# Metallicity Near and Far

GIOVANNI CRESCI
INAF – ARCETRI

F. MANNUCCI, R. MAIOLINO, A. MARCONI,
V. SOMMARIVA, A. GNERUCCI, L. MAGRINI
AND THE LSD/AMAZE TEAM

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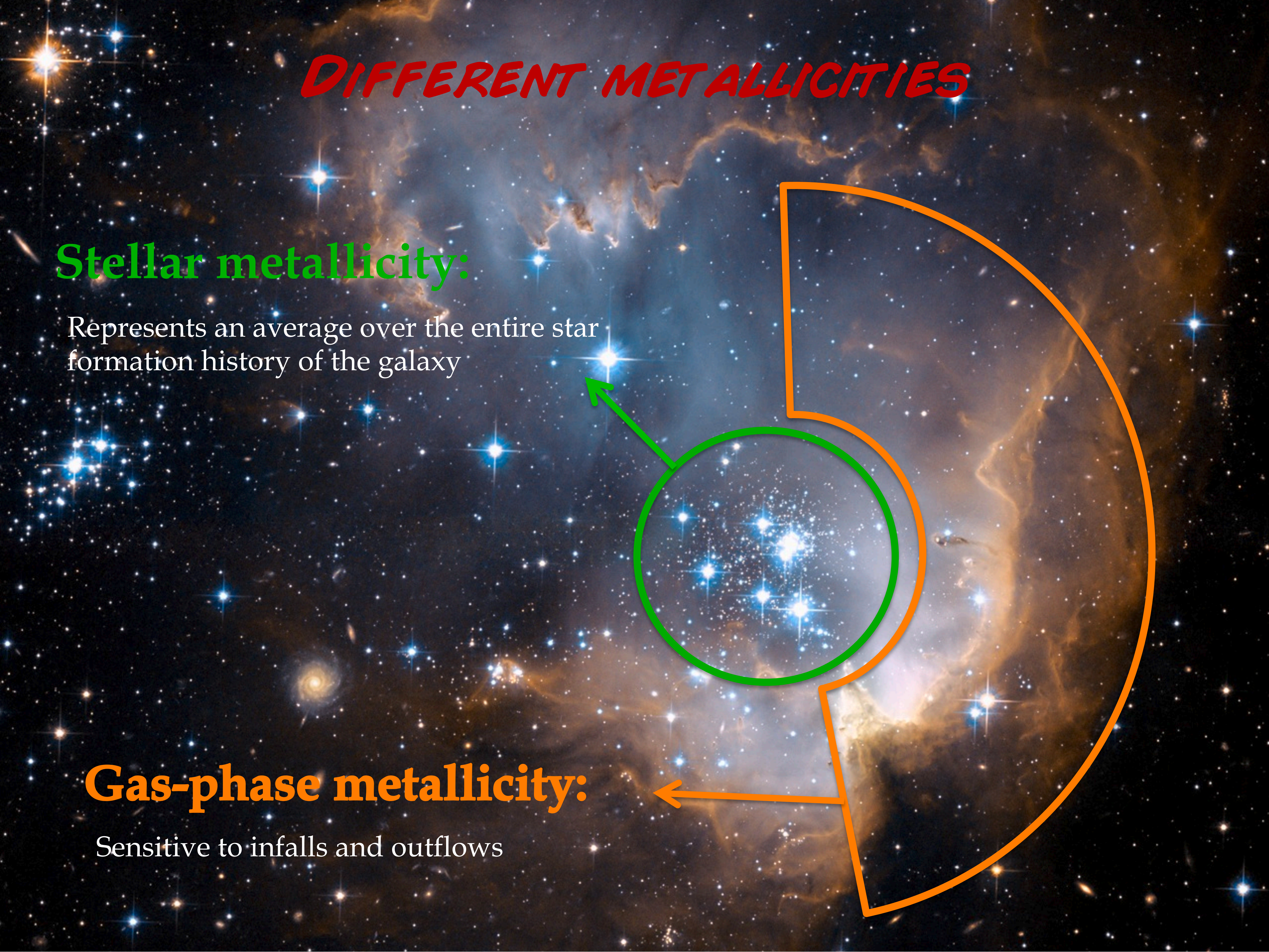
# Metallicity: a fundamental parameter

⋆ Indirectly traces the integrated galaxy SFH, not only the current SFR

⋆ Relative element abundances reflect the cycling of gas through stars, and any exchange of gas between galaxy and its environment (infall/outflows)

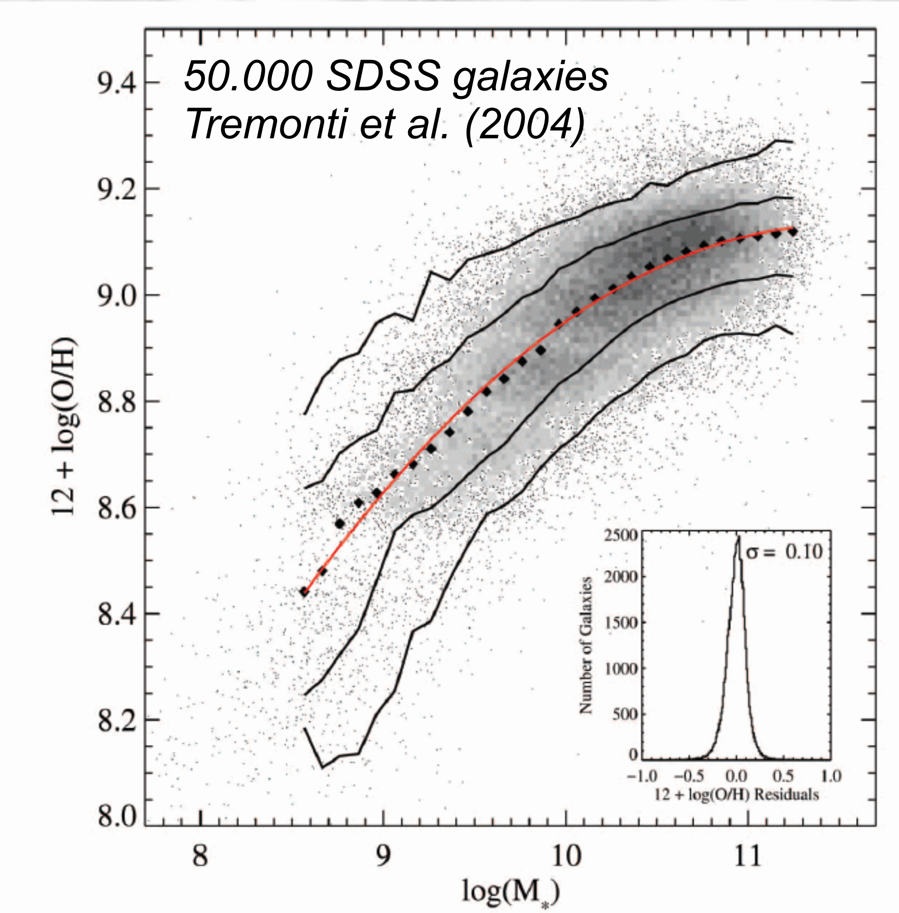
↓

*Understanding its evolution is essential to isolate the physical mechanisms that drive Star Formation*


Different metallicities
Stellar metallicity:
Represents an average over the entire star formation history of the galaxy
Gas-phase metallicity:
Sensitive to infalls and outflows

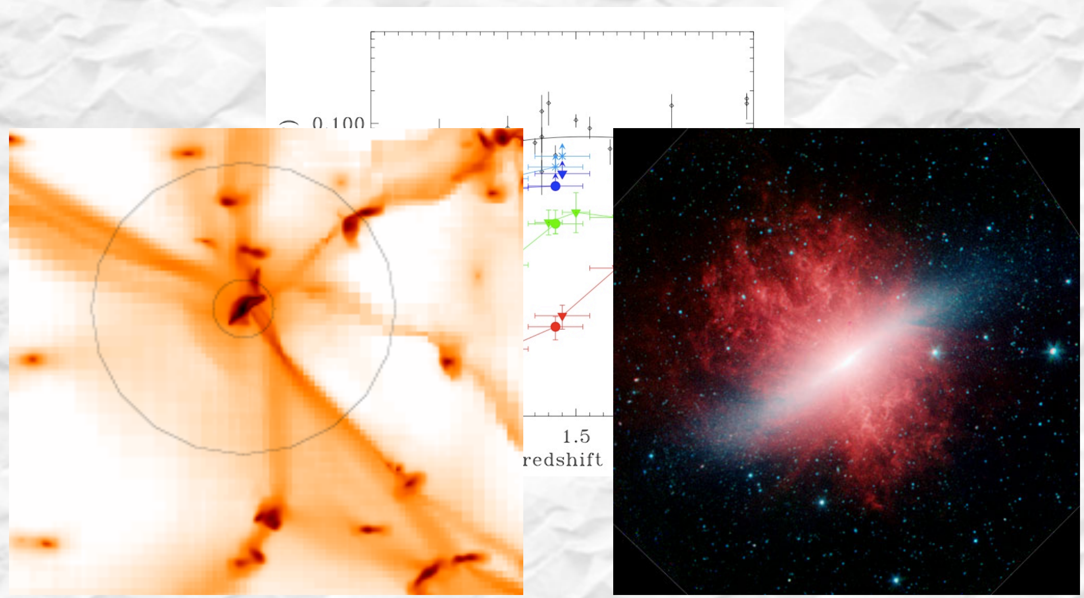
# The mass-metallicity relation

Dispersion ~ 0.1dex




Possible Drivers:

- ✓ star formation history and mass lost
- ✓ downsizing
- ✓ inflows and merging
- ✓ outflows and feedback (AGN, SNe)
- ✓ evolution in IMF
- ✓…

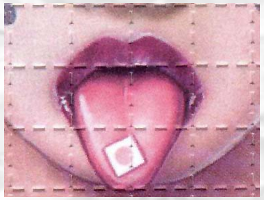



*Crucial test for models!*

Expecially at high-z, where the predictions of different models diverge more

*See Kobayashi+ 2007; Brooks+ 2007; de Rossi+ 2007;Dave' & Oppenheimer 2007; Dalcanton, 2007; De Lucia+ 2004; Tissera+ 2005; Koppen+ 2007; Cid Fernandes+ 2007; Finlator & Dave', 2008, Panter+ 2008, Governato+ 2008, Sakstein+ 2009; Calura+ 2009, Save', Finlator & Oppenheimer 2011…*

# AMAZE… …with LSD

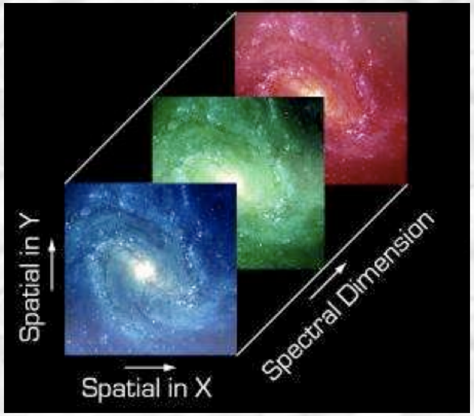


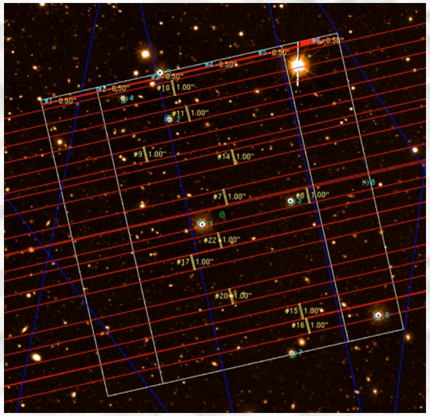
1. Near-IR Integral Field Spectroscopy with SINFONI@VLT

**AMAZE** (Assessing the Mass-Abundance redshift(Z) Evolution):
- seeing limited, a sample of 30 LBGs at 3<z<5
- 180h (PI: Maiolino) Maiolino et al. 2008, Cresci et al. 2010, Troncoso et al. 2011

**LSD** (Lyman-break galaxies Stellar populations and Dynamics):
- diffraction limited with AO, an unbiased sample of 10 LBGs at 3<z<4
- 70h (PI: Mannucci) Mannucci et al. 2009, Gnerucci et al. 2010, Sommariva et al. 11

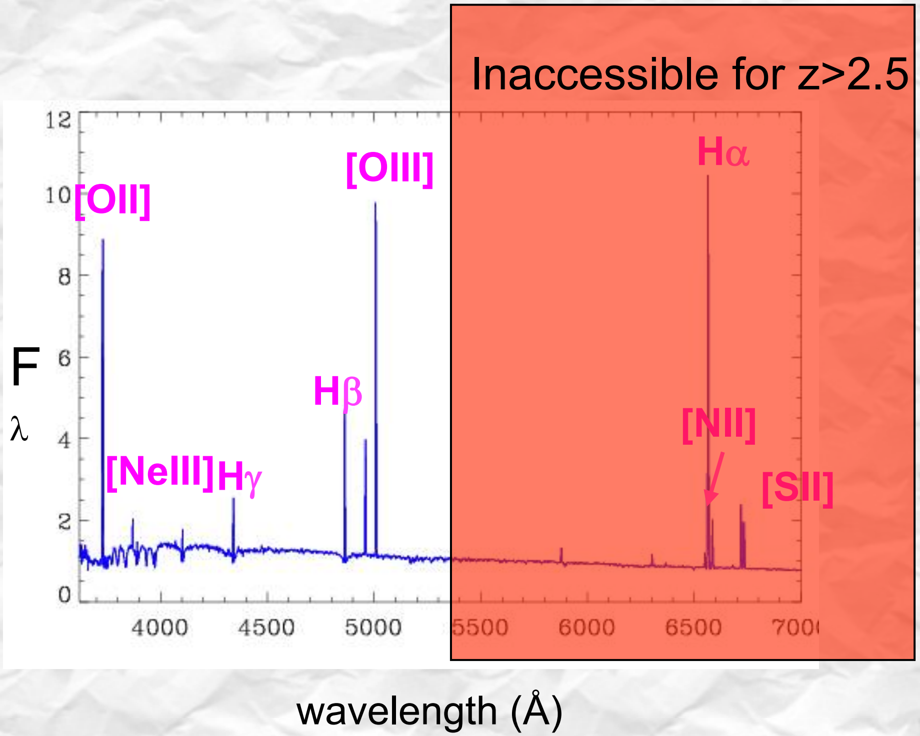
2. Near-IR Multi Object Spectroscopy with LUCIFER@LBT
- 4 Steidel fields, ~10 z=3 LBGs/field
- 40h (PI: Cresci) observations ongoing…

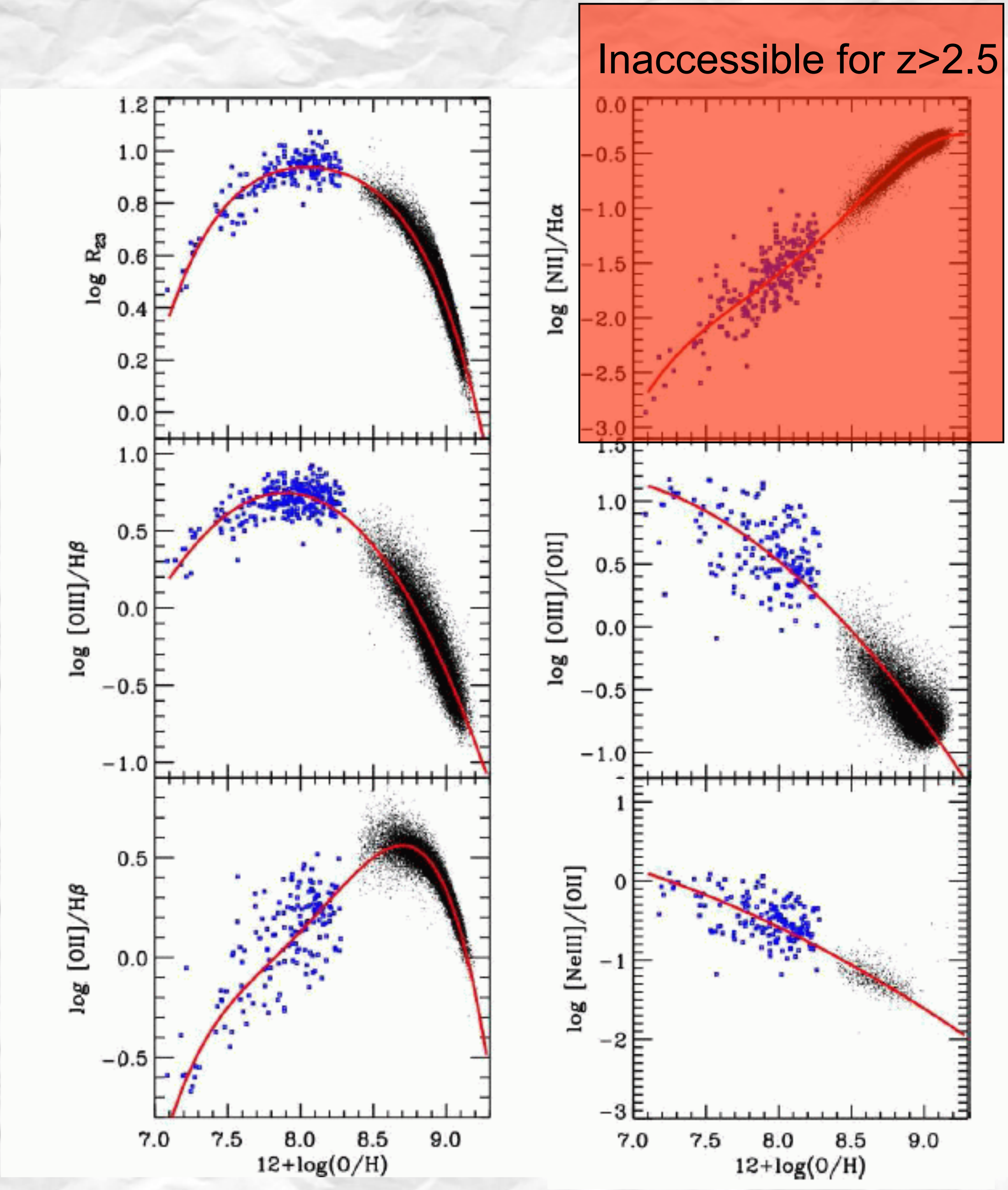


# Measuring metallicities

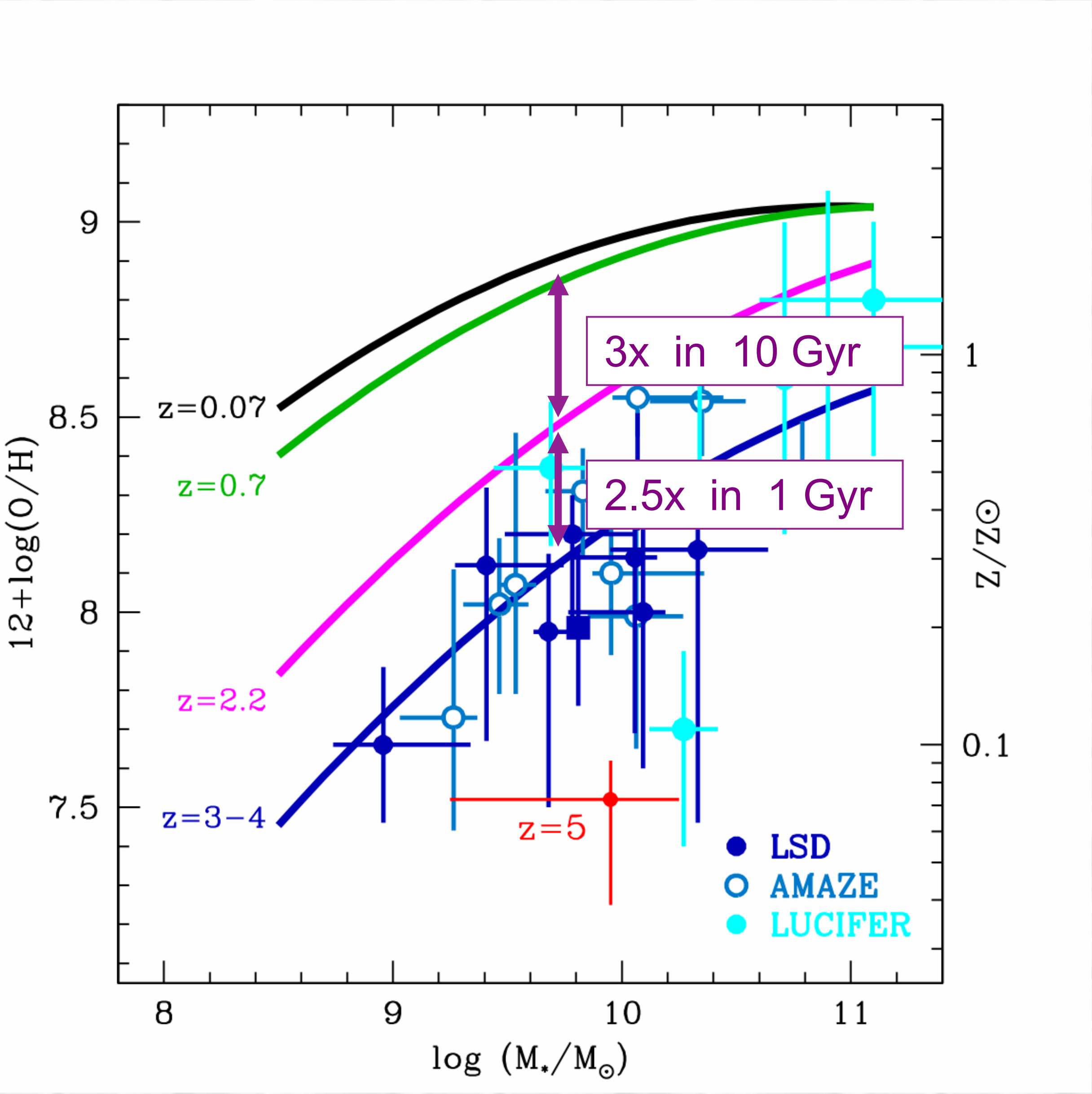
Gas phase metallicity from strong lines:




Nagao et al. 06, Maiolino et al. 08: improved calibrations with low metallicity samples

# Evolution of the mass-metallicity relation




z~0.07 SDSS

z~0.8-1 GDSS+CFRS (Savaglio+05),
GOODS (Cowie & Barger 09)
VVDS (Lamareille+09, Perez-Monteiro+09))
IMAGES (Rodrigues+08)
DEEP2 (Zahid+10)

z~2.2 LBG (Shapley+04, Erb+06)
BzK (Hayashi+11)
Lenses (Richard+10)

z~3.3 ○ AMAZE (Maiolino+08)
● LSD (Mannucci +09)
● LUCIFER (Cresci+11)

z~5 ● AMAZE

M-Z relation already in place at z~3.5

Strong and fast evolution of the M-Z relation beyond z~2?

# Inflows and Outflows

In a "*closed box model*" with instantaneous recycling, instantaneous mixing, and low metallicities:

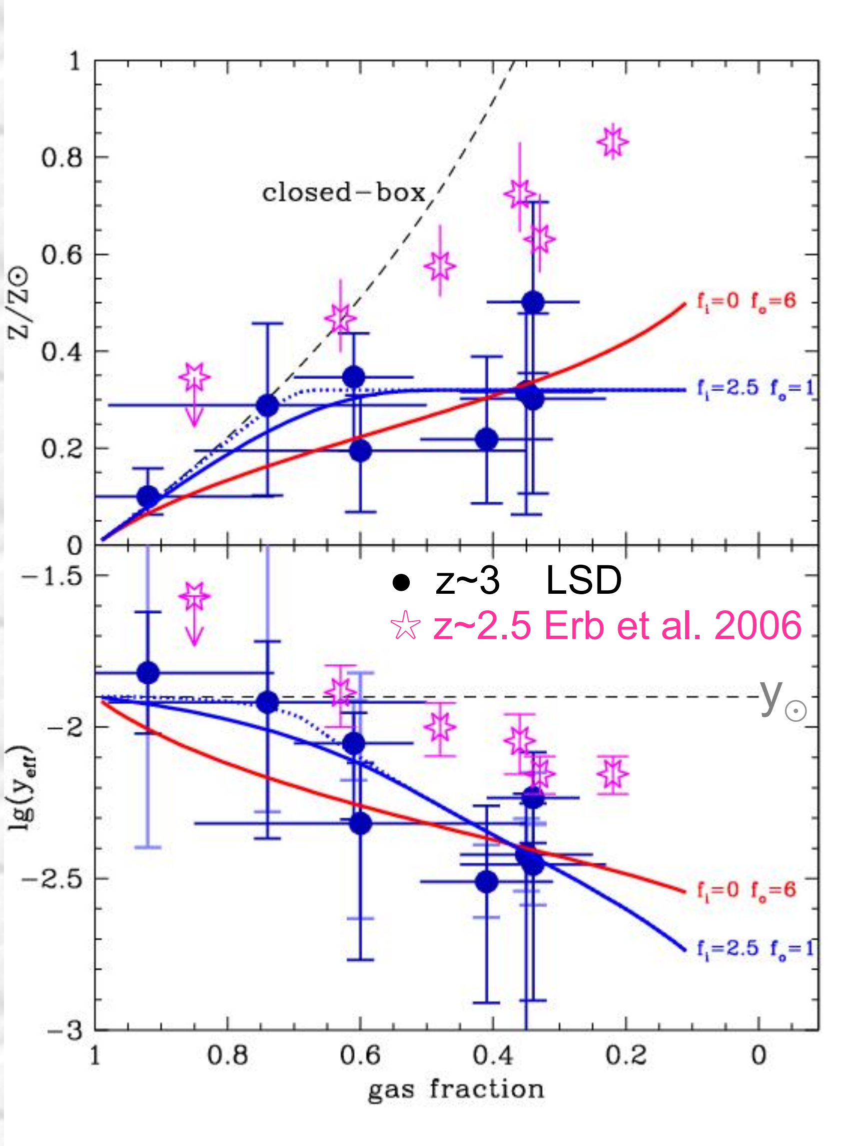
$$Z = y_{true} \cdot \ln(1/f_{gas})$$

$y_{true}$ = stellar yield, i.e., the ratio between the amount of metals produced and returned to the ISM and the mass of stars.

The measured values of $y_{eff} = Z/\ln(1/f_{gas})$ could differ from the true stellar yields y if some of the assumptions do not hold, in particular if the system *is not a closed box*

↓

**Inflows and outlows**



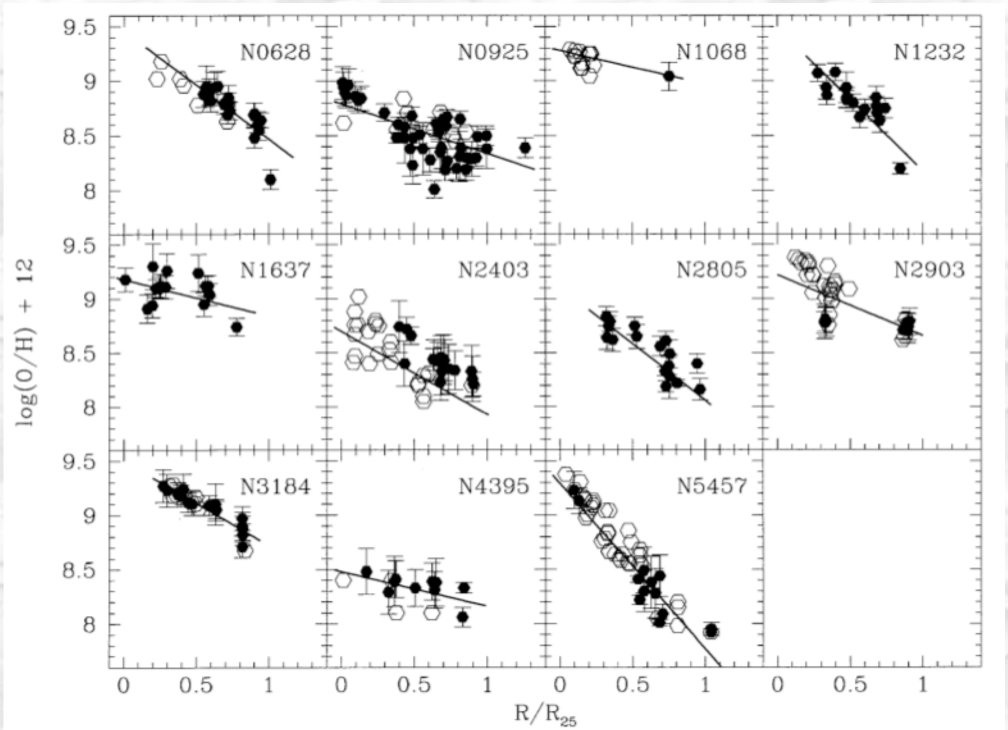
# Metallicity Gradients

Interplay between in- and out-flows, redistribution of mass within galaxies, radially dependent SFH, mixing due to a stellar bar, clump migration, etc

→ *Fingerprints of galaxy evolution!*

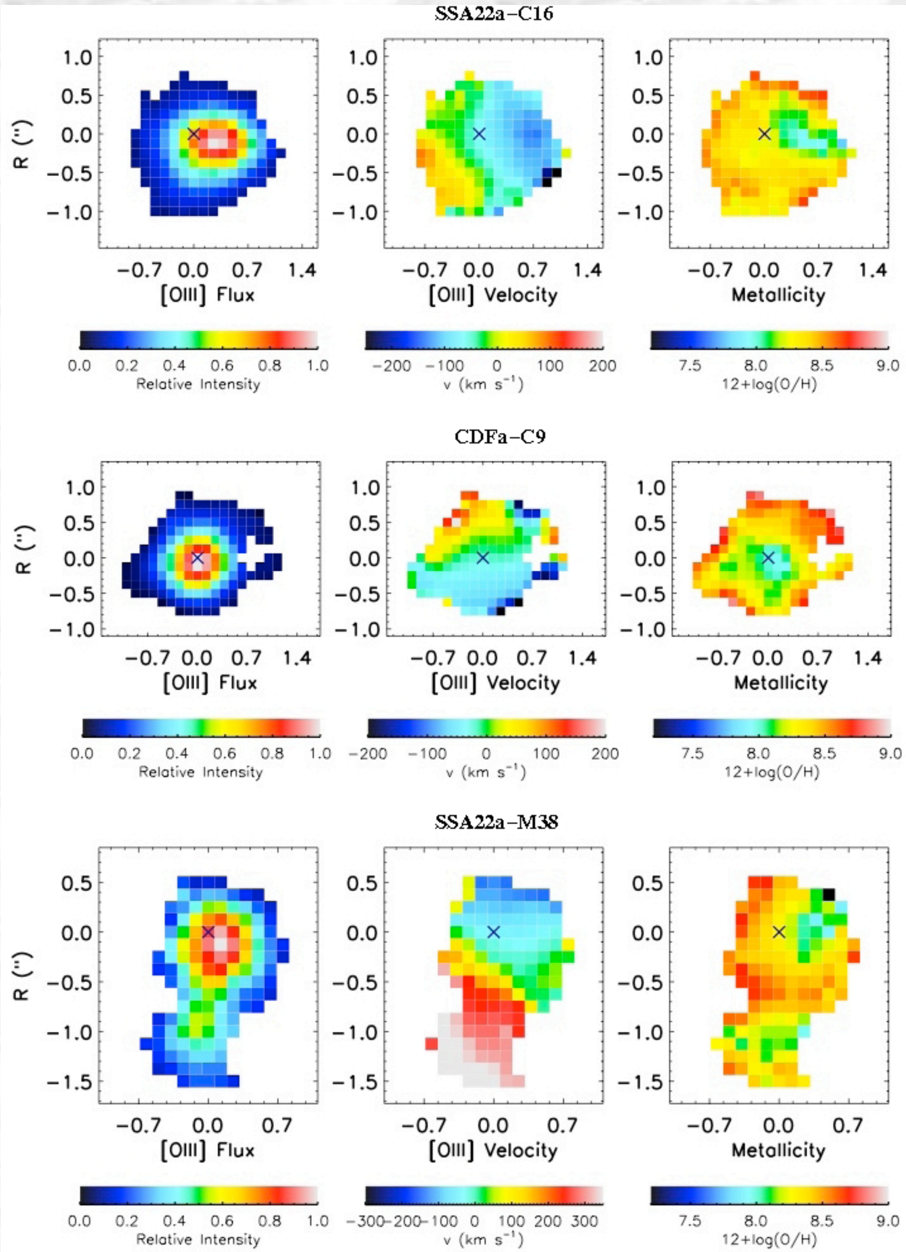
Negative radial metallicity gradient in local spiral galaxies: the central disk region is more metal-enriched than the outer regions.

(but see also Werk et al. 2010)




*Van Zee et al. 1998*

# Metallicity Gradients at z=3




Cresci et al. 2010, Nature

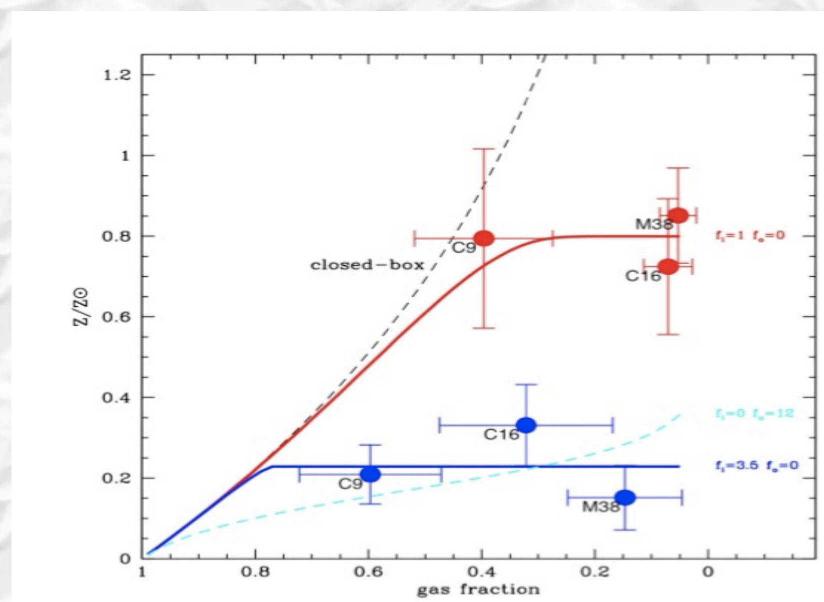
Thanks to the AMAZE/LSD data

First metallicity maps at z~3:

- Three undisturbed disks
- Well defined regions close to the SF peak are less metal enriched than the disk

⬇

*Direct evidence for massive infall of metal poor gas feeding the star formation*



# Cosmology and the MZR

Gas infall

Metal poor: reduces metallcity

Fuel for Star Formation

Metal enrichment

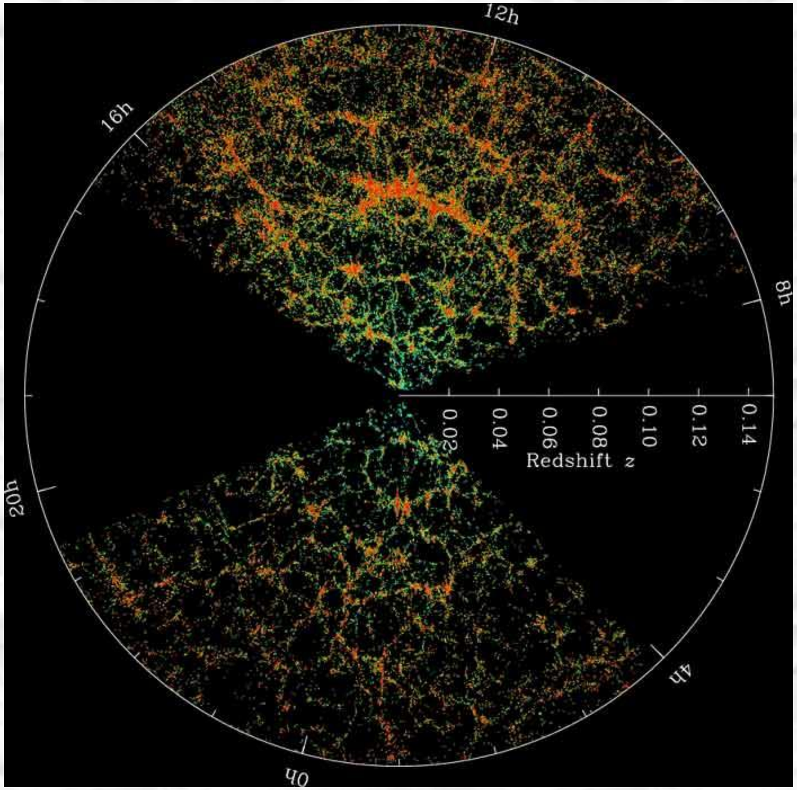
Metal depletion trough outflows

Can we see all this in the scaling relations?
Does SFR affect metallicity?

# Back to local galaxies

**Local SDSS DR7 galaxies:**

- $10^6$ galaxies with fiber spectra (3")
- z<0.3
- MPE/JHU catalog of emission lines and stellar masses



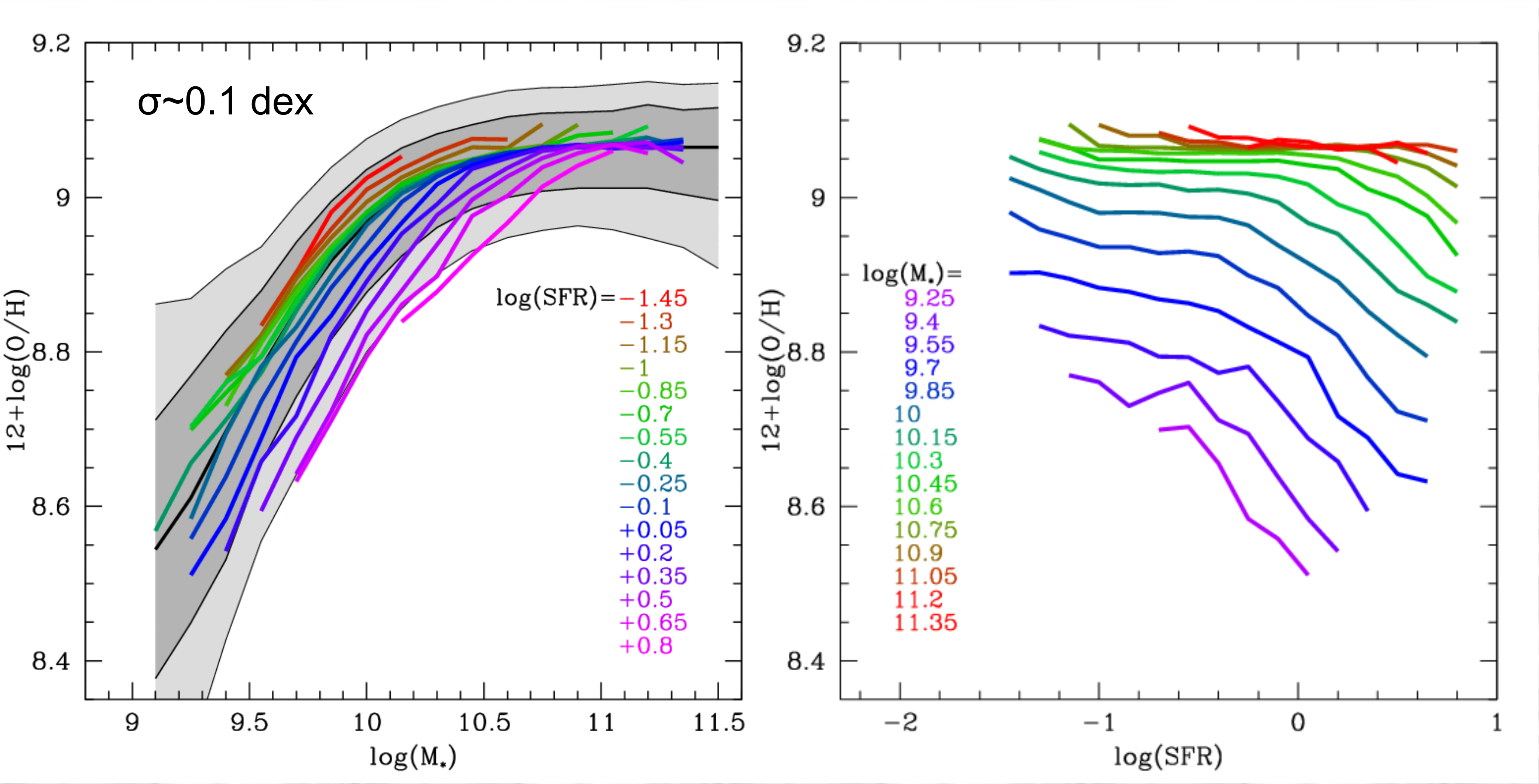

**Selection:**

- signal-to-noise on Hα>25
- no selection on other lines ([OII], [OIII], [NII] …)
- redshift above 0.07: flux in the fiber > 30%
- AGN removed with BPT diagram

final sample: 141.000 galaxies

- Stellar Mass: SED fitting + spectra
- SFR: Hα (Kennicutt) + Balmer dec.
- Gas metallicity: strong lines: average between [NII]/Hα and $R_{23}$

# Is SFR missing?

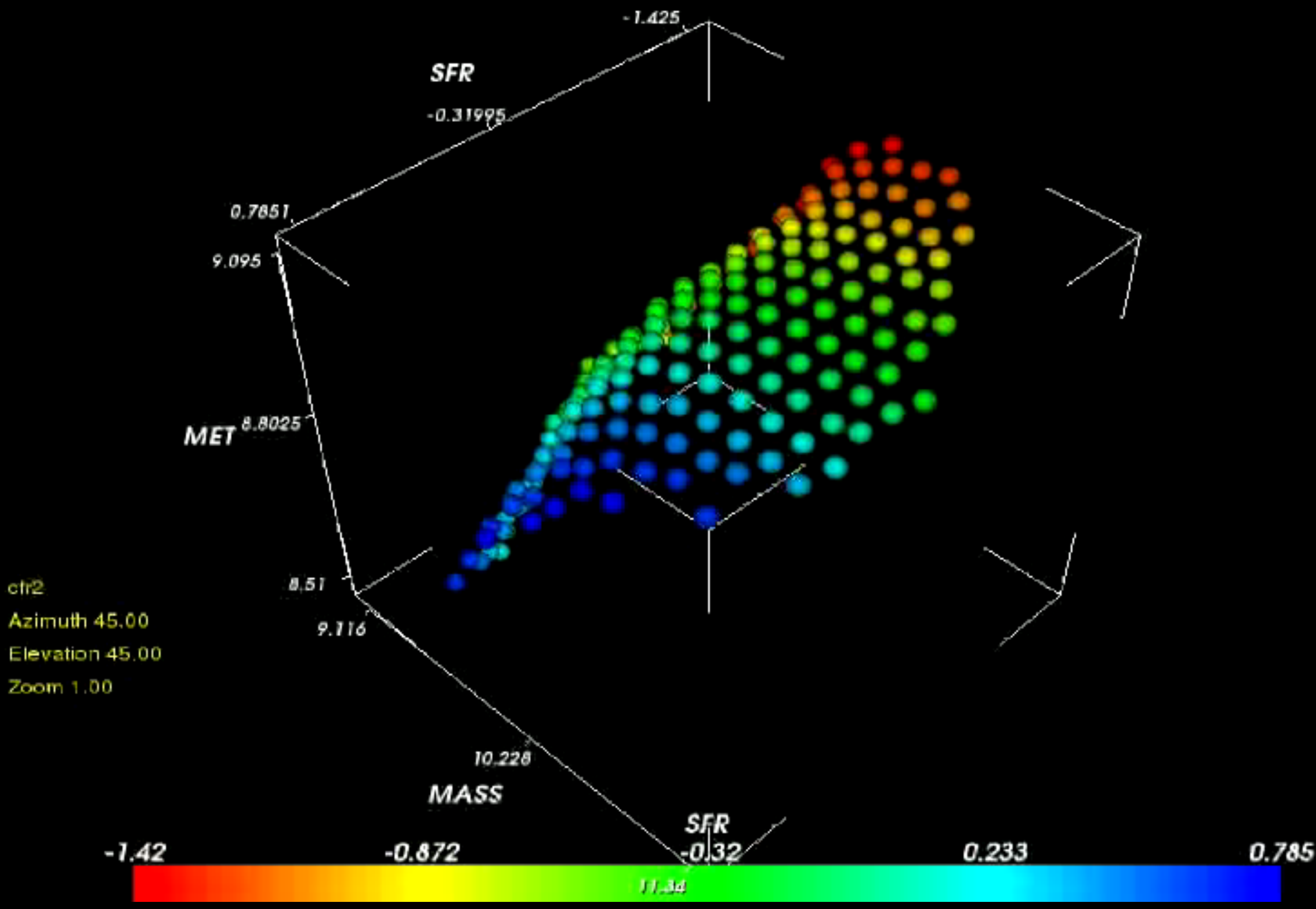



141.000 local SDSS galaxies,
selected to have SNR(Hα)>25, z>0.07

- Stellar Mass: SED fitting + spectra
- SFR: Hα (Kennicutt) + Balmer dec.
- Gas metallicity: strong lines: [NII]/Hα and R23

**Metallicity depends on both mass and SFR**

# The Fundamental Metallicity Relation

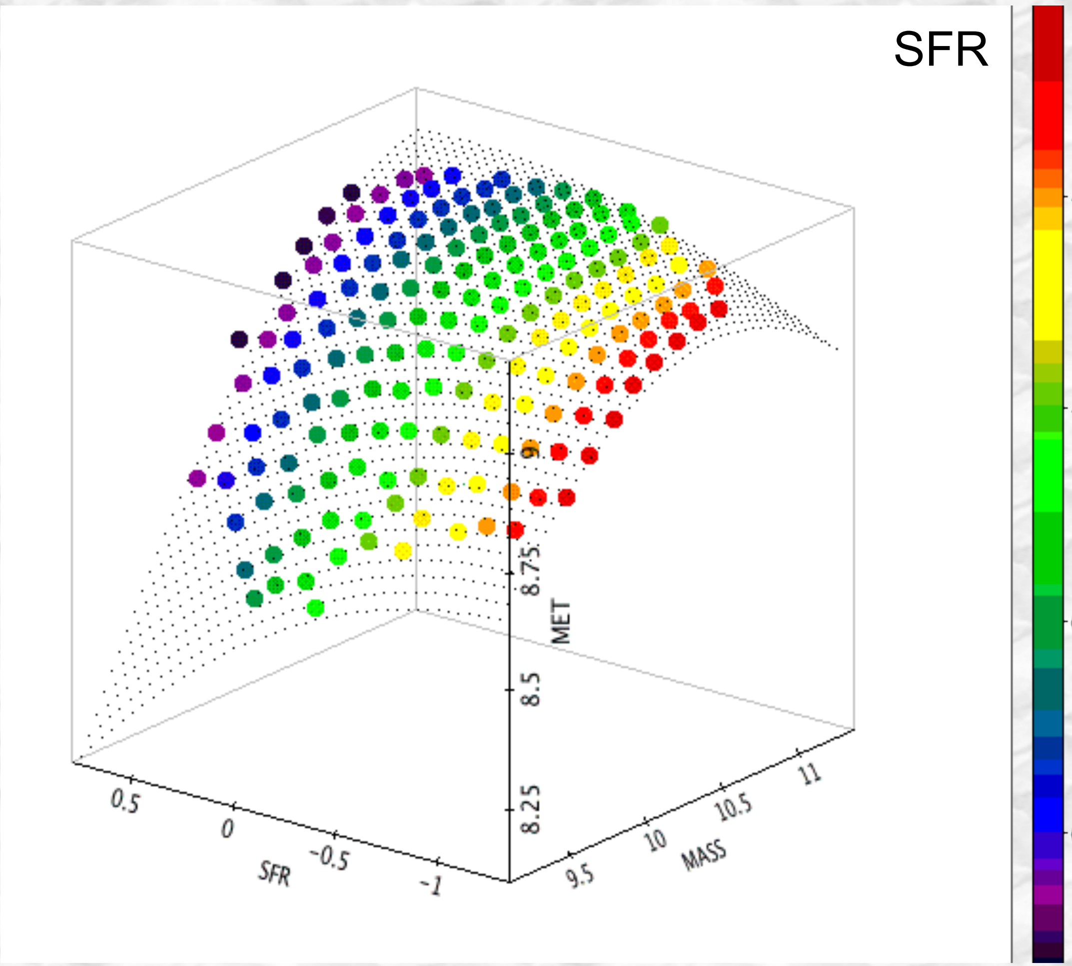


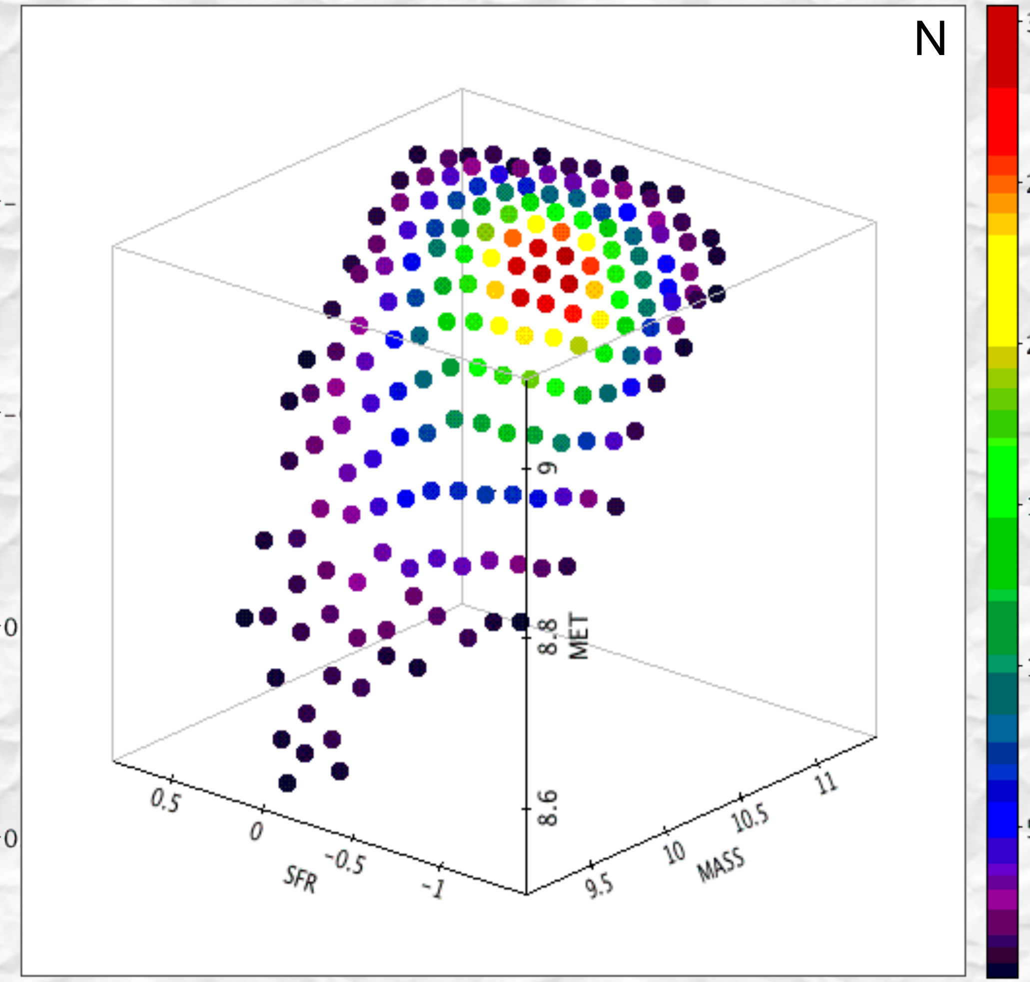

Mannucci, Cresci et al. 2010

# The Fundamental Metallicity Relation

**Small scatter => Long lasting equilibrium between gas accretion, star formation and metal ejection**

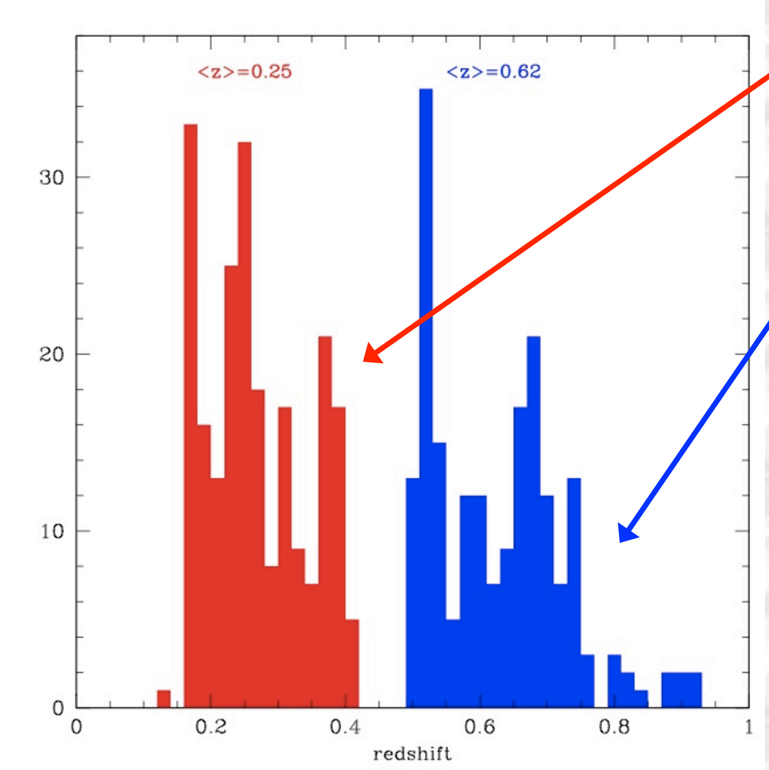
The mass-SFR relation ("main sequence") only defines how the FMR is populated




*Mannucci, Cresci et al. 2010*

# Going to higher z with zCOSMOS




Using [NII]/Hα
131 galaxies

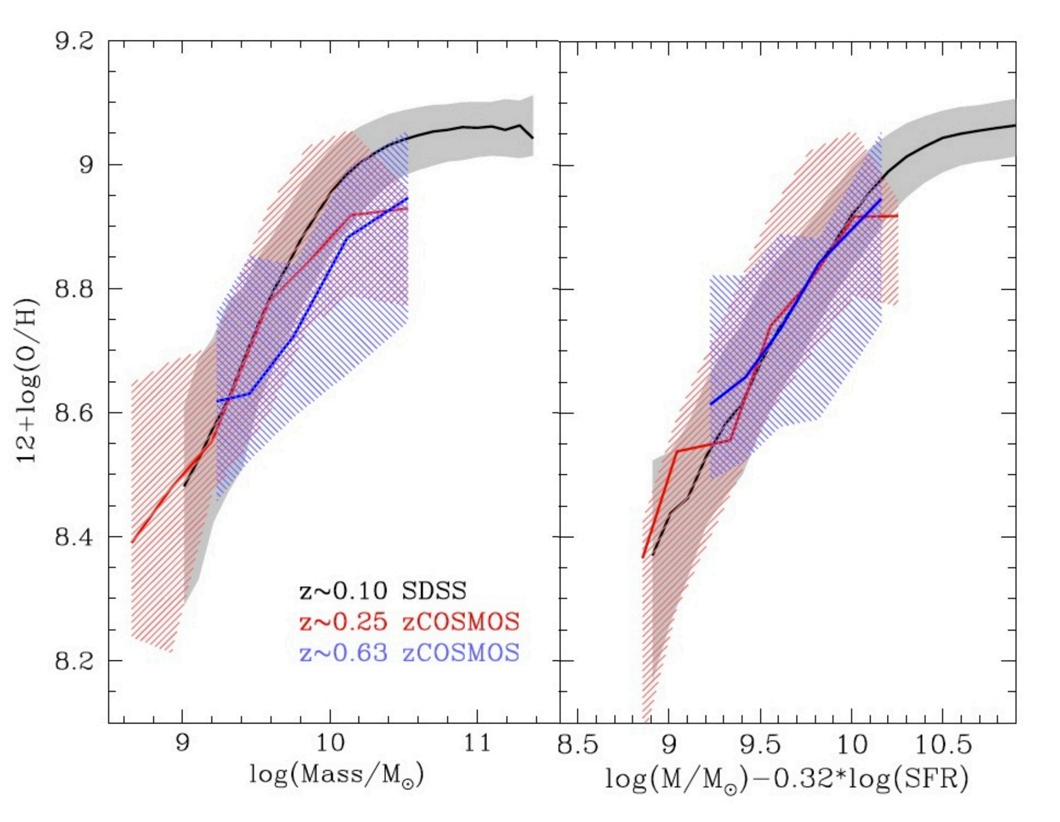
Using $R_{23}$
171 galaxies

From a parent sample of 7700 zCOSMOS DR2 star forming galaxies with VIMOS spectroscopy, with:

- ✓ S/N(Hα)>15 for z<0.45
- ✓ S/N(Hβ)>10 for z>0.49
- ✓ => S/N>2 for all other lines

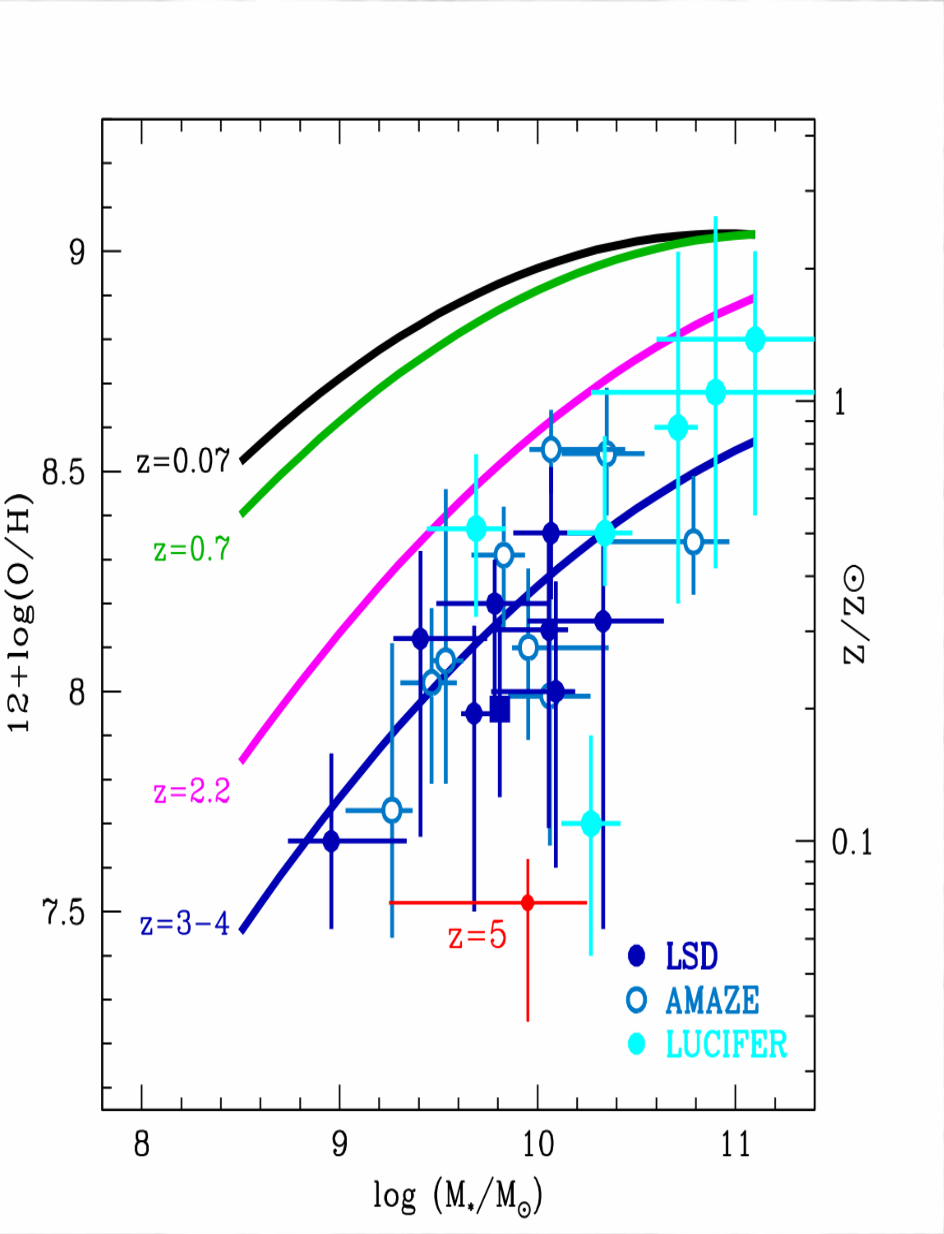
M-Z relation is evolving at z~0.62…

**… but no evolution of the FMR**




*Cresci et al. 2011*

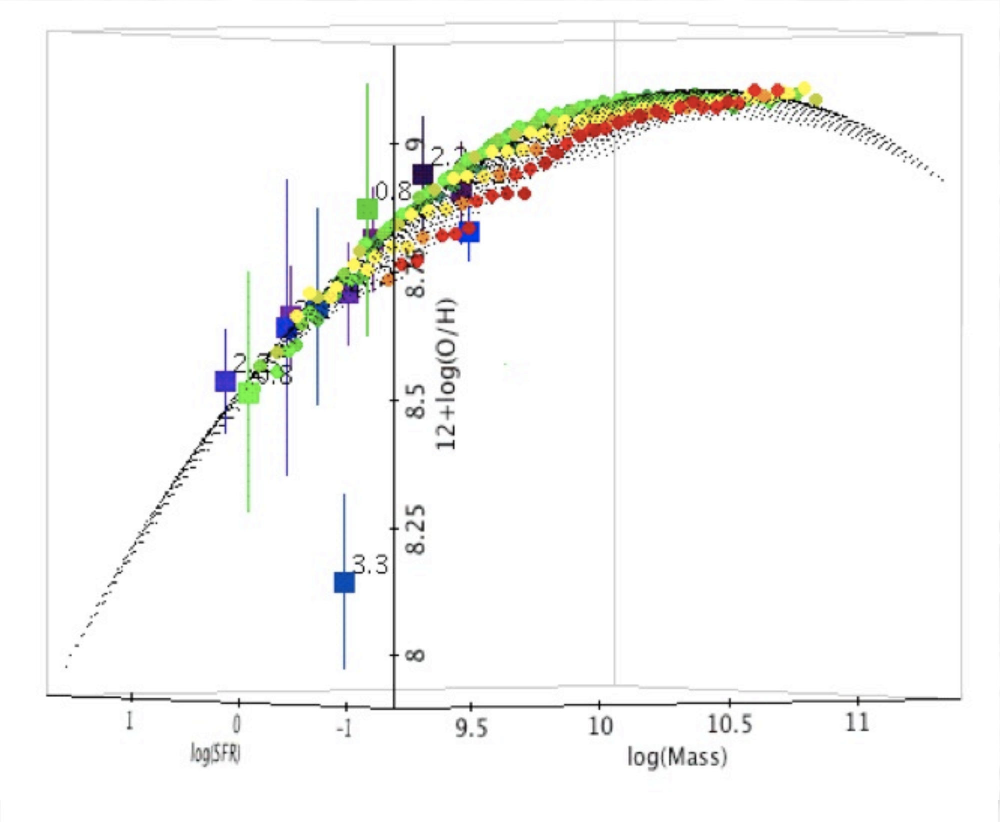
# Is the mass-metallicity really evolving?




Mannucci, et al. 2010, Cresci et al. 2011

Adding distant Galaxies at: z=0.8 (*Savaglio et al 2006*) z=1.4 (*Shapley et al. 2005, Liu et al. 2005, Wright et al. 2009, Epinat et al. 2009*) z~2.2 (*Erb et al. 2006, Law et al. 2008, Lehnert et al. 2009, Forster-Schreiber et al. 2009*) z=3.3 (*Maiolino et al. 2008, Mannucci et al. 2009*)

The Mass-Met evolution seems to be **only related to the increase of the SFR with z**, at least up to z~2



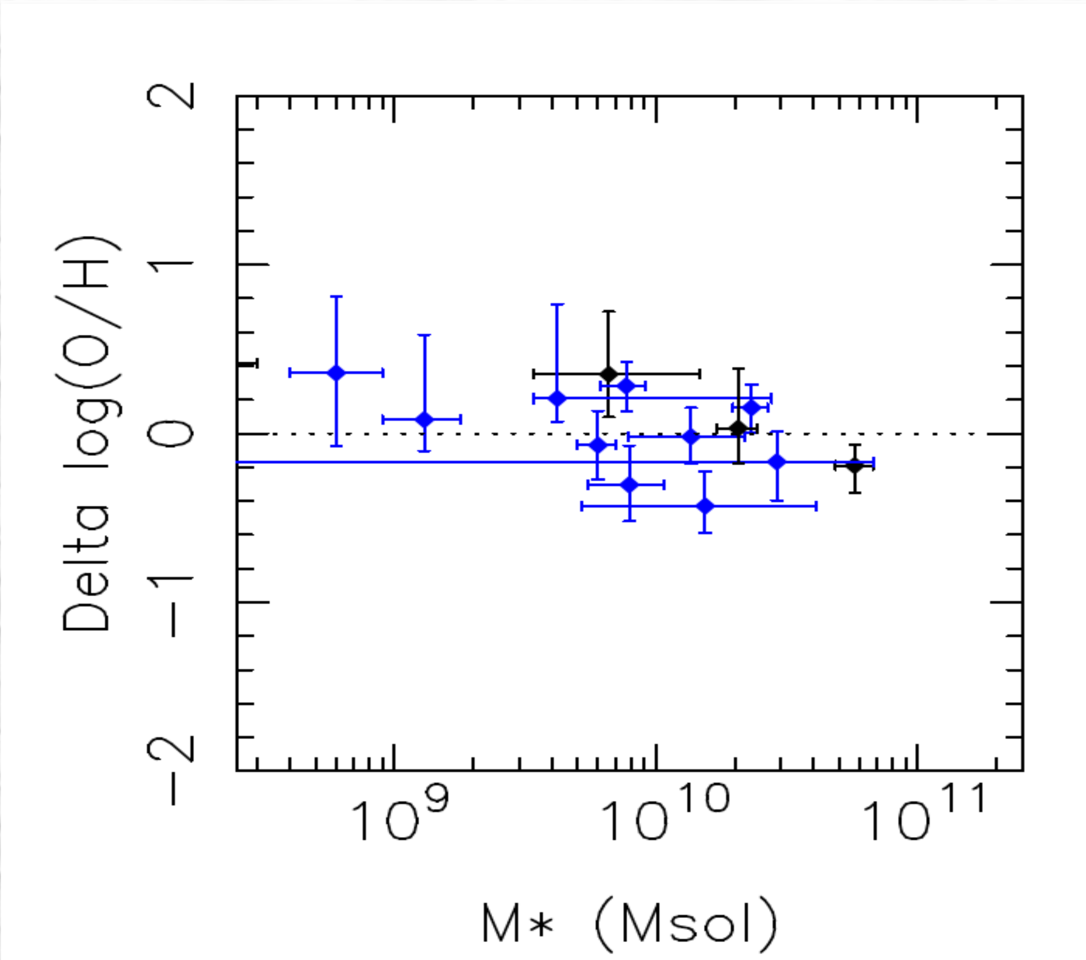

**No evolution up to z=2.5**

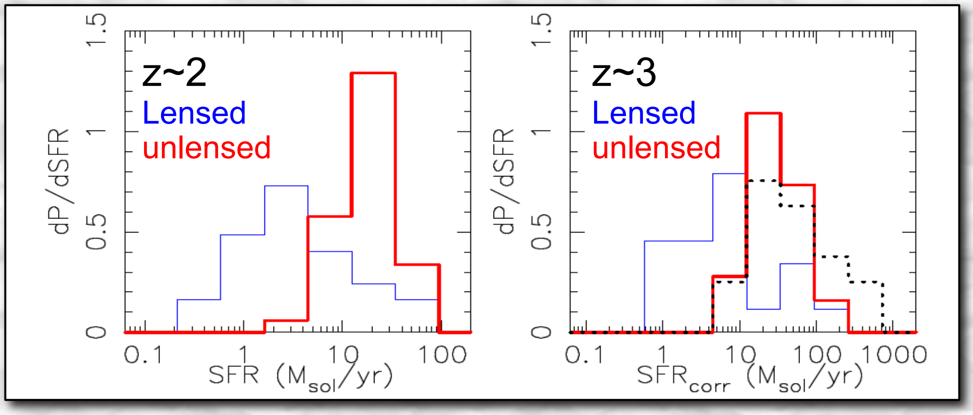
# FMR works!

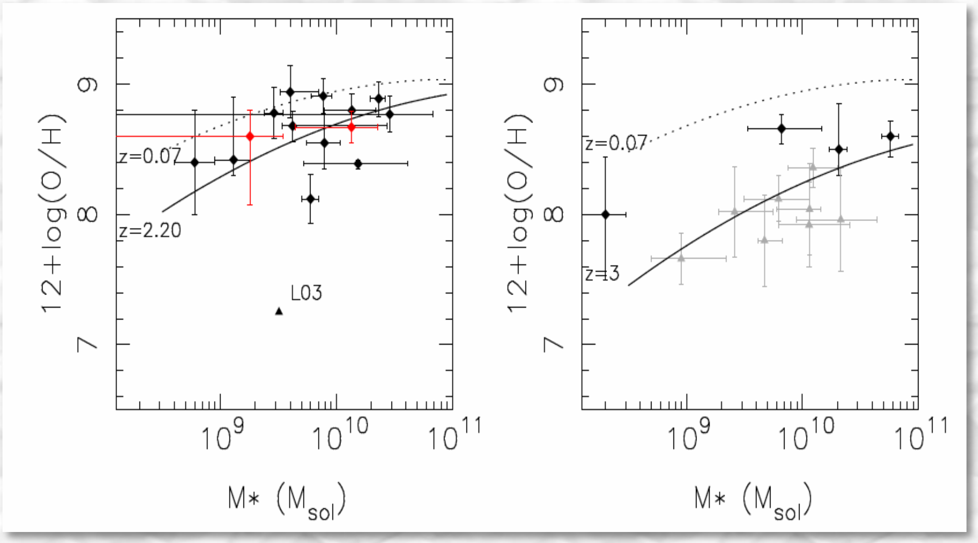
The presence of a FMR up to z~2.5 confirmed by several other *independent* observations of *differently selected* galaxy samples at low and high z

## Richard+2010: Gravitationally Lensed galaxies at z~2.5

Sampling lower SSFRs



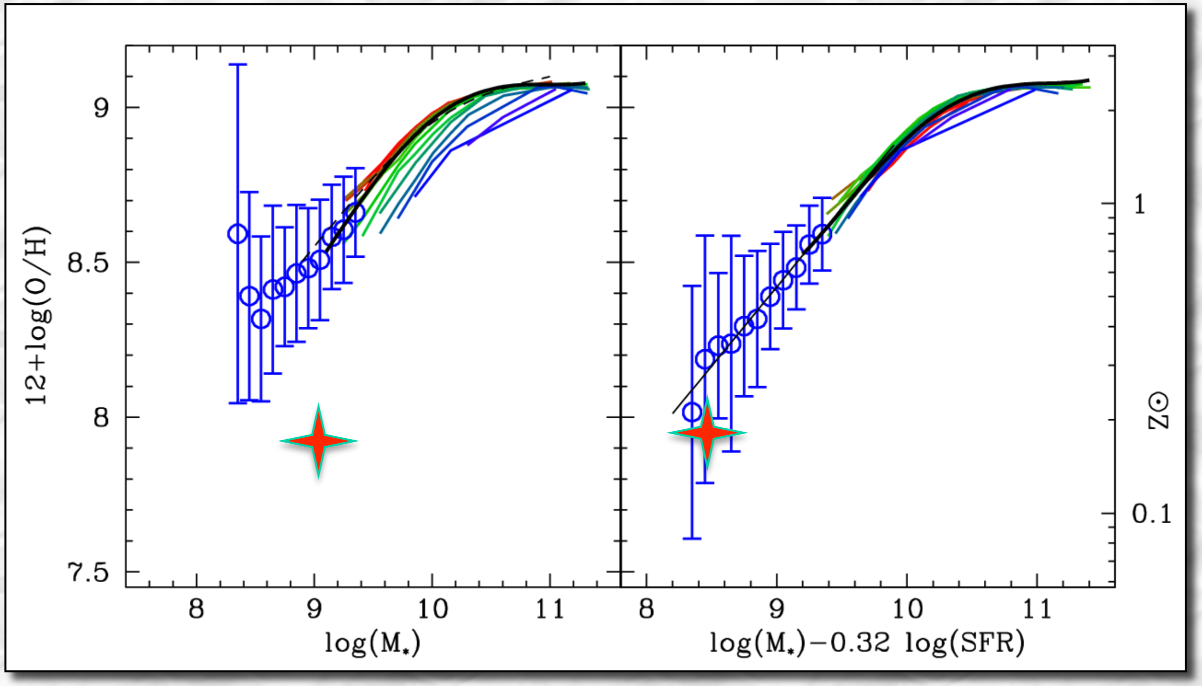



# Still not convinced?

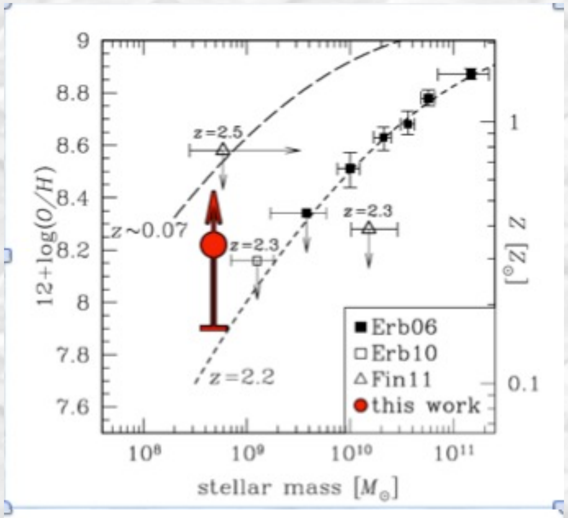
Erb et al. (2010)   Q2343-BX418   z=2.3
Deep spectrum: 12h Keck time

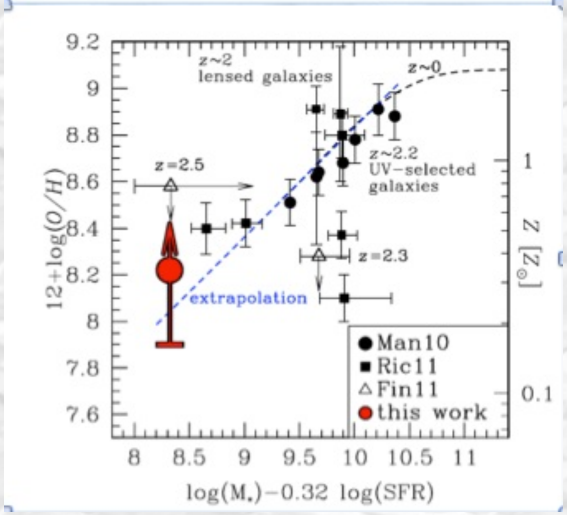
Observed 12+log(O/H)=7.90+/-0.2
SFR = 15 +/- 2 $M_\odot$/yr




See also: Kassin et al. (2011), Contini et al. (2011), Atek et al. (2011), Sanders et al. (2011), Buschkamp et al. (2011) …

Stacked Lyα emitters at z=2.2
(Nakajina et al. 2011)

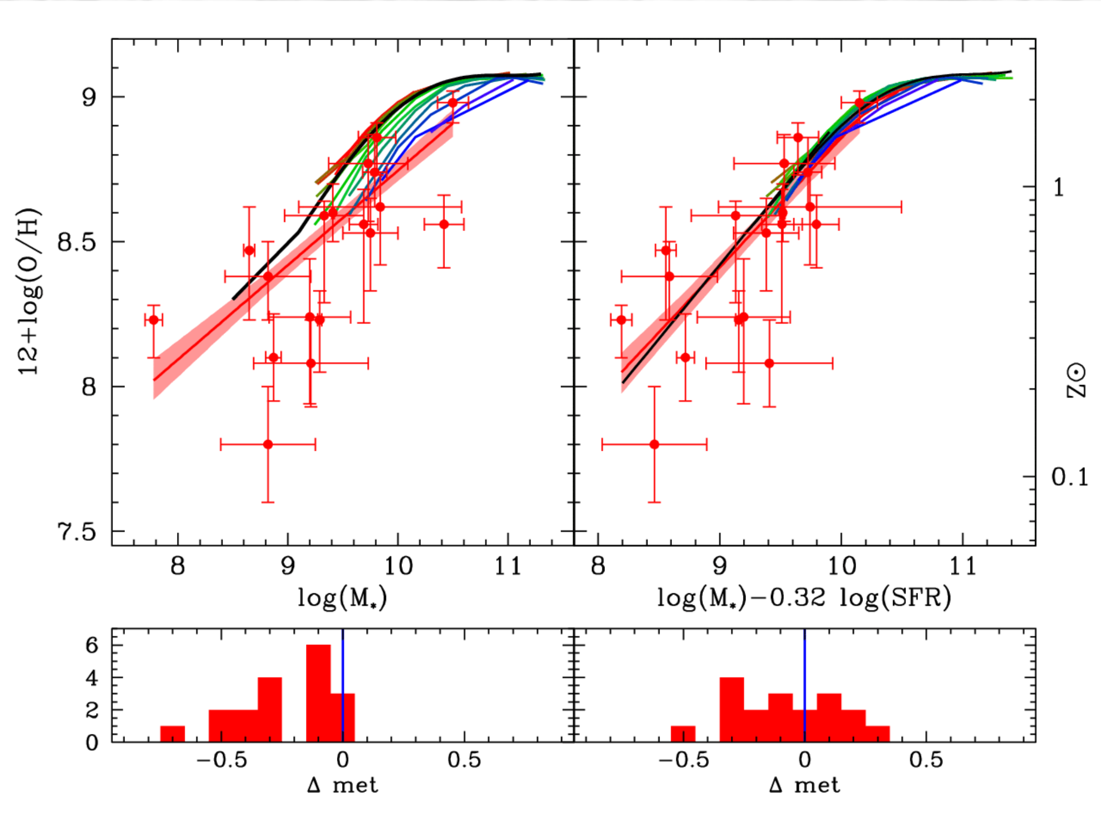


# Not yet??

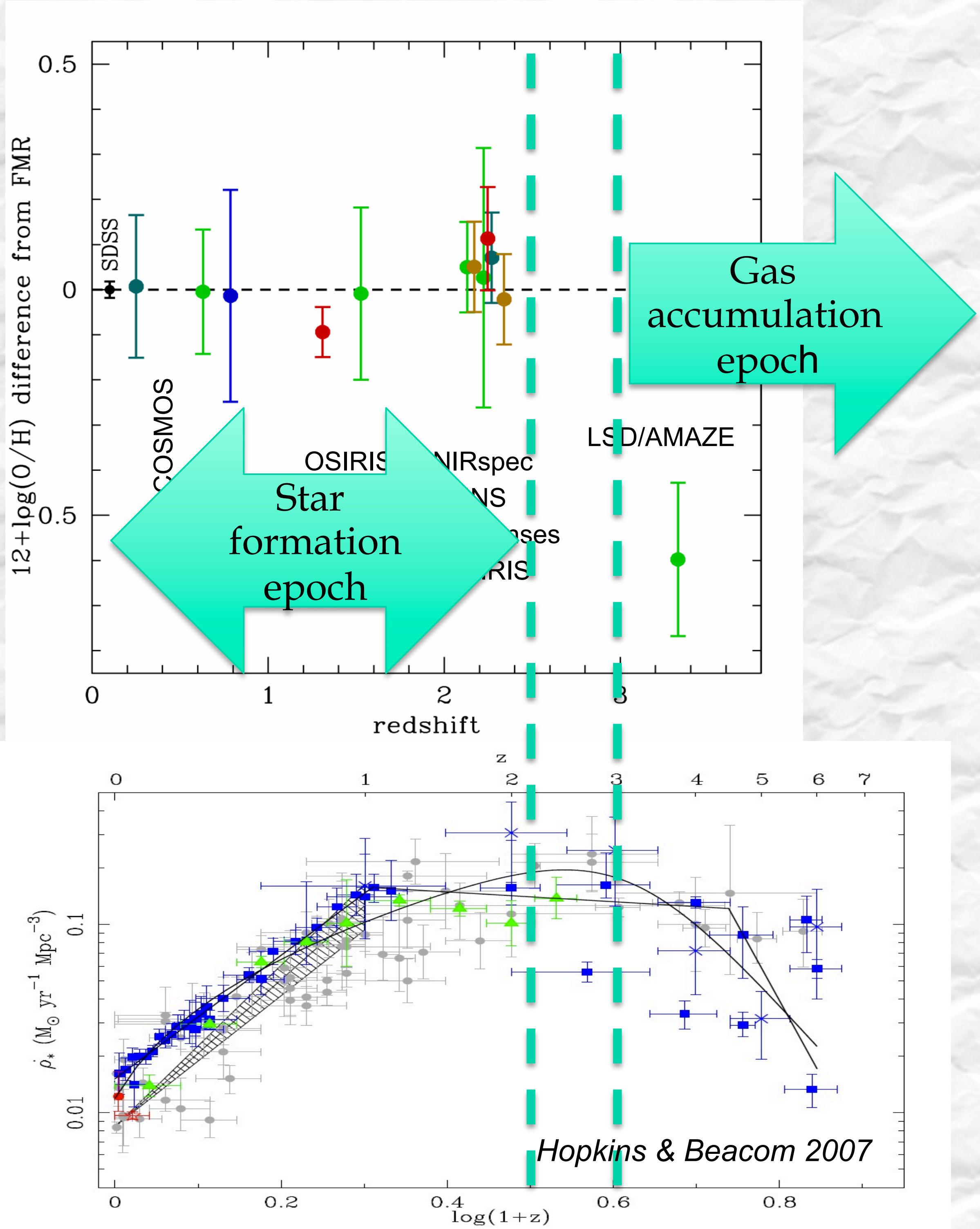
## Low metallicity in long GRB hosts?

## But GRB hosts are known to have high sSFR…




Stanek 2006, Wolf+2007, Modjaz+ 2008, Prieto+2008, Savaglio+2009, Levesque+ 2010, Han+2010

Mannucci et al. 2011, Kocevski et al. 2011, Vergani et al. 2011




# Evolution at z>3

## Is the difference of ~0.6 dex real?

Effects to be considered:

1. Metallicity indicators?
   - R23 + [NII]/Ha for SDSS
   - R23 only at z>2.5 (and z~0.8)
2. Evolution of ionization parameter?
3. Centering on [OIII]$\lambda$5007: bias towards low metallicity regions?
4. Selection effects:

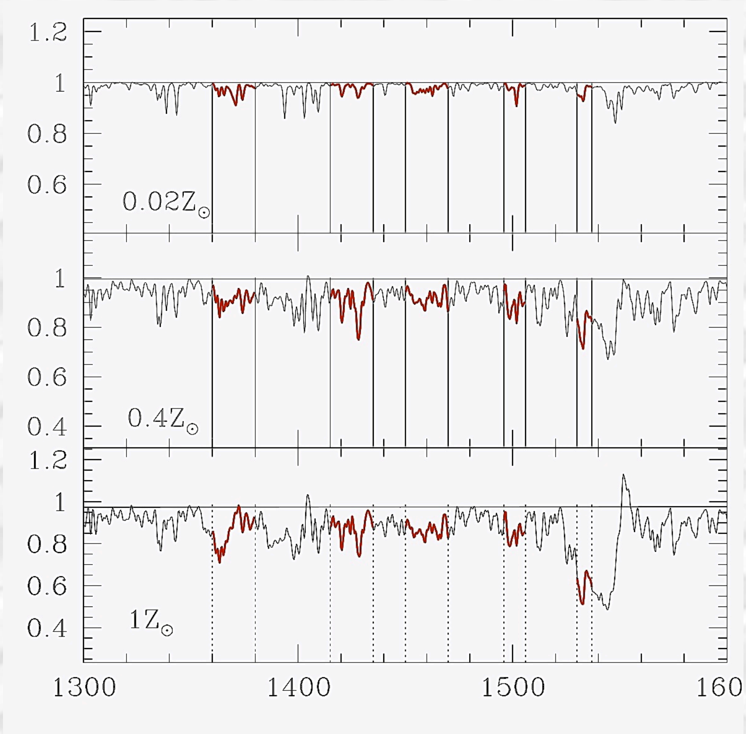
   a) largest SFR: youngest and more metal-poor?

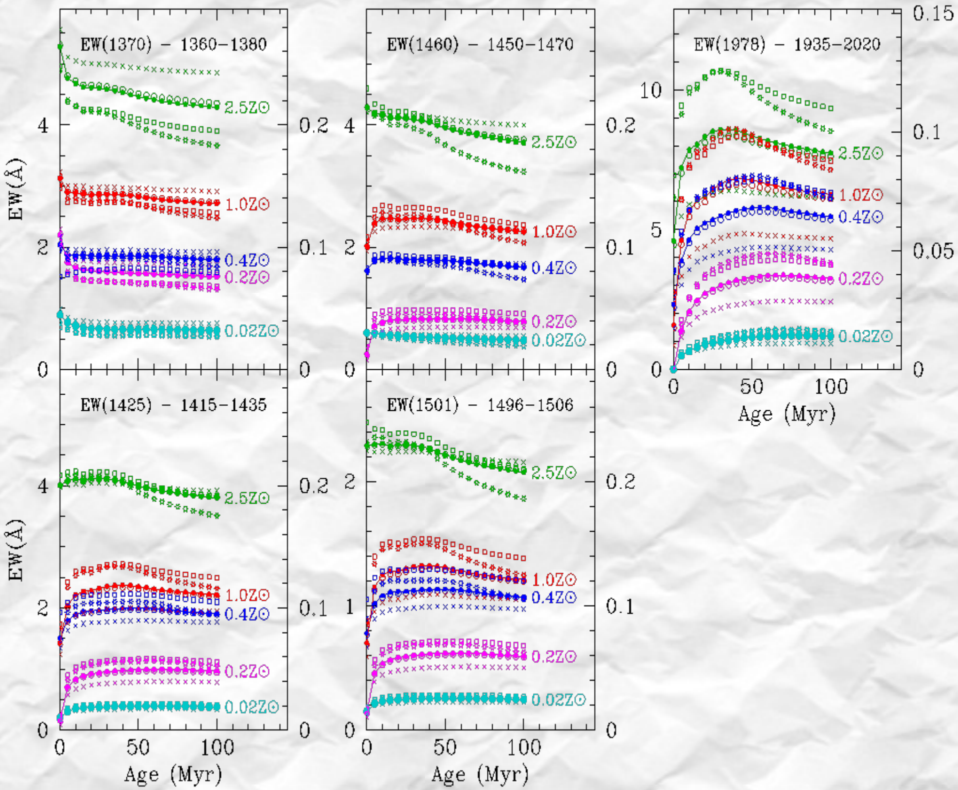
   b) UV-selection: less extincted?

Metallicity gradients also change between z=2 and z=3.5…

# Stellar Metallicities at high-z

Rest frame UV photospheric absorption features from hot stars can be used to derive stellar metallicities at high-z (e.g. Rix et al. 2004, Sommariva et al. 2011)




*Sommariva et al. (2011)*

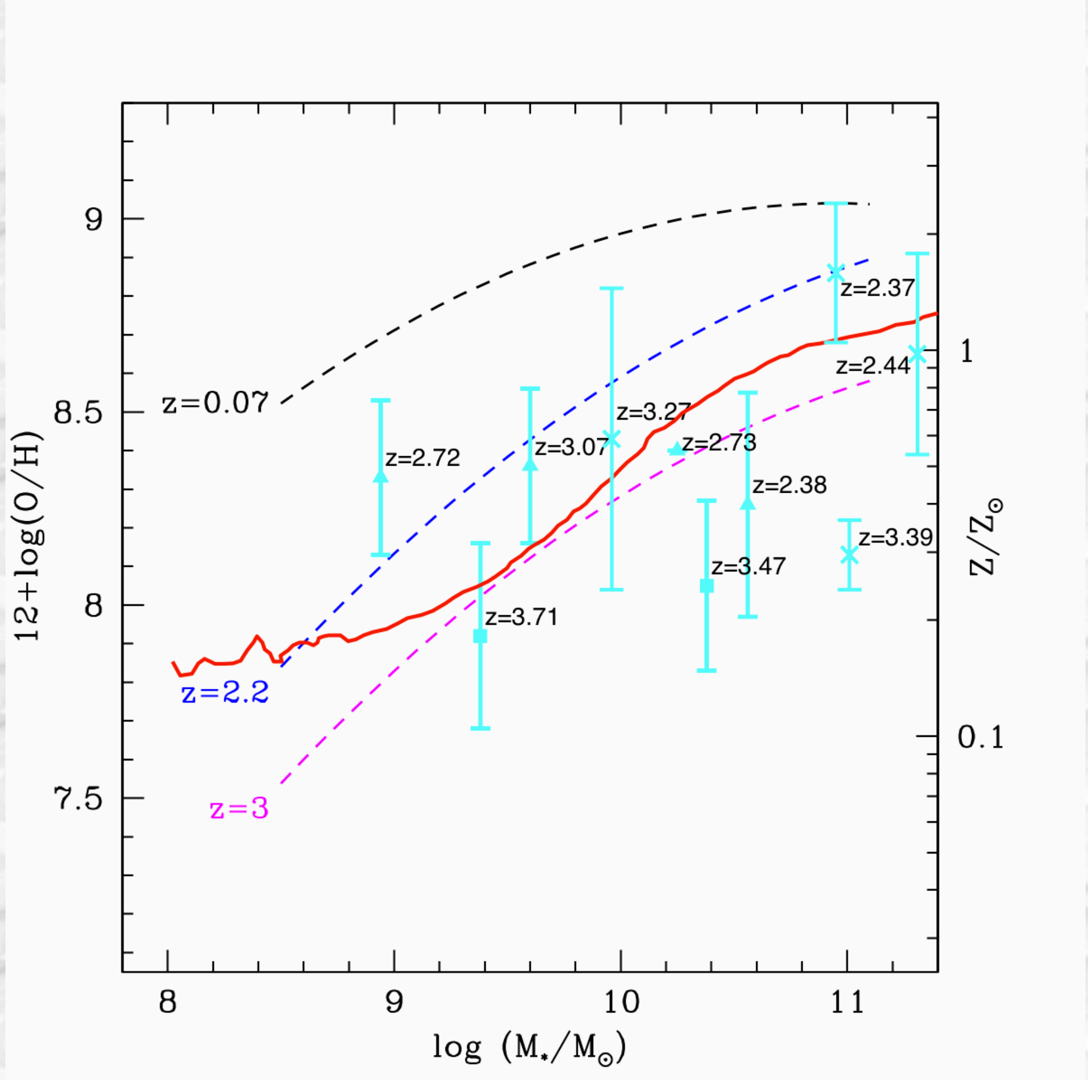
But high S/N on the continuum is required, only few measures available at high-z :

- on stacked spectra (Halliday et al. 2008, z~2)
- or gravitationally lensed galaxies (Pettini+02, Rix et al. 2004, Quider et al. 2009,2010; Dessauges-Zavadsky et al. 2010, z~2).

# Stellar Metallicities at high-z

We obtained FORS optical spectra of 5 AMAZE unlensed galaxies (37 hours total) to measure stellar metallicities at z>3

**Gas phase** and **stellar metallicities are comparable** in these star forming galaxies at high-z




**First mass-stellar metallicity relation at high-z: low chemical abundances confirmed** with an independent measure

*Sommariva et al. (2011)*

# Summary

## ➡ Metal Content in Galaxies

*Fundamental to understand the main drivers of galaxy evolution, especially meaningful when considered in concert with stellar and gas content*

## ➡ Chemical evolution in high-z star-forming galaxy:

*Evidence for rapid metal enrichment and significant inflows/outflows at high-z;*

*Resolved metallicity gradients provide evidence of pristine gas accretion in star forming disks at high redshift;*

*First measure of stellar metallicity in high-z star forming galaxies*

## ➡ Fundamental Metallicity Relation:

*Local galaxies define a tight surface in this 3D space SFR-Met-M$_*$, which appear not to evolve up to z~2.5;*

*It has to be explained by the interplay of infall of pristine gas, outflow of enriched material and star formation history (see e.g. Dave', Finlator & Oppenheimer 2011)*