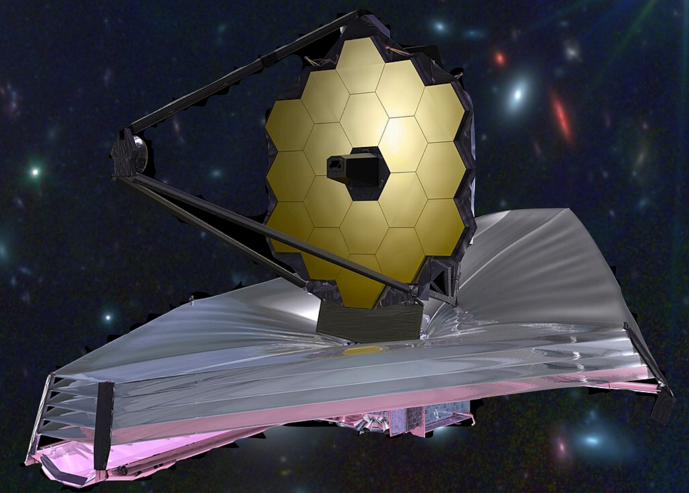
GALAXIES AS AGENTS OF COSMIC REIONIZATION: NEW RESULTS FROM JWST AND MUSE OBSERVATIONS



Jorryt Matthee

jorryt.matthee@ista.ac.at

Institute of Science and Technology Austria

European Research Council
Established by the European Commission

with *Claudia di Cesare, Peter Lechner, Gauri Kotiwale, Ivan Kramarenko (ISTA)*, Ruari Mackenzie (ETH), Rohan Naidu (MIT), Daichi Kashino (NAOJ), Alberto Torralba Torregrosa (Valencia), the EIGER, FRESCO and the ALT teams

THIS TALK

- A Lyman-α emitter Emissivity Model
- Emission-line galaxies and AGN in early JWST data
- Galaxy tomography

Standard approach to the emissivity from SFGs

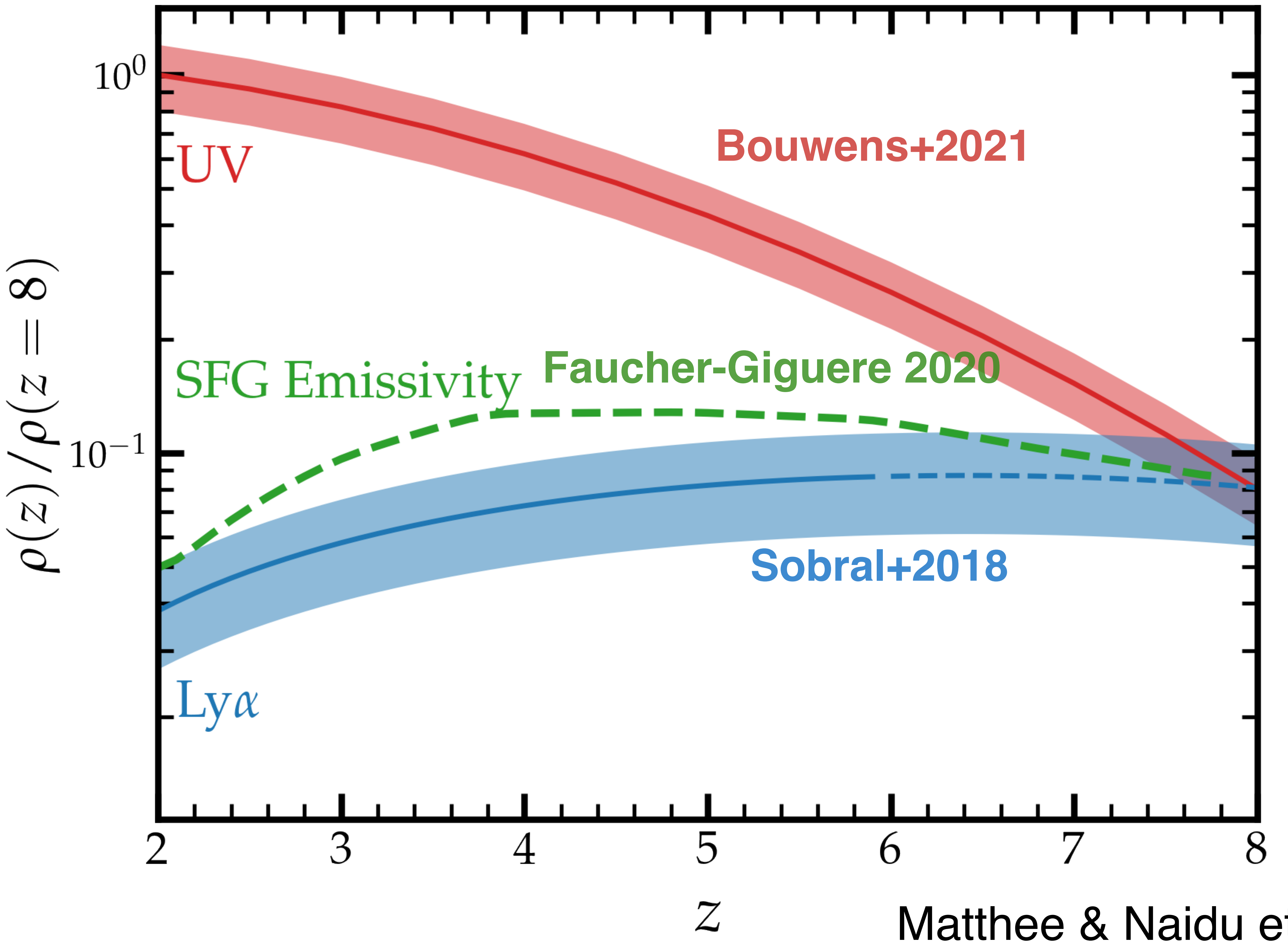
$$\dot{n}_{\rm ion,LBG}(z) = \rho_{\rm UV}(z)\, \xi_{\rm ion}\, f_{\rm esc}^{\rm LyC}\ [{\rm s}^{-1}{\rm Mpc}^{-3}]$$

e.g. Madau+1999, Robertson+2013

STANDARD APPROACH TO THE EMISSIVITY FROM SFGS

STANDARD APPROACH TO THE EMISSIVITY FROM SFGS

Our approach: tie the Galaxy Emissivity to the *known* Lya emissivity



Matthee & Naidu et al. 2022

The evolution of the emissivity resembles the evolution of the *emerging* Lyman-alpha luminosity density

An Empirical, Lyman-alpha anchored approach to the emissivity

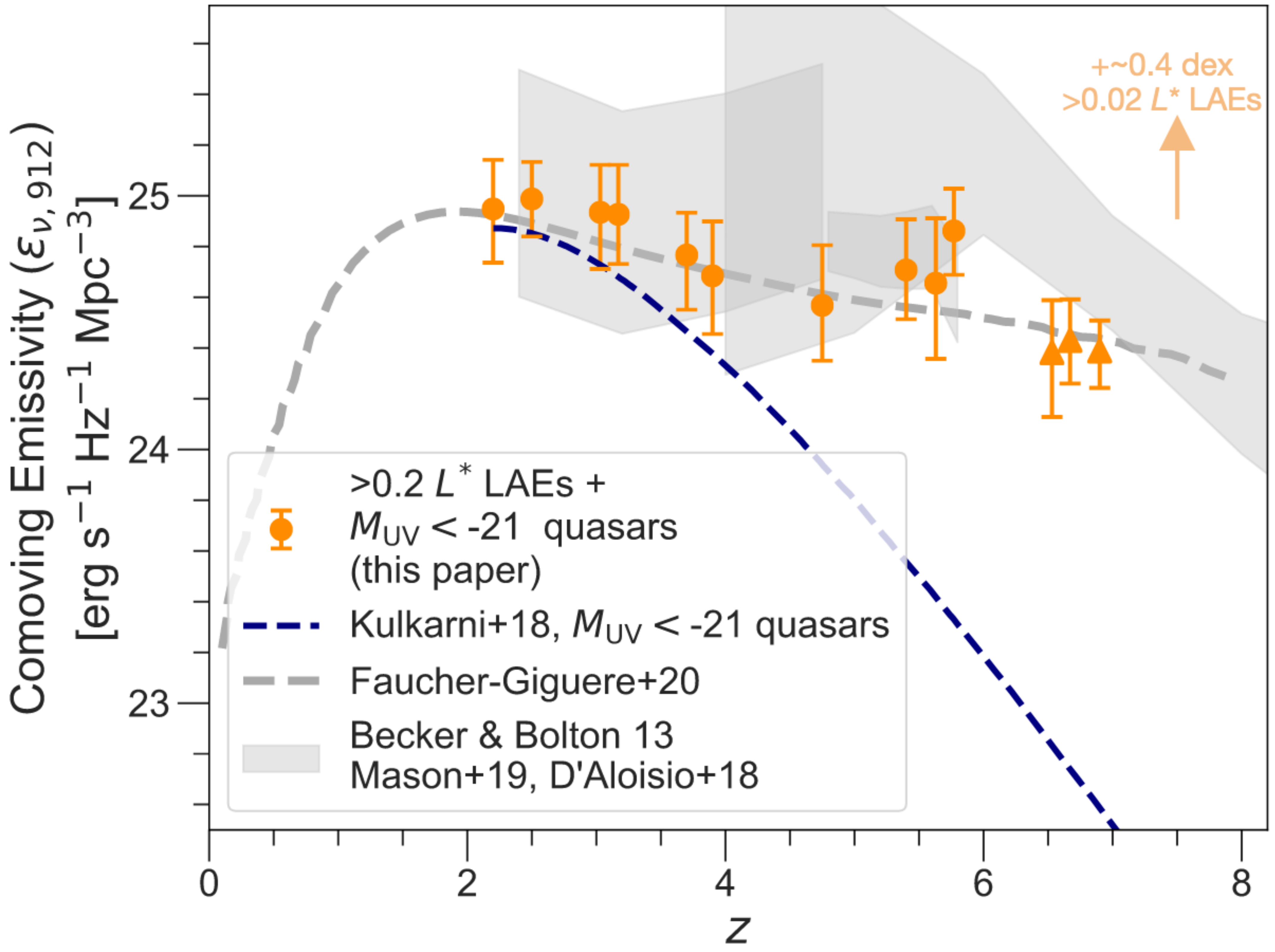
$$\dot{n}_{\rm ion,LBG}(z) = \rho_{\rm UV}(z)\,\xi_{\rm ion}\,f_{\rm esc}^{\rm LyC}\ [{\rm s^{-1}Mpc^{-3}}]$$

e.g. Madau+1999, Robertson+2013

$$\rightarrow\quad \dot{n}_{\rm ion,LAE}(z) = \frac{\rho_{\rm Ly\alpha}(z)\,f_{\rm esc}^{\rm LyC}}{8.7\,f_{\rm esc}^{\rm Ly\alpha}\left(1-f_{\rm esc}^{\rm LyC}\right)c_{\rm H\alpha}}\ [{\rm s^{-1}Mpc^{-3}}].$$

Matthee & Naidu et al. 2022

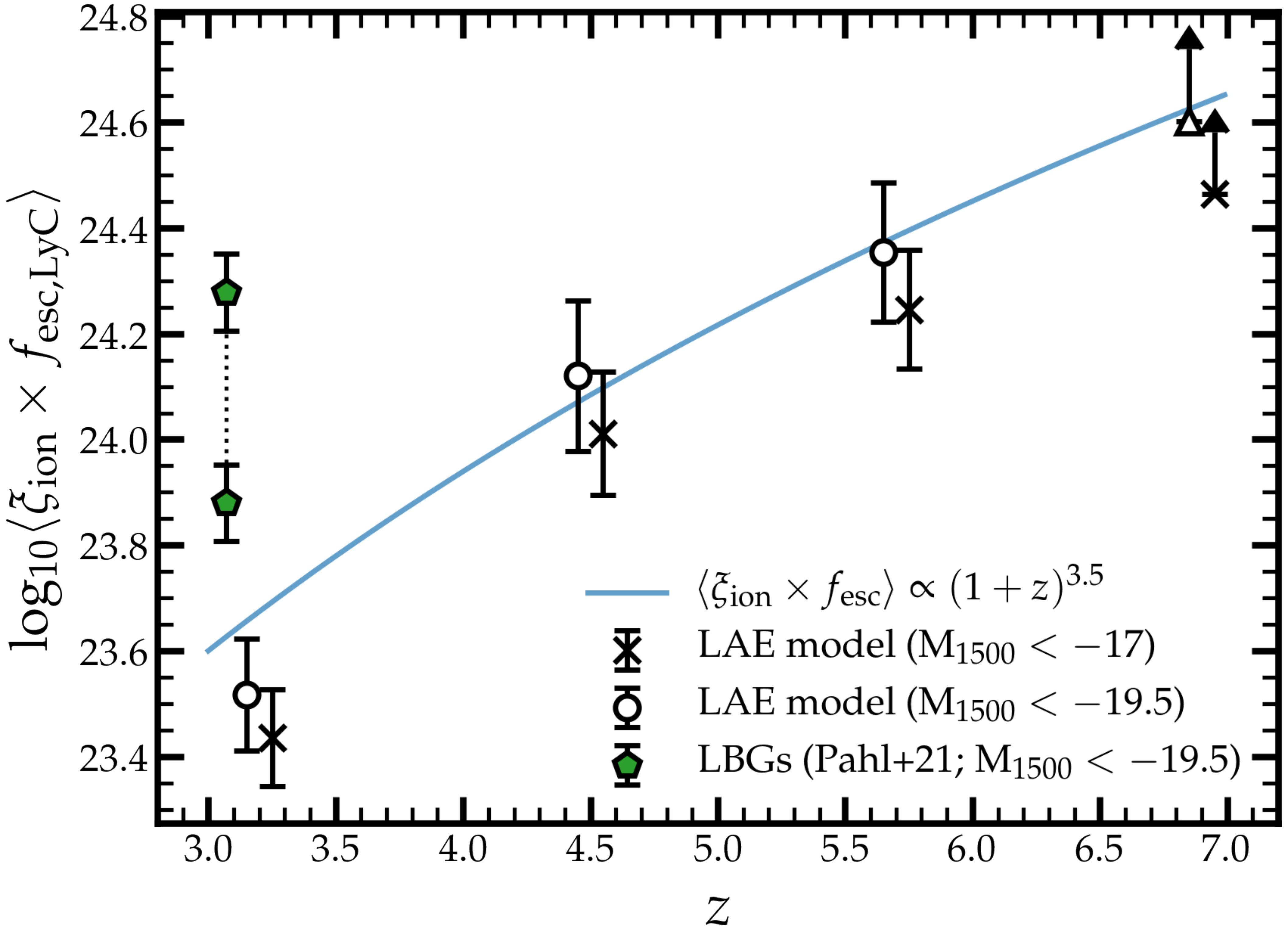
LAEs match the Galaxy emissivity over z=2-8

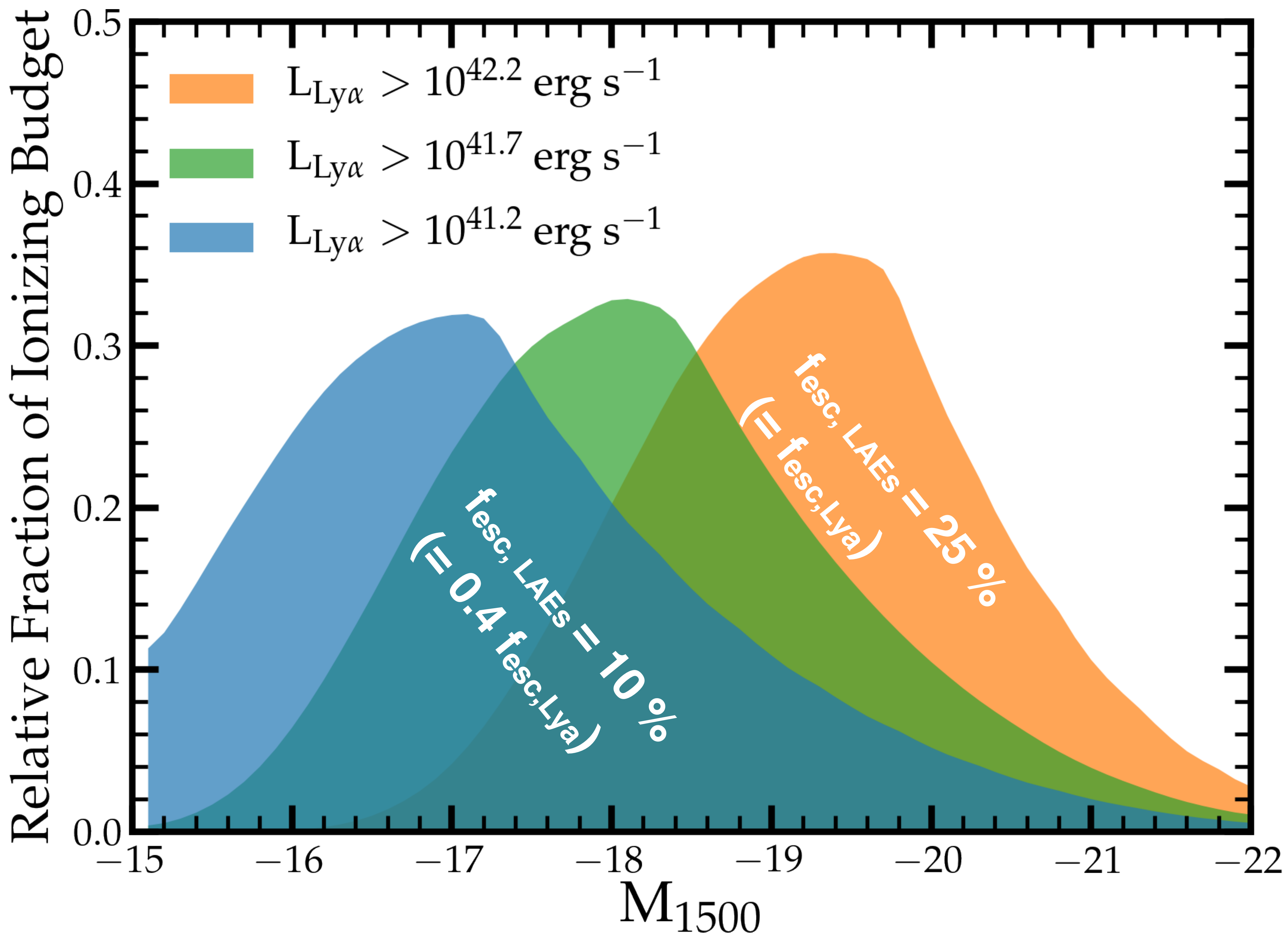


- **LAE-based galaxy emissivity model matches the global emissivity evolution**
- **This *does not require any redshift evolution in their f_{esc} or ξ_{ion}!***

Matthee & Naidu et al. 2022

Generic output of the simple LAE emissivity model



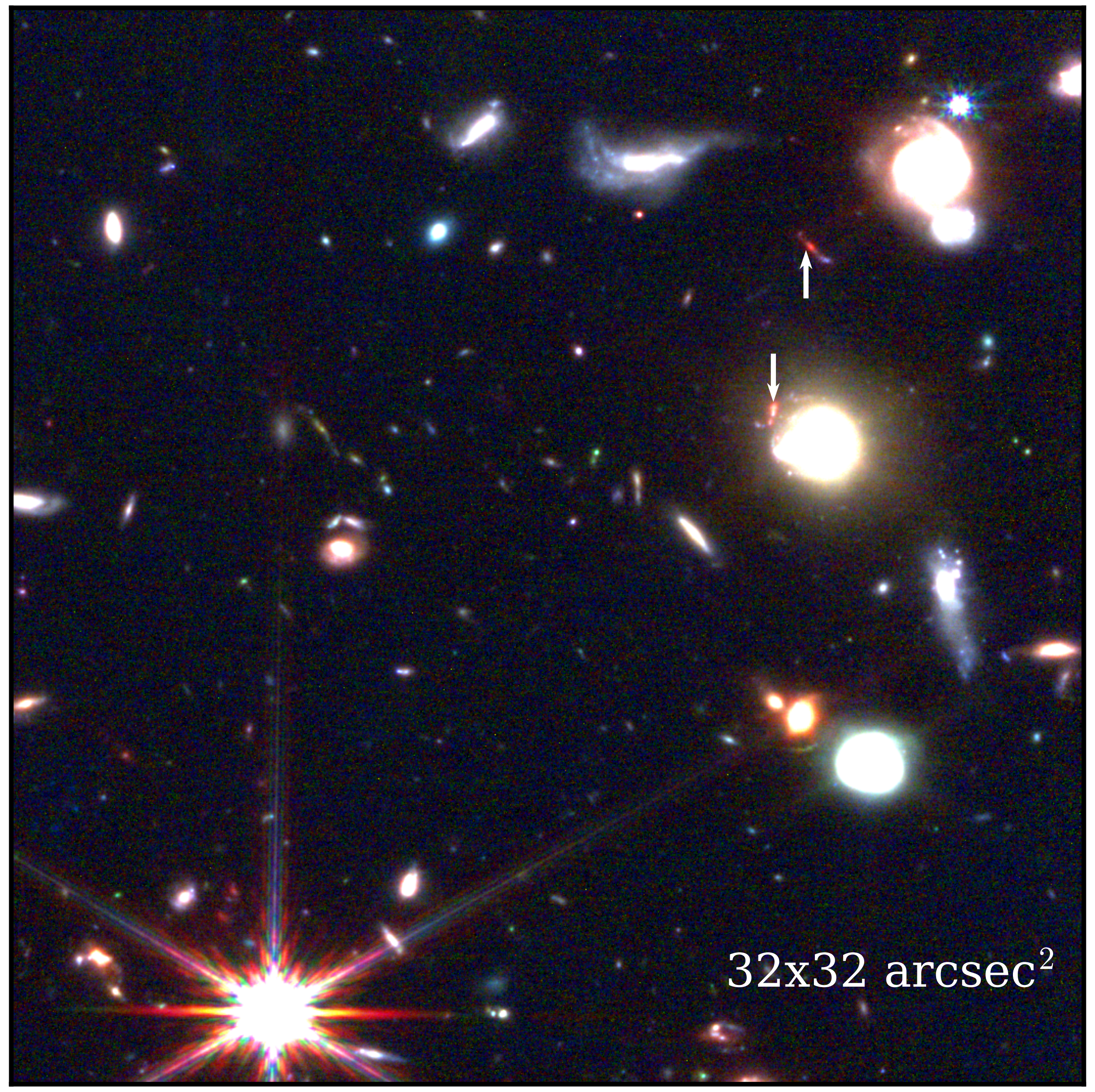


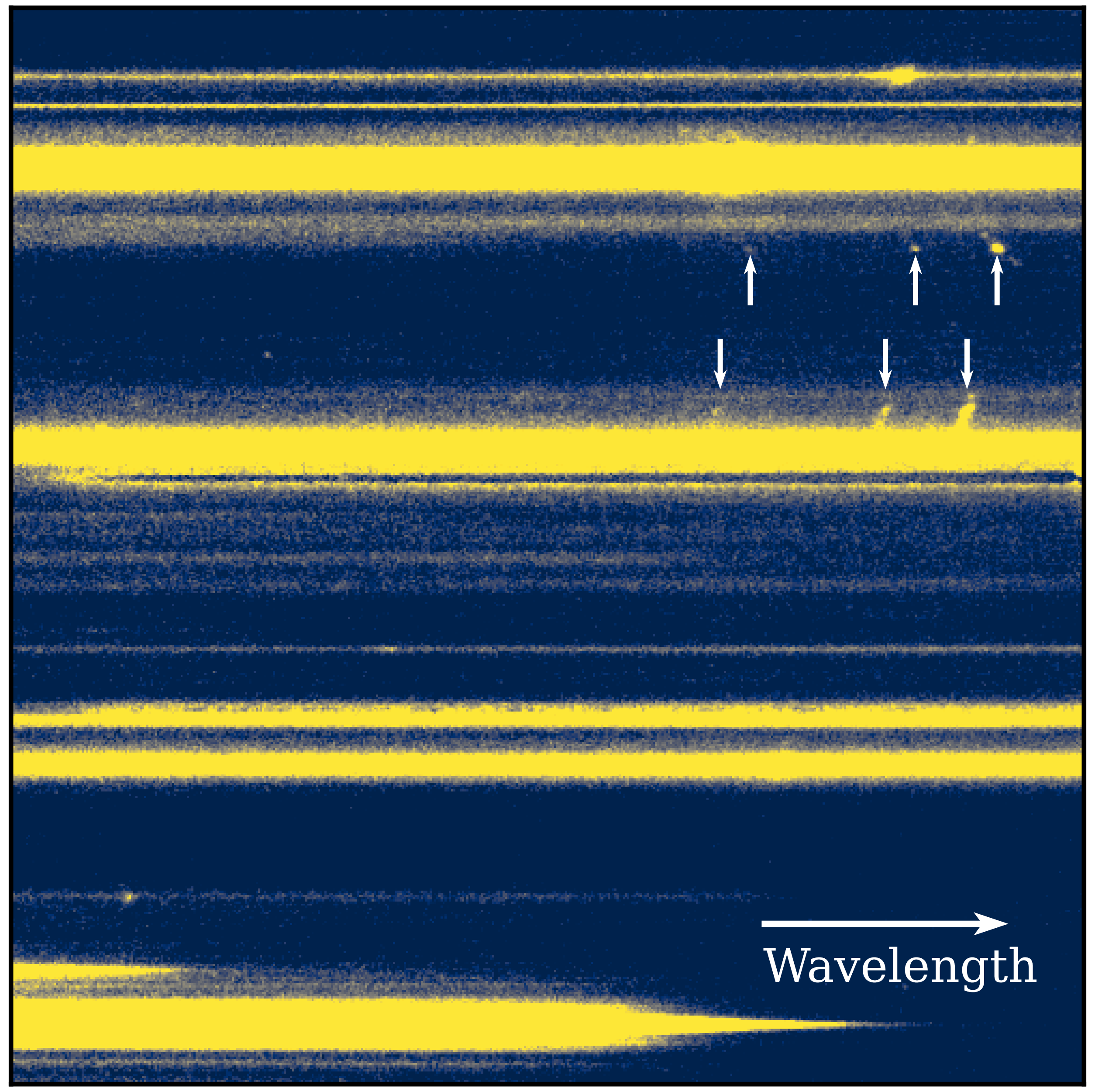
*** A peak in the f_{esc} - M_{UV} relation (set by faintest LyA luminosity of ionisers & differences between UV and Lya LFs)**

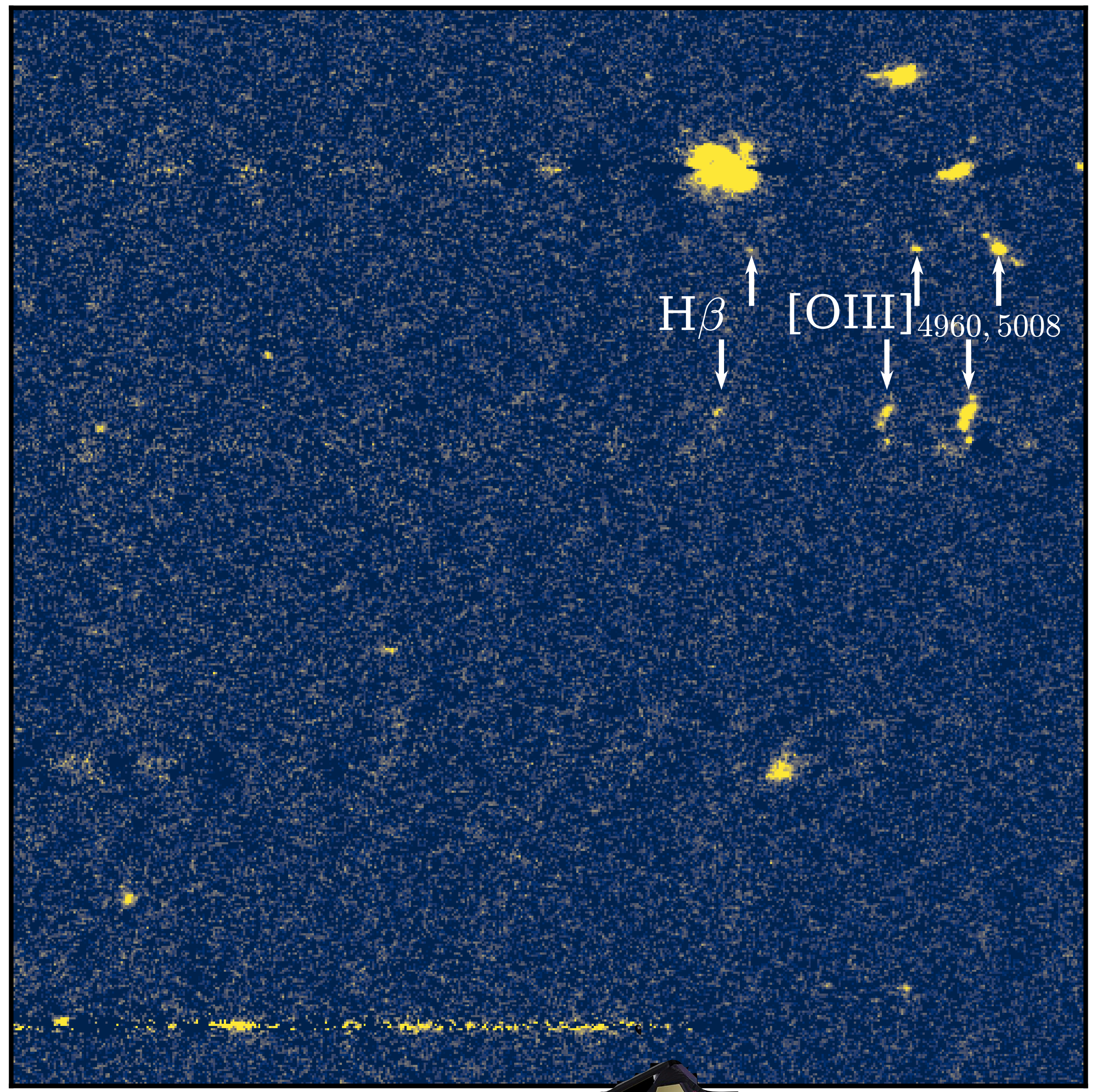
*** Strong redshift evolution in <f_{esc}> of about ~$(1+z)^3$ of the LBG population over z~2-6**

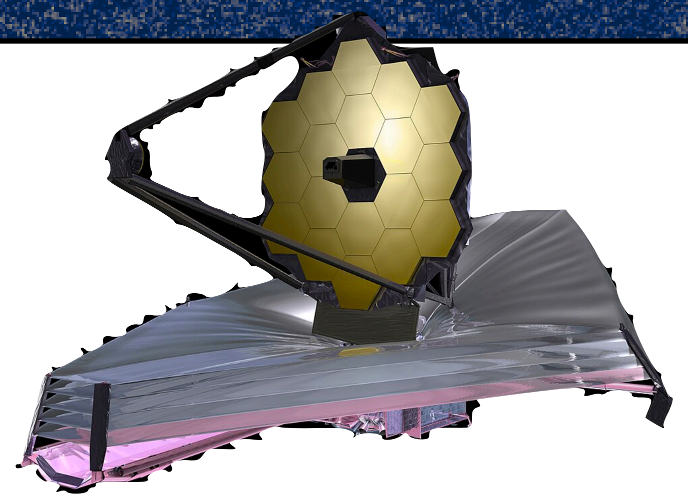
Matthee & Naidu et al. 2022

JWST CENSUS ON EMISSION-LINE GALAXIES





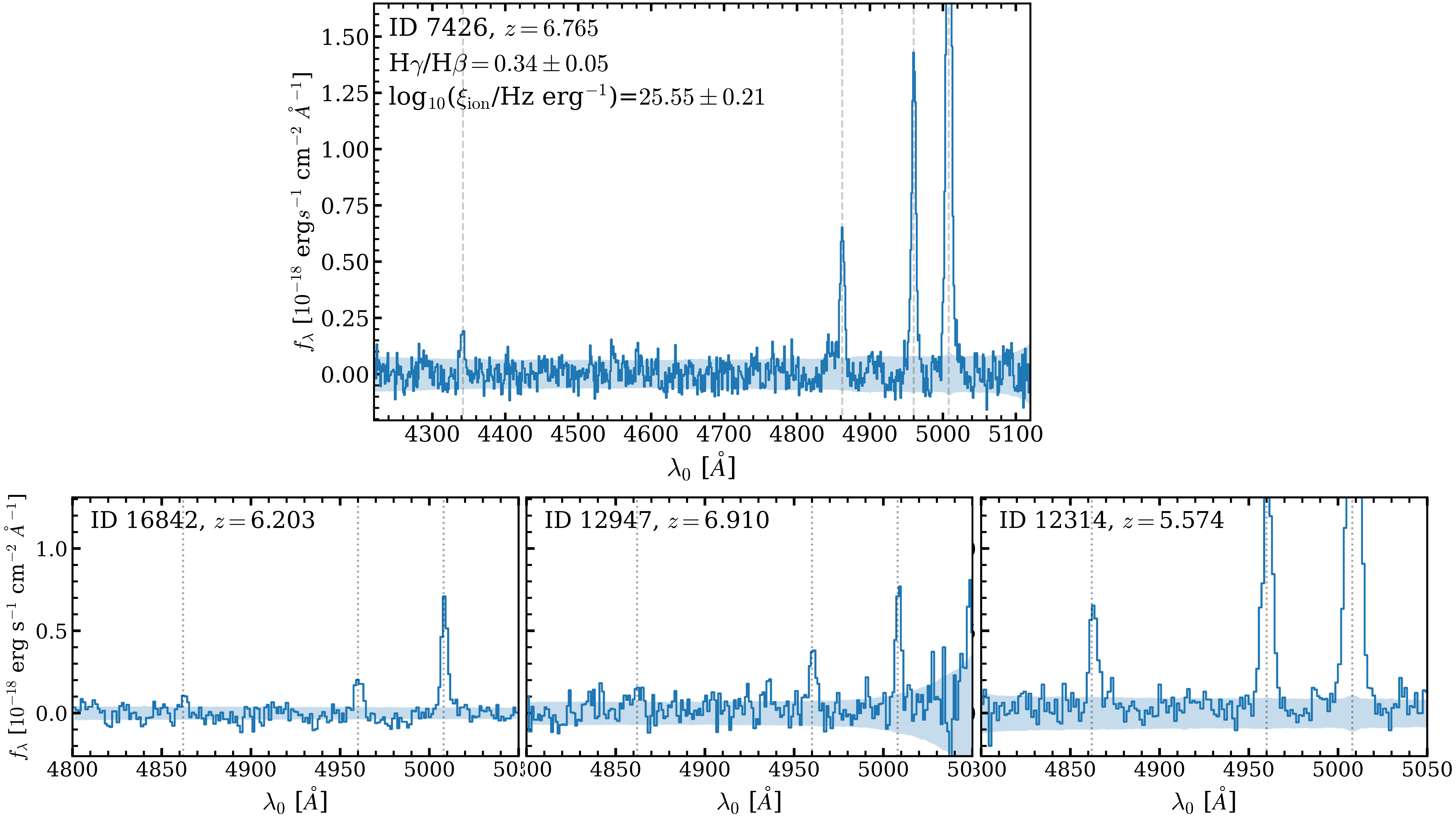




Programs

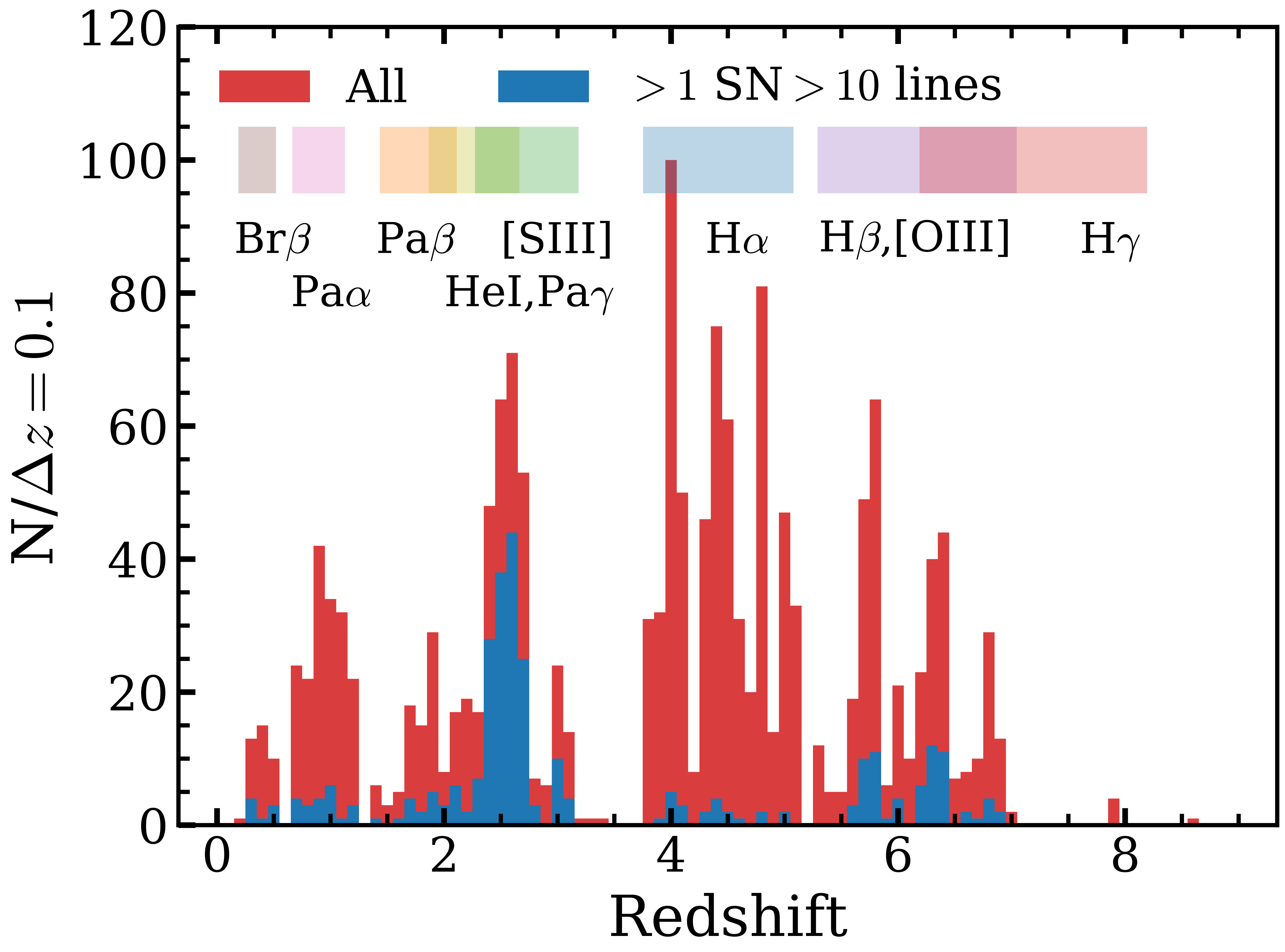
- **EIGER: 120 hrs Quasars Cycle 1 (PI: Lilly),** also in talk by **Daichi Kashino** on Monday
- **FRESCO: 60 hr GOODS fields (PI: Oesch)**
- **COLA1: 18 hr Luminous LAE Cycle 1 (PIs: Matthee & Naidu),** see talk by **Alberto Torralba Torregrosa** tomorrow
- **ALT: 48 hr Abell 2744 Cycle 2 (PIs: Matthee & Naidu), this talk**

TYPICAL NIRCAM WFSS SPECTRA: NOW FOR ~3000 GALAXIES AT Z=4-7



Kashino+23; Matthee+23

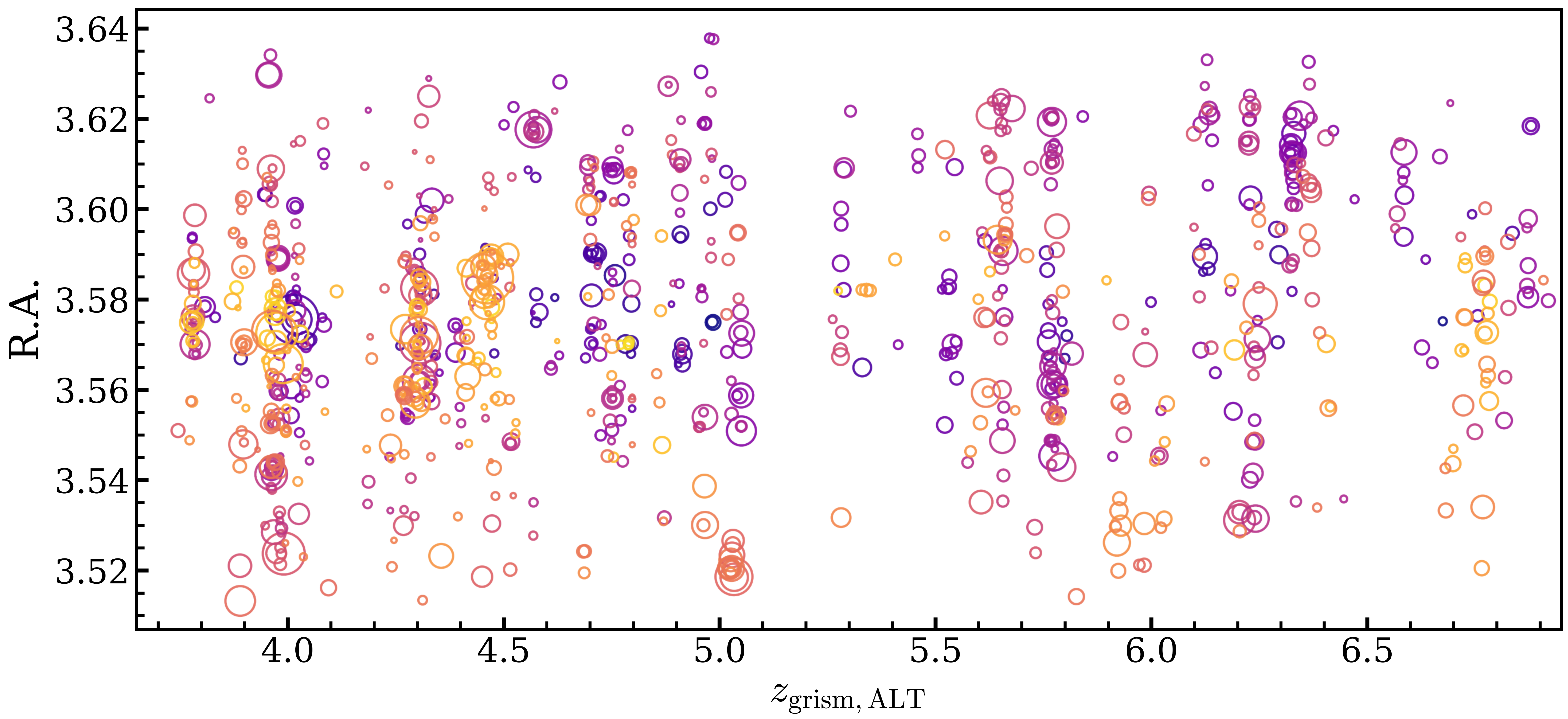
ALT: All Emission-Line Redshifts behind Abell 2744 (F356W)



- **1500 spectroscopic redshifts in/behind Abell 2744 with *Allegro*** *(Kramarenko & Matthee in prep)*

ALT survey paper (Naidu & Matthee et al. in prep)

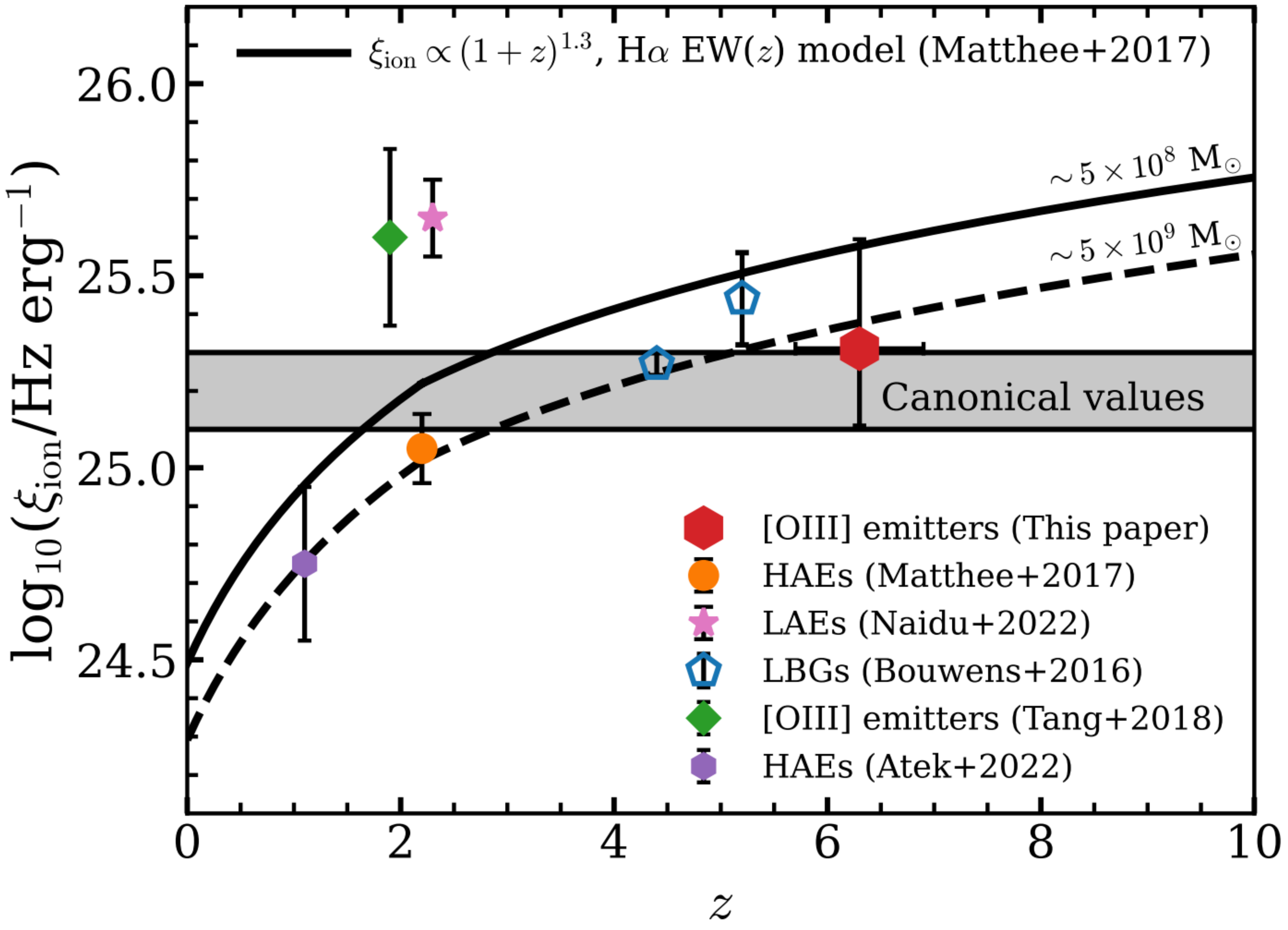
ALT: ALL EMISSION-LINE REDSHIFTS BEHIND ABELL 2744



- Clear and strong galaxy clustering is easily observed with JWST/NIRCam WFSS
- Very promising for IGM - galaxy cross-correlations, and others

ALT survey paper (Naidu & Matthee et al. in prep)

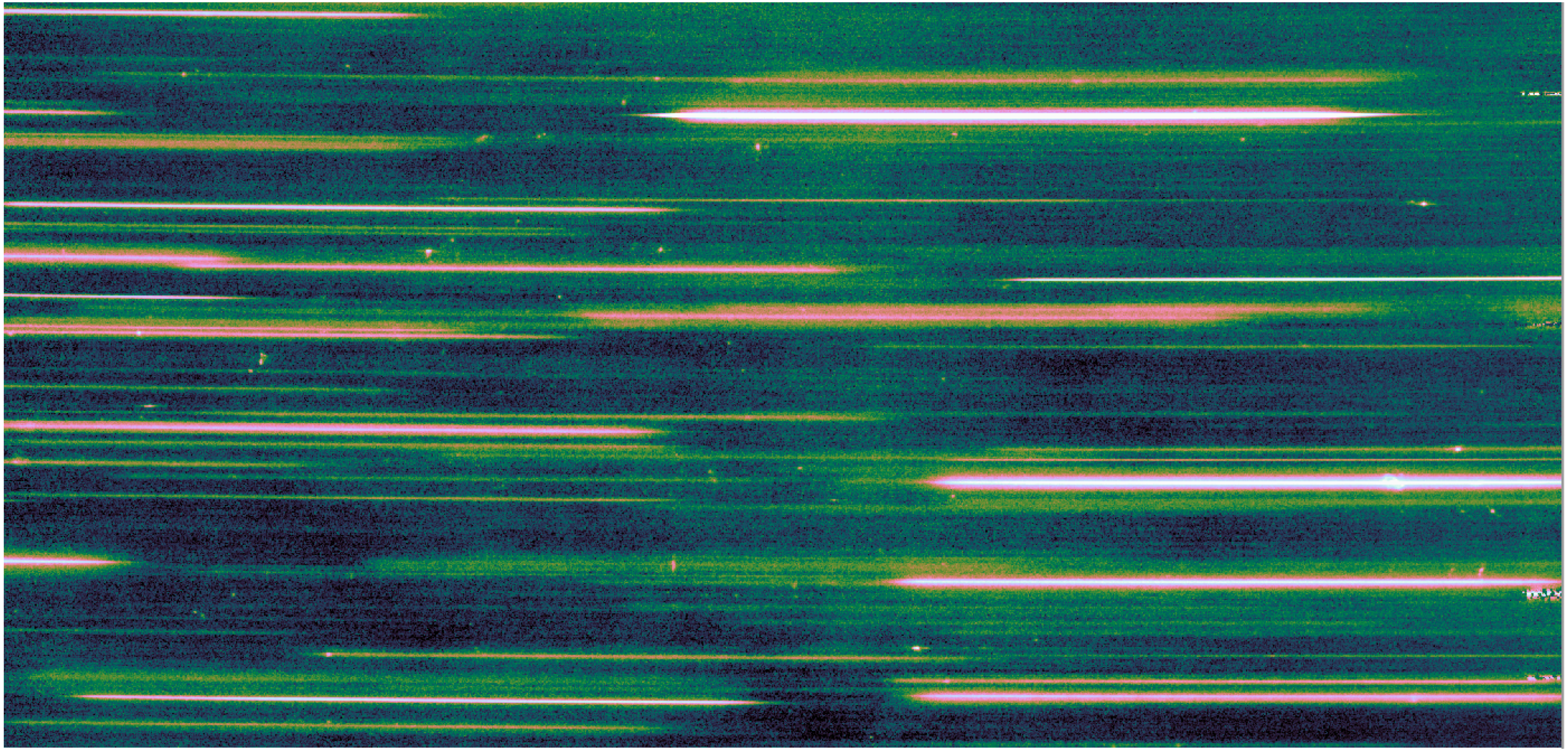
NIRCam WFSS results: z~6 galaxies have *relatively* high ionizing photon production efficiency



- **Our EIGER sample average ξ_{ion} is $10^{25.3\pm0.2}$ Hz erg^{-1}: relatively high, but not extreme for M_{UV}~-19**
- **In the ALT/lensed galaxy sample, we find an increase to ξ_{ion} ~$10^{25.5}$ Hz erg^{-1} for M_{UV}~-17… but unclear whether it's fully representative**

Matthee+23
Di Cesare, Matthee + in prep

TYPICAL DEEP NIRCAM GRISM EXPOSURE IN EIGER

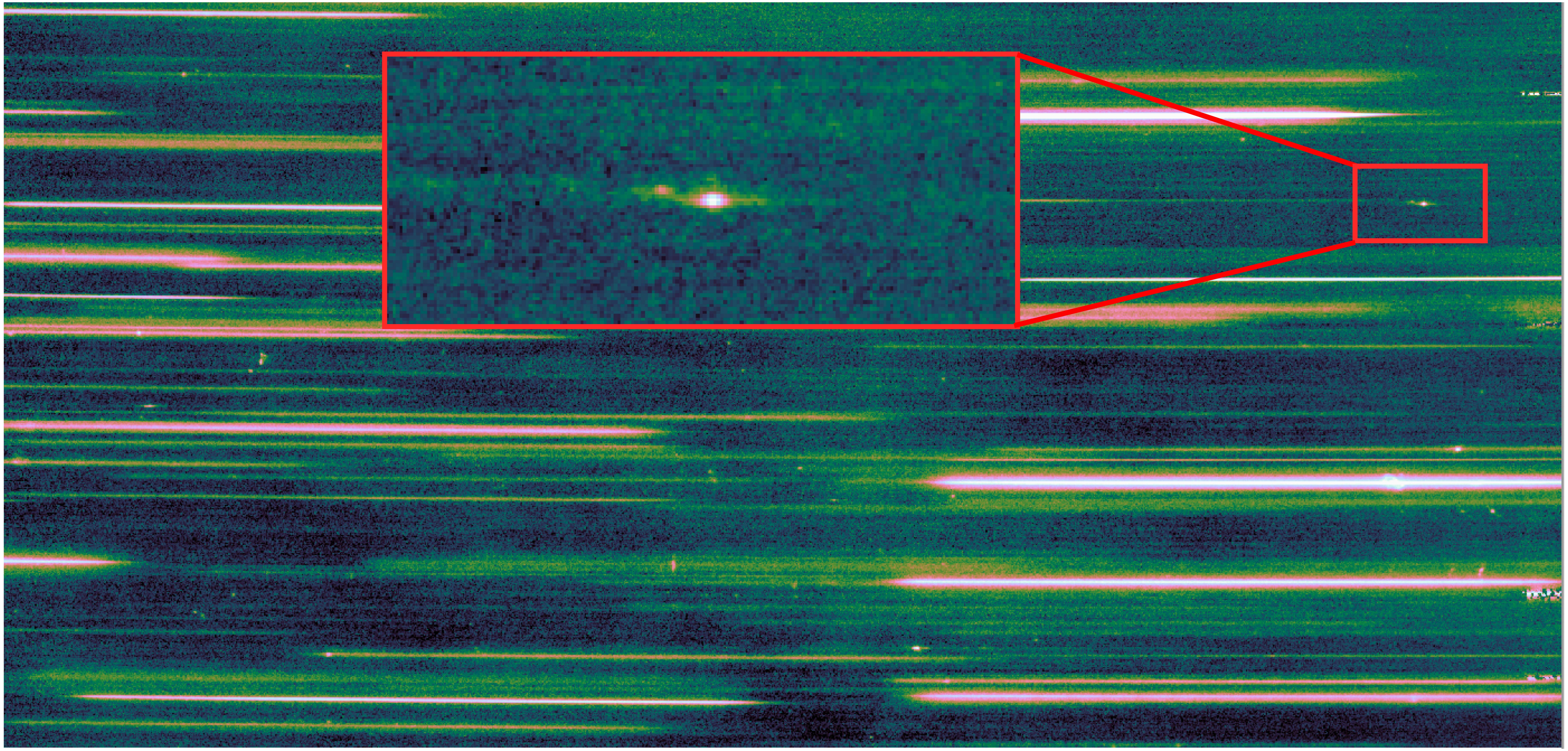


Wavelength

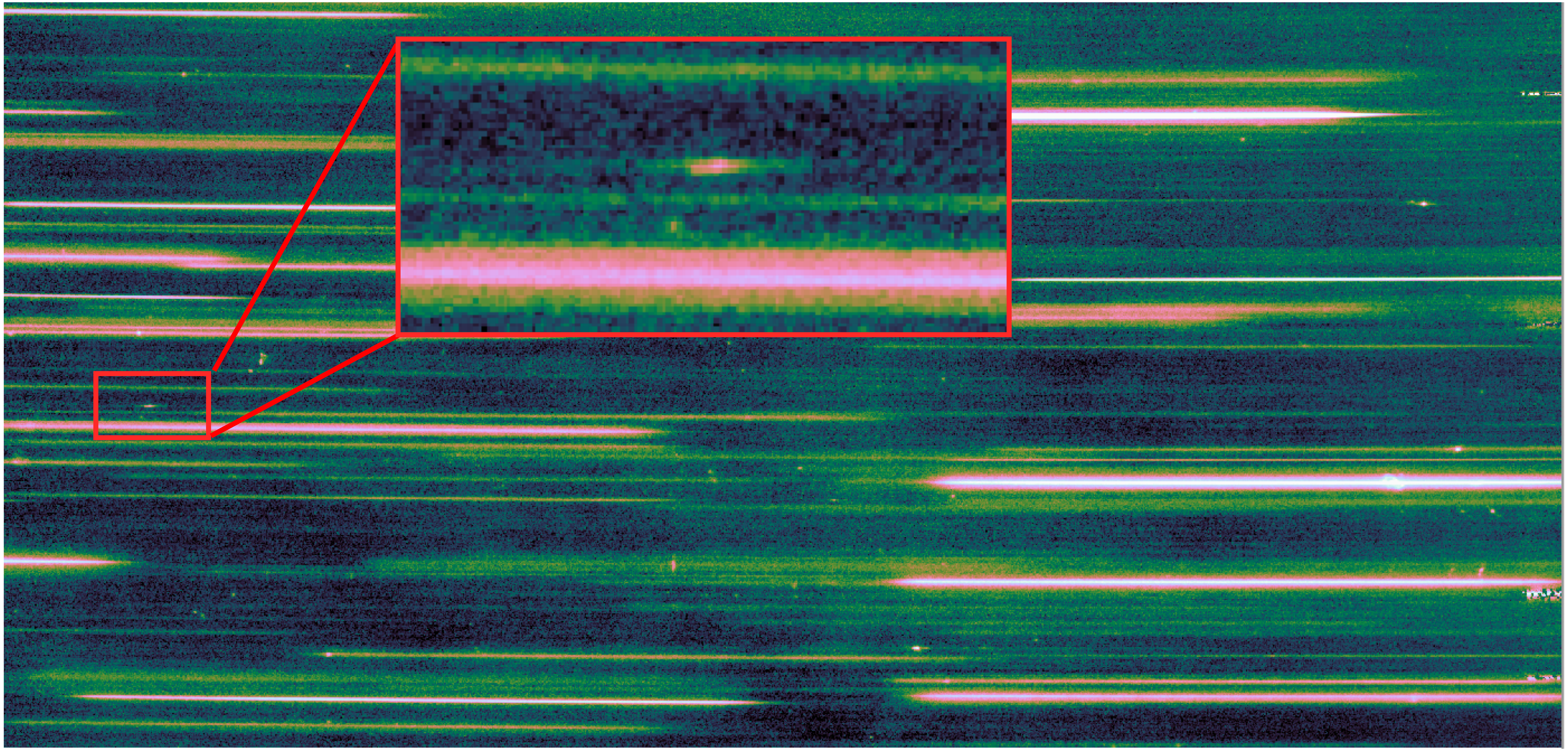
~2 hrs, JWST/NIRCam WFSS F356W

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

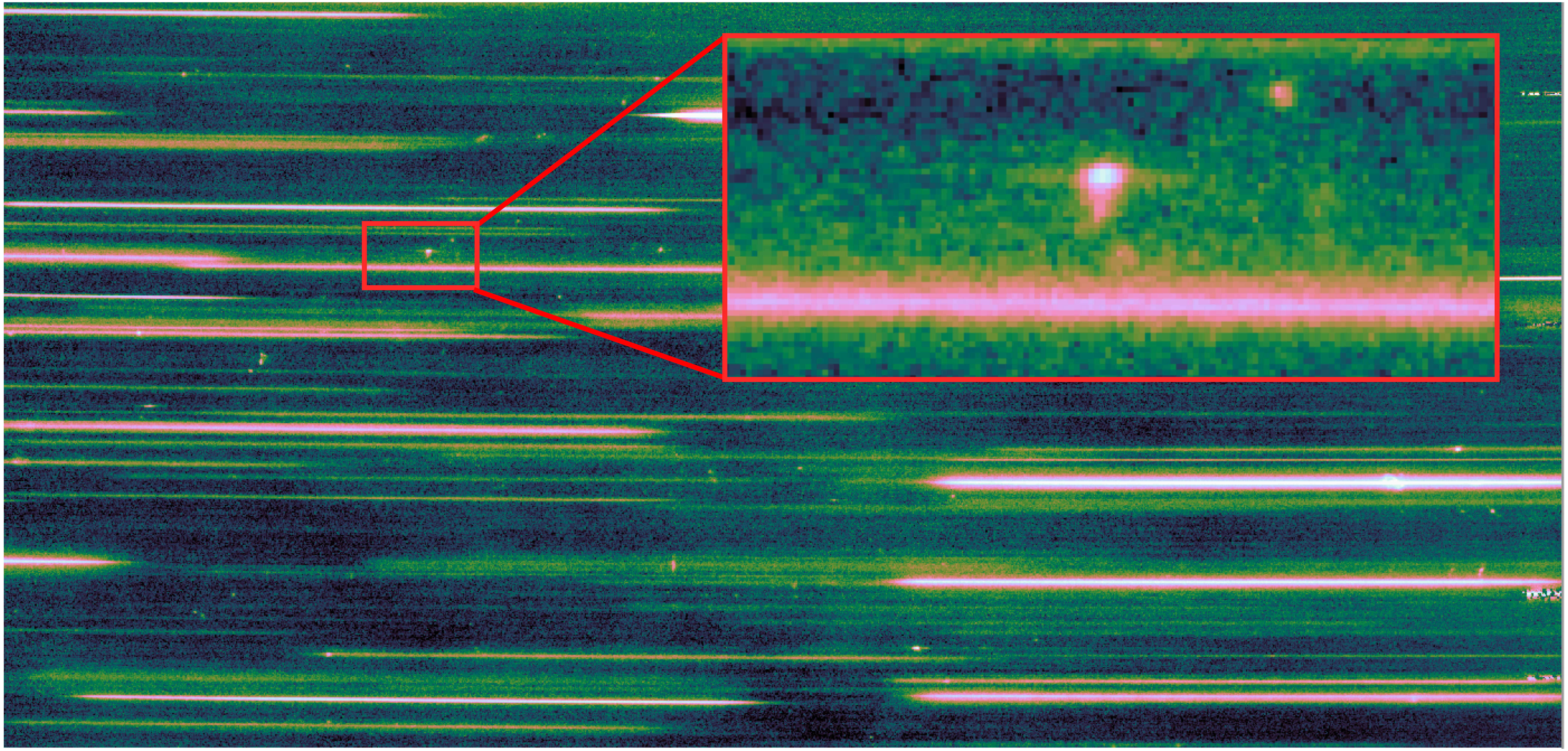
TYPICAL DEEP NIRCAM GRISM EXPOSURE IN EIGER



TYPICAL DEEP NIRCAM GRISM EXPOSURE IN EIGER

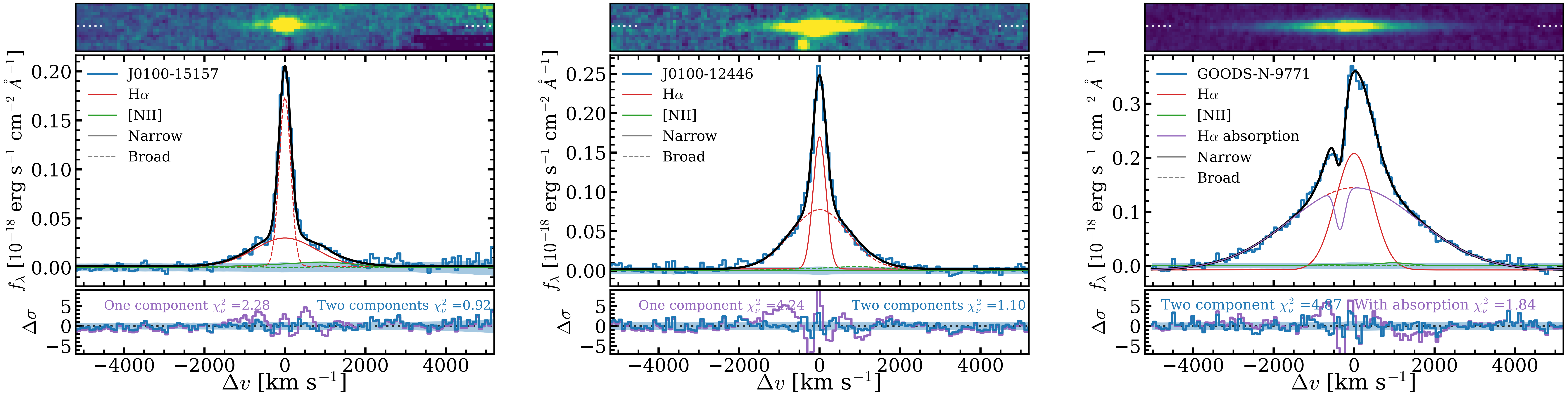


TYPICAL DEEP NIRCAM GRISM EXPOSURE IN EIGER



Every deep JWST pointing shows ~1-2 such objects with broad emission lines

BROAD HALPHA LINES: LOWER MASS, SMBHS AT Z~4-5

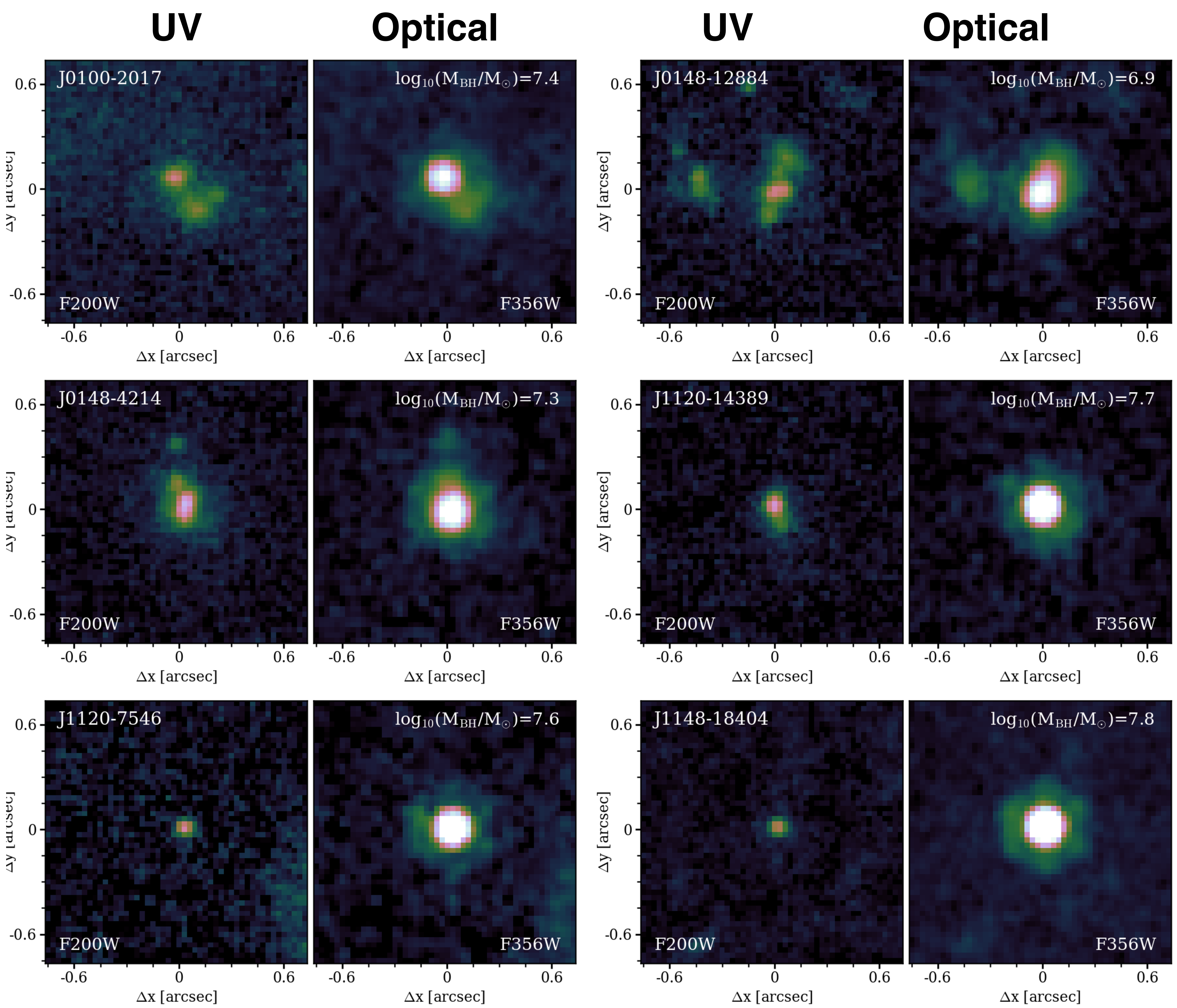


- **20 Broad Halpha lines at z~4-5 FWHM~1000-3000 km/s in the FRESCO+EIGER surveys**
- **BH masses ~10^{7-8} M_{sun}**
- **About ~300 have been identified so far, the record at z=8.5 (Kokorev+23)**

See also Ubler+23, Kocevski+23, Harikane+23, Greene+23, Kokorev+23, Maiolino+23

Matthee+24b

FAINT AGN AND THEIR HOST GALAXIES

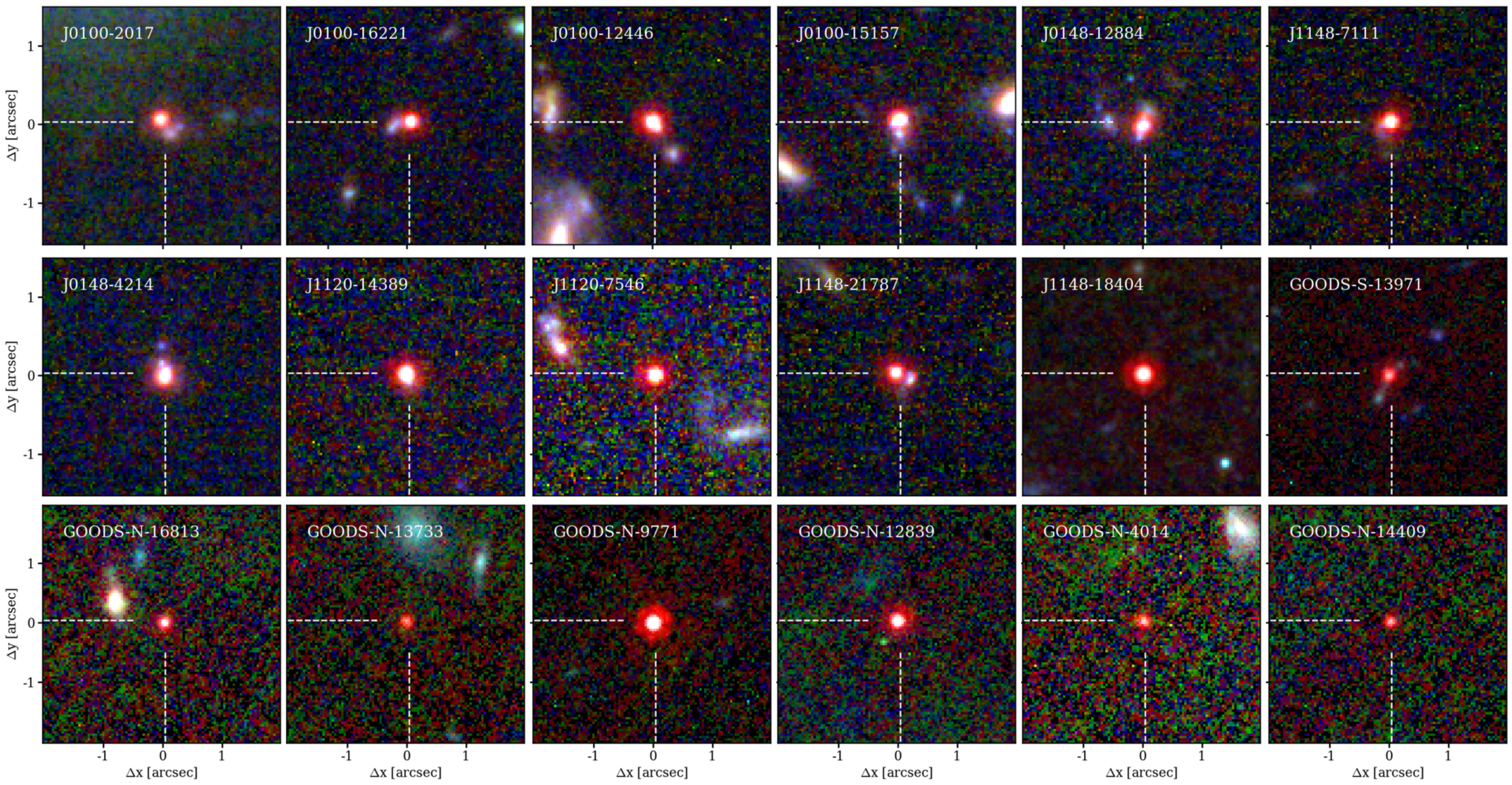


AGN are not extremely dominant in the rest-UV — AGN are heavily attenuated, up to A_V=~4

Some BL-Halpha emitters remain point-sources in rest-UV, the majority not

Matthee+24b

JWST'S *LITTLE RED DOTS*

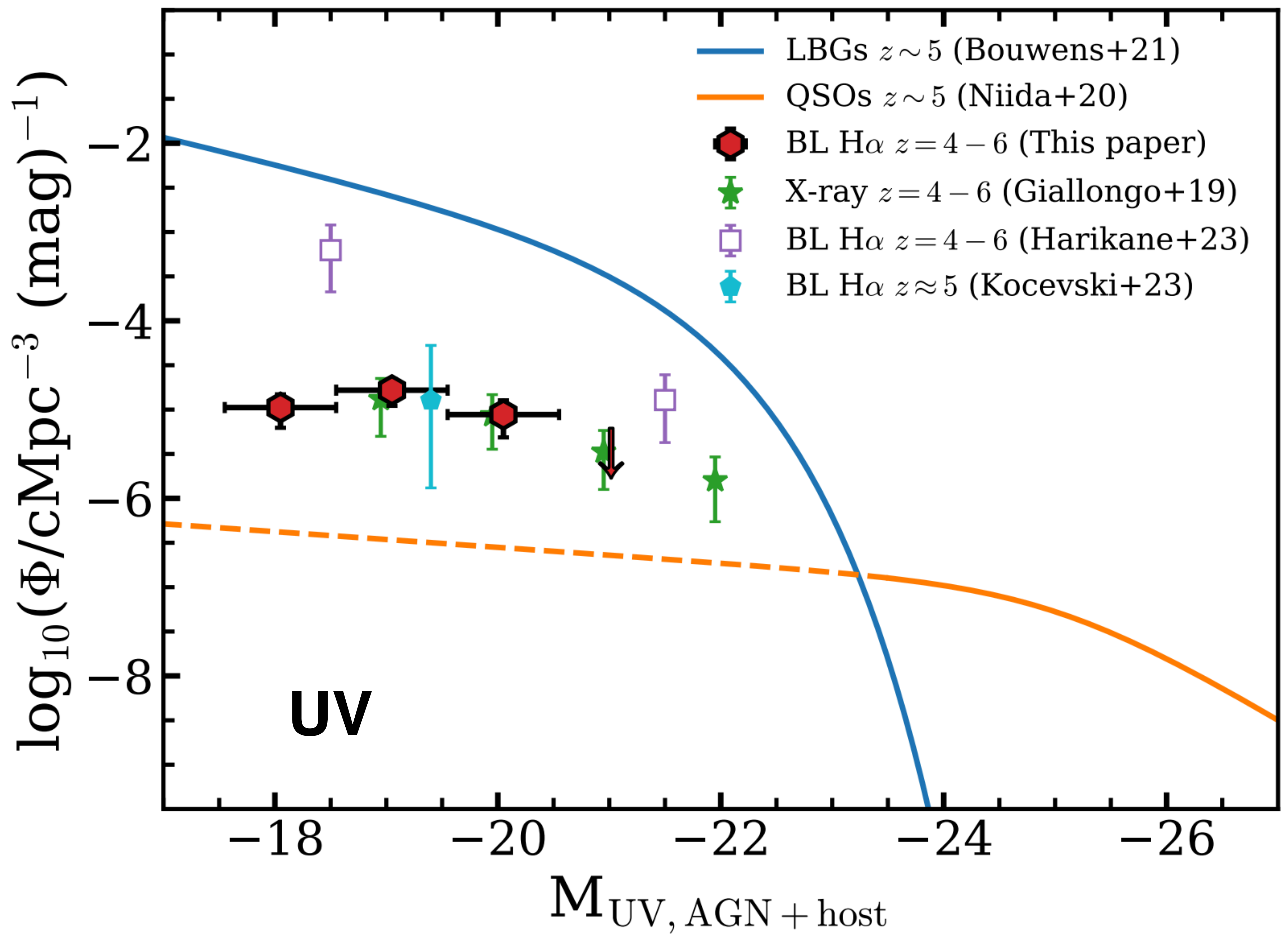


The broad-line Halpha emitters appear as *Little red dots* in JWST NIRCam data

The red color is a result, not our selection criterion

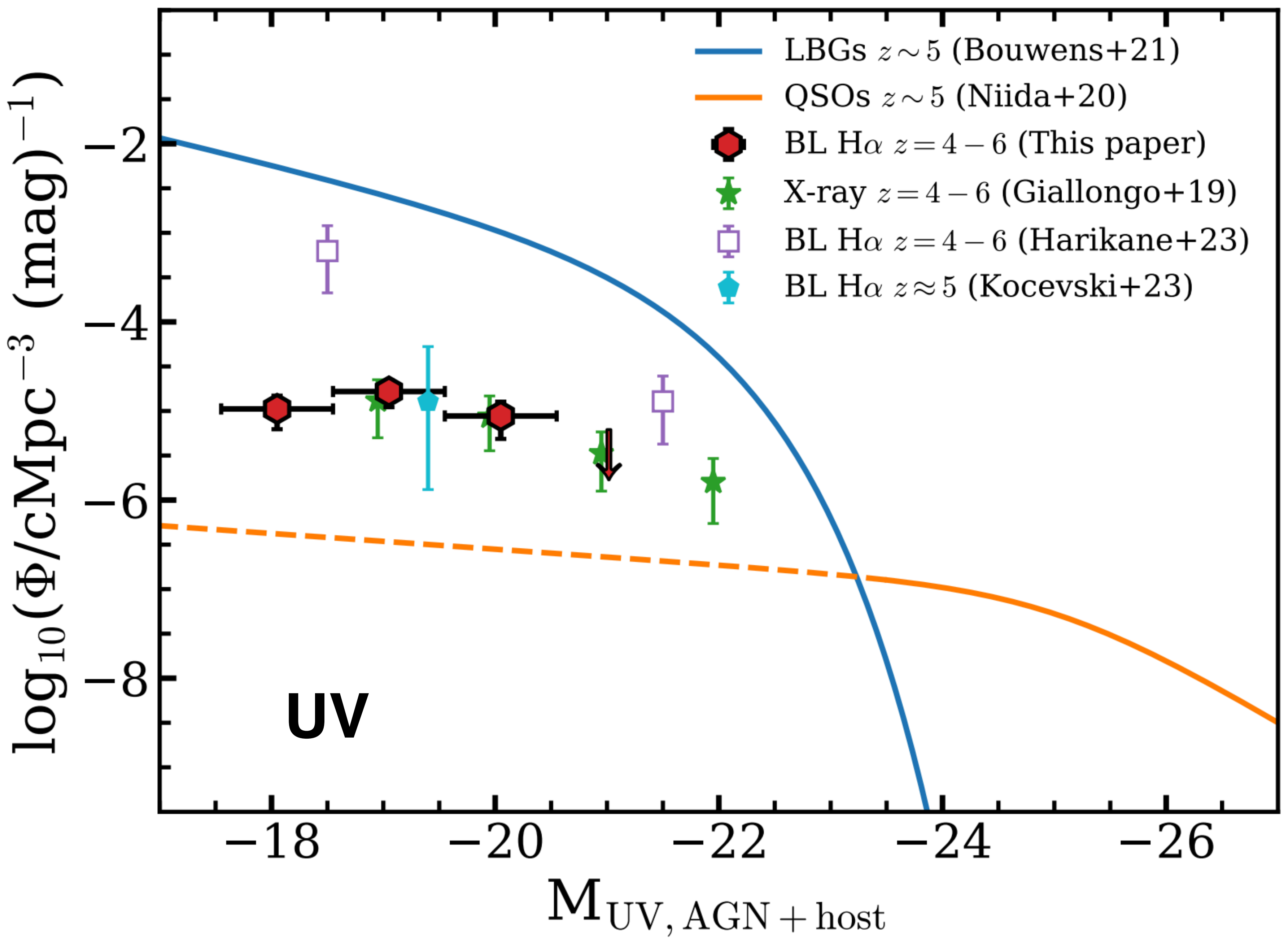
Matthee+24b

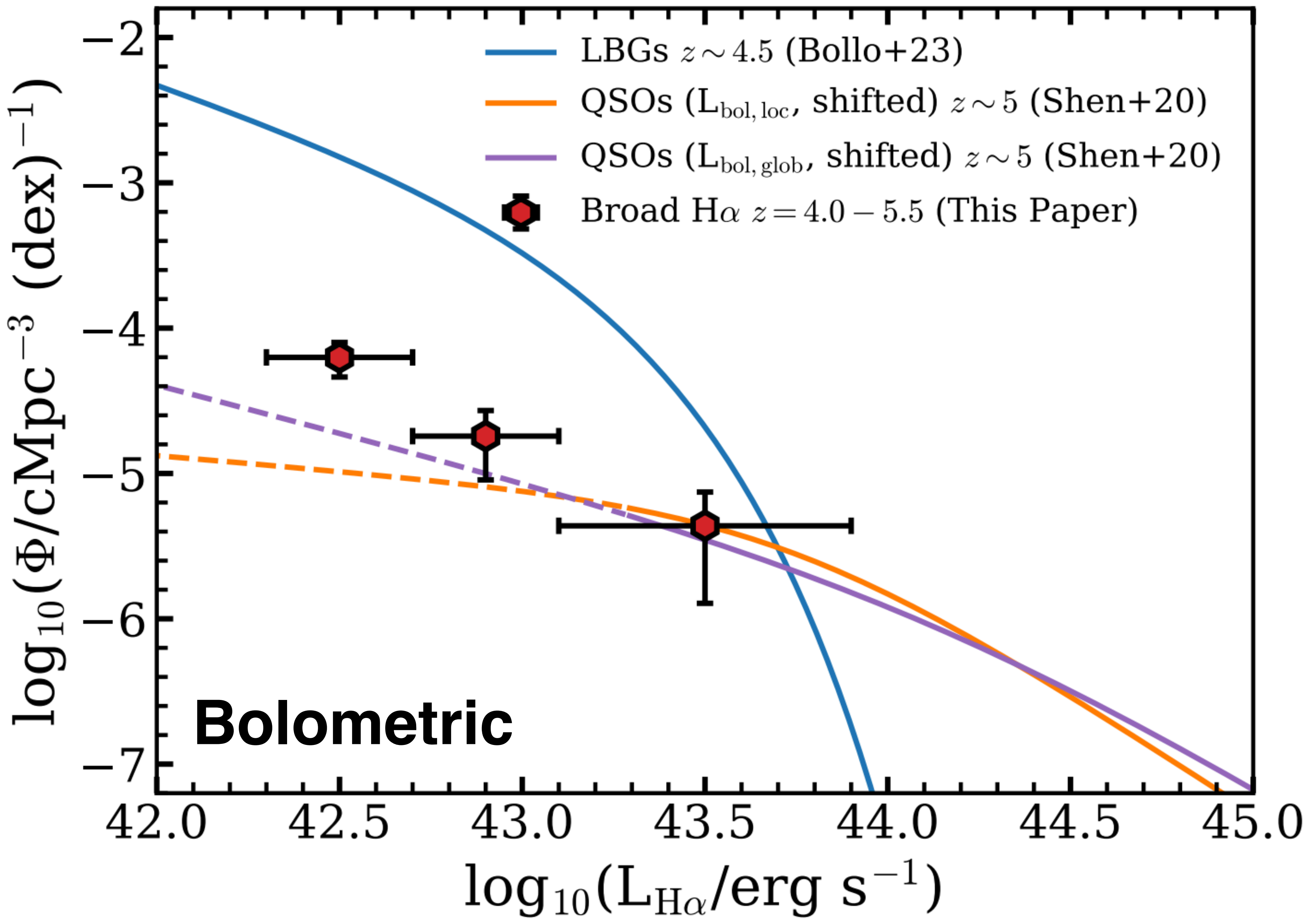
DID JWST FIND MORE AGN THAN EXPECTED?



It depends how you count!

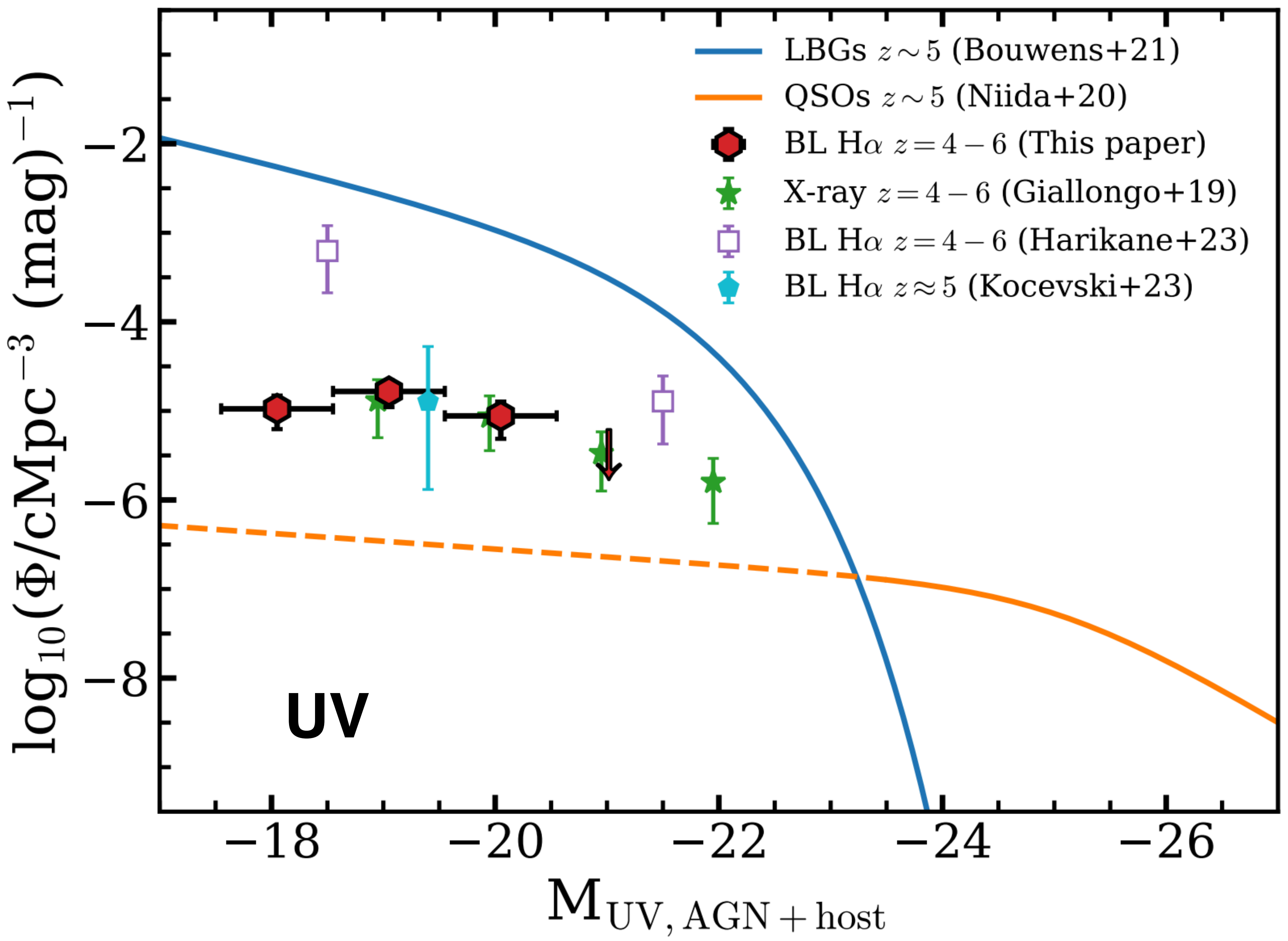
DID JWST FIND MORE AGN THAN EXPECTED?

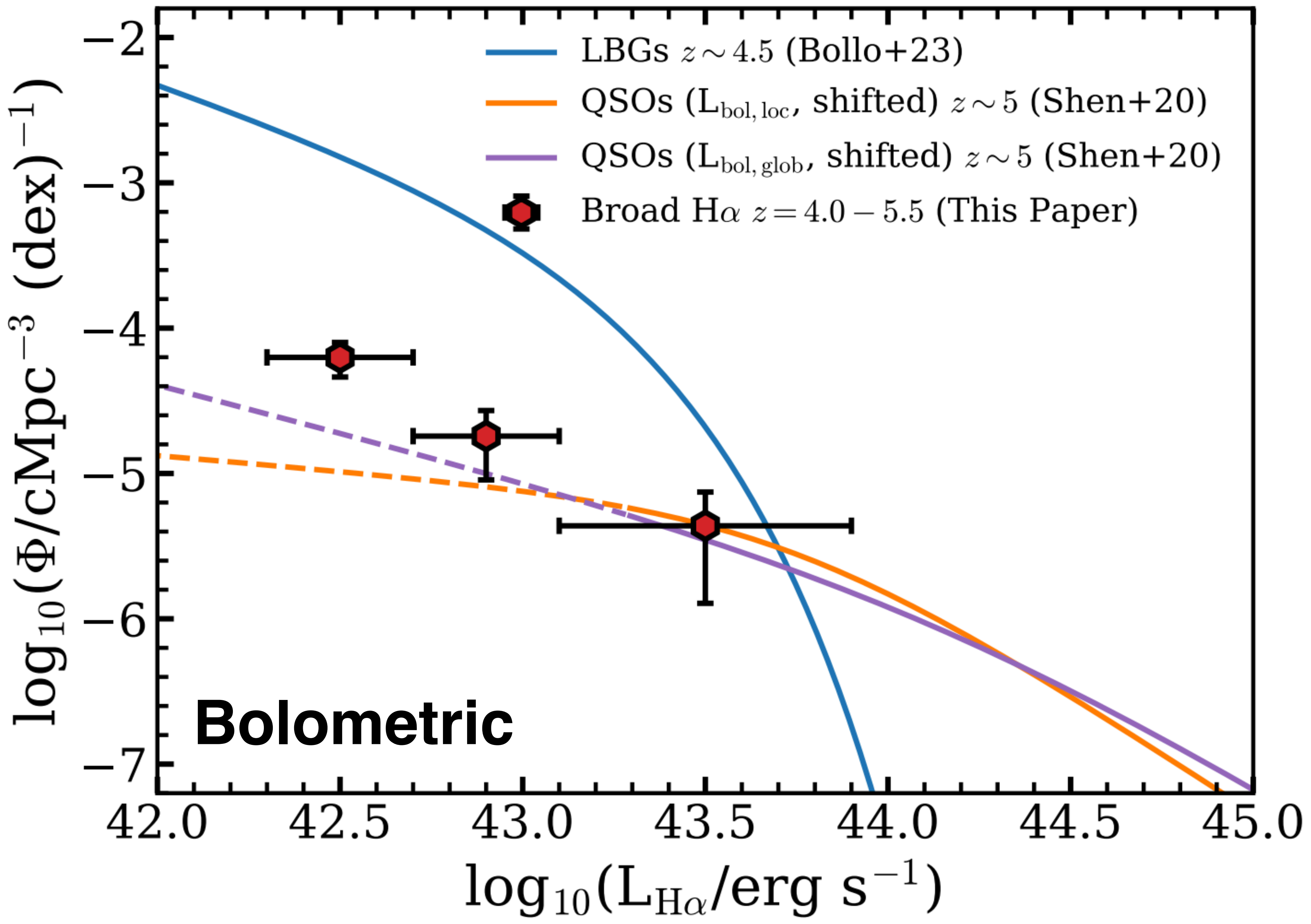


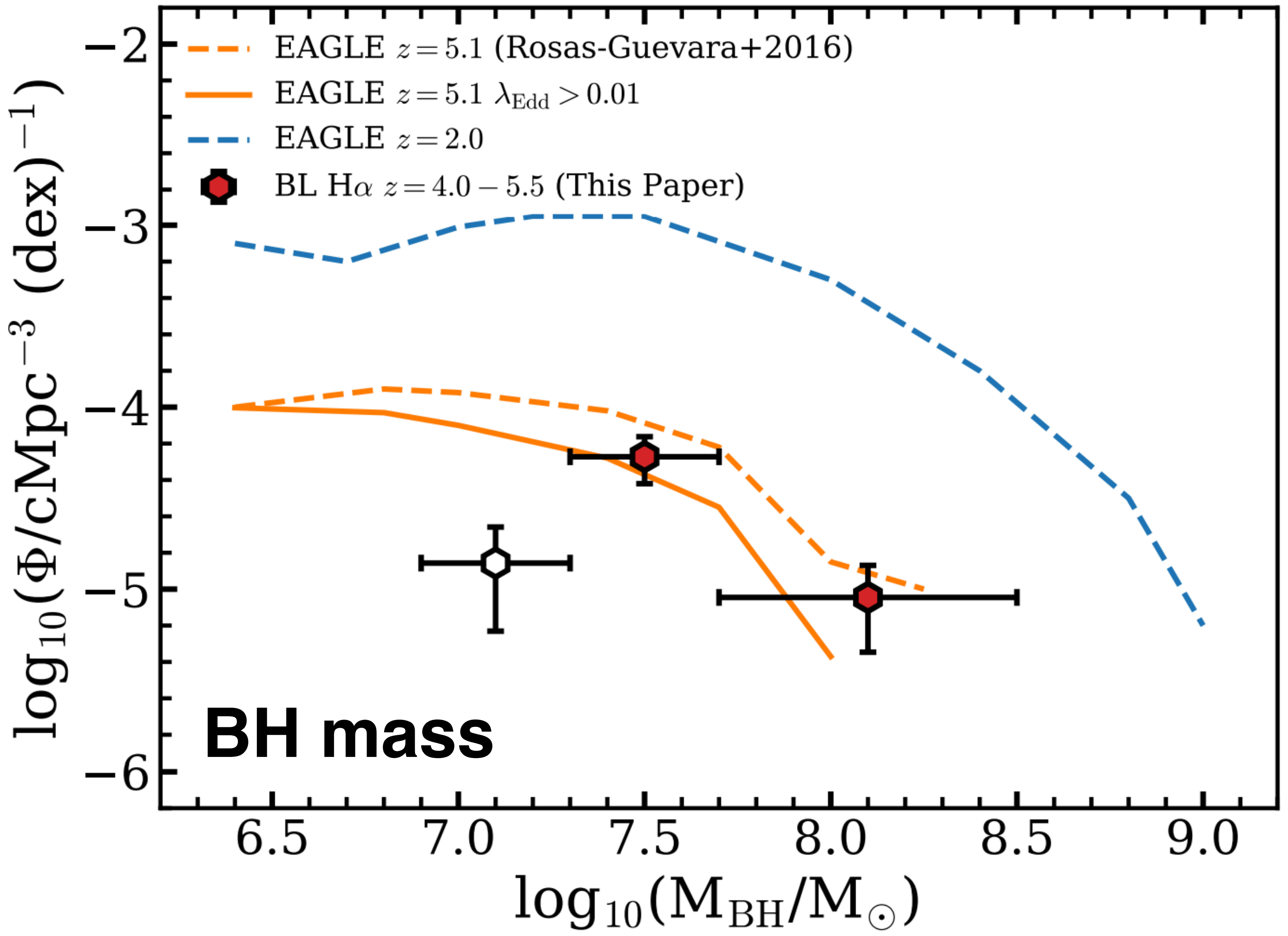


It depends how you count!

DID JWST FIND MORE AGN THAN EXPECTED?



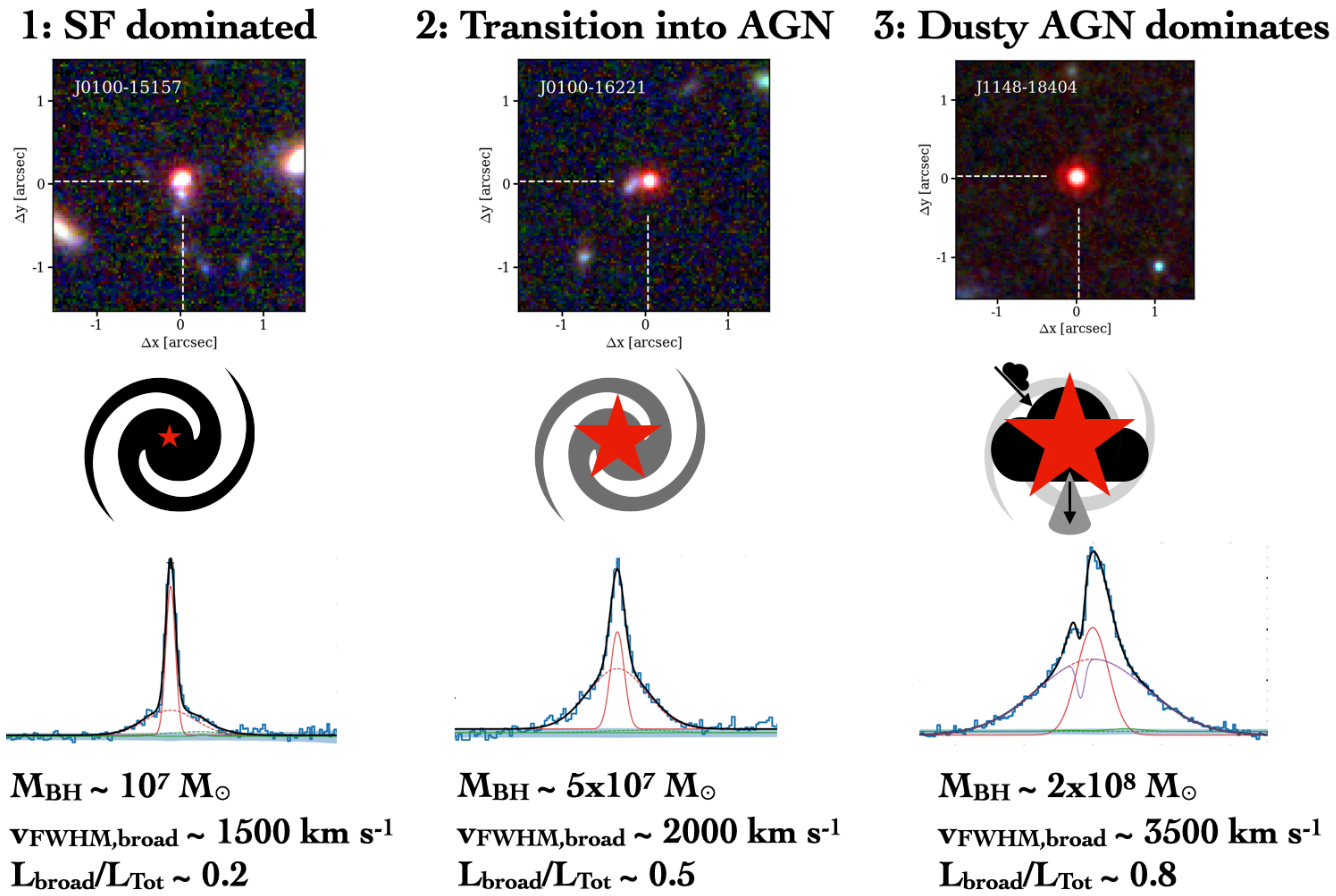




It depends how you count!

See also Habouzit 24 for a detailed discussion

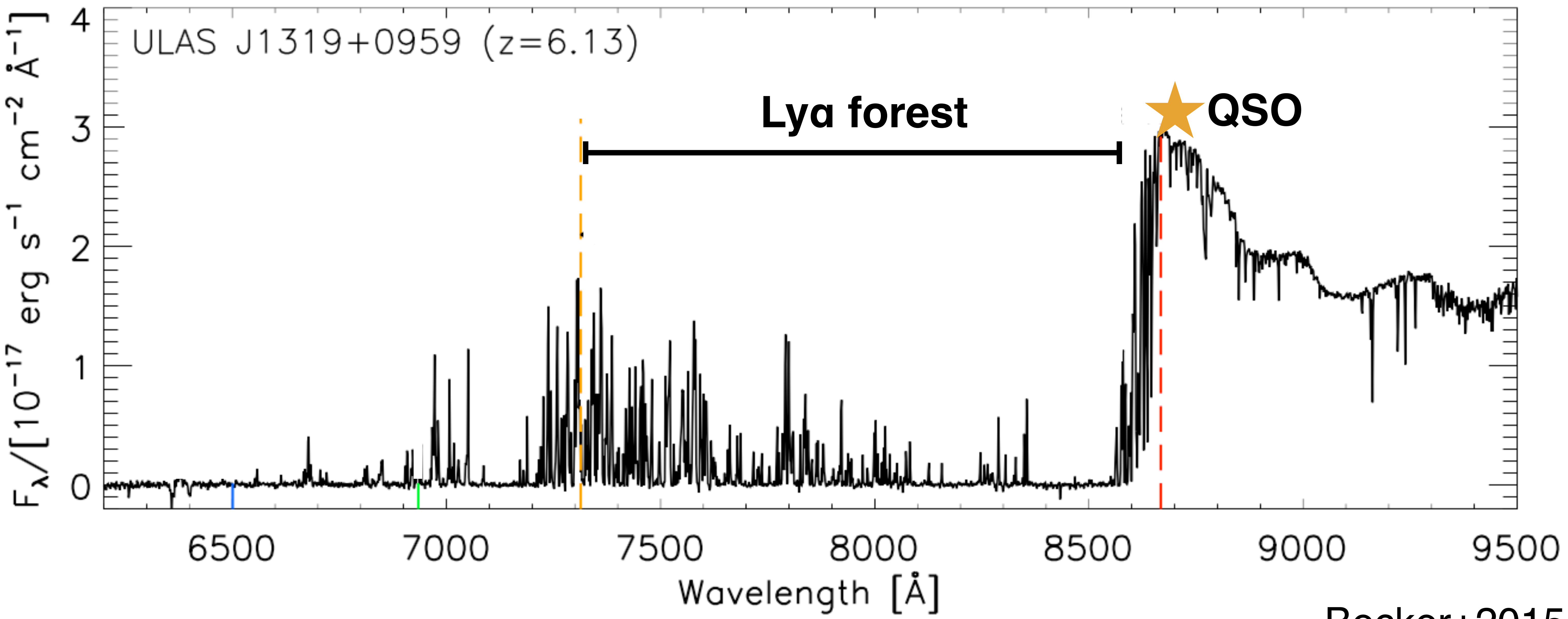
AN EVOLUTIONARY SCENARIO LINKING FAINT AGN TO LUMINOUS QUASARS



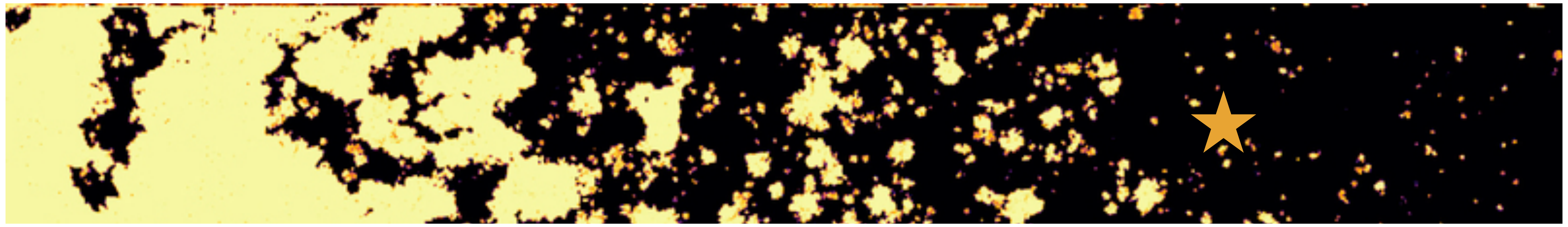
- **Are "red AGN" predecessors of UV-luminous quasars? Seems to agree with the duty cycle of the luminous quasars**

Matthee+24b

LOCAL REIONIZATION EXPERIMENTS (II)



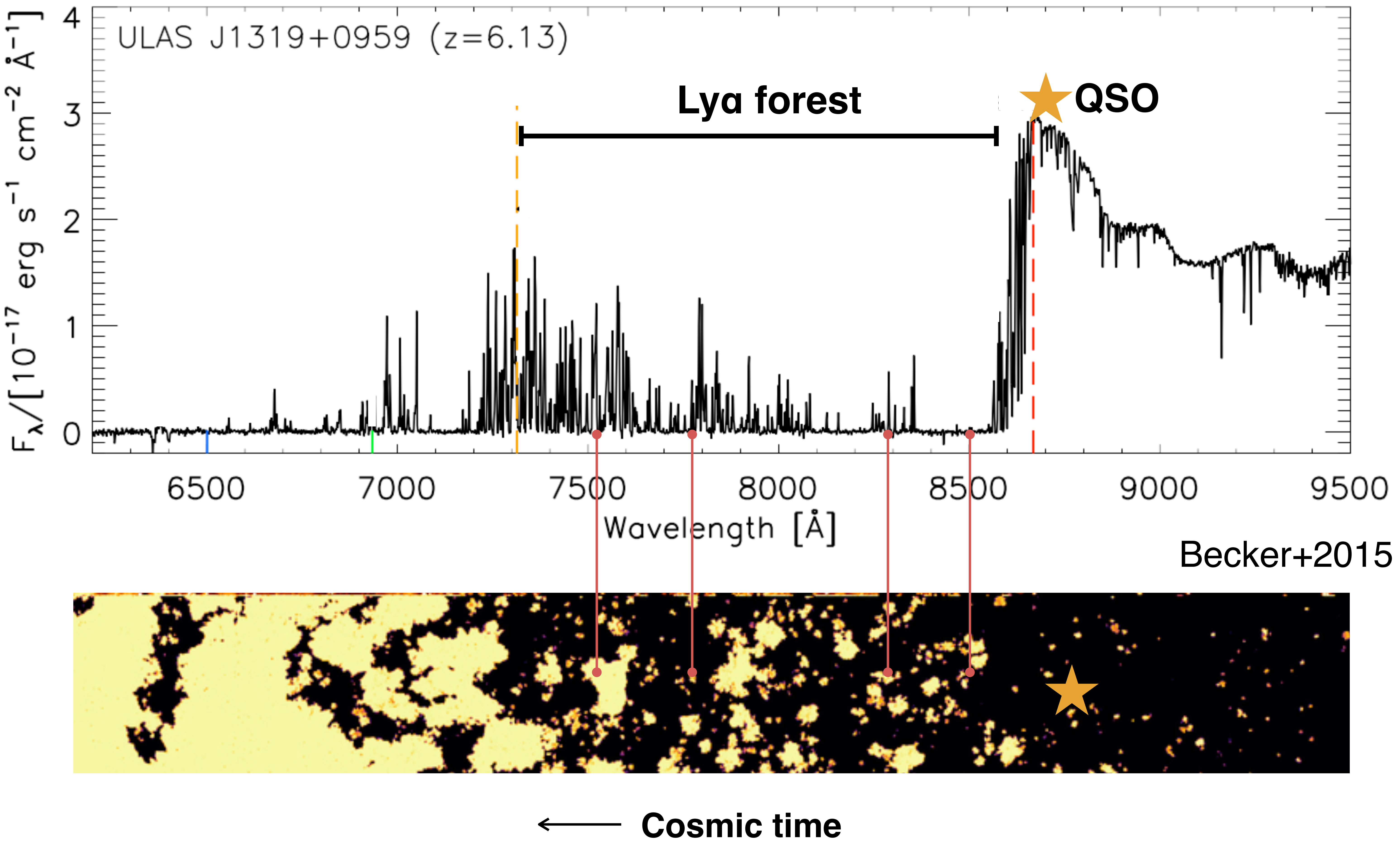
Becker+2015



← **Cosmic time**

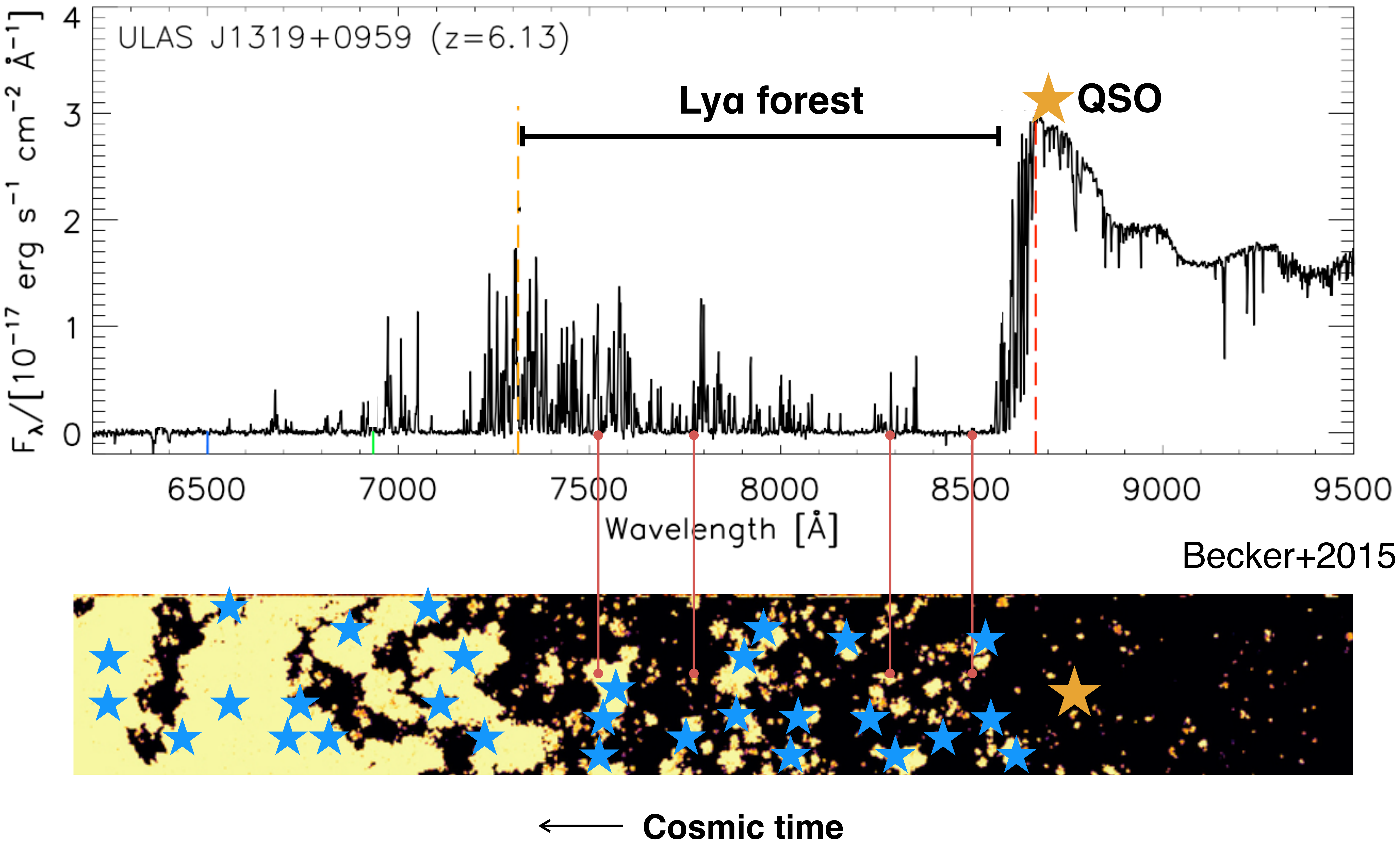
e.g. talks by Daichi Kashino, Koki Kakiichi, Enrico Garaldi

LOCAL REIONIZATION EXPERIMENTS (II)



e.g. talks by Daichi Kashino, Koki Kakiichi, Enrico Garaldi

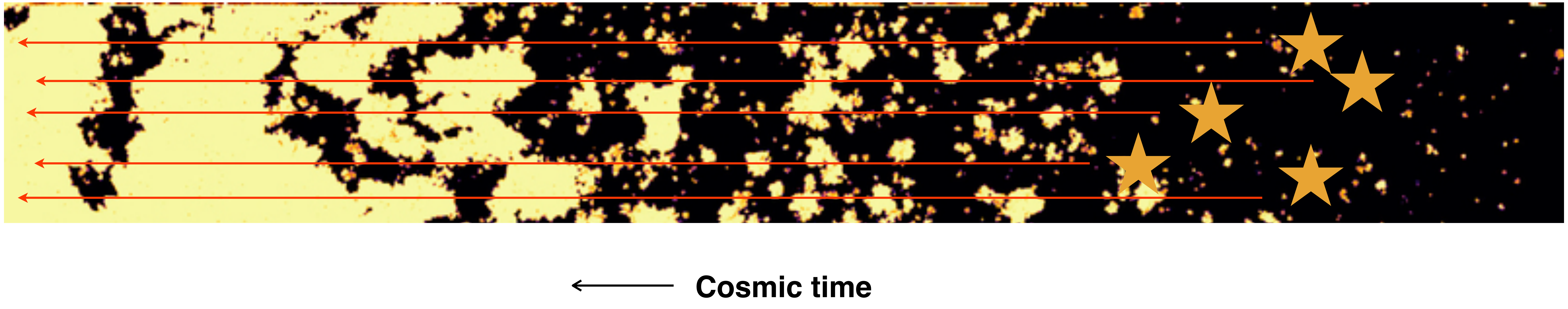
LOCAL REIONIZATION EXPERIMENTS (II)



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

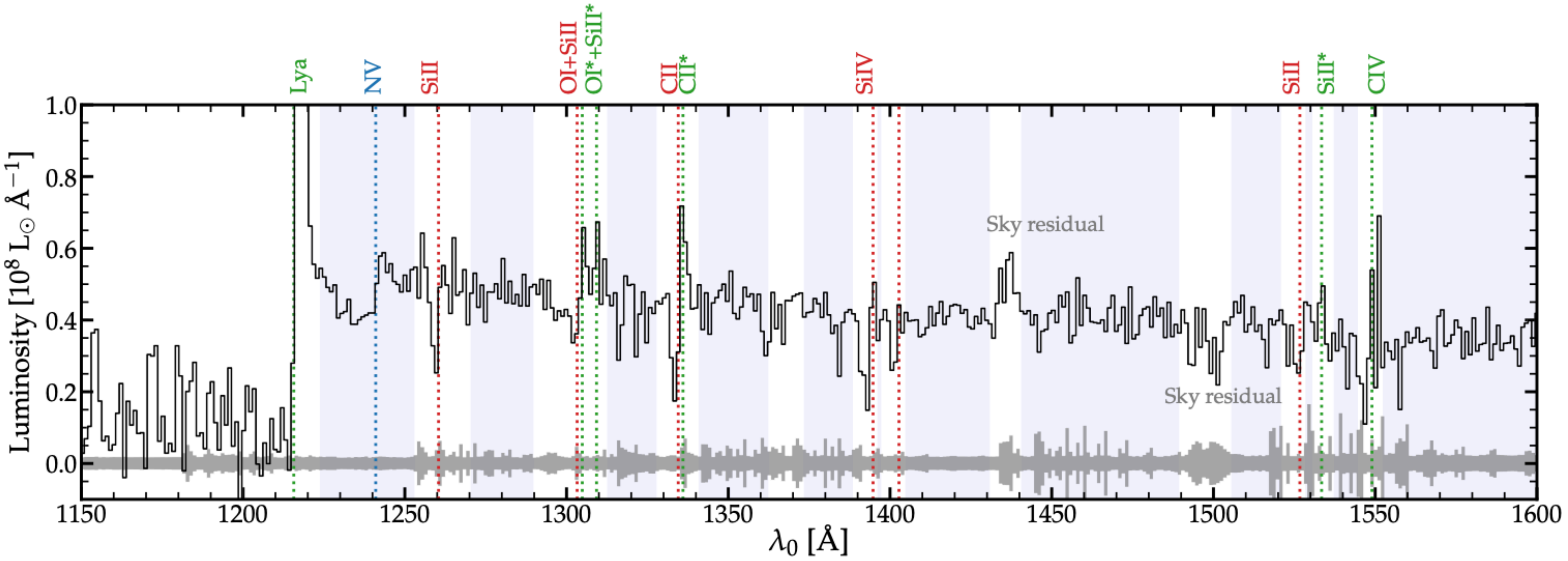
e.g. talks by Daichi Kashino, Koki Kakiichi, Enrico Garaldi

LOCAL REIONIZATION EXPERIMENTS: FUTURE



- **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**

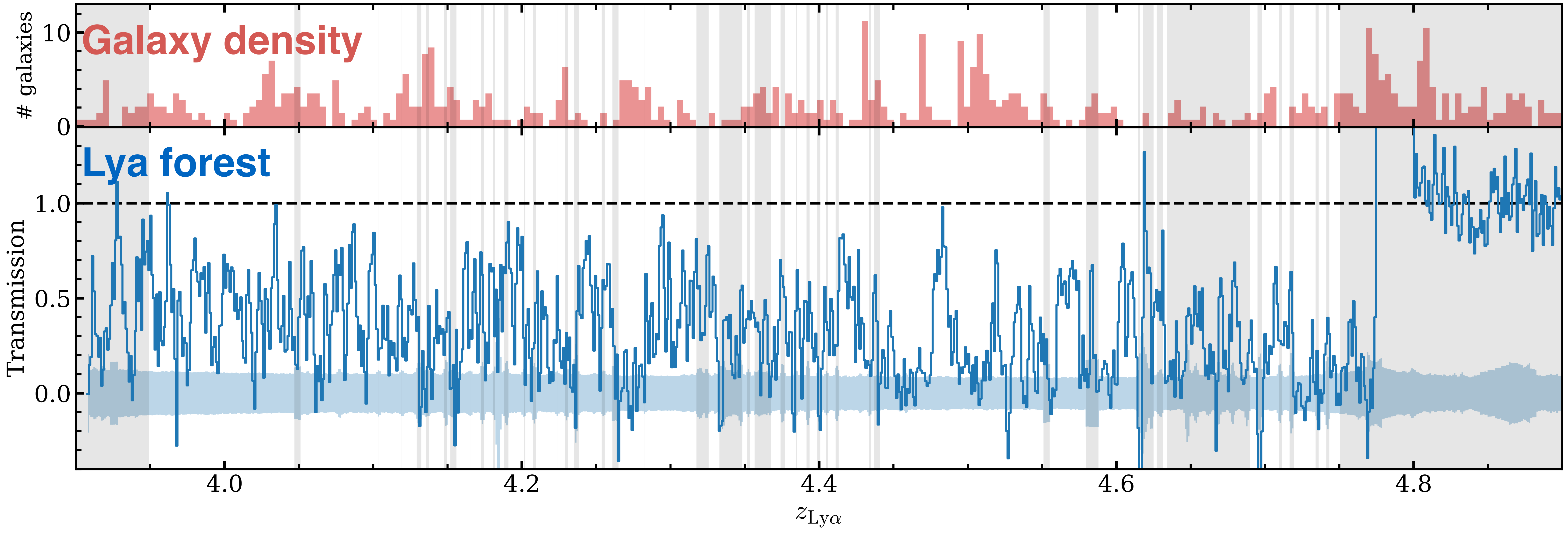
Deep absorption line spectroscopy in an L* z=4.8 galaxy



- **MXDF (Bacon+2021) <u>140hr VLT/MUSE</u> spectrum of a magnitude 25.3 galaxy at z~4.8**
- **Sky density ~0.3/arcmin²**
- **Detailed stellar population fits at z~5: young & low metallicity**

Matthee+22a

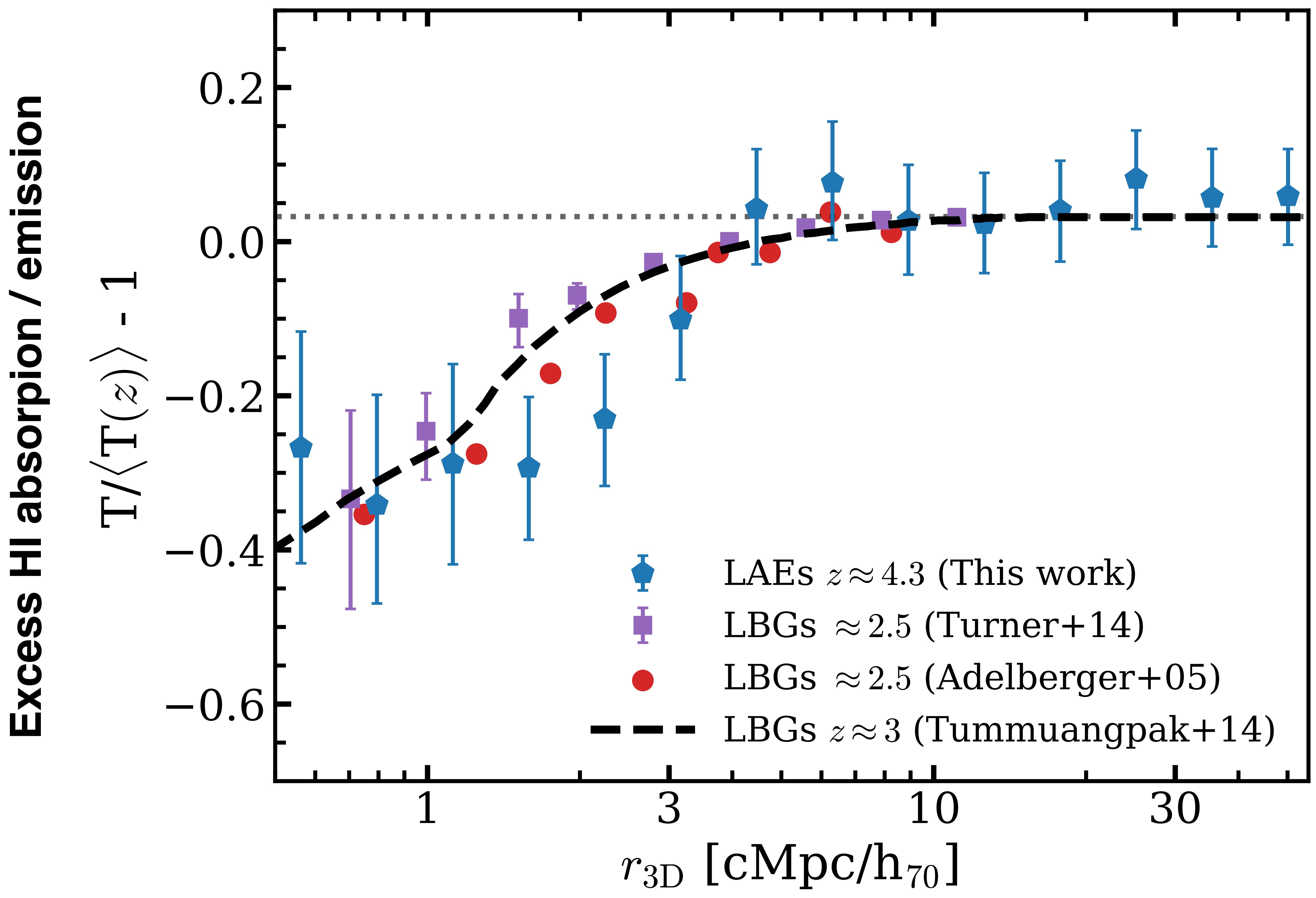
IGM TOMOGRAPHY: PILOT IN THE MXDF AT z~5



- **We measure Lyman-alpha forest spikes at z~4 in the galaxy spectrum**
- **General optical depth agrees with quasar measurements**

Matthee+24a

IGM TOMOGRAPHY: A PILOT IN THE MUSE EXTREME DEEP FIELD 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**
- **ELT/MOSAIC can extend this to much larger samples and higher redshifts**

Matthee+24a

Summary

- A *phenomenological* Lyman-alpha emitter driven emissivity model matches z=3-7 constraints, It naturally leads to an evolving <f_{esc}> of the galaxy population, and to a peak in the <f_{esc}> - M_{UV} relation

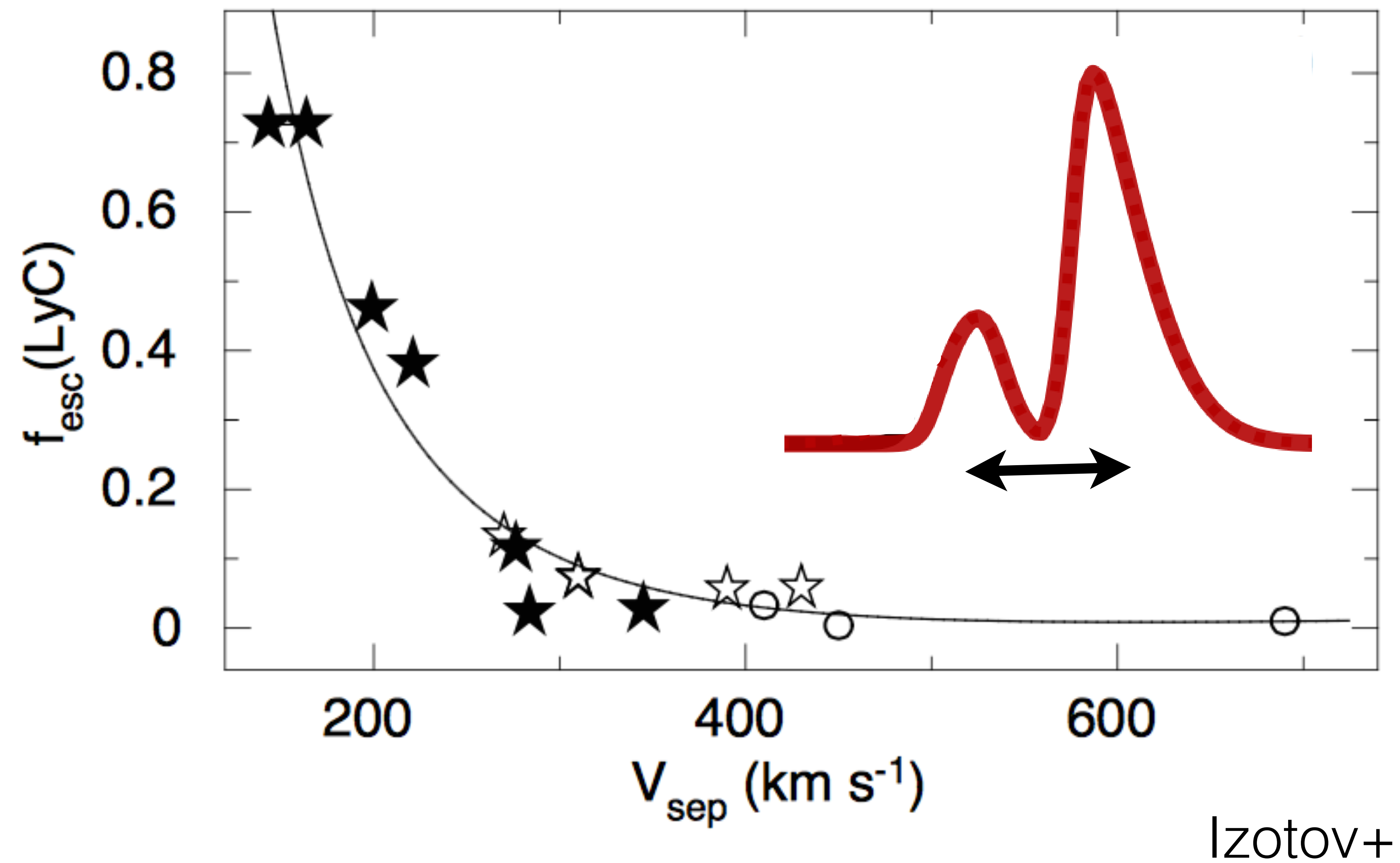
- JWST spectroscopy is confirming redshifts for >1000's of galaxies in the early Universe, enabling clustering and cross-correlation studies.
- The typical ionizing efficiency is ξ_{ion}~$10^{25.3}$ Hz erg-1 for bright galaxies (M_{UV}~ -19), it seems to increase for fainter galaxies (25.5 at M_{UV}~ - 17)

- JWST has identified numerous faint AGN that could be the progenitors of luminous quasars and/or their numerous obscured versions. The dust obscuration implies limited impact on cosmic reionization

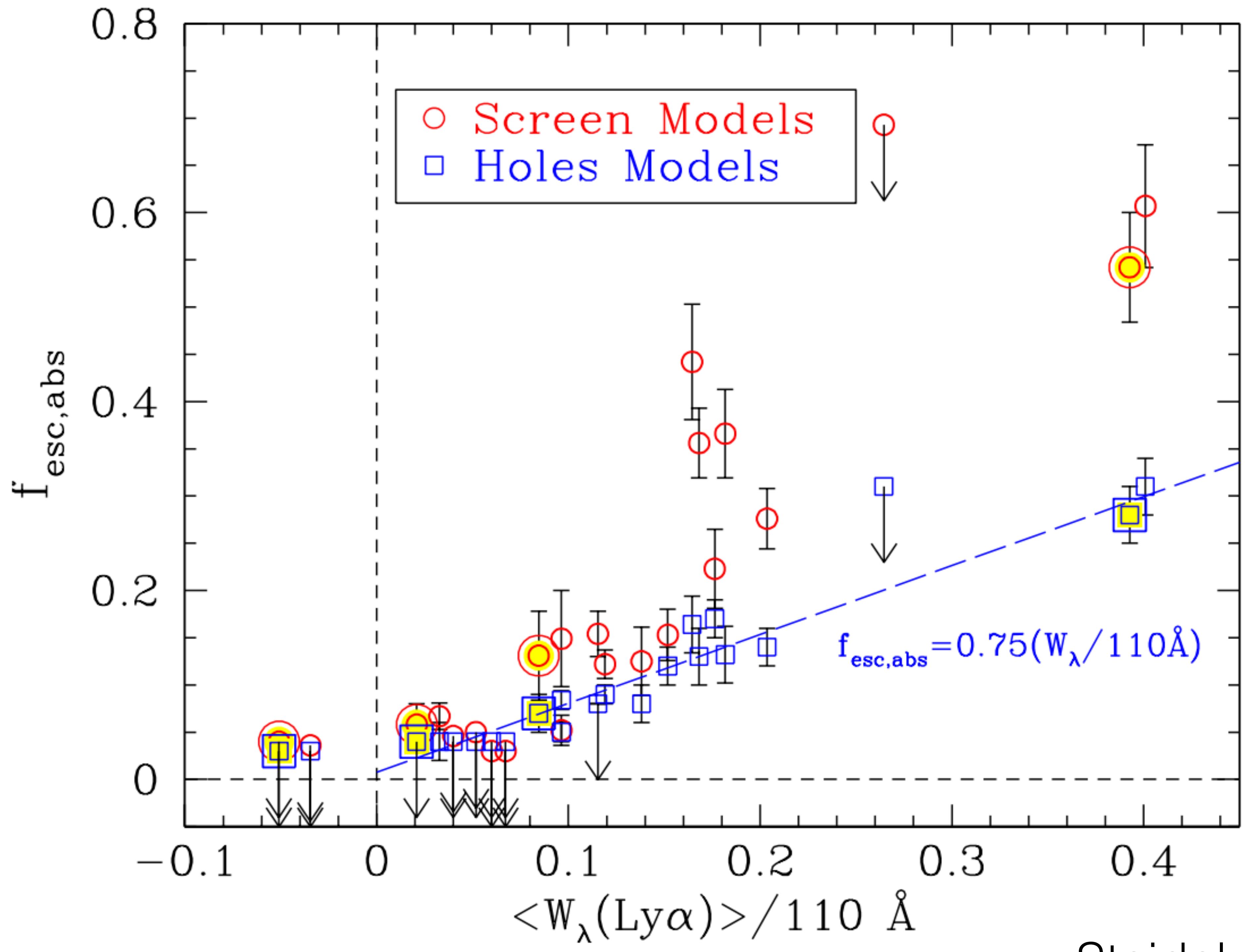
- Galaxy - IGM cross-correlation studies are starting at z>5, and with the ELT can be extended to ~1 arcmin sampling with background galaxies

LAE MODEL

WHICH GALAXIES ARE THE IONIZERS? —> (SOME) LYMAN-ALPHA EMITTERS?



Izotov+18



Steidel+18

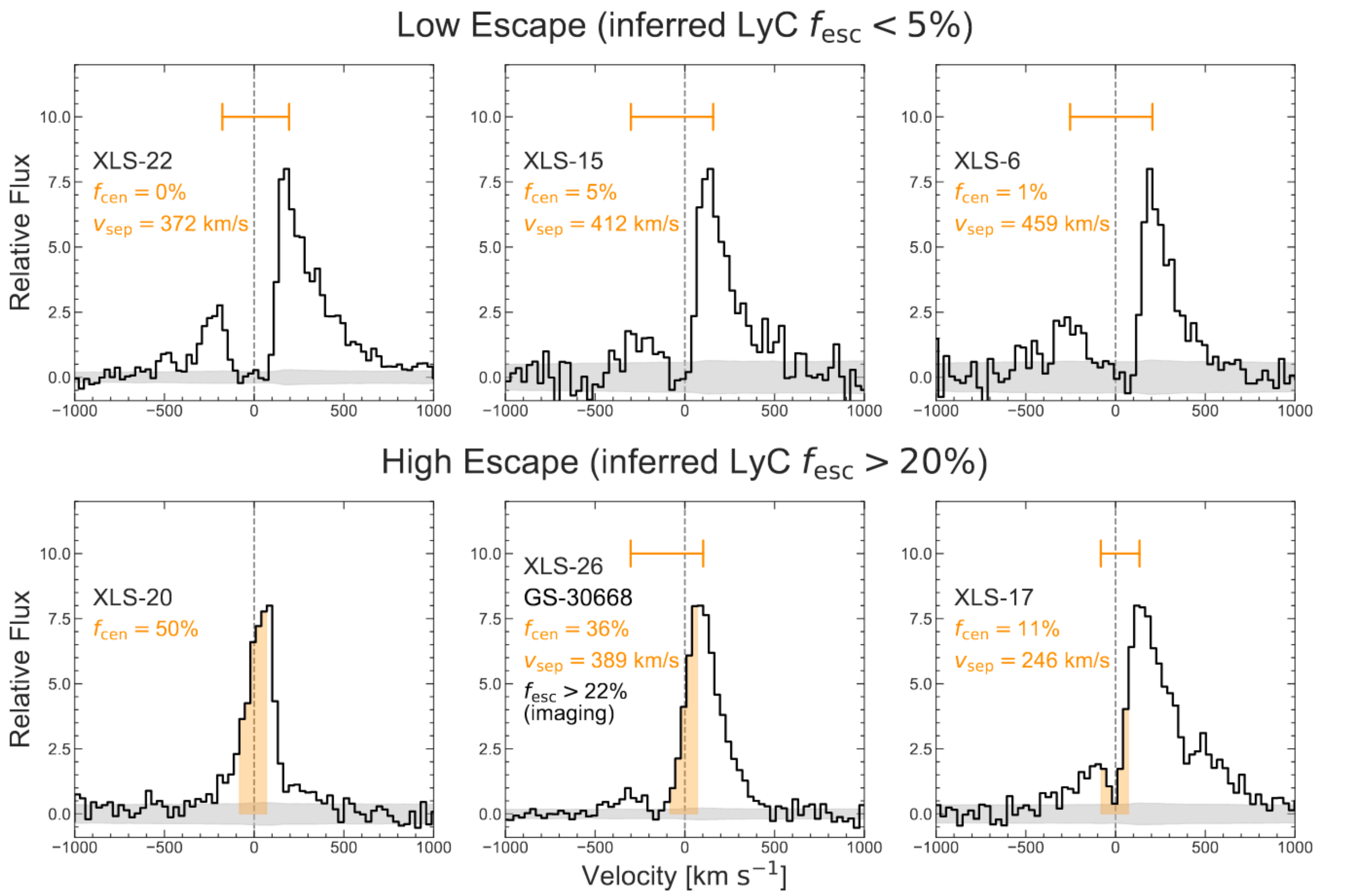
At z~0, the Lyman-alpha line profile correlates with the escape fraction

Izotov+18; see also Verhamme+15, Kakiichi & Gronke 19, Gazagnes+20

At z~3, the escape fraction correlates with emerging Lyman-alpha equivalent width and escape fraction

See also Marchi+19, Pahl+22, Begley+23, …

Inferring Lyman Continuum Escape with the Lya Profile



~35% of sample

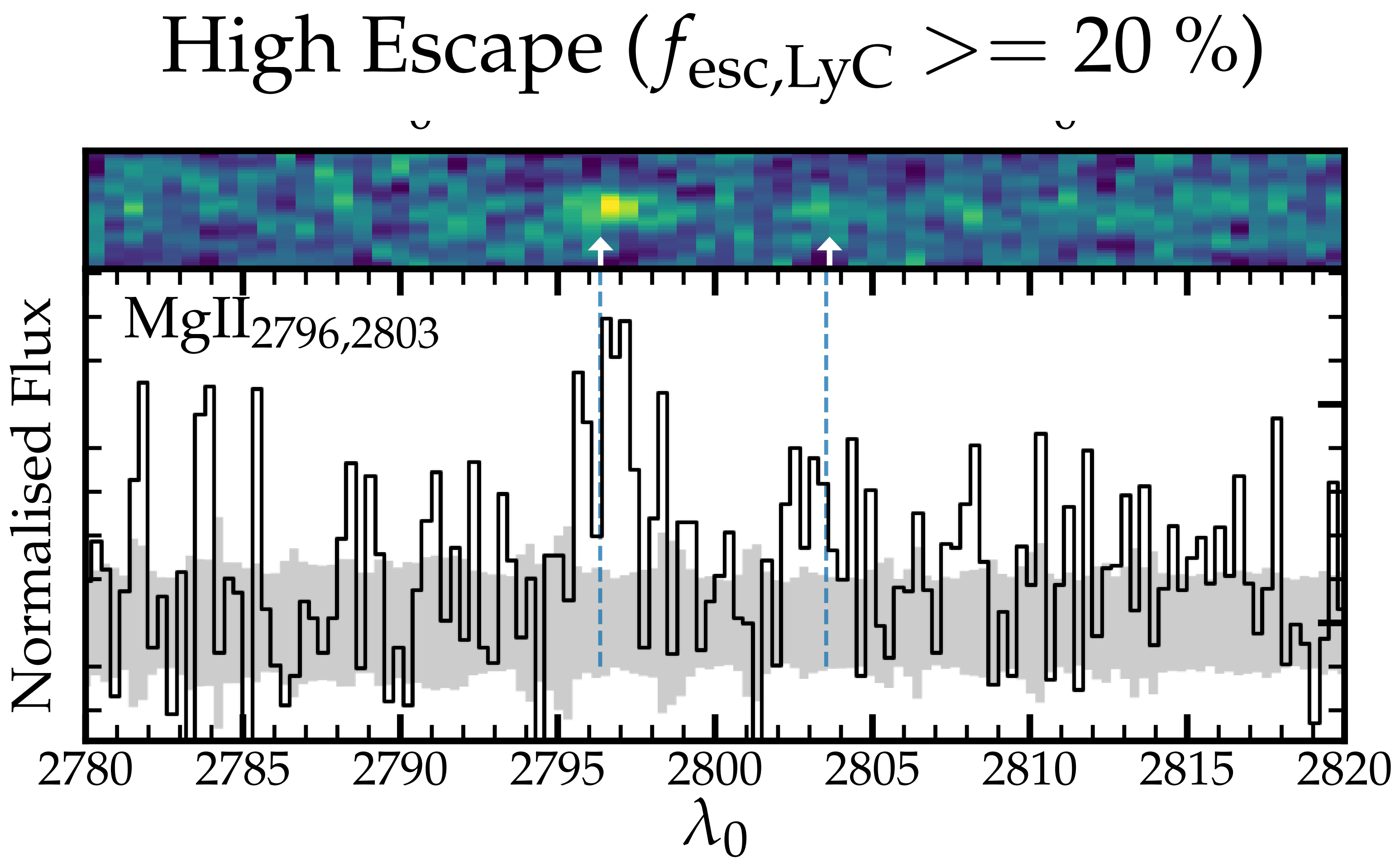
~50% of sample

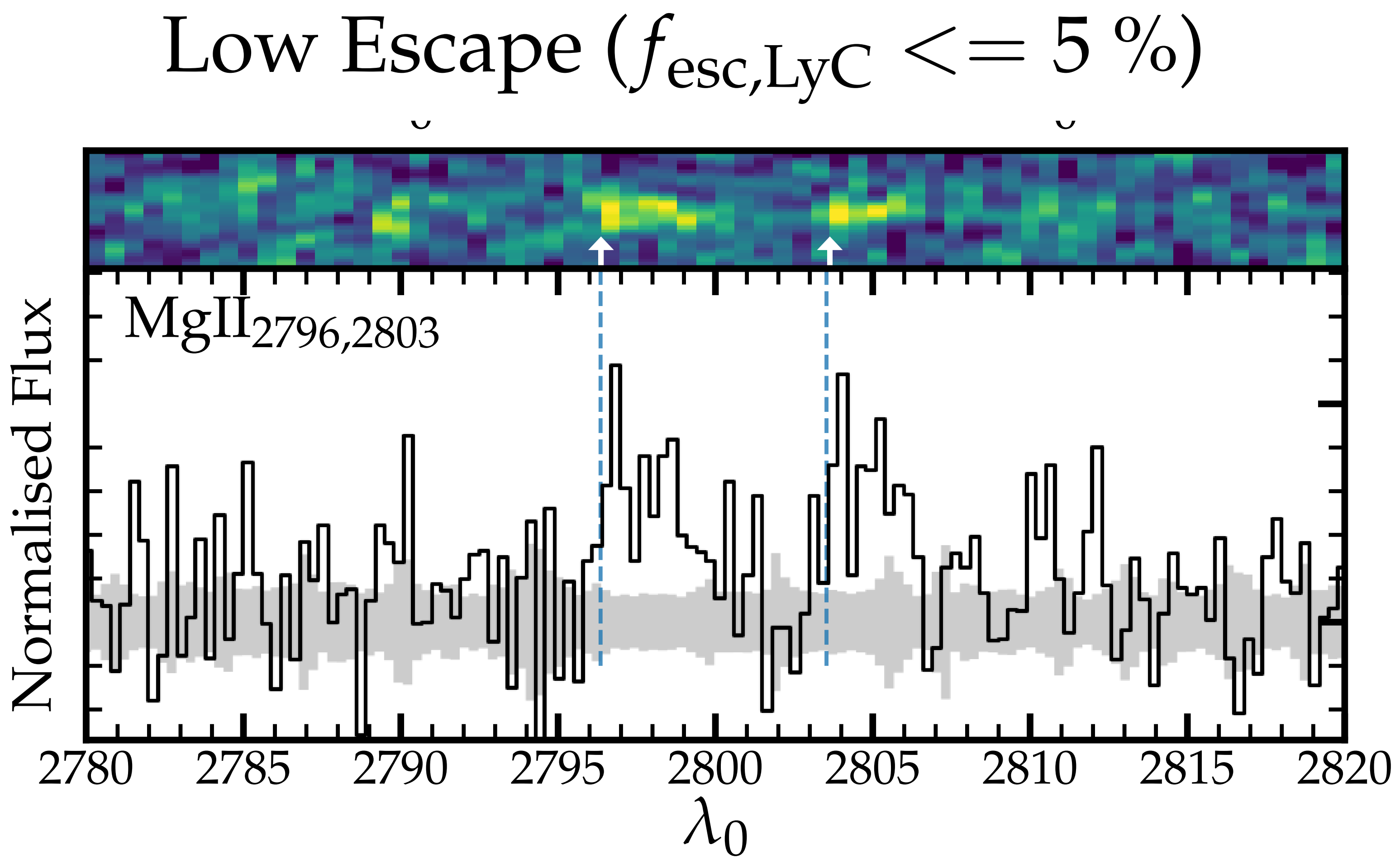
from Naidu & Matthee et al. 2022 arXiv:2110.11961

We used the Lyman-alpha profile to sub-divide classes of galaxies in leakers vs non-leakers ($M_{UV} \sim -19$)

Motivated by Verhamme+15, Izotov+18,Kakiichi & Gronke 19, Pahl+20, and many others

Leakers have a low gas column density



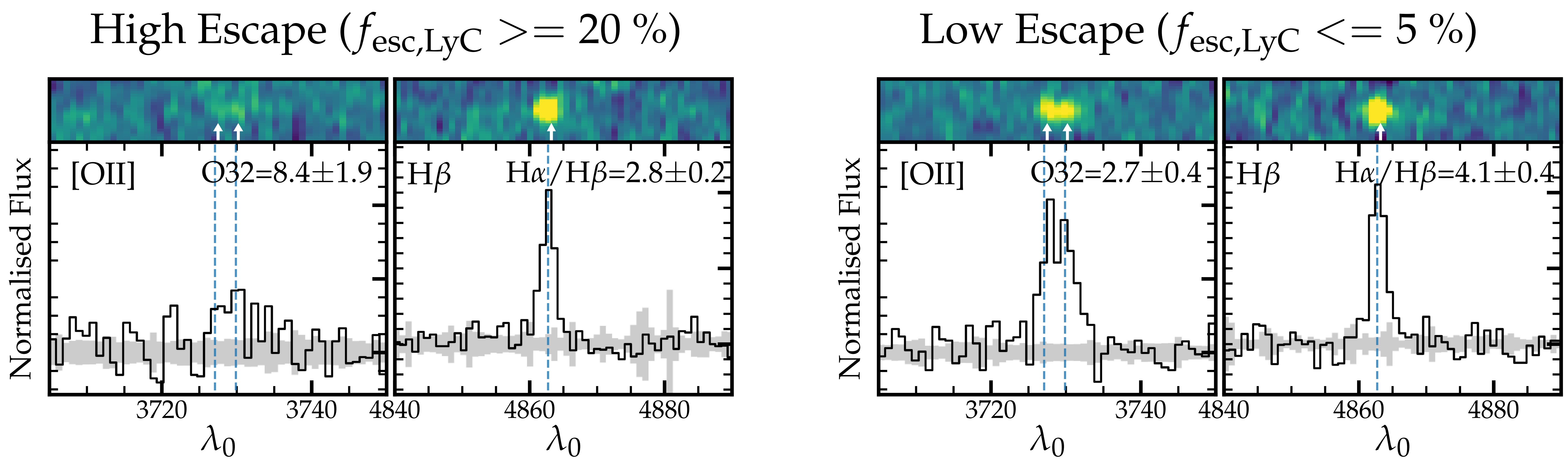


High Escape shows optically thin MgII emission, while Low Escape shows MgII photons resonantly scattered in higher column density gas

Validates our method: Lya Line profile separation traces HI column density

Naidu & Matthee et al. arXiv:2110.11961

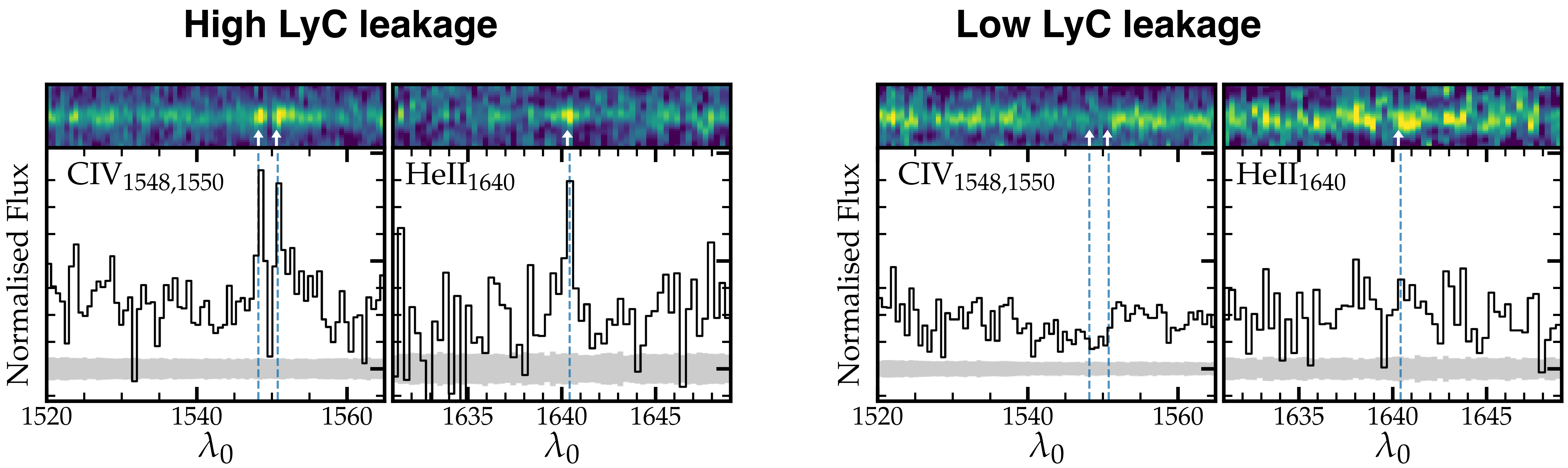
Leakers have a highly ionised, dust-free ISM



- **High Escape stack shows very high O32~8 value indicating an ionisation parameter only seen in extreme super star clusters, while more normal (~3) for Low Escape**
- **High Escape stack further shows no evidence of dust attenuation, while significant dust — E(B-V)~0.3 — is present in Low Escape**

Naidu & Matthee et al. arXiv:2110.11961

RESULTS: THE SYNCHRONY OF PRODUCTION & ESCAPE



- **Our stacks show that high LyC leakage is associated with high ionization state (O32), low dust attenuation, and young hard ionizing sources (CIV emission)**

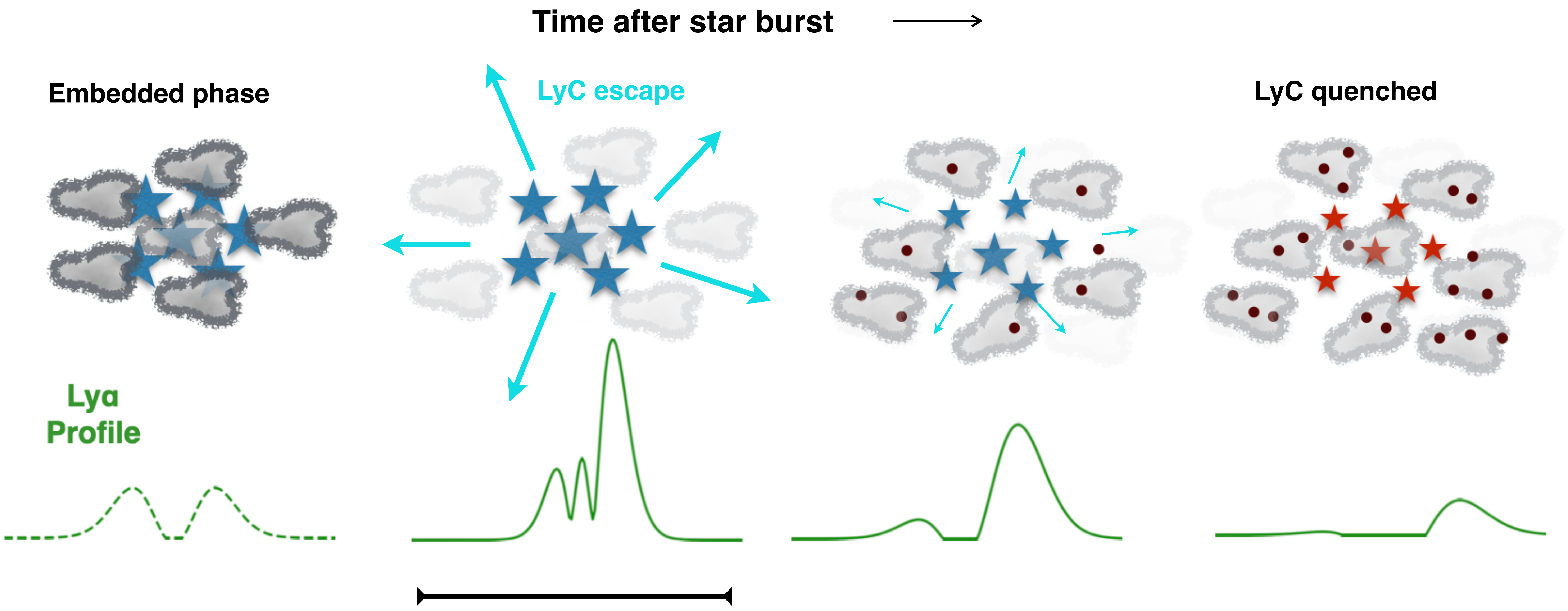
CIV tracing LyC Fesc: see also Schaerer+22, Saxena+22, Mainali+22, Mascia+23

- **Indirectly, our stacks imply implies <f_{esc}> = 25% for bright LAEs (L_{Lya}>10^{42} erg/s),**
  - ***Let's assume f_{esc}=0 for all other galaxies: the fiducial / provocative model***

Note, this fiducial model is in agreement with Pahl+21/Steidel+18 stacks

Naidu & Matthee et al. 2022

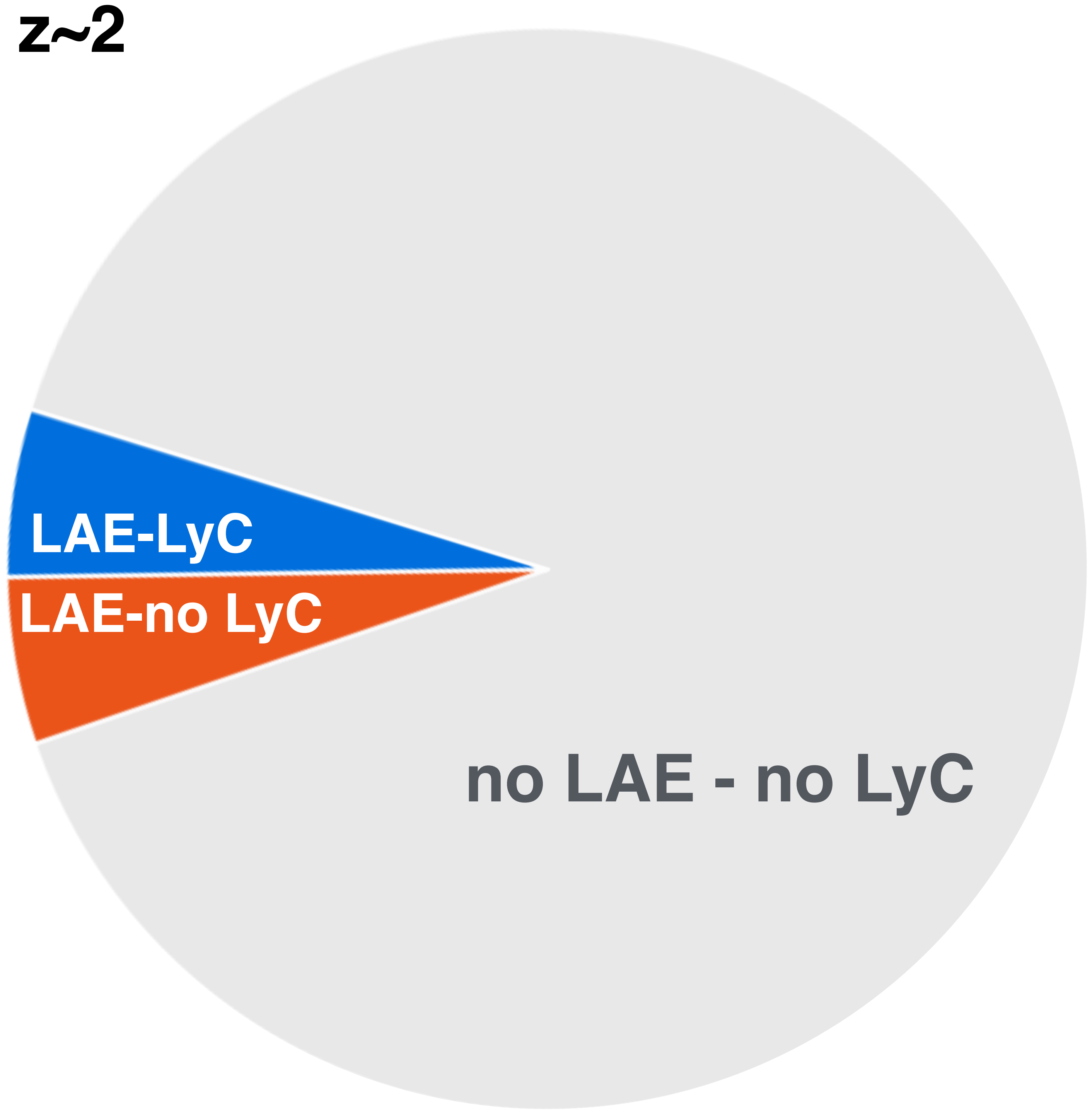
RESULTS: THE SYNCHRONY OF PRODUCTION & ESCAPE



Naidu & Matthee et al. 2022

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

z~2



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

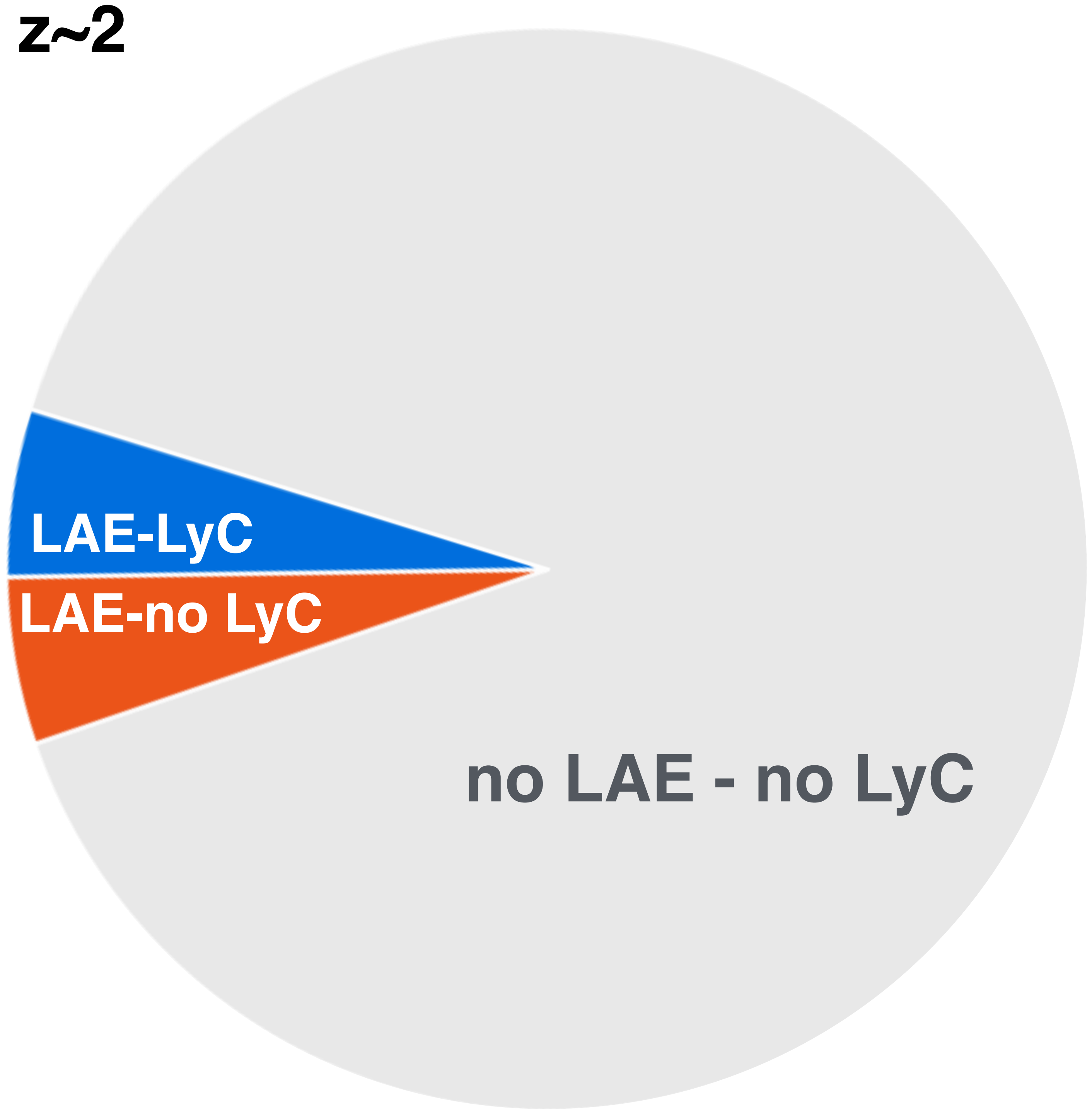
Fiducial / Provocative model: $\langle f_{esc} \rangle$>25% for the LAEs with L_{Lya}>2E42 erg s^{-1}, 0 % for the rest

See Naidu & Matthee et al. 2022 for motivation

Matthee & Naidu et al. 2022

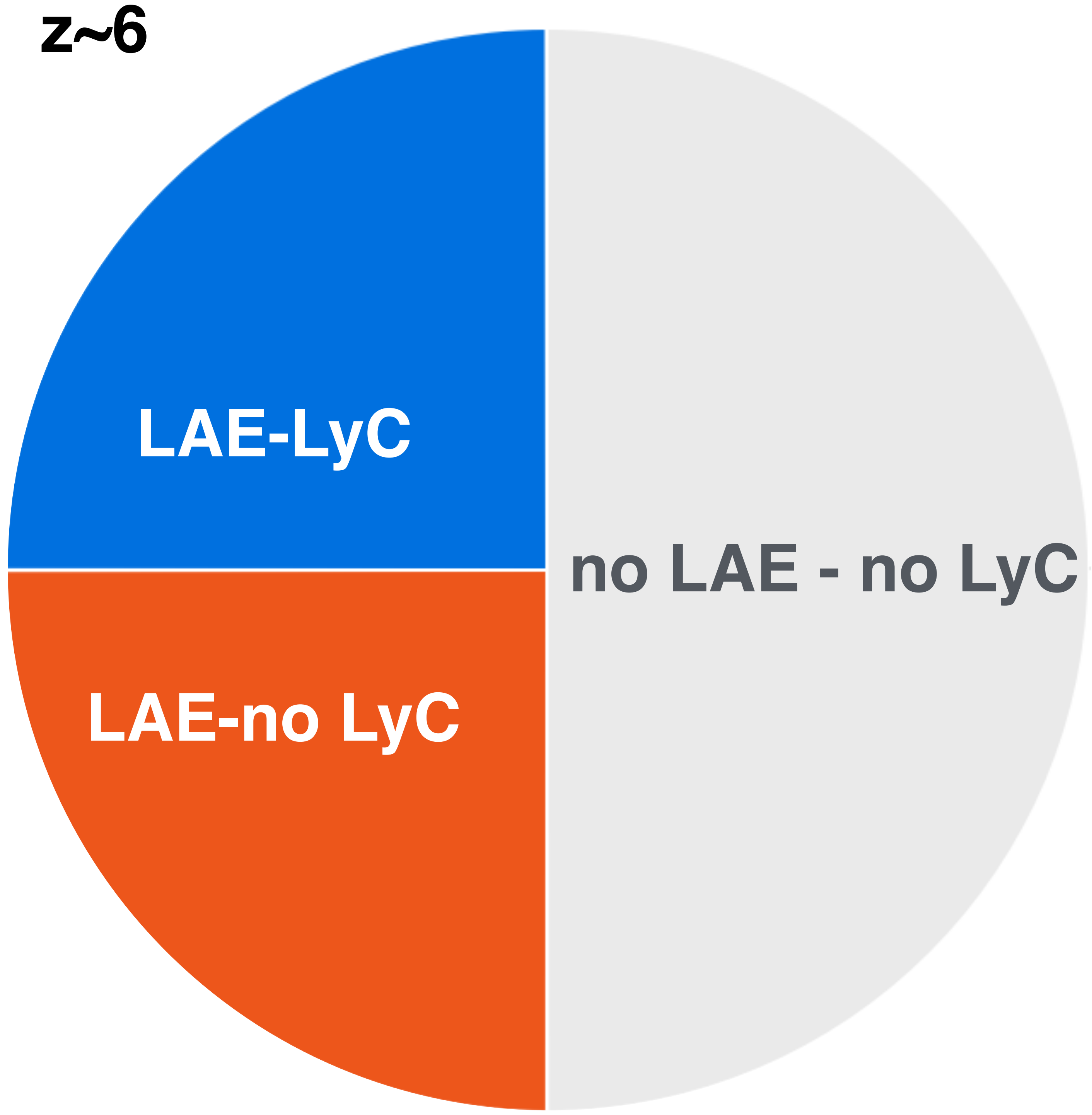
Demographics of F_{esc} among SFGs (based on LFs)

z~2



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

z~6



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

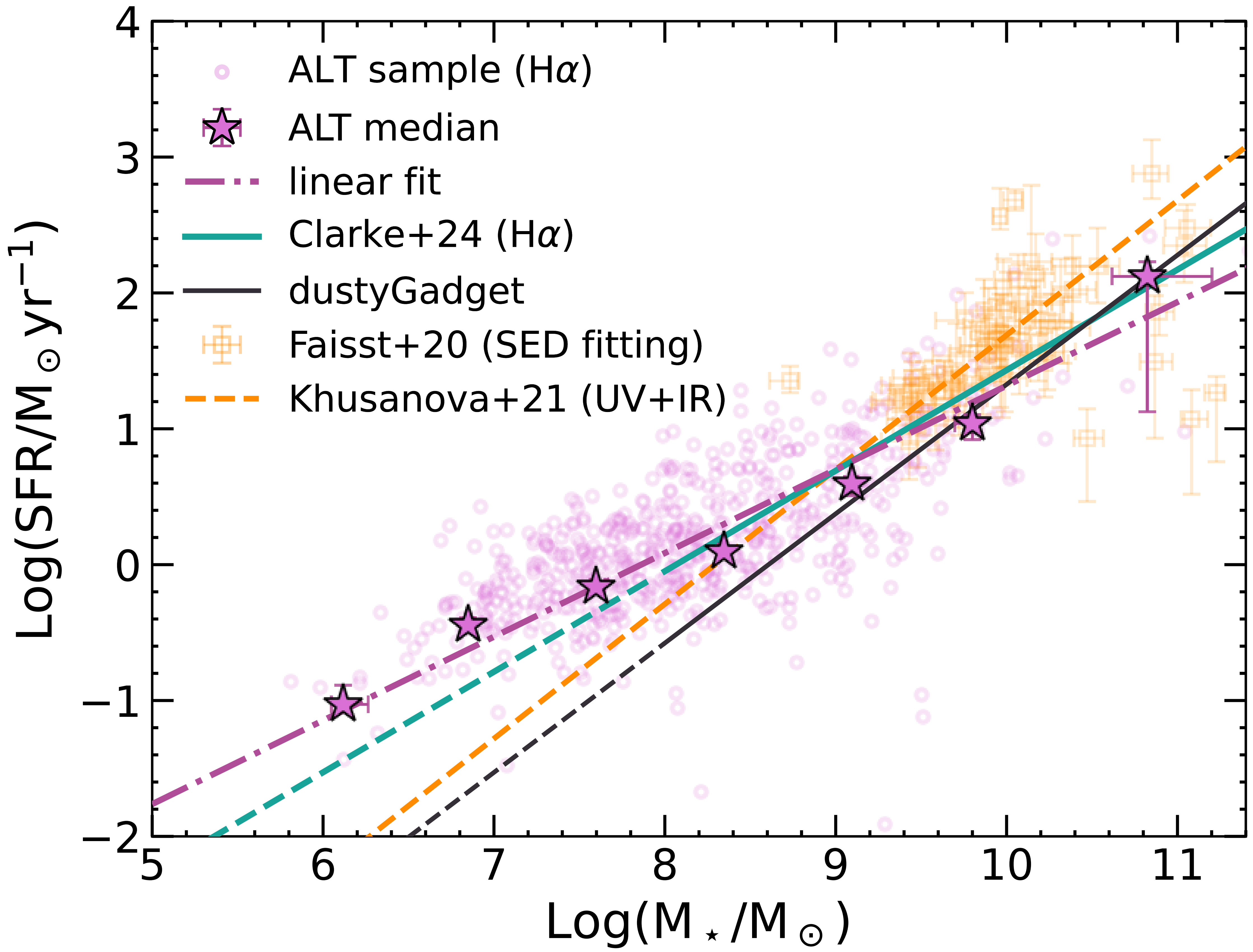
—> The average $\langle f_{esc} \rangle$ of the galaxy population very likely evolves!

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

Matthee & Naidu et al. 2022

GRISM GALAXIES

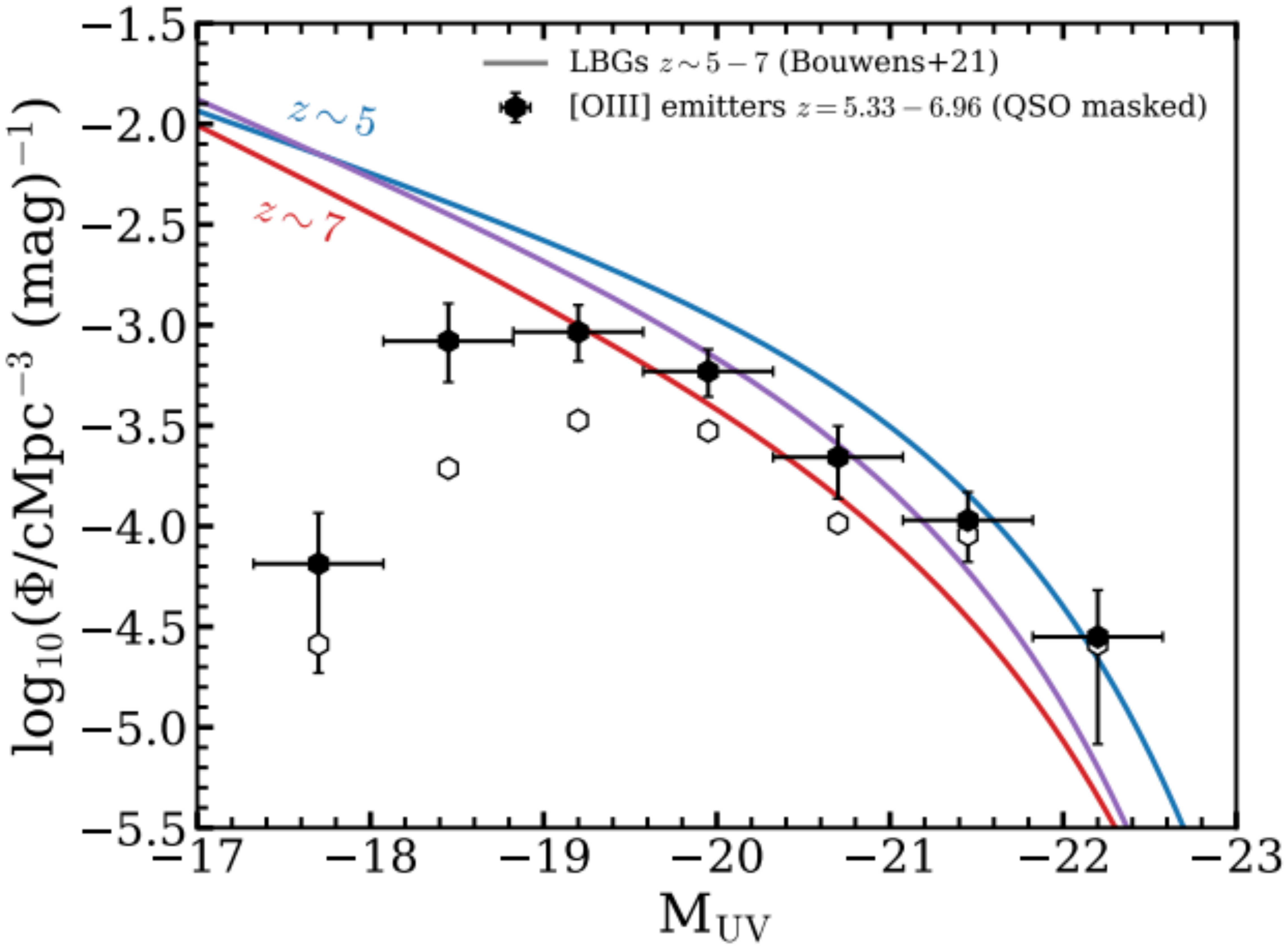
NIRCam WFSS results: a relation between SFR and Mstar down to 10^6 Msun at z~5



- **We extend the SFR(Halpha) - M_{star} at z~4-5 relation 2 orders of magnitude down to 10^6 M_{sun}**

Di Cesare, Matthee + in prep

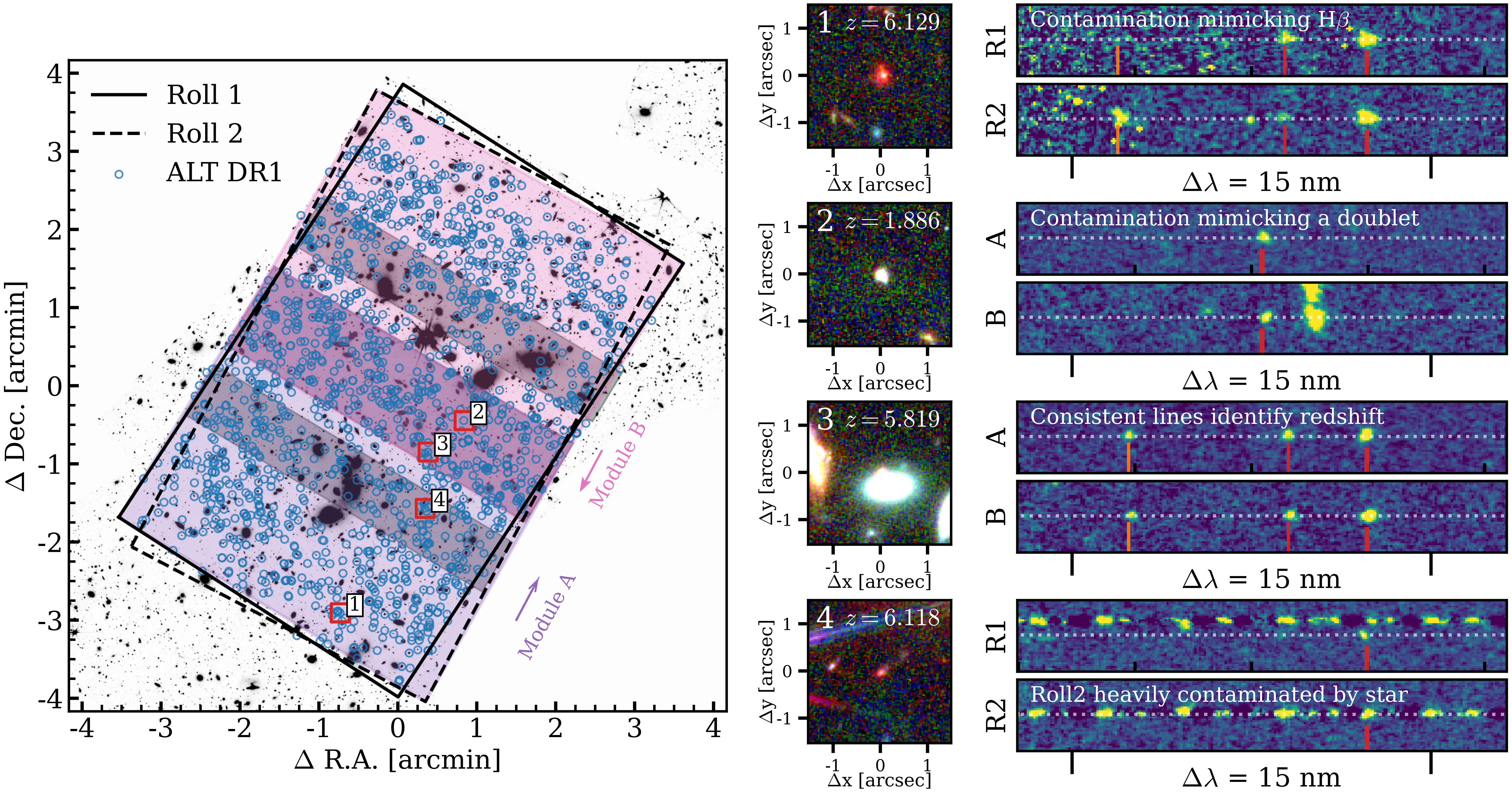
ARE SUCH EMISSION-LINE GALAXIES REPRESENTATIVE?



- UV LF of [OIII] emitters: agrees at bright end, drops at faint end because we sample the high EW end
- Clustering of [OIII] emitters suggests a 20% duty cycle / occupation fraction (Pizzati+24)

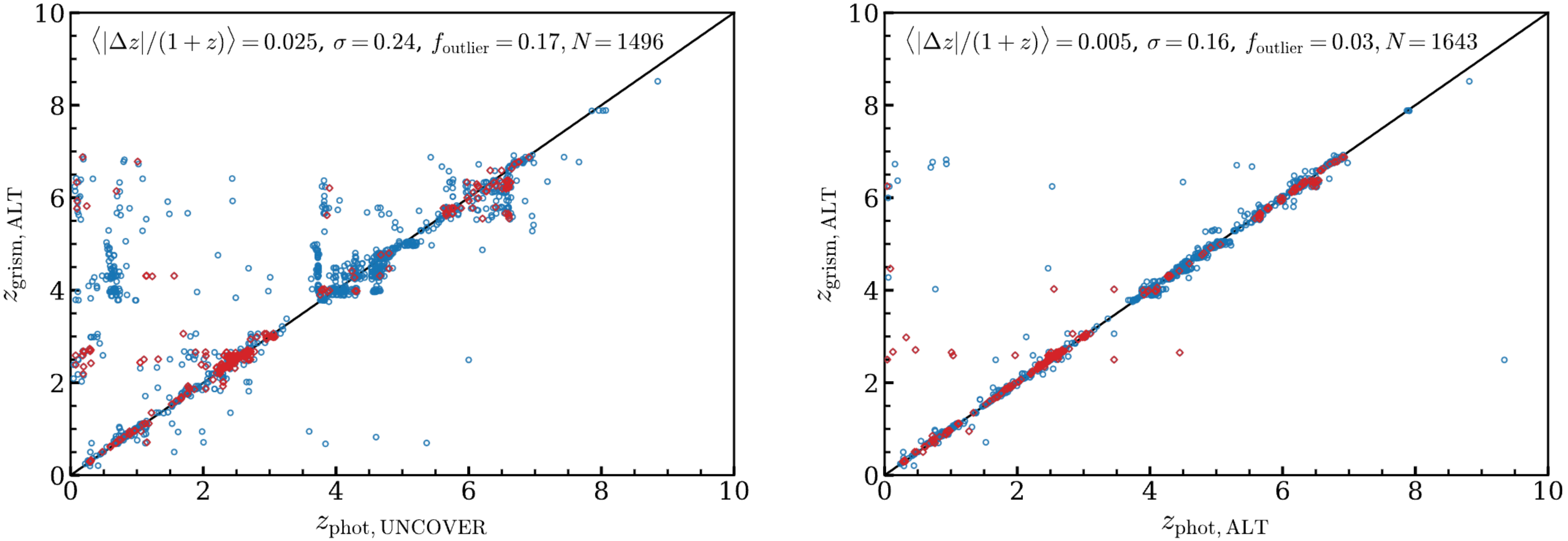
Matthee+23

ALT: All Emission-Line Redshifts behind Abell 2744



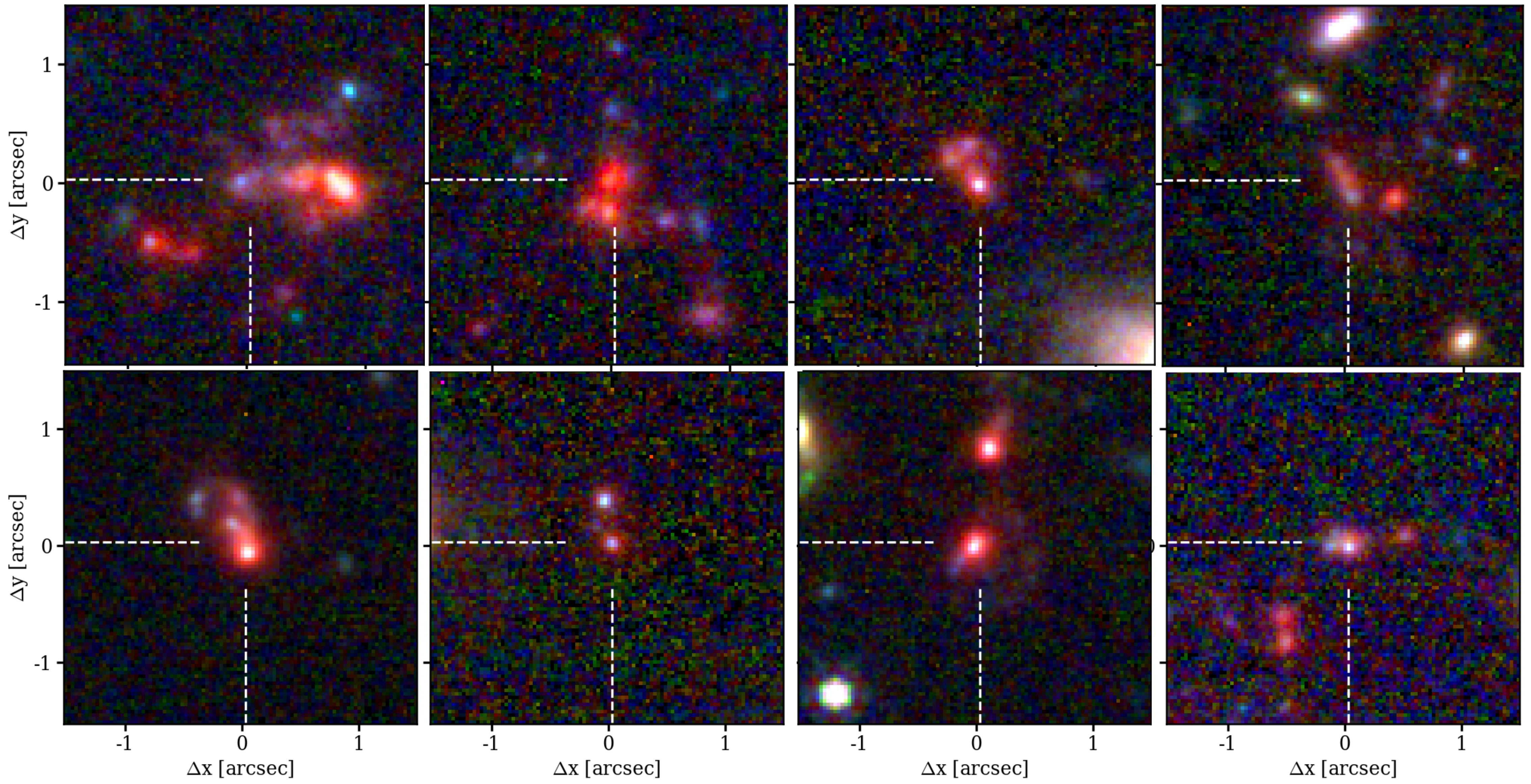
ALT survey paper (Naidu & Matthee et al. in prep)

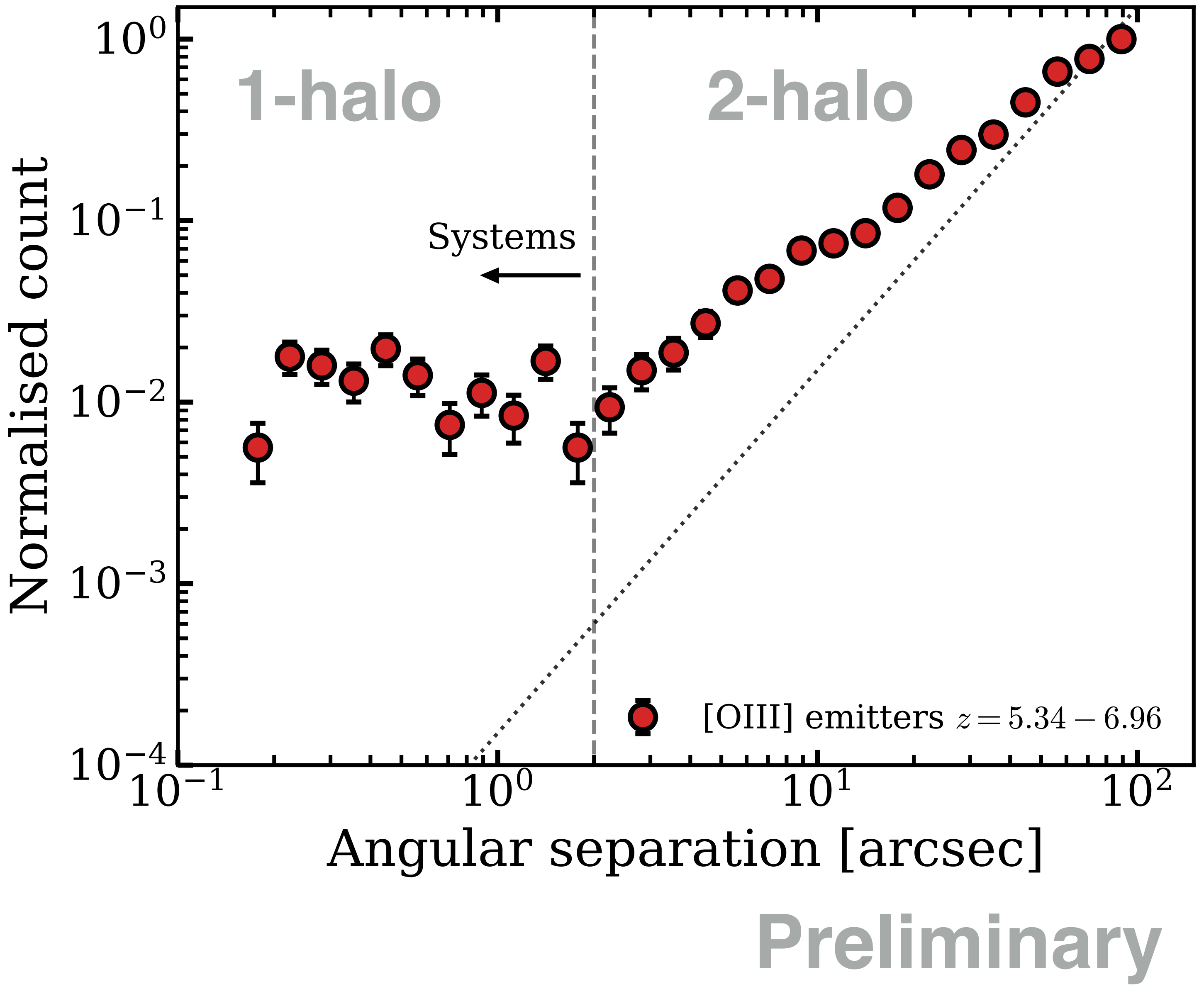
ALT: PHOTO-Z PERFORMANCE



ALT survey paper (Naidu & Matthee et al. in prep)

Galaxies are not isolated

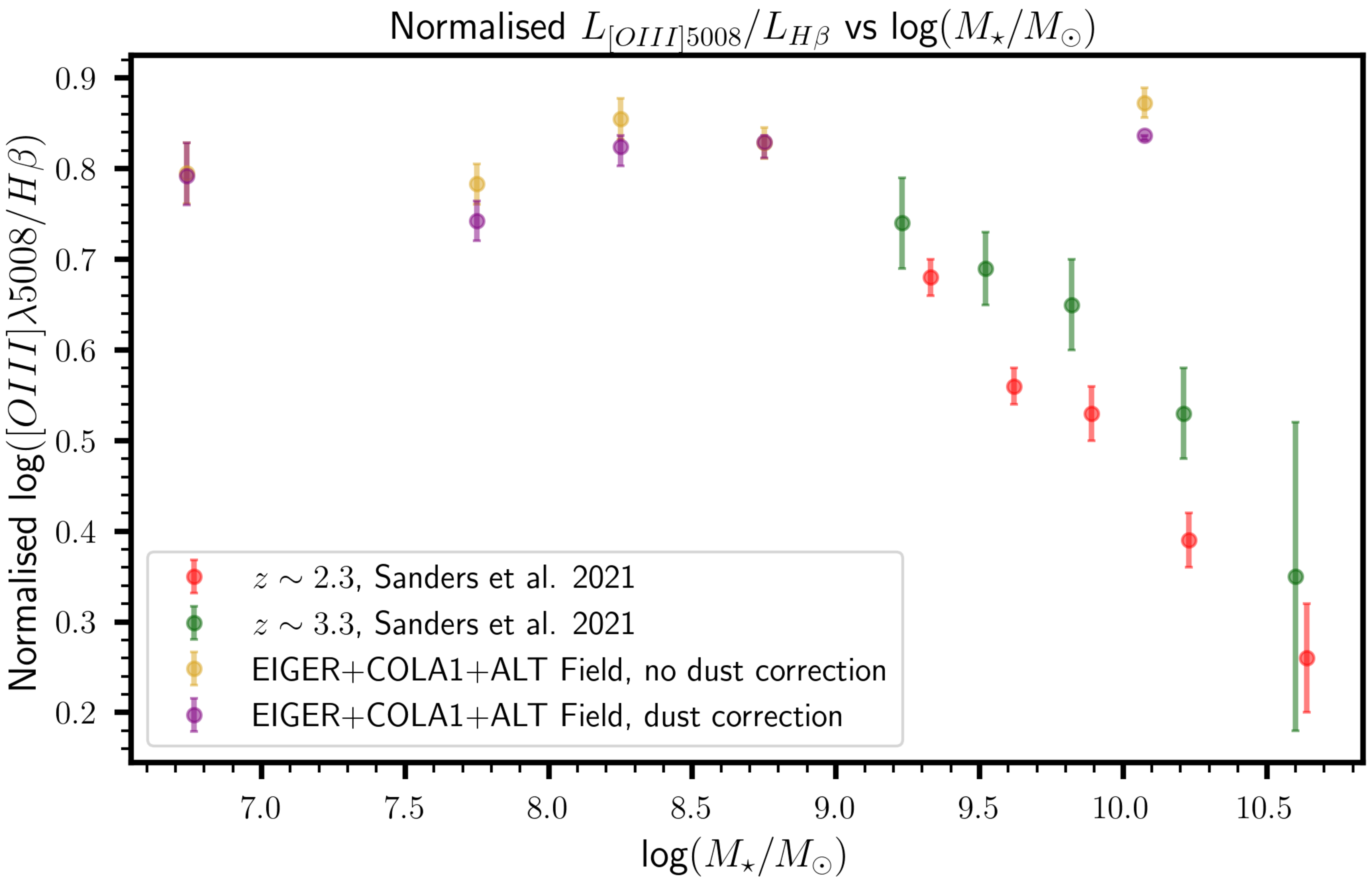




Clear excess clustering on all scales, with a bend at ~2” (~10 pkpc)

Update from Matthee+23

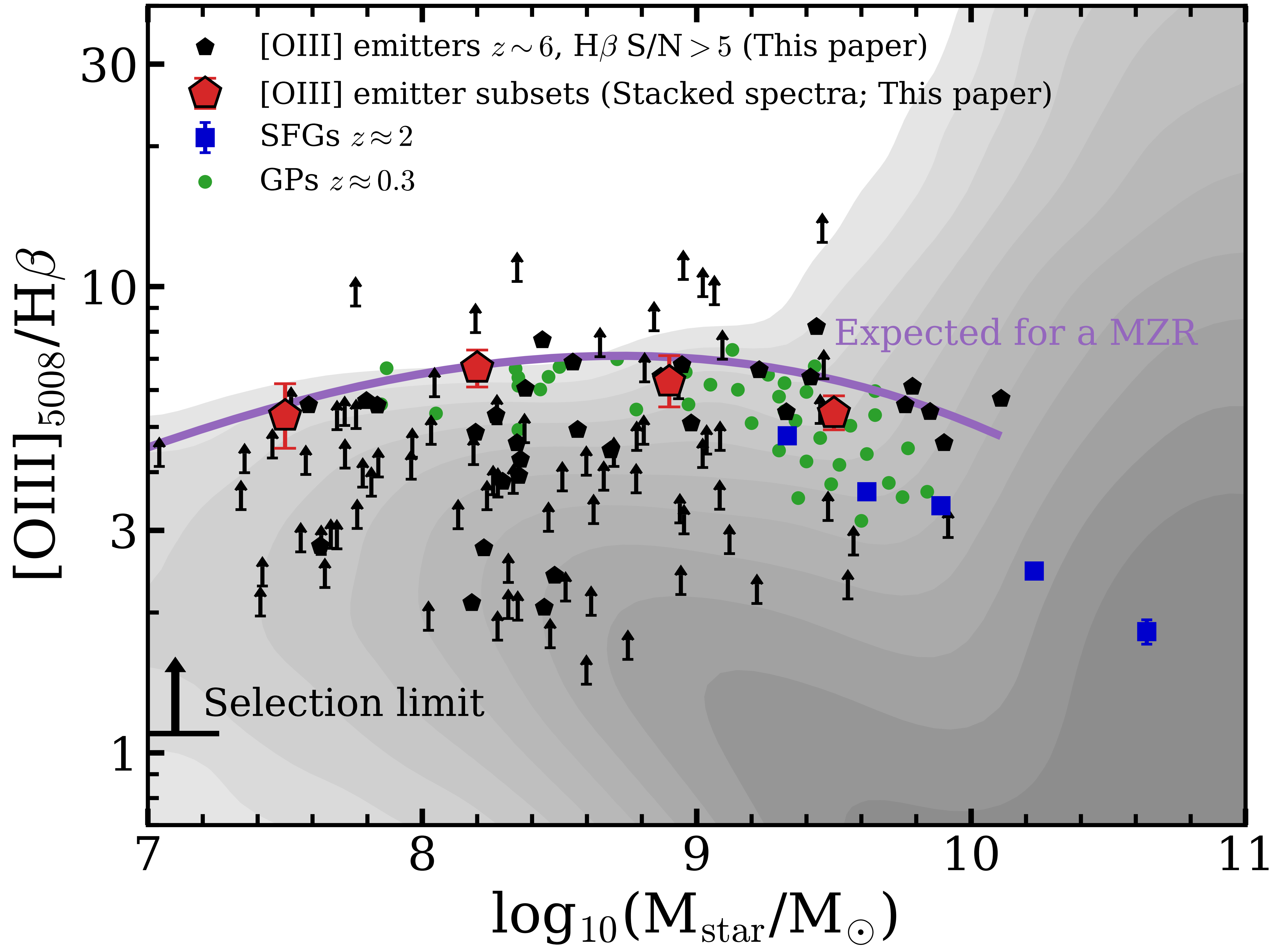
ALT: All Emission-Line Redshifts behind Abell 2744



- **At z~6, we find remarkably high/constant [OIII]/Hb down to masses as low as 10^7 M_{sun}**

Kotiwale, Matthee+ in prep

NIRCam WFSS results: z~6 galaxies have a highly ionized ISM



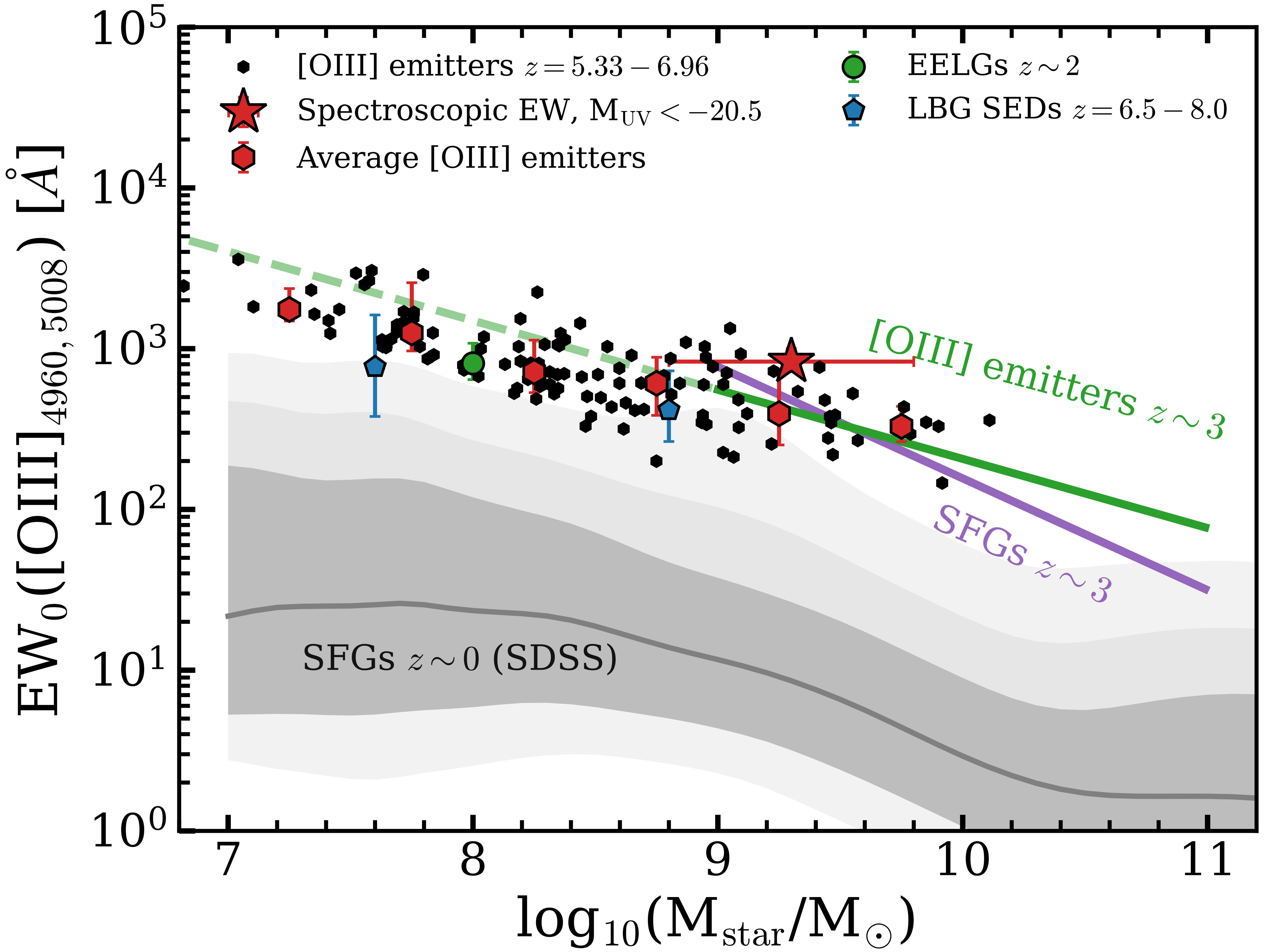
[OIII]/Hb ratios are very high ~5

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

Similar line-ratios as Green Pea galaxies, e.g. Yang+17, Izotov+21

Matthee+23

NIRCam WFSS results: z~6 galaxies have *ubiquitous* strong Hβ+[OIII] lines



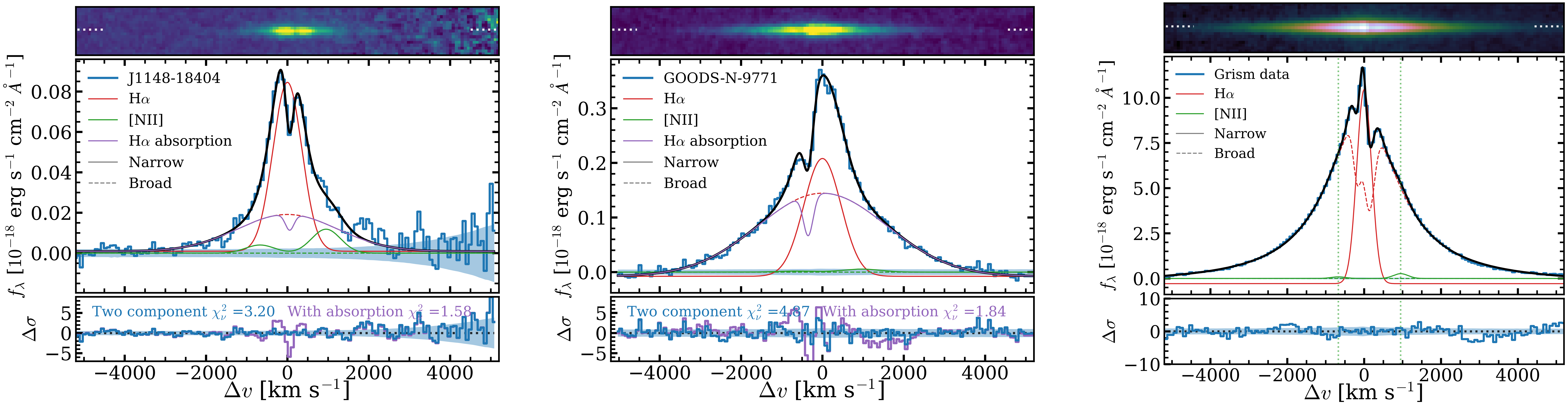
- **Typical EWs ~1000 A, only found in <1% of SDSS galaxies**
- **Prime drivers are very young ages of ~30 Myr and low metallicities (~10% solar)**

Confirms Spitzer/IRAC inferences, e.g. Raiter+10, Labbe+10, Smit+14, Endsley+20

Matthee+23
See also Meyer+24

LRDs

BALMER ABSORPTION IN FAINT-AGN: STARTING OUTFLOWS?

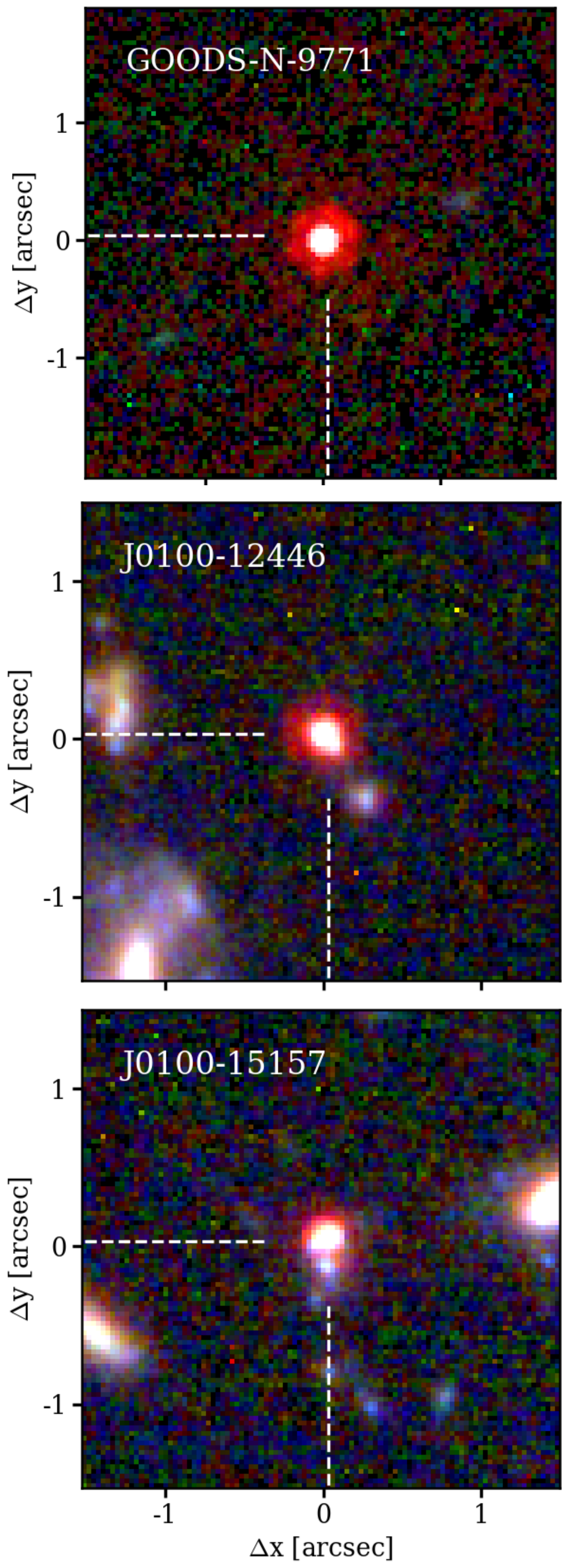


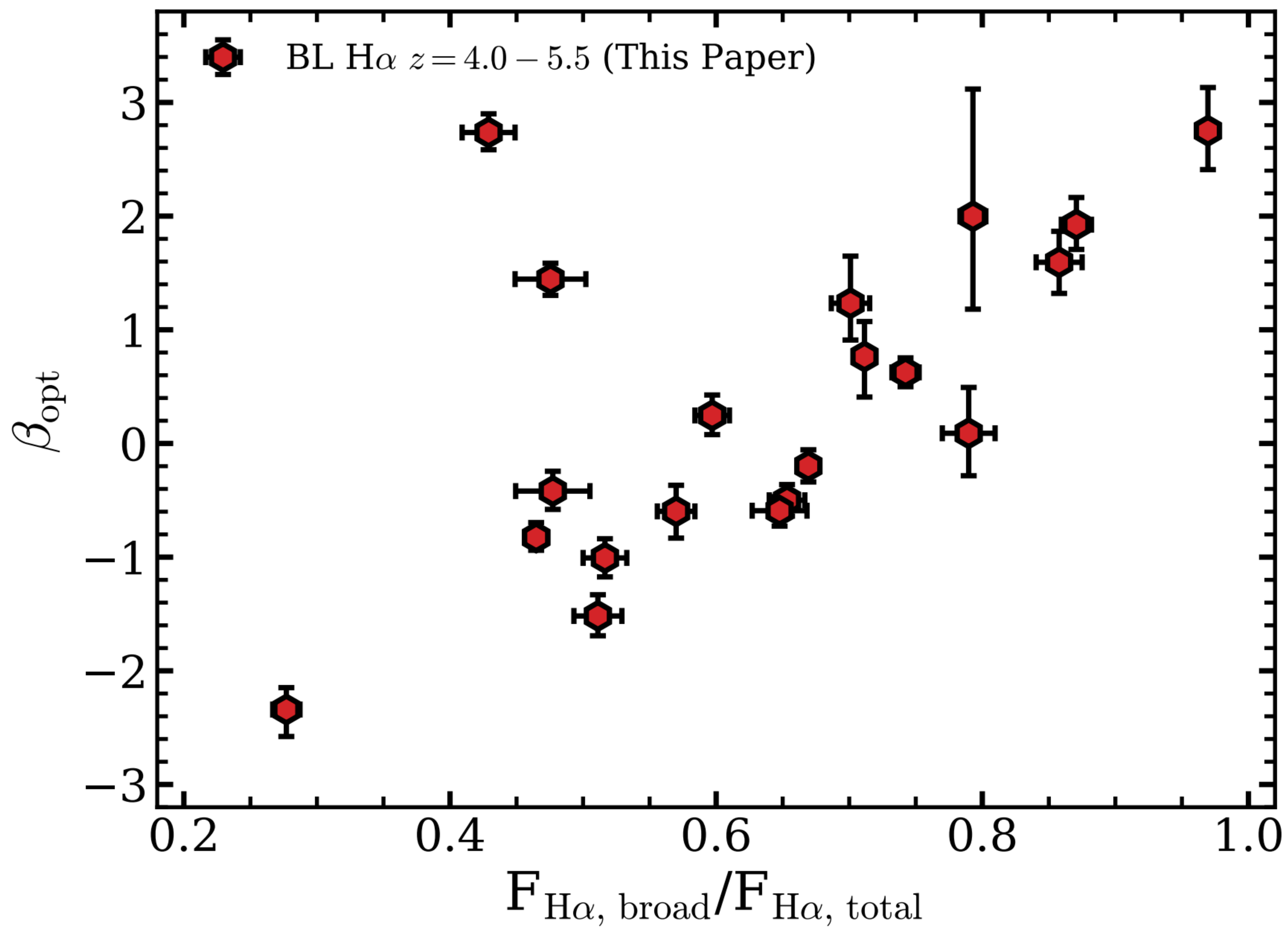
- **Detection of Balmer absorption (EW~ 4 Å) close to the systemic redshift: inflows & outflows in the BLR?**
- **Dense gas causing Balmer absorption may be related to X-Ray weakness**

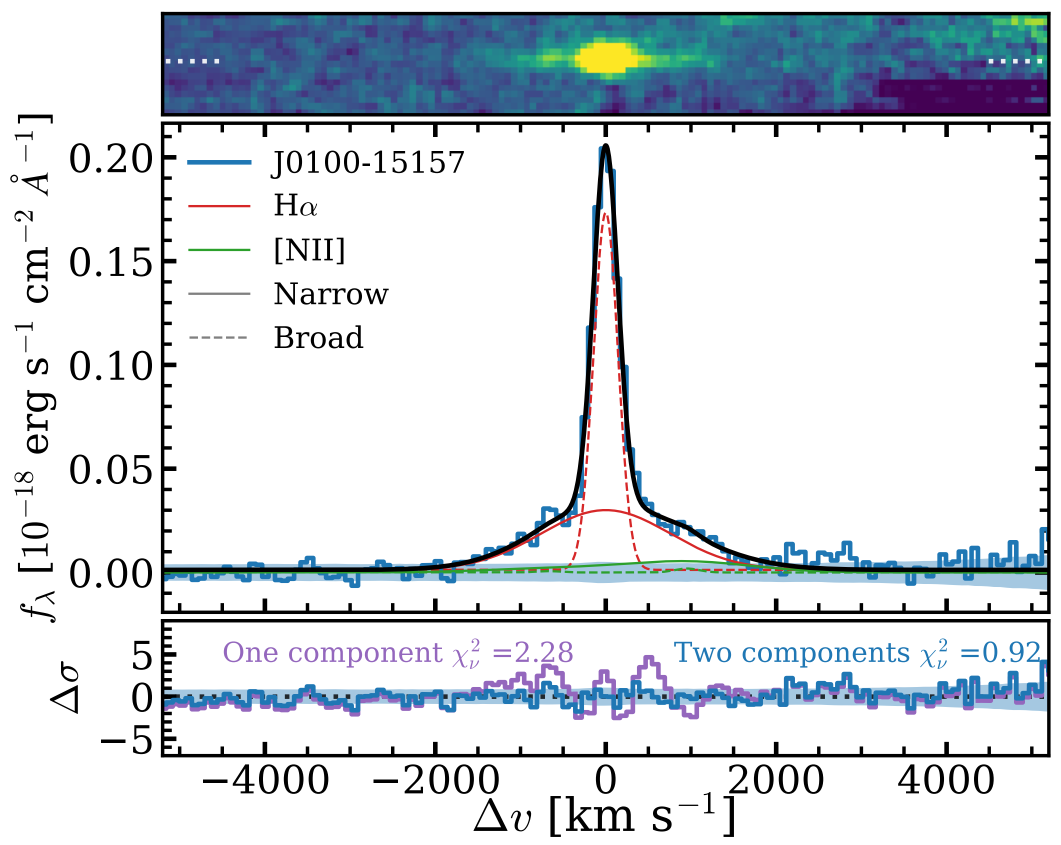
Kocevski+24; Maiolino+24

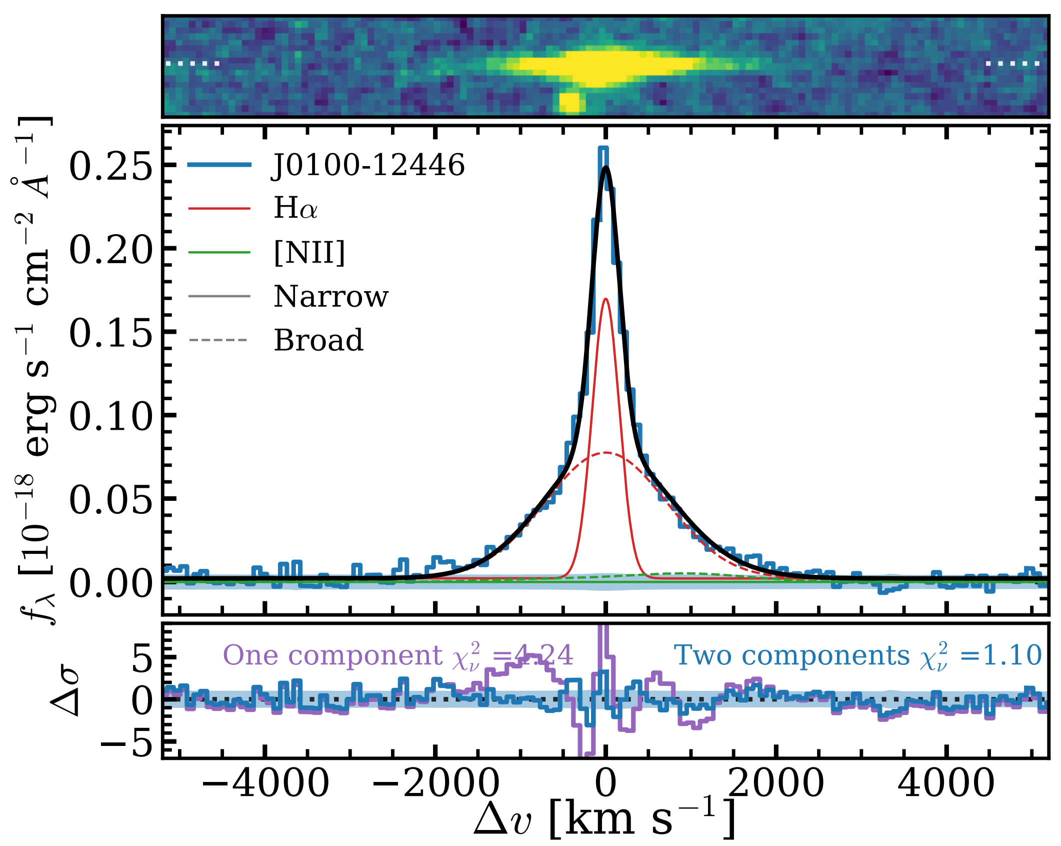
Matthee+24b

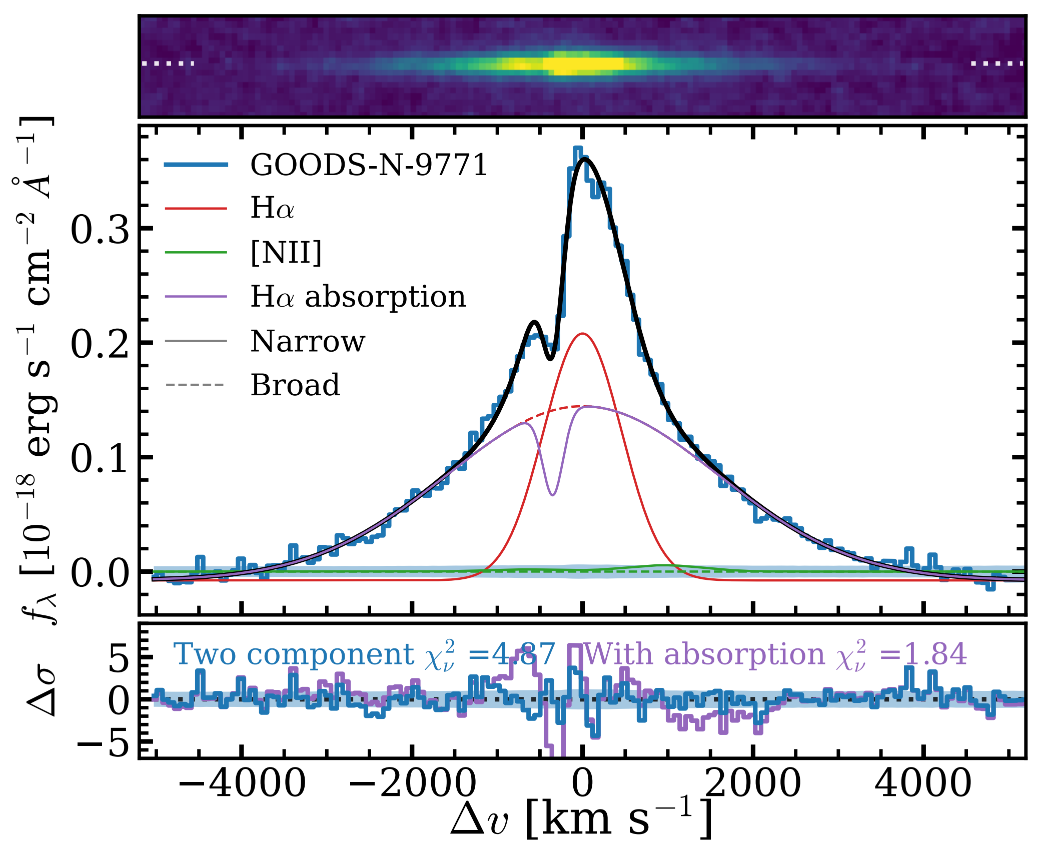
THE REDNESS OF THE LITTLE RED DOTS IS A RESULT, NOT A SELECTION CRITERION





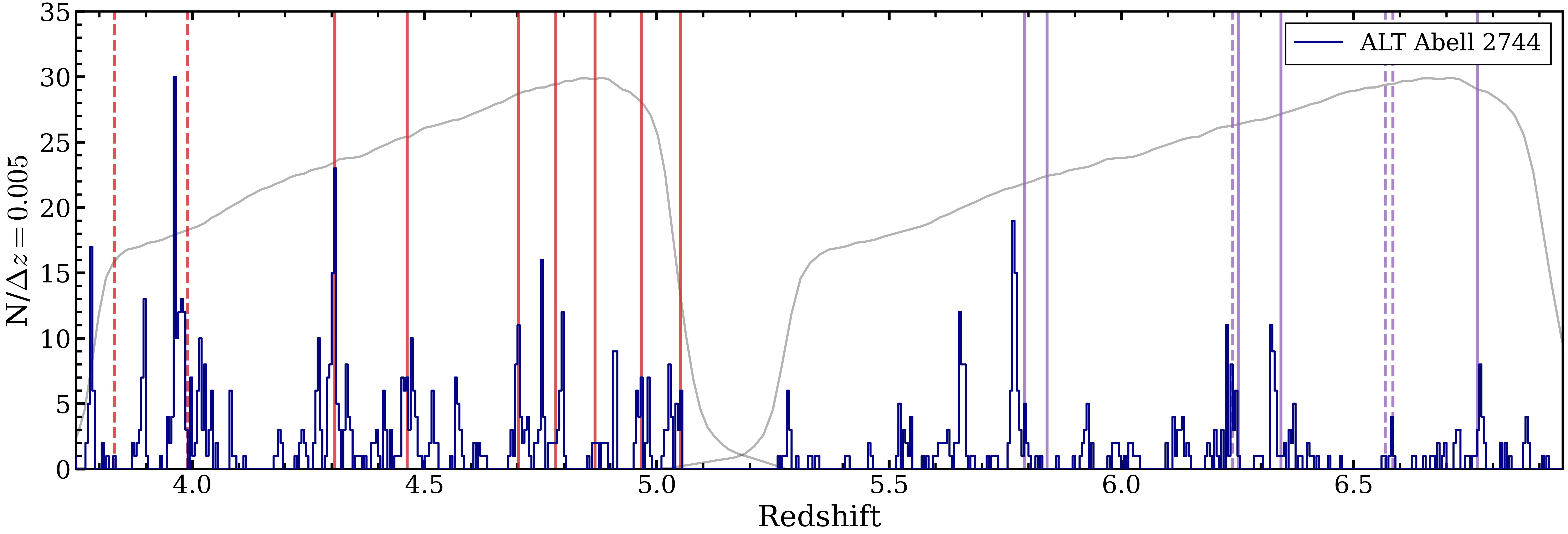






Matthee+24b

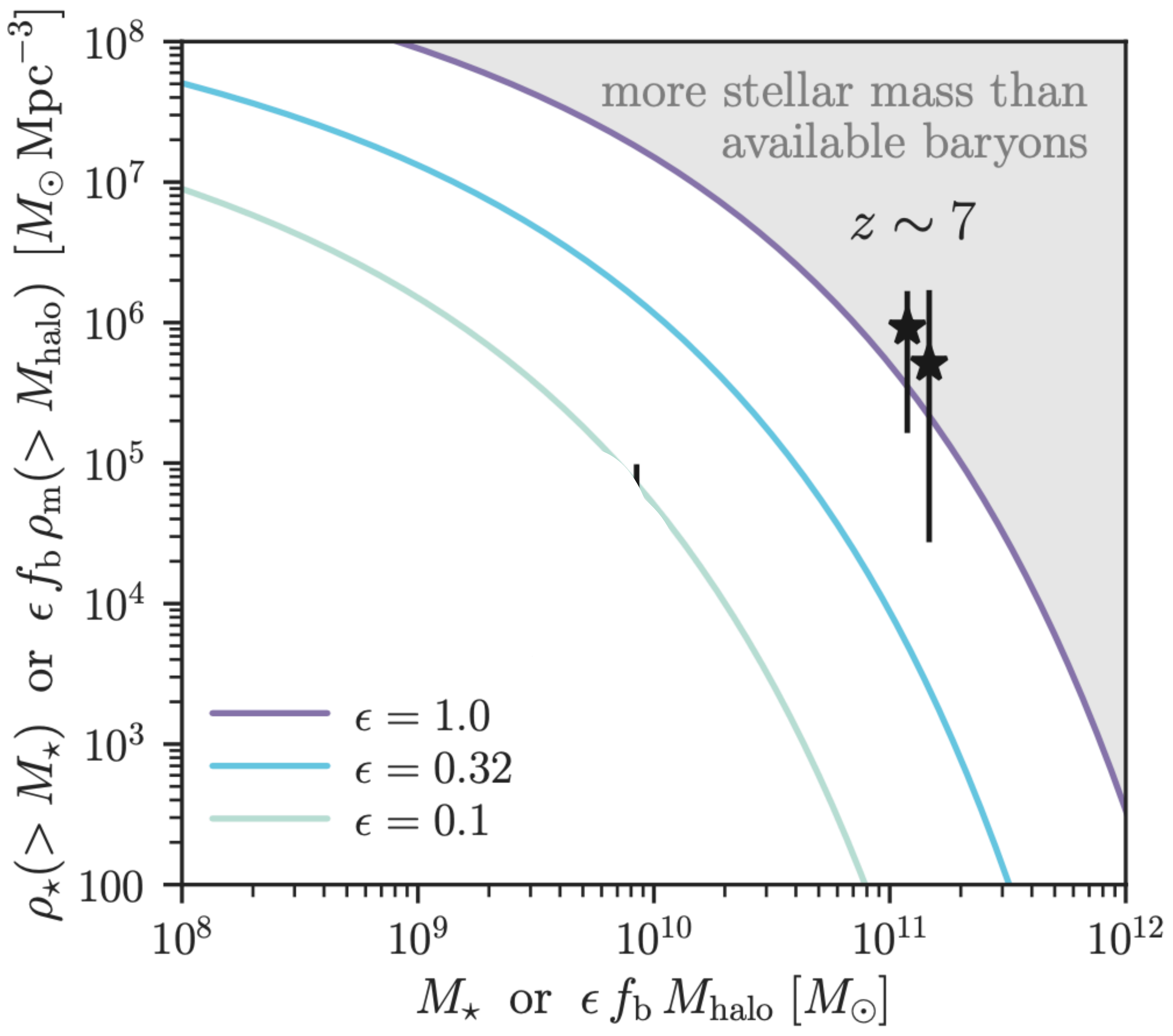
ENVIRONMENTS OF LITTLE RED DOTS

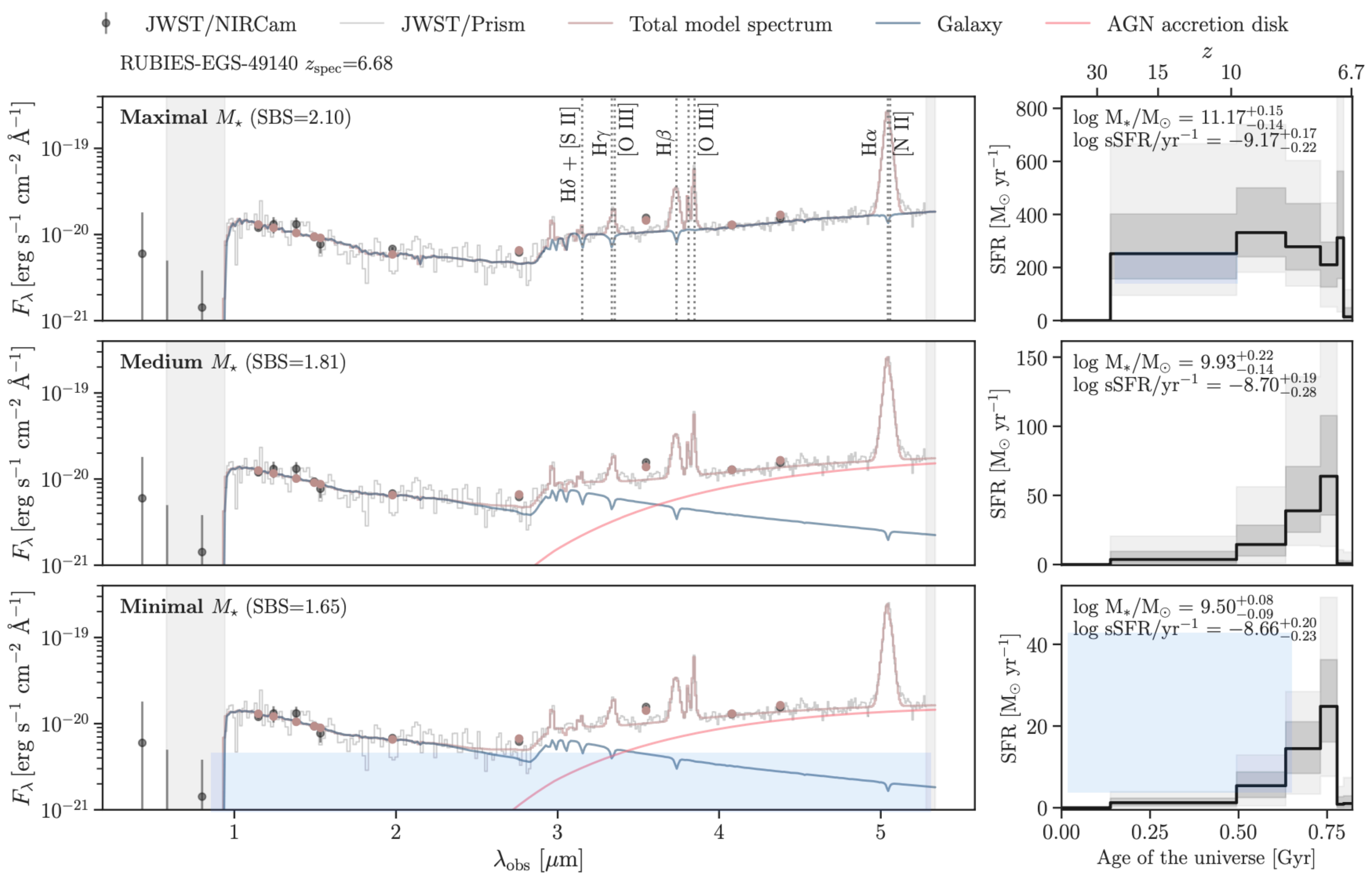


- **Faint AGN are found in a range of environments, similar to luminous quasar results (Eilers+24)**

Matthee+ in prep

TOO MASSIVE TO EXIST? LIKELY AN AGN…



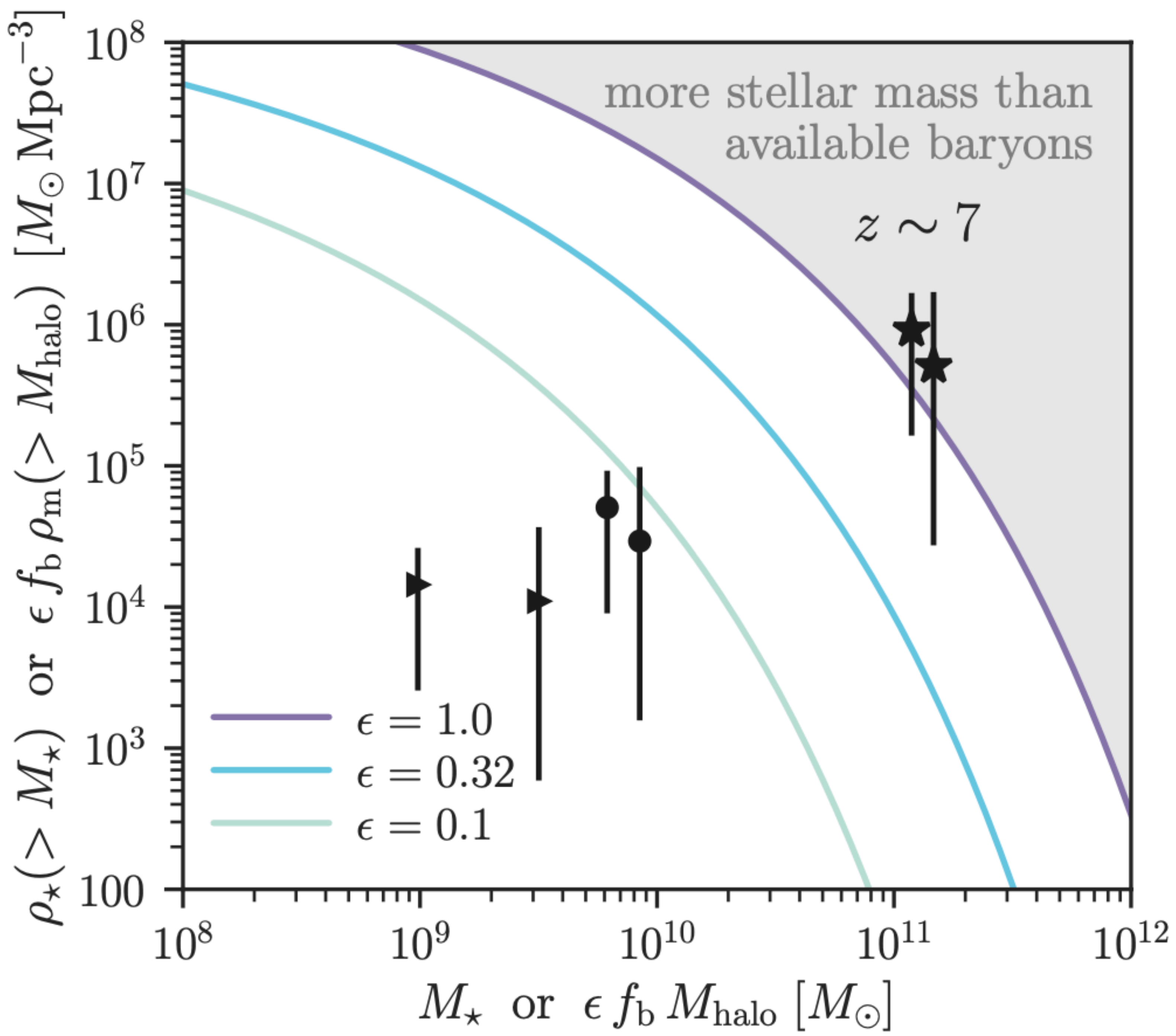


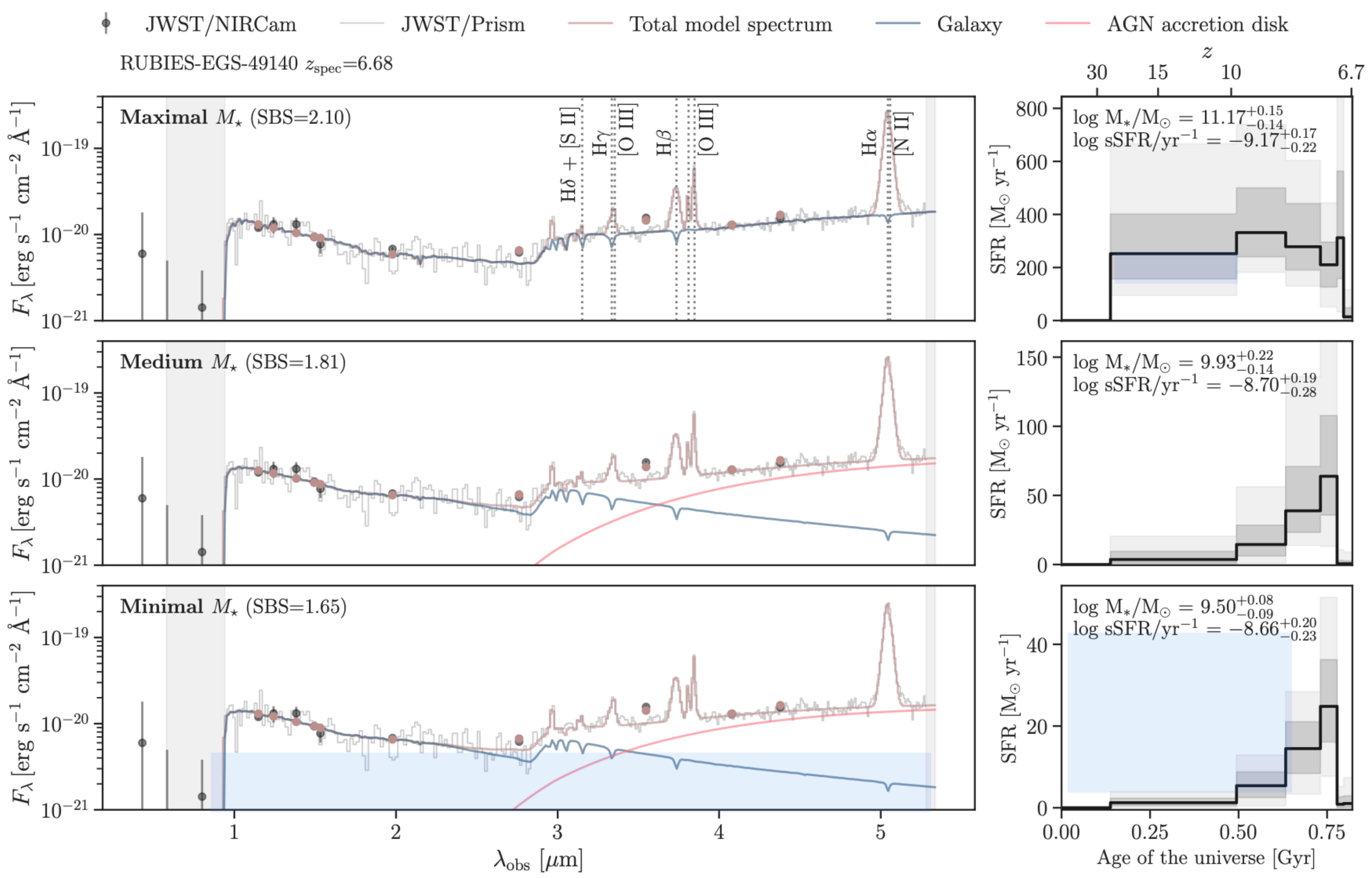
RUBiES

The numerous, red AGN in distant galaxies mimic old stellar populations, leading to severe overestimates of stellar
factor 100!)

B. Wang+ (incl JM) 24

TOO MASSIVE TO EXIST? LIKELY AN AGN…



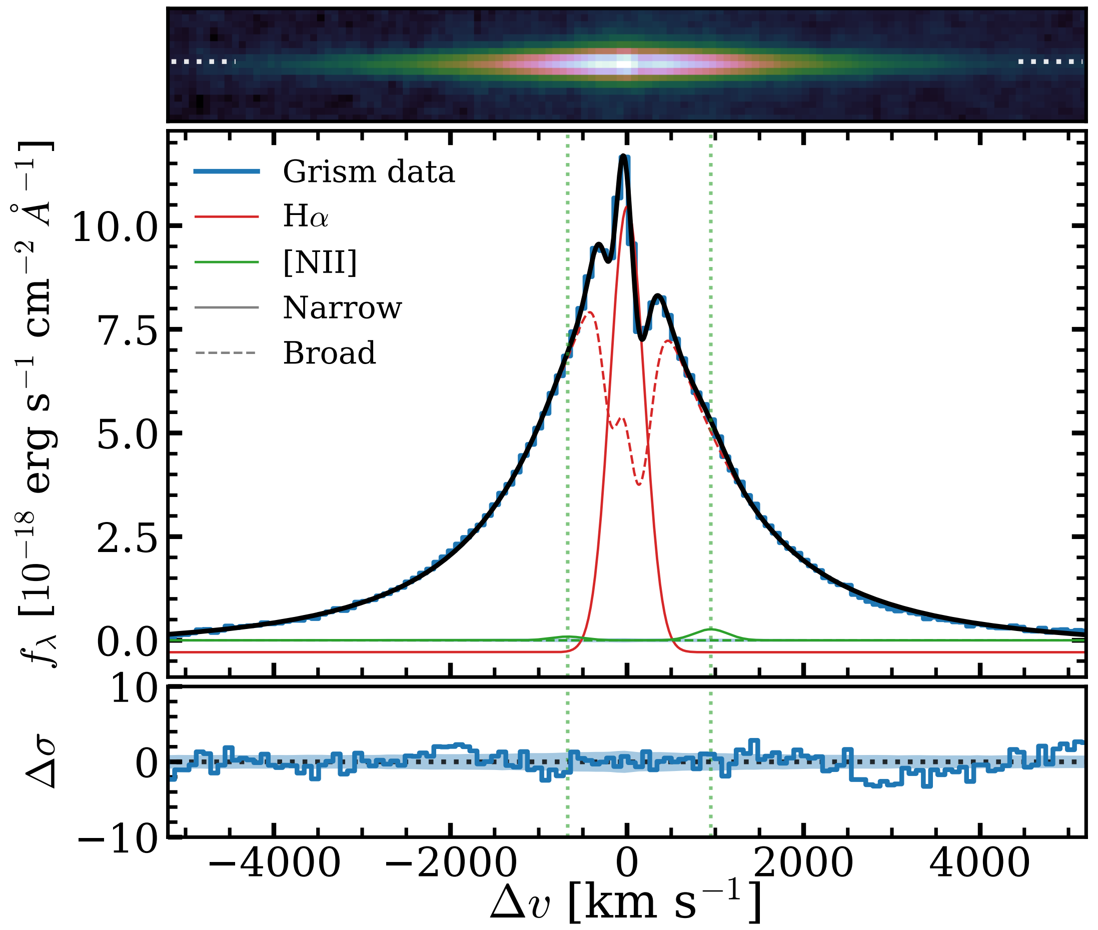


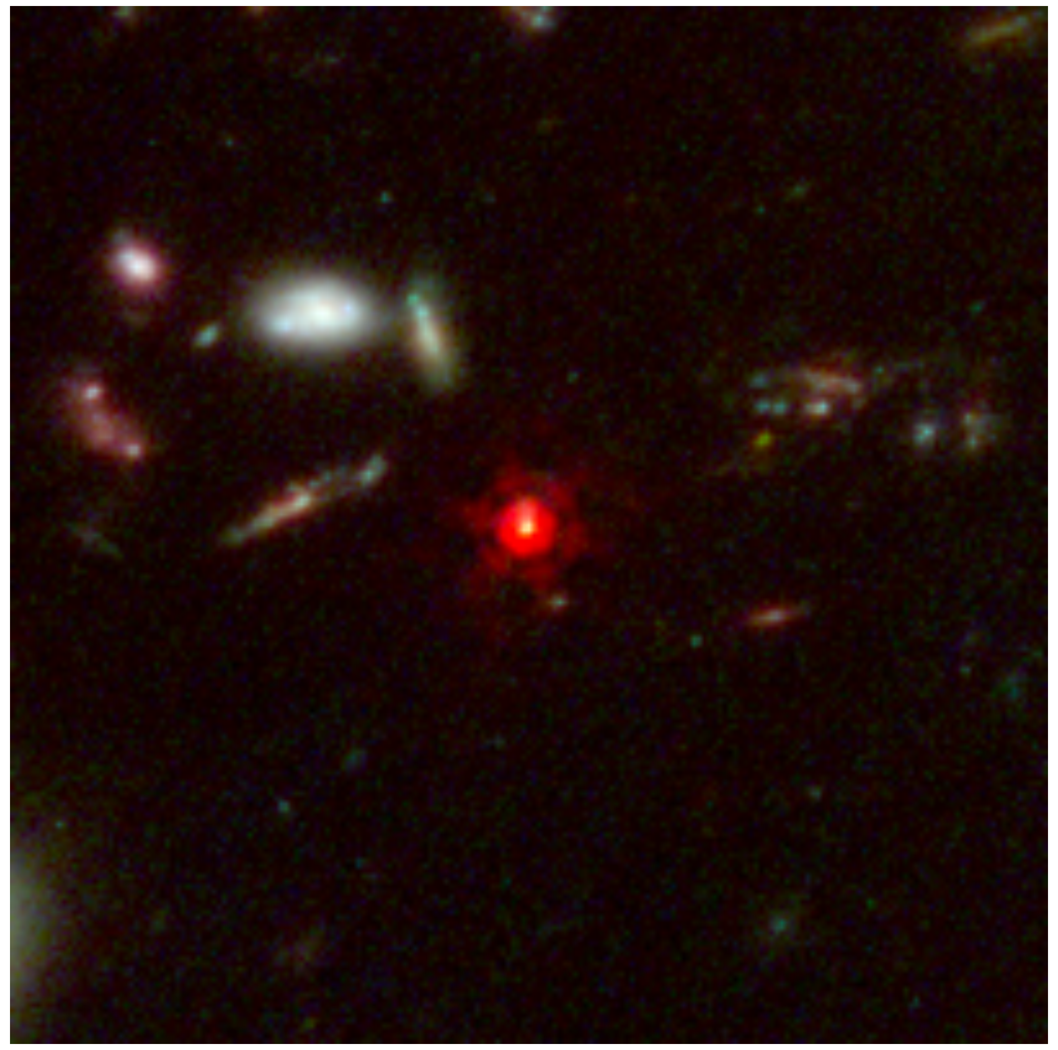
RUBiES

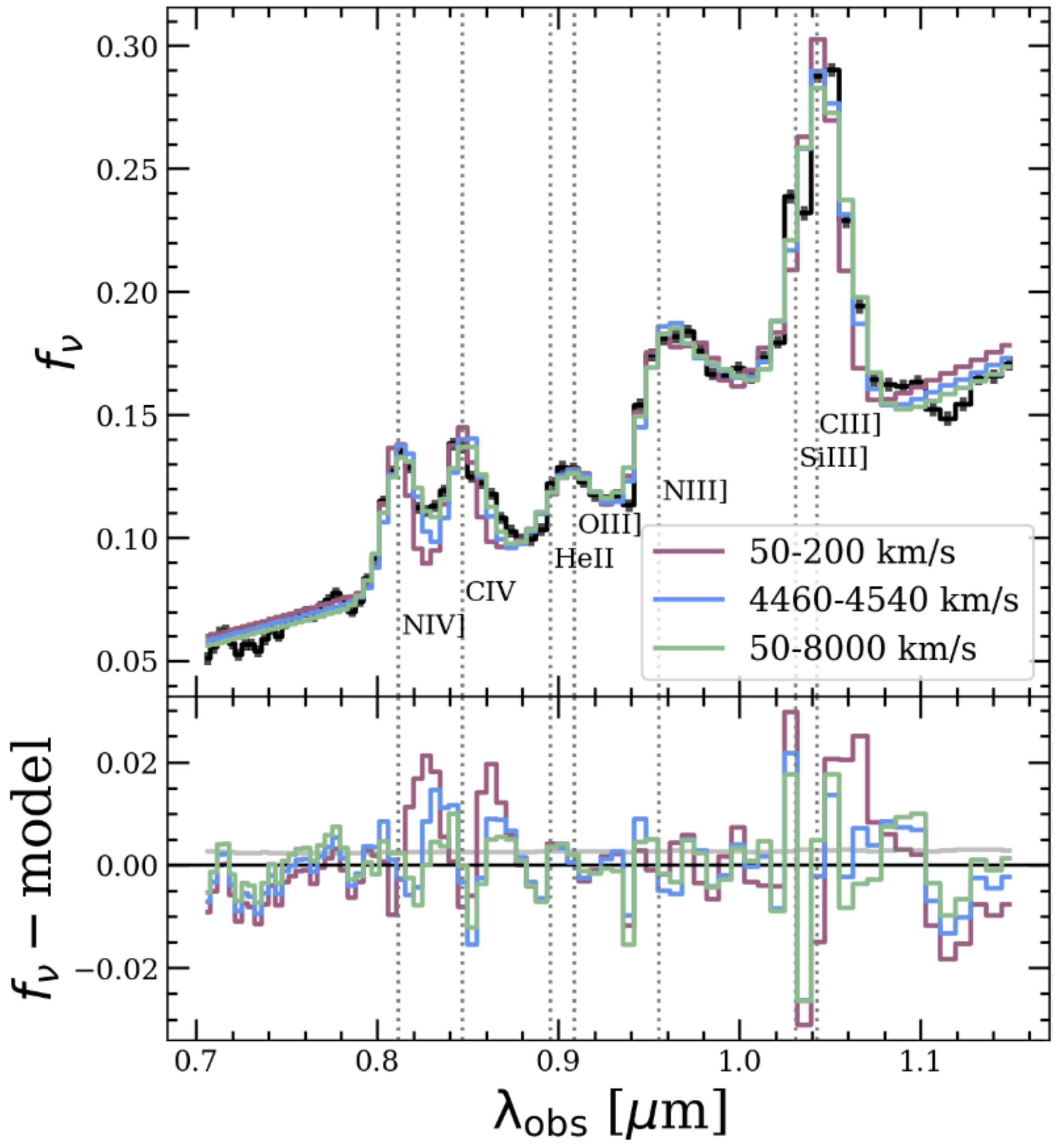
The numerous, red AGN in distant galaxies mimic old stellar populations, leading to severe overestimates of stellar r
factor 100!)

B. Wang+ (incl JM) 24

THE BIG RED DOT







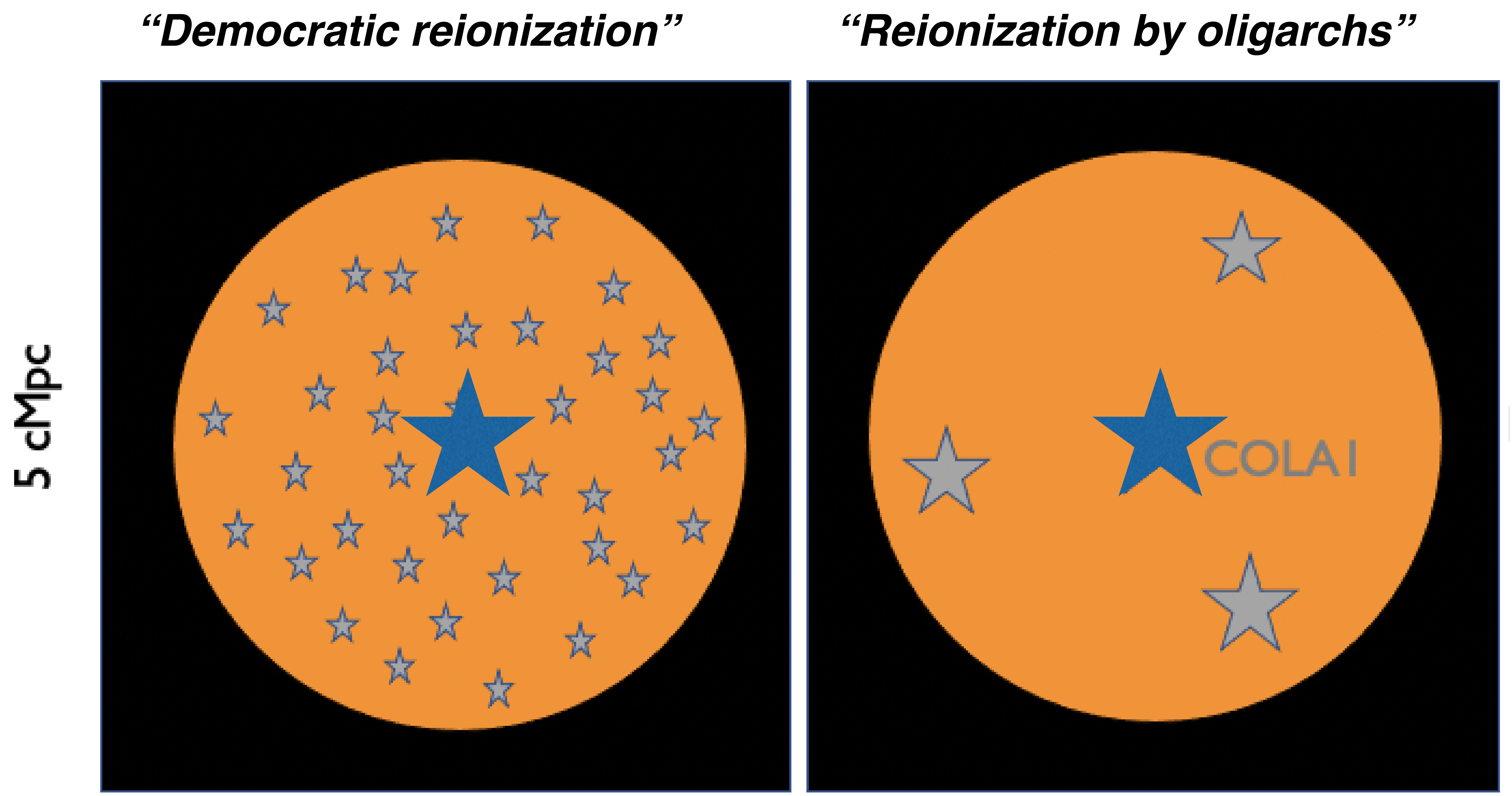
Labbe+ (incl JM) in prep

- **The most luminous "little red dot" known: F444W=22**
- **Lensed by factor 1.8 behind Abell 2744**
- **SMBH mass 10^9 Msun (Greene+23)**
- **A composite AGN + old 10^{11} Msun galaxy**
- **A strong nitrogen emitter!**
- **Strong Balmer absorption!**
- **A large over-density** (δ±30; like the most luminous quasars)

- ***Clustered star formation in the early Universe rapidly built a bulge + a supermassive black hole*** *(e.g. Shi+24)****, with nitrogen as a by-product?***

COLA1

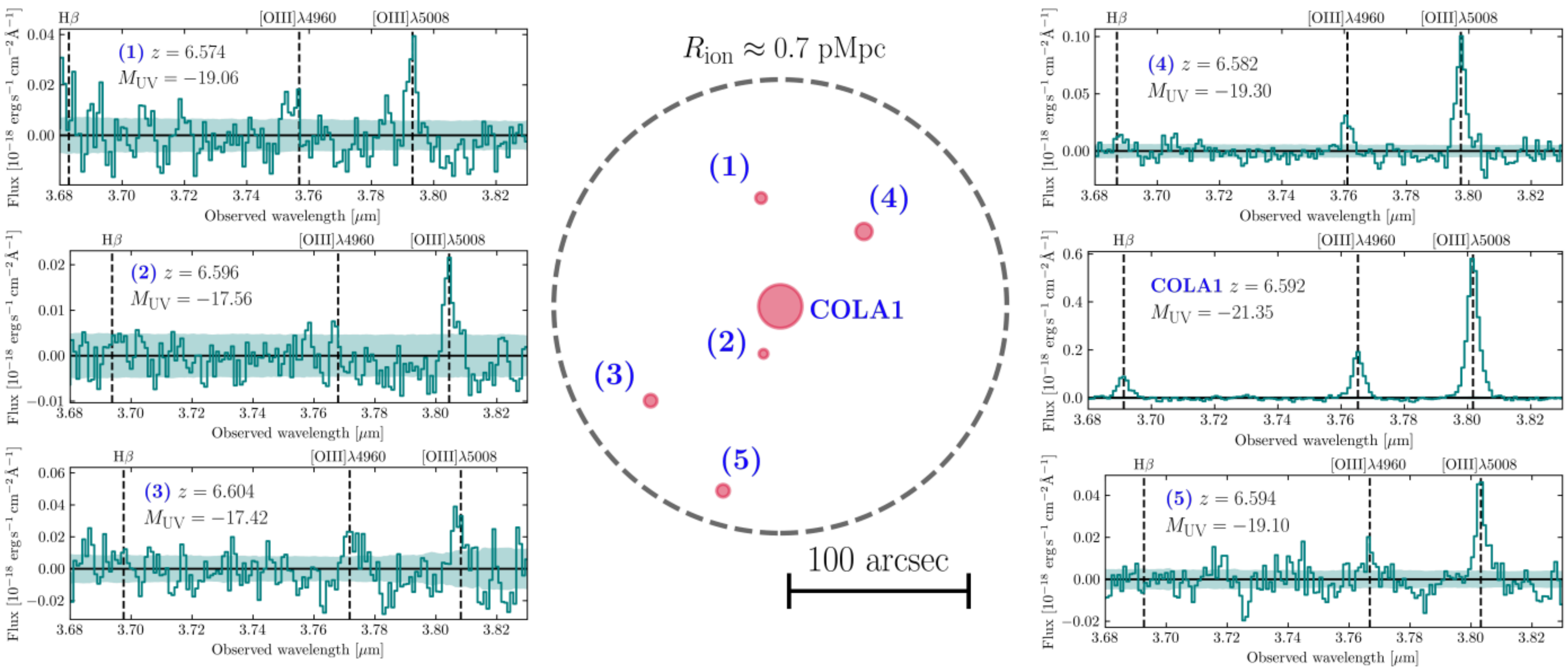
LOCAL REIONIZATION EXPERIMENTS (I)



Hu+2016, Matthee+2018

- **COLA1: a unique bright galaxy where we know the size of the ionised bubble**
  see Alberto Torralba Torregrossa’s talk tomorrow

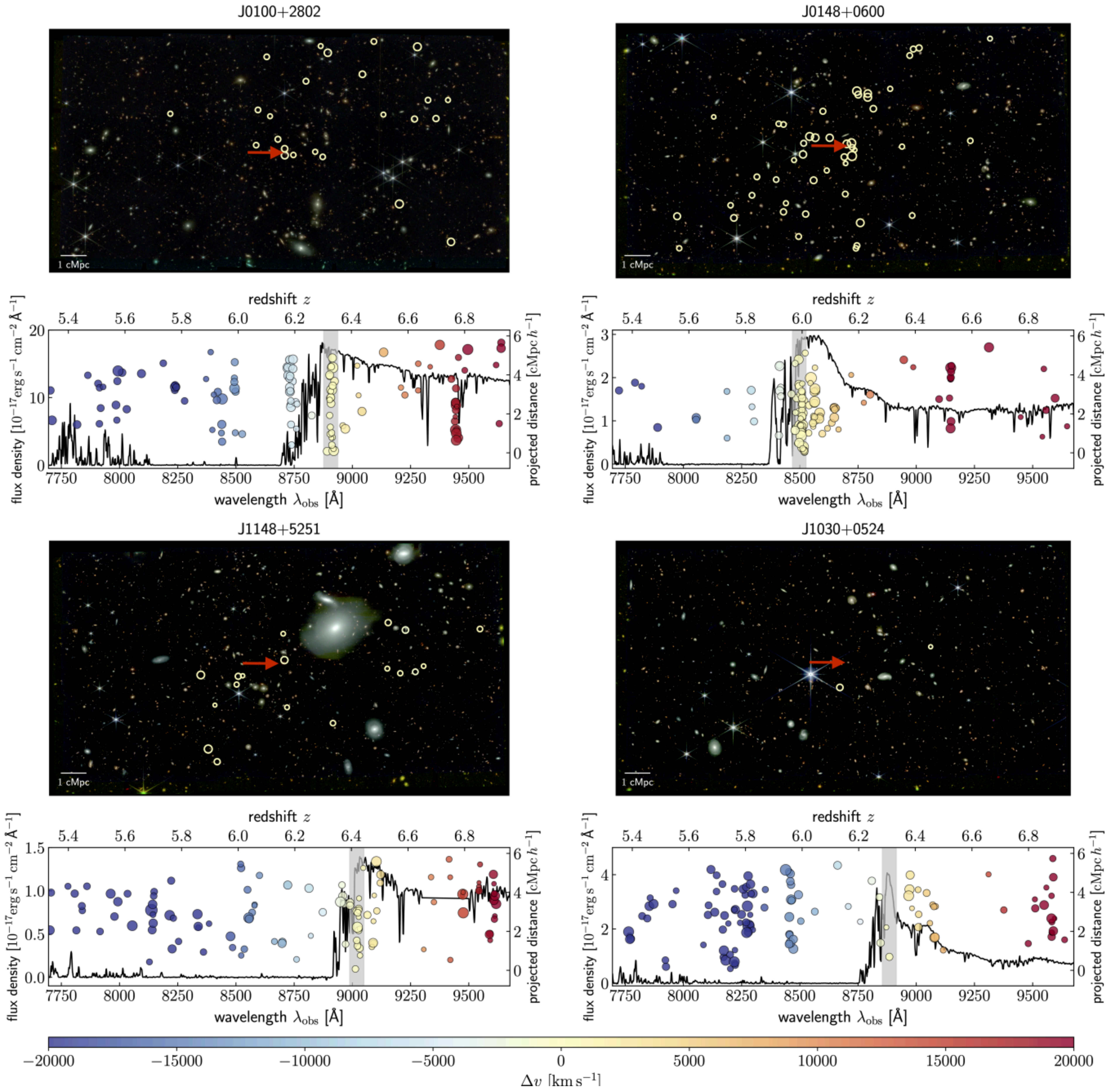
COLA1, A LUMINOUS STARBURST IN A *NORMAL* ENVIRONMENT



- **Surprisingly, there is not an excessively large over-density: did COLA1 ionise the environment itself?**

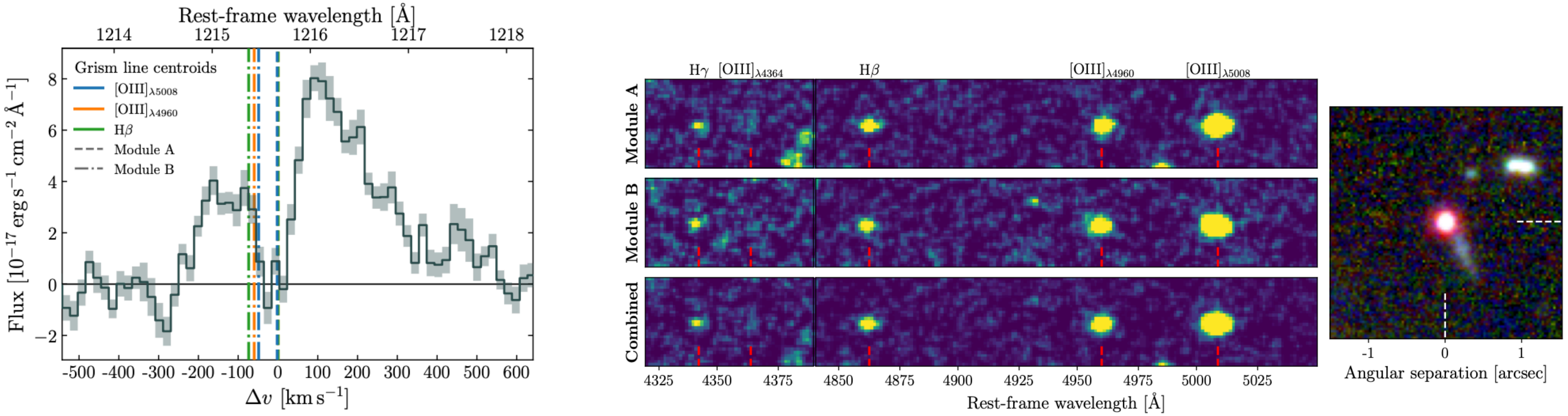
Torralba-Torregrosa, Matthee+24

THE ENVIRONMENTS OF THE MOST LUMINOUS QUASARS



Eilers+24

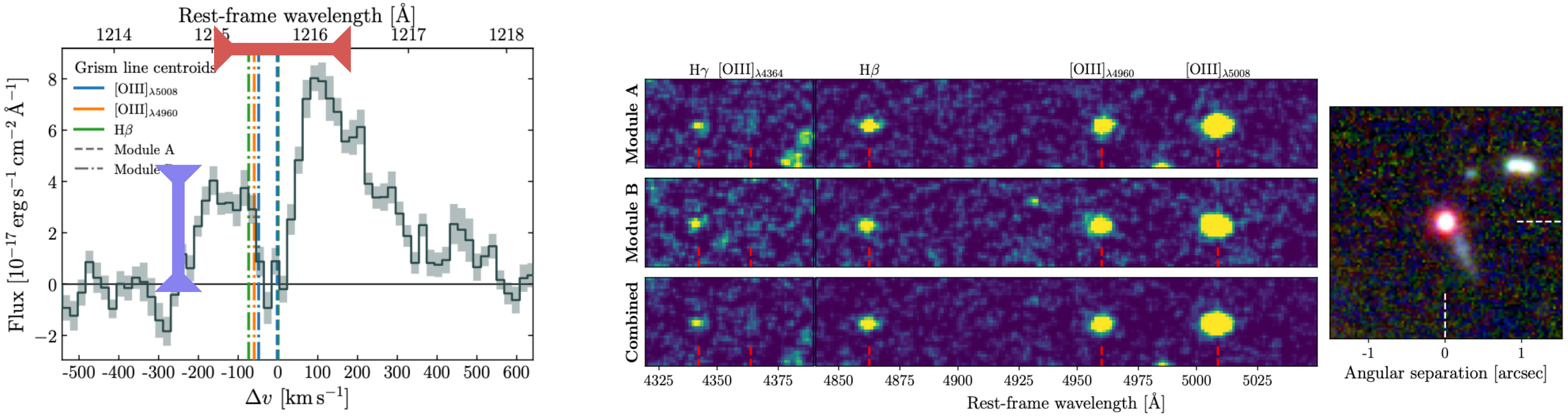
MORE DIRECT EVIDENCE:
COLA1, ALL THE INDICATIONS OF A STRONG IONIZING AGENT



- **Exceptional Lyman-alpha emission at z=6.6 indicate:**
  1) an ionized bubble of ~> 5 cMpc
  2) a highly luminous star-burst with 30% ionising photon escape fraction

Torralba-Torregrosa, Matthee+24

More direct evidence:
COLA1, all the indications of a strong Ionizing Agent

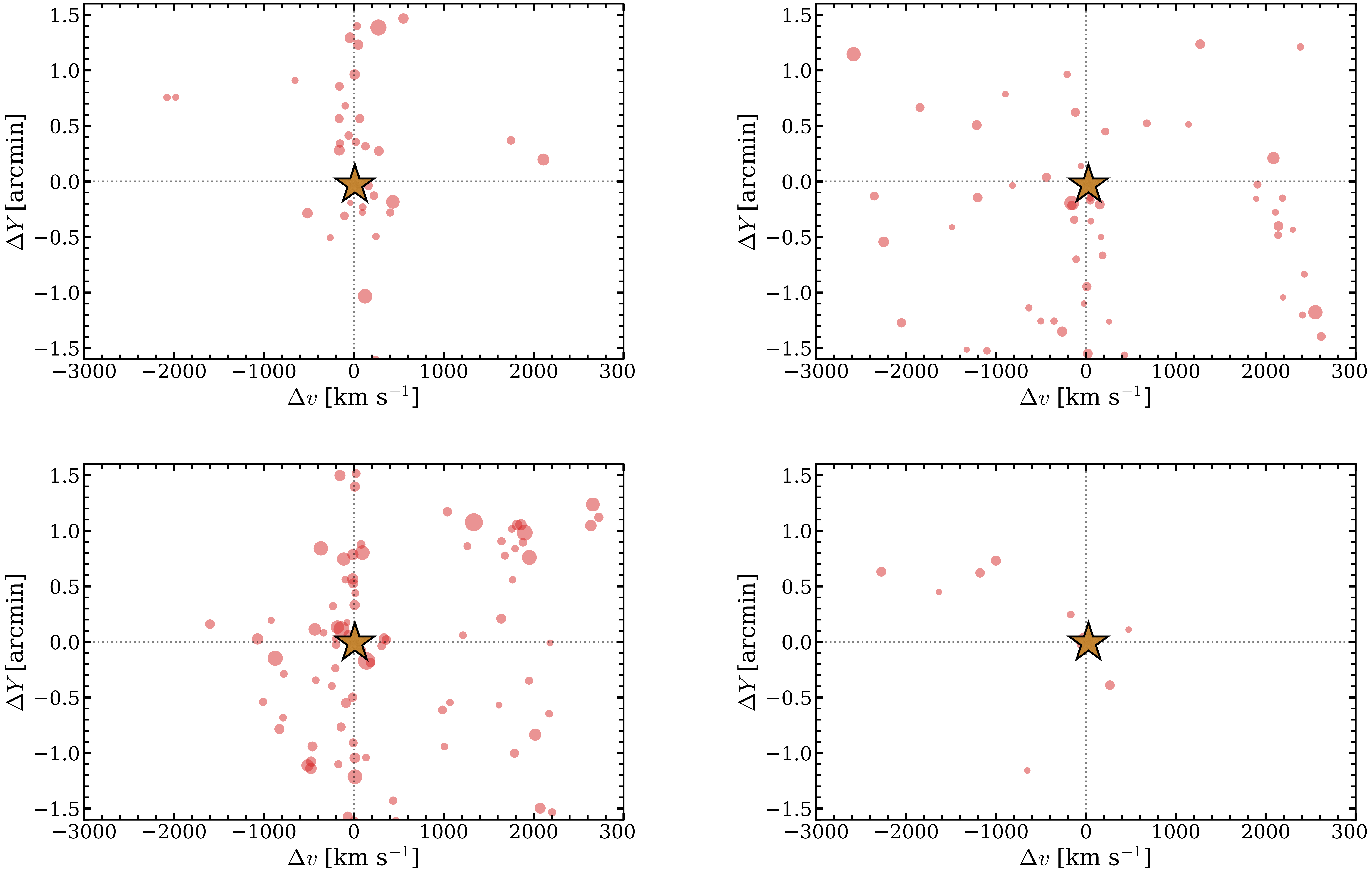


- **Exceptional Lyman-alpha emission at z=6.6 indicate:**
  1) an ionized bubble of ~> 5 cMpc
  2) a highly luminous star-burst with 30% ionising photon escape fraction

Torralba-Torregrosa, Matthee+24

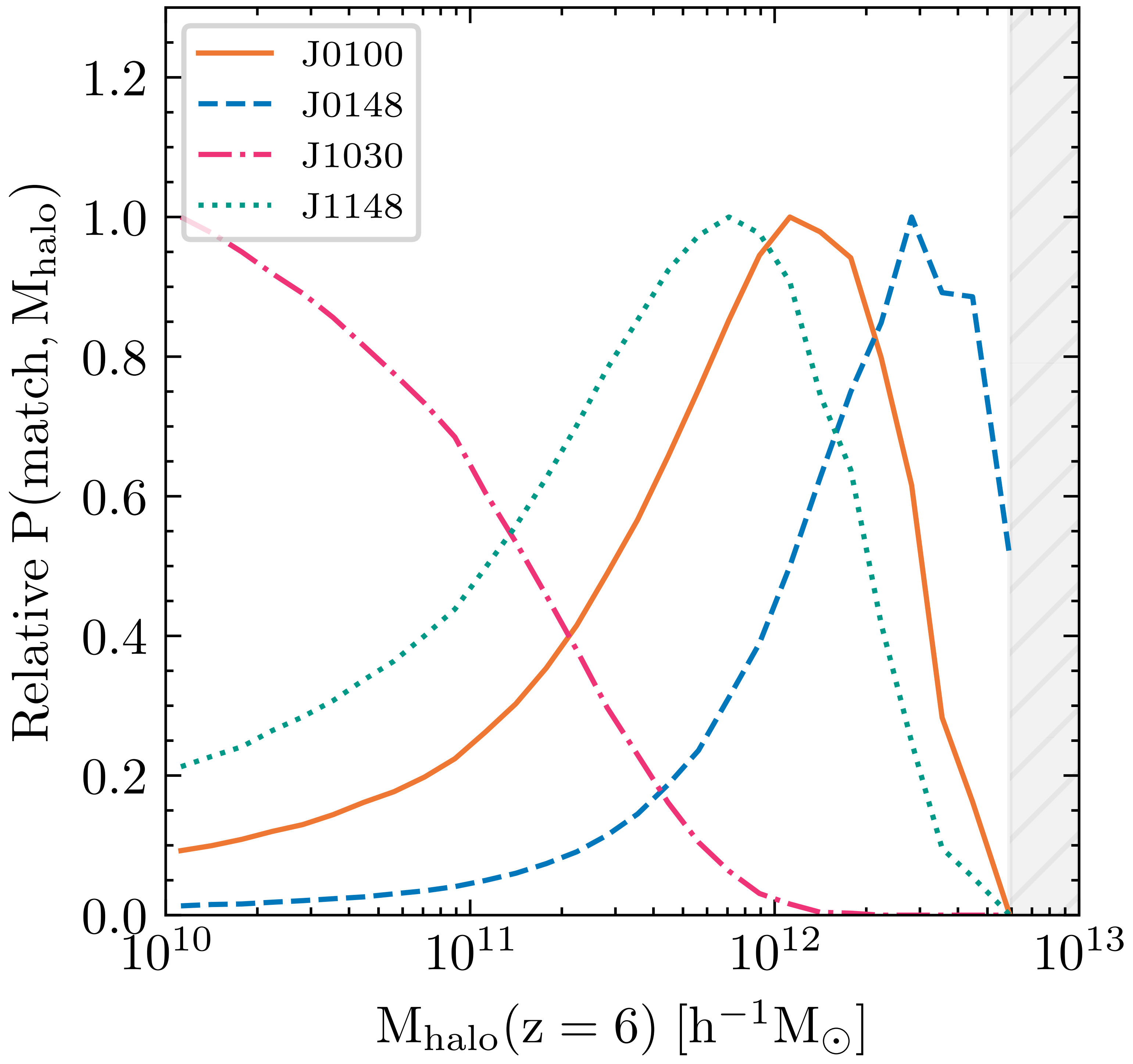
EIGER QUASARS

THE ENVIRONMENTS OF THE MOST LUMINOUS QUASARS



Mackenzie+ incl **JM** in prep

THE RAREST OBJECTS, IN THE HIGHEST OVER-DENSITIES? NOT REALLY...



Mackenzie+ incl **JM** in prep   Eilers+ incl **JM** 24

- **We find a wide range in halo masses for EIGER quasars, average ~$10^{12.3}$ M_{sun}**
- **The number density of such halos is ~1000-10,000x higher than those of the quasars**
- **Where are all the other quasars? Obscured? Short-lived? —> Both imply rapid growth**