ALMA spectroscopic survey (ASPECS) and deep continuum imaging in HUDF: Mgas, number count, SFR region

Aravena+16, Decarli+16 (Rujopakarn+16)

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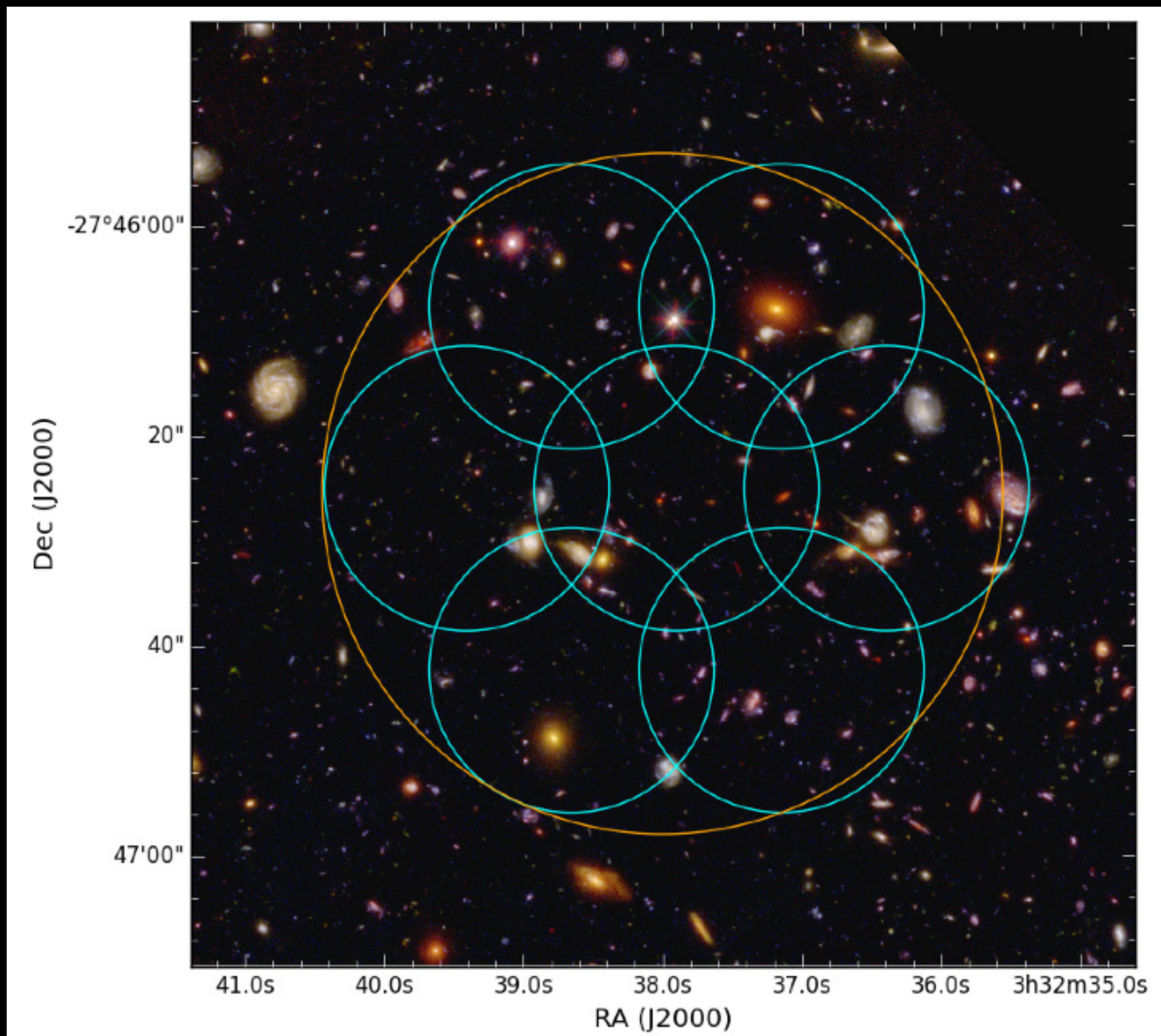
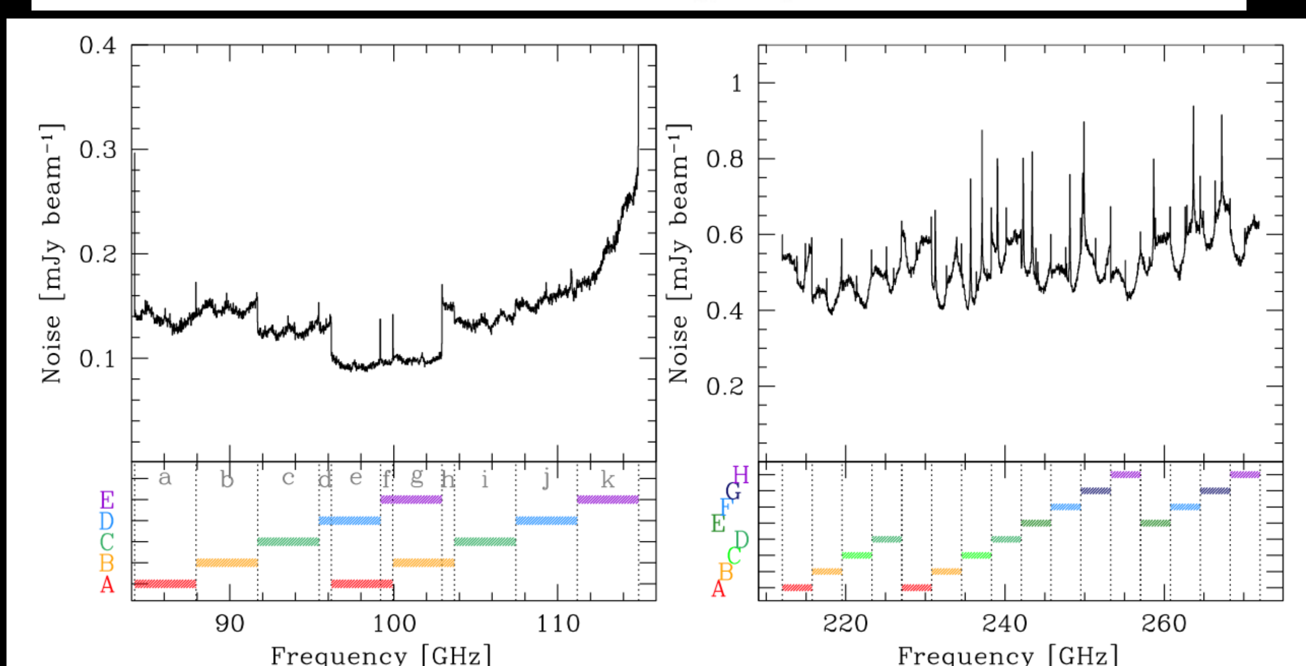
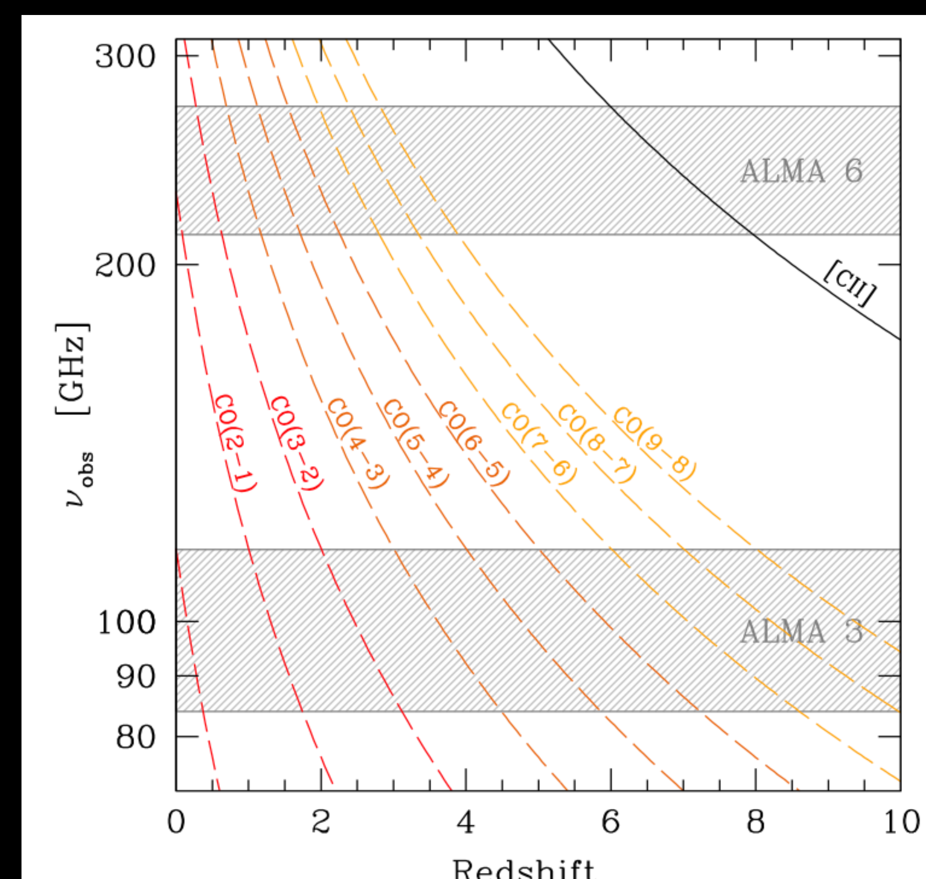
ASPEC survey (Walter+16)

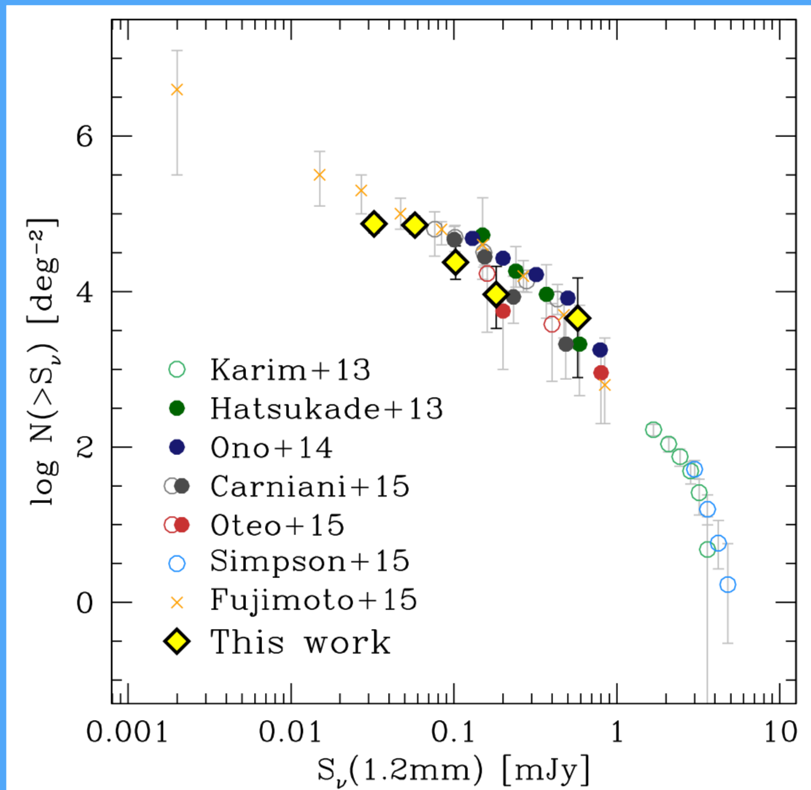
- Paper I : Walter+16 (survey description)
- **Paper II : Aravena+16a (mainly continuum band 6)**
- Paper III : Decarli+16a (CO LF) (by YY)
- **Paper IV : Decarli+16b (bright CO emissions)**
- Paper V : Aravena+16b ([CII] emitters)
- Paper VI : Bowens+16 (uv-selected galaxies; IRX-β, IRX-Mstar)
- Paper VII : Carilli+16 (intensity mapping)

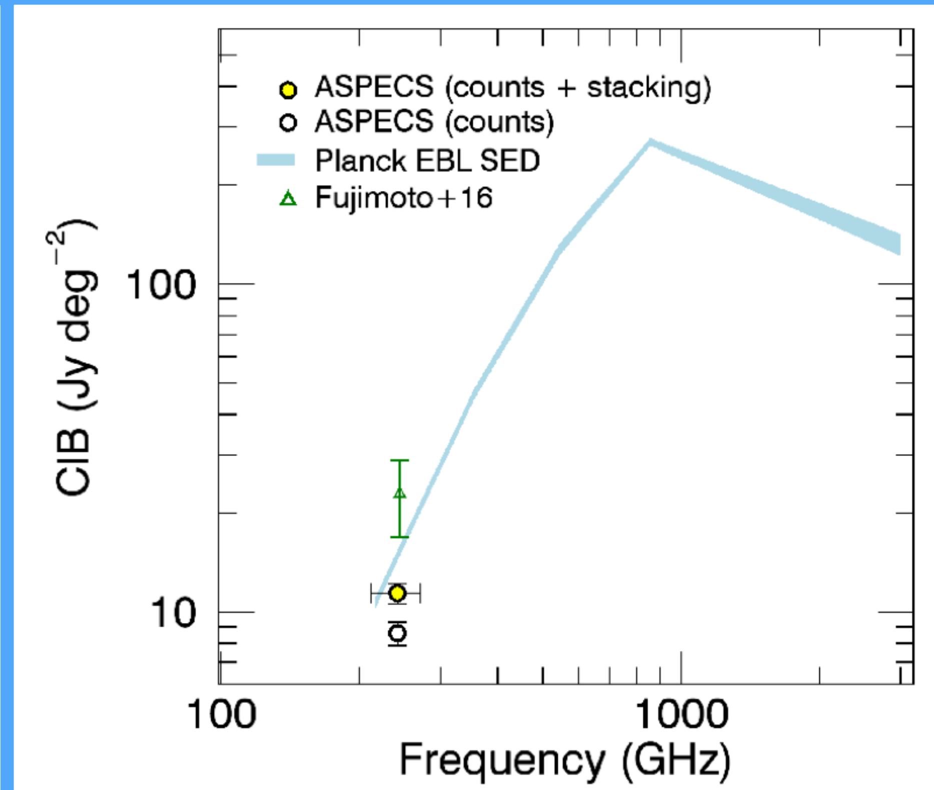


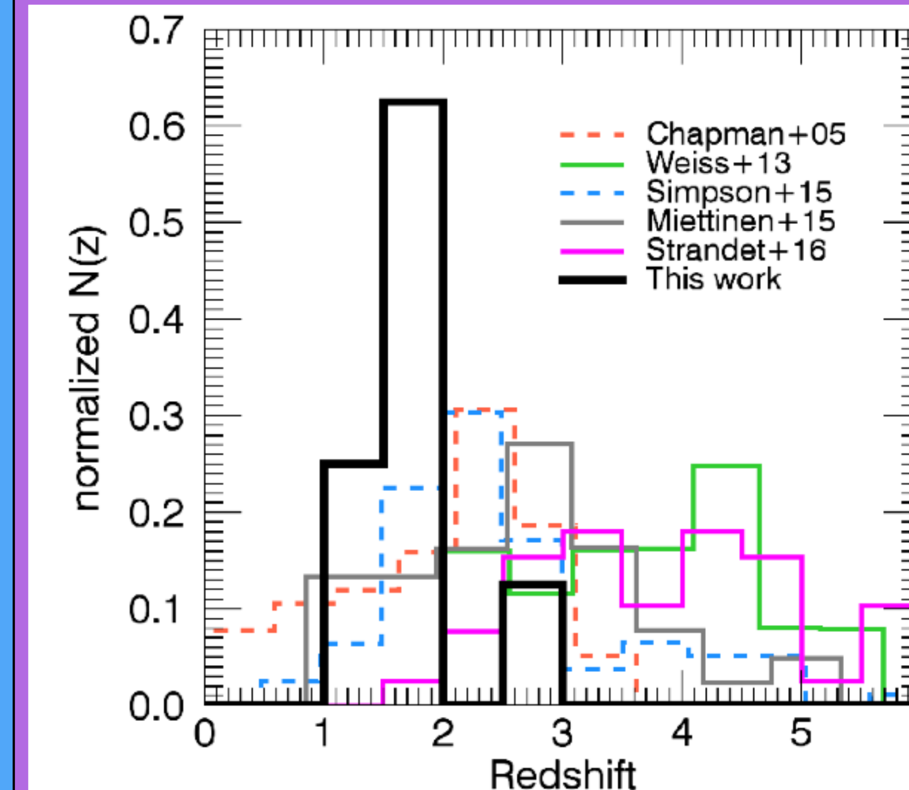


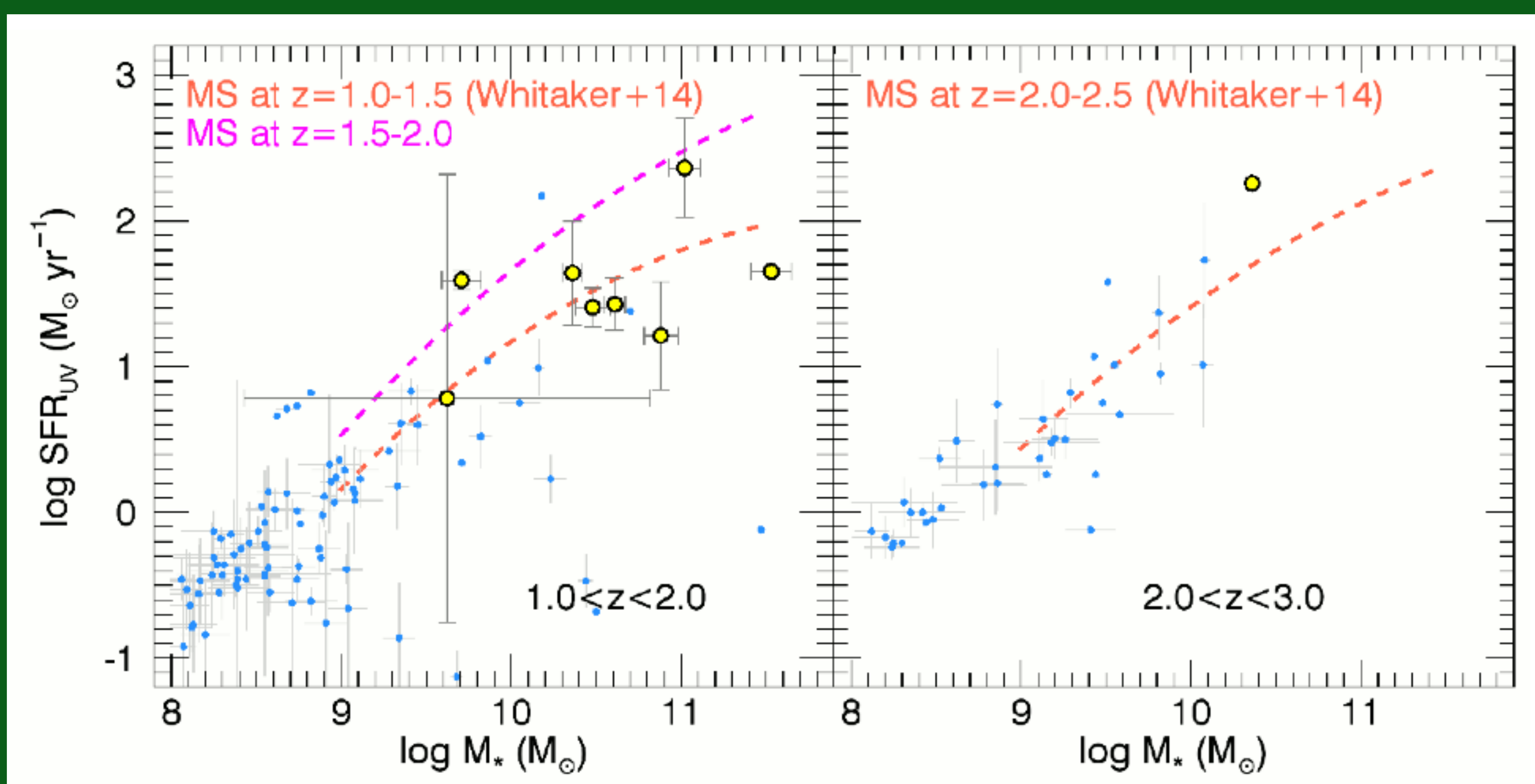


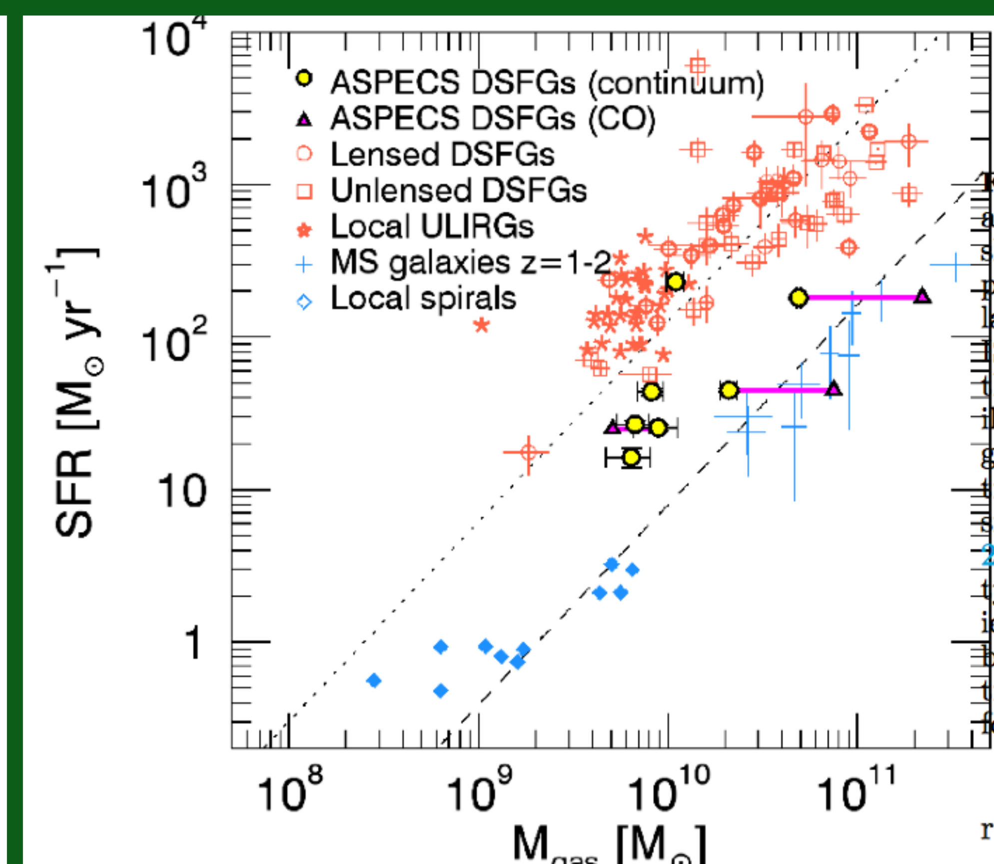
Overview (Aravena+16)



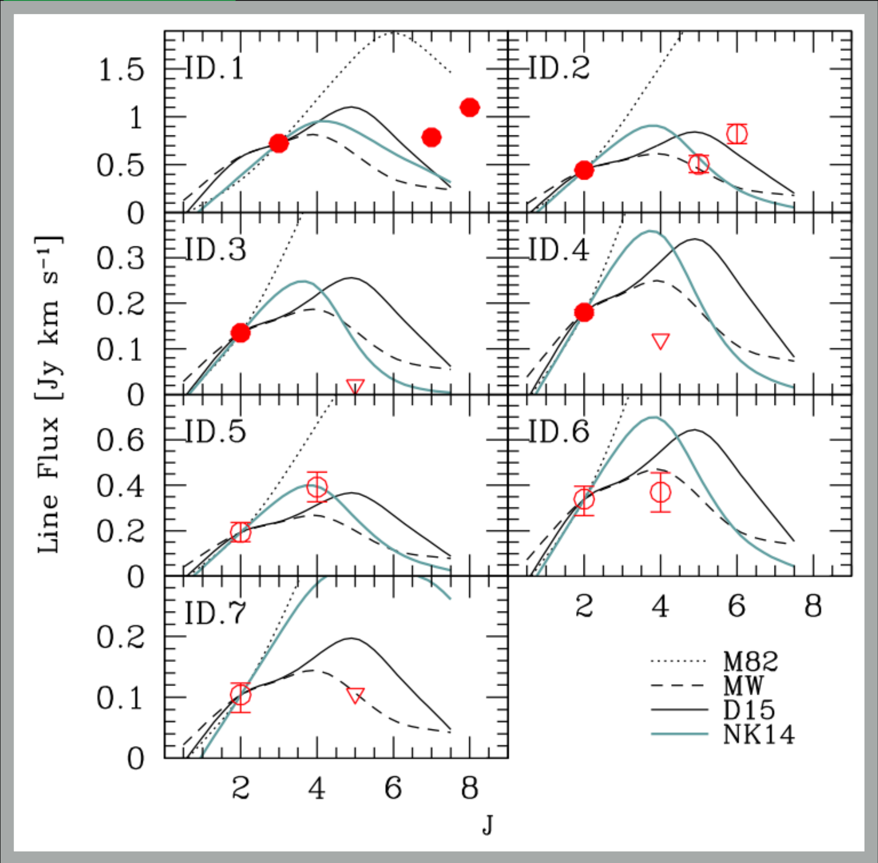


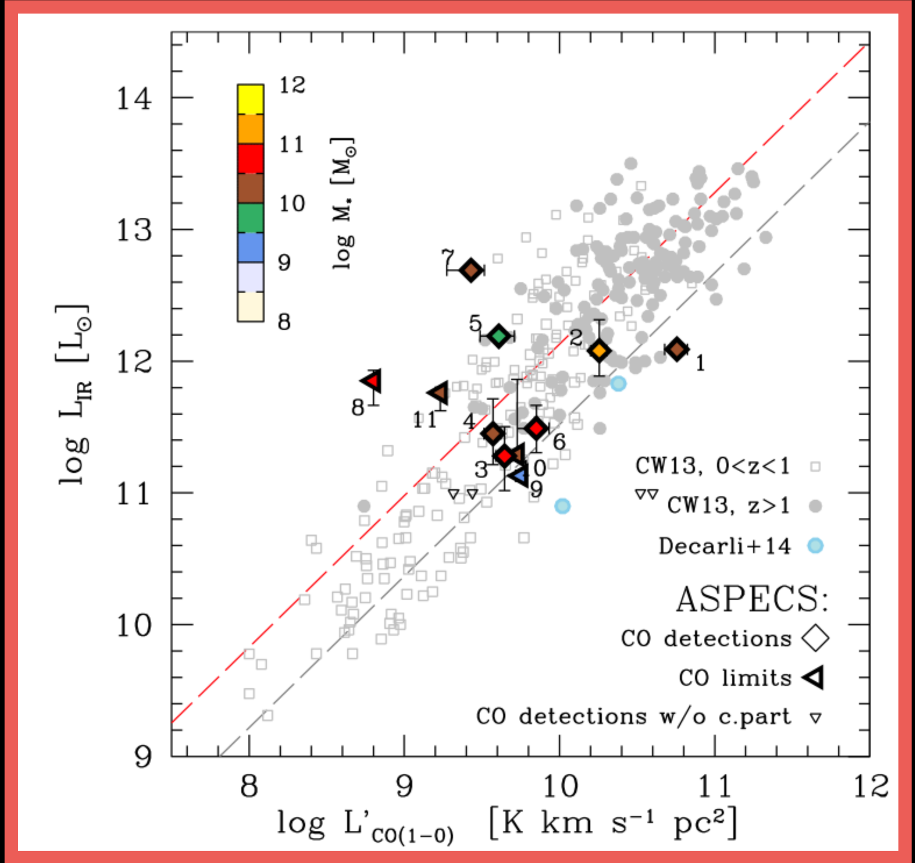


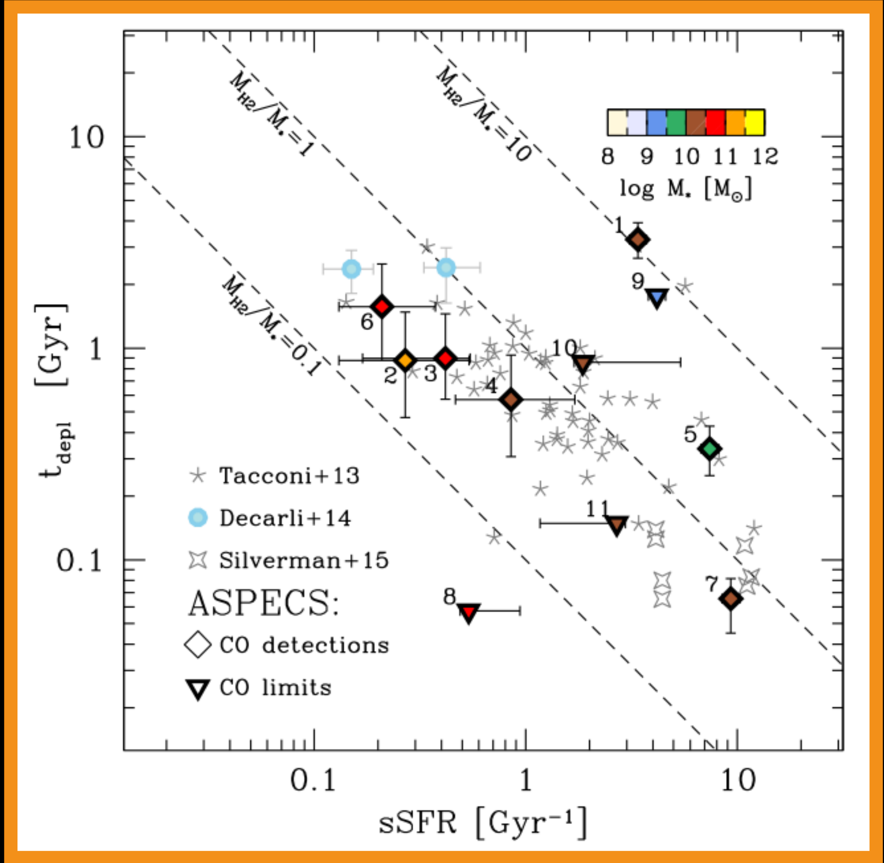


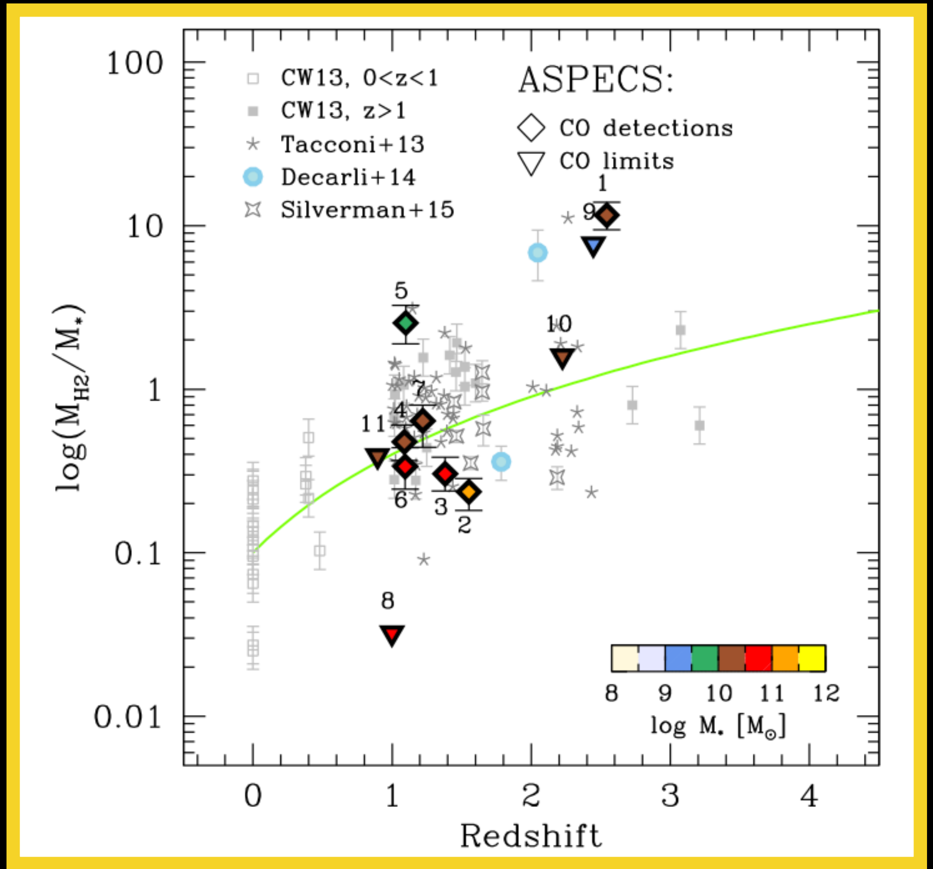


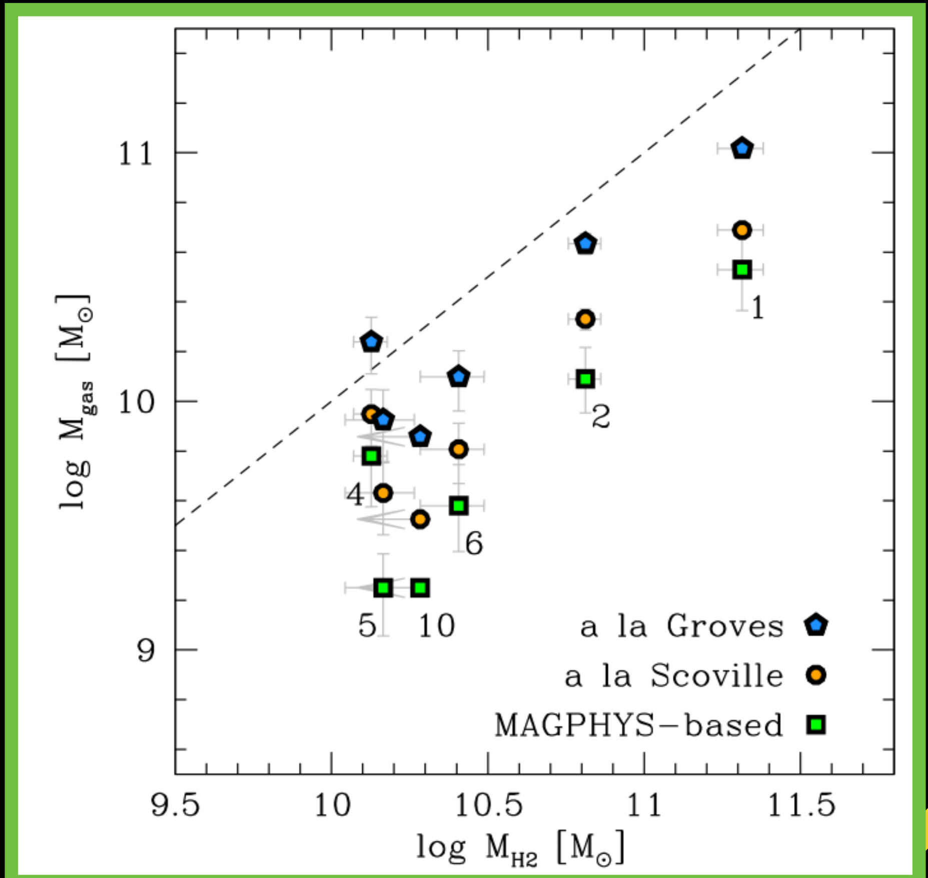
Overview (Decarli+16)











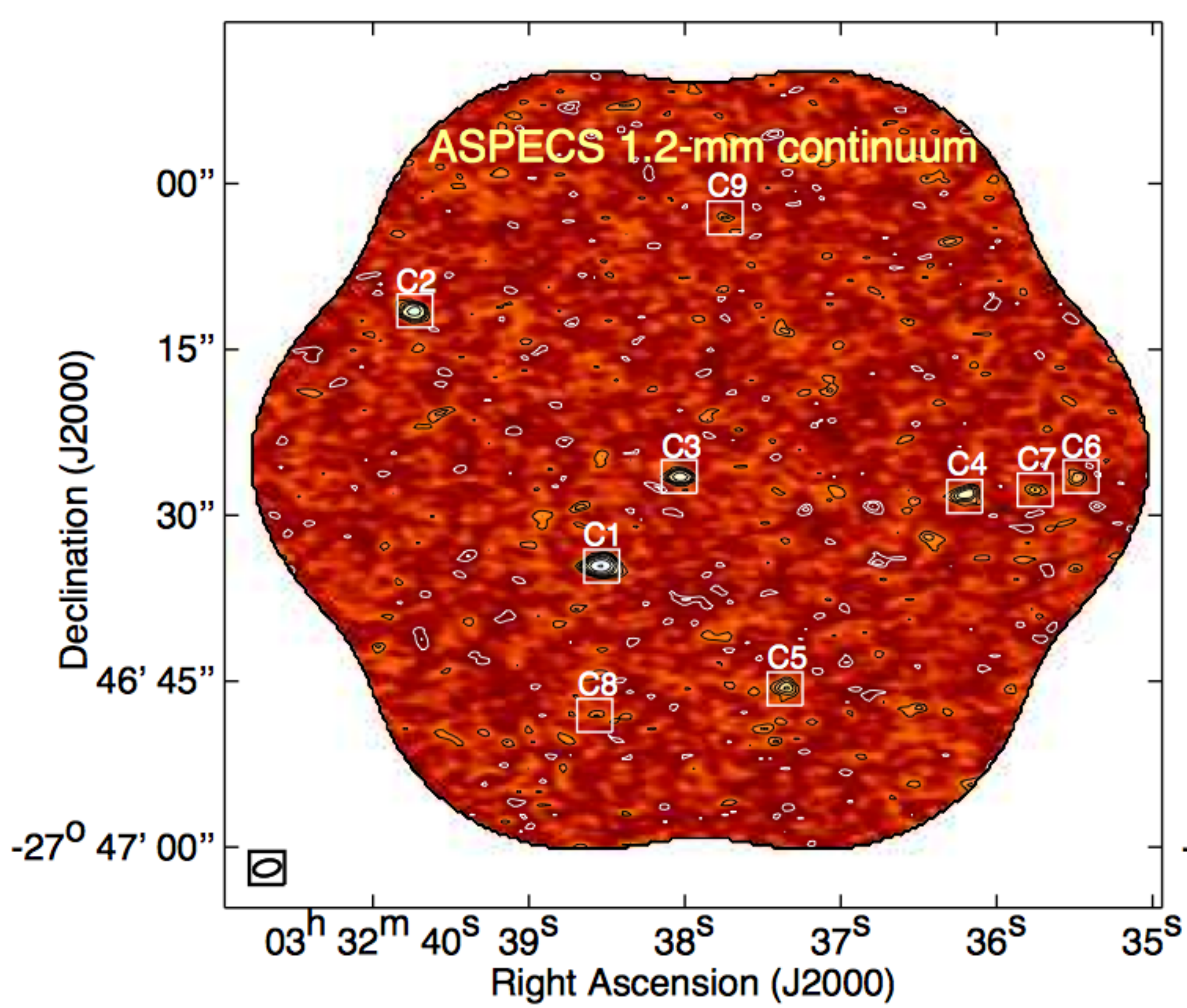
Introduction

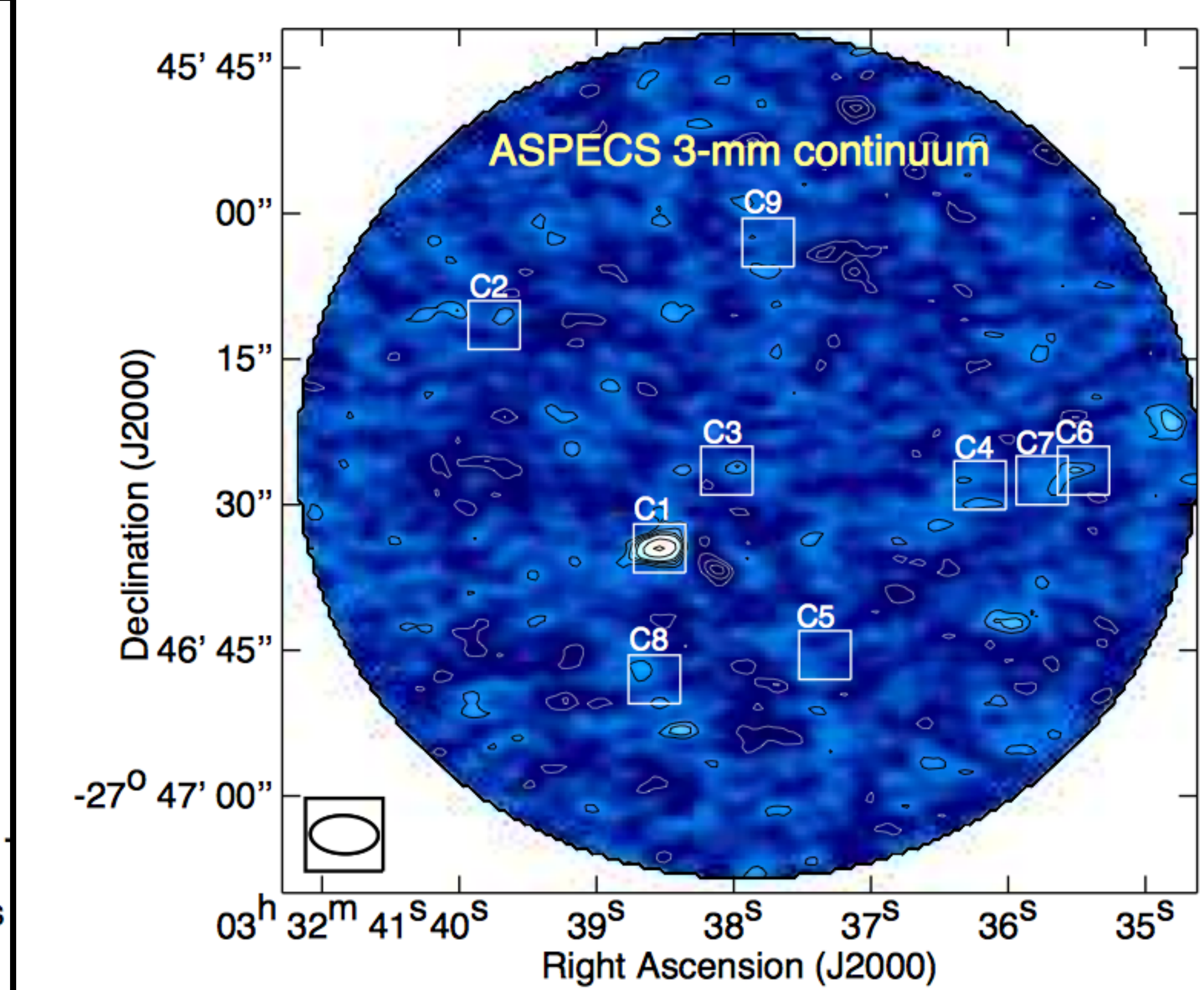
- Extragalactic background light (EBL) at IR-to-mm (CIB): contains information about the history and formation of galaxies, and of the large scale structure of the Universe
  - SMGs (S1.2 mm > 2-3 mJy) were found to contribute only a minor fraction of the EBL at submm
  - the contribution of the fainter galaxy in EBL?

- Molecular gas = the fuel for star formation
  - a vital information in galaxy evolution
  - measurement of molecular gas from dust and CO

Observations : ALMA

- **Resolution : 3″.6x2″.1 - 1″.7 x 0″.9 for band3 and 6**
- CLEAN with natural weighting
  - multi-frequency synthesis (mfs) with nterms=1 (for wide frequency coverage; fitting spectral index)
- rms in the centers :
  - **continuum: 12.7 μJy (B6) and 3.8 μJy (B3) (Aravena+16b)**
  - **line : 0.44 mJy/beam per 50 km/s (B6) and ~0.18 mJy/beam per 50 km/s (B3) (Decarli+16b)**
- coverage : ~1 sq. arcmin (within 4.7 sq. arcmin HUDF)





IAU name ALMA... (1)	Short name ASPECS... (2)	$RA_{1.2mm}$ (J2000) (3)	$Dec_{1.2mm}$ (J2000) (4)	SNR (5)	$S_{1.2mm}$ (μJy) (6)	$PB_{1.2mm}$ (7)	S_{3mm} (μJy) (8)	PB_{3mm} (9)	OID? (10)
9 sources > 3.5 σ		Main sample at $> 3.5\sigma$ significance							
MMJ033238.54-274634.6†	C1 ★	03:32:38.54	−27:46:34.6	39.9	553 ± 14	0.92	31.1 ± 5.0	0.89	Y
MMJ033239.73-274611.6†	C2 ★	03:32:39.73	−27:46:11.6	10.3	223 ± 22	0.59	< 21	0.56	Y
MMJ033238.03-274626.5	C3	03:32:38.03	−27:46:26.5	9.6	145 ± 12	0.95	< 12	1.00	Y
MMJ033236.20-274628.2	C4	03:32:36.20	−27:46:28.2	6.1	87 ± 14	0.89	< 17	0.68	Y
MMJ033237.35-274645.7	C5	03:32:37.35	−27:46:45.7	5.2	71 ± 14	0.92	< 16	0.70	Y
MMJ033235.47-274626.6†	C6 ★	03:32:35.47	−27:46:26.6	3.9	97 ± 25	0.51	< 25	0.45	Y
MMJ033235.75-274627.7	C7	03:32:35.75	−27:46:27.7	3.7	70 ± 19	0.67	< 21	0.55	Y
MMJ033238.57-274648.0	C8	03:32:38.57	−27:46:48.0	3.6	46 ± 13	0.99	< 18	0.62	N
MMJ033237.74-274603.0	C9	03:32:37.74	−27:46:03.0	3.5	55 ± 16	0.80	< 16	0.70	N
+7 sources (3.0-3.5σ)		Supplemetary sample at $3.0 - 3.5\sigma$ significance							
MMJ033237.36-274613.2	C10	03:32:37.36	−27:46:13.2	3.3	45 ± 14	0.93	< 13	0.88	N
MMJ033238.77-274650.1	C11	03:32:38.77	−27:46:50.1	3.2	47 ± 14	0.88	< 21	0.55	N
MMJ033237.42-274650.4	C12	03:32:37.42	−27:46:50.4	3.2	59 ± 18	0.69	< 19	0.60	Y
MMJ033236.50-274647.4	C13	03:32:36.50	−27:46:47.4	3.2	67 ± 21	0.60	< 22	0.52	Y
MMJ033236.43-274632.1	C14	03:32:36.43	−27:46:32.1	3.1	46 ± 15	0.85	< 16	0.73	Y
MMJ033237.49-274649.3	C15	03:32:37.49	−27:46:49.3	3.1	52 ± 17	0.76	< 18	0.63	N
MMJ033237.75-274609.6	C16	03:32:37.75	−27:46:09.6	3.0	41 ± 14	0.93	< 14	0.85	N

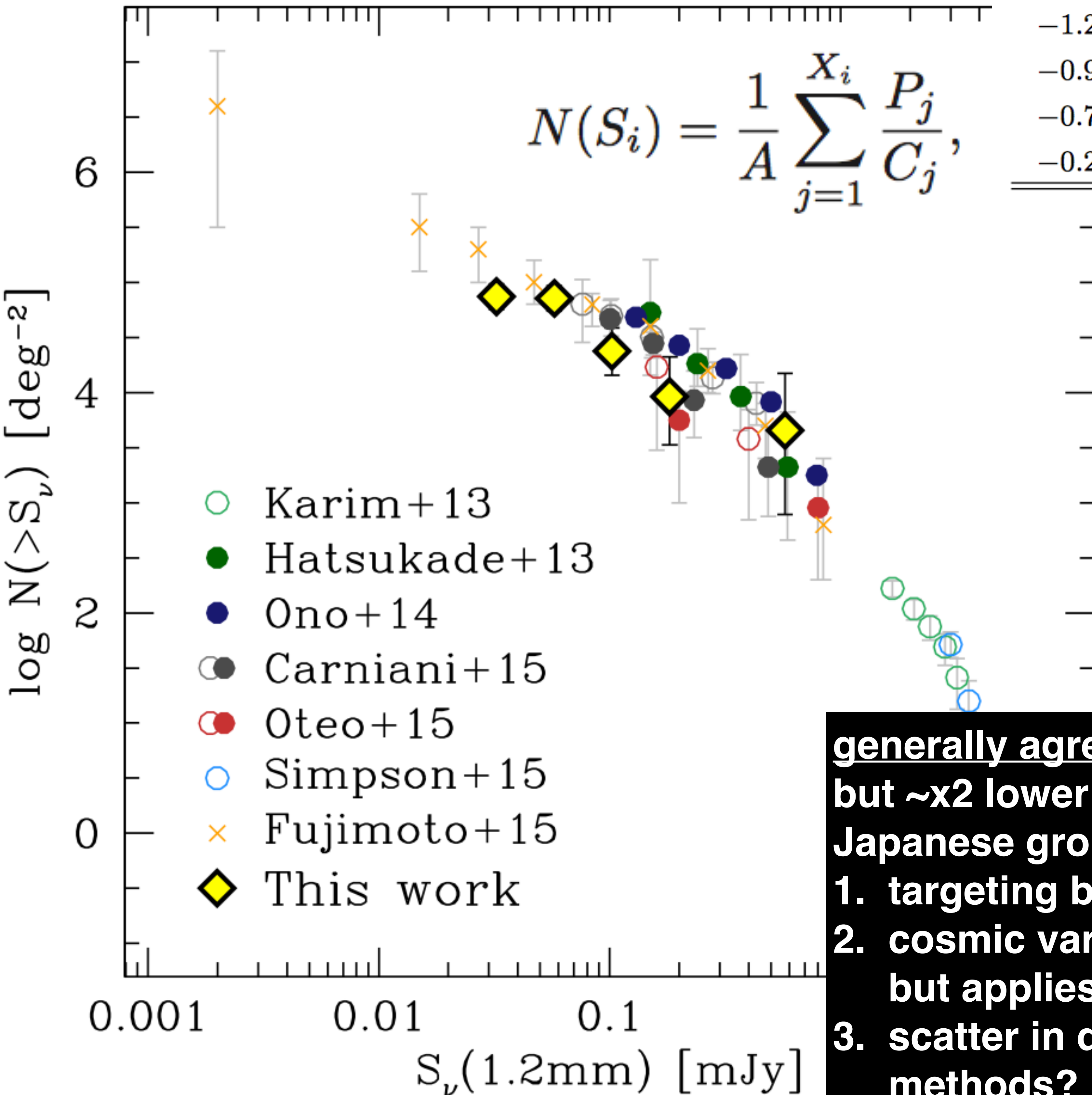
† Sources ASPECS C1, C2 and C6 in this paper correspond to sources 3mm.1, 3mm.2 and 3mm.5 in Decarli et al. (Paper IV).

★ **with CO detection (Decarli+16b)**

Results : Number counts

$\log(S_\nu)$ (mJy) (1)	$dN/d\log(S_\nu)$ (mJy^{-1}) (2)	$N(>S_\nu)$ (deg^{-2}) (3)	δN_- (deg^{-2}) (4)	δN_+ (deg^{-2}) (5)
−1.49	23	132000	3700	43000
−1.24	10	71500	16600	21500
−0.99	3	23700	9400	14700
−0.74	1	9200	5800	11900
−0.24	1	4500	3800	10400

$$N(S_i) = \frac{1}{A}\sum_{j=1}^{X_i}\frac{P_j}{C_j},$$



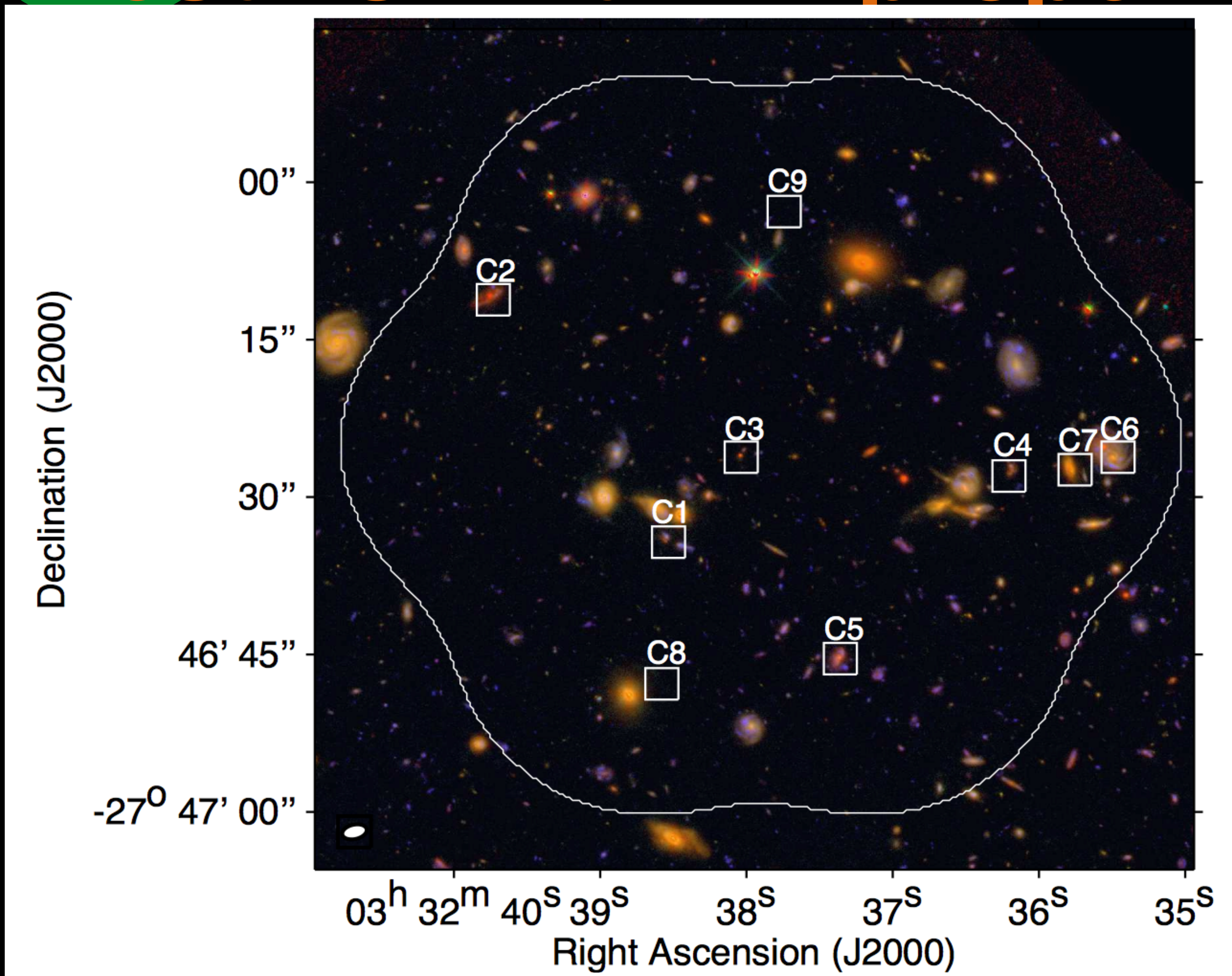
A : effective (survey) area
Xi : number of sources in each particular bin i
Pj : fidelity
Cj : completeness

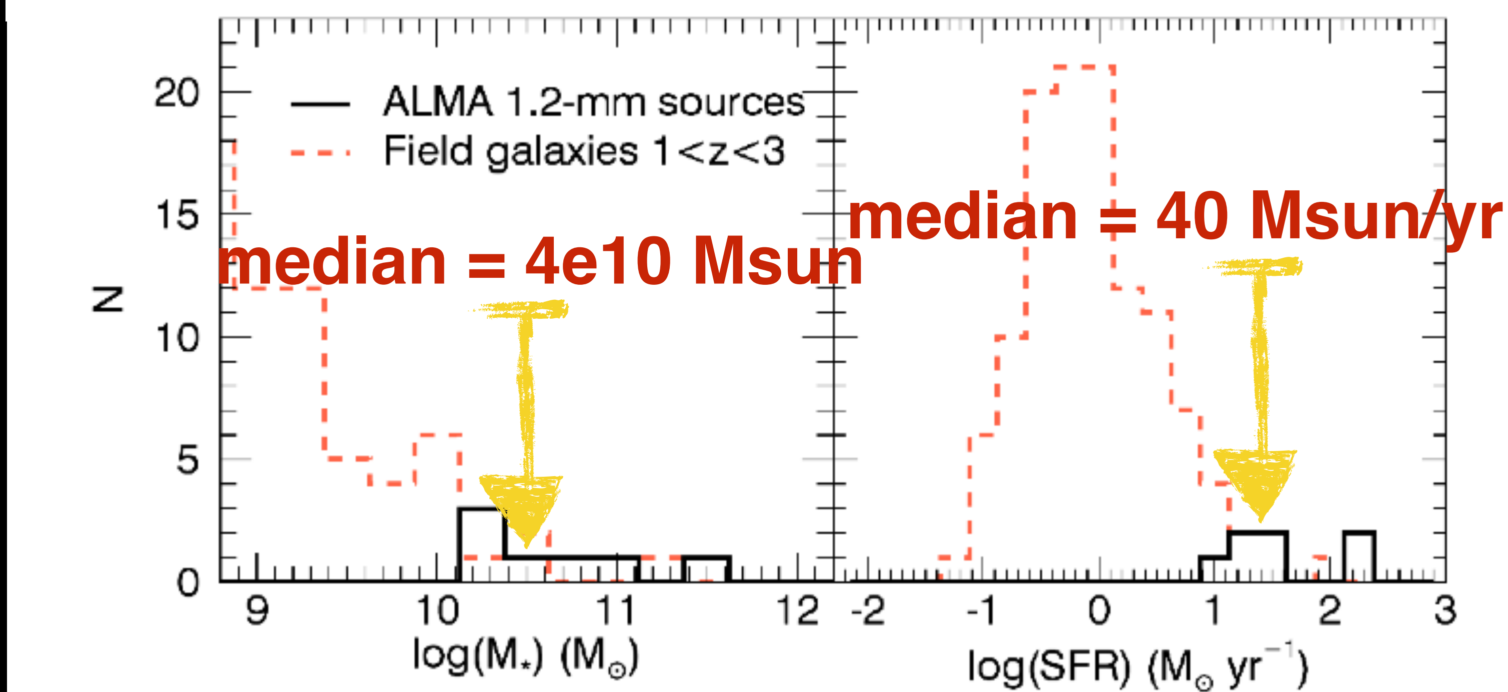
flux density is scaled for consistency with Fujimoto+16
$S_{1.2\,mm} = 0.4\ S_{870um}$
$S_{1.2\,mm} = 0.8\ S_{1.1\,mm}$
$S_{1.2\,mm} = 1.3\ S_{1.3\,mm}$

generally agree with earlier measurements
but ~x2 lower than those values of (aka) Japanese groups at a regime of 0.06-0.4 mJy

1. **targeting biased sample for JP groups?**
2. **cosmic variance? (underdensity of ECDFS, but applies only for bright sources)**
3. **scatter in different analysis technique and methods?**

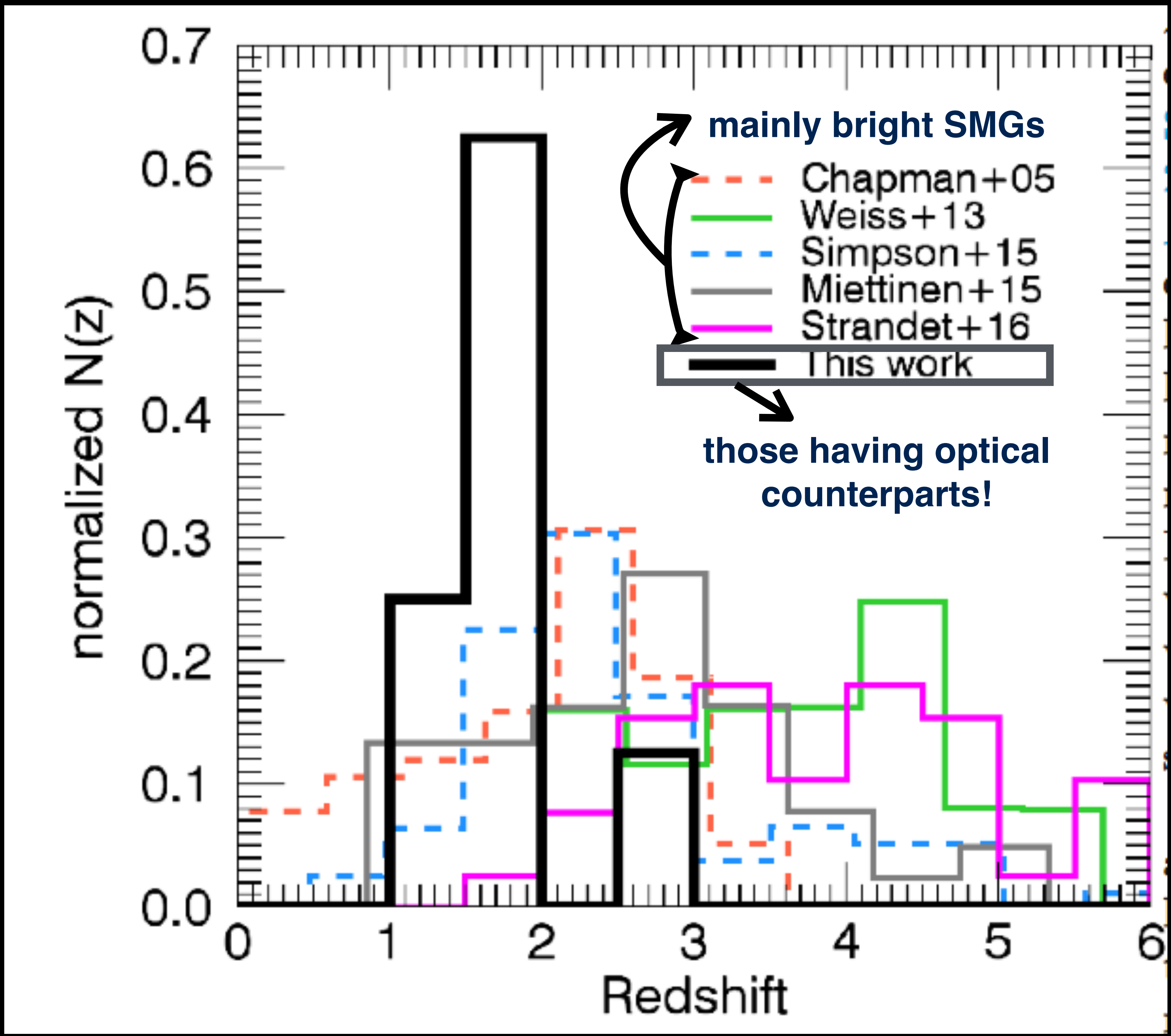
Results : Multi-λ properties of 1.2 mm sources





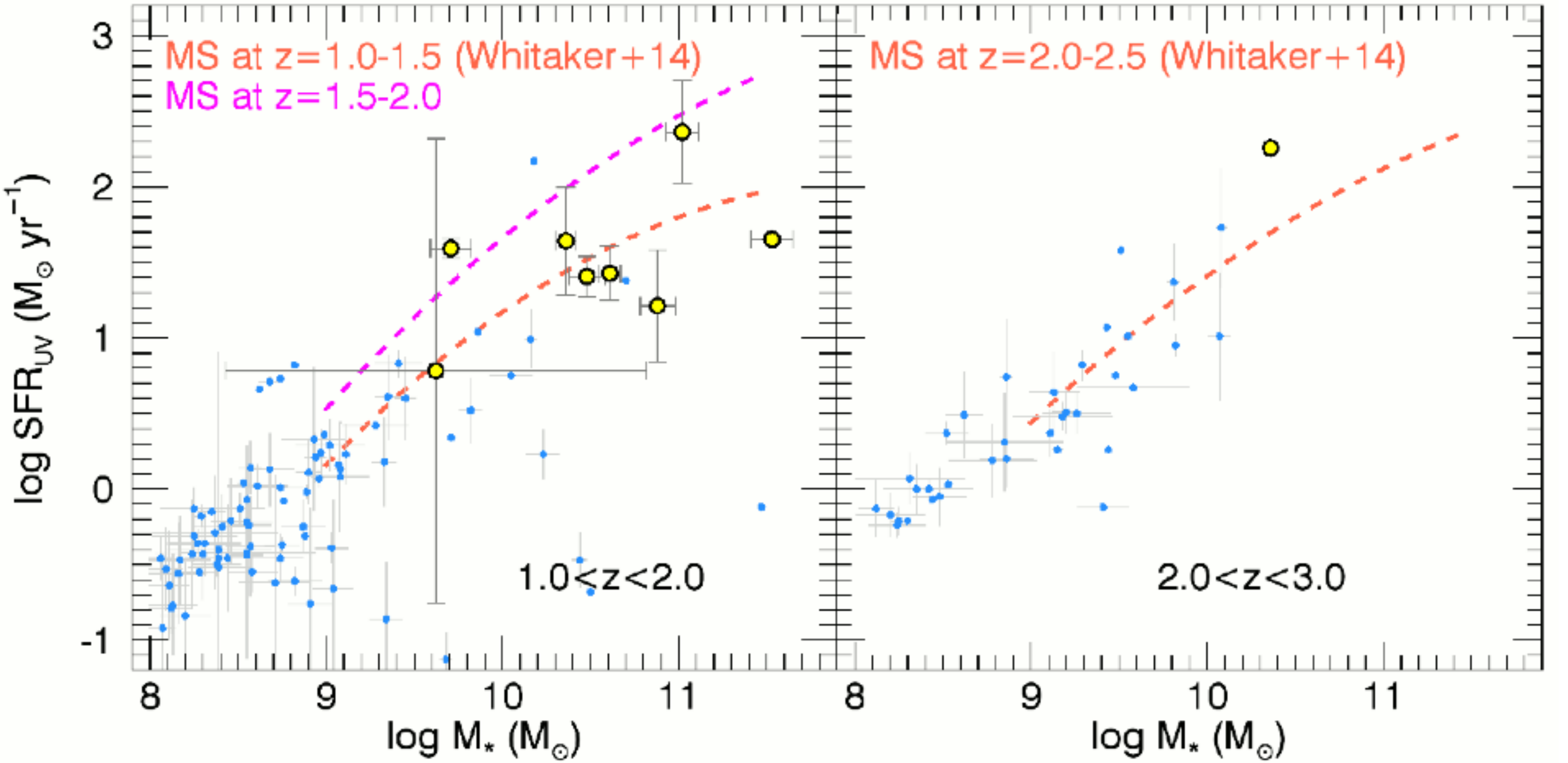
- 1.2-mm sources are not clustered
- search counterpart within 1″
  - **7/9 (main catalog)** have clear counterparts and 5/7 have spec-z
  - **4/7 (low S/N catalog) has no optical counter part** (could be a <u>spurious or, faint dusty galaxies</u>)
- SED fitting using MAGPHYS
  - 26 bands in optical and IR (from U- to 8 um) + ALMA 1.2 mm (no Herschel due to blending)
  - fixed at photometric redshift
  - deriving Mstar, SFR, Mdust, L_{IR}

Results : Redshift distribution



- none are convincingly z>3 (for only those with counterparts)
- viewing different galaxy population found in shallower but wider submm surveys
- **median z = 1.7 for $S_{1.2\,mm}$ <0.5 mJy**
- \`downsizing' of submm sources (evolution of LF)
  - lower flux with lower redshift (Bethermin+15)

Results : SB vs MS



- **faint ALMA 1.2-mm continuum sources are MS galaxies**
  - Hatsukade+15 : $S_{1.3\ mm}$ > 0.2 mJy sources on MS at z=1.3-1.6 (>x2 brighter than ASPECS sources) , but could be associated to the dense environment?
- why no detection having similar SFR?
  - uncertainties in the SED fitting (thus larger Mstar)
  - edges of the mosaic (lower sensitivity)
  - a genuine difference in individual galaxies

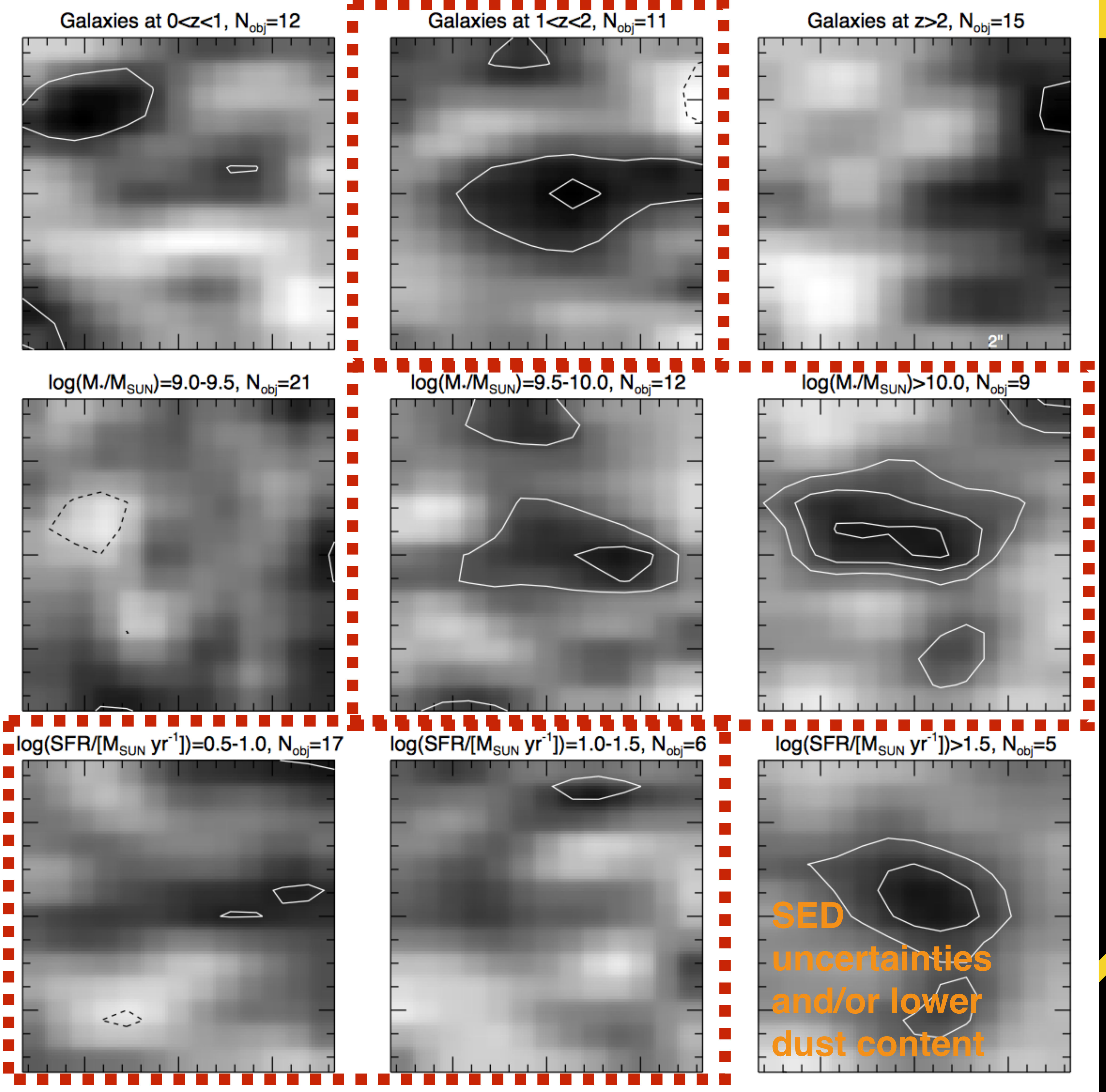
Stacking

redshift
z=1-2

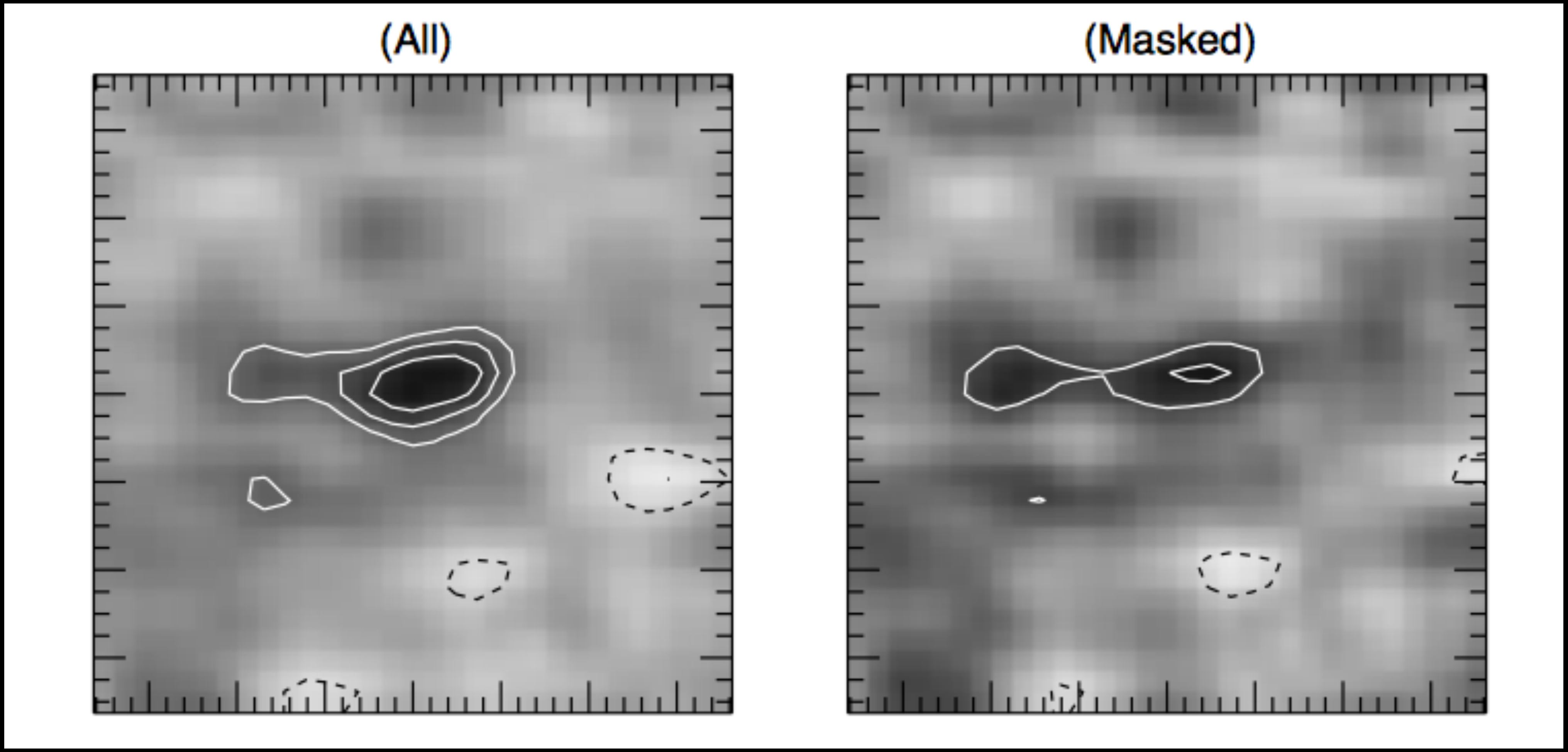
stellar mass
log(Msun) = 9.5-10.5

SFR
SFR ~ 3-10 Msun/yr

±2σ in ±1σ steps



Dust emissivity index from stacking



±2σ in ±1σ steps

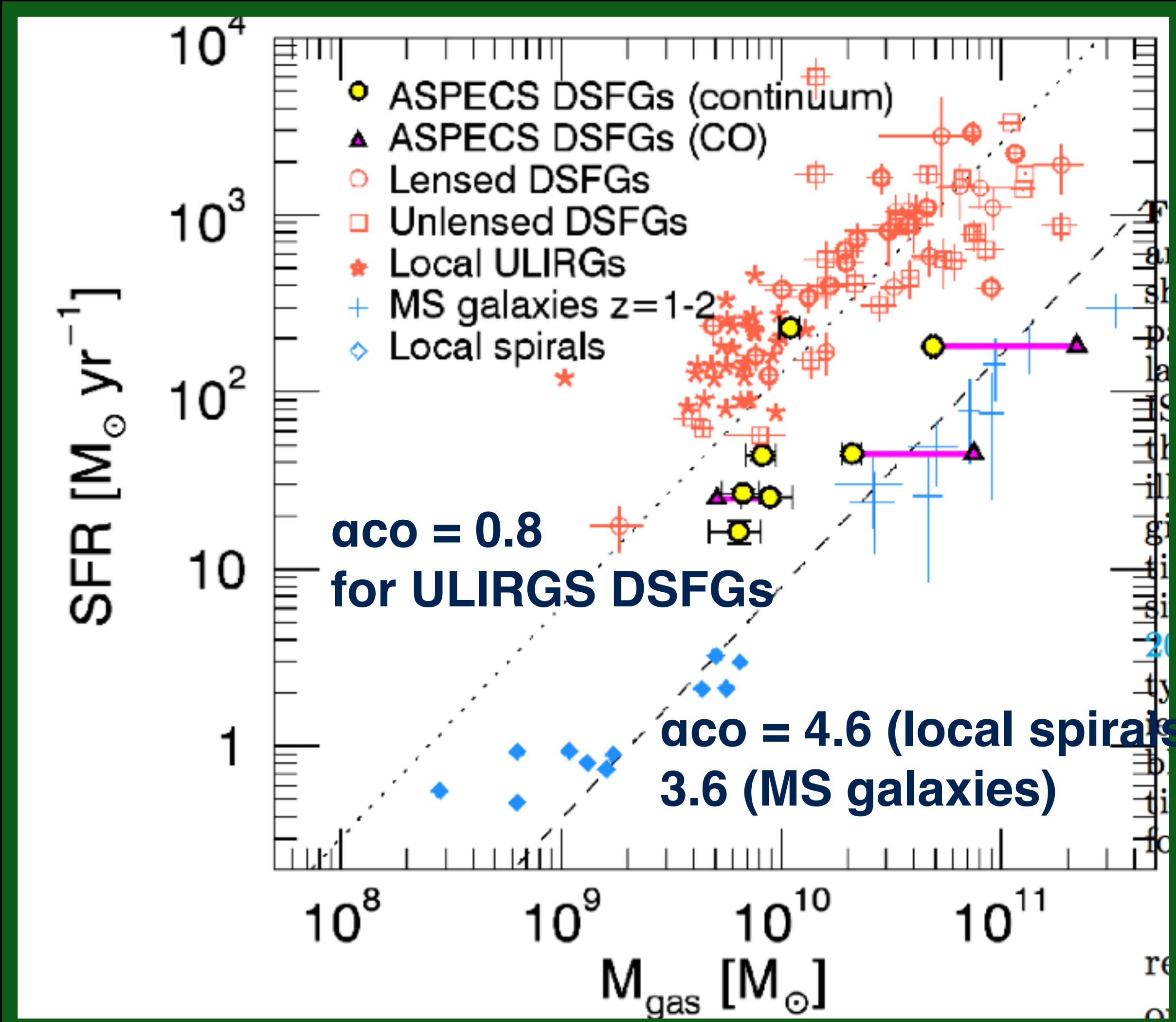
$$\beta = \frac{log(\frac{S(\nu_1)}{S(\nu_2)})}{log(\frac{\nu_1}{\nu_2})} - 2,$$

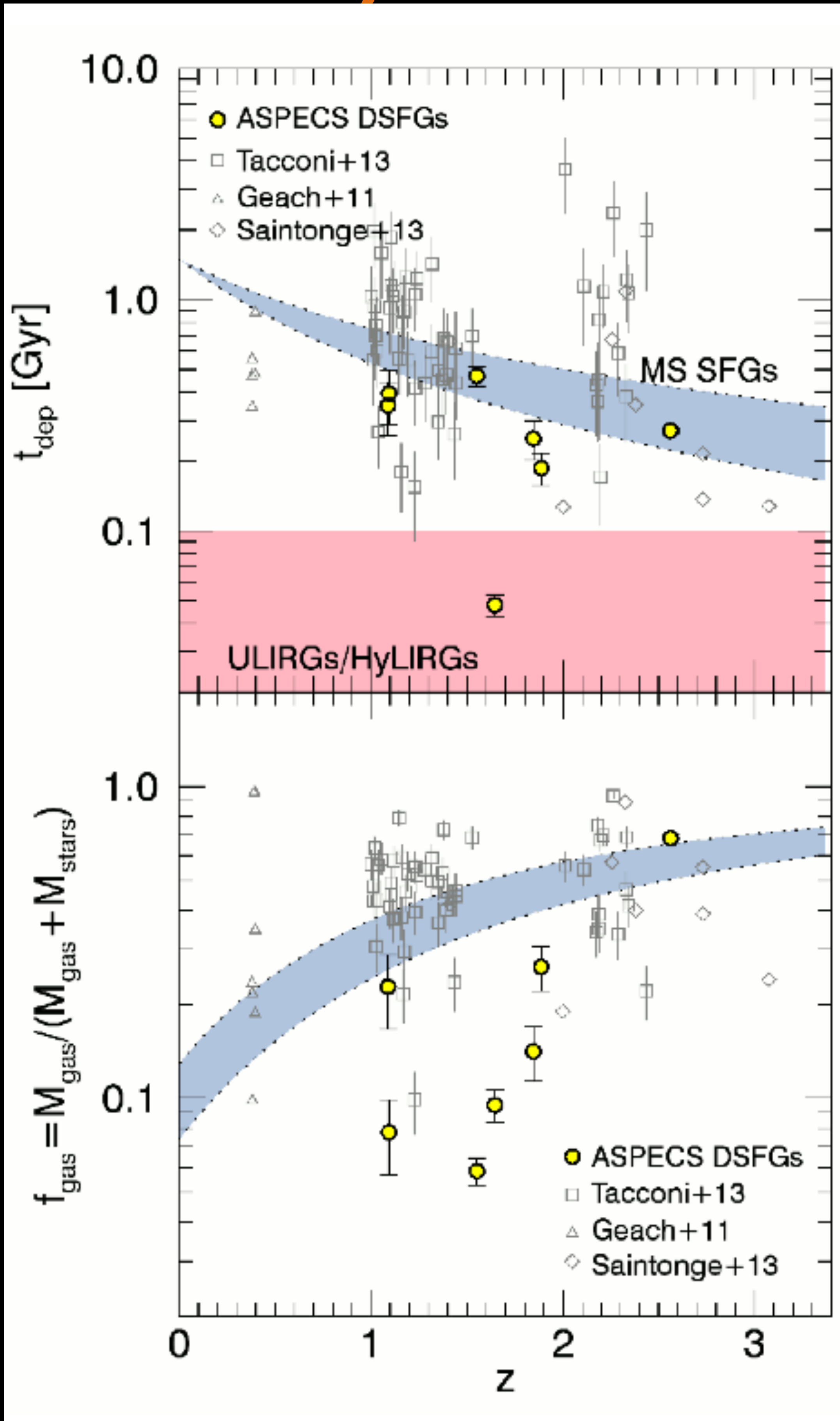
in the RJ-limit

- β = 1.3±0.2
- β = 1.1±0.3 (all)
- **β = 0.9±0.4** (masked the brightest detection in 3 mm)

- lower β = lower flux value at 3 mm or (intrinsically larger) flux
  - missing flux at 1.2 mm or marginal detection of 3 mm? or, 3 mm from free-free?

ISM properties (Aravena+16b)

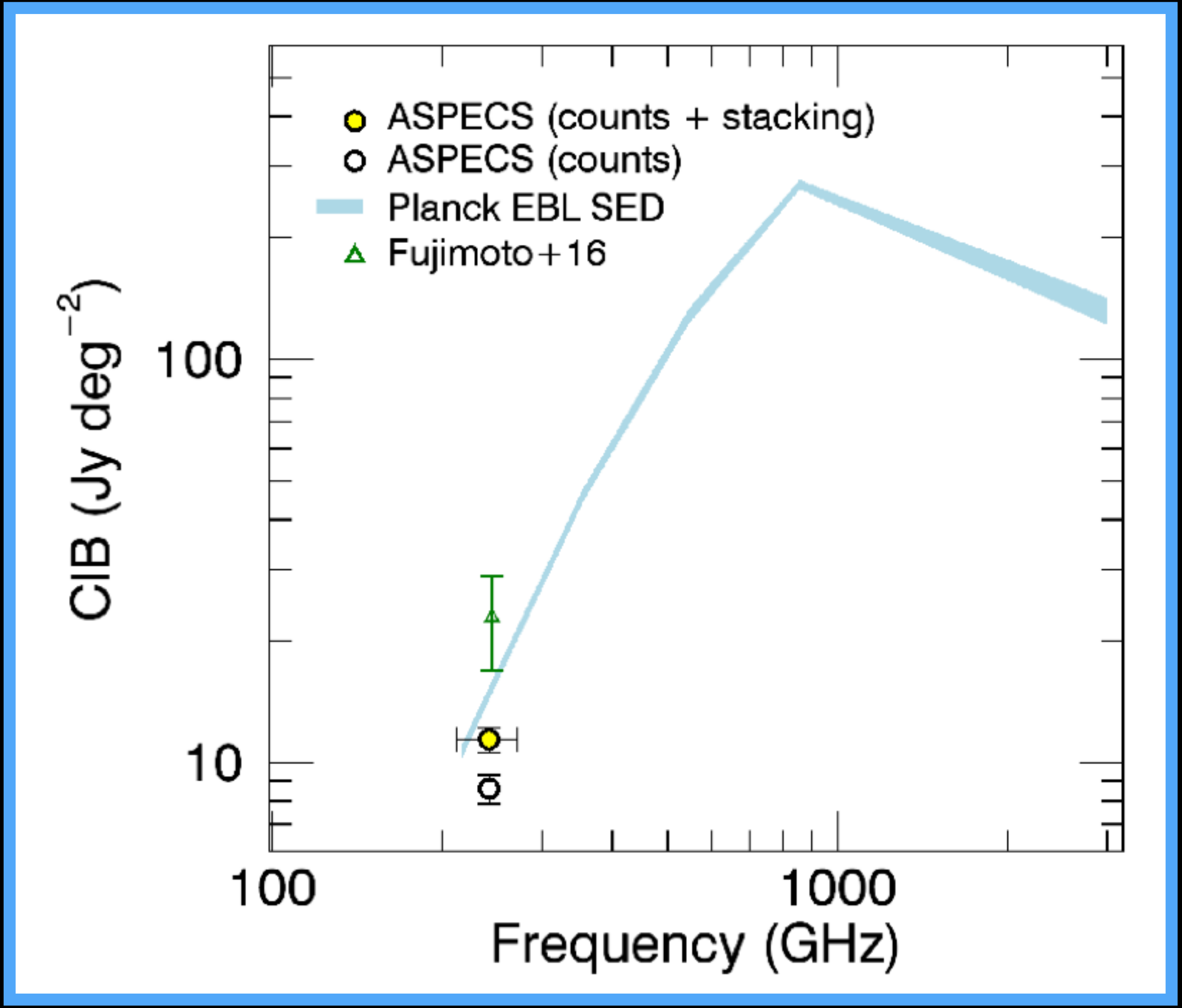




- 2/3 : Mgas from dust (Scoville+14) < Mgas using CO (**aco = 3.6**)
- **in between the SB and MS trends**, (note that dust-based measurement could be underestimated)
  - **fgas is 0.06-0.2 for z~1.5 sample** (significantly lower value) compared to depletion time is in general consistent
- **very large scatter in depletion time scale and fgas**
  - consistent with the scatter obtained in CO
  - hard to discuss any evolutionary trend

EBL at 1.2 mm

- integrated intensity = 7.8±0.4 Jy / sq.deg (but only for <0.6 mJy)
  - for brighter sources, used Karim +13 and Oteo+15
  - then, 8.6±0.7 Jy / sq.deg
  - From Planck, EBL at ~242 GHz : 14.2±0.6 Jy / sq.deg
    →~60±6 % of EBL is recovered at ~242 GHz
- from stacking
  - 11.4±0.8 Jy / sq.deg
    →~80±7 % of EBL is recovered at ~242 GHz



- The resolved sources are on average
  - Mstar ~ 4e10 Msun, SFR ~40 Msun/yr at z~1.7
  - (by stacking) Mstar ~ 0.5-1.5x1e10 Msun, SFR ~10-20 Msun/yr
- The remained unresolved EBL (~10%) is coming from less massive galaxies (Mstar < 1e9 Msun)
- **But, still, cosmic variance is a matter of conflict with many surveys**

Summary (Aravena+16b)

- $S_{1.2\ mm}$ = 0.036-0.57 mJy, number counts are similar with differences within a factor of ~2
- **Mstar ~ 4e10 Msun, SFR ~40 Msun/yr** (lower than SMGs) located at lower redshifts than mm-selected SMGs (**$\langle z \rangle_{med}$ = 1.7**) and on the MS
  - from stacking, finding that galaxies undetected are at similar redshift but less massive with lower SFRs
- ISM mass of faint SMGs are near the relation of SFR-Mgas with **$T_{depl.}$> 300 Myr and large scatter of fgas between 0.1 and 1.0**
- **EBL is 55±4 % resolved from individual detection** at 242 GHz, by adding fainter sources from stacking analysis and brighter sources in other literature, it is resolved by **77-84%**

Decarli+16

- Sample selection
  - from1302 galaxies within ALMA band3 FoV
  - ➡ select 56 that have secure spec-z
  - ➡ then, restrict analysis for those at least having low-J (J<5) transition coverage : J=2-1, 3-2, 4-3
  - ➡ select **11 galaxies** that has LIR > **1e11 Lsun** from SED fitting (MAGPHYS)

➡ **result : 7 are detected, 4 are undetected**

Detection criteria

1. S/N > 3 (Gaussian fitting) at the central position of optical coordinate

2. for undetected, set 3σ upper limit of Lco using FWHM ~ 300 km/s

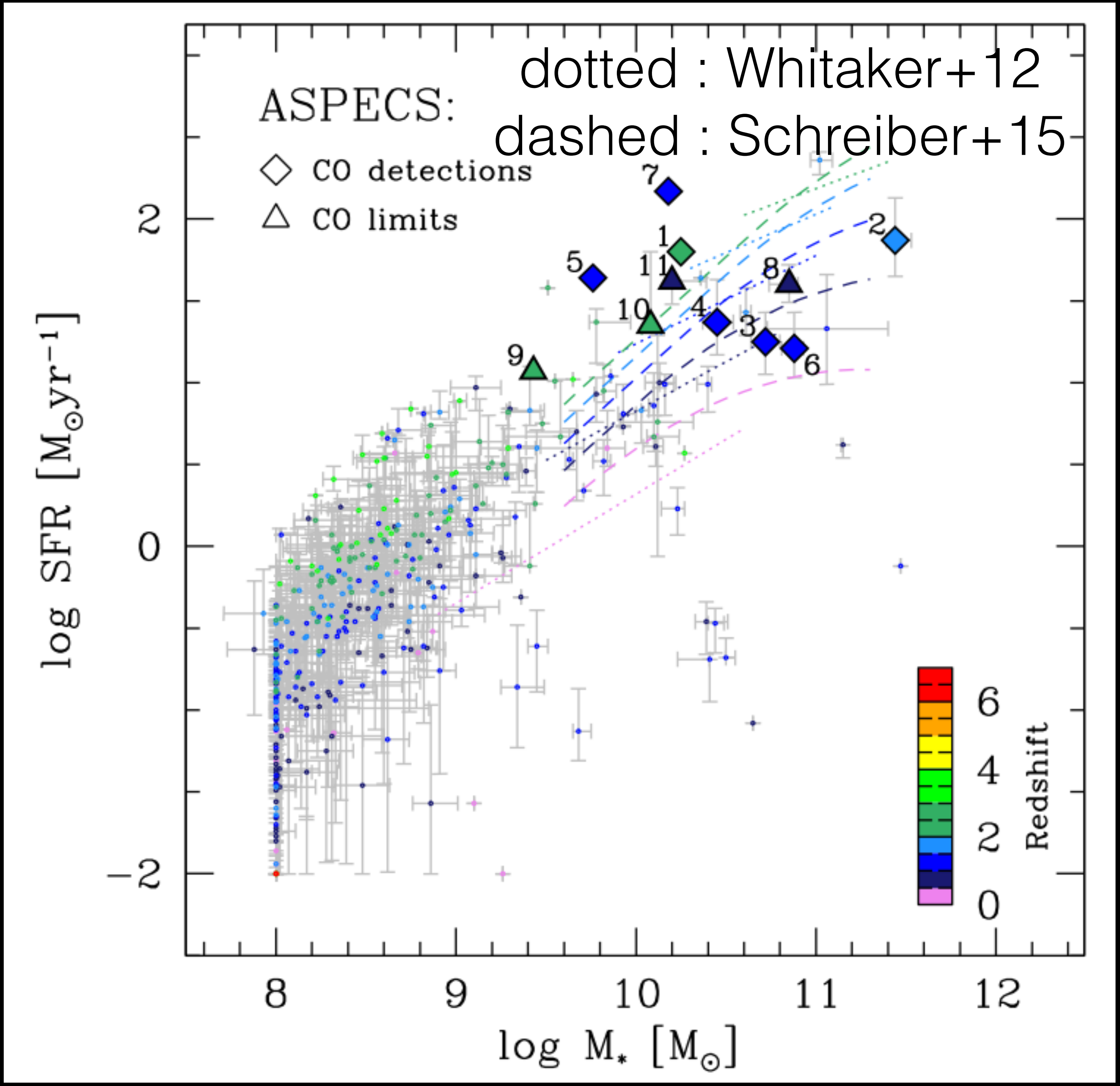


Table 1. The sample of galaxies examined in this work, and their optical/near-IR global properties. The sorting is based on the significance of the CO detection. (1) Source ID. (2) ASPECS name for blind CO detections (3mm.X, see Paper I) and for the blind 1.2mm continuum detections (CX, see Paper II). (3-4) Optical coordinates in Skelton et al. (2014). (5) Redshift. (6) J_{up} of the CO transitions encompassed in our ASPECS data. (7-10) MAGPHYS-derived stellar mass (M_*), star formation rate (SFR), specific star formation rate (sSFR), IR luminosity (L_{IR}). (11) Effective radius from the near-IR analysis by van der Wel et al. (2012).

ID	ASPECS name	Optical RA	Optical Dec	z	Obs.CO trans.	M_* [$\times 10^9$ M$_\odot$]	SFR [M$_\odot$ yr^{-1}]	sSFR [Gyr^{-1}]	L_{IR} [$\times 10^{11}$ L$_\odot$]	R_e [kpc]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	3mm.1*,C1	03:32:38.54	-27:46:34.0	2.543	3,7,8	$17.8^{+1.8}_{-1.7}$	63^{+6}_{-6}	$3.4^{+0.34}_{-0.31}$	$12.3^{+1.2}_{-1.1}$	1.7
2	3mm.2,C2	03:32:39.74	-27:46:11.2	1.551	2,5,6	275^{+70}_{-40}	74^{+60}_{-30}	$0.27^{+0.27}_{-0.14}$	$12.0^{+8.6}_{-4.3}$	8.3
3	3mm.3	03:32:35.55	-27:46:25.5	1.382	2,5	52^{+12}_{-10}	18^{+9}_{-7}	$0.42^{+0.13}_{-0.25}$	$1.9^{+1.3}_{-0.9}$	8.3
4	3mm.5,C6	03:32:35.48	-27:46:26.5	1.088	2,4	28^{+7}_{-5}	23^{+20}_{-9}	$0.9^{+0.9}_{-0.4}$	$2.8^{+2.4}_{-1.2}$	5.8
5		03:32:36.43	-27:46:31.8	1.098	2,4	$5.8^{+0.6}_{-0.5}$	44^{+4}_{-4}	$7.41^{+0.7}_{-0.7}$	$15.5^{+1.5}_{-1.4}$	6.0
6	C7	03:32:35.78	-27:46:27.5	1.094	2,4	75^{+12}_{-13}	16^{+11}_{-6}	$0.21^{+0.17}_{-0.08}$	$3.1^{+1.5}_{-1.1}$	3.8
7		03:32:39.08	-27:46:01.8	1.221	2,5	$15.1^{+1.5}_{-1.4}$	148^{+15}_{-13}	$9.3^{+0.9}_{-0.8}$	$49.0^{+4.9}_{-4.4}$	0.7
8		03:32:36.66	-27:46:31.0	0.999	4	70^{+11}_{-17}	40^{+14}_{-9}	$0.54^{+0.40}_{-0.05}$	$7.1^{+1.5}_{-2.5}$	6.6
9		03:32:39.41	-27:46:22.4	2.447	3,7,8	$2.6^{+0.3}_{-0.2}$	$11.8^{+1.2}_{-1.1}$	$4.2^{+0.4}_{-0.4}$	$1.35^{+0.13}_{-0.12}$	5.8
10		03:32:37.07	-27:46:17.2	2.224	3,6,7	$12.0^{+1.2}_{-1.2}$	22^{+41}_{-2}	$1.86^{+3.53}_{-0.17}$	$1.95^{+5.3}_{-0.18}$	2.7
11		03:32:36.33	-27:46:00.1	0.895	4	$15.9^{+9.0}_{-1.4}$	42^{+4}_{-12}	$2.7^{+0.27}_{-1.5}$	$5.8^{+0.6}_{-1.6}$	1.2

* Also 1mm.1 and 1mm.2, see Paper I.

Table 2. CO lines in the galaxies of our sample. (1) Source ID. (2) Upper J of the CO transition. (3) Velocity shift, compared with the redshift quoted in Tab. 1. (4) Line flux. (5) Line width, expressed as full width at half maximum (FWHM) from the gaussian fit.

ID	J_{up}	Δv [$km\,s^{-1}$]	F_{line} [$Jy\,km\,s^{-1}$]	FWHM [$km\,s^{-1}$]
(1)	(2)	(3)	(4)	(5)
1	3	-45 ± 8	$0.723^{+0.003}_{-0.003}$	504 ± 12
1	7	-150 ± 120	$0.786^{+0.006}_{-0.006}$	504^*
1	8	-45 ± 70	$1.098^{+0.005}_{-0.005}$	504^*
2	2	135 ± 9	$0.443^{+0.007}_{-0.007}$	538 ± 13
2	5	135 ± 45	$0.502^{+0.090}_{-0.090}$	538^*
2	6	-45 ± 45	$0.820^{+0.100}_{-0.100}$	538^*
3	2	-37 ± 8	$0.135^{+0.003}_{-0.003}$	57 ± 12
3	5	—	< 0.021	57^*
4	2	52 ± 7	$0.180^{+0.006}_{-0.006}$	82 ± 11
4	4	—	< 0.121	82^*
5	2	220 ± 35	$0.190^{+0.040}_{-0.040}$	352 ± 11
5	4	-28 ± 40	$0.390^{+0.065}_{-0.065}$	352^*
6	2	-160 ± 70	$0.340^{+0.060}_{-0.070}$	530 ± 11
6	4	230 ± 70	$0.370^{+0.090}_{-0.090}$	182^*
7	2	150 ± 17	$0.104^{+0.019}_{-0.029}$	150 ± 11
7	5	—	< 0.106	150^*
8	4	—	< 0.059	—
9	3	—	< 0.076	—
9	7	—	< 0.012	—
9	8	—	< 0.230	—
10	3	—	< 0.048	—
10	6	—	< 0.144	—
10	7	—	< 0.465	—
11	4	—	< 0.015	—

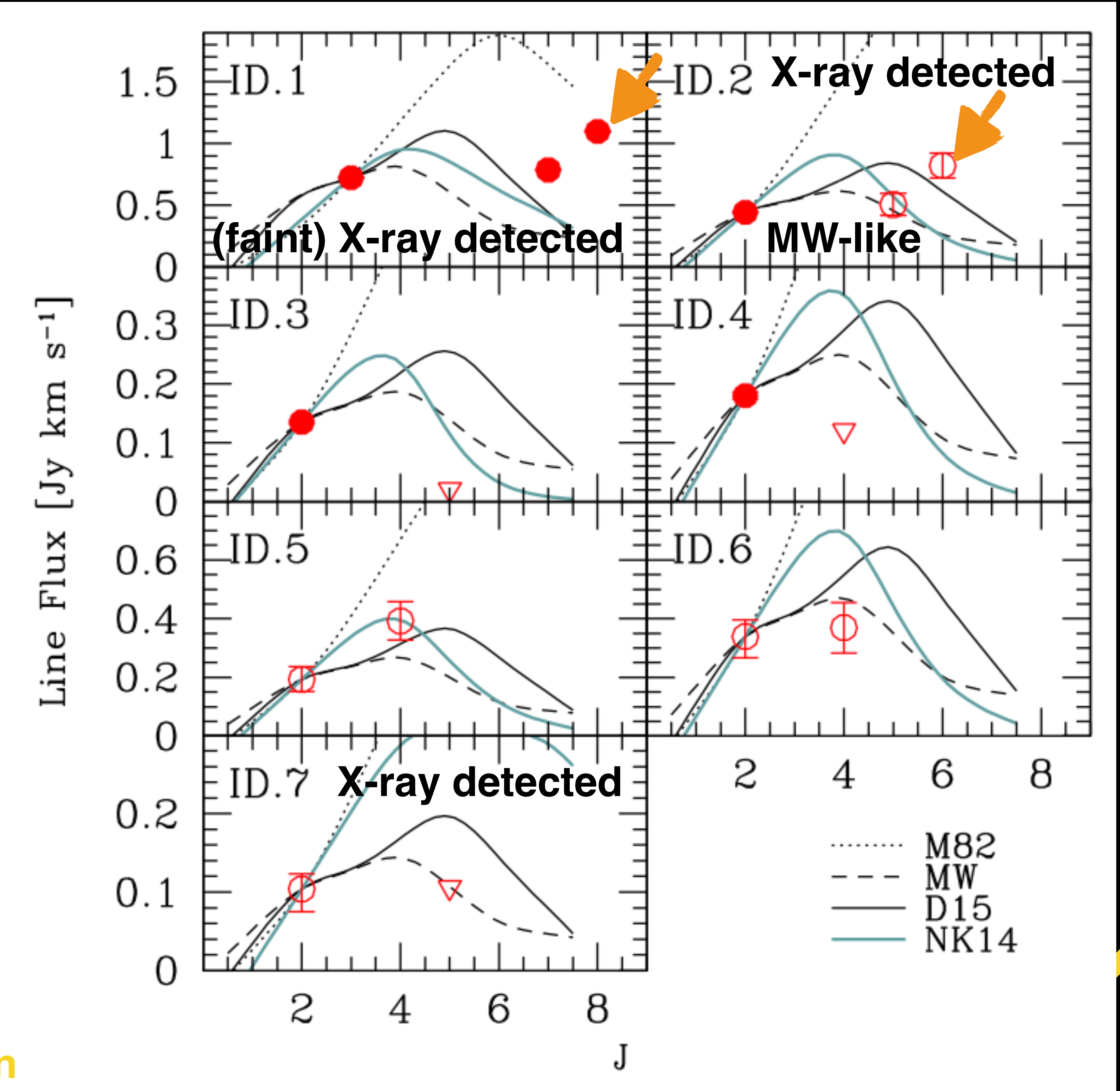
* Fixed from the fit of a lower J line.

- Calculate $L'_{CO(1-0)}$ using Daddi +15 : $r_{21} = 0.76 \pm 0.09$, $r3_1 = 0.42 \pm 0.07$, $r_{41} = 0.31 \pm 0.06$
- $\alpha_{CO} = 3.6$ Msun ($K\,km\,s^{-1}\,pc^2)^{-1}$

ID	z	J_{up}	L' [$\times 10^9$ K $km\,s^{-1}\,pc^2$]	$L'_{CO(1-0)}$ [$\times 10^9$ K $km\,s^{-1}\,pc^2$]	M_{H2} [$\times 10^9$ $M_\odot$]	M_{H2}/M_*	t_{depl} [Gyr]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	2.543	3	$24.03^{+0.10}_{-0.10}$	57^{+10}_{-10}	206^{+34}_{-34}	12^{+2}_{-2}	$3.3^{+0.7}_{-0.6}$
2	1.551	2	$13.71^{+0.21}_{-0.27}$	18^{+2}_{-2}	65^{+8}_{-8}	$0.24^{+0.05}_{-0.05}$	$0.9^{+0.6}_{-0.4}$
3	1.382	2	$3.364^{+0.07}_{-0.08}$	$4.4^{+0.5}_{-0.5}$	$15.9^{+1.9}_{-1.9}$	$0.30^{+0.08}_{-0.07}$	$0.9^{+0.6}_{-0.3}$
4	1.088	2	$2.831^{+0.09}_{-0.09}$	$3.7^{+0.5}_{-0.5}$	$13.4^{+1.7}_{-1.7}$	$0.48^{+0.13}_{-0.11}$	$0.6^{+0.4}_{-0.3}$
5	1.098	2	$3.089^{+0.70}_{-0.66}$	$4.1^{+1.0}_{-1.0}$	15^{+4}_{-4}	$2.5^{+0.7}_{-0.6}$	$0.33^{+0.09}_{-0.09}$
6	1.094	2	$5.388^{+0.91}_{-1.16}$	$7.1^{+1.5}_{-1.7}$	25^{+5}_{-6}	$0.34^{+0.10}_{-0.09}$	$1.6^{+0.9}_{-0.7}$
7	1.221	2	$2.047^{+0.37}_{-0.57}$	$2.7^{+0.6}_{-0.8}$	10^{+2}_{-3}	$0.6^{+0.16}_{-0.2}$	$0.066^{+0.016}_{-0.020}$
8	0.999	4	< 0.20	< 0.63	< 2.3	< 0.03	< 0.06
9	2.447	3	< 2.4	< 5.6	< 21	< 8	< 1.8
10	2.224	3	< 2.2	< 5.3	< 19	< 1.6	< 0.9
11	0.895	4	< 0.53	< 1.7	< 6.2	< 0.4	< 0.15

CO excitation

- **No SB-like excitation comparable to M82 (or high-z SMG)**
- ID. 1 : r_{73} = 0.2 (consistent with high-density PDR), but CO(8-7) goes up that is attributed by its compact emission (~1/5 of ID. 2)
- ID. 2 : lower excitation in CO(5-4)/CO(2-1) like MW
  - r_{73} = 0.16-0.63 in PDR powered by SF, but can be r_{73} = 30 in presence of intense X-ray illumination
  - AGN in ID.2 has not major impact on its global CO excitation

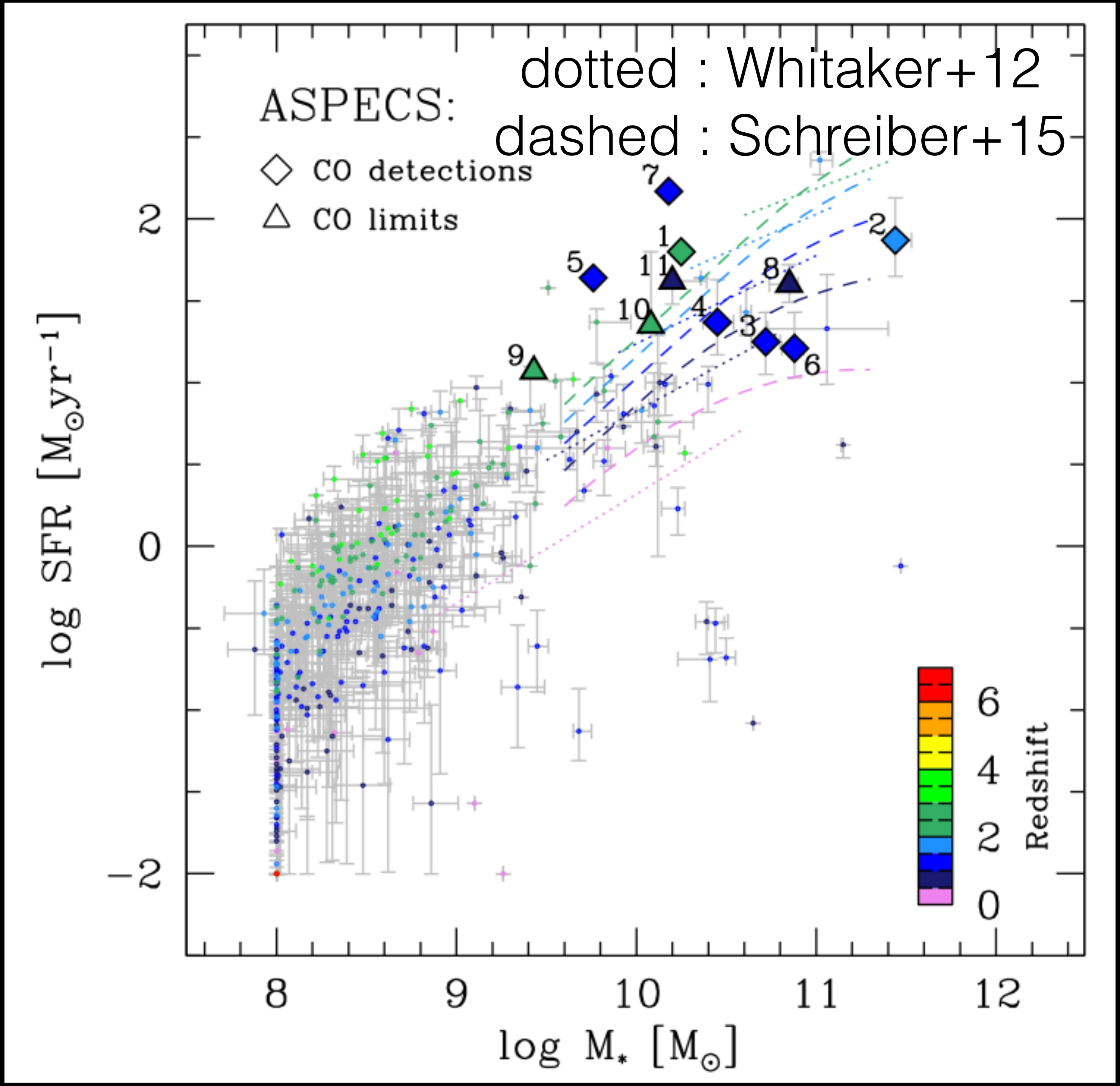


Filled : blind search detection

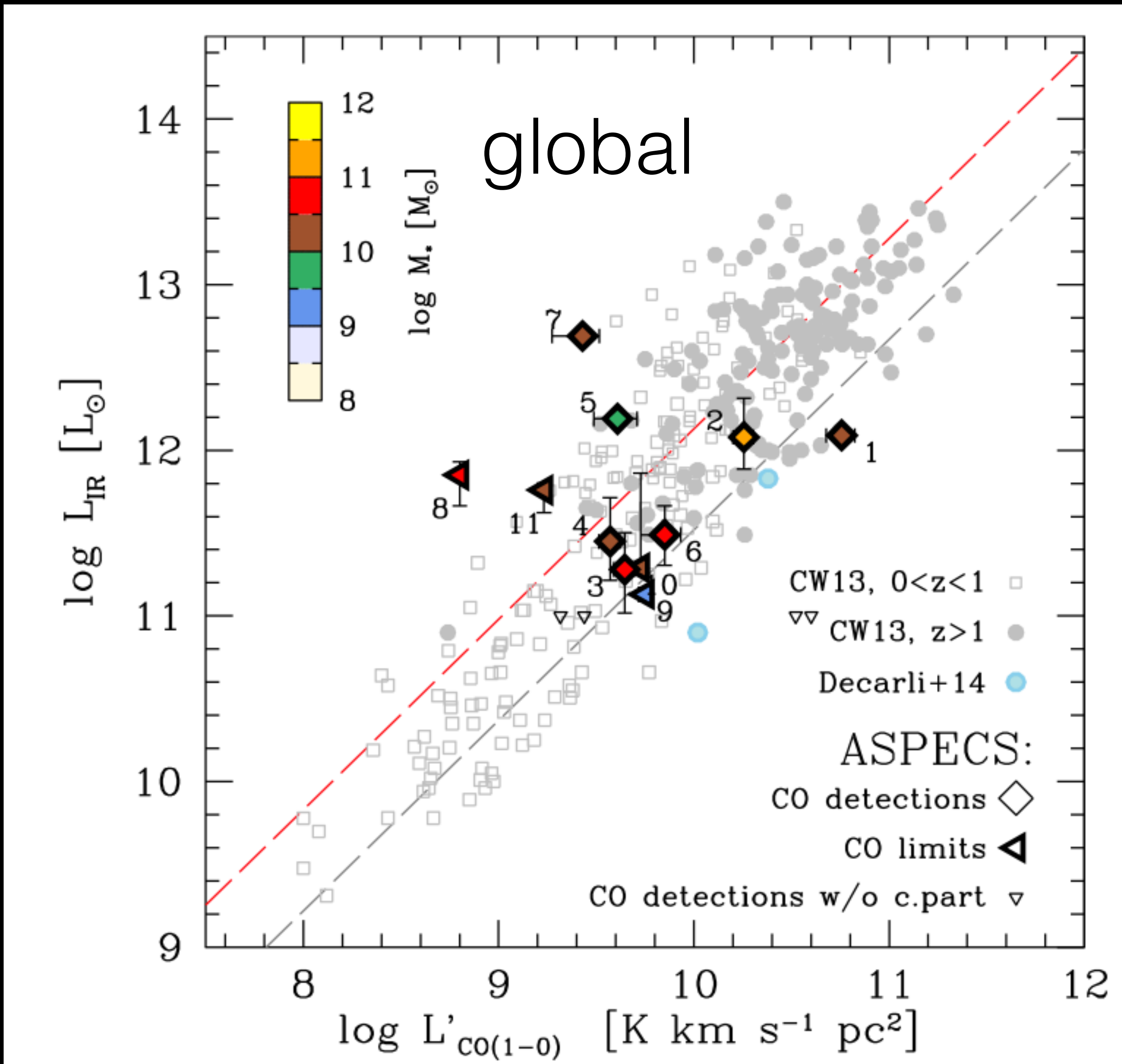
The position of the MS

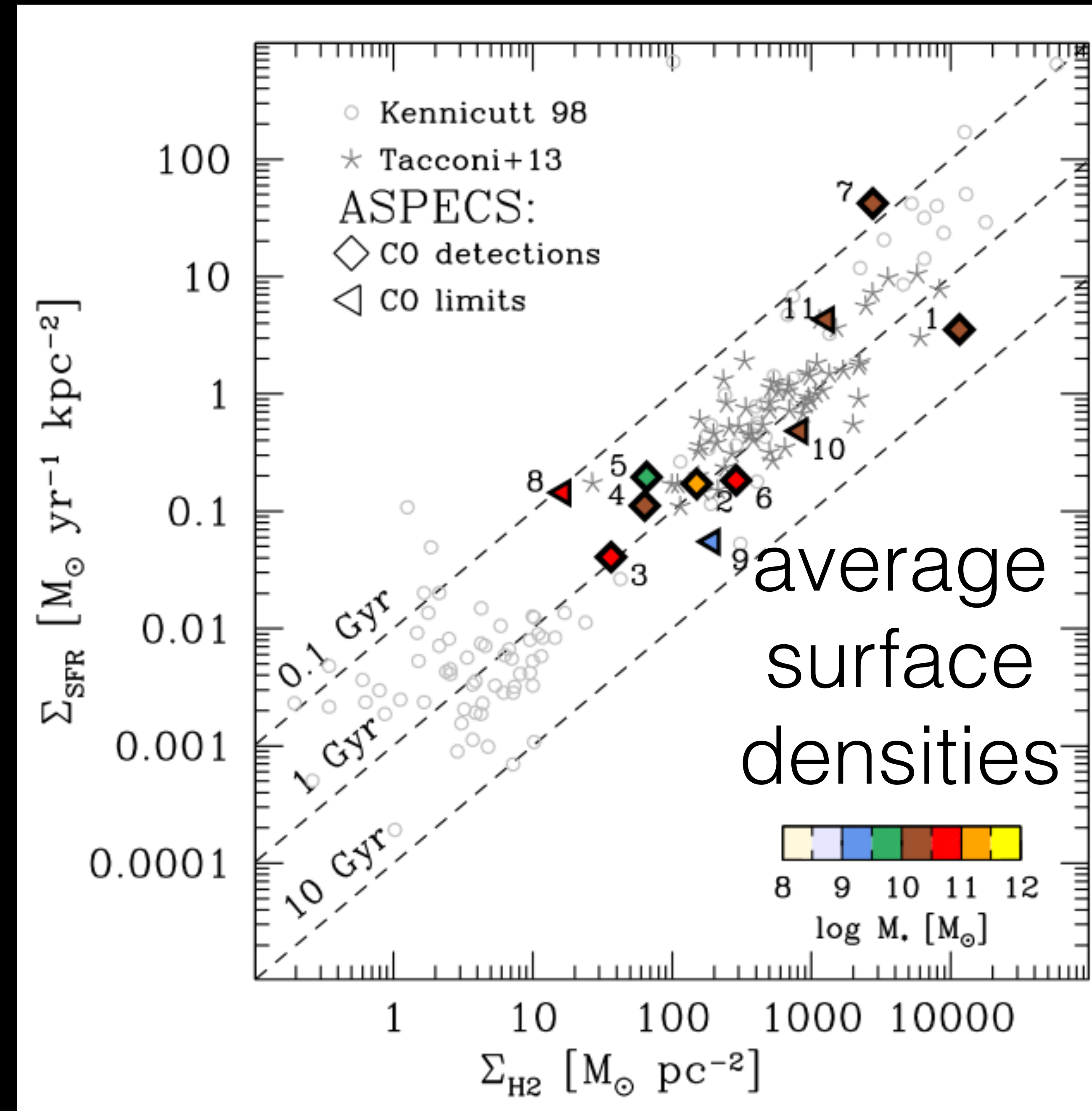
- **Mstar = 2.8-275x1e9 Msun**
- **LIR > 1e11 Lsun**
- **SFR > 10 M/yr (12-150 Msun/yr)**

- **6/11 on the MS (within 0.5 dex)**
- 3/11 above the MS
- 2/11 lower edge (~x1/3) of the MS



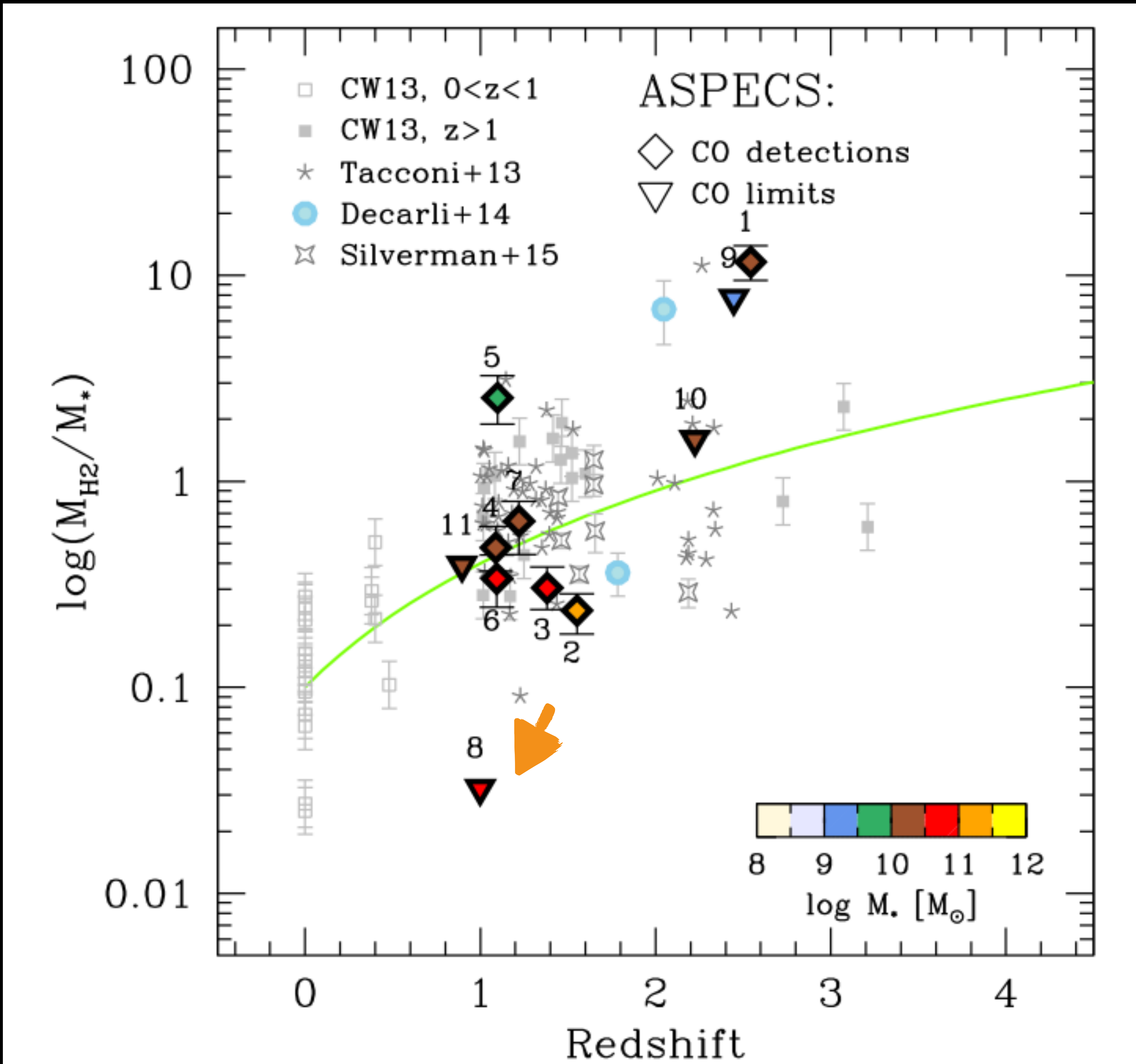
SF law





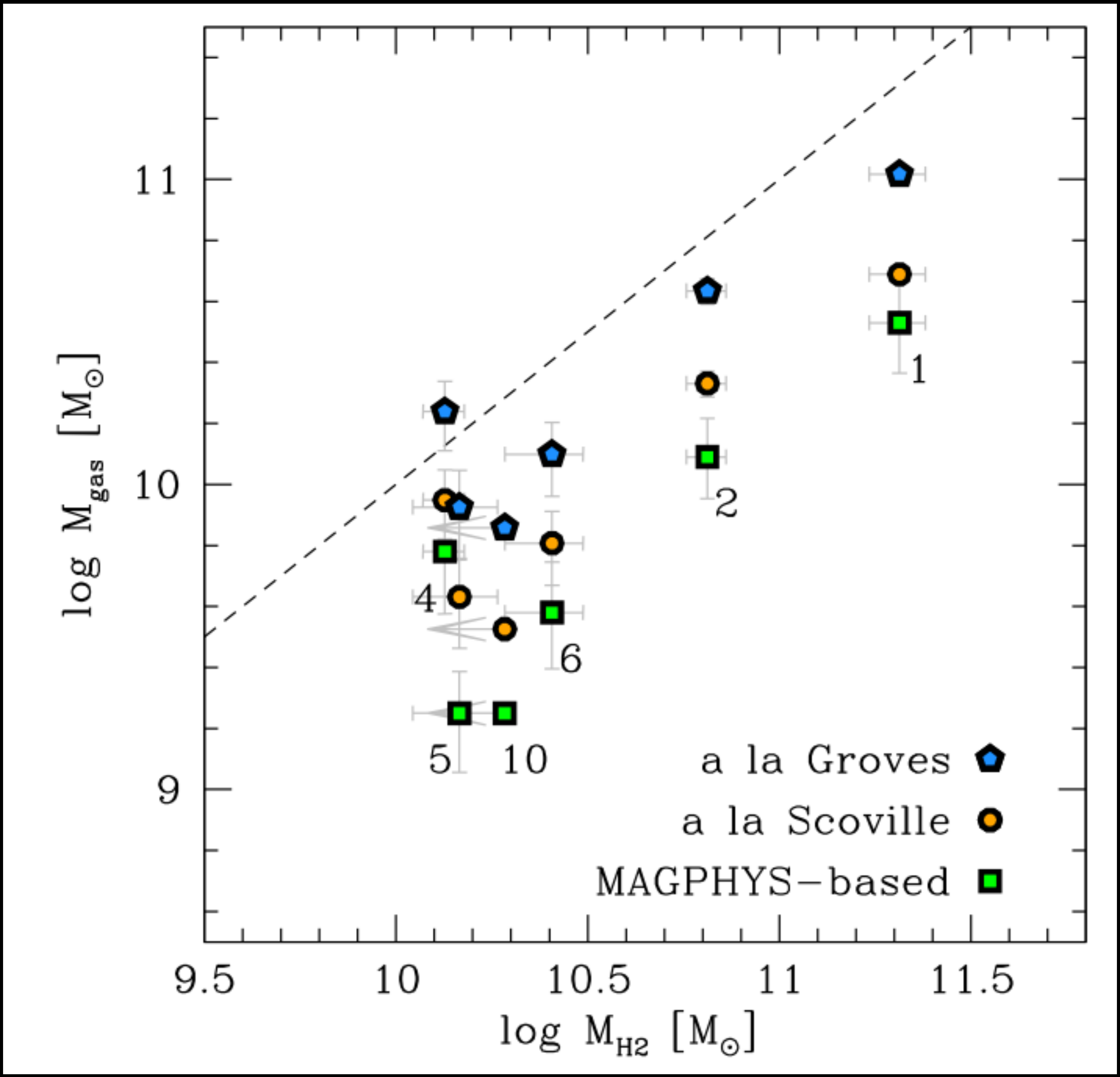
- Most are within a trend of MS galaxies except two (ID. 5 and 7; starburst and ID. 7 has AGN that LIR might have been overestimated)
- ID. 8 and 11 (with the lowest coverage of J=4-3) : lower excitation
- **assuming CO size ~ optical size** : **most of them lie along the τ~ 1 Gyr line**

Mgas/Mstar



- x2 than the average value of PHIBBS
- implying lower excitation than expected?
- still, they are higher than local values

CO vs dust measurement



- <u>CO is problematic?</u>
  - Higher excitation thus, lower Lco10? (difficult, given the higher-J detection matched with MW-like)
  - Lower αco? but, LIR-L'co is similar to MS/ local spiral galaxies and they are MS galaxies
- <u>dust is problematic?</u>
  - calibration
  - β can be lower than assumption of β=1.8
  - missing part of optically thin dust emission (limited by the surface brightness sensitivity)
  - dust-to-gas ratio

Summary (Decarli+16b)

- success of CO (blind) detection
- **CO excitation : no evidence of high excitation**
- **50 % on the main sequence**
  - rest half above the MS, the other below the main sequence
- SF law : close to color-selected galaxies
  - **with depletion time of ~ 1 Gyr**

- gas fractions : slightly lower than other galaxies at similar redshift, but still large compared to local
- CO vs dust : M(gas, dust) < M(gas, CO)
  - a number of assumption, larger sample is required with well-defined dust SED

おまけ (Rujopakarn+16)

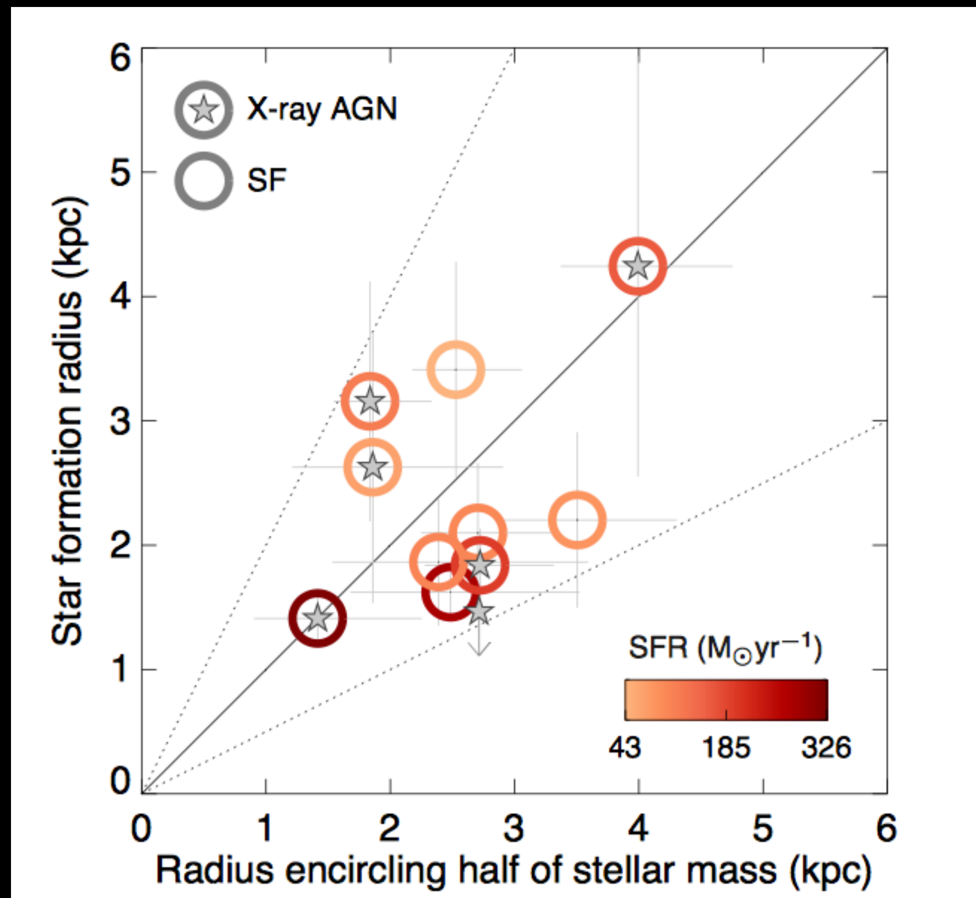
$r_{star} \sim r_{SFR}$

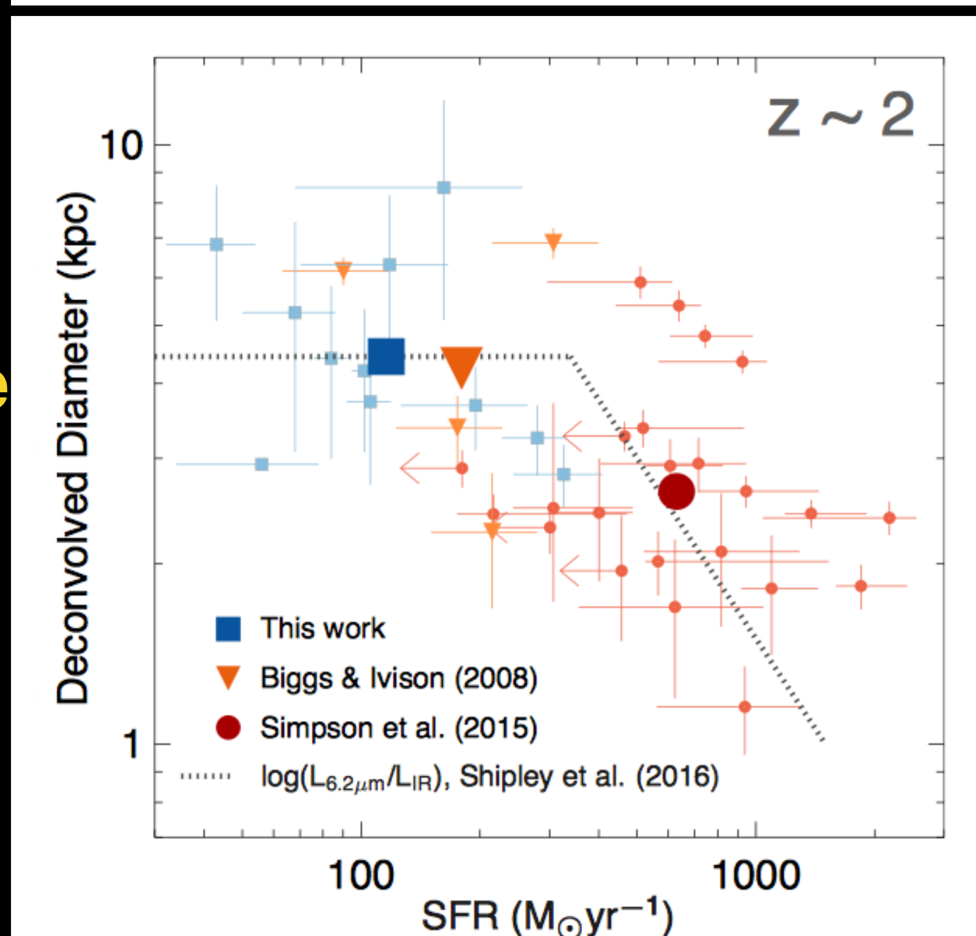
median

~4.2±1.8 kpc

galaxy wide SF

in MS galaxies





MS galaxies are x2 larger than SMGs