interstellar matter (ISM) drives Galaxy Evolution

SFR driven by gas supply ??

starburst vs main sequence ??

ISM gas is dissipative ➔ very different dynamics

new approach to measuring ISM

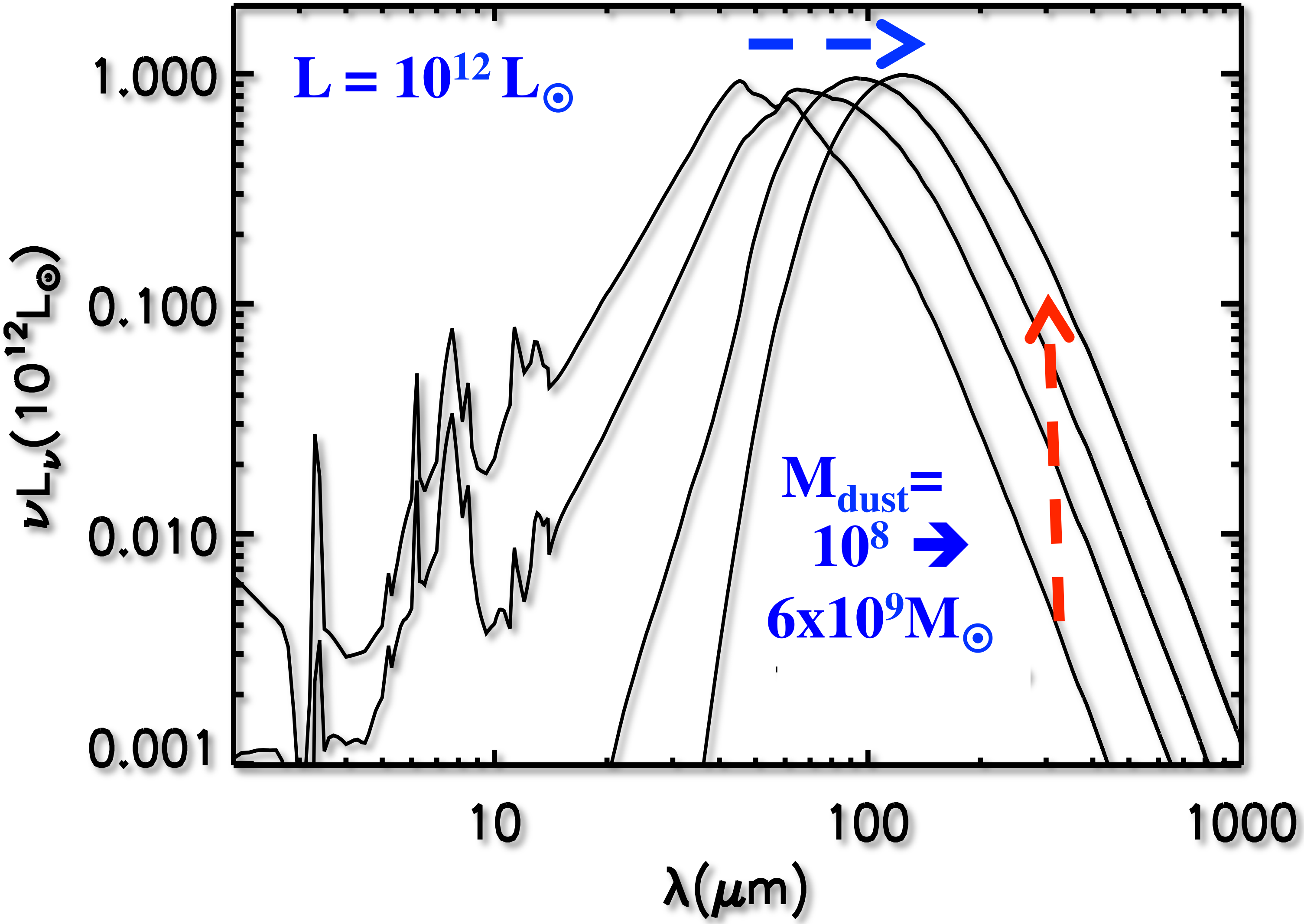
need to measure the mass of SF ISM :

CO vs long λ dust em.

w/ ALMA ➔ high J CO ??

physical understanding of RJ

dust cloud spectrum -- w/ 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}

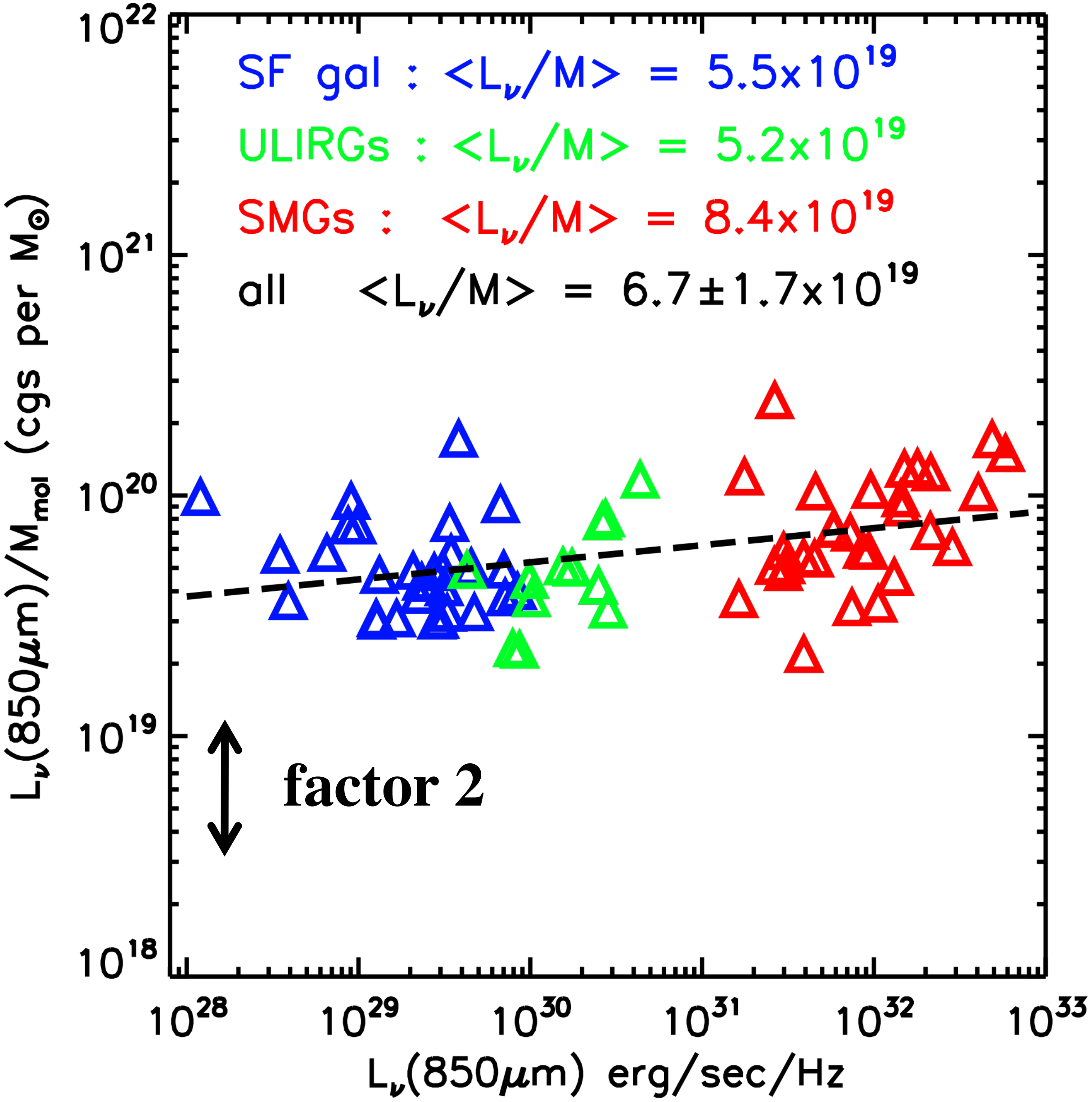
RJ dust continuum optically thin,

$$L_\nu \propto \boxed{T_D \kappa_\nu \frac{\text{dust}}{\text{gas}}} M_{\text{gas}}$$

empirically calibrate ○

w/ low z normal galaxies and ULIRGs + high z SMGs

empirical basis for RJ continuum ➔ ISM masses



Hughes etal ‘17 get $6.4\text{x}10^{19}$
for 67 MS gal. @ z < 0.3

← $6.7\text{x}10^{19}$ erg/s/Hz/$M_{\odot}$

w/ less than factor
2 dispersion

Planck: Milky Way
➔
$6.2\text{x}10^{19}$ erg/s/Hz/$M_{\odot}$

$\beta = 1.8$ +- 0.1

quick and reliable !!

ISM evolution z = 0.3 to 3

RJ dust continuum ➔ ISM masses

ALMA w/ <u>~2 min integrations (CO 100x longer)</u>

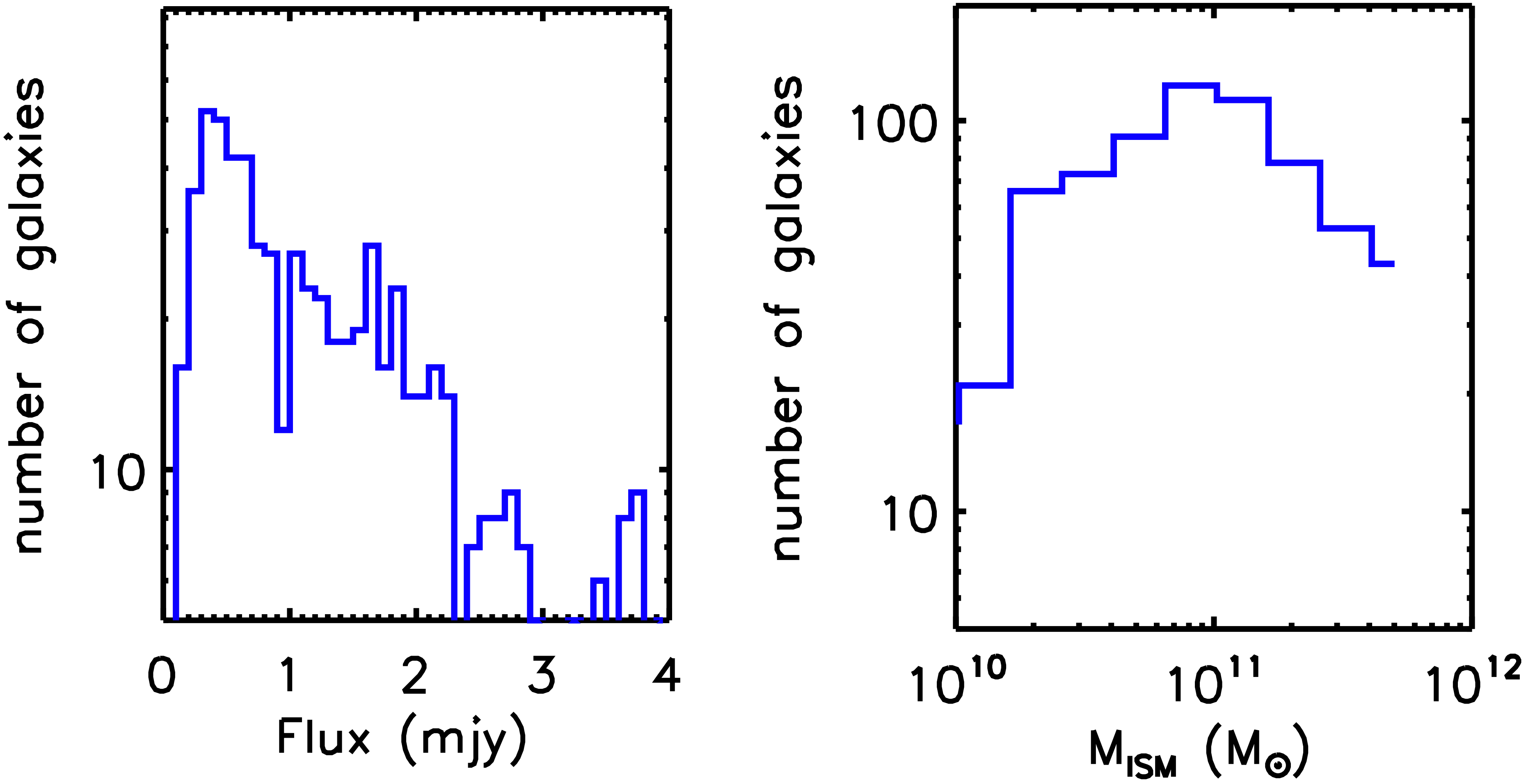
1011 pointings w/i COSMOS field
➔ 687 detections of Herschel far infrared sources !!
(<u>every one detected</u>)

w/ Vanden Bout, Lee, Sheth, <u>Aussel</u>, <u>Capak</u> , Sanders, Bongiorno, Diaz-Santos, Casey, <u>Murchikova</u>, Koda, Laigle, <u>Darvish</u>, Vlahakis, <u>McCracken</u>, <u>Ilbert</u>, Pope, Chu, Toft, Ivison, Morokuma-Matsui, <u>Armus</u>, Masters

Scoville etal 2017, ApJ, 837, 150

flux distribution :

w/ the calibration constant for flux to mass ➔



all Herschel sources have $M_{ISM} = 10^{10} – 5\mathrm{x}10^{11}\ M_\odot$!!

MW ~ $5\mathrm{x}10^9\ M_\odot$

logic of our analysis :

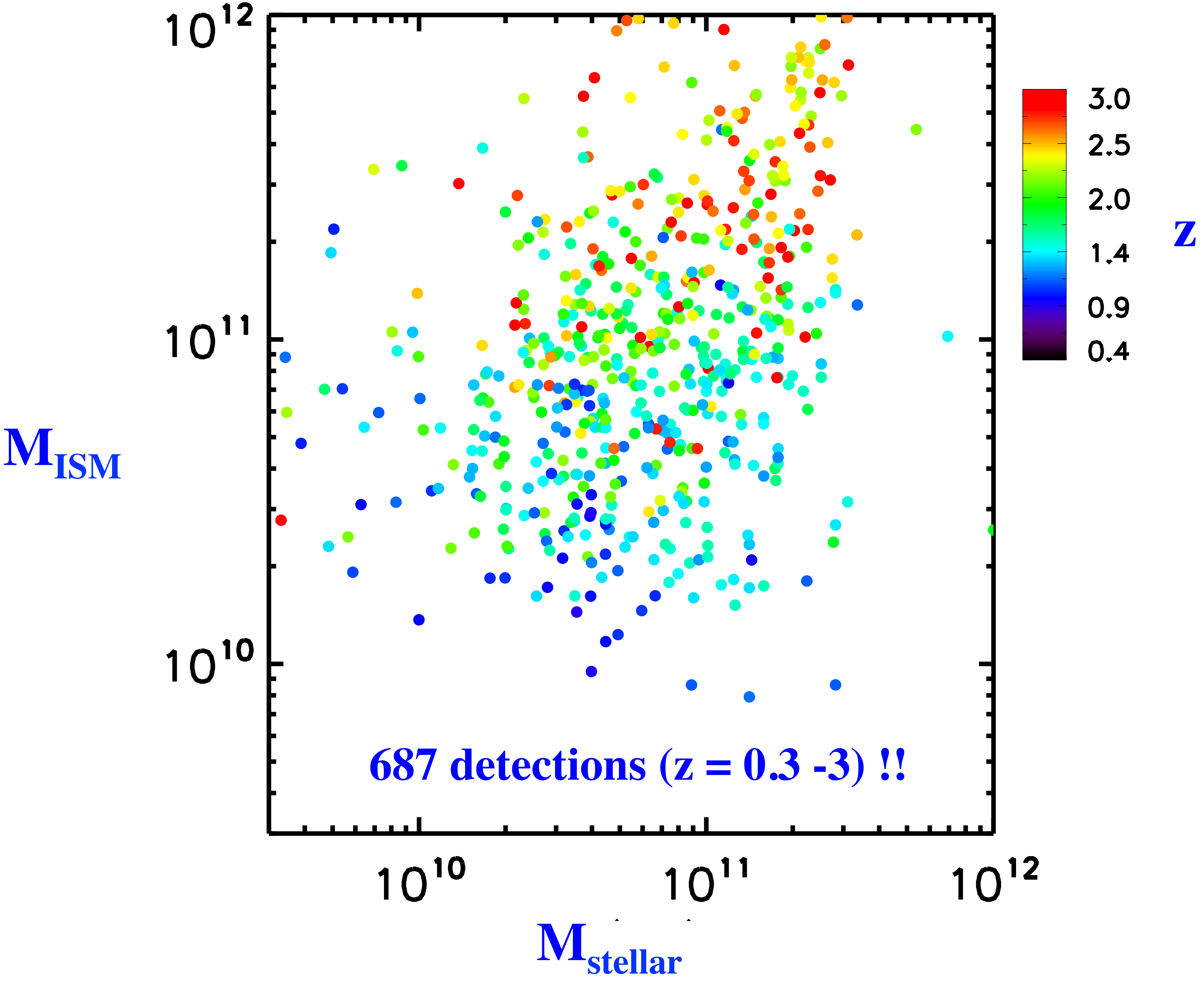
all ALMA 1.3 mm & 850 µm obs. in COSMOS field (~0.2 mJy rms)

search for sources at positions of Herschel FIR sources (14000)

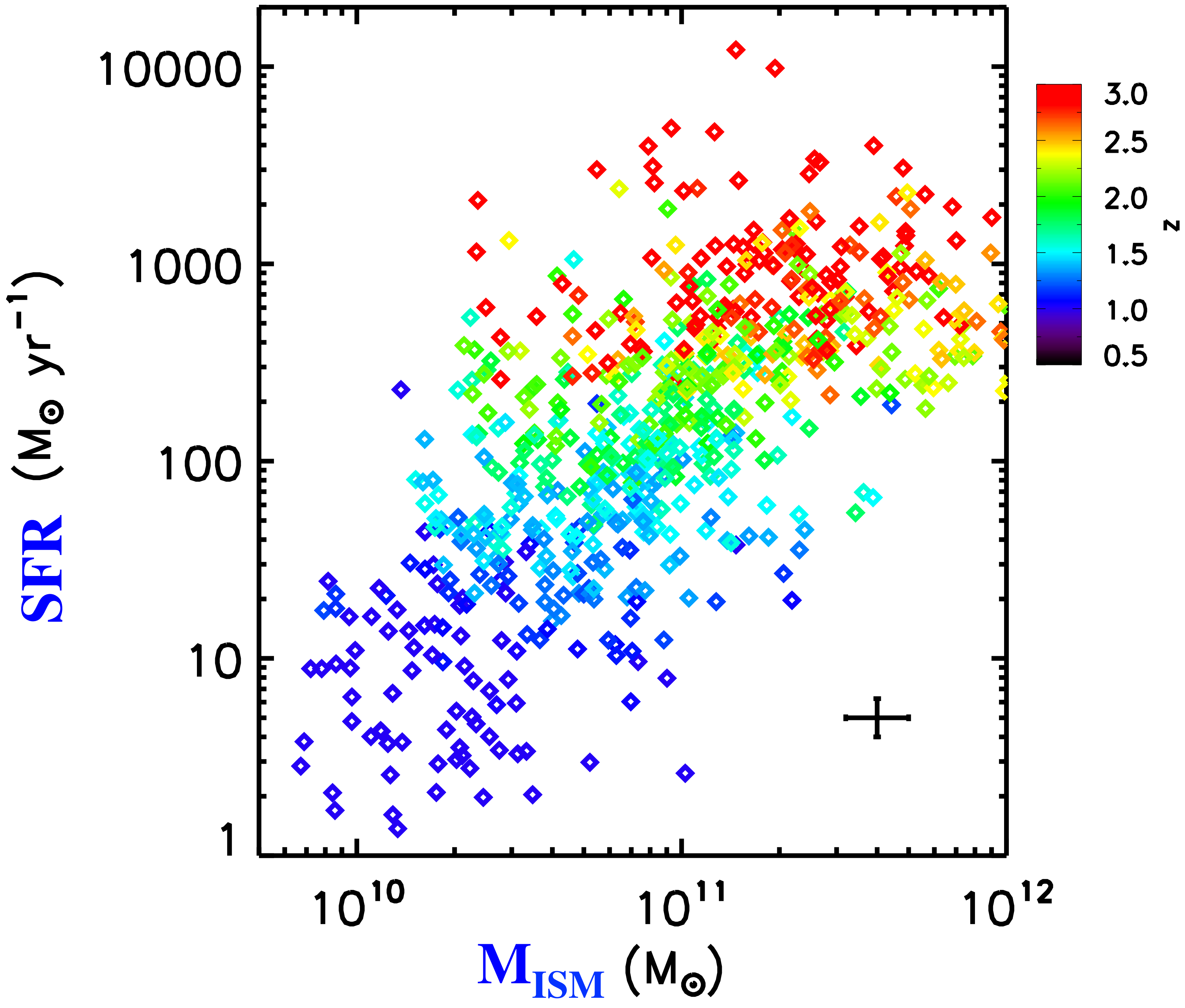
all Herschel sources w/i FOVs detected !! ➔ 687 detections

functional dependence of :

1. ISM (z, M_*, sSFR rel. to MS)
2. SFR / ISM (z, sSFR rel. to MS, M_*)
3. Accretion rates needed to maintain SF



687 detections (z = 0.3 -3) !!


SFR ($M_\odot$ yr^{-1})
10000
1000
100
10
1
10^{10}
10^{11}
10^{12}
M_{ISM} ($M_\odot$)
z
3.0
2.5
2.0
1.5
1.0
0.5

gas contents correlated w/ ??

time in cosmic history (z)

mass of galaxy ($M_{stellar}$)

starburst vs main sequence (sSFR / $sSFR_{MS}$)

gas contents correlated with :

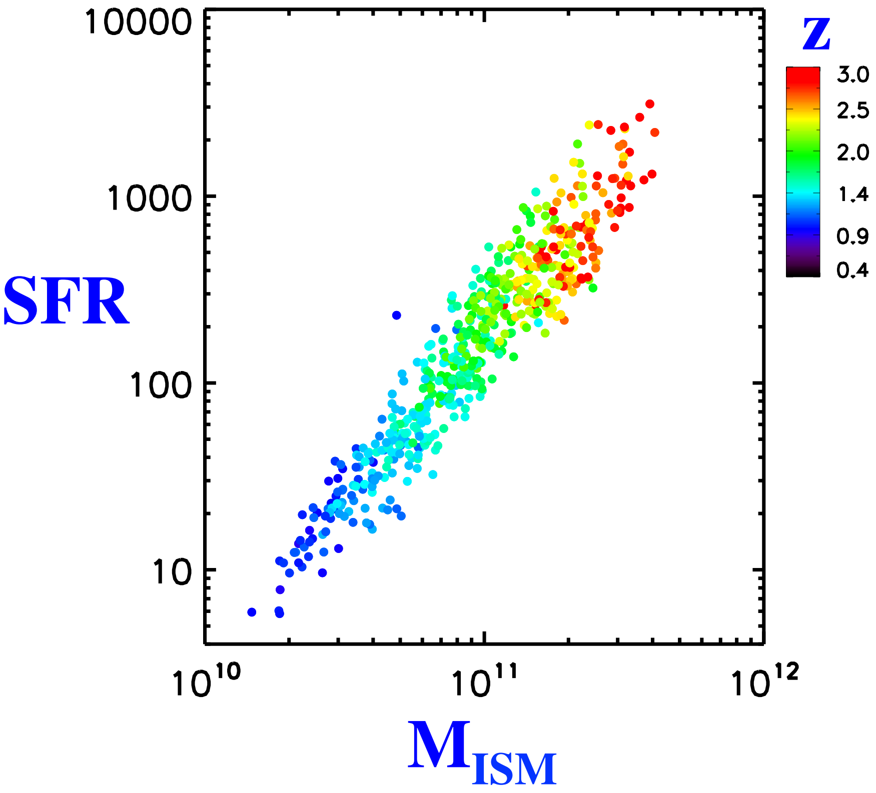
time in cosmic history (z)

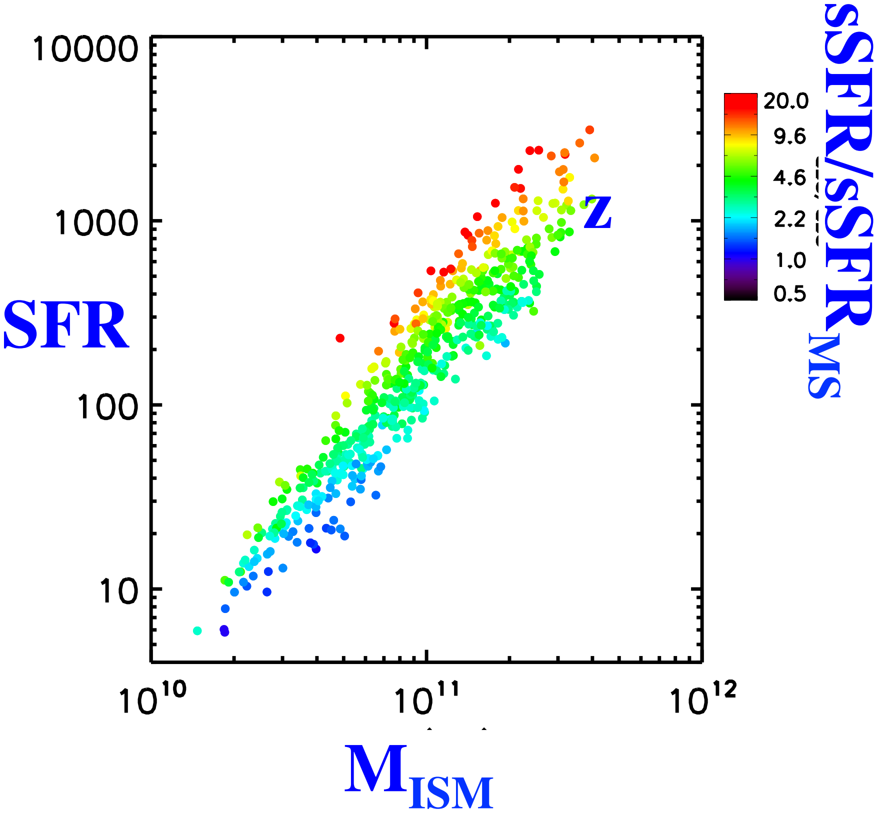
mass of galaxy ($M_{stellar}$)

starburst vs main sequence (sSFR / $sSFR_{MS}$)

$$M_{ISM} = 7.07\times10^{9}M_{sun}\ (1+z)^{1.84}\left(\frac{sSFR}{sSFR_{MS}}\right)^{0.32}\left(\frac{M_{stellar}}{10^{10}M_{sun}}\right)^{0.30}$$

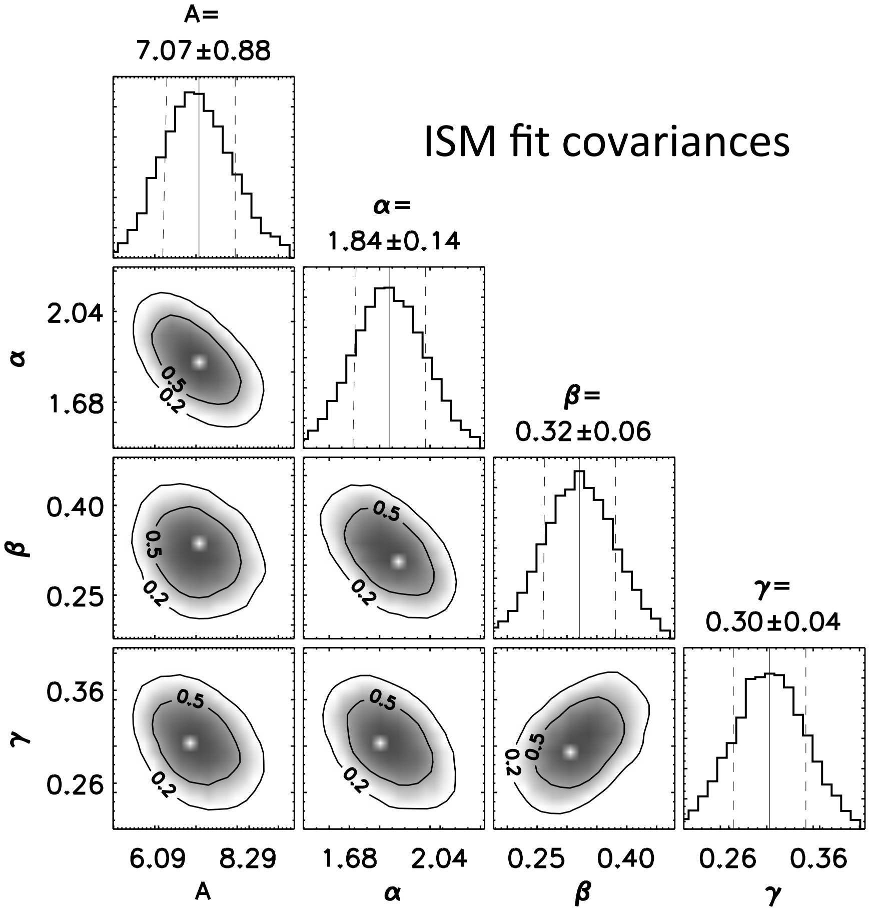
SF law :



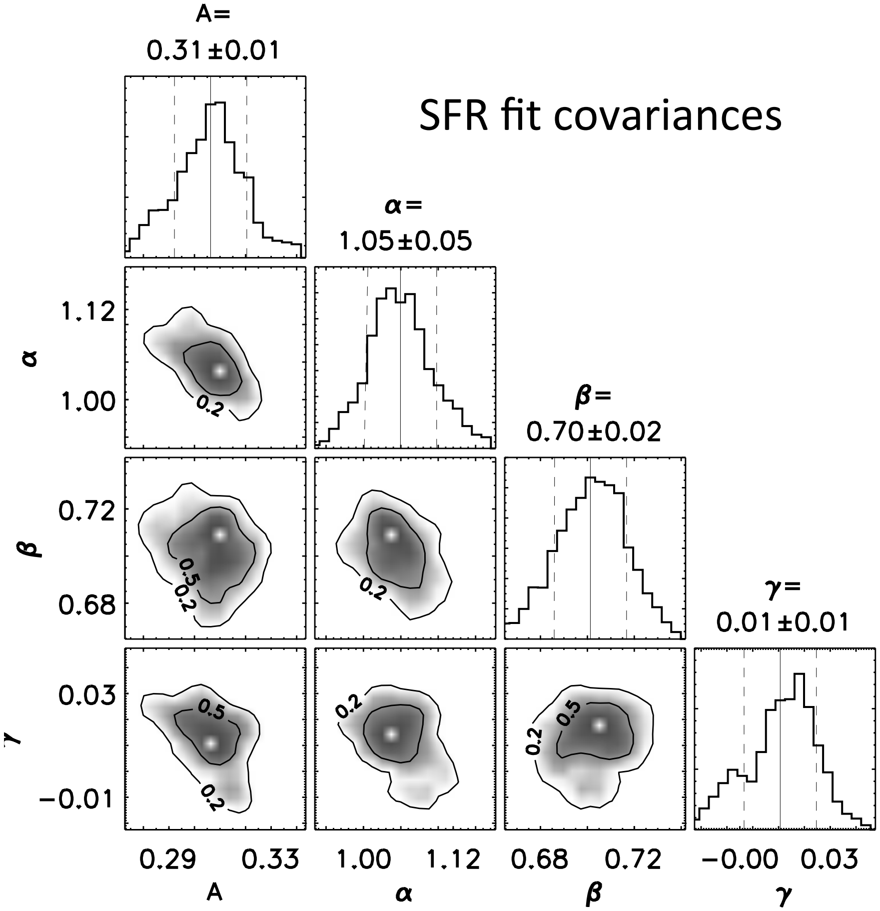


$$\mathrm{SFR}\left(M_{sun}yr^{-1}\right)/\left(\frac{M_{ISM}}{10^{9}M_{sun}}\right)=0.31\;{\overbrace{(1+z)^{1.05}\left(\frac{sSFR}{sSFR_{MS}}\right)^{0.70}\left(\frac{M_{stellar}}{10^{10}M_{sun}}\right)}^{\text{efficiencies}}}^{0.01}$$

covariances from Monte Carlo Markov Chain fitting



ISM fit covariances



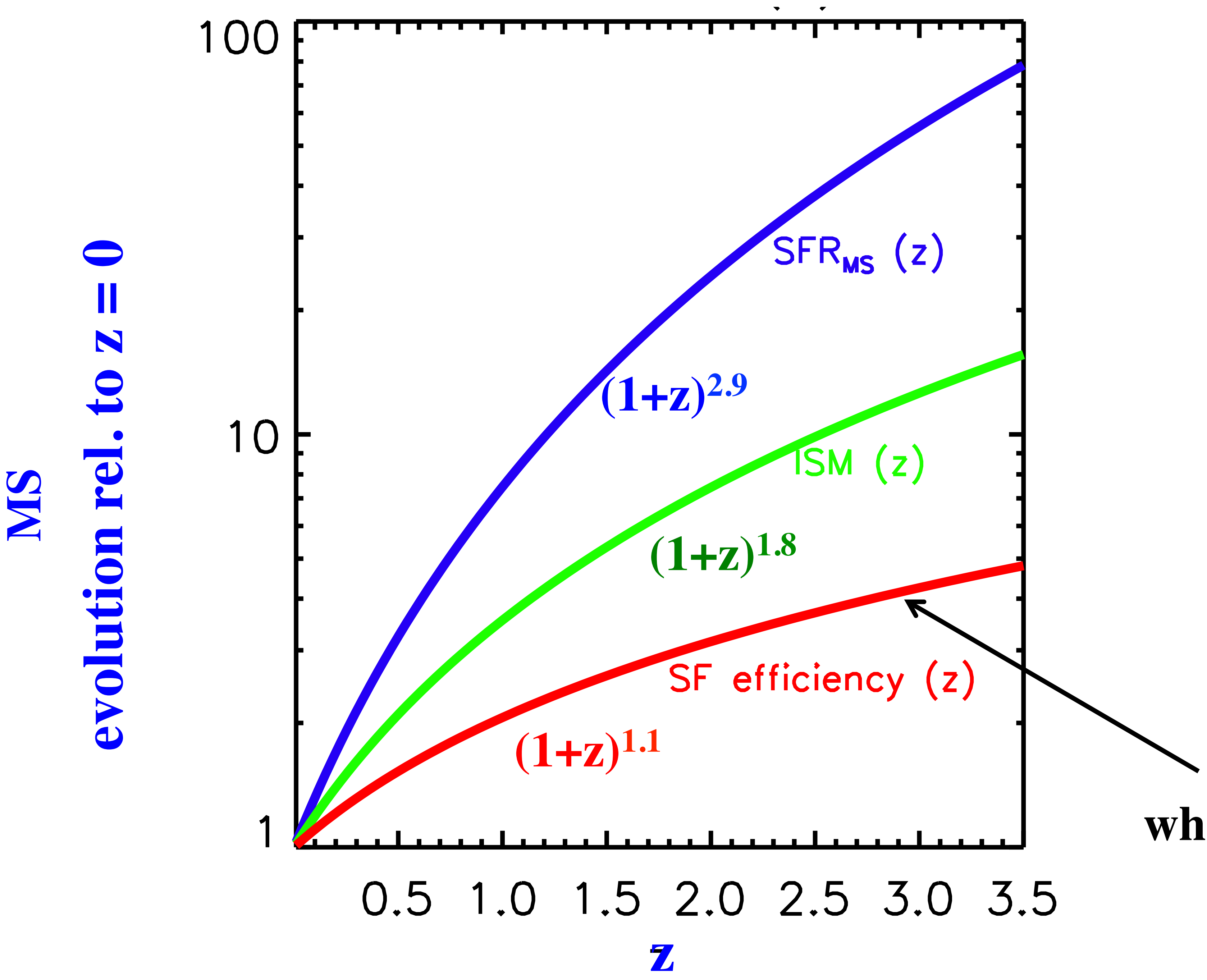
SFR fit covariances

well-behaved w/ single values
uncertainties ~0.1 in exponents

$$M_{ISM} = 7.07 \times 10^{9} M_{\Theta} \left(1+z\right)^{1.84} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.32} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.30}$$

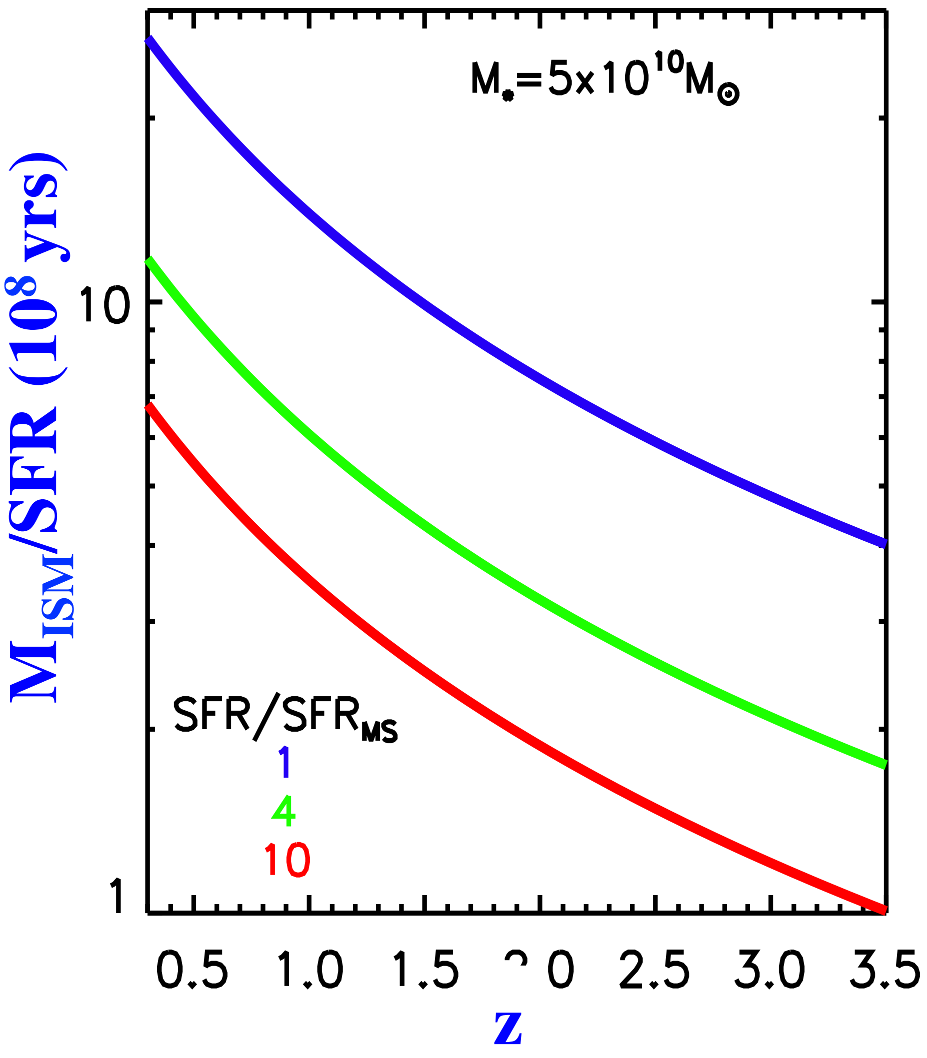
$$SFR\left(M_{sun} yr^{-1}\right) / \left(\frac{M_{ISM}}{10^{9} M_{sun}}\right) = 0.31 \underbrace{\left(1+z\right)^{1.05} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.70} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.01}}_{\text{efficiencies}}$$

- **evolution w/ z : due to both increase in ISM and SF eff.**
- **increase above MS for SBs : higher ISM and SF eff.**
- **ISM varies as $M_{stellar}^{0.3}$ and SF eff. indep. of $M_{stellar}$**
- **not a simple low-z KS law -- higher efficiency H_2 → *'s**


MS
evolution rel. to z = 0
100
10
1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z
SFR$_{MS}$ (z)
$(1+z)^{2.9}$
ISM (z)
$(1+z)^{1.8}$
SF efficiency (z)
$(1+z)^{1.1}$

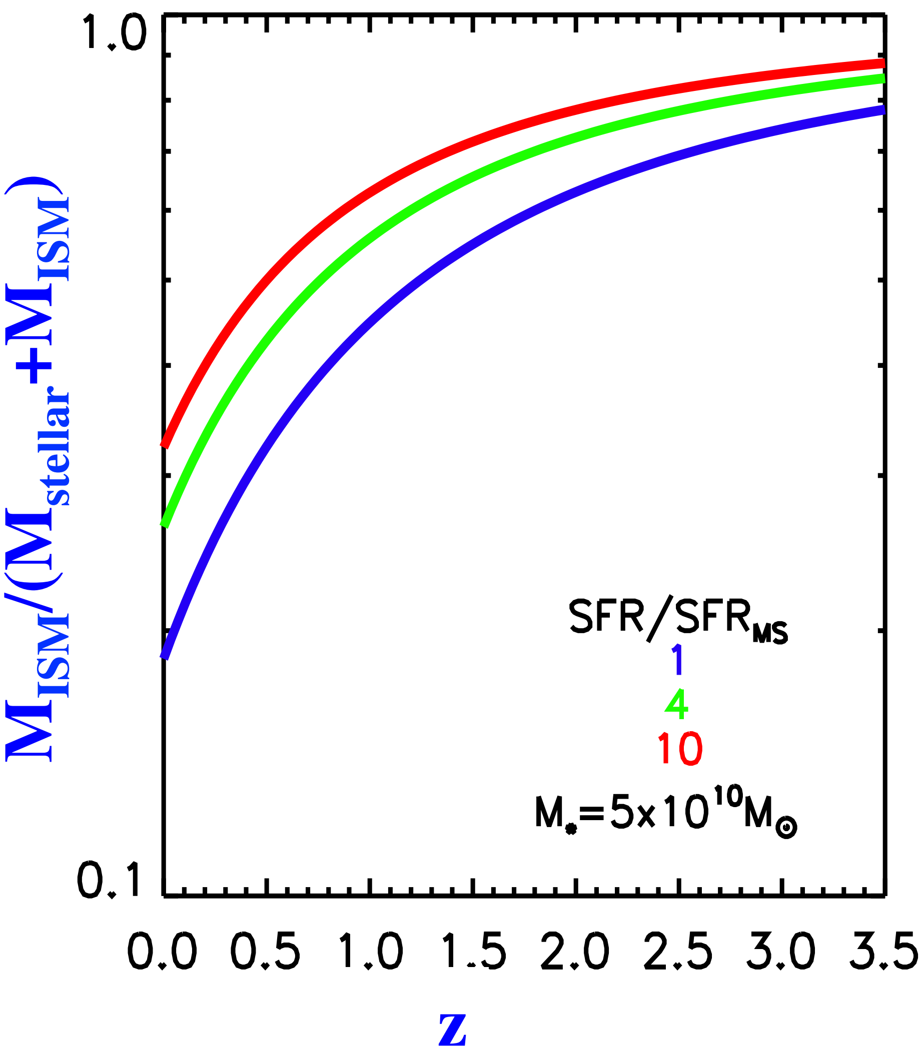
why ?

gas depletion times



at $z > 2$, ~500 Myr MS

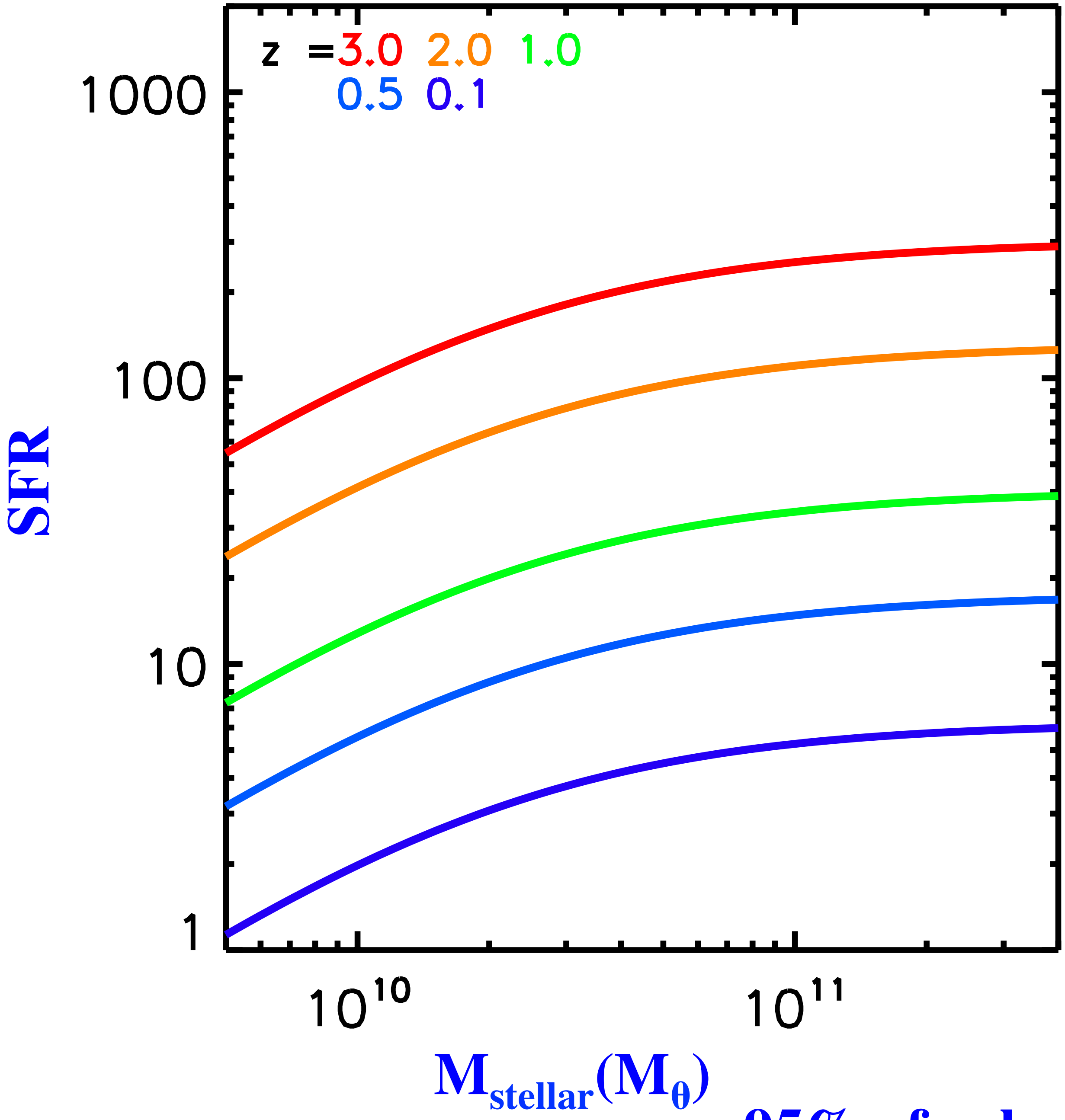
ISM mass fractions



30% -- 80% above MS

➔ accretion

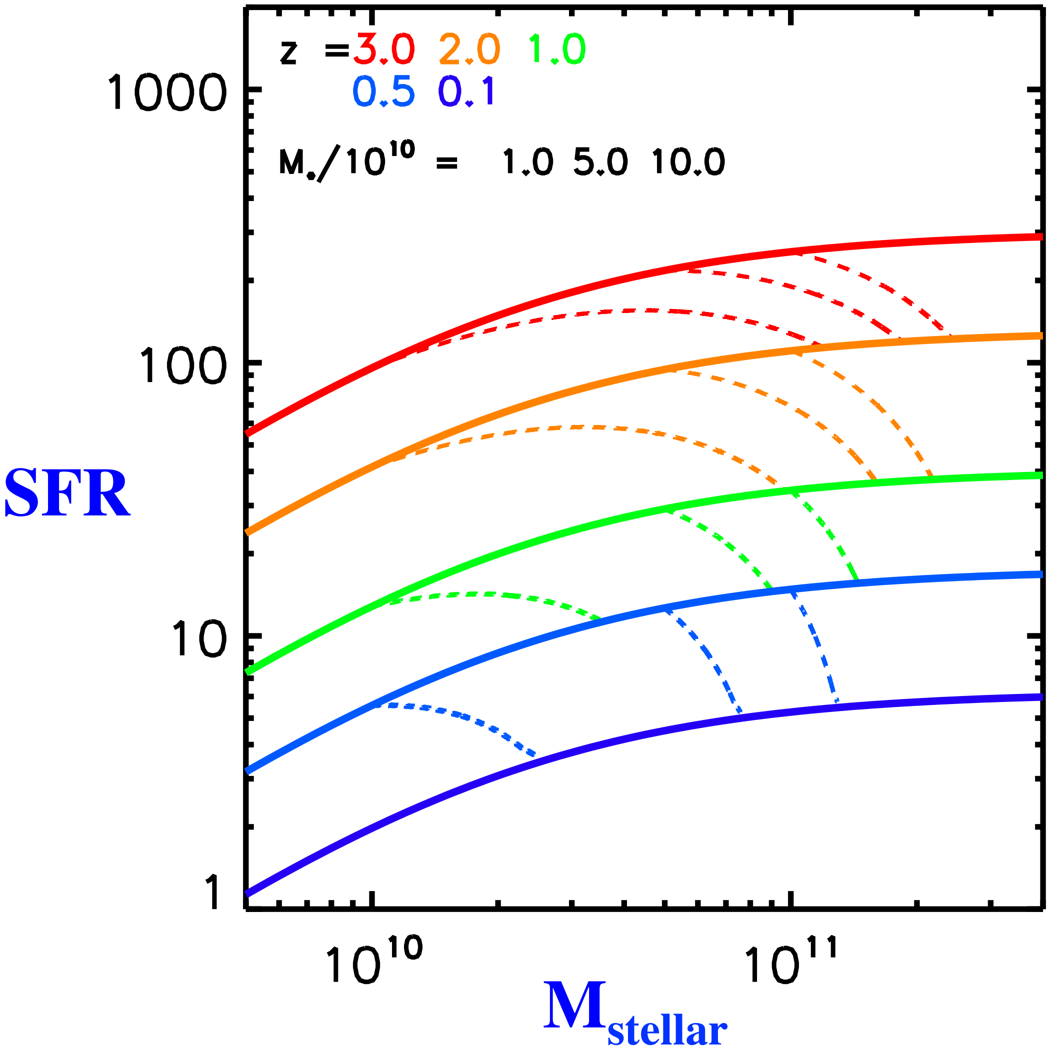
MS vs redshift (age of univ.)



cosmic age	z
2 Gyr	3
3 Gyr	2
5 Gyr	1
9 Gyr	0.5
12 Gyr	0.1

95% of galaxies on main sequence

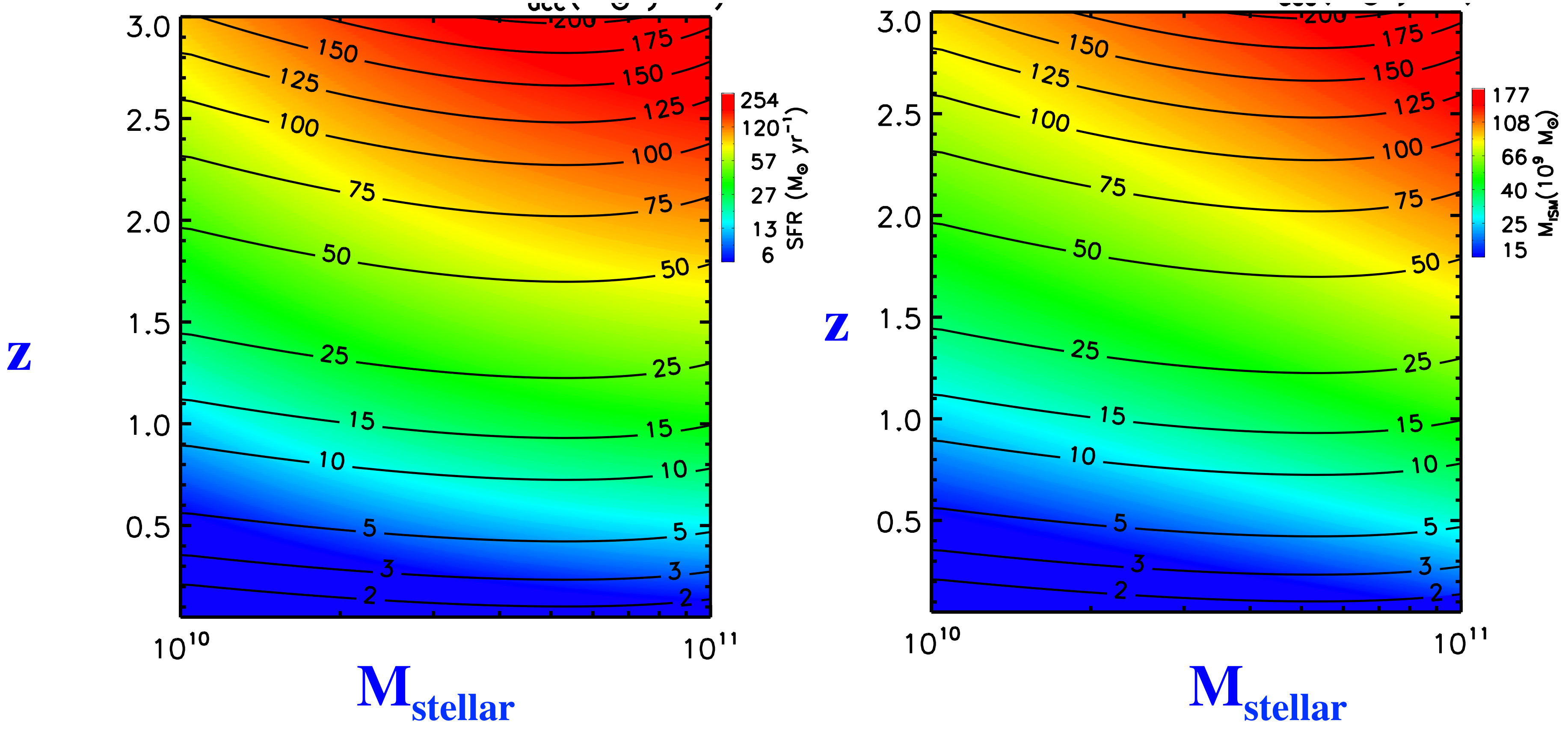
evolutionary continuity of MS



accretion needed to maintain SF :

$$\frac{dM_{ISM}}{dt} = -\ 0.7\ SFR + \dot{M}_{accretion}$$

accretion rate ($M_\odot\ yr^{-1}$) -- contours



SFRs - color

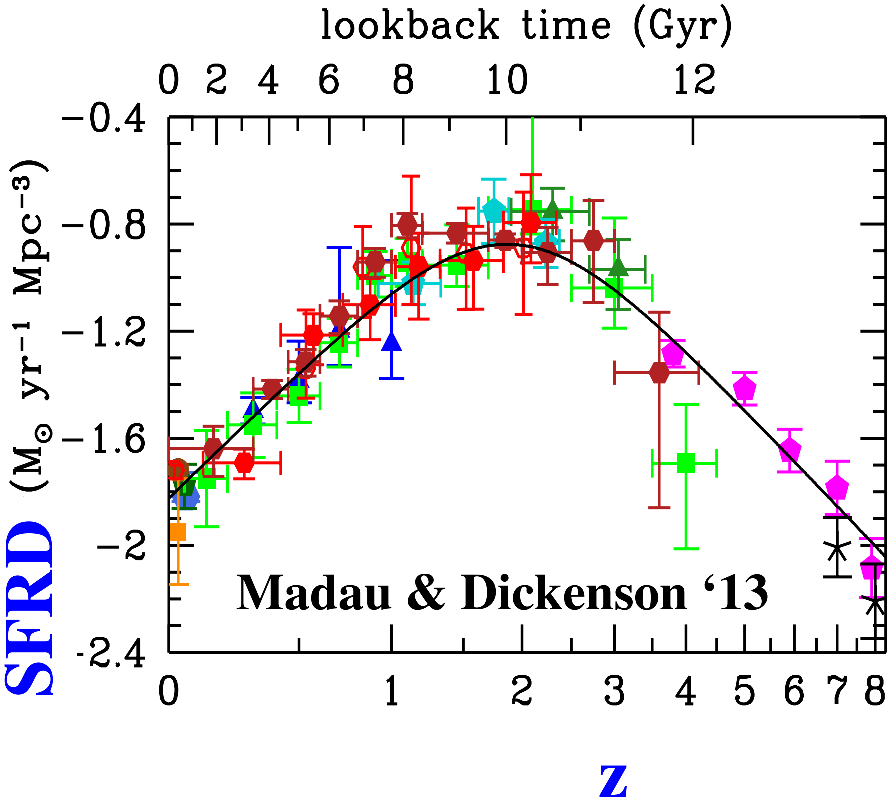
ISM mass - color

$$\dot{M}_{acc} = 1.12\, M_{sun}\, yr^{-1} \cdot (1+z)^{3.6} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.44}$$

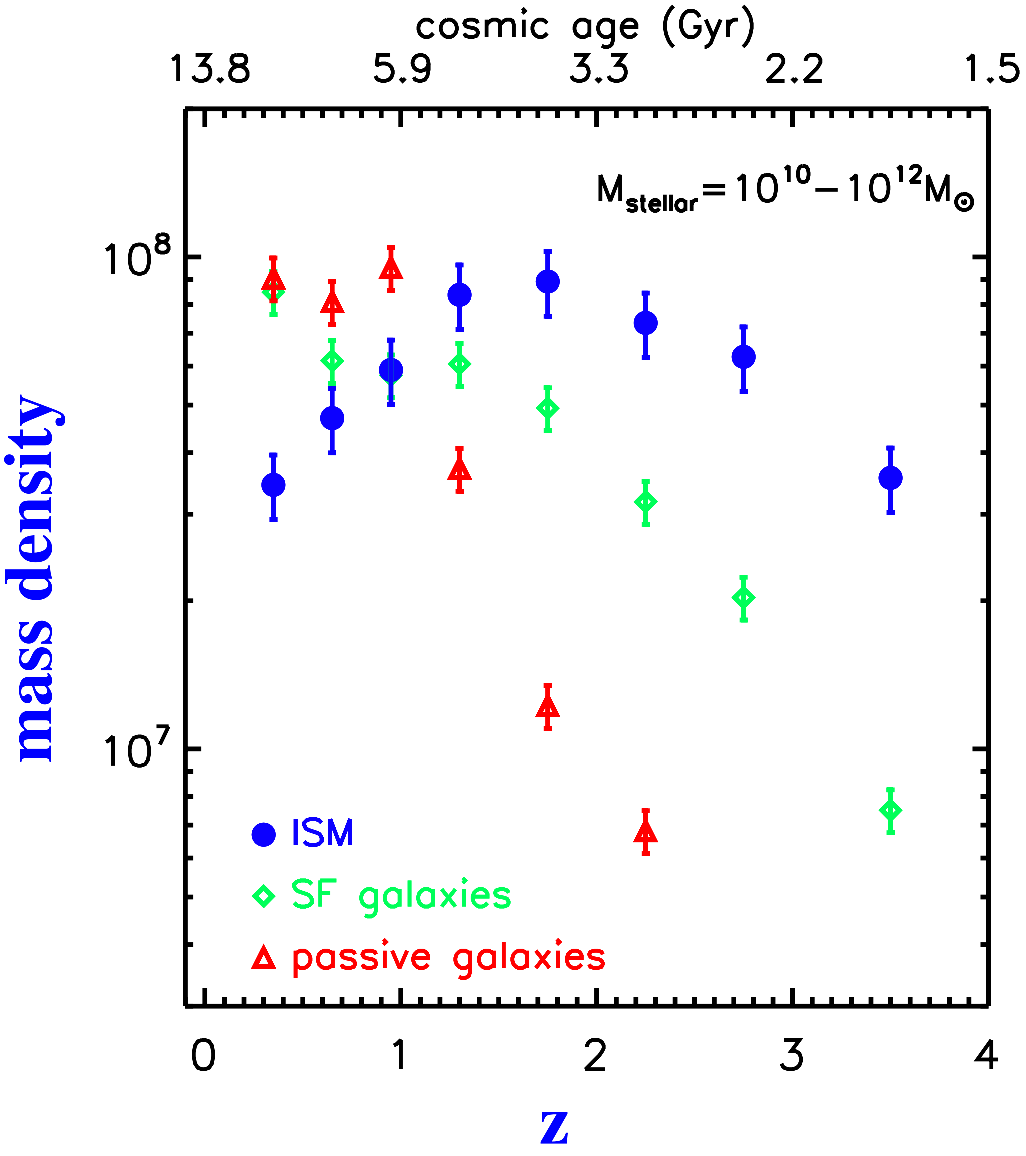
accretion rates are huge : 100 $M_{sun} yr^{-1}$ at z > 2

overall cosmic evolution

cosmic evolution SF



cosmic evol. of ISM and stellar mass



summary :

1. RJ dust continuum is fast (2min) and reliable
2. ISM content and SFE evolve each less rapidly w/ z than SFR
3. ISM mass varies as $M_{stellar}^{0.3}$
4. above MS, SB due to both increased ISM and higher eff.
5. accretion rate are huge $\sim 100\ M_{sun}\ yr^{-1}$

specific accretion rate ($\dot{M}_{acc}$ / $M_{stellar}$) :

==> lower at high $M_{stellar}$