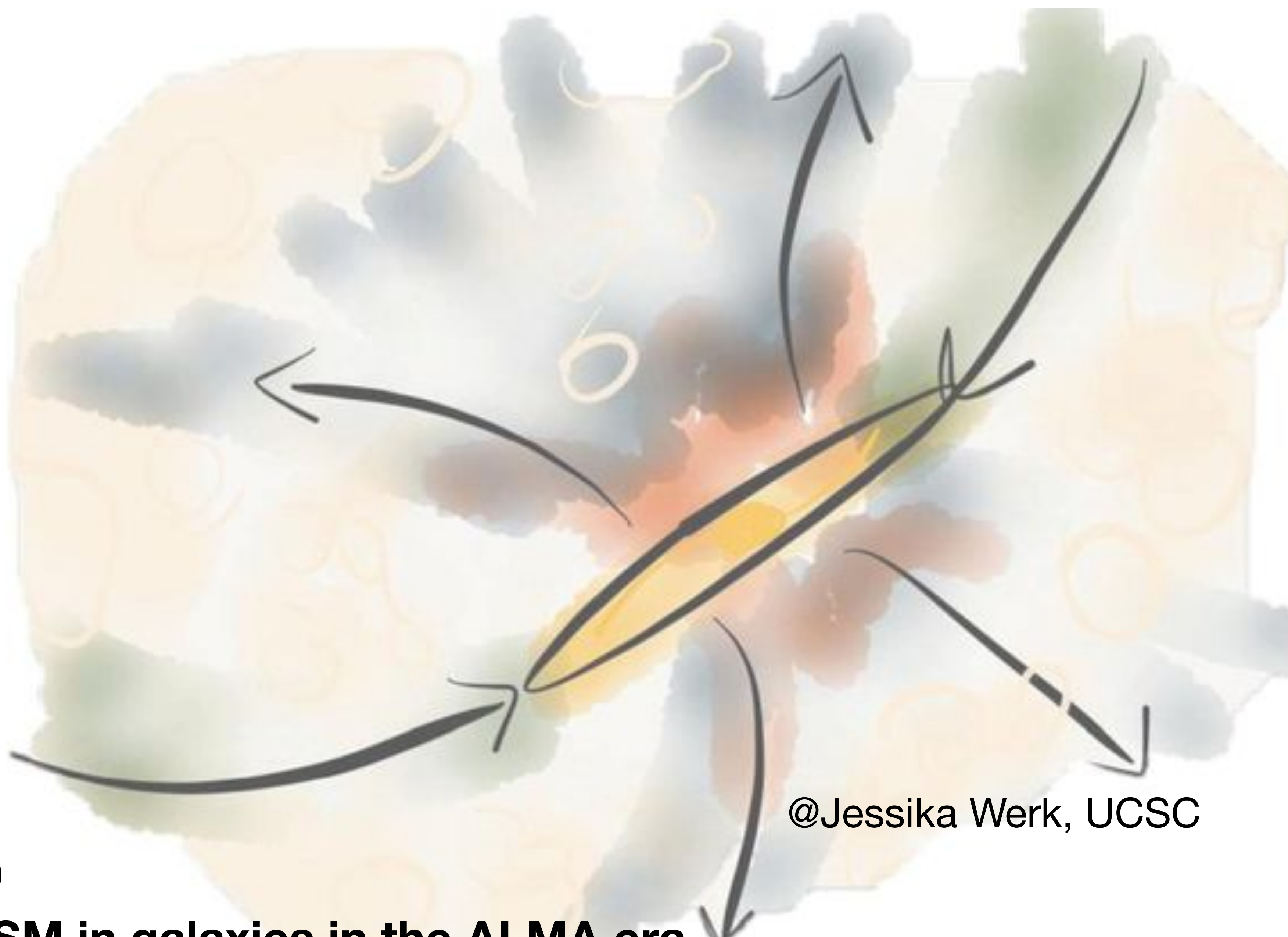
Star formation-driven outflows and circumgalactic enrichment in the early Universe

Michele Ginolfi + ALPINE

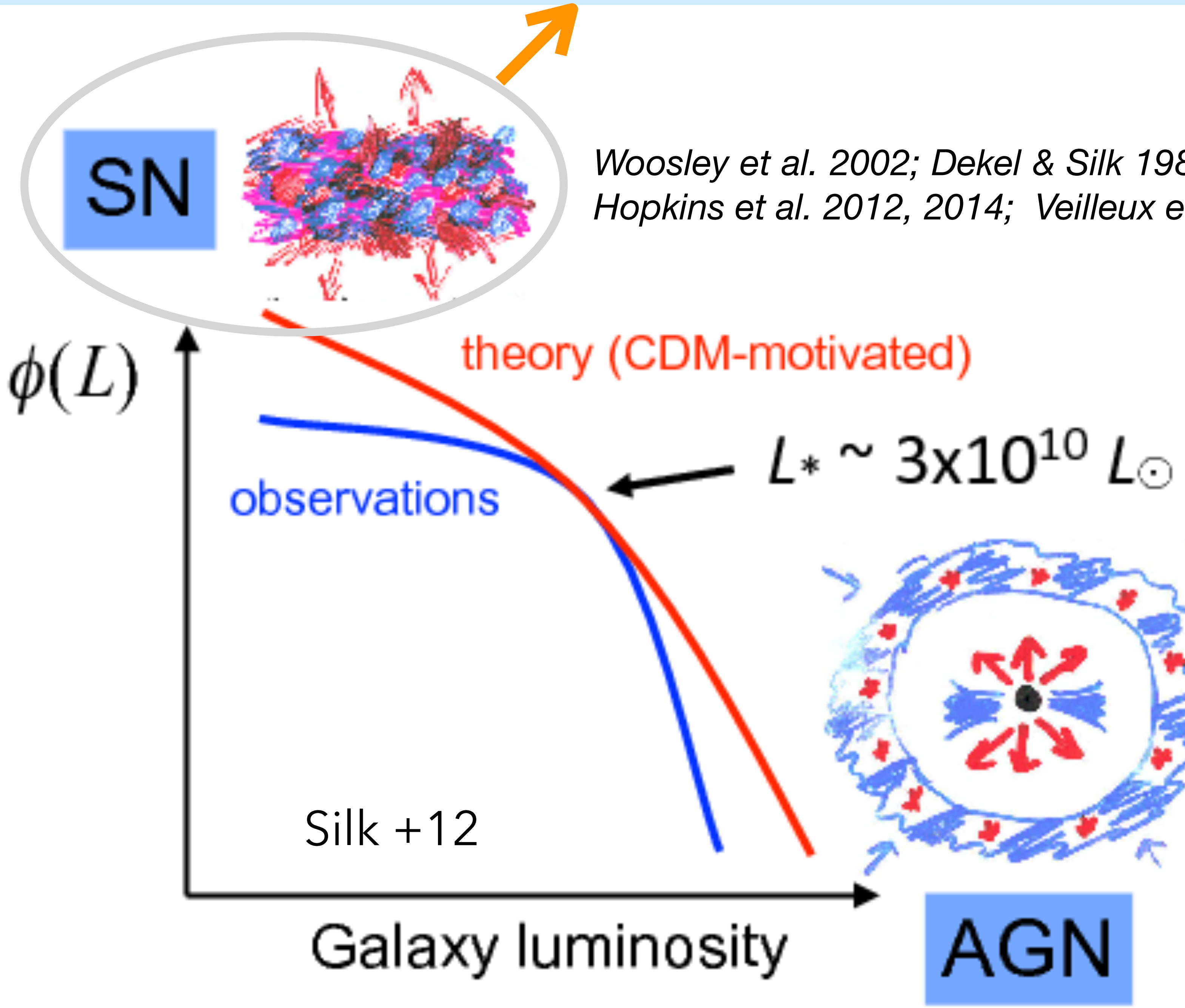


@Jessika Werk, UCSC

ALMABO 2019
Views on the ISM in galaxies in the ALMA era

Massive stars (>8 $M_\odot$) emit copious high-energy photons during their lifetimes, injecting large amounts of energy and momentum in the surrounding gas during SN explosions, in the final stage of their evolution.

Intense episodes of star formation induce powerful SN-driven winds, that can efficiently accelerate the gas to hundreds of km/s.



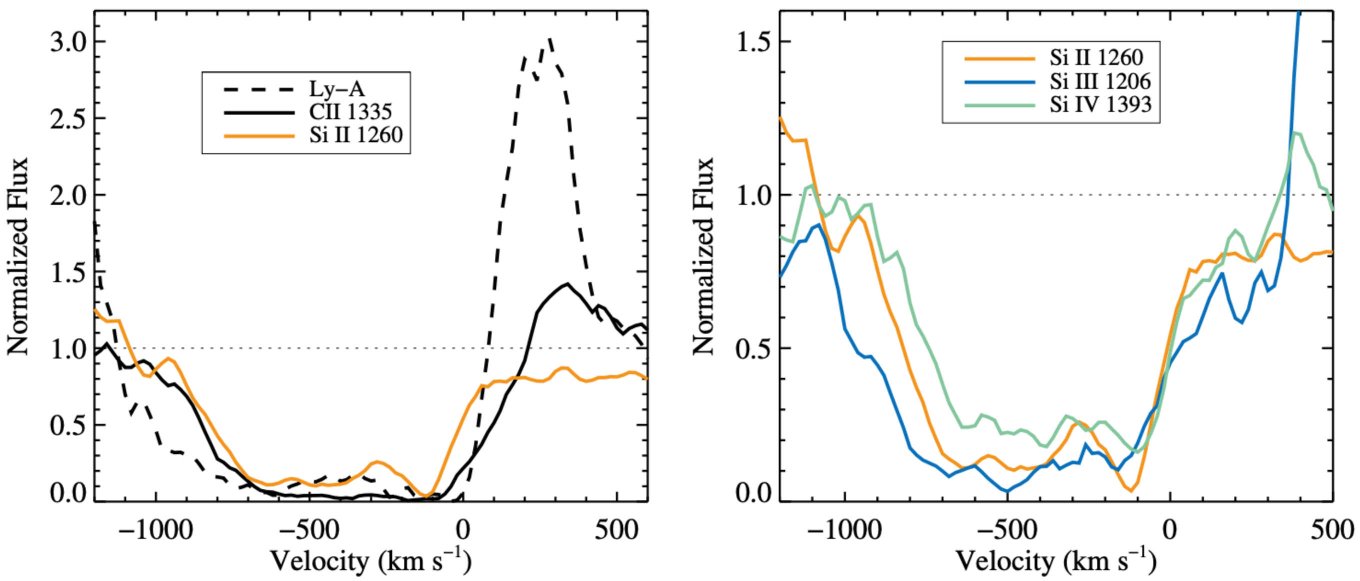
Woosley et al. 2002; Dekel & Silk 1986; Mac Low & Ferrara 1999; Hopkins et al. 2012, 2014; Veilleux et al. 2005; Erb 2015

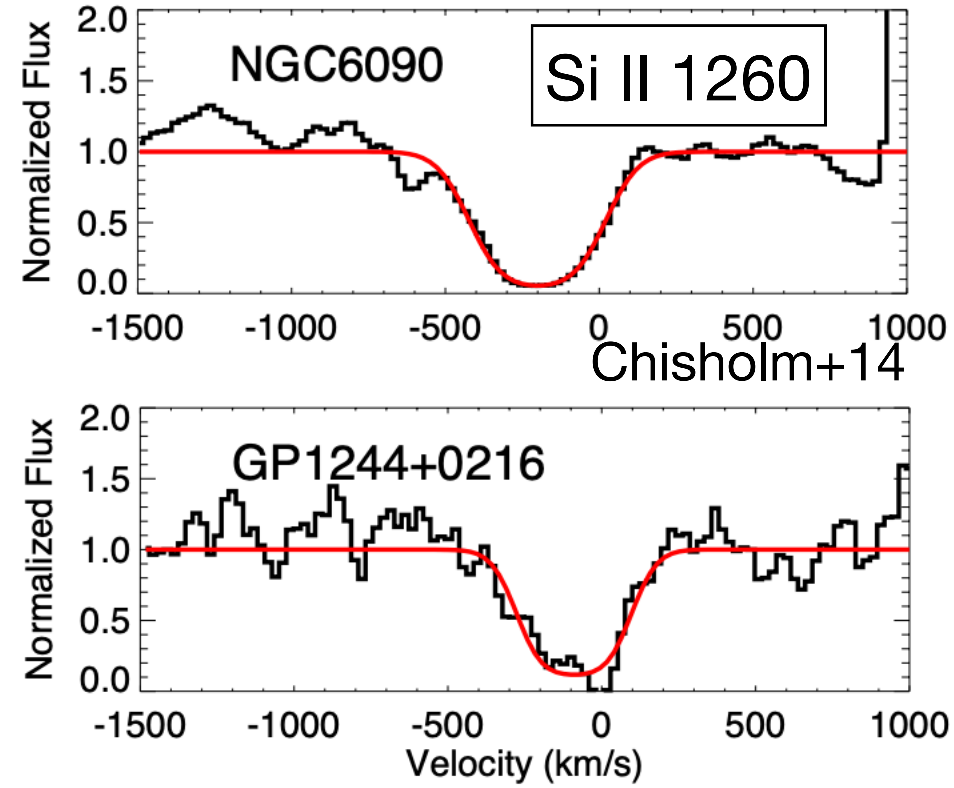
Benson et al. 2003; Silk & Mamon 2012; Behroozi et al. 2013; Bower et al. 2006; Cattaneo et al. 2009; Fabian 2012; Dekel & Silk 1986; Heckman et al. 1990; Hopkins et al 14….

Absorption Line Spectroscopy

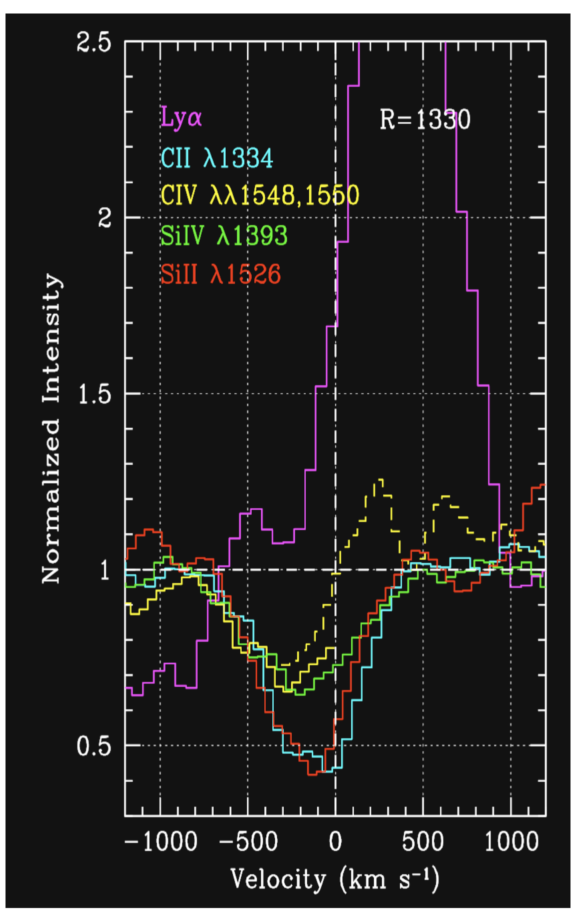
A remunerative method to trace the kinematics of cold and warm outflowing gas consists in measuring the blueshift of **metal absorption lines in the rest-frame UV and optical bands**, respect to the systemic redshift (usually measured through strong optical emission lines).

Wood+15 HST/COS - NGC7552





Chisholm+14



Steidel+10;
Composite spectrum at z~3

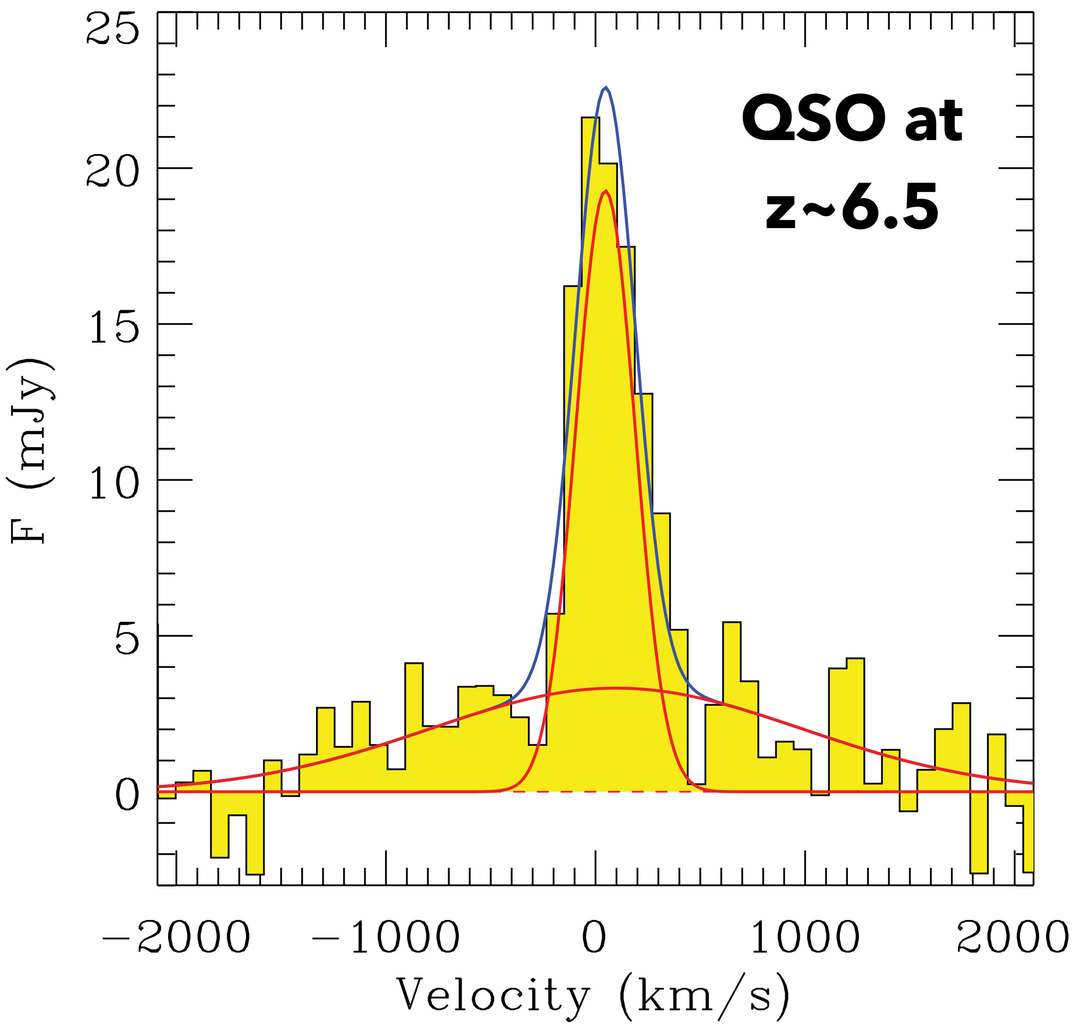
At z>3-4, detecting outflows through absorption line spectroscopy becomes challenging:

(i) increasingly weaker metal absorption features;

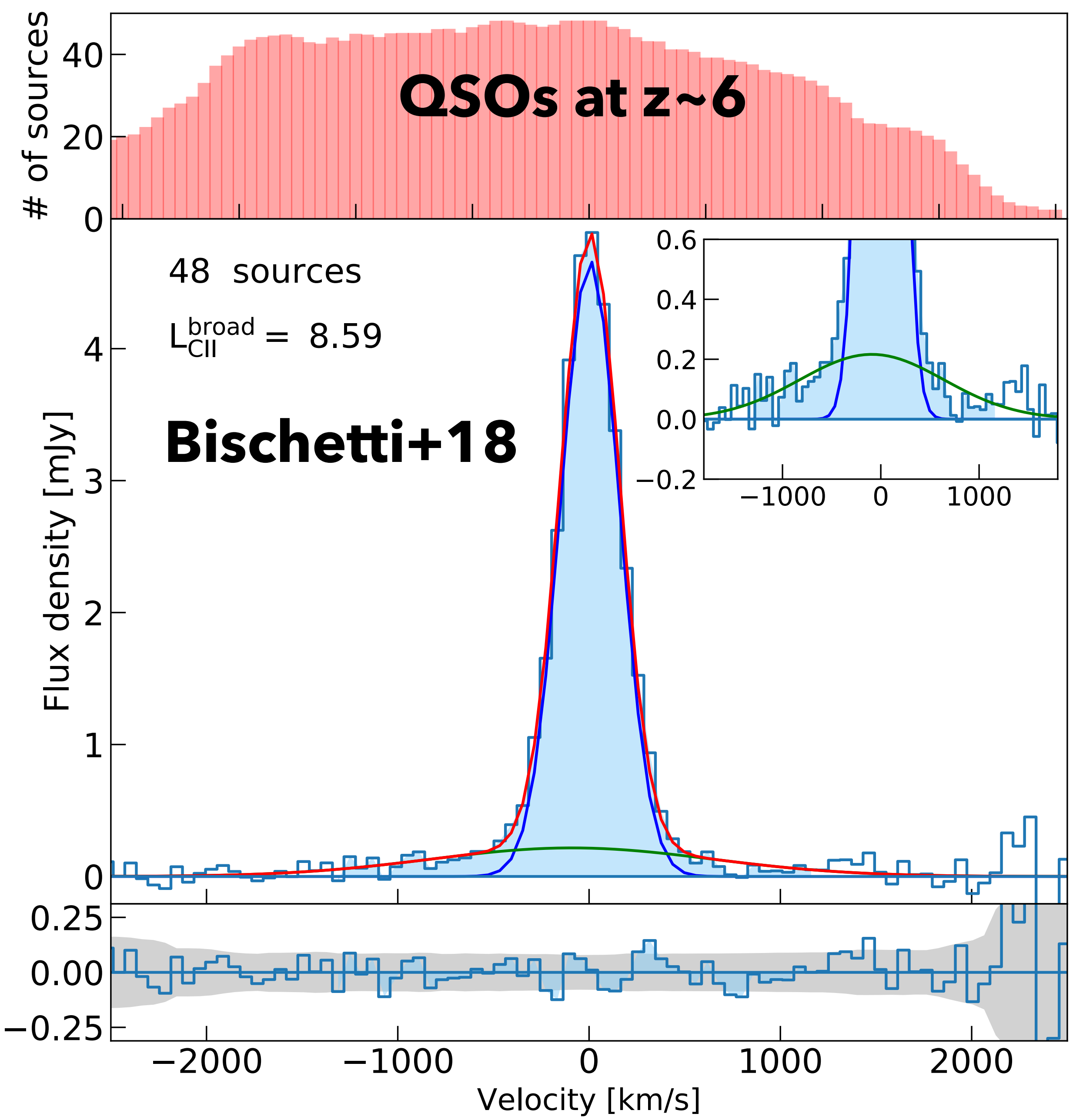
(ii) large uncertainties on the systemic redshifts, which most of the time rely on Lyα.

Arribas et al. 2014; Chisholm et al. 2015; 2016, 2017; Cicone et al. 2016; Shapley et al. 2003; Steidel et al. 2004, 2010; Rubin et al., 2014; Heckman et al. 2015; Sugahara et al. 2019….

An alternative method to rest-frame FUV absorption line spectroscopy consists in studying the broad wings in the high-velocity tails of FIR-line spectra (e.g. the brightest is [C II] 158 μm), similarly to what is commonly done for luminous AGN-driven outflows.



Maiolino+12



Maiolino et al. 2012; Gallerani et al. 2014; Carniani et al. 2017; Feruglio et al. 2018; Decarli et al. 2018; Gallerani et al. 2018; Bischetti et al. 2018; Carniani et al. 2019…

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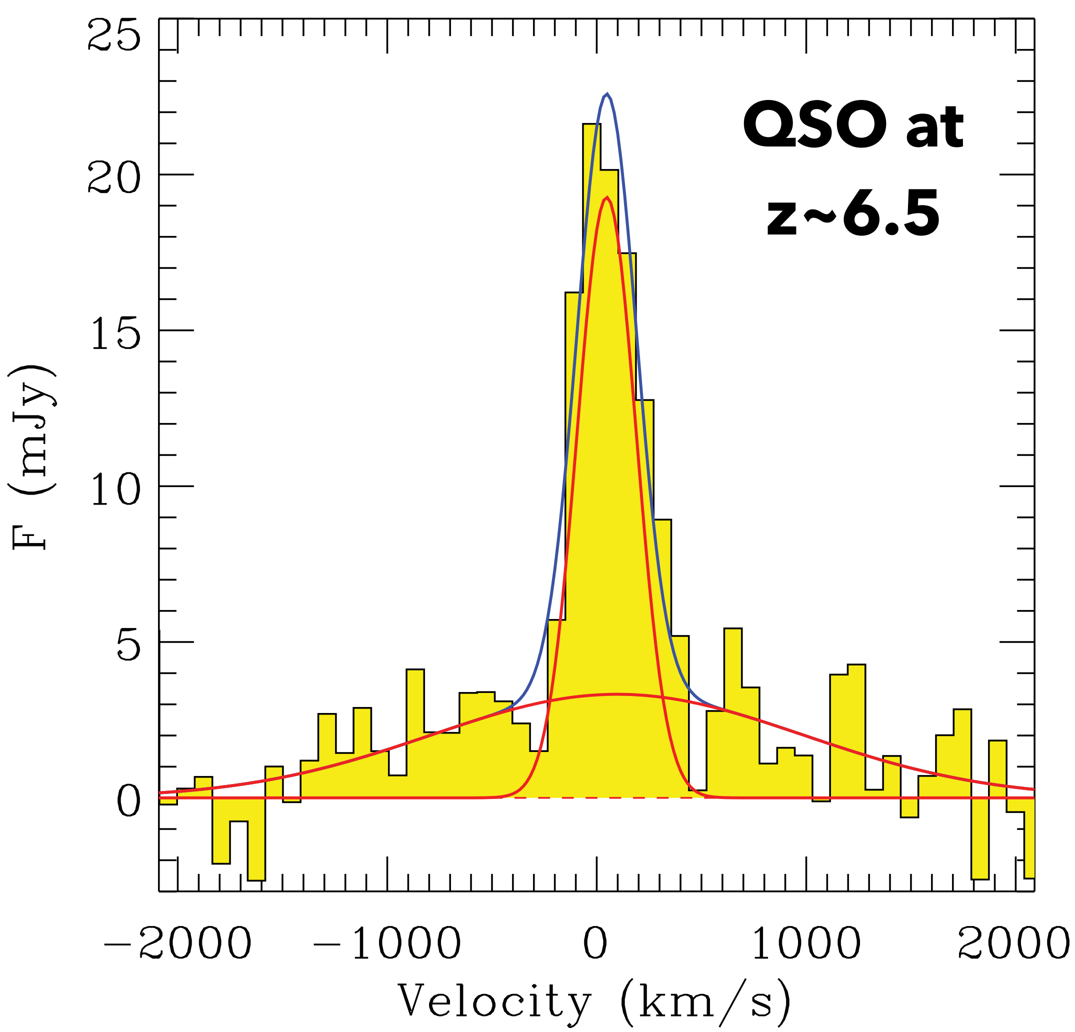
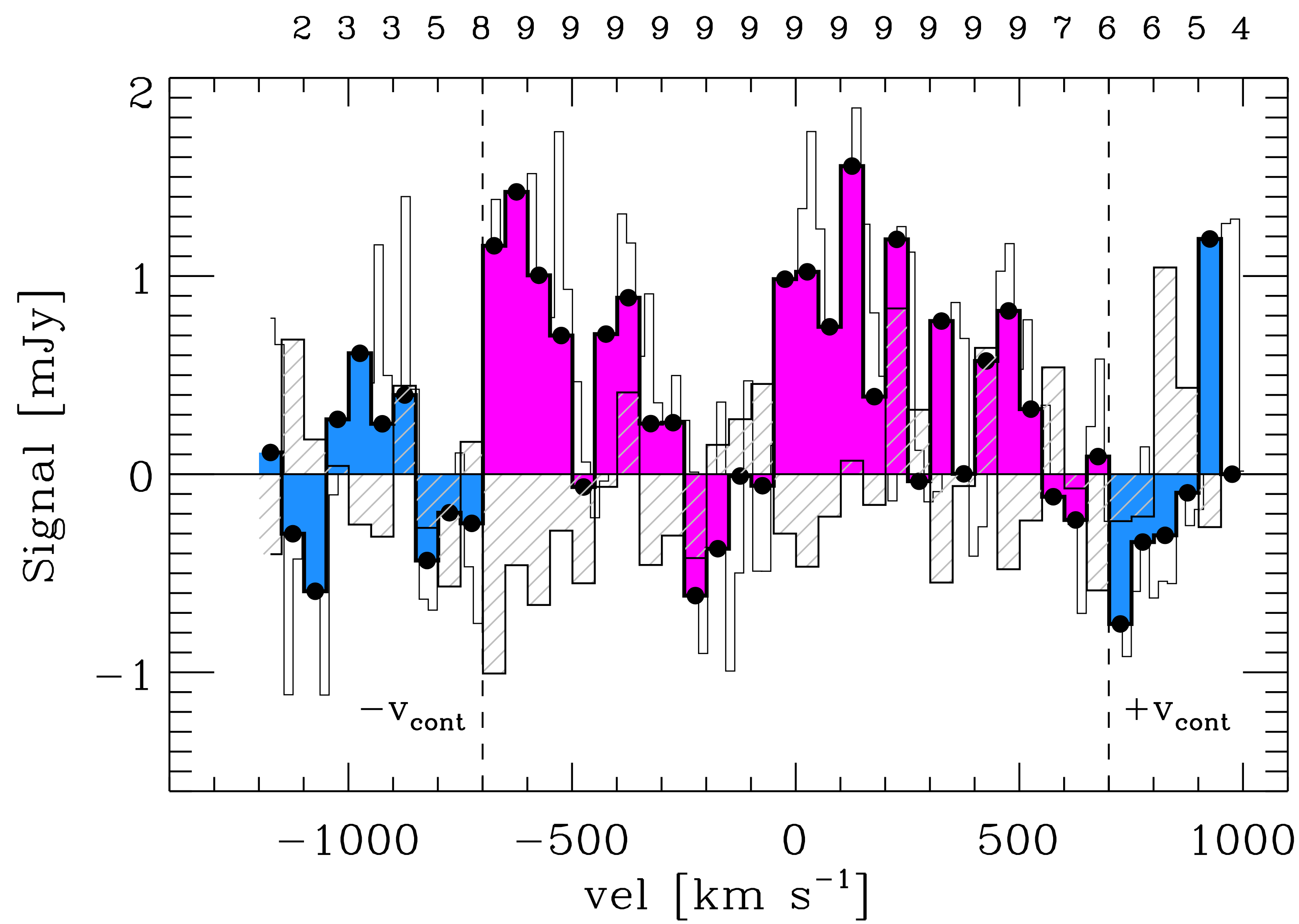


Maiolino+12

<10 normal galaxies at z~5



Gallerani+18

Maiolino et al. 2012; Gallerani et al. 2014; Carniani et al. 2017; Feruglio et al. 2018; Decarli et al. 2018; Bischetti et al. 2018; Gallerani et al. 2018; Carniani et al. 2019…

A2C2S | ALMA ALPINE [CII] Survey

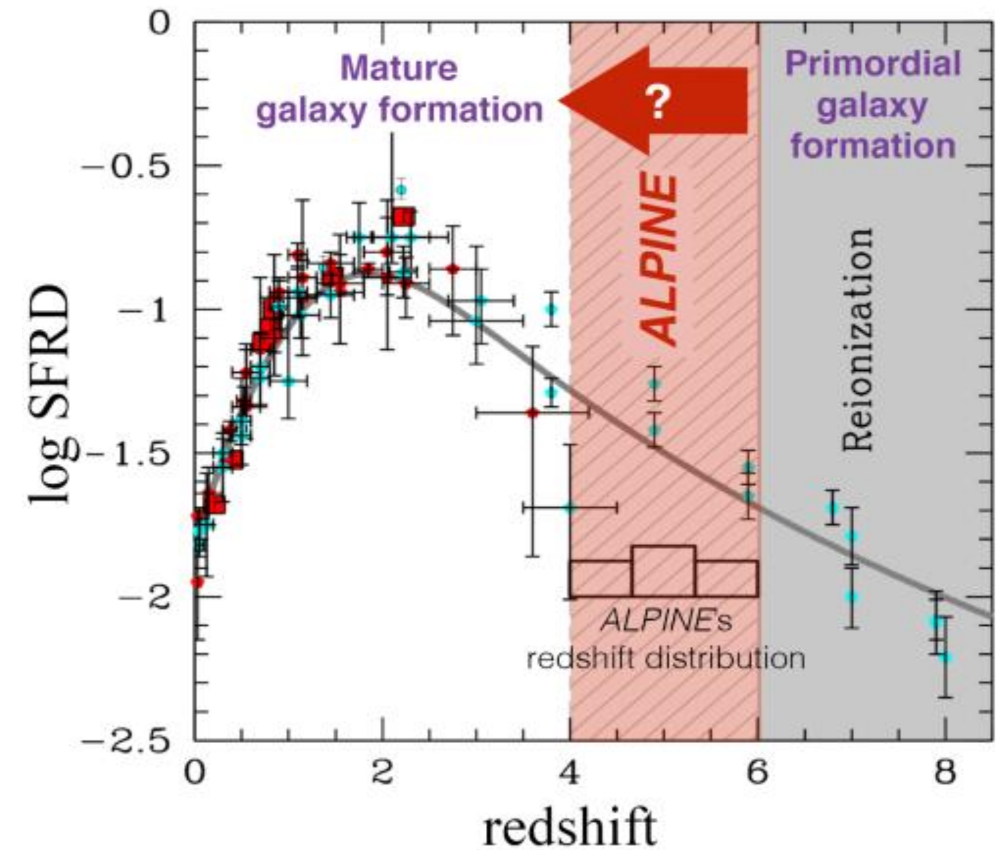
PI: O. Le Fevre; co-PI: M. Bethermin, P. Capak, S. Schaerer, A. Faisst, P. Cassata, L. Yan, J. Silverman + >30 co-Is

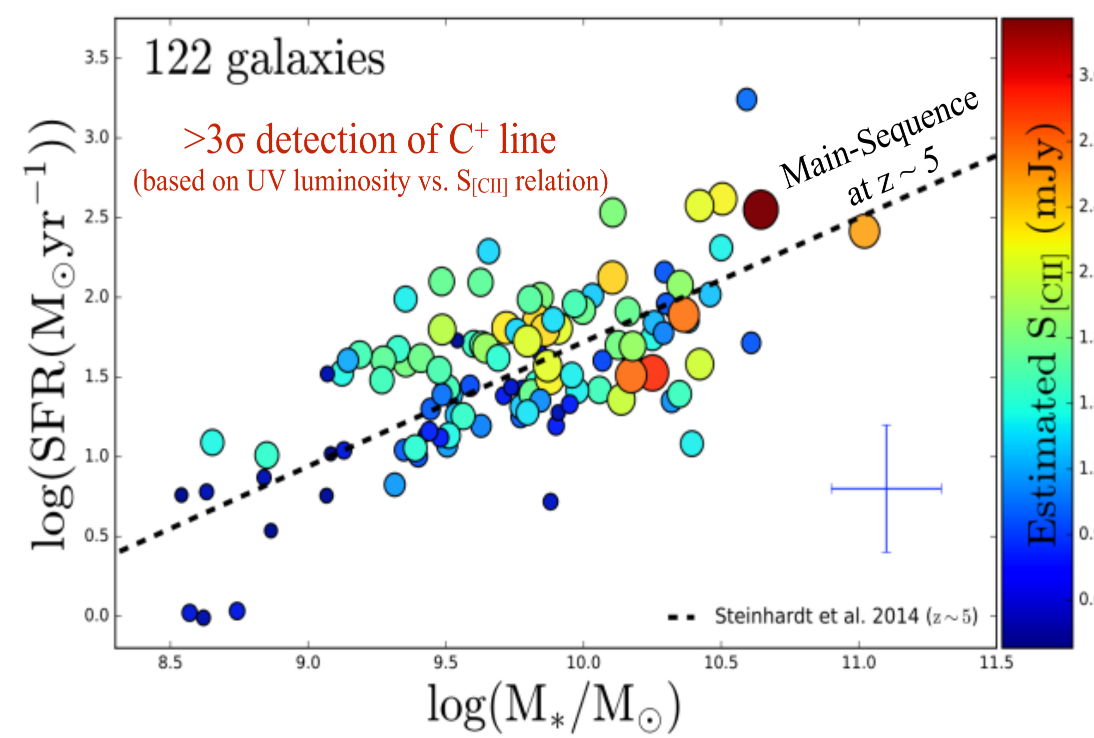
...many ALPINErs are in this room :-)

[CII] and FIR continuum emission for a representative sample of **118** main sequence star-forming galaxies at **4 < z < 6**, with **SFR > 10 M_{sun}/yr** and stellar mass **~9 < log(M_{star}) < ~11**.

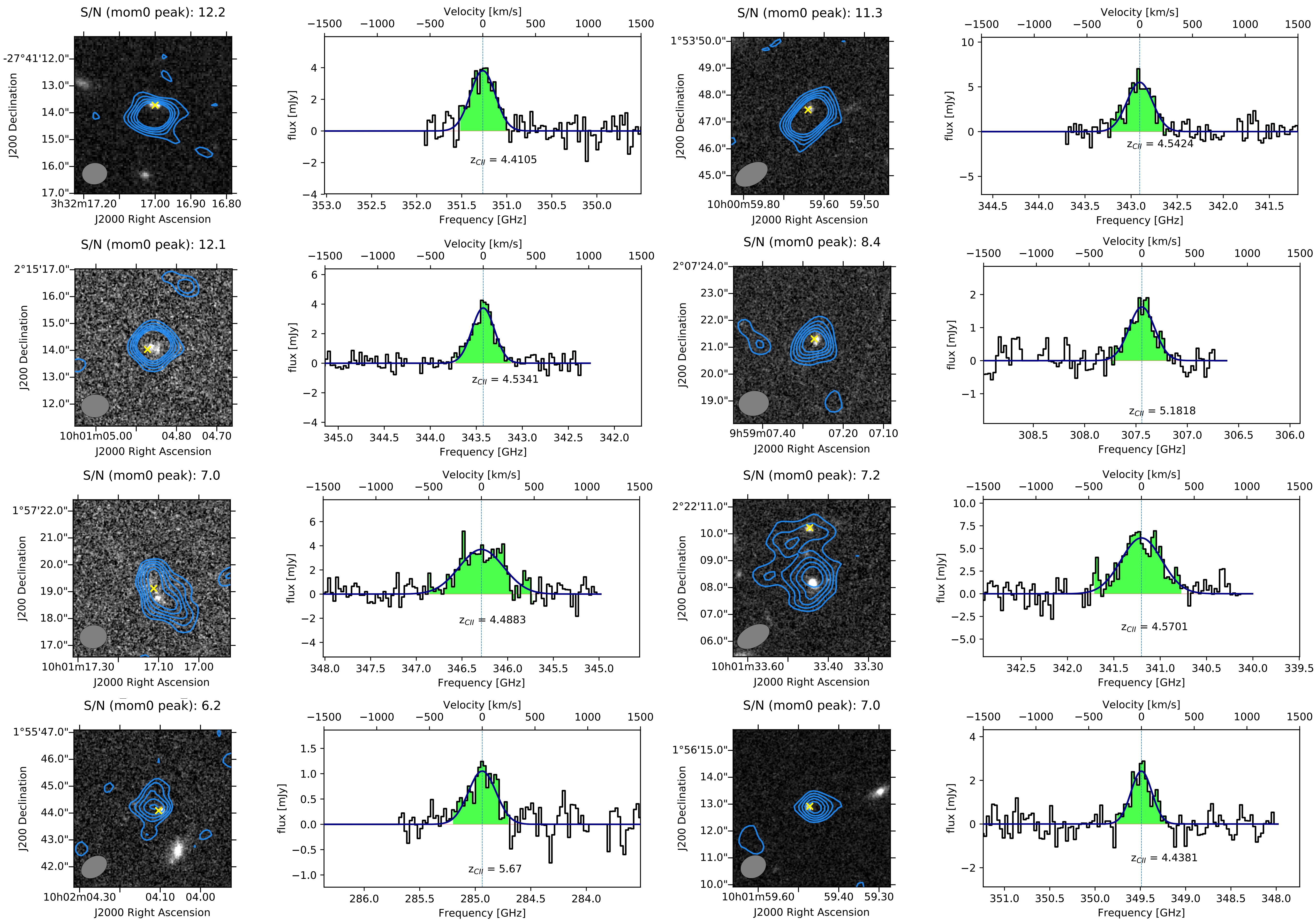
(some) key questions:

- **SFRD at z~4-6 from UV+FIR and [CII];**
- **[CII] - SFR relation at z > 4;**
- **kinematics at z~4-6;**
- **redshift evolution of gas fraction;**
- **SF-driven outflows;**
- **environment & interactions… merger rates;**
- **dust attenuation in the early Universe;**
- **UV / CII / IR offsets;**
- **… many other things.**

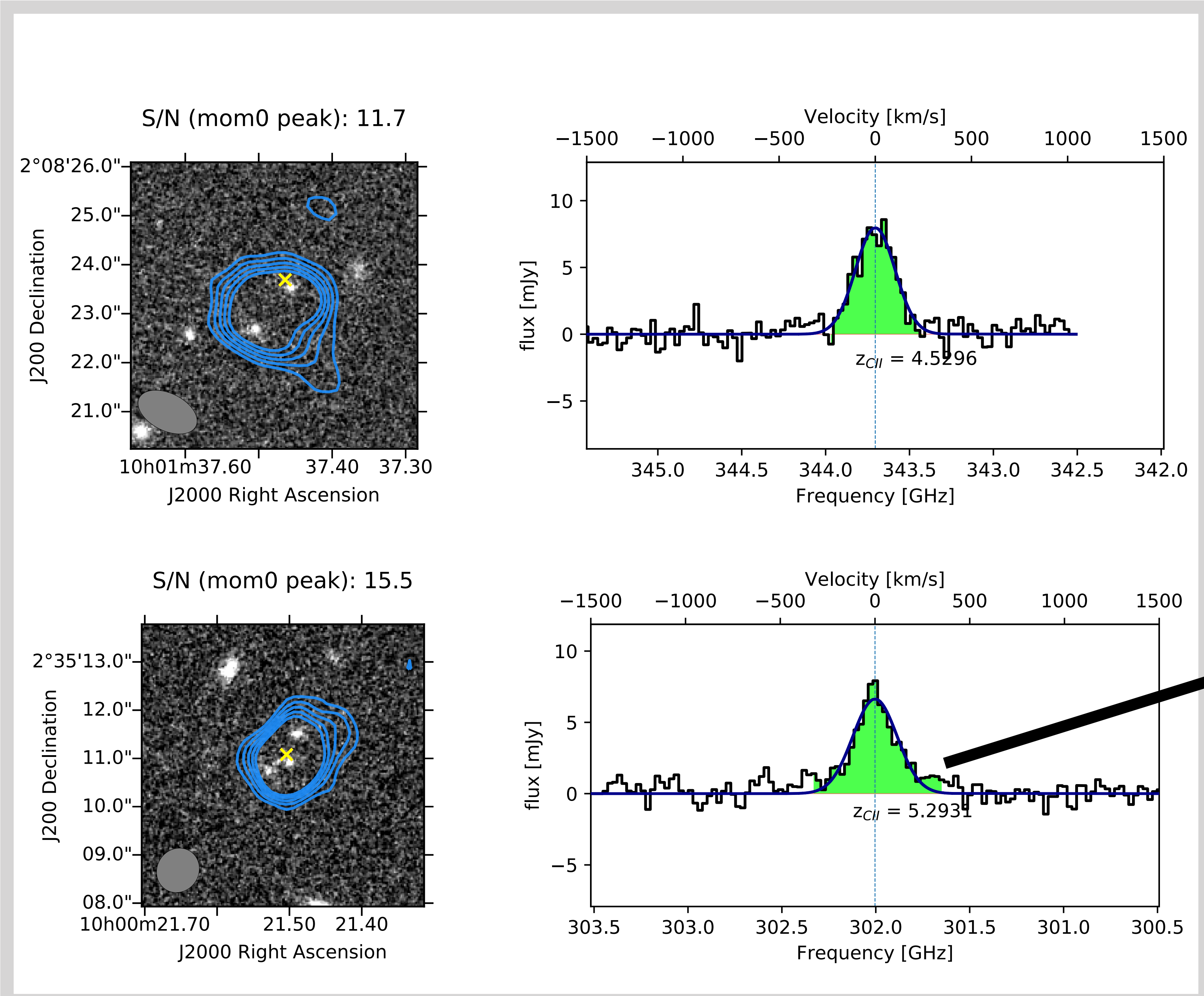


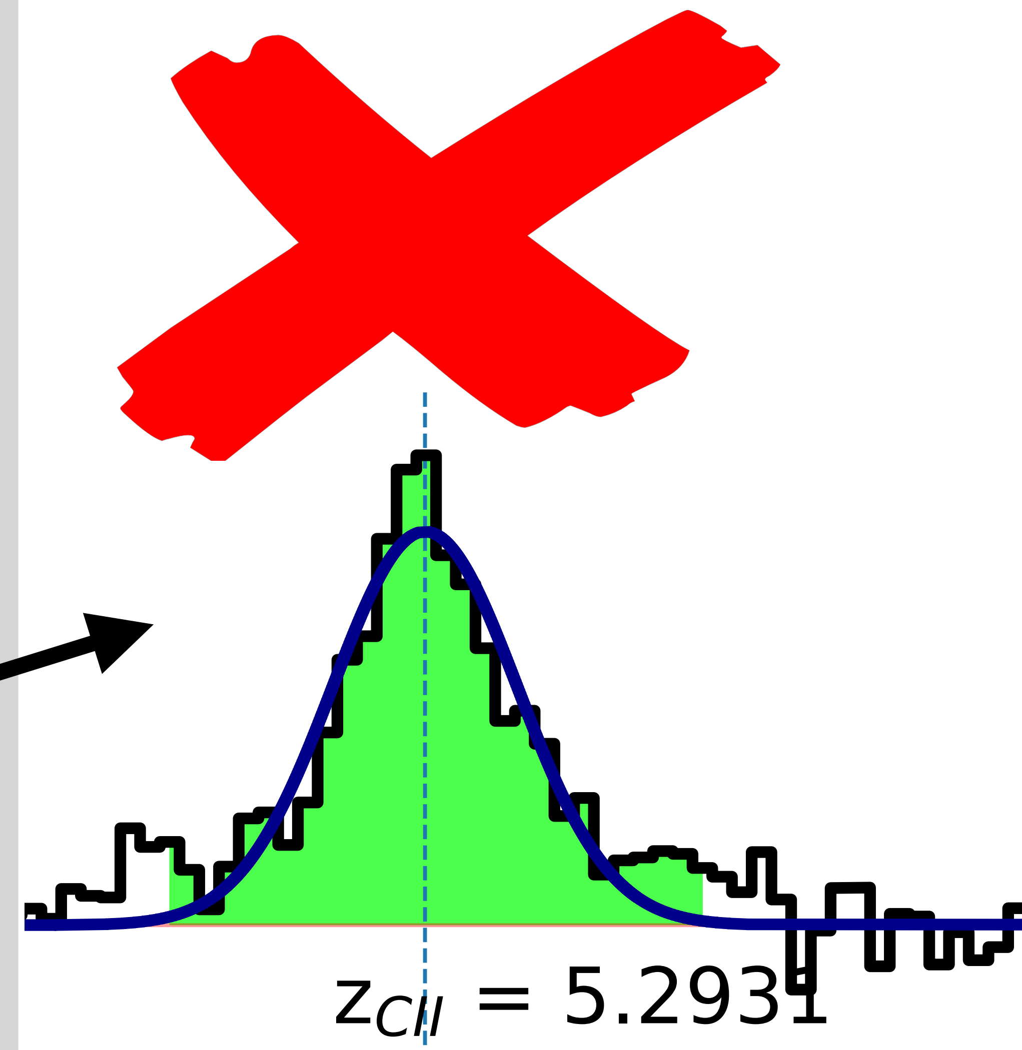


A few examples...



We must exclude mergers!





The final sample adopted in this work consist of **50** ‘non interacting’ normal star forming galaxies at z ~ 4.5 - 6

Note that this does not prevent us from being somehow still contaminated by unresolved, HST/ALMA undetected, faint satellites (<1.5 M_{sun}/yr). However many arguments suggest that this effect should not be significant.

Stacked Residuals

$$R_i = F_i - G_i$$

$$R_i^{\text{stack}} = \frac{\sum_{k=1}^{N} R_{i,k} \cdot w_k}{\sum_{k=1}^{N} w_k}$$

$$w_k = 1/\sigma_k^2$$

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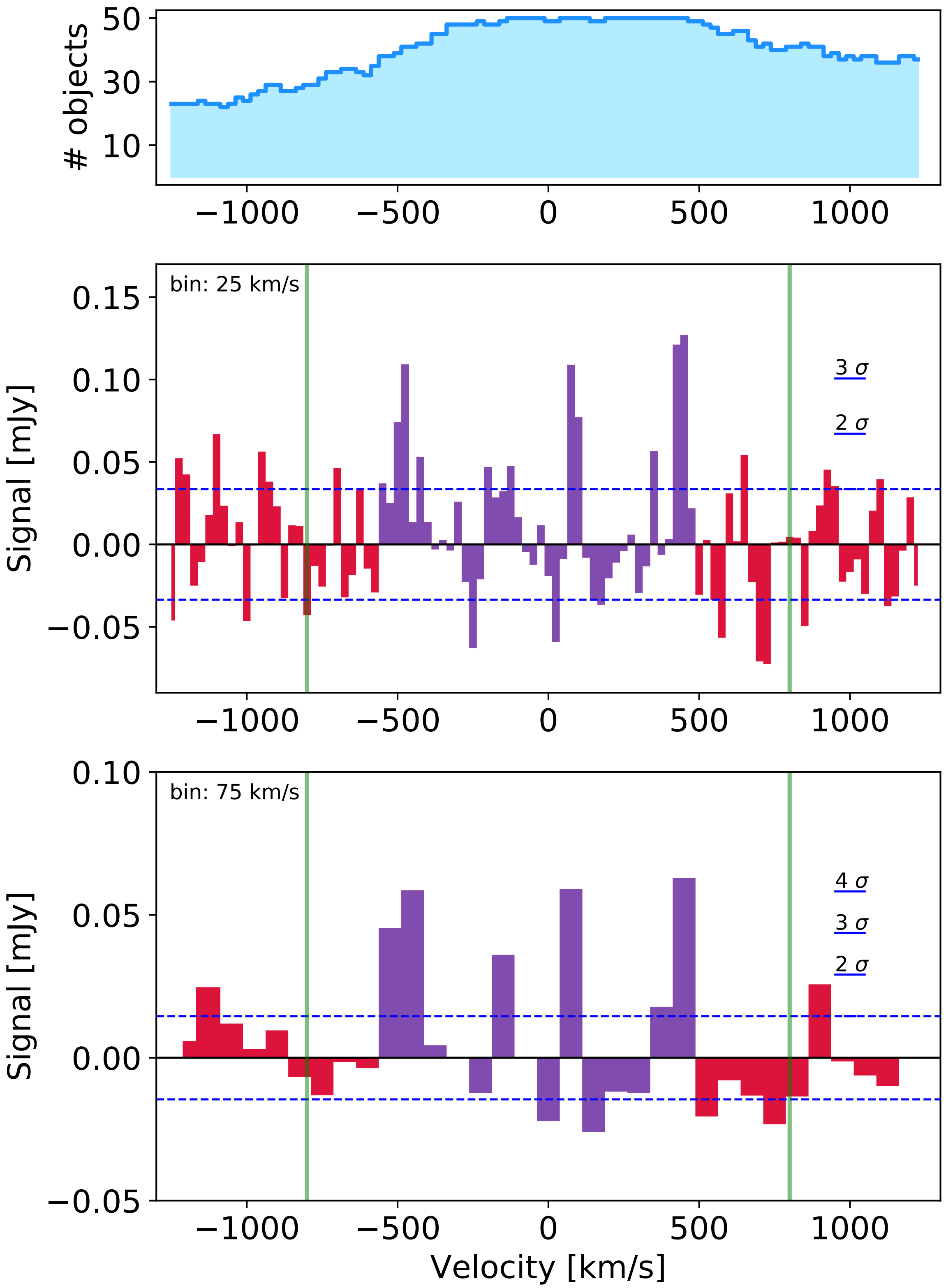
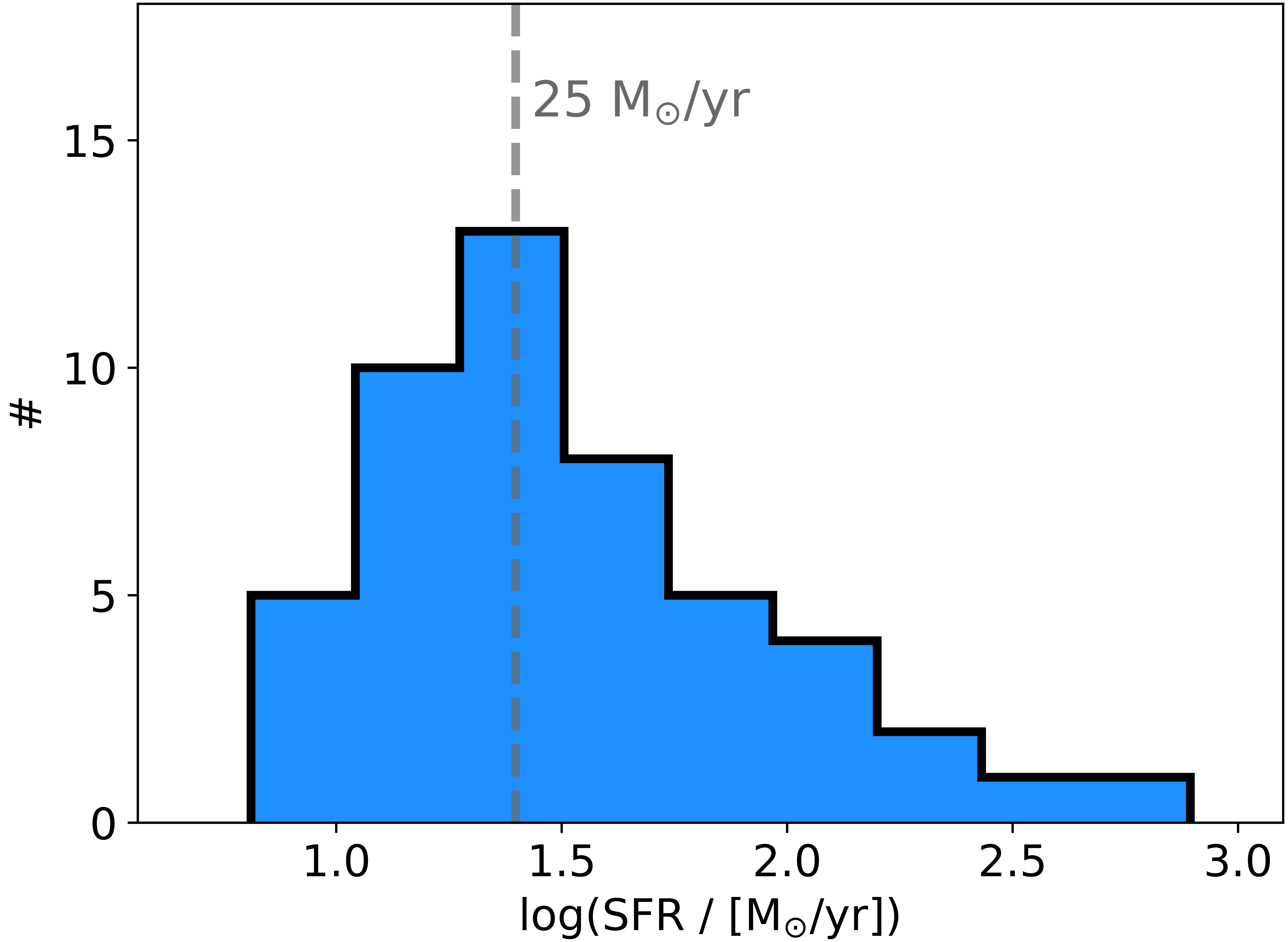


SFR distribution of ALPINE galaxies



Stacked Residuals

$$R_i = F_i - G_i$$

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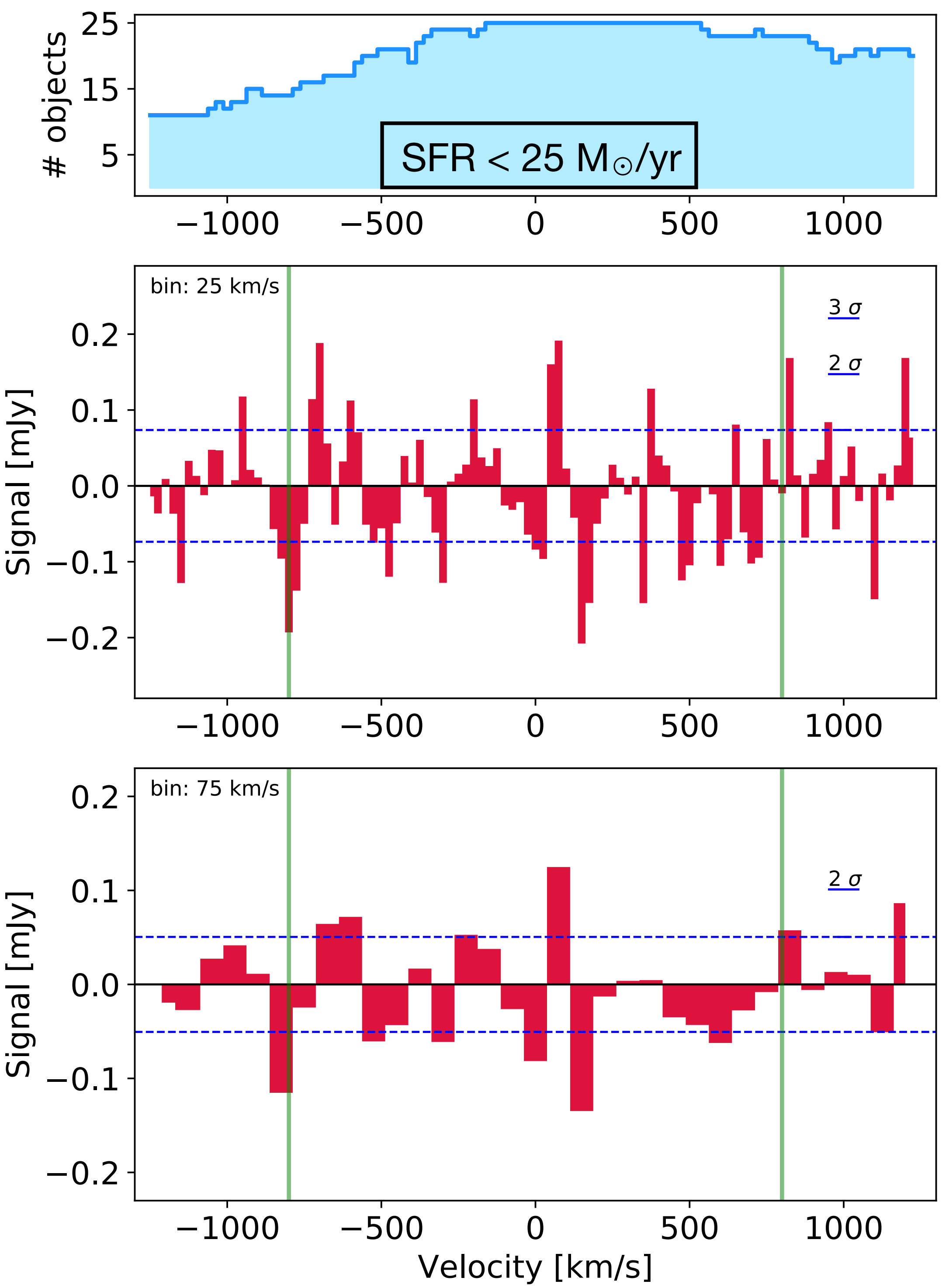
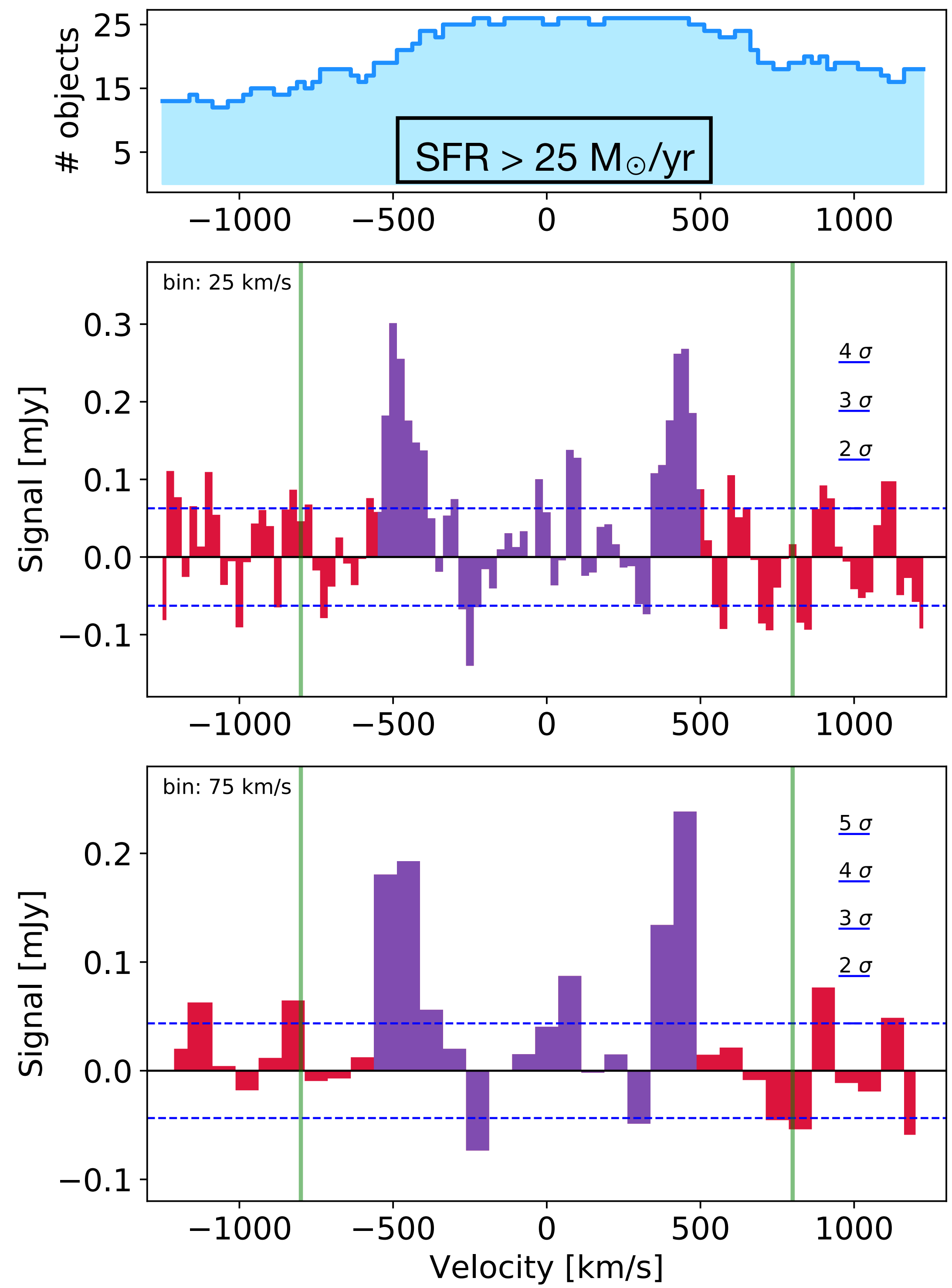
***Low*-SFR (<25 M$_\odot$/yr)**

SFR ----->

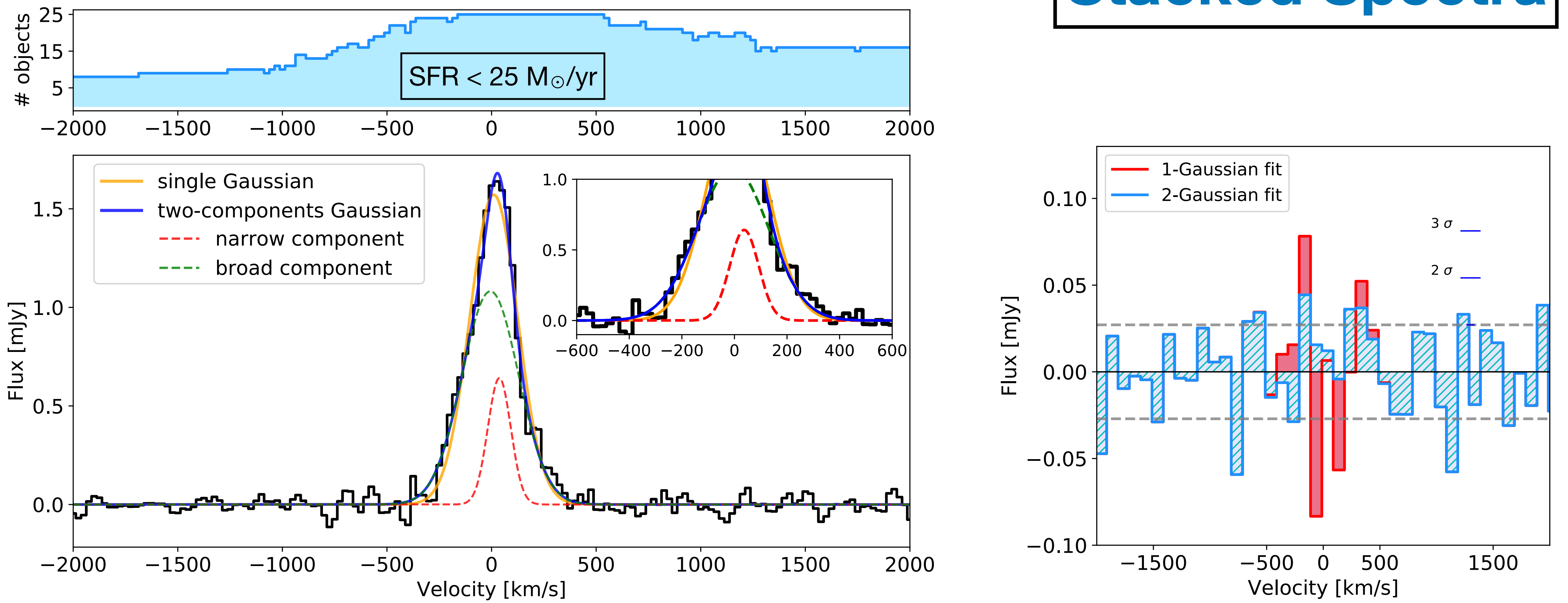
***High*-SFR (>25 M$_\odot$/yr)**



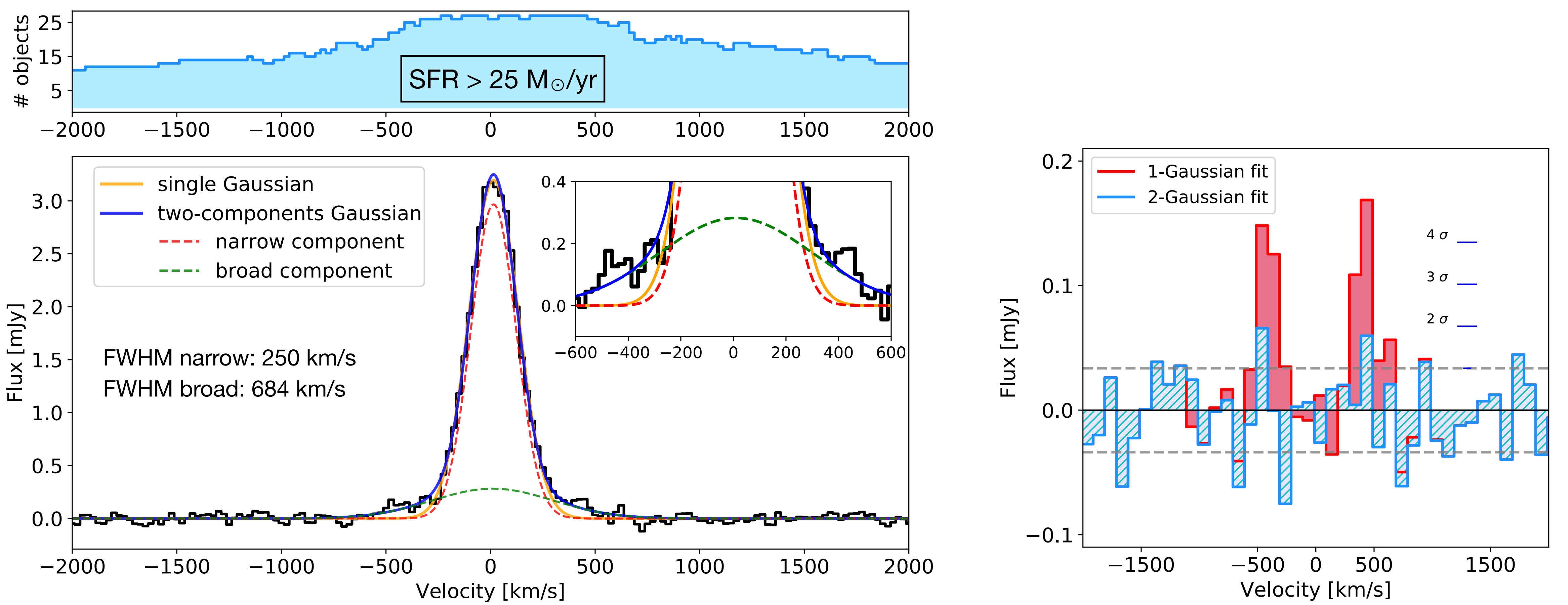


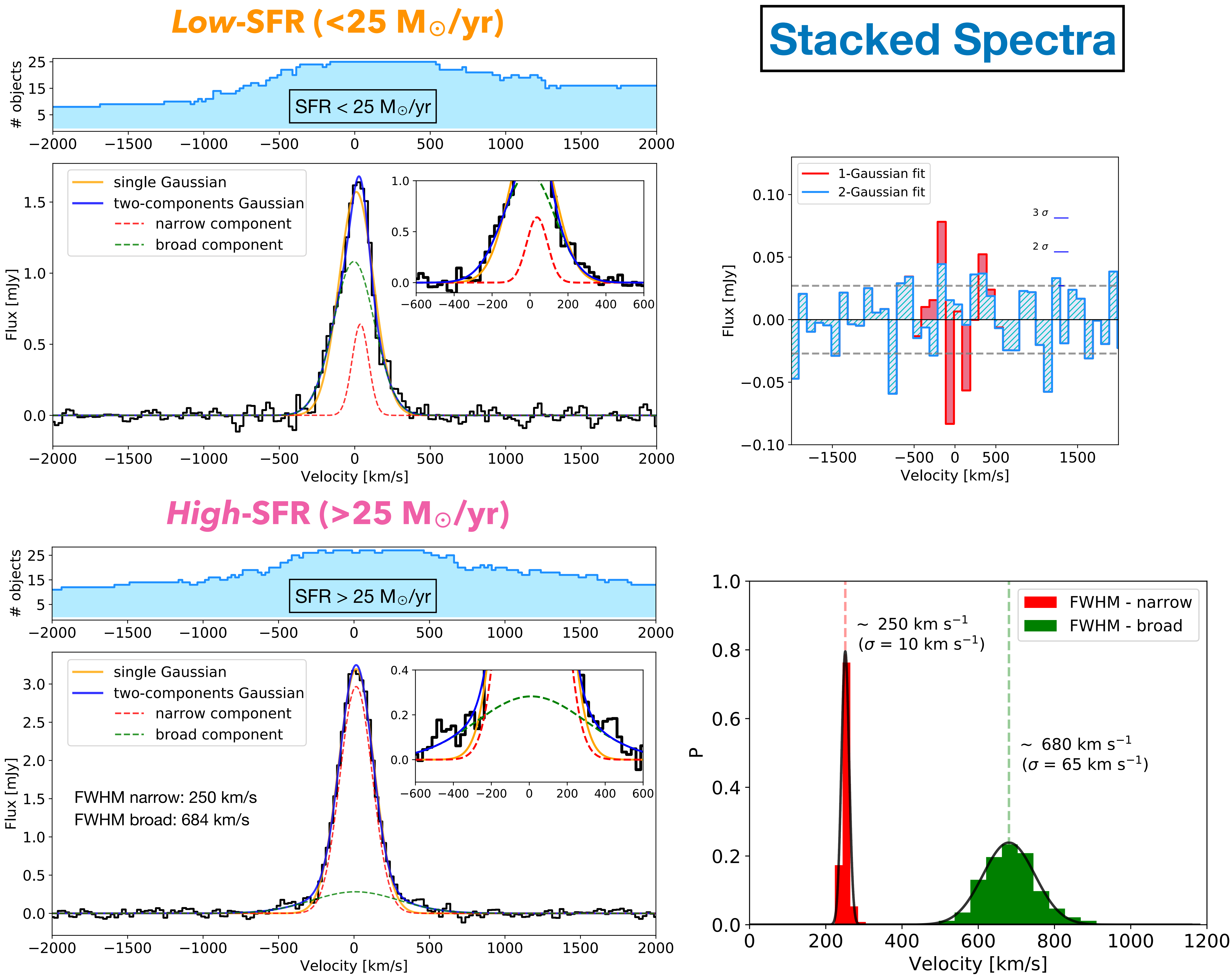
Stacked Spectra

Low-SFR (<25 M⊙/yr)



High-SFR (>25 M⊙/yr)





Low-SFR (<25 M⊙/yr)
Stacked Spectra
objects
SFR < 25 M⊙/yr
single Gaussian
two-components Gaussian
narrow component
broad component
Flux [mJy]
Velocity [km/s]
1-Gaussian fit
2-Gaussian fit
3 σ
2 σ
High-SFR (>25 M⊙/yr)
SFR > 25 M⊙/yr
FWHM narrow: 250 km/s
FWHM broad: 684 km/s
FWHM - narrow
FWHM - broad
~ 250 km s^{-1}
(σ = 10 km s^{-1})
~ 680 km s^{-1}
(σ = 65 km s^{-1})
P

$$\frac{M_{\rm outfl}^{\rm atom}}{\rm M_\odot} = 0.77 \left(\frac{0.7\ L_{\rm [CII]}}{\rm L_\odot}\right) \times \left(\frac{1.4\times10^{-4}}{X_{\rm C+}}\right) \times \frac{1+2e^{-91\ {\rm K}/T}+n_{\rm crit}/n}{2e^{-91\ {\rm K}/T}},$$

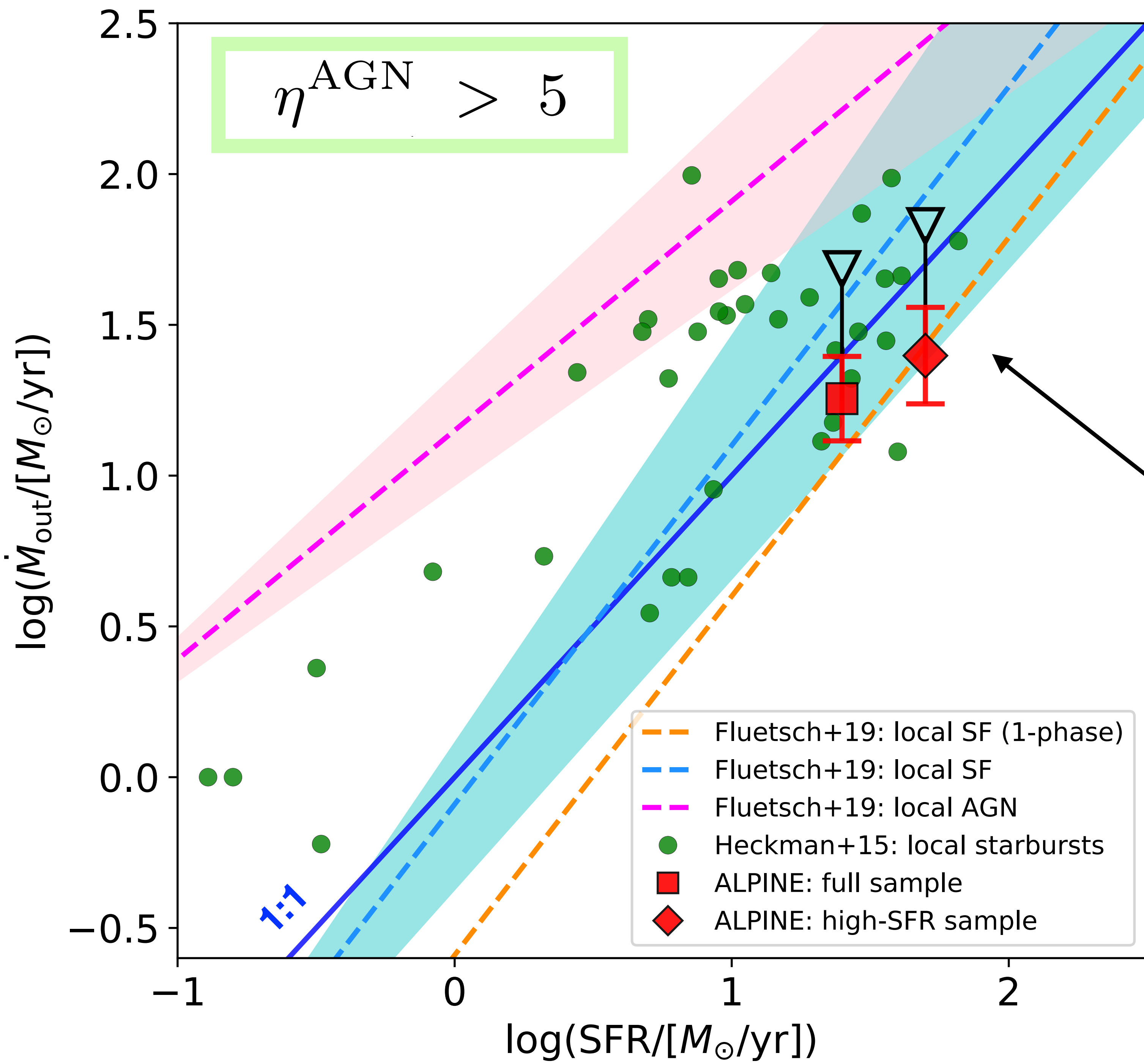
Rupke+05, Maiolino+12, Gallerani+18, Bischetti+19

$$\dot{M}_{\rm outfl} = \frac{v_{\rm outfl}\ M_{\rm outfl}}{R_{\rm outfl}}$$

-->

M_{outf} ~ [2 - 3] x 10^8 $M_\odot$

$\dot{M}_{outfl}$ ~ 20 - 40 $M_\odot$/yr

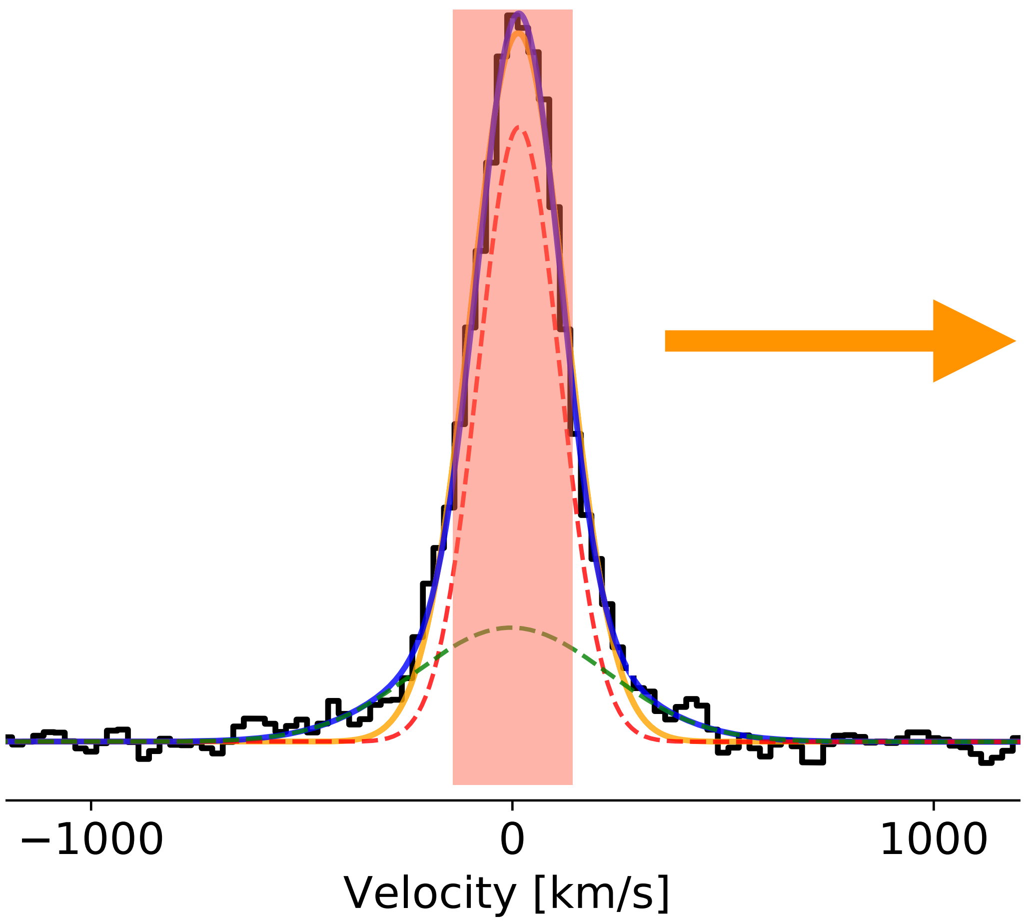


Stellar feedback does not play a dominant role in quenching galaxies at z>4. AGN feedback and additional mechanisms capable of preventing further accretion are needed.

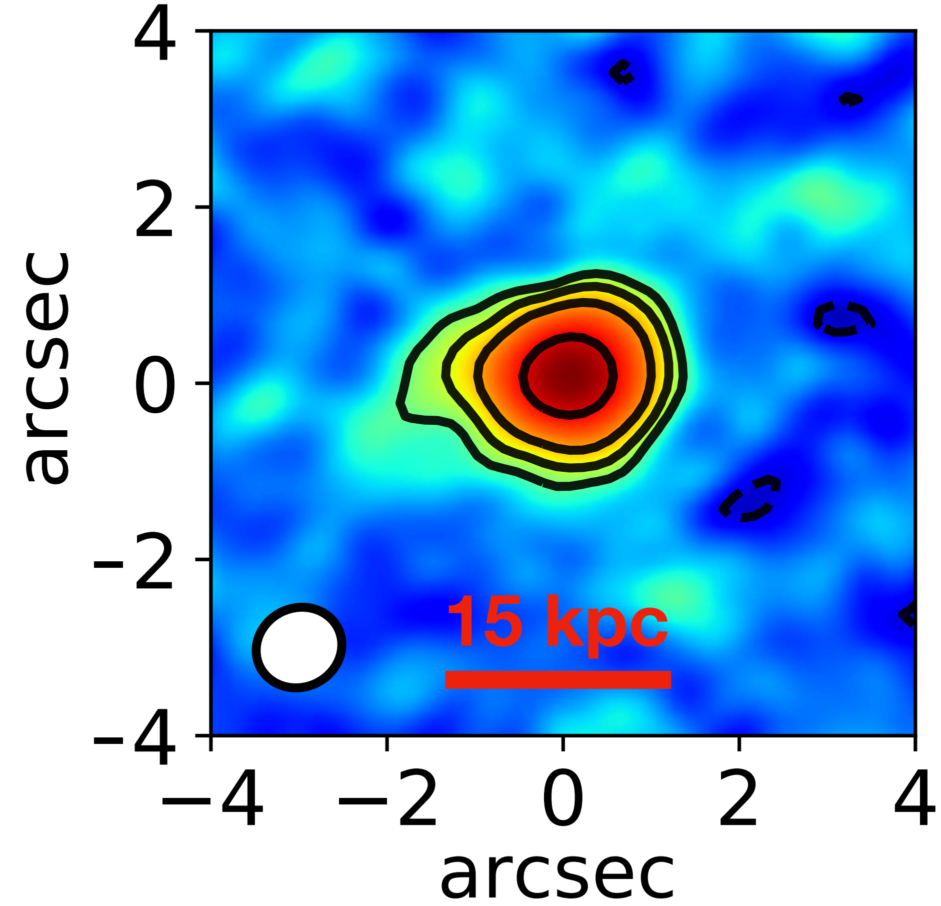
$\eta^{\rm atom} \sim 0.4 - 0.9$

$\eta^{\rm tot} \sim 1 - 3$

Stacked Cube

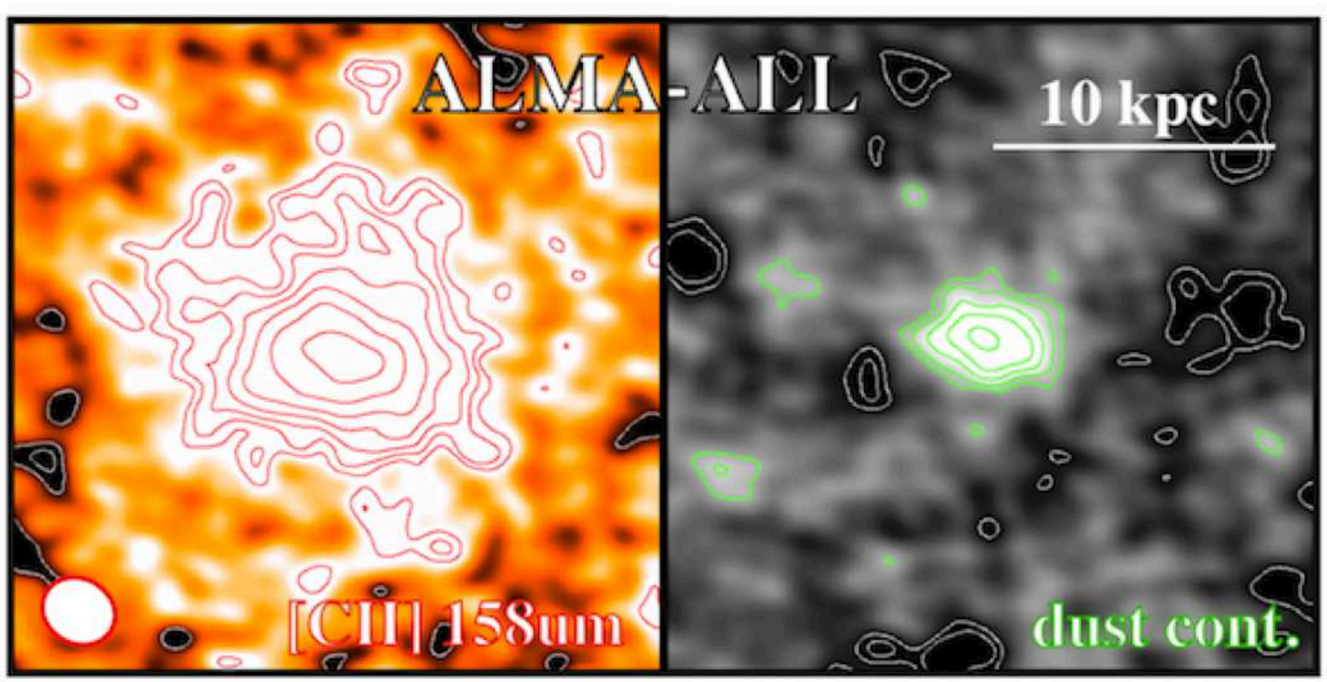


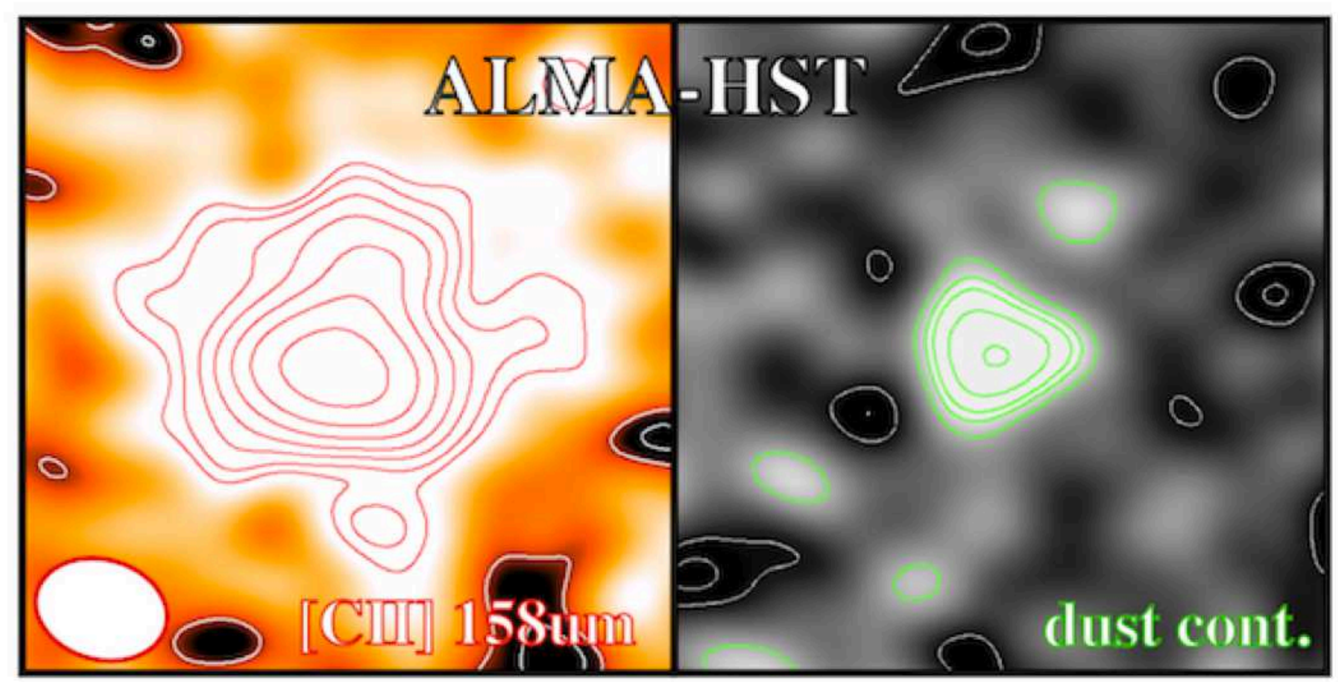
Stacked **[C II] 'core'** is extended on ~15 kpc.



See Seiji's talk tomorrow afternoon!

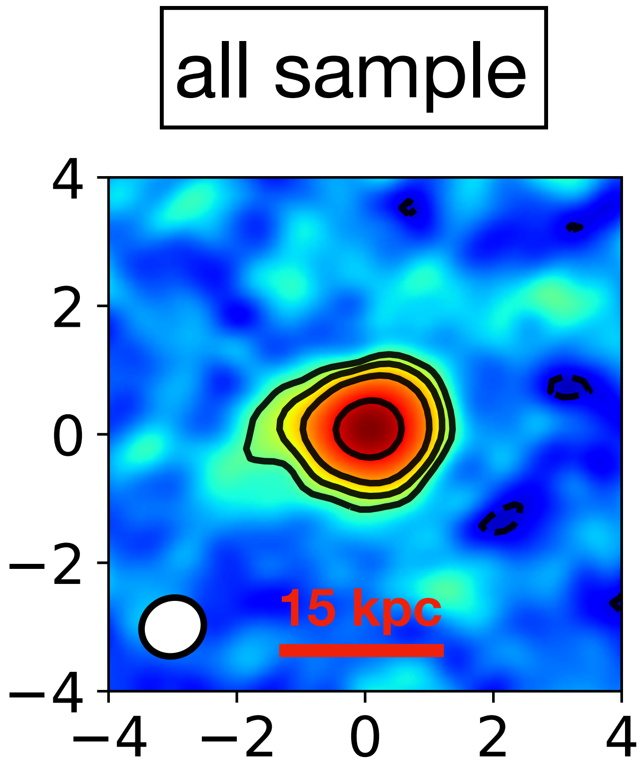
Let's play again the game of splitting in SFR..



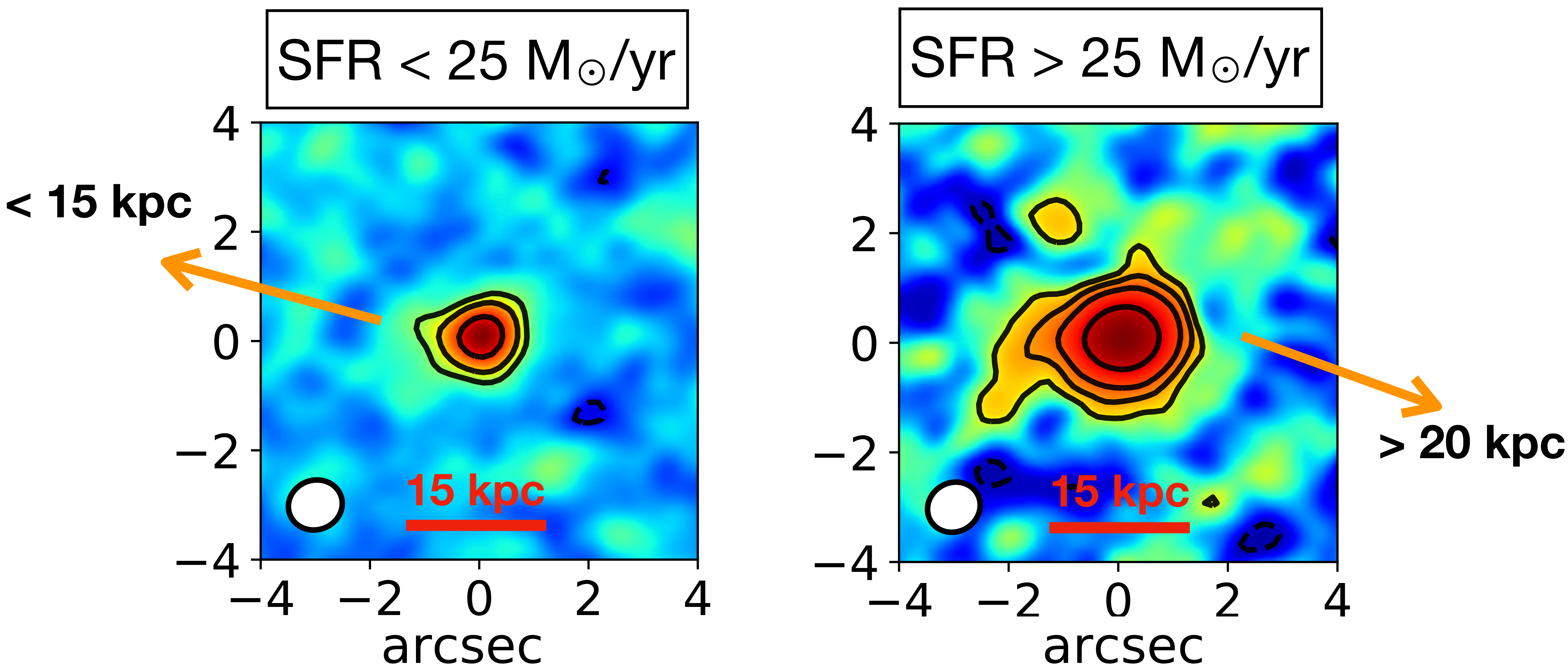


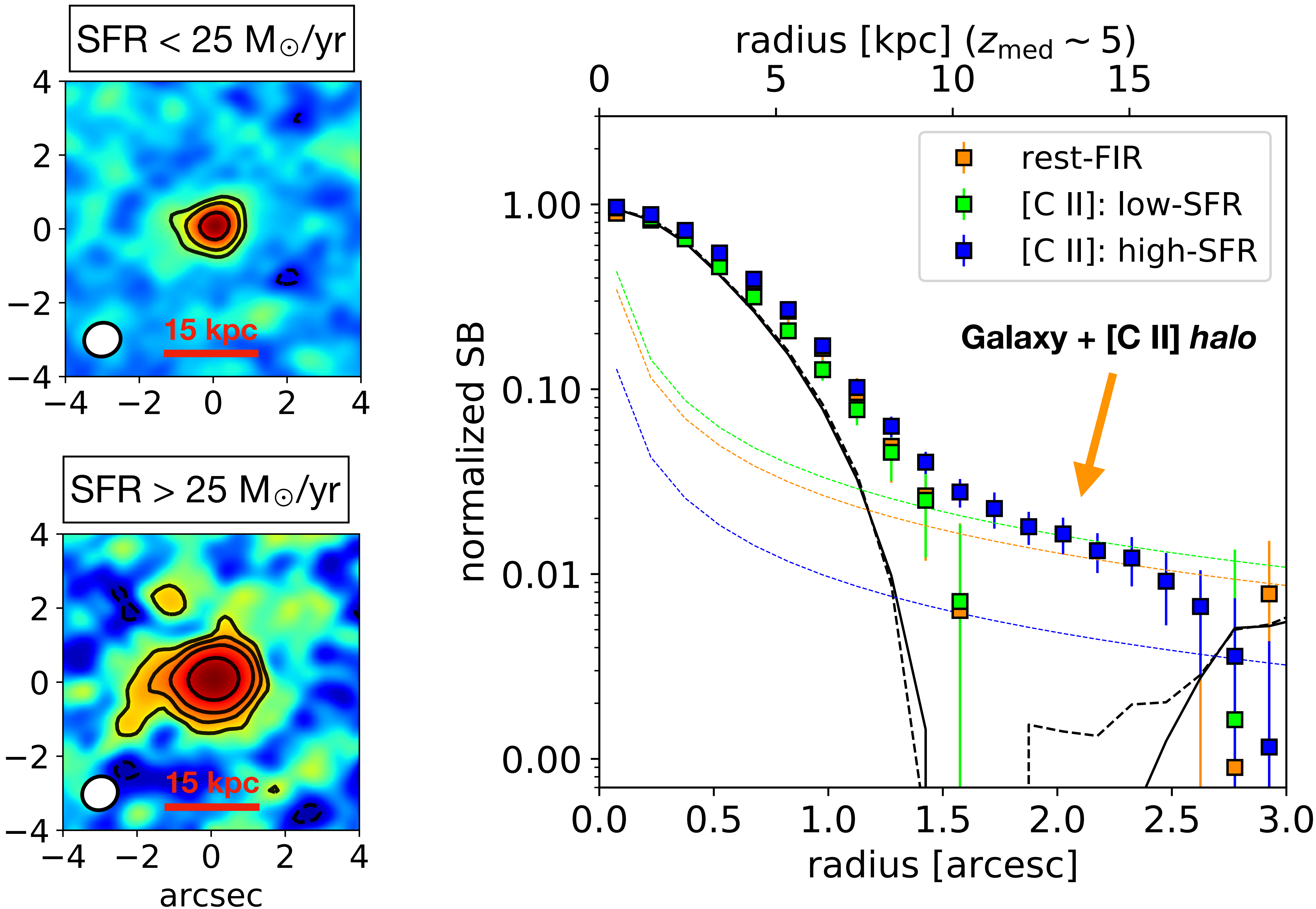
18 galaxies at z~5-7, with SFR~10-70 M_{sun}/yr

Fujimoto+19



The effective contribution to the [C II] *halo* is provided by the high-SFR subsample.

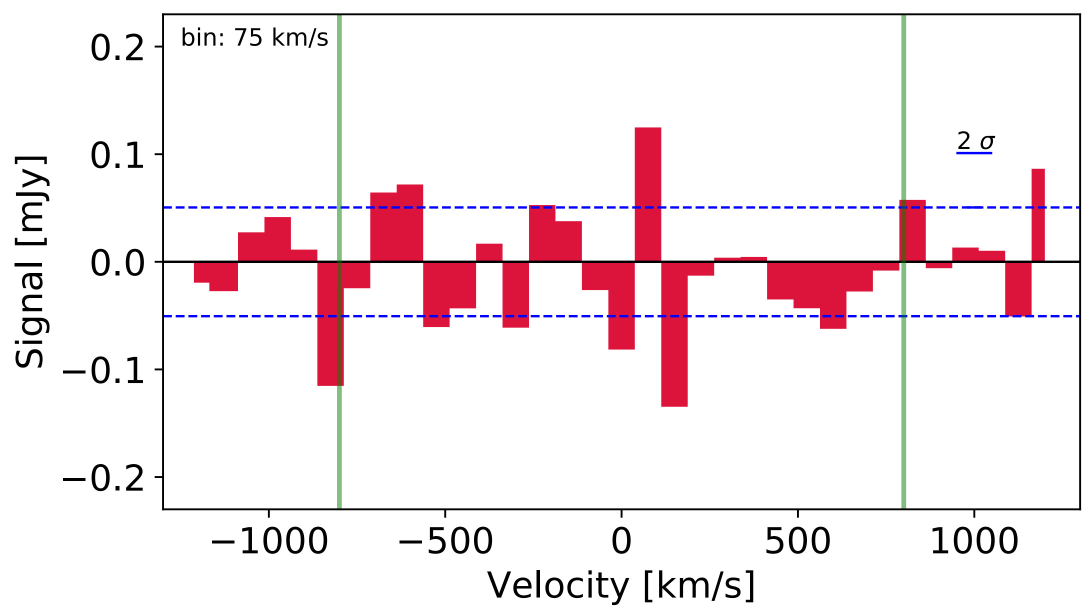




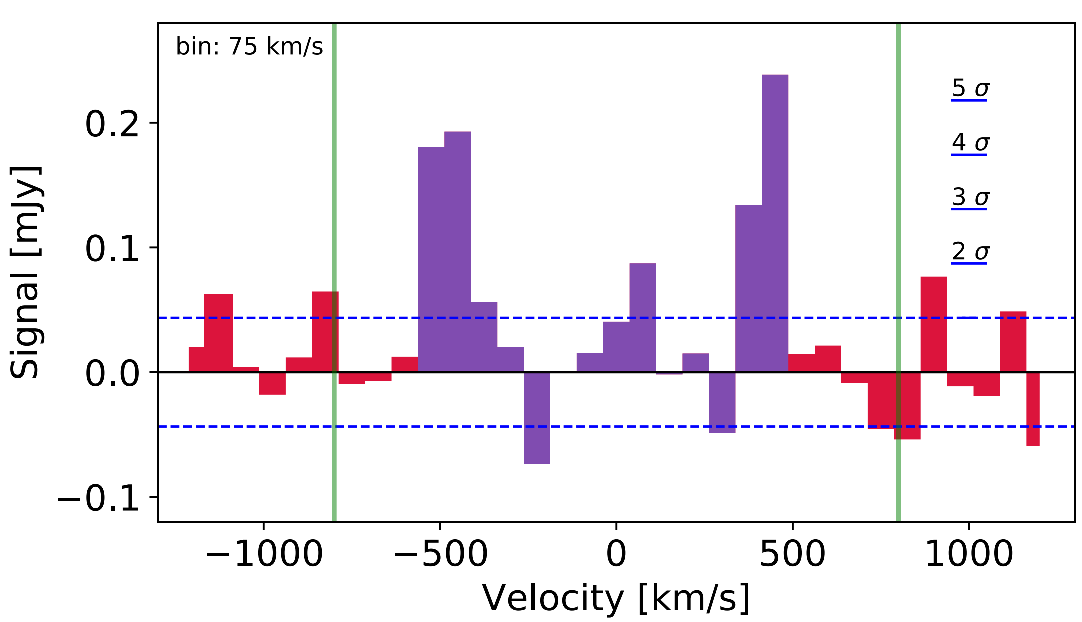
SFR < 25 M⊙/yr
15 kpc
SFR > 25 M⊙/yr
15 kpc
arcsec
radius [kpc] (z_{med} ~ 5)
normalized SB
rest-FIR
[C II]: low-SFR
[C II]: high-SFR
Galaxy + [C II] *halo*
radius [arcsec]

Ginolfi+, in prep

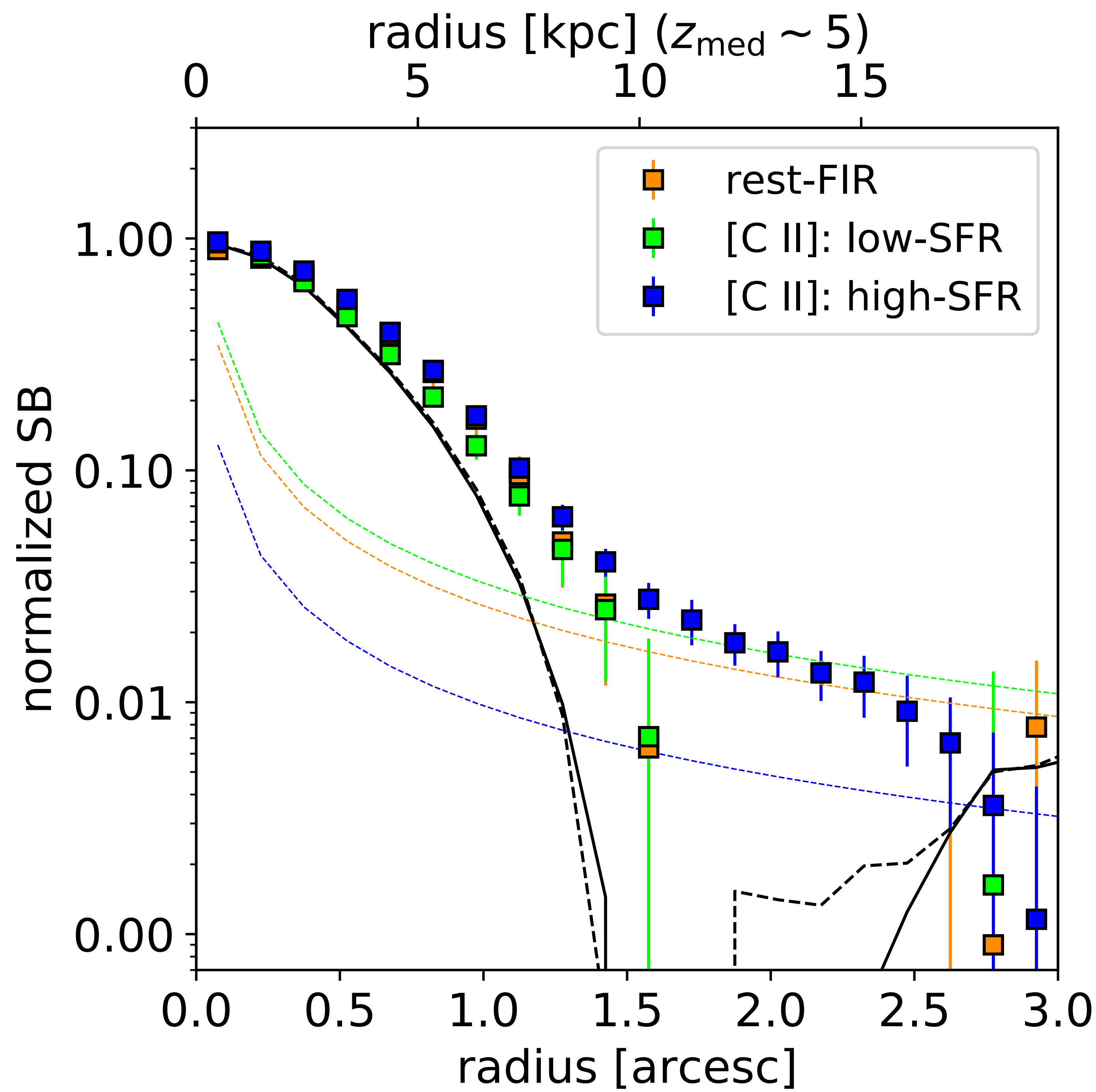
Low-SFR



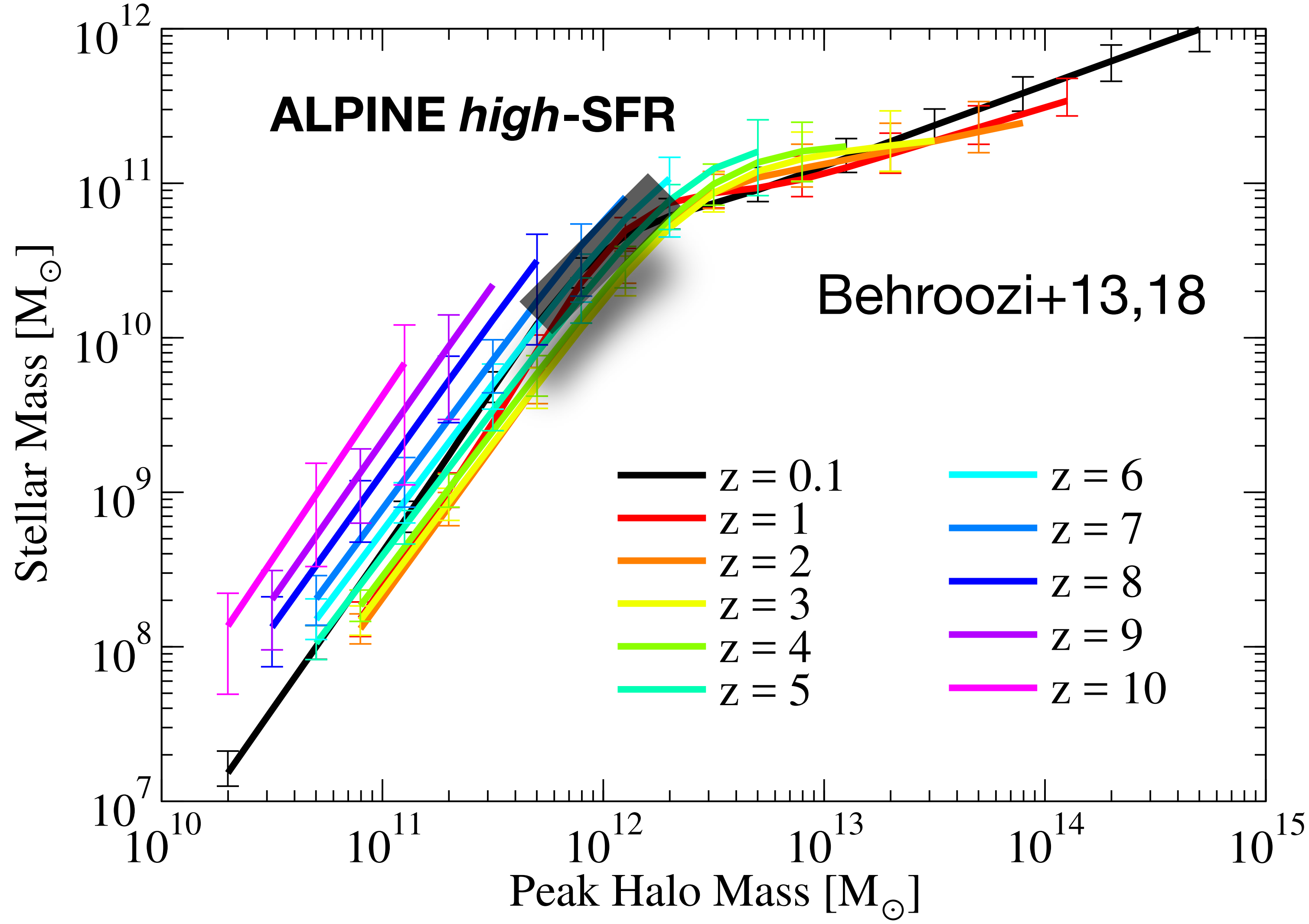
High-SFR



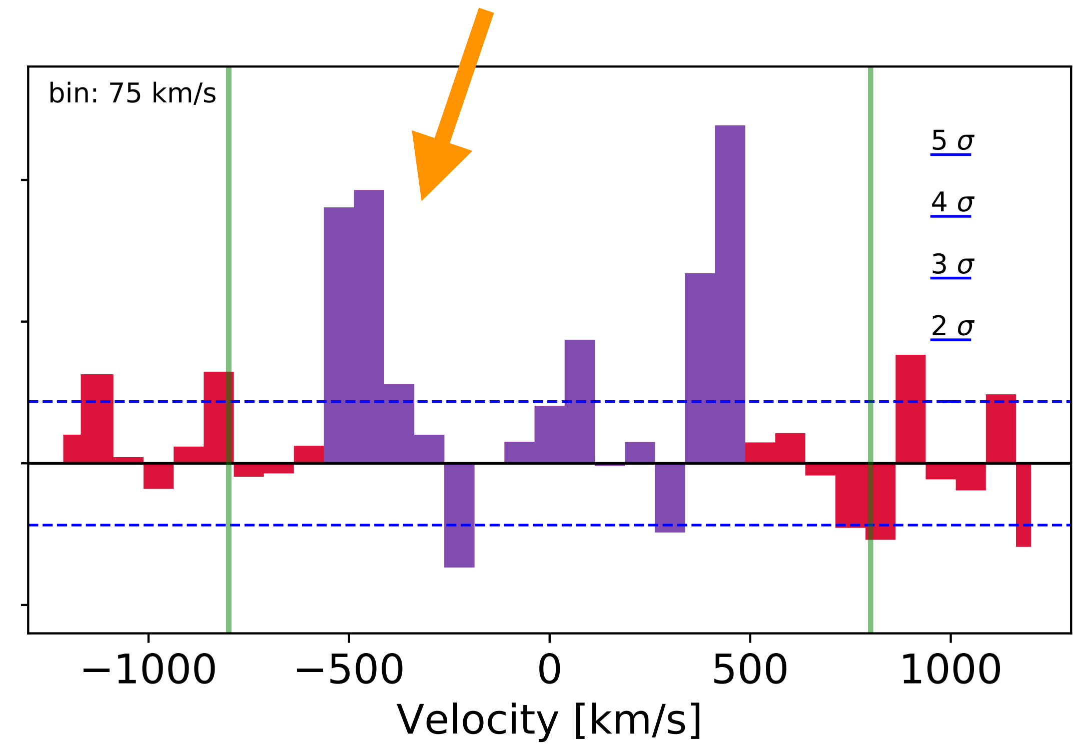
+



Outflows of processed material are needed to enrich the carbon abundance in the CGM of early systems. Therefore the [C II] *halo* is an evidence of (i) star formation-driven outflow remnants, and (ii) gas mixing at play in the CGM of high-z normal star-forming galaxies.



v_{outf} ~ 500 km/s



$$v_{\rm esc} = \sqrt{\frac{2\ G\ M_{\rm DM}}{r_{\rm DM}}}$$

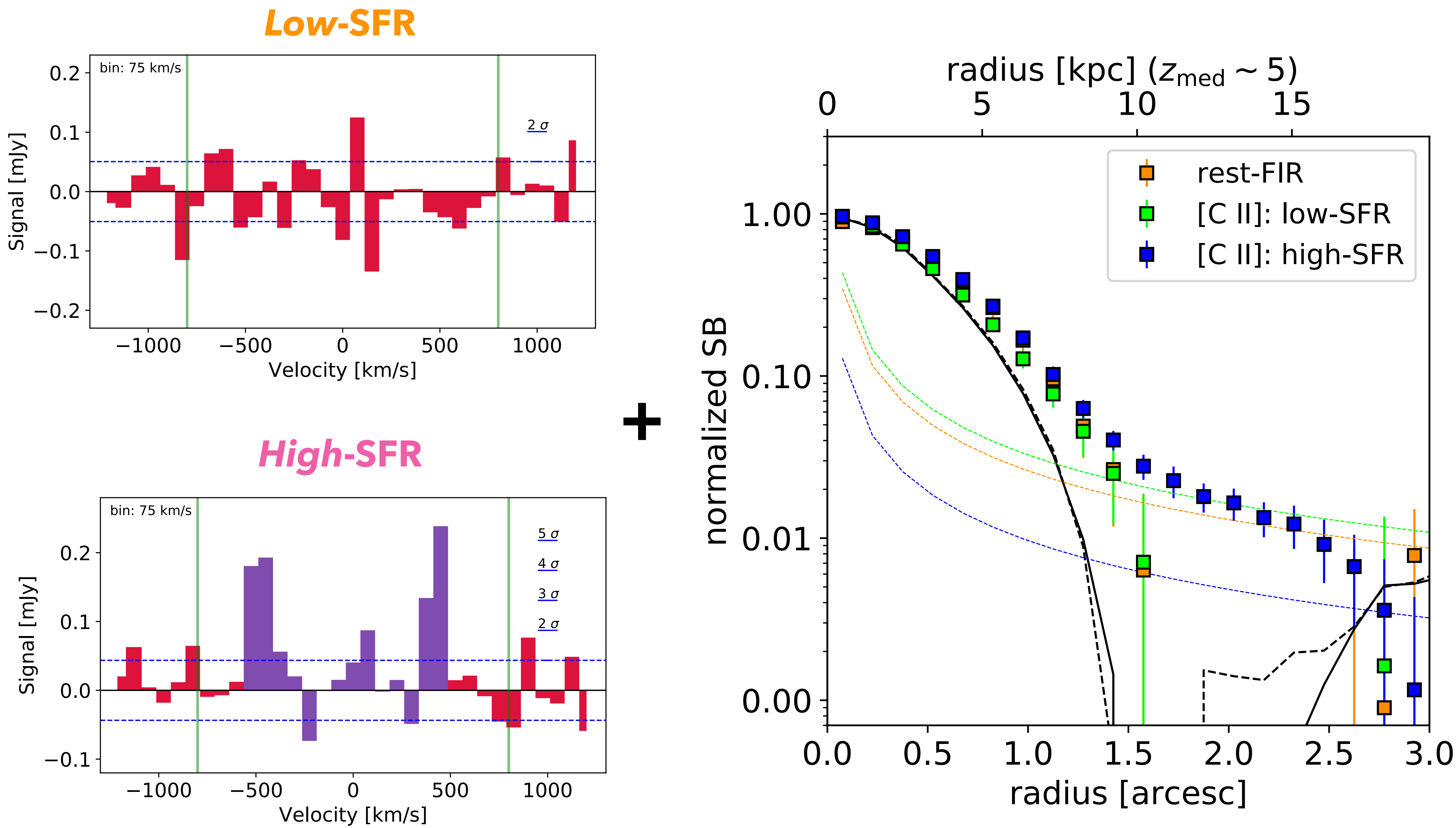
V_{esc} ~ 350-750 km/s

$$M_{\rm DM} \sim 7 \times 10^{11} - 5 \times 10^{12} {\rm M}_\odot$$

$$r_{\rm DM} = \left[\frac{3\ M_{\rm DM}}{4\ \pi\ 200\ \rho_{\rm crit}(z)} \right]^{1/3}$$

$$r_{\rm DM} \sim 40 - 100\ {\rm kpc}$$

A significant fraction of gas won't escape the DM-halo and will be *trapped* in the CGM



A quantitative study of spatially extended outflows and enriched CGM (extension, morphology, kinematics, outflow rate, etc…) at high-z, and their dependence on galaxy properties (mass, SFR, morphology), requires the detection of these components in (many) individual galaxies.

Summary

- We explore the efficiency of galactic feedback in the early Universe by stacking the [C II] 158 μm emission in a large sample of normal star-forming galaxies at 4 < z < 6, drawn from ALPINE.

- we observe:
  # deviations from a single-Gaussian model in the combined residuals;
  # broad emission in the stacked [C II] spectrum, at velocities of ~ 500 km/s;
  # the significance of these features increases with SFR, confirming their star formation-driven nature.

- Average mass outflow rates are consistent with the SFRs, yielding mass-loading factors of the order of the unit.

- Stacking the cubes of high-SFR sub-sample, we find indication of an enriched CGM, traced by a ~30 kpc-sized [C II] halos. This corroborates previous similar studies, and confirms that baryon cycle and gas exchanges with the circumgalactic medium are at work in normal galaxies already at early epochs.

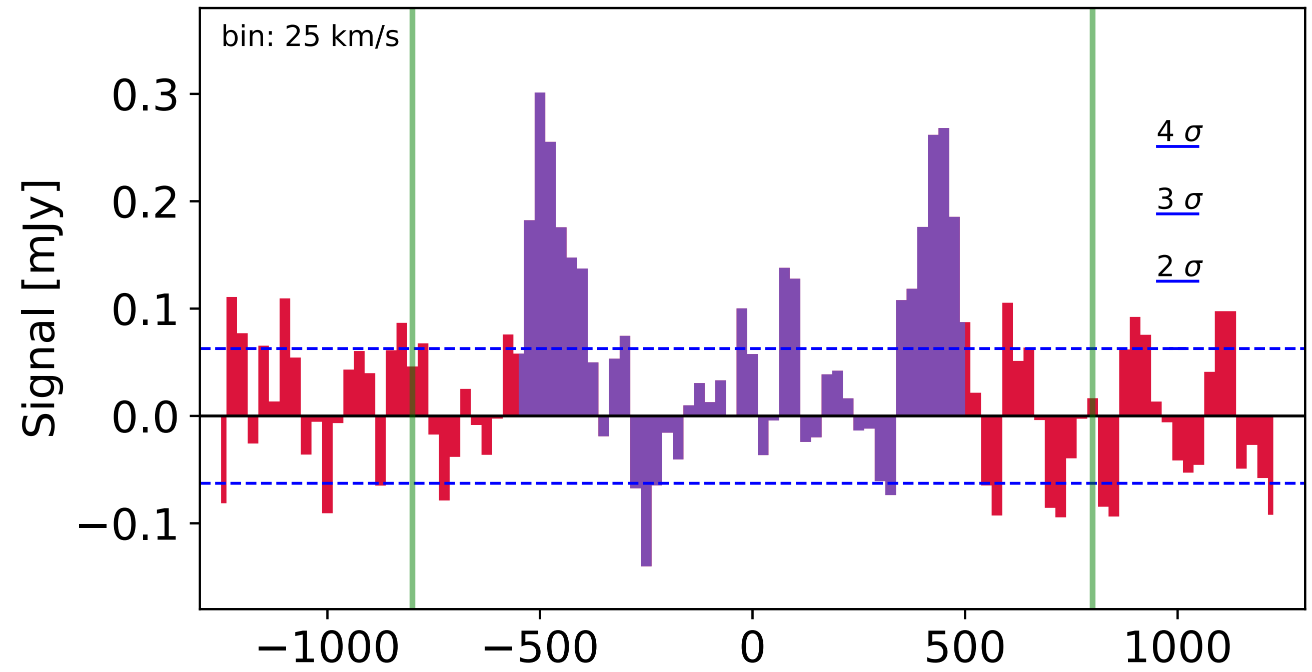

Thanks for your attention!
The coloured Bologna :-)

Additional Slides

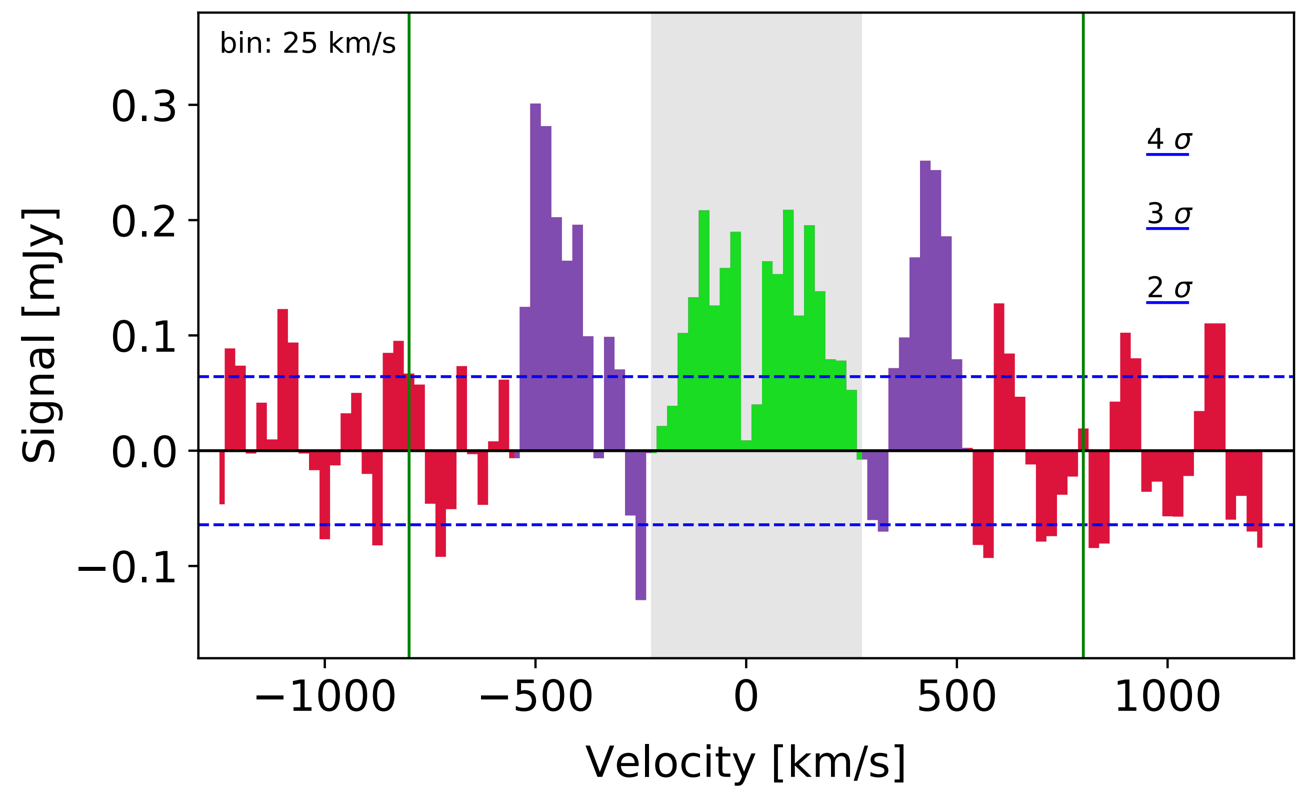
Stacked Residuals

High-SFR (>25 $M_\odot$/yr)

The integrated spectra of rotating disks (typically double-horned profiles) are not well described by a single Gaussian. The symmetric residuals that we see may be caused by the presence of rotating disks in our subsample?



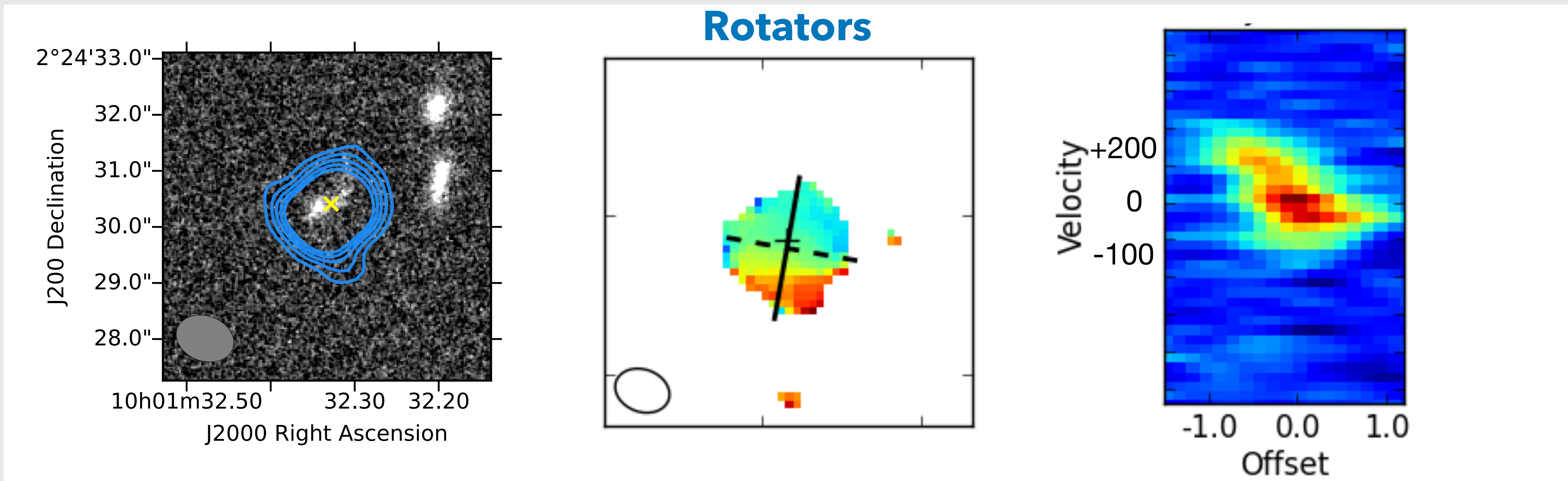
Let's check - we subtract **3DBAROLO** models of our rotators and indeed we find that they lead some residuals but on lower velocities (consistent with the average FWHM of our [C II]-lines).

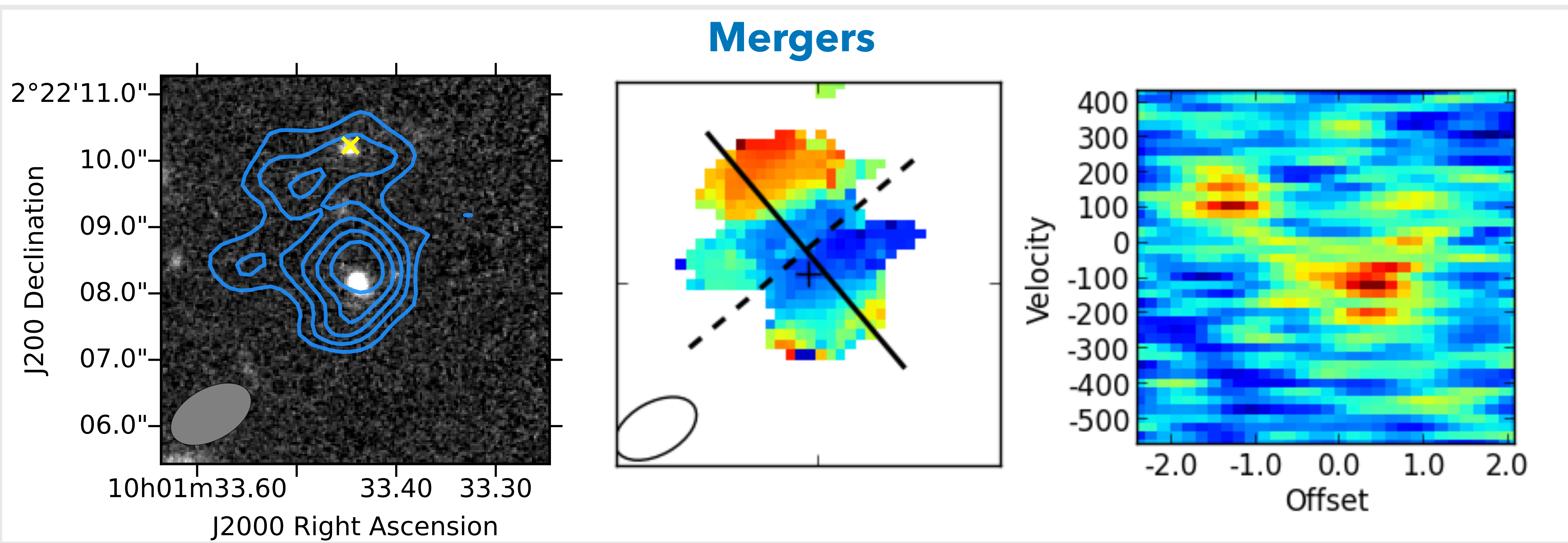


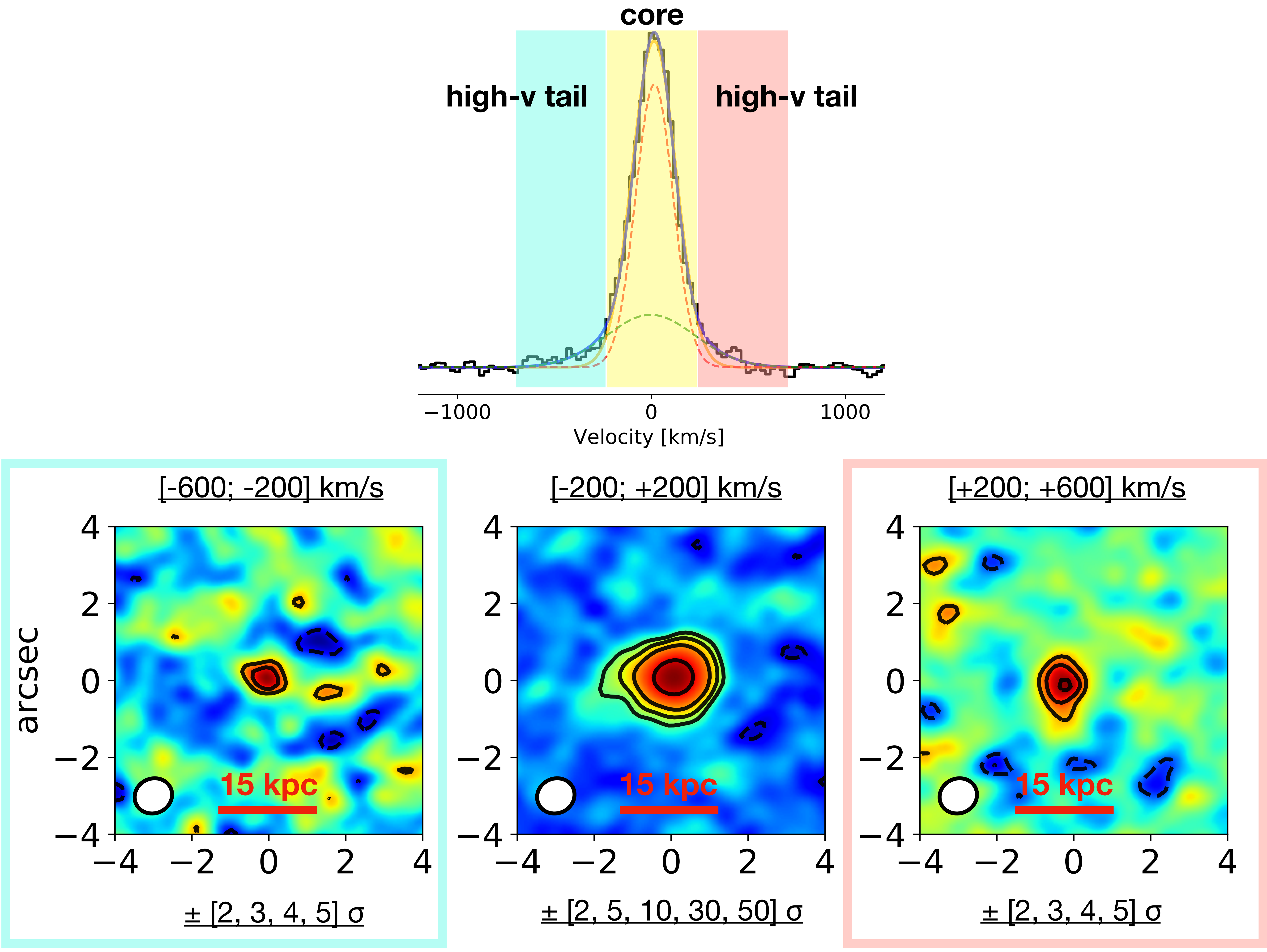
Begeman et al. 1989; Carniani et al. 2013; De Breuck et al. 2014; Di Teodoro & Fraternali 2015; Jones et al. 2017; Talia et al. 2018; Smit et al. 2018; Kohandel et al. 2019..

Morpho-dynamical classification

G. Jones+, in prep





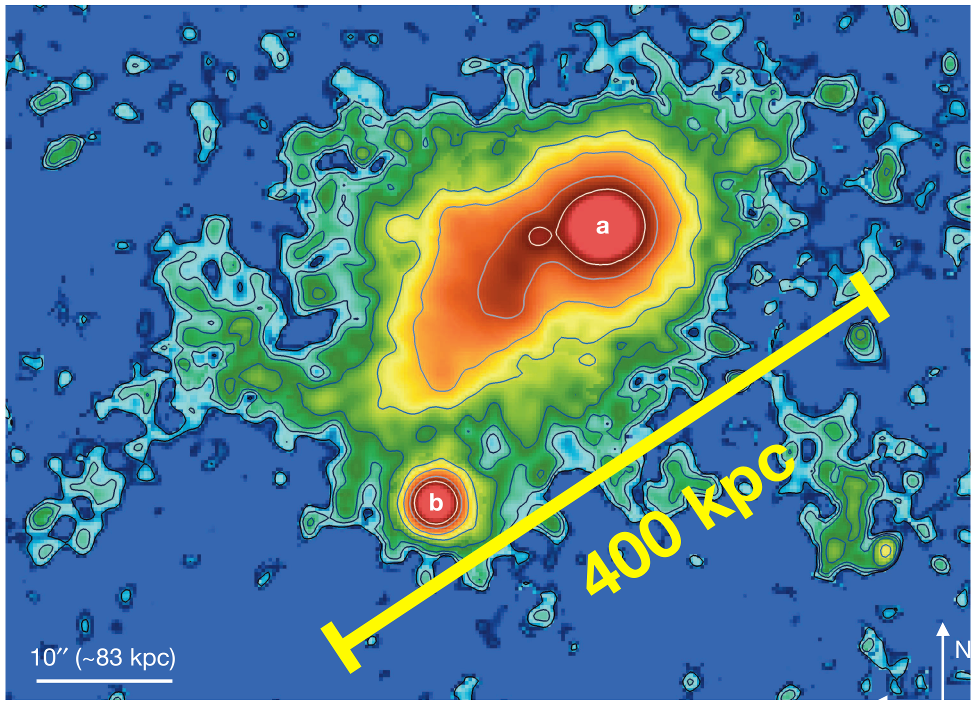


core
high-v tail
high-v tail
−1000
0
1000
Velocity [km/s]
[-600; -200] km/s
[-200; +200] km/s
[+200; +600] km/s
arcsec
15 kpc
15 kpc
15 kpc
± [2, 3, 4, 5] σ
± [2, 5, 10, 30, 50] σ
± [2, 3, 4, 5] σ

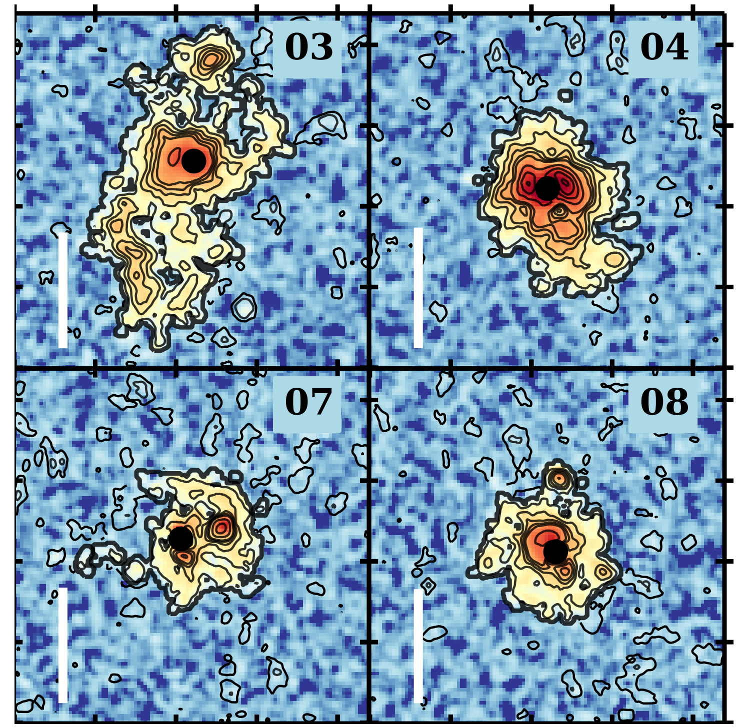
Ubiquitous Lya Nebulae around high-z QSOs

> 10h, NB filter

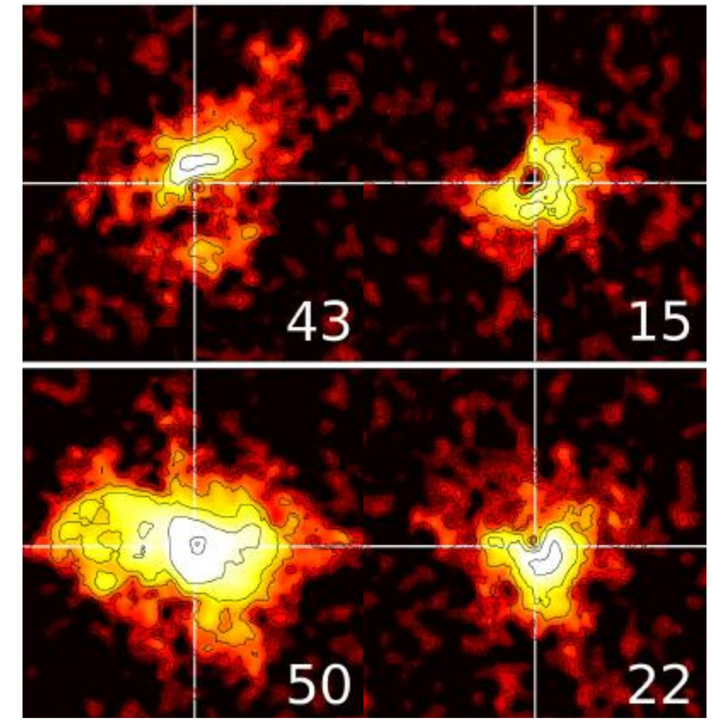
< 1h, MUSE



Cantalupo+14

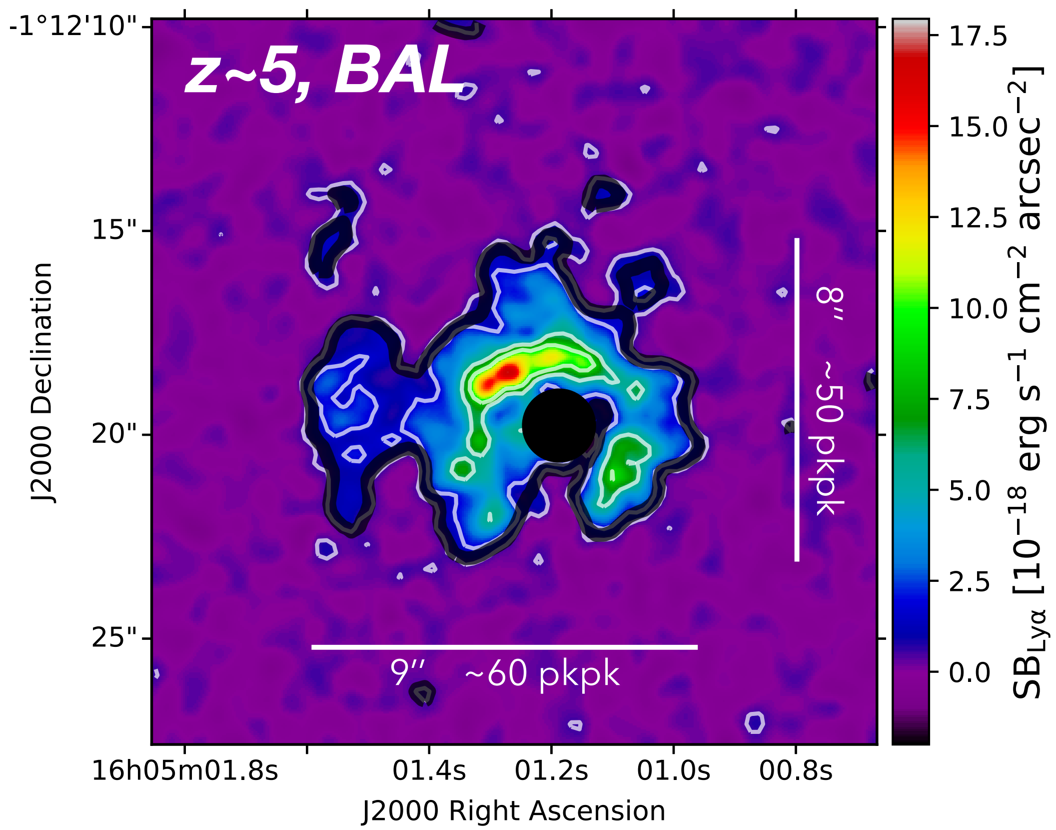


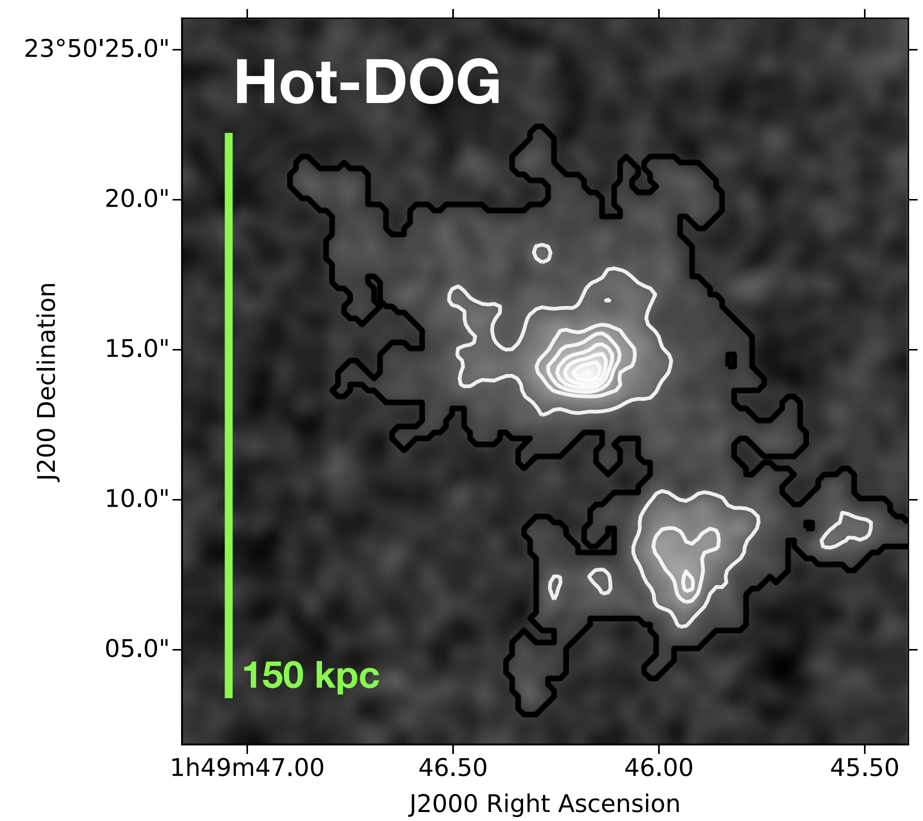
Borisova+16



Arrigoni-Battaia+18

Ginolfi+18

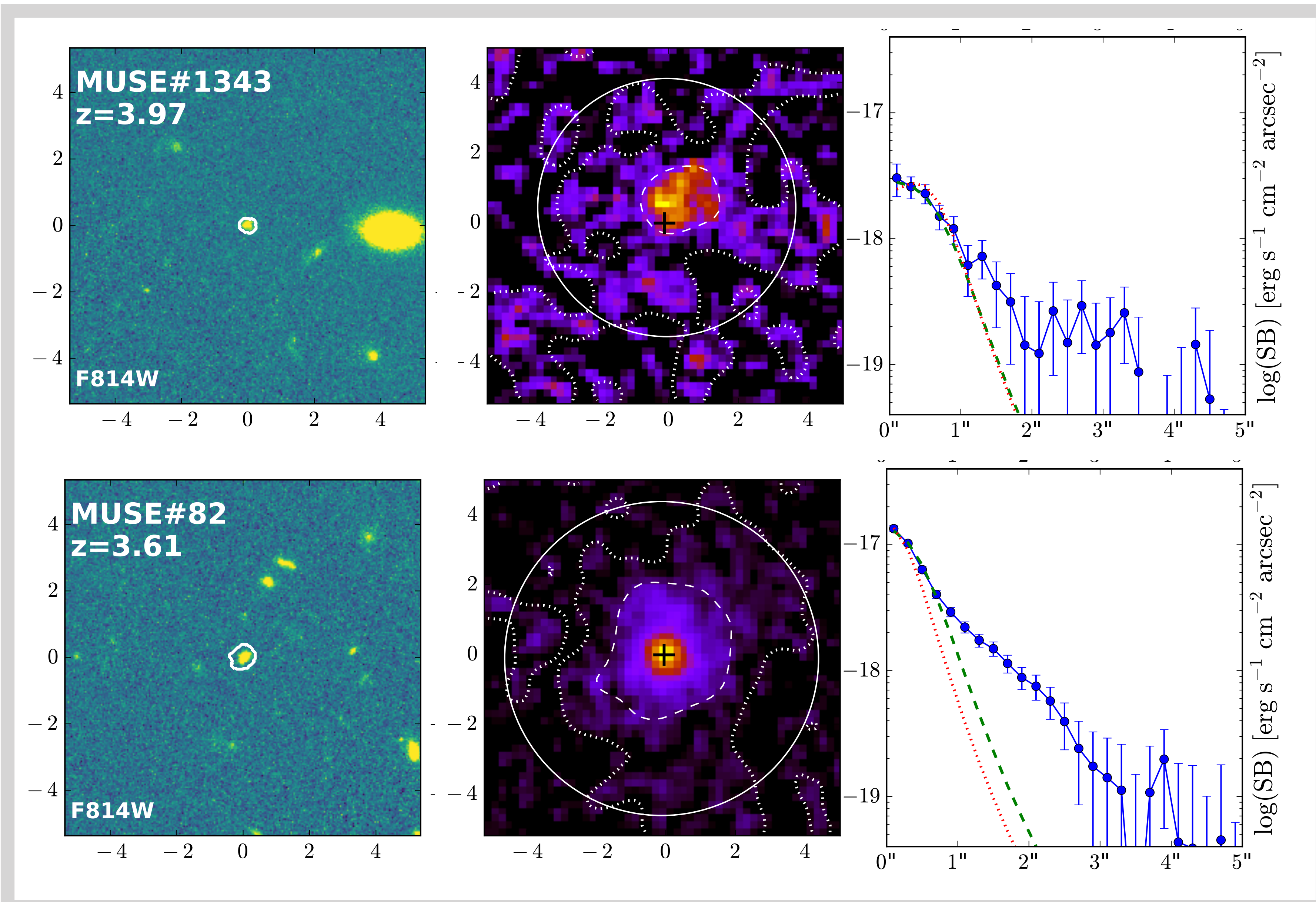




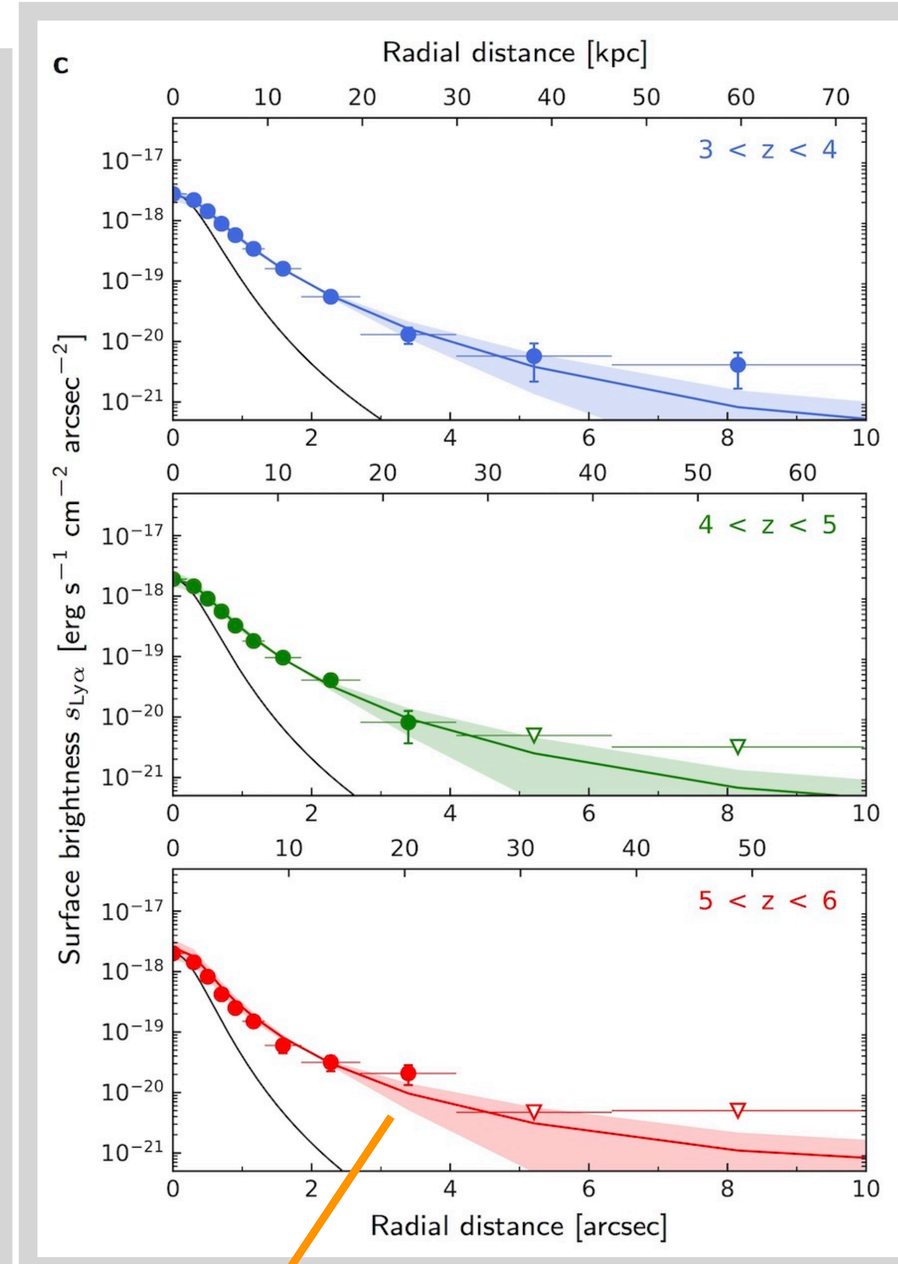
Ginolfi+, in prep

Lya Halo surrounding high-z galaxies

> 30h, MUSE



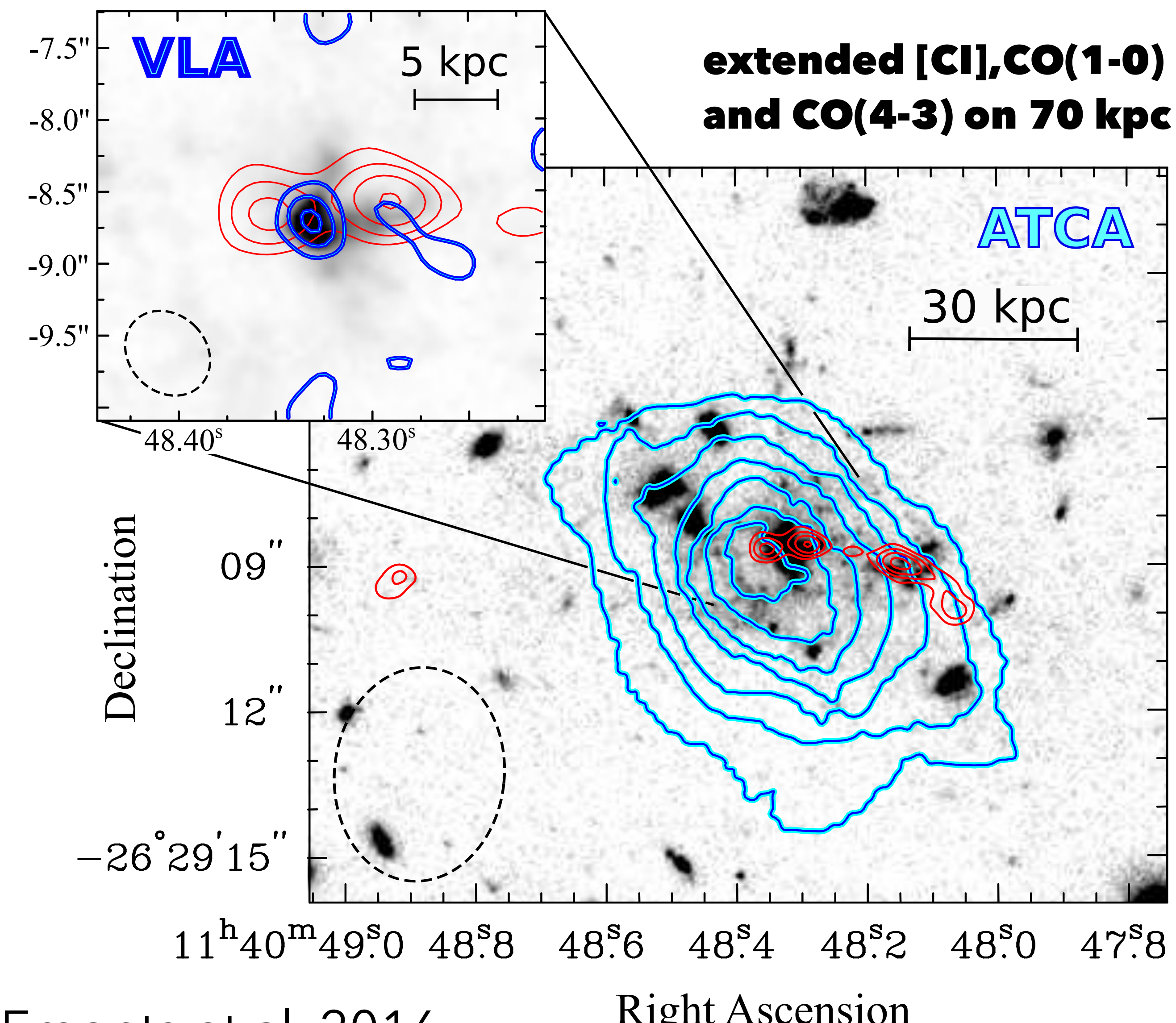
Leclerq+18



Wisotzki+18

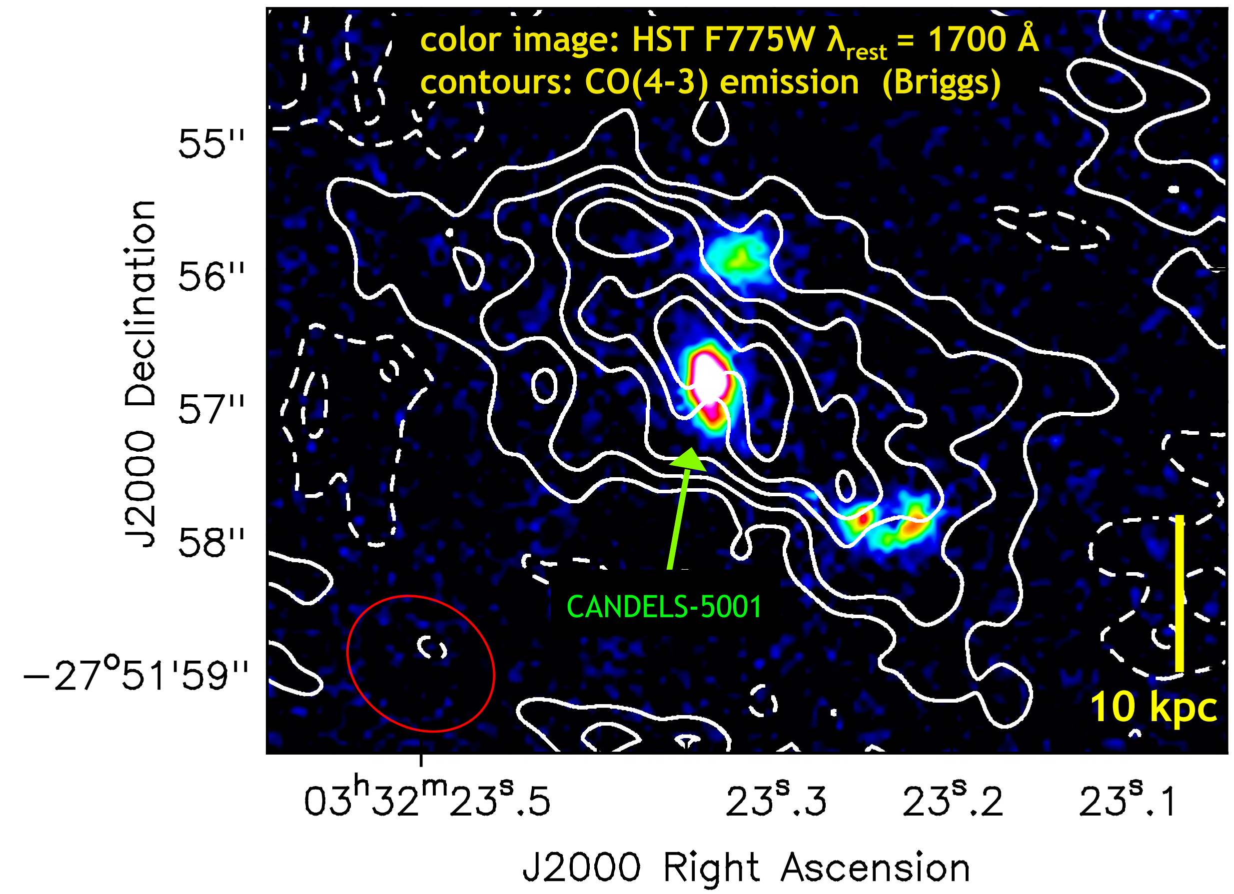
r ~ 20 kpc

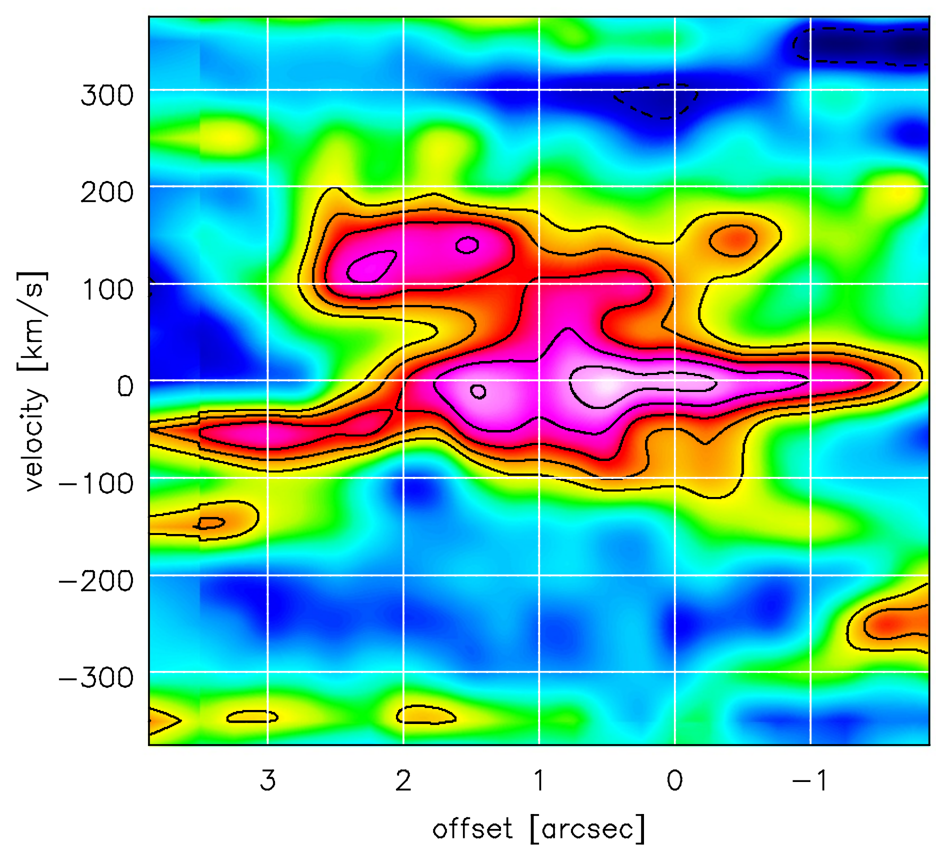
Massive protocluster galaxies can grow out of very extended reservoir of molecular gas. The gaseous halo must have been polluted with recycled material, processed by previous SF and subsequently expelled back into the IGM.

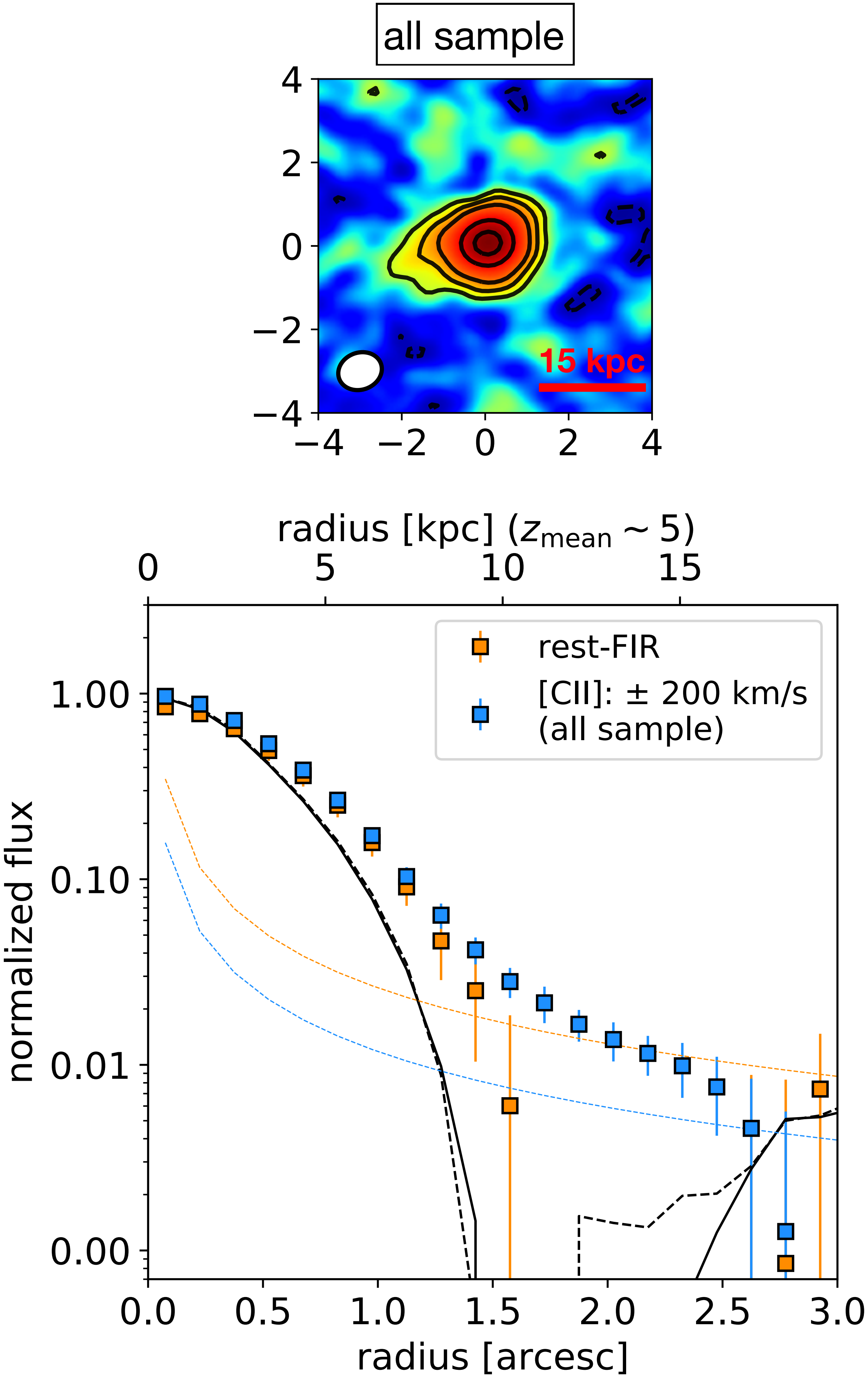


Emonts et al. 2016

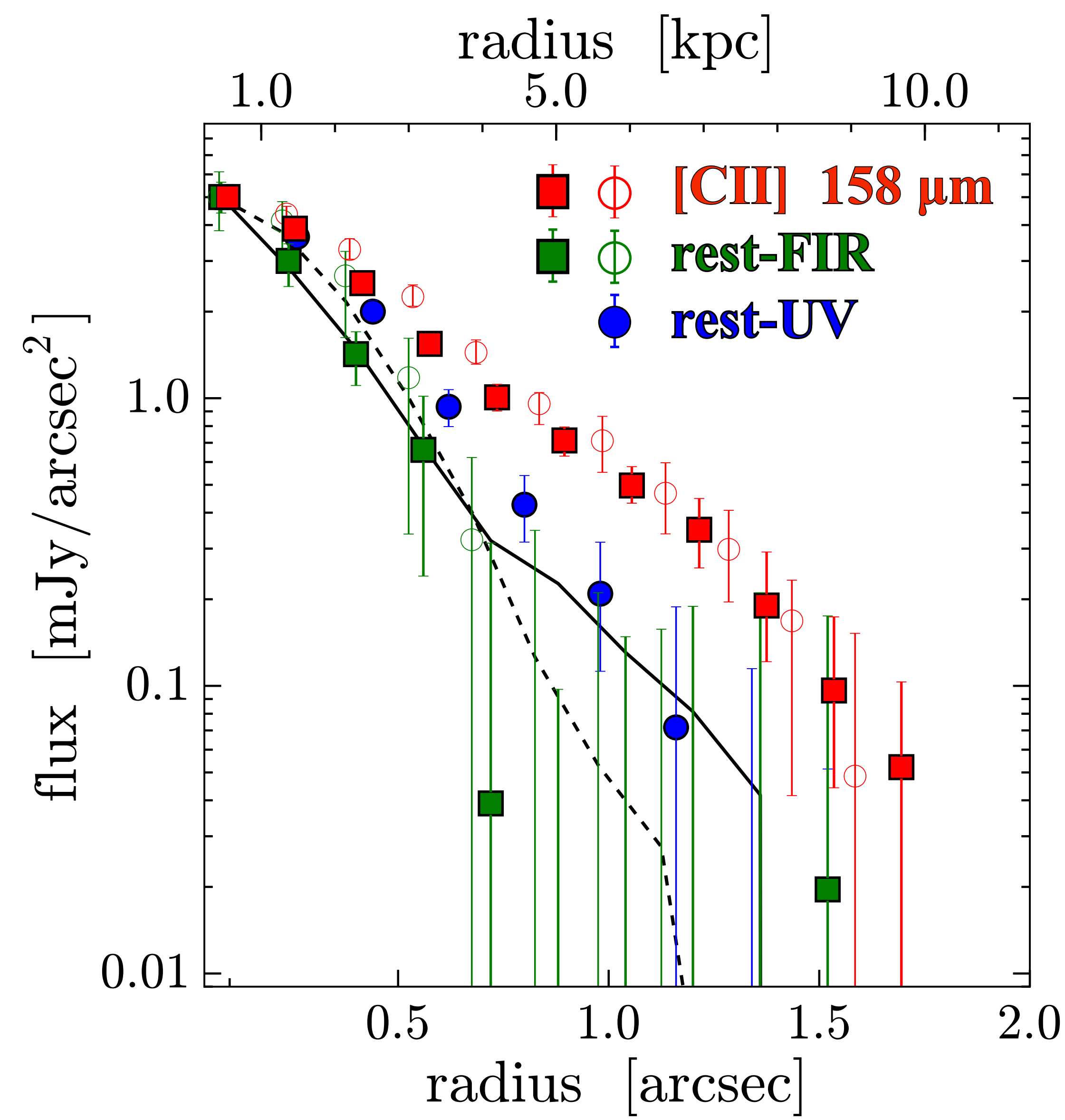
Ginolfi et al. 2017



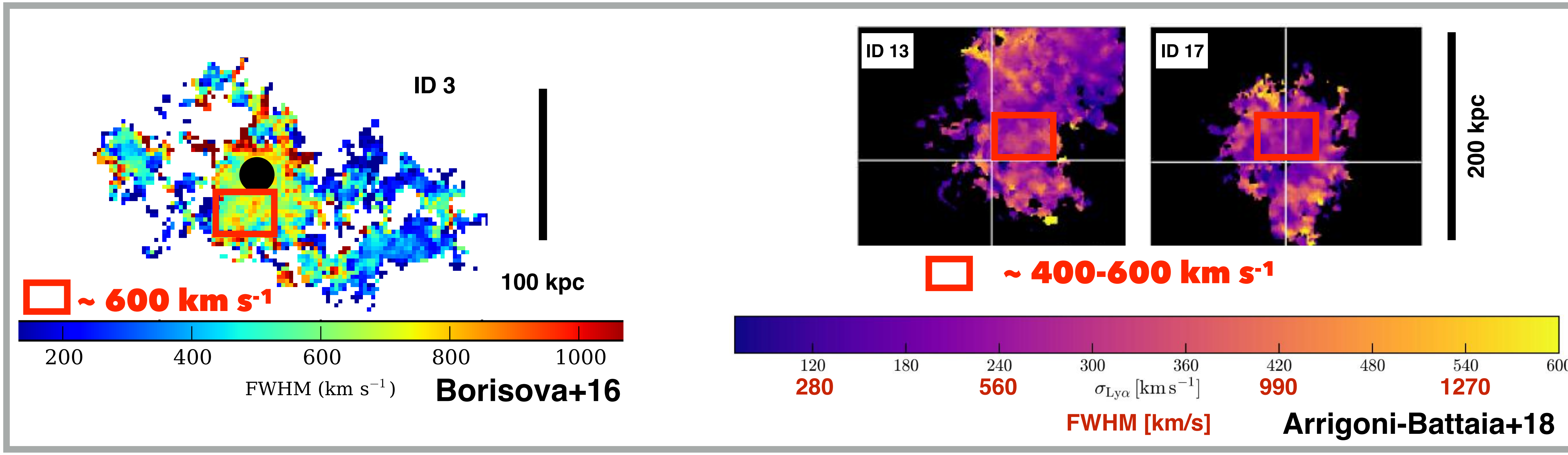




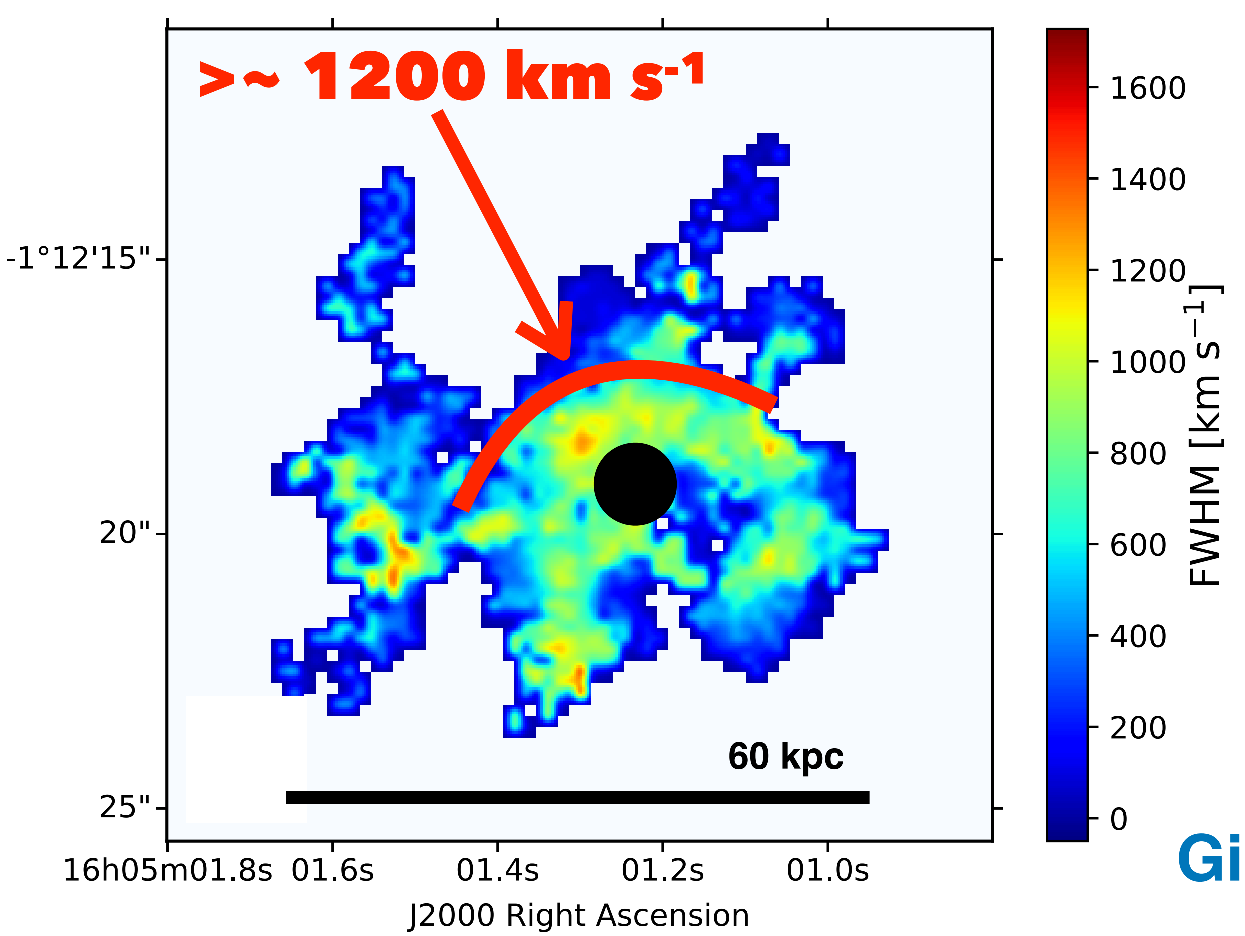
18 galaxies at z~5-7,
with SFR~10-70 M_{sun}/yr



Fujimoto+19



Kinematics from Lya is challenging. But strong outflows may leave signatures of Lya-broadening in the CGM.



Ginolfi+18