Unveiling Early Galaxy Evolution Through Gas Kinematics

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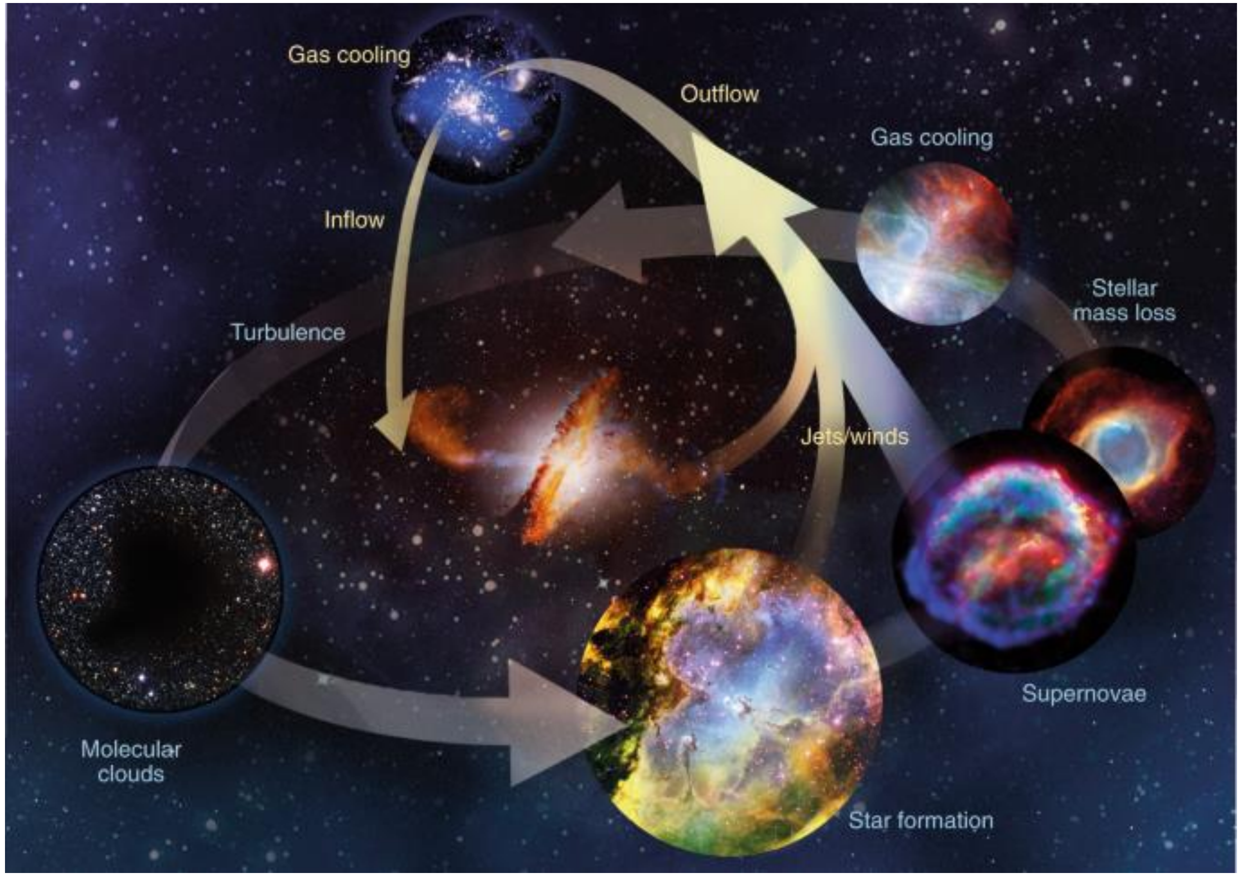
Current in office 260 of UA-Steward

In collaboration with Masami Ouchi, Kimihiko Nakajima, Yuichi Harikane, Hidenobu Yajima, Yuki Isobe, et al.

Galaxy Evolution



"Many aspects of star and galaxy formation can be viewed as ***a cosmic tug-of-war between feedback and gravitational collapse"***

--- Pathways to Discovery in Astronomy and Astrophysics for the 2020s

Tracer of gravity

Circular motions probe mass distribution including star, gas, and dark matter

Galaxies w/ ordered rotation:

$$M_{\rm dyn}(< R) = v_{\rm rot}(R)^2 R/G$$

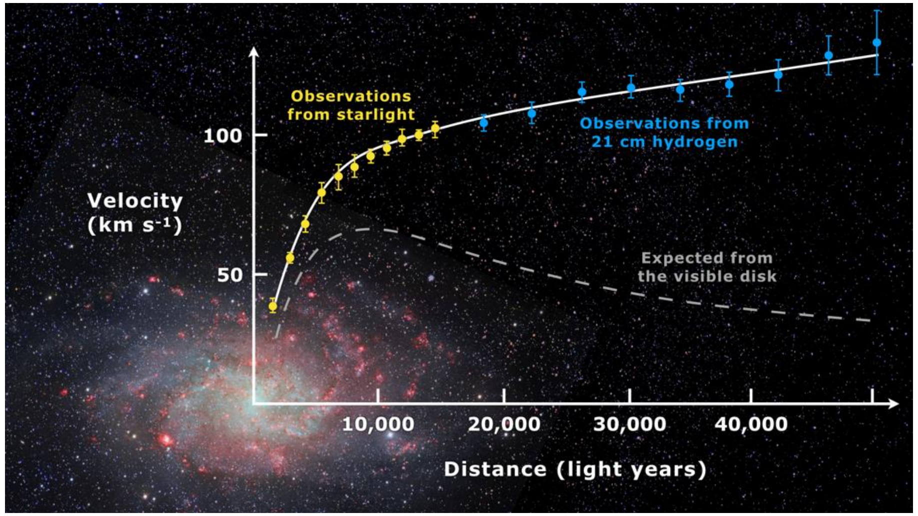
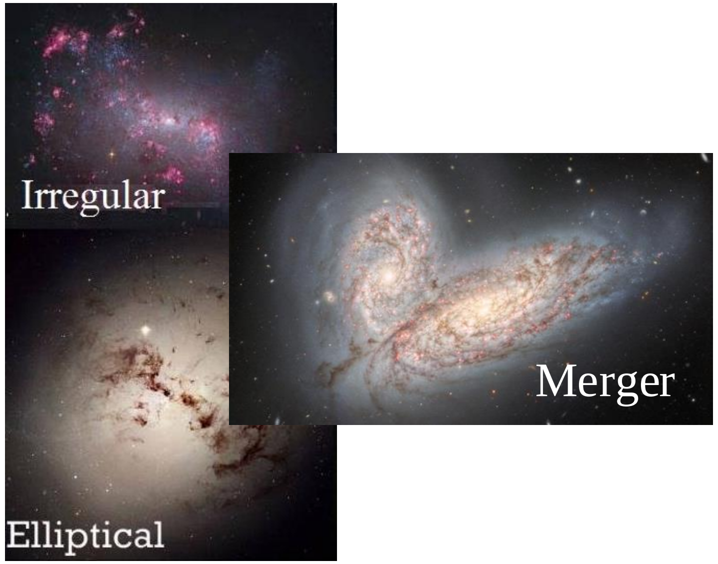


Image credit: Mario De Leo

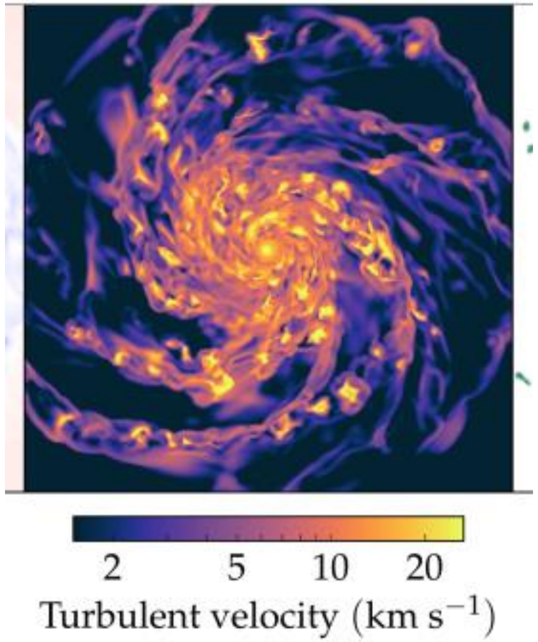
Galaxies w/o ordered rotation:

$$M_{\rm dyn} = a\sigma_{\rm eff}^2 R_{\rm eff}/G \ ?$$

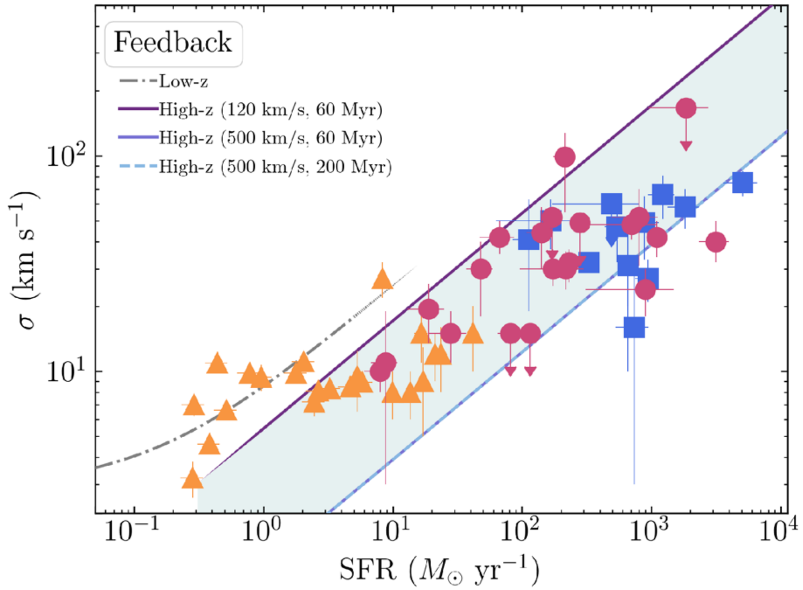


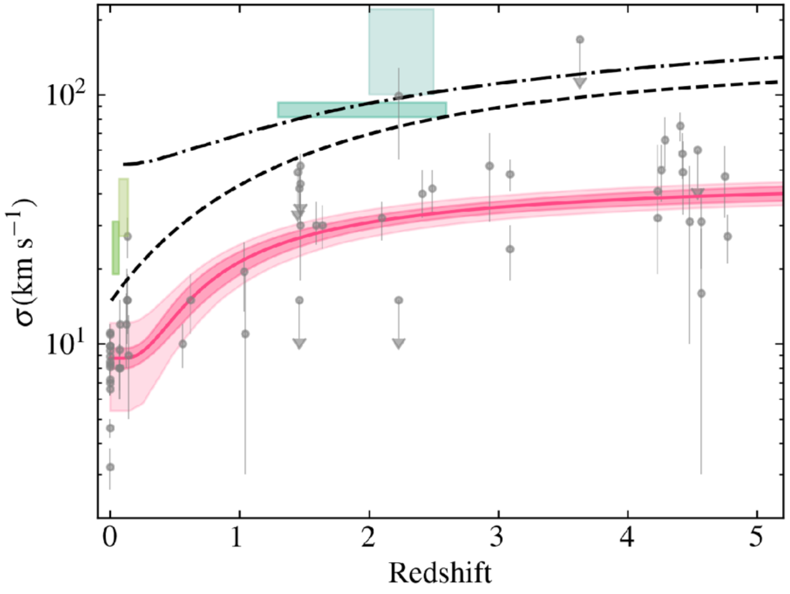
Tracer of feedback

Turbulent motions are produced by feedback



Semenov et al. 2016



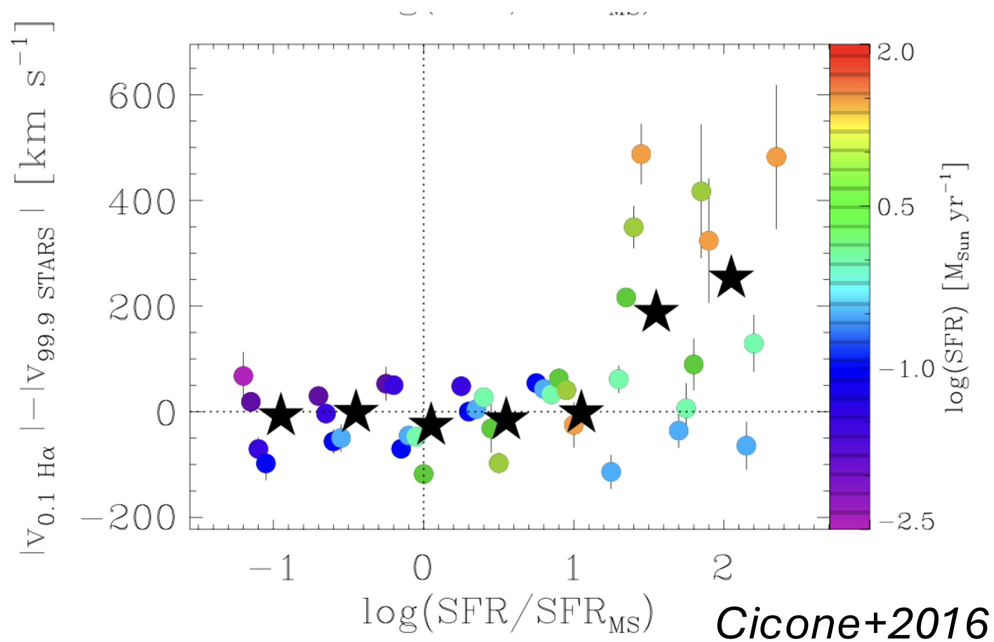


Rizzo+2024

Tracer of feedback

Outflows are connected to energy and momentum injection from supernovae, massive stars, and AGNs

More intense star formation produces stronger outflows ⟷ Stronger outflows suppress star formation



Cicone+2016

Questions to be answered

- Up to what redshift rotation curve can be used as a tracer of dynamical mass? Where is the earliest disk?

- How ordered rotation and turbulence evolve across cosmic time?

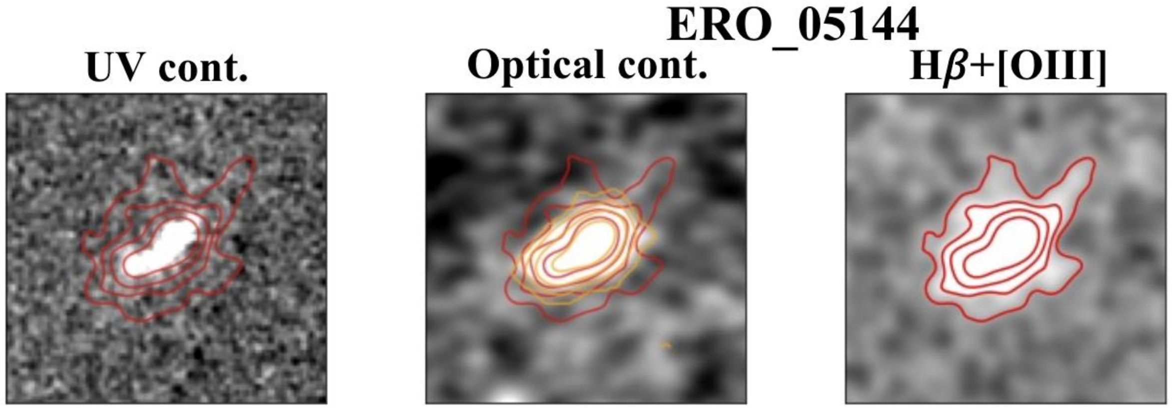
- How outflows depends on galaxy properties at different redshifts

Part I.
Outflows at high redshift

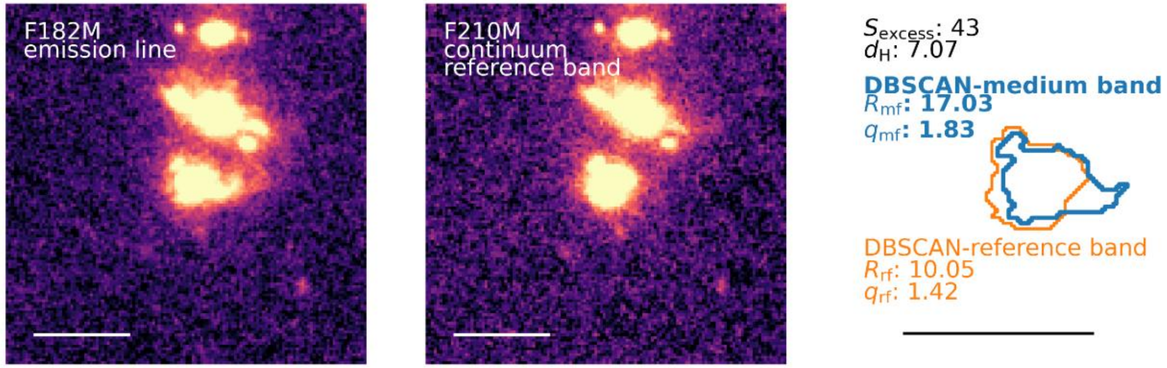
Based on Xu et al. 2023 arxiv:2310.06614

Outflows at high z with JWST

Spatial extension on images

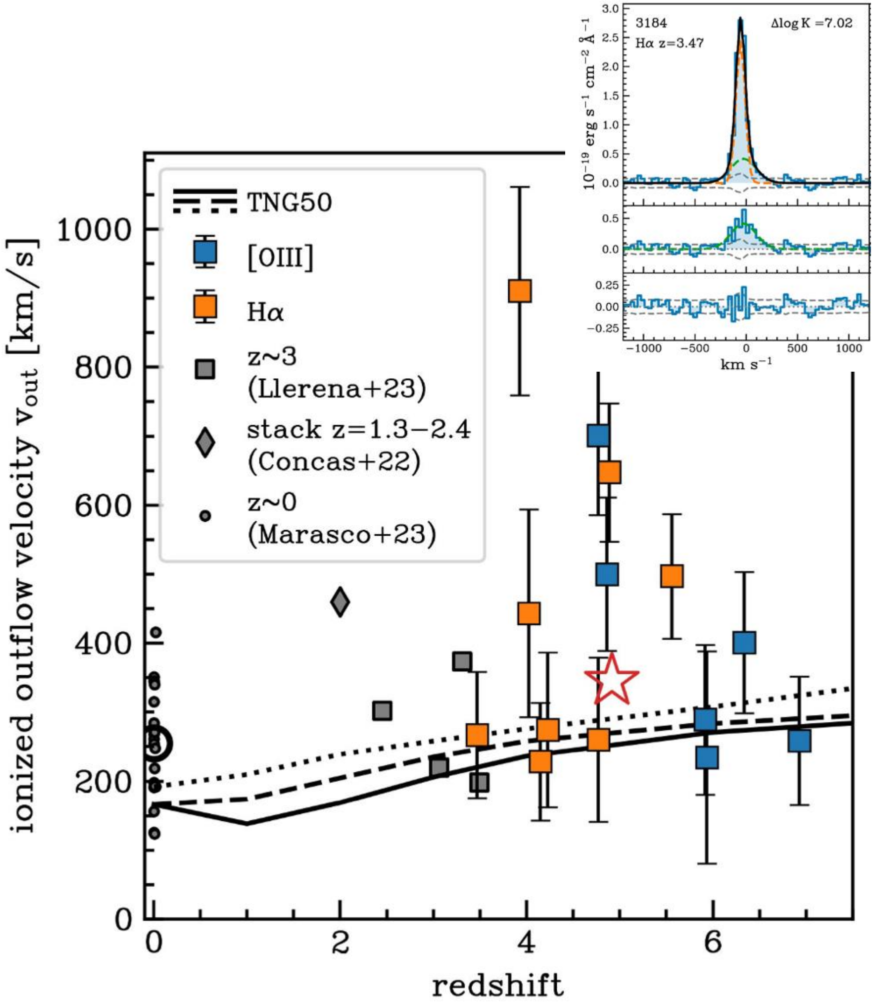


Y. Zhang, ..., YX, et al. 2024



Zhu+2025

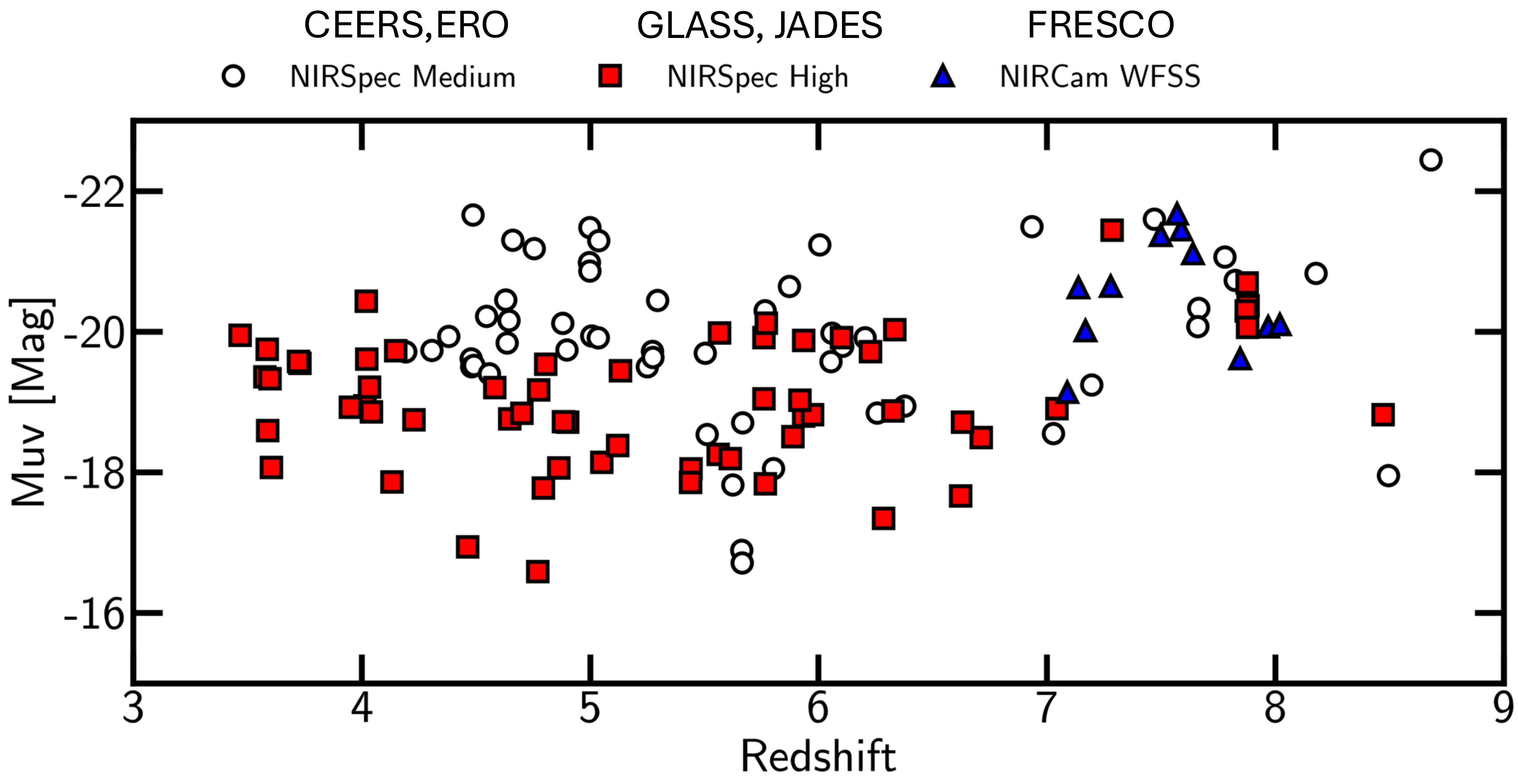
Broad emission line



Carniani+2024 (JADES team)

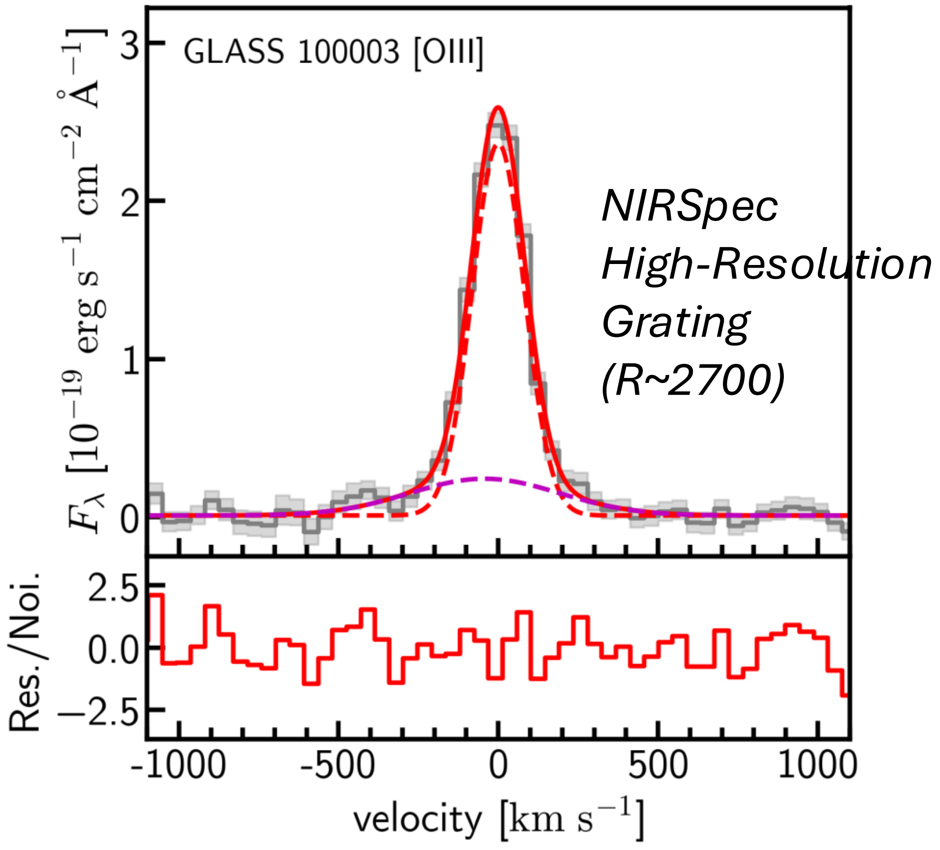
Dataset

130 galaxies at z~3-9 with Hα or [OIII]λ5007 detections



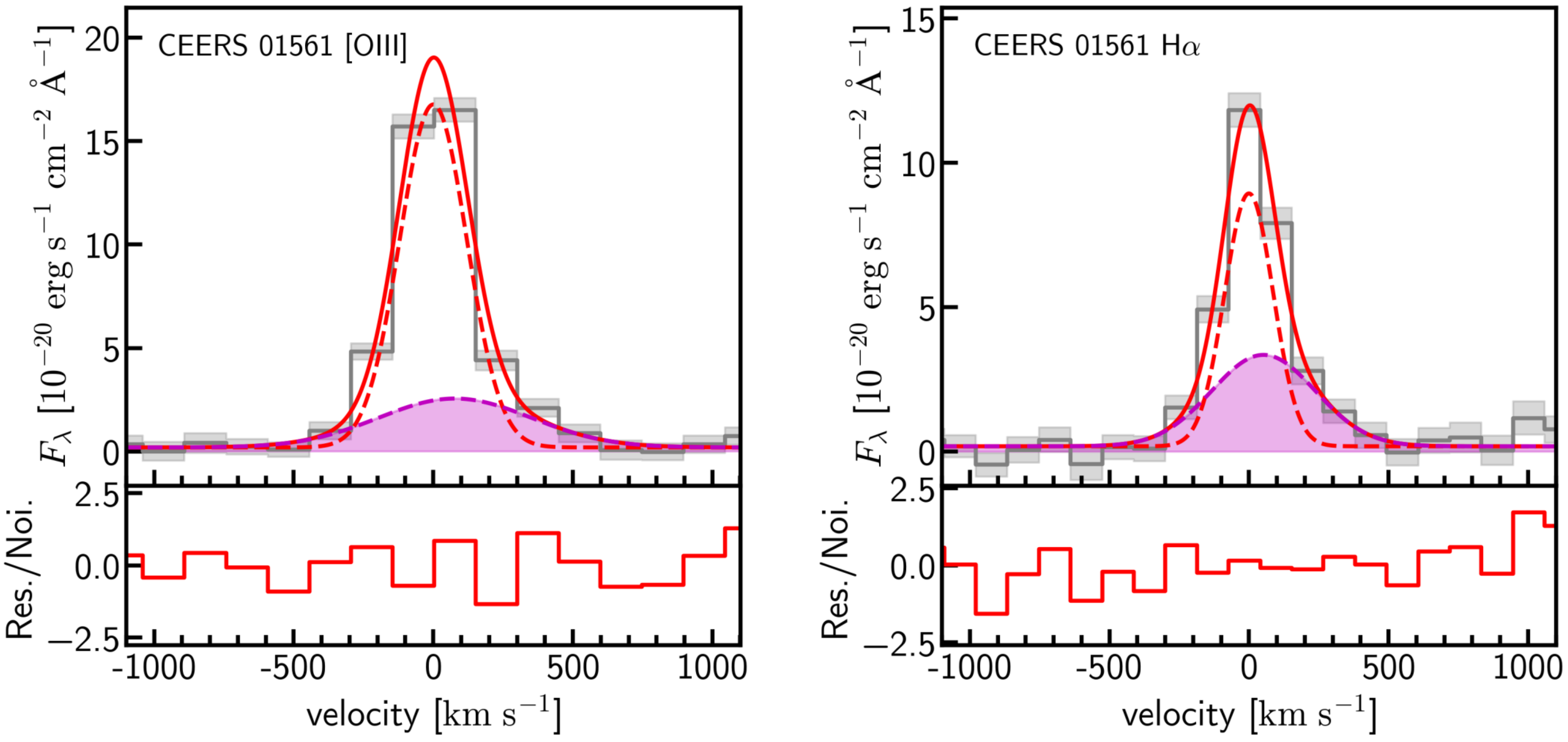
Detecting outflows

Broad wings tracing hot ionized outflows

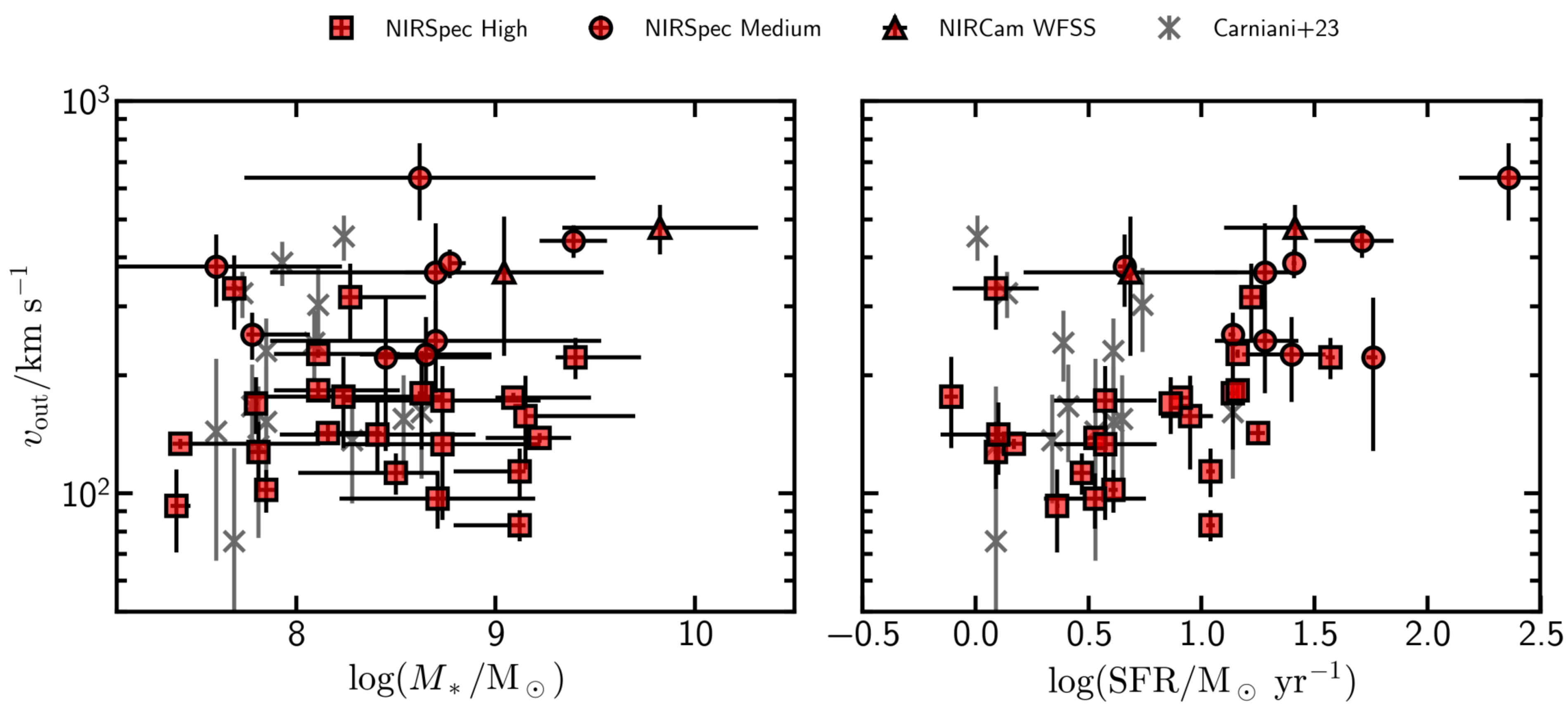


Detecting outflows

detected in [OIII] and Hα even with medium-resolution grating (R~1000)

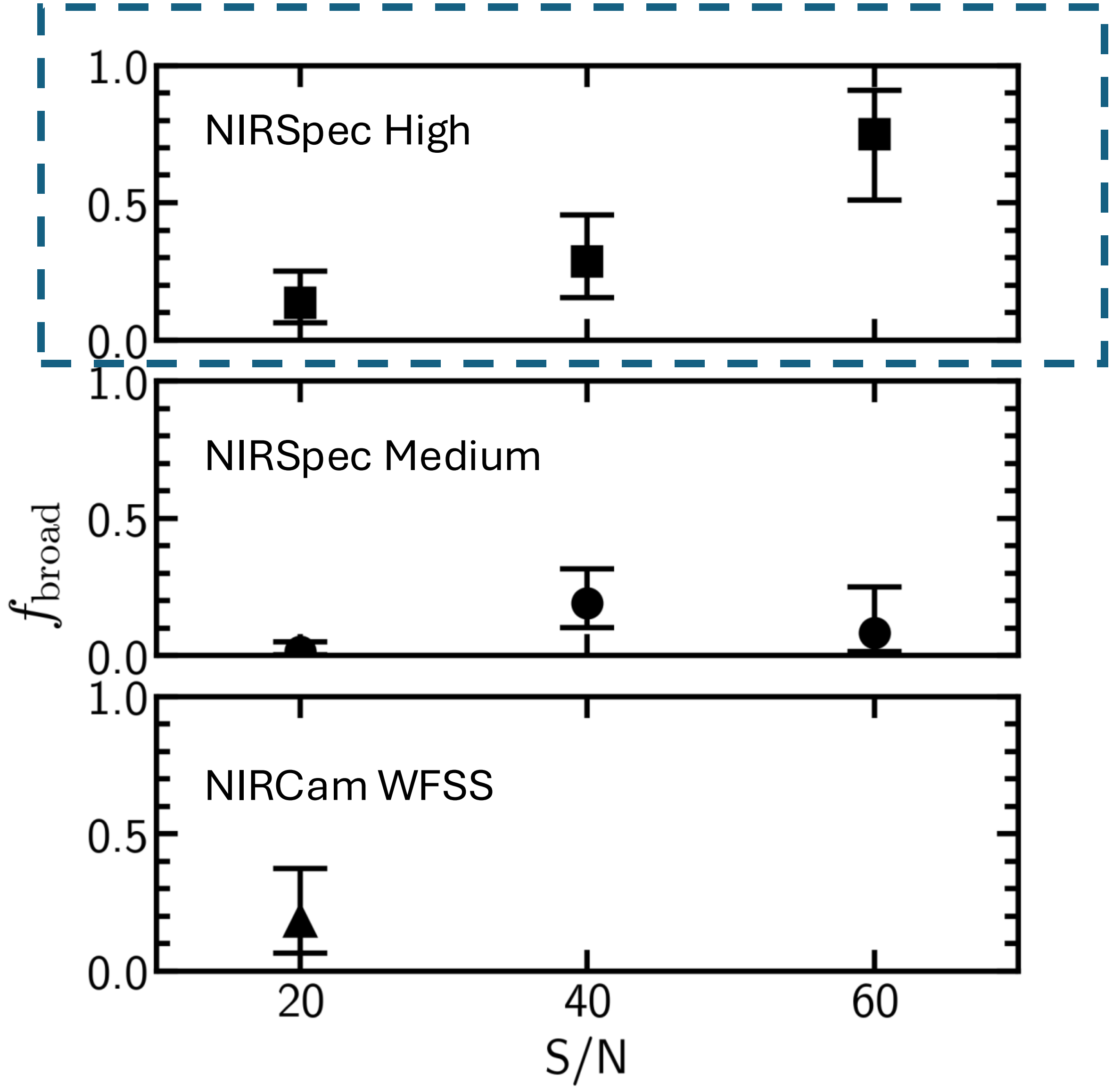


Outflow velocity $v_{\rm out} = |v_{\rm cent,out} - v_{\rm cent,narrow}| + {\rm FWHM}_{\rm out}/2$

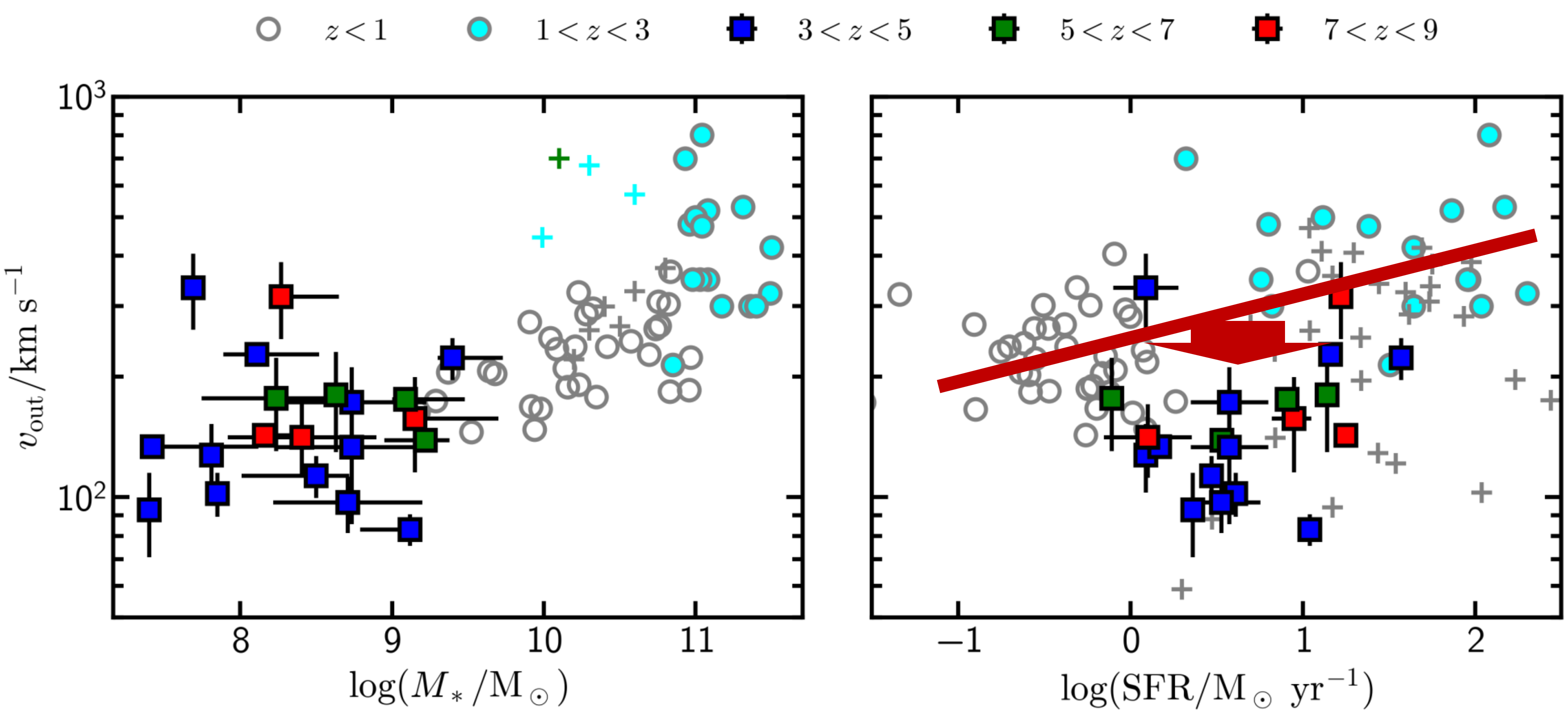


Large scatters exist => careful treatment of subsamples are needed

Outflow detections are subject to data quality

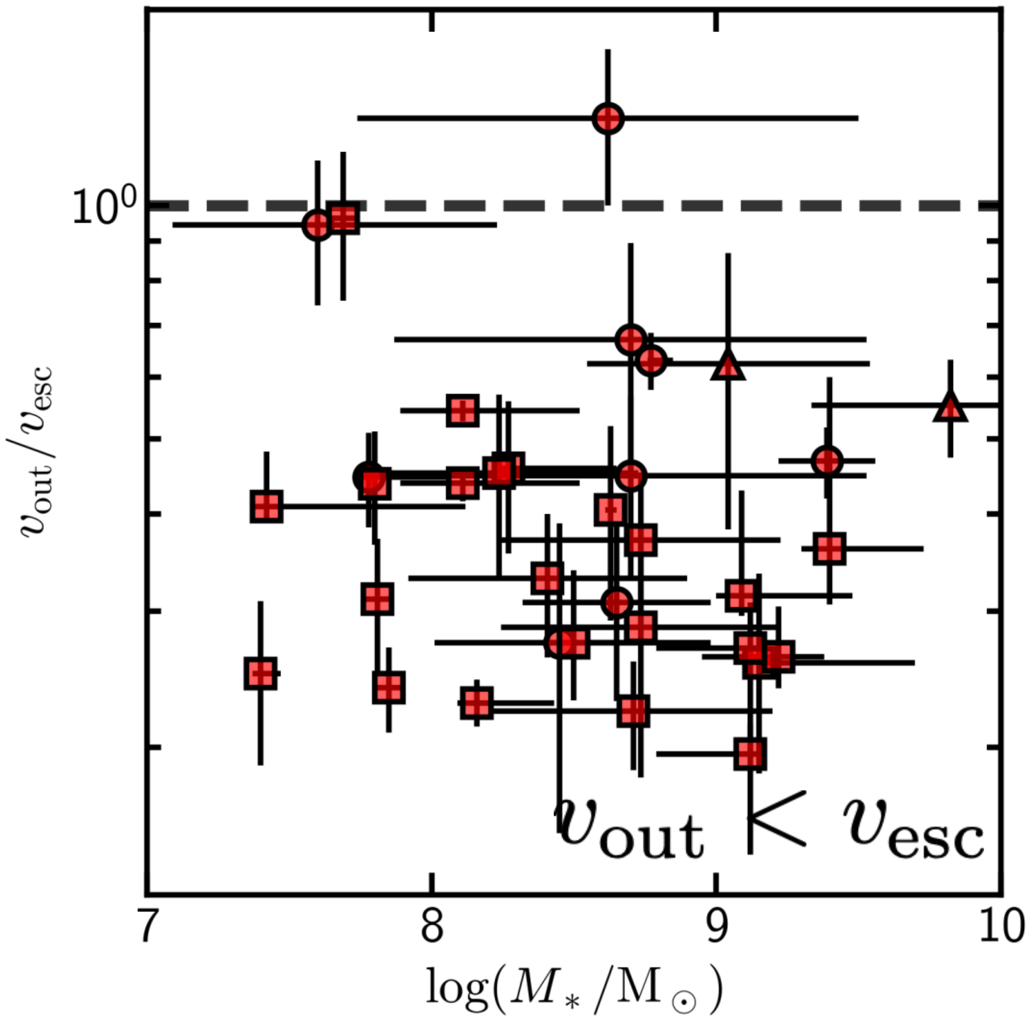


Outflow velocity



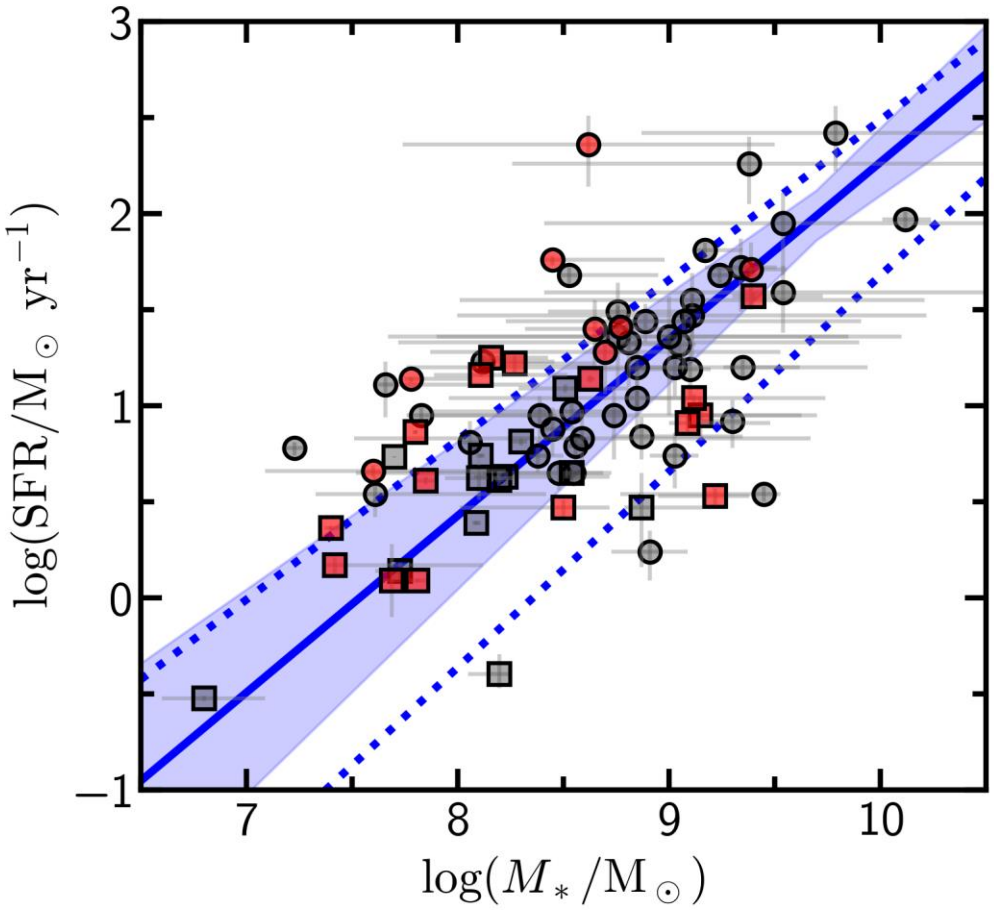
- ➢ Outflow velocities are smaller at high redshift for the same SFR
- ➢ Dependence on stellar mass suggesting effect of gravitation

Discussions on outflows

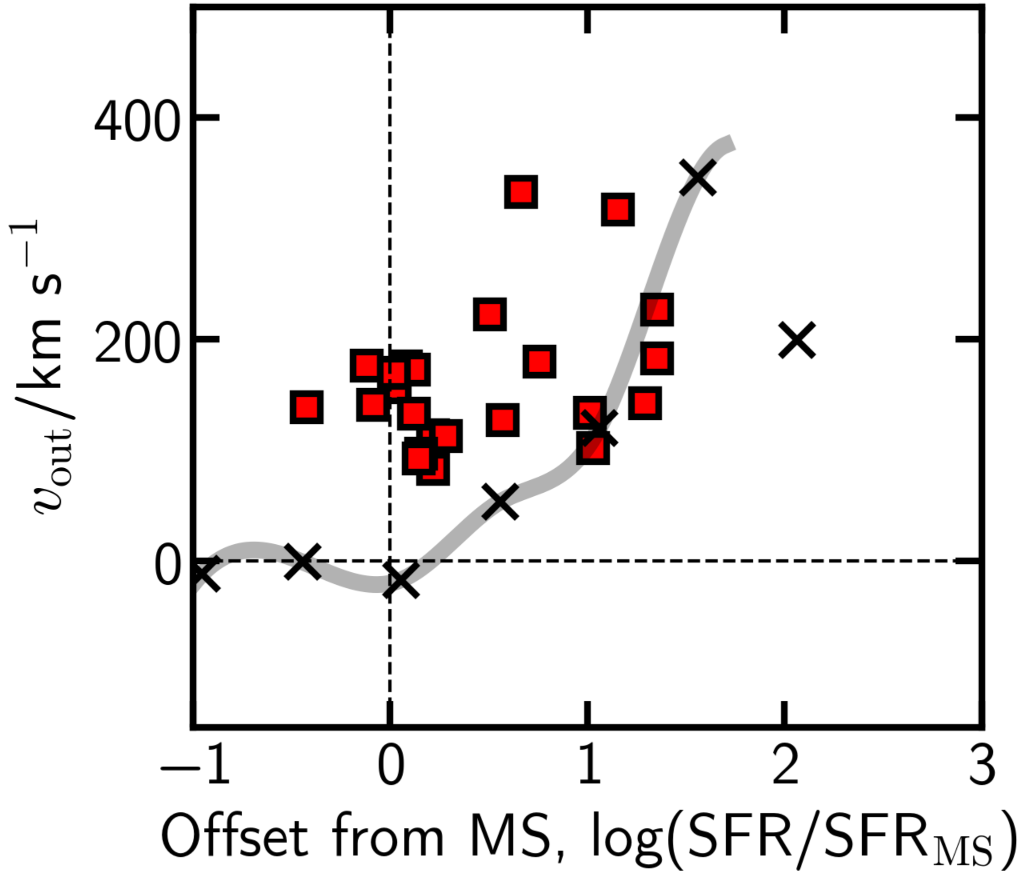


Outflows are not fast enough to escape

Outflows and SF main sequence



Galaxies above SFMS drive stronger outflows



Summary

- We identify 30 out of 130 galaxies with outflow signatures with NIRSpec Medium, NIRSpec High, NIRcam WFSS data
- Outflow velocities can be governed by gravitation at $3<z<9$
- Correlation between outflow incidence and SFMS indicates feedback is at play at high z

Part II.
Earliest rotating disk

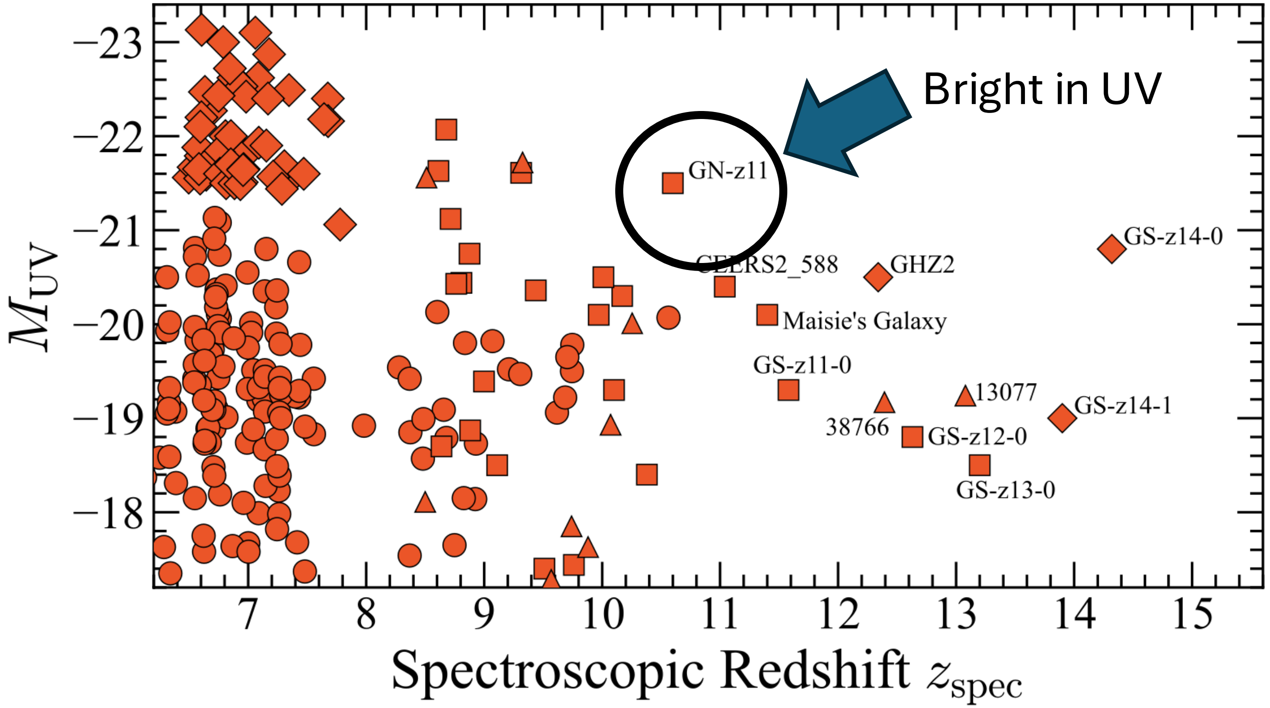
Based on Xu et al. 2024 ApJ

Target

GN-z11 at z=10.6 when the universe is ~500 Myr old

$\log(M_*/M_\odot) = 9.1$, SFR=21 $M_\odot$/yr

Image credit: NASA



Observations

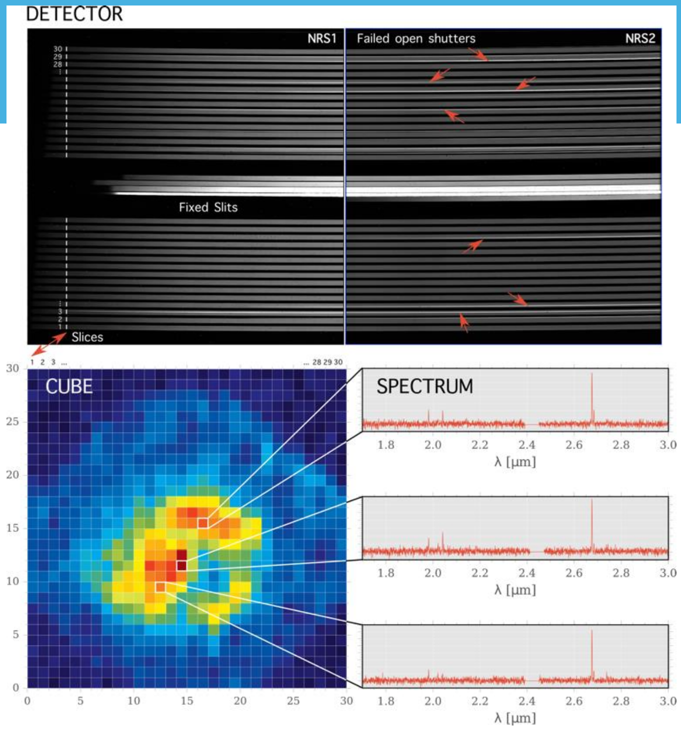
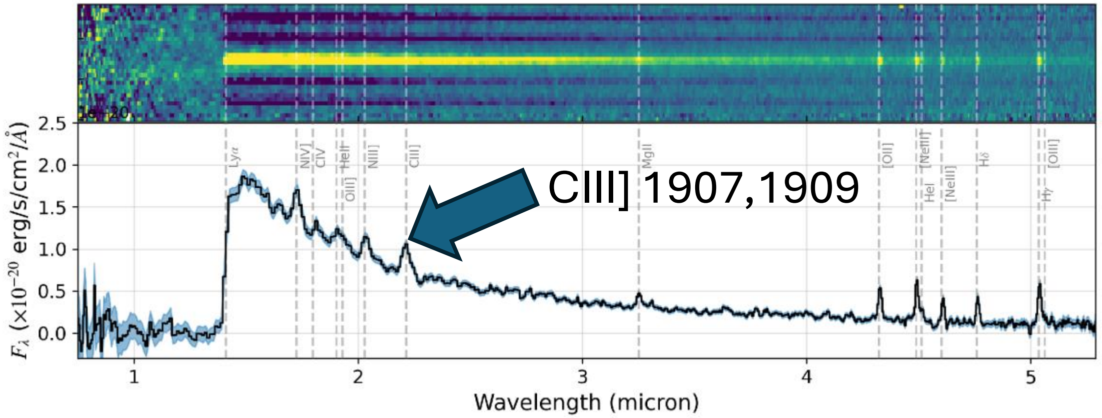


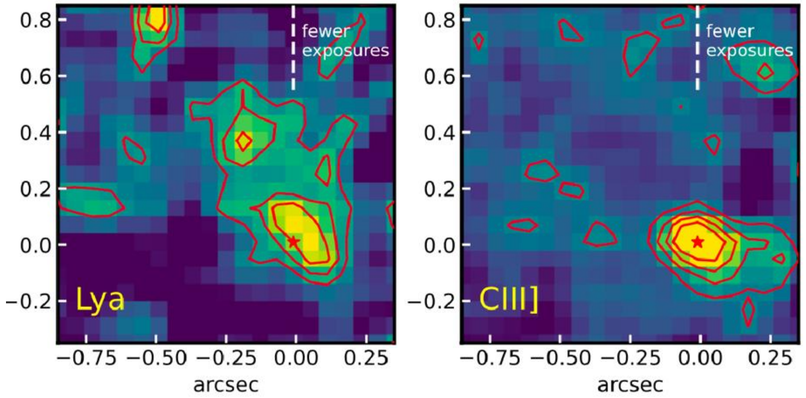
Image credit: NASA

JWST NIRSpec IFU

- G235M/F170LP covers 1.7-3.2 micron
- DDT 4426 (PI: Roberto Maiolino)
- Exposure time: 14 hours (**7 hours more than M23**)
- Prominent C III] emission
- New reduction from scratch

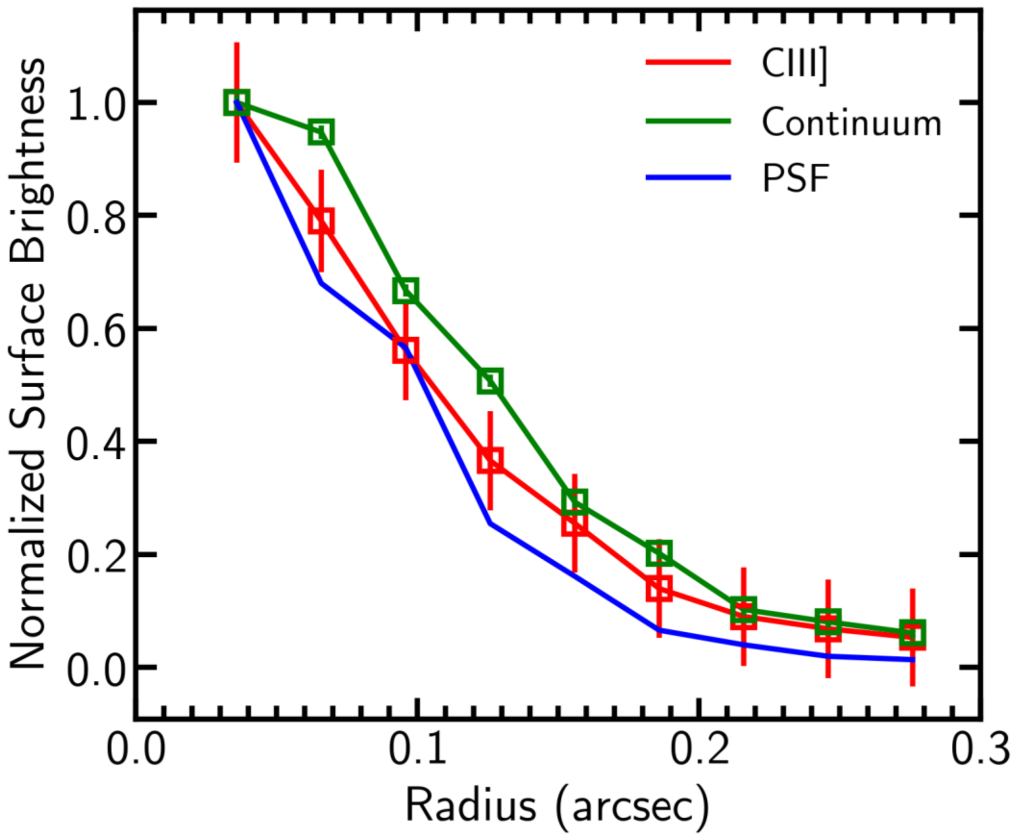


Bunker et al. 2023



Maiolino et al. 2023

Is C III] spatially resolved?

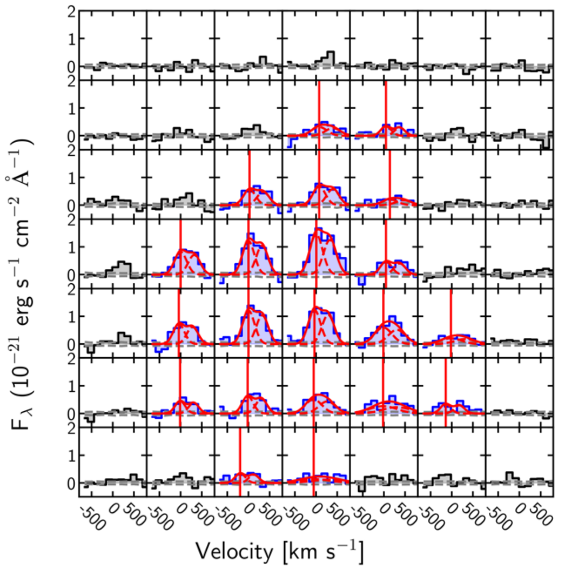


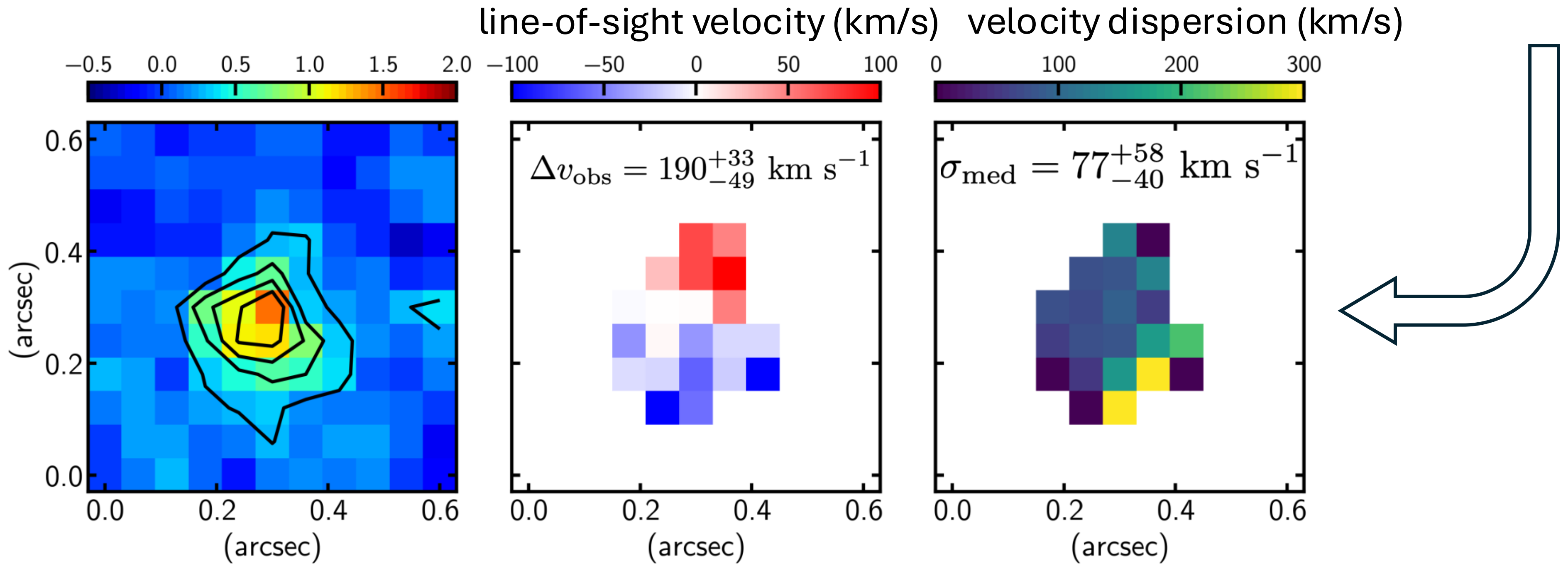
C III] is spatially extended over point-spread function (PSF)

Tracers of gas kinematics?

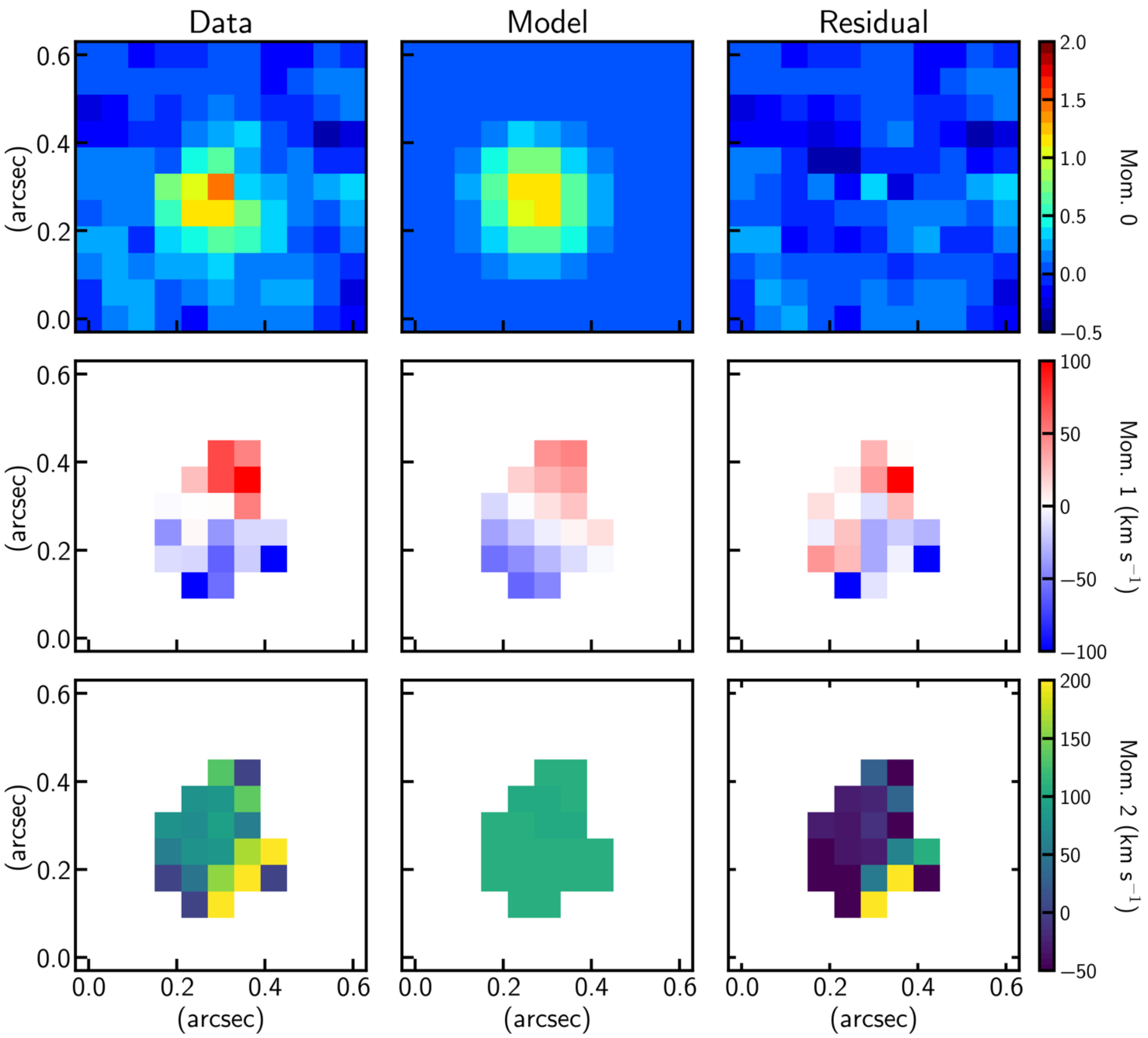
C III] kinematics

- C III] 1907,1909: marginally resolved doublet
- Two-component fitting in each high S/N spaxel
- Result
  - Clear velocity gradient $\Delta v_{\rm obs}/2\sigma_{\rm med} = 1.34^{+0.68}_{-0.98}$
  - Rotating disk at z=10.6?





Forward modelling of rotating disk



GalPak^{3D} model

- exponential disk
- arctan rotation curve
- convolved with line-spread function and PSF

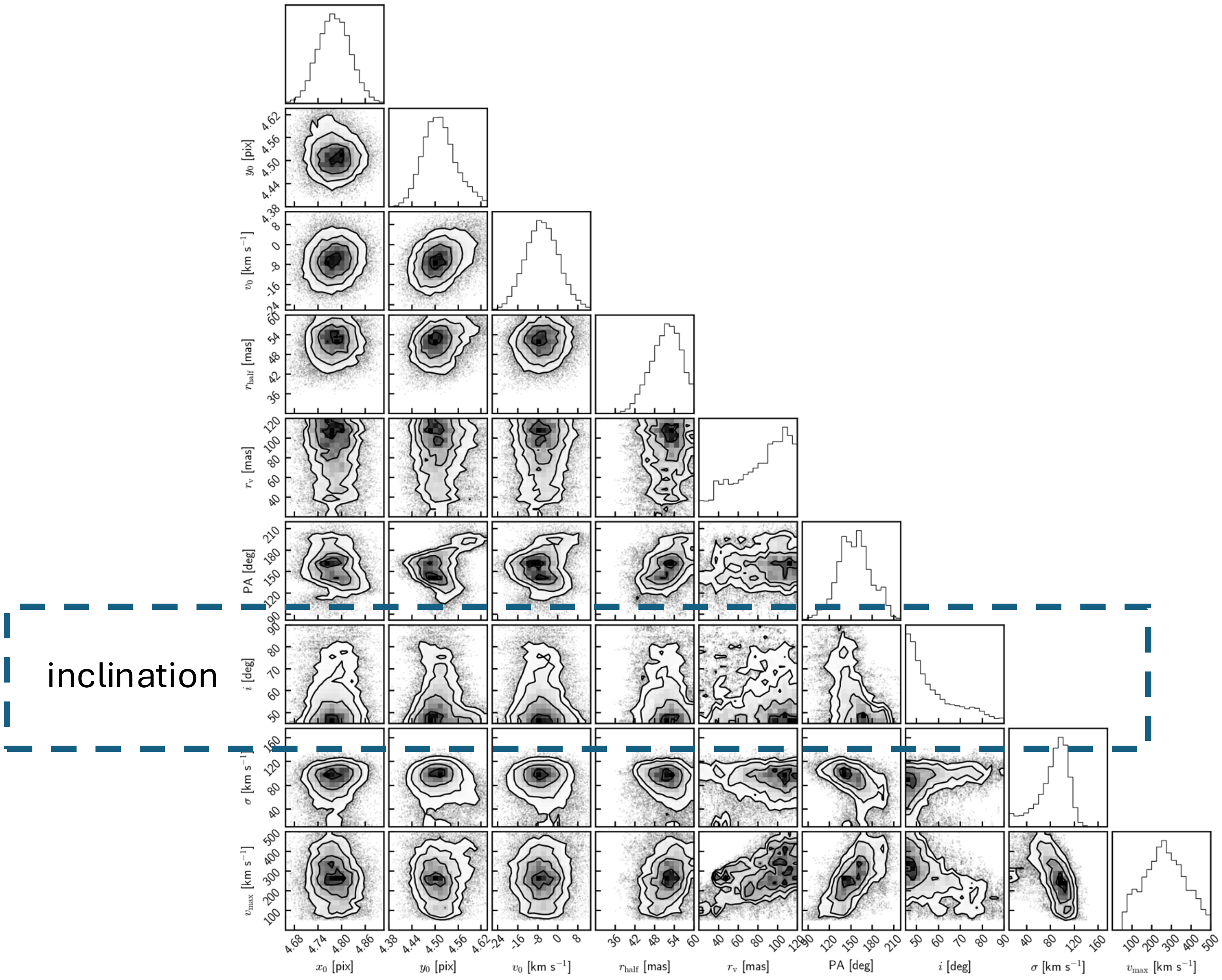
Results:
Explained by a rotating disk

$$v_{\rm rot} = 249^{+111}_{-118}\ \rm km\ s^{-1}$$

$$\sigma = 92^{+16}_{-31}\ \rm km\ s^{-1}$$

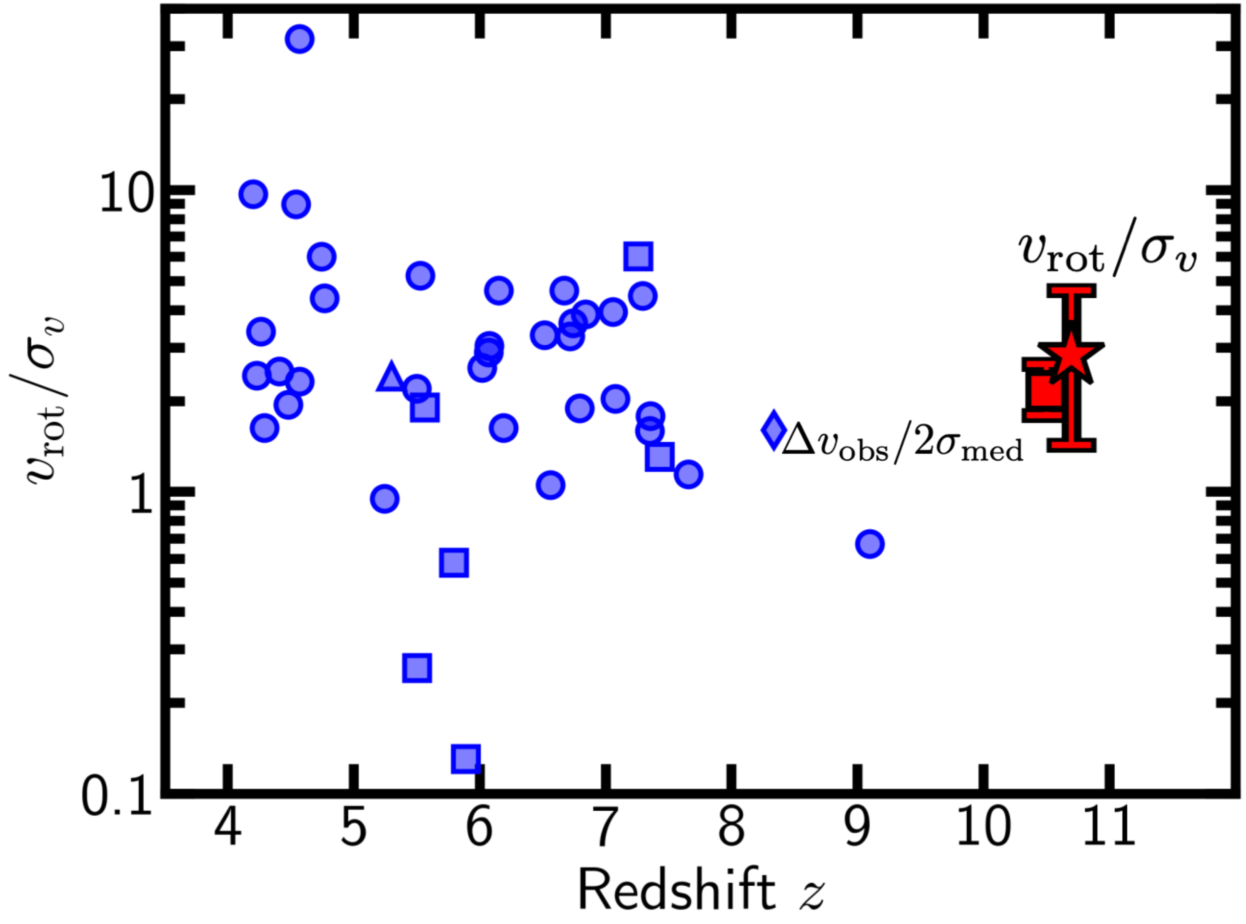
$$v_{\rm rot}/\sigma = 2.8^{+1.8}_{-1.4}$$

Constraint on inclination is still difficult



v/sigma

Rotation-dominated disk in the first 500 Myr of the universe

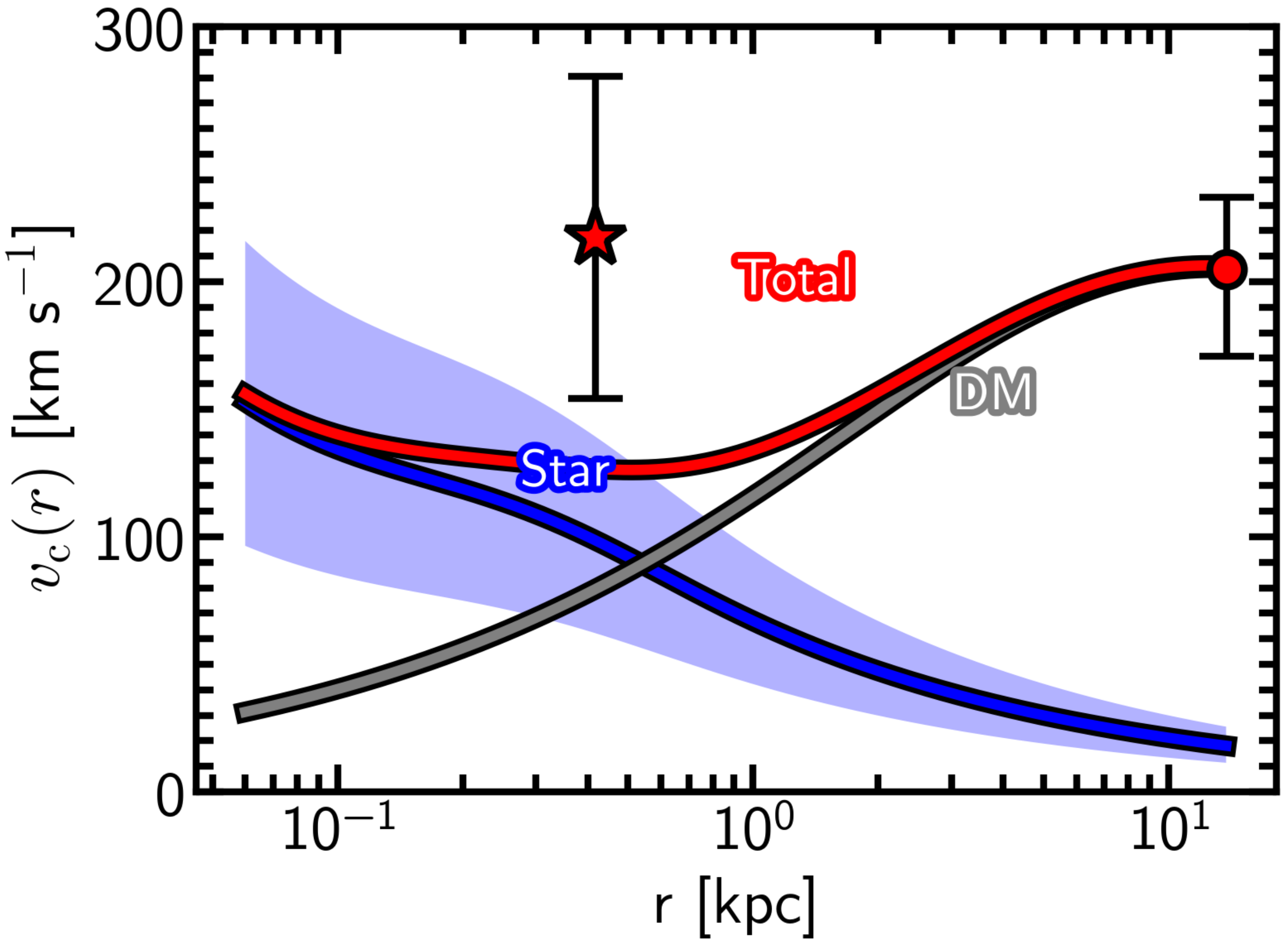


Is this surprising?

- GN-z11 is **massive** for z=10.6 => growing fast and possibly undergo weak feedback
- GN-z11 is **compact** => mass is concentrated in the center

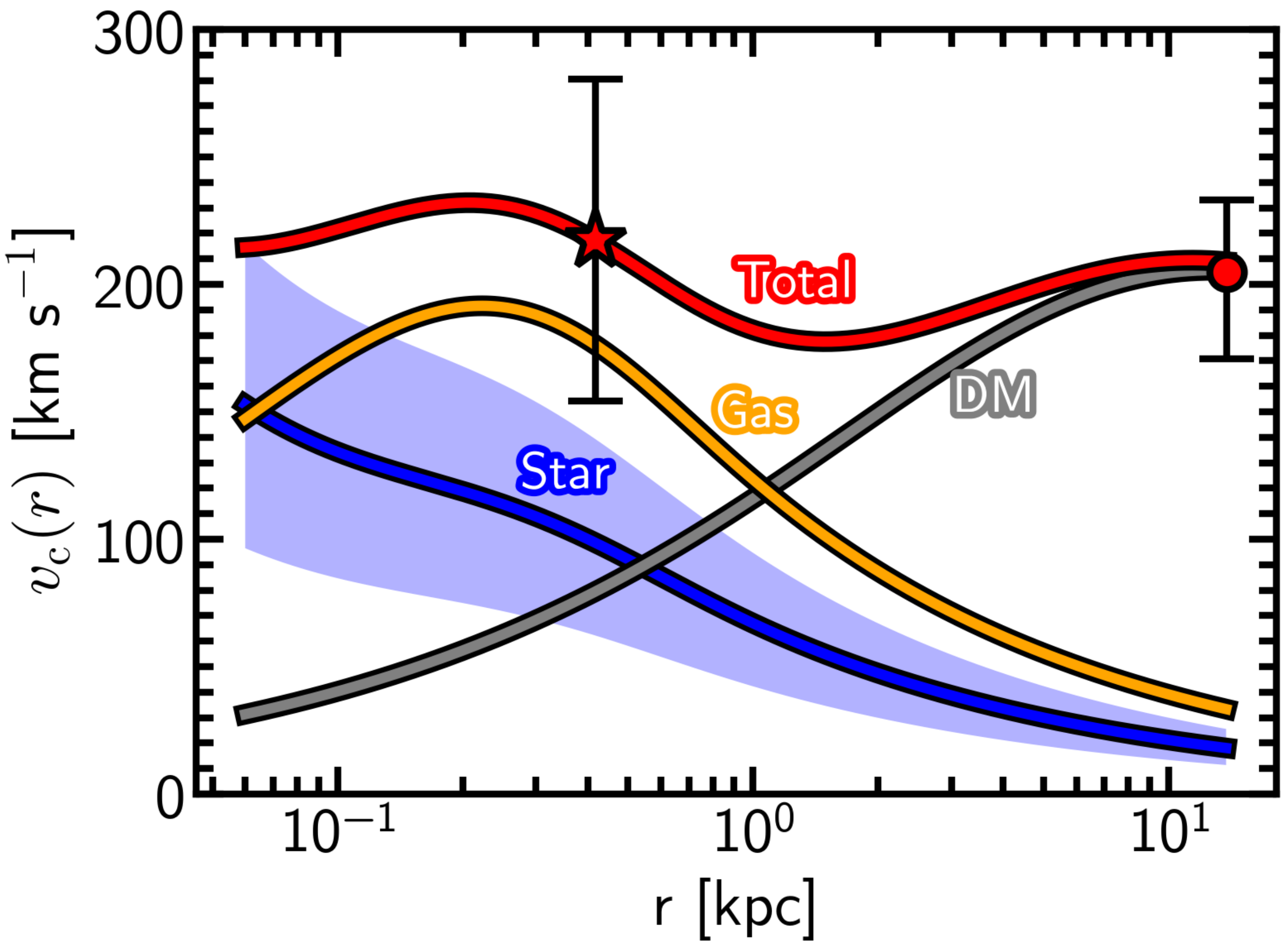
Discussions: rotation curve and mass composition

Star and DM cannot account for v_{rot}

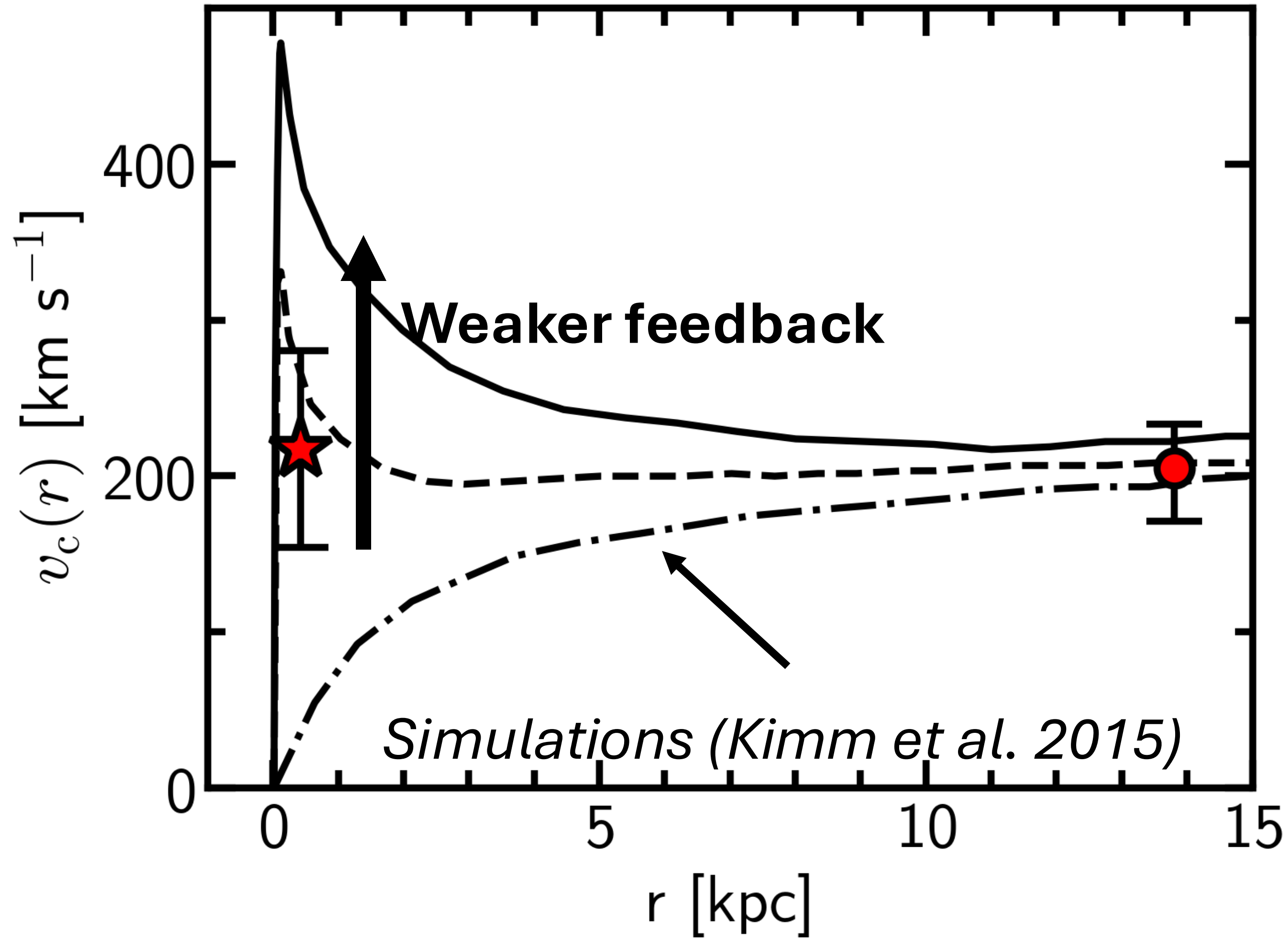


Discussions: rotation curve and mass composition

Star and DM cannot account for v_{rot} => needs large gas fraction



Discussions: rotation curve and feedback



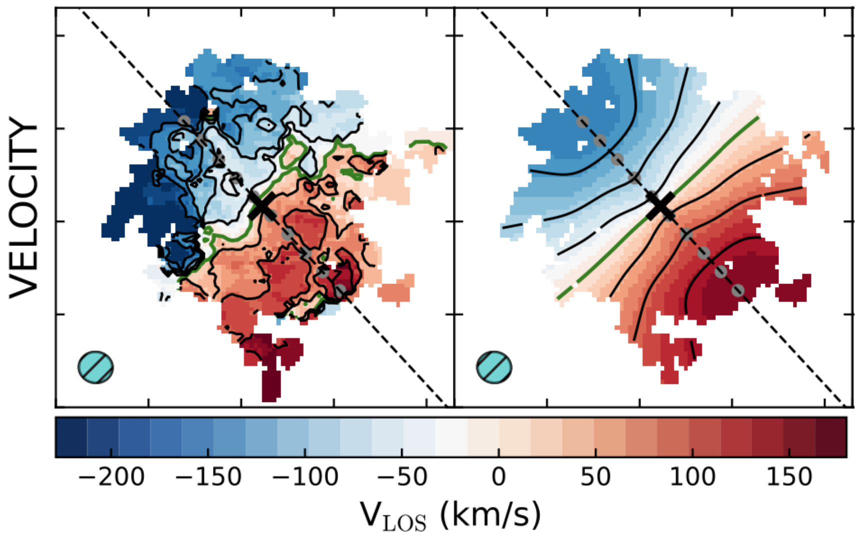
Summary

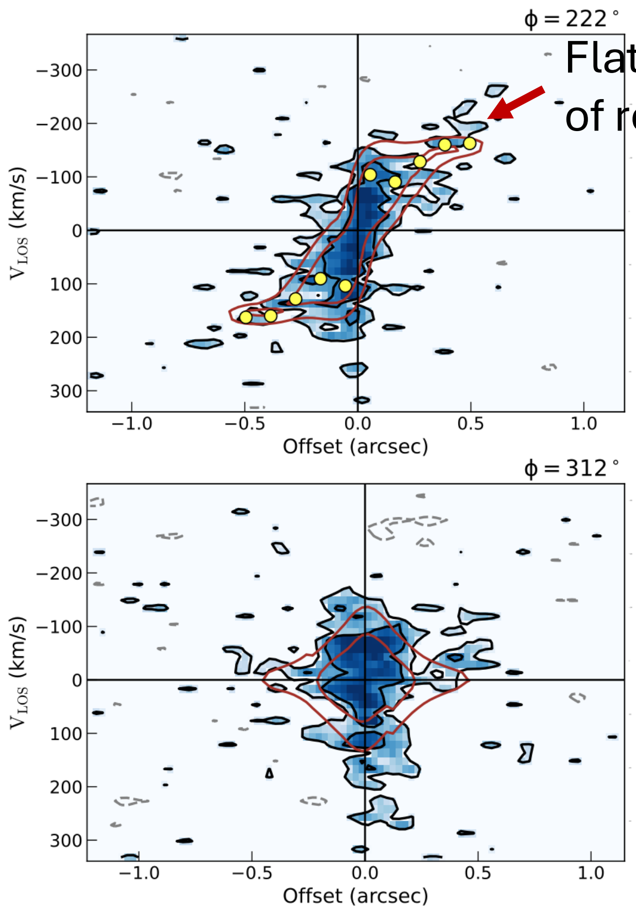
- We identify velocity gradient in GN-z11 that could be given by a rotation-dominated disk at z=10.6
- The rotation velocity can be explained by a compact mass distribution with significant contribution from gas
- Large v/sigma and concentrated rotation curve may attribute to weak feedback such predicted by simulations

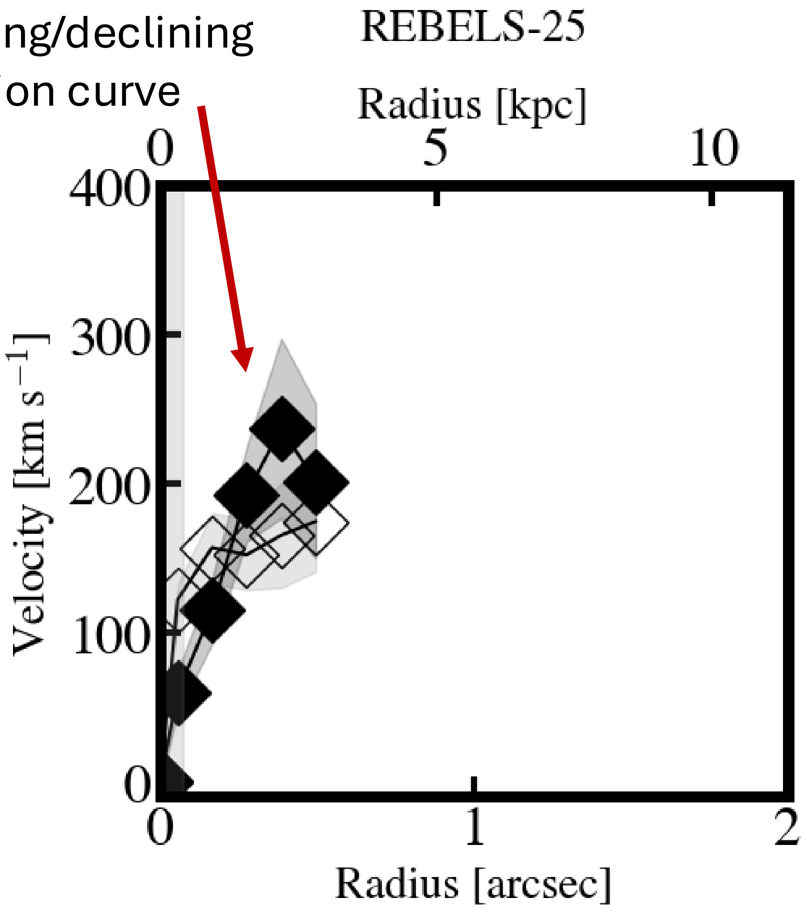
Future prospective

Can we resolve rotation curve at high z?

At slightly lower redshift than GN-z11







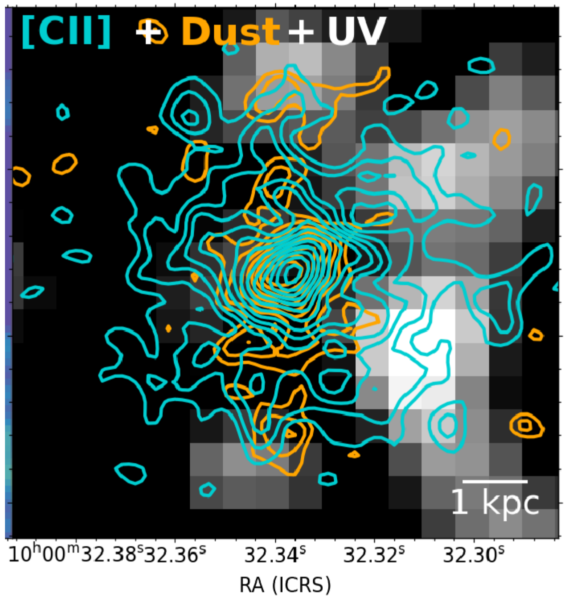
REBESL-25 at z=7.3 (Rowland+2024)

D. Sun, YX, et al. in prep.

High-z disks can look clumpy

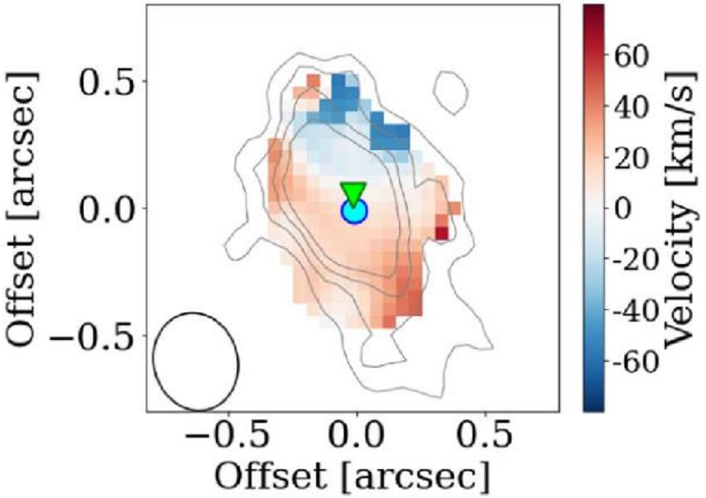
We need novel disk models!

REBELS-25 are clumpy in UV due to dust extinction

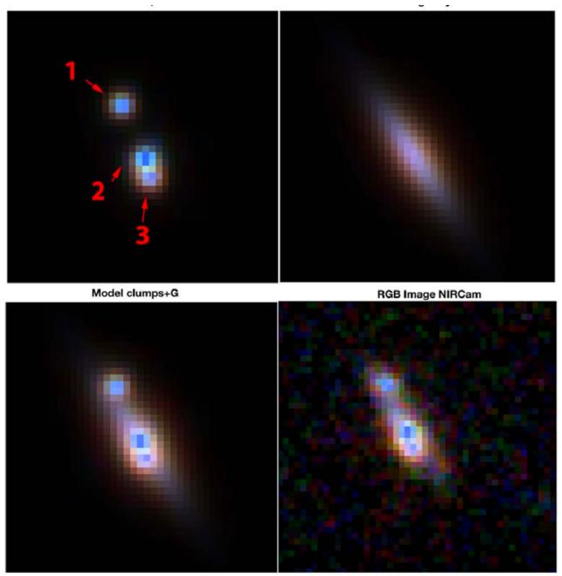


Rowland+2024

MACS1149-JD1 (z=9.1) merger or SF clumps?



Tokuoka+2022

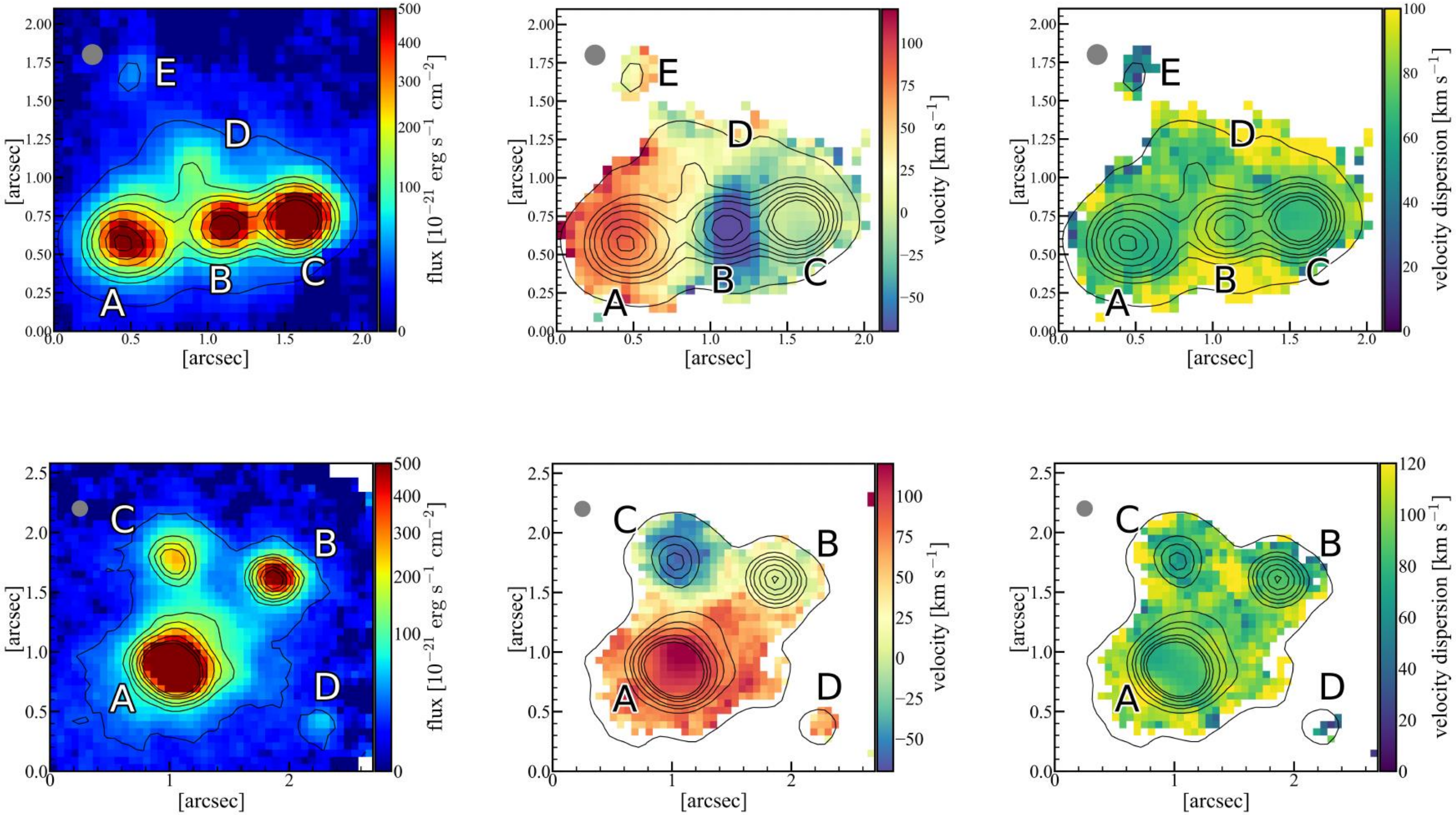


Bradač+2024

Mergers are preferably targeted by JWST NIRSpec IFU?

Himiko

CR7



T. Kiyota, YX, et al. in prep.

Still many possibilities with current instruments

- Isolated, bright targets () proposed in Cycle 4
  - UNCOVER_10646 (z=8.511) and EGS_z910_44164 (z=8.612)
- Exciting observations can be done with JWST or ALMA