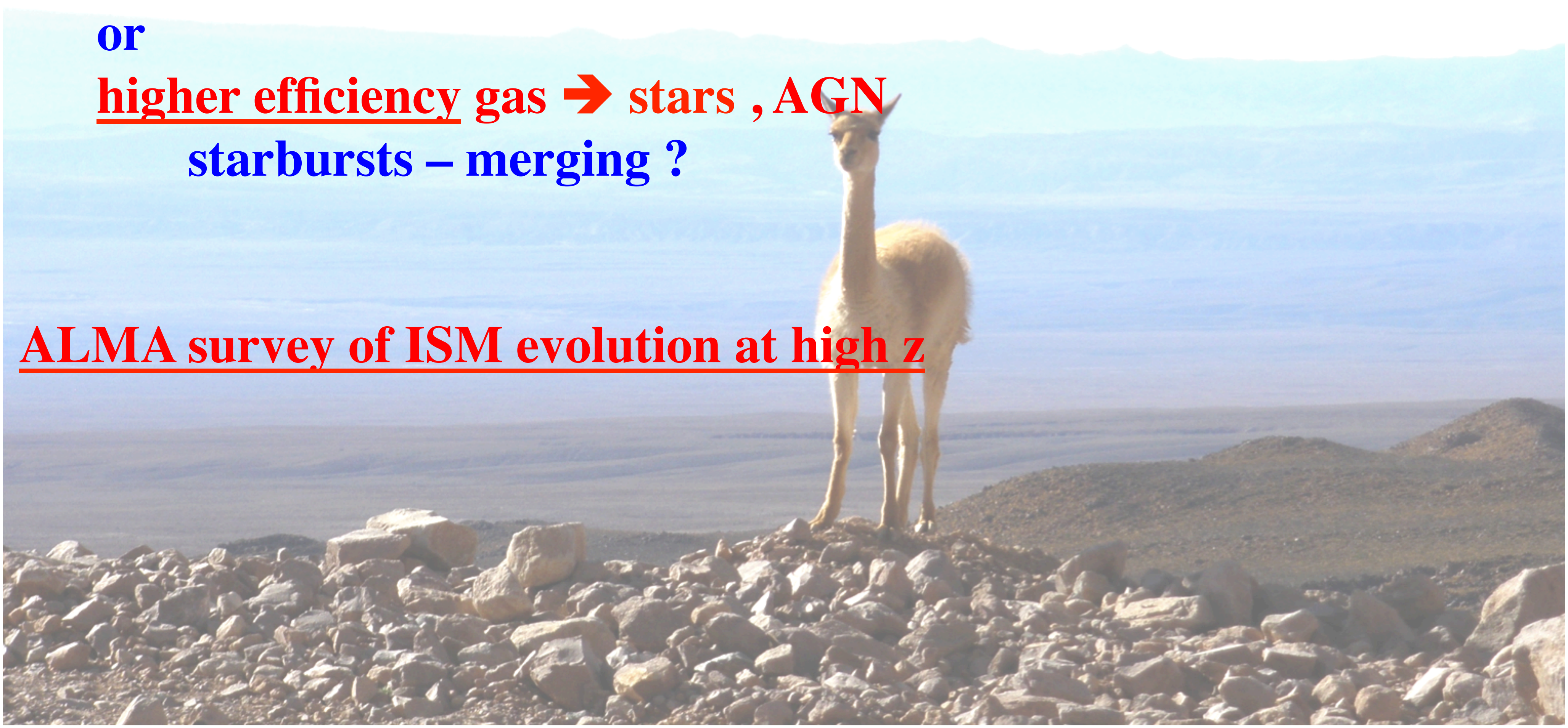
black hole accretion (AGN) & star formation (SF)

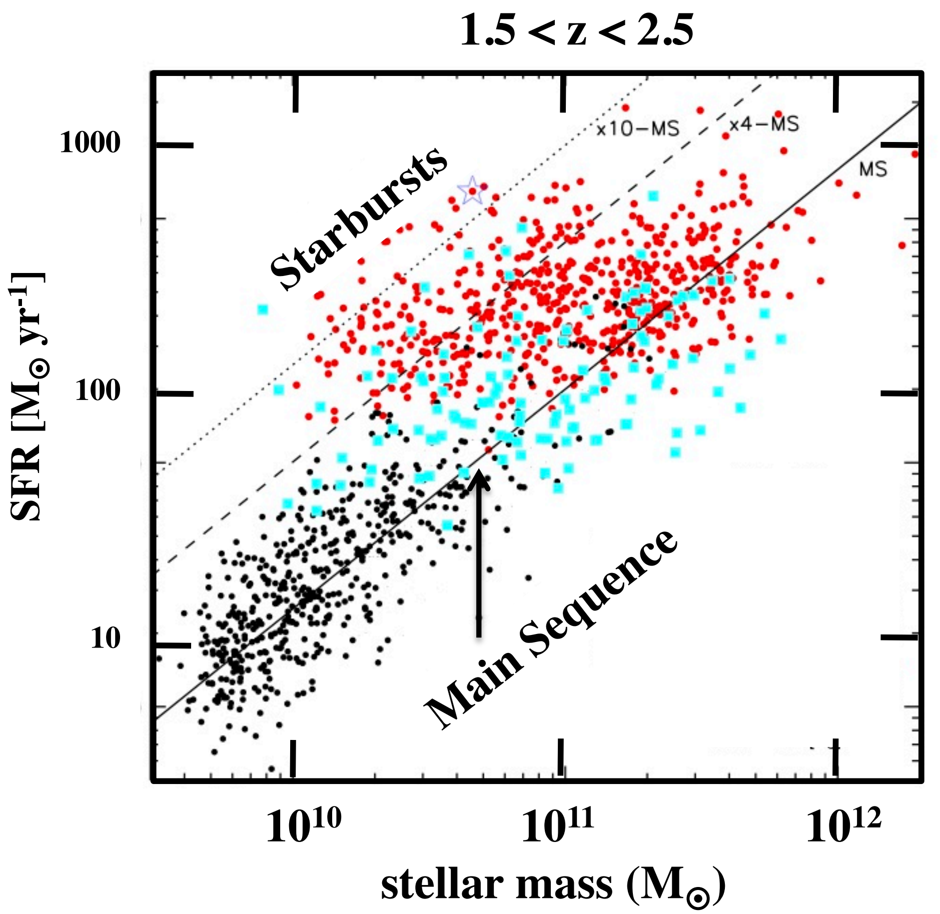
20x increase from z = 0 to 2 !

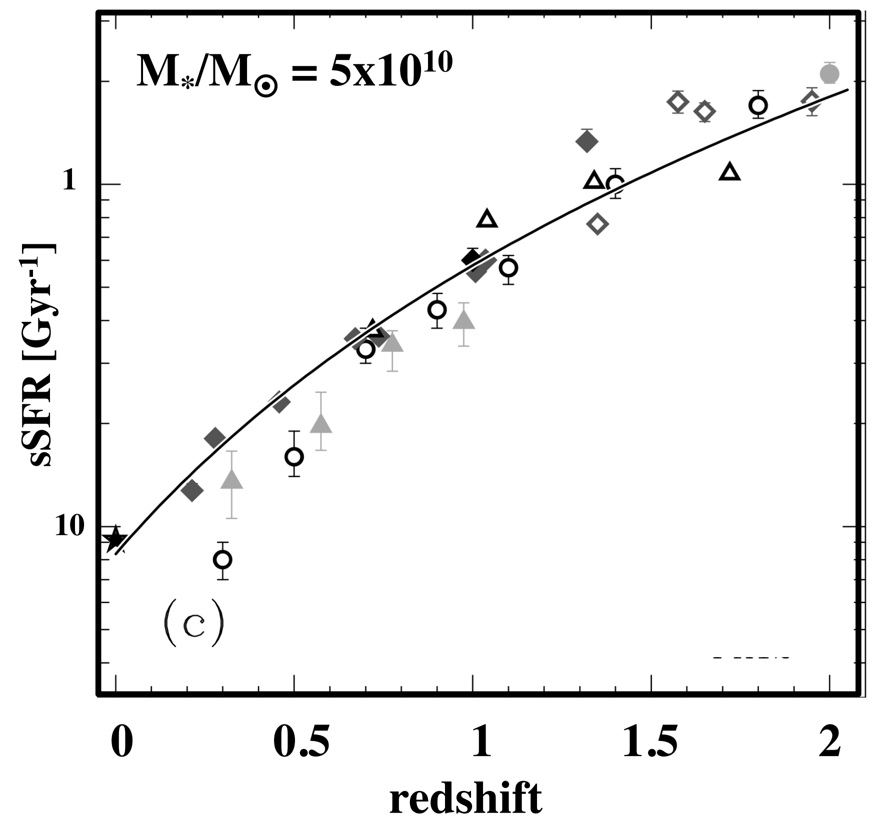
due to

- **<u>more gas</u> (initial supply or accretion)**
- **or**
- **<u>higher efficiency</u> gas ➔ stars , AGN**
  - **starbursts – merging ?**

<u>ALMA survey of ISM evolution at high z</u>







Rodighiero '11, Sargent etal '12

need to measure gas contents

need : robust and fast measure of ISM

CO –

ok , but ...

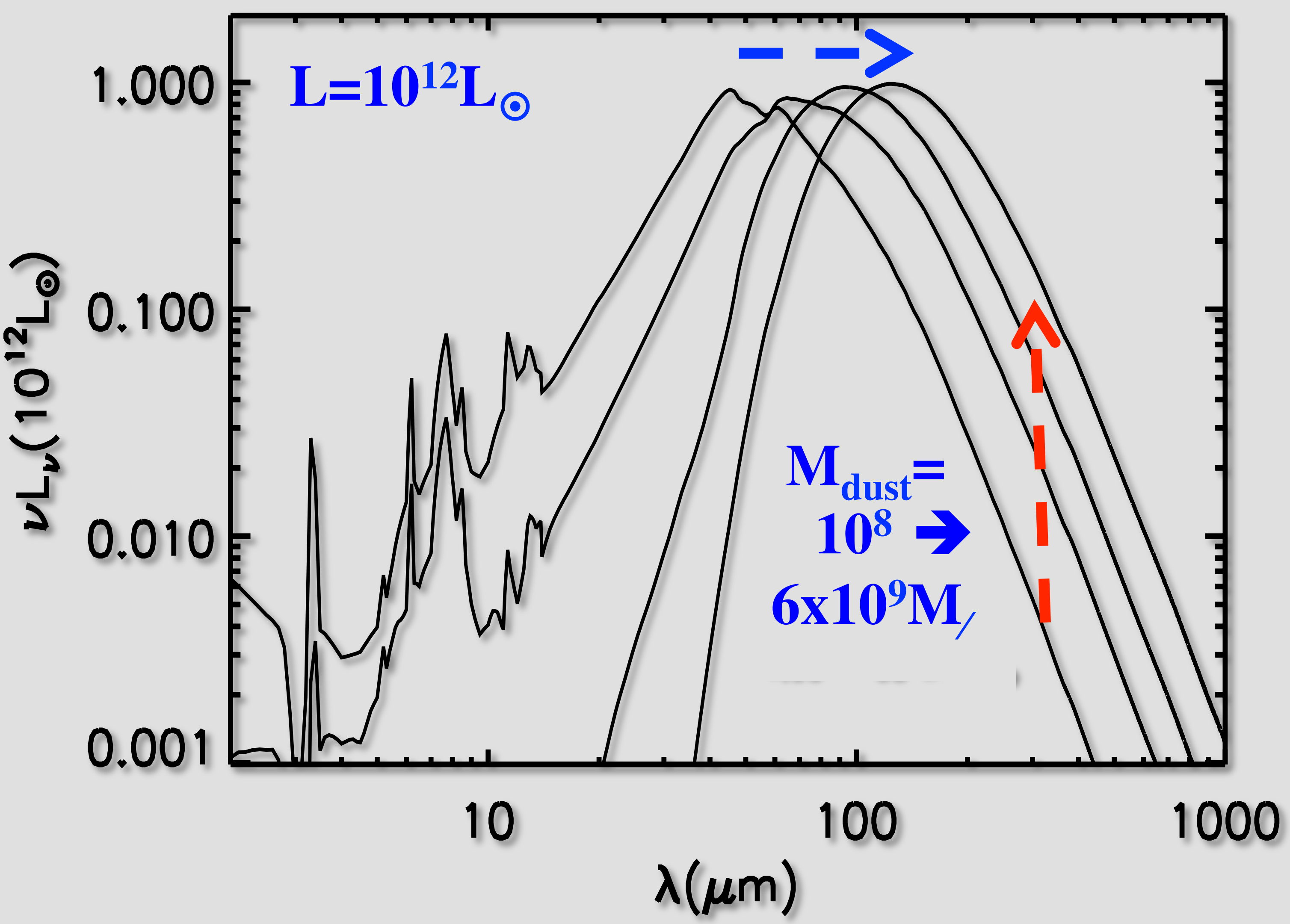
CO/H2 conversion factor
excitation dependence (often measure high J CO)
slow even w/ ALMA (hours per gal.)

alternative,

measure dust IR continuum + dust / gas ratio

ALMA cycle 0, 2 & 3 projects
(110, 180 and 360 galaxies w/i COSMOS field)

emitted SED -- increasing M_{dust}



Scoville, 2011 Canary Is. winter school lectures

- **peak shifts to longer λ for increased τ (or dust mass)**
- **flux on long λ tail scales linearly with M_{dust}**

R-J tail is optically thin,

➔

$$F_{RJ} = \varkappa_\nu \, T_{dust} \, \nu^2 \, M_{dust} \; / \; (4\pi d^2)$$

T_{dust} = 20-25 K in Gal. SF

global T_{dust} **doesn't vary much**

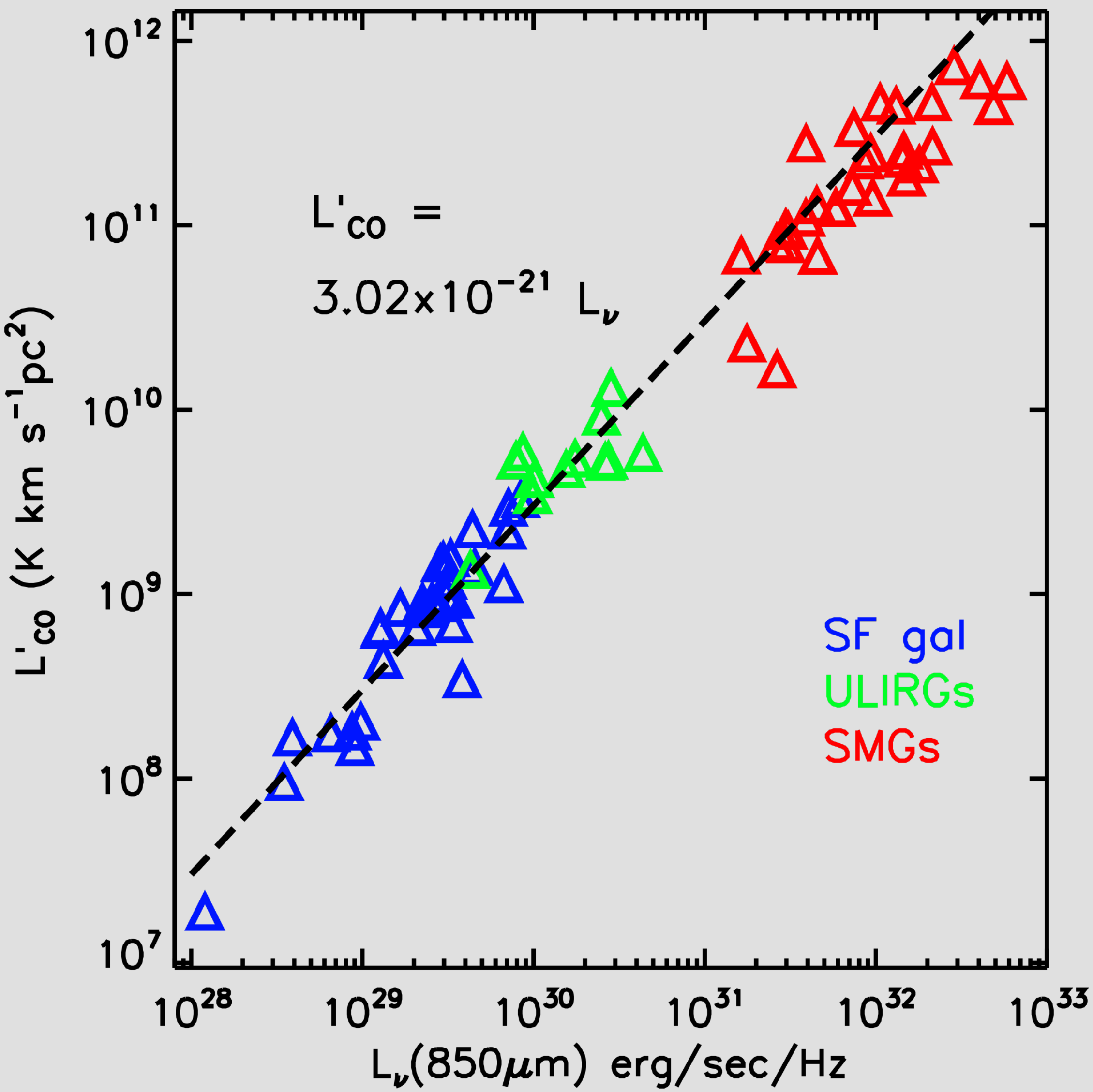
- -

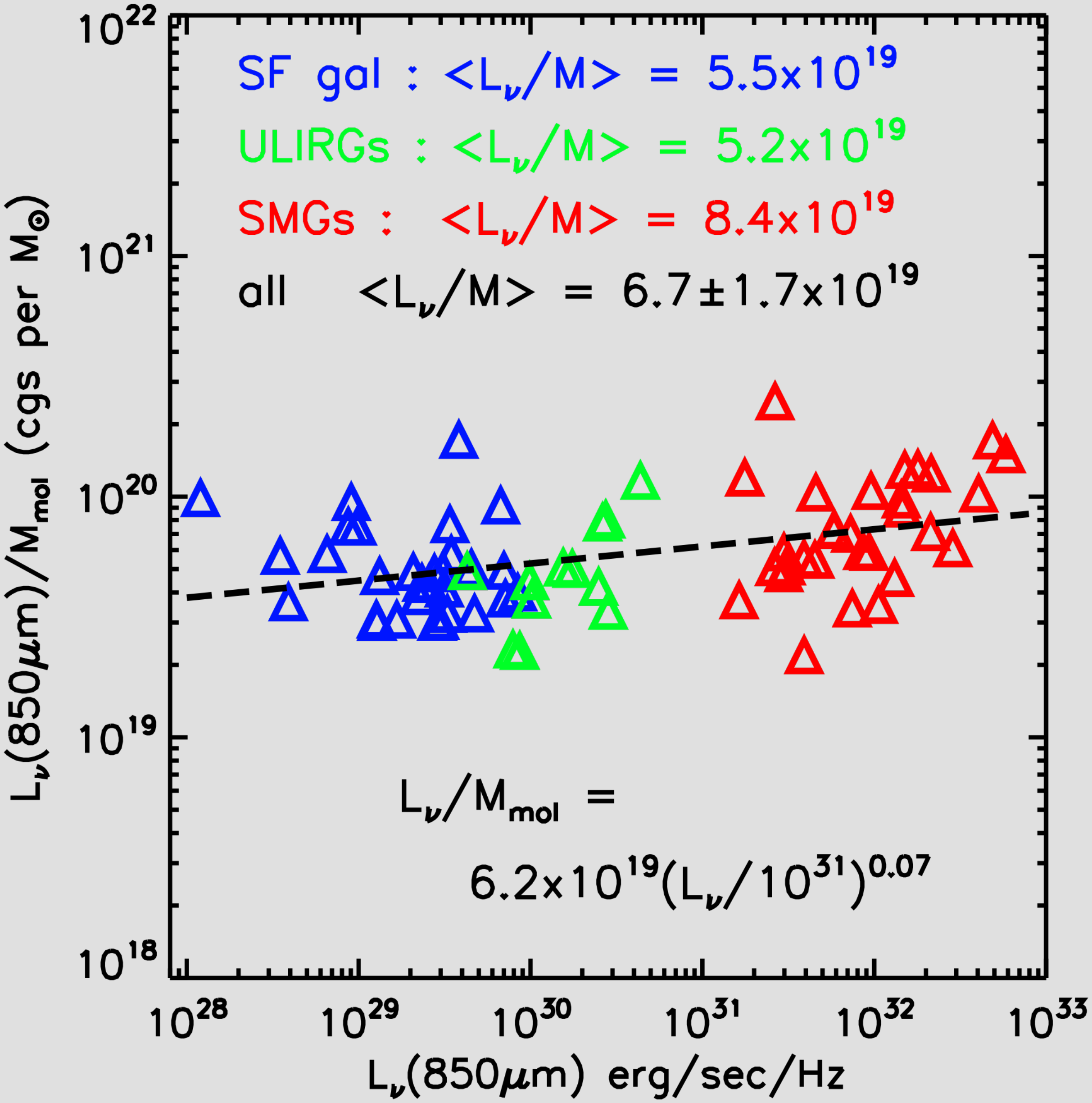
calibrate : $L_\nu / M_{ISM} = \langle \varkappa_\nu \, T_d \, M_{ISM} / M_{dust} \rangle$

local galaxies
Milky Way (Planck)
SMGs

local galaxies **normal SF gal. and ULIRGS**
w/ total Herschel SPIRE 500 µm fluxes & CO 1-0

z = 2- 3 SMGs with CO (1-0) EVLA + SCUBA 850 µm





6.7×10^{19} erg/s/Hz/$M_\odot$

w/ less than factor 2 dispersion

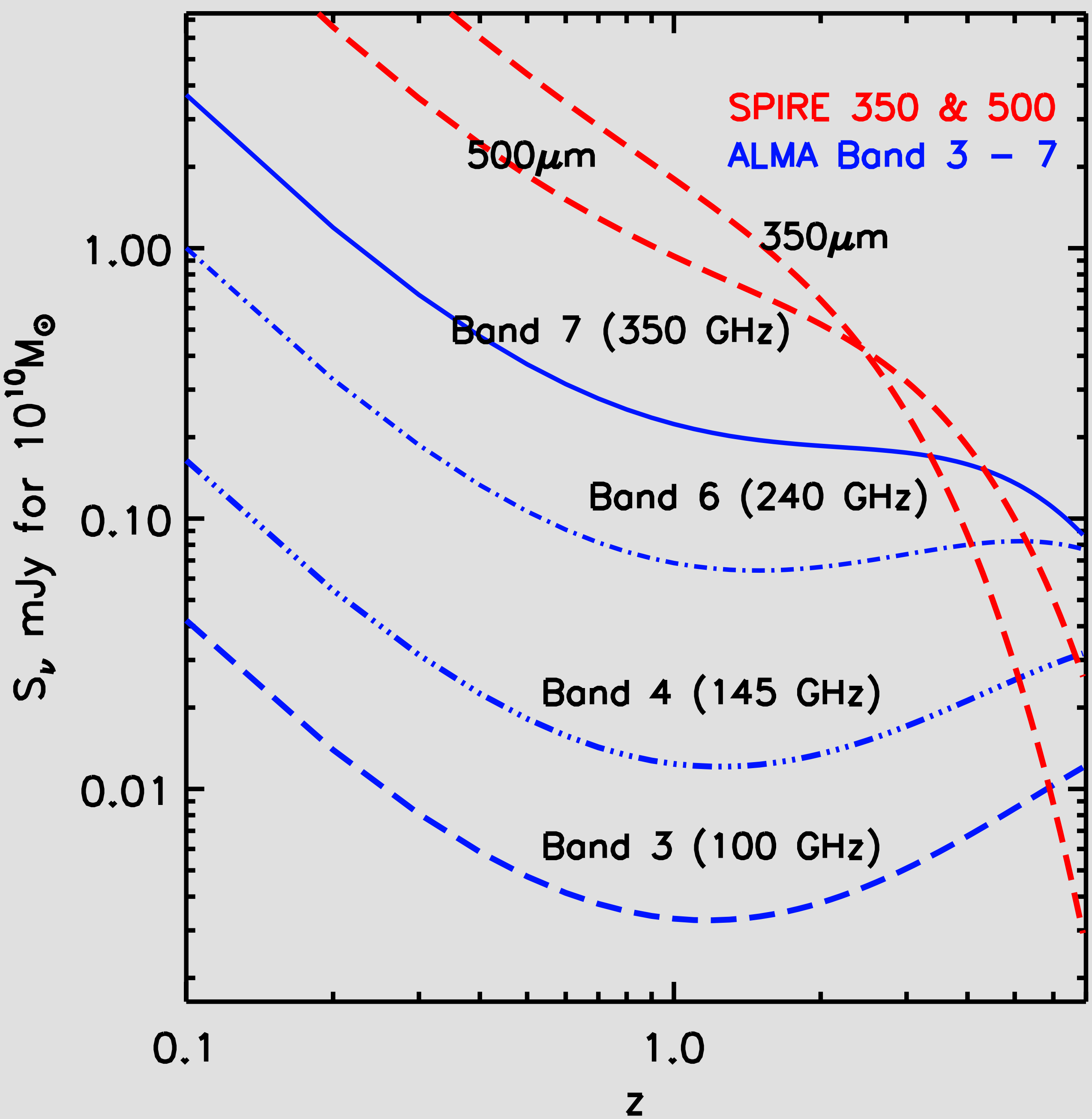
Planck: <u>Milky Way</u>

➔

6.2×10^{19} erg/s/Hz/$M_\odot$

$\beta = 1.8$ +- 0.1

for ALMA Bands 3 - 7 predict :

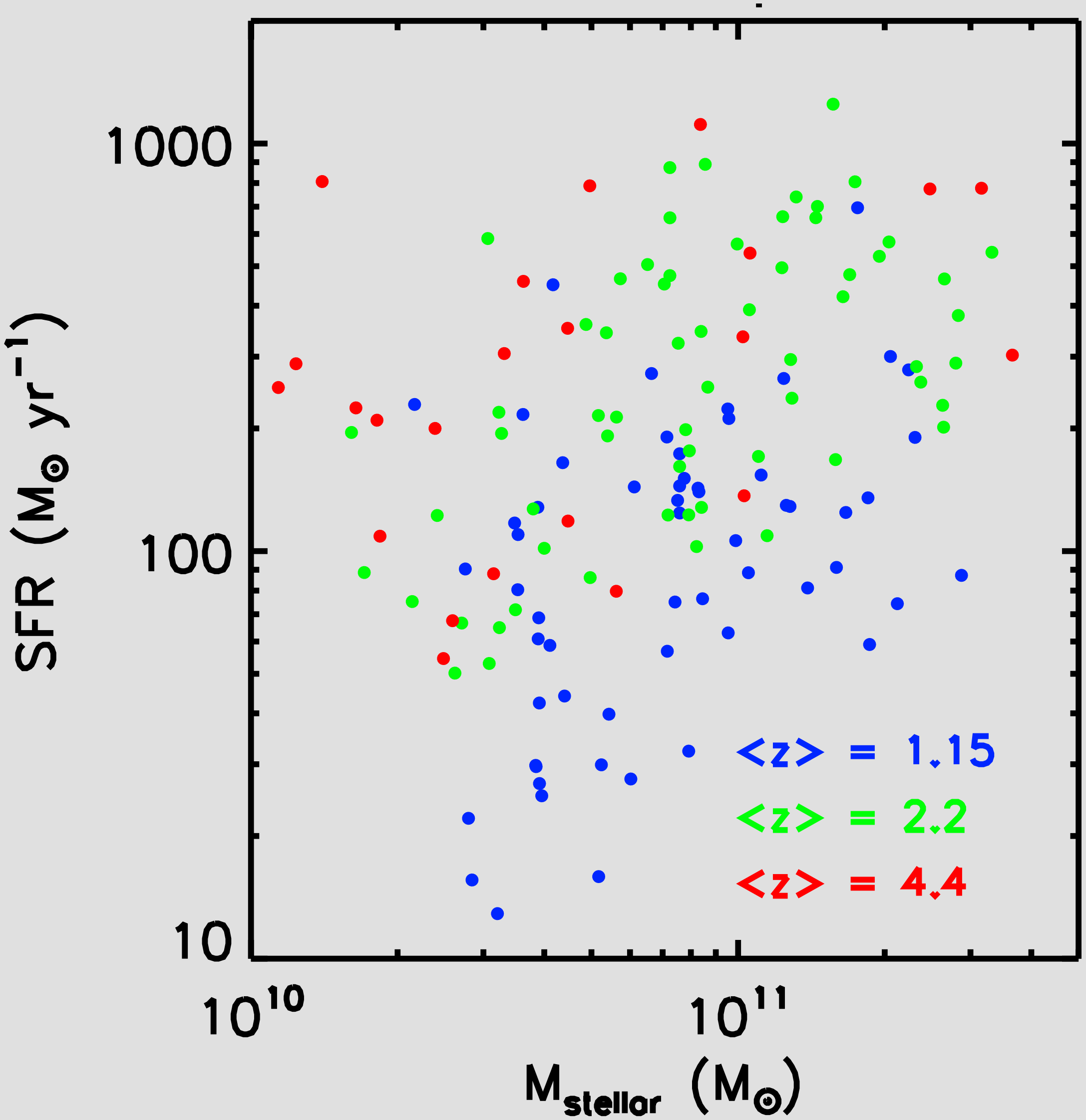


3 σ in ~2 min for $M_{ISM} = 1x10^{10}$

20x faster than CO !

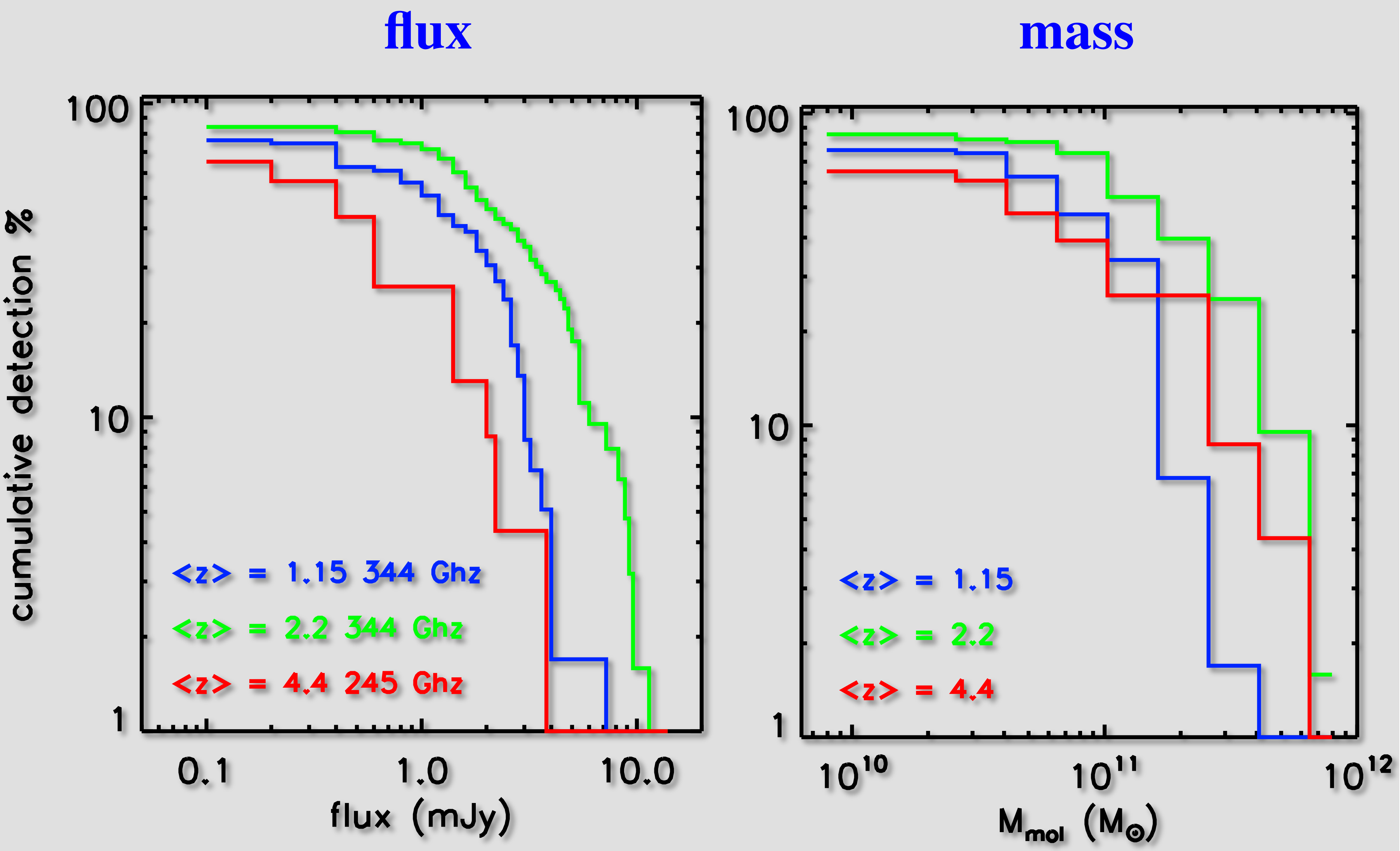
ALMA Cycle 2 – observations --145 galaxies

w/ Sheth, Aussel, Vanden Bout, Capak, Bongiorno, Casey, Laigle, Ilbert, McCracken, Koda, Alvarez-Marquez, Murchikova, Koda, Pope, Toft, Ivison, Sanders, Manohar, Lee, Chu,

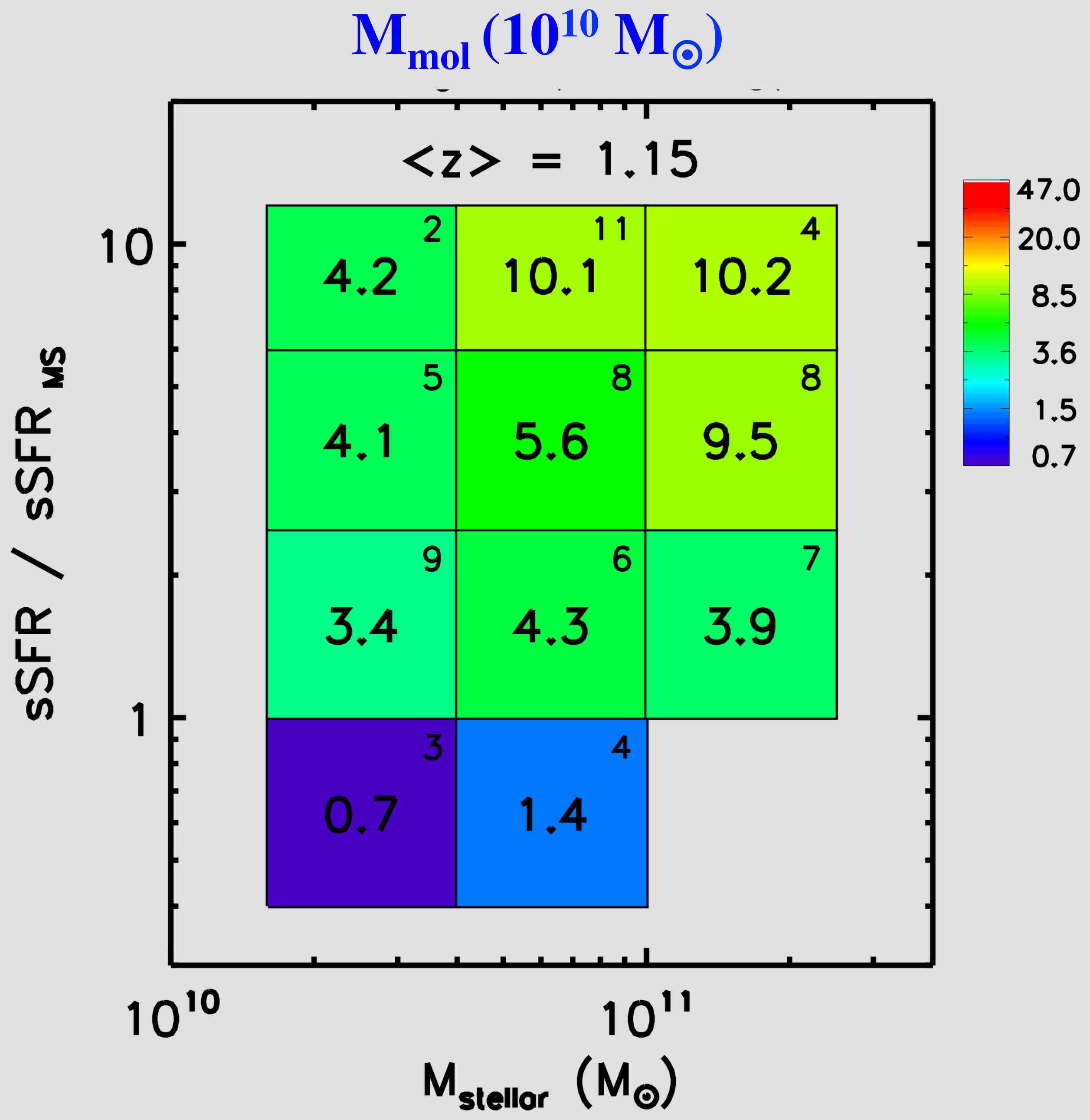


50, 60, 35 gal.

detection rates (2 min) -- 3 redshift ranges :

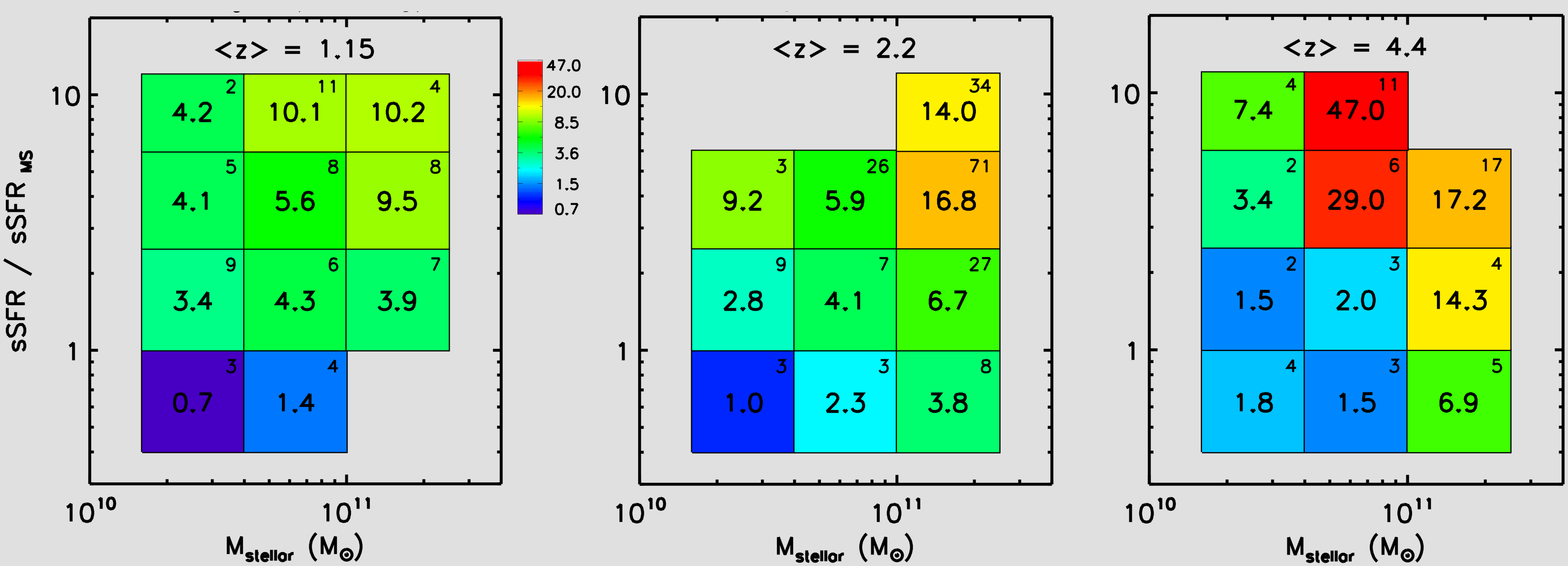


ISM masses vs sSFR = SFR / M_*



ISM masses vs sSFR = SFR / M_*

M_{mol} (10^{10} $M_\odot$)

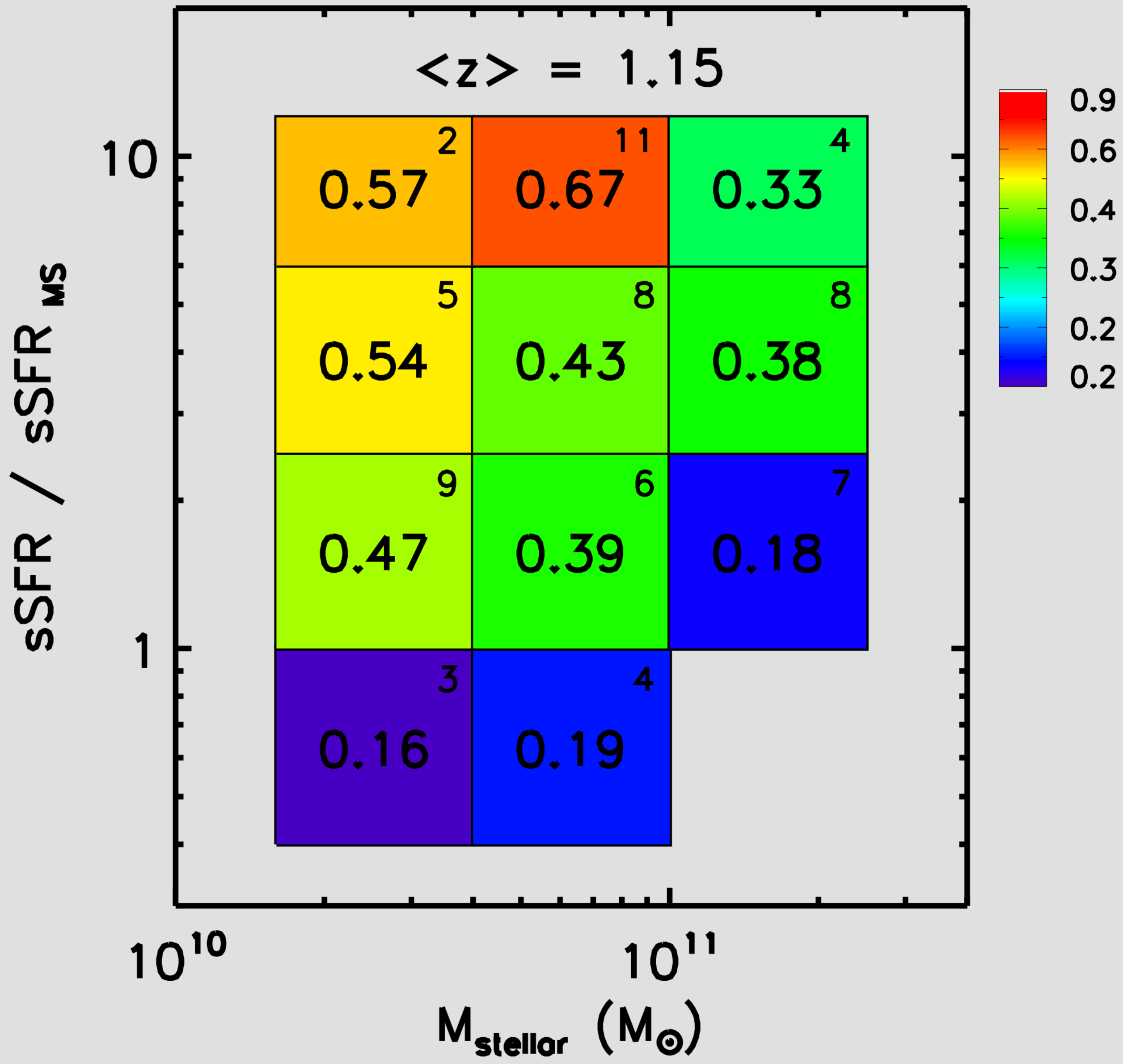


very similar masses at z = 2 to 1
perhaps a little higher at z ~ 5

mass up ot 4×10^{11} $M_\odot$!!!

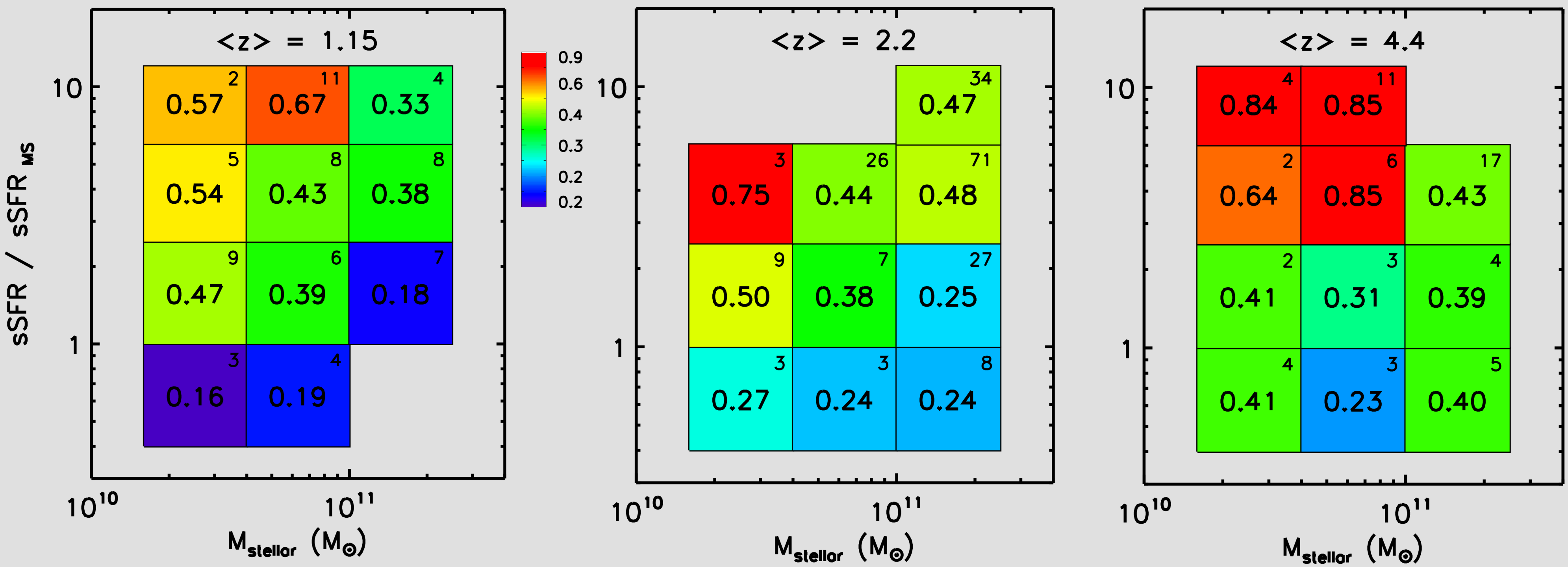
gas mass fraction :

$M_{mol} / (M_{mol} + M_{stellar})$

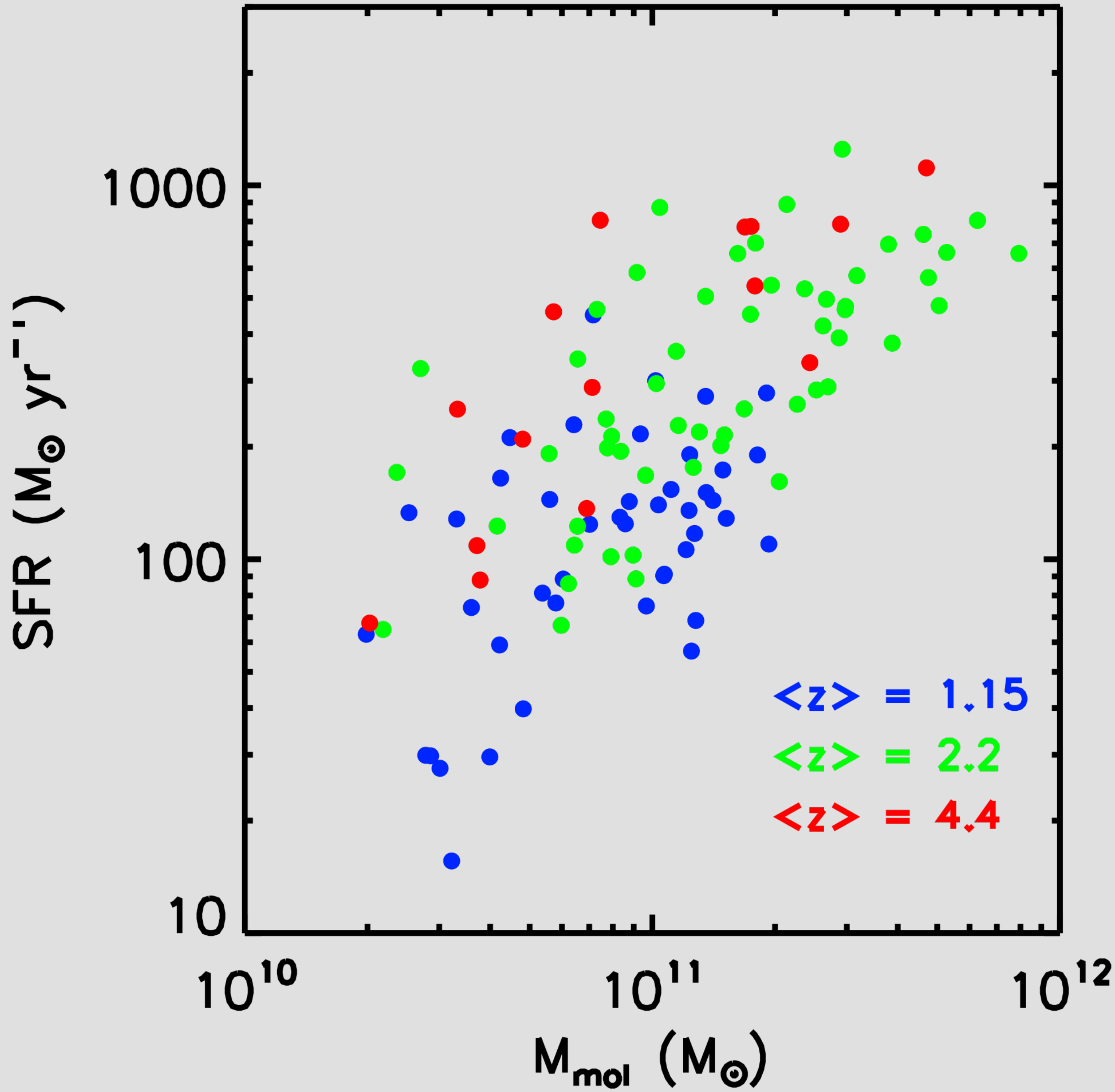


ISM mass fraction :

$M_{ISM} / (M_{ISM} + M_{stellar})$



individual galaxies : gas masses



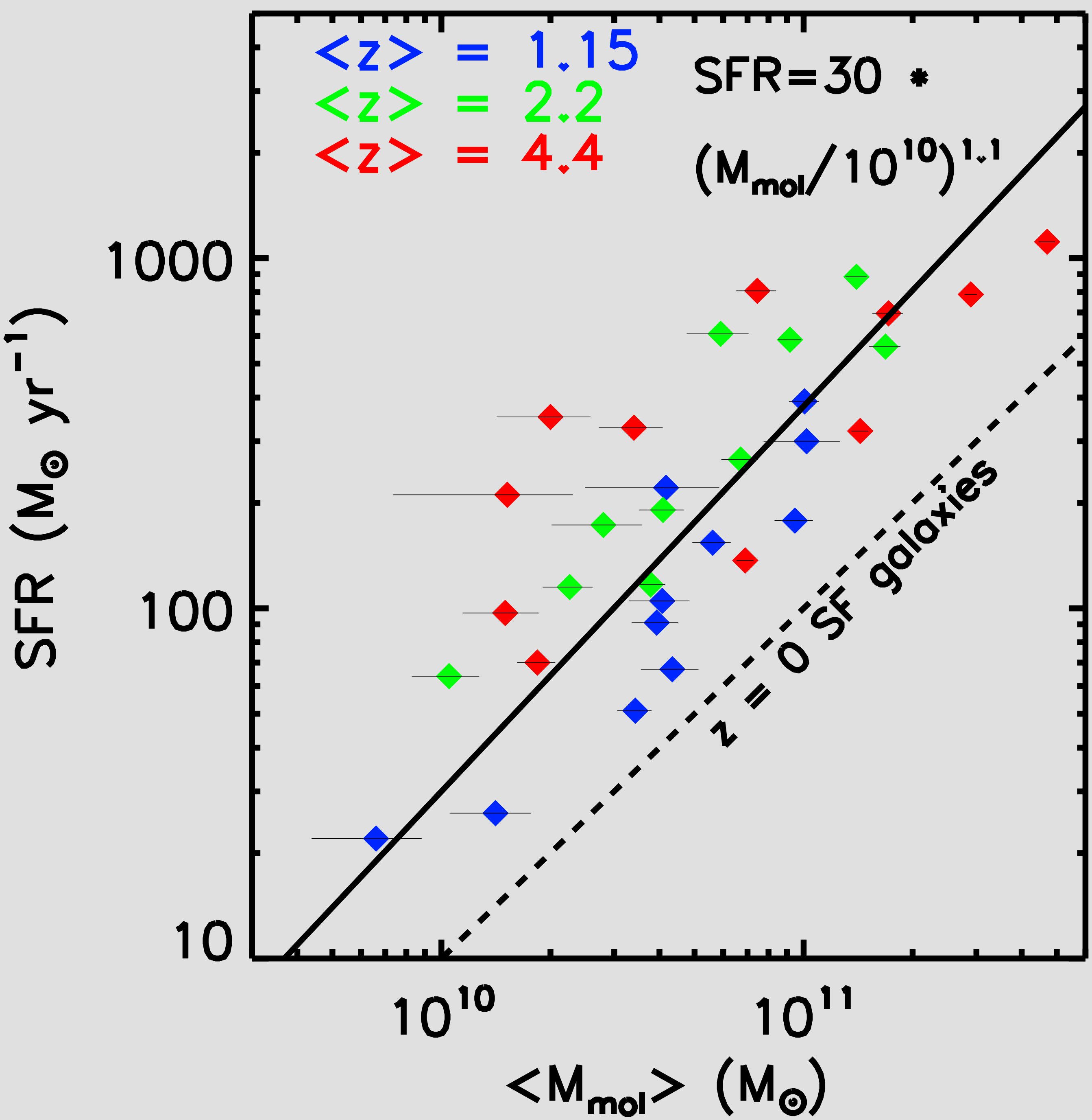
ISM masses increase above the main sequence !!

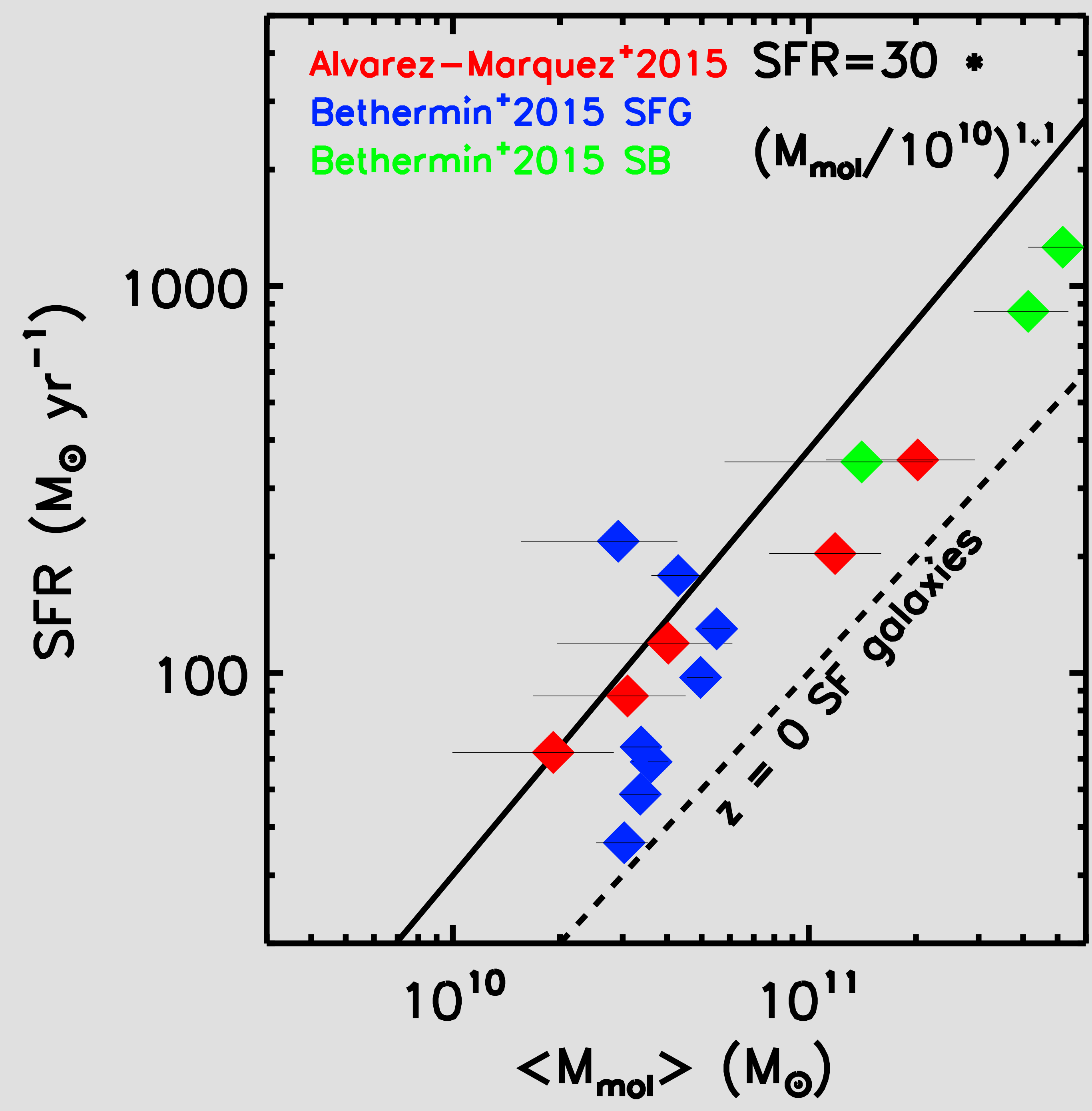
➔ increase in SFRs above the MS
due to larger ISM masses

analytic fit :

$$SFR = 30 \pm 12 \left(\frac{M_{mol}}{10^{10} M_{sun}}\right)^{1.1\pm0.1} \left(\frac{1+z}{3}\right)^{0.8\pm0.3} M_{sun} yr^{-1}$$

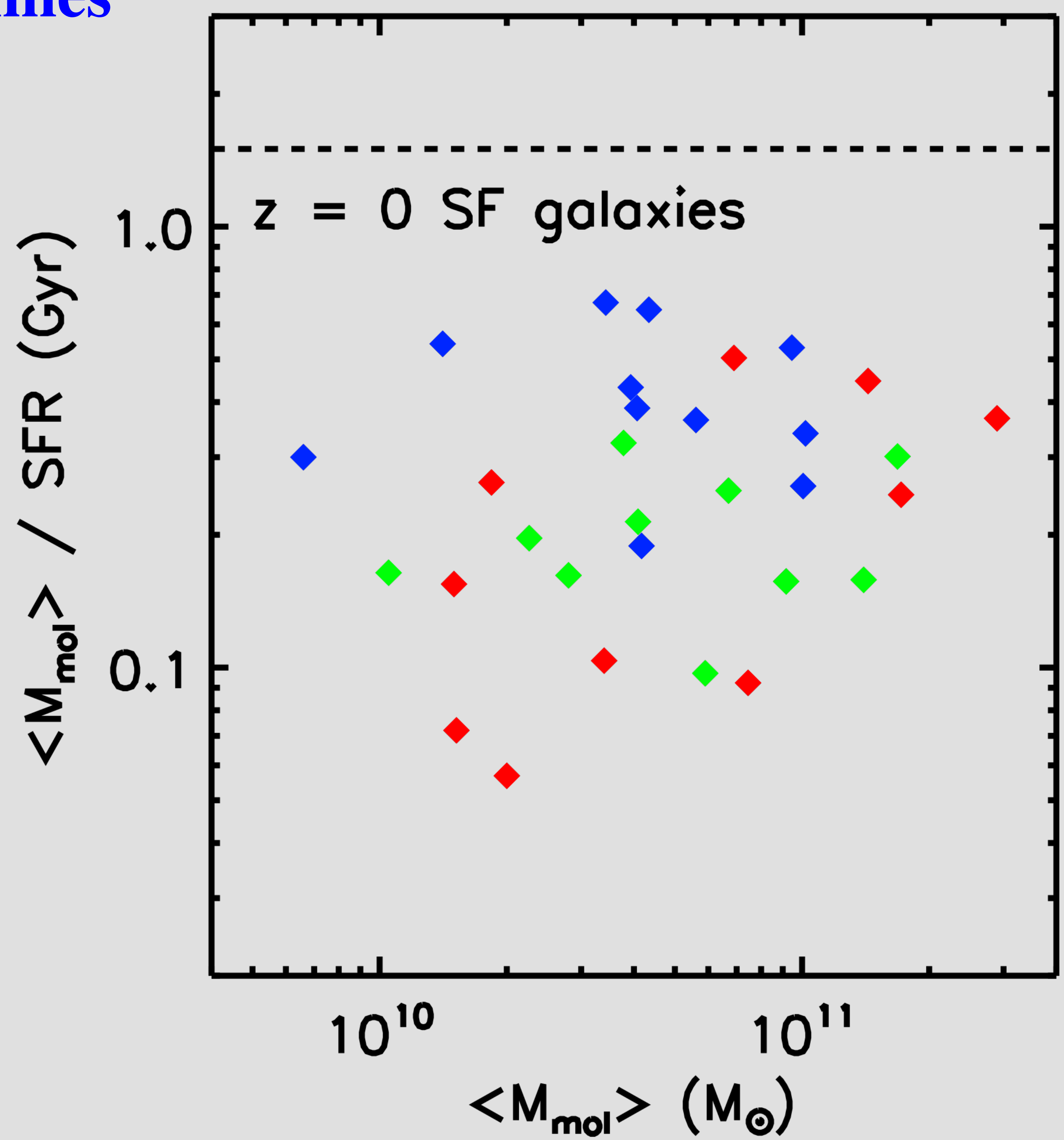
stacks of galaxies ➔ a single ‘linear’ SF law



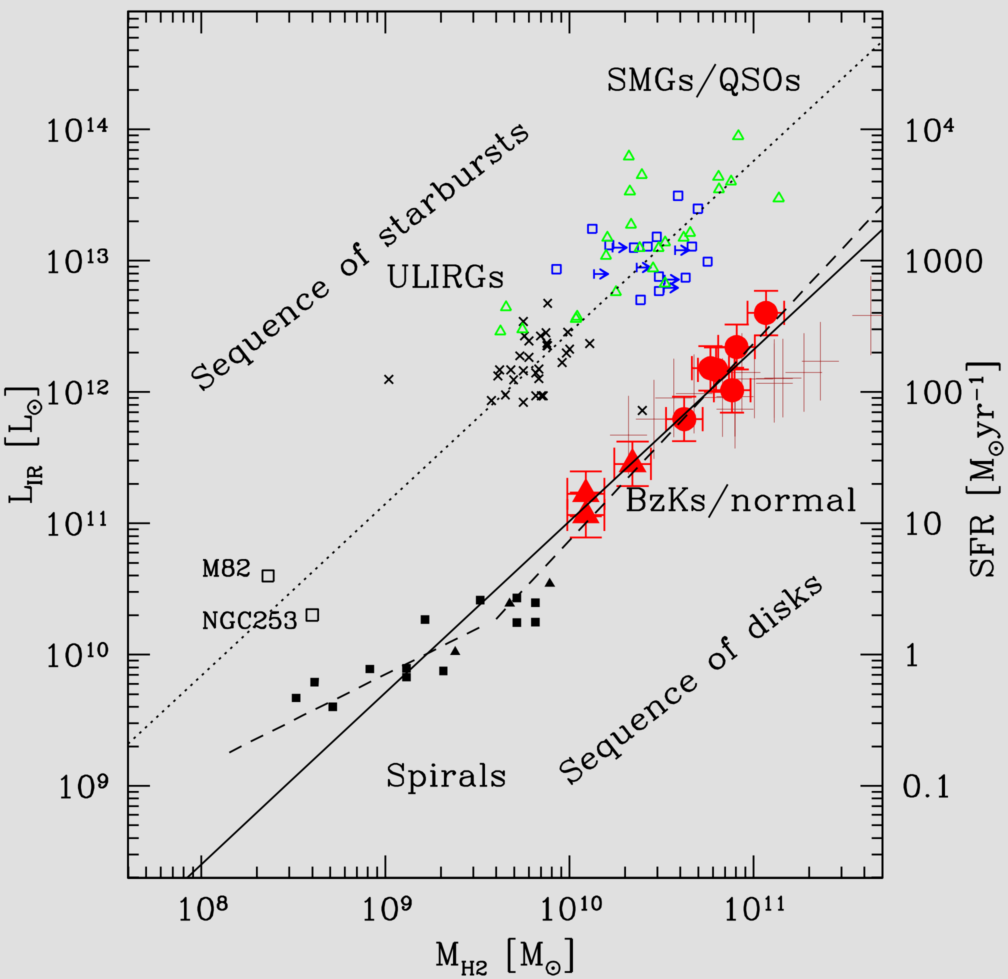


Alvarez−Marquez+2015
Bethermin+2015 SFG
Bethermin+2015 SB
SFR=30 * (Mmol/10^10)^1.1
z = 0 SF galaxies
SFR (M⊙ yr−1)
1000
100
10^10
10^11
<Mmol> (M⊙)

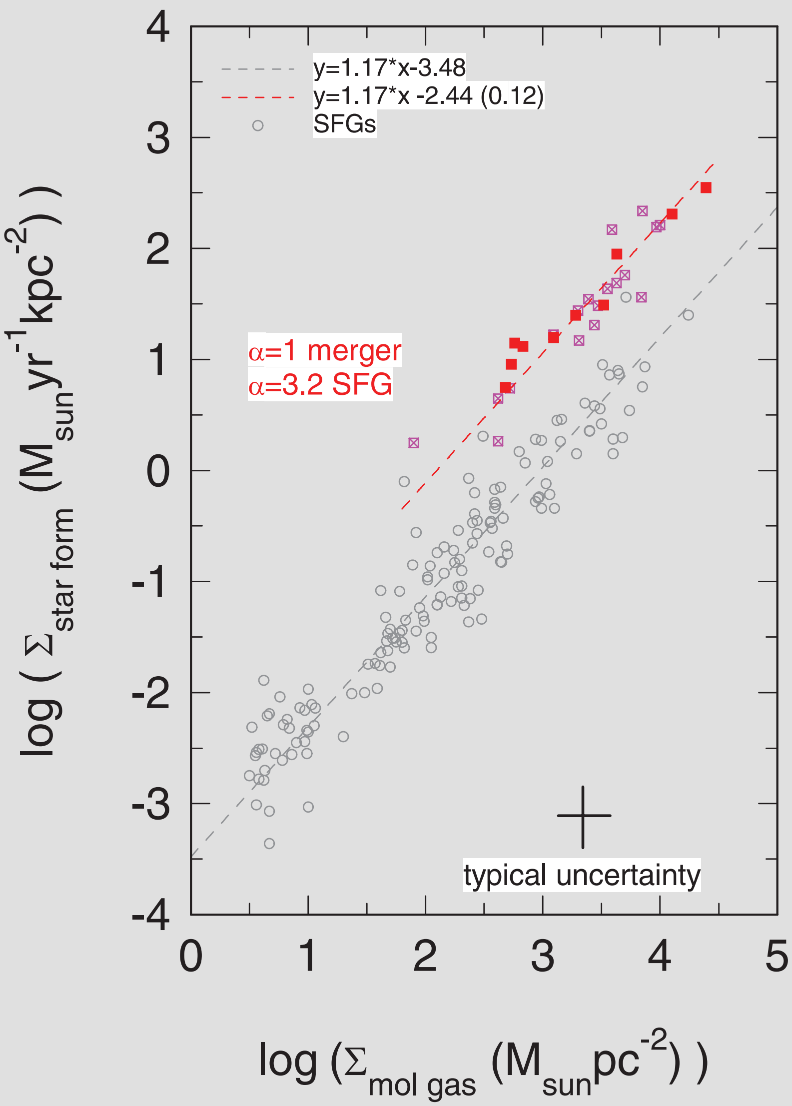
gas depletion times



very different than previous work from CO



Daddi etal 2010



Genzel etal 2010

both used different CO conversion factors for SB and MS

our work ➔

single, linear SF law

at z = 1 to 6 and on MS and above MS

$$SFR = 30 \left(\frac{M_{mol}}{10^{10} M_{sun}}\right)^{1.1\pm0.1} \left(\frac{1+z}{3}\right)^{0.8\pm0.3} M_{sun} yr^{-1}$$

$$\Rightarrow \tau_{ISM \rightarrow stars} = \frac{M_{ISM}}{SFR} \approx 2-6x10^{8} yrs \;\; (2-5x \text{ faster than } z=0)$$

huge accretion rates

replace entire ISM w/i 3-7x10^8 yrs

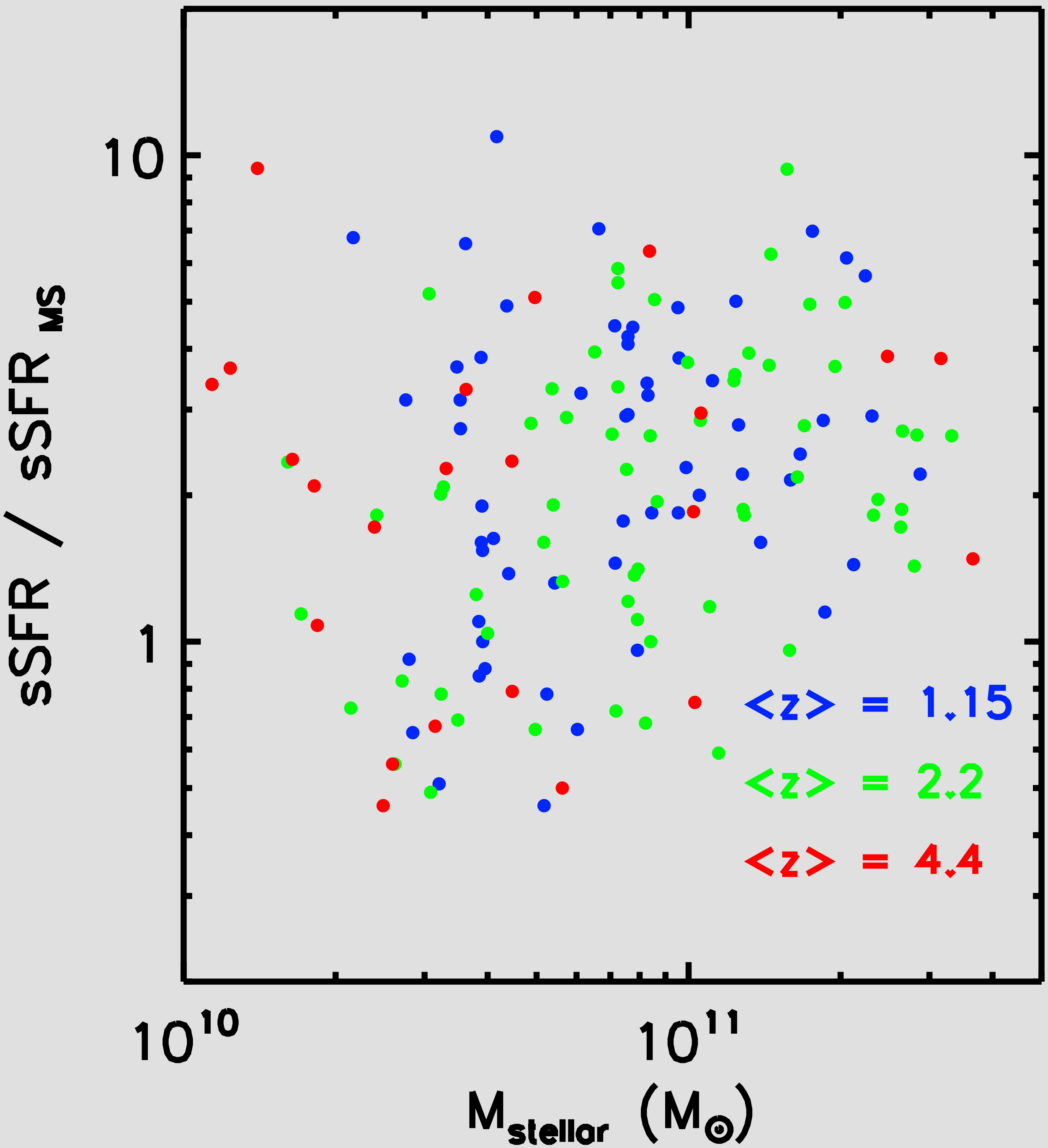
why is SF more rapid at z > 1 ??

Note – do not fit for T_d -- Lum.- vs mass-weigthed

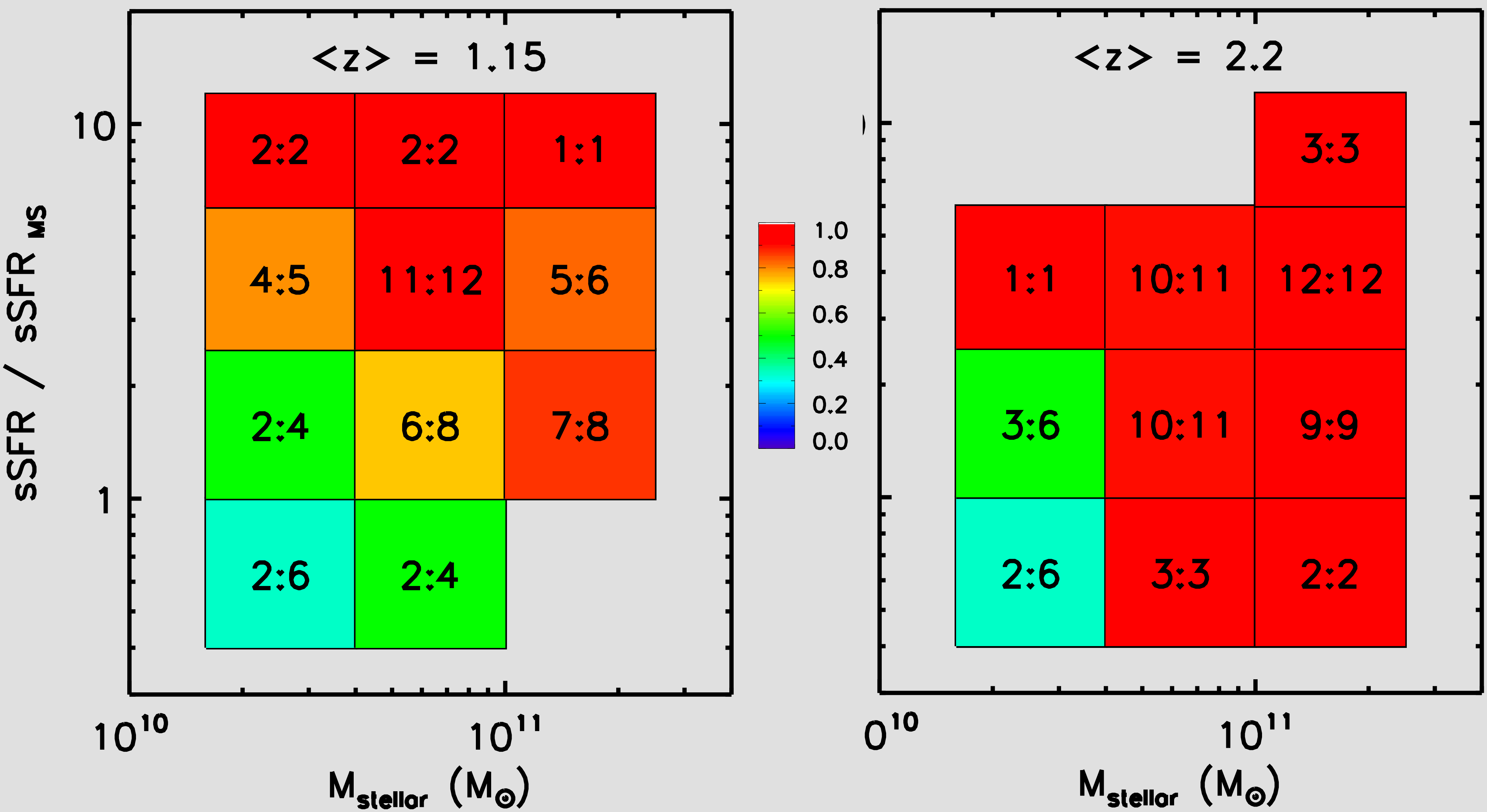
MS vs above the MS (starbursts ?)

Sample	# gal.	$< z >$	$< M_{\rm mol} >$ $10^{10} M_\odot$	$< f_{\rm mol} >$	$< M_{\rm mol}/SFR >$ Gyr
$< z >= 1.1$					
MS	19	1.16	6.3±0.8	0.42±0.04	1.09±0.13
above MS	25	1.20	10.6±0.9	0.55±0.04	0.65±0.07
all	44	1.19	9.0±0.7	0.50±0.03	0.84±0.07
$< z >= 2.2$					
MS	29	2.24	10.8±1.3	0.52±0.03	0.61±0.05
above MS	26	2.28	29.3±3.3	0.67±0.02	0.51±0.05
all	55	2.27	19.5±2.2	0.59±0.02	0.56±0.04
$< z >= 4.4$					
MS	6	4.28	4.3±0.6	0.58±0.05	0.42±0.04
above MS	9	4.07	13.4±2.4	0.68±0.06	0.24±0.03
all	15	4.20	10.6±2.2	0.64±0.04	0.31±0.04
all z					
MS	54	2.07	8.8±0.8	0.49±0.02	0.76±0.05
above MS	60	2.10	18.9±2.3	0.62±0.02	0.53±0.04
all	114	2.10	14.2±1.3	0.56±0.02	0.64±0.04

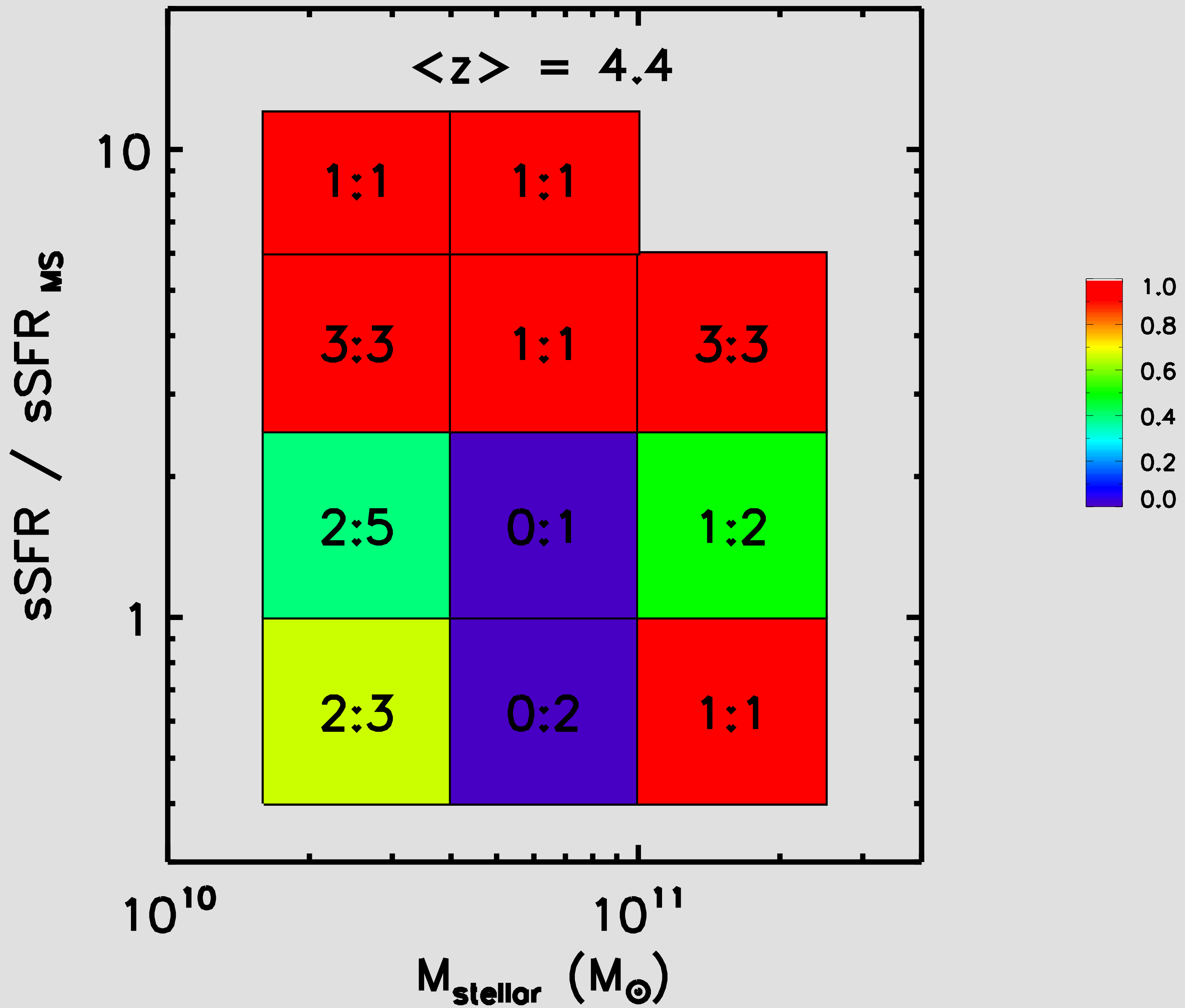
➔ **most of higher SFR due to increased gas** specific SFR (sSFR) relative to main sequence



stack obs for each z
in cells of M_* and SFR

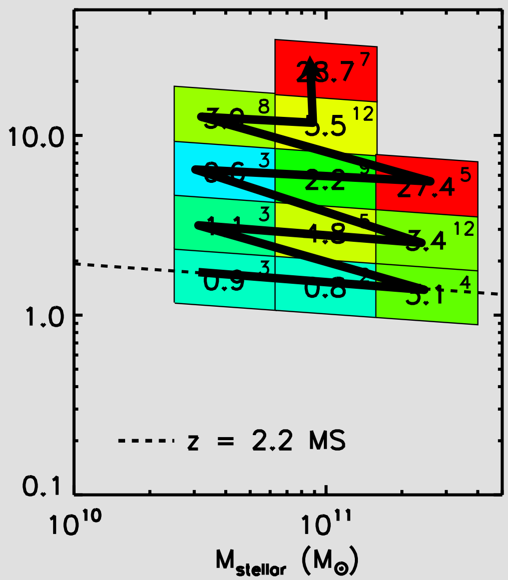


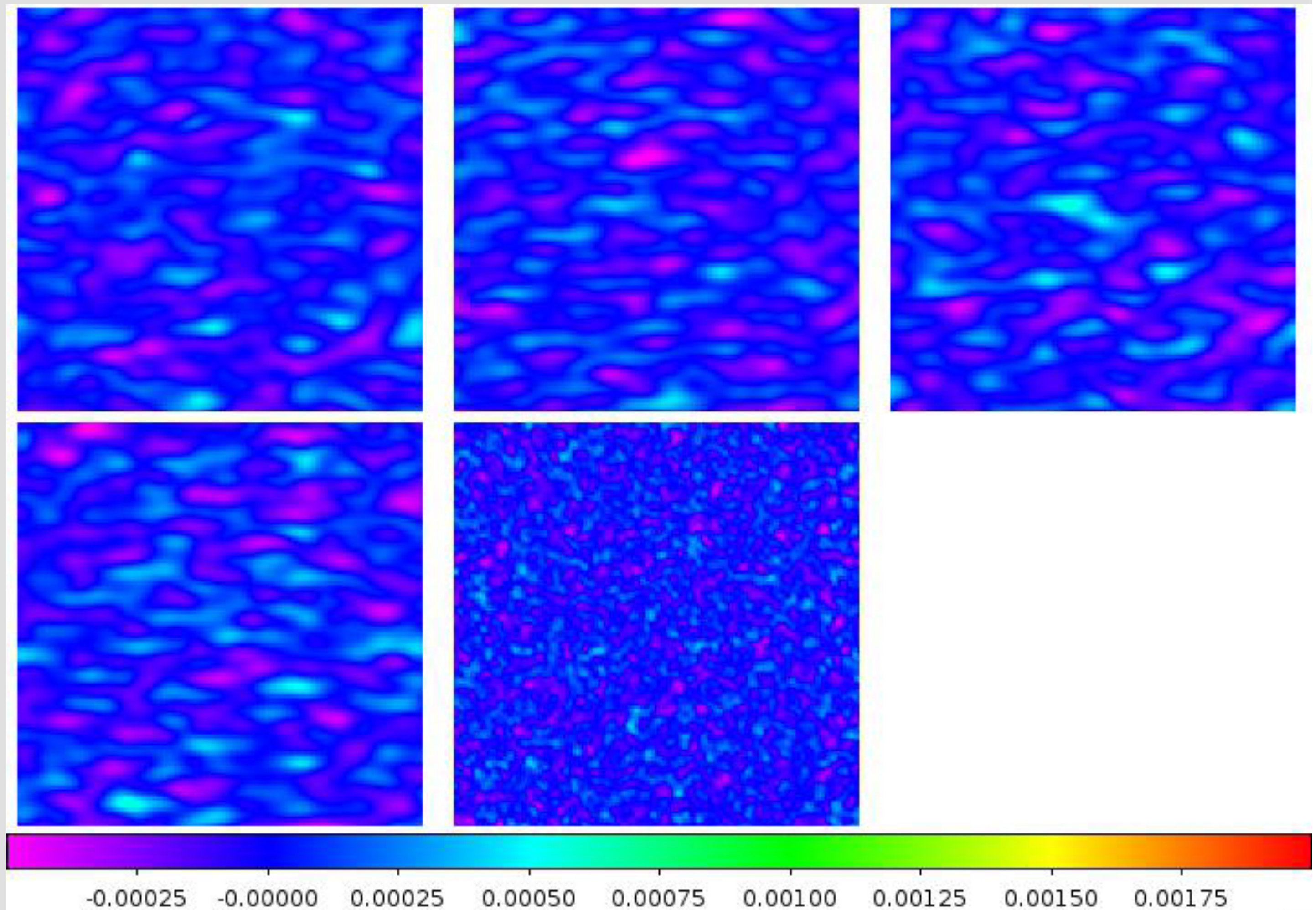
<z> = 1.15
<z> = 2.2
sSFR / sSFR MS
10
1
2:2
2:2
1:1
4:5
11:12
5:6
2:4
6:8
7:8
2:6
2:4
1.0
0.8
0.6
0.4
0.2
0.0
3:3
1:1
10:11
12:12
3:6
10:11
9:9
2:6
3:3
2:2
10^{10}
10^{11}
$M_{stellar}$ ($M_\odot$)
$M_{stellar}$ ($M_\odot$)



<z> = 4.4
1:1
1:1
3:3
1:1
3:3
2:5
0:1
1:2
2:3
0:2
1:1
10
1
sSFR / sSFR_MS
10^10
10^11
M_stellar (M_⊙)
1.0
0.8
0.6
0.4
0.2
0.0

z = 2.2 images :


10.0
1.0
0.1
10^{10}
10^{11}
$M_{stellar}$ ($M_\odot$)
z = 2.2 MS


-0.00025
-0.00000
0.00025
0.00050
0.00075
0.00100
0.00125
0.00150
0.00175

ISM masses increase above the main sequence !!

➔ increase in SFRs above the MS
due to larger ISM masses

analytic fits :

$$\text{gas frac} = \frac{M_{mol}}{M_{mol} + M_{stellar}}$$

$$= 0.30 \left(\frac{M_{stellar}}{10^{11} M_{sun}}\right)^{-0.02\pm0.02} \left(\frac{1+z}{3}\right)^{0.44} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.32}$$

$$SFR = 30 \pm 12 \left(\frac{M_{mol}}{10^{10} M_{sun}}\right)^{1.1\pm0.1} \left(\frac{1+z}{3}\right)^{0.8\pm0.3} M_{sun}\,yr^{-1}$$