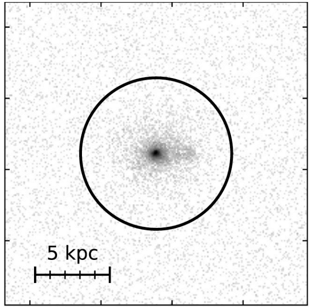
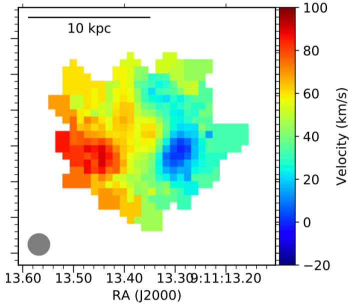
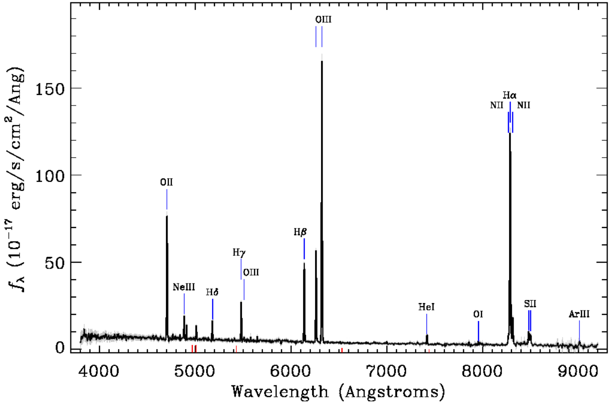
A LOW-REDSHIFT LOOK AT LYC ESCAPE

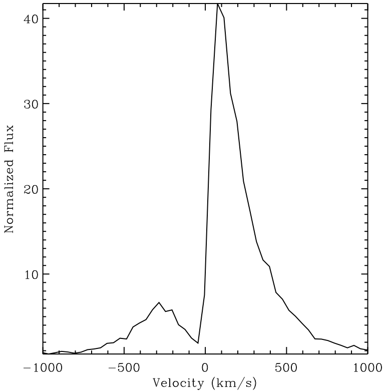
Anne Jaskot, Williams College

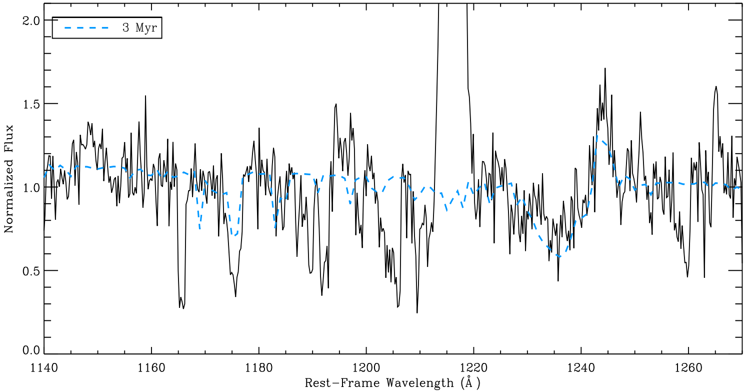
OAC, April 2023



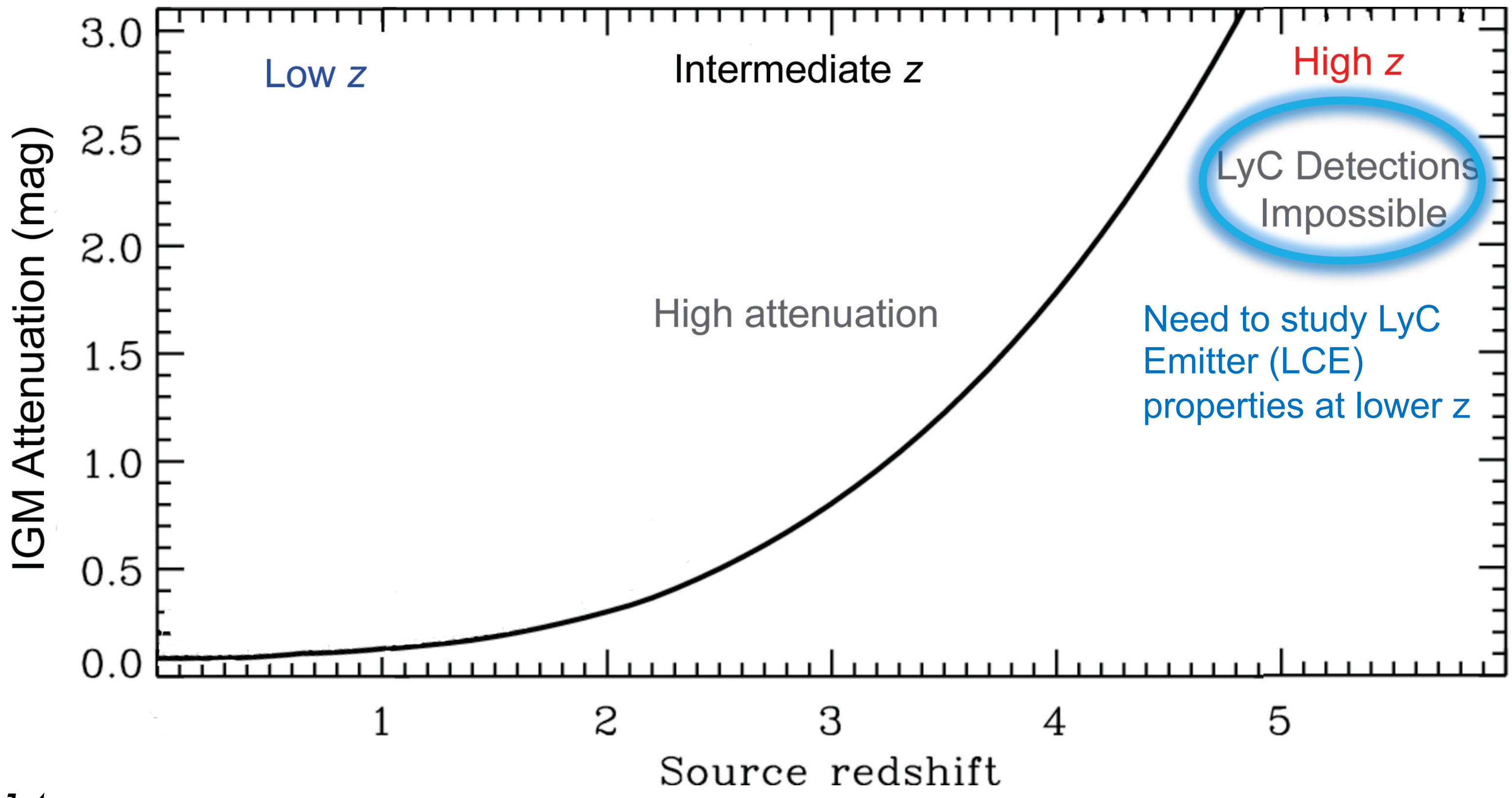








WHY LOW REDSHIFT?



Inoue+14

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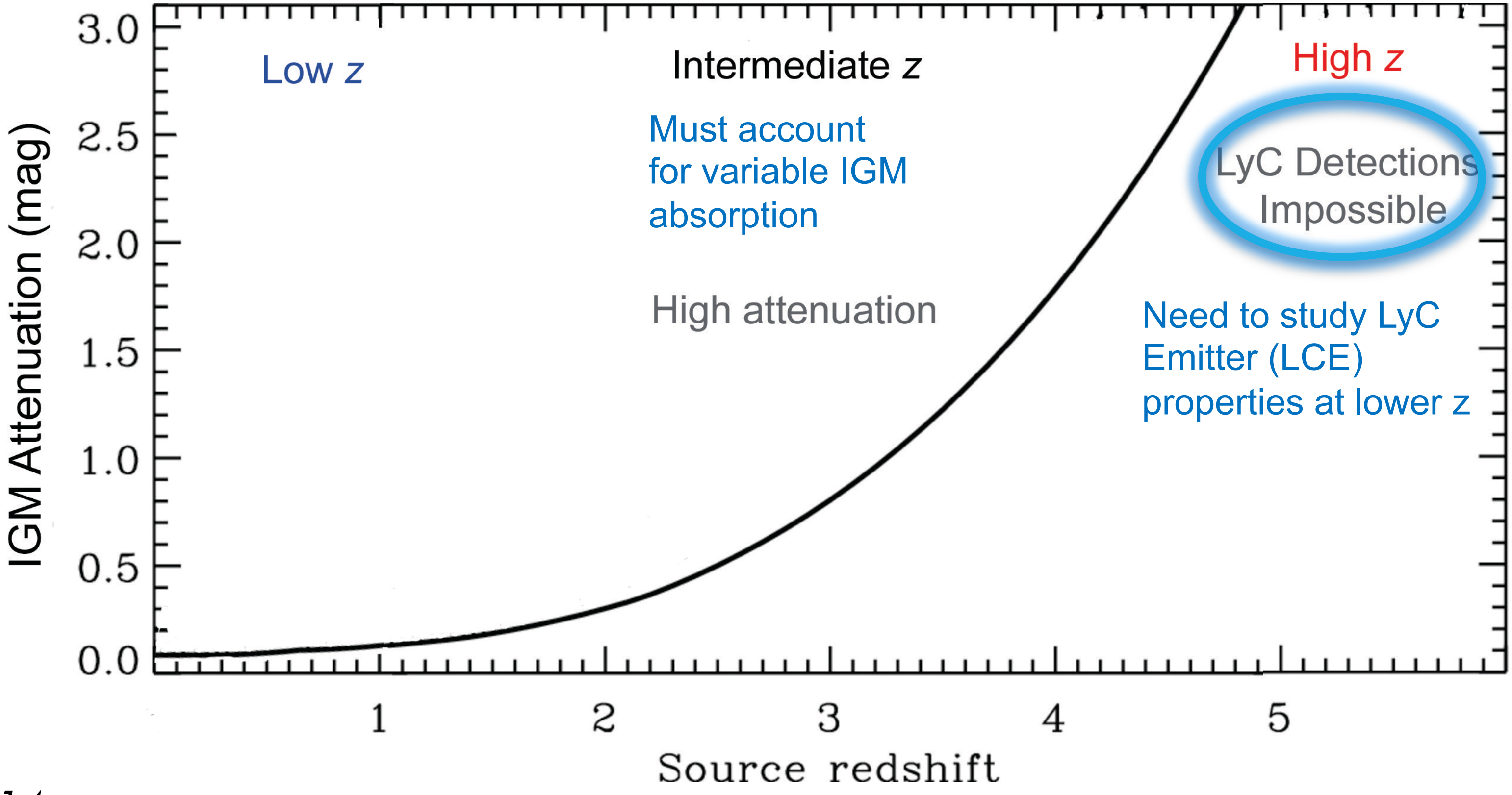

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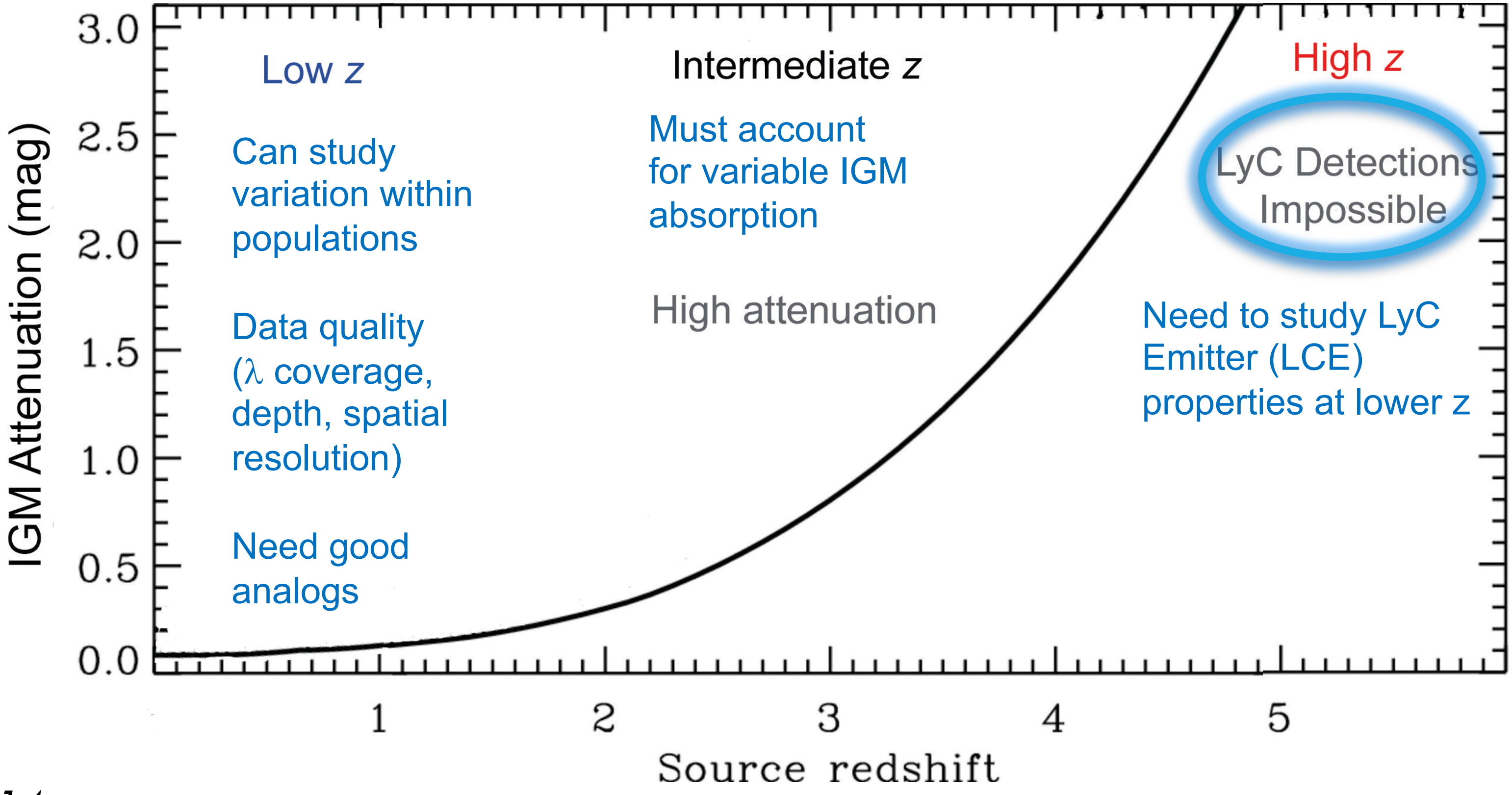


Inoue+14

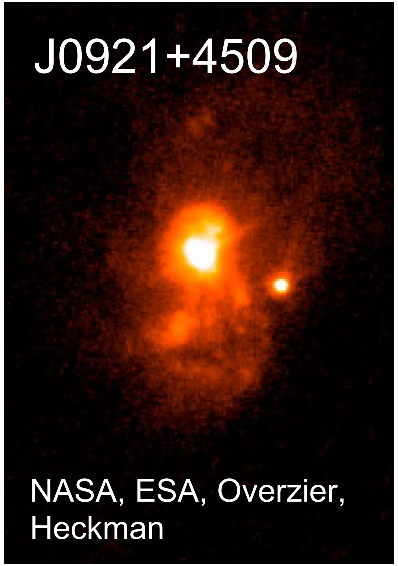
“HISTORY” (~10 YEARS AGO)

fesc: ≤ 2-10%

Bergvall+06
Grimes+07
Leitet+11

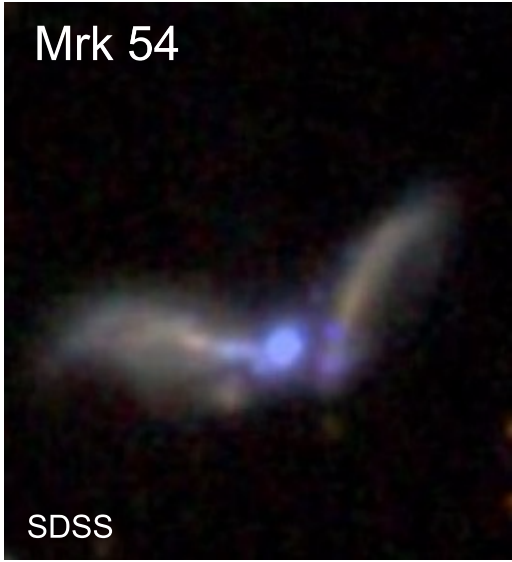
1.5-4.5%

Leitet+13
Leitherer+16
Puschnig+17



1%

Borthakur+14



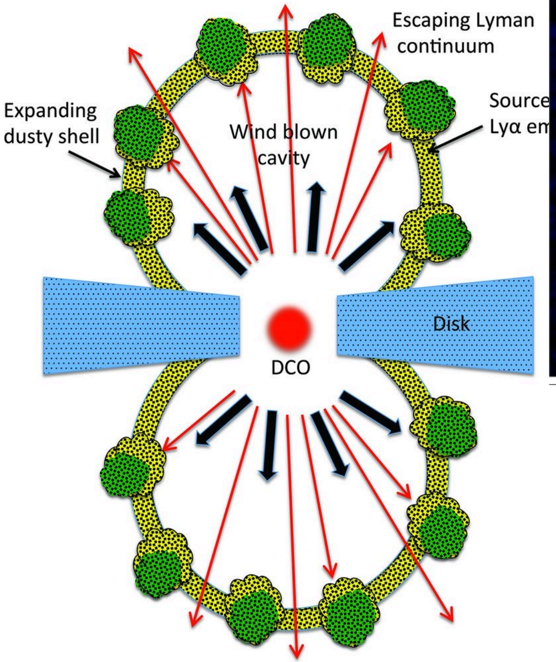
1.5-2.5%

Leitet+13
Leitherer+16

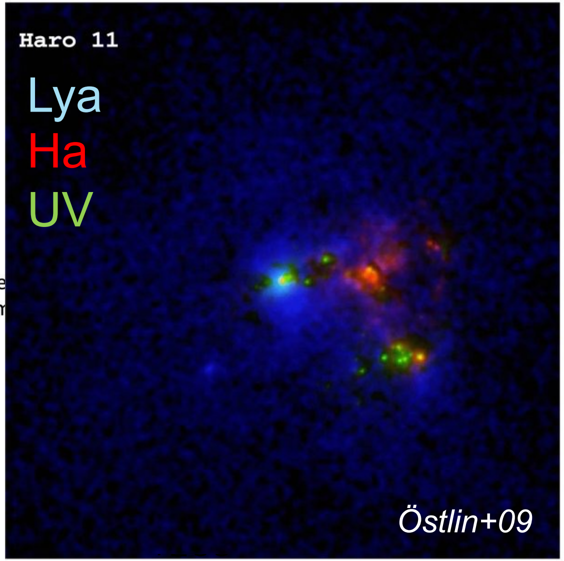
IMPLICATIONS

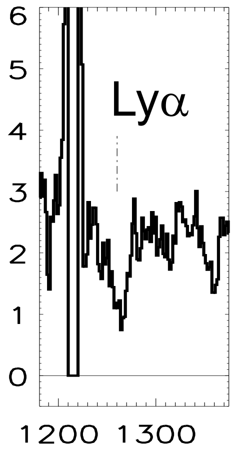
- Compactness and outflows? *(Heckman+11, Borthakur+14)*
- Lyα or absorption lines as tracers:
  - Conflicting evidence *(Leitet+13, Leitherer+16)*
  - Anisotropic escape?
- Low mass? High sSFR? Low E(B-V)?
  - fesc,rel ~20% in several targets *(Borthakur+14, Leitherer+16)*

J0921+4509



Borthakur+14





Mrk 54

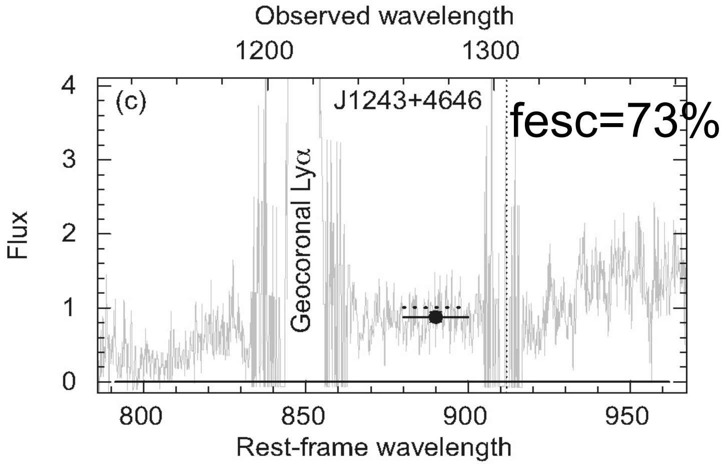
Leitet+13

THE FIRST SAMPLE: THE GREEN PEAS

fesc = 2-73%

11/11 detections!

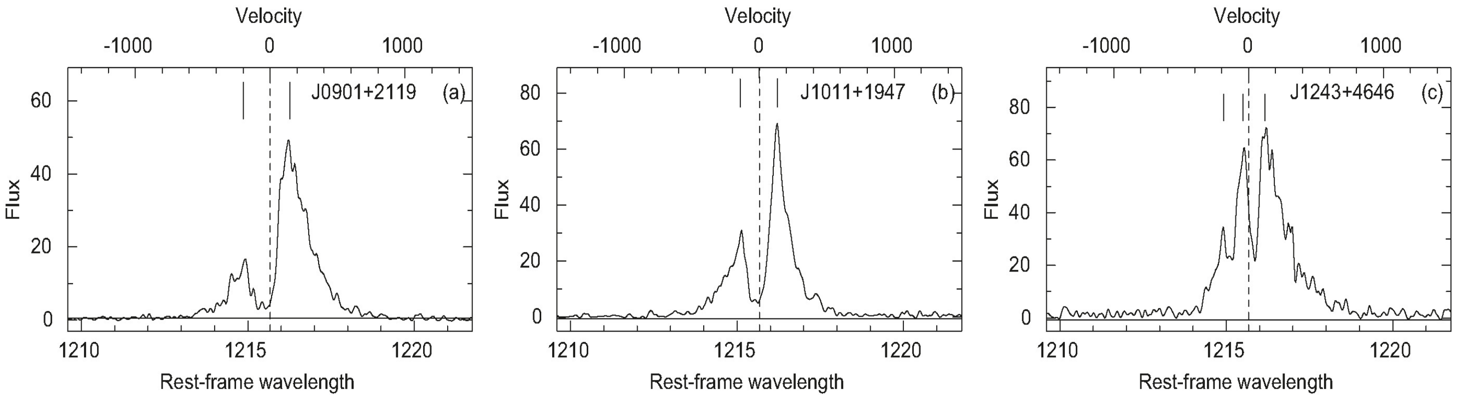
Izotov+16a,16b,18a,18b



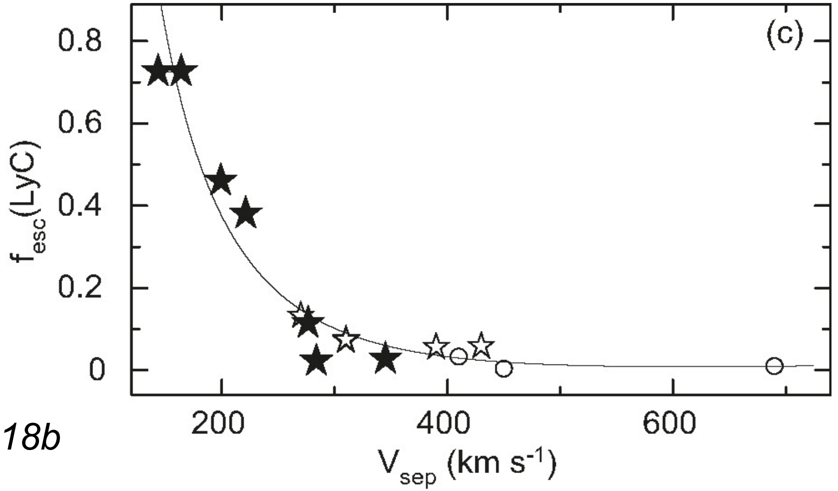
- Compact ELGs
- Low mass (10^9 $M_\odot$)
- Low metallicity (0.2 $Z_\odot$)
- High ionization (O32 = 5007/3727 > 5)

Izotov+18b

IMPLICATIONS



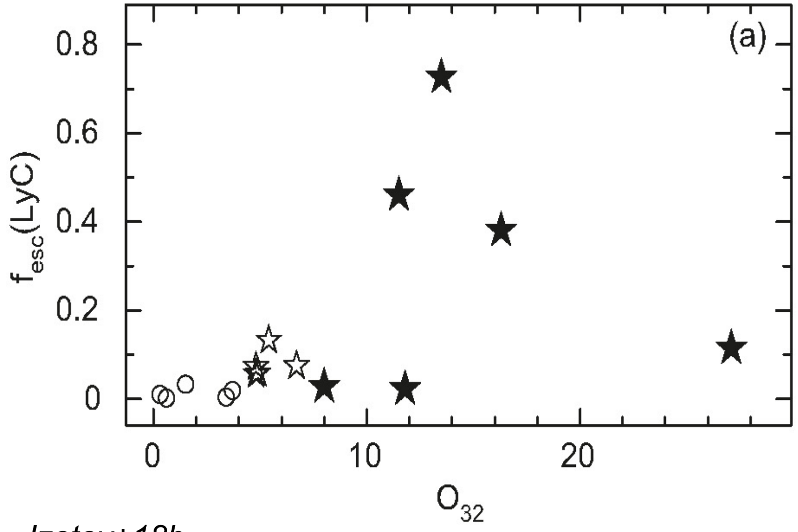
- Lyα traces LyC
- Narrow Lyα = low optical depth
  - e.g., Verhamme+15,+17



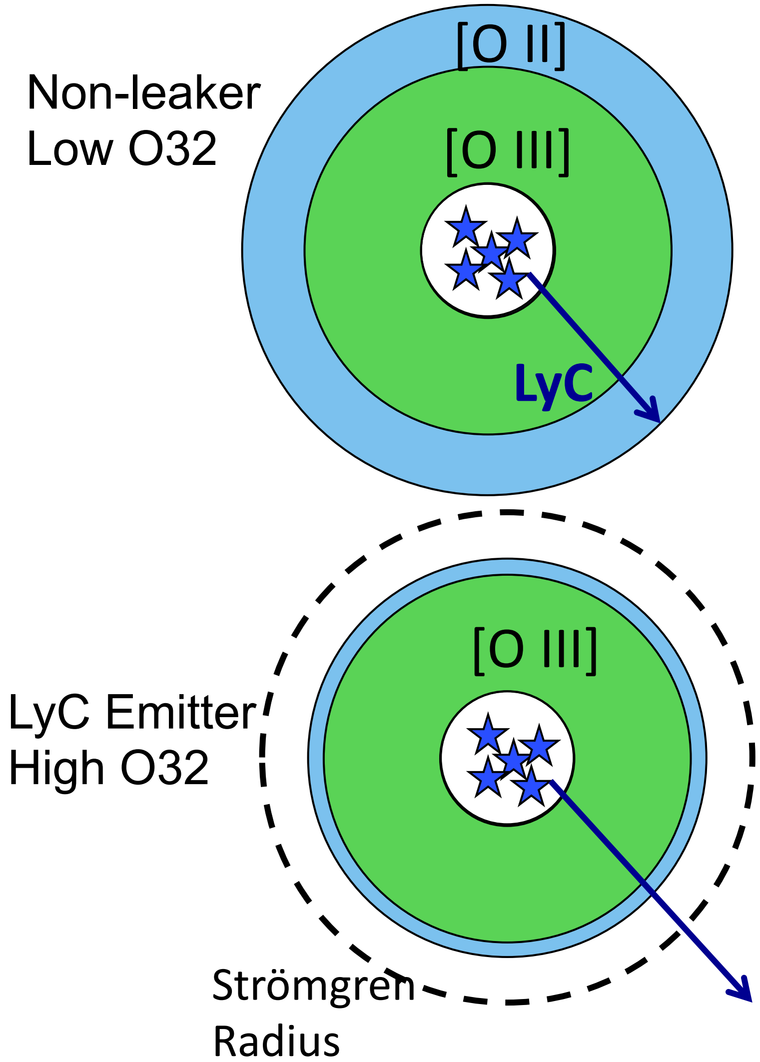
Izotov+18b

IMPLICATIONS

Density-bounded ISM?
e.g., Jaskot+Oey 13, Nakajima+Ouchi 14



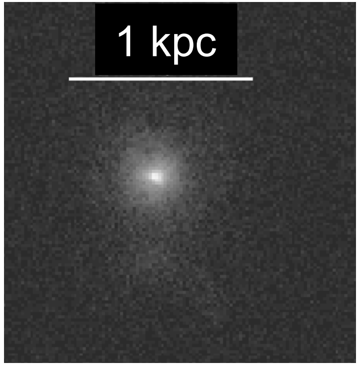
Izotov+18b



IMPLICATIONS

What role does feedback play?

Compact, high Σ_{SFR}



GP J1608 – Jaskot+17, +19

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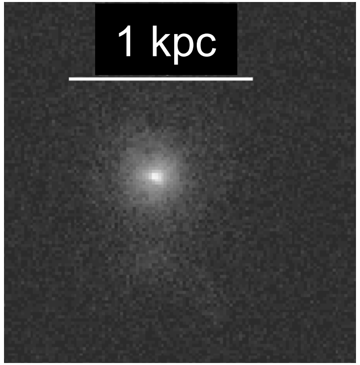
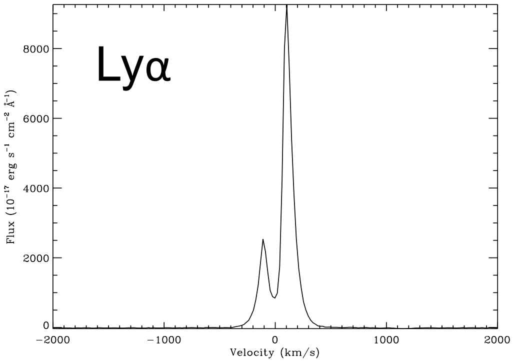


Low optical depth



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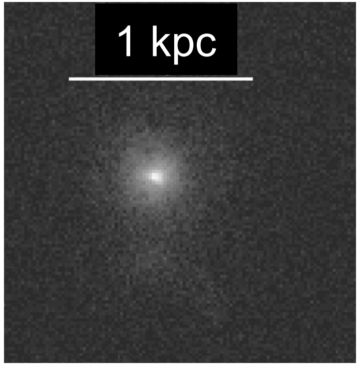

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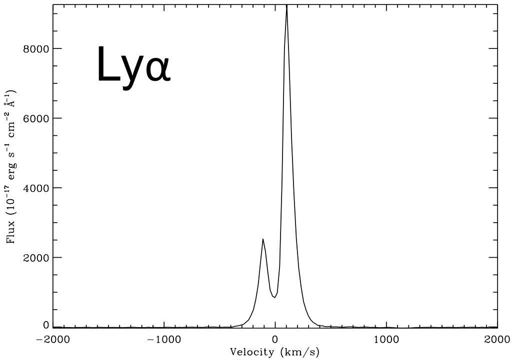
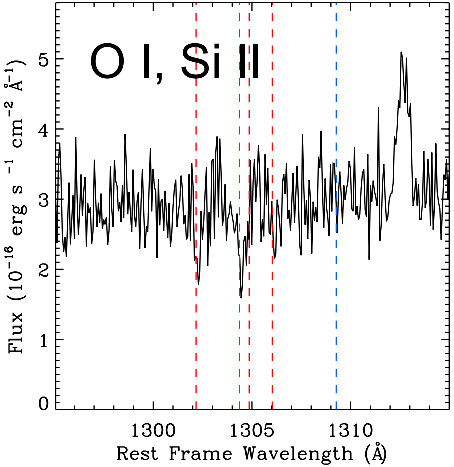


Outflow velocities not always high



c.f. Chisholm+17

GP J1608 – Jaskot+17, +19

IMPLICATIONS

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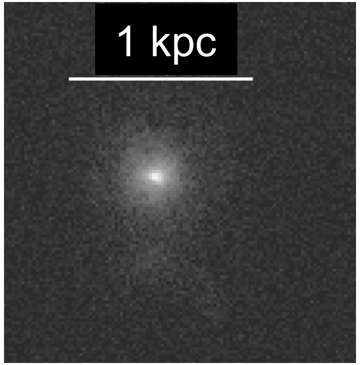

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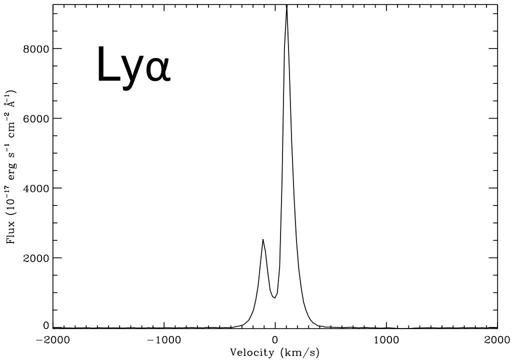

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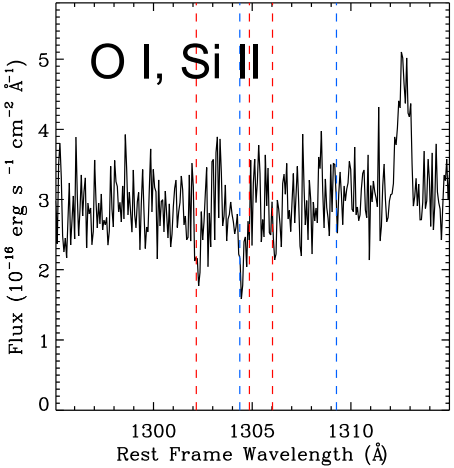
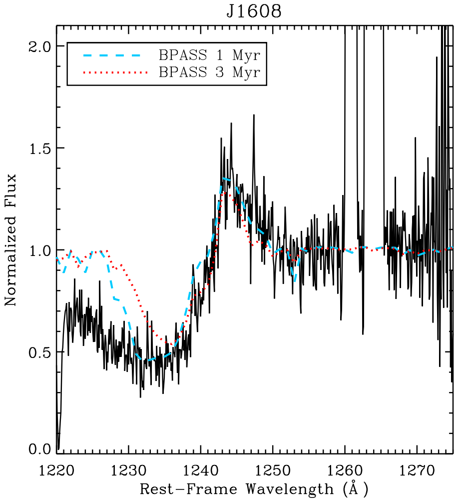


c.f. Chisholm+17

Very young
< 3 Myr
No SNe?
c.f. Izotov+17

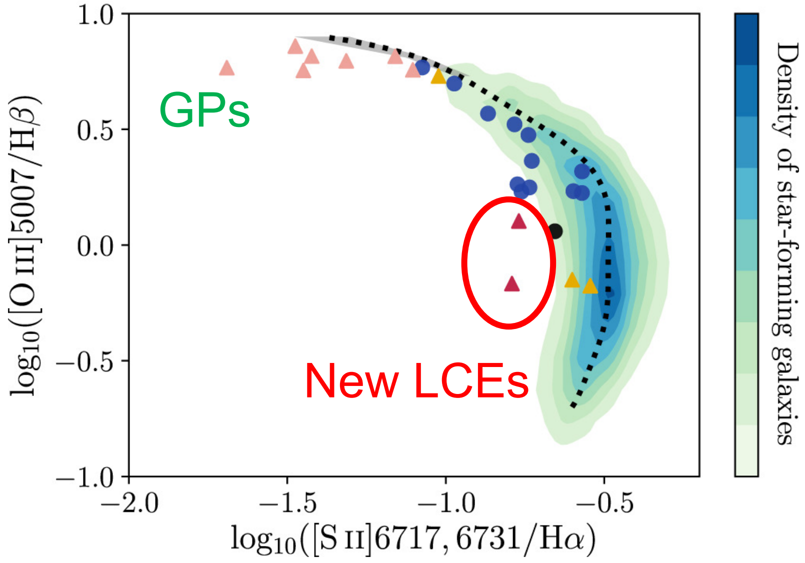


Komarova+21: radiation-driven outflows?

GP J1608 – Jaskot+17, +19

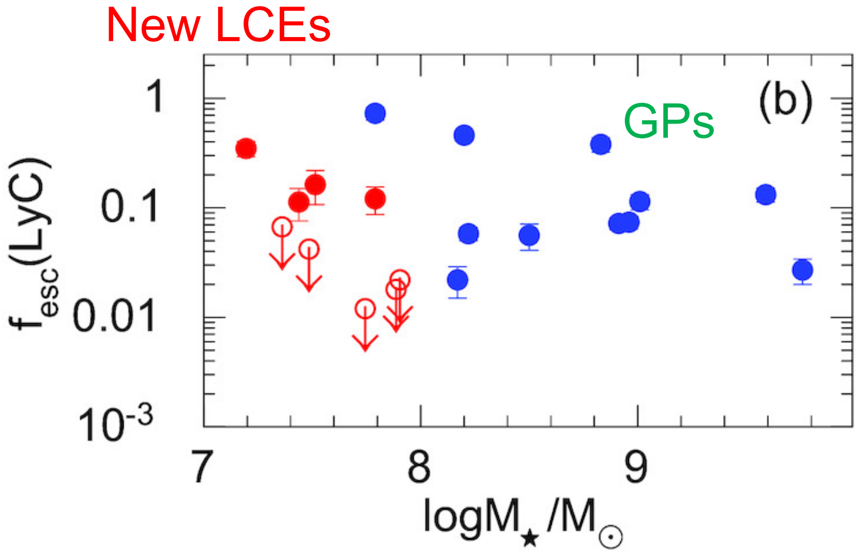
MORE SAMPLES

Wang+19; fesc=2.7-4.0%



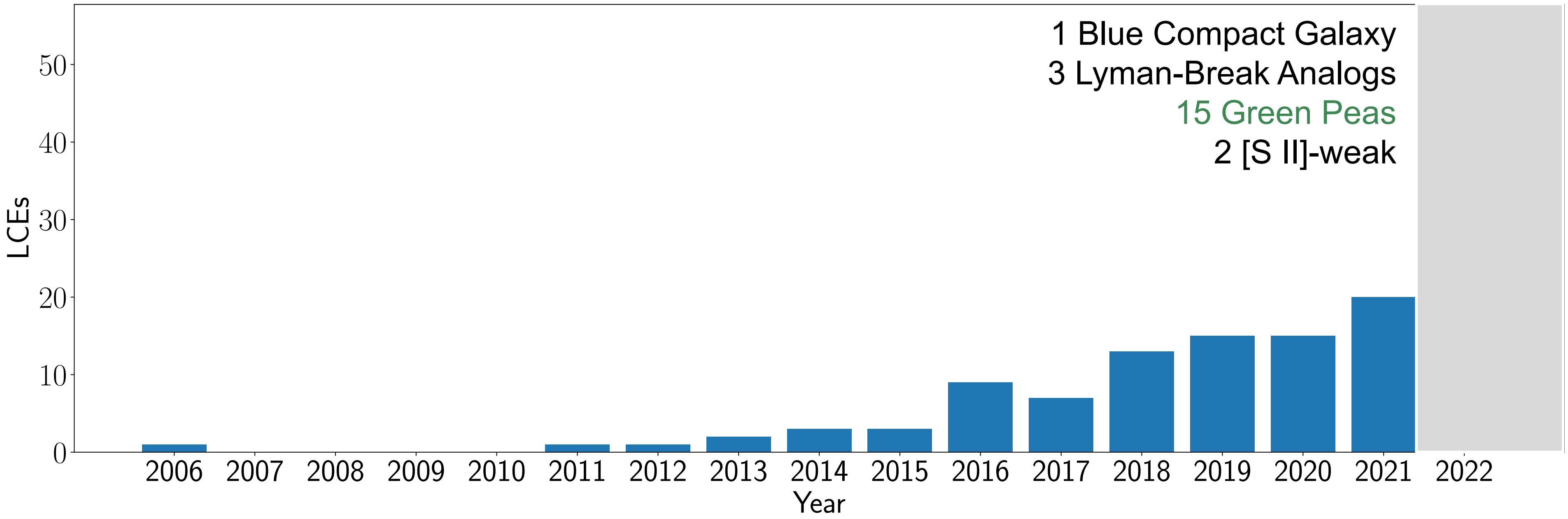
Higher M_* (>10^{10} $M_\odot$)
Compact
Dusty, high fesc,rel

Izotov+21; fesc=11-35%



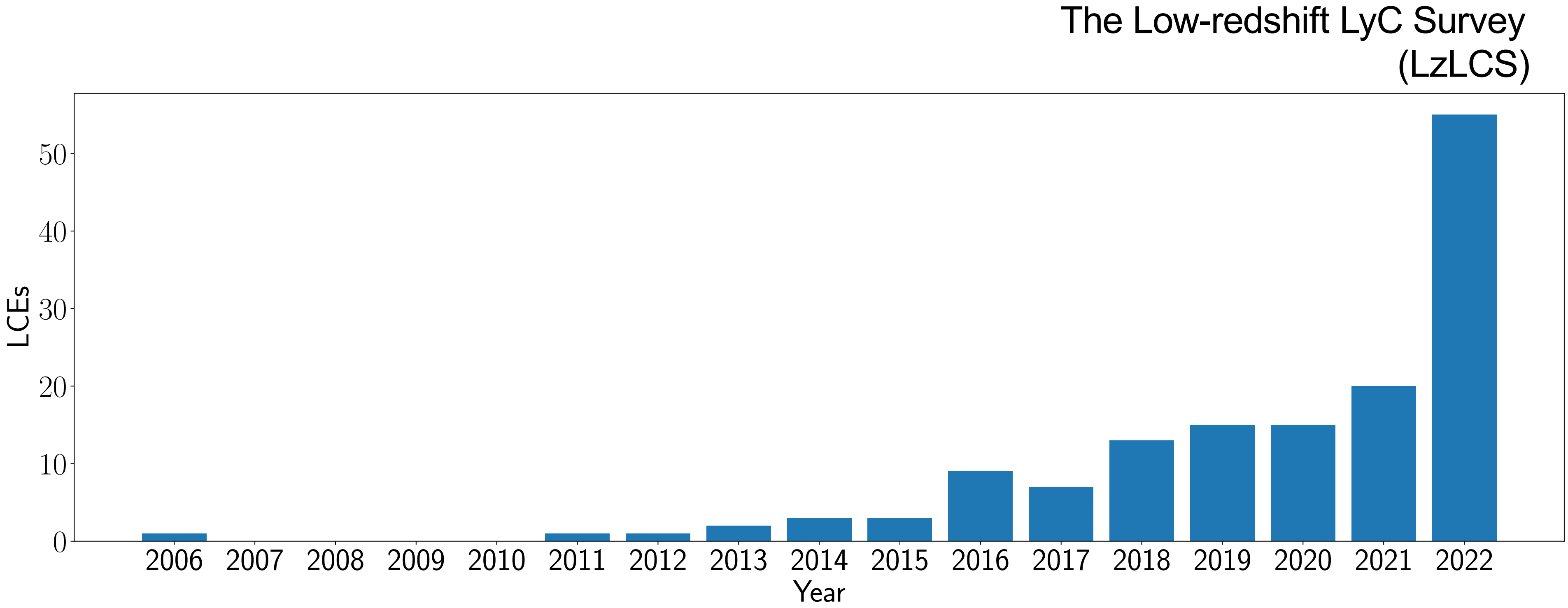
Lower M_* (<10^8 $M_\odot$)
Compact
High O32 (4-14)

KNOWN LOW-Z LCES



Bergvall+06, Grimes+07, Leitet+11, Leitet+13, Borthakur+14, Izotov+16a,b, Leitherer+16, Chisholm+17, Izotov+18a,b, Wang+19, Izotov+21

KNOWN LOW-Z LCES



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THE HST LOW-REDSHIFT LYMAN CONTINUUM SURVEY

134 orbits, 66 new galaxies
Wide parameter space

GO 15626 PI: Jaskot

Flury+2022a & b
Saldana-Lopez+22

Wang et al., 2021
Marques-Chaves+22
Chisholm+22
Trebitsch+22
Xu+23

THE LZLCS TEAM

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Cody Carr
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Stephane De Barros
Mark Dickinson
Harry Ferguson
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Steven Finkelstein
Brian Fleming
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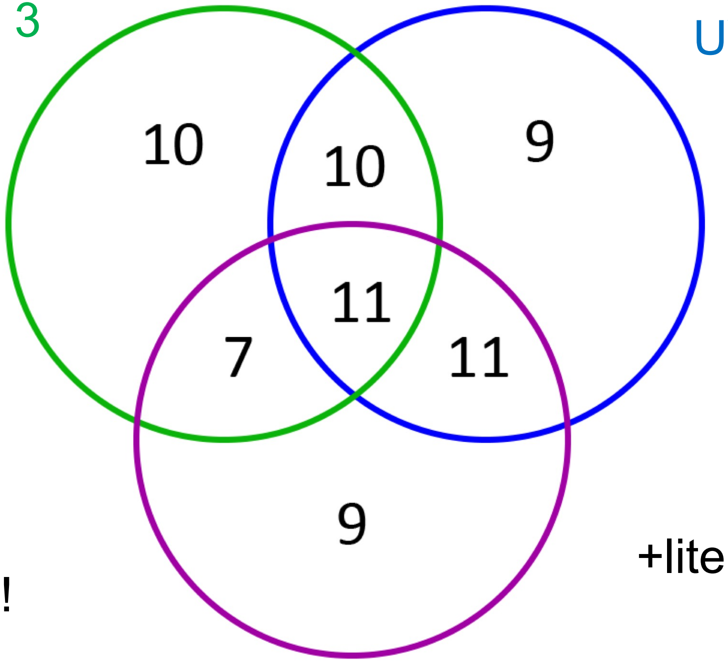
Rui Marques-Chaves
Valentin Mauerhofer
Stephan McCandliss
Genoveva Micheva
Sally Oey
Ivana Orlitova
Goran Ostlin
Casey Papovich
Laura Pentericci
Isu Ravi
Swara Ravindranath
Matias Rodriguez
Joakim Rosdahl
Michael Rutkowski
Alberto Saldana Lopez
Paola Santini
Claudia Scarlata
Daniel Schaerer
Harry Teplitz
Trinh Thuan
Maxime Trebitsch
Eros Vanzella
Anne Verhamme
Bingjie Wang
Isak Wold
Gabor Worseck
Xinfeng Xu

SAMPLE SELECTION

High ionization
[O III]/[O II] > 3

Star-forming, low dust

UV slope $\beta < -2$



Redshift z~0.3

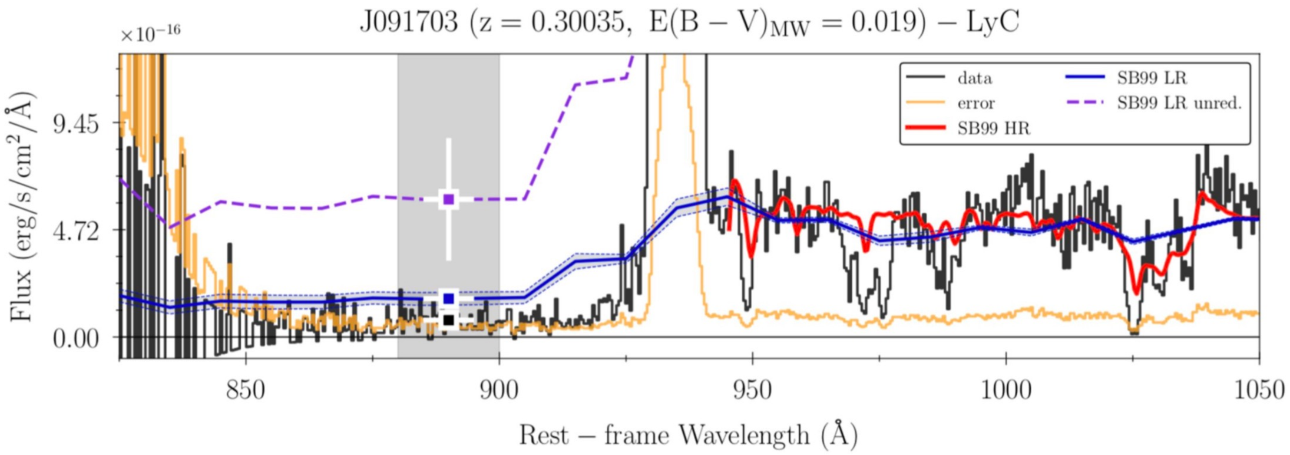
Not typical low-z galaxies!

+literature detections

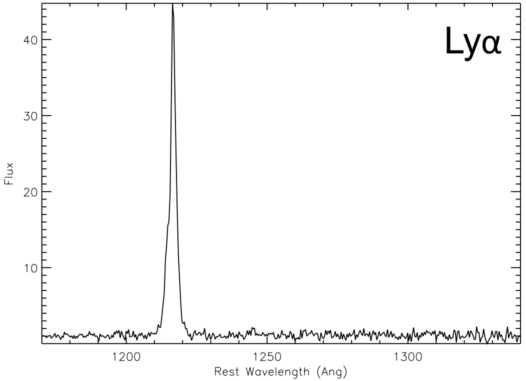
Concentrated star formation
$\Sigma_{SFR} > 0.1\ M_{\odot} yr^{-1} kpc^{-2}$

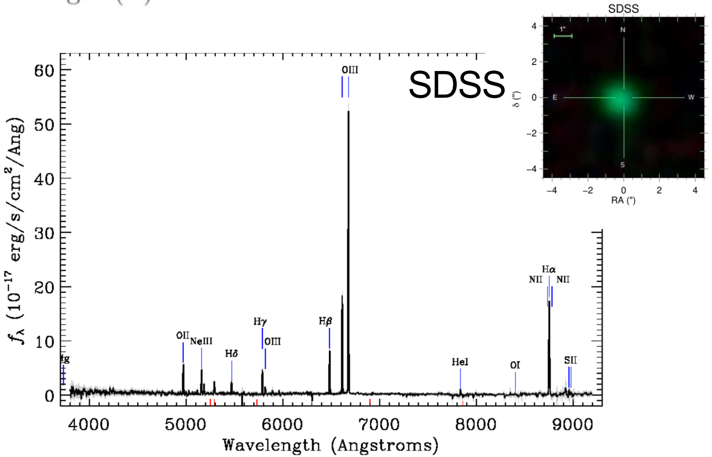
THE DATA

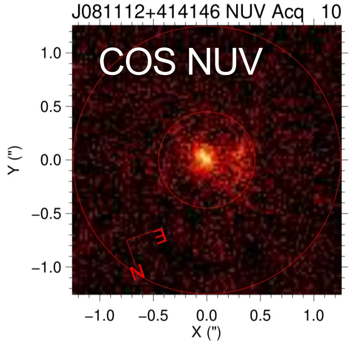
Flury+22a
Saldana-Lopez+22



- 35 detections: (probabilities > 98%)
- 12 strong LCEs; fesc > 5%







WHICH PROPERTIES CHARACTERIZE LCES?

- Strong, narrow Lyα
- Weak absorption lines
- Low dust attenuation, blue UV slopes
- Compactness
- High O32

All correlations have high scatter
LCEs are diverse

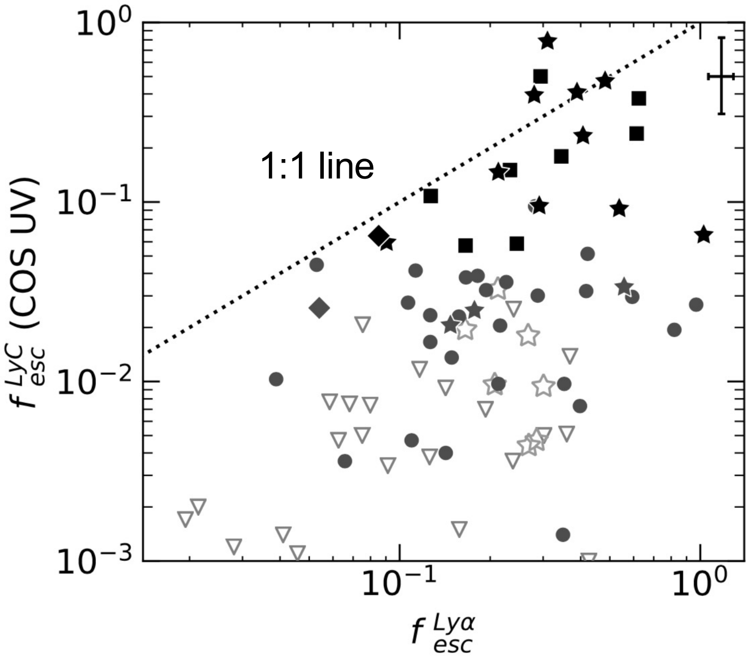
Flury+22b, Saldana-Lopez+22

LCES ARE LAES

Flury+22b

- ■ Strong detection (>5σ+fesc>5%)
- ● Weak detection (>2σ)
- ▽ Non-detection (1σ limit)

Low HI optical depth = escape of Lyα + LyC



fesc,Lyα > fesc,LyC because of scattering

LCES ARE LAES

Flury+22b

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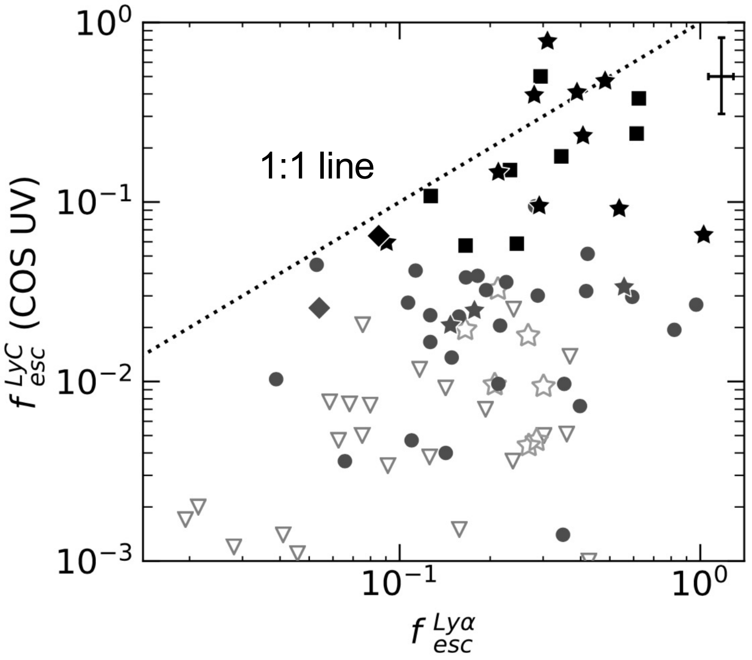
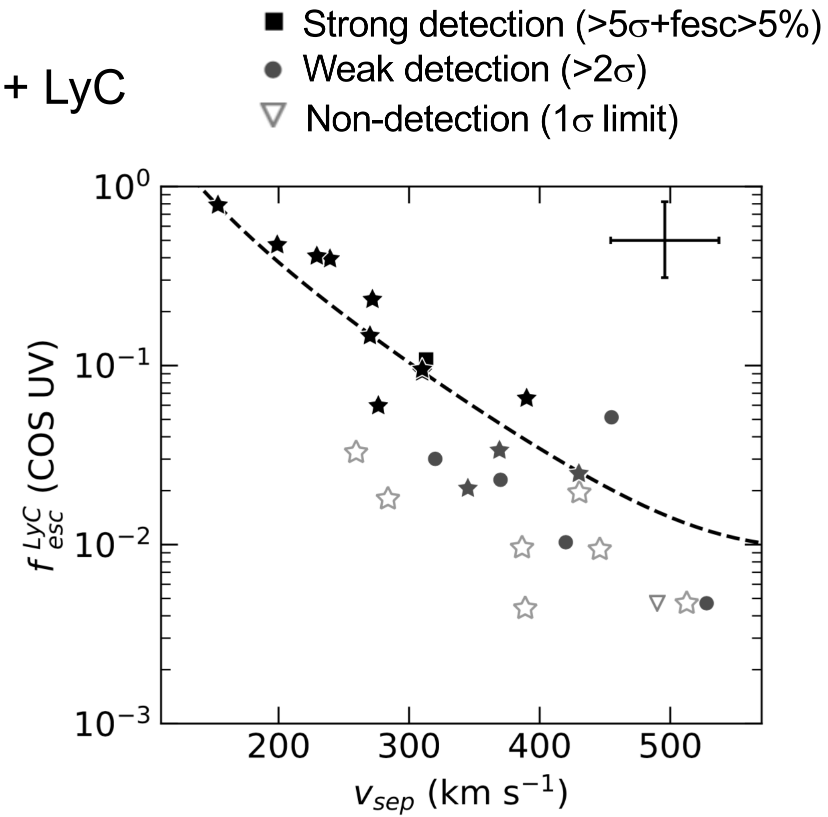


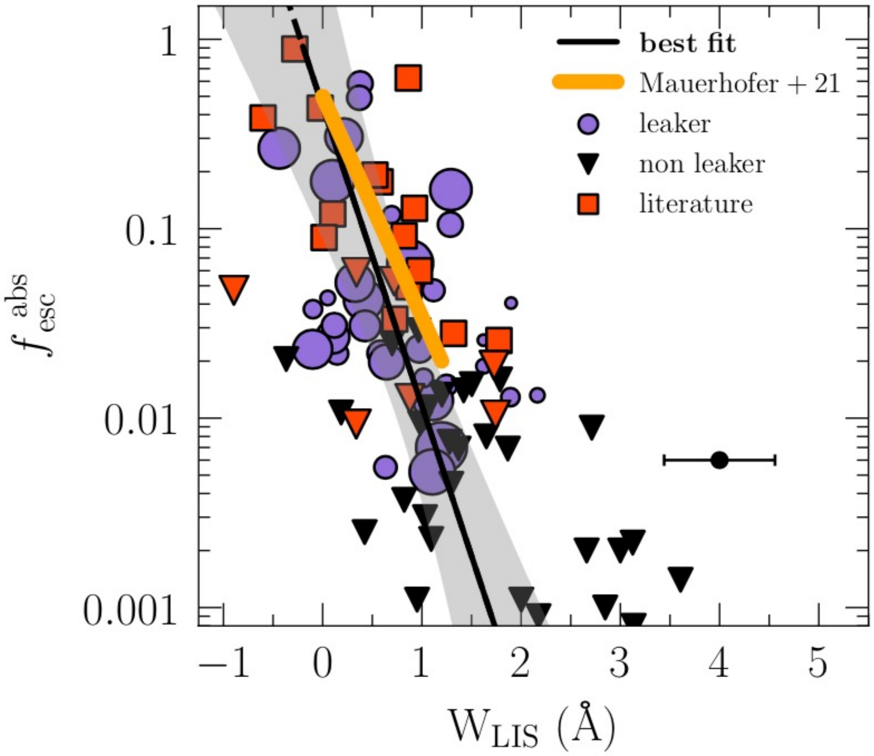


fesc,Lyα > fesc,LyC because of scattering

Narrow profiles (but smaller sample)

LOW COVERING FRACTIONS+LOW DUST

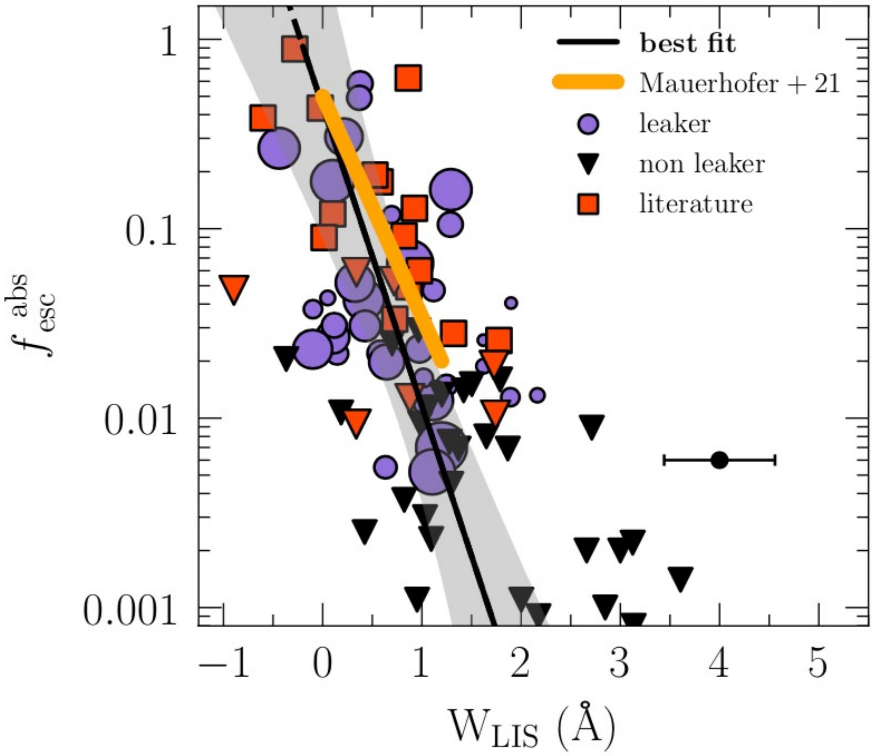
Saldana-Lopez+22

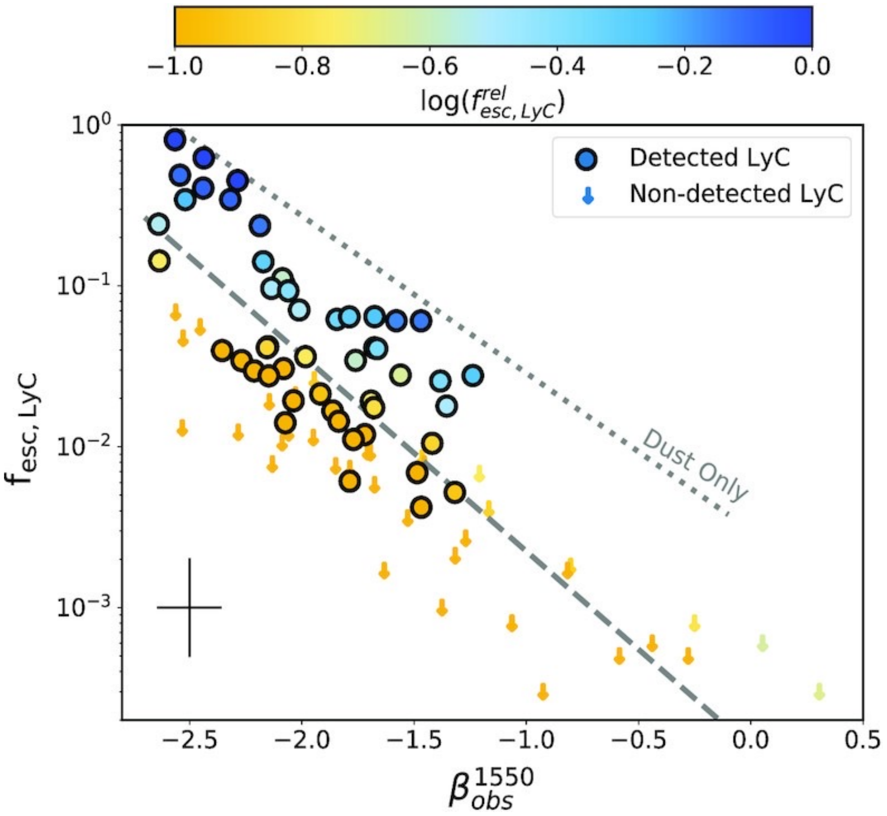


LOW COVERING FRACTIONS+LOW DUST

Chisholm+22

Saldana-Lopez+22





NEBULAR DIAGNOSTICS

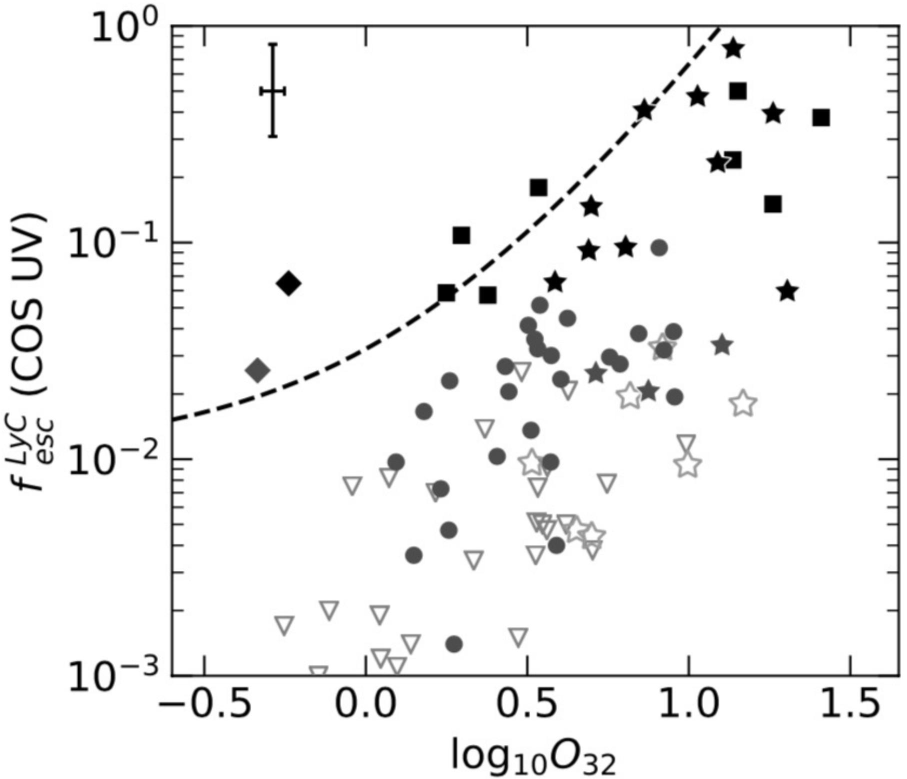
Flury+22b

- ■ Strong detection (>5σ+fesc>5%)
- ● Weak detection (>2σ)
- ▽ Non-detection (1σ limit)

Dashed line:
Correlation from Izotov+18a

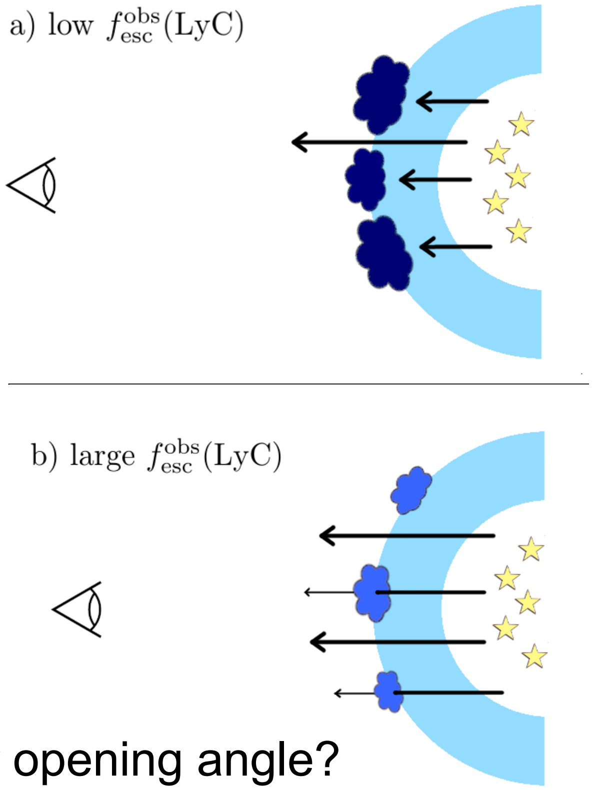
Other emission lines (e.g., [S II]) can also work as diagnostics (Wang+21)

Strong leakers more common at high O32



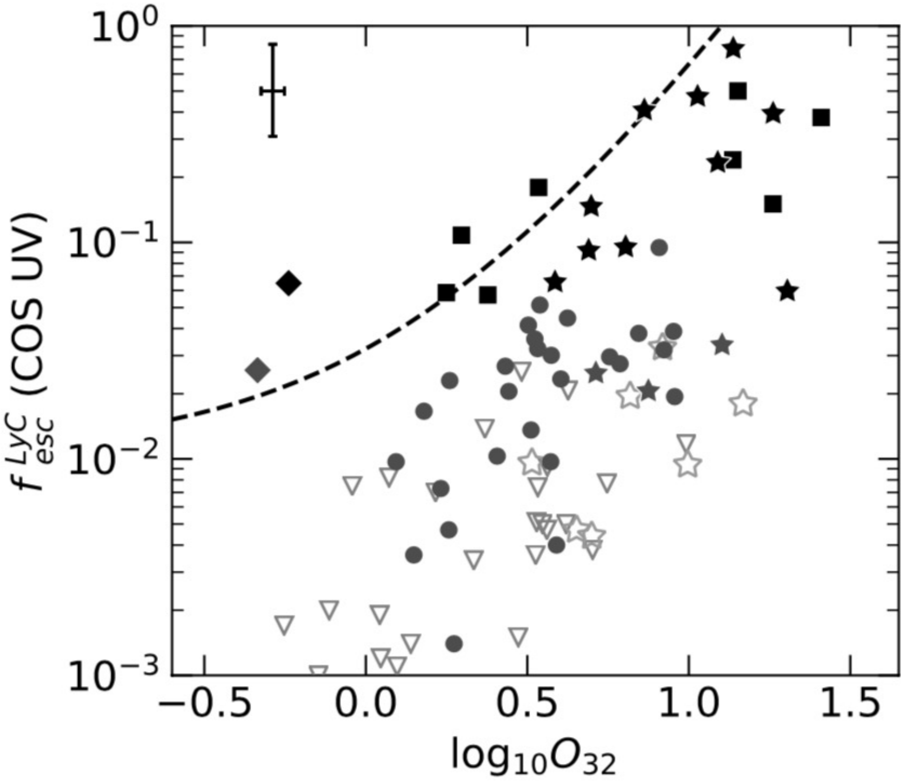
NEBULAR DIAGNOSTICS

Flury+22b



Wider opening angle?

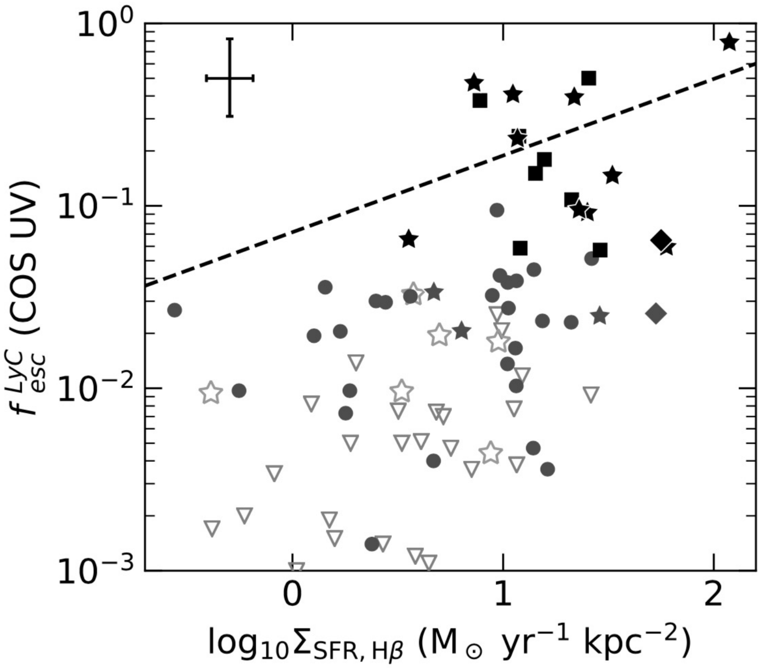
Gazagnes+20



FEEDBACK DIAGNOSTICS

Flury+22b

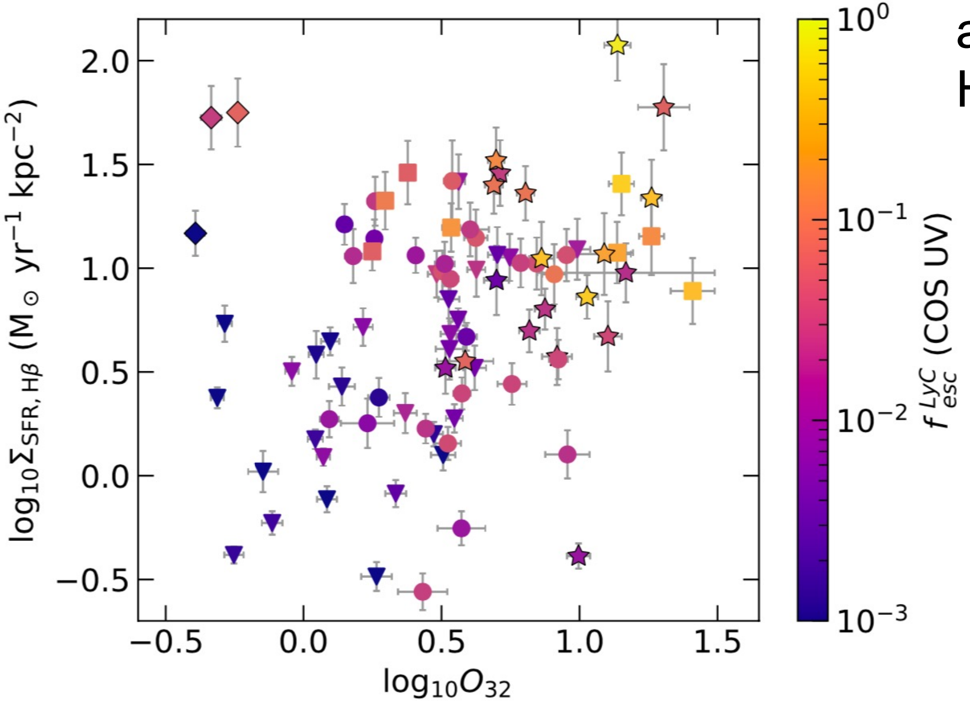
Strong LyC Emitters are compact



Dashed line:
Naidu+20 best-fit relation to match reionization constraints

DIFFERENT TYPES OF LCES?

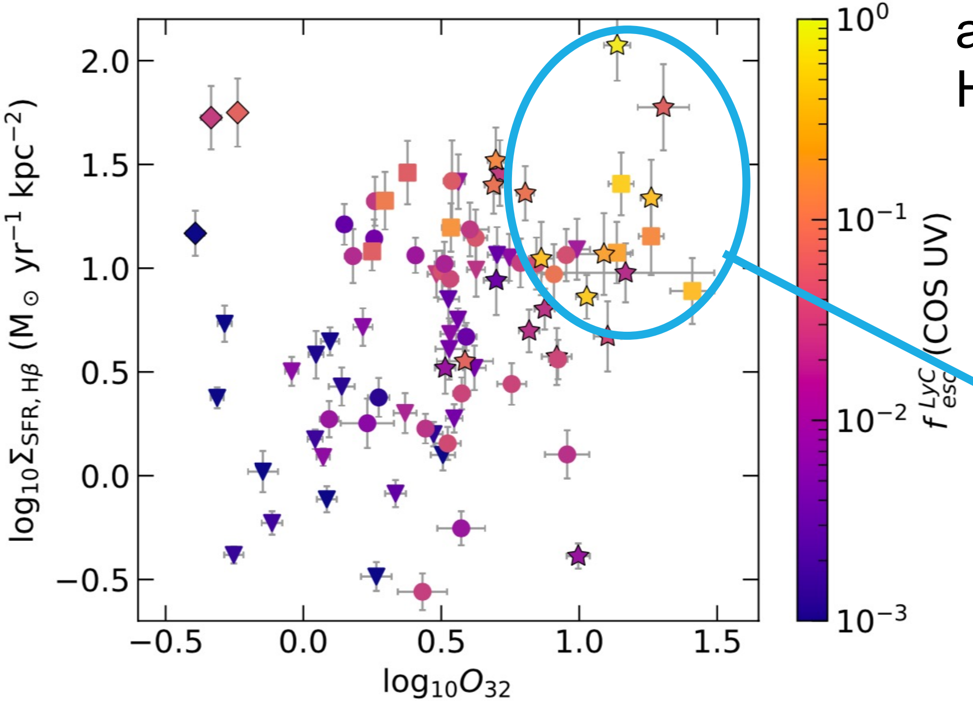
Flury+22b
Flury+ in prep



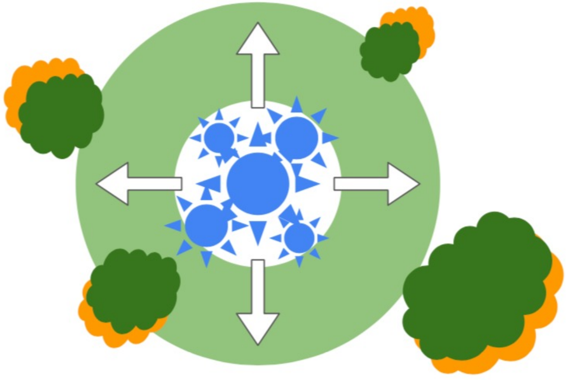
High Σ_{SFR}
and/or
High O32

DIFFERENT TYPES OF LCES?

Flury+22b
Flury+ in prep



High Σ_{SFR}
and/or
High O32

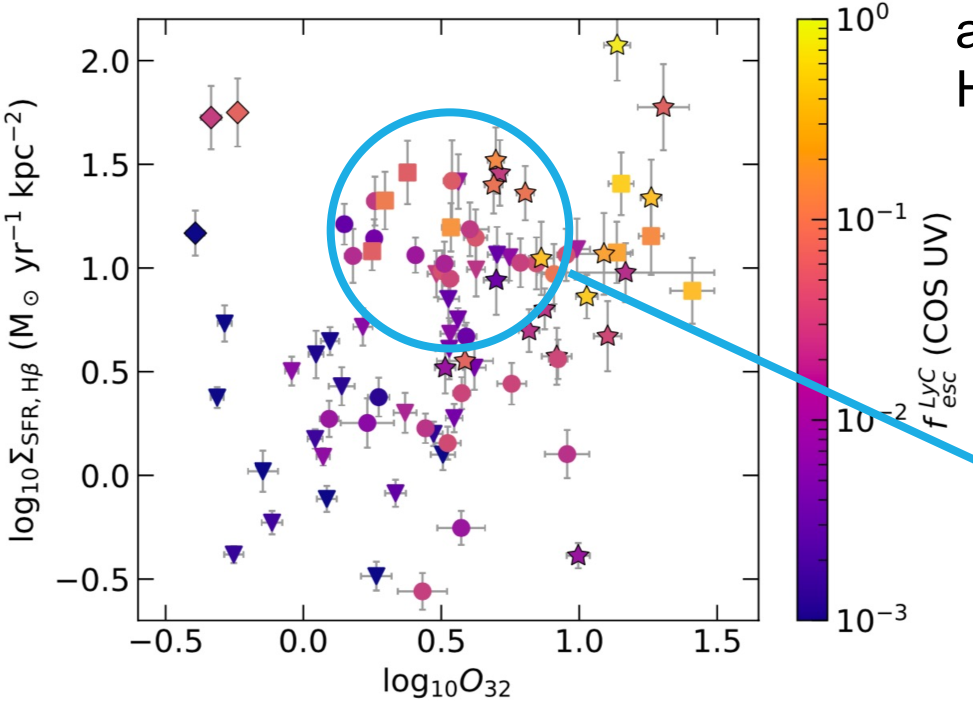


Young, highest Hβ EWs
Metal poor, M_*~$10^8\,M_\odot$
Strong radiation
Large opening angle

Cf., Jaskot+19, Gazagnes+20, Komarova+21

DIFFERENT TYPES OF LCES?

Flury+22b
Flury+ in prep



High Σ_{SFR}
and/or
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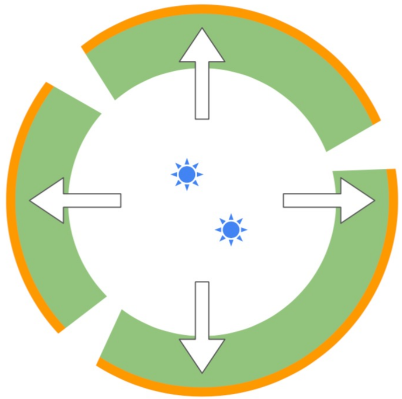


Older, more metal-rich,
M_* 10^9-10^{10} $M_\odot$
Classical SN-driven
feedback punching holes?

Cf., Jaskot+19, Gazagnes+20, Komarova+21

LZLCS – KEY RESULTS

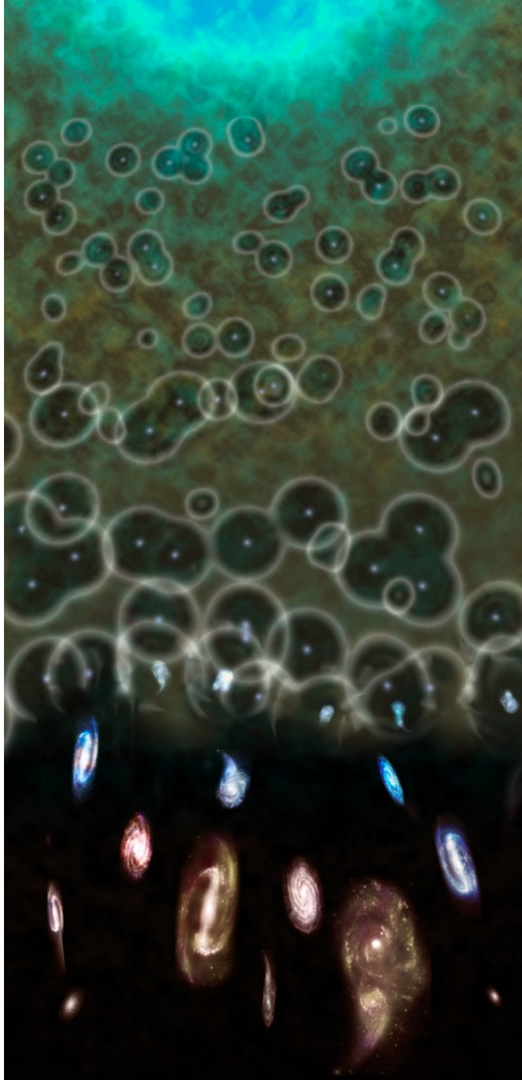
- The LzLCS has ~tripled the number of known low-z LCEs
- How to find LCEs: Lyα, [O III]/[O II], Σ_{SFR}, low dust, weak absorption
- LCEs are diverse; different feedback mechanisms?
- Trends have high scatter

Would multivariate predictions work better? (see Sara Mascia's talk!)

Do different types of galaxies follow different trends?

Do high-z galaxies follow the same trends?

What are the implications for fesc at z>6?



MULTIVARIATE PREDICTIONS: SURVIVAL ANALYSIS

Multivariate linear regression?

- Can’t be done with upper limits

MULTIVARIATE PREDICTIONS: SURVIVAL ANALYSIS

~~Multivariate linear regression?~~

- Can't be done with upper limits

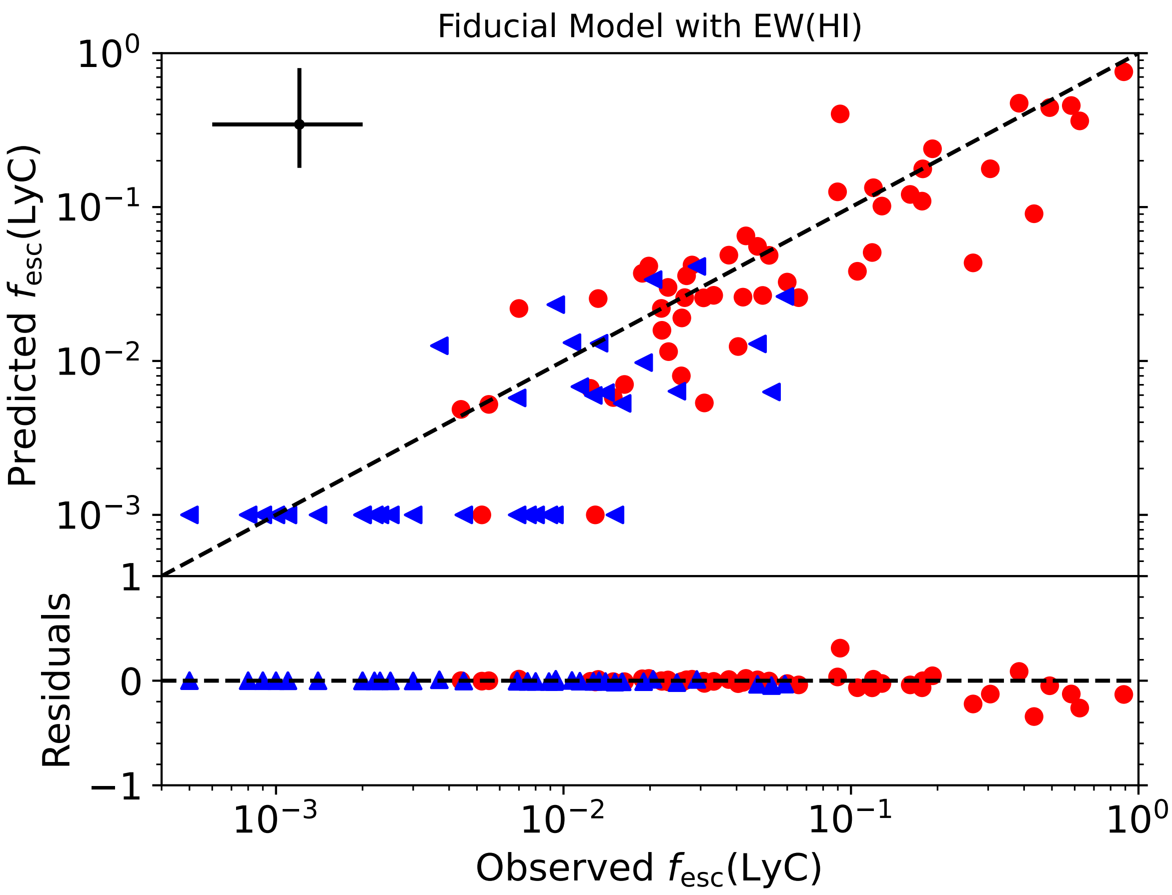
Instead: Survival Analysis

- Known lifetimes and limits
- Model the *probability* of detection at a particular fesc given a set of variables
- Cox Proportional Hazards Model *(Cox 1972; Feigelson+85, Isobe+86)*
  - $P(f_{esc}|X_i) = P_0(f_{esc})\exp\left(\beta_i X_{i1} + \cdots + \beta_p X_{ip}\right)$

BEST MODEL

10 Variables:

EW(Ly,abs), E(B-V)$_{UV}$, E(B-V)$_{neb}$, f$_{esc}$(Lya), O32, M$_{1500}$, Σ_{SFR}, M$_*$, 12+log(O/H), EW(Hβ)



Jaskot+ in prep.

BEST MODEL

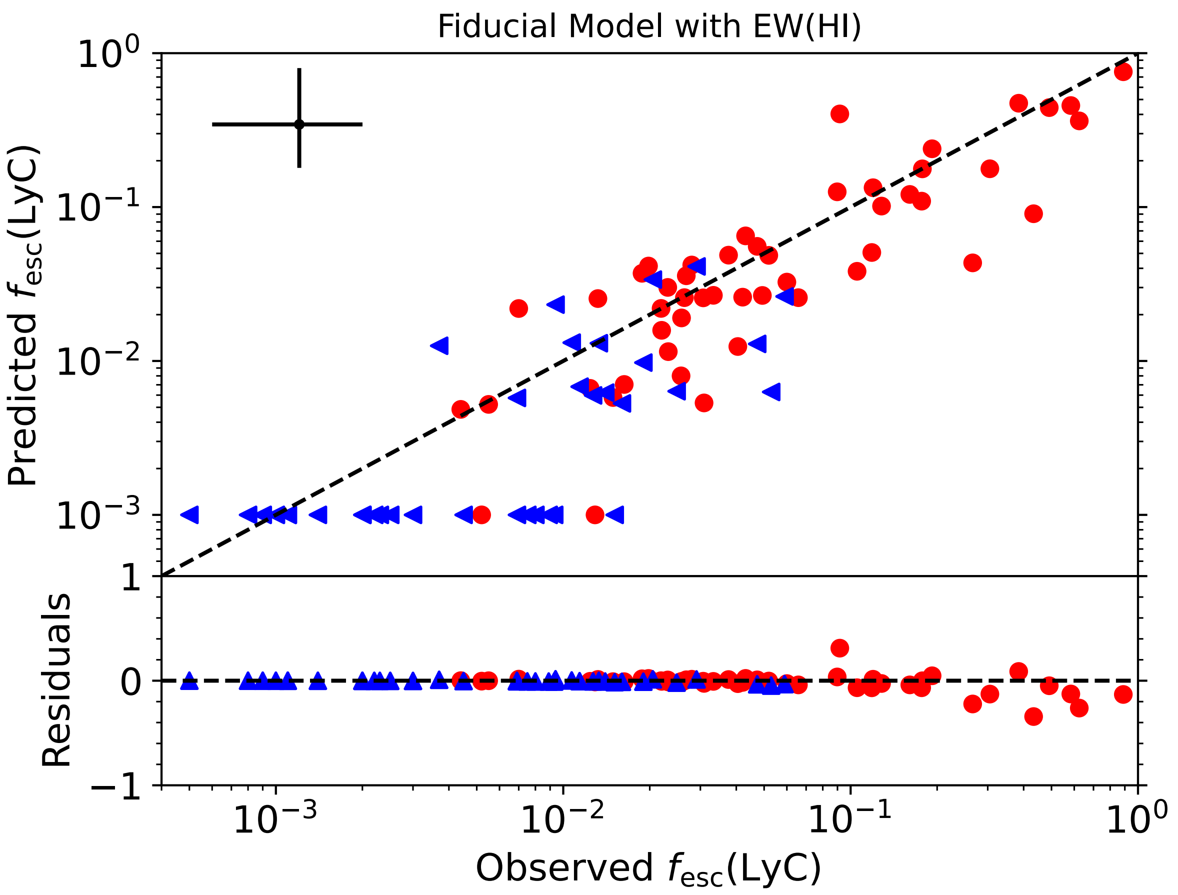
10 Variables:

EW(Ly,abs), E(B-V)$_{UV}$, E(B-V)$_{neb}$, f$_{esc}$(Lya), O32, M$_{1500}$, Σ_{SFR}, M$_*$, 12+log(O/H), EW(Hβ)

Top-ranked variables:

1. EW(Ly,abs)
2. UV slope β or E(B-V)$_{UV}$

3-4. M$_{1500}$, M$_*$, R$_l$(Ly,abs), f$_{esc}$(Lya)



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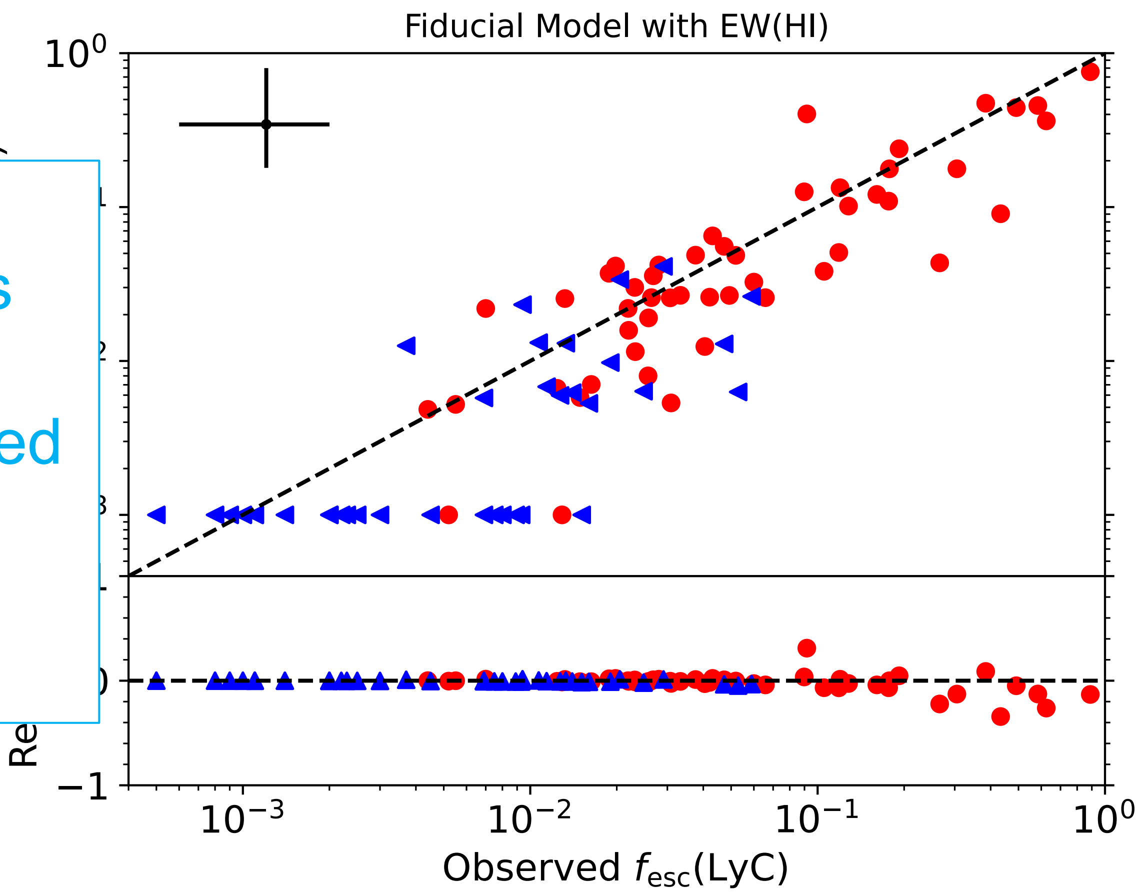
BEST MODEL



Takeaways:

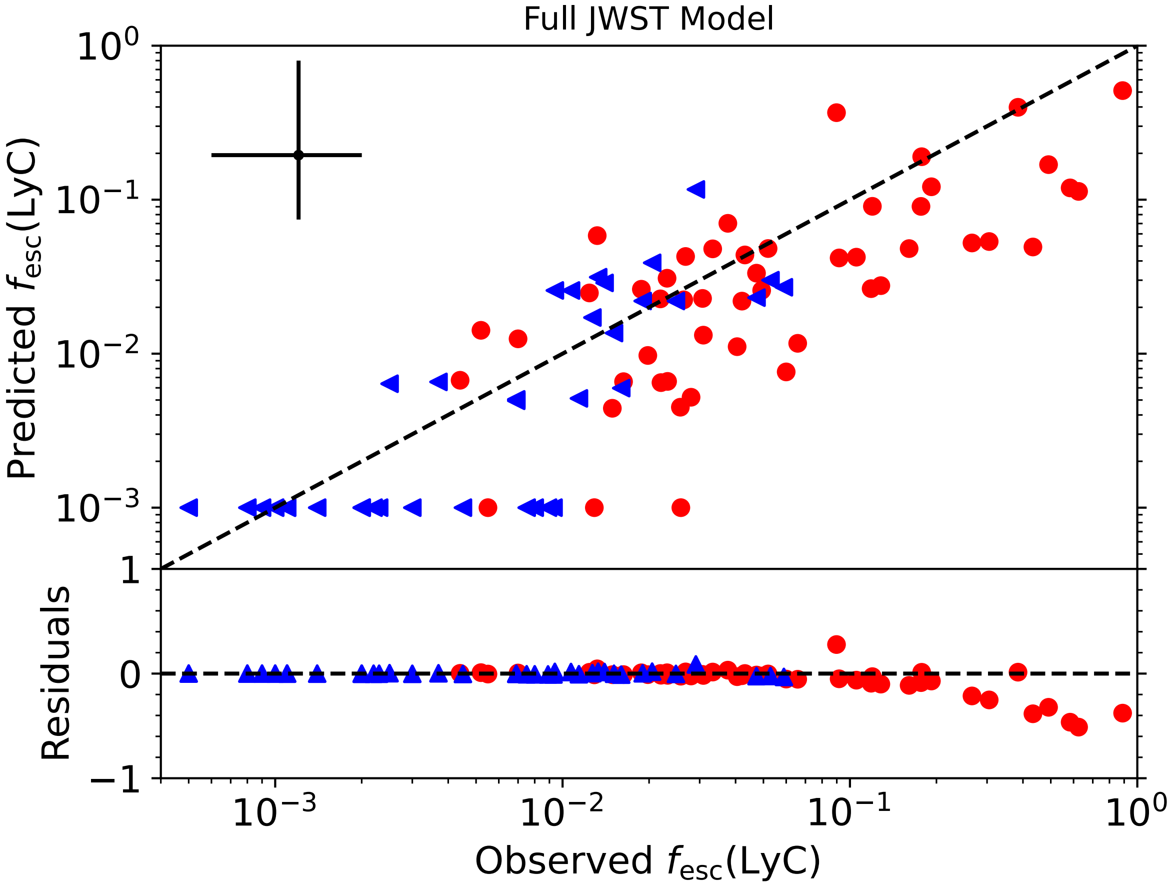
- Multivariate predictions work!
- Line-of-sight info needed
- HI info helps
  - problem for z>6 predictions

Jaskot+ in prep.

JWST MODEL

Variables:

UV slope β, O32, Σ_{SFR},
E(B-V)$_{neb}$, M_{1500}, M_*,
12+log(O/H), EW(Hβ)



Jaskot+ in prep.

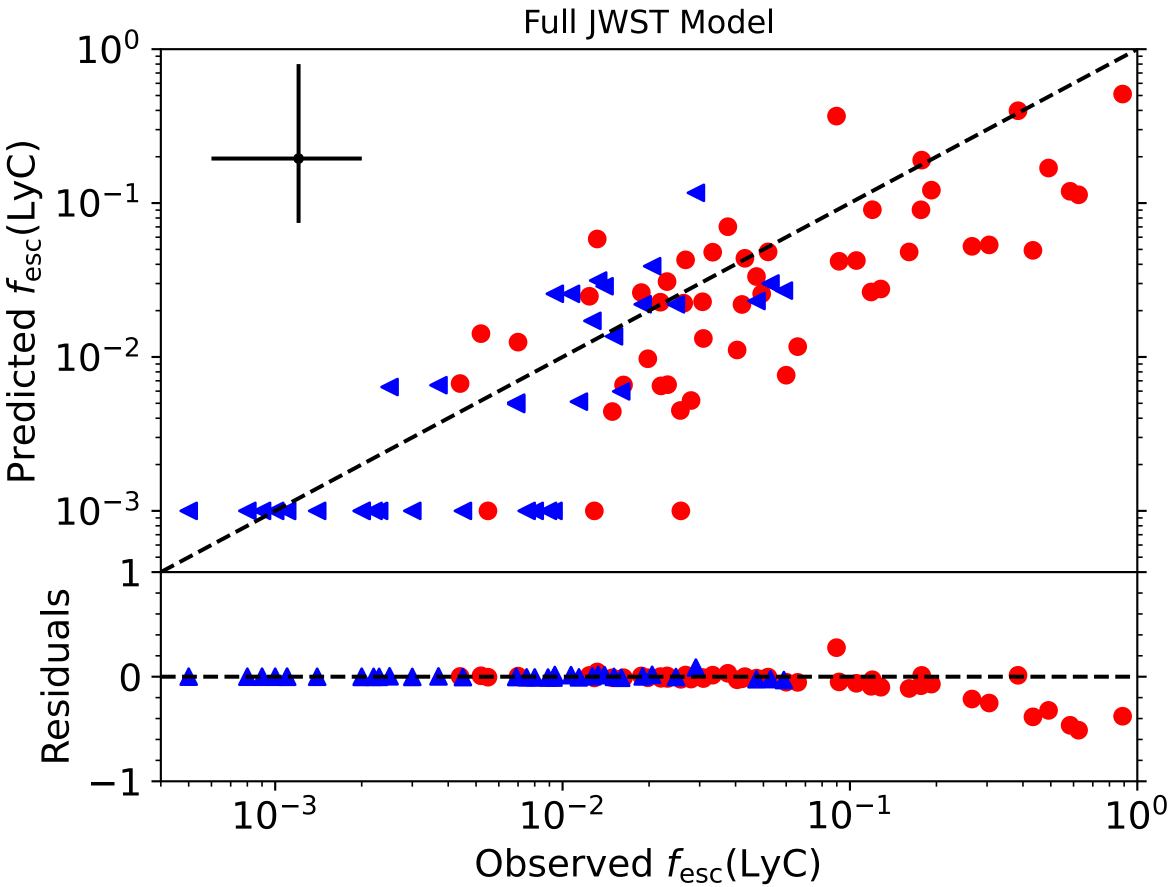
JWST MODEL

Variables:

UV slope β, O32, Σ_{SFR},
E(B-V)$_{neb}$, M_{1500}, M_*, 12+log(O/H), EW(Hβ)

Top-ranked variables:

1. UV slope β
2. Σ_{SFR}
3. O32



Jaskot+ in prep.

JWST MODEL

Variables:

UV slope β, O32, Σ_{SFR},
E(B-V)$_{neb}$, M$_{1500}$, M$_*$,
12+log(O/H), EW(Hβ)

Top-ranked variables:

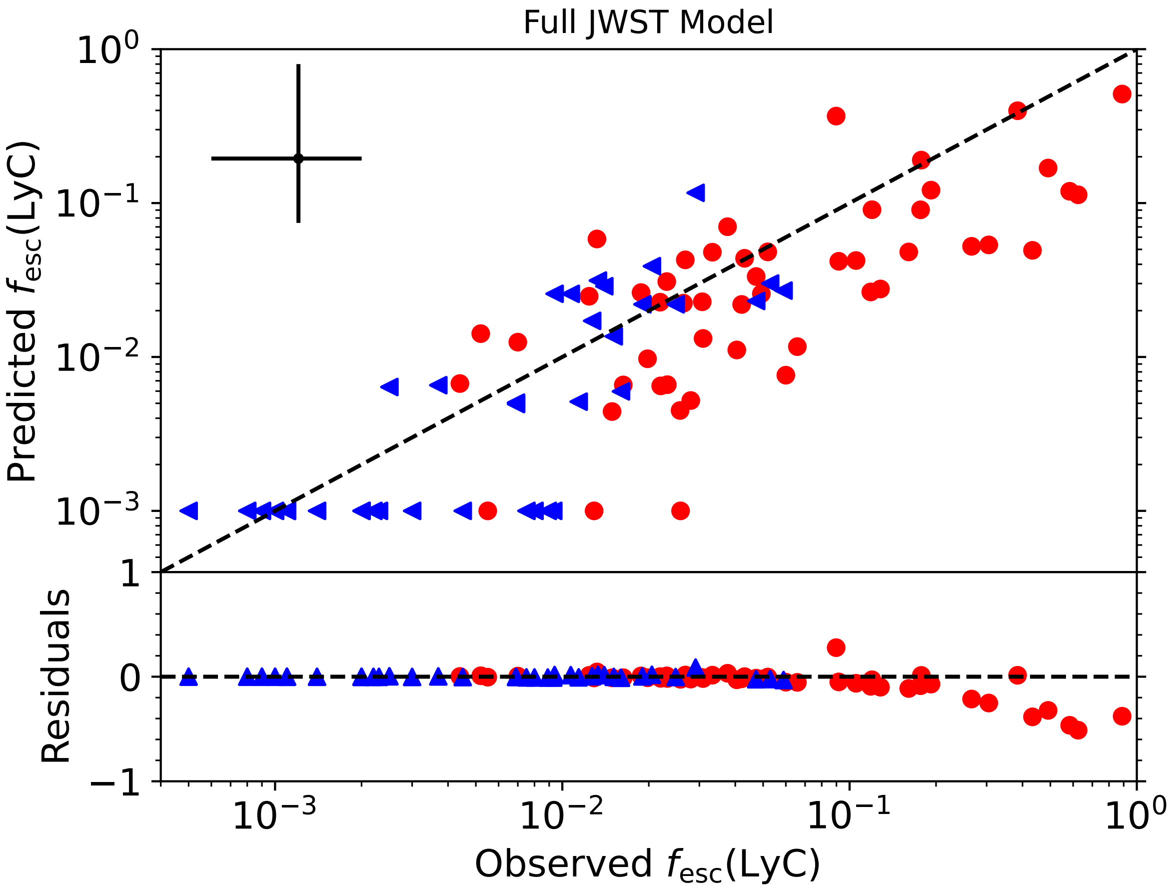
1. UV slope β
2. Σ_{SFR}
3. O32

For high mass (> $10^{8.8}$ $M_\odot$):

1. Σ_{SFR}

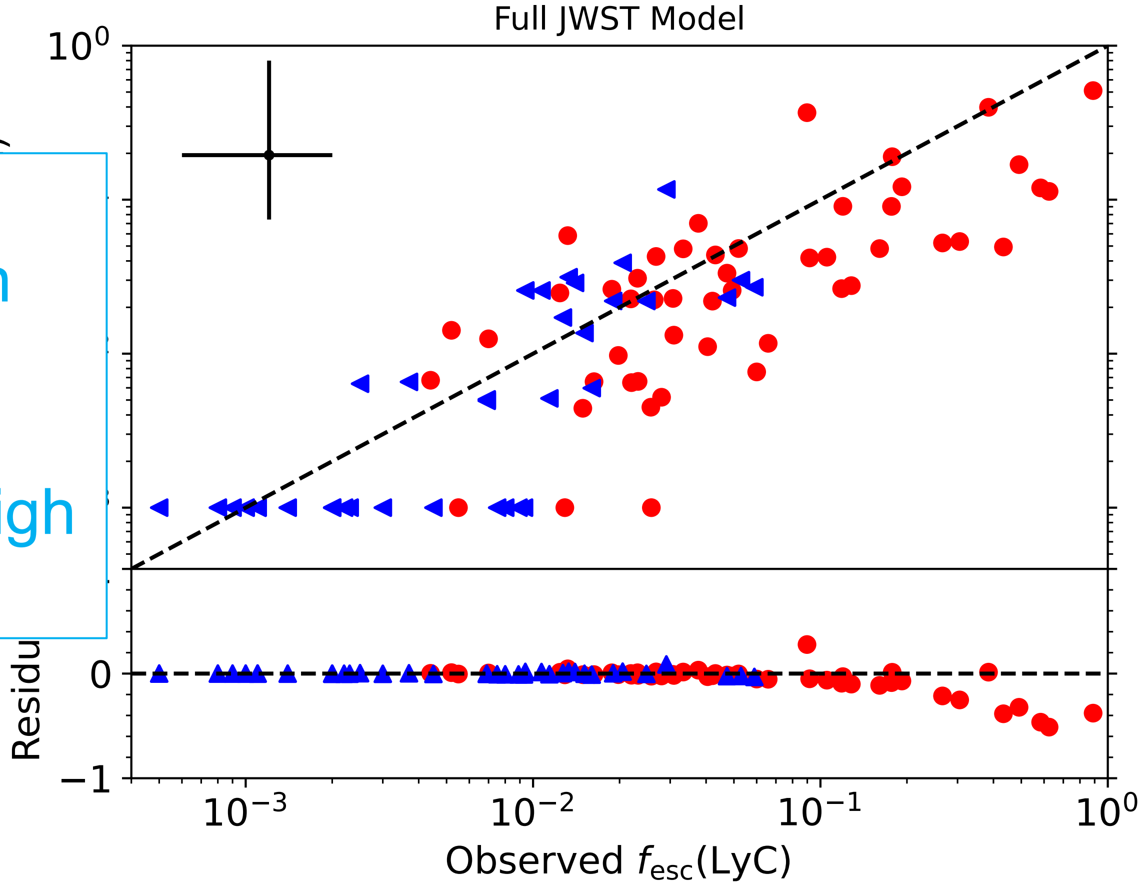
For low mass (< $10^{8.8}$ $M_\odot$):

1. O32



Jaskot+ in prep.

JWST MODEL

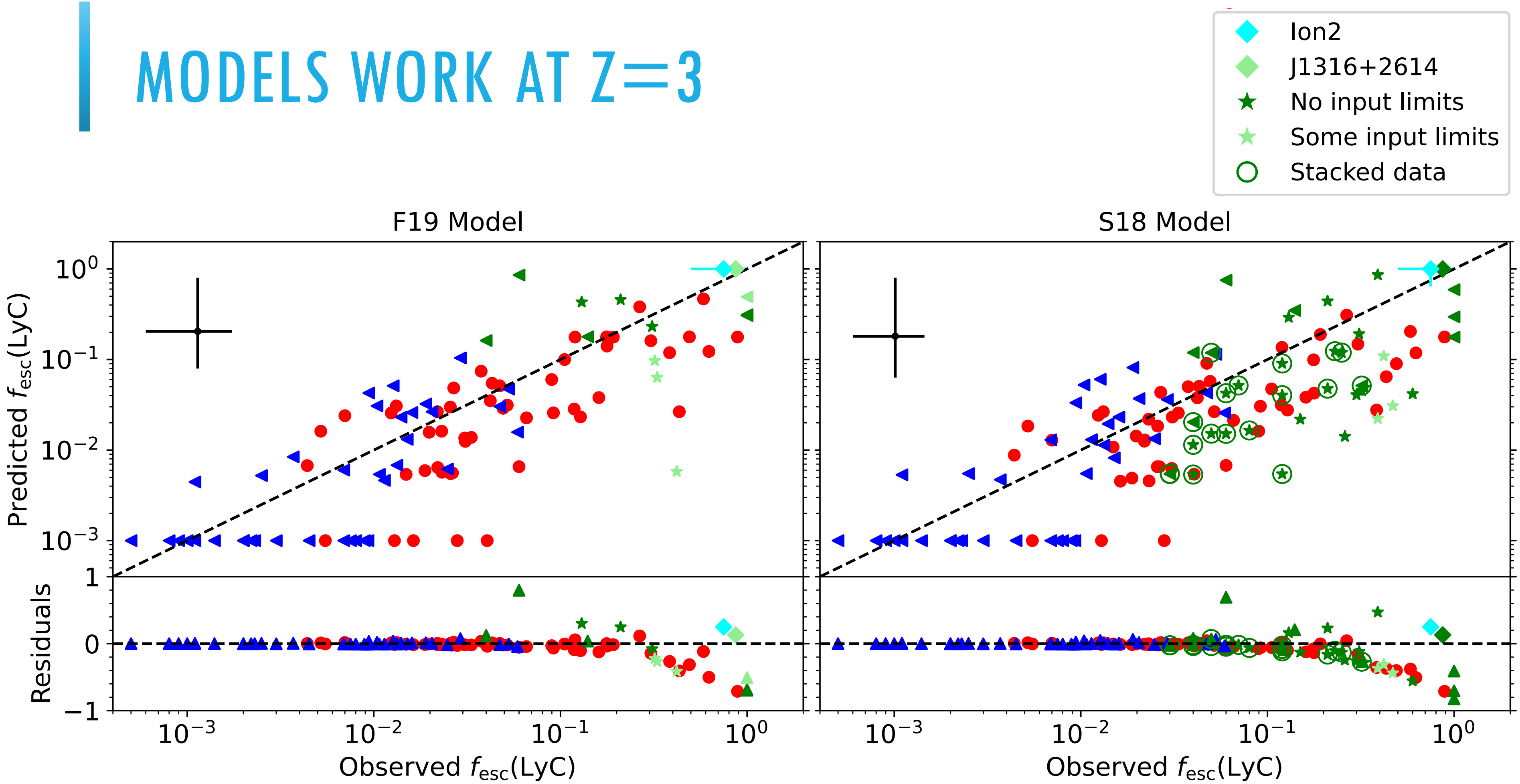


Takeaways:

- We can still distinguish LCEs and non-LCEs
- f_{esc} may depend on different variables in high vs. low mass galaxies

Jaskot+ in prep.

MODELS WORK AT Z=3

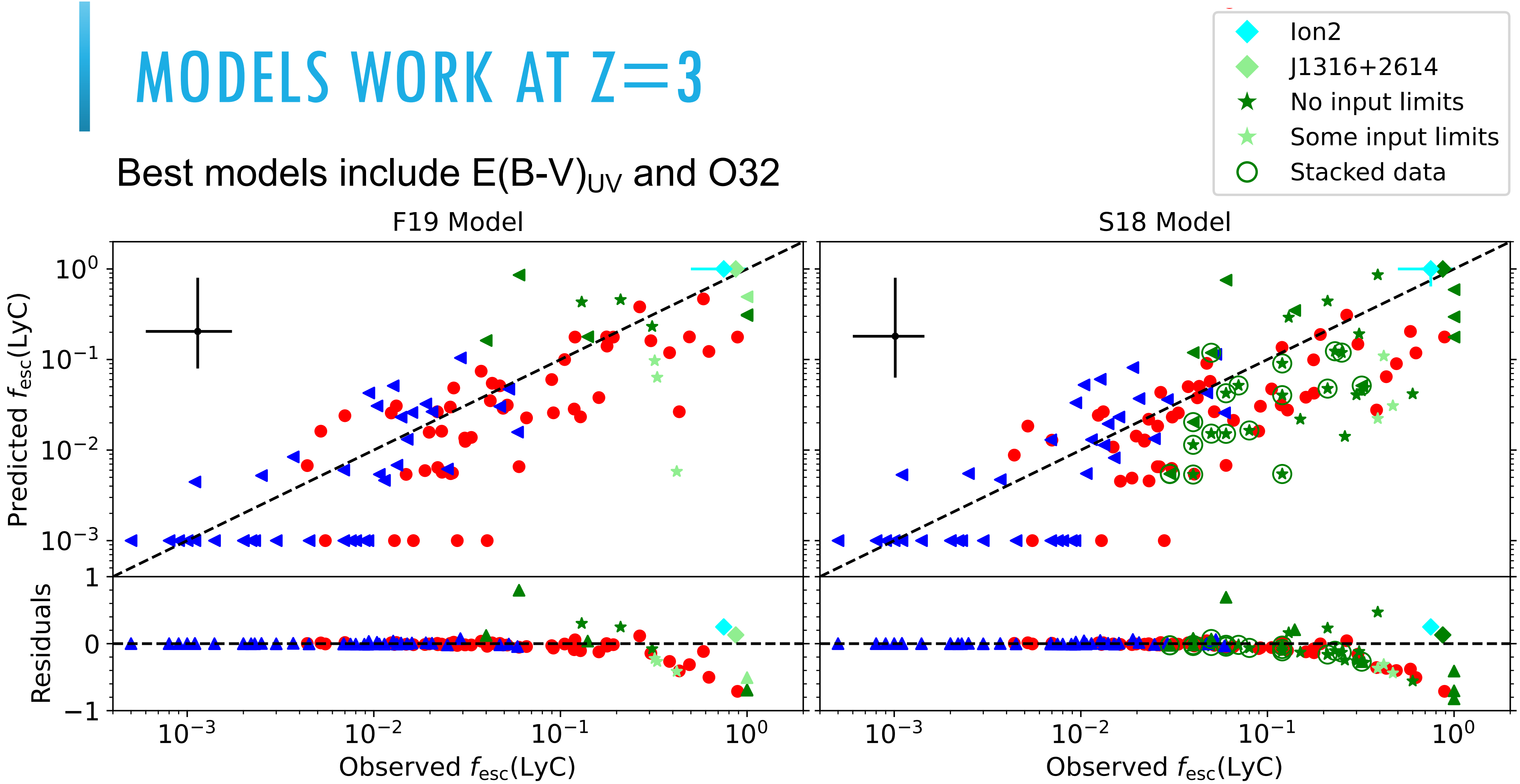


M_{1500}, M_*, $E(B\text{-}V)_{UV}$,, O32, $EW(Ly\alpha)$

M_{1500}, $E(B\text{-}V)_{UV}$,, $EW(Ly\alpha)$

MODELS WORK AT Z=3

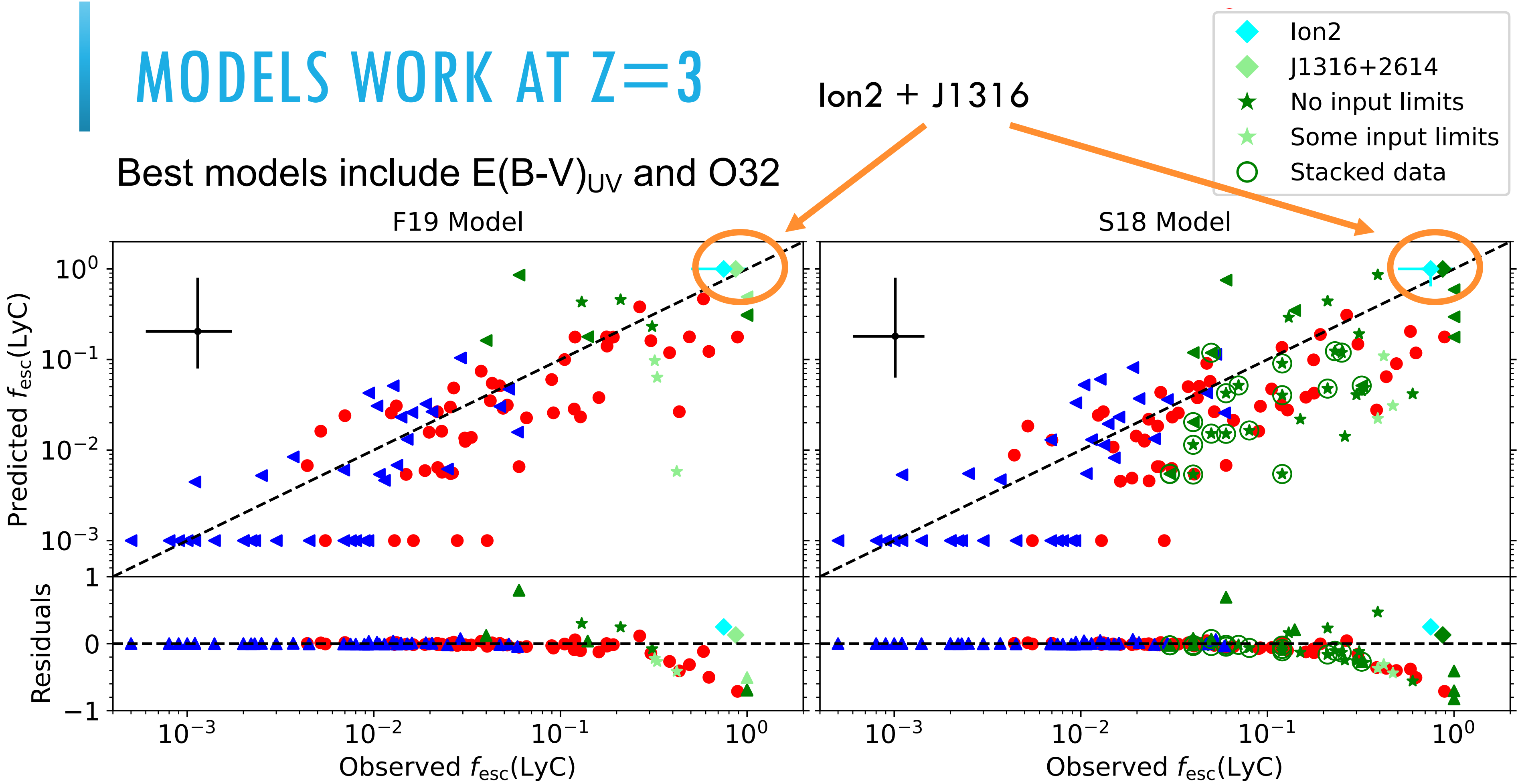
Best models include $E(B\text{-}V)_{UV}$ and O32



Jaskot+ in prep.

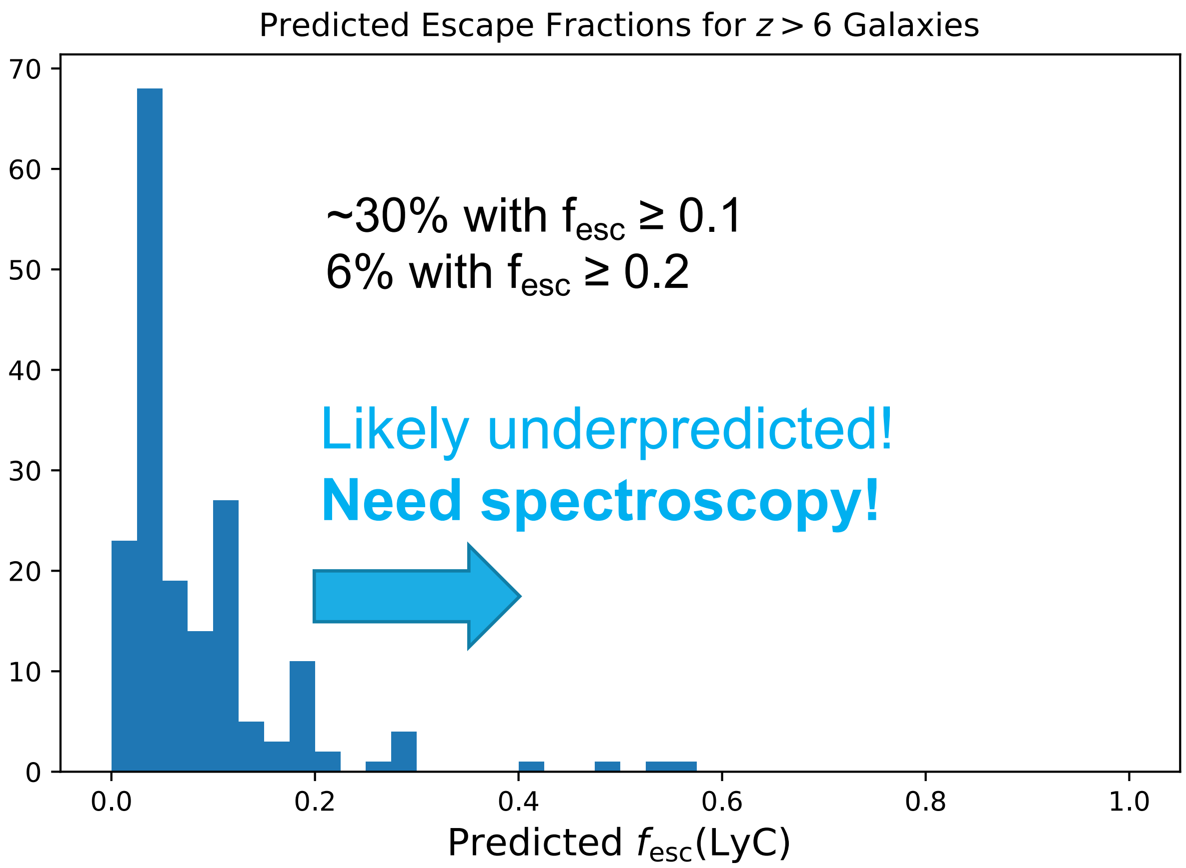
MODELS WORK AT Z=3

Best models include E(B-V)$_{UV}$ and O32



Jaskot+ in prep.

APPLICATION TO Z>6

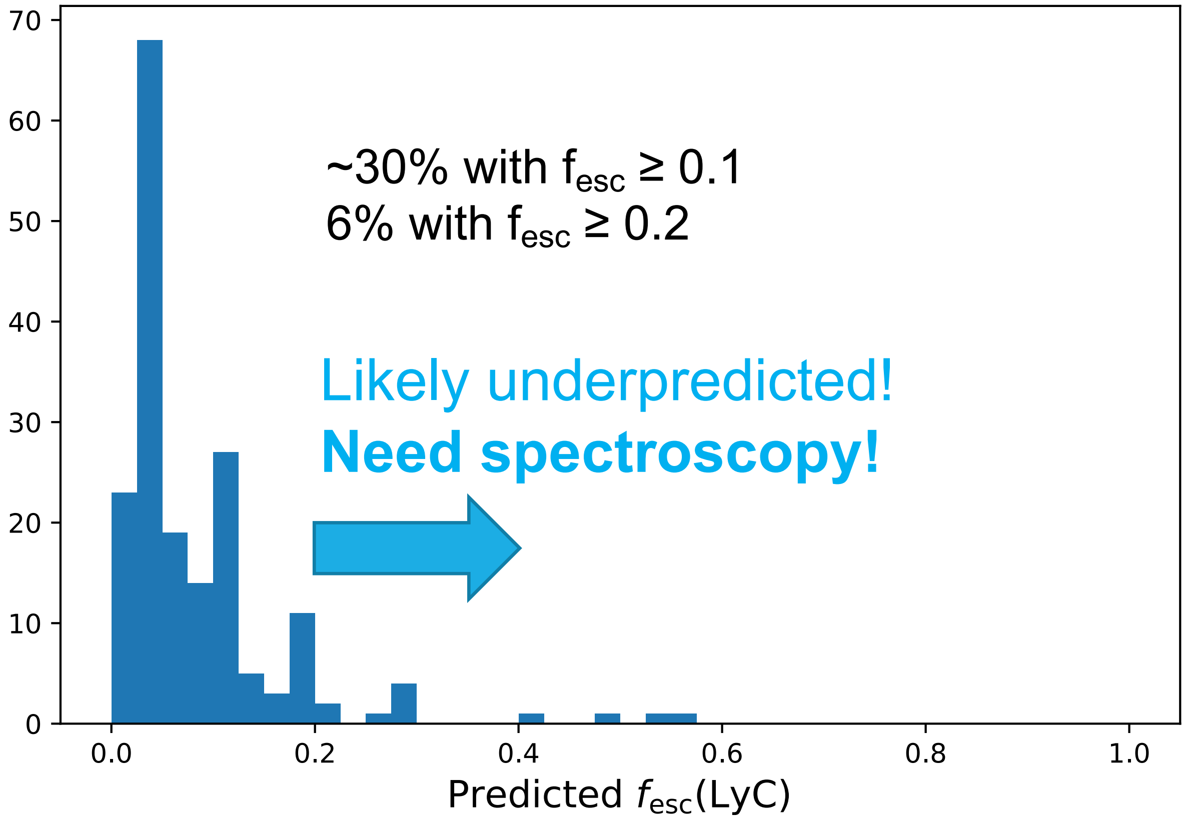


Samples:
183 galaxies
Endsley+21,22, Bouwens+22, Tang+23, Fujimoto+23, Saxena+23

Variables:
M_{1500}, M_*,
$E(B\text{-}V)_{UV}$, $EW(O3+H\beta)$

APPLICATION TO Z>6

Predicted Escape Fractions for $z > 6$ Galaxies



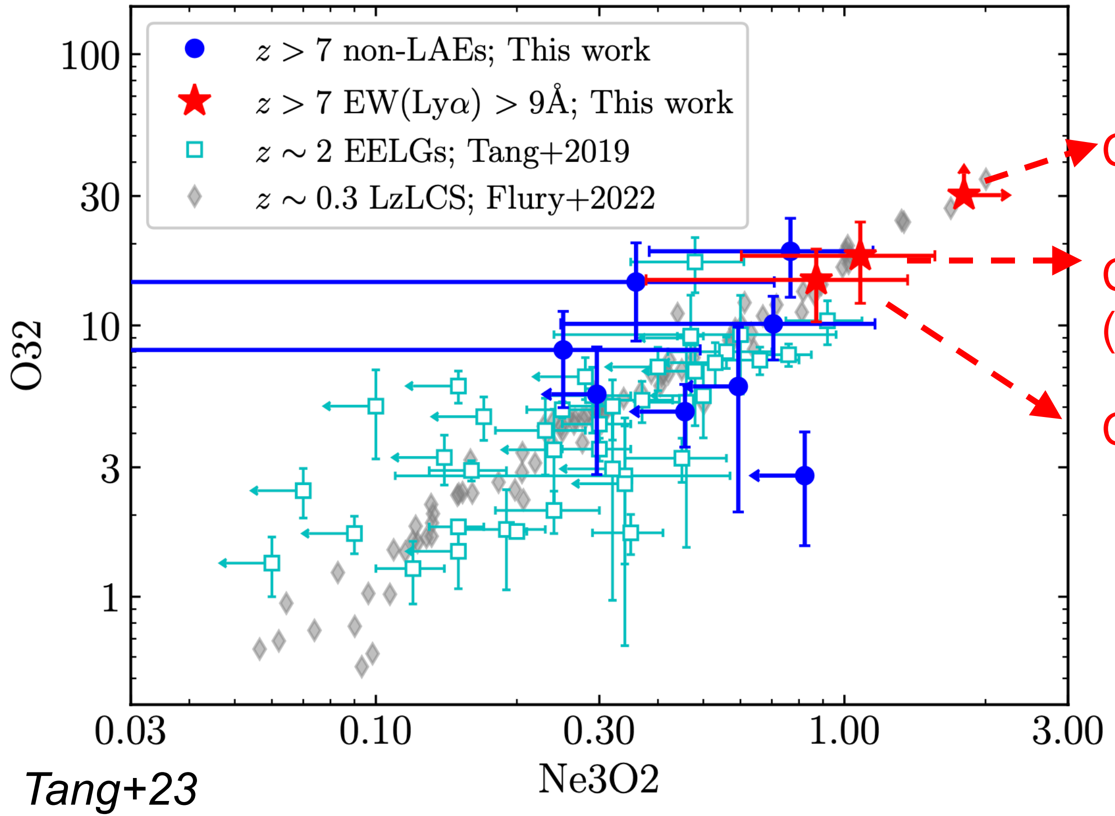
Samples:
183 galaxies
Endsley+21,22, Bouwens+22, Tang+23, Fujimoto+23, Saxena+23

Variables:
M_{1500}, M_*,
$E(B\text{-}V)_{UV}$, $EW(O3+H\beta)$

Spectroscopic Samples:
17 galaxies
Tang+23, Fujimoto+23, Saxena+23, Williams+22
O32 instead of $EW(O3+H\beta)$

>35% with $f_{esc} \geq 0.2$
Better model + stronger ELGs

STRONG LCES AT Z>6



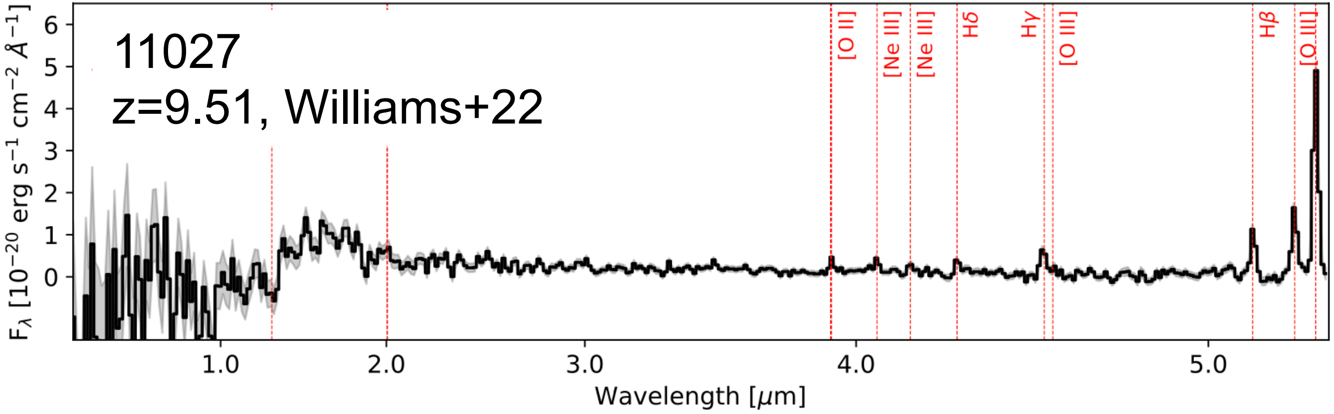
Tang+23

CEERS 1027, $f_{esc,pred}$ = 0.6

CEERS 1019, $f_{esc,pred}$ = 1
(possible AGN? Larson+23)

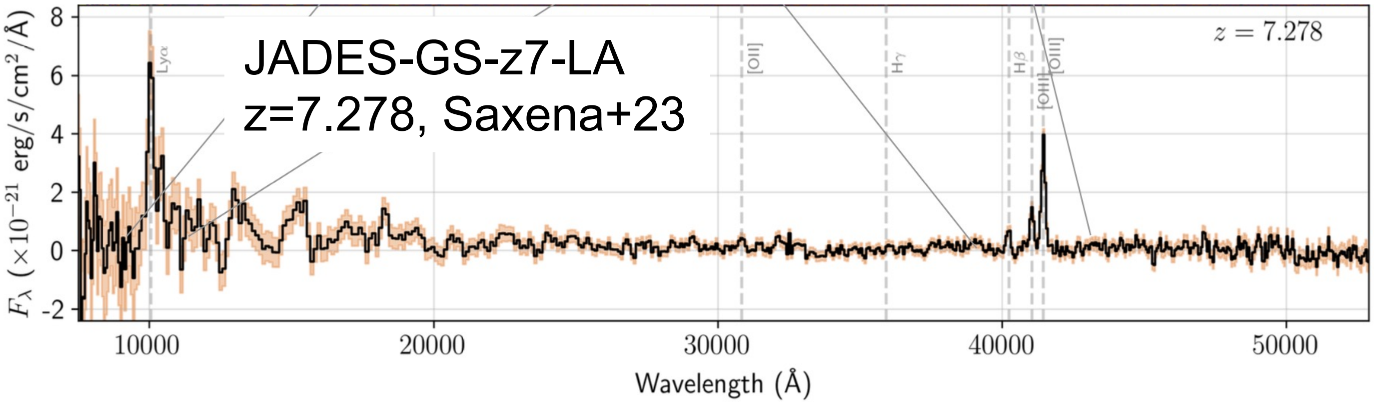
CEERS 698, $f_{esc,pred}$ = 0.7

SURPRISINGLY WEAK LCES



O32 = 12

$f_{esc,pred}$ **≤ 0.02**



f_{esc}(Lya) = 0.96!

O32 = 8.8

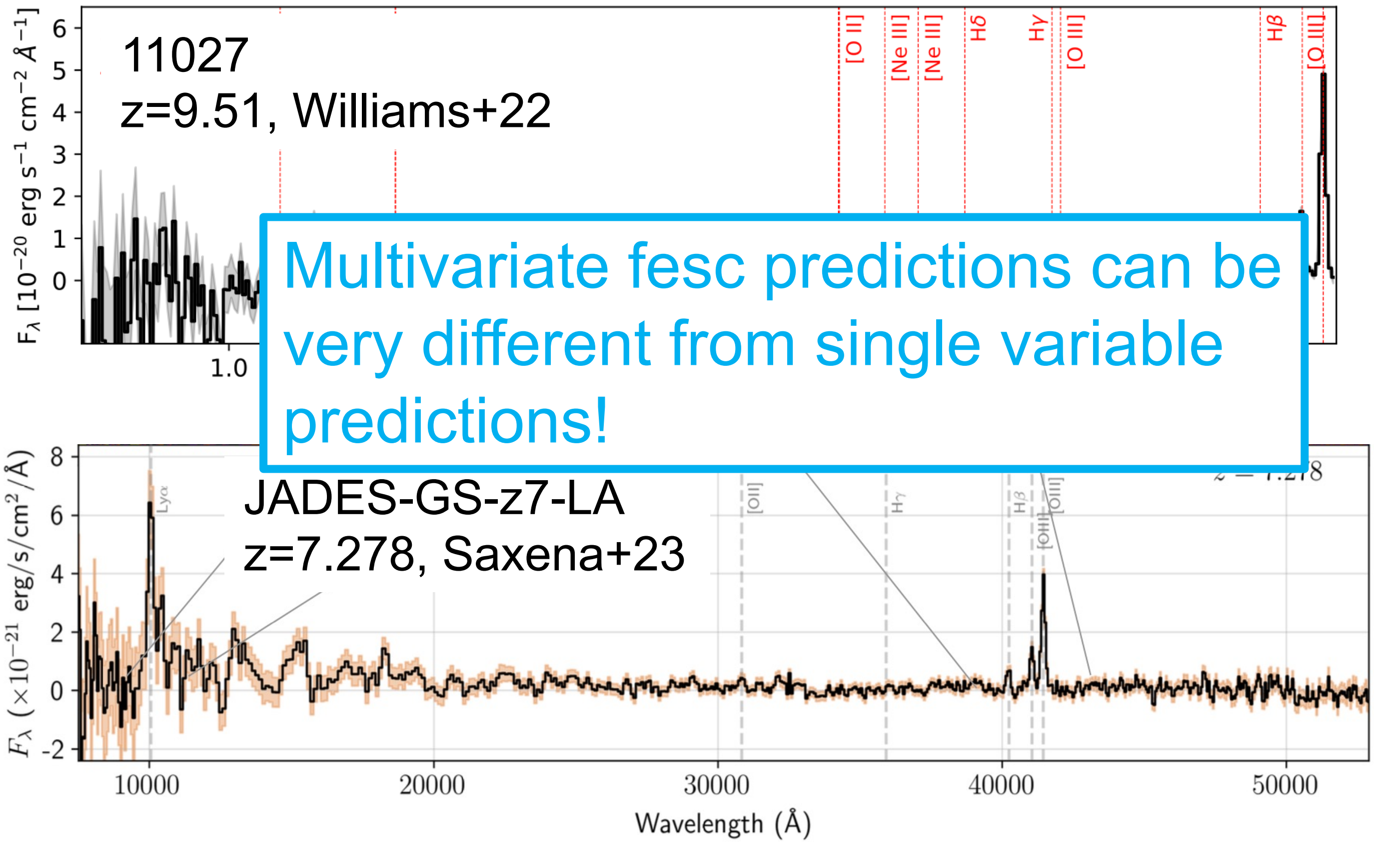
Without Lya info:

$f_{esc,pred} = 0$

With most info:

$f_{esc,pred}$ = 0.02-0.09

SURPRISINGLY WEAK LCES



Multivariate fesc predictions can be very different from single variable predictions!

O32 = 12

$f_{esc,pred}$ ≤ 0.02

f_{esc}(Lya) = 0.96!

O32 = 8.8

Without Lya info:

$f_{esc,pred}$ = 0

With most info:

$f_{esc,pred}$ = 0.02-0.09

SUMMARY

- LCEs are diverse – no one unique property
- LyC escape is a multi-parameter problem
- High f_{esc} = low line-of-sight HI and dust
  - How? From SN feedback or radiative feedback (may vary)

At z~0: Follow-up work on detailed properties, feedback processes, sites of LyC escape

- z~3 galaxies seem to follow the same trends as z~0.3 LCEs

At z~3: Need more measurements of relevant properties to test

- At z>6, numerous strong LCEs with f_{esc} > 0.1
  - Multivariate predictions can differ from single variable estimates; use all available info

At z>6: Need more measurements, larger samples