Sexten Center for Astrophysics

January 12, 2023

Cold gas and dust properties of the first QSOs

Speaker: Roberta Tripodi

PhD student at UniTs

Supervisor: F. Fiore

Co-supervisor: C. Feruglio

The importance of study AGN at high-z

- ✦ Progenitors of giant galaxies in rich environments (e.g. ellipticals in clusters of galaxies)
- ✦ Often signposts of overdensities/proto-clusters (Decarli+17, Willott+17)
- ✦ History of formation of massive objects
- ✦ Kinematics and Dynamics of peculiar galaxies in the early Universe with ALMA

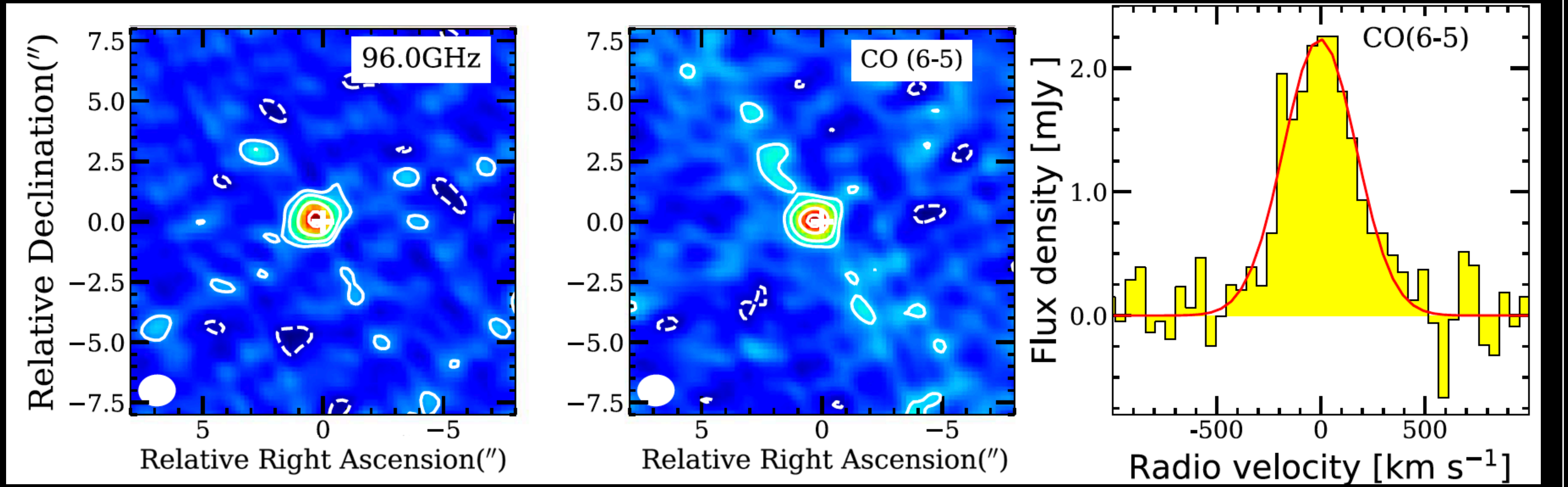
Intriguing mysteries

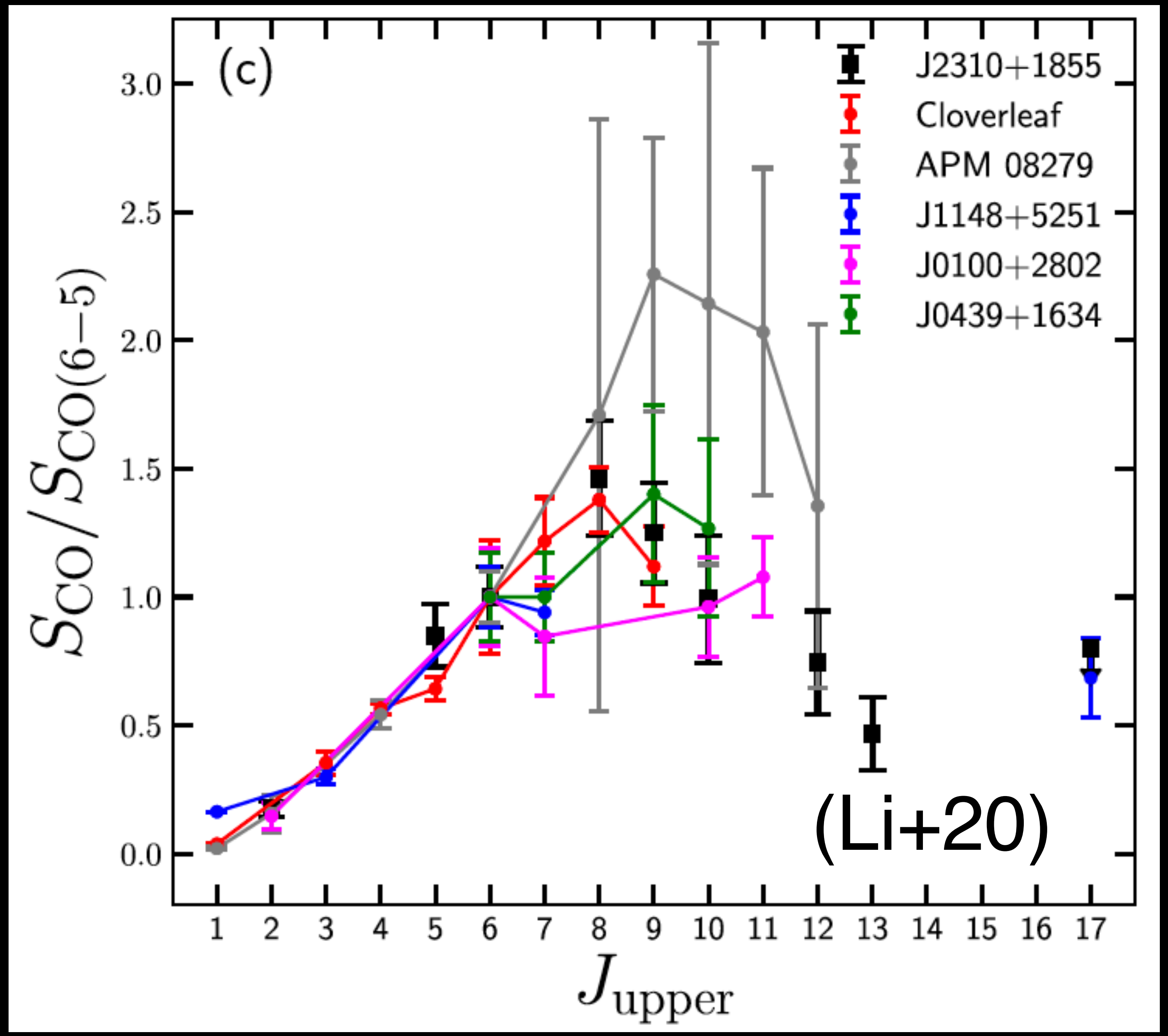
- How did this massive systems form in short timescales?
- Which is the relation between BH and its host galaxy?

General knowledge of high-z QSOs

Gas

- H_2 cannot be observed
- CO molecules as main tracer of molecular gas
- Quantify the molecular mass, i.e. SF reservoir (Combes+18 and therein)
- Only few QSOs observed in molecular gas with ~kpc resolution and high S/N ratio at this epoch (Feruglio+18)





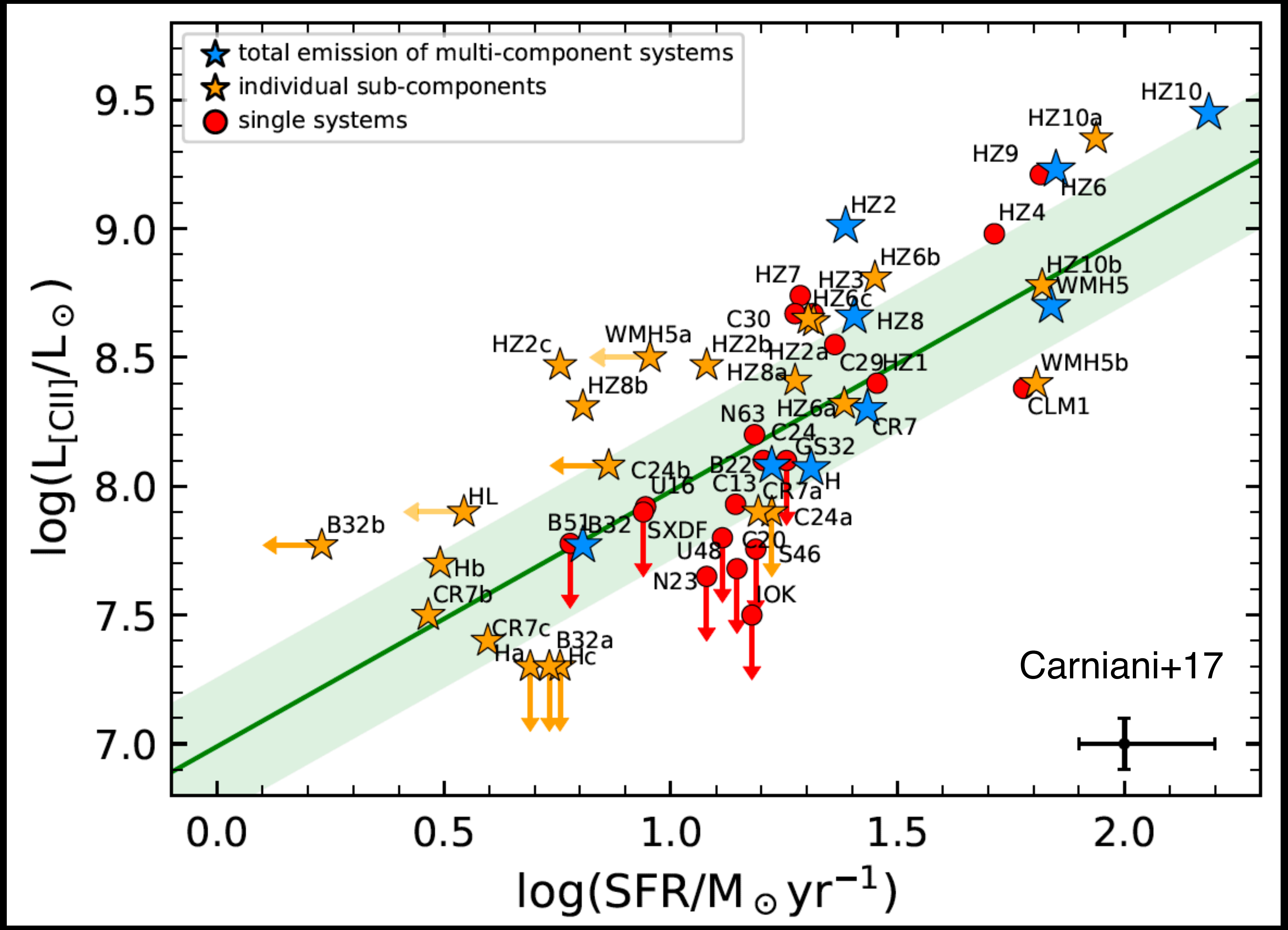
✤CO transitions probe different regions

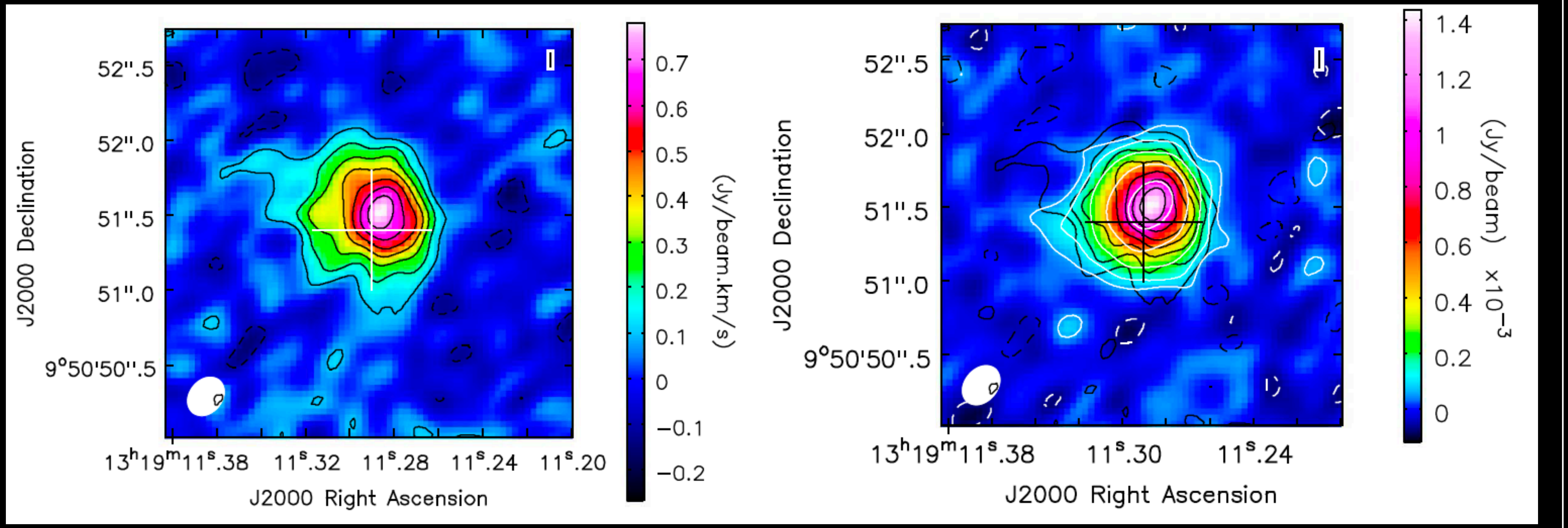
✤CO SLED as useful diagnostic of the physics of the emitting ISM (quiescient/straburst)

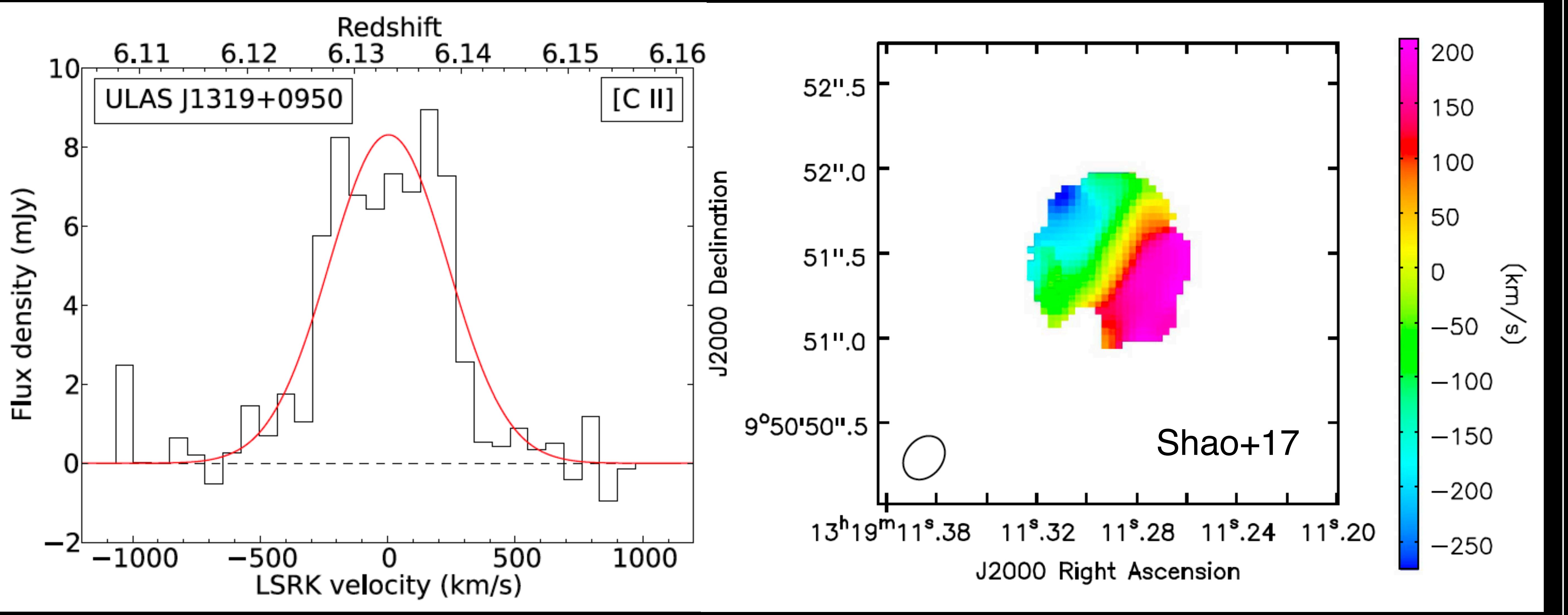
General knowledge of high-z QSOs

Gas ▸ [CII] as tracer of the multi-phase gas

✤[CII] for identifying high-z objects
✤[CII] for studying kinematics and dynamics







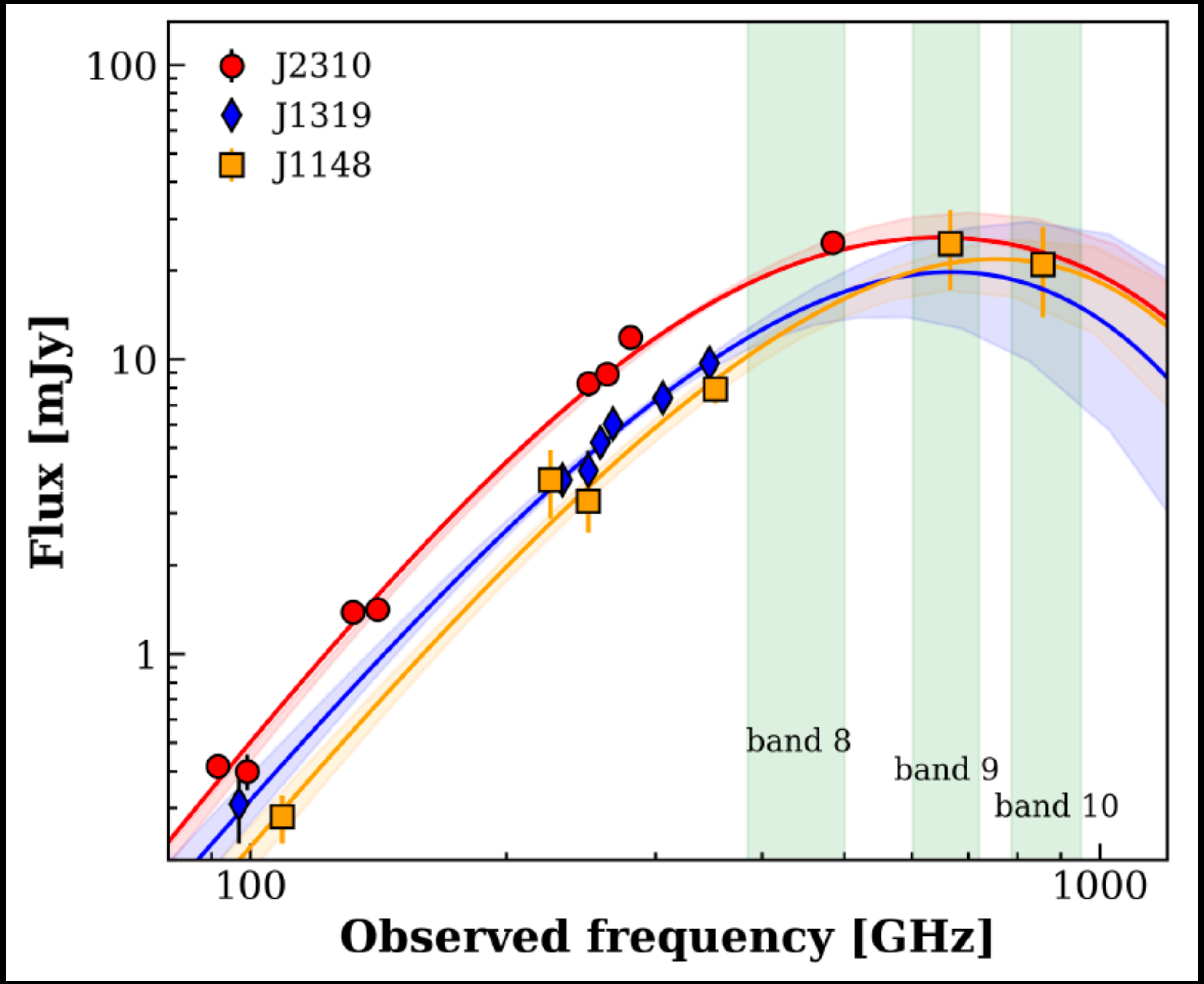
General knowledge of high-z QSOs

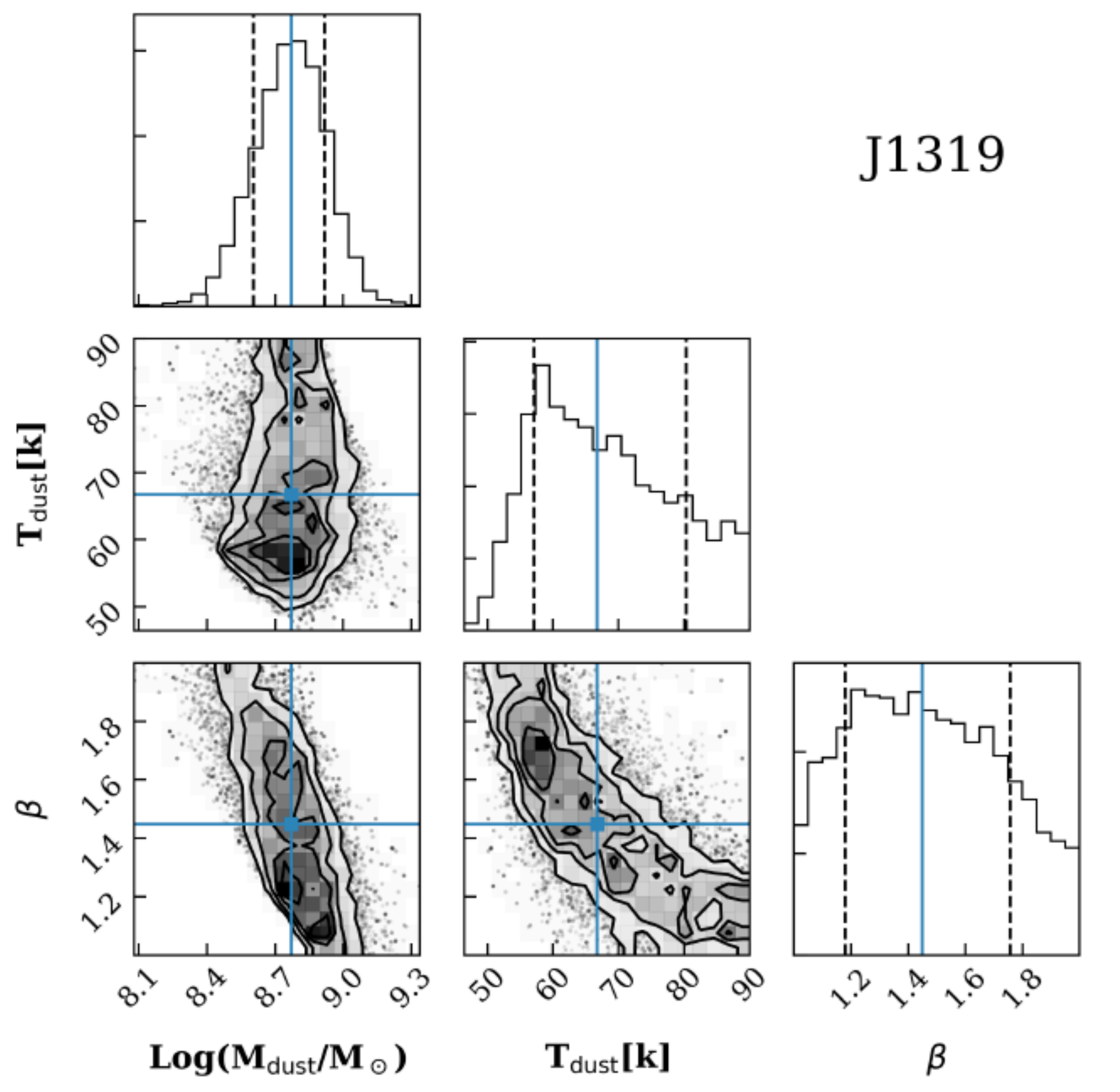
Dust

- Key in star formation process, e.g. PopIII (Schneider+2011)
- Quantify dust-reprocessed SFR and dust properties
- At high-z, the peak of dust SED shifted in ALMA bands

$$\mathrm{SFR} \propto L_{\mathrm{TIR}}$$

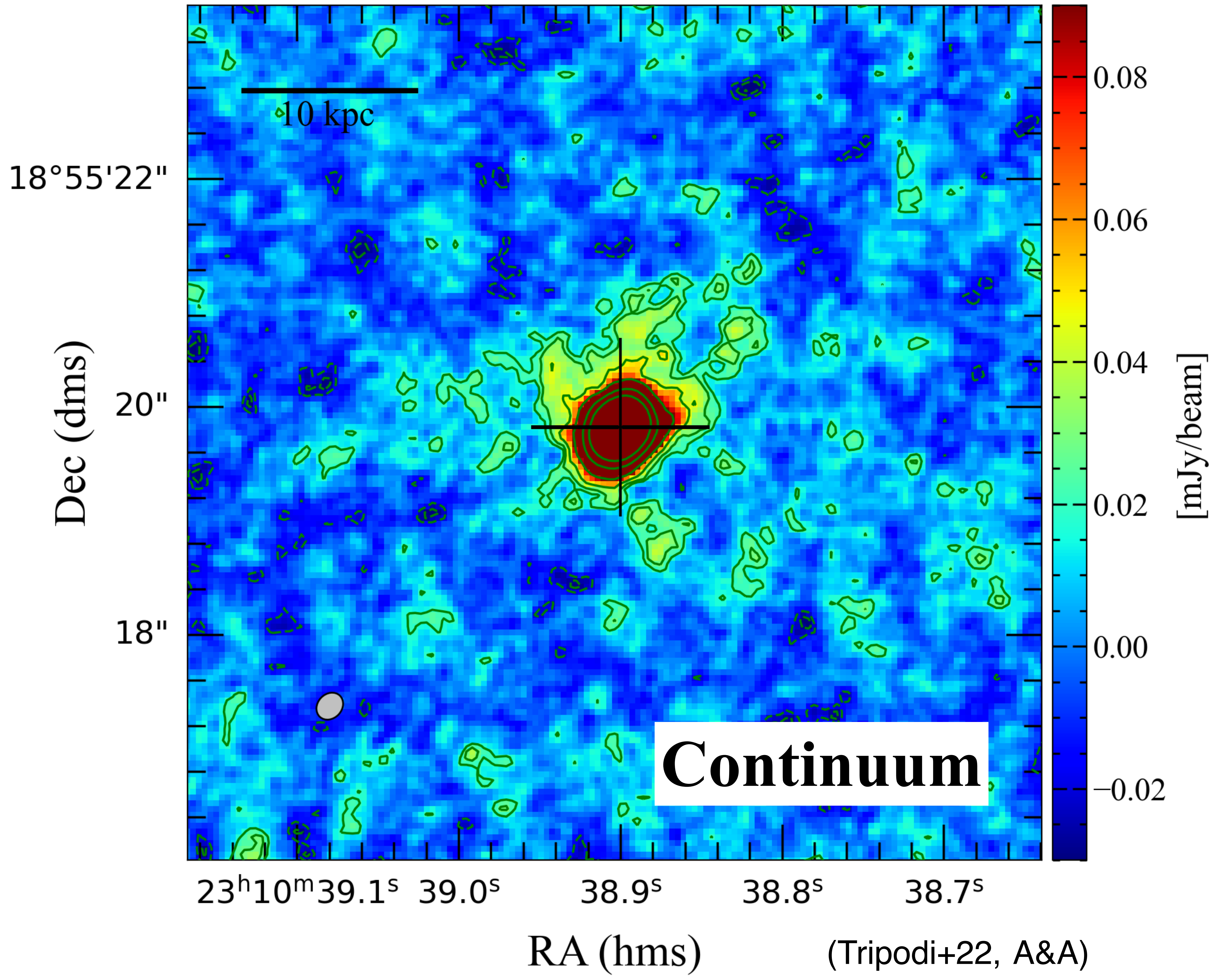
❖ Very few QSOs with accurately sampled SEDs





The case of QSO SDSS J2310+1855 at $z = 6.003$

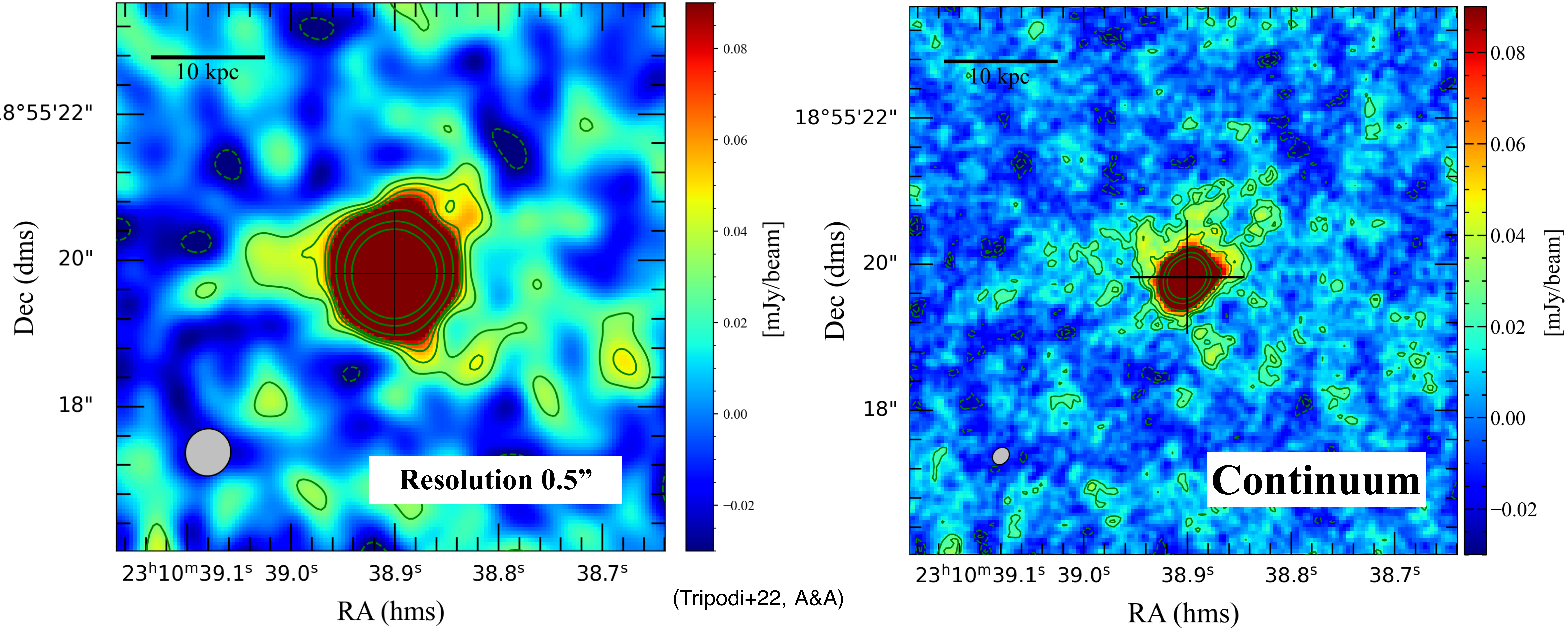
✳ Spatially and spectral resolving power (0.1" resolution) ——> size ~ $1.3 \times 1.1\ \mathrm{kpc}^2$



(Tripodi+22, A&A)

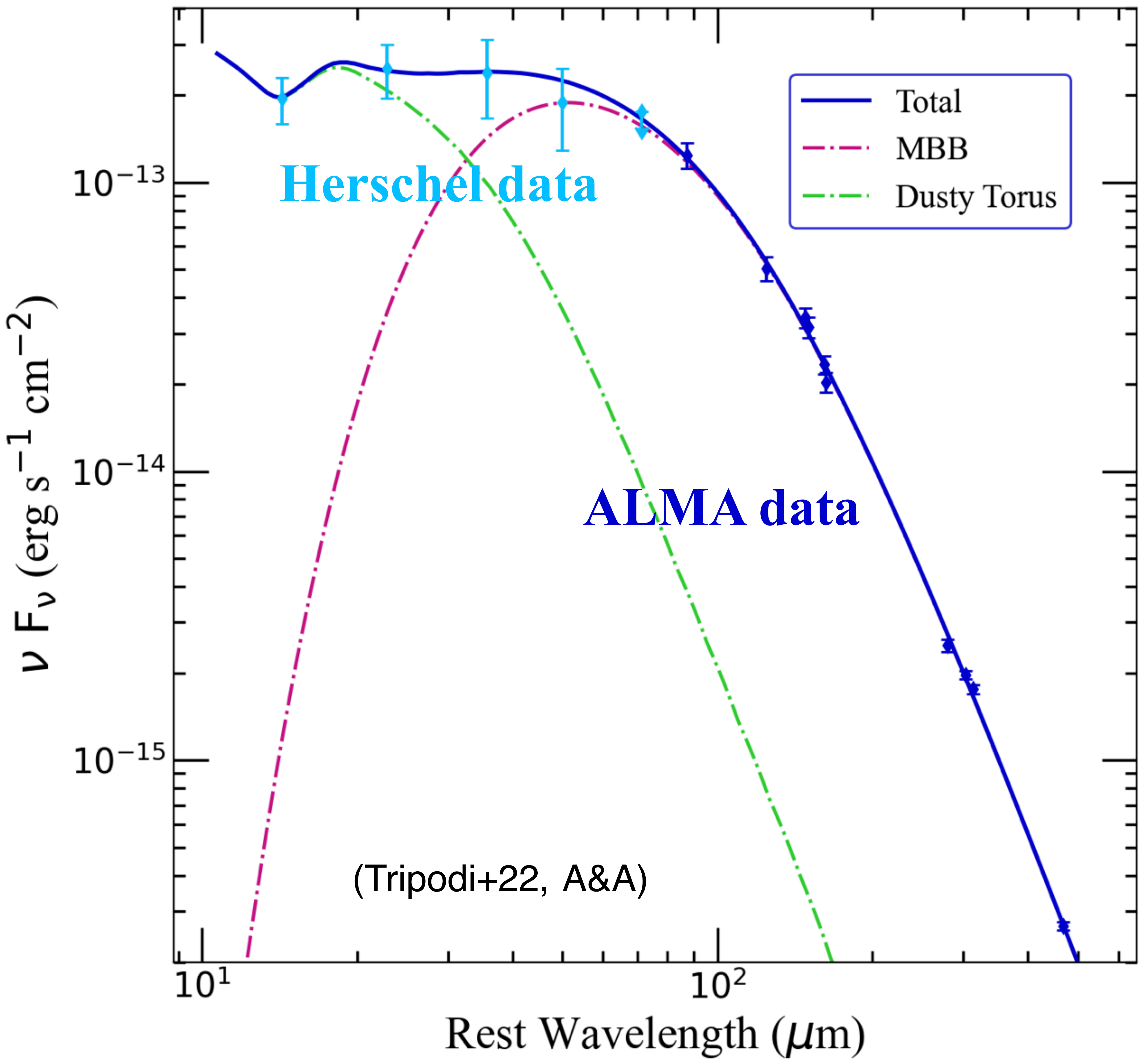
The case of QSO SDSS J2310+1855 at $z = 6.003$

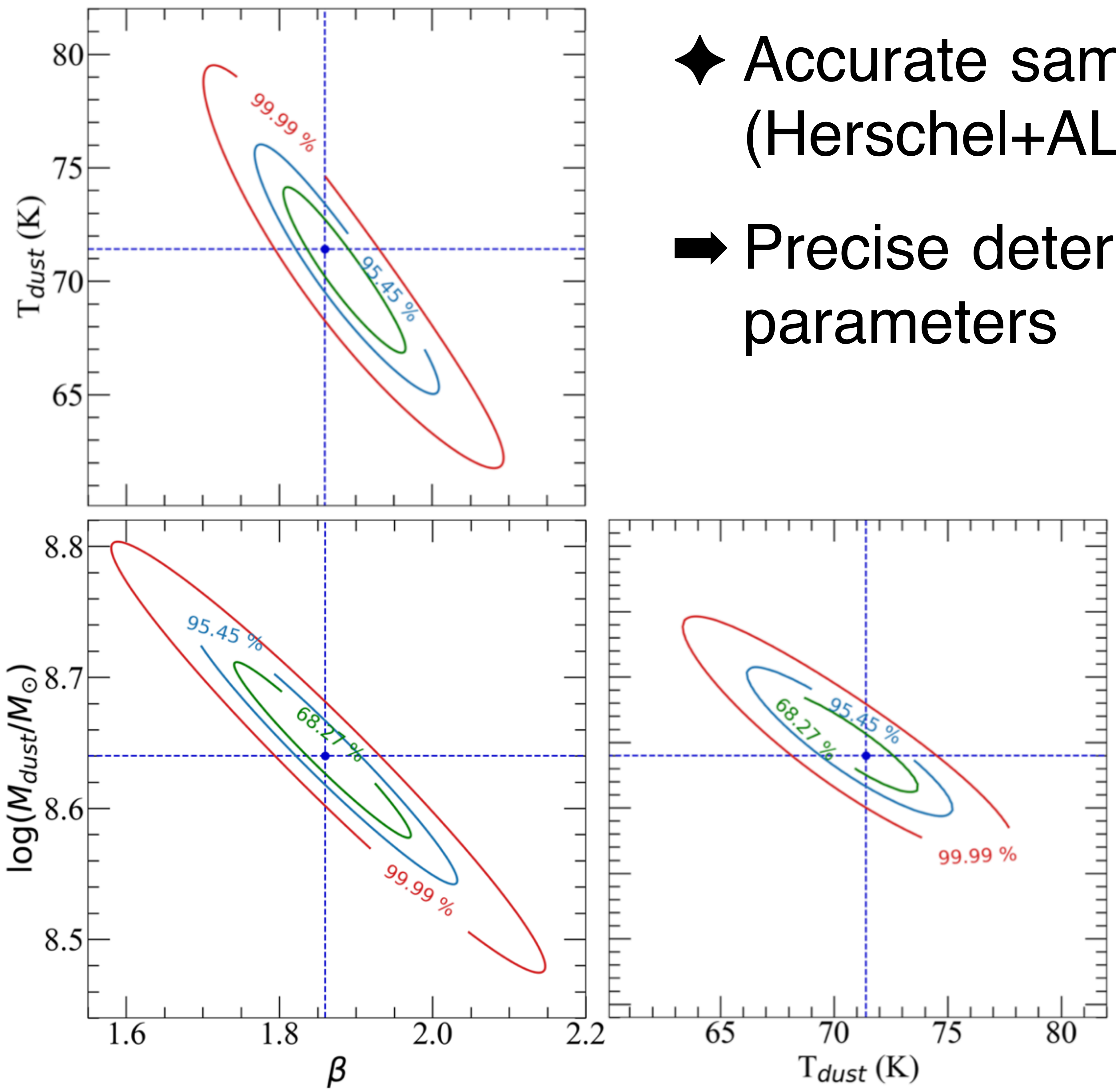
✳ Spatially and spectral resolving power (0.1” resolution) ——> size ~ $1.3 \times 1.1\ \mathrm{kpc}^2$



(Tripodi+22, A&A)

The case of QSO SDSS J2310+1855 at $z = 6.003$





- ✦ Accurate sampling of the distribution (Herschel+ALMA data)
- ➡ Precise determination of fitting parameters
- ✦ At least 2 points for $M_{\rm dust}, \beta$
- ✦ At least 1 point for $T_{\rm dust}$ at higher frequency
- ➡ $T_{\rm dust} = 71 \pm 4$ K
- ➡ $\frac{M_{\rm dust}}{10^8\ M_\odot} = 4.4 \pm 0.7$
- ➡ $\mathrm{SFR} \sim 1240 \pm 300\ M_\odot \mathrm{yr}^{-1}$

The case of QSO SDSS J2310+1855 at $z = 6.003$

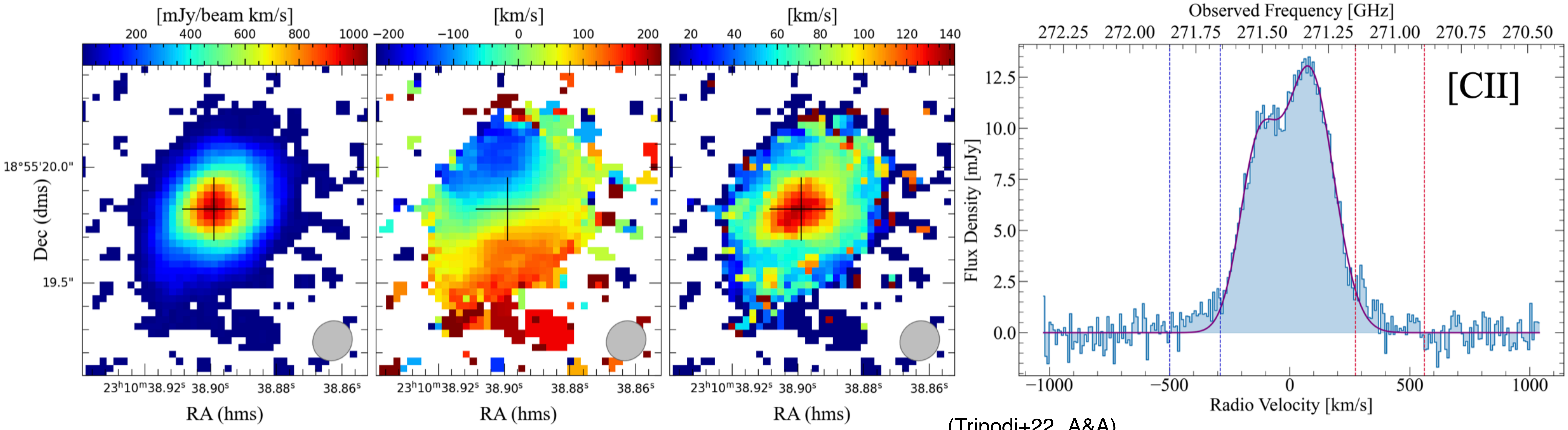
- ✳ Spatially and spectral resolving power (0.1” resolution)
  - ➡ size [CII] $\sim 2.6 \times 1.9\ \mathrm{kpc}^2$
- ✳ Rotating disk (velocity gradient)

(Feruglio+18, Wang+13)

- ✳ Detection of outflow emissions
  - ➡ $M_{\rm out} = 5\,\%\,M_{\rm disk}$
  - ➡ $\dot{M}_{\rm out} = 1800 - 4500\ \mathrm{M_\odot yr^{-1}}$

(Shao+22, Barai+18)

- ✳ Low $\dot{E}_{\rm out}/L_{\rm bol} \sim 0.0005 - 0.002$ compared to other molecular winds (Fiore+17)



(Tripodi+22, A&A)

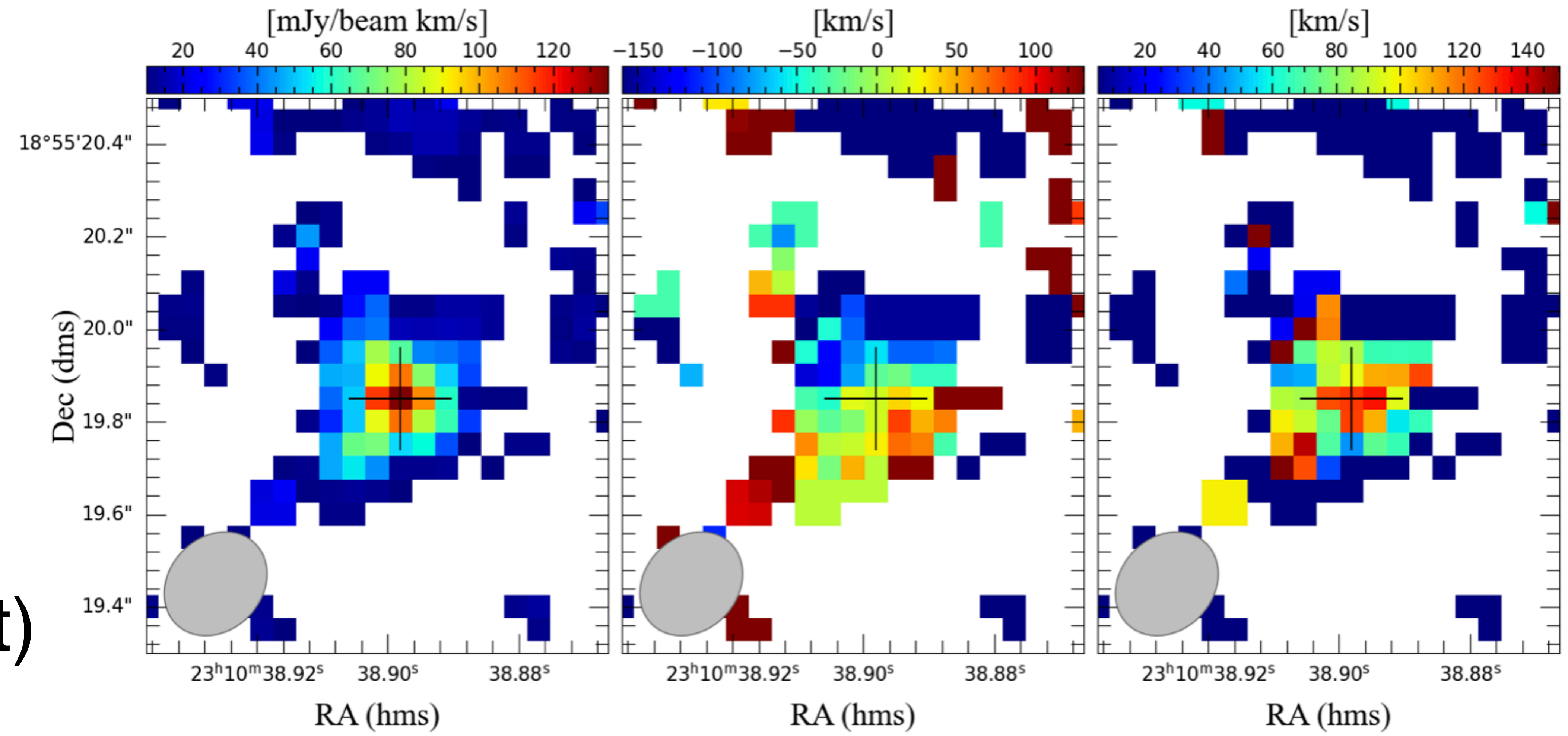
The case of QSO SDSS J2310+1855 at $z = 6.003$

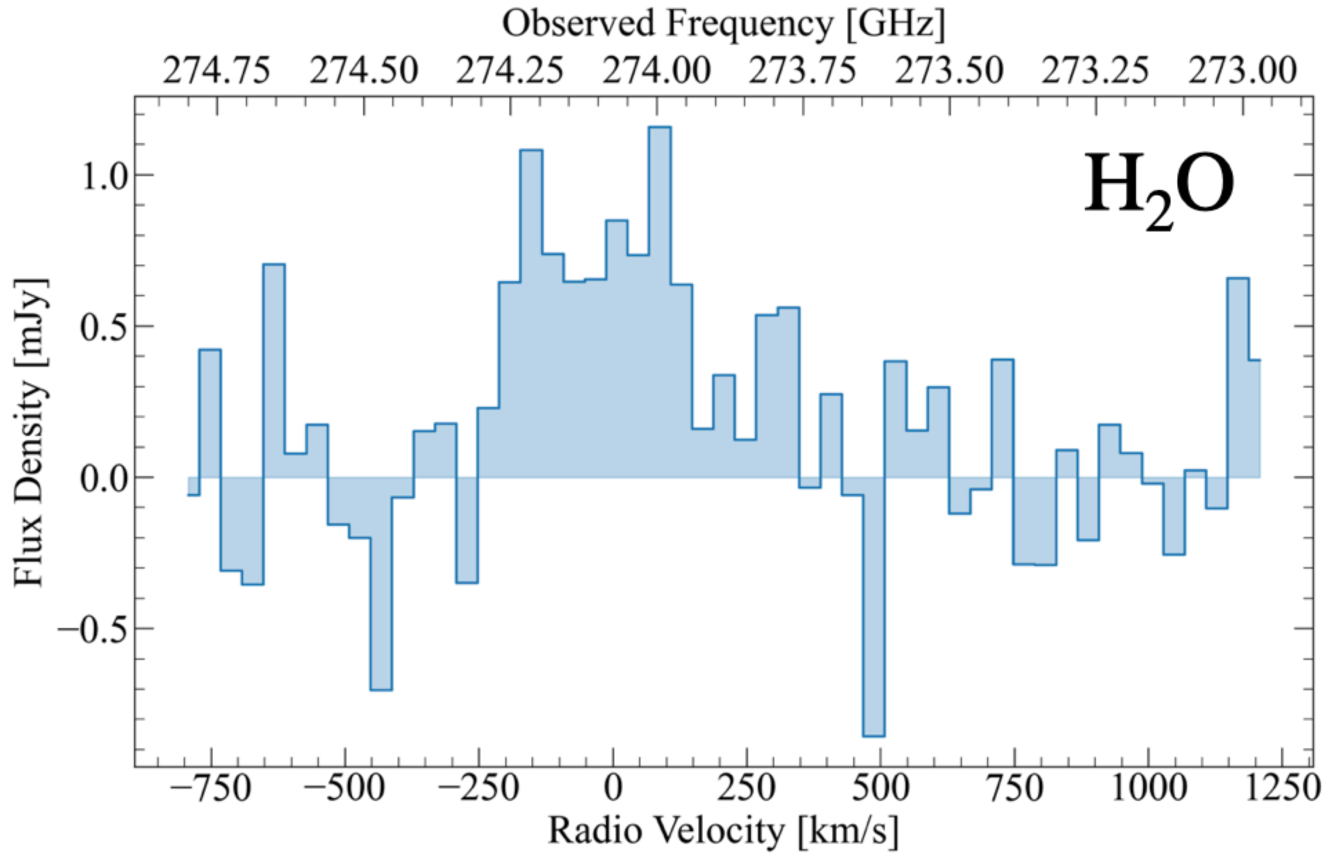
✳ Spatially and spectral resolving power (0.1” resolution)

➡ size [CII] $\sim 2.6 \times 1.9$ kpc^2

➡ size $H_2O \sim 1.9 \times 1.1$ kpc^2

✳ Rotating disks (velocity gradient)



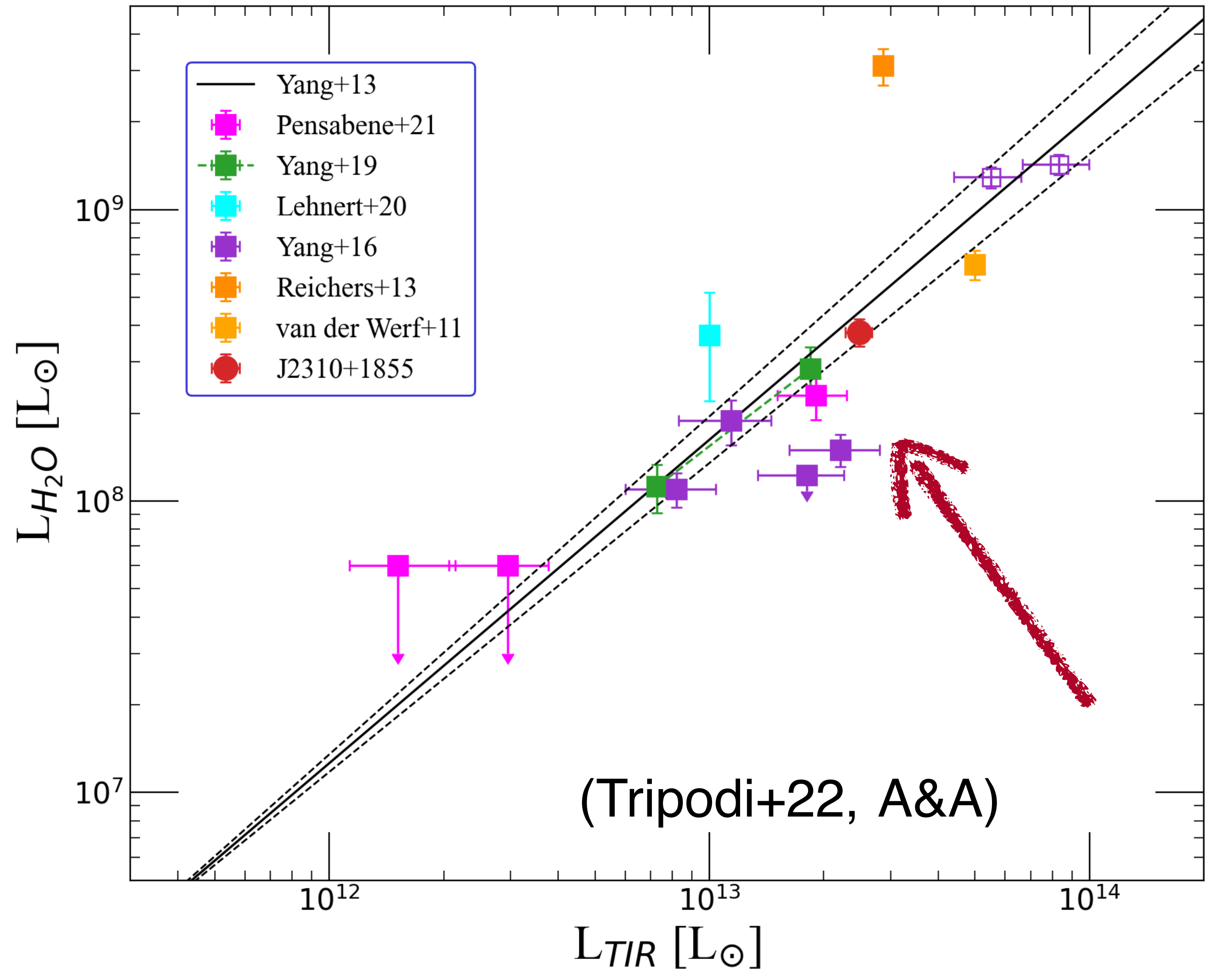


✤ First spatially resolved H_2O (v = 0) $3_{(2,2)} - 3_{(1,3)}$ line emission in a z~6 QSO

➡ $L_{H_20} = 3.6 \times 10^8\ L_\odot$

✤ H_2O emission consistent with $L_{H_2O} - L_{TIR}$ correlation

(Pensabene+21)

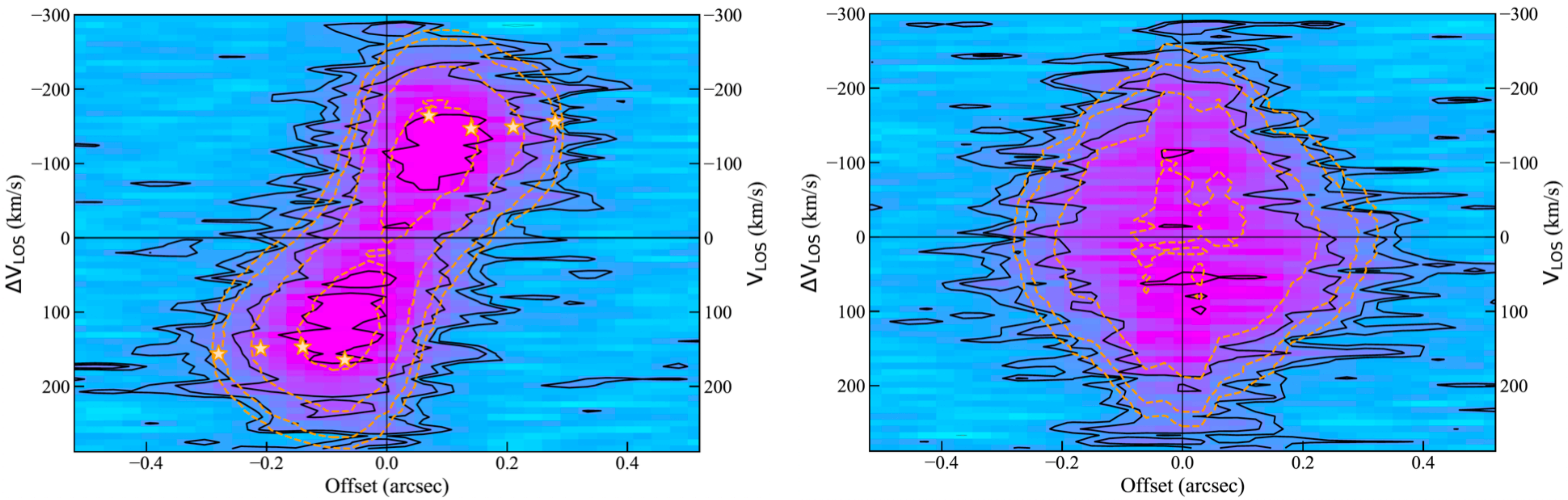


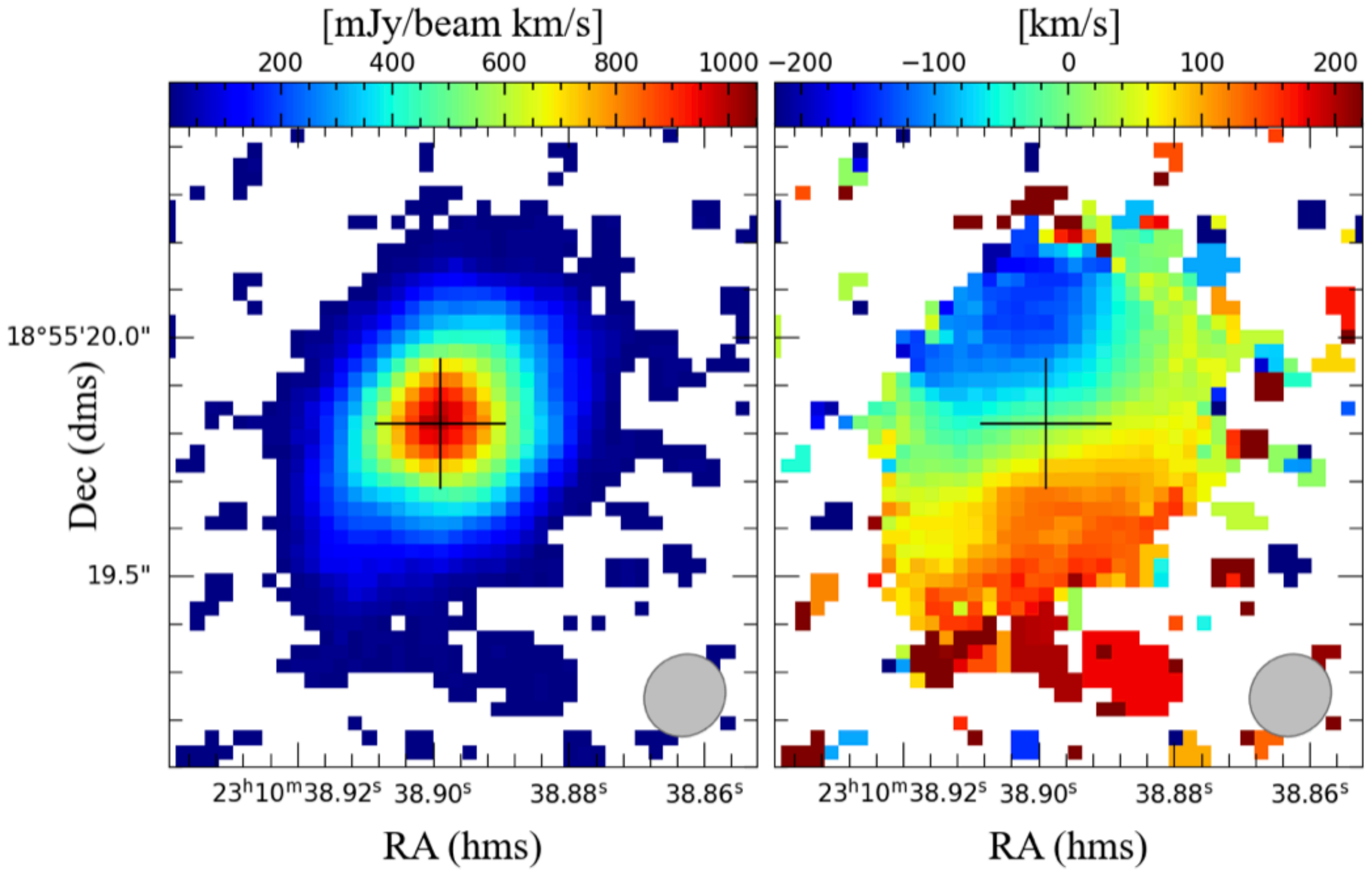
(Tripodi+22, A&A)

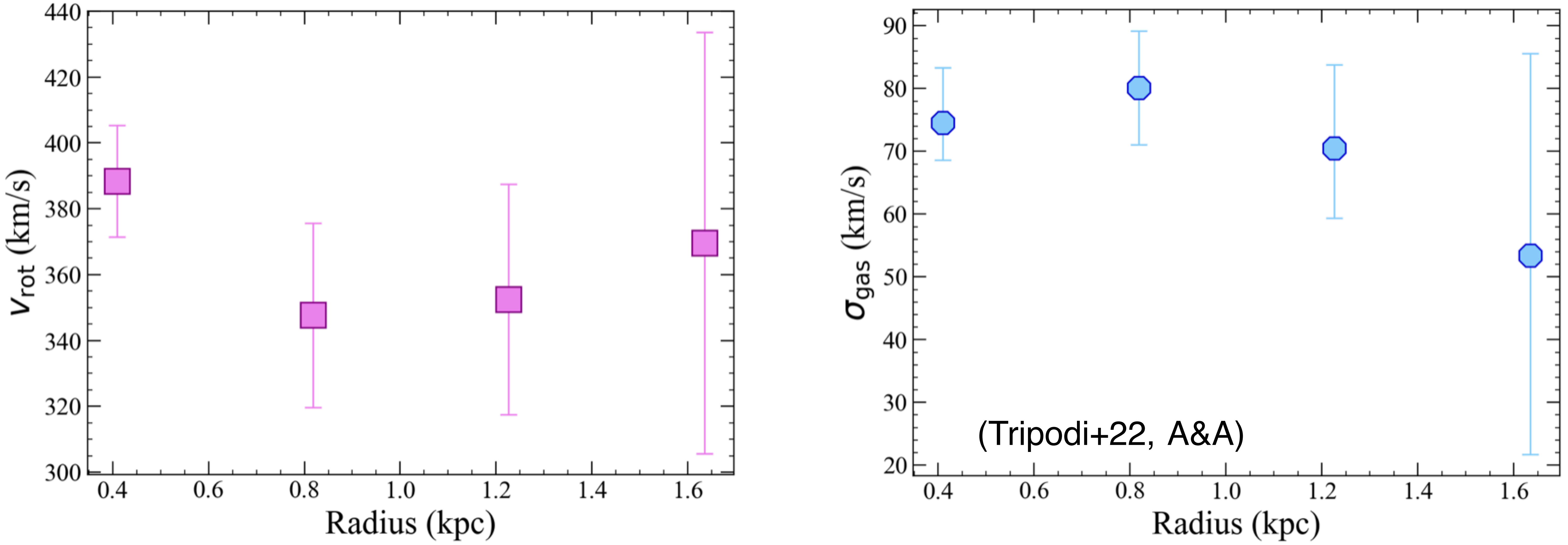
The case of QSO SDSS J2310+1855 at $z = 6.003$

- ✳ Detailed analysis of the rotation curve
- ✳ Best estimate of $M_{\rm dyn}$ through dynamical modeling (Di Teodoro+15)

➡ $M_{\rm dyn} = 5.2^{+2.3}_{-0.6} \times 10^{10}\ {\rm M}_\odot$



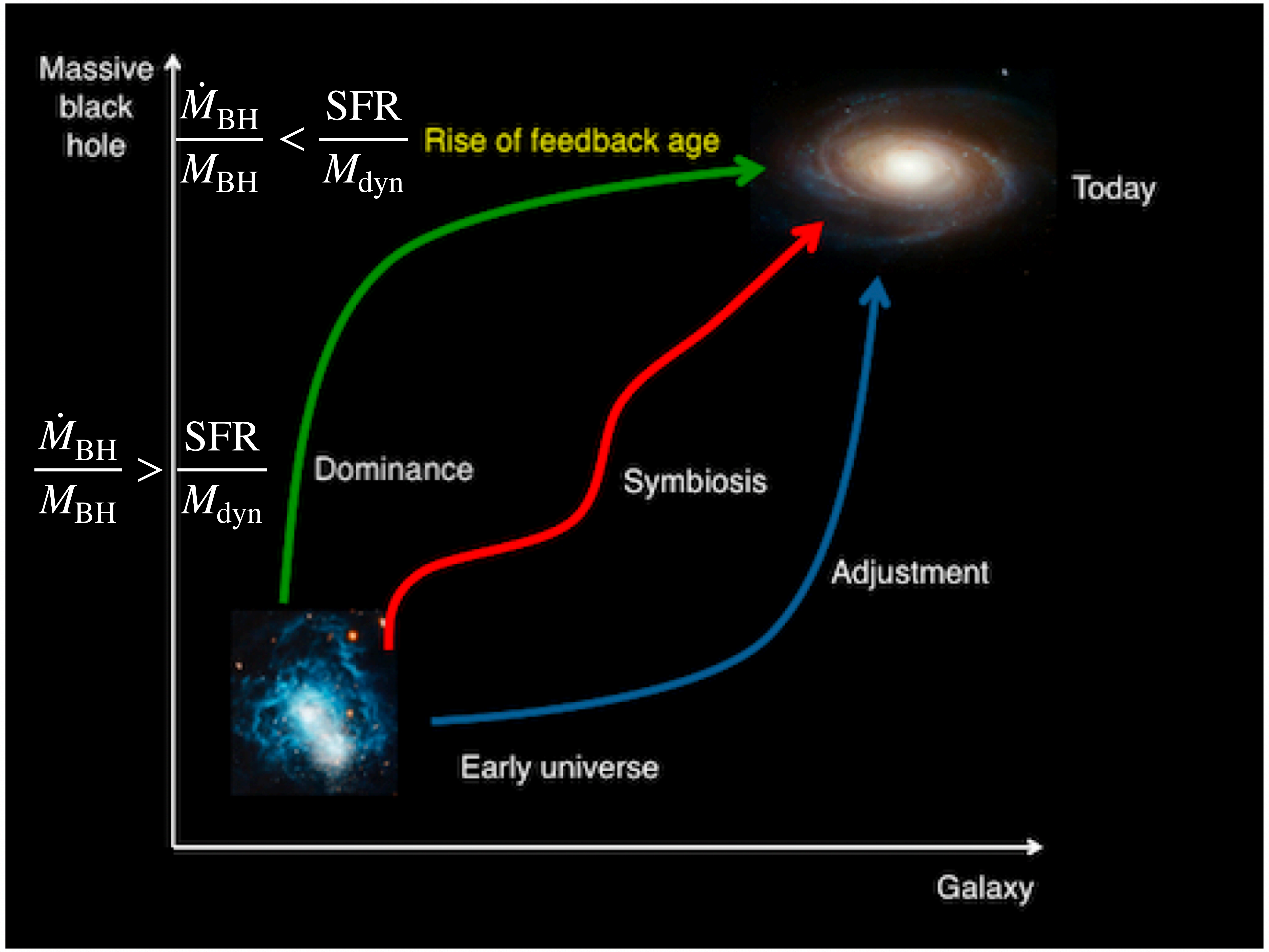




The case of QSO SDSS J2310+1855 at $z = 6.003$

Study the evolutionary paths of the SMBH and its host galaxy

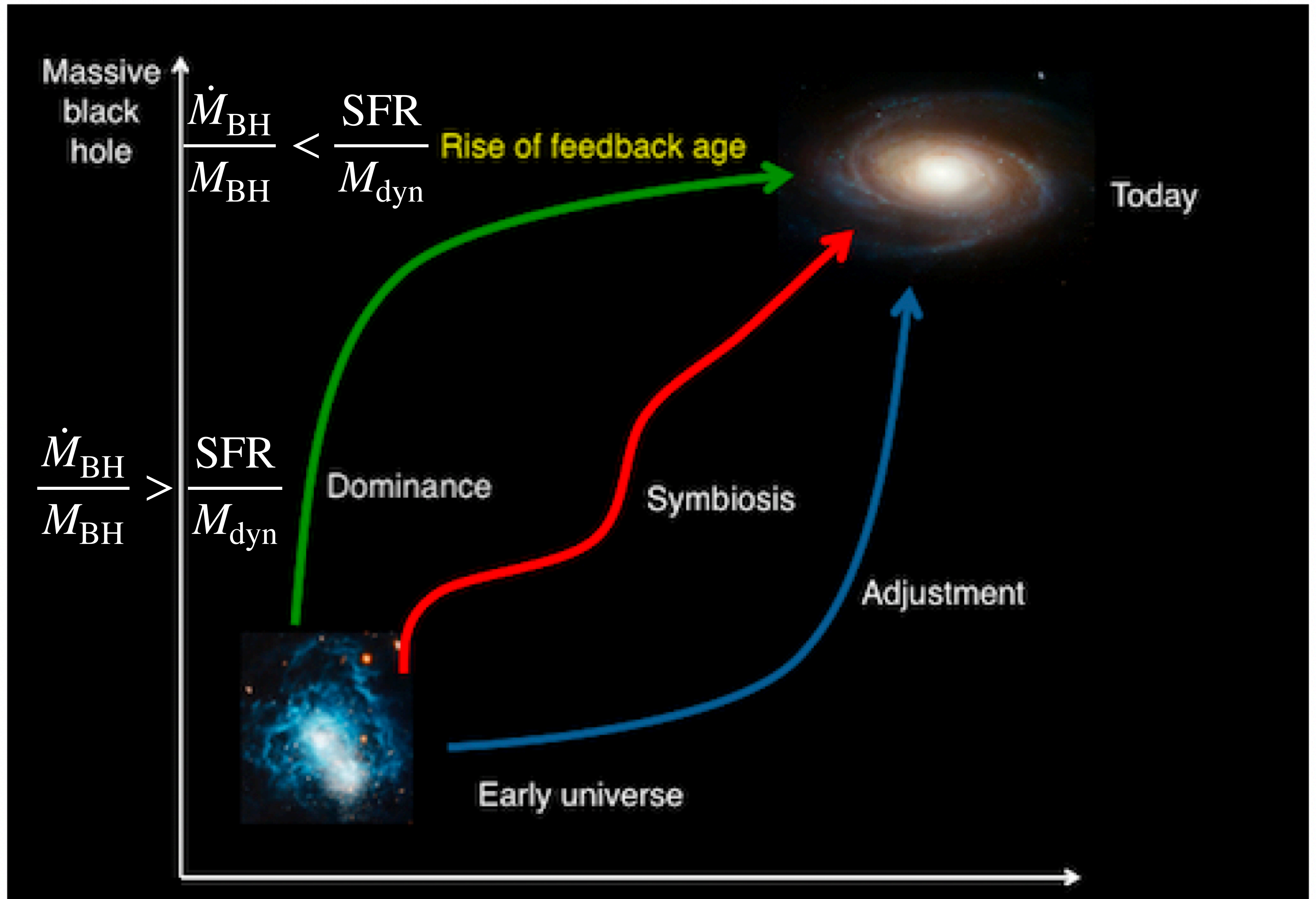
(Volonteri 2012, adapted)



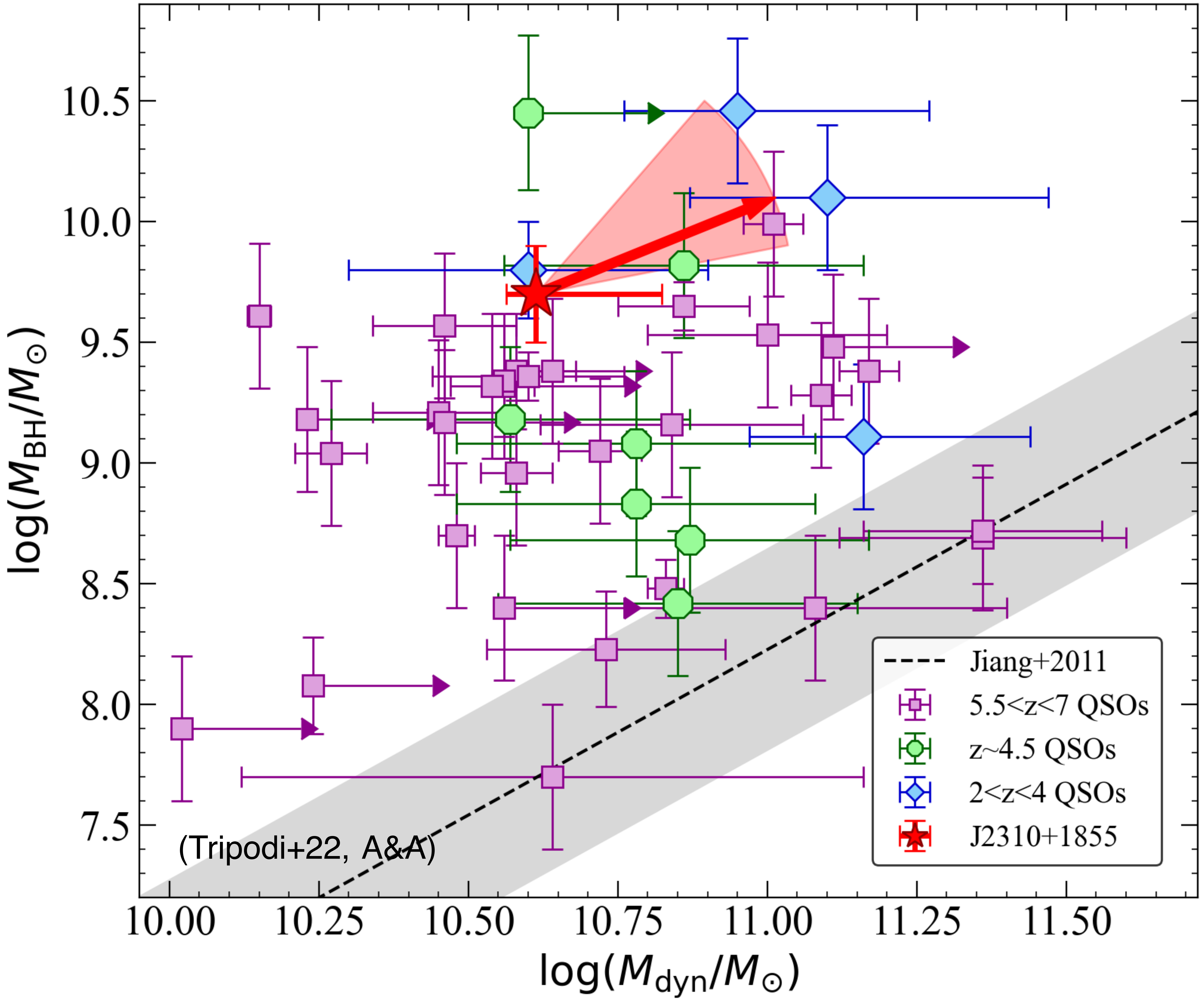
The case of QSO SDSS J2310+1855 at $z = 6.003$

- ✳ $\frac{\dot{M}_{BH}}{M_{BH}} \lesssim \frac{1}{2} \frac{SFR}{M_{dyn}}$, the BH build-up slower than host galaxy
- ✳ Possible cause: AGN radiatively-driven winds

(Bischetti+22, Shao+22)



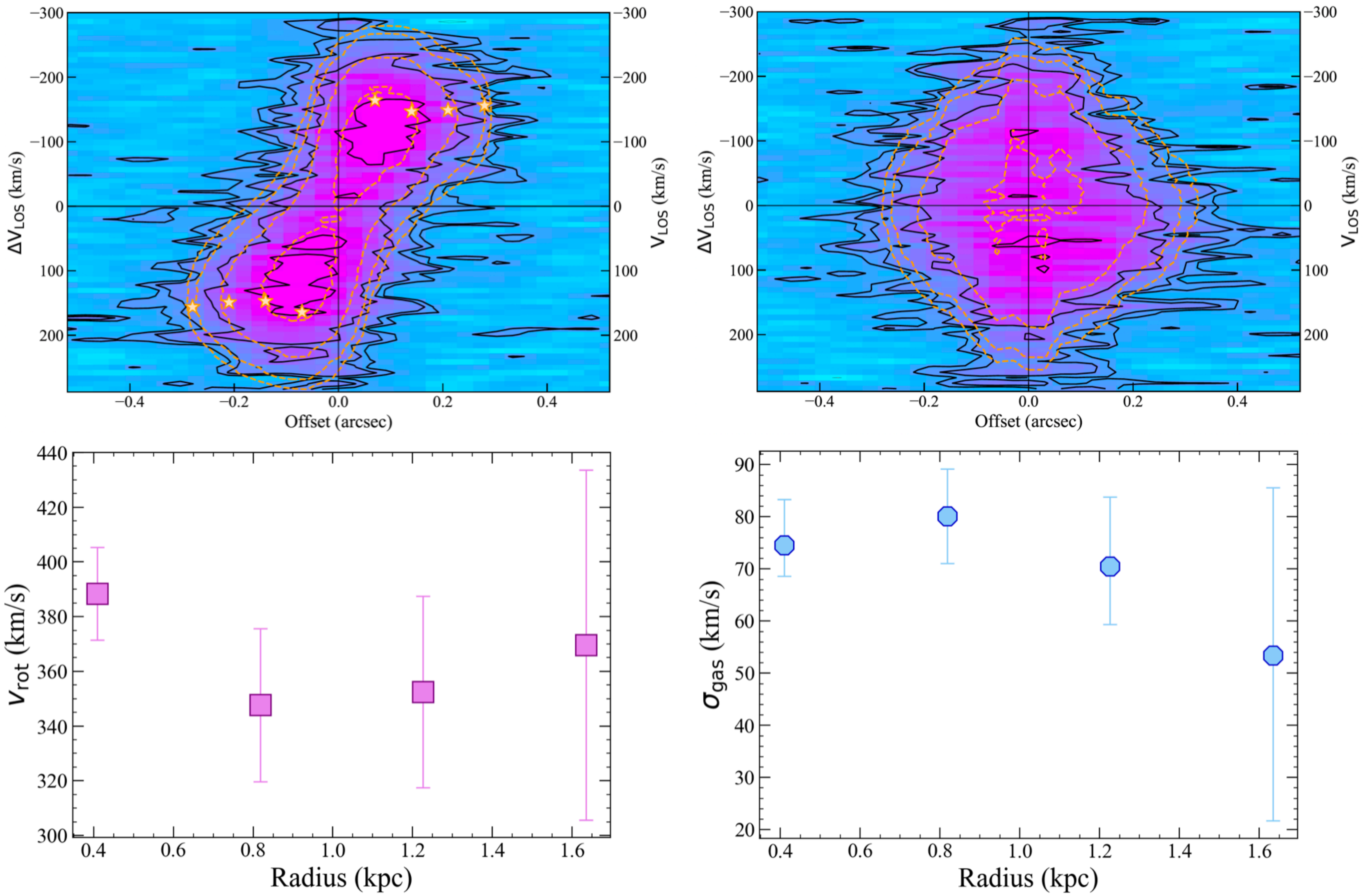
(Volonteri 2012, adapted)



(Tripodi+22, A&A)

The case of QSO SDSS J2310+1855 at $z = 6.003$

The study of the rotation curve is not over yet



The case of QSO SDSS J2310+1855 at $z = 6.003$

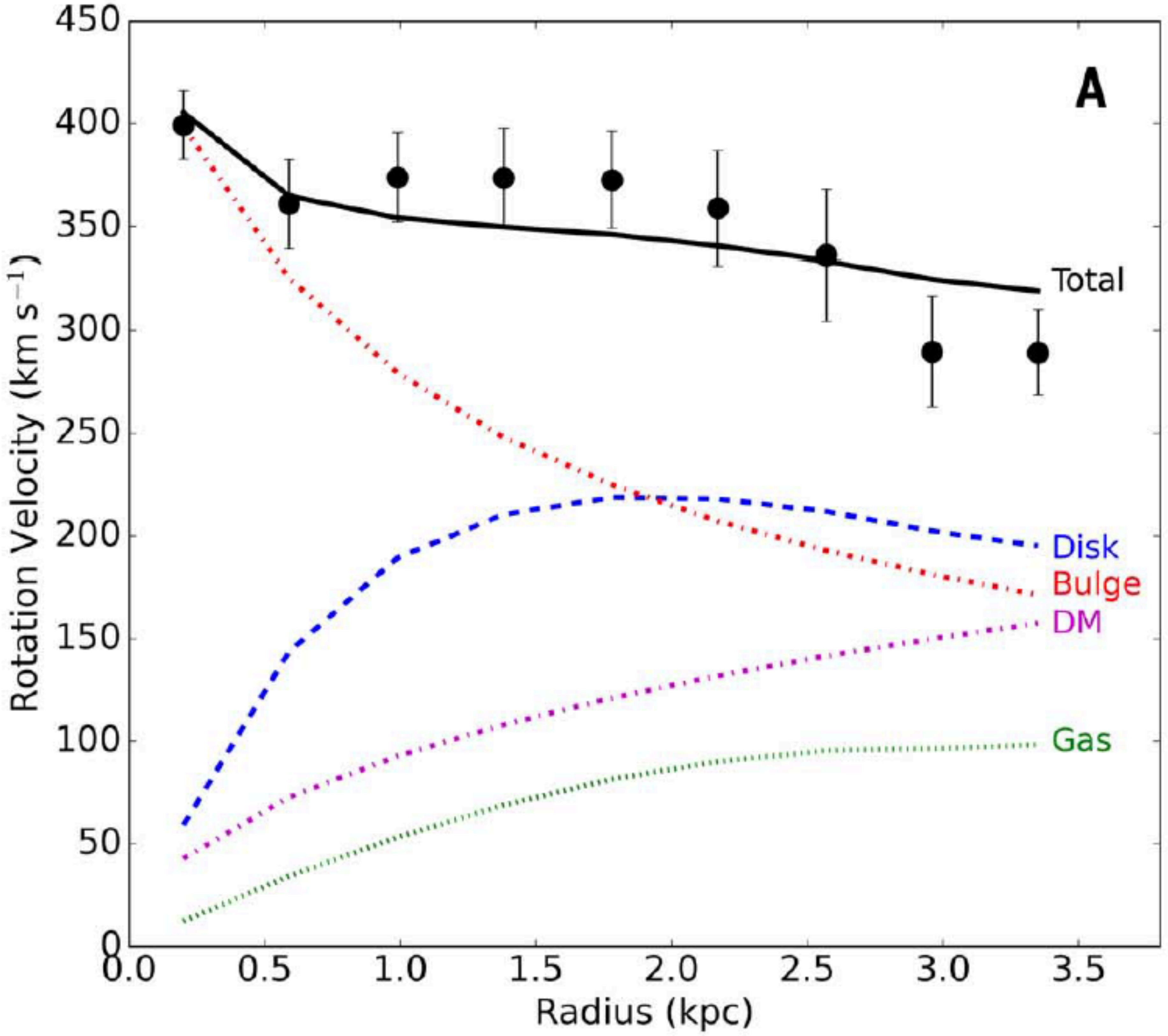
➡ Dynamical modeling of the rotation curve

REPORT

GALAXIES

A massive stellar bulge in a regularly rotating galaxy 1.2 billion years after the Big Bang

Federico Lelli[1,2]*, Enrico M. Di Teodoro[3], Filippo Fraternali[4], Allison W. S. Man[5], Zhi-Yu Zhang[6], Carlos De Breuck[7], Timothy A. Davis[1], Roberto Maiolino[8,9]



The case of QSO SDSS J2310+1855 at $z = 6.003$

Dynamical modeling of the rotation curve

3/4 components:

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

Modeling:

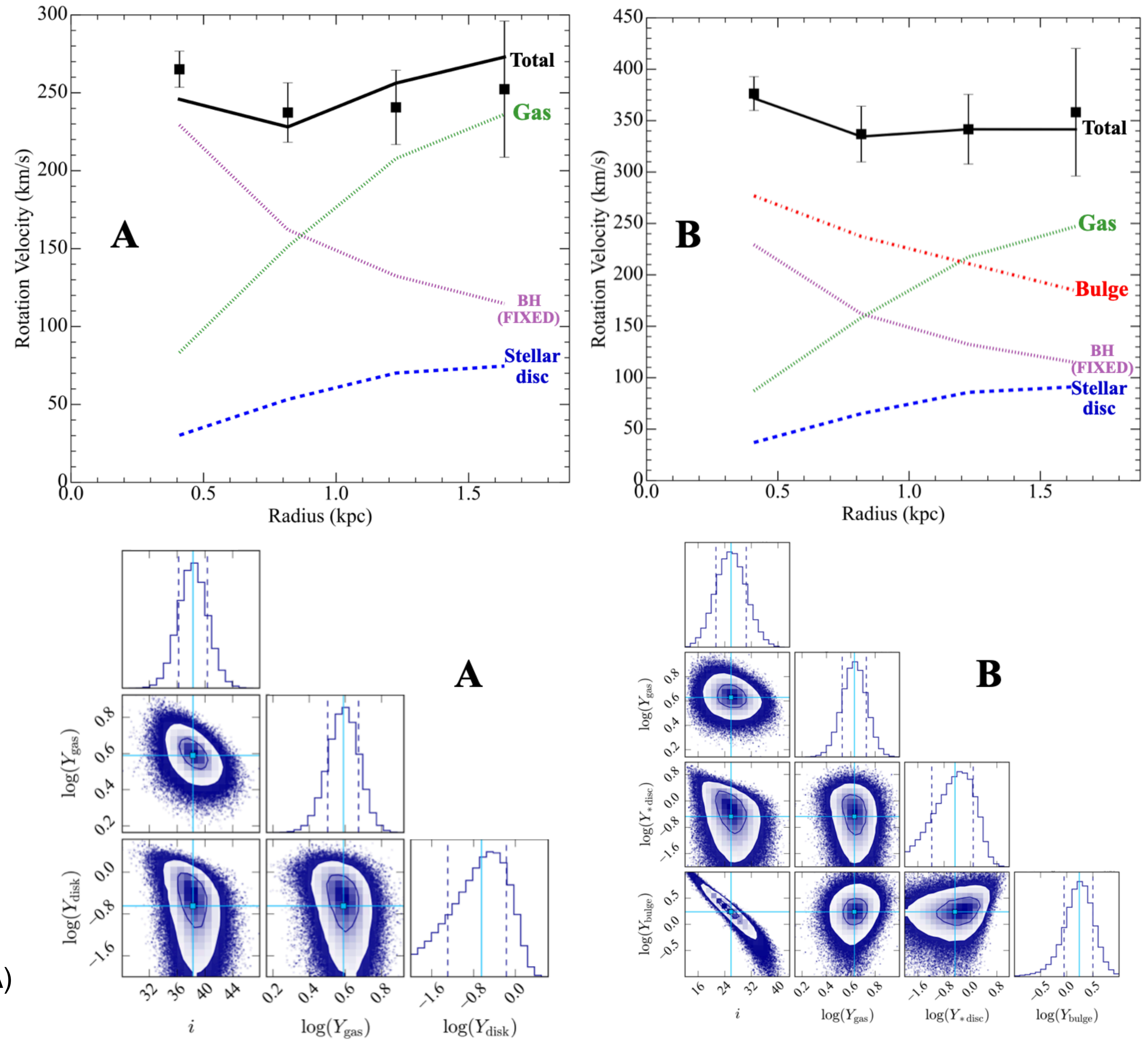
- ✦ 2 thick disks
- ✦ Point mass
- ✦ Sérsic profile (n=4)

The case of QSO SDSS J2310+1855 at $z = 6.003$

Dynamical modeling of the rotation curve

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

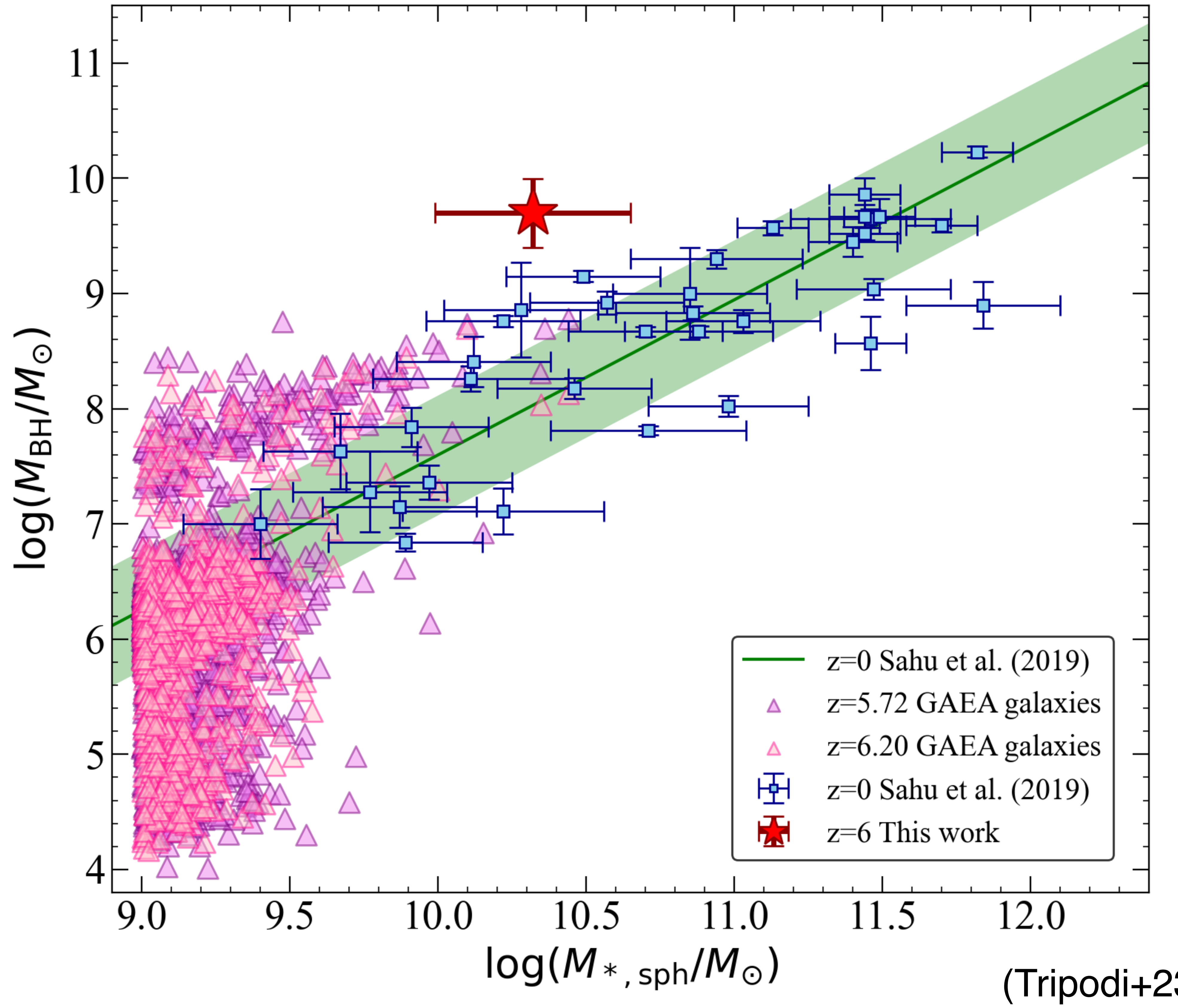
Highest-z Bulge candidate!

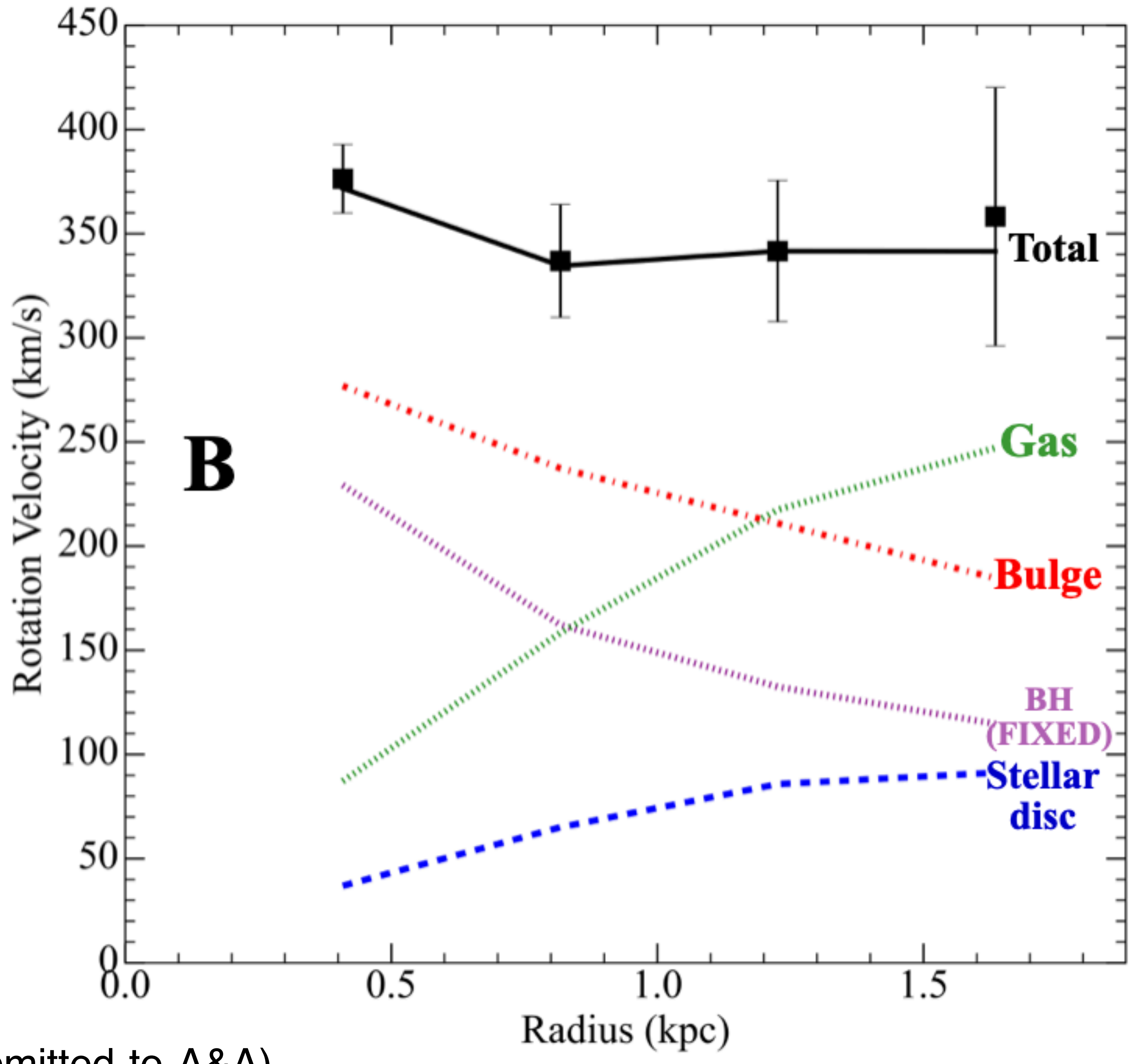


(Tripodi+23, submitted to A&A)

The case of QSO SDSS J2310+1855 at $z = 6.003$

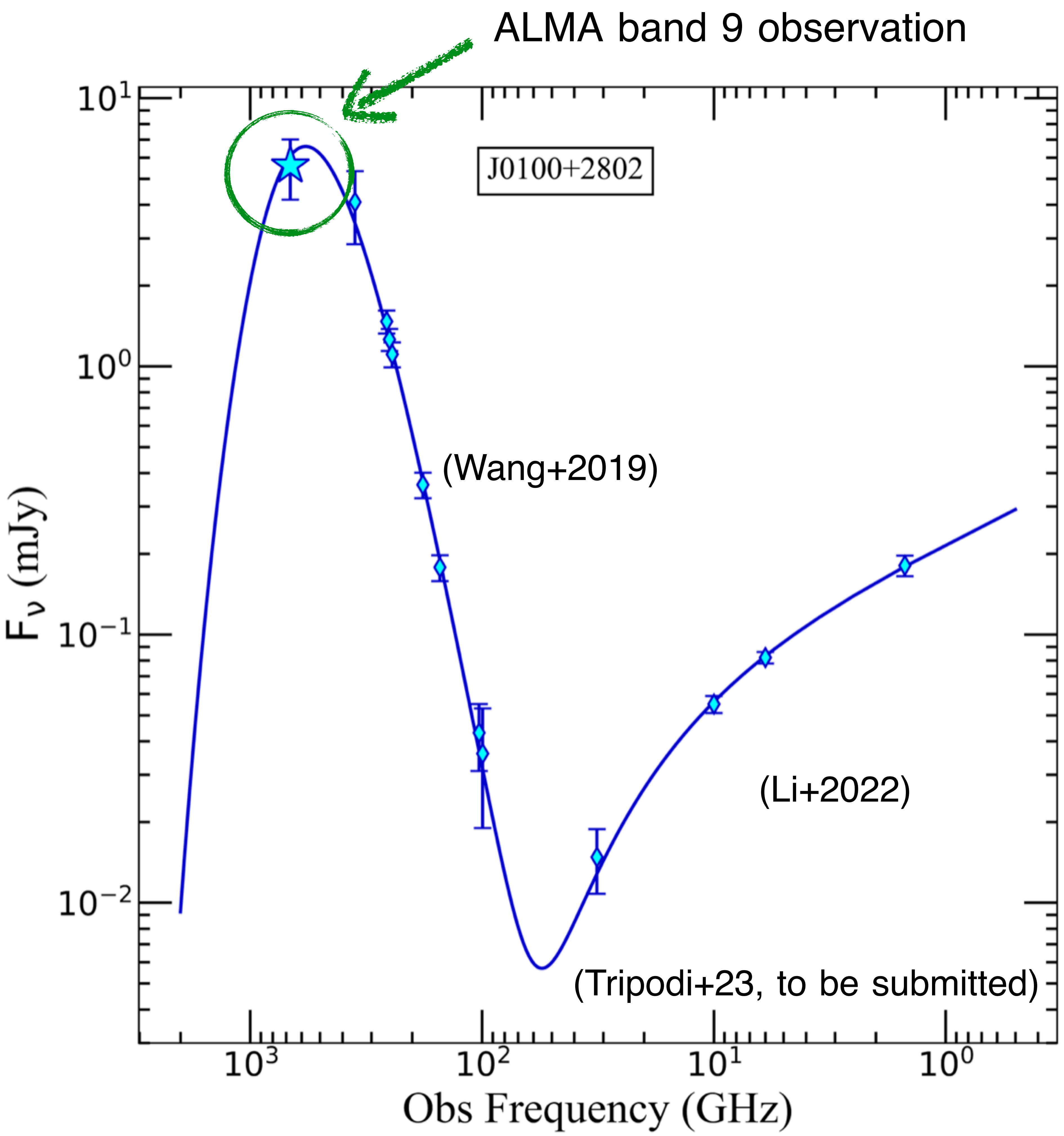
- Bulge with $M_{\rm bulge} \sim 10^{10}$ $M_\odot$
- Comparison with GAEA galaxies (Fontanot+2020)
- Which is the mechanism of bulge formation for J2310?

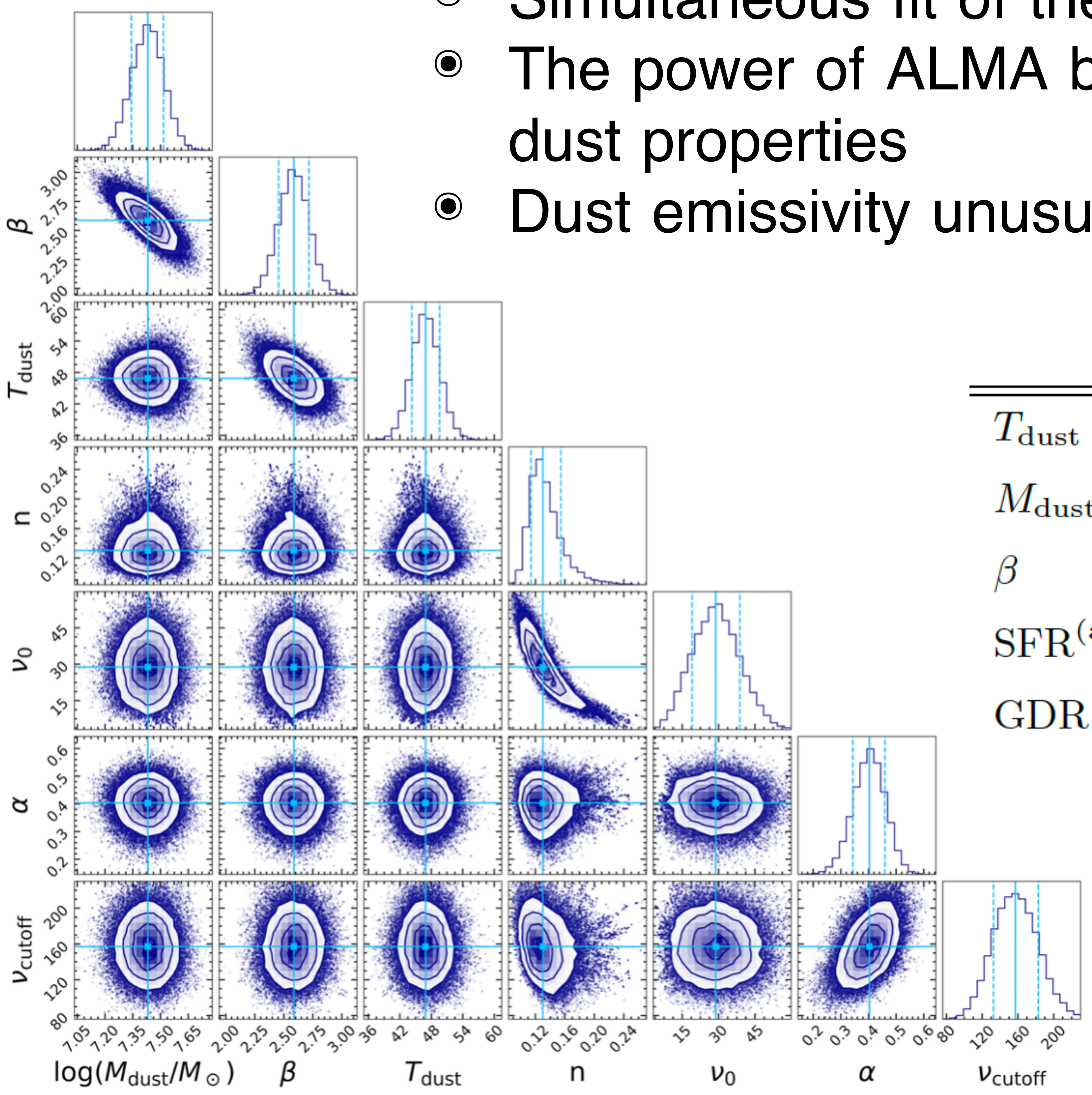




(Tripodi+23, submitted to A&A)

The most luminous QSO at $z > 6$: SDSS J0100+0228

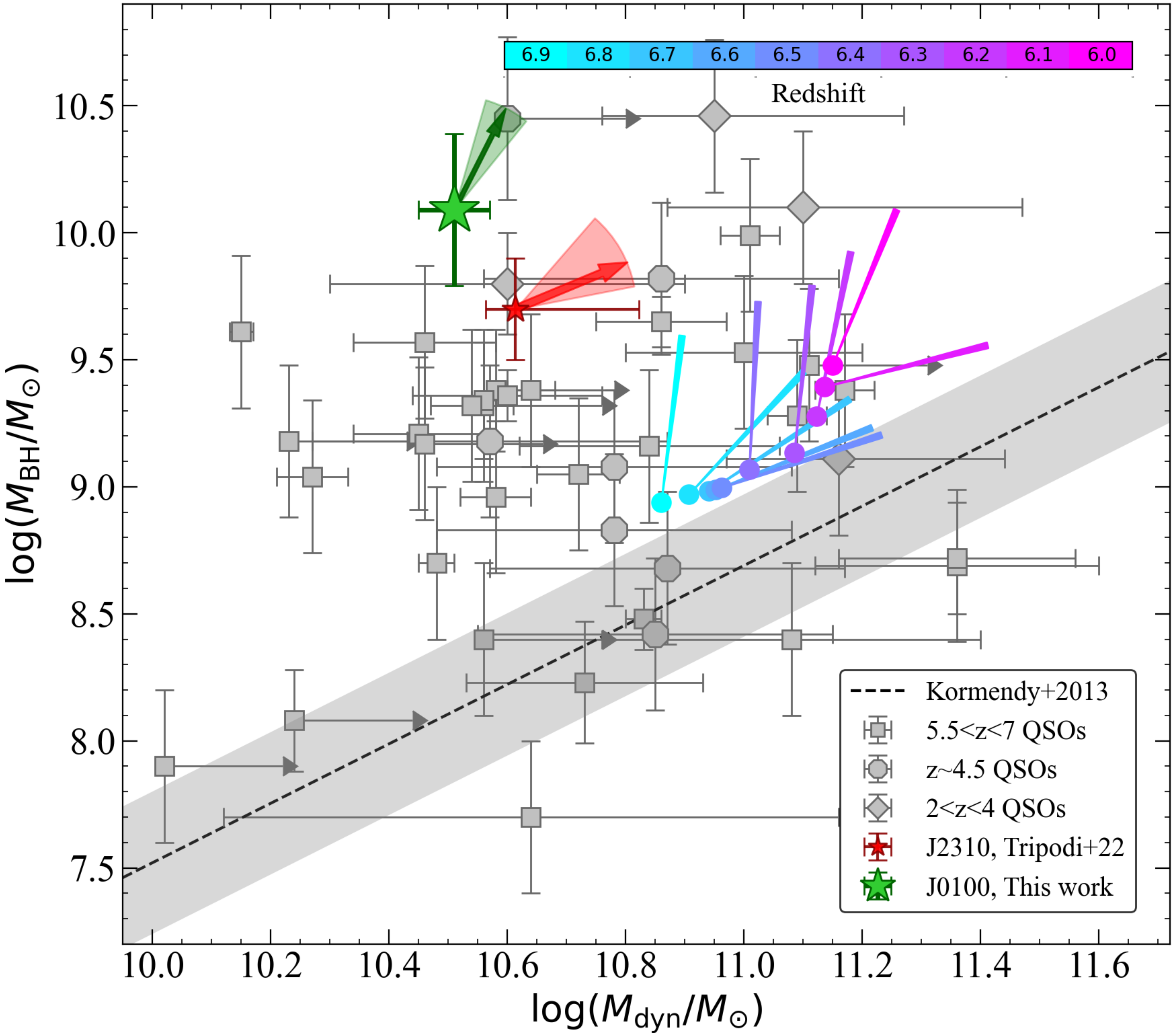




- Simultaneous fit of the sub-mm and radio SED
- The power of ALMA band 9: high accuracy for dust properties
- Dust emissivity unusually high

T_{dust}	[K]	47 ± 3
M_{dust}	[10^7 $M_\odot$]	2.70 ± 0.55
β		2.59 ± 0.13
SFR[a]	[$M_\odot$ yr^{-1}]	227.5 ± 47.5
GDR		200 ± 60

The most luminous QSO at $z > 6$: SDSS J0100+0228



- BH dominance regime
- Time distance J0100-J2310: only 61 Myr

(Tripodi+23, to be submitted, Costa+14a)

Conclusions

- High resolution and high frequency observations allow us to perform detailed studies of the properties of high-z QSOs
- ALMA band 8-9 essential for precise determination of $T_{\rm dust}$, $M_{\rm dust}$, SFR
- Outflow in QSO J2310+1855, $\dot{M}_{\rm out} = 1800 - 4500\ {\rm M_\odot yr^{-1}}$, low $\dot{E}_{\rm out}/L_{\rm bol}$
- First spatially resolved water vapor disk in z~6 QSO J2310, consistent with $\rm H_2O$ line excitation by dust-reprocessed SF in the host galaxy ISM
- Resolved rotation curves allow precise dynamical modeling; highest-z bulge candidate for J2310
- In J2310 the SMBH accretion is slowing down, while J0100's evolution is BH dominated


Back-up slides

Dust Spectral Energy Distribution

Methods: Modified Black Body (e.g. Carniani+2019)

$$S^{\rm obs}_{\nu/(1+z)} = \frac{\Omega}{(1+z)^3}\left[B_\nu(T_{\rm dust}(z)) - B_\nu(T_{\rm CMB}(z))\right](1-e^{-\tau_\nu}) \qquad (4)$$

$$T_{\rm dust}(z) = \left((T_{\rm dust})^{4+\beta} + T_0{}^{4+\beta}[(1+z)^{4+\beta} - 1]\right)^{\frac{1}{4+\beta}}$$

$$\Omega = (1+z)^4 A_{\rm galaxy} D_{\rm L}^{-2}$$

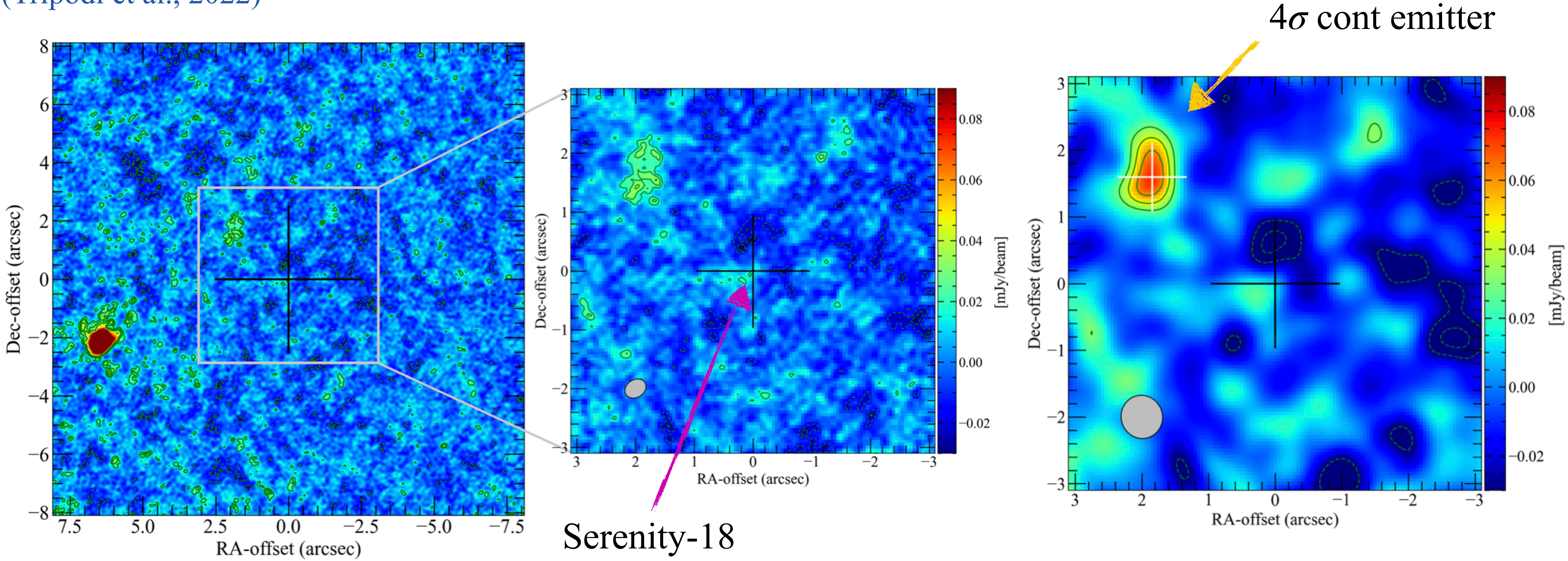
$$\tau_\nu = \Sigma_{\rm dust} k_\nu = \Sigma_{\rm dust} k_0 \left(\frac{\nu}{\nu_0}\right)^{\beta},$$

$$\Sigma_{\rm dust} = M_{\rm dust}/A_{\rm galaxy}$$

$$k_\nu = 0.45 \times (\nu/250\ {\rm GHz})^{\beta}\ {\rm cm}^2\ {\rm g}^{-1}$$

(Tripodi et al., 2022)

Environment of J2310+1855



✳ Serenity-18, candidate CO(6-5) emitter at $z = 5.9386$, associated to proximate metal-poor DLA system

✳ 3σ continuum upper limits: $S_{265.4\mathrm{GHz}} < 0.026$ mJy, $M_{\mathrm{dust}} < 6 \times 10^6\ \mathrm{M}_\odot$

✳ 3σ line upper limits: $L_{[\mathrm{CII}]} < 2.7 \times 10^7\ \mathrm{L}_\odot$, SFR $< 2.5\ \mathrm{M}_\odot \mathrm{yr}^{-1}$ (Carniani+18, Herrera-Camus+18)

✤ Total scan of the cube: no companions or signatures of ongoing mergers for J2310

High-resolution view of J2310+1855: outflow

Very few cases of outflows in QSOs at high redshift

(Maiolino+2005, Bischetti+2019, Izumi+2021a,b)

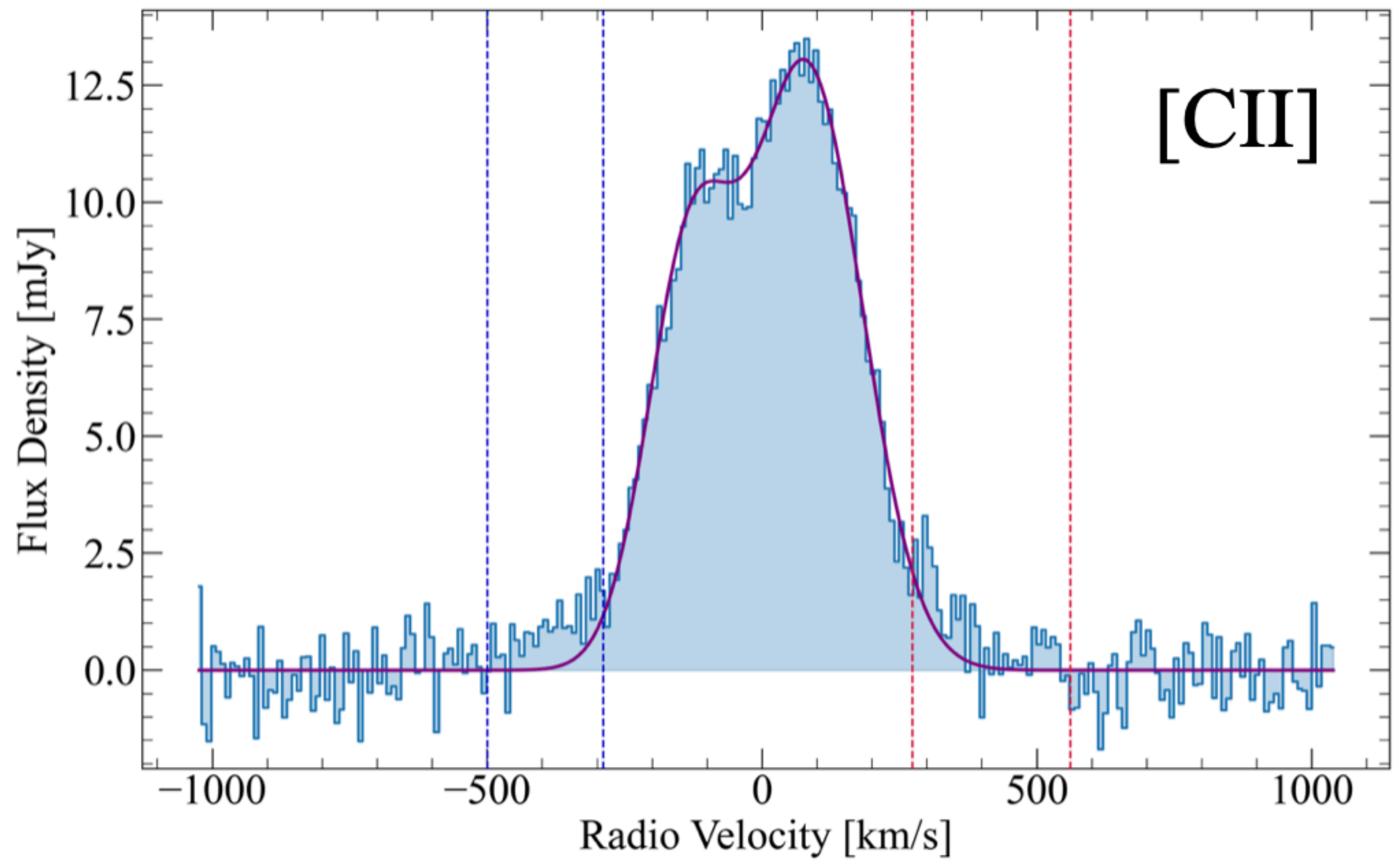
✳ Detection of outflow emissions

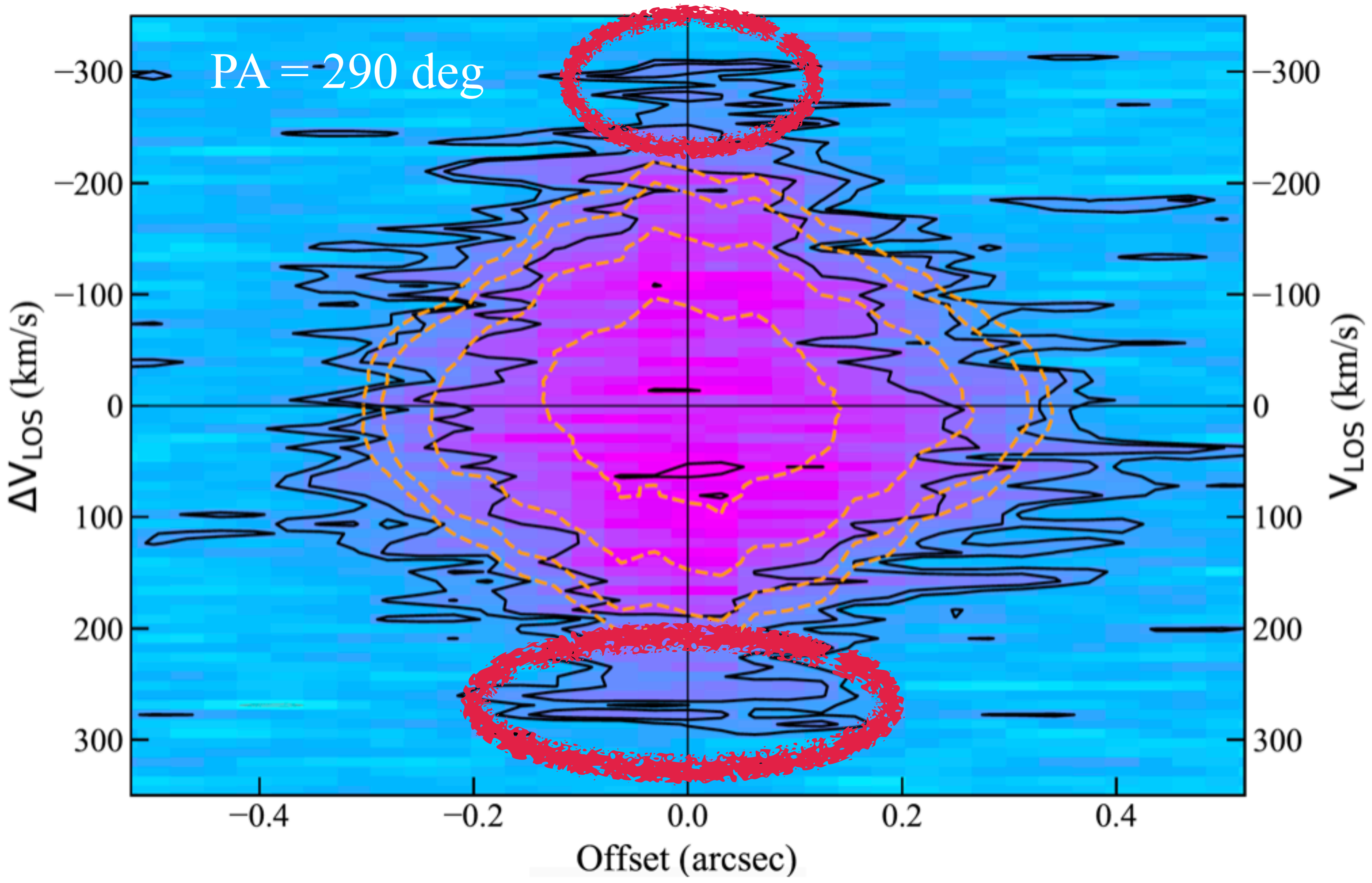
➡ $M_{\rm out} = 5\,\%\,M_{\rm disk}$

➡ $\dot{M}_{\rm out} = 1800 - 4500\ {\rm M_{\odot}yr^{-1}}$ (Barai+18)

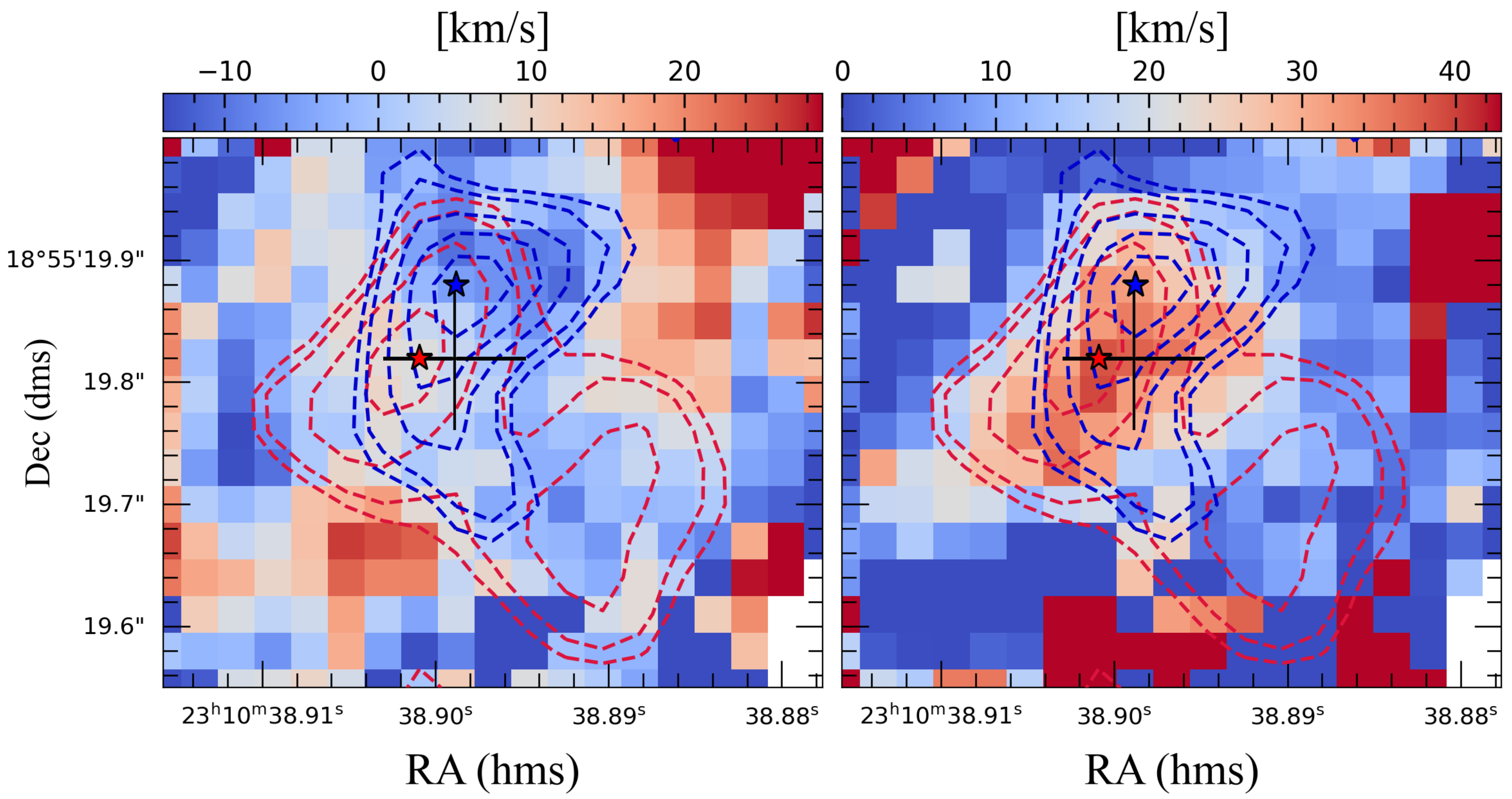
✳ Low $\dot{E}_{\rm out}/L_{\rm bol} \sim 0.0005 - 0.002$ compared to other molecular winds (Fiore+17)

(Tripodi et al., 2022)

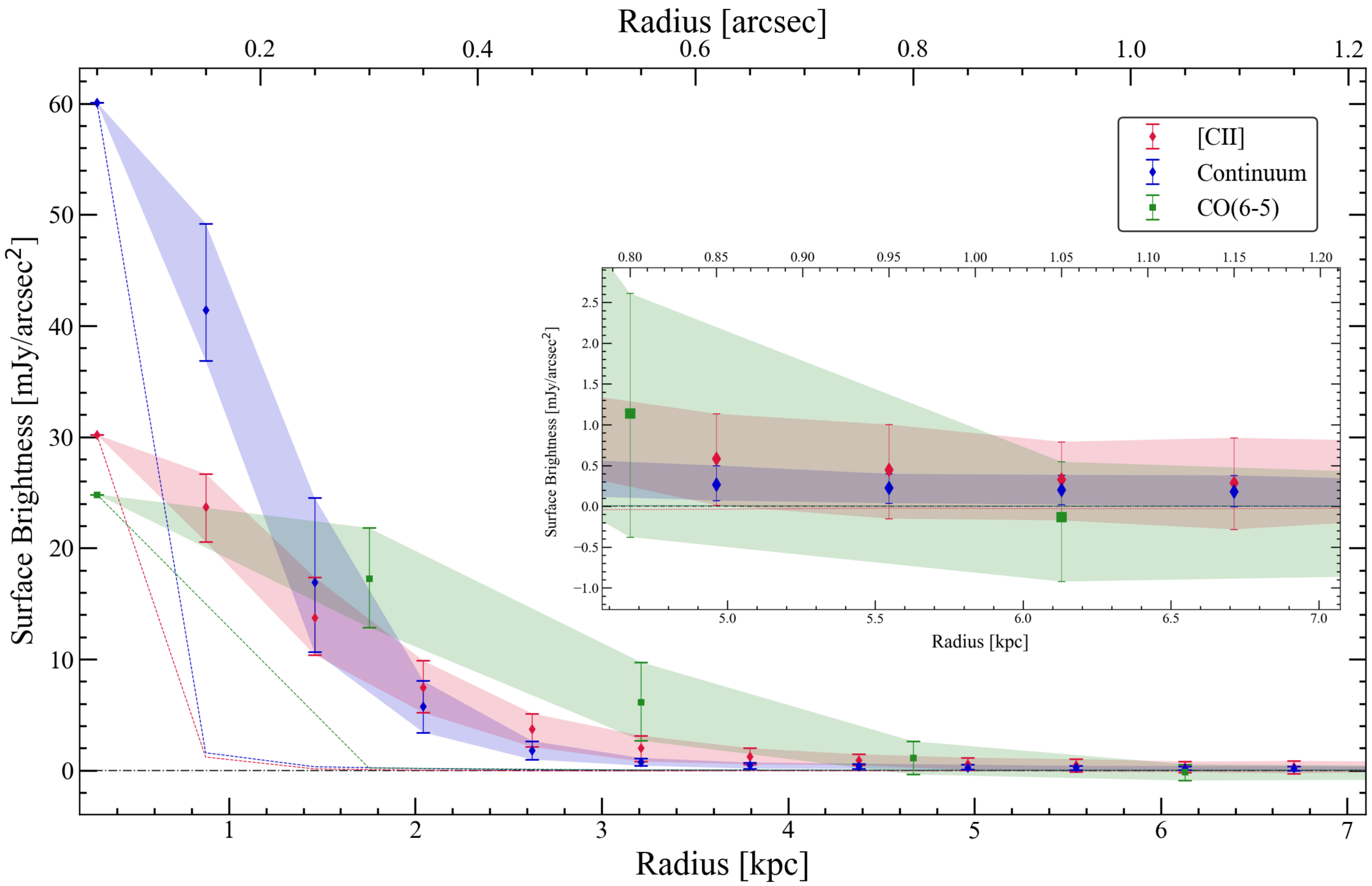




3D BBAROLO residuals for moment 1 and 2



Comparing dust and gas sizes in J2310+1855



- Surface brightness profiles in annular concentric regions

✳ Dust size (~6.7 kpc) > [CII] size (~5.5 kpc)

✳ CO(6-5) size of ~4.7 kpc, from Feruglio+18

✳ [CII] deficit in the center (Walter+22)

➡ $\Sigma_{gas} = 84\ M_{\odot} pc^{-2}$, that places J2310 above the KS relation

(Tripodi et al., 2022)

Extension to a large sample of z~6 QSOs

Sample drawn from the HYPerluminous QSOs at the Epoch of ReionizatION (HYPERION) Survey

Hyperion selection criteria:

❖ $M_{\rm SMBH} > 10^9\ M_\odot$ at $z > 6$

❖ XMM-Newton Multi-Year Heritage program (accepted in Dec 2020, 2.4 Ms)

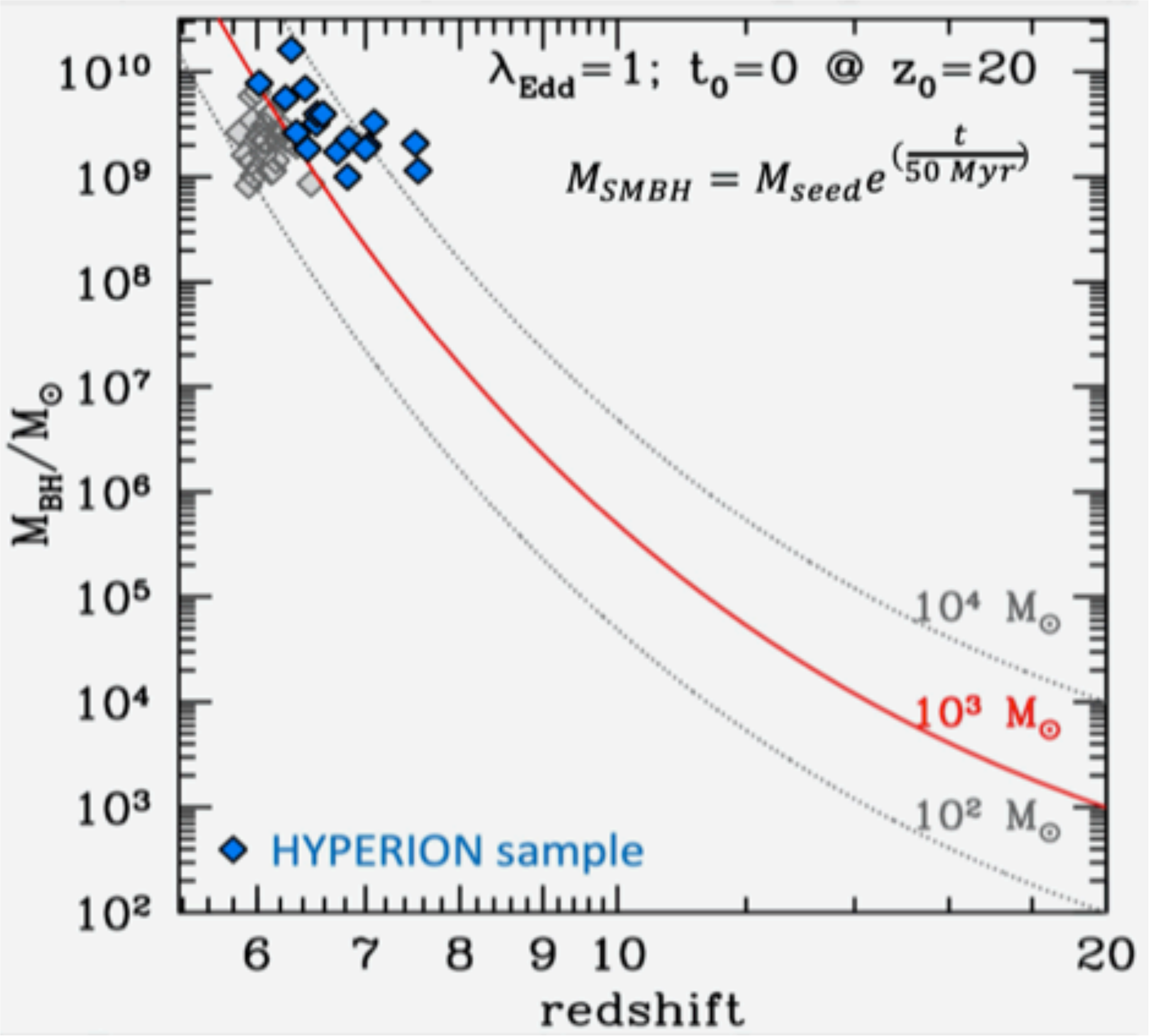
Objectives:

✓ Physics of the disk/corona complex

✓ Evolution on z and nuclear winds

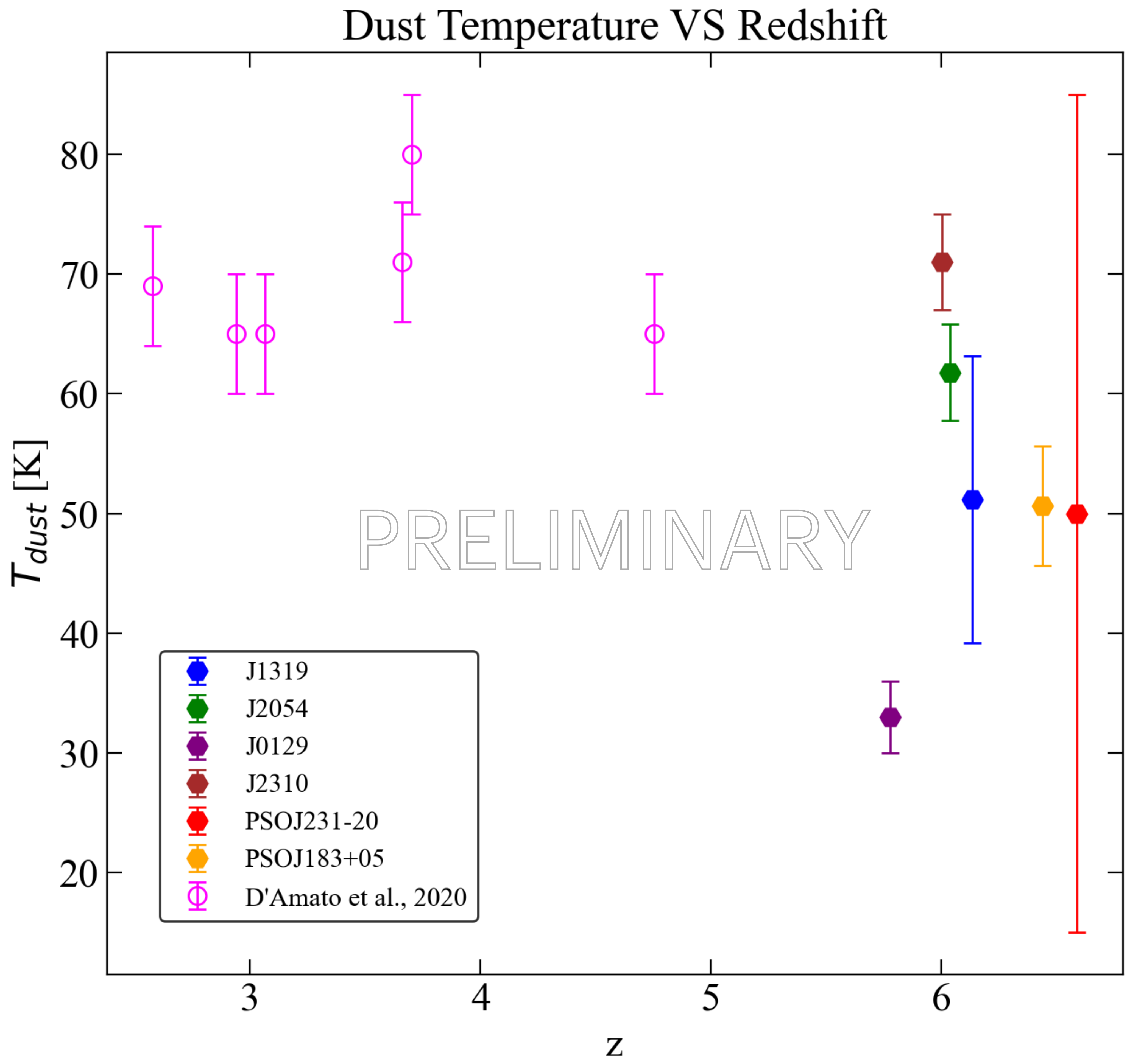
✓ Investigate the nuclear and host ISM

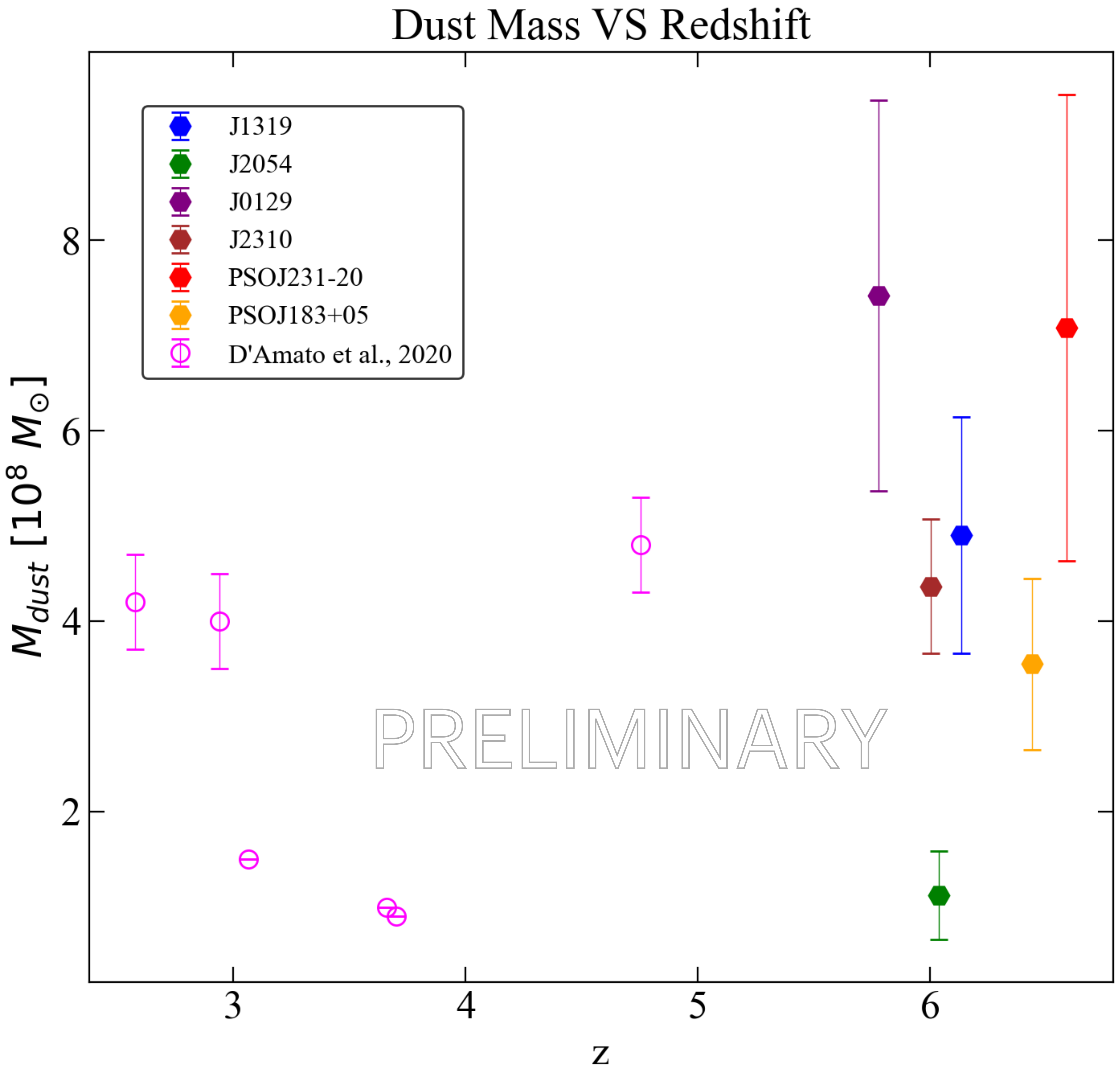
✓ Legacy sample to address with multi-λ data: SMBH formation, accretion/ejection, AGN/host formation/evolution at EoR



PI: L. Zappacosta

Dust Temperature and Mass distributions



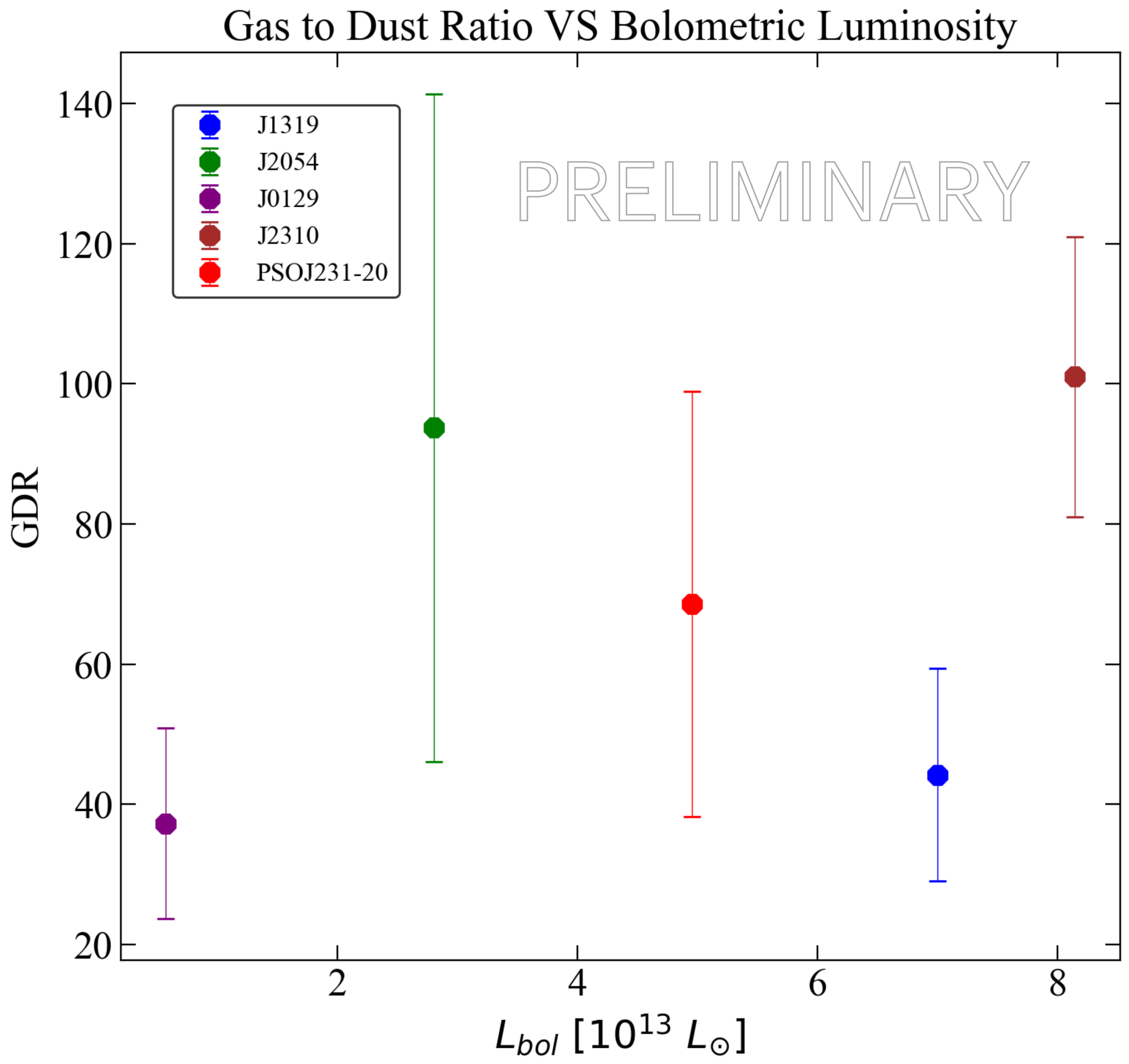


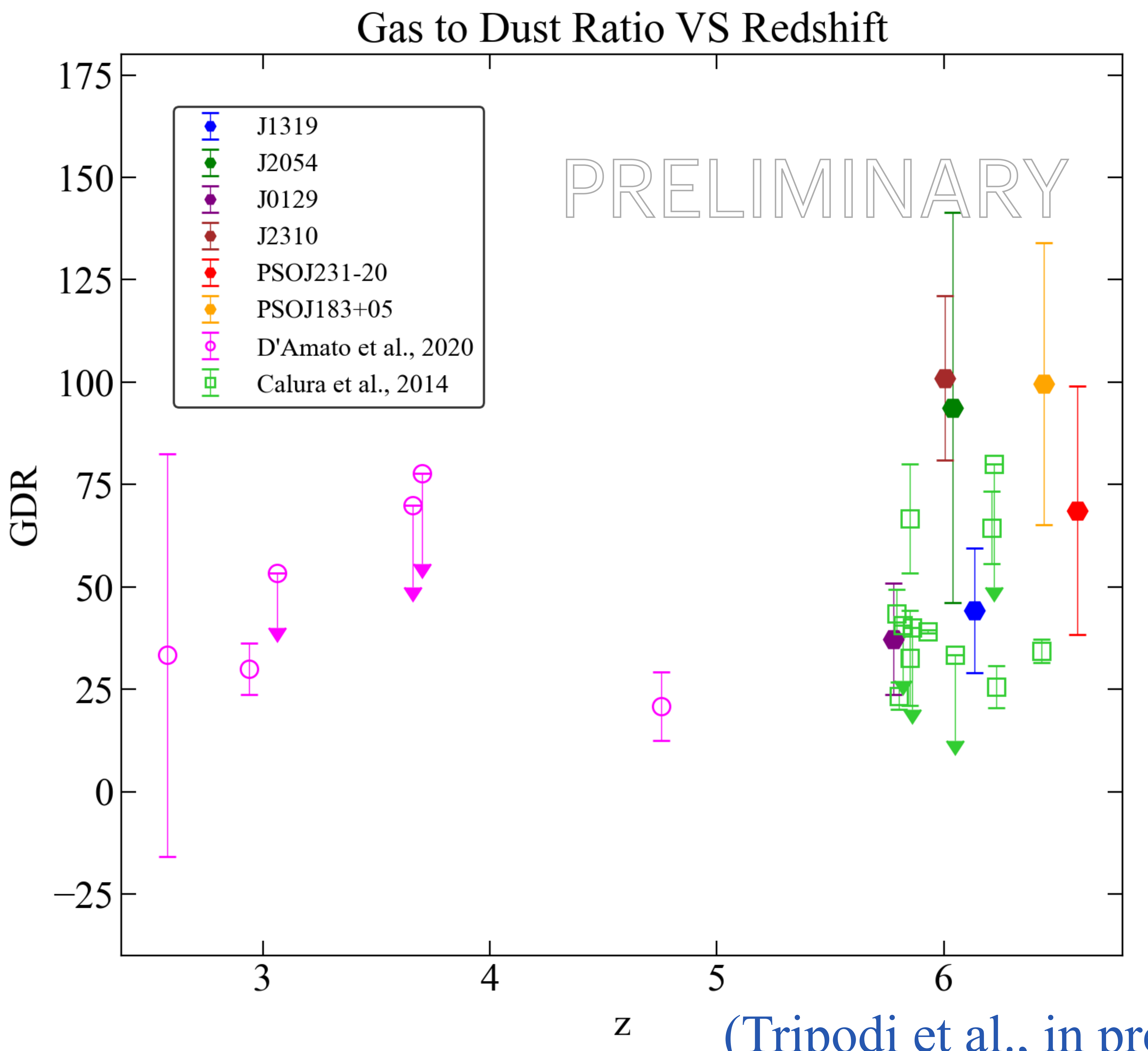
(Tripodi et al., in prep)

✦High accuracy = Accurate sampling of the distribution

✦$T_{\rm dust} \sim (30-80)$ K, $M_{\rm dust} \sim (1-8) \times 10^8$ $M_\odot$

Gas to Dust Ratio





(Tripodi et al., in prep)

- ✦ Large variation in GD ratio [30, 140] → investigation in larger sample
- ✦ Comparison with low-z samples: GD ratio almost independent of redshift