What metallicity can tell us about galaxy formation

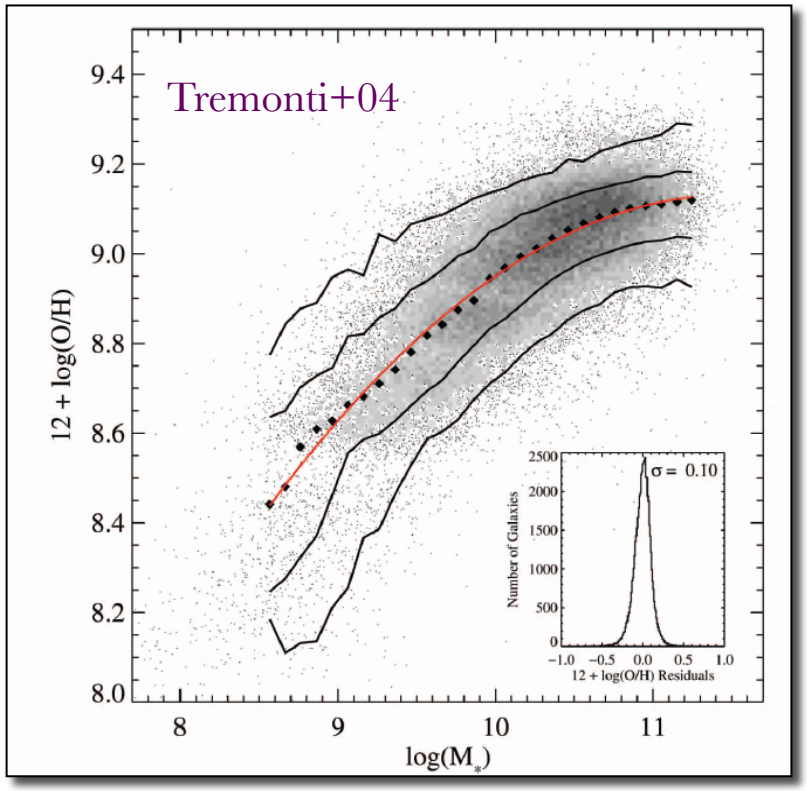
F. Mannucci – Arcetri

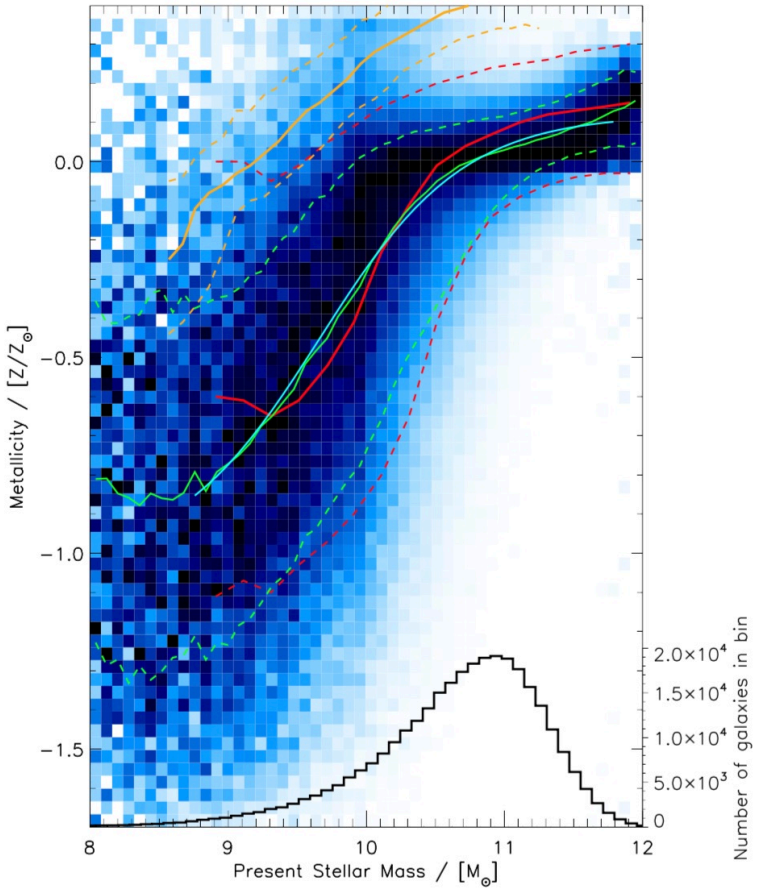
G. Cresci, A. Marconi, R. Maiolino, T. Nagao, A. Gallazzi, S. Zibetti, Y. Peng, M. Bothwell, P. Troncoso, V. Sommariva, S. Carniani, M. Curti

IGM@50, Spineto, Jun 2015

Scaling relations

Mass-metallicity





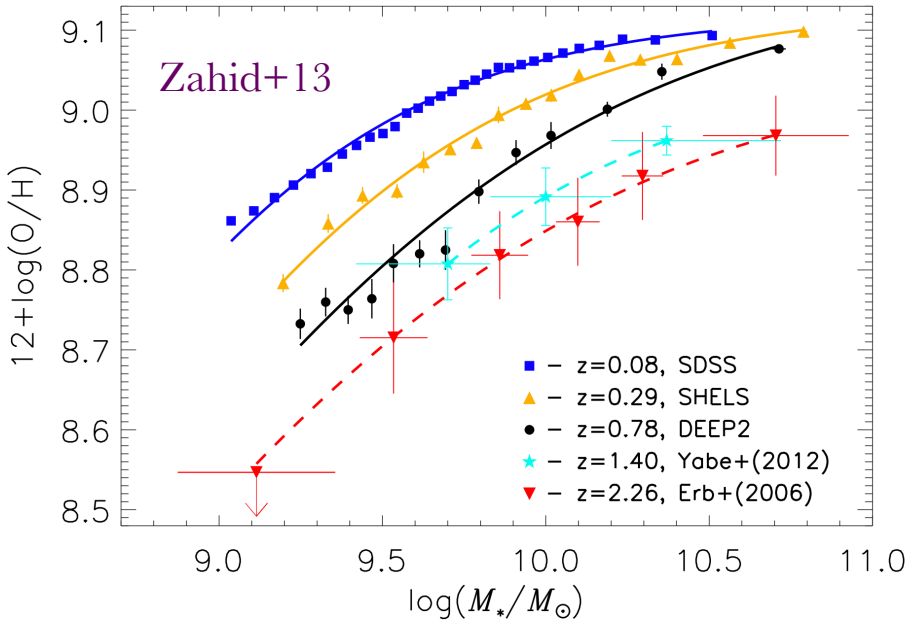
Panter+08

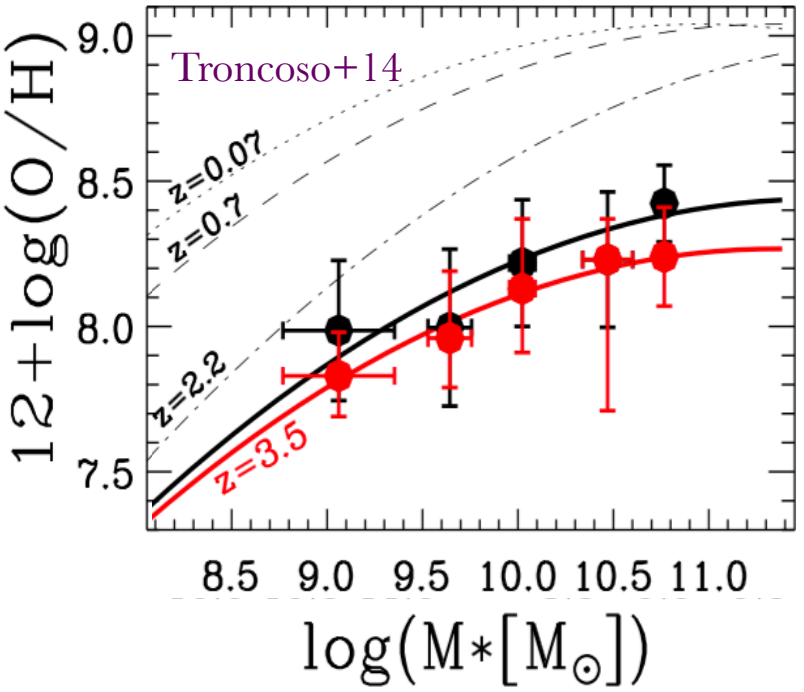
gas-phase

stellar

Mass metallicity

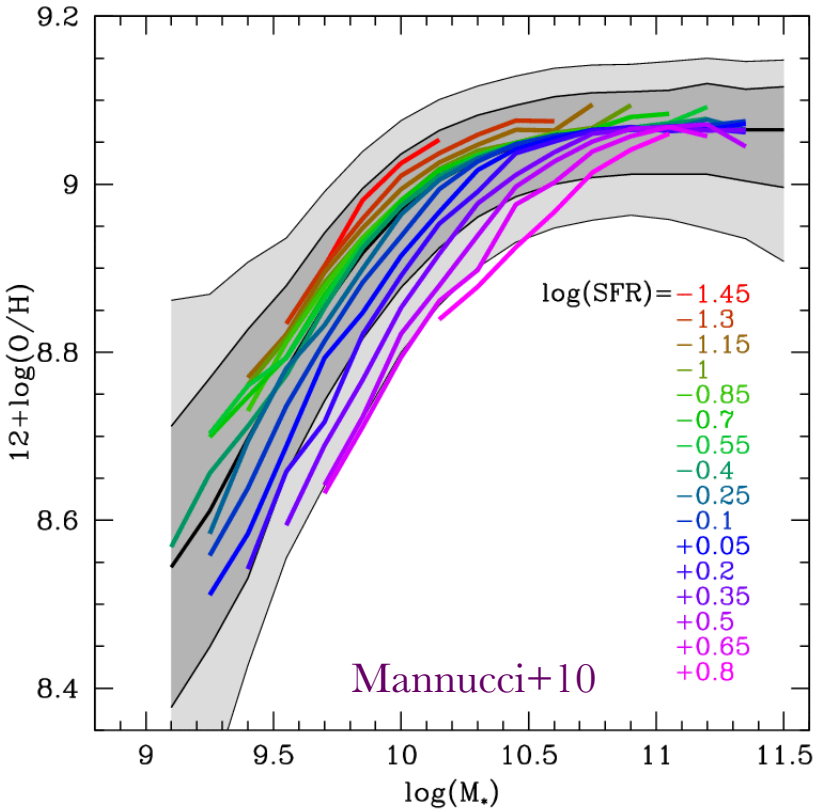
- redshift evolution

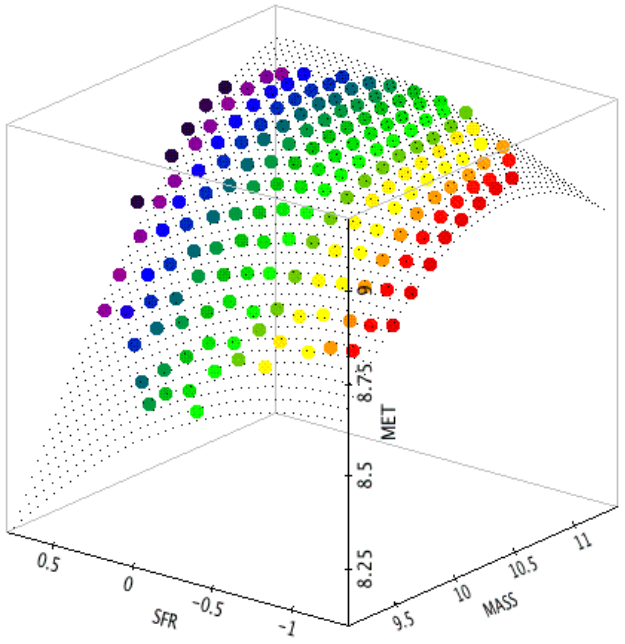


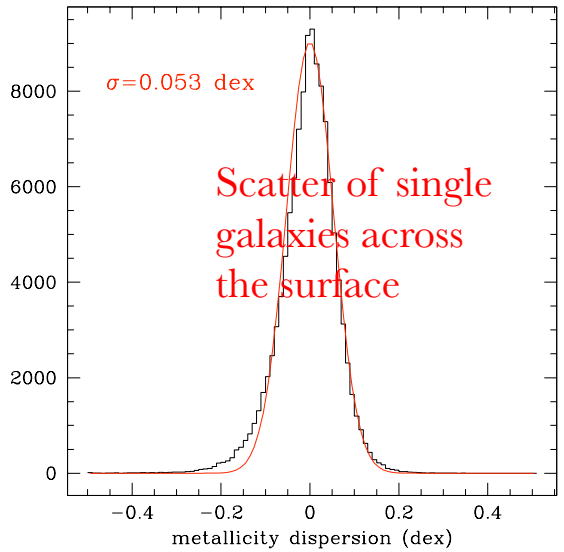


Shapley+04, Maier+04,05,06, Savaglio+05, Erb+06, Hayashi+08, Rodrigues+08, Lamareille+08, Cowie & Barger 08, Perez-Montero+09,13, Kewley+08, Maiolino+08, Mannucci+09, Richard+10, Zahid+11,12,14, Cresci+11, Troncoso+14

The Fundamental Metallicity Relation (FMR)



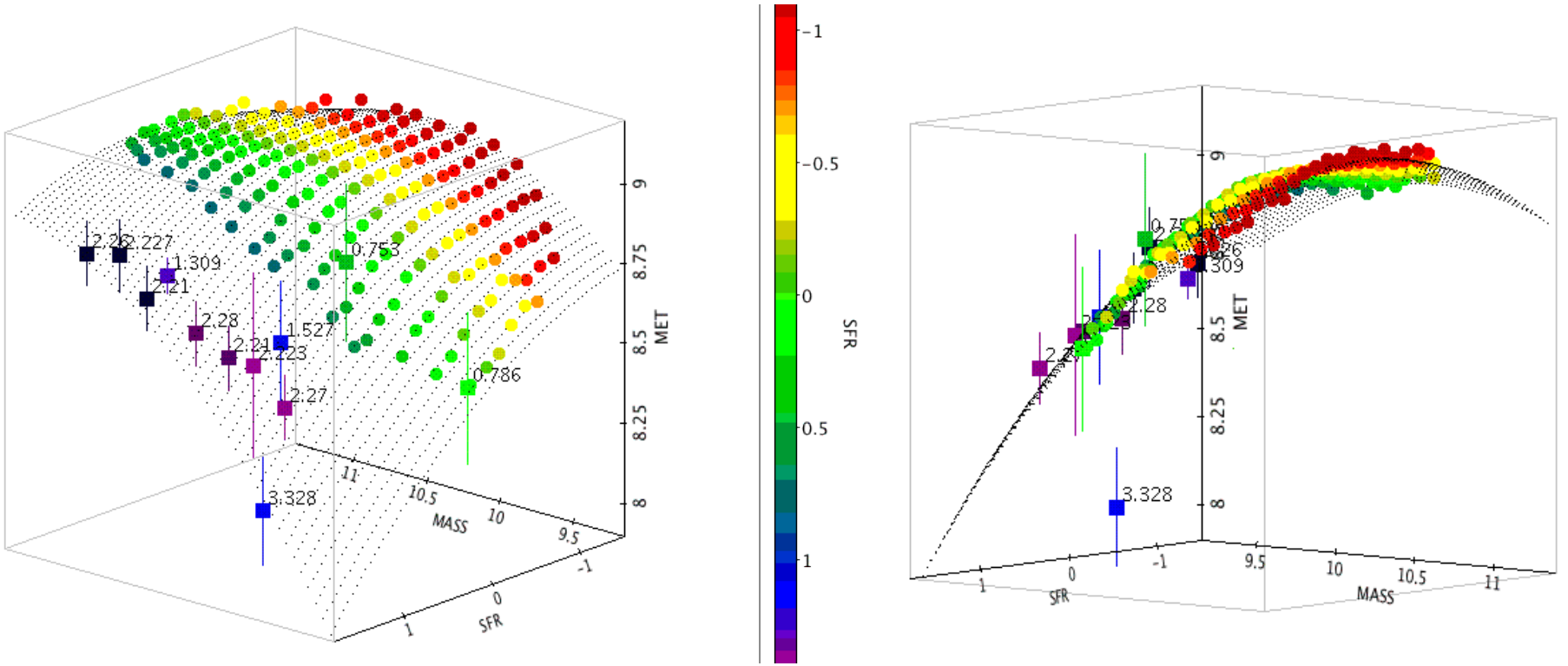




Metallicity depends on both mass and SFR

Extension towards lower masses: Mannucci+11

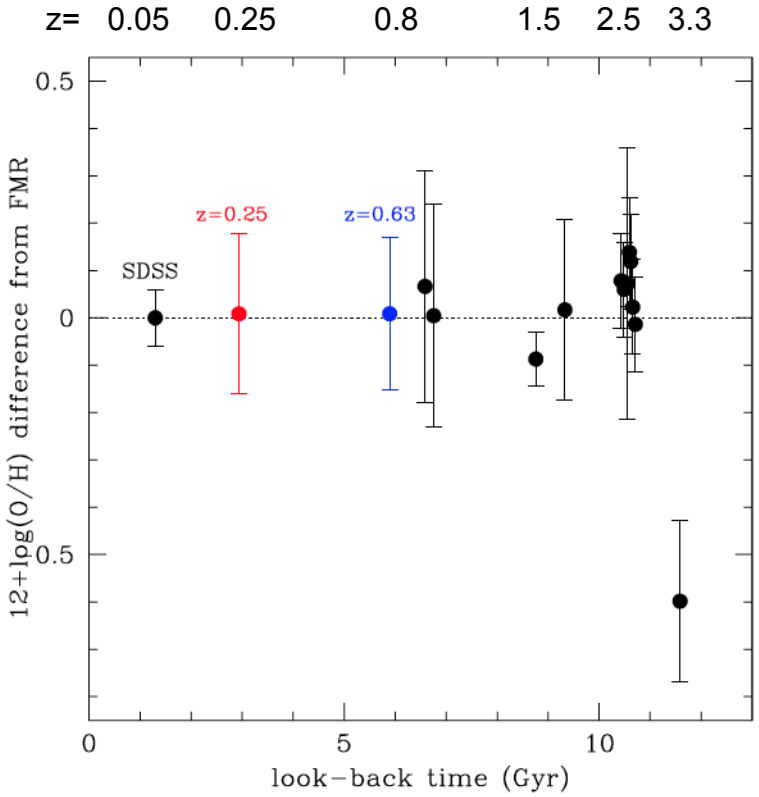
Redshift evolution of FMR



$$\mu = \log(M) - 0.32 \log(SFR)$$

- No evolution up to z=2.5, evolution of ~0.6 dex at z=3.3
- galaxies at z<2.3 are no less metal abundant than local galaxies
- evolution of the mass-met.: only apparent, due to higher SFR at higher redshifts

Redshift evolution of FMR



Mannucci+10,
Cresci+12

prediction of the metallicity of high-redshift galaxies of a given mass and SFR based only on local galaxies

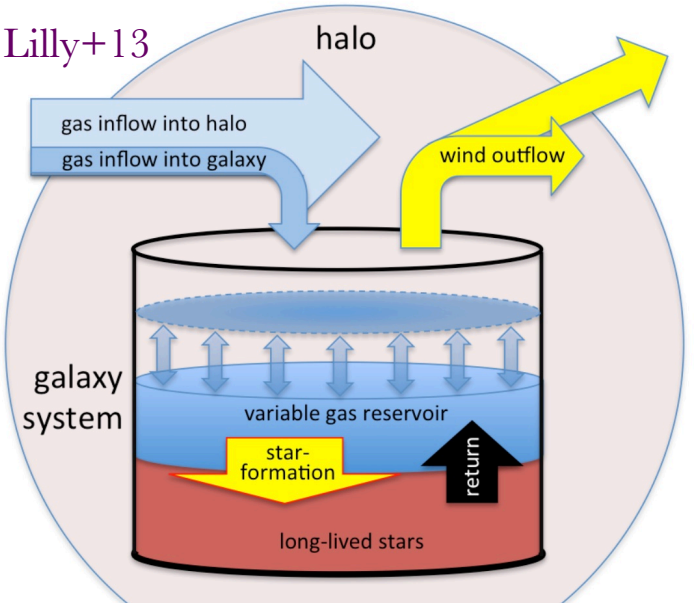
Equilibrium models

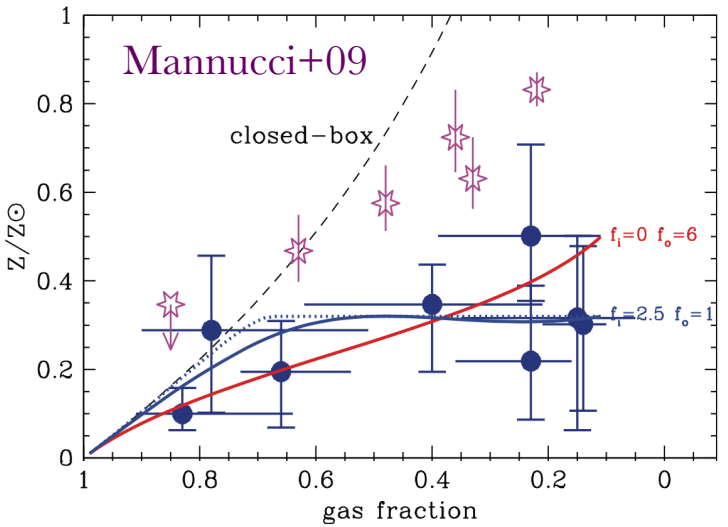
1. numerical simulations
2. analytic formulations

Reproducing trends and scatter

Many parameters:

- SFR efficiency vs. mass
- gas fraction vs. mass
- in-falling gas
- gas exchange galaxy-halo
- preventive and depleting feedbacks
- properties of the galactic wind





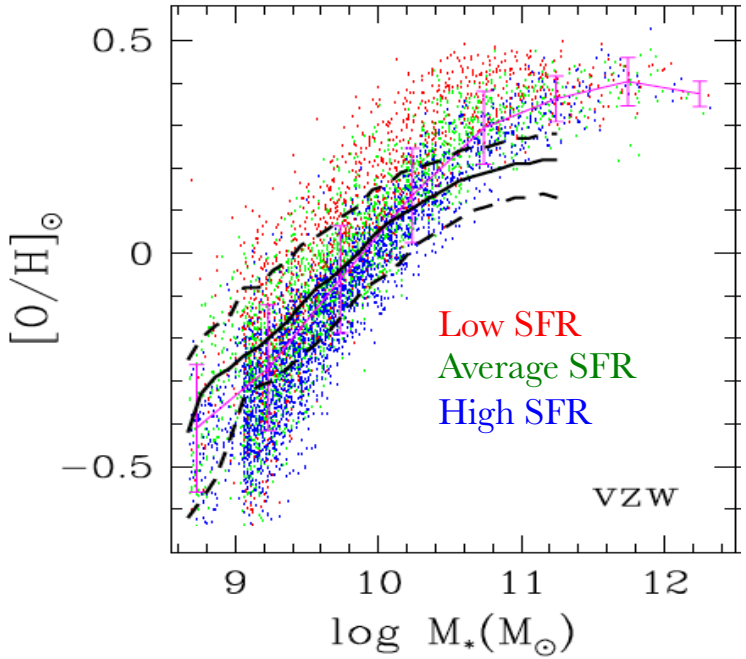
Davé+11, Campisi+11, Krumholz+11, Fu+13, Dayal+13, Romeo-Velona+13,, Lilly+13, Forbes+14, Peng+14,15, Pipino+14, Muñoz & Peeples 14, Lu+14, Creasy+15, Mitra+15, Lu+15

Equilibrium models

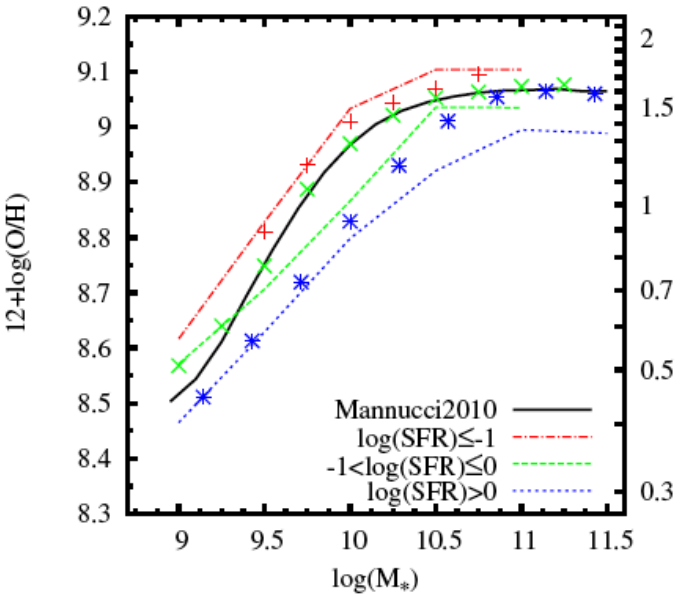
1. numerical simulation

Davé+11:

- balance between inflows, outflows, star formation, recycling and feedback
- mass-metallicity due to outflow rate
- scatter set by the timescale to re-equilibrate stochastic variations in the inflow rate
- metallicity depends on SFR
- slow evolution of the FMR with redshift
- momentum-driven wind



Campisi+11, using De Lucia & Blaizot 07, Wang+08, Croton+06

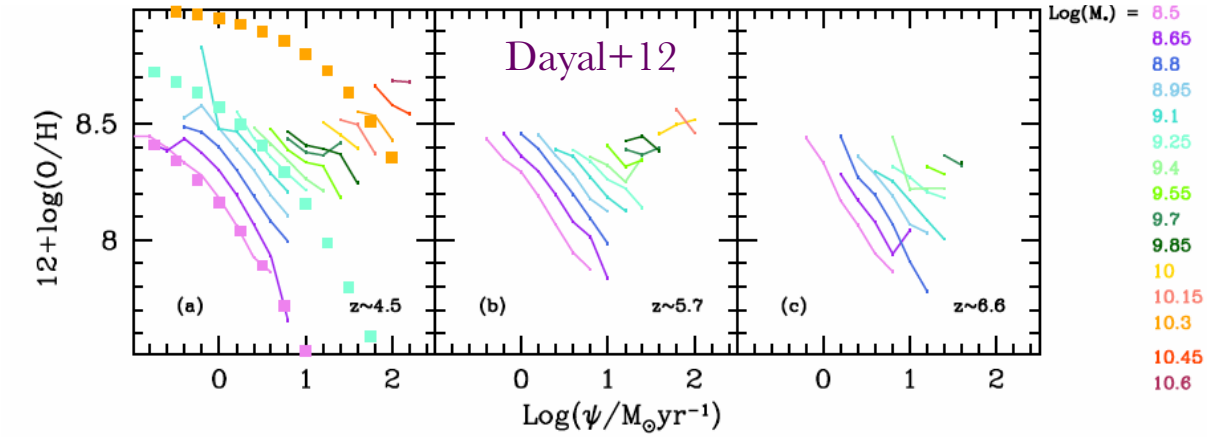


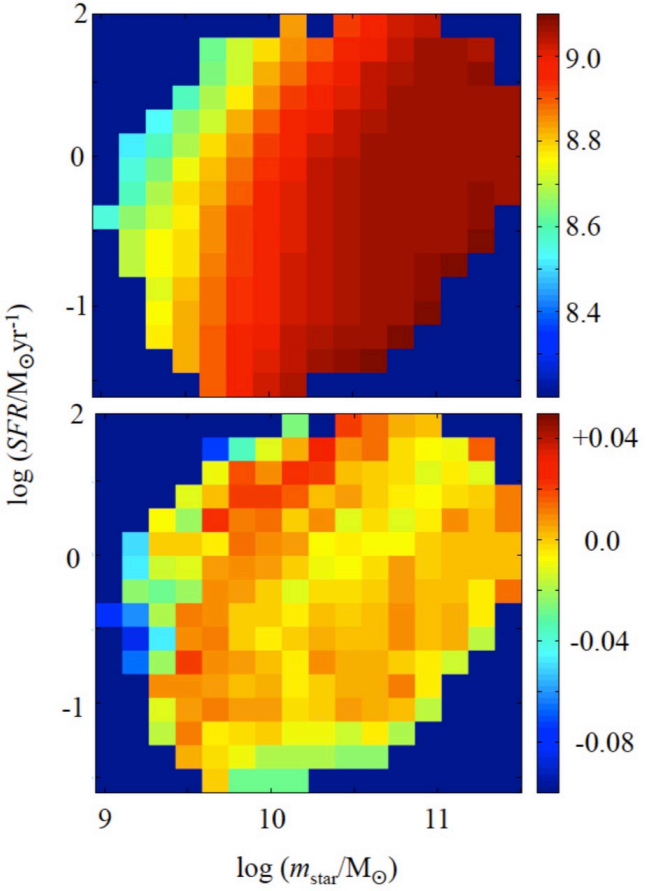
Equilibrium models

2. analytic formulation

Lilly+13, Pipino+14

- timescales: gas consumption < evolution
- metallicity driven by the instantaneous equilibrium
- equilibrium naturally produces the FMR with no redshift evolution

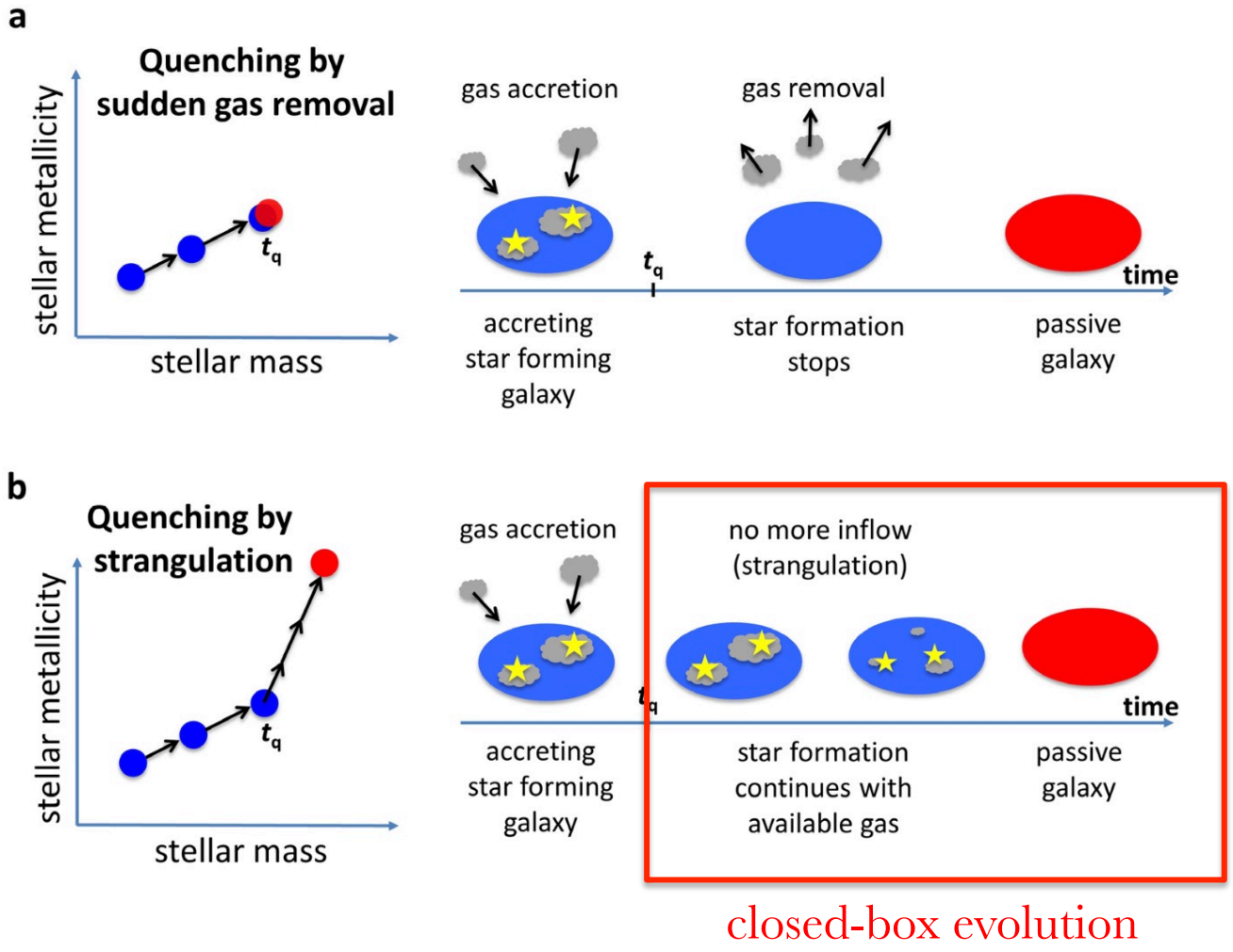




1. A dependence of metallicity on SFR is expected/reproduced by all models
2. Many models produce an un-evolving relation

Strangulation model

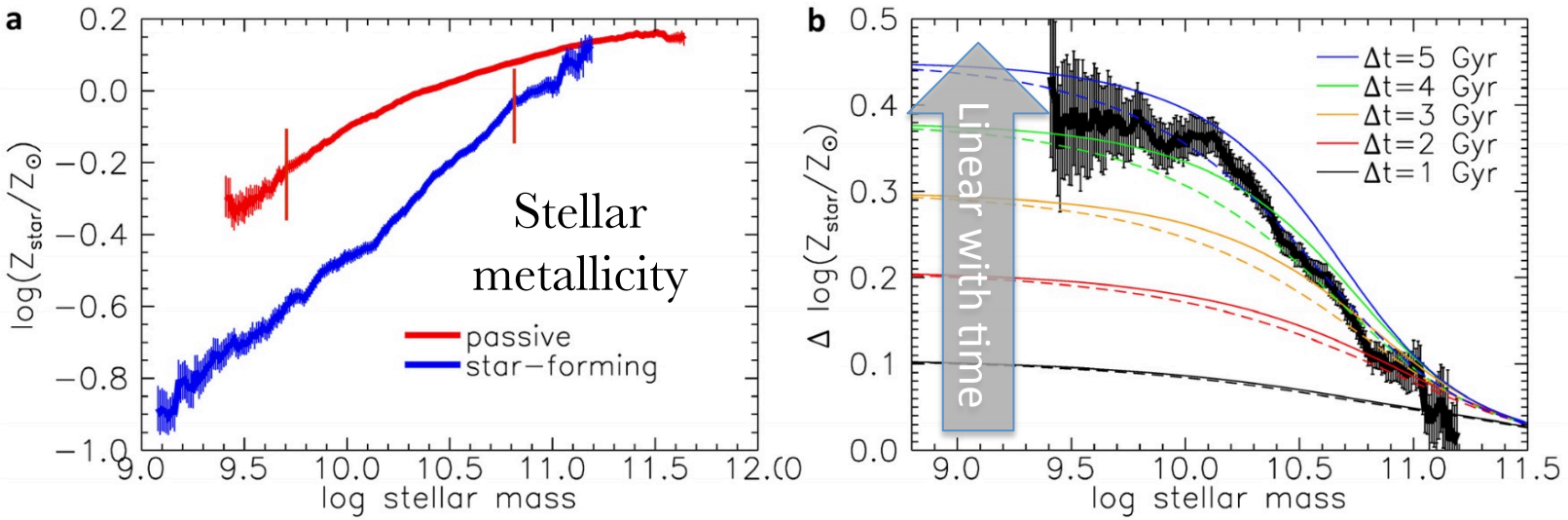
Peng+15



closed-box evolution

Strangulation model

Peng+15



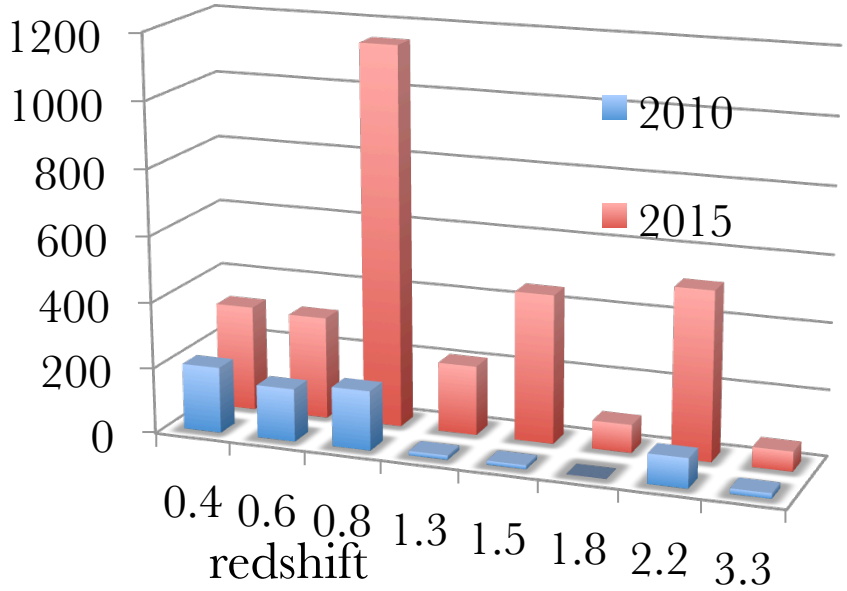
no outflows after strangulation

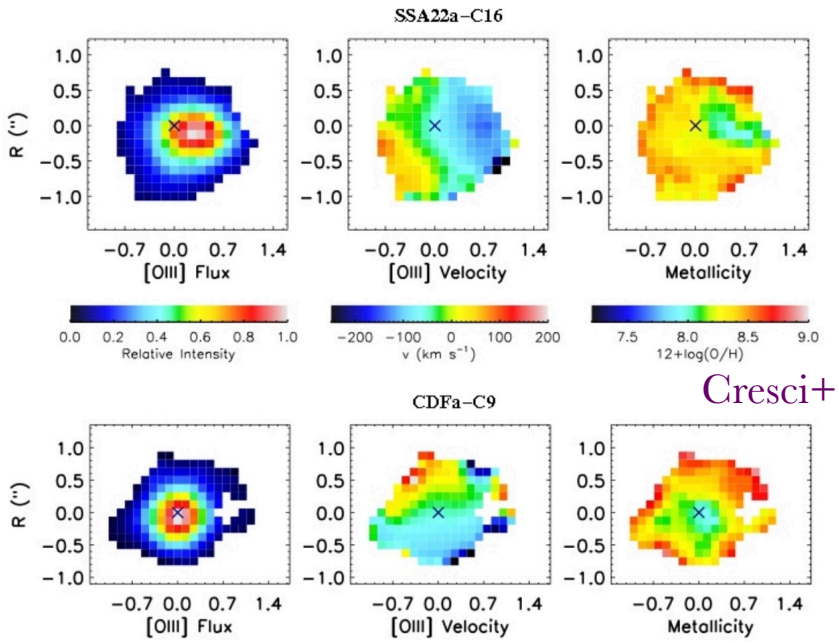
Gas-phase metallicity:
after strangulation SFR keeps reducing while metallicity keeps increasing:
origin of the FMR in the gas-phase metallicity?

Testing the models

- low and high redshifts
- excellent databases:
  - SDSS
  - LBT/LUCI
  - Keck/MOSFIRE
  - Subaru/FMOS
  - VLT/KMOS
  - VLT/SINFONI
  - VLT/MOONS (2019)

strong and weak points of
current datasets
on metallicity scaling relations



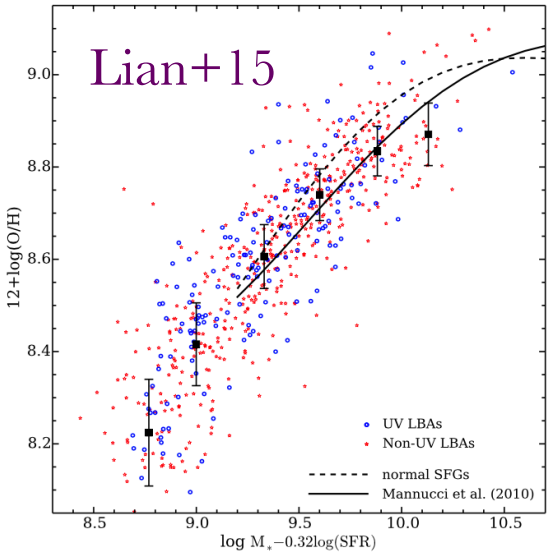


Cresci+10

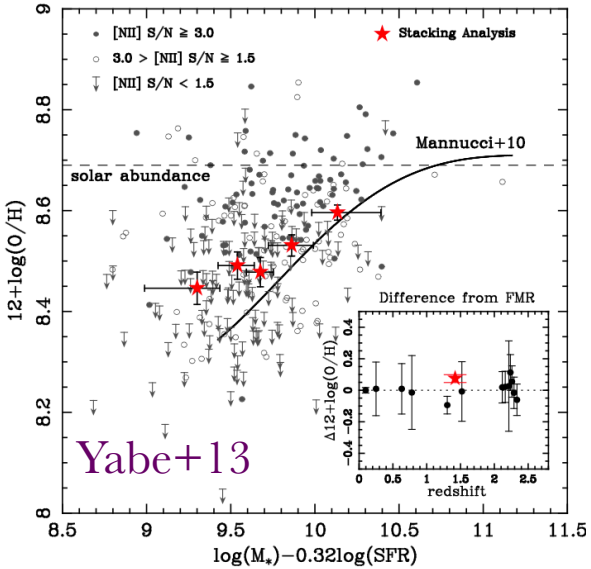
Observational status of FMR

- Numerous confirmations (predictions!) at all redshifts

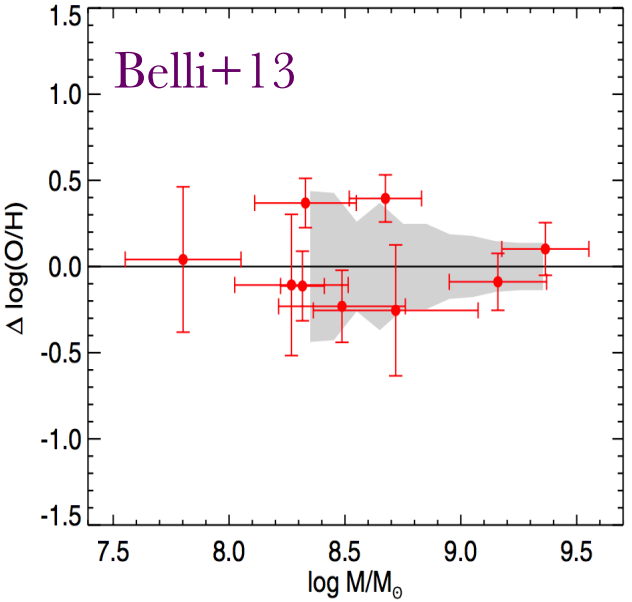
LBG-analogs,
z~0.1, high SFRs



K-selected, z~1.4



grav. lensed galaxies,
1.5<z<3, low-mass



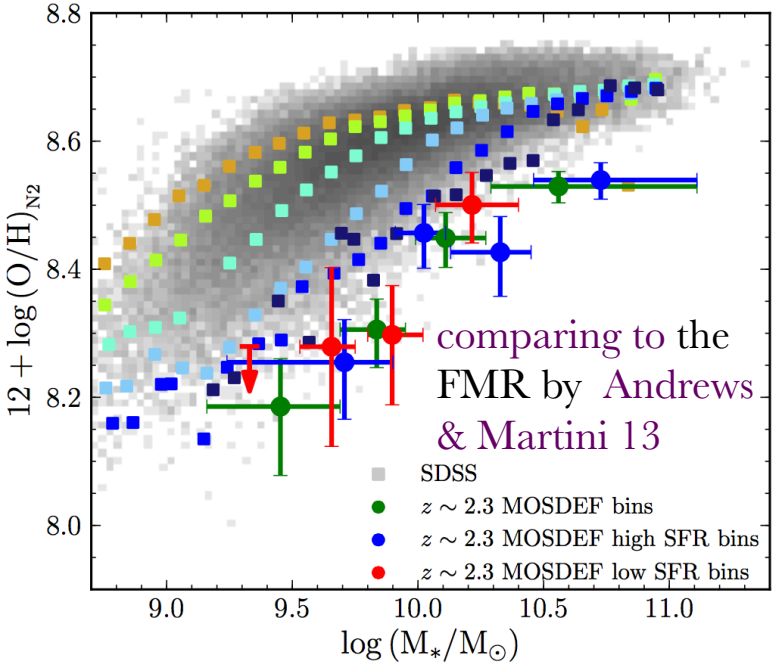
- wide range of selections, properties, and redshifts
- cautions when selecting in metallicity (OIII4363, OIII5007)

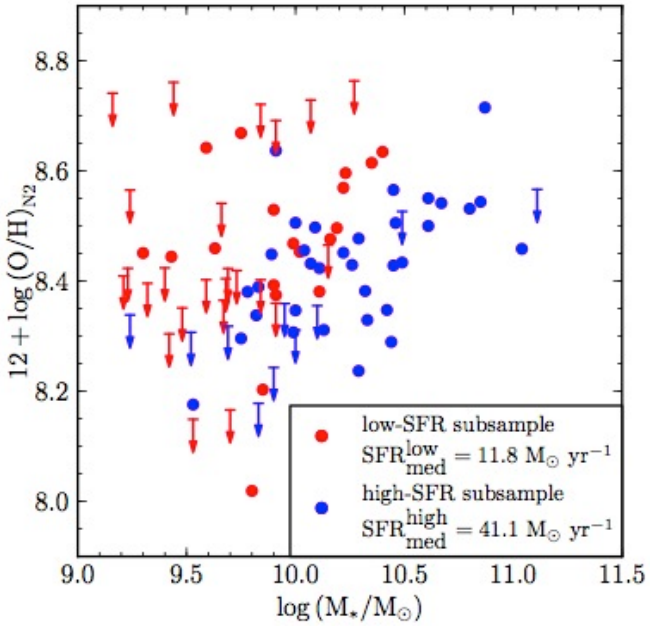
Richard+10, Nakajina+11, Erb+10, Contini+11, Sanders+11, Dessauges+11, Cresci+12, Wuyts+12, Roseboom+12, Cullen+13, Pilyugin+13, Ly+13, Belli+13, Henry+13a,13b, Yabe+13, Maier+14, Stott+14, Lian+15

Redshift evolution of the FMR

Sanders et al. 2014: 87 z~2 galaxies with MOSFIRE:

"When the sample is divided at the median star-formation rate (SFR), we do not observe significant SFR dependence of the z ~ 2.3 MZR…. . This suggests that high-redshift galaxies do not fall on the local FMR





Different systems:

- metallicity
- mass (IMF)
- SFR (aperture)

Redshift evolution of the FMR

Sanders+14

Table 1
Galaxy properties and emission-line luminosites from $z \sim 2.3$ composite spectra

$\log(\frac{M_*}{M_\odot})^a$	$\langle\log(\frac{M_*}{M_\odot})\rangle^b$	$N_{gal}{}^c$	$SFR_{med}{}^d$ ($M_\odot$ yr^{-1})	$L_{[N\ II]}{}^e$ (10^{42} erg s^{-1})	$L_{H\alpha}{}^e$ (10^{42} erg s^{-1})	$L_{[O\ III]}{}^e$ (10^{42} erg s^{-1})	$L_{H\beta}{}^e$ (10^{42} erg s^{-1})
Full sample							
9.15-9.68	9.45	22	11.6	0.11 ± 0.04	2.03 ± 0.05	2.78 ± 0.14	0.60 ± 0.03
9.68-9.94	9.84	22	23.4	0.27 ± 0.05	3.03 ± 0.08	3.21 ± 0.14	0.82 ± 0.05
9.99-10.27	10.11	22	26.8	0.49 ± 0.08	3.05 ± 0.10	2.44 ± 0.20	0.76 ± 0.06
10.29-11.11	10.56	21	53.8	1.07 ± 0.10	4.82 ± 0.12	2.01 ± 0.21	$.98 \pm 0.08$

tions and metallicity calibration. The fourth-
the median mass–metallicity relation is

$$12 + \log(\mathrm{O/H}) = 8.96 + 0.31m - 0.23m^2 - 0.017m^3 + 0.046m^4,$$

where $m = \log(M_\star) - 10$ in solar units.
We have computed the median metallicity of SI

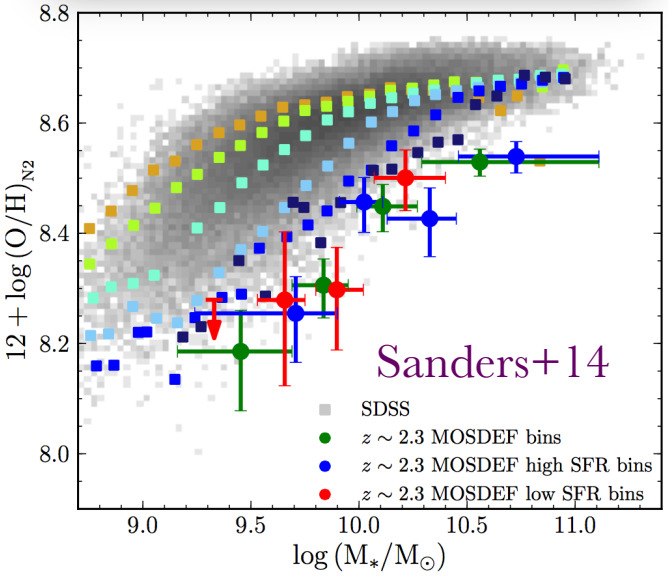
Mannucci+10

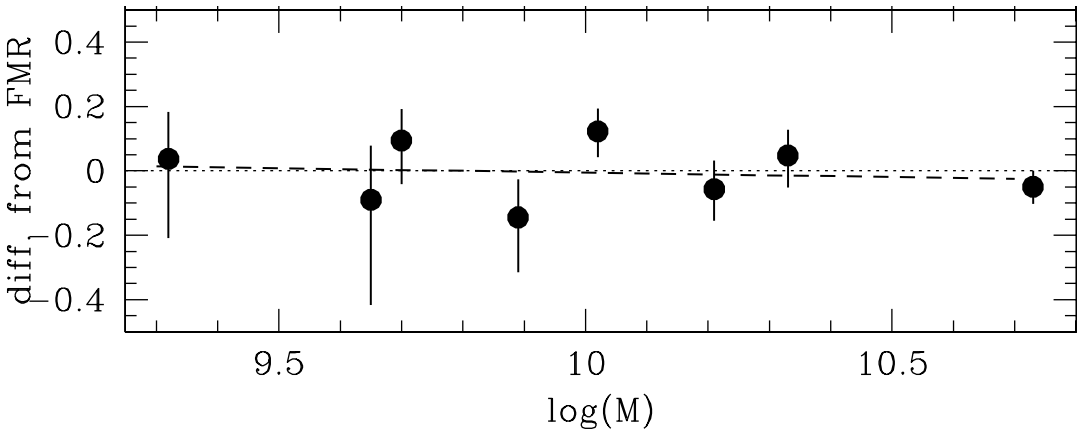
metallicity interval. ... el, in some cases a fourth order polynomial is required. Th... neral functional form for describing the strong-line metallicity calibration is therefore:

Maiolino+08

$$\log R = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4 \quad (1)$$

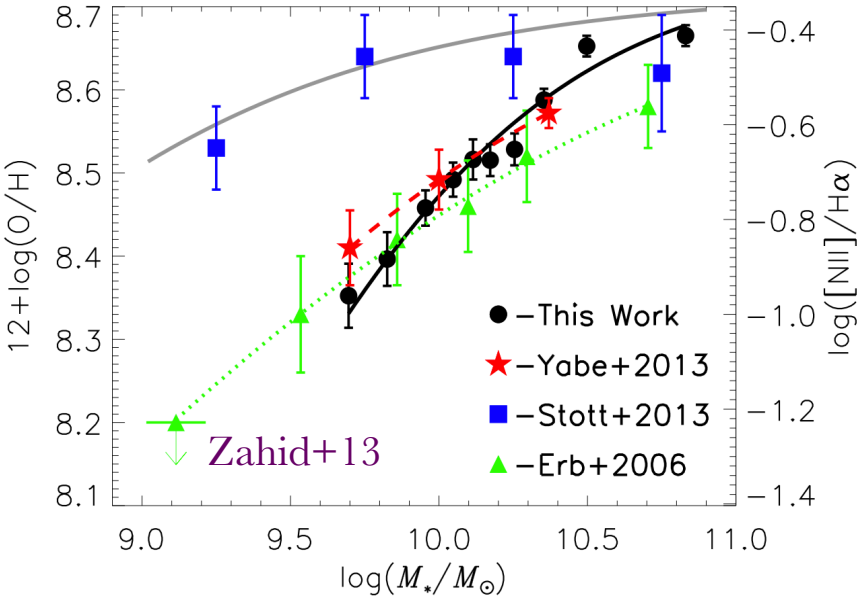
where $\log R$ is the logarithm of the strong-line ratio, and x is the metallicity relative to sol... ($x = \log(Z/Z_\odot) = 12 + \log(\mathrm{O/H}) - 8.69$. Allende Prieto et ... 2001). The coefficients $c_0 - c_4$ for

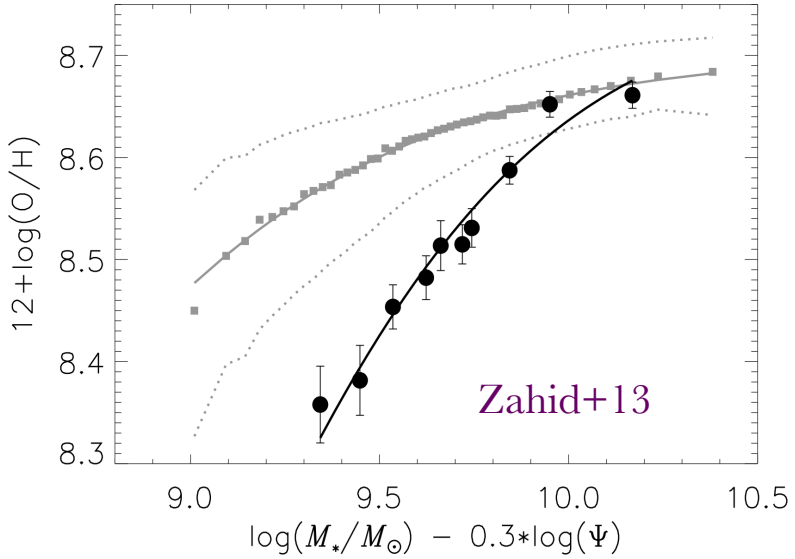


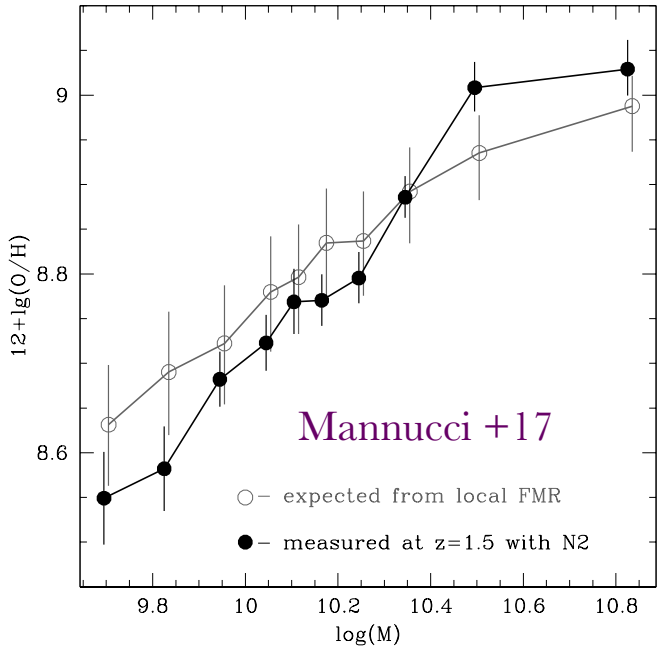


same data compared to Mannucci+10

Contradictions and Translations



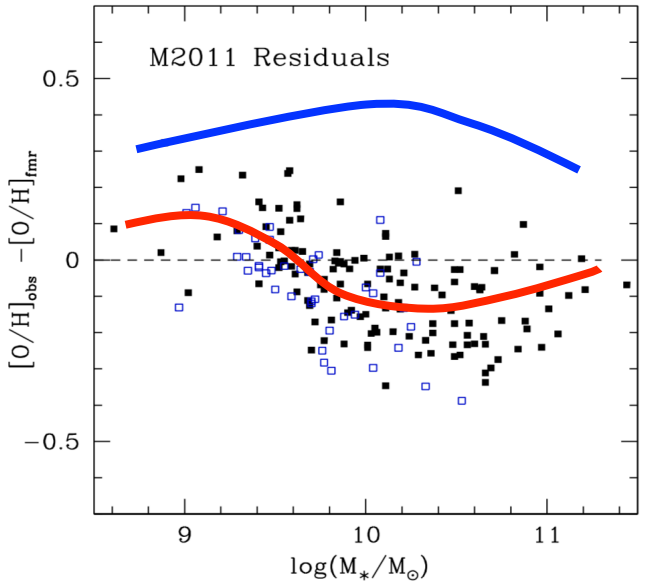


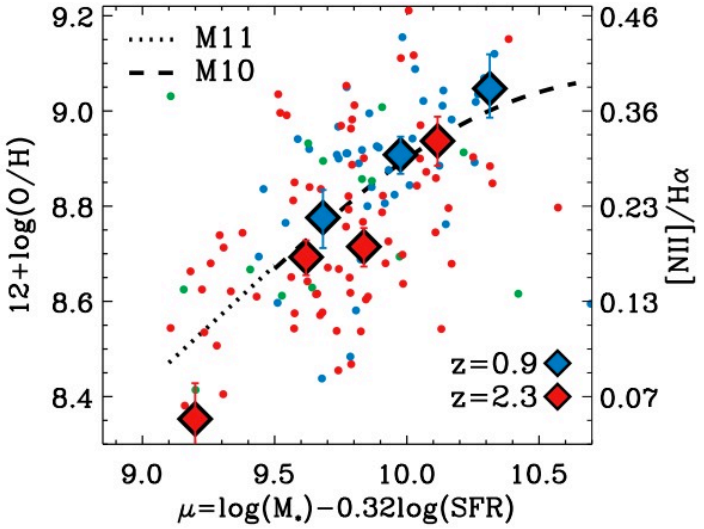


Redshift evolution of the FMR

Steidel et al. 2014: 179 galaxies at z~2.3 with MOSFIRE:

We find that the dependence of inferred gas-phase metallicity on SFR at a given M is much weaker at high redshift than at z ~ 0, indicating that z ~ 2.3 galaxies do not adhere to the same "fundamental metallicity relation" as star-forming galaxies at low redshift.*

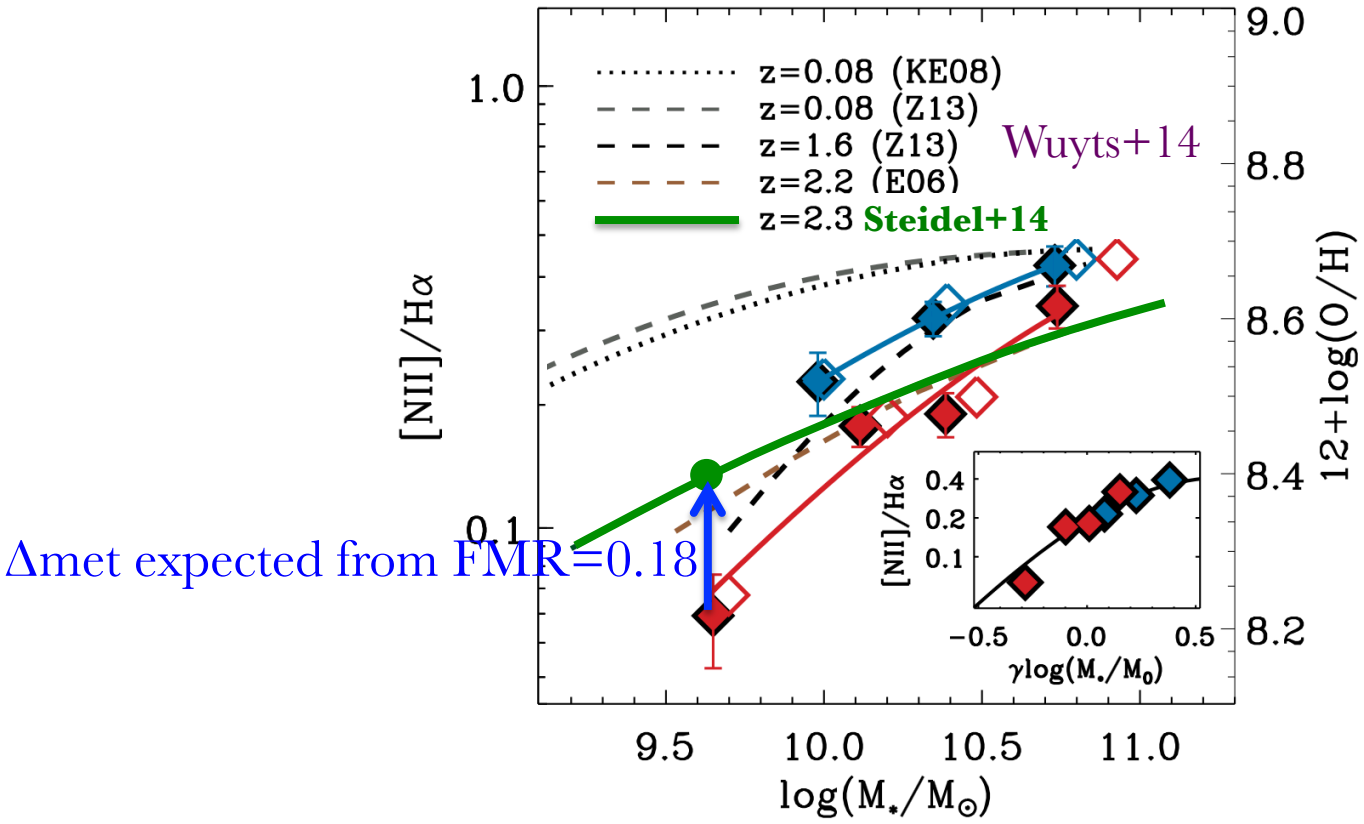




Wuyts et al. 2014: 222 z~2.2 with SINFONI/KMOS:

"*our data do not show a correlation between the [N II]/Ha ratio and SFR, which disagrees with the 0.2-0.3 dex offset in [N II]/Ha predicted by the "fundamental relation" between stellar mass, SFR and metallicity discussed in recent literature*"

Redshift evolution of the FMR



There is no "absolute" mass-metallicity relation at any redshift

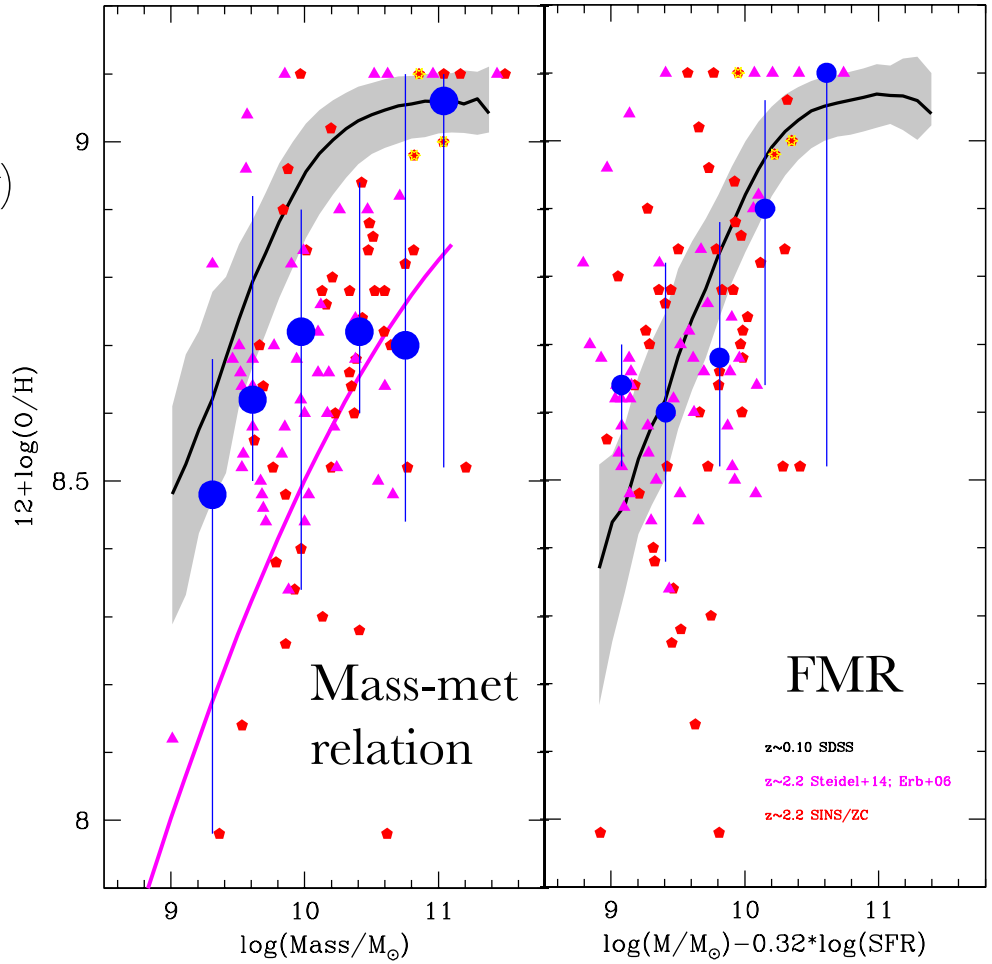
Redshift evolution of the FMR

scatter can be reduced by considering SFR only if the intrinsic scatter is smaller than the dependence on SFR

1. quality of data:
   - metallicity
   - SFR
   - mass
2. range in SFR (usually narrow)
3. mass range
4. larger intrinsic scatter at high redshifts

FMR: prediction of the median value of metallicity from local galaxies

mass-metallicity relations: different parts of the same FMR



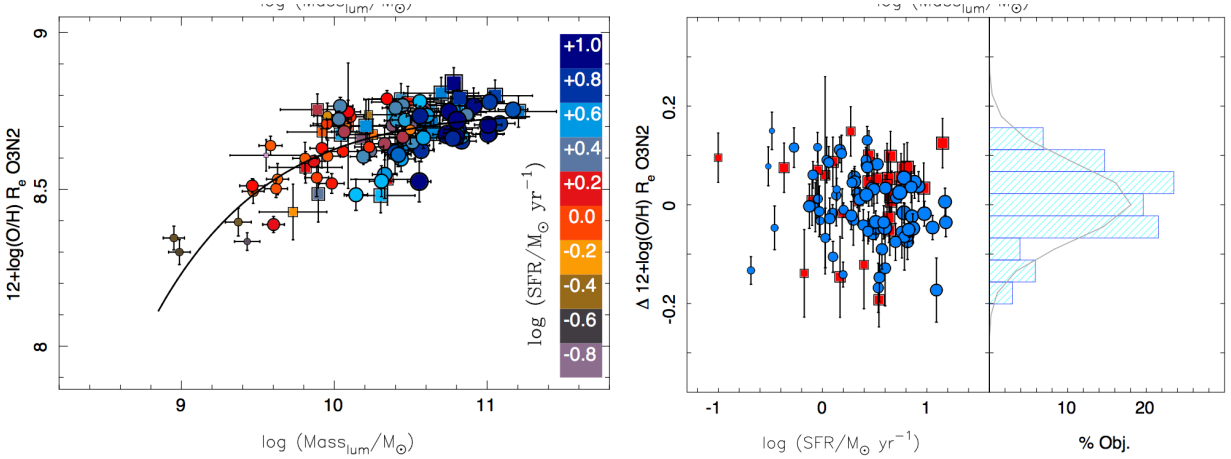
FMR and apertures

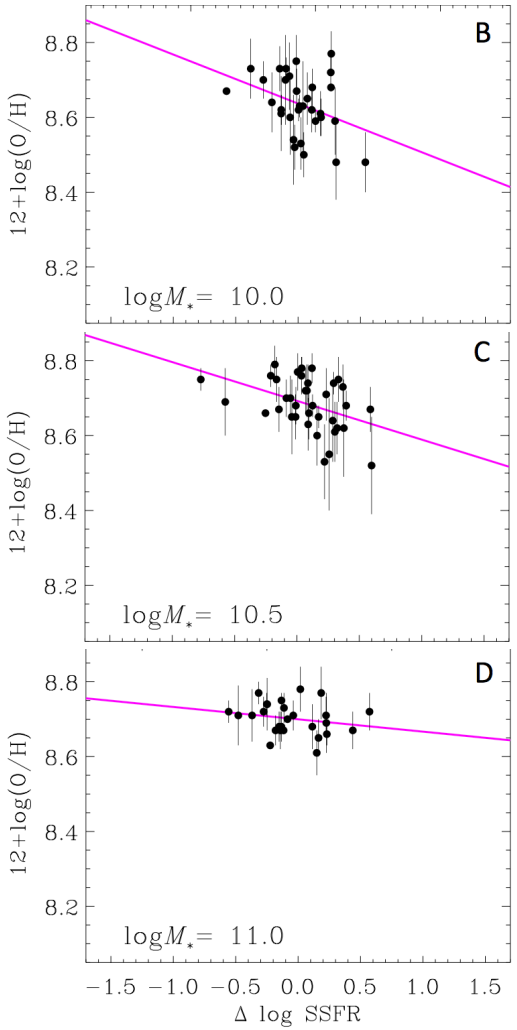
FMR: due to aperture because of gradients?

SDSS spectra: 3" fiber
metallicity gradients and dimensions correlated to SFR?

1. min dist = 300Mpc, aperture=4kpc (median 6kpc)
2. no dependence on distance
3. no dependence on light fraction

Sanchez et al 2012"*The Mass-Metallicity relation explored with CALIFA: Is there a dependence on the star formation rate?*"
"..we do not find any secondary relation with the star-formation rate.."

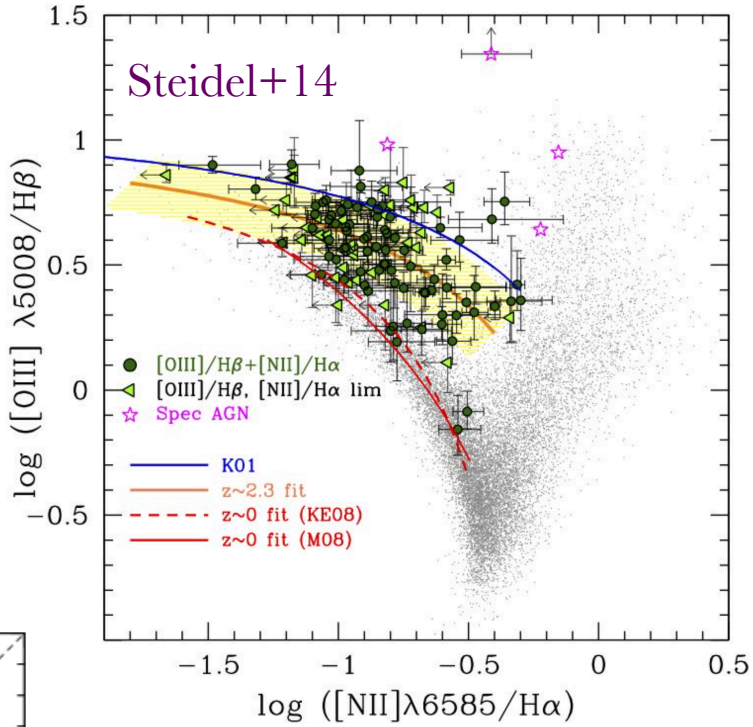


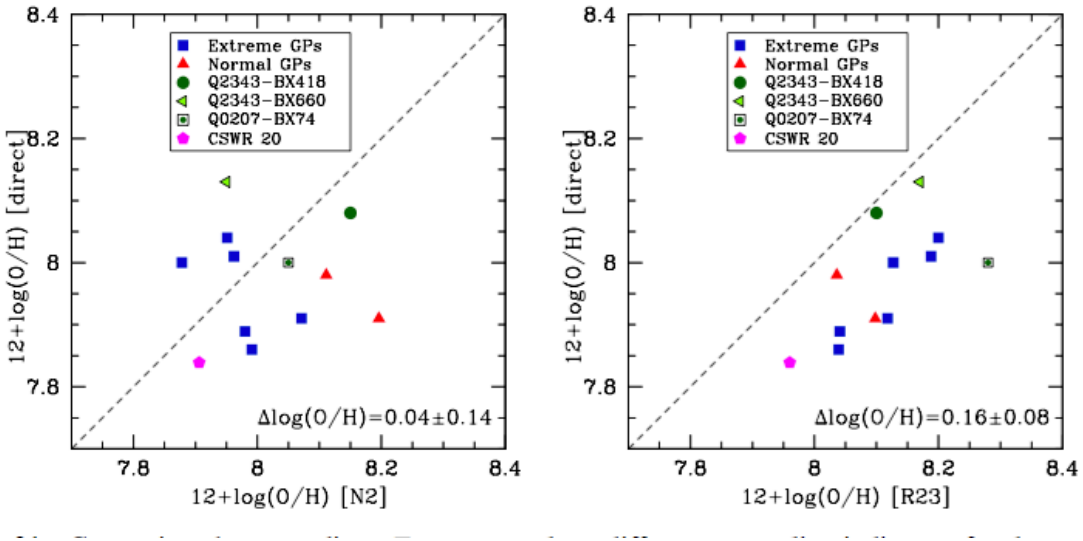


Salim+14

Calibrations and evolutions

- shape depends on metallicity calibration
- different conditions at high redshift
- evolution in the BTP diagram
- significant spread when using Te

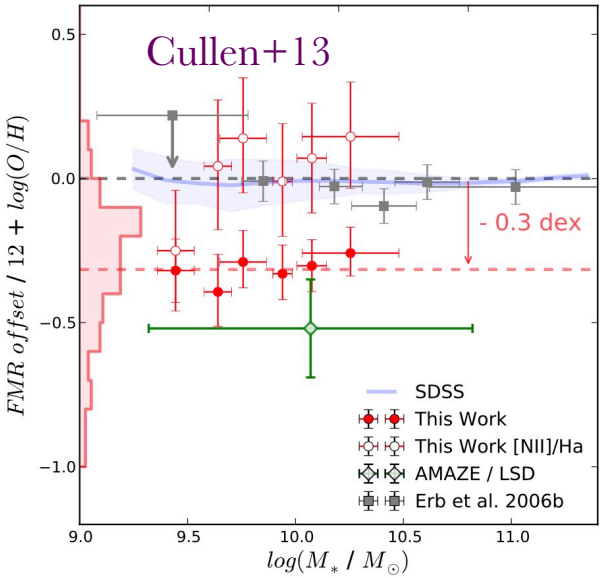


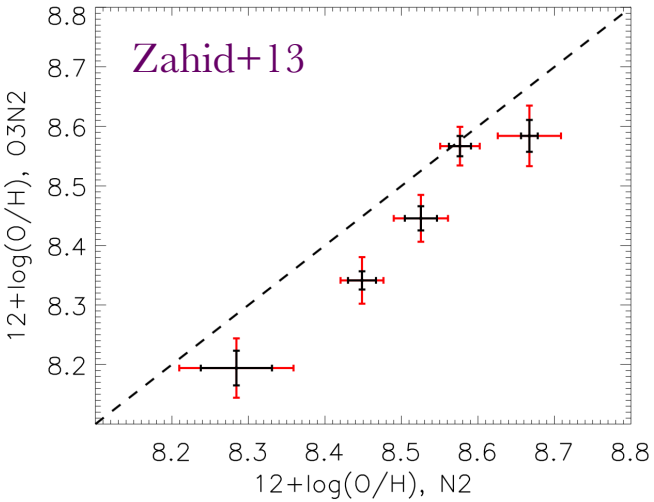


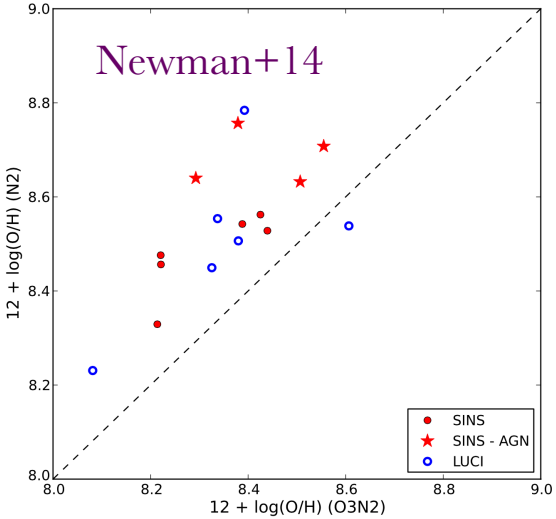
Shapley+05, Brinchman+08, Cullen+13, Wuyts+14, Steidel+14, Shapley+14, Kweley+13, Cullen+13

Calibrations and evolutions

- systematic offset between NII/Ha and O3+O2

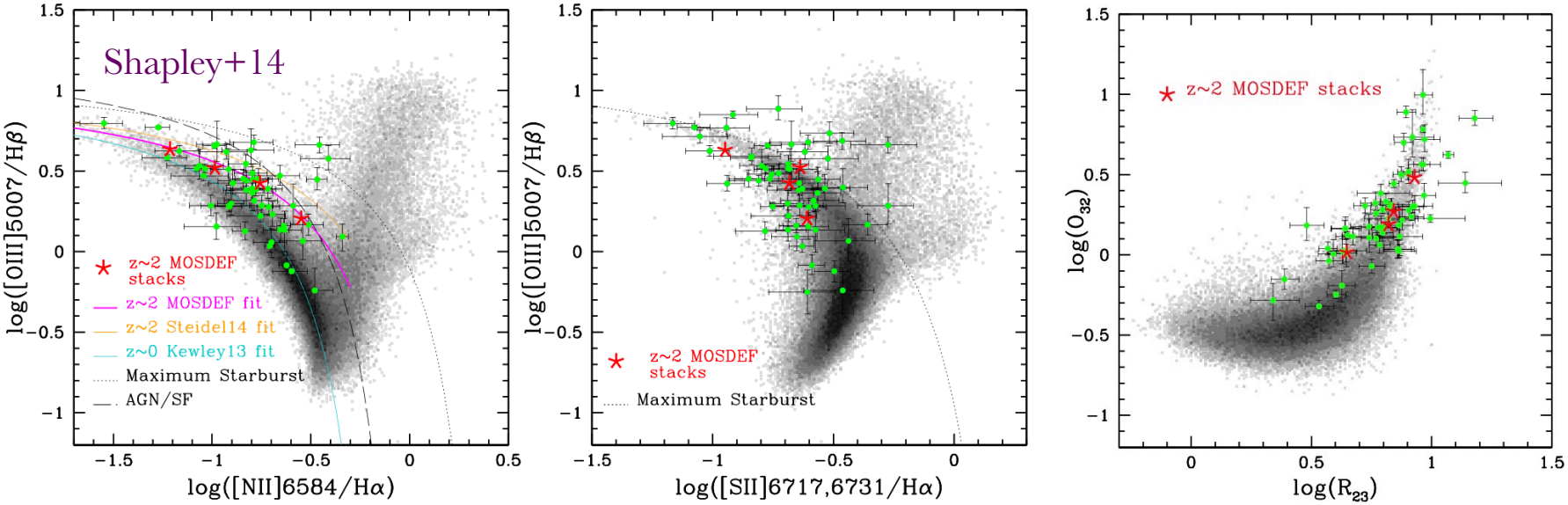


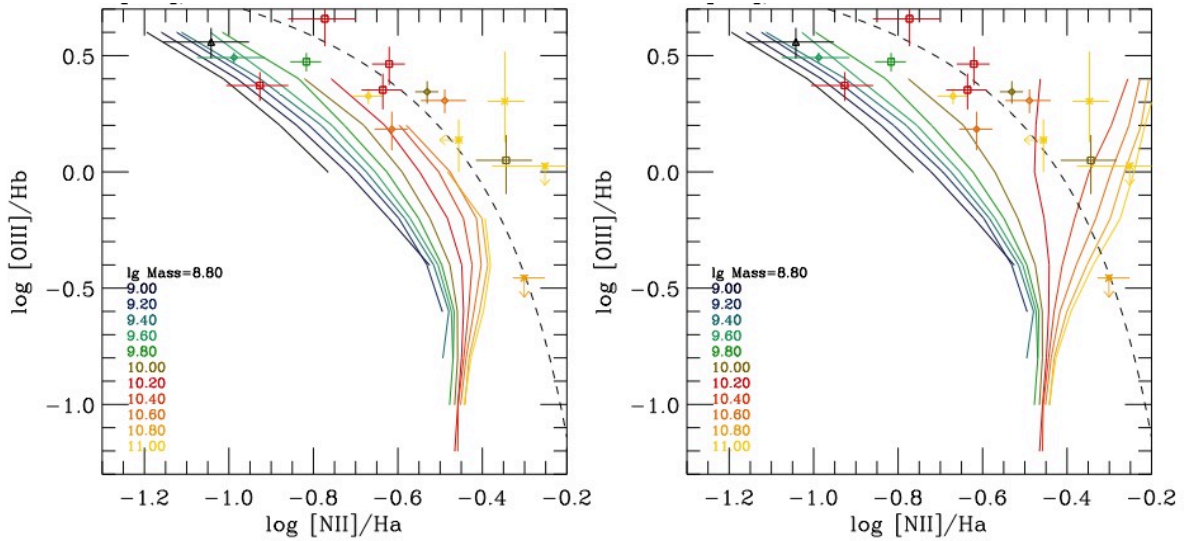




Calibrations and evolutions

Oxygen better than Nitrogen?

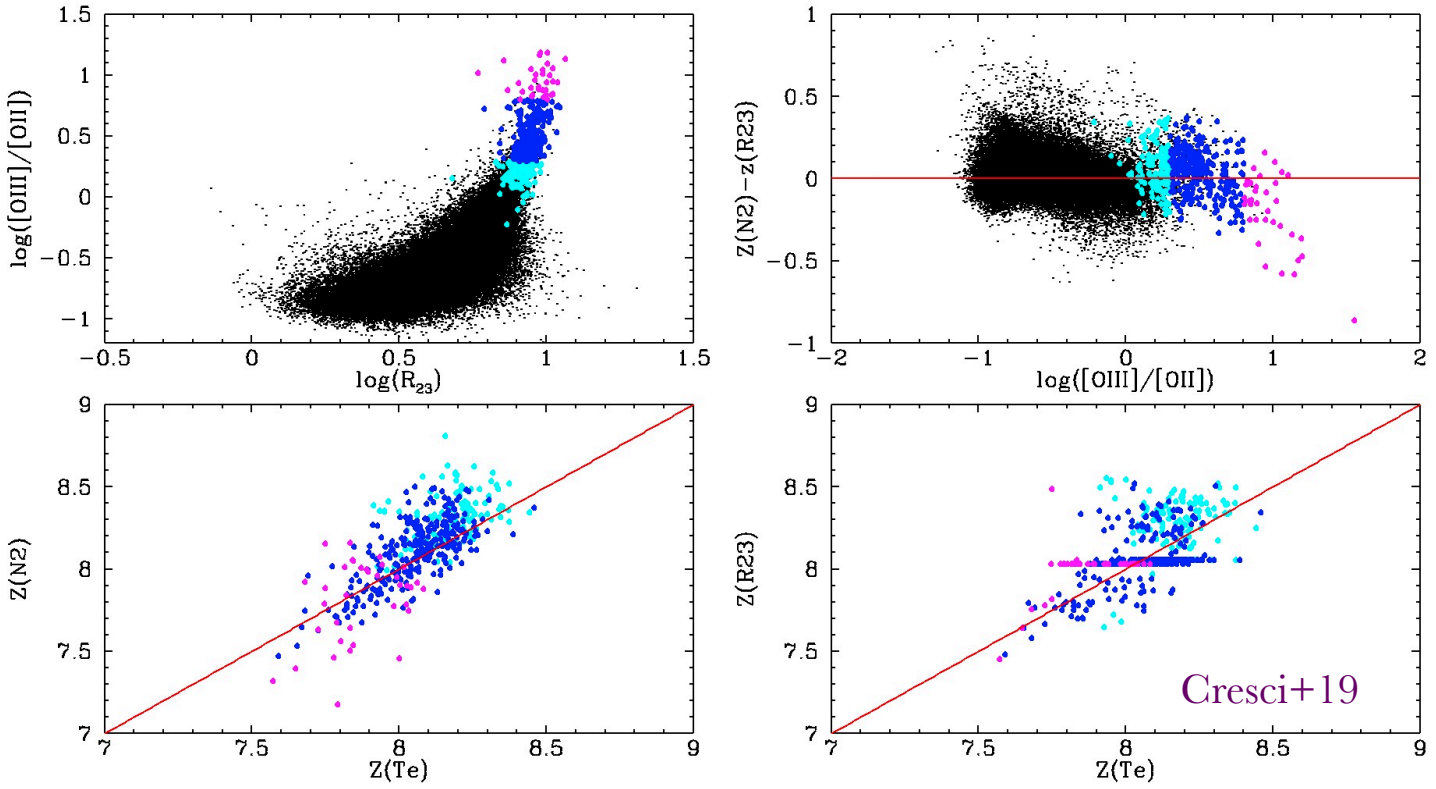




Maiolino+18

Calibrations and evolutions

Oxygen better than Nitrogen?



SDSS galaxies with [OIII]4363 detection, binned in OIII/OII (i.e. ionization parameter): no clear trend with ionization parameter, and no differences with Te and N2 metallicity

Conclusions

- Metallicity to study galaxy evolution
  - many accurate models producing trends and scatter
  - large number of observed spectra up to z=3
  - spatially-resolved observations
  - really possible discriminate among models
- Scaling relations: handle with care
  - aperture not a problem
  - metallicity calibration and evolution of properties
  - FMR does not evolve up to z=2.3, predicts metallicities
  - moderate evolution (~0.2 dex at z=2) is possible
- Observe the models
  - reproduce the FMR – both scatter and no (or slow) evolution
  - MZR? same selection effects (SFR) must be taken into account
  - observed evolution of the MZR is likely to be due ONLY to selection effects