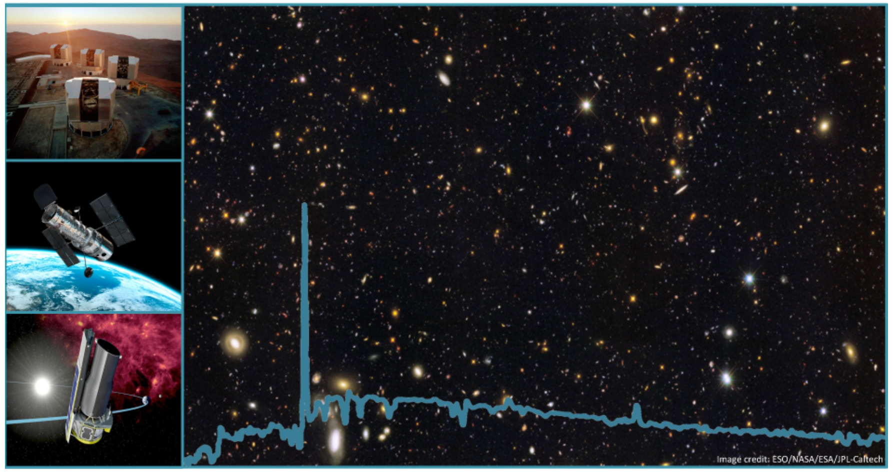
THE UNIVERSITY *of* EDINBURGH
School of Physics
& Astronomy



VANDELS
A deep VIMOS survey of the CANDELS UDS and CDFS fields

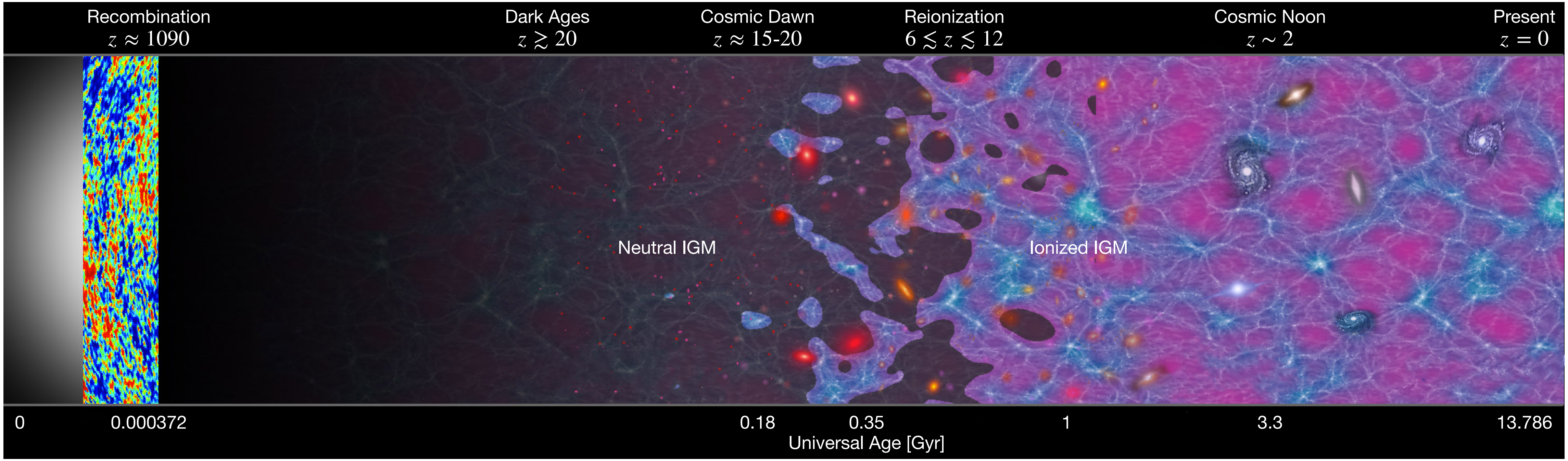
SUPA

Understanding cosmic reionization:
The production and escape of Lyman-continuum photons in high-redshift galaxies unveiled with VANDELS and JWST

Dr Ryan Anthony Begley

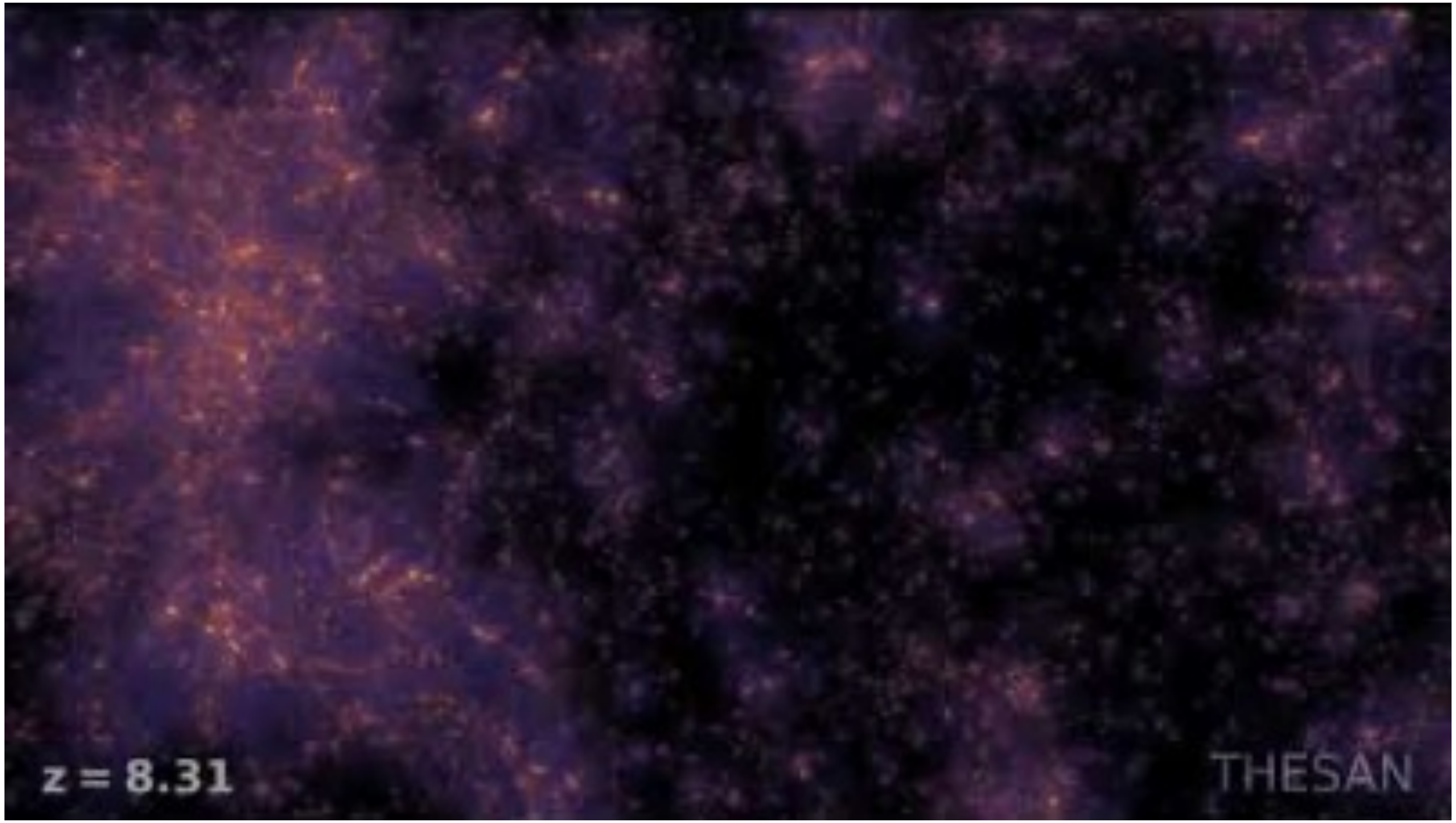
Prof. Ross McLure, Dr Fergus Cullen, Prof. Jim Dunlop

The Epoch of Reionization

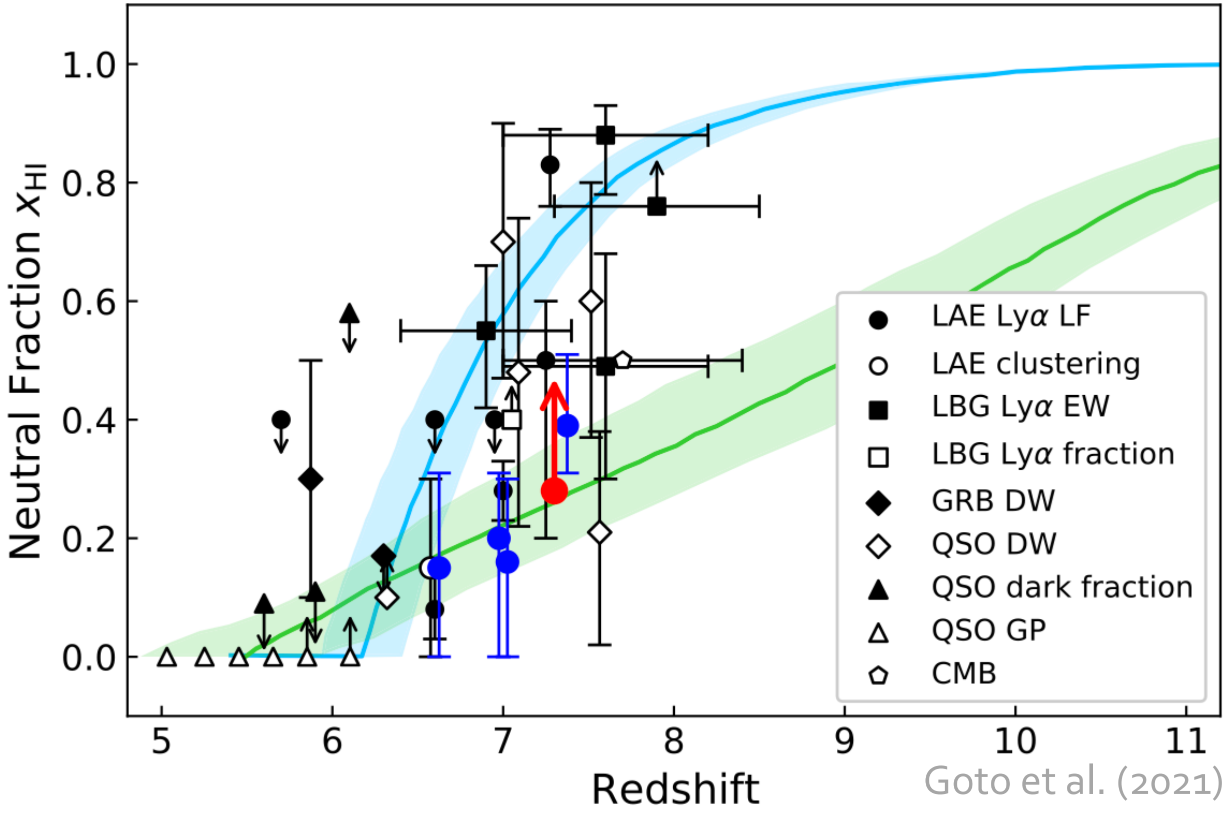


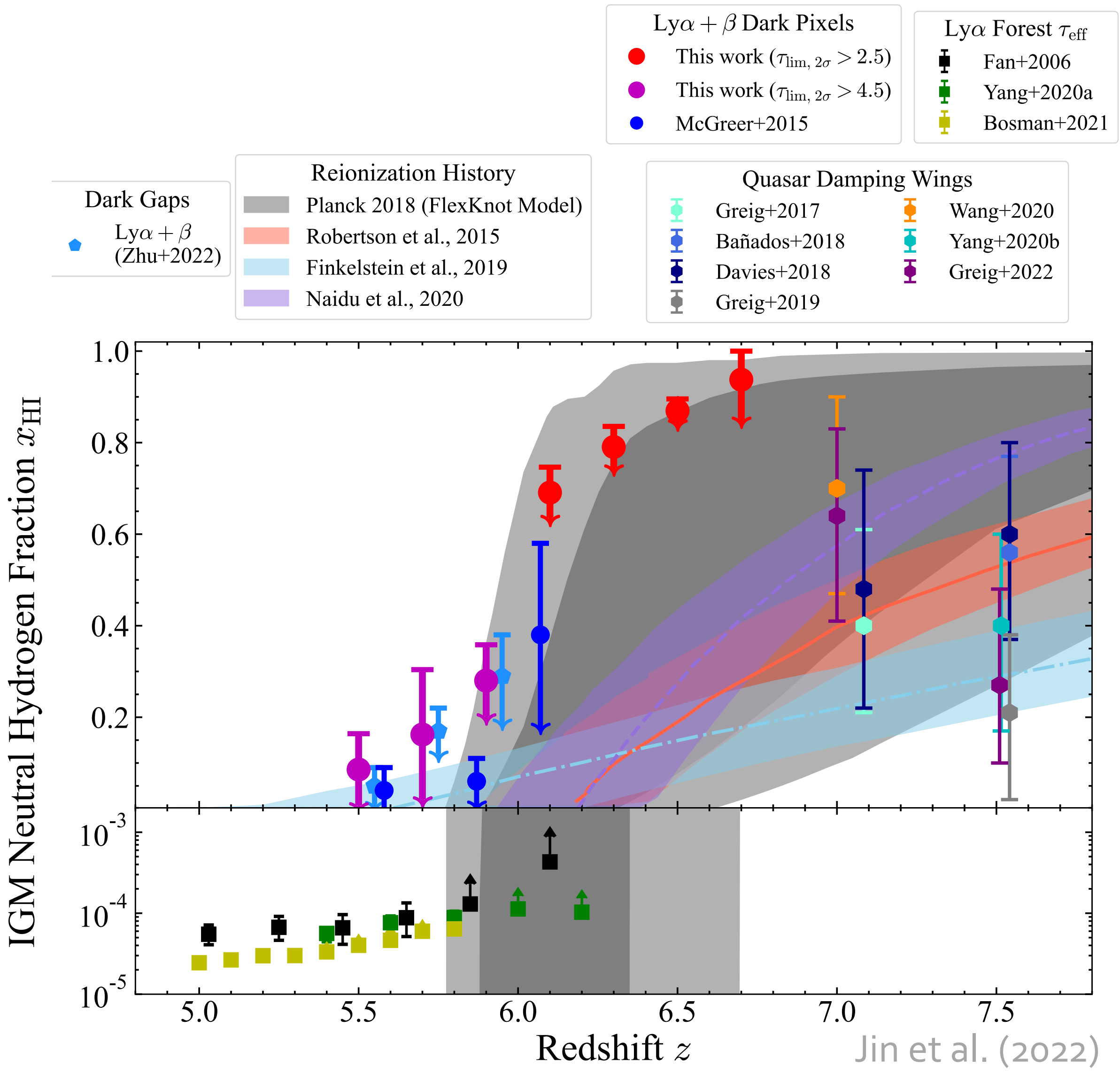
"This phase transition marks the important point at which structure formation has impacted every baryon in the Universe." – D. Stark (2016)

The Epoch of Reionization



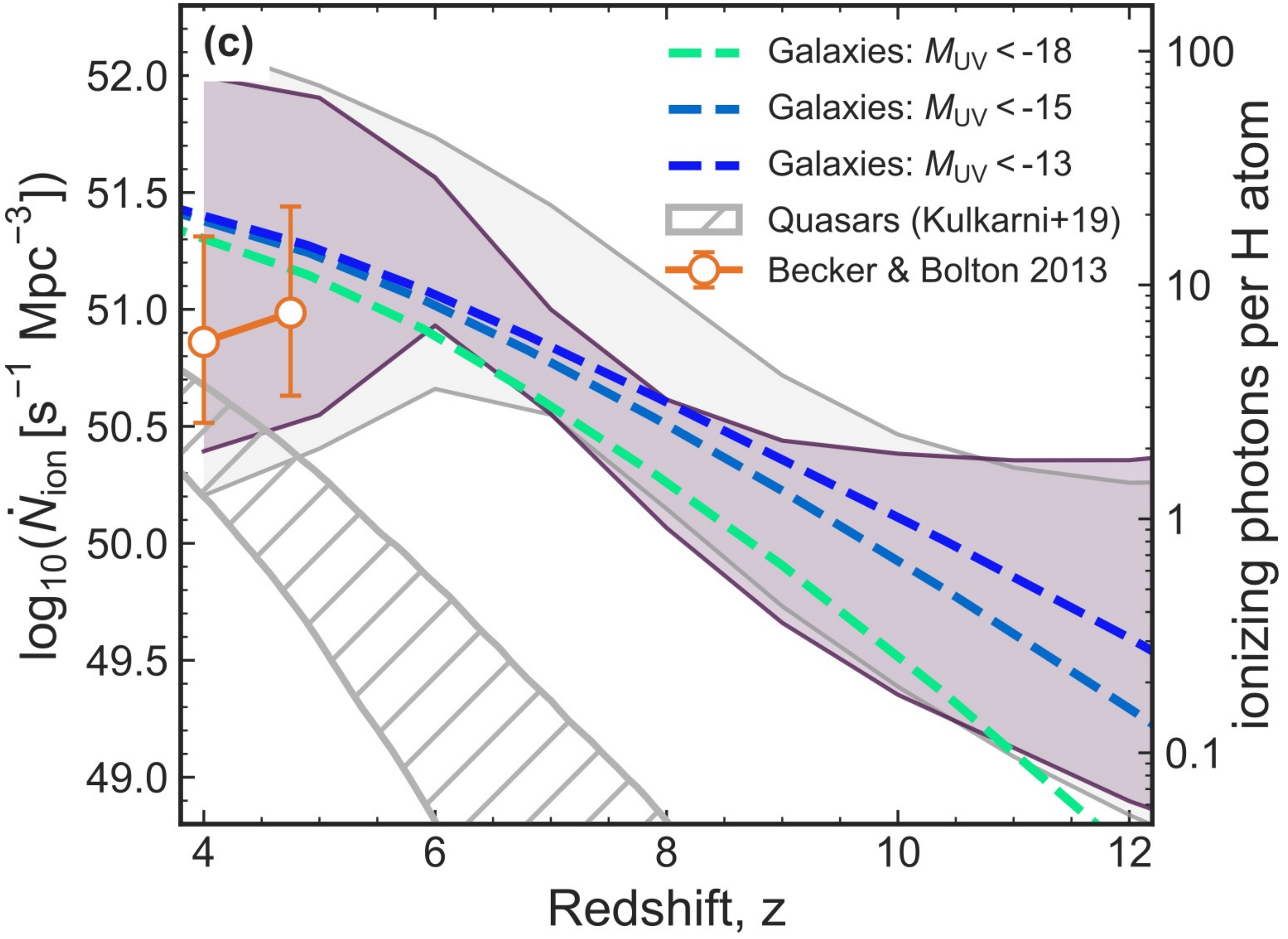
Challenges of understanding the EOR





Challenges of understanding the EOR

Mason et al. (2019)



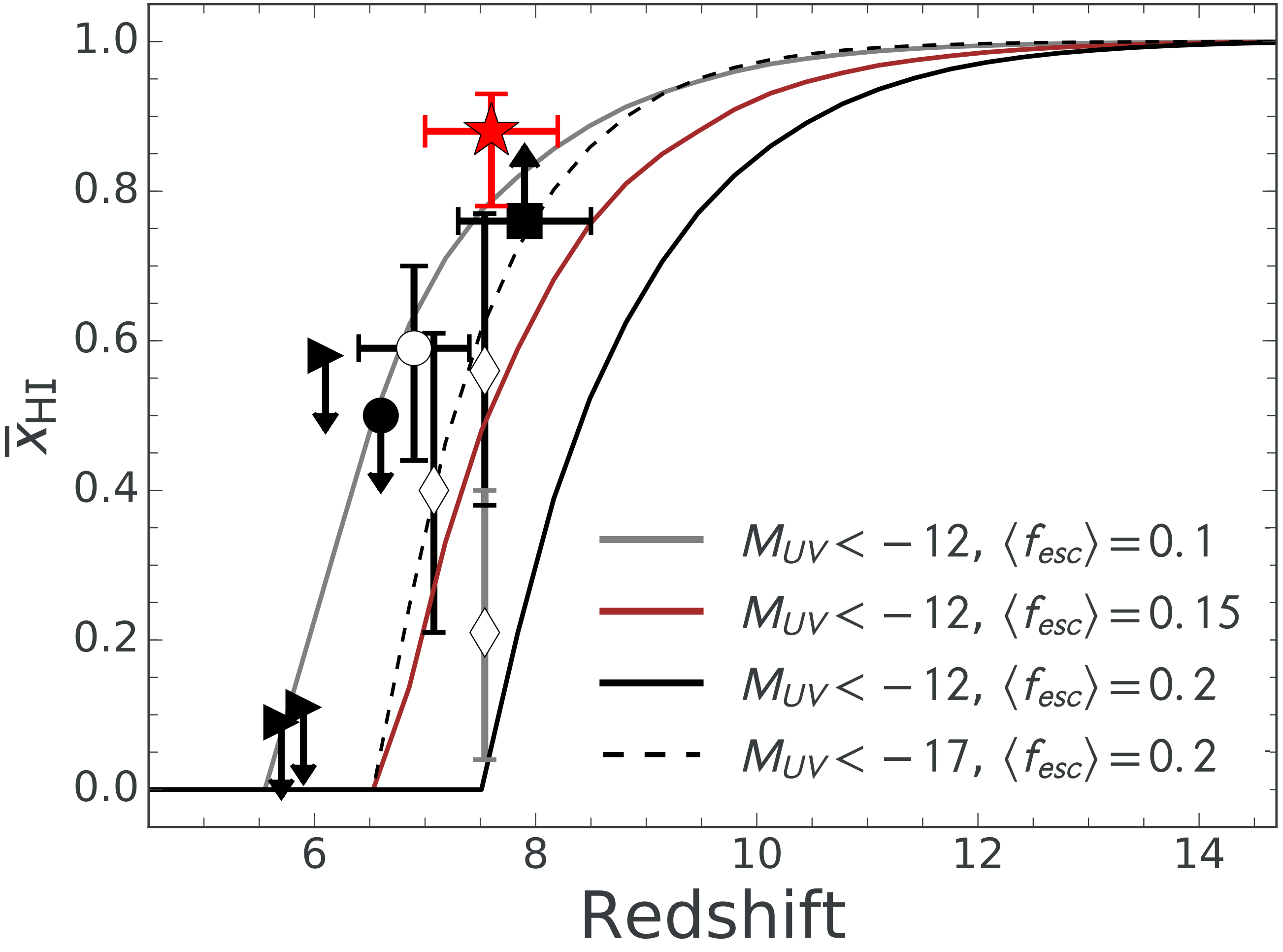
The ionizing photon budget required to drive reionization is dominated by the emerging star-forming galaxy populations at $z \gtrsim 5$–6,

+ a possible contribution from AGN, but only minor due to the declining population
  e.g., Aird et al. (2015), Kulkarni et al. (2019)

$$\dot{N}_{\rm ion} = f_{\rm esc}^{\rm LyC} \times \xi_{\rm ion} \times \rho_{\rm UV}$$

Challenges of understanding the EOR

Hoag et al. (2019)



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$$\dot{N}_{\rm ion} = f_{\rm esc}^{\rm LyC} \times \xi_{\rm ion} \times \rho_{\rm UV}$$

Governed by the population statistics, and galaxy stellar population and gas properties

The VANDELS Survey

An ESO VIMOS spectroscopic survey of the CANDELS UDS/CDFS fields

- Primarily targeting star-forming galaxies at $2.4 < z < 7.0$ (N≃1700/2100)
- 20—80 hours on-source per target
- R=600, across the observed wavelength range $0.48\ \mu m < \lambda < 1.0\ \mu m$
- N≥13 band photometry ($0.3\ \mu m < \lambda < 4.5\ \mu m$) to compliment the spectra and obtain robust physical properties (stellar masses, dust attenuation etc..)

→ McLure et al. (2018), Pentericci et al. (2018), Garilli et al. (2021)

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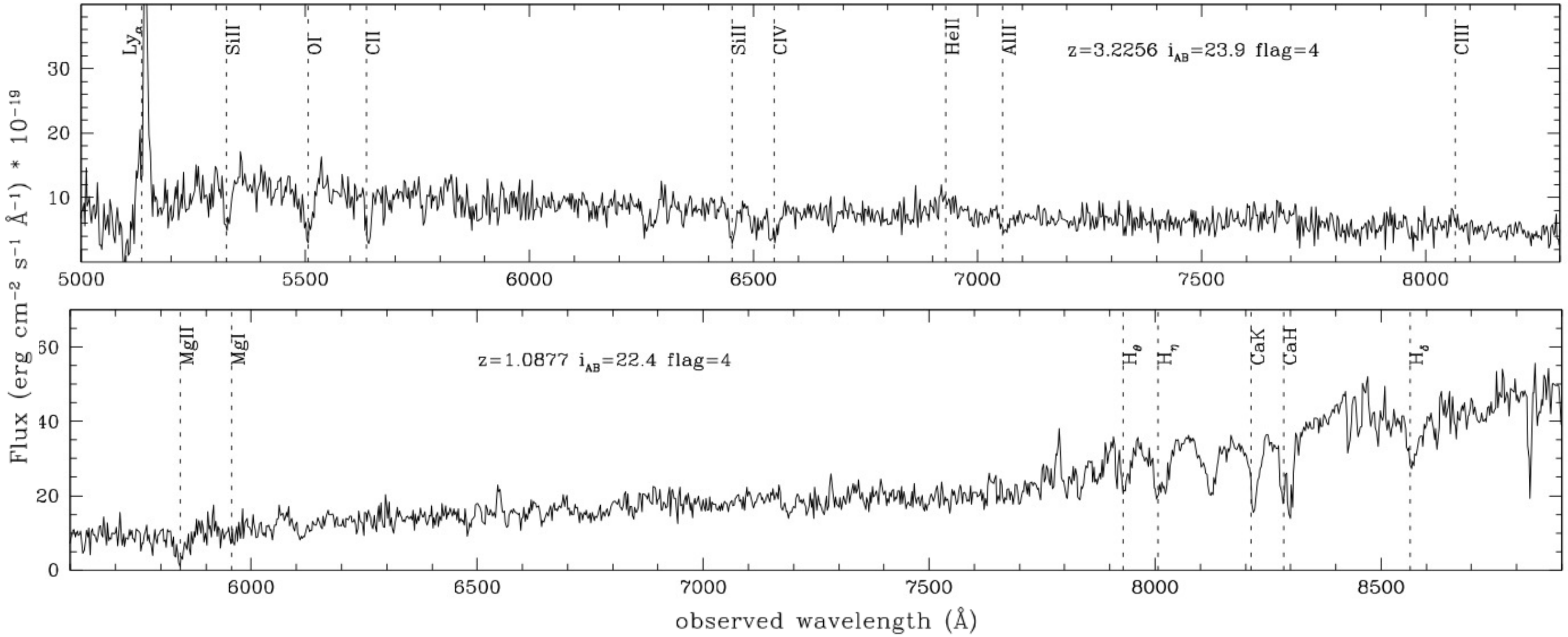

Garilli et al. (2021)
(VANDELS DR4)

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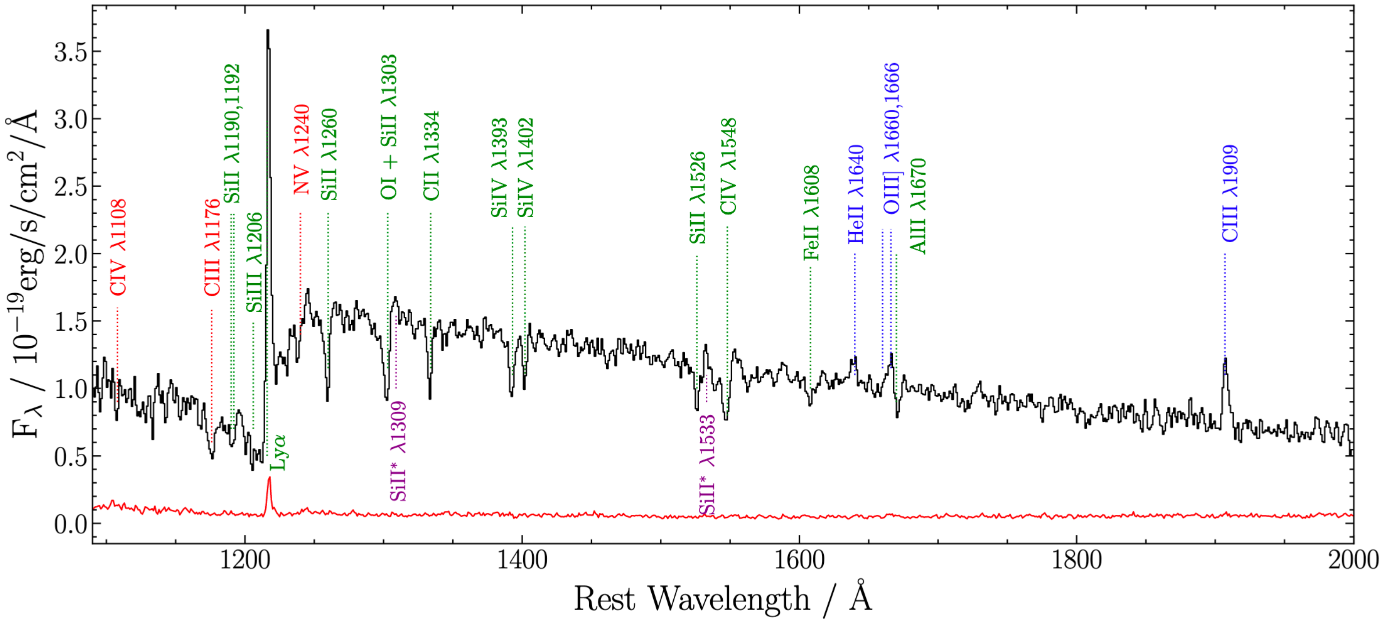
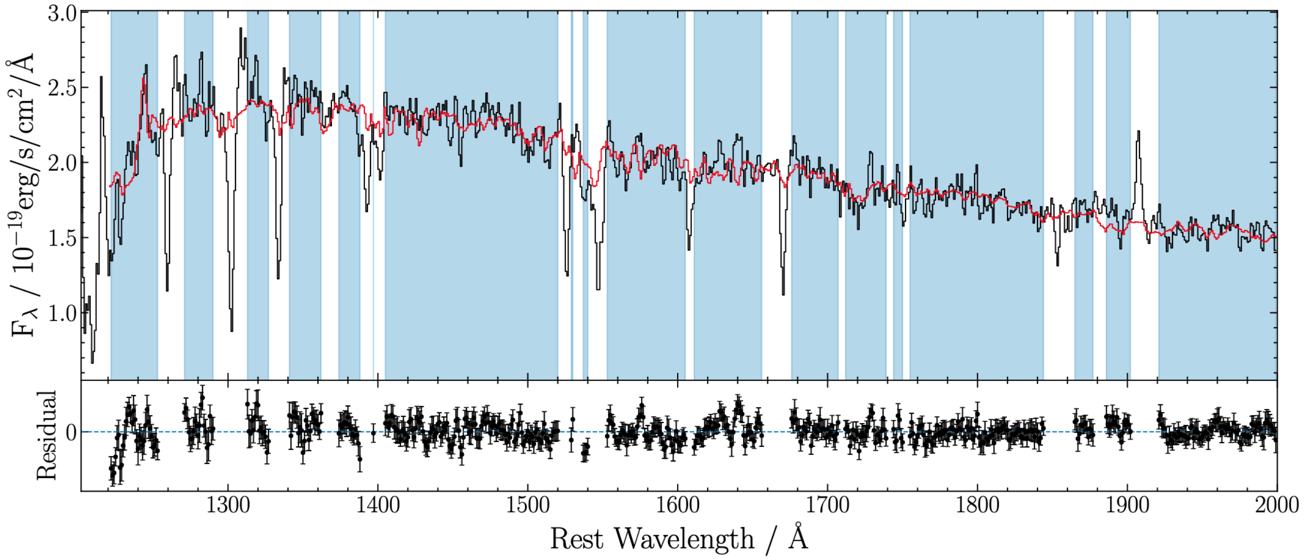


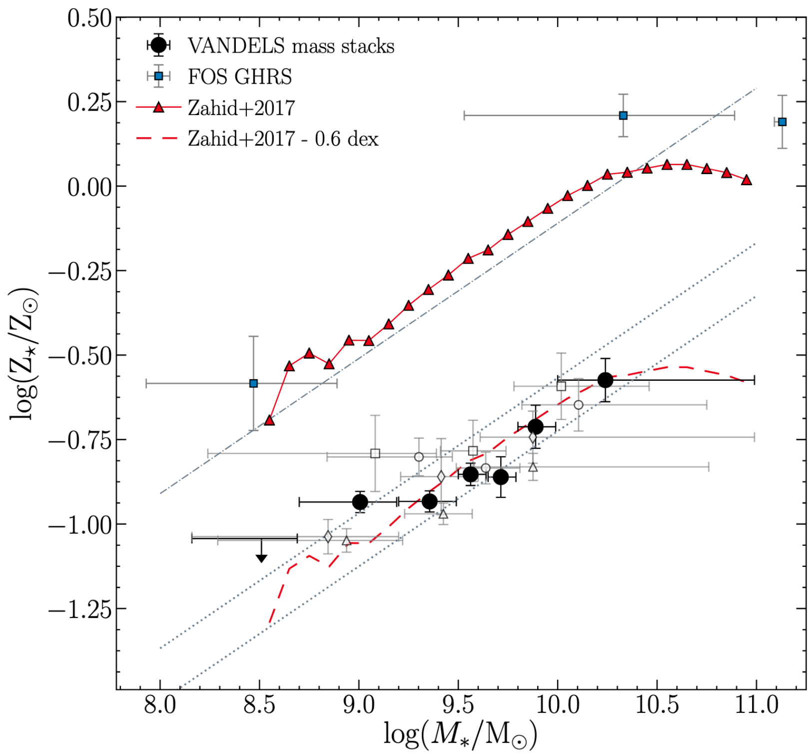
McLure et al. 2018

The VANDELS Survey – Key science results

An ESO VIMOS spectroscopic survey of the CANDELS UDS/CDFS fields

- A key goal for VANDELS was measuring properties of high-z SFGs including metallicity (Z_*) e.g., Cullen et al. (2019, 2020, 2021), Calabrò et al. (2021)





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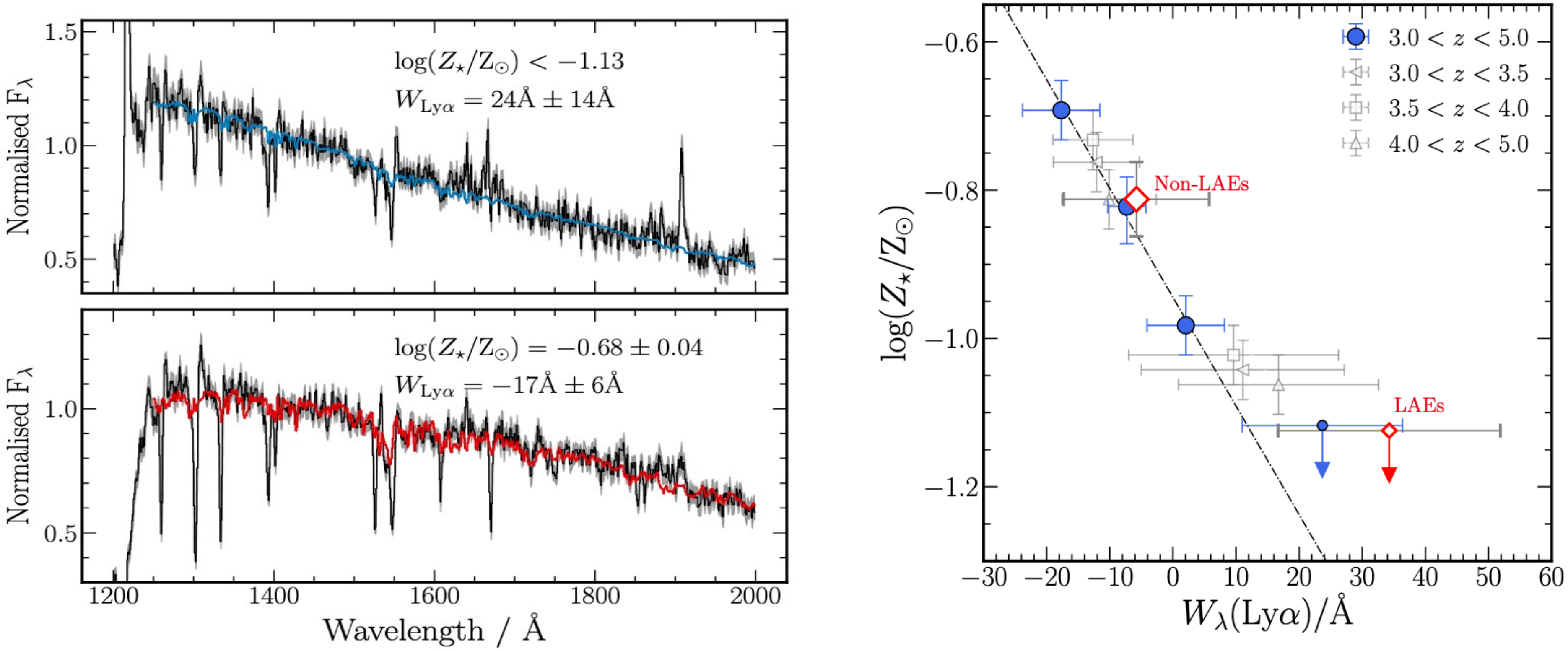
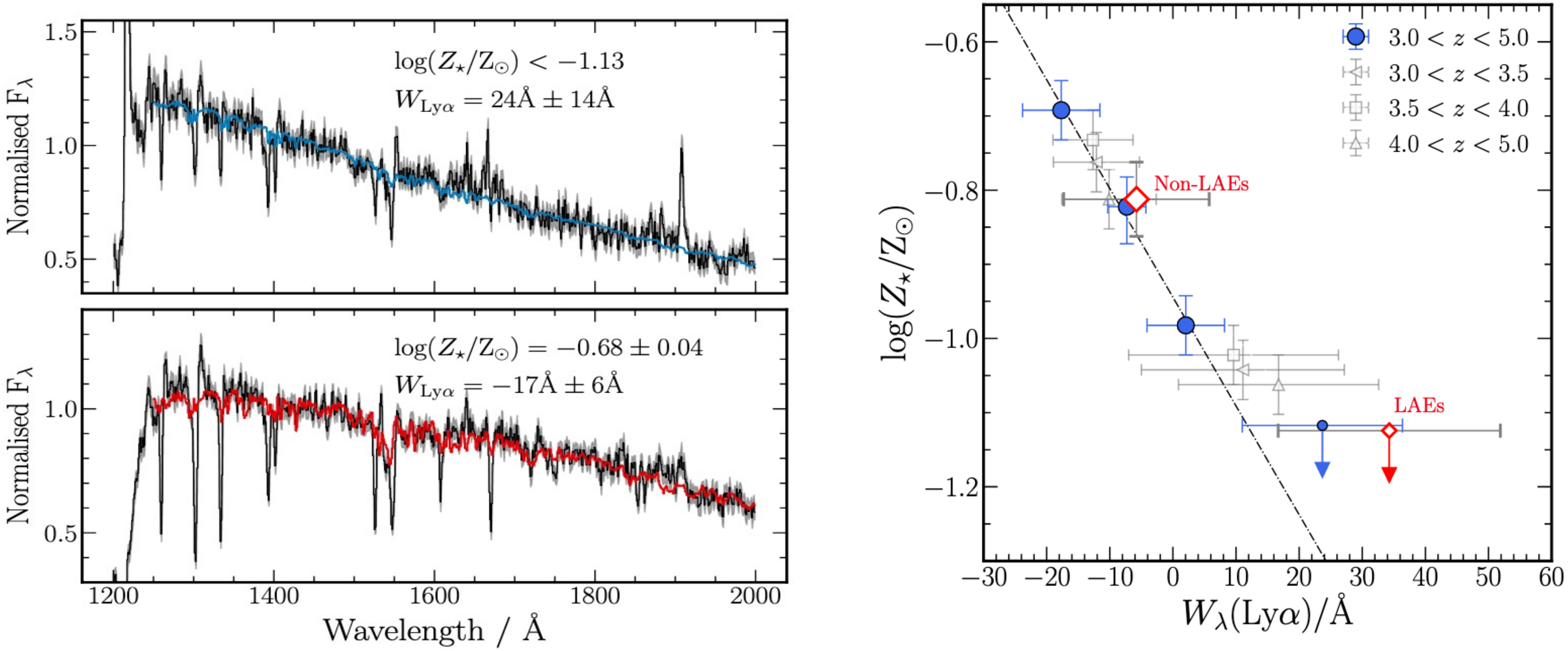


The VANDELS Survey – Key science results

An ESO VIMOS spectroscopic survey of the CANDELS UDS/CDFS fields

- A key goal for VANDELS was measuring properties of high-z SFGs including metallicity (Z_*) e.g., Cullen et al. (2019, 2020, 2021), Calabrò et al. (2021)

  + studies on the evolution of passive galaxies and quenching mechanisms (Carnall et al., Hamadouche et al.)



The VANDELS Survey: the average LyC $f_{\rm esc}$ of SFGs at $z \simeq 3.5$

→ Begley et al. (2022), MNRAS, 513, 3510
→ Link to arXiv (2202.04088)

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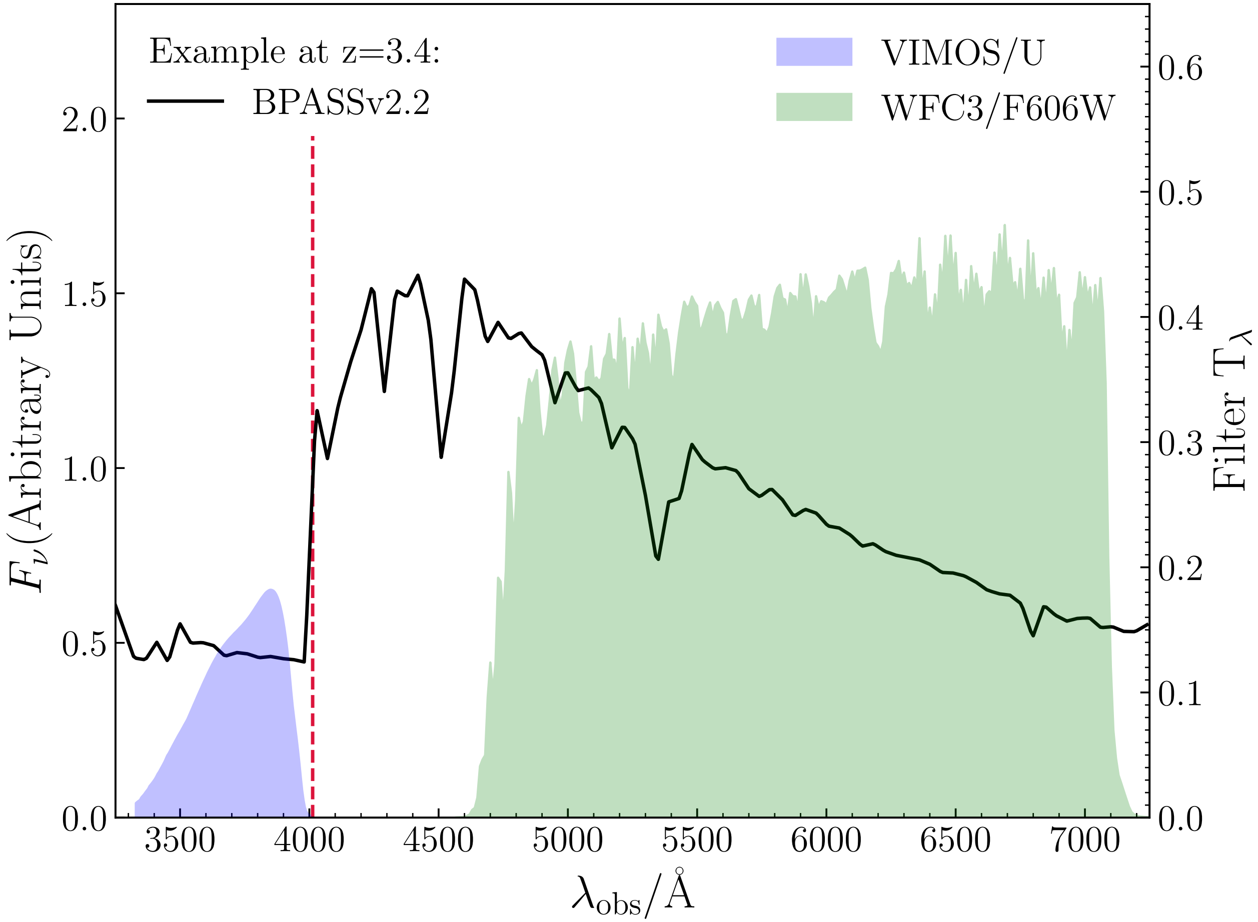
→ Begley et al. (2022), MNRAS, 513, 3510
→ Link to arXiv (2202.04088)

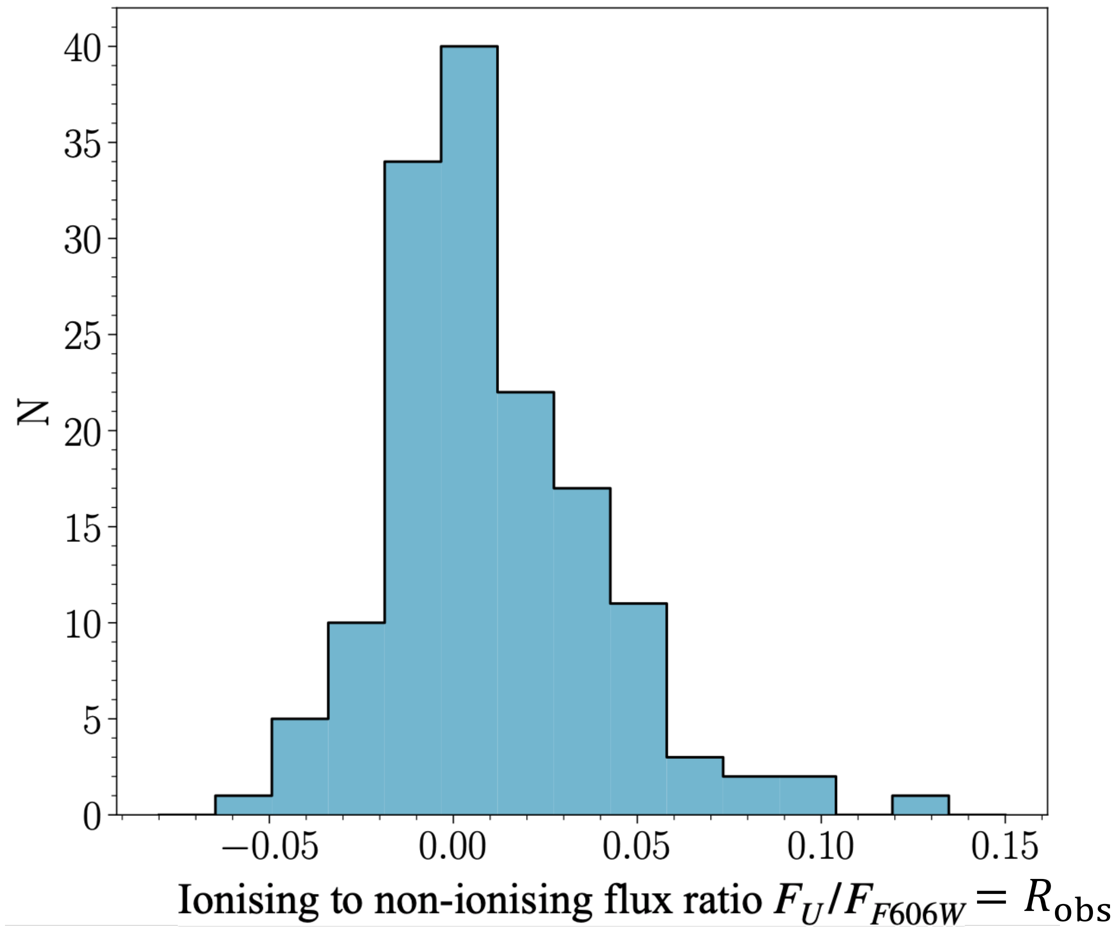
- We assemble a large sample of N=148 SFGs at $3.35 \leq z_{\rm spec} \leq 3.95$ from the VANDELS survey.

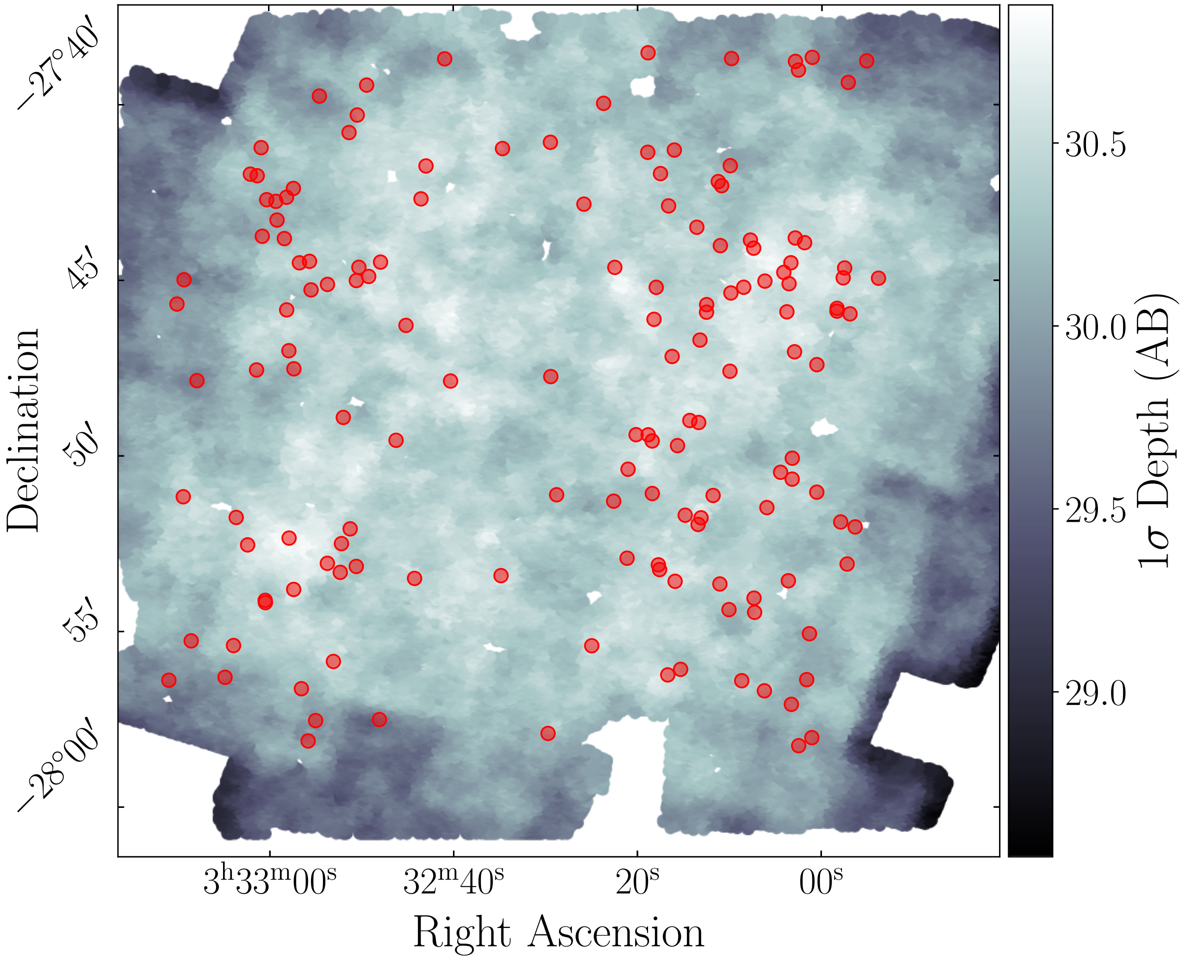
- By utilizing deep, publicly available VLT/VIMOS ***U***—band imaging and high-resolution HST/ACS ***F606W***—band imaging, we measure the ionizing to non-ionizing flux ratio for our galaxy sample → $R_{\rm obs}$



The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

- Robust photometric measurements on the carefully decontaminated sample of galaxies.





Extracting $f_{\rm esc}$ constraints from the $R_{\rm obs}$ distribution:

To compare with $R_{\rm obs}$ we construct a realistic empirically motivated model governed by the equation:

$$R_{\rm obs} = f_{\rm esc} \times e^{-\tau_{\lambda}^{\rm HI}} \times R_{\rm int} \times 10^{0.4 A_{\rm UV}}$$

The VANDELS Survey: the average LyC $f_{\rm esc}$ of SFGs at $z \simeq 3.5$

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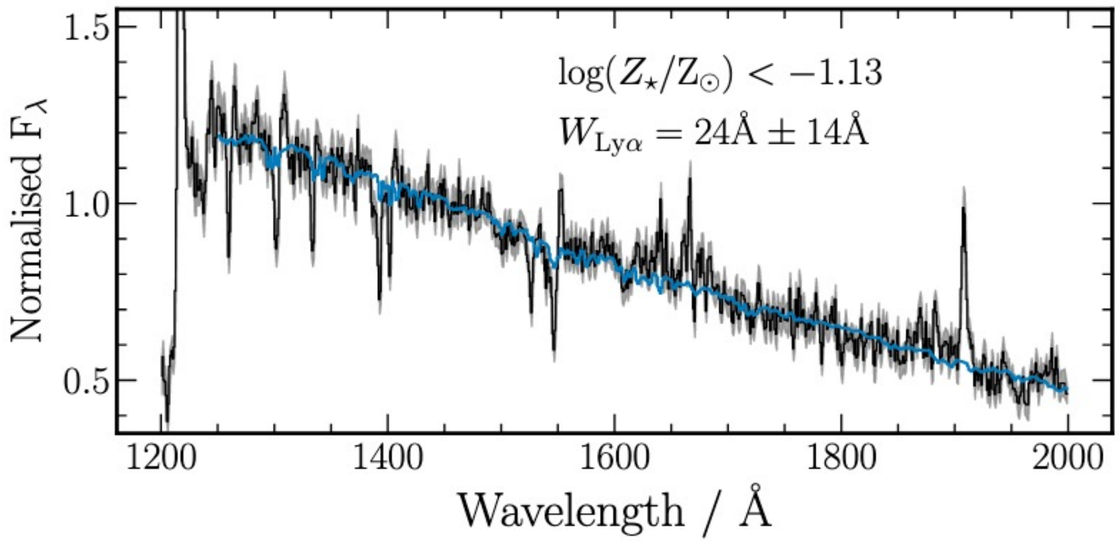
→ $\boldsymbol{R_{\rm int}}$ is estimated from a fiducial SED model

Cullen et al. (2019) showed that a $\simeq 0.07\ Z_\odot$ BPASSv2.2 model is consistent with VANDELS SFGs at $z \simeq 3.0$–5.0



The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

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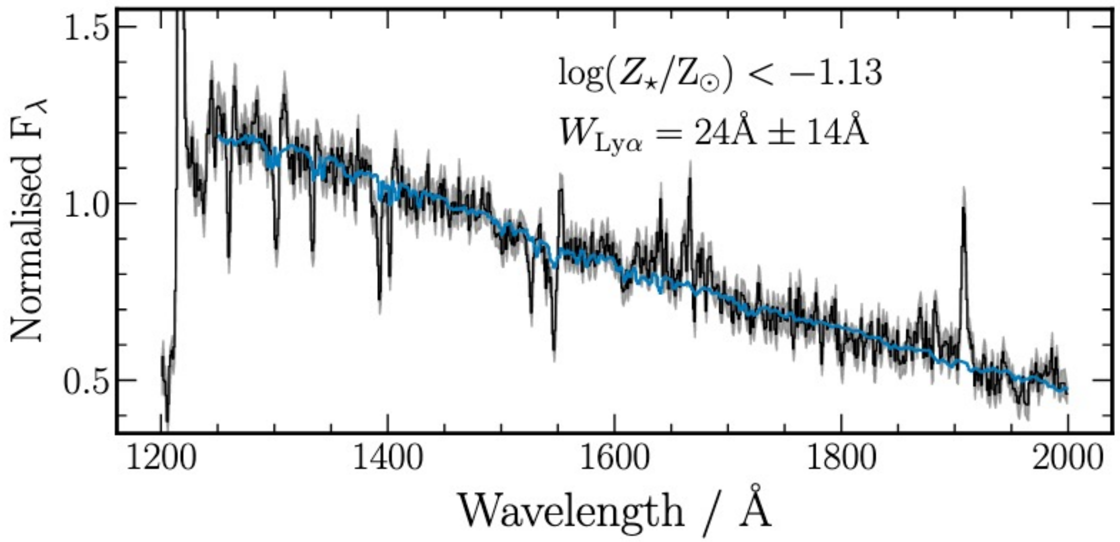
→ $\mathbf{A_{UV}}$ is calculated on an individual galaxy-by-galaxy basis using the UV spectral slope (β_{obs}) + an assumed dust attenuation law e.g., Calzetti et al. (2000)



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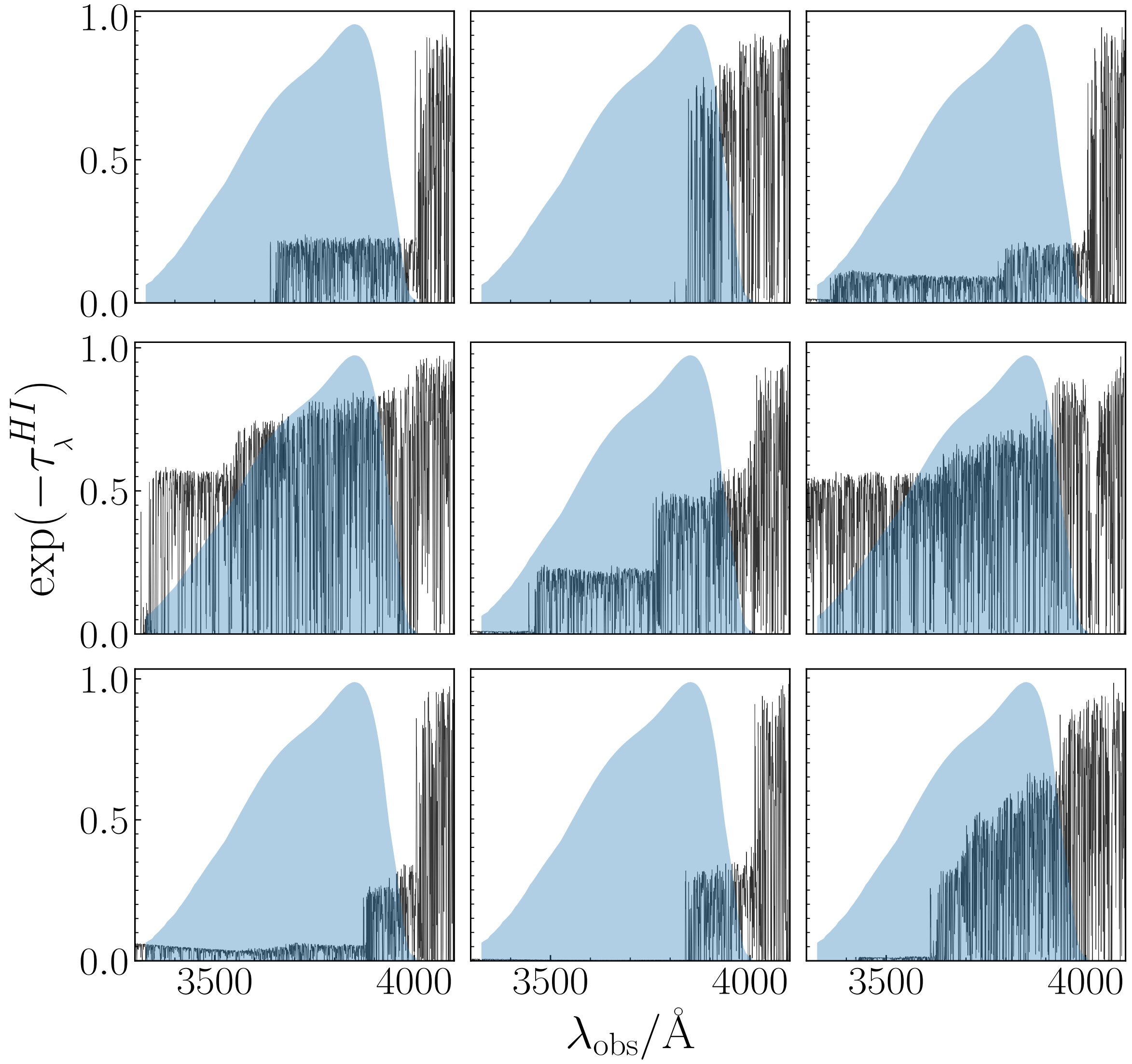
→ $e^{-\tau_\lambda^{HI}}$ which parameterises the optical depth of the IGM+CGM, has *largest influence* on the derived f_{esc} due to its large stochasticity

→ To overcome this challenge, we generate a large number of representative transmission sightlines e.g., Inoue et al. (2014), Steidel et al. (2018)



The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

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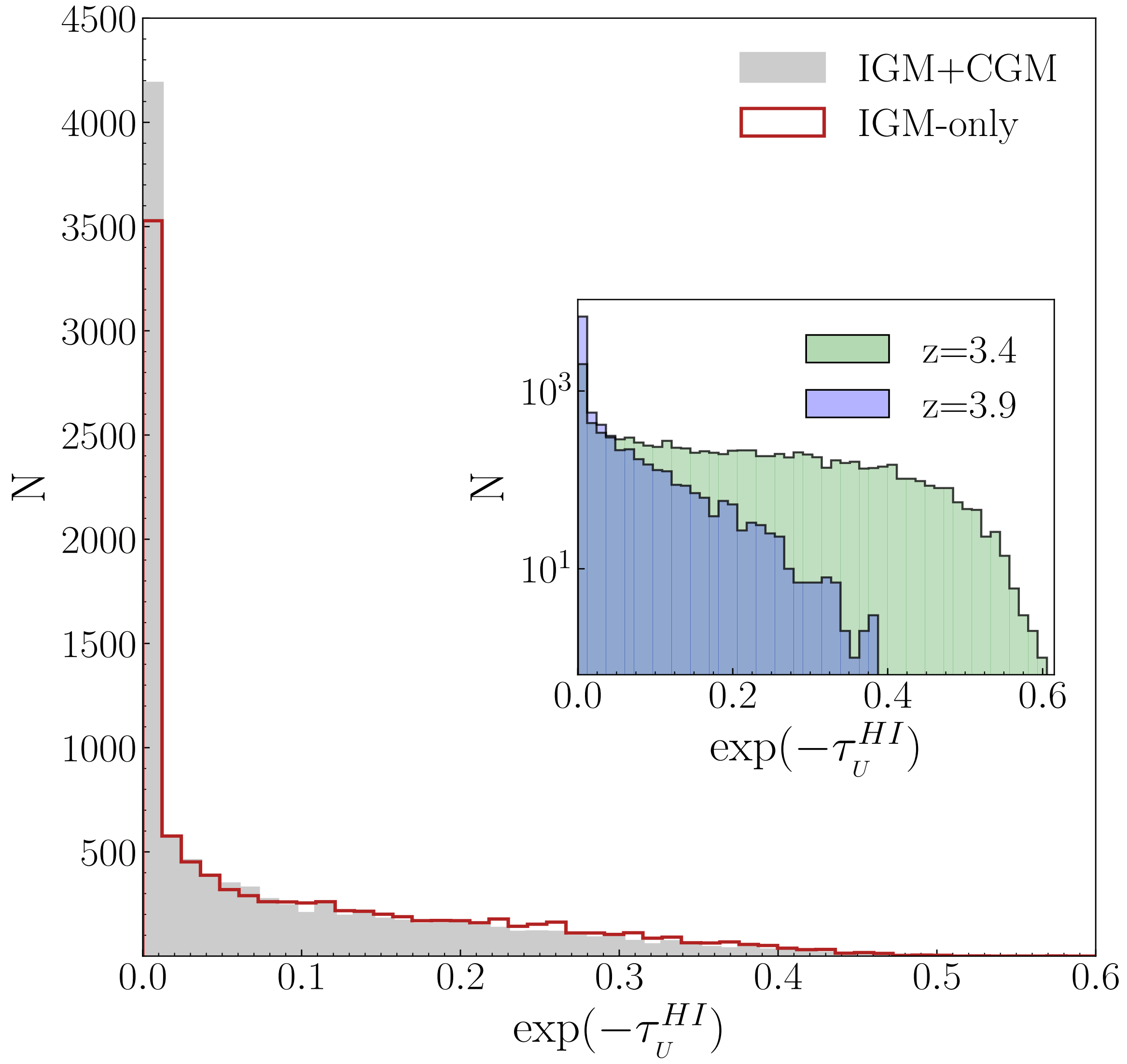
→ This allows a more rigorous ***statistical*** approach in our model



The VANDELS Survey: the average LyC $f_{\rm esc}$ of SFGs at $z \simeq 3.5$

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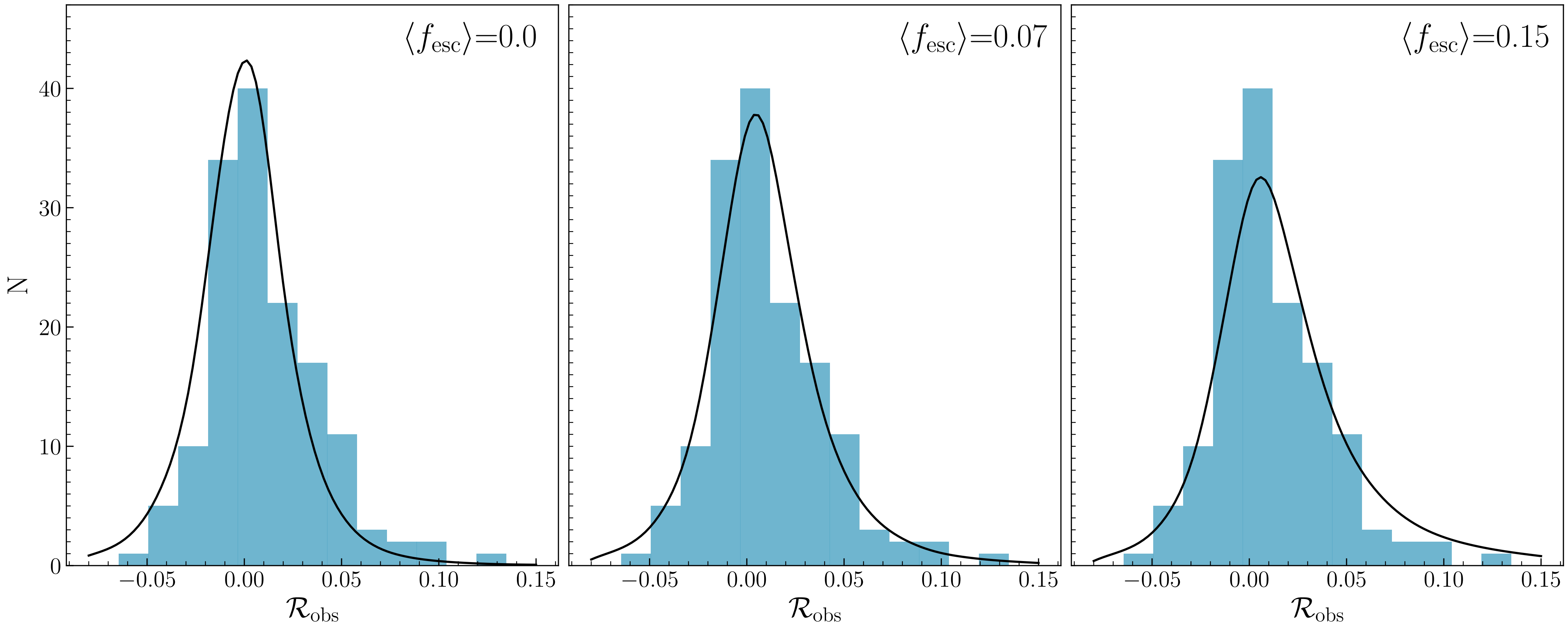
→ Now generate a large N of model $R_{\rm obs}$ distribution realisations over a grid of $\langle f_{\rm esc} \rangle$

The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

Extracting f_{esc} constraints from the R_{obs} distribution:

→ Now generate a large N of ***model*** "R_{obs}" distribution realisations over a grid of $\langle f_{esc} \rangle$



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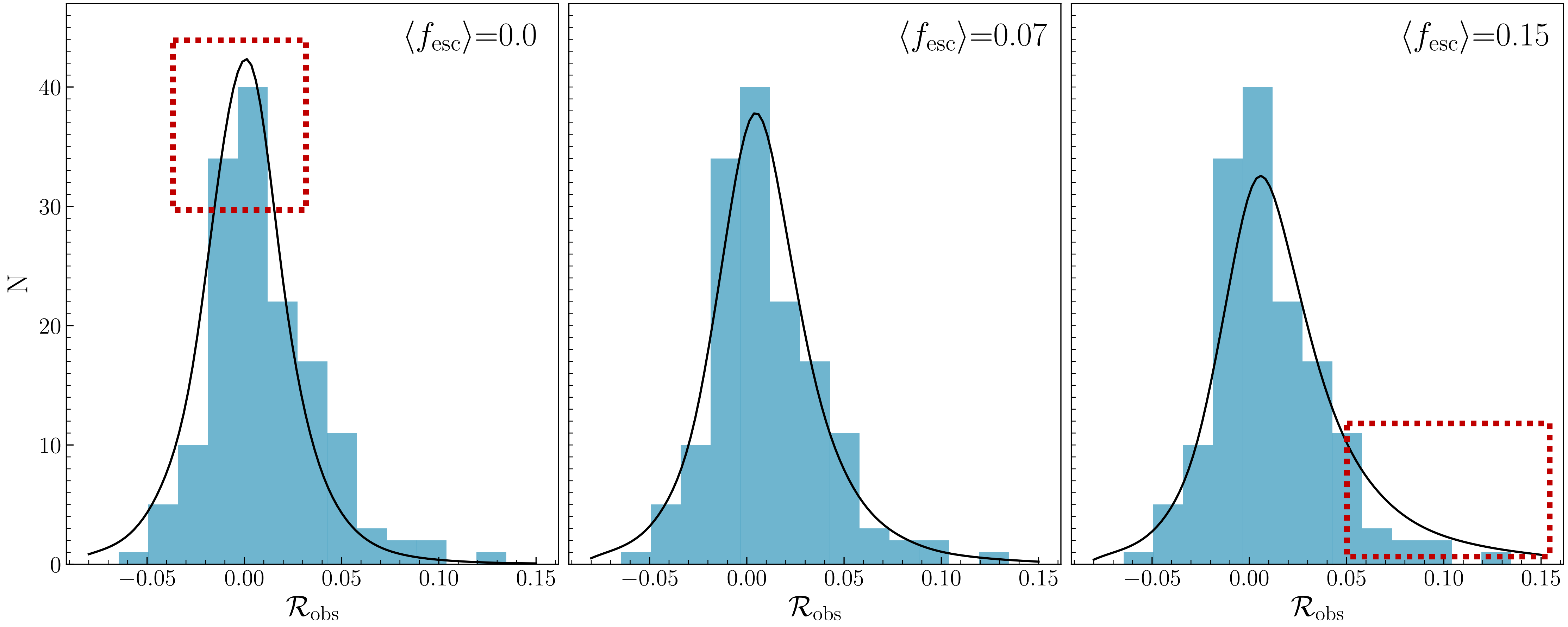
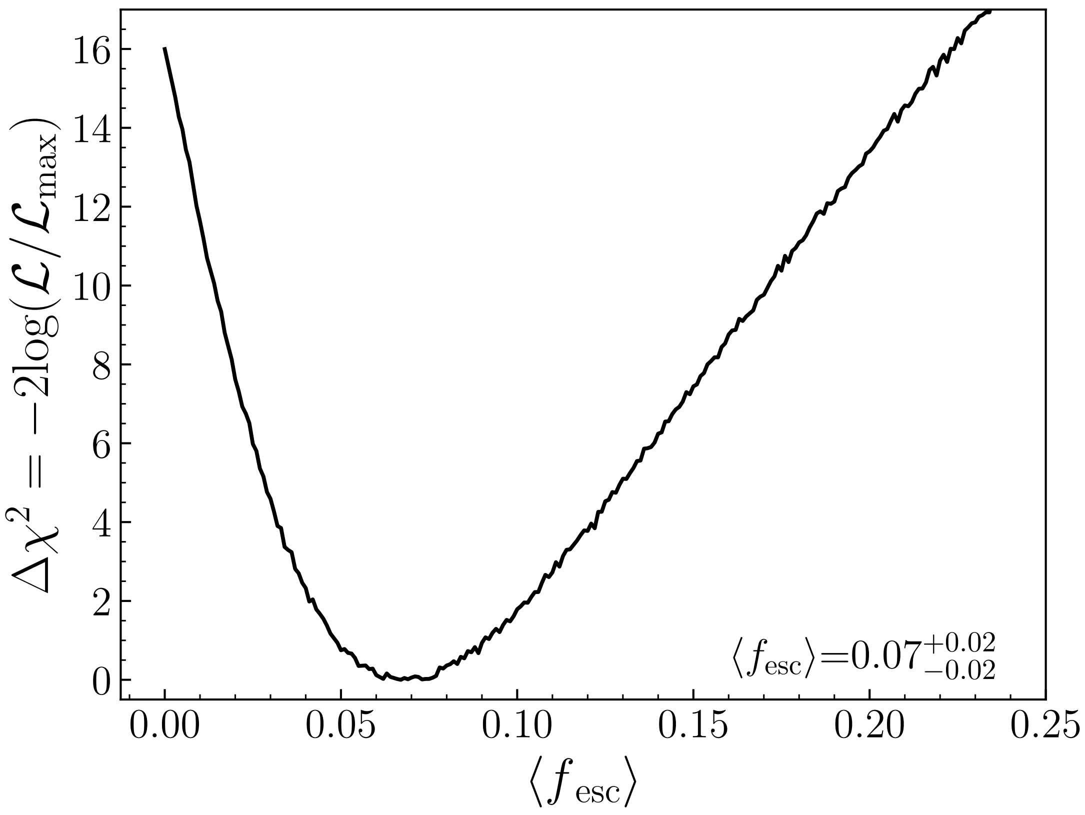
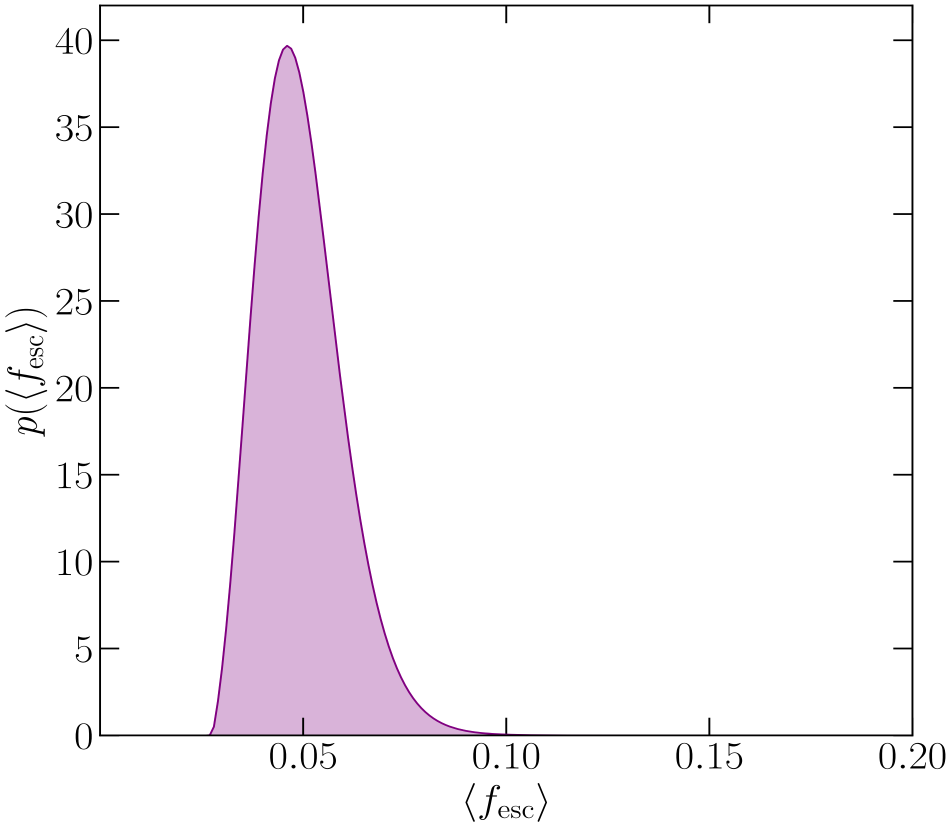


Extracting f_{esc} constraints from the R_{obs} distribution:

→ Perform a statistical comparison to the observed R_{obs} distribution;

1) Binned maximum $\mathcal{L}$ 2) Bayesian inference





The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

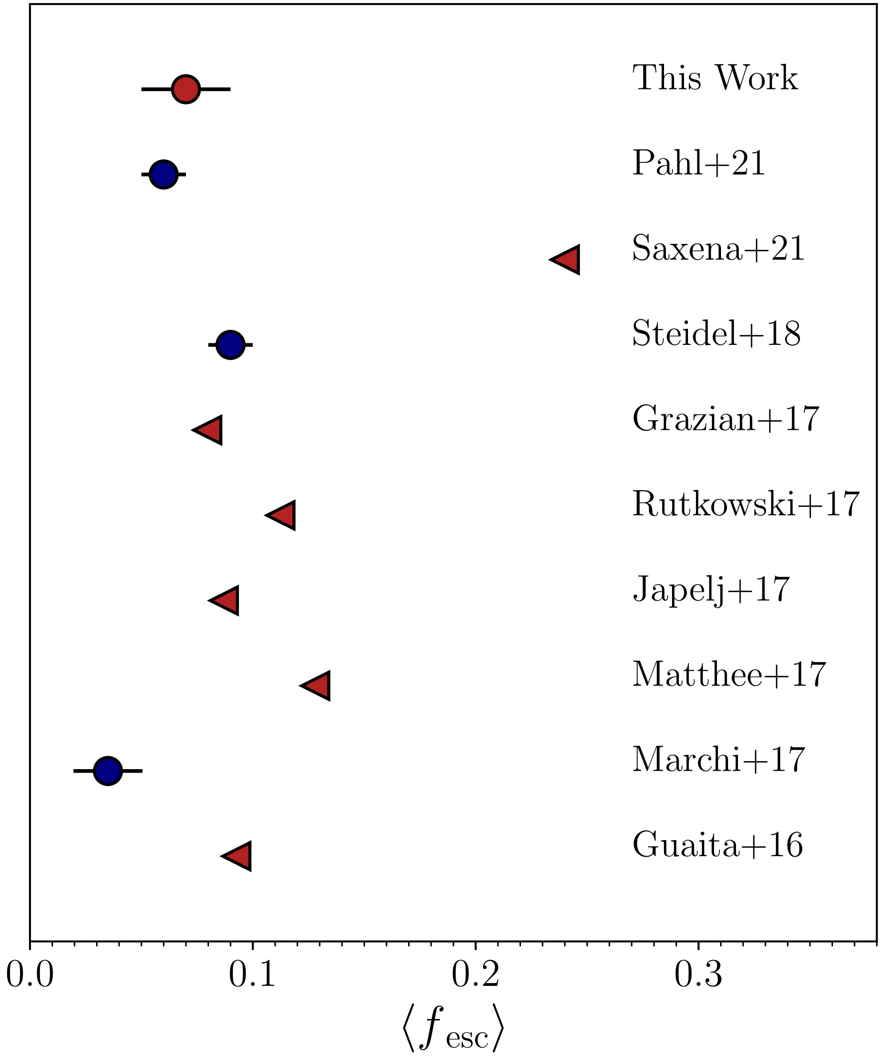
Comparing our constraints with existing literature:

→ Here, we have established a $\gtrsim 3.5\sigma$ $\langle f_{esc} \rangle$ constraint for VANDELS SFGs from ground-based *U*–band photometry

For the time first at this redshift

→ Excellent agreement with deep ***spectroscopic*** results
e.g., Pahl et al. (2021), Steidel et al. (2018), Marchi et al. (2017)

→ Massive improvement over ***photometric*** constraints that typically only provide upper limits on $\langle f_{esc} \rangle$ based on stacking



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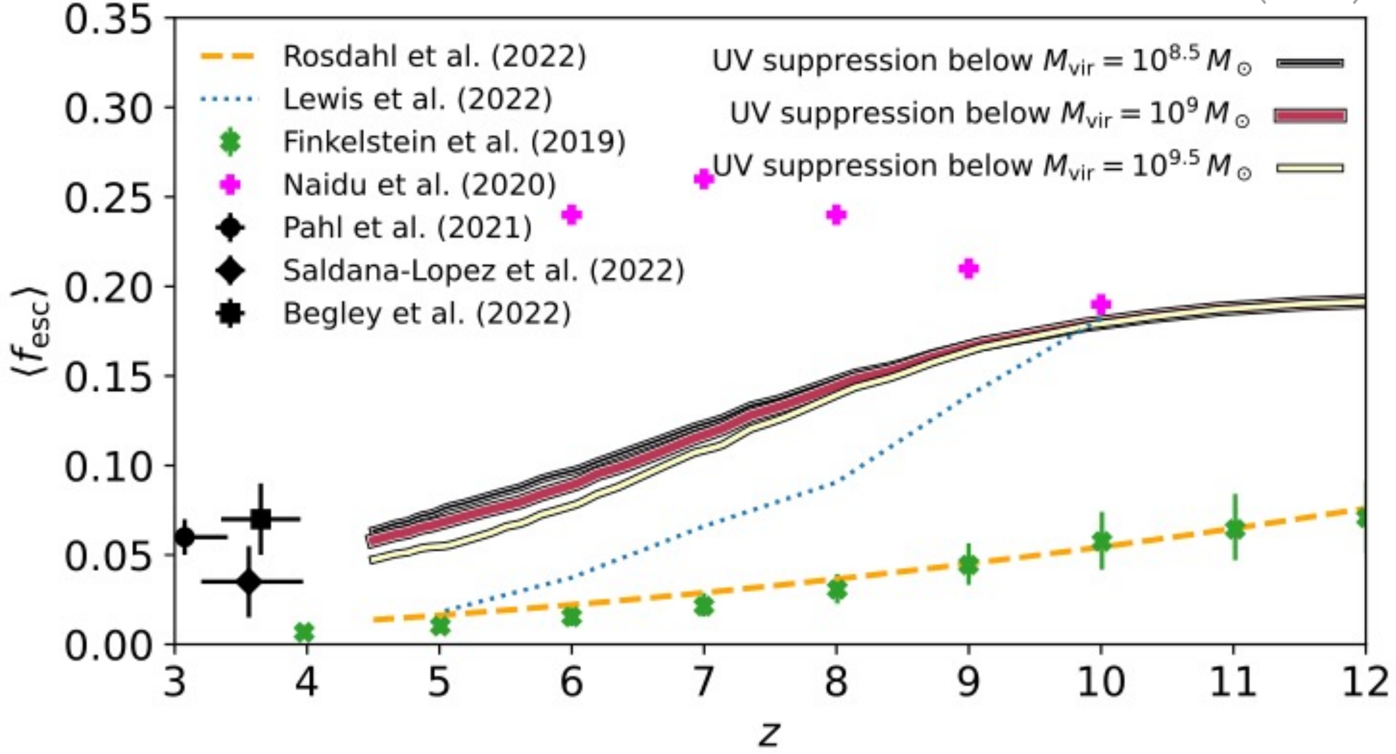
Trebitsch et al. (2022)



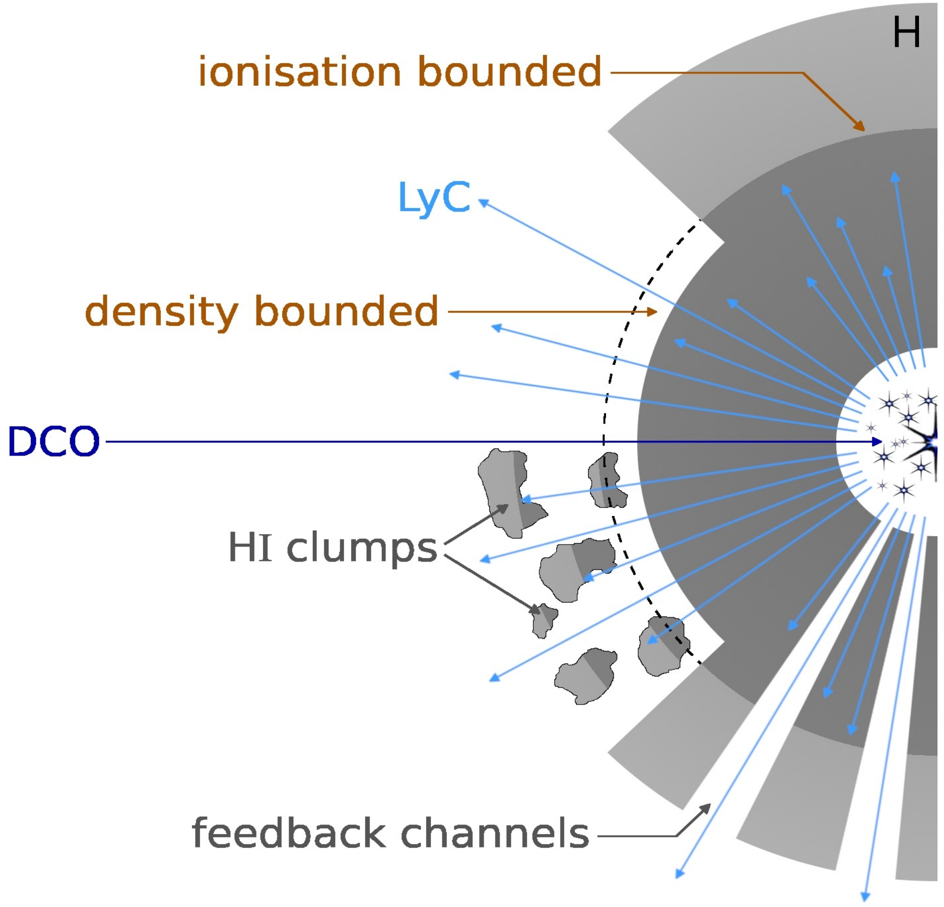
The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

What else can we learn about the galaxies that emit LyC?

→ A number of other physical properties have been investigated for their connection to LyC and $\langle f_{esc} \rangle$

Lyα has been particularly promising …
e.g., – observationally from local LCEs and at $z \simeq 3$ with KLCS
– simulations: Dijkstra et al. (2016), Maji et al. (2022)
– indirectly from FUV spectra

Reddy et al. (2016), Verhamme et al (2017), Gazagnes et al. (2020)
Kimm & Cen (2019), Saldana-Lopez et al. (2022) **+ *more***



Credit: Enders et al. (2023)

The VANDELS Survey: the average LyC f_{esc} of SFGs at $z \simeq 3.5$

What else can we learn about the galaxies that emit LyC?

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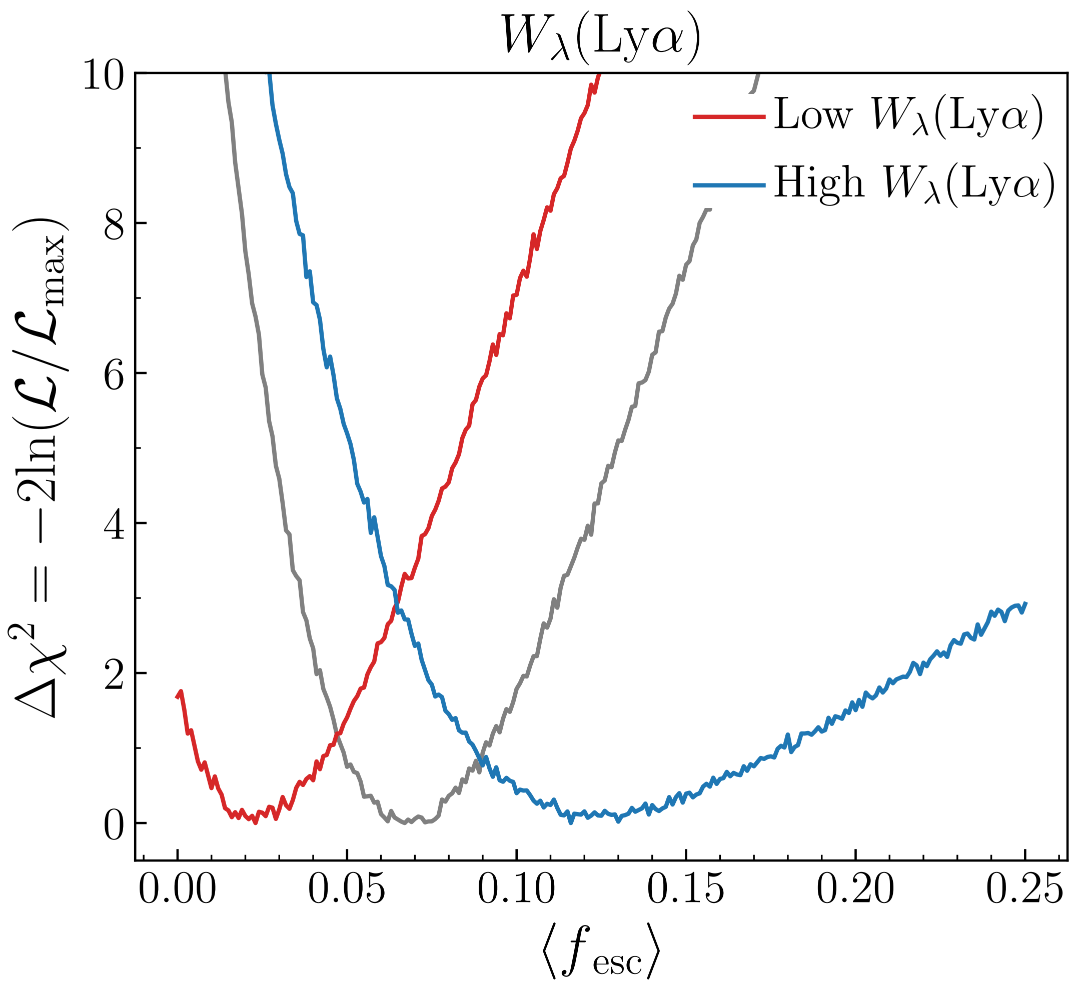
Lyα has been particularly promising …

Motivated by this, we split our sample in two based on their Lyα equivalent width and estimate $\langle f_{esc} \rangle$ as before:

Upper W_λ(Lyα) : $\langle f_{esc} \rangle = 0.12^{+0.06}_{-0.04}$

Lower W_λ(Lyα) : $\langle f_{esc} \rangle = 0.02 \pm 0.02$



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What else can we learn about the galaxies that emit LyC?

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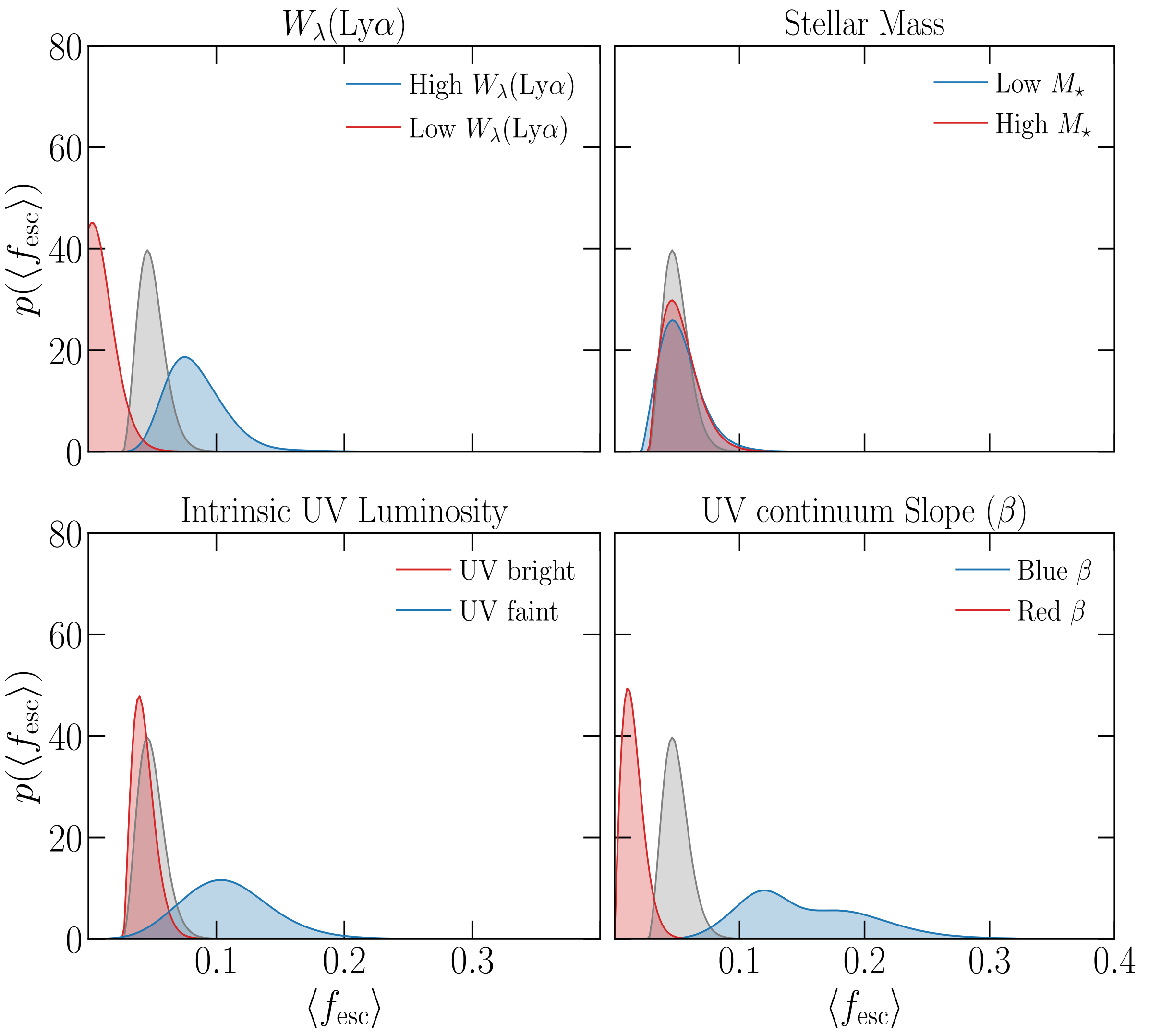
Other likely indirect travers include the ***dust*** content (traced by $\beta_{\rm obs}$) and ***stellar mass*** (M_*)

e.g., both physical properties have been linked to the escape of Lyα; Cullen et al. (2019), Du et al. (2020)

→ Investigating for any potential dependence on the ***intrinsic UV luminosity*** is also highly relevant for EOR studies.



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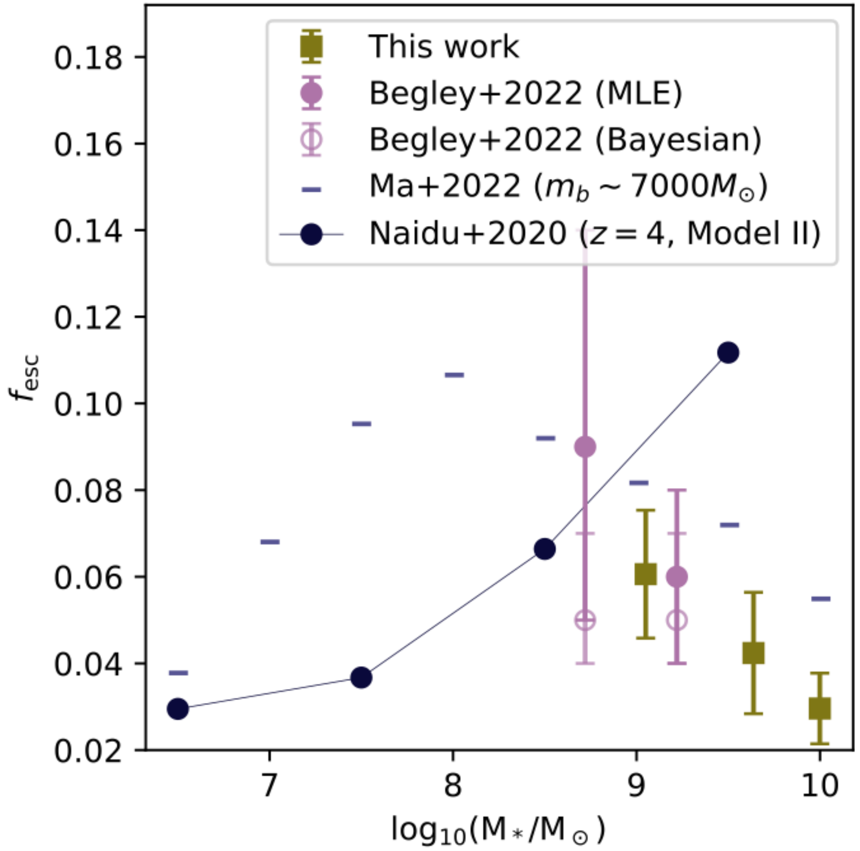
Pahl et al. (2022)



What else can we learn about the galaxies that emit LyC?

To summarise Part I …

- ✓ We have established a $\gtrsim 3.5\sigma$ $\langle f_{\rm esc} \rangle$ constraint for VANDELS SFGs from ground-based *U*–band photometry, combining a carefully selected sample free from L.O.S. contamination and an empirically motivated model.

- ✓ After splitting the sample based on properties that show potential links with LyC escape, we find that the low-dust, UV faint population of galaxies common at $z > 6$ are likely to display $\langle f_{esc} \rangle \gtrsim 0.1$, the threshold often quoted as necessary to drive reionization.

Begley et al. (2022)
2202.04088

The VANDELS Survey: the average LyC $f_{\rm esc}$ of SFGs at $z \simeq 3.5$

What else can we learn about the galaxies that emit LyC?

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Look out for future work in an Dawn (Copenhagen) – Edinburgh collaboration expanding this work for $g(f_{\rm esc})$
Kreilgaard, Mason, Cullen, Begley et al. (*in prep)*

The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq$4–5

→ We still lack a comprehensive understanding of the physical mechanisms facilitating the escape of LyC

→ Motivated by the success of linking Lyα and LyC, we investigate the Lyα-LyC connection by assembling a sample of N≈130 SFGs from VANDELS in the redshift range $3.85 \leq z_{spec} \leq 4.95$

→ Begley et al. (2023), MNRAS, ***Accepted***
→ Link to arXiv (2306.03916)

The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

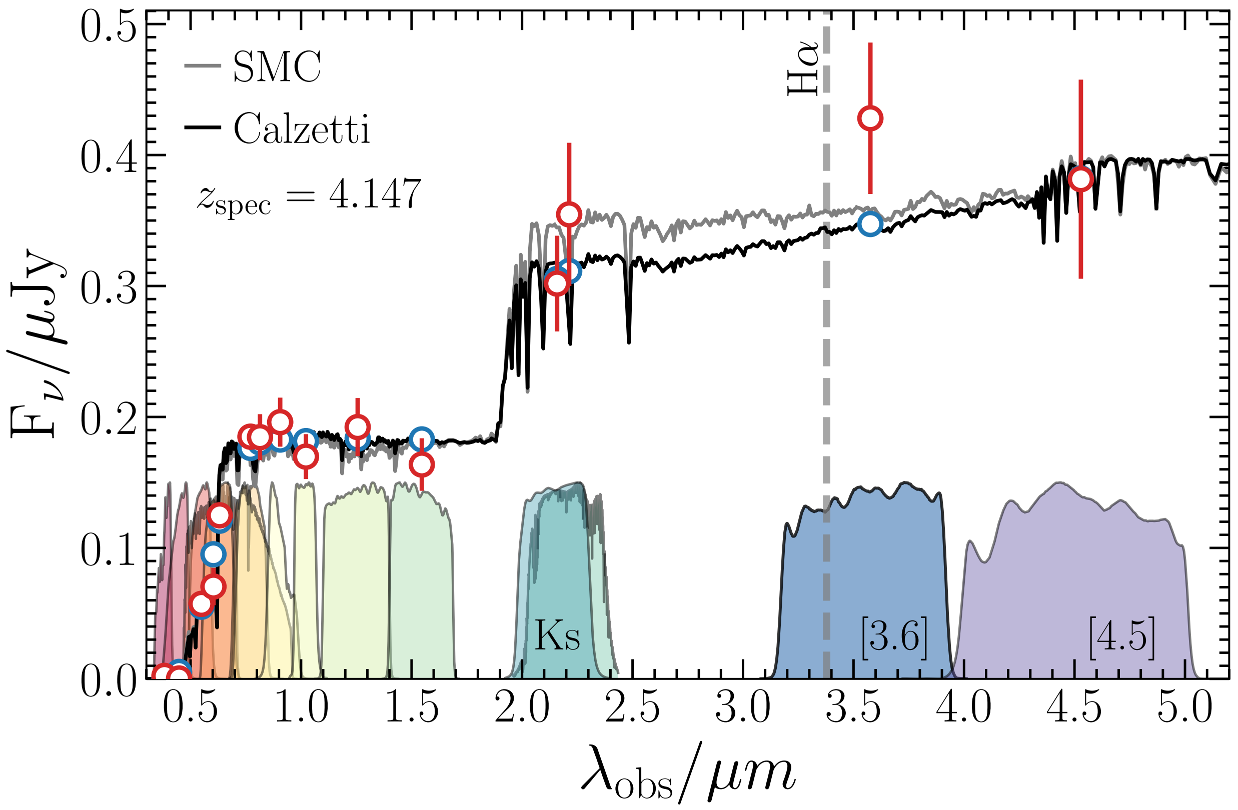
The Lyα escape fraction of VANDELS galaxies $f_{\rm esc}^{\rm Ly\alpha}$:

→ VANDELS provides high SNR measurements of the ***observed*** **Lyα** flux as well as robust $z_{\rm spec}$

→ Make use of the multi-wavelength photometry available for VANDELS to perform SED fitting

FAST++; Schreiber et al. (2018)
– Bruzual & Charlot (2003) stellar population models
– Chabrier (2003) IMF, $Z/Z_* = 0.2$–0.4, CSFH

→ Use the photometric-excess technique with the IRAC/3.6μm photometry to measure the **Hα flux**



The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

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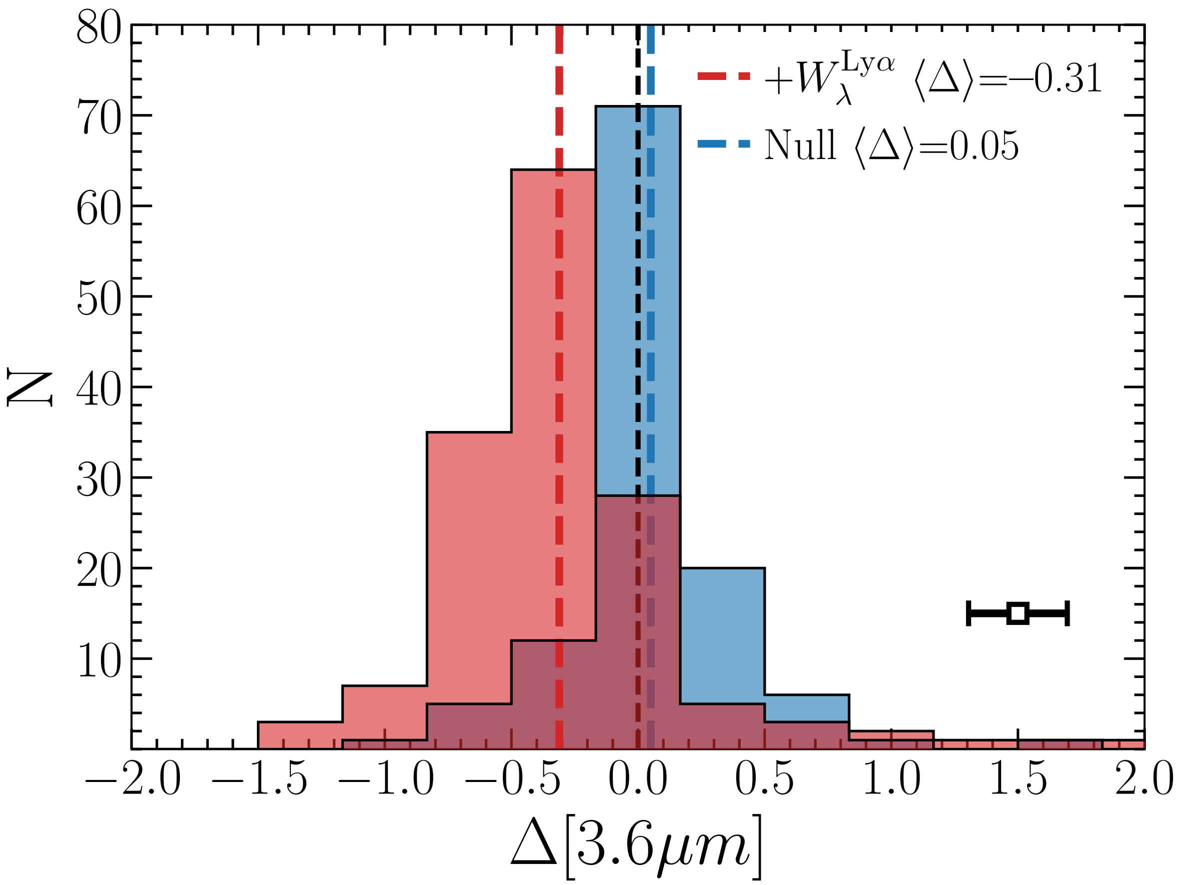
→ Use the photometric-excess technique with the IRAC/3.6μm photometry to measure the **Hα flux**

∴ we have an estimate of the ***intrinsic* Lyα** flux

$$f_{esc}^{Ly\alpha} = \frac{F_\nu^{obs}(Ly\alpha)}{F_\nu^{intr}(Ly\alpha)} = \frac{F_\nu^{obs}(Ly\alpha)}{8.7 \times F_\nu^{intr}(H\alpha)}$$

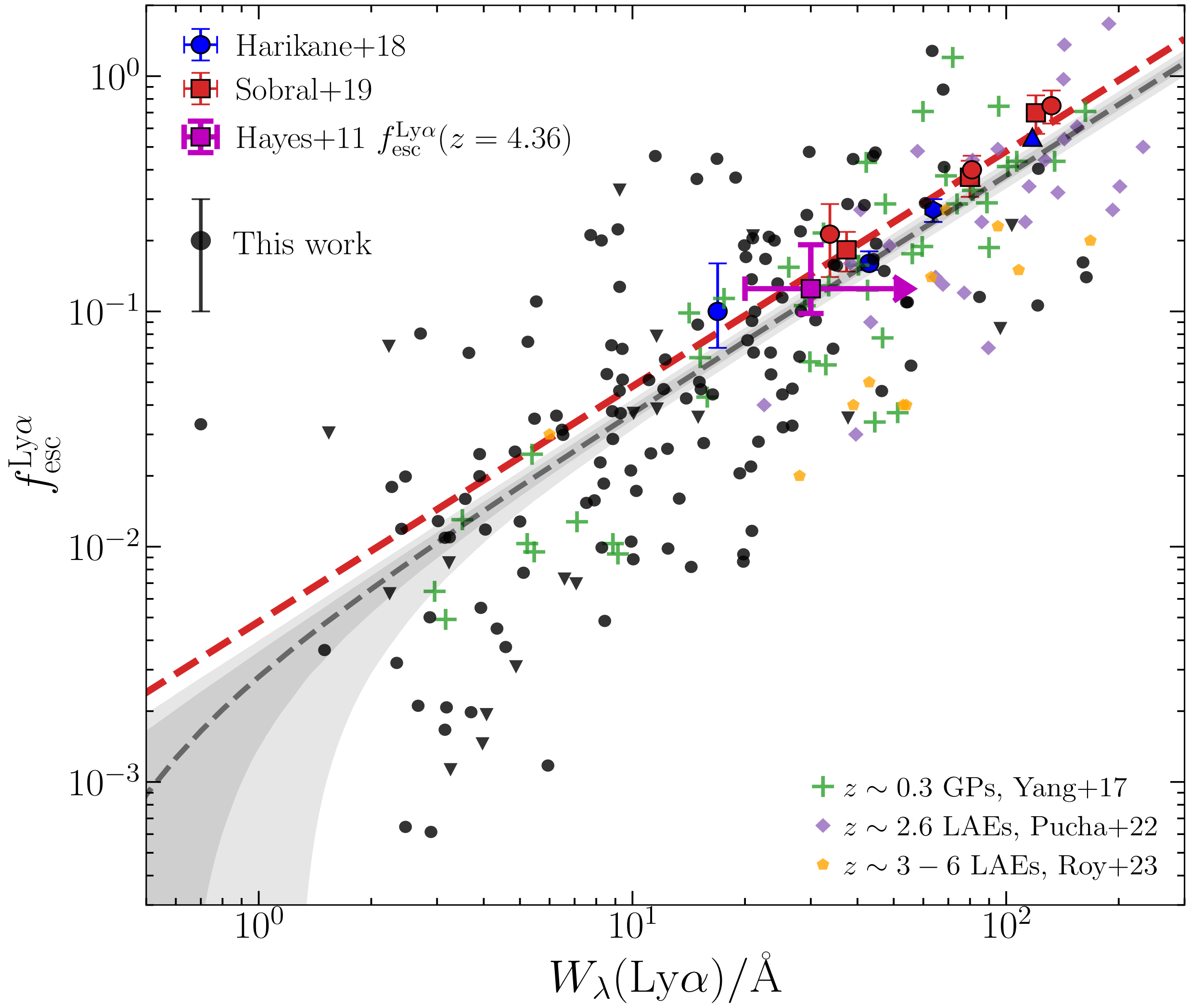
Case–B + Wuyts et al. (2013)



The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

The Lyα escape fraction of VANDELS galaxies $f_{esc}^{Ly\alpha}$:

- ✓ $W_\lambda(\mathrm{Ly\alpha}) - f_{esc}^{Ly\alpha}$ relation consistent with that found at $z \simeq 0.3 - 2.6$ by Sobral et al. (2019)
- ✓ Extends to weak LAEs with $W_\lambda(\mathrm{Ly\alpha}) \lesssim 20$ Å
- ✓ In good agreement with expected $f_{esc}^{Ly\alpha}(z)$ evolution presented Hayes et al. (2011)

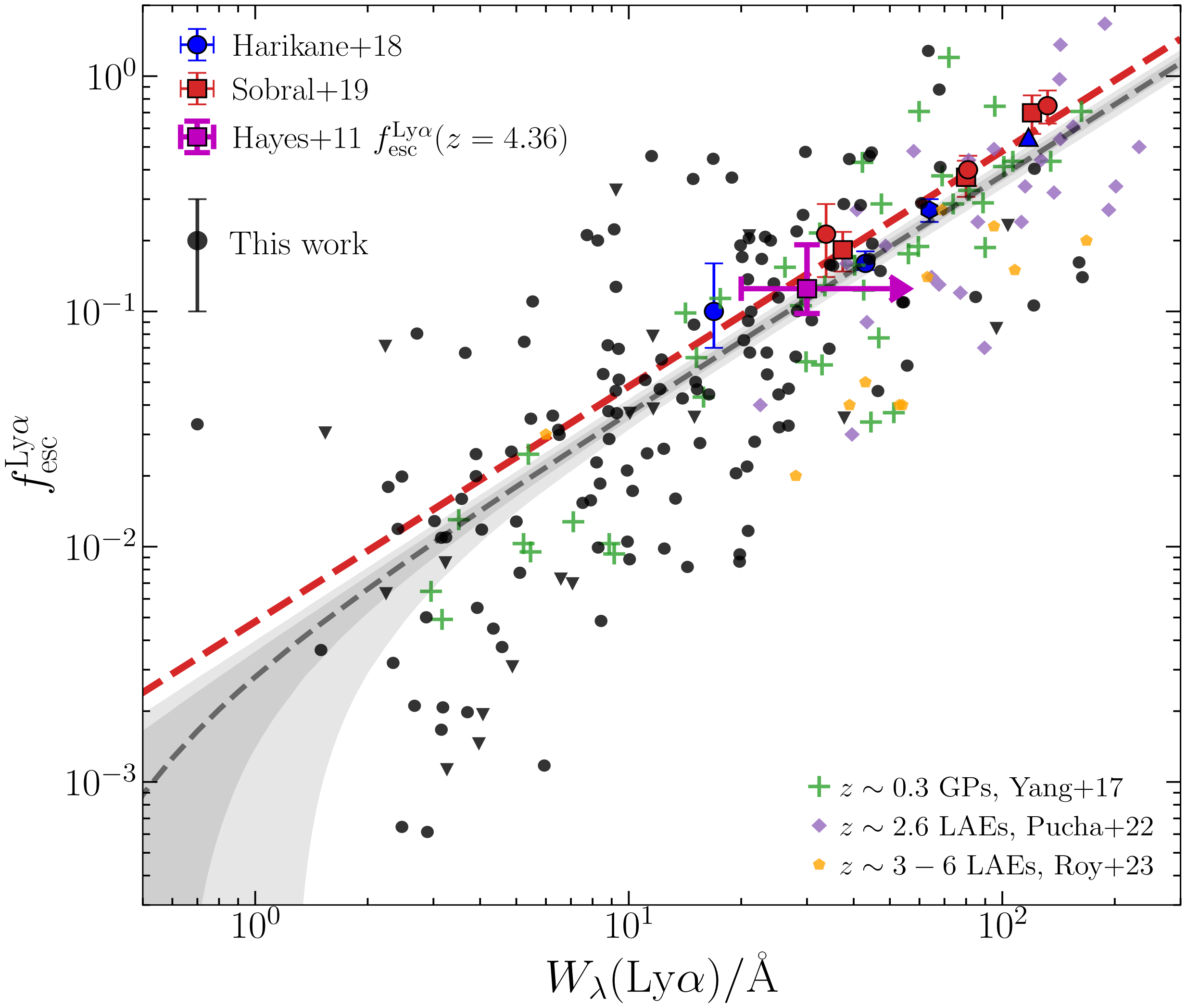


The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

The Lyα escape fraction of VANDELS galaxies $f_{esc}^{Ly\alpha}$:

- ✓ $W_\lambda(\mathrm{Ly}\alpha) - f_{esc}^{Ly\alpha}$ relation consistent with that found at $z \simeq 0.3 - 2.6$ by Sobral et al. (2019)
- ✓ Extends to weak LAEs with $W_\lambda(\mathrm{Ly}\alpha) \lesssim 20$ Å
- ✓ In good agreement with expected $f_{esc}^{Ly\alpha}(z)$ evolution presented Hayes et al. (2011)

The lack of evolution in the $W_\lambda(\mathrm{Ly}\alpha) - f_{esc}^{Ly\alpha}$ relation implies that the physical processes governing the production and escape of Lyα photons from low-metallicity, high ξ_{ion} galaxies do not vary significantly over ≃11Gyr (≈90%) of cosmic time



The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4-5$

The Lyα escape fraction of VANDELS galaxies $f_{esc}^{Ly\alpha}$:

→ Now we want to investigate how $f_{esc}^{Ly\alpha}$ correlates with f_{esc}^{LyC}

To place constraints on f_{esc}^{LyC}, we use the empirical relation established between low-ionization-state ISM line strength (W_{LIS}) and f_{esc}^{LyC} in LzLCS by Saldana-Lopez et al. (2022)

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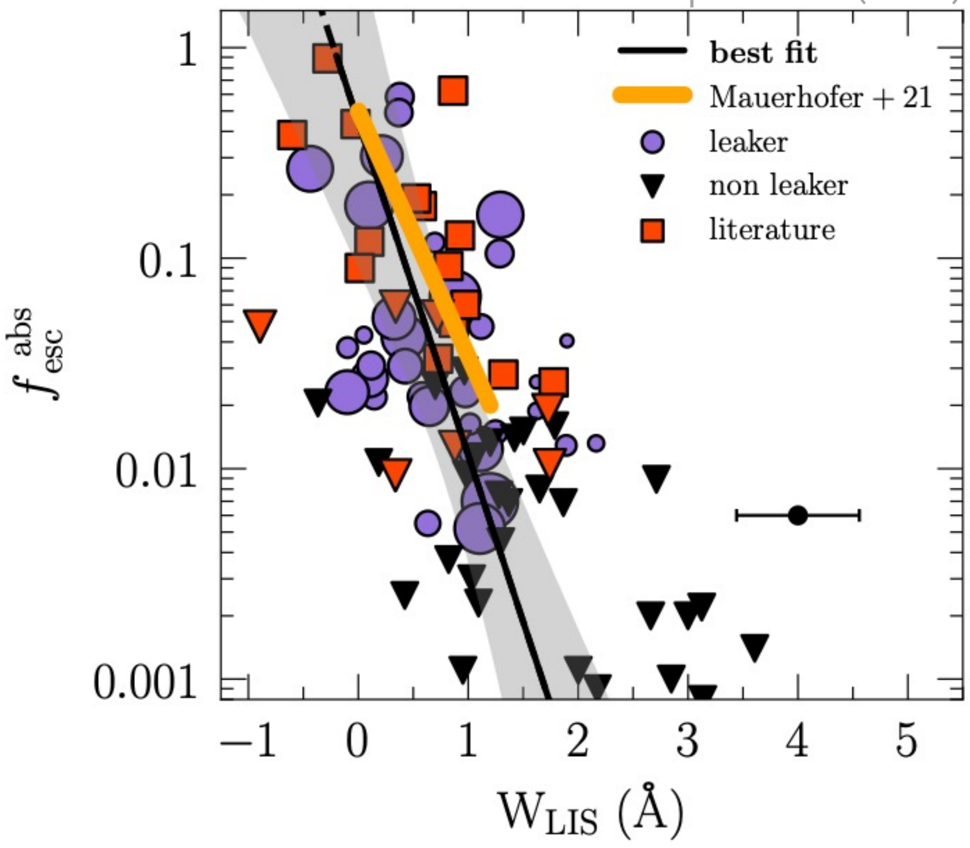

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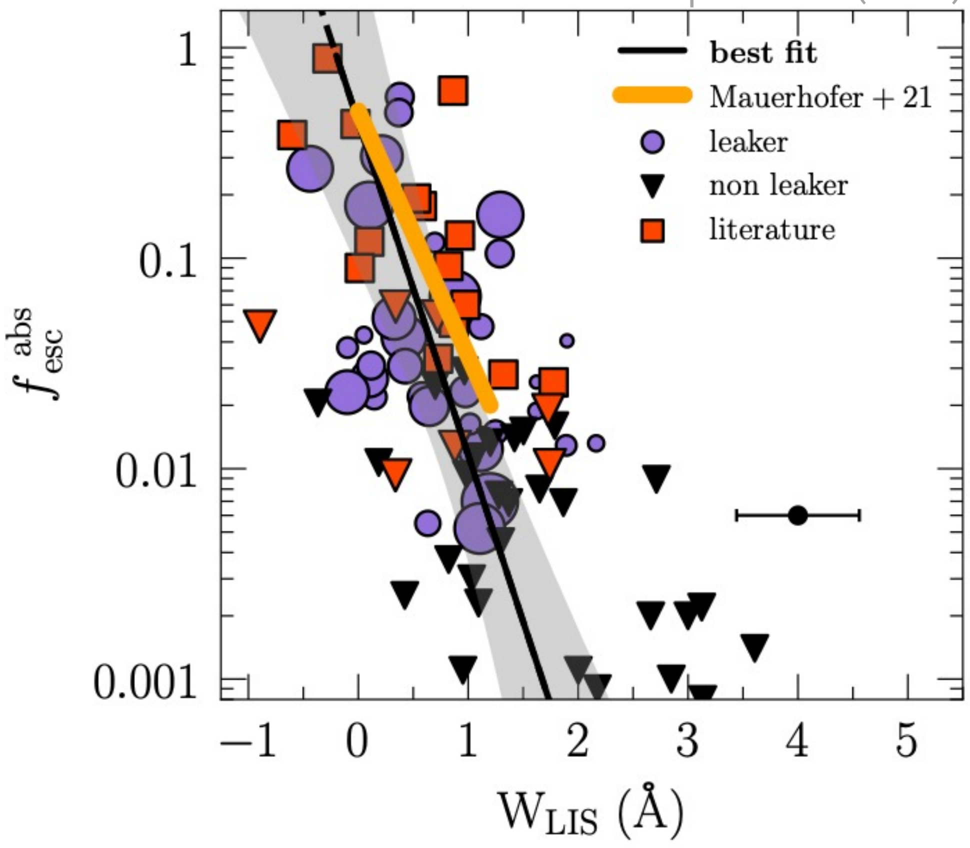
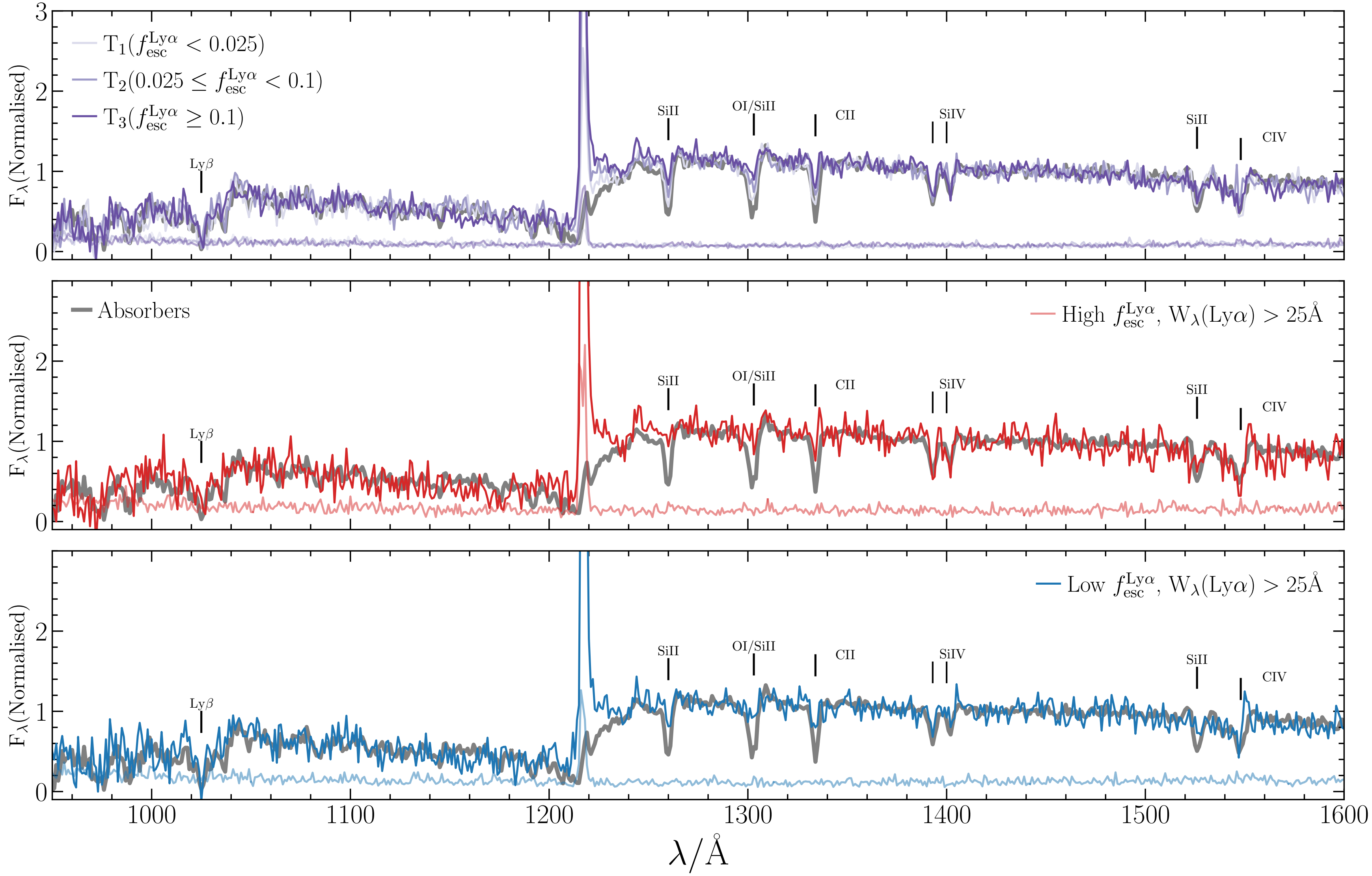


→ We construct VANDELS composite spectra in the rest-frame FUV to measure LIS ISM features :

- Three equally-occupied bins split in $f_{esc}^{Ly\alpha}$
- "High" $f_{esc}^{Ly\alpha}$ composite with $f_{esc}^{Ly\alpha} \geq 0.2$
- "Low" $f_{esc}^{Ly\alpha}$ composite with $f_{esc}^{Ly\alpha} < 0.2$

The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5



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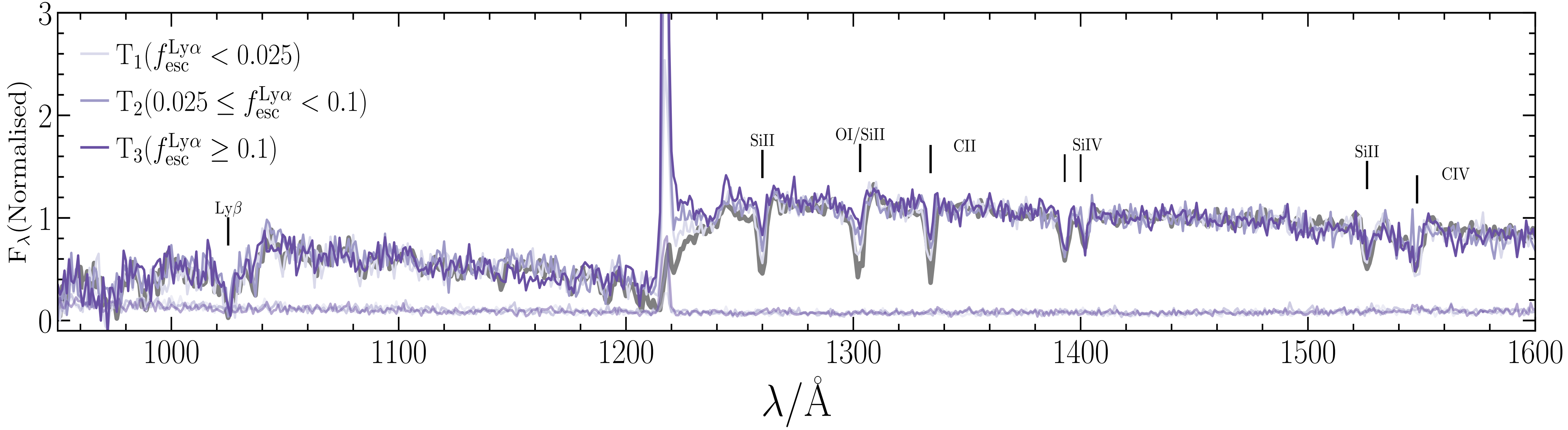

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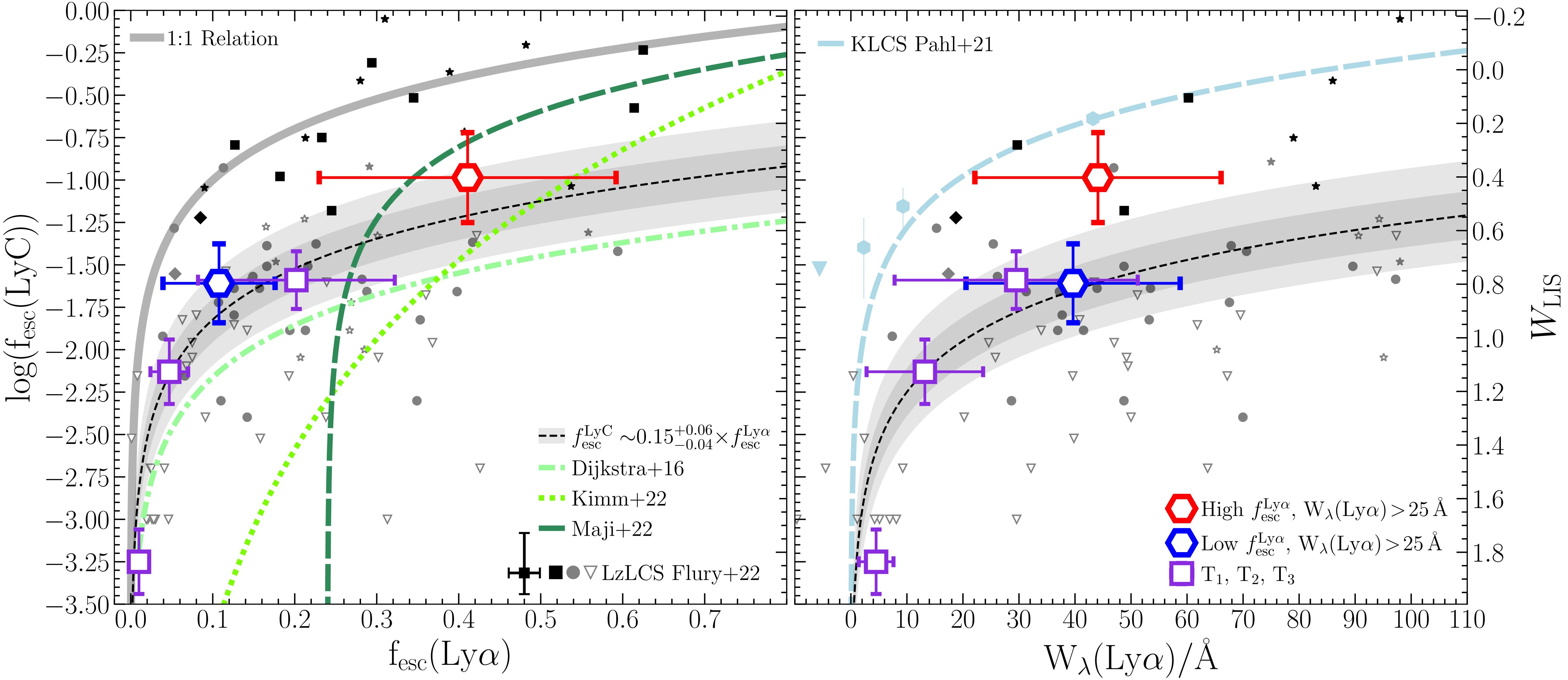

The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

To summarise Part II …

- ✓ We have demonstrated a clear correlation between $f_{\rm esc}^{\rm Ly\alpha}$ and $f_{\rm esc}^{\rm LyC}$ for our sample of VANDELS SFGs – a first at $z \simeq 4-5$.

- ✓ Supports evidence that the escape of both Lyα and LyC is primarily modulated by neutral gas geometry and dust.
  e.g., Chisholm et al. (2018), Gazagnes et al. (2020), Flury et al. (2022),
  Maji et al. (2022) **+ *more***

- ✓ Indicates LyC leakage indicators calibrated to trace these characteristics can be employed to better understand $f_{\rm esc}^{\rm LyC}$ during the EOR.

Begley et al. (2023),
MNRAS, ***Accepted***
arXiv # 2306.03916

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→ Future studies … ?

Begley et al. (2023),
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The VANDELS Survey: the Lyα–LyC connection in SFGs at $z \simeq 4$–5

- Incoming paper from a collaboration using zoom-in RHD simulations to predict the f_{esc}^{LyC} of VANDELS spectra
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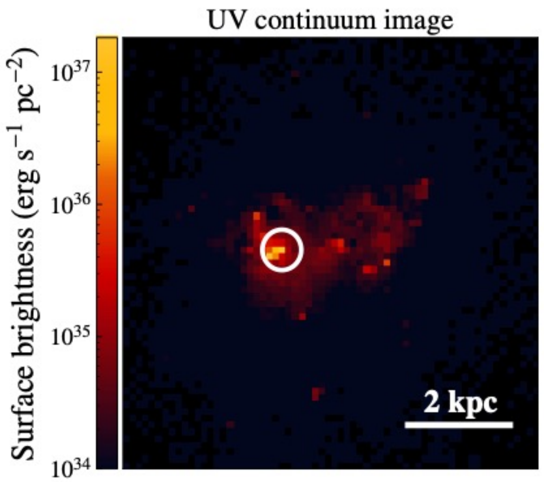

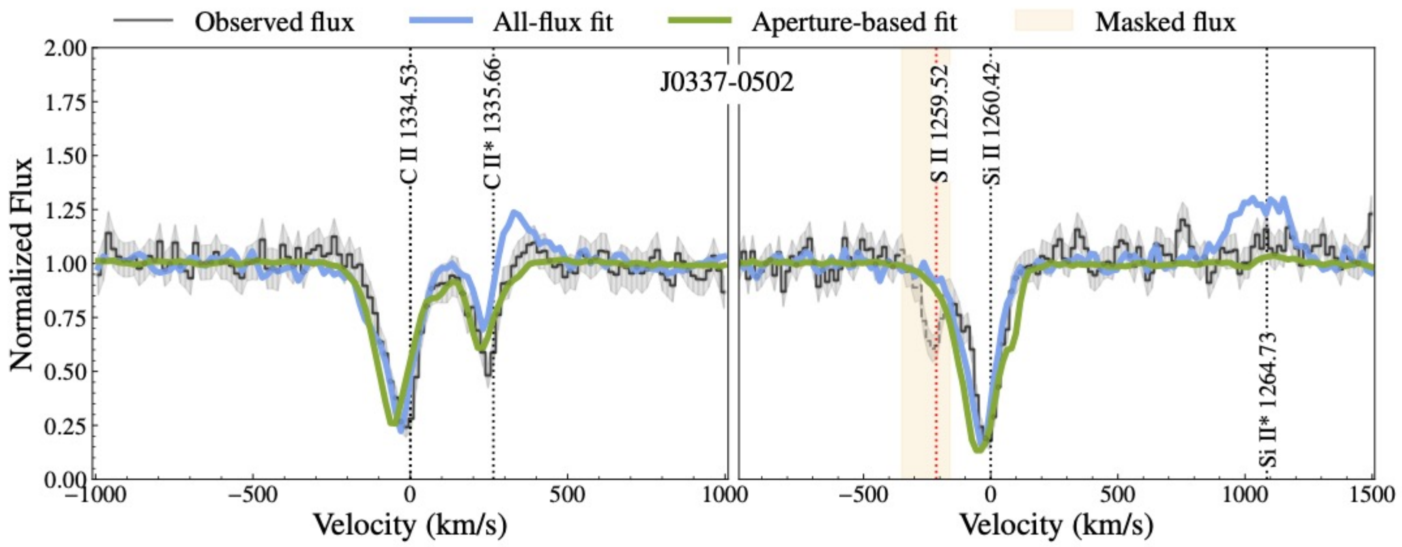

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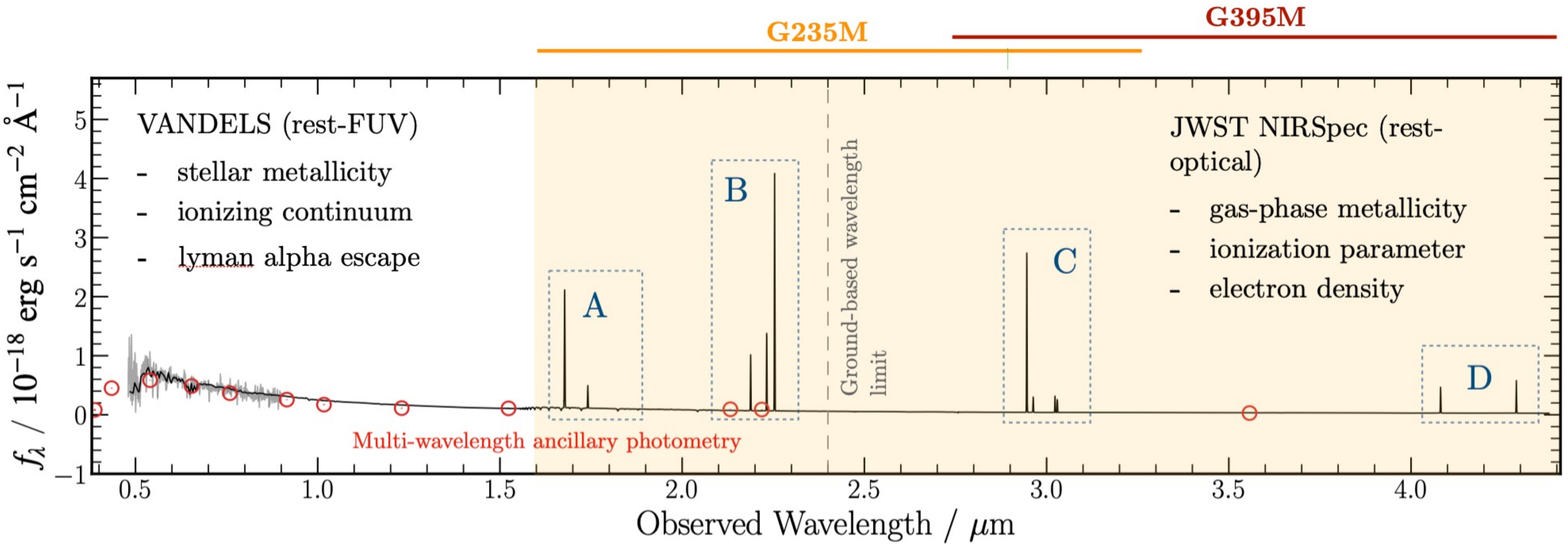
- **EXCELS** survey (Co-I on JWST Cycle 2 programme incoming ~January, led by A. C. Carnall, F. Cullen)

EXCELS



Now back to the high-redshift frontier with JWST

PRIMER

EXCELS

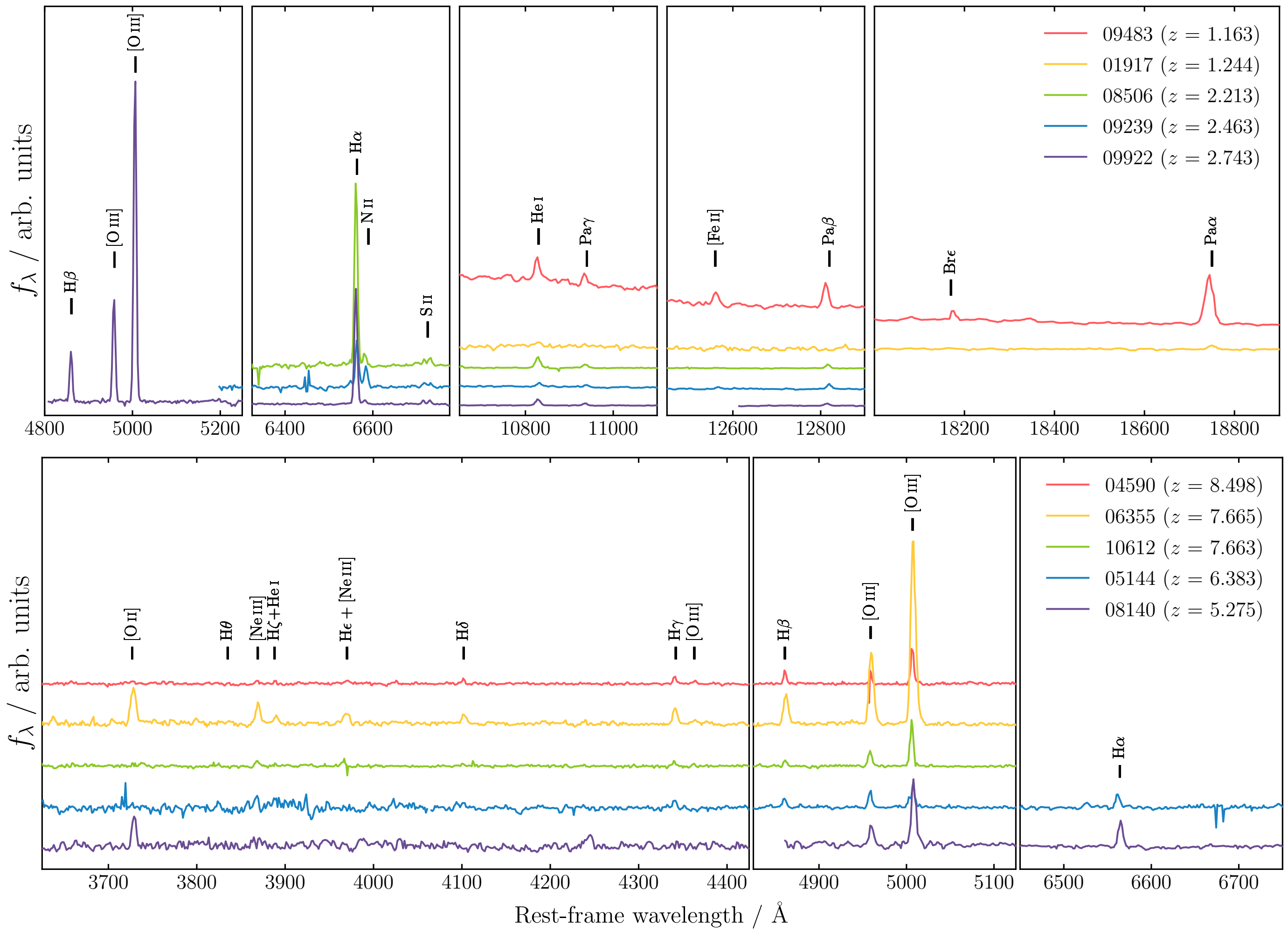
CEERS

JADES JWST ADVANCED DEEP EXTRAGALACTIC SURVEY

UNCOVER

+ Upcoming Cycle 3 proposals & much more in the future!

Some exciting JWST results so far…



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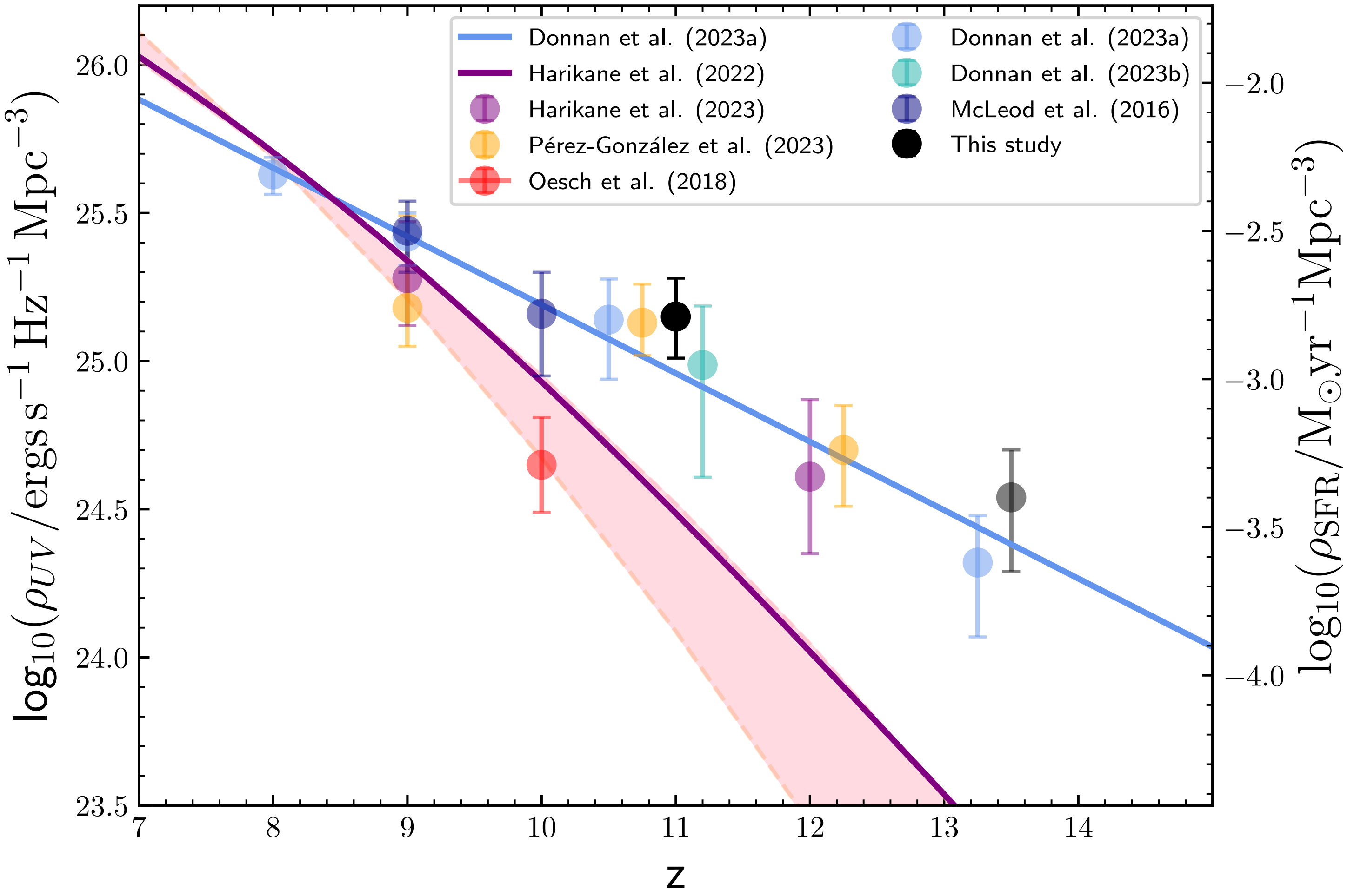

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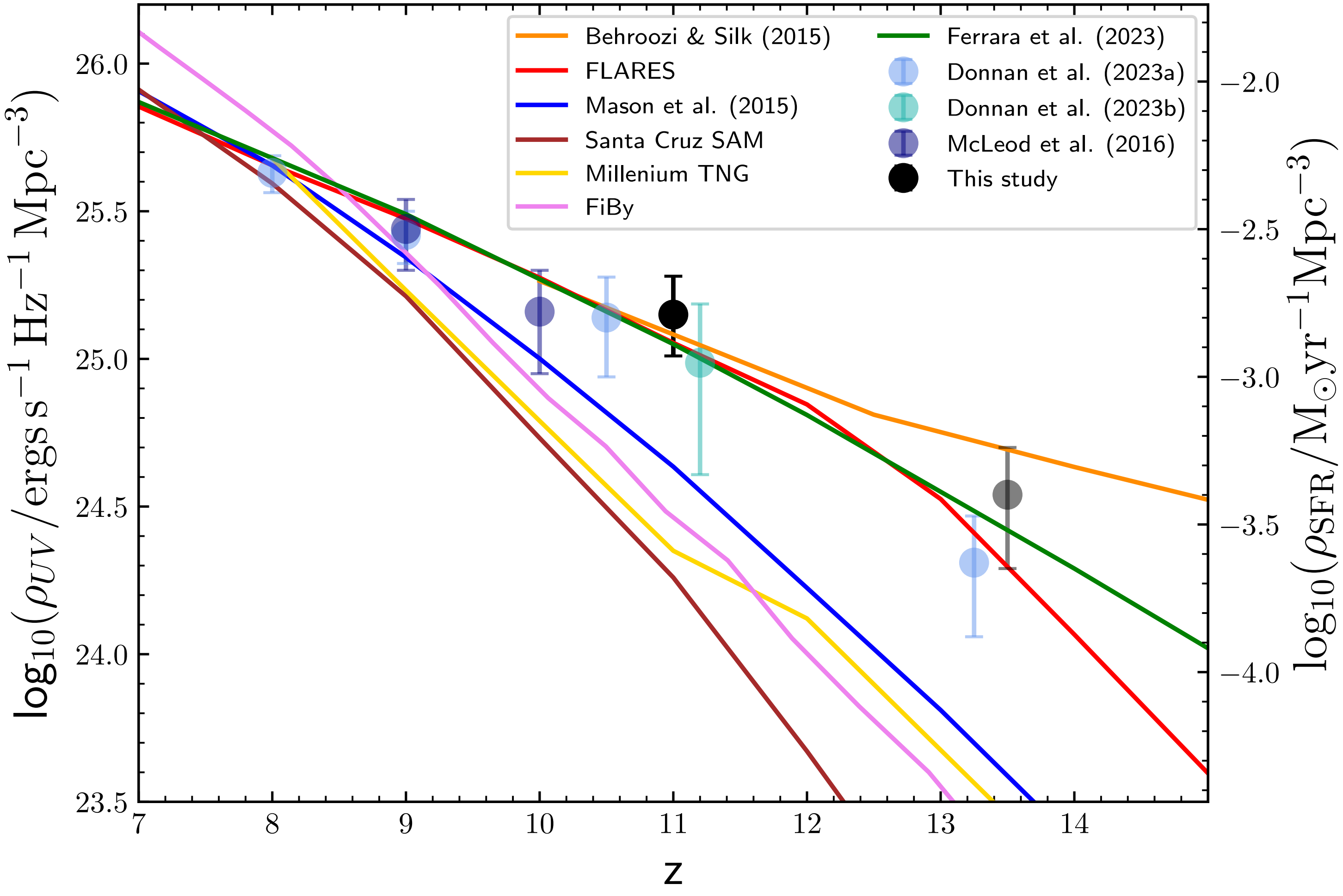

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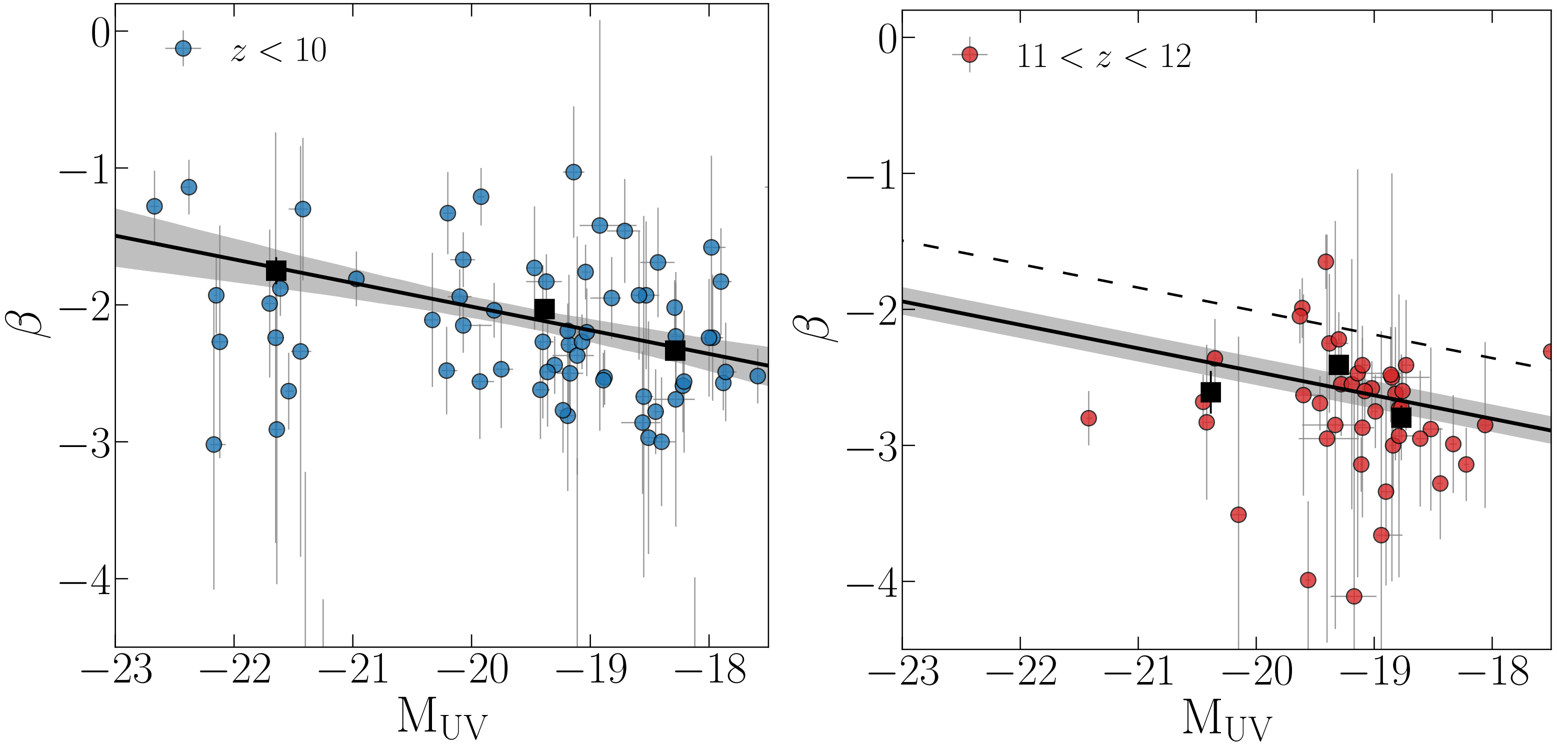

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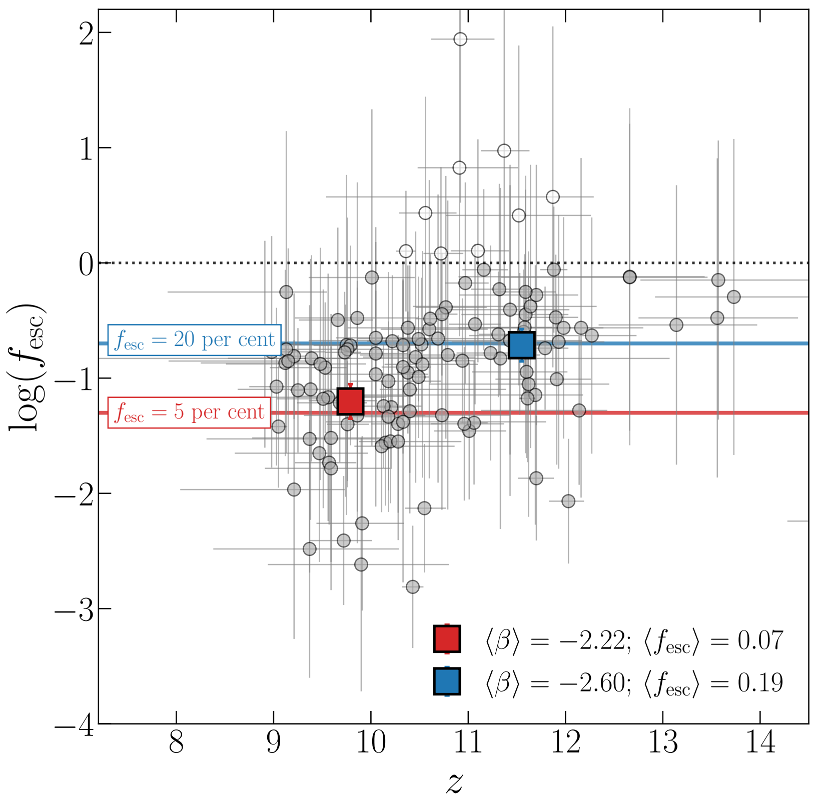

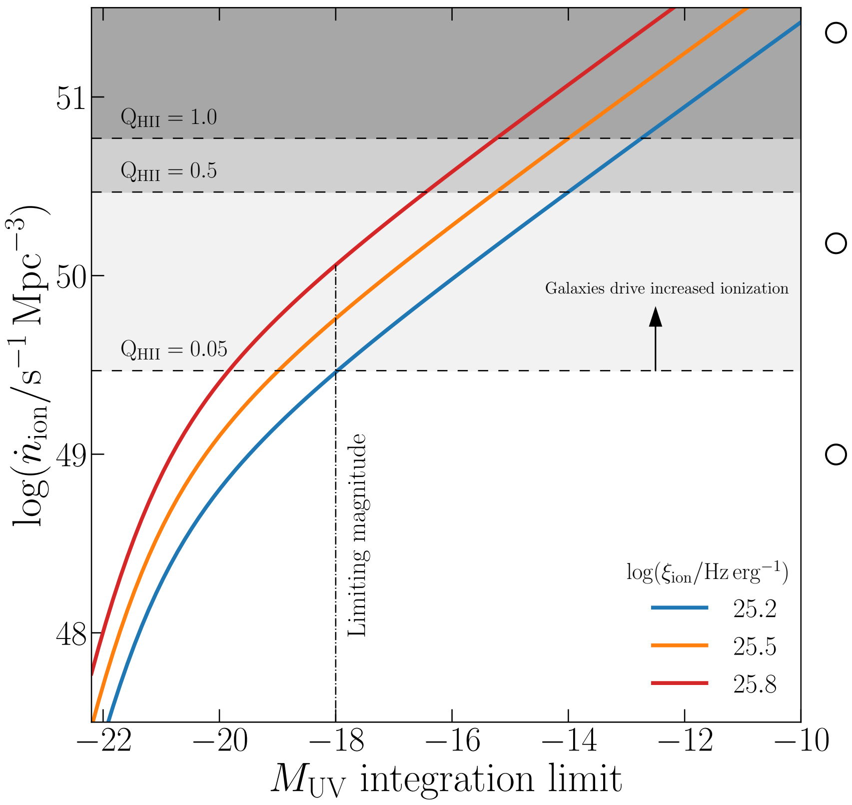

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  → "dust-free" stellar populations
  → capable of driving reionization

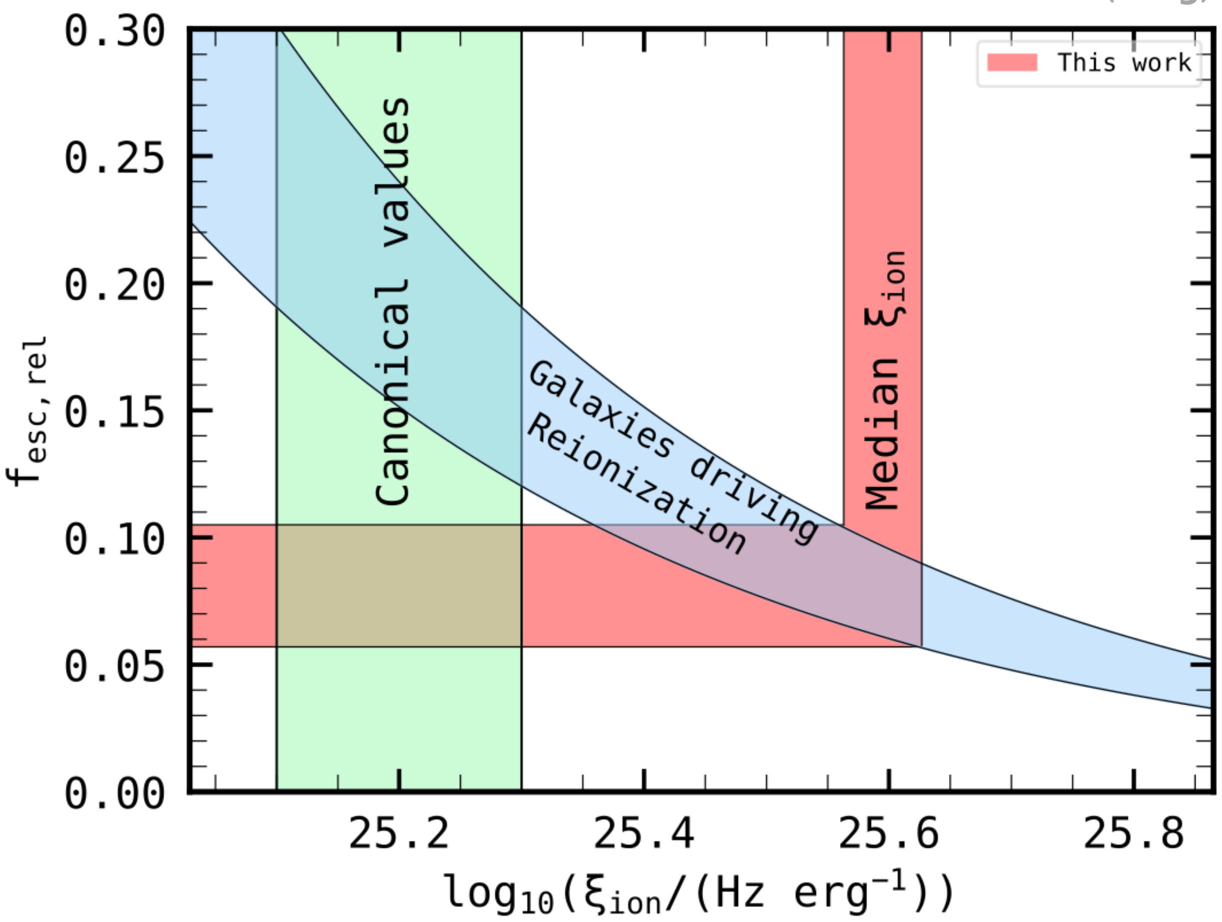
The redshift evolution of [OIII]+Hβ ➔ ξ_{ion}

ξ_{ion} = ionizing photon production efficiency = $N(H^0)/L_{UV}$

→ f_{esc}^{LyC} is only one **part of the picture**

The ionizing properties of SFGs of galaxies, and how this varies with different properties is also vital ➔ $\boldsymbol{\xi_{ion}}$

Rinaldi et al. (2023)



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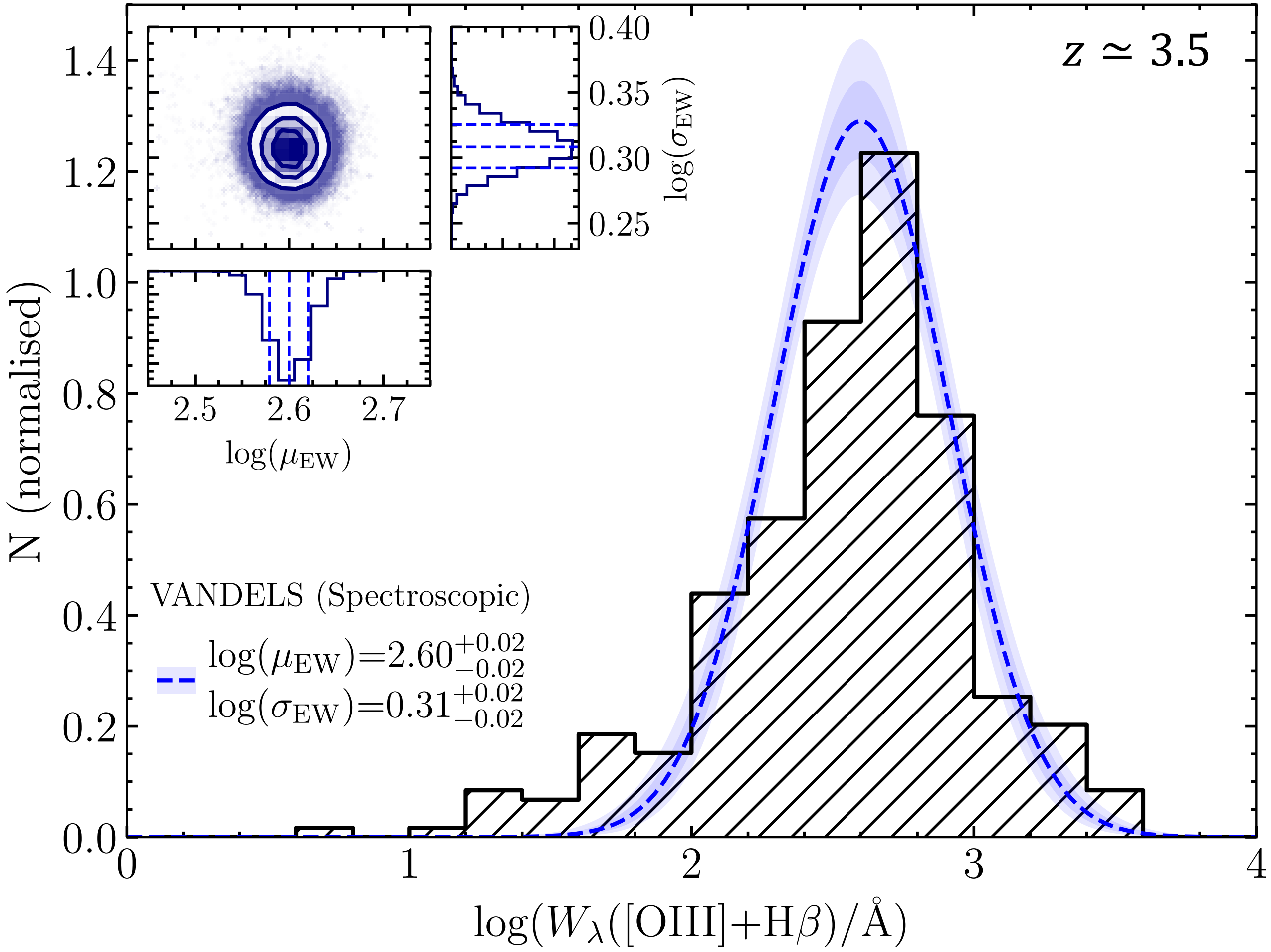
→ Strong [OIII]+Hβ emission is a smoking gun of **high ξ_{ion}**

→ Measure the [OIII]+Hβ equivalent width distribution from $z \simeq 2-8$ combining:

- Literature results at $z \simeq 2$ +
- **VANDELS** at $z \simeq 3.5$ +
- **CEERS** Epoch1 at $z \simeq 7.5$



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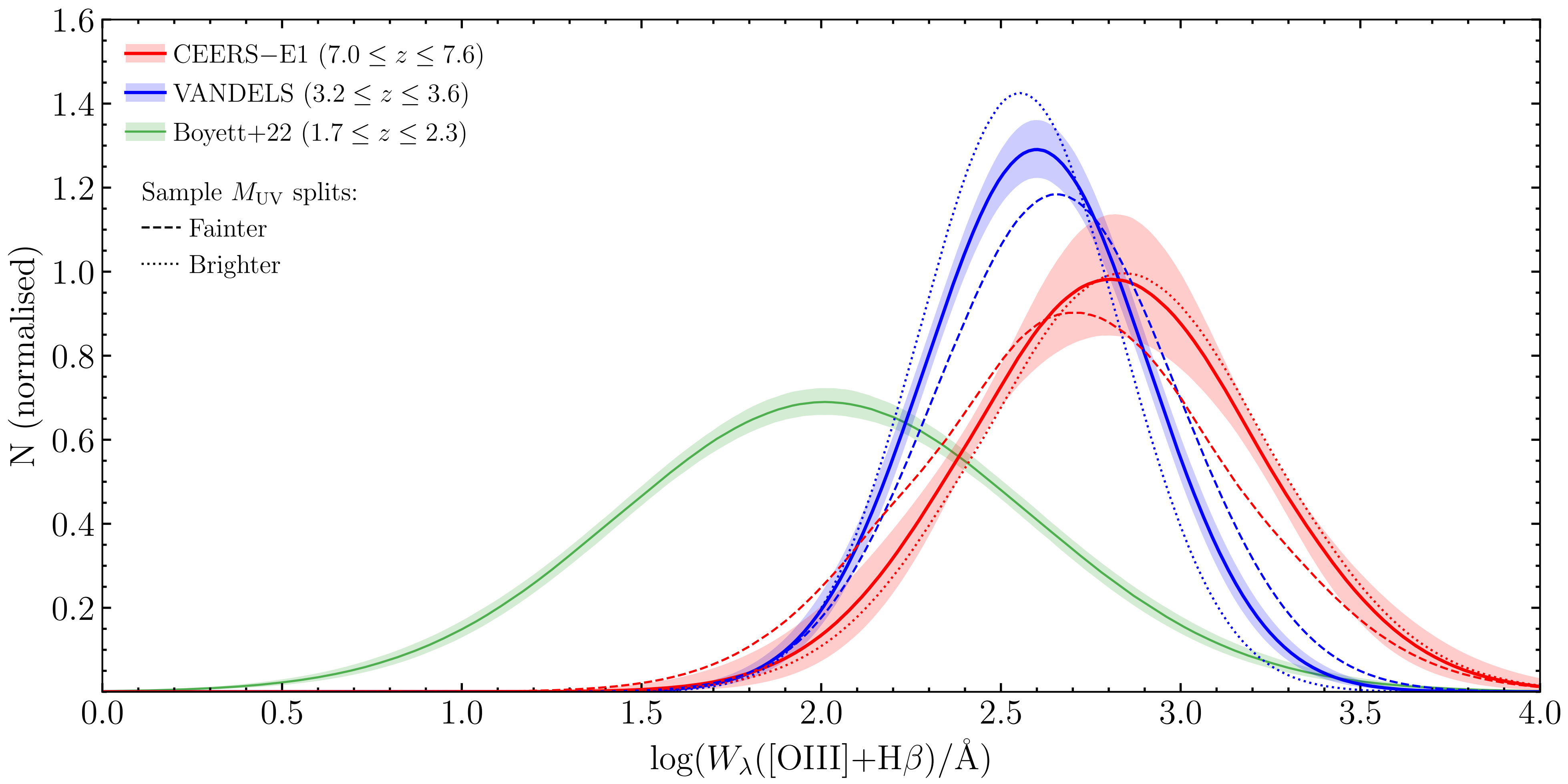

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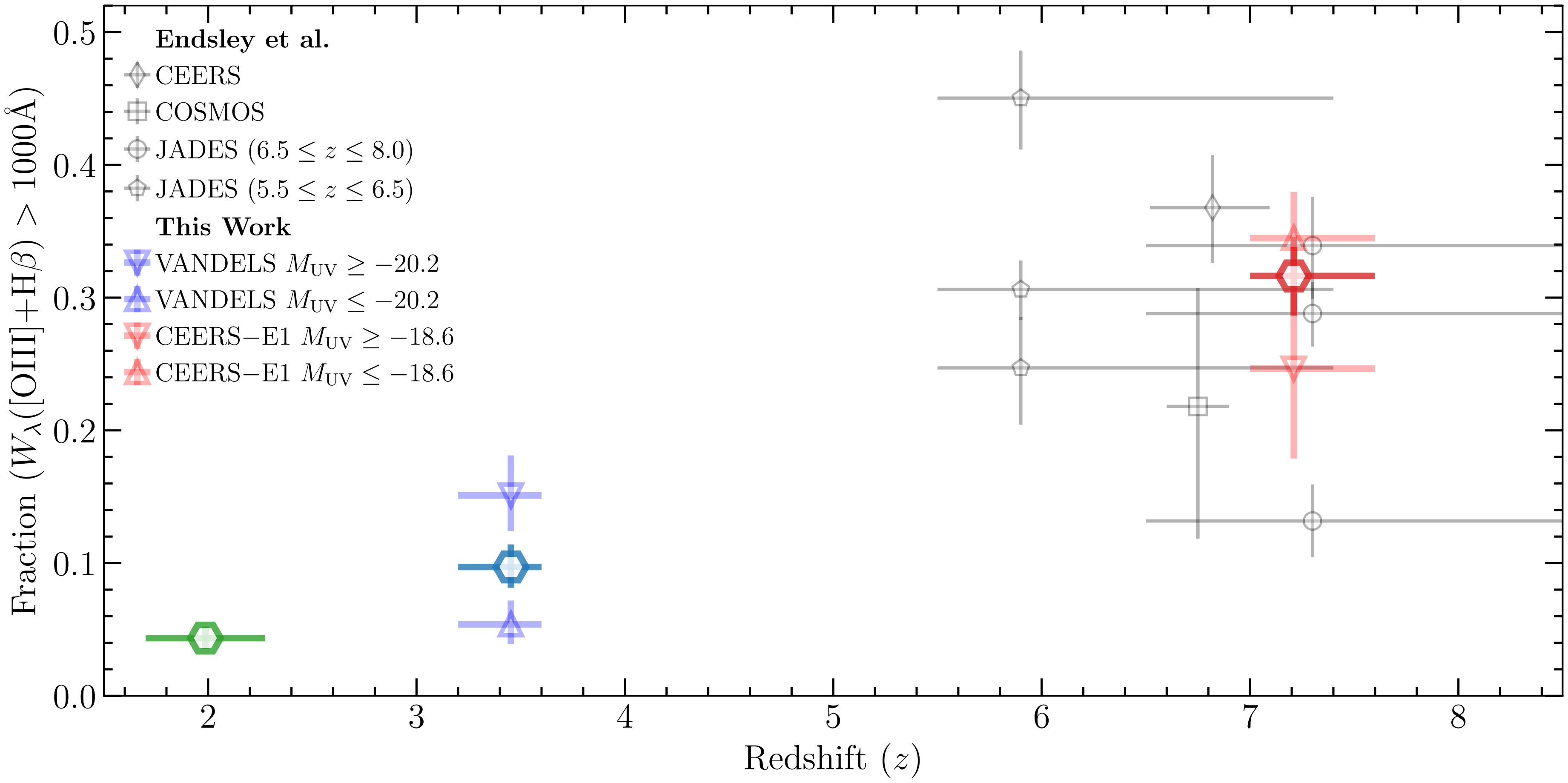

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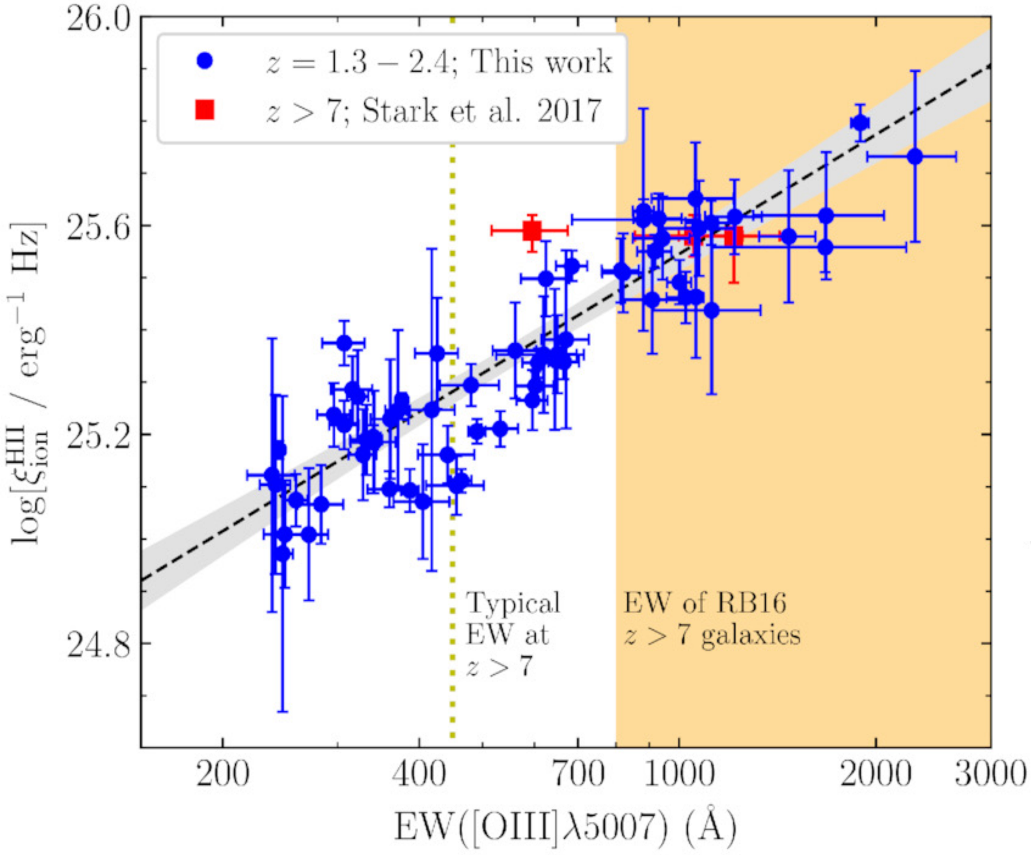

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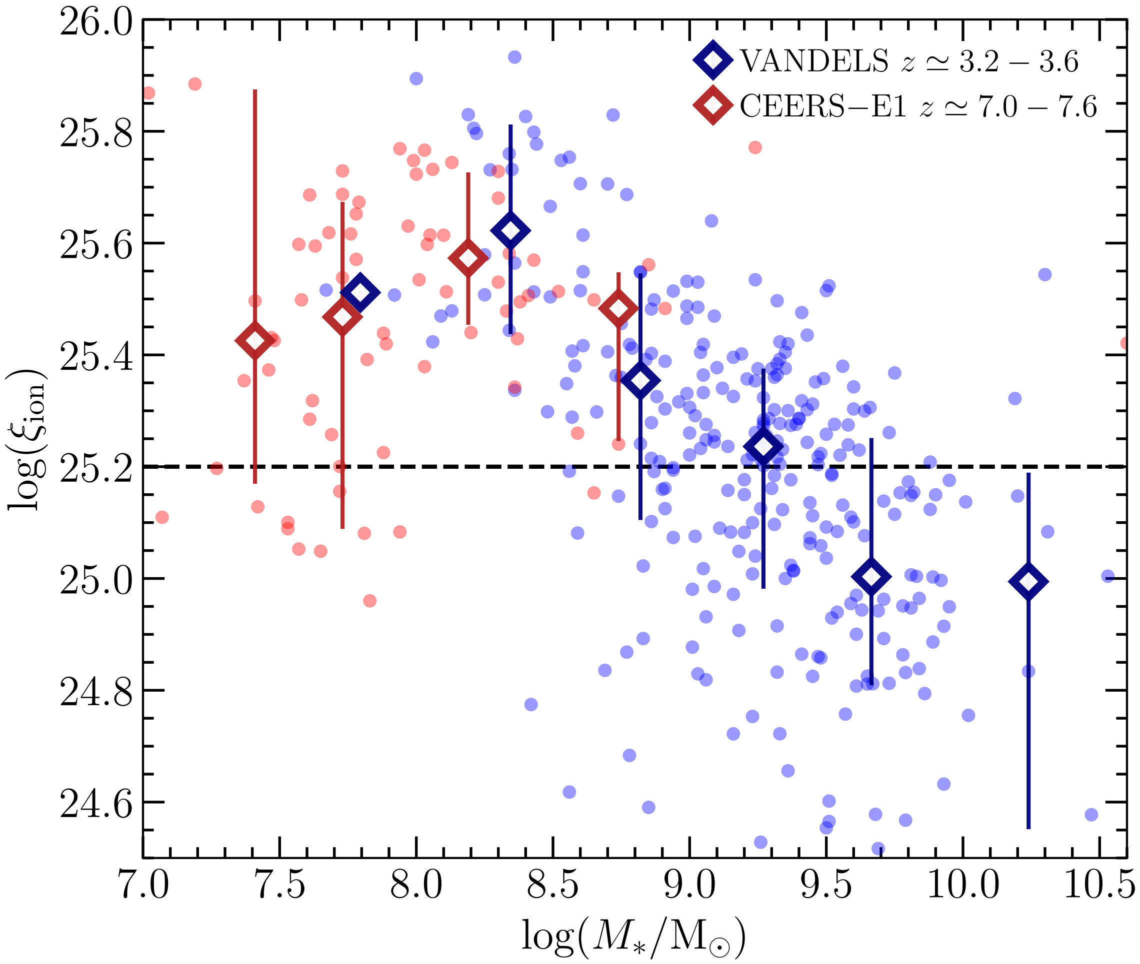
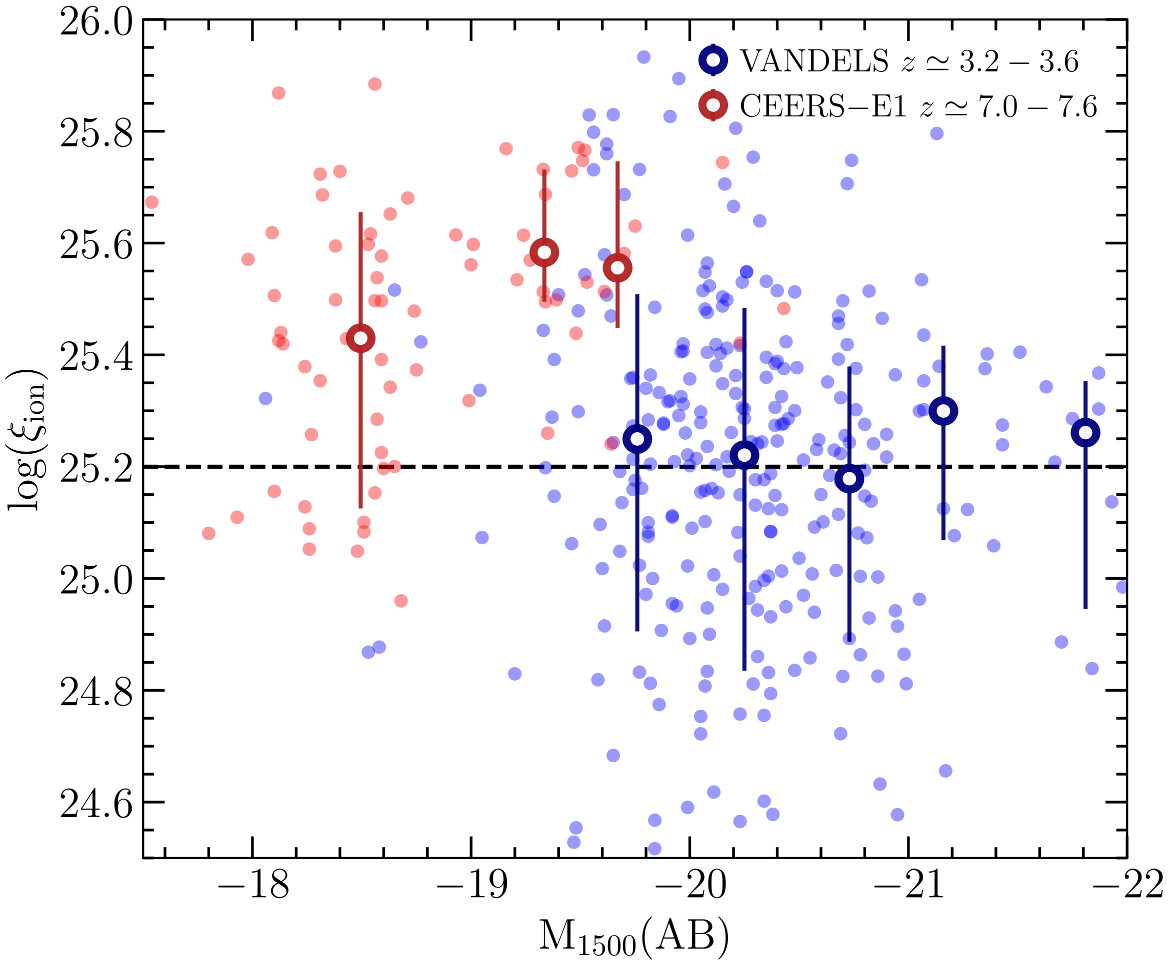


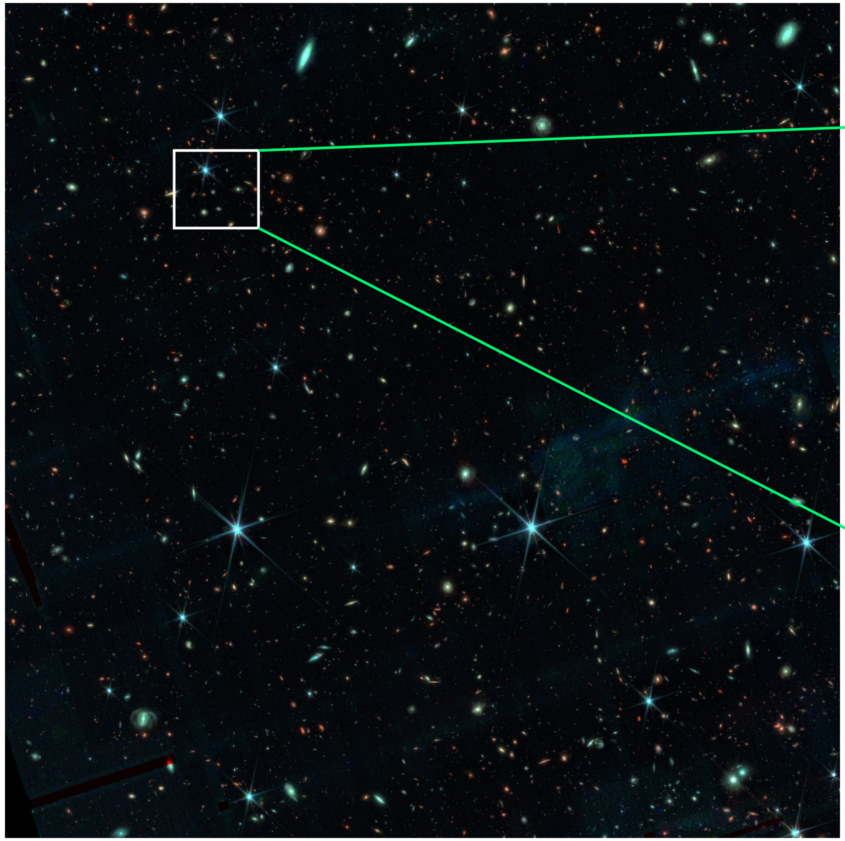


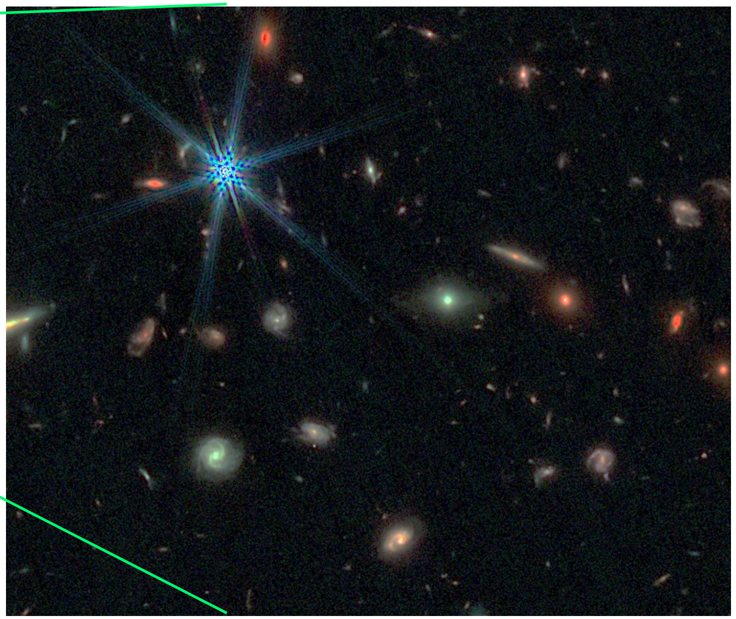
The PRIMER Survey

PRIMER will provide ~400 sq arcmin of imaging in N=10 NIRCam + MIRI bands in the COSMOS & UDS fields

→ Will increase numbers of [OIII]+Hβ measurements at $z \simeq 7.5$ by an order of magnitude

$\approx 1/10^{\text{th}}$ of PRIMER/COSMOS





Credit: M. Hamadouche