Tracing HI distribution and ionizing photon escape in star-forming galaxies across cosmic time

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— The LzLCS and MUSE collaboration —

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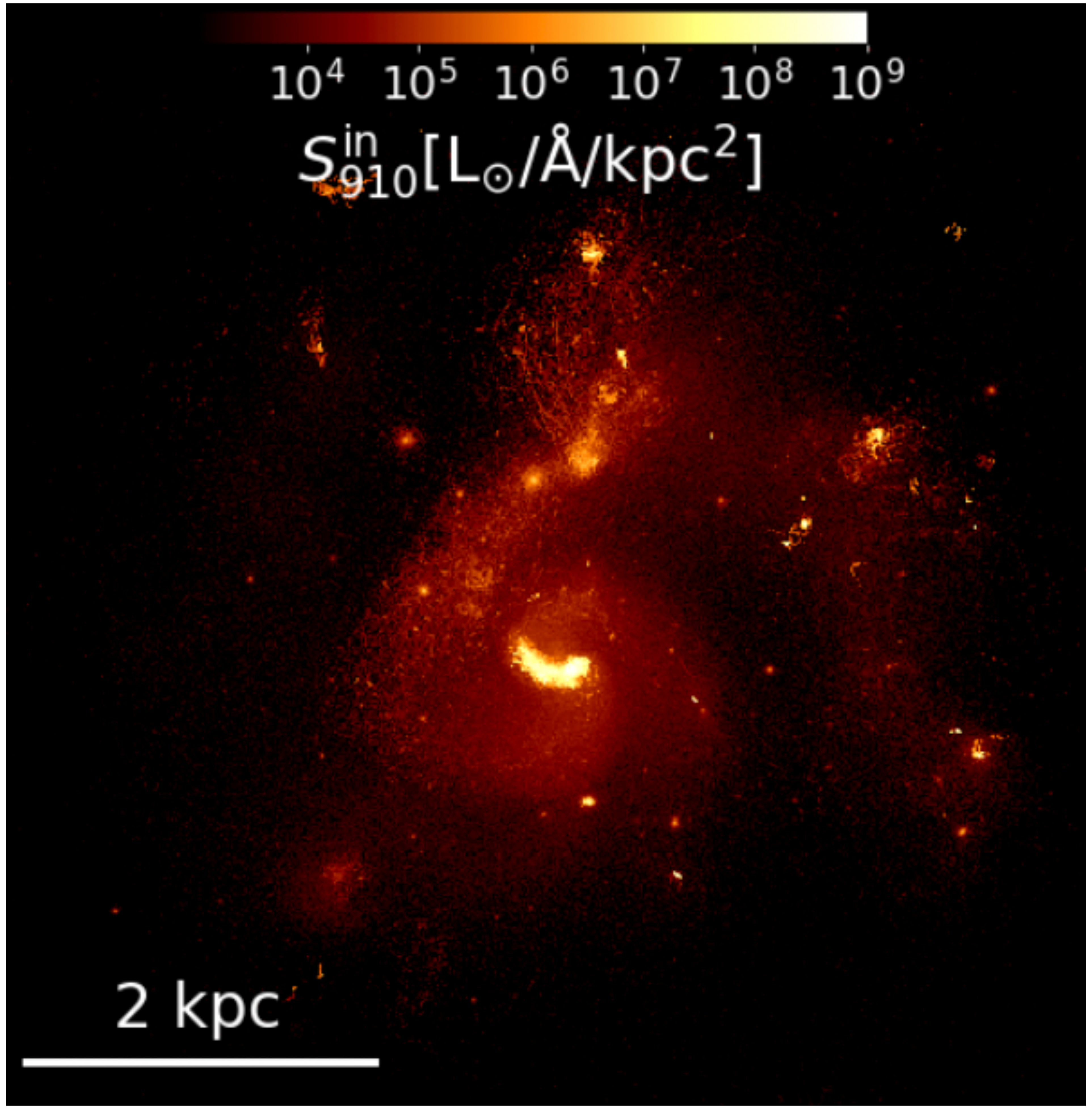
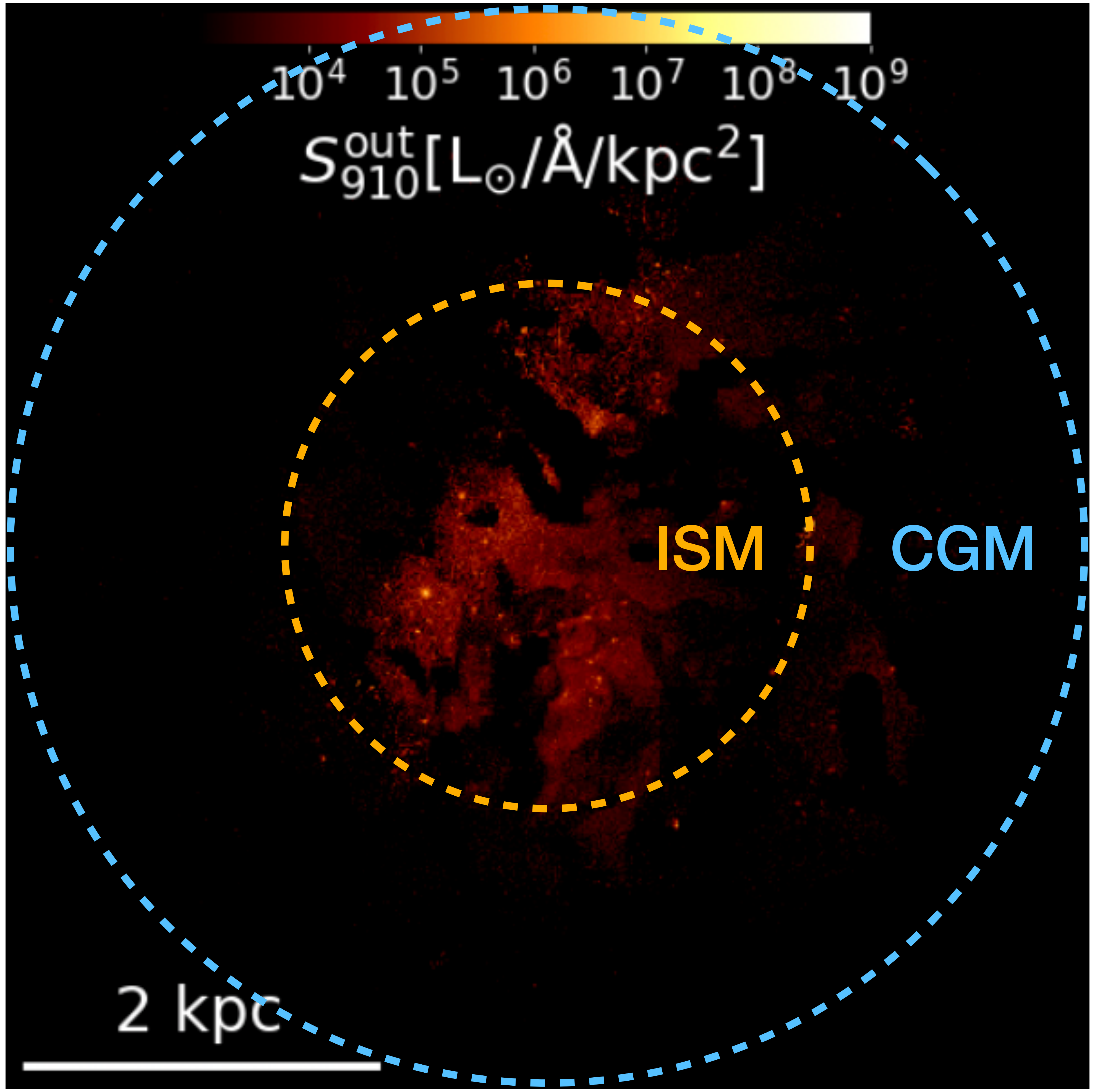
CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

HI distribution and ionizing photons escape

Intrinsic LyC



Observed LyC



Two sinks for LyC photons :

1) Neutral gas

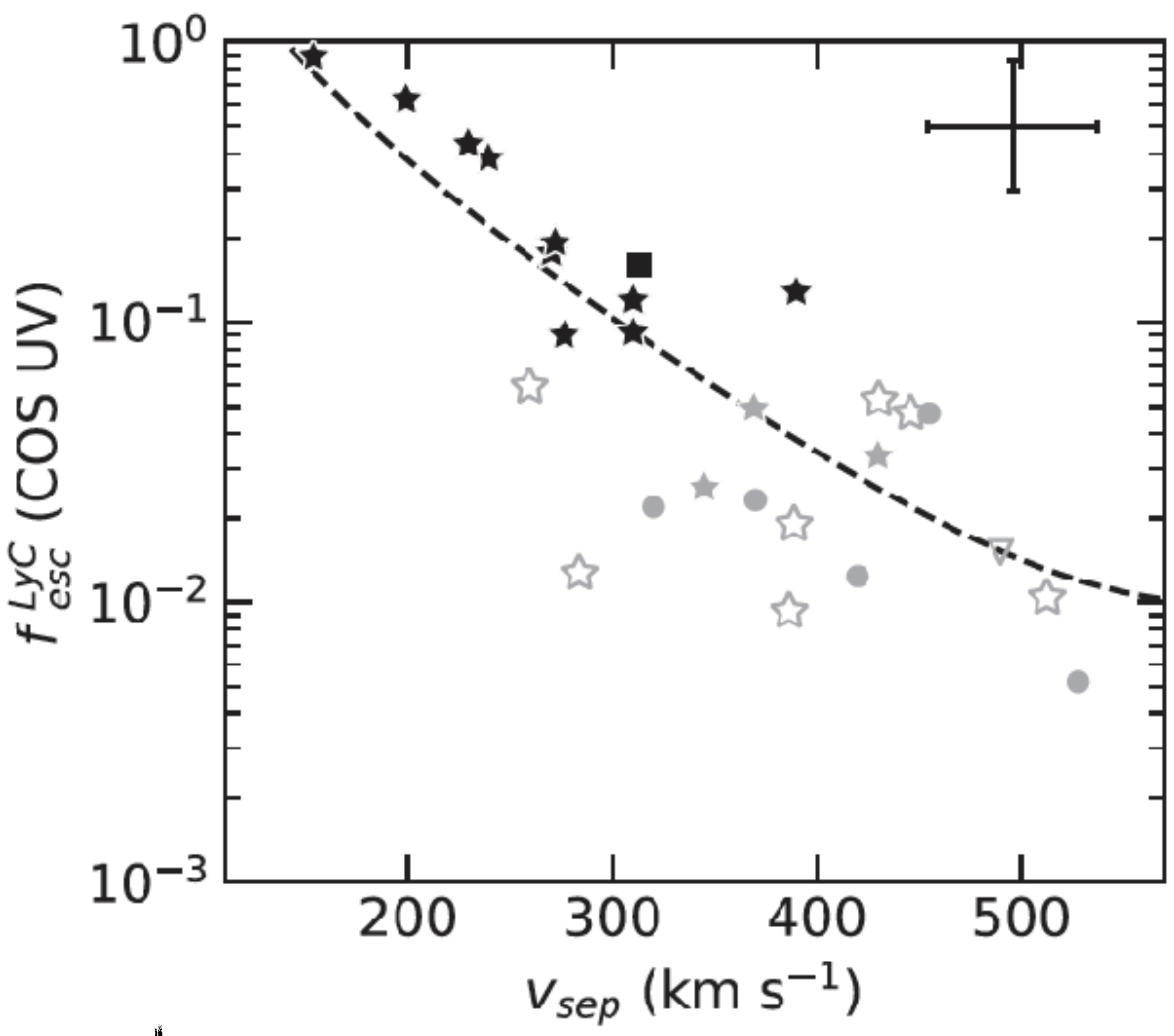
2) Dust

Probing the dust and **HI geometry** is important to understand LyC escape

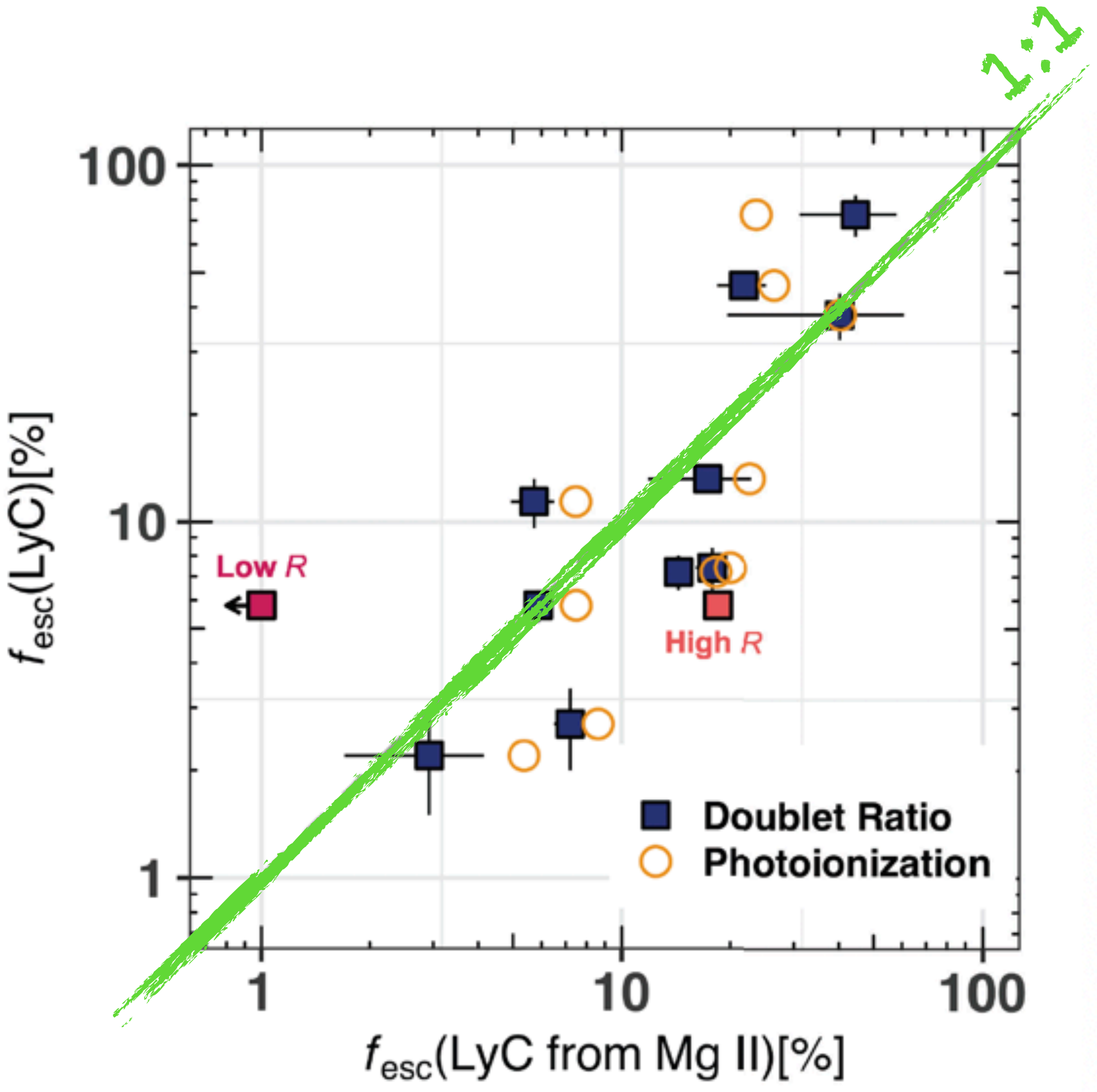
Mauerhofer et al. 2021

HI distribution probes are the best f_{esc} indicators

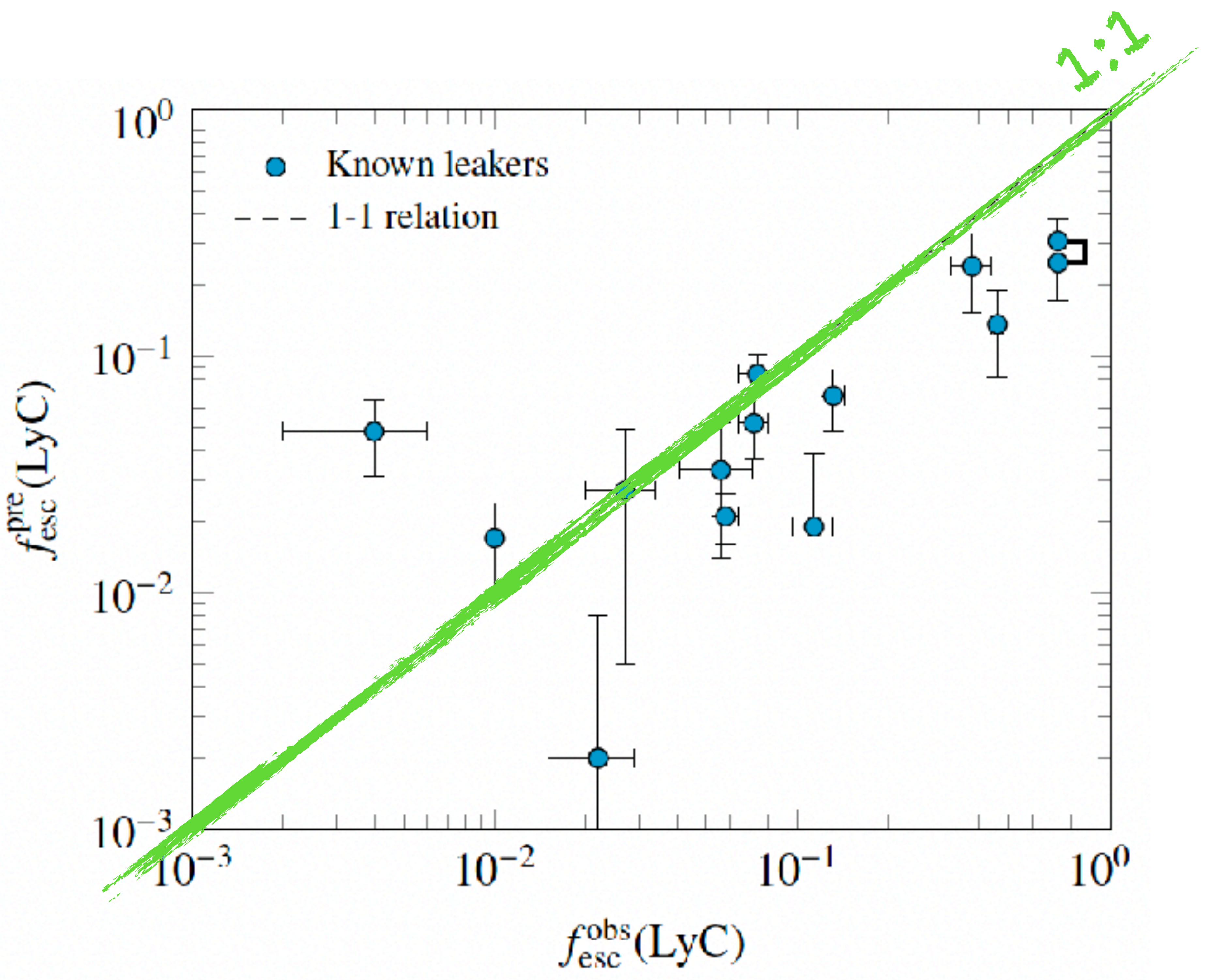
Lyα line



MgII doublet



UV absorption lines



Probe of the global gas geometry
= **global f_{esc}** ?

Pencil beam probe
= **Line of sight f_{esc}**

Flury et al. 2022a, Chisholm et al. 2020, Gazagnes et al. 2020

Connecting f_{esc} to HI distribution in known (non-)leakers

- **IFU** observations of **22 galaxies** from the **LzLCS** and Izotov et al. 2022

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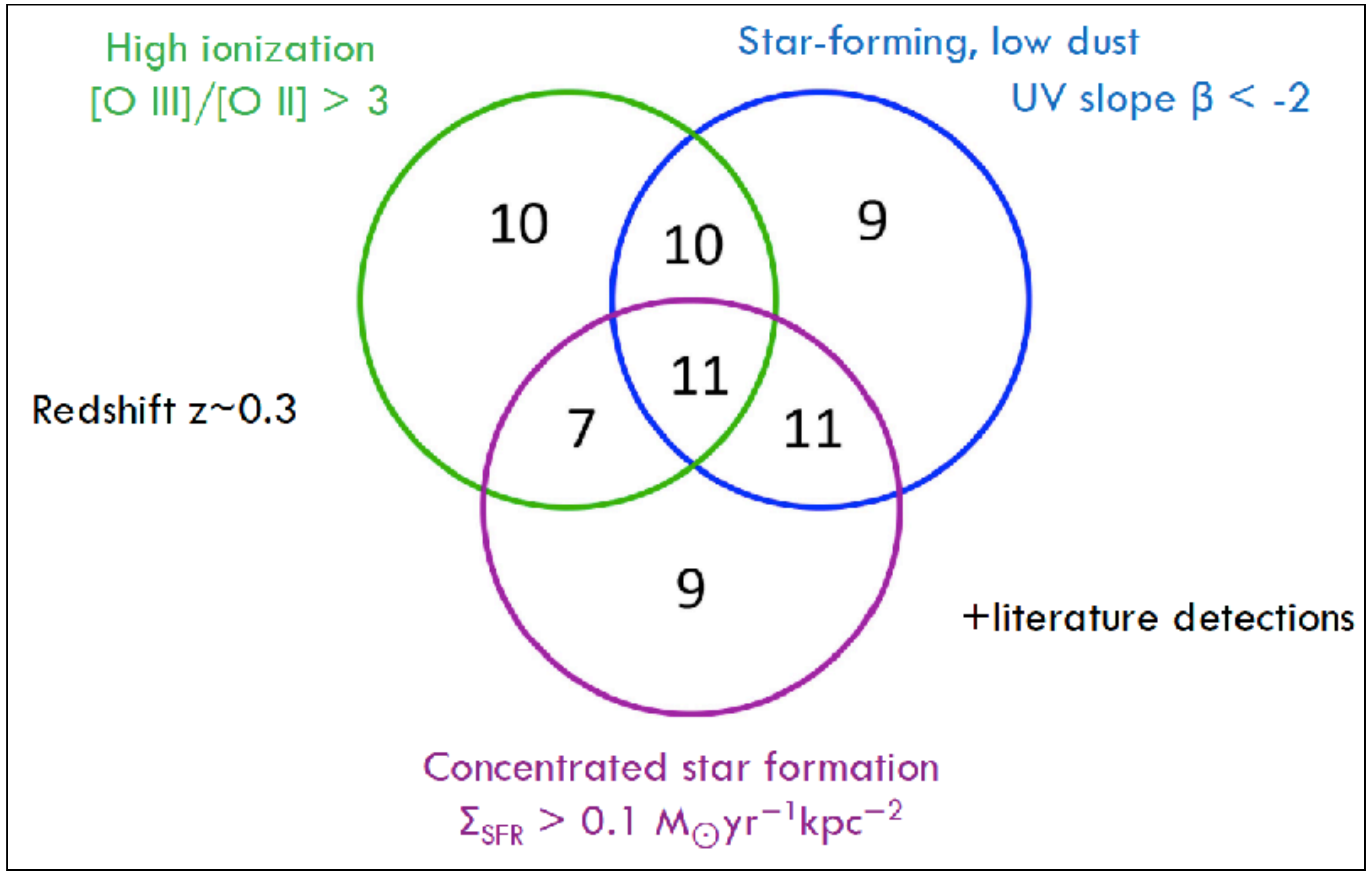
THE LzLCS SURVEY: LOW-REDSHIFT LYMAN CONTINUUM SURVEY

- HST/COS PID: 15626, PI: Anne Jaskot
- Sample of 66 star-forming galaxies at z~0.3
- 35 new LyC detections
- **Statistical sample of 89 LyC leakers and non-leakers**

→ **Sample with selection criteria to find LyC leakers**

Sophia's talk



Flury et al. 2022a, Saldana-Lopez et al. 2022

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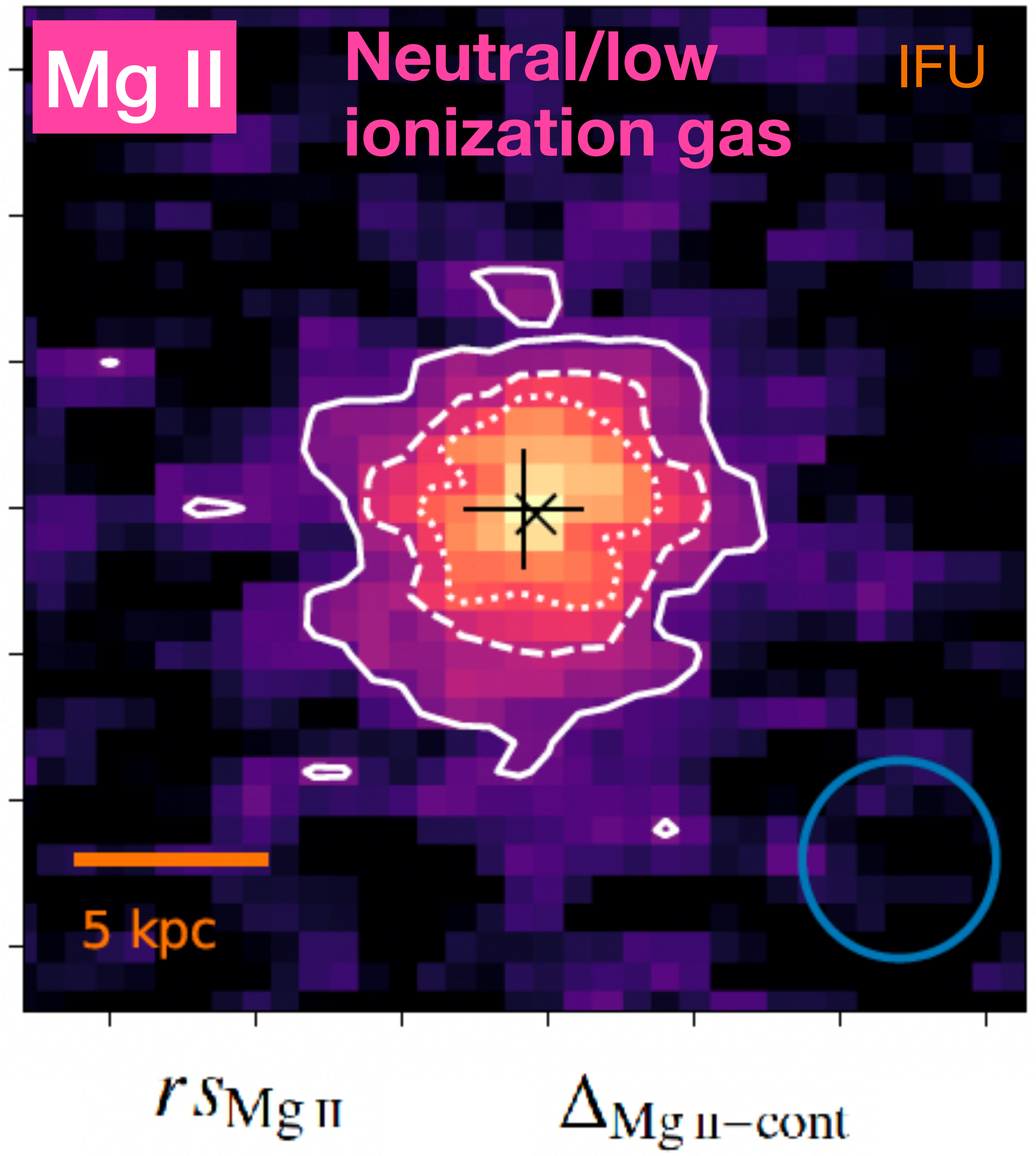

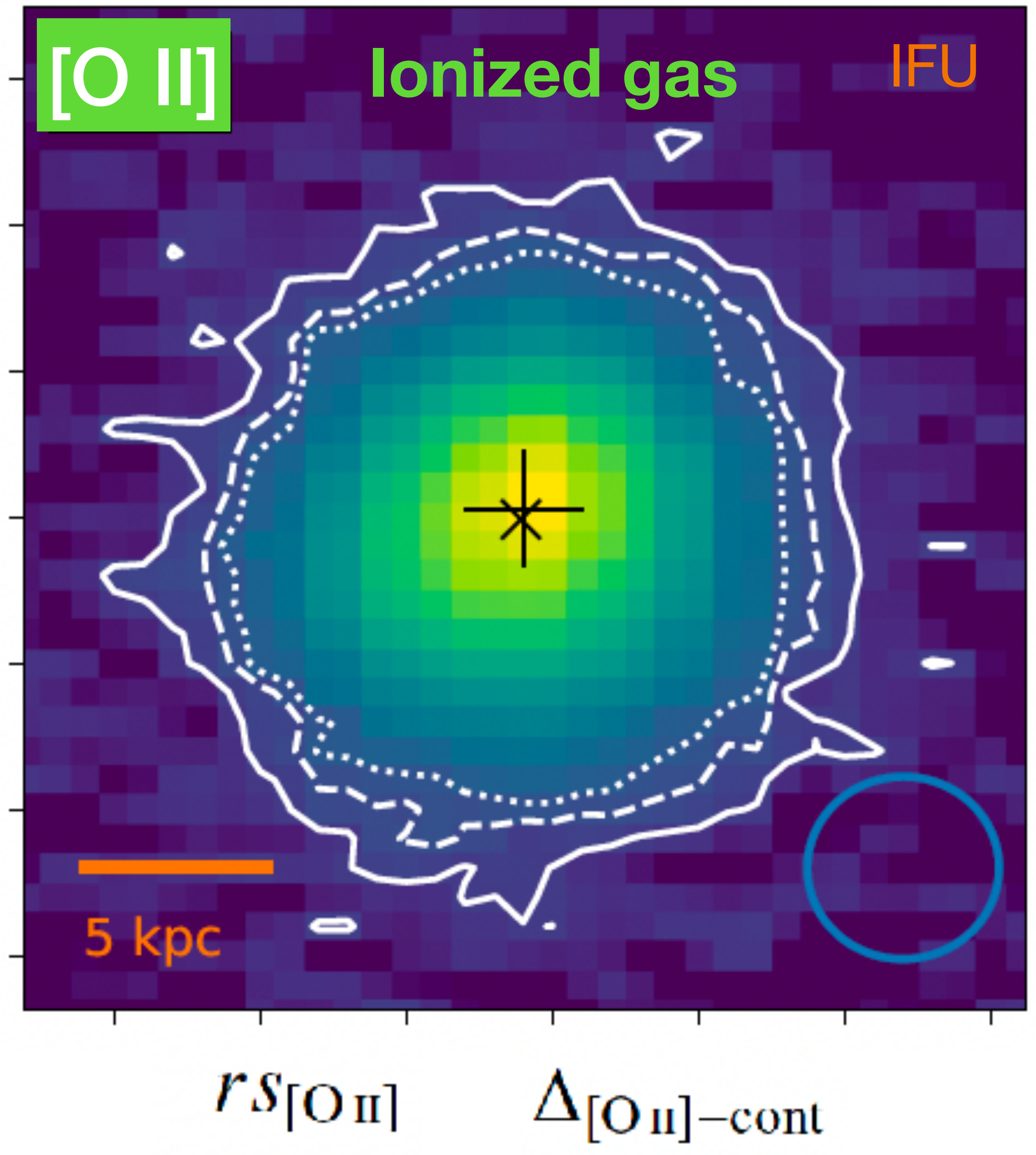

Leclercq et al. 2024

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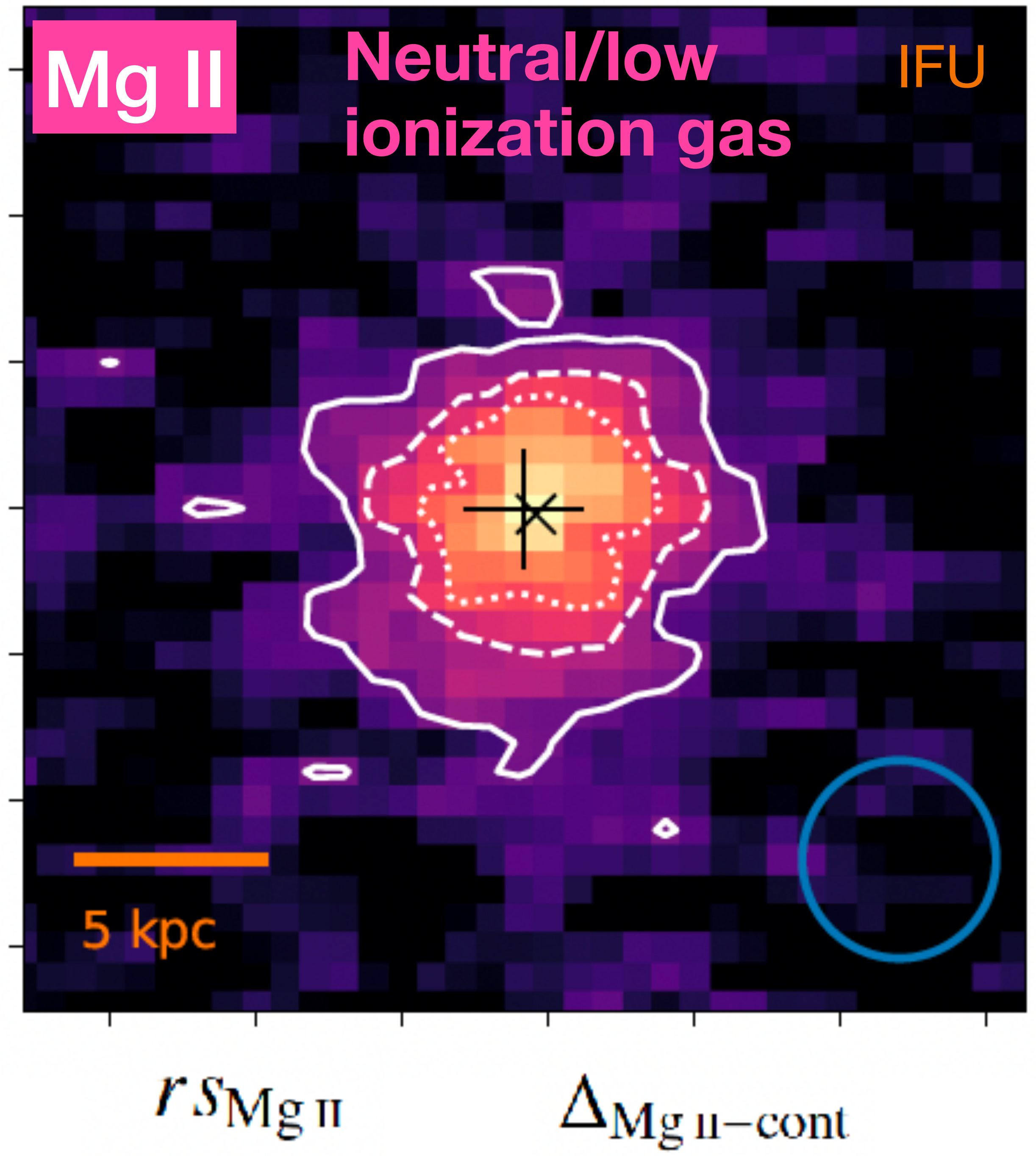

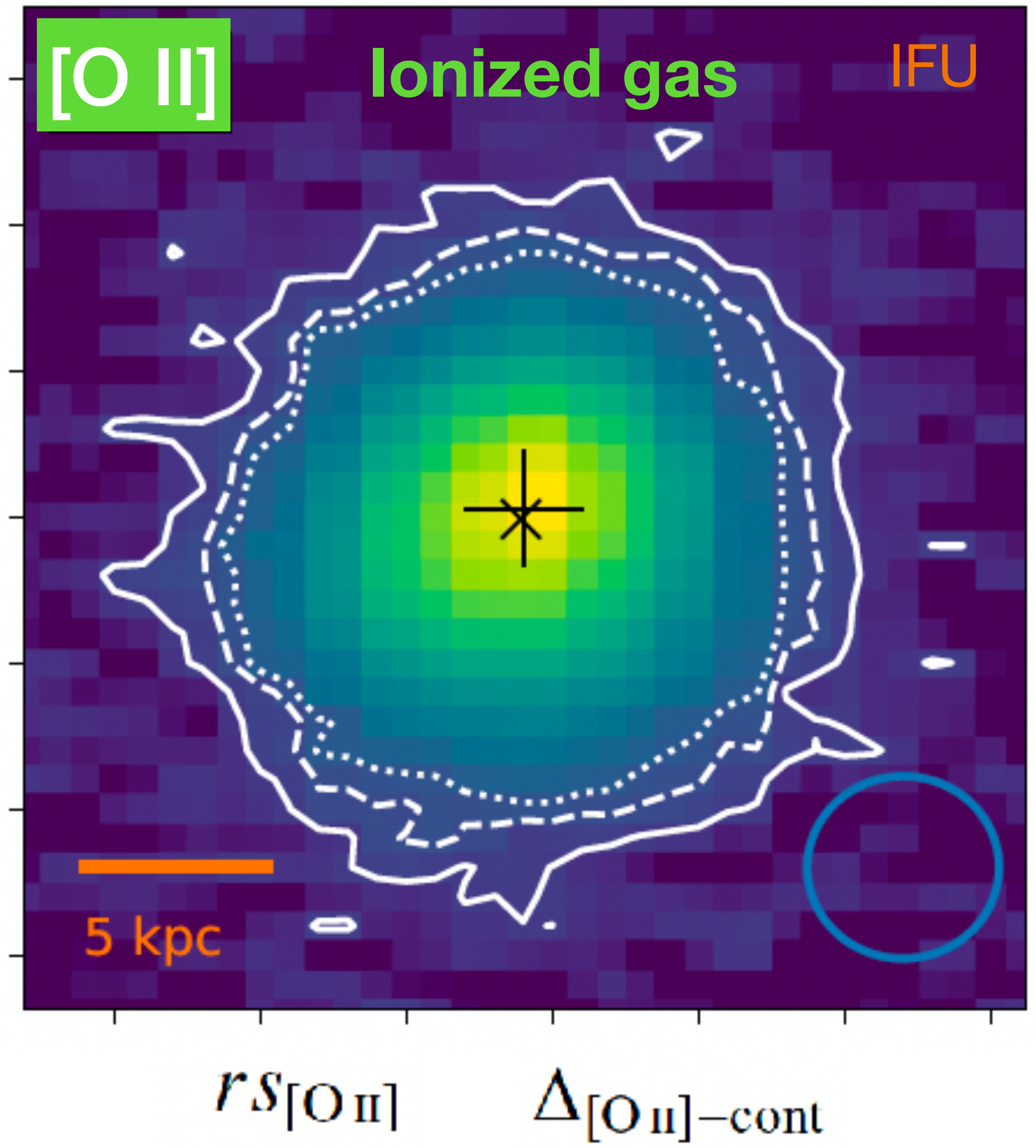

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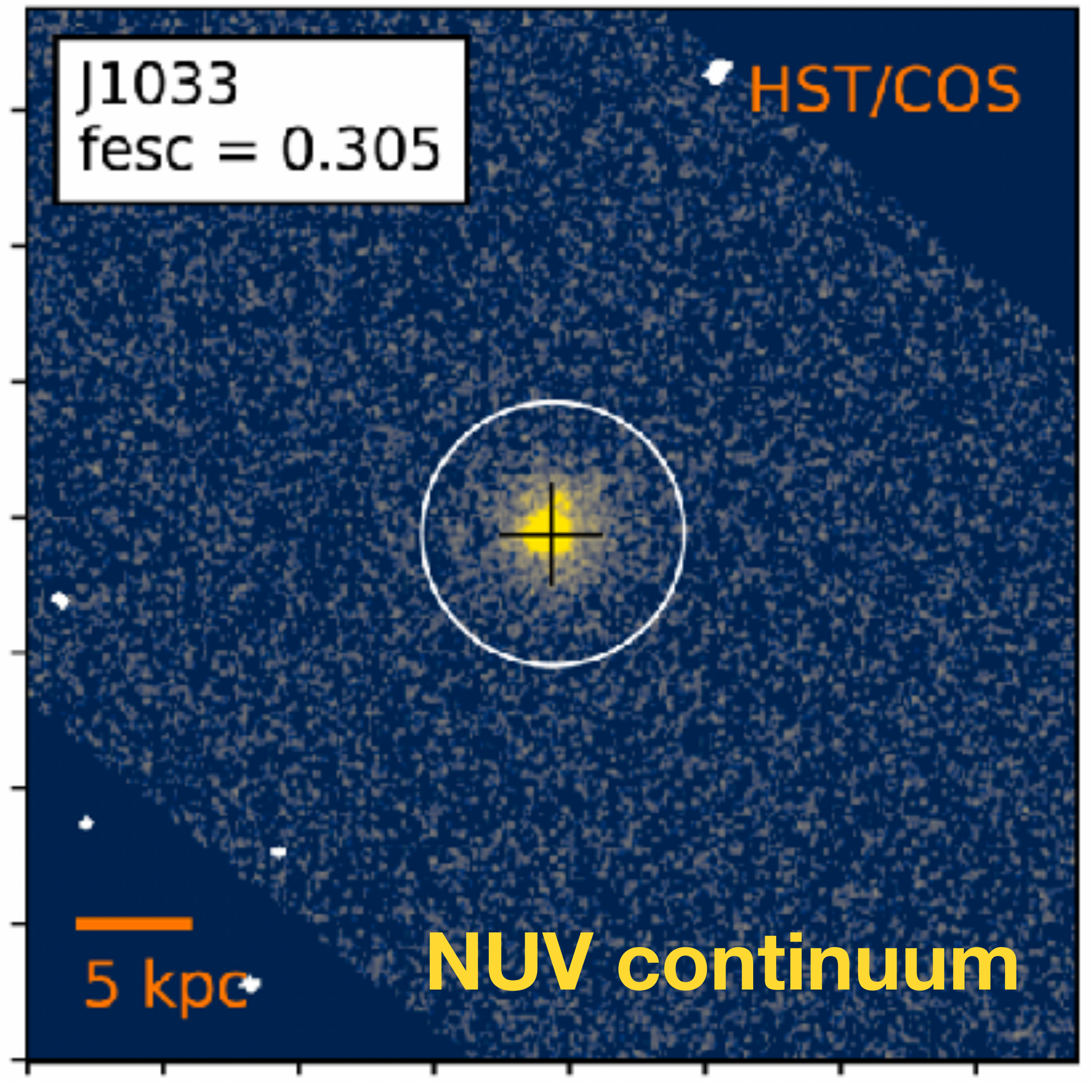


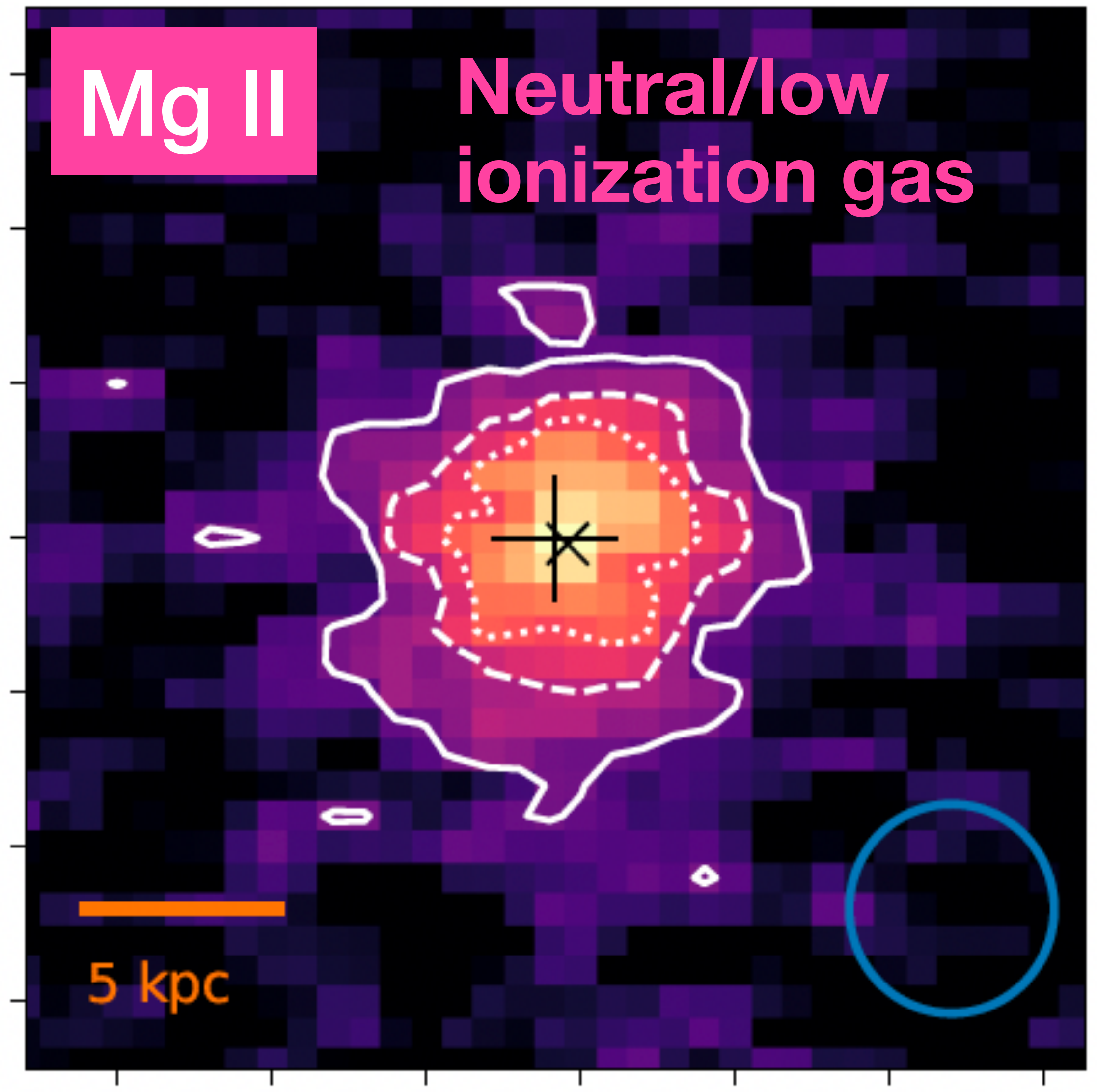
$f_{\mathrm{esc}}^{\mathrm{LyC}}(\mathrm{UV})$ EW(Hβ) $12+\log_{10}(\frac{\mathrm{O}}{\mathrm{H}})$ SFR $\beta_{\mathrm{obs}}^{1550}$

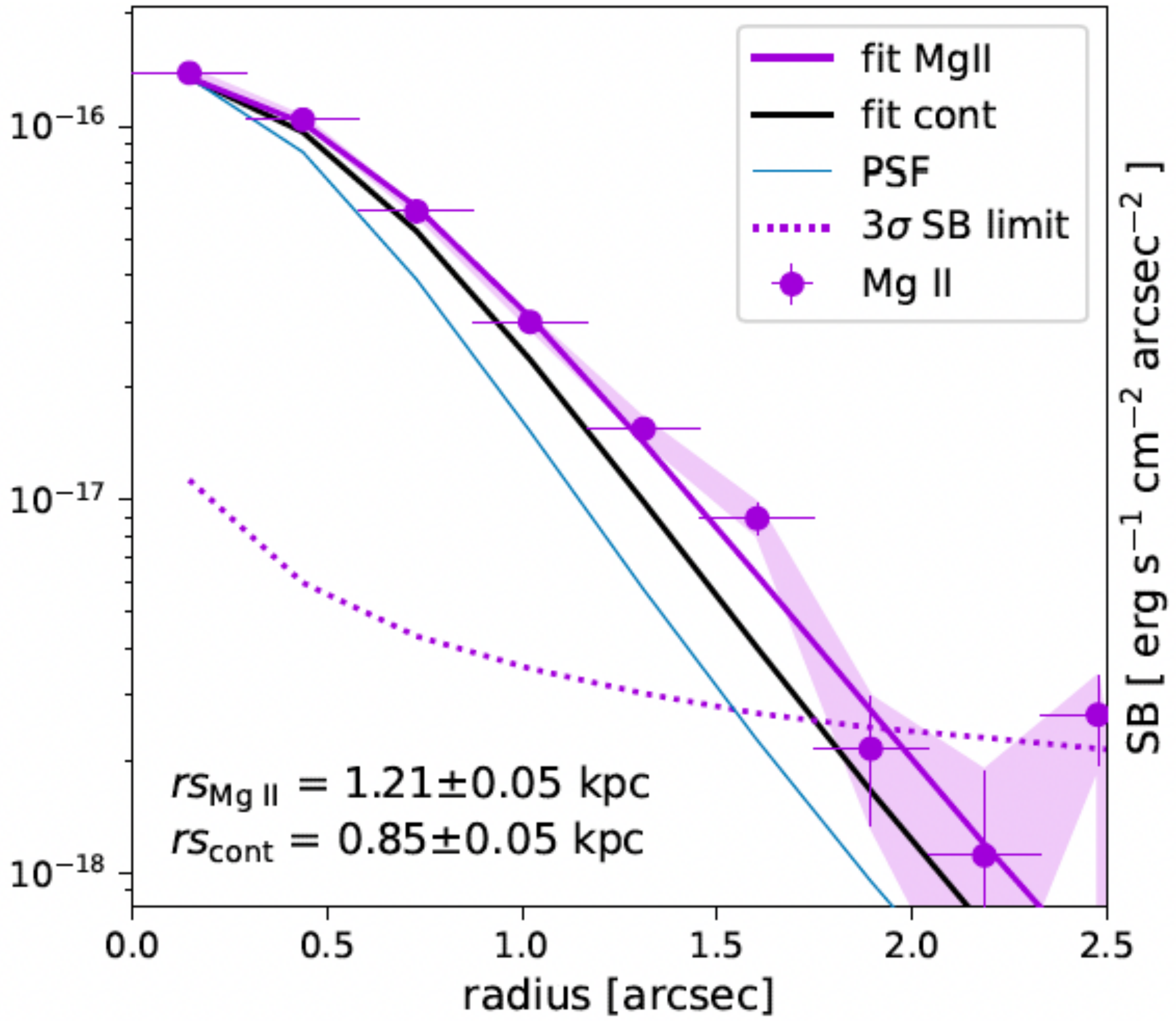
r_{50}^{UV} O_{32} $E(\mathrm{B-V})$ M_*

Leclercq et al. 2024

Flury et al. 2022a, Saldana-Lopez et al. 2022

Spatial extent of the nebular emission





Leclercq et al. 2024

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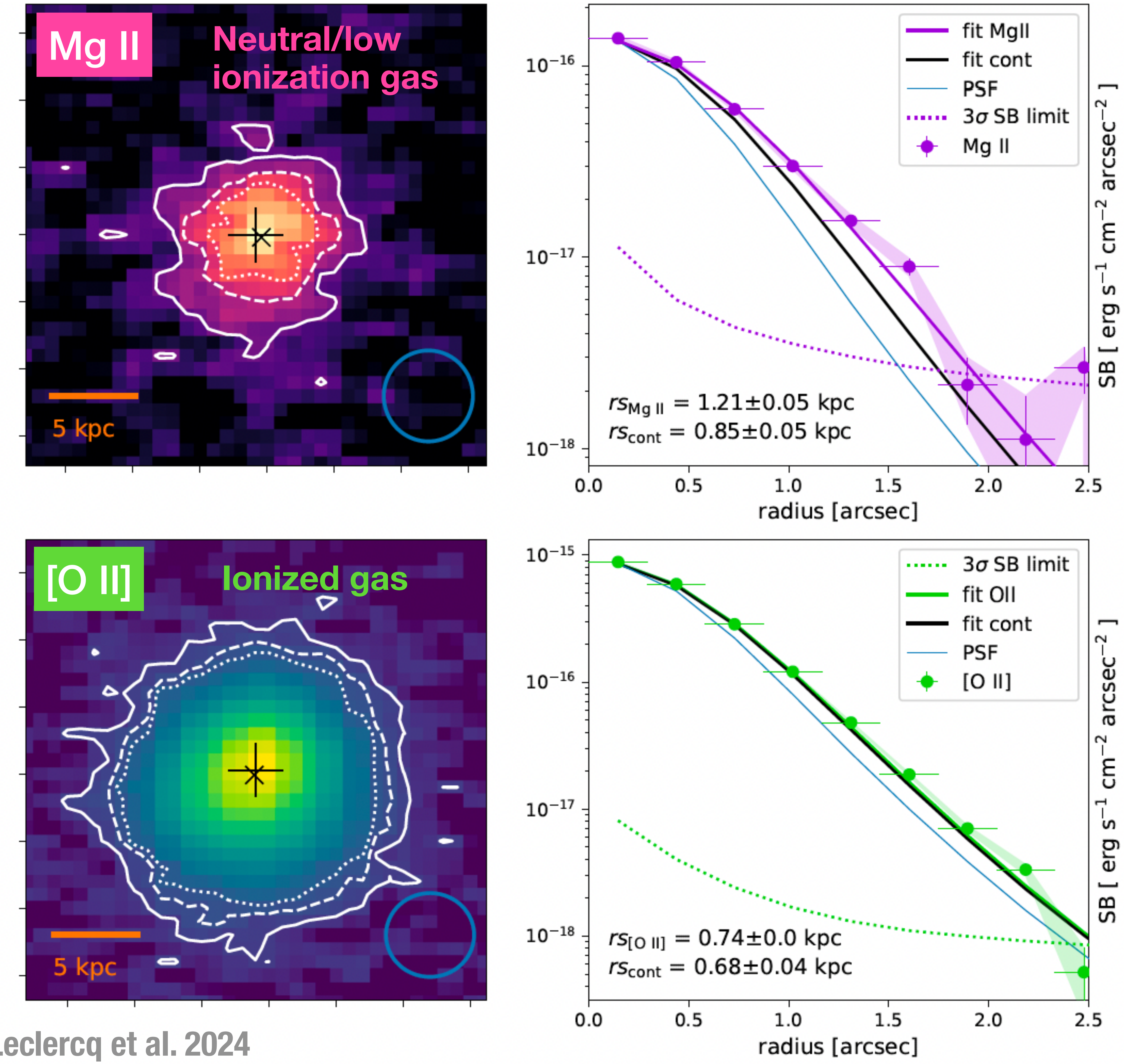

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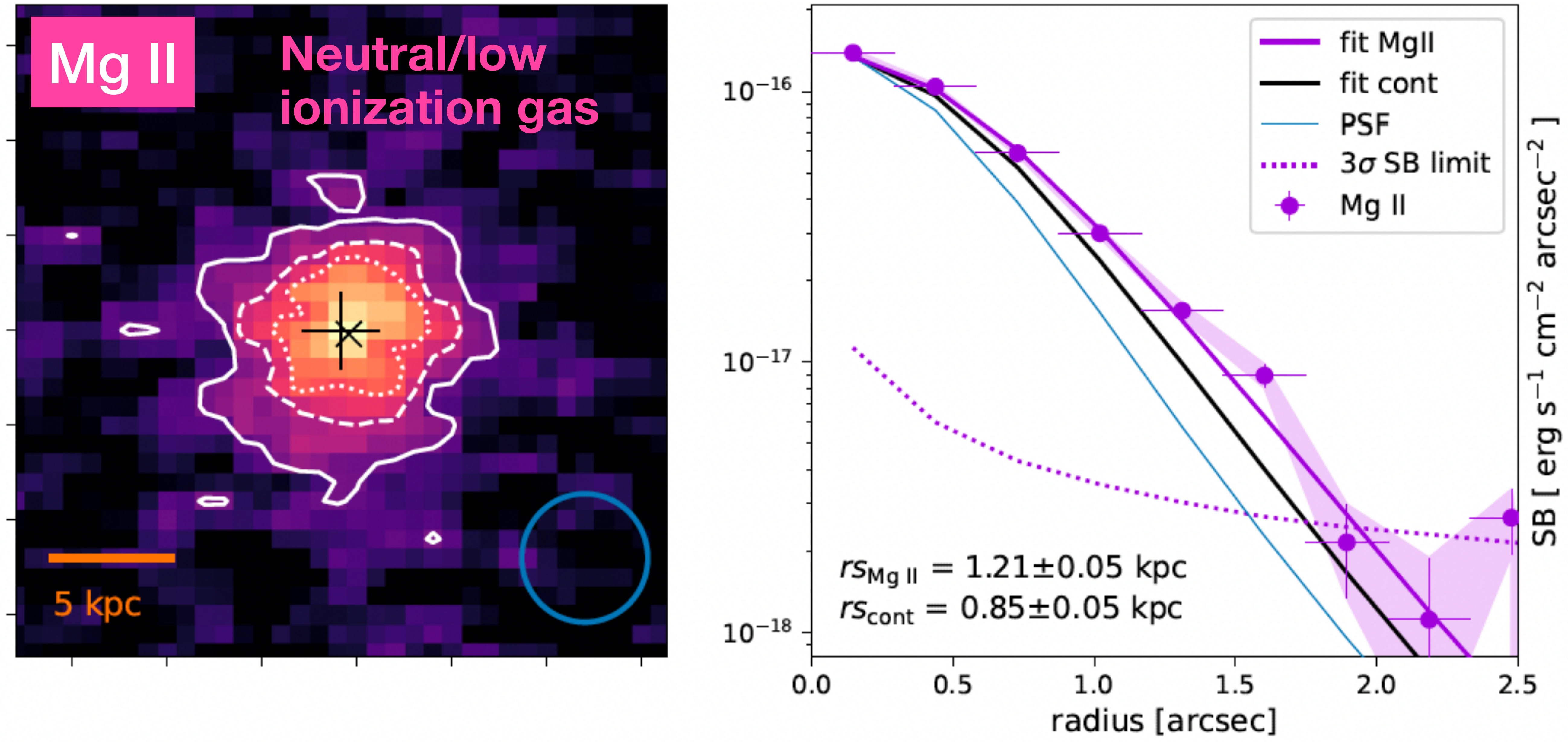
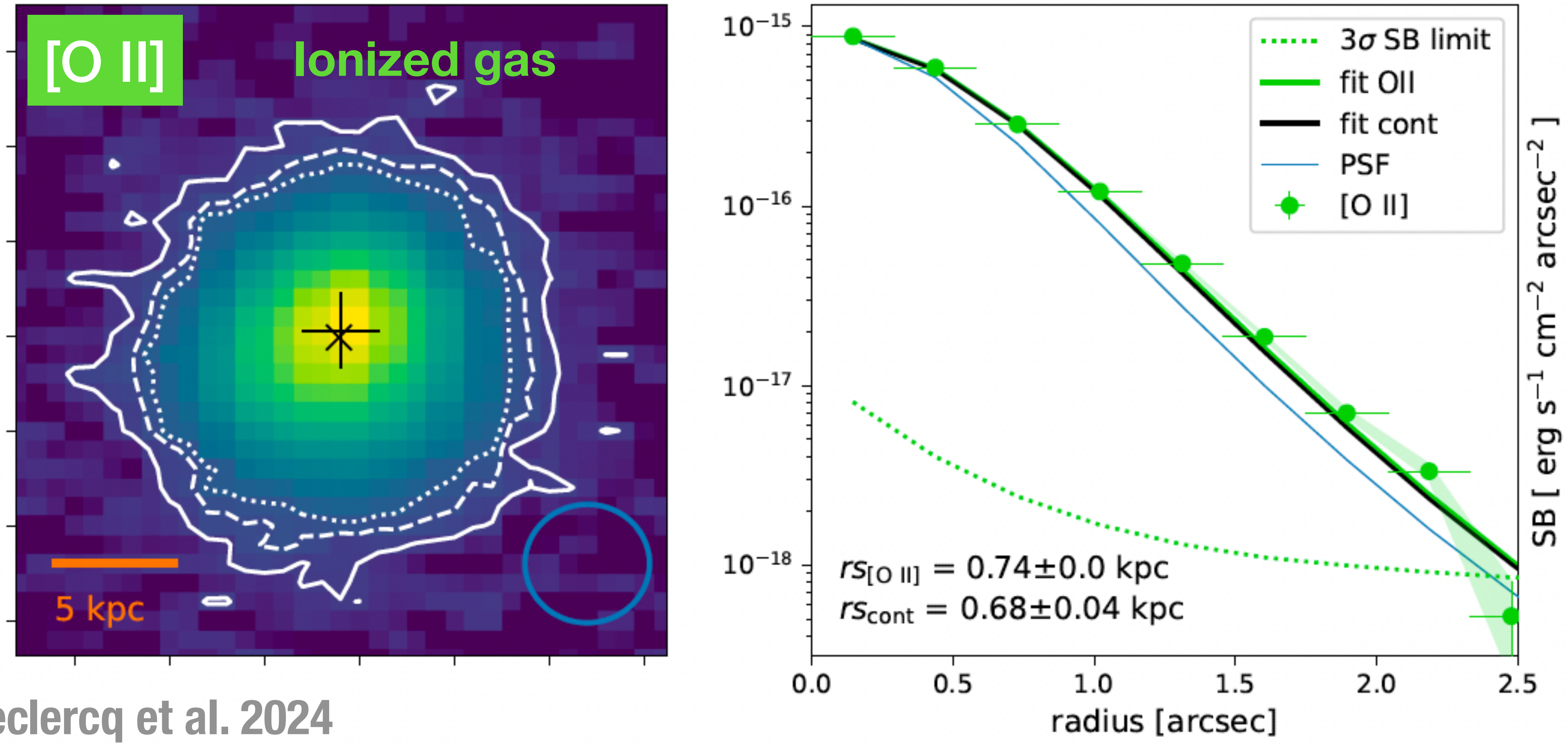
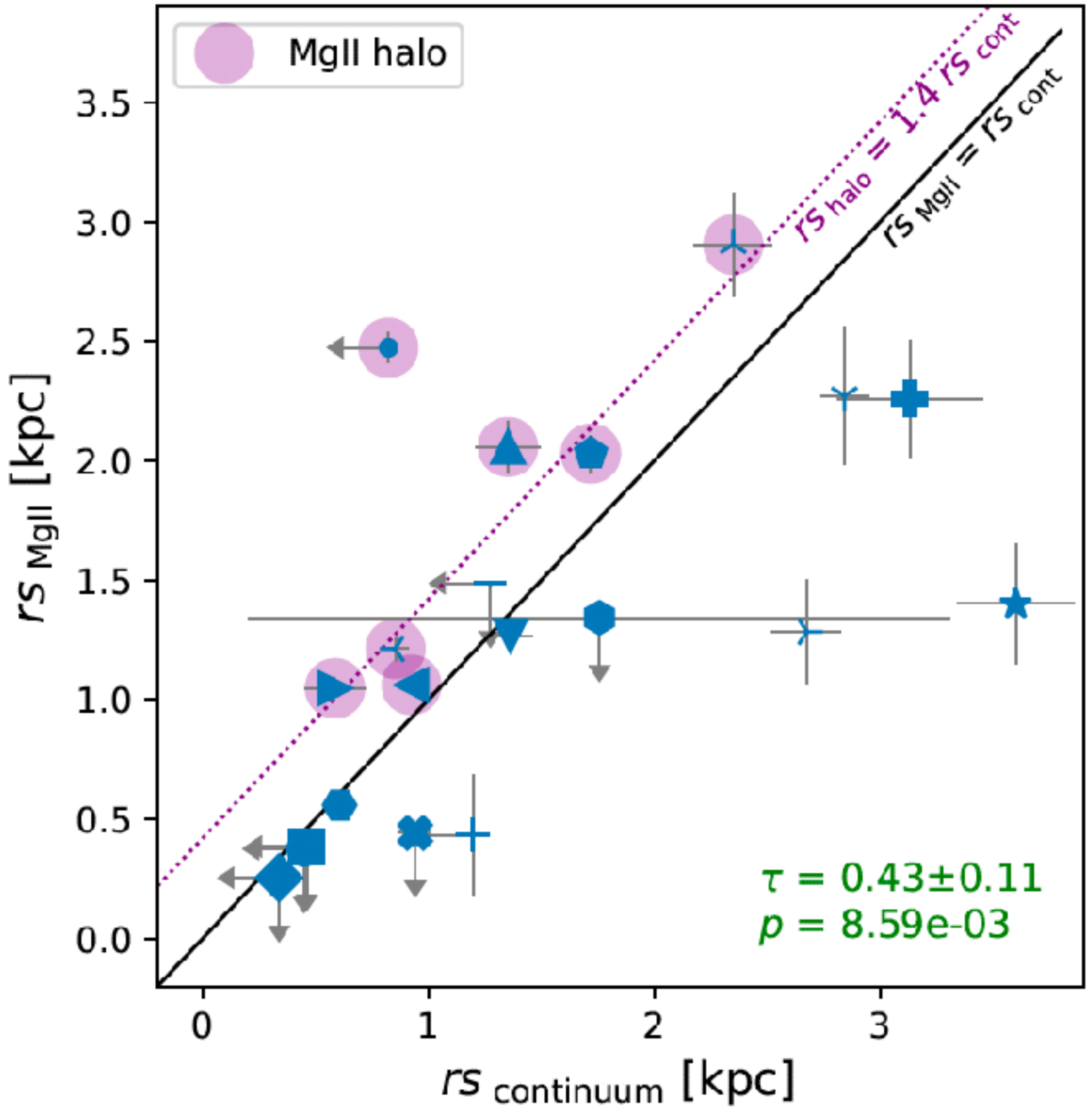




Leclercq et al. 2024



➜ 7 Mg II halos
➜ 10 [O II] halos

Nebular emission **~1.5 more extended** than the continuum

Connecting the gas distribution to the LyC escape

Leclercq et al. 2024

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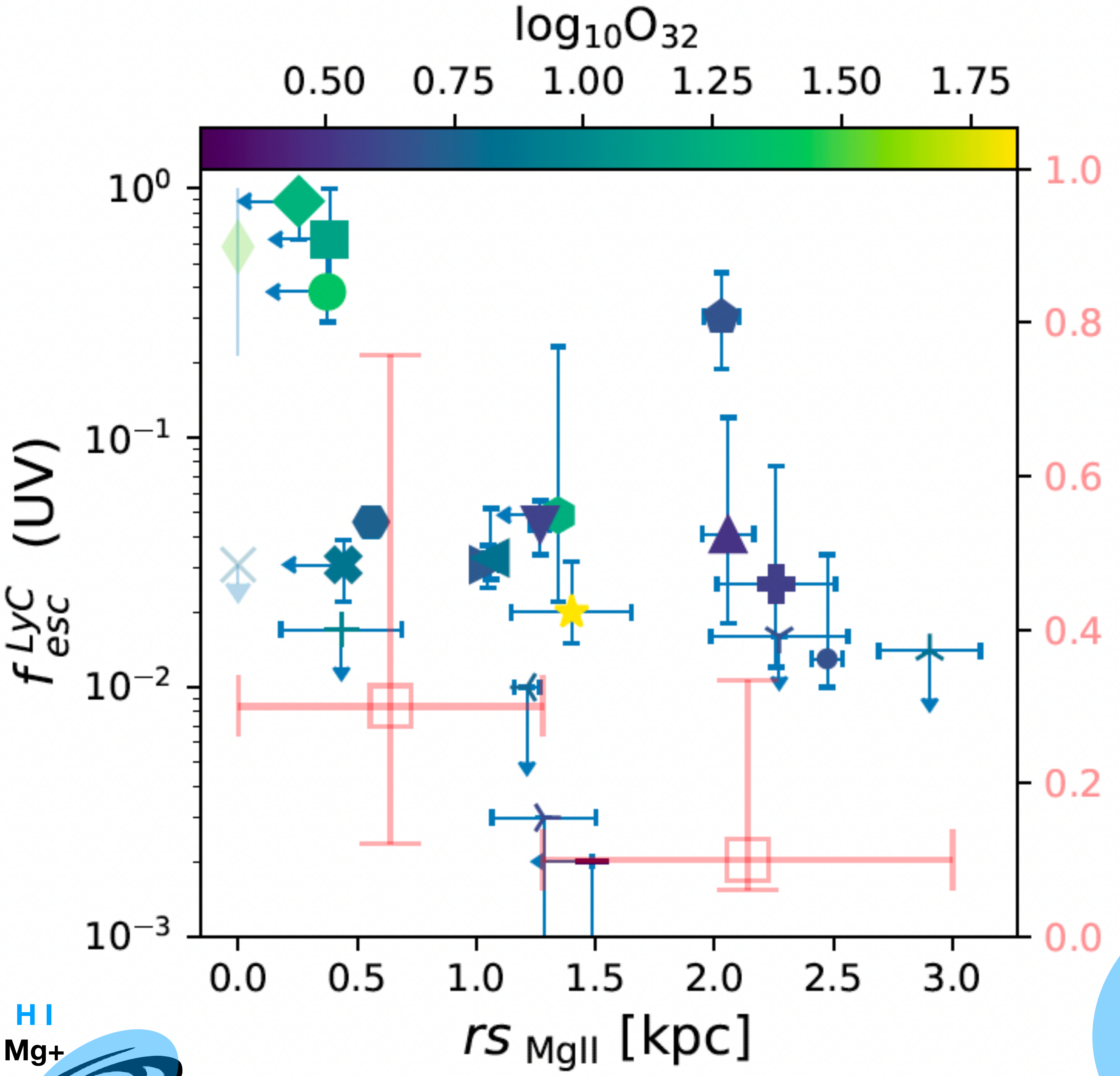

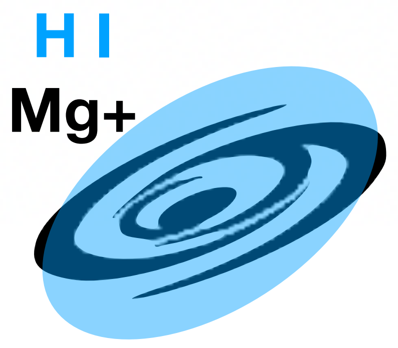

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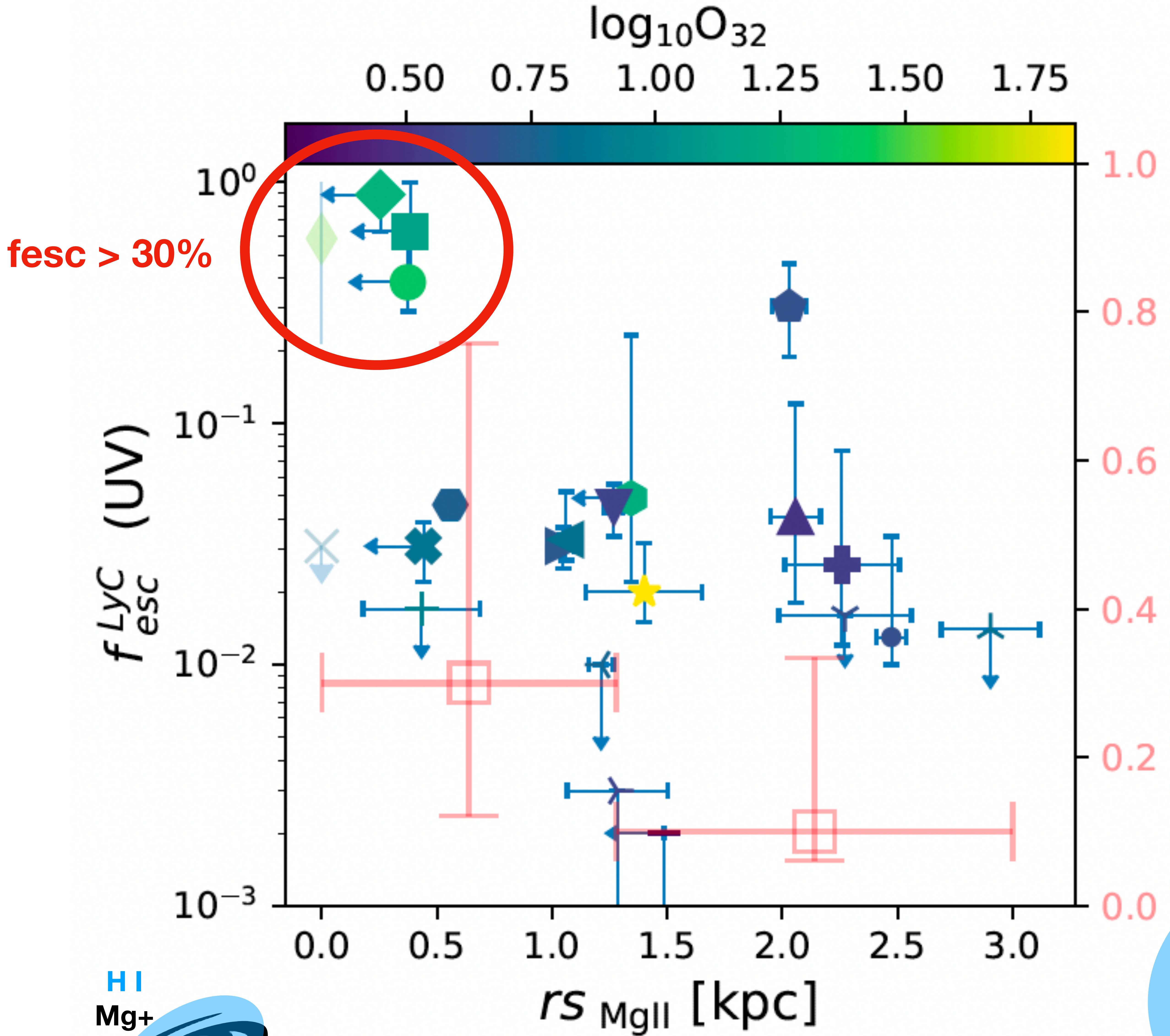

- **Strong leakers are compact** in both MgII and [O II], ***except J1033***
- Weak/non leakers have **diverse** nebular configurations

Leclercq et al. 2024

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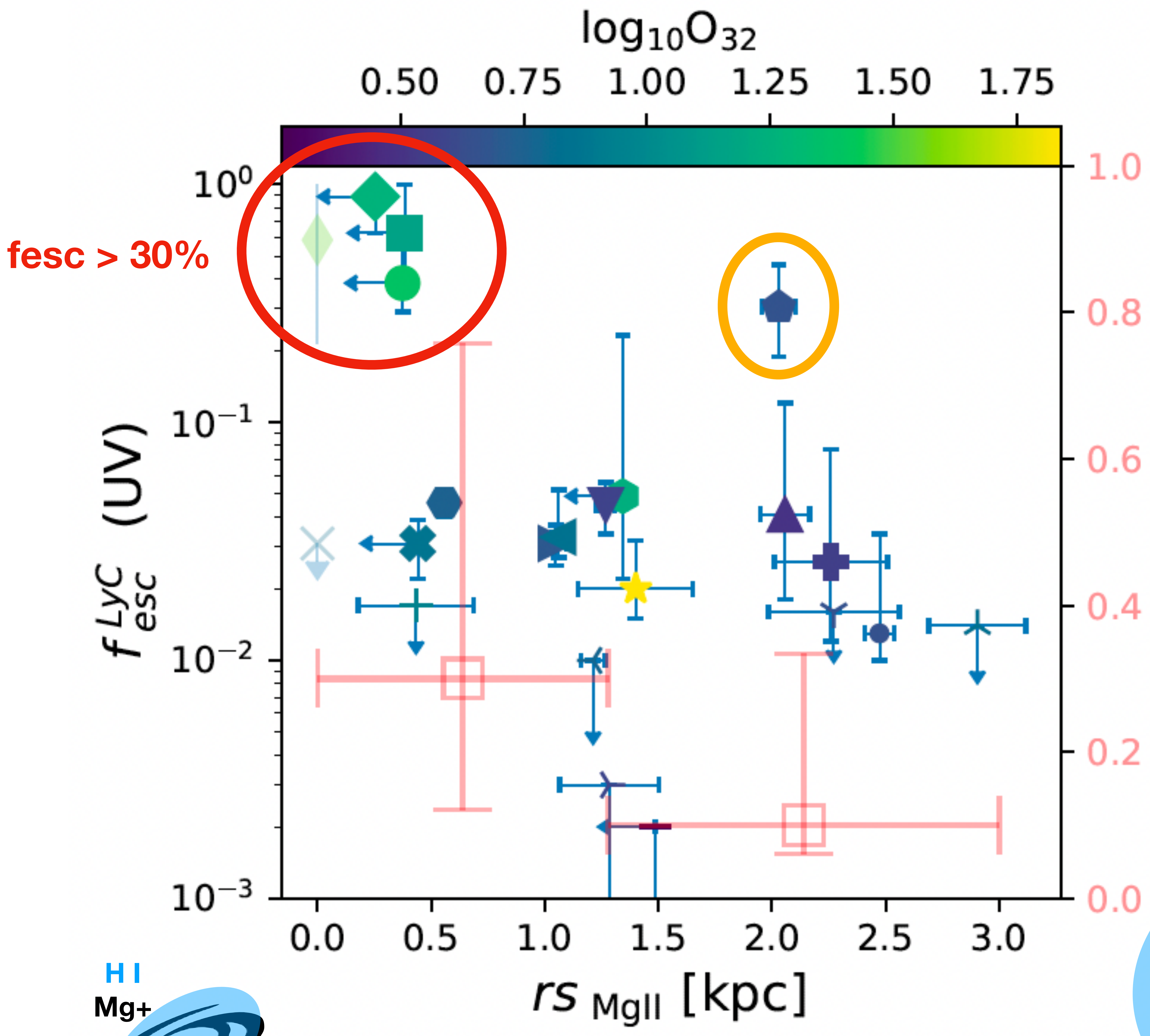

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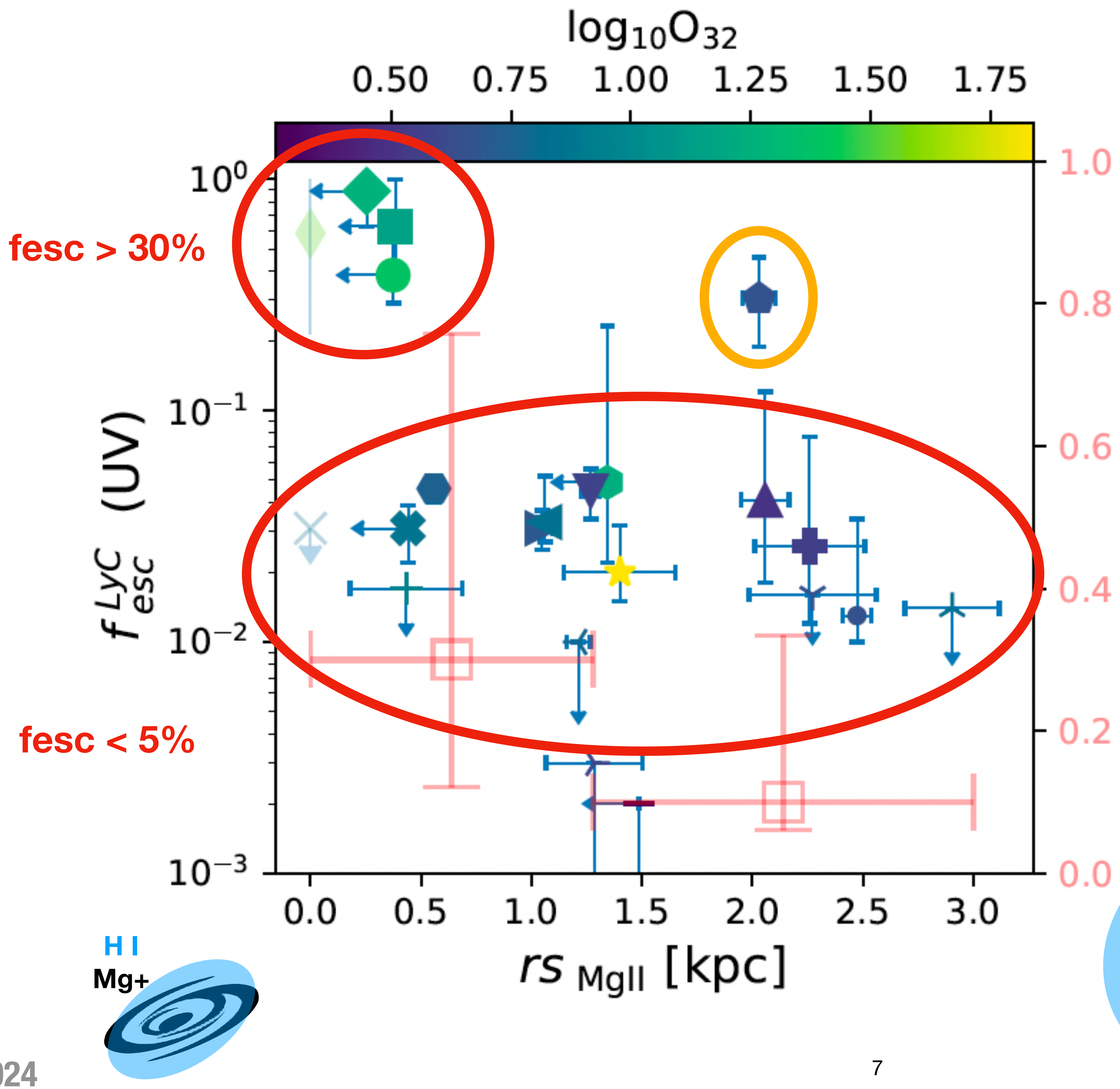

- **Strong leakers are compact** in both MgII and [O II], *except J1033*
- Weak/non leakers have **diverse** nebular configurations

➜ Nebular compactness + high O32 ratios = strong LyC leakage

Leclercq et al. 2024

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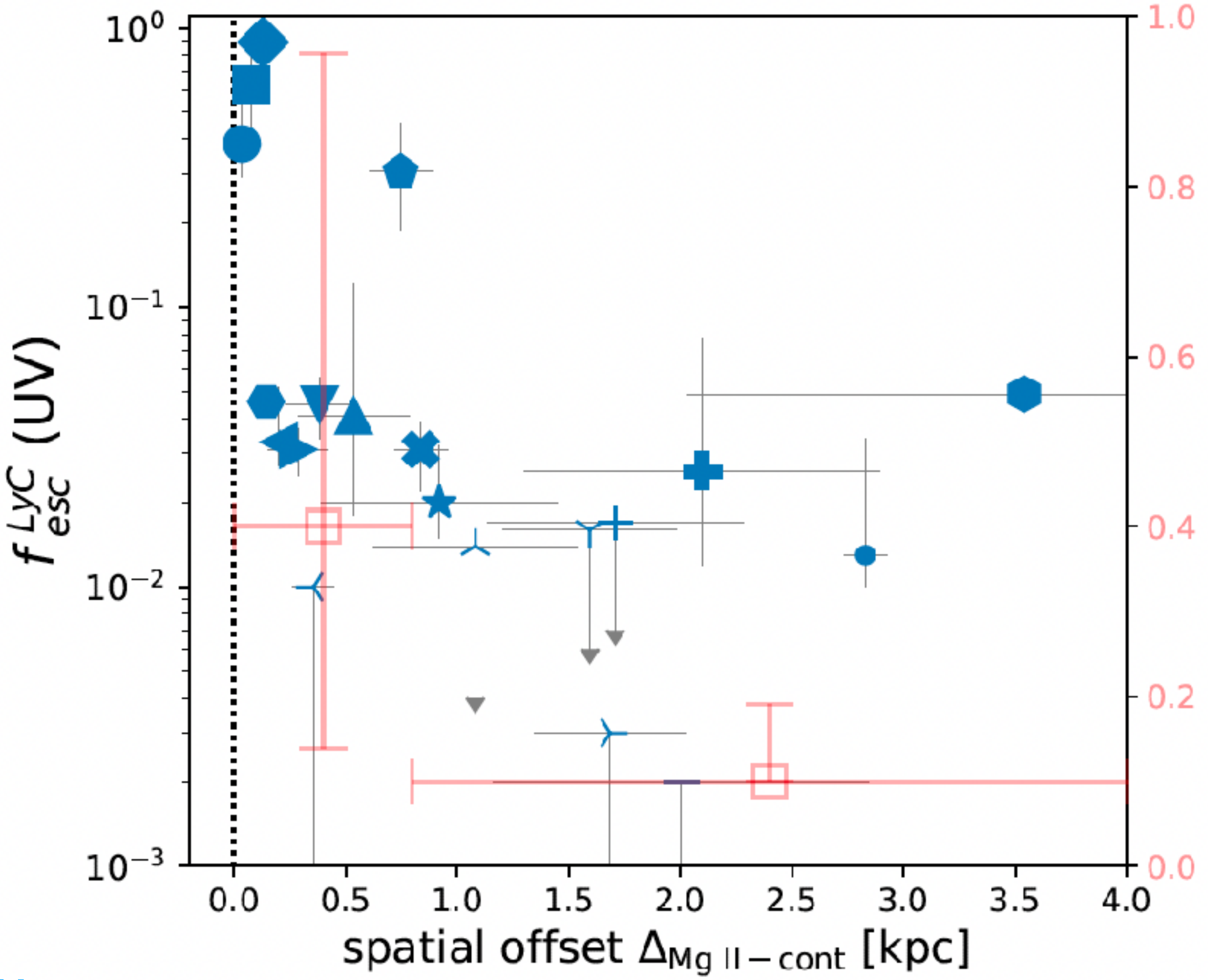

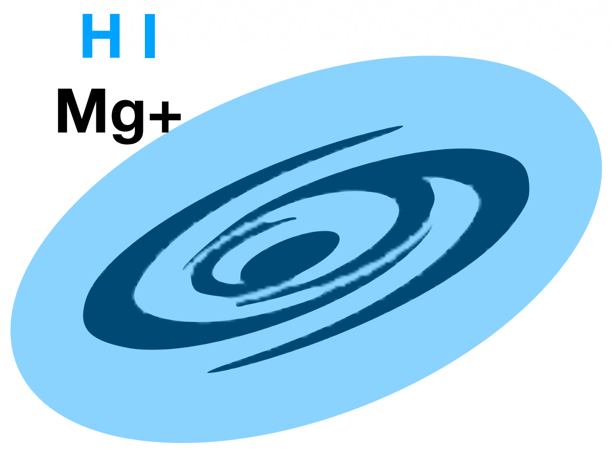

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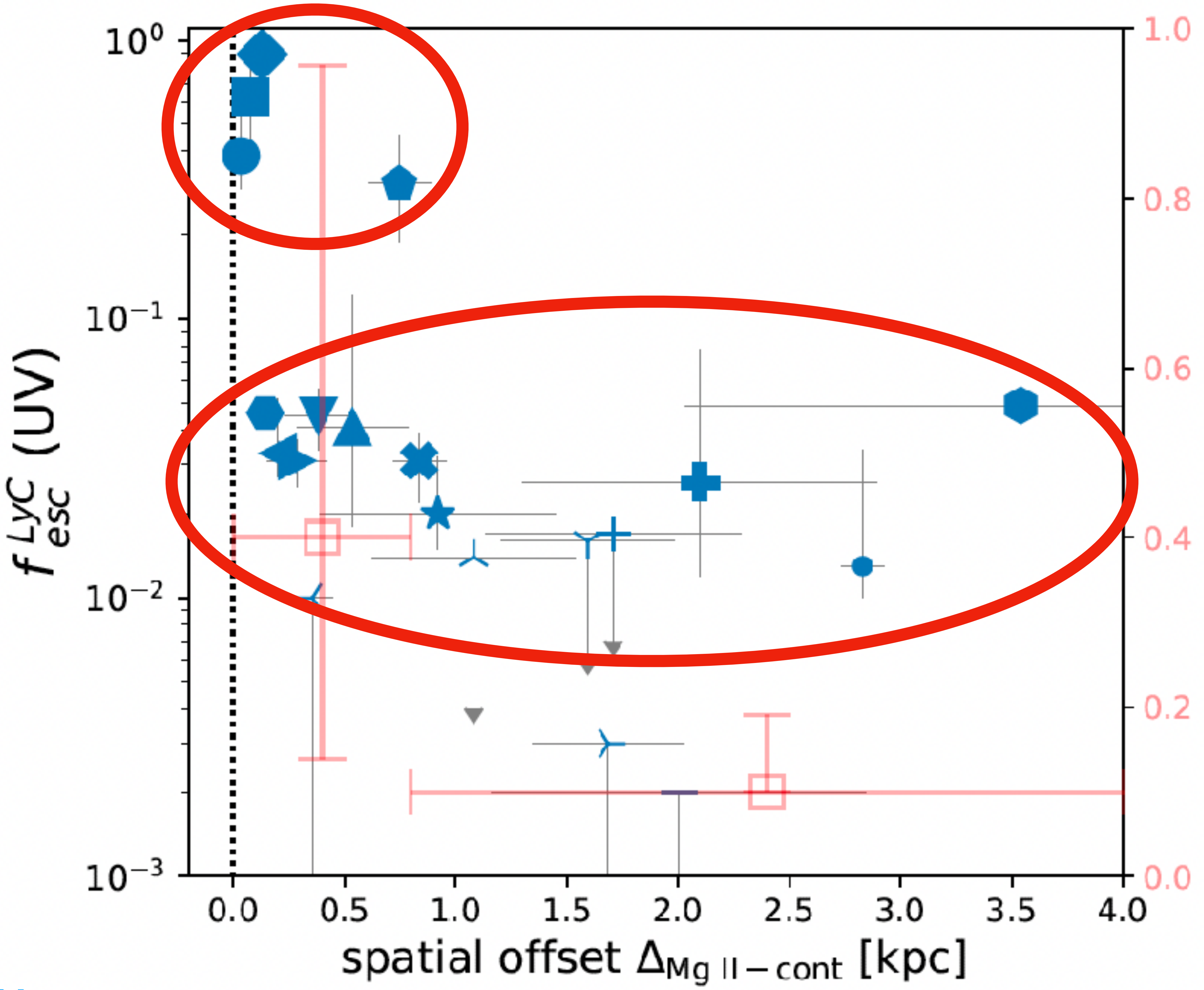
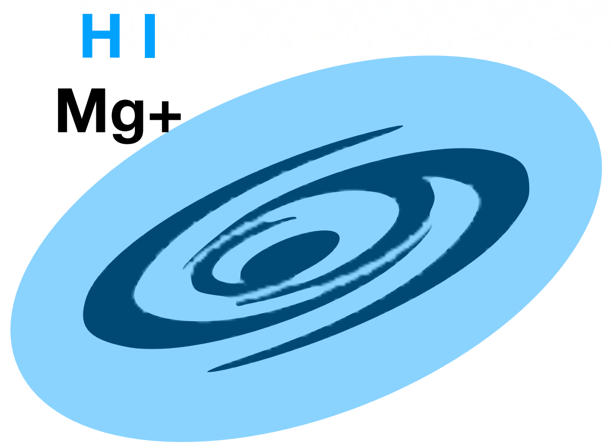


- **Strong LyC leakers show no or small (<1kpc) spatial offset** between Mg II and the stellar continuum
- Weak/non leakers are more diverse with offsets up to 4 kpc



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Gas distribution vs. LyC escape in stacks

STACKING EXPERIMENTS

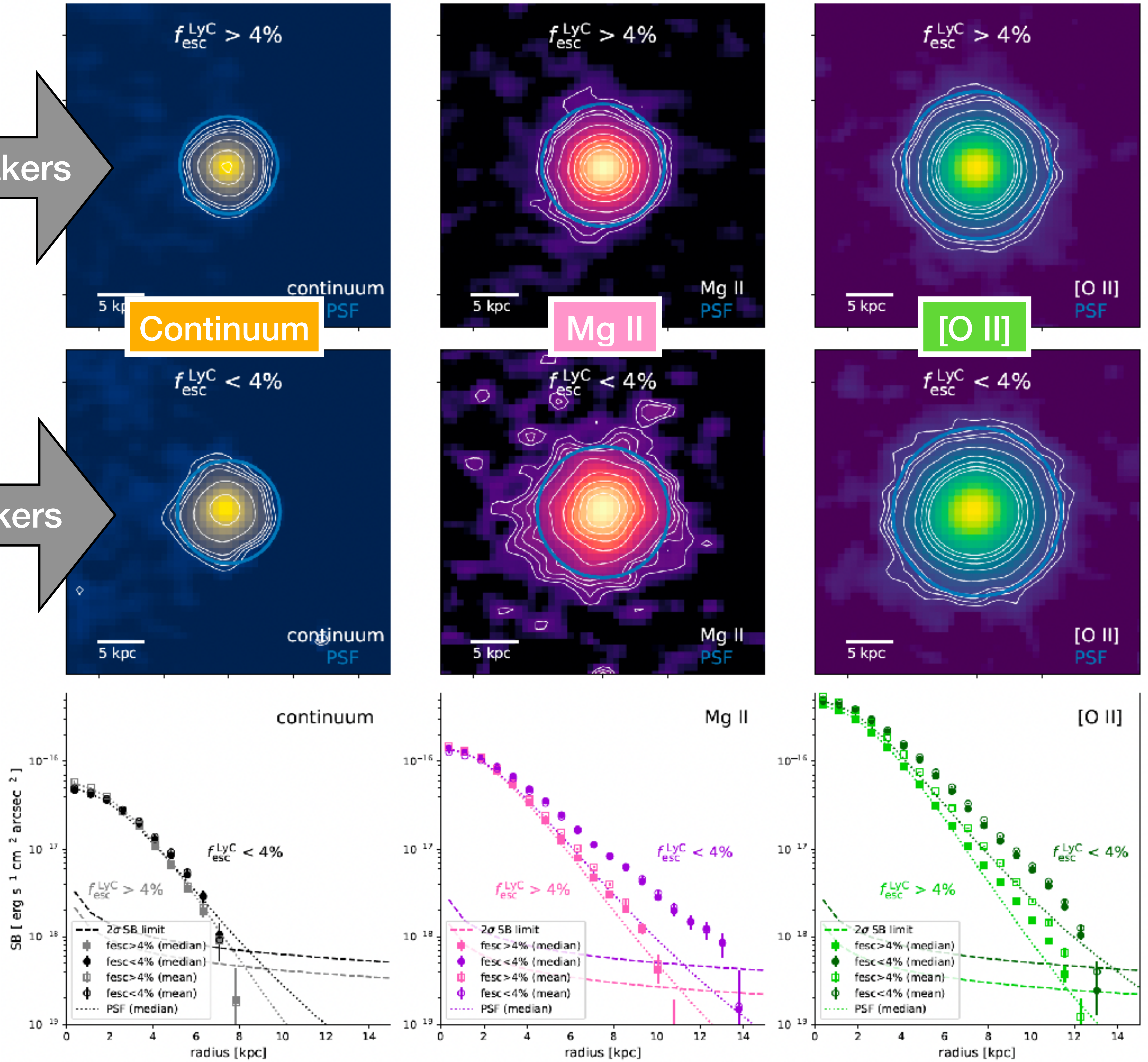
KCWI data only (seeing ~ 1”)

5 objects in each sub-samples

—> x 2.5 gain in SB limit (1e-18 cgs)

Strong leakers

Weak leakers



➜ On average, **strong and weak LyC emitters** have **different nebular** (neutral and ionized) **configurations**

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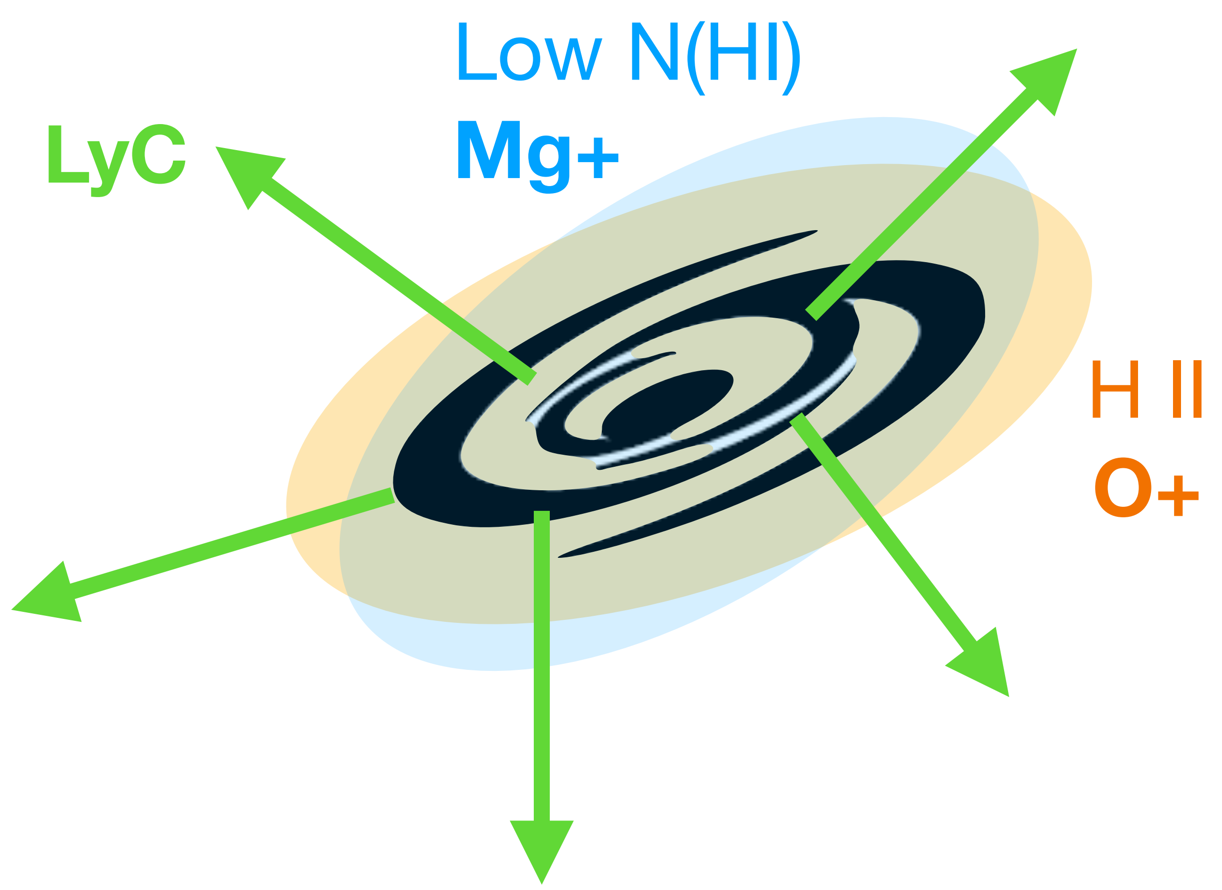
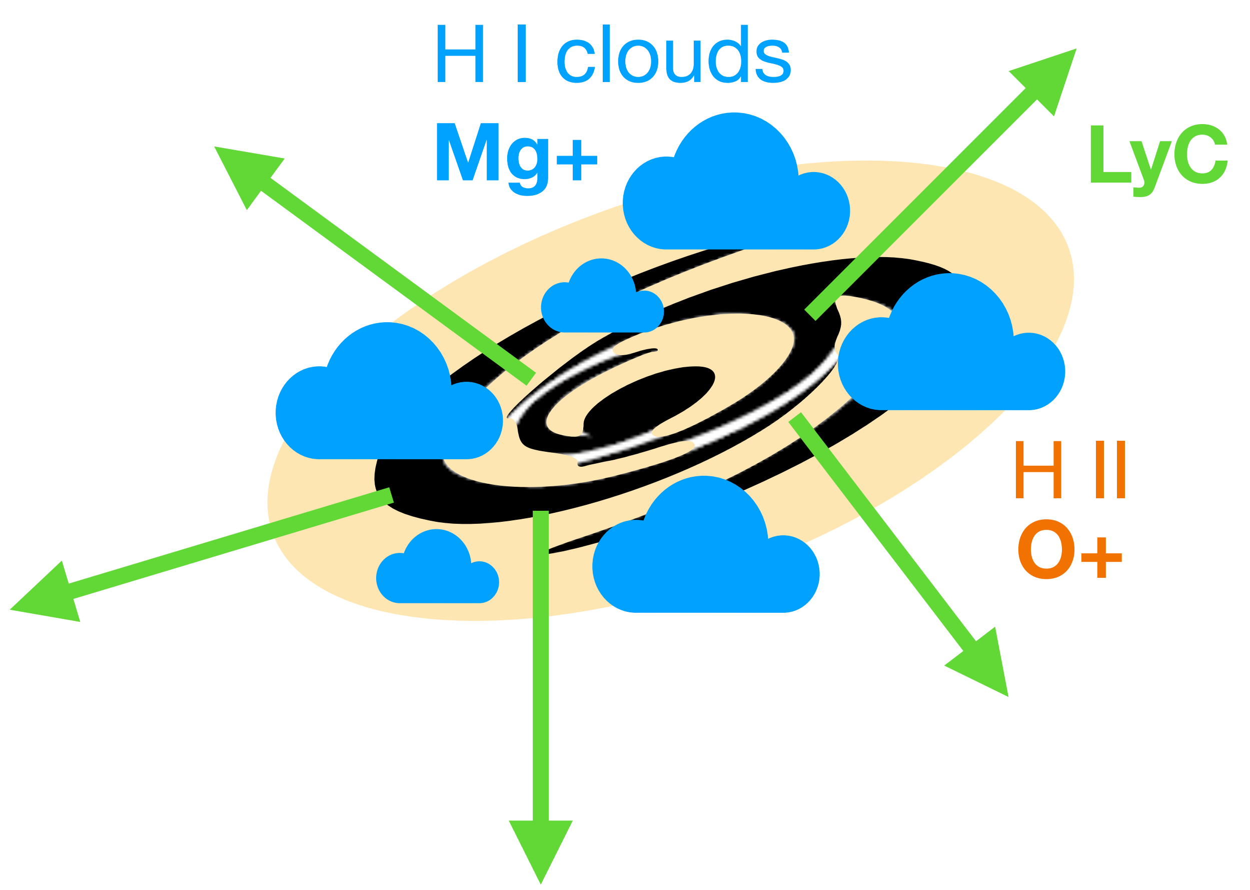
Different mechanisms for LyC escape

Highly ionized galaxies



widespread ionization



numerous porous lines of sights

Leclercq et al. 2024

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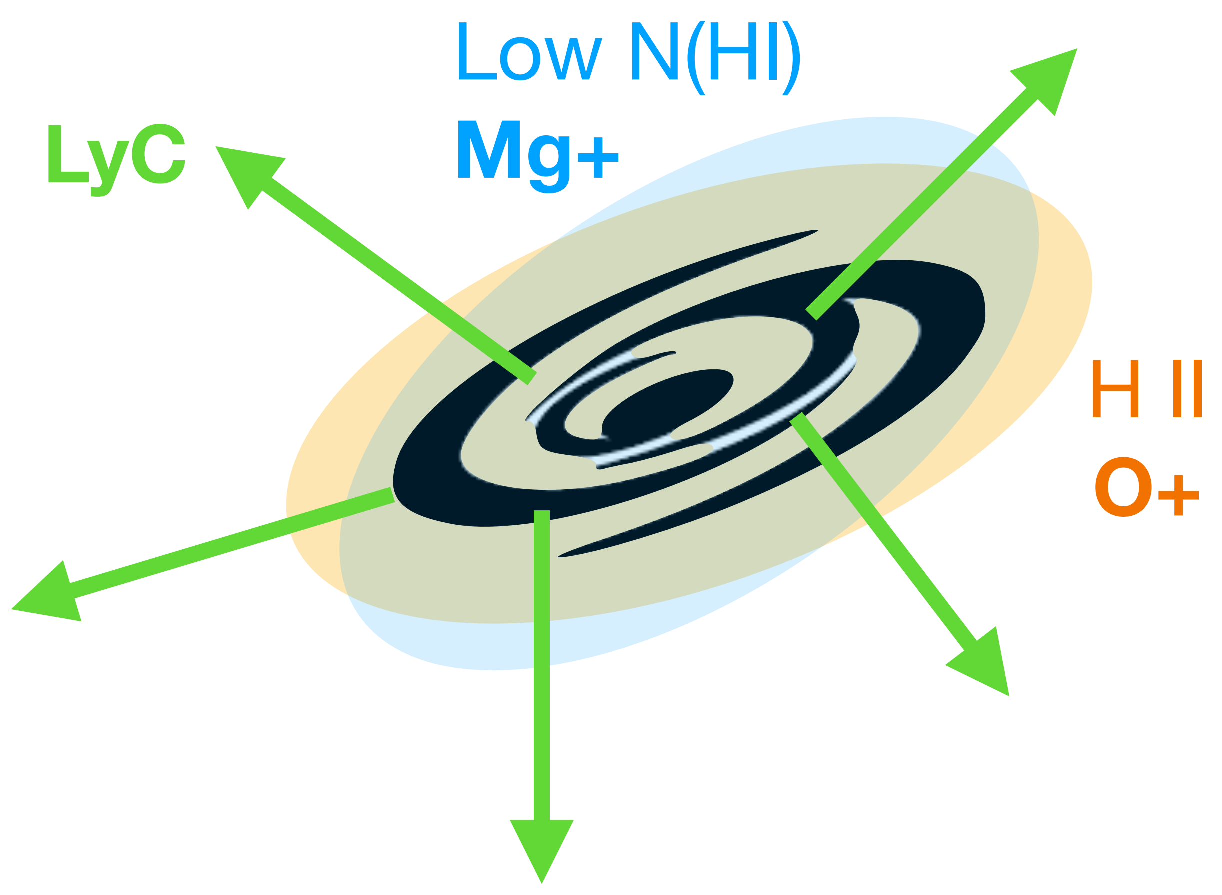

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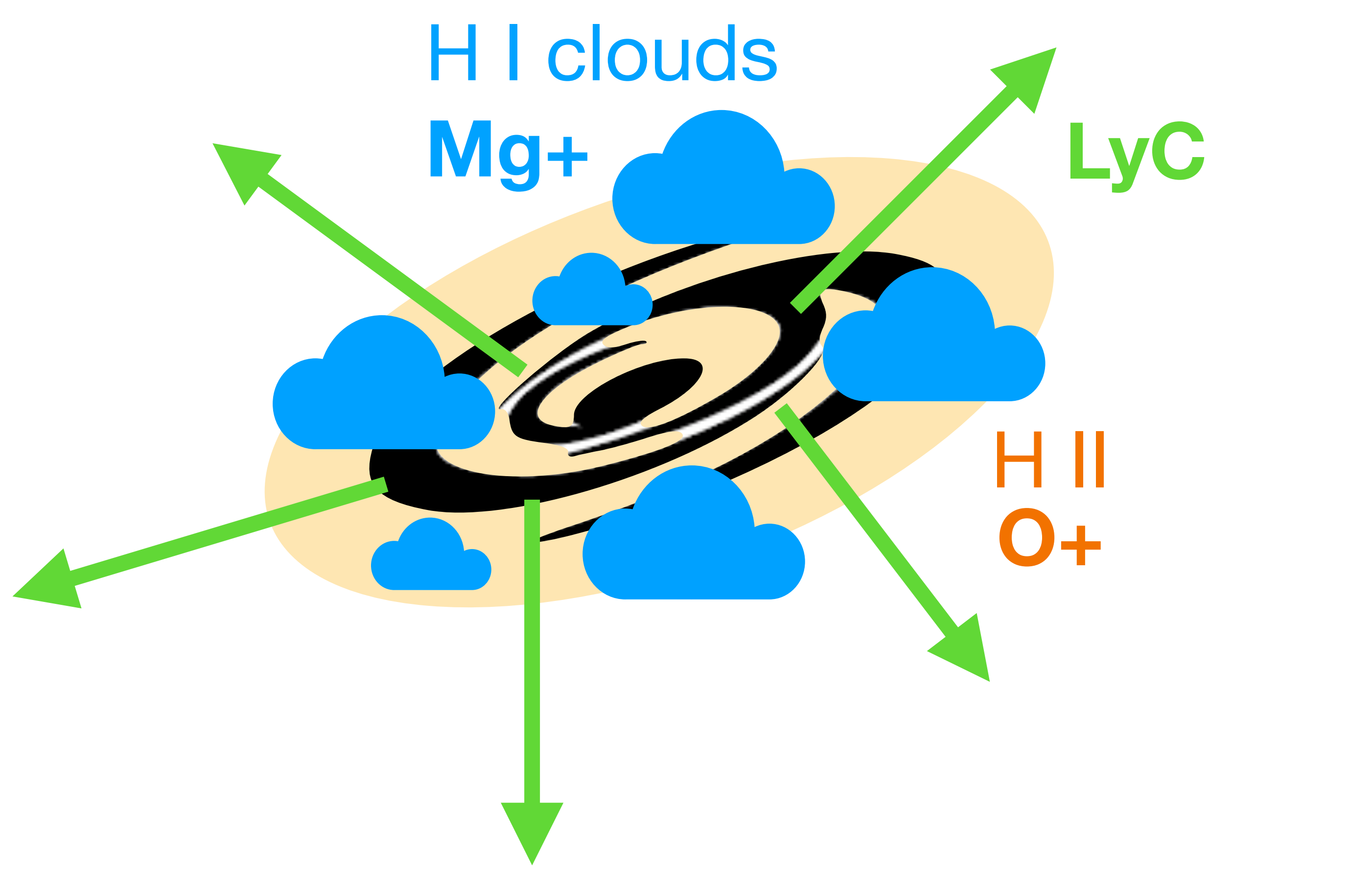

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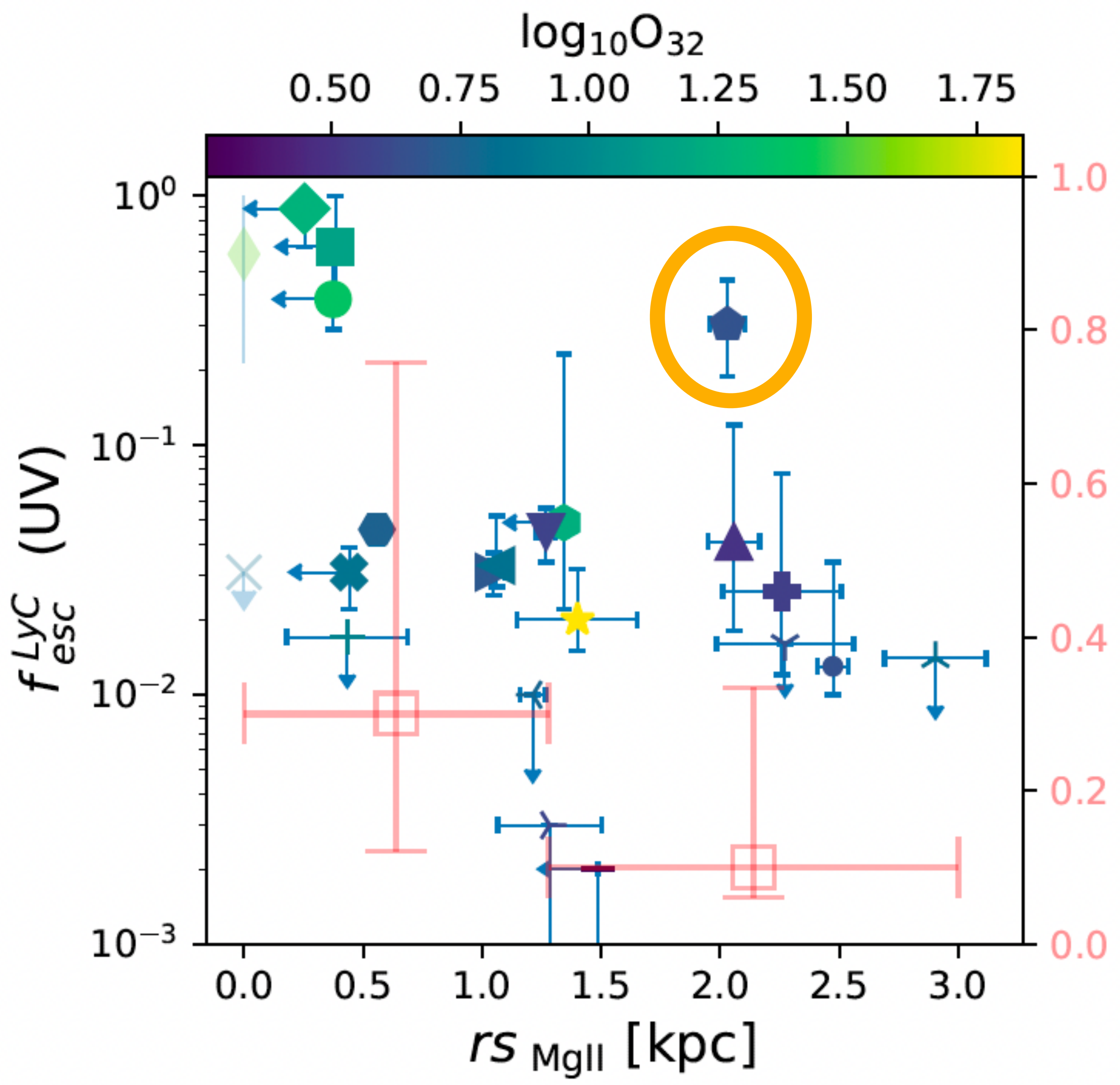

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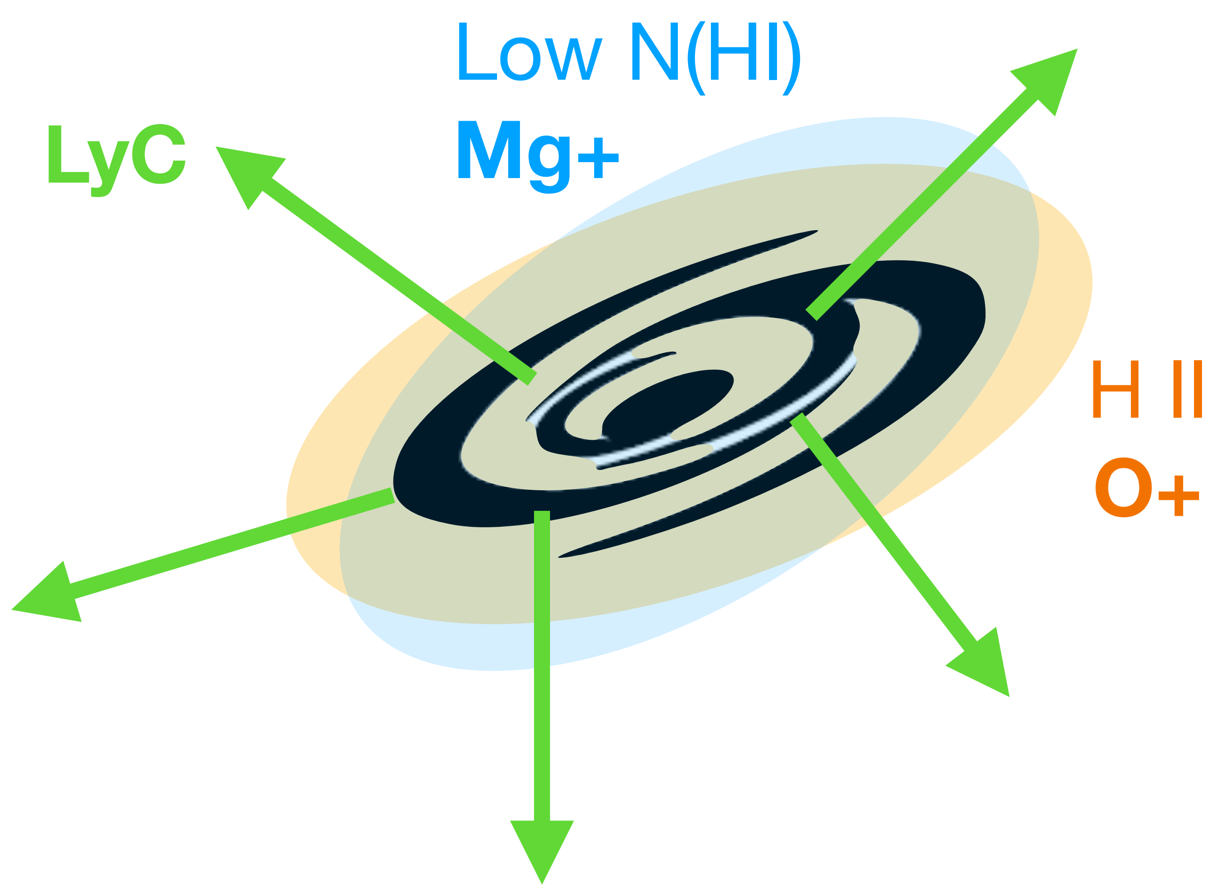

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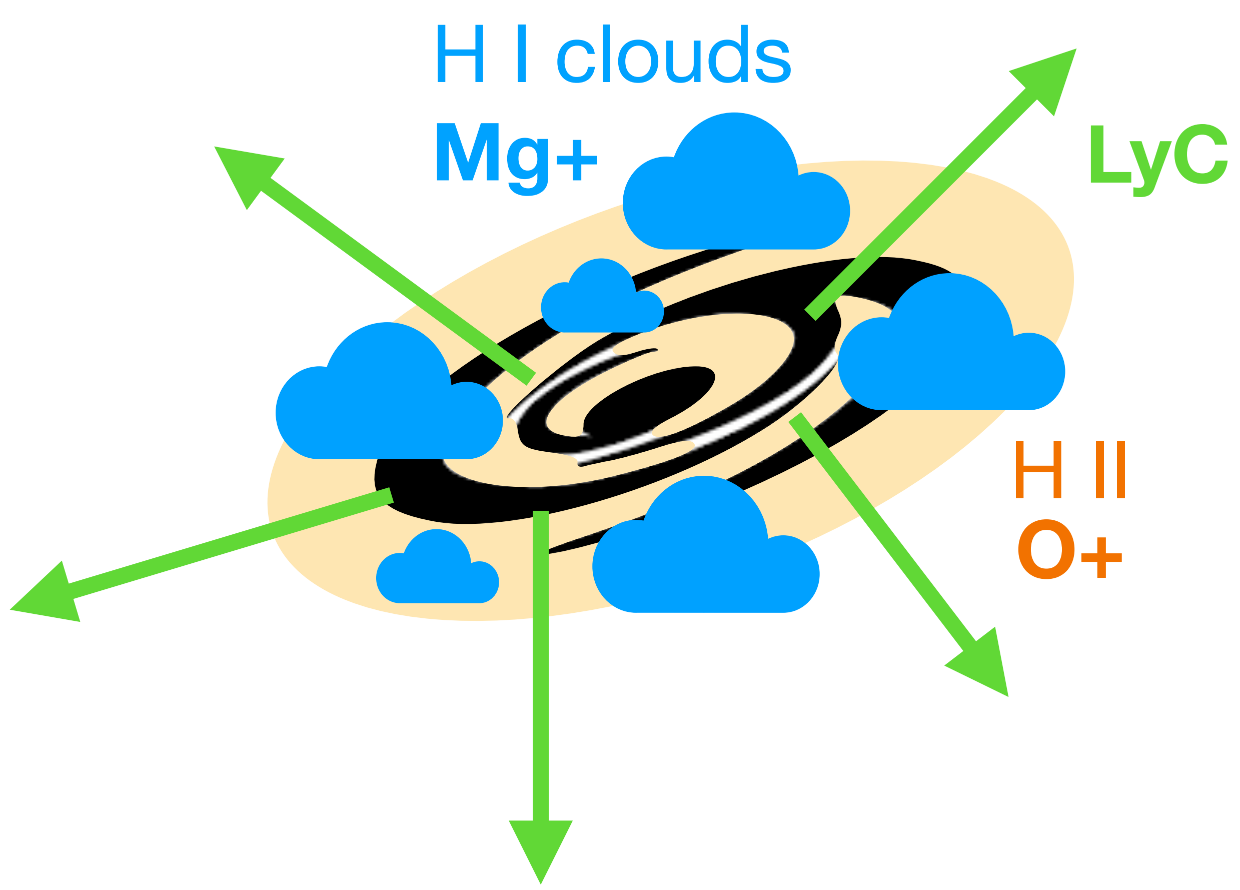

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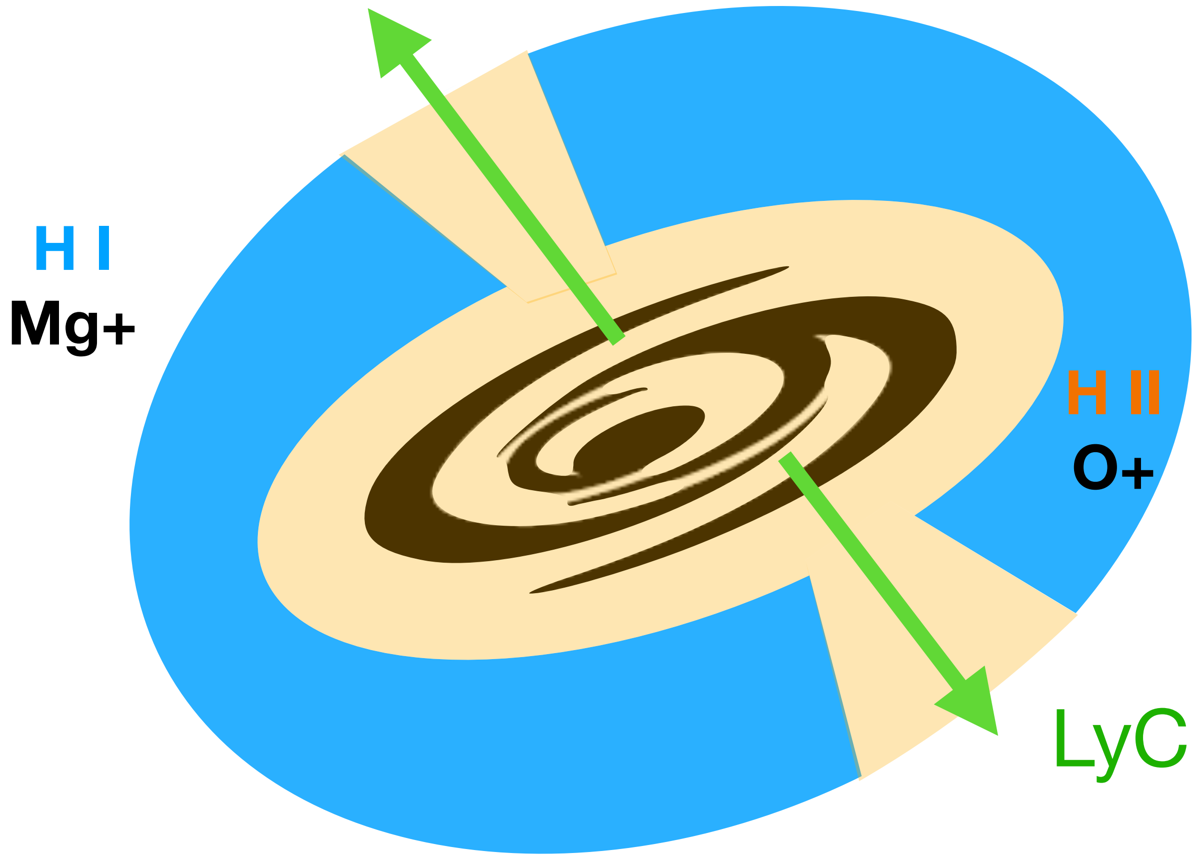

ionized channels in the ISM + CGM

Leclercq et al. 2024

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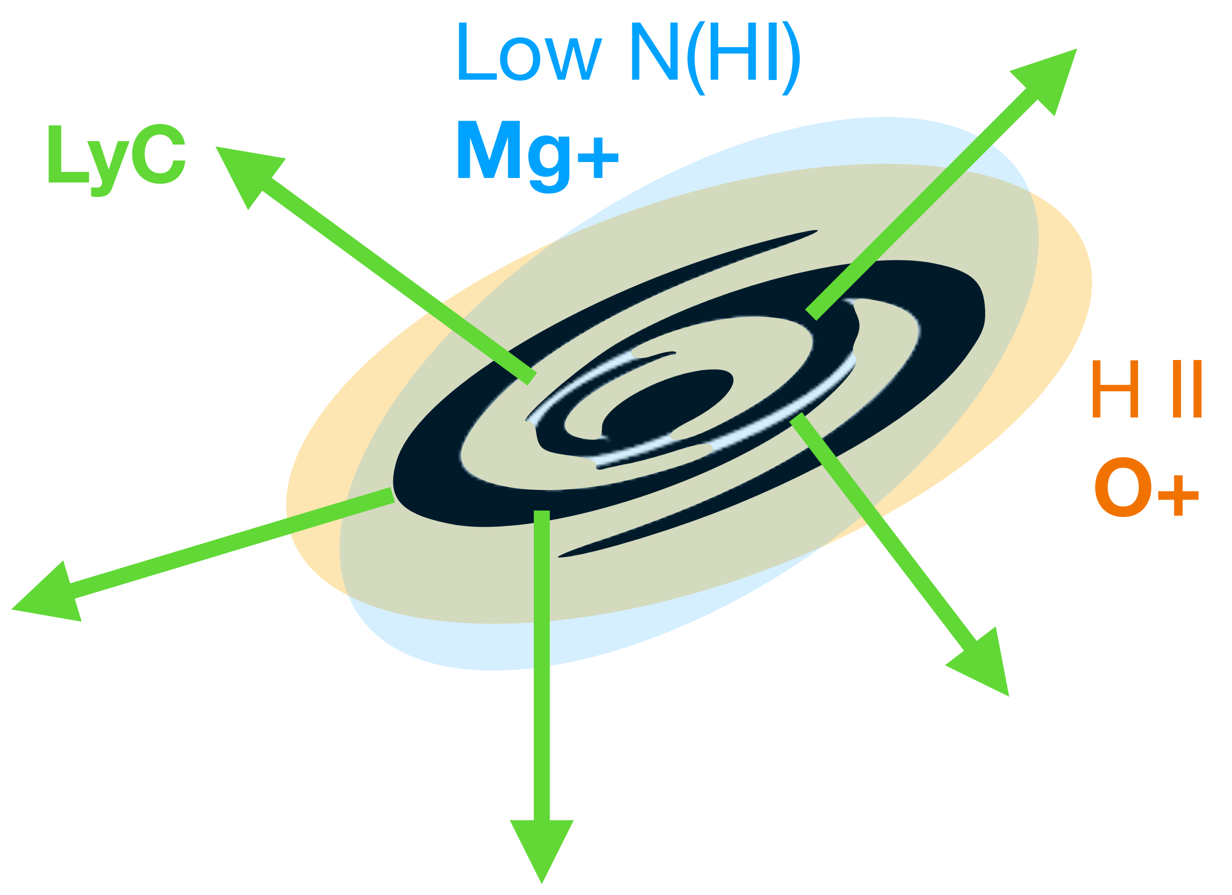
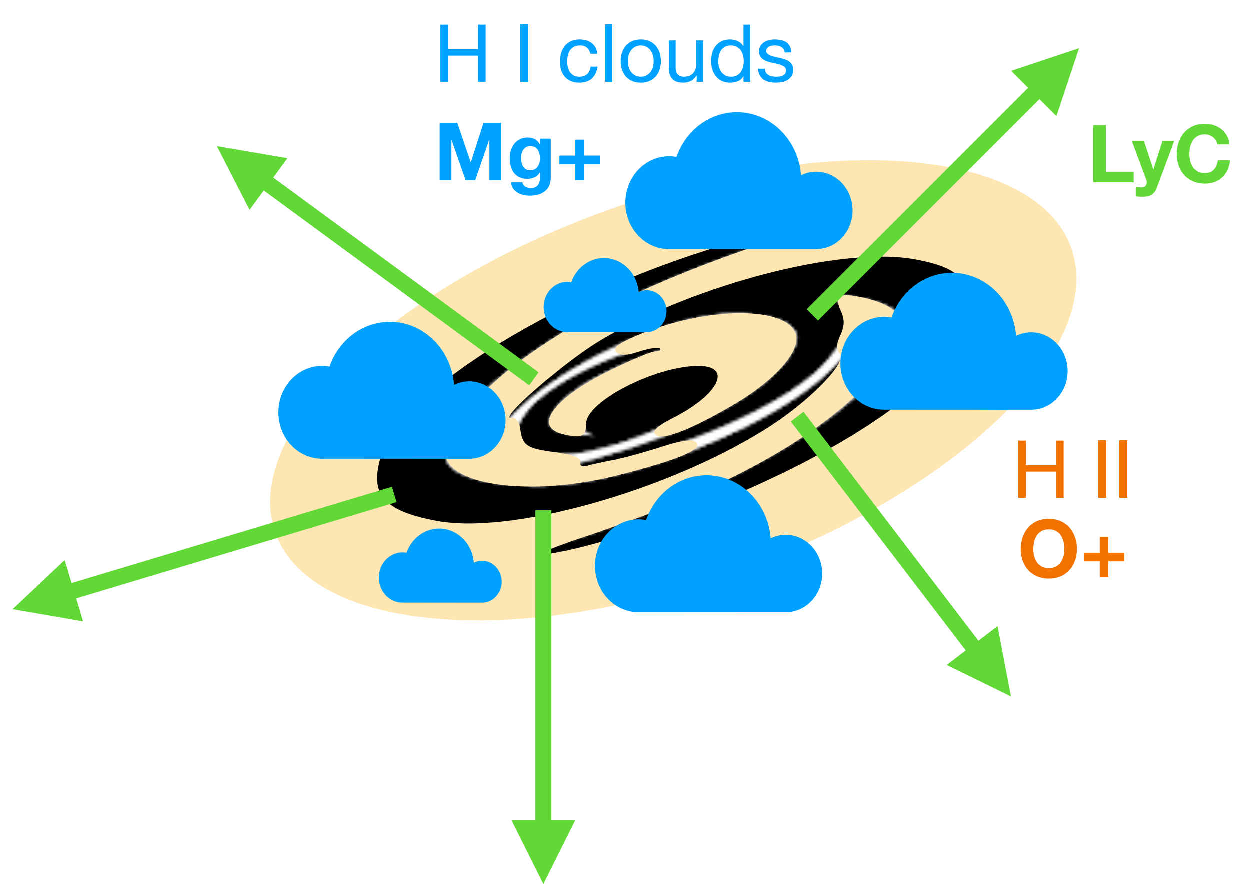
Highly ionized galaxies



widespread ionization



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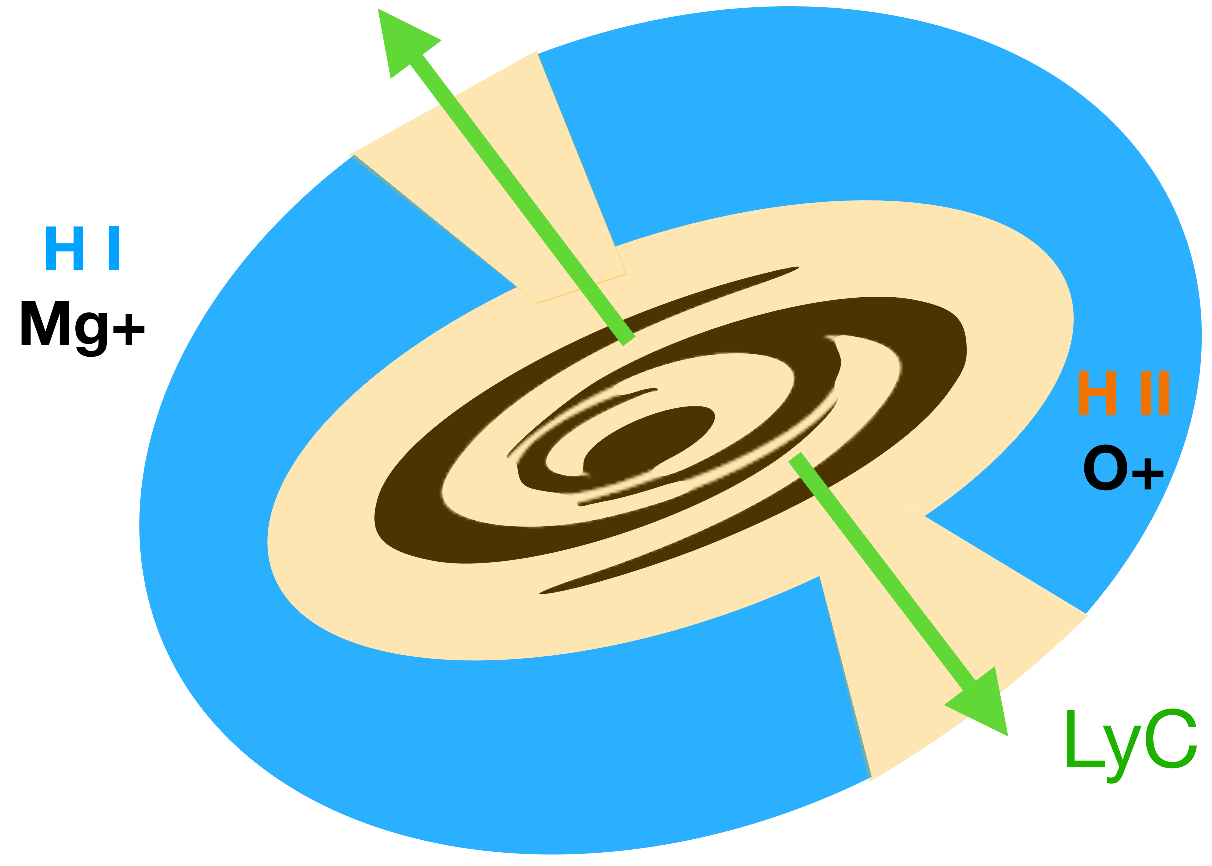


ionized channels in the ISM + CGM

Stellar populations ionizing most of the neutral gas in the ISM/CGM

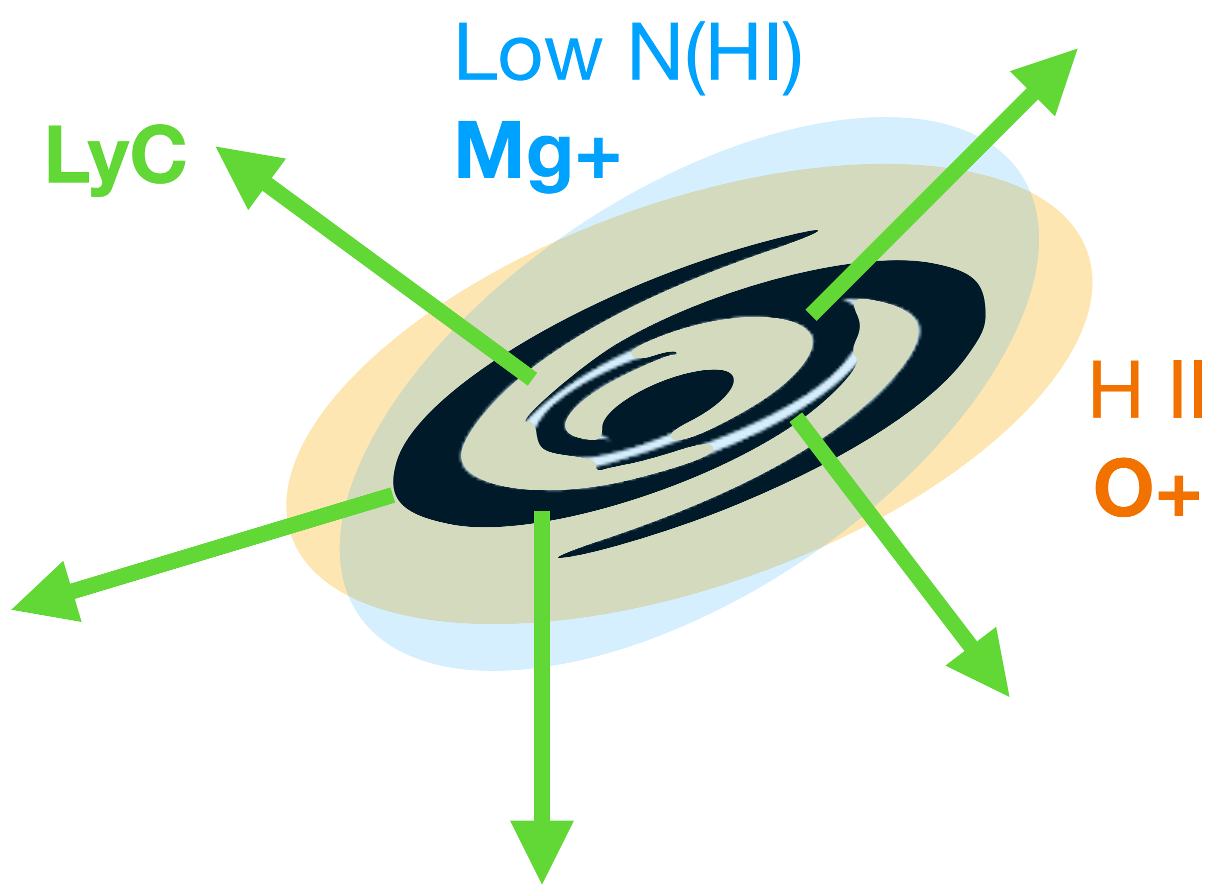
and

Powerful outflows and feedback effects clearing the galaxy surroundings

Leclercq et al. 2024

Different mechanisms for LyC escape

Highly ionized galaxies



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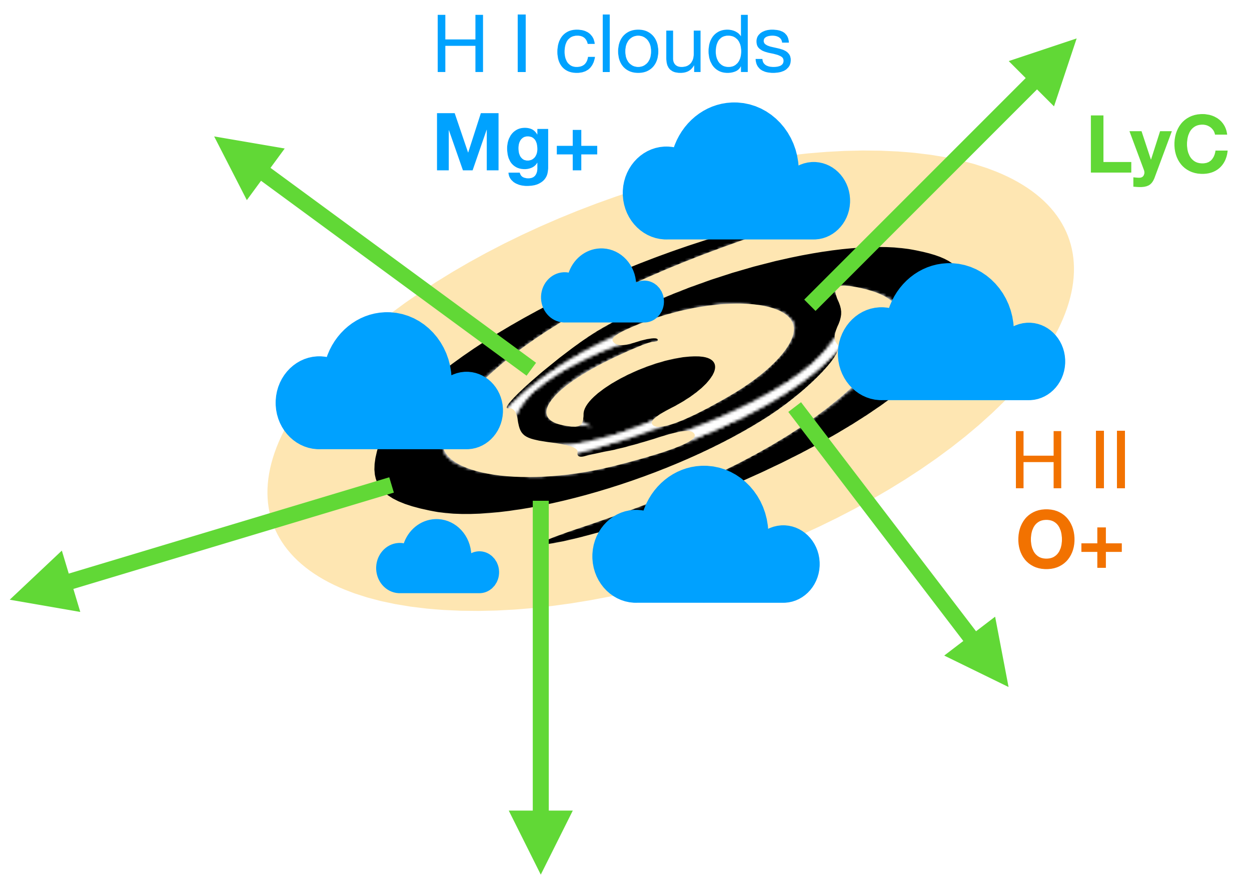

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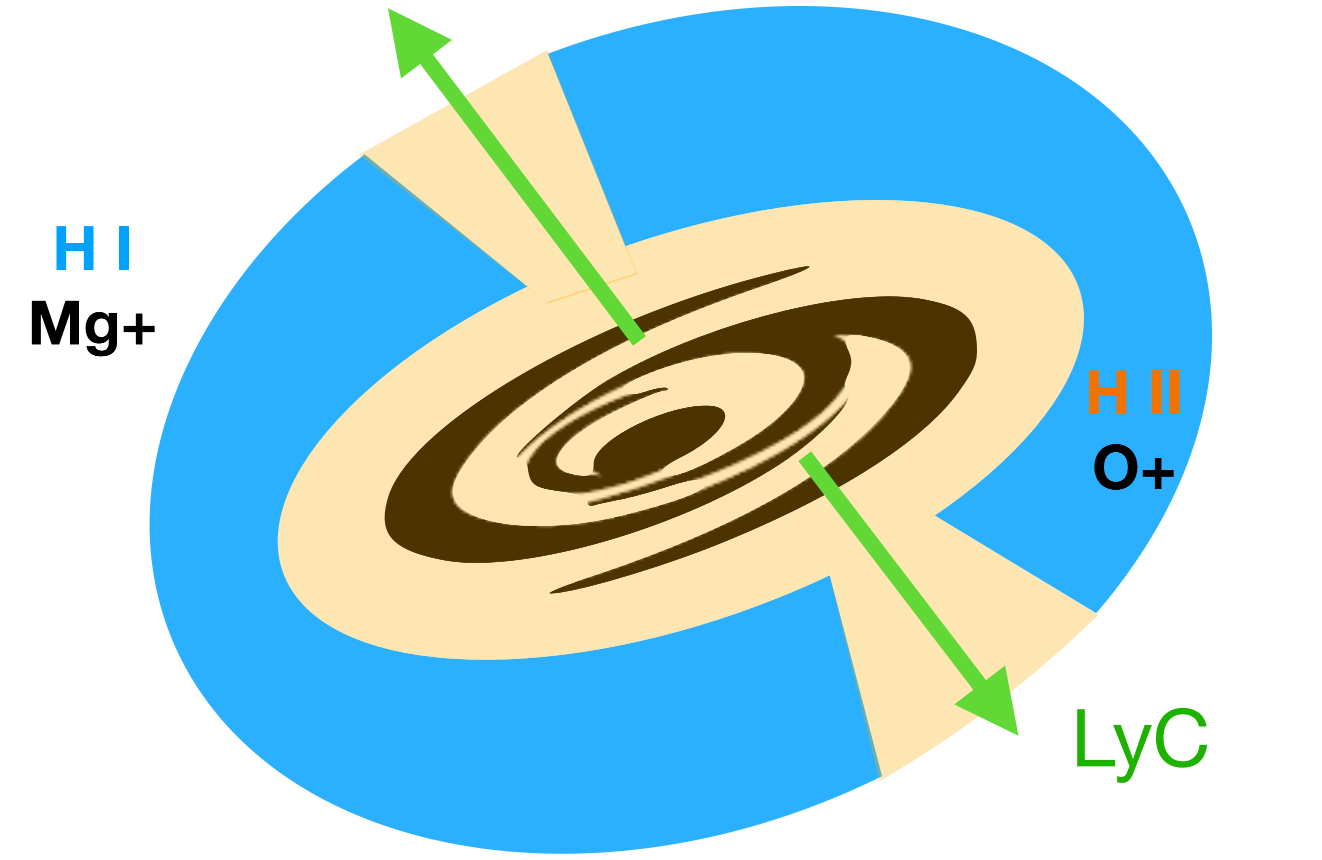

ionized channels in the ISM + CGM

Stellar populations ionizing most of the neutral gas in the ISM/CGM

and

Powerful outflows and feedback effects clearing the galaxy surroundings

Nebular spatial compactness + high ionization = indicators of LyC escape in high-redshift galaxies

Leclercq et al. 2024

Spatially resolved spectral analysis

Preliminary

Leclercq et al. in prep.

Spatially resolved spectral analysis

Preliminary

Sample: 12 objects with KCWI data

- [O II] : ionized gas kinematics
- Mg II : neutral gas kinematics
- Mg II flux ratio : predicted LyC fesc

Leclercq et al. in prep.

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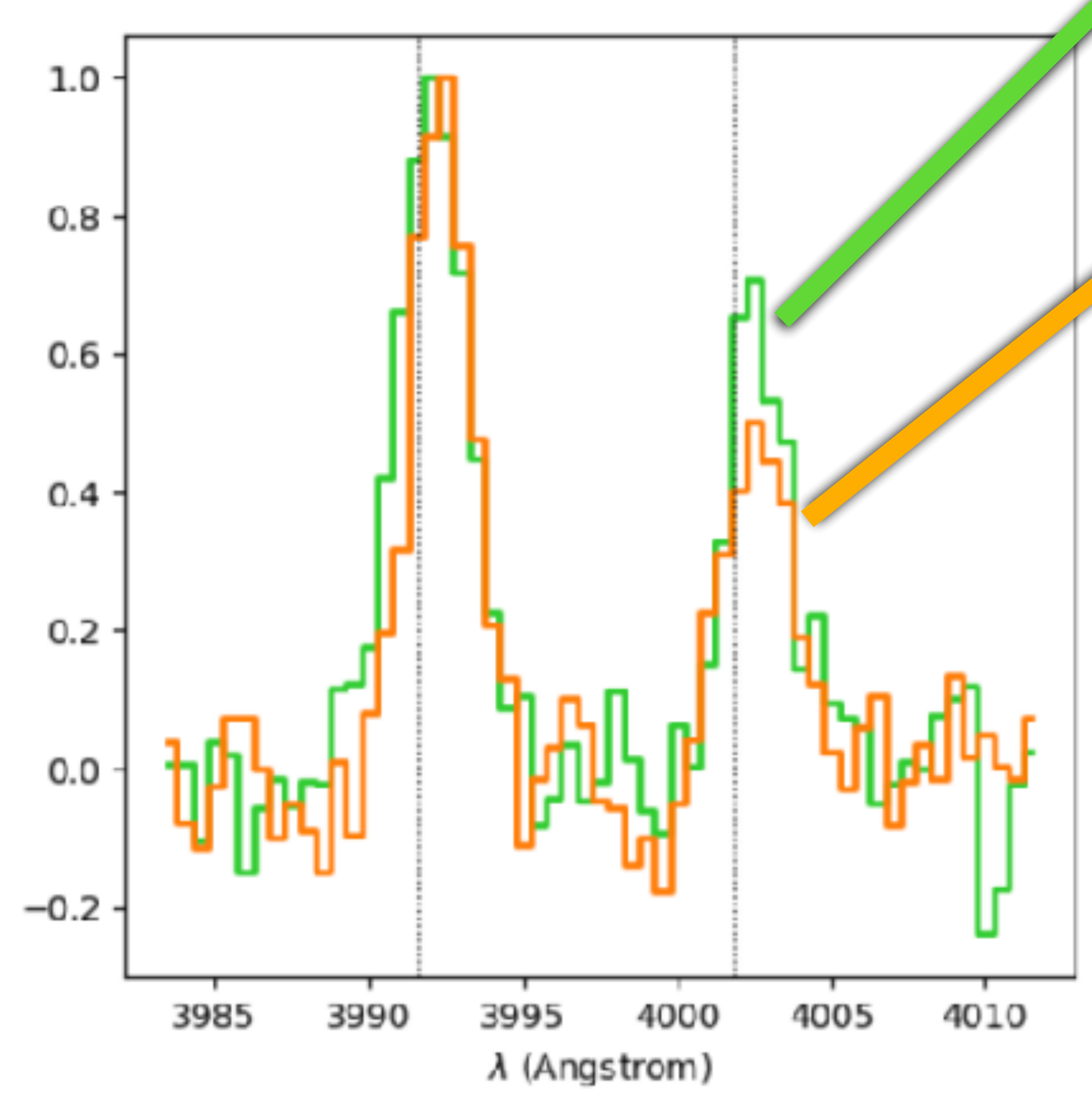

Leclercq et al. in prep.

Spatially resolved spectral analysis

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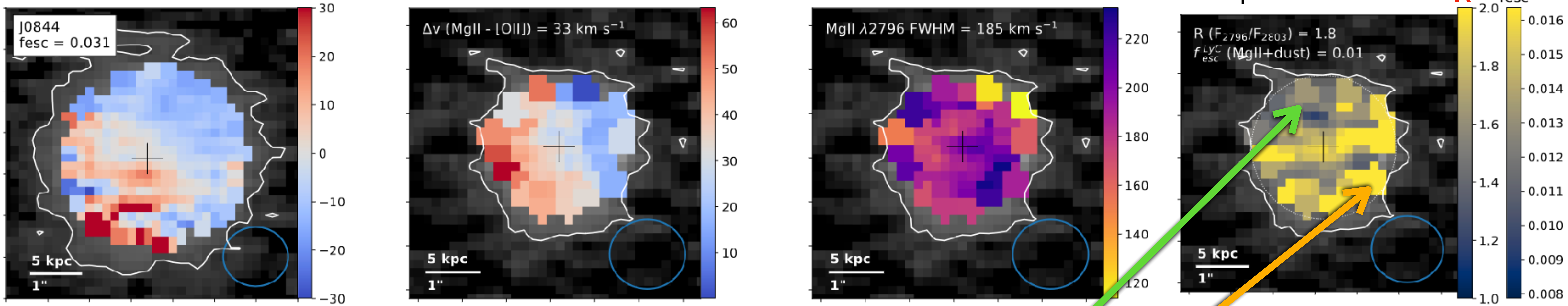
[O II] peak shift [km s^{-1}] | Mg II peak shift [km s^{-1}] | Mg II FWHM [km s^{-1}] | Mg II flux ratio + predicted fesc | R | Fesc predicted



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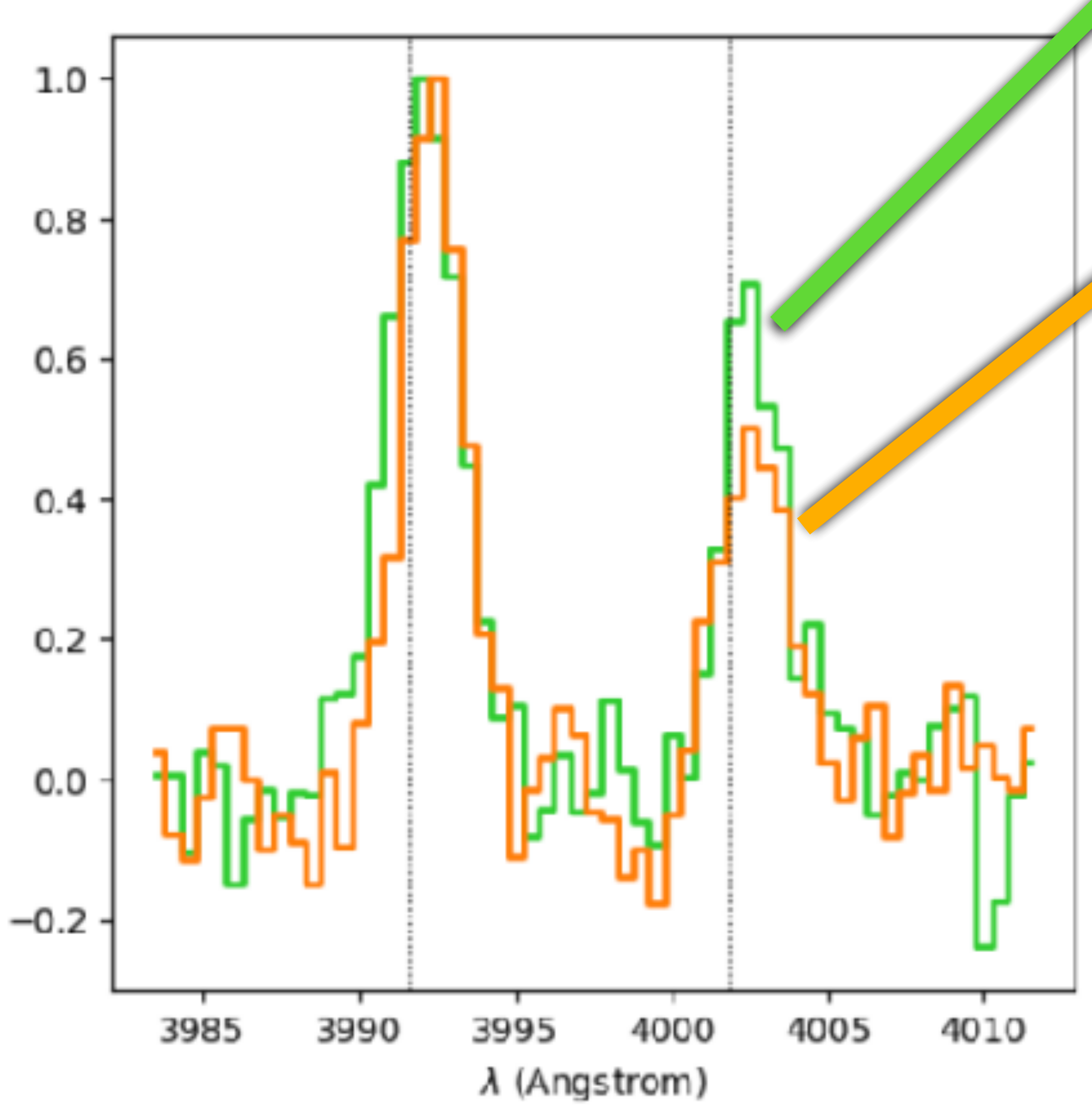


$$R = F_{2796}/F_{2803}$$

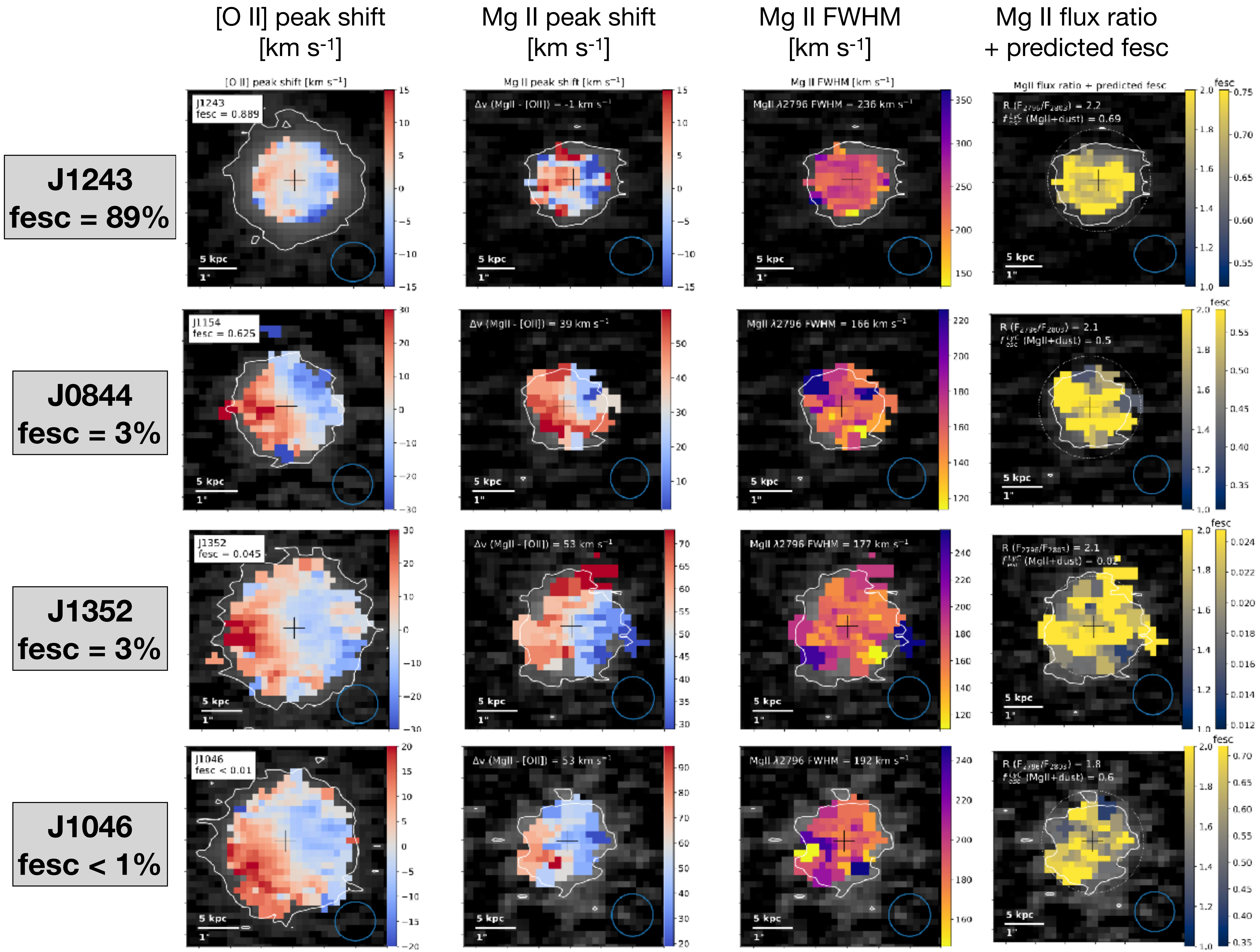
$$N_{\mathrm{H}^0} = 5.1 \times 10^5\ \mathrm{cm}^{-2}\ N_{\mathrm{Mg}^+} = -2.2 \times 10^{17}\ \mathrm{cm}^{-2} \ln{(R/2)}\,.$$

$$f_{\mathrm{esc}}\,(\mathrm{LyC}) = e^{-N_{\mathrm{H}^0}\sigma_{\mathrm{ph}}} \times 10^{-0.4E(B-V)k(912)}$$

Leclercq et al. in prep.

Chisholm et al. 2020

Spatially resolved spectral analysis



- [O II] velocity gradient <u>in both leakers and non-leakers</u>
- Mg II velocity gradient consistent with [O II] but shifted toward higher values (+40 km/s)
- Spatial variations in the doublet spectral properties

➜ spatial variations of LyC escape

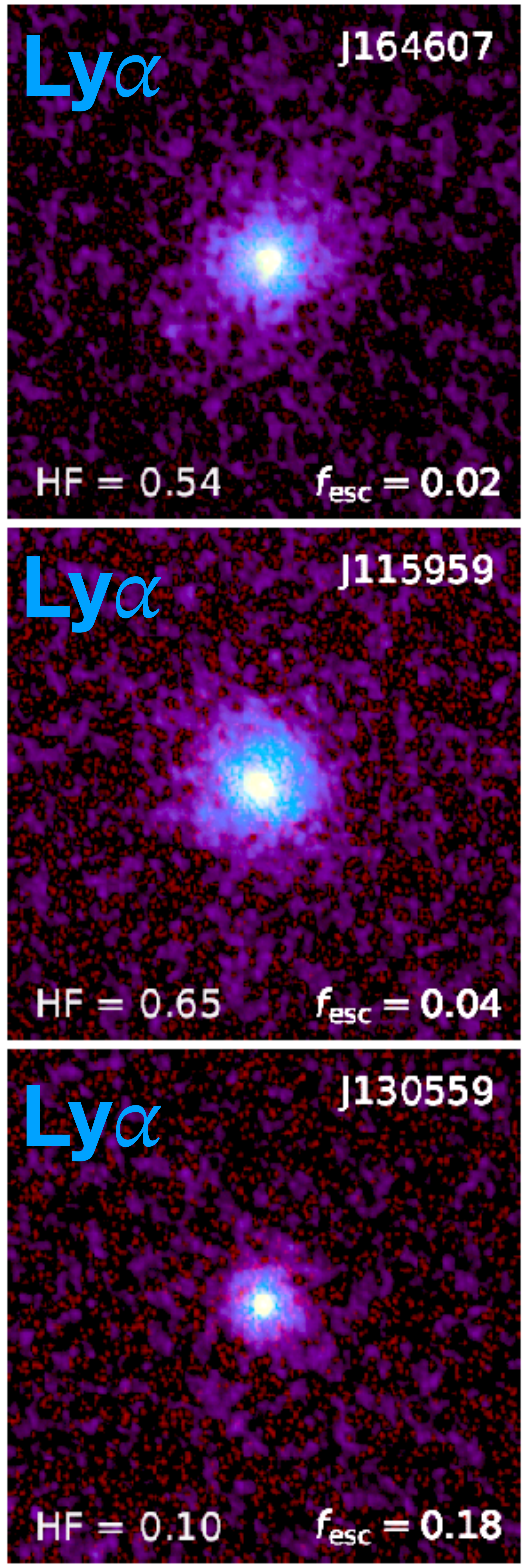
Leclercq et al. in prep.

Lyα mapping of 41 LzLCS galaxies

The **LaCOS** survey: Lyman Alpha and Continuum Origins Survey

Alexandra's talk

Lyα mapping of 41 LzLCS galaxies



THE **LACOS** SURVEY: LYMAN ALPHA AND CONTINUUM ORIGINS SURVEY

Alexandra's talk

Saldana-Lopez et al. in prep., Le Reste et al. subm.

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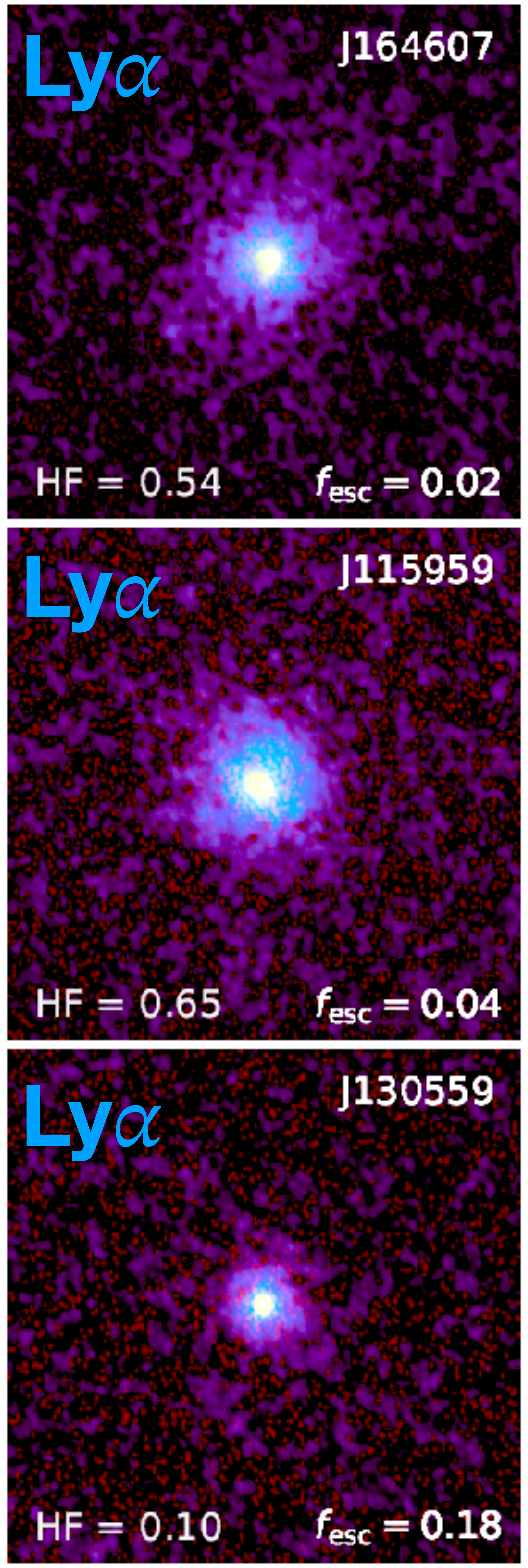

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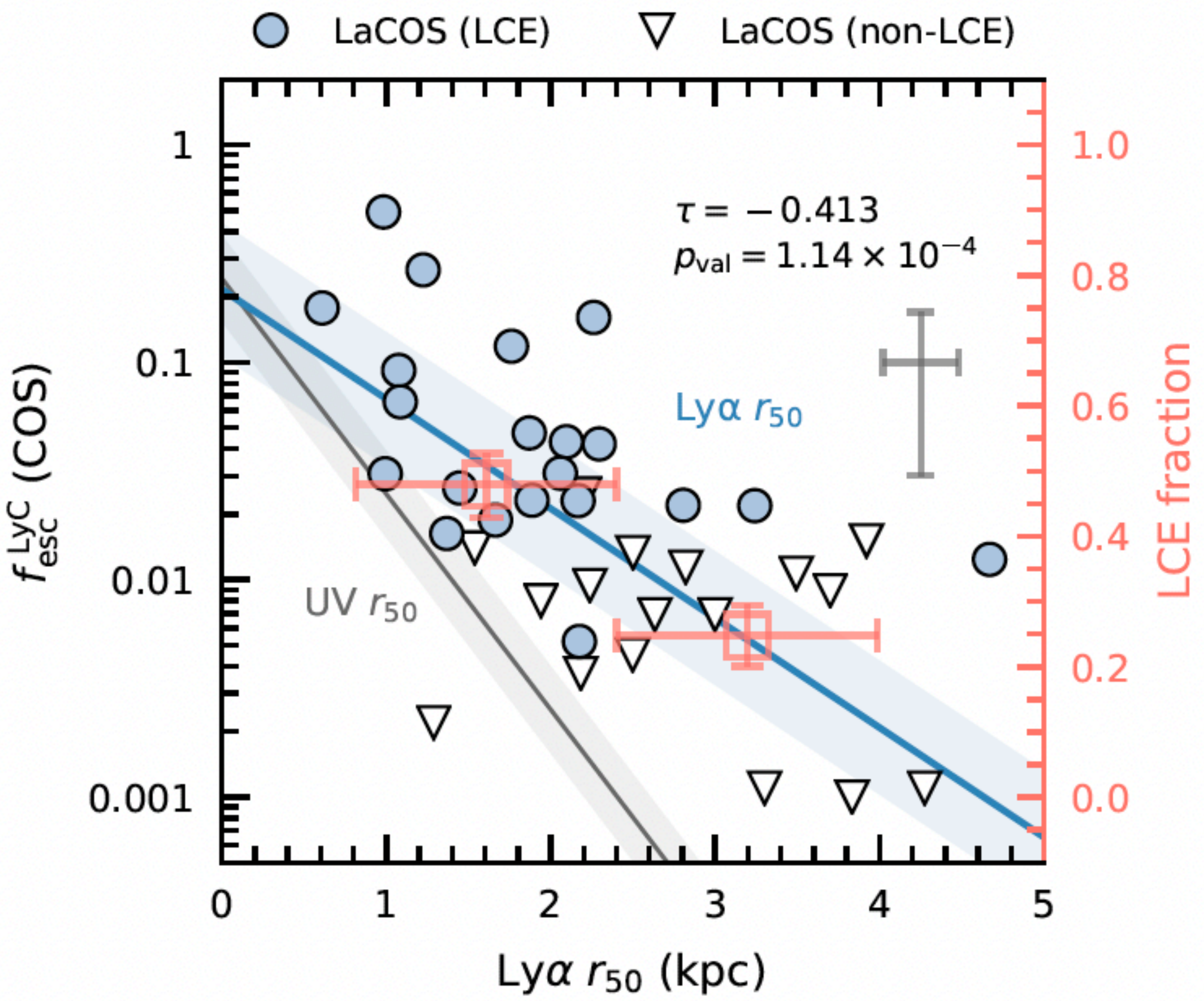
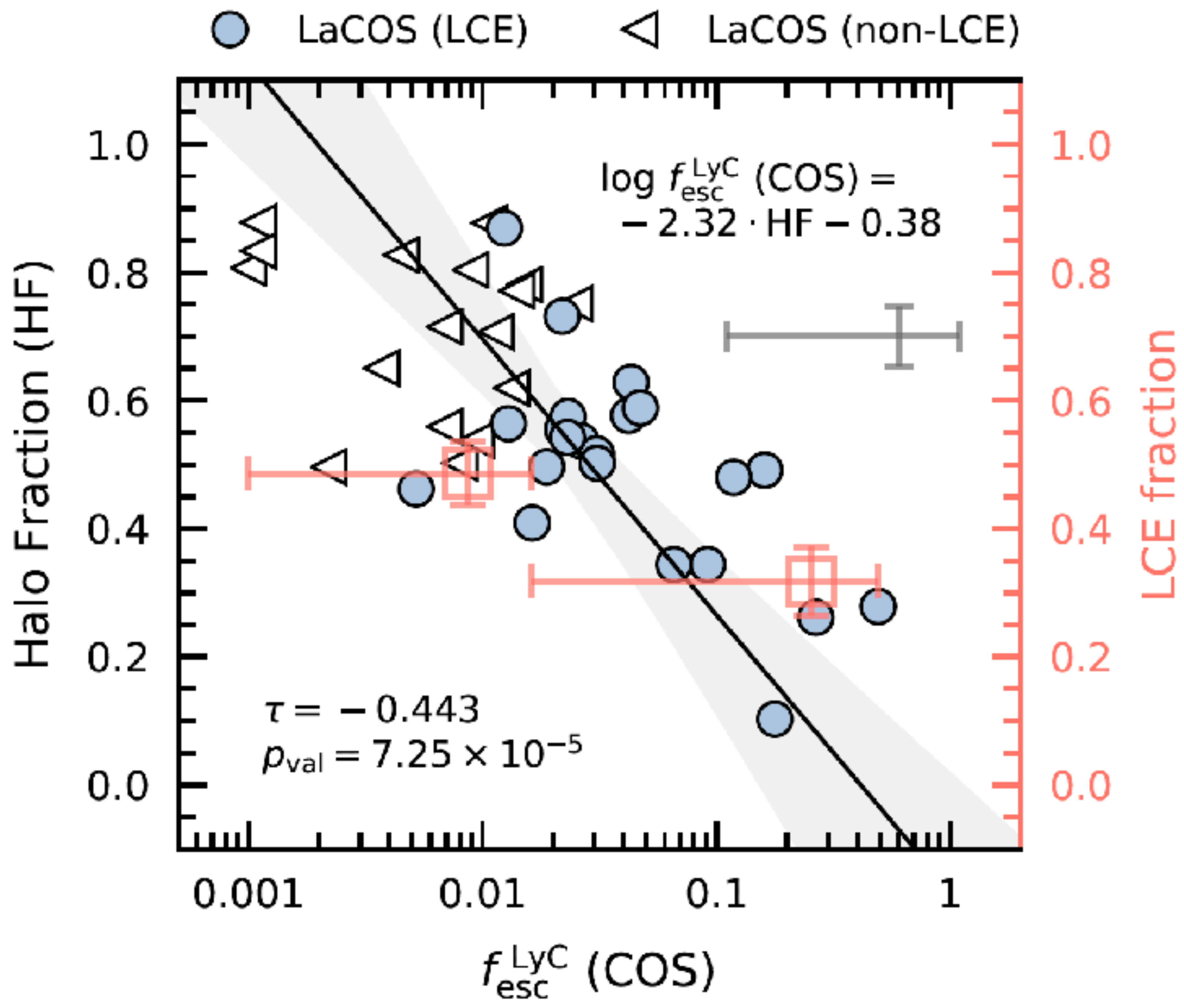




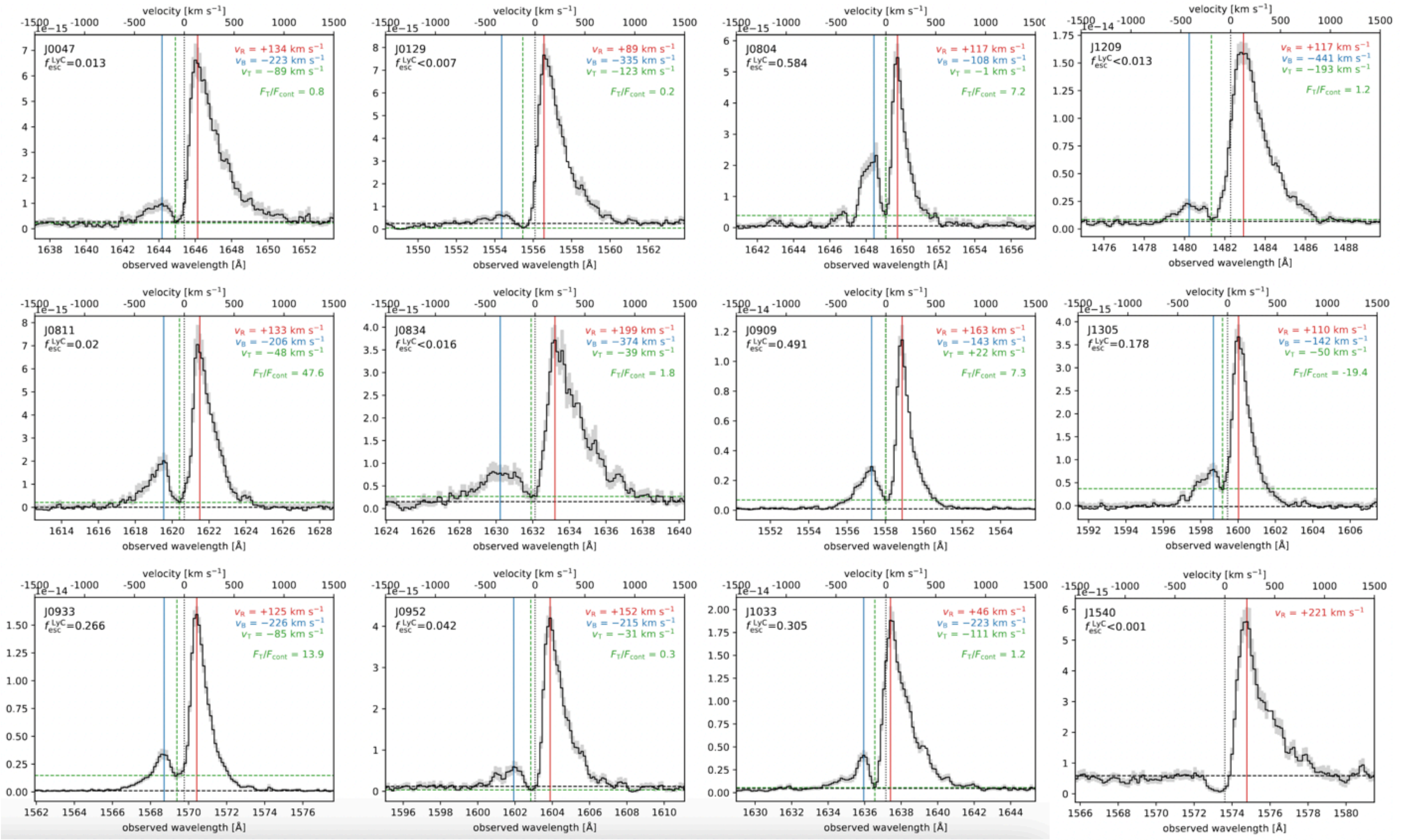
LyC emitters have more compact Lyα morphologies than non-LCEs

➜ *Good agreement with MgII study <u>but not the same sample</u>*

Saldana-Lopez et al. in prep., Le Reste et al. subm.

High resolution Lyα spectra of LyC leakers

Medium HST/COS program — PI: Leclercq — 49 orbits —> **15 LzLCS galaxies**



+ 27 archival objects

Henry et al. 2015,
Yang et al. 2017a,
Izotov et al. 2016a,b
Izotov et al. 18a,b
Izotov et al. 2021,

- 6 HST/COS programs

- Same data reduction
- Same spectral binning
- Same measurements

Leclercq et al. in prep.

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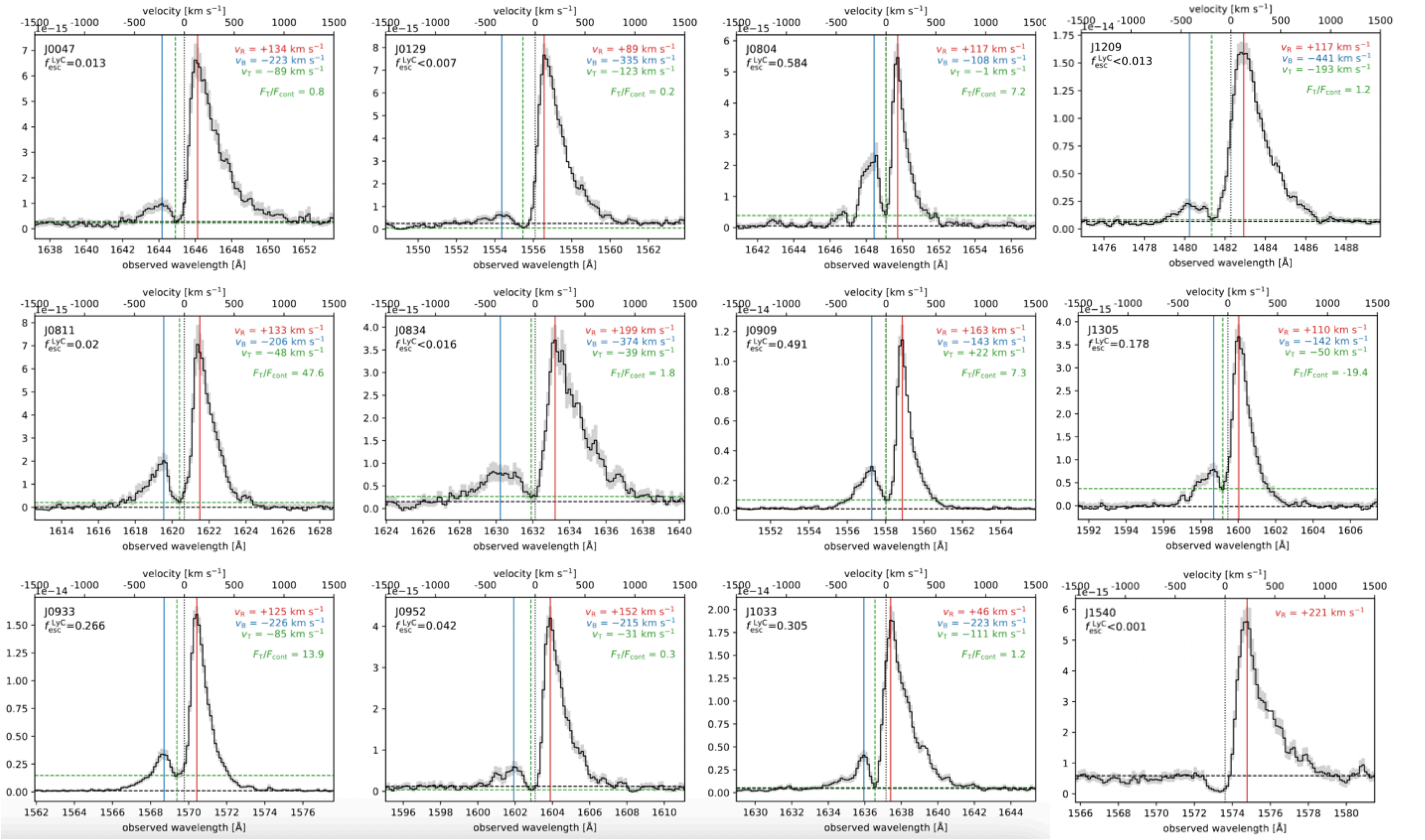

- 6 HST/COS programs

- Same data reduction
- Same spectral binning
- Same measurements

➜ First homogenous and statistical sample of **42 galaxies with high-res LyA spectra**

Leclercq et al. in prep.

Connecting LyC escape with LyA spatial and spectral properties

Preliminary

➡ **16** LzLCS galaxies with **both spatial and spectral LyA** observations

Leclercq et al. in prep.

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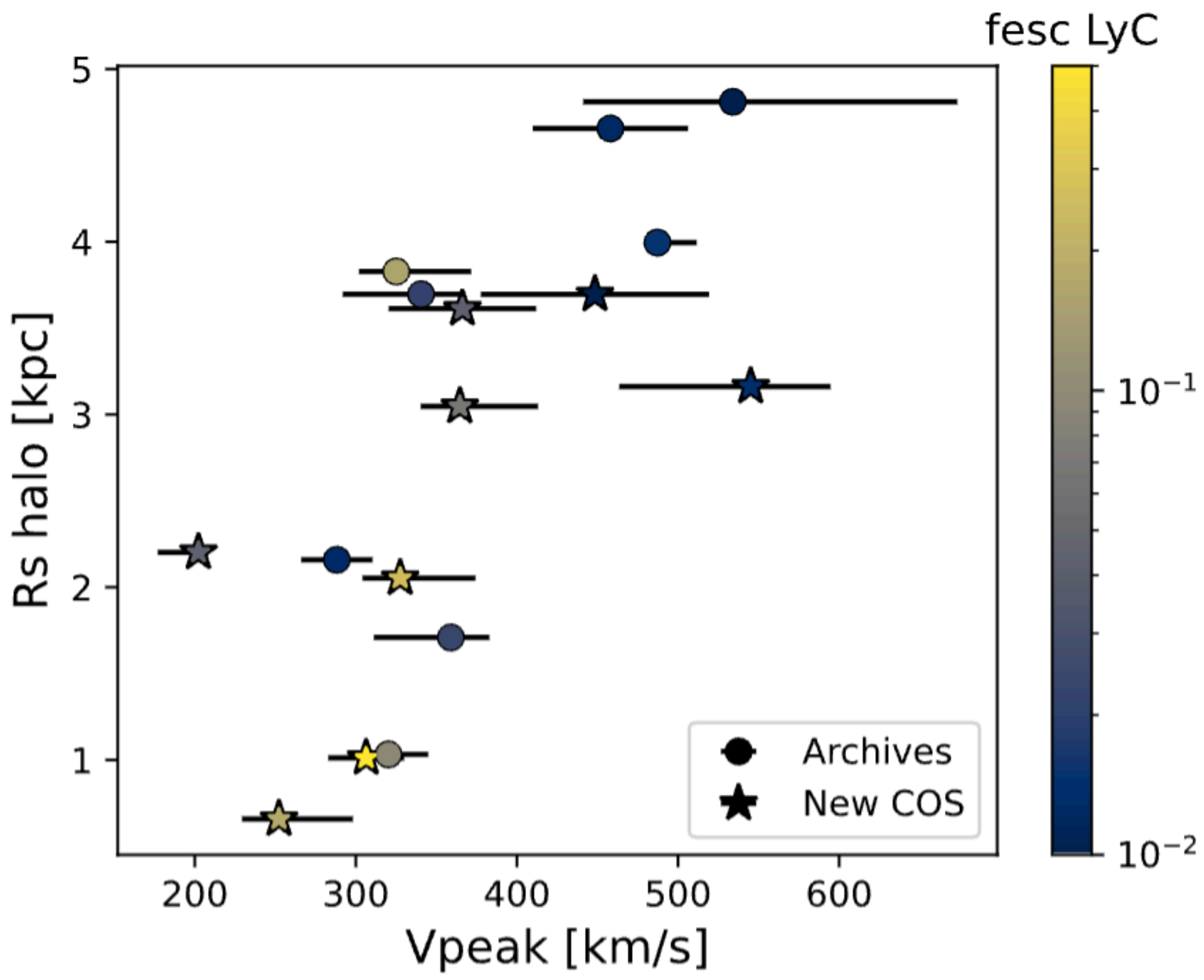


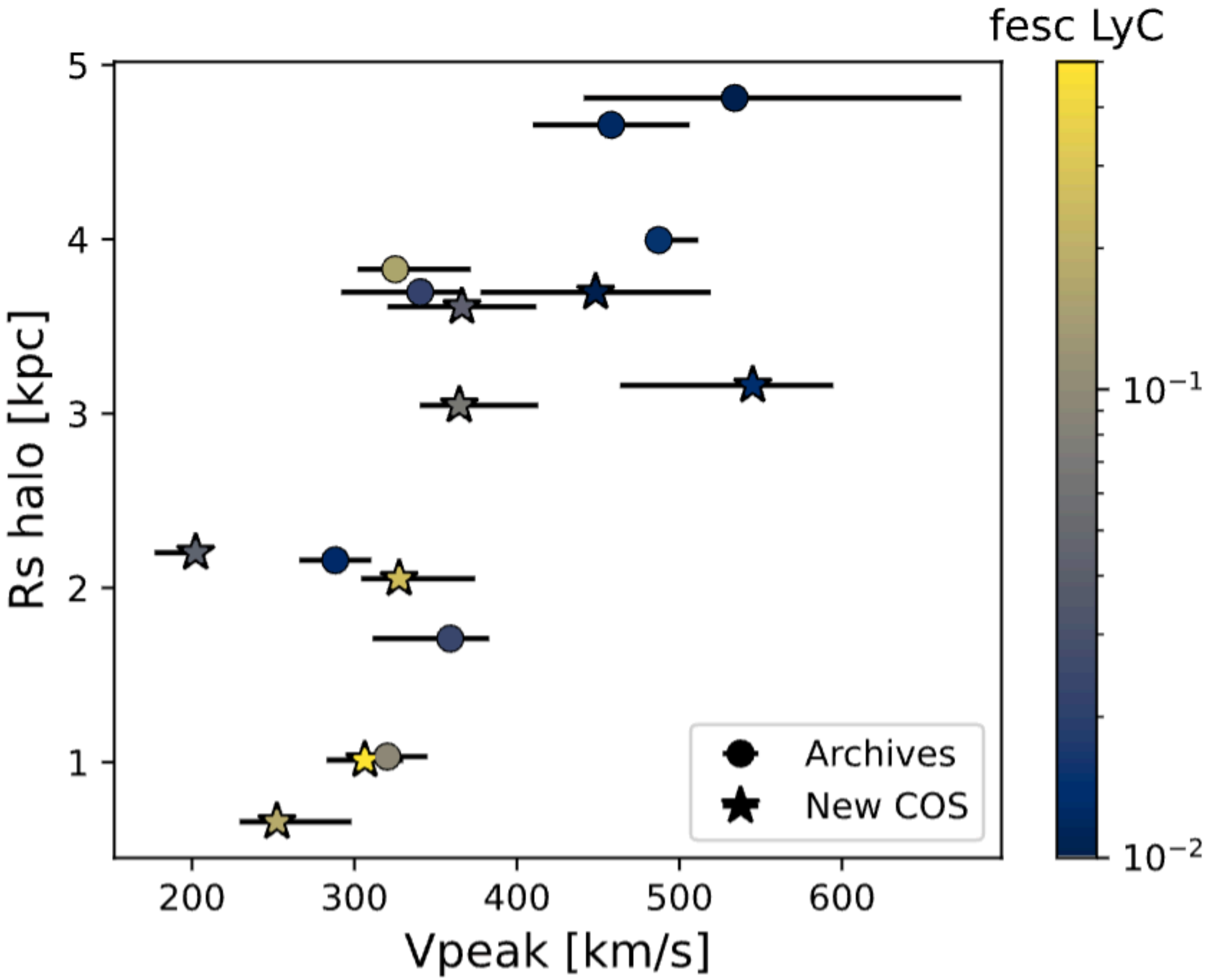
- LAH size and peak separation correlate
- Strong LCEs are more compact in LyA and have smaller peak separation

Leclercq et al. in prep.

Connecting LyC escape with LyA spatial and spectral properties

Preliminary

➡ **16** LzLCS galaxies with **both spatial and spectral LyA** observations

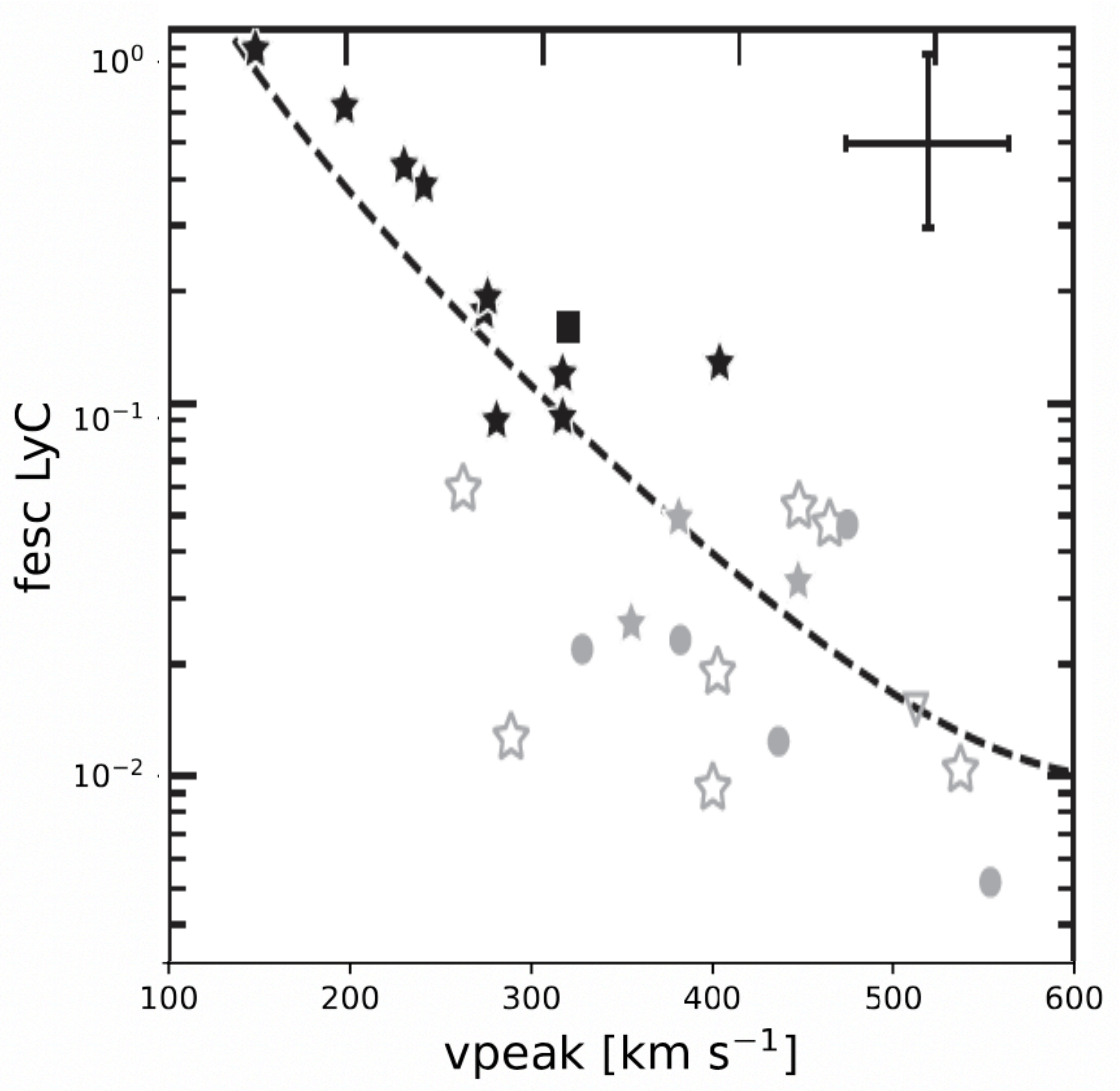


- LAH size and peak separation correlate
- Strong LCEs are more compact in LyA and have smaller peak separation

It's now possible to link **LyC** escape with both **Lya** spectral and spatial properties in **statistical sample**

Leclercq et al. in prep.

Updating the LyC fesc – LyA Vpeak relation



Flury et al. 2022b, Leclercq et al. in prep.

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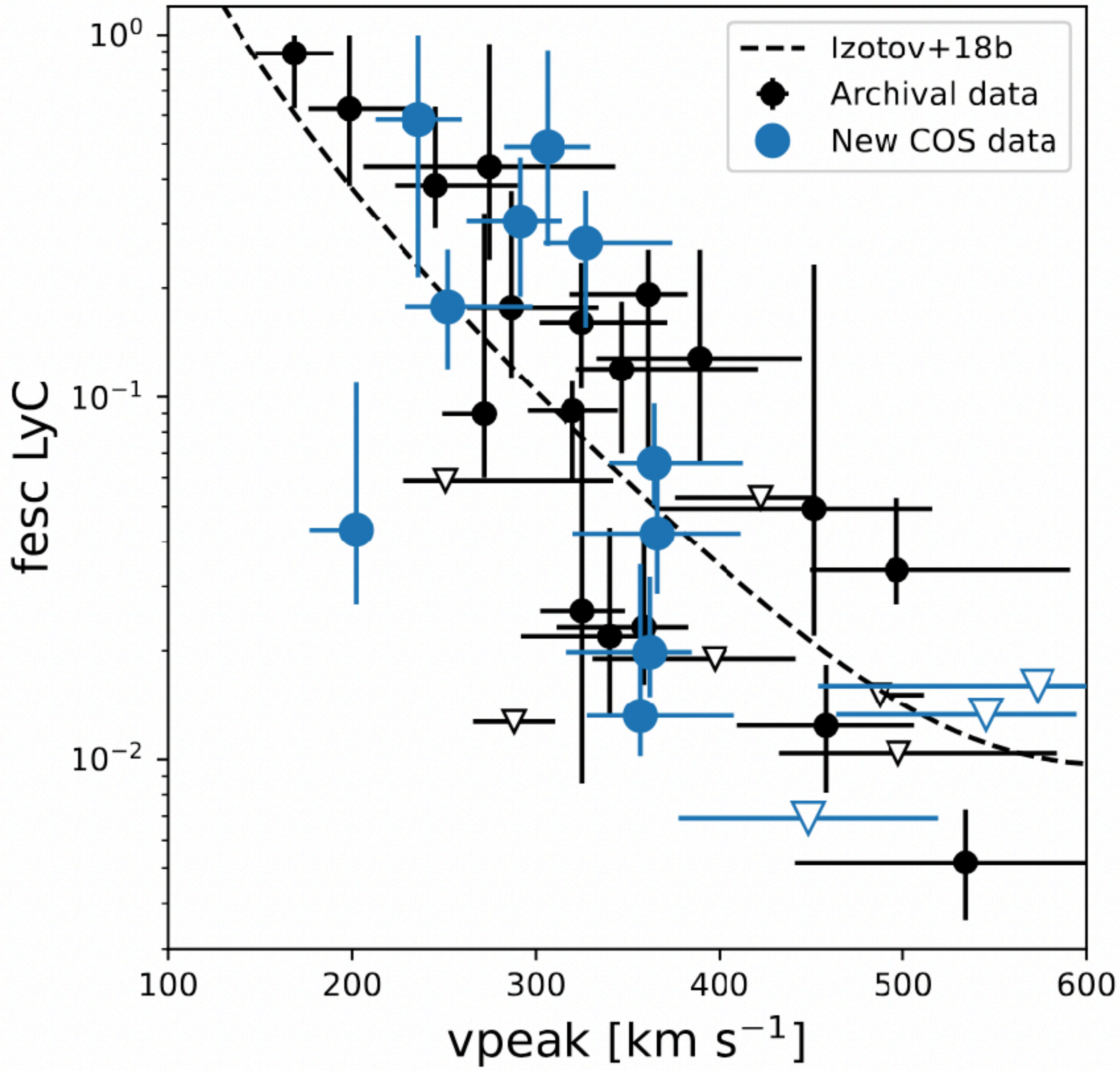

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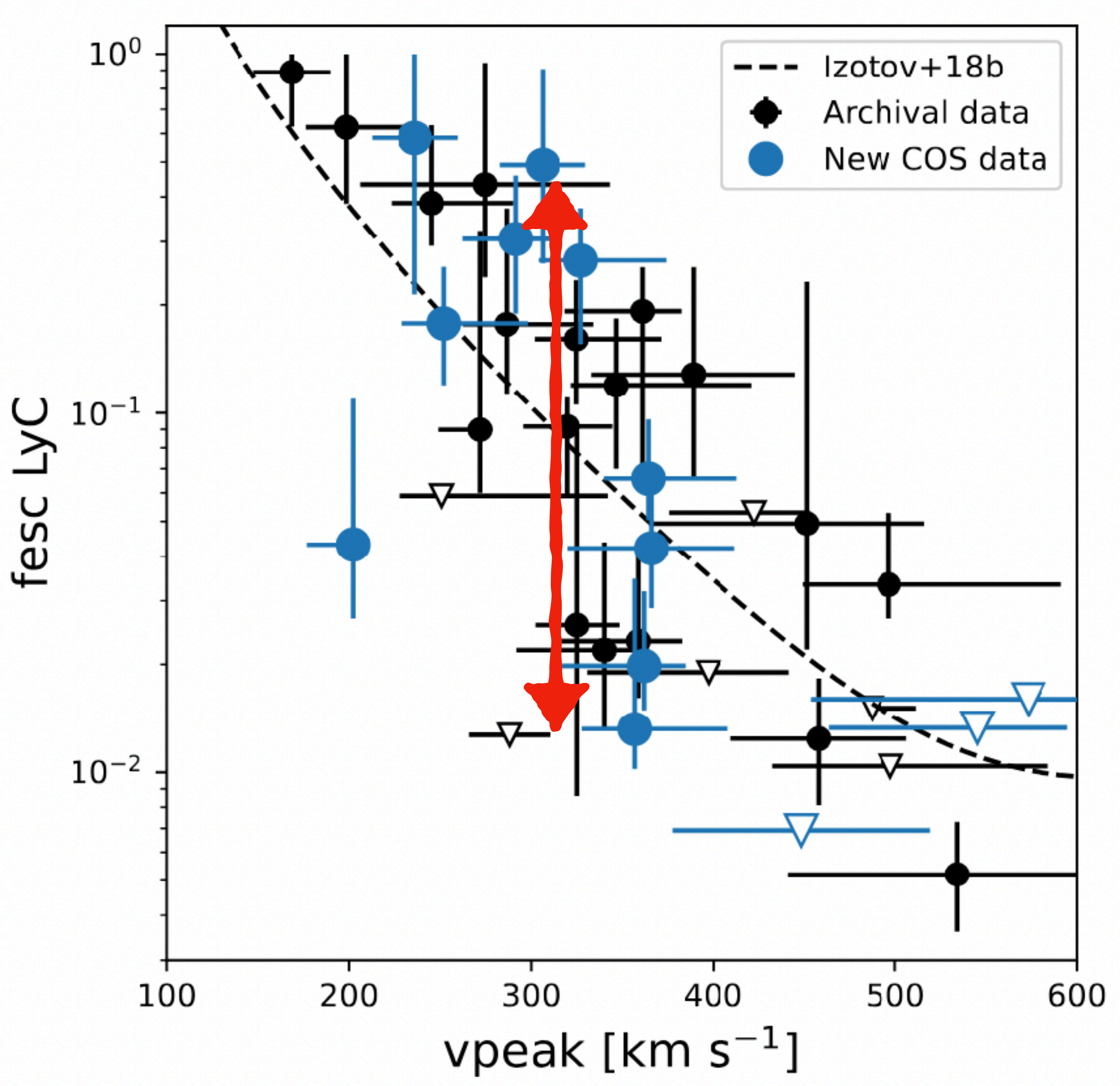


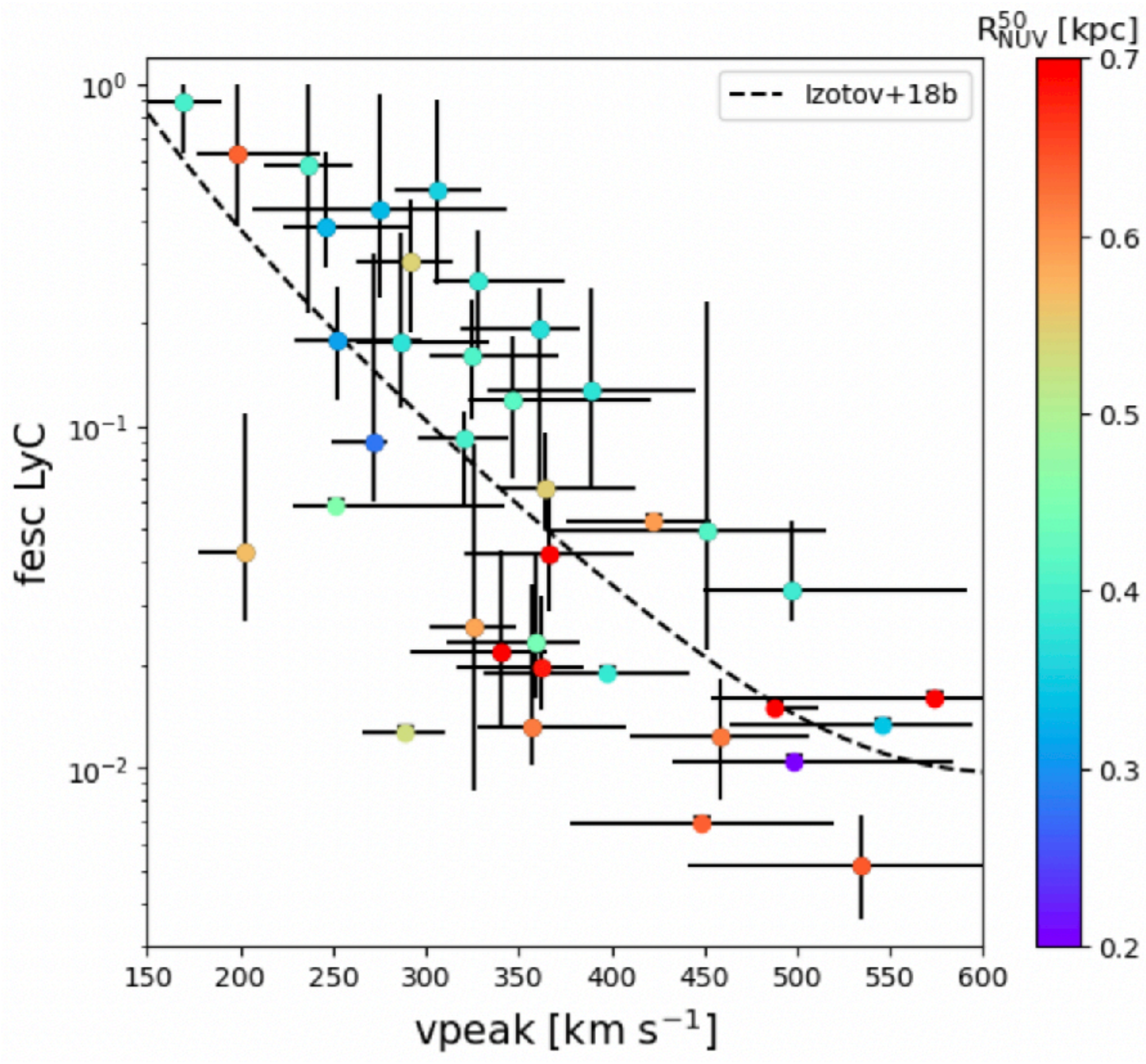
➜ correlation between fesc(LyC) and Lyman alpha peak separation holds

➜ Scatter increased at vpeak ~ 300 km/s

Is the scatter due to secondary parameters ?

Flury et al. 2022b, Leclercq et al. in prep.

Understanding the scatter in the LyC fesc – LyA Vpeak relation



Leclercq et al. in prep.

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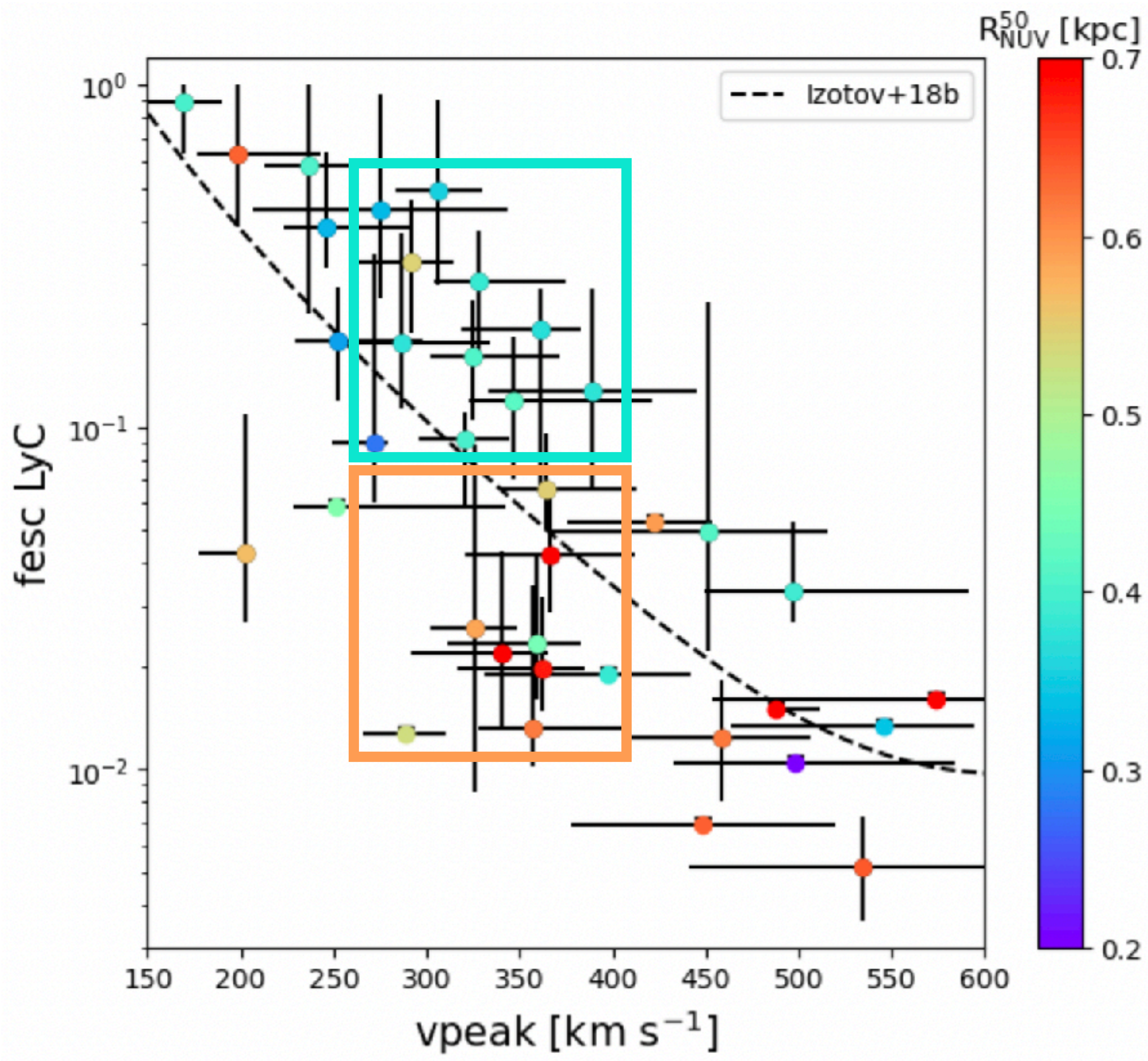

For vpeak = [250 - 400] km/s :

$R_{UV} \lesssim$ 0.5 kpc ➜ fesc(LyC) $\gtrsim$ 8 %

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Our results suggest that the scatter is driven by the **galaxy UV size**

Leclercq et al. in prep.

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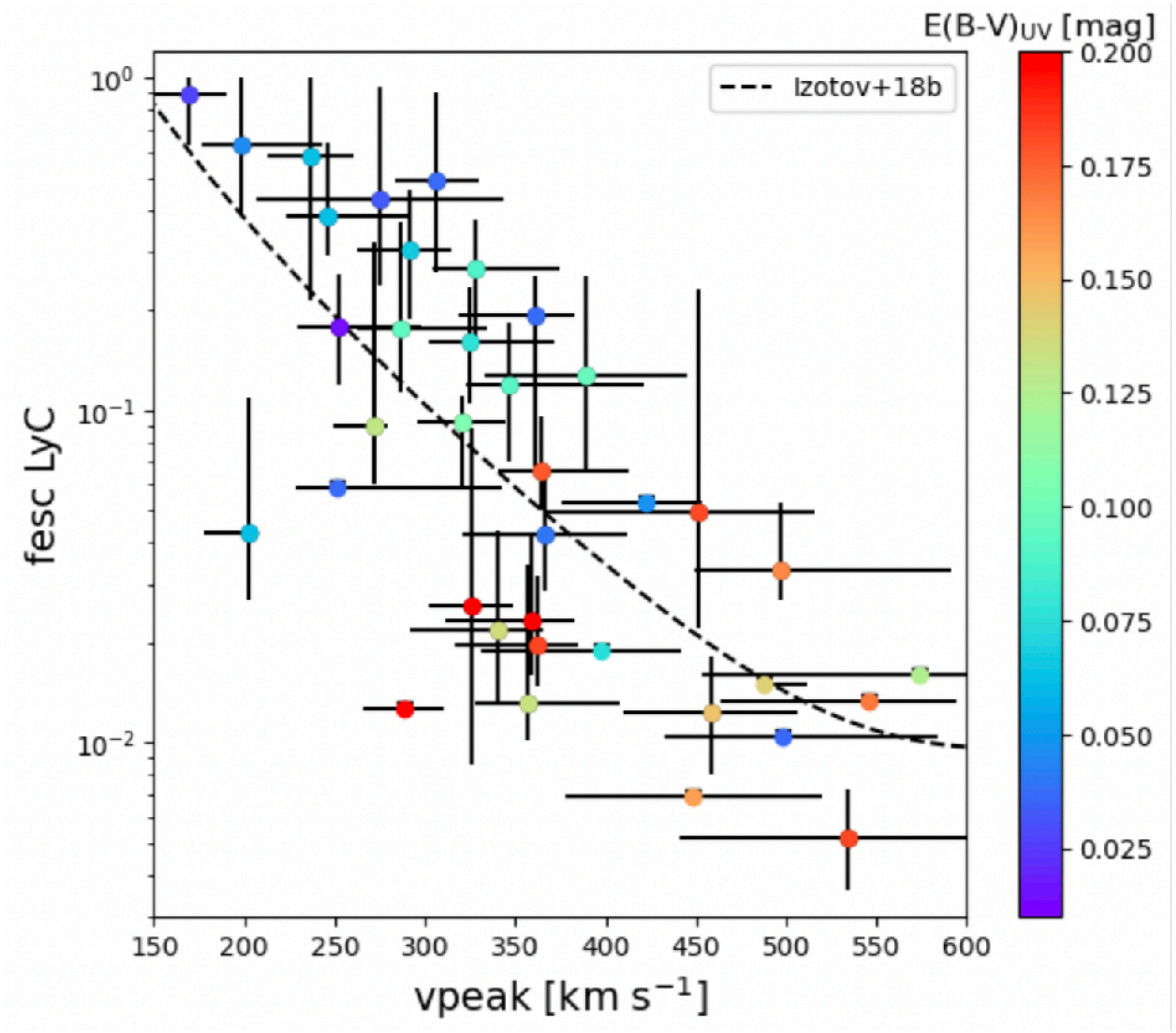

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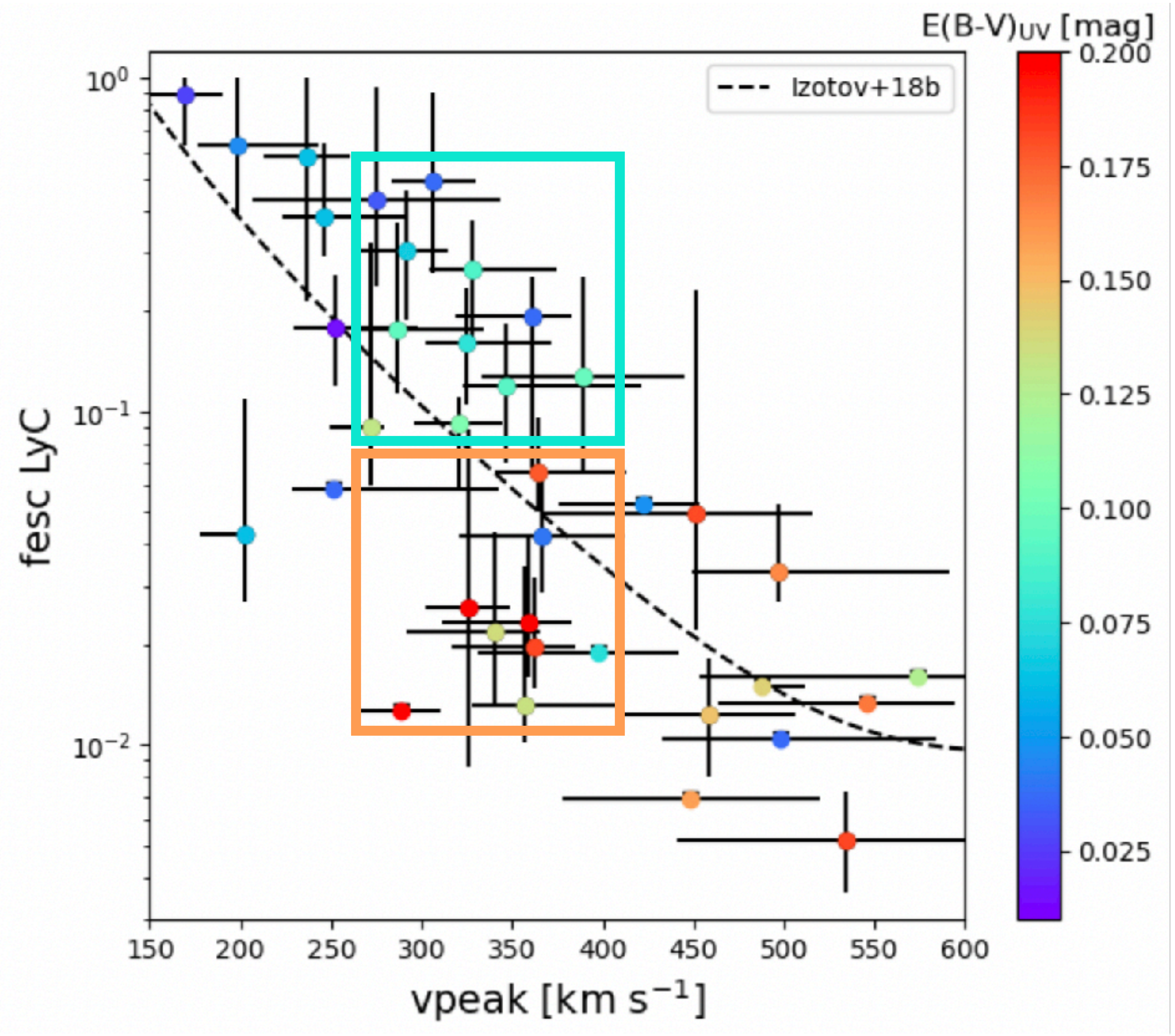

For vpeak = [250 - 400] km/s :

E(B-V) ≲ 0.1 mag ➜ fesc(LyC) ≳ 5%

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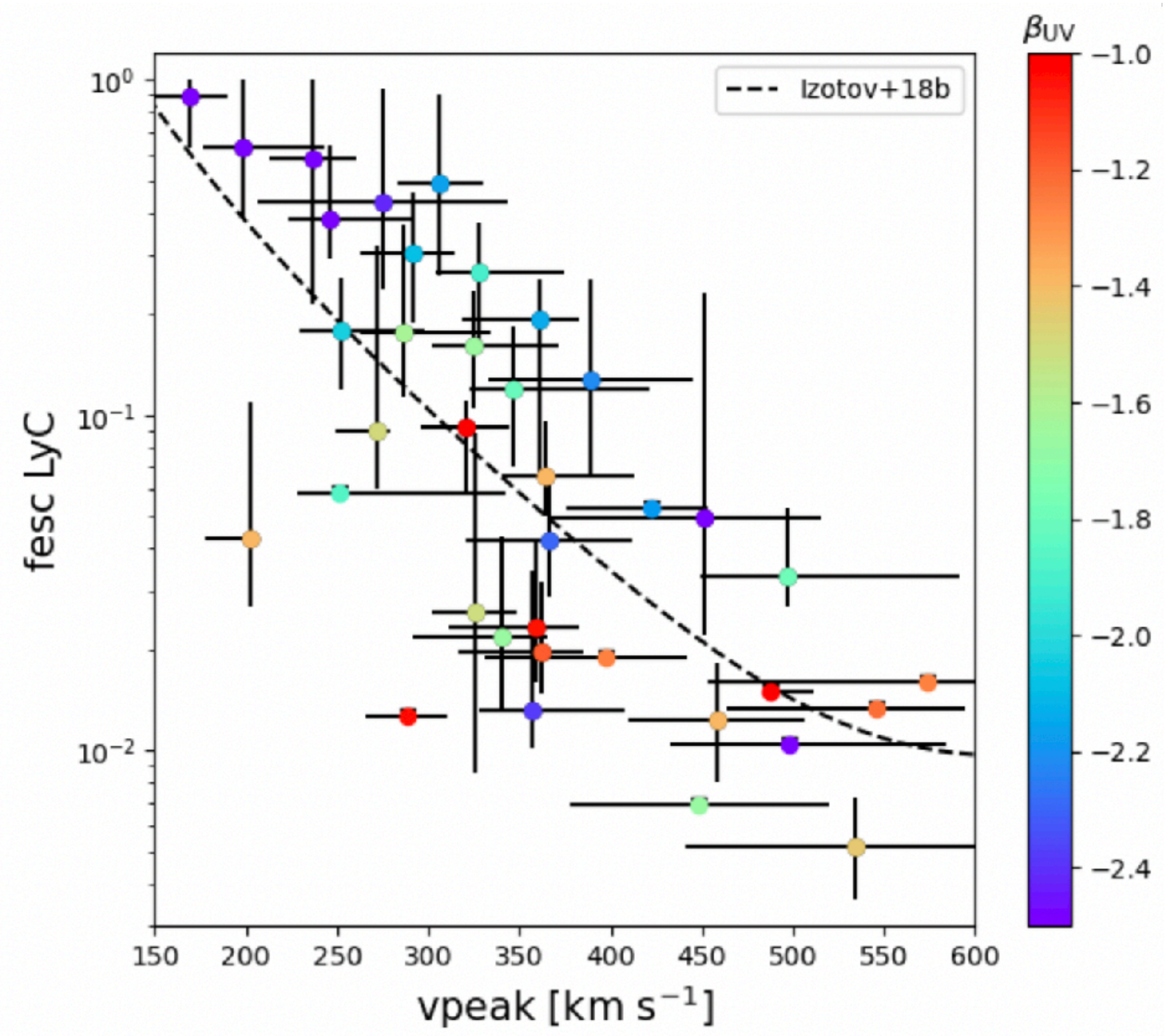
Our results suggest that the scatter is driven by the **dust extinction**

Leclercq et al. in prep.

Understanding the scatter in the LyC fesc – LyA Vpeak relation



Leclercq et al. in prep.

No obvious trends seen with other parameters…

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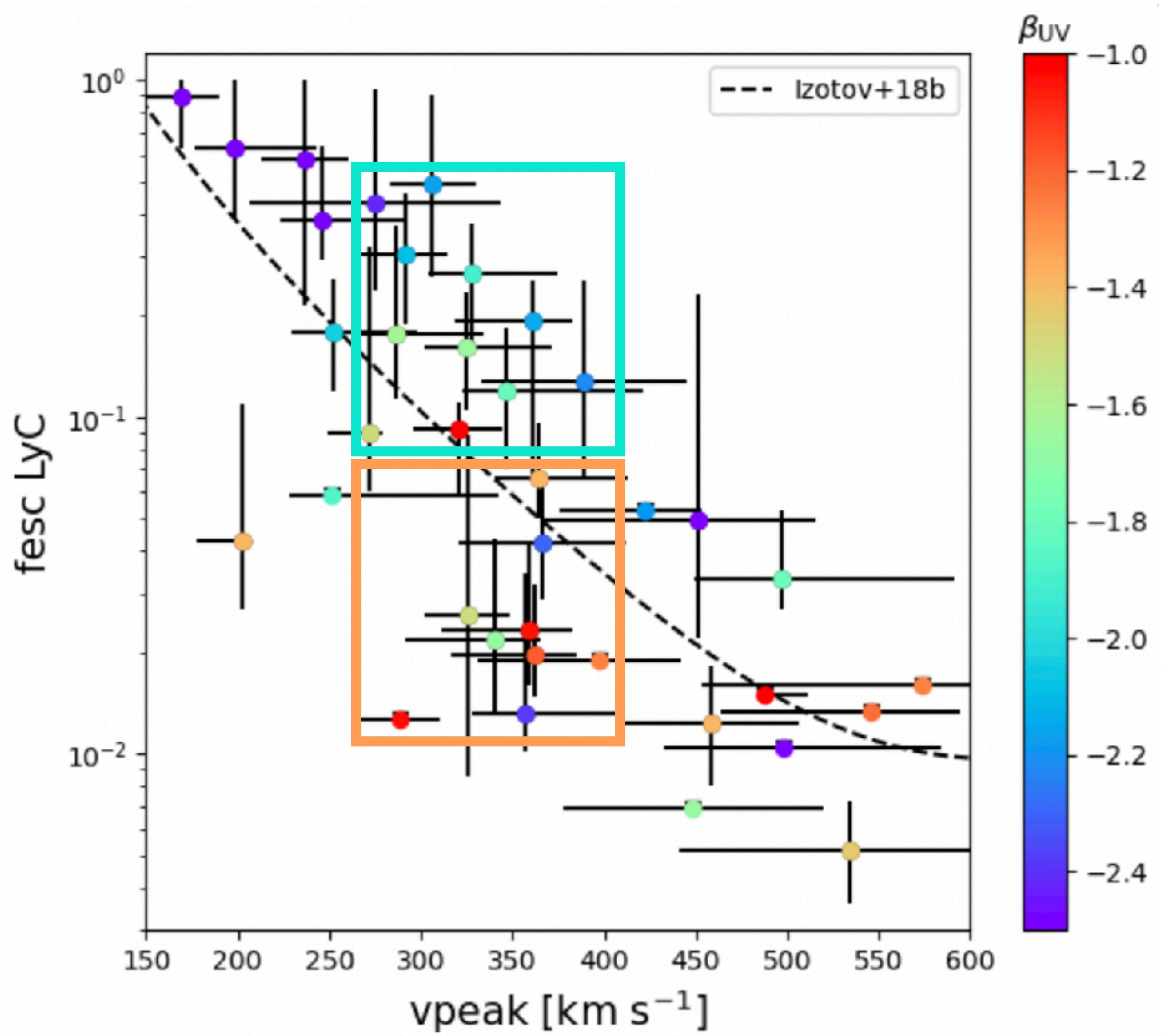


For LyA vpeak = [250 - 400] km/s bin :

β slope ≲ - 1.8 ➜ fesc(LyC) ≳ 5%

β slope ≳ - 1.5 ➜ fesc(LyC) ≲ 5%

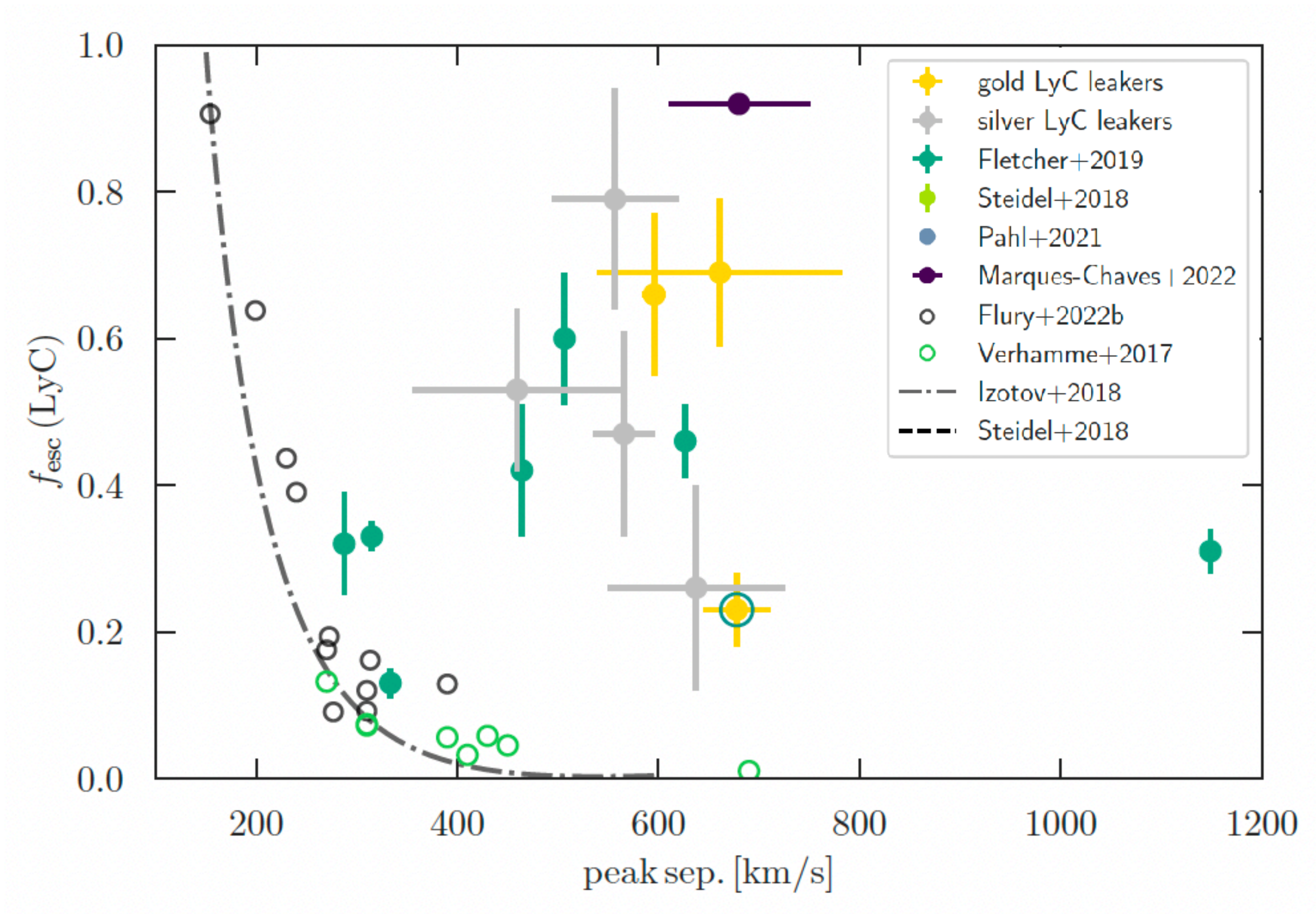
The scatter can also be due to the UV beta slope

LyA peak separation + UV size + dust = refining of the fesc(LyC) prediction

Leclercq et al. in prep.

No obvious trends seen with other parameters…

The LyC fesc – LyA Vpeak relation at high z



Kerutt et al. 2024

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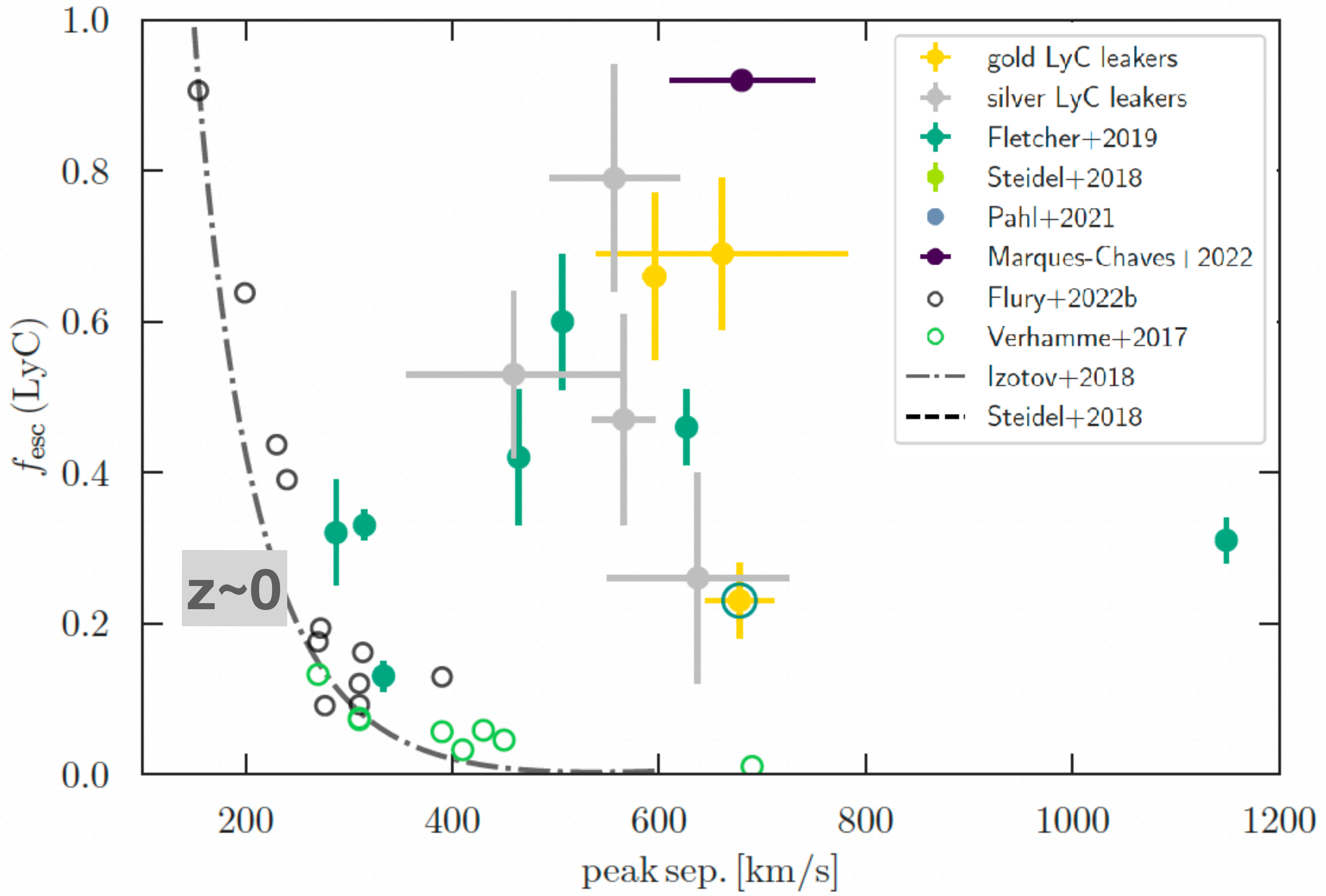

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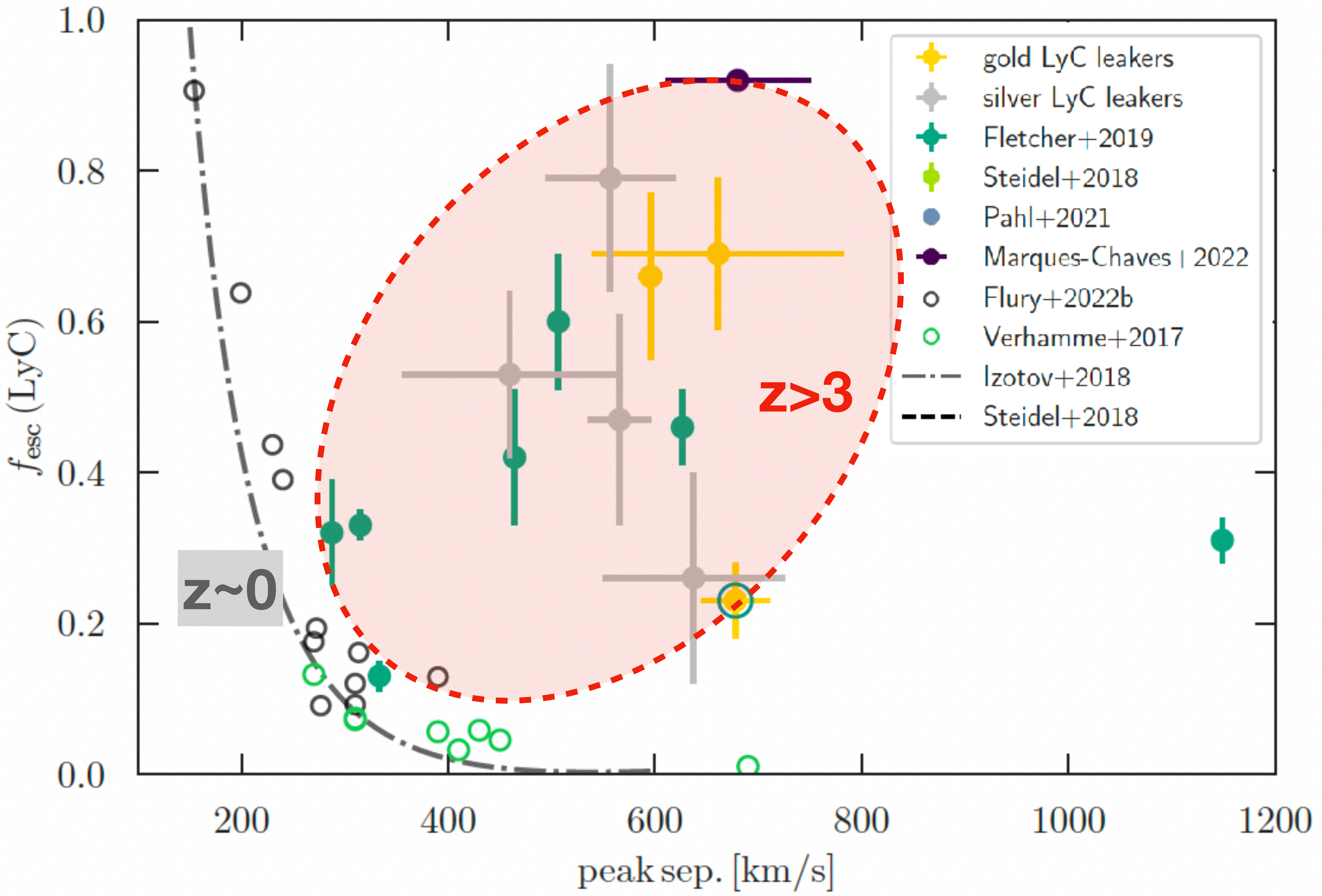

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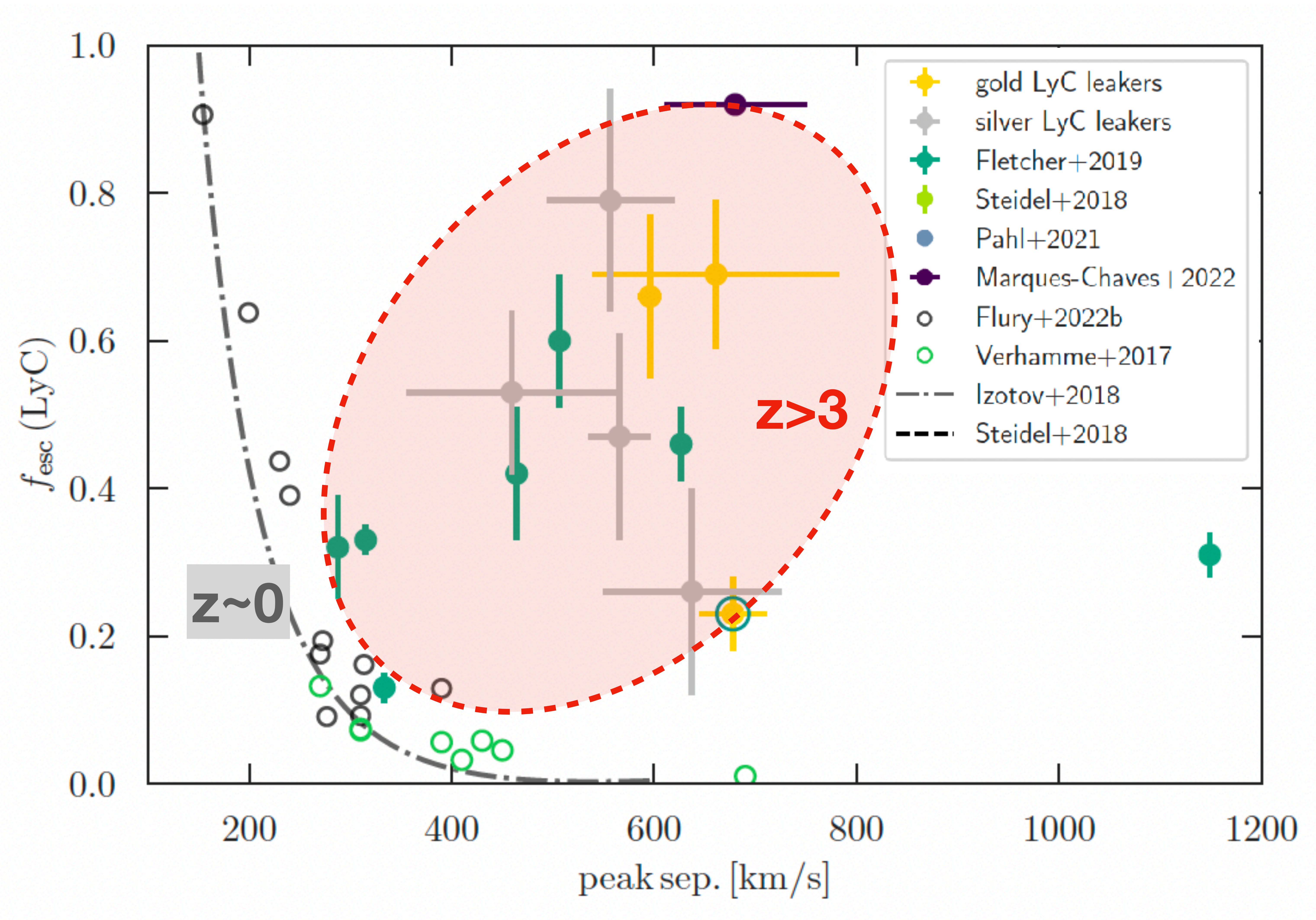


Redshift evolution
or selection effects ?

Need larger and non-biaised samples at all z

Kerutt et al. 2024

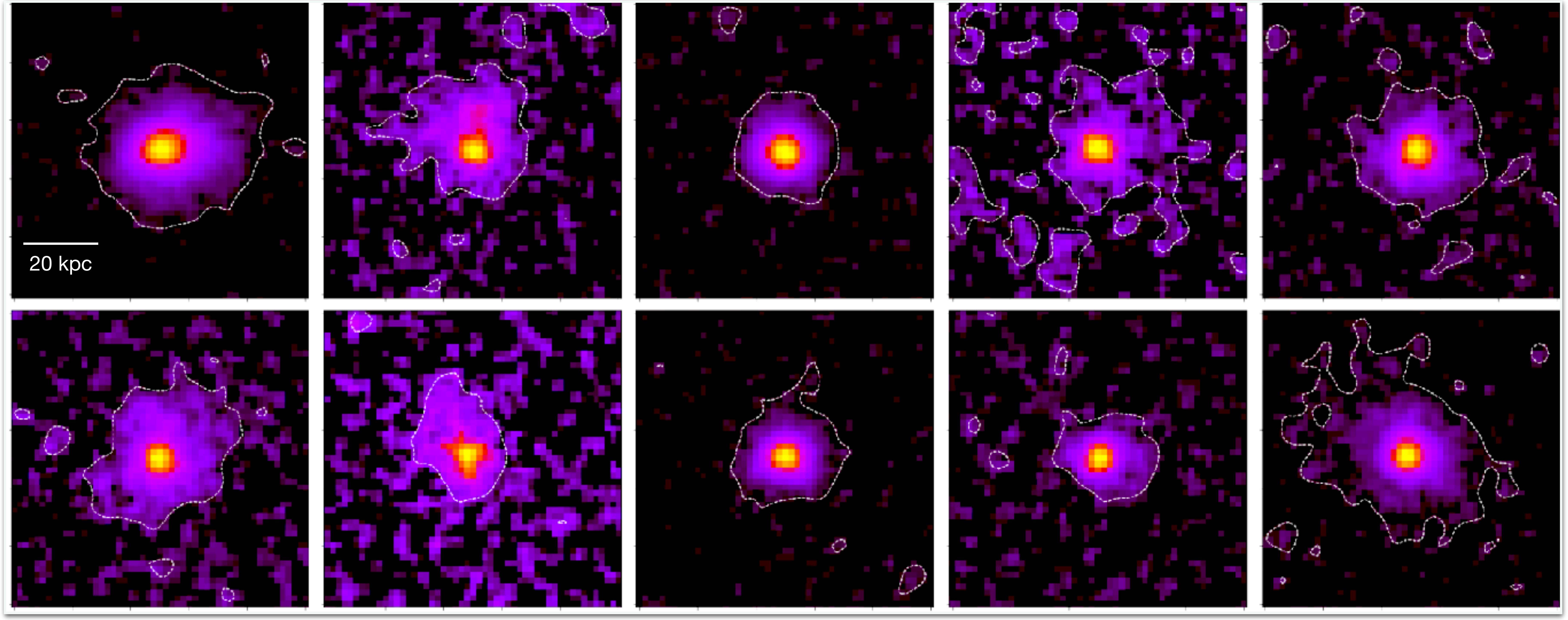
HI mapping with LyA at high z

HI mapping with LyA at high z

MUSE GTO deep fields
(texp >10h) : UDF (Bacon et al. 2017)

Also Daniil and John's talks

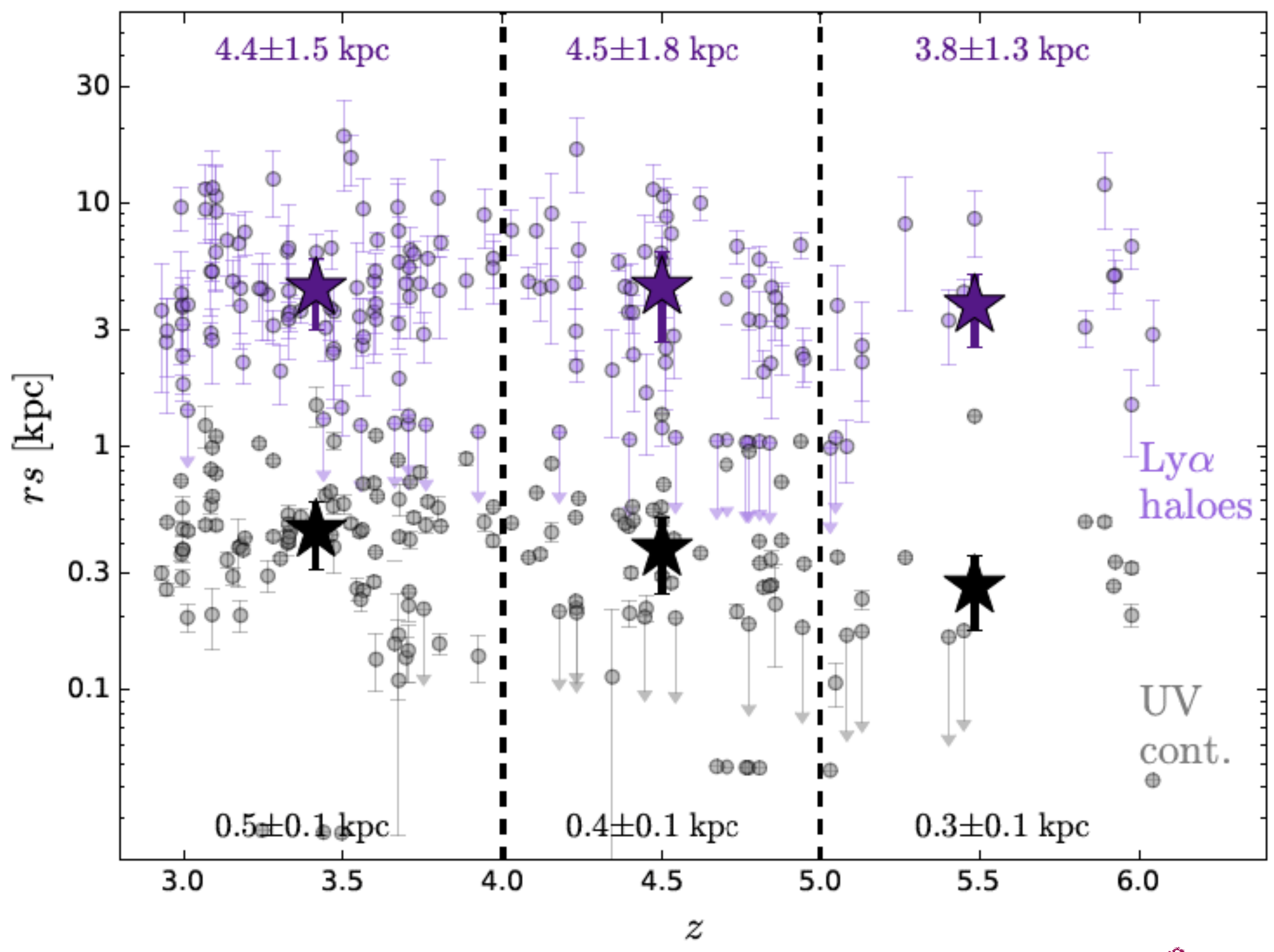
Leclercq et al. 2017
Wisotzki et al. 2016



Lya haloes are ubiquitous around galaxies at z > 3

- Extend over tens of pkpc (10-30)
- 10 times more extended than UV continuum
- 65% of the total Lya flux is in the halo !

HI mapping with LyA at high z



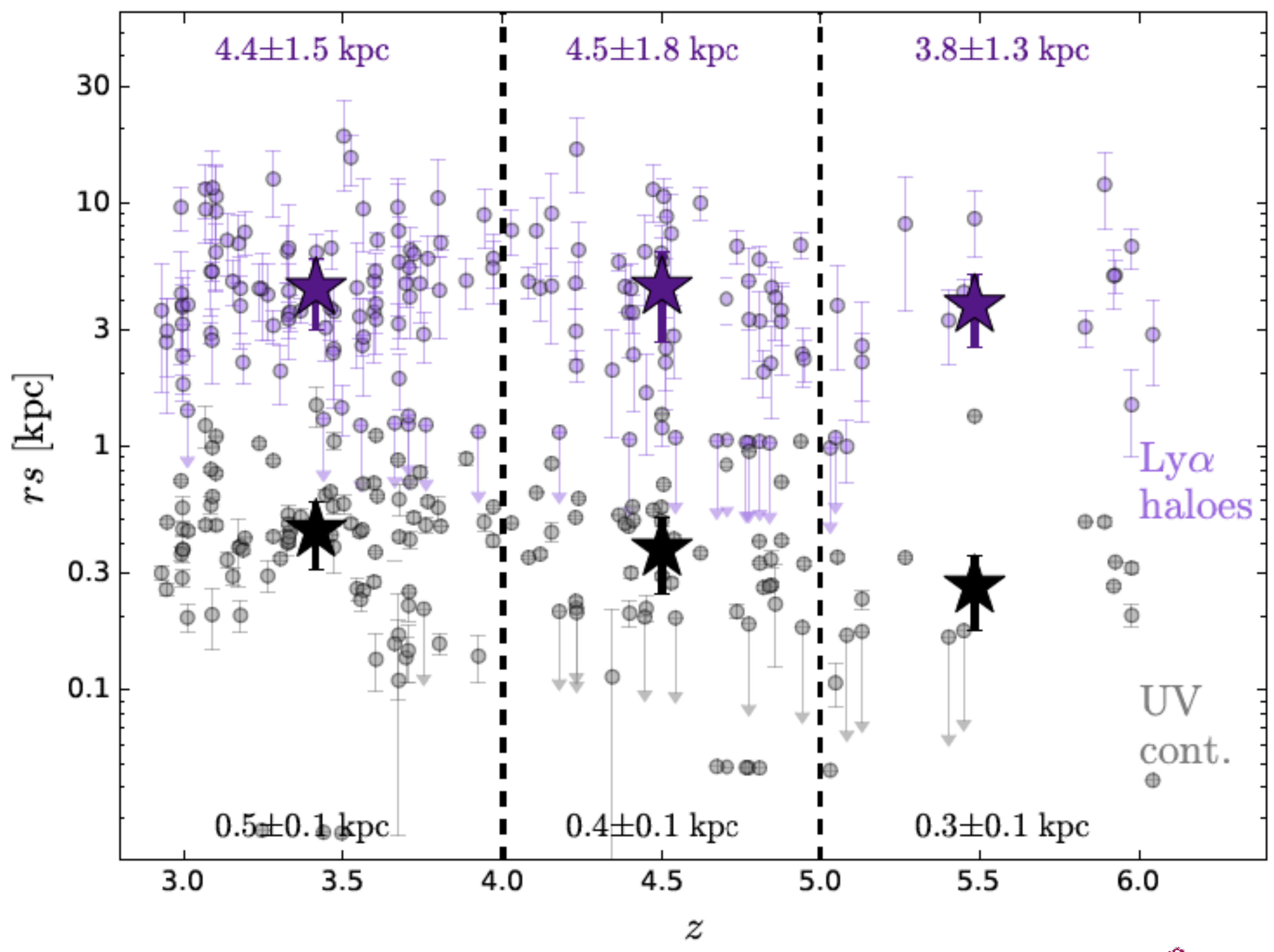
Lya haloes size does not evolve between z=3 and 6

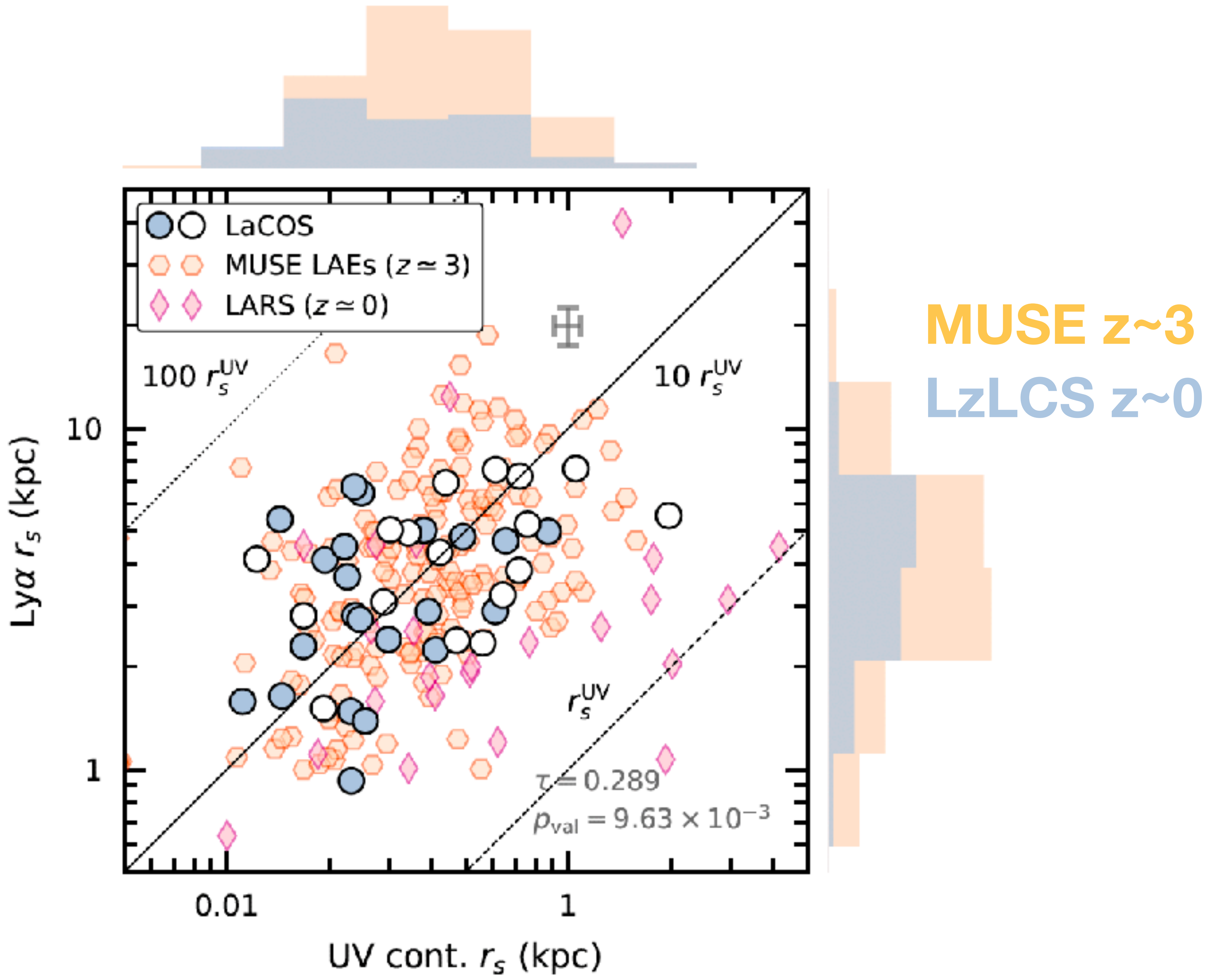
But see Daniil's talk !

Leclercq et al. 2017

Saldana-Lopez et al. in prep.

HI mapping with LyA at high z





Lya haloes size does not evolve between z=3 and 6

But see Daniil's talk !

No evolution of the LAH extent with z

➜ Is that OK to rely on the HI distribution properties to estimate fesc LyC at high z ?

Leclercq et al. 2017

Saldana-Lopez et al. in prep.

Connecting the HI distribution to the LyC escape at high z

Nice review by Sara

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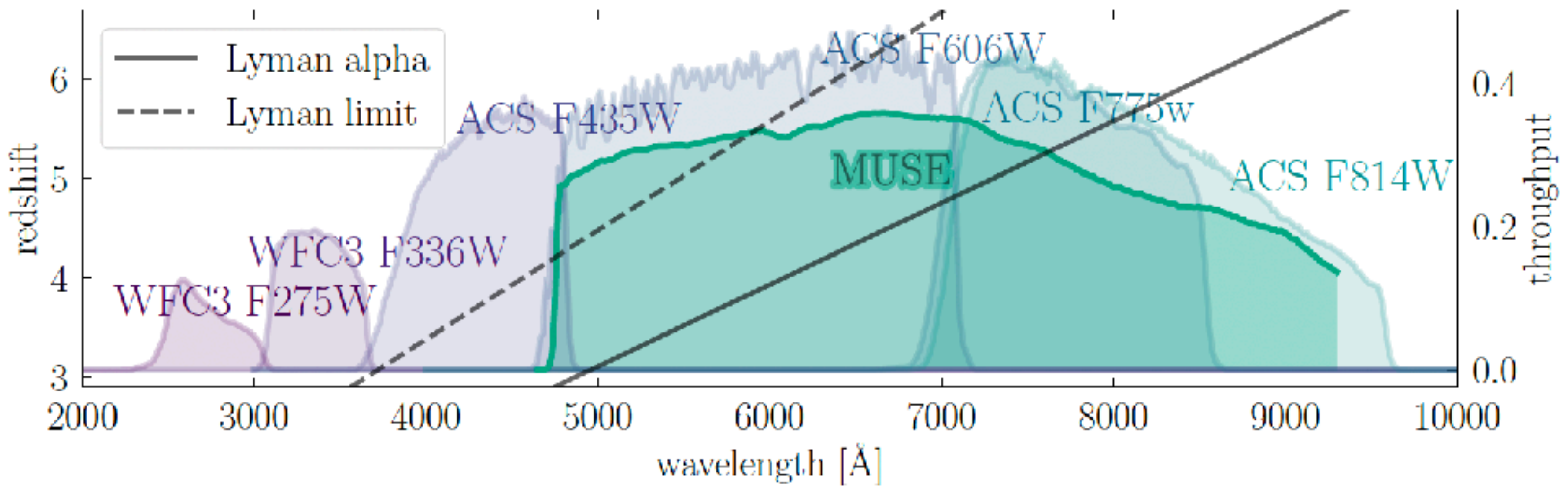


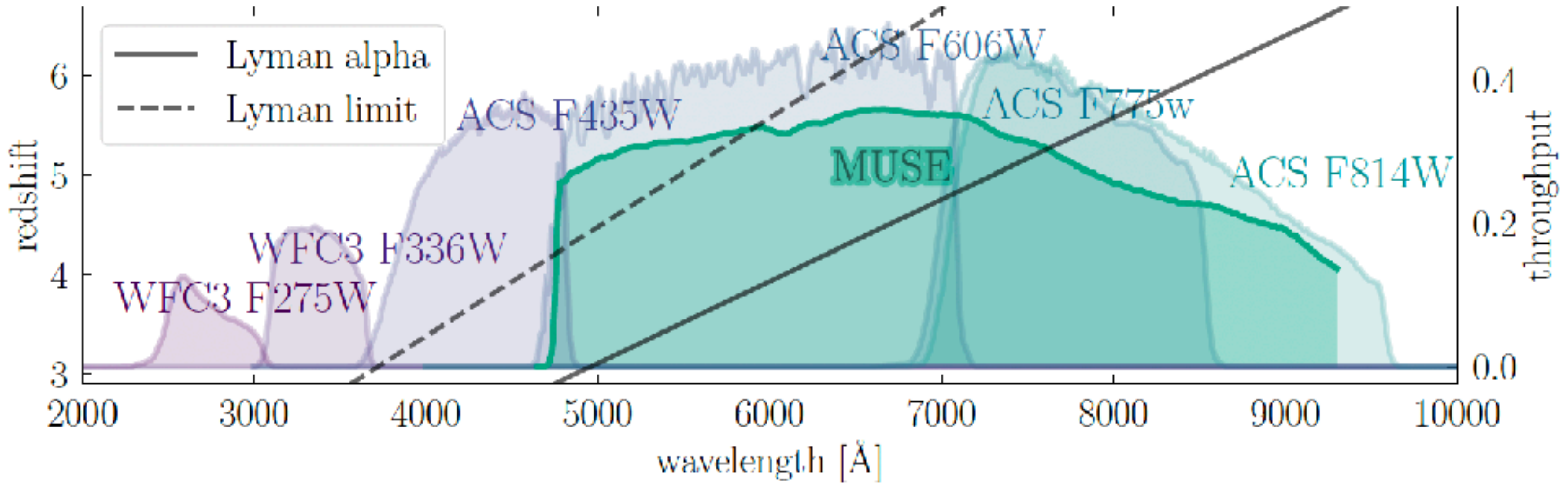
- 5 very likely LCE candidates
- 7 potential LCE candidates
- Fesc > 20%

Kerutt et al. 2024, Oesch et al. 2018, Leclercq et al. 2017

Connecting the HI distribution to the LyC escape at high z

Nice review by Sara

+



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7 in the MUSE Deep fields

4 isolated LAEs with **<u>LAH measurements</u>**

Kerutt et al. 2024, Oesch et al. 2018, Leclercq et al. 2017

Connecting the HI distribution to the LyC escape at high z

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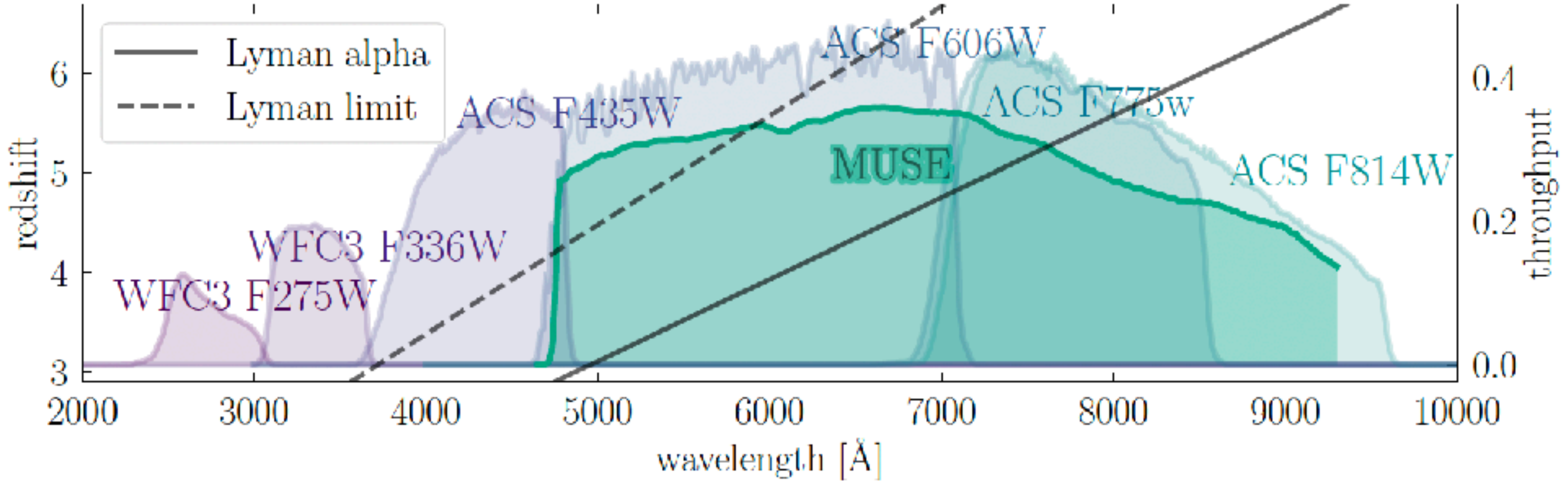
HDUV LEGACY FIELDS + MUSE multi unit spectroscopic explorer



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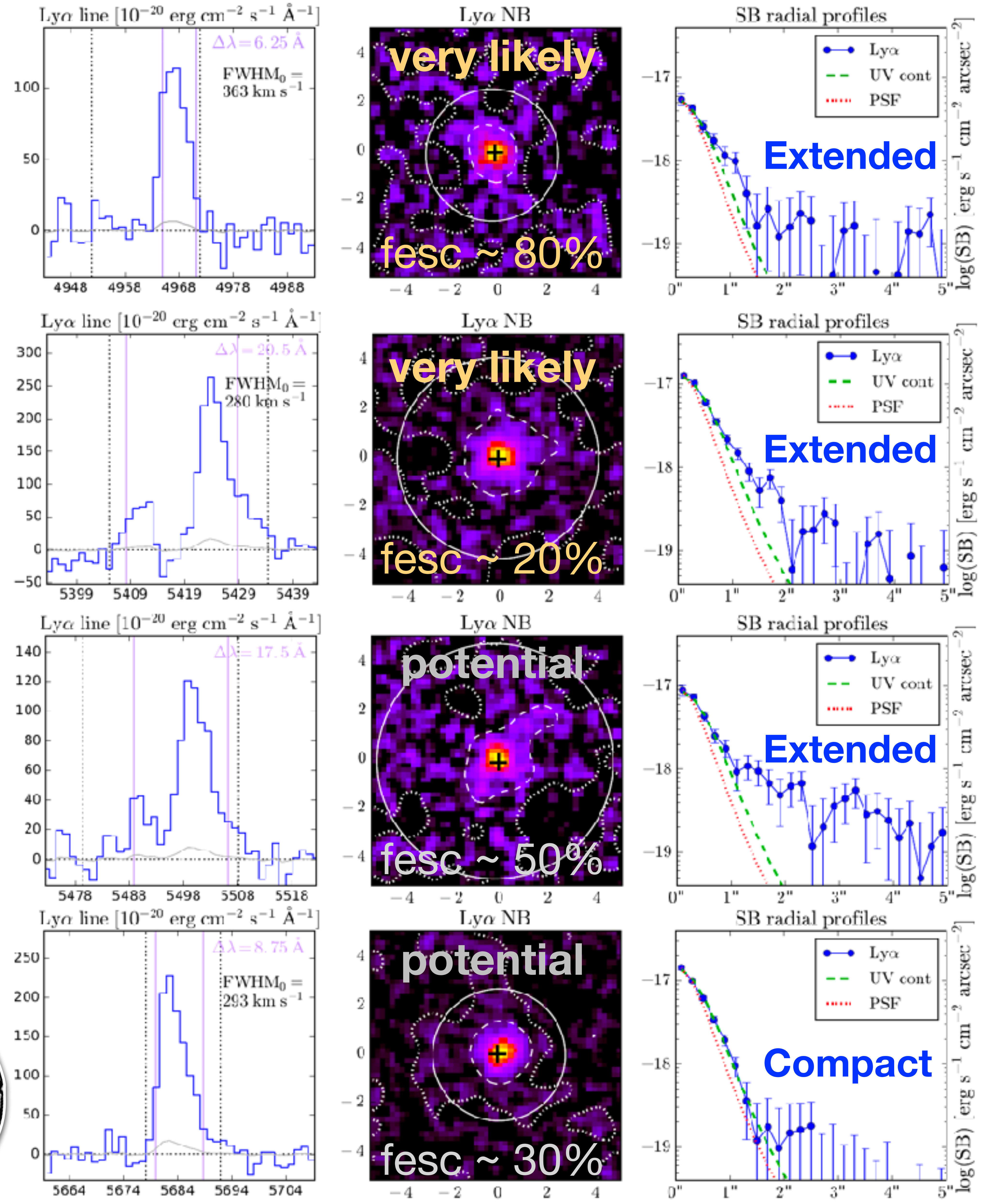
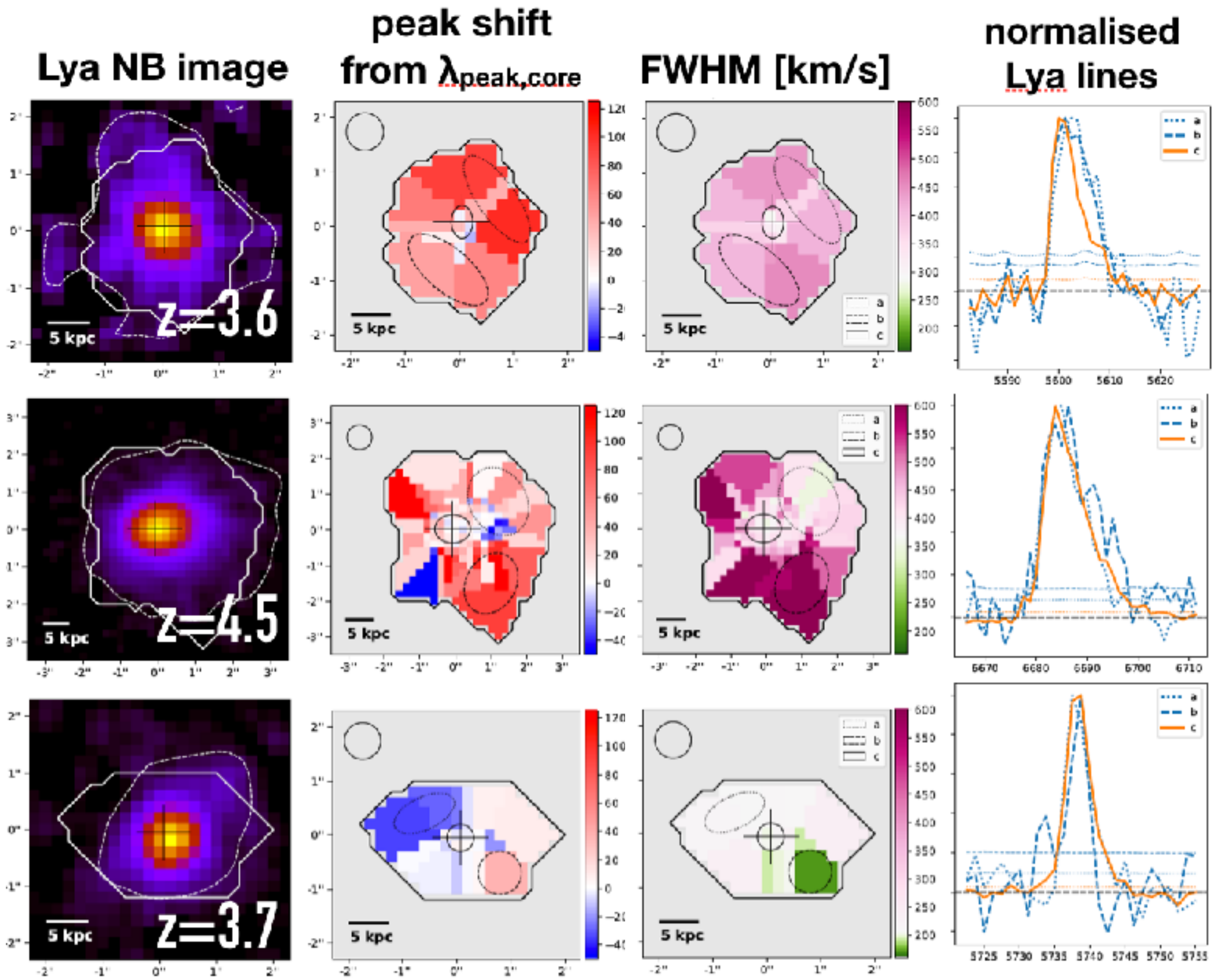


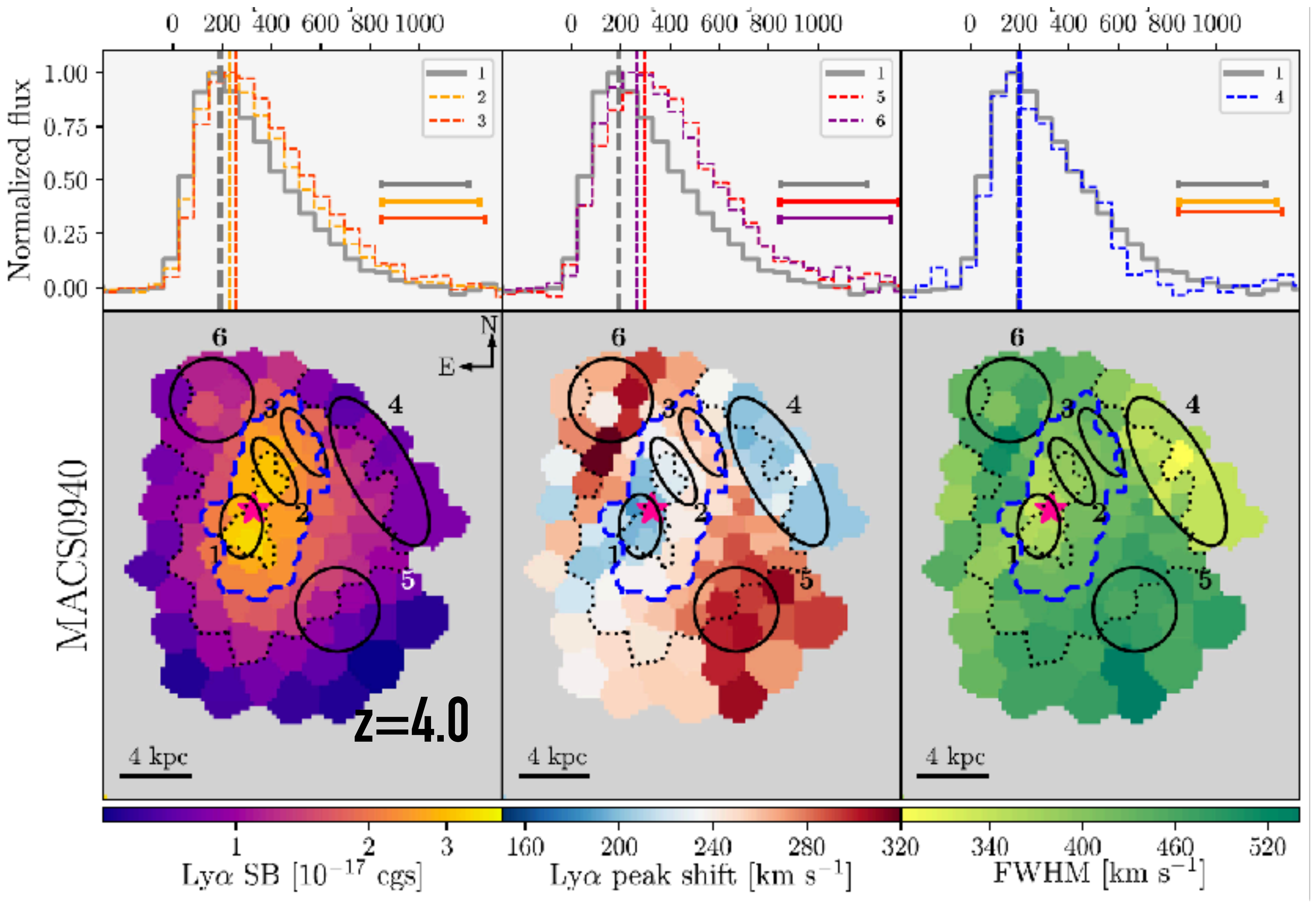
Kerutt et al. 2024, Oesch et al. 2018, Leclercq et al. 2017

LyA spectro-mapping at high z

MUSE GTO deep fields
(texp >10h) : UDF (Bacon et al. 2017)

MUSE GTO lensed fields
(Richard et al. 2020)





Leclercq et al. 2020

Claeyssens et al. 2019

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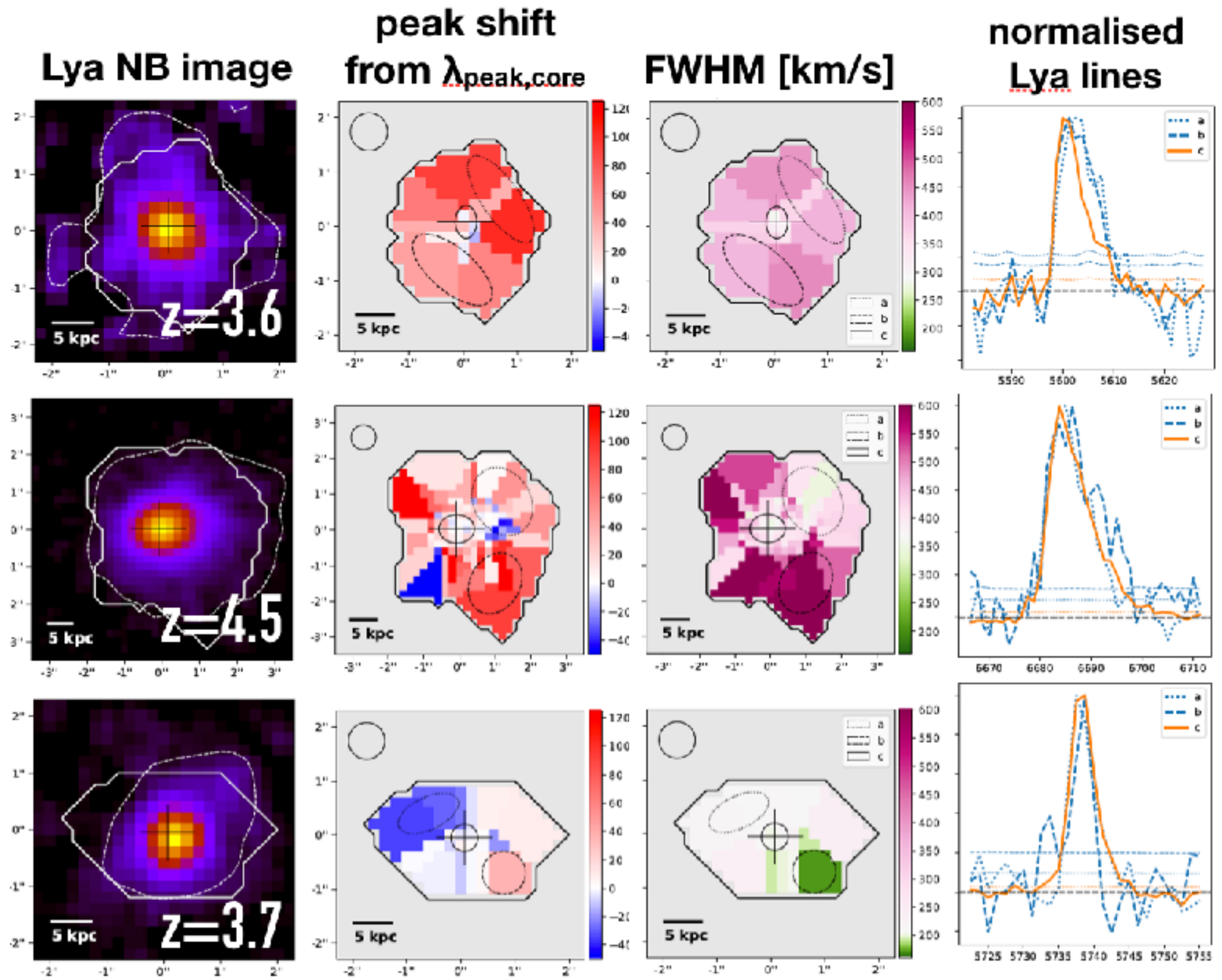
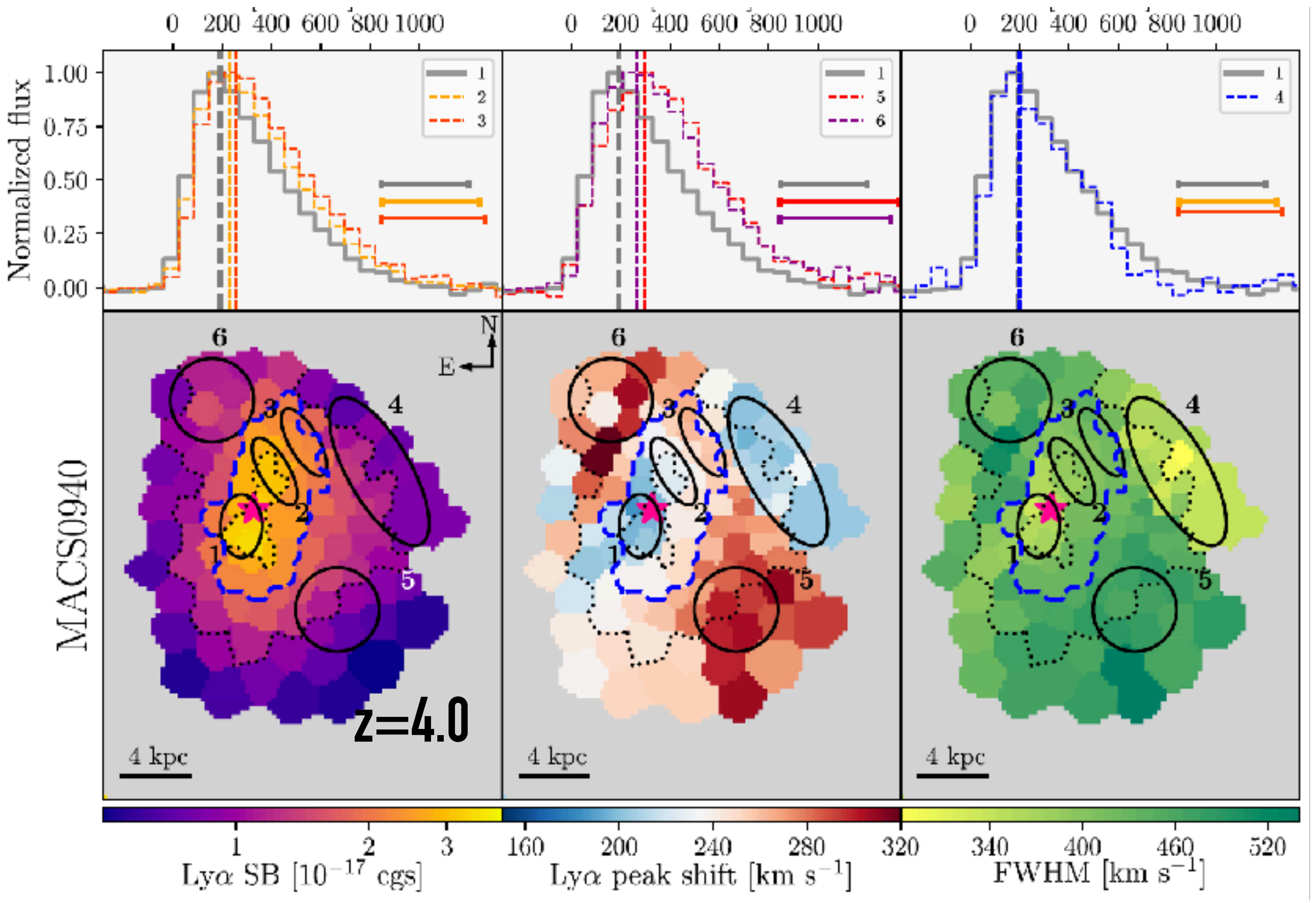




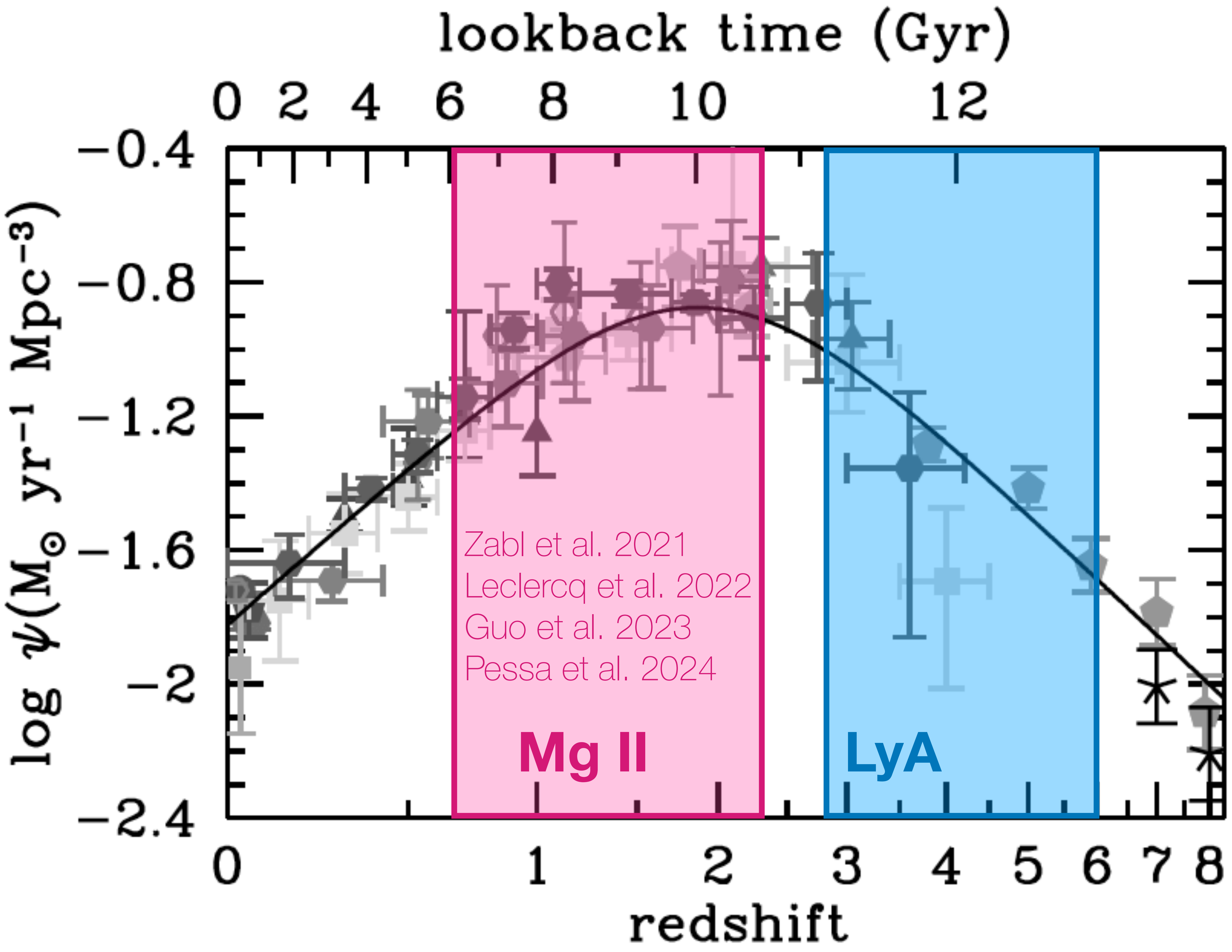
Small-scale variations in the Lya line profiles within LAH

➡ The HI gas has complex and diverse configurations = **complex LyC escape ?**

Leclercq et al. 2020

Claeyssens et al. 2019

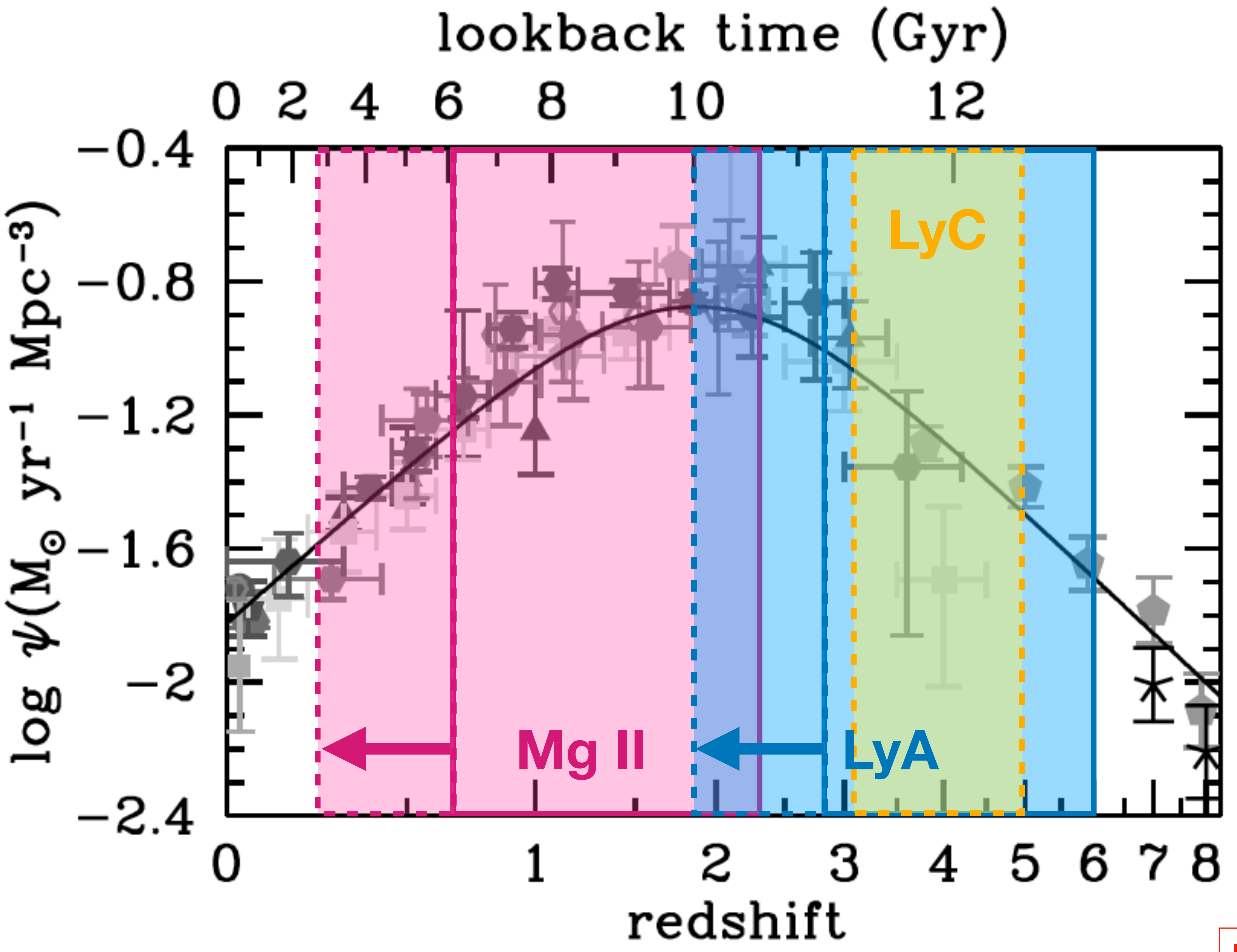
HI mapping across cosmic time with large FoV IFU



muse
multi unit spectroscopic explorer

Madau & Dickinson 2014

HI mapping across cosmic time with ground-based IFU



Madau & Dickinson 2014

+

See Peter's talk on Friday

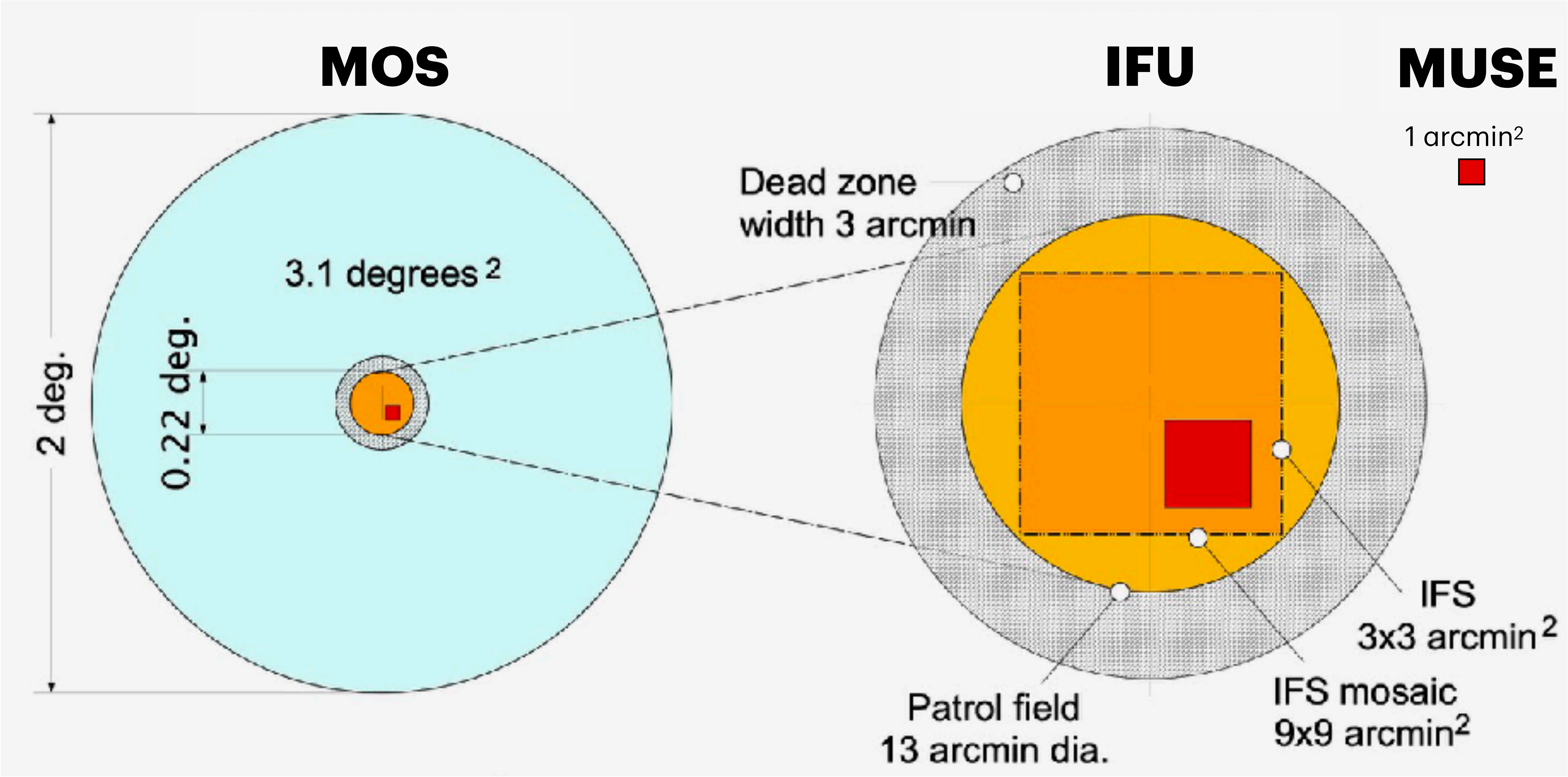
- **HI maps over 11 bilions years**
- Overlap LyA / Mg II at z~2
- new LCEs at z~3-4 ?

Large IFU samples with no pre-selection !

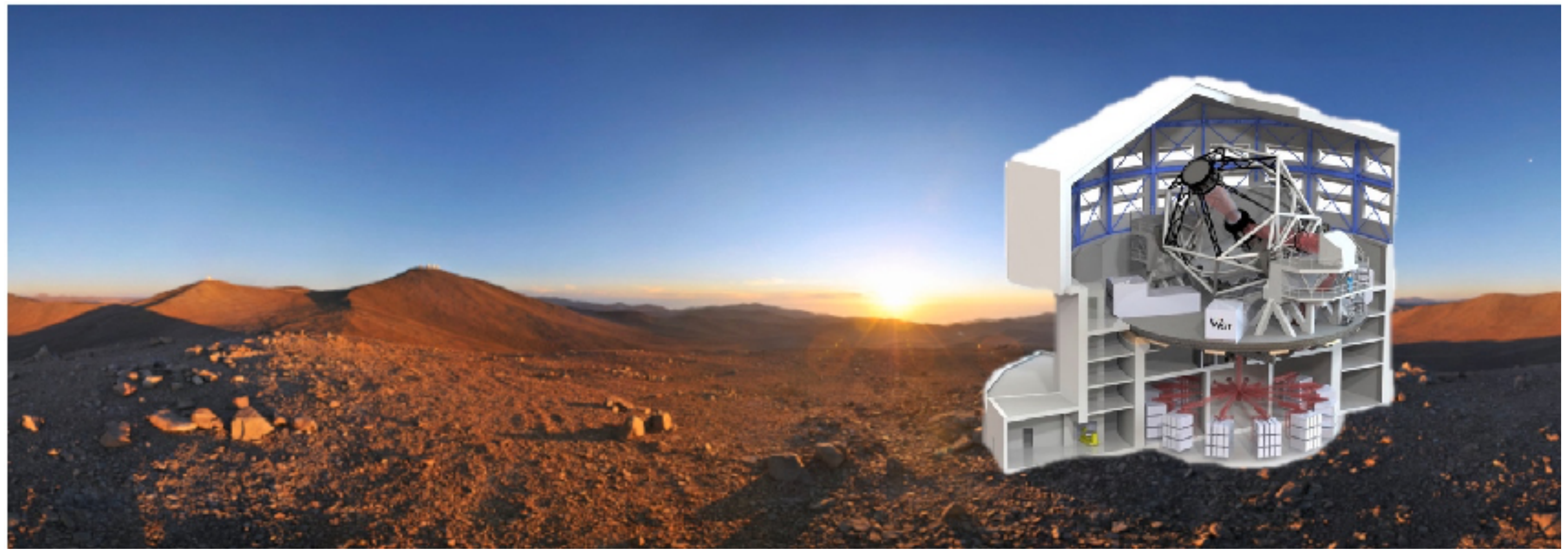
The statistical revolution with WST-like surveys

See Roland's talk on Friday

- **Mega IFU** 3x3 arcmin² + 3 deg² **MOS**
- R~3500, λ = 370-970nm



Wide field **S**pectroscopic **T**elescope



➡ From few hundreds to **millions of HI maps** !

➡ Many more **LCEs** at high z ?

Bacon et al. 2024, Mainieri et al. 2024

Summary

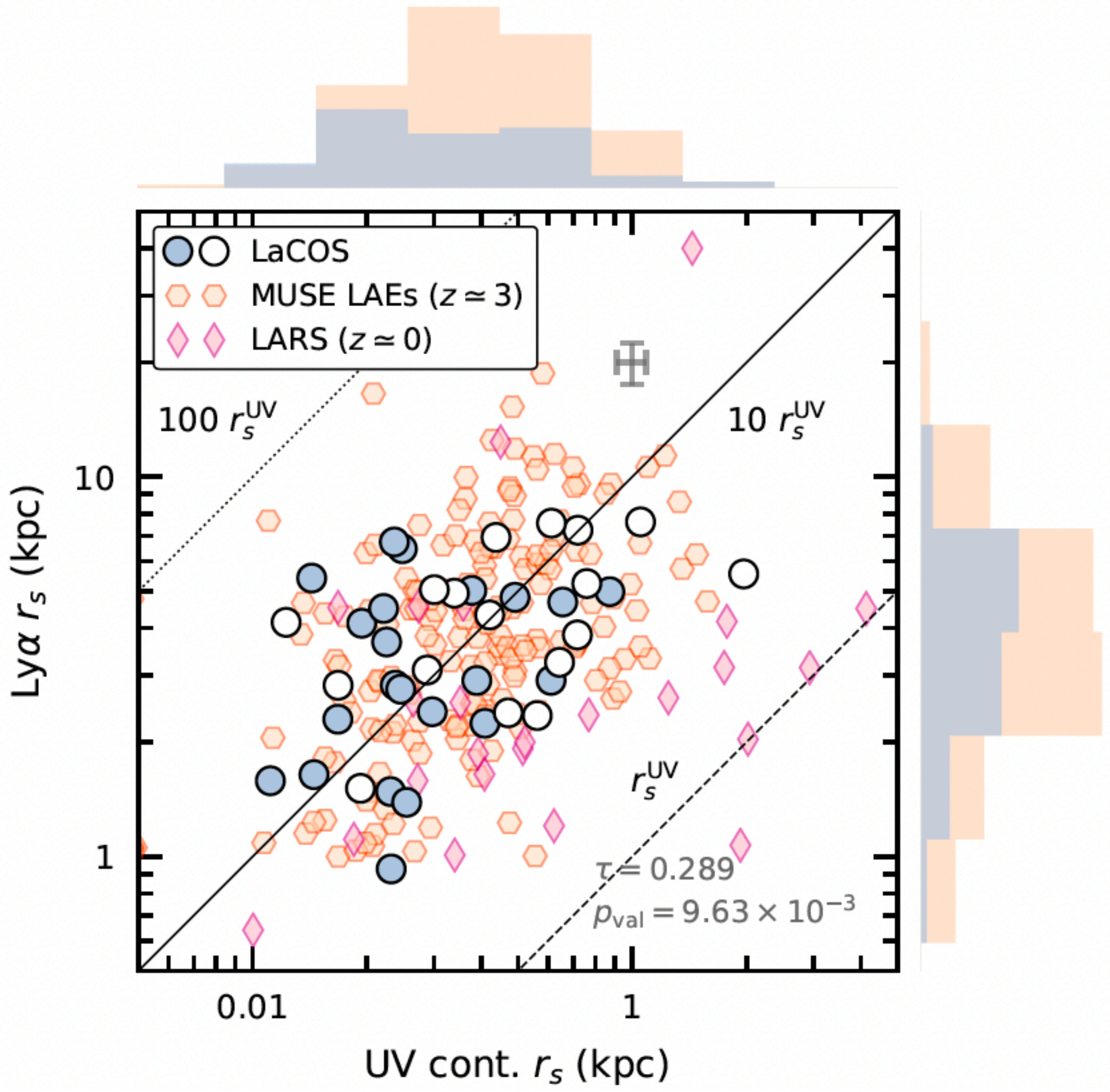
Summary

➡ The neutral gas is one of the main sink for LyC photons > important to map it to understand LyC escape !

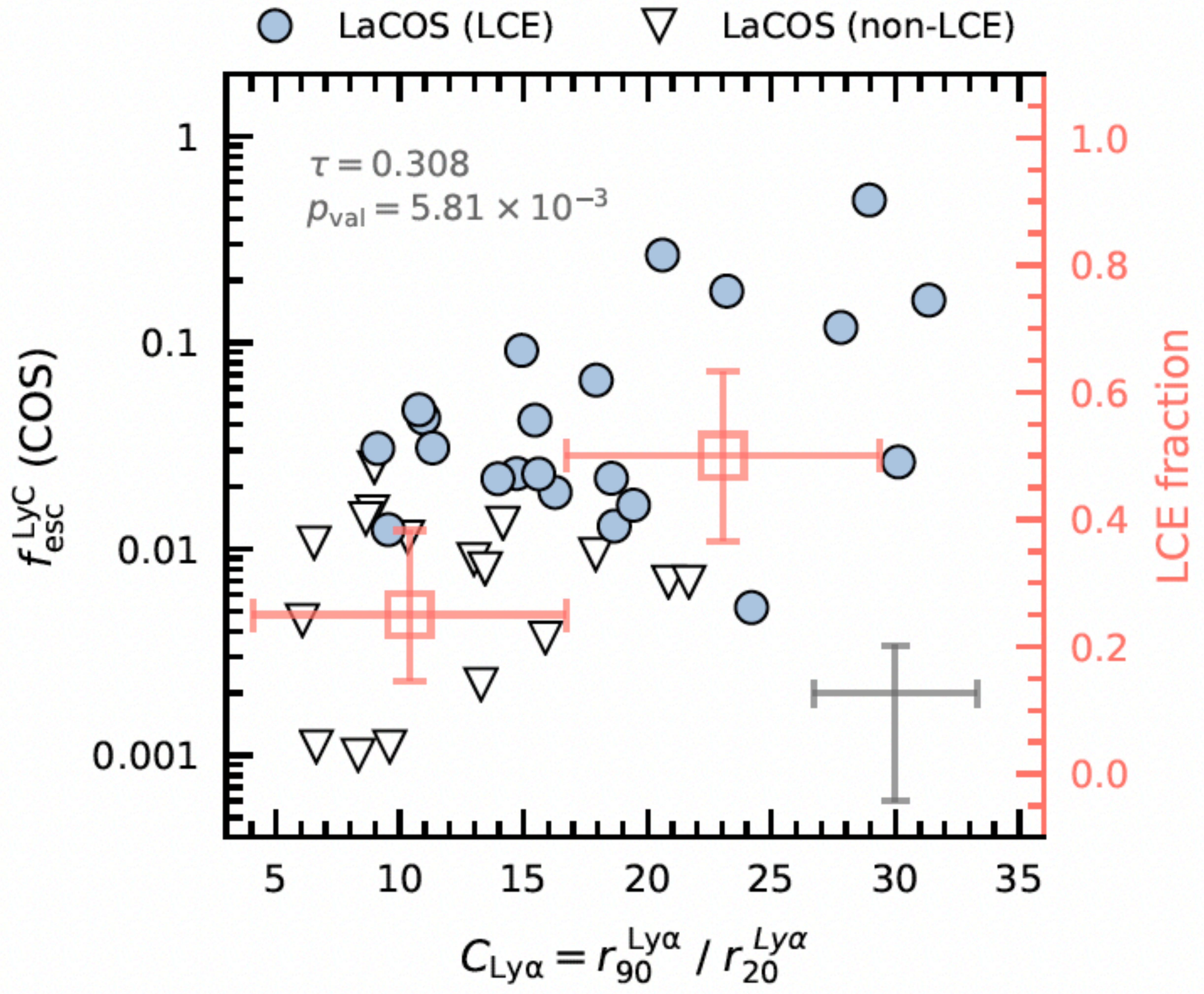
- **From low-z LyC studies :**
  - IFU HI maps reveals that **LyC leakage at low-z depends on the nebular gas extent** in the ISM+CGM
  - Preliminary resolved Mg II maps show that **LyC escape is anisotropic** in the LzLCS sample
  - We can now link LyC with LyA spatial and spectral properties in tens of galaxies from the LzLCS
- **At higher redshift :**
  - LyC/LyA connection is difficult — very low statistics
  - **Trends look different** than the ones observed at lower z — redshift evolution or selection bias ?
  - We need to increase the statistics and work on representative samples
- **Future is bright :**
  - BlueMUSE+MUSE = blind and consistent analysis of LAH over 11 bilions years + **new LCEs at z~3** !
  - WST = statistical power with **millions of HI maps** and many more LCEs

Bonus slides

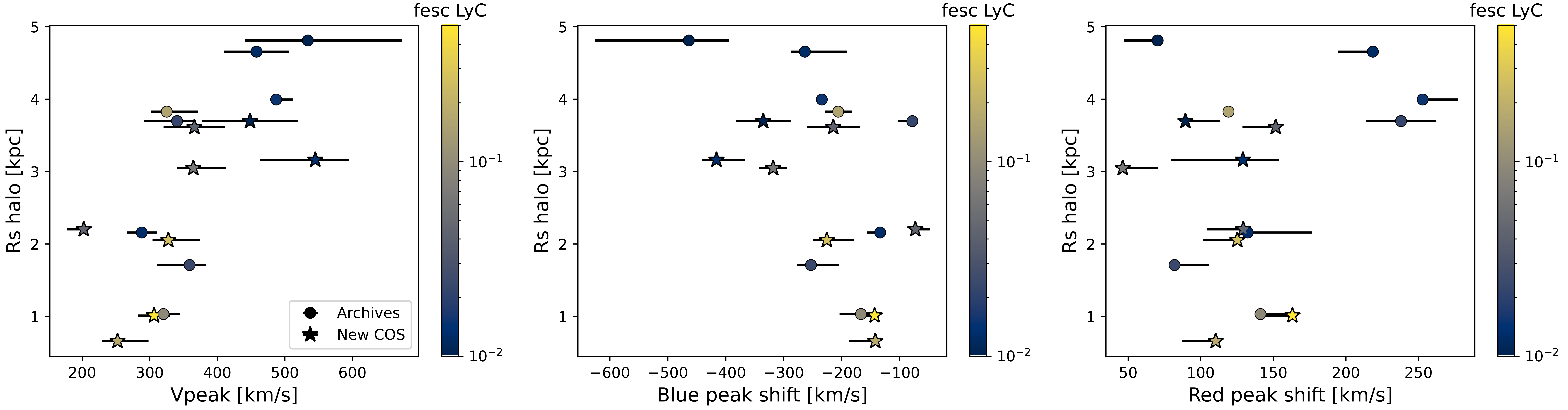
LaCOS LAHs



LaCOS
MUSE LAEs ($z \simeq 3$)
LARS ($z \simeq 0$)
100 r_s^{UV}
10 r_s^{UV}
r_s^{UV}
$\tau = 0.289$
$p_{val} = 9.63 \times 10^{-3}$
Lyα r_s (kpc)
UV cont. r_s (kpc)
10
1
0.01
1

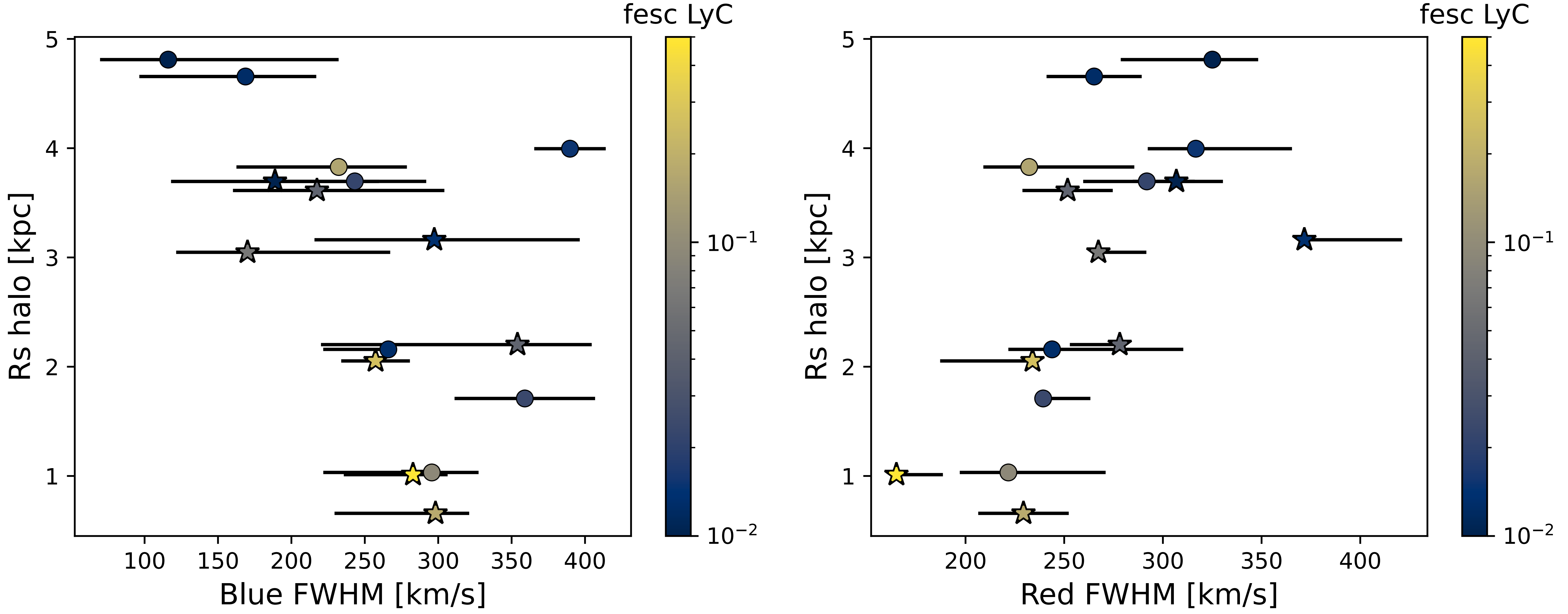


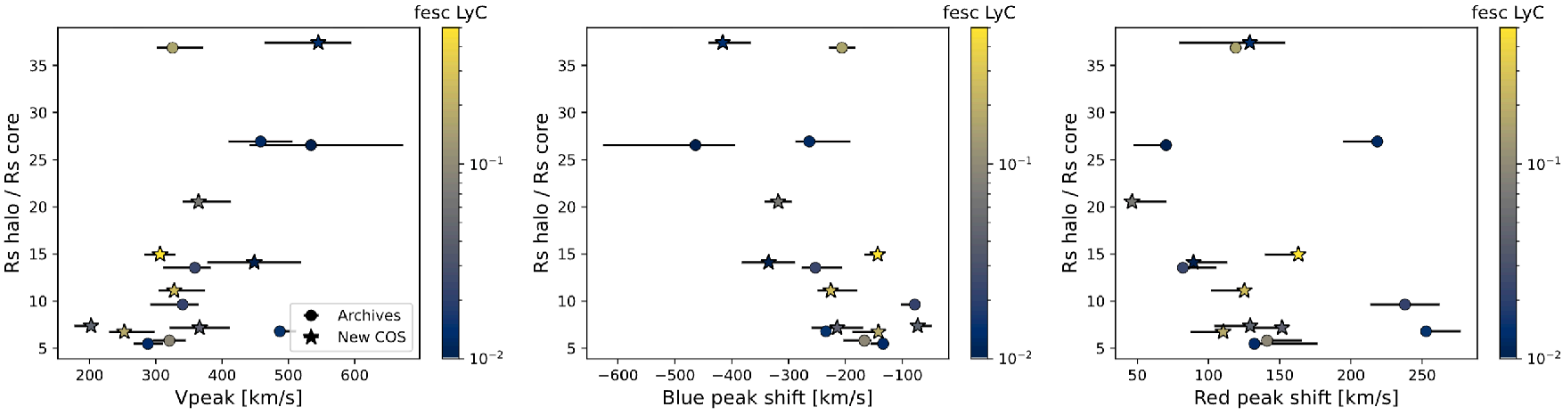
LaCOS (LCE)
LaCOS (non-LCE)
$\tau = 0.308$
$p_{val} = 5.81 \times 10^{-3}$
f_{esc}^{LyC} (COS)
LCE fraction
$C_{Ly\alpha} = r_{90}^{Ly\alpha} / r_{20}^{Ly\alpha}$
1
0.1
0.01
0.001
5
10
15
20
25
30
35
1.0
0.8
0.6
0.4
0.2
0.0



LaCOS LAHs

VS. Lya lines





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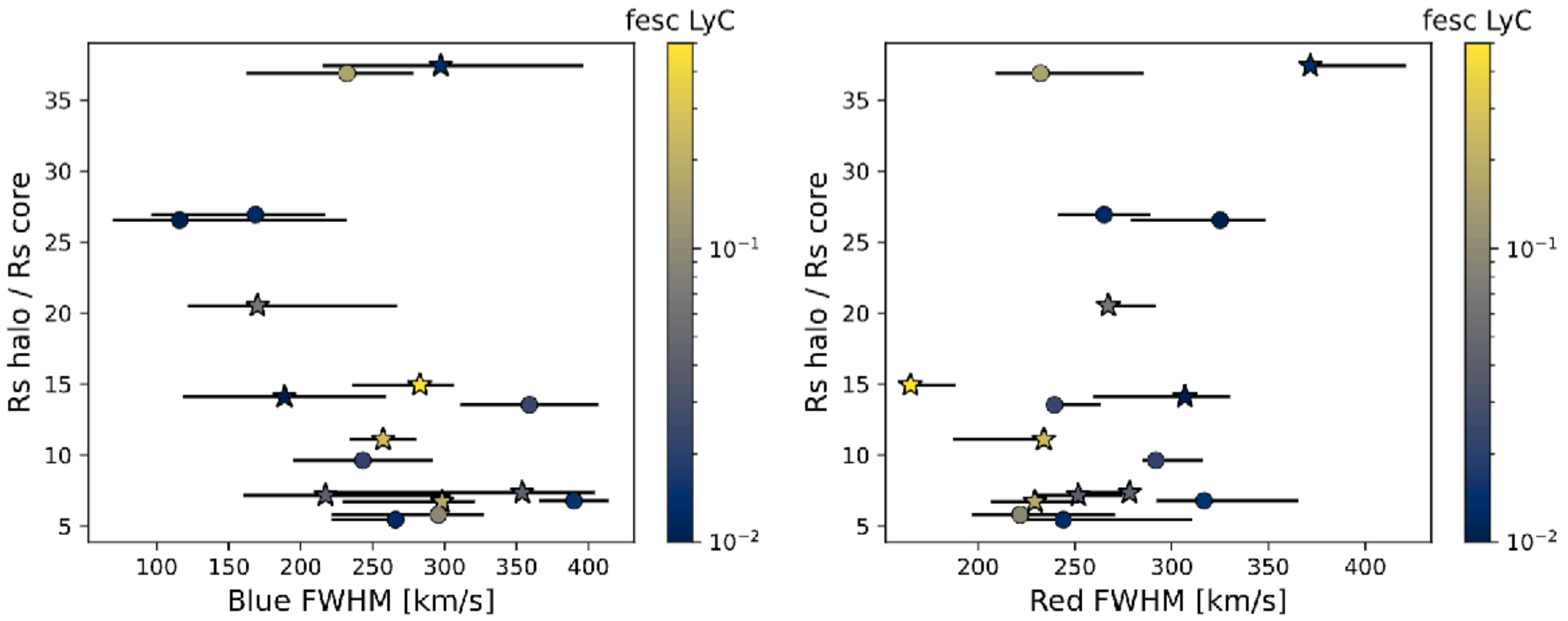

LaCOS LAHs

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