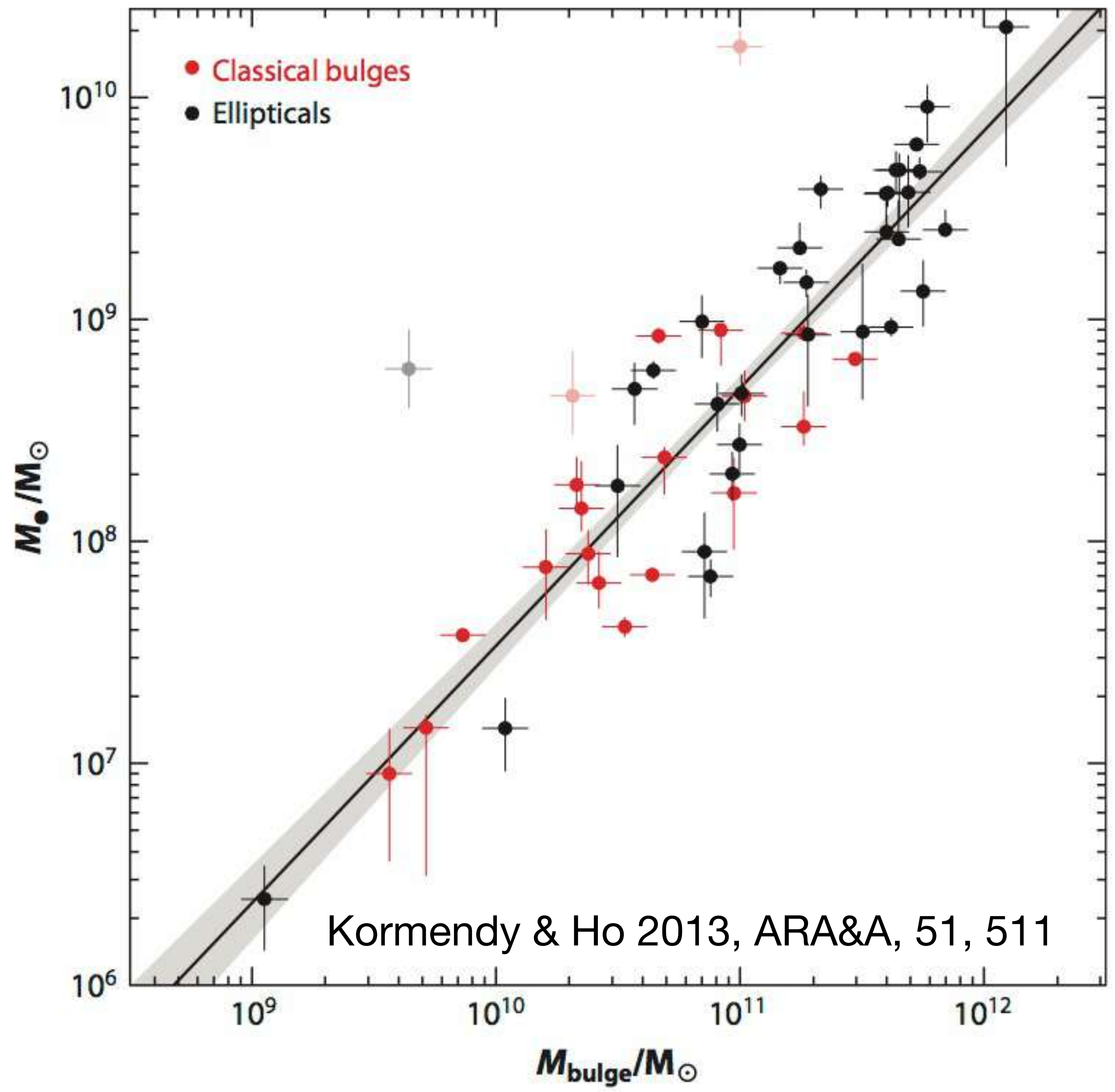
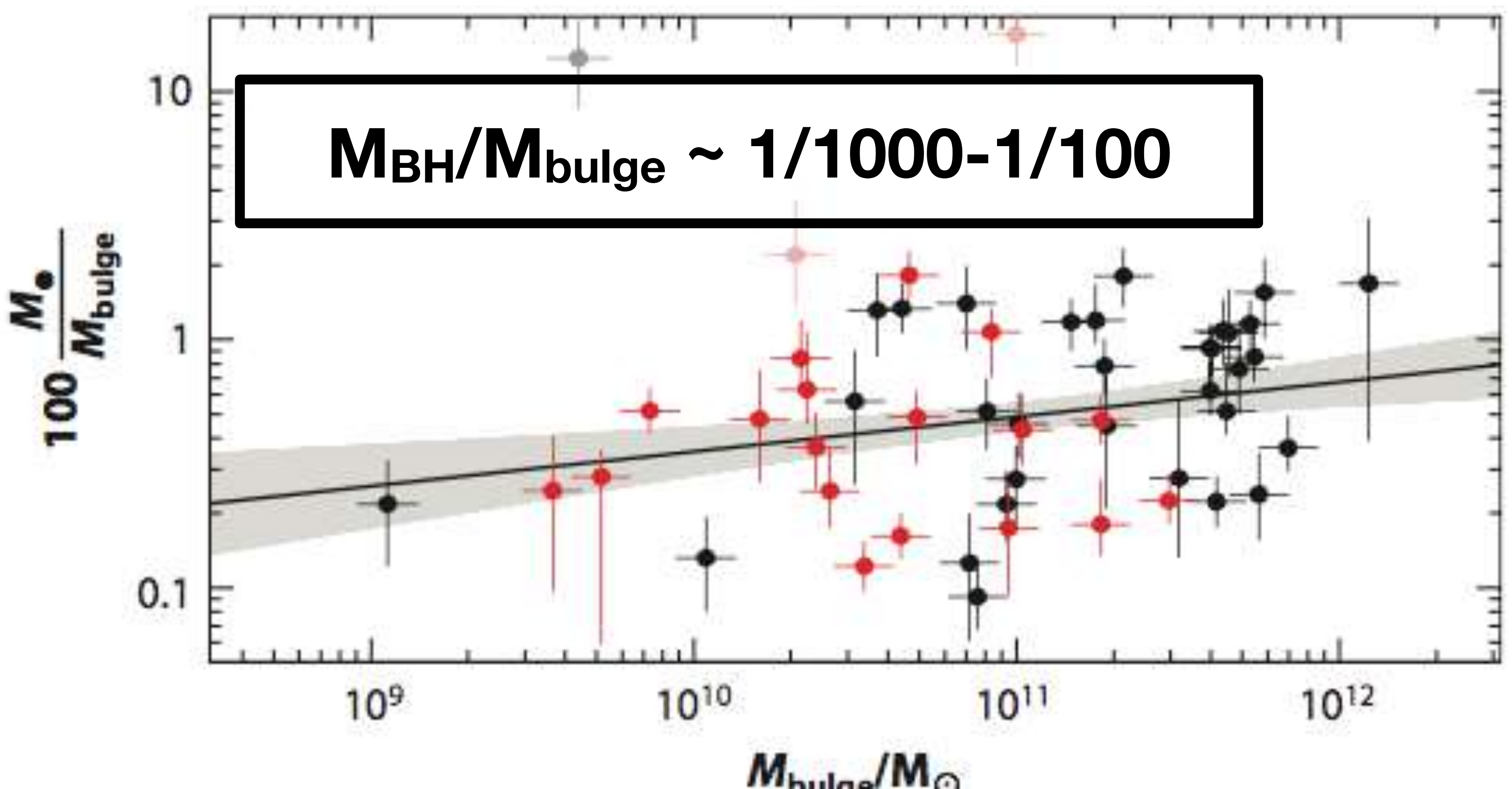
2025 Dec 1
初代星・初代銀河研究会@福井

最新観測で迫る銀河とブラックホールの始原的共進化

泉拓磨（国立天文台/東京大）
+ SHELLQs collaboration

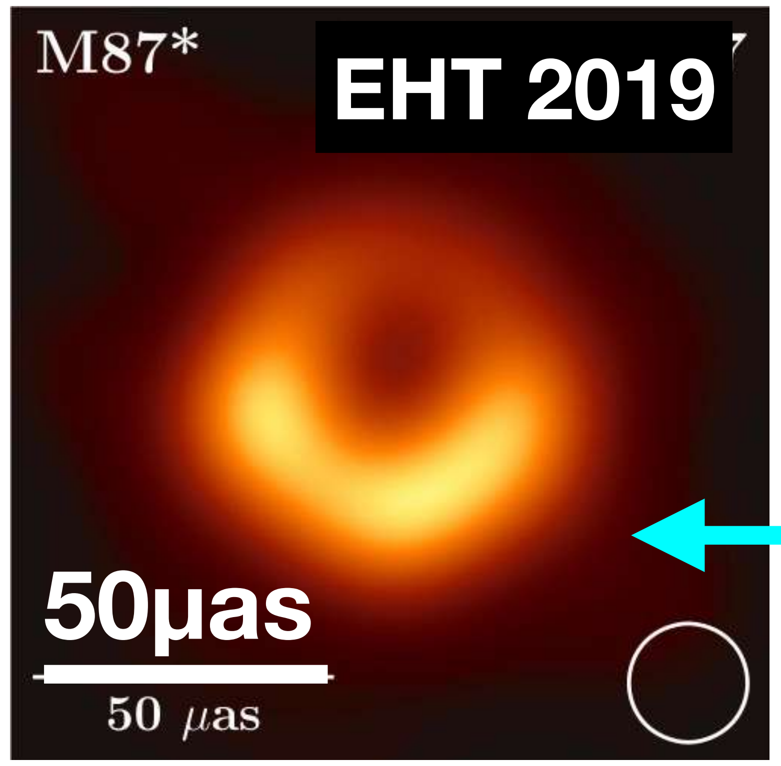
Co-evolution of SMBHs and Host Galaxies?

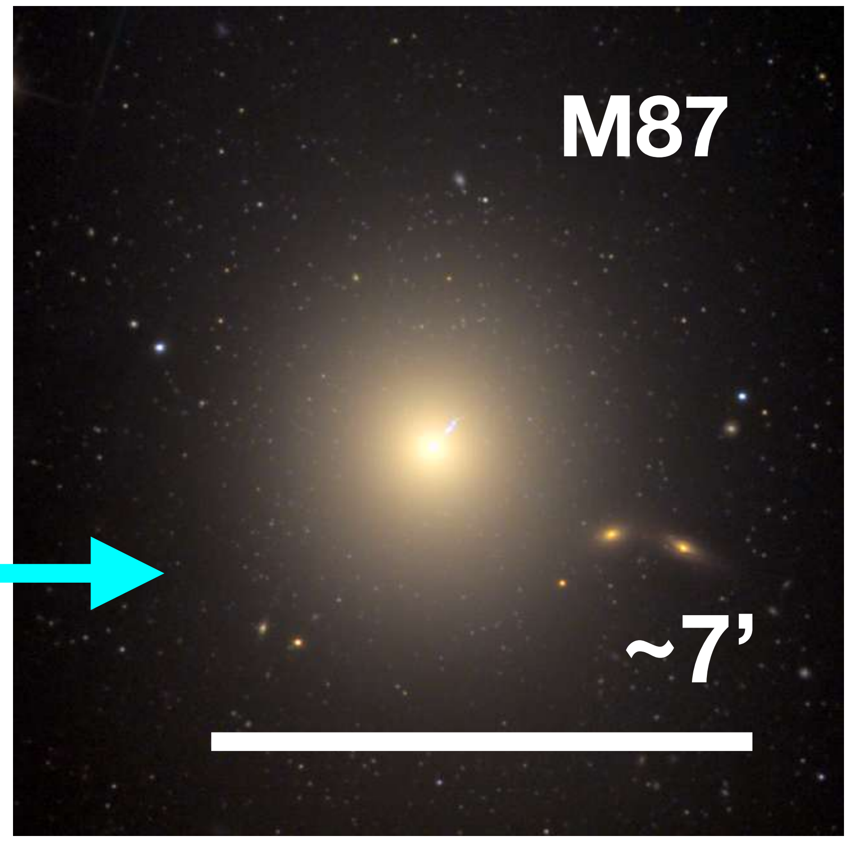


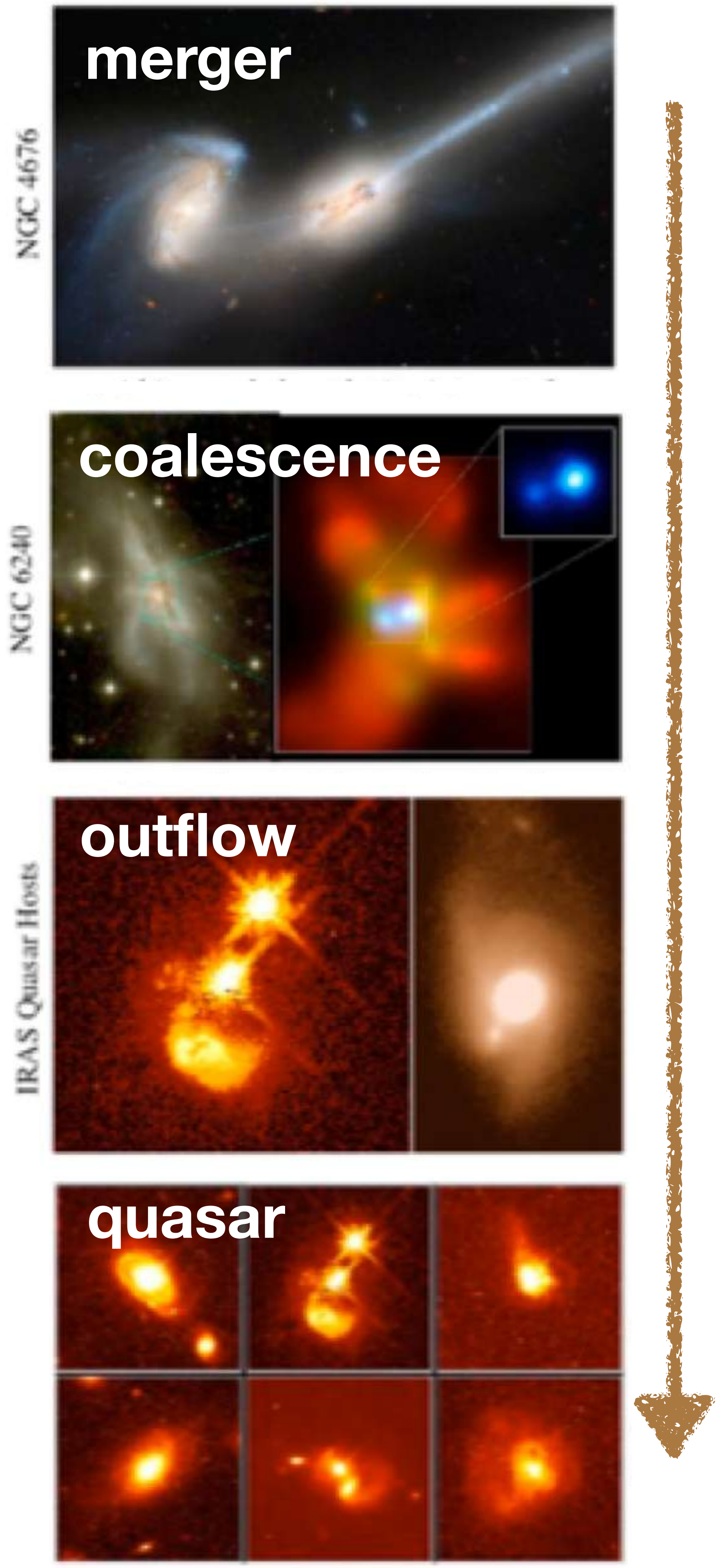


- M_{BH} is tightly correlated with M_{bulge} and σ_* → ***Co-evolution(?)***
- *Why do they know each other* despite their orders of magnitude difference in spatial scale…?
- ***When, where, and how the relation has arisen?***

Trace <u>(i) SMBH growth</u> and <u>(ii) galaxy growth</u> over the cosmic time





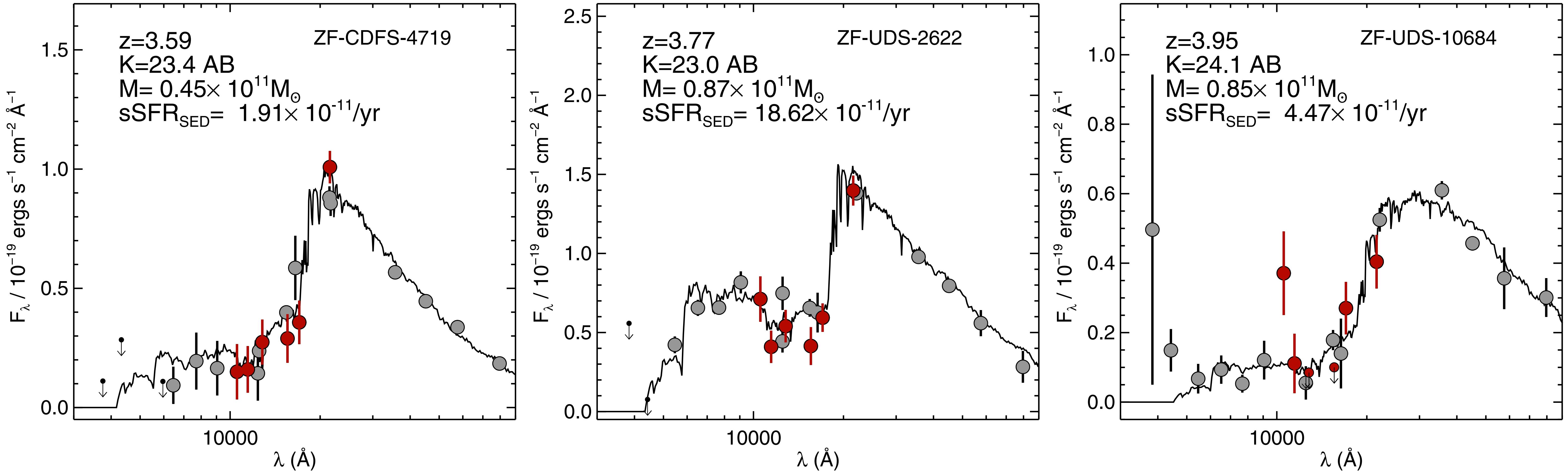


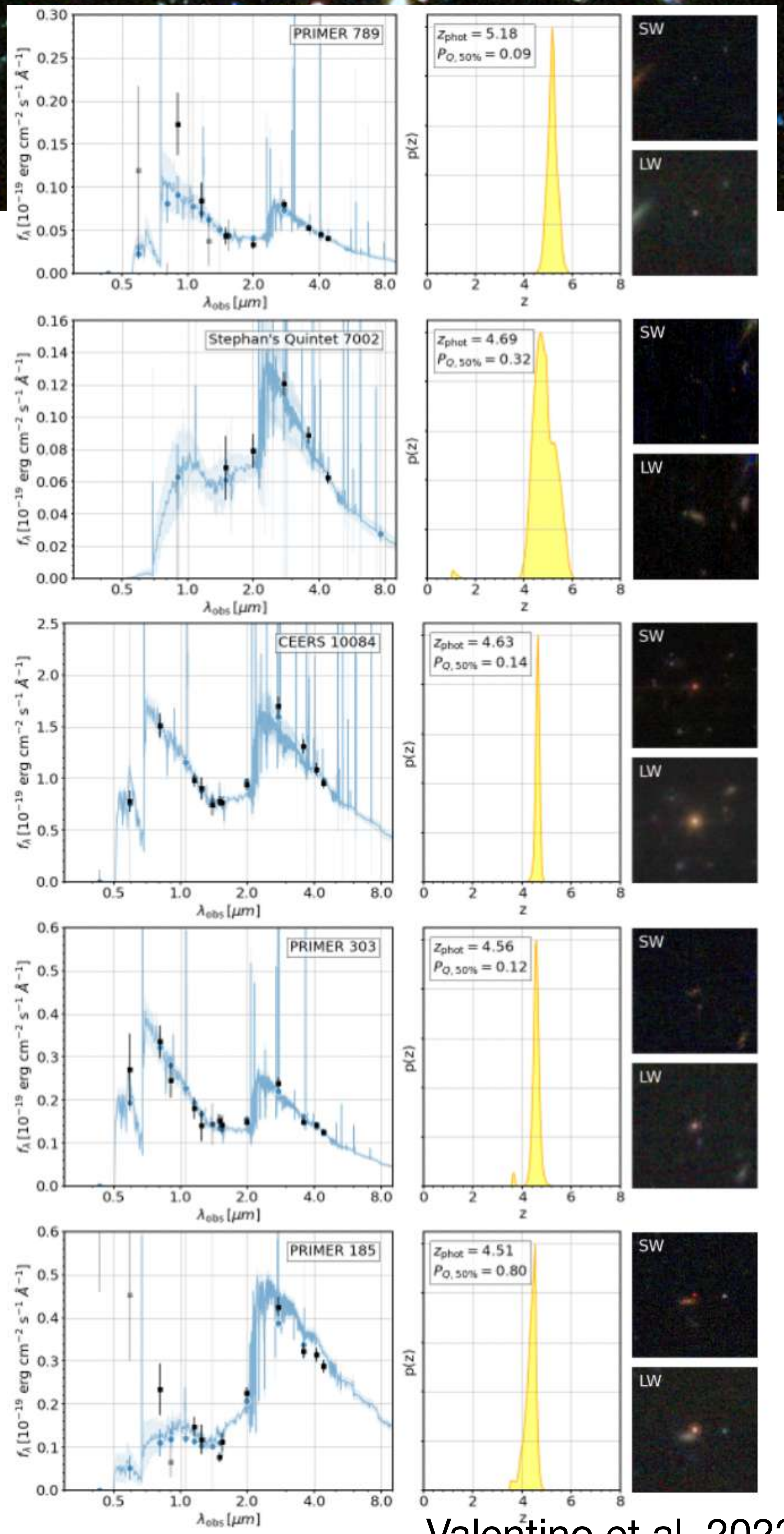
Hopkins et al. 2008

Massive, quiescent, and old galaxies

- These quiescent galaxies will require rapid star formation, also likely rapid BH growth, and then associated feedback, at even higher redshift.
  → now JWST routinely discover this kind of objects.
- Strong motivation for us to explore z > 6 universe!

Straatman et al. 2014



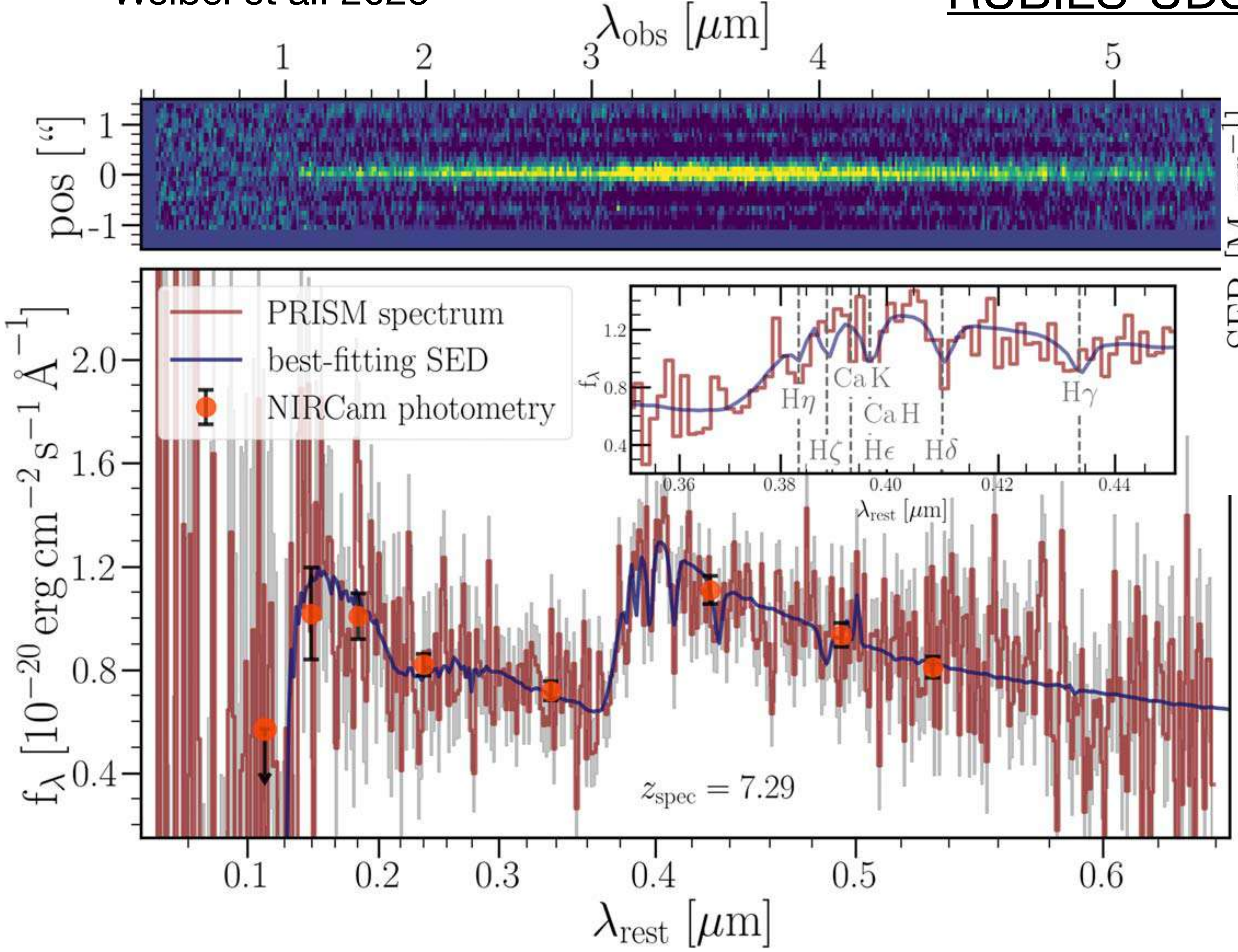


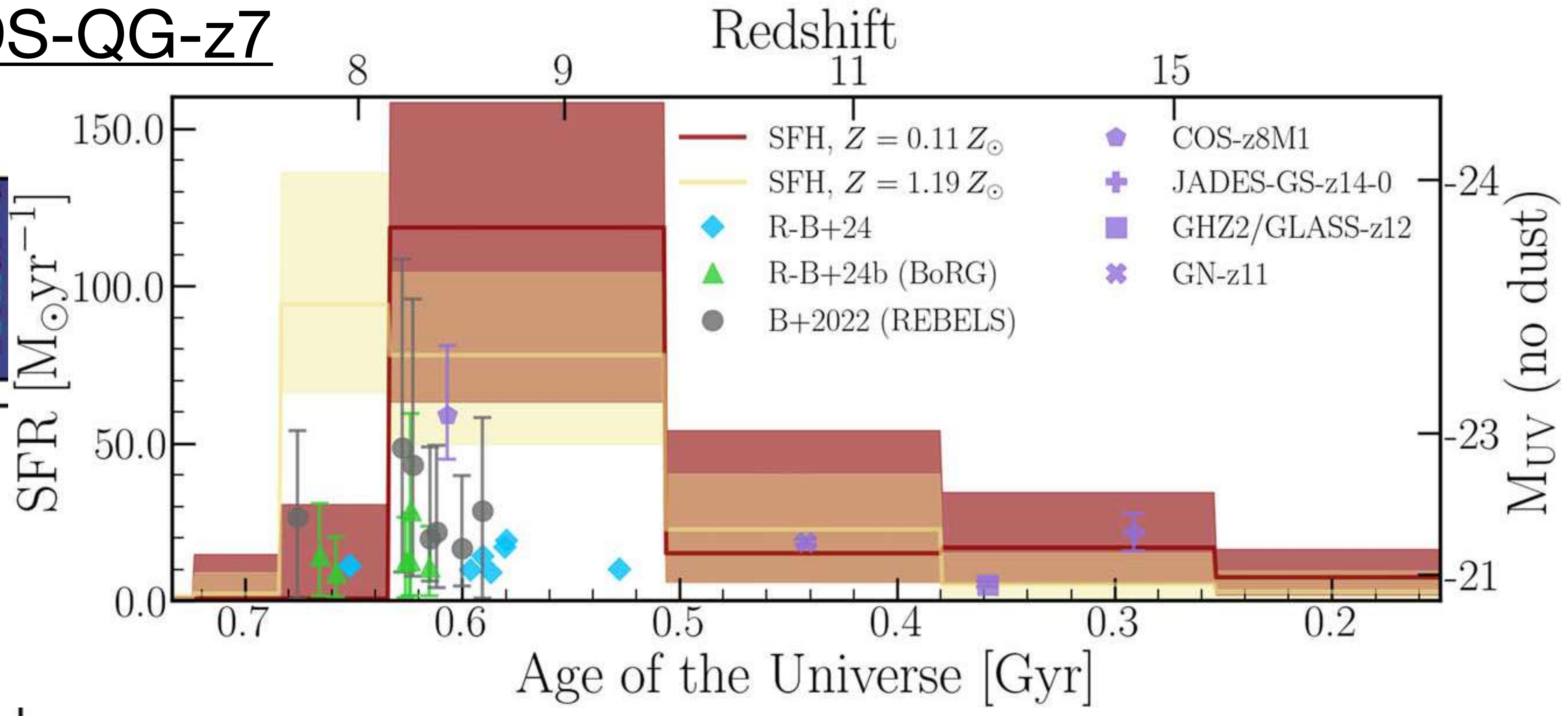
Valentino et al. 2023

Massive, quiescent, and old galaxies already at z = 7.3

Weibel et al. 2025

RUBIES-UDS-QG-z7



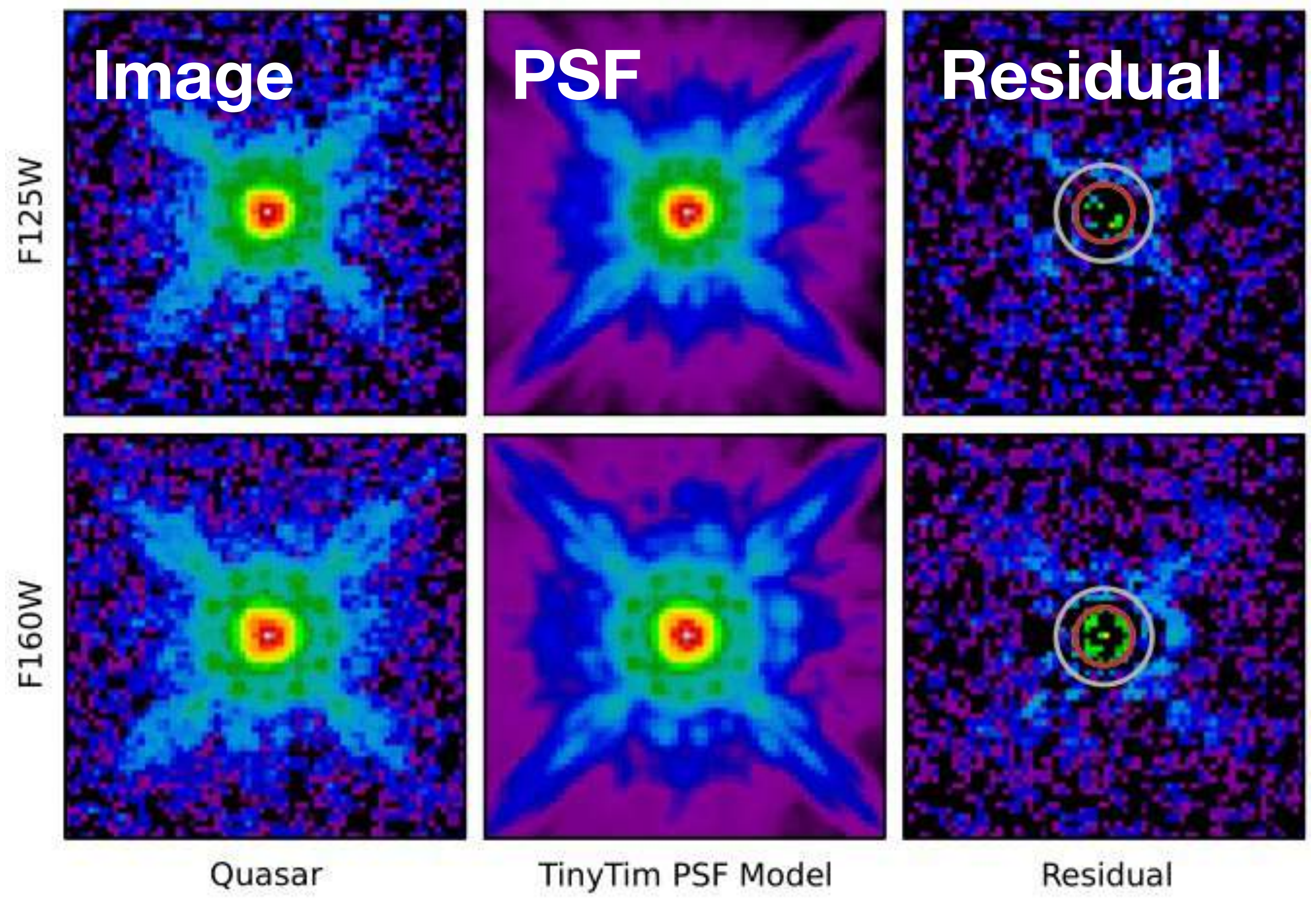


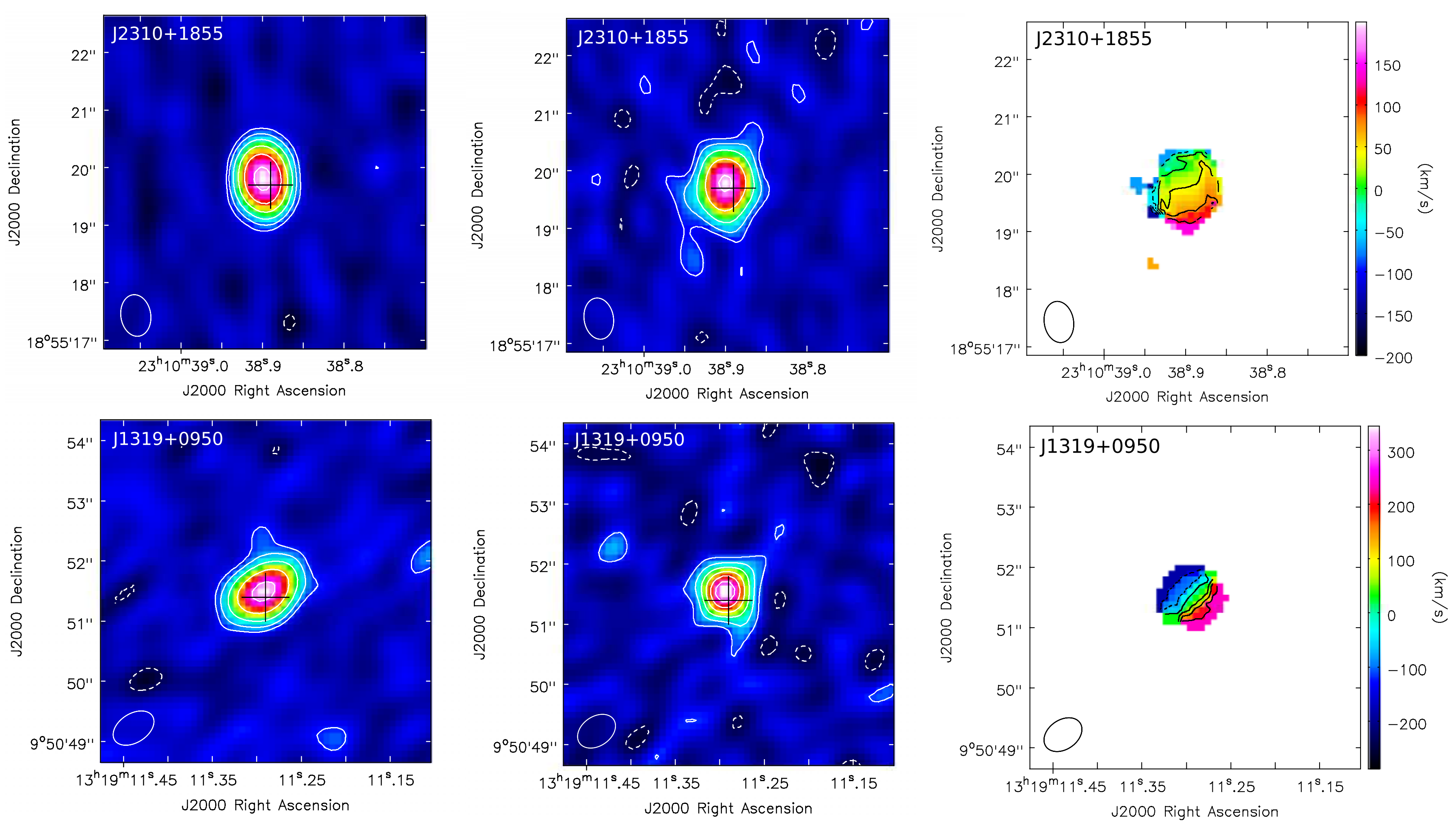
log (M_{star}/M_{sun}) ~ 10.2, SFR ~ 1 M_{sun}/yr

- Star formation history modeling suggests a rapid quenching at z~9.
- Hydrodynamic simulation supports the presence of AGN feedback, which overwhelms mass accretion (Turner et al. 2025).

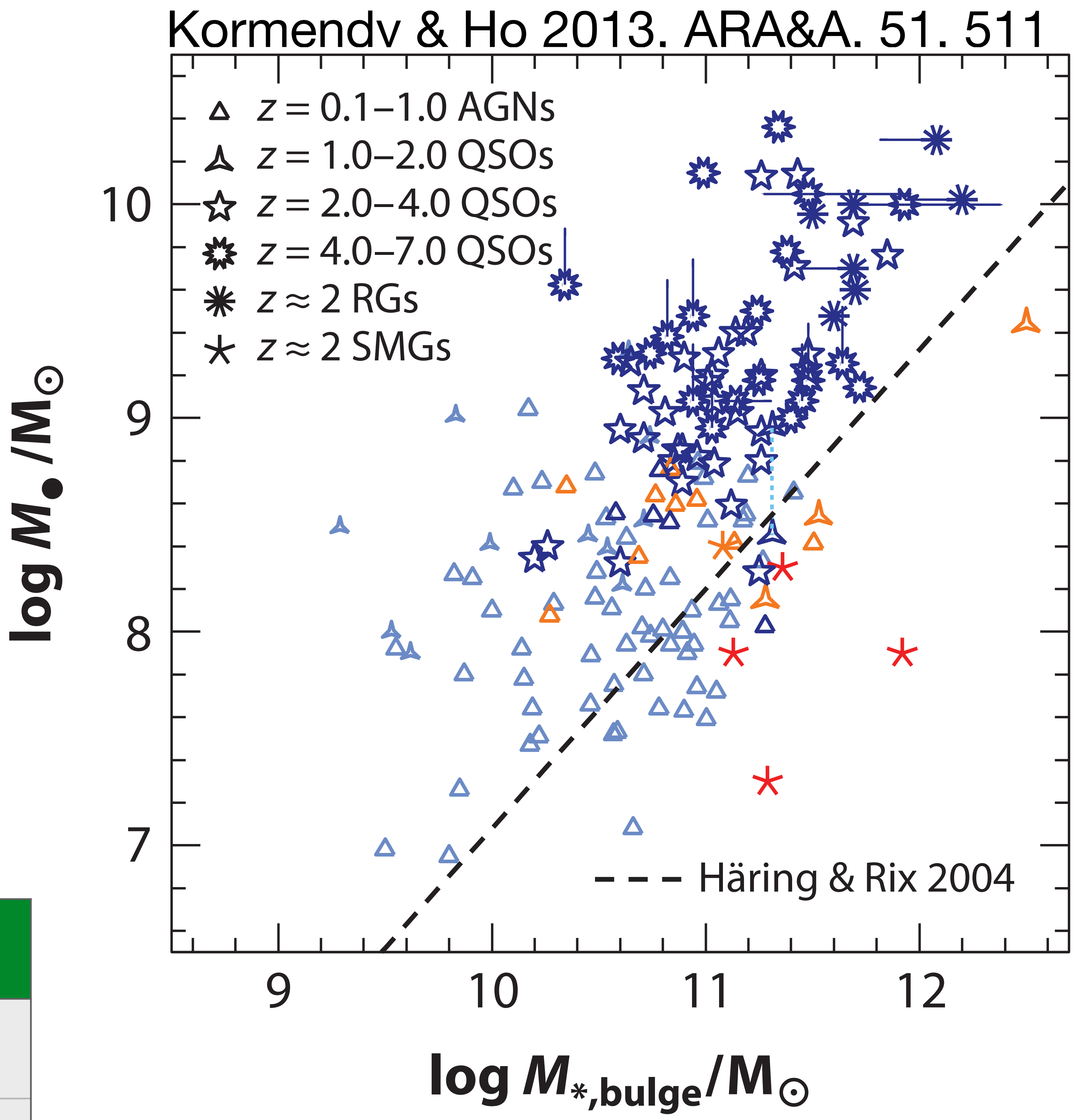
Previous Sub/mm Observations at High-z (Lum. quasars)

HST **images (Mechtley et al. 2012)**





Wang et al. 2013, ApJ, 773, 44 w/ ALMA



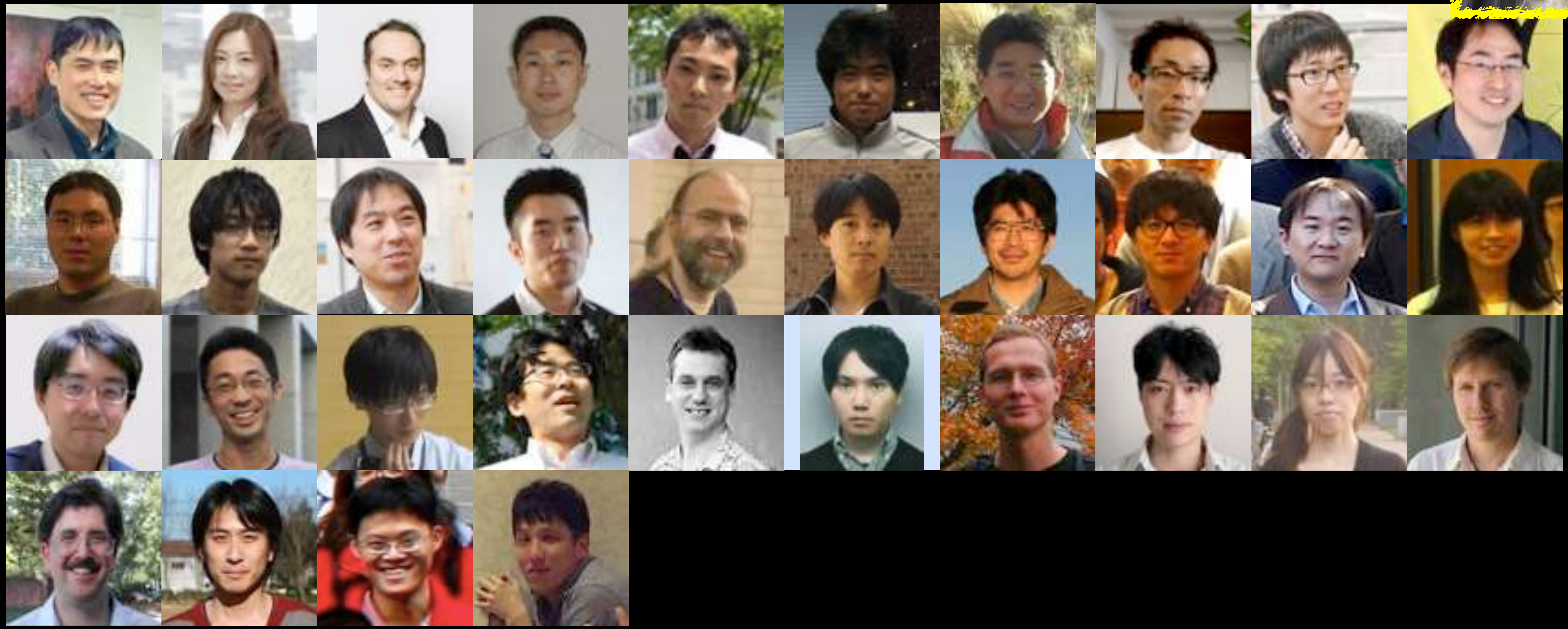
- @z > 6, <u>sub/mm obs</u> are vital
- ULIRG/SMG-class star formation
- Rapid and vigorous galaxy evolution coeval with SMBH growth
  → How M_{BH}-M_{star} relation looks like in these most active systems?

	Typical value
SFR	~100 - 1000 M_{sun}/yr
M_{gas}	~a few E10 M_{sun}
M_{dust}	~a few E8 M_{sun}
M_{BH}	~a few E9 M_{sun}

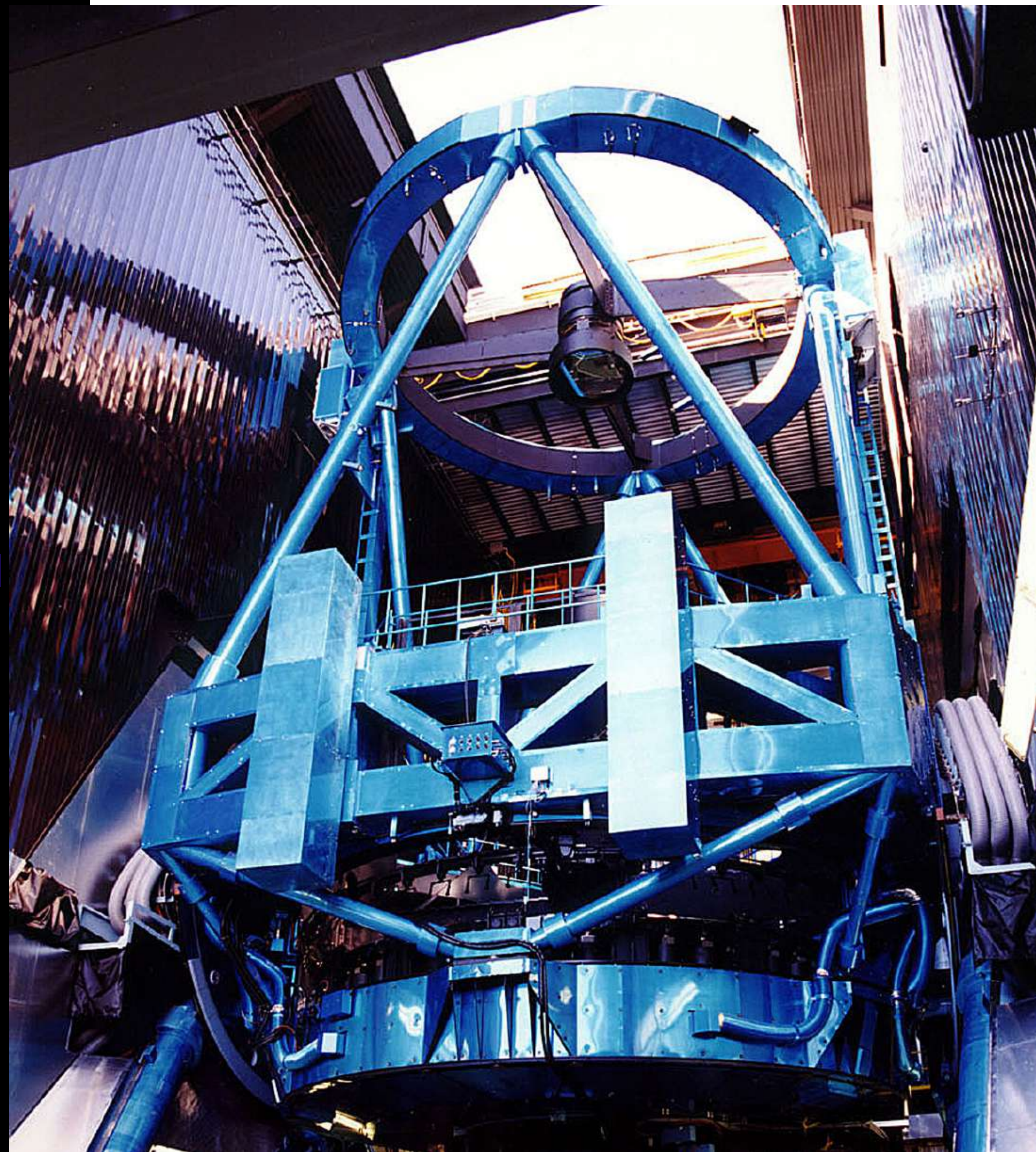
e.g., Wang+10; Venemans+16

SHELLQs

Subaru High-z Exploration of Low-Luminosity Quasars



- Subaru Hyper Suprime-Cam (**HSC**)
- First **1000 deg² class** survey with an 8m class telescope
- ***g,r,i,z,y*** bands
- **>~2 mag deeper** than previous surveys (e.g., r_{AB} < 27.1 mag in the Deep 27 deg² layer)



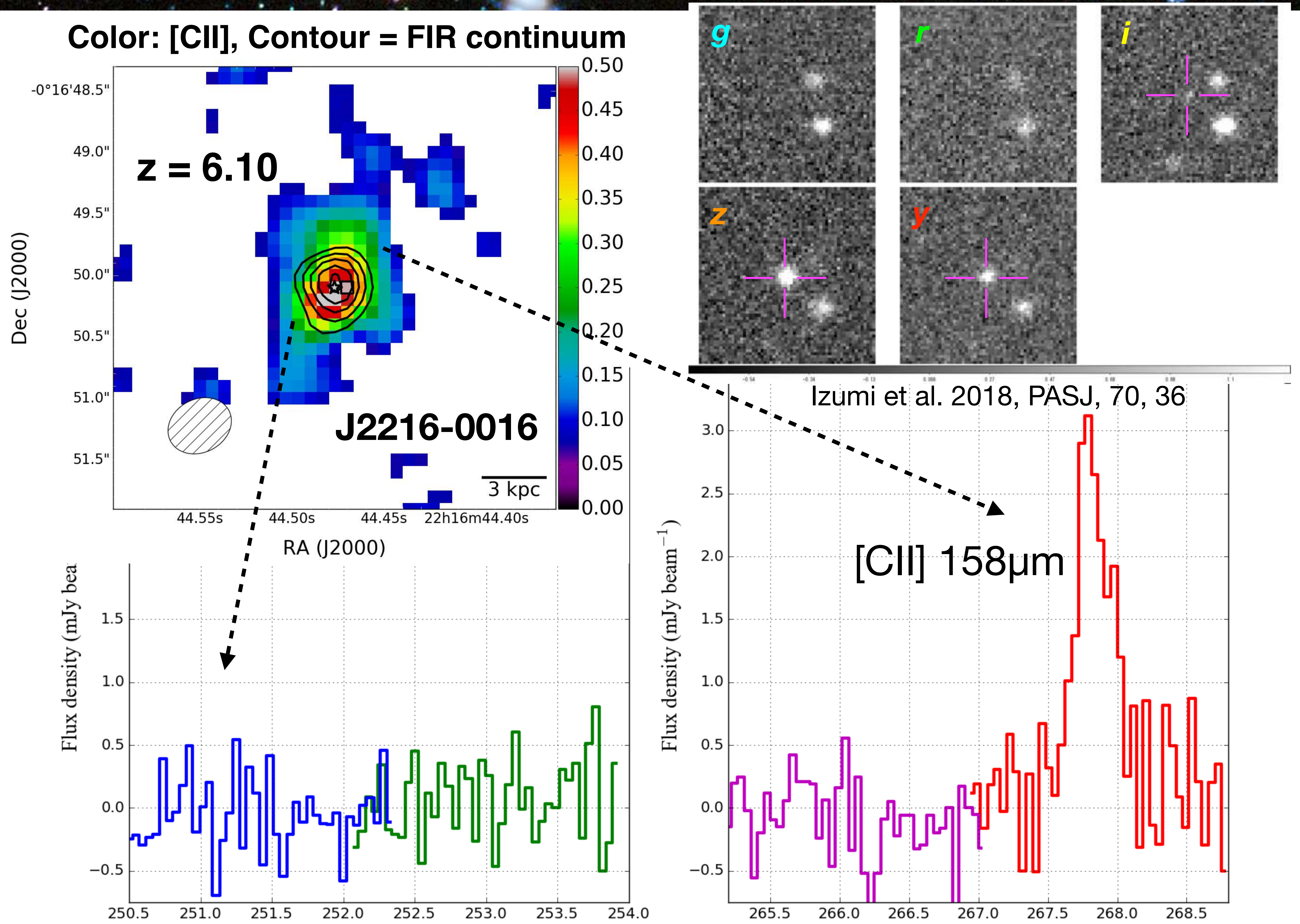
Members

Y. Matsuoka[1] (PI)

M. Akiyama[2], N. Asami[3], S. Foucaud, T. Goto[4], Y. Harikane[5], H. Ikeda[1], M. Imanishi[1], K. Iwasawa[6], T. Izumi[5], N. Kashikawa[1] T. Kawaguchi[7], S. Kikuta[1], K. Kohno[5], C.-H. Lee[1], R. H. Lupton[9], T. Minezaki[5], T. Morokuma[5], T. Nagao[8], M. Niida[8], M. Oguri[5], Y. Ono[5], M. Onoue[1], M. Ouchi[5], P. Price[9], H. Sameshima[10], A. Schulze[5], T. Shibuya[5], H. Shirakata[11], J. D. Silverman[5], M. A. Strauss[9], M. Tanaka[1], J. Tang[12], Y. Toba[8]

[1]NAOJ, [2]Tohoku, [3]JPSE, [4]Tsinghua, [5]Tokyo, [6]Barcelona, [7]Sapporo Medical, [8]Ehime, [9]Princeton, [10]Kyoto Sangyo, [11]Hokkaido, [12]ASIAA

ALMA Observations: [CII]158μm + FIR cont.

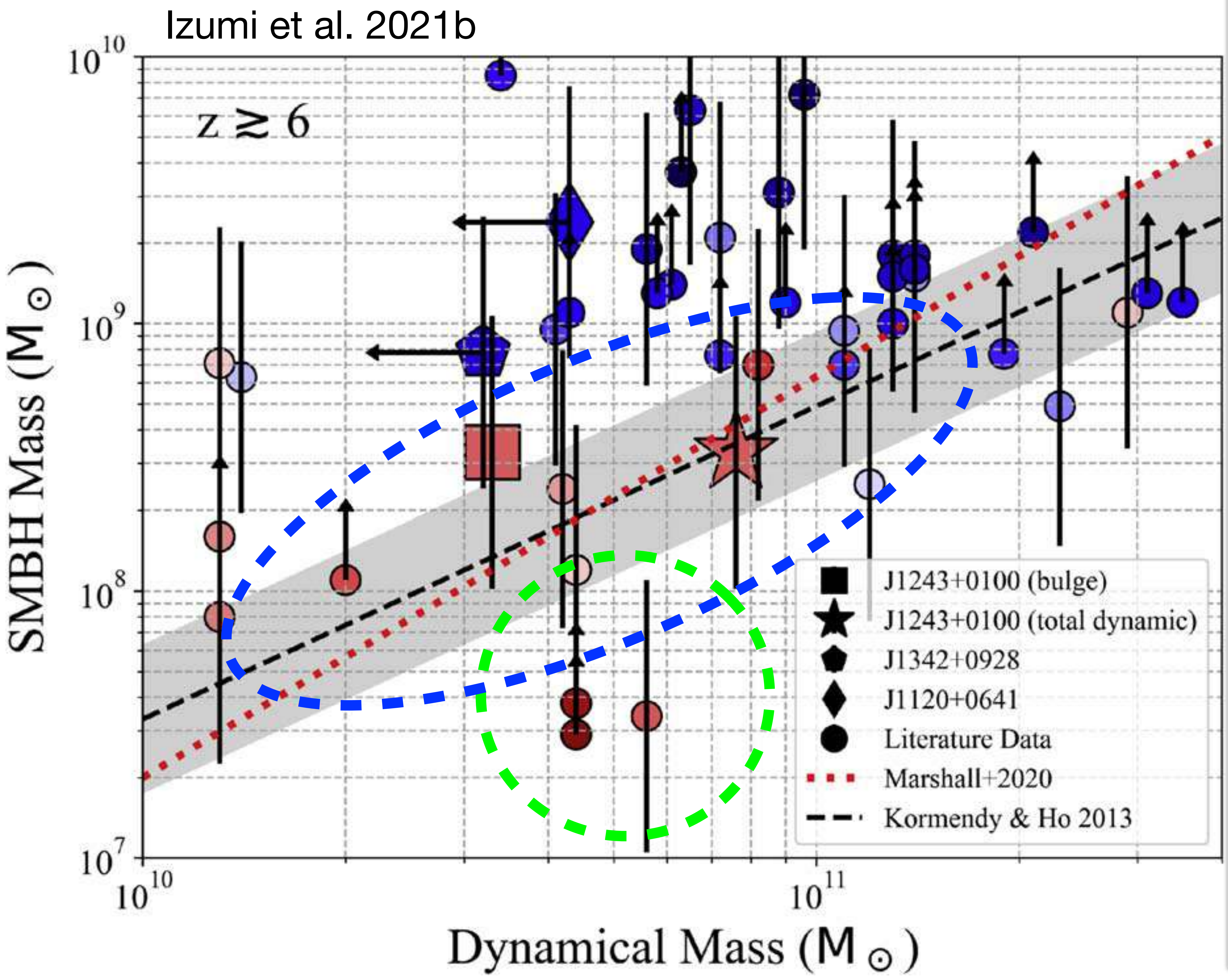


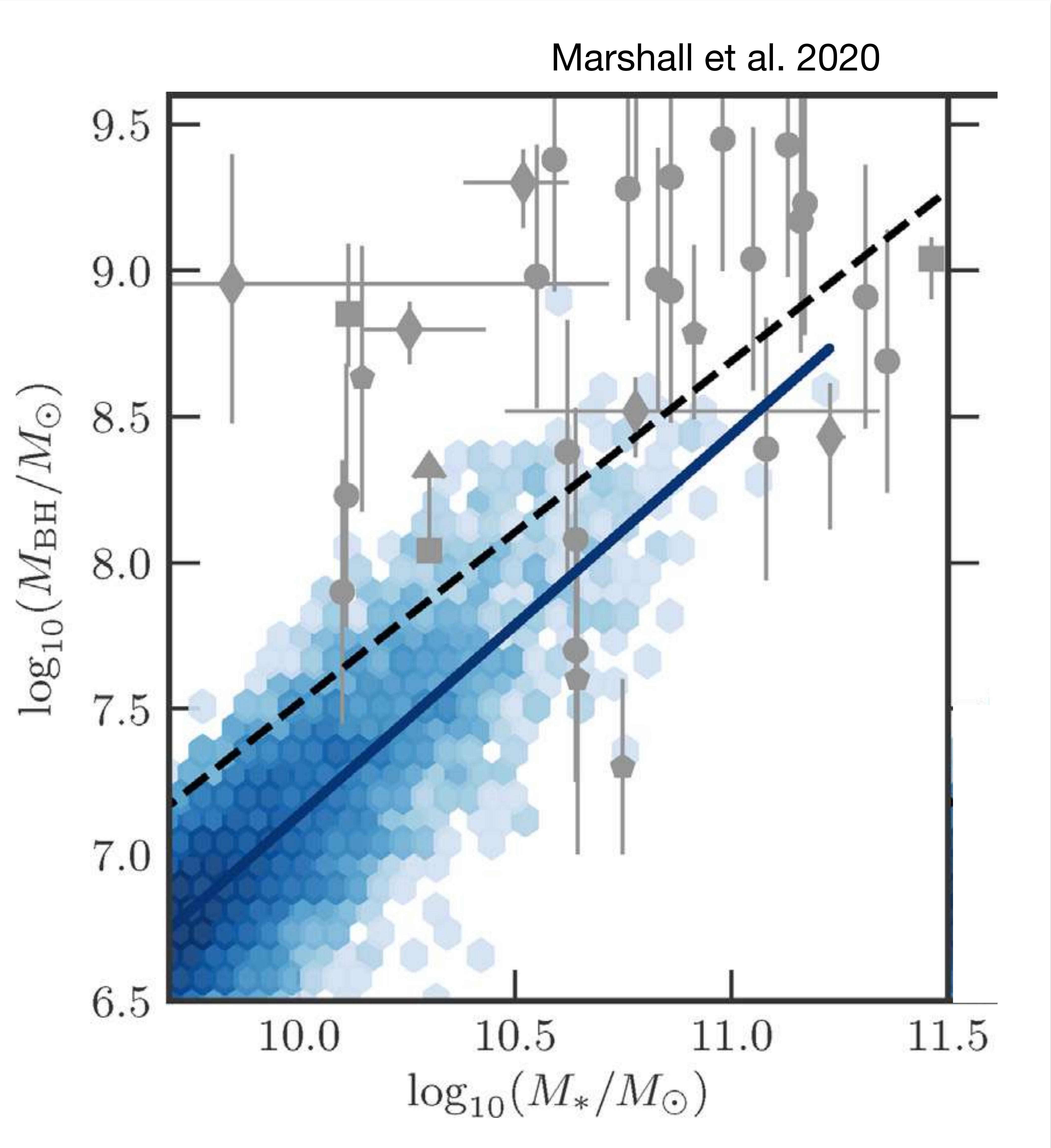
What we're doing:

- Study HSC quasars (**LLQSOs**) to:
- Characterize basic star formation (**SFR**)
- Constrain the host galaxy mass (**M_{dyn}**)
- Discuss less-biased early **BH-host mass relation**
- Search for the key physical processes of co-evolution (**merger**, **outflow**, **environment**, etc?)

1. Shape of the Early M_{gal}-M_{BH} relation

ALMA's dynamical mass measurement



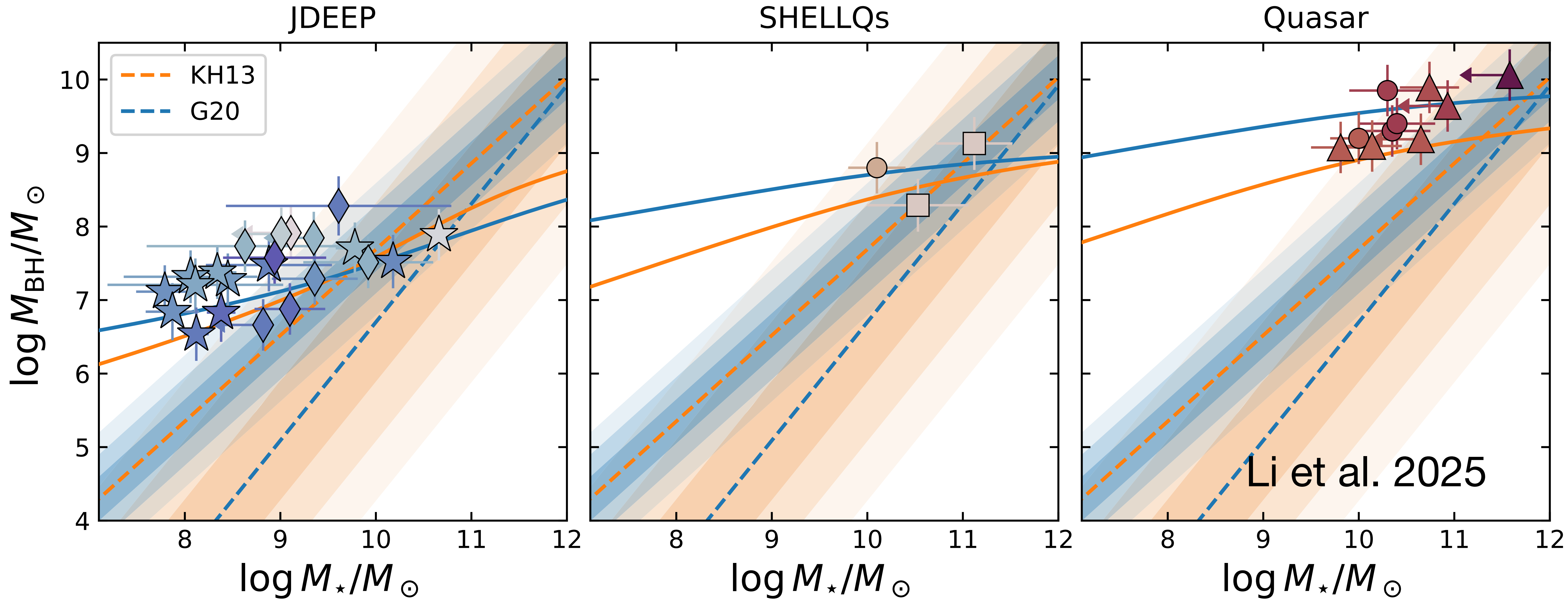


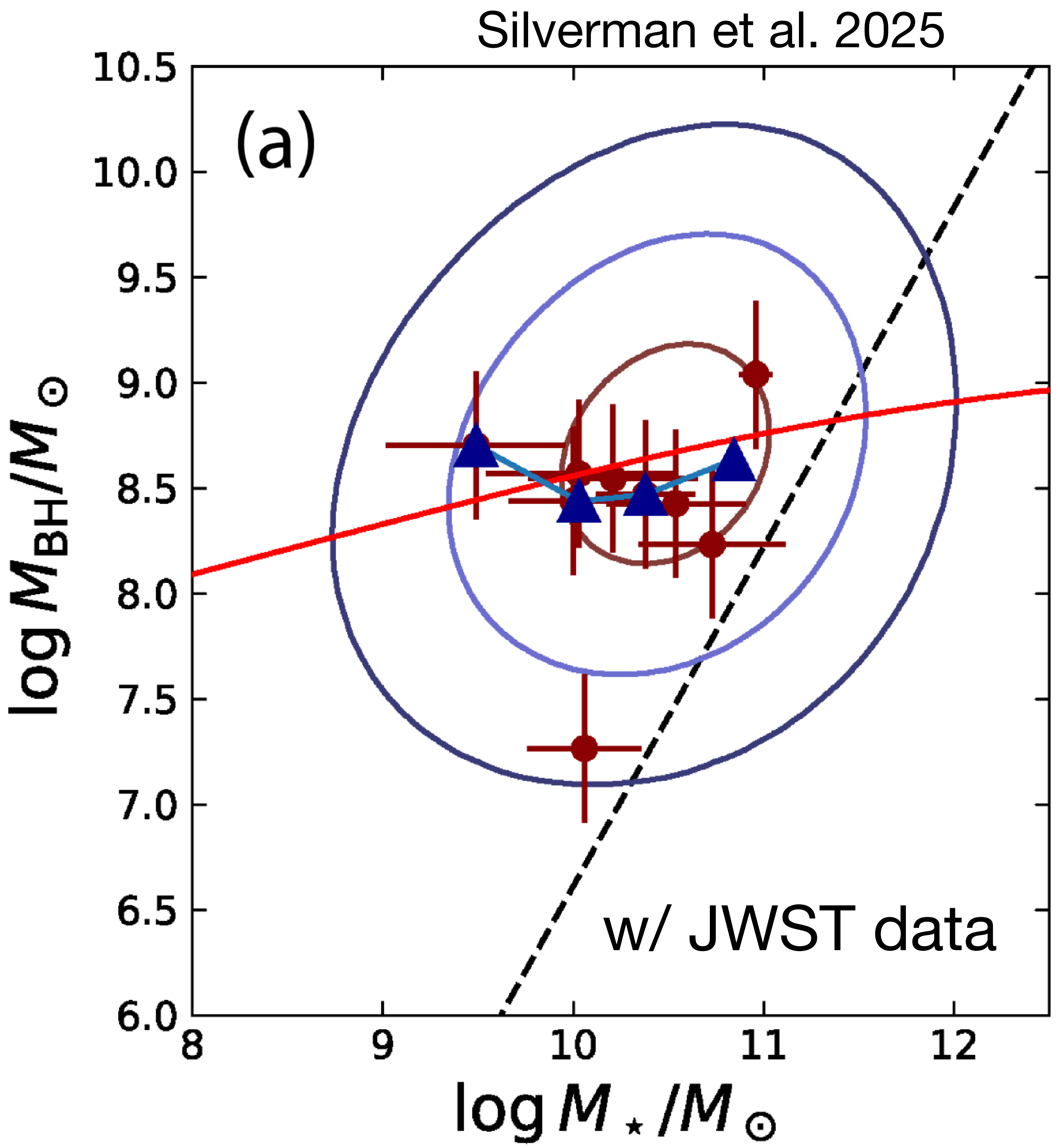
JWST/NIRCam host galaxy decomposition

F356W map (X. Ding et al. 2025; see also Ding et al. 2023)

- Observed image = Host galaxy + QSO (PSF). In total 12 LLQSOs have been observed.
- F150W + F356W straddles the 4000Å break, allowing us to estimate the stellar mass.
- Together with ALMA (SFR, gas), we can measure sSFR, SFE, etc (in relation with the quasar property).

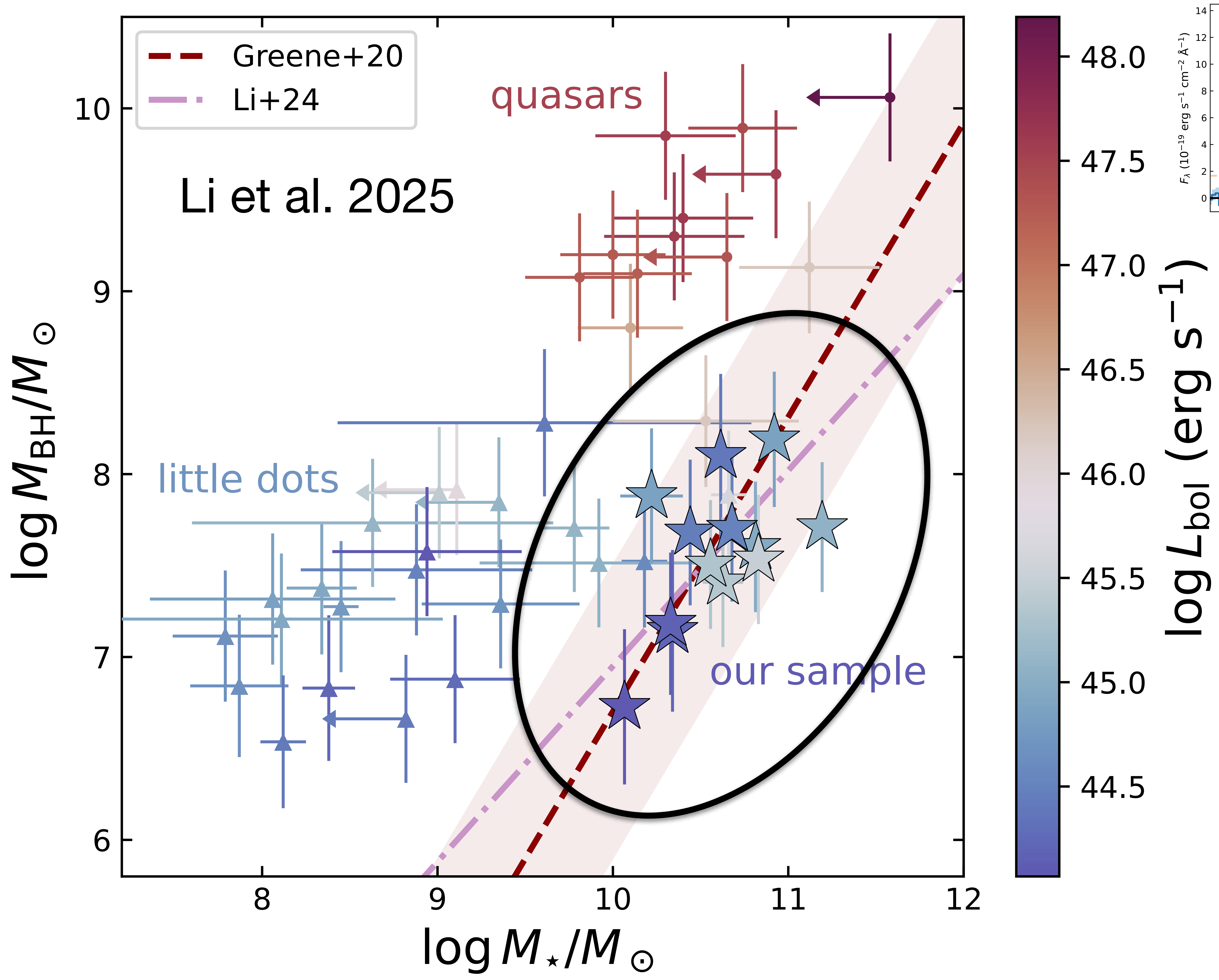
Selection bias (no redshift evolution)?

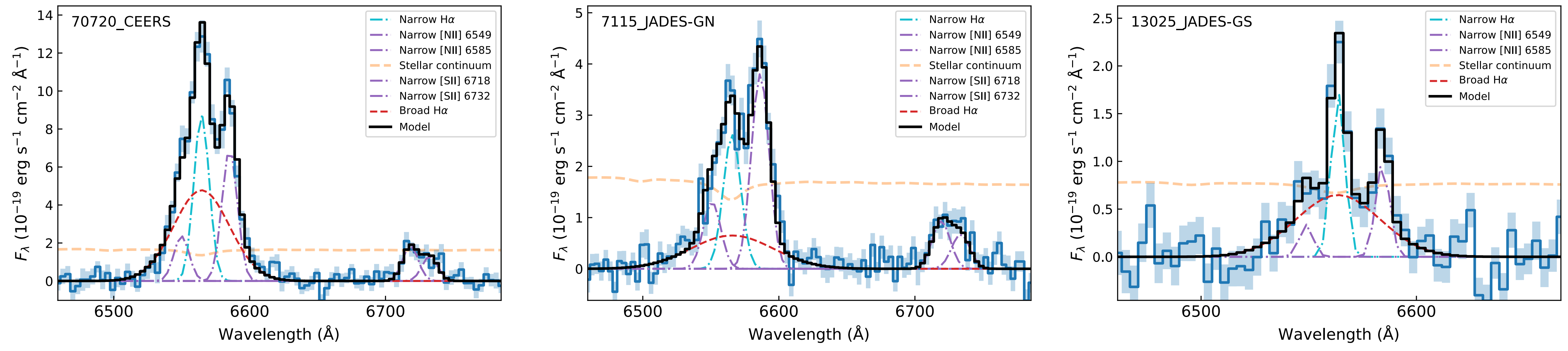




- Selection bias (preferring luminous objects) + observational errors → We only pick-up most massive BHs.
- Once the above items are accounted for, we don't see a redshift evolution of the M_{gal}-M_{BH} relation toward high-z.
- Same argument for the SHELLQs quasars at z~6 (w/ JWST). But the dispersion (~0.8 dex) is higher than the local (~0.4 dex). → Growth in tandem + cosmic averaging with mergers.

Search for BHs in "galaxies"

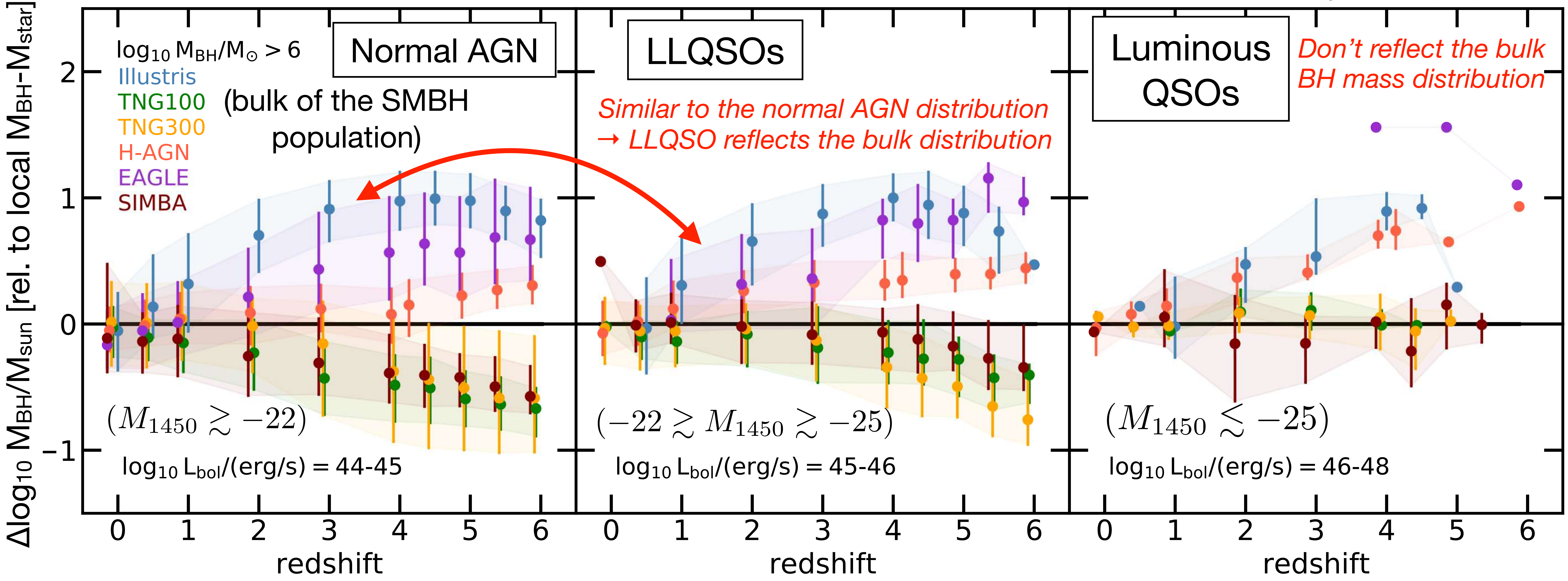




- Deep spectroscopy of massive "galaxies" revealed the presence of broad Balmer lines originating from AGN's BLR.
- Fully consistent M_{BH}/M_{gal} ratio with the local value (~0.1%).
- Need a more statistical survey toward a complete sample.
  → "Measure" the shape of the relation.
- Note: we also need to consider how to make the overmassive BHs.

Constraint on galaxy evolution models

From TI's ALMA Cycle 12 proposal

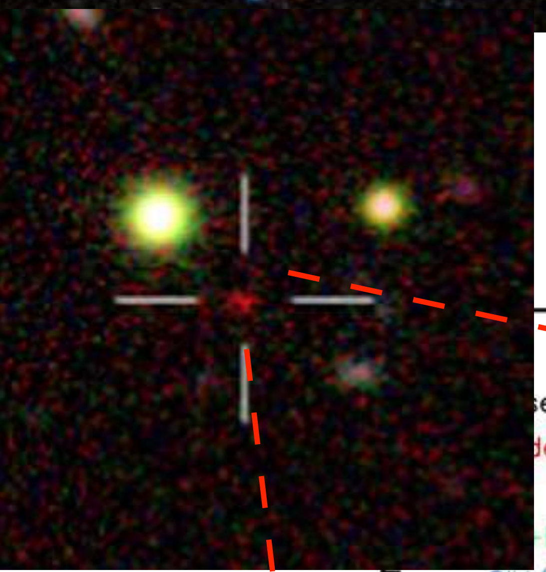


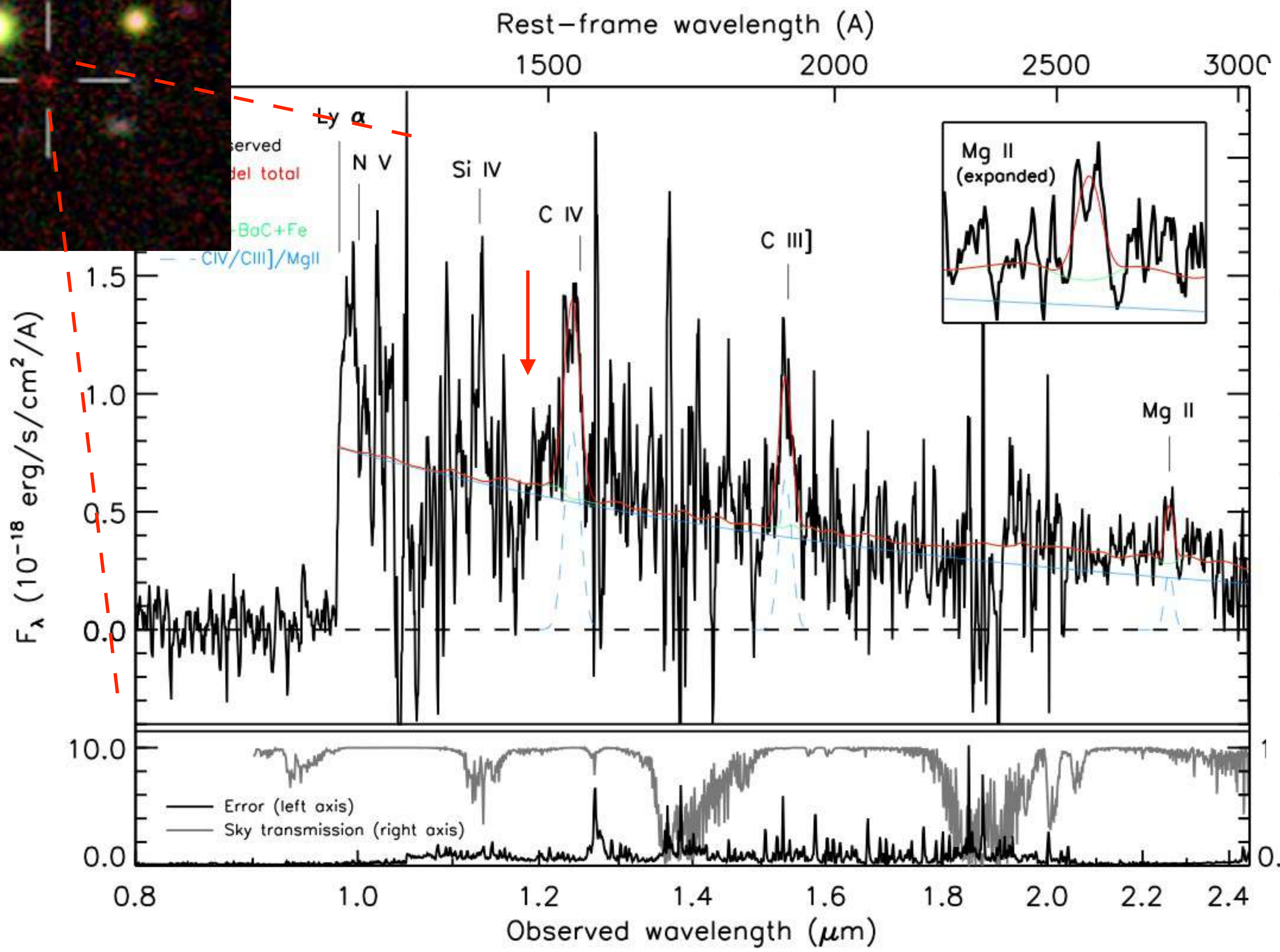
- Less-luminous, less-biased population is the key to reveal the genuine shape of the co-evolution.

2. AGN Feedback (Outflow) + Levels of star-formation

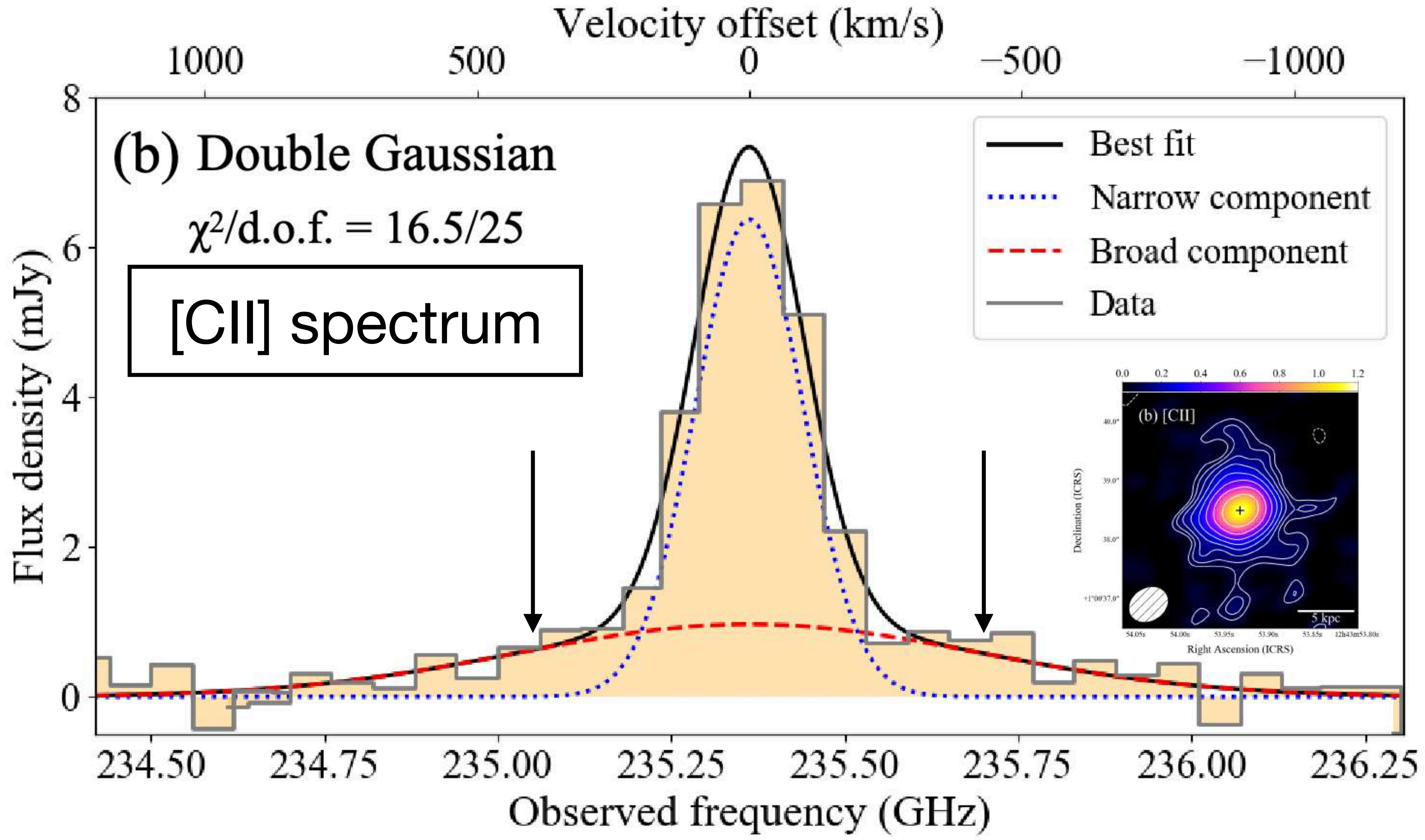
The Highest-z Low-luminosity Quasar (z = 7.07) w/ [CII] outflow

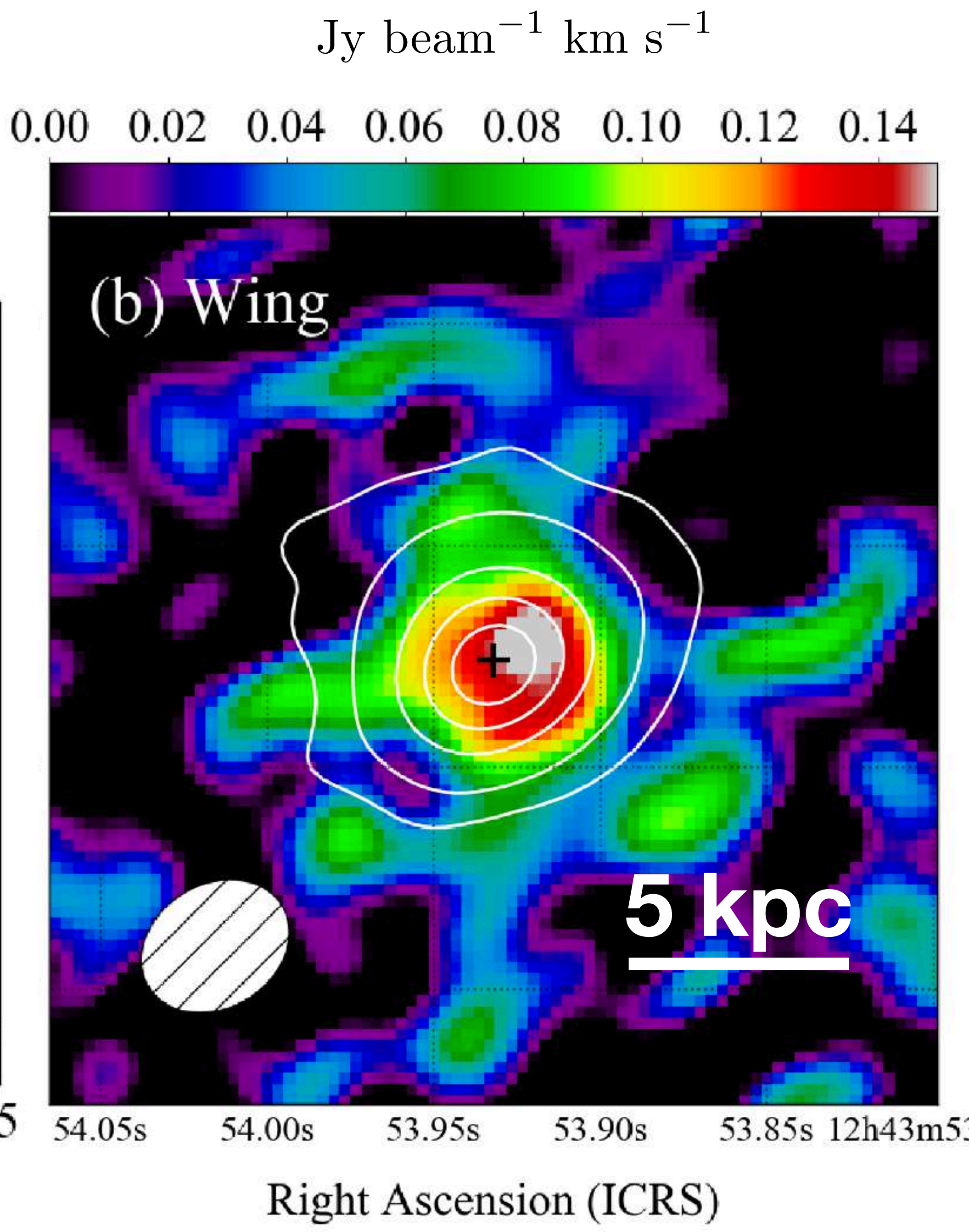
Matsuoka et al. 2019





Izumi et al. 2021b

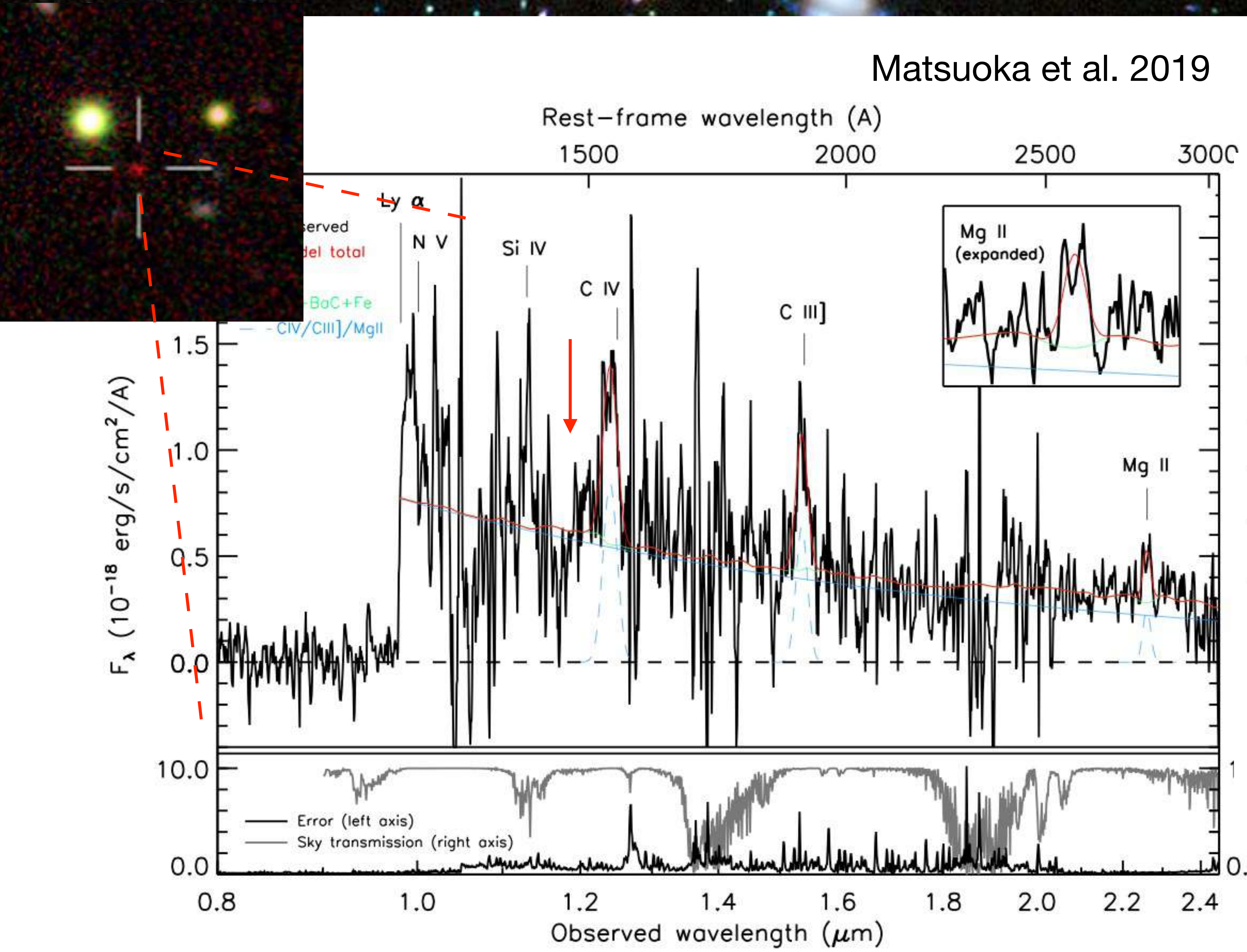


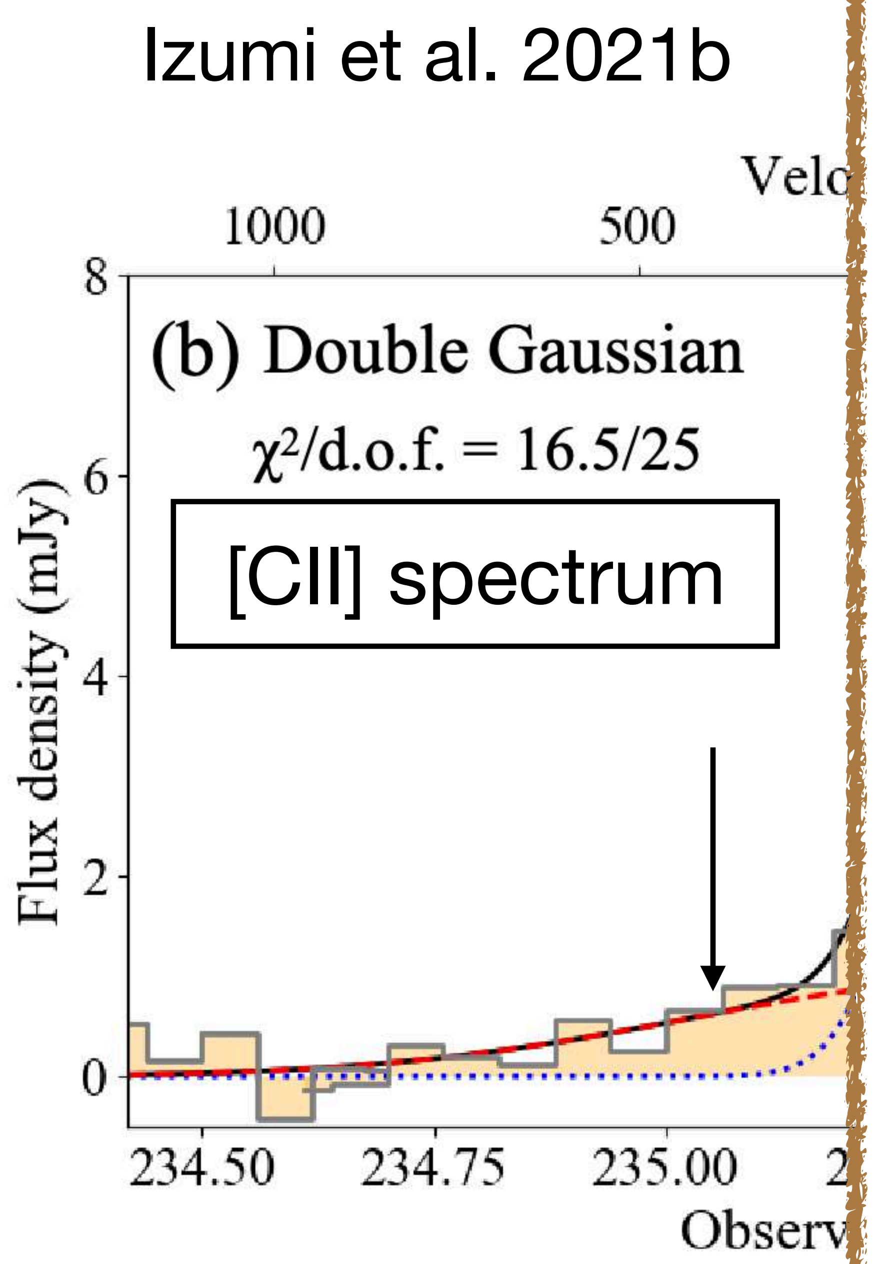


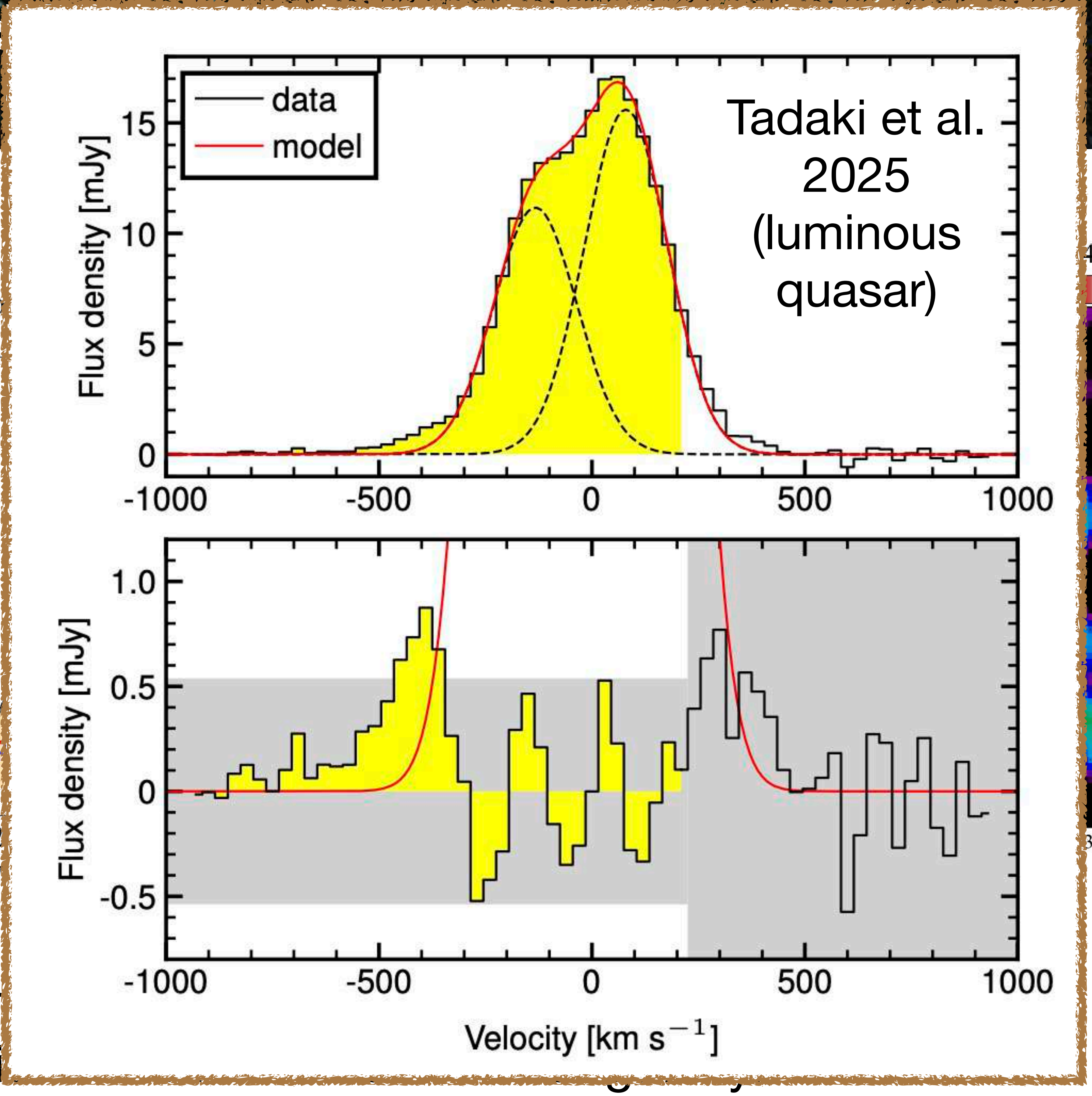
- L_{Bol} = 1.4 × 10^{46} erg/s (~10% of the other z > 7 quasars)
- M_{BH} = 3.3 × 10^{8} M_{sun} (Eddington ratio = 0.3)
- With a CIV BAL(?) → Fast (~2400 km/s) nuclear outflow
  → Intriguing target to study host-galaxy scale feedback.

- Wing is very compact: < 2.7 kpc, which is even inside the host galaxy.
- **Fast outflow** (>450 M_{sun}/yr).
  → Total outflow rate (incl. mol) > 1400 M_{sun}/yr ??
- **Quasar-driven**…? (∵Narrow [CII]-based $SFR_{[CII]}$ = 165 M_{sun}/yr)

The Highest-z Low-luminosity Quasar (z =







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- Wi
  whi
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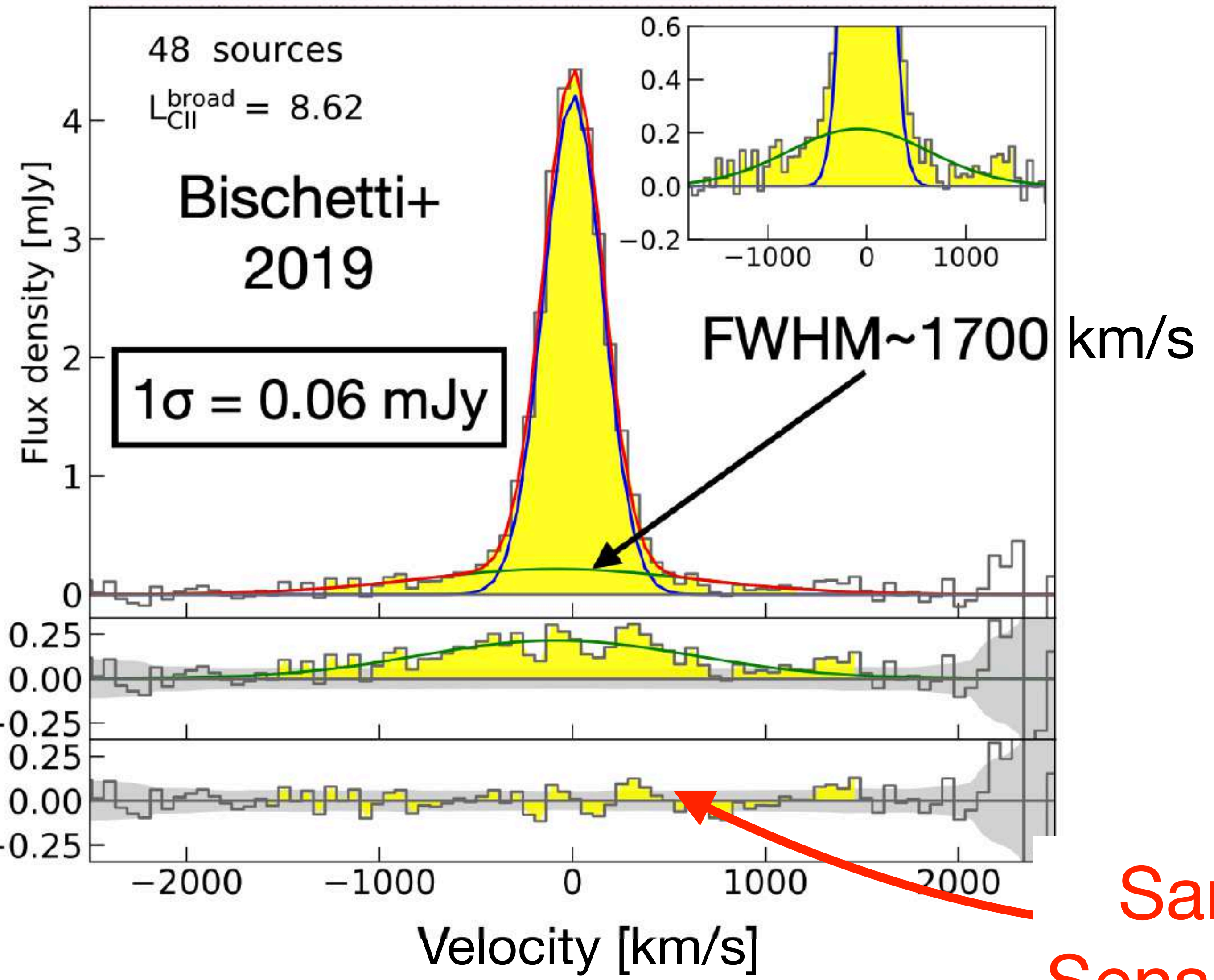
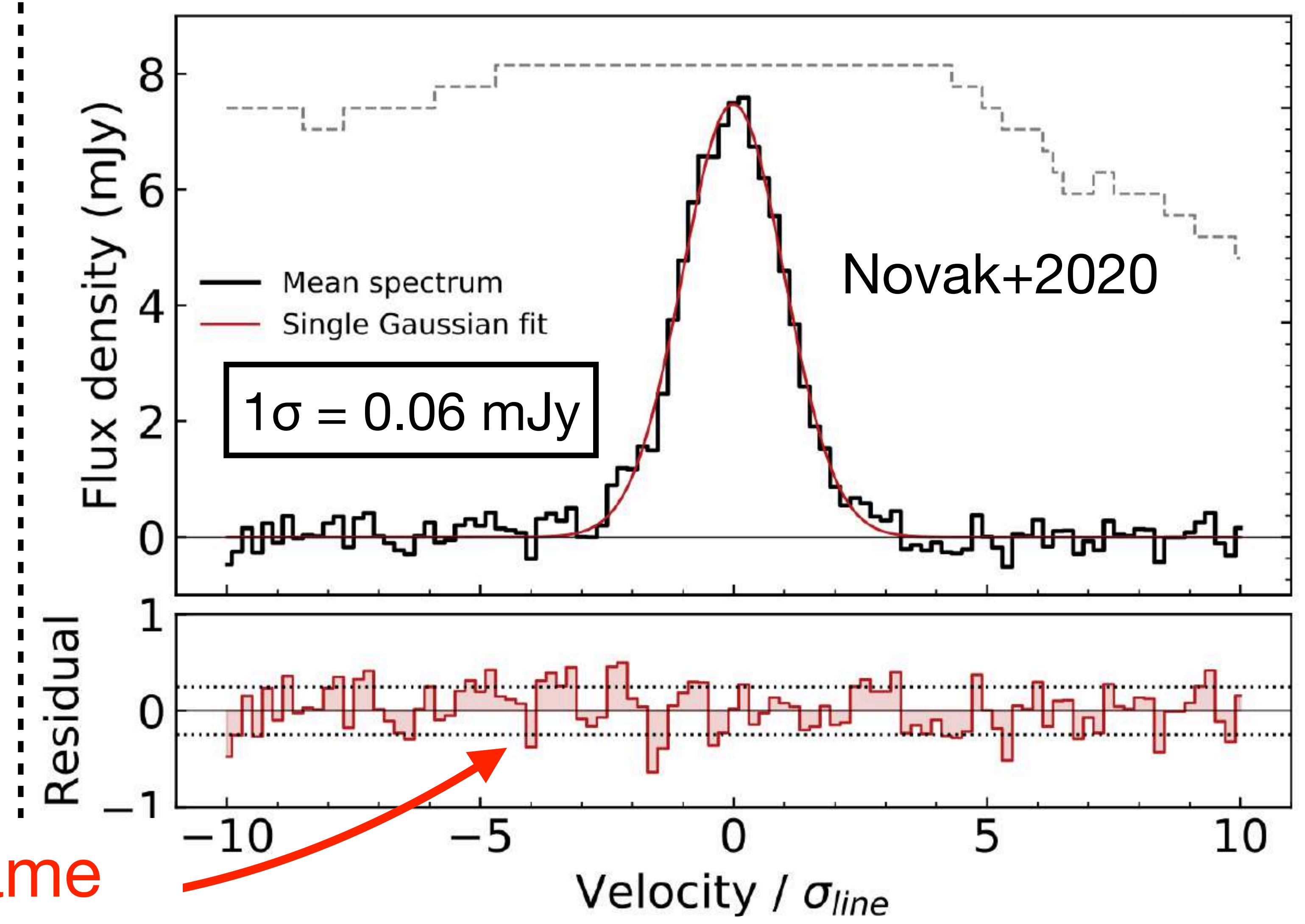
Are quasar-driven "cool" outflows prevalent??

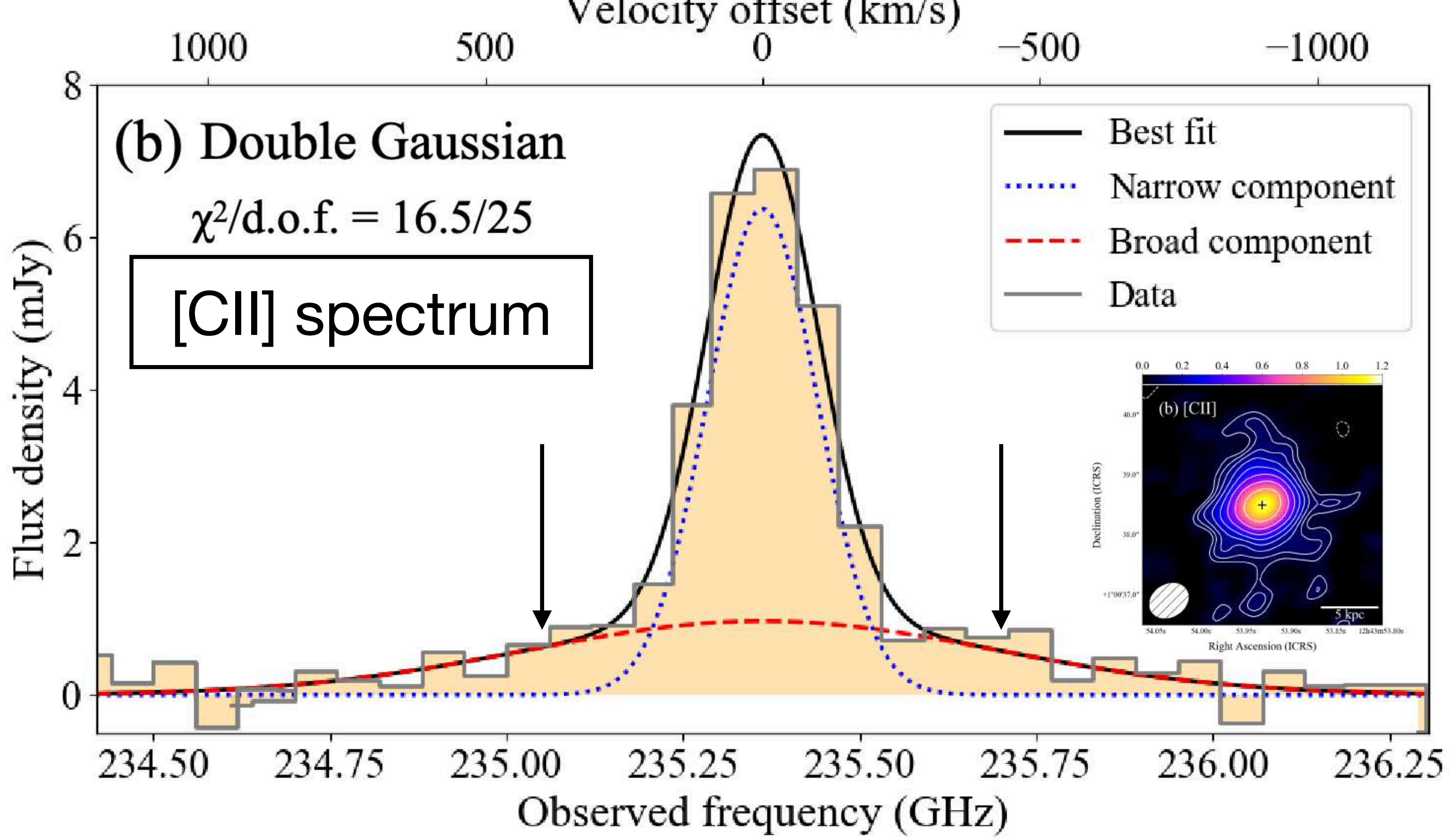
[CII] Outflow (Stack): YES!



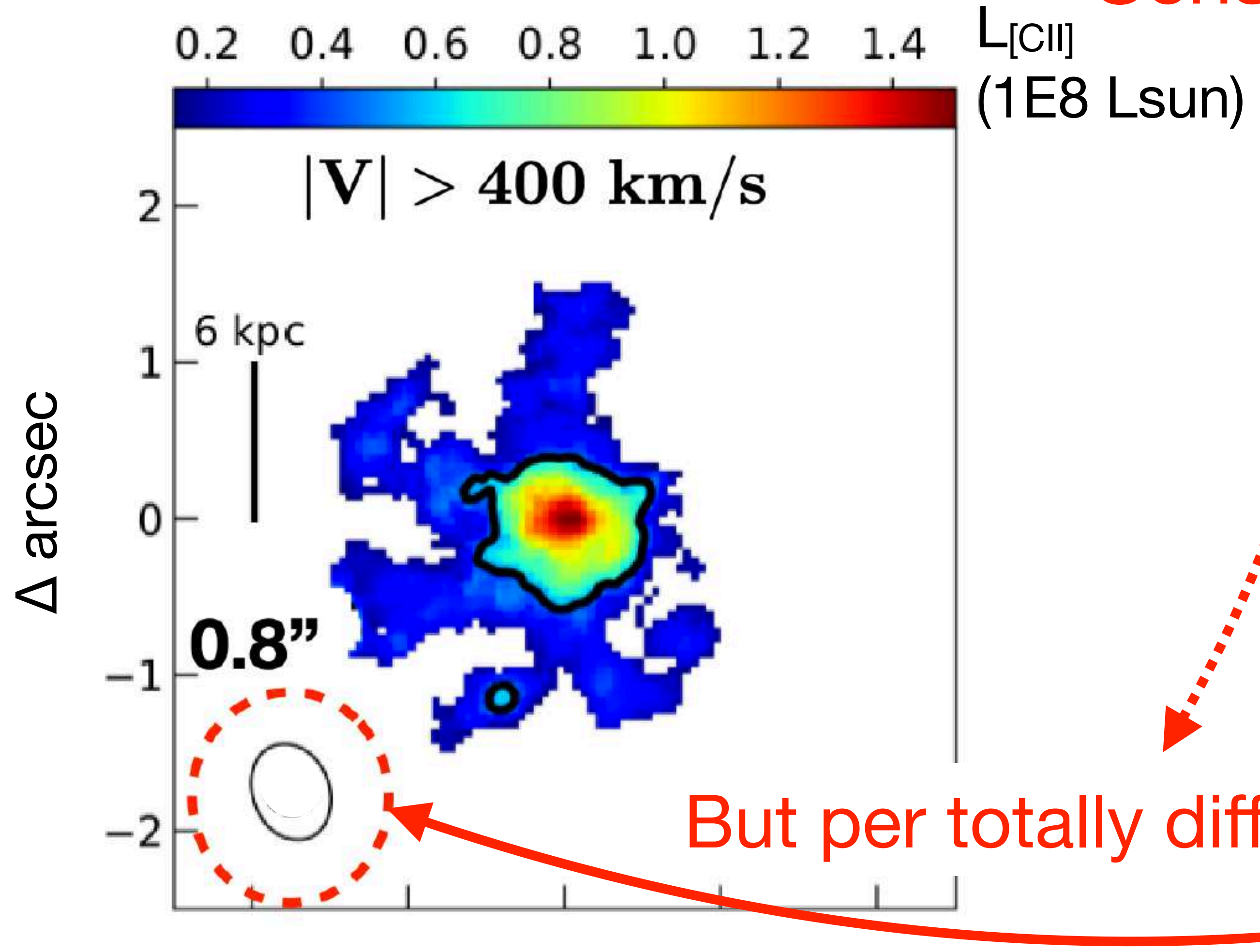
[CII] Outflow (Stack): NO!



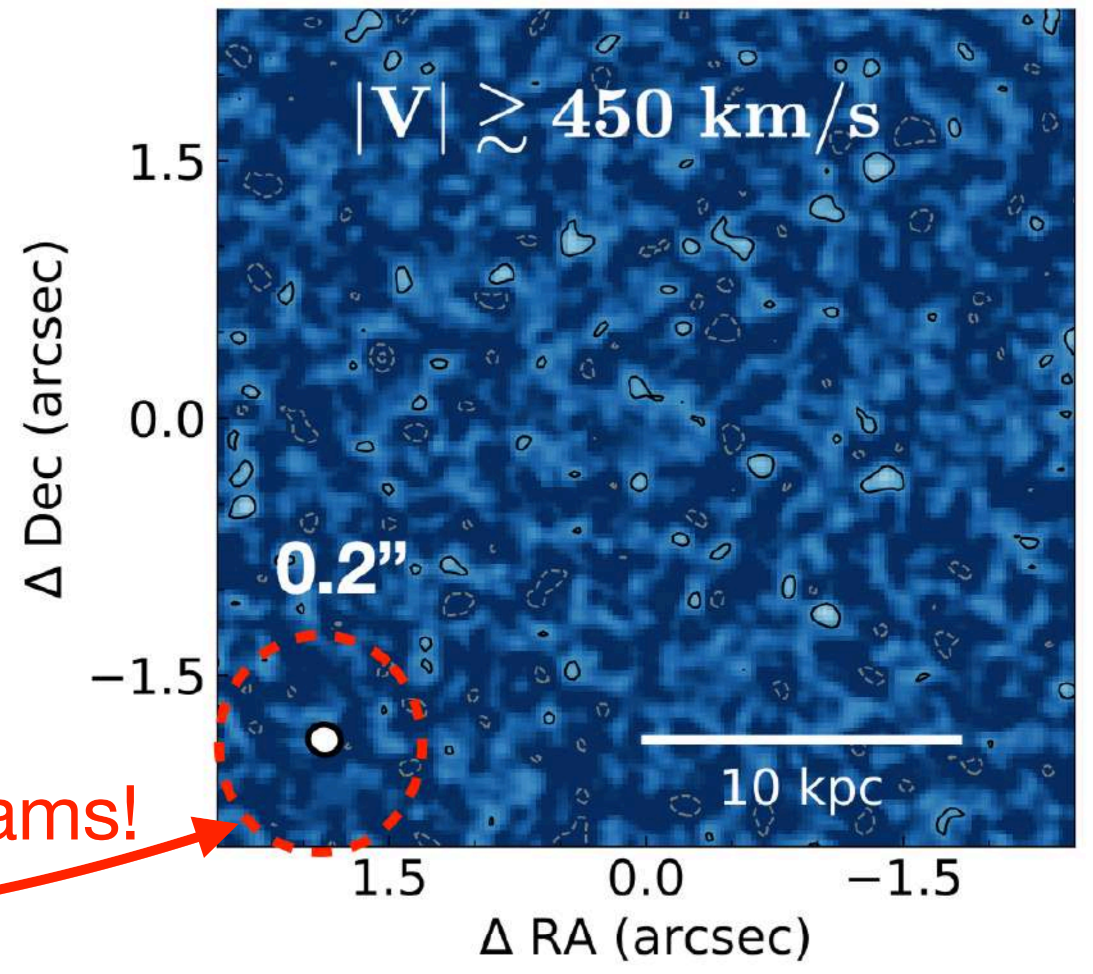
Izumi et al. 2021b



Same Sensitivity



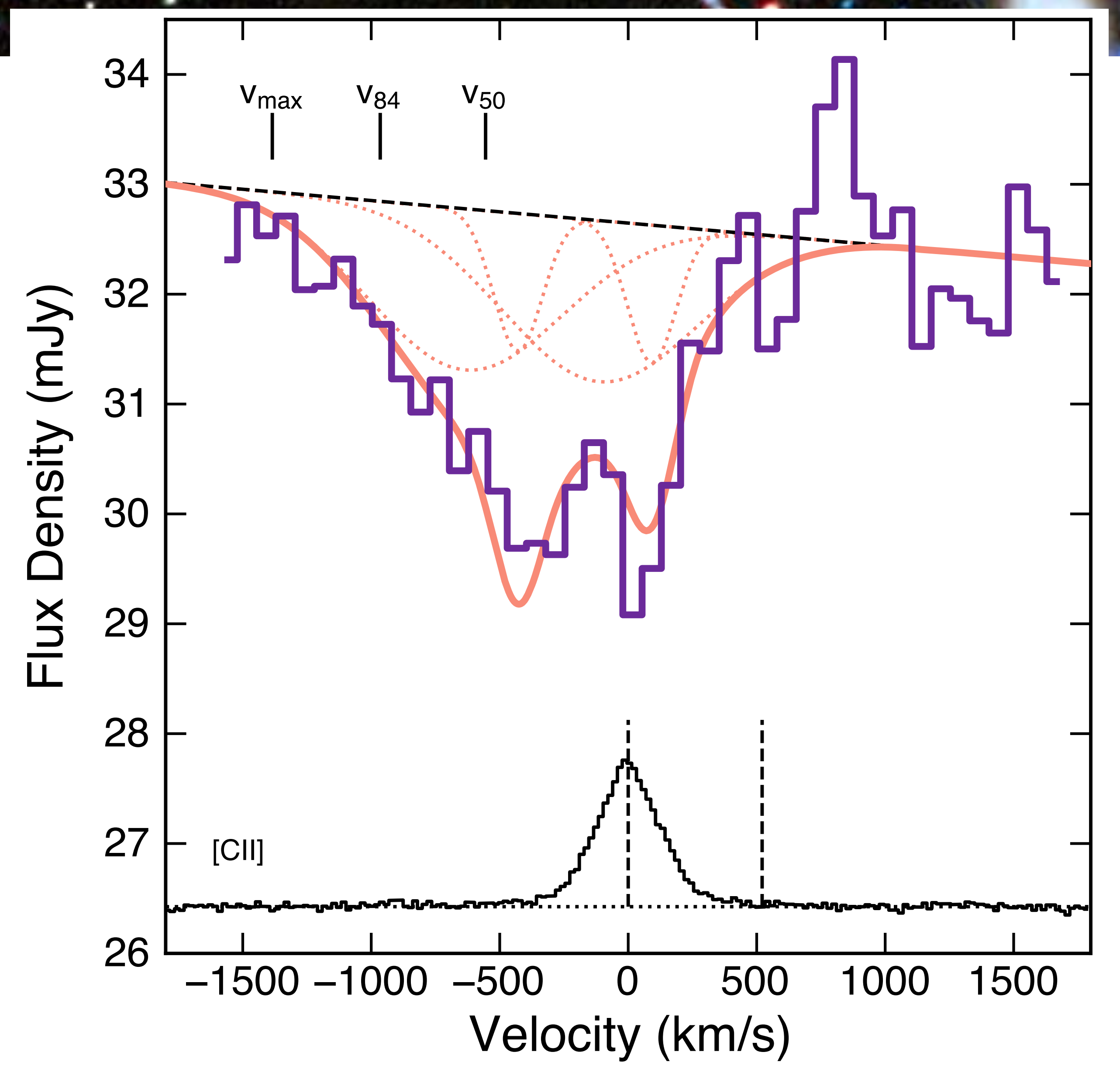
No wing component (moment 0)

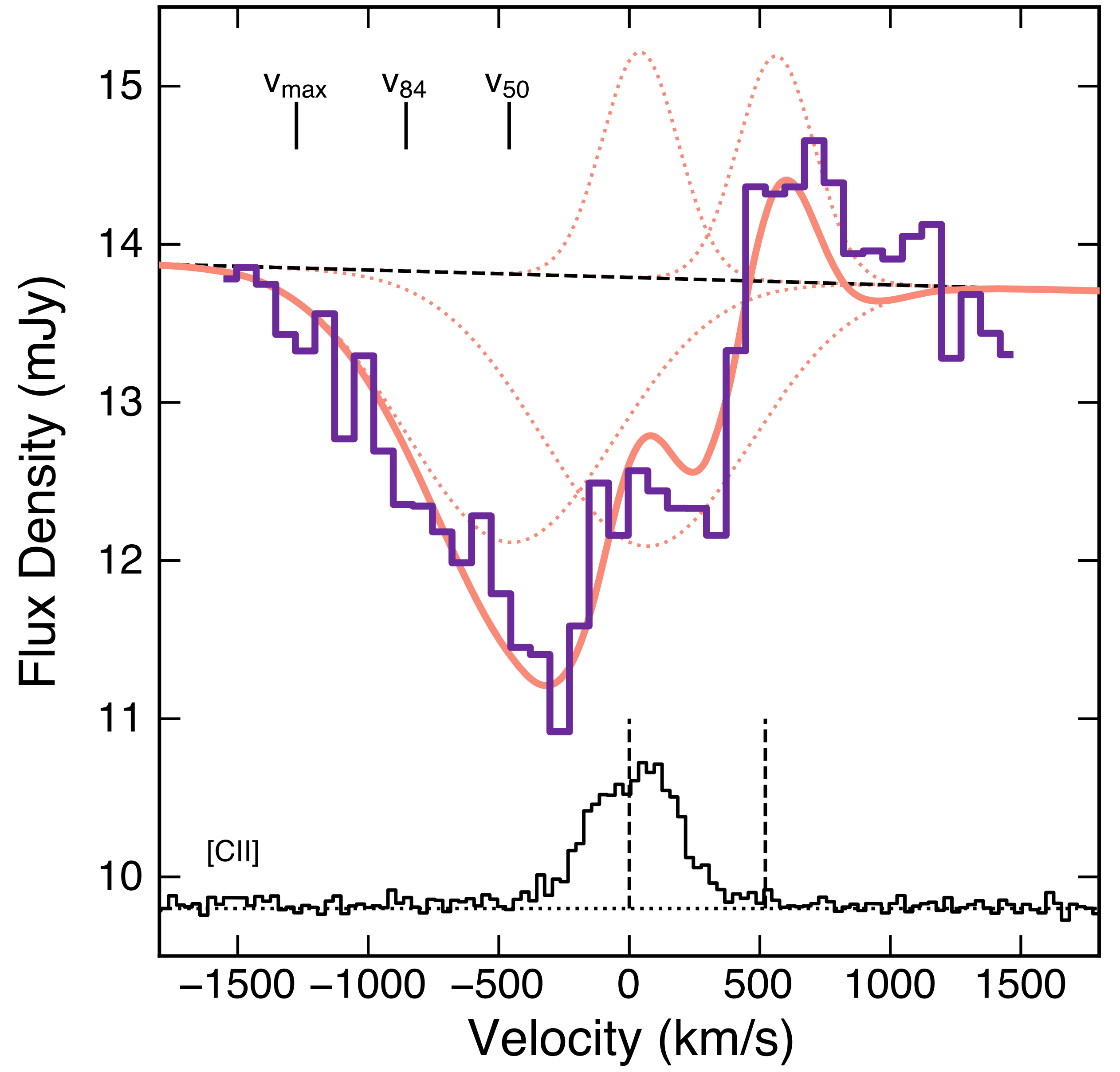


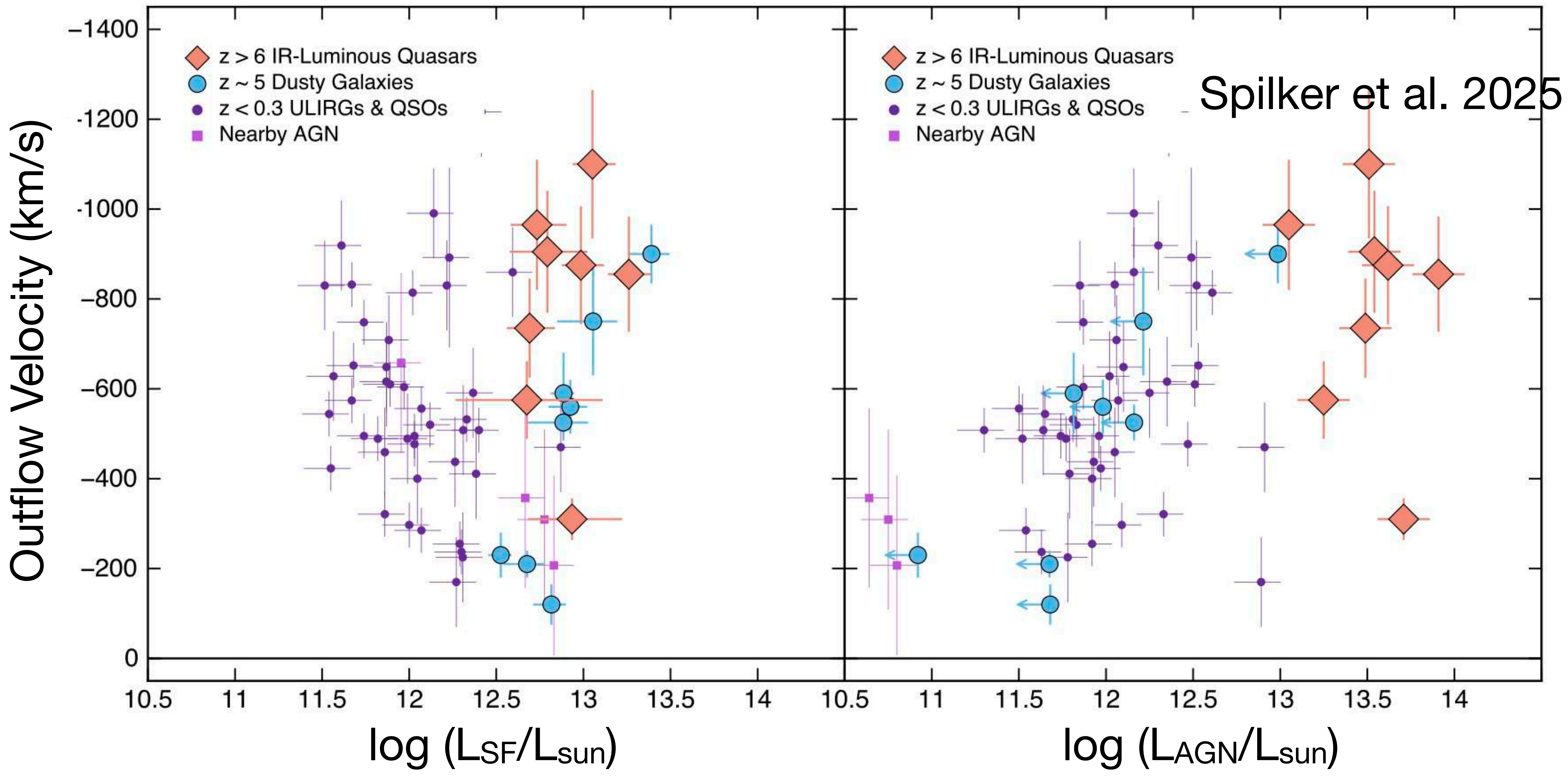
But per totally different beams!

- Some works claim the detections of [CII] outflows, whereas others do not.
- Maybe due to surface sensitivity issue (for the case of luminous quasars)…?? → Extended outflow?
- Our "detected" [CII] outflow in the HSC quasar is indeed compact (< 3 kpc)

Quasar-driven "dense" molecular outflow



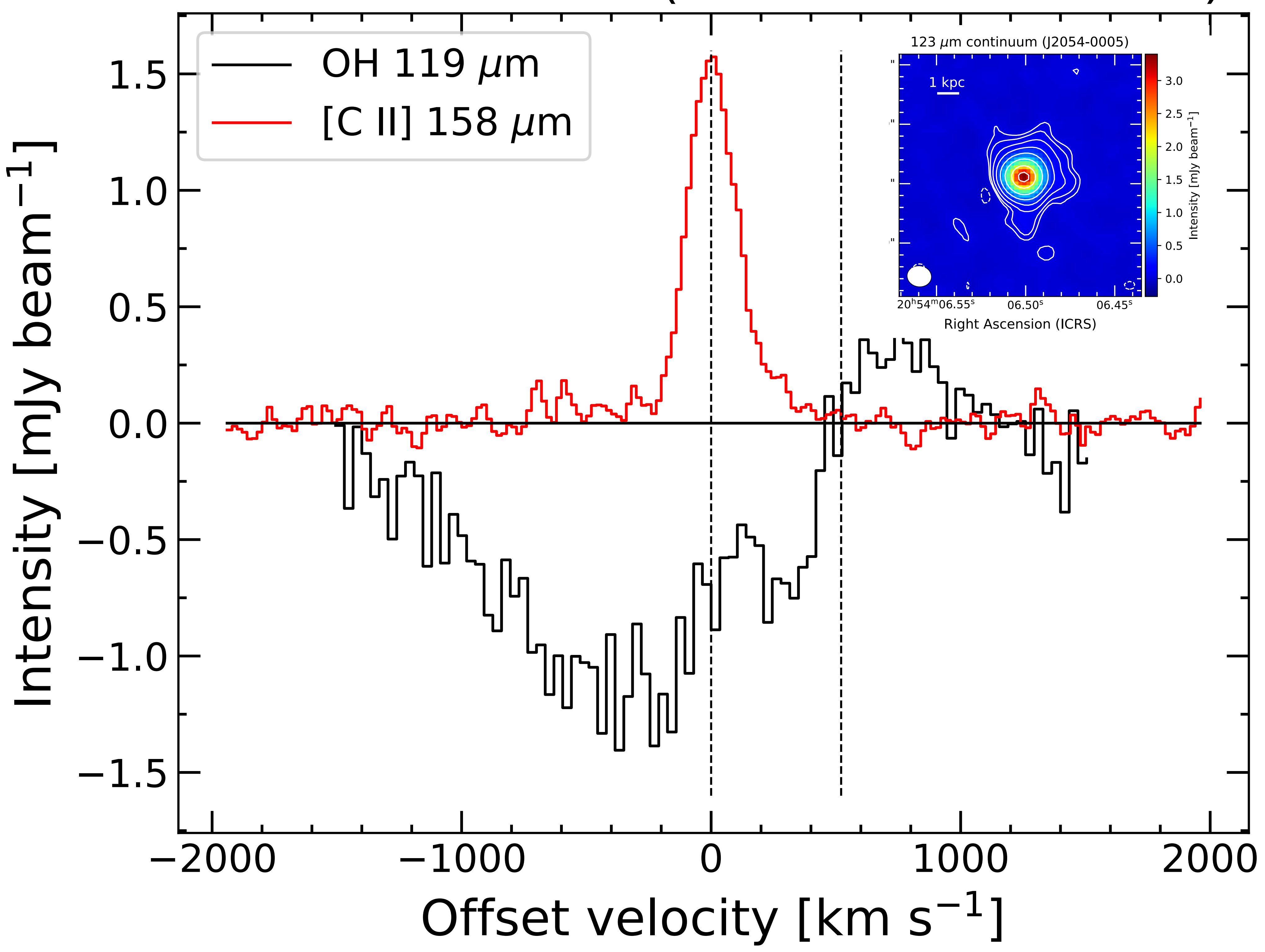


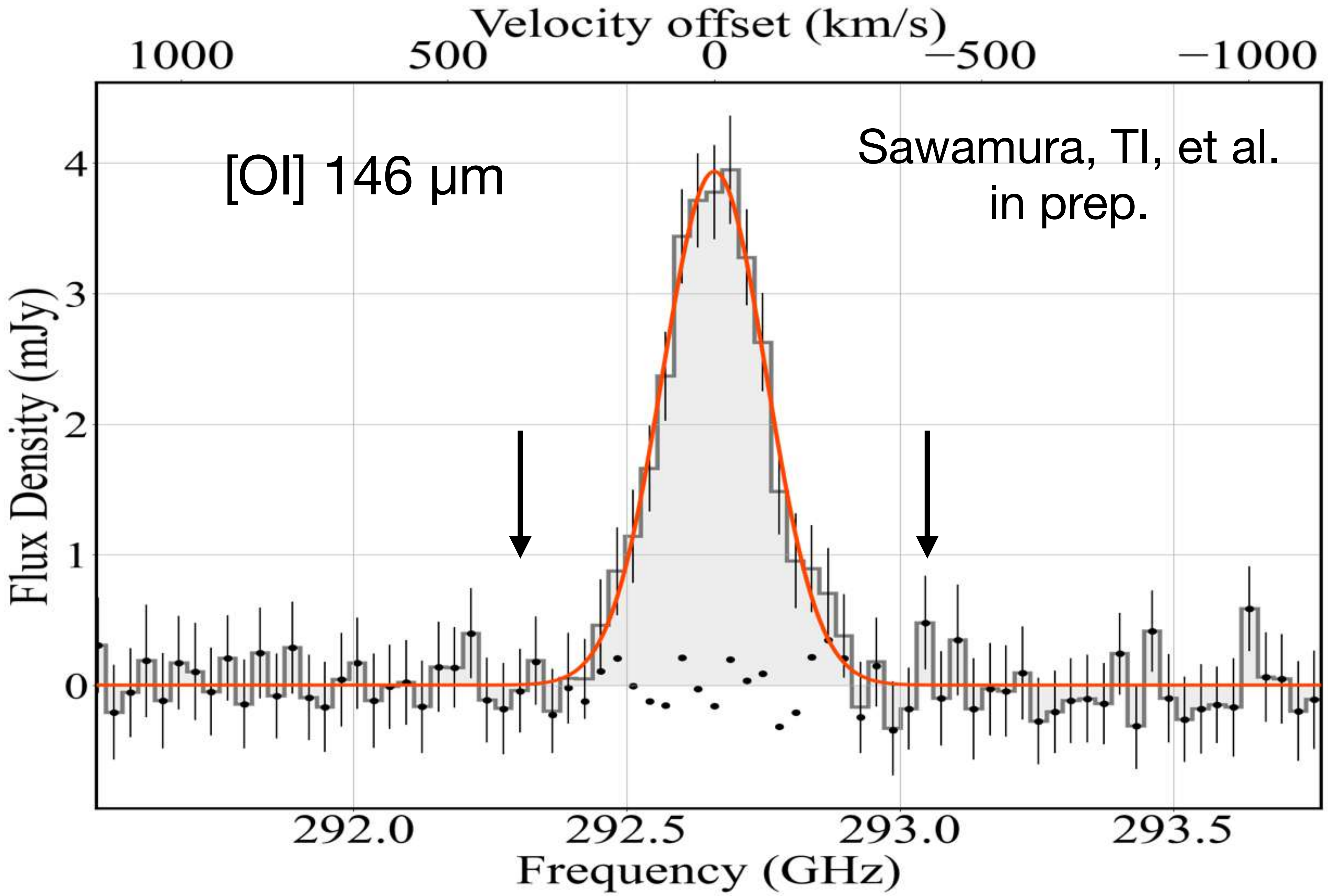


- Blue-shifted OH 119 μm absorption in ~70% quasars → Outflow
- Positive correlation of AGN luminosity vs Outflow Velocity
  → Suggestive of being AGN-driven?
- Outflow's kinetic power is ~0.5% AGN power. (~30% of SNe power)
  → AGN can easily drive this outflow.

Is there AGN-driven cool and “dense” outflow?

Salak et al. 2024 (J2054-0005 at z = 6)

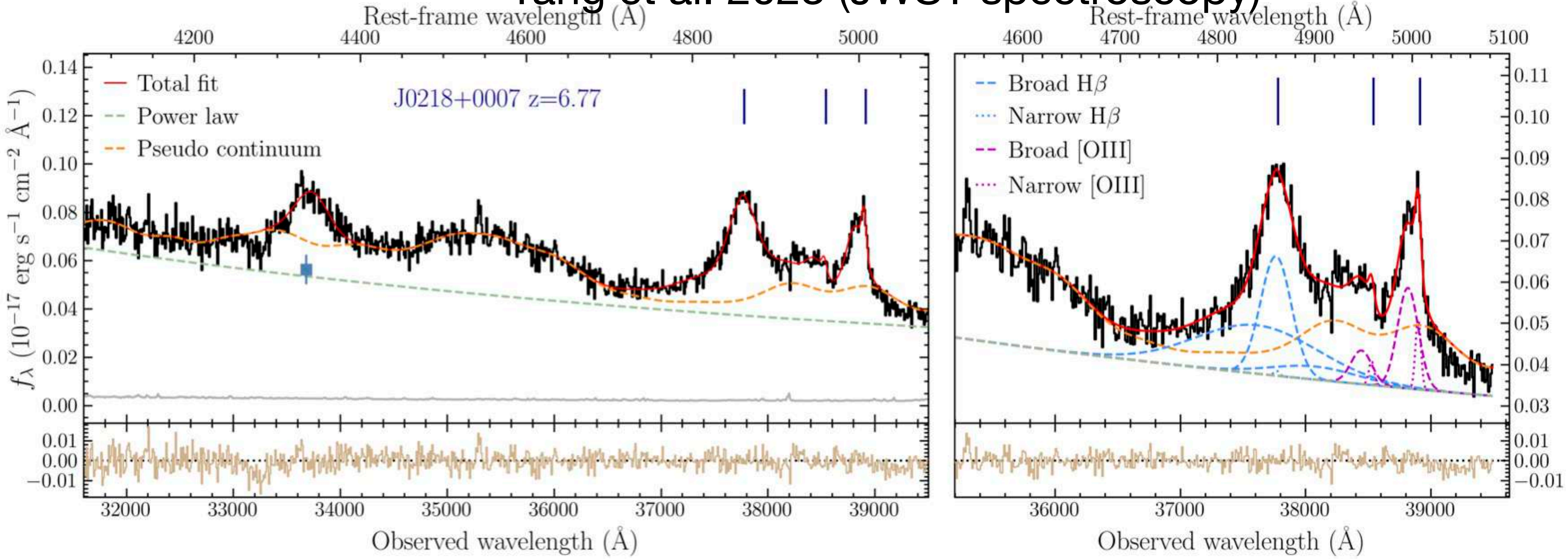


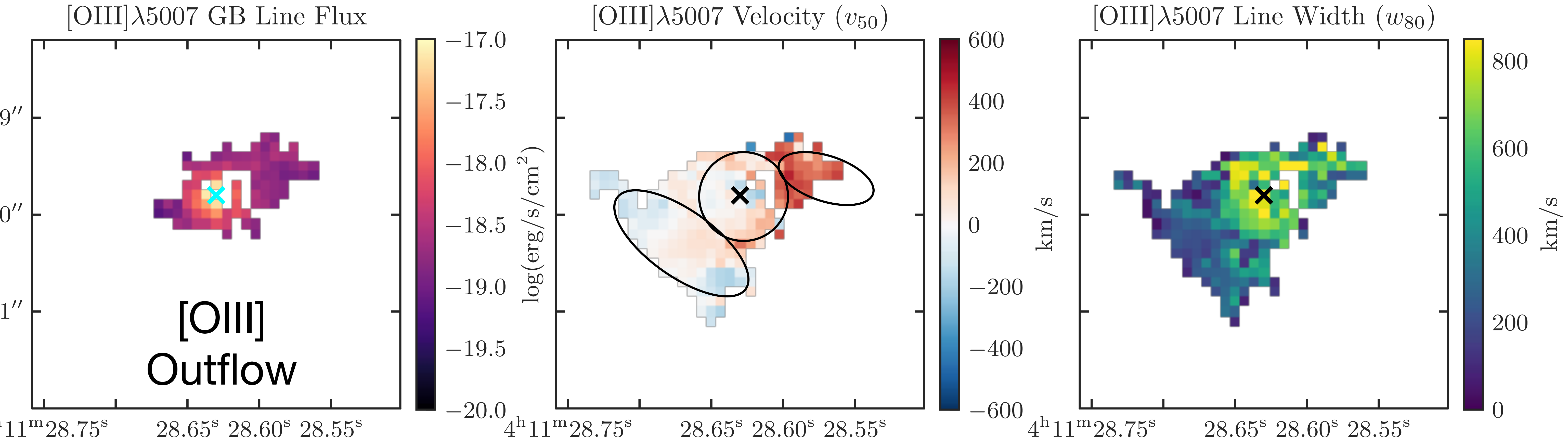


- Note: the line critical density of [CII] 158 μm is low. It can be collisionally de-excited in dense gas.
- We then performed deep [OI] 146 μm observation toward a luminous quasar at z~6.
- But still we don’t see any wing feature…

Prevalence of AGN-driven ionized outflows

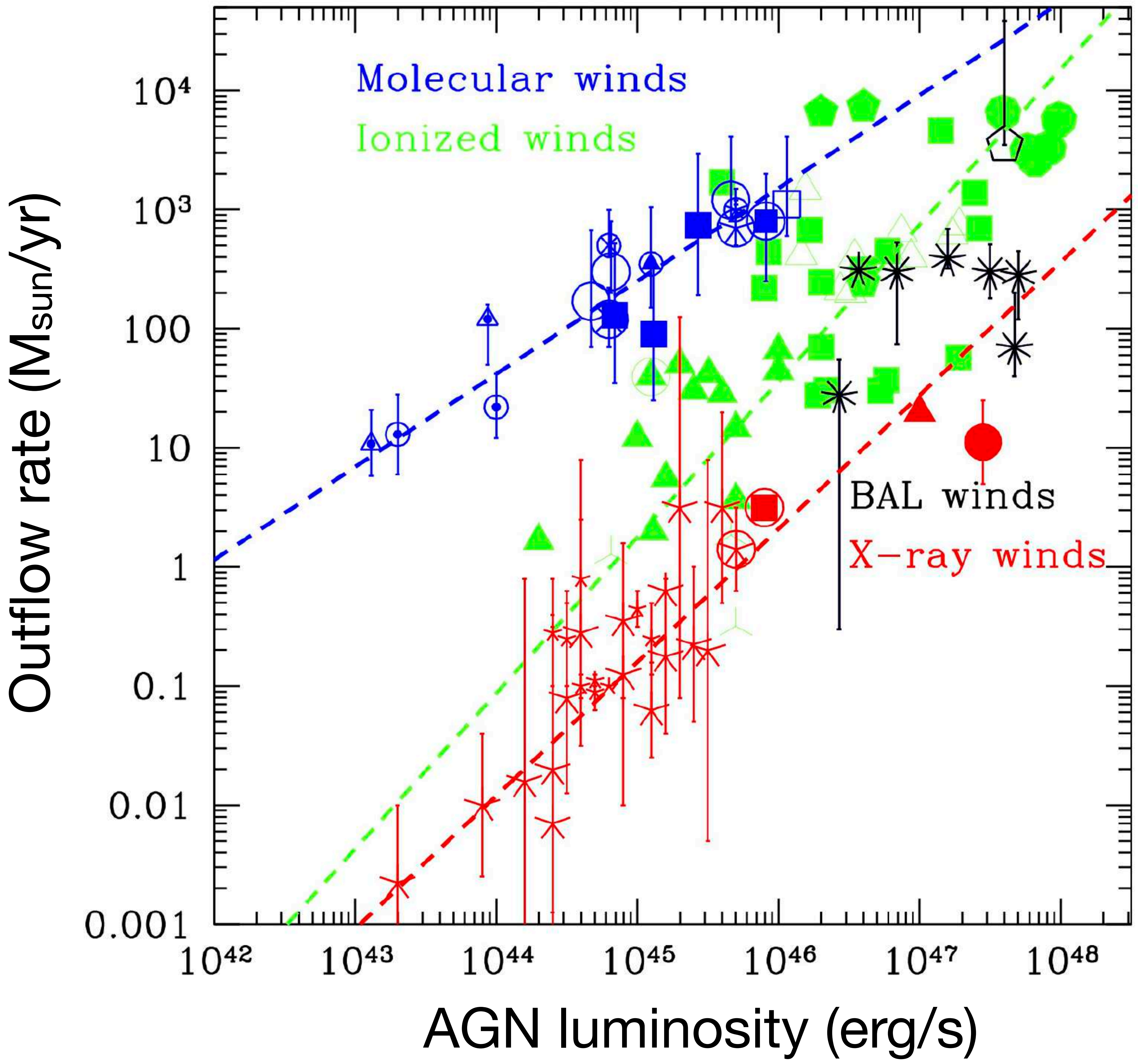
Yang et al. 2023 (JWST spectroscopy)





Marshall et al. 2023 (JWST IFU)

Fiore et al. 2017

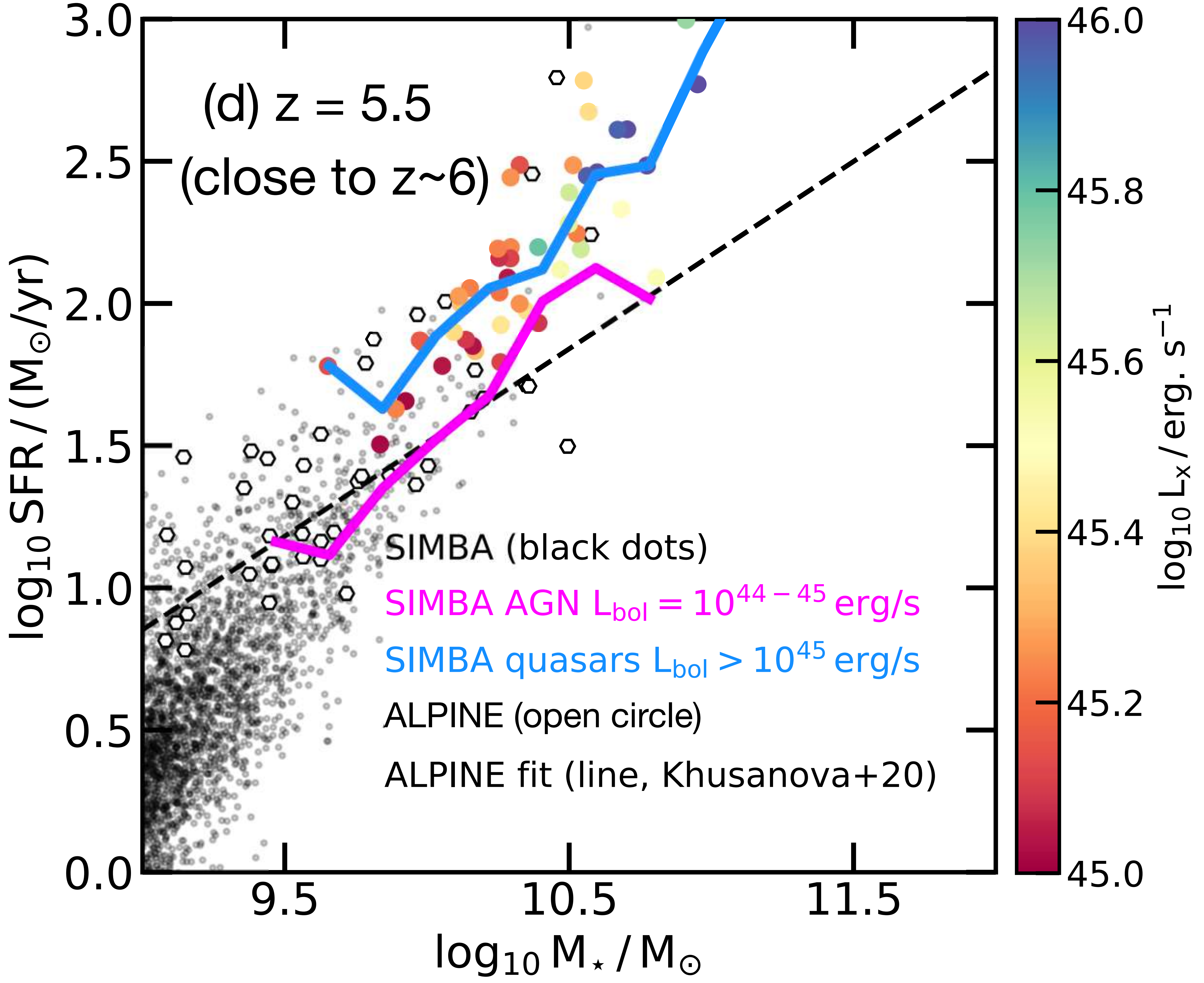


- Ionized outflows in almost all quasars.
- Carry bulk wind mass???

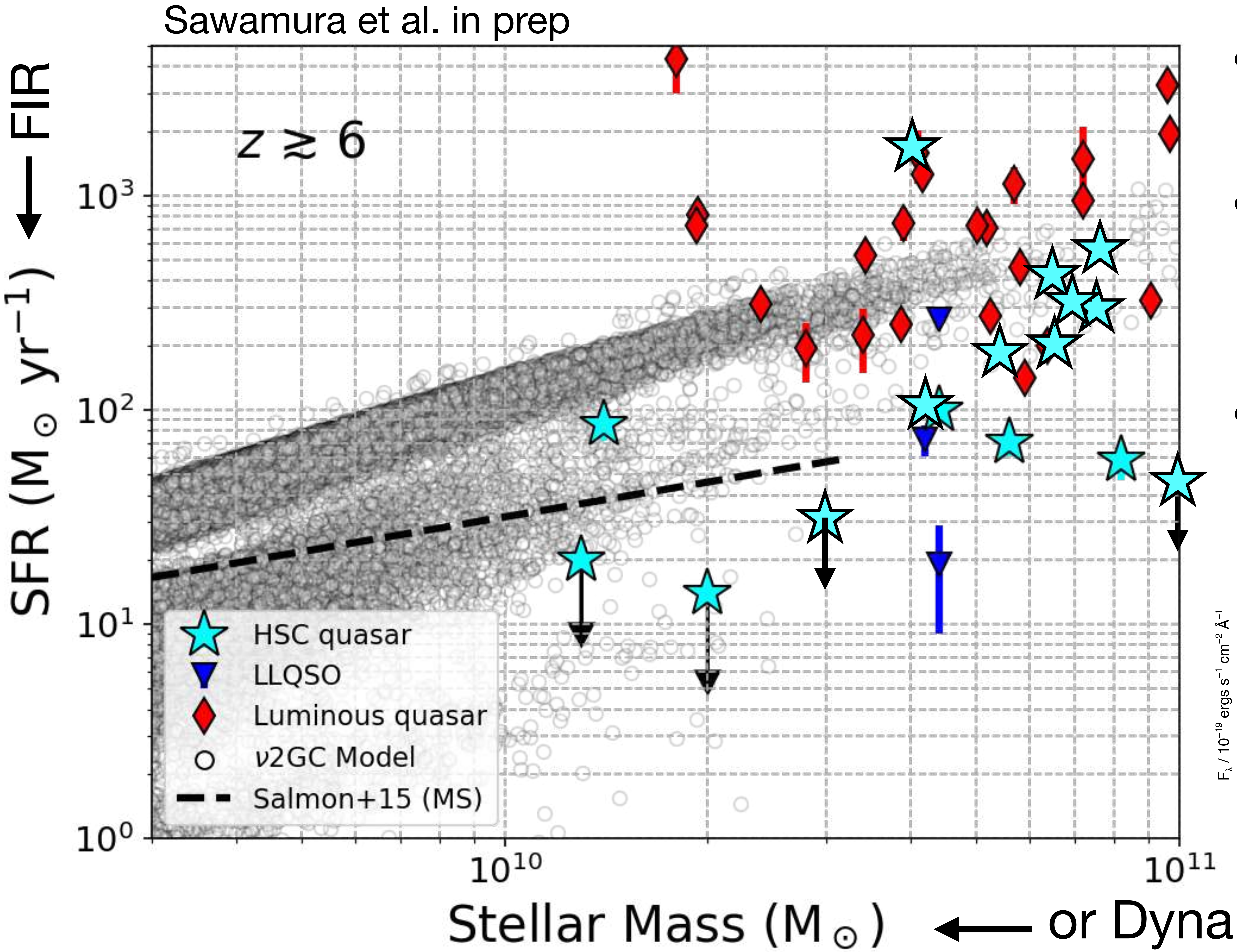
Levels of star formation

- [CII] and FIR cont → SFR estimator
- We can constrain the fractions of quasar hosts **on, above, and below the z~6 main sequence**.
- Current cosmological simulations managed to produce a number galaxies with < 10^10.5 Msun.
  → Low-luminosity QSOs will be a good comparison sample.
- We can also estimate **sSFR**, and look at correlations with AGN power.
  → negative correlation → AGN feedback?

from TI's ALMA Cycle 12 proposal

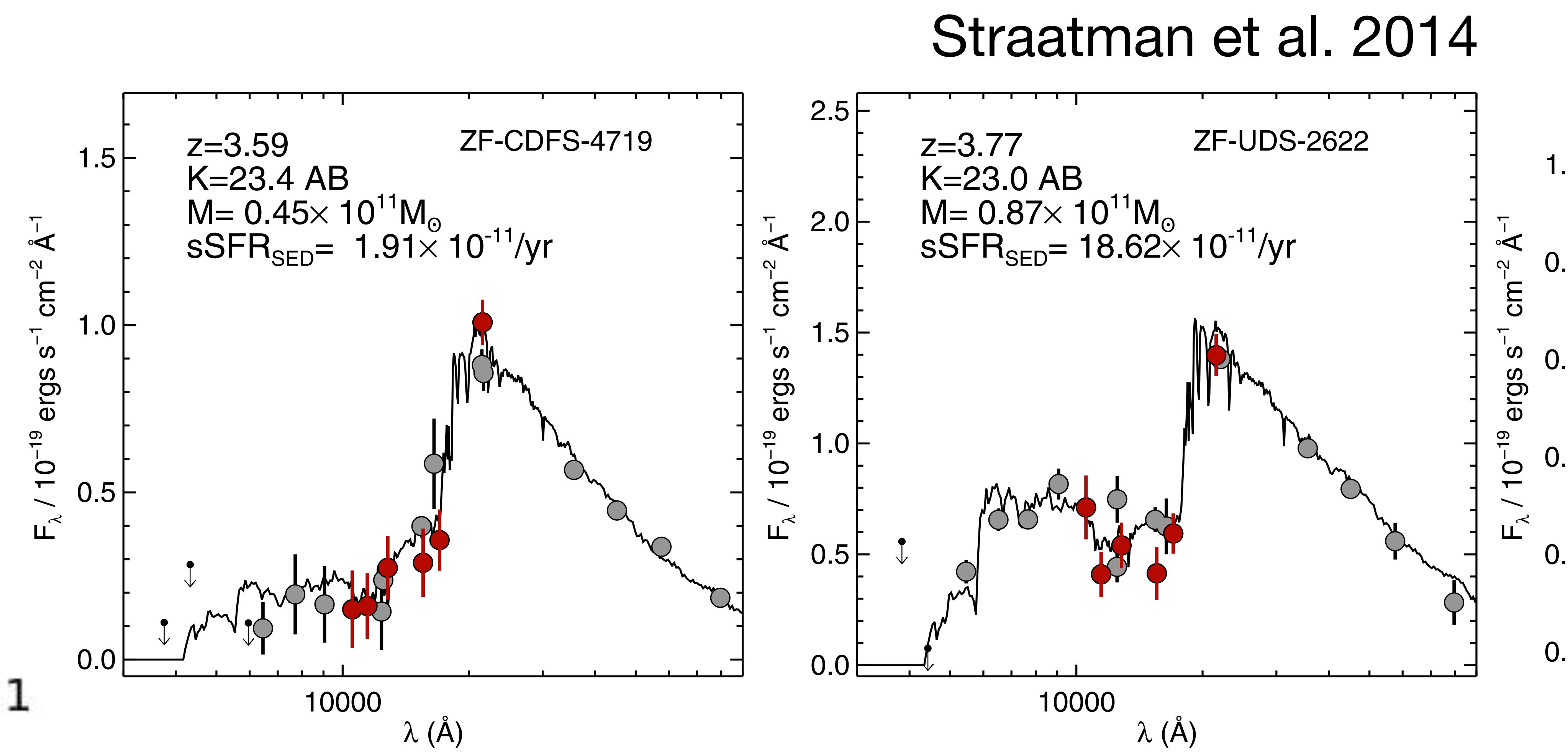


Wide spread in Star Formation Activity



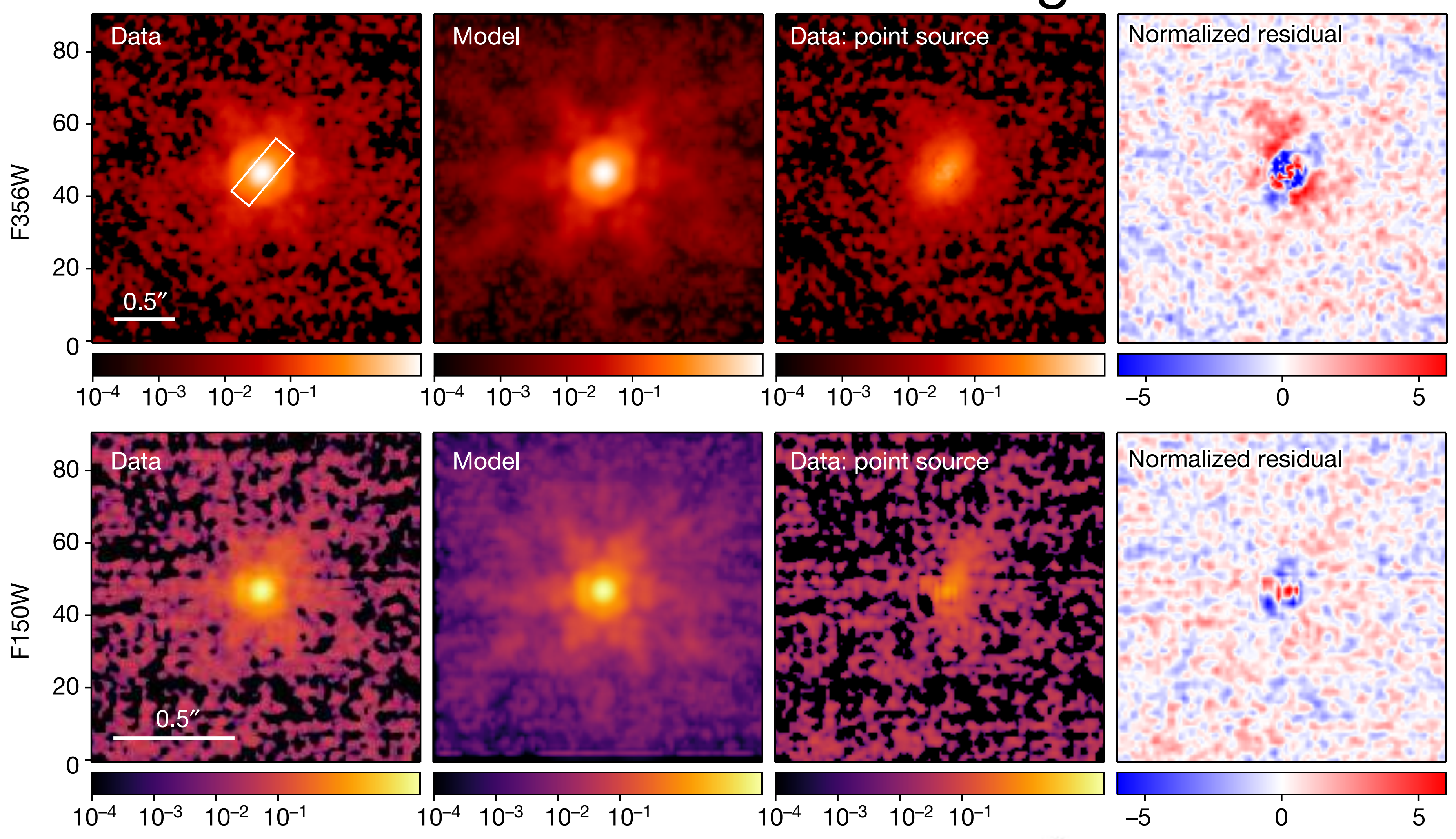
or Dynamical mass

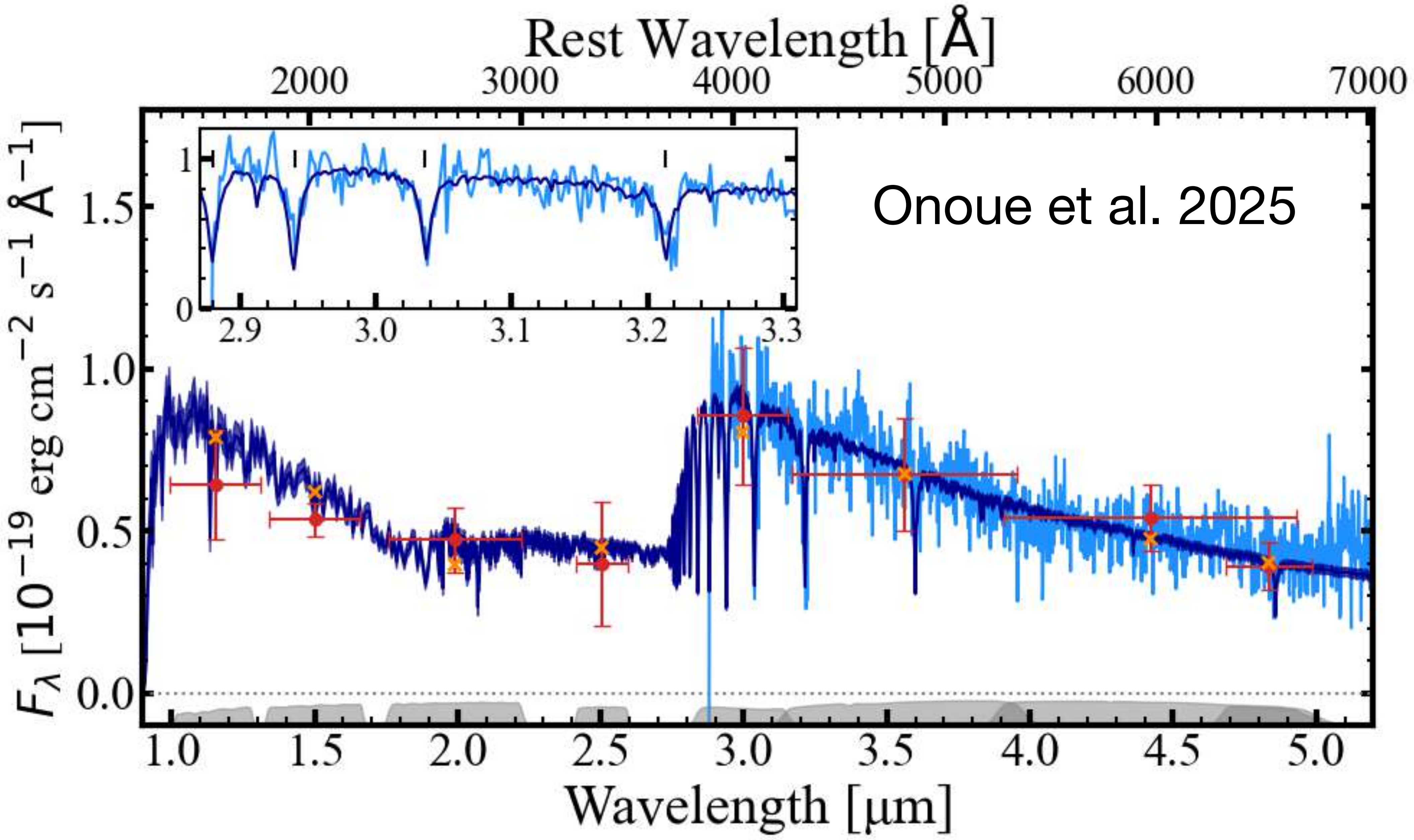
- Very wide (×100) variation in SFR among our HSC quasars.
- Some are **starburst**, some are **MS**, and some are going to **quiescent, already at z~6**.
- Progenitor of cQGs at z~4-5??



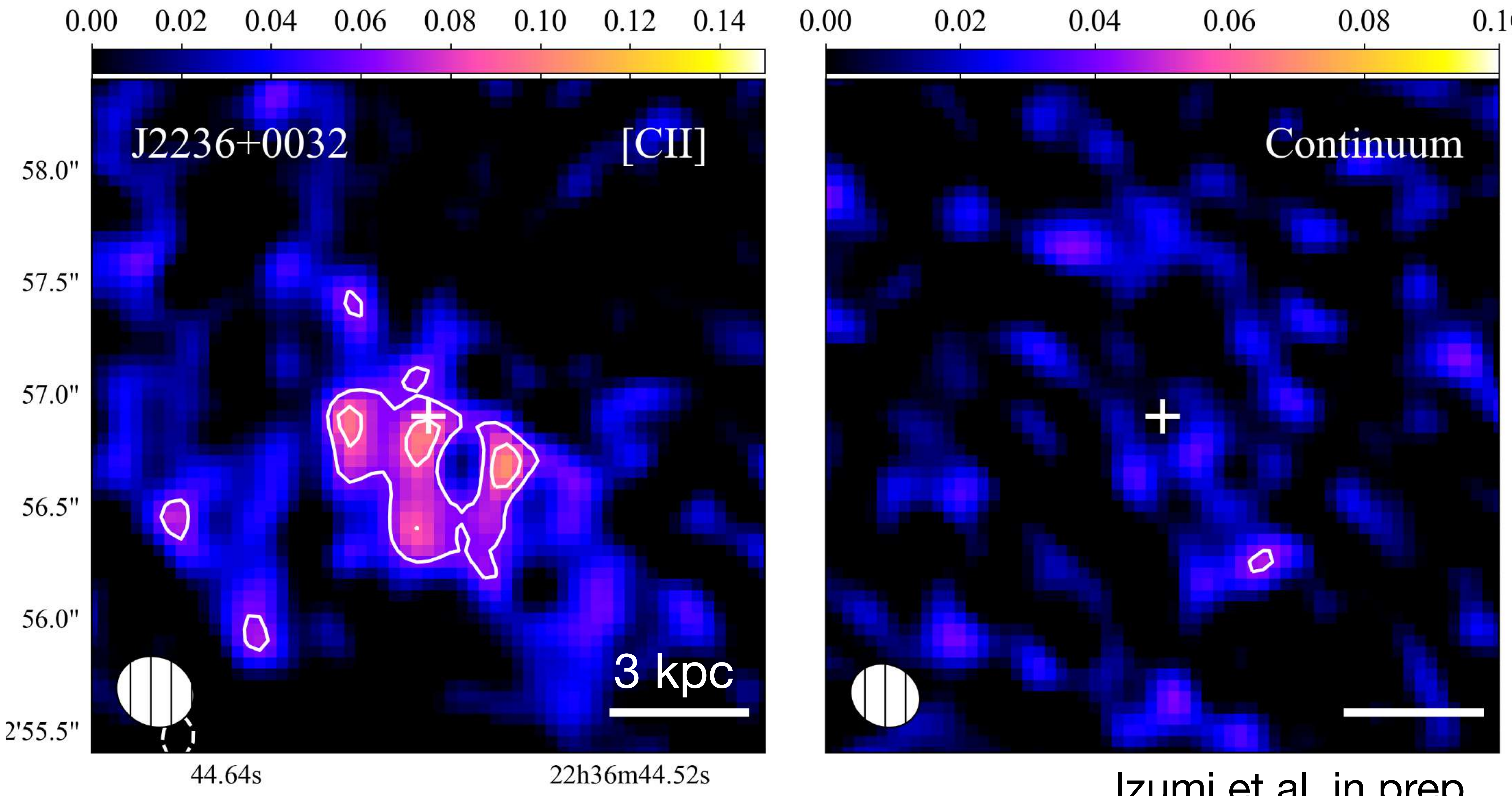
Wide spread in Star Formation Activity (incl. JWST)

Ding et al. 2023





Onoue et al. 2025

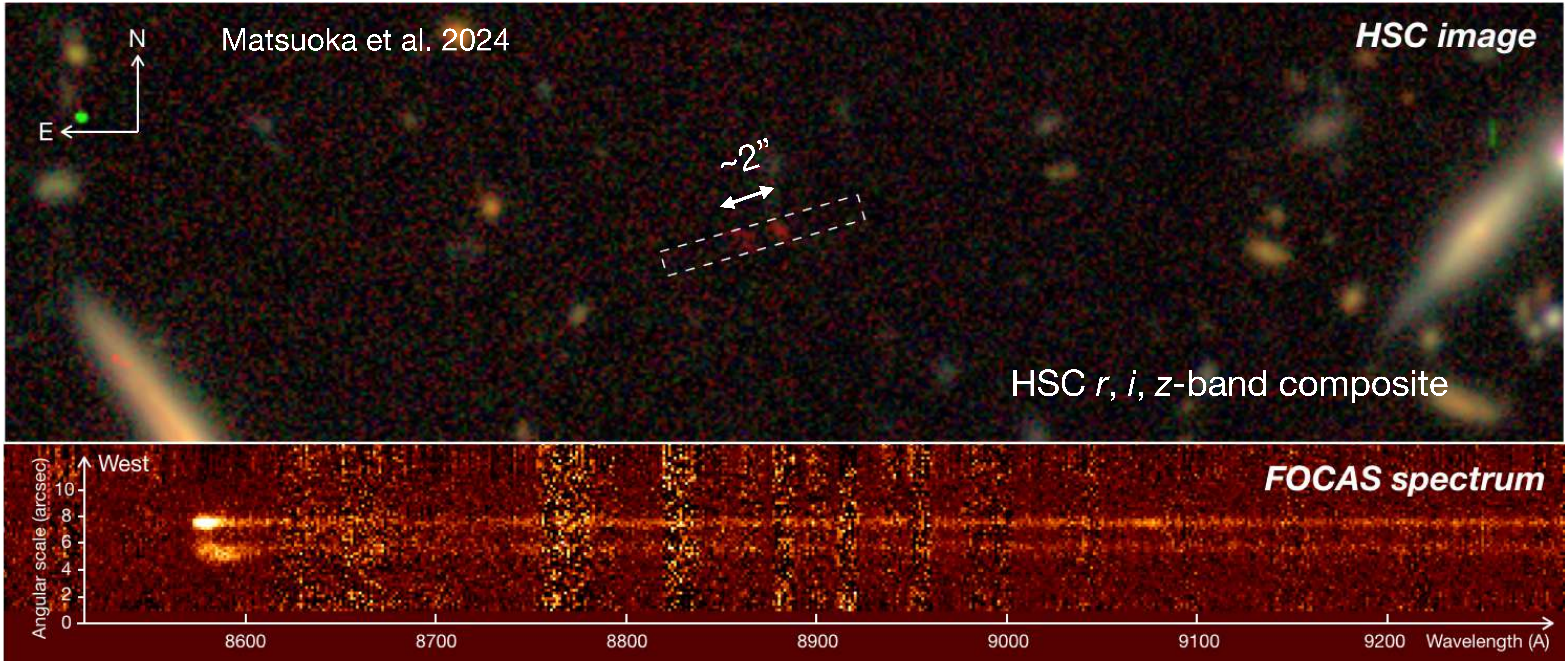


Izumi et al. in prep.

- J2236+0032 (example): log M_{star} = 10.6, with little star formation (at most a few M_{sun}/yr).
- [CII] is barely detected (3σ), continuum is not detected → Quiescent host galaxy at z~6.

3. Mergers of galaxies

HSC Discovery of a z = 6.05 Pair System (very faint!)



- We discovered a pair system (separation ~ 2”) by using the Subaru/HSC-SSP survey data.

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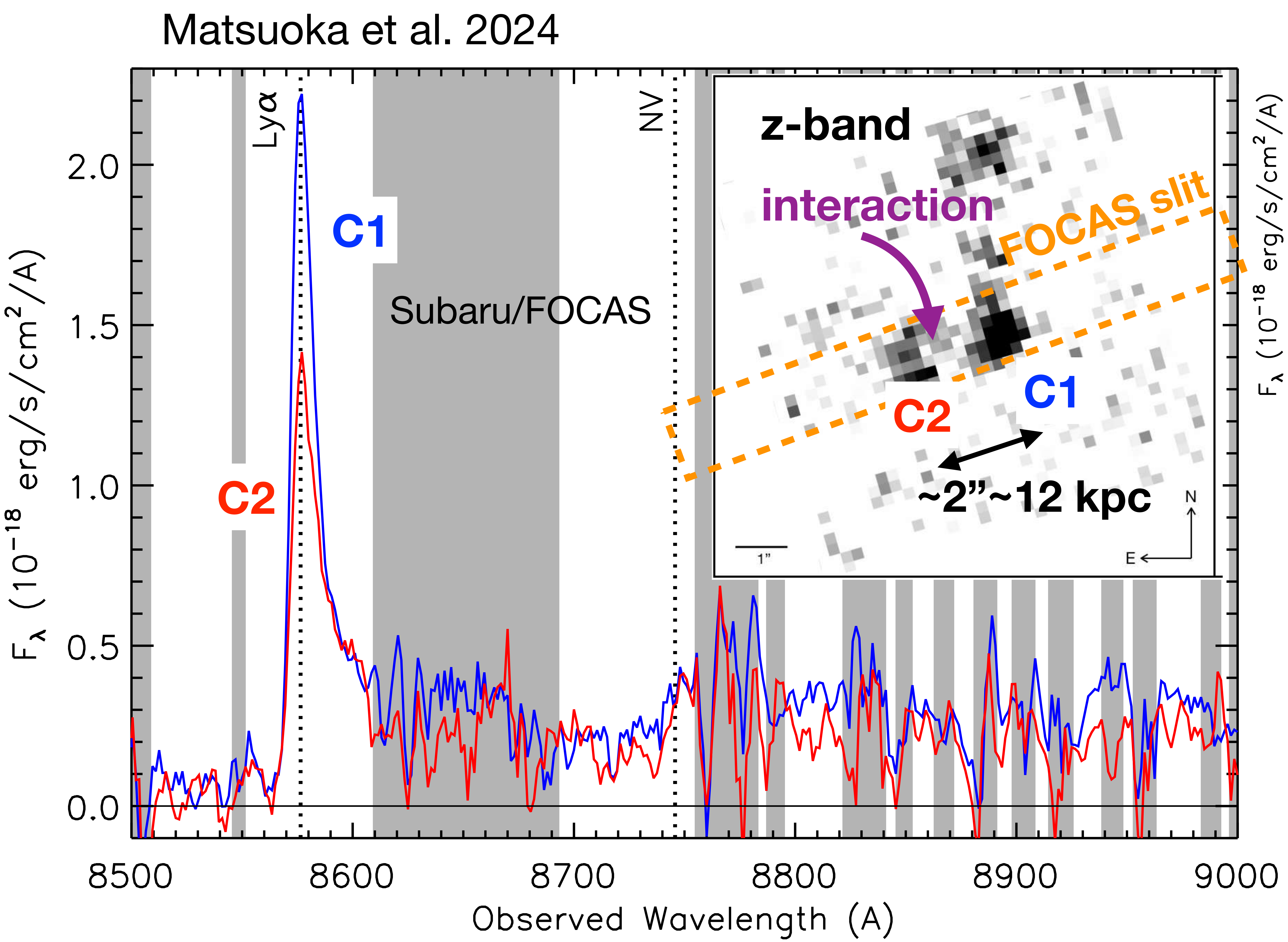
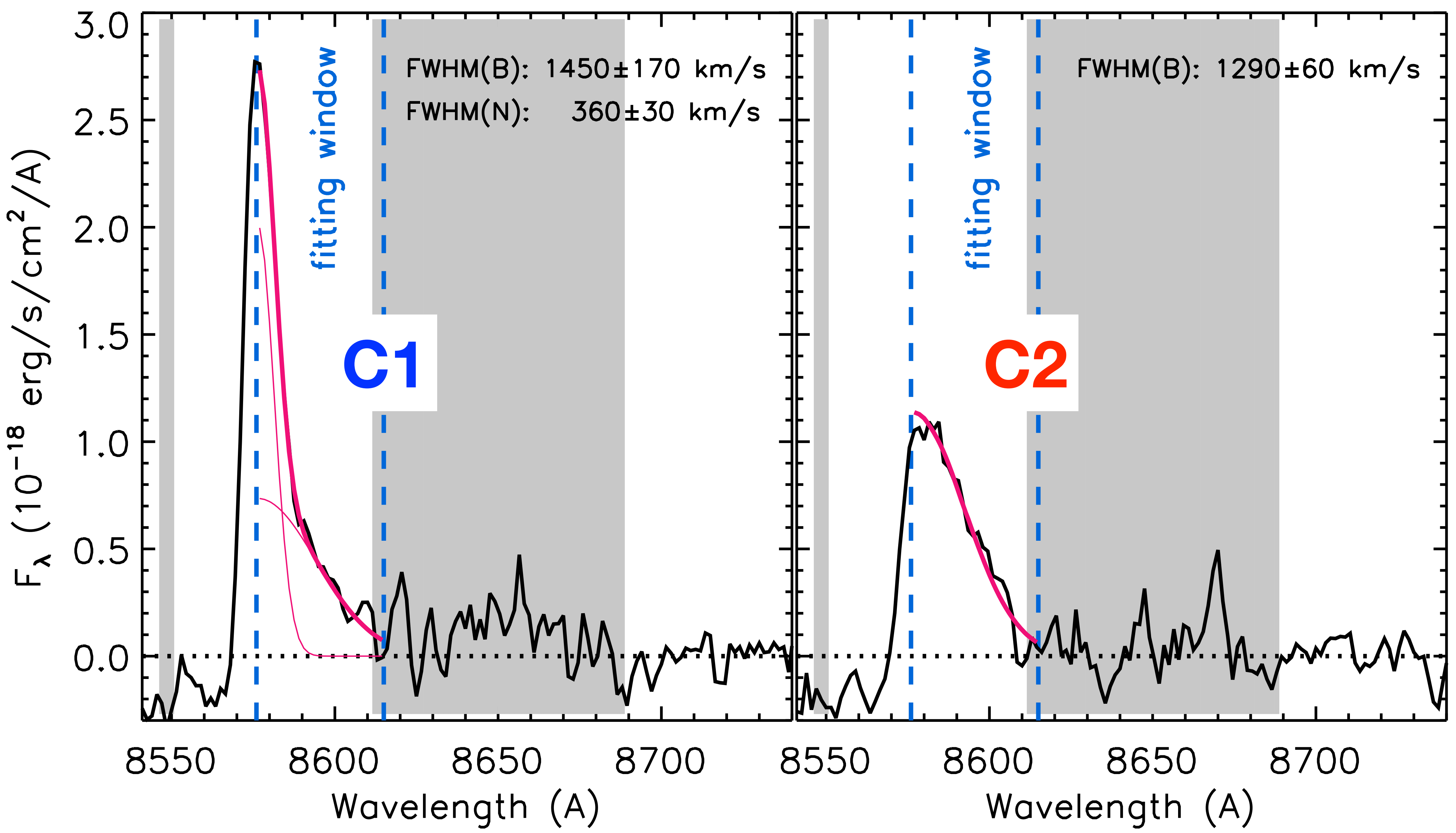
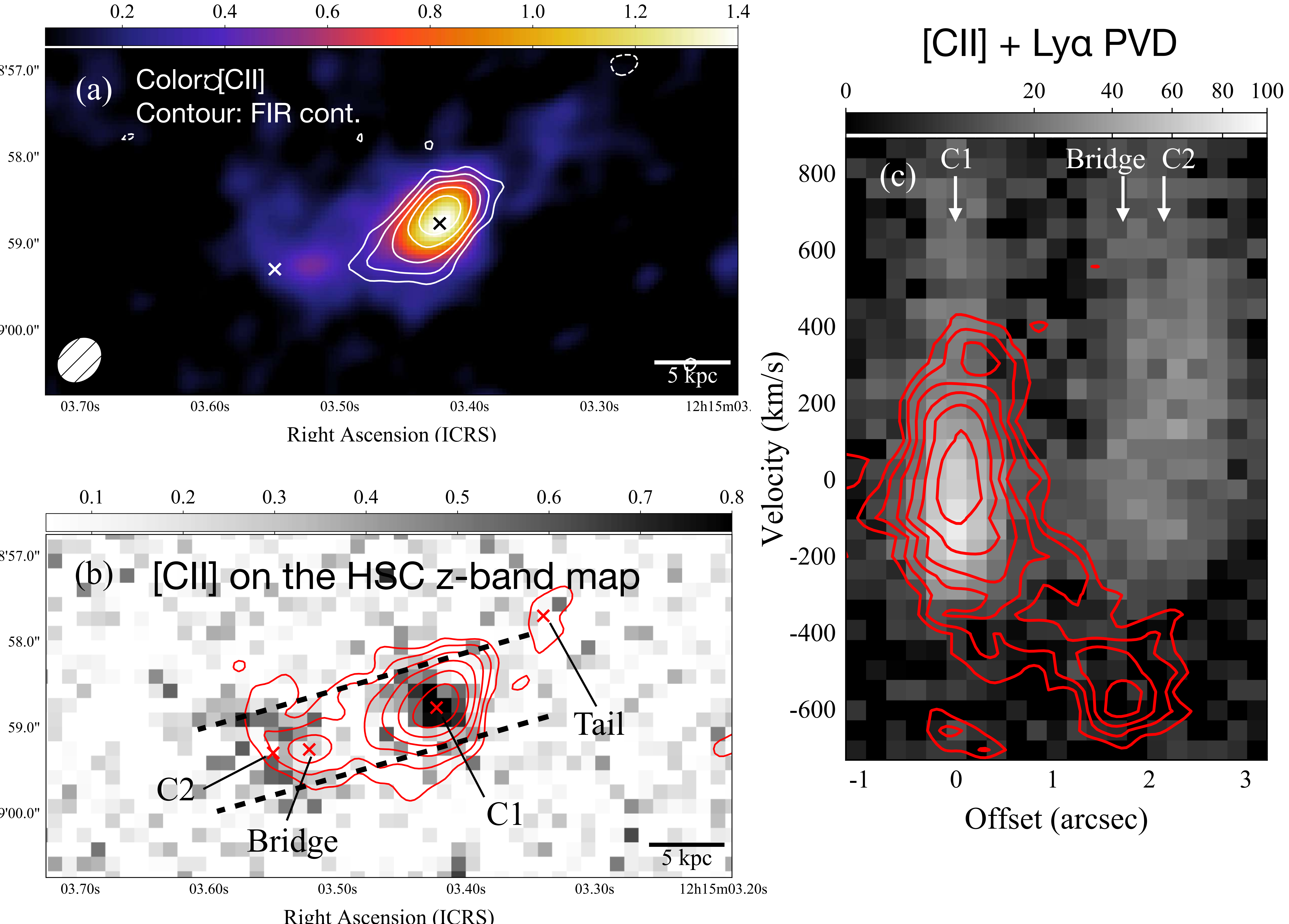




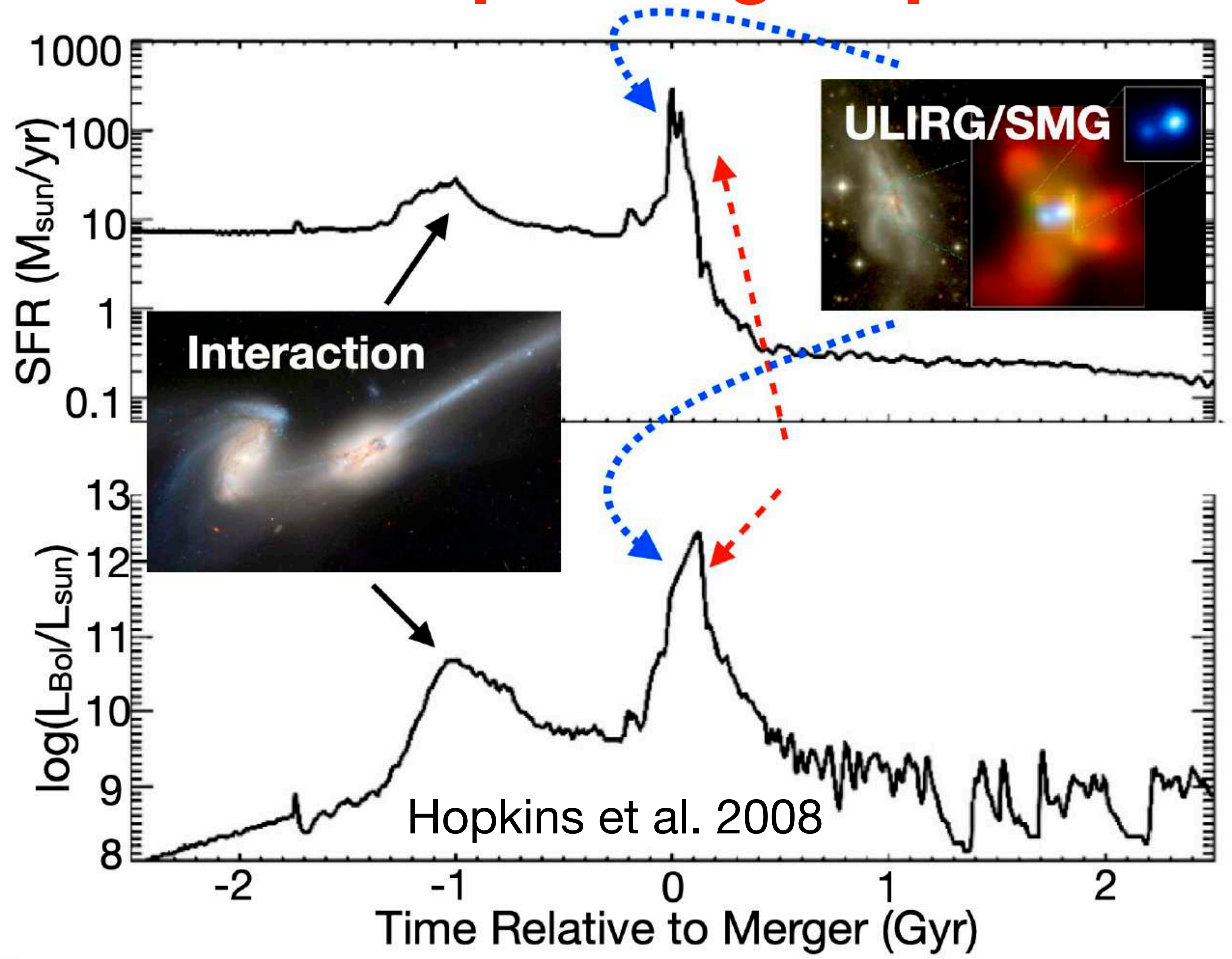
- Highest-z quasar-quasar pair known to date.
- **The Lyα line is bright and broad** (indicator of AGN) in both A and B. We also see a hint of Nv line.
- Very faint (M_{1450} = -23.1 and -22.7 mag).
  → **~100× fainter** than SDSS quasars

ALMA follow-up ([CII] + FIR cont.)

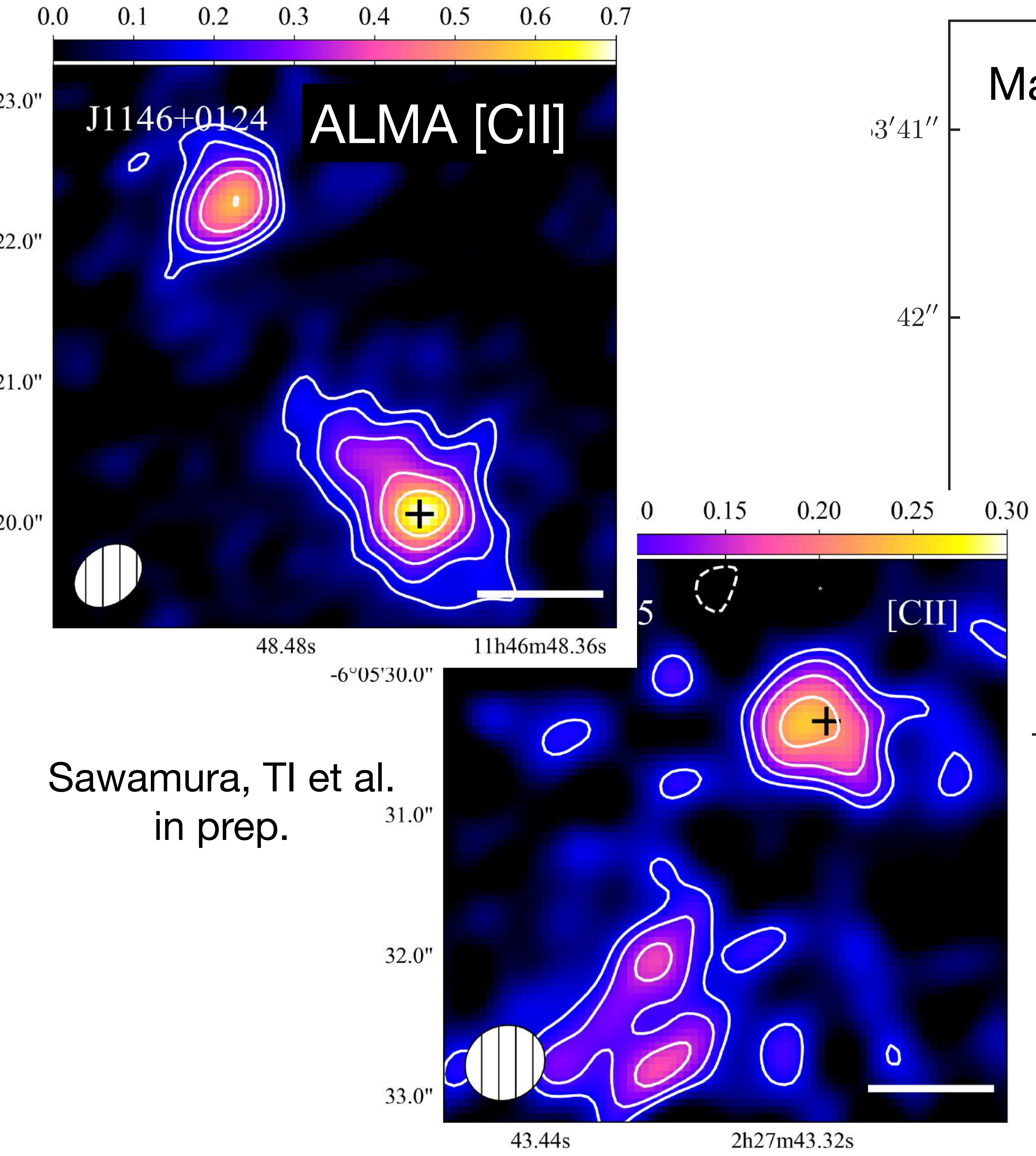
Izumi et al. 2024



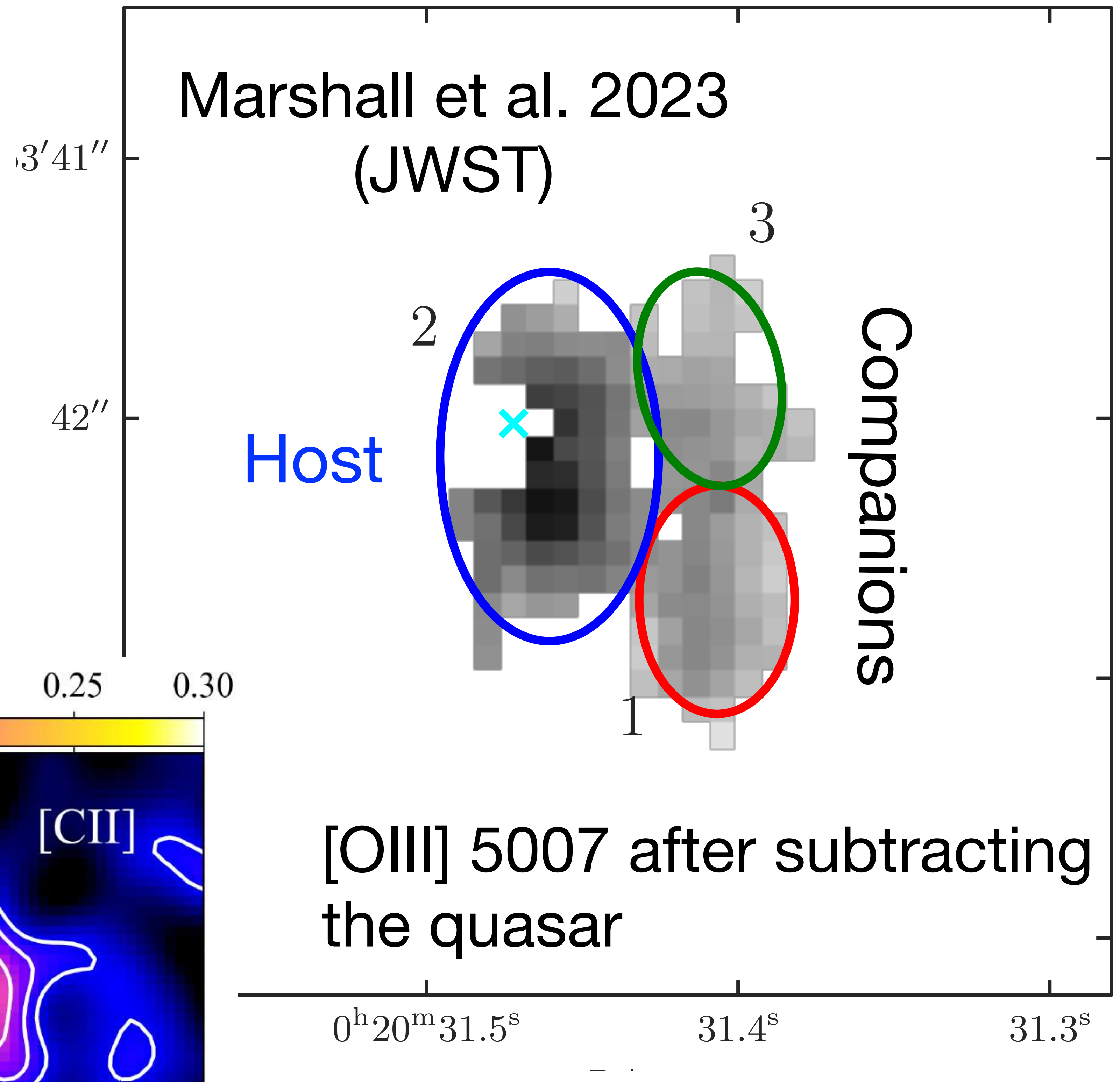
- Very clear interaction.
- Spatial/velocity offset between C2 and the local [CII] maximum
  → Offset-AGN (kicked-out)?
- One of the [CII]-brightest galaxies ($L_{[CII]}$ ~6 × 10^9 L_{sun}) at z > 6
  → M_{H2} ~ 10^11 M_{sun} (!)
- **Will be a super-bright quasar!**



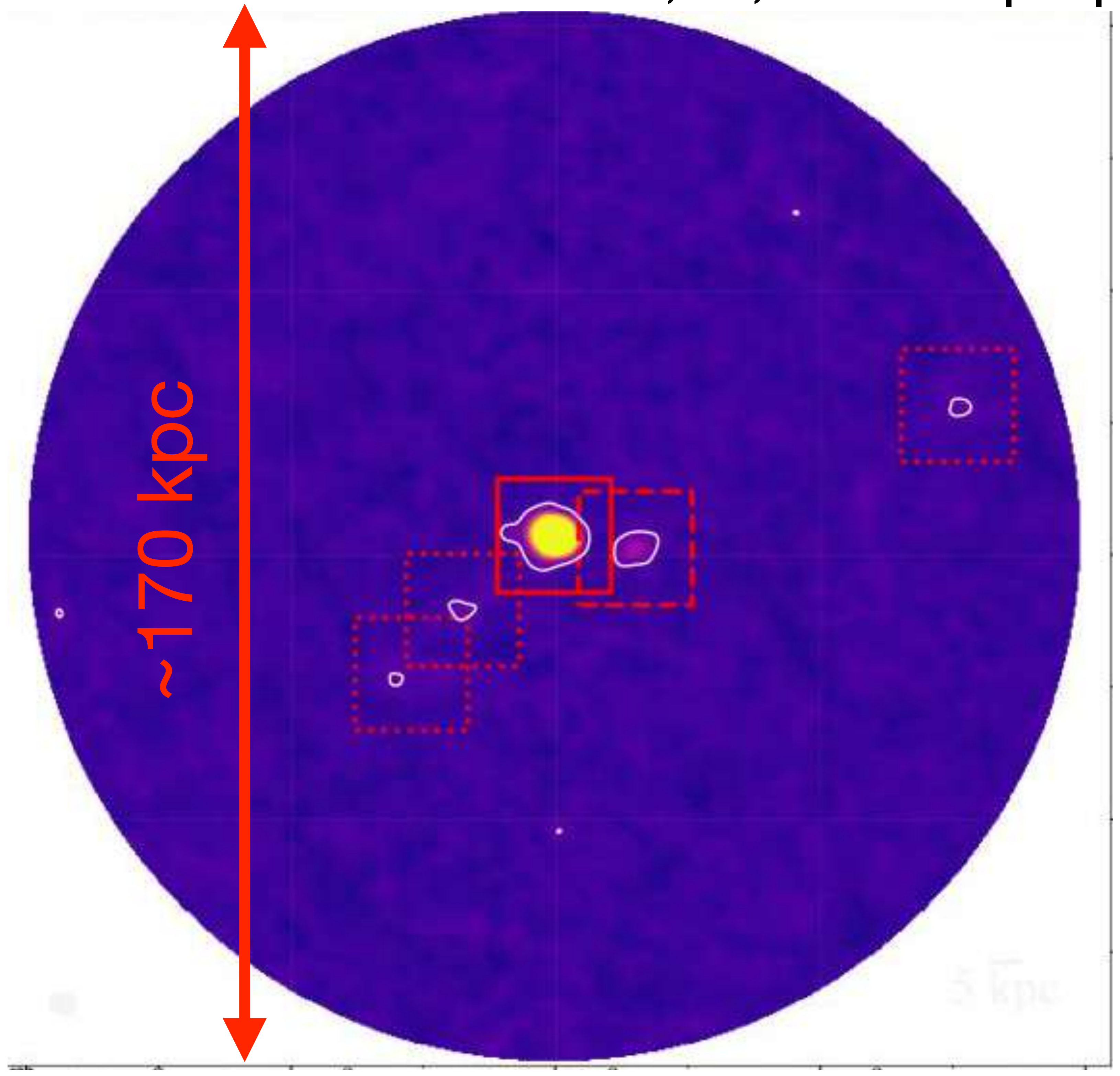
High resolution, deep, multi-wavelength observation is the key



Sawamura, TI et al. in prep.



Sawamura, TI, et al. in prep.



- Carefully considered observations are necessary to probe the prevalence of mergers in high-z quasars.
- …and for a **proper comparison** with normal galaxies!

Summary

- ✦ Exploration of lower-luminosity, less-biased quasars is on-going.
- ✦ No redshift-evolution of the co-evolution relation is suggested (although there are some non-trivial assumptions).
- ✦ AGN-driven outflows are NOT so frequently detected in cold gas emission, except for OH absorption. But ionized outflows are prevalent. More advanced assessment of physical properties will be required.
- ✦ There is a wide spread in SFR. Some are starburst, some are normal, and some are quiescent already at $z > 6$.
- ✦ Mergers of galaxies are re-assessed. We need careful design of observations. Statistical comparison with normal galaxies will be a next step.
- ✦ Other topic: dust obscured, earlier phase AGN should be studied in detail.