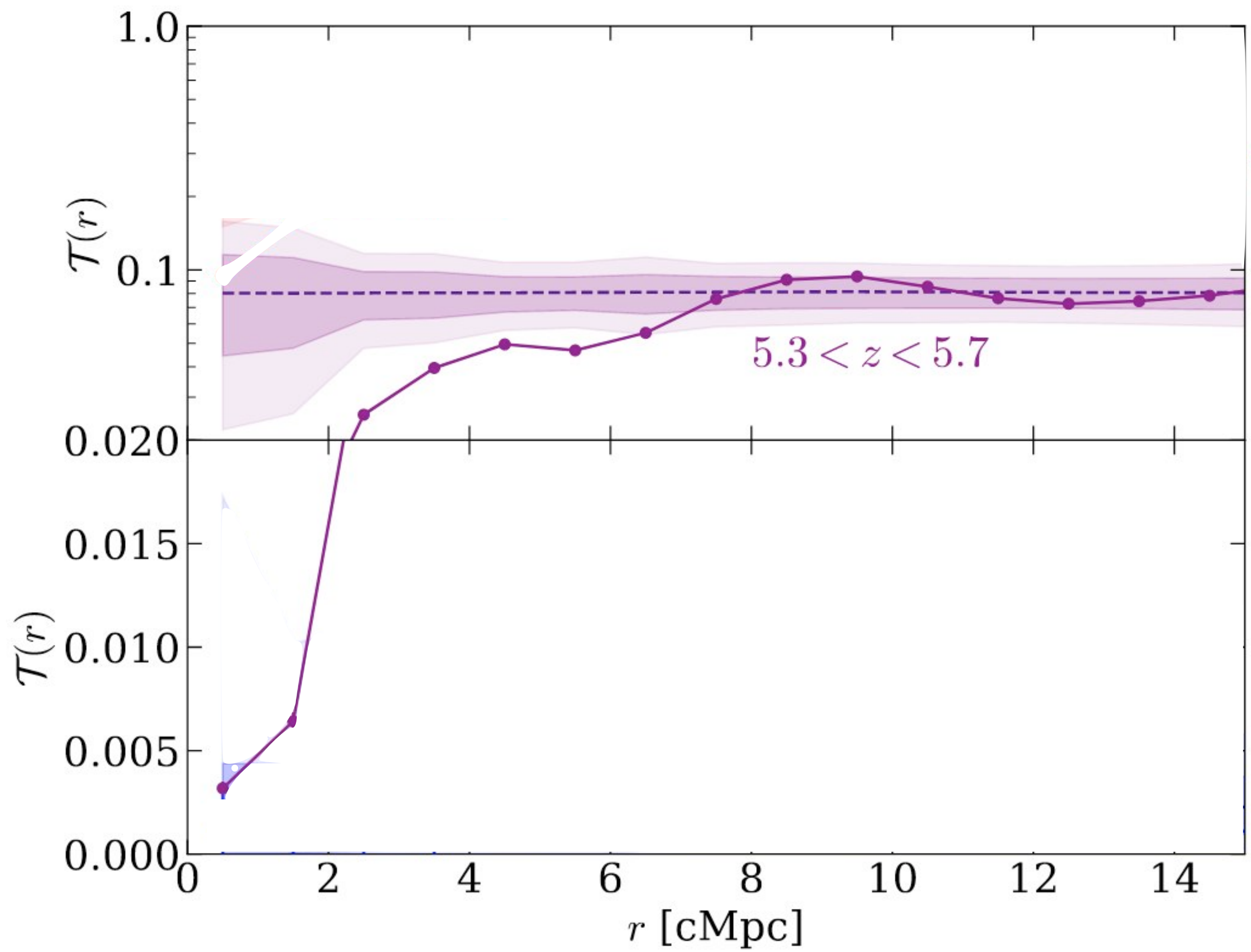


Kashino+23

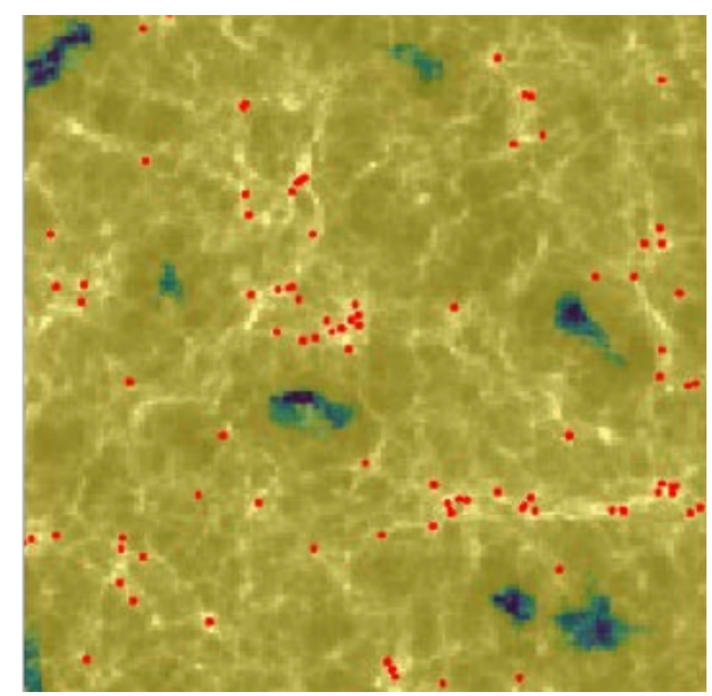
Most galaxies are surrounded by spikes, but not at low impact parameters

EIGER:

CROSS-CORRELATION INTERGALACTIC GAS & GALAXIES



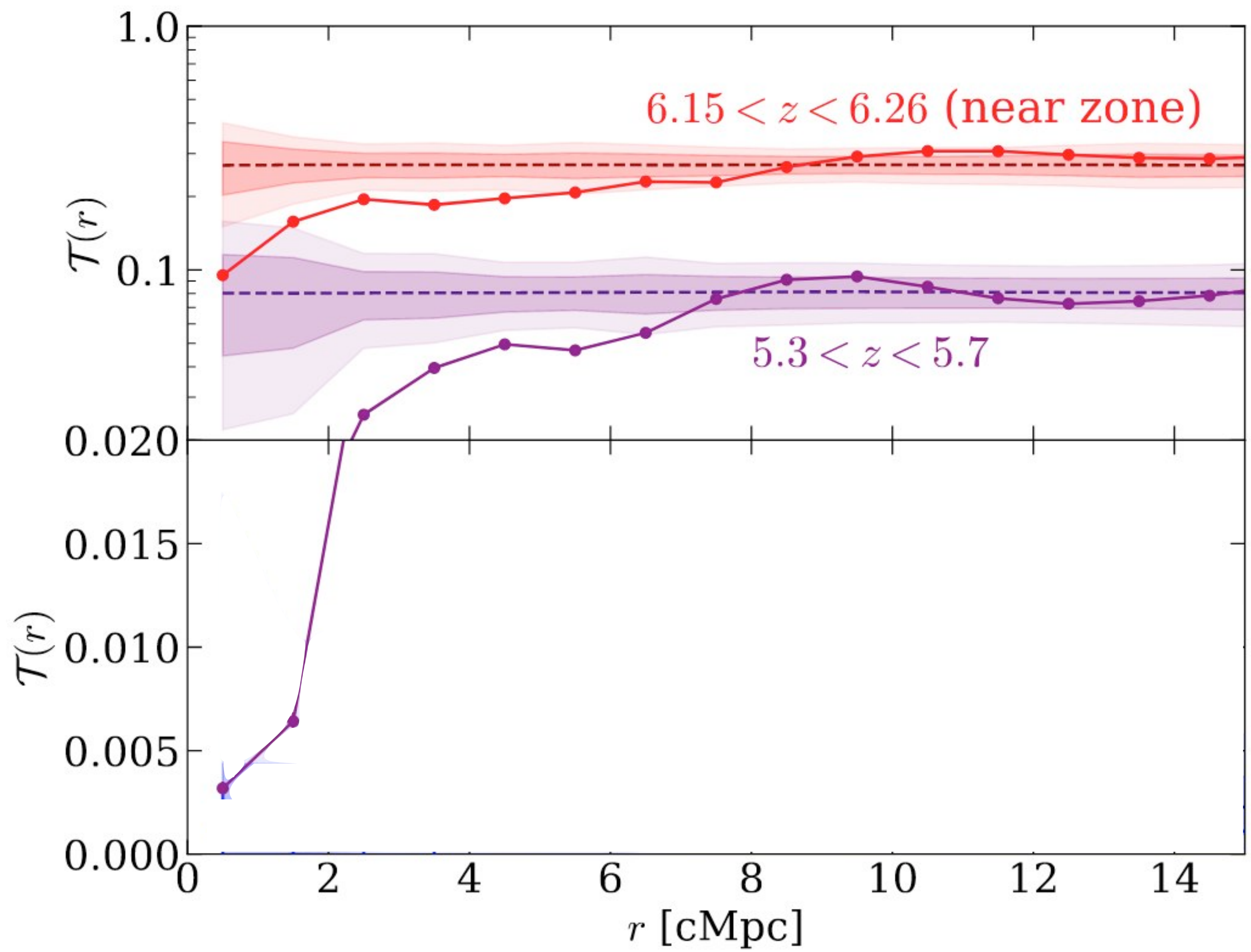
After EoR



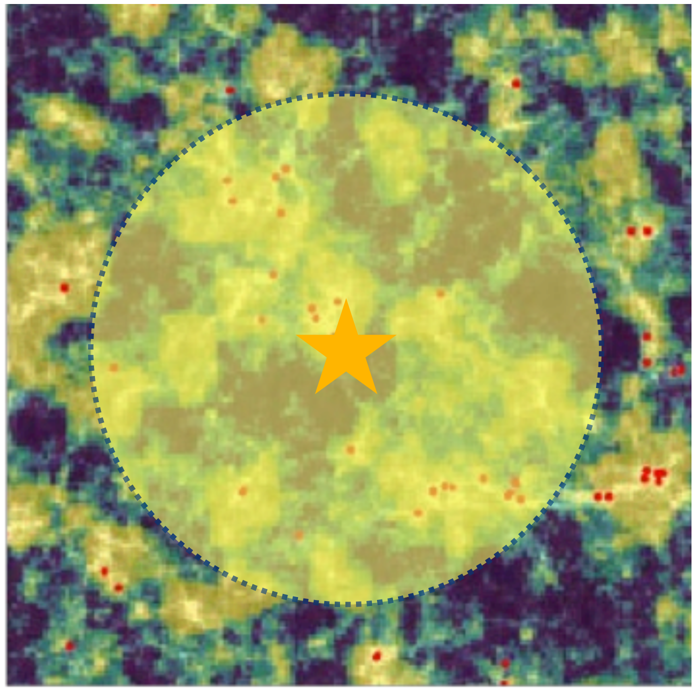
At z~5 and in the quasar near zone, galaxies are surrounded by opaque regions

Kashino+23

EIGER:
CROSS-CORRELATION INTERGALACTIC GAS & GALAXIES



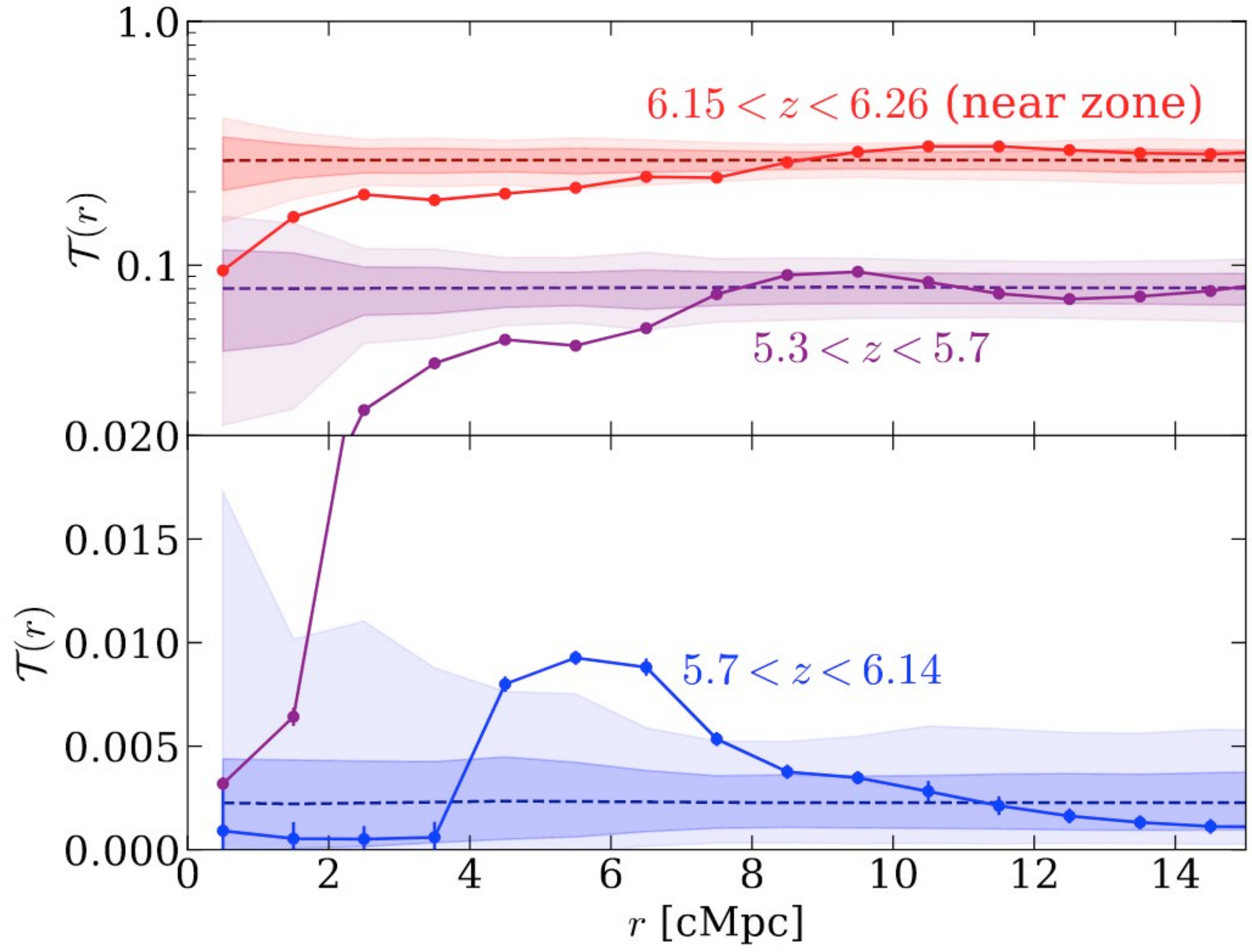
QSO near zone



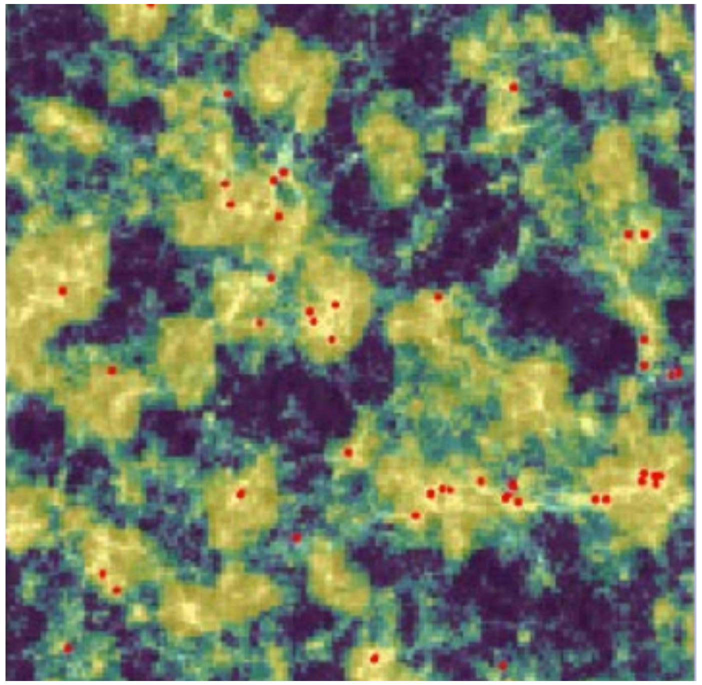
At z~5 and in the quasar near zone, galaxies are surrounded by opaque regions

Kashino+23

EIGER:
CROSS-CORRELATION INTERGALACTIC GAS & GALAXIES



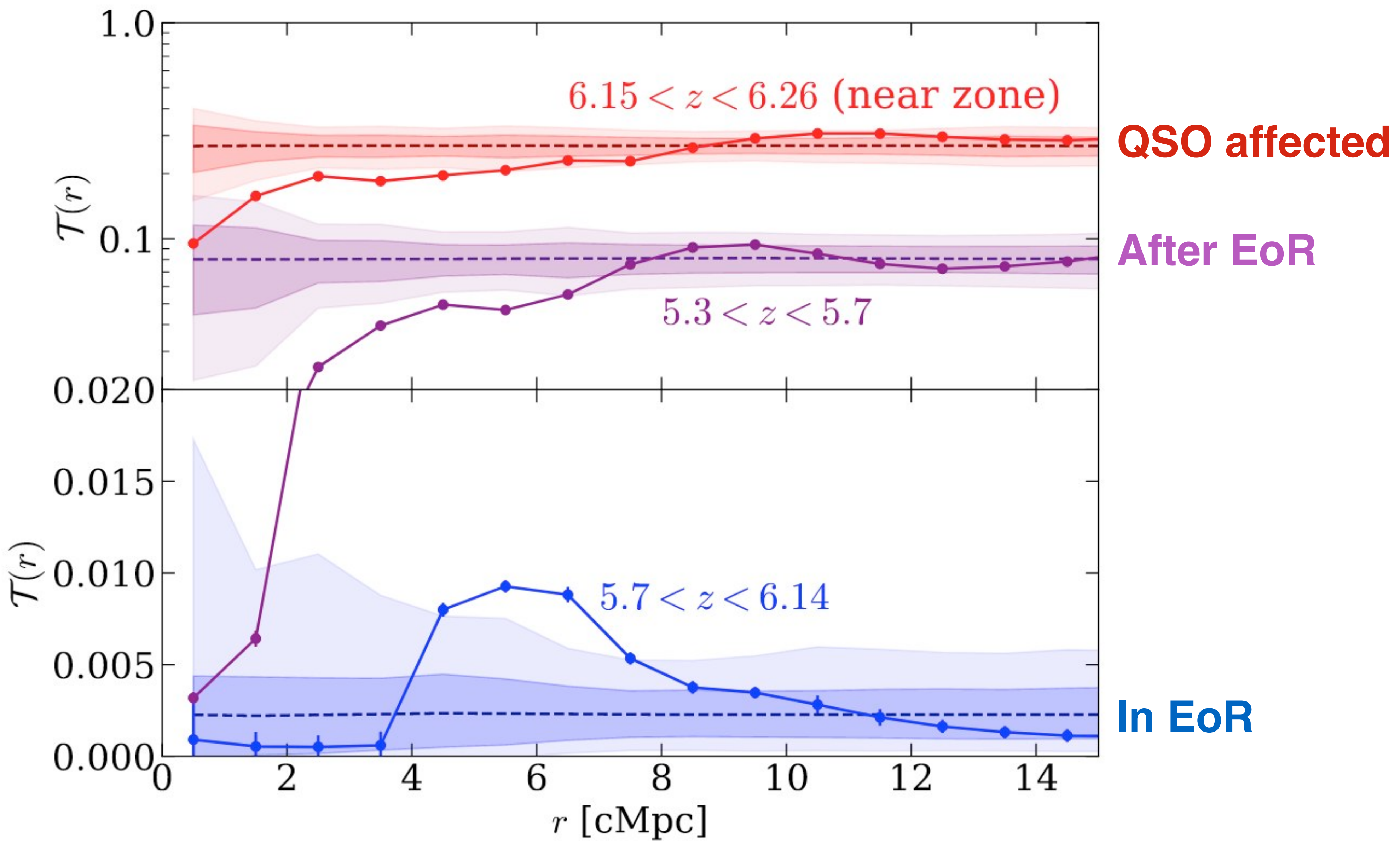
In EoR



At z~6, galaxies are surrounded by Lya (and LyB) transmission spikes at ~5 cMpc

Kashino+23

EIGER:
CROSS-CORRELATION INTERGALACTIC GAS & GALAXIES

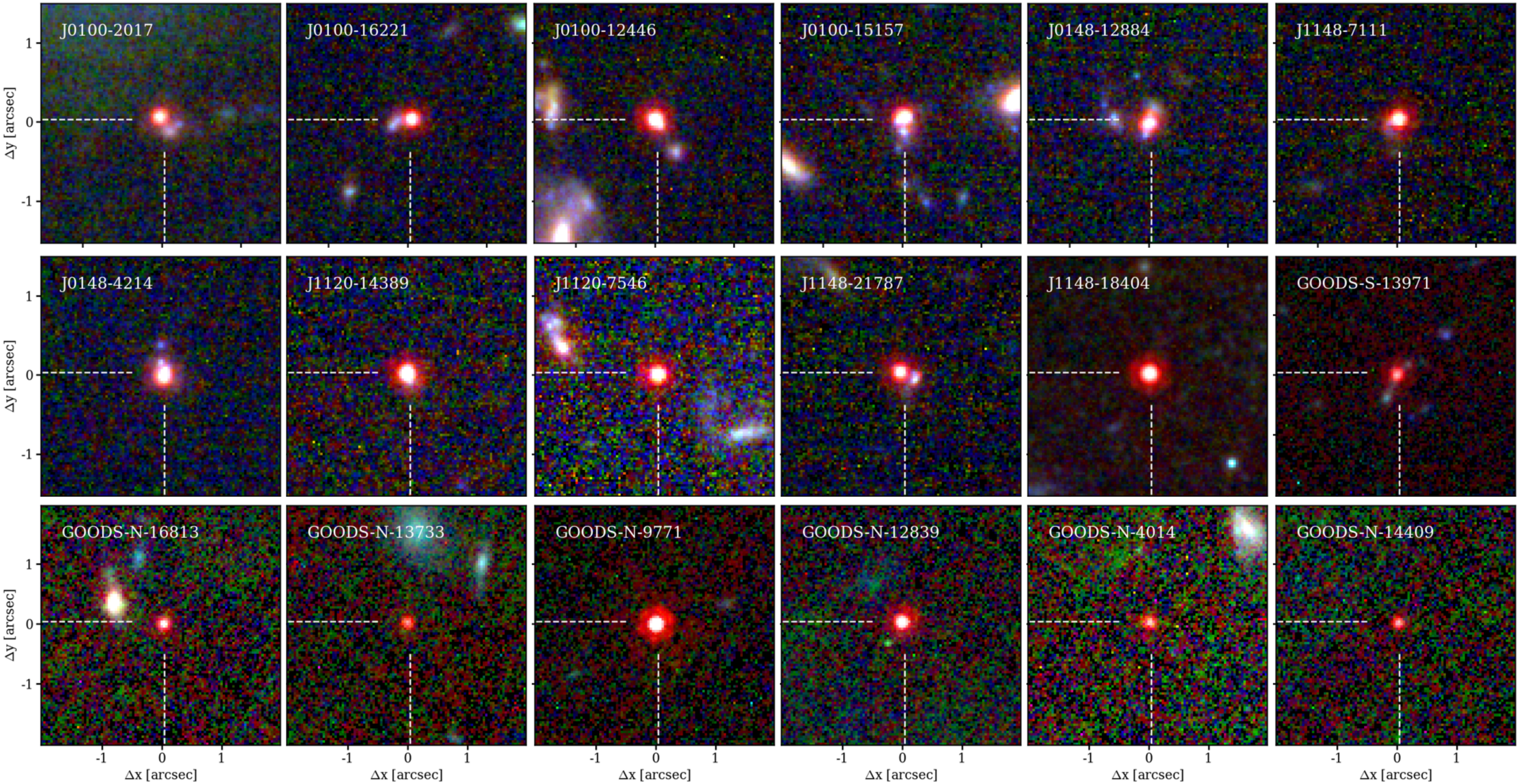


Direct evidence for excess ionising emissivity around galaxies at z~6

These galaxies (M_{UV}~-19.5, Mstar~3x10^8 M_{sun})?
Fainter clustered galaxies?

Kashino+23

WHAT ABOUT FAINT AGN?

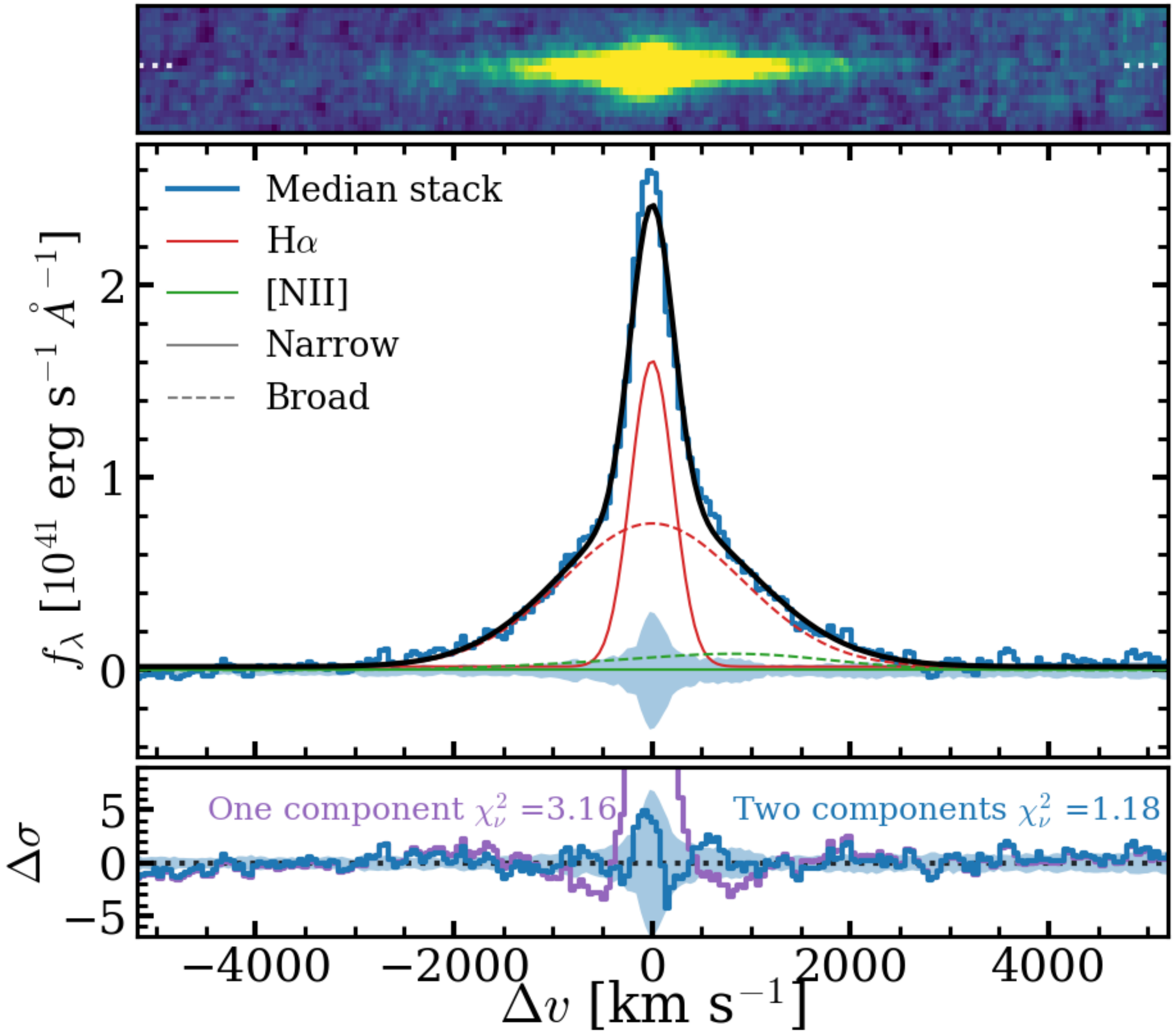


JWST data is full of *Little Red Dots (LRDs):* compact, rest-frame optically red galaxies

We identify 18 in a combination of EIGER + FRESCO (PI Oesch) grism surveys, total 100 hrs

Matthee+23c (in prep)

WHAT ABOUT FAINT AGN?

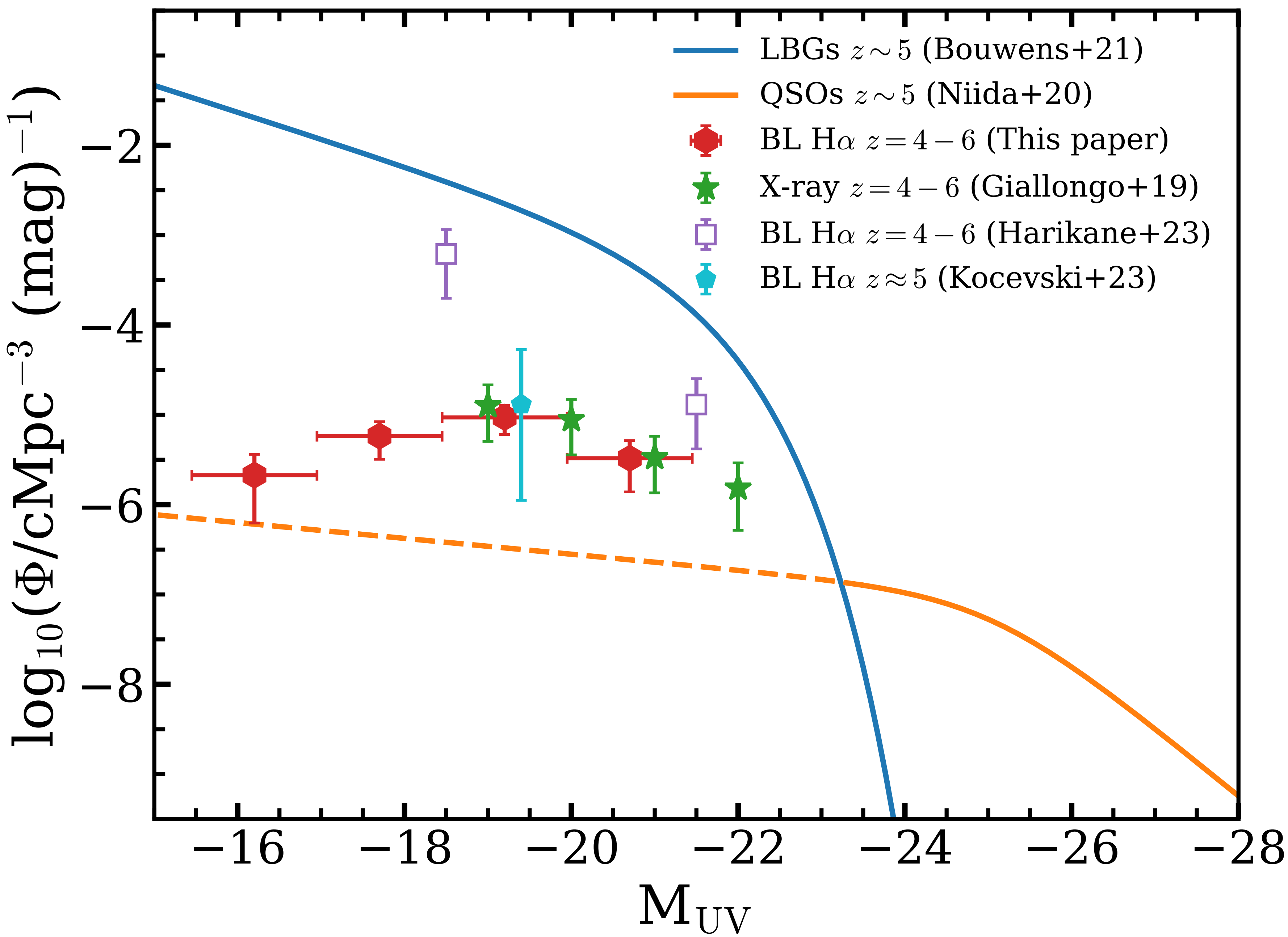


A fraction of these are broad line Halpha emitters at z~4-5, which we interpret as faint AGN with BH masses ~$10^{7\text{-}8}$ Msun

See also Kocevski+23, Harikane+23

Matthee+23c (in prep)

WHAT ABOUT FAINT AGN?

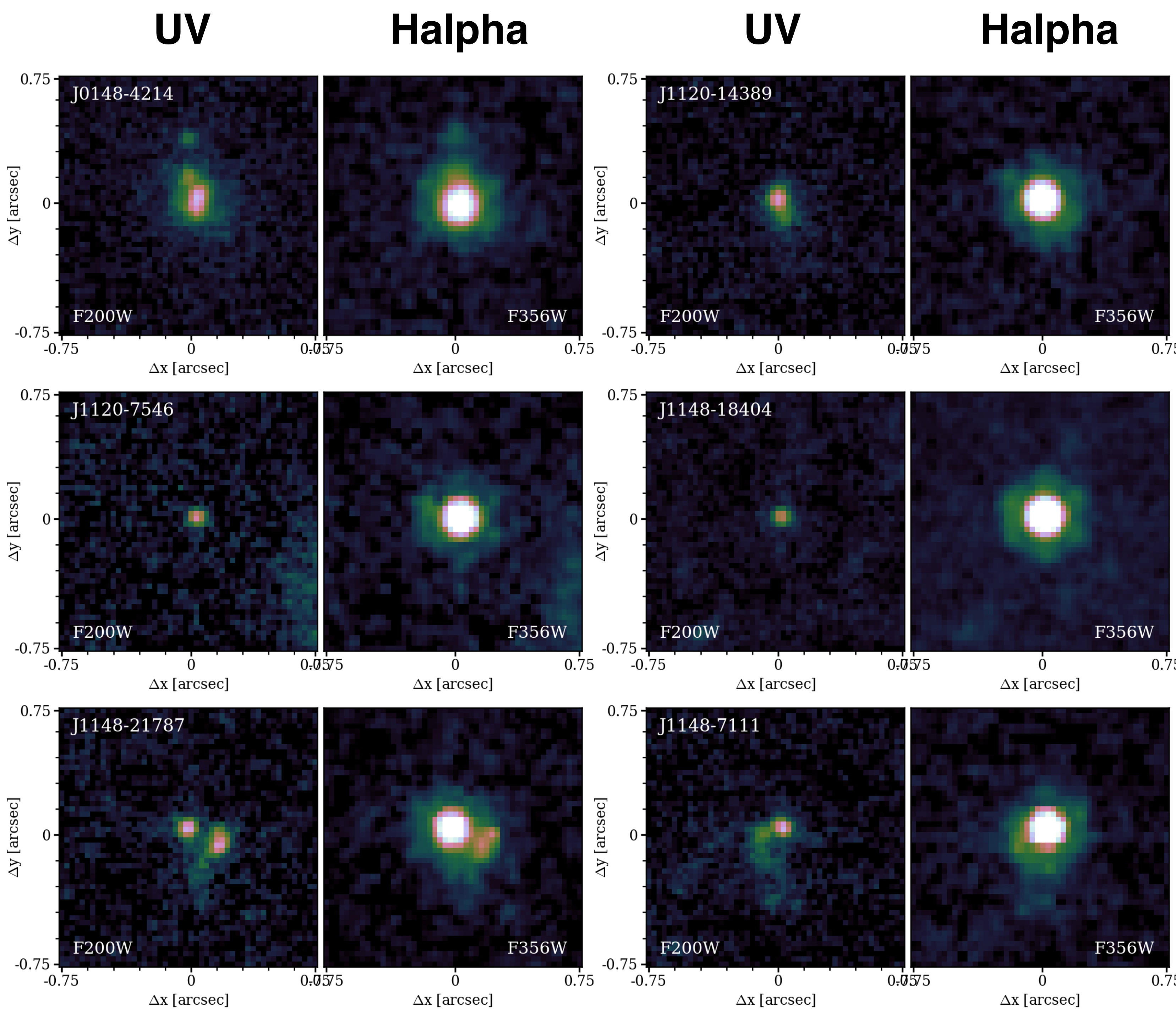


UV luminosity function of these faint AGNs agrees with Giallongo+19

but, in the GOODS fields we find zero overlap in the samples

Matthee+23c (in prep)

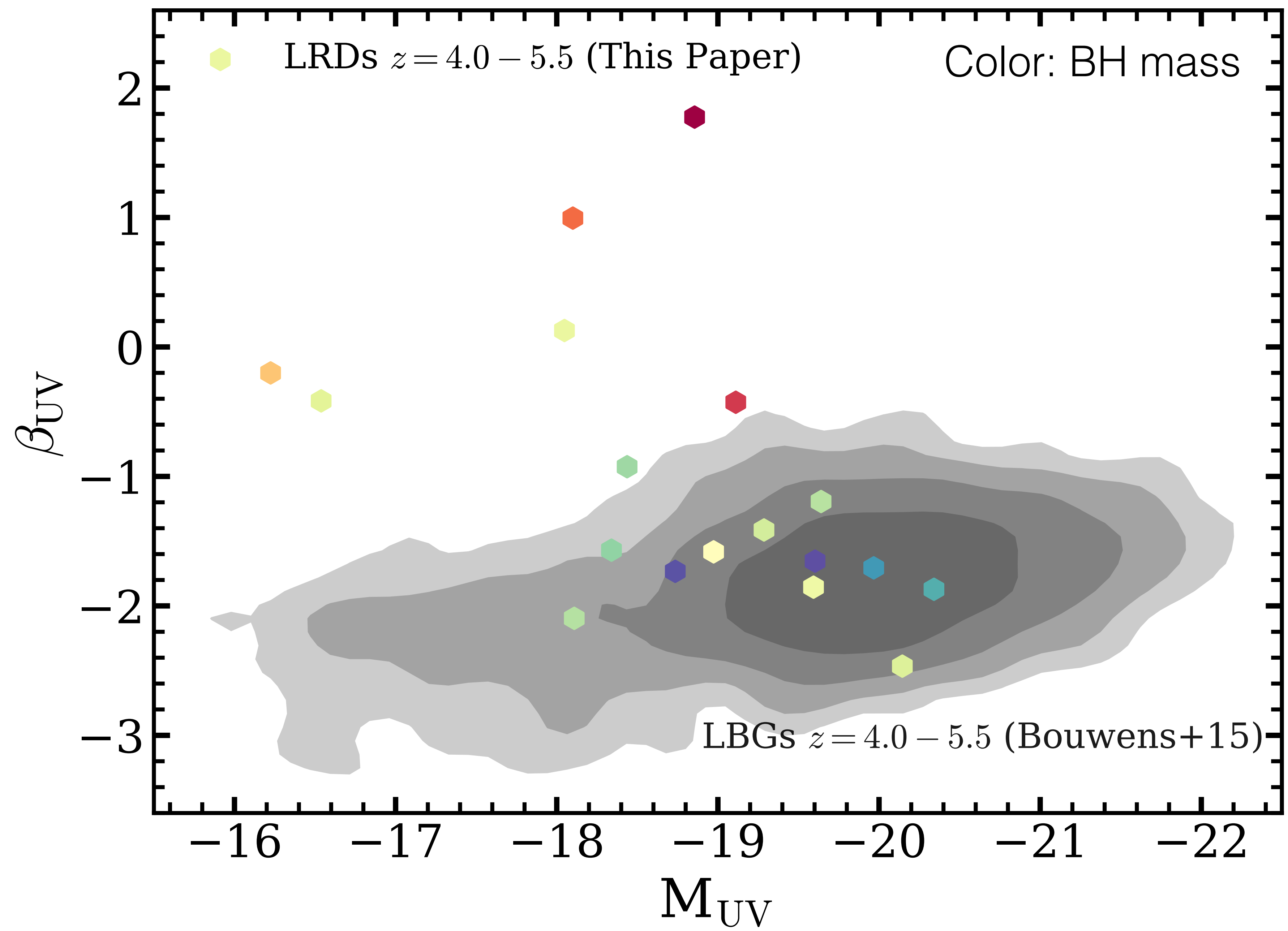
WHAT ABOUT FAINT AGN?



AGN are not extremely dominant in the rest-UV

Matthee+23c (in prep)

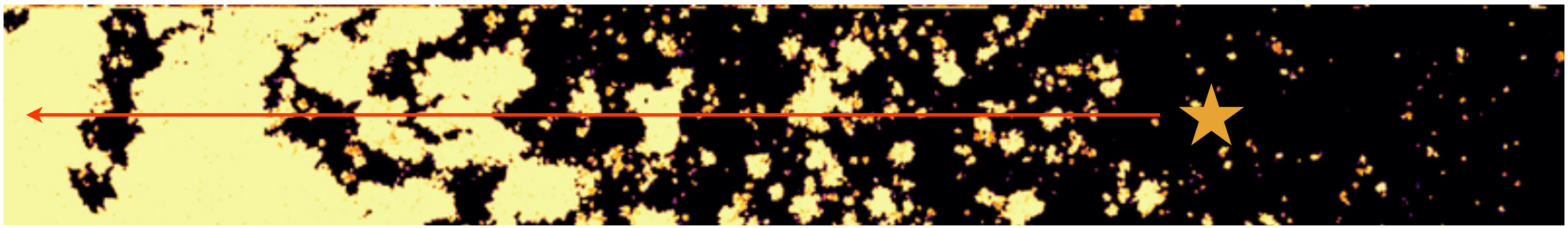
WHAT ABOUT FAINT AGN?



They can be relatively red in the UV,
and otherwise only contribute mildly (~20-40%) to the UV light

Matthee+23c (in prep)

FUTURE PROSPECTS: WHAT'S NEXT?

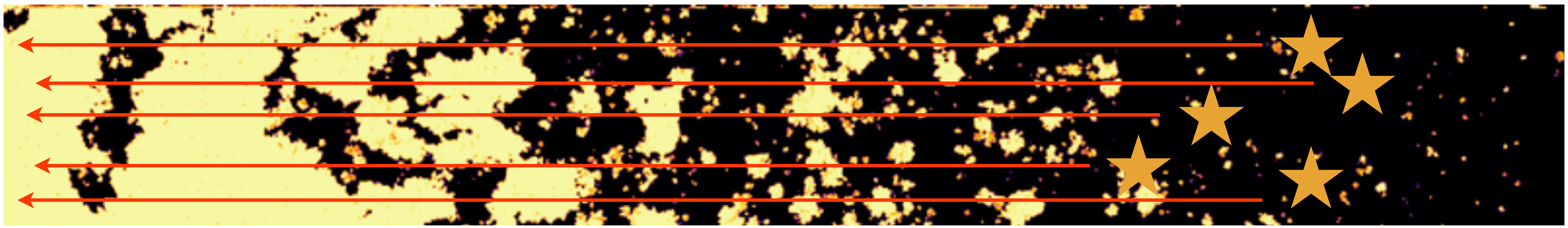


⟵ Cosmic time

- Multiple closely separated sight-lines — we need ~1-10 arcmin separations for these typical bubbles sizes

- Quasars are too rare, so we should use background galaxies

Future Prospects: What's next?

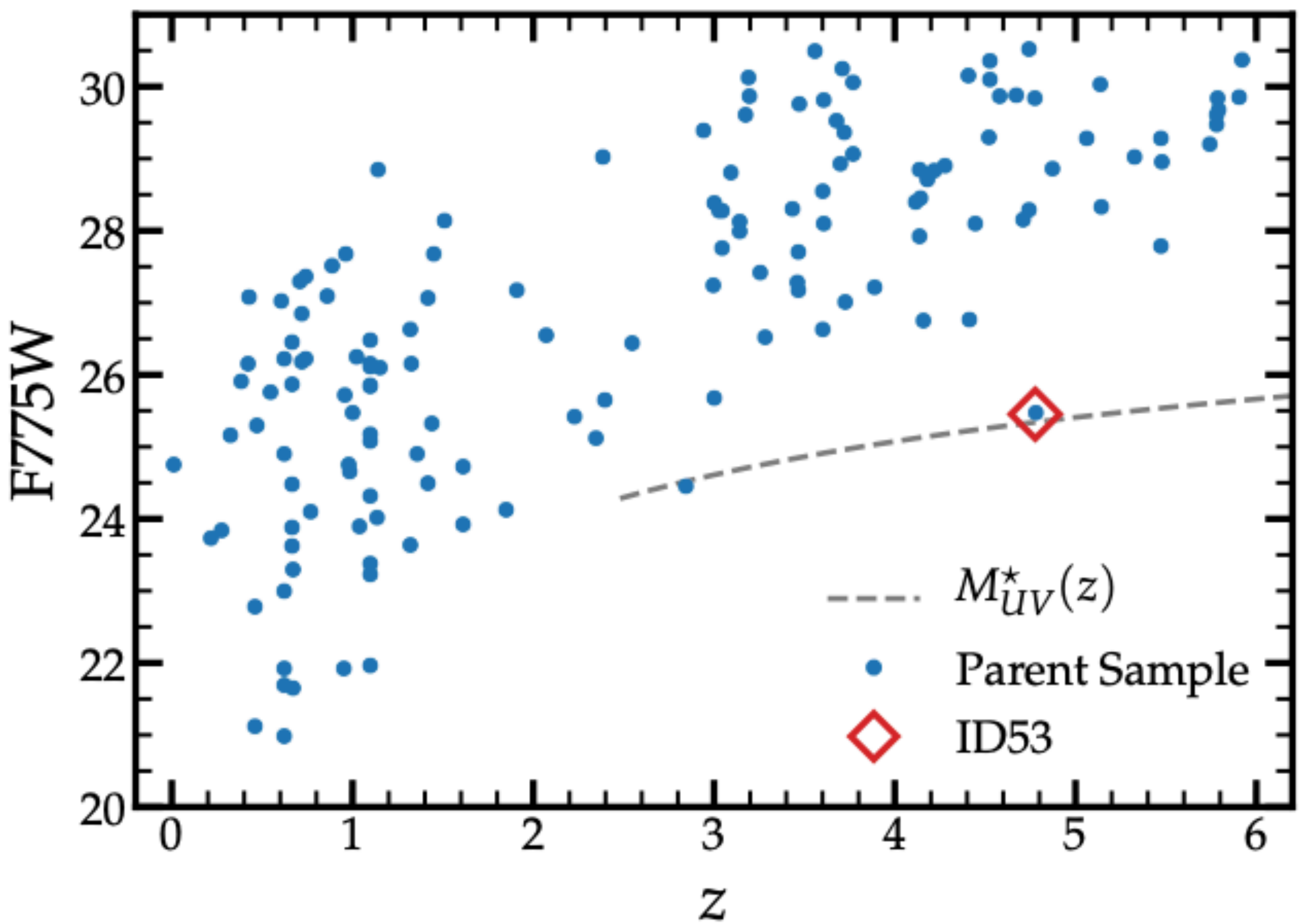


⟵ Cosmic time

- **Multiple closely separated sight-lines — we need ~1-10 arcmin separations for these typical bubbles sizes**

- **Quasars are too rare, so we should use background galaxies**

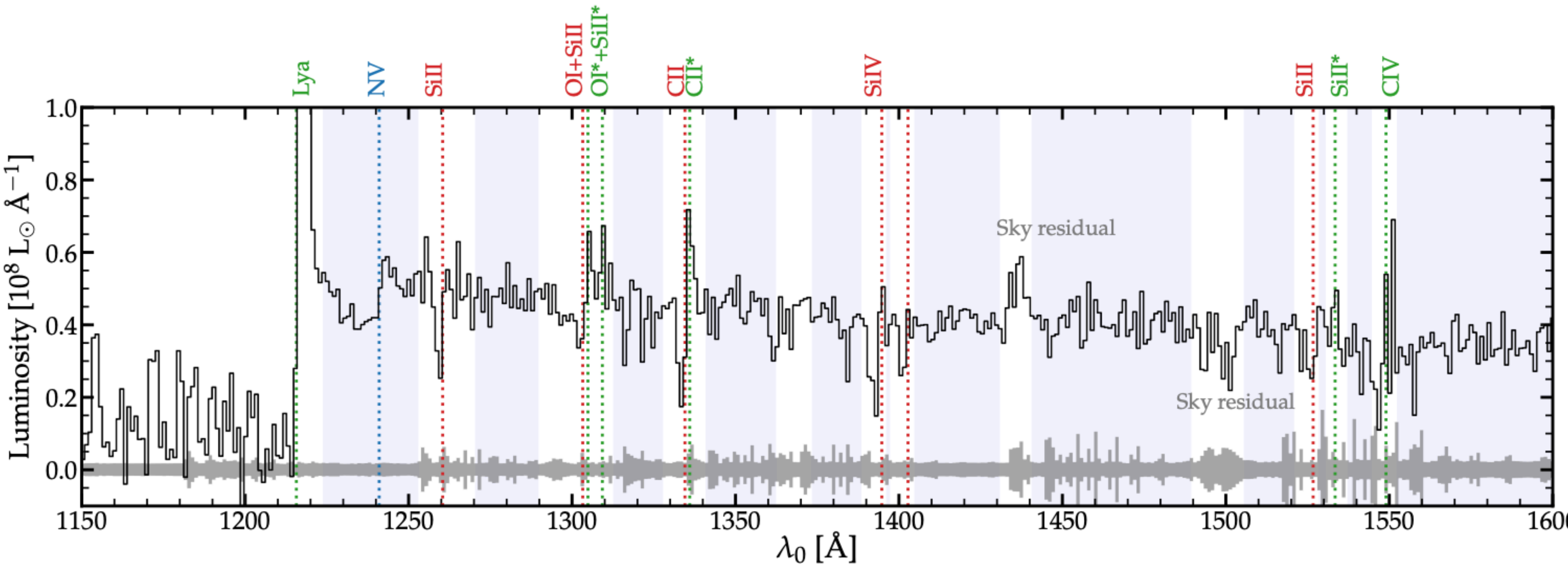
REIONIZATION *TOMOGRAPHY* WITH MULTIPLE BACKGROUND SOURCES



- **MXDF (Bacon+2021) 140hr VLT/MUSE spectrum of a magnitude 25.3 galaxy at z~4.8**
- **Sky density ~0.3/arcmin²**

Matthee+22a, Matthee+23 (in prep)

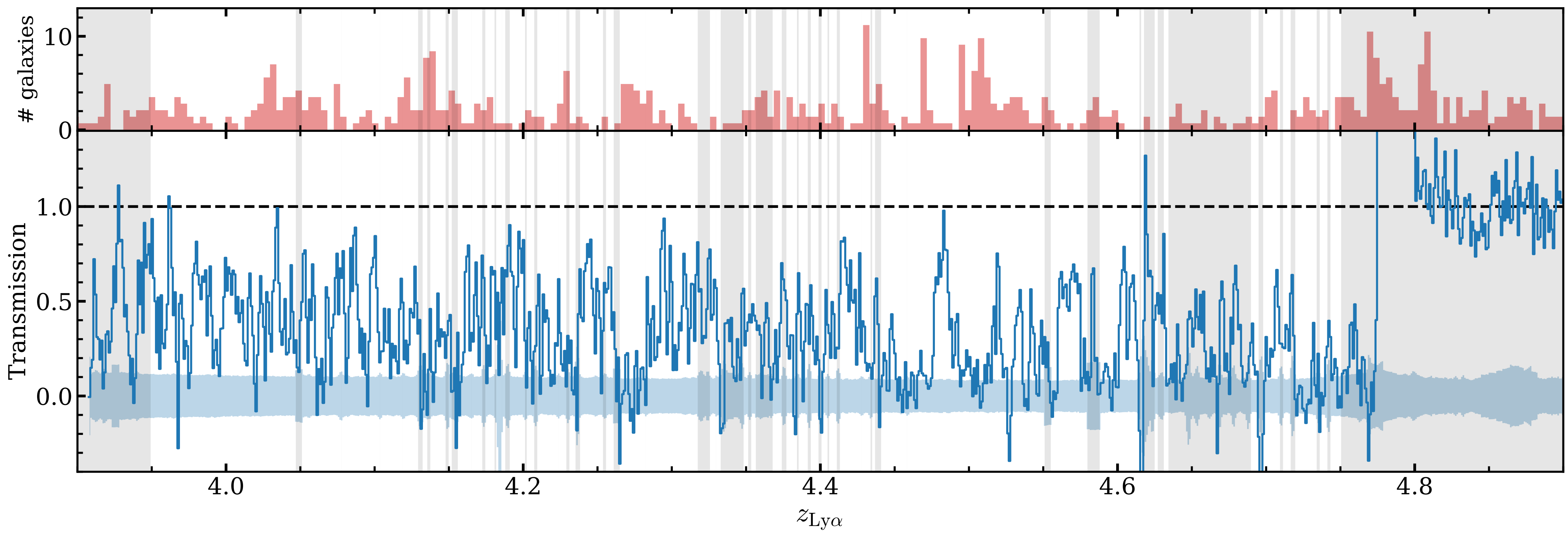
REIONIZATION *TOMOGRAPHY* WITH MULTIPLE BACKGROUND SOURCES



- **Detailed stellar population fits at z~5**

Matthee+22a

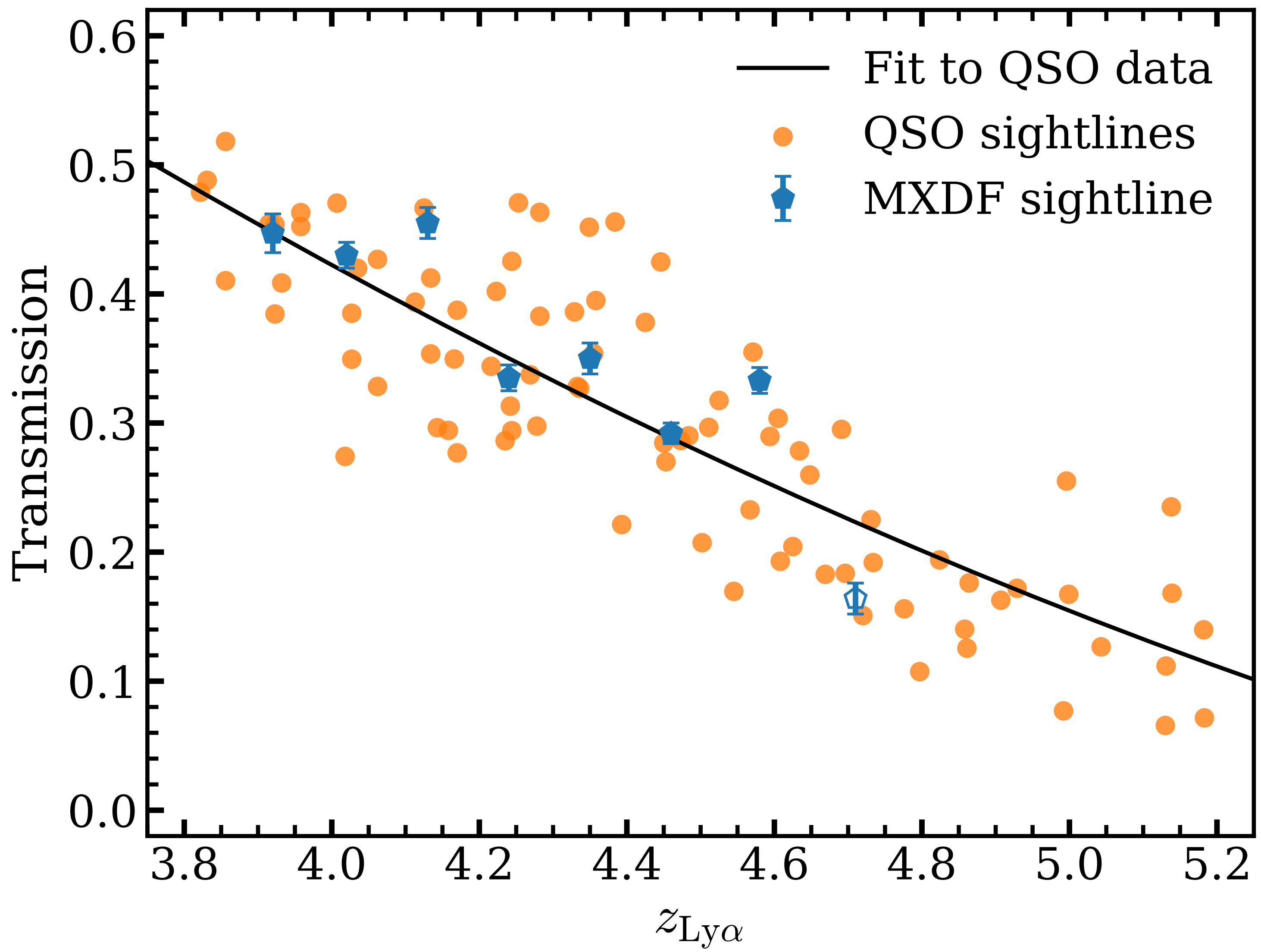
REIONIZATION *TOMOGRAPHY* WITH MULTIPLE BACKGROUND SOURCES



- **We measure Lyman-alpha forest spikes at z~4 in the galaxy spectrum**

Matthee+22a, Matthee+23b (in prep)

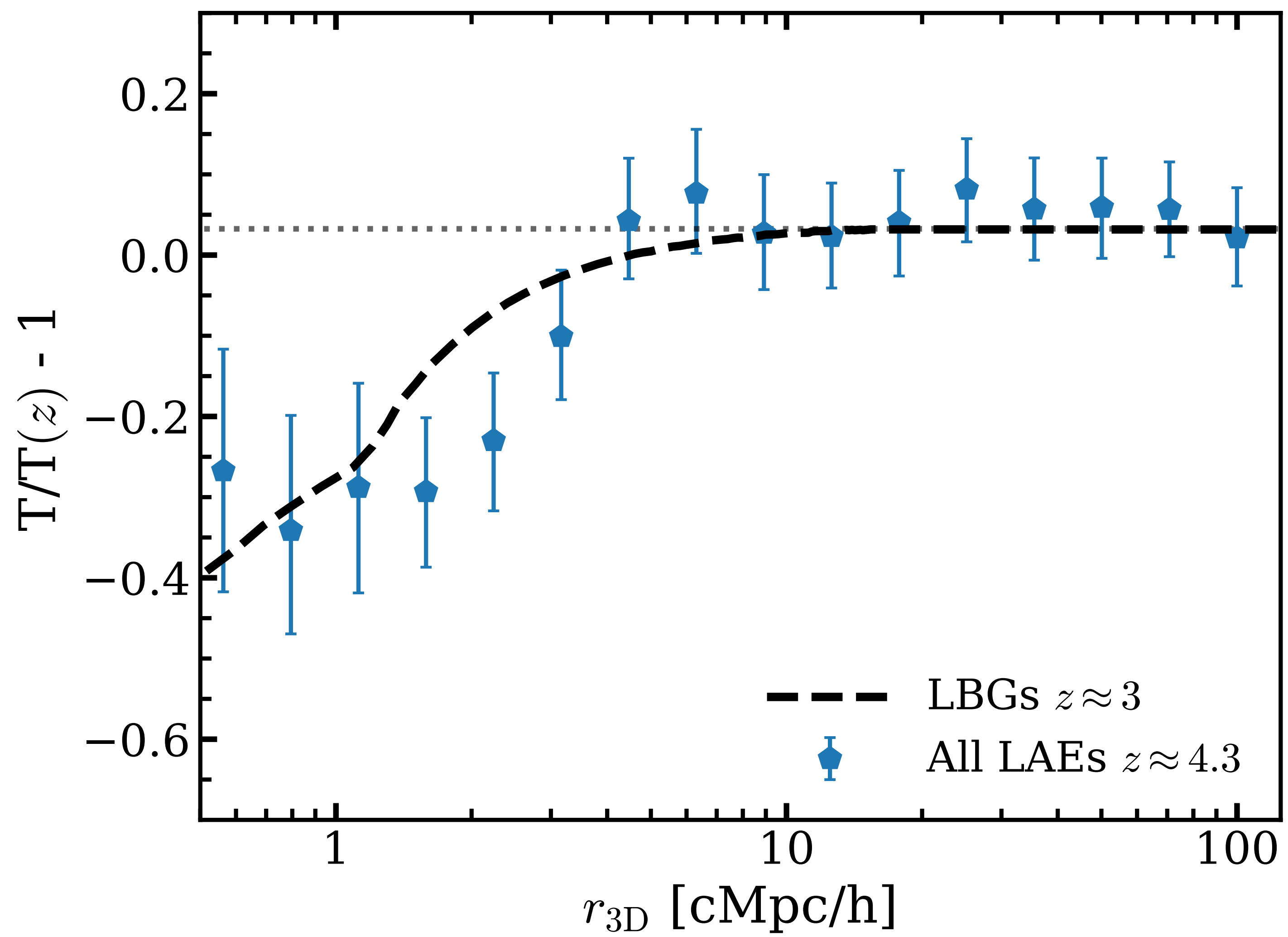
IGM TOMOGRAPHY: PILOT IN THE MXDF AT Z~5



- **Lya forest at z~4 agrees very well with quasar measurements**

Matthee+23b (in prep)

IGM TOMOGRAPHY: PILOT IN THE MXDF AT Z~5



- **Large number of 500 redshifts in MUSE fields in and around the MXDF yield a clear cross-correlation signal: z~4 galaxies are preferentially in opaque & over-dense regions of HI**
    - ***Note this analysis suggests average Δv_{Lya} =180 km/s for z~4 LAEs***

Matthee+23b (in prep)

Summary

- **Half of the Lyman-alpha emitters at z~2 are strong leakers *while* they are also efficient producers of ionising photons.**

- **JWST/EIGER confirms that galaxies ubiquitously have strong optical emission-lines, with a highly ionised ISM and a metallicity that increases with mass**

- **The brightness of the [OIII] doublet in distant galaxies make complete line-scans very efficient in tracing the galaxy density at redshifts z~3-9**

- **EIGER shows direct evidence that galaxies at z~6 are surrounded by ionised bubbles of ~5 Mpc**

- **JWST NIRCam grism surveys show that faint AGN are quite abundant, but reside either in red galaxies or contribute only a fraction of the UV light**

- **The MXDF survey demonstrates how future deep spectroscopy of distant galaxies can be used for tomographic mapping of ionised bubbles around galaxies**

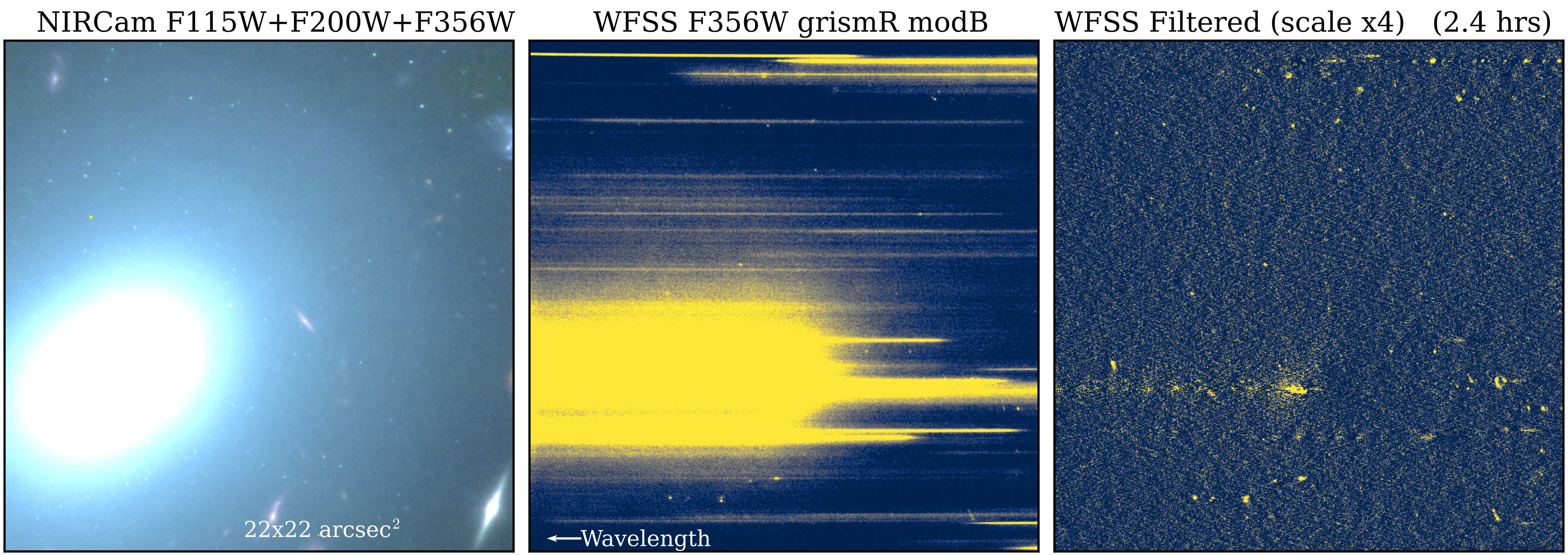
Key references:
Synchronised production & Escape in LAEs: Naidu, Matthee et al. 2022, MNRAS, 510, 4582
LAE emissivity model: Matthee, Naidu et al. 2022, MNRAS, 512, 5960
First EIGER papers: Kashino et al. 2023, arXiv: 2211.08254. Matthee et al. 2023, arXiv: 2211.08255

ERC STG AGENTS

- **Key goals of AGENTS (Sept 2023 — …)**
  - **JWST emission-line surveys trace the full emission-line population**
  - **Lyman-alpha observations (with MUSE) to estimate the ionizing output from the galaxies**
  - **Quasar fields to allow comparison to the (re)ionisation state**

Backup slides

JWST/NIRCAM WFSS CONTAMINATION

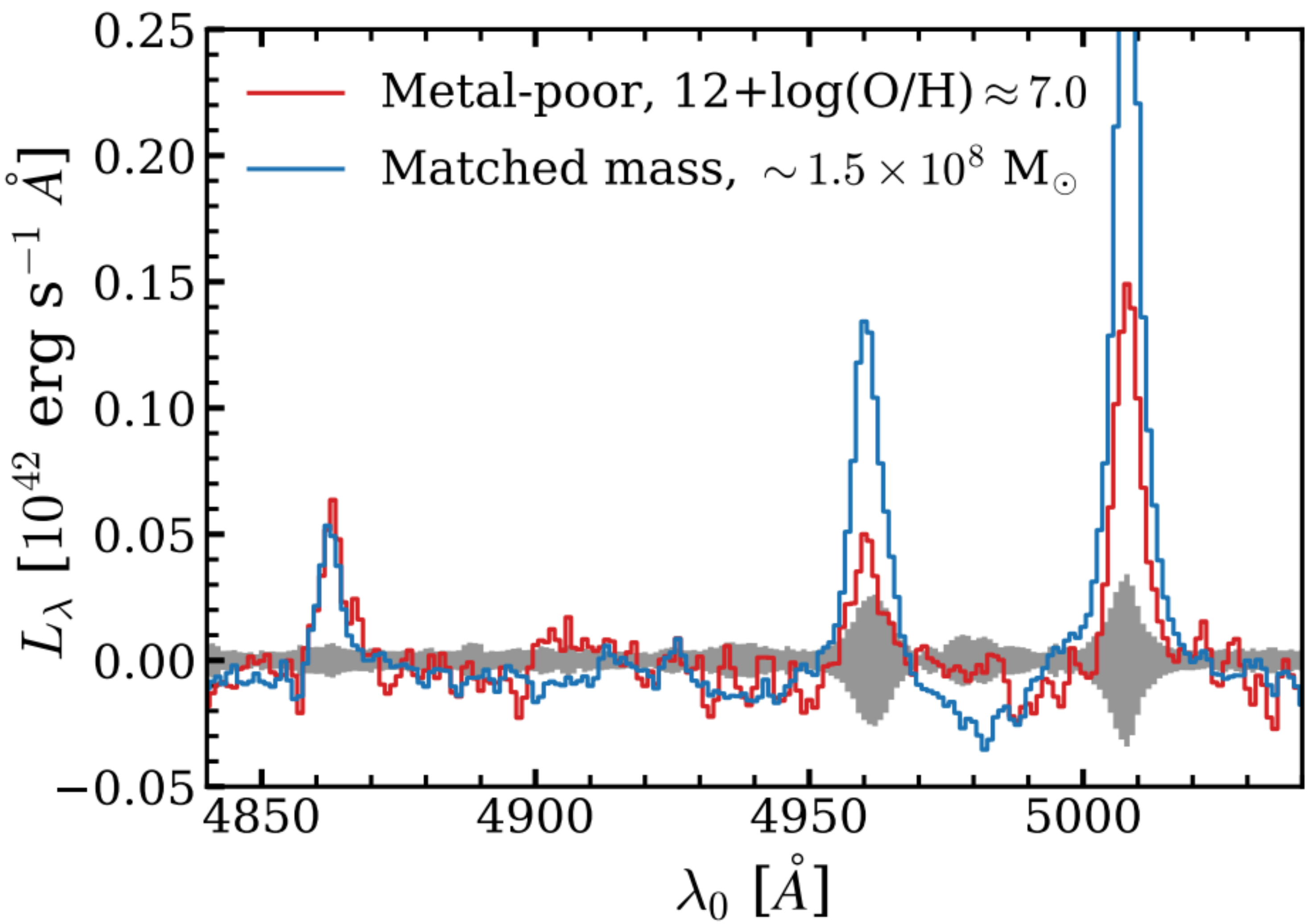


For *emission-line* science, contamination is really a minor issue

Kashino+23, Matthee+23

EIGER:

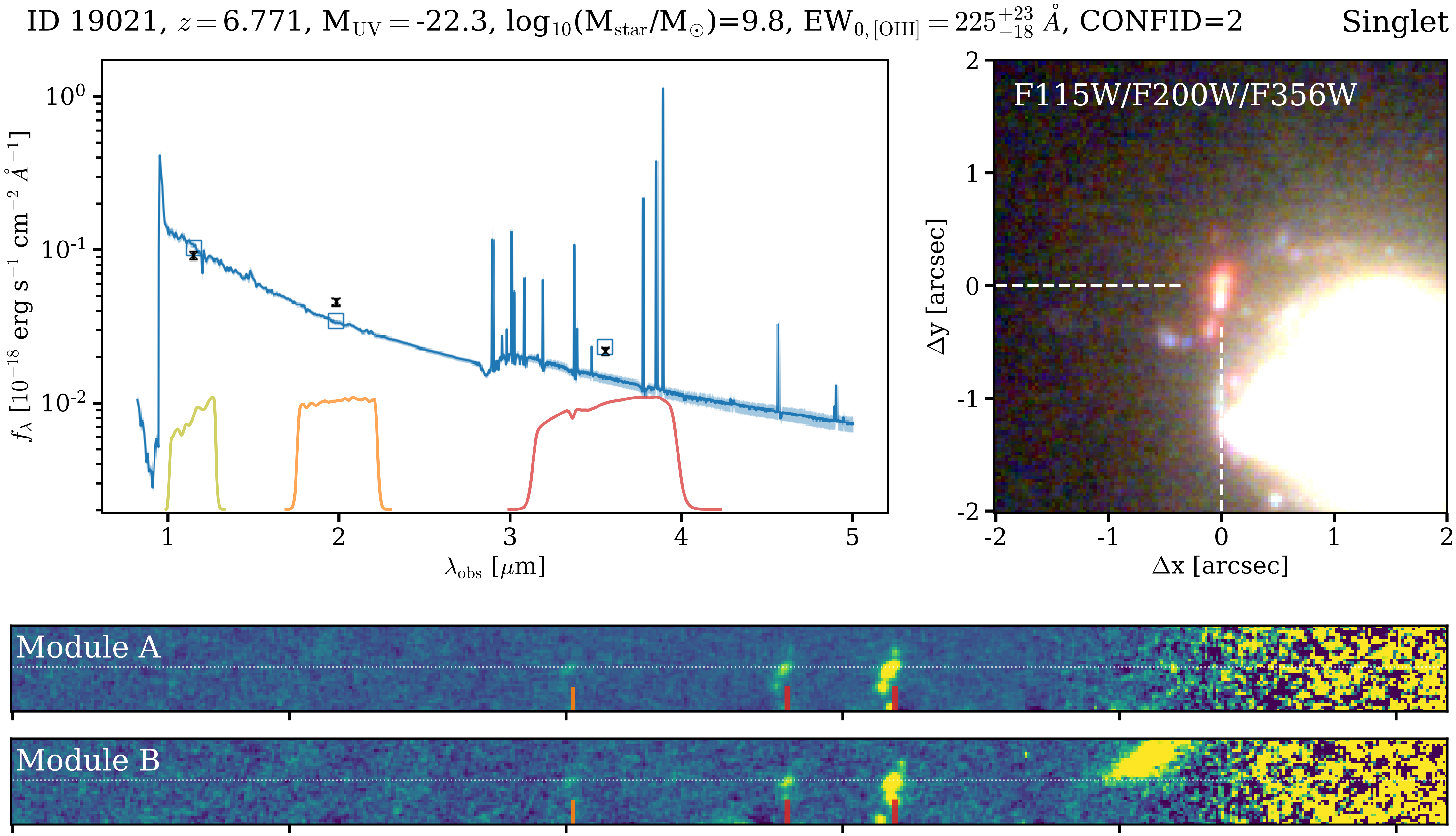
SOME CANDIDATE LOW METALLICITY GALAXIES AT Z~6



Stacked spectrum of the five galaxies with the lowest O3/Hb ratios suggest some galaxies with 12+log(O/H)~7 (2% solar)…

Matthee+22b

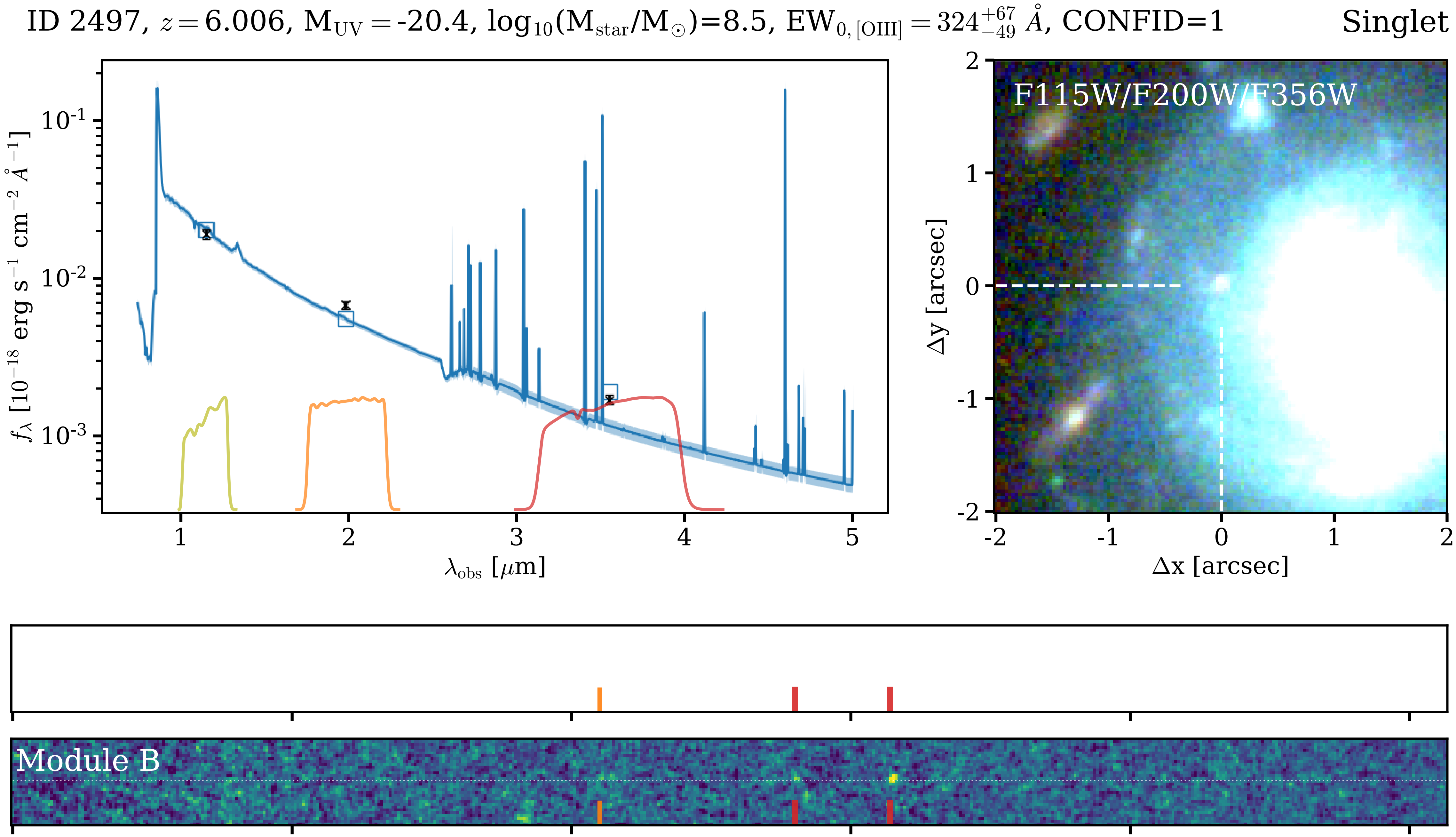
SOME EXAMPLE [OIII] EMITTERS ~800 MYR AFTER BIG BANG



Gravitationally lensed?

Matthee+22b

SOME EXAMPLE [OIII] EMITTERS ~800 MYR AFTER BIG BANG

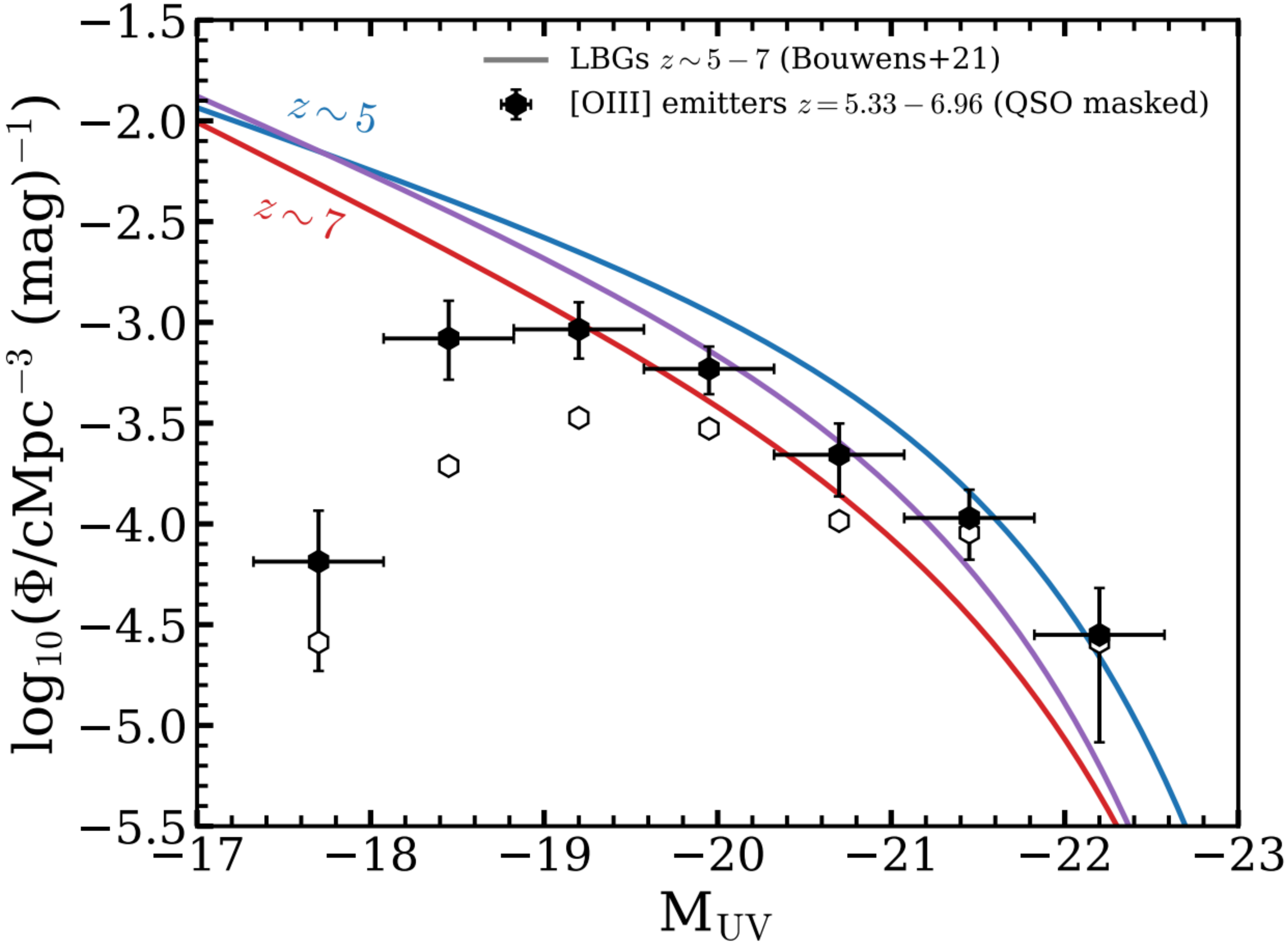


You would never put a slit on this object..

Matthee+22b

EIGER:

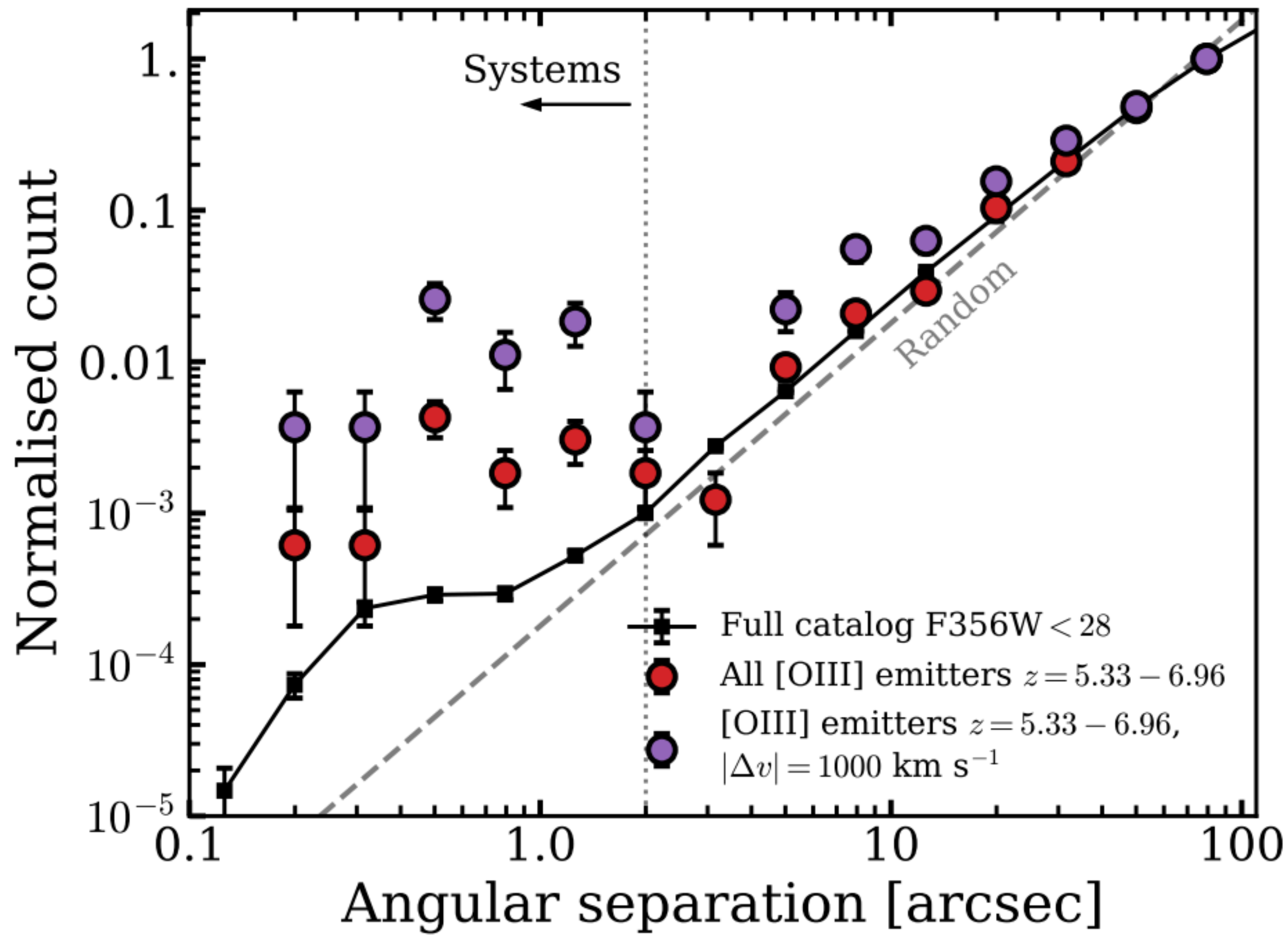
CONFIRMATION THAT Z~5-7 GALAXIES HAVE *UBIQUITOUS* STRONG HB+[OIII] LINES



UV LF of [OIII] emitters matched UV LF of LBGs quite well

Matthee+22b

WE NEED TO TALK ABOUT WHAT WE CALL "A GALAXY"?

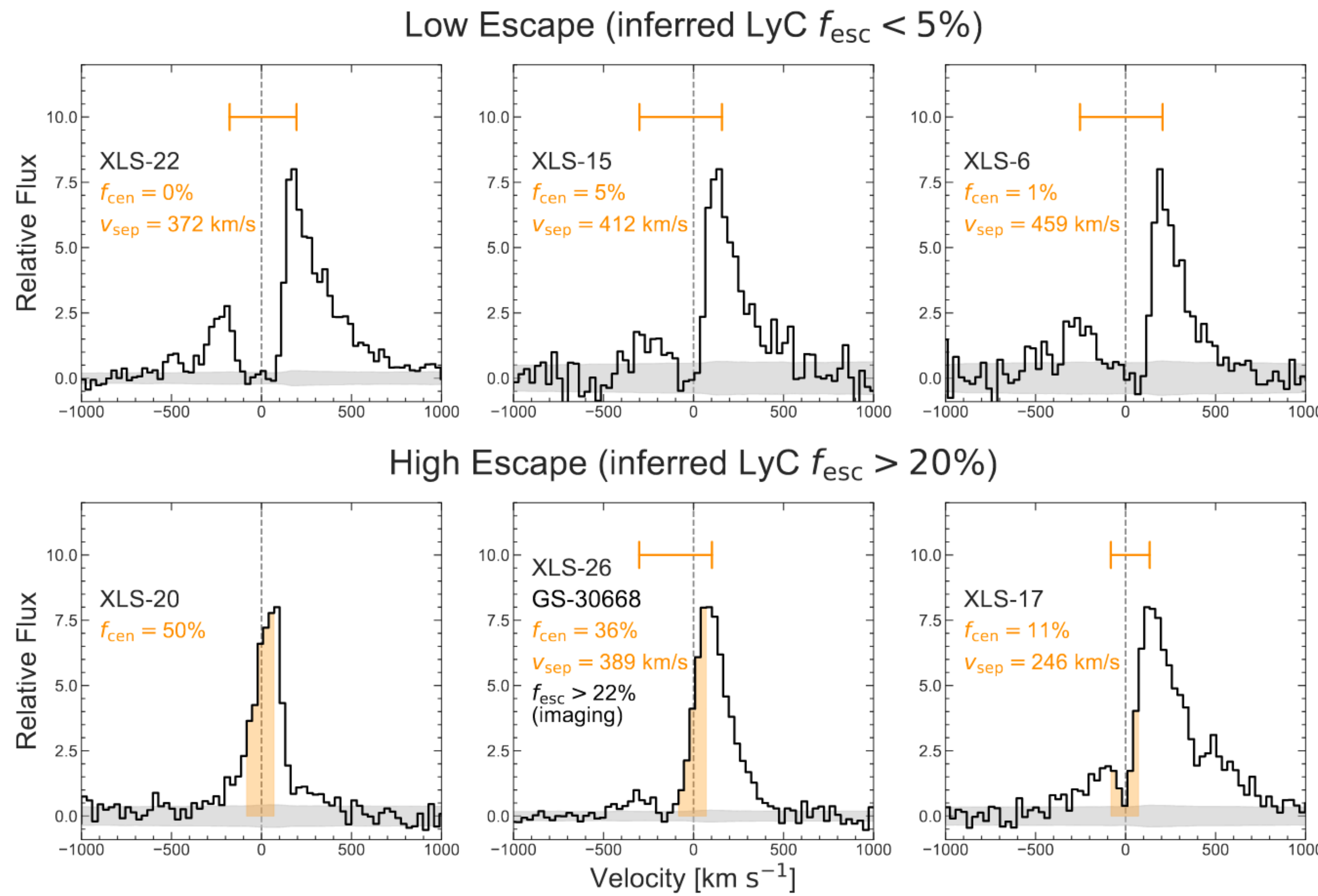


- x **SExtractor deblending parameters?**
- x **Resolution of the data?**
- x **Viewing angle to a multiple component system?**

☑ **Merge delta-v<1000 km/s and separation < 2 arcsec: 133 doublets —> 117 *galaxies***

Matthee+22b

Separating High vs Low LyC f_{esc} based on LyA



~35% of sample

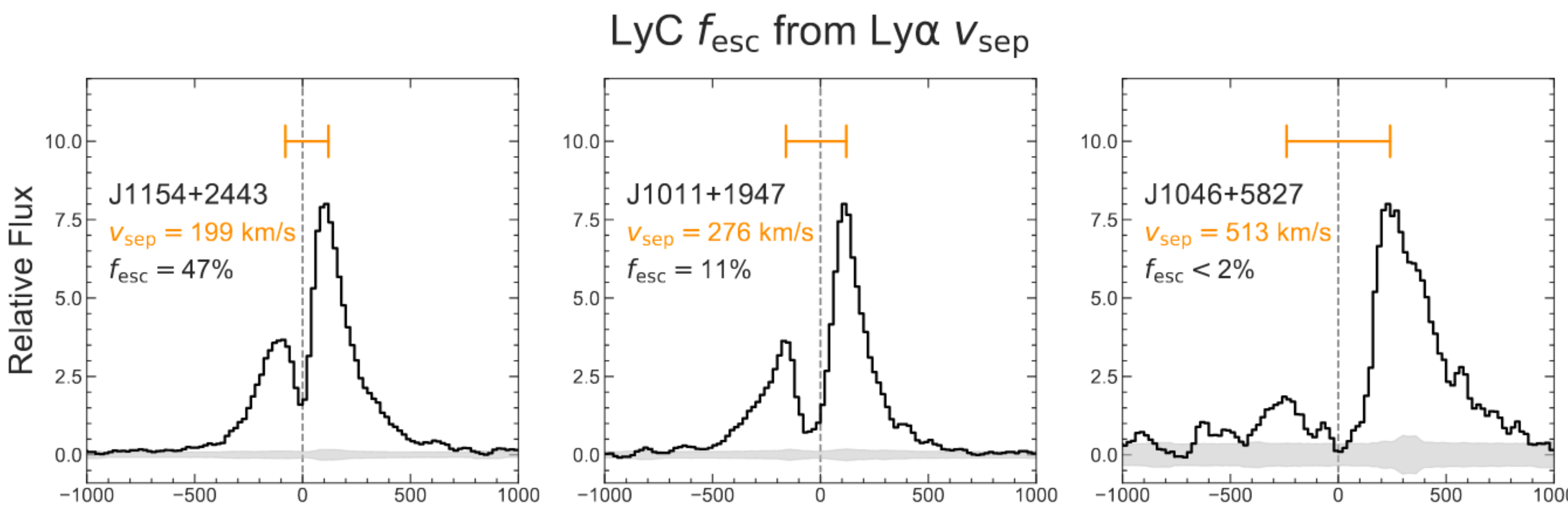
~50% of sample

We find that ~50% of the LAEs at z~2 have high inferred f_{esc} (20-50%), other LAEs have negligible f_{esc}

***No significant* differences in Mass, SFR, UV luminosity, UV slope in parent sample**

Naidu & Matthee et al. arXiv:2110.11961

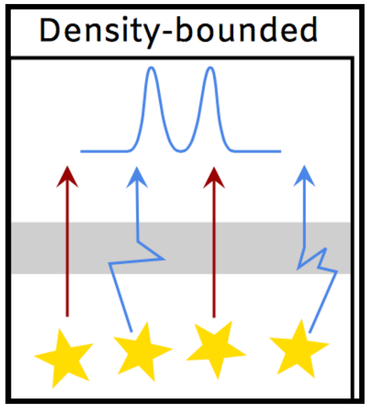
LYMAN-ALPHA LINE-PROFILE & F_{ESC}



High Escape

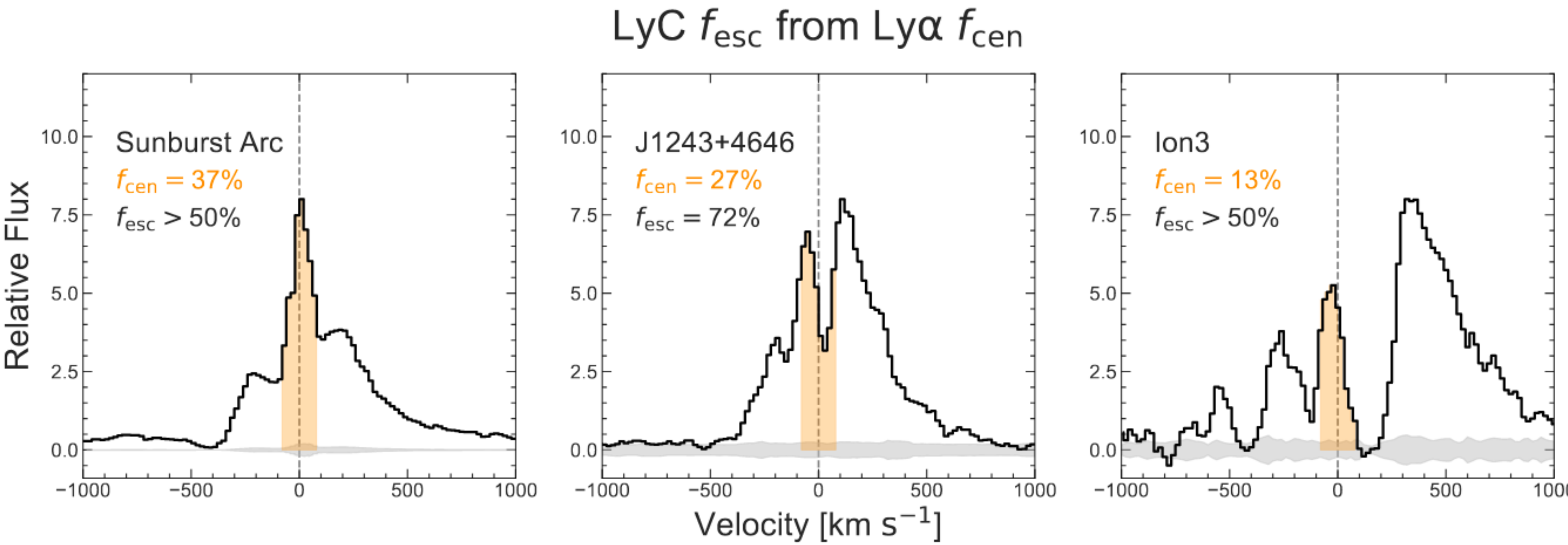
Low Escape

from Naidu & Matthee et al. arXiv:2110.11961

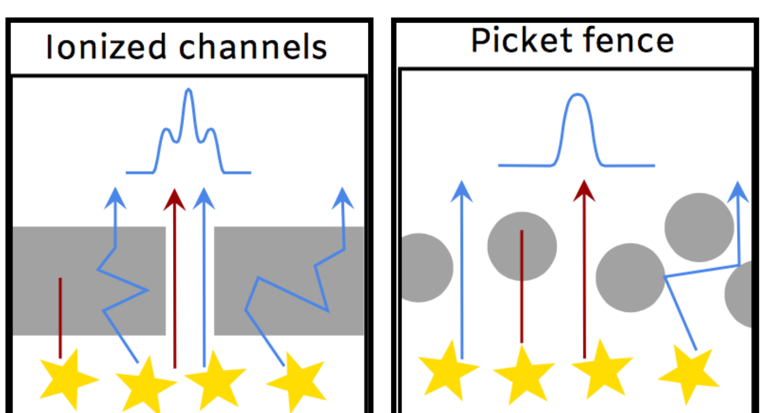


Inset sketches from Rivera-Thorsen+2017

The Central Lya fraction



from Naidu & Matthee et al. arXiv:2110.11961
see also Gazagnes+2020 for the “valley flux”



e.g. Kakiichi & Gronke 2019