The z-GAL survey

First results

Stefano Berta

on behalf of the z-GAL Team

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The mm Universe – Grenoble – June 27th, 2023

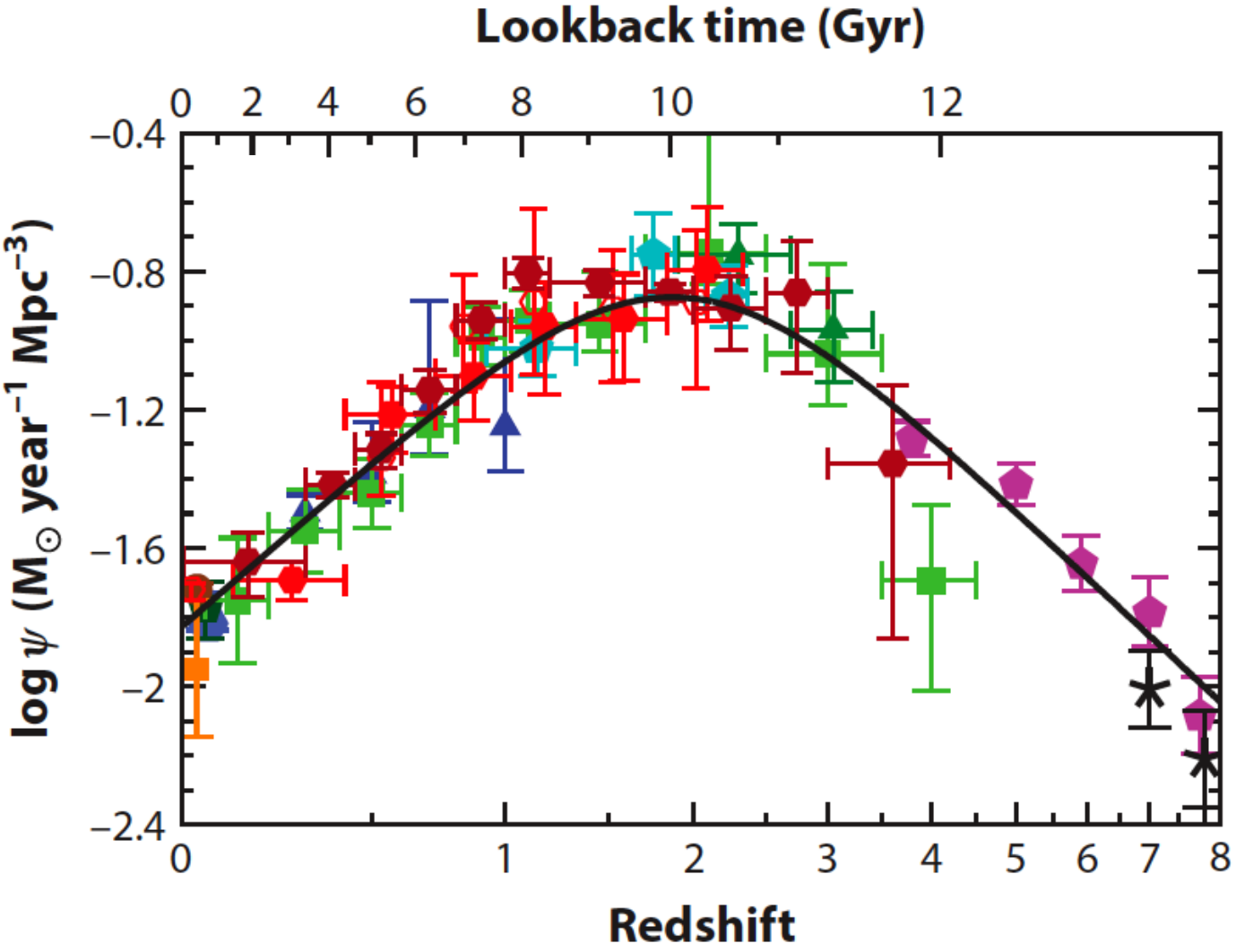
Brief Outline

- Motivation & Introduction
- The z-GAL NOEMA Project
- Observing Strategy
- Spectroscopic redshifts
- SED fitting: dust properties
- Molecular gas properties
- Nature of the z-GAL sources
- Conclusions & Perspectives

Paper I: Cox, Neri, Berta et al. (2023, A&A sub.)
Paper II: Ismael, Beelen, Buat et al. (2023, A&A sub.)
Paper III: Berta, Stanley, Ismail et al. (2023, A&A sub.)

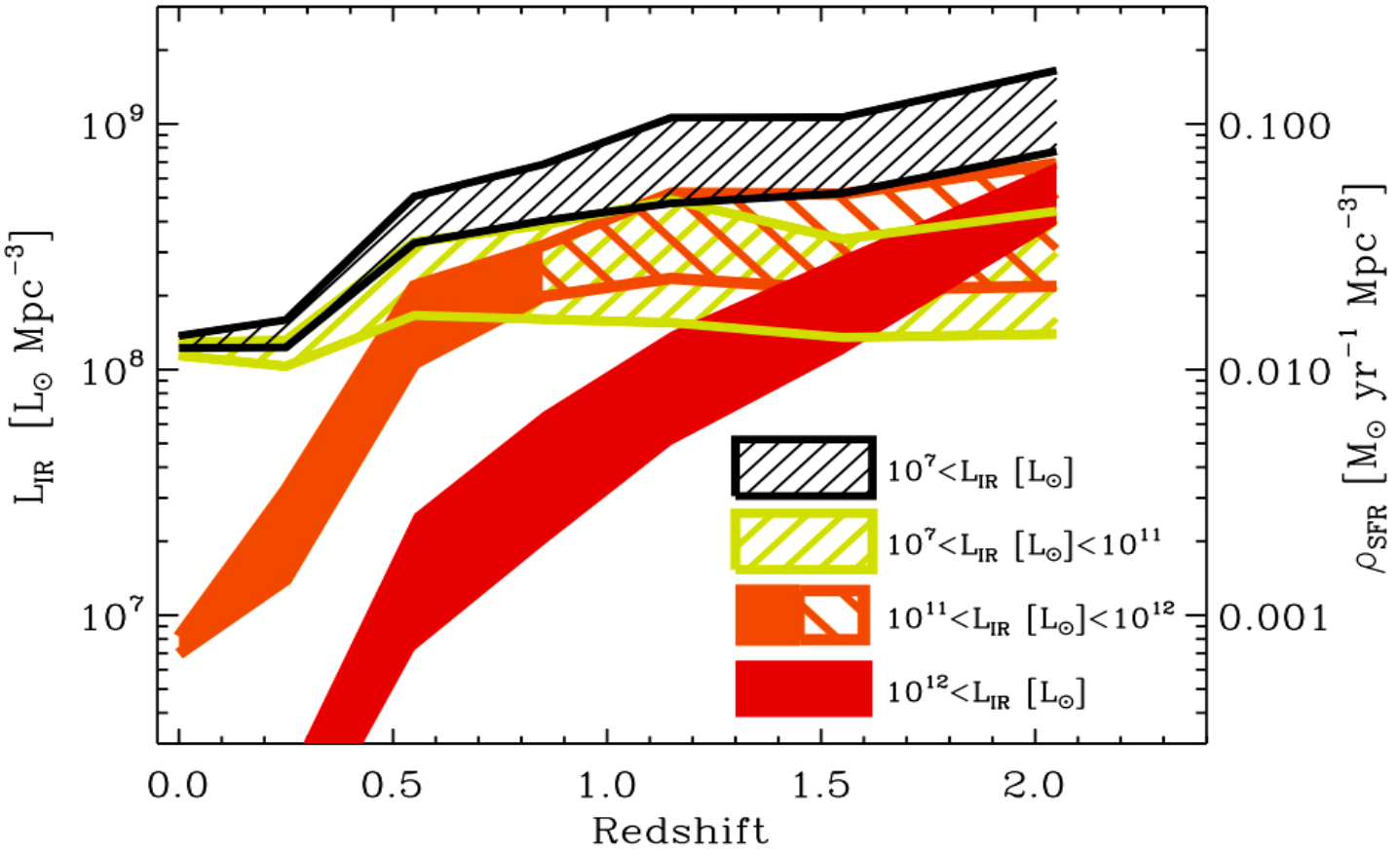
Neri+ (2020, A&A, 635, A7); Berta+ (2021, A&A, 646, A122); Stanley+ (2023, ApJ, 945, 24)

Star formation across cosmic time



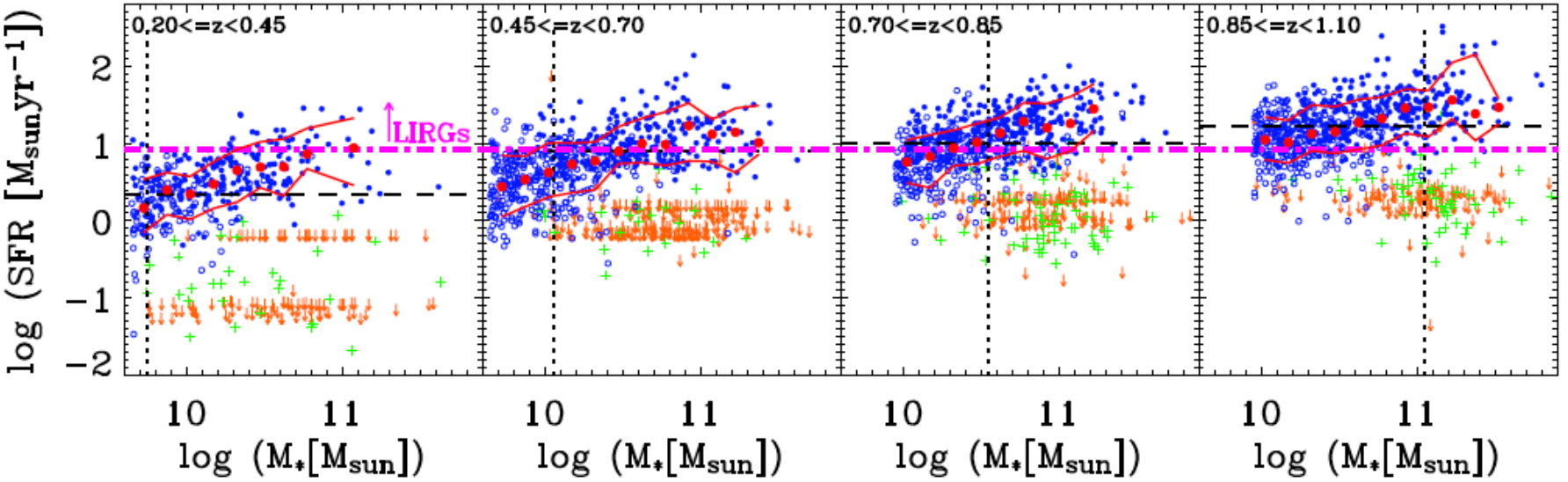
e.g. Madau & Dickinson (2014)

Star formation across cosmic time



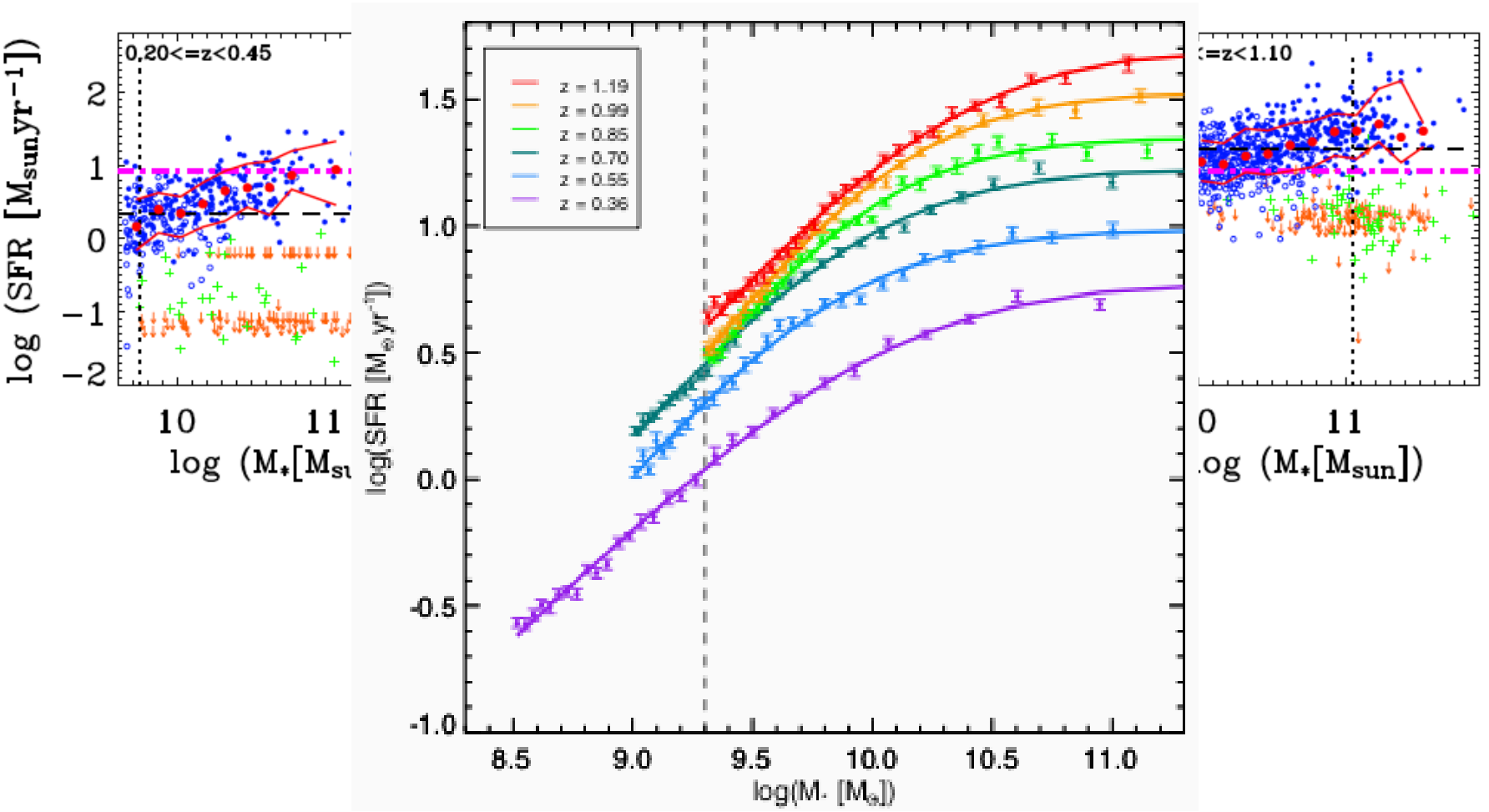
e.g. Magnelli+ (2011, 2013), Le Floch+ (2005), Goto+ (2010), Lim+ (2019), among many

Star formation main sequence



Guzman+ (1997), Brinchmann & Ellis (2000), Perez-Gonzalez+ (2005), Papovich+ (2006), Caputi+ (2006), Reddy+ (2006), Noeske+ (2007), Elbaz+ (2007), Daddi+ (2007), Rodighiero+ (2011), Sargent+ (2014), Schreiber+ (2015), Lee+ (2015), and many many many others.

Star formation main sequence



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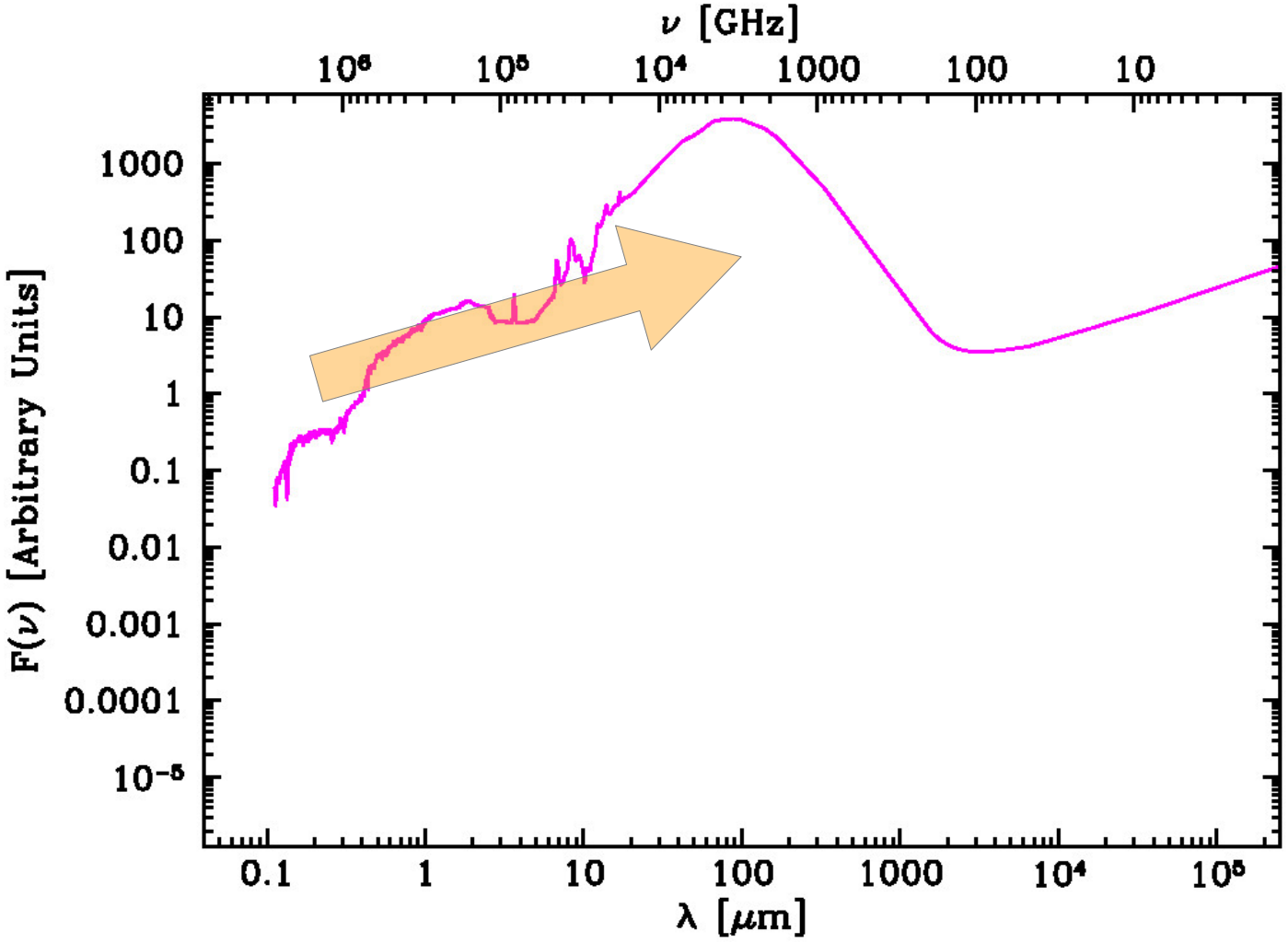
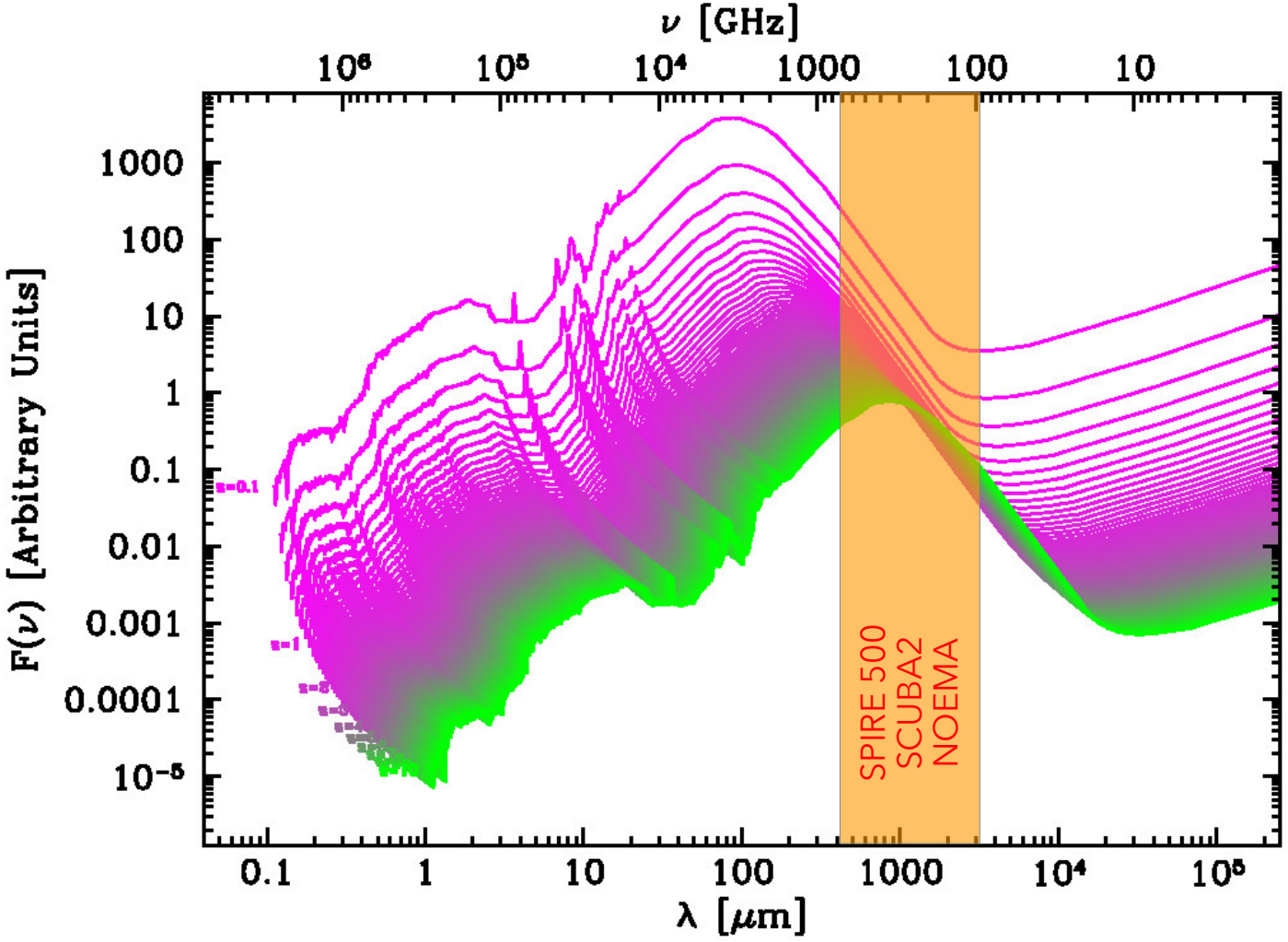
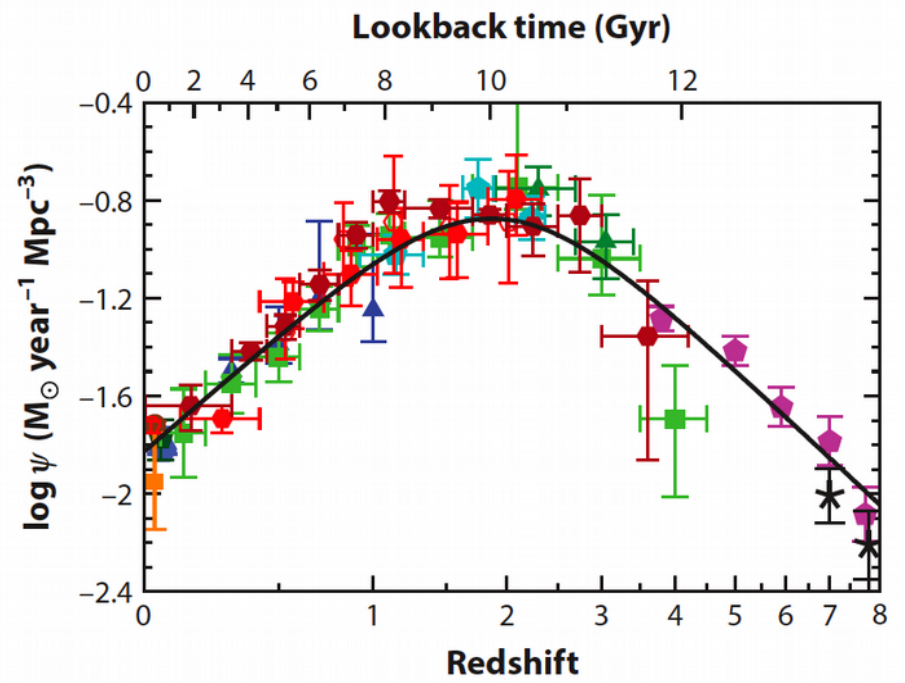
Observing at long wavelengths

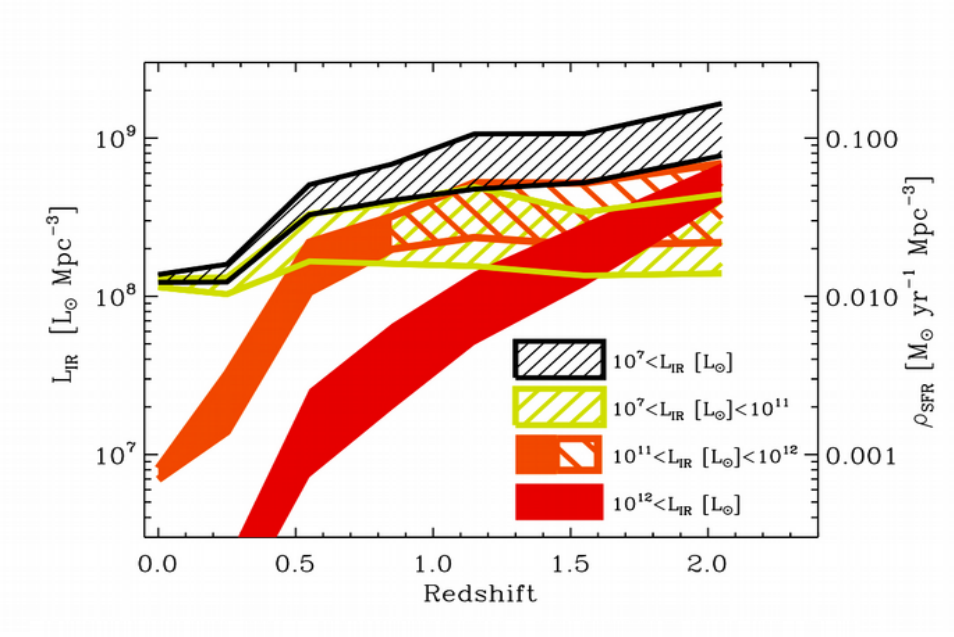


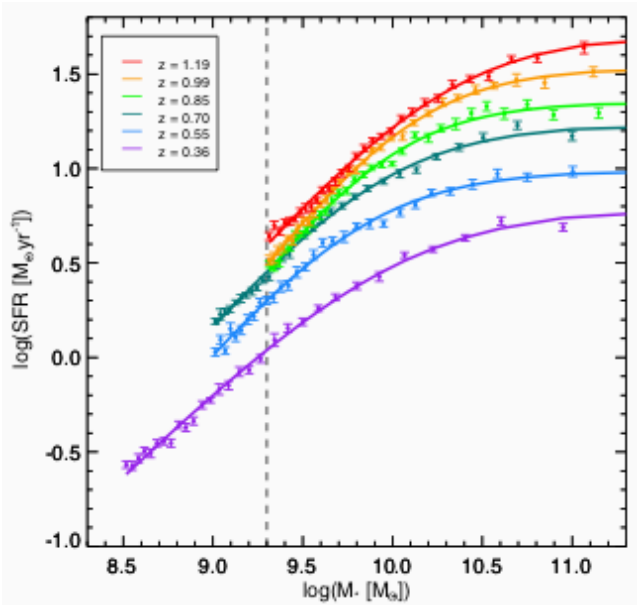
Observing at long wavelengths

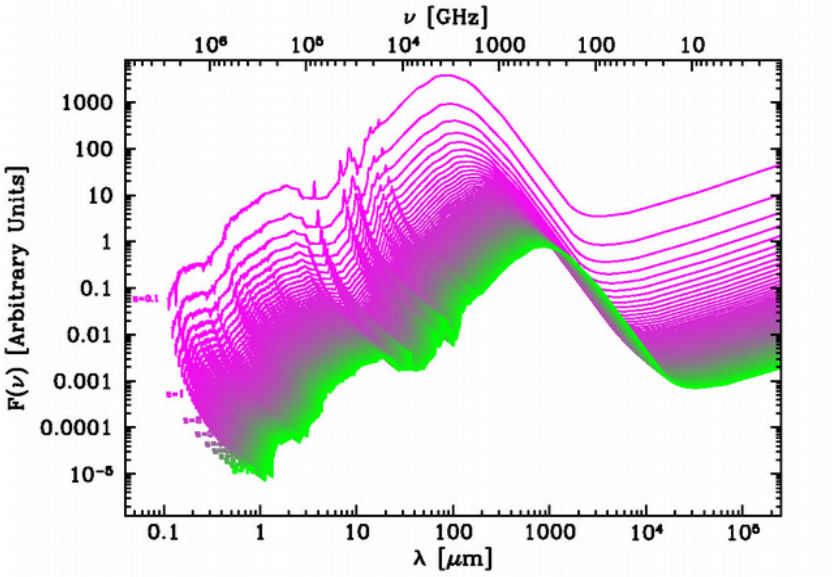


Ingredients



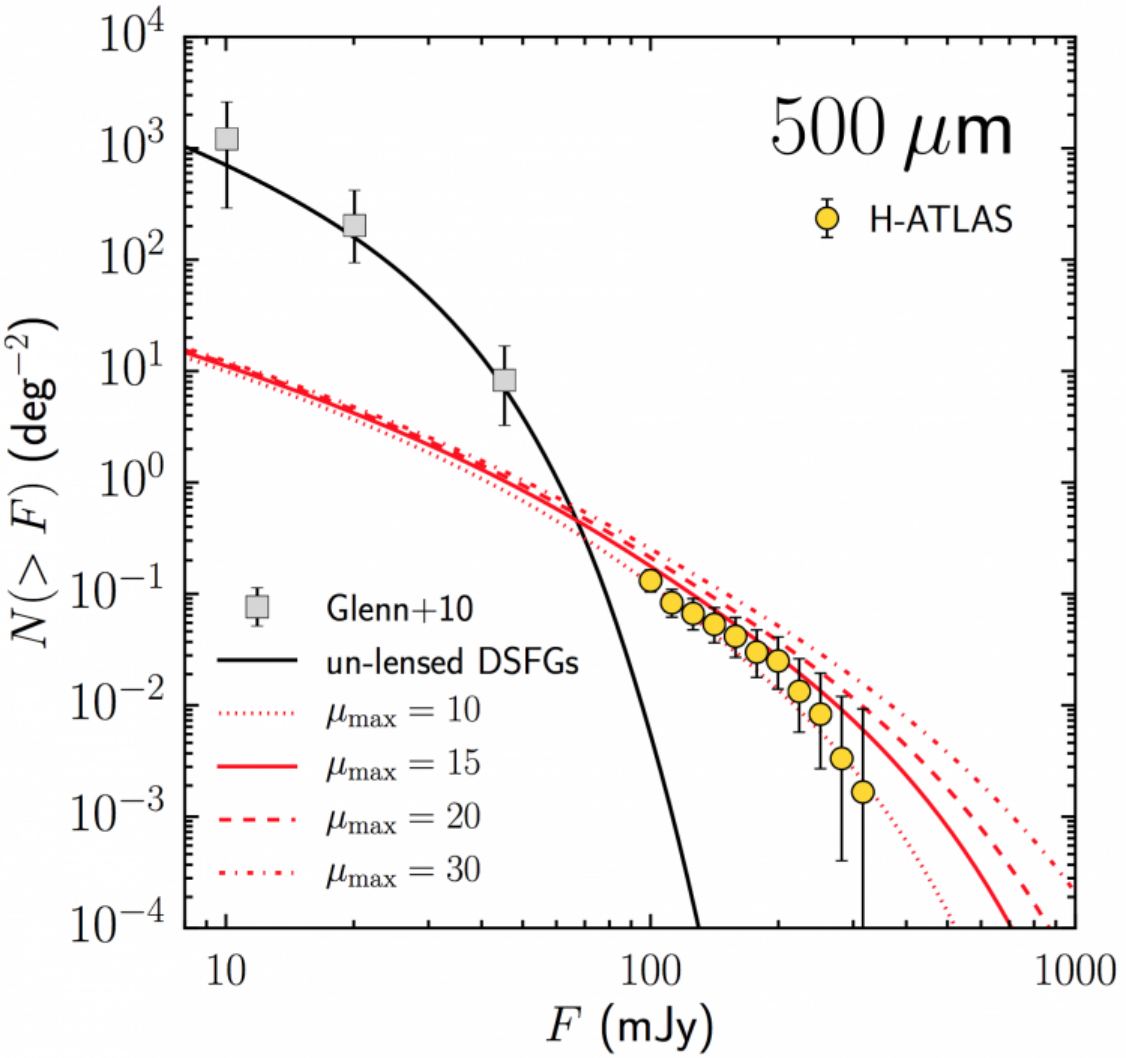






Herschel

- *Herschel* SPIRE surveys (250, 350, 500 μm) covered more than 1000 deg2 (e.g. H-ATLAS 550 deg^2, HerMES ~350 deg^2)
- More than 5e5 high-*z* *Herschel* sub-mm galaxies
- Ideal to find rare objects, e.g. extreme HyLIRGs
- ...and bright, lensed galaxies

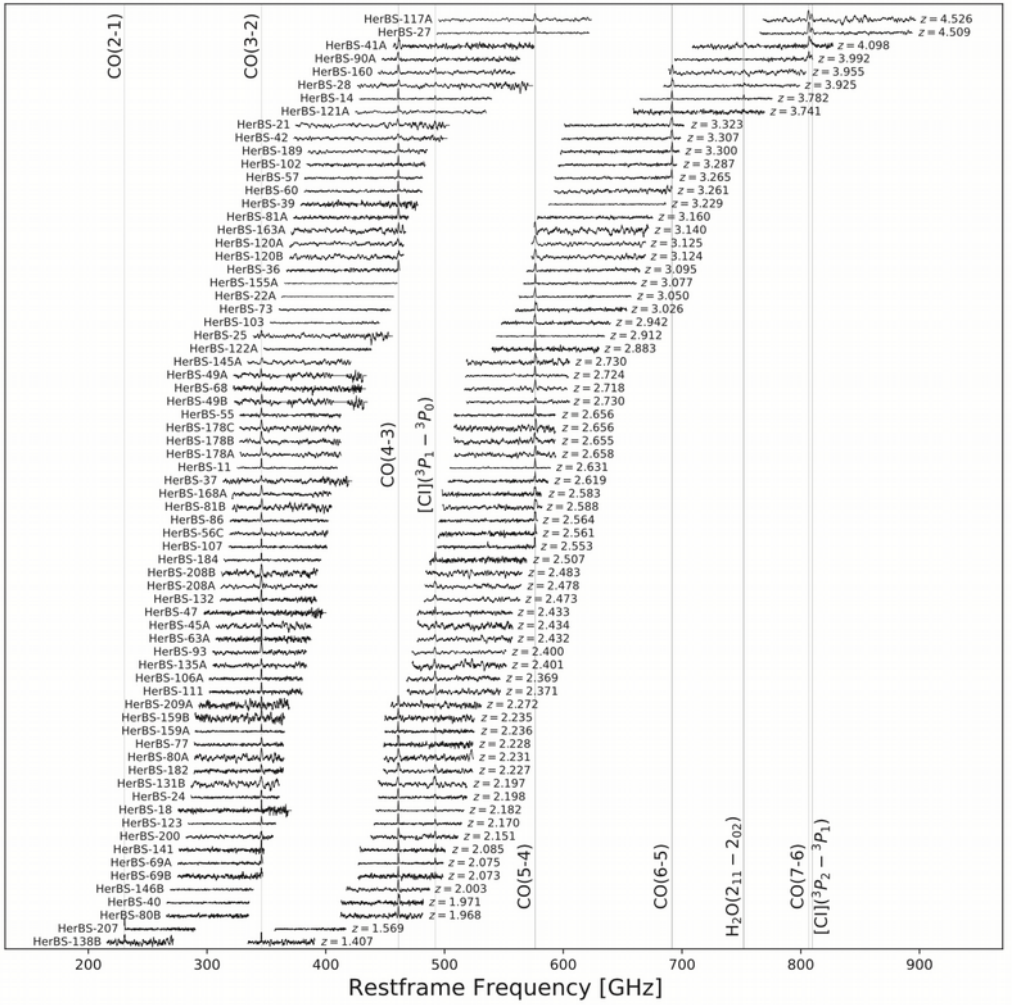


e.g. Negrello et al. (2010, 2017), Weiß et al. (2013), Omont et al. (2013), Canameras et al. (2015), Nayyeri et al. (2016), Bakx et al. (2018), Enia et al. (2018), ...

Other surveys and follow up

~150 bright mm sources with spec-z so far

- 2500 deg2 SPT-SZ 150 GHz survey also revealed gravitationally lensed high-*z* sub-mm galaxies.
- ALMA follow-up: 81 galaxies, average z=3.5
- ALMA follow-up of Herschel-selected galaxies (BEARS survey): 85 targets, 62 redshifts (one or two emission lines); average z=2.75
- Other pointed observations on individual or small nr. of sources



Vieira+ (2010); Spilker+ (2016); Weiss+ (2013, 2016); Reuter+ (2020); Urquhart+ (2022); Bendo+ (2023), Hagimoto+ (2023)

NOrthern Extended Mm Array

- Twelve 15-m antennas on the Plateau de Bure
- PolyFix correlator + receivers: 2x ~8 GHz coverage in one single setup
- 1, 2, 3mm bands
- 1.7 km baseline in the most extended configuration
  (~0.2 arcsec resolution at 1.3 mm)

Image credits: IRAM, J. Boissier

z-GAL in a nutshell

- Observe bright Herschel-selected targets with NOEMA, to determine their redshift and study their nature
- Selection (Bakx+ 2018, Nayyeri+ 2017):
  NGP H-ATLAS S(500)>80 mJy
  Equatorial HerMES and HerS fields S(500)>100 mJy
- Pilot program on 11 targets to demonstrate the method
- Large Program (190 h) targeting 126 Herschel sources
- 99% success! Except 2 sources, all targets have at least 2 emission lines detected, i.e. a robust spec-z determination

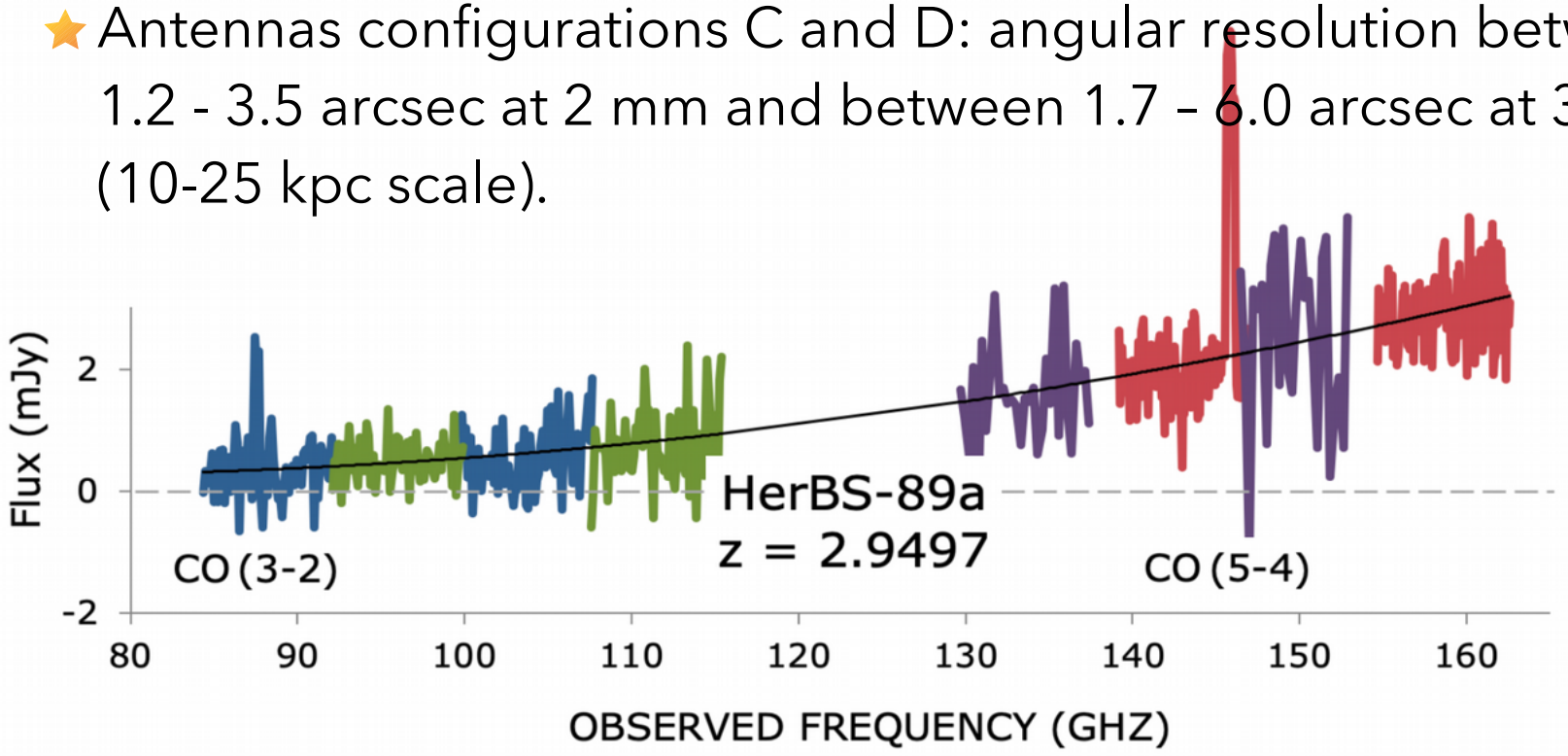
^{12}CO (2-1) to (7-6)

[CI] (1-0) in 27 sources; [CI] (2-1) in 3 sources

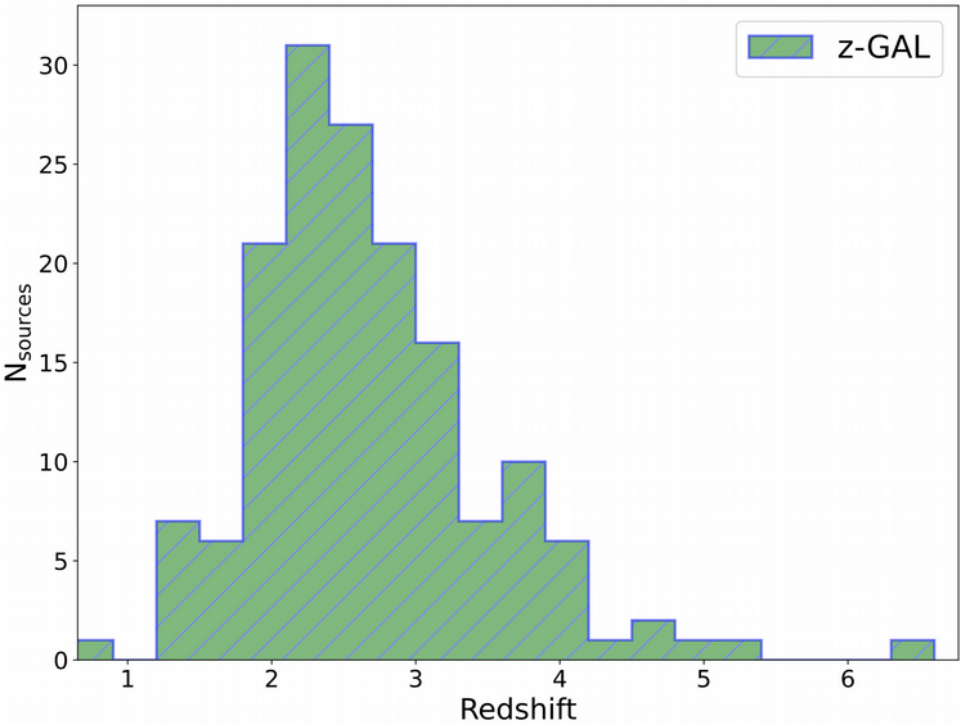
H_2O in 7 sources

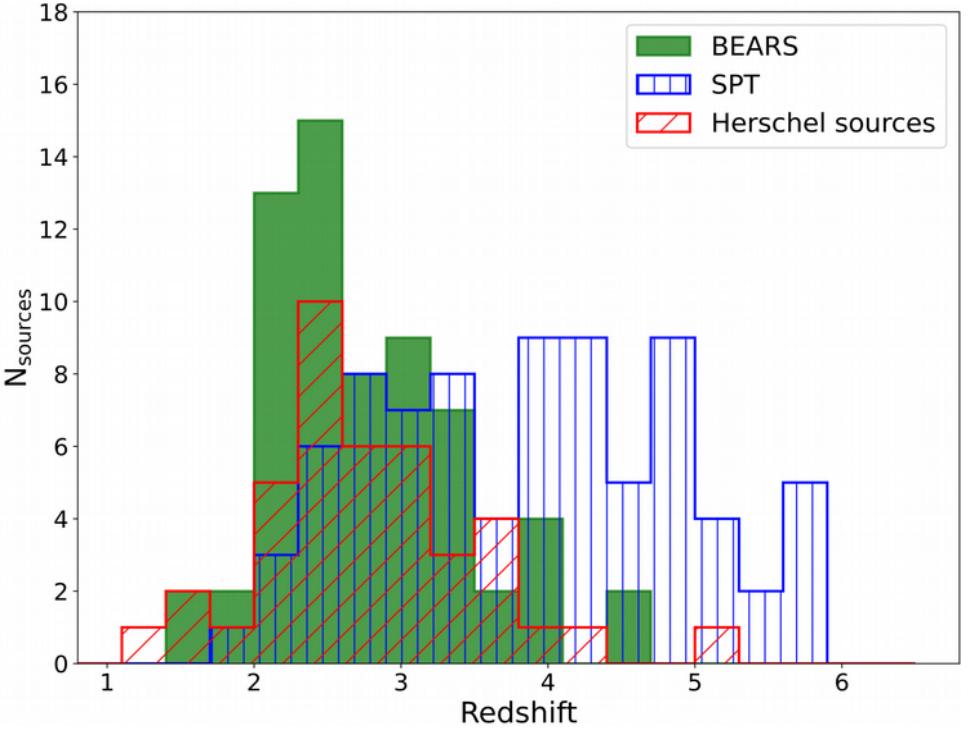
z-GAL observations

- Carried out from Dec 2018 to July 2020, followed by DDT
- Track sharing, thanks to proximity of targets.
- Starting with lower 3mm setting. If detected, then tuning at 2mm; otherwise second 3mm tuning.
- On average 1.5 hours of telescope time per target
- Antennas configurations C and D: angular resolution between 1.2 - 3.5 arcsec at 2 mm and between 1.7 – 6.0 arcsec at 3 mm (10-25 kpc scale).



z-GAL redshifts

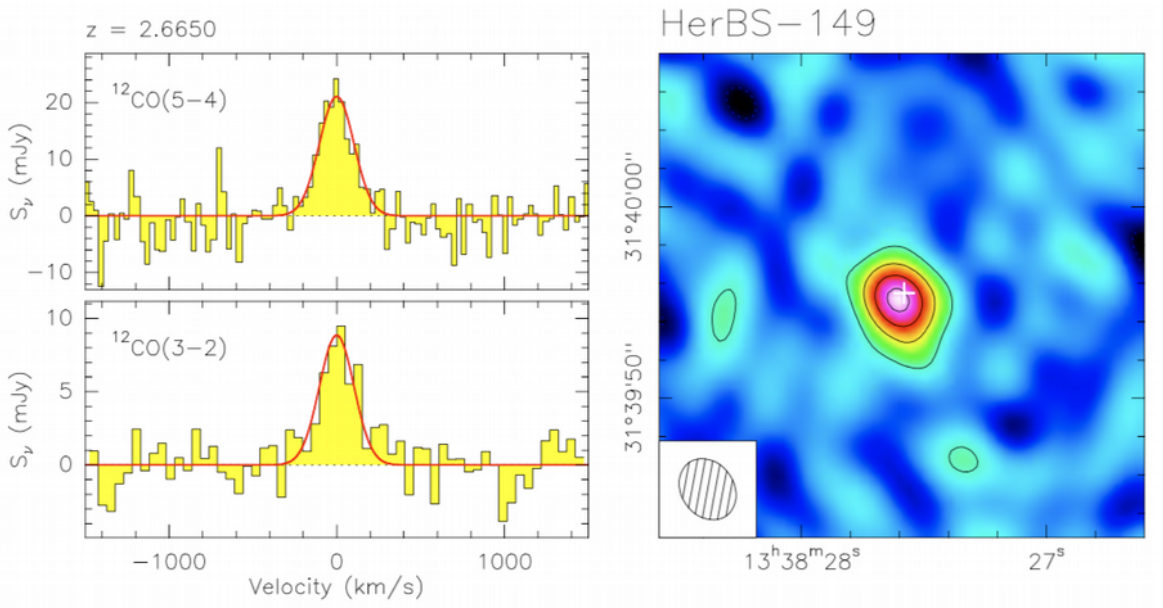


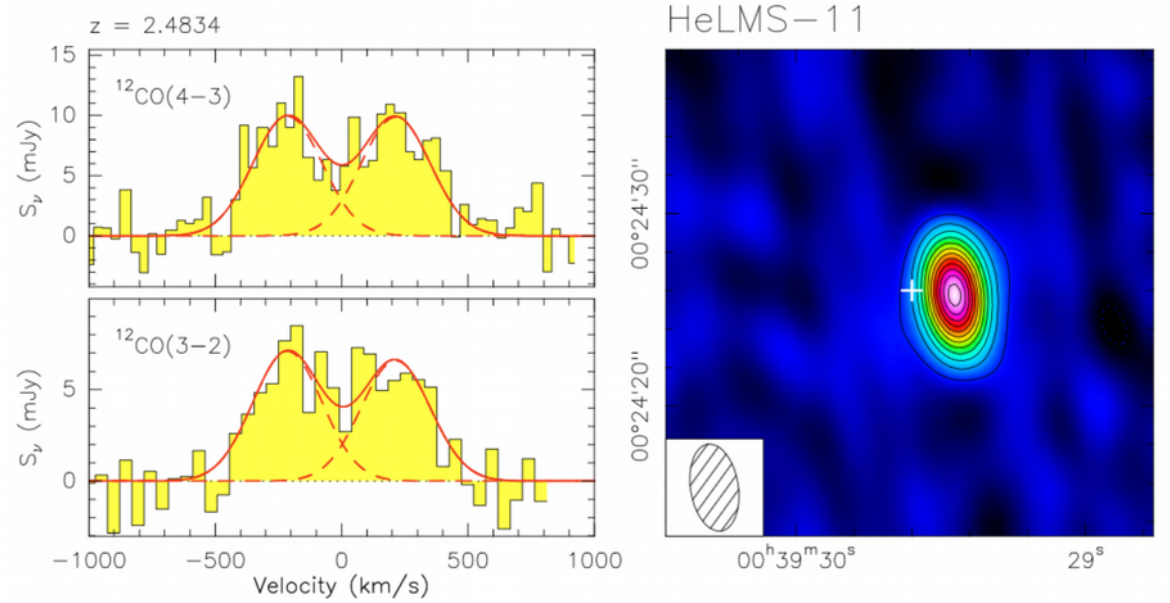


- 126+11 targets
- 135 with at least 2 lines detections
- Multiple objects: 165 individual sources with robust spec-z
- Median z=2.56 +/- 0.1

Cox+ (2023)

z-GAL variety of sources

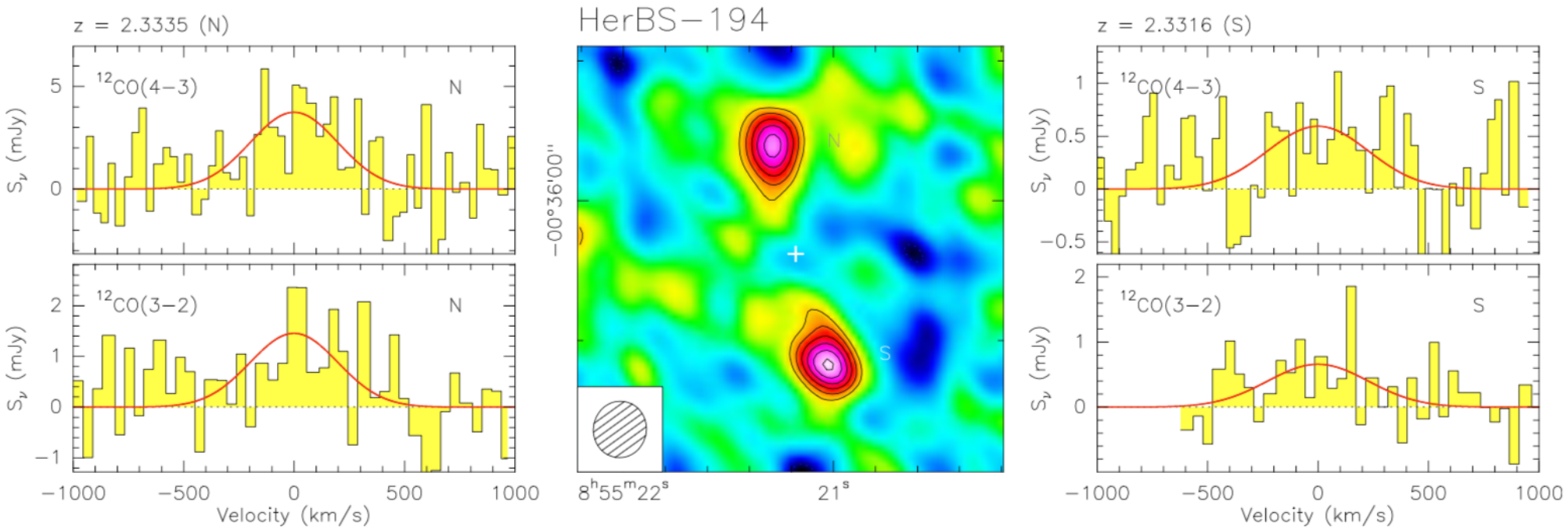




Cox+ (2023)

z-GAL variety of sources

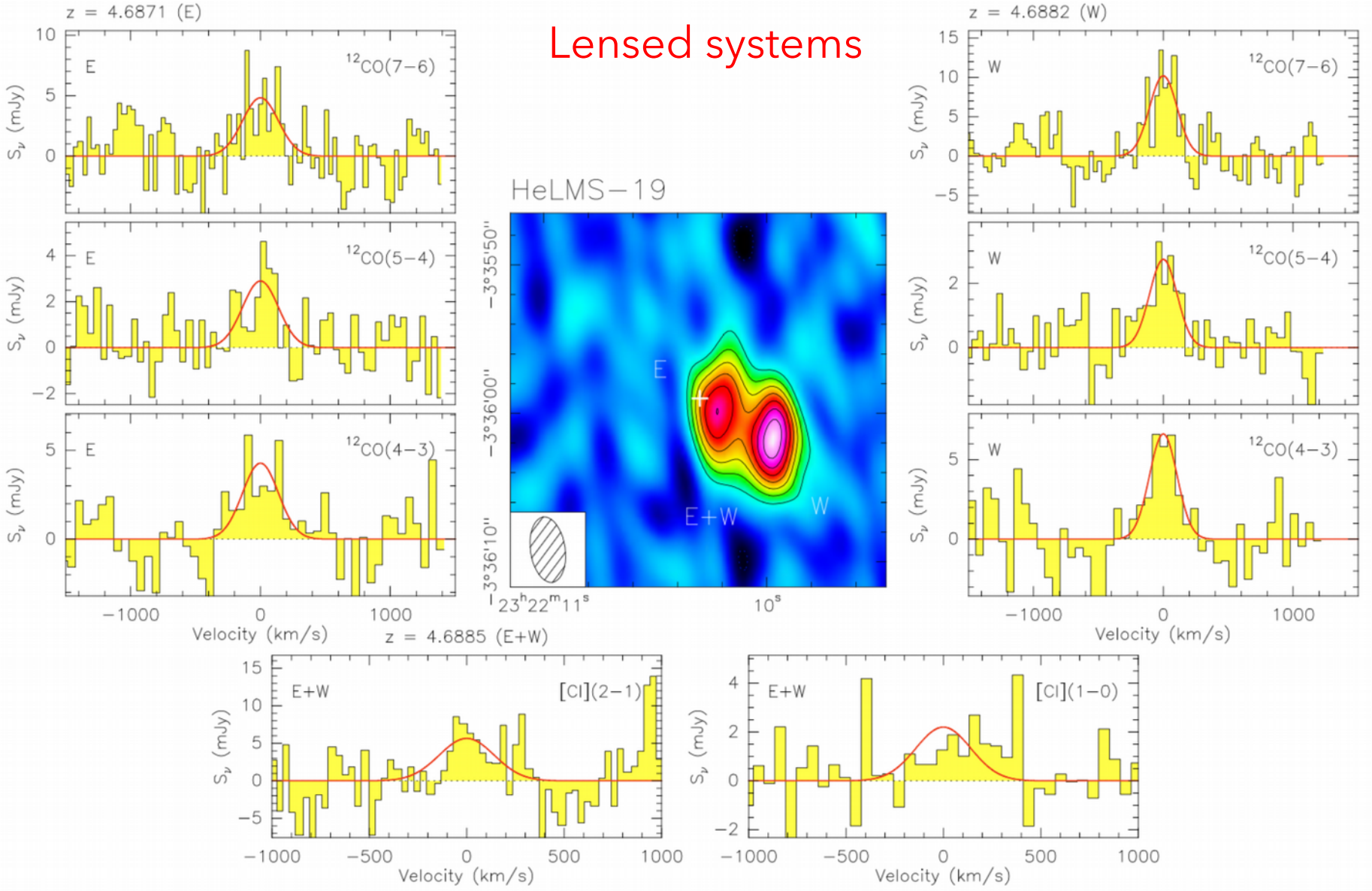
Binary systems



Cox+ (2023)

z-GAL variety of sources

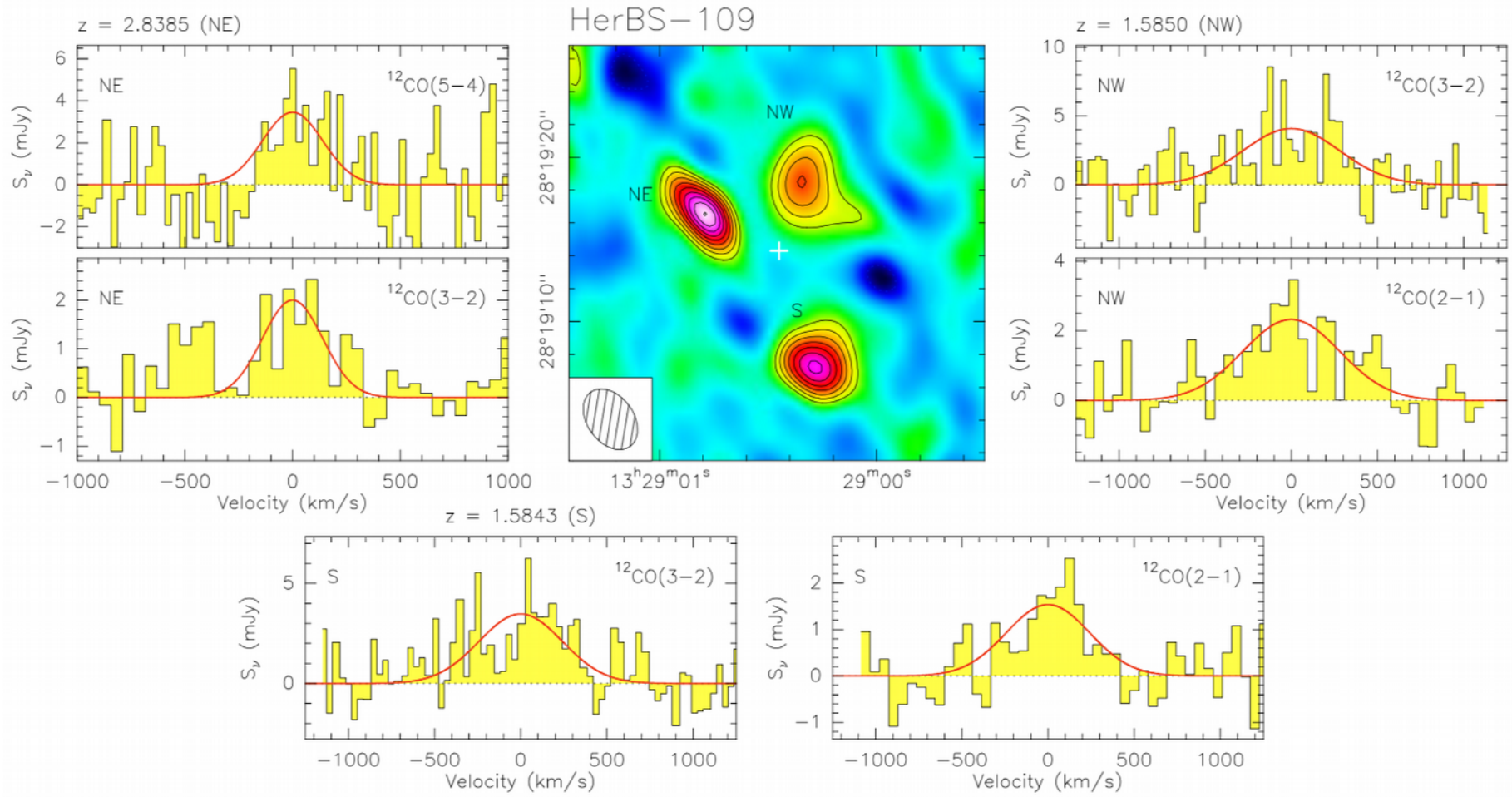
Lensed systems



Cox+ (2023)

z-GAL variety of sources

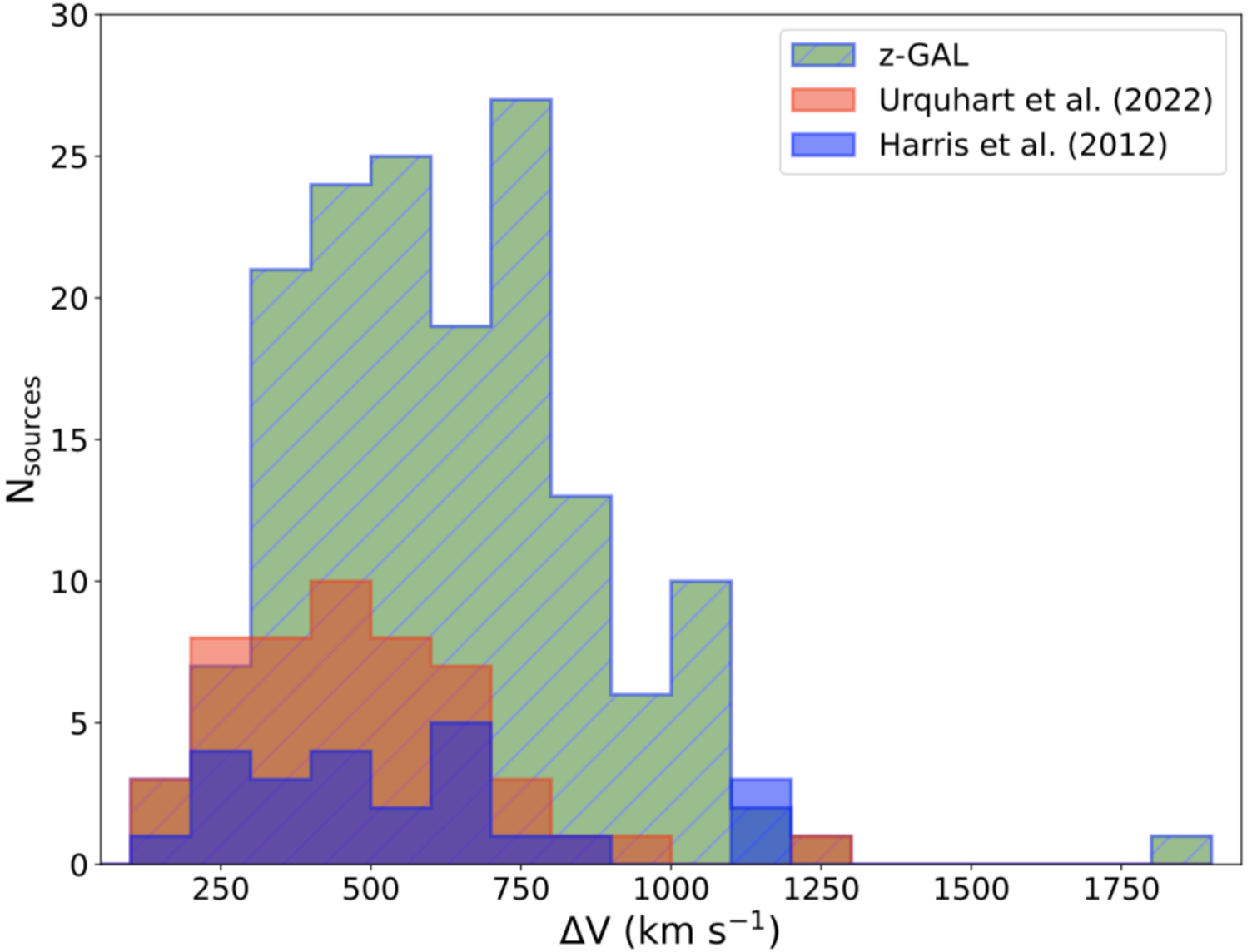
Multiple systems



(in this case at different redshift)

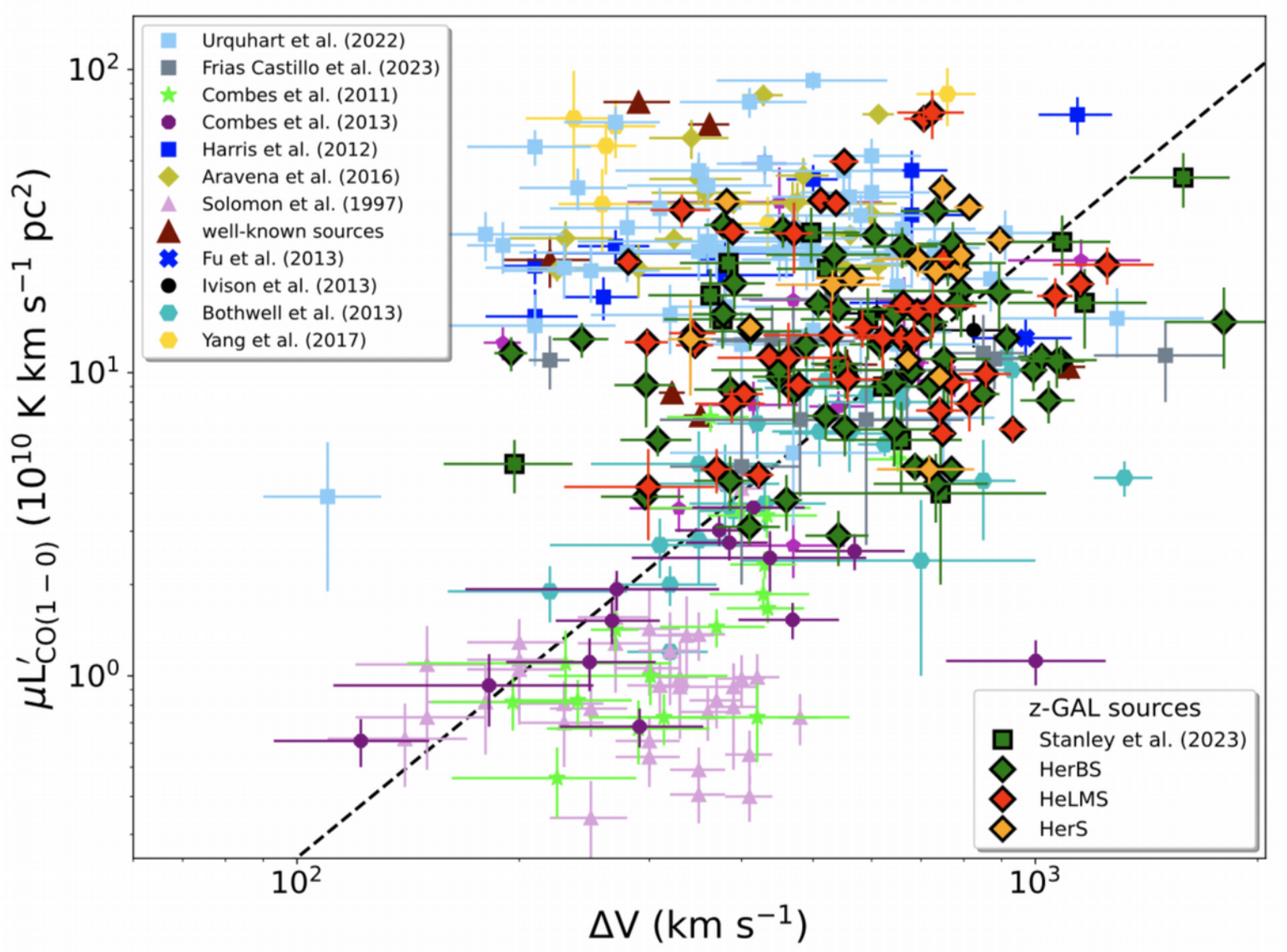
Cox+ (2023)

z-GAL line widths



Cox+ (2023); Bakx+ (in prep.)

z-GAL line widths



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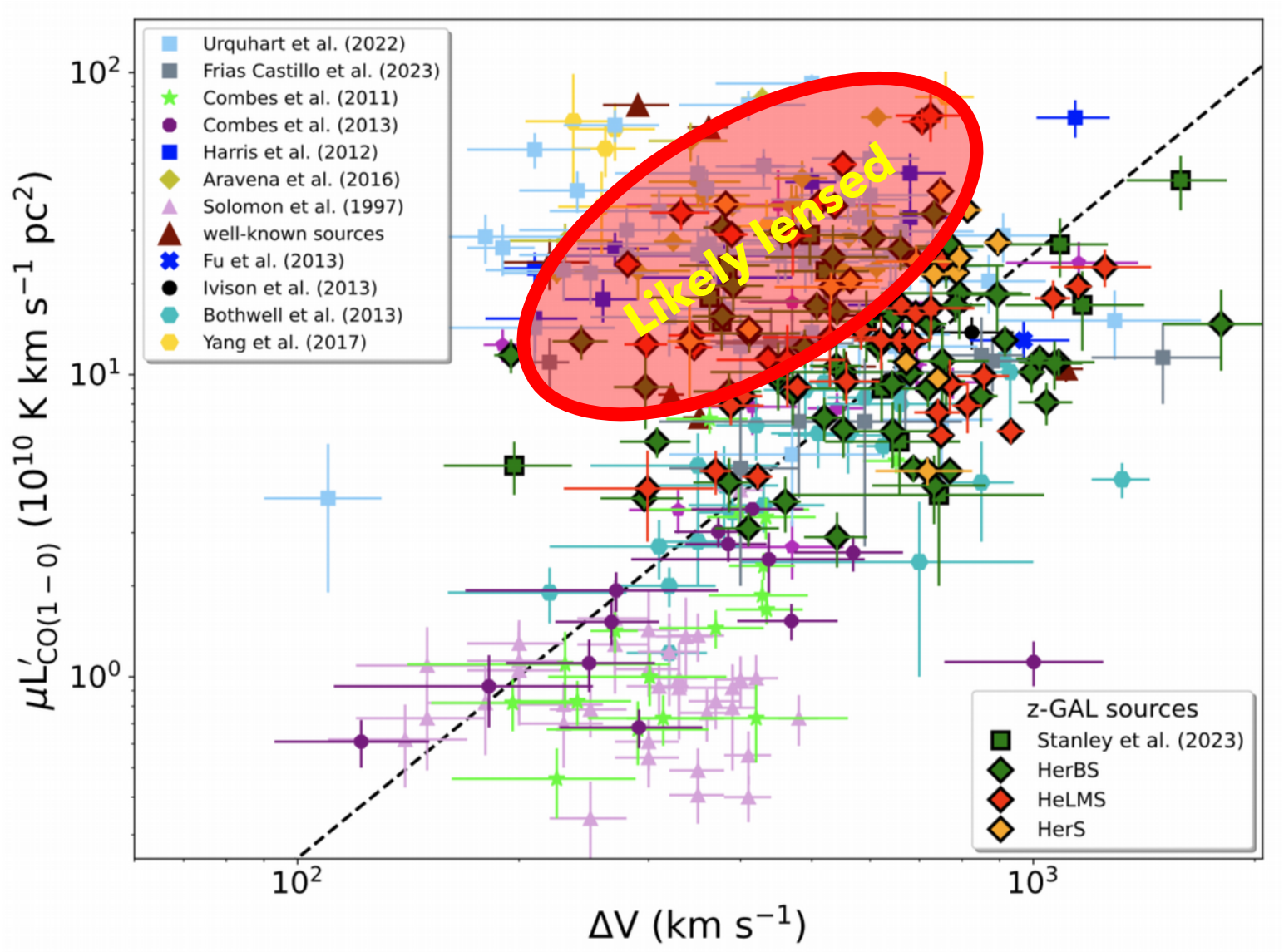
z-GAL line widths



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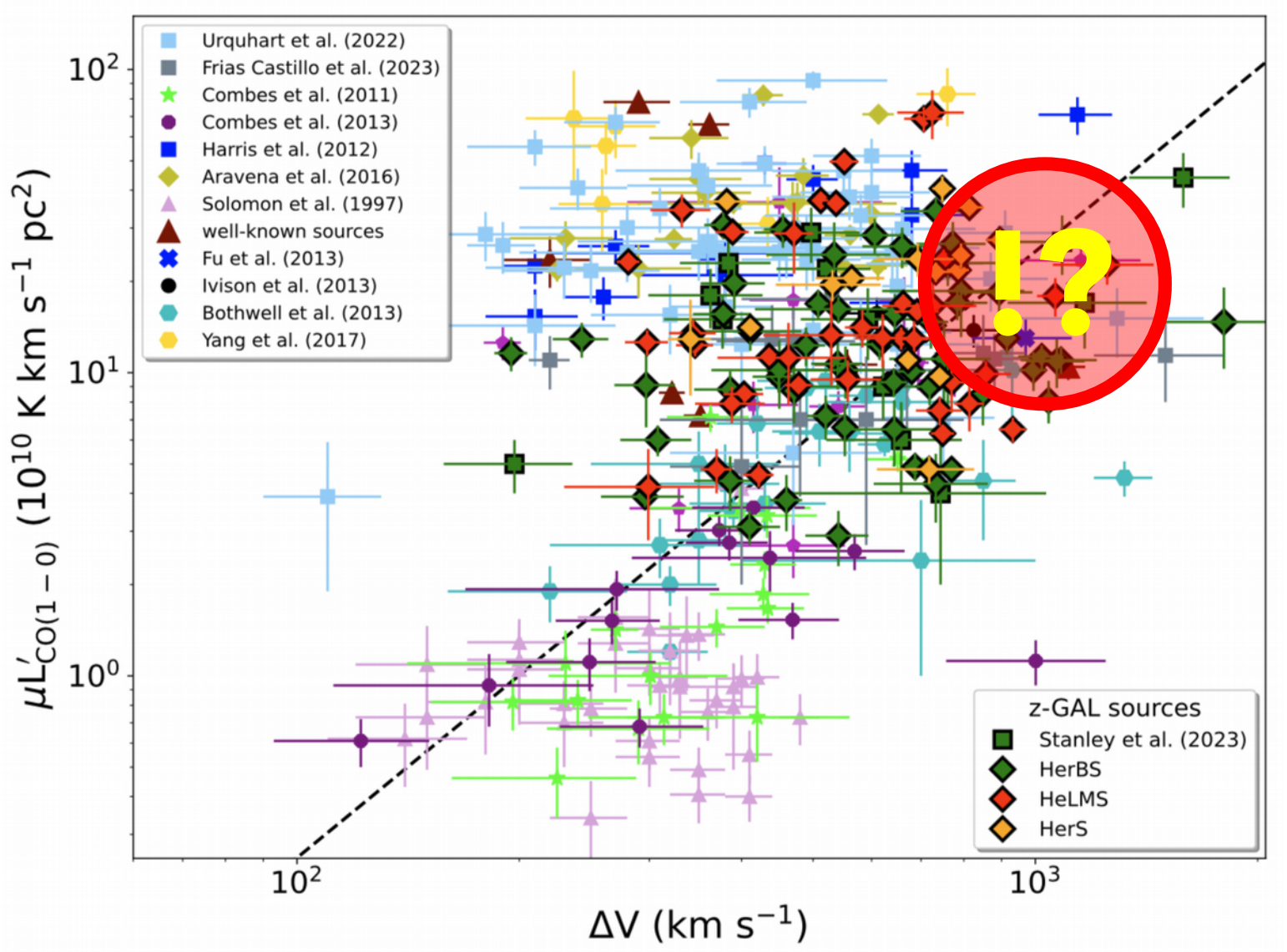
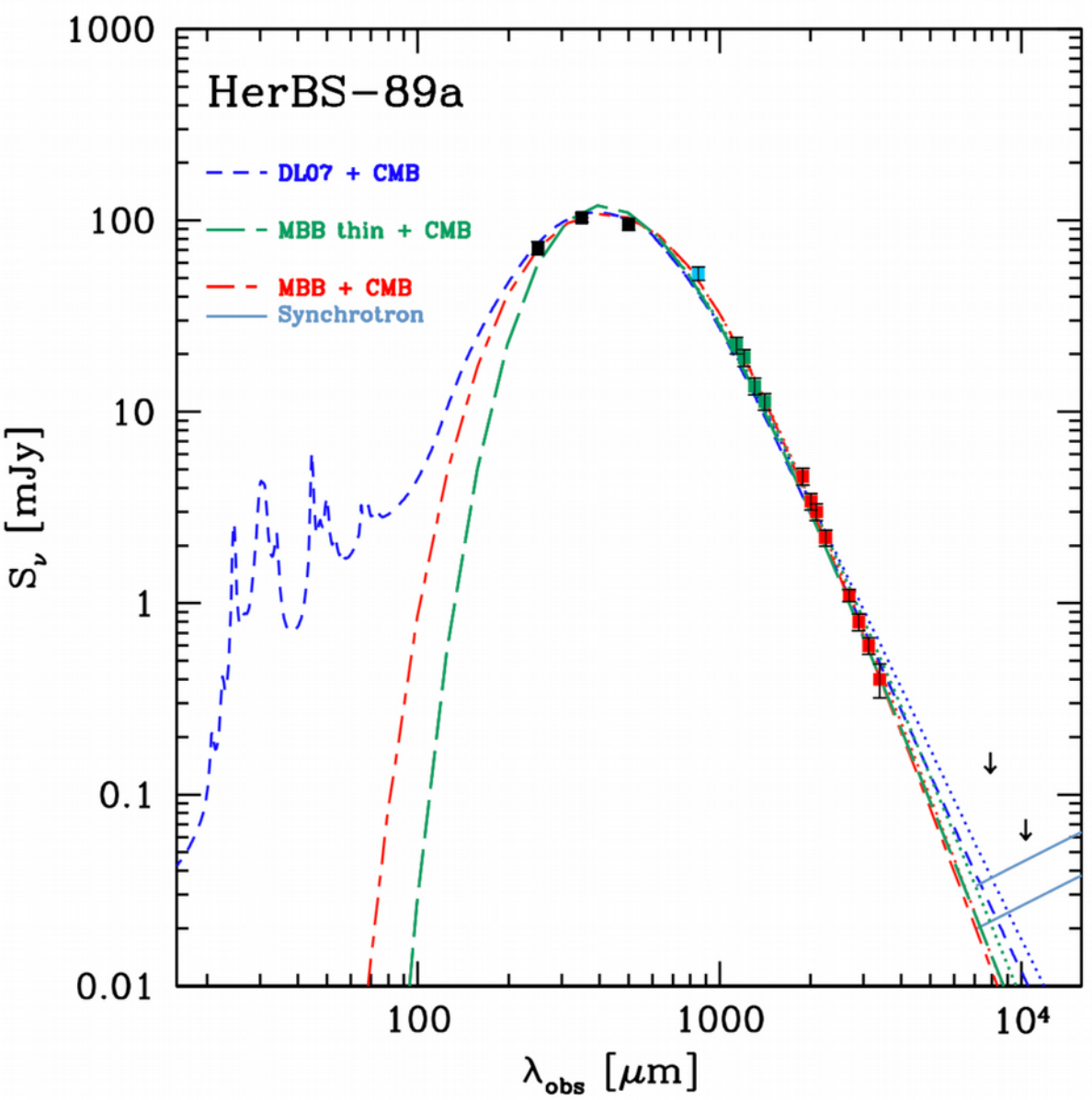
z-GAL line widths



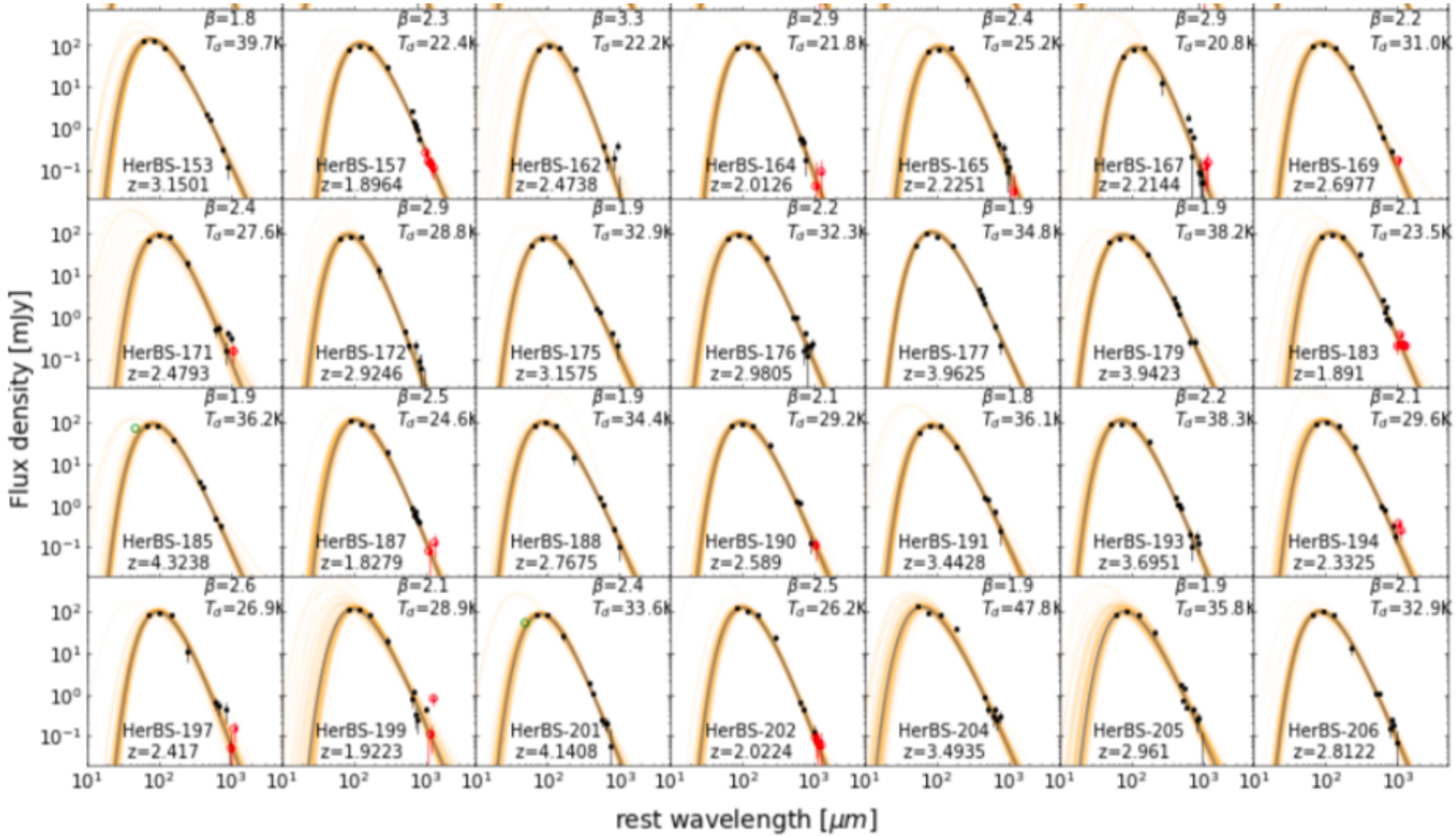
Cox+ (2023); Bakx+ (in prep.)

z-GAL SEDs



Berta+ (2021); Ismail+ (2023)

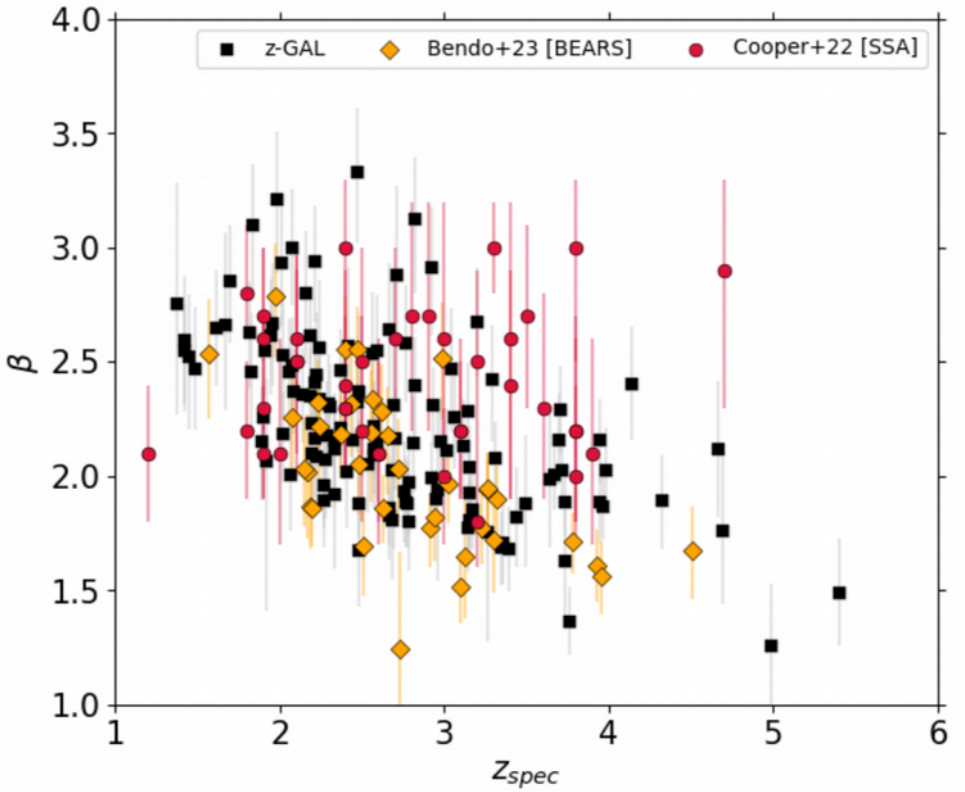
z-GAL SEDs

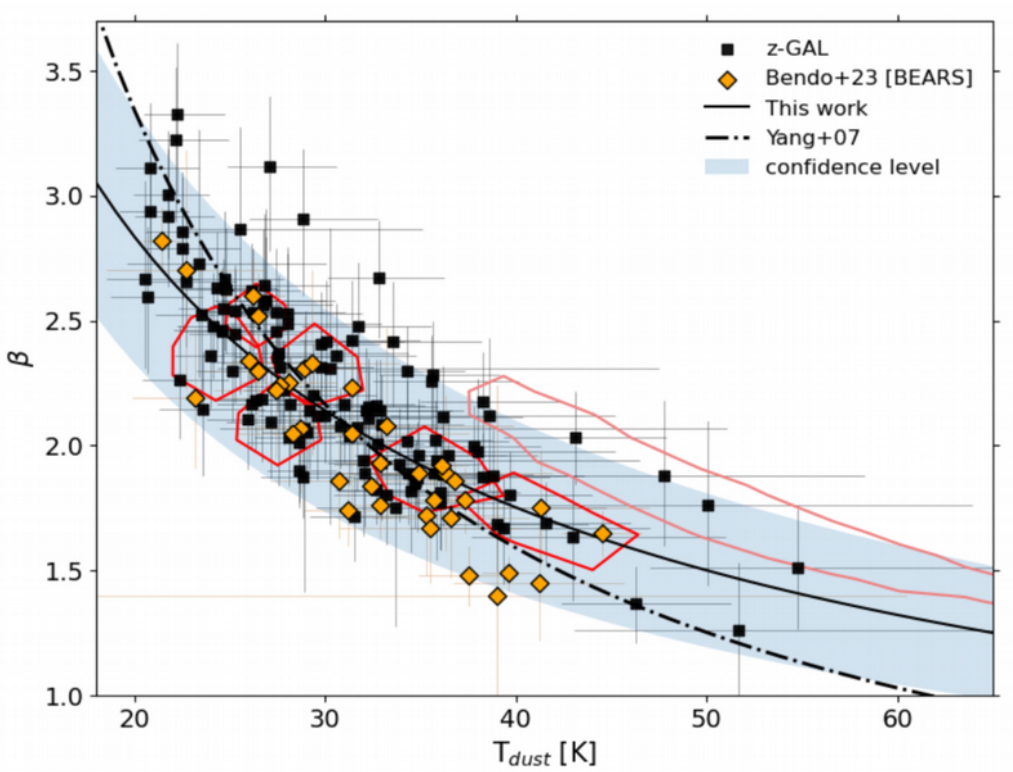


- Modified Black Body fit (MBB), optical thin and general form
- Mock simulations to determine the effects intrinsic to the fitting method
- Determine M(dust), T(dust), β, L(FIR)

Ismail+ (2023)

z-GAL MBB results





- β in the range 1.5 – 3.0, median 2.2 +/- 0.3. NOEMA plays critical role
- No clear evolution of β vs. redshift
- Anti-correlation β-T: might be physical (dust grains and environment), but see discussion in Kelly+ (2012). To be studied further.

Ismail+ (2023)

z-GAL derived quantities

Mass (gas and dust)*

SFR, depletion time, stellar mass**

Source	Lowest CO Transition	$\mu L'_{^{12}CO(1-0)}$ [10^{10} K km s^{-1} pc^2]	$\mu M_{mol,^{12}CO}$ [10^{11} $M_\odot$]	$\mu M_{mol,850\mu m}$ [10^{11} $M_\odot$]	$\delta_{GDR,^{12}CO}$	μL_{IR} [10^{11} $L_\odot$]	μSFR [$M_\odot$ yr^{-1}]	$\tau_{dep,^{12}CO}$ [10^9 yr]	$\mu^E M^*$ [10^{11} $M_\odot$]	E	$\log(\mu SFR/SFR(MS))$
HeLMS-1	2-1	23.09±1.40	9.24±0.56	13.26 ± 0.89	63.32 ± 18.60	467.39 ± 32.02	5094.58 ± 498.67	0.18 ± 0.05	4.72 ± 3.61	1.23	1.08 ± 0.58
HeLMS-3	2-1	36.89±2.82	14.75±1.13	12.16 ± 1.37	105.36 ± 18.63	387.38 ± 37.81	4222.45 ± 588.77	0.35 ± 0.05	23.13 ± 11.58	1.27	0.69 ± 0.39
HeLMS-11	3-2	24.07±2.10	9.63±0.84	20.84 ± 1.58	70.54 ± 13.01	318.67 ± 14.77	3473.50 ± 229.93	0.28 ± 0.04	8.48 ± 3.74	1.20	0.56 ± 0.35
HeLMS-12	3-2	50.47±3.54	20.19±1.42	9.98 ± 1.29	271.50 ± 78.34	337.84 ± 18.07	3682.43 ± 281.42	0.55 ± 0.14	48.41 ± 33.49	1.21	0.03 ± 0.54
HeLMS-14	2-1	35.99±2.17	14.40±0.87	7.36 ± 1.33	146.60 ± 30.45	195.88 ± 14.12	2135.10 ± 219.83	0.67 ± 0.08	48.13 ± 20.40	1.25	0.06 ± 0.33
HeLMS-16	3-2	33.60±4.81	13.44±1.92	7.42 ± 1.23	220.62 ± 50.15	425.34 ± 19.46	4636.20 ± 303.08	0.29 ± 0.05	13.80 ± 6.63	1.19	0.45 ± 0.38
HeLMS-17 E	4-3	2.60±0.58	1.04±0.23	–	–	–	–	–	–	–	–
HeLMS-17 W	4-3	11.26±0.87	4.50±0.35	–	–	–	–	–	–	–	–
HeLMS-17 E+W	4-3	13.86±1.04	5.55±0.42	7.98 ± 1.21	85.98 ± 14.88	331.14 ± 19.47	3609.41 ± 303.12	0.15 ± 0.02	2.05 ± 0.83	1.21	1.09 ± 0.32
HeLMS-19 E	4-3	17.12±4.59	6.85±1.84	–	–	–	–	–	–	–	–
HeLMS-19 W	4-3	20.22±4.37	8.09±1.75	–	–	–	–	–	–	–	–
HeLMS-19 E+W	4-3	37.34±6.34	14.94±2.54	9.47 ± 1.76	514.65 ± 229.89	830.36 ± 46.08	9050.92 ± 717.48	0.17 ± 0.07	11.35 ± 11.96	1.15	0.60 ± 0.85
HeLMS-20	4-3	13.23±2.53	5.29±1.01	9.24 ± 0.81	68.36 ± 16.05	267.58 ± 14.73	2916.61 ± 229.40	0.18 ± 0.04	2.38 ± 1.40	1.21	0.97 ± 0.46

Emission Lines **SED Fitting** **Combination**

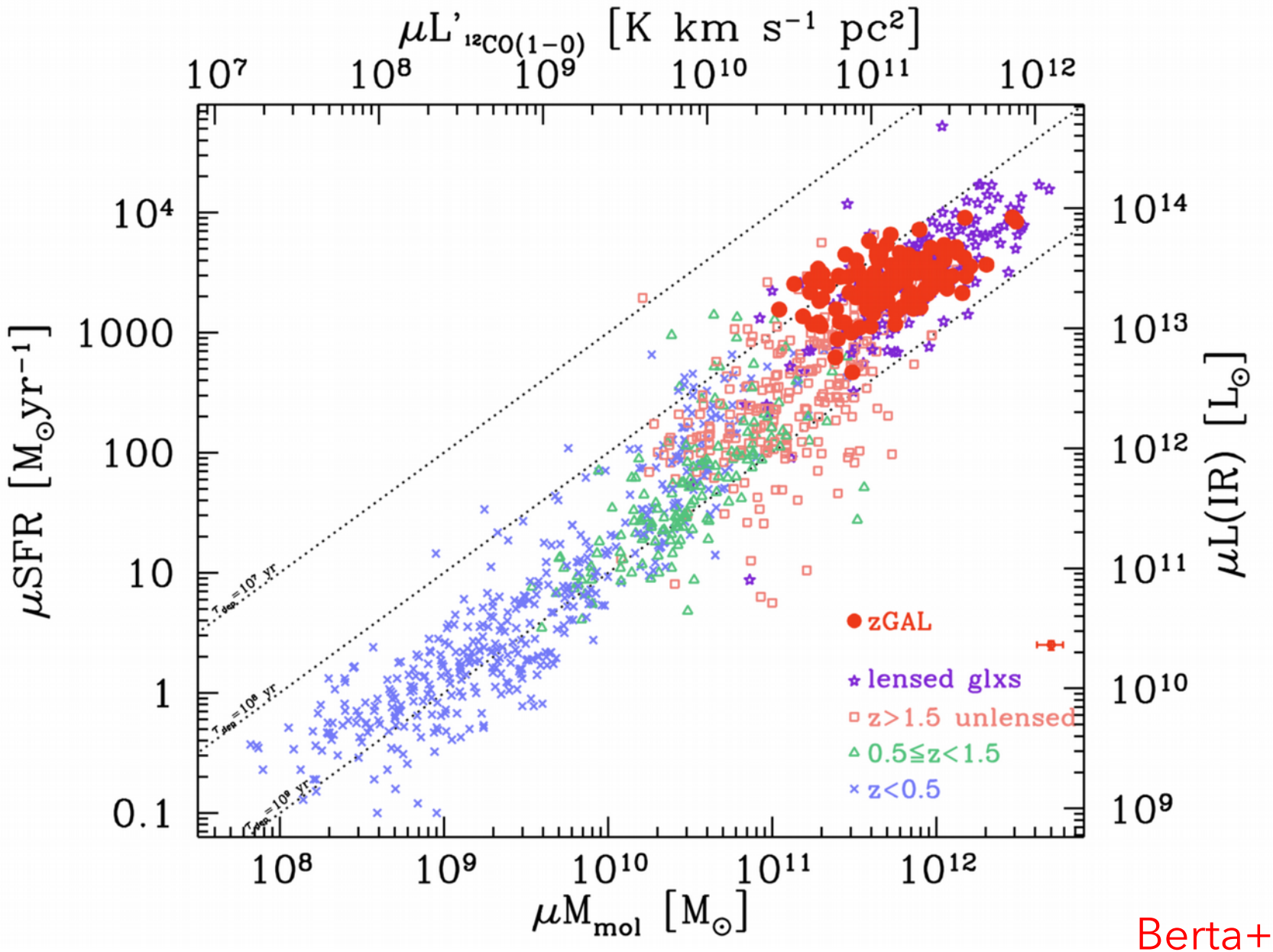
* α(CO)=4.0 (see Dunne+ 2022)

SMG line excitation (e.g. Carilli & Walter 2013)

** Inversion of Tacconi+ (2020) scaling relations

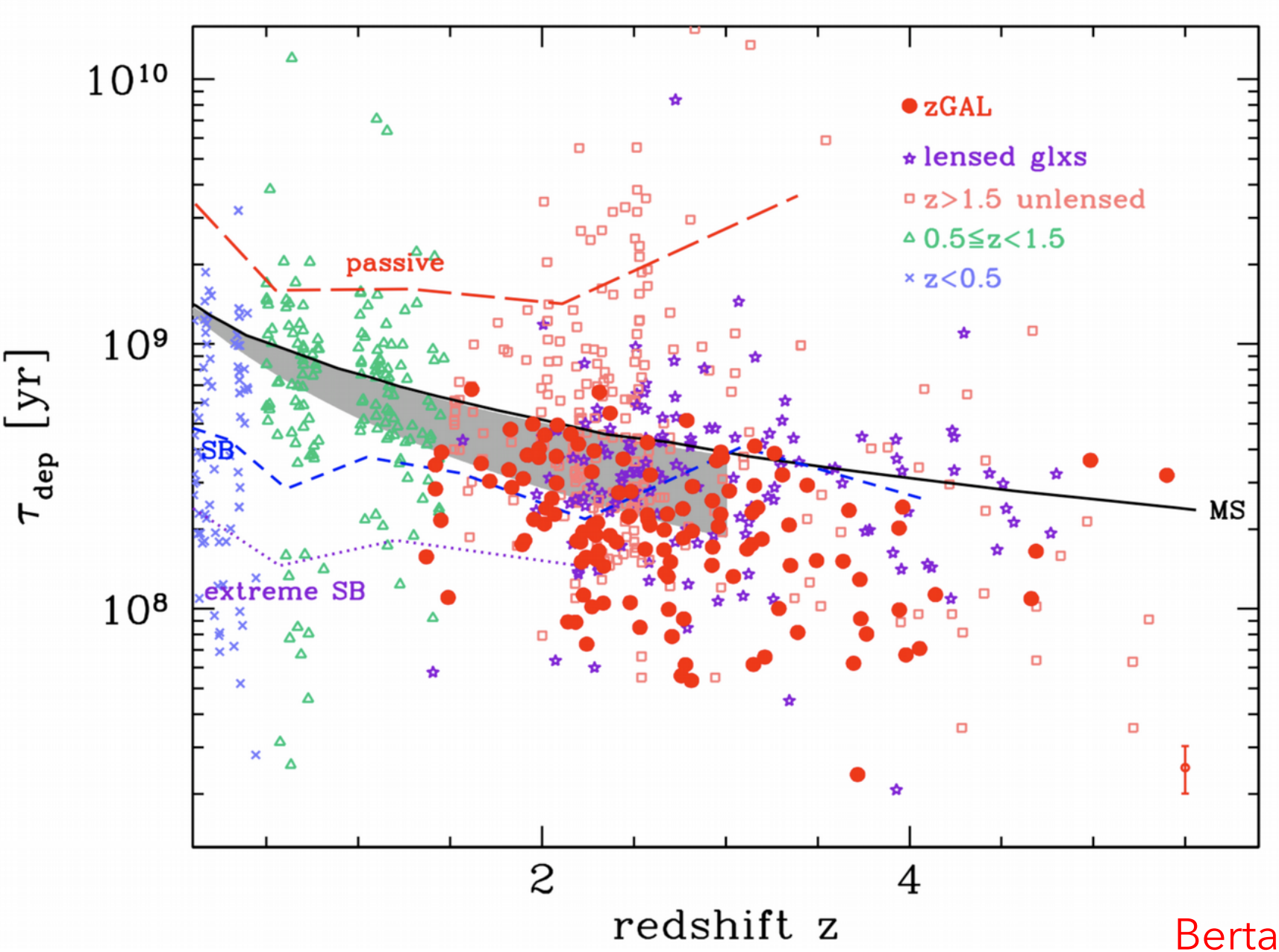
Cox+ (2023), Ismail+ (2023), Berta+ (2023)

z-GAL physical nature



Berta+ (2023)

z-GAL depletion time scale



Berta+ (2023)

Take home messages

- z-GAL doubles the number of high-z bright SMGs with spec-z -> now more than 300 galaxies!
- Wealth of information: mm spectral lines (^{12}CO, [CI], H_2O, ...), dust continuum, ancillary data (HST, JVLA, Herschel, ...)
- Includes lensed and non-lensed objects
- Very broad line widths (mergers? rotating disks?)
- Most sources are powerful starbursts w short τ(dep), but interestingly ~25% are MS sources

Multi-wavelength ancillary data and follow-up are paramaount to study feedback, fueling, evolution of dust and metals, peculiar objects such as real HyLIRGs, AGN hosts and proto-clusters.

Cox+ (2023), Ismail+ (2023), Berta+ (2023), Stanley+ (2023), Berta+ (2021), Neri+ (2020)

Special Thanks

- To IRAM for making this survey and this work possible and for the continuous support received over the past four years from the NOEMA staff.
- To the members of the z-GAL **Cat** and **Tiger Teams** for their relentless efforts and dedication to calibrate, reduce, review and release the data:

Cat: S. Berta, D. Ismail, F. Stanley, P. Cox

Tiger: Cat + R. Neri, A. Young, S. Jin, T.J. Bakx, H. Dannerbauer, A. Beelen

And also: I. Cortzen, M. Krips, C. Herrera

Data release: the first 3 z-GAL papers are under revision; when accepted, they will be on the arXiv and will come with a data package (IRAM LP webpage and z-GAL dedicated page). **Stay tuned!**