ALMA follow up on a $z>10$ galaxy candidate: Story, Lessons and Prospects

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Story:

GHZ1: Why does ALMA need to follow up on it and how did it do it?

Lessons:

GHZ1: What does the ALMA observation tell us?

Prospects:

Wideband and High sensitivity ALMA: what can we do with ALMA for the study of first galaxy formation?

Story:

GHZ1: Why do we need to follow up on it and how did we do it?

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ALMA Observation of a $z \gtrsim 10$ Galaxy Candidate Discovered with JWST

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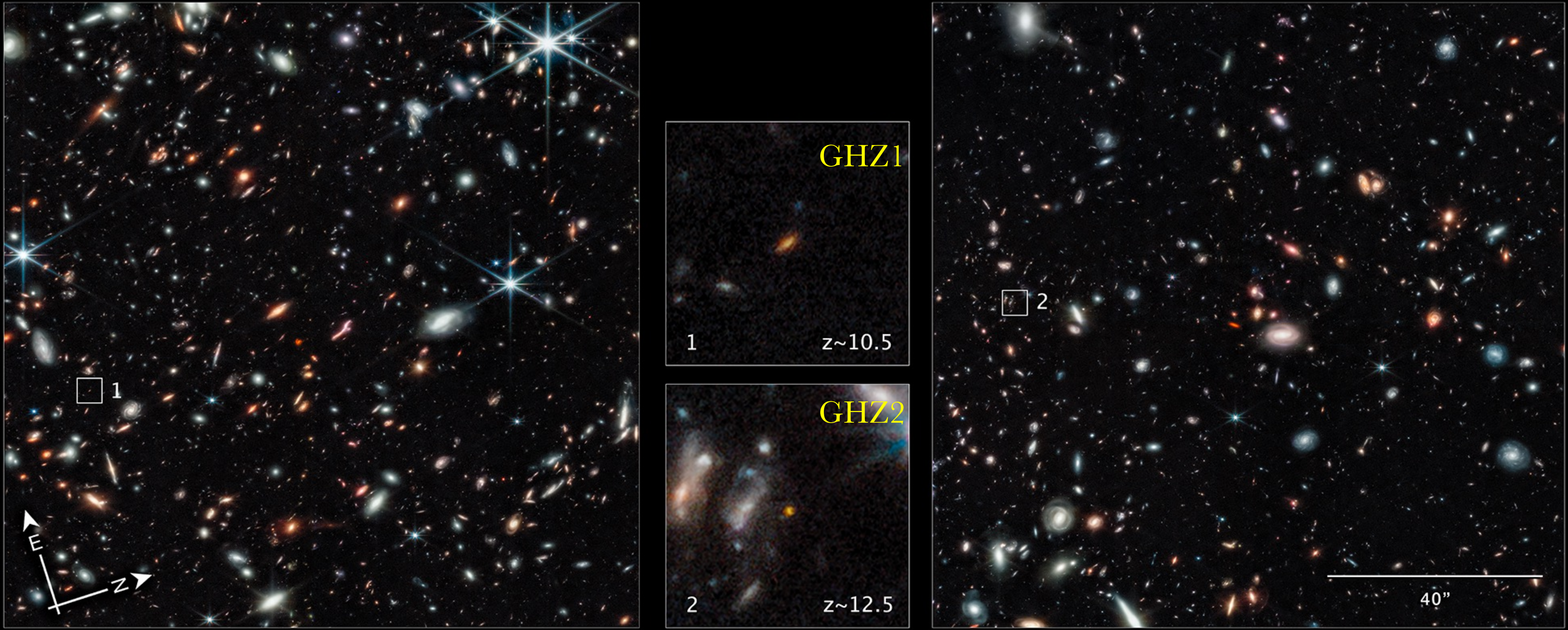
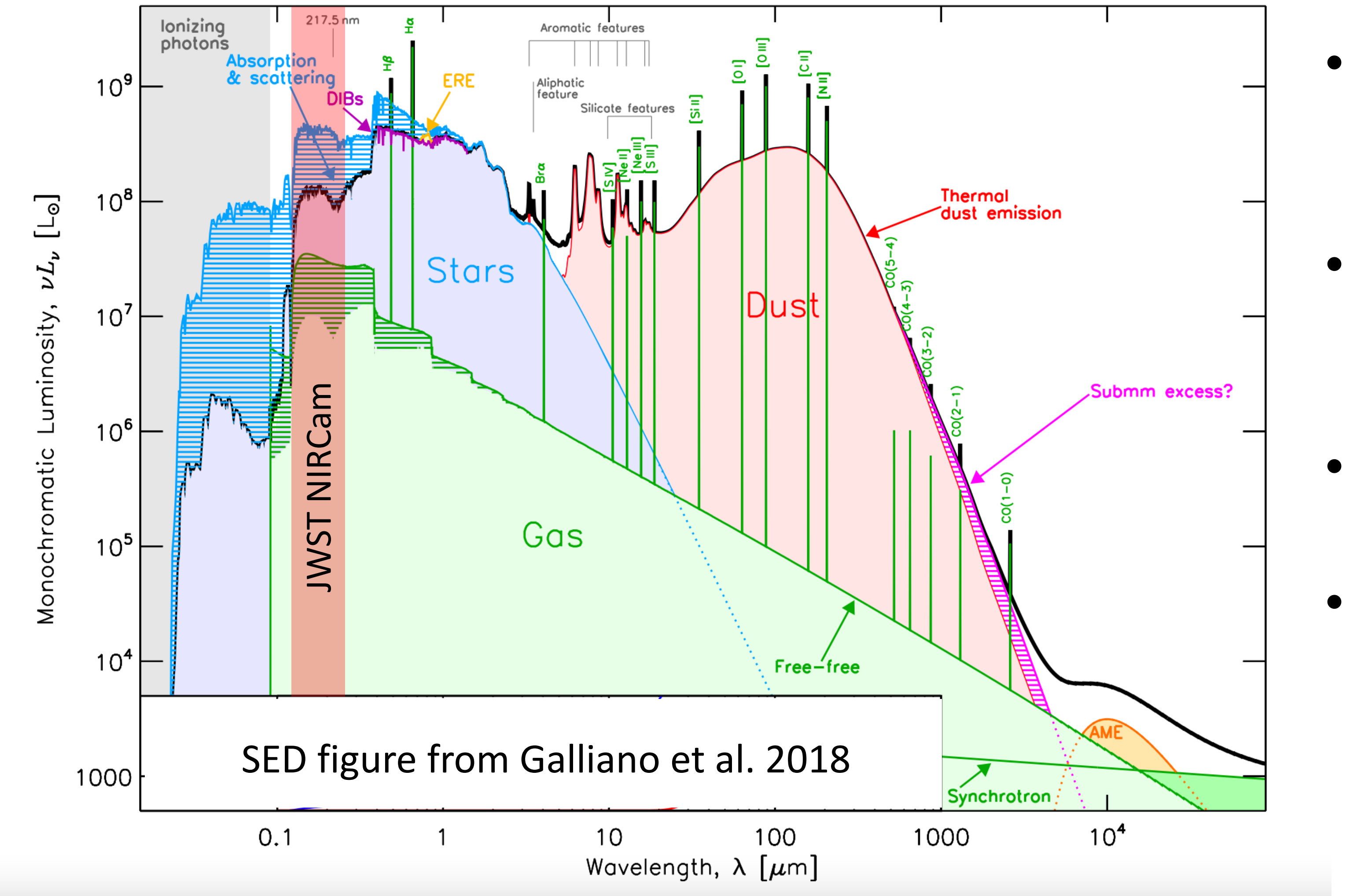
JWST GLASS Program (PI: Treu)
From Two Parallel Fields



NIRCam Filters | F090W F115W F150W F200W F277W F356W F444W

Image credit: Zolt G. Levay (STScI)

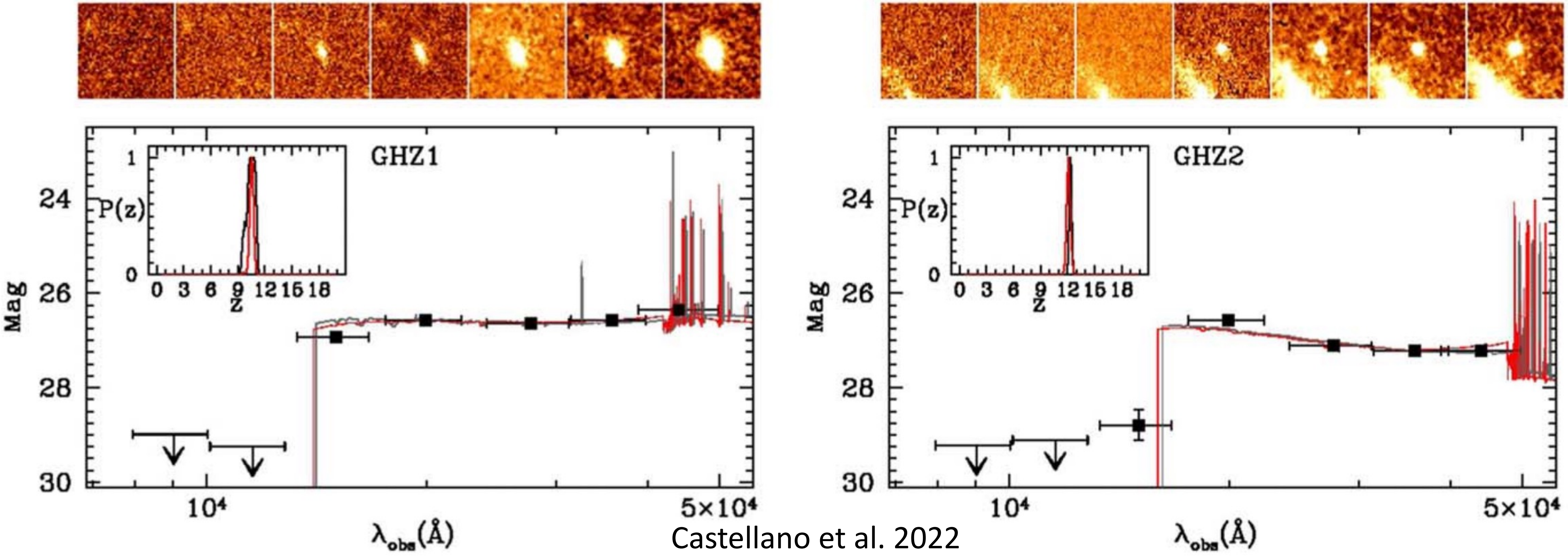
FIR observation of the JWST $z>10$ galaxy candidates



SED figure from Galliano et al. 2018

- ALMA can confirm the spectroscopic redshift when JWST NIRSpec is not available
- Studying $z>10$ galaxies with JWST alone cannot reveal a complete picture
- FIR lines are powerful diagnostics for studying the galaxy ISM
- FIR continuum observation is important to constrain the properties of dust

GHZ1 (GLASS-z10) and GHZ2 (GLASS-z12) on July 2022 firstly and independently reported by Naidu+22 and Castellano+22



Castellano et al. 2022

- One of the two most reliable $z>10$ galaxy candidates with $M_*=10^{9.1}M_\odot$, SFR = 20-25 $M_\odot$/yr and $M_{uv}\sim -21$mag
- Strong Lyman Continuum Break (2.9 mag drop for GHZ1)
- Chose GHZ1 because of the isolated and regular disk-like extended (R_e=450 pc) morphology and its strong and robust LyC break feature

GHZ1: ALMA observing setup and spectrum

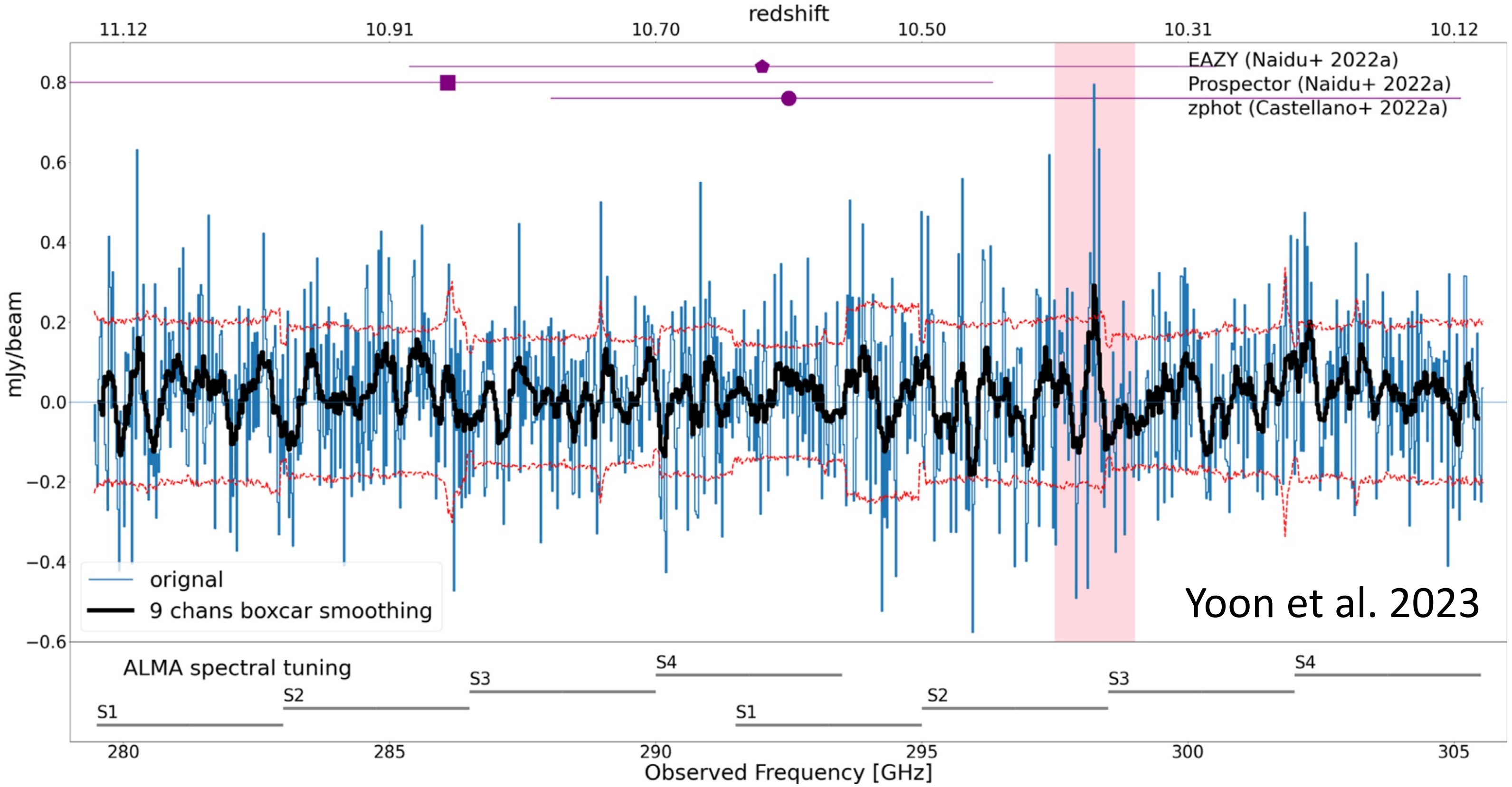


Table 1
ALMA Resolution and Sensitivity with Natural Weighting

Beam (Line) FWHM	Beam (Cont.) FWHM	[a]rms (Line) (μJy beam^{-1}) (Δv)	rms (Cont.) (μJy beam^{-1})
0.″84 × 0.″65	0.″80 × 0.″60	186.0 (25 km s^{-1})	6.0

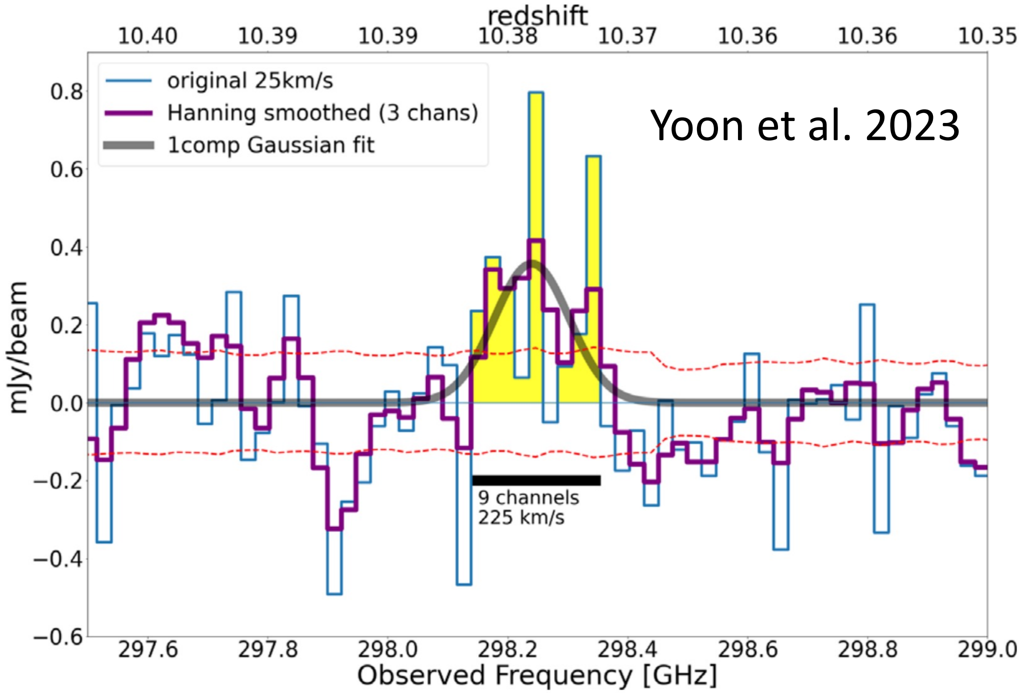
Note.
[a] Averaged over the frequential and spatial domain.

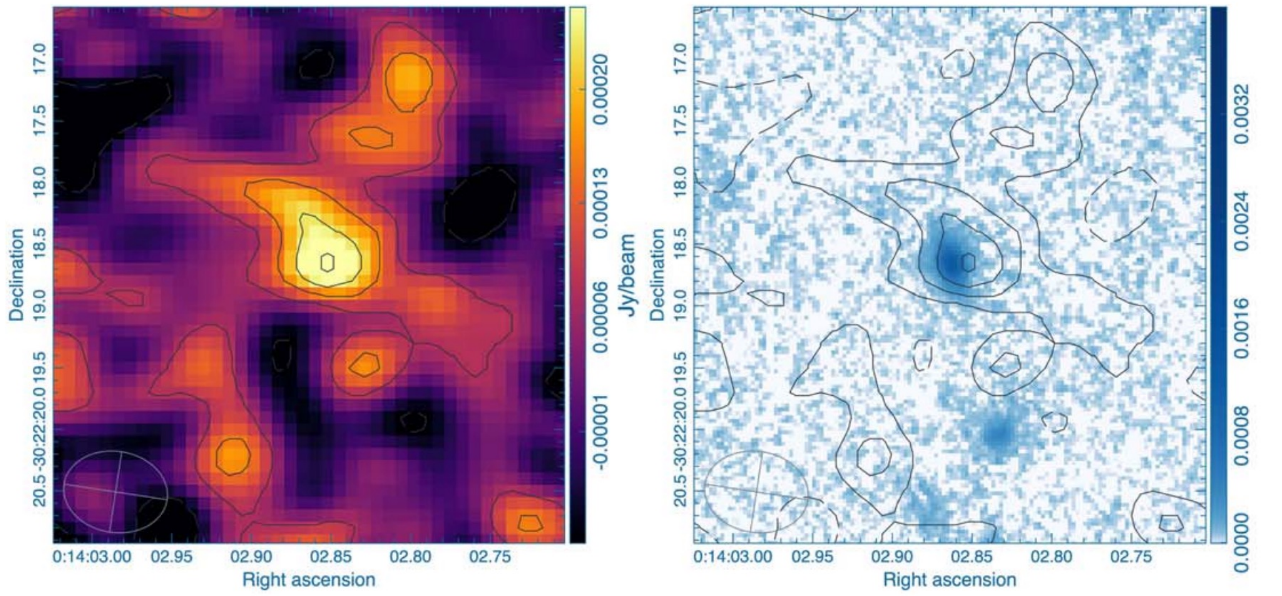
- Aims to detect [OIII]88μm for spectroscopic redshift confirmation
- 4 spectral tunings with 26.12GHz frequency coverage (1.7 hours on source time per tuning)
- Band 7 in very good weather
- Robust spectral ‘feature’ at 298.25GHz persistent in multiple spectral smoothings

Lessons:

GHZ1: What does ALMA observation tell us?

GHZ1: 4.1σ spectral feature in the ALMA cube



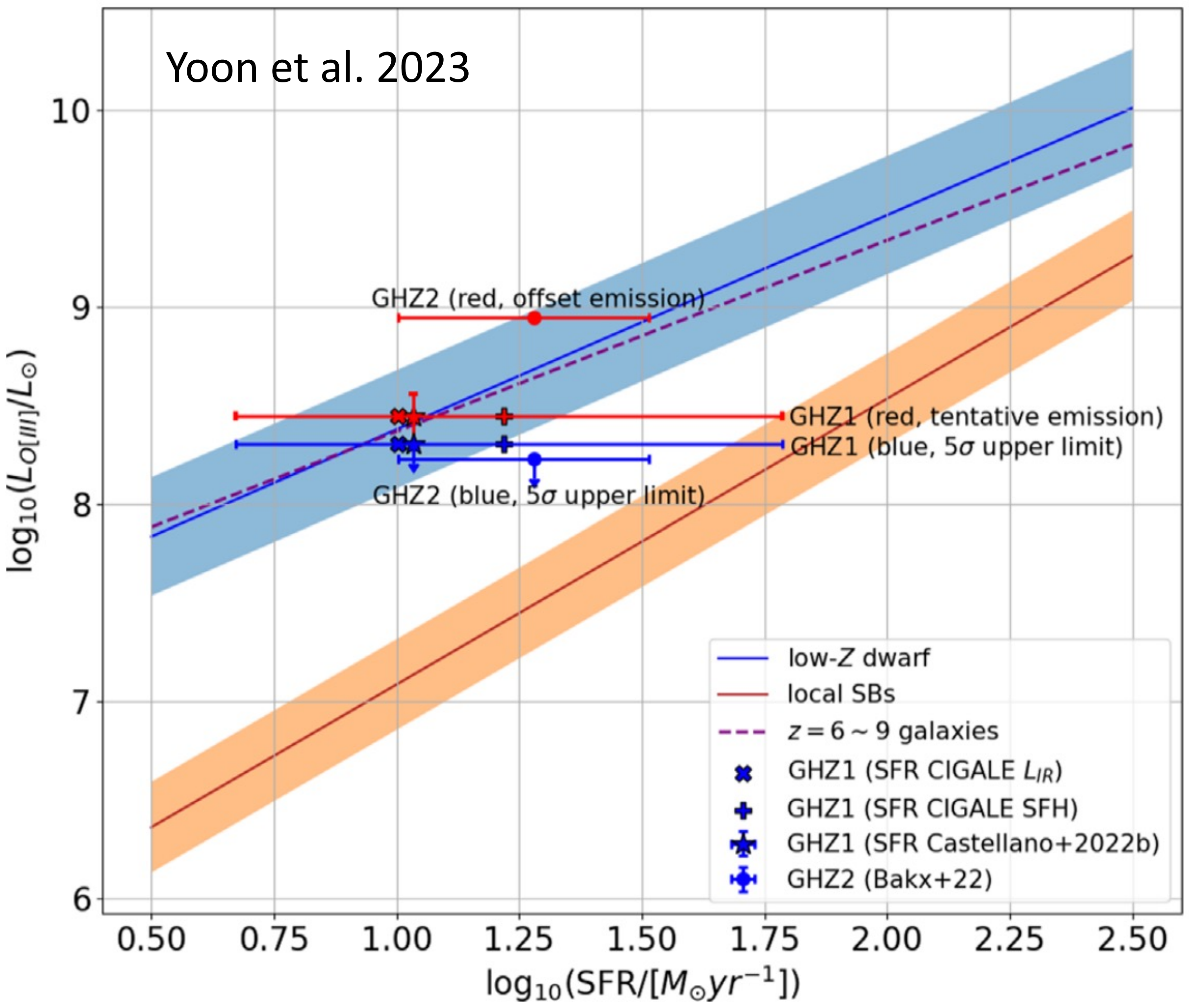


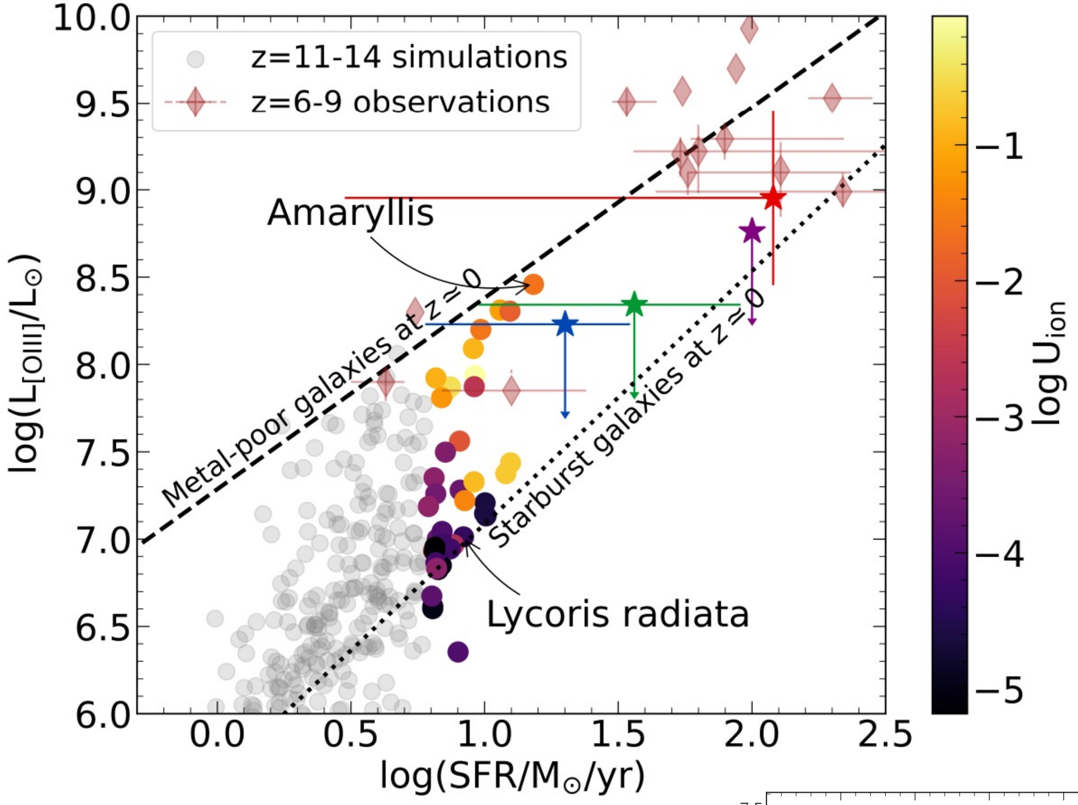
(a) [OIII]$_{88\mu m}$ emission channel map

[O III] (225 km s^{-1} resolution)					
Peak (mJy beam^{-1})	rms (mJy beam^{-1})	[a]$S\Delta v$ (Jy km s^{-1})	[b]$S\Delta v$ (Jy km s^{-1})	[a]$L_{[OIII]}$ ($L_\odot$)	[b]$L_{[OIII]}$ ($L_\odot$)
0.31	0.075	0.056	0.078 ± 0.023	2.06×10^8	$2.83^{+0.83}_{-0.83} \times 10^8$

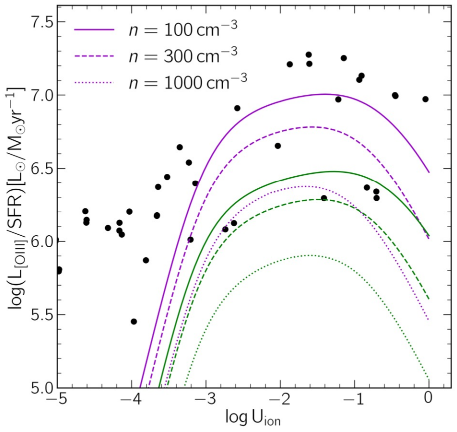
- 225 km/s channel width (9 channels) cube produce 4.1 sigma emission
- 0.17arcsec offset from the JWST position

GHZ1: [OIII] luminosity



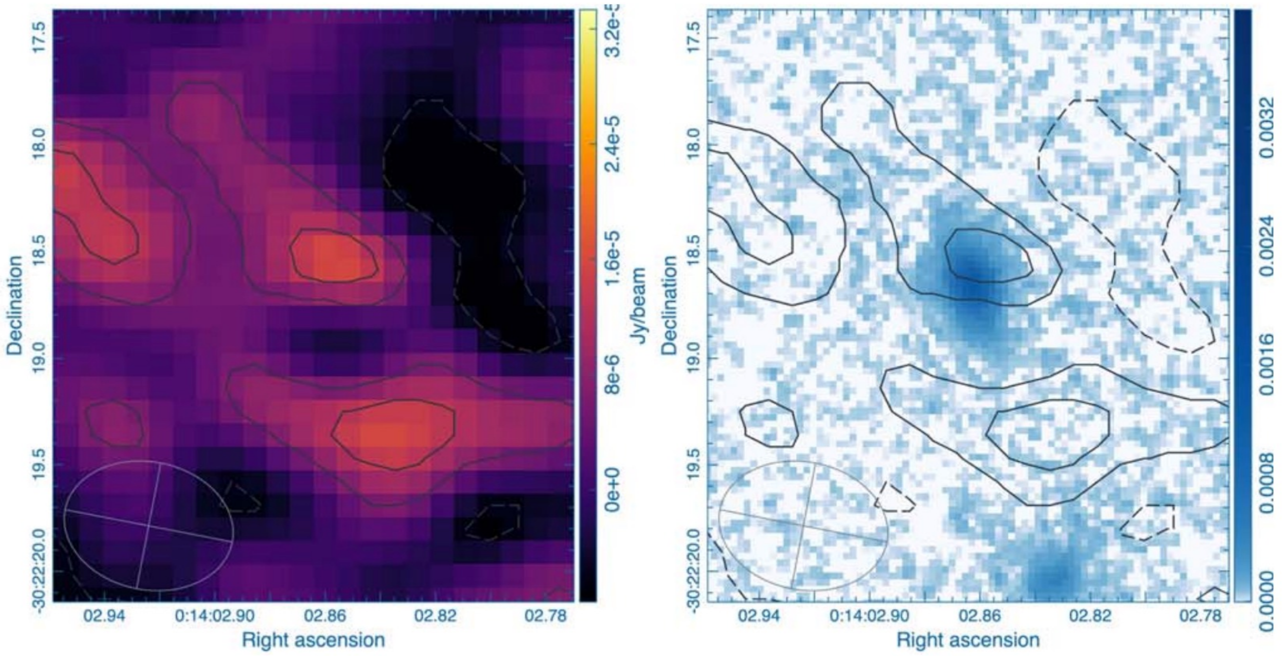


Kohandel+23



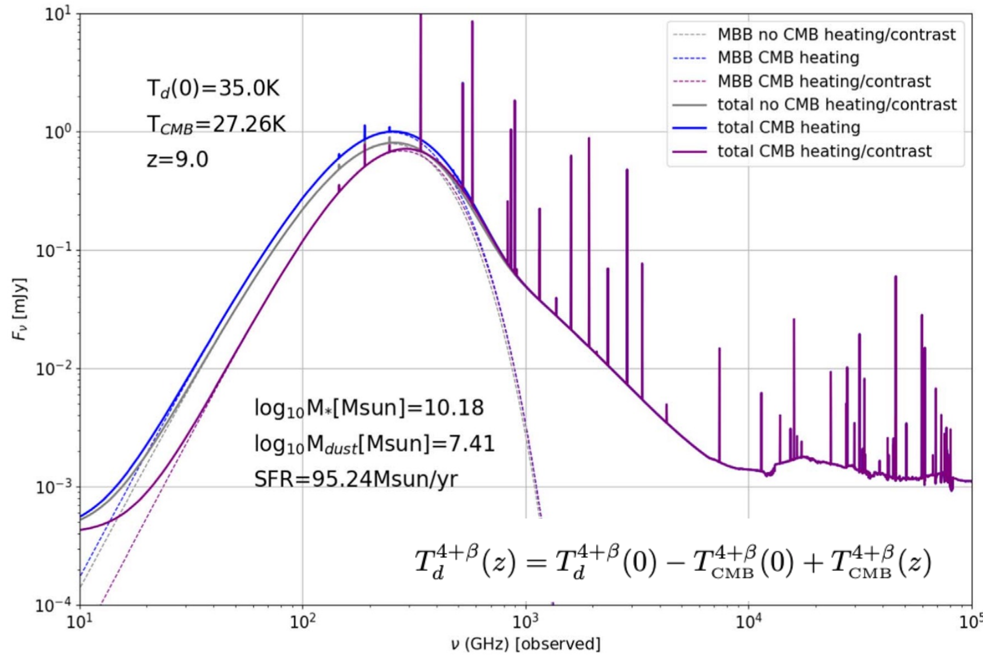
- Non-detection can be explained by low metallicity and low ionization parameter
- Firm detection is important to constrain the model

GHZ1: continuum emission map and SED model



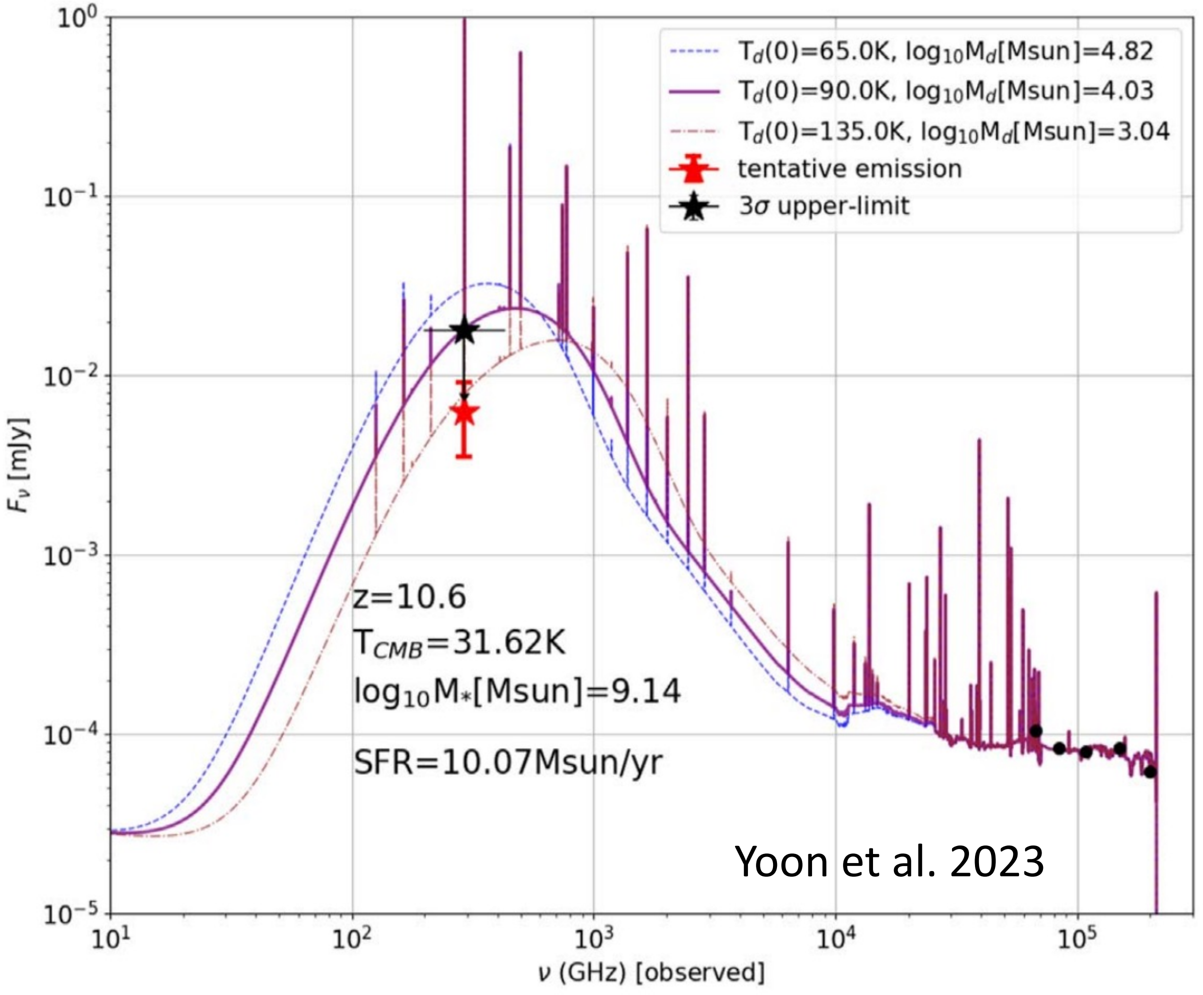
(b) FIR continuum emission map

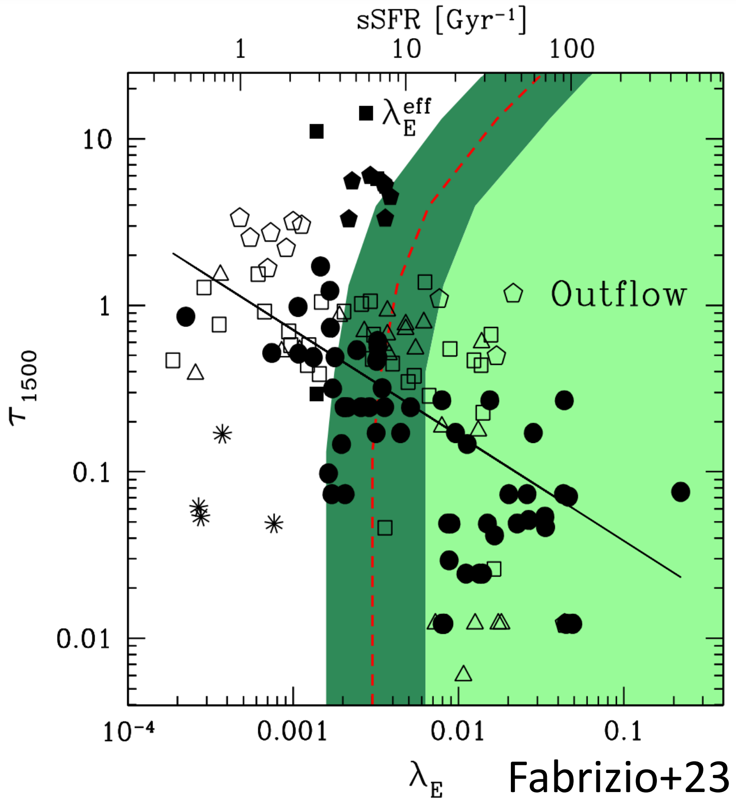
Continuum			
Peak (μJy beam^{-1})	rms (μJy beam^{-1})	[a]$F_{292.5\mathrm{GHz}}$ (μJy)	[b]$F_{292.5\mathrm{GHz}}$ (μJy)
15.6	6.0	18.0	6.3 ± 2.8



- CIGALE SED model with CMB effect
- CMB heating: $$L_{\rm IR}^{\rm tot} = 2.29 \times 10^{21} \left(\frac{T_d(z)}{\rm K}\right)^{5.6} \left(\frac{M_{dust}}{M_\odot}\right) = 2.29 \times 10^{21} \left(\frac{T_{\rm CMB}(z)}{\rm K}\right)^{5.6} \left(\frac{M_{dust}}{M_\odot}\right) + L_{\rm IR}^{\rm abs}$$
- CMB contrast: $1 - \{B_\nu\left[T_{\rm CMB}(z)\right] / B_\nu\left[T_d(z)\right]\}$

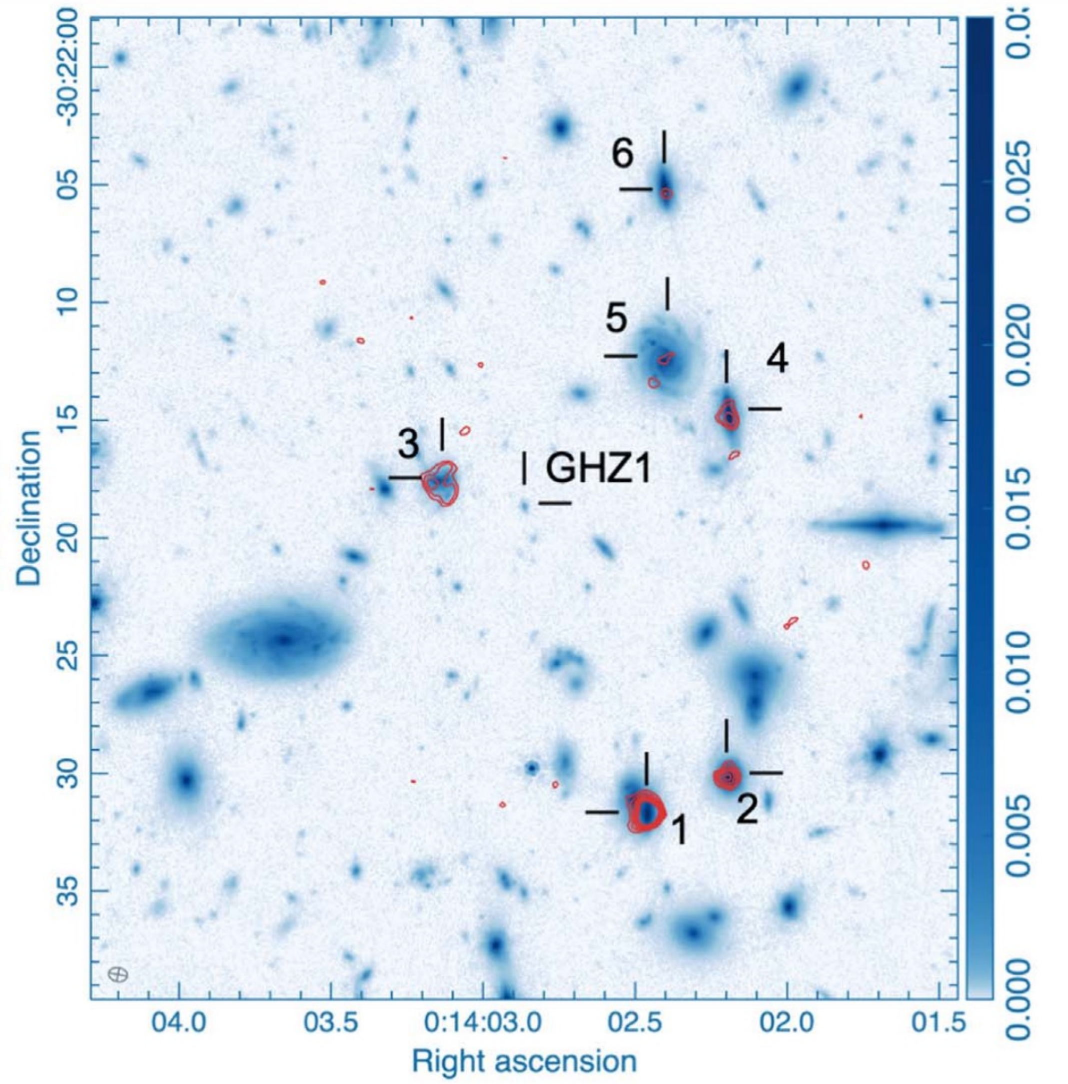
GHZ1: Implications of the FIR continuum observation



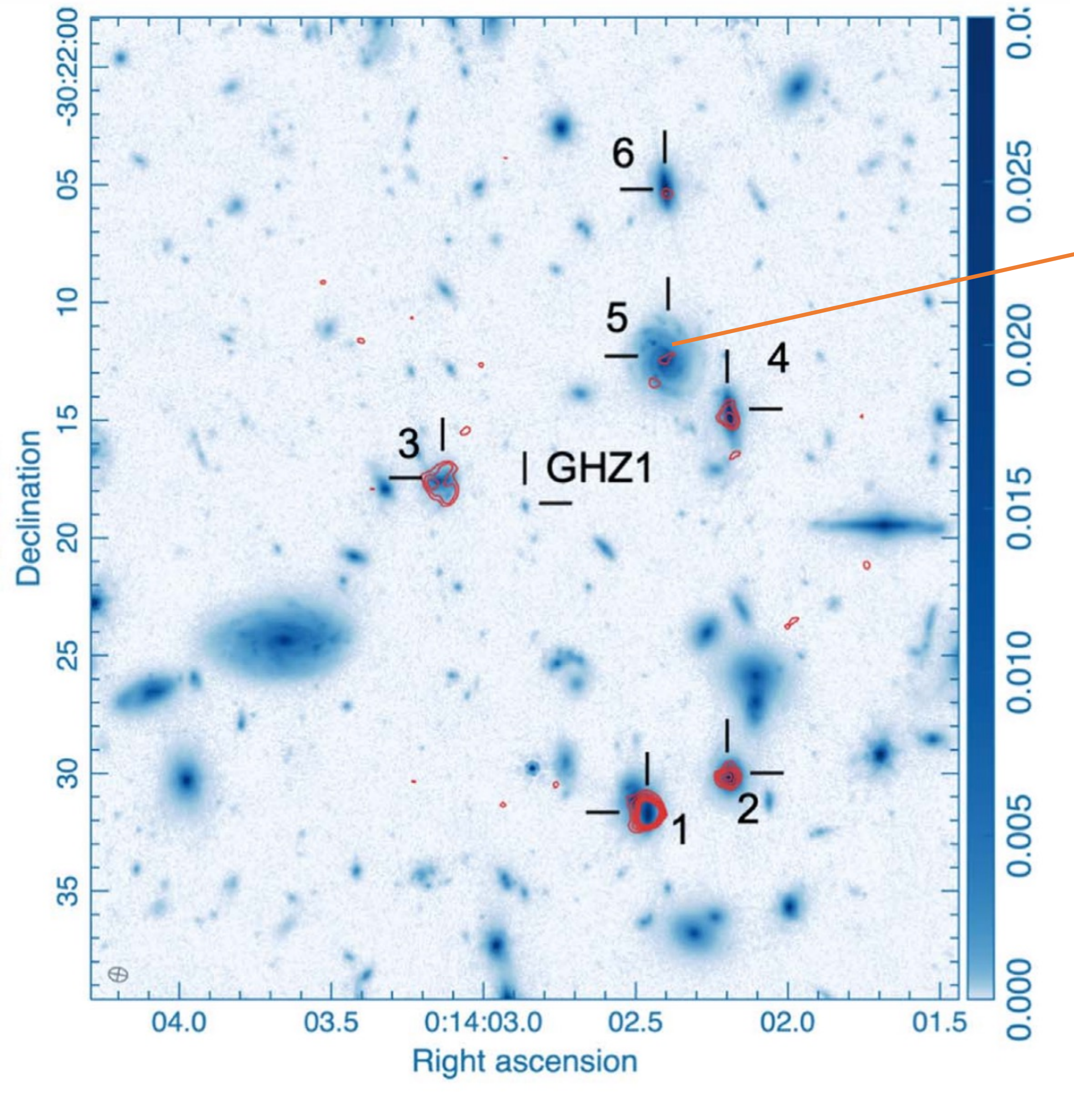


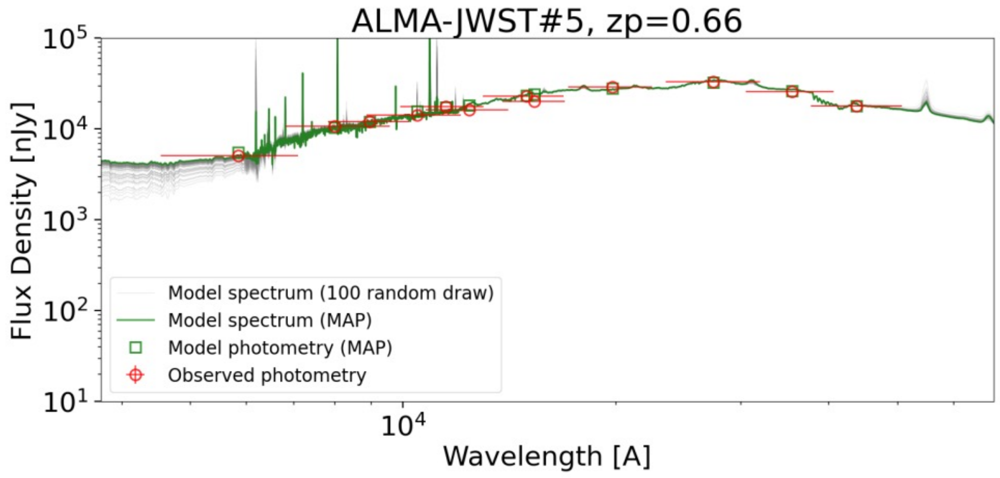
- Very small dust content ($M_d < 10^4 M_\odot$)
- High dust temperature (T_d>90K)
- Dust ejection due to strong radiation feedback?

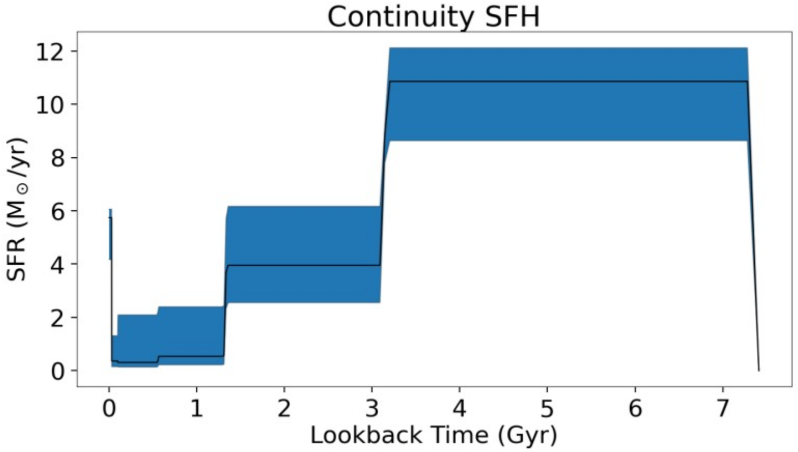
Serendipitous Continuum Sources (ongoing work)



Serendipitous Continuum Sources (ongoing work)



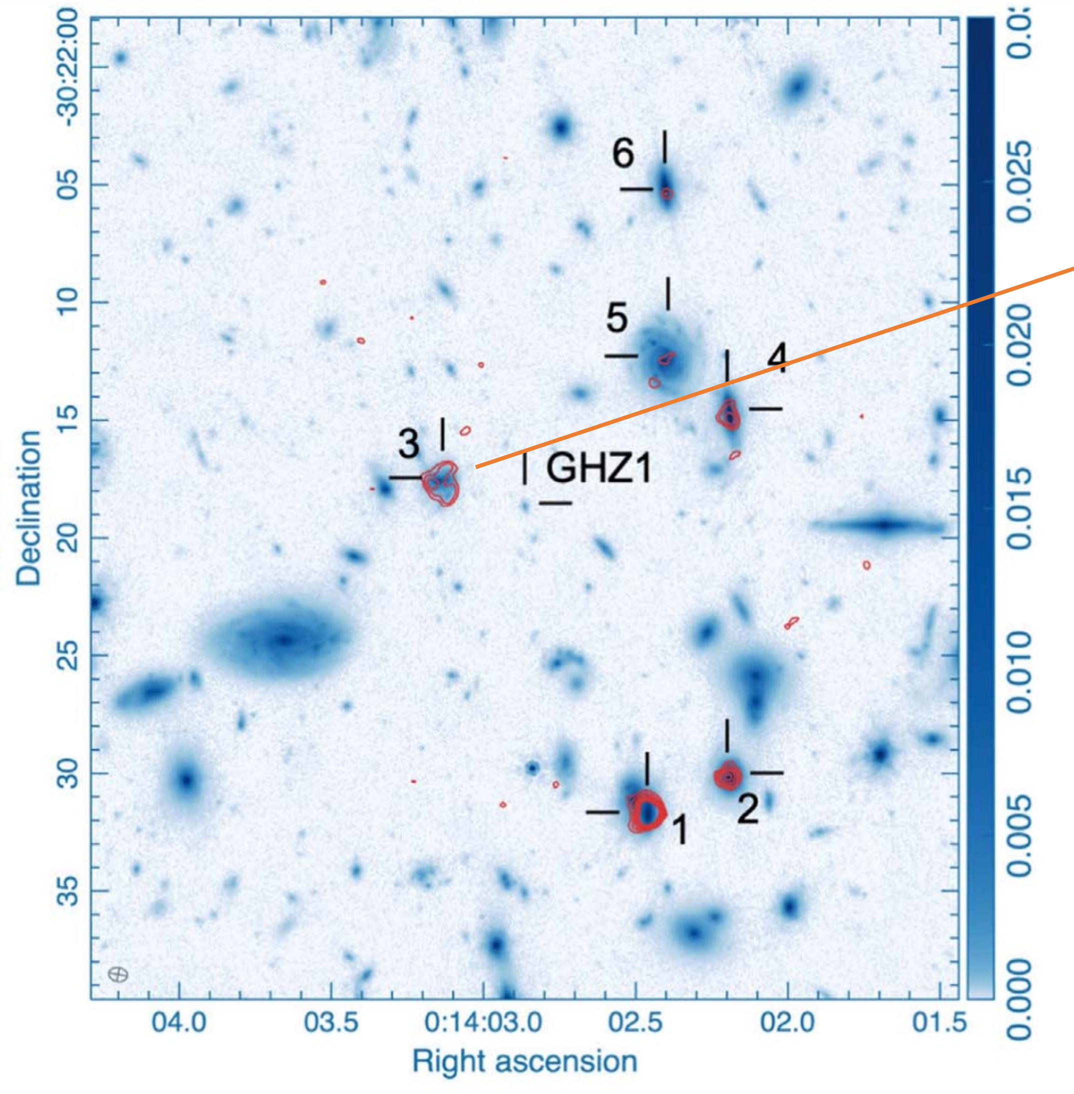


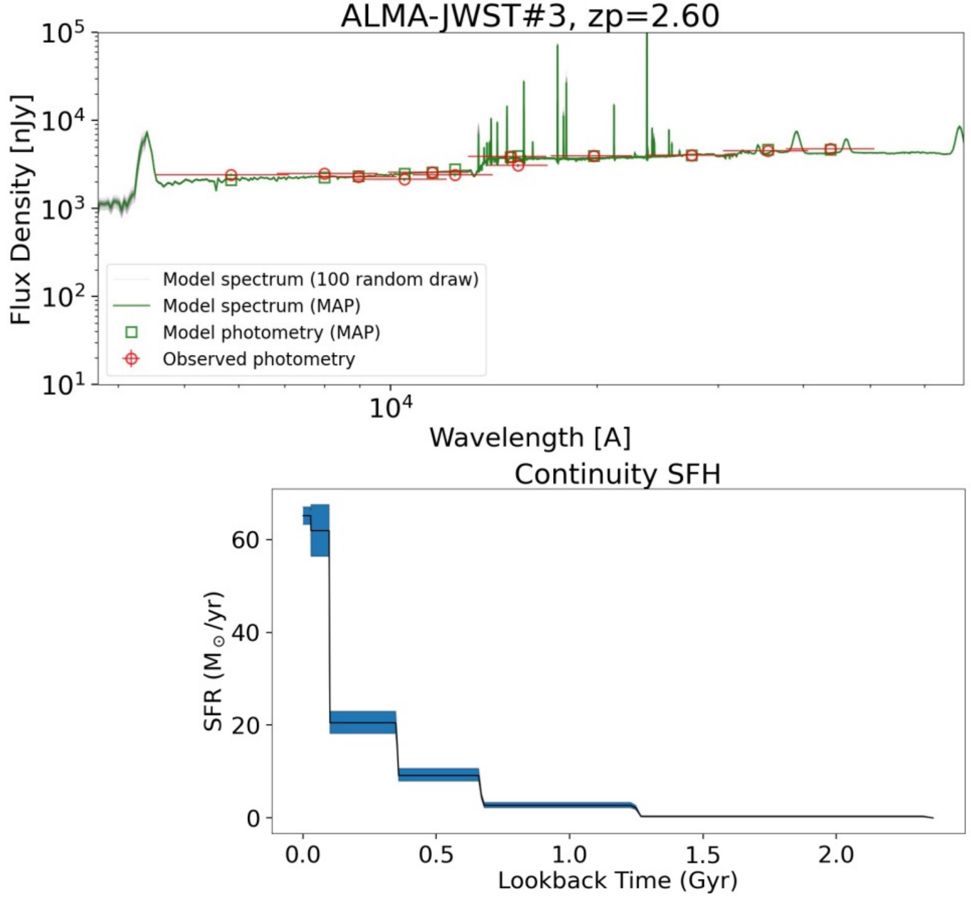


Example

Prospector SED model

Serendipitous Continuum Sources (ongoing work)

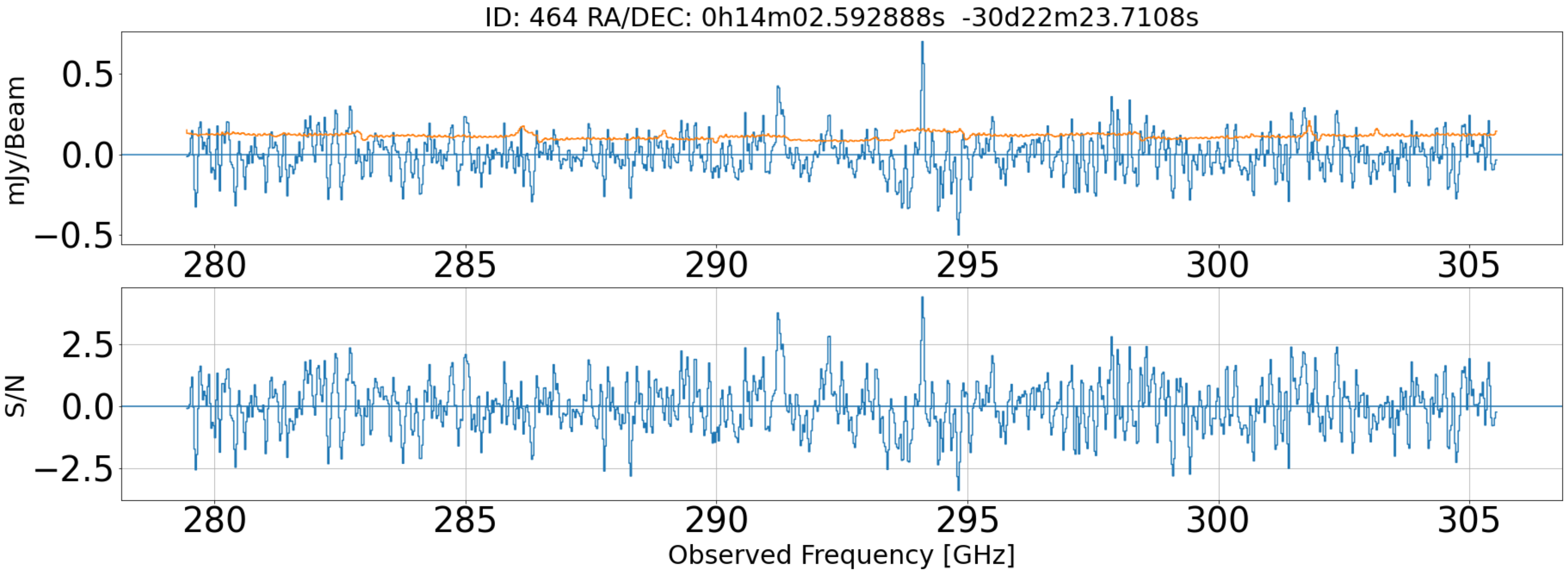


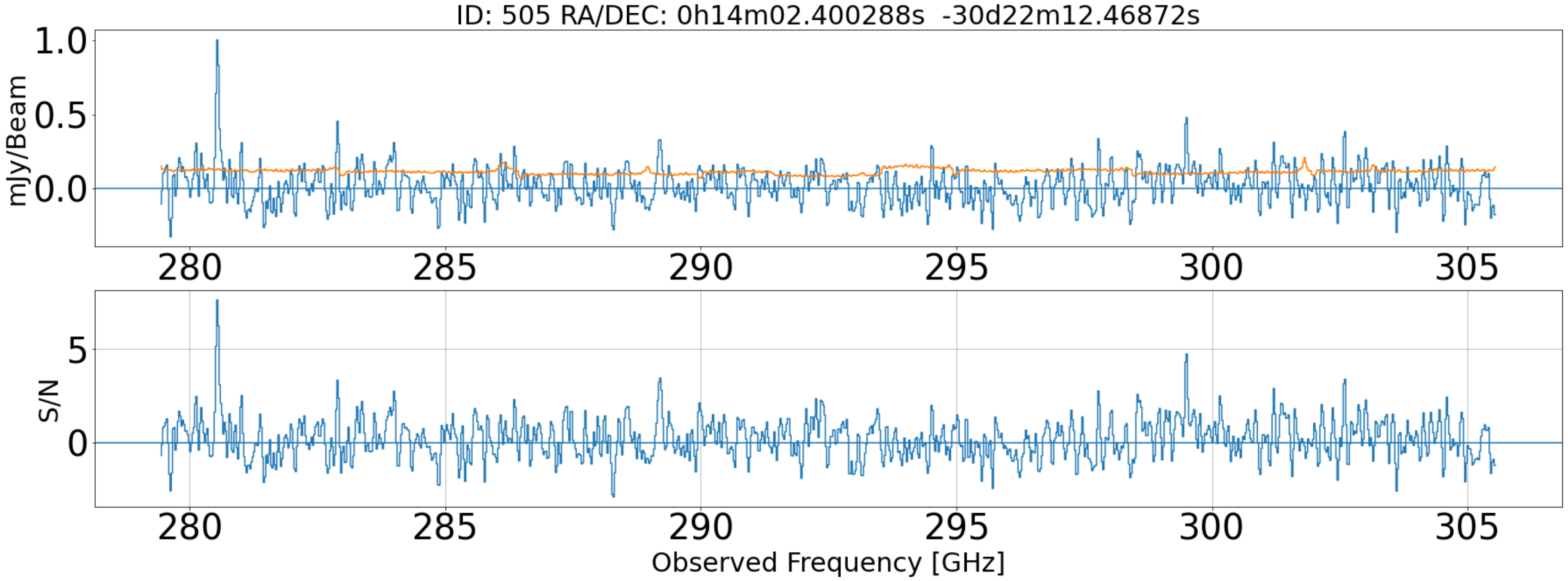


Example

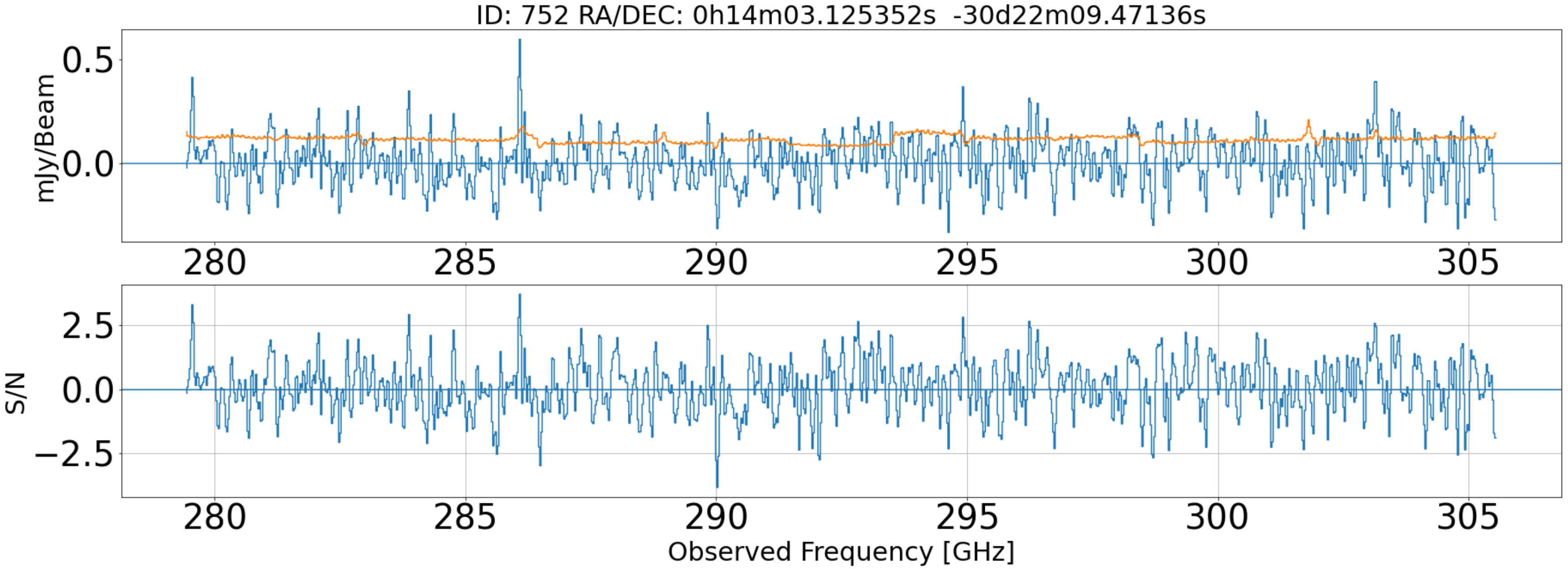
Prospector SED model

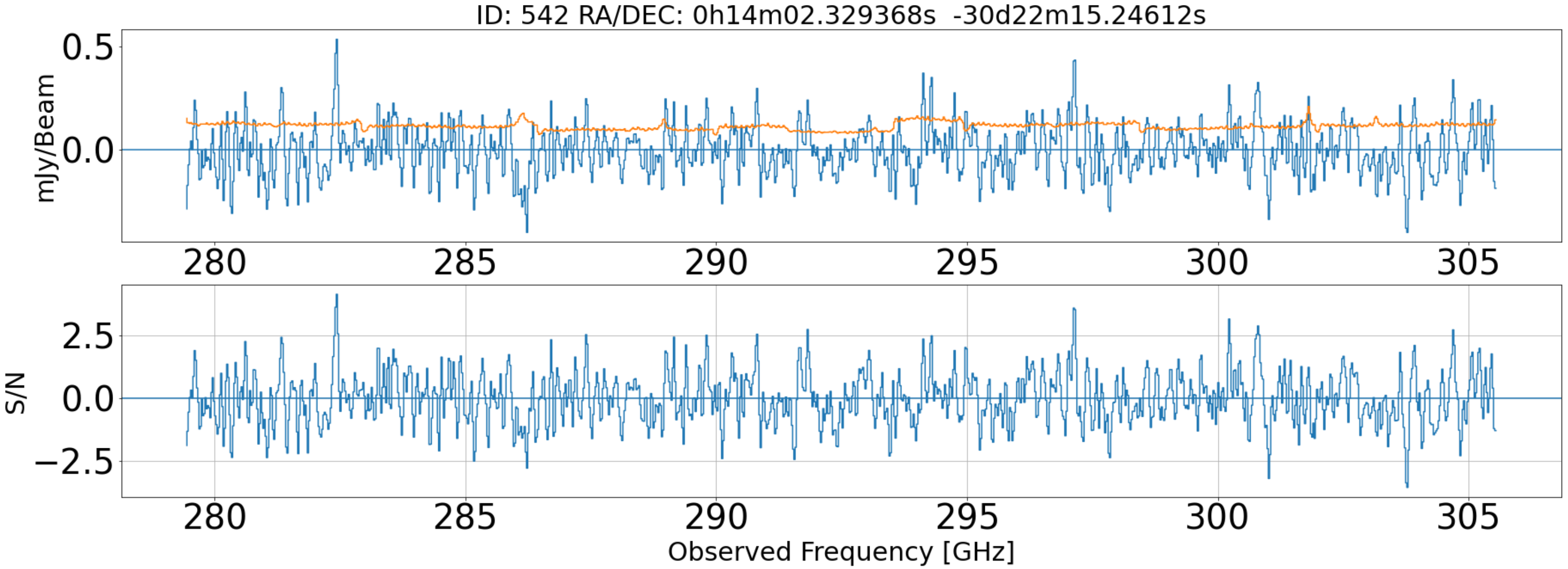
Serendipitous Line Emitters (ongoing work)





Serendipitous Line Emitters (ongoing work)





Prospects:

Wideband and High sensitivity ALMA: what can we do with ALMA for the study of first galaxy formation?

ALMA Wideband Sensitivity Upgrade (WSU)

Table 4. Increase in the spectral scan speed with the 2× bandwidth WSU

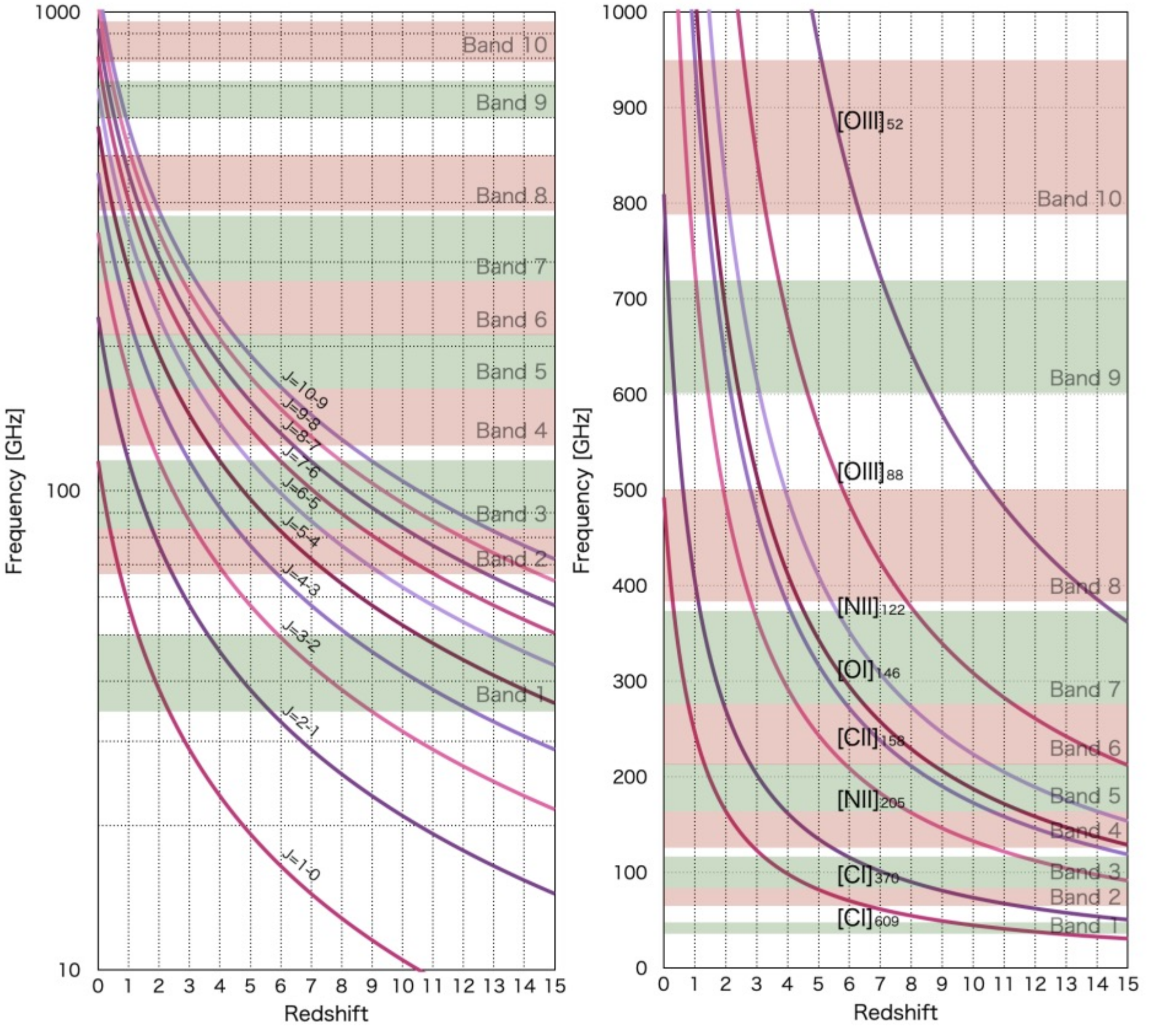
Band Properties			Low Spectral Resolution				High Spectral Resolution (0.1–0.2 km s^{-1})				
			Current		WSU		Current			WSU	
Band	Rep. Freq. (GHz)	RF BW (GHz)	Velocity Res. (km s^{-1})	Number Tunings	Number Tunings	Time Savings Factor	Velocity Res. (km s^{-1})	Max CBW (GHz)	Number Tunings	Number Tunings	Time Savings Factor
1	35	15	8.36	2	1	2.0	0.26	0.234	64	1	64.0
2	75	49	3.90	8	4	2.0	0.12	0.234	209	4	52.3
3	100	32	2.93	5	2	2.5	0.19	0.469	68	2	34.0
4	150	38	1.95	7	3	2.3	0.12	0.468	81	3	27.0
5	185	48	1.58	8	4	2.0	0.10	0.468	103	4	25.8
6v2	230	64	1.27	9	4	2.1	0.16	0.938	68	4	17.0
7	345	98	0.85	17	7	2.4	0.11	0.938	105	7	15.0
8	460	115	0.64	18	9	2.0	0.16	1.875	61	9	6.8
9	650	118	0.45	10	8	1.3	0.11	1.875	63	8	7.9
10	870	163	0.34	13	10	1.3	0.17	3.75	43	10	4.3

Notes: Comparison of the number of spectral tunings currently required to span each band's RF range, for the "low" and "high" spectral resolution regimes. The exact spectral resolution is defined by what the BLC can achieve. The time savings only considers the efficiency of spectral scan tunings, and does not include the expected improvements in the digitizer and correlator efficiencies or receiver performance.

https://ui.adsabs.harvard.edu/abs/2023pcsf.conf..304C/abstract

- ALMA 2030 development plan: study of z>10 galaxies
- More efficient spectral scanning for redshift search (2-4 times faster for the same sensitivity and bandwidth)
- Larger bandwidth combined with improved sensitivity shortens the observing time down to 30% of the current ALMA
- Larger instantaneous frequency grasp enabling simultaneous molecular detections and improving ability to trace large-velocity outflows

Pair of lines in the rest frame frequency

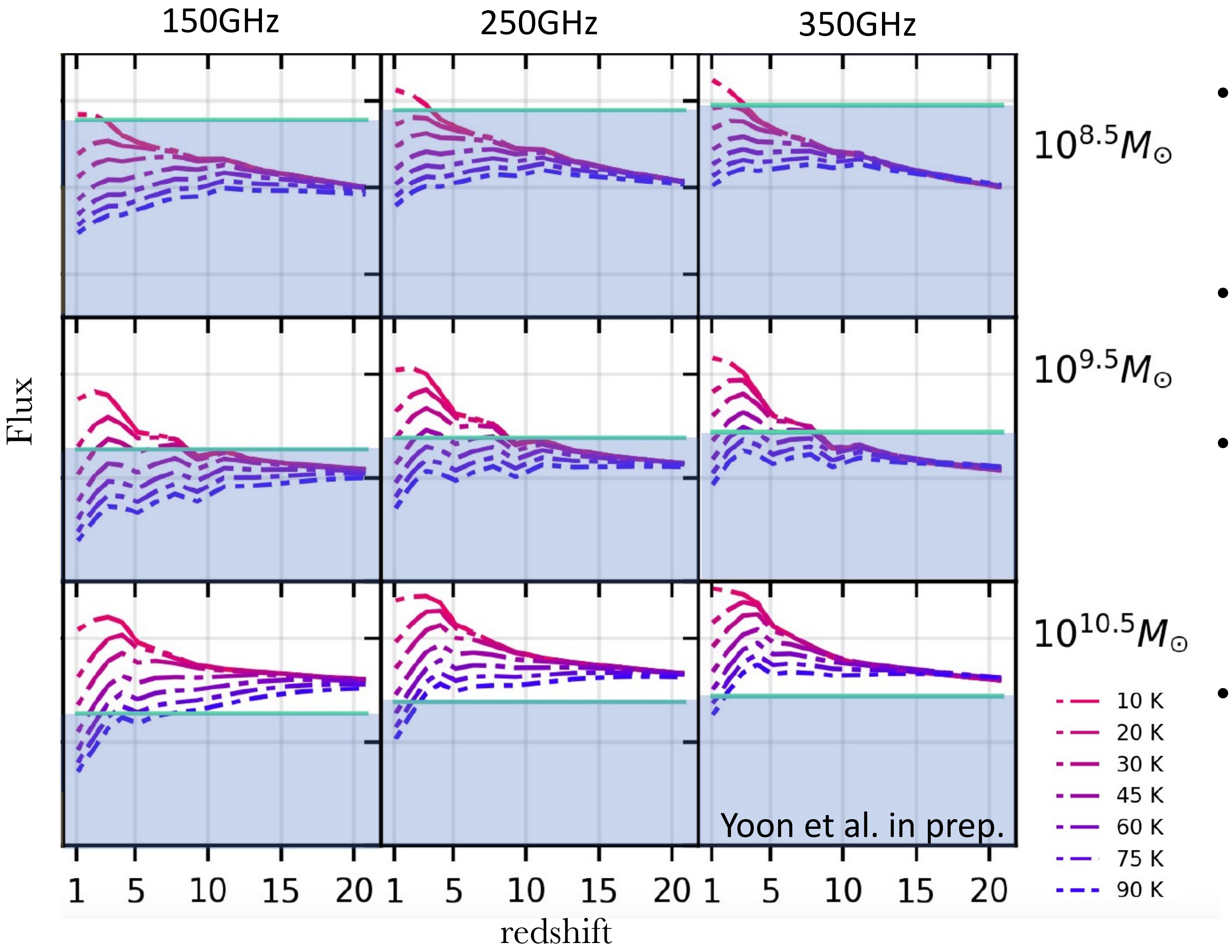


[CI]: 809GHz−CO(7-6): 806GHz → $\delta\nu$ = 3 GHz
[CI]: 492GHz−CO(4-3): 461GHz → $\delta\nu$ = 31 GHz
[CII]: 1900GHz−CO(16-15): 1844GHz → $\delta\nu$ = 56 GHz
[CII]: 1900GHz−CO(17-16): 1959GHz → $\delta\nu$ = 59 GHz
[NII]: 1461GHz−CO(13-12): 1498GHz → $\delta\nu$ = 38 GHz
[OI]: 2060GHz−CO(17-16): 1959GHz → $\delta\nu$ = 61 GHz
[OI]: 2060GHz−CO(18-17): 2075GHz → $\delta\nu$ = 15 GHz

- $\delta\nu$ in the observing frame only gets smaller by $1/(1+z)$
- some pairs of lines can be observed with one tuning

https://ui.adsabs.harvard.edu/abs/2023pcsf.conf..304C/abstract

ALMA FIR continuum observation of high-z galaxies
(UV selected galaxy from JAGUAR catalog)



- Simulating galaxy SED using the mock catalog of the JWST Advanced Deep Extragalactic Survey (Williams et al. 2018)
- Expected ALMA FIR continuum flux compared with 3 σ sensitivity for 1 hour integration
- Current ALMA is not sensitive enough to detect low mass galaxies but ALMA WSU (w/ 3× better continuum sensitivity) will be able to detect them
- Detection is biased toward a massive galaxy with cool dust

Conclusion

- ALMA follow up on $z>10$ galaxy candidates GHZ1 does not have enough sensitivity to claim a detection
- A tentative 4.1σ line emission feature from the location of JWST galaxy suggests that GHZ1 is metal poor
- Dust continuum emission is faint (currently under the ALMA sensitivity limit) and the 3σ upper limit suggests a small amount of hot dust
- Wide band spectral tuning also discovers serendipitous line emitters and continuum sources
- ALMA WSU will improve the efficiency of detection of the lines and continuum from high-z galaxies