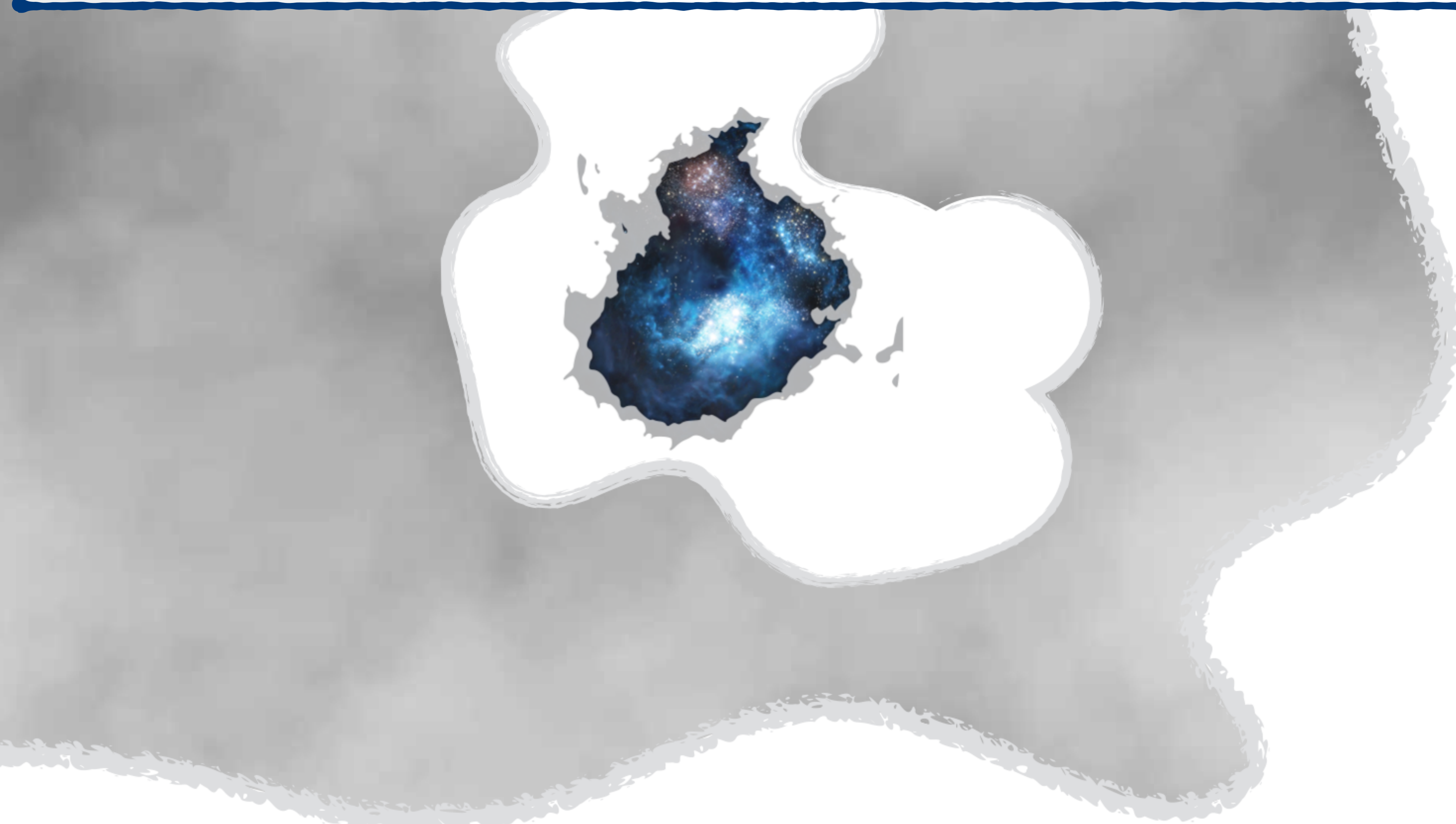
THE HOSTS OF EARLY IONISED BUBBLES

UNVEILING THE MOST LUMINOUS LYMAN-ALPHA EMITTERS IN THE EPOCH OF REIONISATION



Jorryt Matthee **Zwicky Fellow @** ETH zürich

collaborators include David Sobral, Max Gronke, Ana Afonso, Huub Röttgering, Bahram Mobasher, Sergio Santos, Gabriele Pezzulli, Behnam Darvish and others

T

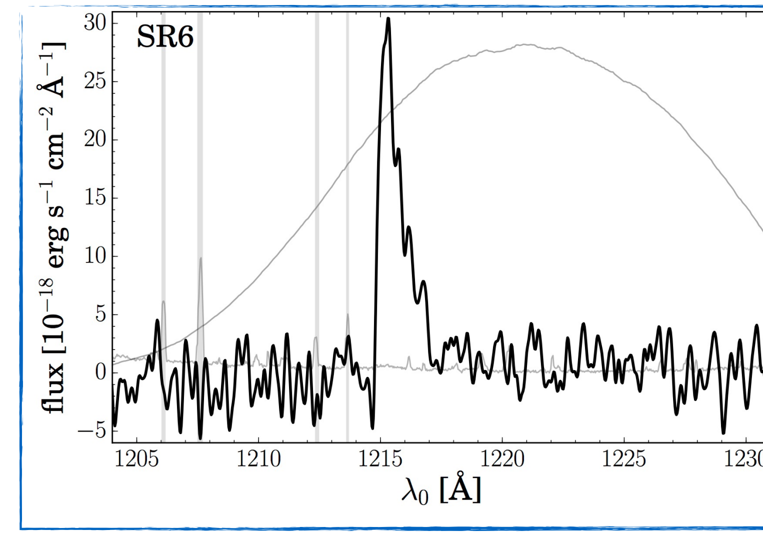
1. How did galaxies reionize the Universe,
and how can we trace this process?

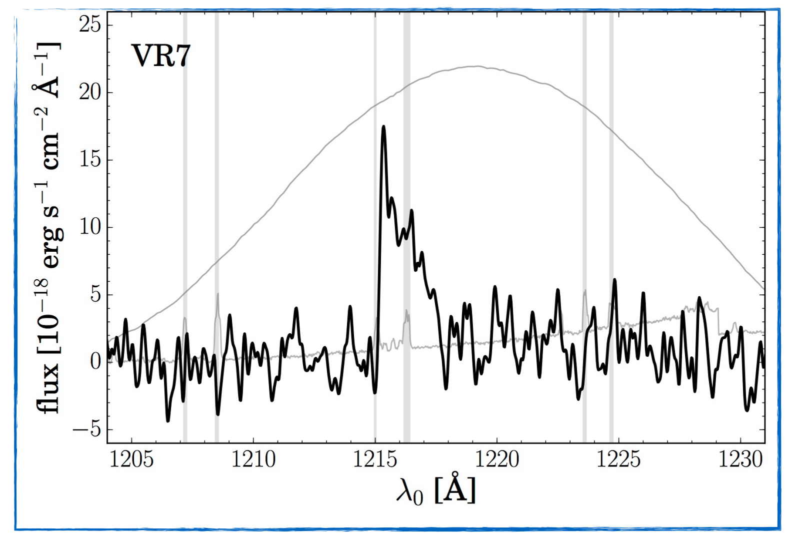
2. How did early galaxies assemble?
What are the properties of their gas & stars?

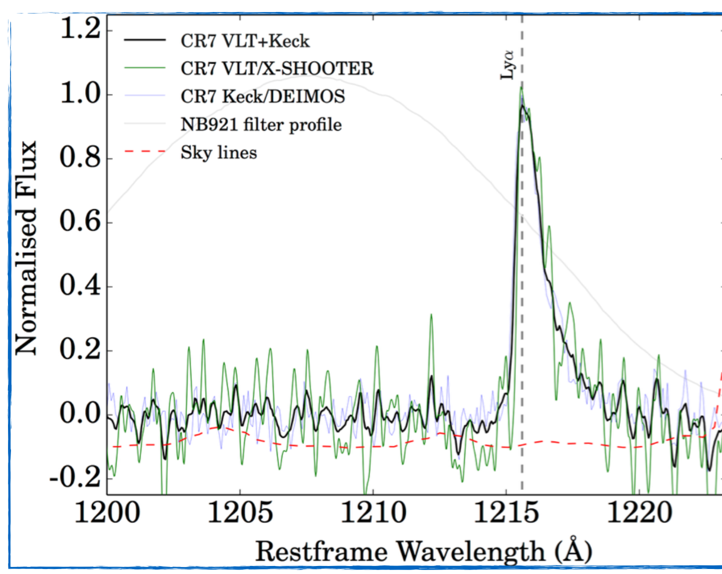
Galaxy Sample : Luminous Lyman-alpha selected

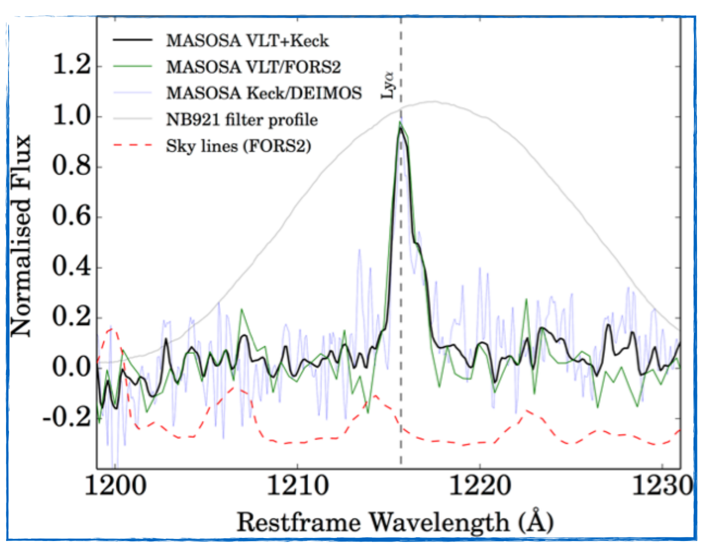
- **$z \sim 6.5$** ($t_{Universe} \sim 800$ Myr)
- **Number density: ~ 10-20 per deg^2 Δz^{-1}**
- **$M_{1500} \sim -20.5$ to -22.5** ($\sim$1-5 $M^{\star}_{1500}$)
- **$EW_{0, Ly\alpha} \sim 30$ - 200 Å**

~>2000x brighter than the Vanzella+ z=6.62 LAE









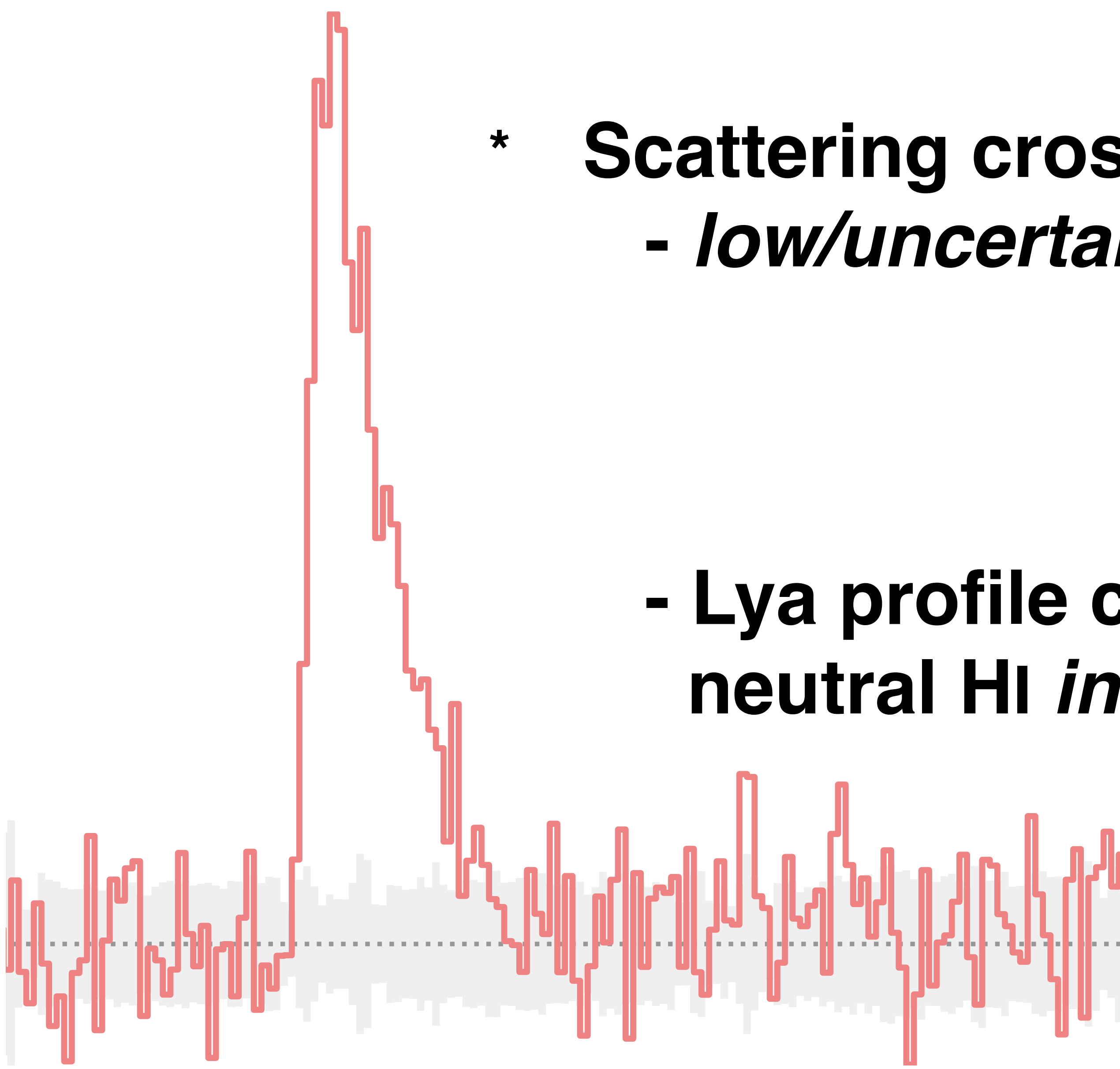
flux > 2E-17 erg s^{-1} cm^{-2}

~2hr @ 10m class telescope

Sobral+2015, ApJ, 808, 139
Matthee+2017c, MNRAS, 472, 772

Why select and study Lyman-alpha?

* λ_0=1215.67 Å:
  most efficient line for confirming & identifying samples of *young* galaxies at z~2-7 until we have JWST

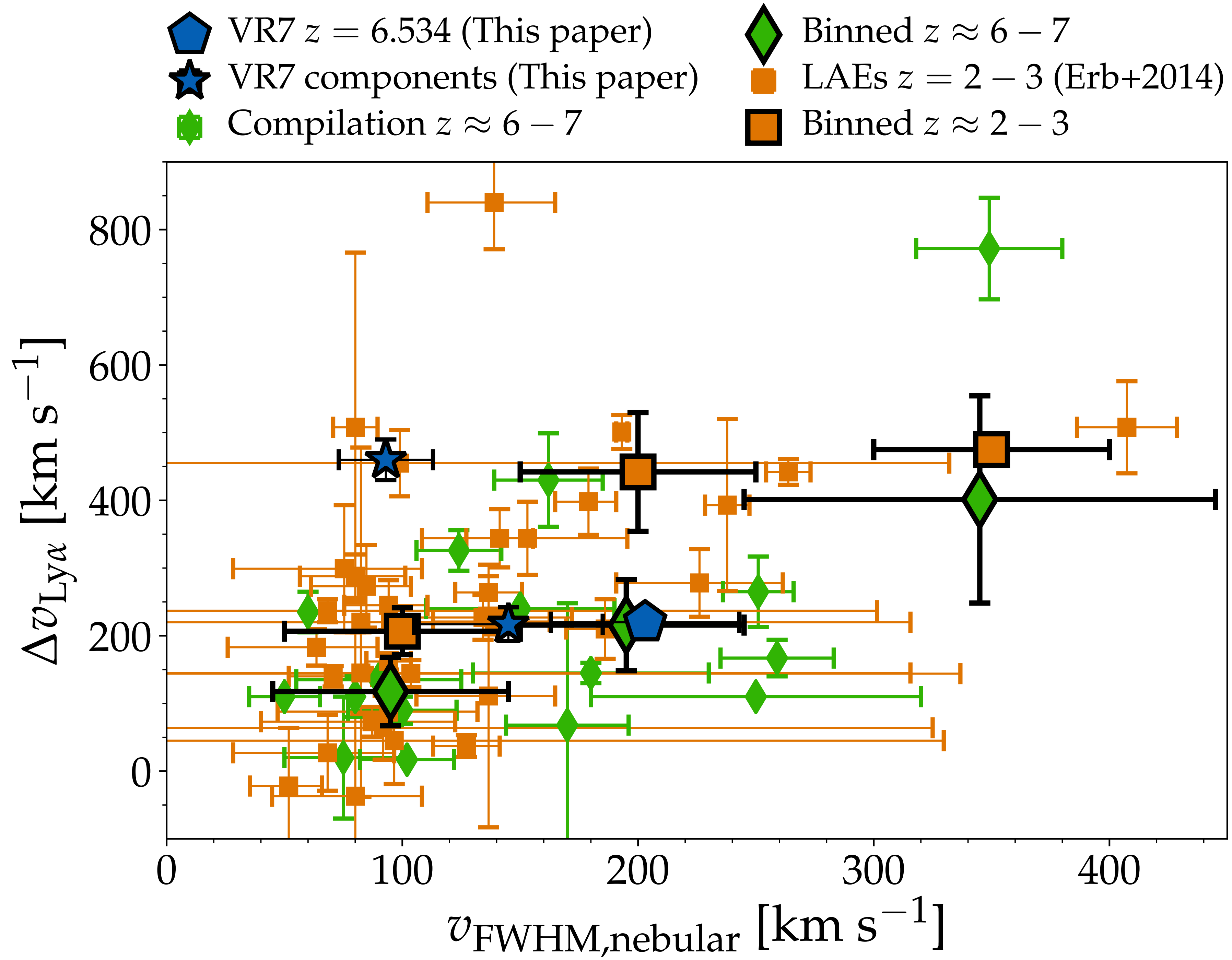


* Scattering cross section ~10^{-14} cm^{-2} at line centre:
  - *low/uncertain* Lya escape fraction curse?

  but...

  - Lya profile contains information on neutral HI *in* and *around* galaxies blessing!

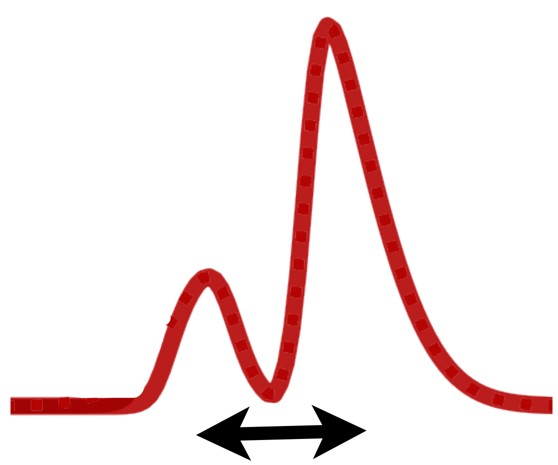
Observed velocity offsets Lya-systemic smaller at z>6 than at z~2-3

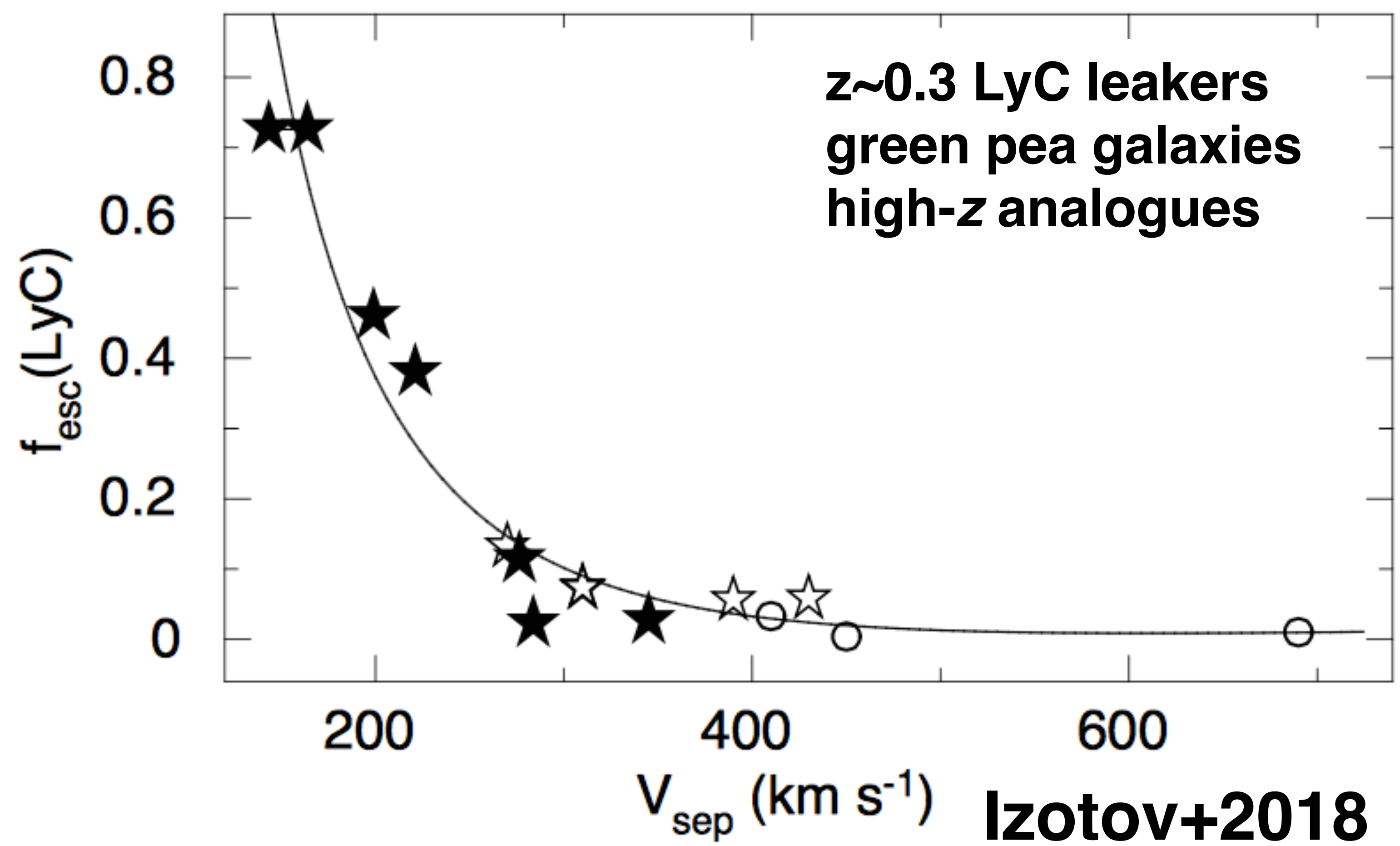


ISM in z~7 LAEs more ionised than ISM in z~2 LAEs

Matthee et al. submitted

The shape of the Lya line carries information on HI content





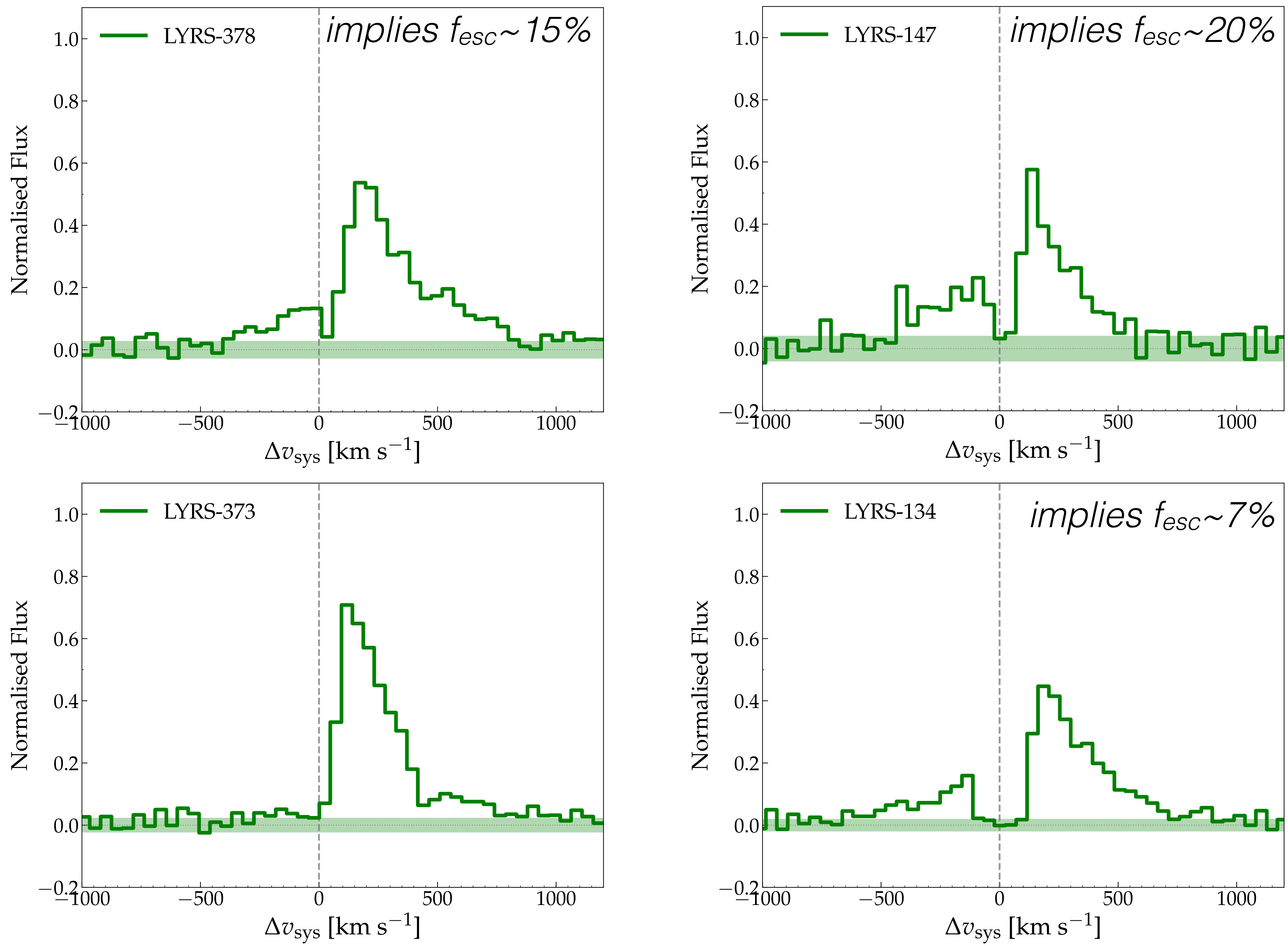
Izotov+2018

Lya peak separation clear *predictor* of Lyman-continuum escape

see also Verhamme+2015
Kakiichi & Gronke 2019

Double peaked Lya is common among LAEs* (>50%) at z~2

* R>4000



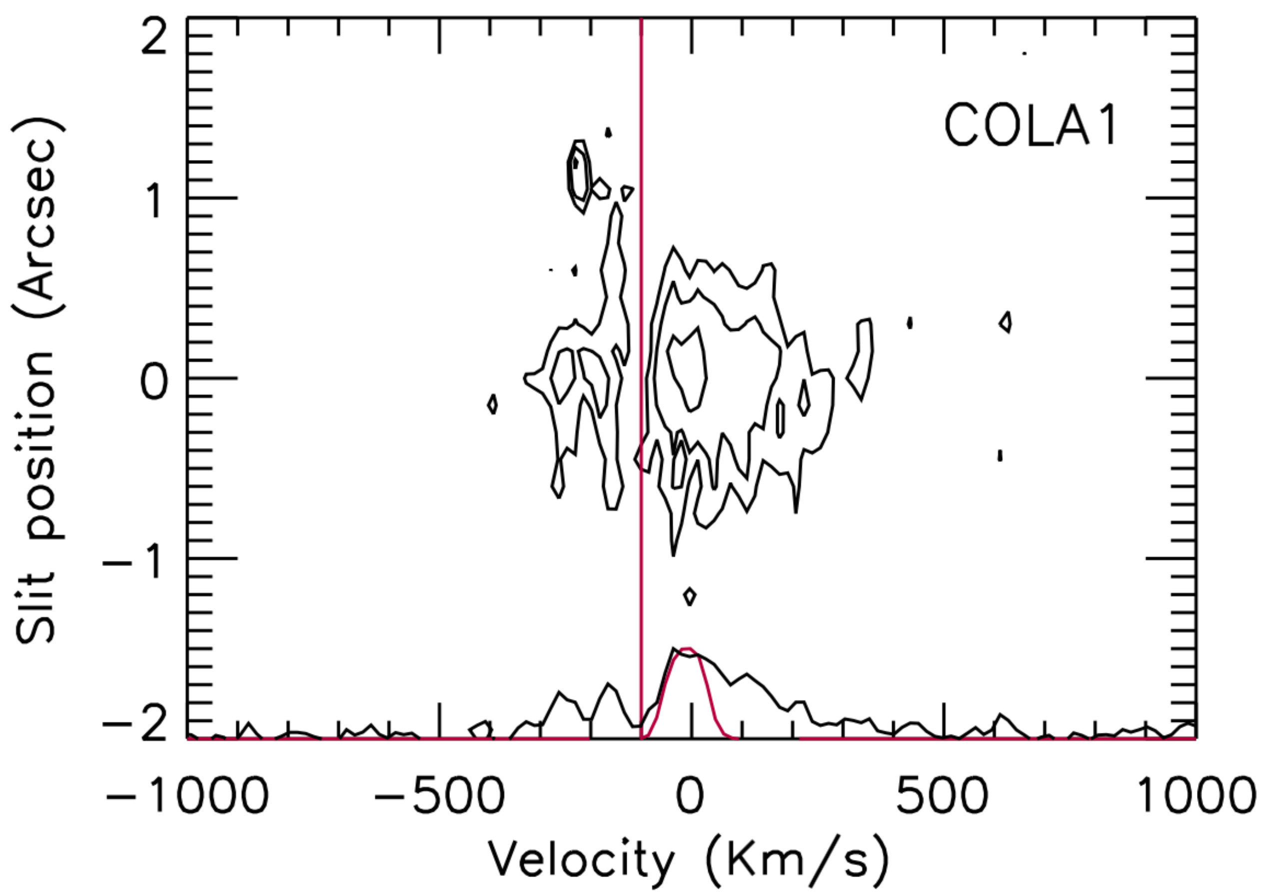
Early results from VLT/X-SHOOTER CALYMHA

Calibrating Lyman-alpha with matched Halpha

Matthee+ in prep

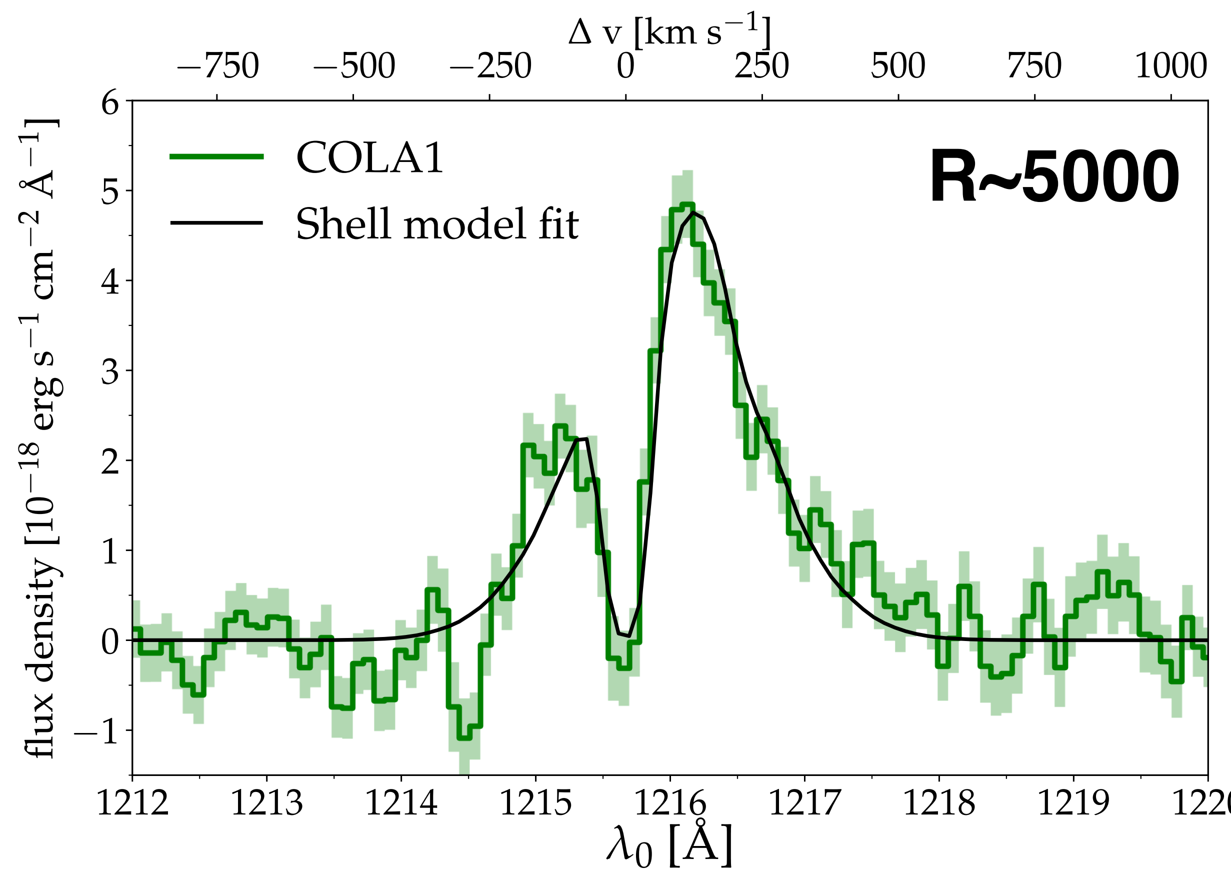
global results:
see talk by David Sobral

COLA1 - THE FIRST DOUBLE PEAKED LYA EMITTER AT z>6



found by Hu+2016;

see also Songaila+2018

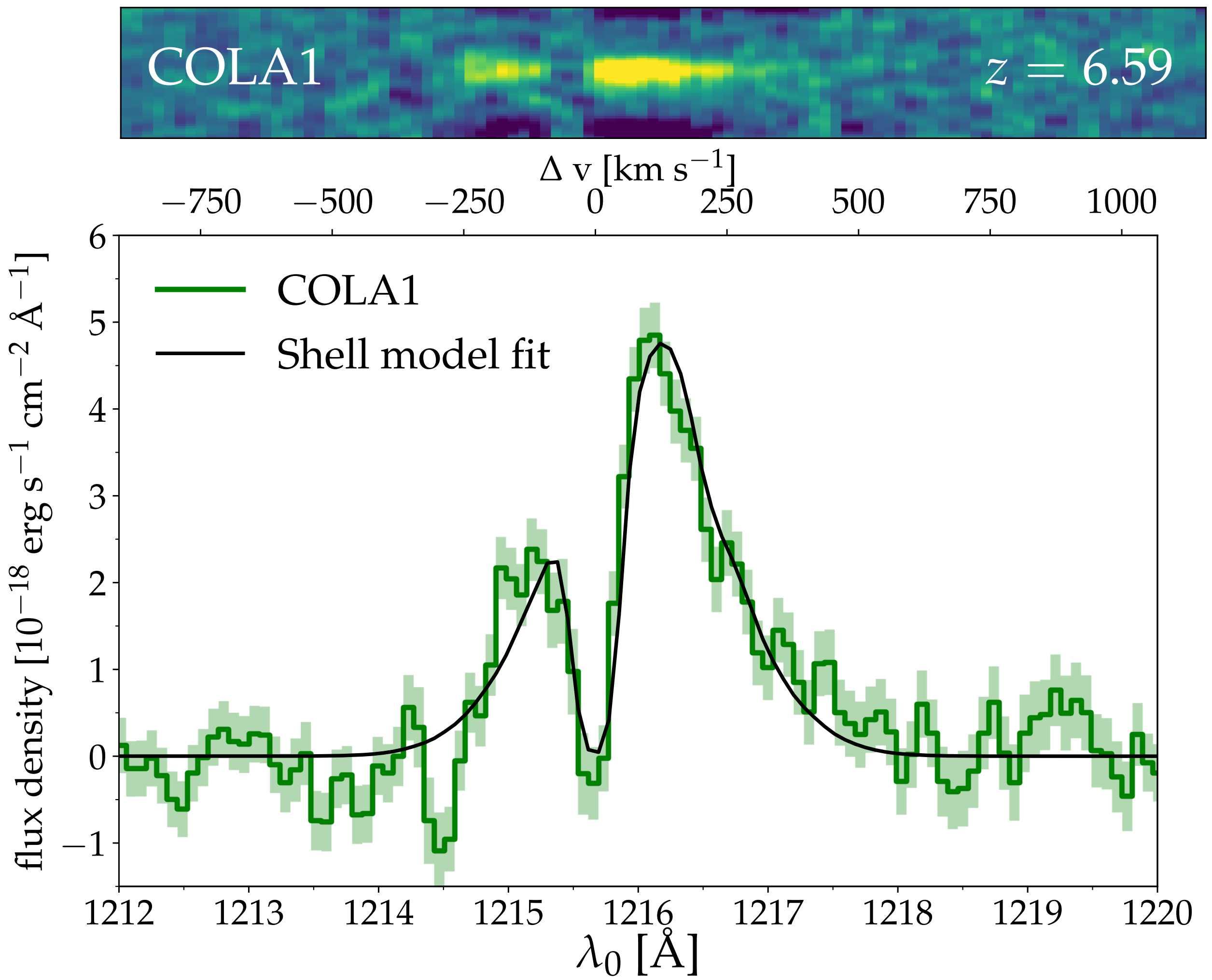


z=6.591

2hrs VLT/X-SHOOTER

Matthee et al. 2018, A&A, 619, 136

COLA1 - double peaked Lya emission at z=6.6

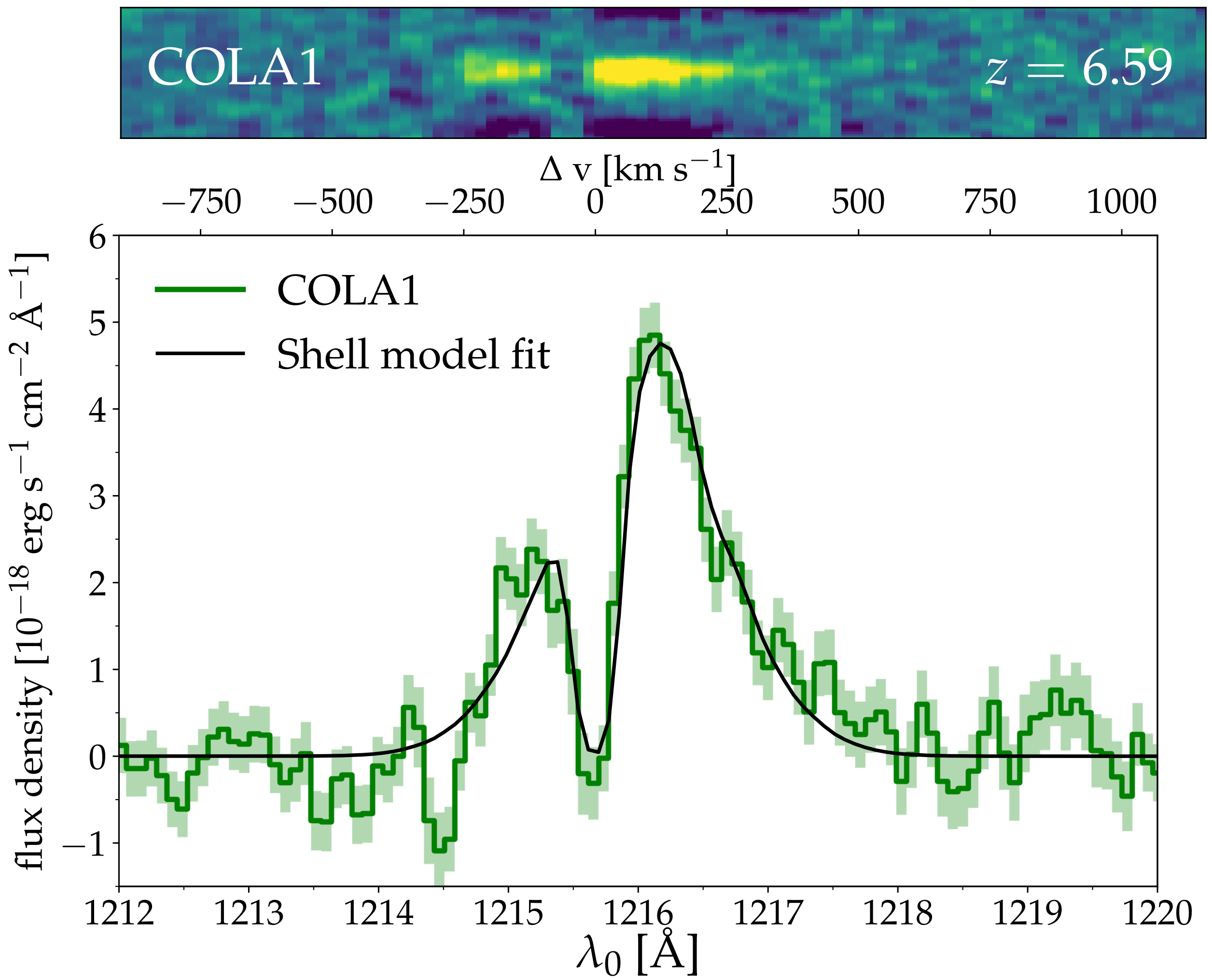


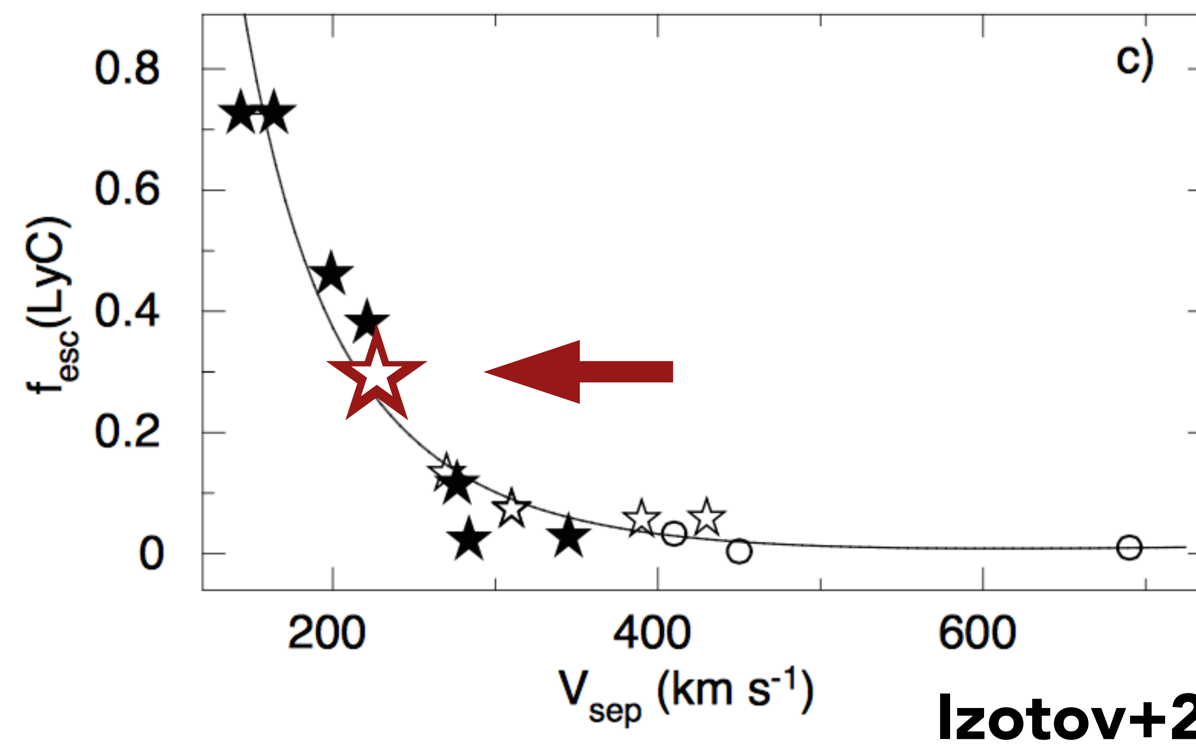
Lya EW$_0$~120 Å   v$_{sep}$ = 220+-20 km s^{-1} :

extremely low column density in the ISM: N$_{HI}$~10^{17} cm^{-2}

Matthee et al. 2018, A&A, 619, 136

COLA1 - DOUBLE PEAKED LYA EMISSION AT Z=6.6





Izotov+2018

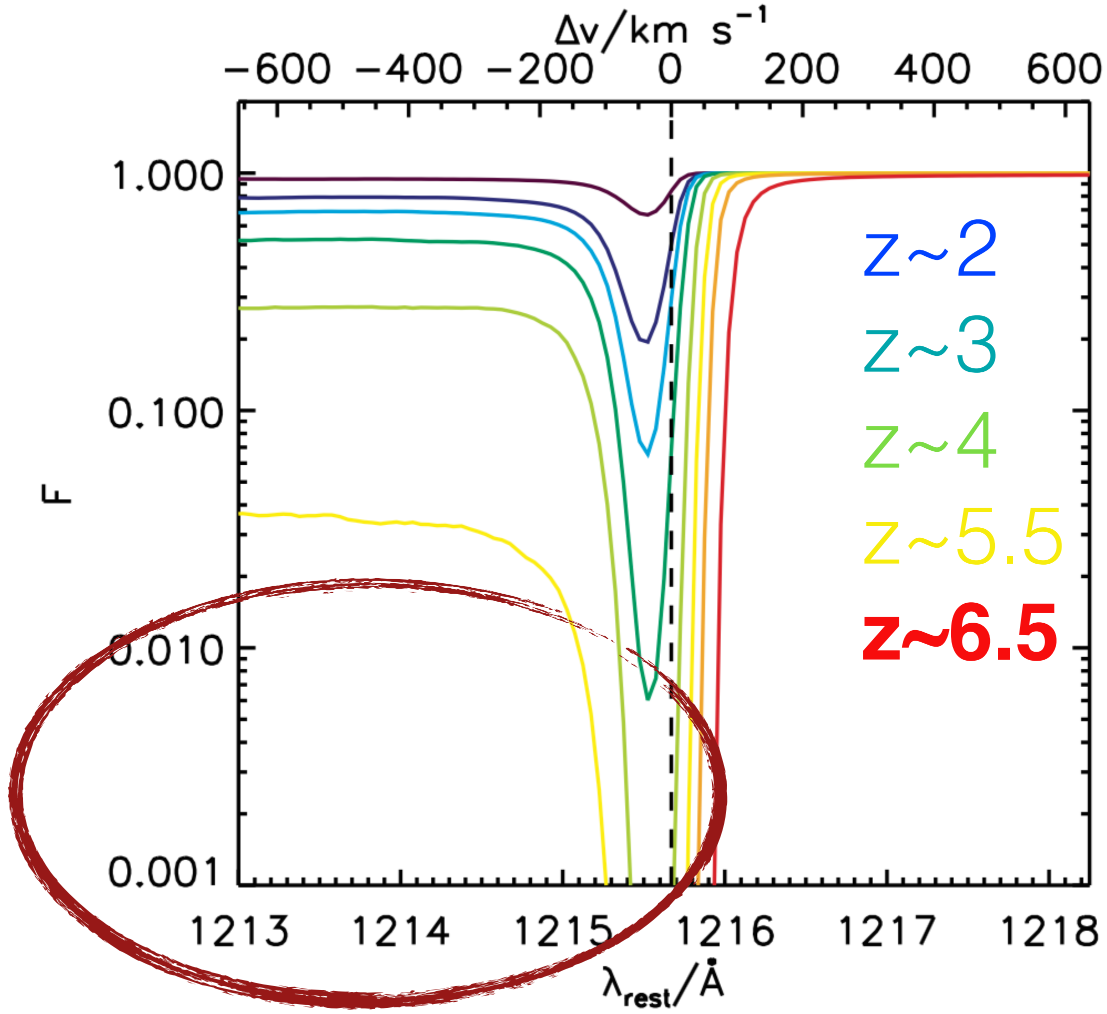
$f_{esc,LyC}$ ~ 30 %

Lya EW_0~120 Å v_{sep} = 220+-20 km s^{-1} :
extremely low column density in the ISM: N_{HI}~10^{17} cm^{-2}

<u>Directly witnessing a galaxy contributing to reionization!</u>

Matthee et al. 2018, A&A, 619, 136

How can we see double peaked Lya emission at z=6.6?

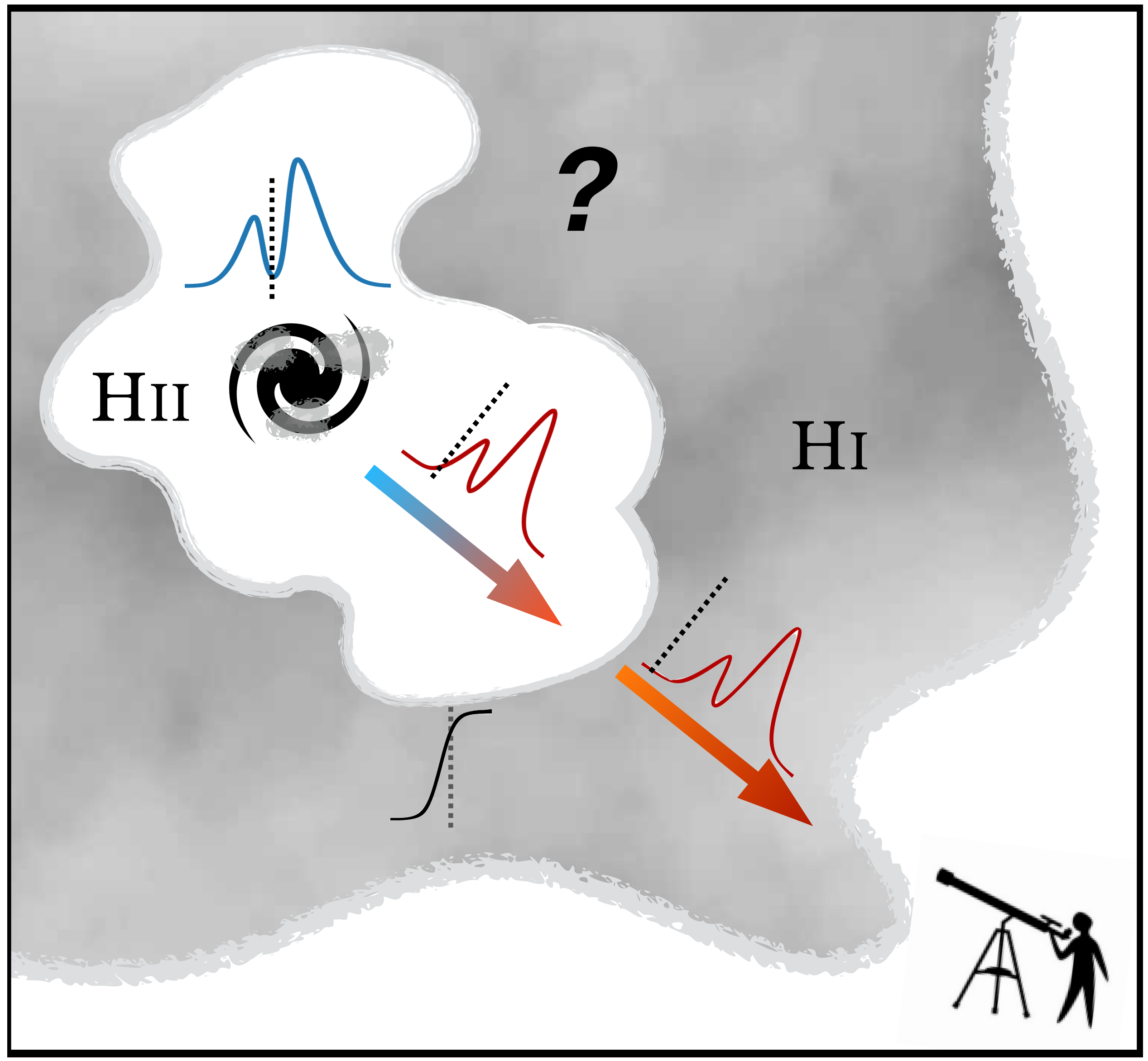


Laursen+2011

Transmission at the blue “should be” < 0.001 at z~6.5

*** in case of uniform UV background**

How can we see double peaked Lyα emission at z=6.6?

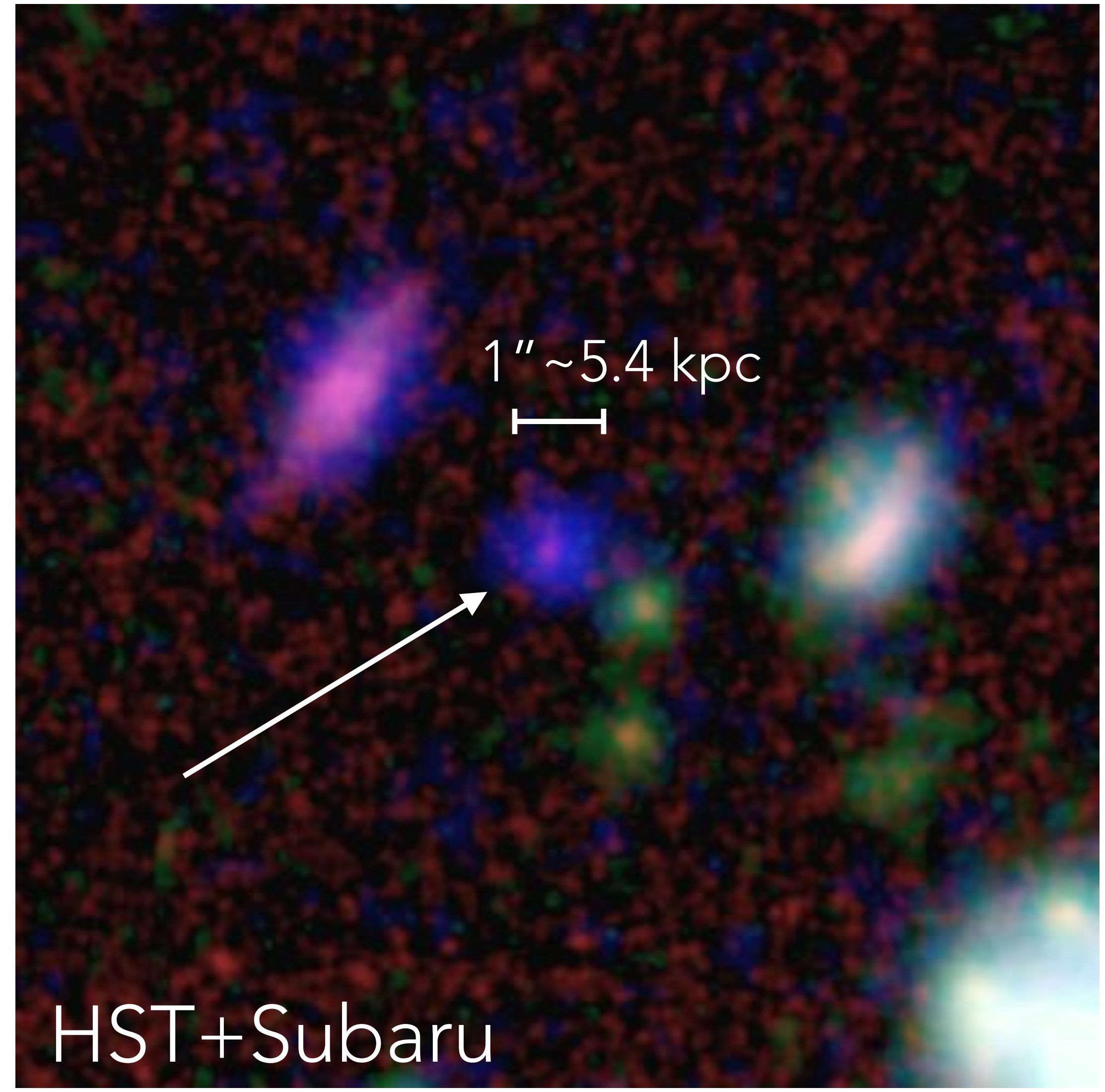


Need to ionise 0.3 pMpc to redshift 220 km s^{-1} on the Hubble flow

Could COLA1 host an ionised bubble on its own?

Relevant properties:

* $f_{esc,LyC} \sim 30$ % (Lya profile)
* SFR=30±10 M_{sun}/yr (*Y* band)



Also interesting…

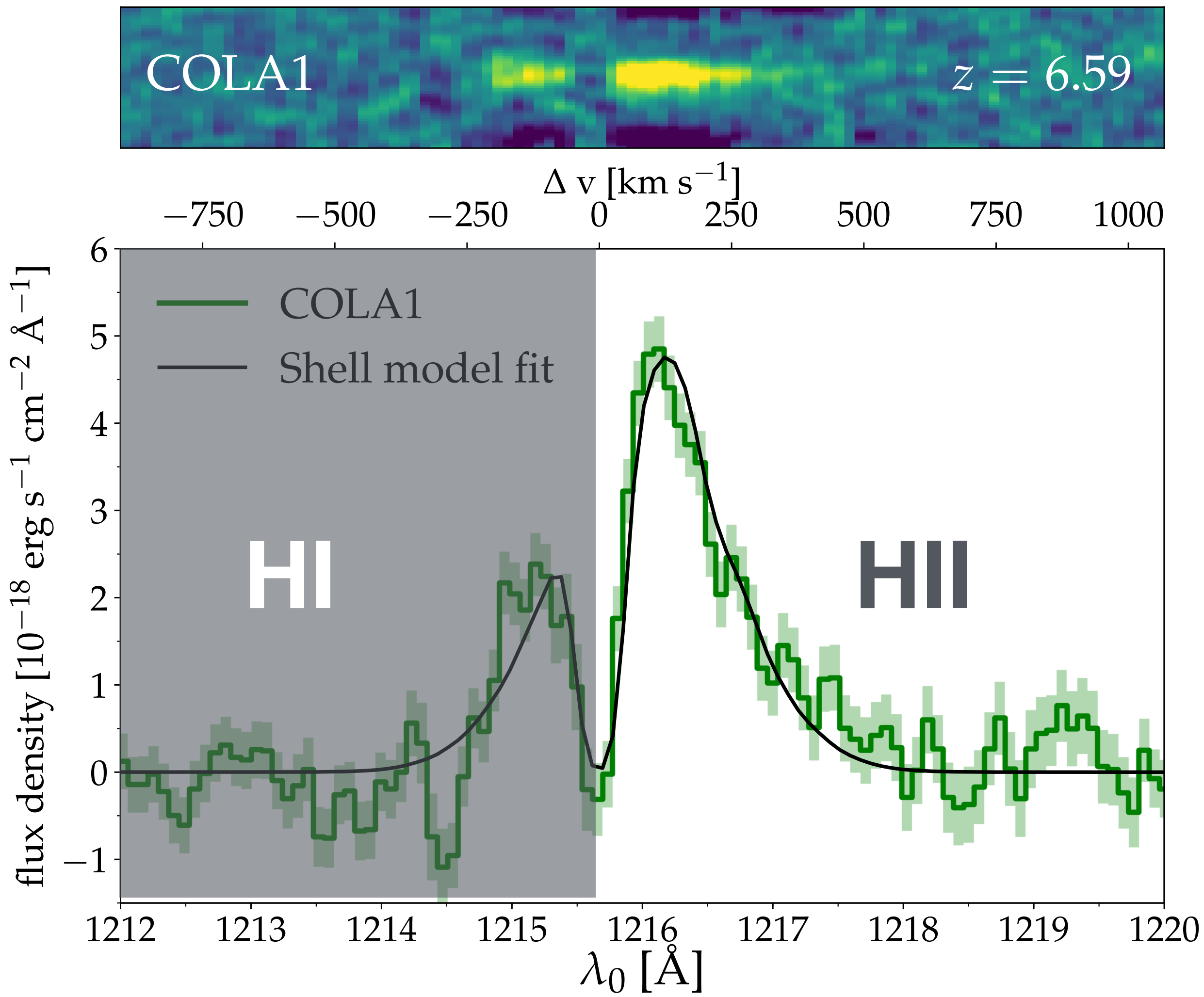
* Compact: r_{50} = 0.3 kpc (0.06”)
* *relatively* flat IRAC [3.6]-[4.5]:
  low [OIII]+Hβ: low metallicity?

c.f. talk by Roberts-Borsani

Note the systemic redshift is not known yet, but likely between the Lya lines

Matthee et al. 2018, A&A, 619, 136

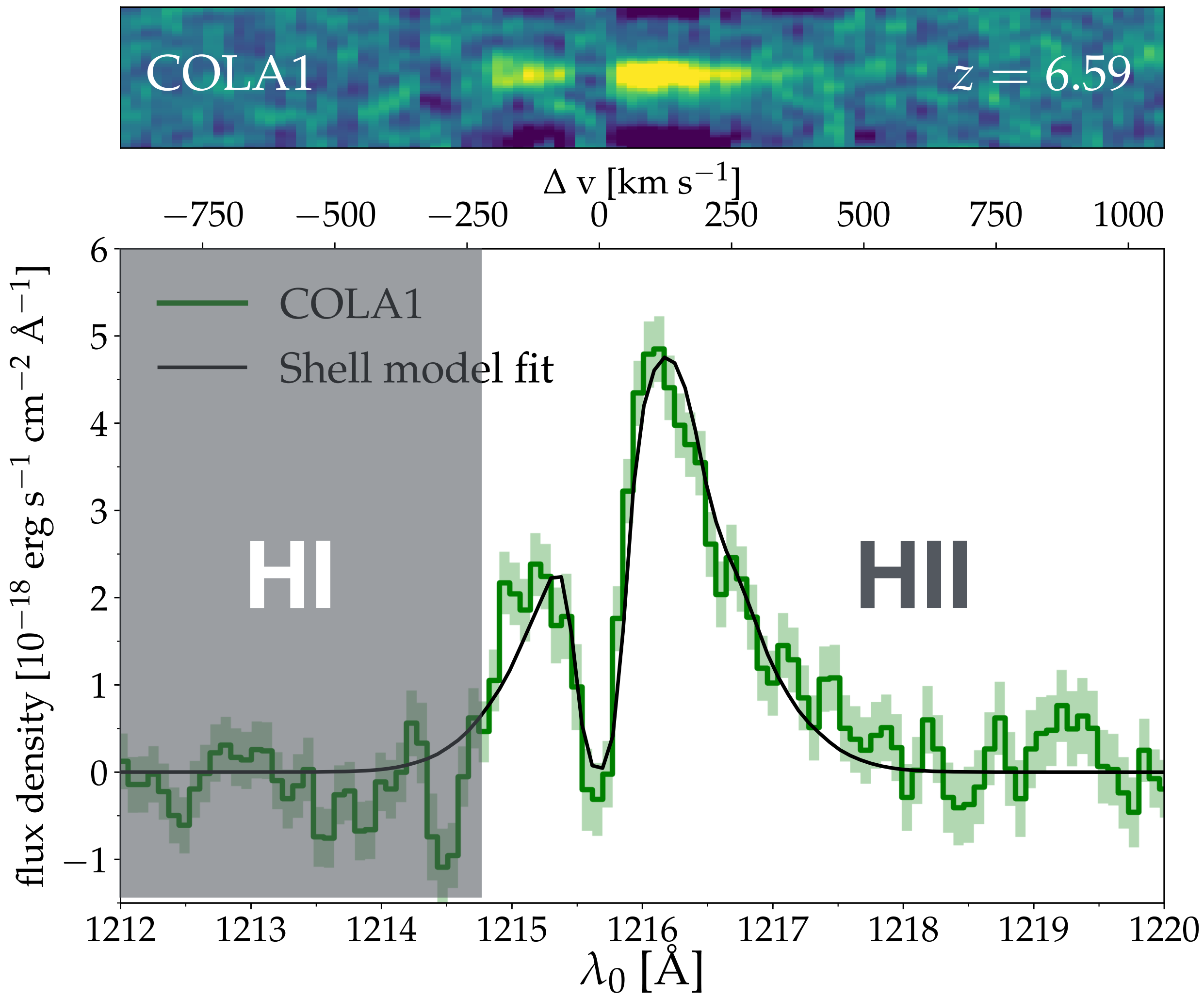
COLA1 - CAN THE BLUE PEAK BE EXPLAINED WITH A BUBBLE?



Adopt:

f_{esc} =15 %, SFR=30 M_{sun}/yr, ξ_{ion}=$10^{25.4}$ Hz erg^{-1} (e.g. Bouwens+2016):

COLA1 - CAN THE BLUE PEAK BE EXPLAINED WITH A BUBBLE?



Adopt:

f_{esc} =15 %, SFR=30 M_{sun}/yr, ξ_{ion}=$10^{25.4}$ Hz erg^{-1} (e.g. Bouwens+2016):

☑ **ionises the required 0.3 pMpc in 10^7 yr**

see also talk by Castellano on bright galaxies in bubbles

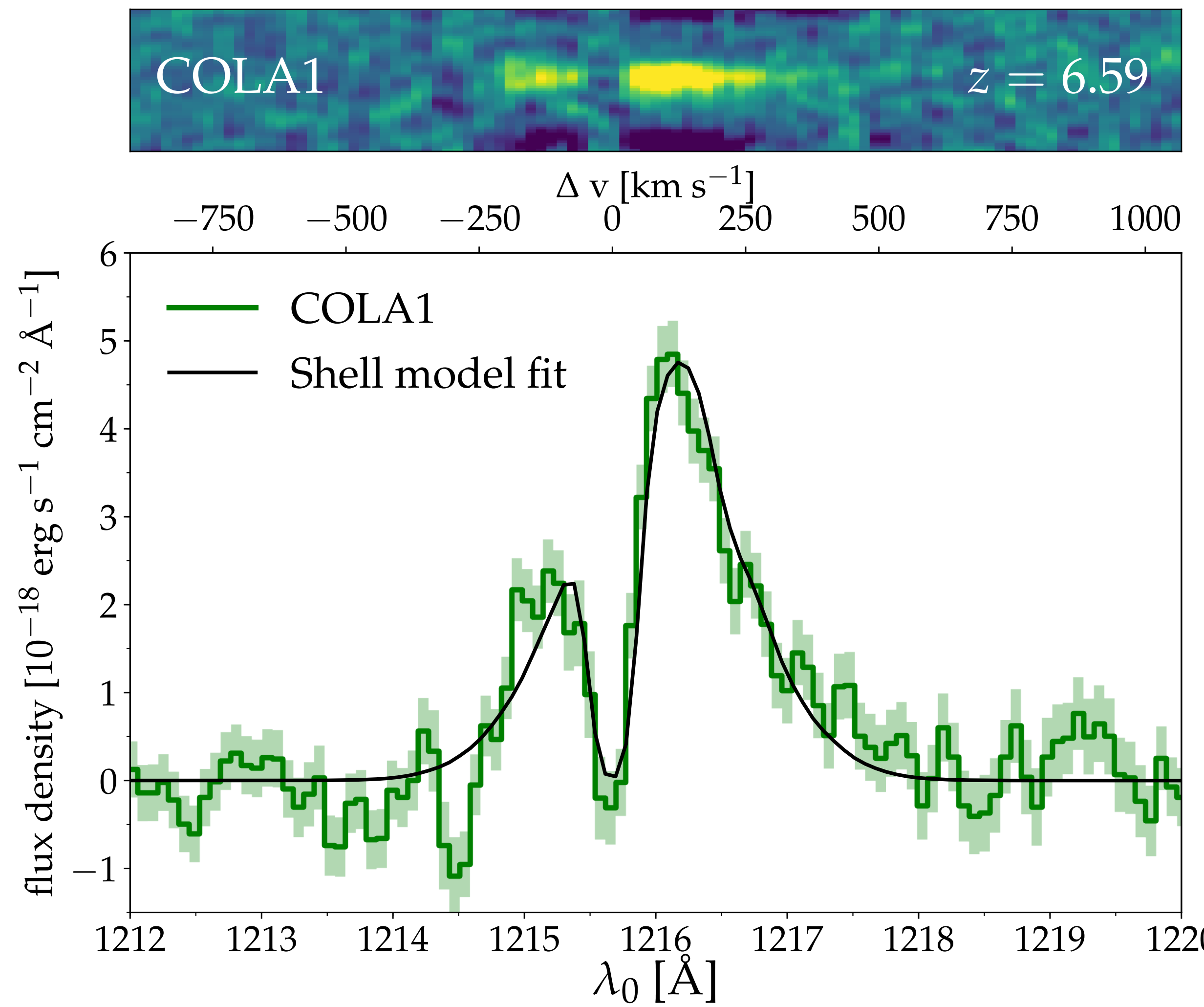
COLA1 - AN AGENT *AND* A TRACER OF REIONISATION

<u>**Prospects — Statistics needed!**</u>

*** Are there more of such systems?**

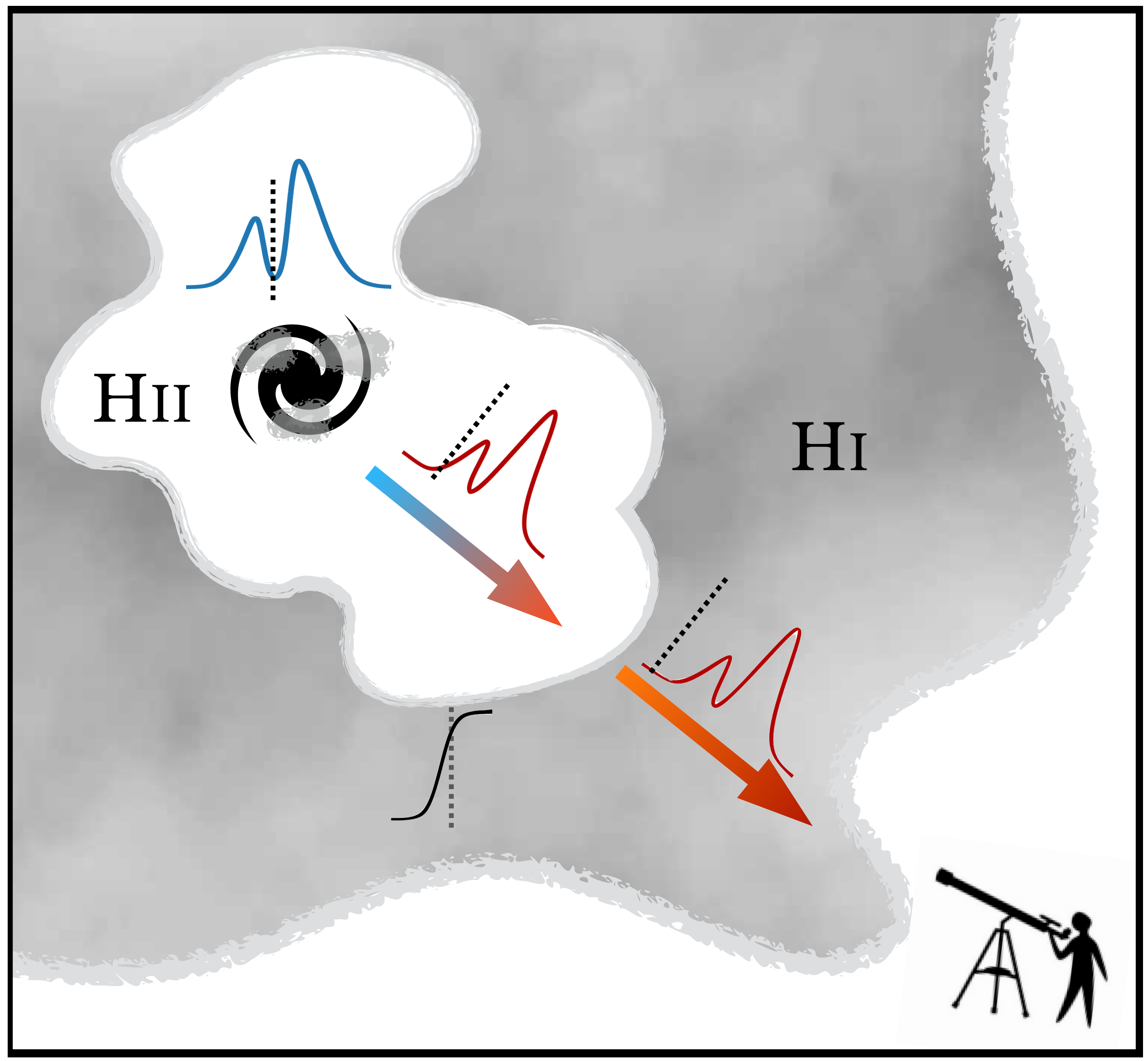
*** How abundant are they at z~0-6?**

*** Can we use them to get p(f_{esc} | M_{1500}, *z*)**



Exciting prospects for further <u>10m-class</u> follow-up!

Matthee et al. 2018, A&A, 619, 136



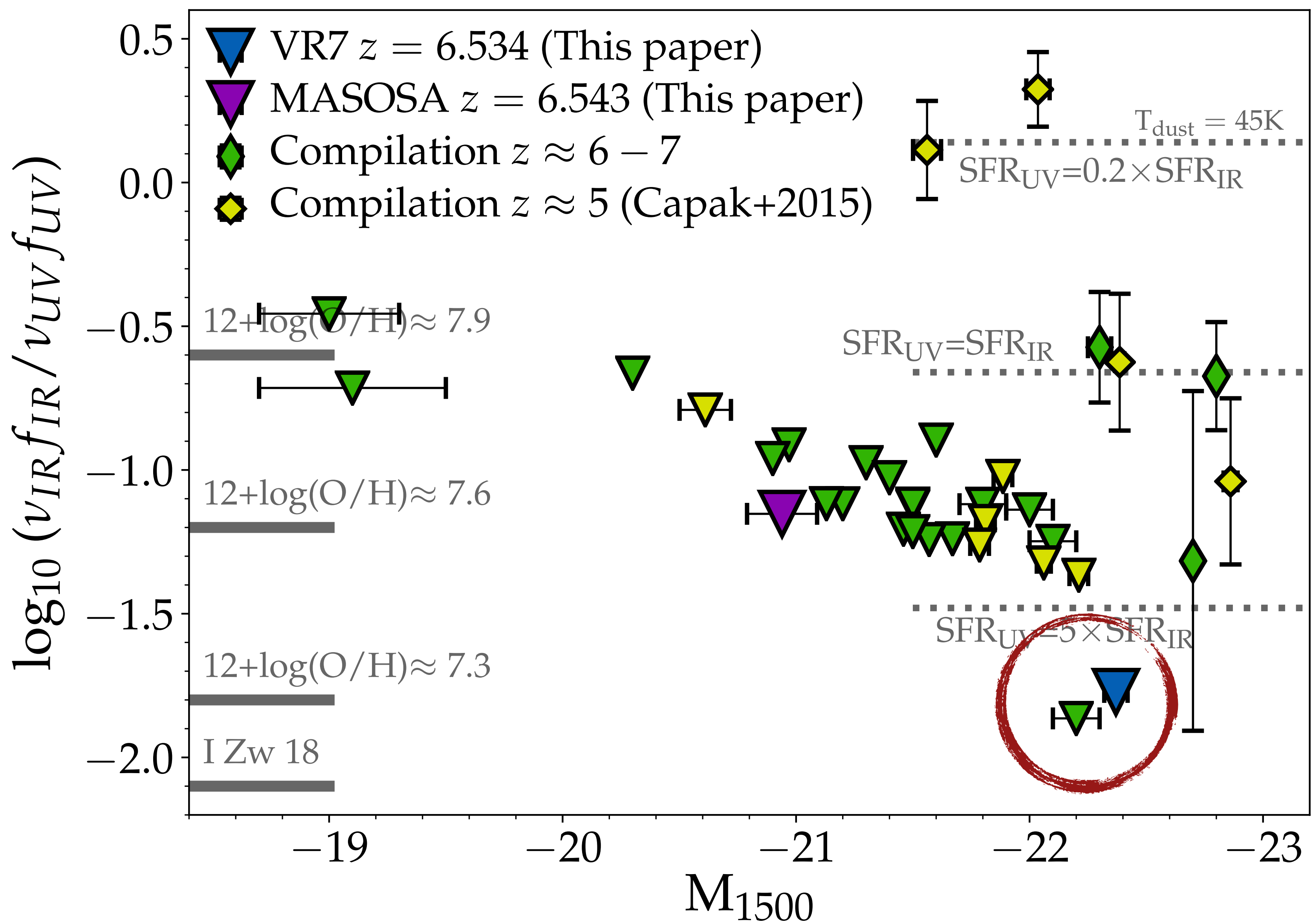
H II
H I

ALMA, HST & MUSE view of luminous LAEs

HST: rest-frame UV continuum
MUSE: Lyman-alpha
ALMA: [CII] 158 micron cooling line & dust continuum

ALMA: (No) Dust continuum in high-z LAEs

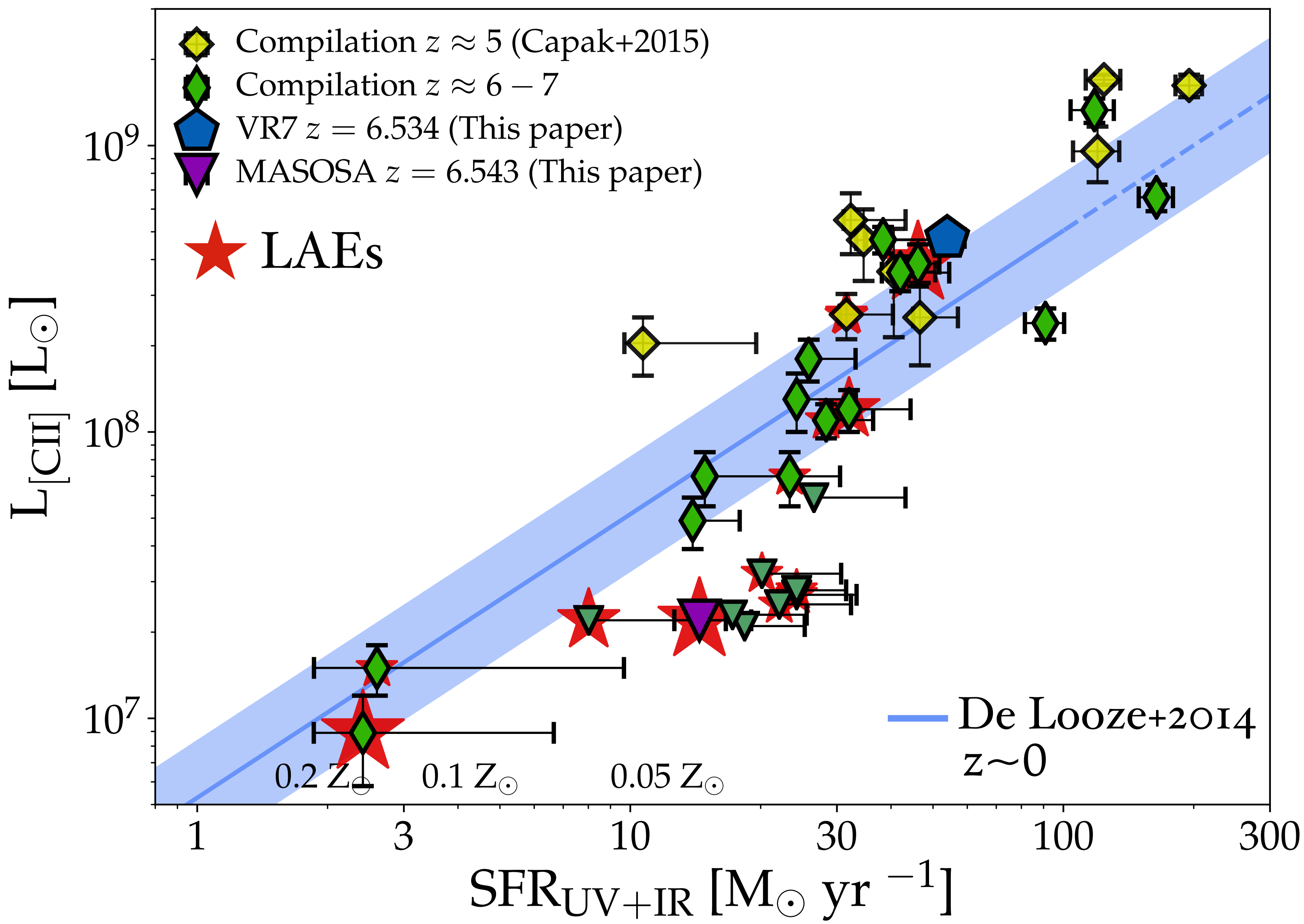
IR continuum / UV flux



Detecting dust continuum (or not) depends on M_{1500}

Matthee et al. 2019, ApJ, 881, 124

Integrated relation between $[CII]_{158\mu m}$ - UV luminosity

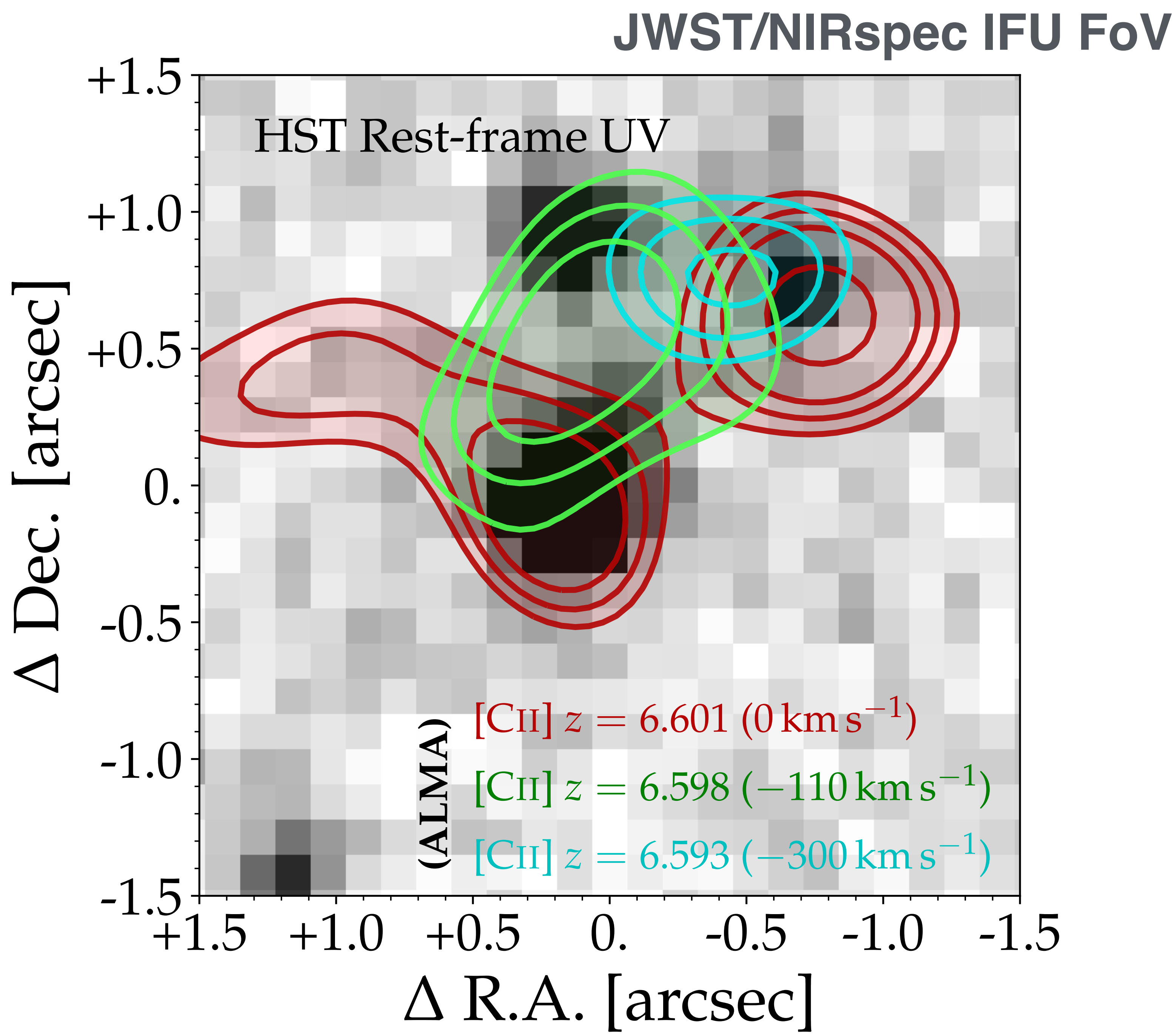


* No [CII] deficit for SFR > 25 M_{sun} yr^{-1}

* Below L^*_{UV} steeper relation than steeper at low redshift,
but significant scatter

Matthee et al. 2019, ApJ, 881, 124

THE FUTURE IS RESOLVED: ALMA + HST+ JWST/NIRSPEC + ELT



CR7:

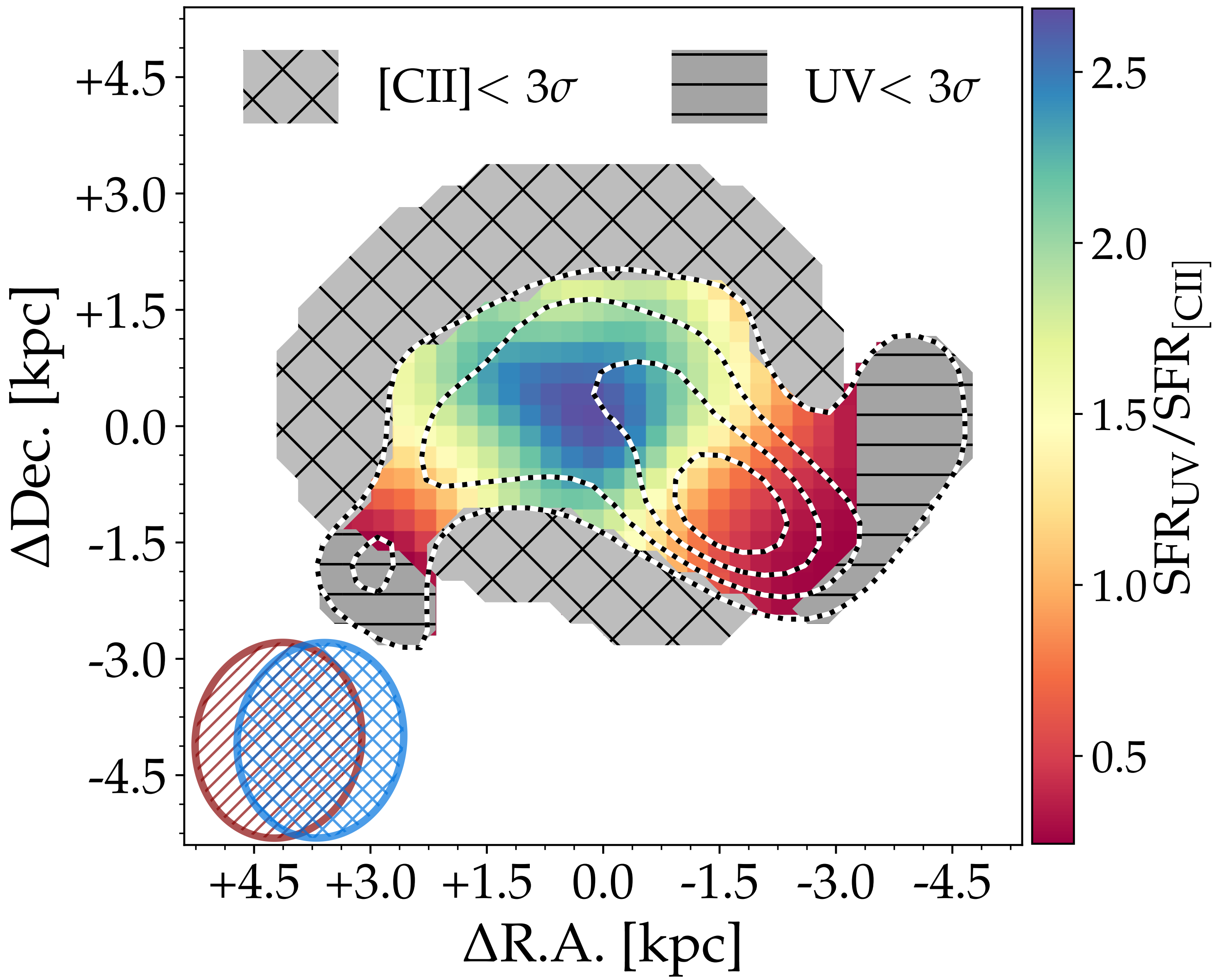
z=6.60, very high Lya EW, UV bright
3 UV components, 4 [CII] components
dispersion dominated on ~> 2kpc scales

Matthee et al. 2017, ApJ, 851, 145; Sobral et al. 2019, MNRAS, 482, 2422

VR7 with HST/WFC3 & ALMA:

z=6.53, bright Lyman-break galaxy, "typical" Lya EW

2 UV & [CII] components



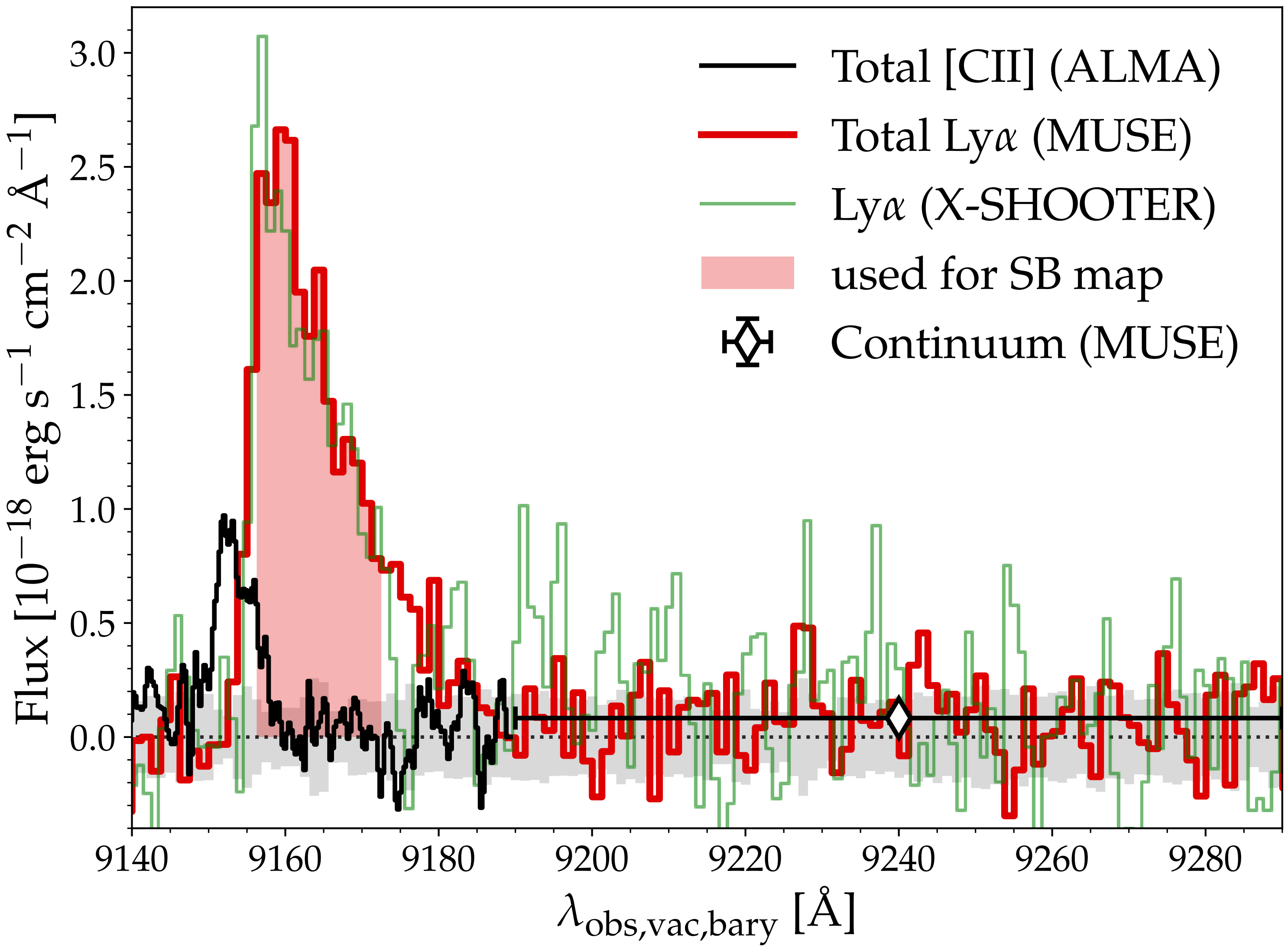
UV/[CII] variations of factors ~5 on ~2 kpc scales

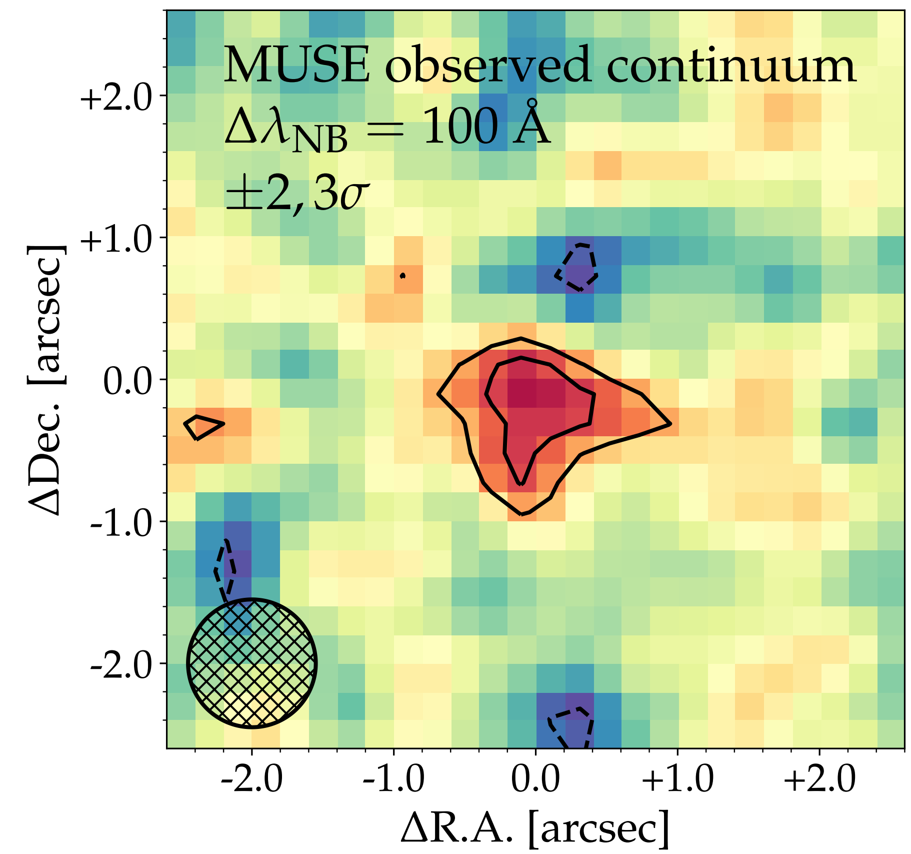
— metallicity? density? burstiness?

Matthee et al. 2019, ApJ, 881, 124

VR7 with VLT/MUSE:

z=6.53, bright Lyman-break galaxy, “typical” Lya EW
2 UV & [CII] components



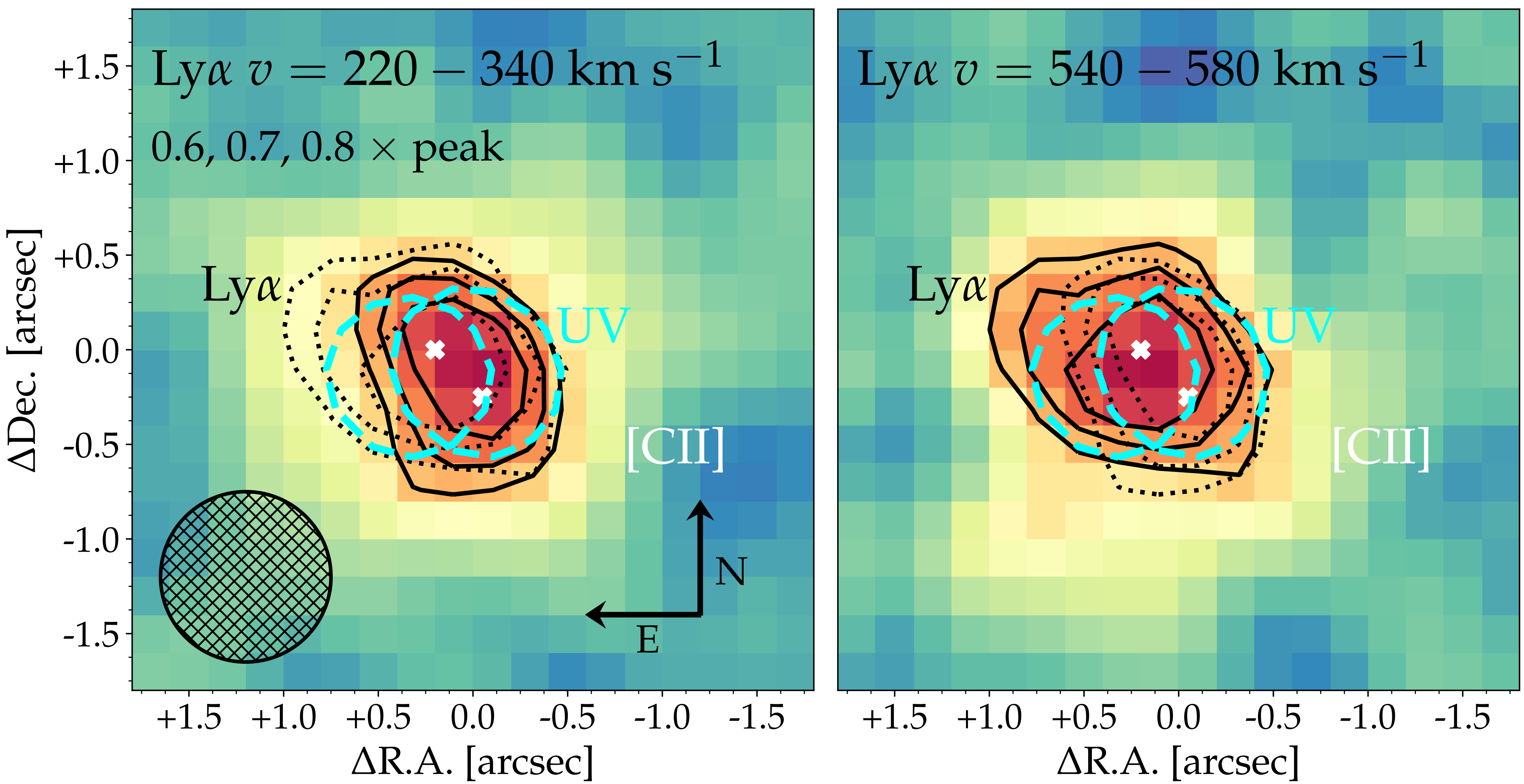


VLT/MUSE detects UV continuum of a z~6.5 star-forming galaxy in 5 hr (Non-AO, 0.9” seeing)

Matthee et al. submitted (arXiv: 1909.06376)

VR7 with VLT/MUSE:

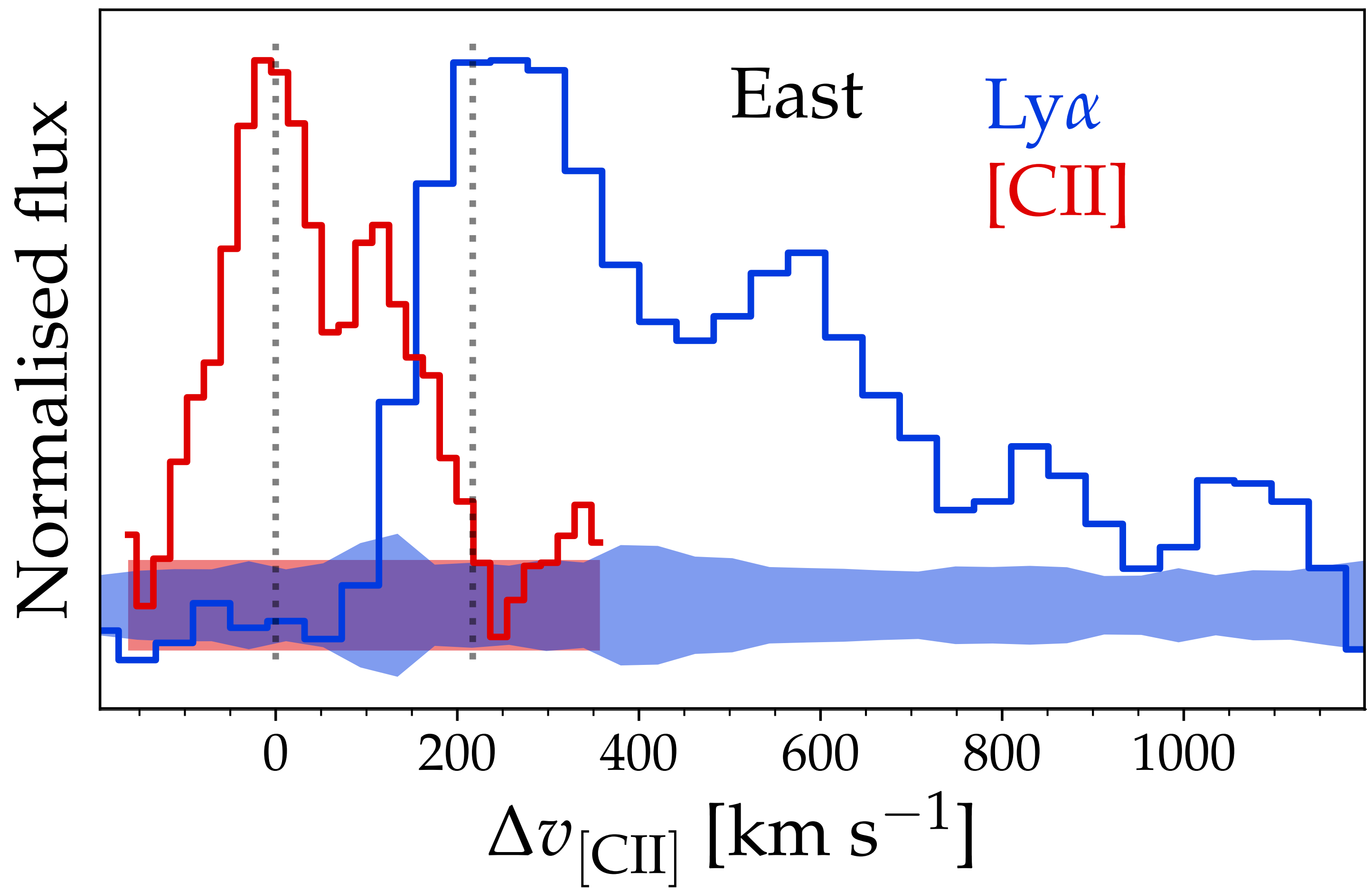
z=6.53, bright Lyman-break galaxy, “typical” Lya EW
2 UV & [CII] components



IFU data reveals two Lyman-alpha components, coincide with UV

Matthee et al. submitted (arXiv: 1909.06376)

ALMA & VLT/MUSE:
Comparing [CII] and Lya spectral line profiles in VR7



Lya is redshifted & broader compared to [CII]

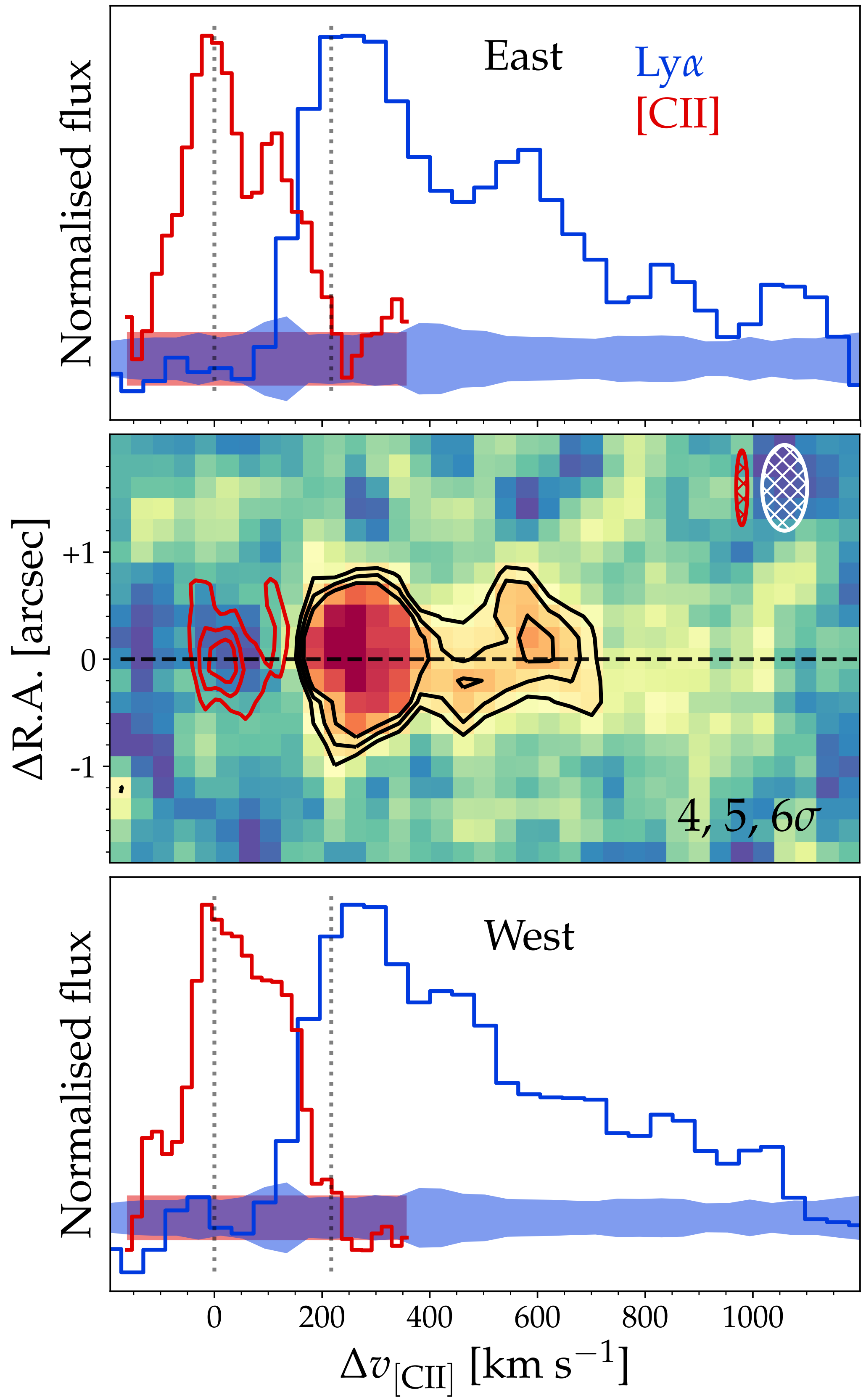
… but qualitatively [CII] and Lya profiles remarkably similar

see also resemblance [CII] and Lya extent (Fujimoto's talk)

Matthee et al. submitted (arXiv: 1909.06376)

ALMA & VLT/MUSE:

Complex *resolved* [CII] and Lya line profile in VR7



East:
Second faint Lya component
Δv_{Lya} = +460 kms

West:
dominated by bright Lya source
Δv_{Lya} = +220 kms

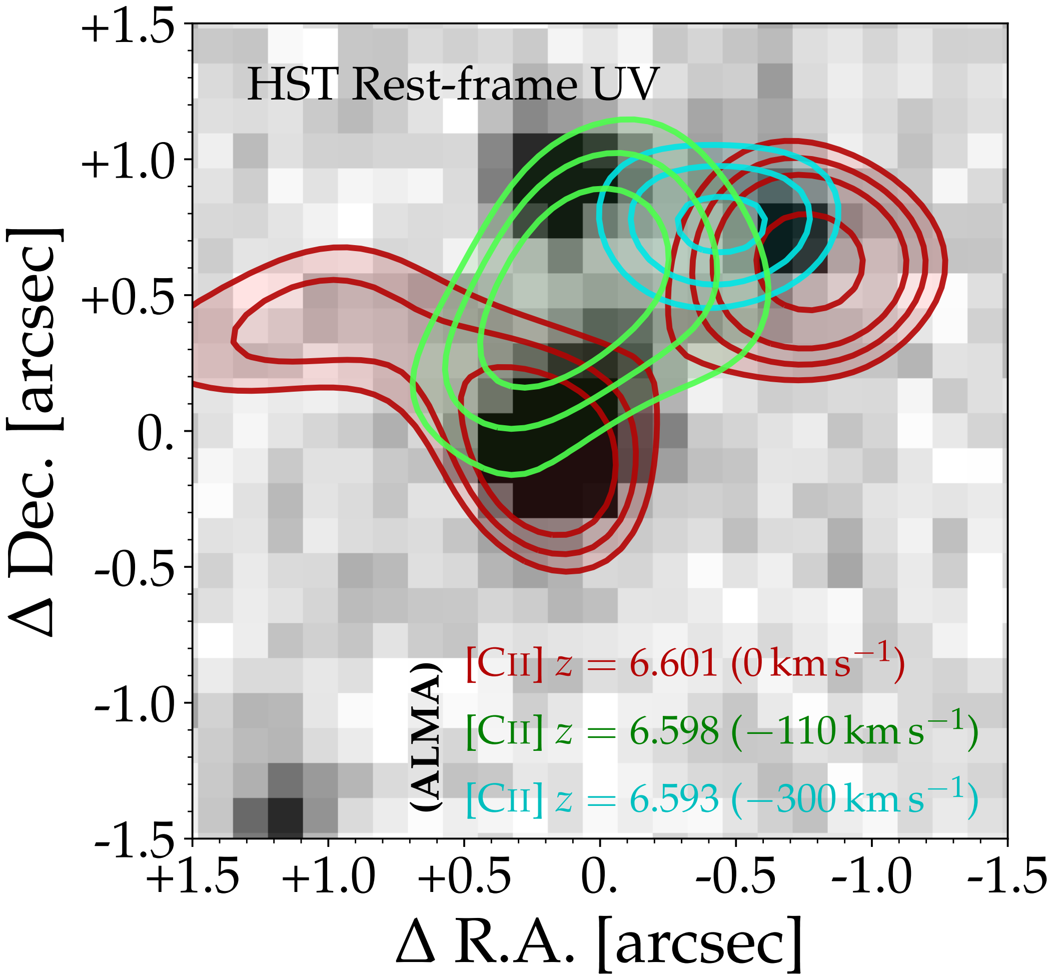
→ **spatially varying N_{HI}**
Δv_{Lya} variations have local origin

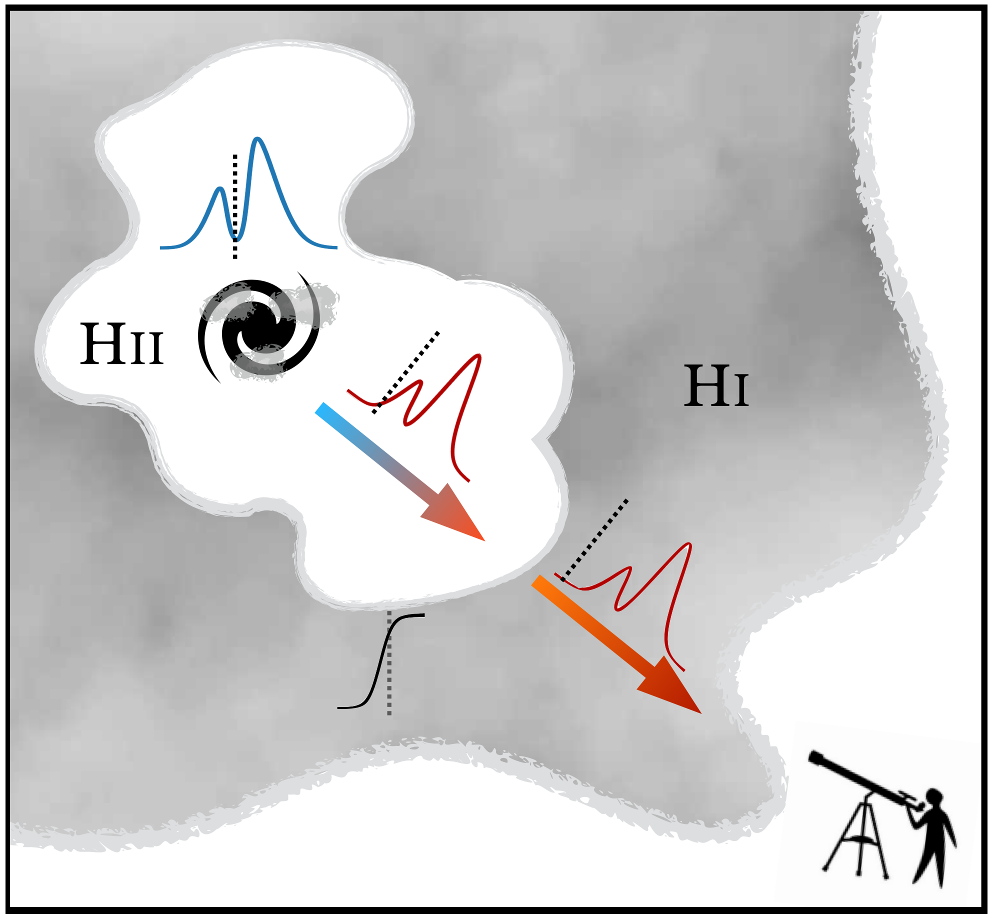
Matthee et al. submitted (arXiv: 1909.06376)

Recap - Luminous LAEs at z~7:

Build-up of massive galaxies through assembly of multiple components

These galaxies reside in large (re)ionised bubbles





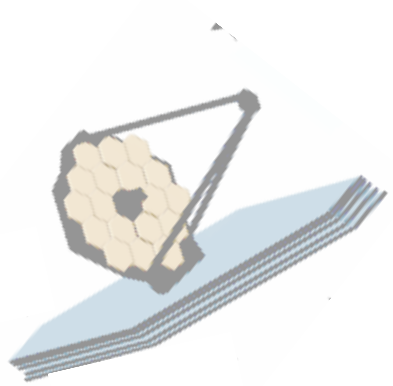
Matthee et al. 2018, A&A, 619, 136

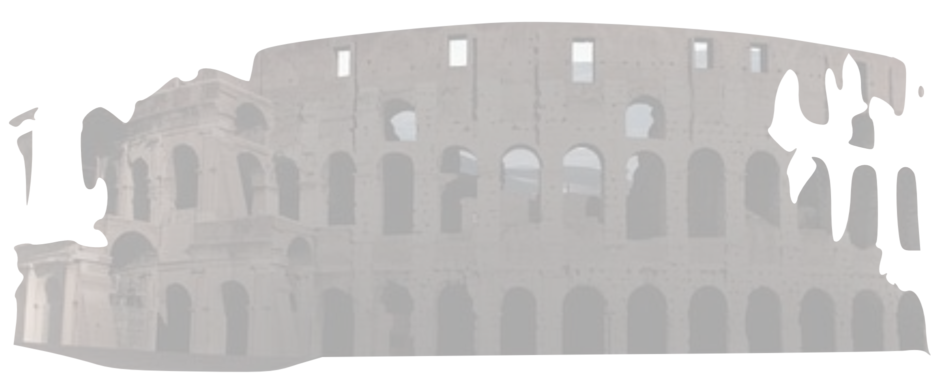
Prospects for future "Big Eyes" *regarding bright EoR galaxies

J~25

Deep, *spatially* and *spectrally* resolved spectroscopy 1-5 micron (ELTs+JWST)

- **Fraction of (UV) light faint AGN vs star-formation? Early SMBH formation?**
- **Stellar metallicity? Binaries? Any signs for PopIII? (yields?) (in satellites?)**
- **ISM abundances (O/H, C/O, N/O), Z_{gas} vs Z_{stars} (alpha-enhancement?)**
- **ISM densities, temperature**





TAKE AWAY POINTS:

- **High resolution Lyman-alpha observations are an extremely powerful probe of the HI structure *in* and *around* high-z galaxies**

- **COLA1 - the first double peaked LAE at z>6 resides in a highly ionised bubble and has $f_{esc,Lyc}$ ~30%**

- **Luminous galaxies are clumpy: [CII]/UV may vary by factors ~5 on ~2 kpc scales.**

- **Overall trends in spatial variations in [CII] profile are *preserved* in spatial variations of Lya profile**

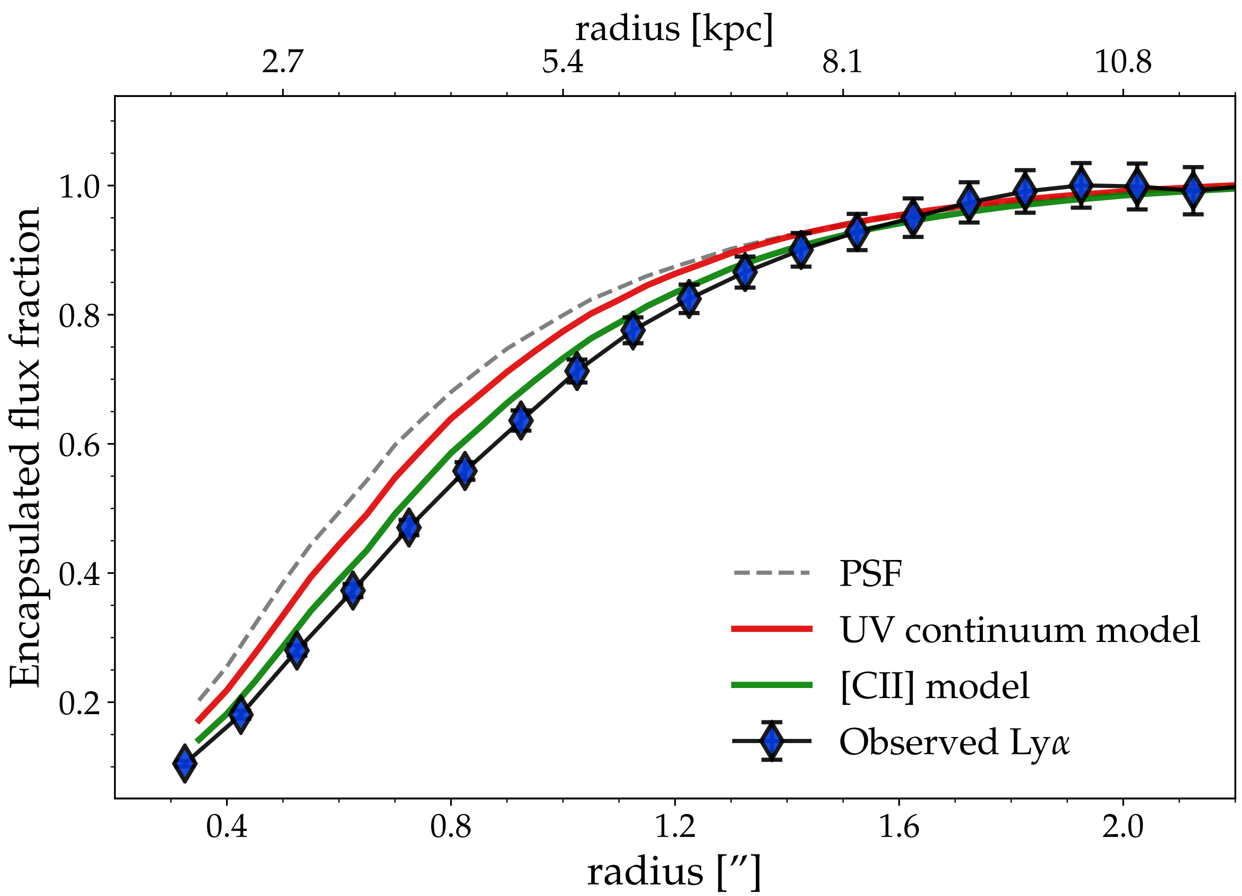
COLA1 - double peaked LAE: Matthee et al. 2018, A&A, 619, 136

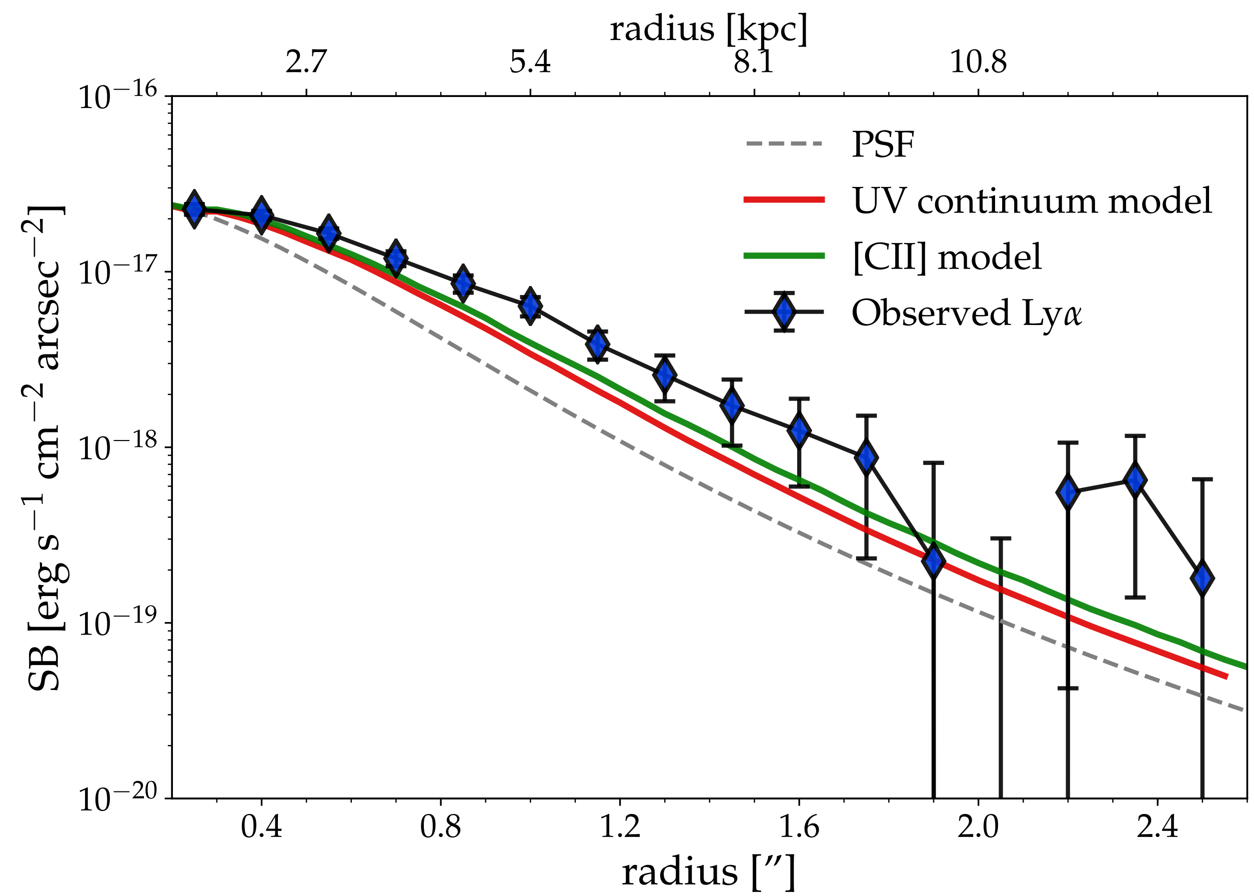
Resolved [CII] in high-z LAEs: Matthee et al. 2019, ApJ, 881, 124

Resolved Lya in high-z LBG: Matthee et al. submitted (arXiv: 1909.06376)

Extra slides

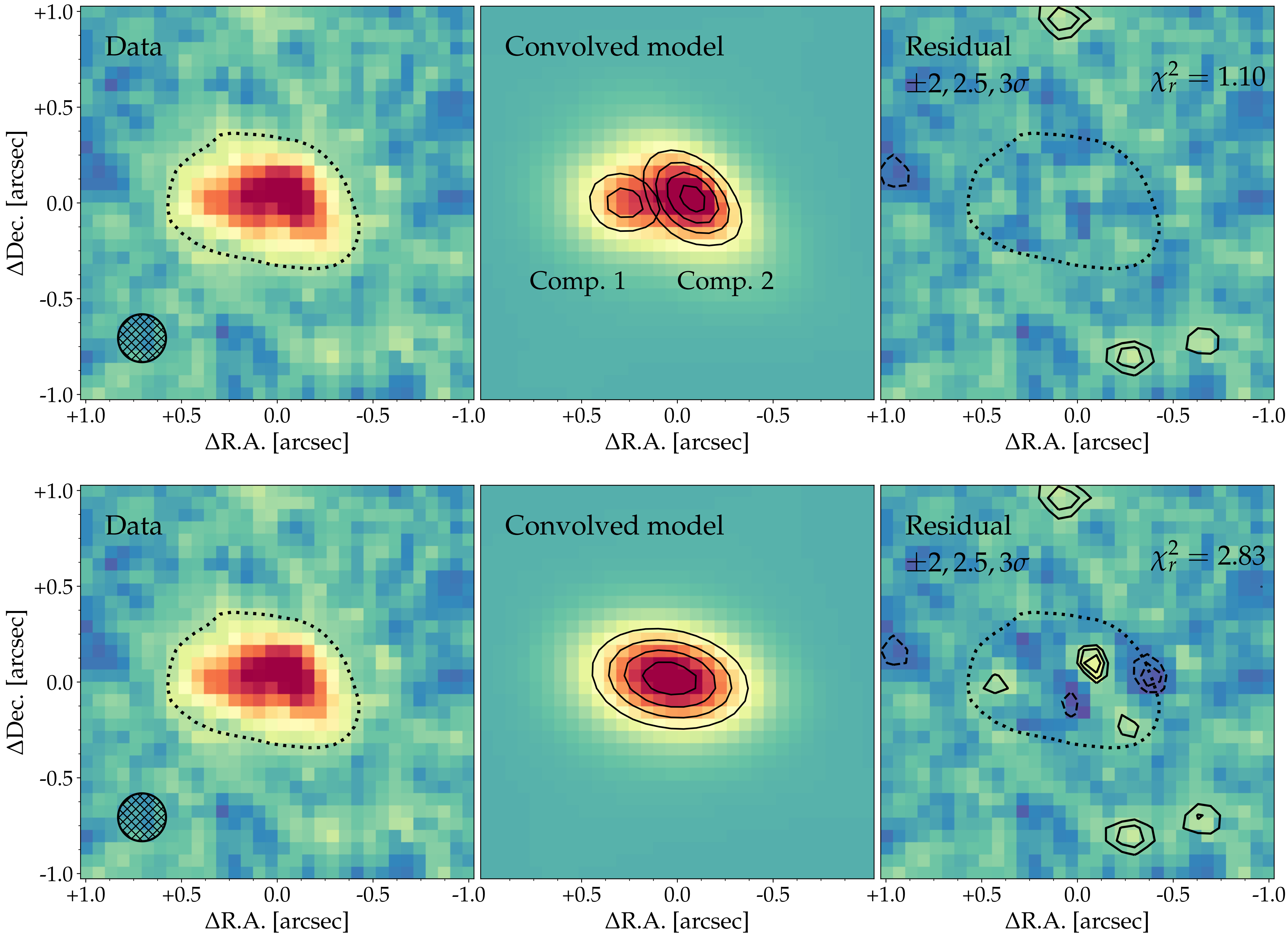
VR7: growth curves of UV, [CII] and Lya





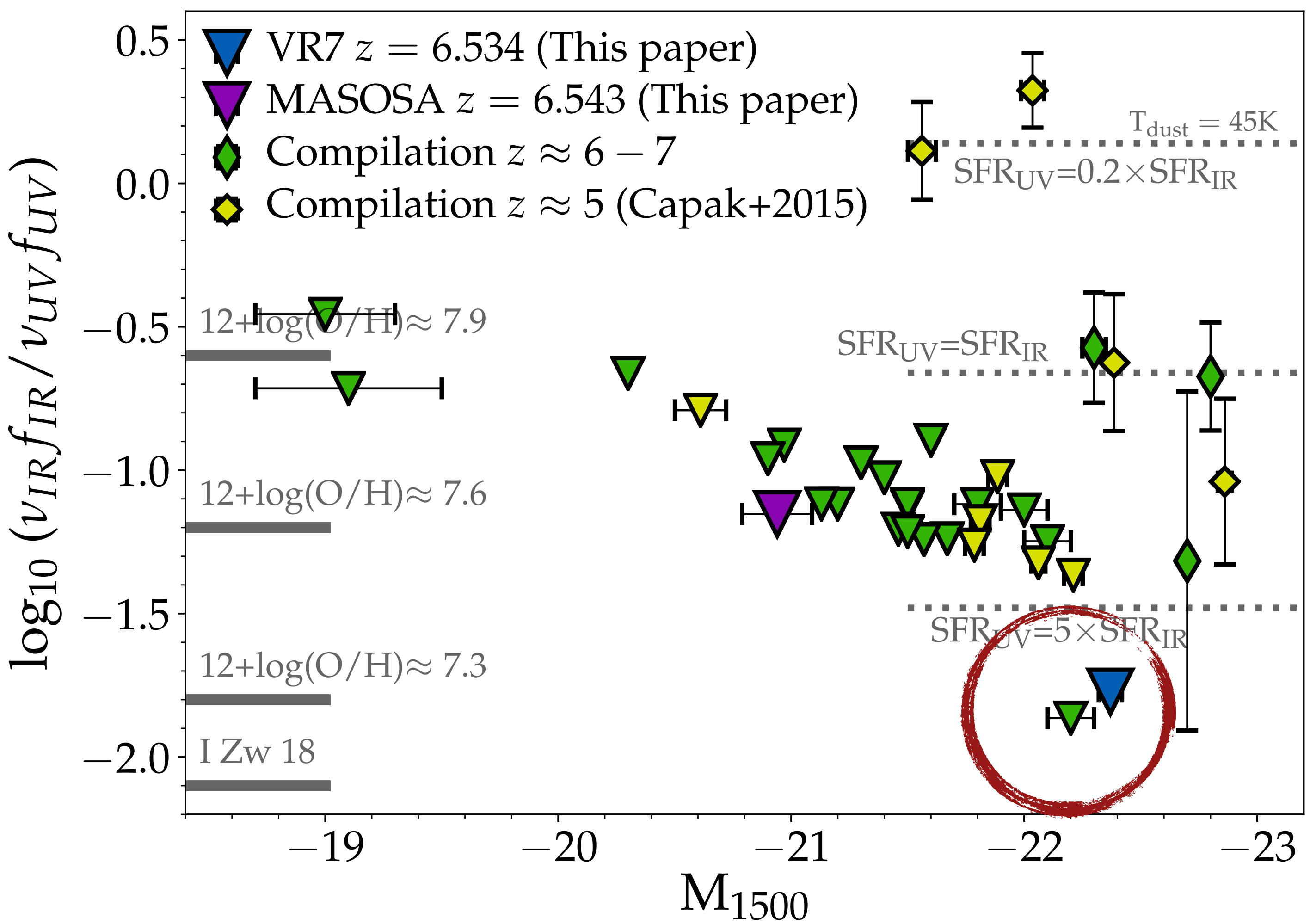
Matthee et al. submitted (arXiv: 1909.06376)

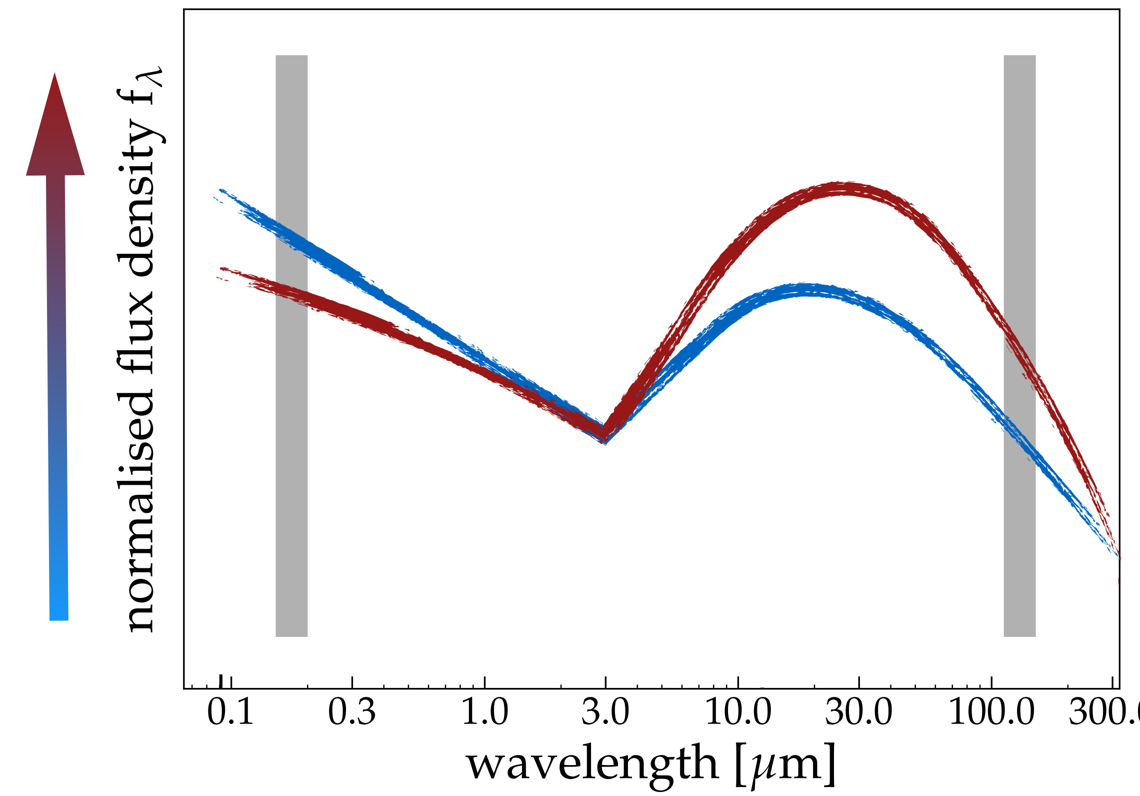
Multiple components in VR7 — HST/WFC3



Matthee et al. 2019, arXiv: 1903.08171

(No) Dust continuum in high-z LAEs



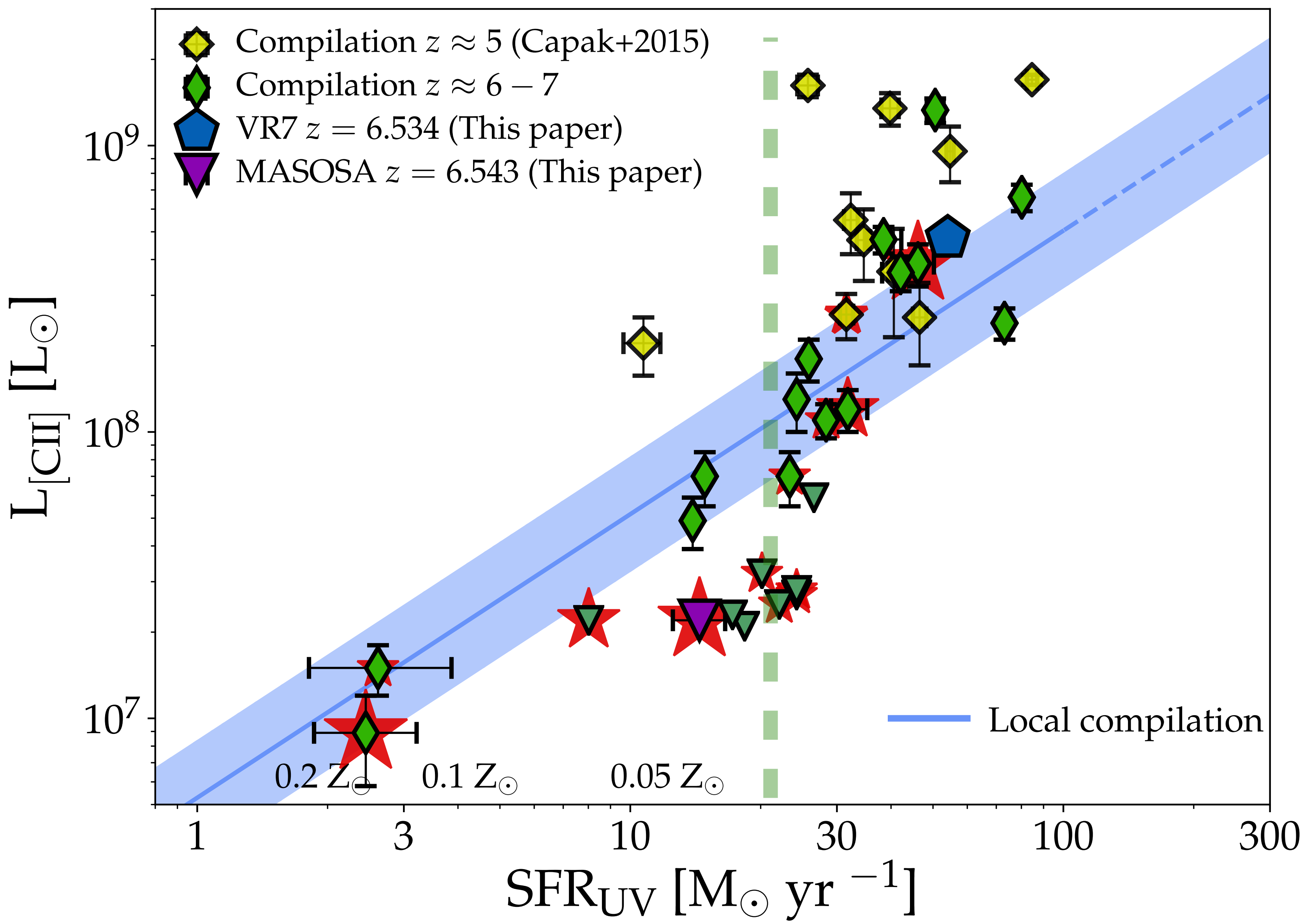


Luminous LAEs have lowest $f_{160\mu m}/f_{1500Å}$ ratios

T_{dust}~70-90K in case $SFR_{UV} = SFR_{IR}$

Matthee et al. 2019, arXiv: 1903.08171

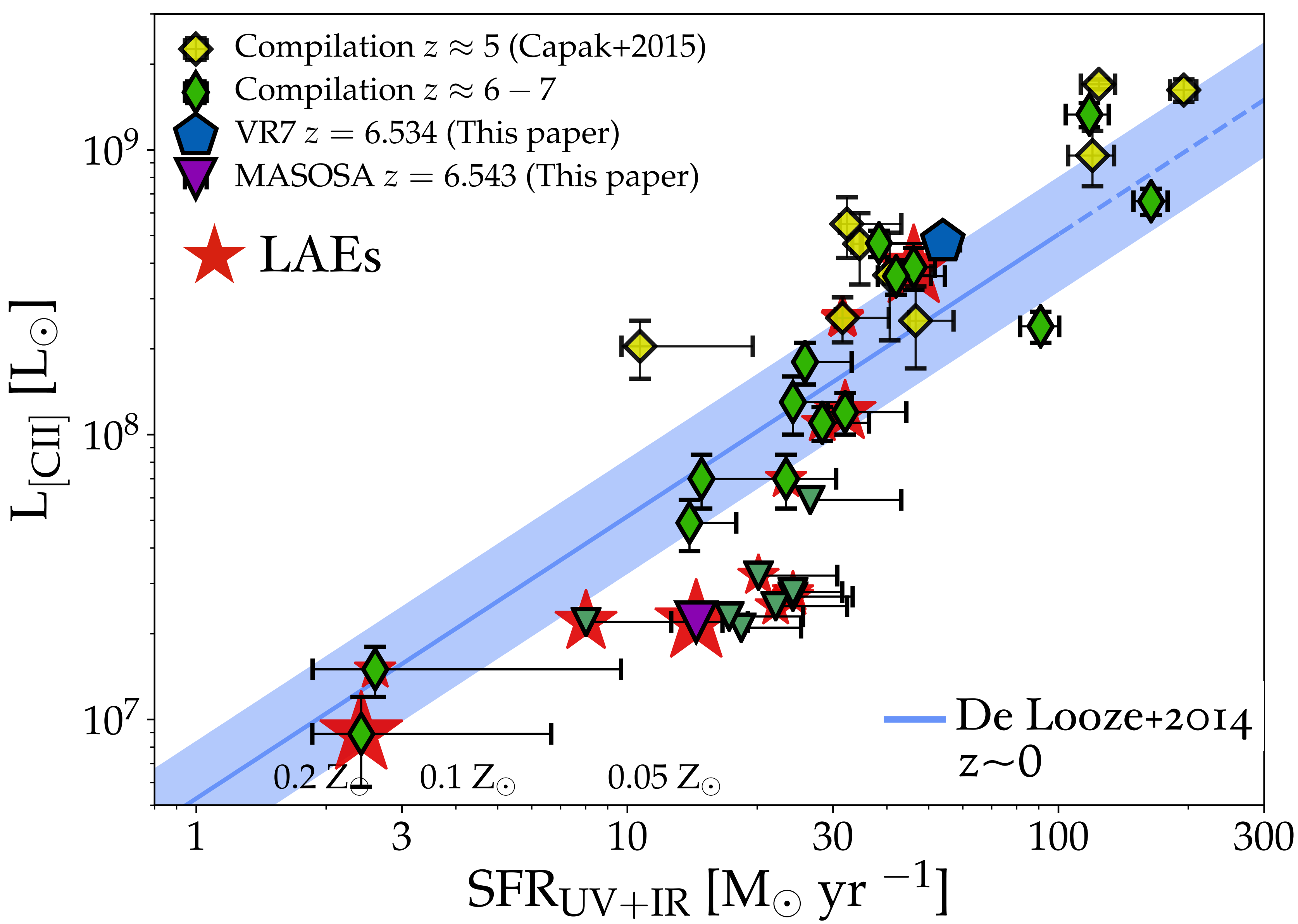
Integrated relation between $[CII]_{158}$ - UV luminosity



Extremely steep dependence [CII] - UV for *observed* UV luminosity

Matthee et al. 2019, arXiv: 1903.08171

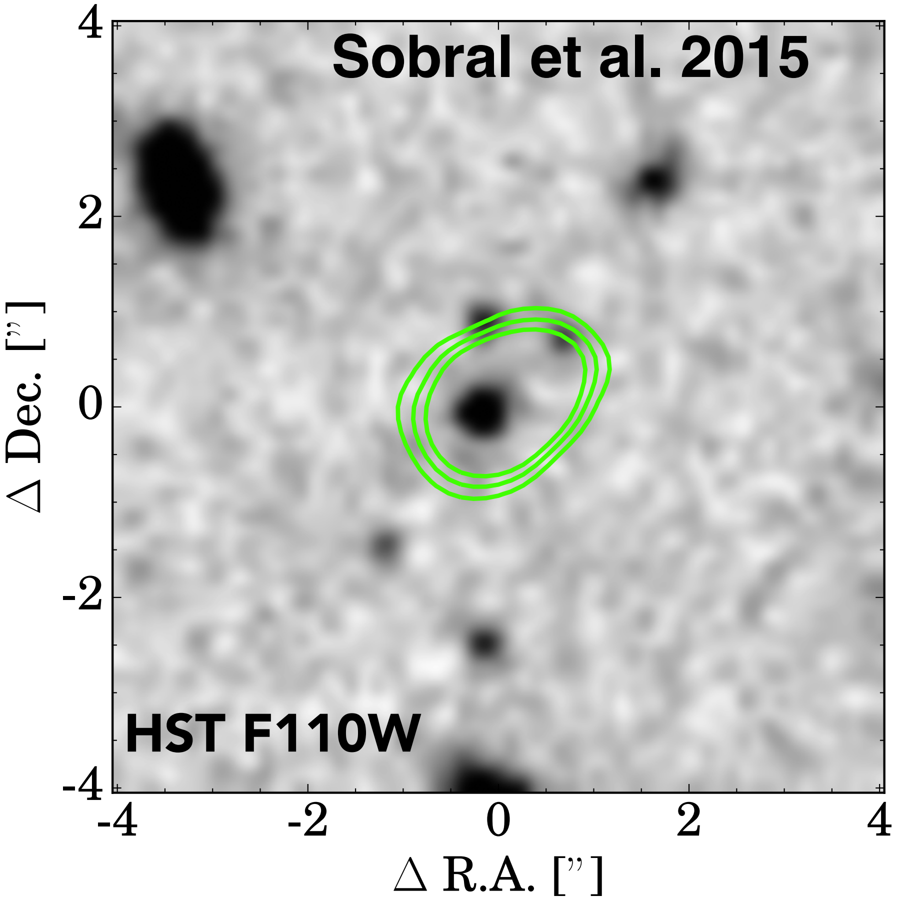
Integrated relation between $[CII]_{158}$ - UV luminosity

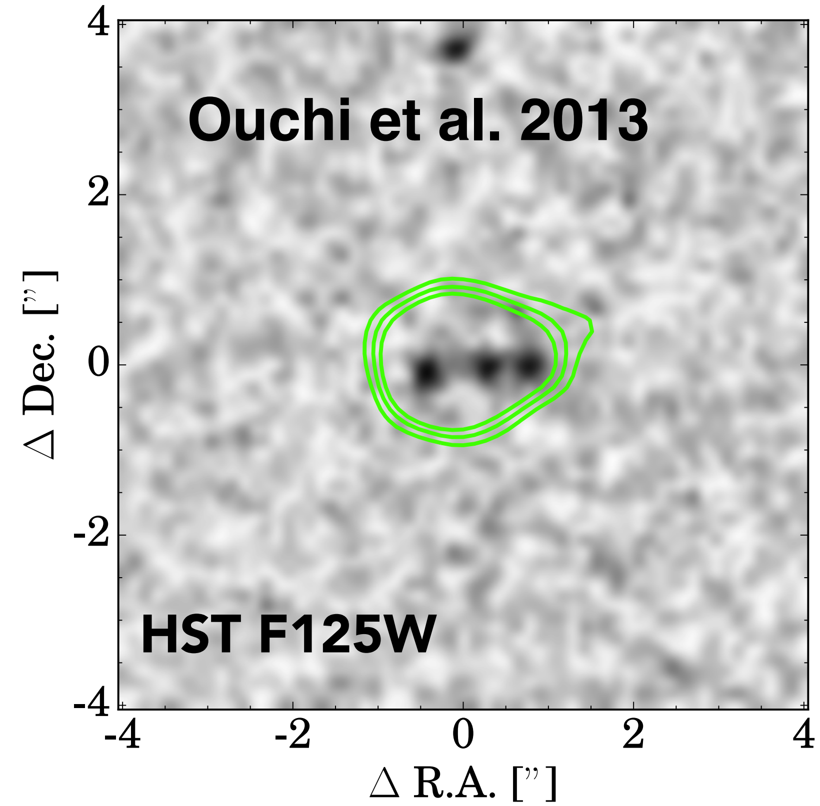


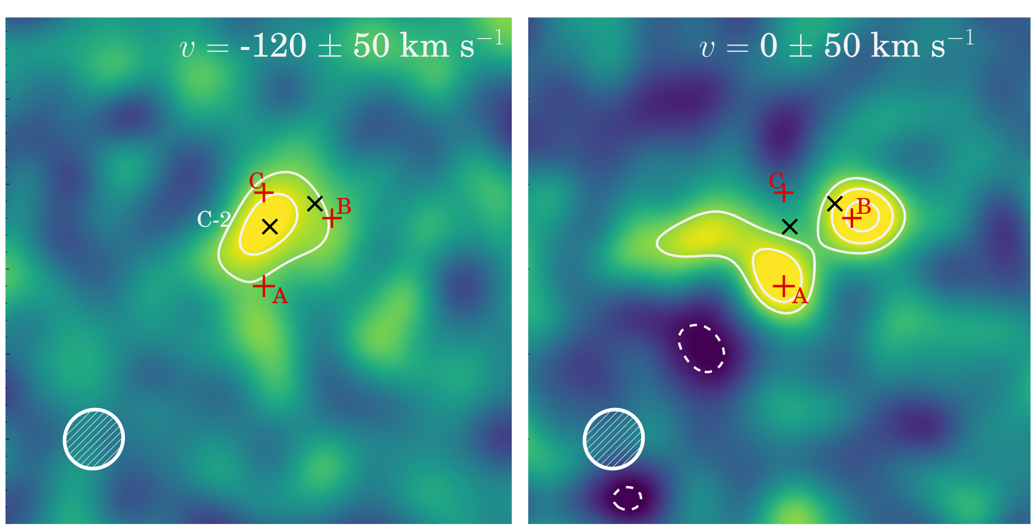
Below L^*_{UV} steeper relation than at low redshift, but significant scatter

Matthee et al. 2019, arXiv: 1903.08171

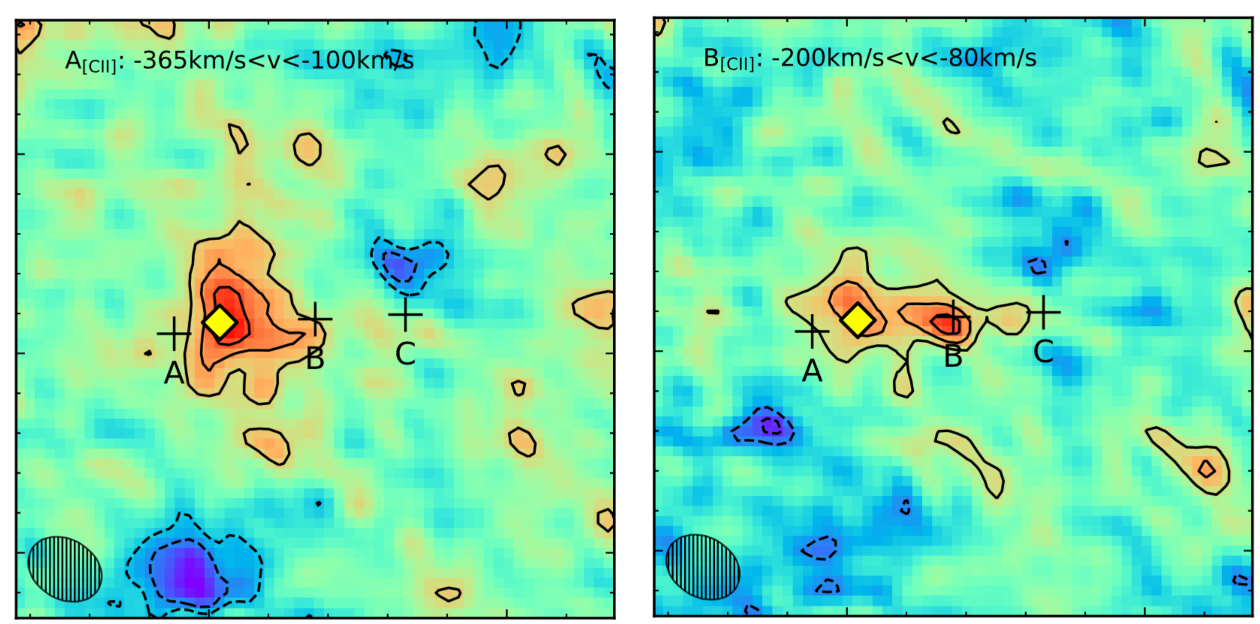
Luminous z~7 LAEs have multiple components in UV and [CII]





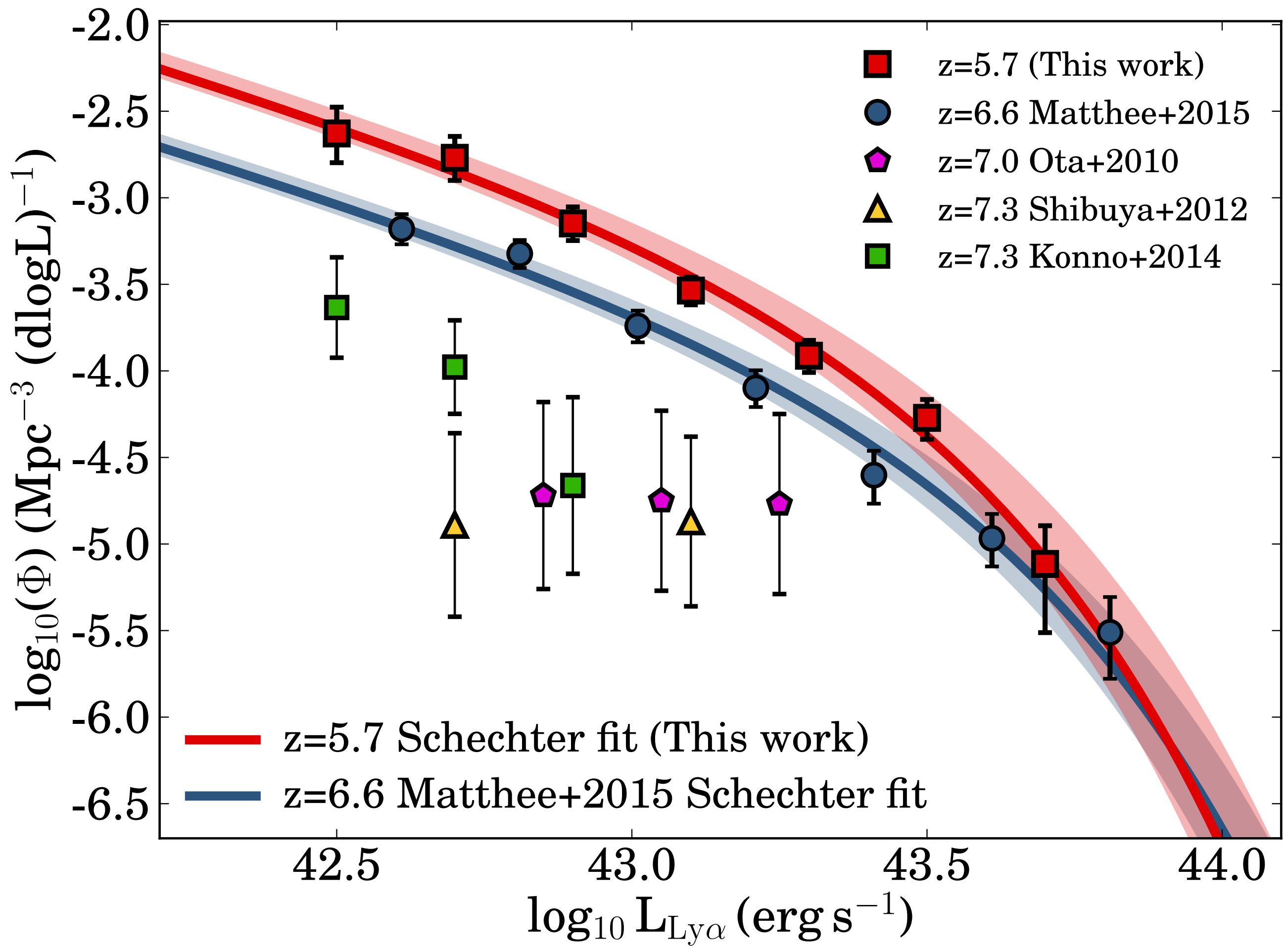


Matthee+2017



Carniani+2017

Observed evolution of LAEs z~6-7



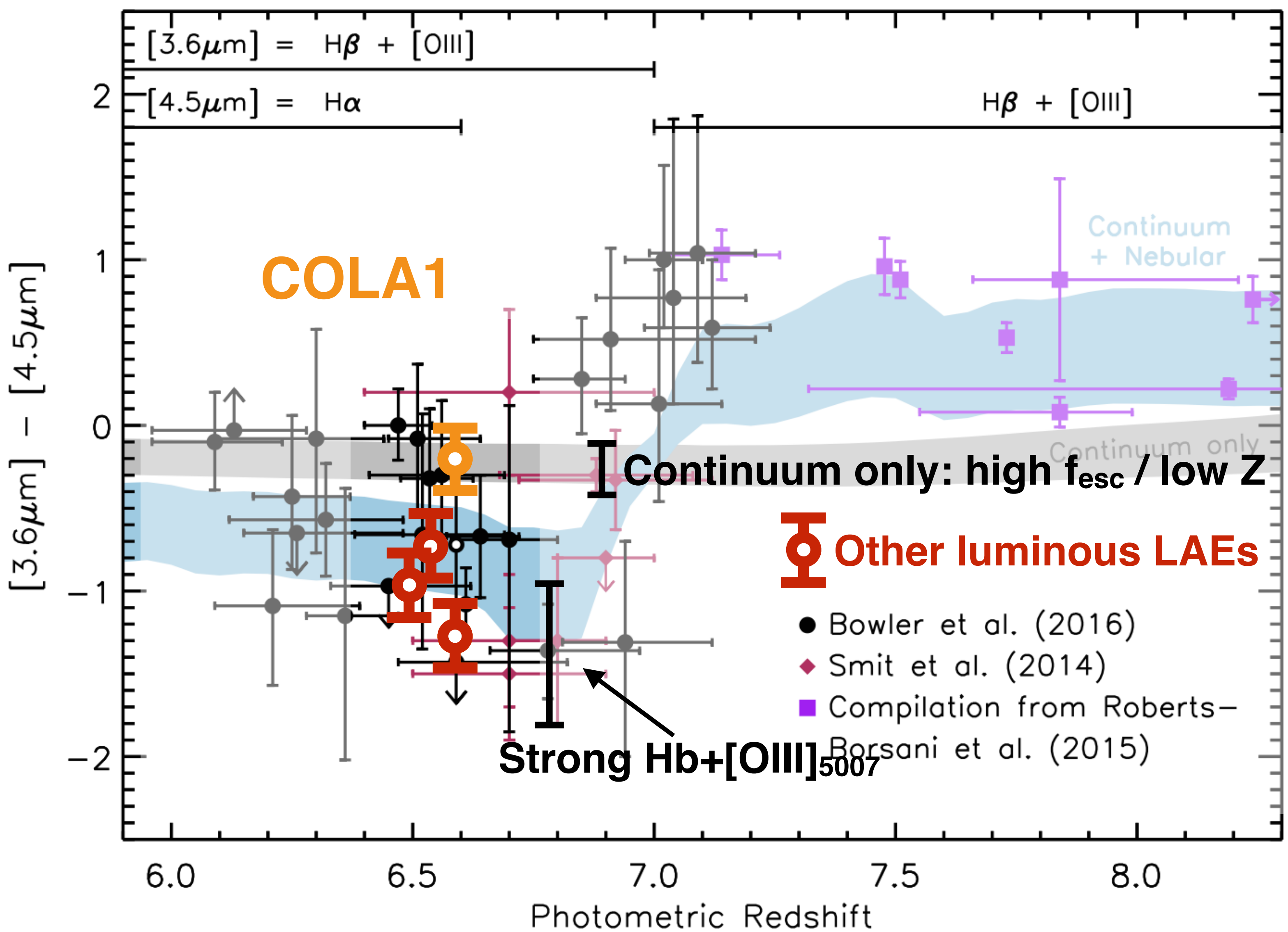
*** Number density of luminous LAEs does not evolve from z~6-7 (HSC regime)**

*** Decrease in the number density of faint LAEs (S-Cam/MUSE regime)**

Matthee et al. 2015 MNRAS 451, 4919

Santos, Sobral & Matthee, 2016, MNRAS, 463, 1678

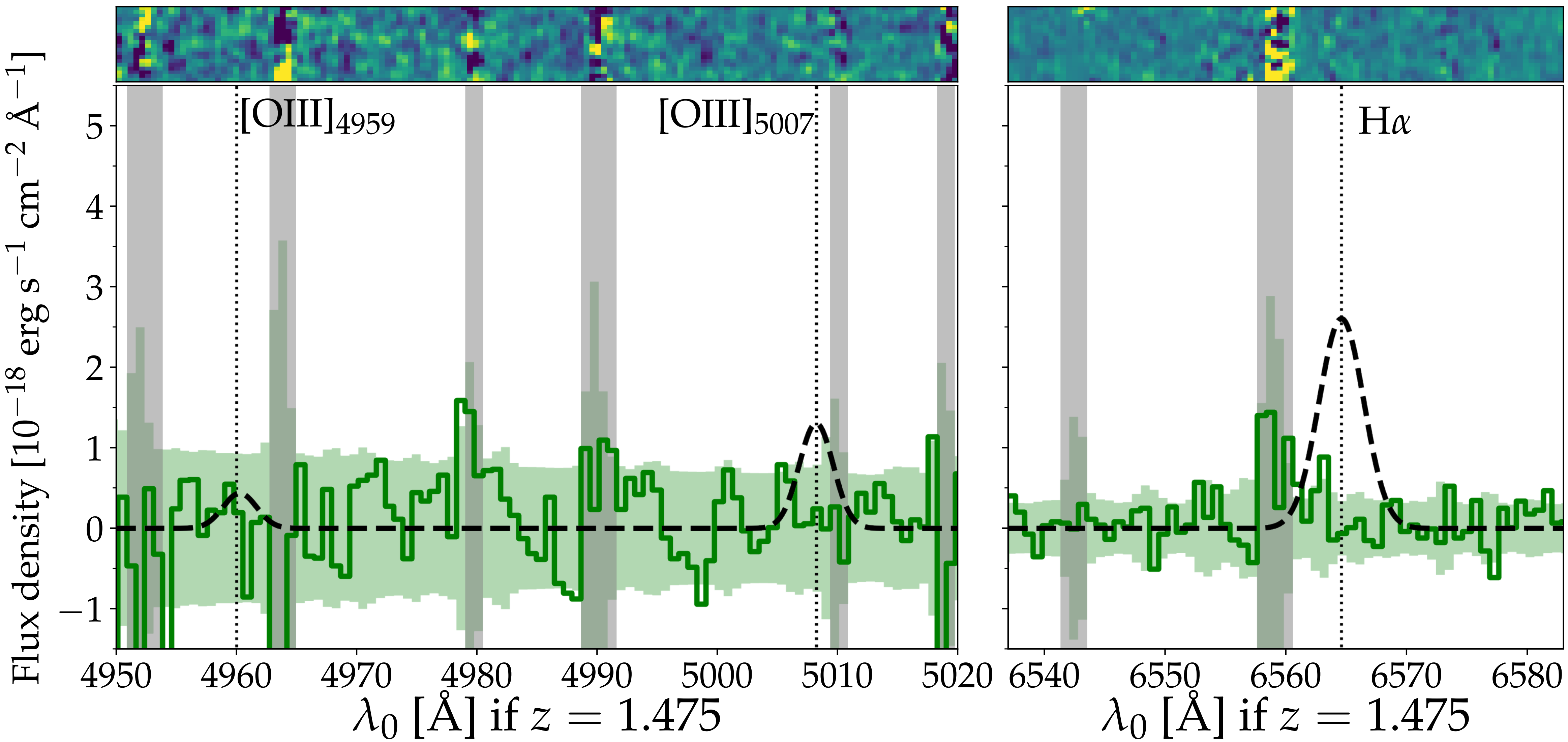
Spitzer/IRAC [3.6]-[4.5] colour of COLA1



relatively flat colour indicates faint [OIII]+Hb emission: low metallicity and/or high f_{esc}?

Matthee et al. 2018, A&A, 619, 136

COLA1 - Why not [OII] at z=1.477?   1:

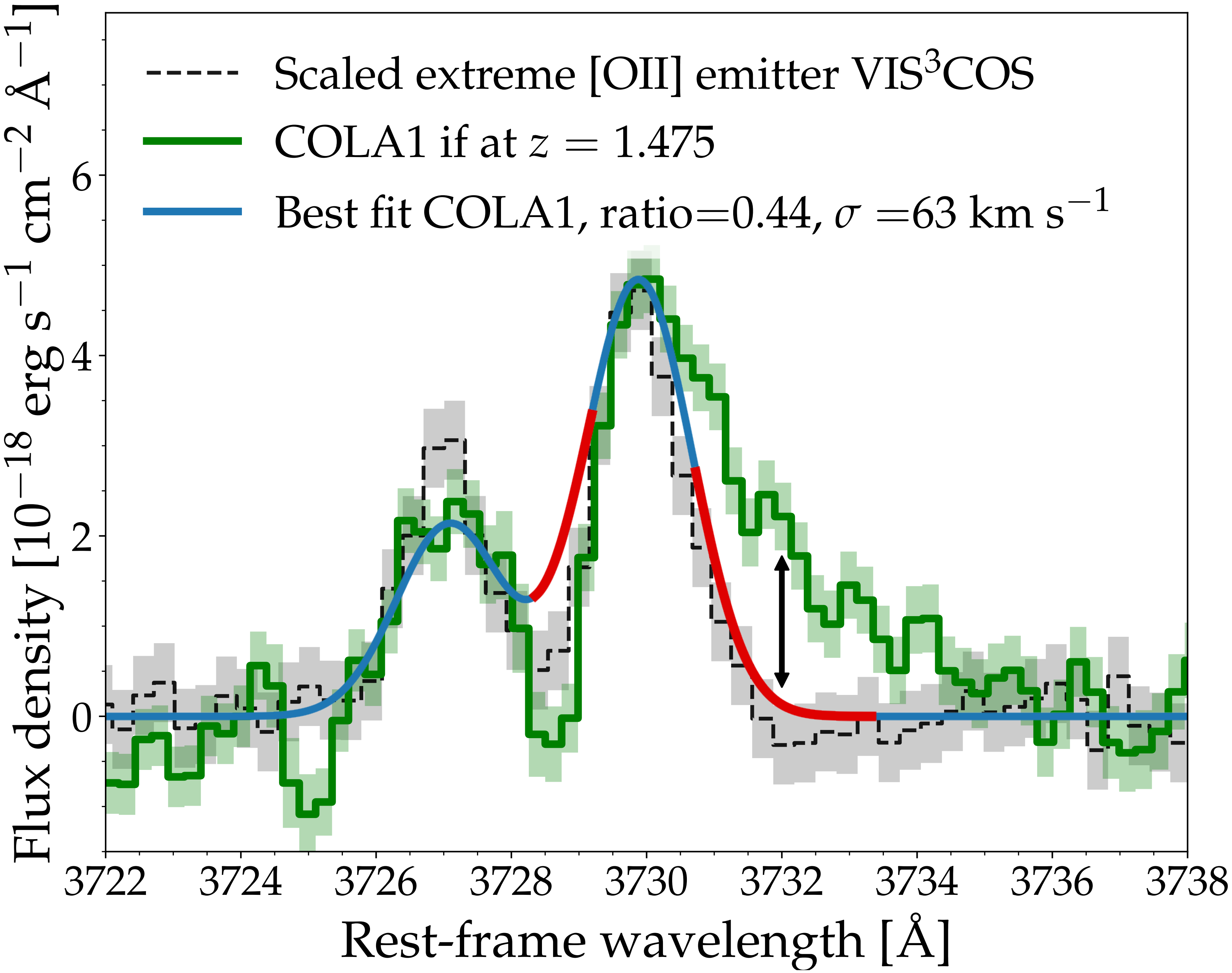


No Halpha at the expected position if COLA1 were [OII] at z=1.47

***most extreme SDSS [OII]/Halpha ratio**

Matthee et al. 2018, A&A, 619, 136

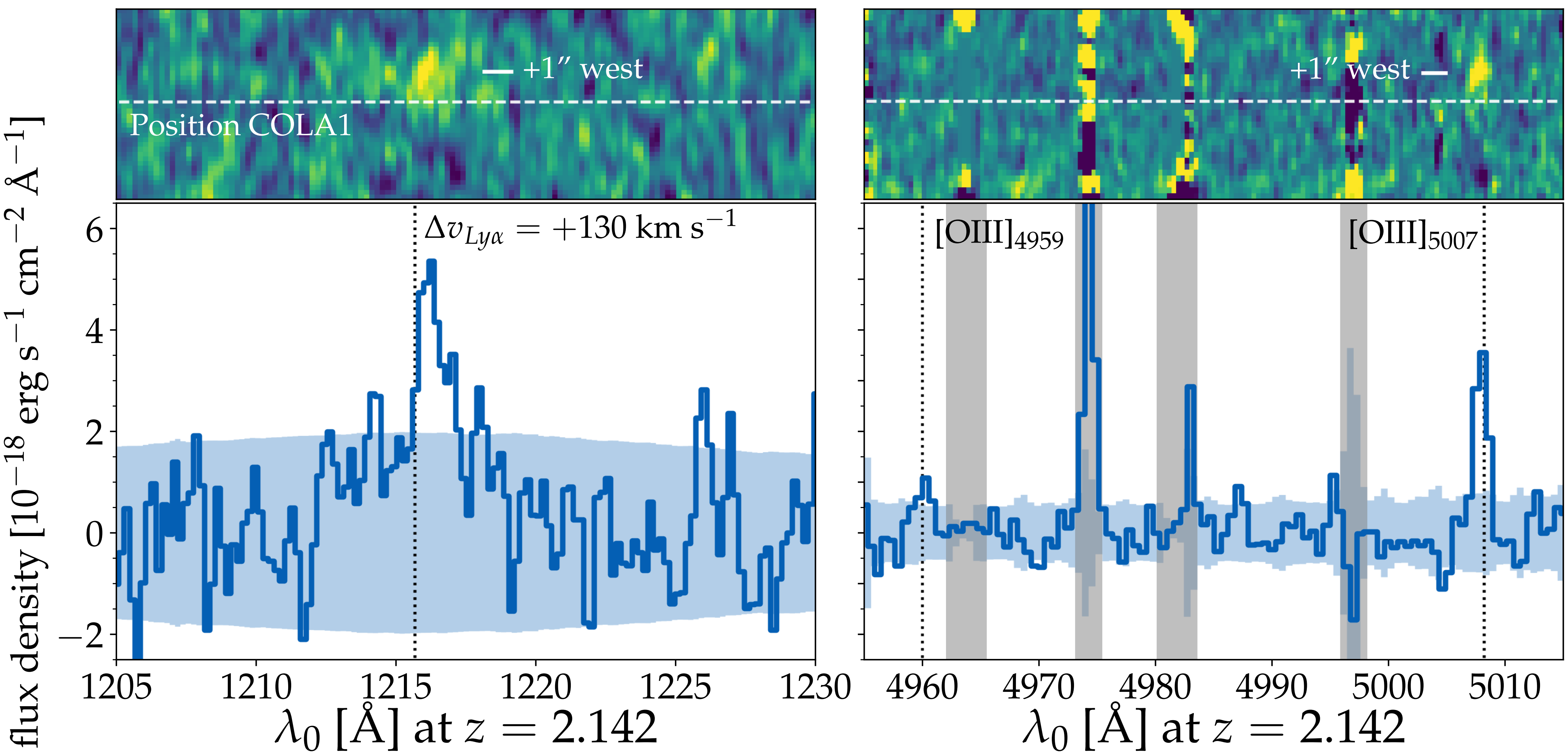
COLA1 - Why not [OII] at z=1.477?   2:



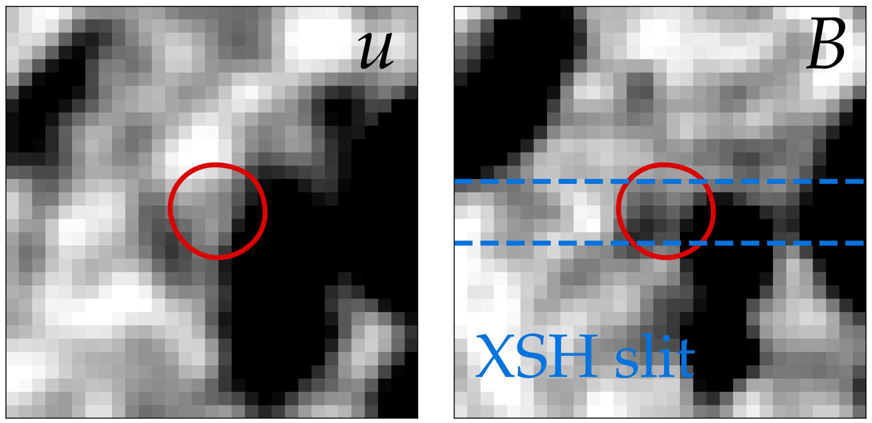
COLA1's line profile can't be fitted with [OII] at z=1.47

Matthee et al. 2018, A&A, 619, 136

COLA1 - Why not [OII] at z=1.477? 3:

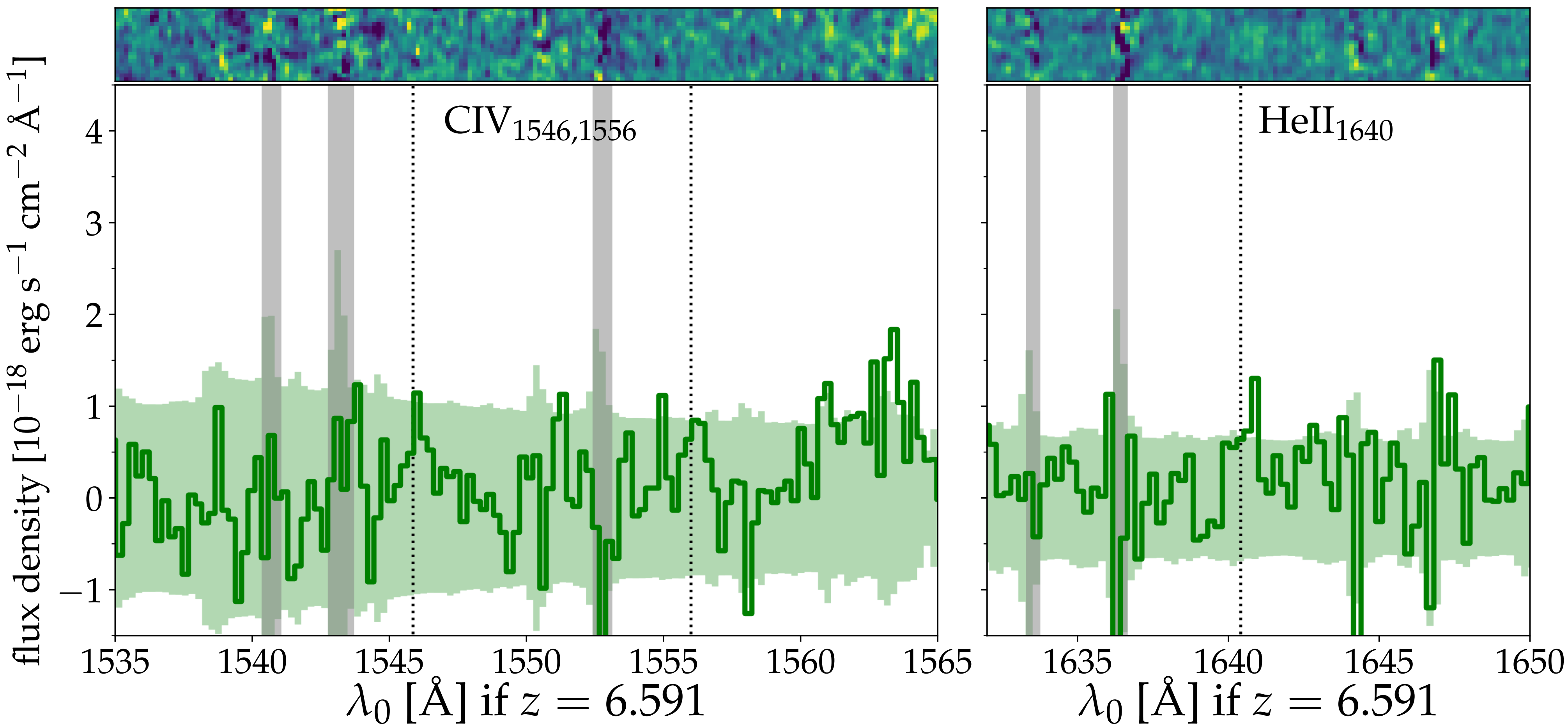


Tentative B flux explained by foreground LAE at z=2.142



Matthee et al. 2018, A&A, 619, 136

COLA1 - PROPERTIES



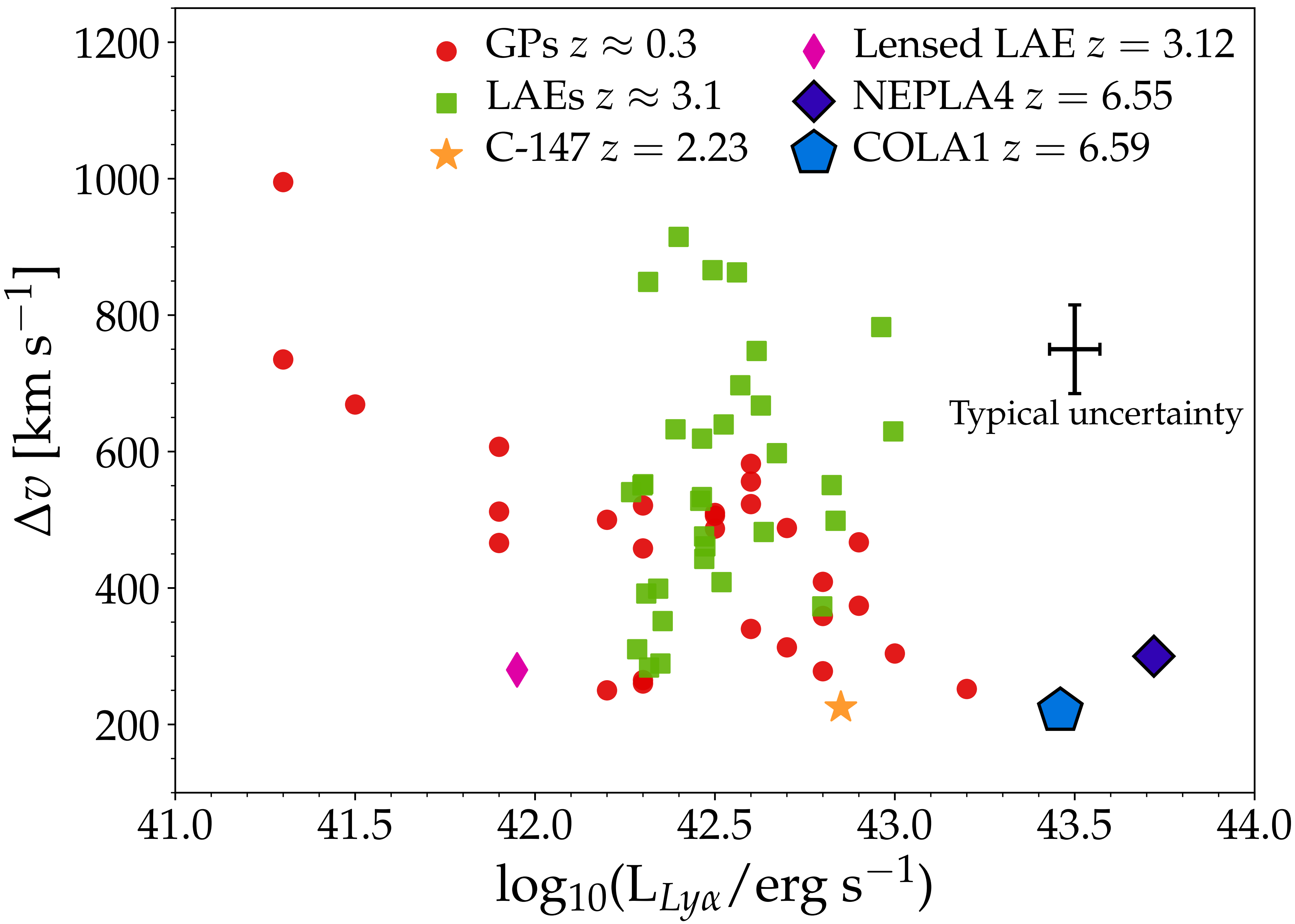
No obvious CIV or HeII emission detected in COLA1 so far

(EW_0<12 Å)

Matthee et al. 2018, A&A, 619, 136

Why no other double peaks known at z>6?

Matthee et al. 2018, A&A, 619, 136



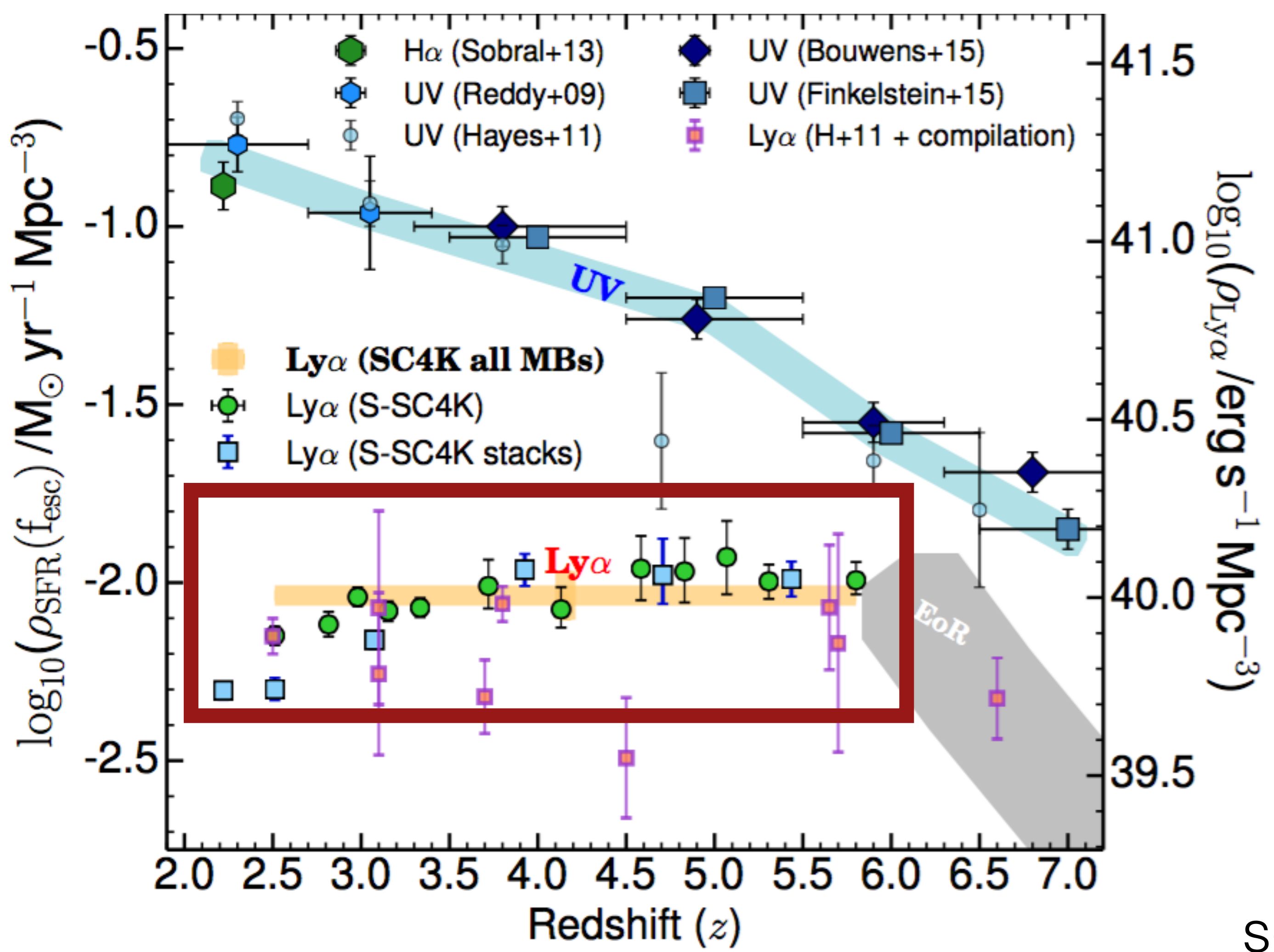
Easier to observe smaller separations (higher fesc & smaller bubbles)
Peak separation anti-correlates with luminosity

1. **low S/N (blue ~0.3*red), low resolution (R>3000)**
2. **only observable in bright, rare LAEs?**

Lya luminosity density remarkably constant from z~2.5-6

ρ_{Lya}~10^{40} erg s^{-1} Mpc^{-3}

Lya density



see also Ouchi+2008

SC4K: Slicing COSMOS with 4K LAEs

4000 LAEs z=2-6. Volume 10^8 Mpc^3

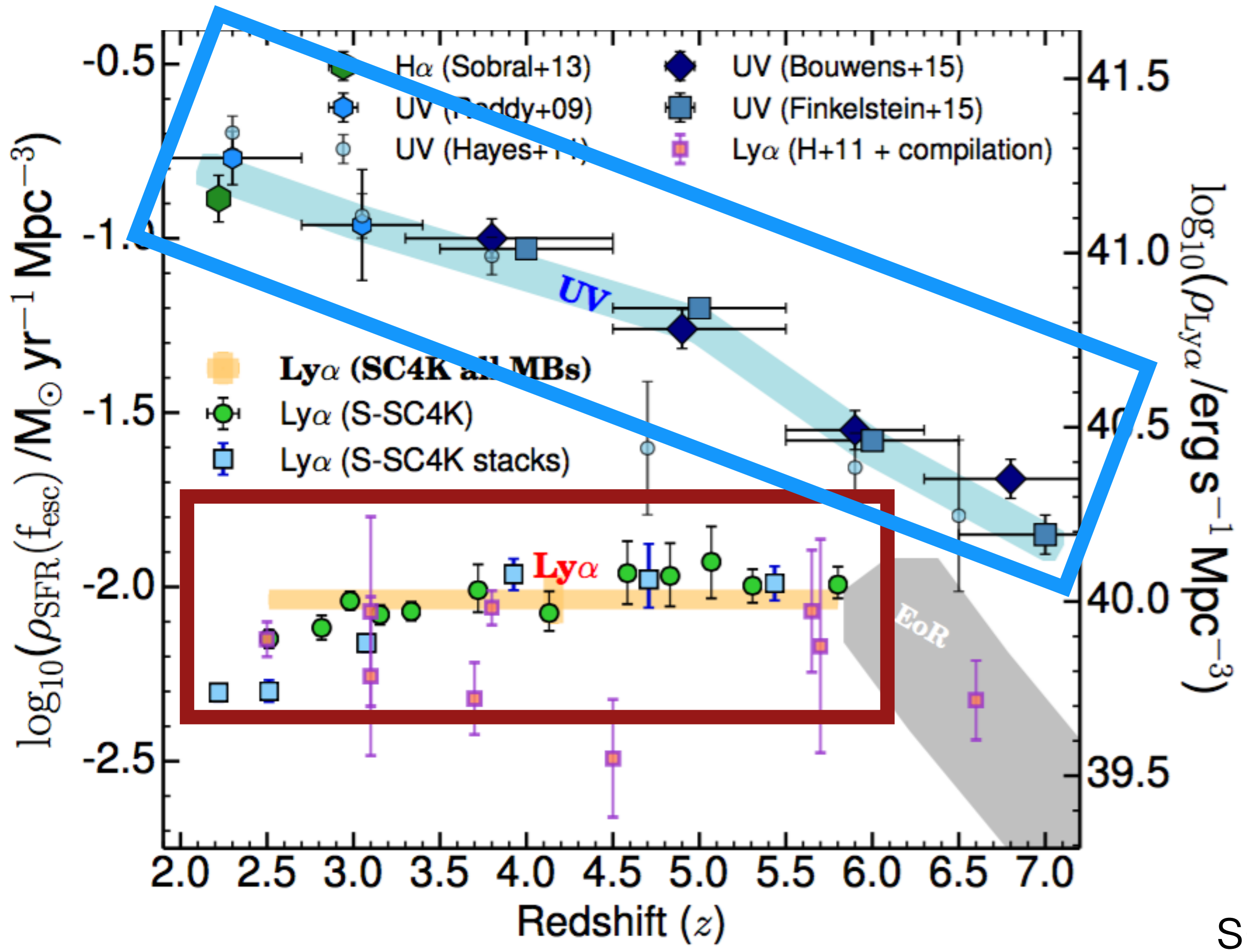
Sobral, Santos, Matthee et al. 2018, MNRAS, 476, 4725

Lya luminosity density remarkably constant from z~2.5-6

ρ_{Lya}~10^{40} erg s^{-1} Mpc^{-3}

UV density

Lya density



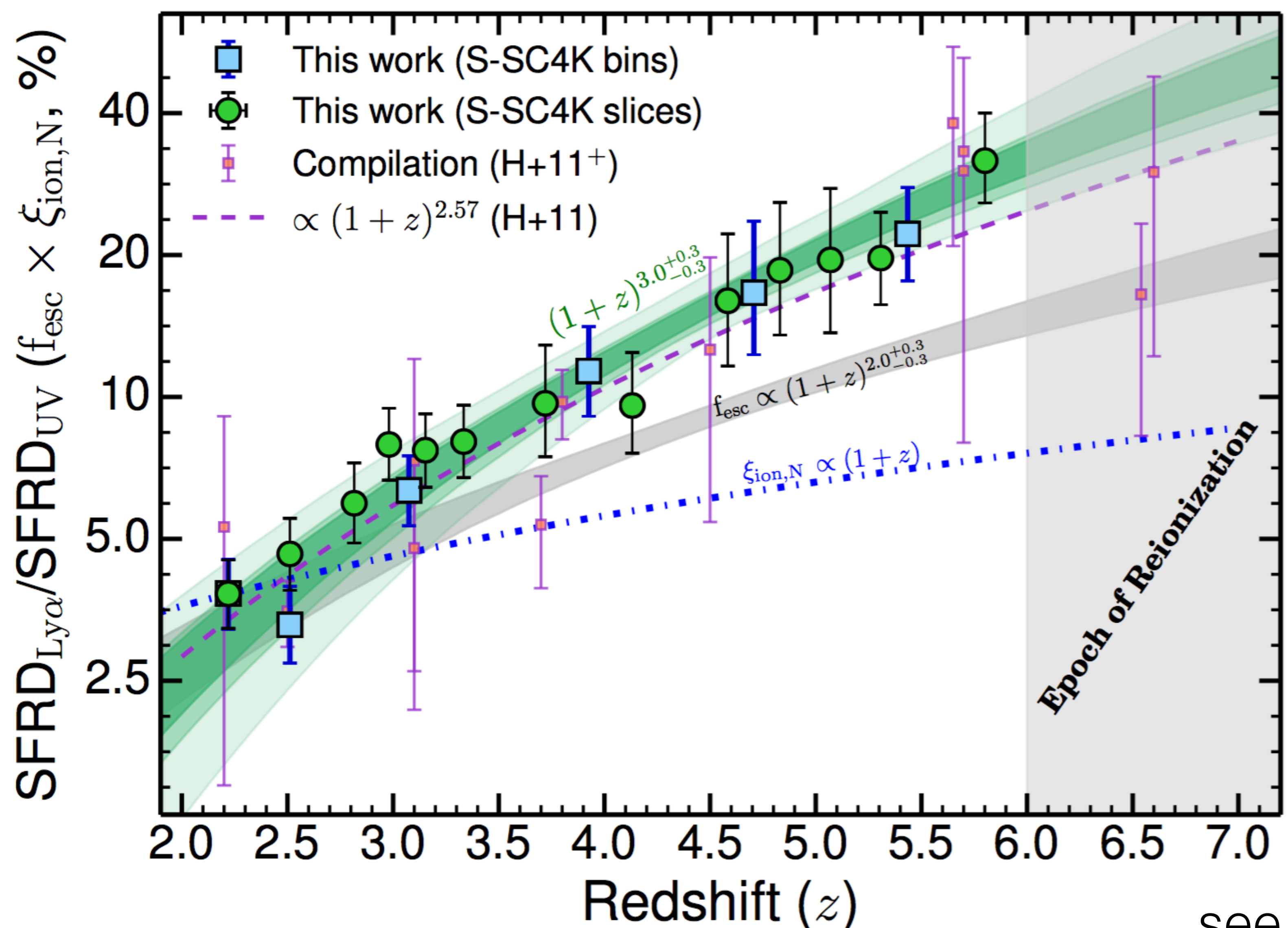
see also Ouchi+2008

SC4K: Slicing COSMOS with 4K LAEs

4000 LAEs z=2-6. Volume 10^8 Mpc^3

Sobral, Santos, Matthee et al. 2018, MNRAS, 476, 4725

Lya actually becomes brighter compared to UV from z=3-6!



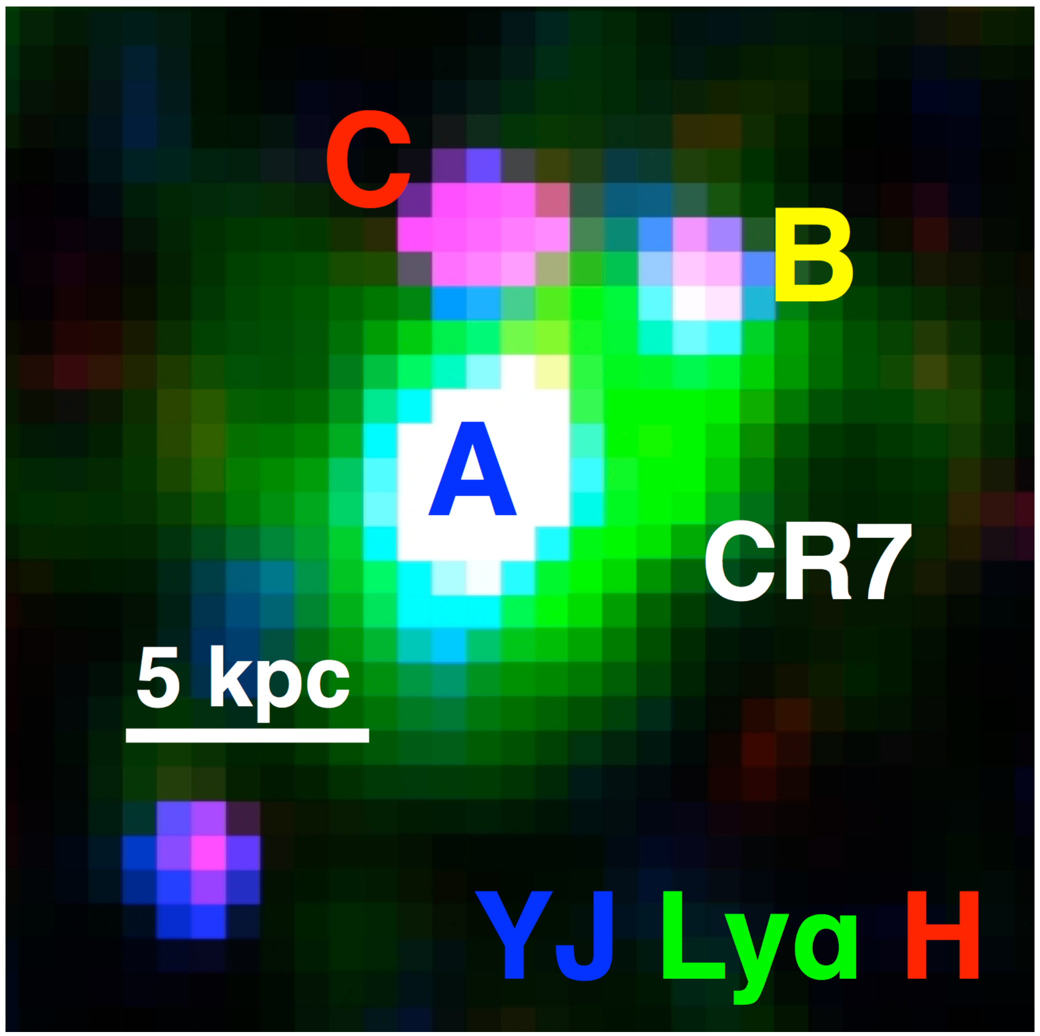
see also Hayes+2011

+ Evolution in the dust content (less dust), higher $f_{esc,Lya}$

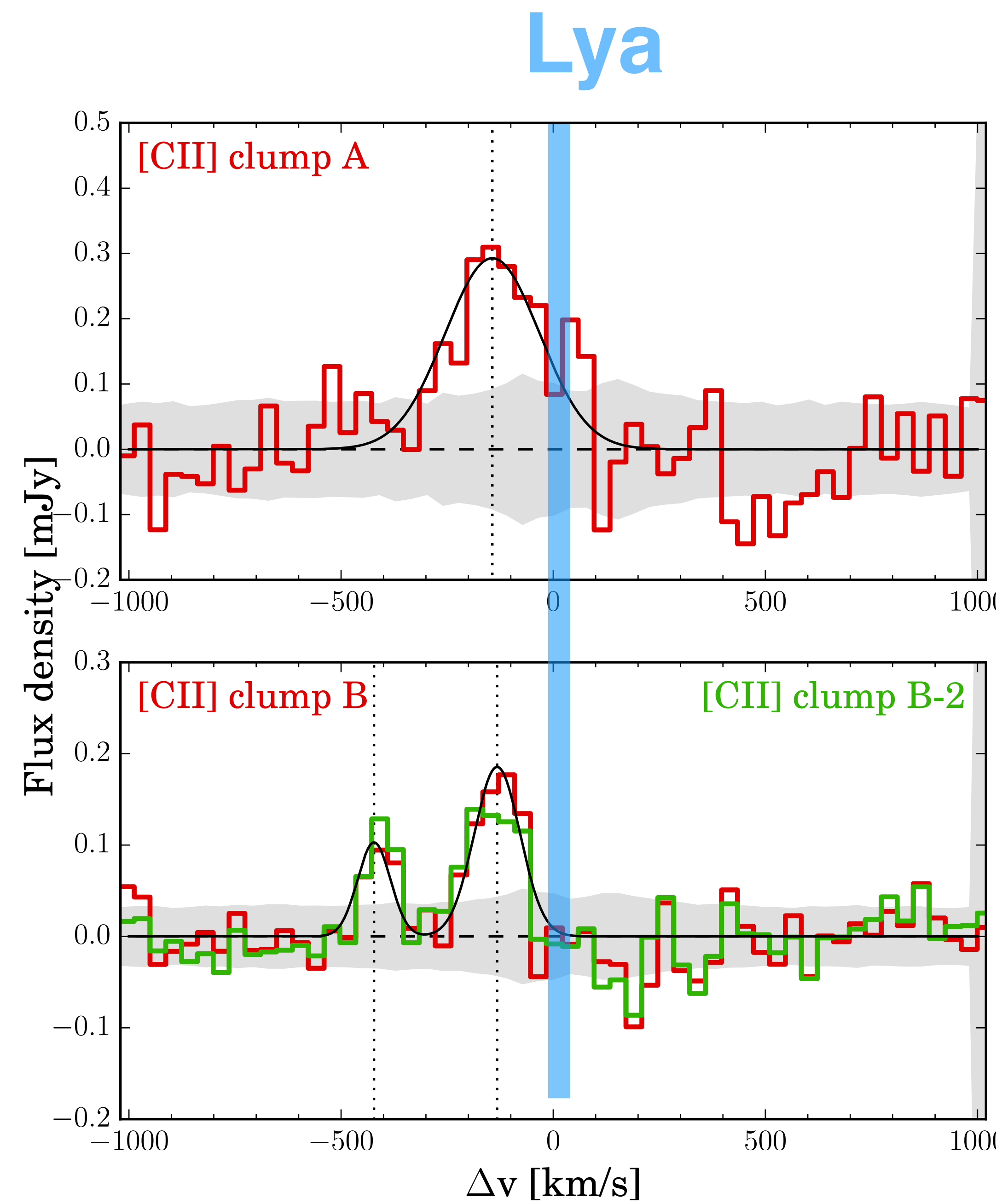
+ Increased ionising photon production efficiency

Sobral, Santos, Matthee et al. 2018, MNRAS, 476, 4725

Multiple [CII] components in *frequency* space

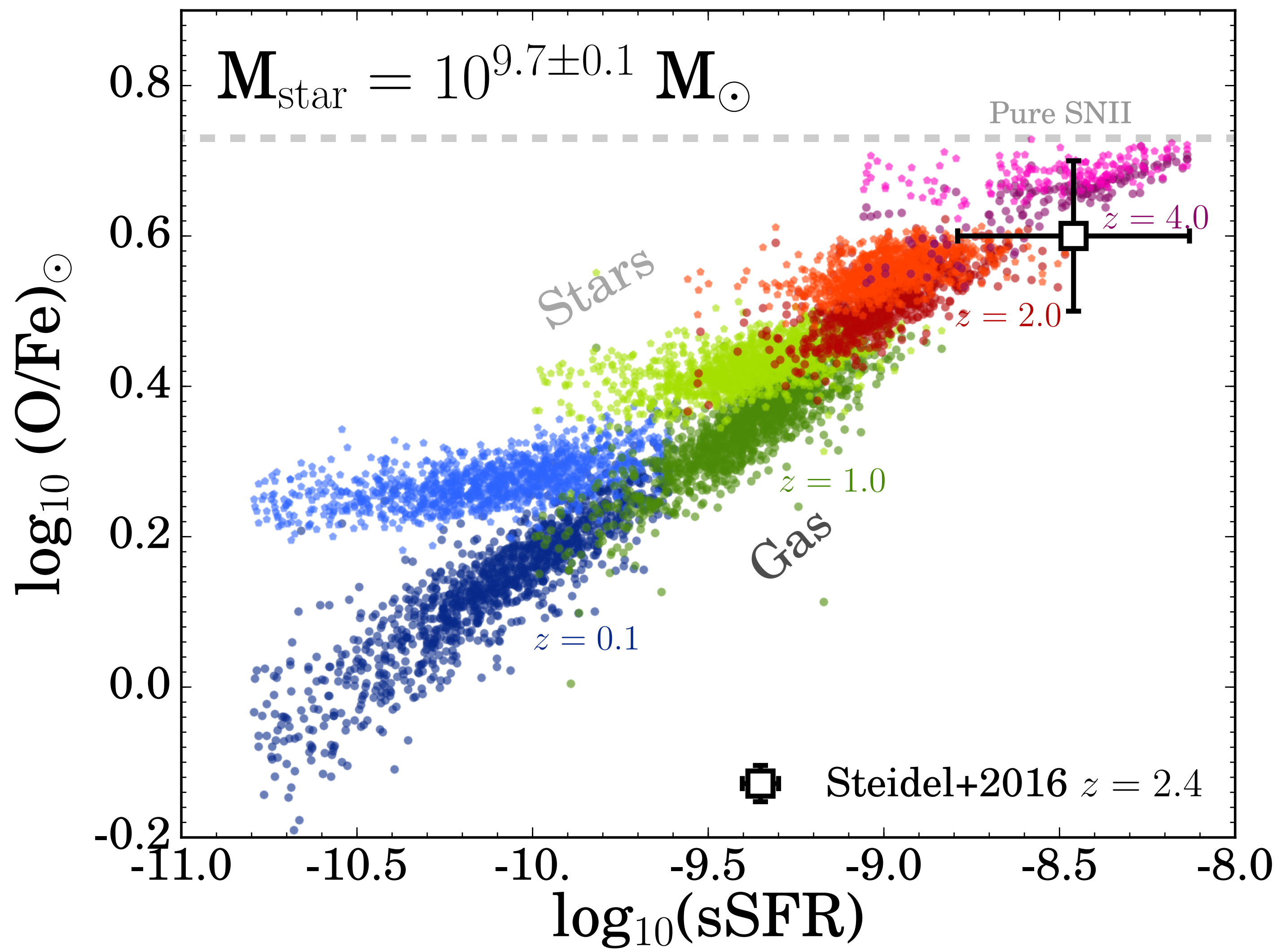


Sobral+2015



Matthee et al. 2017, ApJ, 851, 145

Why stellar metallicities ? Related results from the EAGLE simulation



* **higher sSFR = more alpha-enhanced gas (& stars)**
* **higher redshift = more alpha-enhanced gas**

implications for interpreting nebular emission line strengths

Matthee & Schaye 2018,MNRAS, 479L, 34