Escape of Lyman radiation from galactic labyrinths
7-11 April 2025, OAC, Kolymbari, Crete

Institute of Science and Technology Austria

A (not so) Complete Unknown:

multiple predictors of Lyman Continuum escape in the early Universe

Sara Mascia, ISTA prize fellow
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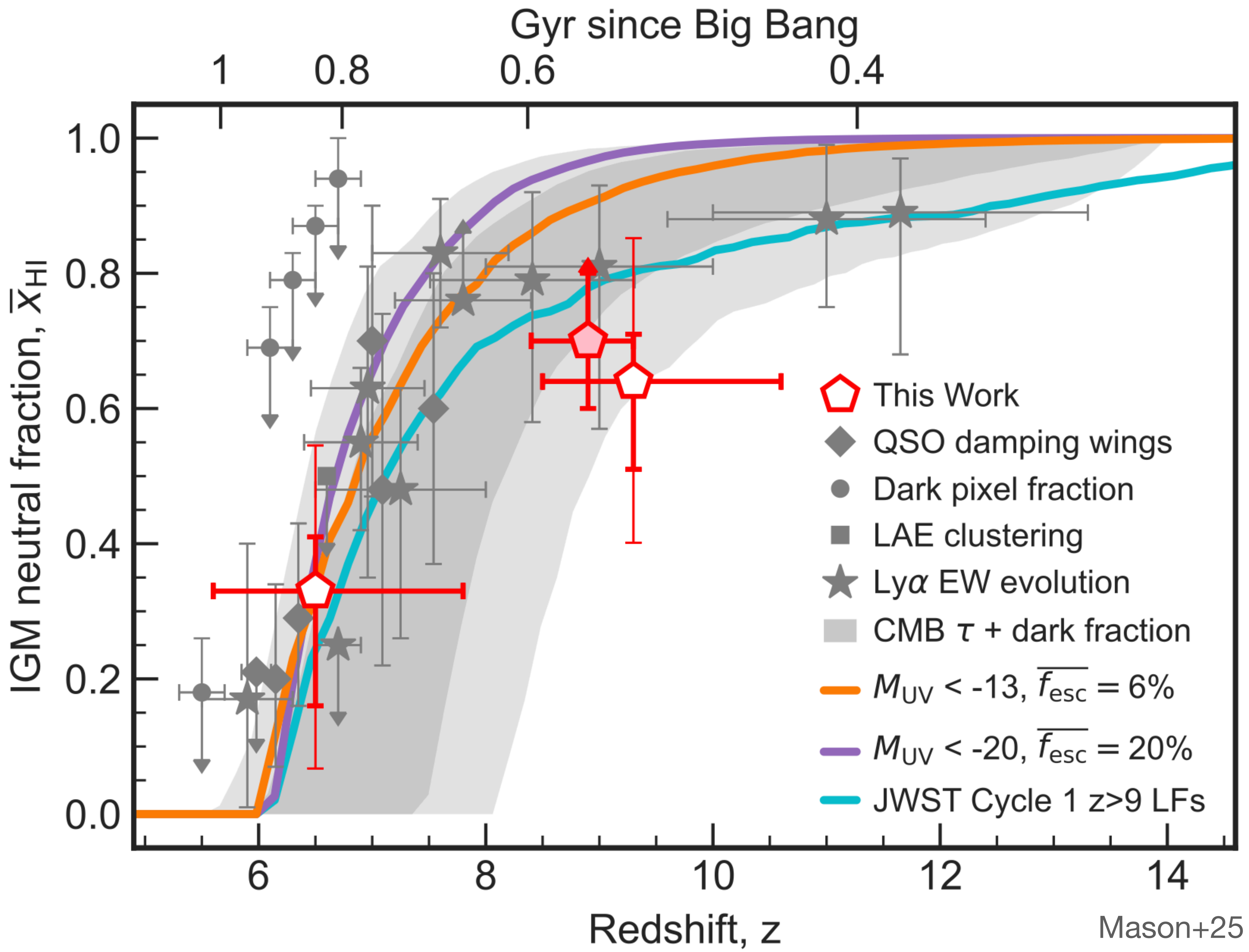
Laura Pentericci, Lorenzo Napolitano, Antonello Calabró, GLASS & CEERS teams

Reionization timeline



See Yuta & Hiroya's talks!

The total ionizing radiation

$$\dot{n}_{ion} = \int \xi_{ion}(M_{UV})\ \phi_{UV}(M_{UV})\ f_{esc}(M_{UV}) dM_{UV}$$

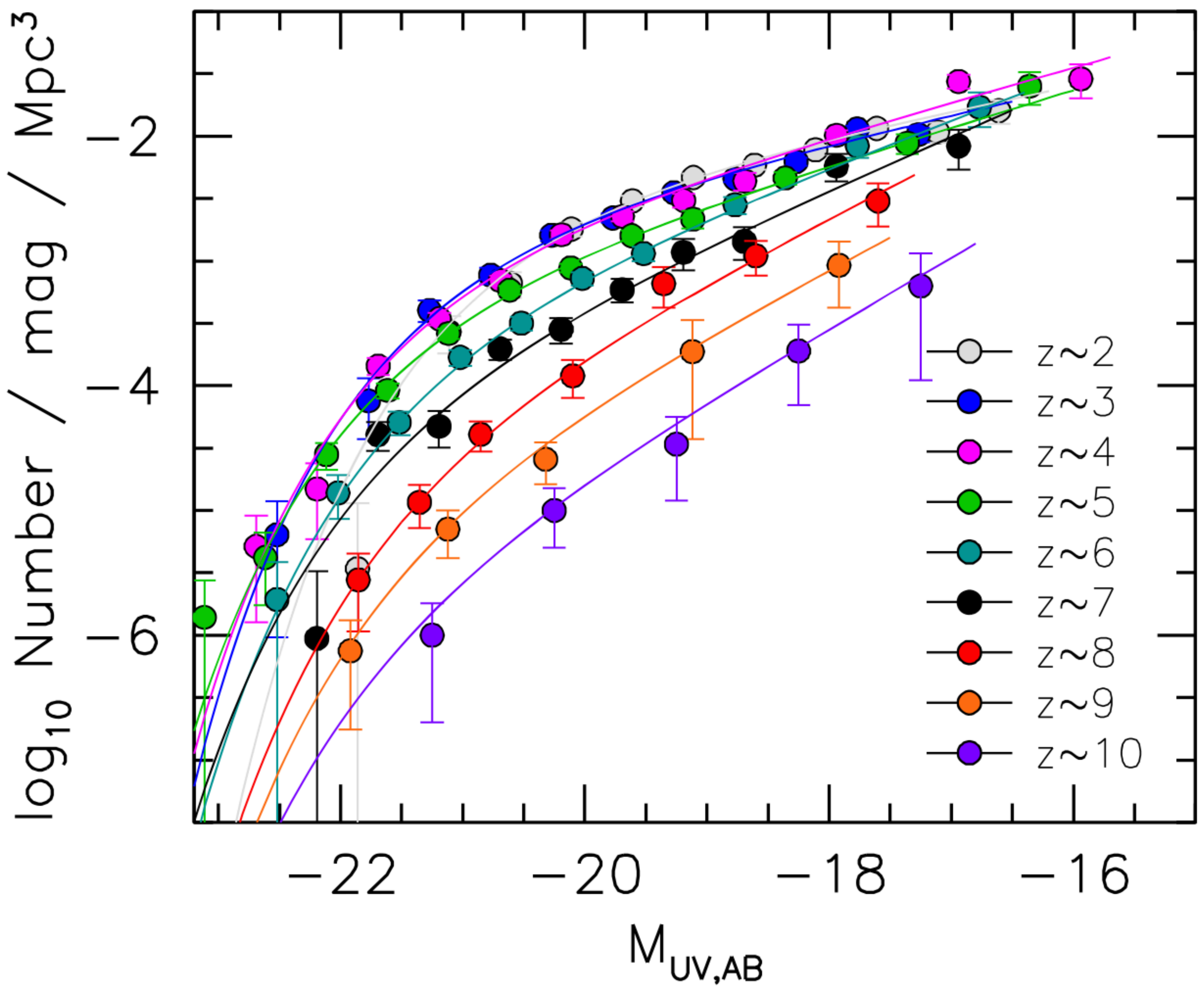
The total ionizing emissivity is the number of **ionizing photons** produced per unit time per unit volume that **escape the galaxy**

The total ionizing radiation

UV luminosity density

$$\dot{n}_{ion} = \int \xi_{ion}(M_{UV})\ \phi_{UV}(M_{UV})\ f_{esc}(M_{UV}) dM_{UV}$$

Bouwens+21



The total ionizing radiation

escape fraction of ionizing photons

$$\dot{n}_{ion} = \int \xi_{ion}(M_{UV})\, \phi_{UV}(M_{UV})\, f_{esc}(M_{UV}) dM_{UV}$$

ionizing photon production efficiency

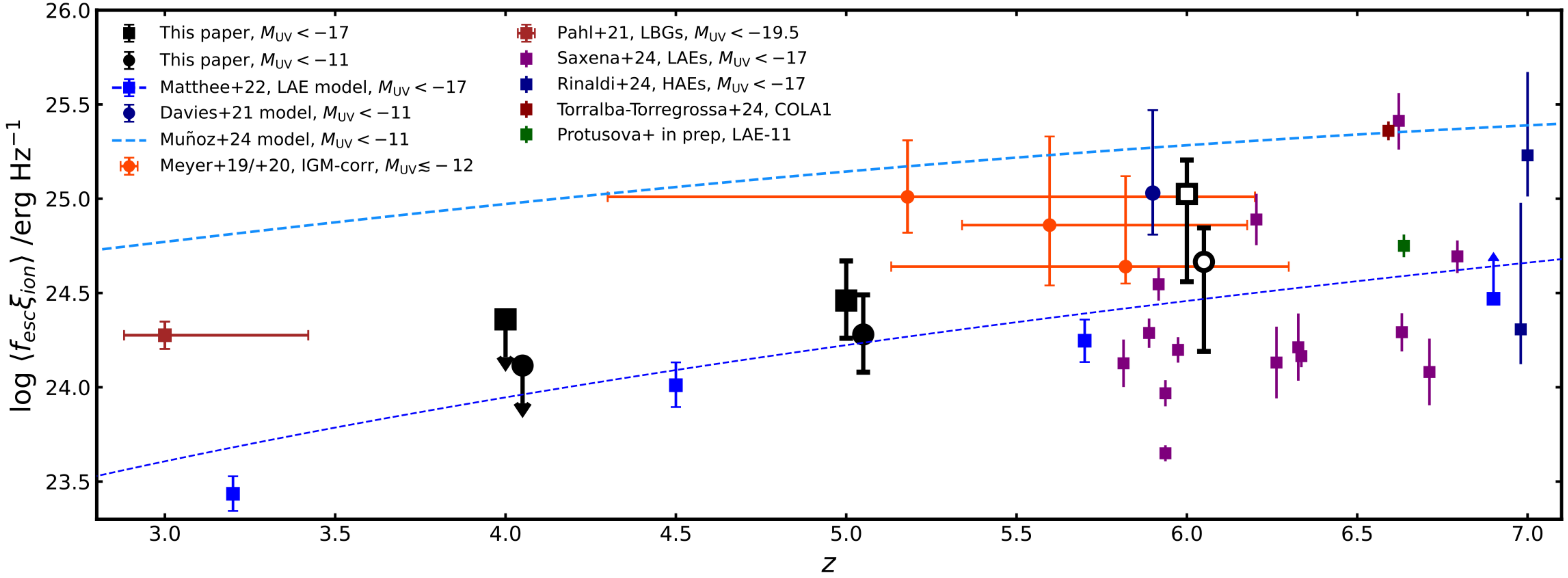
The total ionizing radiation

escape fraction of ionizing photons

$$\dot{n}_{ion} = \int \xi_{ion}(M_{UV})\, \phi_{UV}(M_{UV})\, f_{esc}(M_{UV})\, dM_{UV}$$

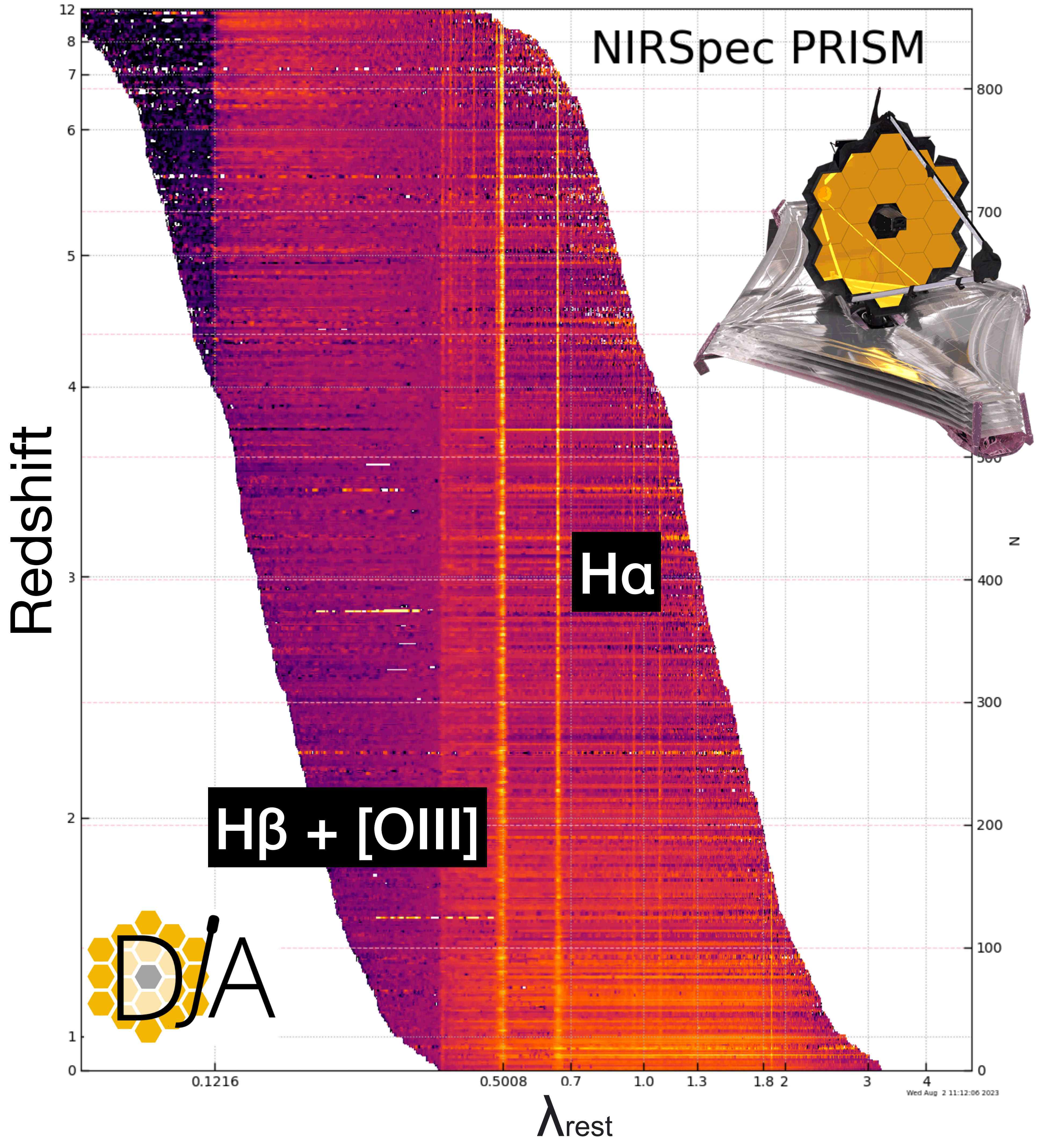
ionizing photon production efficiency

Bosman+24

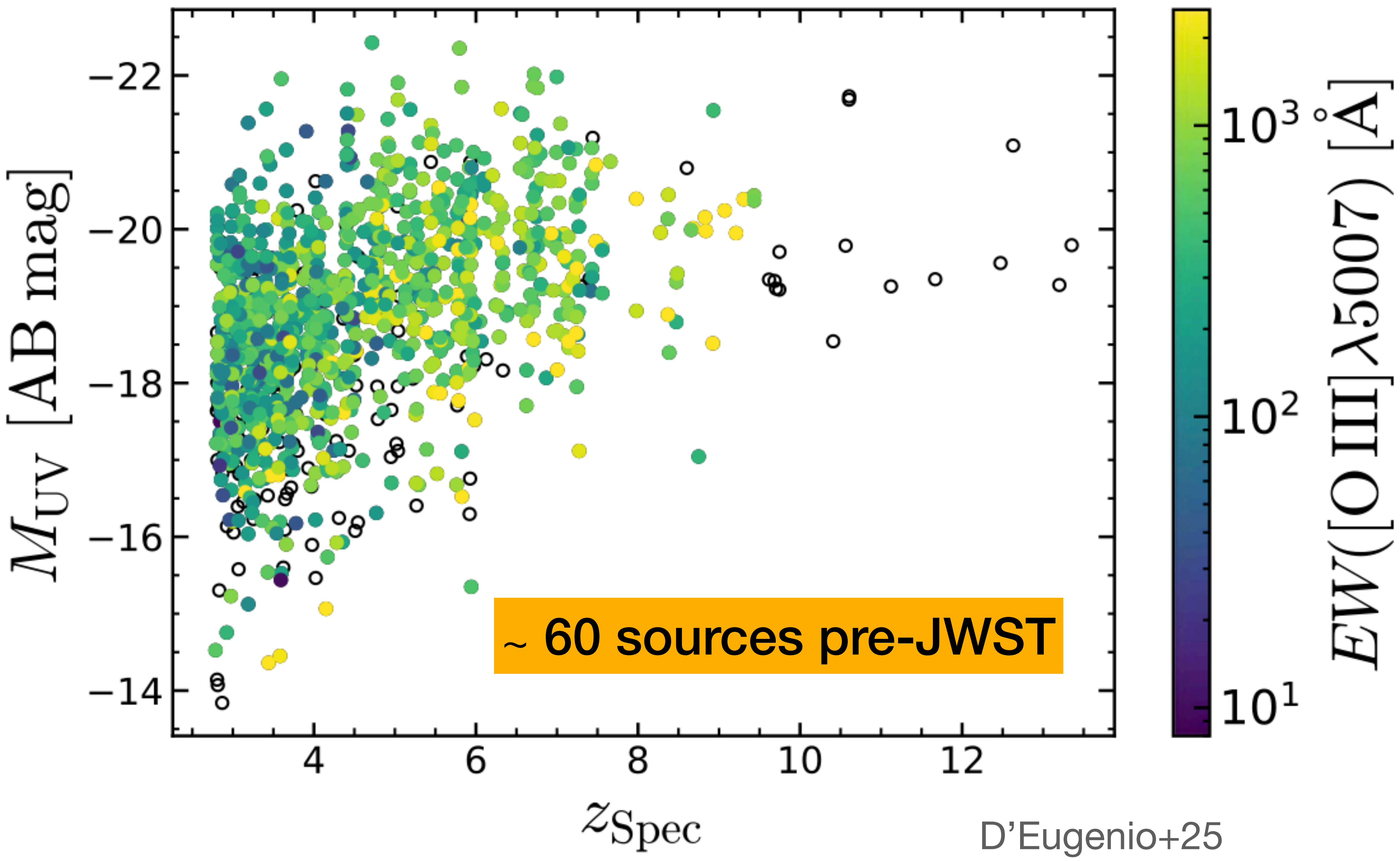


See also Cain+25

The galaxies during the EoR



Thanks to JWST, we are now spectroscopically confirming **hundreds** of galaxies during the EoR

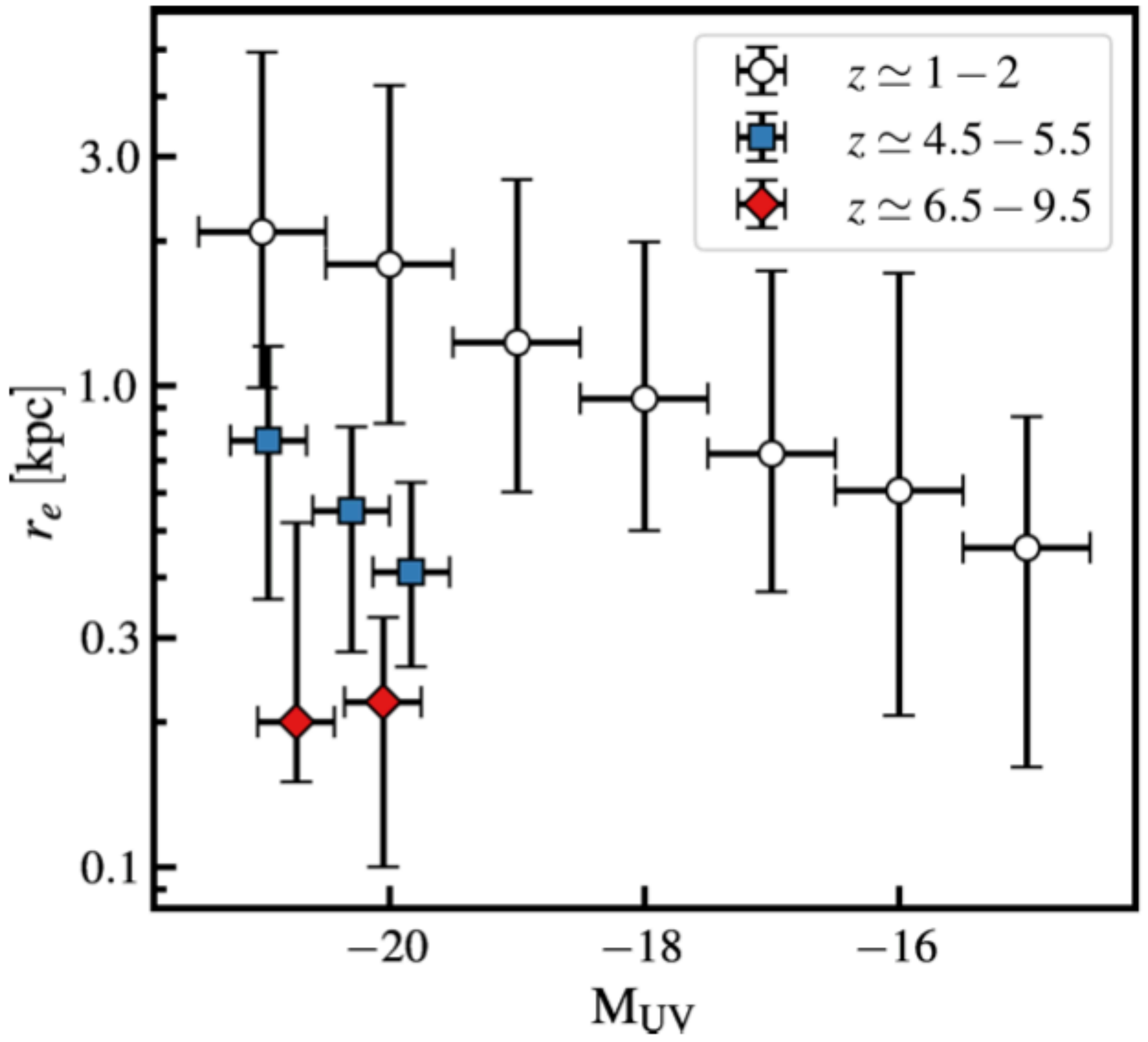


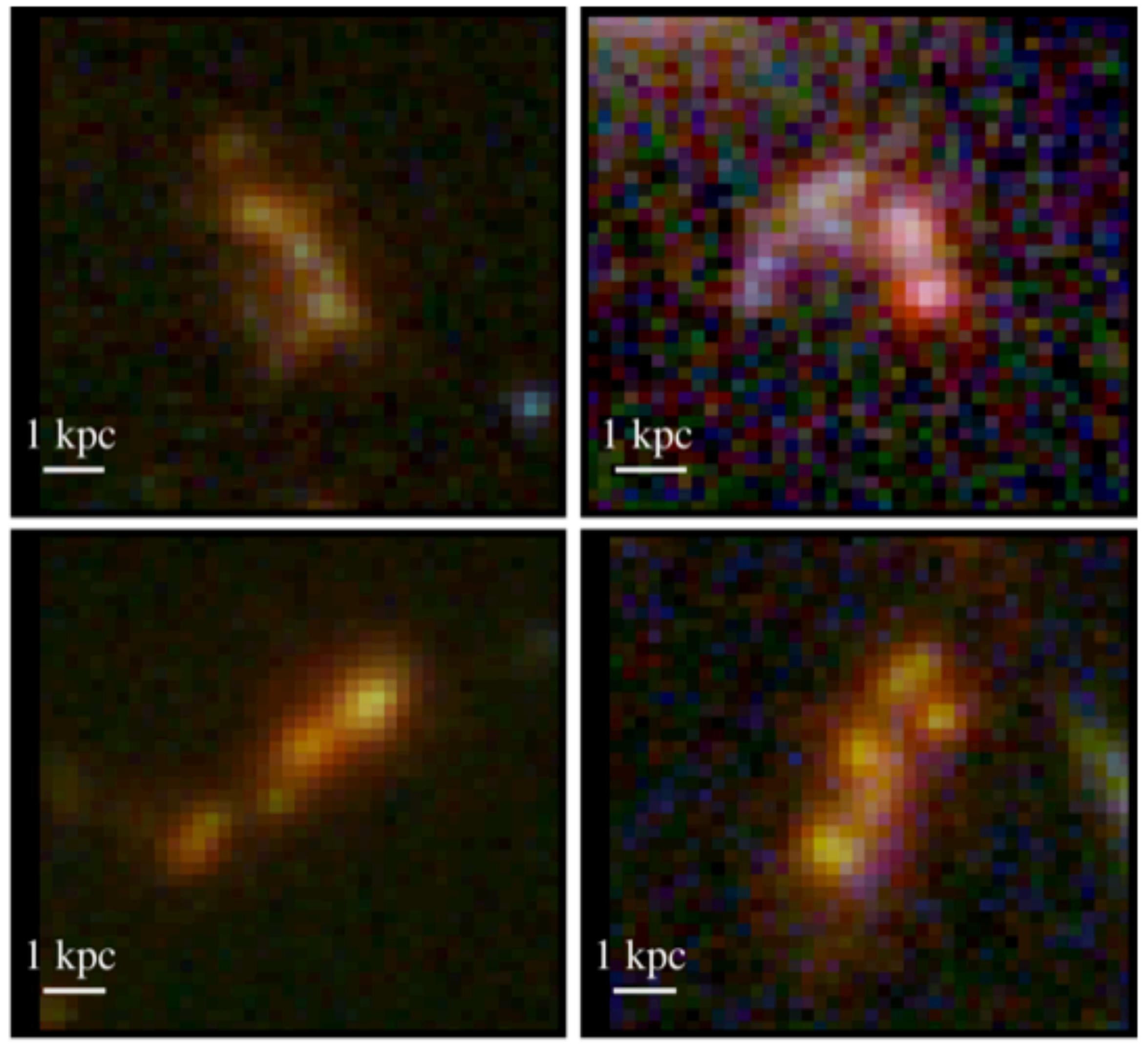
D'Eugenio+25

See also …

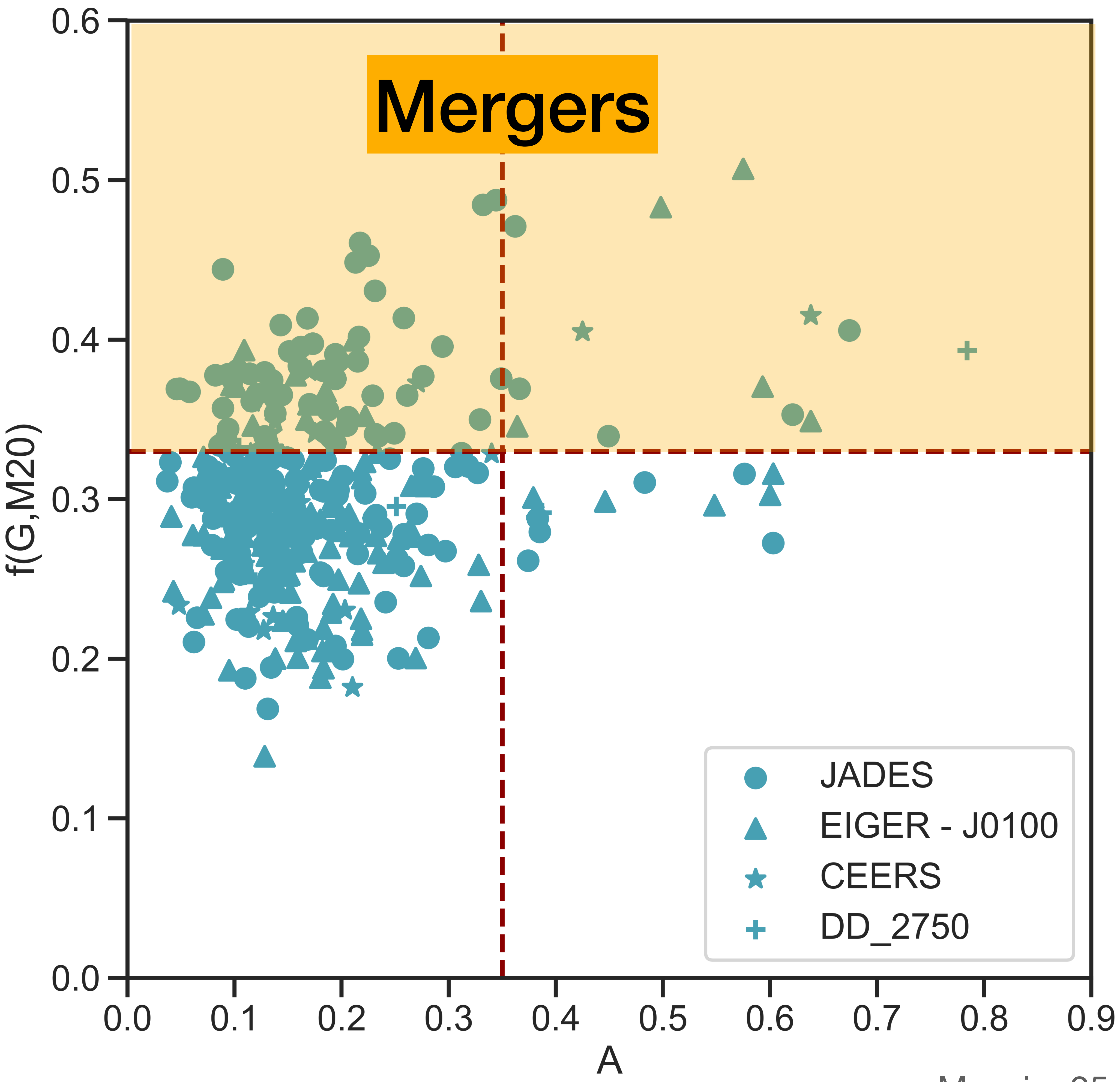
The galaxies during the EoR

Galaxies are very small at z > 5, with a small fraction of mergers.





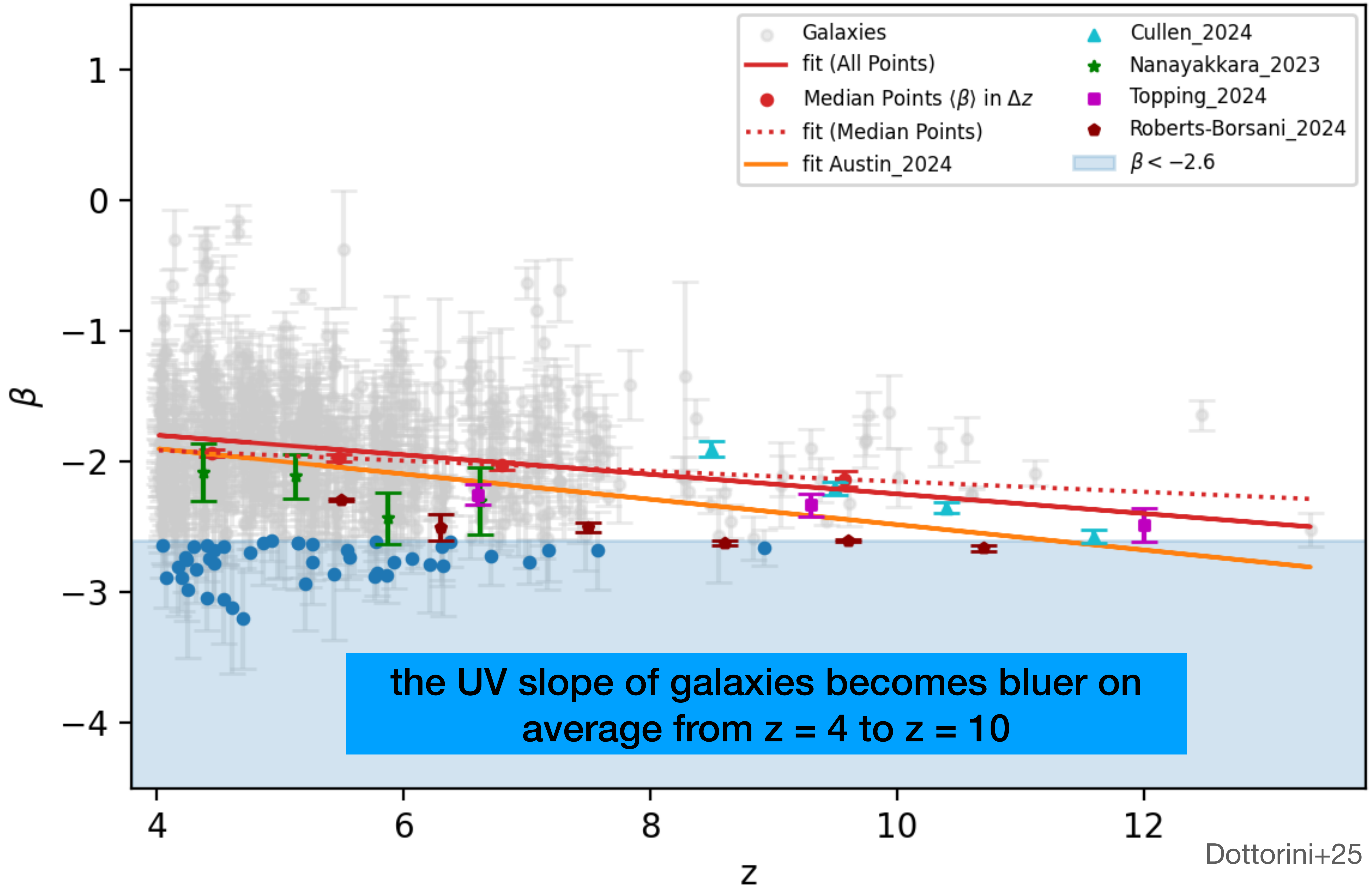
Stark+25



Mascia+25

See also Morishita+24, Sun+24, Ono+24, Ormerod+24, Yang+22, Dalmasso+24, Treu+23, Mascia+23,24

The galaxies during the EoR

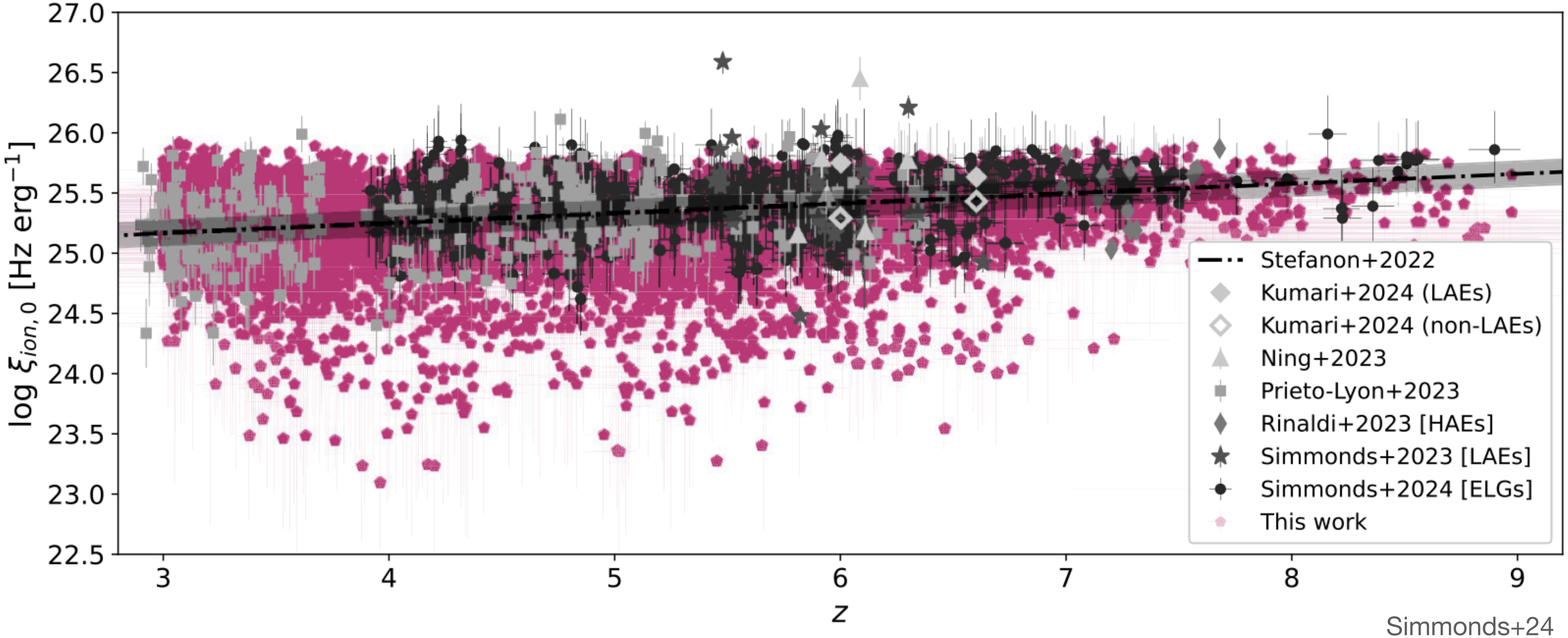


See Michelle's talk!

See also Topping+22, Tacchella+22, Roberts-Borsani+22, Cullen+23, Austin+24

The galaxies during the EoR

Evidence for a modest redshift evolution of ξion.

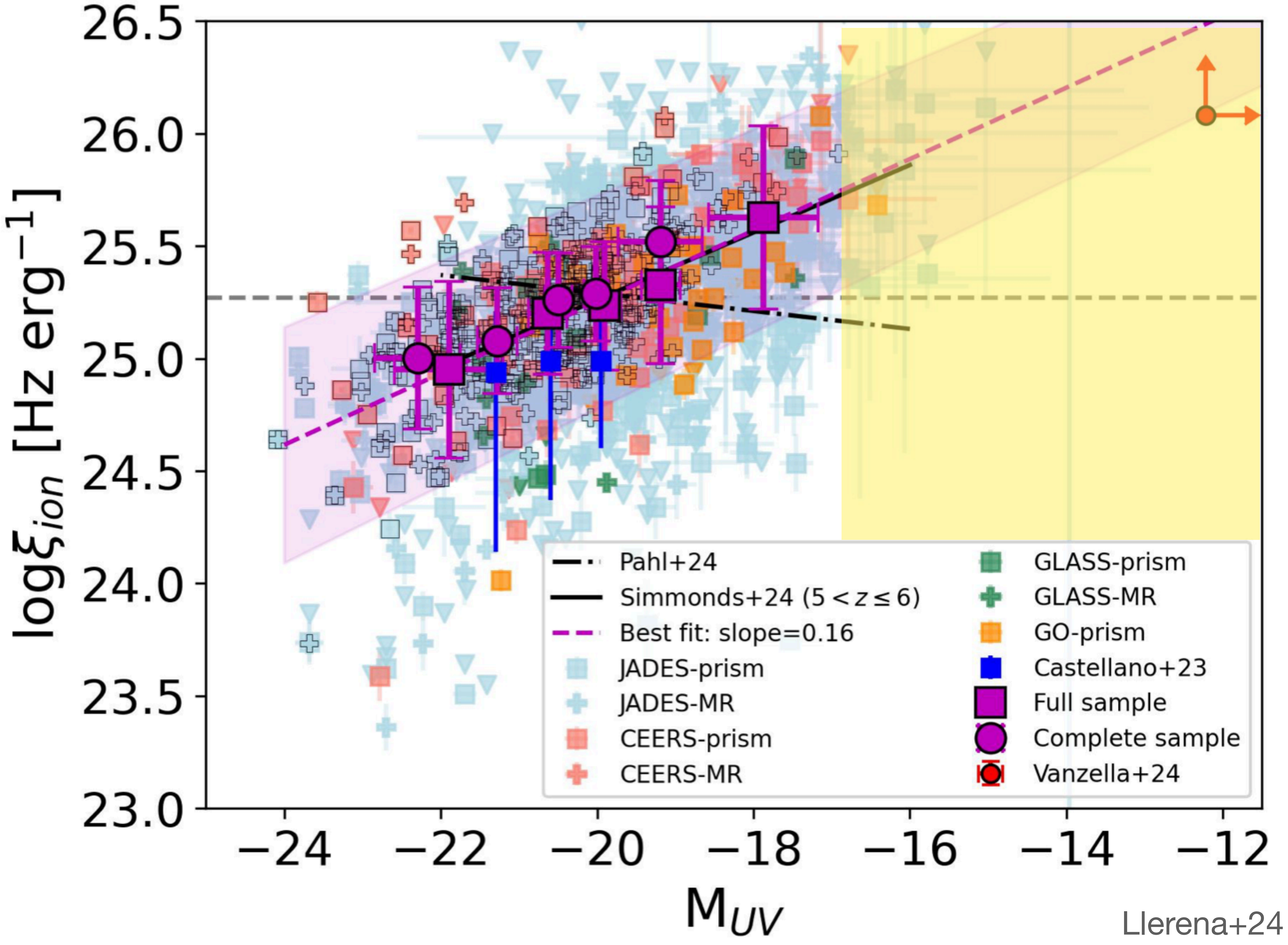


Simmonds+24

See Mario & Charlotte's talks!

See also Llerana+25, Pahl+25, Atek+24, Rinaldi+23, Matthee+23

The galaxies during the EoR



Llerena+24

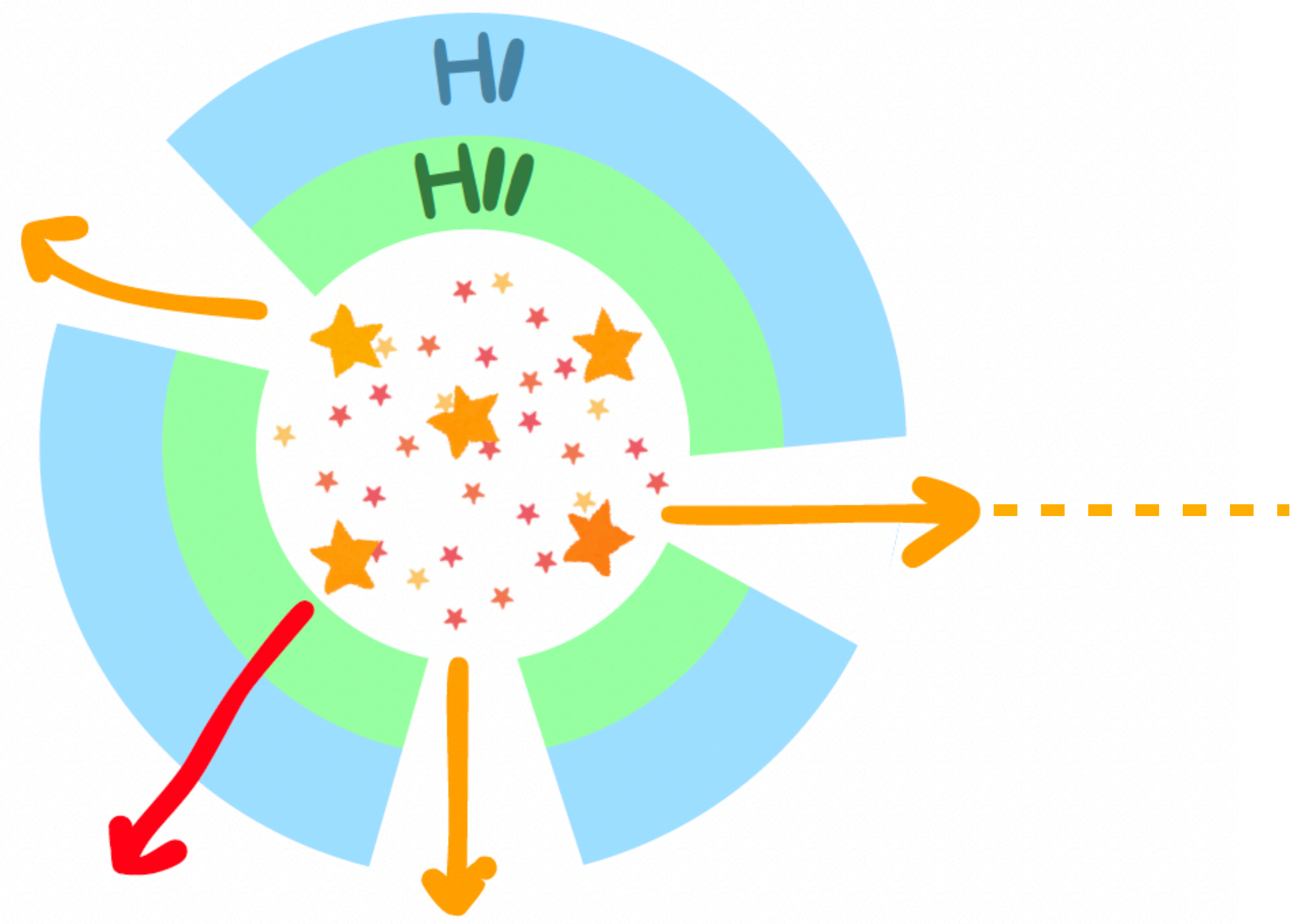
Faint galaxies with bursty SFH seem to have elevated ξion (e.g., Atek+24).

See also Simmonds+24, Pahl+25, Atek+24, Rinaldi+23, Matthee+23

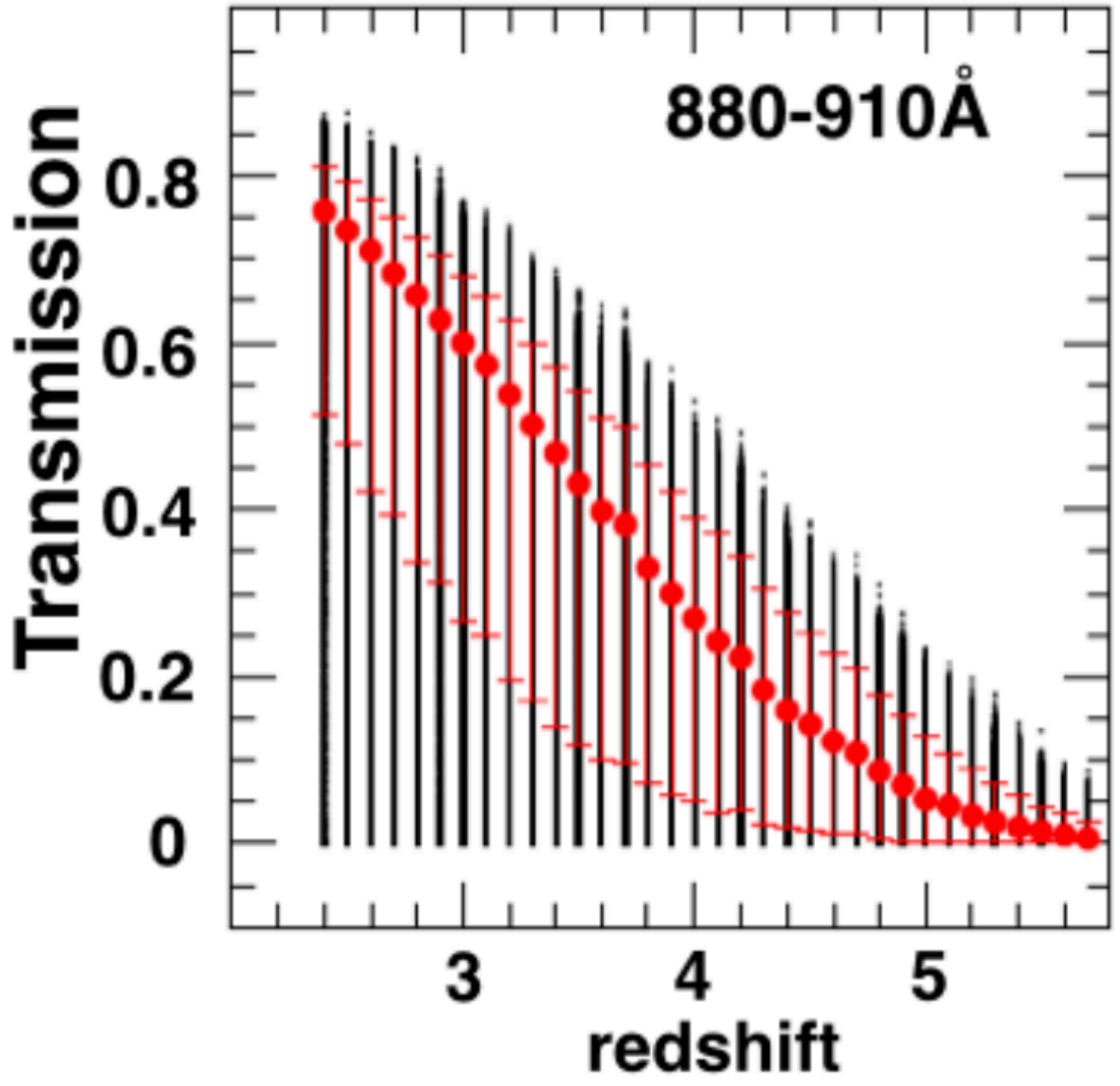
The escape of Lyman continuum photon from galaxies

Directly detecting LyC becomes difficult above z > 4 due to IGM attenuation (Inoue+14).

Radiation from cosmic sources is absorbed by neutral hydrogen in the IGM, even after reionization (Gunn & Peterson, 1965).



Vanzella+15



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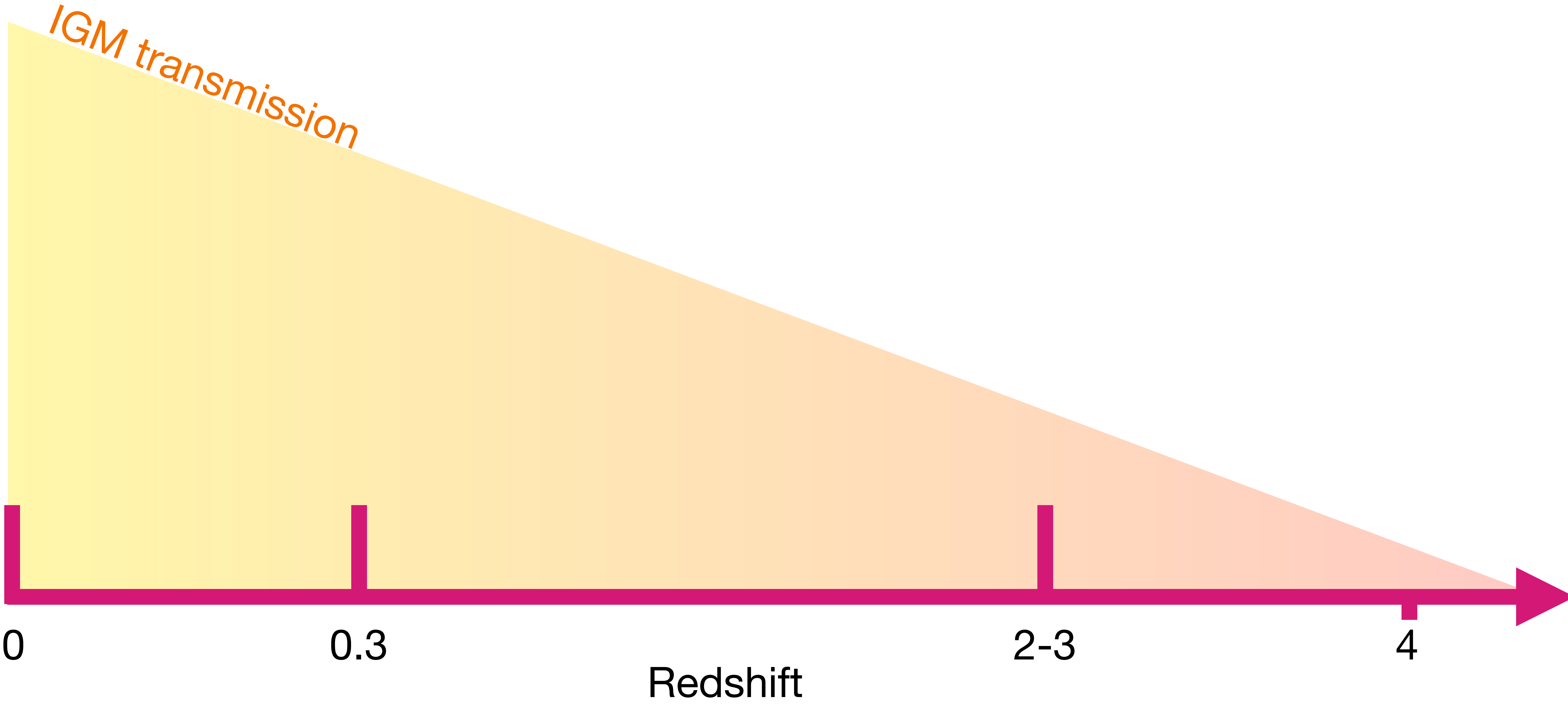
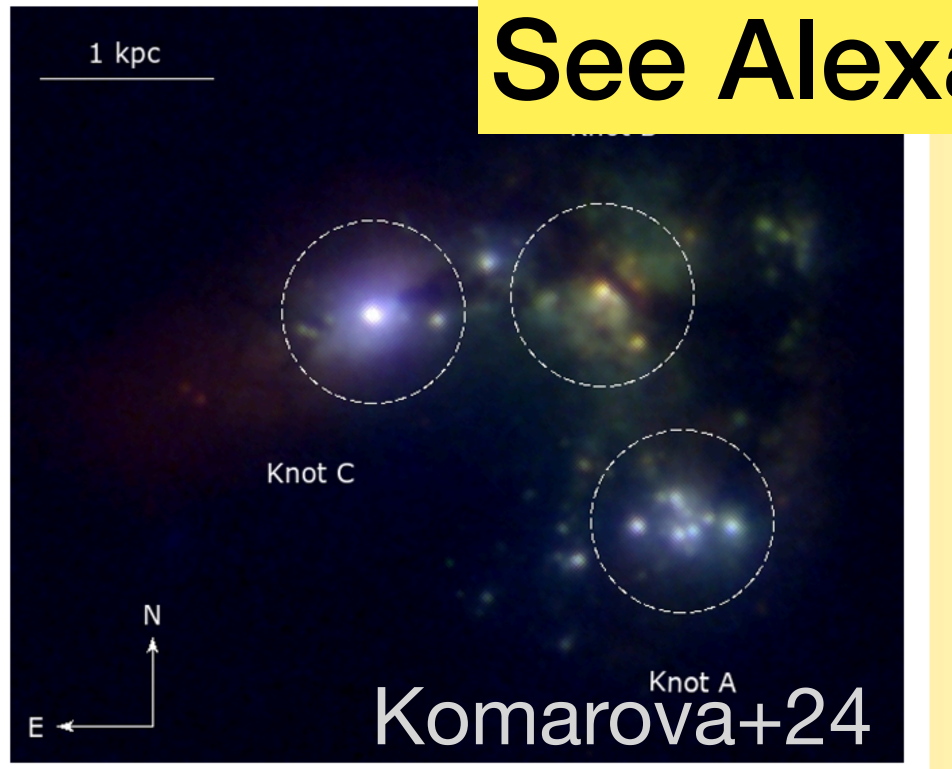
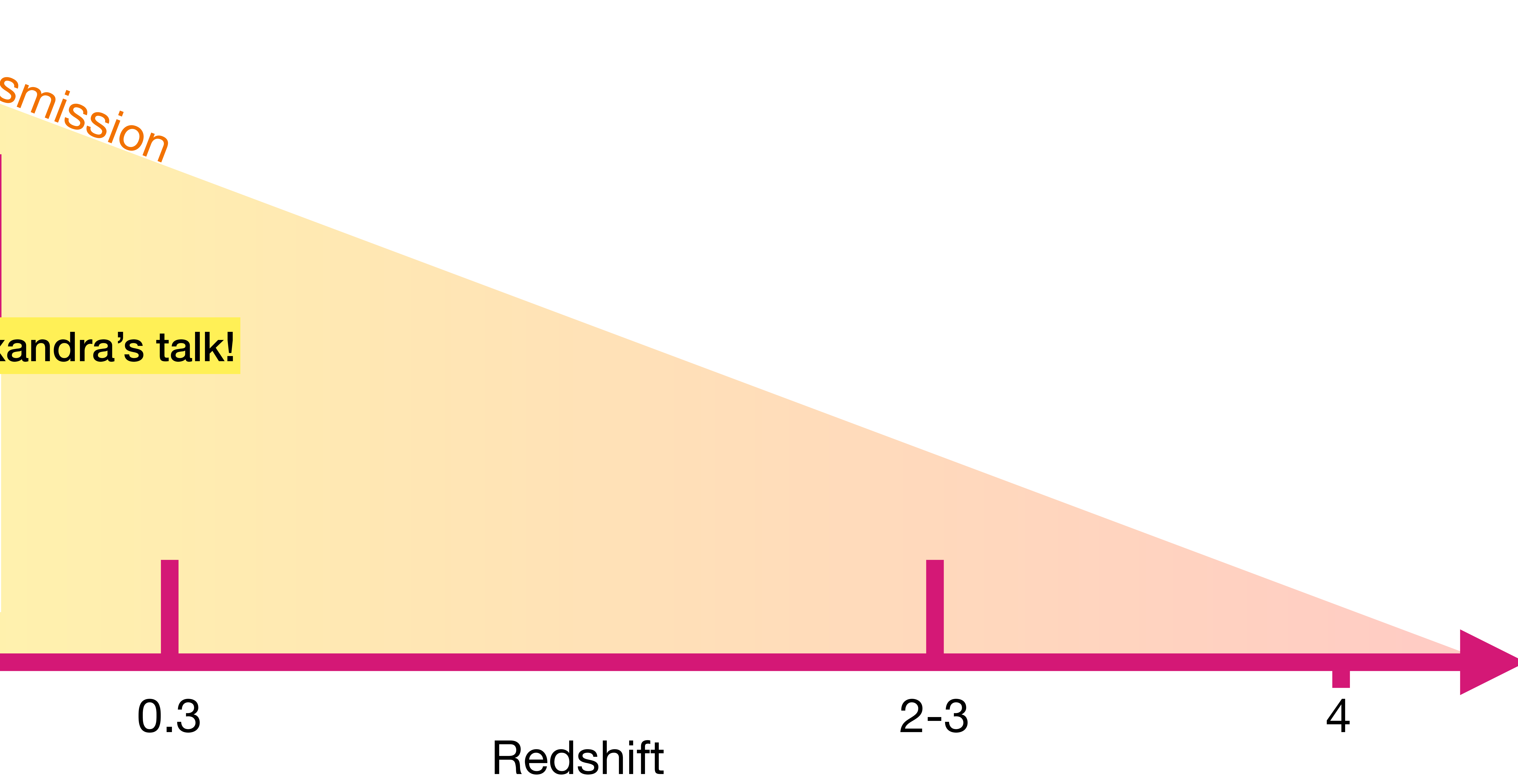


The escape of Lyman continuum photon from galaxies

Haro 11, Tol 1247-232
- highly disturbed and irregular morphology
- modest f_{esc}



See Alexandra's talk!



The escape of Lyman continuum photon from galaxies

IGM transmission

See Sophia's talk!

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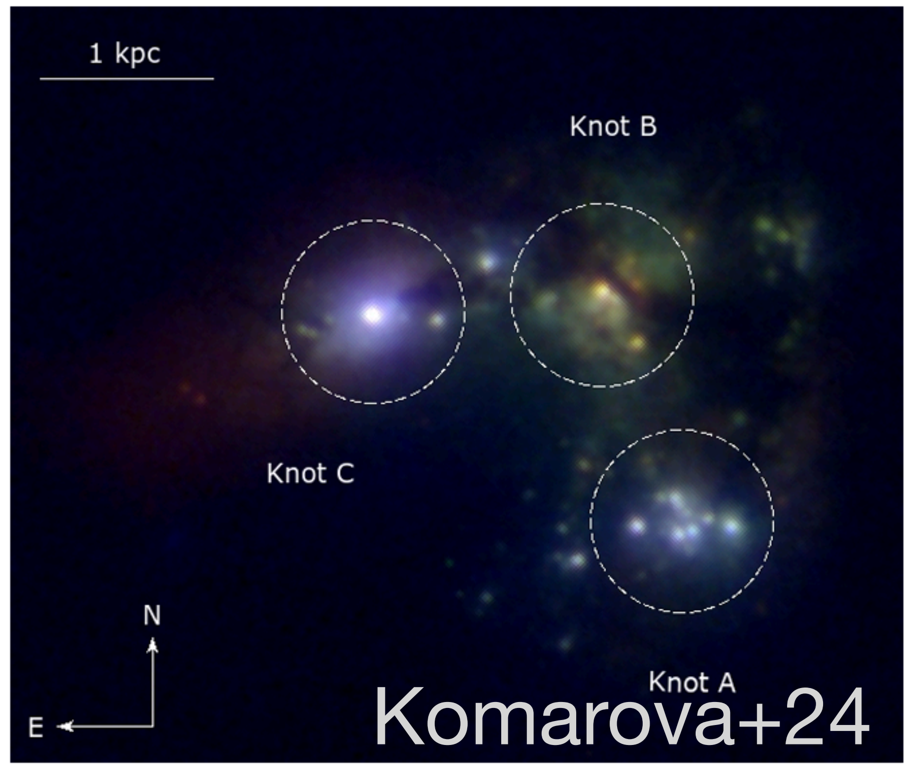

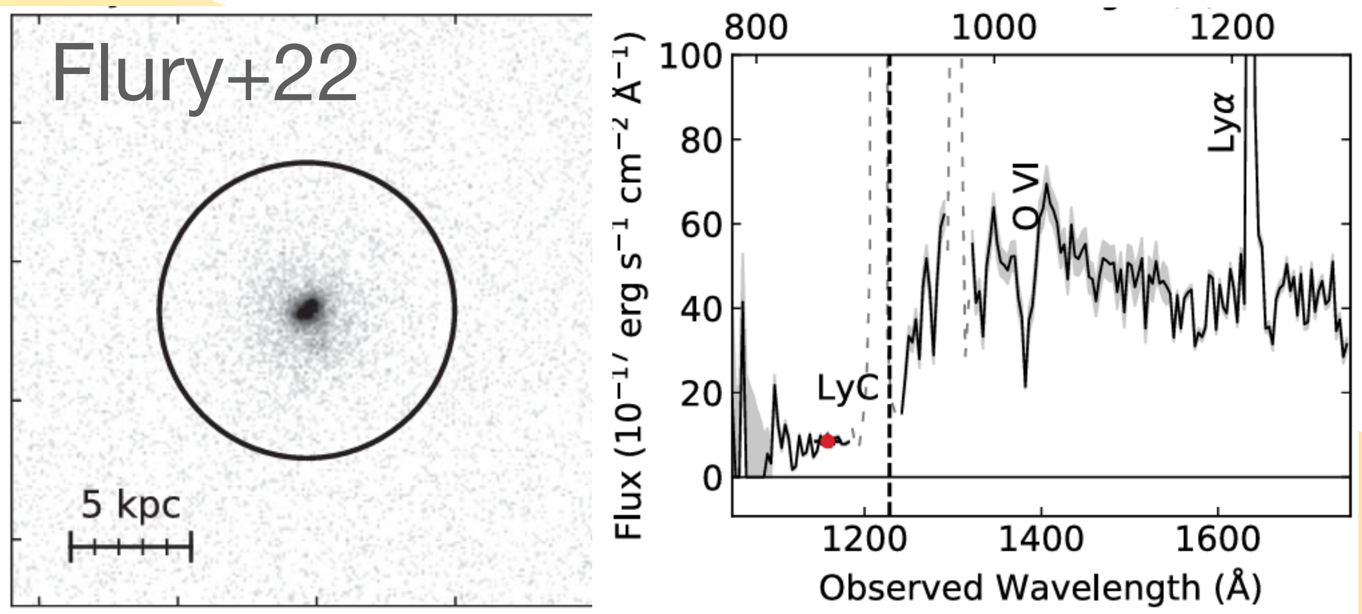

Low-Redshift Lyman Continuum Survey (LzLCS, PI Jaskot). 88 sources for which we have direct detections (or upper limits) on the f_{esc}

0 0.3 2-3 4

Redshift

See also Leitet+11,+13, Borthakur+14, Izotov+16, Leitherer+16; Izotov+18, Wang+19, Izotov+21

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IGM transmission

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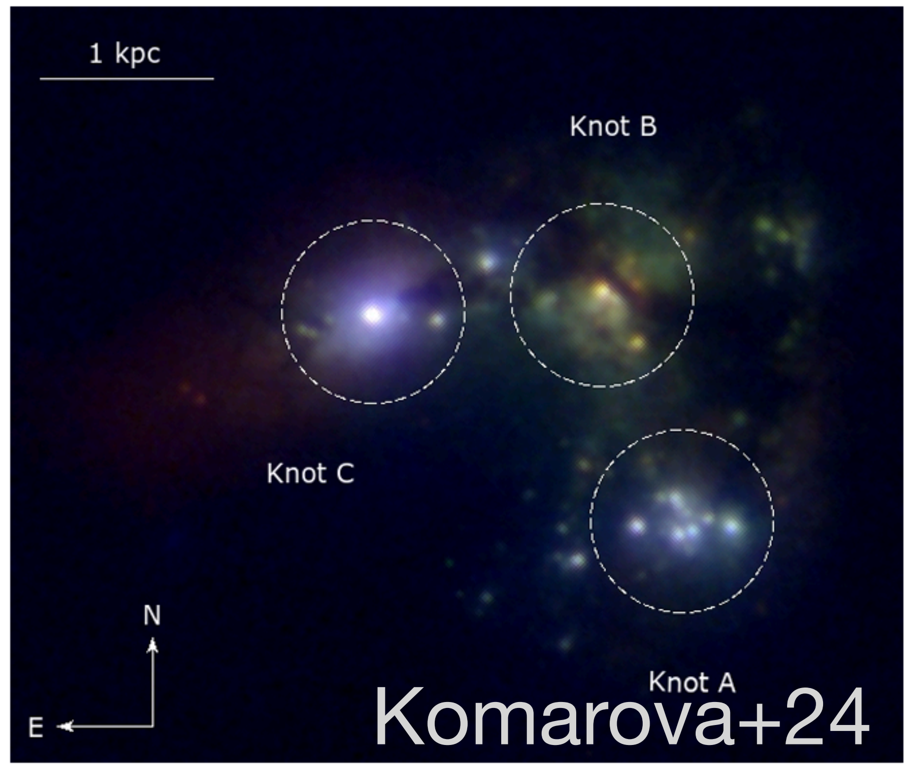

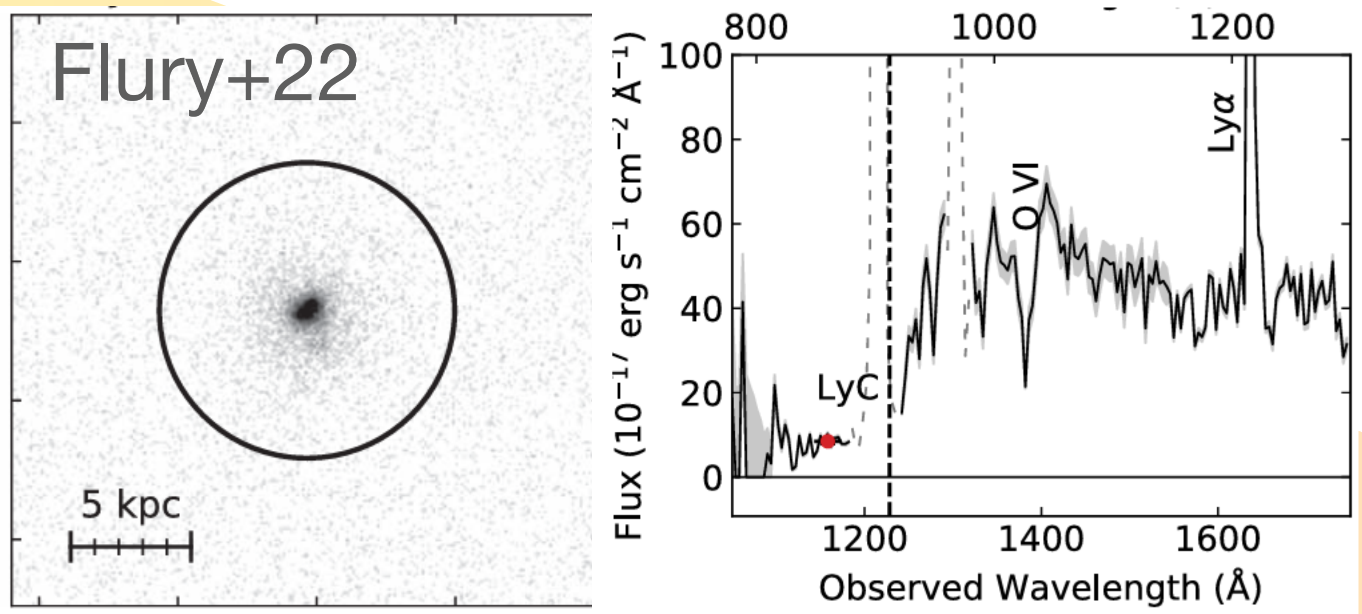

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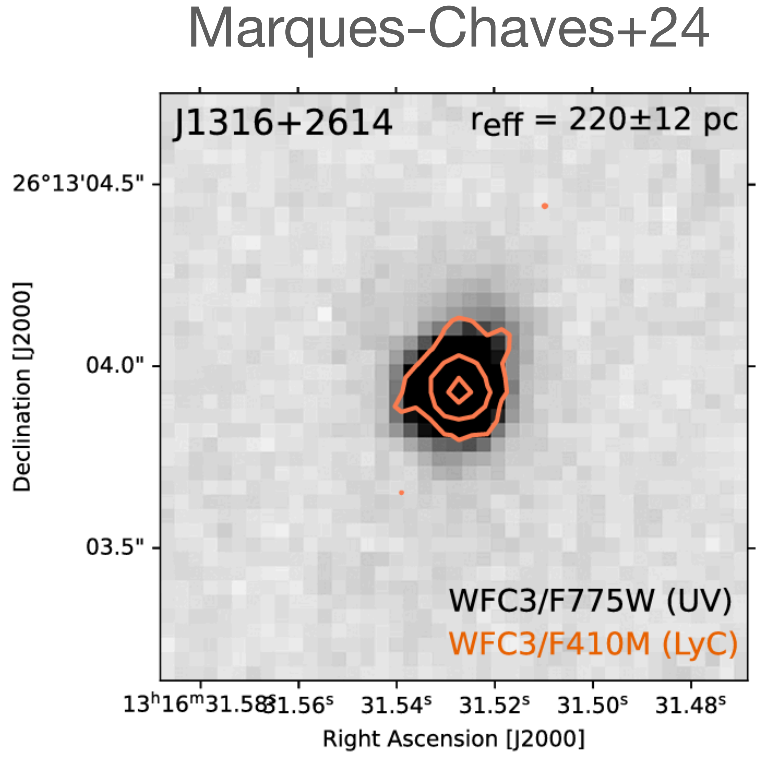

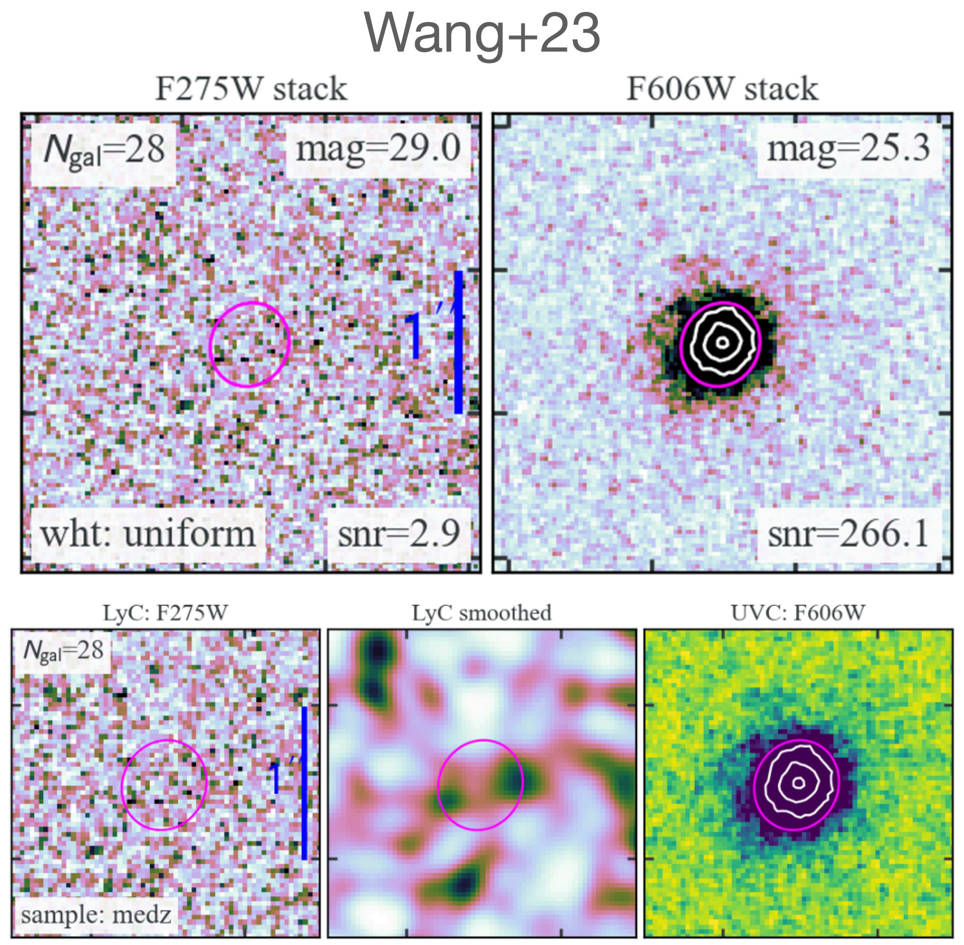

- Few strong emitters: Sunburst Arc, Ion1, Ion2, Ion3, J0121+0025, J1316+2614.
- Some stacks, mostly non-detections

See Tamal's talk!

0 | 0.3 | 2-3 | 4

Redshift

See also Mostardi+15, Shapley+16, Vanzella+16,+18, Bassett+19, Fletcher+19, Rivera-Thorsen+19, Ji+20, Saxena+22, Marchi+18, Steidel+18, Bian & Fan 20, Nakajima+20, Yuan+21,24, Citro+24, Liu (in prep.)

The escape of Lyman continuum photon from galaxies

IGM transmission

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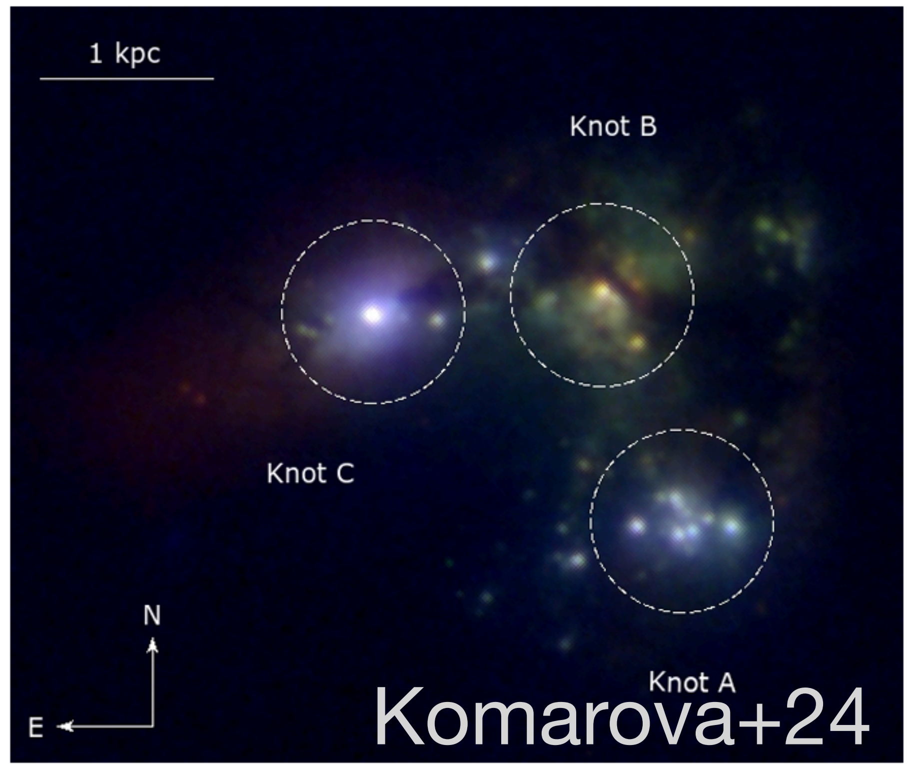

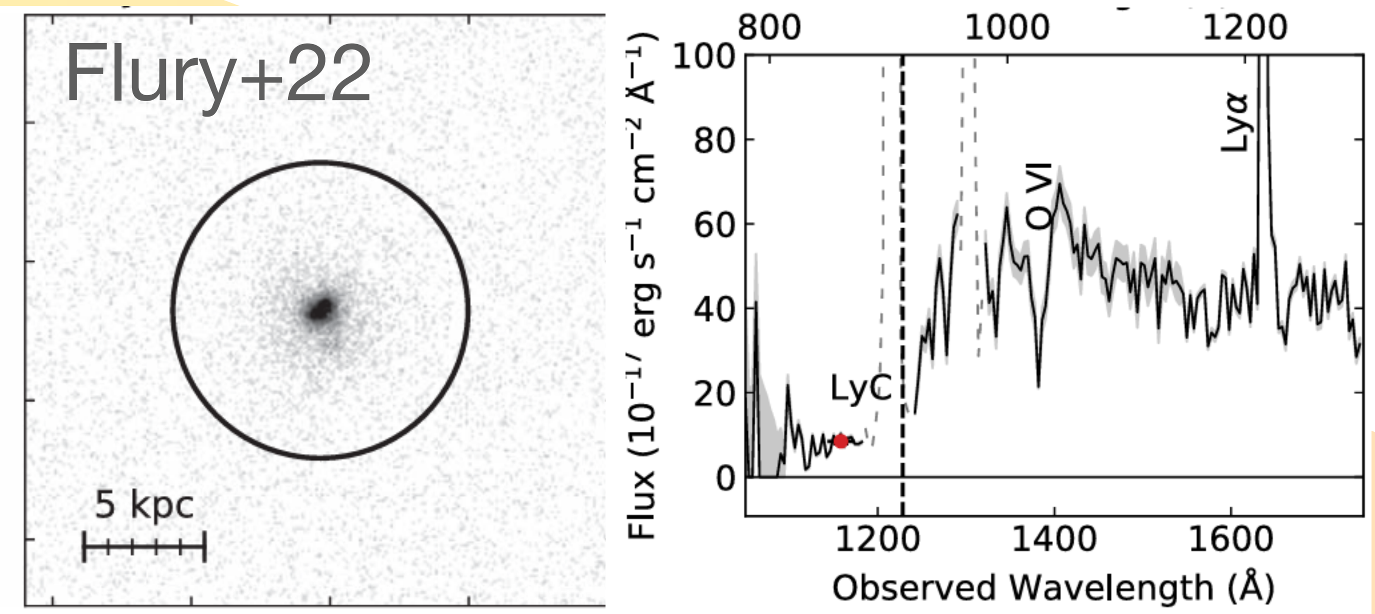

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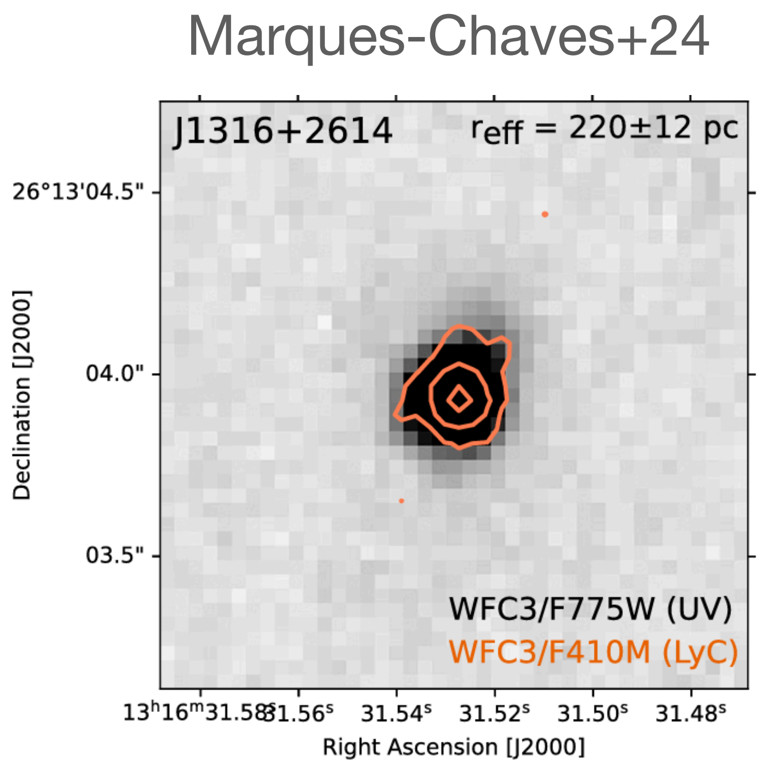
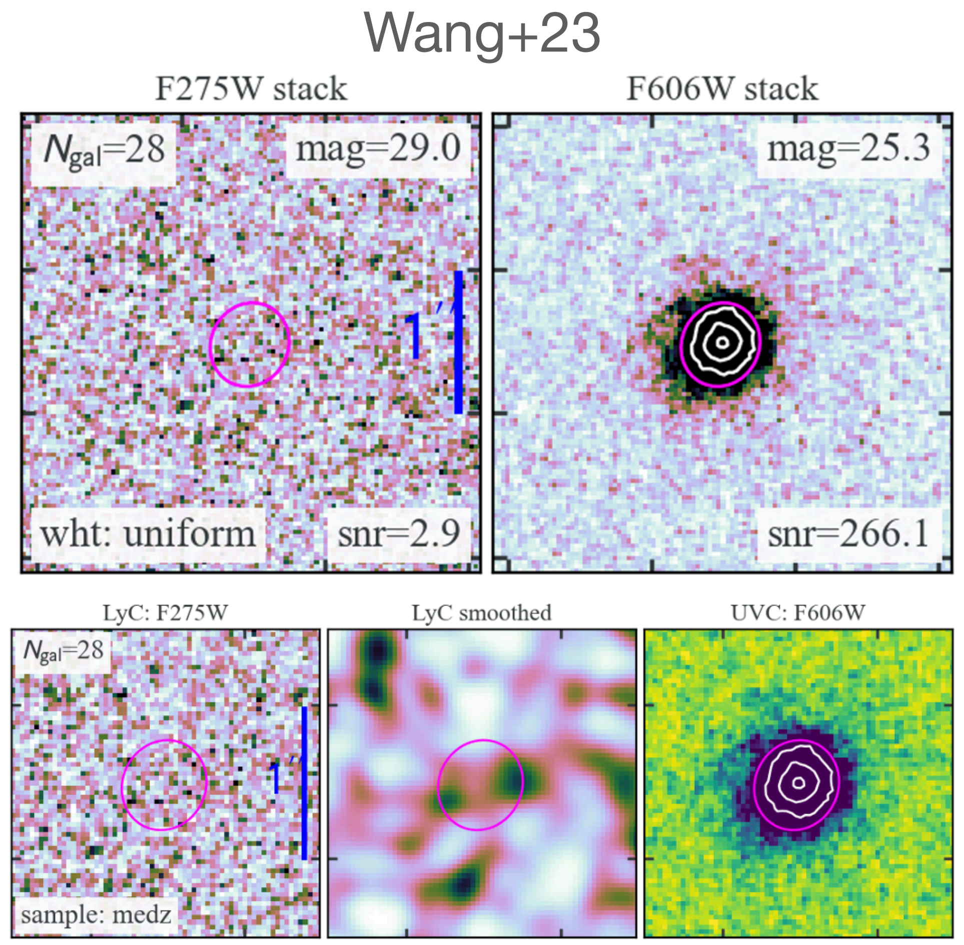




- Few strong emitters: Sunburst Arc, Ion1, Ion2, Ion3, J0121+0025, J1316+2614.
- Some stacks, mostly non-detections

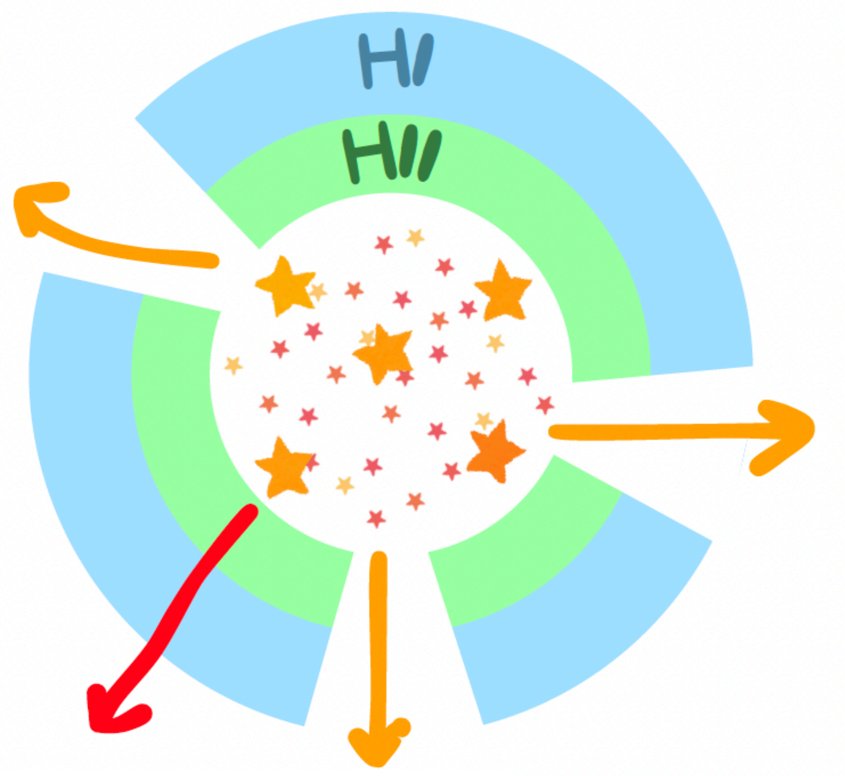
0 | 0.3 | 2-3 | 4 | EoR

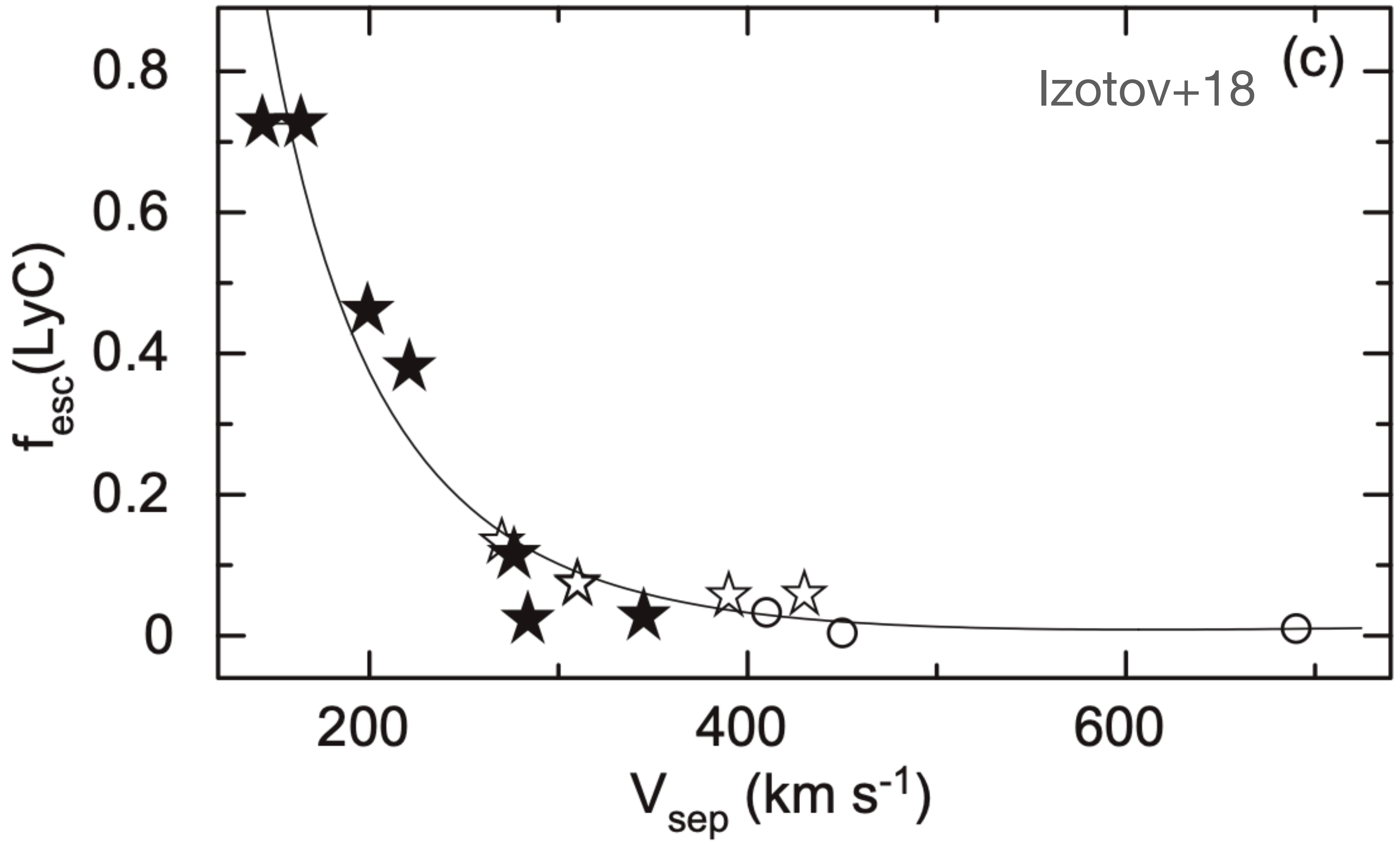
Redshift

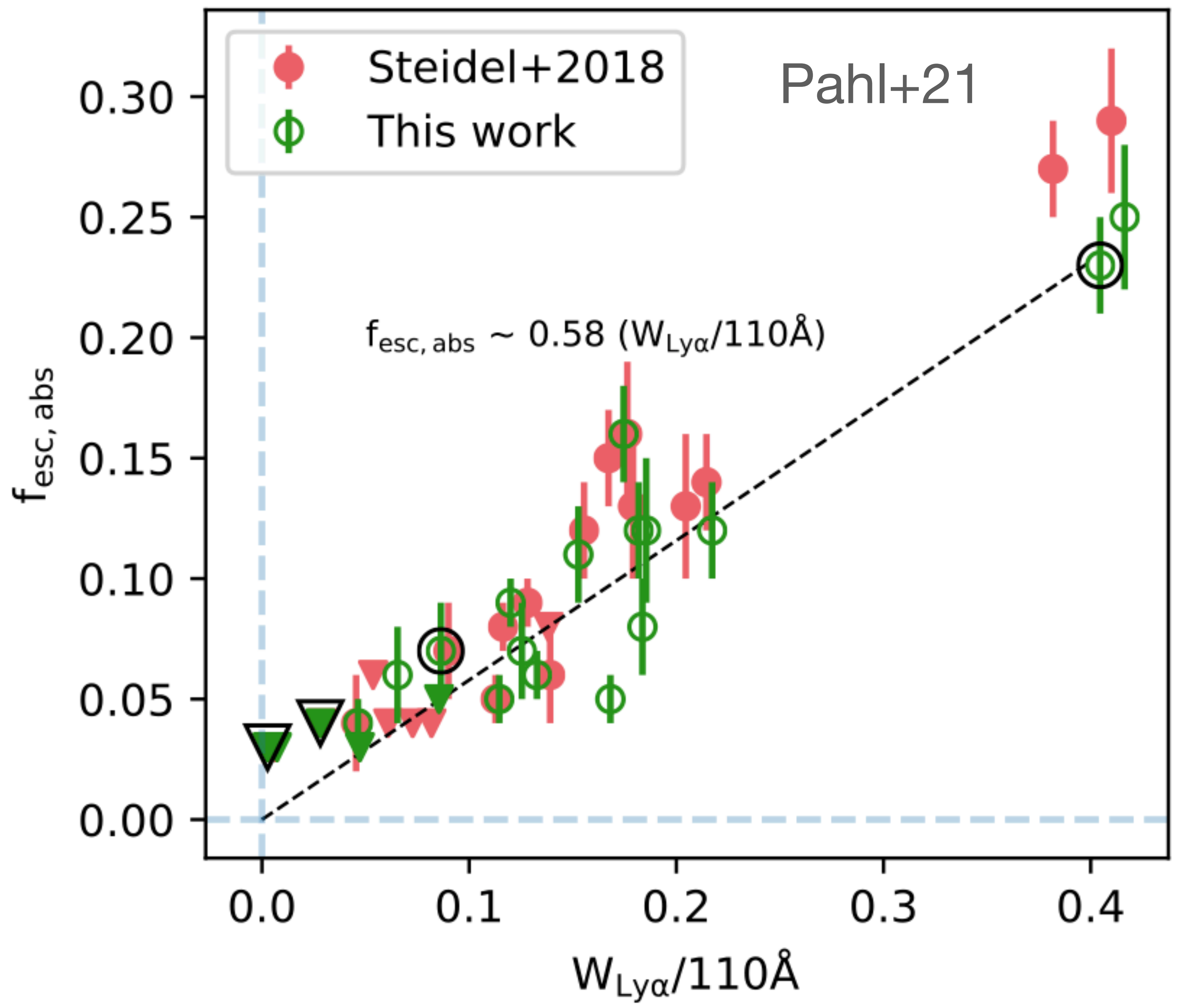
The “indirect indicators” of LyC escape fraction

- Lyα line

At low-to intermediate redshift Lyα is the best indirect indicator of LyC emission.
However, at z ≥ 6, Lyα is attenuated by the neutral IGM.



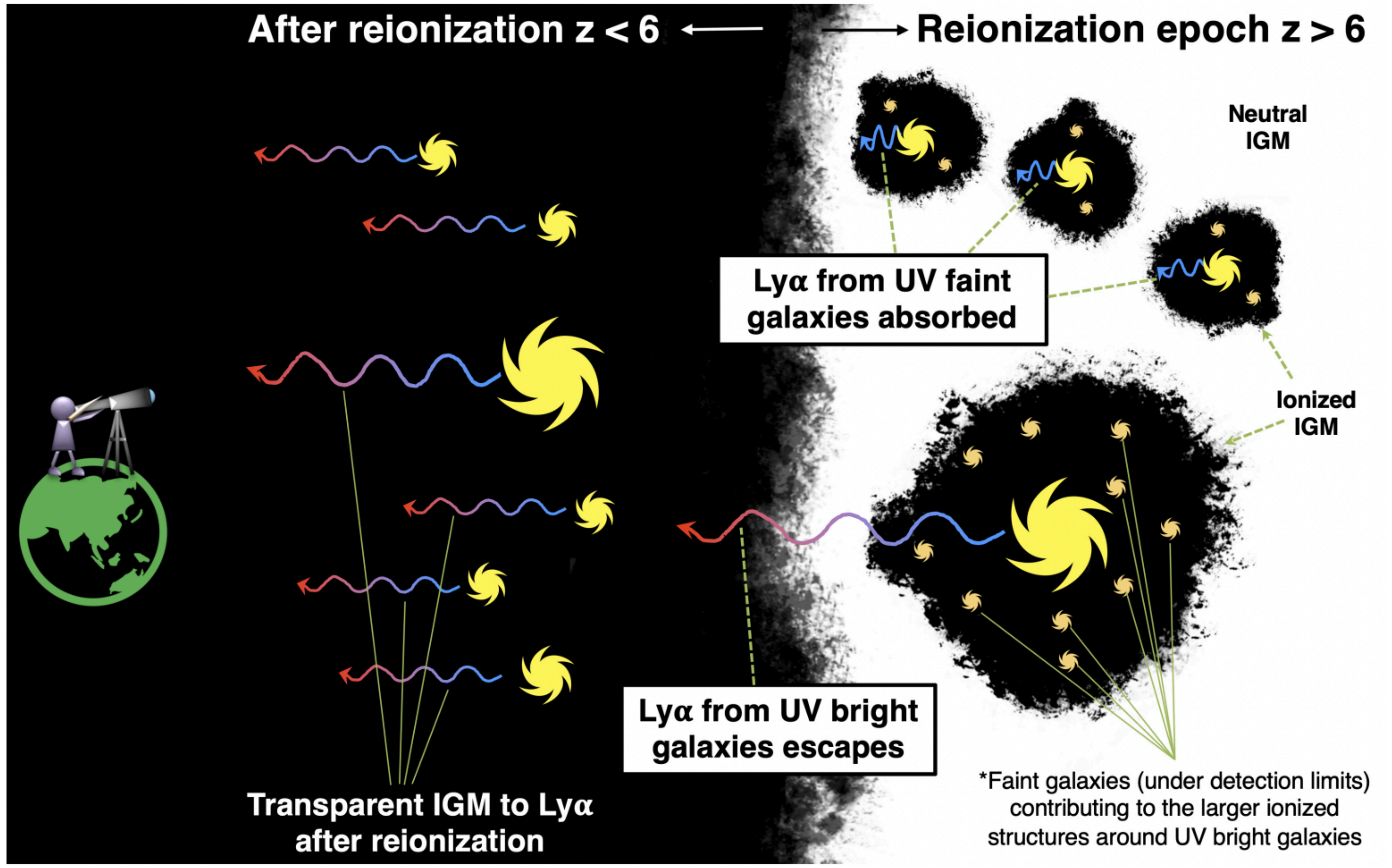




See also Naidu+22, Flury+22, Verhamme+17

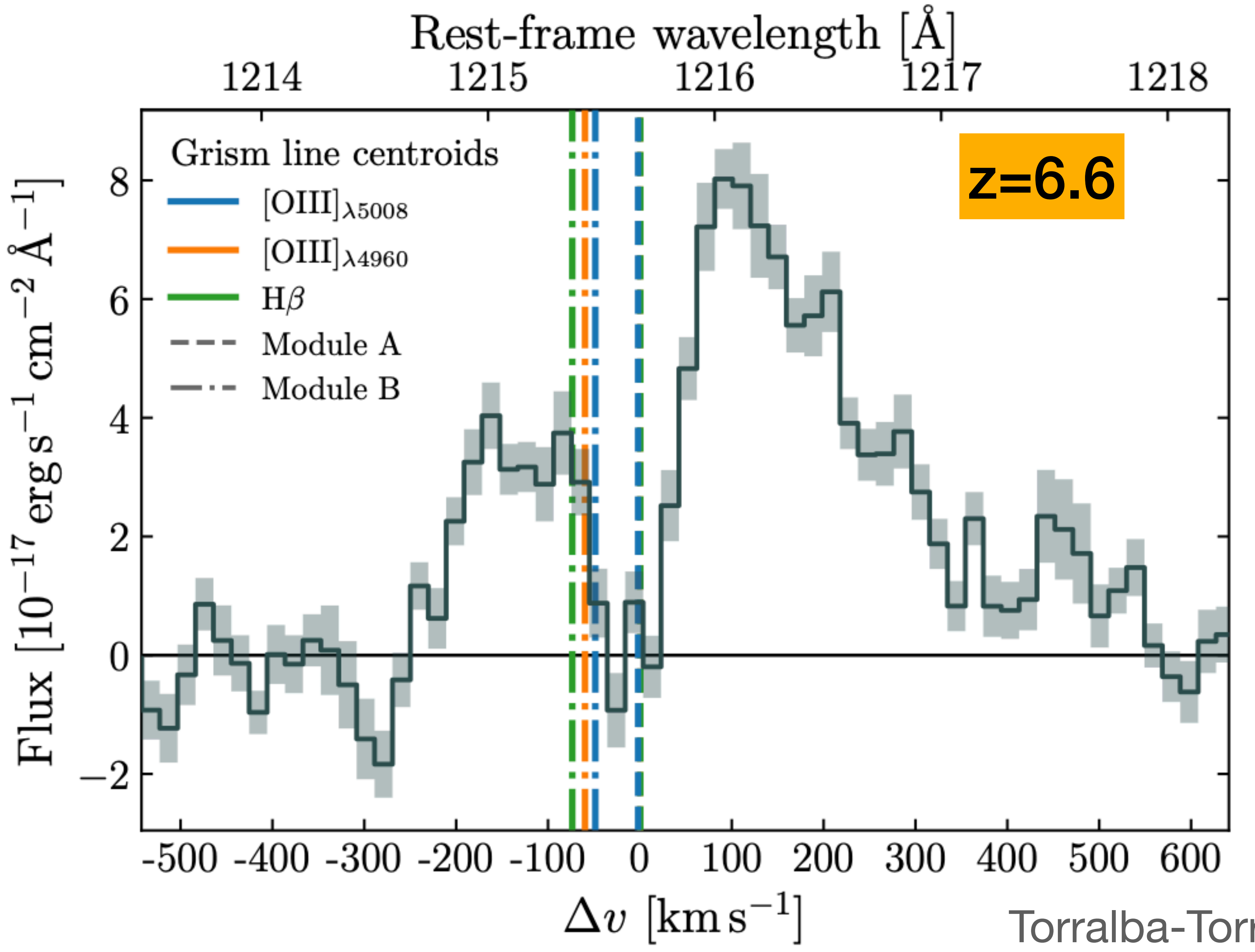
The “indirect indicators” of LyC escape fraction

- Lyα line during the EoR



Jung+22

- Detecting a Lyα blue peak indicates the presence of an ionized bubble
- The shape of the peak constrains the size of the bubble along the line of sight



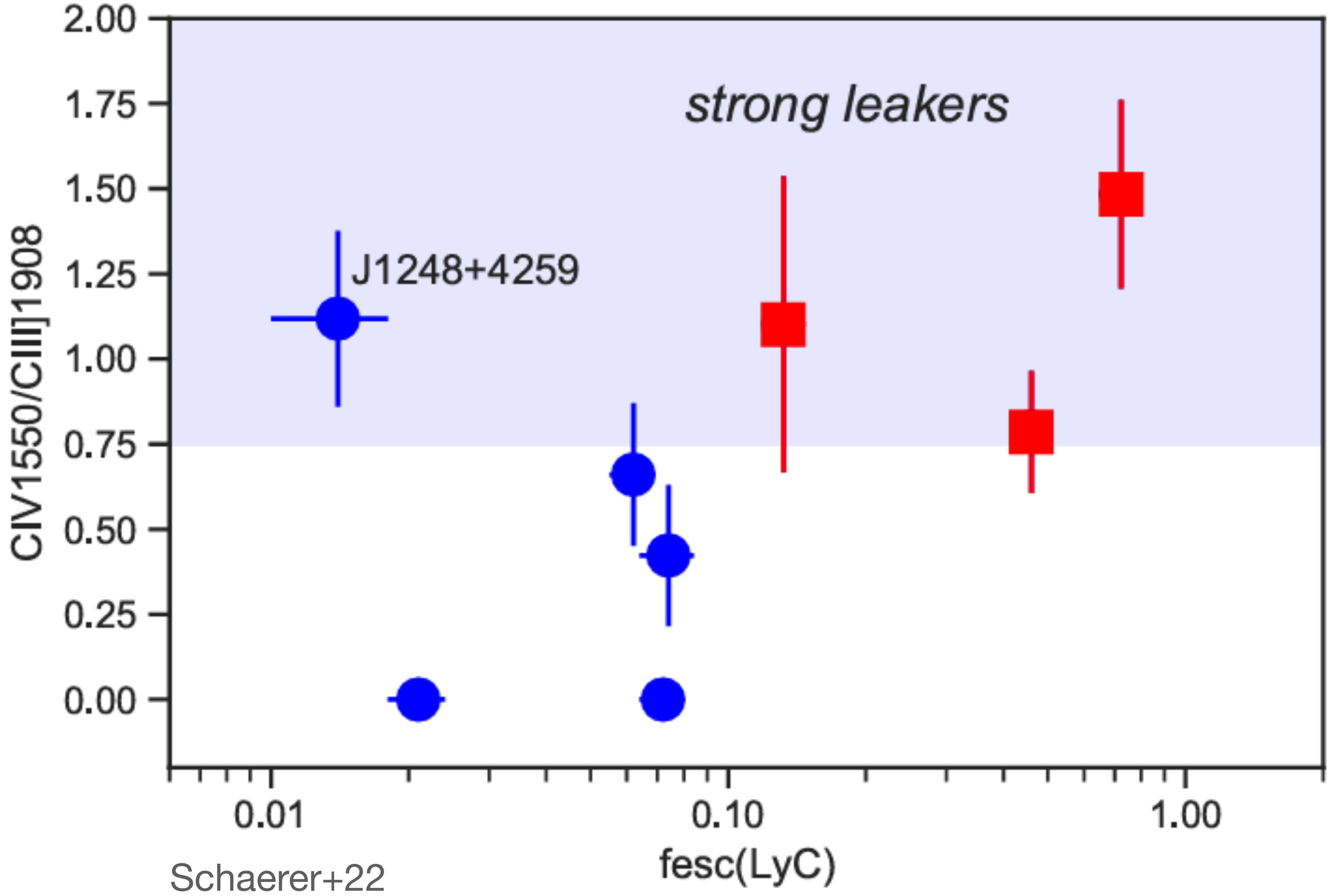
Torralba-Torregrosa+24

See also Songaila+18, Meyer+20, Protušová+24

The "indirect indicators" of LyC escape fraction

- Other rest-frame UV lines

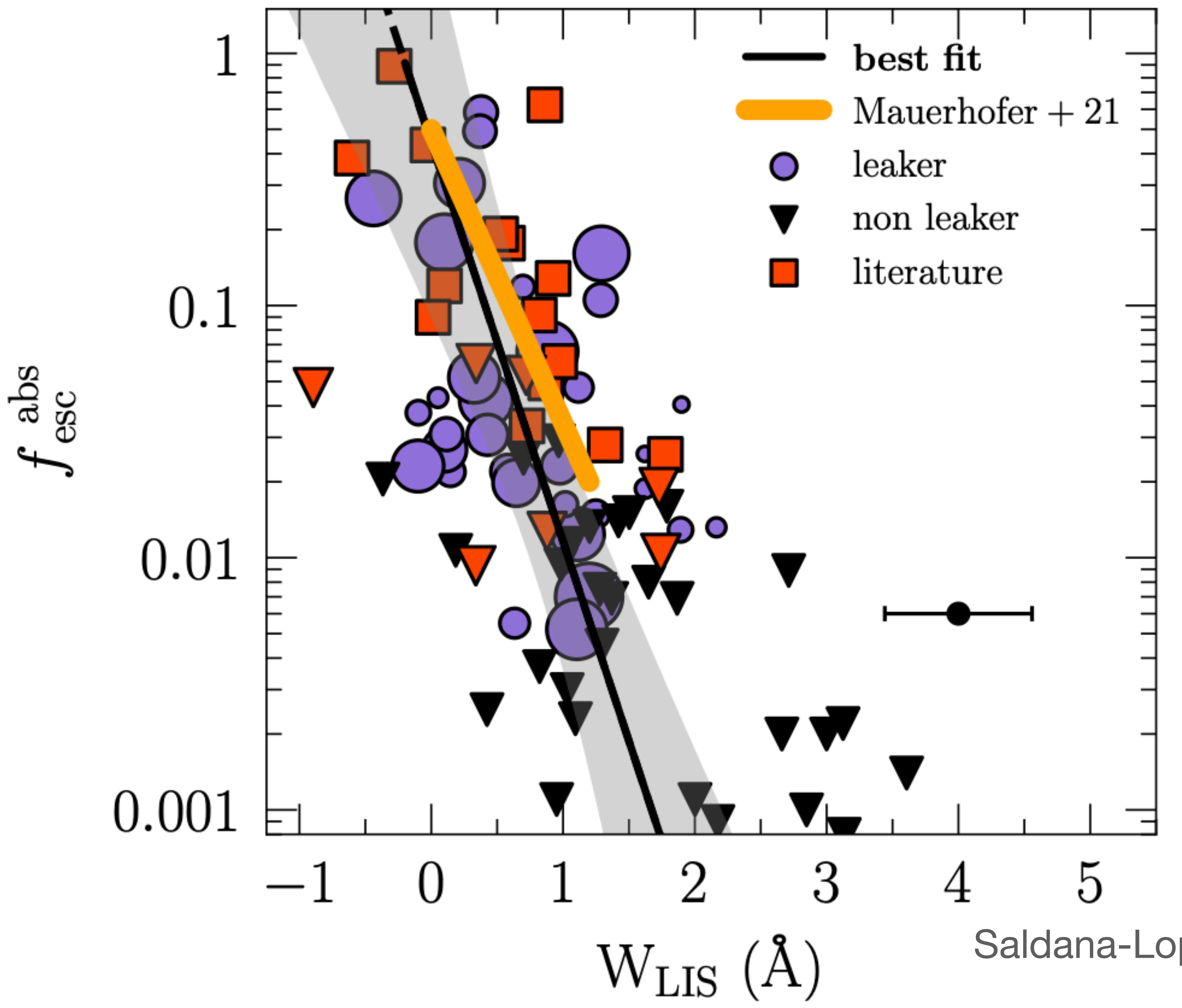
Nebular CIV is detected in most low-z confirmed LyC leakers.



Schaerer+22

- Low-Ionization State absorption lines

See Valentin & Cody's talks!

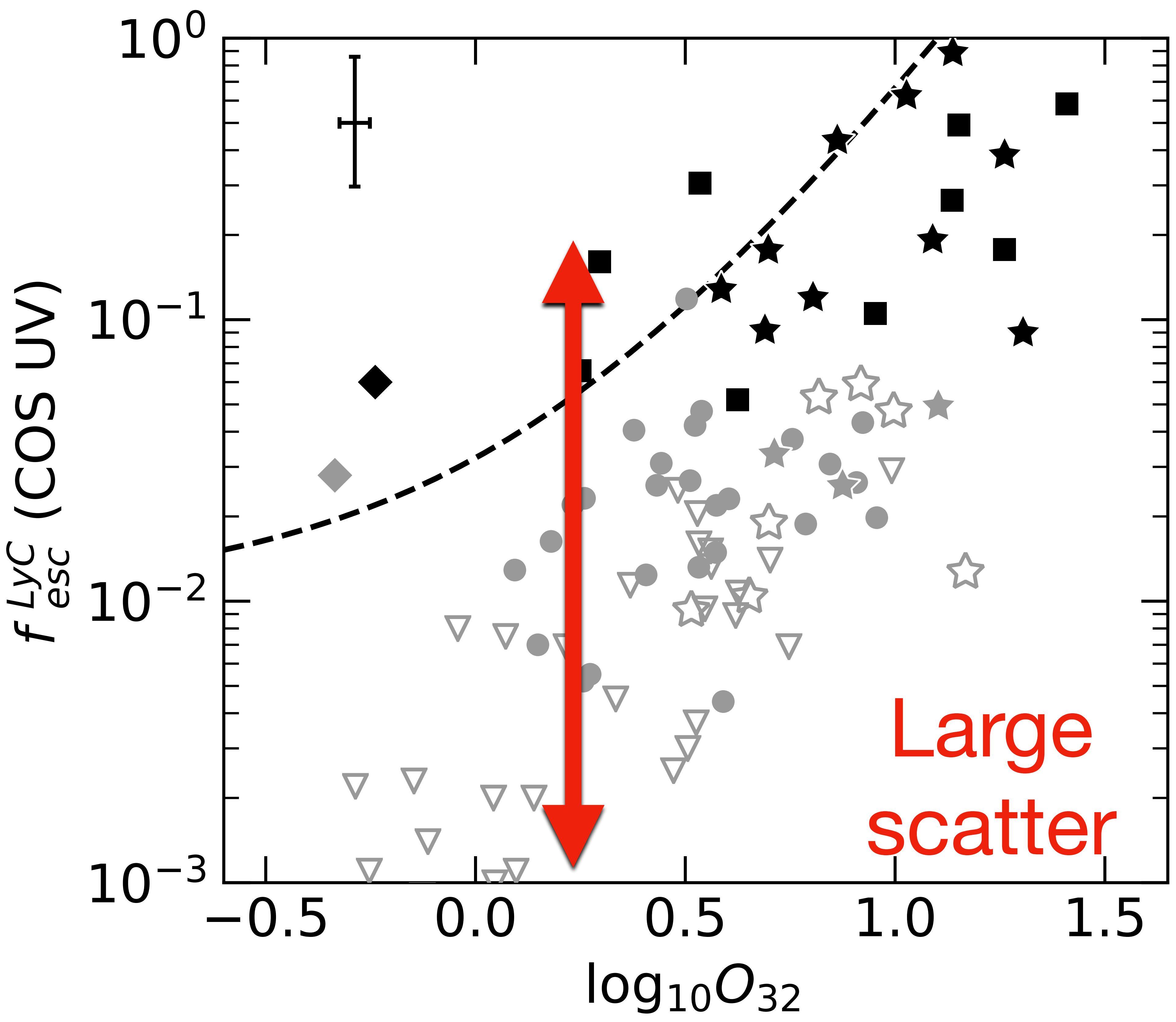


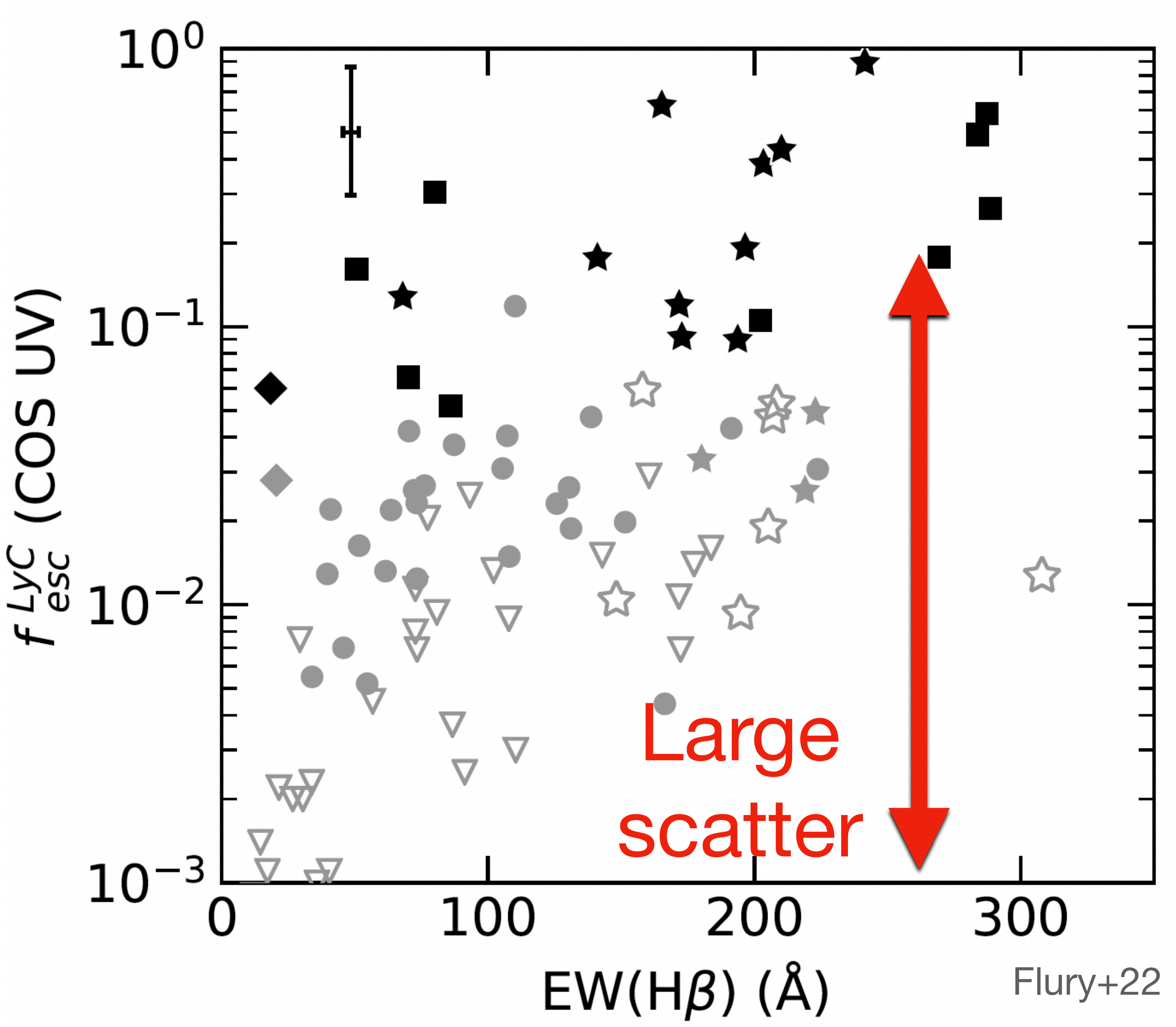
Saldana-Lopez+22

See also Naidu+22, Saxena+22, Mascia+23

The "indirect indicators" of LyC escape fraction

- Nebular properties



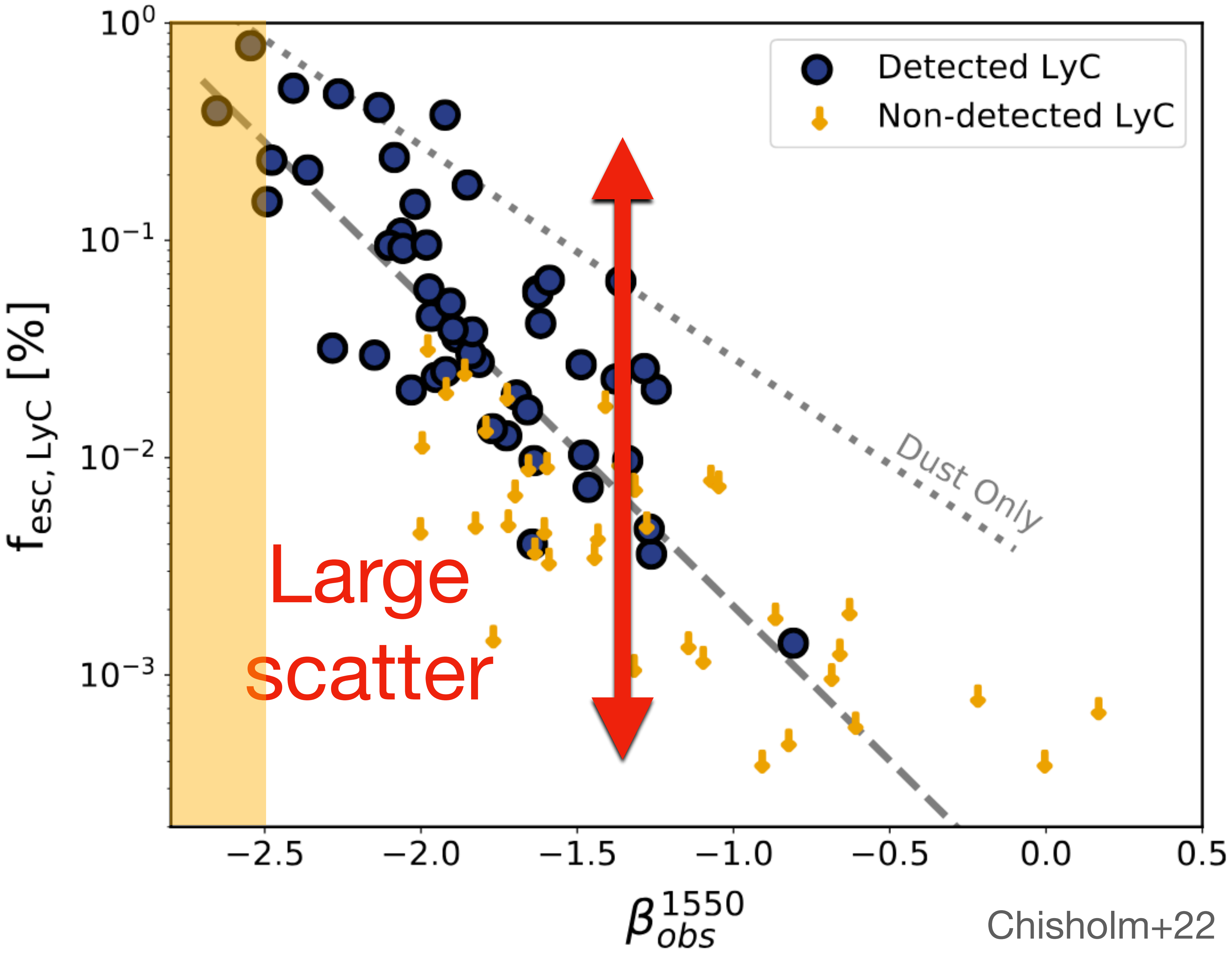


See also Izotov+16b,18a,18b

The “indirect indicators” of LyC escape fraction

- Dust

Bluer UV β slopes generally linked to higher f_{esc}.



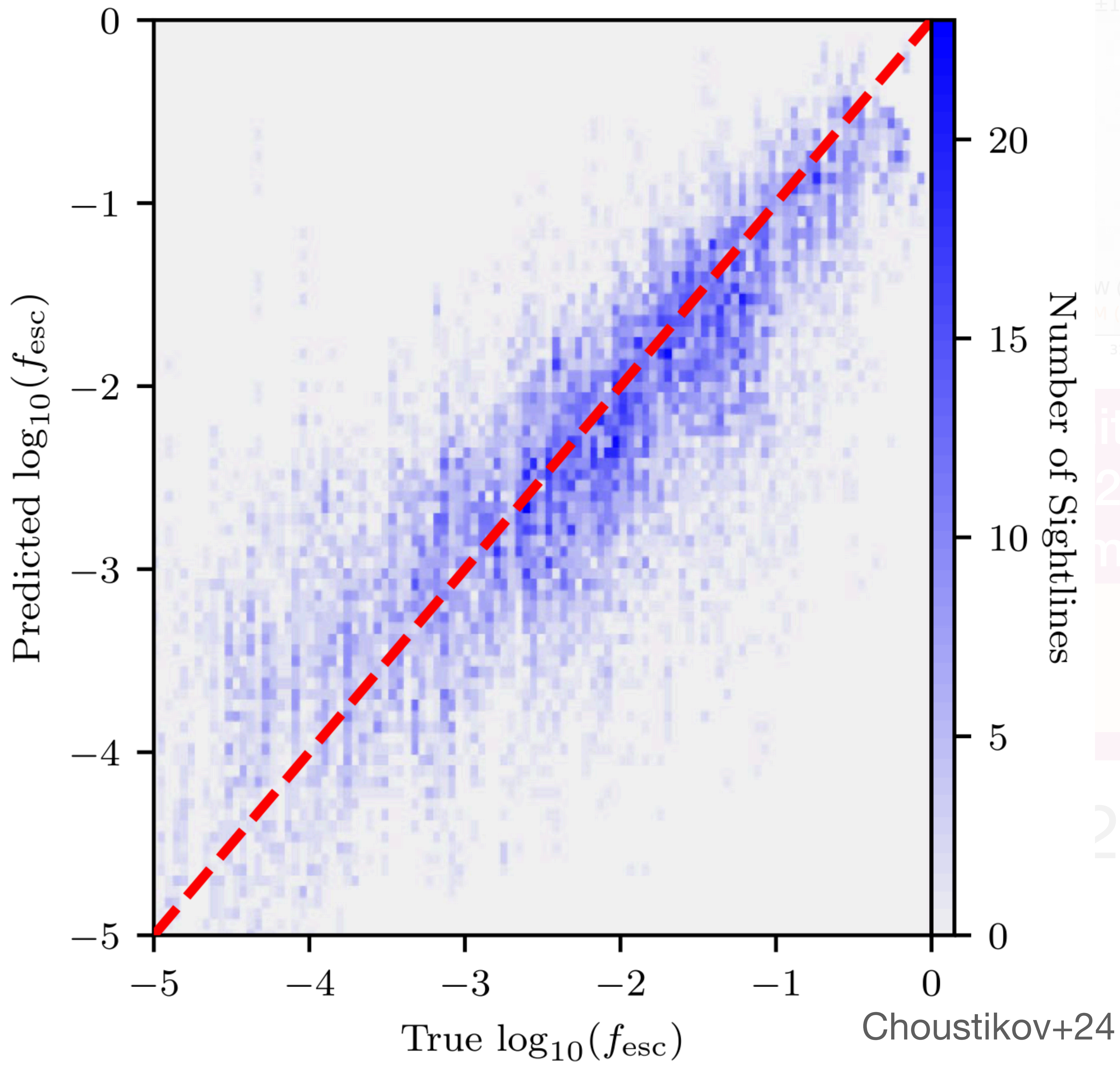
Chisholm+22

Other indirect indicators are:

- stellar mass, $M_\star$
- M_{UV}
- galaxy UV half light radius, r_e
- Dust reddening, E(B-V)
- Σ_{SFR}
- ...

The escape of Lyman continuum photon from galaxies

Using **SPHINX simulation**, Choustikov+24 predict f_{esc} based on a combination of observables, including the UV slope, E(B– V), Hβ luminosity, MUV, and nebular line ratios (R23 and O32).

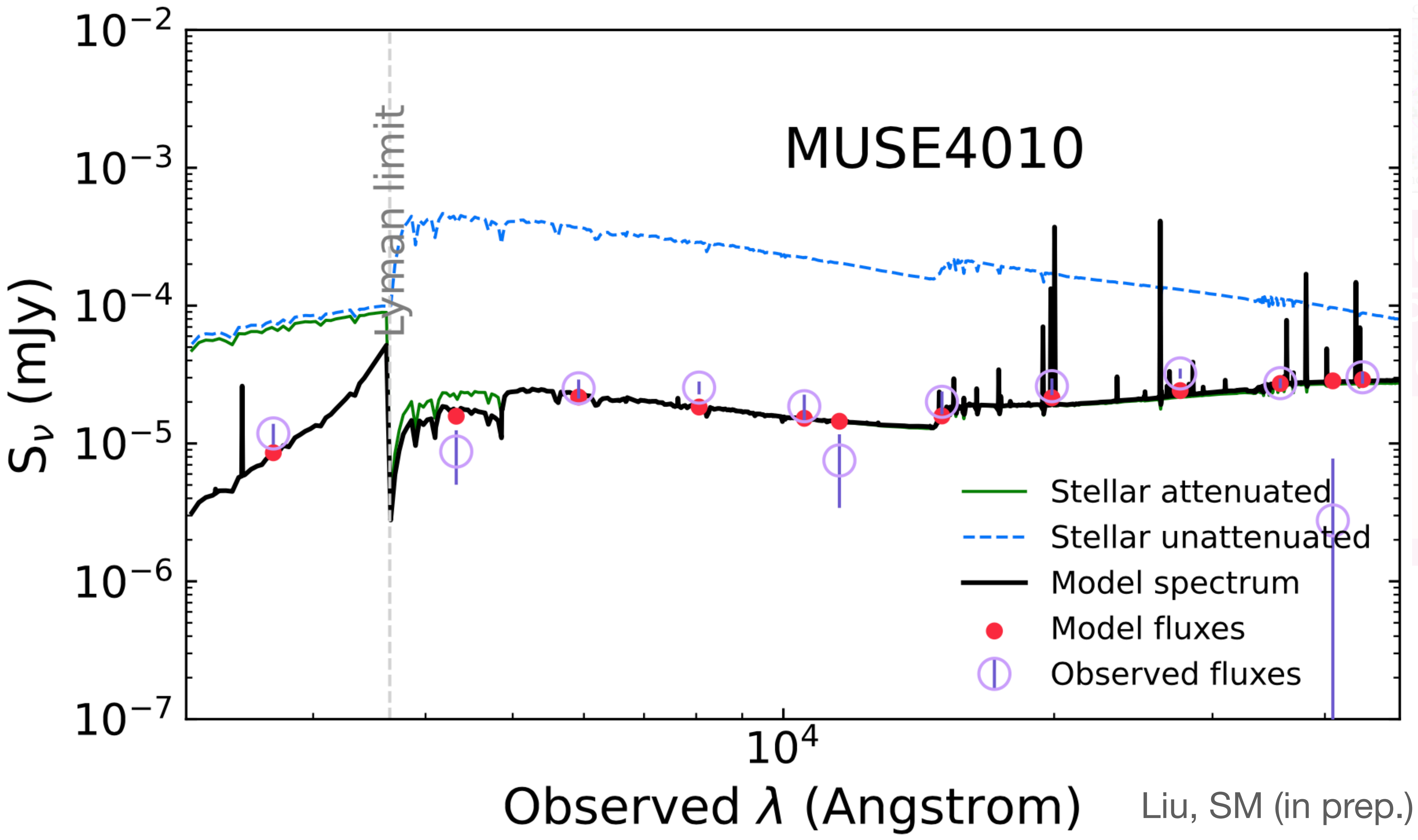


Choustikov+24

The escape of Lyman continuum photon from galaxies

Using **SED fitting**, we can also estimate f_{esc}.

Note that SED fitting relies on the assumption of stellar population, star formation history, and other models.



Liu, SM (in prep.)

See Yuchen, Amanda and Emma's talks!

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IGM transmission

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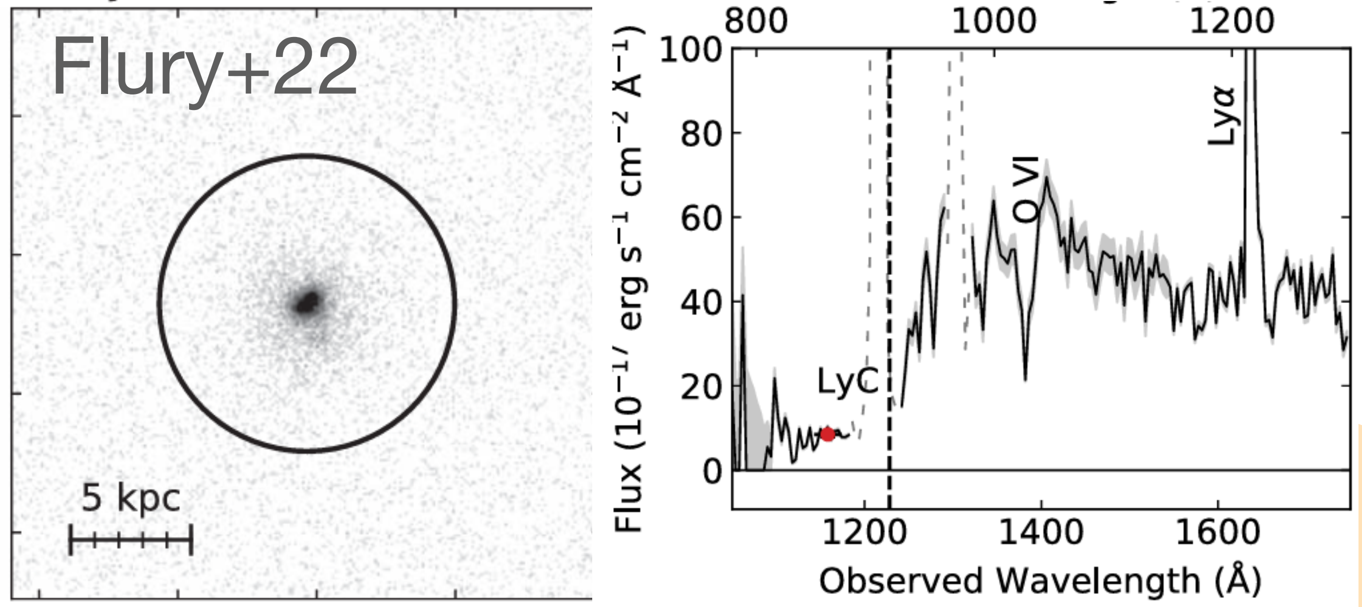


Low-Redshift Lyman Continuum Survey (LzLCS, PI Jaskot). 88 sources for which we have direct detections (or upper limits) on the f_{esc}

See Sophia's talk!

- Few strong emitters: Sunburst Arc, Ion1, Ion2, Ion3, J0121+0025, J1316+2614.
- Some stacks, mostly non-detections

0 0.3 2-3 4 EoR

Redshift

Predicting f_{esc} of EoR galaxies combining multiple indicators

Using the LzLCS+ dataset (88 galaxies at $z \sim 0.3$), we calibrate an empirical relation between the f_{esc} values and the most correlated indirect indicators that che be measured during the EoR.

$$\log_{10}(f_{esc}) = A + B\log_{10}(O32) + Cr_e + D\beta$$

A = −1.92 [−2.51, −1.71]

B = 0.48 [0.38, 0.69]

C = −0.96 [−1.20, −0.62]

D = −0.41 [−0.58, −0.31]

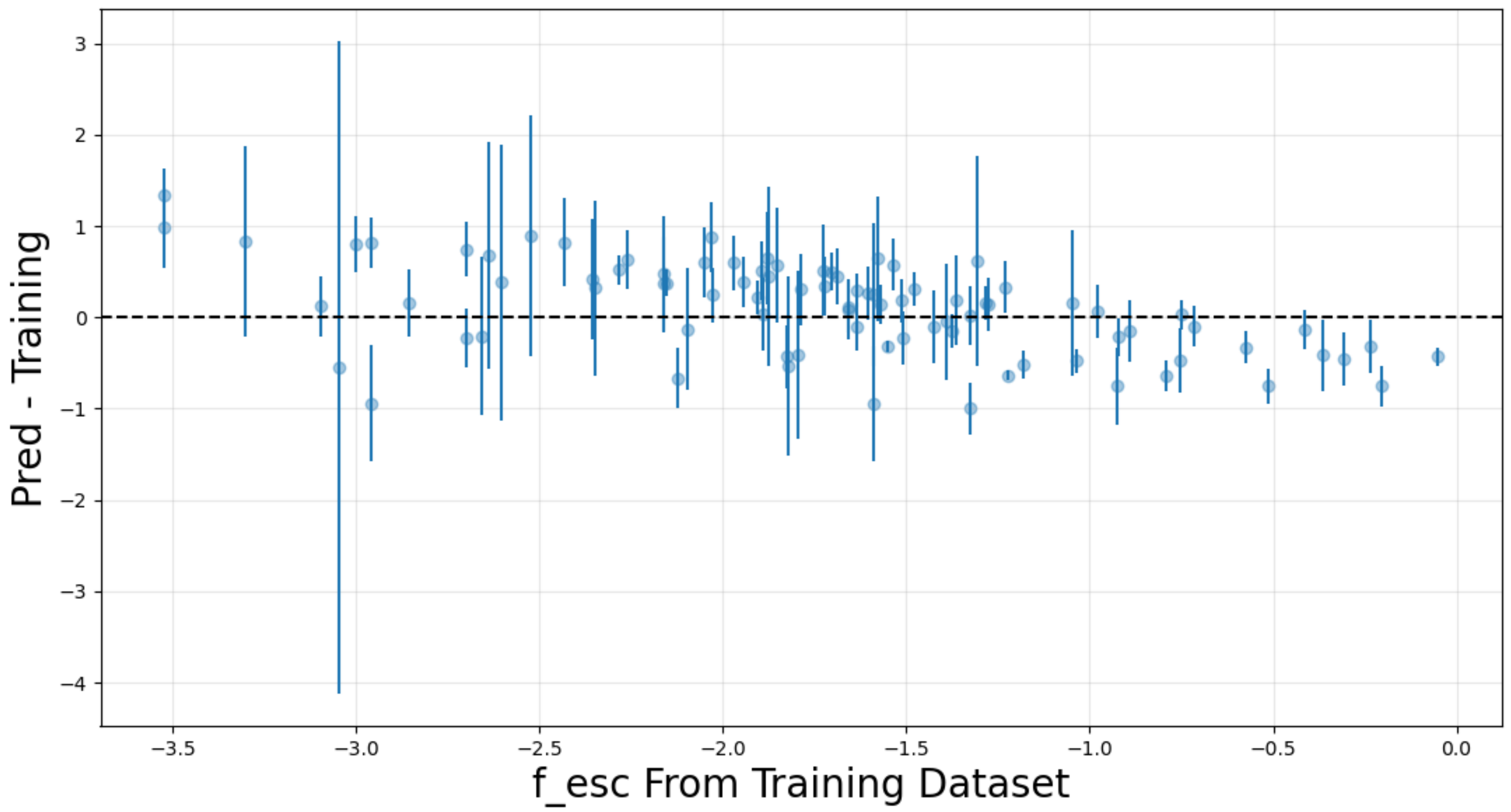
$$\log_{10}(f_{esc}) = A + BEW(H\beta) + Cr_e + D\beta$$

A = −1.92 [−2.46, −1.75]

B = 0.0026 [0.0019, 0.0035]

C = −0.94 [−1.14, −0.67]

D = −0.42 [−0.59, −0.33]



Mascia+23b, Mascia+24a

See also Lin+24

Predicting f_{esc} of EoR galaxies combining multiple indicators

- Jaskot+24 employed the **Survival Analysis**, originally from medical research, to better handle the broad f_{esc} range and numerous non-detections in the LzLCS+ dataset.

- Survival analysis models the likelihood of detecting f_{esc} given indirect indicators, treating non-detections as censored data.

Model	Variables				
	Dust	Lyα	Nebular	Luminosity	Morphology
TopThree	E(B-V)$_{\rm UV}$	–	log(O32)	–	log(Σ(SFR))
LAE	E(B-V)$_{\rm UV}$	EW(Lyα)	–	M_{1500}	–
LAE-O32	E(B-V)$_{\rm UV}$	EW(Lyα)	log(O32)	M_{1500}, log(M_*)	–
LAE-O32-nodust	–	EW(Lyα)	log(O32)	M_{1500}	–
ELG-EW	E(B-V)$_{\rm UV}$	–	log(EW([OIII]+Hβ))	M_{1500}, log(M_*)	–
ELG-O32	E(B-V)$_{\rm UV}$	–	log(O32)	M_{1500}, log(M_*)	–
ELG-O32-β	β_{1550}	–	log(O32)	M_{1500}	–
ELG-O32-β-Lyα	β_{1550}	$f_{\rm esc}^{\rm Ly\alpha}$	log(O32)	M_{1500}, log(M_*)	–
R50-β	β_{1550}	–	–	M_{1500}, log(M_*)	log($r_{50,\rm NUV}$))
β-Metals	β_{1550}	–	12+log(O/H)	M_{1500}, log(M_*)	–

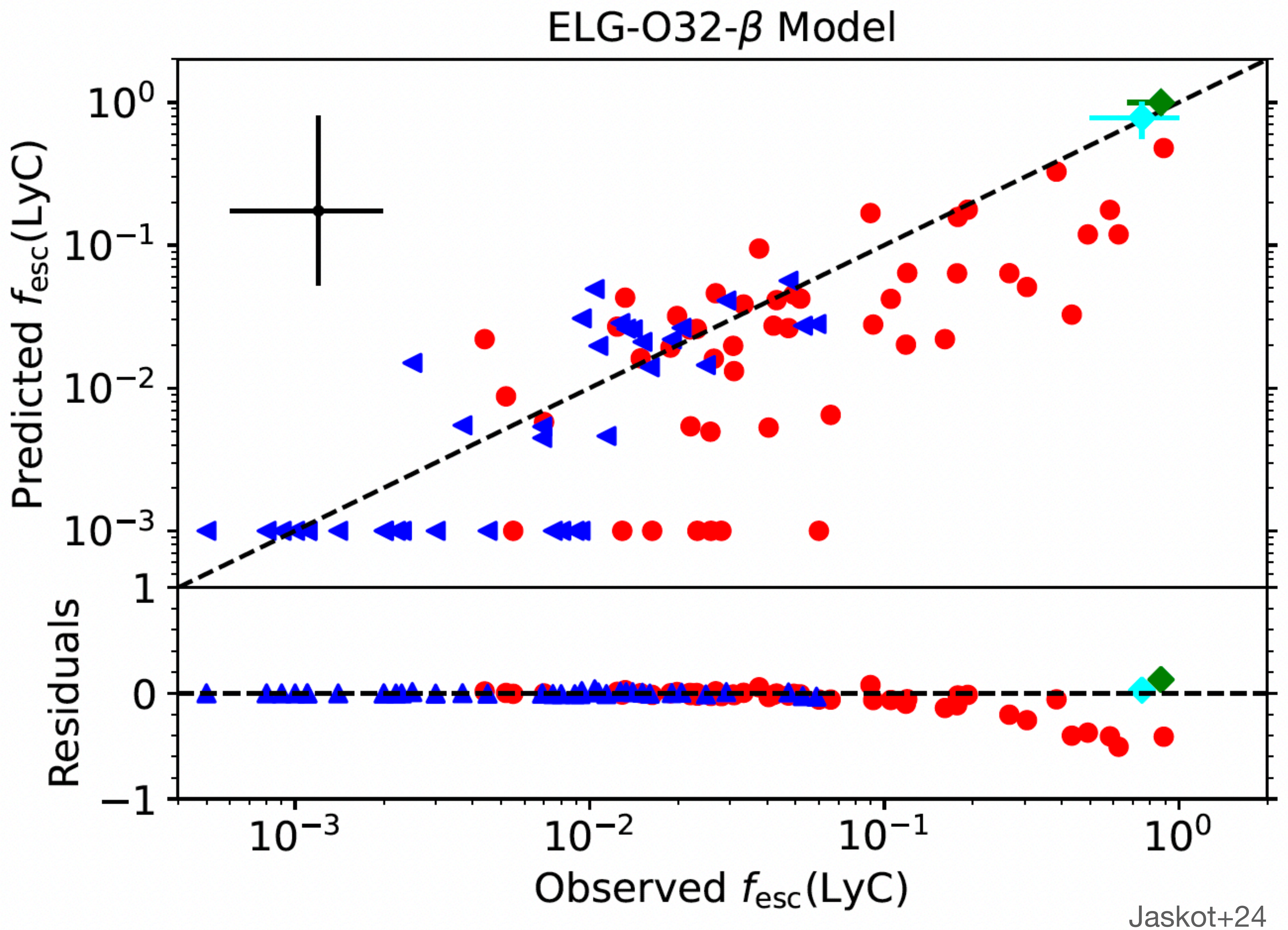
Jaskot+24

Predicting f_{esc} of EoR galaxies combining multiple indicators

Model calibrated using:

- β
- log(O32)
- M_{UV}

The Cox models can be used also to predict $f_{esc,Ly\alpha}$



Jaskot+24

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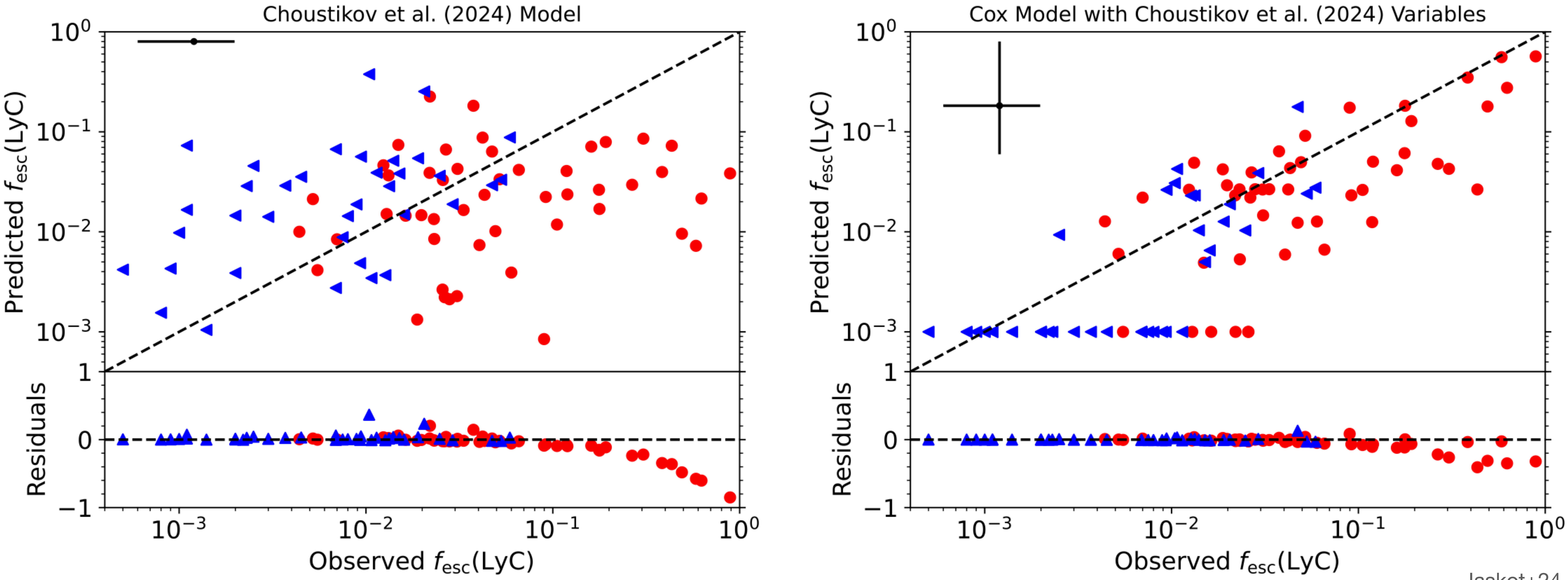
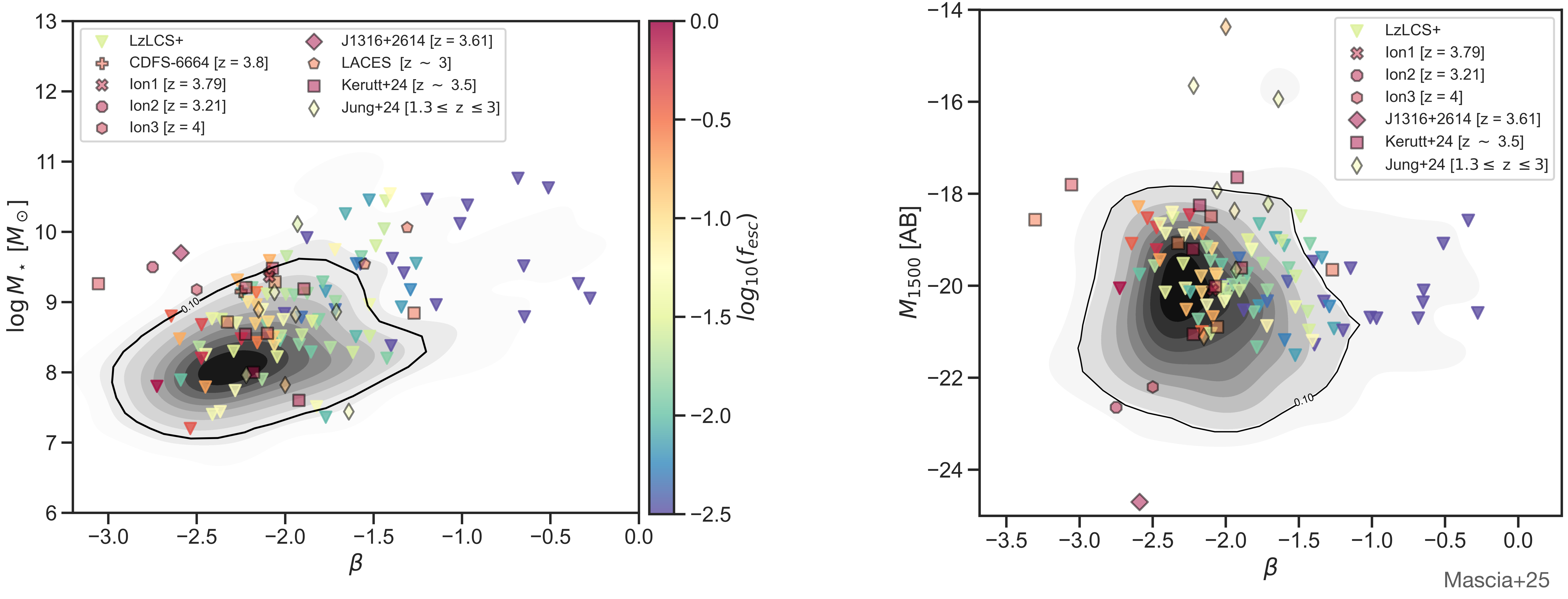


Jaskot+24

Comparison with SED fitting results?

Matching EoR galaxies and low-redshift sources

Grey-shaded area: z = 5-7 sample from several JWST programs

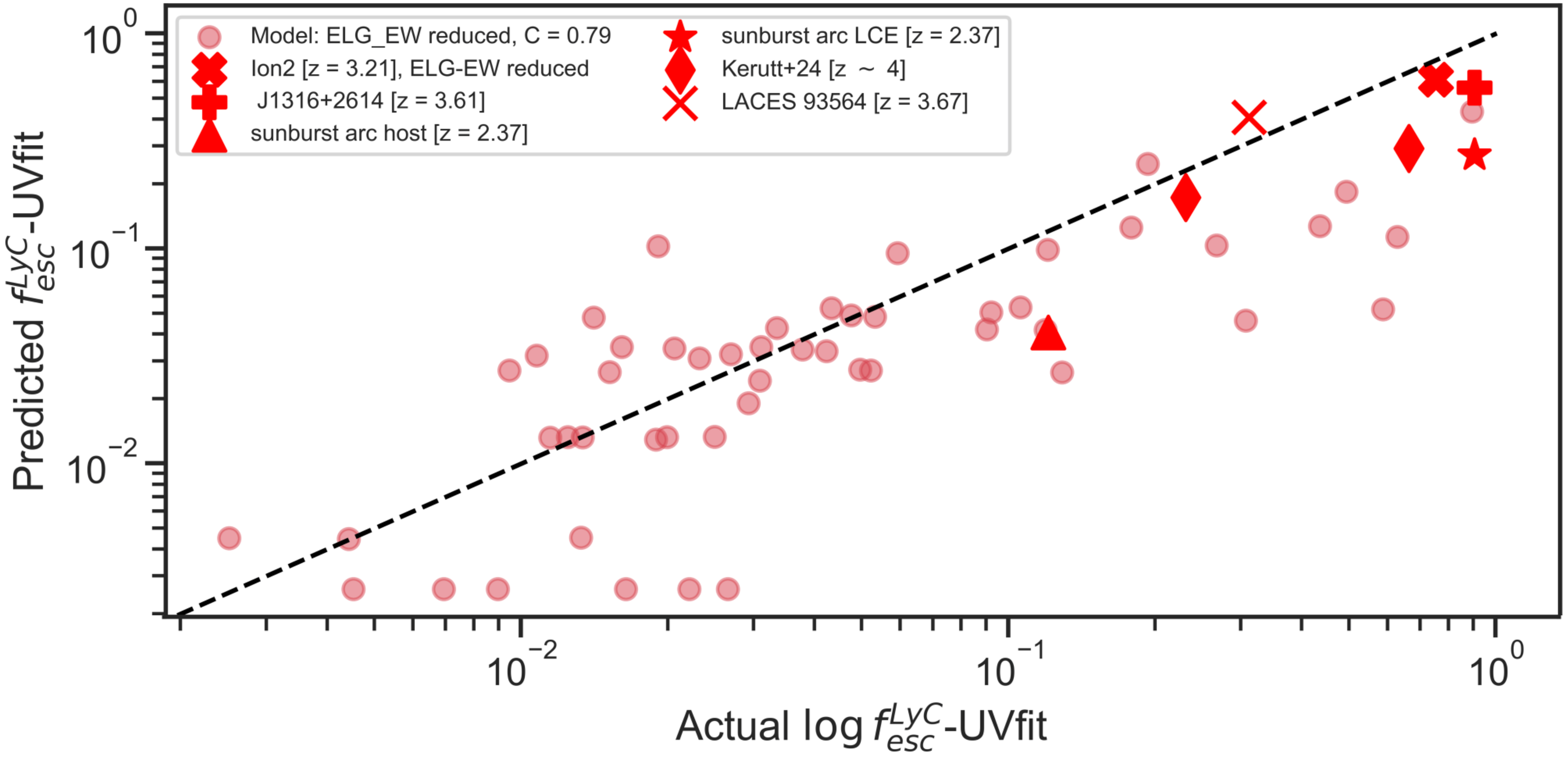


Testing the new models on the few z = 3 known leakers

Predictions are effective

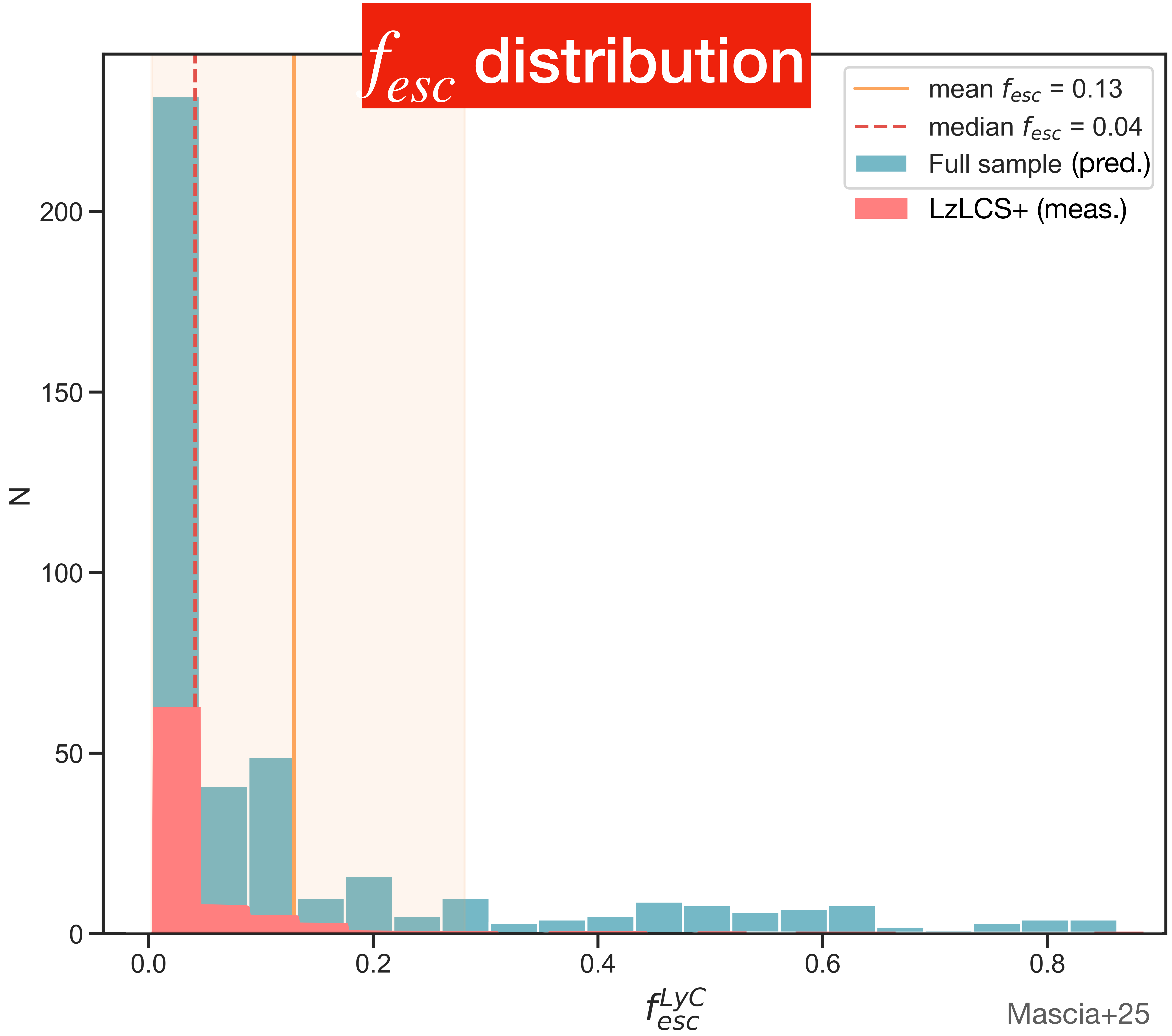
BUT

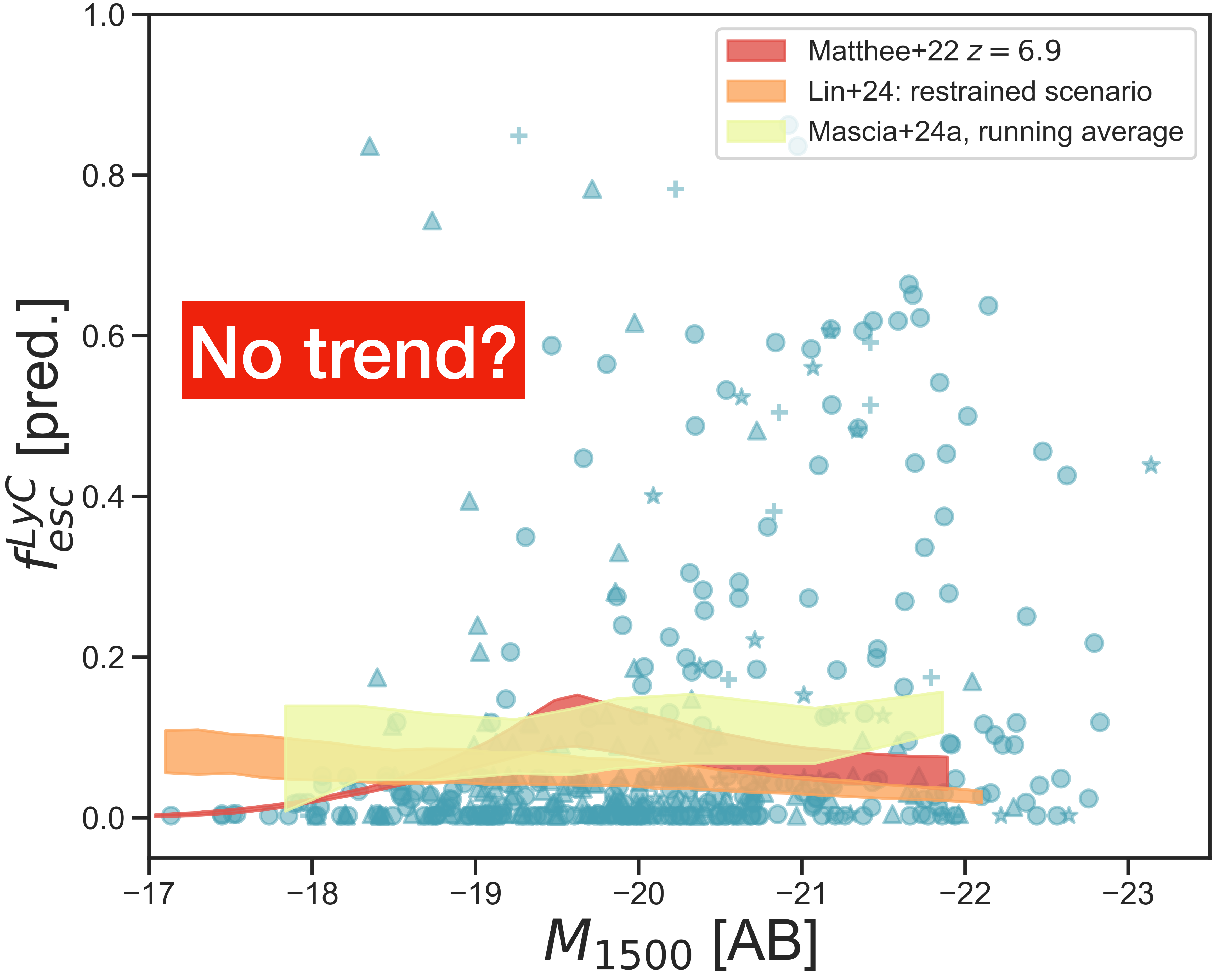
we still need to increase the statistics of known leakers at intermediate redshifts.



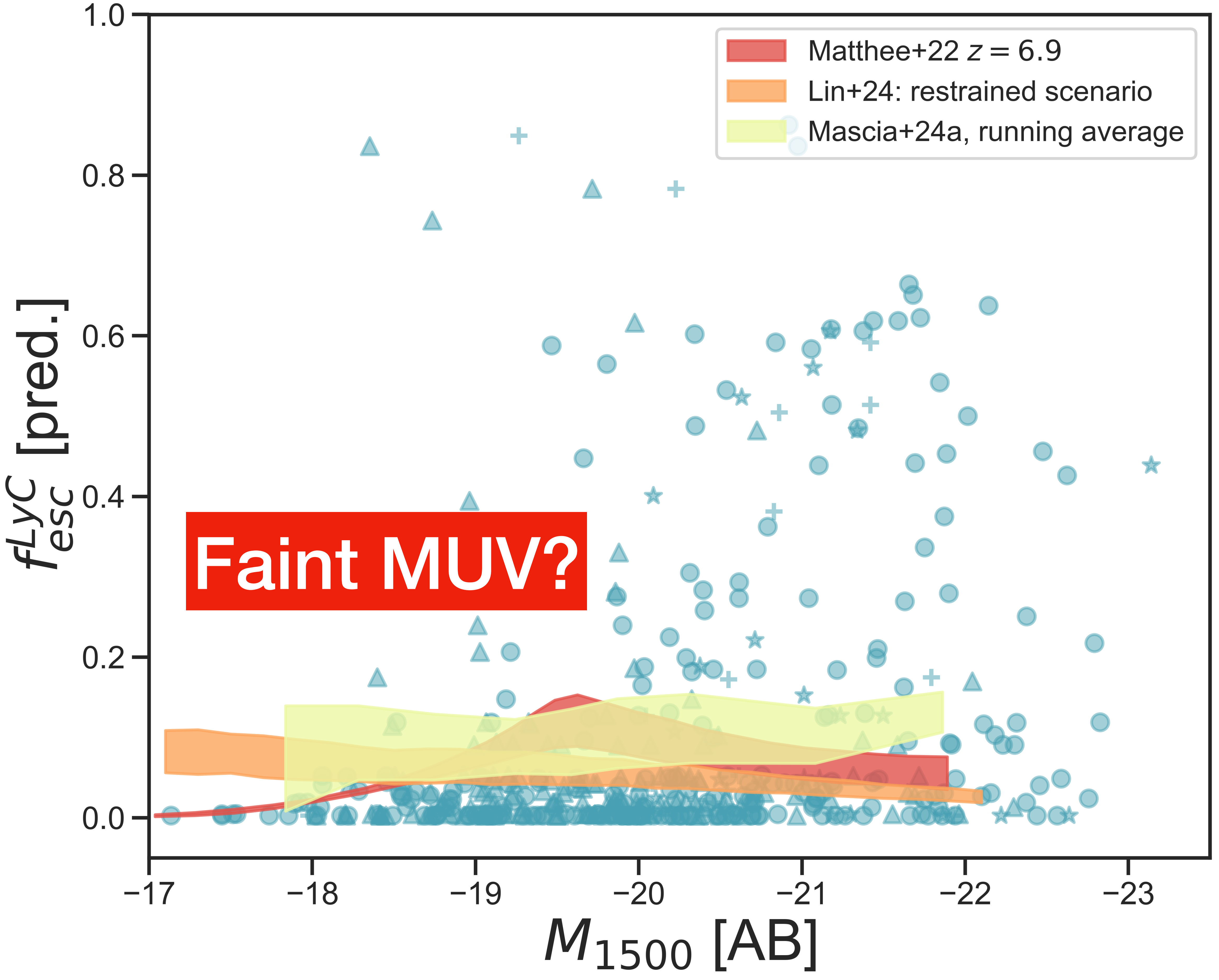
Mascia+25

Predicted f_{esc} of EoR galaxies





Reionization after JWST

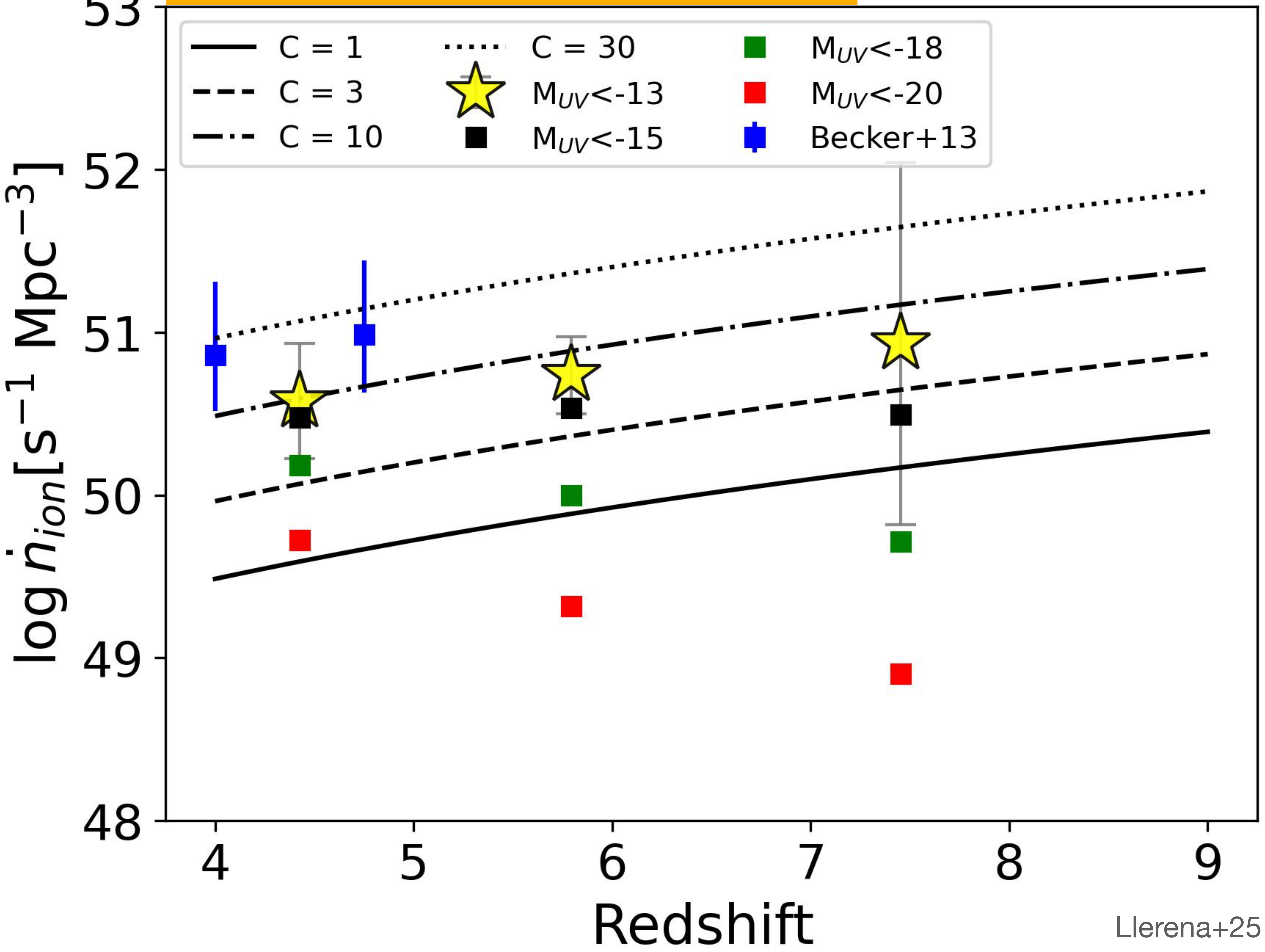


- Gravitational lensing enables the detection of faint EoR galaxies.
- JWST programs (e.g., ALT, UNCOVER, CANUCS) are uncovering lensed galaxies with $M_{UV} \sim -16$ with [OIII] and Hβ detections.
- Follow-up UV/optical data will refine f_{esc} predictions and thus their ionizing photon contribution.

Reionization after JWST

- UV LF from Bouwens+21
- f_{esc} combining multiple predictors
- ξion(M_{UV}) from Llerena+25

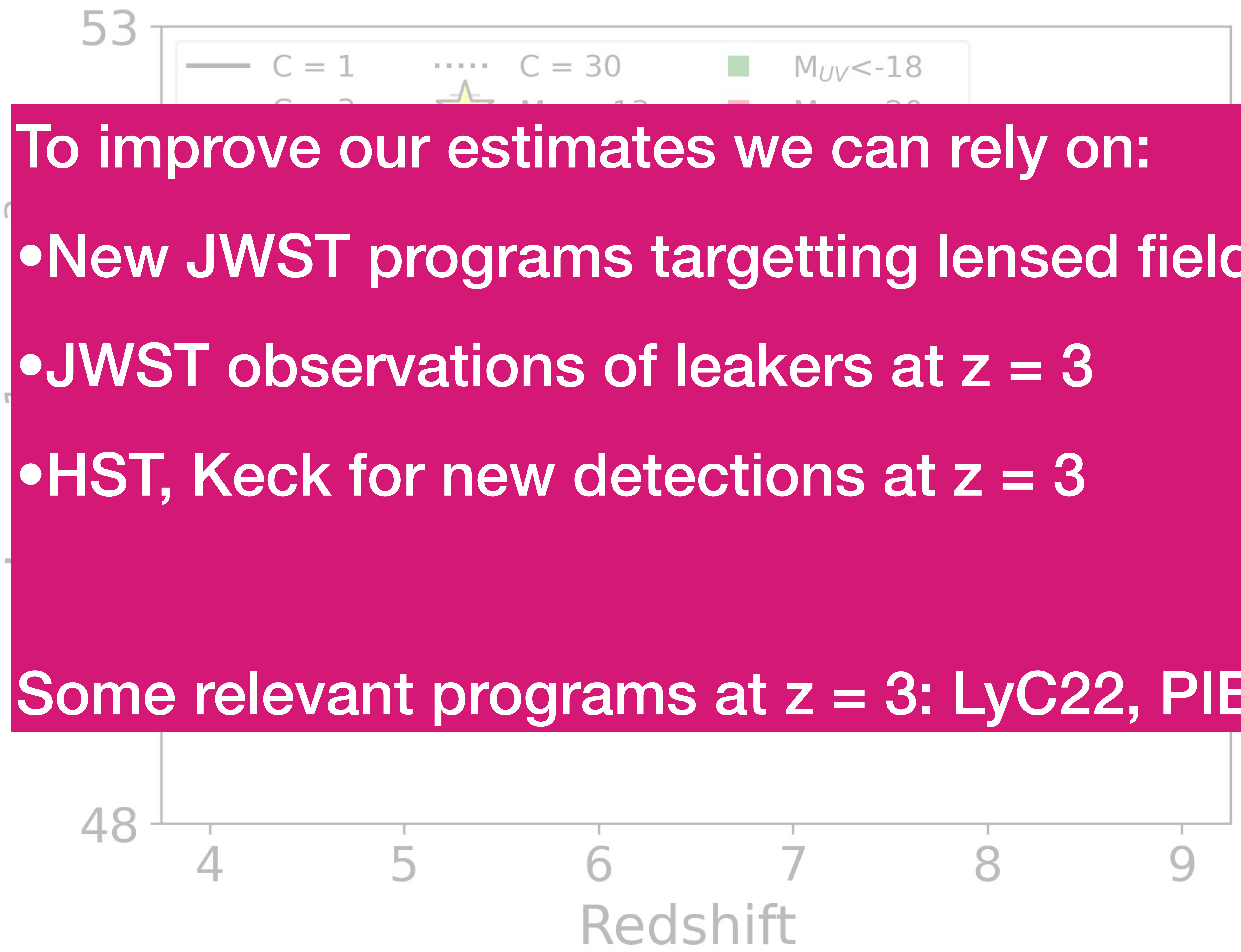
(★ = integrated on M_{UV} $[-13, -23]$)



Llerena+25

Agreement with $< f_{esc}\xi_{ion} >$ predictions from Lyα forest!

Reionization after JWST

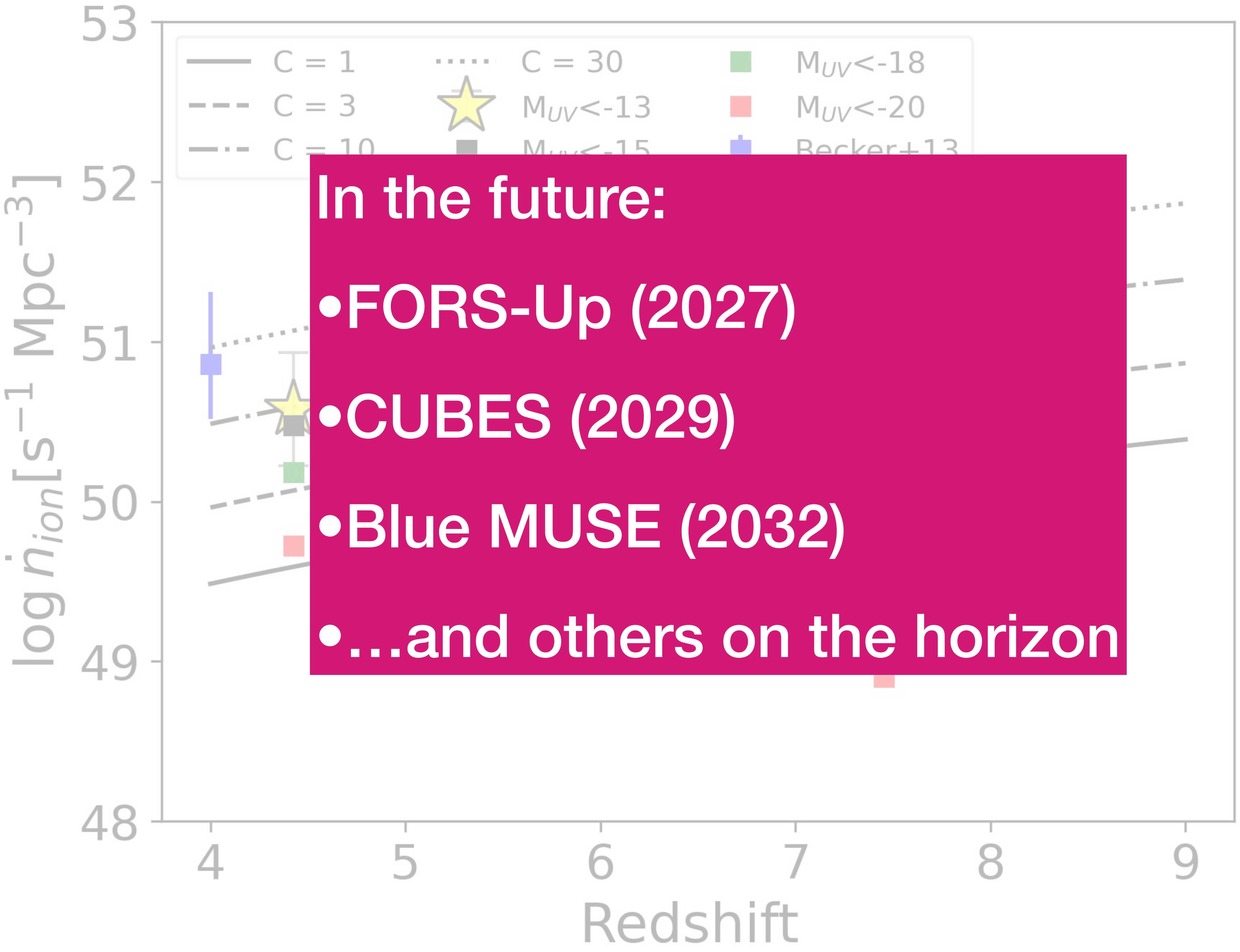


To improve our estimates we can rely on:

- New JWST programs targetting lensed fields
- JWST observations of leakers at z = 3
- HST, Keck for new detections at z = 3

Some relevant programs at z = 3: LyC22, PIE

Reionization after JWST



In the future:

- FORS-Up (2027)
- CUBES (2029)
- Blue MUSE (2032)
- ...and others on the horizon

Thank you!

Conclusions

- At z ≈ 0.3, we have a large statistical sample of confirmed LCEs, which we are currently characterizing in terms of both spectroscopic and morphological properties.
- The mechanisms driving LyC emission appear to be diverse. Single property cannot reliably predict LyC escape

- At z ≈ 2–3, only a few robust LyC detections are currently available.
- Existing prediction methods appear to hold at these redshifts as well, but a larger statistical sample is needed.

- During the Epoch of Reionization, we can apply prediction methods calibrated at z ≈ 0.3 and tested at z ≈ 3 to estimate LyC escape on a source-by-source basis.
- Expanding the sample at these redshifts is crucial, especially toward fainter magnitudes, to better assess the contribution of faint galaxies.

0 0.3 2-3 EoR

Redshift