Insights into the Lyman continuum radiation escape

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$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

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It is **possible** to **observe**

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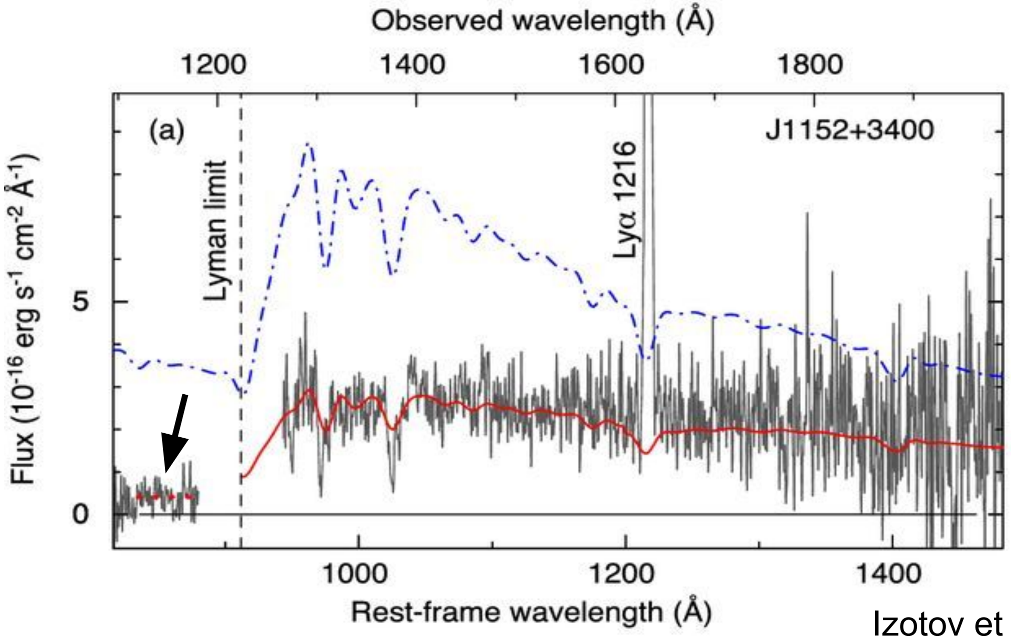
$$\dot{n}_{ion}\big]_{escaped}$$

It is **possible** to **observe** but with lots of **caveats**

Lyman continuum emission from galaxies is in general **very faint**



Izotov et al. (2016)

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

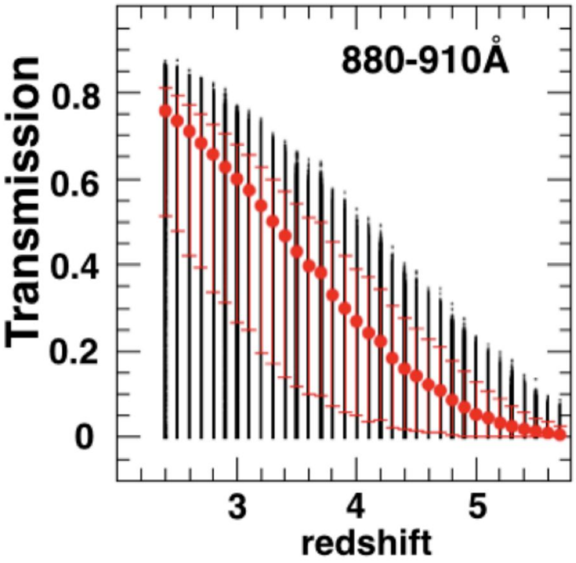
$\dot{n}_{ion}\big]_{escaped}$

It is **possible** to **observe** but with lots of **caveats**

Direct **detection** of **ionizing radiation** gets close to **impossible** at **z > 4.5** given the **very high IGM opacity**

↓

By definition we are **not able to measure** this key ingredient of reionization for the galaxies in this **epoch**



Vanzella et al. (2016)

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

$\dot{n}_{ion}]_{escaped}$

It is **possible** to **observe** but with lots of **caveats**

It is better if we **split** the **problem** in parts

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

$$\dot{n}_{ion}]_{escaped} = \dot{n}_{ion}]_{produced} \times f^{LyC}_{escaped}$$

It is **possible** to **observe** but with lots of **caveats**

Not possible to **observe** directly
We need to **understand** the **LyC sources** to constrain it

Values between 0 and 1
0 no escape
1 total escape
Global, **line of sight**, different regions

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

$$\dot{n}_{ion}]_{escaped} = \dot{n}_{ion}]_{produced} \times f^{LyC}_{escaped}$$

$$\dot{n}_{ion}]_{produced} = \rho_{UV} \times \xi_{ion}$$

$\dot{n}_{ion}]_{escaped}$: It is **possible** to **observe** but with lots of **caveats**

$\dot{n}_{ion}]_{produced}$: **Not** possible to **observe** directly. We need to **understand** the **LyC sources** to constrain it

ρ_{UV}: Flux density of **UV**. **Easier** to **observe**

ξ_{ion}: Ionizing photon production **efficiency**. Measure of the **hardness** of the radiation (**LyC vs UV**)

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

$$\dot{n}_{ion}]_{escaped} = \rho_{UV} \times \xi_{ion} \times f^{LyC}_{escaped}$$

ρ_{UV}: **Non-ionizing UV** radiation is **easier** to **observe** and does **not interact** with **HI**

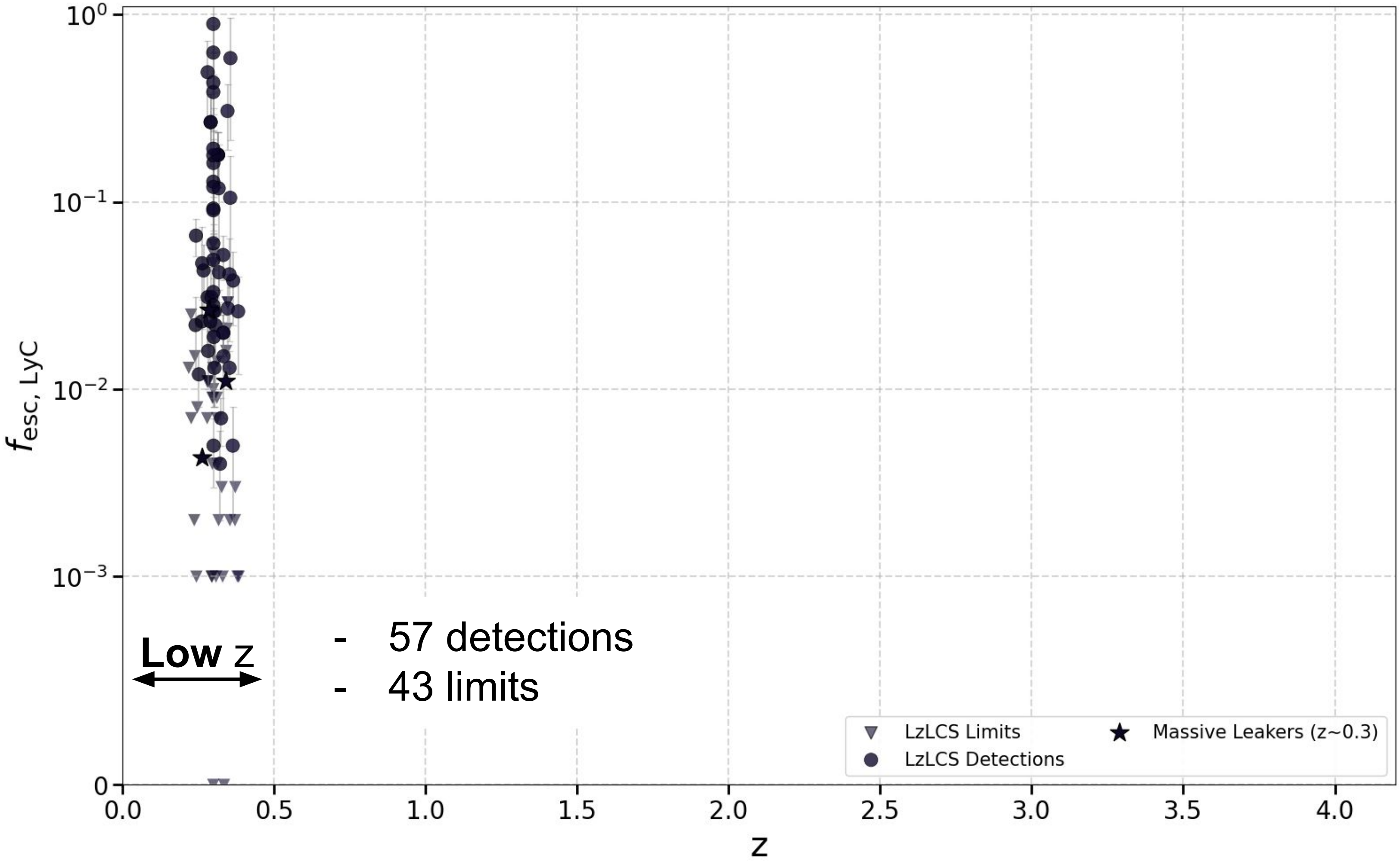
ξ_{ion}: **Depends** on the LyC **sources**

$f^{LyC}_{escaped}$: Depends on the amount of **HI** and **dust** that the **LyC photons encounter** during their **travel**

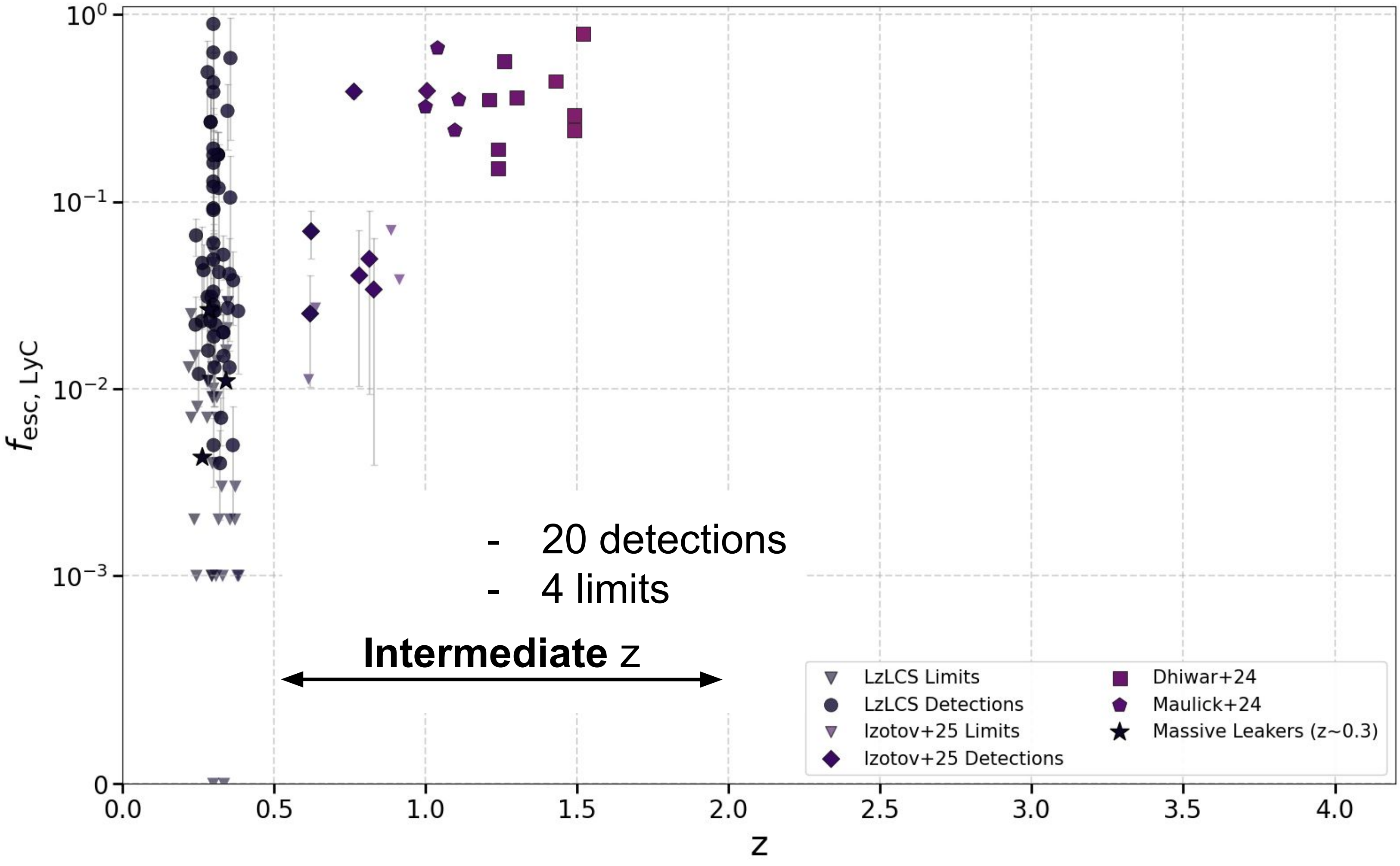
- Do **LyC escape** mechanisms **evolve** with **z**?

- It is known that **galaxy populations evolve** with **z** but among **subgroups** of **galaxies** with **similar properties** there is an **evolution** with **z**?

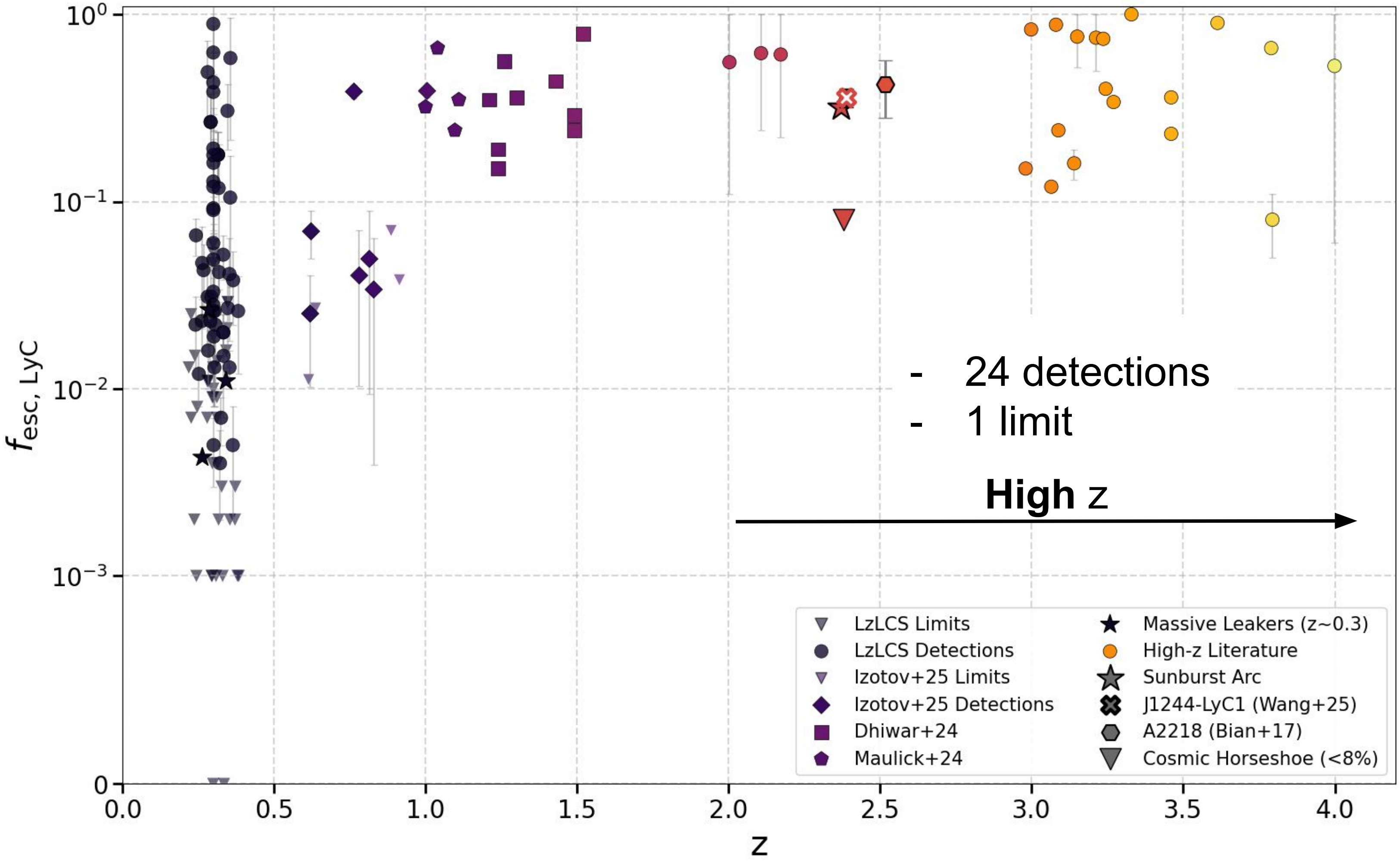
- $\mathbf{f_{esc}}$ **LyC** vs z, **sSFR**, O32, β_{1500} for around 100 **SF galaxies** at z < 4



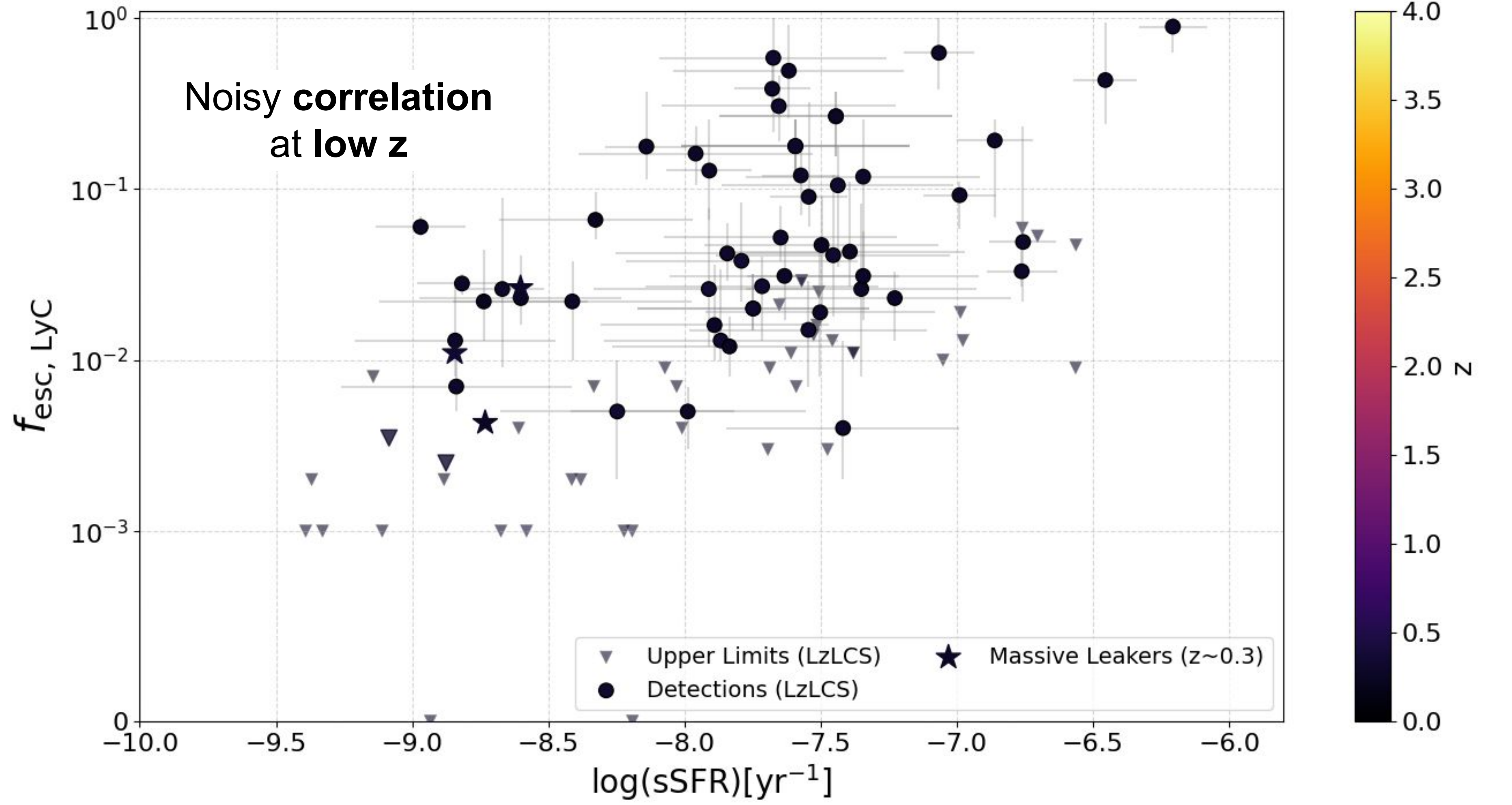
- 57 detections
- 43 limits



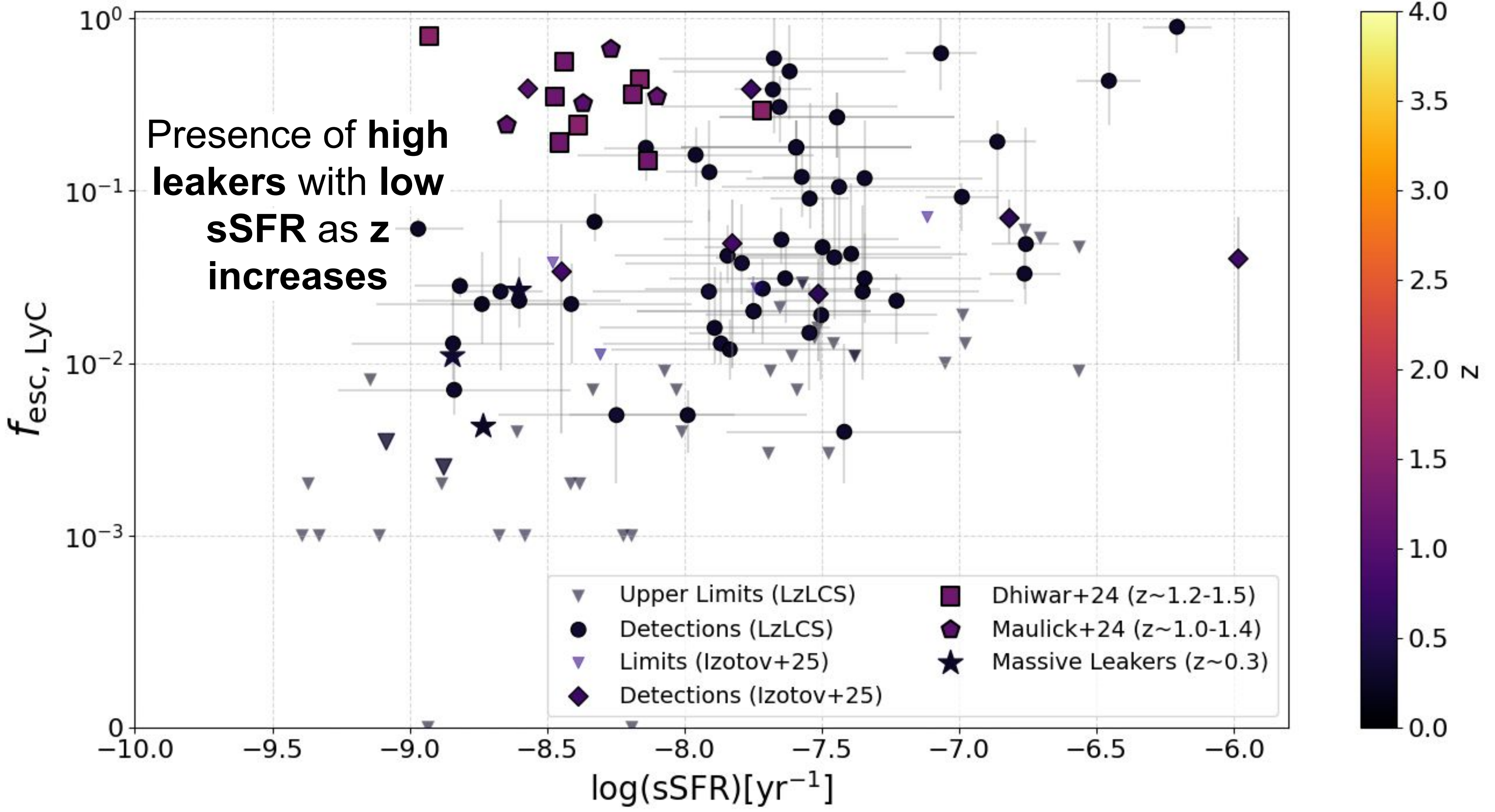
$f_{esc, LyC}$
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
z
- 20 detections
- 4 limits
Intermediate z
LzLCS Limits
LzLCS Detections
Izotov+25 Limits
Izotov+25 Detections
Dhiwar+24
Maulick+24
Massive Leakers (z~0.3)

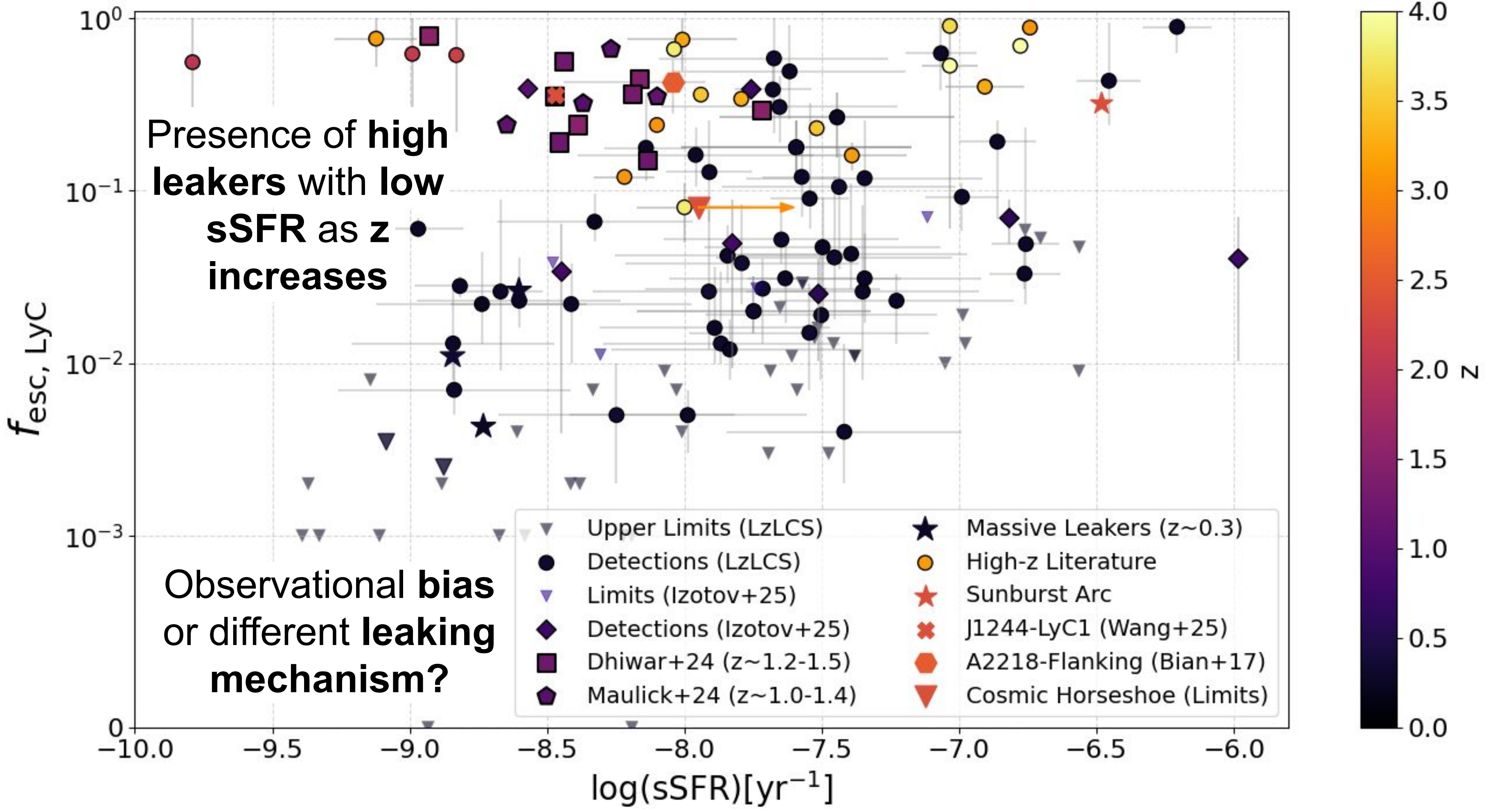


10^0
10^{-1}
10^{-2}
10^{-3}
0
$f_{\mathrm{esc,\,LyC}}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
z
- 24 detections
- 1 limit
High z
LzLCS Limits
LzLCS Detections
Izotov+25 Limits
Izotov+25 Detections
Dhiwar+24
Maulick+24
Massive Leakers (z~0.3)
High-z Literature
Sunburst Arc
J1244-LyC1 (Wang+25)
A2218 (Bian+17)
Cosmic Horseshoe (<8%)

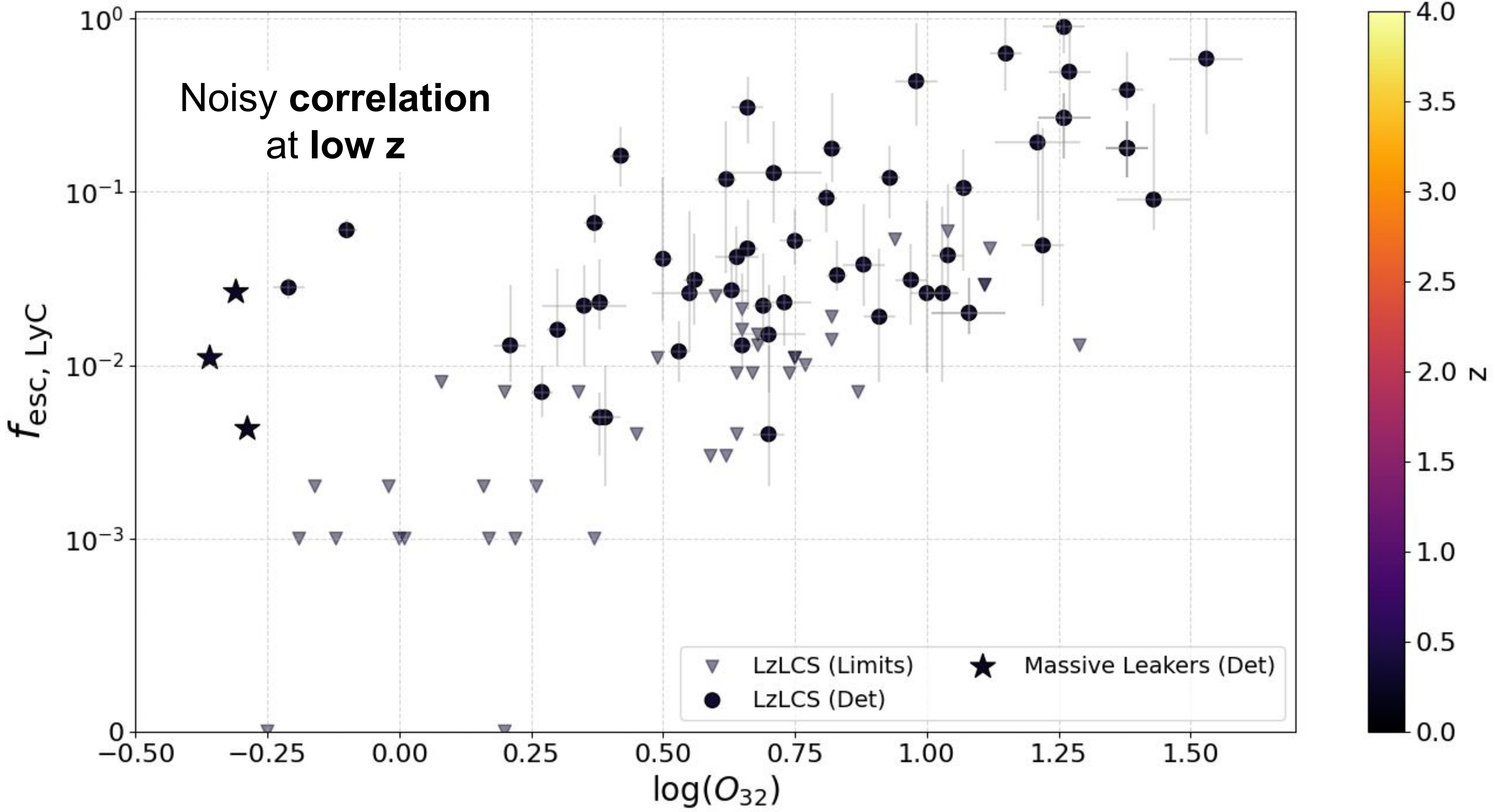


Noisy **correlation** at **low z**
$f_{\rm esc,\,LyC}$
log(sSFR)[yr^{-1}]
Upper Limits (LzLCS)
Detections (LzLCS)
Massive Leakers (z~0.3)
z

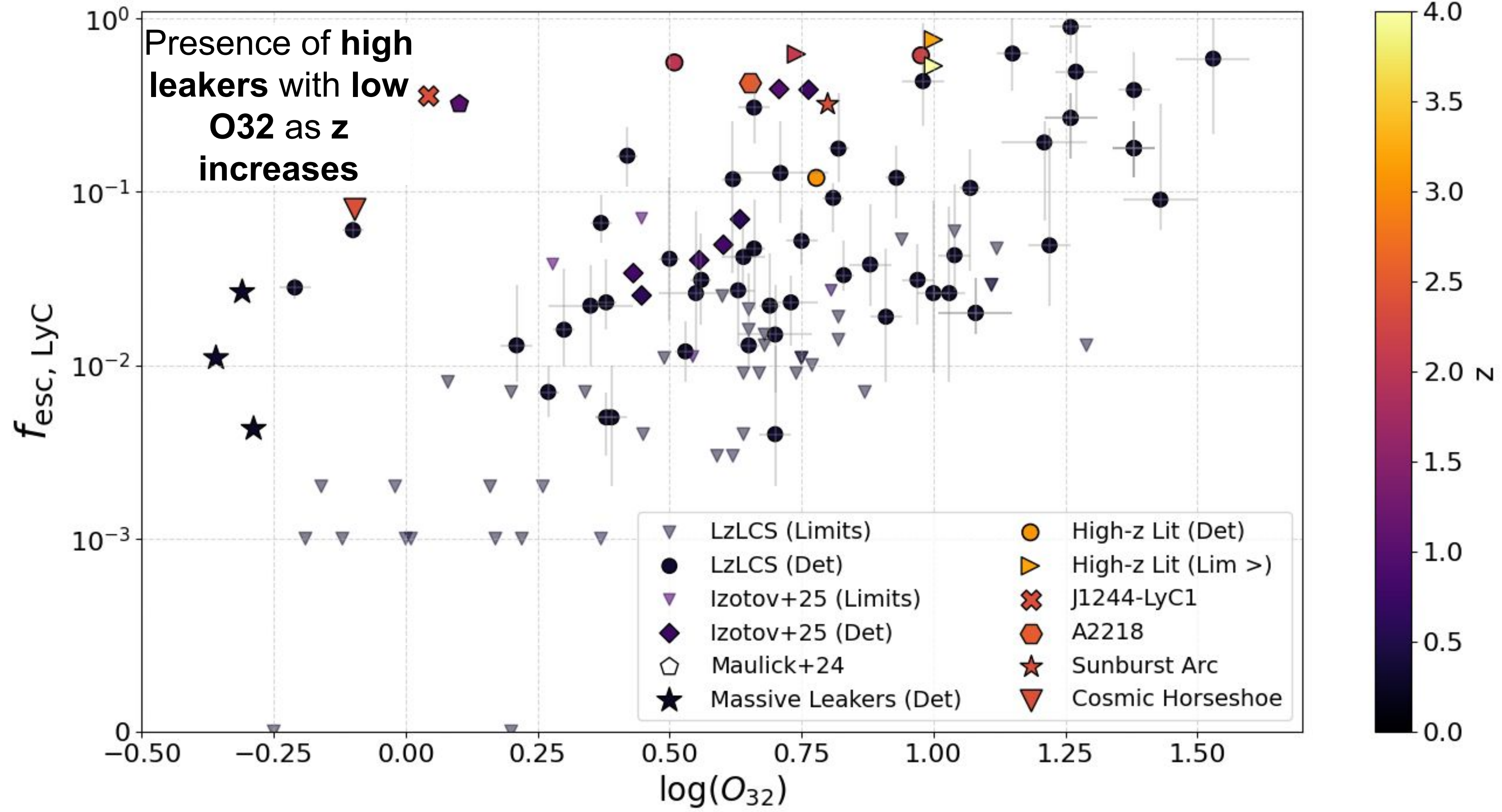

Presence of **high leakers** with **low sSFR** as **z increases**
$f_{esc, LyC}$
log(sSFR)[yr^{-1}]
z
Upper Limits (LzLCS)
Detections (LzLCS)
Limits (Izotov+25)
Detections (Izotov+25)
Dhiwar+24 (z~1.2-1.5)
Maulick+24 (z~1.0-1.4)
Massive Leakers (z~0.3)

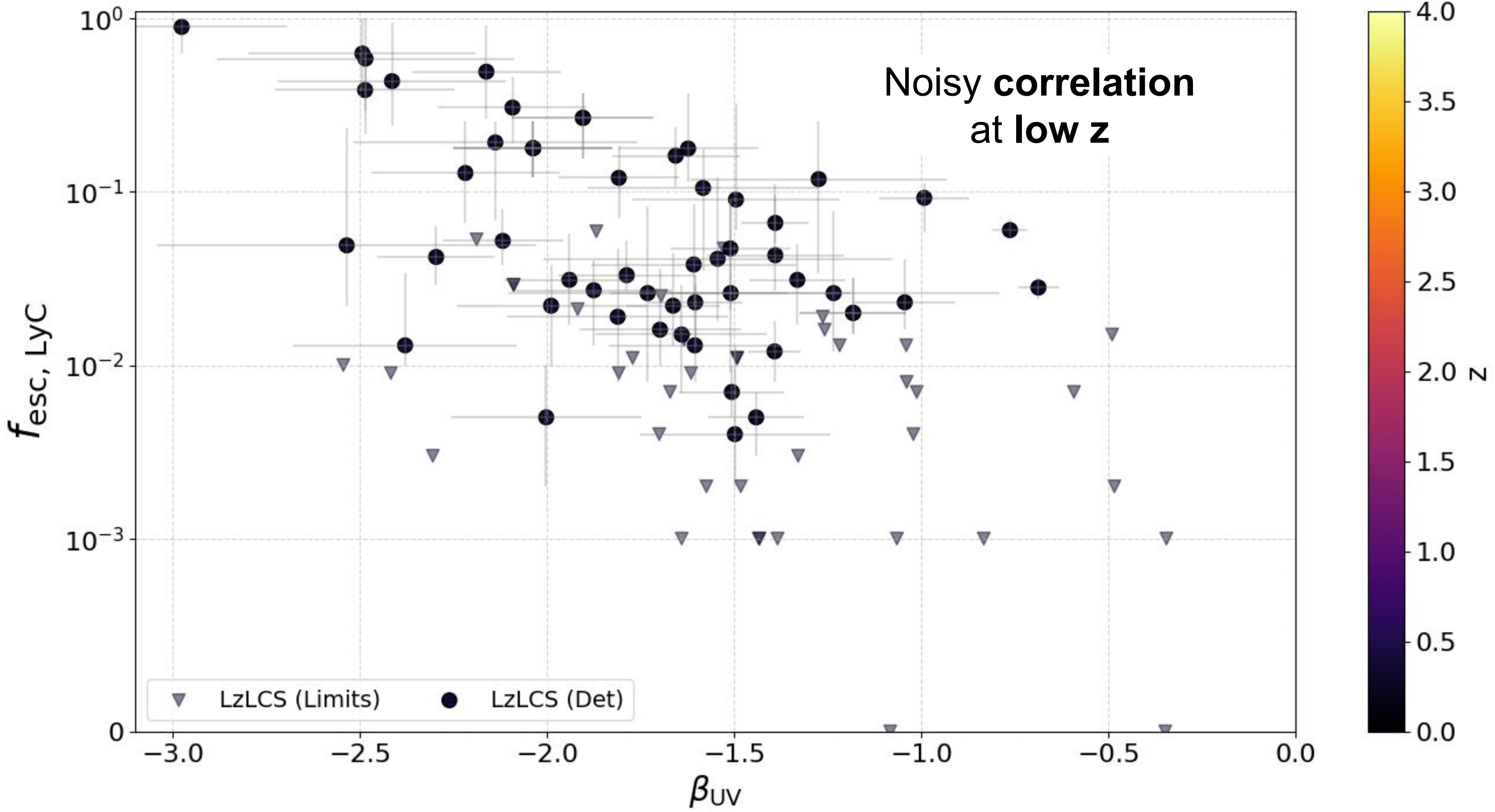


Presence of **high leakers** with **low sSFR** as **z increases**
Observational **bias** or different **leaking mechanism?**
$f_{esc, LyC}$
10^0
10^{-1}
10^{-2}
10^{-3}
0
log(sSFR)[yr^{-1}]
−10.0
−9.5
−9.0
−8.5
−8.0
−7.5
−7.0
−6.5
−6.0
z
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Upper Limits (LzLCS)
Detections (LzLCS)
Limits (Izotov+25)
Detections (Izotov+25)
Dhiwar+24 (z~1.2-1.5)
Maulick+24 (z~1.0-1.4)
Massive Leakers (z~0.3)
High-z Literature
Sunburst Arc
J1244-LyC1 (Wang+25)
A2218-Flanking (Bian+17)
Cosmic Horseshoe (Limits)

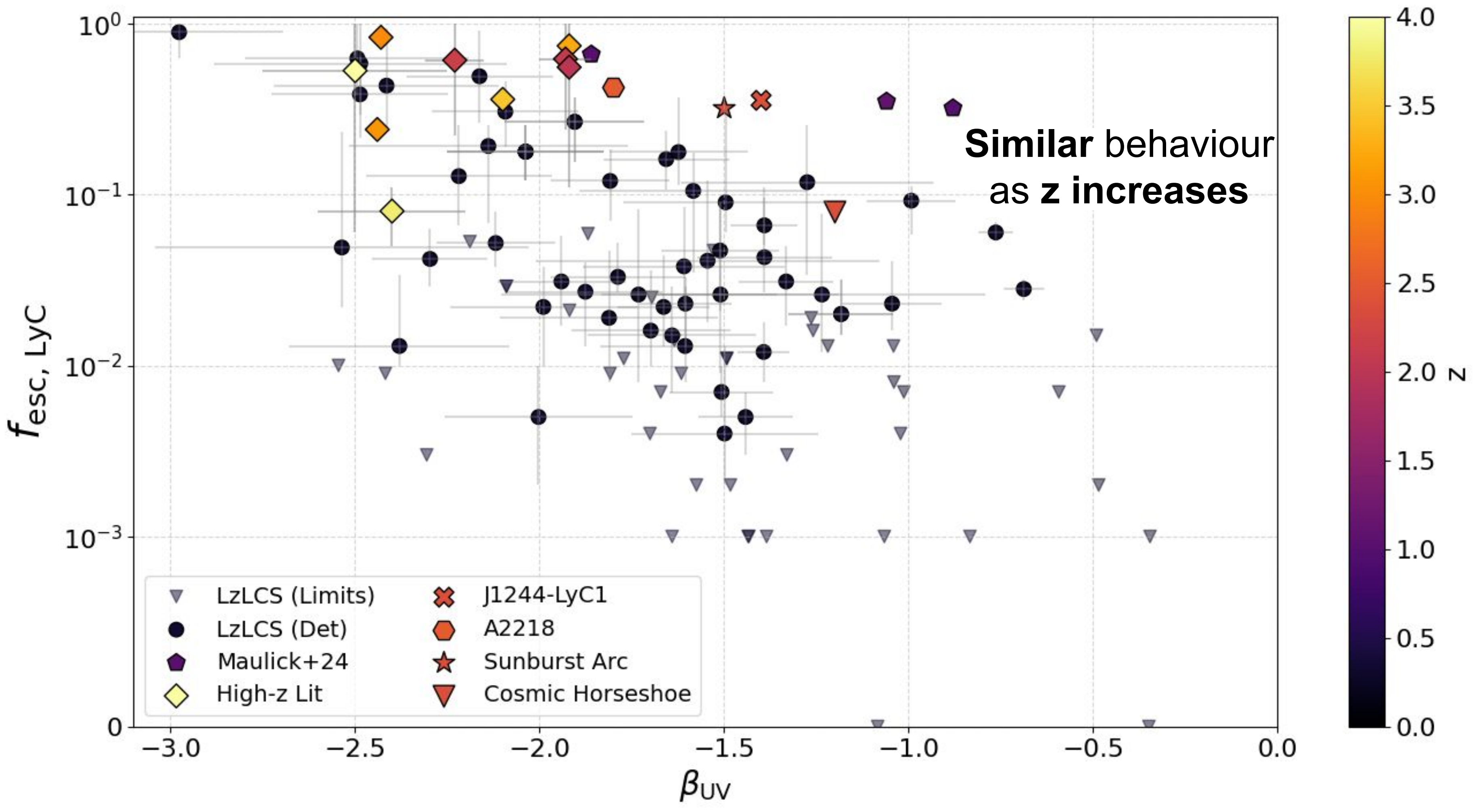


Noisy **correlation** at **low z**
$f_{\rm esc,\,LyC}$
$\log(O_{32})$
LzLCS (Limits)
LzLCS (Det)
Massive Leakers (Det)
z
10^0
10^{-1}
10^{-2}
10^{-3}
0
−0.50 −0.25 0.00 0.25 0.50 0.75 1.00 1.25 1.50
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0


Presence of **high leakers** with **low O32** as **z increases**
$f_{esc, LyC}$
$\log(O_{32})$
z
LzLCS (Limits)
LzLCS (Det)
Izotov+25 (Limits)
Izotov+25 (Det)
Maulick+24
Massive Leakers (Det)
High-z Lit (Det)
High-z Lit (Lim >)
J1244-LyC1
A2218
Sunburst Arc
Cosmic Horseshoe



Noisy **correlation** at **low z**
$f_{\rm esc,\,LyC}$
$\beta_{\rm UV}$
LzLCS (Limits)
LzLCS (Det)
z
10^0
10^{-1}
10^{-2}
10^{-3}
0
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0



Similar behaviour as z increases
$f_{esc,\,LyC}$
β_{UV}
z
LzLCS (Limits)
LzLCS (Det)
Maulick+24
High-z Lit
J1244-LyC1
A2218
Sunburst Arc
Cosmic Horseshoe

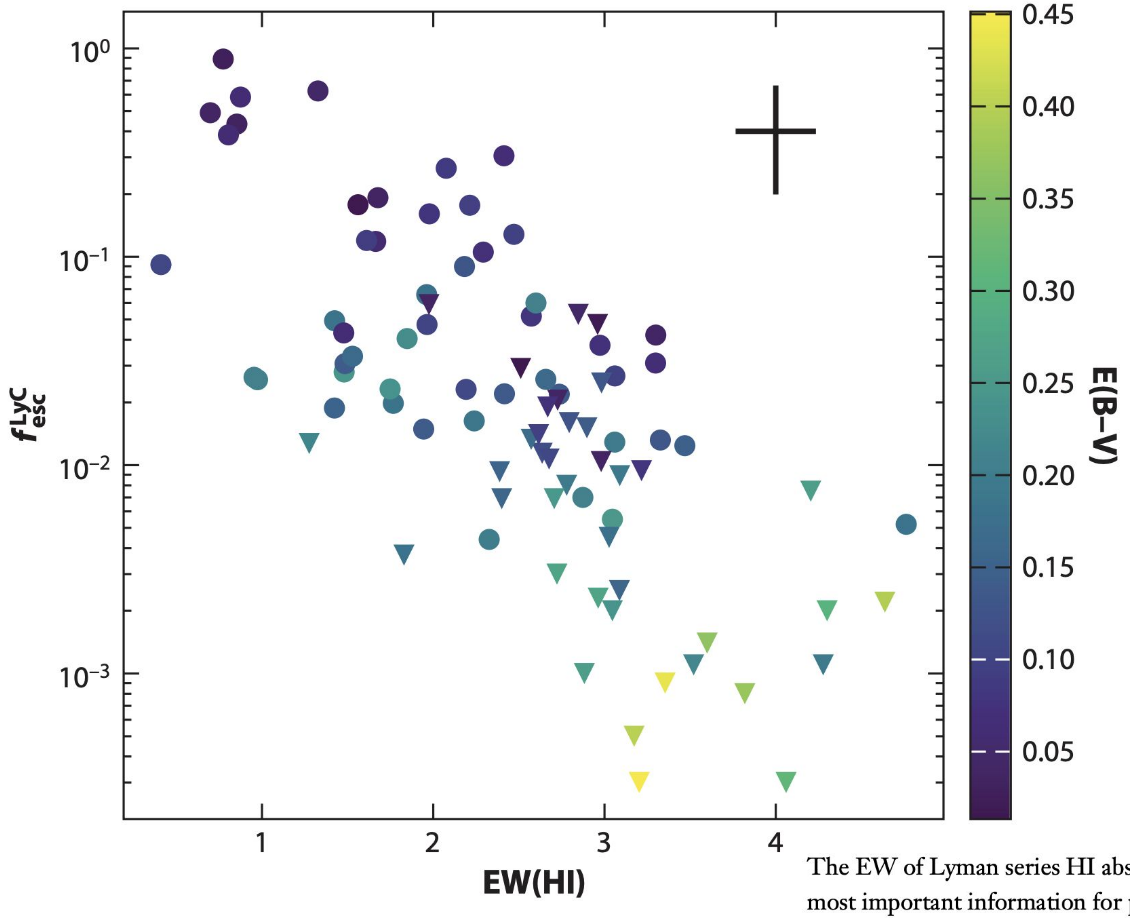
To **predict f_{esc}LyC** in the **line of sight** we need to know how much **HI** and **dust** there is in the **line of sight**

HI: **EW** of the **absorption** in **Lyman series** (**β** and **above**)

Absorption lines are related to processes in the **line of sight**
Lyman (**β** and **above**) photons are **absorbed** by **HI**

Dust: **Attenuation** derived from β_{1500}

UV emission is likely **emitted** from the **LyC sources** (e.g. O, B stars).
If the **stellar population** is **characterized** well enough, β_{1500} contains the information related to the **dust absorption** in the **line of sight** (E(B-V))



Noisy **correlation** **f_{esc}LyC** vs **EW(HI)** but at **fixed EW(HI) higher** values of **f_{esc}LyC** are associated with **lower dust attenuation**

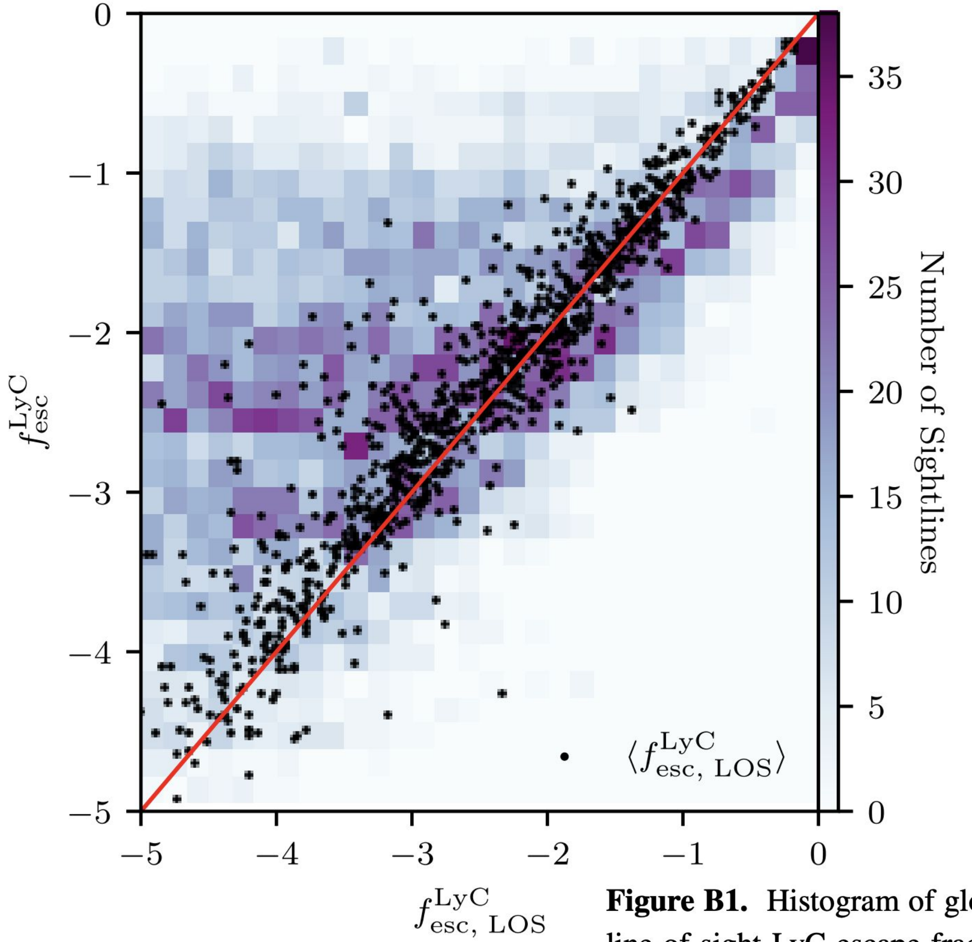
Anne E. Jaskot (2025)

The EW of Lyman series HI absorption lines [EW(HI)], and the UV dust attenuation E(B–V) provide the most important information for predicting f_{esc}^{LyC} in the LzLCS+ dataset. These two variables trace the two sources of line-of-sight absorption of LyC photons: HI gas and dust. At fixed EW(HI), higher values of f_{esc}^{LyC} are associated with lower dust attenuation. Figure adapted with permission from Saldana-Lopez et al. (2022); copyright ESO. Abbreviations: EW, equivalent width; LyC, Lyman continuum; LzLCS, Low-redshift Lyman Continuum Survey; LzLCS+, the combined LzLCS dataset; UV, ultraviolet.

What **questions** can **simulations** answer?

Are there **physical parameters** that have a **tight correlation** with **global f_{esc}**? And if so, which one correlates better?

How well can we constrain the **scatter** between **LOS f_{esc}** and **global f_{esc}**? Does this scatter depends on the **feedback mechanism(s)** at play?



Red line = perfect isotropic leakage

LyC **leakage** is pretty **anisotropic** so we have an **inherent scatter** between **global** and **line of sight escape**

Choustikov et al (2024)

Figure B1. Histogram of global LyC escape fractions, f_{esc}^{LyC} against the 10 line-of-sight LyC escape fractions, $f_{esc,\ LOS}^{LyC}$ measured for each galaxy. We also include the angle averaged line-of-sight values for each true global value as black points. The one-to-one relation is shown in red.

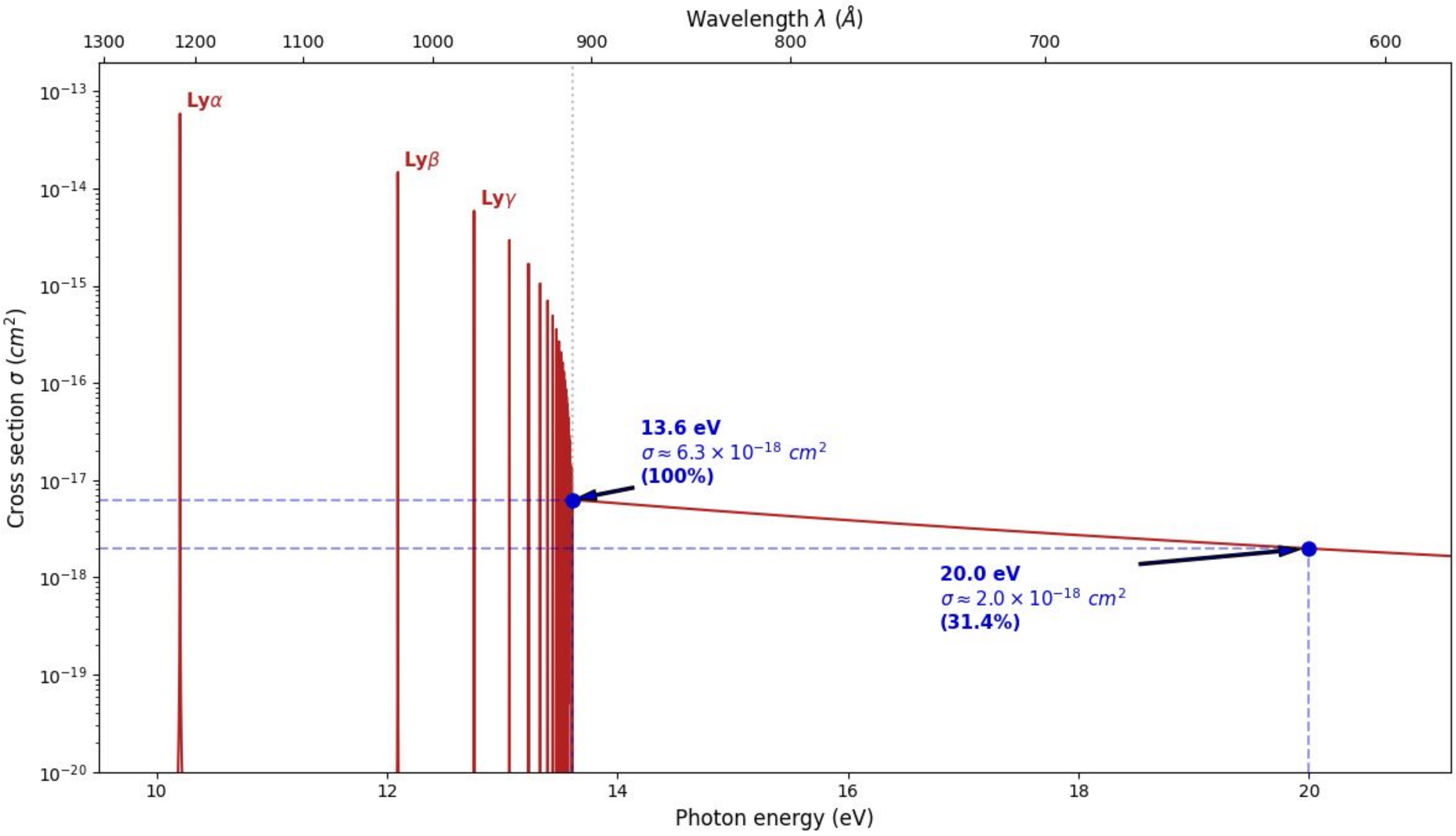
Conclusions

- **EoR Key Ingredient**: Knowing $\boldsymbol{\rho_{UV}}$, $\boldsymbol{\xi_{ion}}$, and $\mathbf{f_{esc}}$ gives the **number** of **escaping ionizing photons** from a source, which is the key ingredient to understand the EoR

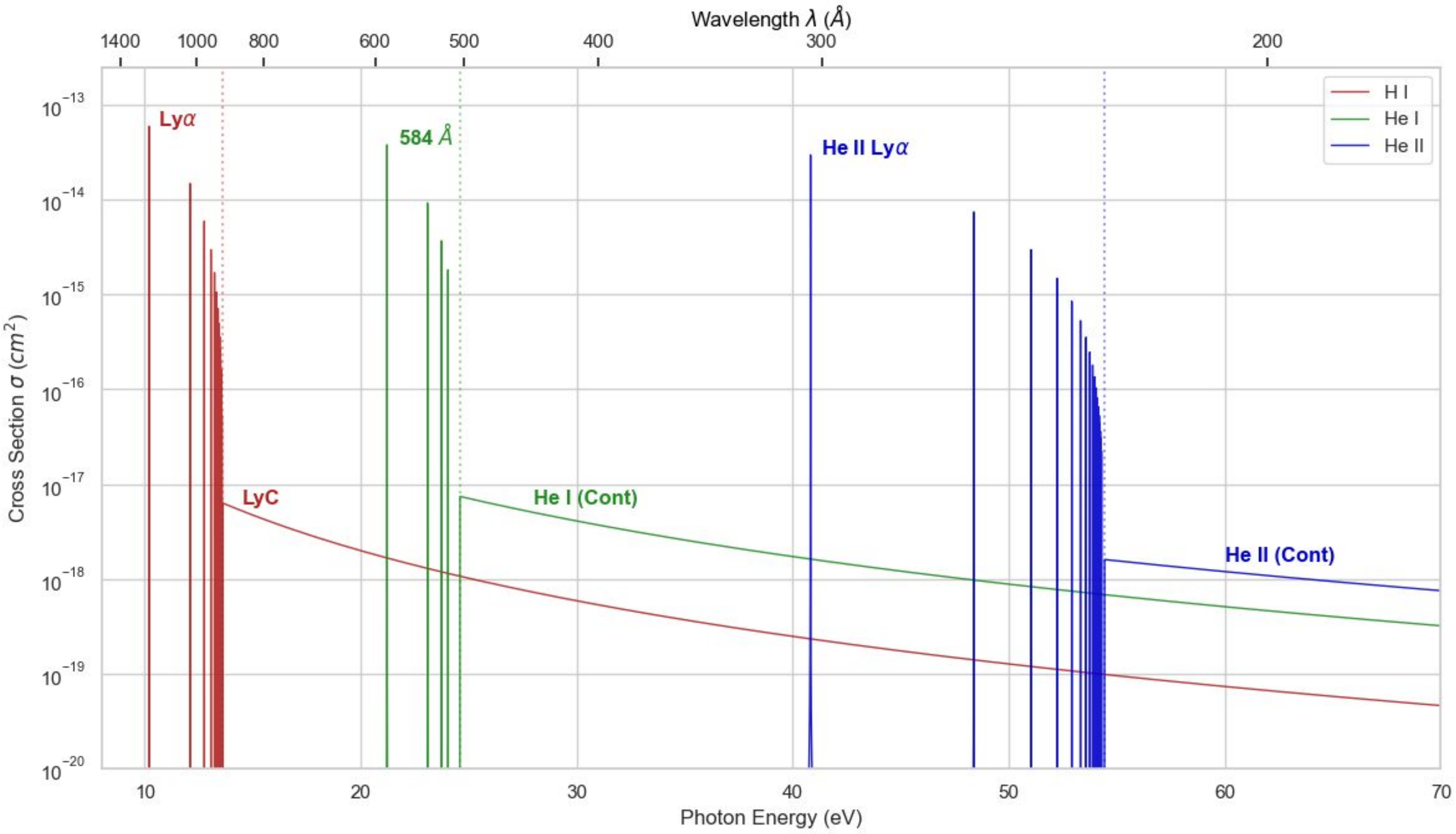
- **Tracers** & **Evolution**: $\mathbf{f_{esc}}$ broadly **correlates** with **sSFR**, **O32**, and $\boldsymbol{\beta_{UV}}$. Notably, **high leakers** with **low sSFR emerge** at **higher z**

- **LOS Physics**: **LOS escape** depends on **LOS neutral gas** and **dust**. At fixed EW(HI), less dust yields higher f_{esc}

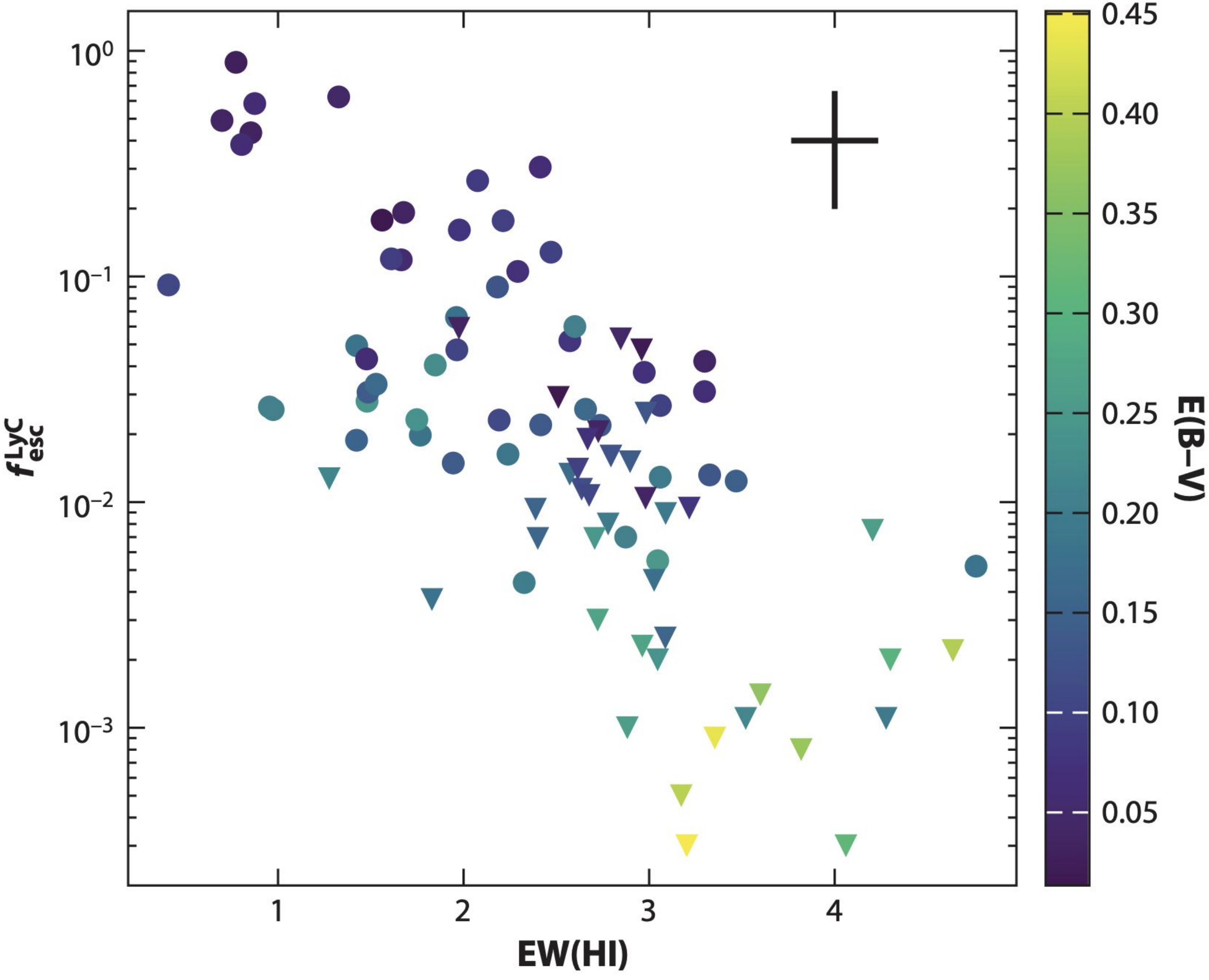
- **Anisotropy**: **Simulations** and **high scatter** in **observational correlations** show LyC **leakage** is highly **anisotropic**, driving **inherent scatter** between **LOS** and **global** $\mathbf{f_{esc}}$



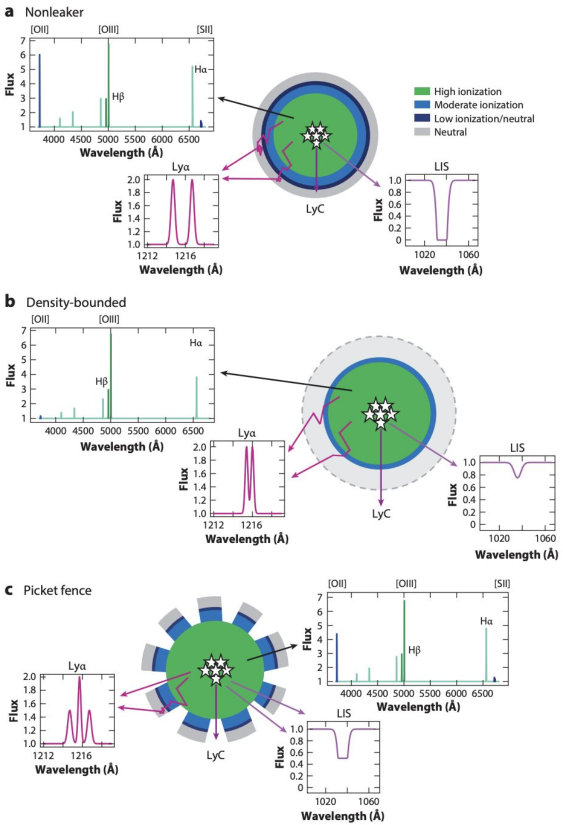
Wavelength λ (Å)
1300
1200
1100
1000
900
800
700
600
Lyα
Lyβ
Lyγ
13.6 eV
σ ≈ 6.3 × 10^−18 cm^2
(100%)
20.0 eV
σ ≈ 2.0 × 10^−18 cm^2
(31.4%)
Cross section σ (cm^2)
10^−13
10^−14
10^−15
10^−16
10^−17
10^−18
10^−19
10^−20
10
12
14
16
18
20
Photon energy (eV)



Wavelength λ (Å)
1400
1000
800
600
500
400
300
200
H I
He I
He II
Lyα
584 Å
He II Lyα
LyC
He I (Cont)
He II (Cont)
Cross Section σ (cm²)
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10
20
30
40
50
60
70
Photon Energy (eV)



f_{esc}^{LyC}
EW(HI)
E(B–V)



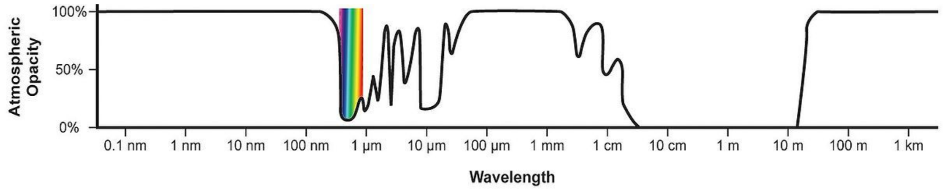
a Nonleaker
b Density-bounded
c Picket fence
High ionization
Moderate ionization
Low ionization/neutral
Neutral
[OII]
[OIII]
[SII]
Hβ
Hα
Lyα
LIS
LyC
Flux
Wavelength (Å)

$\dot{n}_{ion}$ — **Number** of (hydrogen) **ionizing photons** (LyC radiation) **per** unit of **time** in a system

$\dot{n}_{ion}]_{escaped}$

It is **possible** to **observe** but with lots of **caveats**

LyC radiation with current telescopes is **not easy to observe**



The **restframe range** of **LyC** (800 Å-910 Å) is **observable** from **Earth** only at **z > 2.5**

For **lower redshift** objects we need **space** observations (**HST** or UV satellites)