Departamento de Astronomía
Universidad de La Serena

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Green Pea chemodynamics, feedback and the escape of Lyman radiation

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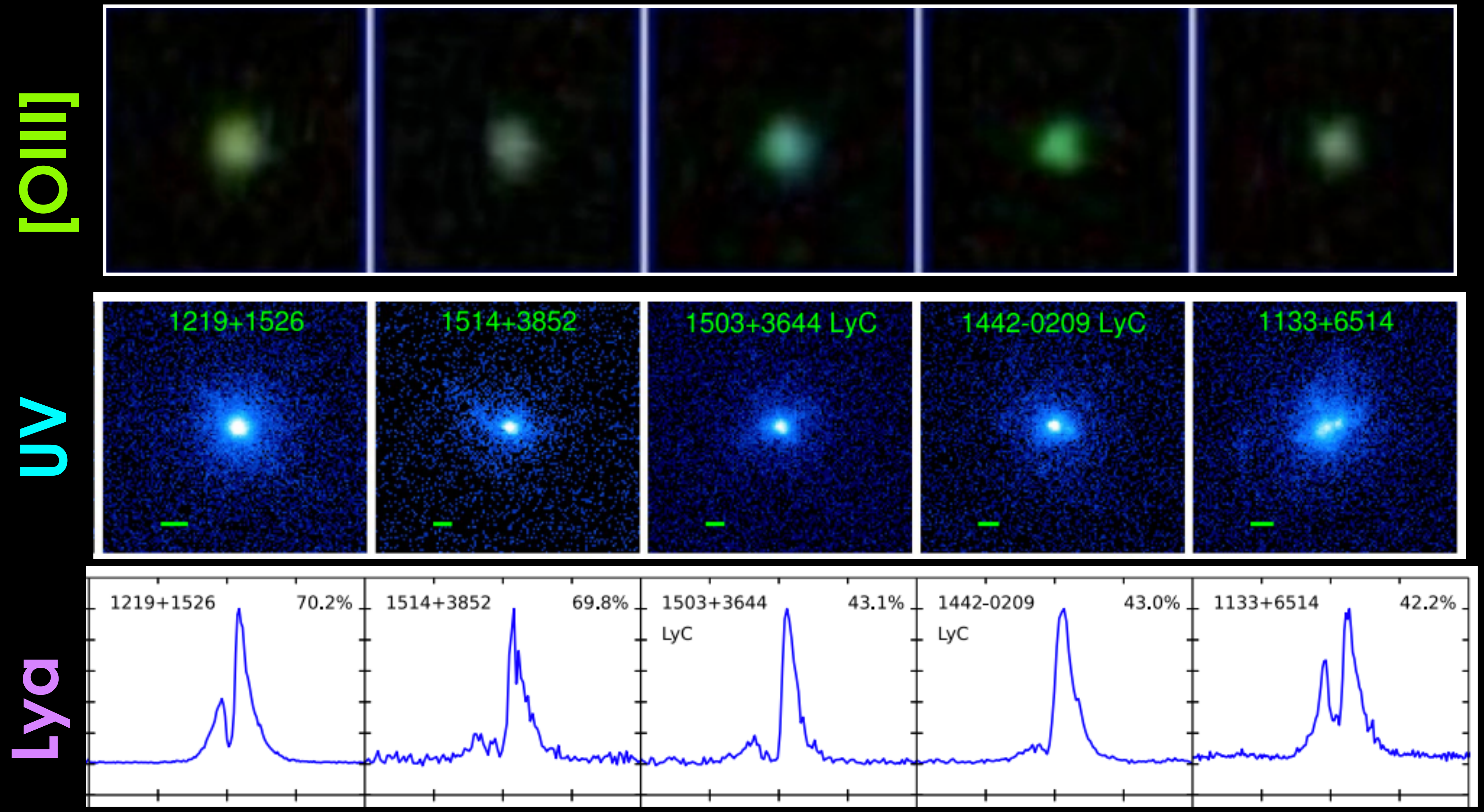
Sunset in La Serena

OAC, Crete
Escape of Lyman radiation from galactic labyrinths
2023

Escape of Lyman radiation from galactic labyrinths - Crete, 20 April 2023

GREEN PEAS: LOCAL ANALOGS OF REIONIZATION GALAXIES

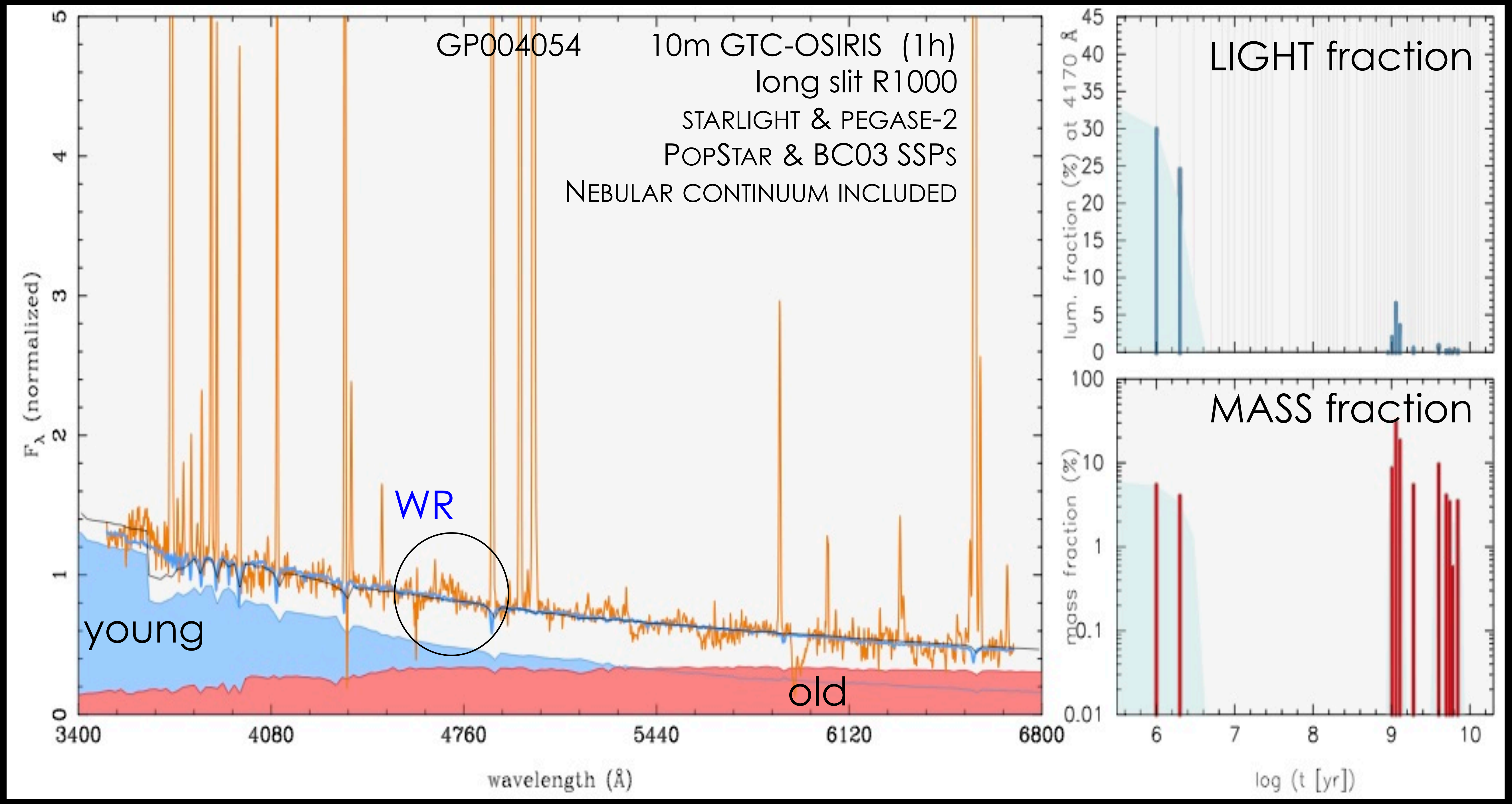
Starbursting dwarf galaxies at 0.11<z<0.36 (a.k.a. Extreme emission-line galaxies)
Selected by compactness and high emission-line EWs
(Cardamone+09; Amorín+10,12,14,15; Jaskot & Oey 13; Henry+15; Yang+17,18)



Best laboratories to study:

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

Under similar conditions to high-z galaxies!!



Amorín et al. 2012a, Fernández et al. 2021

GPs are rapidly forming between 4-30% of their total mass (~10^9 M_{sol}) in an intense starburst

GREEN PEAS: LOCAL ANALOGS OF REIONIZATION GALAXIES

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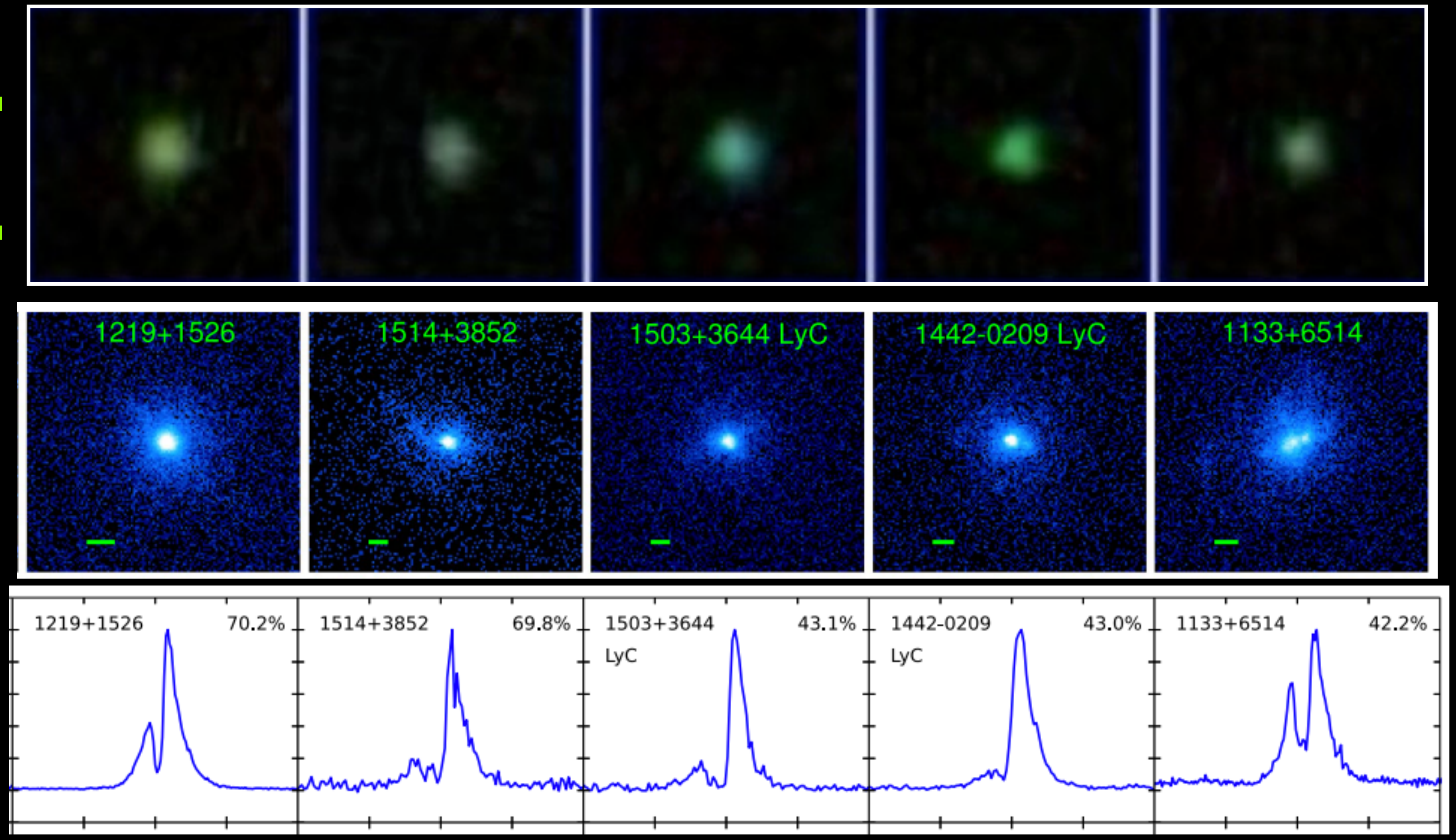
[OIII]

UV

Lya



Best laboratories to study:

- *Massive star formation and feedback at low metallicity*
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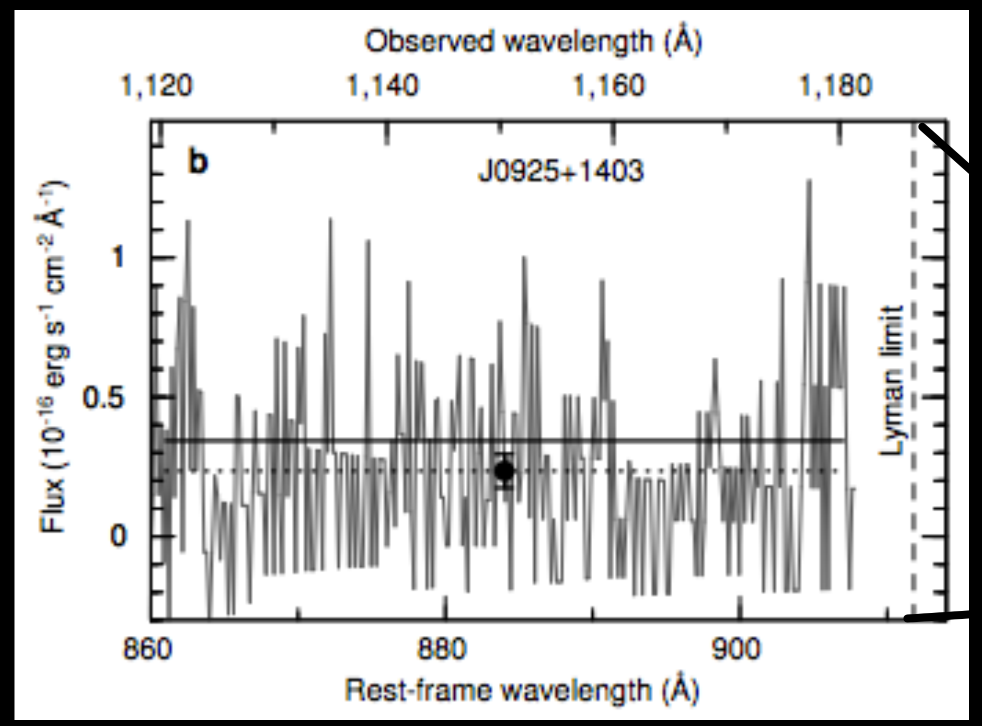
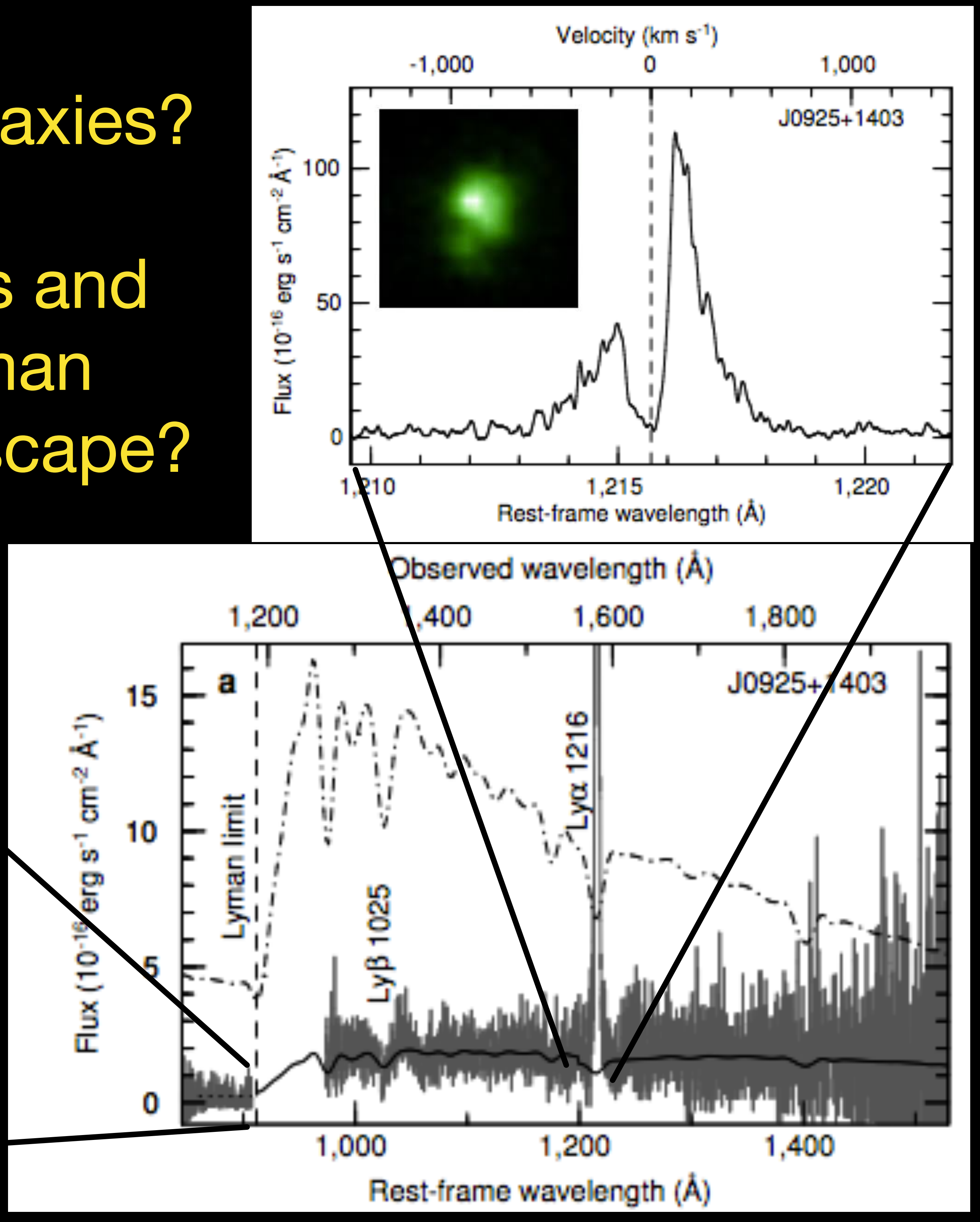
Under *similar conditions to high-z galaxies!!*

How LyC escape from galaxies?

What physical properties and mechanisms favor Lyman photon production and escape?

See Anne's reviews



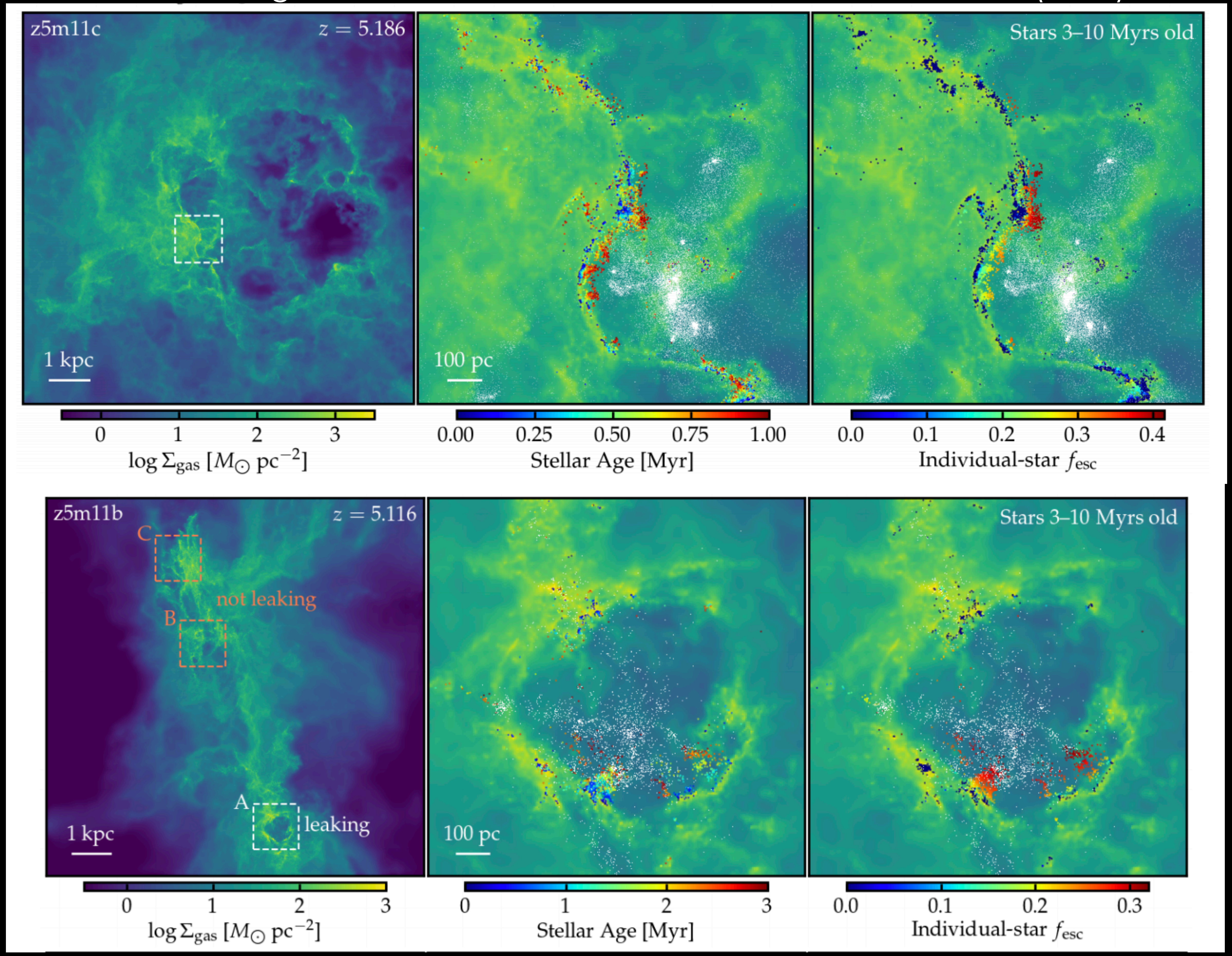


Most GPs at z~0.3-0.4 observed so far with HST/COS show strong Lya and LyC emission with *Fesc* ~ 5-75%
Izotov+16,18,21; Verhamme+16; Schaerer+17

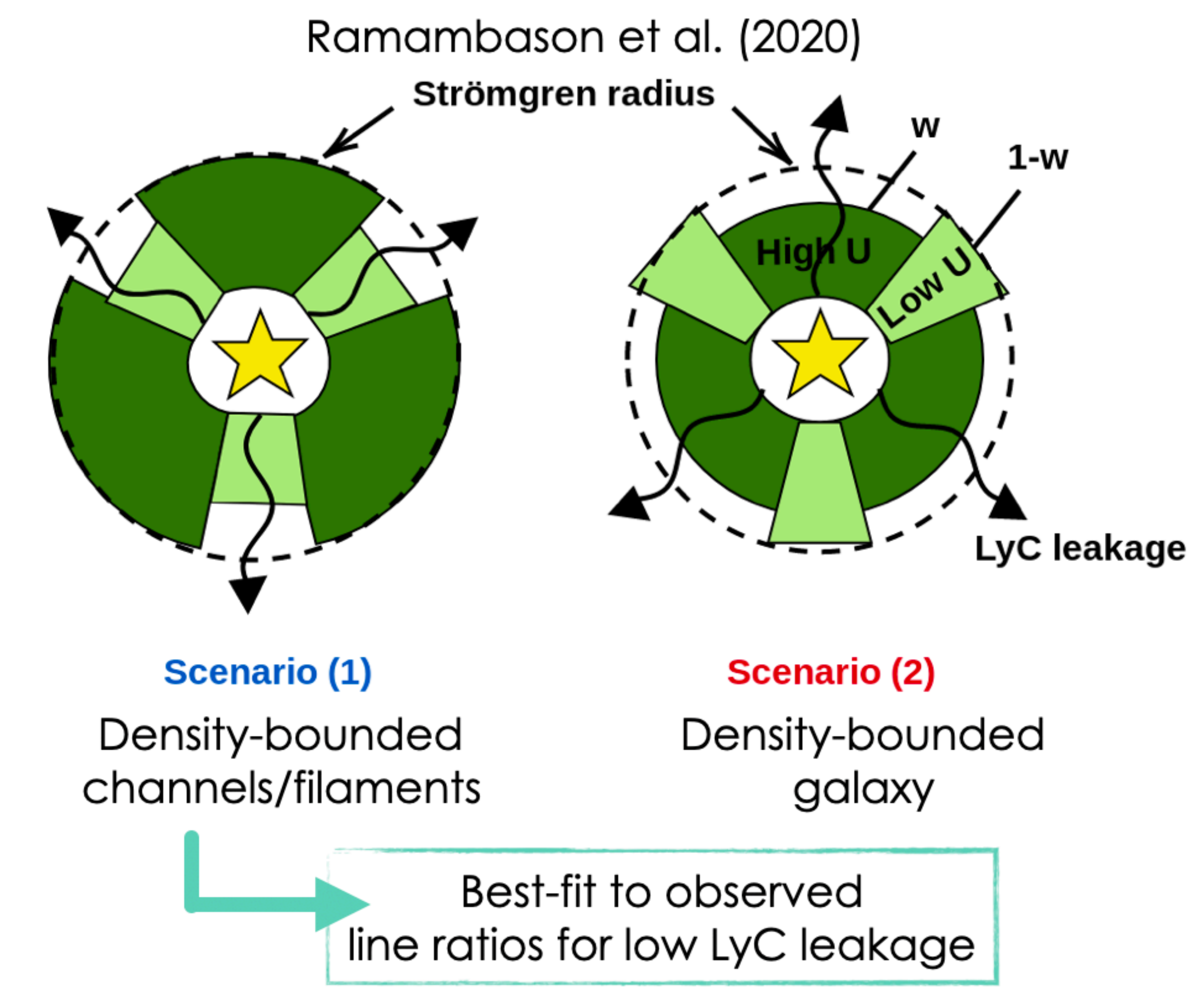
Ionizing photon escape: Simulations and models

Strong stellar feedback leading to winds/outflows from massive stars and SNe are responsible for clearing channels in the ISM from which ionizing photons can escape

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



Simple models: Nakajima & Ouchi 13, Zackrisson+13; Jaskot & Oey 13, Ramambason+20



Galaxies are far more complex than single HII regions
Picket fence models with holes, channels, filaments…

GPs HAVE COMPLEX GAS KINEMATICS

First evidence of stellar feedback and strong turbulence in the ionized gas

Amorín et al. (2012b)

High S/N, high-res (R~9000) WHT/ISIS spectra

Multiple narrow components possibly associated to resolved SF clumps
Δv~50-500 km/s and σ_{int} =40-120 km/s

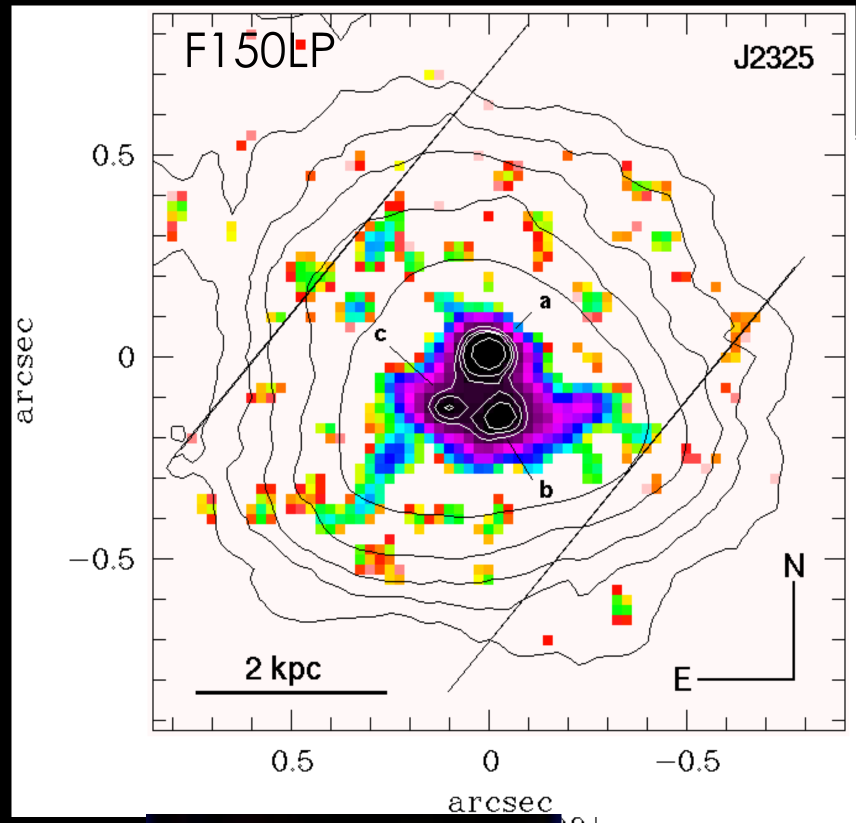
Turbulent ISM in thick/clumpy disks?
Coalescence/accretion of SF clumps? Minor mergers?

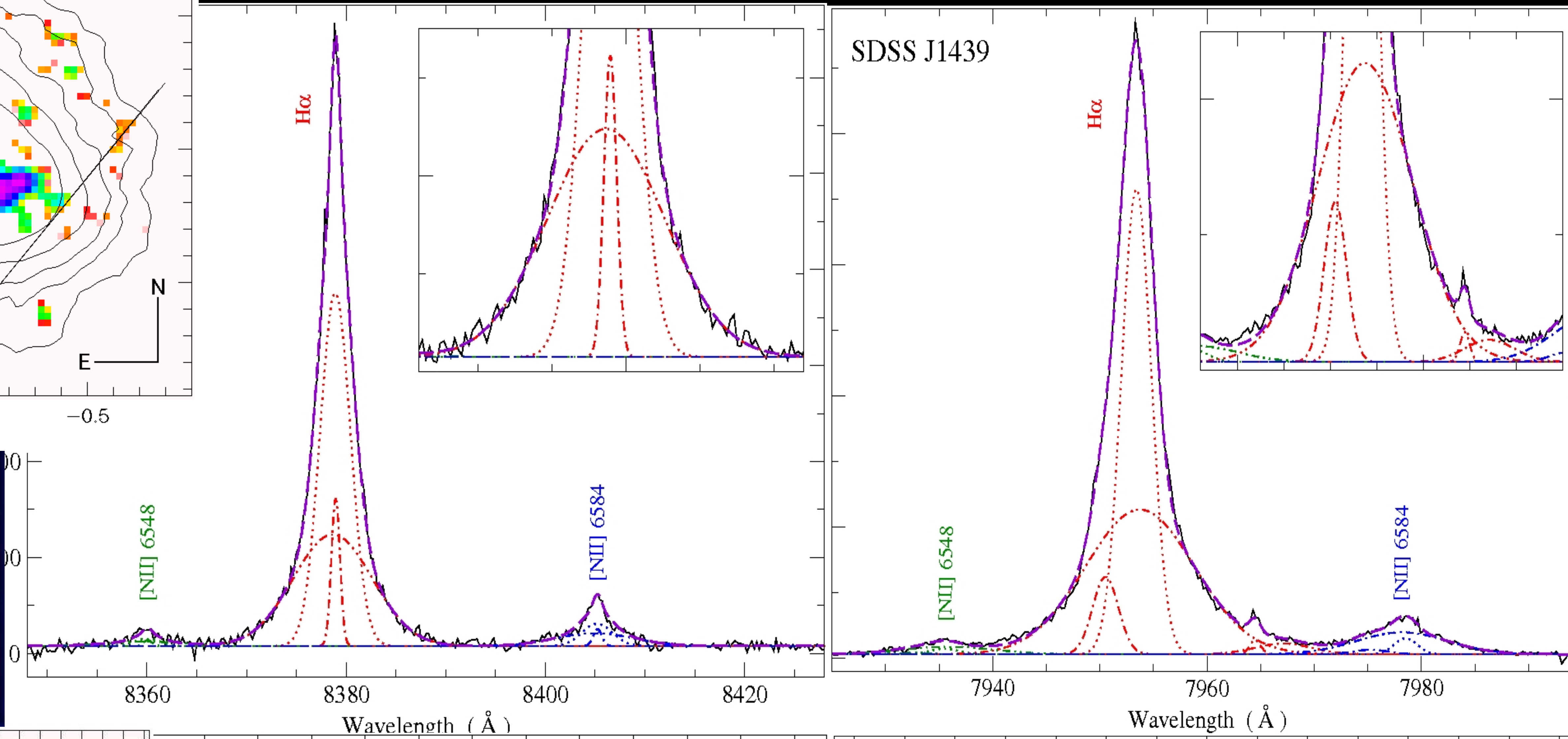
Broad emission associated to high velocity gas
σ_{int} =100-250 km/s FWZI ~ 650-1750 km/s
$L_{H\alpha}$~10^{41}-10^{42} erg/s (up to 40% of the total Ha)

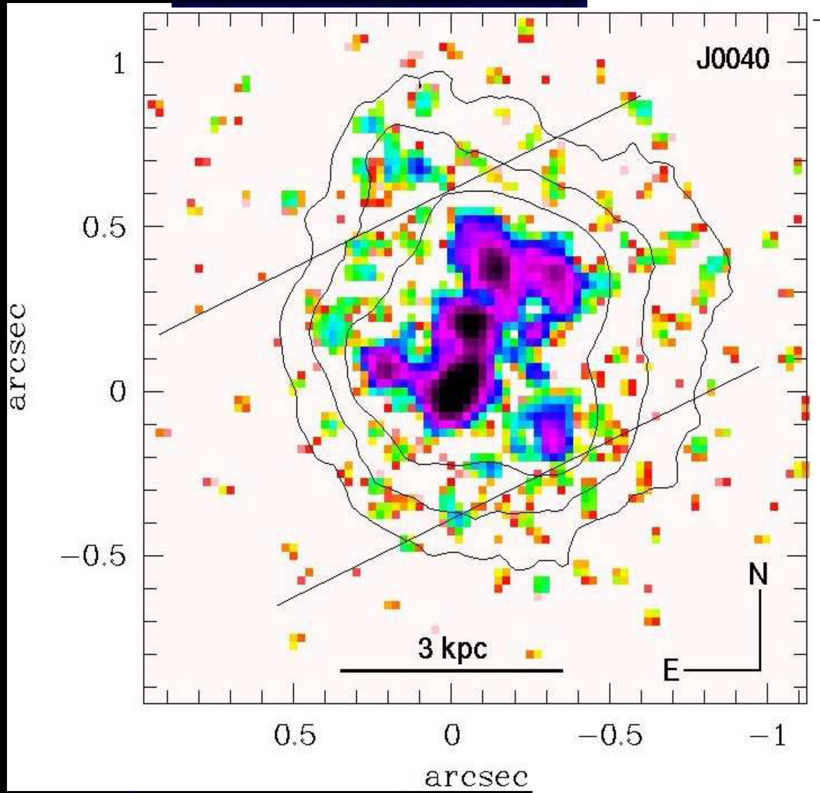
Signature of outflows: strong winds and SNe
Fast shocks? Turbulent mixing layers?

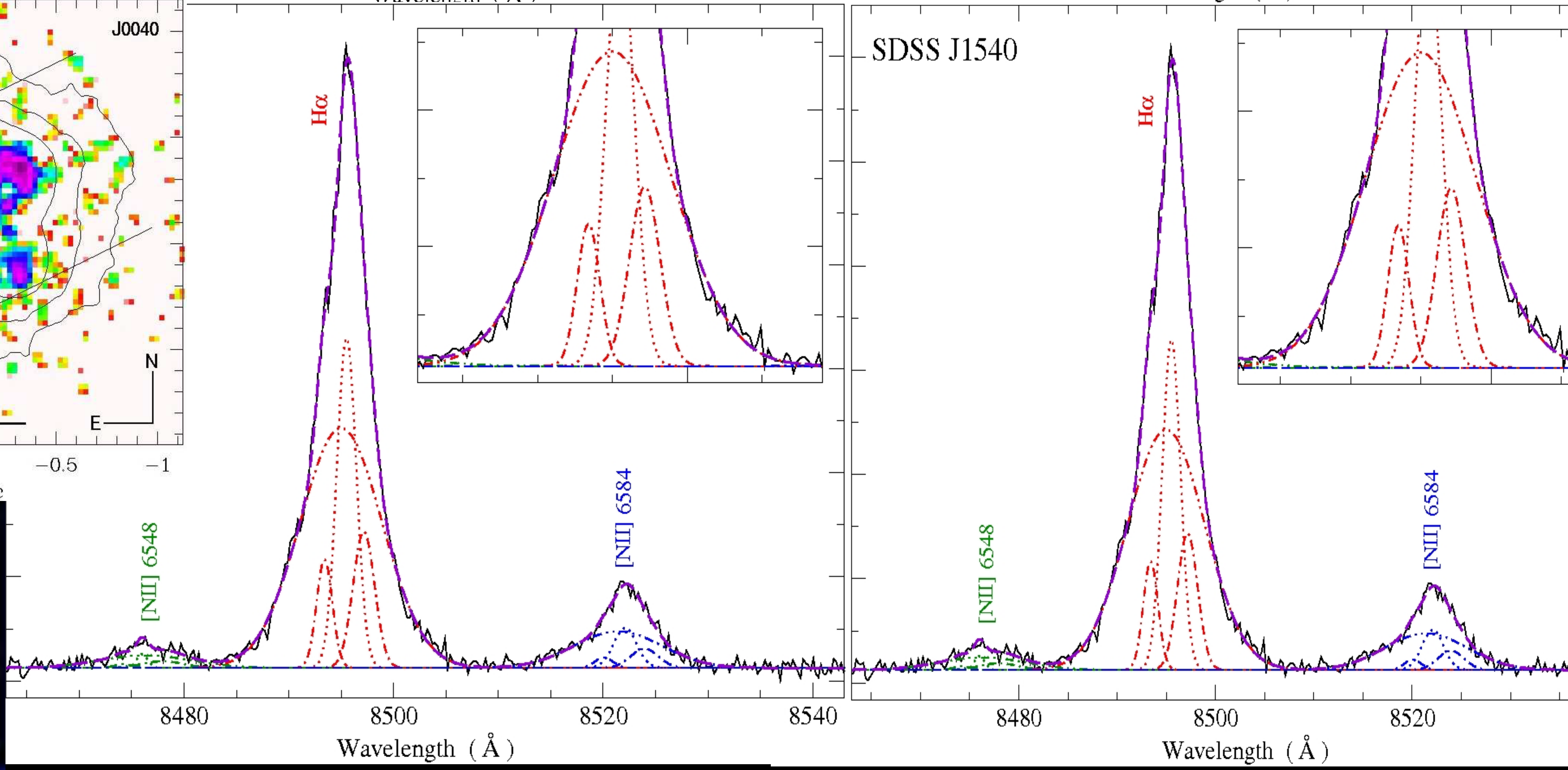
HST/ACS F150LP (unsharped)
HST/ACS F606W (contours)

Hα + [NII] profiles









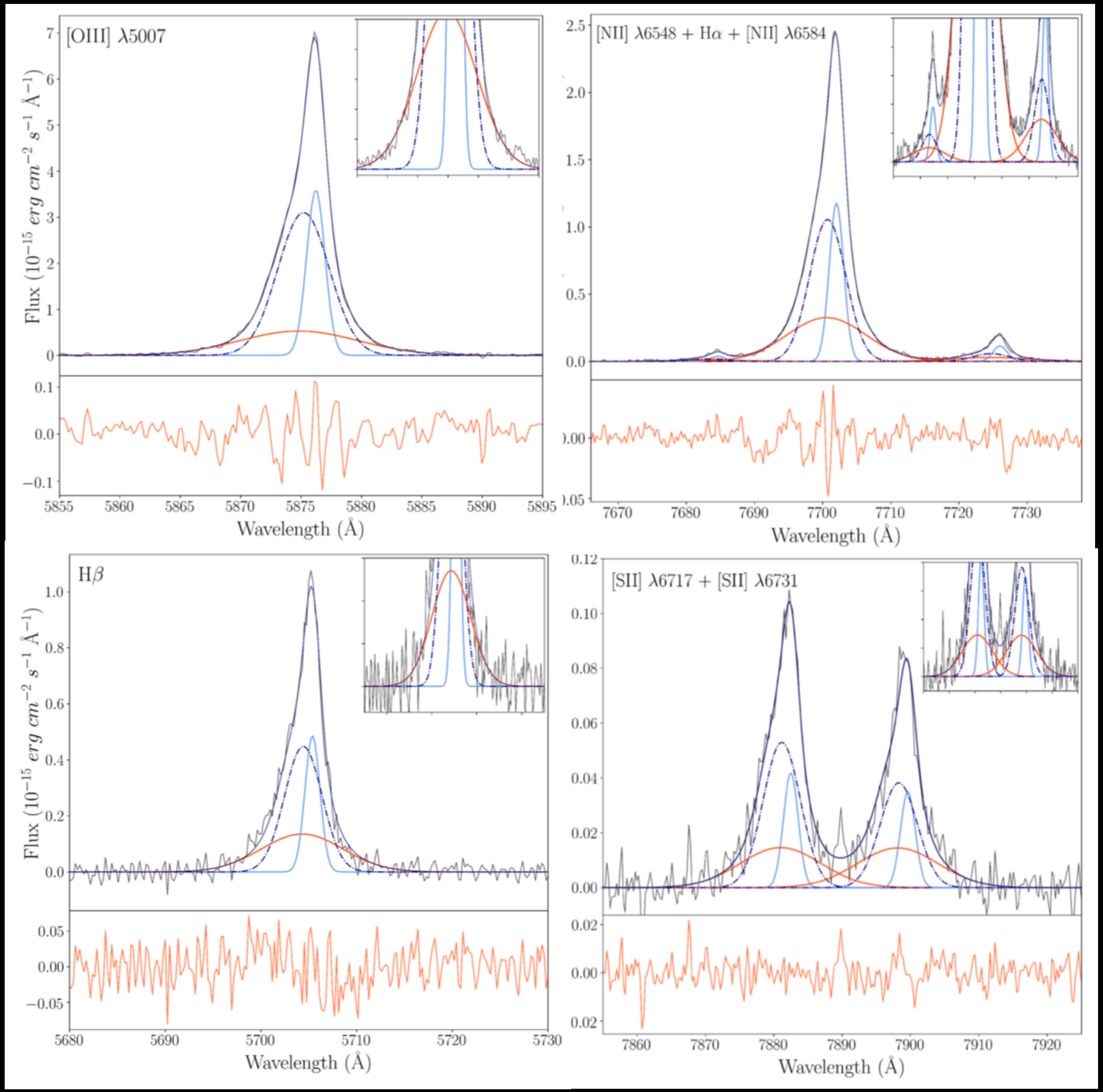
GPs HAVE COMPLEX GAS KINEMATICS

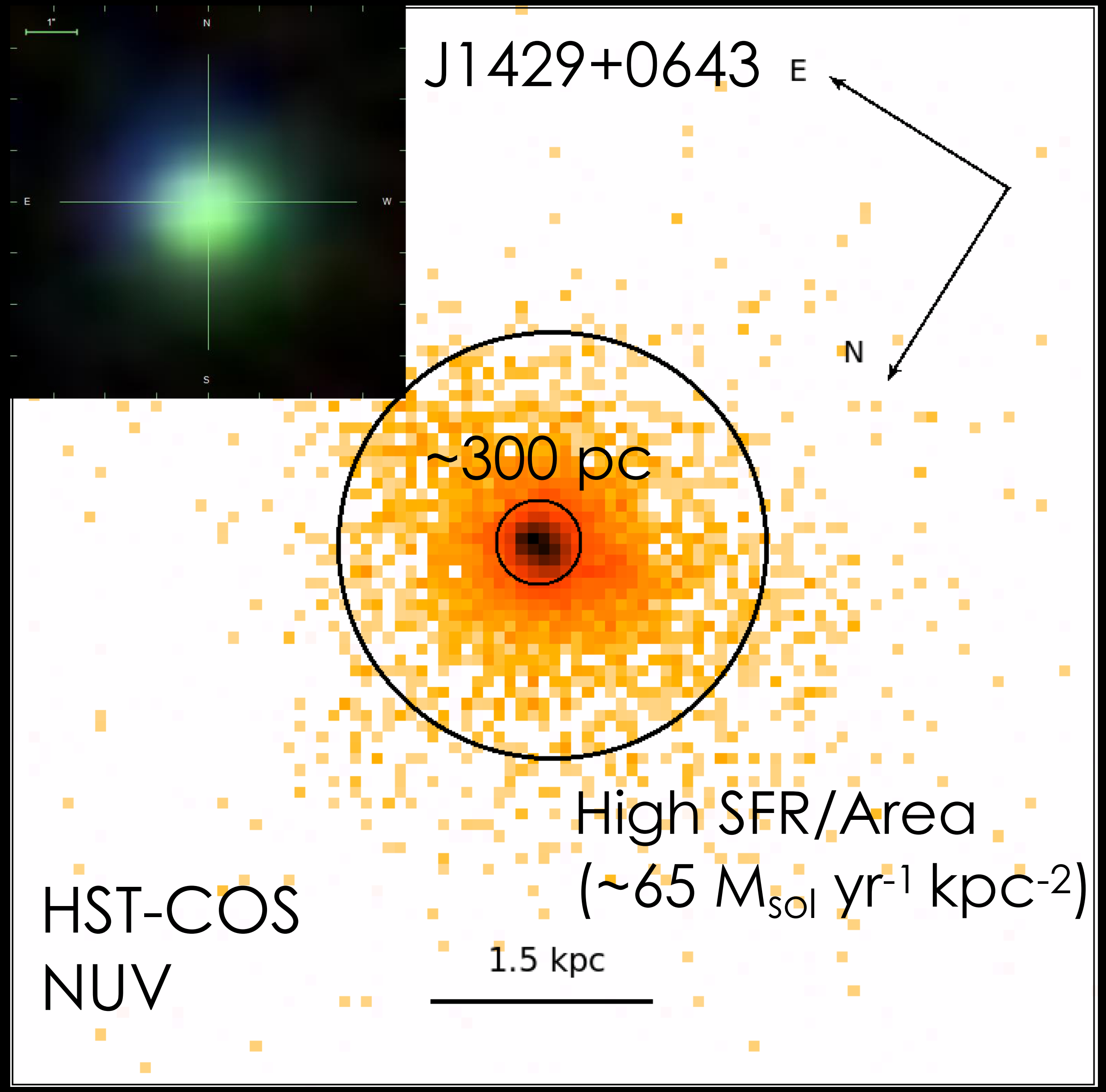
Hogarth et al. (2020, incl.RA)

High S/N, high-res (R~9000) WHT/ISIS spectra

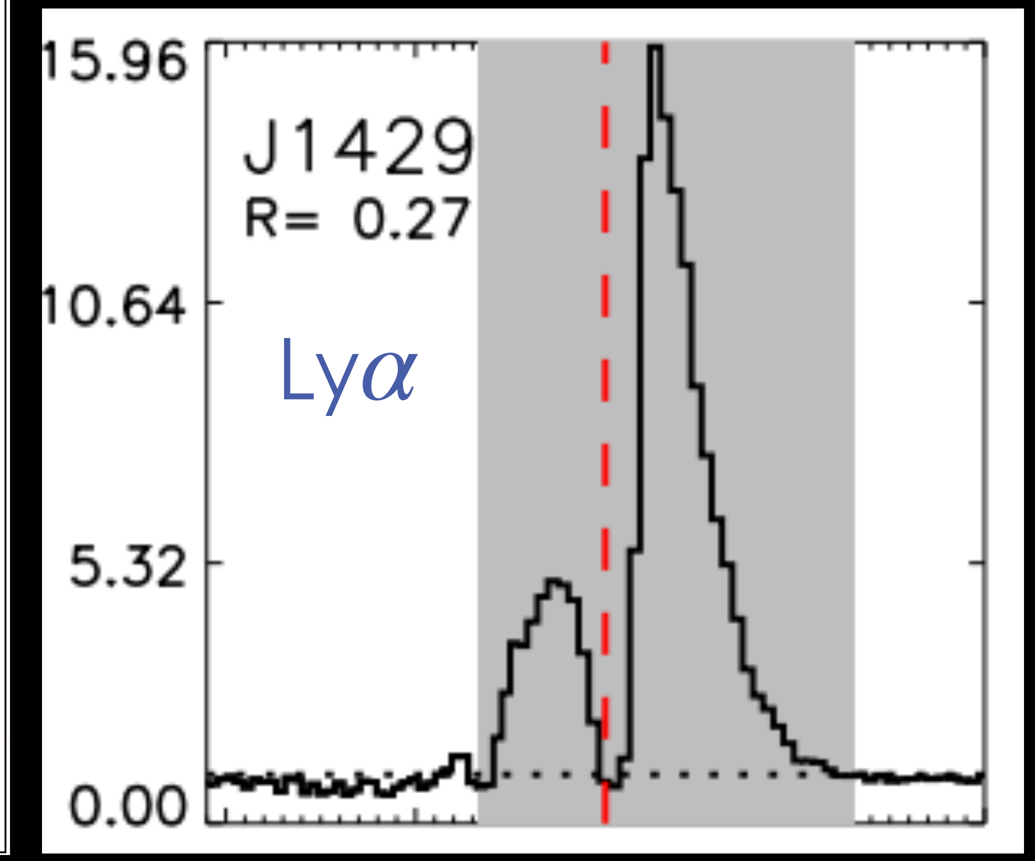
- Blue-shifted broad optical emission
  - σ_{int} ~240 km/s
  - FWZI~1500 km/s
  - Δv~ -65 km/s

Consistent kinematics for all lines!





J1429+0643: a LyC leaking candidate (Alexandroff+2015)



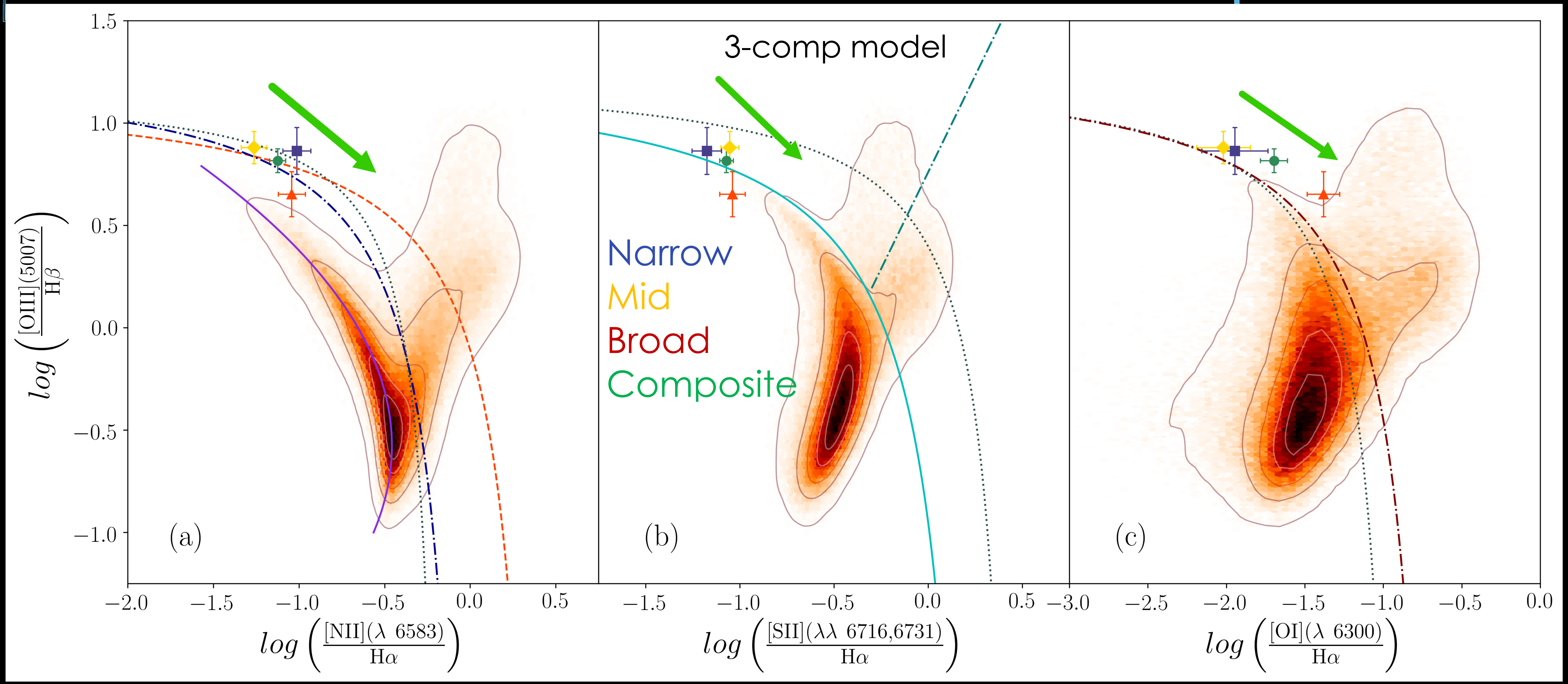
Broad/total~30-40%
Narrow/total~25%

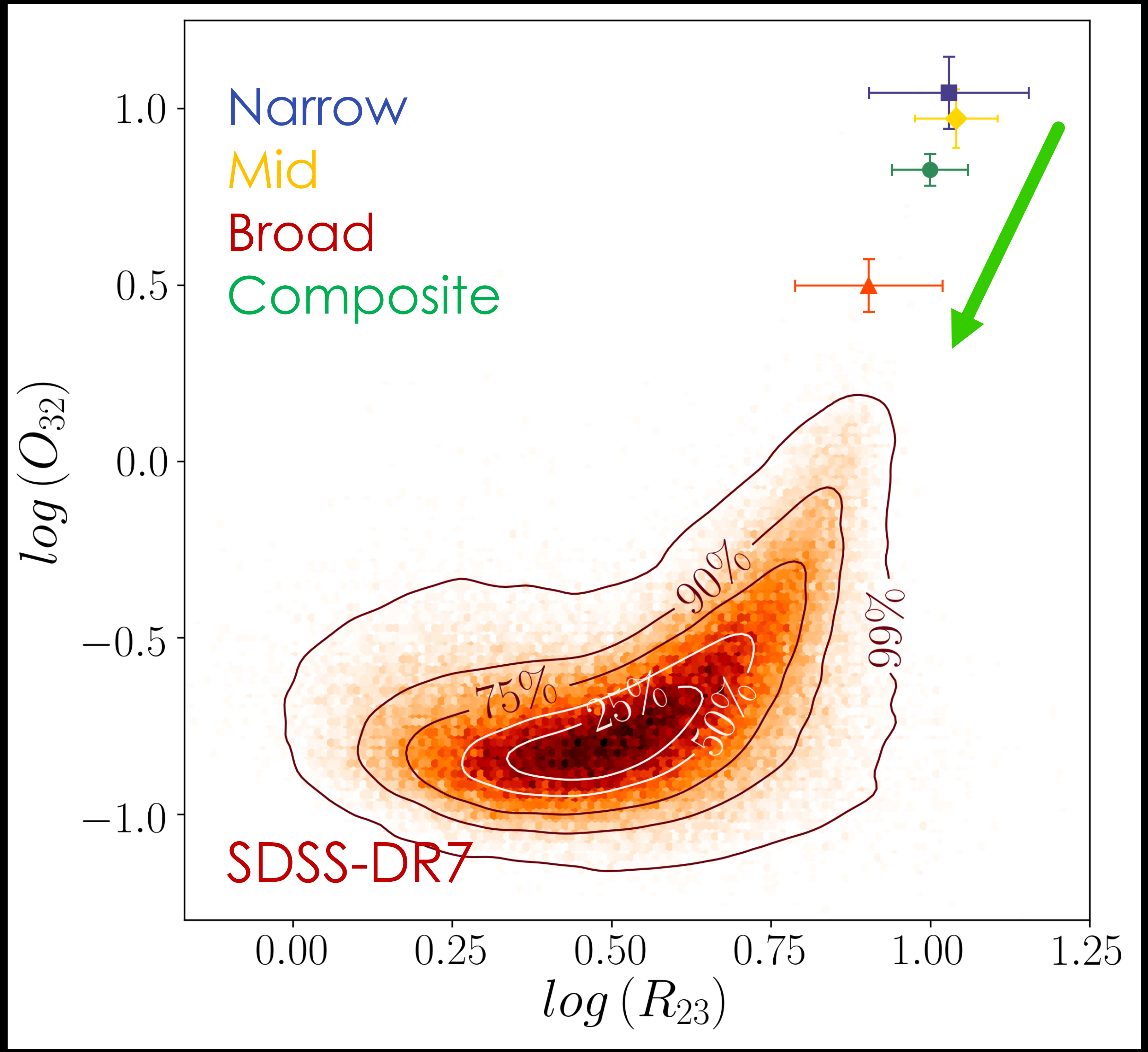
$\Delta v_{(broad,\ mid)}$~60 km/s
σ_N=45 km/s, σ_M =120 km/s, σ_B=240 km/s

IMPACT ON EMISSION LINE DIAGNOSTICS

Broad emission show slightly lower excitation/ ionization

Broad is 2-3 times denser (~500 cm^{-3}) and it has 20% lower T_e than narrower components

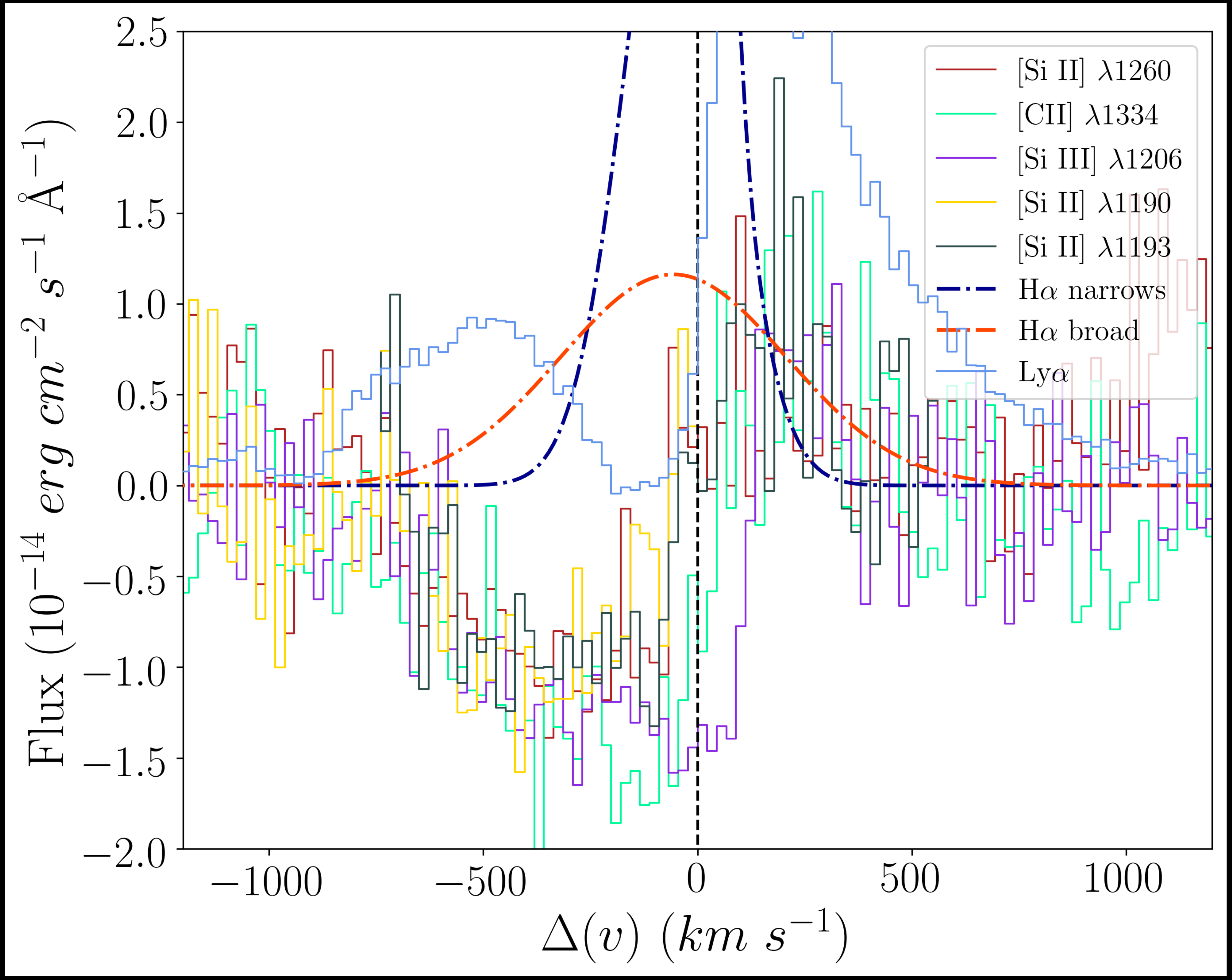




Hogarth+20

EVIDENCE OF OUTFLOWS IN GPs

UV and optical kinematics



Hogarth et al. (2020)

Comparison HST/COS high-res UV and ISIS optical spectra

- UV interstellar abs. lines trace lower-density gas

(*Heckman & Borthakur+15,Chisholm+15*)

  - V_{max}~660 km/s

- Optical emission lines may trace denser gas

Assuming a *simple* model:

V_{out}~550 km/s

η~0.25-0.7 ; v_{out}/v_{esc}~5.5

→ some gas could escape

A HST/COS SURVEY OF LYC EMITTERS AT Z~0.3

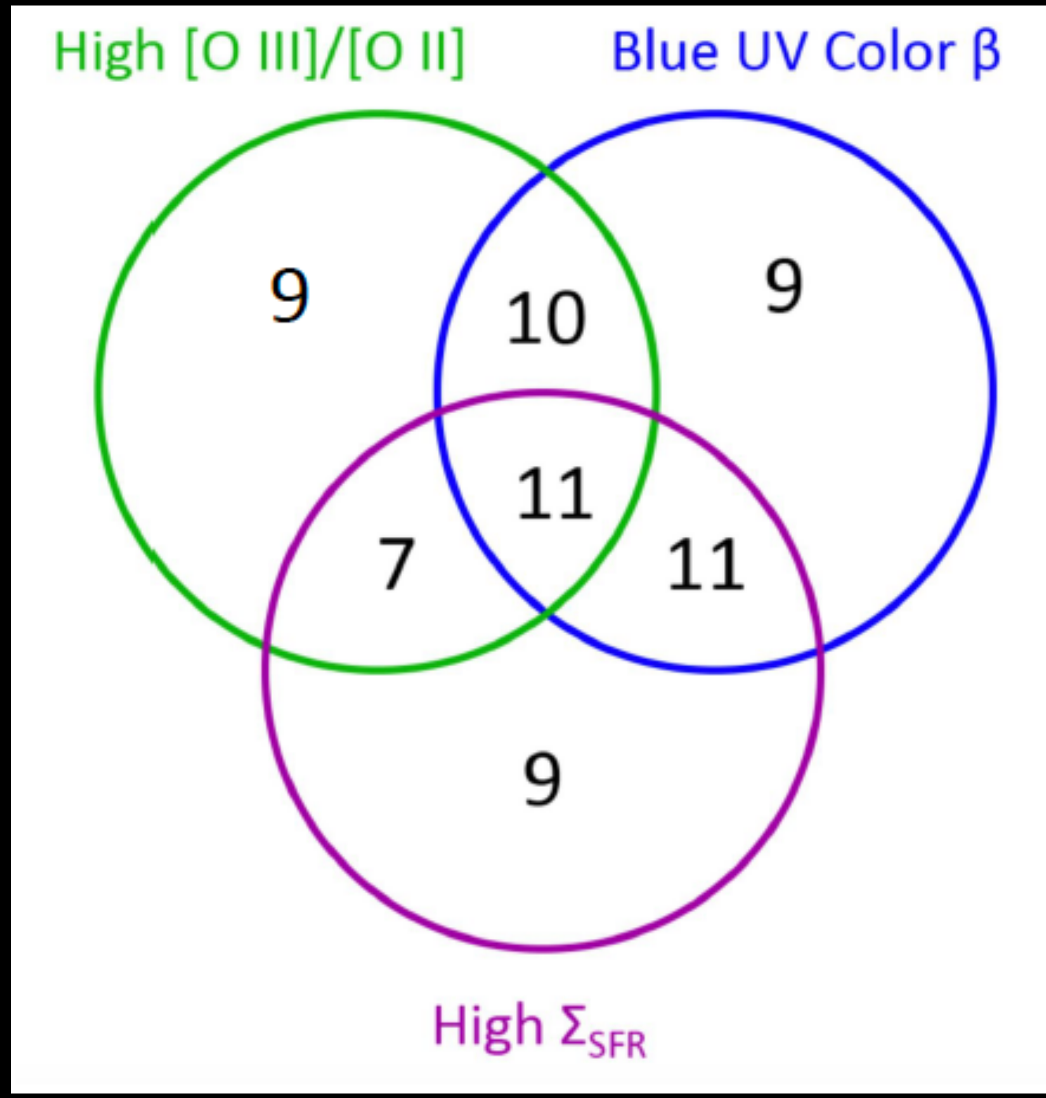
The Astrophysical Journal Supplement Series, 260:1 (17pp), 2022 May https://doi.org/10.3847/1538-4365/ac5331

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 Amorin[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)

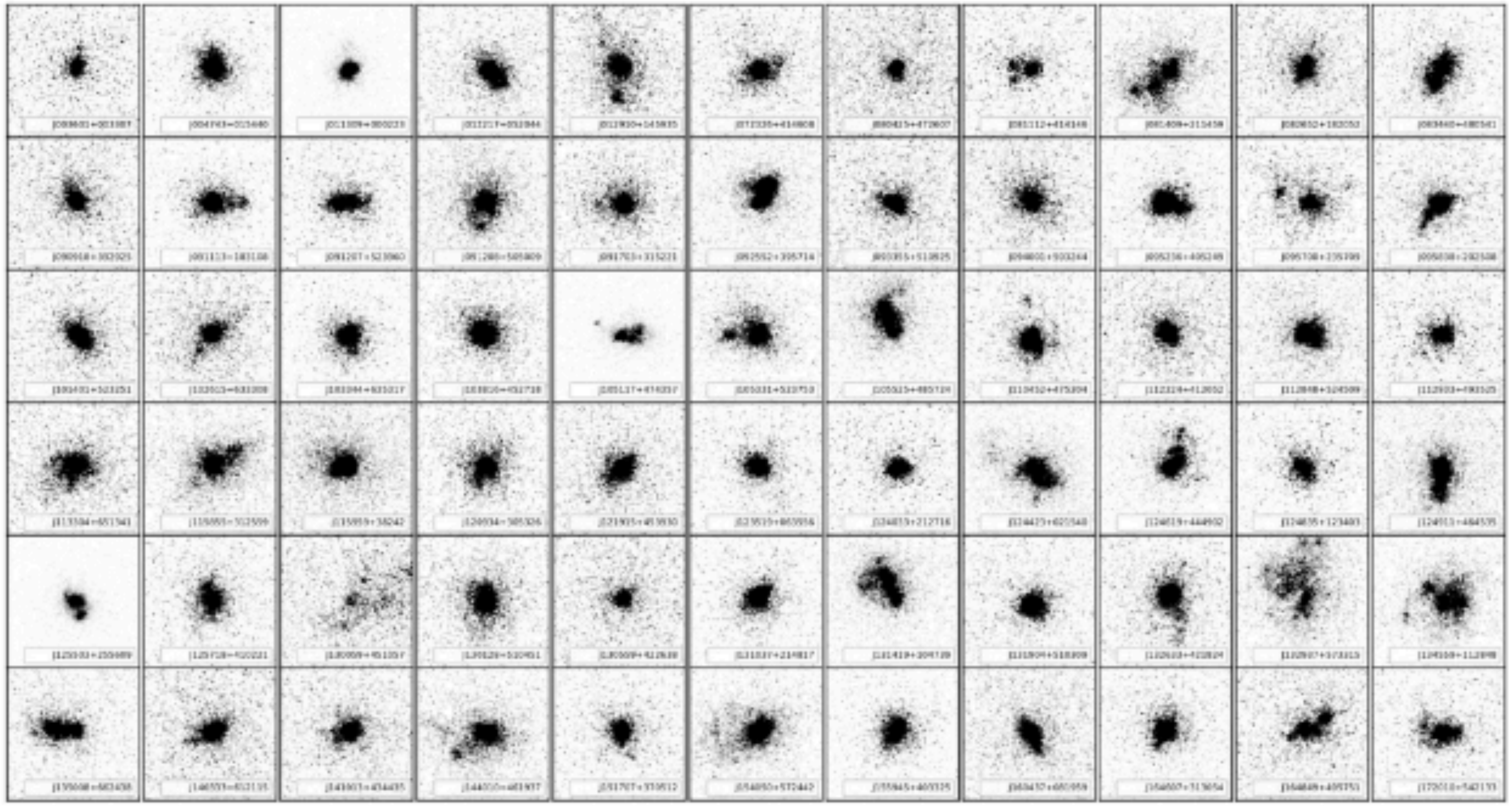
- Large HST/COS Program (160 orbits; PI: A. Jaskot)
- LyC observations for 66 *diverse* SFGs at z~0.2-0.4 with SDSS spectra + GALEX photometry.
- 35 newly confirmed LCEs, several have Fesc>5% !!
- Consistent reanalysis of 12 previous detections (Izotov+21)



Sample selection

Flury et al. 2022a

See Anne Jaskot's review

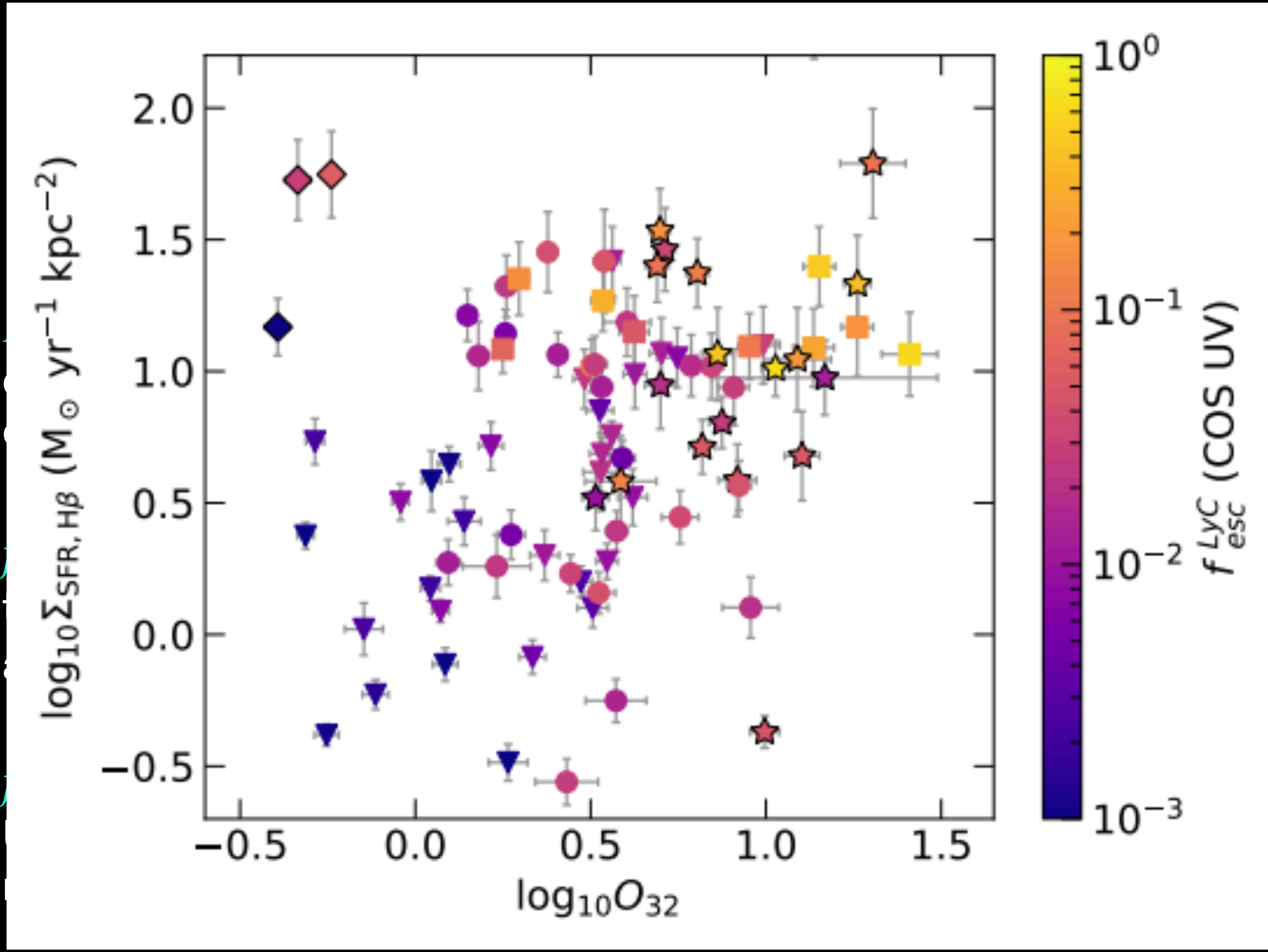


LzLCS sample imaged by HST/COS

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



THE ASTROPHYSICAL JOURNAL, 930:126 (21pp), 2022 May 10 https://doi.org/10.3847/1538-4357/ac61e4

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]

See Anne Jaskot's review

Diagnostic	$F_{\lambda LyC}/F_{\lambda 1100}$ (Wang+21)			f_{esc}^{LyC} (Hβ) (Izotov+18)			f_{esc}^{LyC} (UV) (Saldaña-López+22)		
	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

Linking ionized gas kinematics with Lyman photon escape

Main questions

- What can we learn from the emission-line kinematics of LyC emitters?
- Is ionized gas kinematics causally connected to Lya and LyC escape?
- Can we use emission line kinematics to constrain models/simulations?
- Could ionized gas kinematics be an additional indirect diagnostic for LyC emission?

Linking ionized gas kinematics with Lyman photon escape

Our main goals

- Ionized gas kinematics characterization from emission line profiles
  - High-resolution deep optical spectra (long-slit and IFU)
  - Representative sample of LyC emitters and non-emitters at low-z
- Detection of high-velocity gas flows and characterize their properties (energetics, density, temperature, ionization and other diagnostics..)

Sample and data

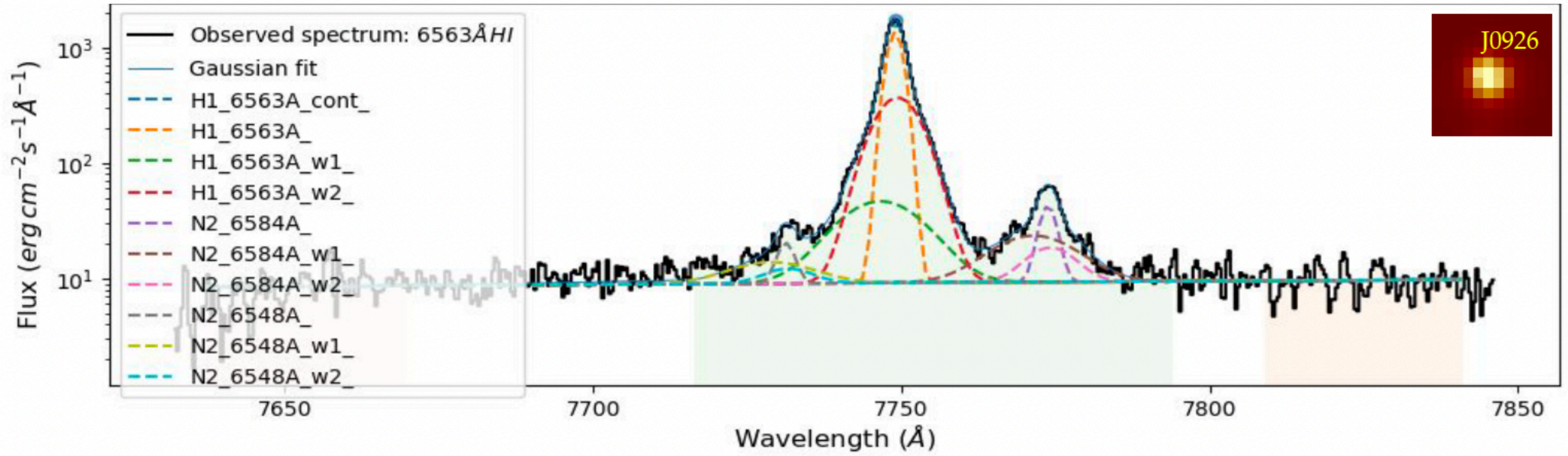
- Sample: Subsample of 17 GPs from LzLCS (Flury+22) + 5 GPs from Izotov+16,18.
  In total: 4 non-LCEs; 11 weak and 7 strong LCEs
- Data: Long-slit spectra from VLT/XShooter (R~8800) and WHT/ISIS (R~9000) ~1-3h on-source (allows continuum detection)
- Methodology: Multi-component Gaussian fitting inspired in our previous work (Amorín+12, Bosch+19; Hogarth+20)

Methods

A Line Measuring library for astronomical spectra

Documentation

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



github.com/Vital-Fernandez/lime

https://lime-stable.readthedocs.io/

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

We use a new versatile code LiMe; developed by Vital Fernández. (Fernández et al. 2023)

LiMe measurements

Integrated

- Line fluxes
- Peak flux
- Peak wavelength
- Line redshift
- FWHM
- Continuum level
- Continuum gradient
- Continuum intercept
- Continuum noise
- Velocity percentiles

Eqw

Gaussian

- Amplitude
- Profile center
- Profile sigma
- FWHM
- Line Fluxes
- Radial velocity
- Velocity dispersion

Identity

- Transition ion
- Transition label latex
- mask (rest frame)
- Transition wavelength
- blended/merged group

Diagnostic

- S/N line
- S/N continuum
- χ^2
- χ_ν^2
- AIC
- BIC
- observations (errors)
- comments (user)

- The measurements physical/mathematical description can be found in the online documentation

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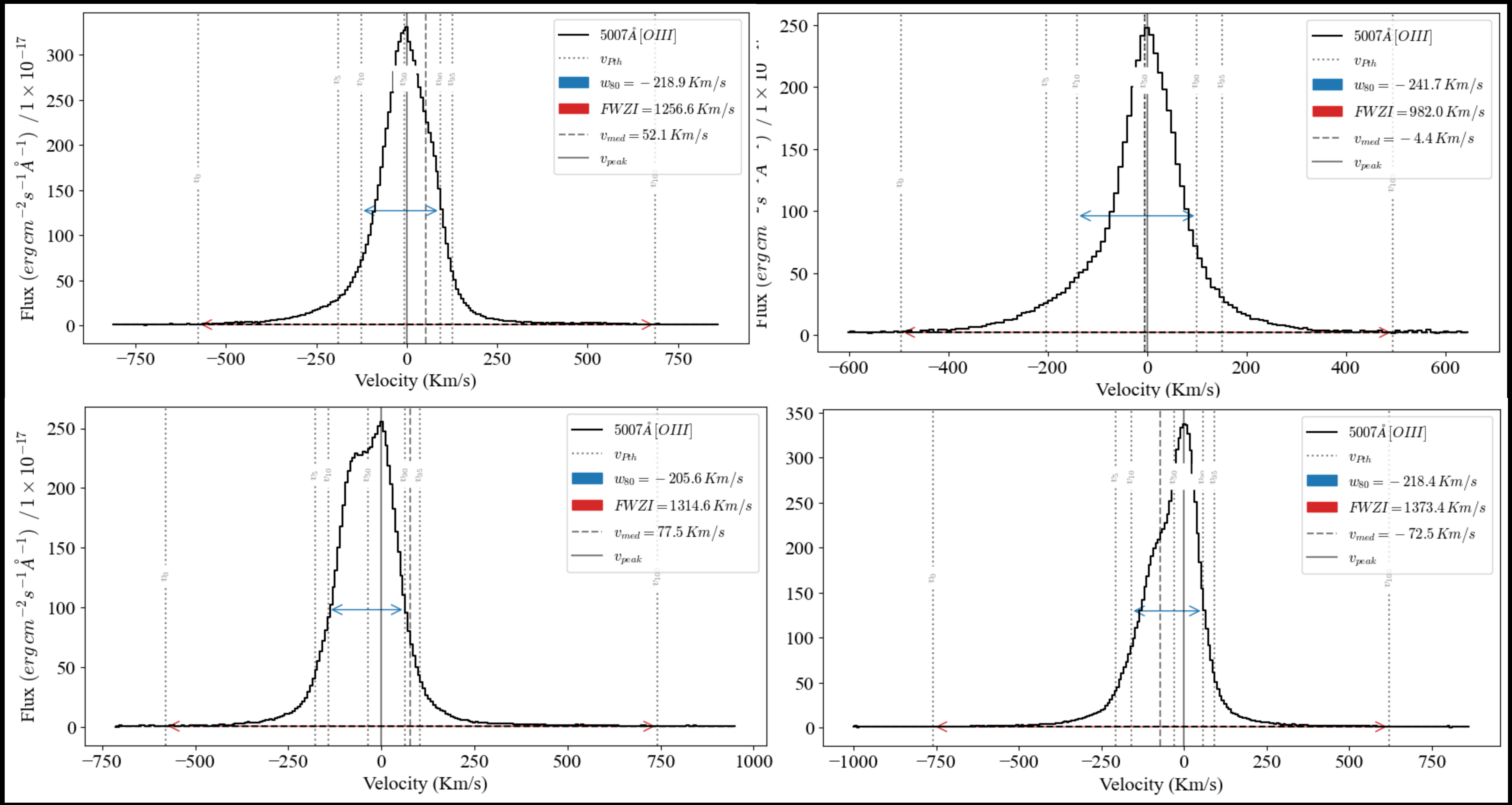
LiMe → Direct method space sampling Fernández et al (2019) → Direct method + photoionization grids space sampling Fernández et al (2021) → Chemical + kinematics space sampling →

Non-parametric analysis

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

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

A few examples of observed [OIII]5007 profiles from strong LCEs



Rodríguez et al. (in prep)

Evidence of ionized gas outflows in LyC leakers

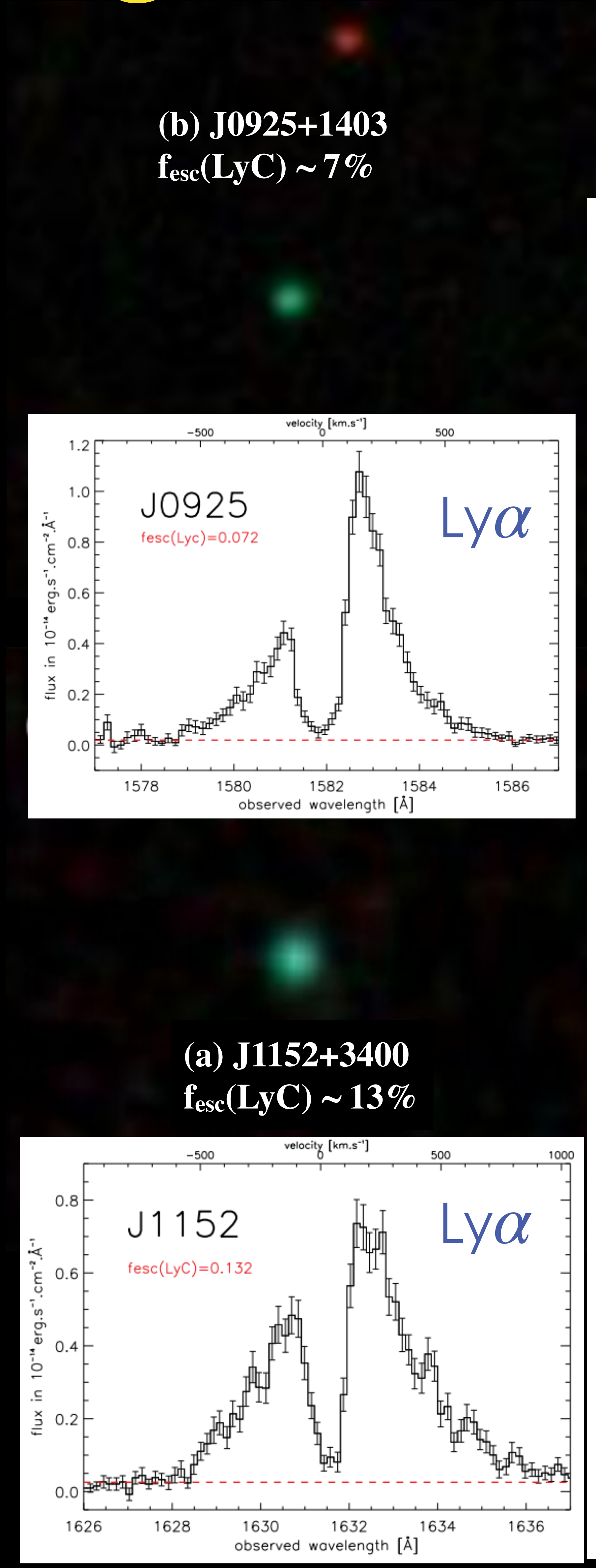
Matías Rodríguez
MSc thesis (2022)

Dania Muñoz PhD thesis
(in prep)

Full kinematic modelling of bright and faint lines

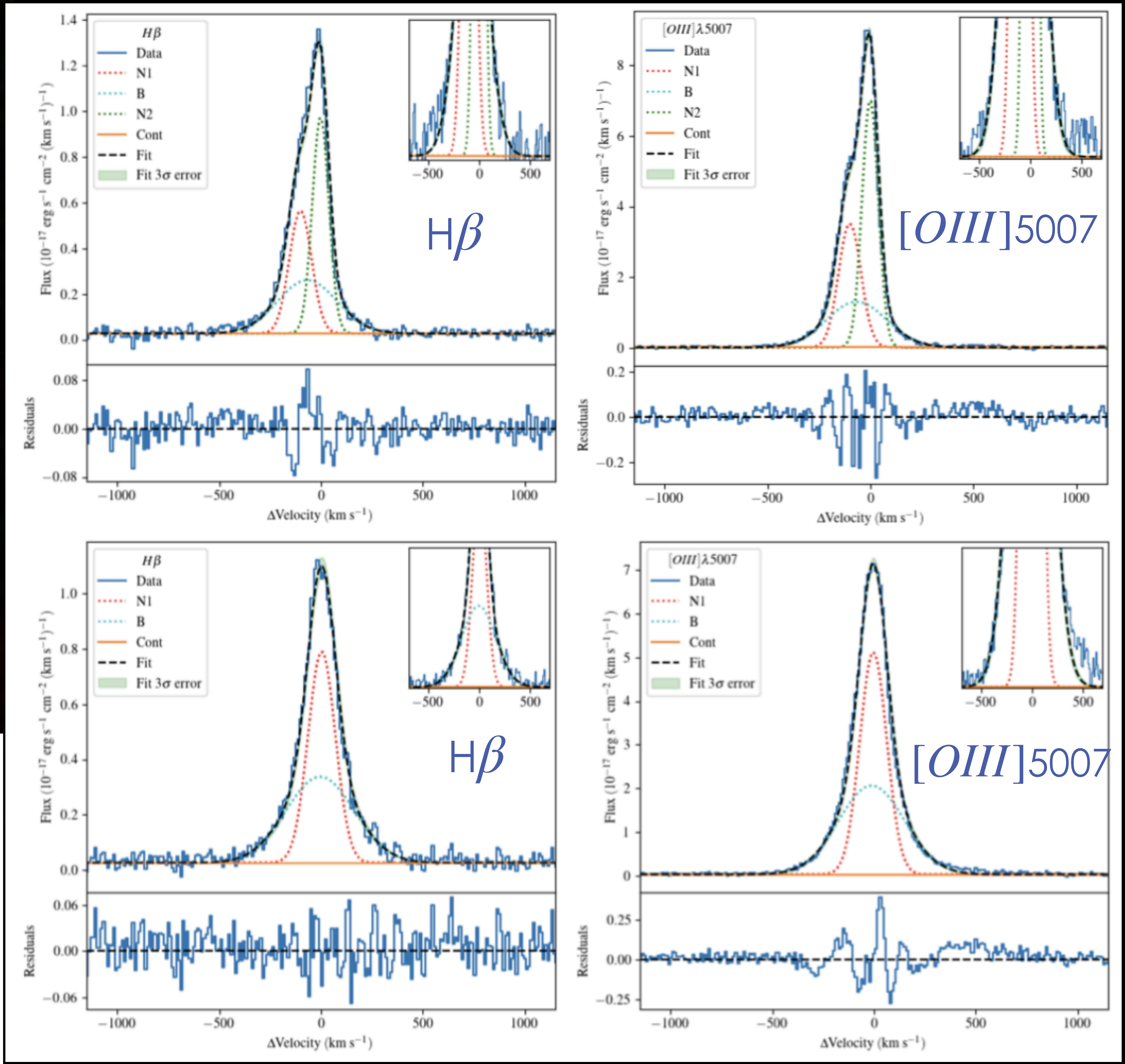
First clear evidence for broad emission heavy line wings in strong LCEs, which contribute ~20-50% of the total line flux

IMPORTANT: Bright Balmer AND CELs show similar kinematics! No AGN behavior (see Hogarth+20)



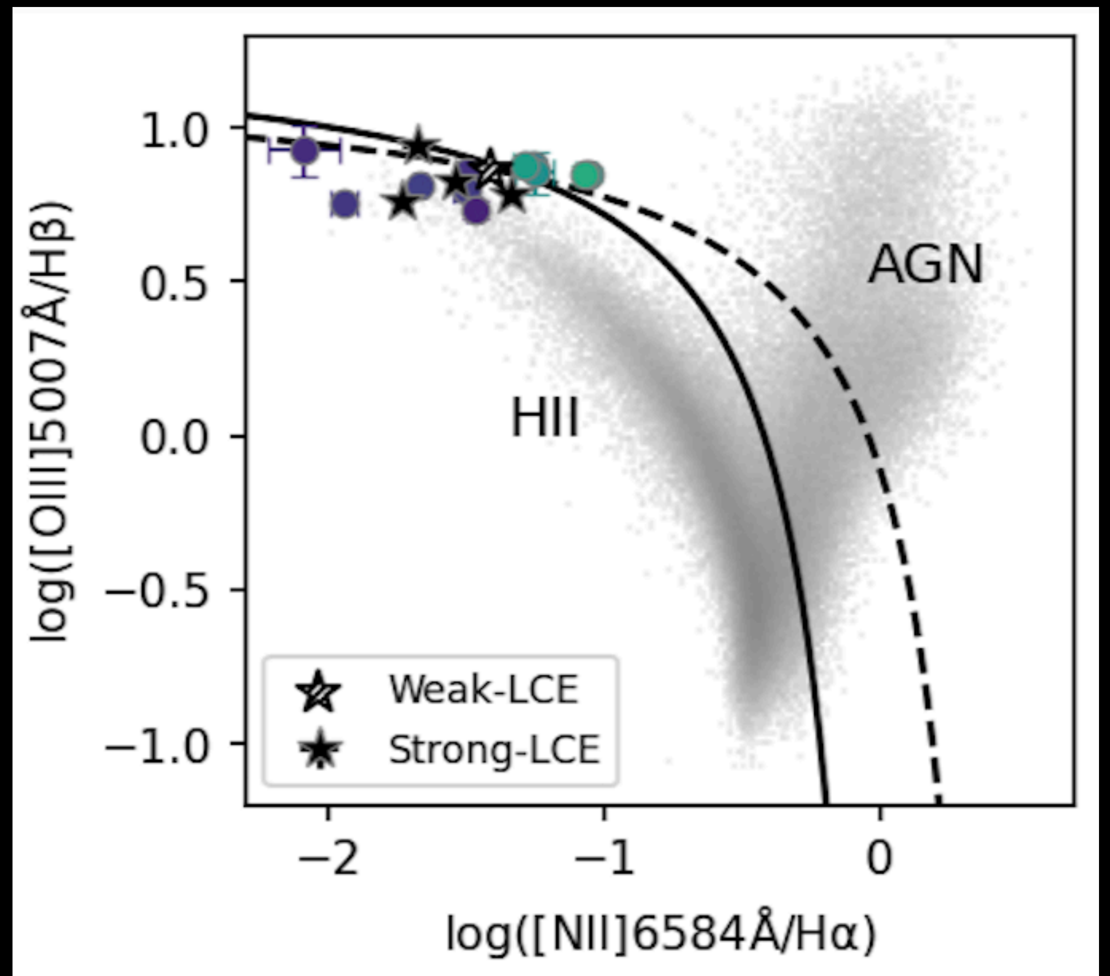
Rodríguez et al, in prep

WHT/ISIS data

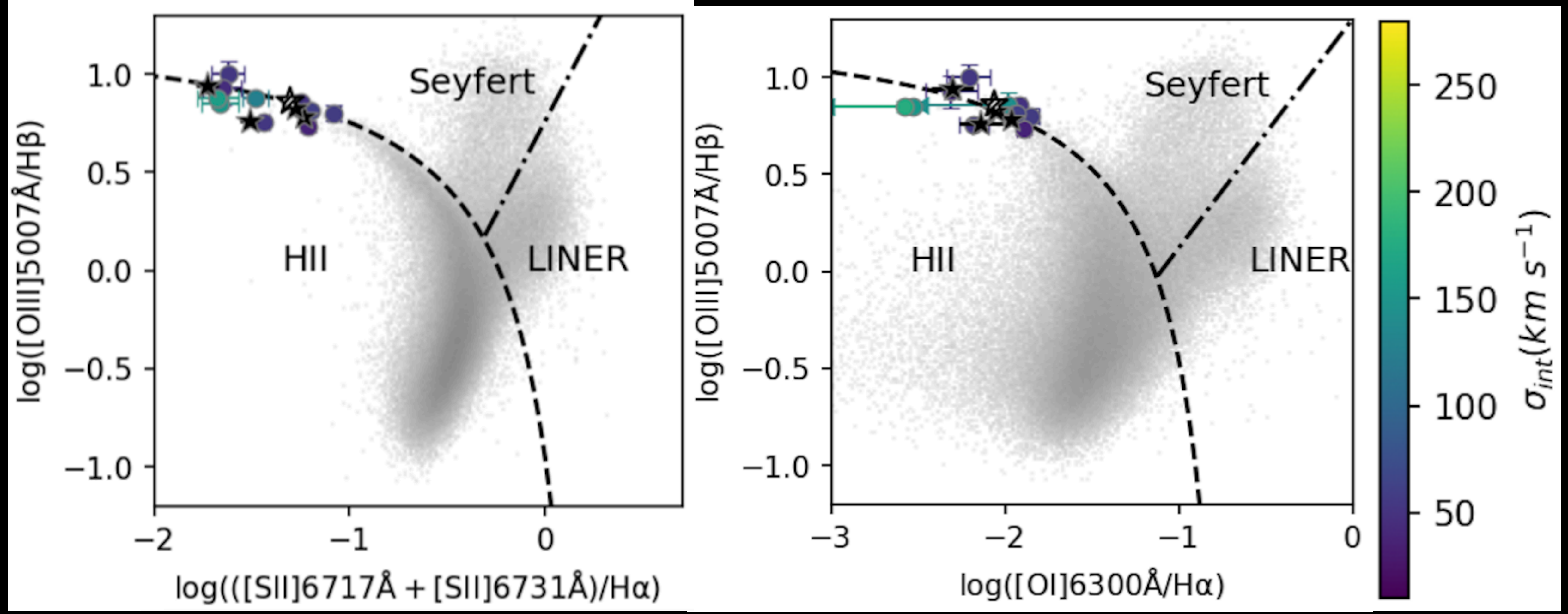


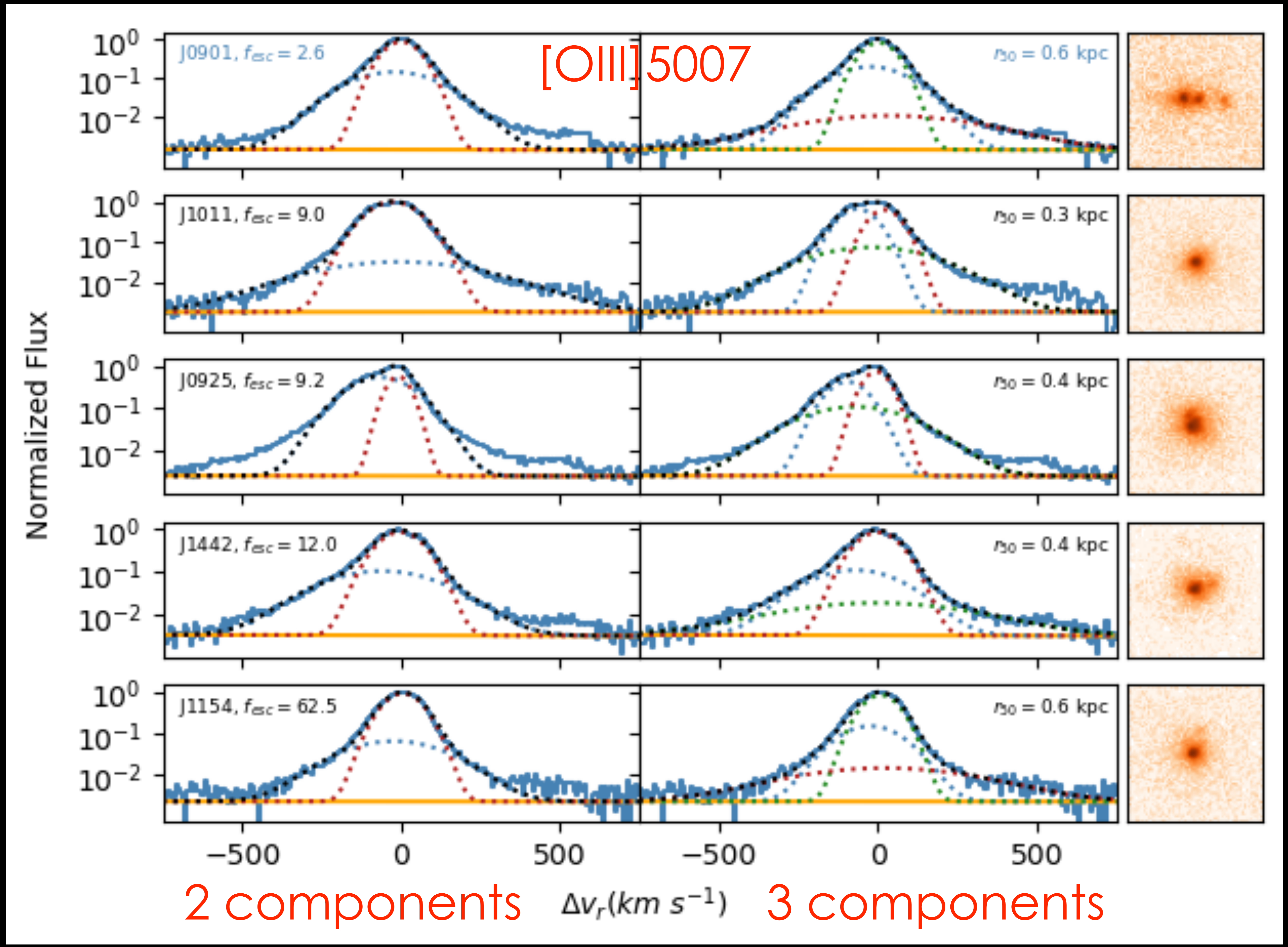
Evidence of ionized gas outflows in LyC leakers

Izotov+16 sample



- All emission components are photoionized by massive stars but broad emission show larger [NII]/Hα
- Broad emission in SLCEs is highly excited and fainter in [SII]/Hα and [OI]/Hα, as expected from density-bounded regime (cf. Wang et al., 2021; Ramambason et al., 2020)

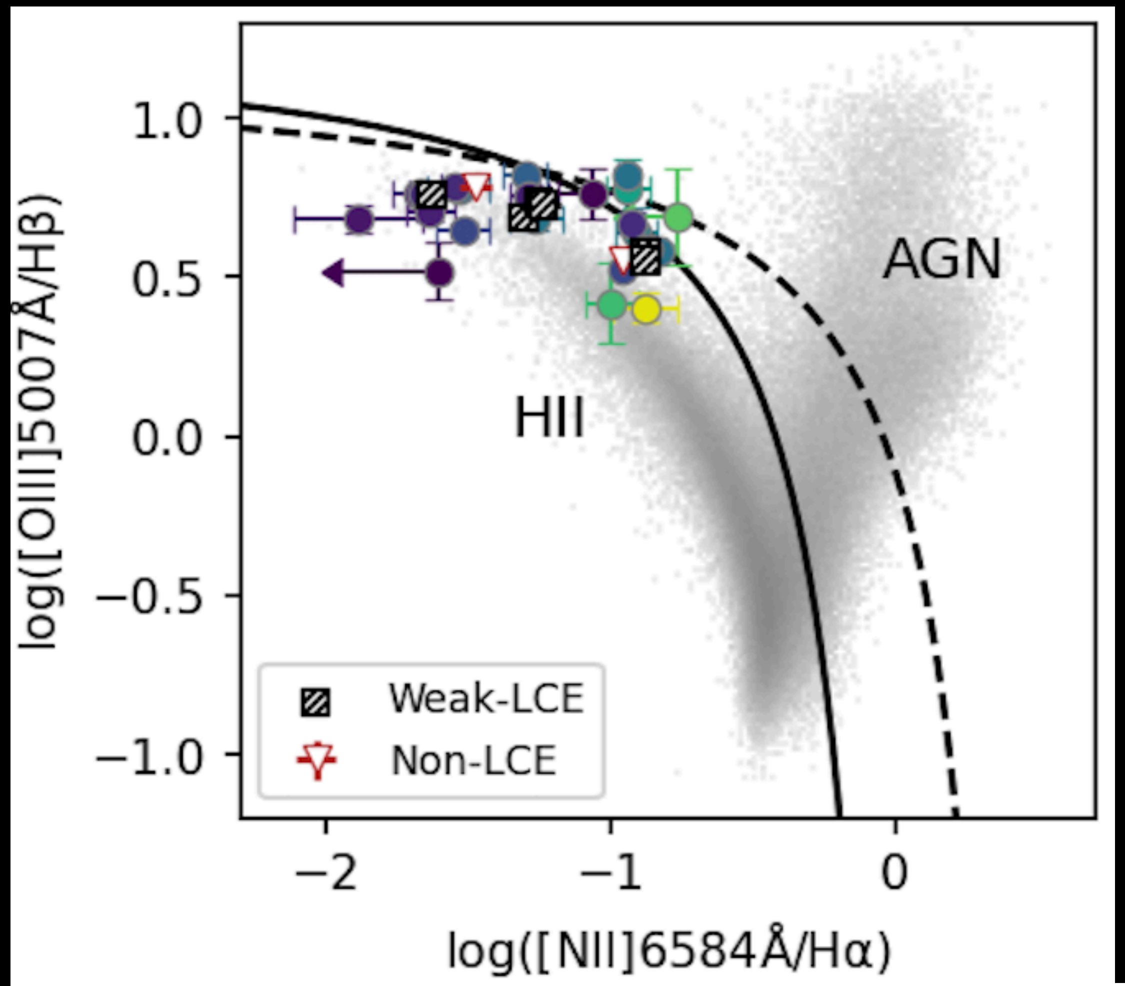




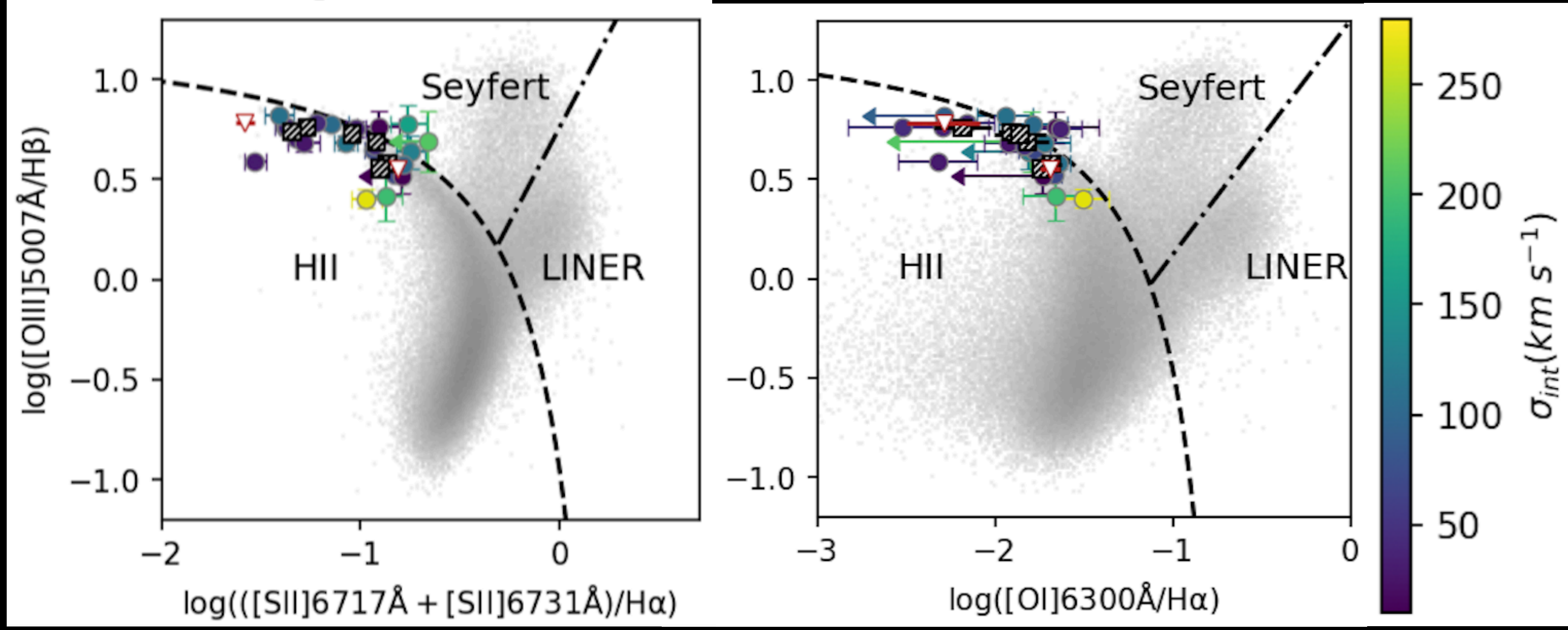
Broad/total up to ~40%

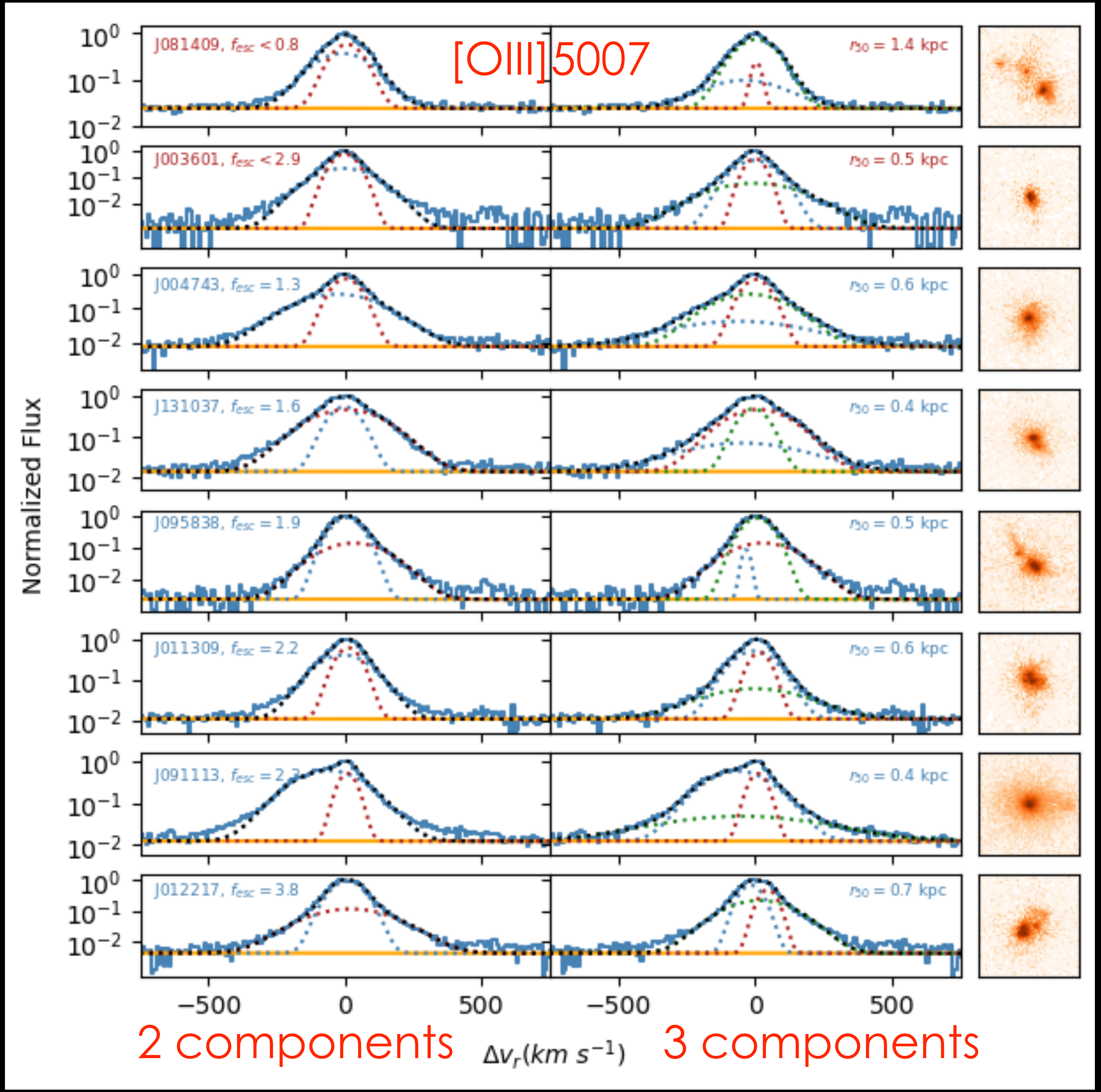
Evidence of ionized gas outflows in LyC leakers

LzLCS Flury+22 subsample



- All emission components are photoionized by massive stars but broad emission show larger [NII]/Hα
- Broad emission in WLCEs and NLCEs appear larger in [SII]/Hα and [OI]/Hα, in contrast to SLCEs which also show higher excitation



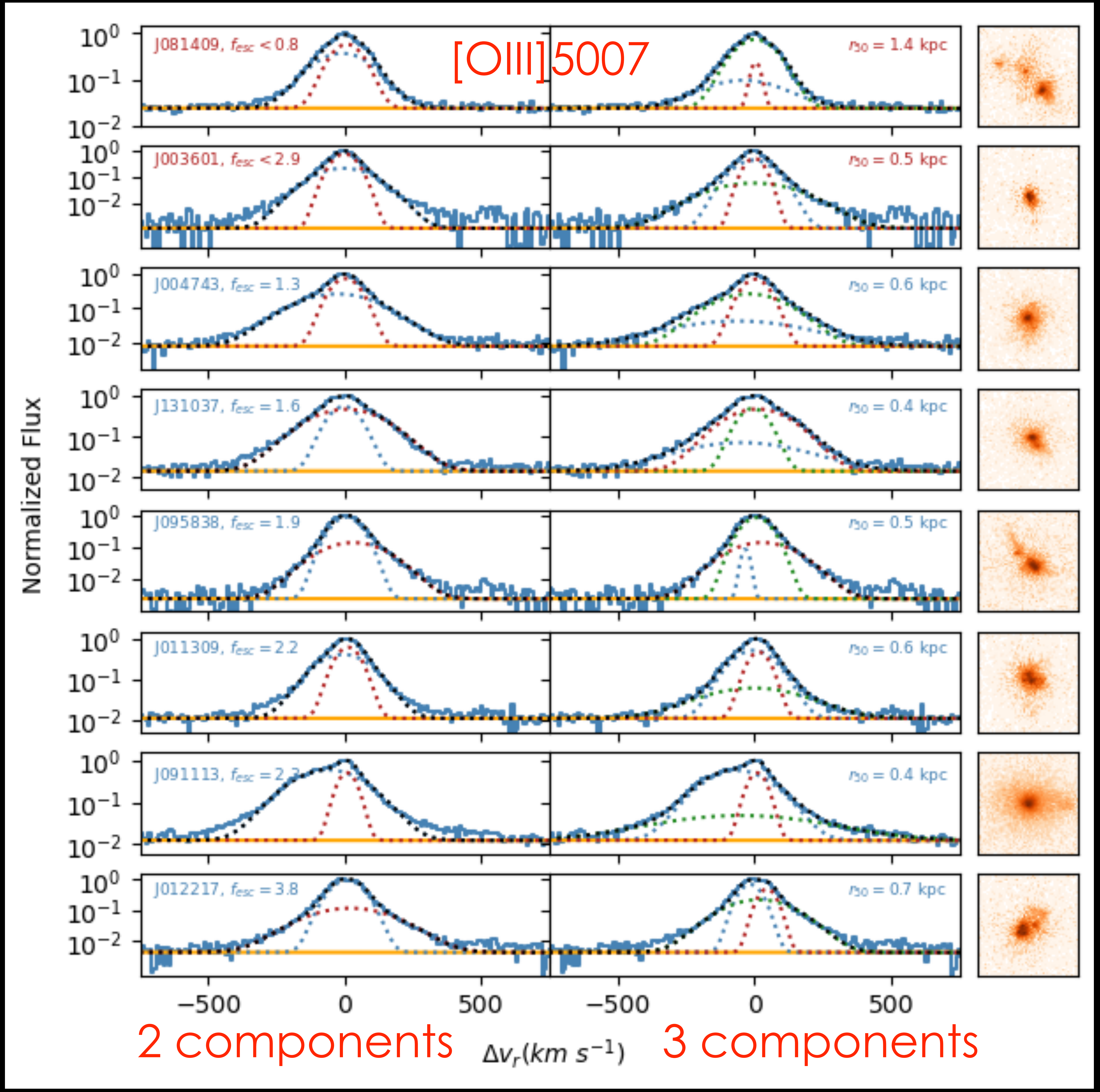


Evidence of ionized gas outflows in LyC leakers

LzLCS Flury+22 subsample

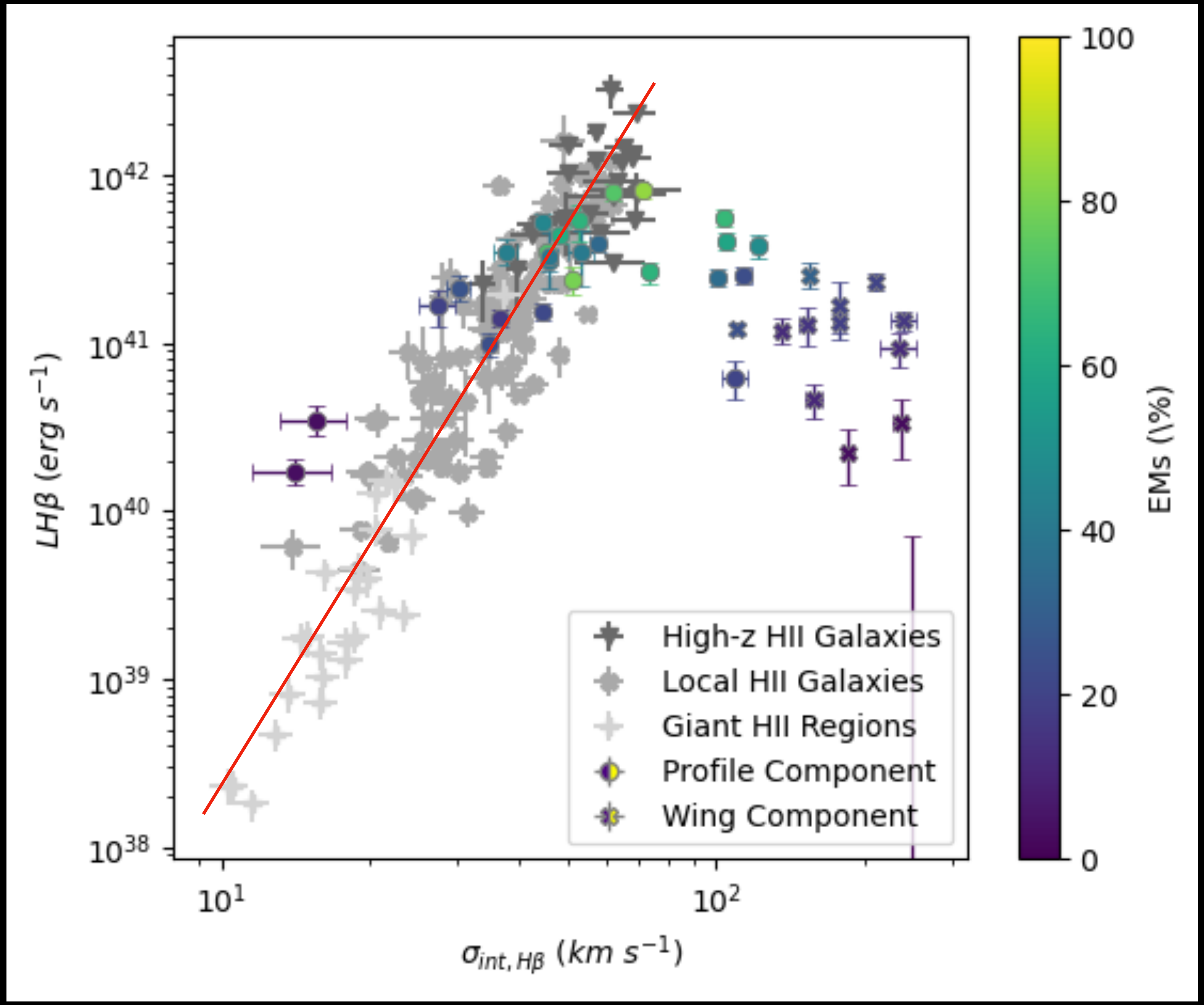
Weak LCEs show lighter broad wings and narrower/less asymmetric profiles

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



What is the nature of the line components?

L-sigma relation (Terlevich & Melnick 1981, Terlevich+2015)



Traces **virial motions** through the gravitational potential of a star-forming galaxy or giants star-forming regions

I. AGNs
II. Stellar feedback (winds + radiation)
III. Expansion of SNe remnants
IV. SNe-driven superbubble blow-up
V. Turbulent mixing layers

(See Amorín+12b, Hogarth+20)

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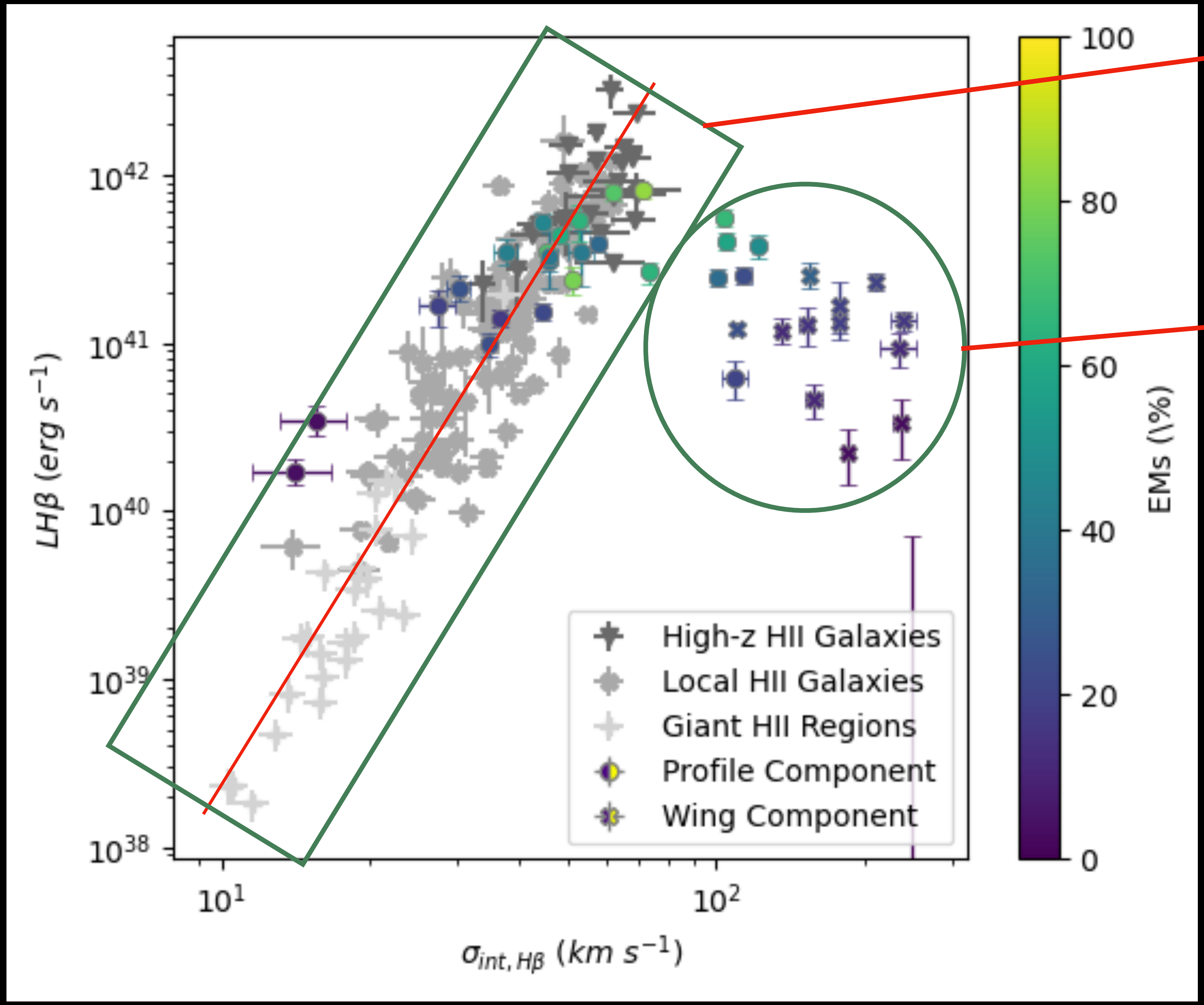


Traces **virial motions** through the gravitational potential of a star-forming galaxy or giants star-forming regions

- **Narrow components** follow the relation for local HII regions/galaxies and high-z HII galaxies (Terlevich+15). **No additional input needed** to describe virial motions.
- **Broad components** show velocity dispersion higher than those expected for its luminosity. **Additional broadening mechanism** is required to contribute to the gas turbulence

I. AGNs
II. Stellar feedback (winds + radiation)
III. Expansion of SNe remnants
IV. SNe-driven superbubble blow-up
V. Turbulent mixing layers

(See Amorín+12b, Hogarth+20)

Does broad emission scale with LyC detection?

Kendall-τ (Akritas & Siebert 1996)

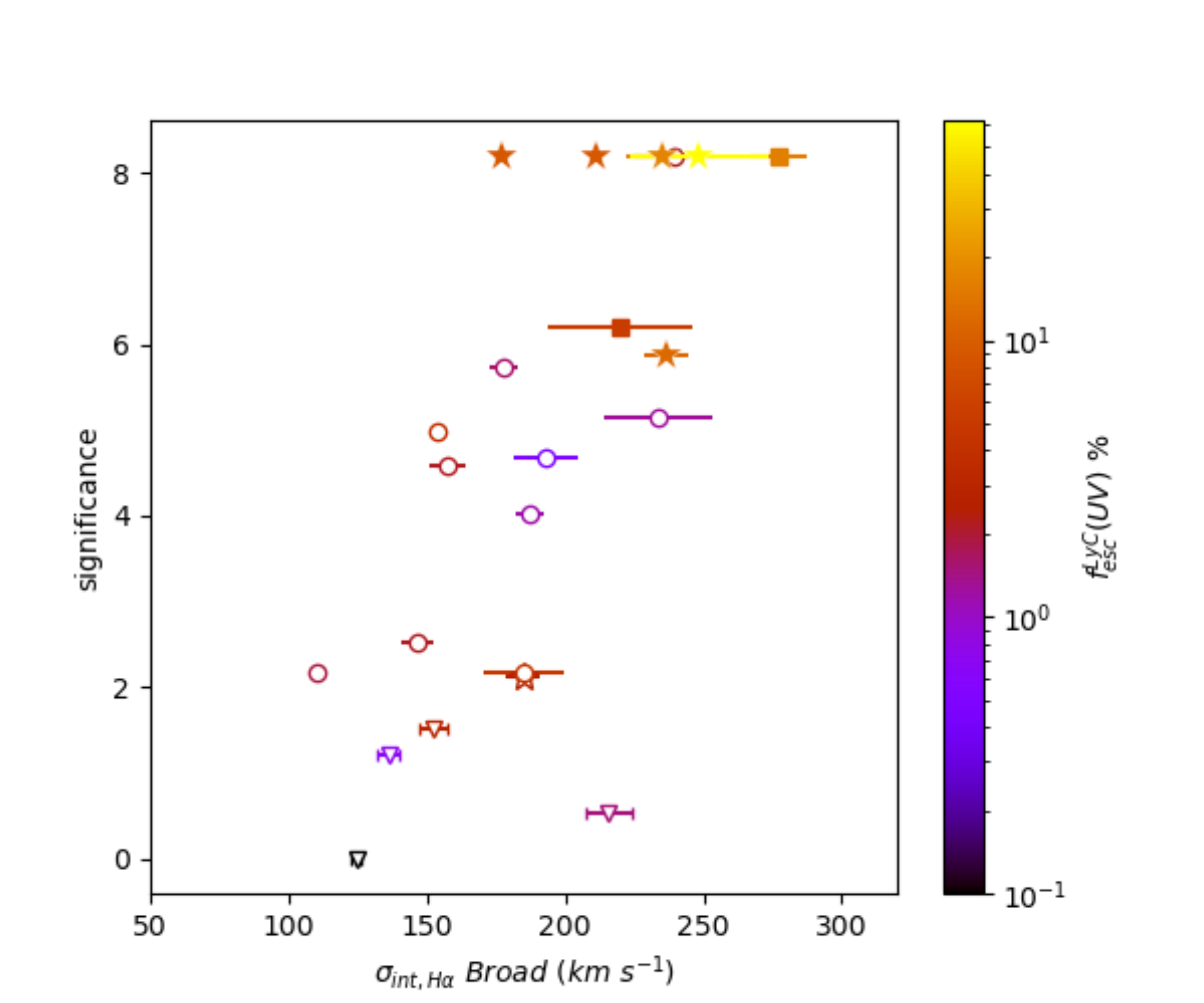
- τ: strength of the correlation
- p: probability of no correlation

Significant correlation (2σ):

$|\tau| \geq 0.261, p < 2.275 \times 10^{-2}$

Weak correlation (1σ):

$|\tau| \geq 0.162, p < 1.587 \times 10^{-1}$



The significance of LyC detection appears strongly correlated with the extent of of emission line wings

Strong LCEs: significance of LyC detection $> 5\sigma$ and f_{esc}>5%

Weak LCEs: significance of LyC detection ~ $2\sigma - 5\sigma$ and f_{esc}<5%

Non-emitter: significance of LyC detection <2σ

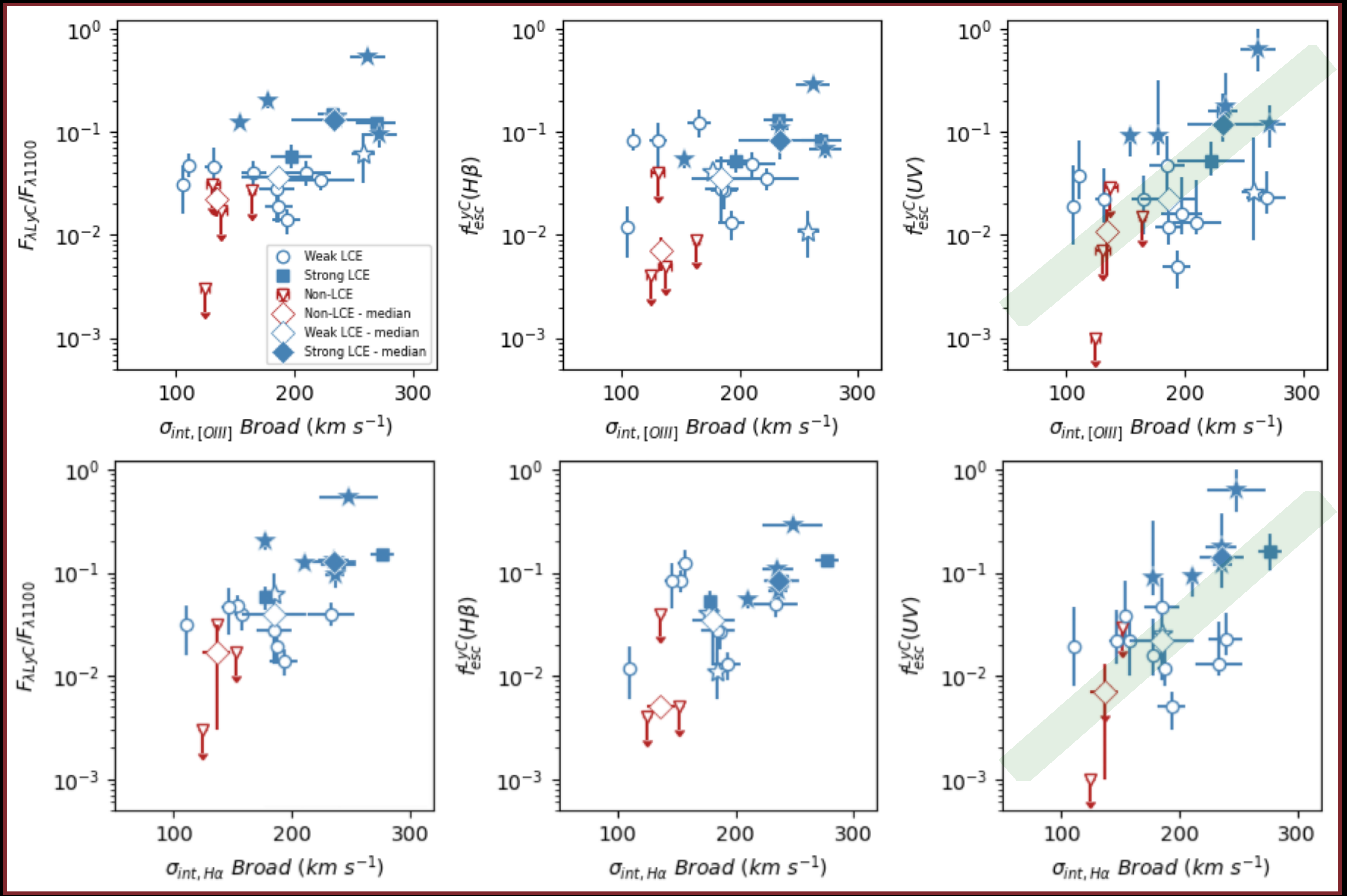
	$\sigma_{int,H\alpha-\mathrm{Broad}}$		$\sigma_{int,[\mathrm{OIII}]-\mathrm{Broad}}$	
	τ	p	τ	p
significance	$0.605^{+0.083}_{-0.077}$	1.907×10^{-4}	$0.437^{+0.121}_{-0.108}$	7.084×10^{-3}

→ SIGNIFICANT CORRELATION!

Escape fraction vs. outflow velocity traced by broad emission

- Stronger LCEs show broader wings —> larger f_{esc}
- Large scatter as in other indirect diagnostics (cf. Flury+22b)

Kendall-tau analysis indicates significant correlation between intrinsic velocity dispersion of the broader component and f_{esc}

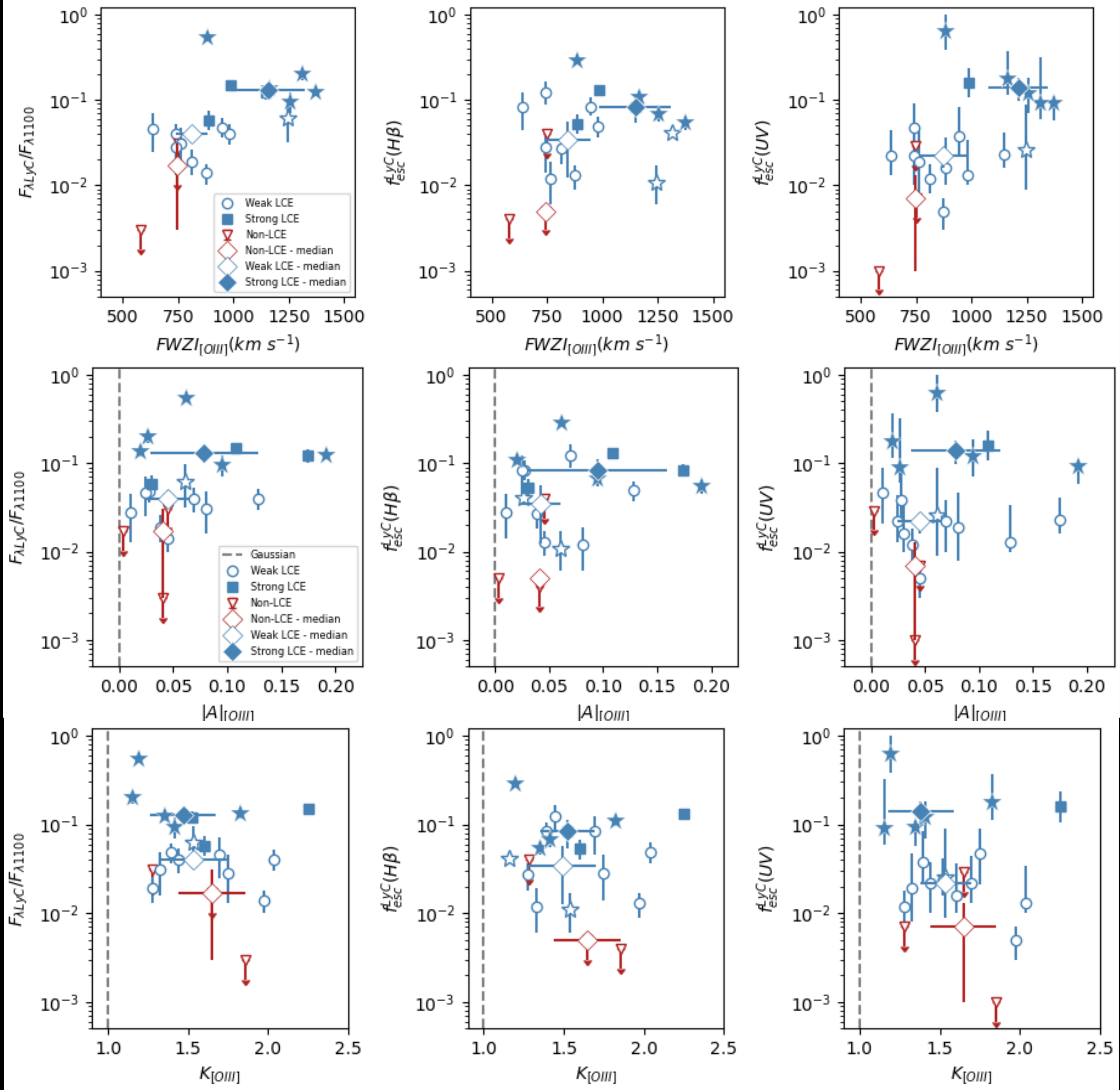


[OIII]5007

Halpha

	$F_{\lambda LyC}/F_{1100}$		$f_{esc}^{LyC}(H\beta)$		$f_{esc}^{LyC}(UV)$	
	τ	p	τ	p	τ	p
$\sigma_{int,H\alpha}$–Broad	$0.458^{+0.121}_{-0.121}$	4.763×10^{-3}	$0.426^{+0.121}_{-0.127}$	8.589×10^{-3}	$0.432^{+0.121}_{-0.122}$	7.804×10^{-3}
$\sigma_{int,[OIII]}$–Broad	$0.363^{+0.093}_{-0.098}$	2.518×10^{-2}	$0.247^{+0.128}_{-0.136}$	1.273×10^{-1}	$0.316^{+0.104}_{-0.121}$	5.158×10^{-2}

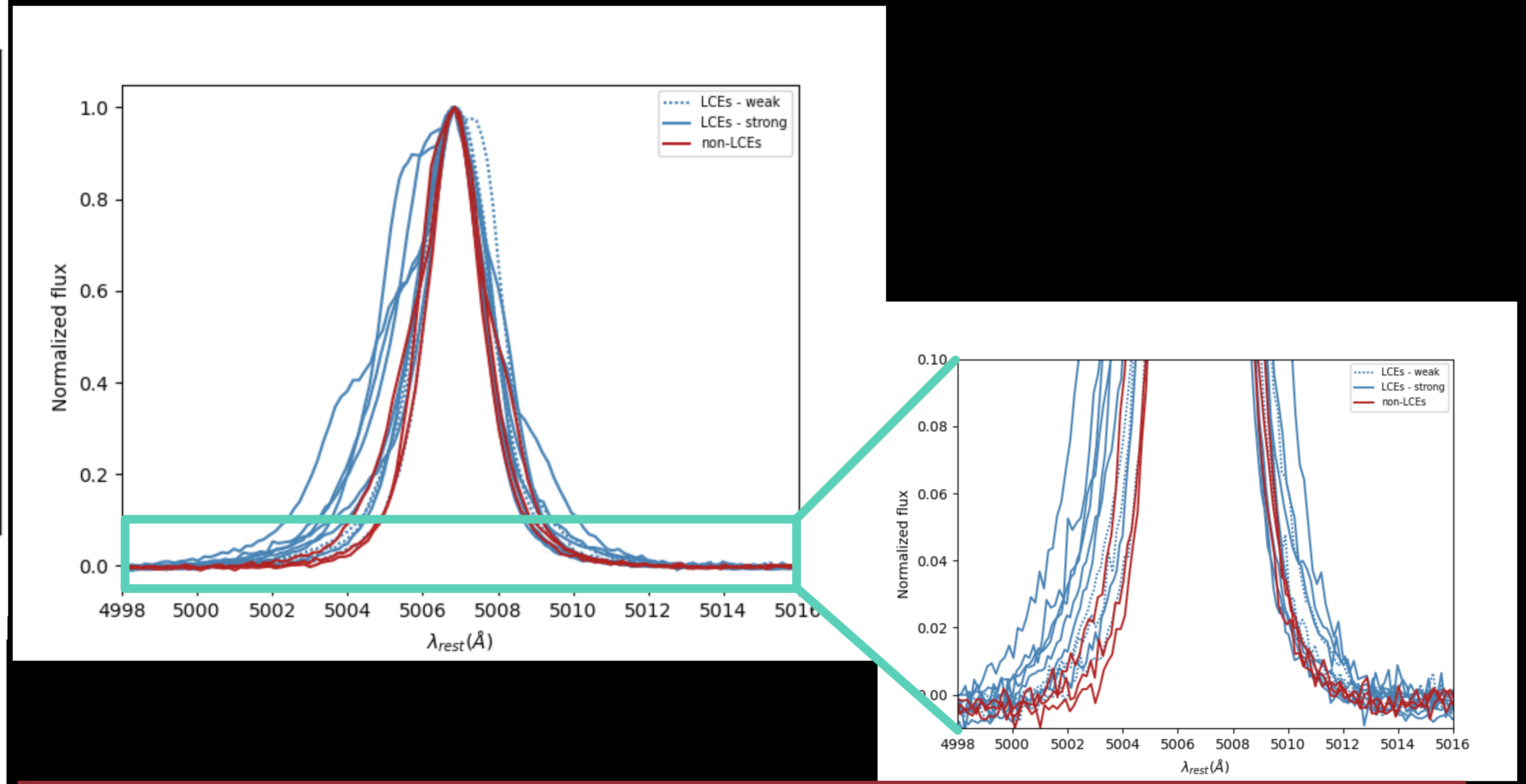
→ STRONG CORRELATIONS!



SLCEs show larger asymmetries in emission-line profiles

All GPs show deviations from gaussianity (K≠1, |A|≠0)

SLCEs with larger fesc have more extended emission-line wings. Full-width zero intensity (FWZI and W95 ≳ 1000 km/s)



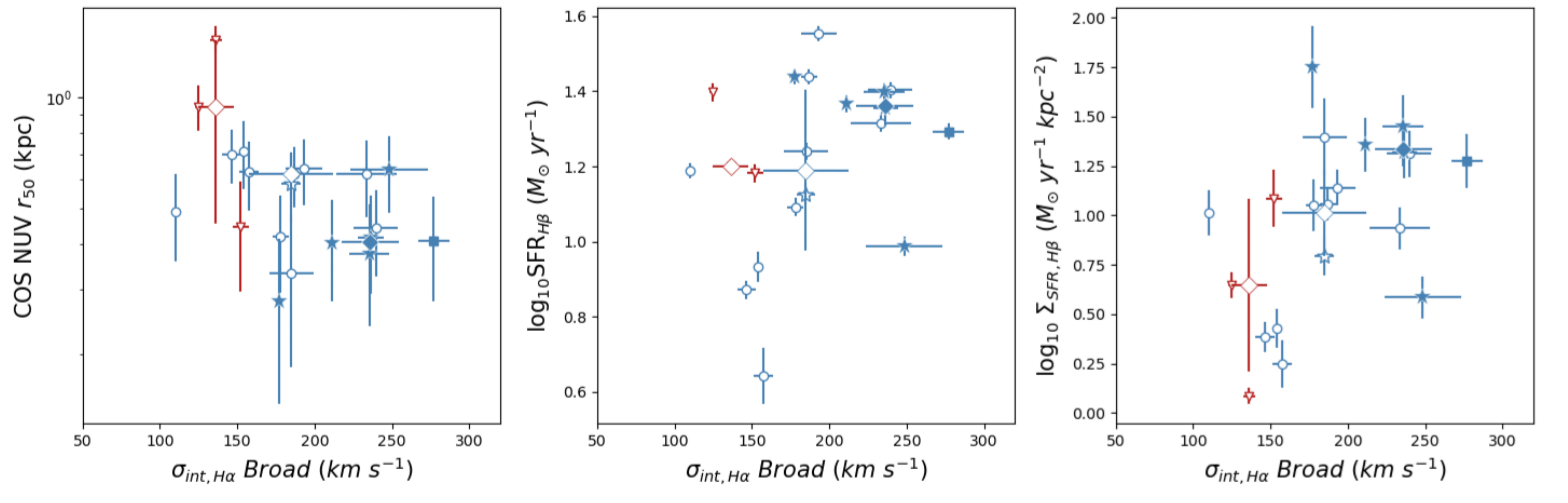
Asymmetry and shape parameter (Liu et al., 2013)

- Skewness: Symmetric profile: A=0

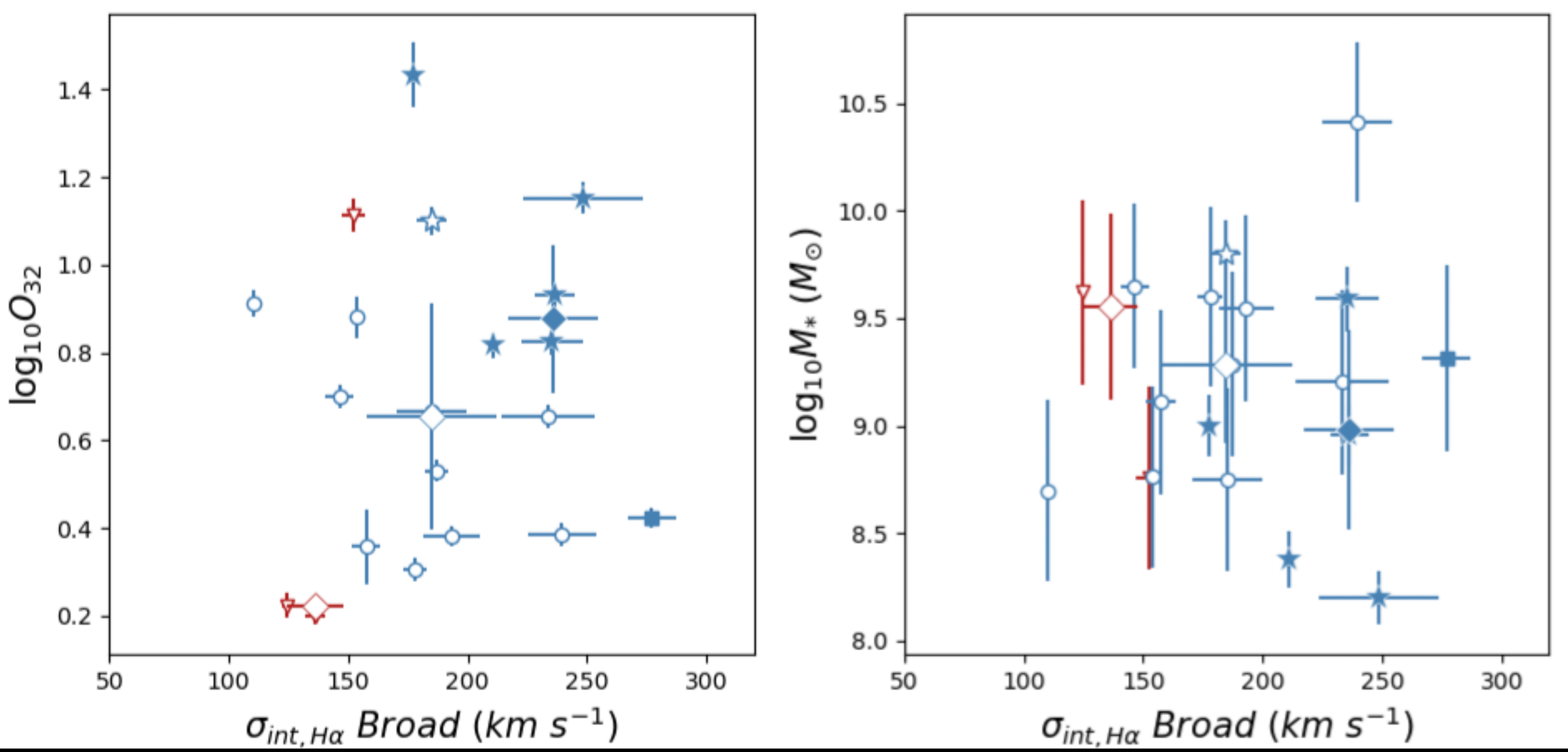
-Kurtosis
Heavy wings: K>1
Gaussian wings K=1
No wings K<1

Broad emission vs other indirect tracers

Physical properties



- Mild correlation with size, R_{50}(UV)
- Mild correlation with SFR/Area
- No significant correlation with stellar mass
- No significant correlation with O32

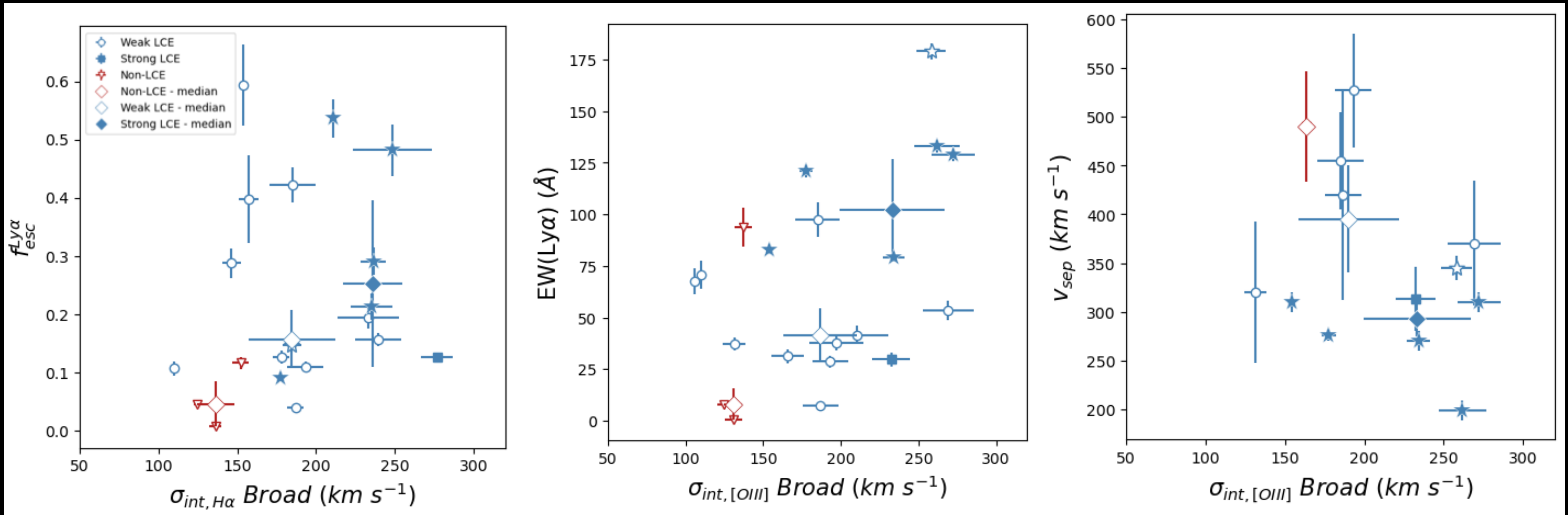


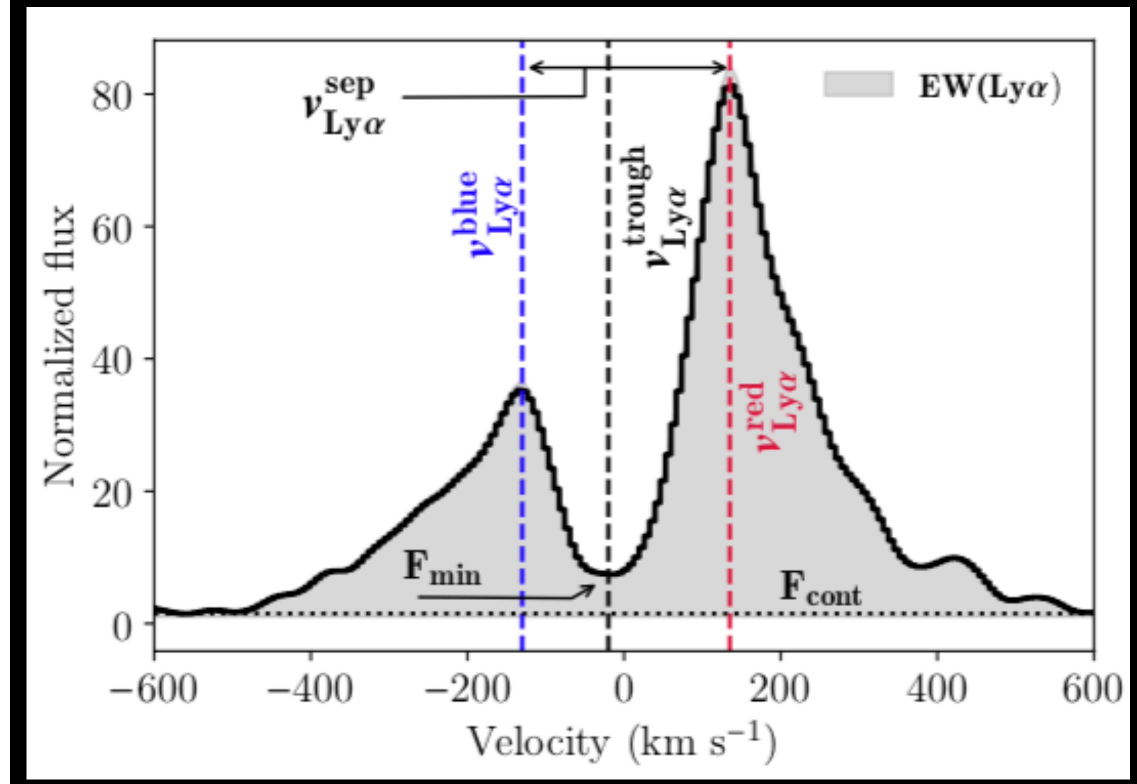
	$\sigma_{int,H\alpha-\text{Broad}}$ τ	p	$\sigma_{int,[\text{OIII}]-\text{Broad}}$ τ	p
$\log_{10}O_{32}$	$0.095^{+0.130}_{-0.153}$	5.592×10^{-1}	$0.084^{+0.130}_{-0.147}$	6.037×10^{-1}
$\log_{10}M_*$	$-0.011^{+0.154}_{-0.154}$	9.483×10^{-1}	$0.189^{+0.168}_{-0.145}$	2.428×10^{-1}

	$\sigma_{int,\text{H}\alpha-\text{Broad}}$ τ	p	$\sigma_{int,[\text{OIII}]-\text{Broad}}$ τ	p
COS NUV r_{50}	$-0.289^{+0.123}_{-0.123}$	7.435×10^{-2}	$-0.279^{+0.129}_{-0.121}$	8.551×10^{-2}
$\log_{10}\text{SFR}_{H\beta}$	$0.211^{+0.112}_{-0.109}$	1.944×10^{-1}	$0.158^{+0.104}_{-0.114}$	3.304×10^{-1}
$\log_{10}\ \Sigma_{\text{SFR},H\beta}$	$0.316^{+0.121}_{-0.126}$	5.158×10^{-2}	$0.242^{+0.103}_{-0.140}$	1.356×10^{-1}

Broad emission vs other indirect tracers

Lya properties





Gazagnes et al., 2020

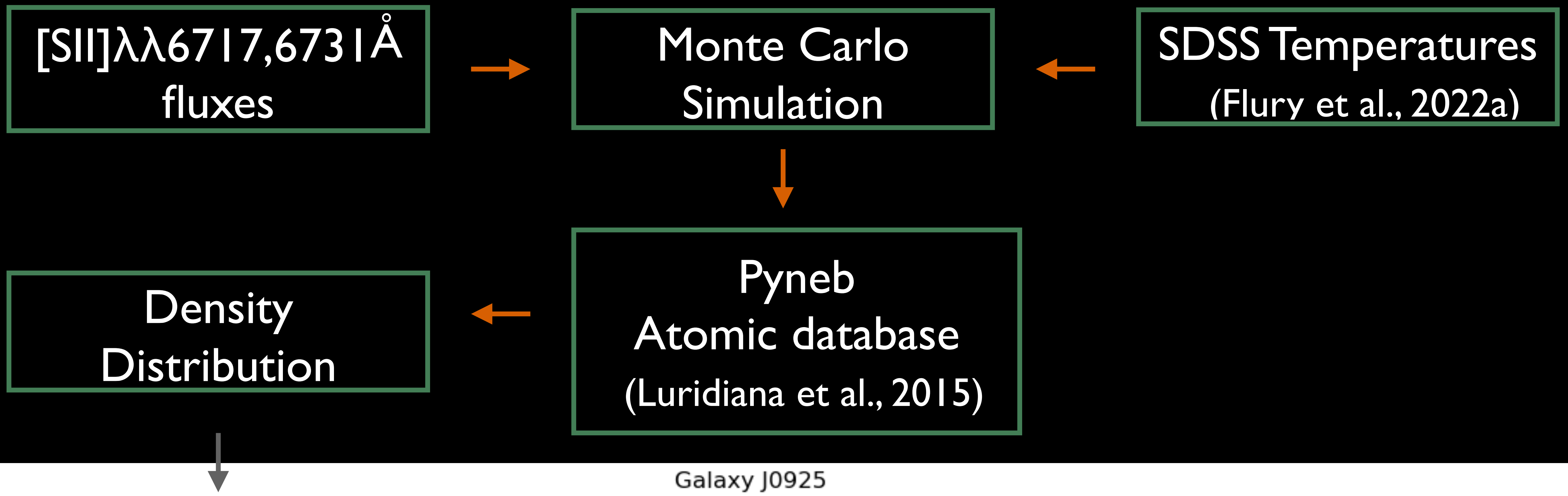
	$\sigma_{int,H\alpha-\text{Broad}}$ τ	p	$\sigma_{int,[\text{OIII}]-\text{Broad}}$ τ	p
$f_{esc}^{Ly\alpha}$	$0.263^{+0.129}_{-0.121}$	1.048×10^{-1}	$0.189^{+0.160}_{-0.143}$	2.428×10^{-1}
$\text{EW}(Ly\alpha)$	$0.200^{+0.123}_{-0.141}$	2.176×10^{-1}	$0.274^{+0.098}_{-0.114}$	9.158×10^{-2}
v_{sep}	$-0.167^{+0.167}_{-0.163}$	4.507×10^{-1}	$-0.136^{+0.143}_{-0.143}$	5.371×10^{-1}

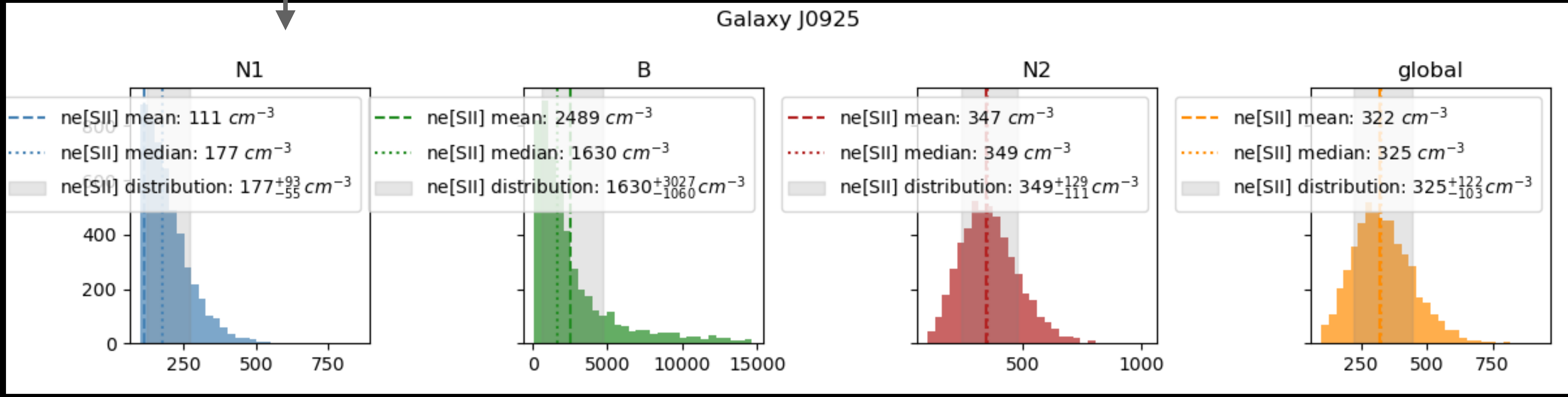
- **Weak trend with Lya Fesc and EW**
- **Stronger LCEs with broader components show shorter Lya peak separation (need more high-res Lya)**

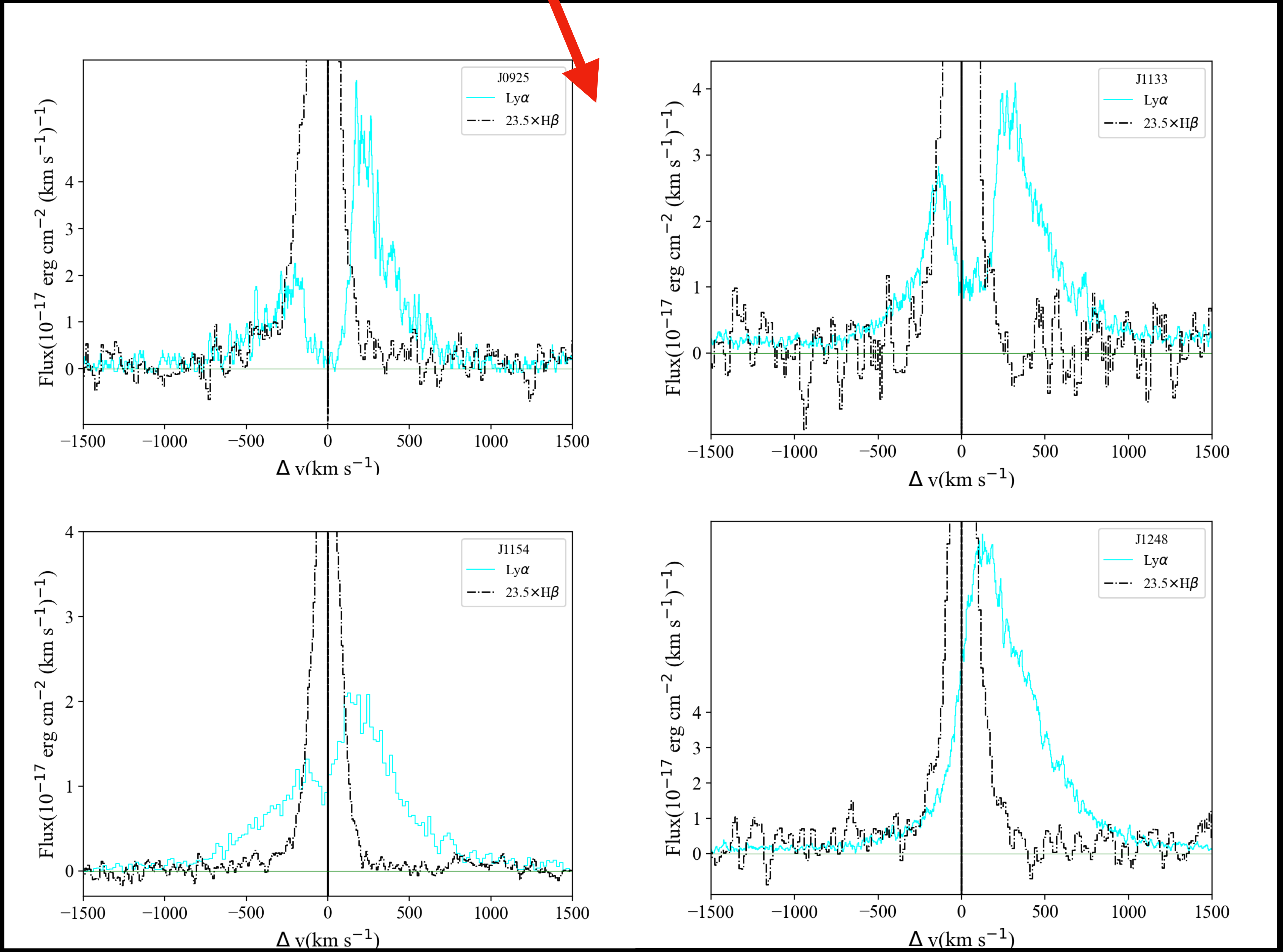
Ongoing work

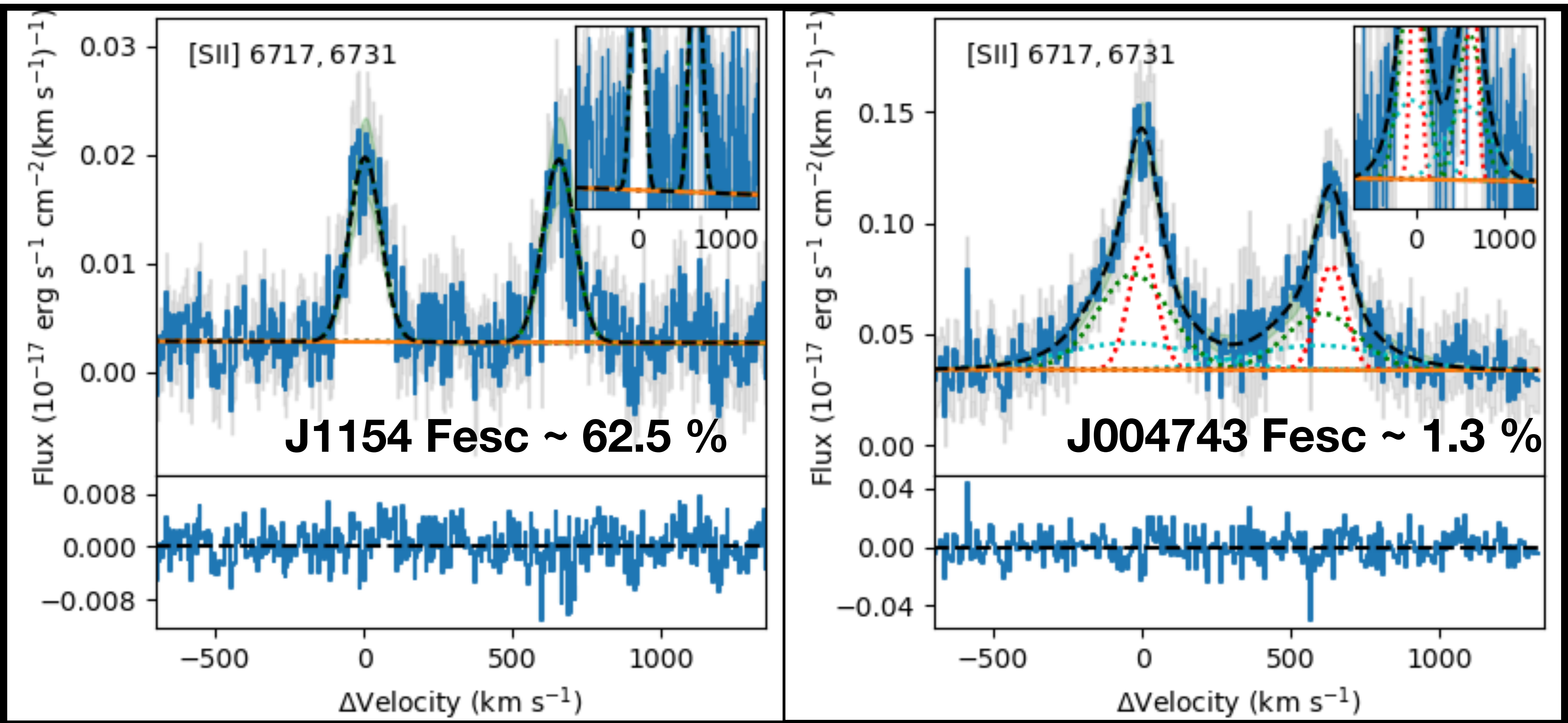
Nebular properties

Lya shapes





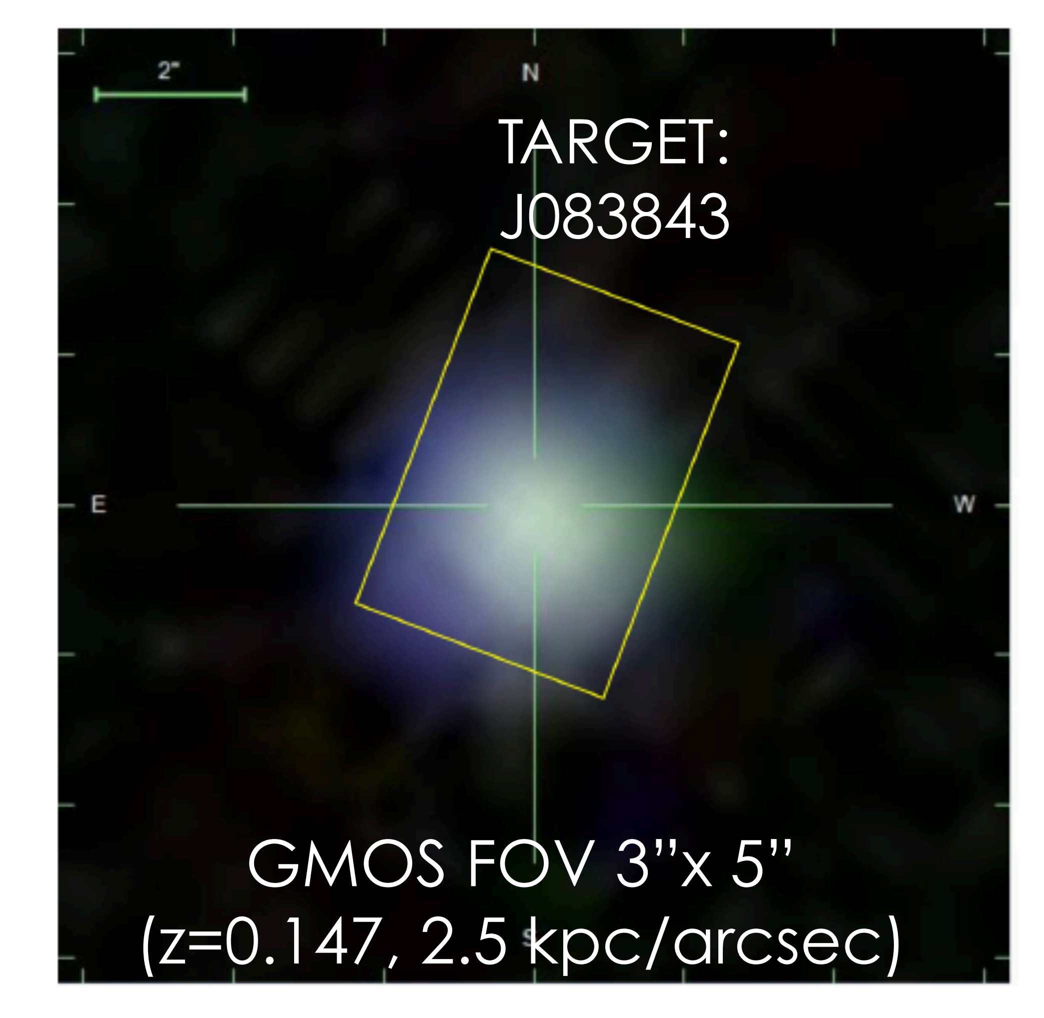




SPATIALLY RESOLVED Hα KINEMATICS OF GREEN PEAS

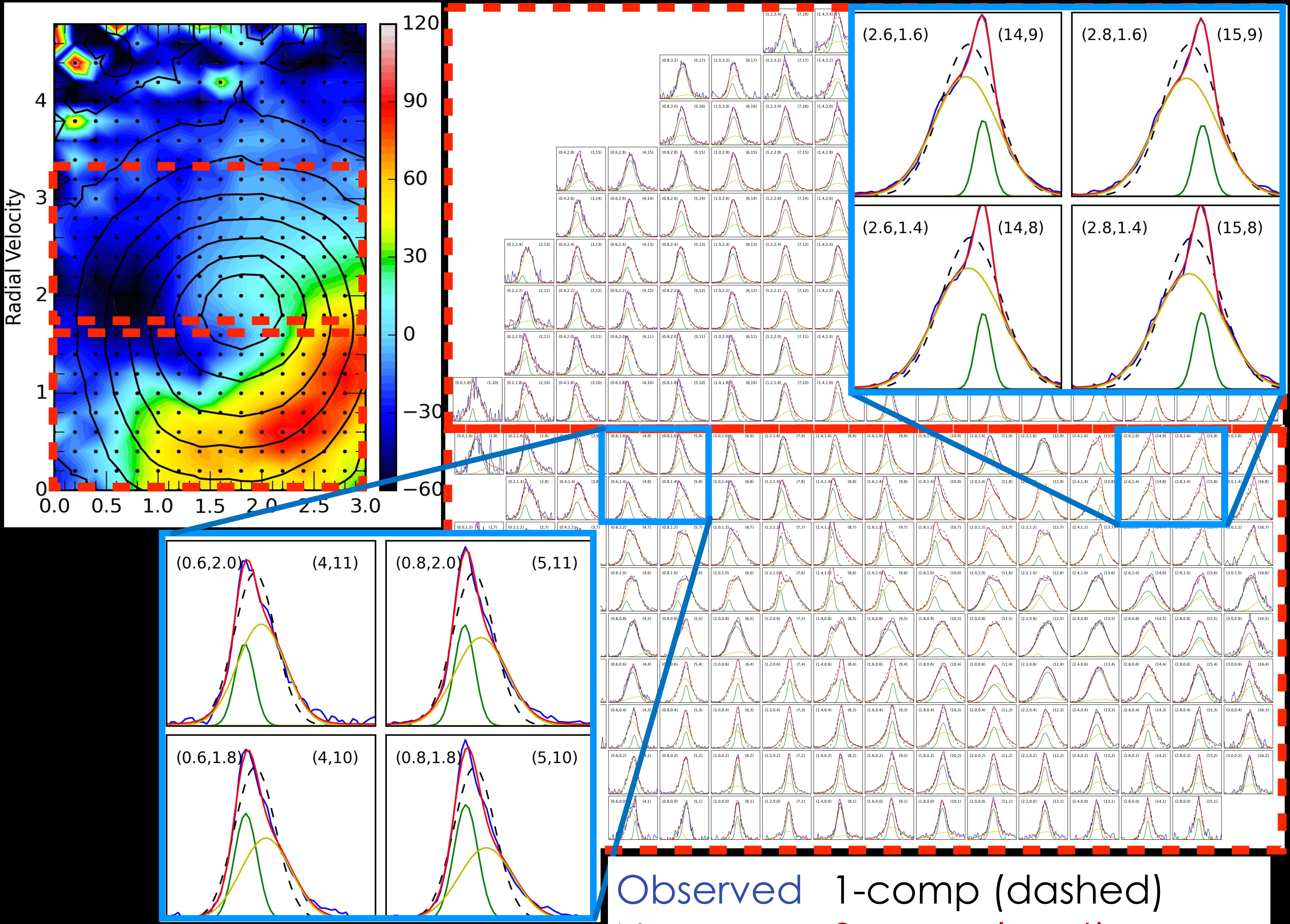
Bosch et al. (2019)

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'')



Observed 1-comp (dashed)
Narrow 2-comp (cont)
Broad

SPATIALLY RESOLVED Hα KINEMATICS OF GREEN PEAS

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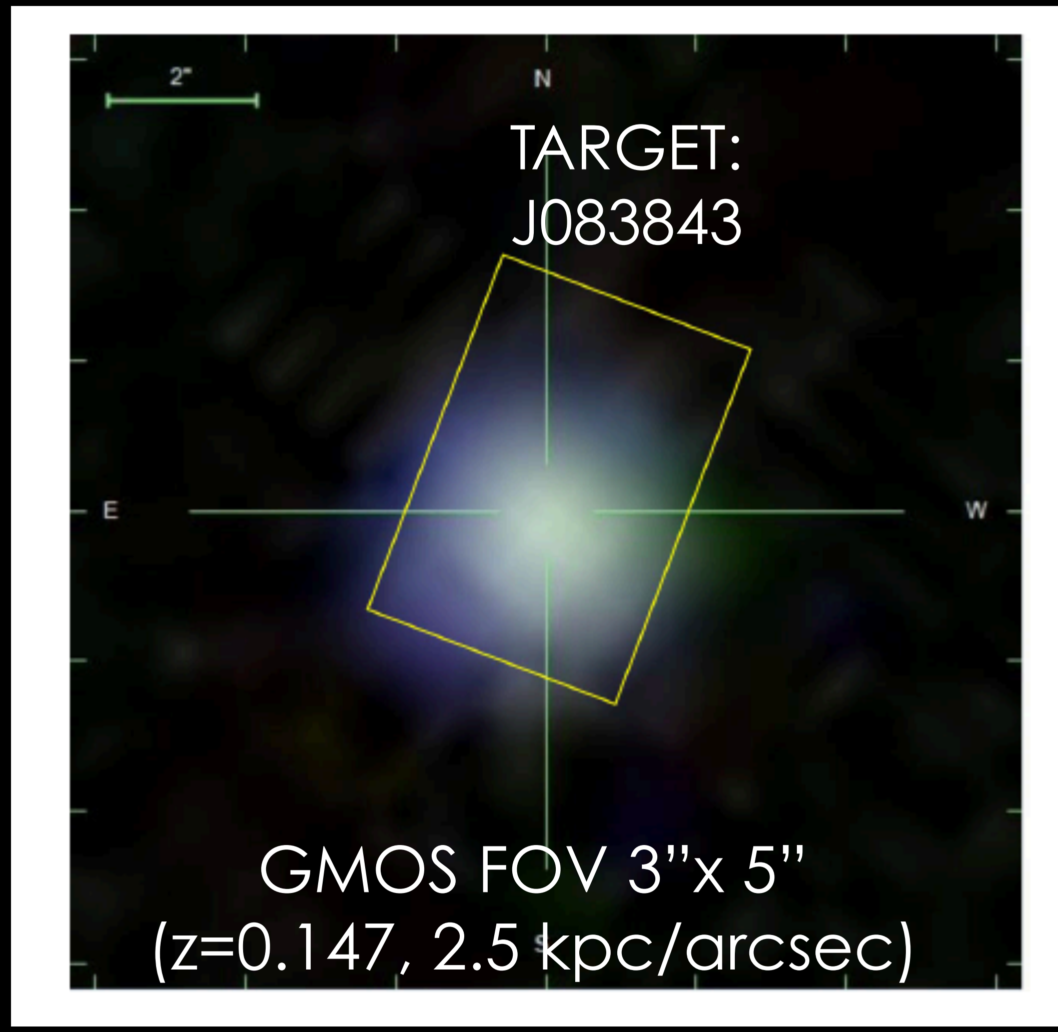

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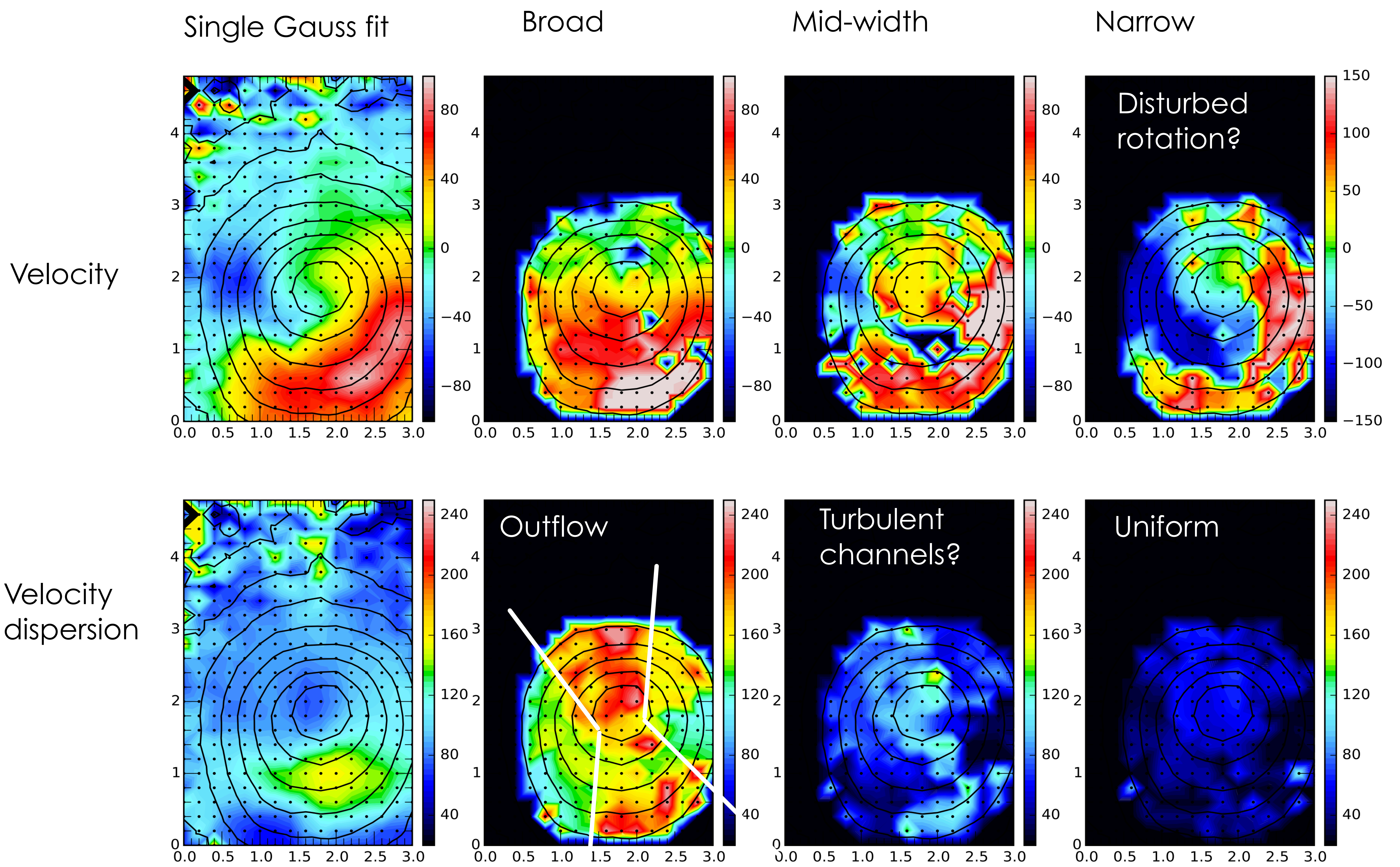
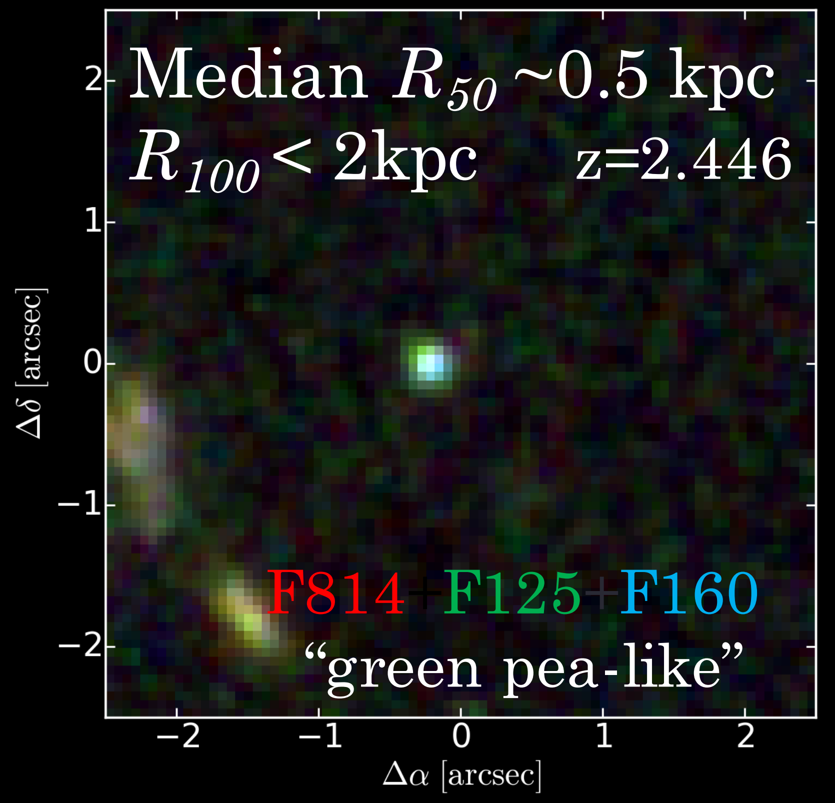


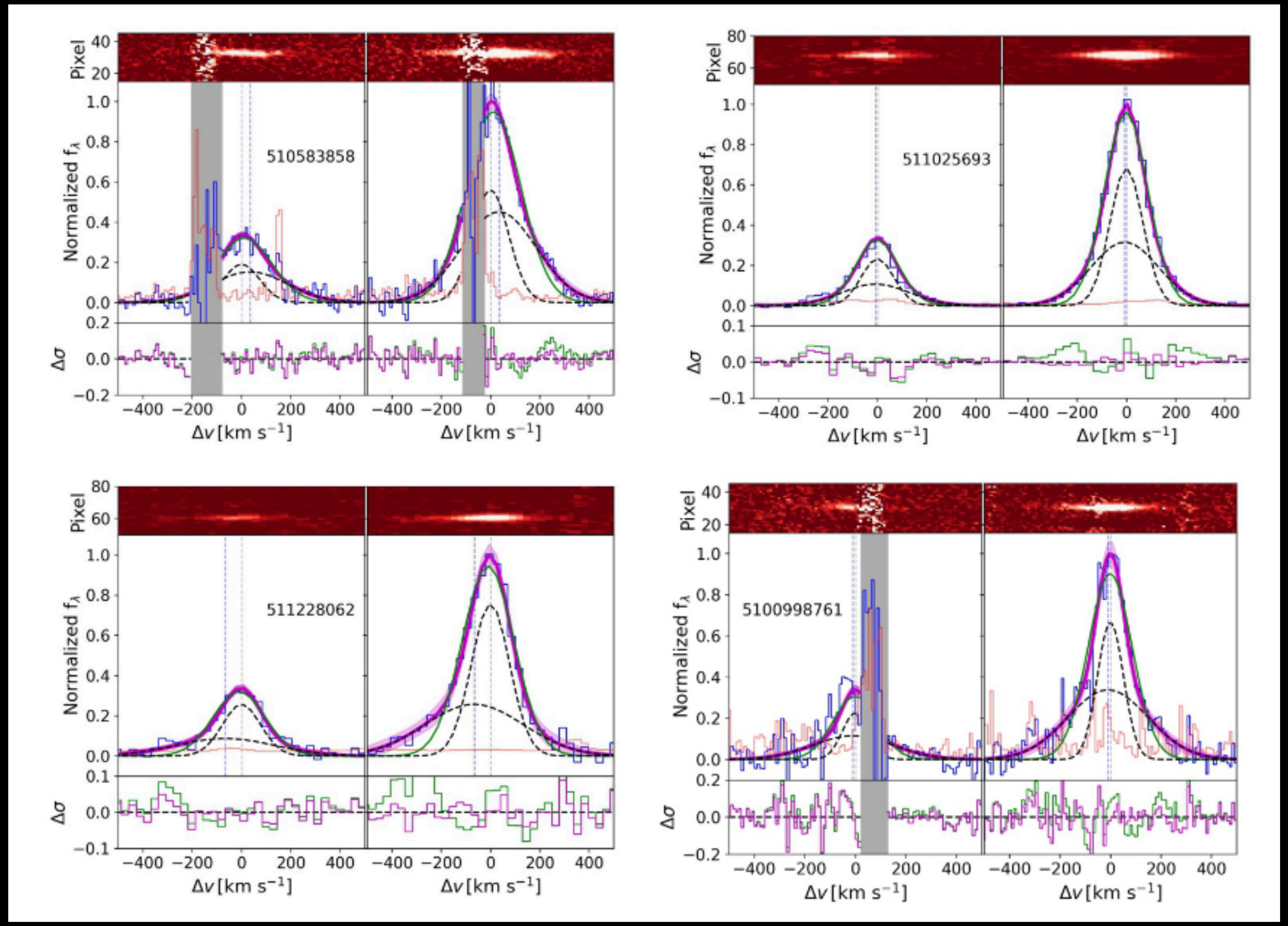
JWST/NIRSpec IFU will provide similar data for compact EELGs at high-z

BROAD EMISSION IN REIONIZATION ANALOGS AT Z~1-3



Complex line profiles and broad emission in bright z~3 LAEs in deep X-shooter and MOSFIRE spectra

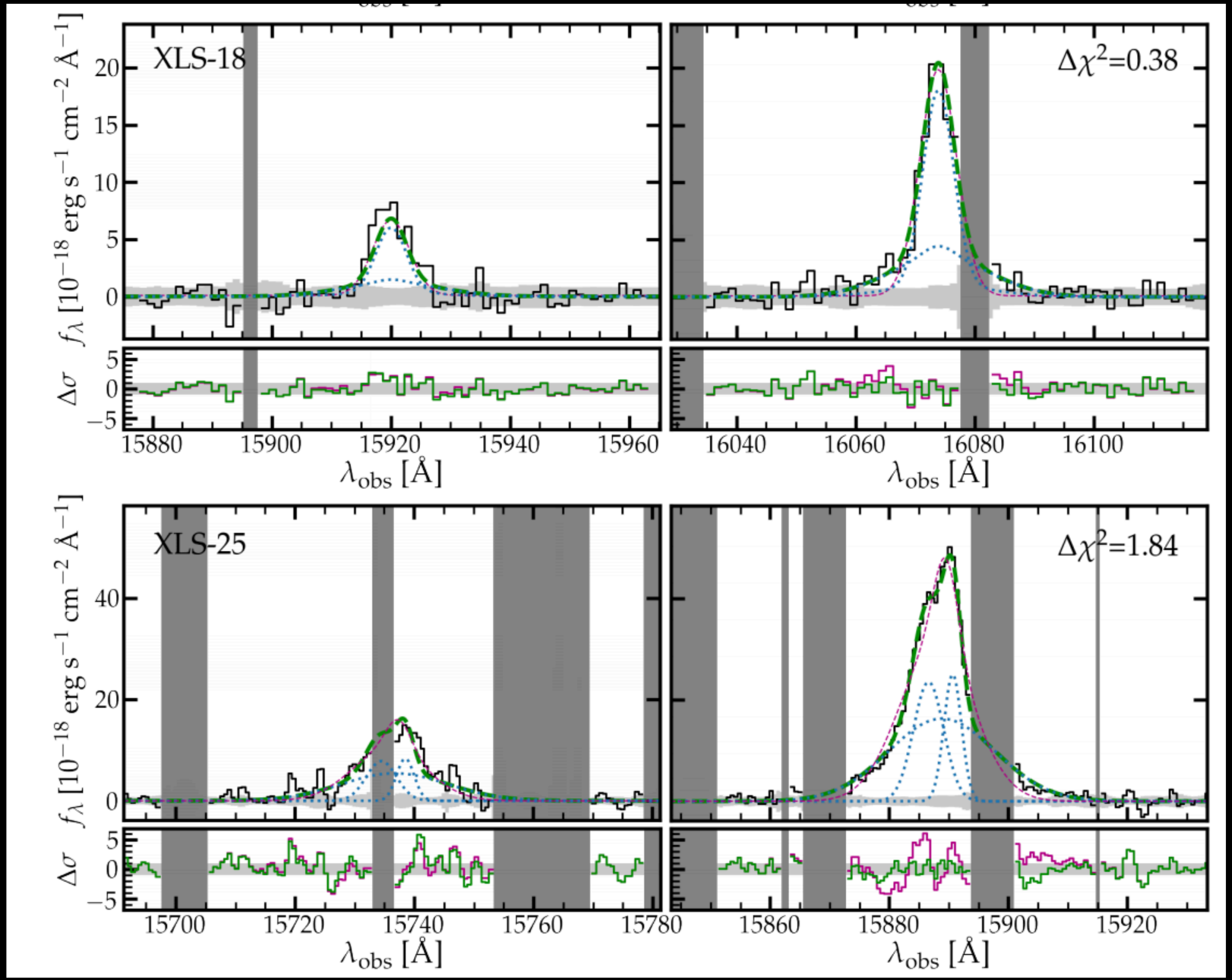
Llerena, RA+ (2023, arXiv:2303.01536)



Blue and red-shifted wings and multiple components in bright LAEs (B/Tot~20-50%)

Similar analysis is now possible with JWST

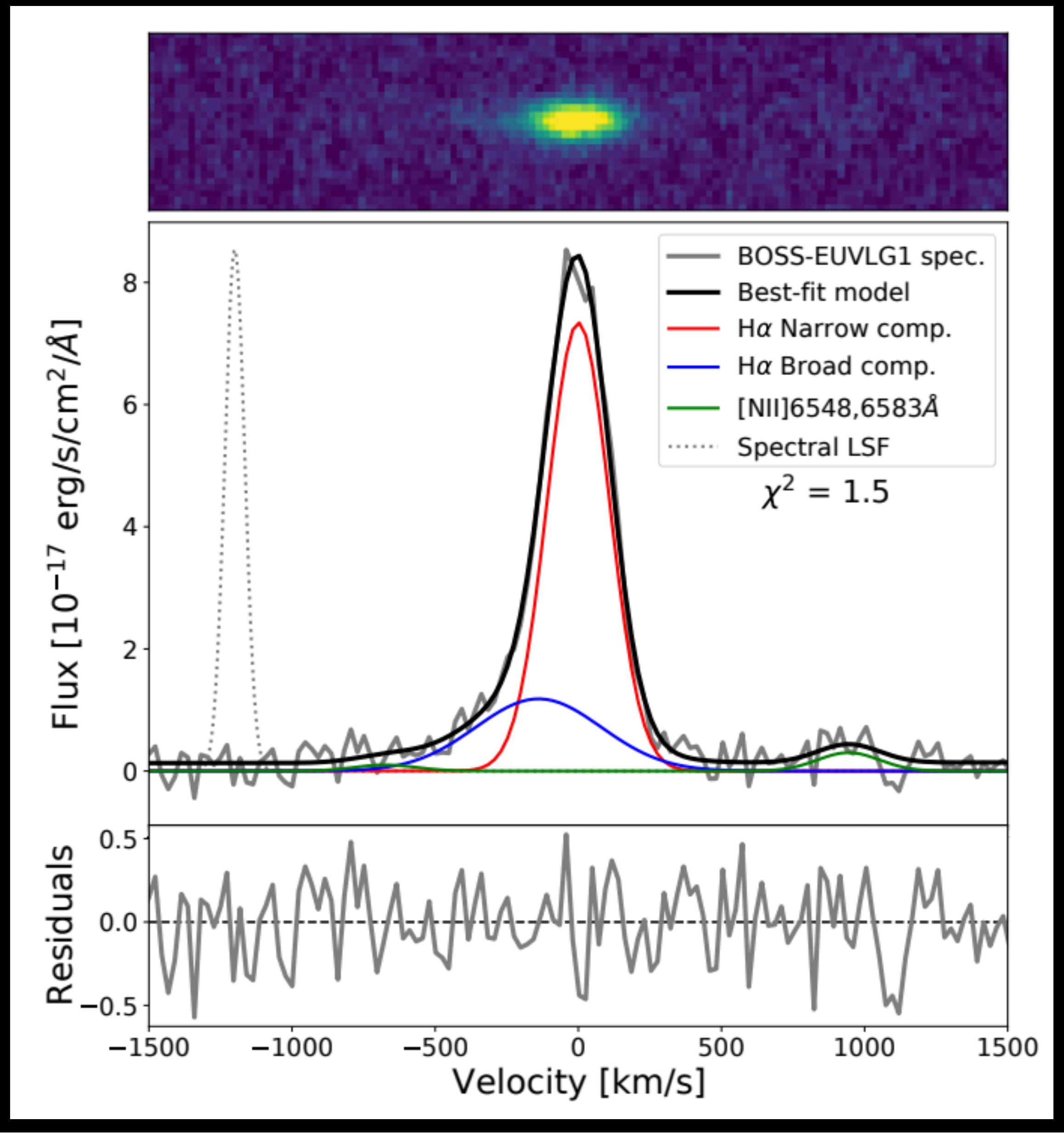
Matthee+2021



FUTURE AVENUES OF EXPLORATION

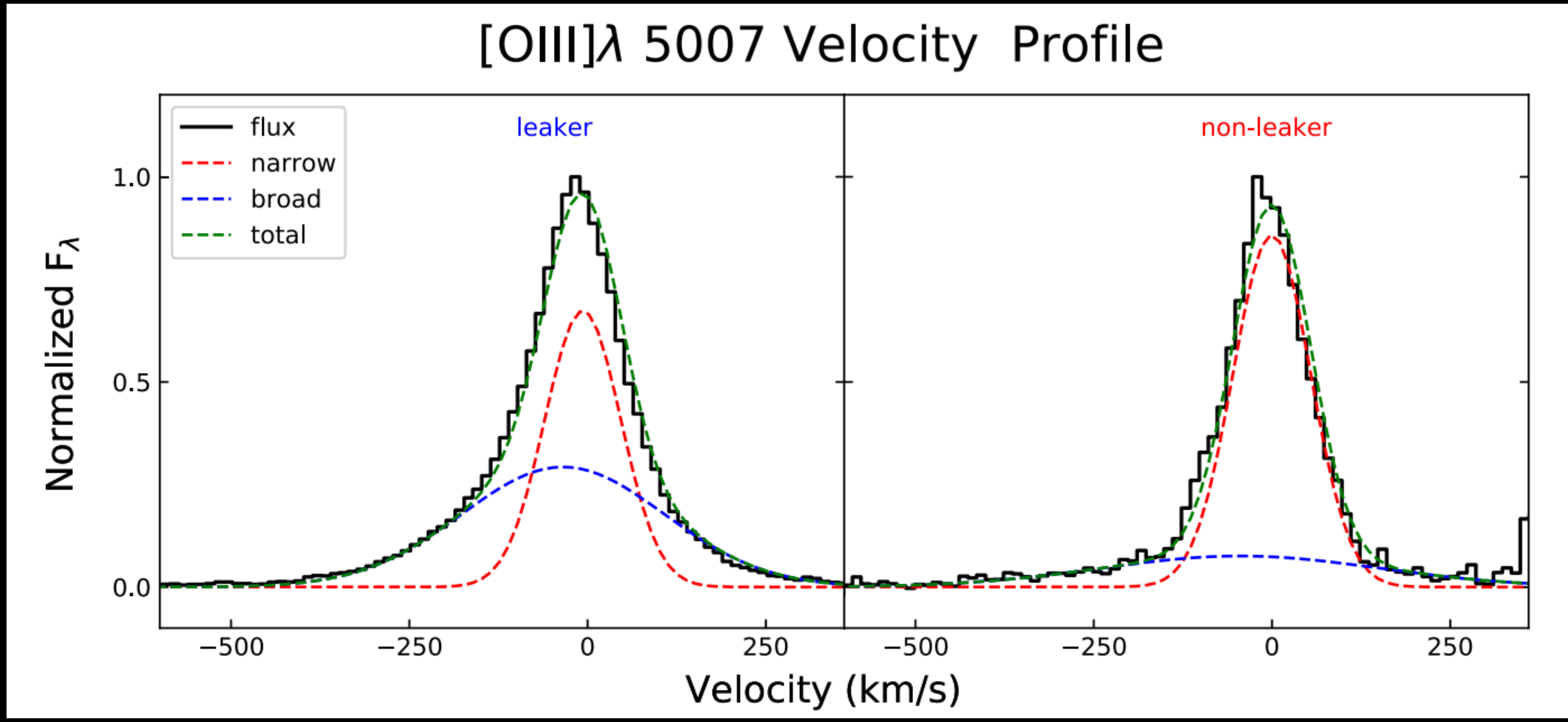
Broad emission in high-z galaxies and confirmed LCEs at z~3

Now possible for strongly magnified systems and with JWST/NIRSpec

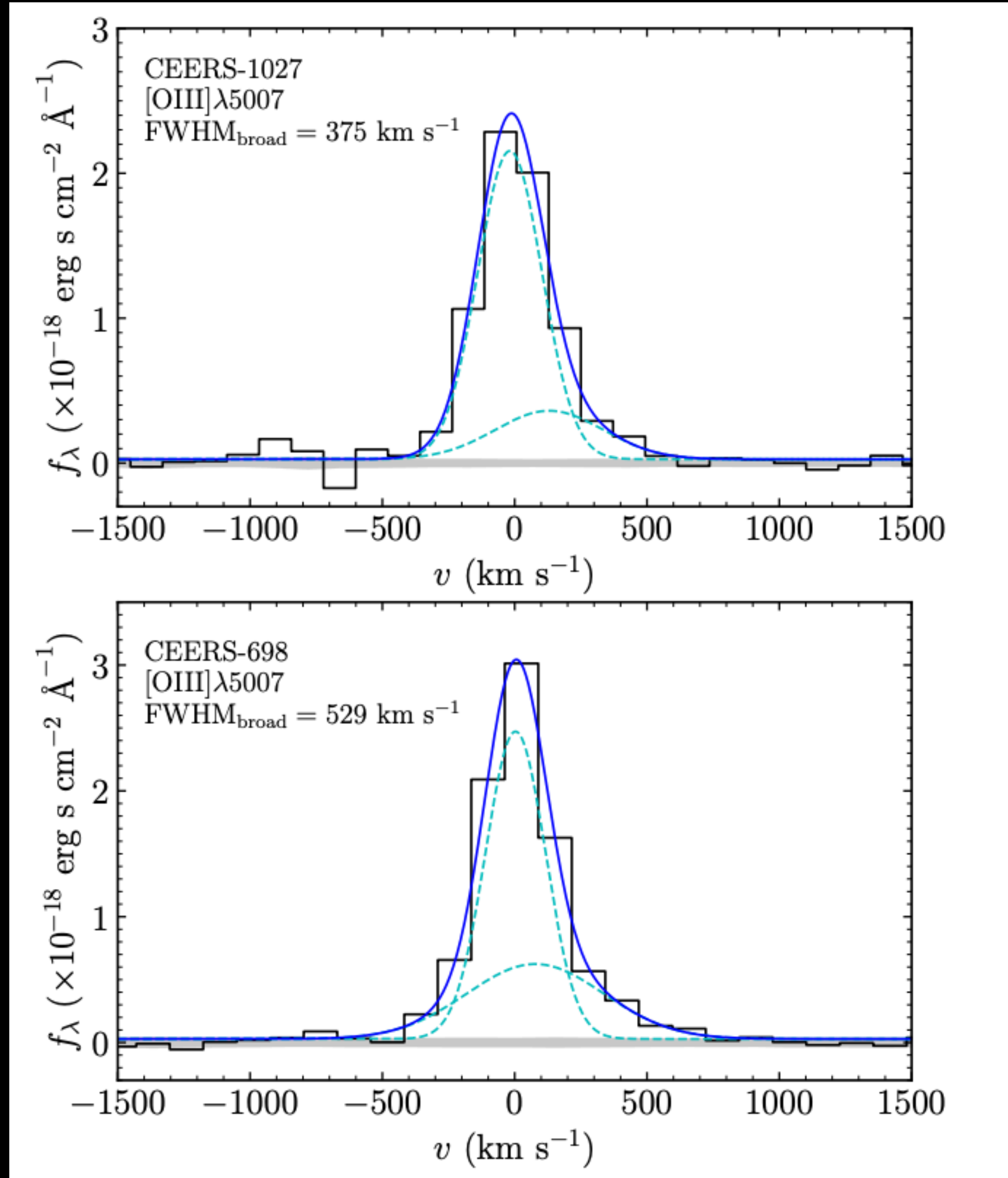


Alvarez-Marquez et al. 2021

Mainali et al. 2022 (LCO/FIRE stacked spectra) Sunburst Arc



Tang et al. 2023



(CEERS JWST/NIRSpec R1000 spectra)

Conclusions…

- Green pea galaxies have very complex ionized gas kinematics. Single gaussian fitting is insufficient so far, multicomponent or non-parametric analysis required
    - Narrow (σ_{int}~25-100km/s) + Broad (σ_{int}>100-250 km/s). Broad/Total can be as large as ~40% in strong leakers
    - Clear evidence of ubiquitous broad emission in LCEs. SF-driven feedback — Outflow
    - Ionized outflow (broad emission) in LCEs traces higher density gas likely coming from the youngest compact SF clump. Blue-shifted broad emission seem to prefer nearly face-on configuration
        - Line ratios consistent with highly photoionized gas, no need of more extreme sources (e.g.AGN)
    - Strong LCEs show more extended and heavy (B/Tot) wings (larger V_{out}) than non-leaking SFGs. Evidence of a correlation between $\sigma_{int}(\propto v_{out})$ with f_{esc}
        - We propose this as a new, complementary indirect diagnostic for LCE at higher redshift
    - Deep high-dispersion spectra with JWST could be a powerful tool for exploring the connection between kinematics and Lyman escape at z>1

And more questions for discussion…

- Is the broad emission mostly driven by radiative feedback or SNe? Both?
- What is the localized origin of the broad emission in LCE and non-LCEs? Line-of-sight/ geometric effects?
- Is the broad emission a galactic outflow in NLCEs and a more localized effect in SLCEs?
    - What are the associated resolved properties of the broad emission? (ionization, extinction, metallicity…) Requires deep high-res IFU data
    - What is the localized origin of the broad emission in LCE and non-LCEs? Is it the same place from where the LyC photons come from? —> Sunburst LCE say yes
- Can we connect the ionized gas kinematics with the Lya shapes we observe in LCEs?

THANK YOU !!


Sunset in La Serena