ESTALLIDOS XIII - CSIC MADRID, MAY 18TH, 2022

Fondecyt-Regular 1202007

IONIZED GAS KINEMATICS OF GREEN PEA GALAXIES : THE ROLE OF FEEDBACK IN LYMAN PHOTON ESCAPE

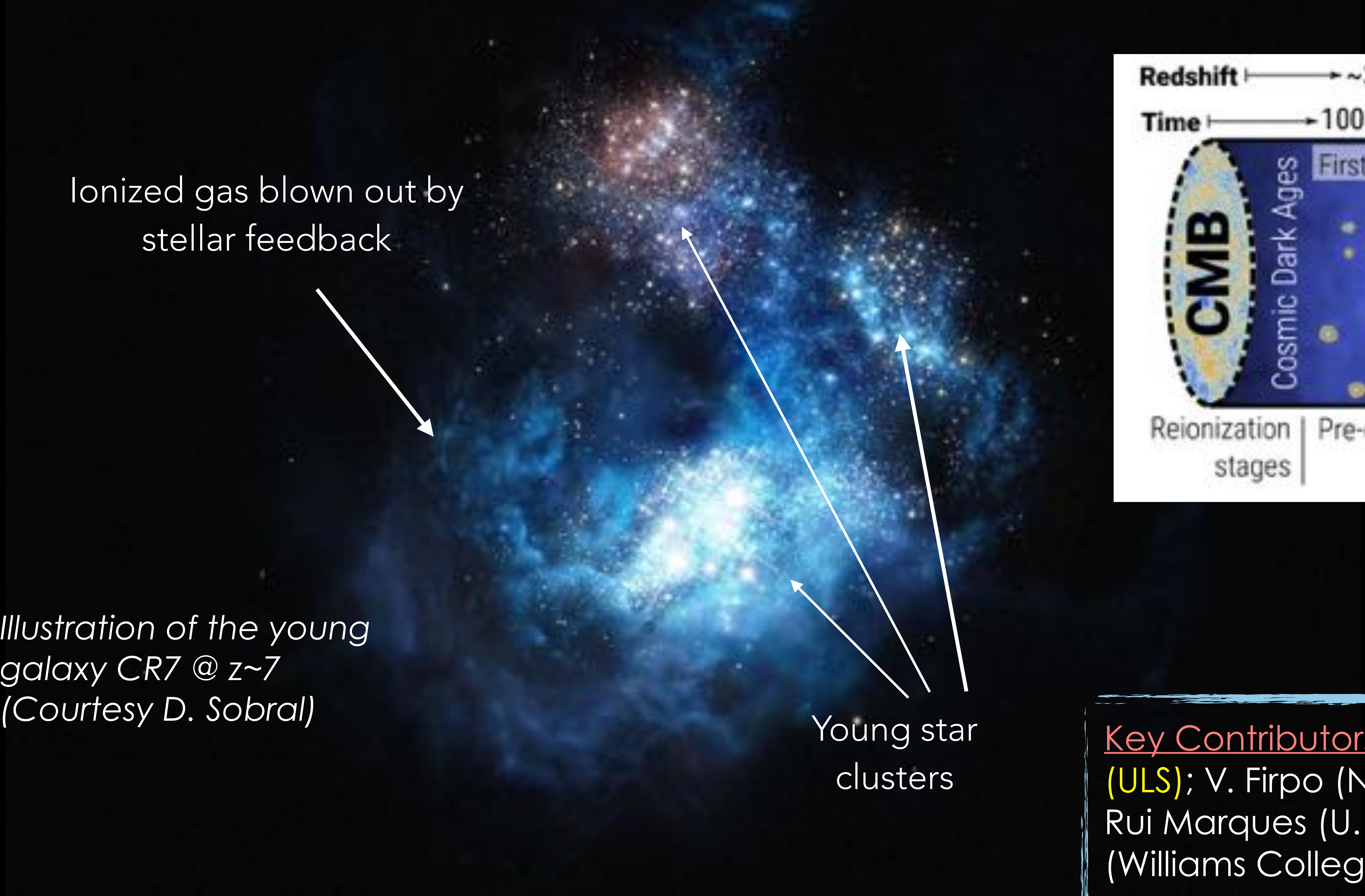
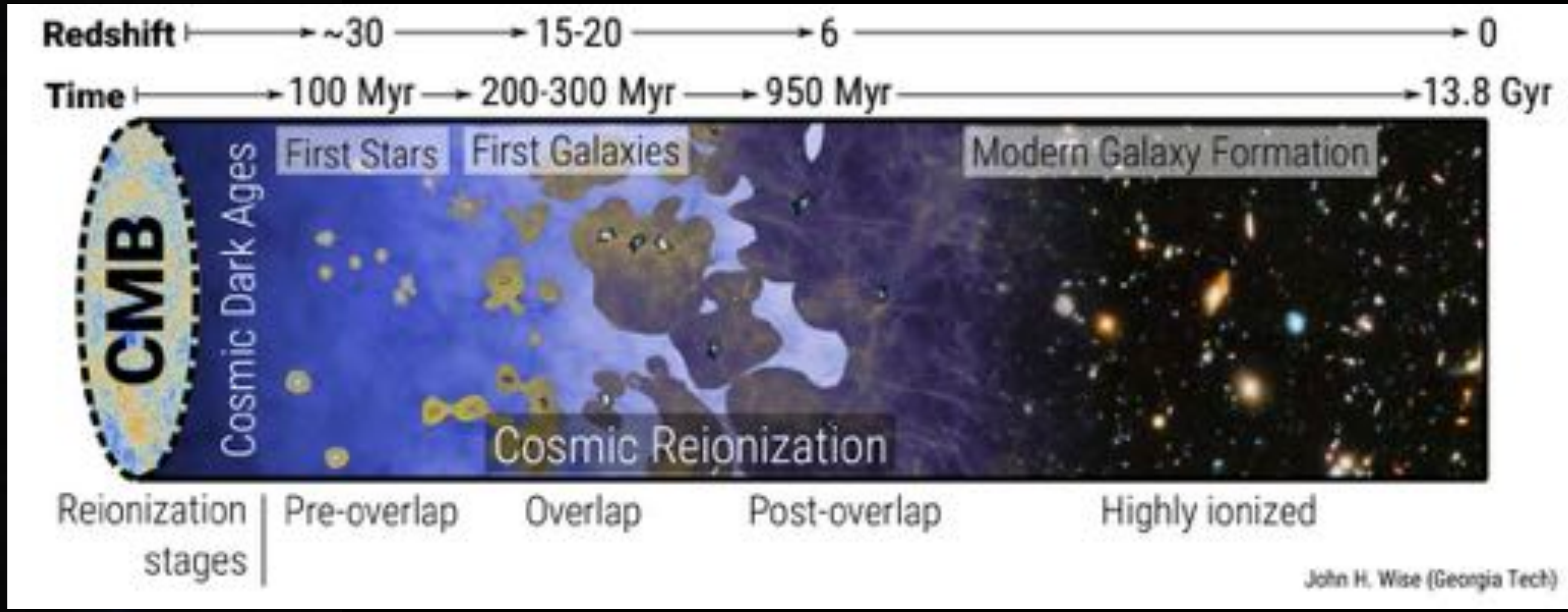


Illustration of the young galaxy CR7 @ z~7 (Courtesy D. Sobral)



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UNDERSTANDING REIONIZATION

RELEVANT QUESTIONS

- What sort of objects dominate/lead reionization?
  - Bright galaxies or faint SF dwarfs? Both?
  - Role of QSO/AGNs?

- How do they do it?
  - What are their LyC escape fractions?
  - Which galaxy properties favor LyC escape?
  - Can we use Lyα as a proxy for reionization galaxies?
  - Other indirect methods tracing LyC emitters?

PROBLEM

At z>4, the strong drop-down of the IGM transmission makes impossible the *direct* detection of the LyC photons responsible for reionization, even for JWST or ELTs

THE LOW-Z ANALOG APPROACH

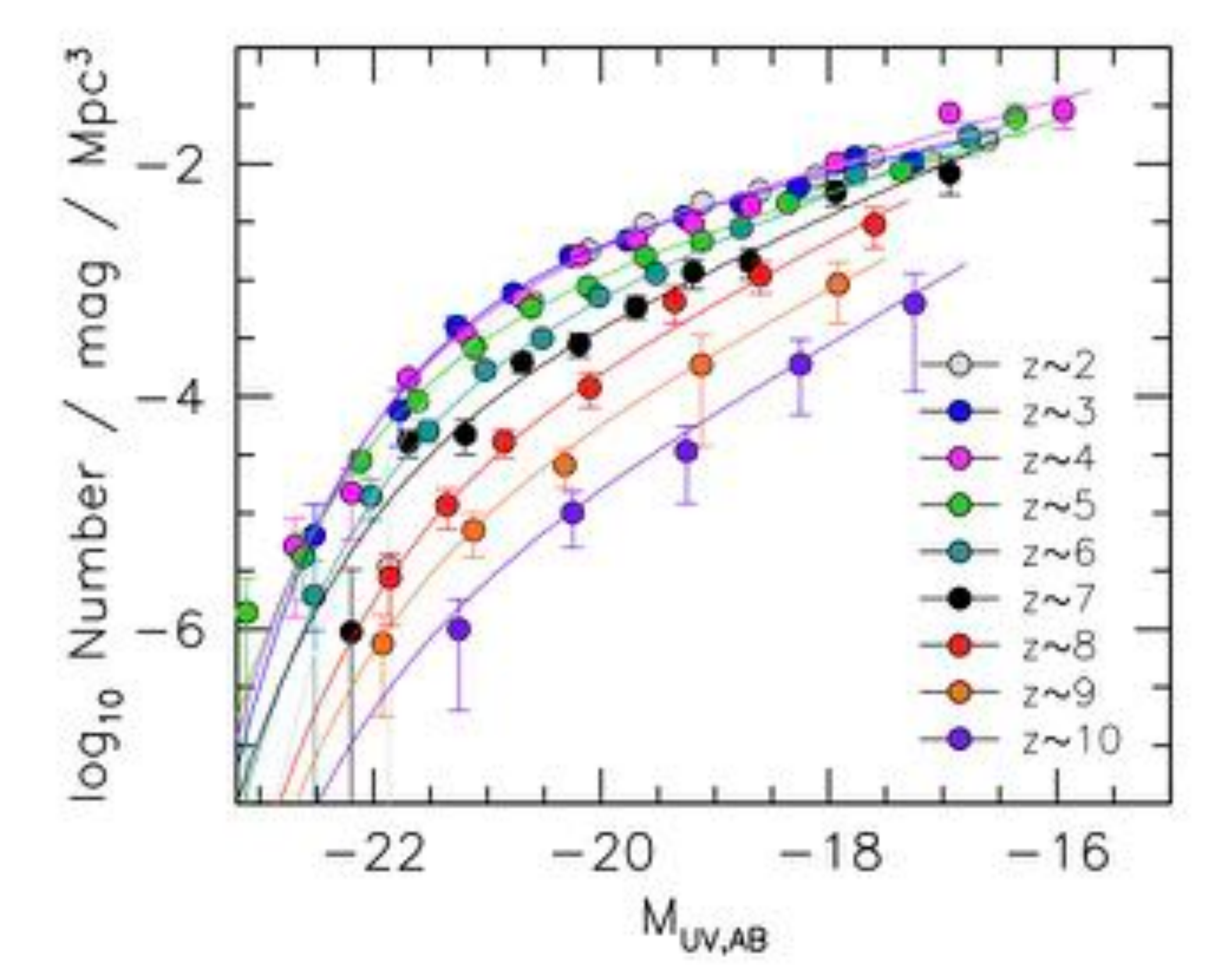
At z<4, LyC is directly observable with HST. Probing well-characterized analogs of reionization galaxies (LAEs, LBGs) may help to provide new insight on these questions

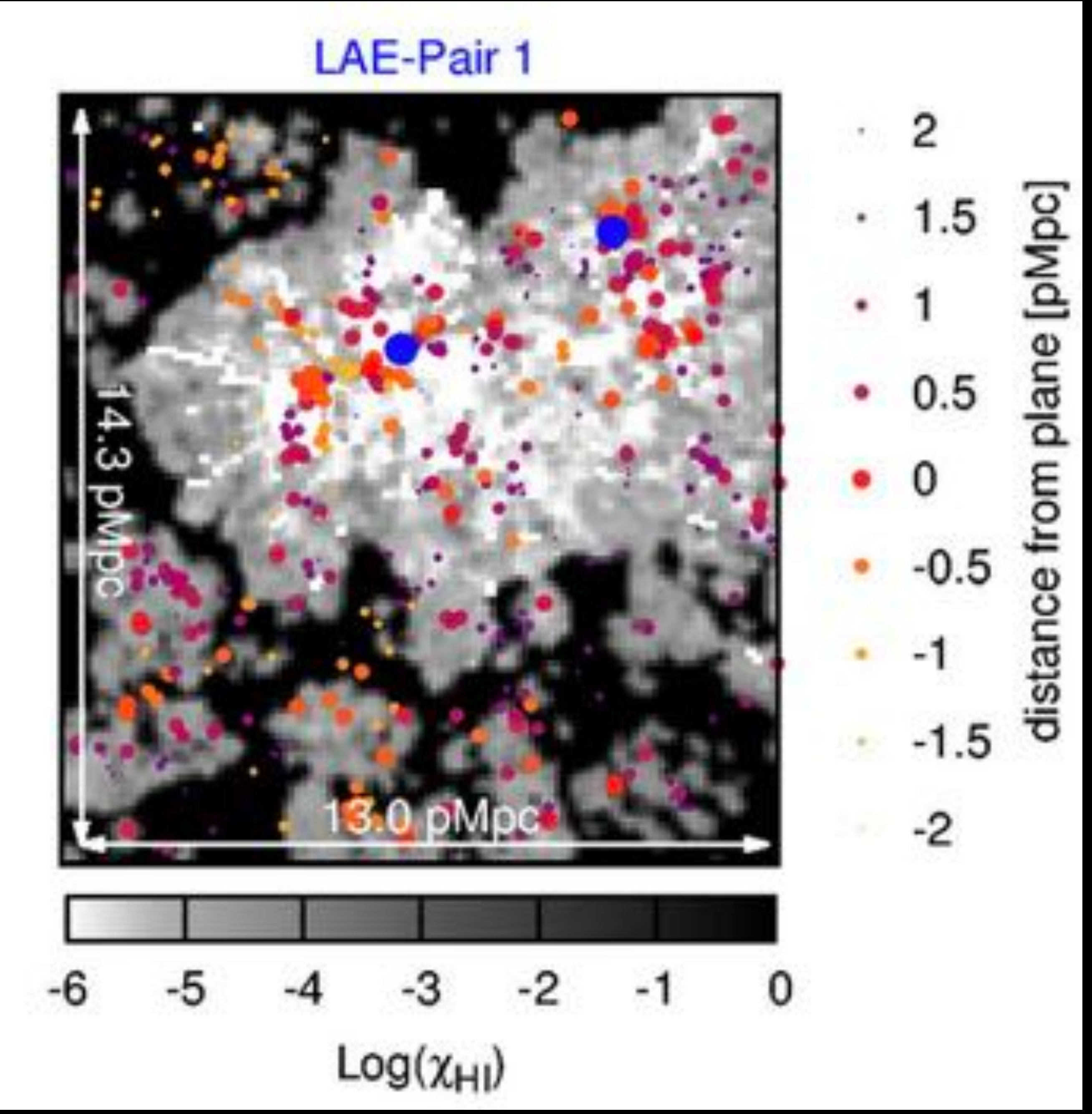
$$N_{\rm ion} = \rho_{\rm SFR}\ \xi_{\rm ion}\ f_{\rm esc,LyC}$$

Total photons — Number of galaxies — Ionizing photons/galaxy — Fraction of photons that escape eluding dust+HI

Ionizing bubbles Castellano+16

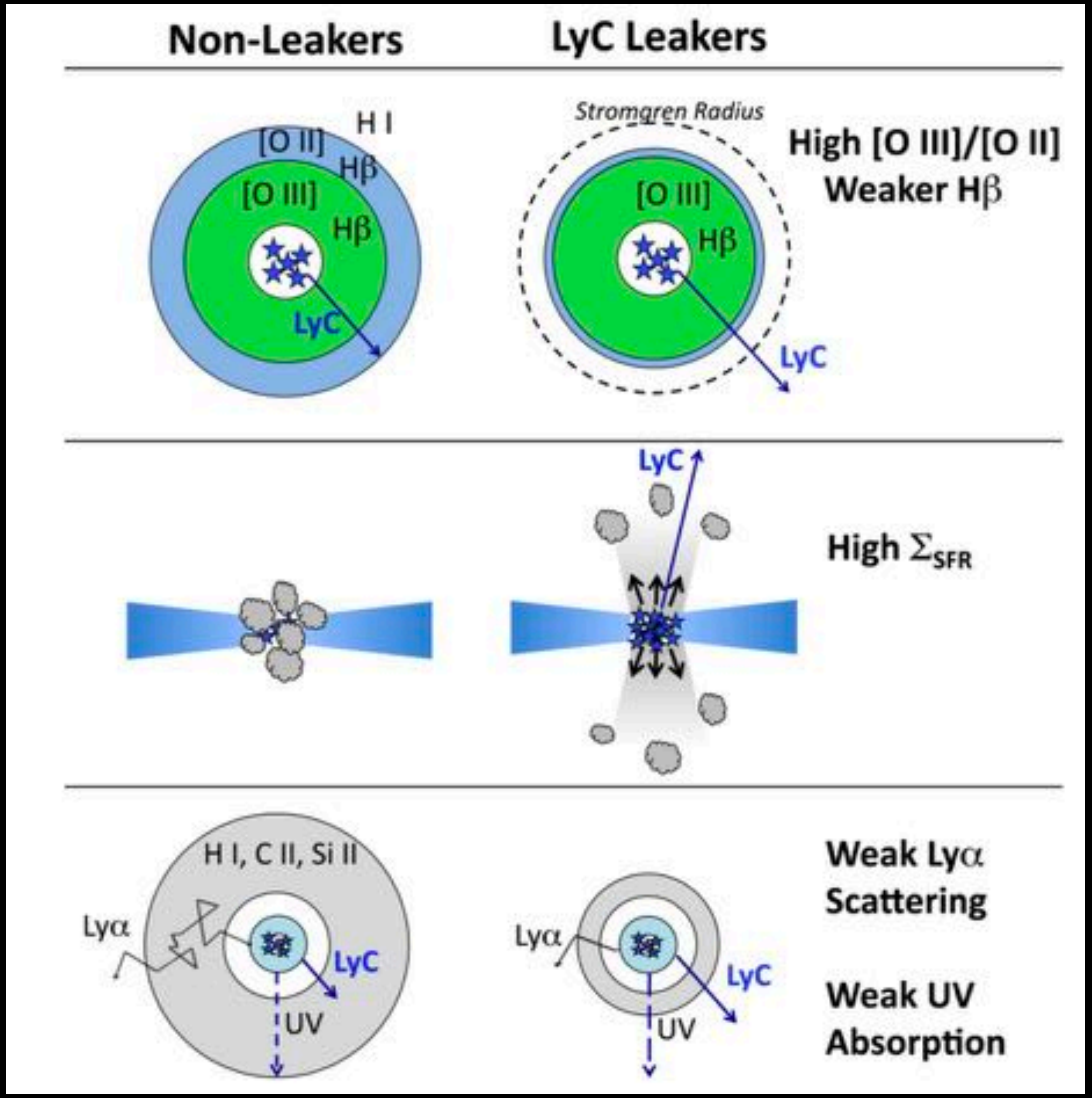
UV LF Bouwens+21



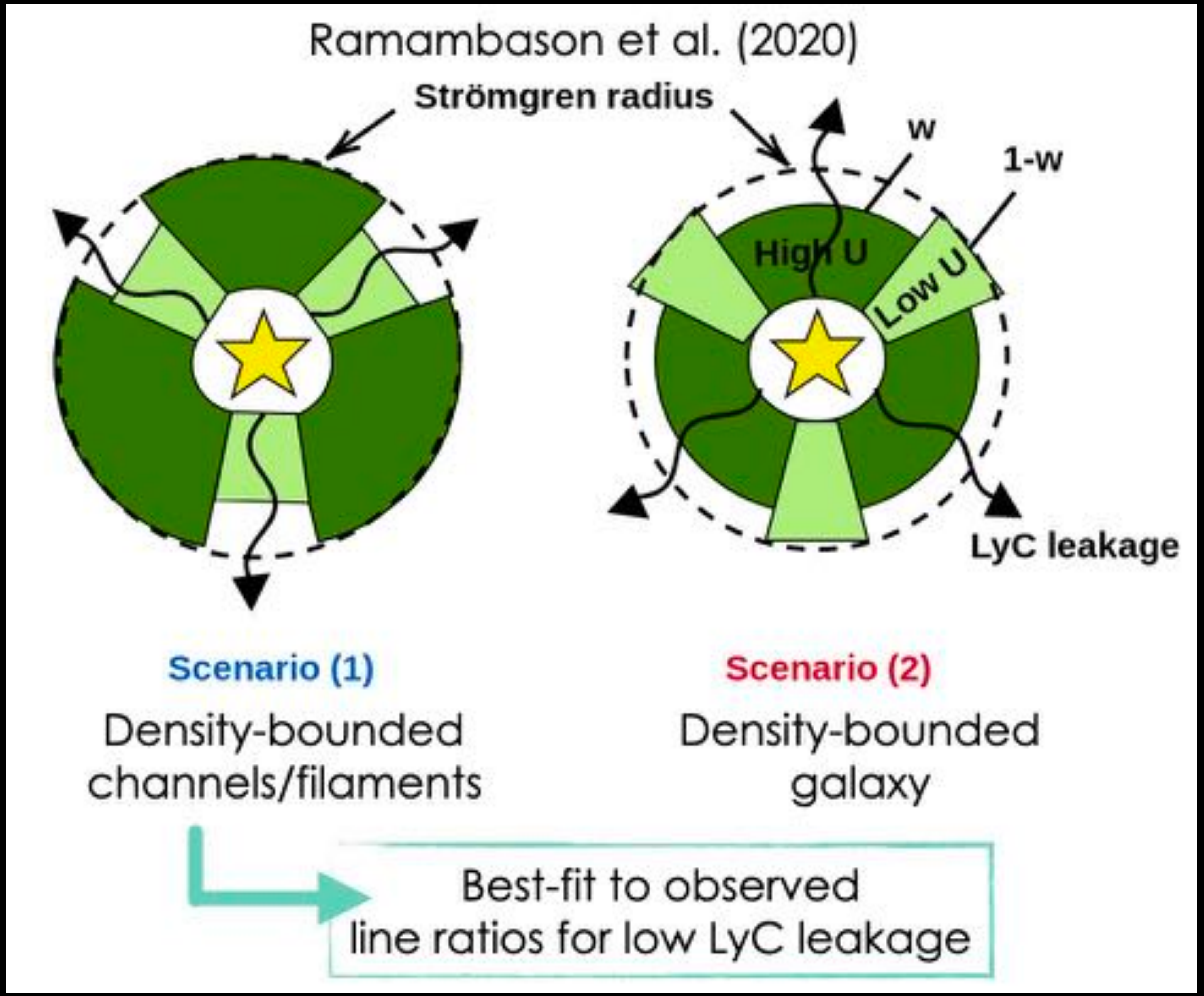


SIMPLE MODELS FOR LEAKING HII REGIONS

e.g. Zackrisson+13; Nakajima & Ouchi 13, Jaskot & Oey 13, Ramambason+20



Giant HII regions approaching density bounded conditions ?

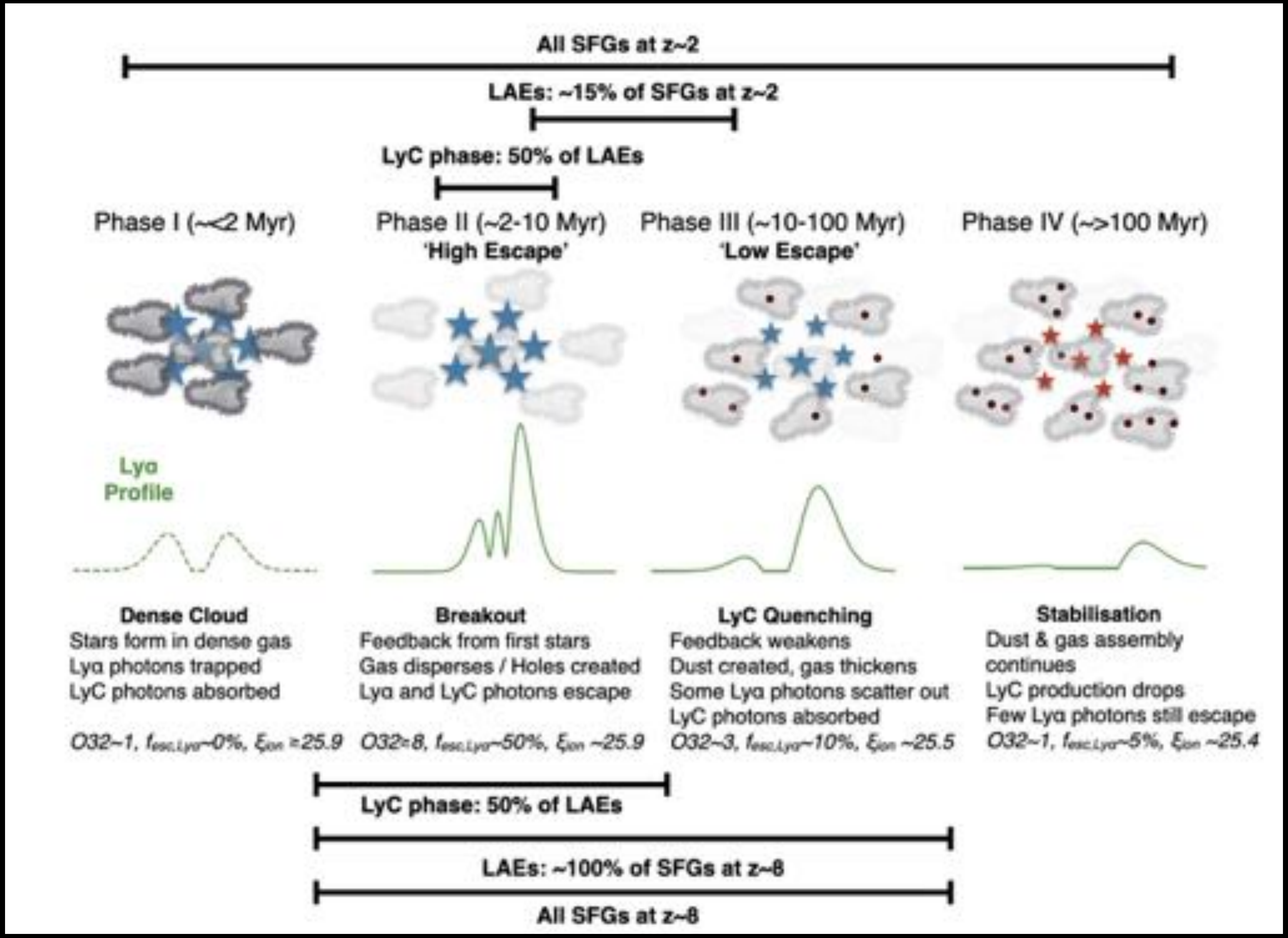


Picket fence model: ISM with holes, channels, filaments

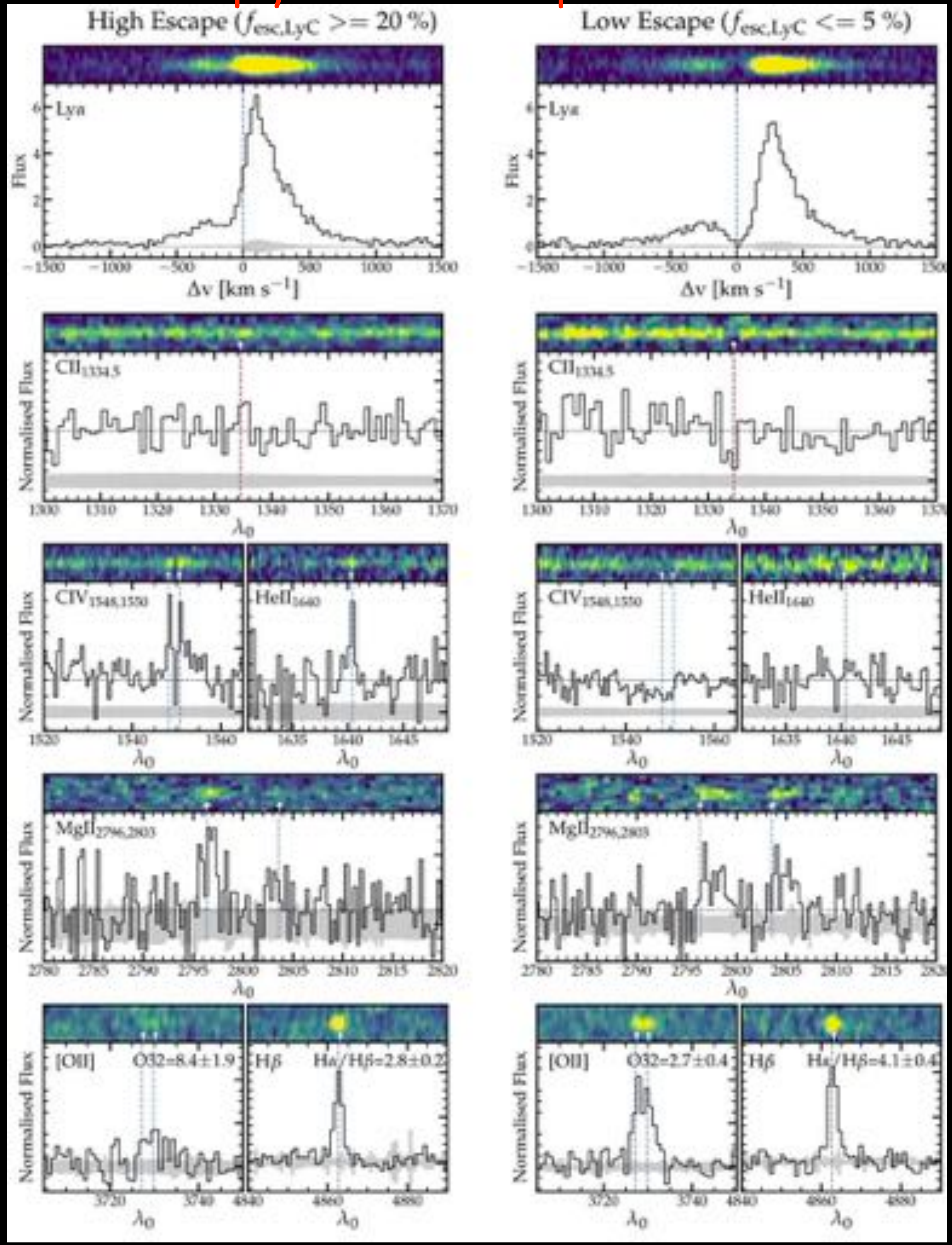
LYMAN ALPHA EMITTERS PLAY A KEY ROLE IN REIONIZATION

Synchronicity and escape of ionizing photons *Naidu & Matthee et al. 2021*

LAEs play a key role in reionization *Matthee & Naidu et al. 2021*

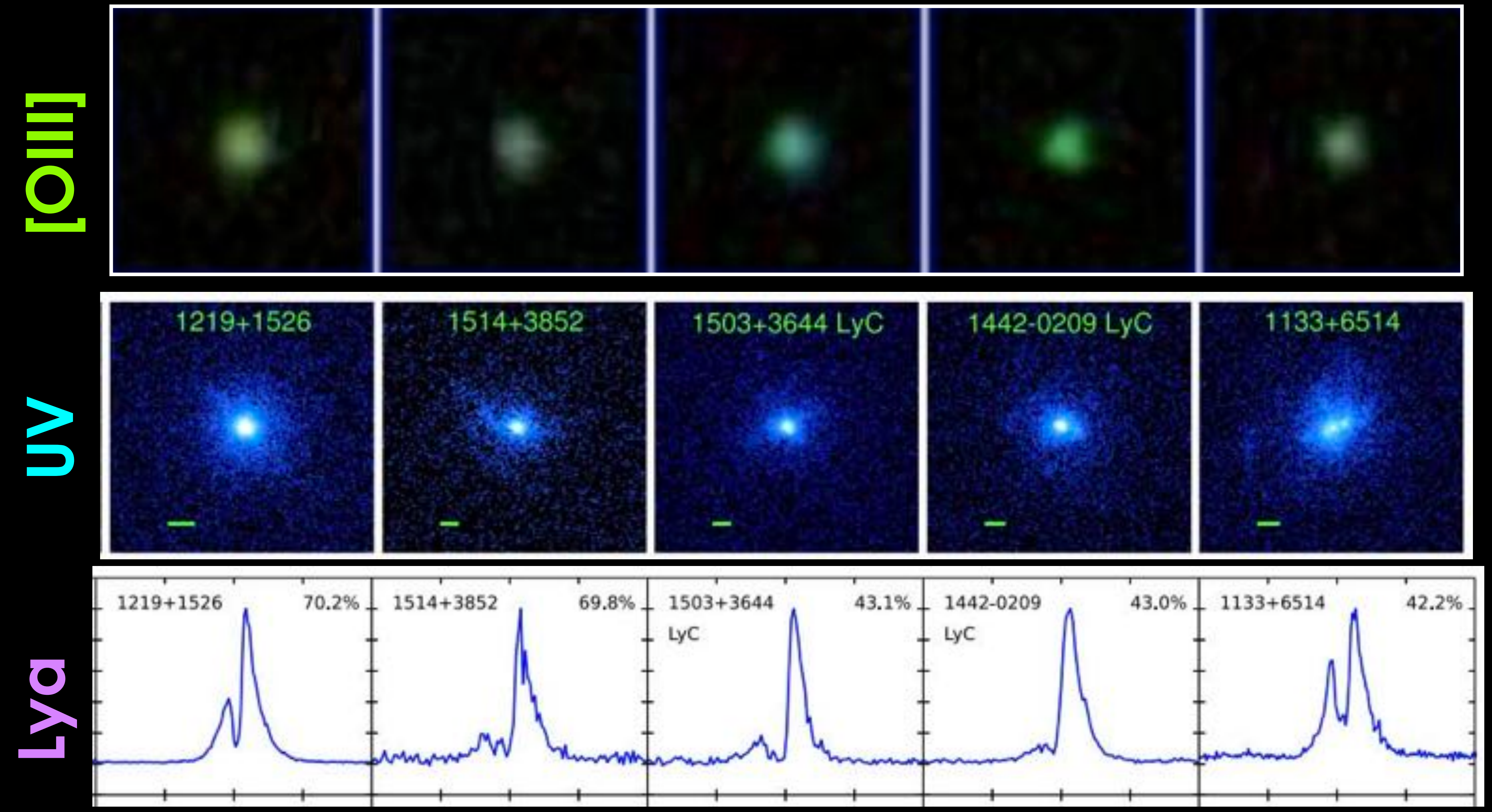


High and low escape fraction in galaxies at z<4 imply different spectral features

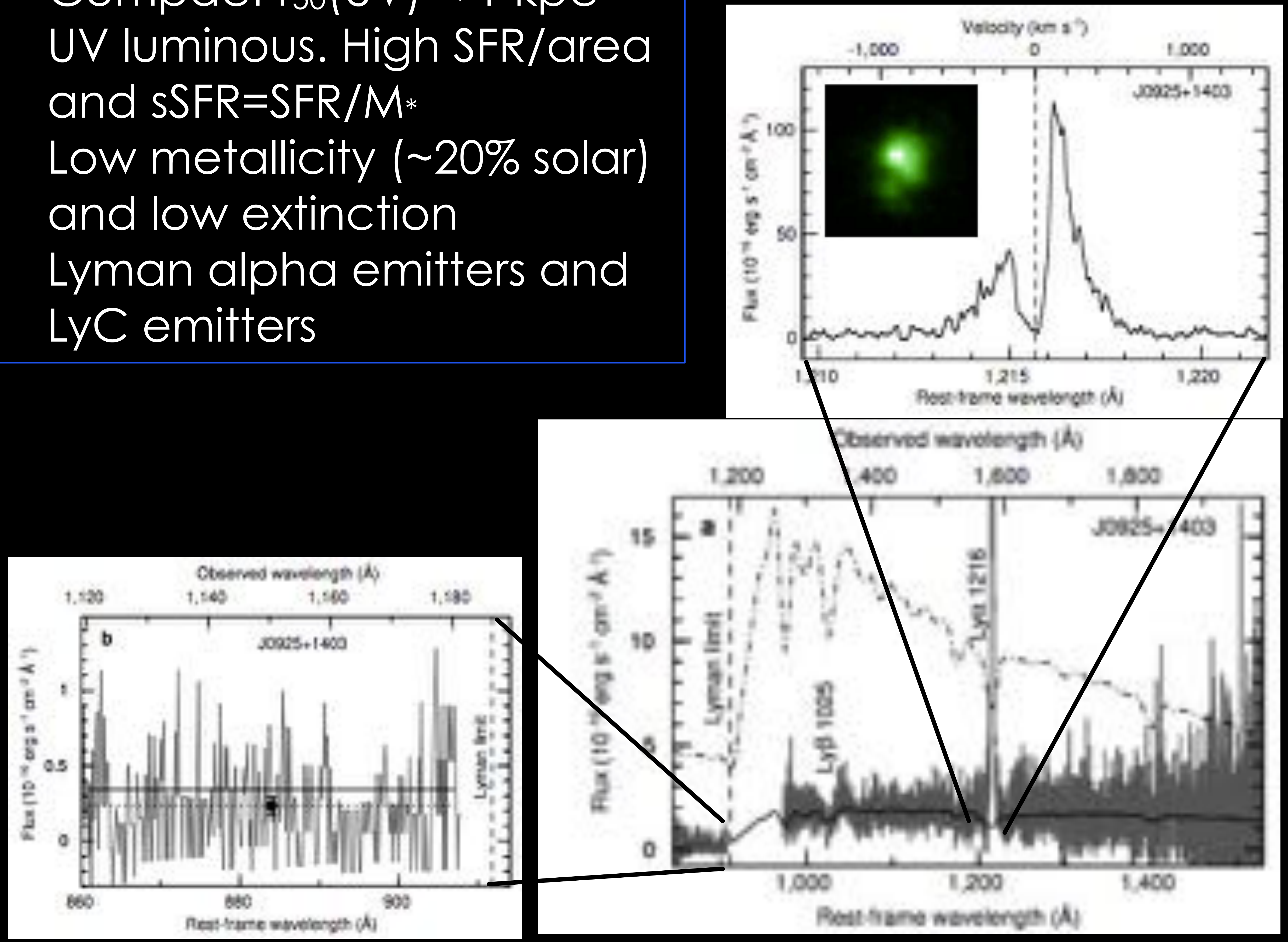


GREEN PEAS: LOCAL ANALOGS OF IONIZATION GALAXIES

Starbursting dwarf galaxies at 0.11<z<0.36
Selected by compactness and high emission-line EWs
(Cardamone+09; Amorín+10,12,15; Jaskot & Oey 13; Henry+15; Yang+17,18)



- Compact r_{50}(UV) < 1 kpc
- UV luminous. High SFR/area and sSFR=SFR/M_*
- Low metallicity (~20% solar) and low extinction
- Lyman alpha emitters and LyC emitters



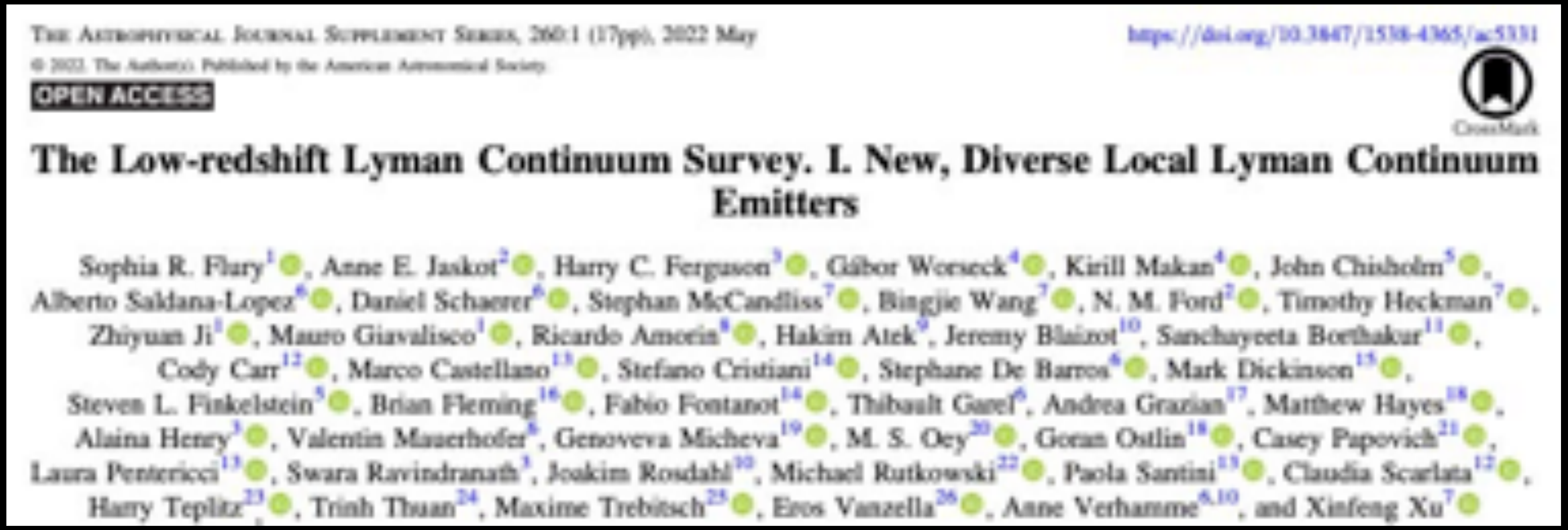
Ideal laboratories to study:

- *Massive star formation and feedback*
- *Physical mechanisms favoring the production and escape of ionizing photons*

Under *similar conditions to high-z galaxies!!*

Most GPs at z~0.3-0.4 observed so far with HST/COS show strong Lya and LyC emission with *Fesc* ~ 5-75%
Izotov+16,18,21; Verhamme+16; Schaerer+17

WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?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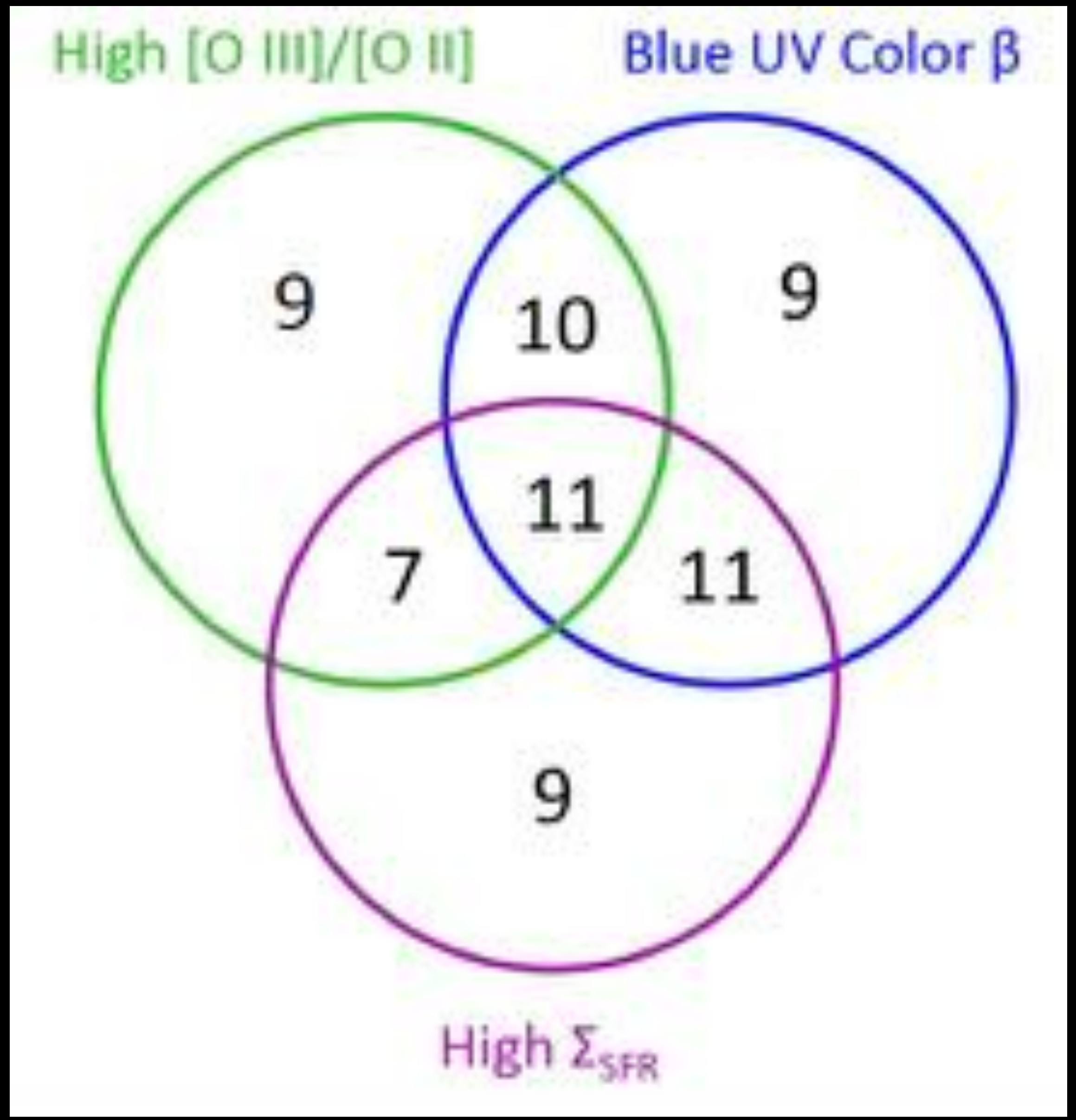
The Low-redshift Lyman Continuum Survey. I. New, Diverse Local Lyman Continuum Emitters

Sophia R. Flury[1], Anne E. Jaskot[2], Harry C. Ferguson[3], Gábor Worseck[4], Kirill Makan[4], John Chisholm[5], Alberto Saldana-Lopez[6], Daniel Schaerer[6], Stephan McCandliss[7], Bingjie Wang[7], N. M. Ford[2], Timothy Heckman[7], Zhiyuan Ji[1], Mauro Giavalisco[1], Ricardo Amorín[8], Hakim Atek[9], Jeremy Blaizot[10], Sanchayeeta Borthakur[11], Cody Carr[12], Marco Castellano[13], Stefano Cristiani[14], Stephane De Barros[6], Mark Dickinson[15], Steven L. Finkelstein[5], Brian Fleming[16], Fabio Fontanot[14], Thibault Garel[6], Andrea Grazian[17], Matthew Hayes[18], Alaina Henry[3], Valentin Mauerhofer[6], Genoveva Micheva[19], M. S. Oey[20], Goran Ostlin[18], Casey Papovich[21], Laura Pentericci[13], Swara Ravindranath[3], Joakim Rosdahl[10], Michael Rutkowski[22], Paola Santini[13], Claudia Scarlata[12], Harry Teplitz[23], Trinh Thuan[24], Maxime Trebitsch[25], Eros Vanzella[26], Anne Verhamme[6,10], and Xinfeng Xu[7]

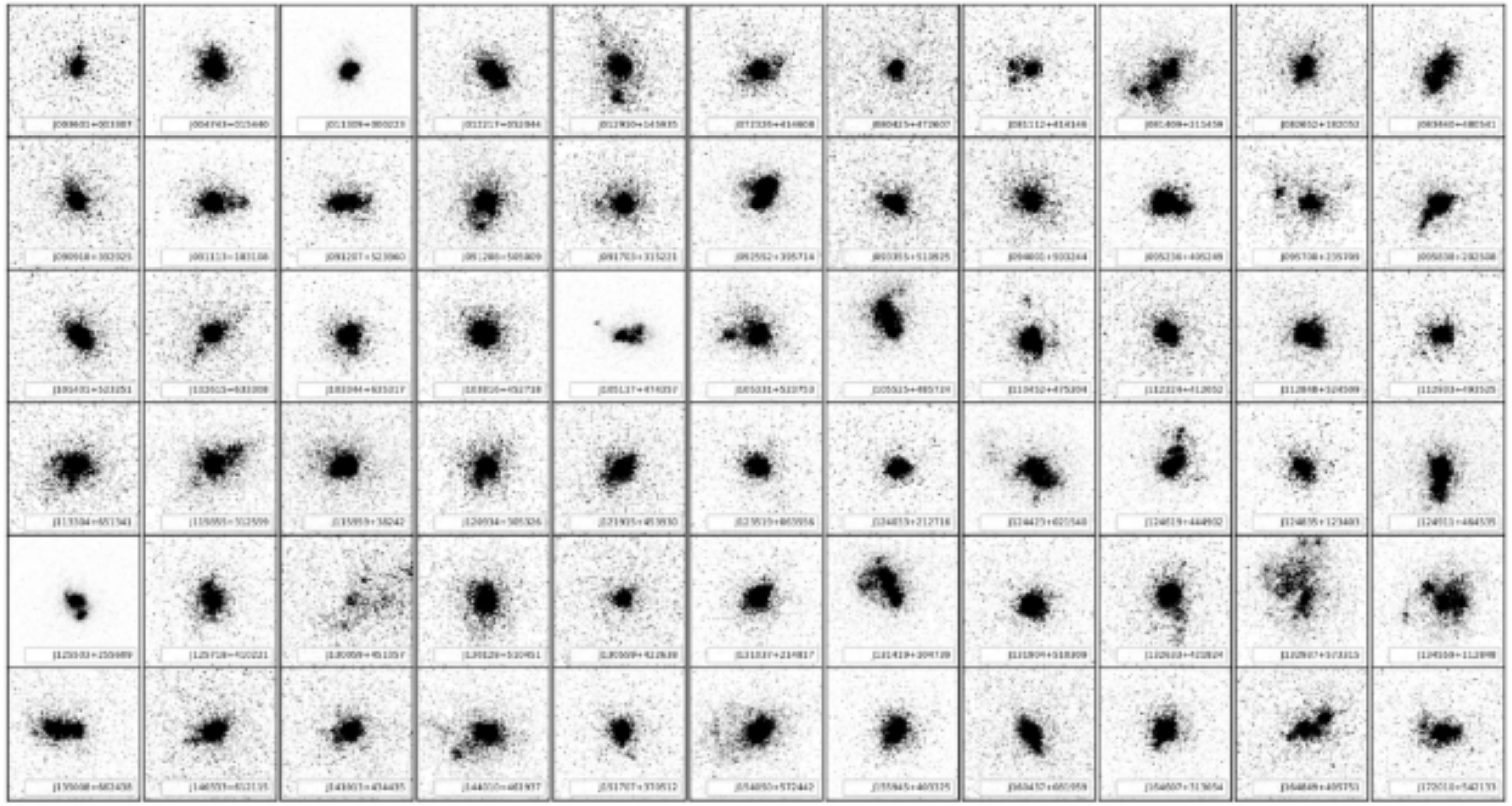
The Low-redshift Lyman Continuum Survey (LzLCS)

- Large HST/COS Program (160 orbits; PI: A. Jaskot)
- LyC observations for *66 diverse* SFGs at z~0.2-0.4 with SDSS spectra + GALEX photometry
- 35 newly confirmed LCEs, several have Fesc>5% !!
- Consistent reanalysis of 12 previous detections (Izotov+21)



Sample selection

Flury et al. 2022a



LzLCS sample imaged by HST/COS

WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?

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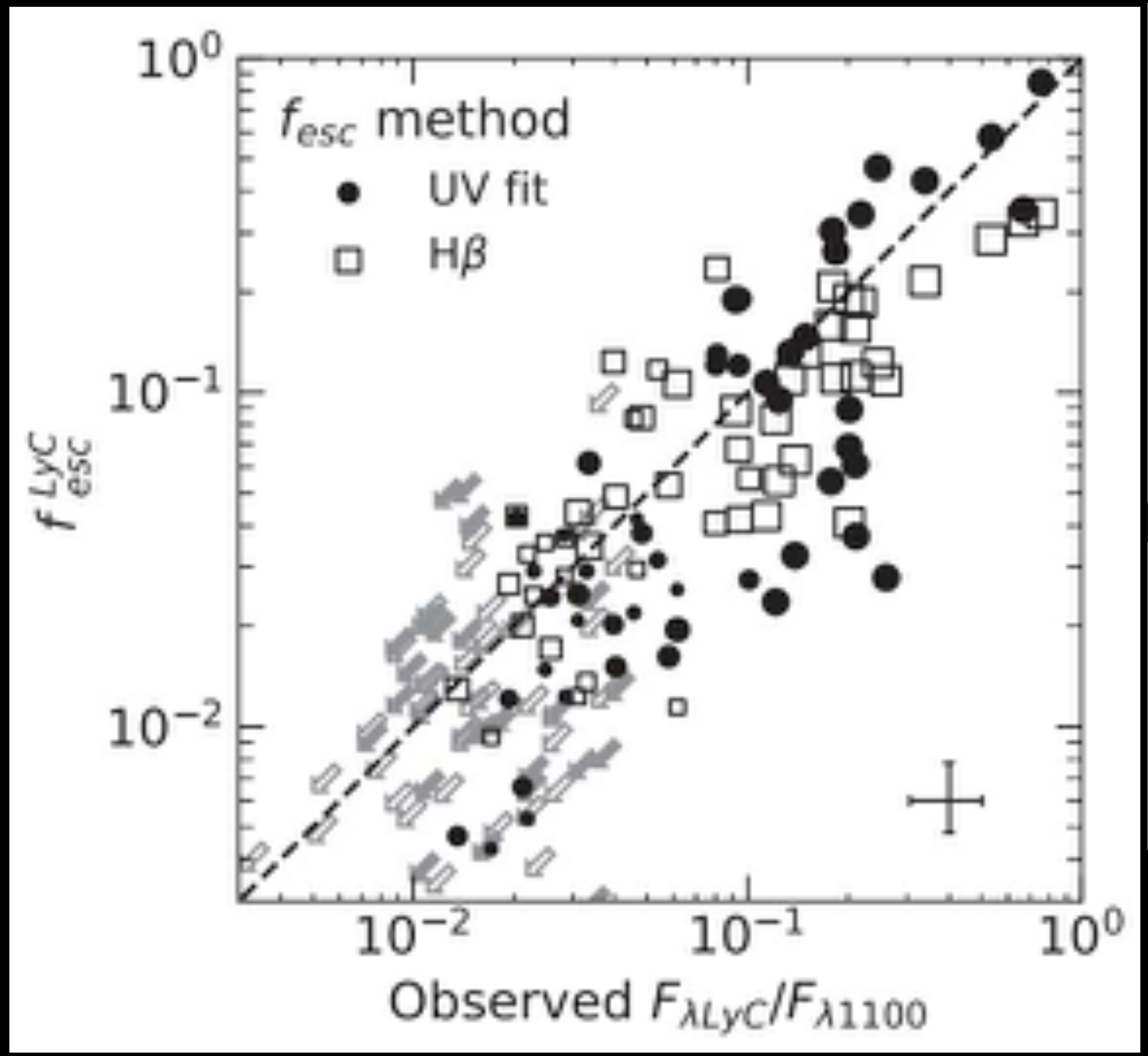

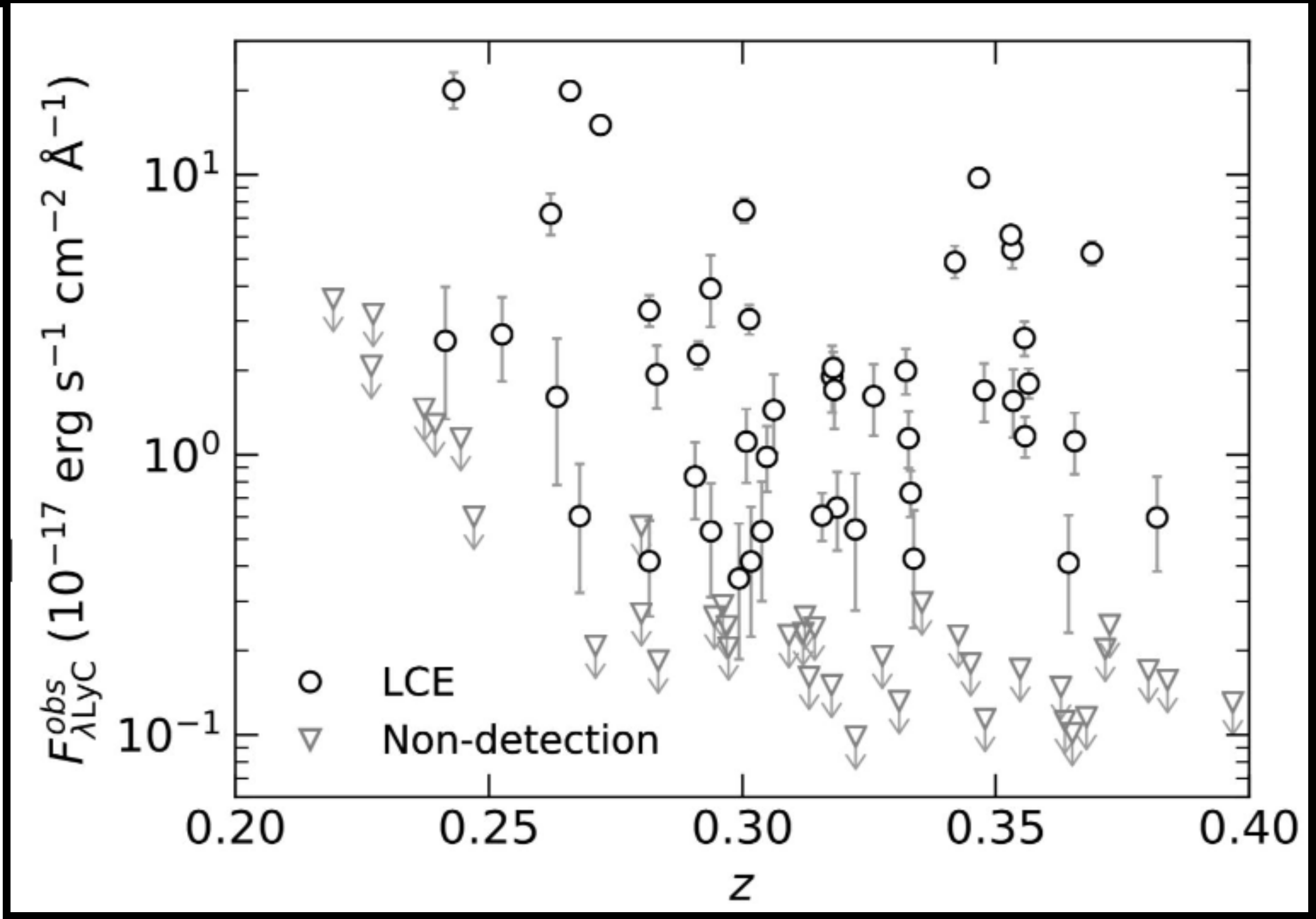

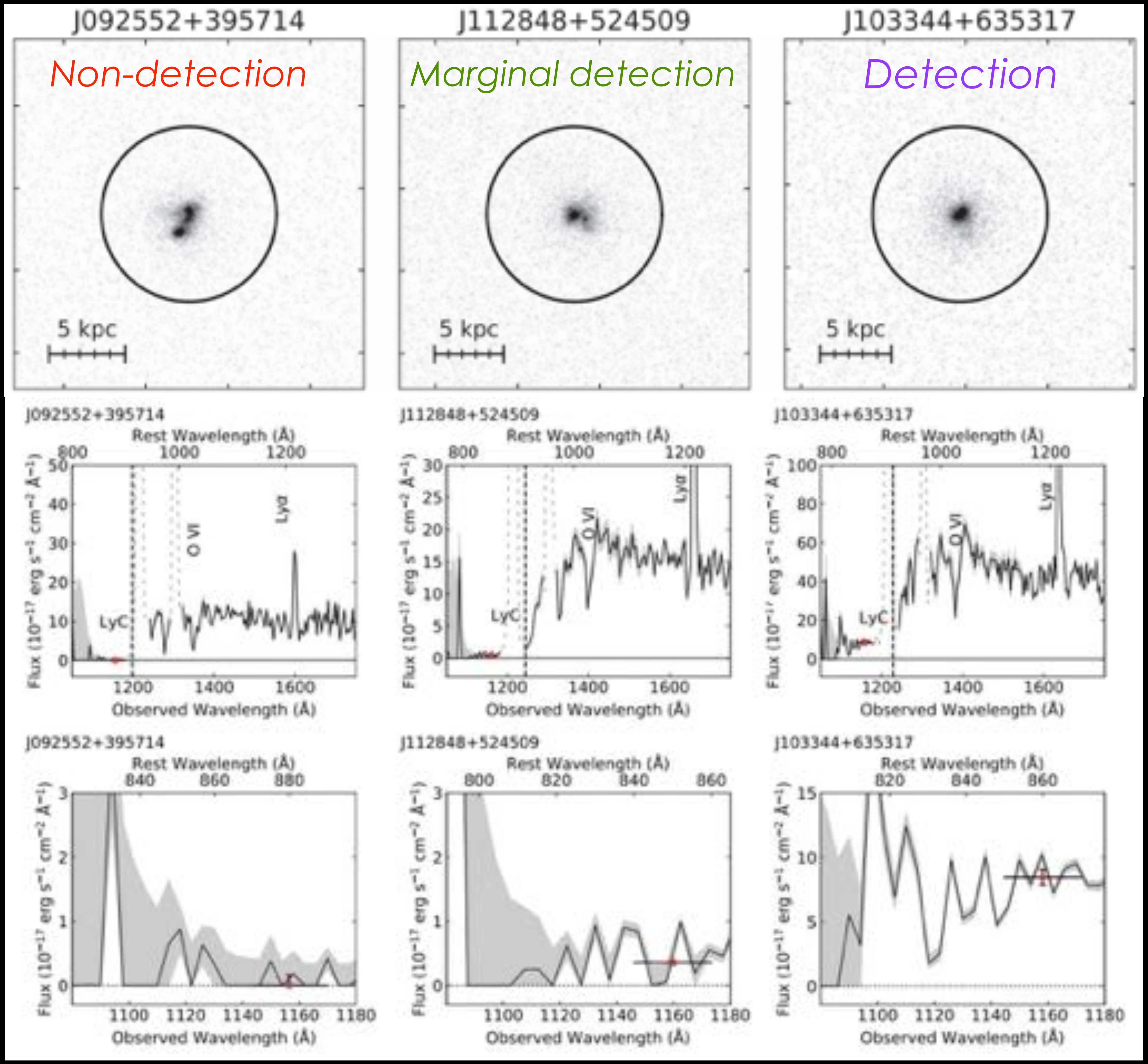

WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?

Goals of LzLCS

- Probe key LyC indicators which are testable with JWST at z>6
- Diverse sample help to discriminate different diagnostics, provide statistics and study scaling relations+scatter
- Combine with state-of-the-art models and simulations

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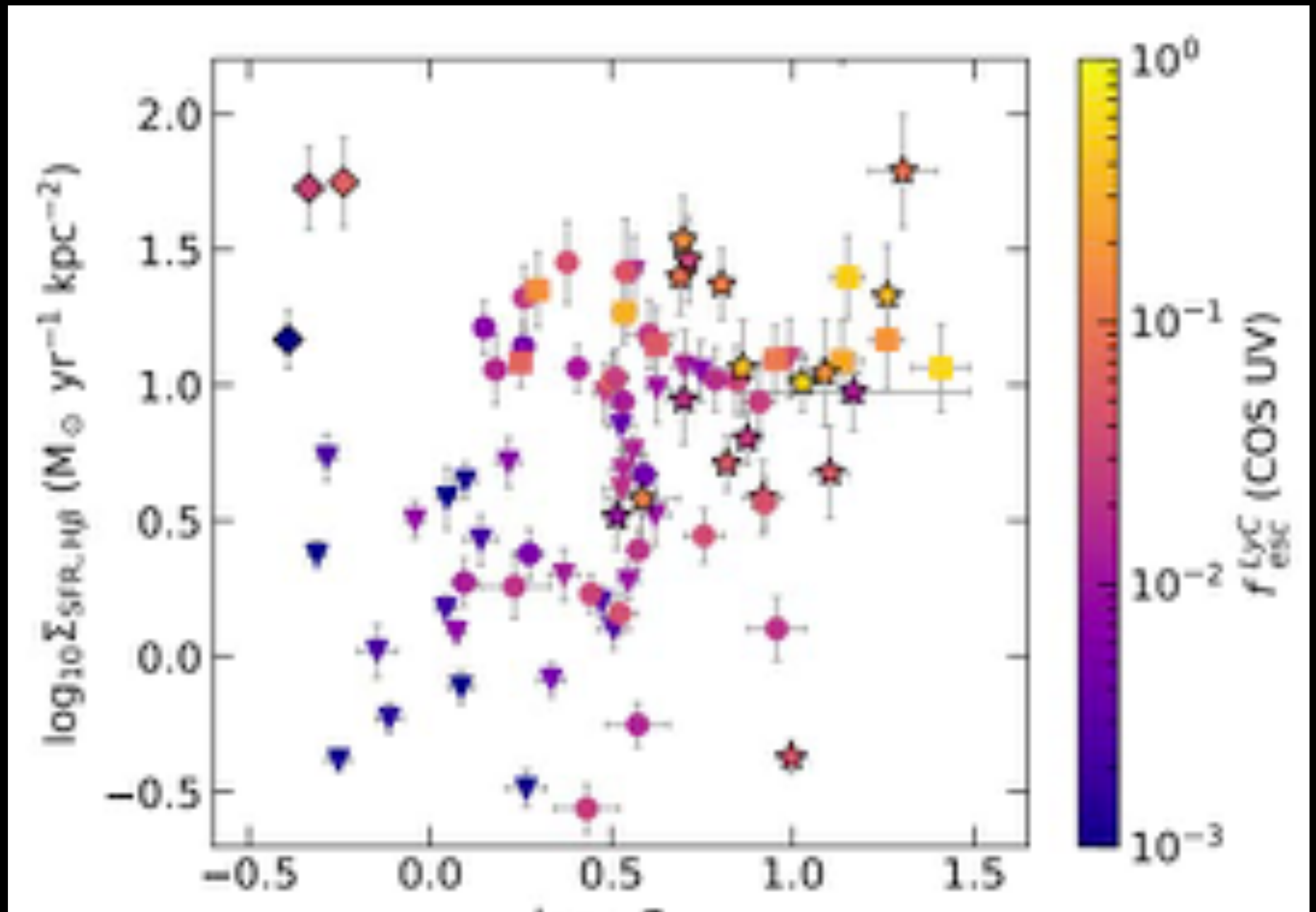
The Low-redshift Lyman Continuum Survey. II. New Insights into LyC Diagnostics

Sophia R. Flury[1], Anne E. Jaskot[2], Harry C. Ferguson[3], Gábor Worseck[4], Kirill Makan[4], John Chisholm[5], Alberto Saldana-Lopez[6], Daniel Schaerer[6], Stephan R. McCandliss[7], Xinfeng Xu[8], Bingjie Wang[8], M. S. Oey[9], N. M. Ford[2], Timothy Heckman[8], Zhiyuan Ji[1], Mauro Giavalisco[1], Ricardo Amorín[10,11], Hakim Atek[12], Jeremy Blaizot[13], Sanchayeeta Borthakur[14], Cody Carr[15], Marco Castellano[16], Stephane De Barros[6], Mark Dickinson[17], Steven L. Finkelstein[5], Brian Fleming[18], Fabio Fontanot[19], Thibault Garel[6], Andrea Grazian[20], Matthew Hayes[21], Alaina Henry[3], Valentin Mauerhofer[6,22], Genoveva Micheva[23], Goran Ostlin[21], Casey Papovich[24], Laura Pentericci[16], Swara Ravindranath[3], Joakim Rosdahl[13], Michael Rutkowski[25], Paola Santini[16], Claudia Scarlata[15], Harry Teplitz[26], Trinh Thuan[27], Maxime Trebitsch[28], Eros Vanzella[29], and Anne Verhamme[6,22]

Three LyC escape estimators

Diagnostic	Wang+21 $F_{\lambda LyC}/F_{\lambda 1100}$			Izotov+18 f_{esc}^{LyC}(Hβ)			Saldaña-López+22 f_{esc}^{LyC}(UV)		
	τ	p	σ	τ	p	σ	τ	p	σ
$f_{esc}^{Ly\alpha}$	0.292	5.186×10^{-5}	3.882	0.343	1.942×10^{-6}	4.618	0.324	6.774×10^{-6}	4.351
EW(Lyα)	0.320	8.687×10^{-6}	4.296	0.234	1.141×10^{-3}	3.051	0.342	2.011×10^{-6}	4.610
v_{sep}	−0.493	3.103×10^{-4}	3.422	−0.422	2.033×10^{-3}	2.873	−0.530	1.055×10^{-4}	3.705
$\log_{10} O_{31}$	−0.149	0.039	1.761	−0.144	0.045	1.693	−0.151	0.036	1.796
$\log_{10}$[O I]/Hβ	−0.148	0.041	1.745	−0.145	0.044	1.709	−0.145	0.044	1.705
$\log_{10} O_{32}$	0.290	5.678×10^{-5}	3.860	0.198	6.024×10^{-3}	2.511	0.347	1.438×10^{-6}	4.679
EW(Hβ)	0.223	1.953×10^{-3}	2.886	0.109	0.132	1.117	0.283	8.366×10^{-5}	3.764
$M_{1500,obs}$	0.045	0.533	0.000	−0.013	0.857	0.000	0.098	0.174	0.940
$M_{1500,int}$	0.228	1.591×10^{-3}	2.950	0.157	0.029	1.895	0.320	8.978×10^{-6}	4.289
β_{1200}	−0.221	2.200×10^{-3}	2.848	−0.261	2.966×10^{-4}	3.435	−0.283	8.366×10^{-5}	3.764
$\log_{10} M_\star$	−0.089	0.216	0.785	−0.074	0.307	0.503	−0.167	0.021	2.040
COS NUV r_{50}	−0.388	7.179×10^{-8}	5.261	−0.301	2.938×10^{-5}	4.018	−0.382	1.193×10^{-7}	5.166
$\log_{10} \Sigma_{SFR,H\beta}$	0.368	3.884×10^{-7}	4.941	0.264	2.650×10^{-4}	3.465	0.325	7.099×10^{-6}	4.341
$\log_{10} \Sigma_{SFR,F_{\lambda 1100}}$	0.070	0.334	0.429	0.068	0.347	0.394	−0.035	0.632	0.000
$\log_{10}$ sSFR	0.110	0.128	1.138	0.043	0.554	0.000	0.181	0.012	2.254
$\log_{10} \Sigma_{sSFR,H\beta}$	0.290	6.320×10^{-5}	3.833	0.208	4.167×10^{-3}	2.638	0.346	1.859×10^{-6}	4.627
$12+\log_{10}\left(\frac{O}{H}\right)$	−0.187	9.484×10^{-3}	2.346	−0.130	0.070	1.475	−0.211	3.420×10^{-3}	2.705



(Flury+22b)

WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?

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- Diverse sample help to discriminate different diagnostics, provide statistics and study scaling relations+scatter
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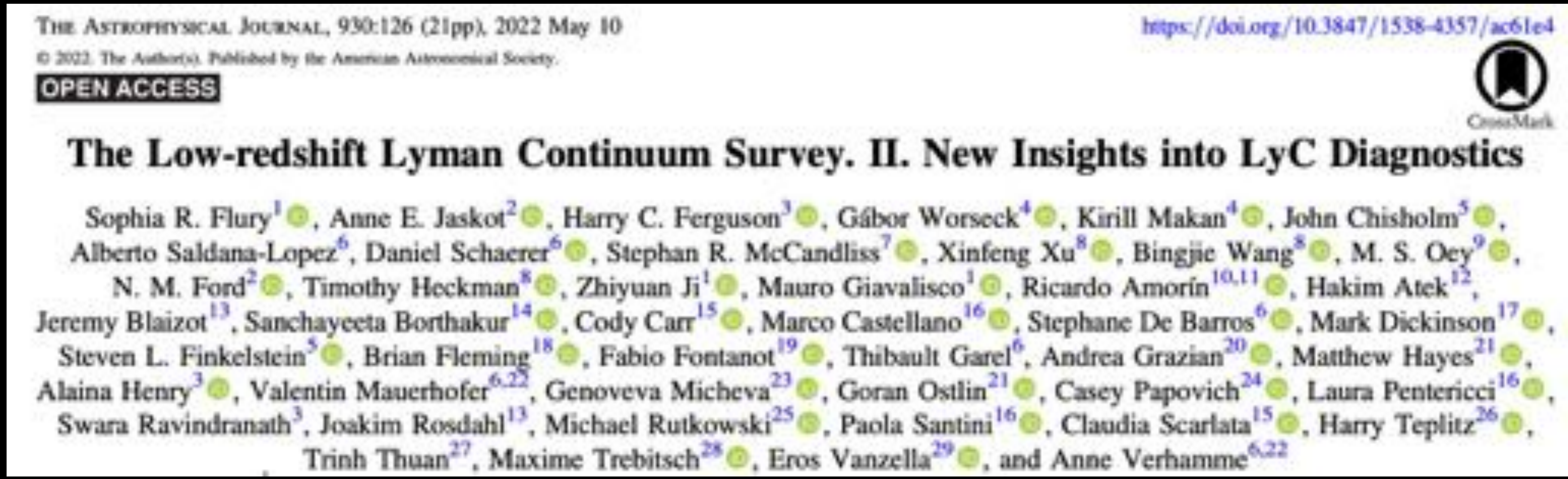
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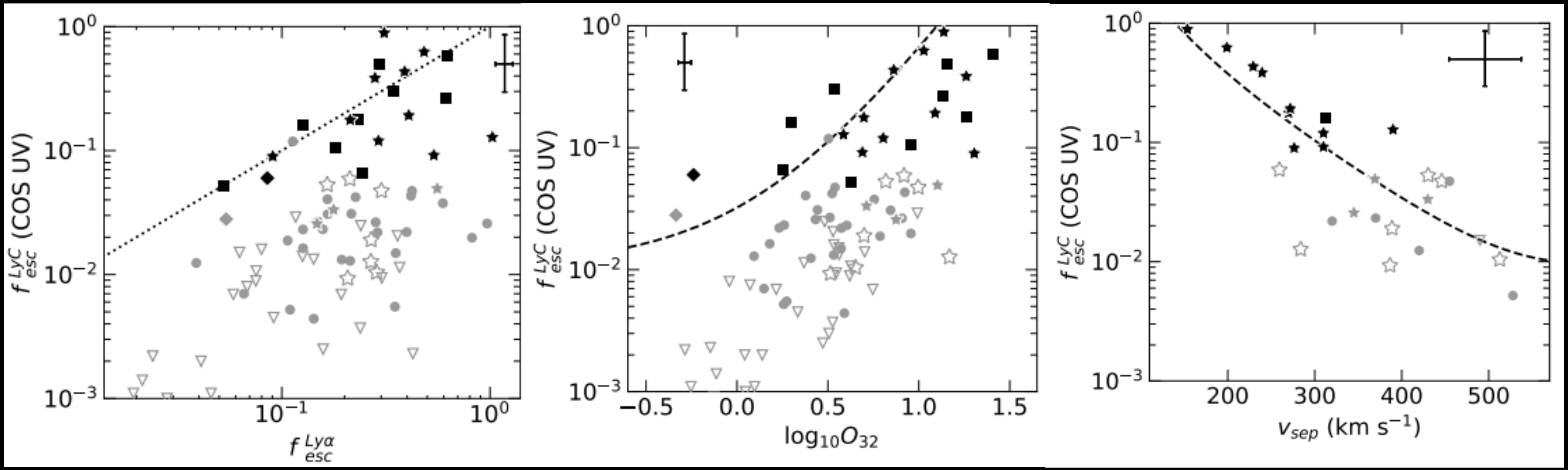
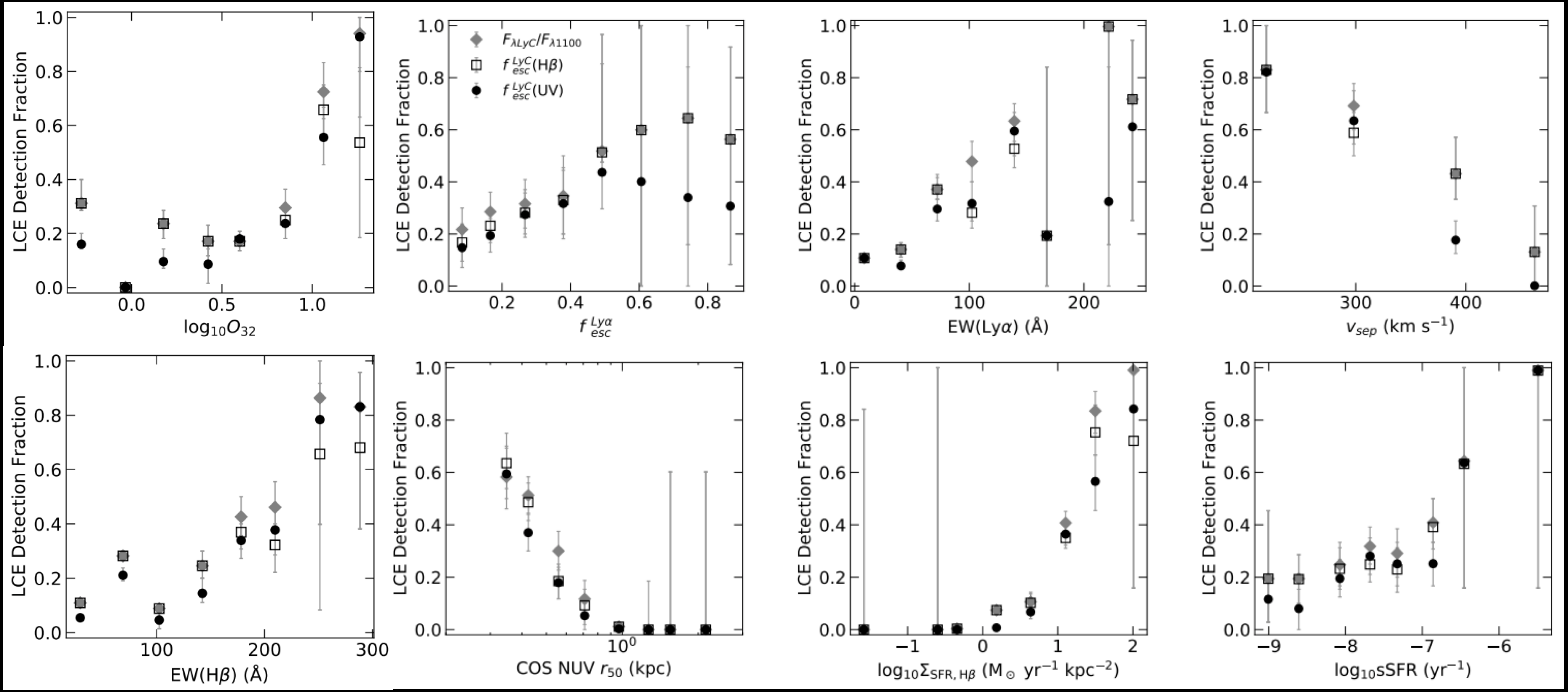


(Flury+22b)

WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?

First results of LzLCS



WHAT PROPERTIES FAVOR LYMAN PHOTON ESCAPE?

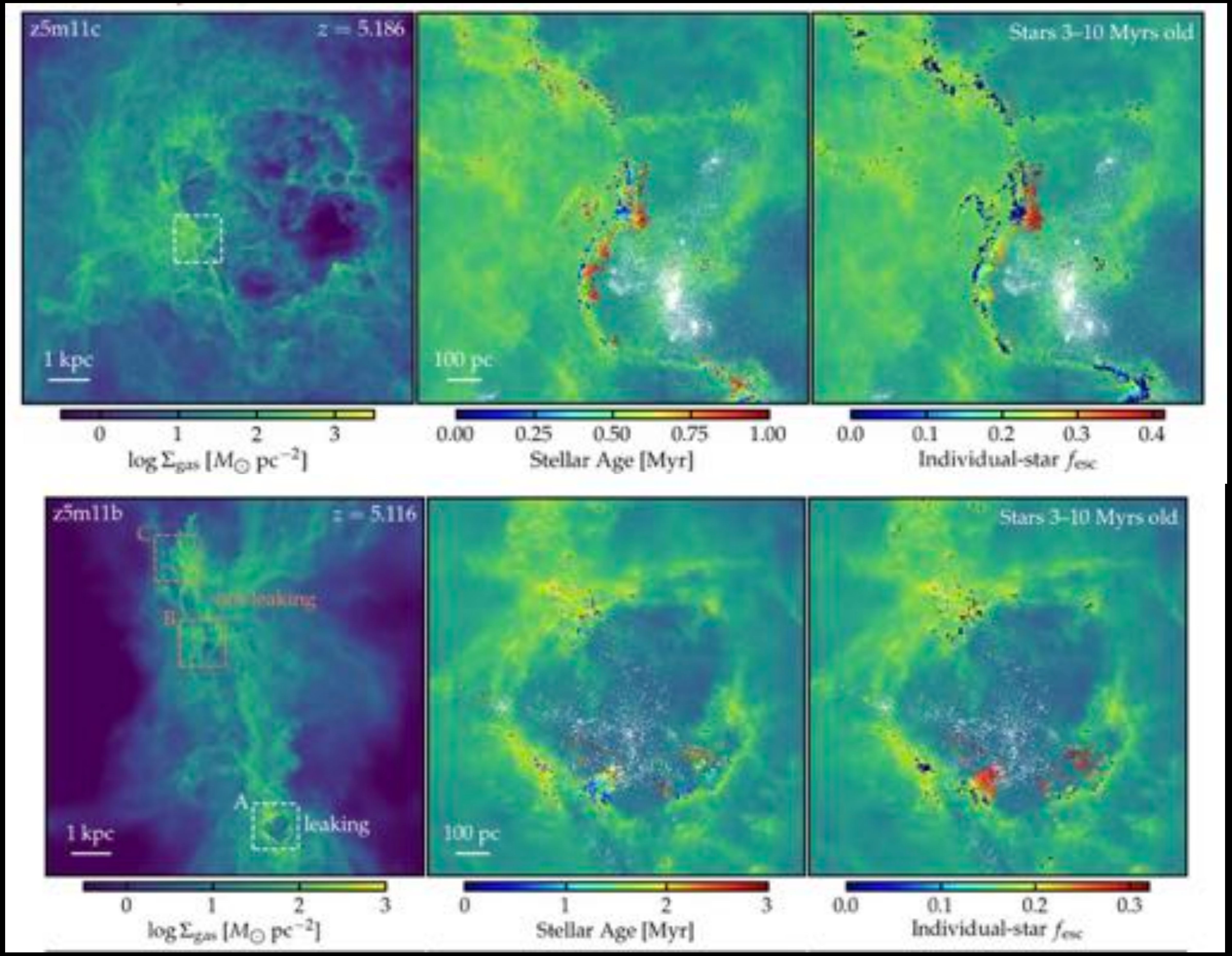
First conclusions of LzLCS (Flury+22a,b)

- Compact, UV-faint, low-mass galaxies are far more likely to be significant LCEs → BCD/HII/GP galaxy types !!
- Concentrated SF is a significant indicator LyC escape but we don't find an increase at higher masses, as simulations predict → Regardless of mechanism, locally intense SF is needed - SSCs - Strong feedback expected
- Lya is the best LyC Fesc predictor at z~0.3, similarly to the population of leakers found at z~2-4 → PROBLEM!! Lya is strongly suppressed at z>6
- LCEs cannot be described by a simple density-bounded HII region with isotropic photon escape → Challenge for models!! More work TBD

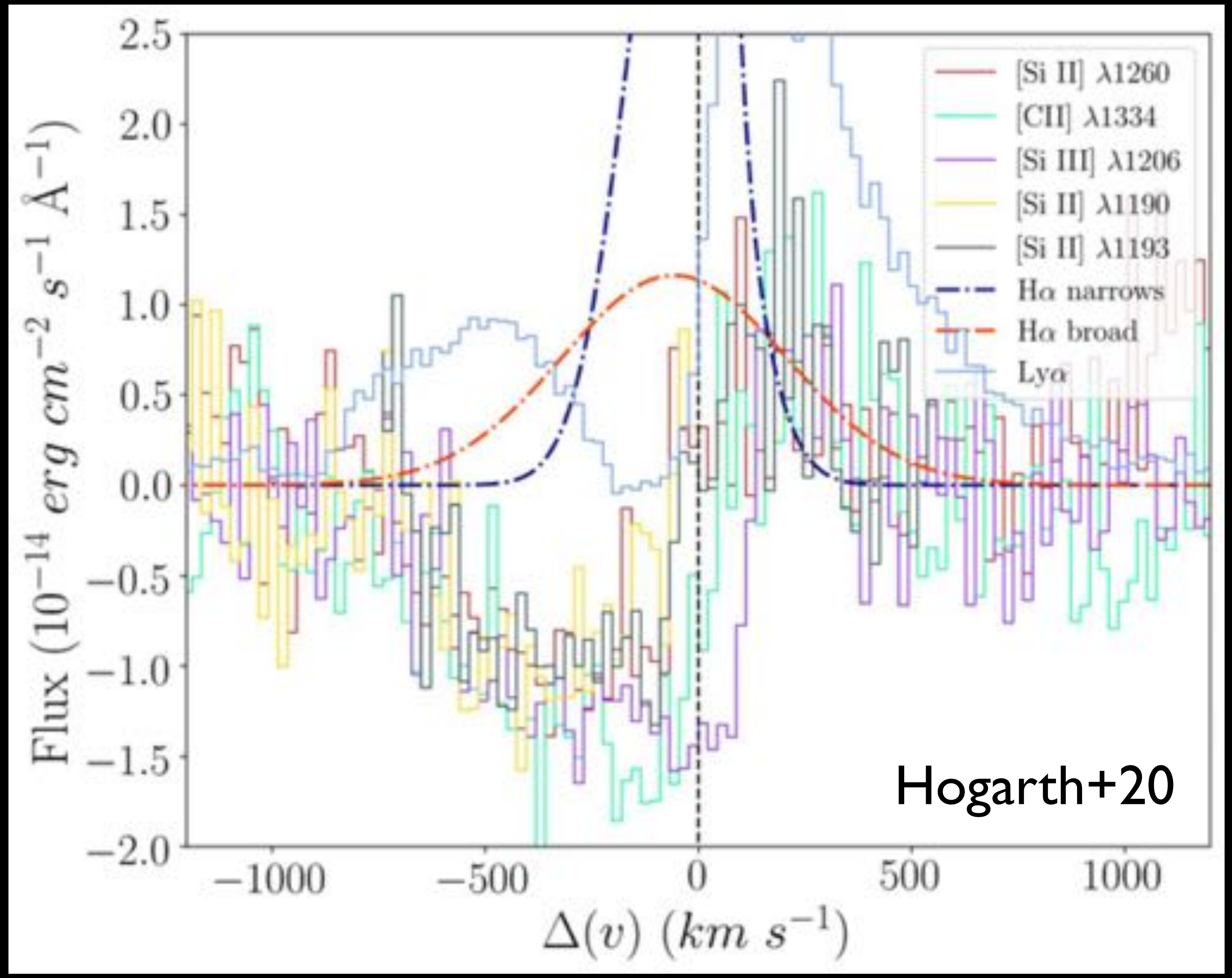
Holistic interpretation of other LyC indicators: A compact blue galaxy with high Lya EW and fesc, high O32 and EW(Hbeta), low beta slope, faint NUV and small R50(UV) and high SFR/Area is likely a LCE — Ideal targets for JWST

CONNECTING IONIZED GAS KINEMATICS WITH LYMAN PHOTON ESCAPE

Simulations show strong stellar feedback (mechanical and/or radiative) leading to winds/outflows from massive stars and SNe are responsible for clearing channels in the ISM from which ionizing photons can escape



Evidence of unresolved outflows with velocities of several hundred km/s are found in absorption and emission in local analogs (e.g. Amorín+12, Bosch+20, Hogarth+20).

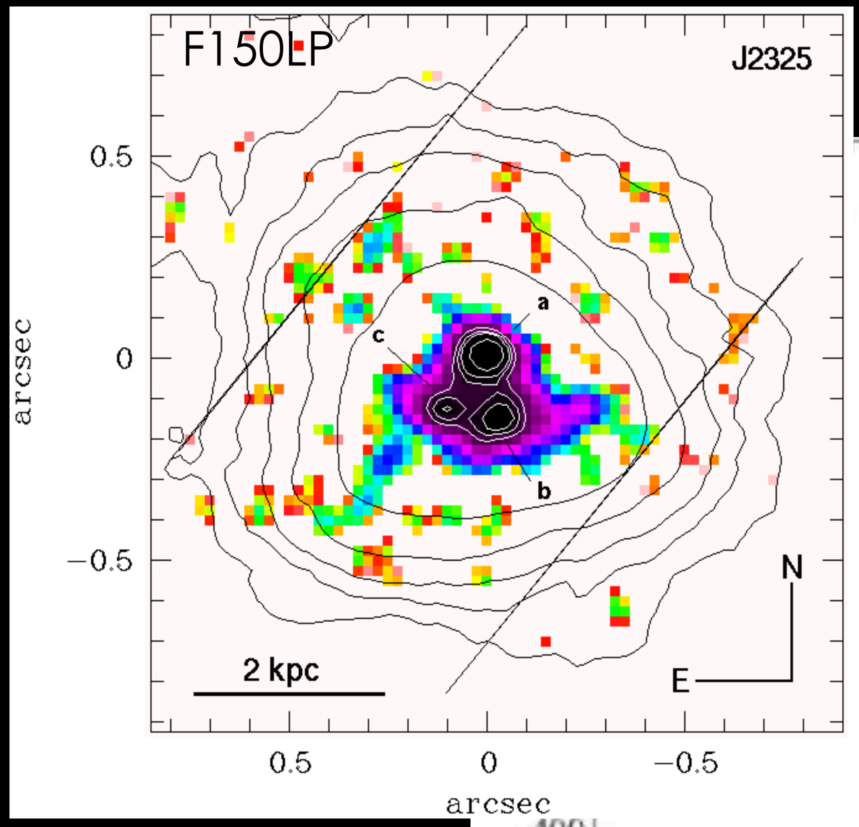


Wise & Cen 2009; Kimm+19; Trebisch+17, among others…
Cosmological zoom-in simulations with FIRE @ z>5 Ma et al. (2020)

CONNECTING IONIZED GAS KINEMATICS WITH LYMAN PHOTON ESCAPE

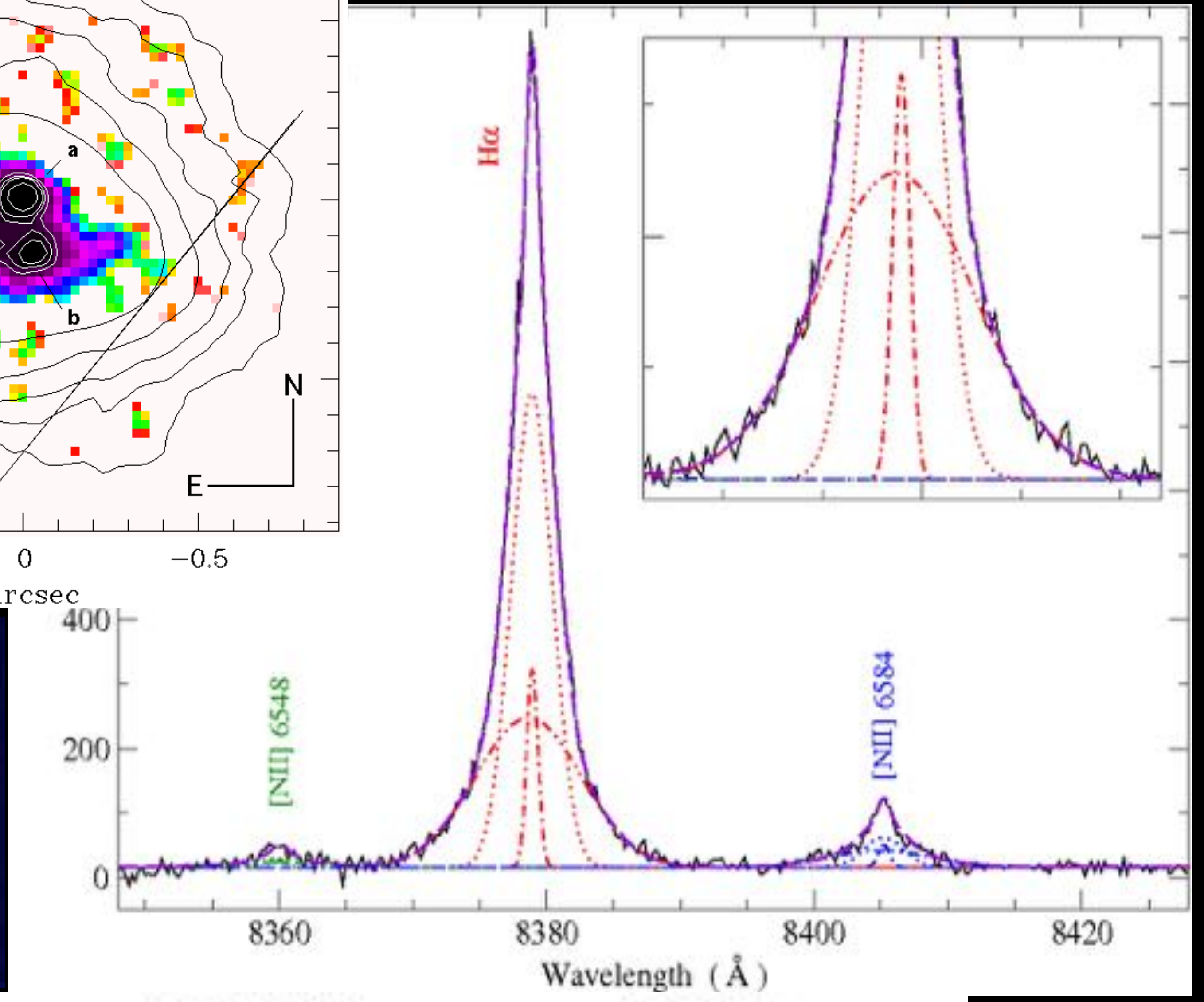
- Questions:
  - Is the ionized gas kinematics an indirect diagnostic for LyC emission?
  - Is strong turbulence in the warm ionized gas of GPs causally connected to Lyα and LyC escape?
  - Can we constrain theory from what we learn from the physical properties (extinction, ionization, densities, temperatures..) of different kinematic components?

- Some specific goals:
  - Detailed multi-component modeling of emission lines using Gaussian and non-gaussian profiles
  - Non-parametric analysis of line profiles. Quantification of outflow velocities and line asymmetries from inter percentile analysis
  - Extent the analysis from echelle 1D spectra to spatially-resolved IFU data

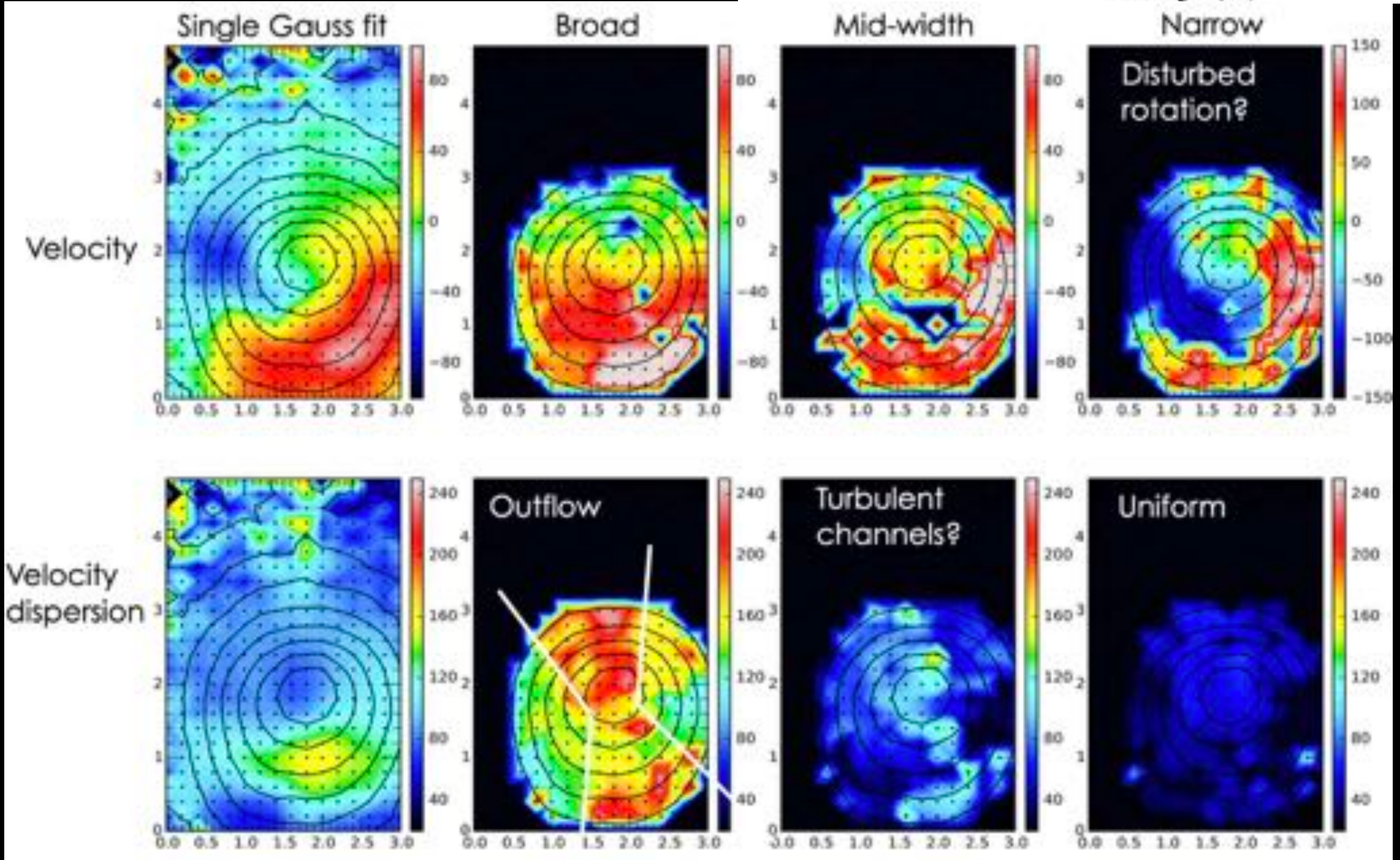


HST/ACS F150LP (unsharped)
HST/ACS F606W (contours)

Amorín et al. (2012)



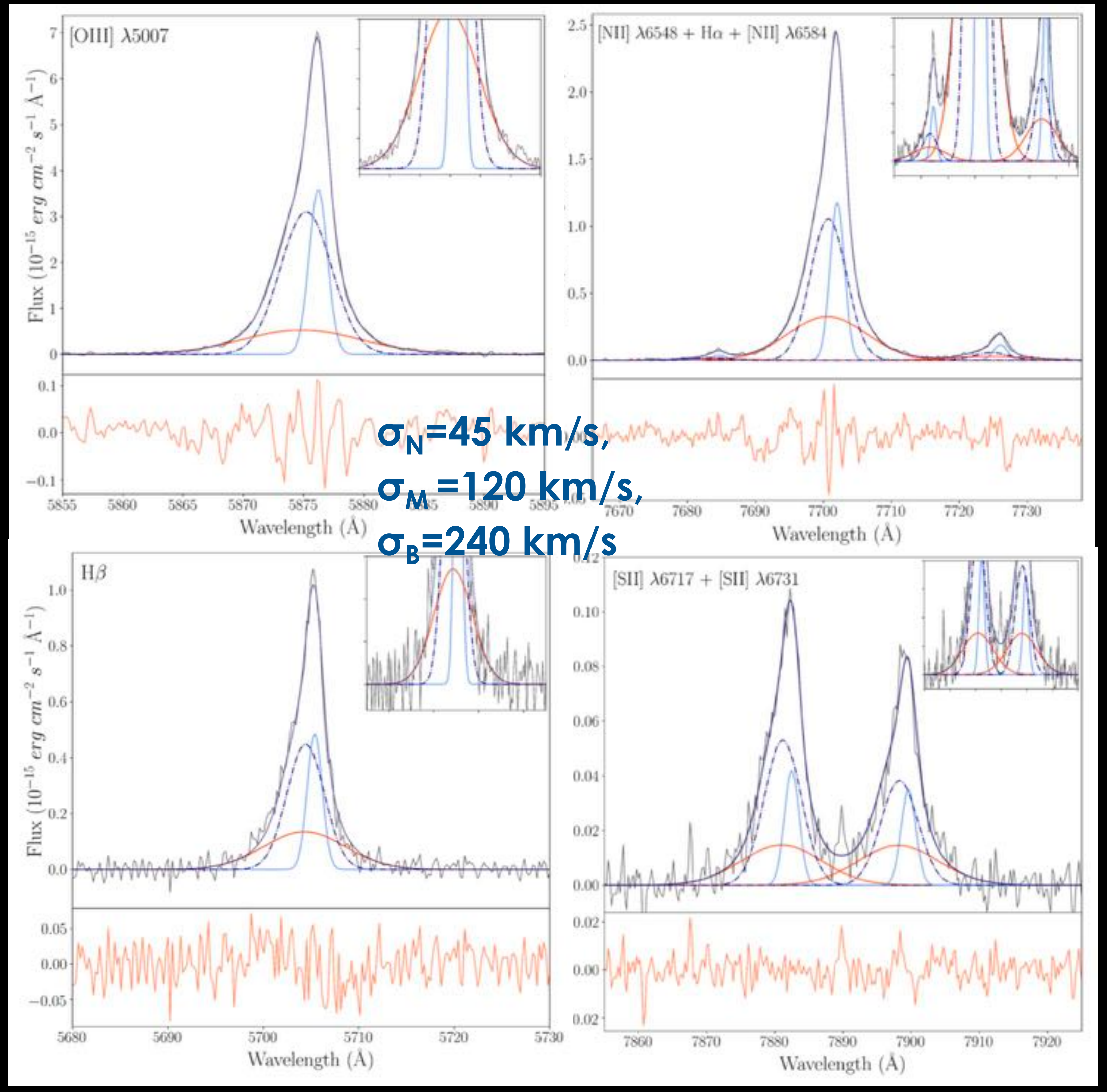
Bosch et al. (2019)



METHODOLOGY

Hogarth+20

- Sample: 23 targets: 5 non-LCEs; 11 weak and 8 strong LCEs
- Data: VLT/XShooter (R~8000); WHT/ISIS (R~10000) and LCO/MIKE (R~20000). ~1-3h on-source
- Methodology: Inspired in our previous work (Firpo+10; Amorín+12, Bosch+19; Hogarth+20)




```
[[Model]]
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[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 59
    # data points      = 250
    # variables        = 6
    chi-square         = 254.904483
    reduced chi-square = 1.04469051
    Akaike info crit   = 16.8569955
    Bayesian info crit = 37.9857610
```

FitELP code for fitting echelle spectra (Firpo+, in prep) using the LMFIT package (Newville+14)

```
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[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 81
    # data points      = 250
    # variables        = 9
    chi-square         = 91.0942029
    reduced chi-square = 0.37798424
    Akaike info crit   = -234.391687
    Bayesian info crit = -202.698539
[[Variables]]
    linintercept:  3.914282e-17 (fixed)
    linslope:     -4.03671
    c1_sigma:      1.16615
    c1_center:     6513.3
    c1_amplitude:  4.6832
    c1_fwhm:       2.7461
    c1_height:     1.6021
    c2_sigma:      0.8559
    c2_center:     6515.5
    c2_amplitude:  6.9066
    c2_fwhm:       2.0156
    c2_height:     3.2190
    c3_sigma:      3.1545
    c3_center:     6514.1
    c3_amplitude:  4.6880
    c3_fwhm:       7.4283
    c3_height:     5.9287
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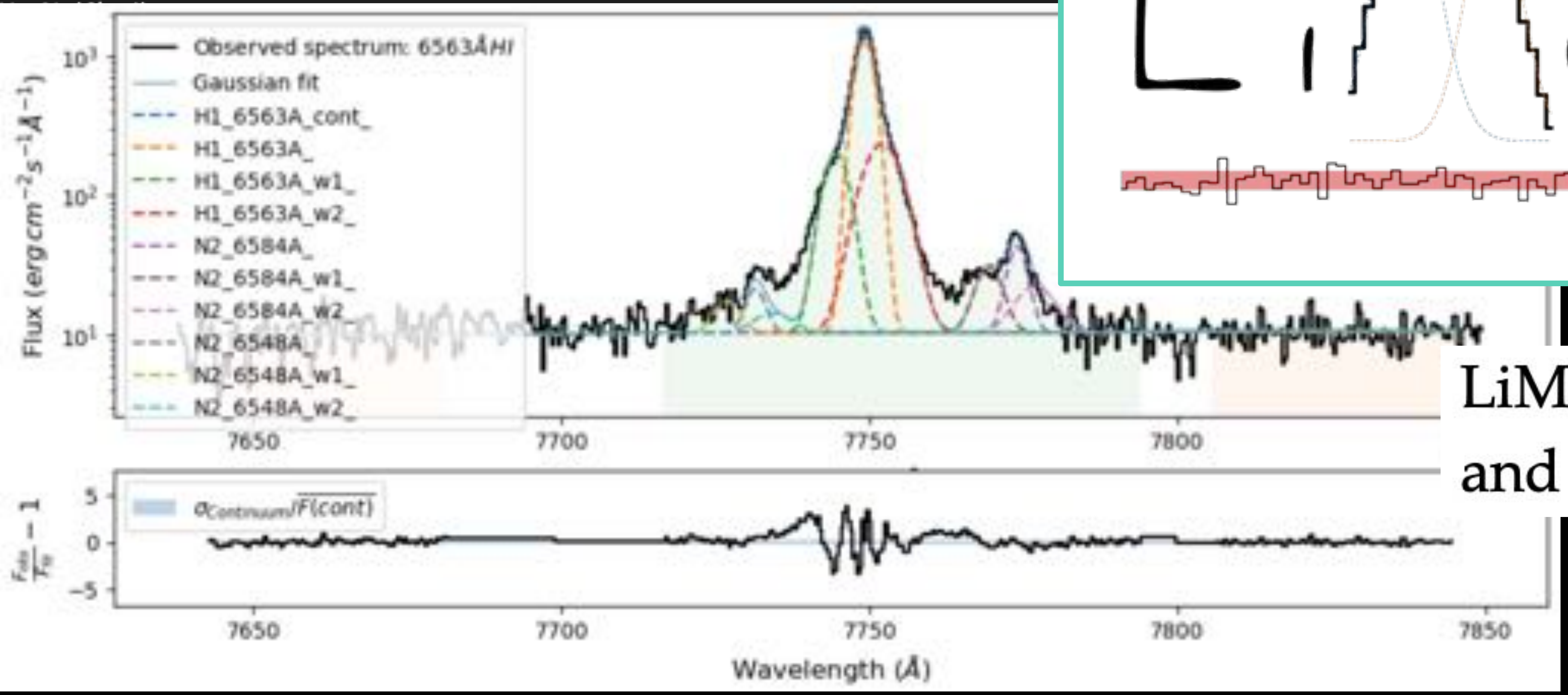
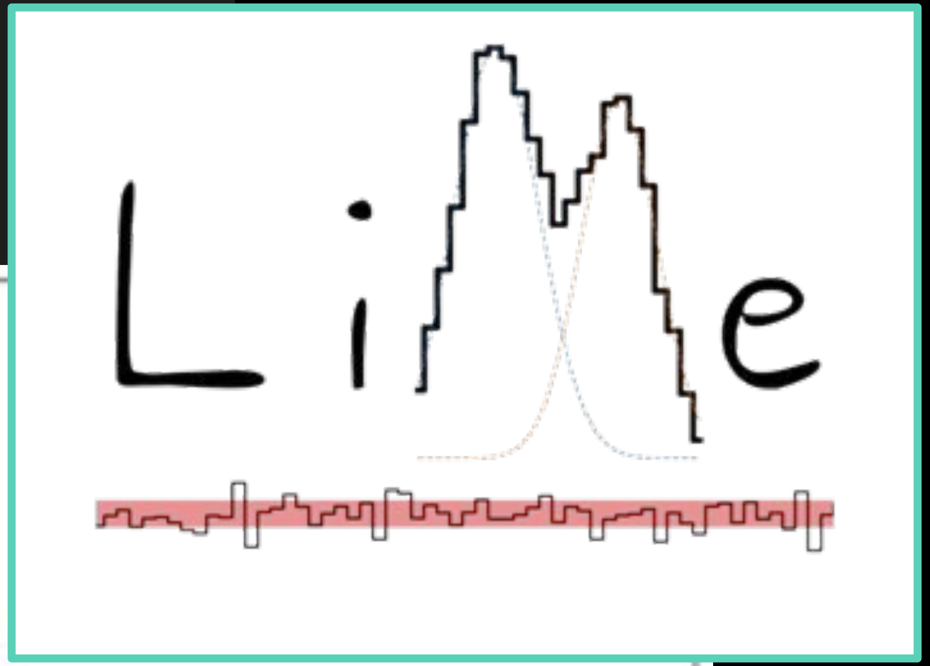




Extremely complex line profiles require very demanding voxel-by-voxel modeling

We use a new versatile code LiMe; developed by ULS postdoc Vital Fernández

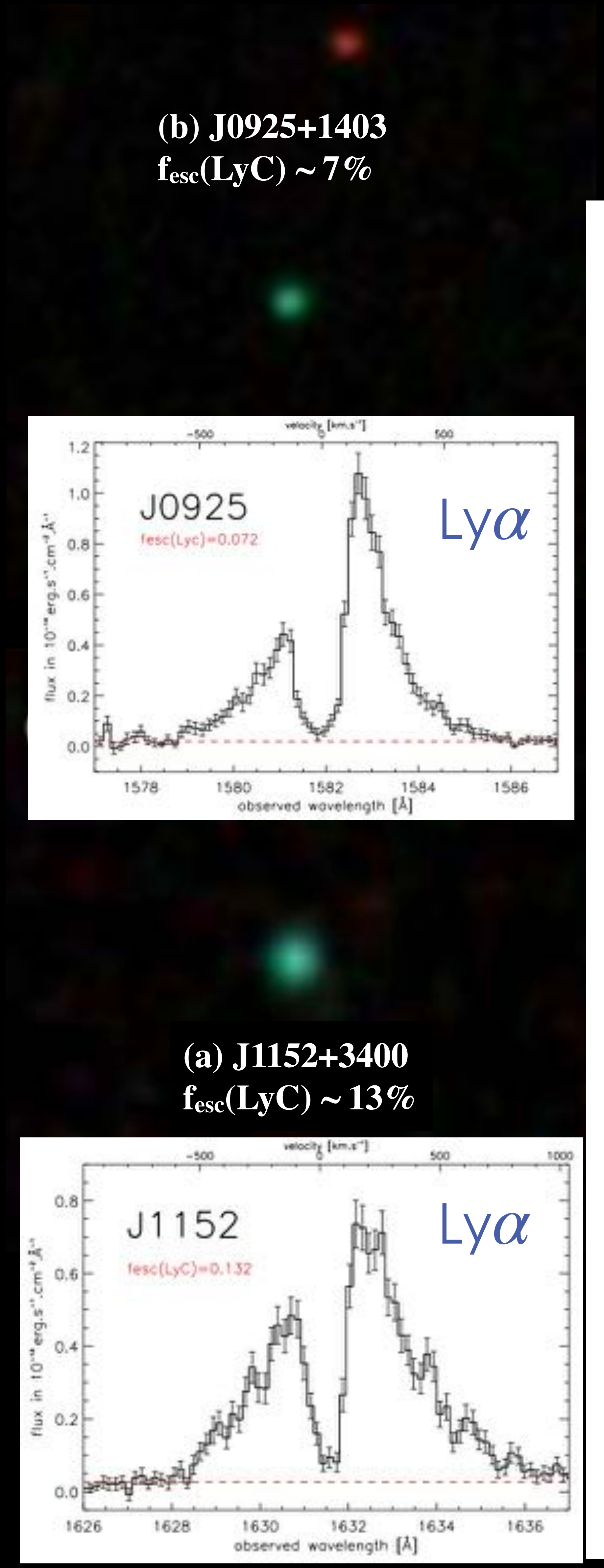
LiMe: A Line Measuring library for the chemical and kinematic analysis of the ionized gas .

See Vital's talk for details!!

EVIDENCE OF IONIZED GAS OUTFLOWS IN LYC LEAKERS

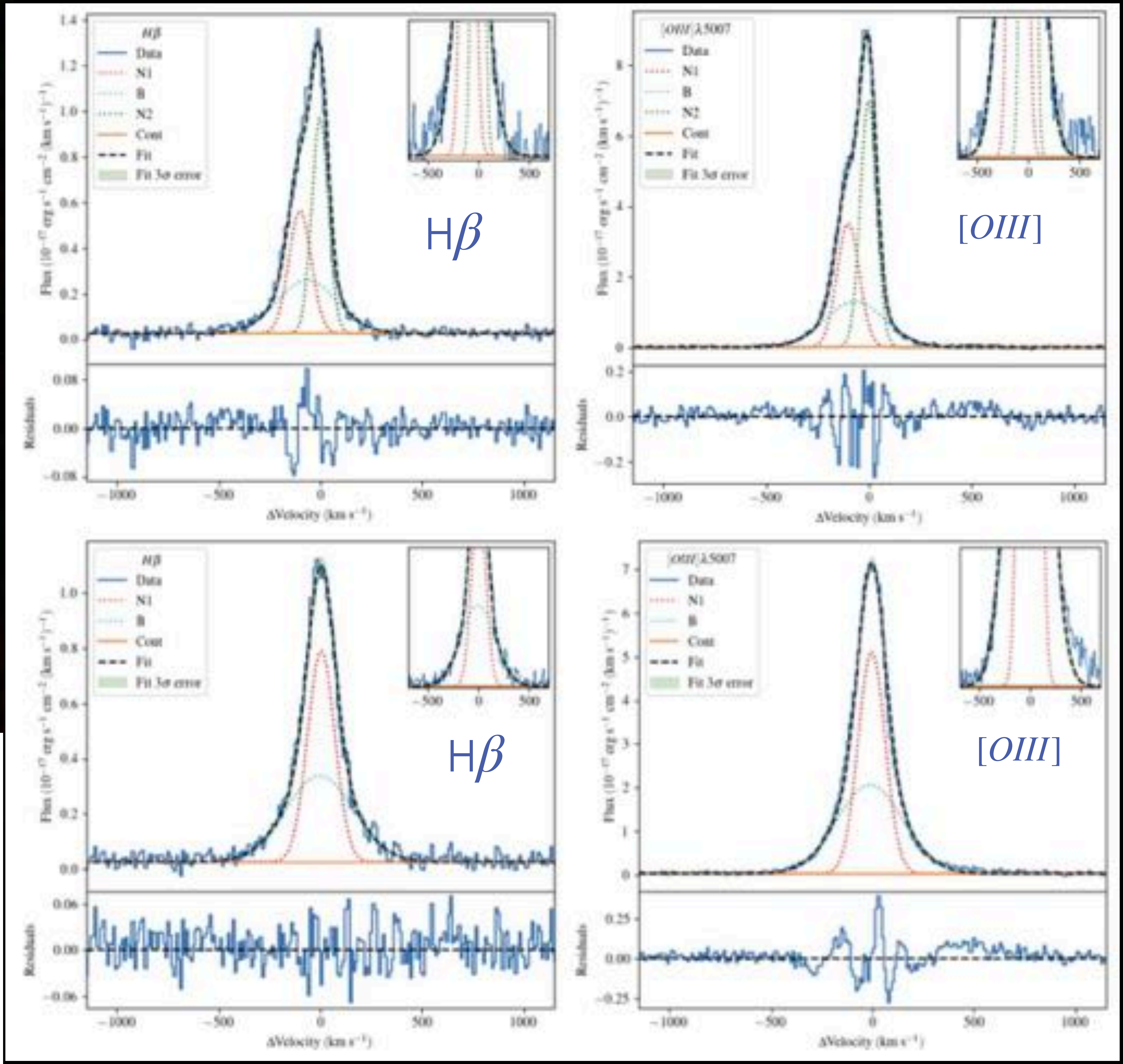
Matías Rodríguez
MSc thesis (in prep)

Dania Muñoz PhD thesis



Rodríguez et al, in prep

WHT/ISIS data



Improving FitELP capabilities

Full kinematic modelling of bright and faint lines

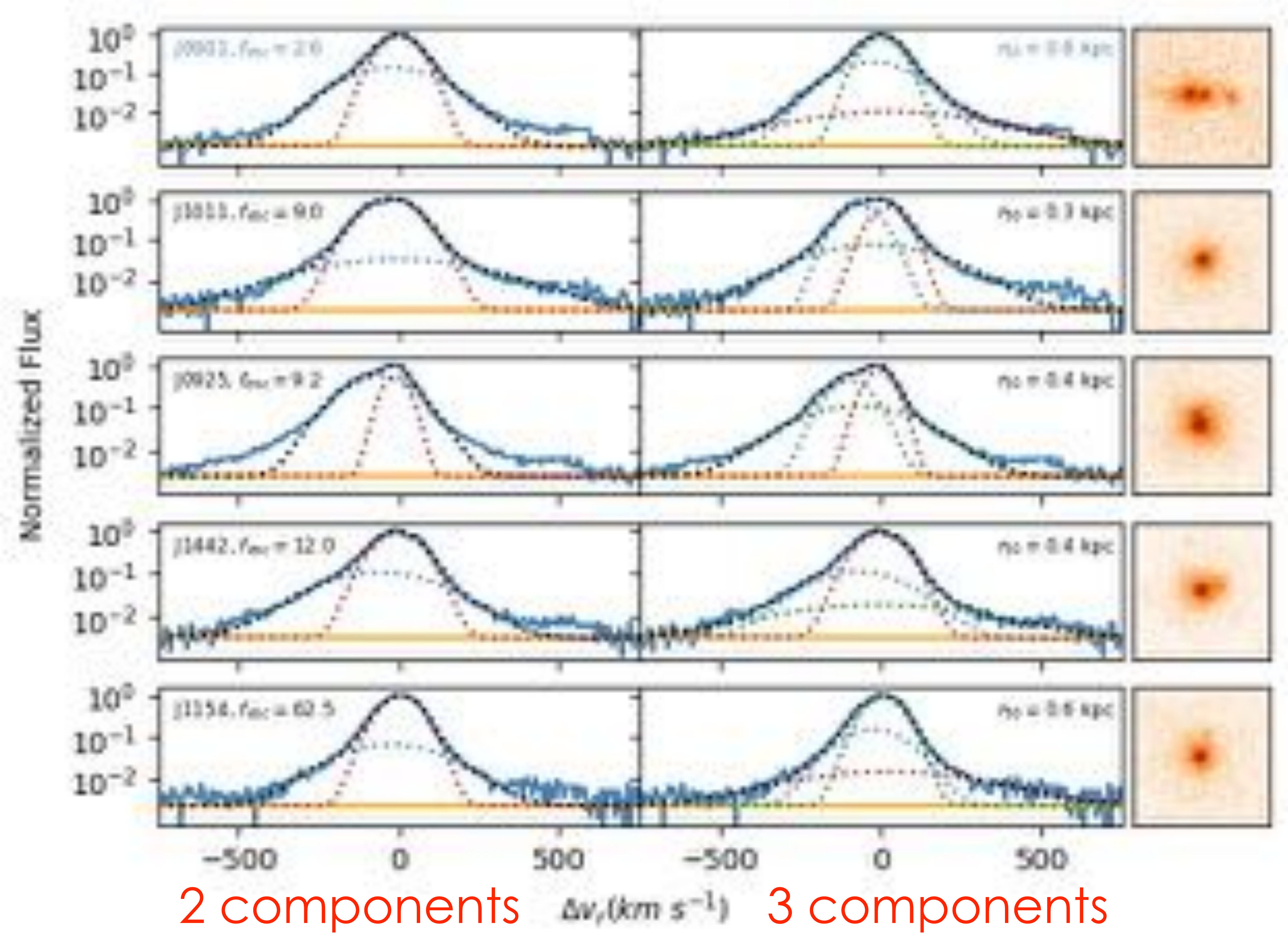
First clear evidence for broad emission heavy line wings in strong LCEs, which contribute ~20-50% of the total line flux

IMPORTANT: ALL BALMER AND CELs show similar kinematics! No AGN behavior (see Hogarth+21)

FIRST RESULTS

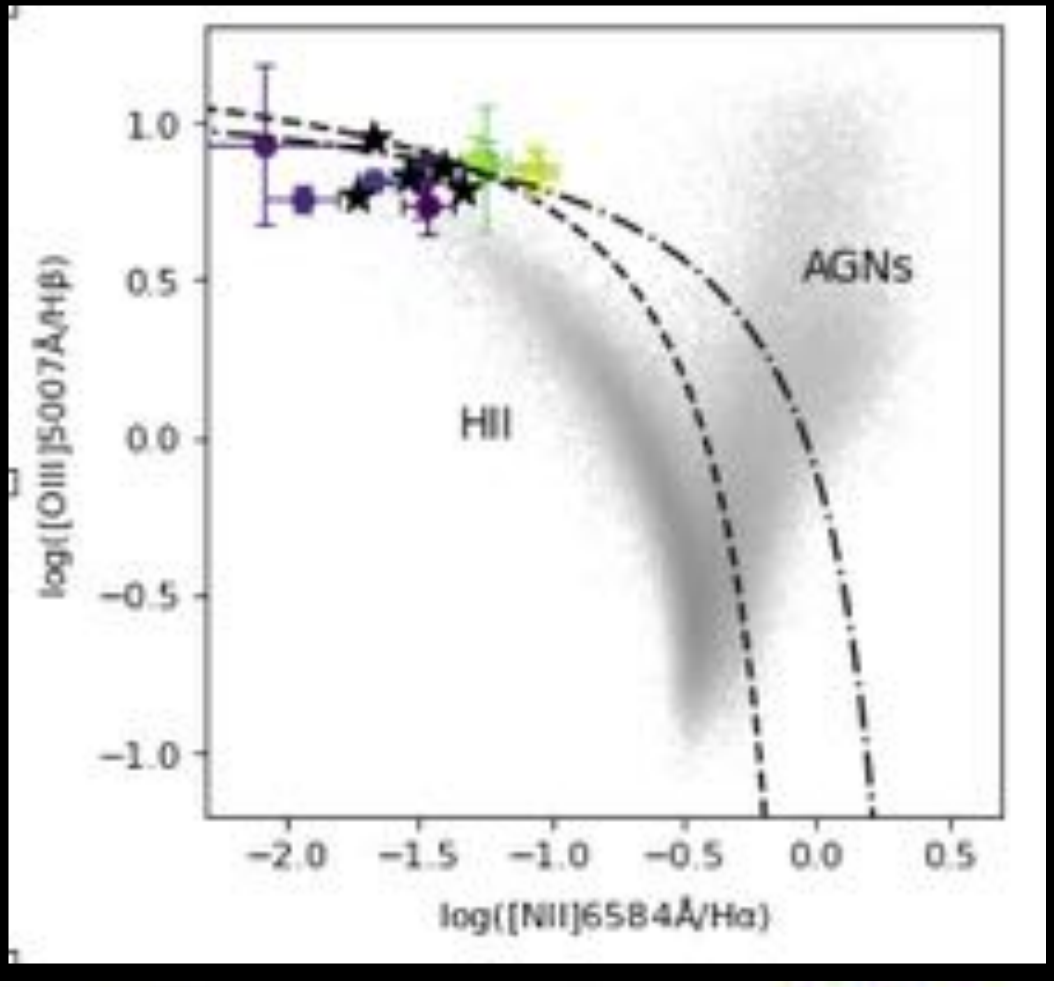
Strong LCEs appear to have broader and more asymmetric line profiles

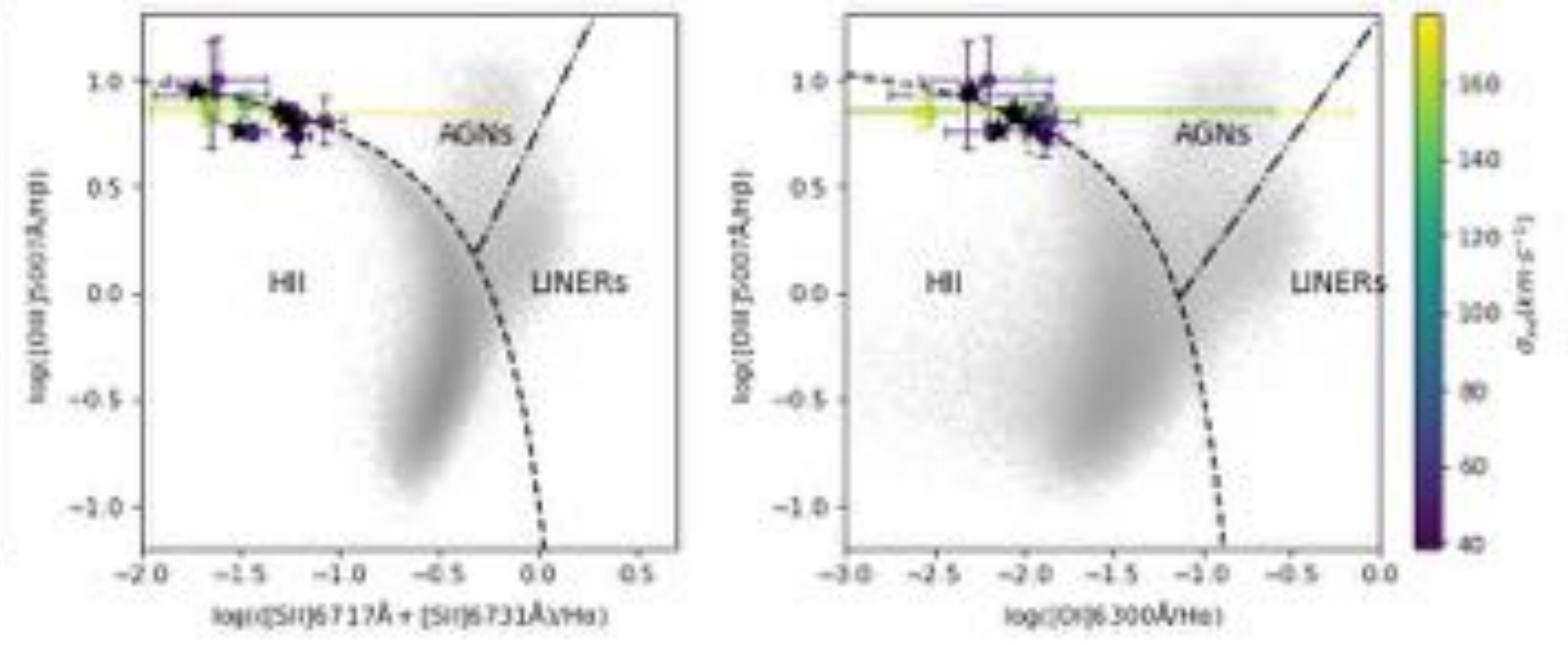
[OIII]5007



Rodríguez et al. (in prep)

- Most LCEs are compact and appear in face-on configuration in UV images
- Broad emission is not so different in BPTs





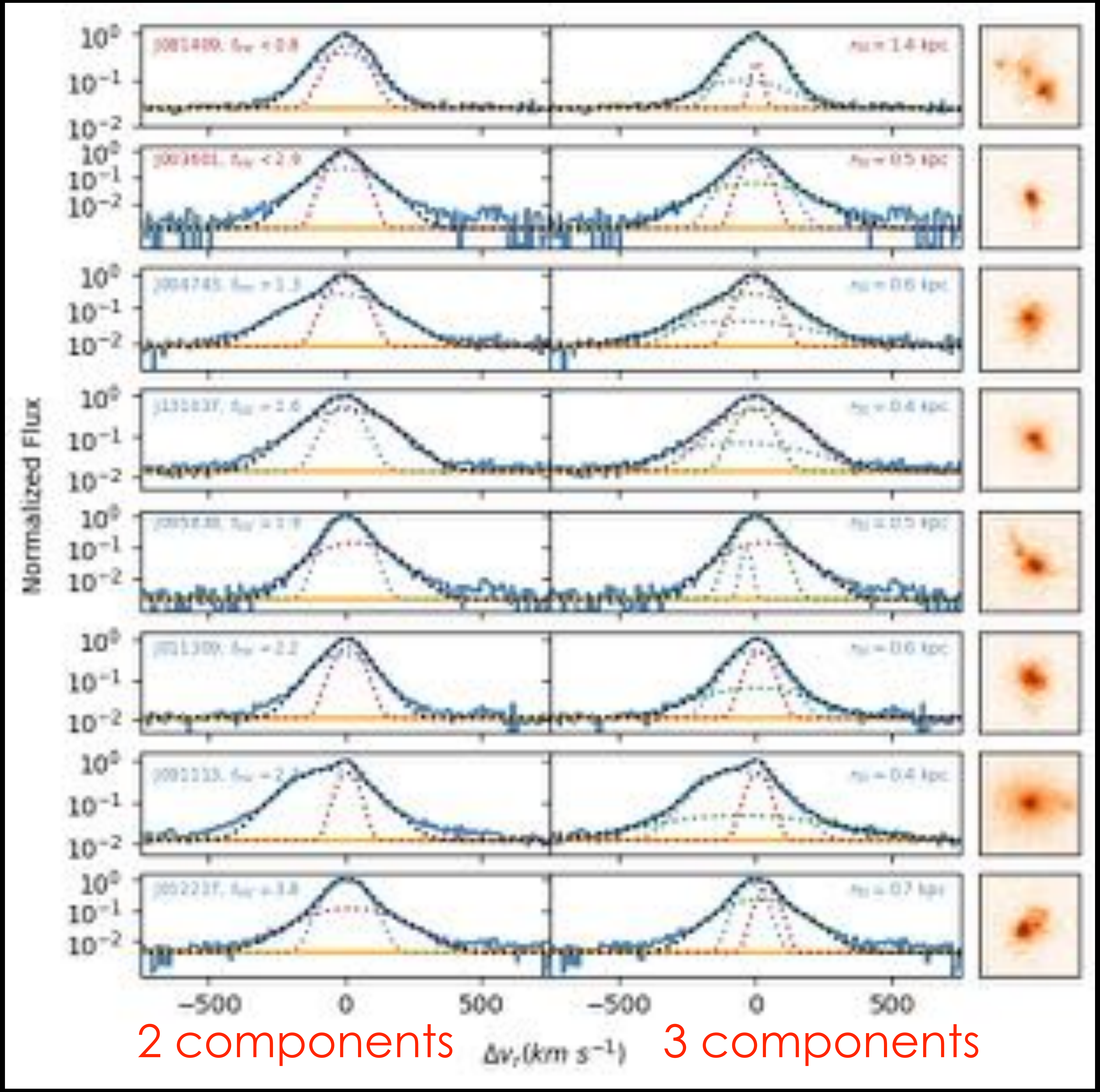
Five LCEs from Izotov+16b

FIRST RESULTS

Weak LCEs show lighter broad wings and narrower/less asymmetric profiles

- Broad emission tend to be blue-shifted in strong leakers: Classic signpost of unresolved outflows
- Most LCEs them appear in face-on configuration in UV images
- Intriguing: non-LCEs UV morphologies are more clumpy/distorted but emission lines are more symmetric and Gaussian
- Conversely, stronger leakers are more compact and small in size but they sow more distorted and broader profiles apparently coming from unresolved regions (i.e. <250 pc)

[OIII]5007



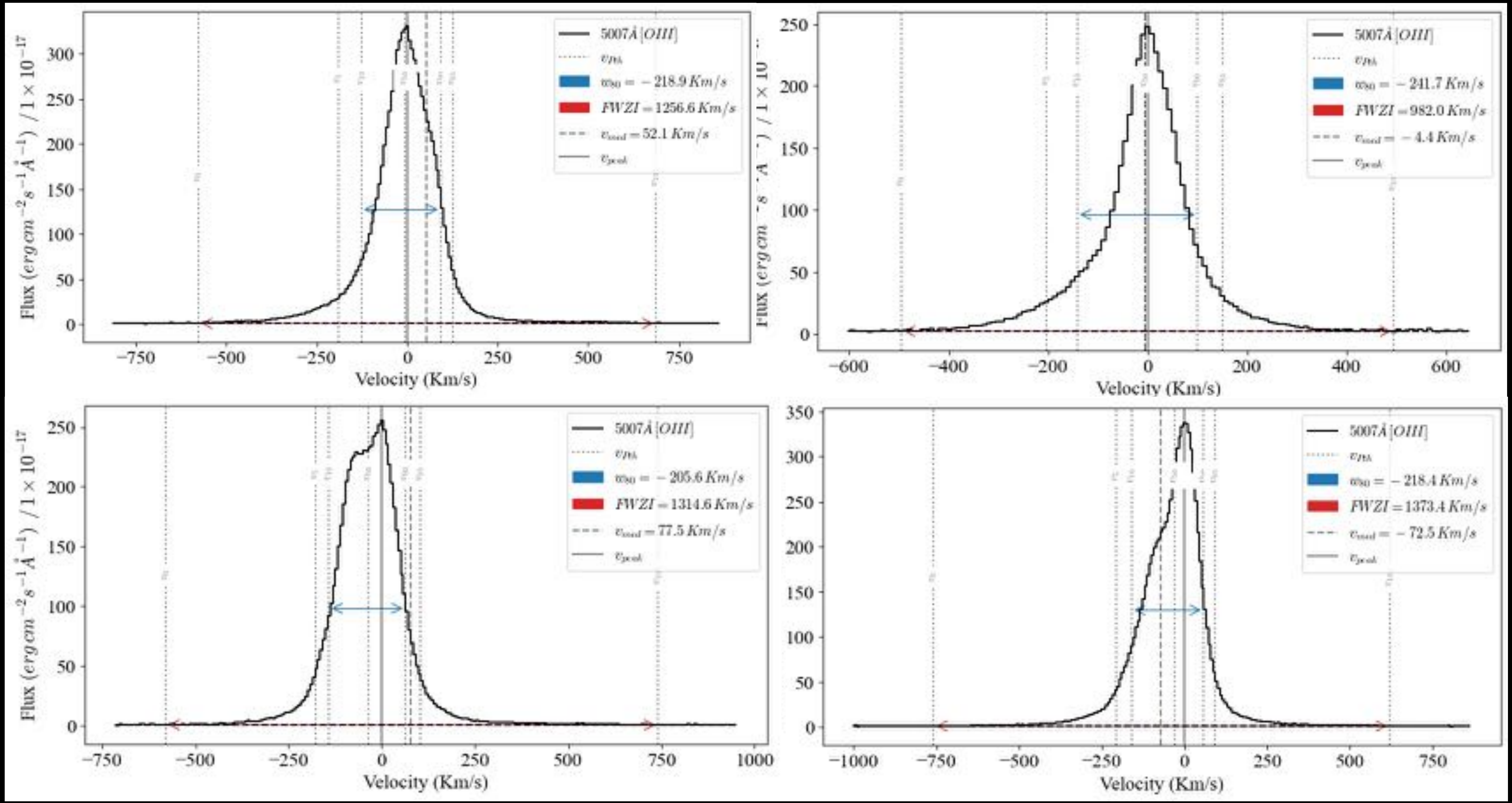
FIRST RESULTS

- Inter-percentile range measurements (e.g. Veilleux+20)
  - Outflow kinematics from $W_{80}=V_{90}-V_{10}$, $v_{max} = \Delta v + 2\sigma_{\mathrm{broad}}$
  - Asymmetry and shape parameter (Liu+13) emission

$$A \equiv \frac{(v_{90} - v_{\mathrm{med}}) - (v_{\mathrm{med}} - v_{10})}{W_{80}} \quad K = \frac{W_{90}}{1.397 \times \mathrm{FWHM}}$$

- Intriguing: non-LCEs UV morphologies are more clumpy/ distorted but emission lines are more symmetric and Gaussian

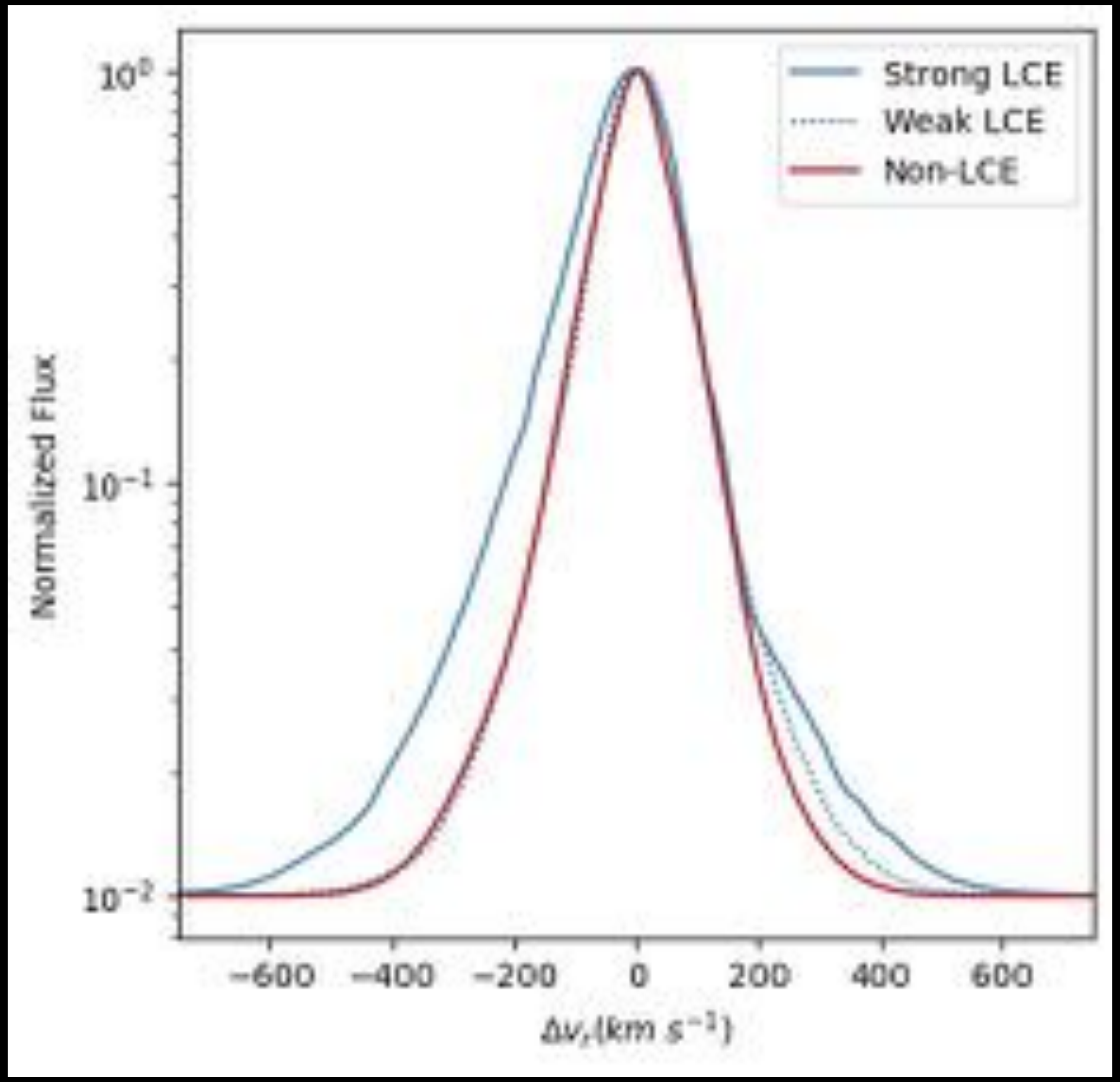
Non-parametric analysis using LiME

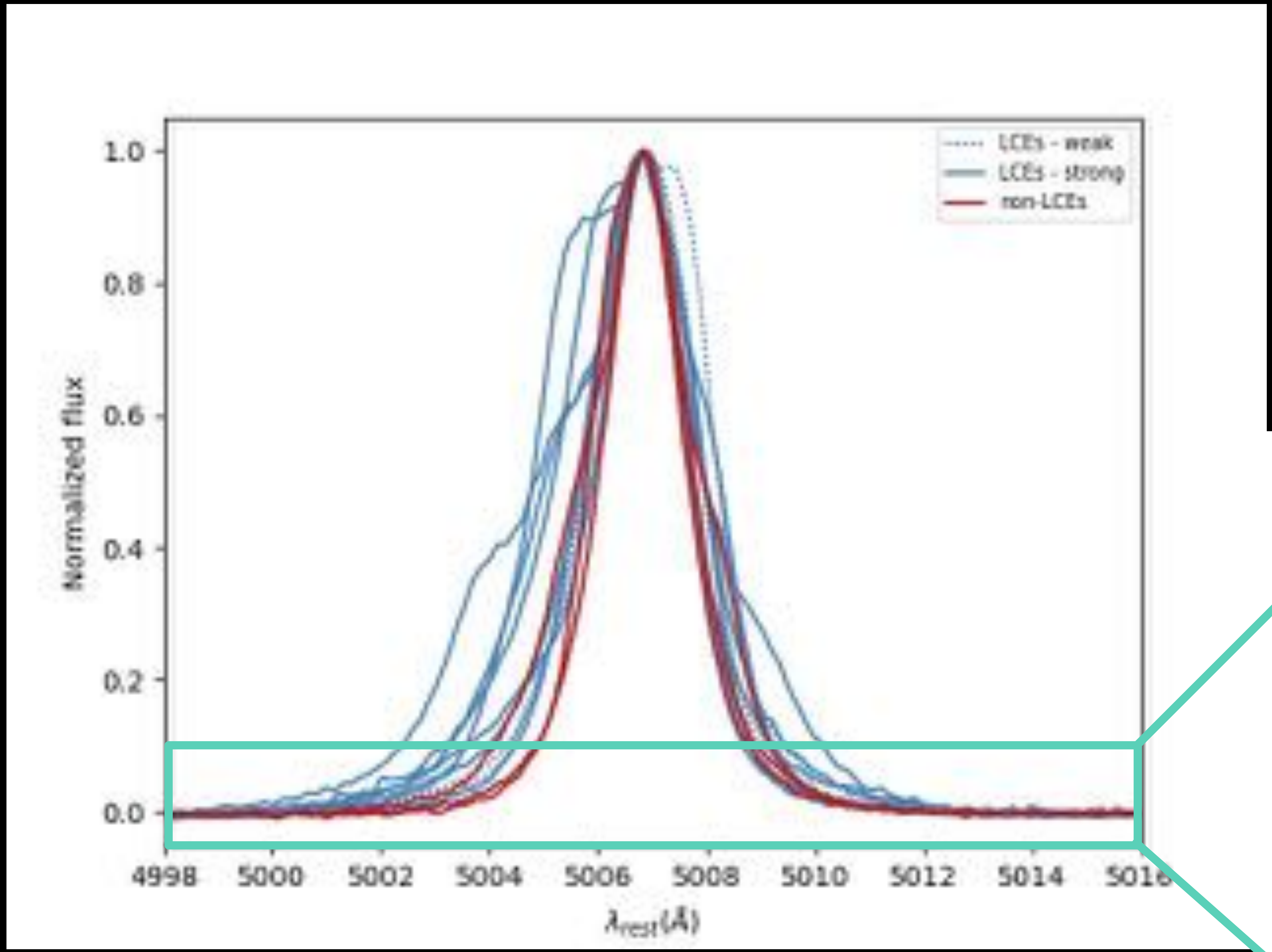


Rodríguez et al. (in prep)

FIRST RESULTS

Mean-weighted stacking of:
Strong leakers
Weak leakers
Non-Leakers

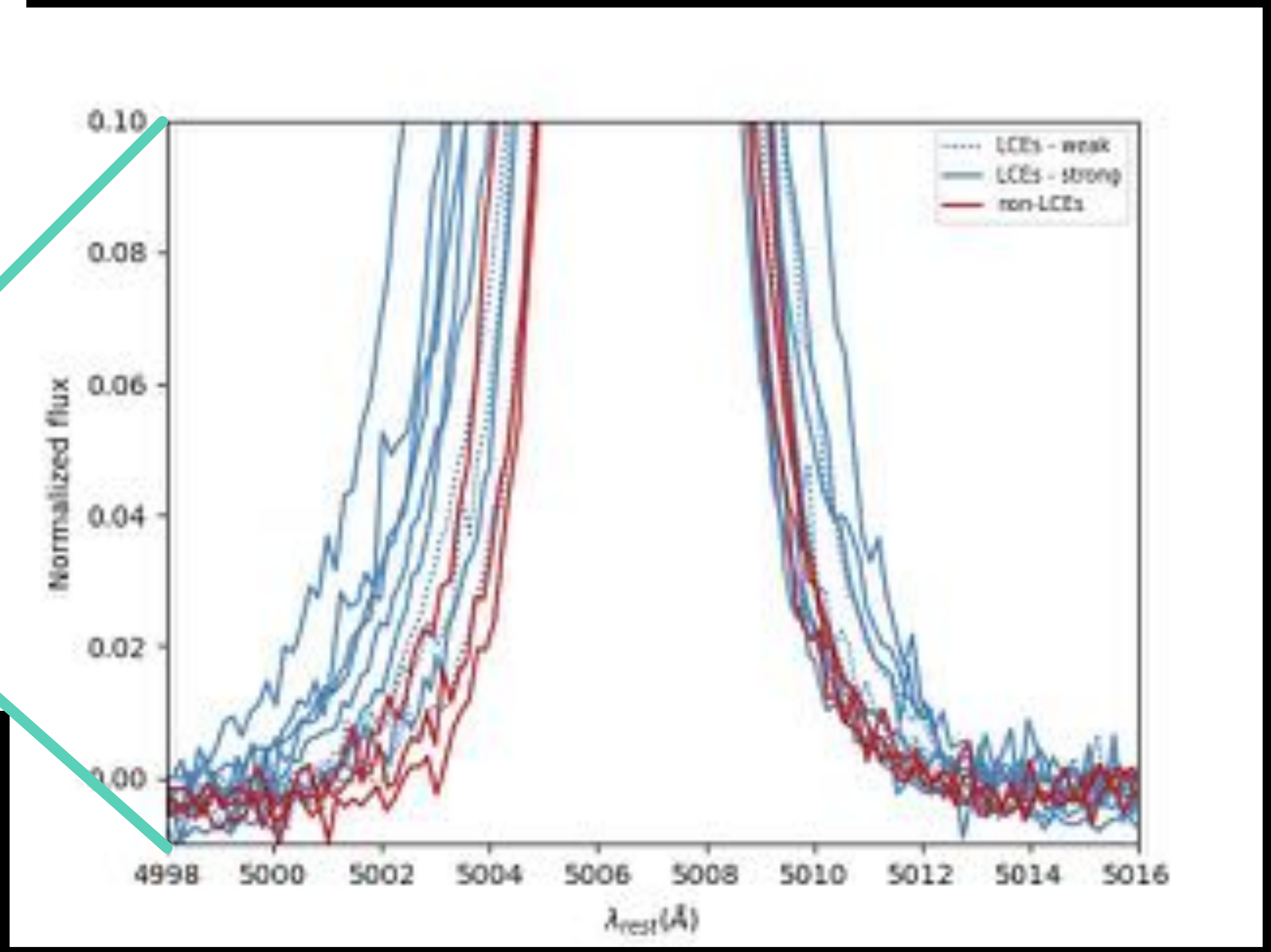




Rodríguez et al. (in prep)

Strong LCEs are defined by:
- significance of LyC detection ($\sigma > 5$)
- Fesc>5%

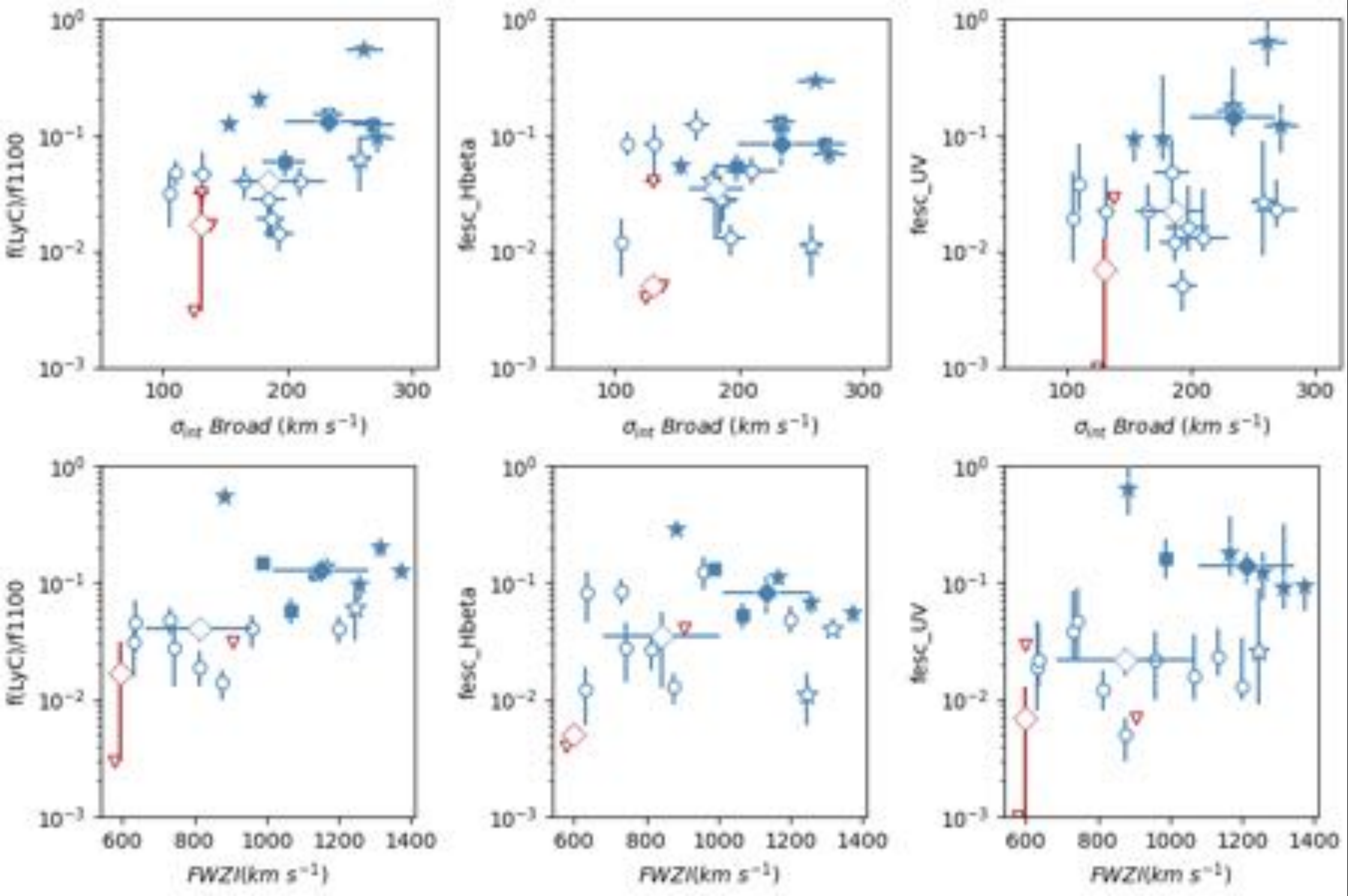
Weak LCEs are defined by:
- significance of LyC detection ($2 < \sigma < 5$)
- Fesc<5%



FIRST RESULTS

Strong LCEs appear to have broader and more asymmetric profiles

- We find a tendency showing broader gaussian components at larger Fesc
- Similar trend is found for FWZI
- Large scatter as in other indirect diagnostics

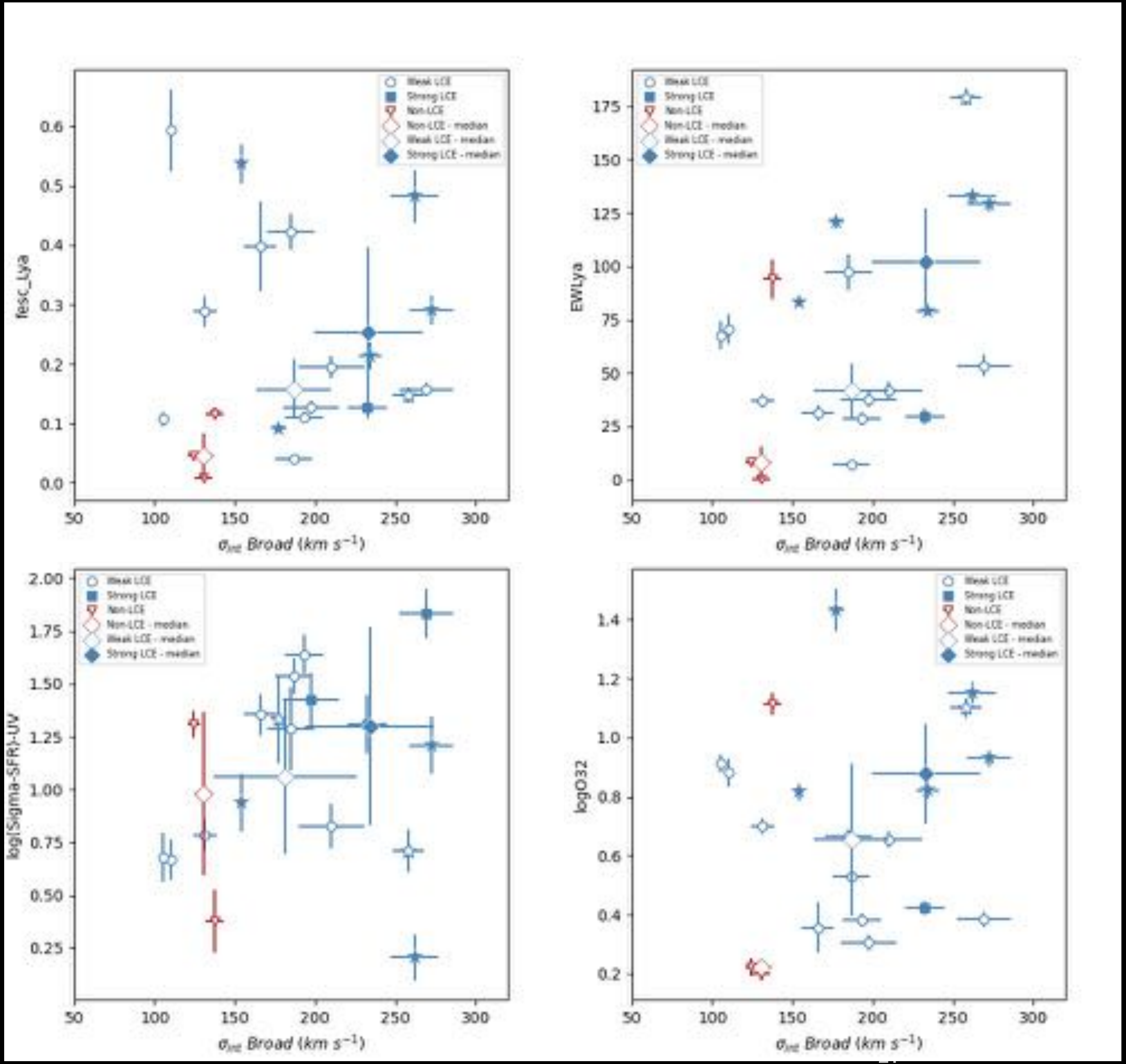


Rodríguez et al. (in prep)

FIRST RESULTS

Strong LCEs appear to have broader and more asymmetric profiles

Rodríguez et al. (in prep)



Broad emission is a manifestation of feedback effects, which include:

- Radiative feedback
- Mechanical/Adiabatic feedback (MS winds and SNe)

Irrespective the source of feedback our results show first evidence of the significant role turbulence and outflows may have in the escape of LyC photons

Promising results for high-z studies: Cosmological relevant leakers (Fesc>5-10%) at low-z show broad emission with $\sigma > 200\ kms^{-1}$

Detectable with JWST spectra at z>6

A new indirect diagnostic?

To take away…

- Complex emission lines are ubiquitous in GPs - highly asymmetric, no single gaussian
- Broad emission is prominent and likely originated in strong stellar feedback.
- Strong leakers show more complex and broader profiles than weak or non-leakers
    - Another indirect diagnostic for reionization studies?
    - Broad component appears mostly gaussian and often blue-shifted —unresolved outflow?
    - Broad emission is in all Balmer and CELs of low and high ionization
    - First steps for a thorough characterization in LCEs
- Similar analysis using IFU is desirable but challenging
- Non-parametric analysis and other functional forms for the broad emission under exploration (Komarova+21)

THANK YOU ESTALLIDOS!!

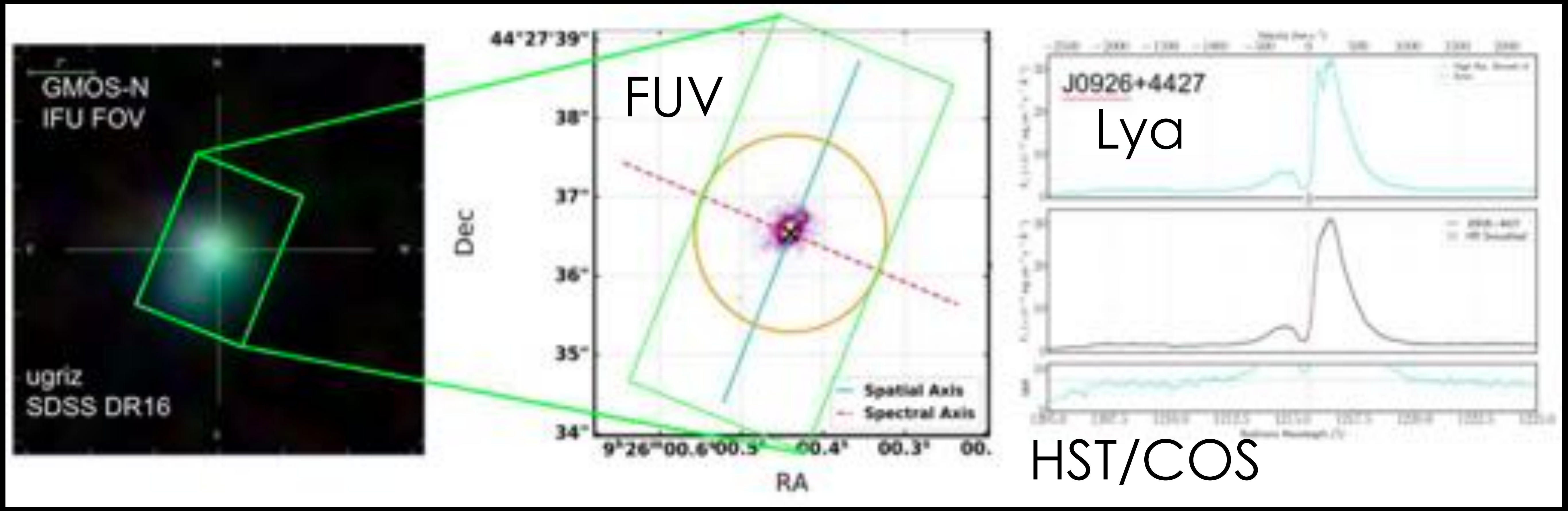
Sunset in La Serena

Ongoing work: Spatially resolved Hα Kinematics of green peas

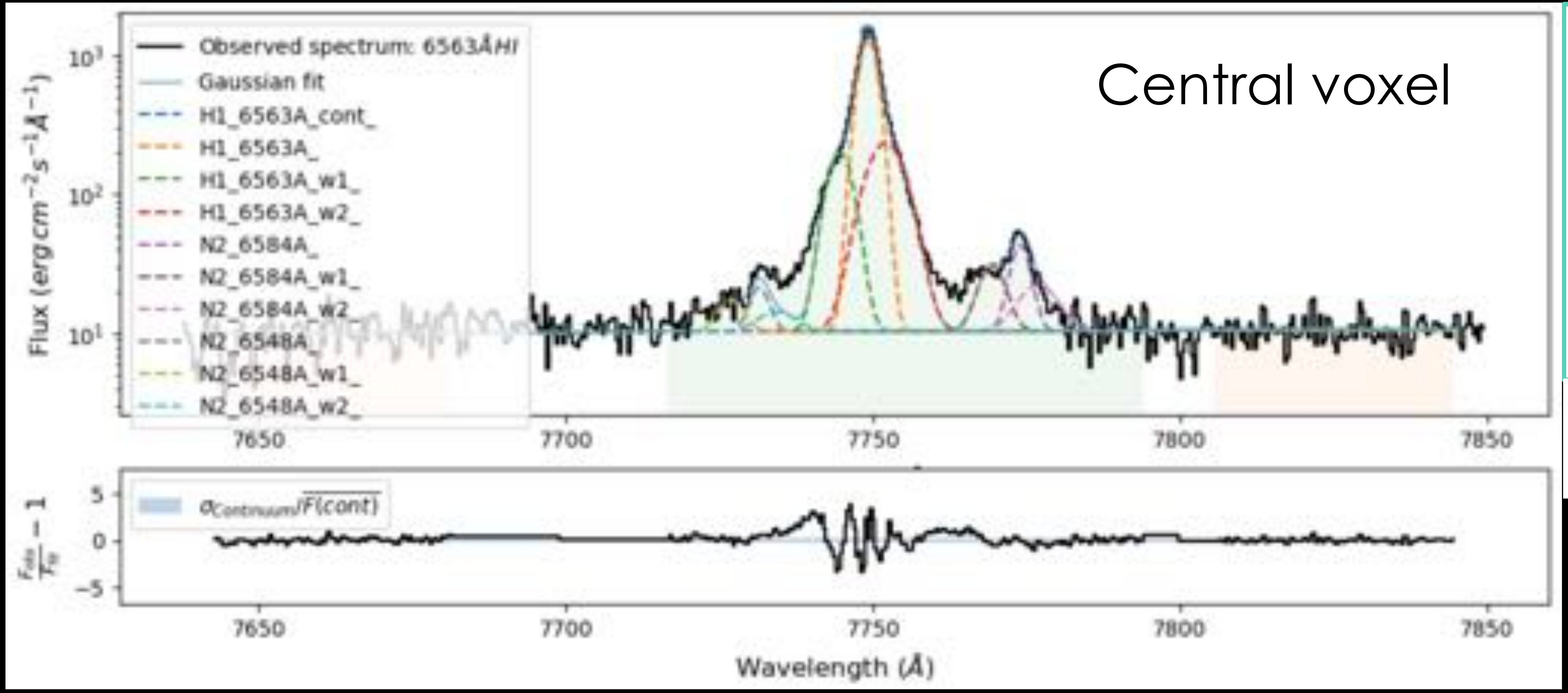
A small representative sample of local analogs with HST/COS data

GMOS-S and GMOS-N IFU reveals complex kinematics

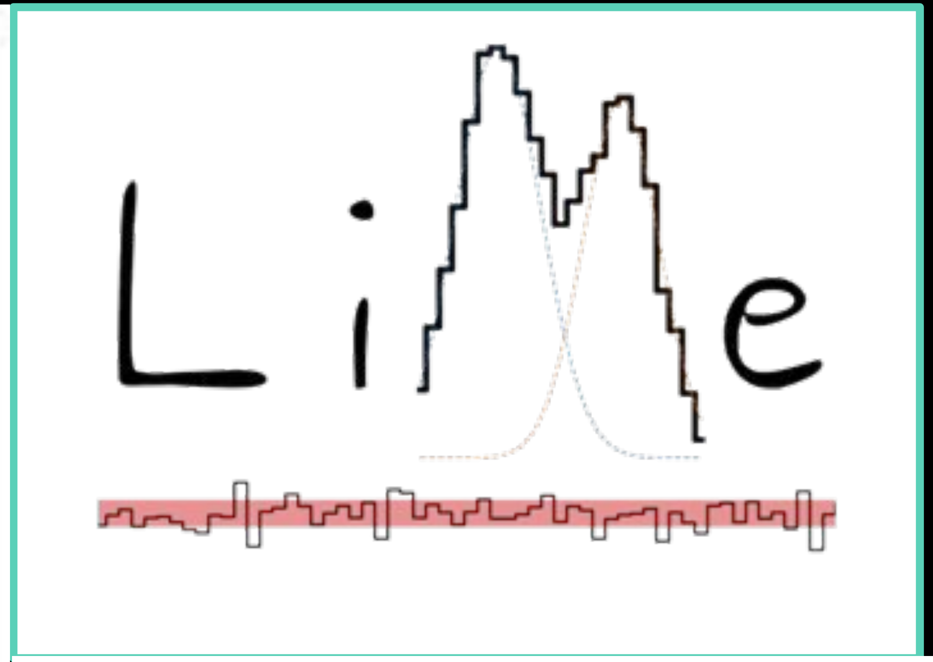
Dania Muñoz PhD thesis



Work in progress



Extremely complex line profiles require very demanding voxel-by-voxel modeling



LiMe: A Line Measuring library for the chemical and kinematic analysis of the ionized gas .

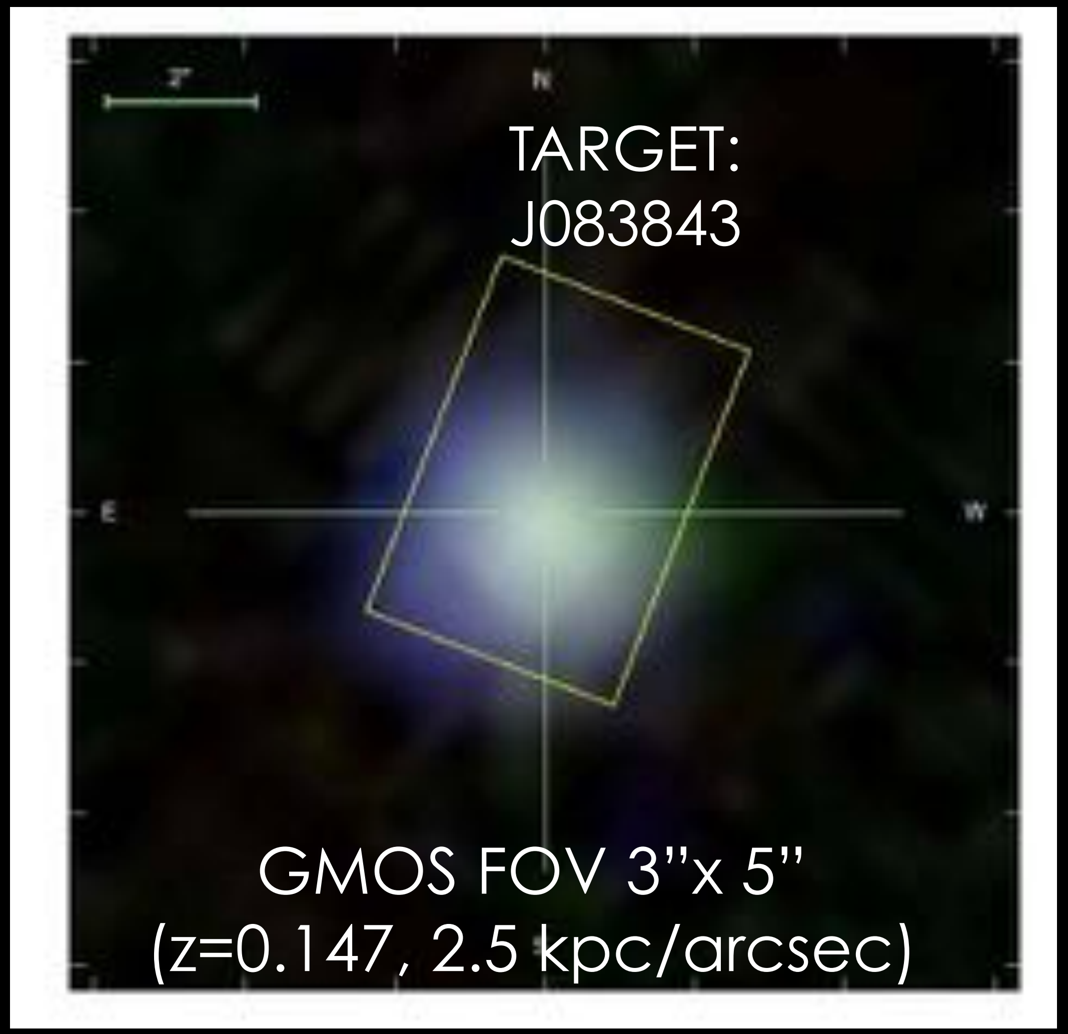
We use a new versatile code LiMe; developed by ULS postdoc Vital Fernández

See Vital's talk for details!!

Spatially resolved Hα Kinematics of green peas

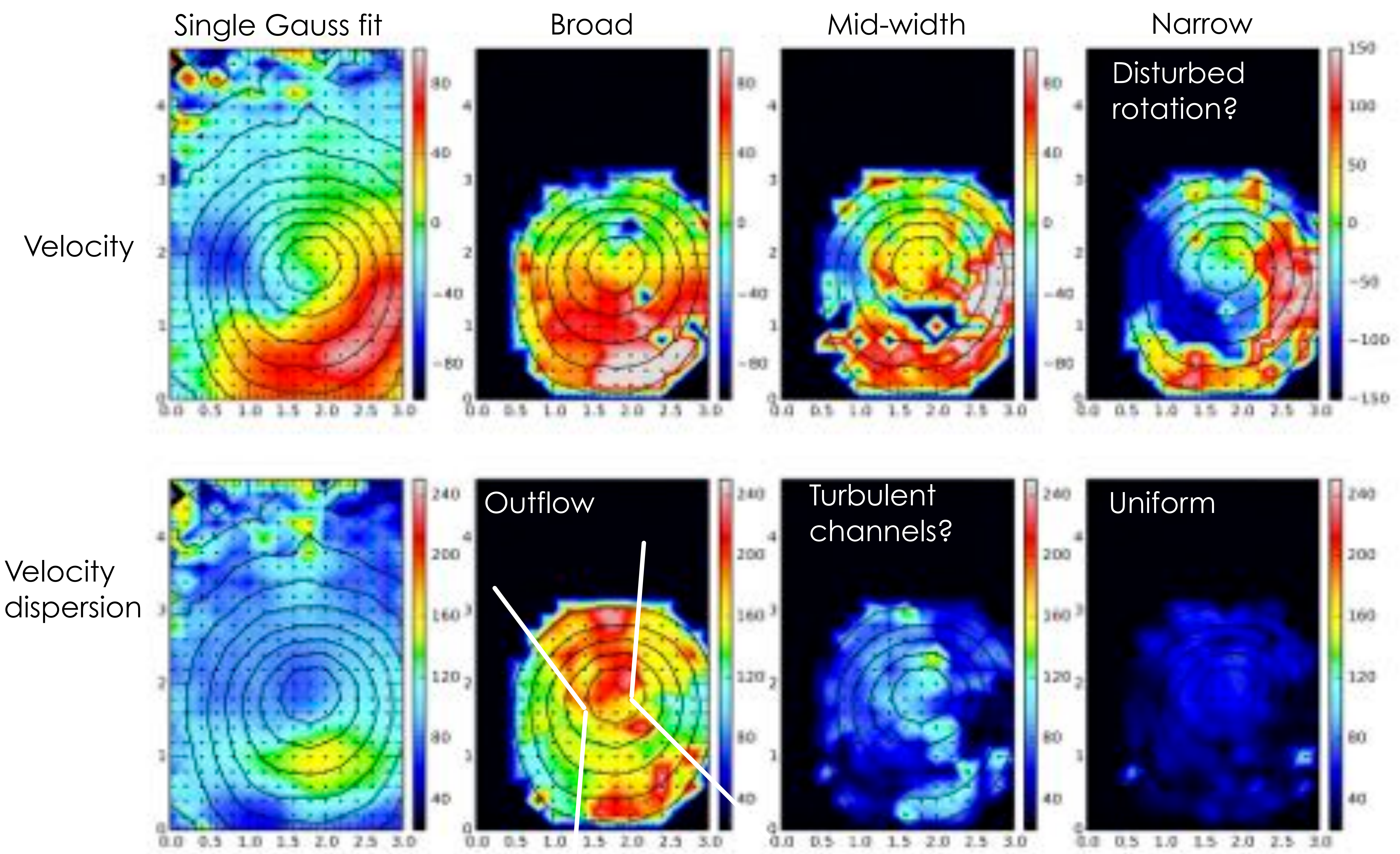
Bosch et al. (2019)

Multiple kinematic components



Requires high-quality data

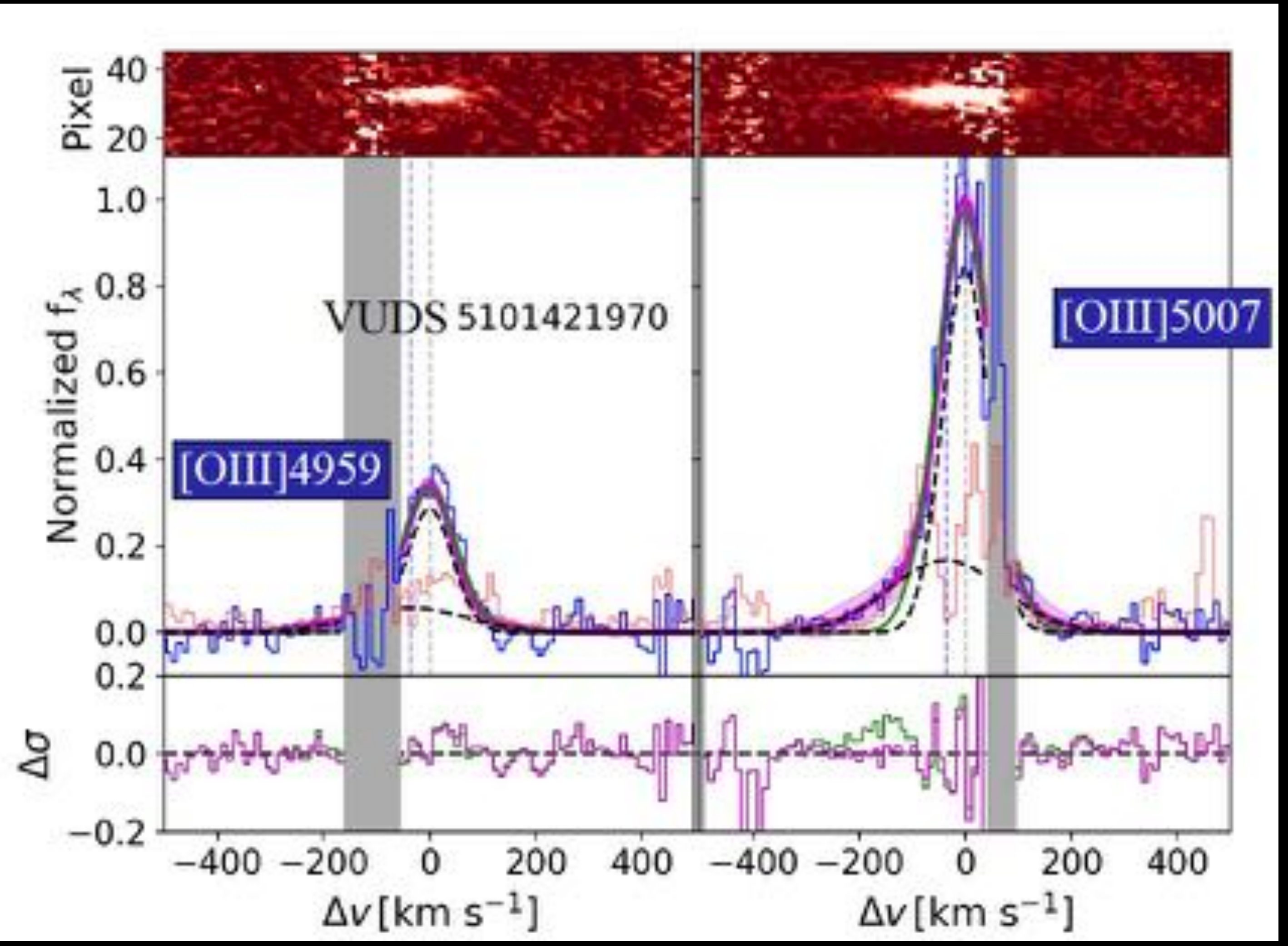
R831 (R=5100 at λ~7250)
λ_{obs}=6500-8200Å
σ_{inst} = 25 km/s
0.2" pixel size ~ 500pc
High S/N   Texp~3h
Excellent weather IQ20 (aver. seeing ~0.5'')



JWST will provide similar data for compact EELGs at high-z

BROAD EMISSION IN REIONIZATION ANALOGS AT Z~2-3

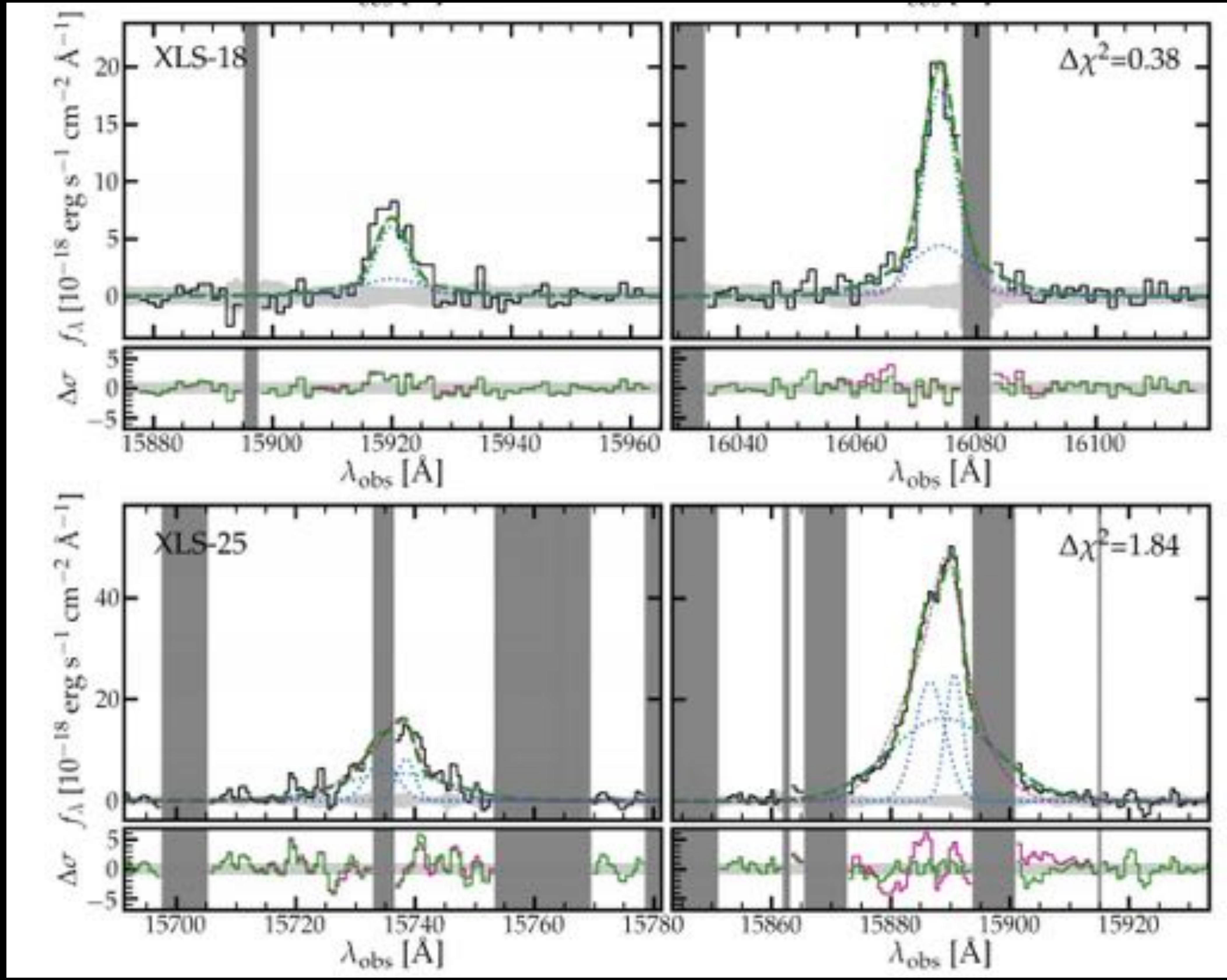
Complex line profiles in bright LAEs in deep X-shooter and MOSFIRE spectra



Blue and red-shifted wings and multiple components in bright LAEs

B/Tot~20-50%

Matthee+21



Similar analysis will be possible with JWST

Llerena+ (in prep)