Properties of Interstellar Medium in Star-Forming Galaxies at z~1.4 revealed with ALMA

(Seko et al. to be submitted soon!)

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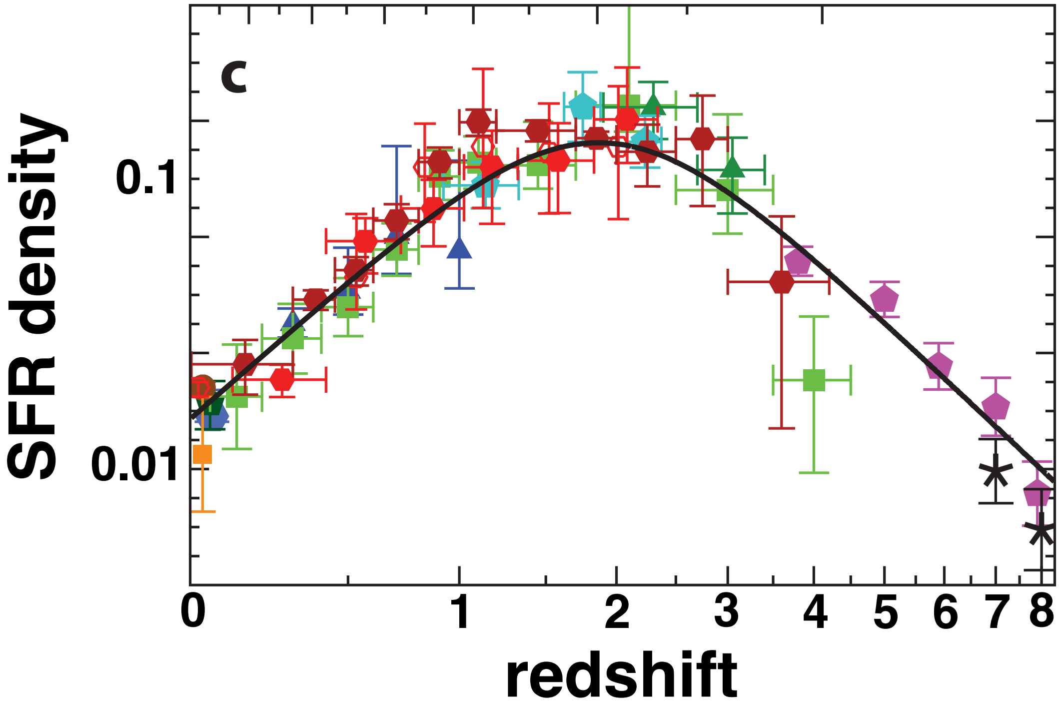
Peak of SFRD

galaxies evolve by transforming gas into stars

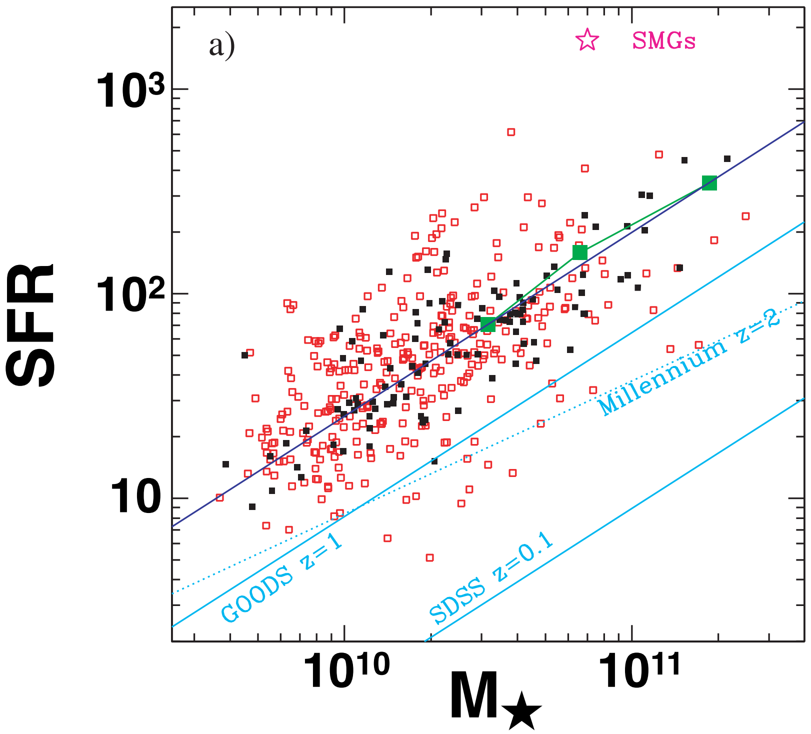
star formation rate density peaked at z~2



Madau & Dickinson 2014, ARA&A, 52, 415

main sequence of galaxies

- most of star-forming galaxies are located

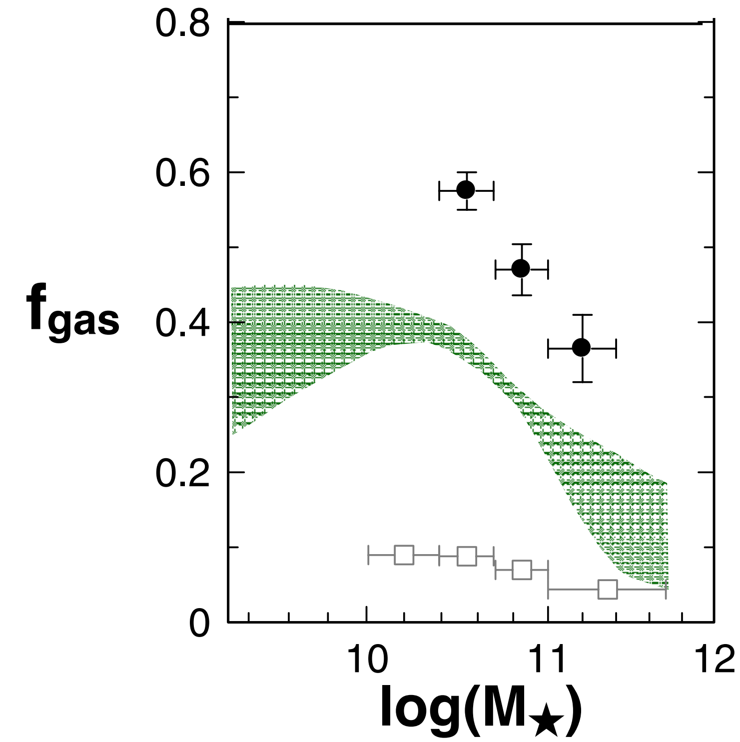


Daddi et al. 2007, ApJ, 670, 156

ISM in MS galaxies at z=1-3

CO observations of main-sequence galaxies at z~2

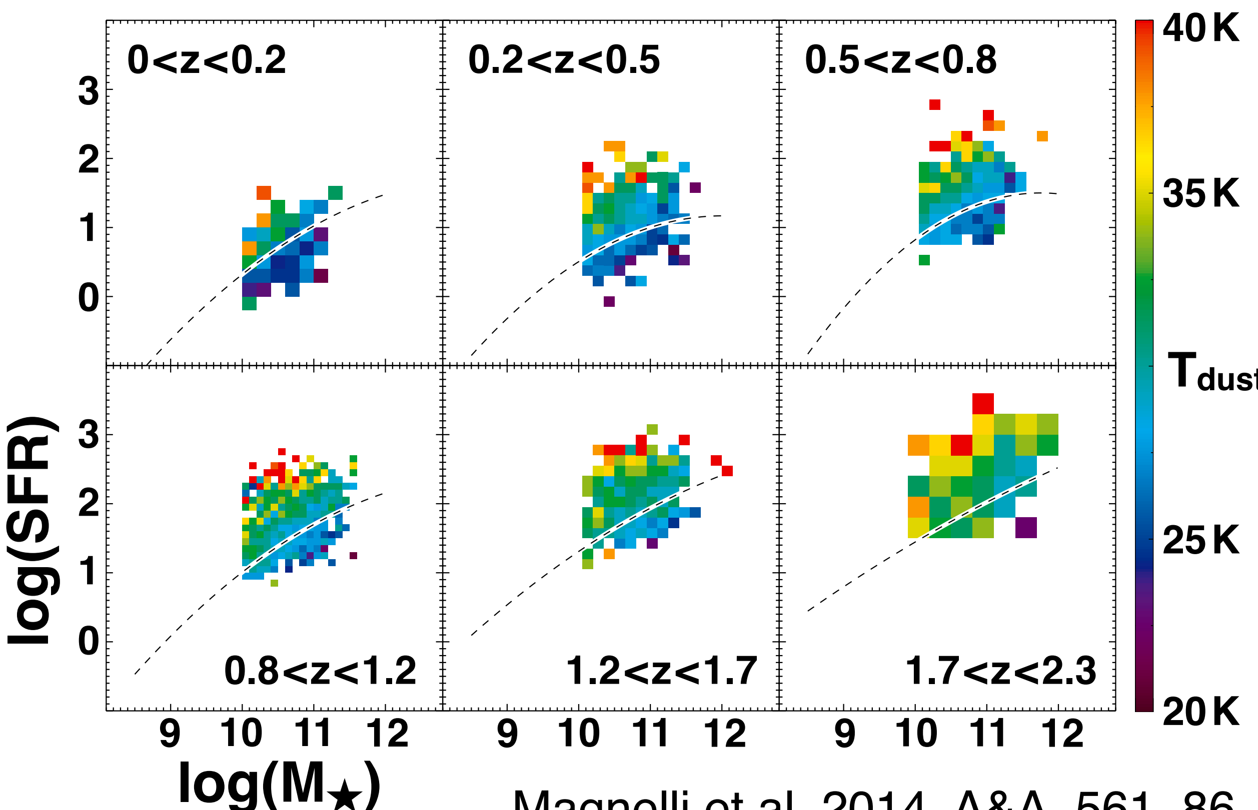
- gas mass/gas mass fractions (f_{gas}) are higher than those in local spiral galaxies
- f_{gas} decreases with $M_\star$



Tacconi et al. 2013, ApJ, 768, 74

Dust observations of main-sequence galaxies up to z~2

- dust temperature is 25-35 K in all redshifts



Magnelli et al. 2014, A&A, 561, 86

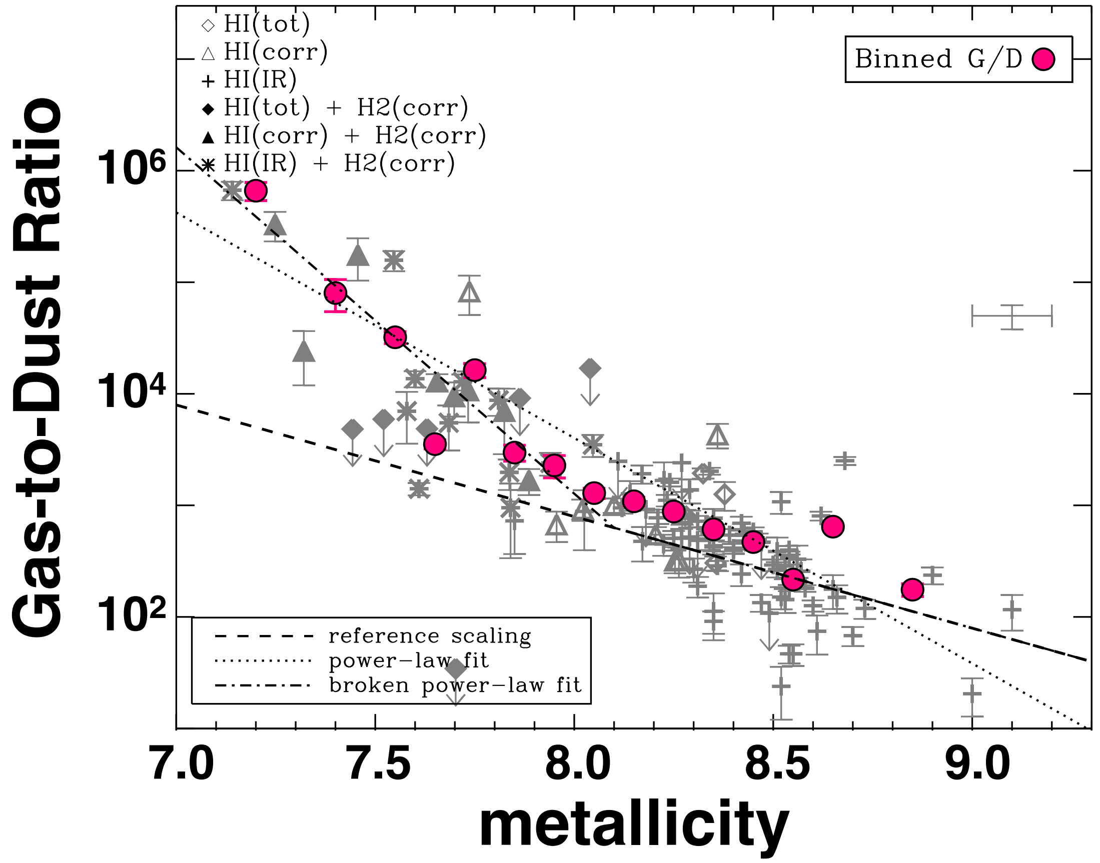
Importance of metallicity

☆metallicity reflects a result of past star-forming activity in a galaxy
= a stage of galaxy evolution

- correlations between gas mass/gas mass fraction and metallicity?
- inflow and outflow rate by using chemical evolution model

Gas-to-Dust mass ratio in local galaxies depends on metallicity

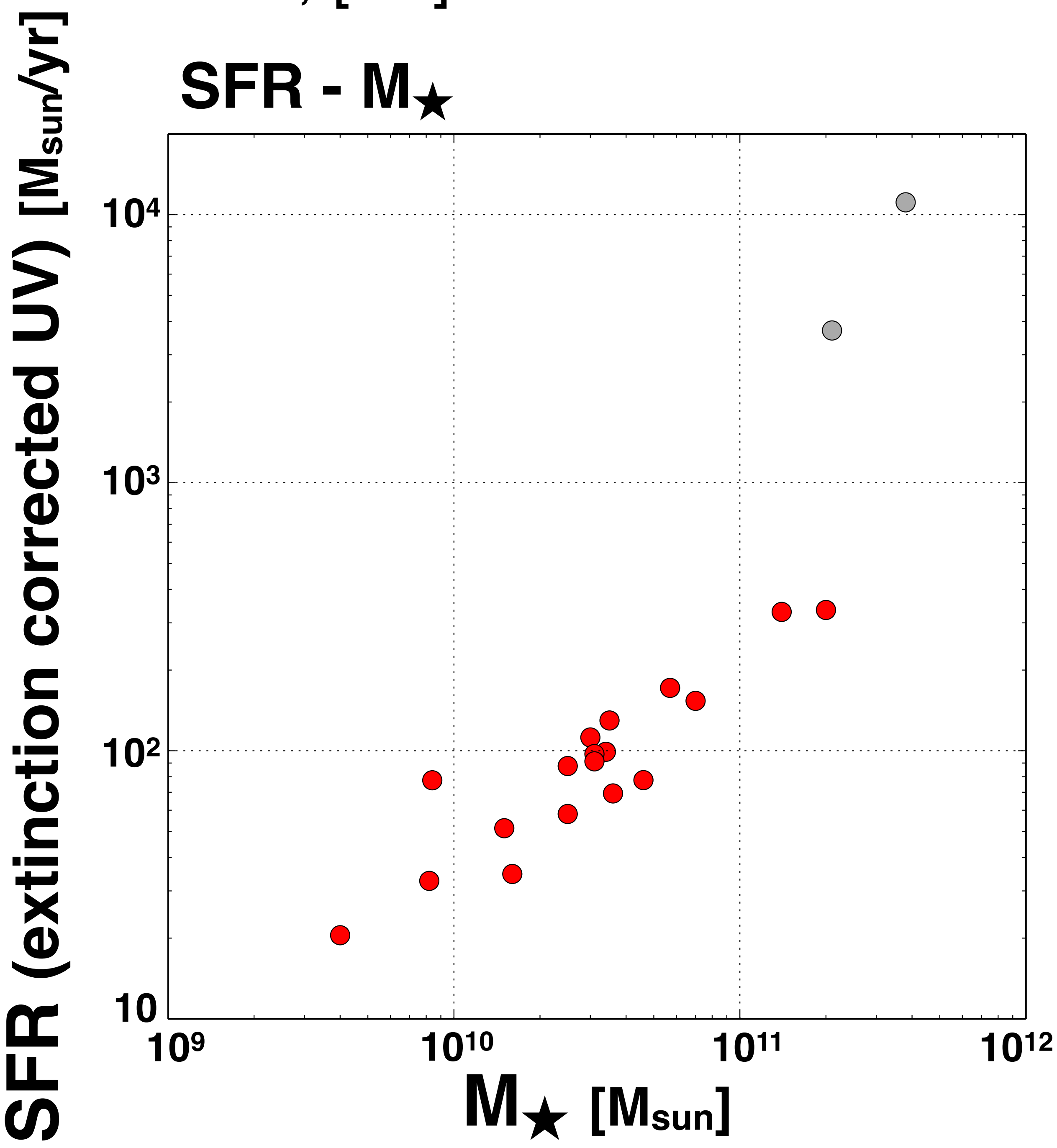
- metallicity dependence of gas-to-dust ratio at high redshift?

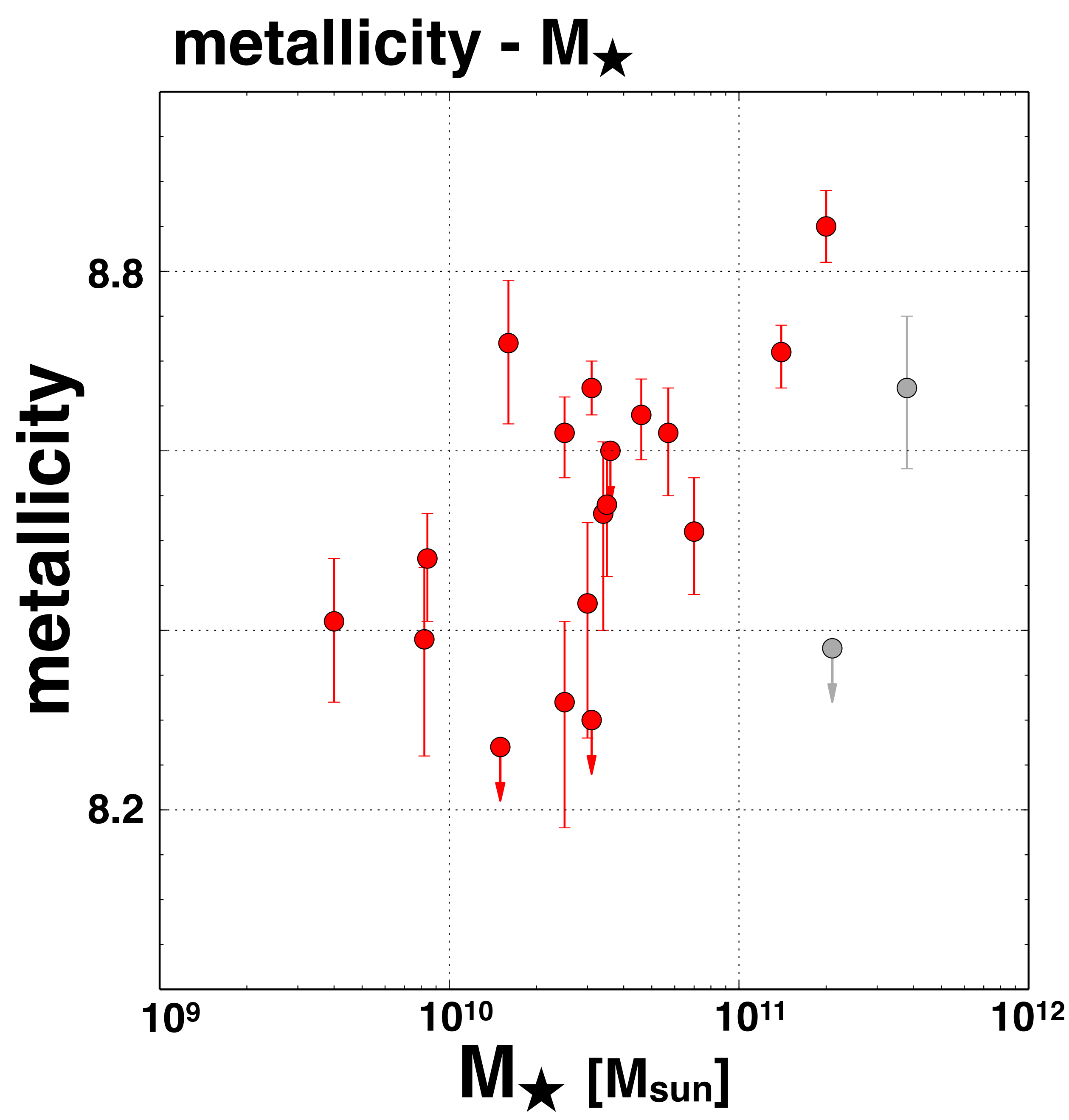


Rémy-Ruyer et al. 2014, A&A, 563, 31

Sample

- 20 star-forming galaxies at z~1.4 with known metallicity in the SXDS field
  - Hα, [NII] lines are observed with Subaru/FMOS → metallicity



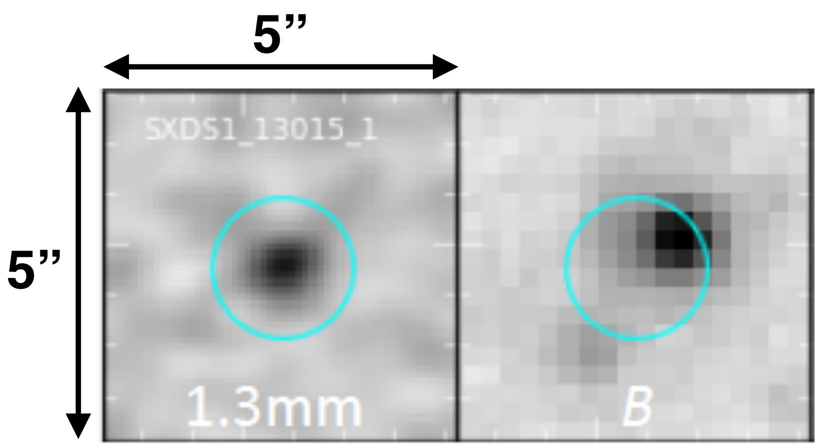


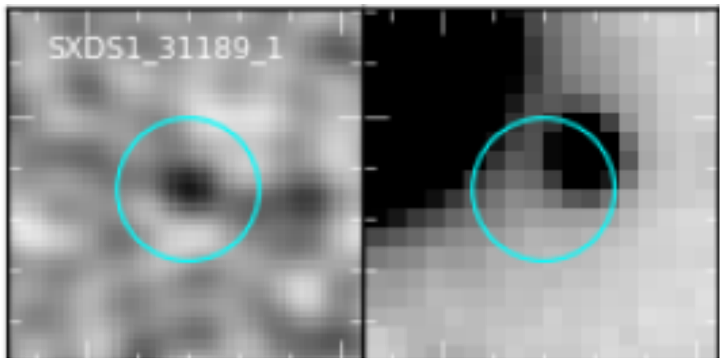
Observations

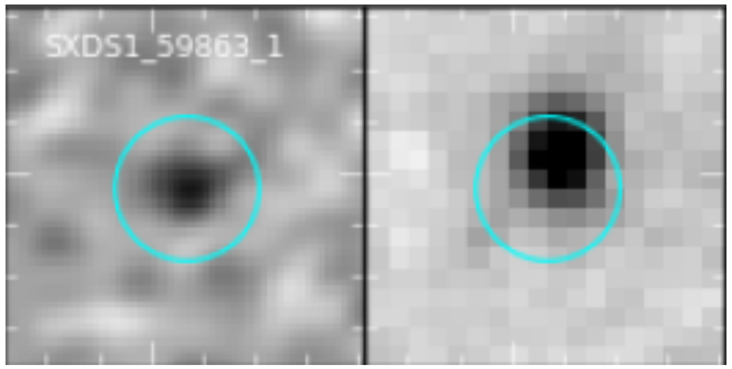
- **ALMA**
- Aug / 2012 (Cycle0)
- observing line : **CO(J=5-4)**
- observing frequency : 221-254 GHz (Band-6)
- Tsys : 66-100 K
- on-source time : 8-15 min (for a galaxy)
- noise level : 0.5-1.1 mJy/beam (50 km/s binning)

Phase re-calibration

offset from the positions in optical images





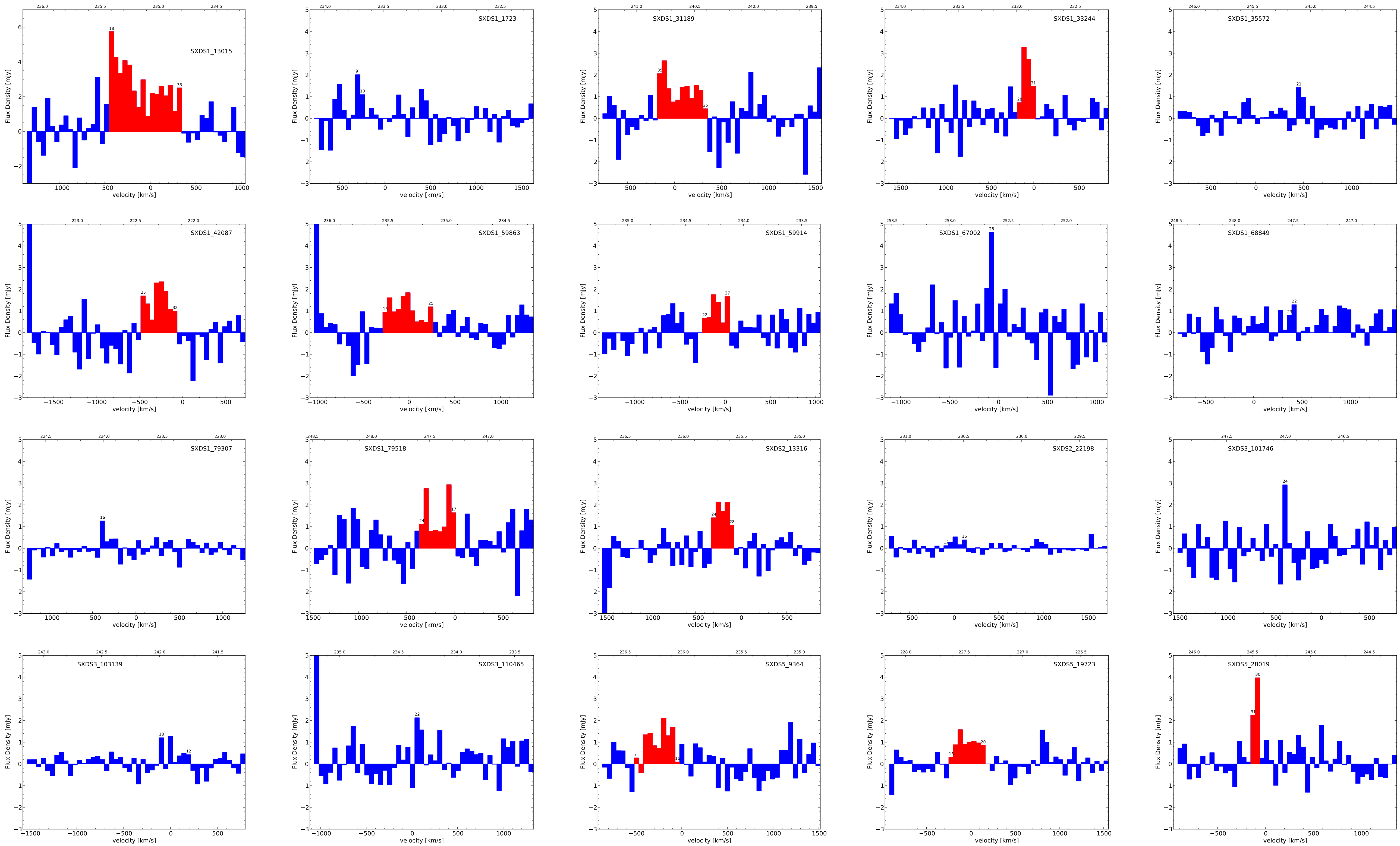


left: ALMA
right: B-band

→ the coordinates of the phase calibrator were turned out to be wrong!

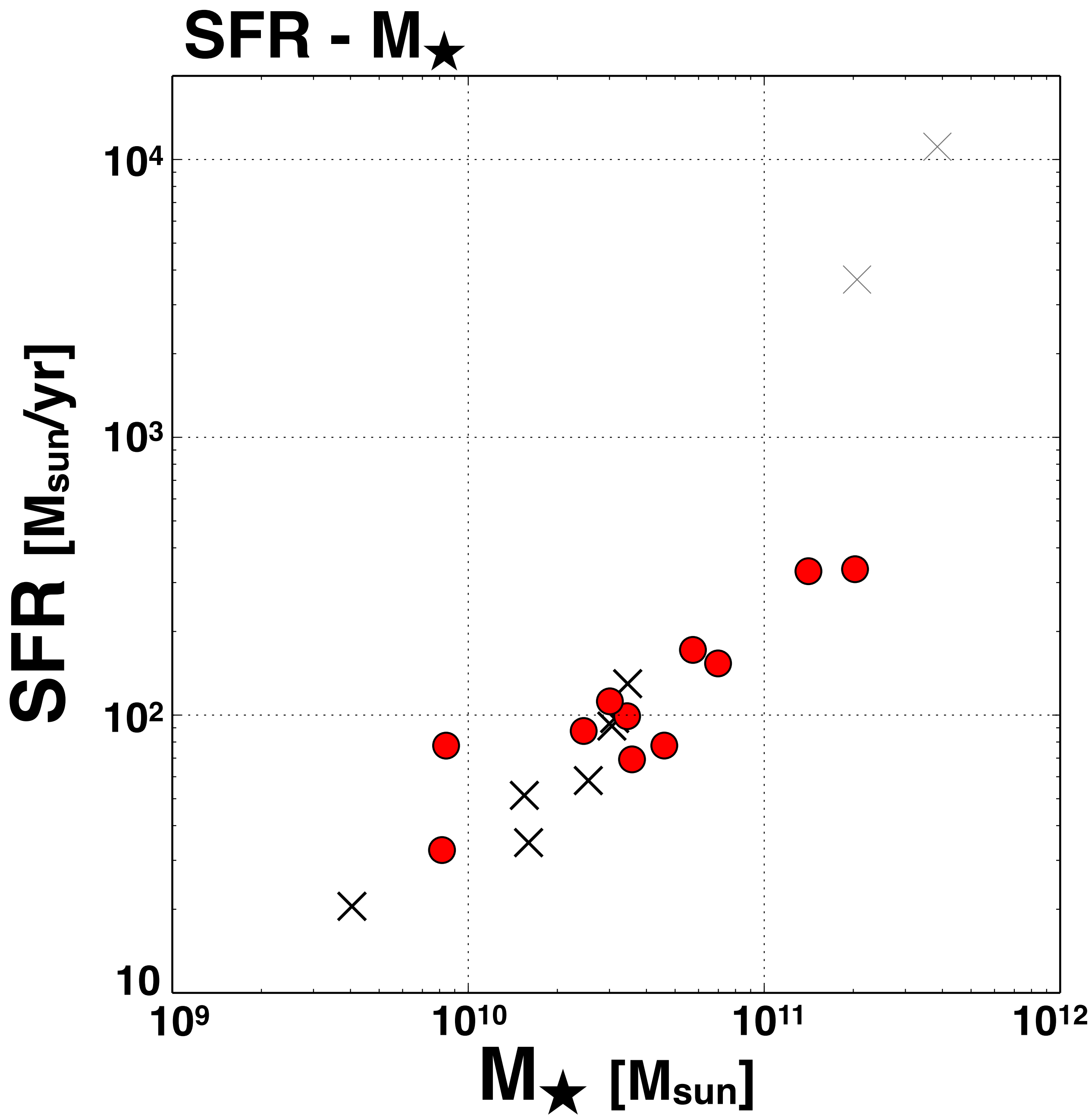
We re-calibrated with the corrected coordinates

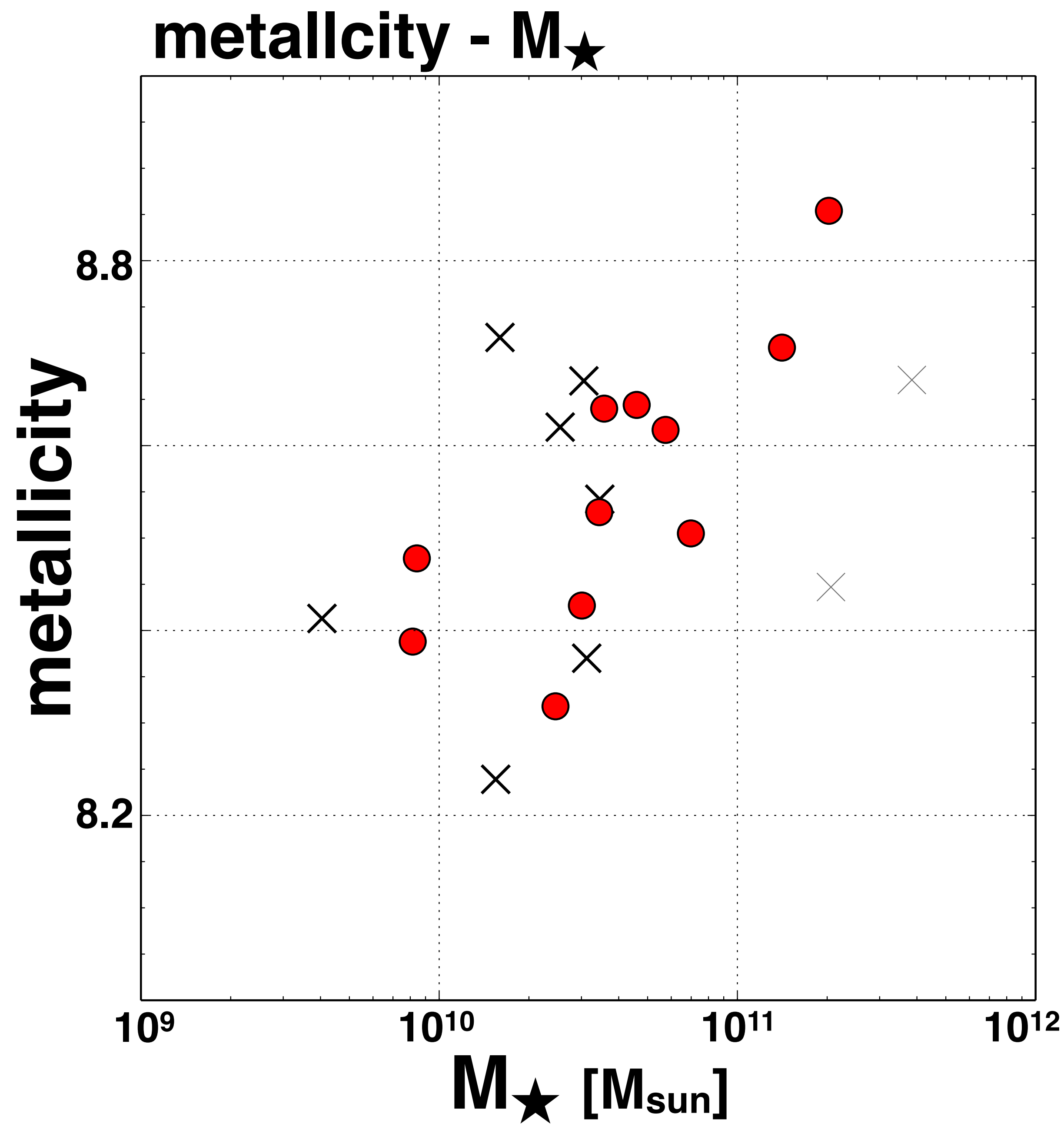
Results | line profiles



We detect CO emission from 11 galaxies!

Detected sources

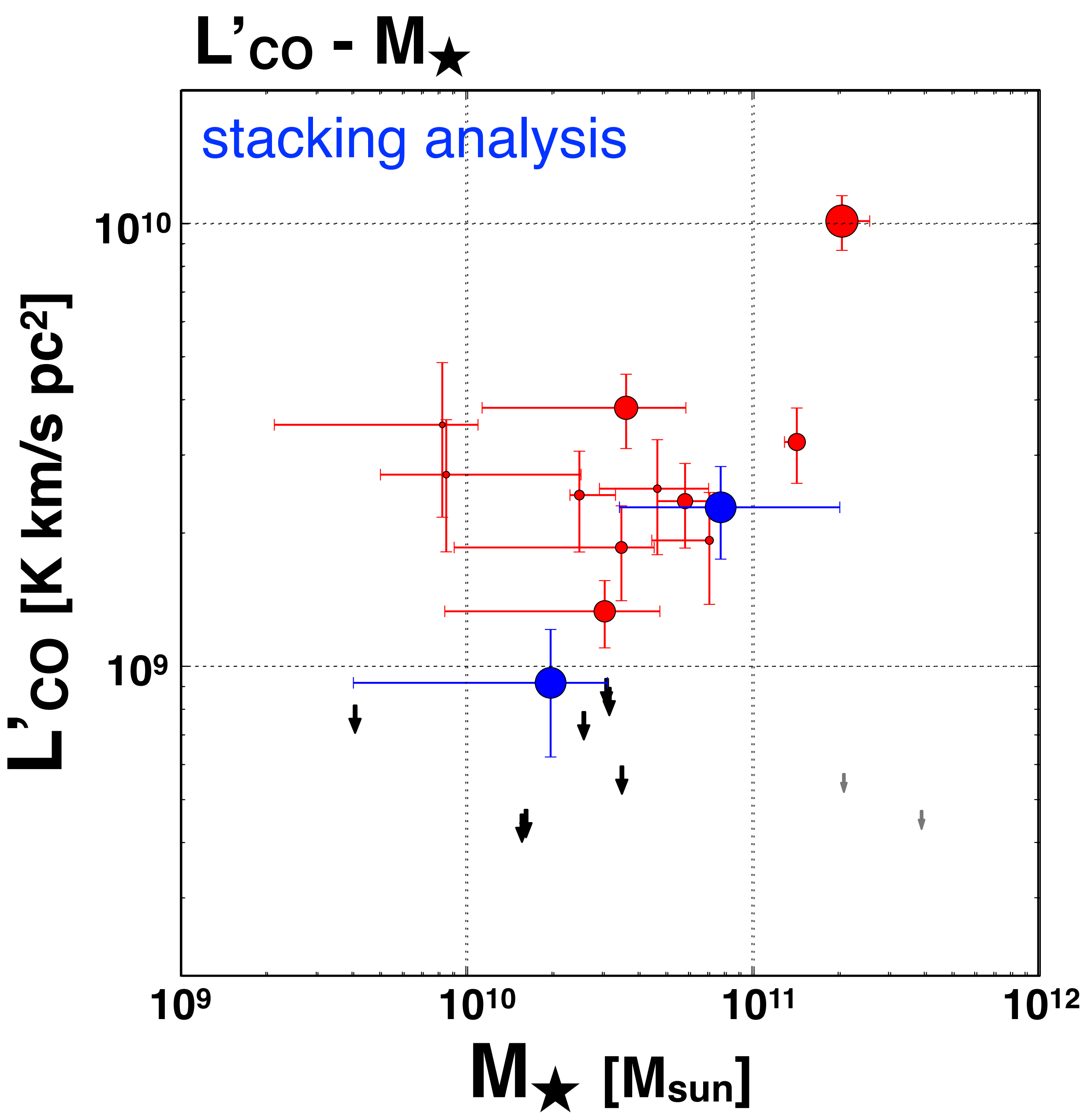


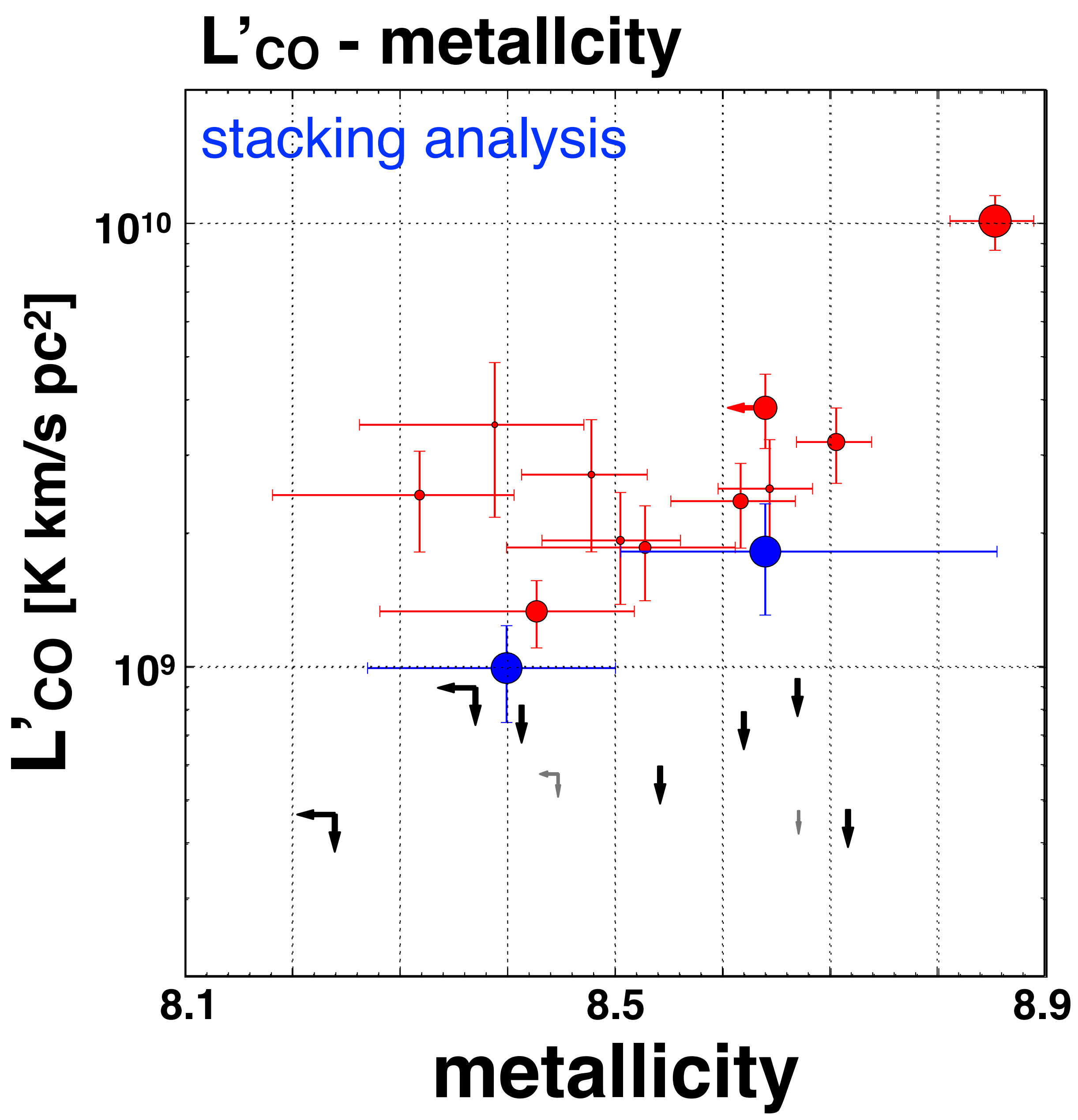


CO lines tend to be detected for galaxies with more massive/ higher SFR

No clear dependence on metallicity is seen

L'co(5-4) vs M★/metallicity



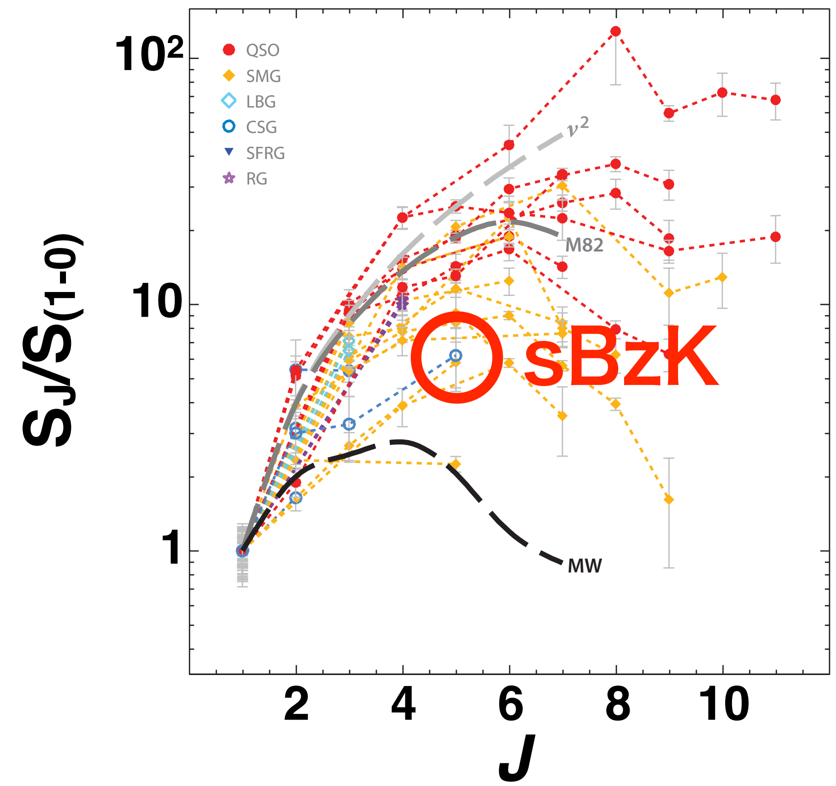


Molecular gas mass

CO(5-4)/CO(1-0) ratio

$$\frac{\int S_{\mathrm{CO}(5-4)}dv}{\int S_{\mathrm{CO}(1-0)}dv} \sim 6$$

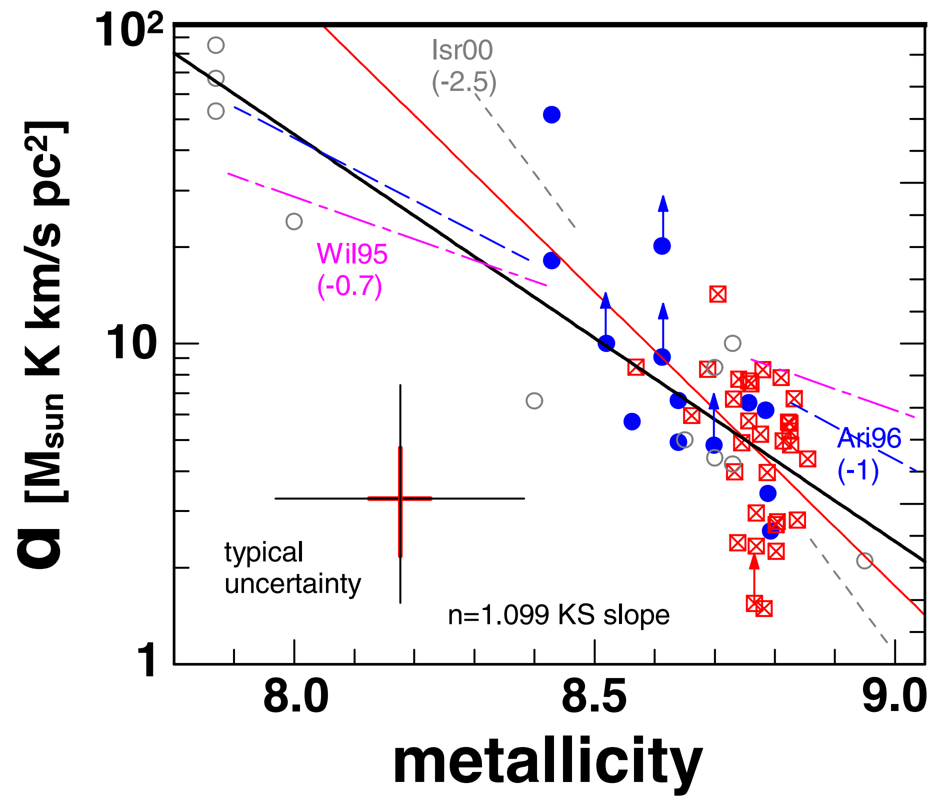
Carilli & Walter 2013, ARA&A, 51, 105
Daddi et al. 2014, arXiv:1409.8158



CO-to-H_2 conversion factor

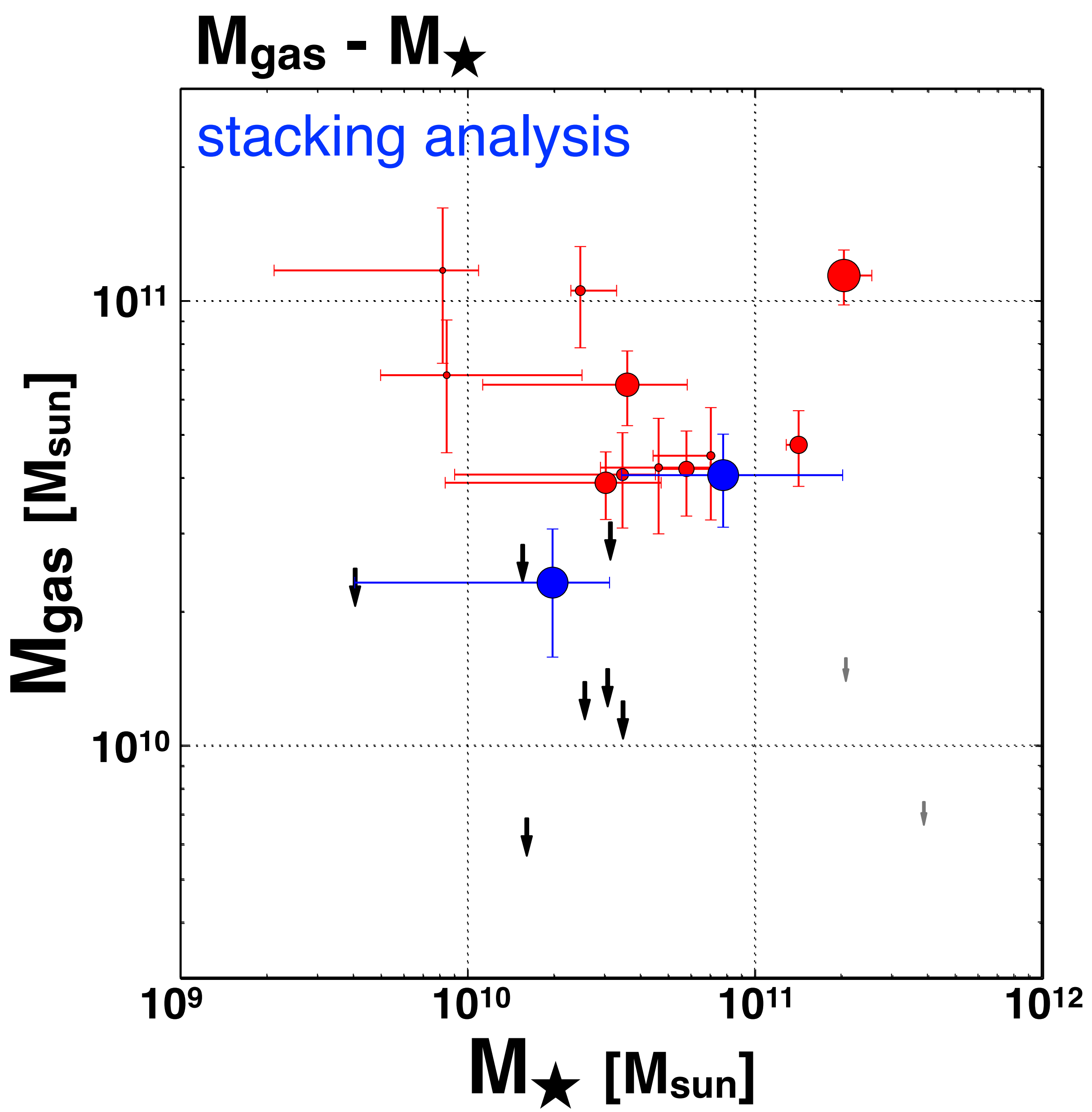
- metallicity dependence

$$M(\mathrm{H_2}) = \boxed{\alpha} \times L'_{\mathrm{CO}(1-0)}$$

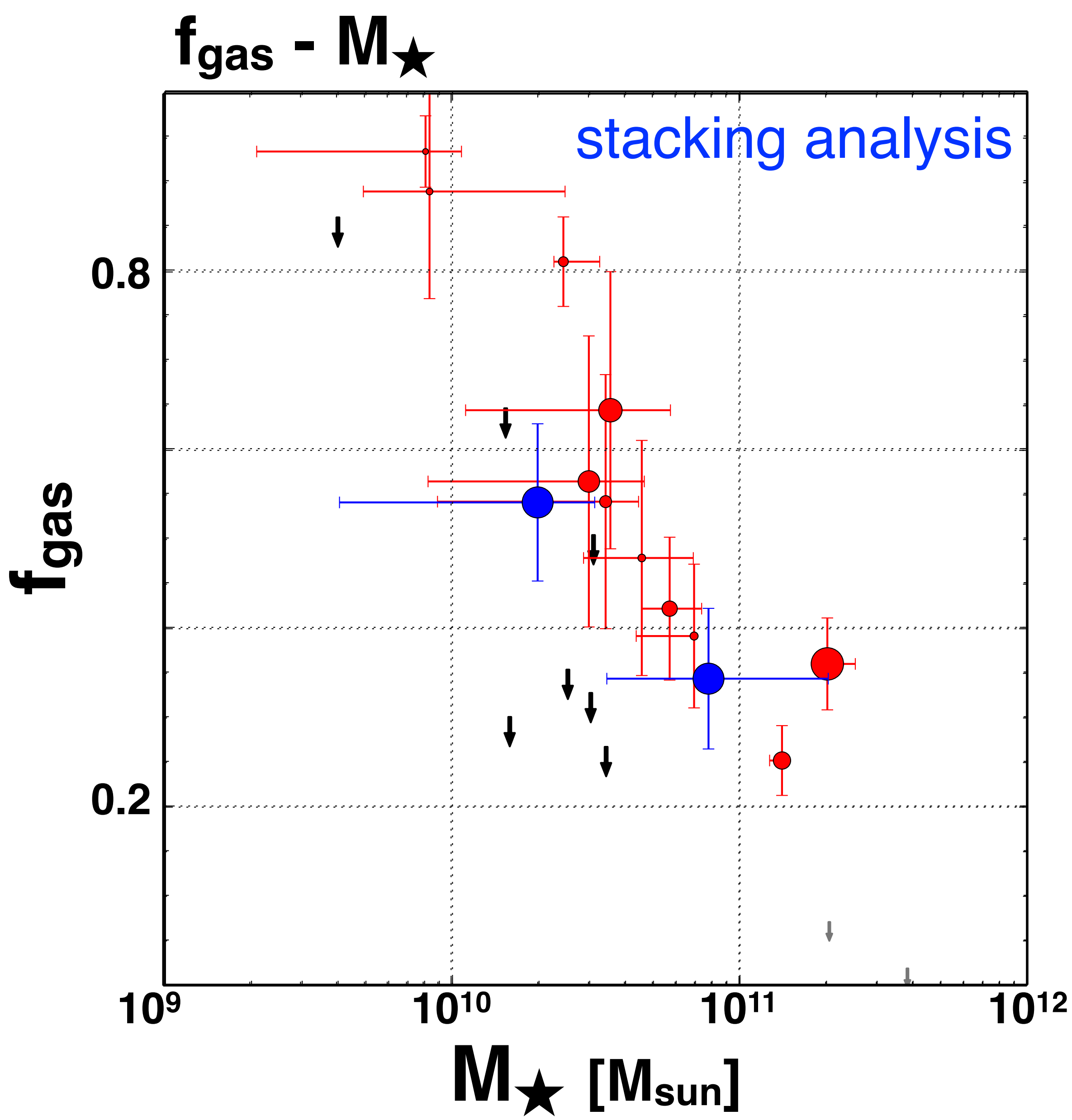


Genzel et al. 2012, ApJ, 746, 69

M_{gas}/f_{gas} vs $M_\star$

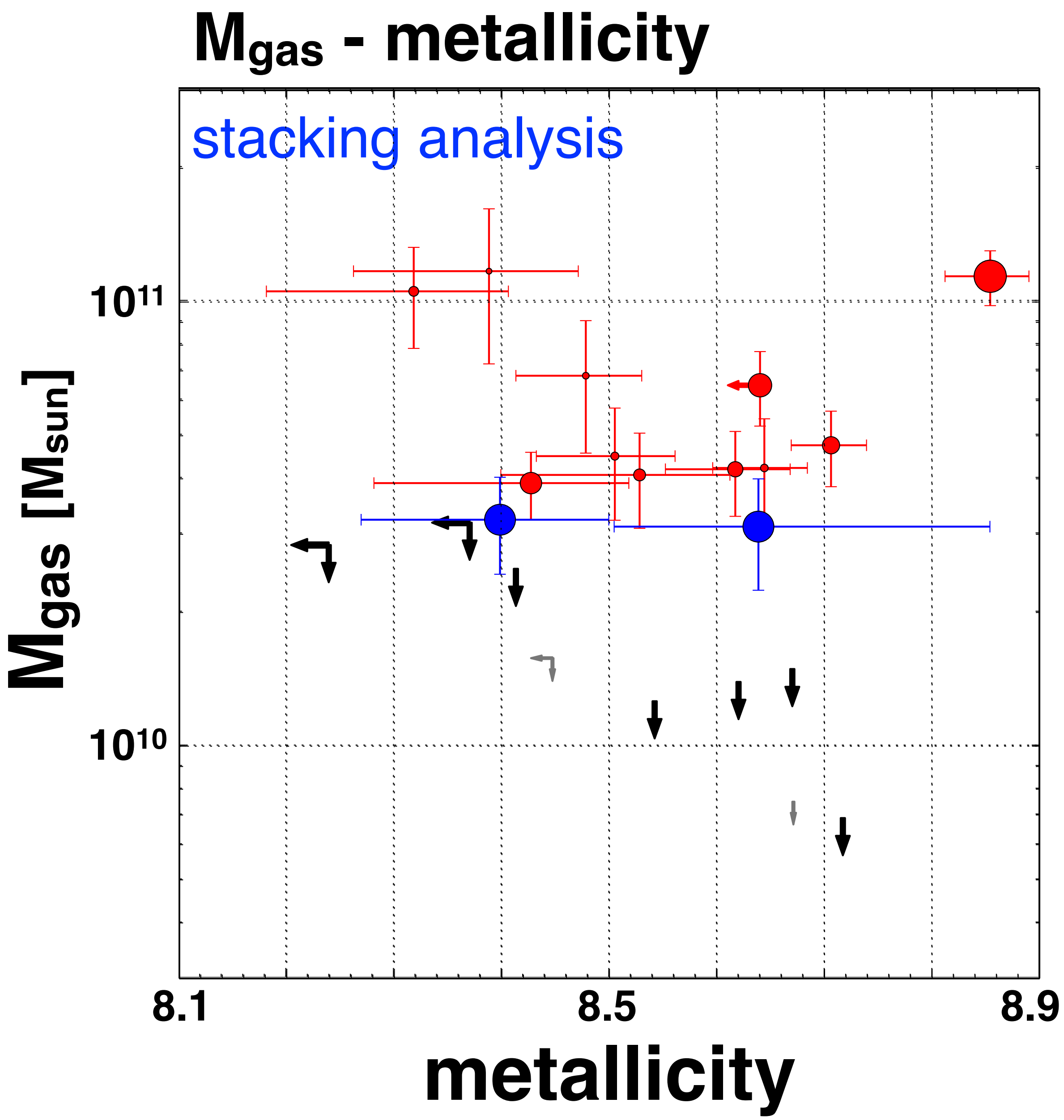


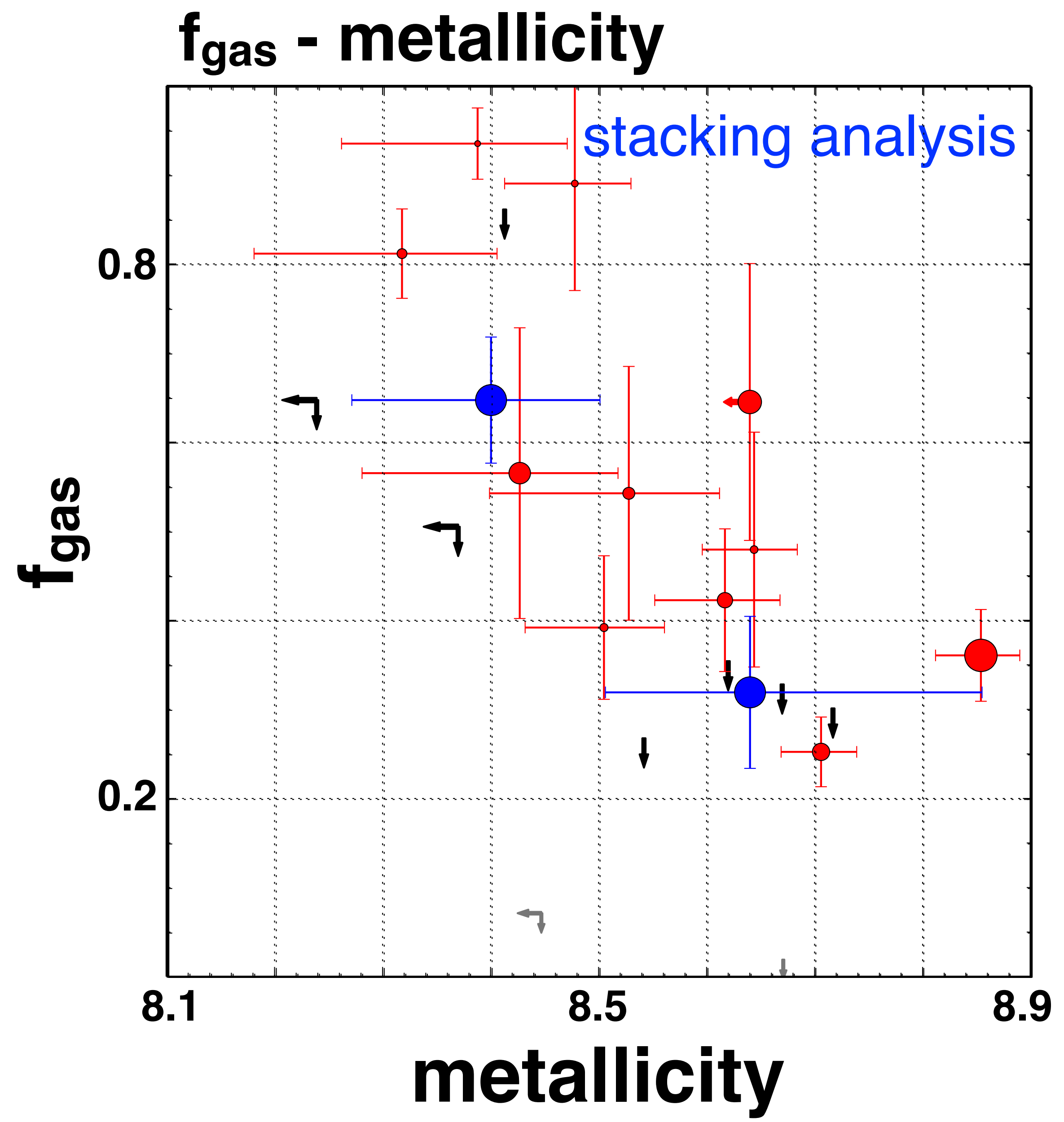
- M_{gas} is larger than the typical value in local spiral galaxies
- M_{gas} seems to depend on stellar mass



- f_{gas} is larger than the typical value in local spiral galaxies
- f_{gas} decreases with $M_\star$

M_{gas}/f_{gas} vs metallicity





M_{gas} does not seem to depend on metallicity

f_{gas} decreases with metallicity

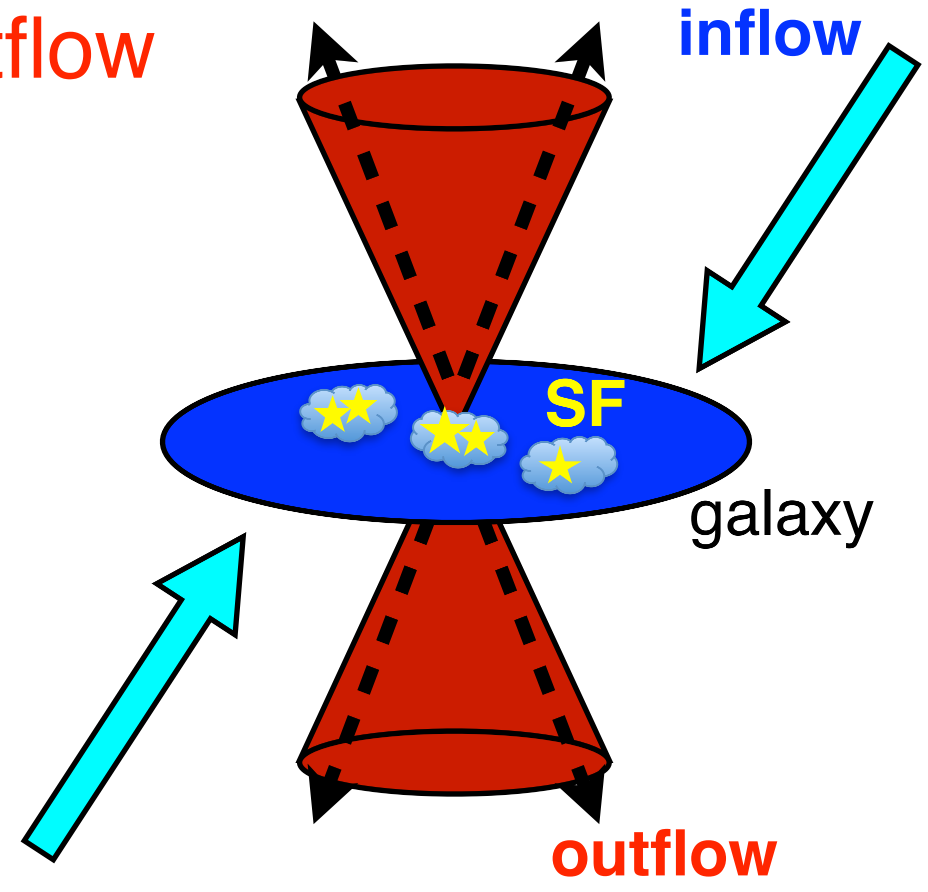
Chemical evolution model

$$\frac{dM_{\rm gas}}{dt} = -(1-R)\psi(t) + \underbrace{f_i(1-R)\psi(t)}_{\text{inflow}} - \underbrace{f_o(1-R)\psi(t)}_{\text{outflow}}$$

$$\frac{d(ZM_{\rm gas})}{dt} = -(1-R)\psi(t)Z(t) + y_Z(1-R)\psi(t) + \underbrace{f_i(1-R)\psi(t)Z_A(t)}_{\text{inflow}} - \underbrace{f_o(1-R)\psi(t)Z(t)}_{\text{outflow}}$$

- considering star-formation, inflow and outflow
  - assuming the inflow and outflow rate are proportional to star-formation rate
- analytic solutions can be expressed as a function of $f_{\rm gas}$

$$\boxed{Z} = \frac{y_Z}{f_i}\left(1 - \left[(f_i - f_o) - (f_i - f_o - 1)\frac{1}{\boxed{f_{\rm gas}}}\right]^{\frac{f_i}{f_i - f_o - 1}}\right)$$



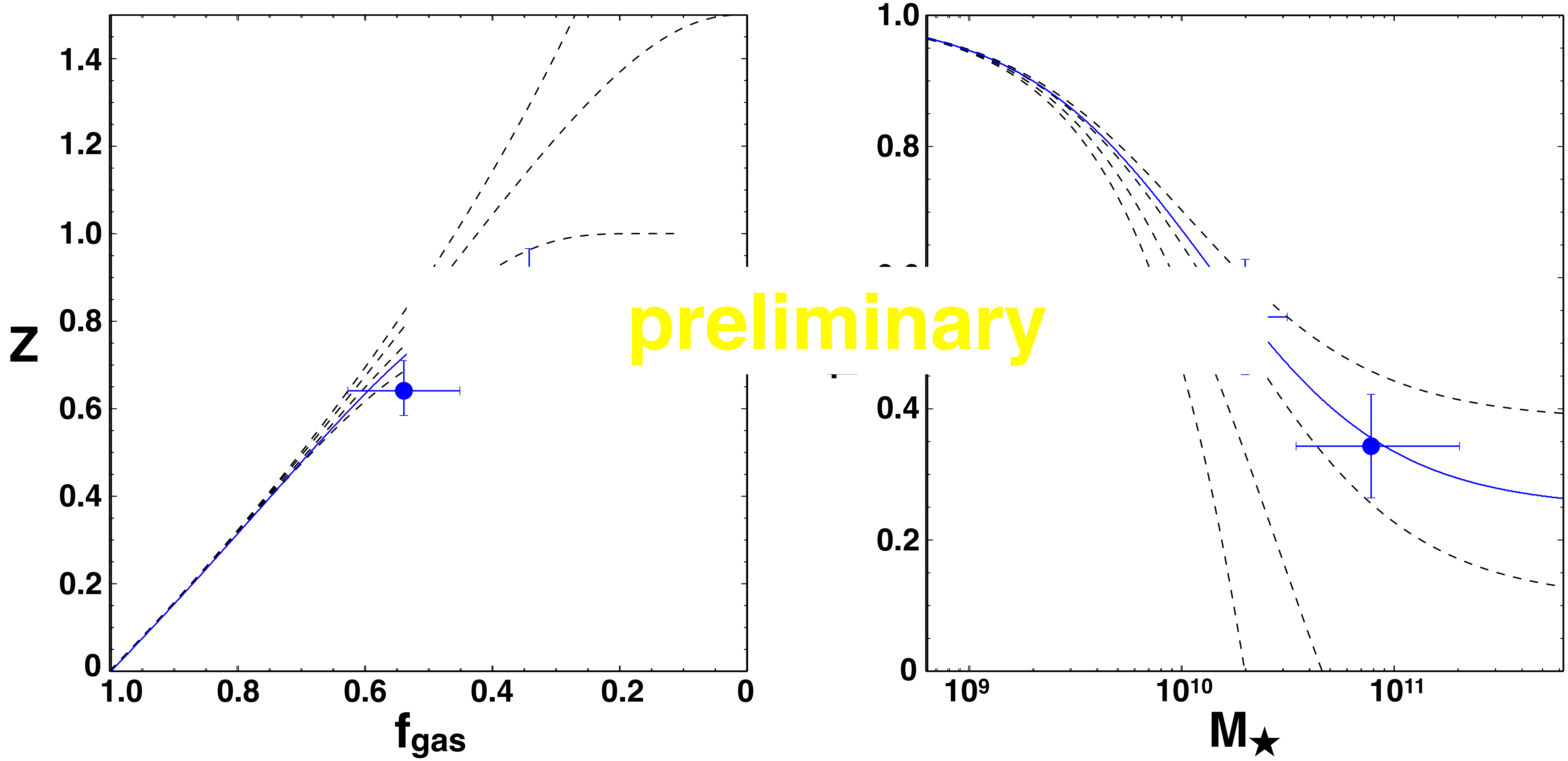
Chemical evolution model

best fit values

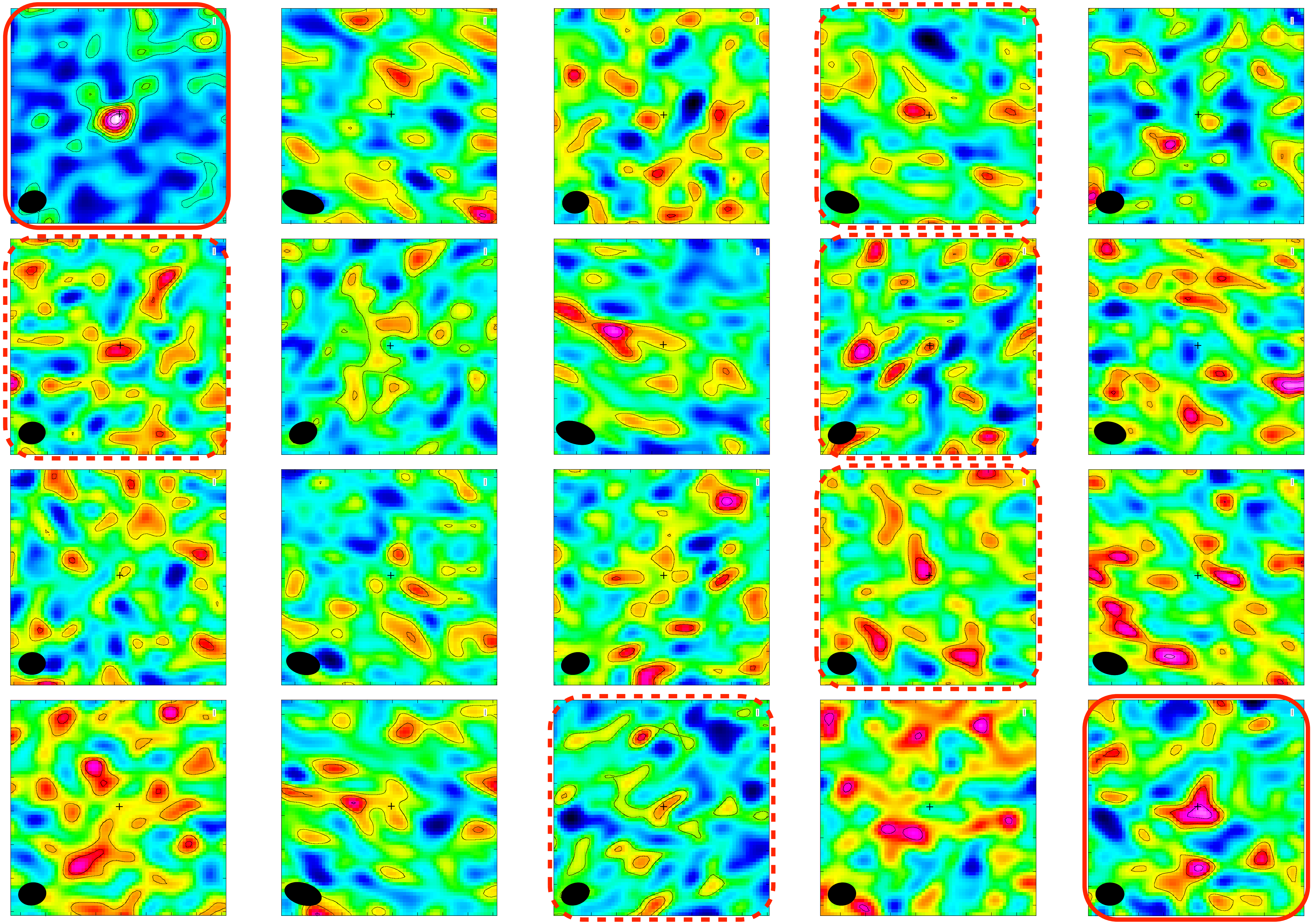
inflow rate : **1.7** × SFR

outflow rate : **0.4** × SFR

inflow rate (1.7)
~ outflow rate + SFR (0.4+1)

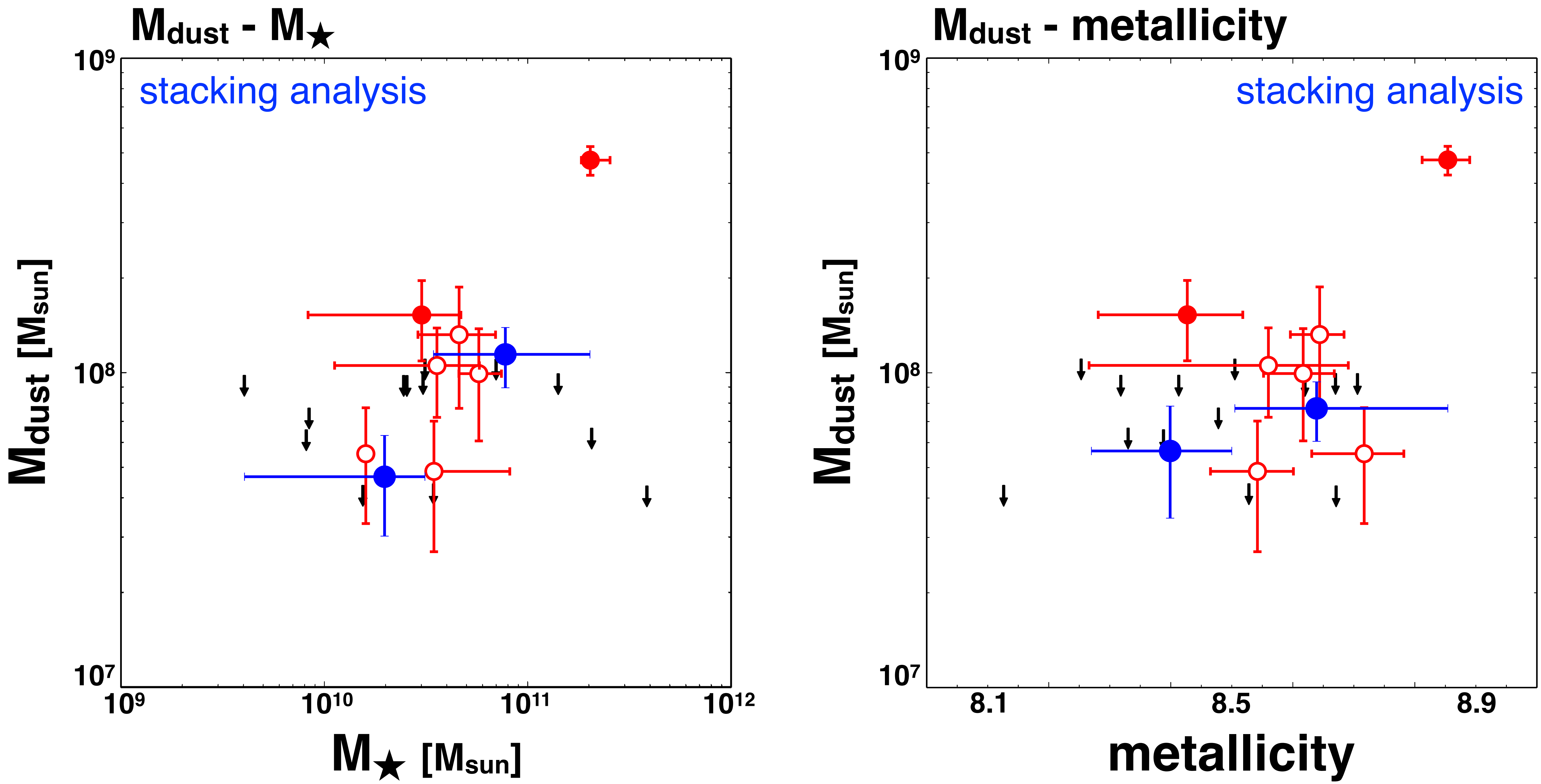


Continuum map

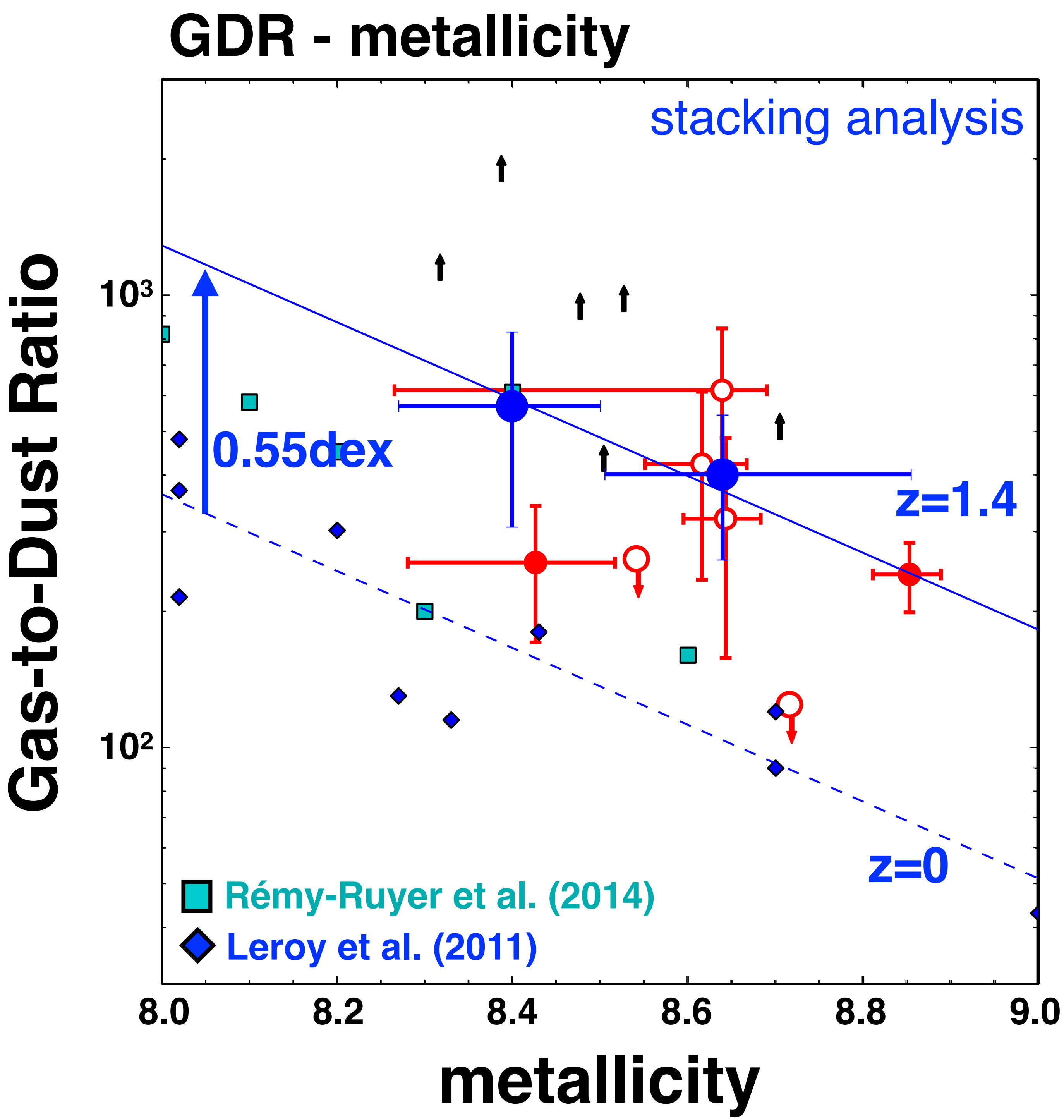


Dust mass

$$M_{\rm dust} = \frac{L_{\nu({\rm rest})}}{4\pi\kappa_\nu B_{\nu({\rm rest})}} = \frac{c^2 L_{\nu({\rm rest})}(e^{\frac{h\nu({\rm rest})}{k_B T_{\rm dust}}} - 1)}{8\pi\kappa_0 h\nu^3_{({\rm rest})}}(\frac{\nu_{({\rm rest})}}{\nu_{125\mu{\rm m}}})^\beta \quad \beta = 1.5 \quad T_{\rm dust} = 30\ {\rm K}$$



Gas-to-Dust Ratio



- GDR seems to decrease with metallicity
  (The same trend as local galaxies)

- GDR is ~3-4 times larger than the local values

Summary

- We conducted CO(5-4) observations of 20 star-forming galaxies with known metallicity at z~1.4 with ALMA
- We found correlation between f_{gas} and $M_\star$/metallicity
  - however, it is difficult to say whether these correlations are mainly caused by $M_\star$ or metallicity
- By comparing the analytic chemical evolution model, we try to constrain inflow/outflow rate
  - inflow rate = 1.7×SFR, outflow rate = 0.4×SFR
  - close to equilibrium model?
- Gas-to-Dust Ratio seems to depend on metallicity at high redshift
  - 3-4 times larger than those in local galaxies.
  - be careful to derive M_{gas} from dust continuum emission