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Shedding new light on the first billion years of the Universe

Unveiling the properties of the first QSOs and their host galaxies

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High-z QSOs

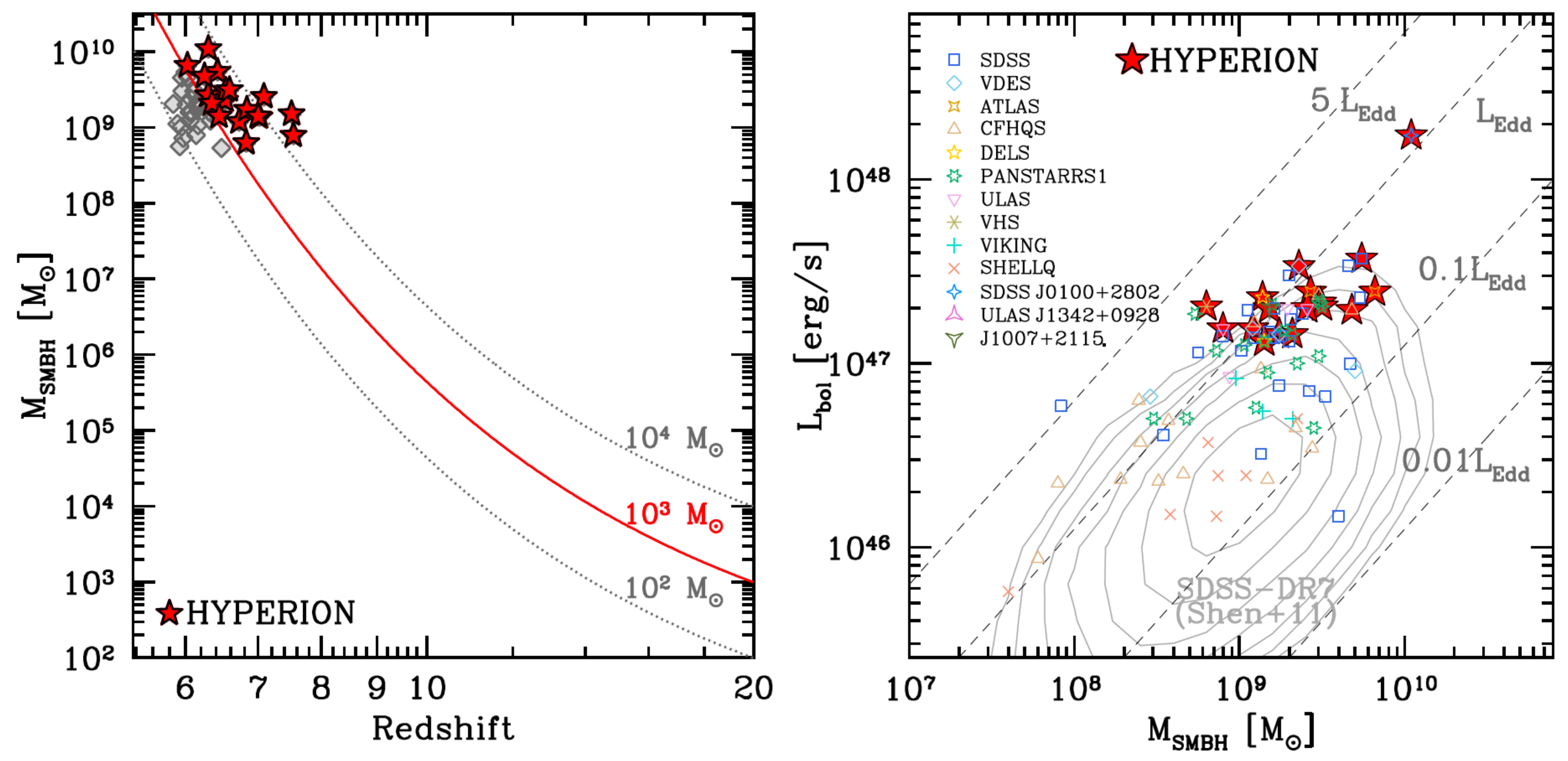
- Active galaxies with massive BHs
- What are the properties of QSOs host galaxies?
  - Dust
  - Gas
  - Stars
- Are these different from low-z ones?
- What can these tell us about the evolution of galaxies over time?

Fundamental questions

- How these SMBHs are able to in short timescales?
- Do the SMBHs and their host-galaxies co-evolve?
- How effective is the feedback in influencing the evolution of these objects?

HYPerluminous QSOs at the Epoch of ReionizatION (HYPERION)

- ❖ HYPERION sample comprises 18 QSOs which experienced the most rapid SMBH mass growth
- ❖ Deep X-ray survey: first systematic, homogeneous X-ray spectral characterization of the accretion processes onto these extreme QSOs
- ❖ They are expected to witness the phase of strong feedback and to show powerful outflows



Zappacosta+23, arXiv:2305.02347

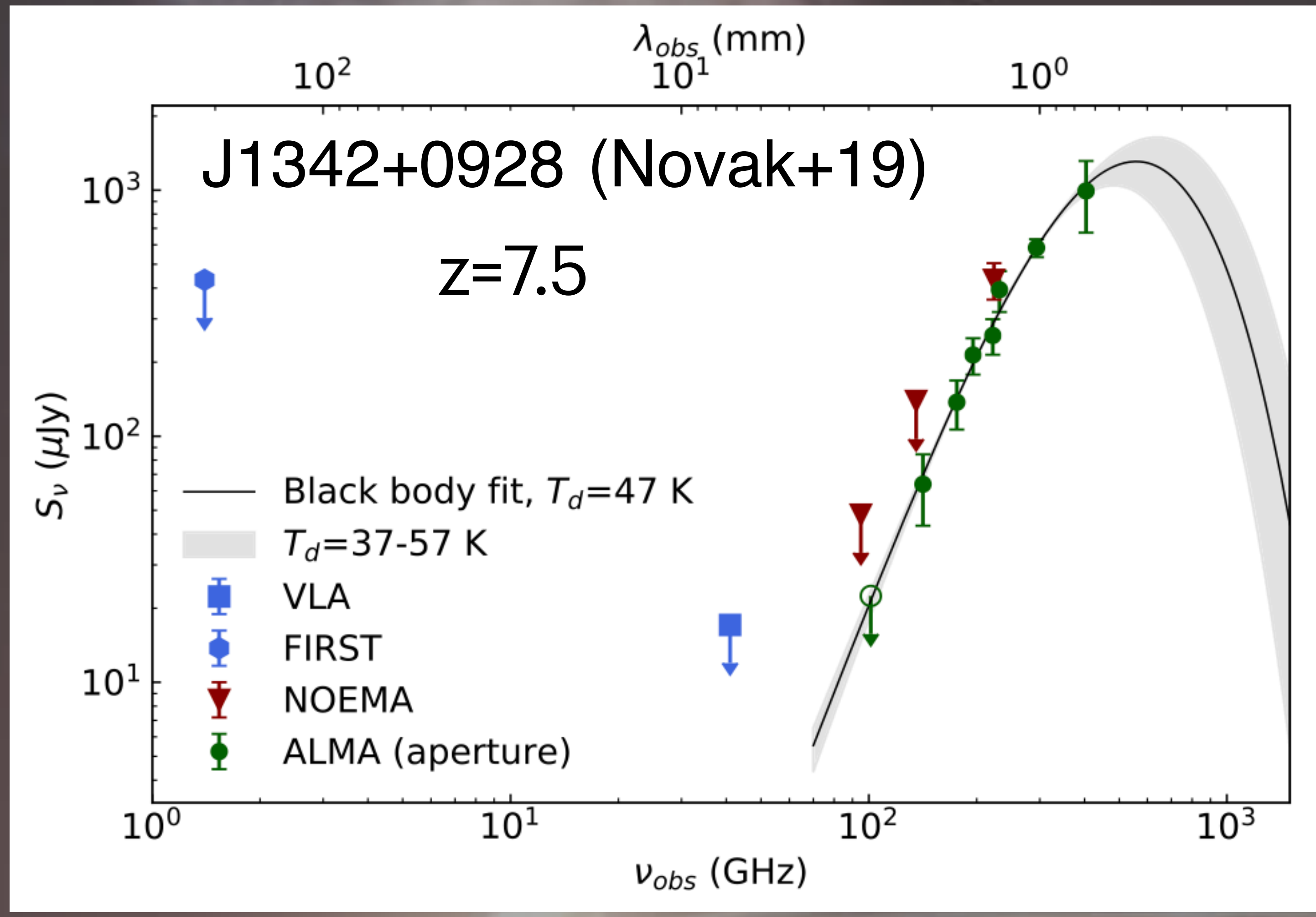
Objectives:

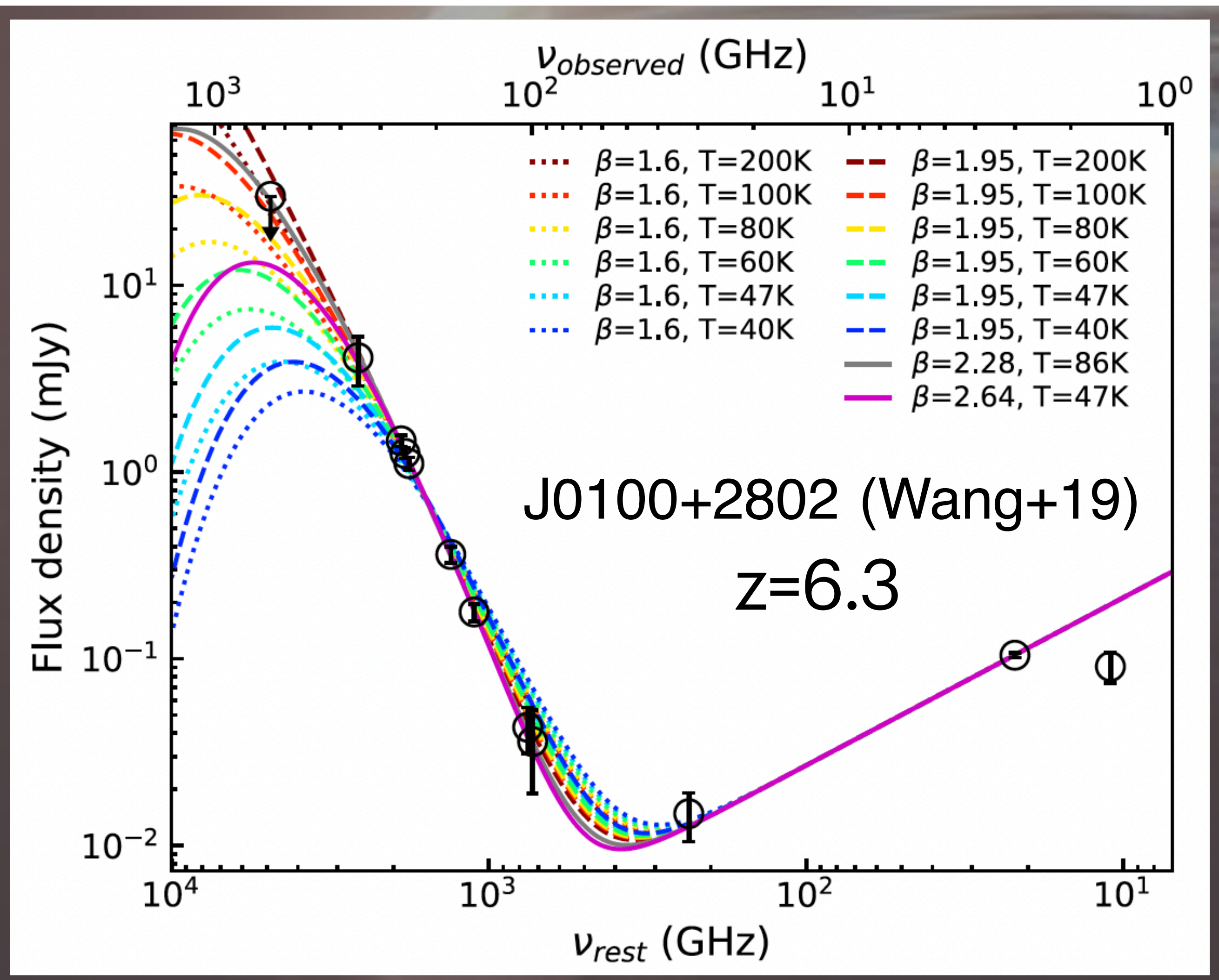
- ✓ Investigate the properties of their host galaxies
- ✓ Draw a picture of the whole population

How:

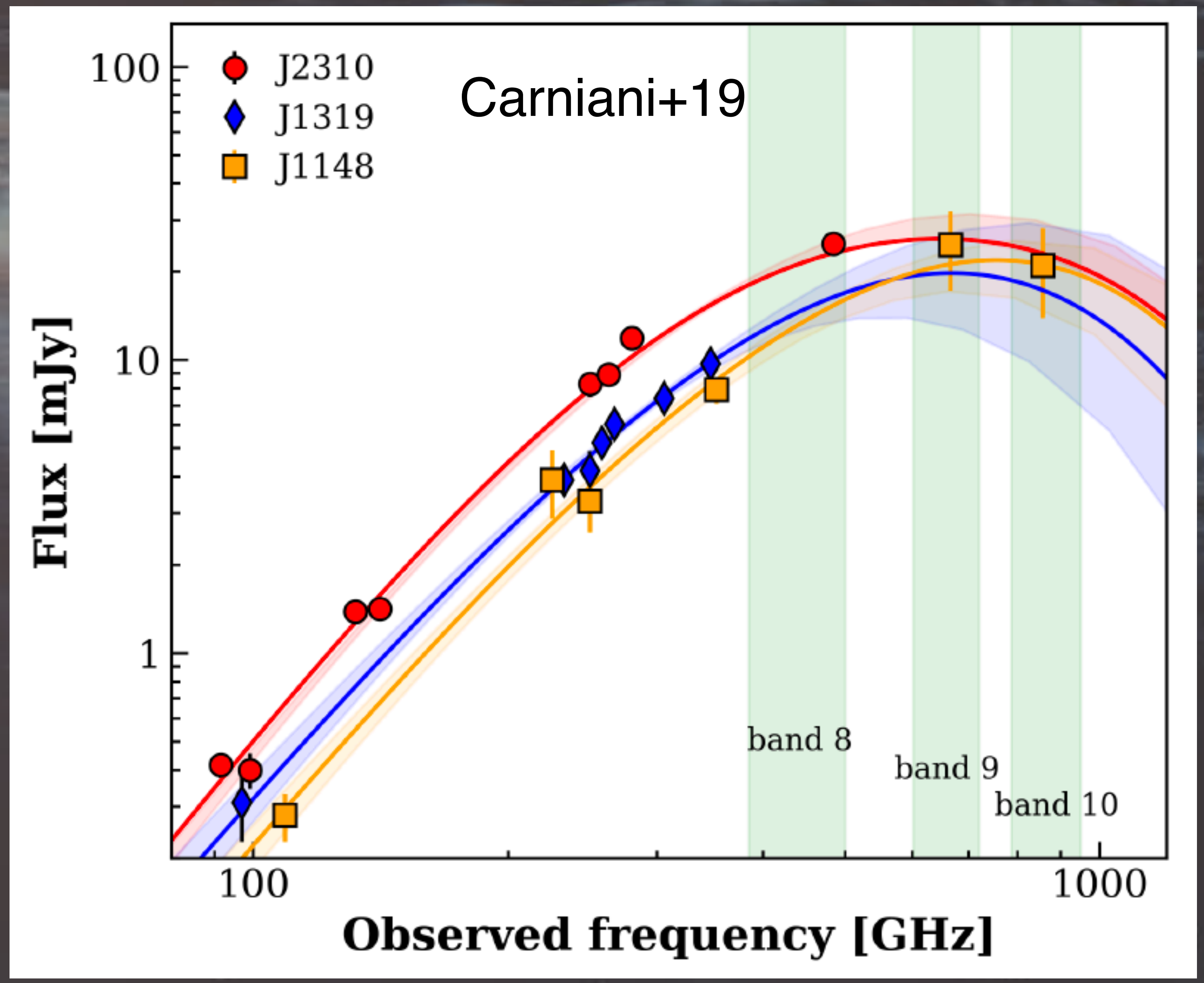
- ✓ ALMA-NOEMA observations of the dust and cold gas
- ✓ Focus on high resolution, high sensitivity, high frequency

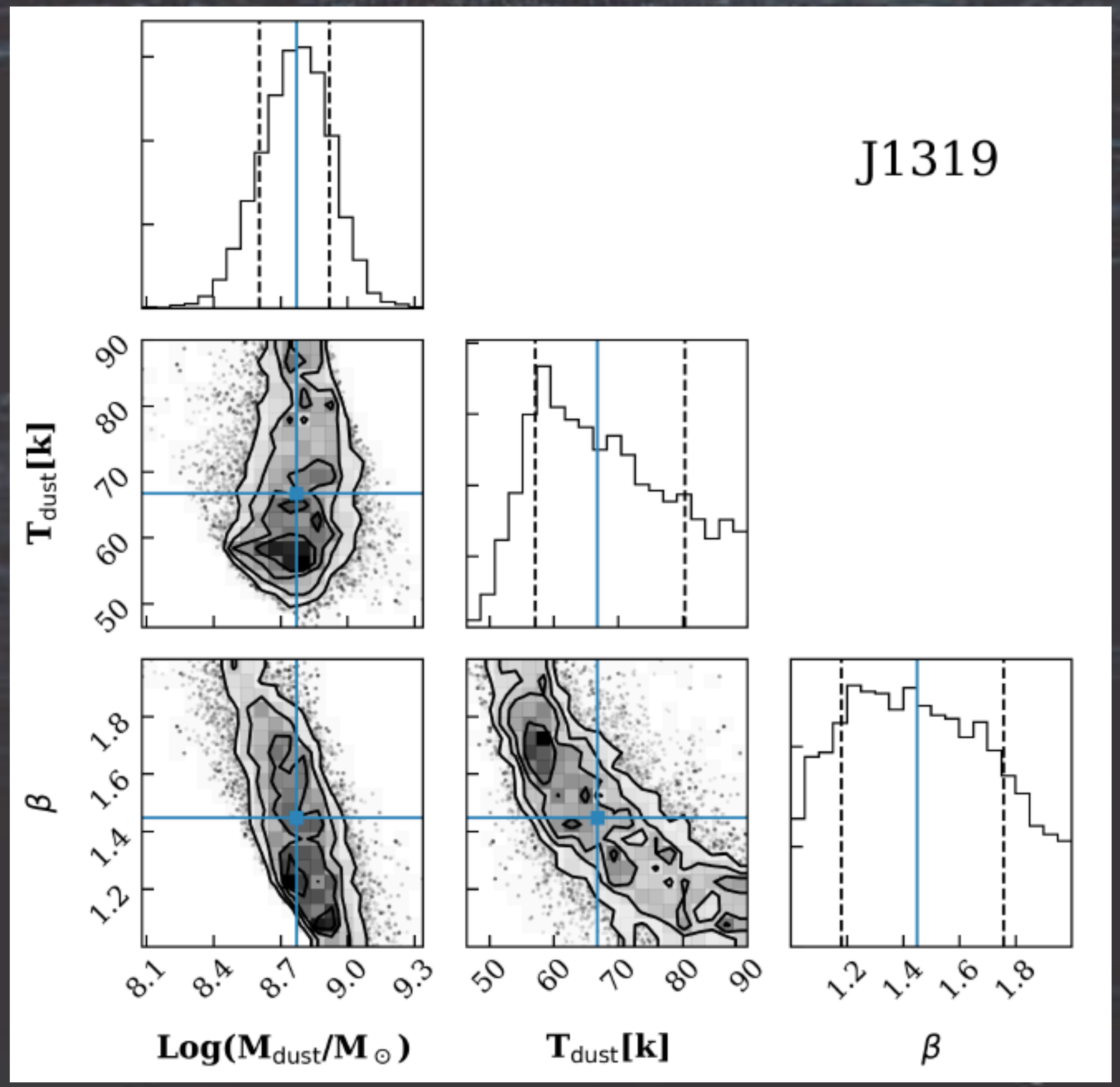
Dust properties of high-z QSOs



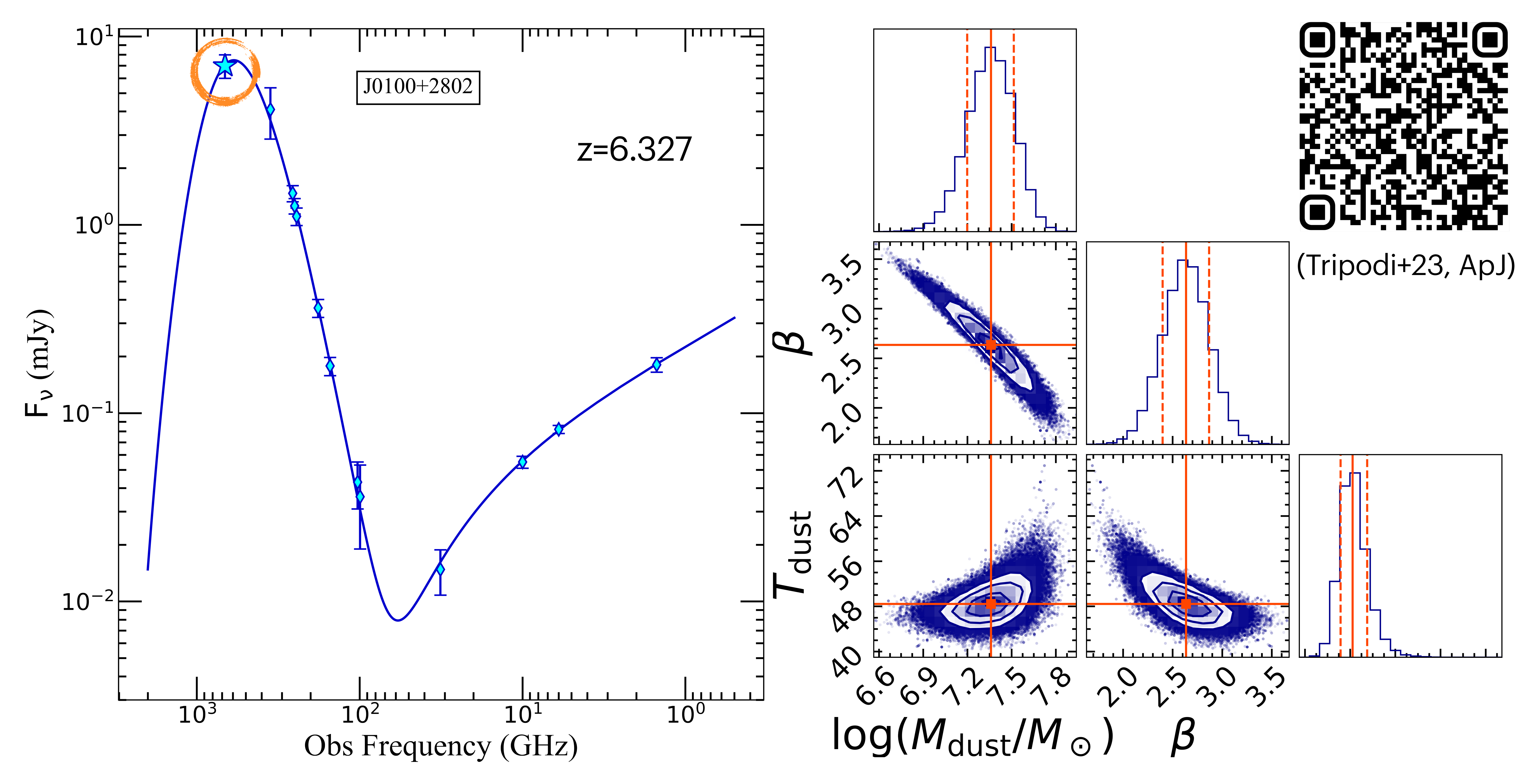


- Key in star formation process, e.g. PopIII (Schneider+2011)
- Determine SF efficiency, dust accretion time scales (Calura+13)
- Quantify dust-reprocessed SFR and dust properties (Carniani+19, Shao+19, Walter+22, Di Mascia+22,+23)
- At high-z, the peak of dust SED shifted in ALMA bands





Dust properties of high-z QSOs



(Tripodi+23, ApJ)

- Previously only rough estimates of T_{dust} (Wang+19)
- The power of ALMA band 9: high accuracy for dust properties

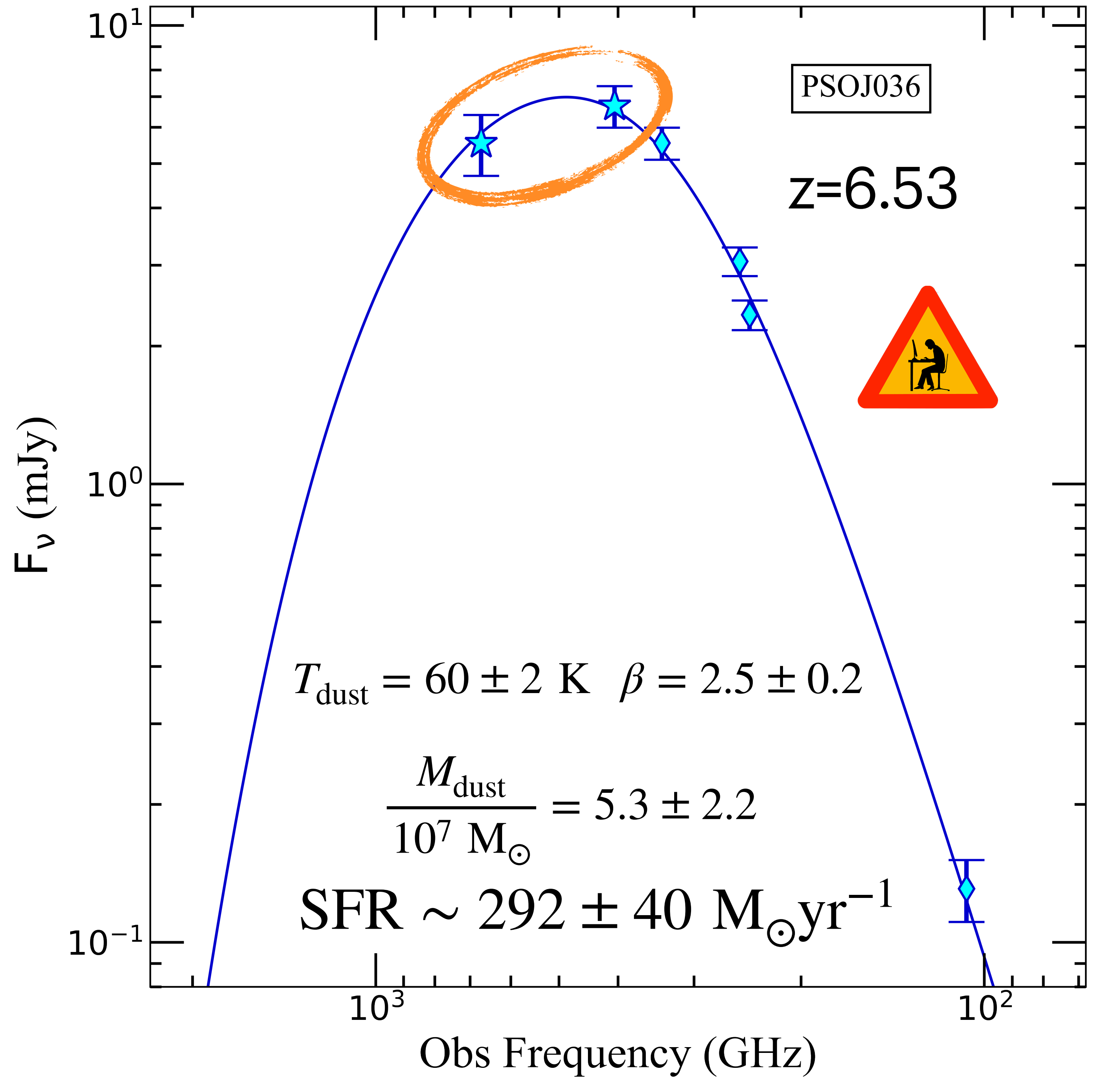
$$T_{dust} = 48 \pm 2 \text{ K} \quad \beta = 2.6 \pm 0.23$$

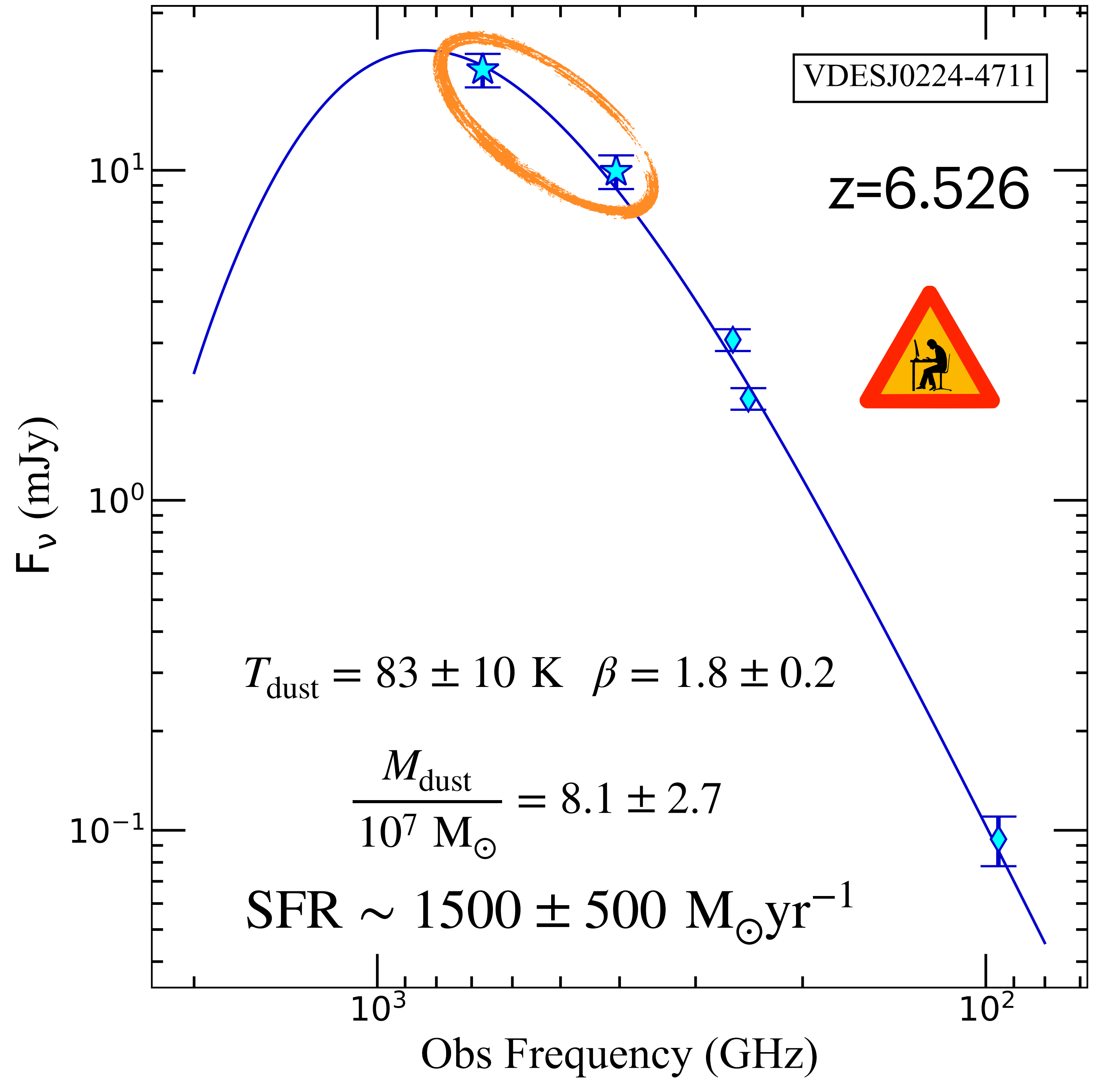
$$\frac{M_{dust}}{10^7 \text{ M}_\odot} = 2.3 \pm 0.8$$

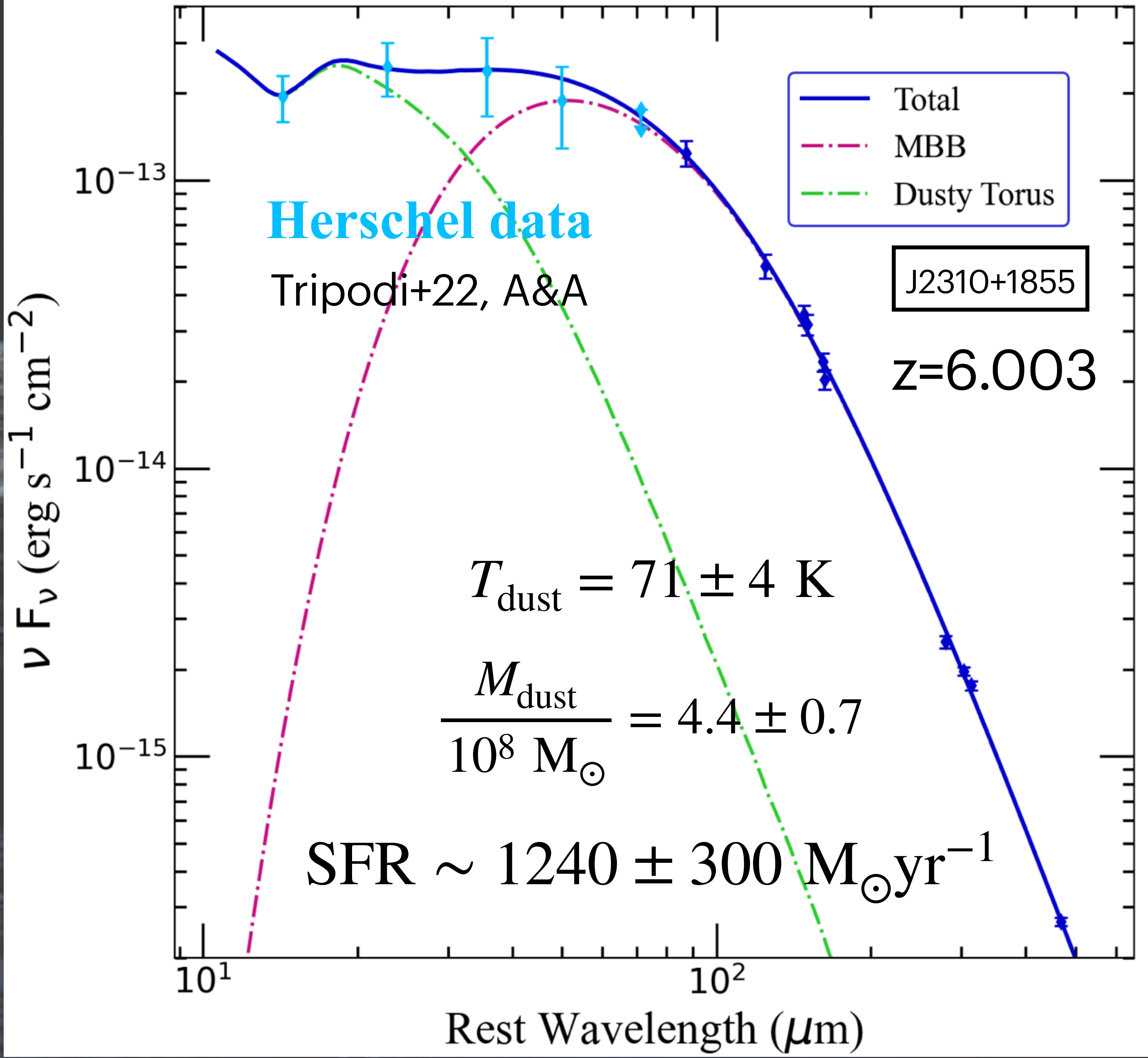
$$\text{SFR} \sim 265 \pm 32 \text{ M}_\odot \text{yr}^{-1}$$

- Bennett+23 suggest a growth path for J0100+2802

Dust properties of high-z QSOs







- Up to <~10% uncertainty on T_{dust}
- Up to ~10% uncertainty on β
- Up to ~30% uncertainty on M_{dust}

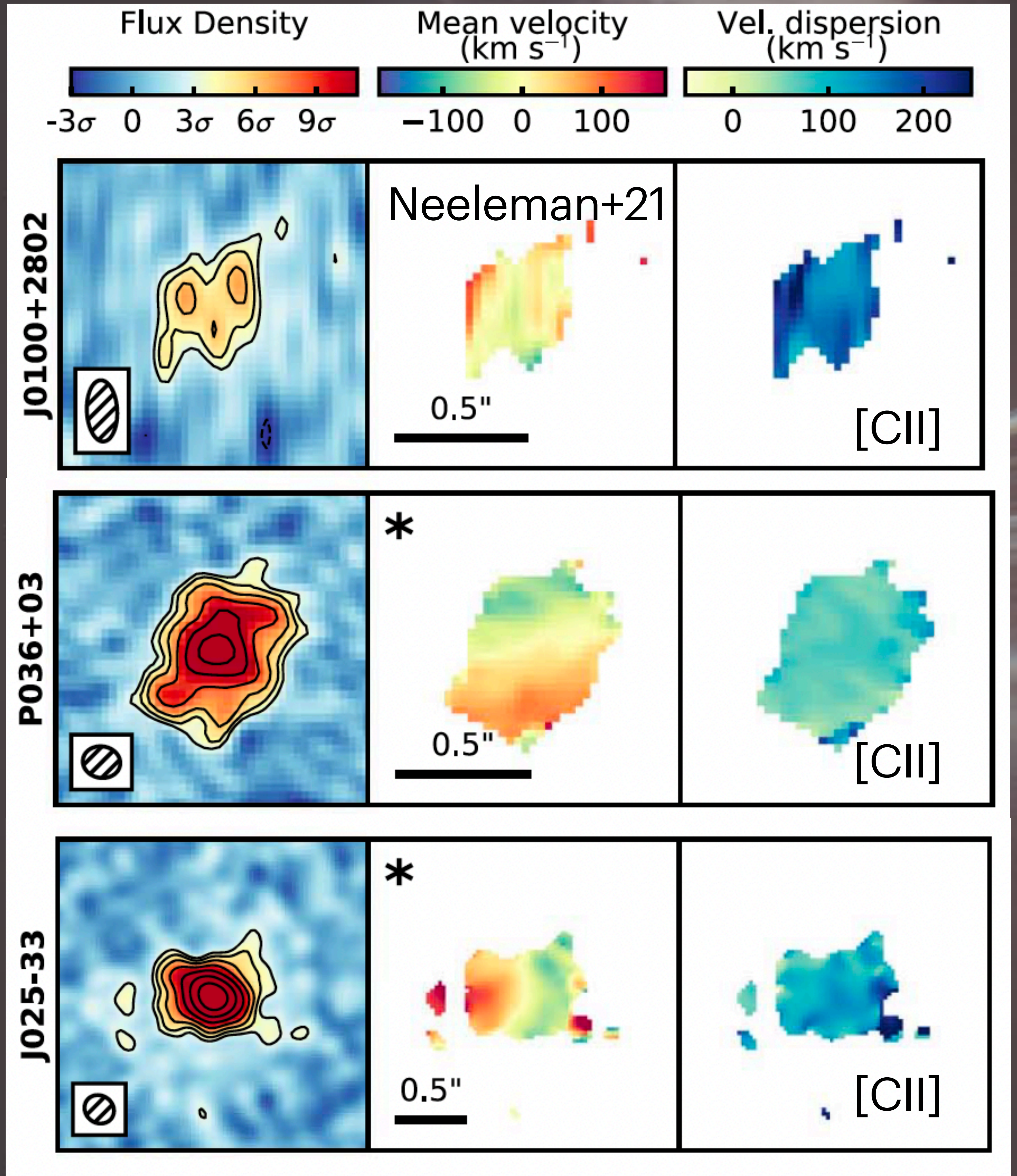
- Range T_{dust} : [40-80] K
- Range β : [1.8-2.6]
- Range M_{dust} : [2-8] $\times 10^7\ M_\odot$

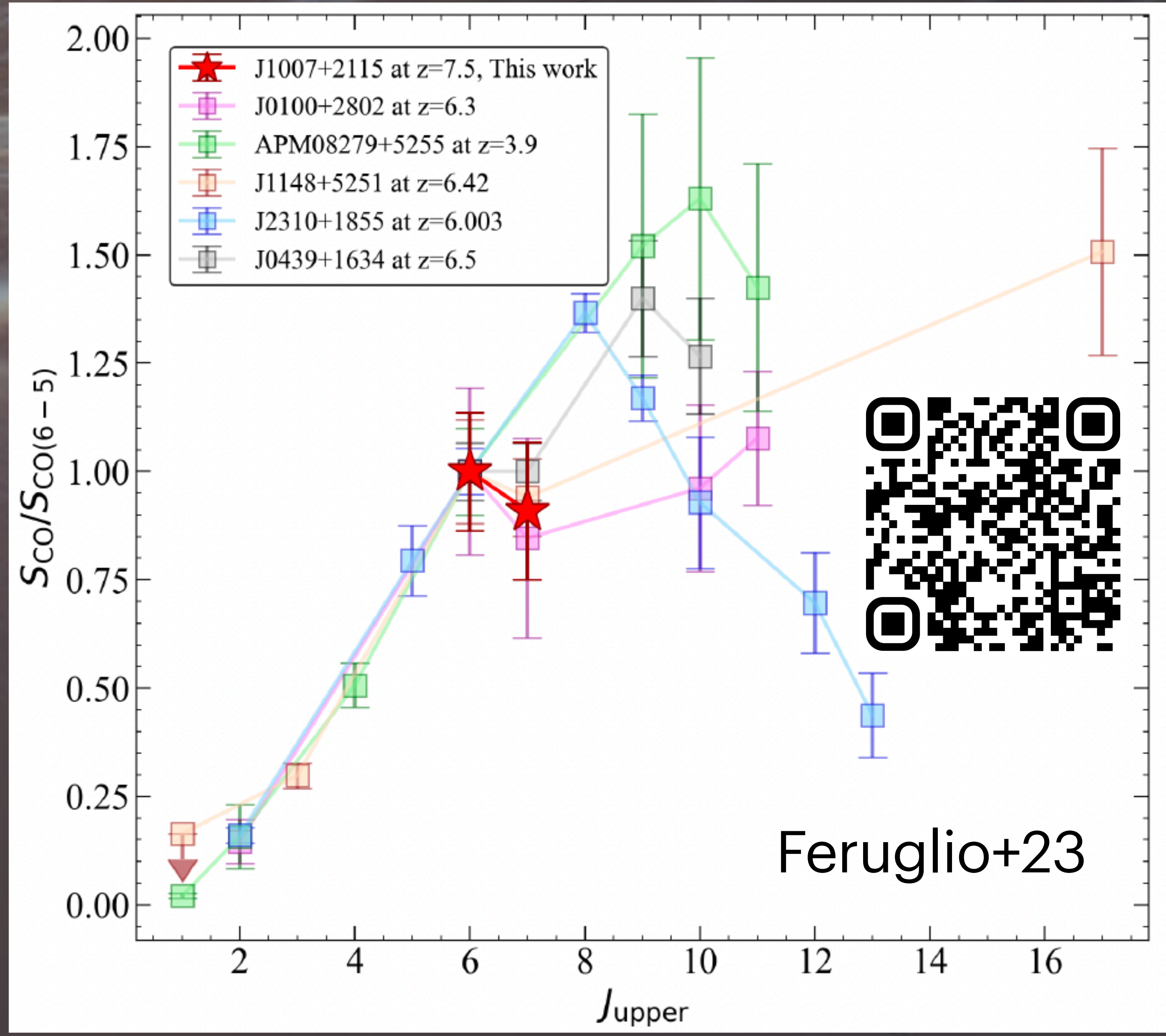
New ACA band 8 and band 9 observations (PI: C. Feruglio)

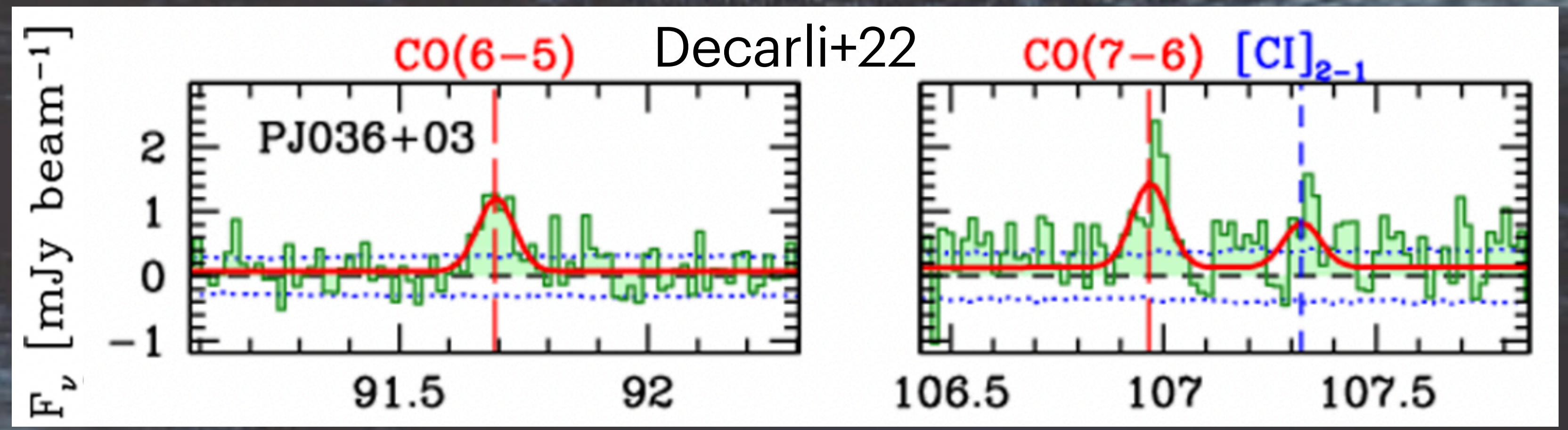
Cold gas in high-z QSOs

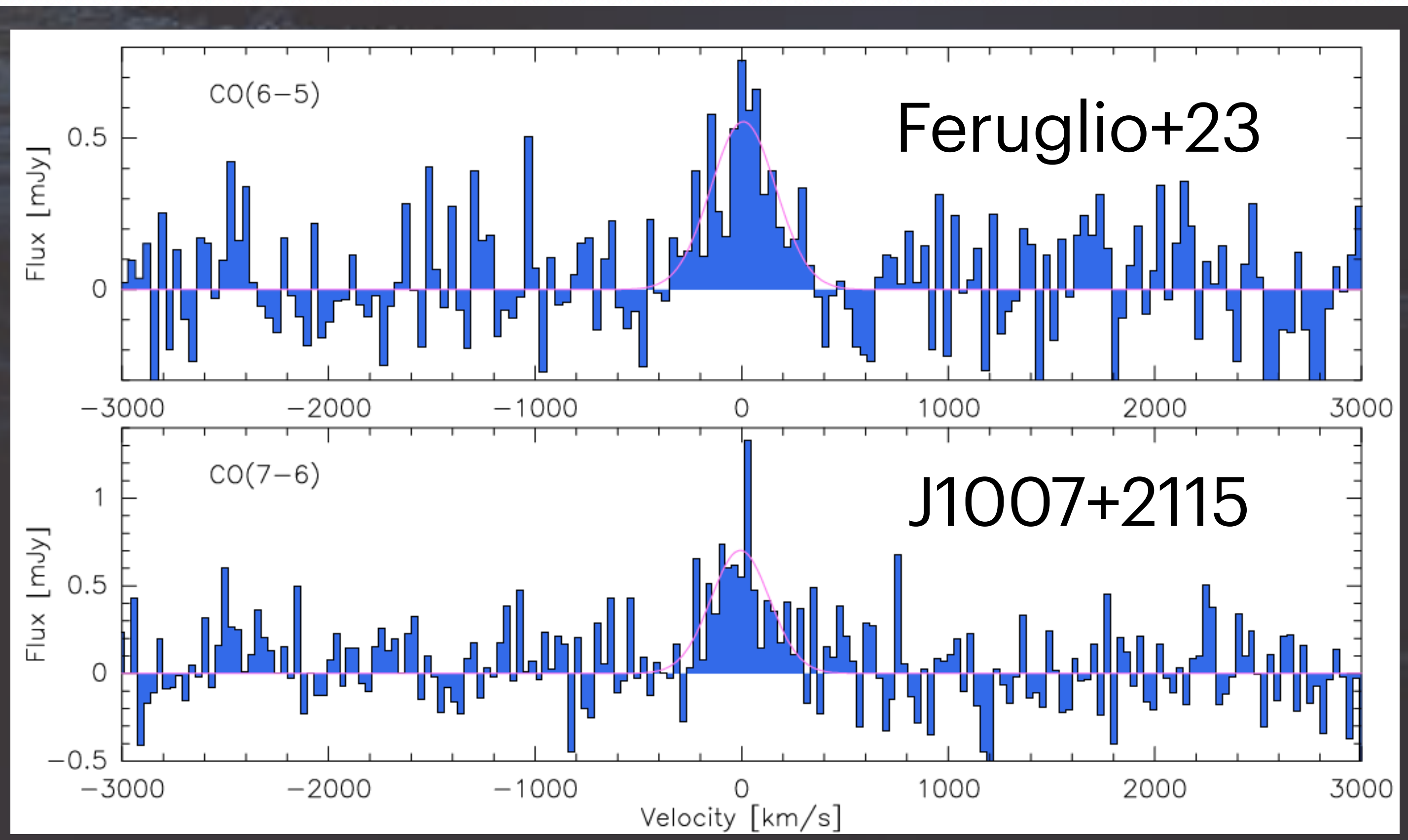
- All HYPERION QSOs observed in [CII] (Novak+19, Neeleman+21, Venemans+20)
- 5 Hyperions in Neeleman+21
- Kinematic analysis suggests rotating disks
- CO(6-5),(7-6) for J036+03 in Decarli+22
- New detections of CO(6-5),(7-6) in J1007+2115 at z~7.5 (Feruglio, Maio, RT+23, ApJL)

- Gas masses of order $\sim 10^{10}\ M_{\odot}$
- Multi phase gas

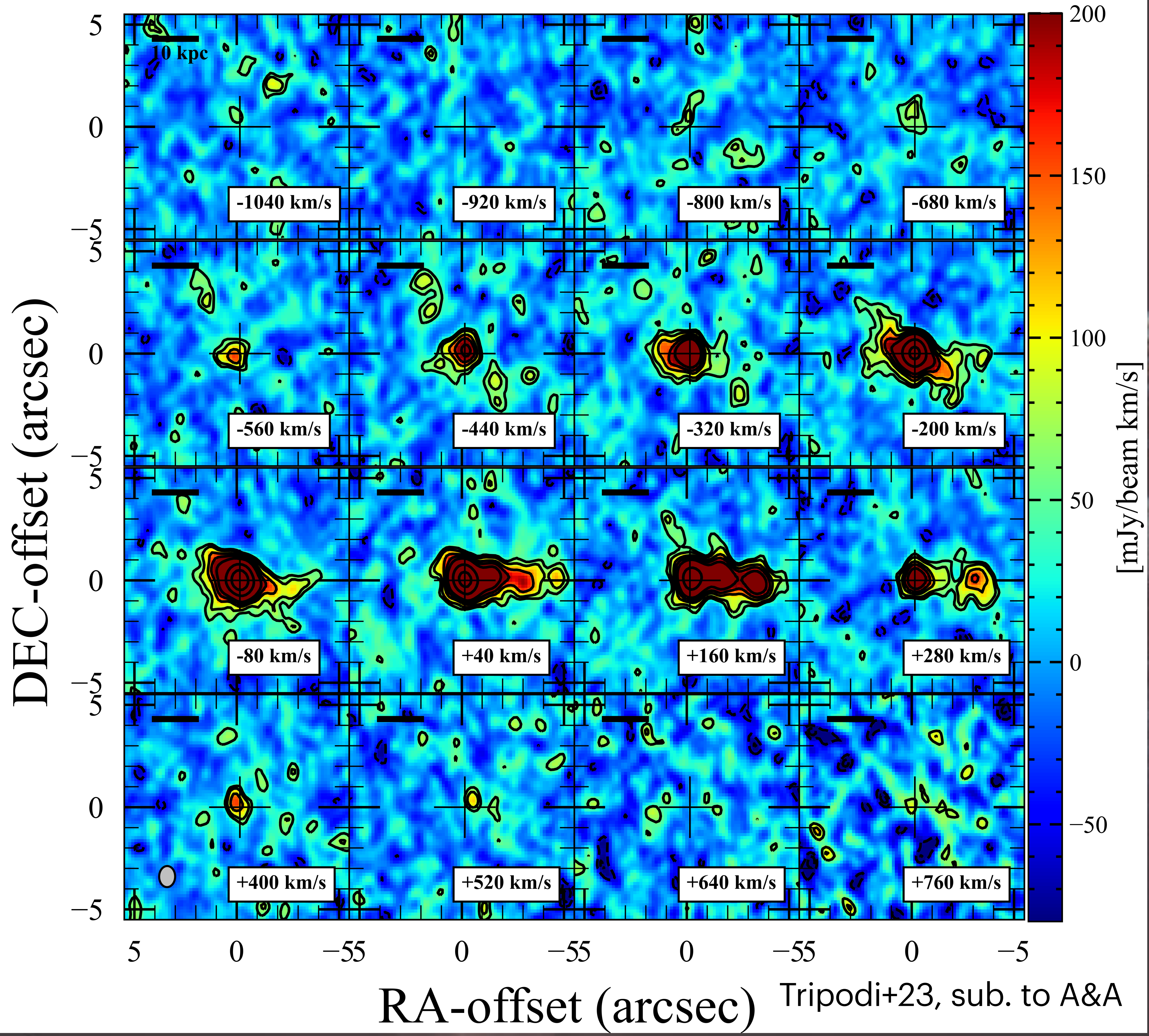






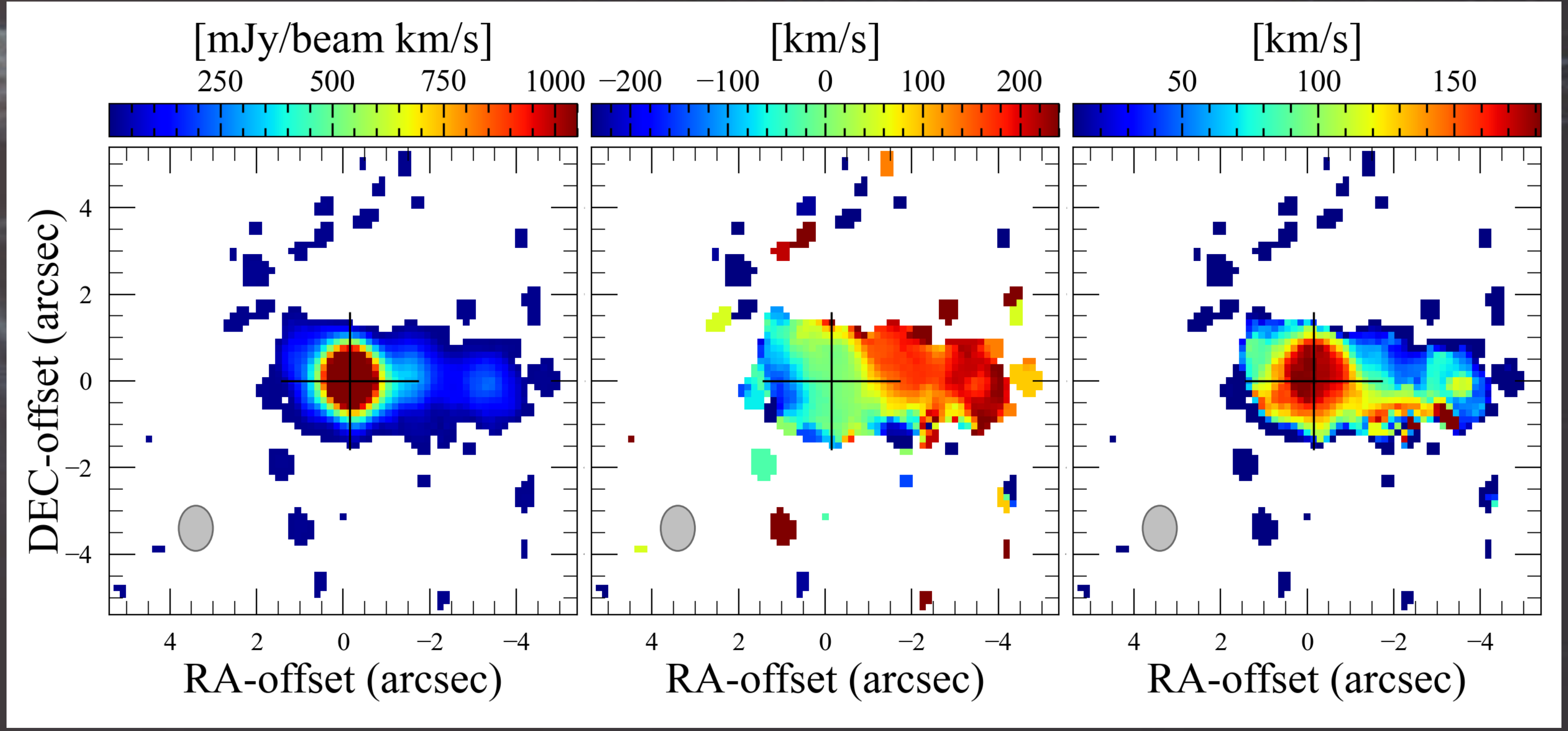


Cold gas in J0100+2802

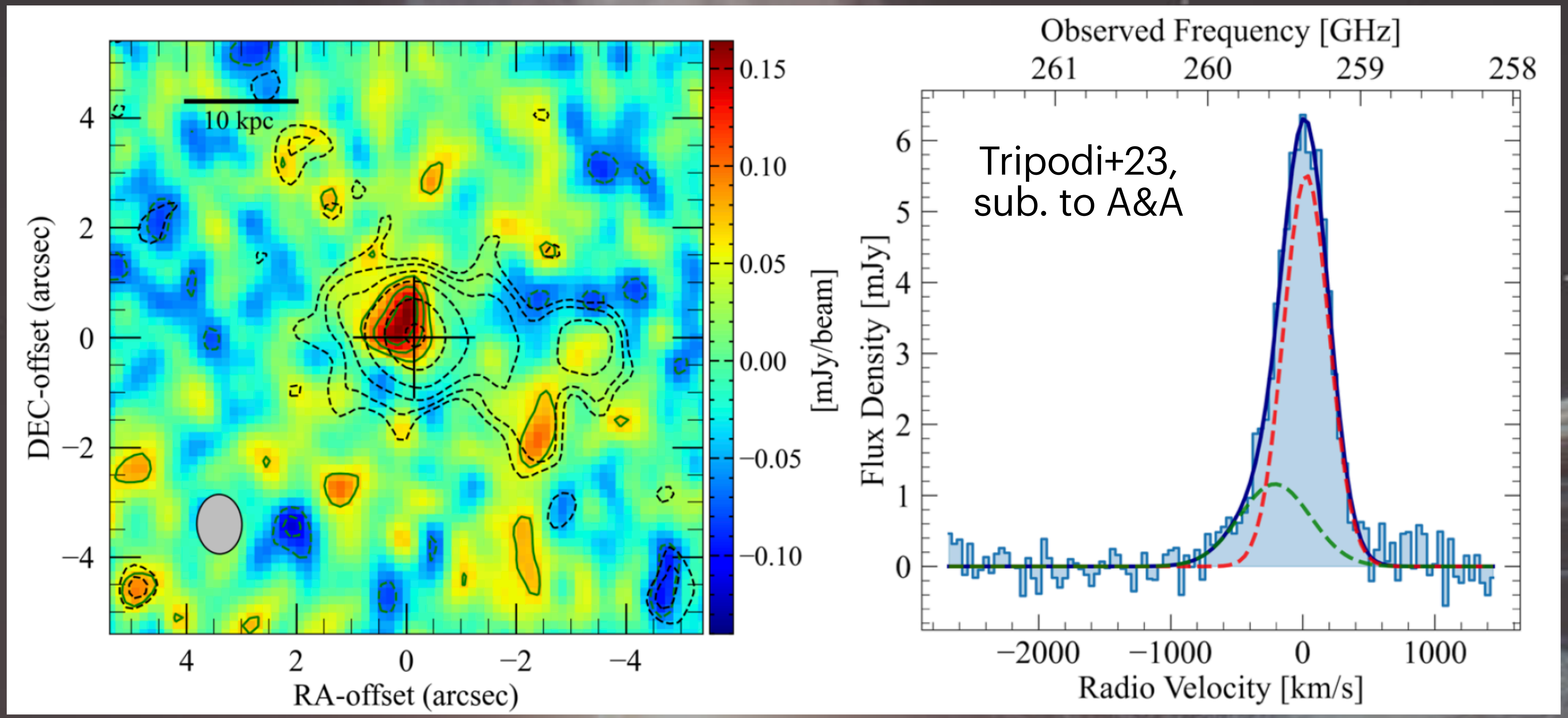


Tripodi+23, sub. to A&A

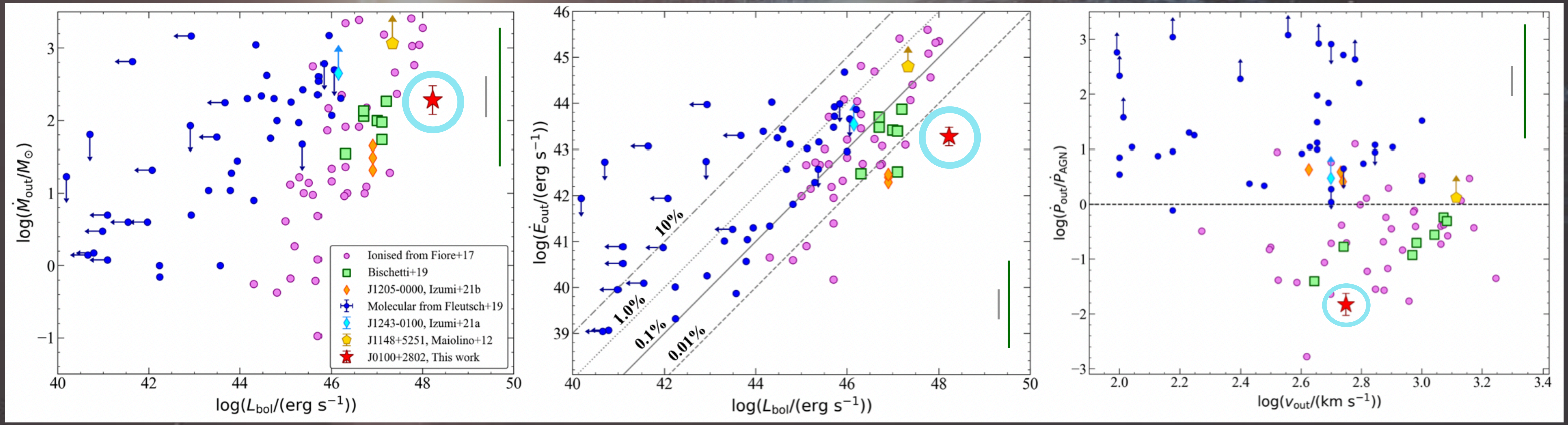
- No near companion in JWST (Eilers+23)
- Strong over density (Kashino+22)
- No relevant kinematic features (Neeleman+21)
- ✦ New deep ALMA observations in band 3 and band 6
- ✦ Elongated structure in [CII] and continuum
- ✦ Companion with SFR~[50-400] $M_{\odot} yr^{-1}$ (Di Mascia+21, Zana+22)



Cold gas in J0100+2802



- Radio jet perpendicular to the merging (Sbarrato+21)
- Outflow with velocities up to 1000 km/s
- Resolved with R~2-4 kpc
- $\dot{M}_{out} = [115 - 269]\ M_{\odot} yr^{-1}$
- Outflow rate and energetics comparable to other ionized outflows
- Low momentum load (in agreement with Valentini+21)



arXiv:2306.01644

Cold gas in J2310+1855

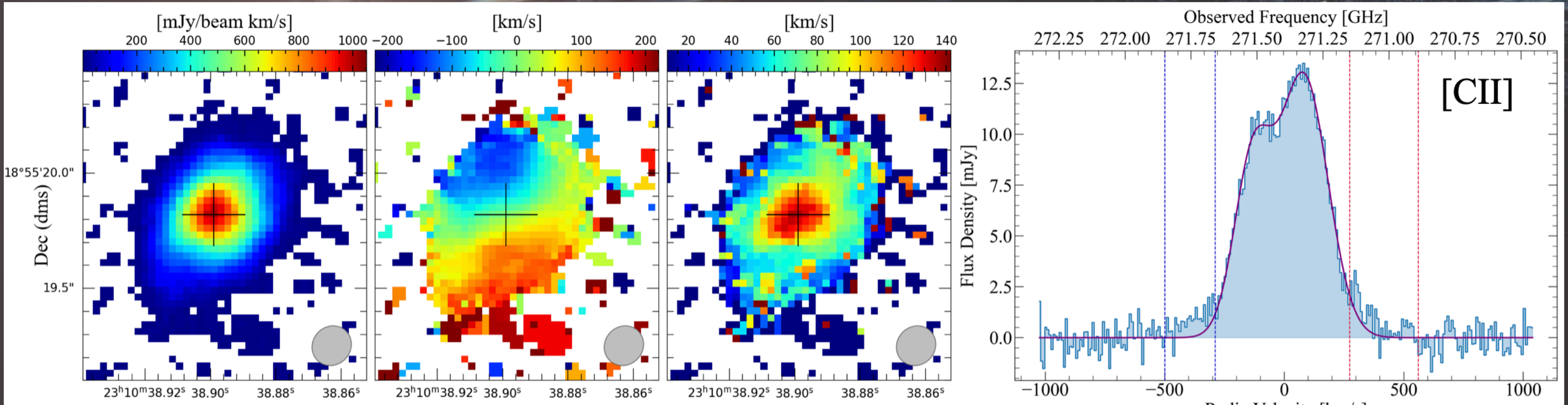
- ✳ Spatially and spectral resolving power (0.1″ resolution)
  - ➡ size [CII] ~ $2.6 \times 1.9\ \mathrm{kpc}^2$
- ✳ Rotating disk (velocity gradient)

  (Feruglio+18, Wang+13)

- ✳ Best estimate of $M_{\rm dyn}$ through dynamical modeling (Di Teodoro+15)
  - ➡ $M_{\rm dyn} = 5.2^{+2.3}_{-0.6} \times 10^{10}\ \mathrm{M}_\odot$

- ✳ Detection of outflow emissions
  - ➡ $M_{\rm out} = 5\,\%\,M_{\rm disk}$
  - ➡ $\dot{M}_{\rm out} = 180 - 450\ \mathrm{M_\odot yr^{-1}}$

In agreement with OH+ and OH outflows from Shao+22, Butler+23



(Tripodi+22, A&A)

Cold gas in J2310+1855

Dynamical modeling of the rotation curve

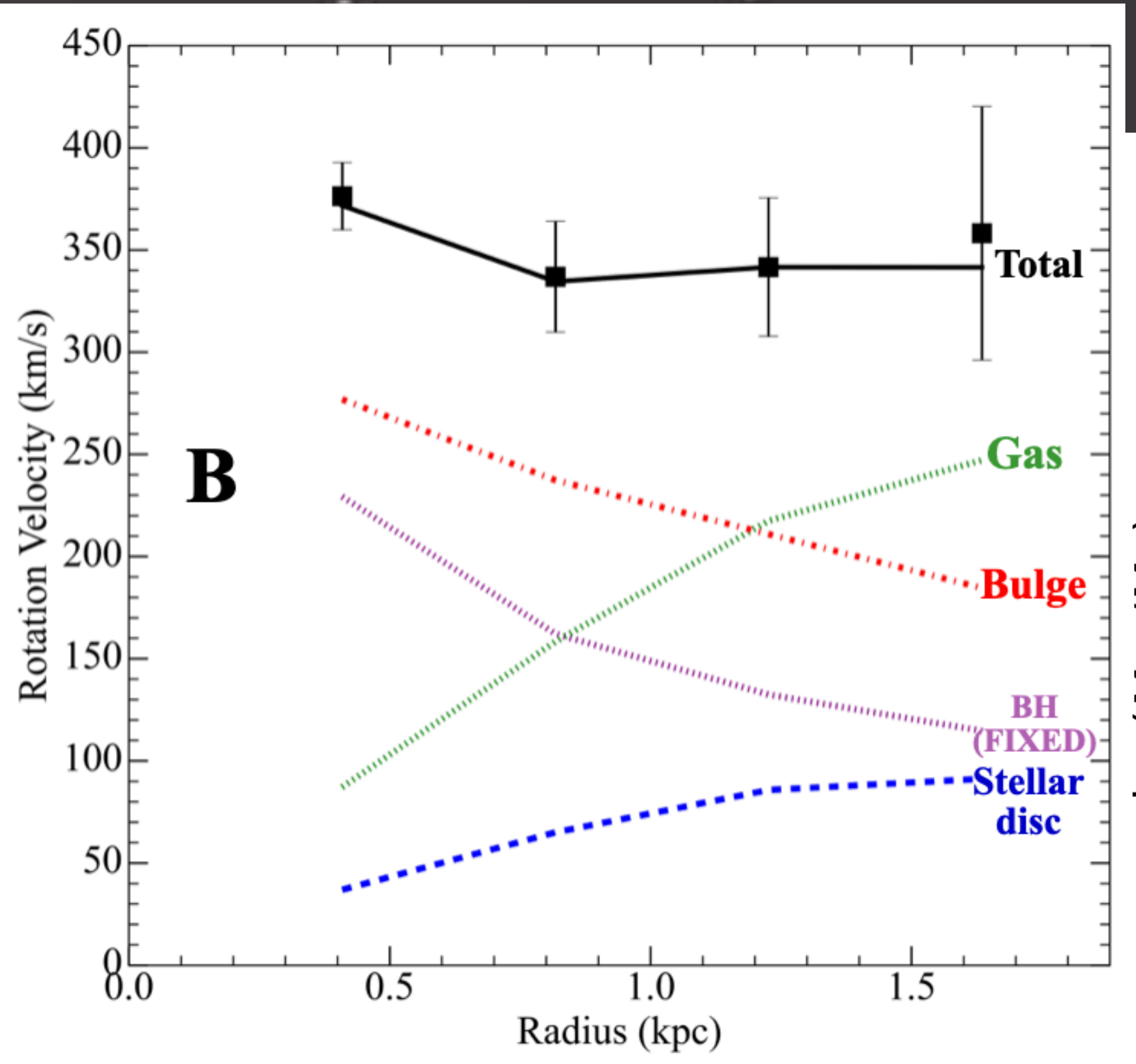
3/4 components:

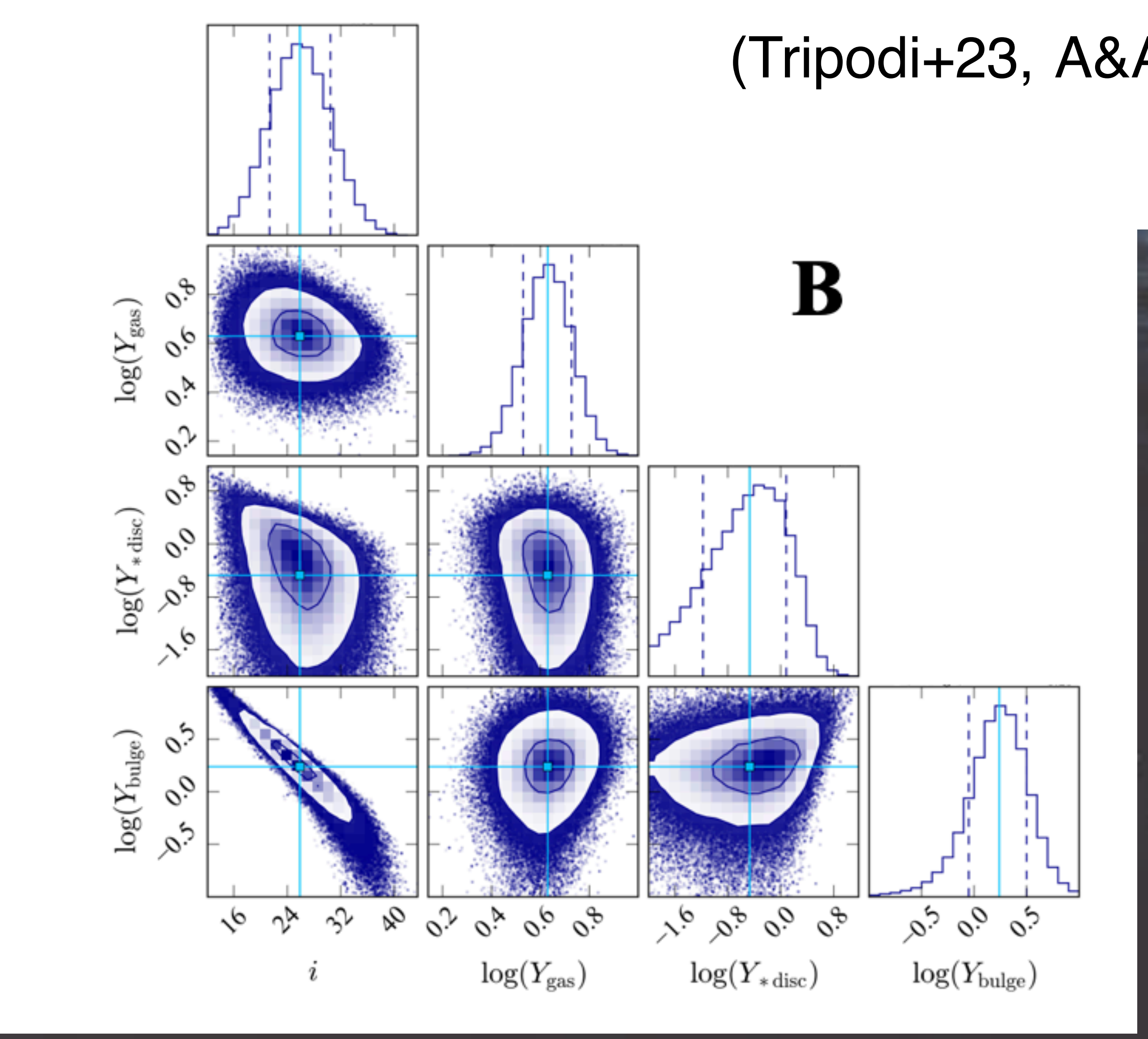
- ✦ Gas disk
- ✦ Stellar disk
- ✦ Black Hole
- ✦ Bulge

(Tripodi+23, A&A)

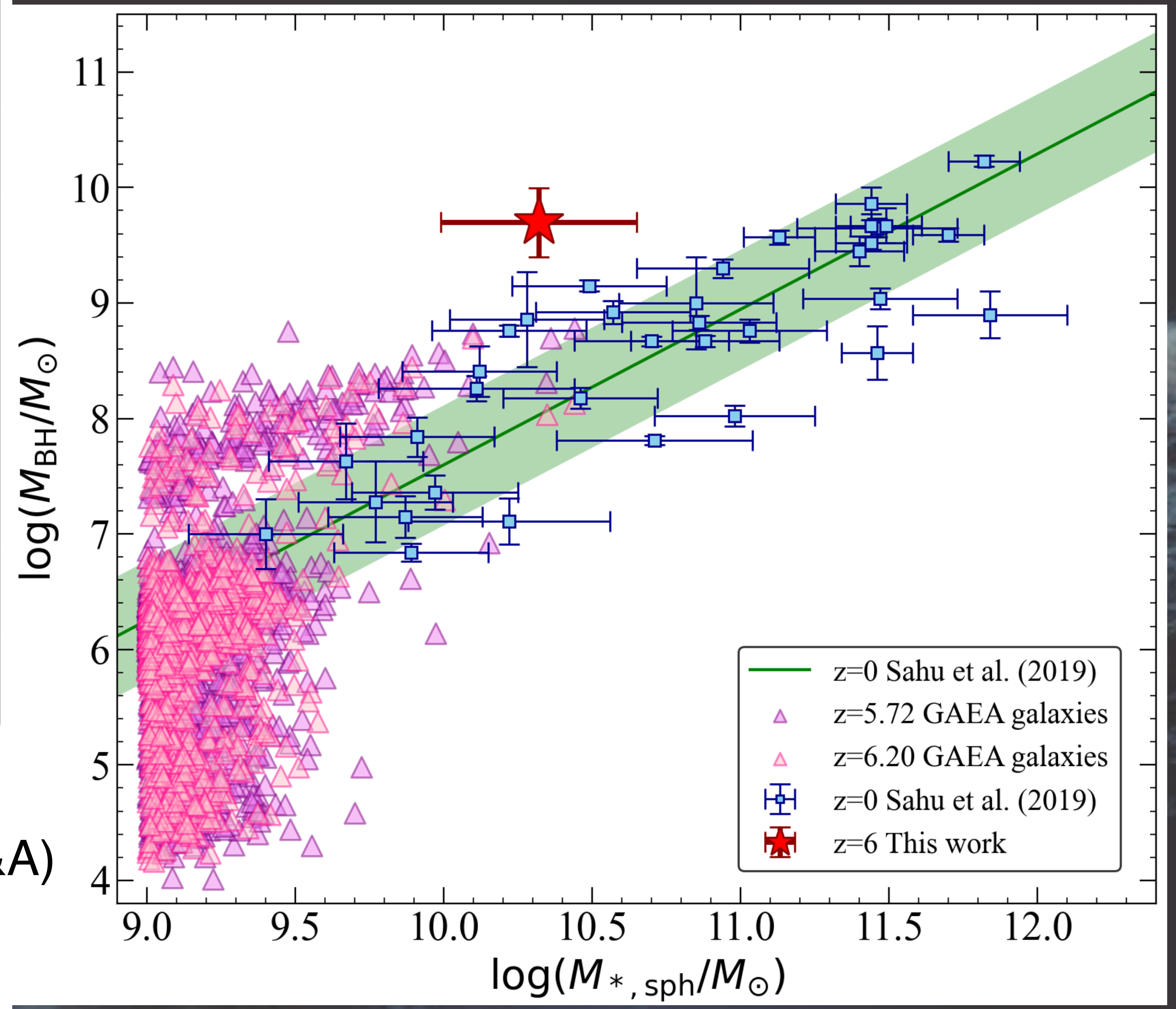
- BH only is not enough
- Bulge with $M_{\rm bulge} \sim 10^{10}\ {\rm M}_\odot$

Highest-z Bulge candidate!





(Tripodi+23, A&A)



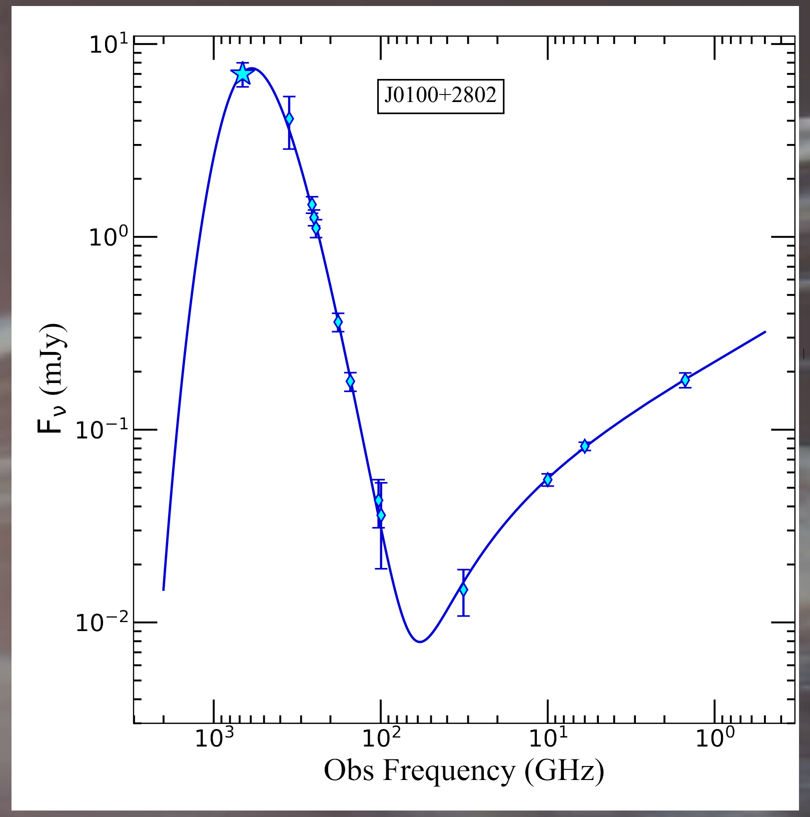
- Comparison with GAEA galaxies (Fontanot+2020)
- Which is the mechanism of bulge formation for J2310?

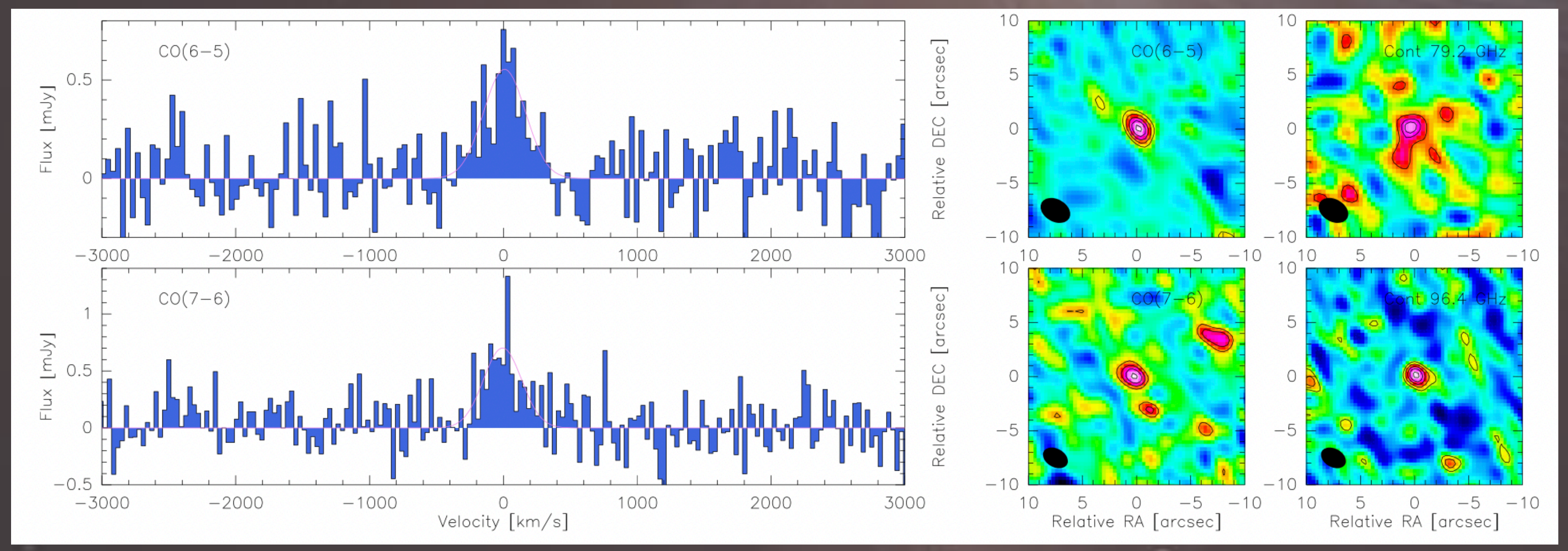
Evolution of SMBHs and their host galaxies

Galaxy growth vs Black hole growth

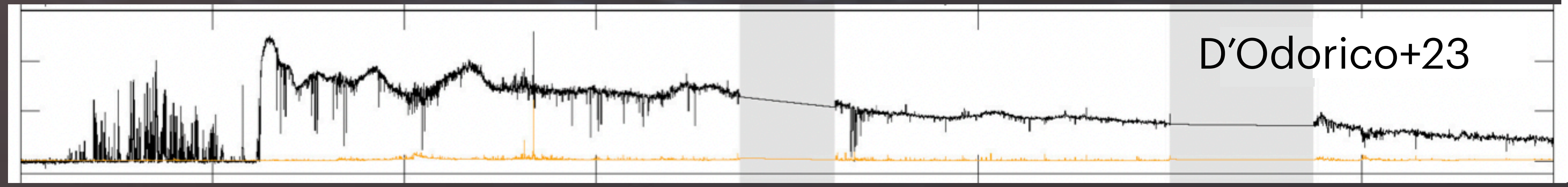
$$\frac{\mathrm{SFR}}{M_{\mathrm{gal}}} \qquad \frac{\dot{M}_{\mathrm{BH}}}{M_{\mathrm{BH}}}$$

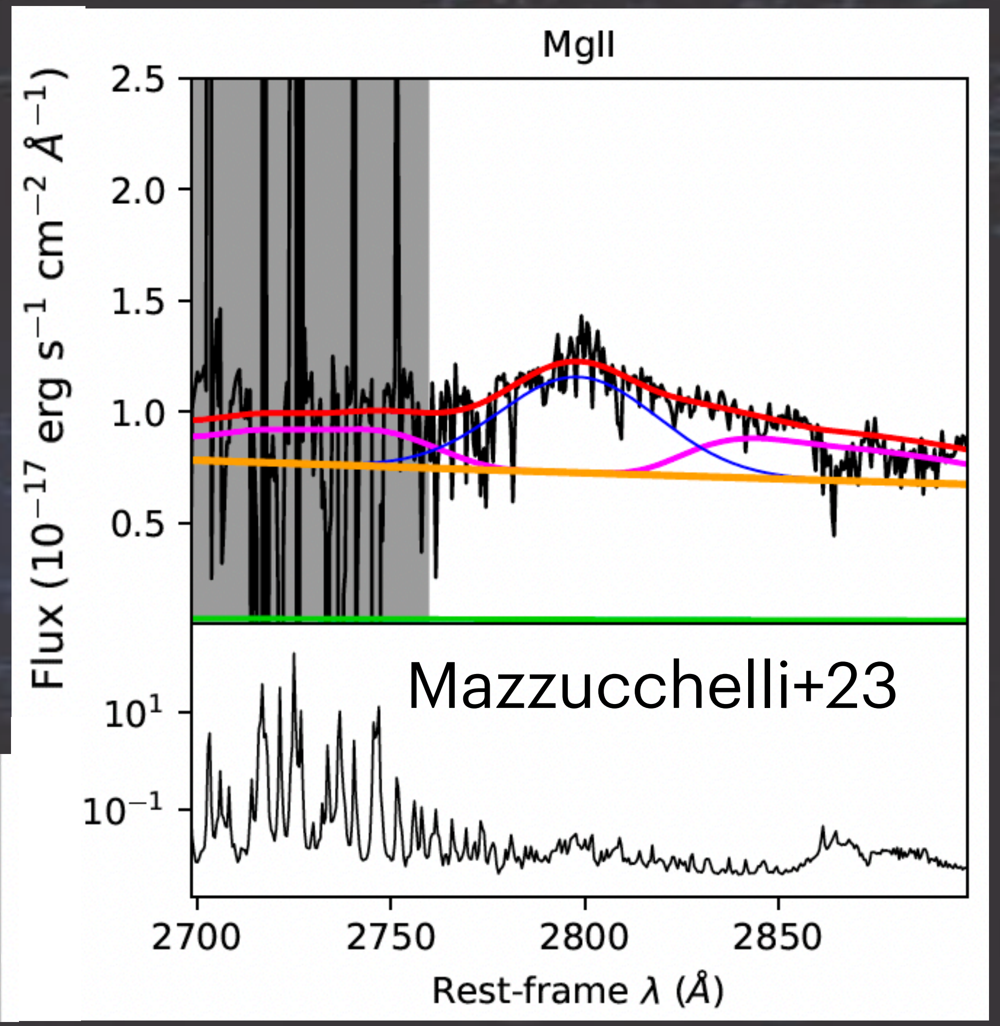
L_{bol}



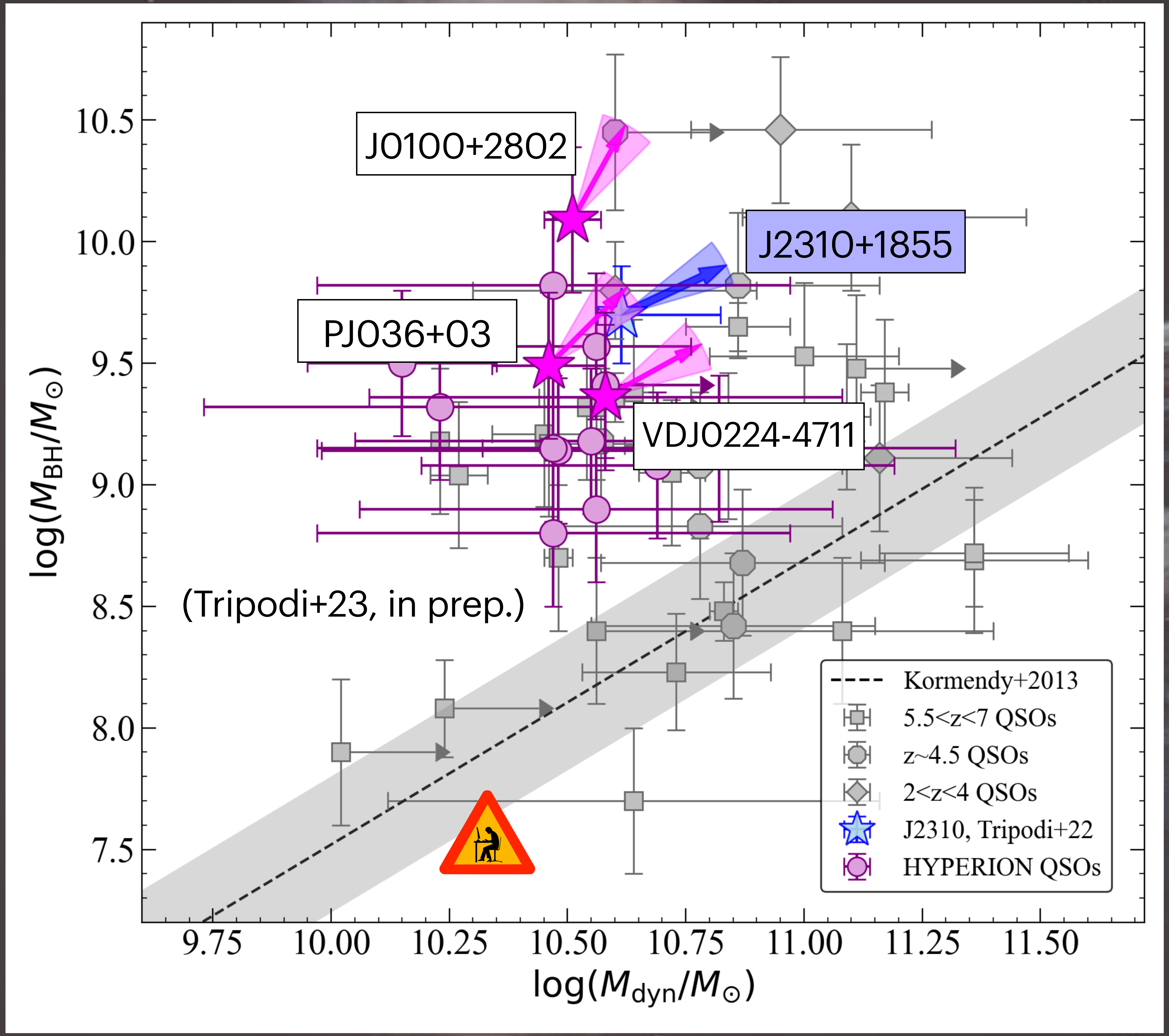


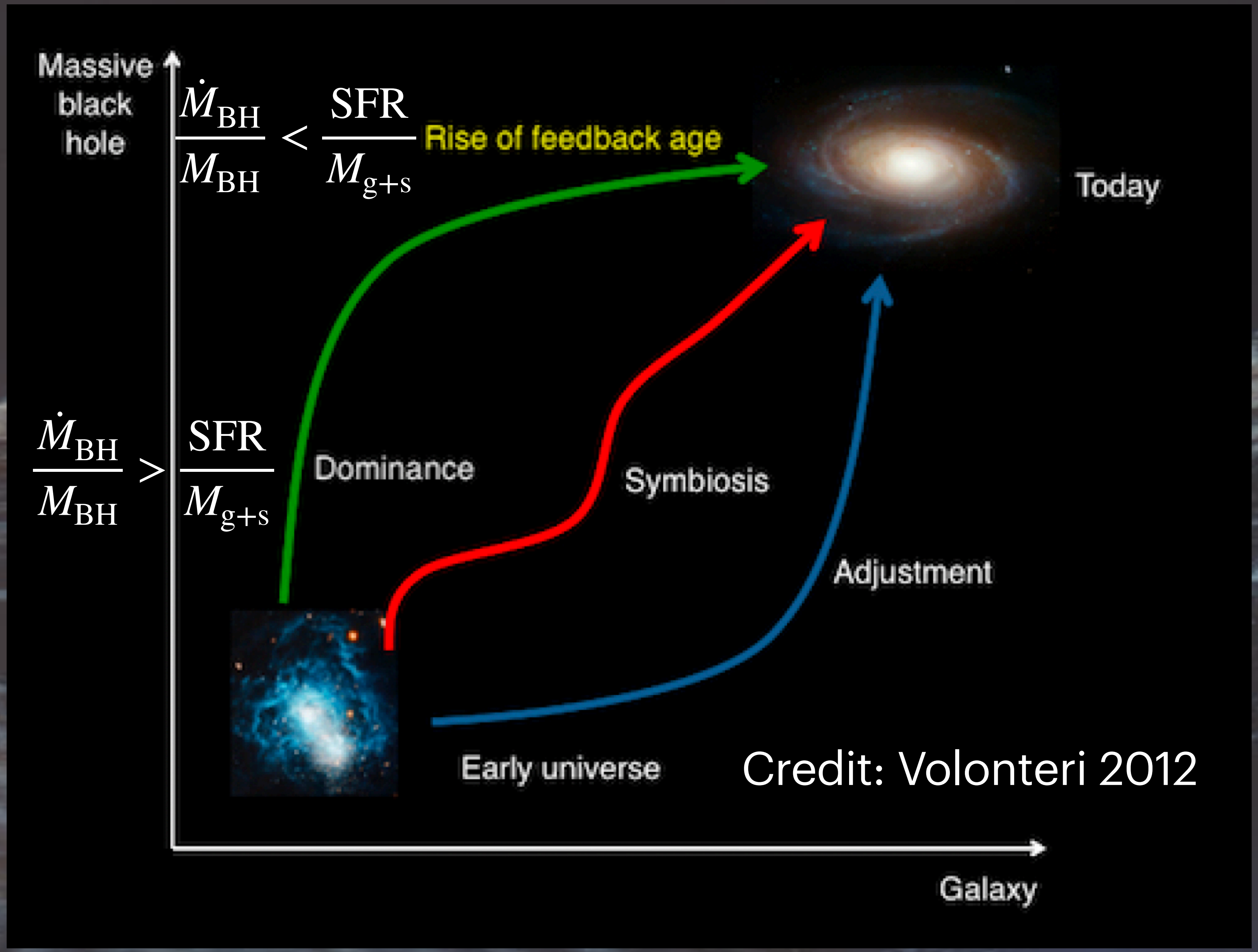
From NIR emission lines
(MgII, CIV, Hβ)





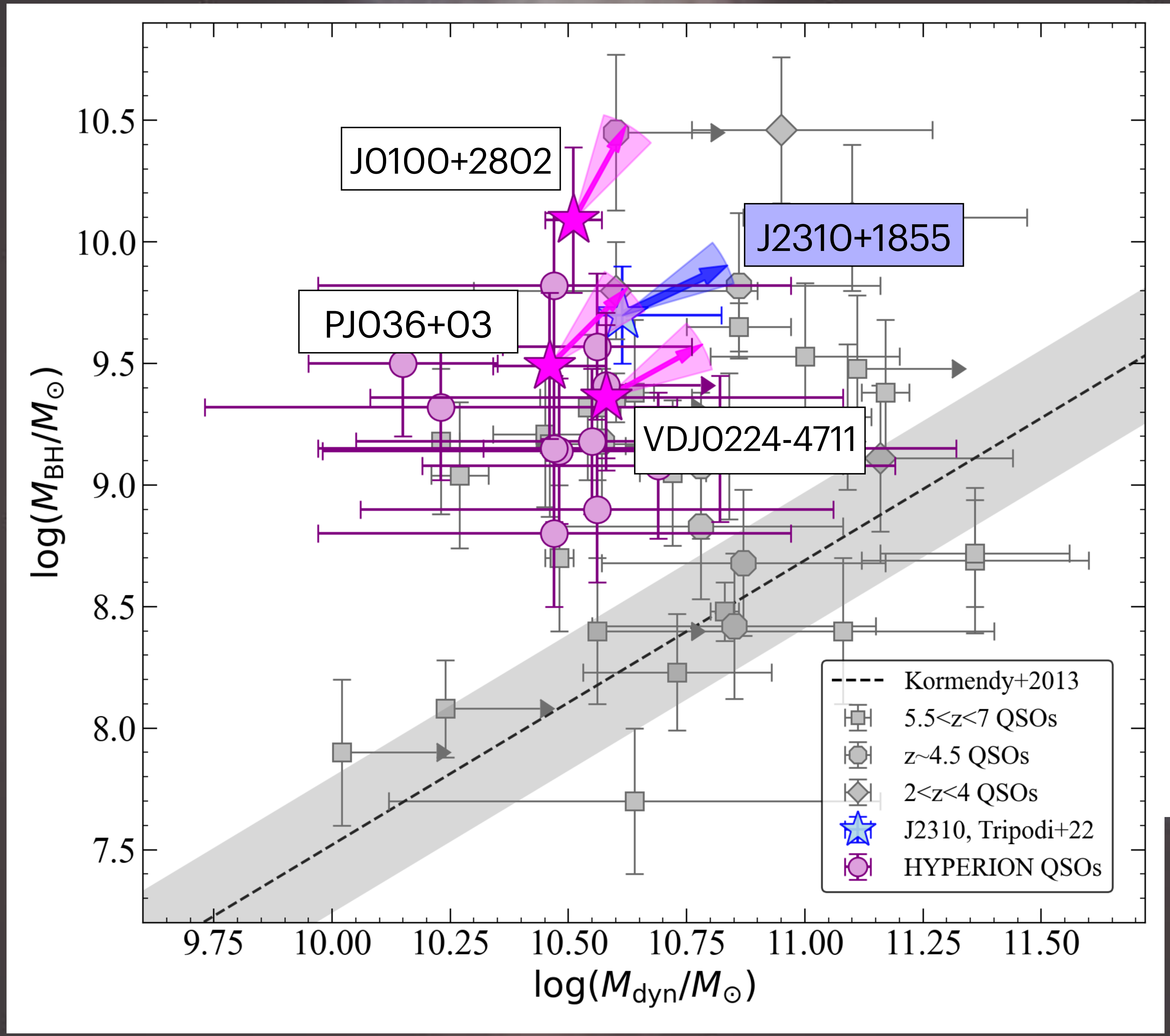
Evolution of SMBHs and their host galaxies

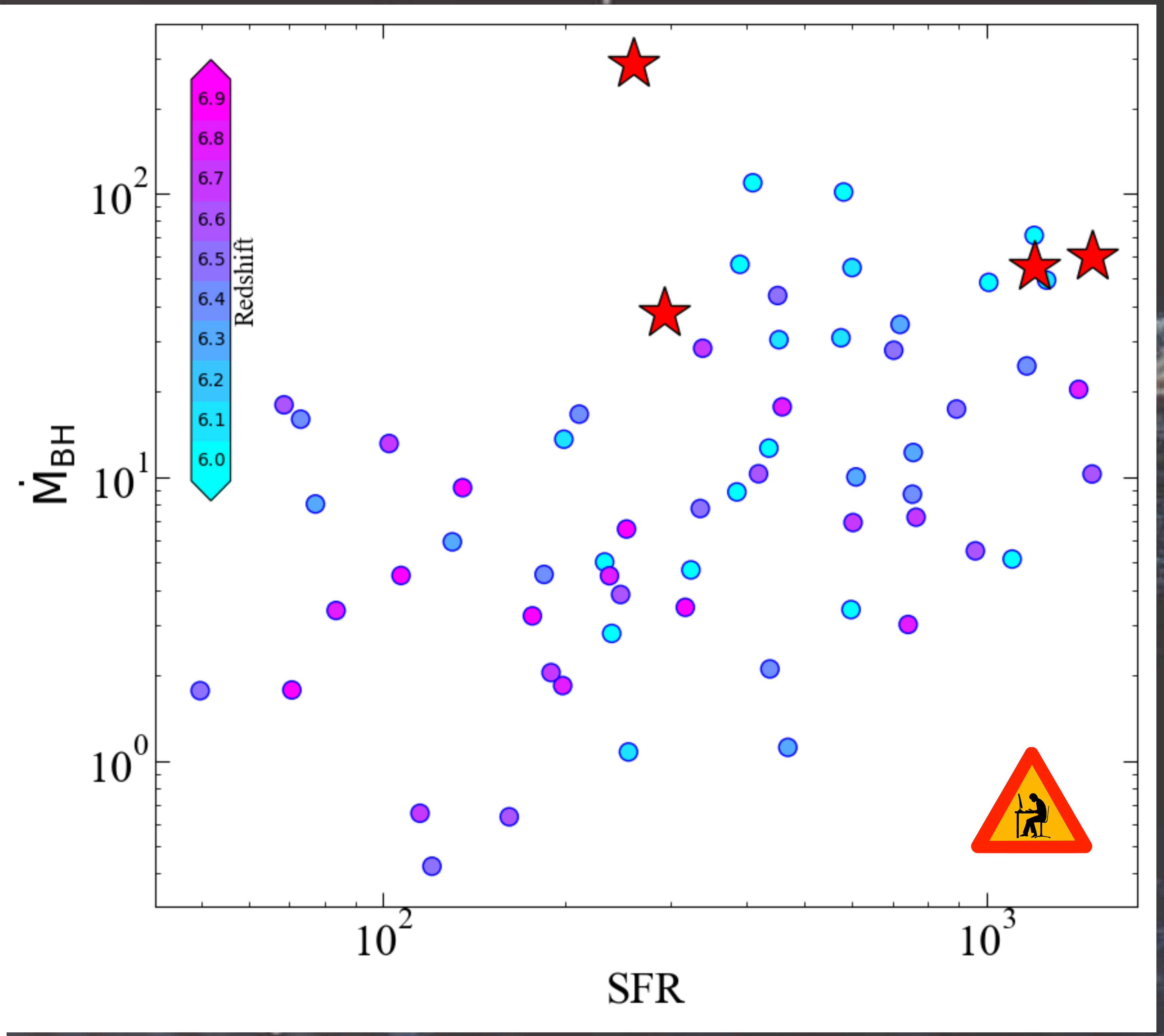




- BH dominance for J0100+2802
- Galaxy dominance for J2310+1855, VDJ0224-4711
- Symbiotic growth for PJ036+03

Evolution of SMBHs and their host galaxies





- Instantaneous information (arrow)
- Predictive power?
- Different diagnostic?
- Goal: investigate the evolution of the whole population

- Zoom-in simulations with AREPO (Costa+14,Costa+15)
- 6 halos from z~7 to z~6
- Red stars: J2310+1855, J0100+2802, PSOJ036+03, VDESJ0224-4711

Conclusions

- Amazing science with ALMA: understanding the properties of the first QSOs
- Large reservoirs of gas, extended and massive dust component
- Detailed analysis down to sub-kpc scales
- Resolved rotation curves allows precise kinematical and dynamical modelling
- SFR with very high precision (up to ~25% uncertainty) using B8-B9
- Cold gas reveals signatures of mergers and outflows
- Study the evolutionary scenarios of SMBH and host galaxies

Cold gas in J0100+2802

✦ Outflow kinetic power

$$\dot{E}_{out} = (1.1 - 2.7) \times 10^{43}\ erg/s$$

✦ Radio jet perpendicular to the plane of merging (Sbarrato+21)

✦ Jet power

$$P_{jet} = 9 \times 10^{45} - 3 \times 10^{47} erg/s$$

✦ Jet driving possible