The interstellar medium and SFR of high redshift quasars/galaxies

(and GRB hosts)

Chiara Feruglio, Sexten, Jan 12, 2023

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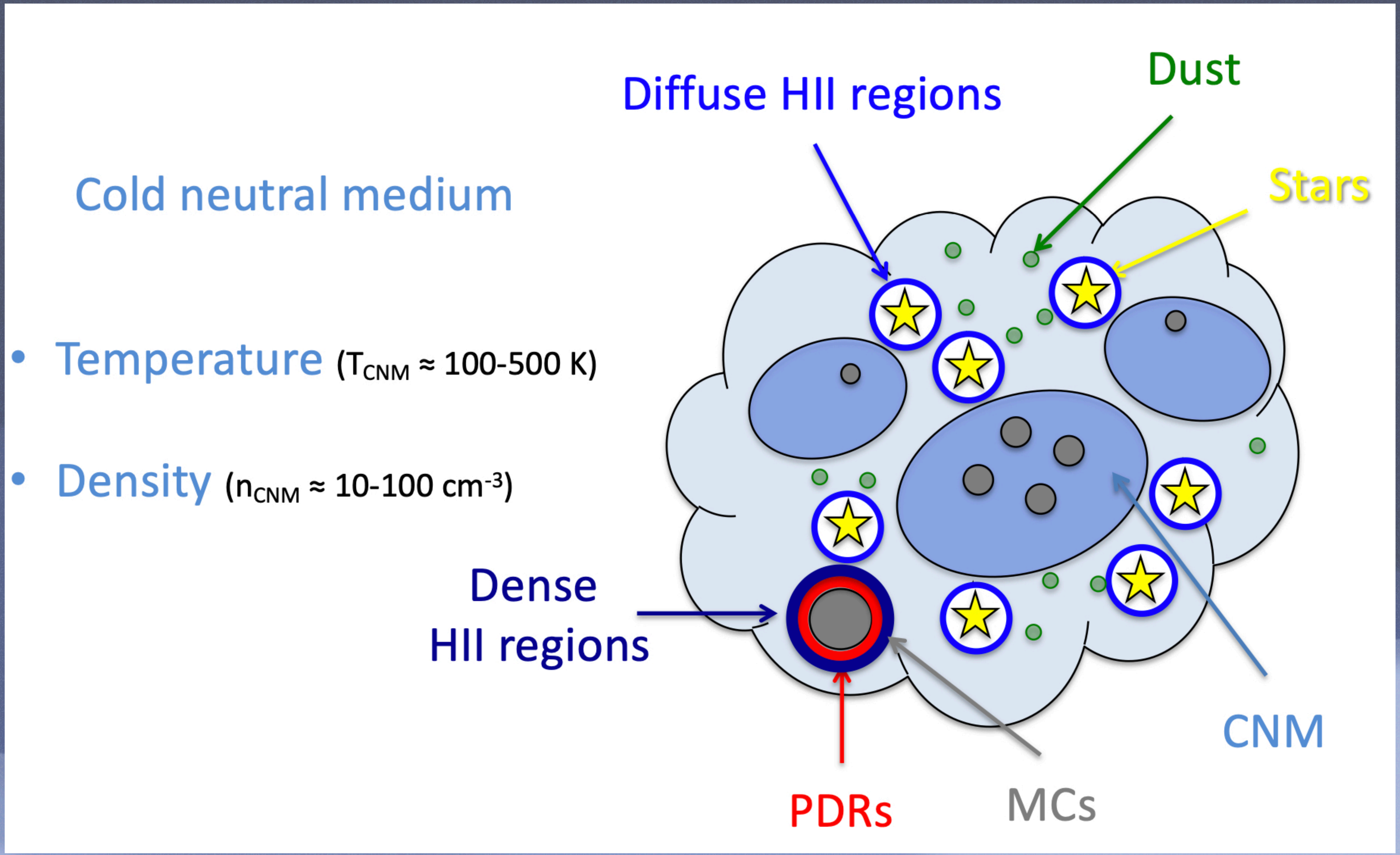
Outline

- ISM **composition and dynamics** at high redshift z>6
- Composition: molecular gas, cold neutral gas, dust
- Gas dynamics: disks, outflows
- SFR in biased systems (luminous QSOs) and normal galaxies (JWST)

ISM Composition

H2/HI & Gas-to-dust ratio along cosmic time

- a very complex environment
- Dense molecular gas
- PDR
- Cold Neutral Medium
- Dust



Courtesy S. Gallerani

ISM Composition

H2/HI & Gas-to-dust ratio along cosmic time

- Warm/cold neutral medium dominates mass and volume
- Dense molecular medium, small H

Major ISM phases in Milky Way

PHASE	Dens (cm^{-3})	T (K)	VFF (%)	M ($10^9 M_o$)	H (pc)
Hot Intercloud (HIM)	0.003	10^6	?50	?	3000
Warm Ionized Medium (WIM)	0.1	8000	25	1	1000
Warm Neutral Medium (WNM)	0.5	8000	30	2.8	220
Cold Neutral Medium (CNM)	50	80	1	2.2	100
Molecular Clouds	>200	>10	0.05	1.3	75
HII Regions	$1\text{-}10^5$	10^4	-	0.05	70

MASS OF THE STARS= $10^{11} M_O$

Courtesy C. Ceccarelli

ISM Composition

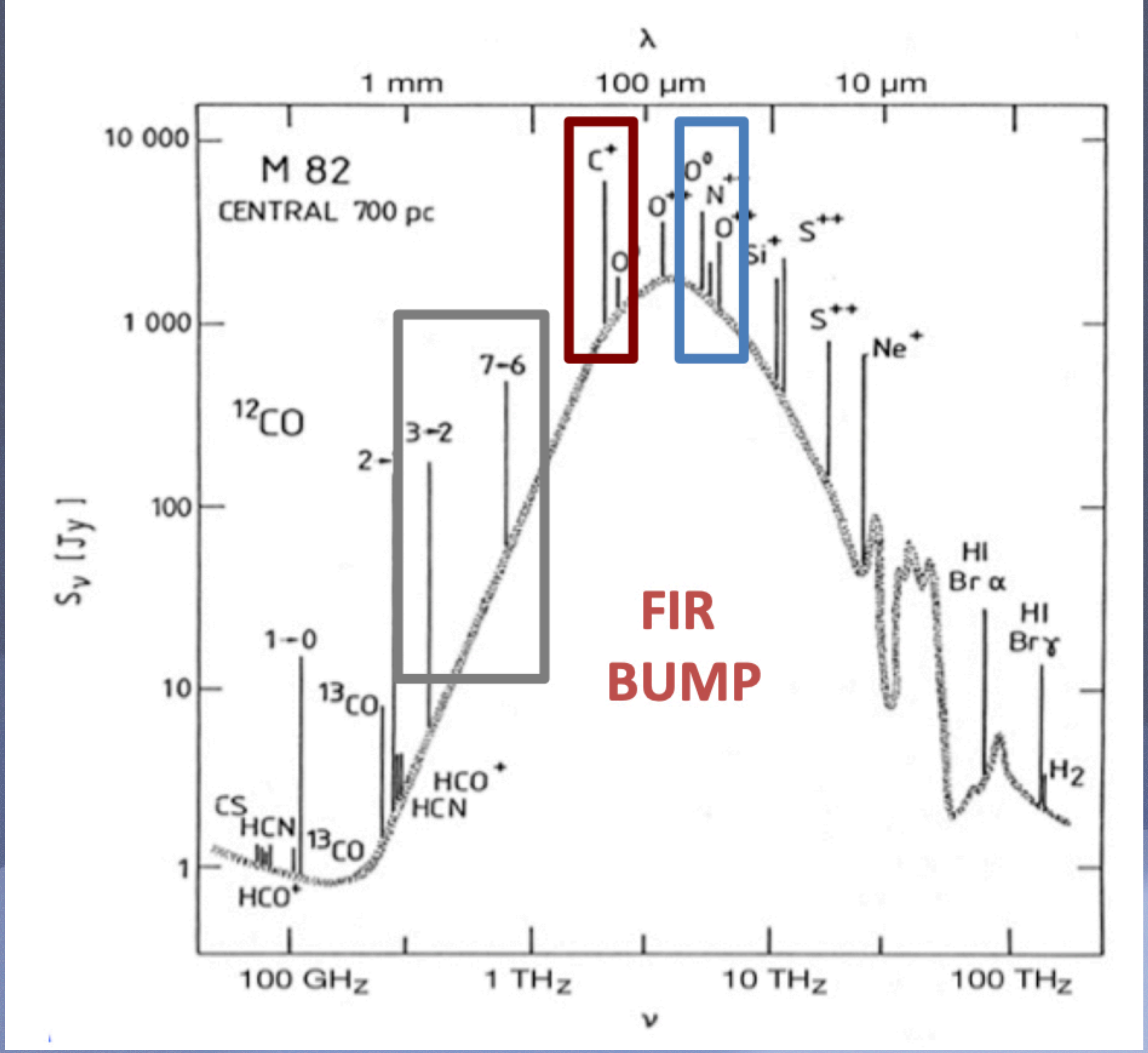
Cold gas at high redshift

Cold molecular

Cold atomic

warm ionised

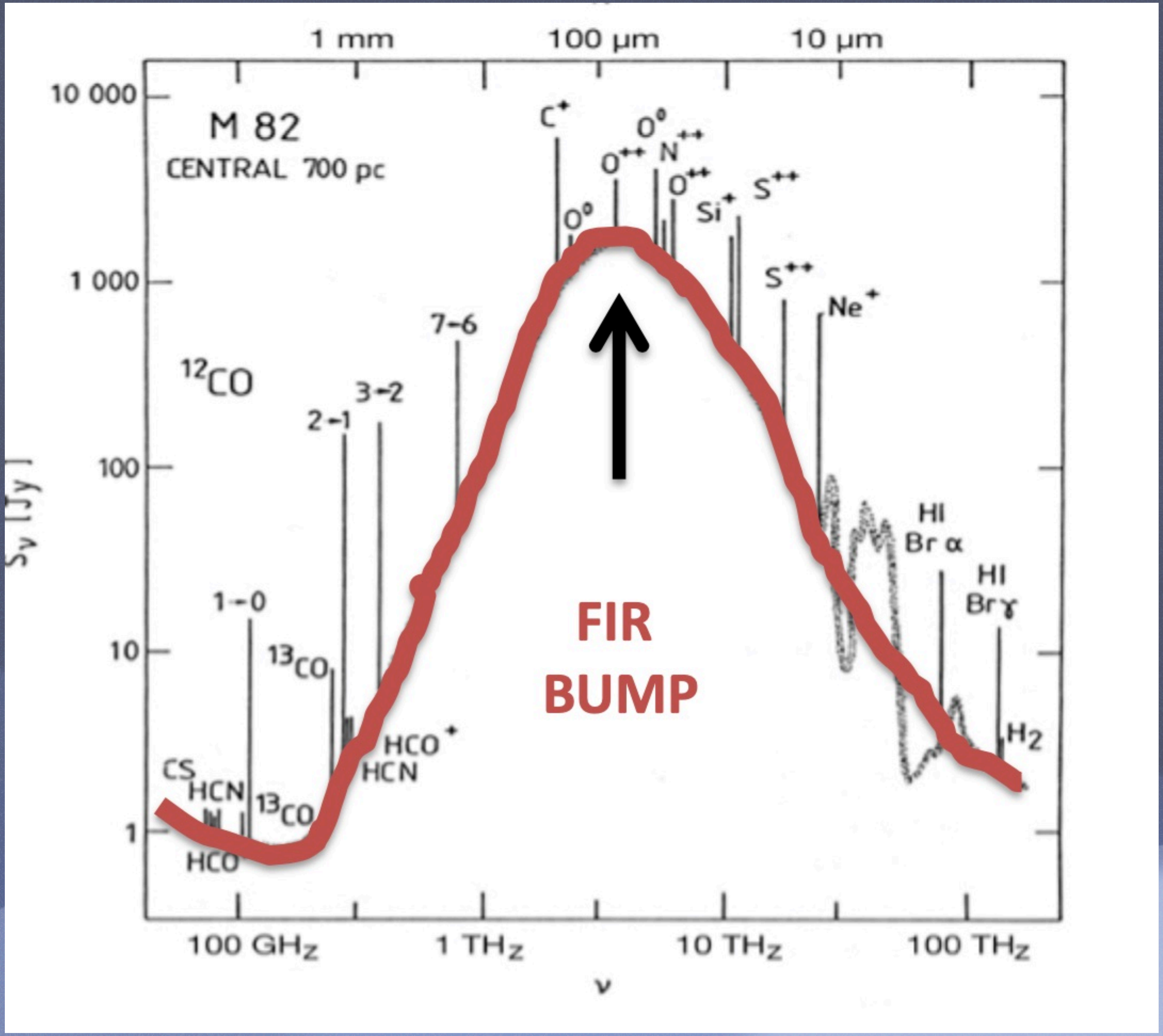
- main coolants submm/ FIR emission lines
- CO (J->J-1) @J*115GHz
- [CI] @369um
- [CII] @158um (11.3 eV)
- [NII] @205um (14.5 eV)
- [OIII] @88um



Courtesy S. Gallerani

ISM Composition
Cold dust

- FIR - submm continuum
- Dust mass & emissivity
- Dust Temperature
- Star formation rate

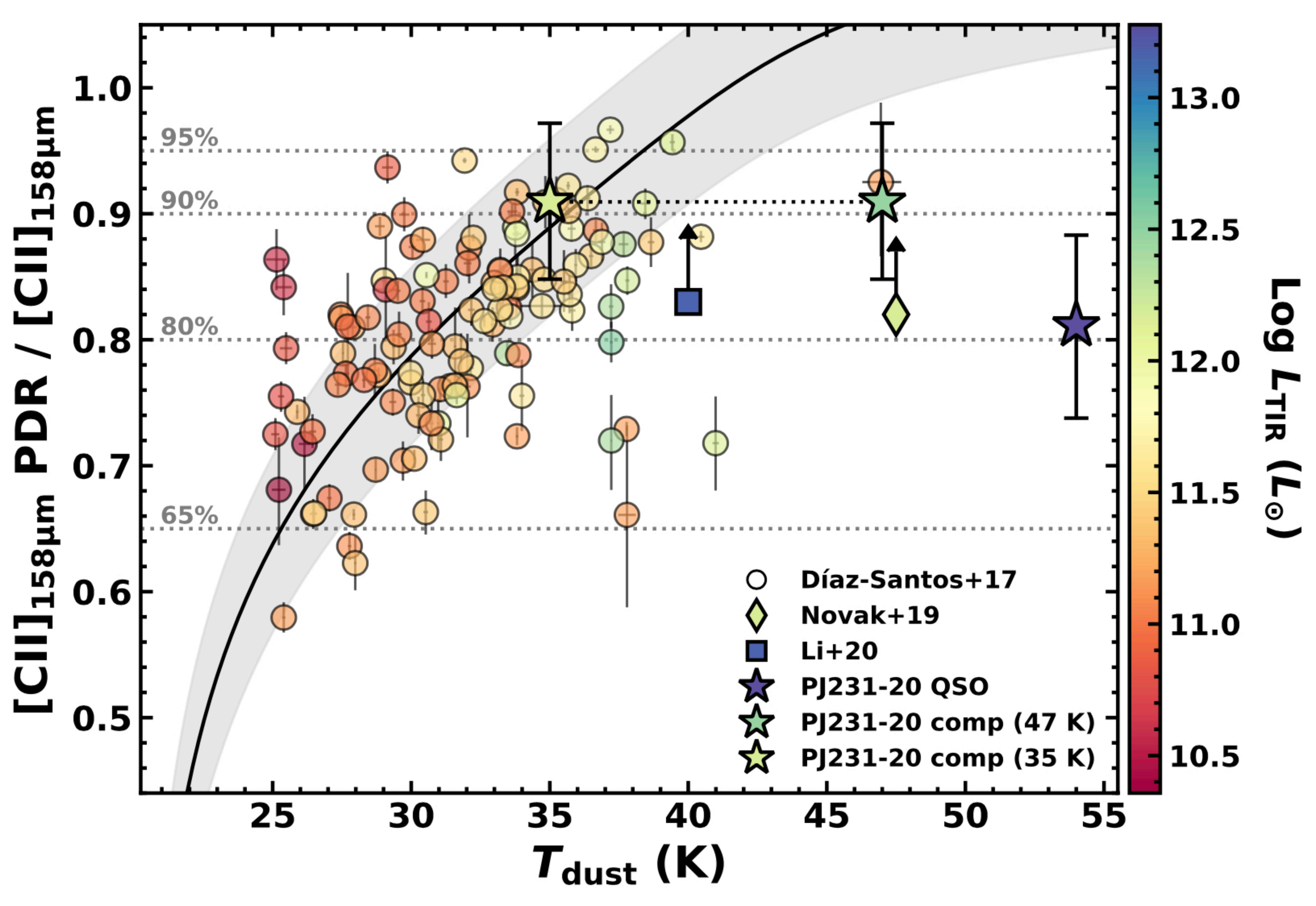


Courtesy S. Gallerani

ISM Composition

Atomic gas in z>6 QSO hosts

- [CII] 158 um emission line main ISM coolant
- ionisation potential 11.3 eV
- ~80% from neutral ISM (cold neutral medium and PDR, Kauffman+1999, Pensabene+21)
- ~20% diffuse ionised medium (Carral et al. 1994; Lord et al. 1996; Colbert et al. 1999, Decarli20,22).



Pensabene+21

ISM Composition

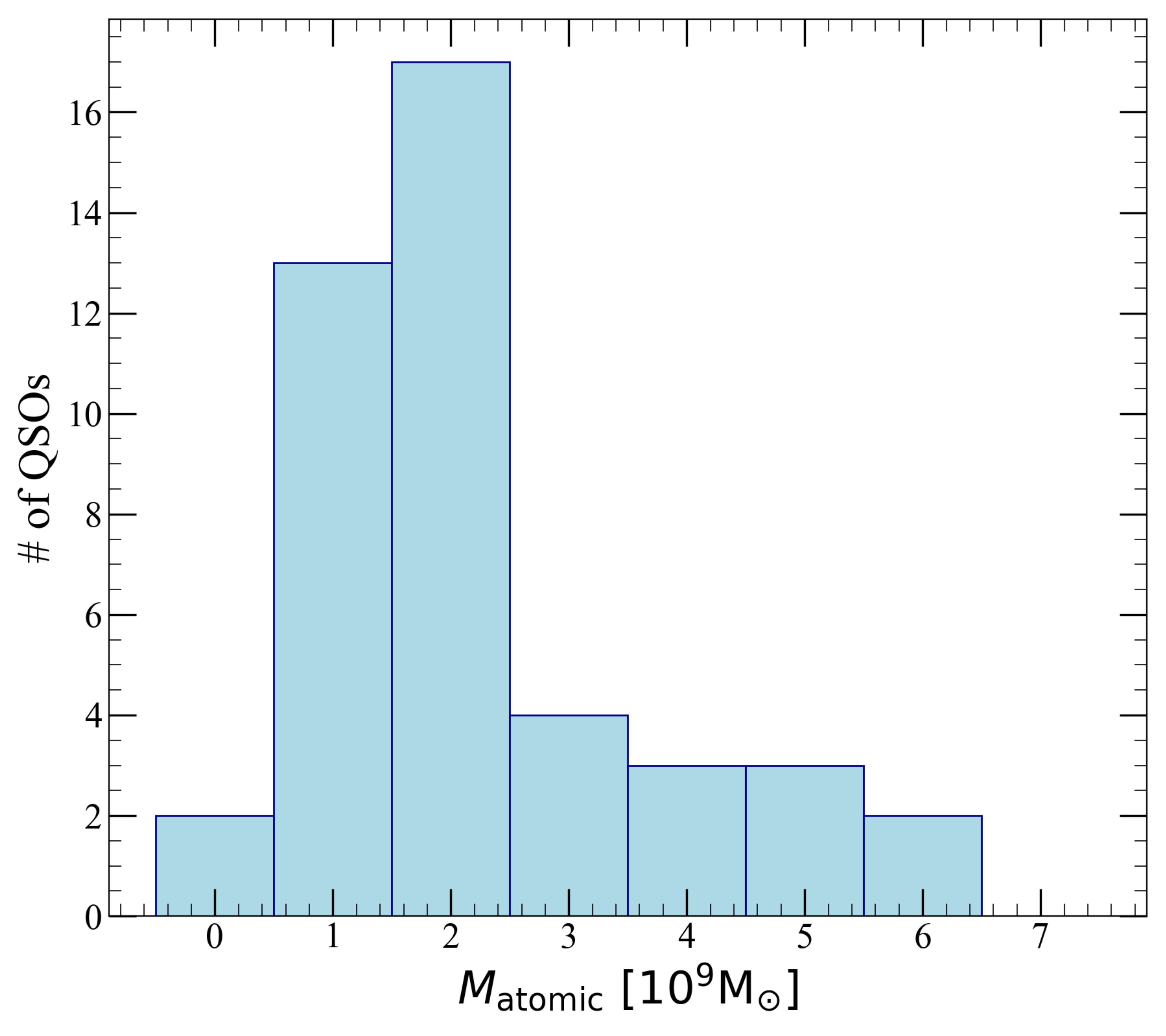
Atomic gas in z>6 QSO hosts

- HI reservoirs at high redshift from [CII] (Hailey Dunsheath+2010)

$$\frac{M_a}{M_\odot} = 0.77(\frac{0.77 L_{[CII]}}{L_\odot})(\frac{1.4 \times 10^{-4}}{X_{C+}}) \times \frac{1 + 2exp(-91K/T) + n_{crit}/n}{2exp(-91K/T)}$$

$$X_{C+} = 1.4 \times 10^{-4} \qquad n_{crit} = 2.7 \times 10^3 cm^{-3}$$

- surface temperature of PDR with n=10^4 cm^{-3} and $G_0=10^{3.2}$ is T=230K (Kaufman1999, Decarli+22 for high z quasars)

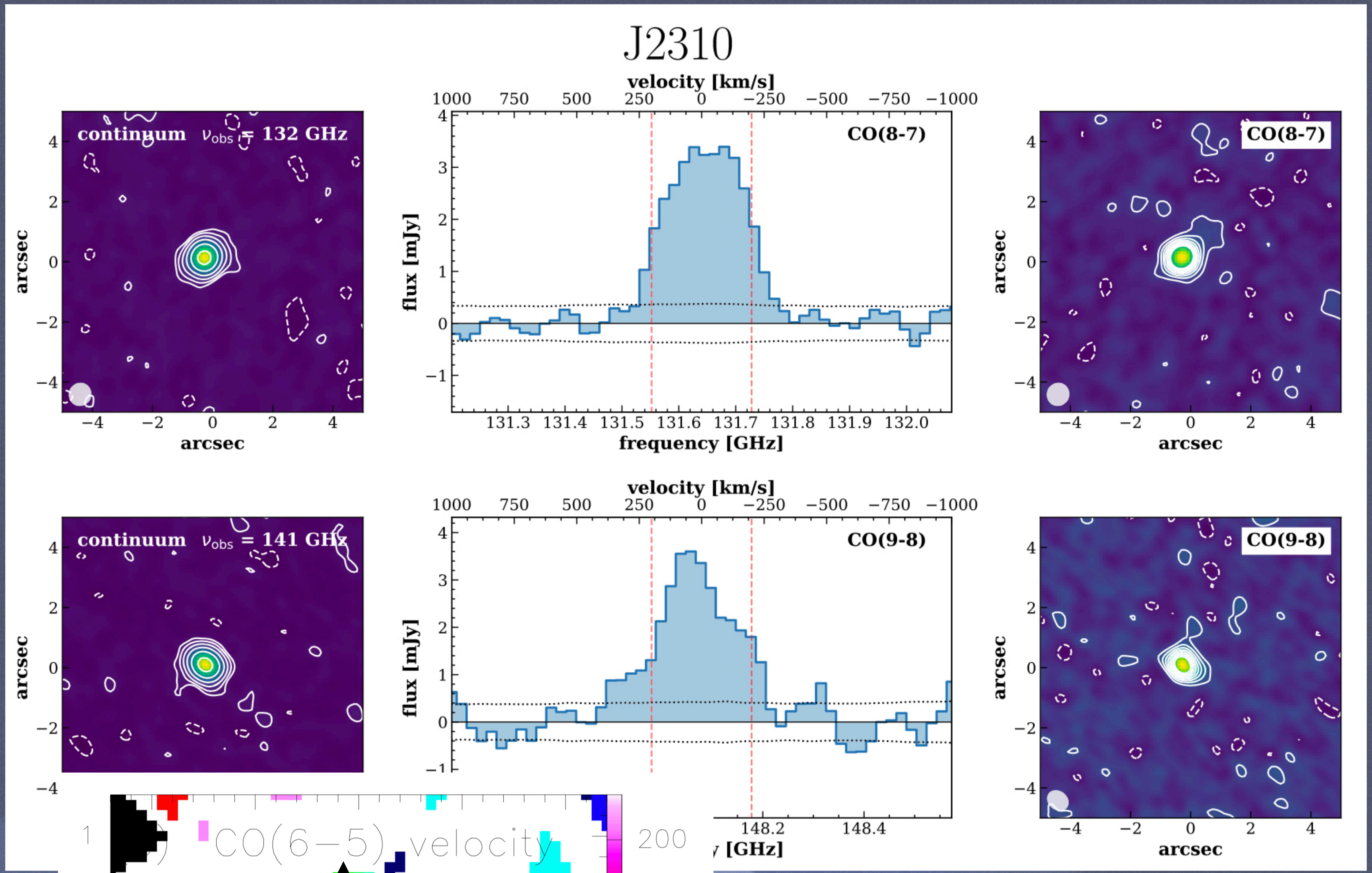


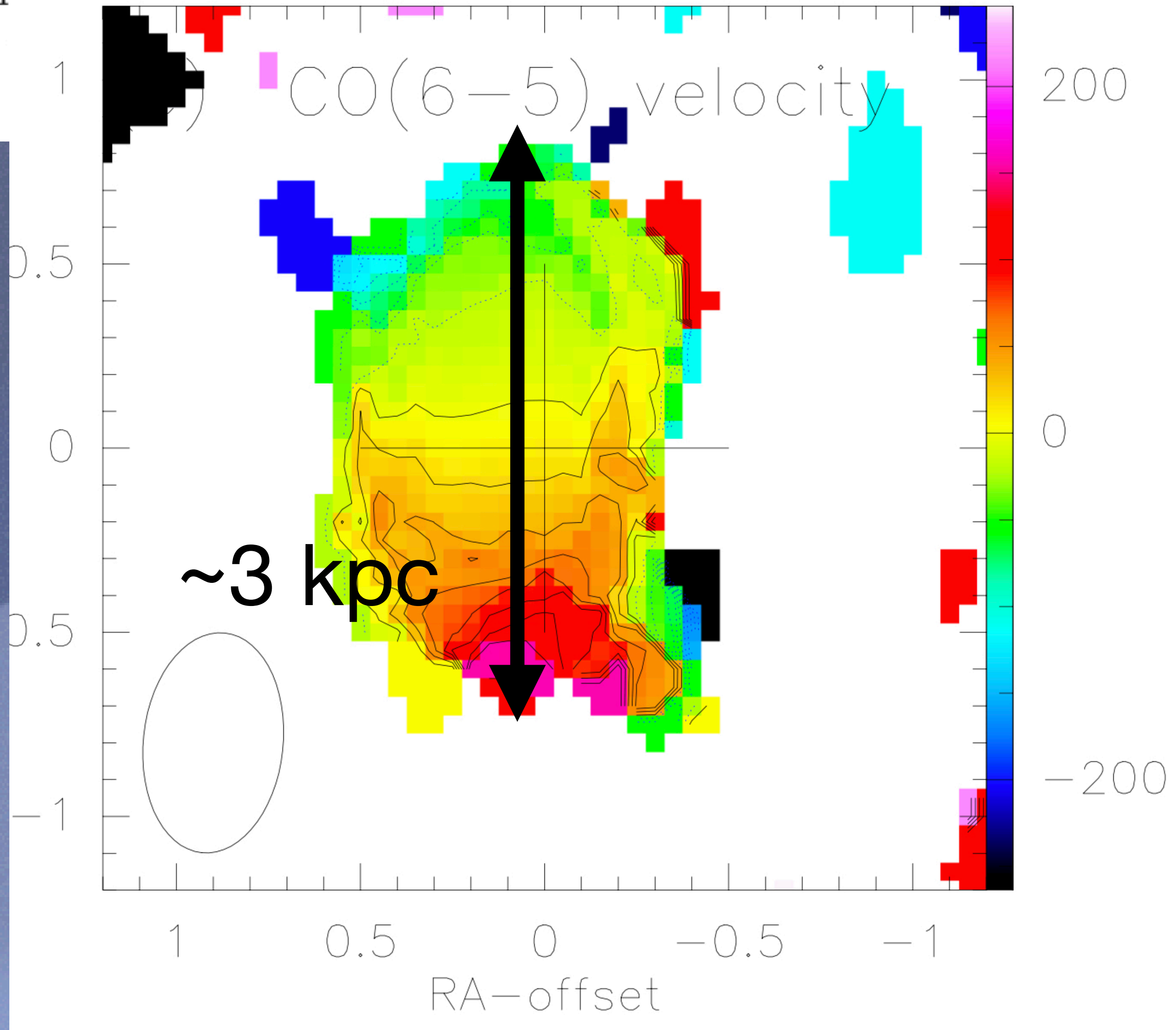
ISM Composition

H_2 in z>6 QSO hosts

- Cold dense gas/ Star formation reservoir traced by CO
- CO fainter than [CII]
- few tens CO detections
- Traces massive molecular reservoirs of 10^{10} - 10^{11} $M_\odot$ over few kpc
- Large molecular gas fractions $\mu = M(H_2)/M_* \sim 4$

(Feruglio+2018, LI+2022)

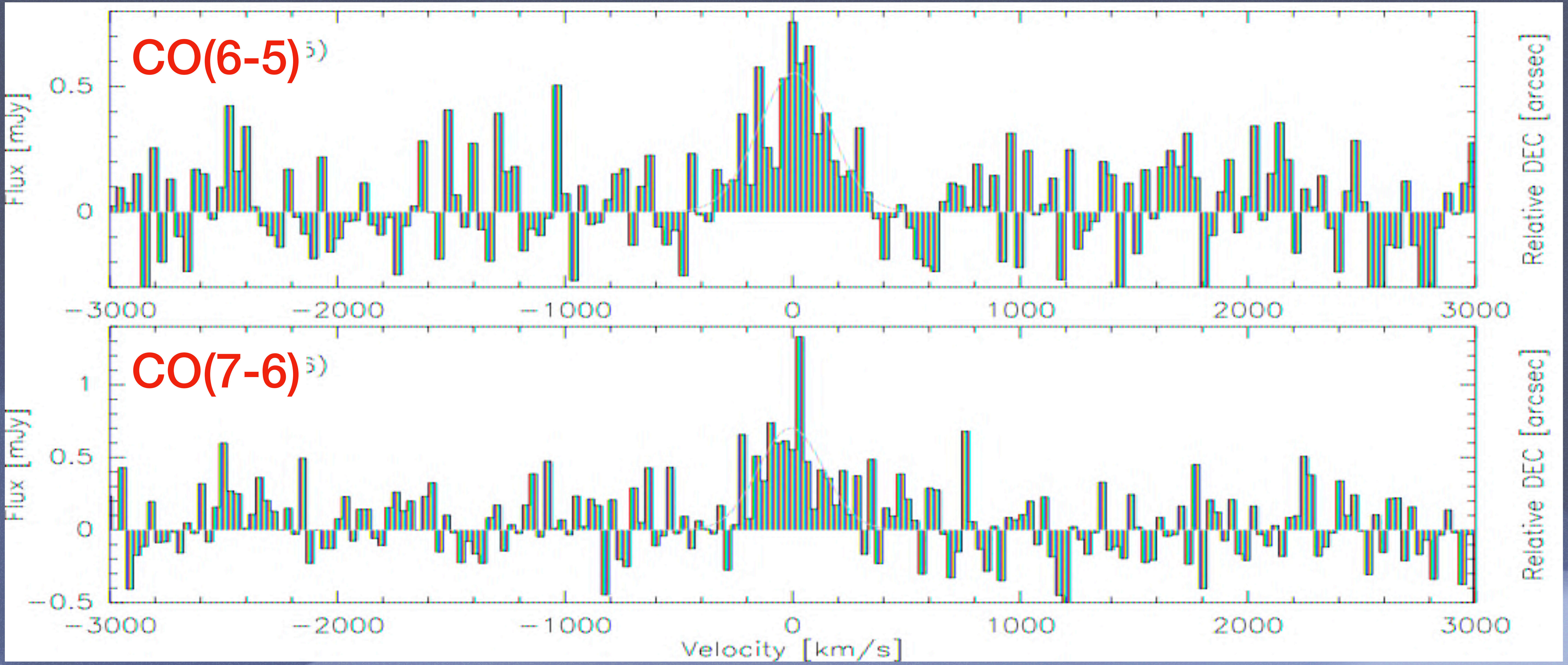




ISM Composition

H2 in z=7.5!! QSO Pōniuāʻena

- highest z CO detections to date obtained with NOEMA
- massive H_2 reservoir $M(H_2)=1.2\ 10^{10}\ M_\odot$
- $t_H \sim 700$ Myr
- Similar to z~6 molecular reservoirs

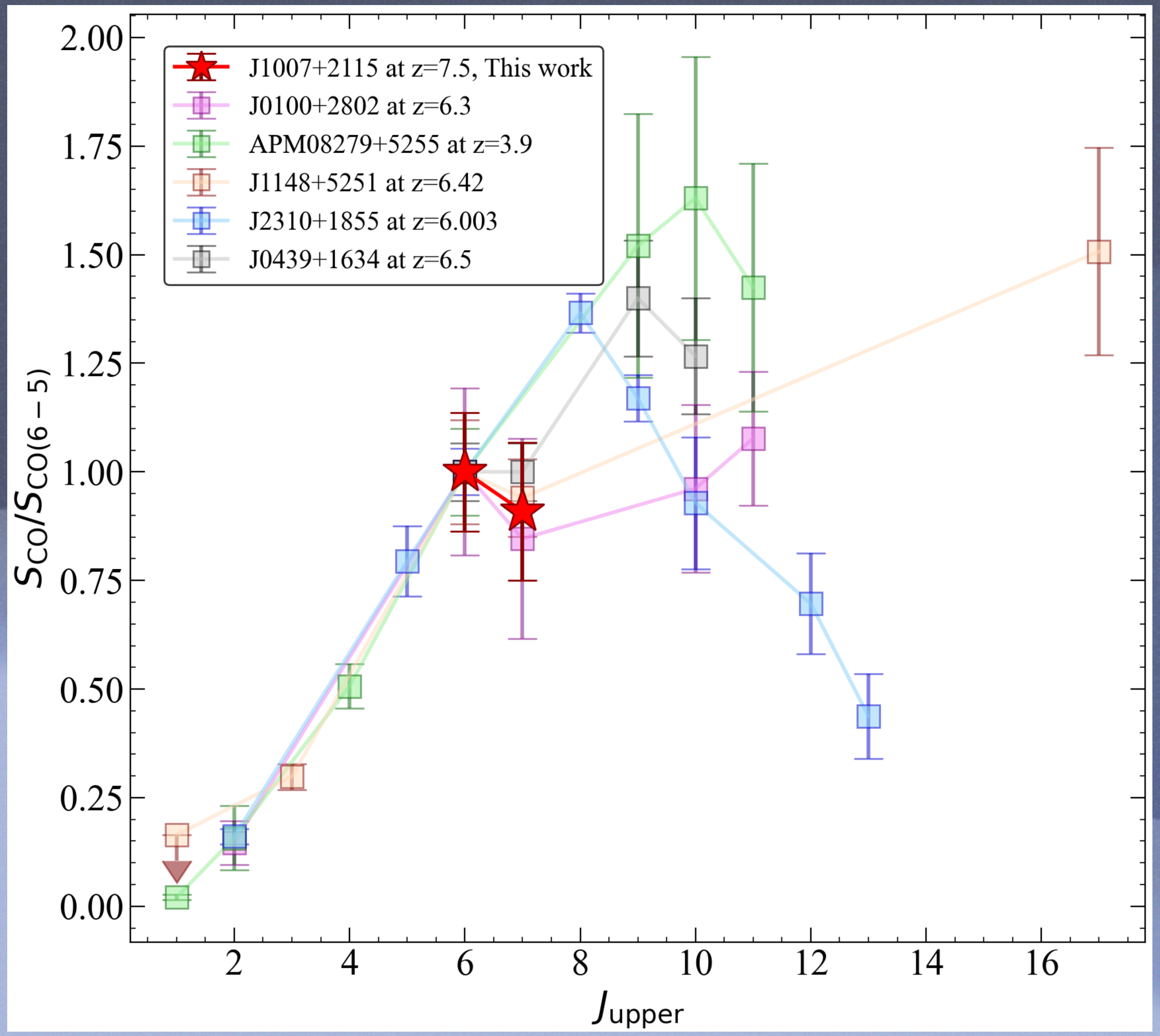


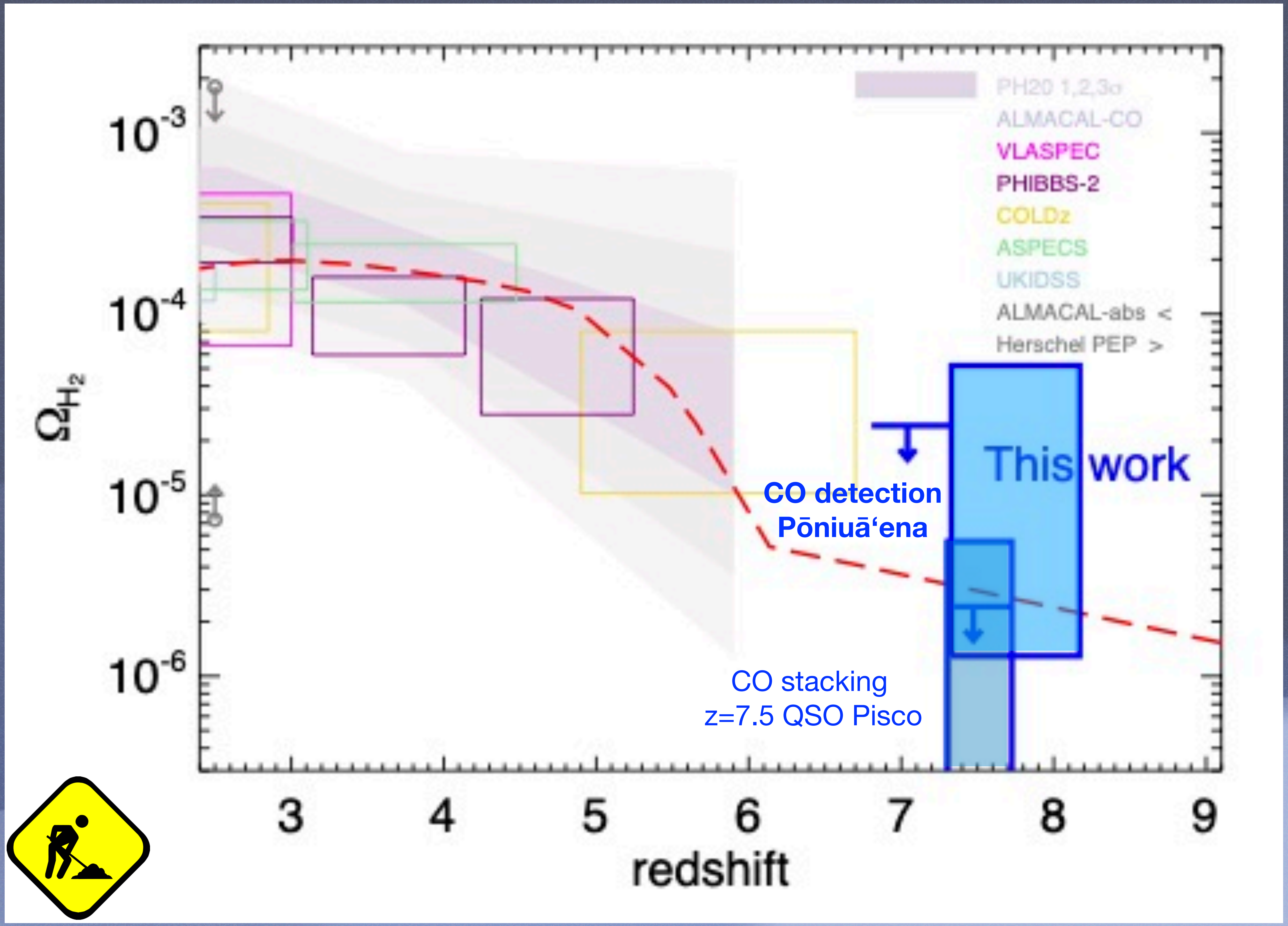
Feruglio in prep.

ISM Composition

The cosmic density of H2 at z=7-8

- Ω_{H_2} consistent with model predictions (Maio+2022)



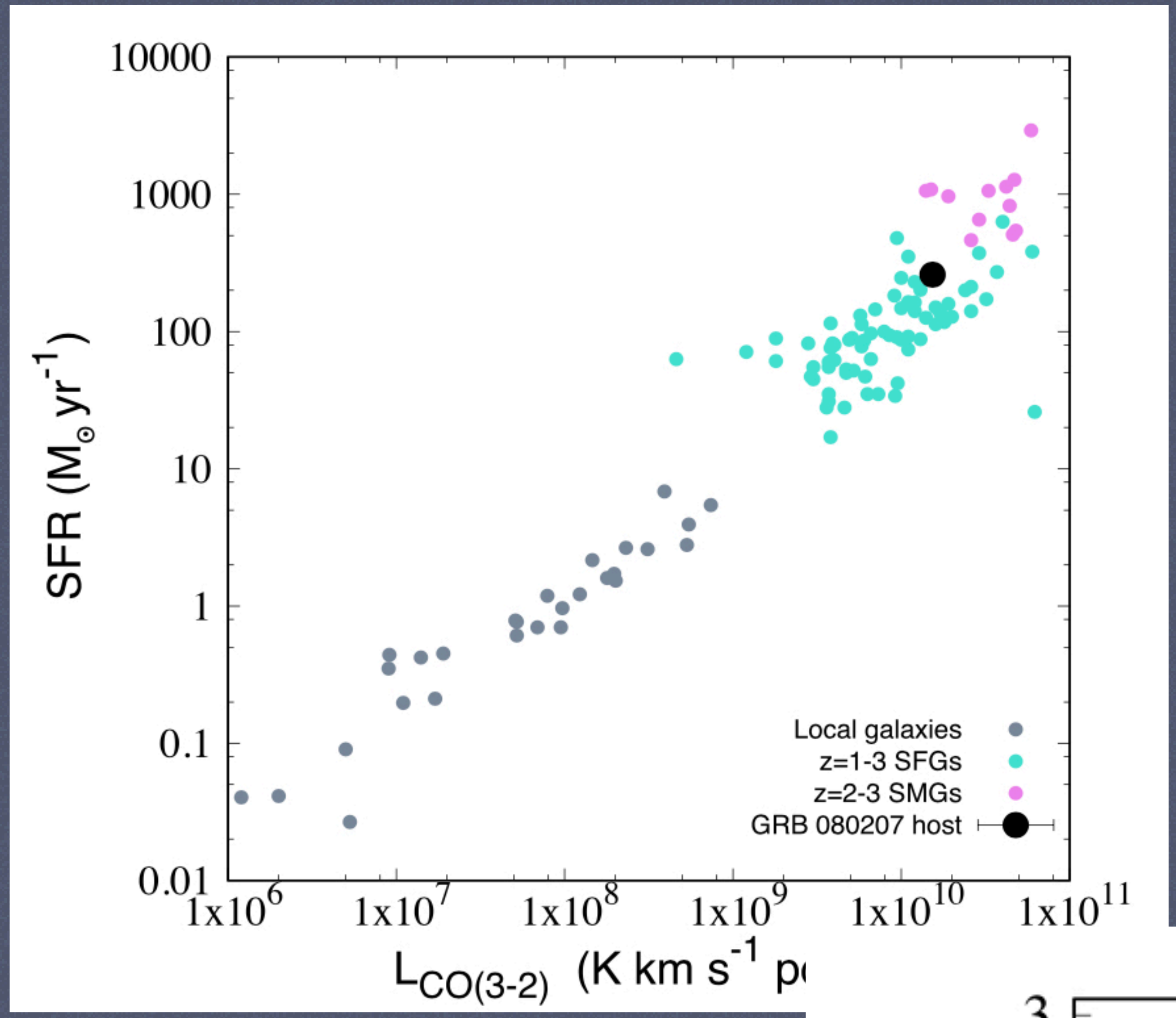


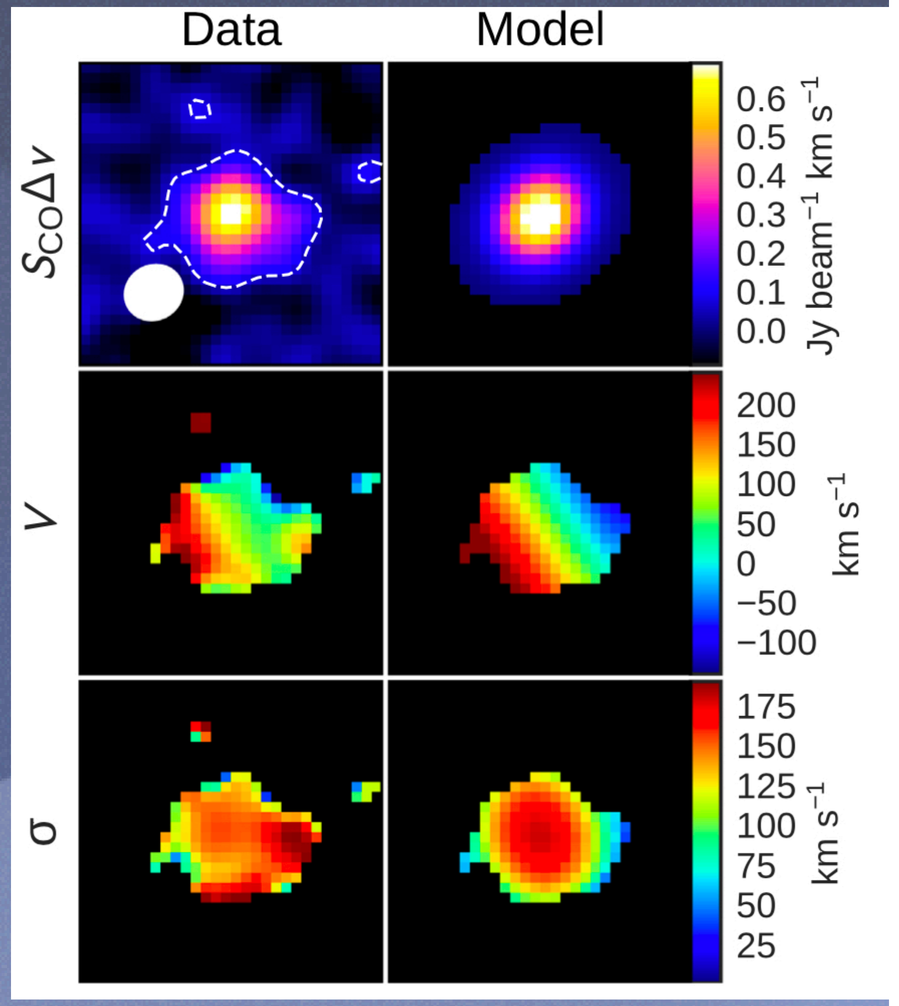
Feruglio, Tripodi, Maio, in prep.

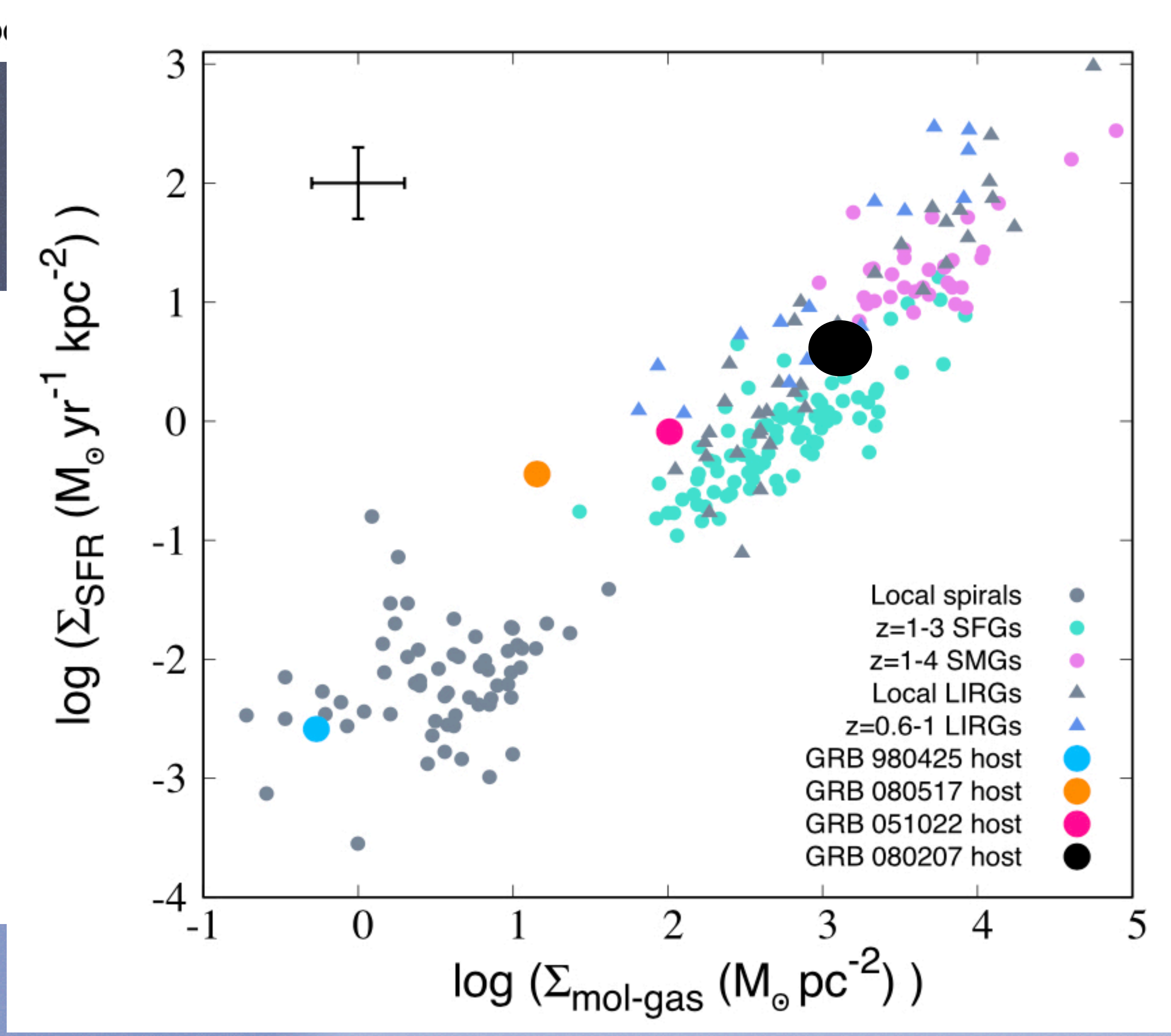
ISM Composition

GRB 080207 host galaxy z~2

- Massive H2 reservoir, in a SF disk galaxy , $M(H_2) \sim 10^{11}$ Msun
- About solar metallicity
- Consistent with SK relation for galactic CO luminosity to mass conversion factor
- long GRB can occurr in normal SF disk environements at z~2
- Arabsalmani+2018 (see also Hatsukade+2019)
- Mdust = 1.5e8 MSun
- GDR~600







ISM Composition

GRB 080207 host galaxy z~2

- Massive H2 reservoir, in a SF disk galaxy , M(H2)~10^{11} Msun
- ~solar metallicity
- Consistent with SK relation for galactic CO luminosity to mass conversion factor
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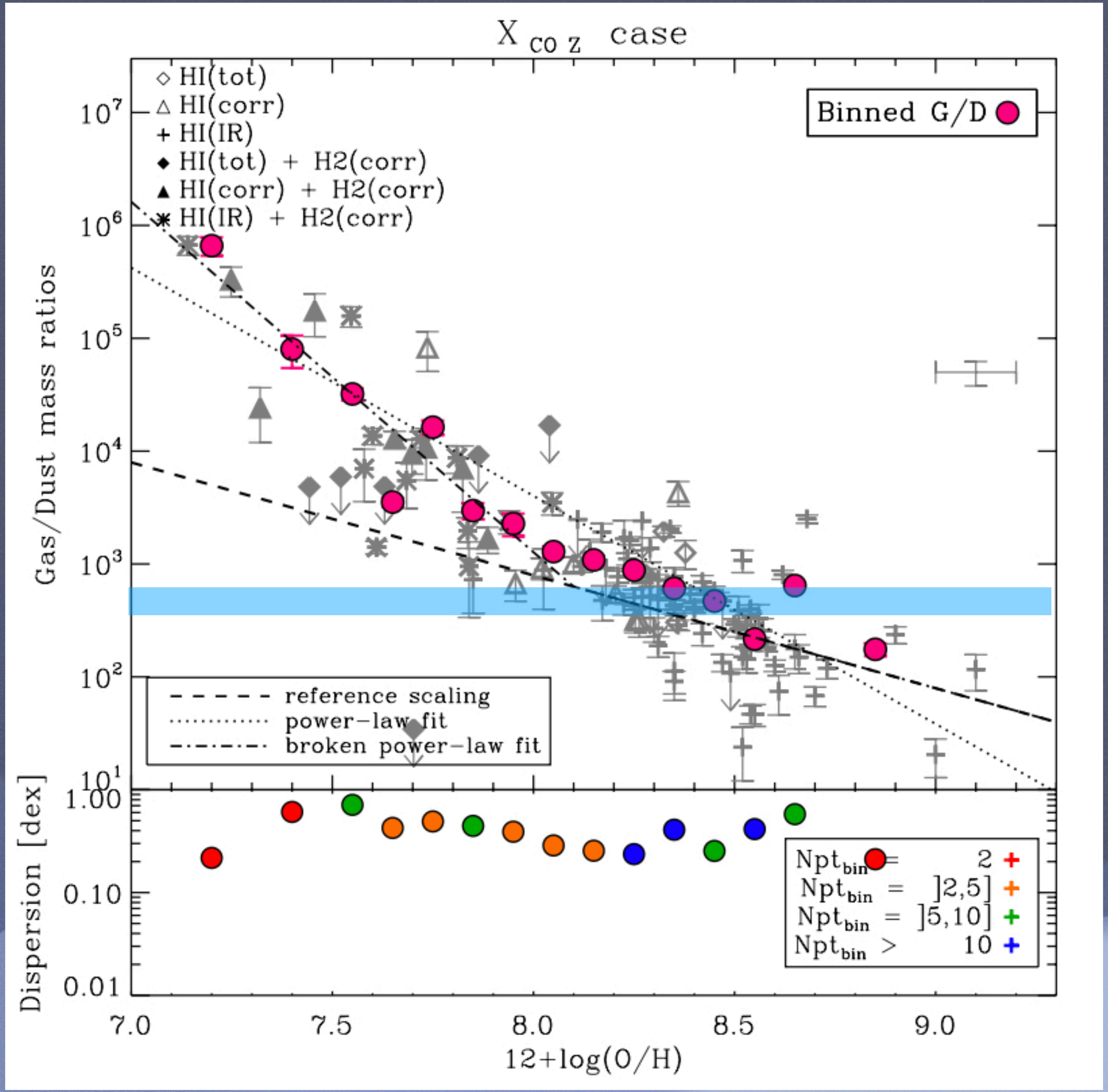
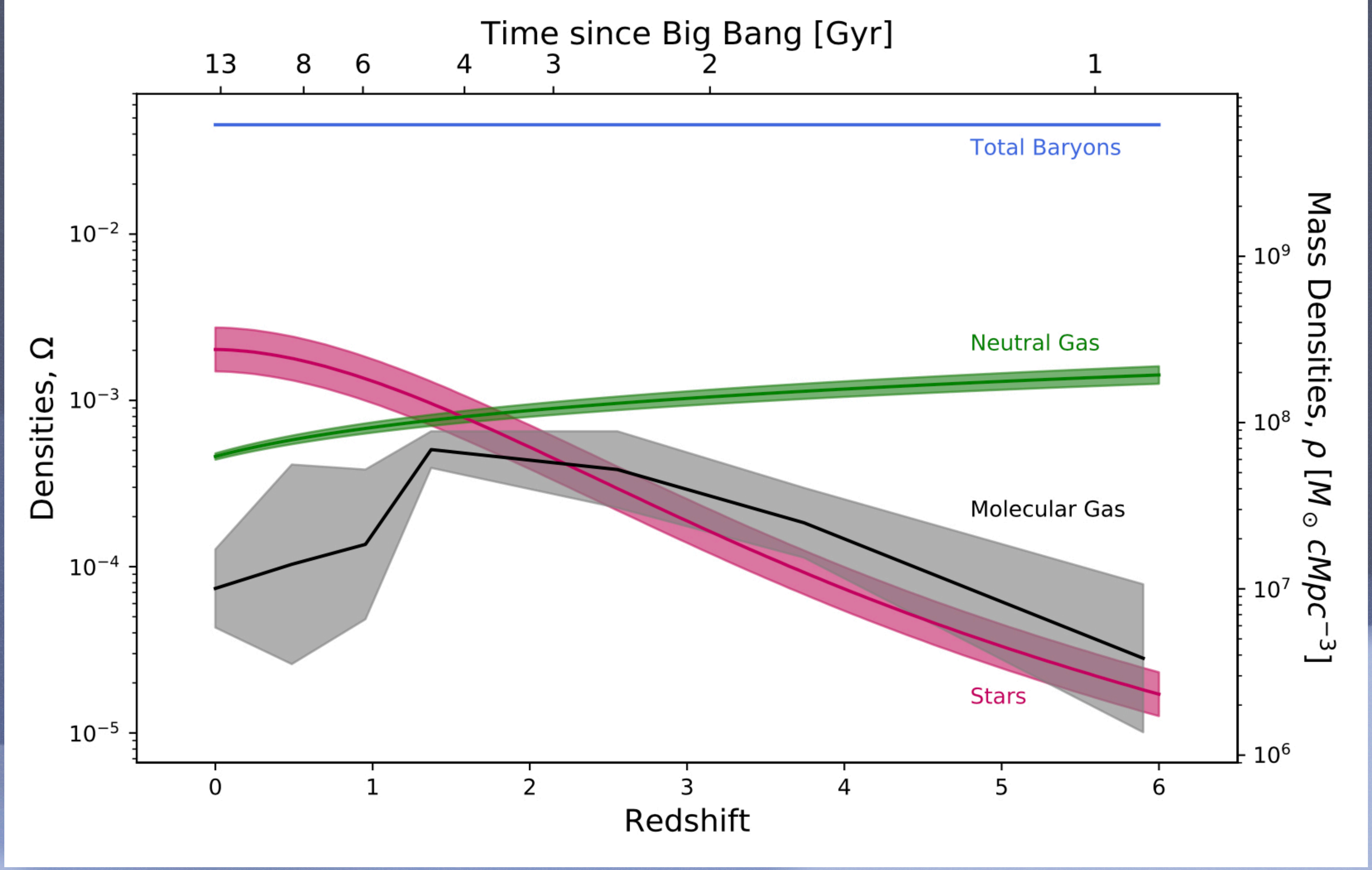


Remy-Ruyere+2014

ISM Composition

H2/HI mass ratio in z>6 QSO hosts

- Neutral gas >> molecular gas at all redshifts (Peroux&Howk2020)
- Considering ISM+CGM+IGM
- Within galaxies neutral gas is negligible at high redshift (Tacconi+2020)



ISM Composition

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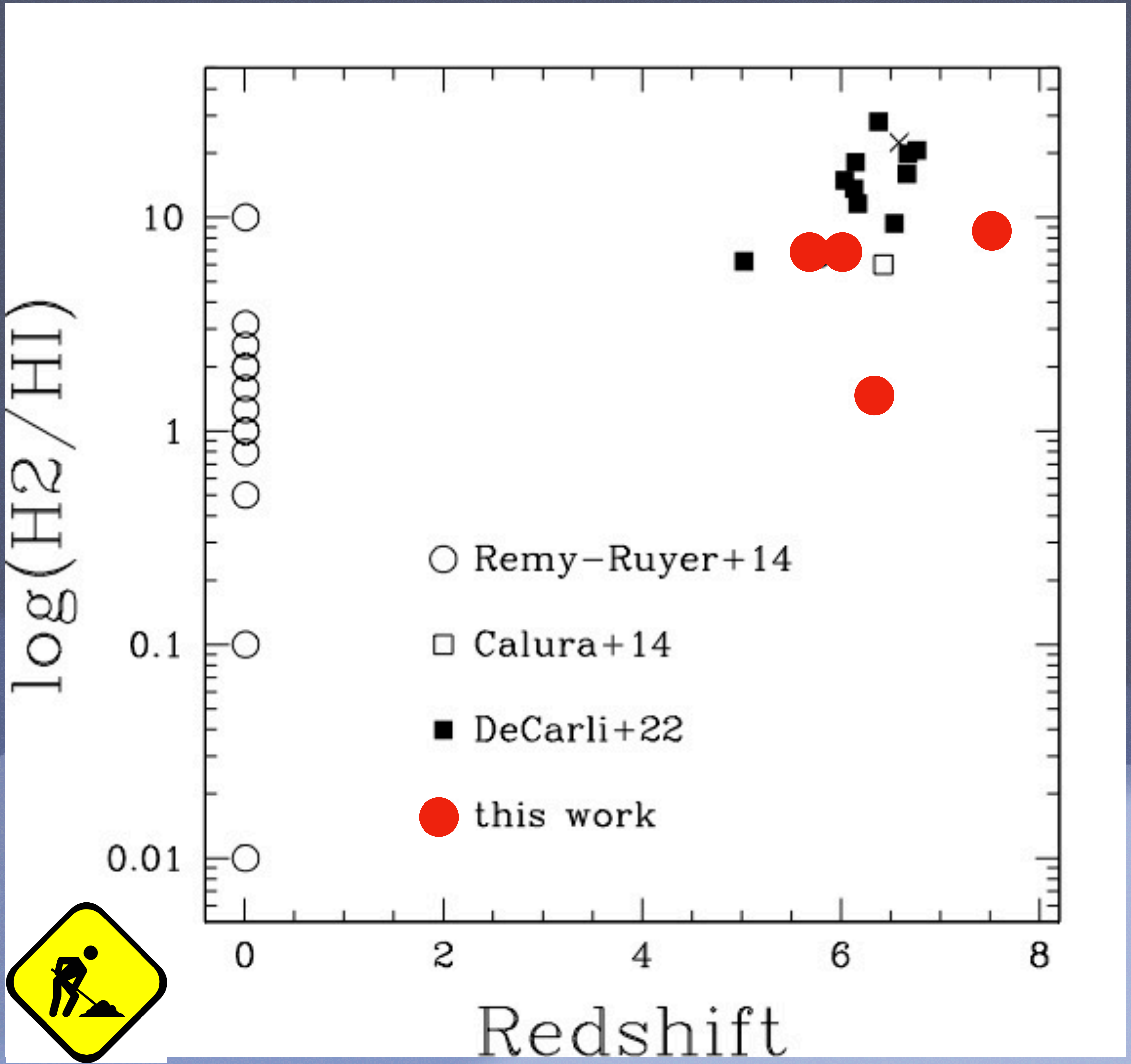


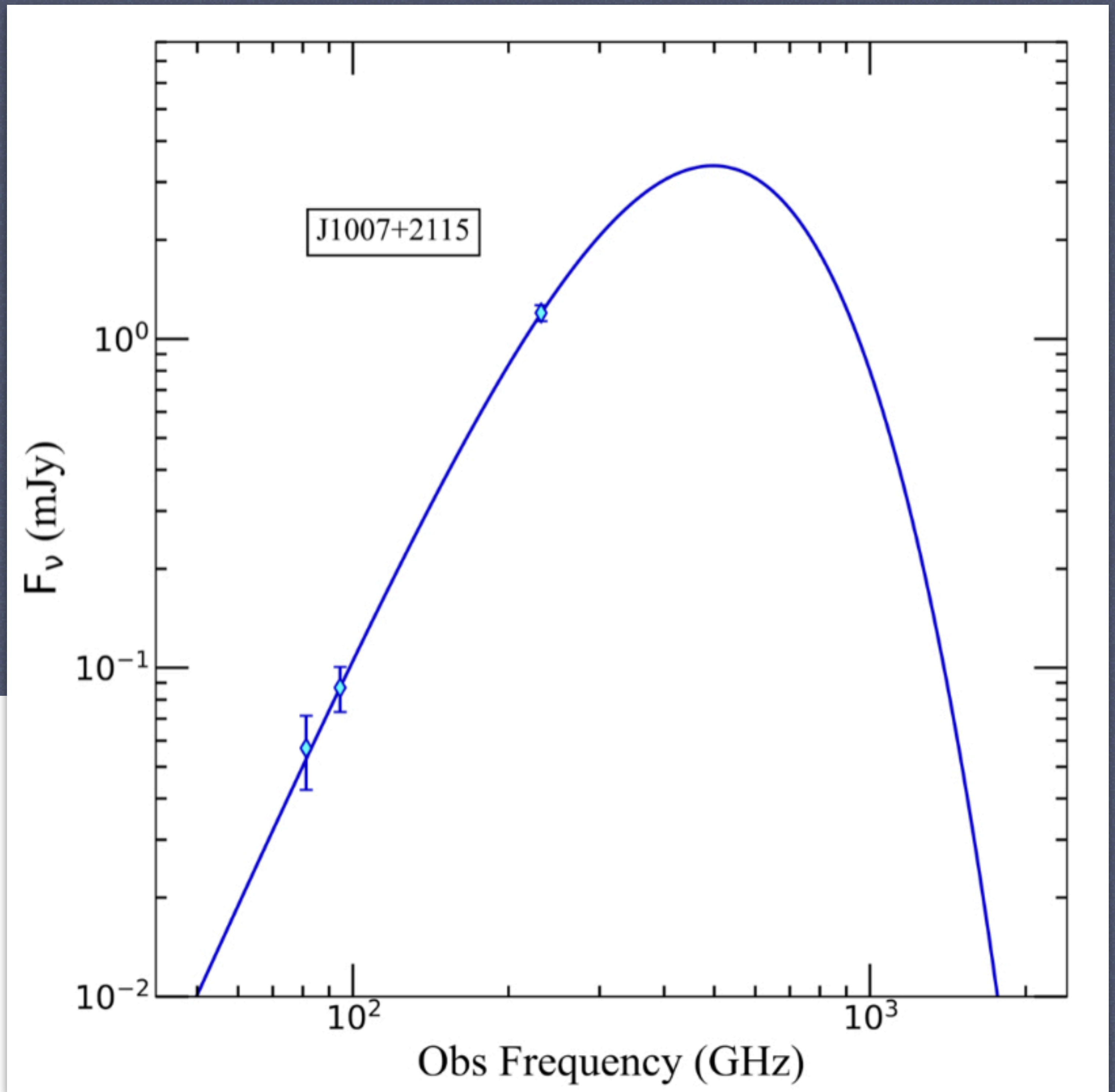
ISM Composition

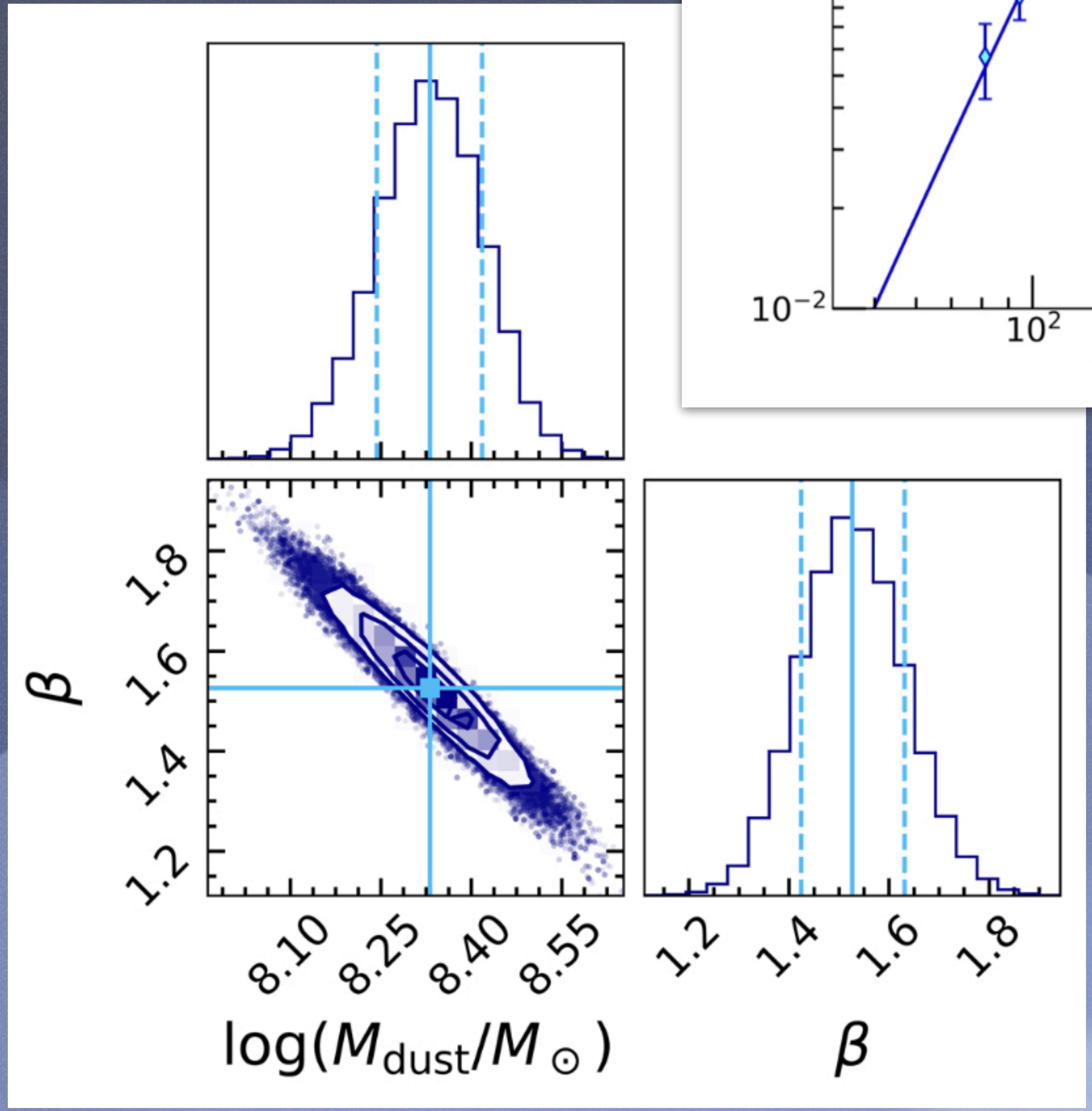
Dust in z>6 QSO hosts

- Pōniuā'ena QSO @z=7.5
- 3 continuum data points on RJ tail, tight constraints on Mdust and emissivity index

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

$$\tau_\nu = \frac{M_{\mathrm{dust}}}{A_{\mathrm{galaxy}}} k_0 \left(\frac{\nu}{250\ \mathrm{GHz}}\right)^\beta$$

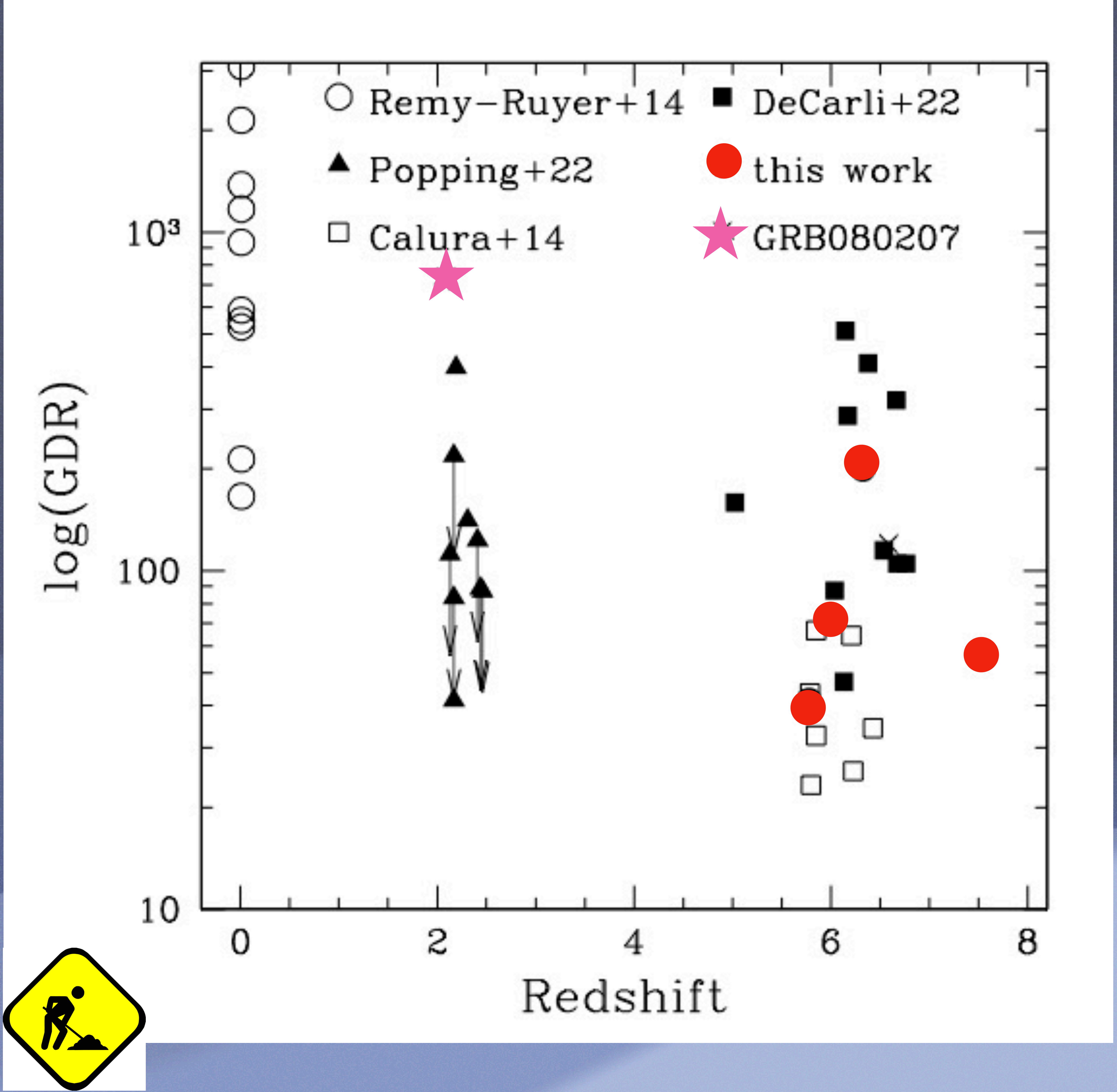




ISM Composition

Gas to dust ratio

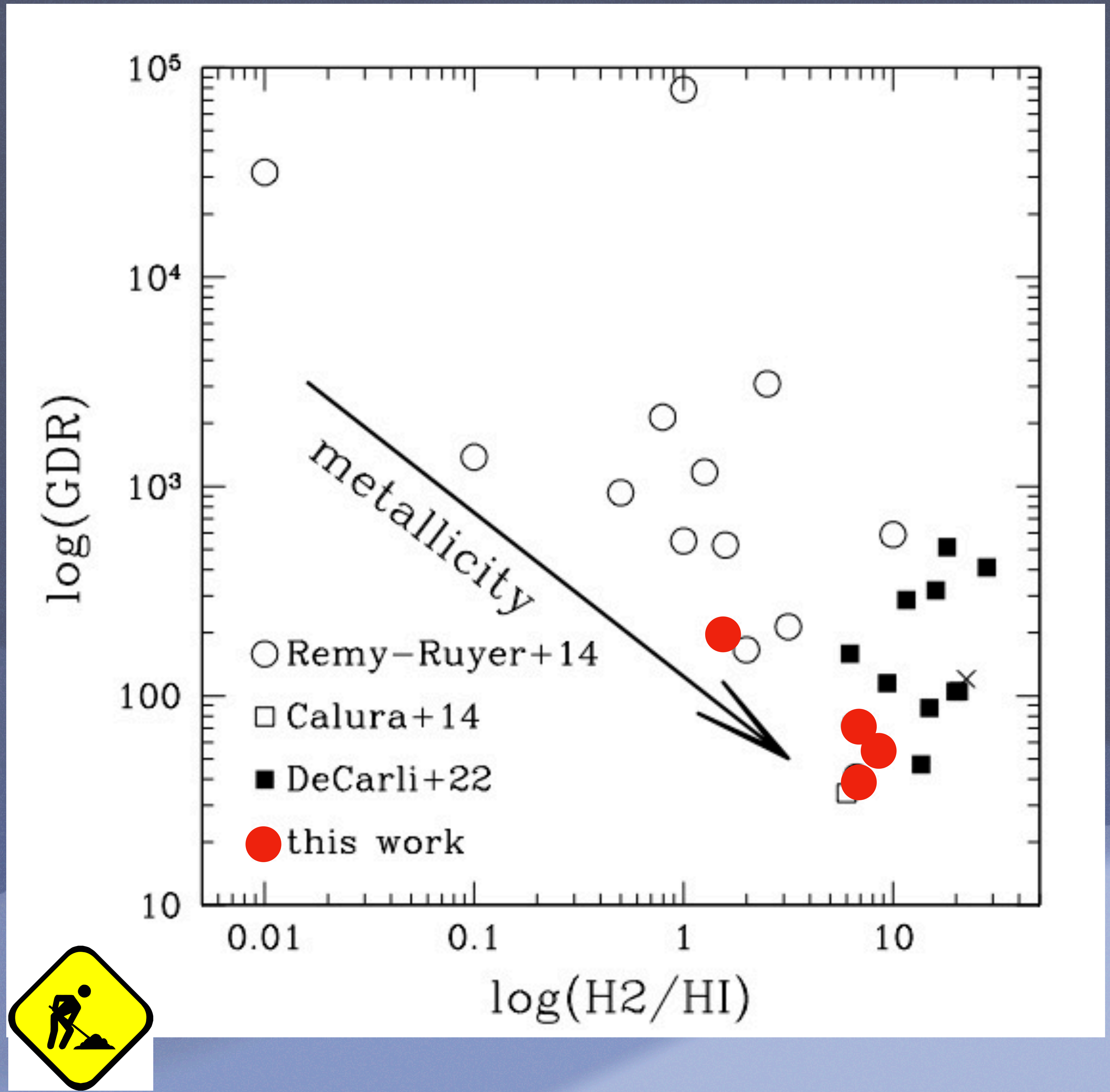
- Remy-Ruyer+2014 local galaxies with broad range of metallicity
- Popping+22: galaxies with 0.5 – 1.25 $Z_\odot$



ISM Composition

Gas to dust ratio

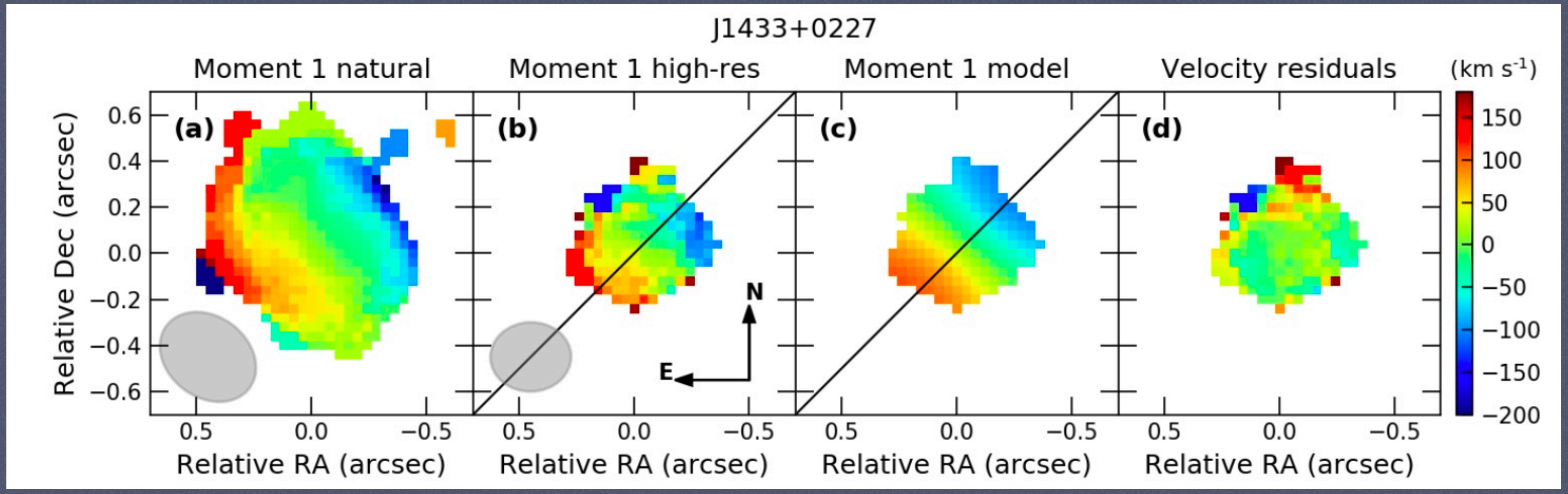
- z> 6 QSO have high metallicity



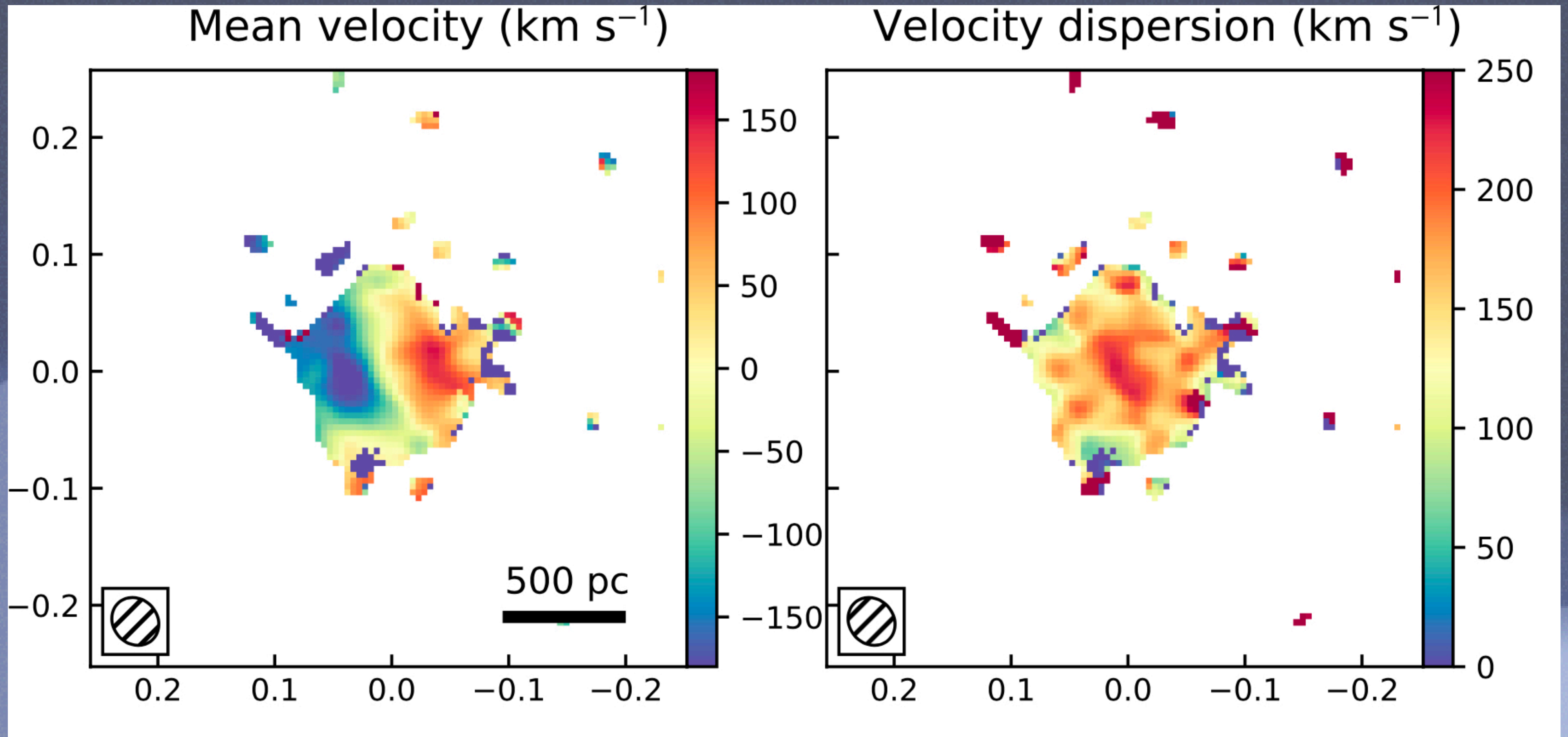
ISM dynamics
Disks

- Disk ubiquitous up to the highest redshifts
- Dynamical masses 10^{10} - 10^{11} $M_\odot$ over
- Sizes few kpc

QSO z=4.7 [CII]
Bischetti, CF+21

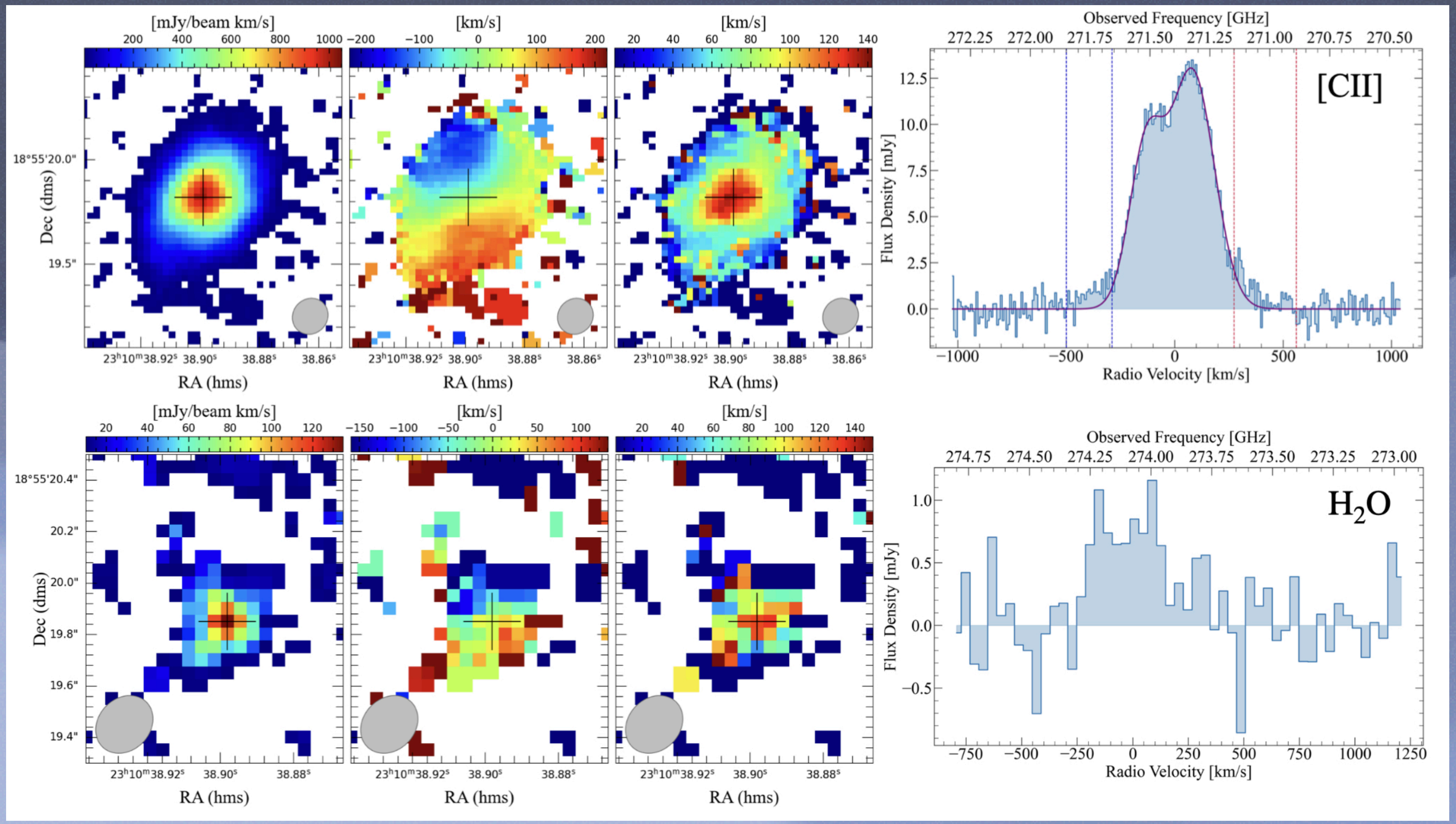


QSO z~7
Walter+22



QSO z=6
[CII] & H20
Tripodi, CF+22

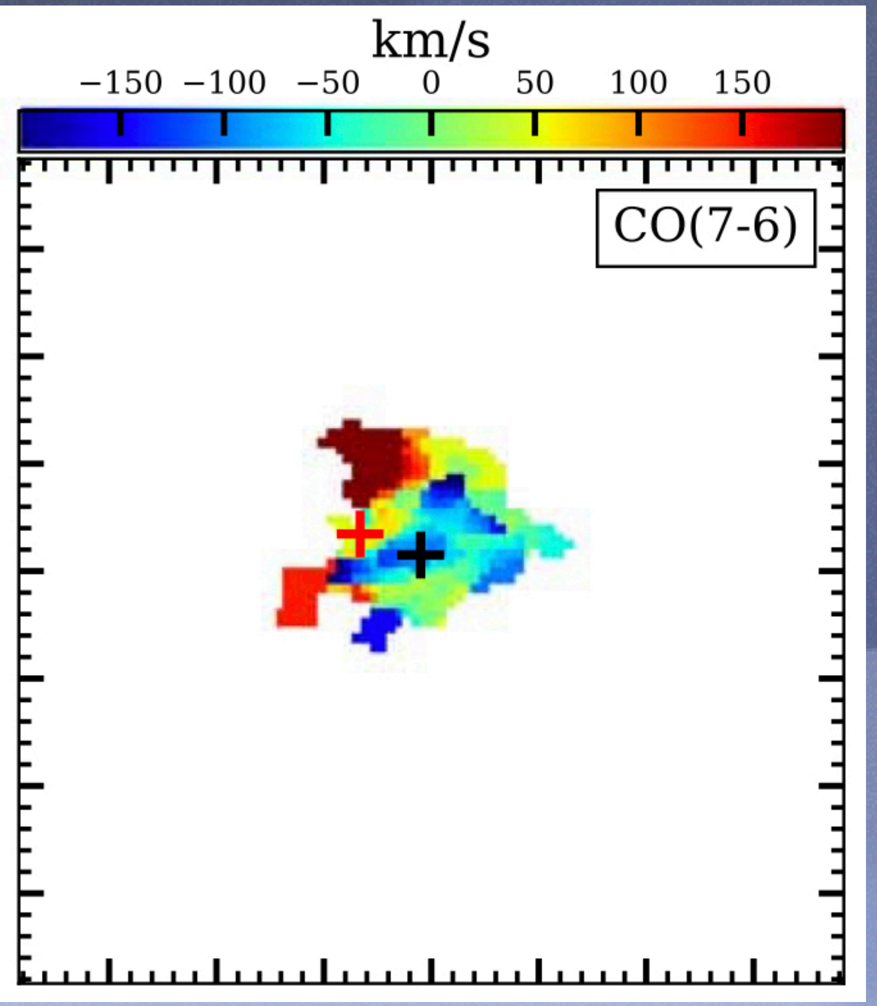
Roberta's talk today



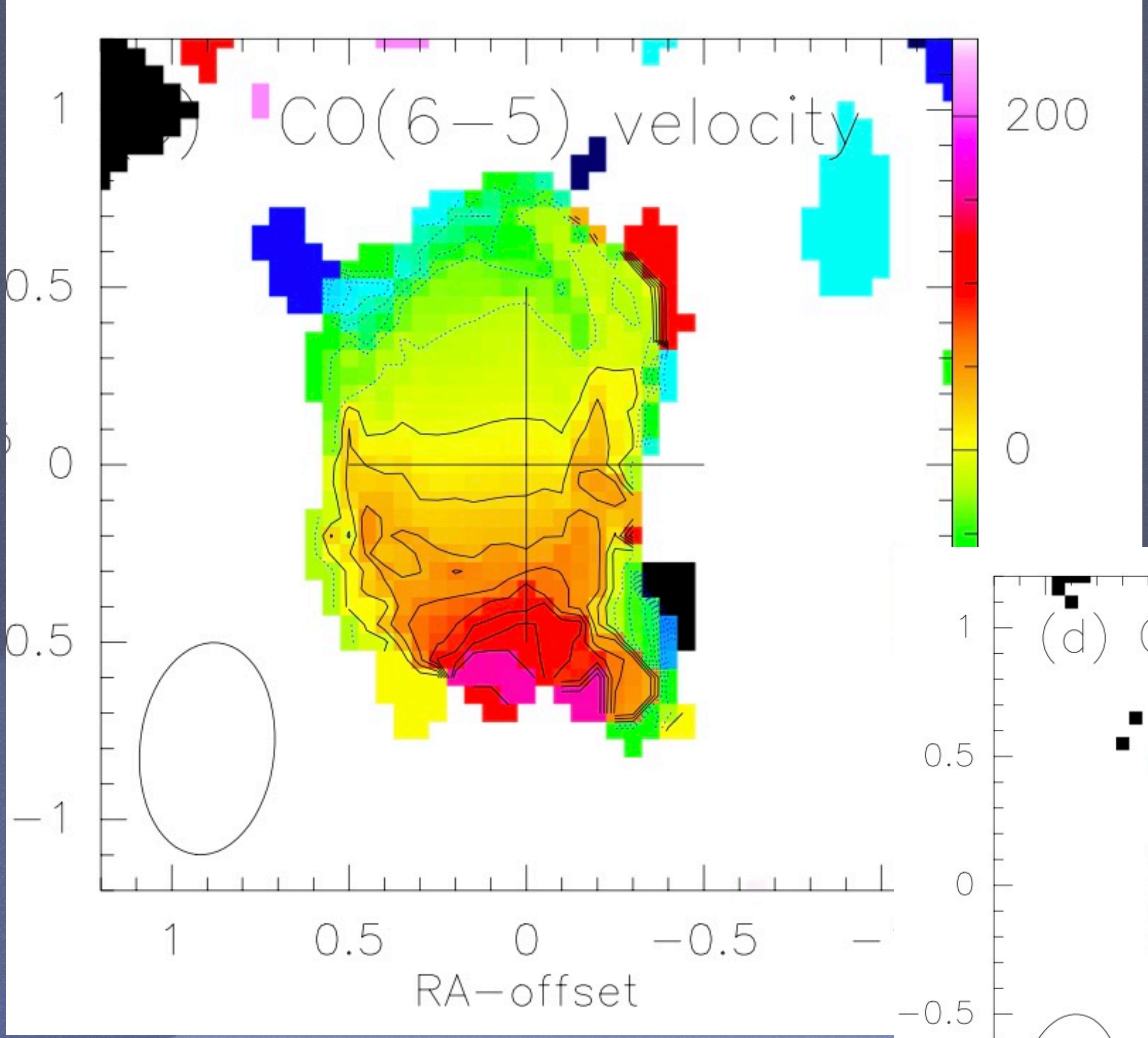
also Feruglio+2018, Neeleman+2021

ISM dynamics
Disks

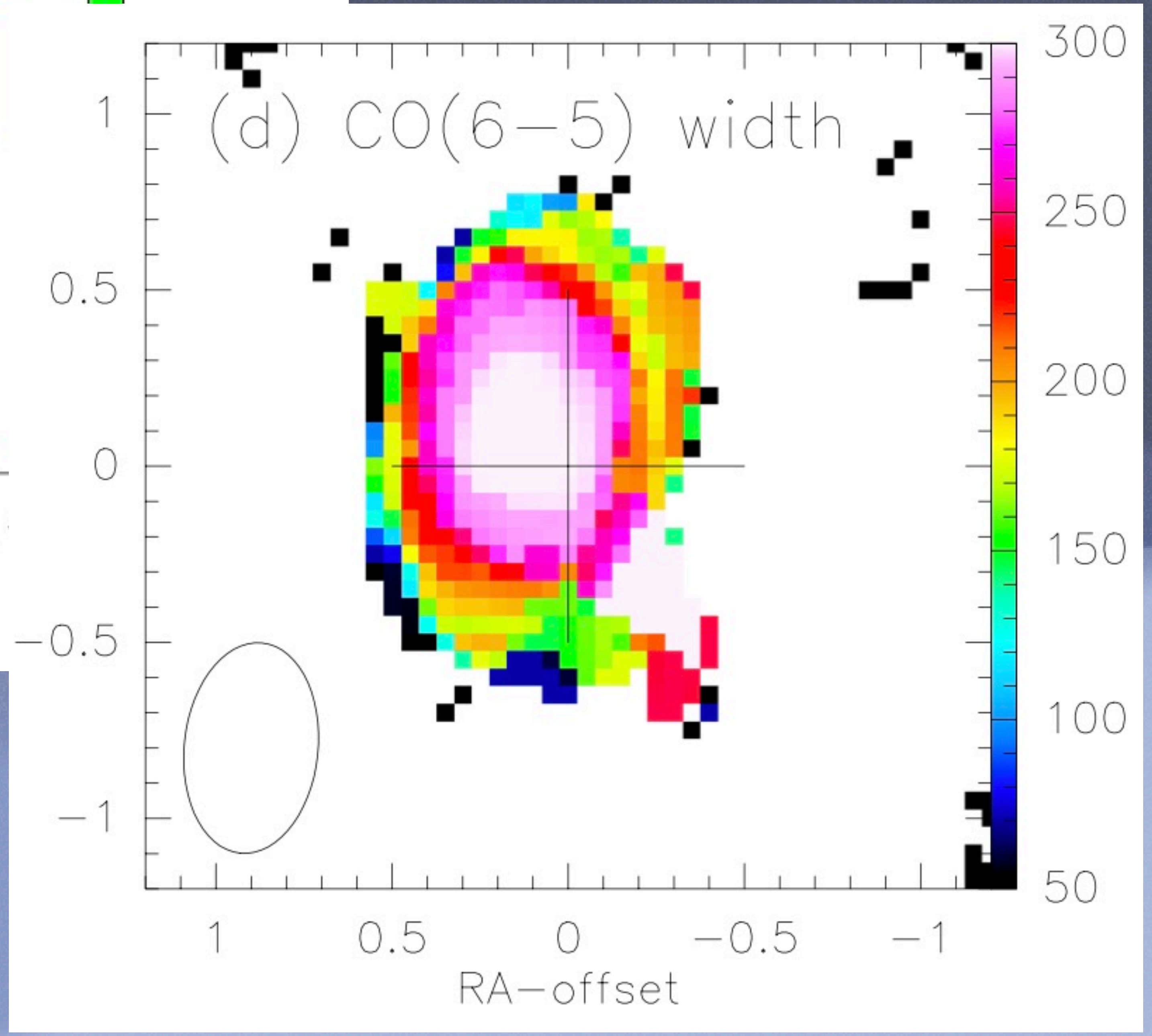
- Few molecular disk mapped J2310+1855 (Feruglio+2018)
- Turbulent disks $v_{rot}/\sigma \sim 2$
- dynamically hot disk, or inflows/outflows



CO65 velocity



vel dispersion

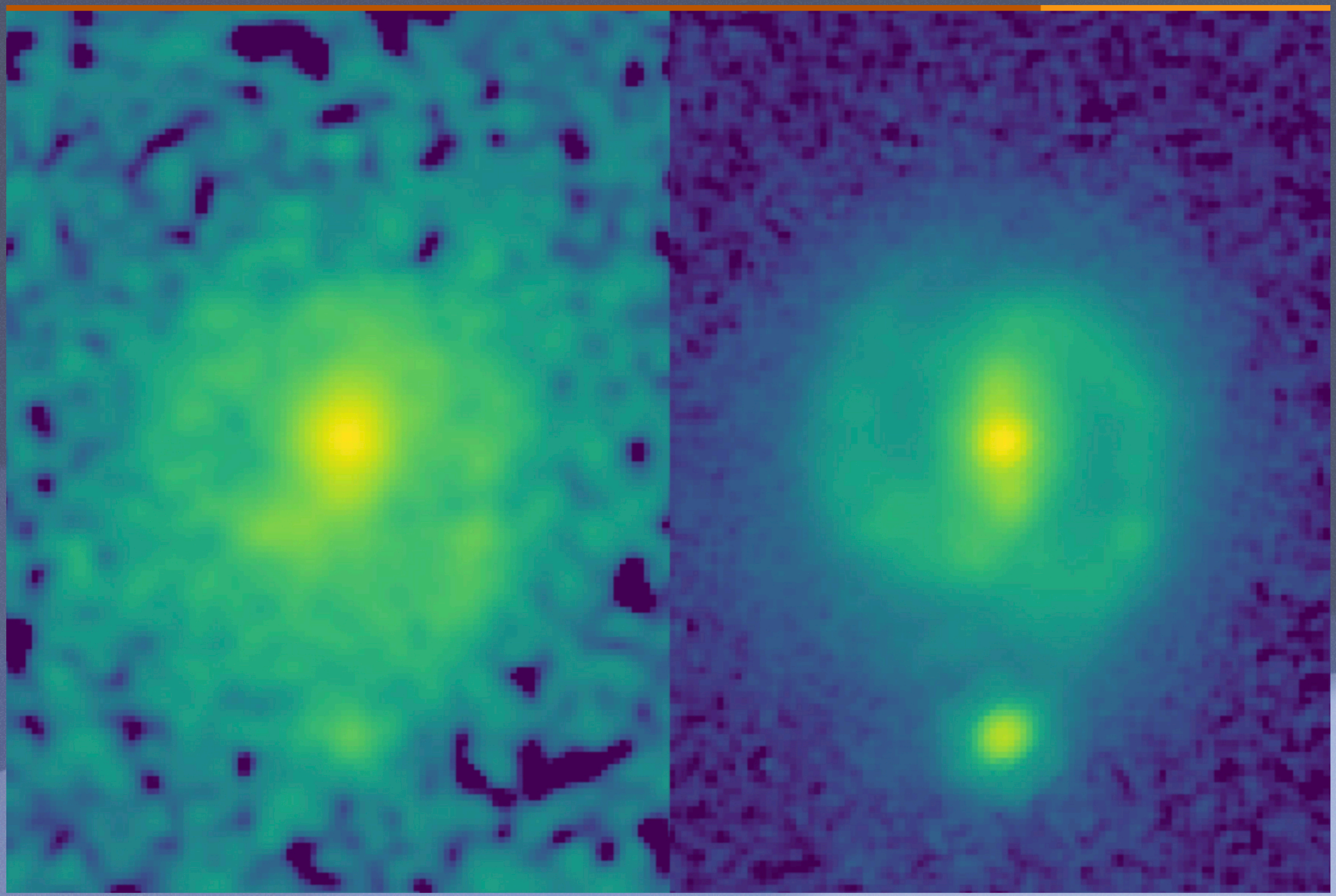


Feruglio+2018, Li+2022

ISM dynamics

Disks + bars

- Not only disks but also bars are in place at z>1
- Recent JWST image of a bar at z~2 in CEERS survey (Guo+2022)
- https://twitter.com/AAS_Press/status/1611047123063279616



ISM dynamics

Outflows ubiquitous at high z

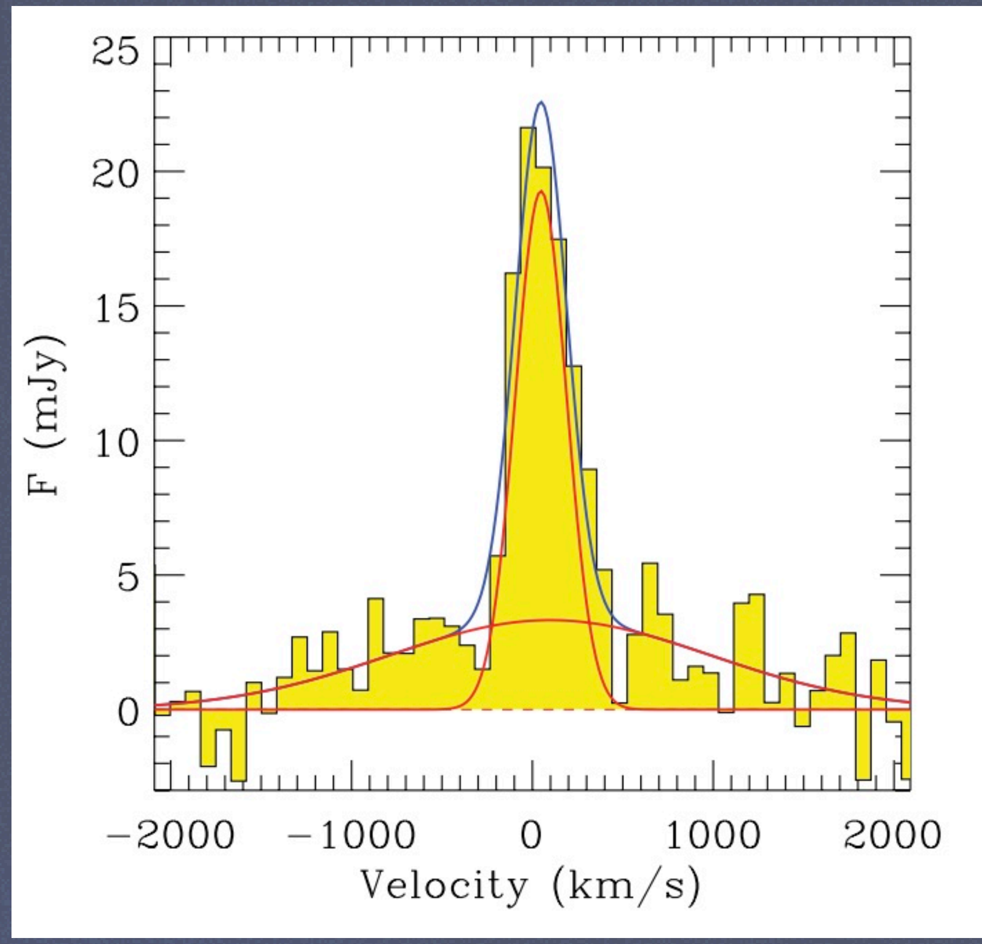
- Cold/molecular outflows in emission (broad lines [CII]) and absorption (OH, OH+)

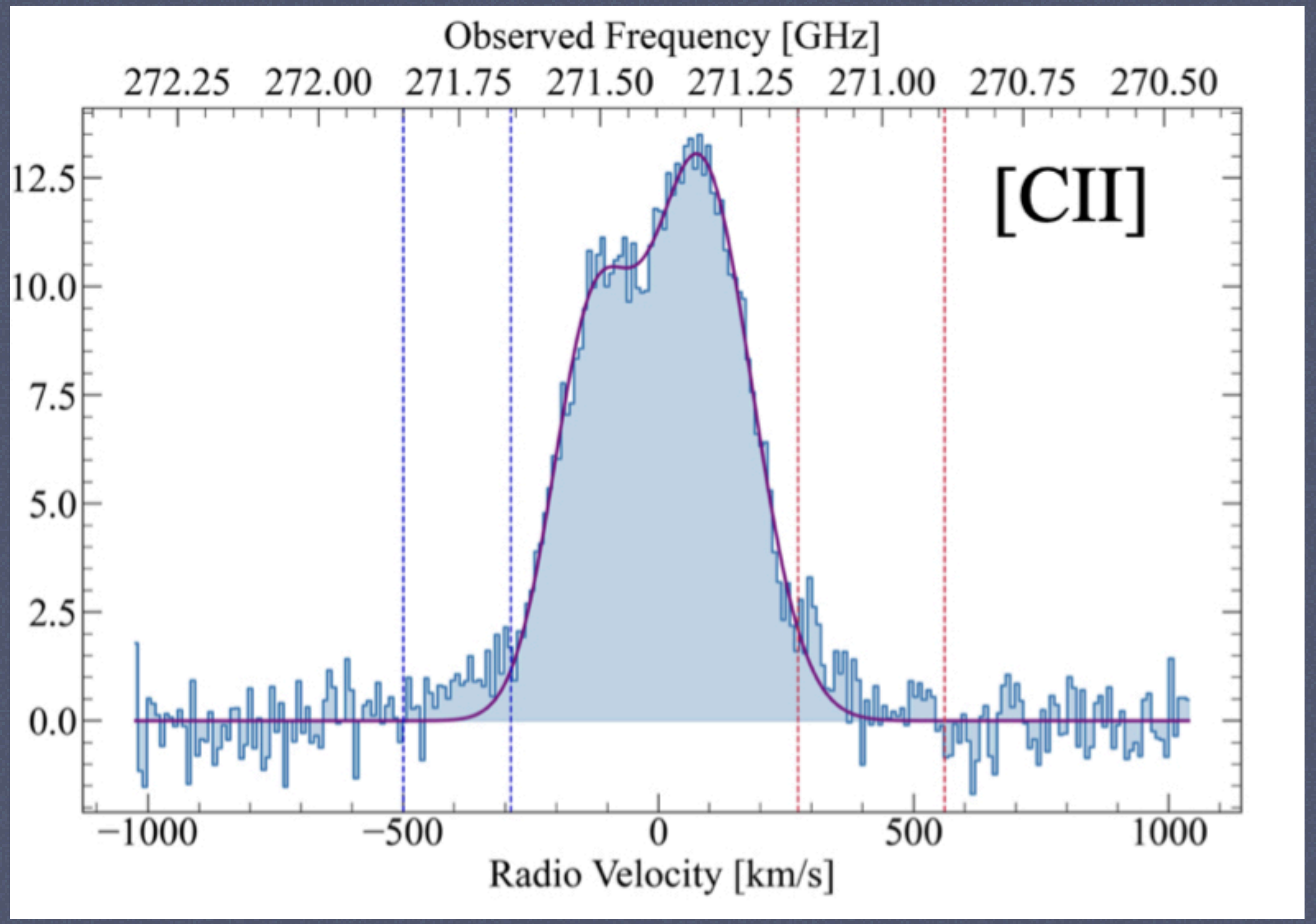
- Maiolino+2012, Feruglio+2018, Shao+2022, Bischetti+2019

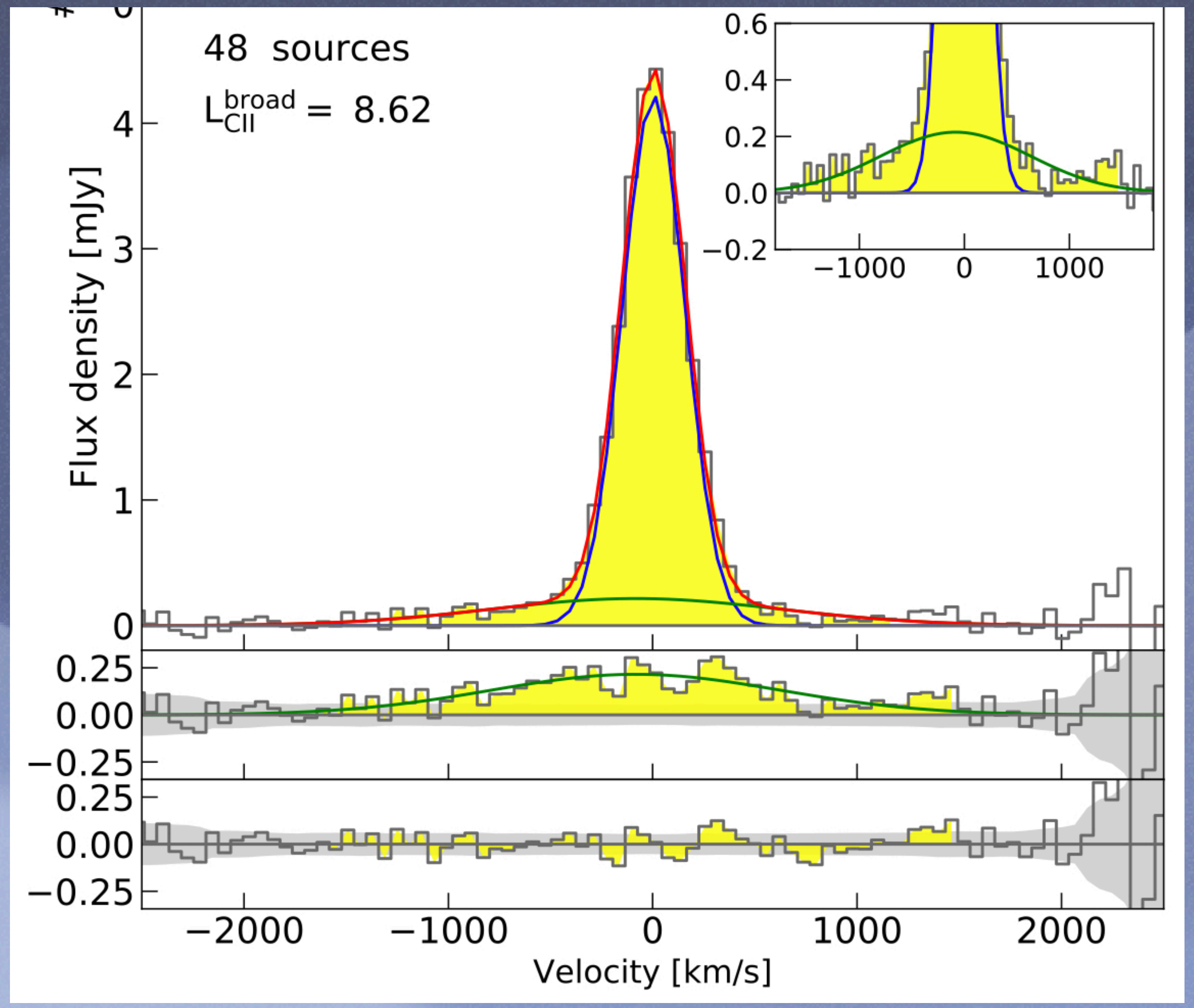
- Inferred outflow rates

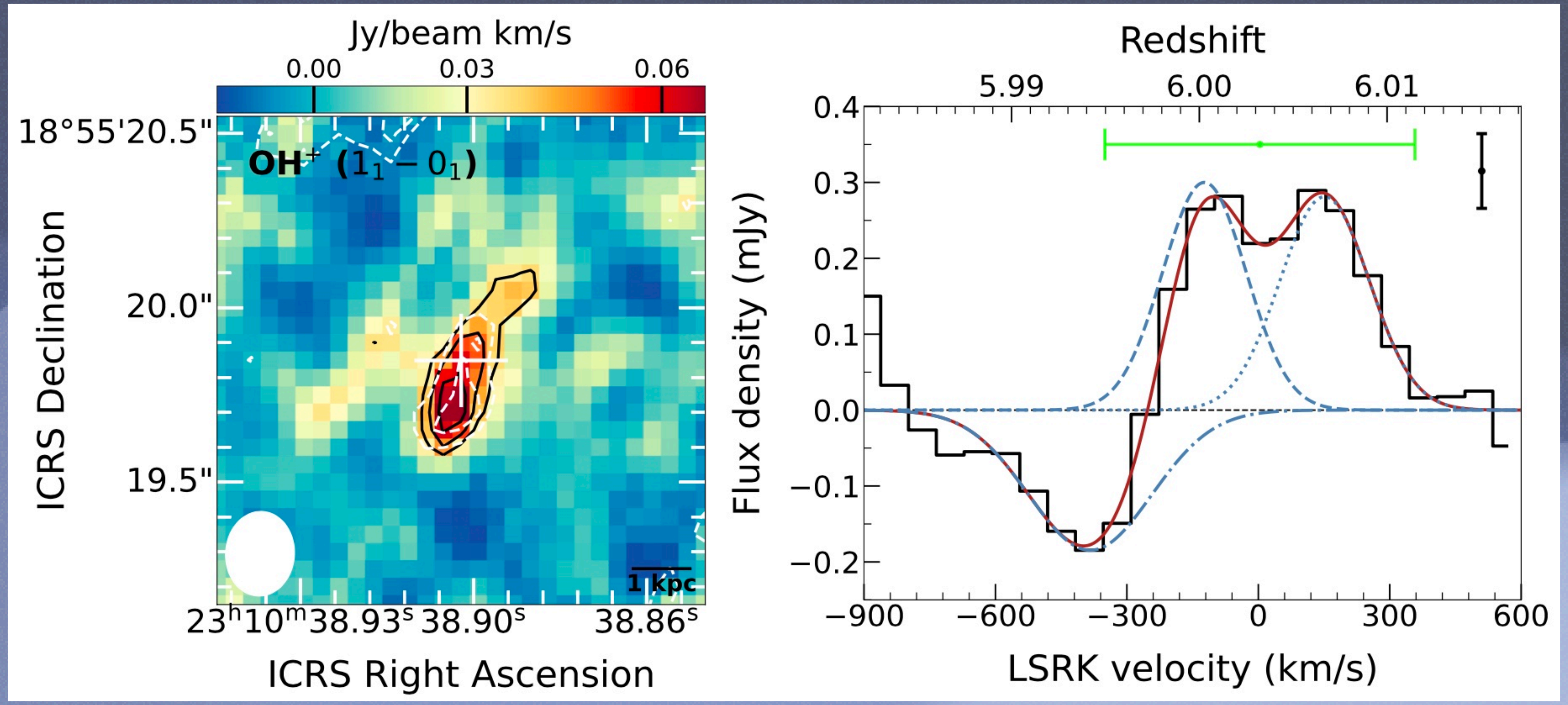
  100-1000 M⊙ /yr

- Feedback in action





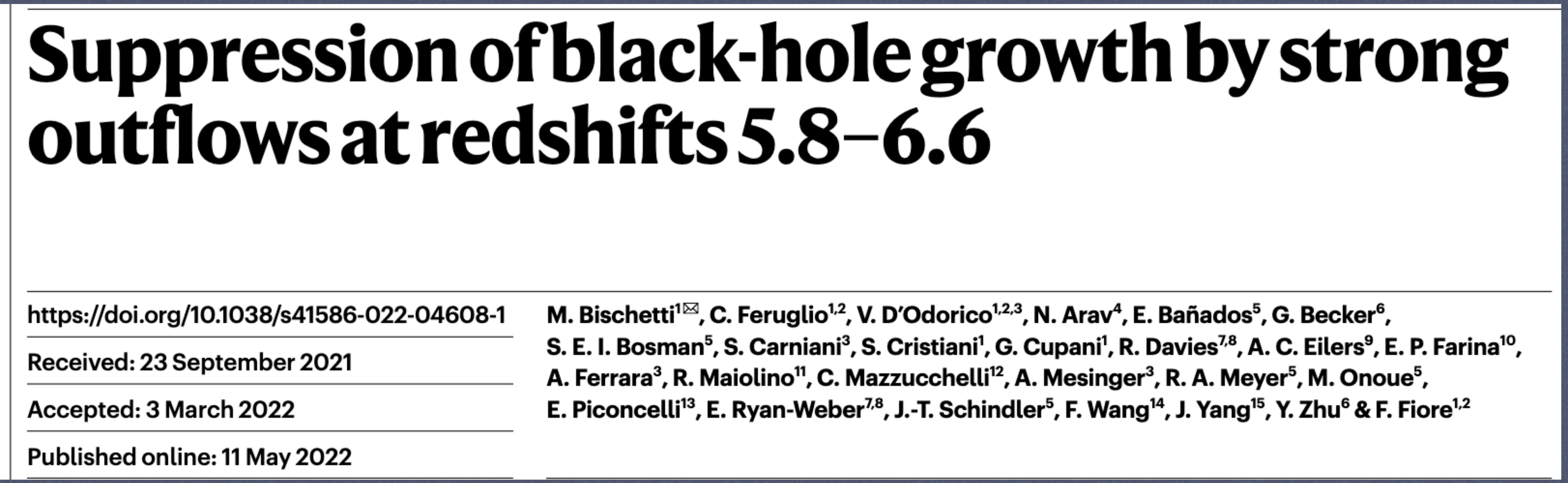




ISM dynamics

Outflows ubiquitous

- **First investigation of BH-driven outflows in quasars at z=5.8-6.6**, traced by BAL systems in UV spectra. 30 targets with high-quality X-shooter data in the **XQR-30 The Ultimate XShooter survey of QSOs at Reionisation Epoch**
- **Widespread presence of BAL outflows**, detected in ~50% of z~6 quasars.
- BAL fraction significantly higher than in lower-z quasars.
- Bischetti, CF+2022, Nature


Suppression of black-hole growth by strong outflows at redshifts 5.8–6.6

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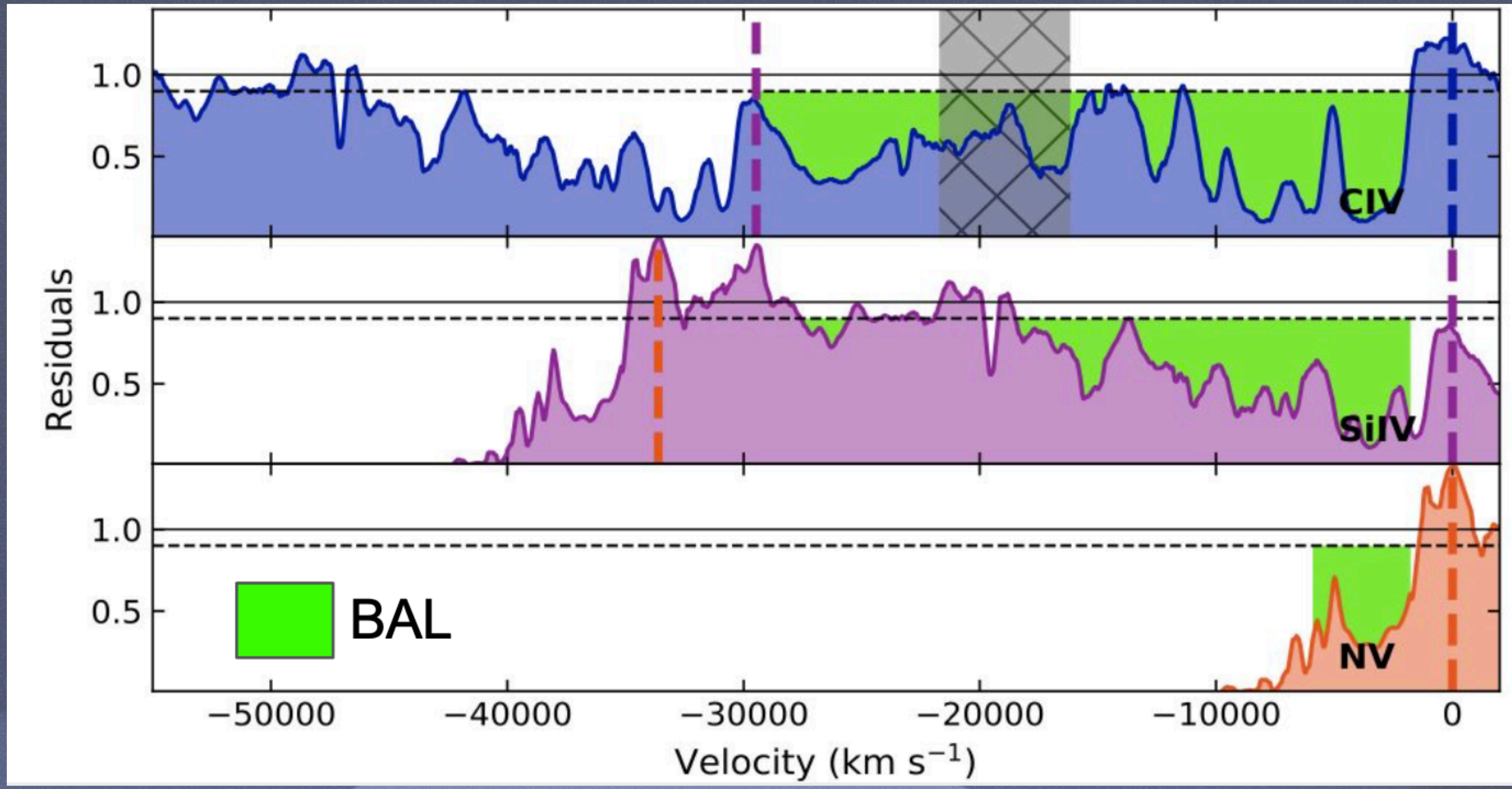
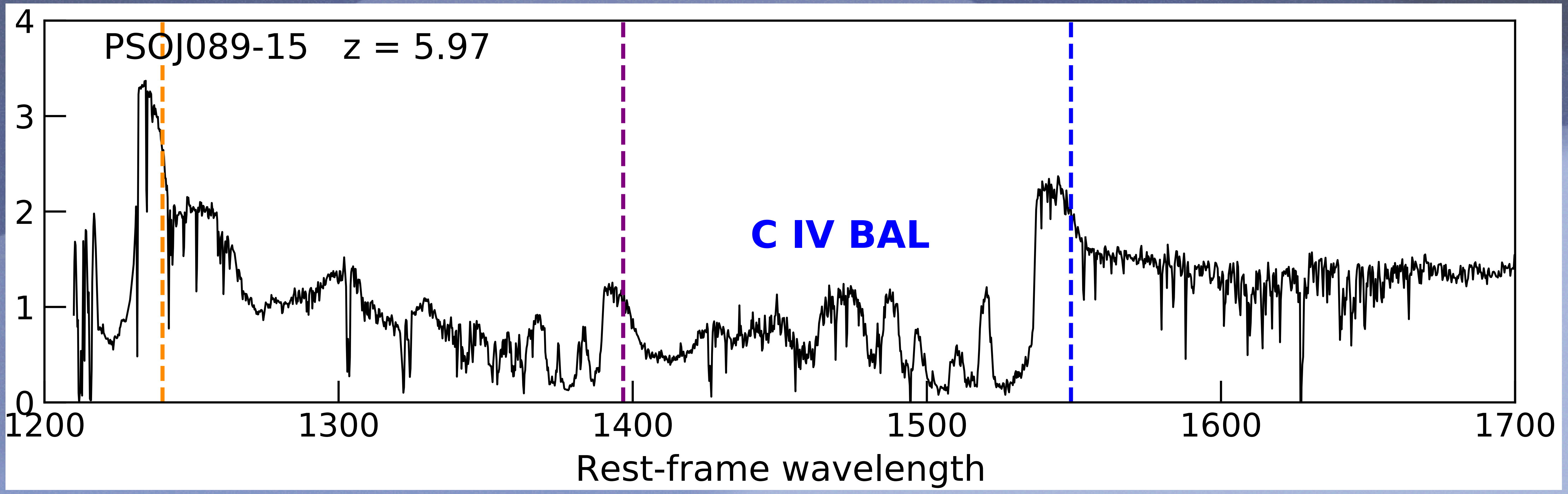
M. Bischetti[1]✉, C. Feruglio[1,2], V. D'Odorico[1,2,3], N. Arav[4], E. Bañados[5], G. Becker[6], S. E. I. Bosman[5], S. Carniani[3], S. Cristiani[1], G. Cupani[1], R. Davies[7,8], A. C. Eilers[9], E. P. Farina[10], A. Ferrara[3], R. Maiolino[11], C. Mazzucchelli[12], A. Mesinger[3], R. A. Meyer[5], M. Onoue[5], E. Piconcelli[13], E. Ryan-Weber[7,8], J.-T. Schindler[5], F. Wang[14], J. Yang[15], Y. Zhu[6] & F. Fiore[1,2]





ISM dynamics

Outflows ubiquitous

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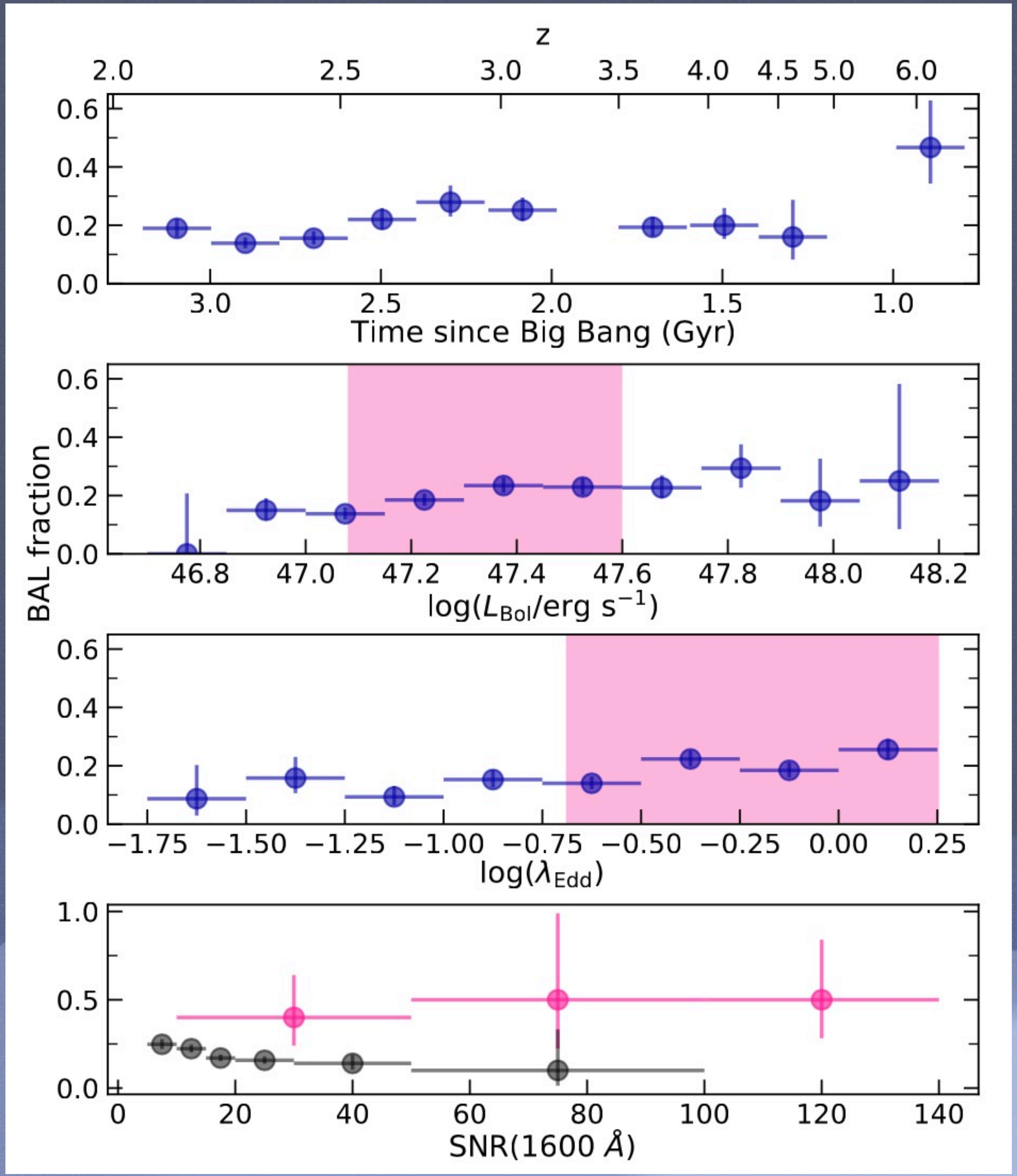
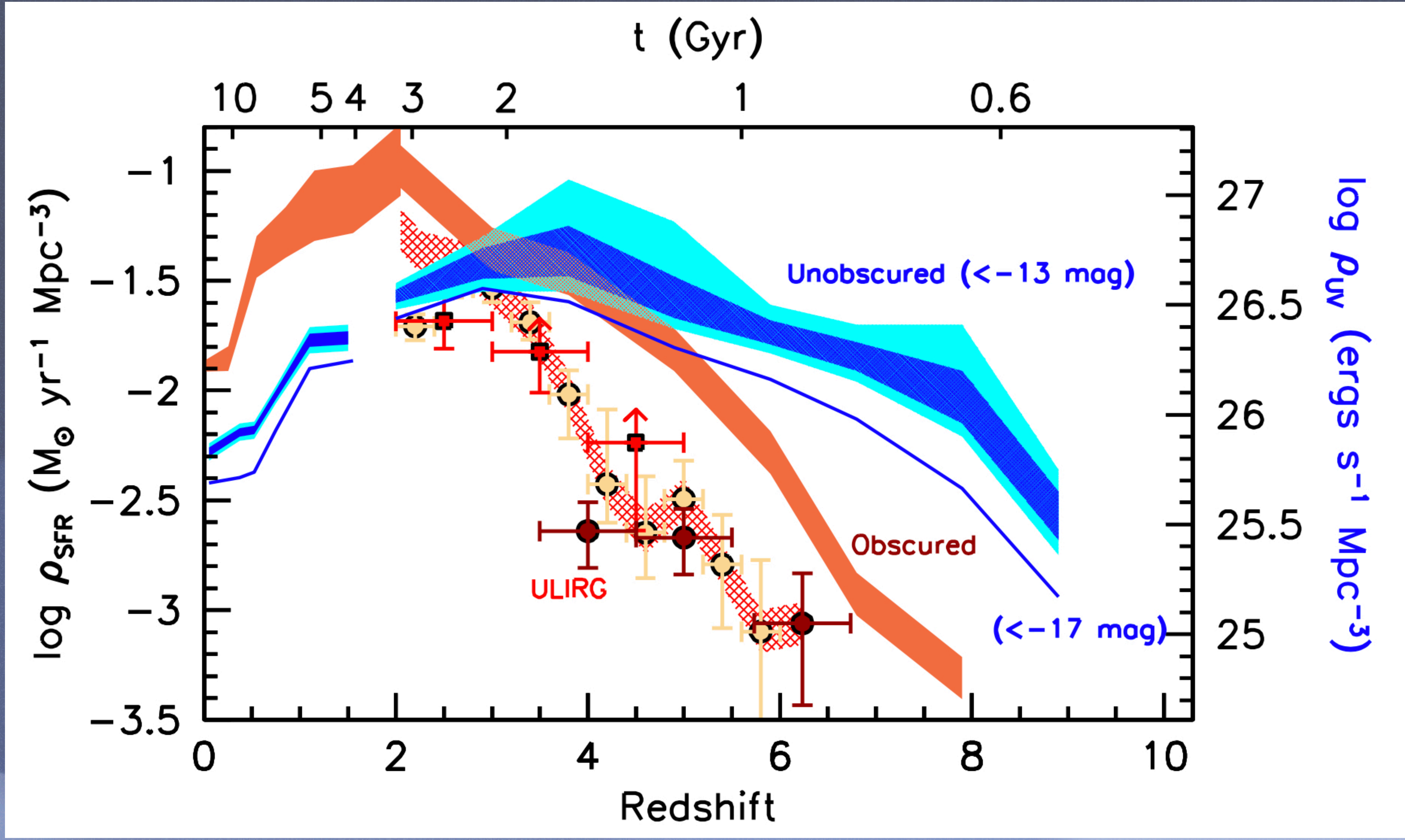
- **Widespread presence of BAL outflows**, detected in ~50% of z~6 quasars.
- BAL fraction significantly higher than at lower z
- Bischetti+2023, submitted



SFR density
obscured vs. unobscured

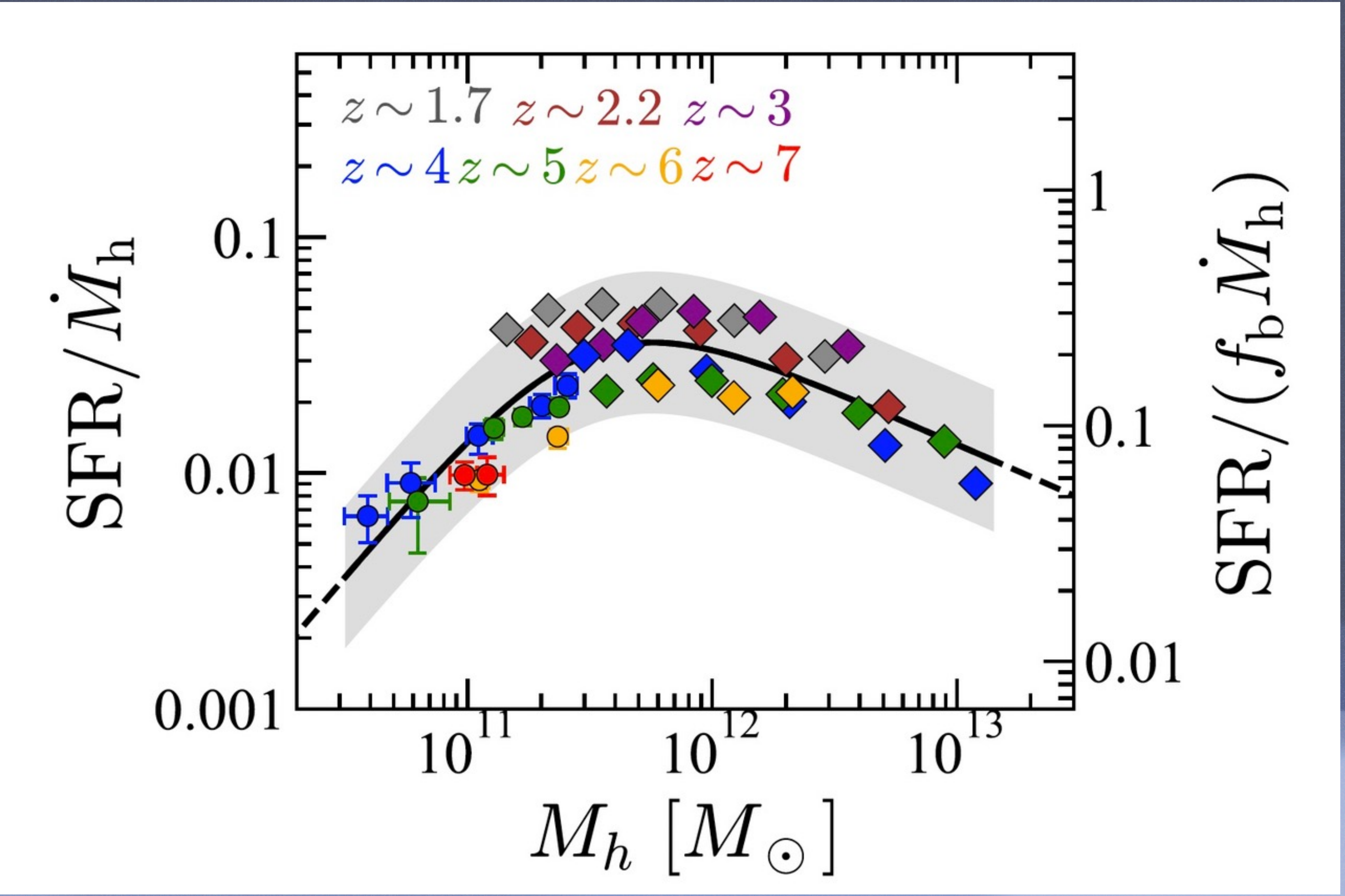
- UV-derived SFR density
Bouwens+2022



Star Formation Efficiency

Harikane+2022a

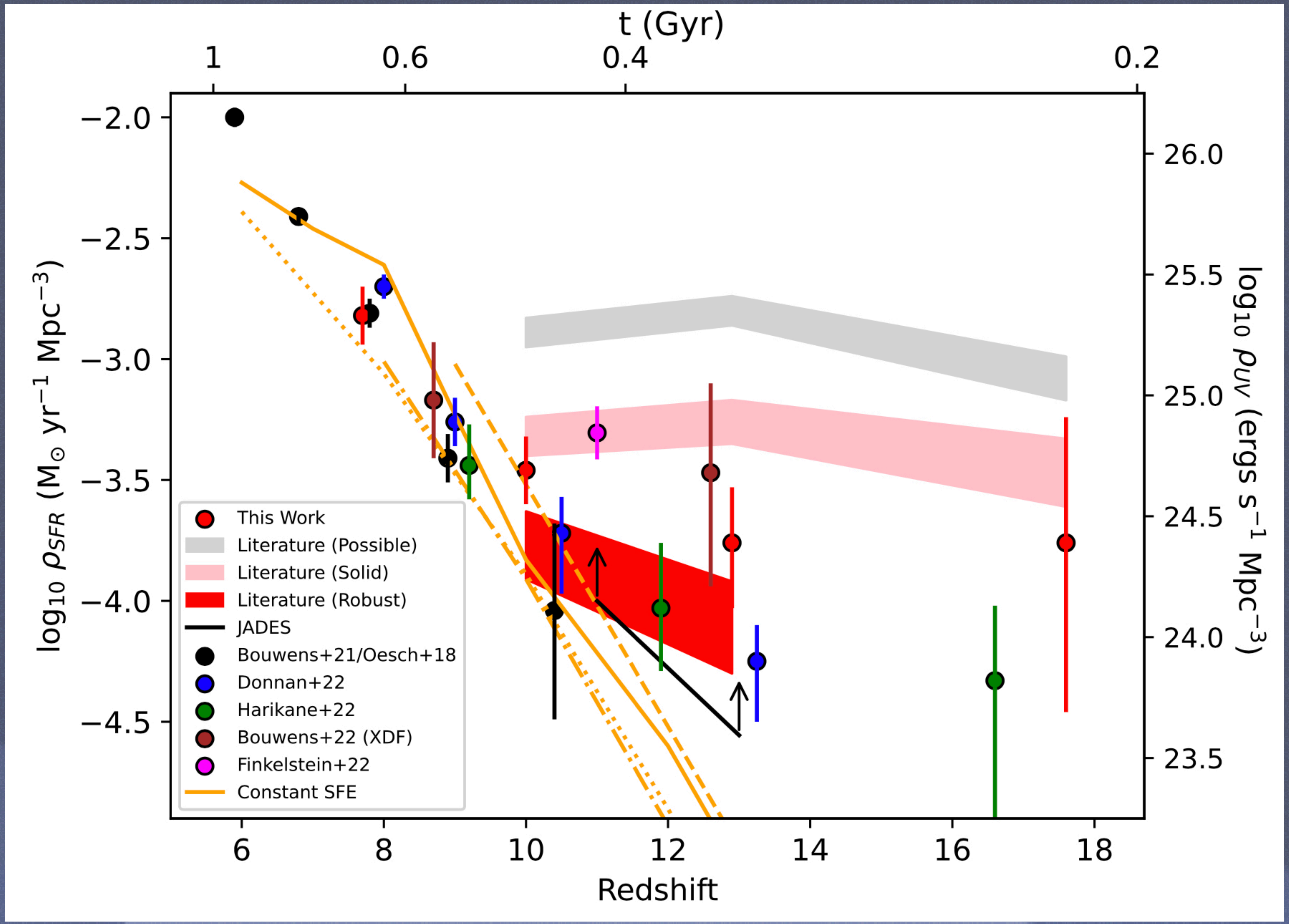
- SFE peaks at 0.1-0.2
- ~constant with z from z=1.7 to z=7

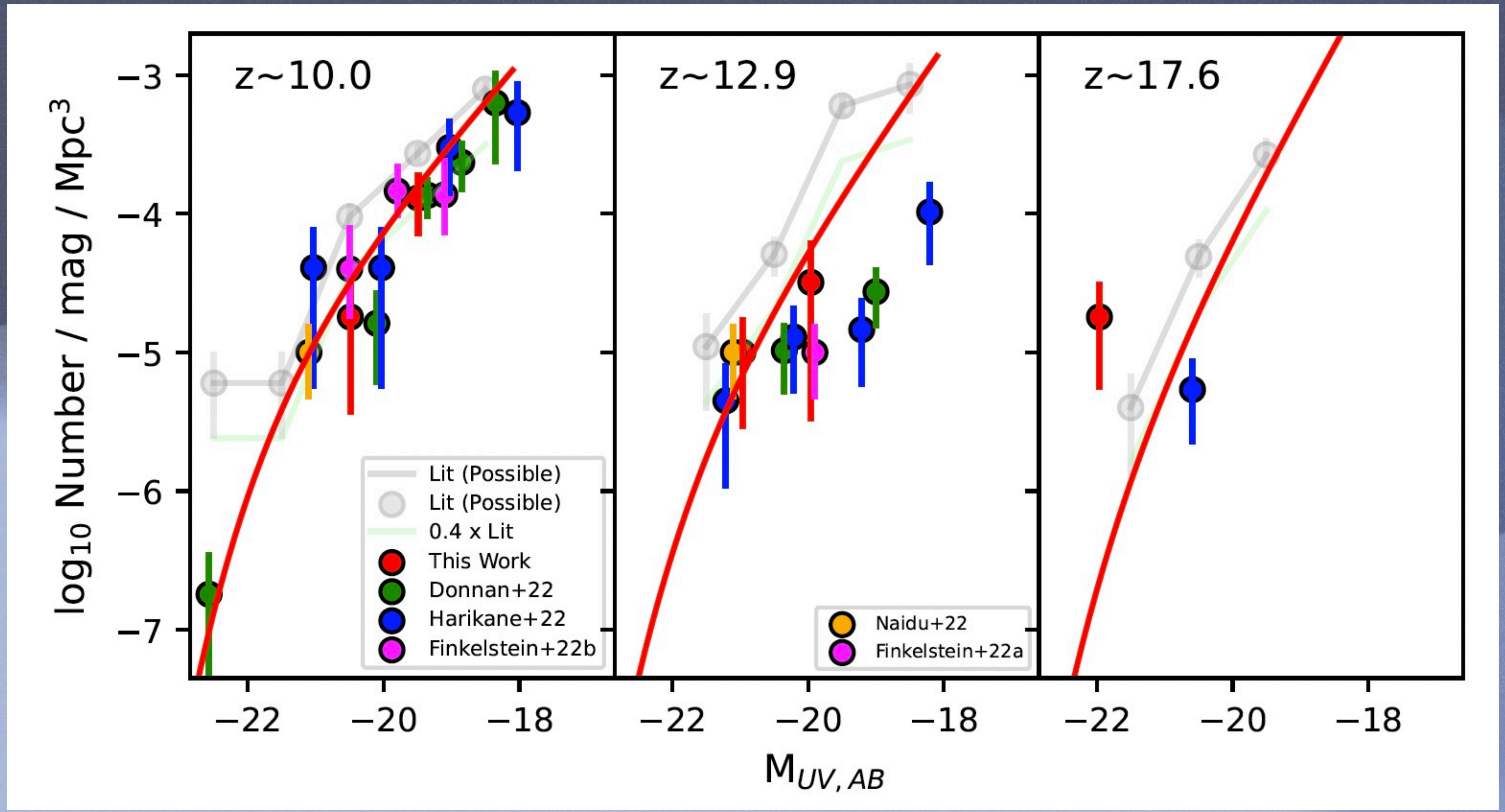


SFR density at z>6

from JWST

- SFR density z=6 to 18 Bouwens+2022
- spectroscopy confirms 80% photo-z (Carniani, priv. comm.)
- z=17 galaxy confirmed by ALMA



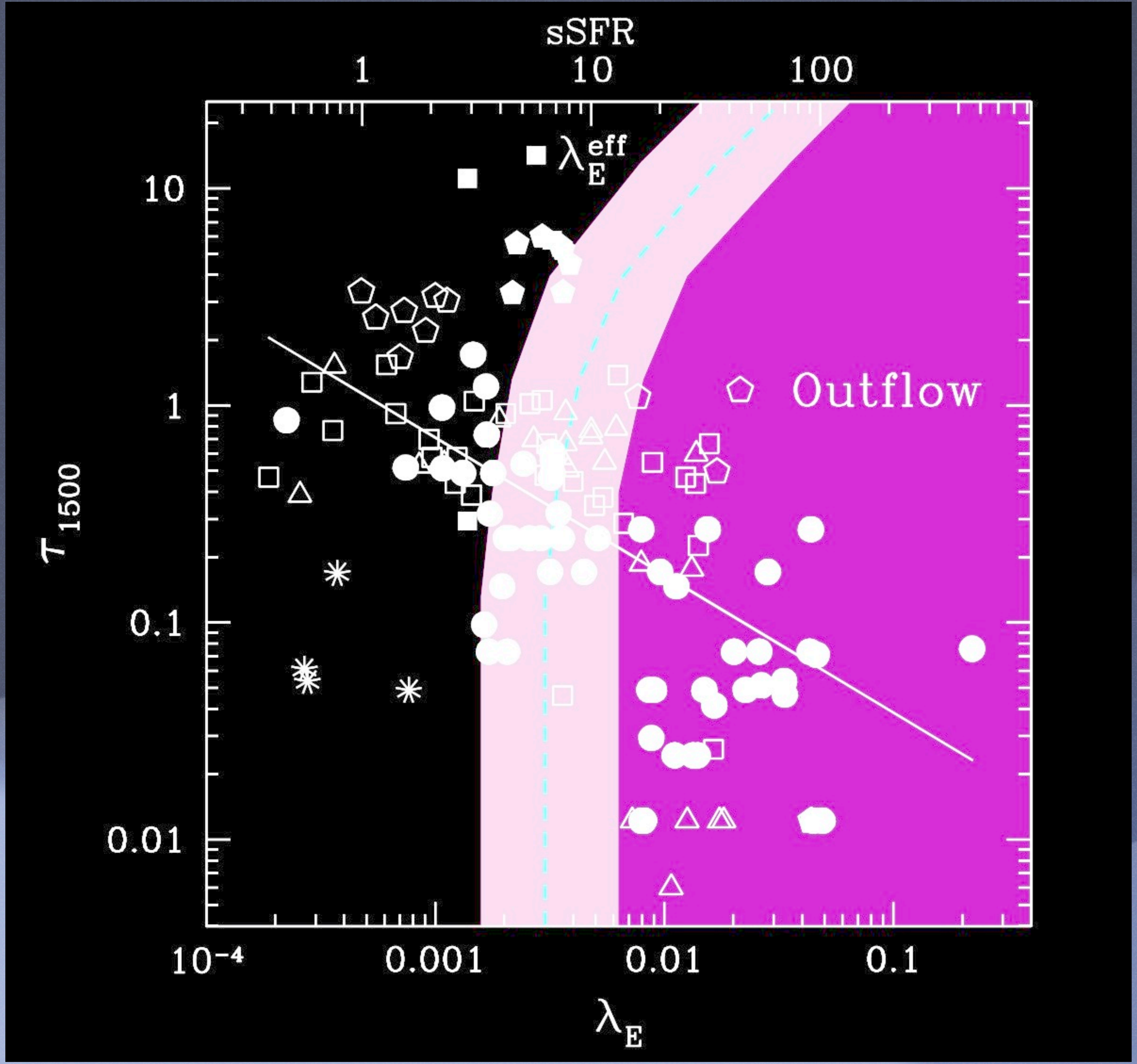


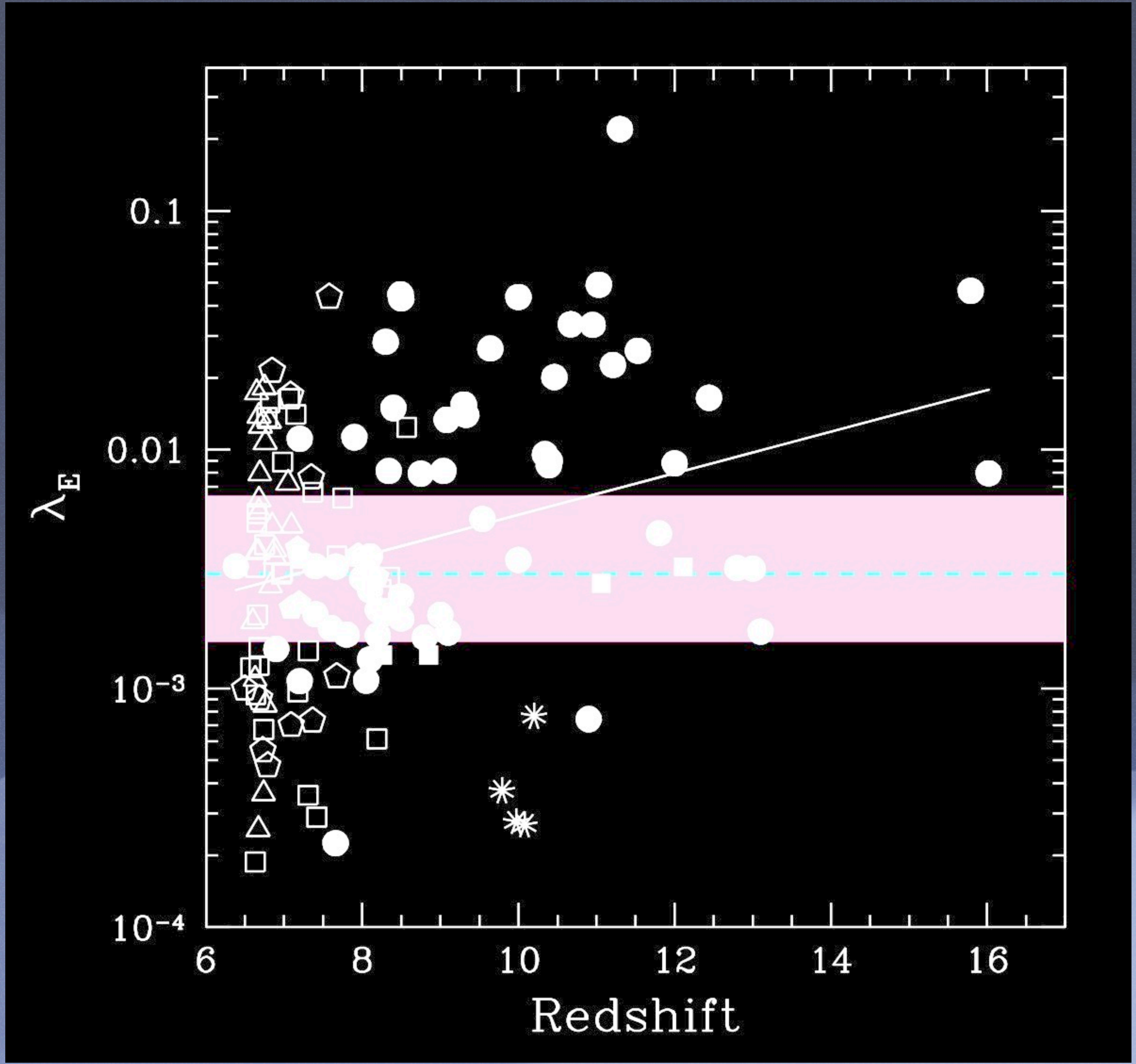
- Assumes SFE ~0.1-0.2
- Data imply >>SFE , close to 1, problem for λCDM

Dusty winds clear up JWST galaxies

Fiore+2022

134 galaxies at z>6.5 , filled = JWST detected galaxy candidates





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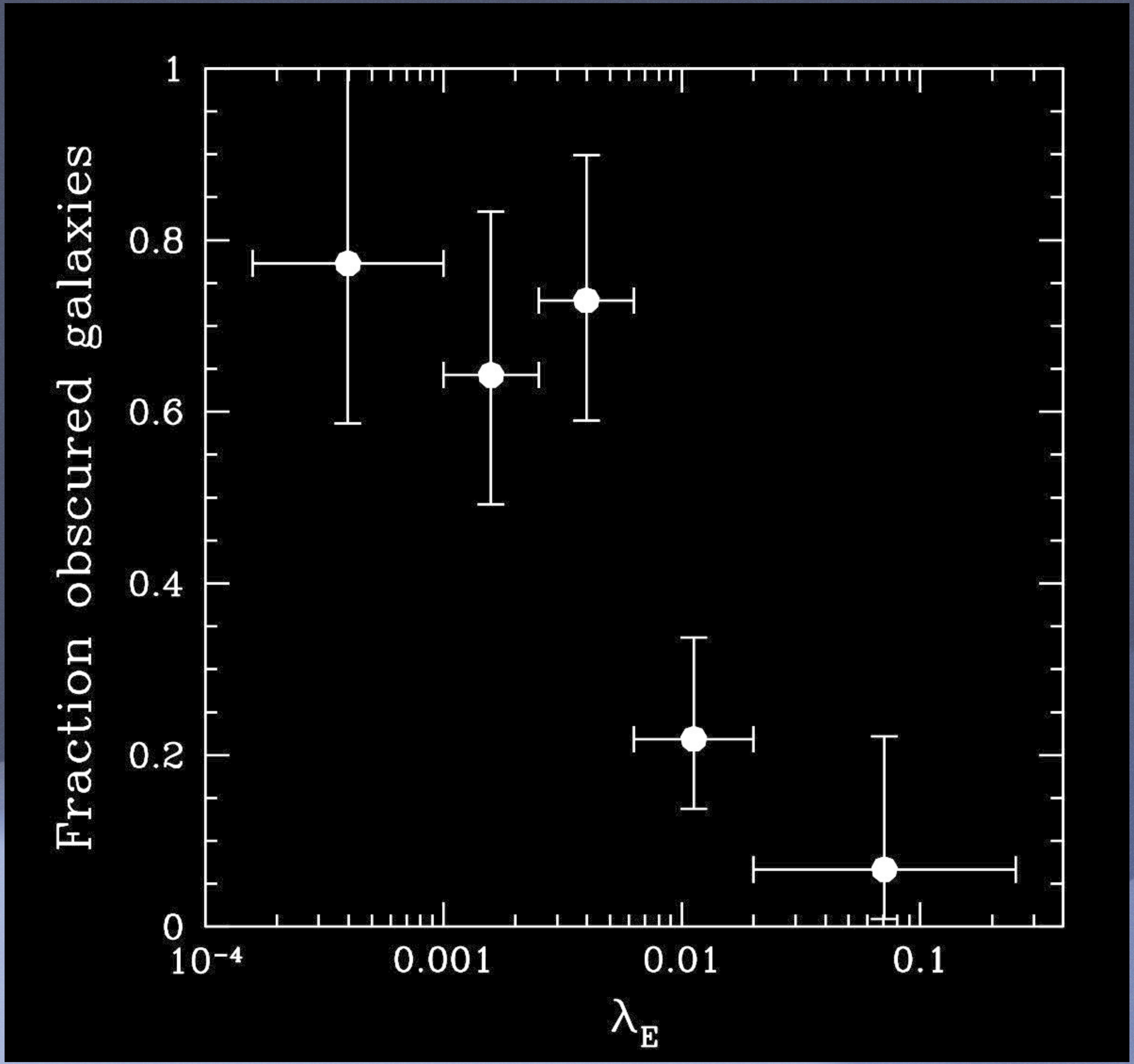
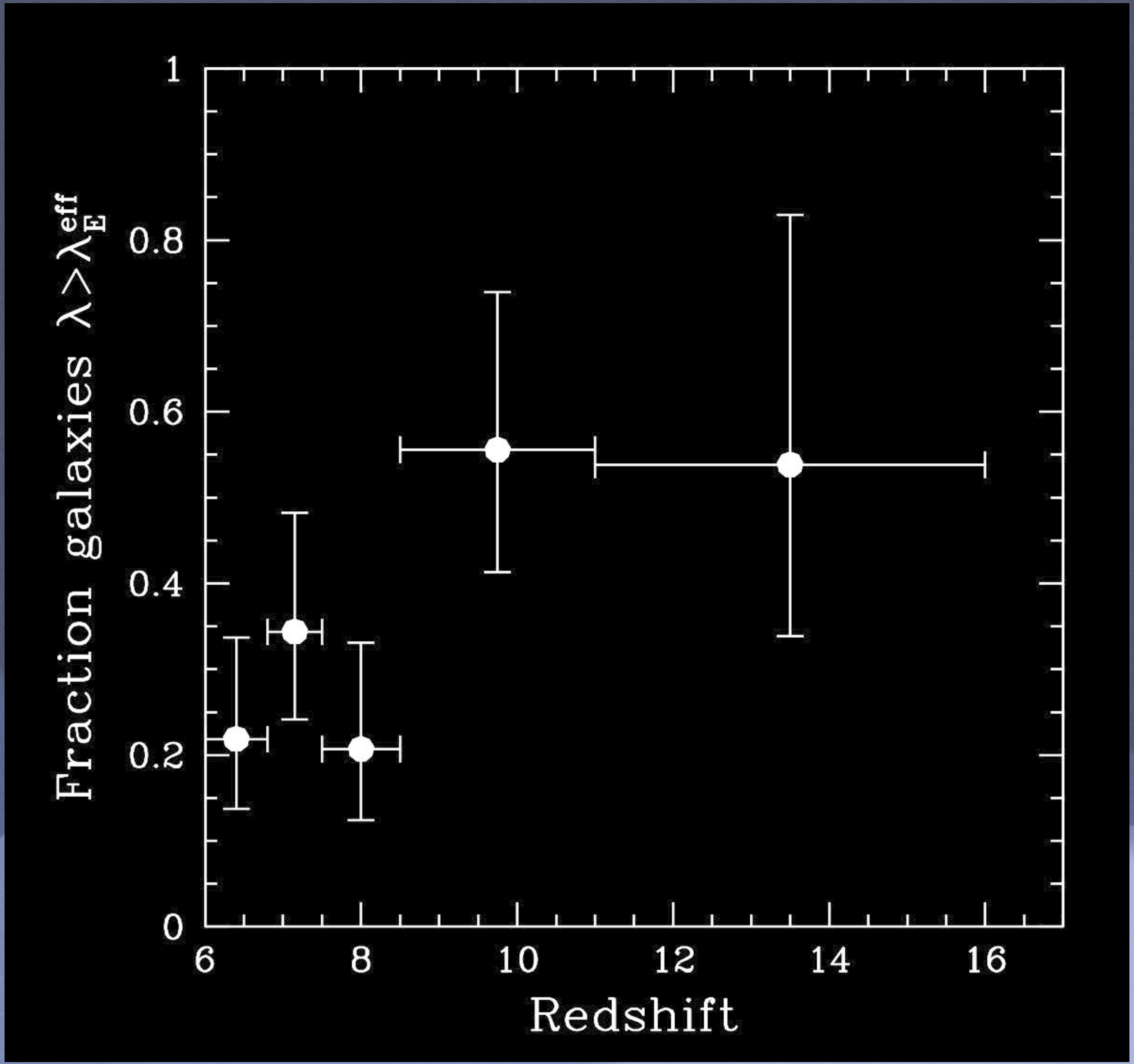
Fiore+2022





Conclusions

The interstellar medium and SFR of high redshift quasars & galaxies

- H_2 dominates the mass within galaxies at high z
- GDR implies high metallicity in QSO host galaxies $z>6$
- JWST suggest $SFE>0.2$ at $z>8$
- SF-AGN feedback is efficient in clearing early galaxies from gas/dust