Metallicity Near and Far

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Multiwavelength Views of the ISM in High-Redshift Galaxies

Santiago, 29/06/2011

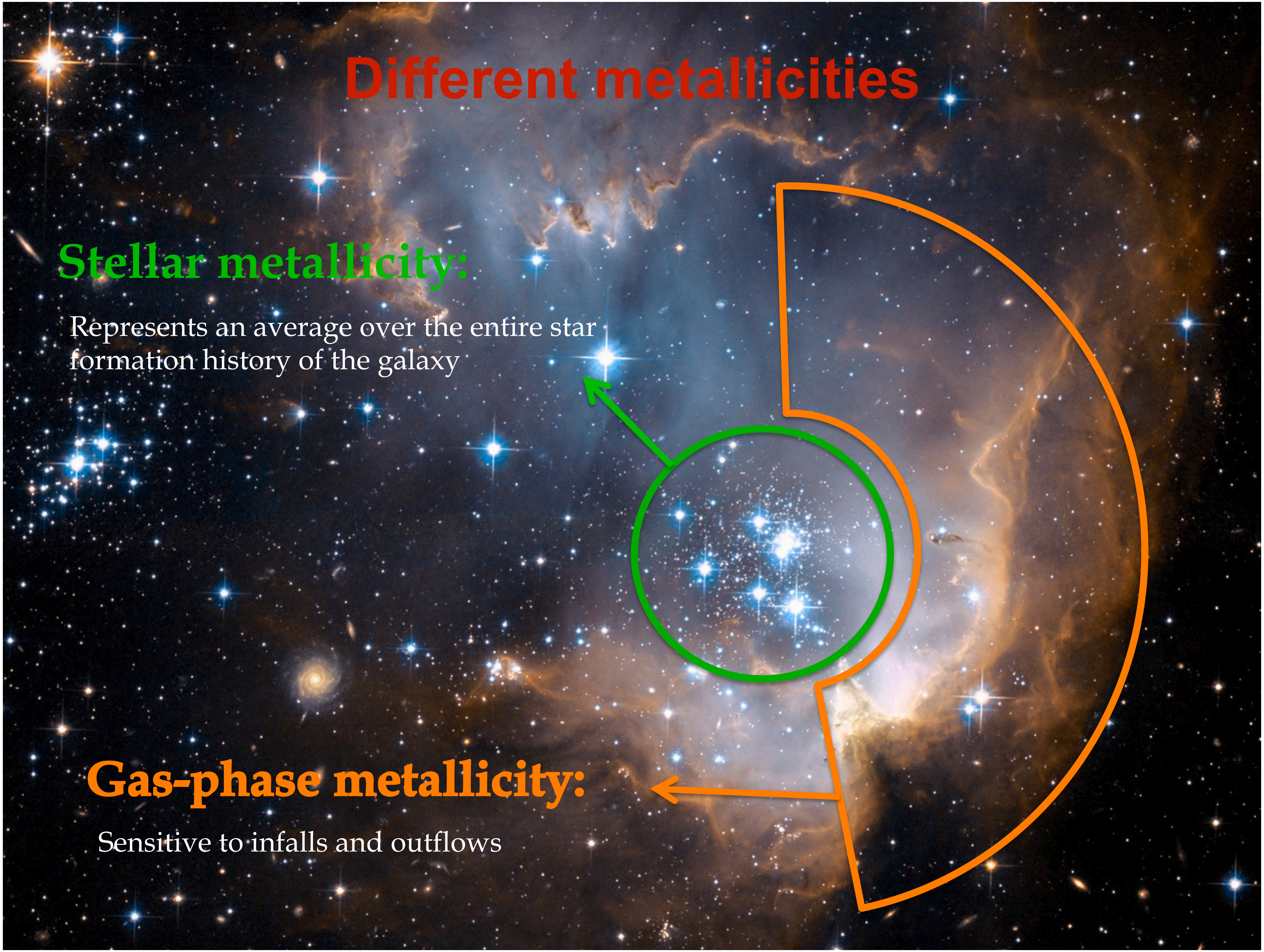
metallicity: a fundamental parameter

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

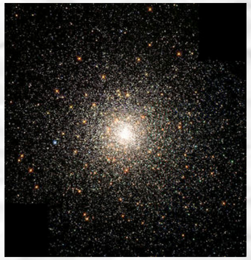
⋆ Relative element abundances reflect the cycling of gas through stars, and any exchange of gas between galaxy and its environment (infall/outflows)

↓

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

Measuring metallicities



Stellar Metallicity:

- Measured comparing the observed spectra with population synthesis models; high S/N, very hard at high-z

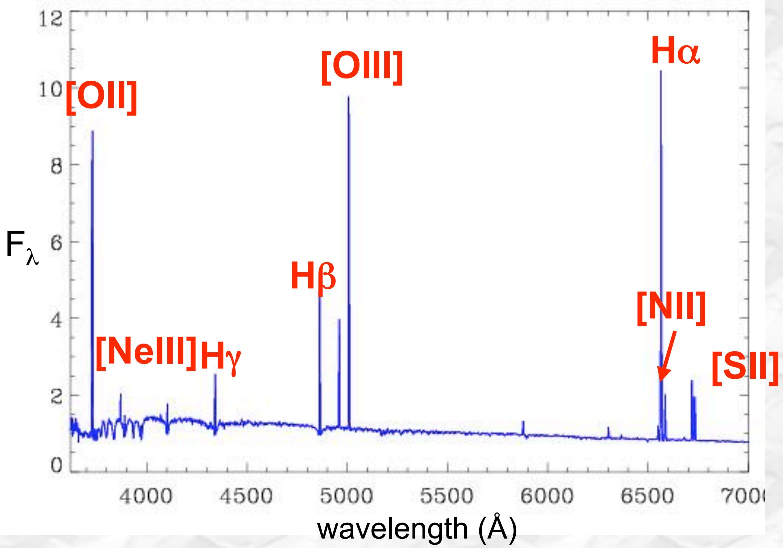
Gas Phase Metallicity:

- can be accurately determined through the measurement of *electron temperature* (collisionally excited lines as [OIII]λ4363, Pilyugin+01; Izotov+06; Pilyugin+10)
- or *faint recombination lines* (Peimbert 2003; Garcia-Rojas+04, 05, 06; Esteban+09)
- but accessible only in nearby low metallicity HII regions

Strong line calibrations:

R23=([OIII]5007+[OIII]4959+[OII]3727)/(Hβ)
[NII]6584/Hα
[NII]6584/[OII]3727 etc

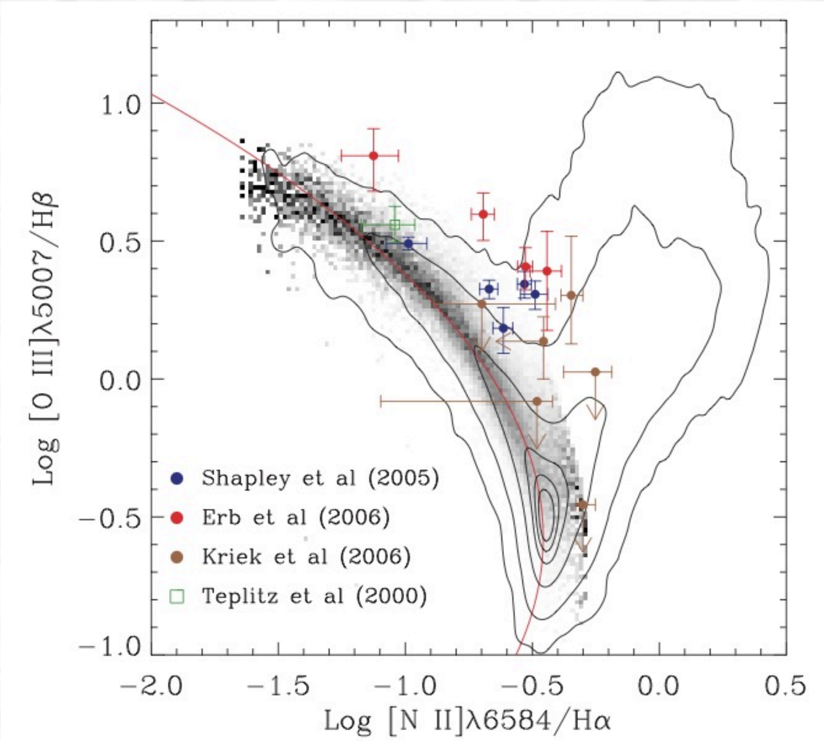
- Calibrated empirically (Kobulnicky & Zaritsky 99, Pilyugin+01, 10; Pettini & Pagel 04, Liang+06),
- through photoionization models (Kewley & Dopita 02; Tremonti+04; Kobulnicky+04, Dopita+06, Dors +11)
- or a combination of the two (Denicolo' et al. 2002; Nagao et al. 2006; Maiolino et al. 2008)



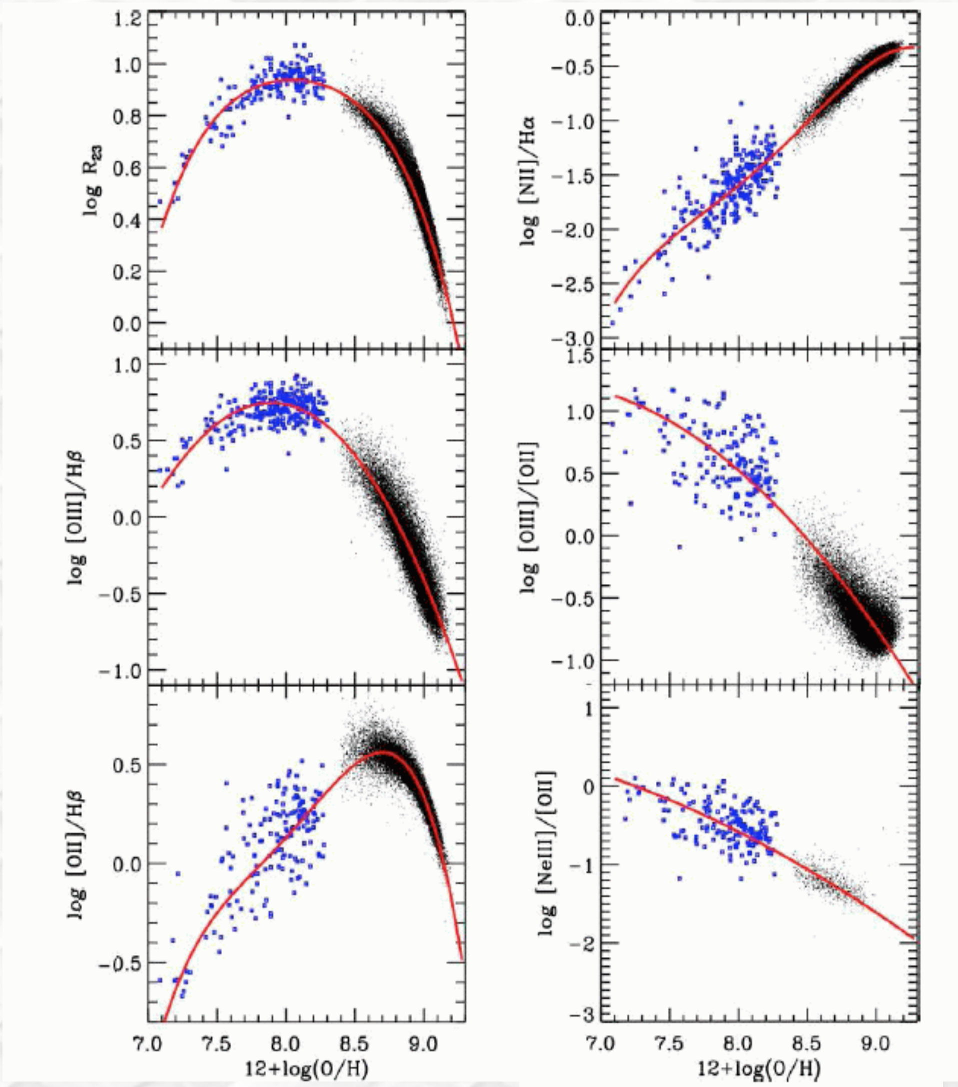
Strong Line calibrations

Warning!

- Different calibrations do not agree
- Some sensitive to extinction
- some have a double solution
- all depend also on other physical parameters: ionization, density, N/O abundances etc…
- possible "evolution" due to different conditions at high-z

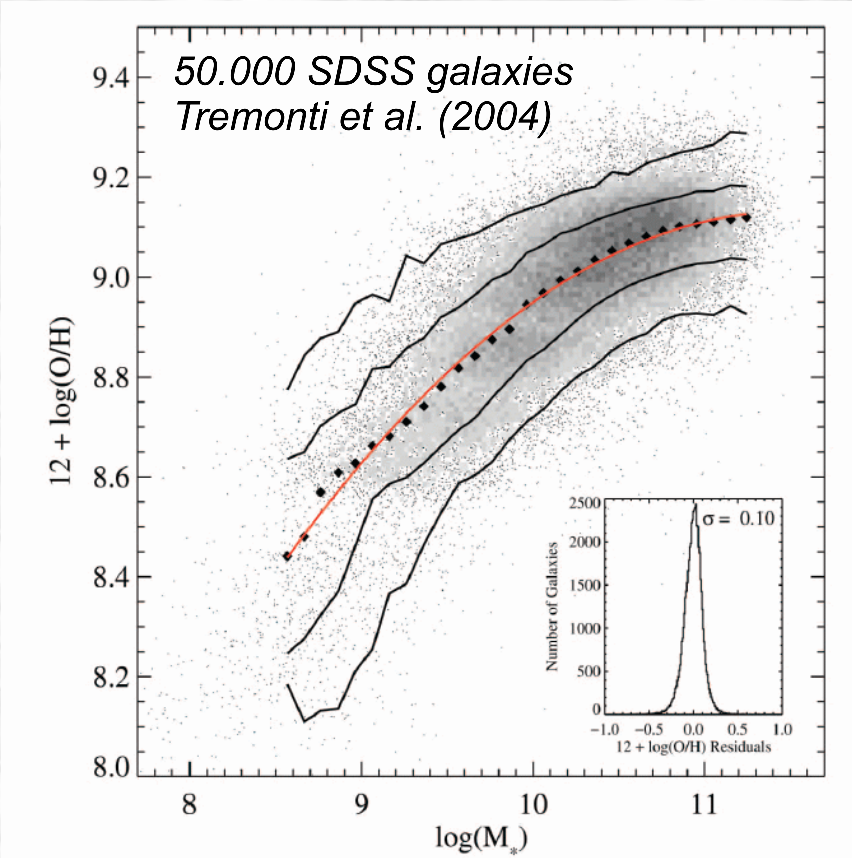


Brinchmann et al. 2008



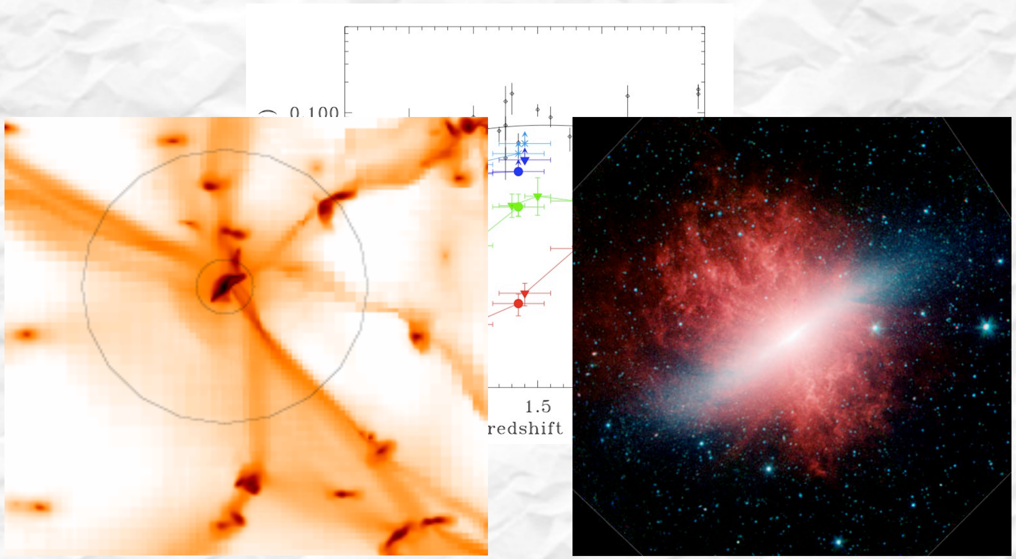
Nagao et al. 06

The mass-metallicity relation



Possible Drivers:

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

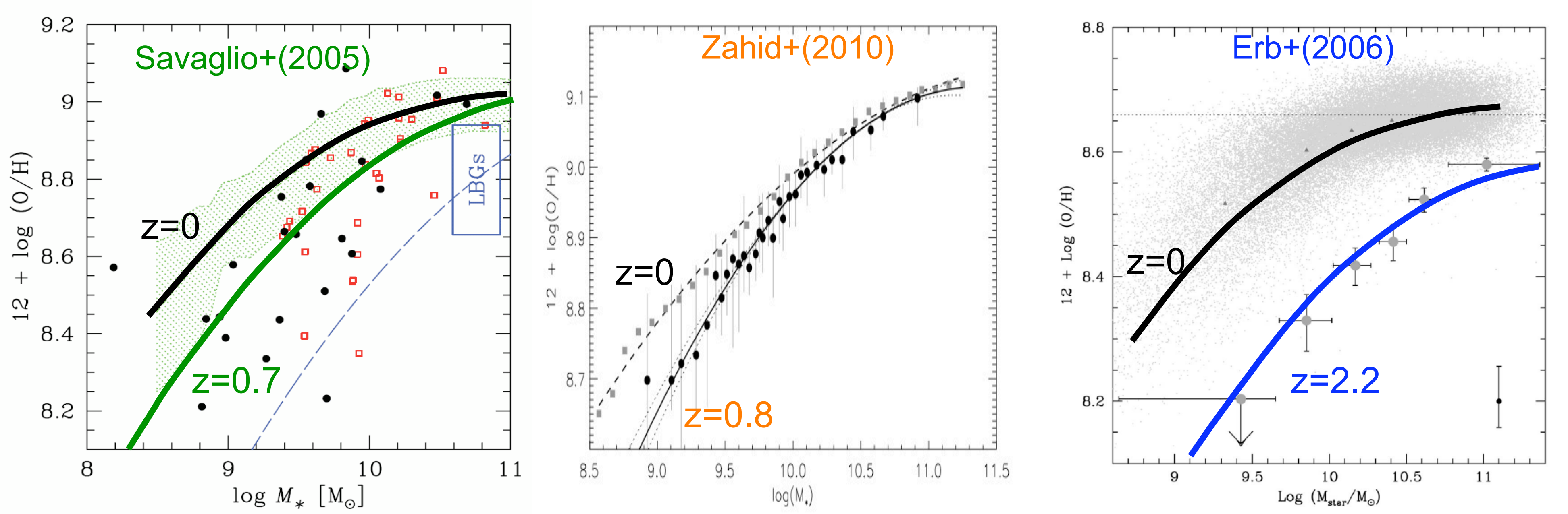


Crucial test for models!

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…

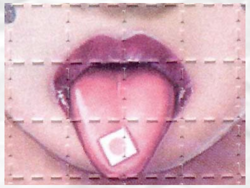
Mass-Metallicity Evolution



Higher redshifts, z>3:

- Large evolution of the model expectations from z=0
- Before the peak of cosmic star formation (5-10% of stars formed)
- Strong Evolution of the merger rate
- Formation of massive galaxies

AMAZE… …with LSD



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

AMAZE (Assessing the Mass-Abundance redshift(Z) Evolution):

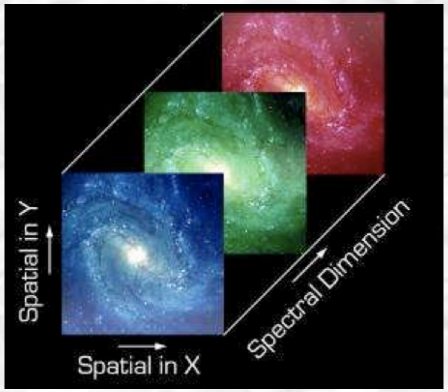
- seeing limited, a sample of 30 LBGs at 3<z<5
- 180h (PI: Maiolino) Maiolino et al. 2008, Cresci et al. 2010, Troncoso et al. 2011

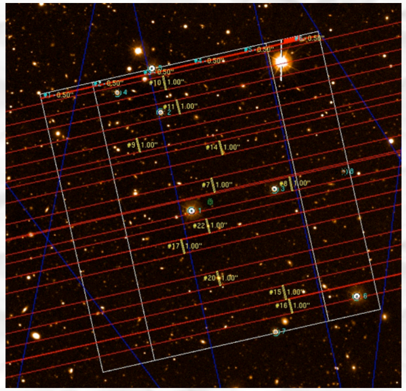
LSD (Lyman-break galaxies Stellar populations and Dynamics):

- 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

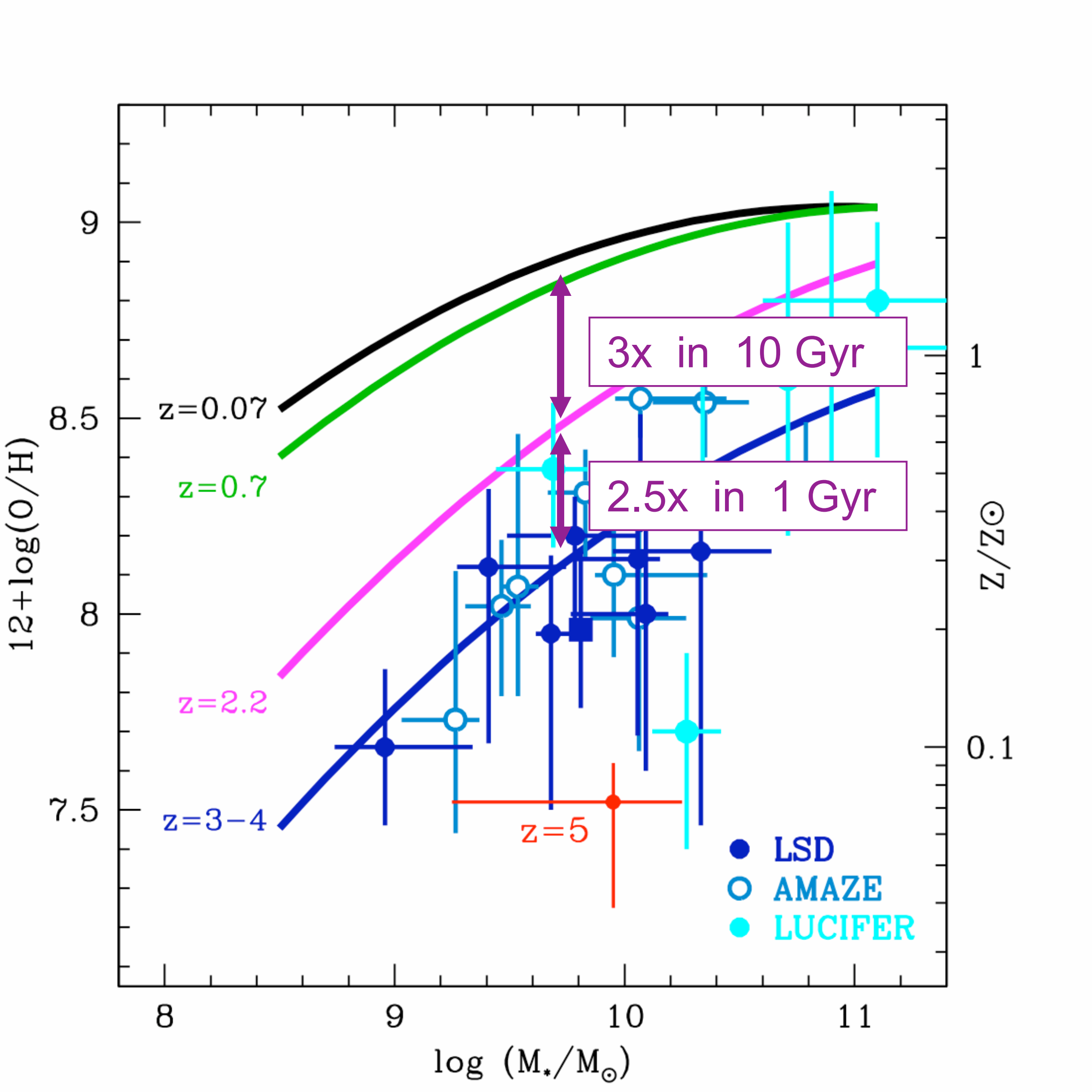
2. Near-IR Multi Object Spectroscopy with LUCIFER@LBT

- 4 Steidel fields, ~10 z=3 LBGs/field
- 40h (PI: Cresci) observations ongoing…





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, Troncoso+11))
● LSD (Mannucci +09)
● LUCIFER (Cresci+11)

z~5 ● AMAZE

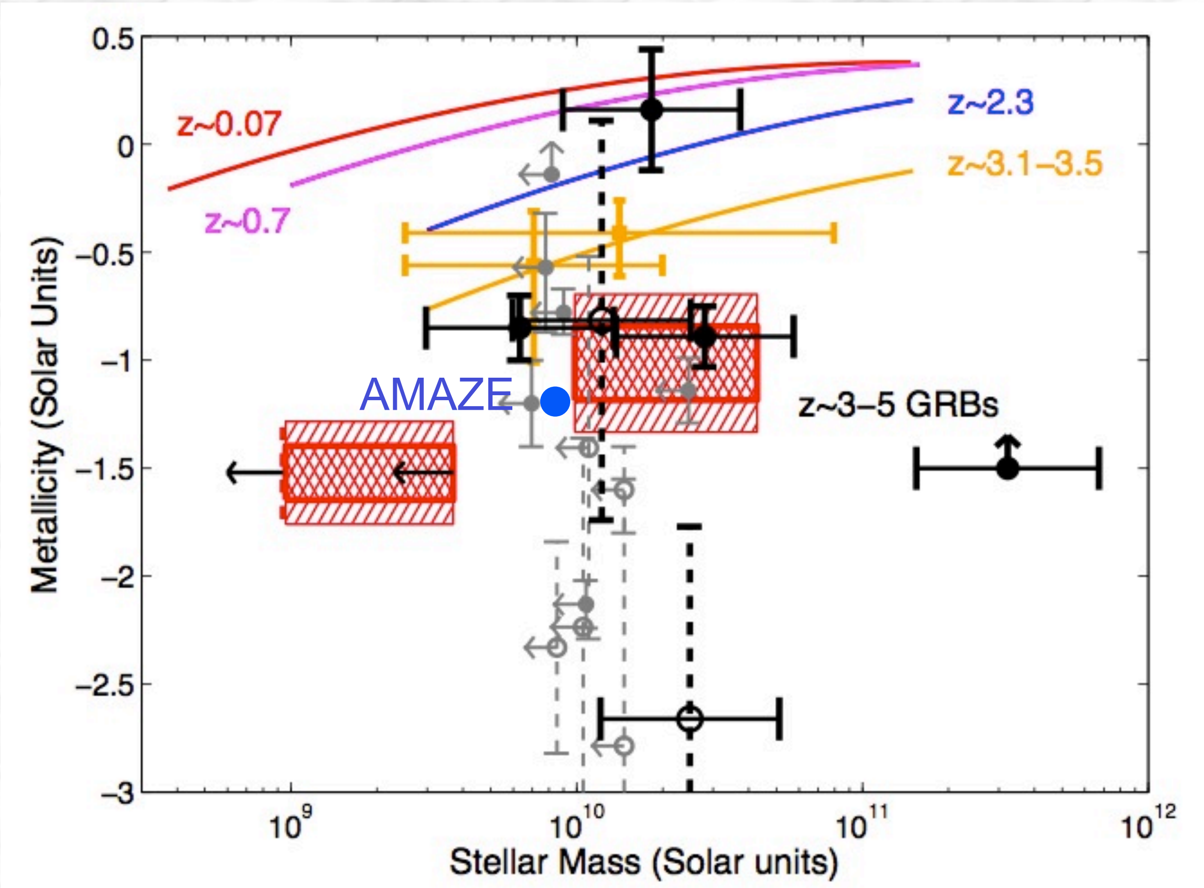
M-Z relation already in place at z~3.5

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

(BUT: it is not tracing the evolution of individual galaxies)

Evolution of the mass-metallicity relation

At z>3 conventional direct metallicity measurements are extremely challenging, but long duration GRBs can be used at probes of the hosts ISM



Afterglow absorption metallicity from SII+Lyα in 20 GRB hosts at z~3-5 (Laskar et al. 2011)

Suggests further evolution of the M-Z relation at z>3, confirming AMAZE result on a single lensed LBG

Laskar et al. 2011

Inflows and Outflows

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

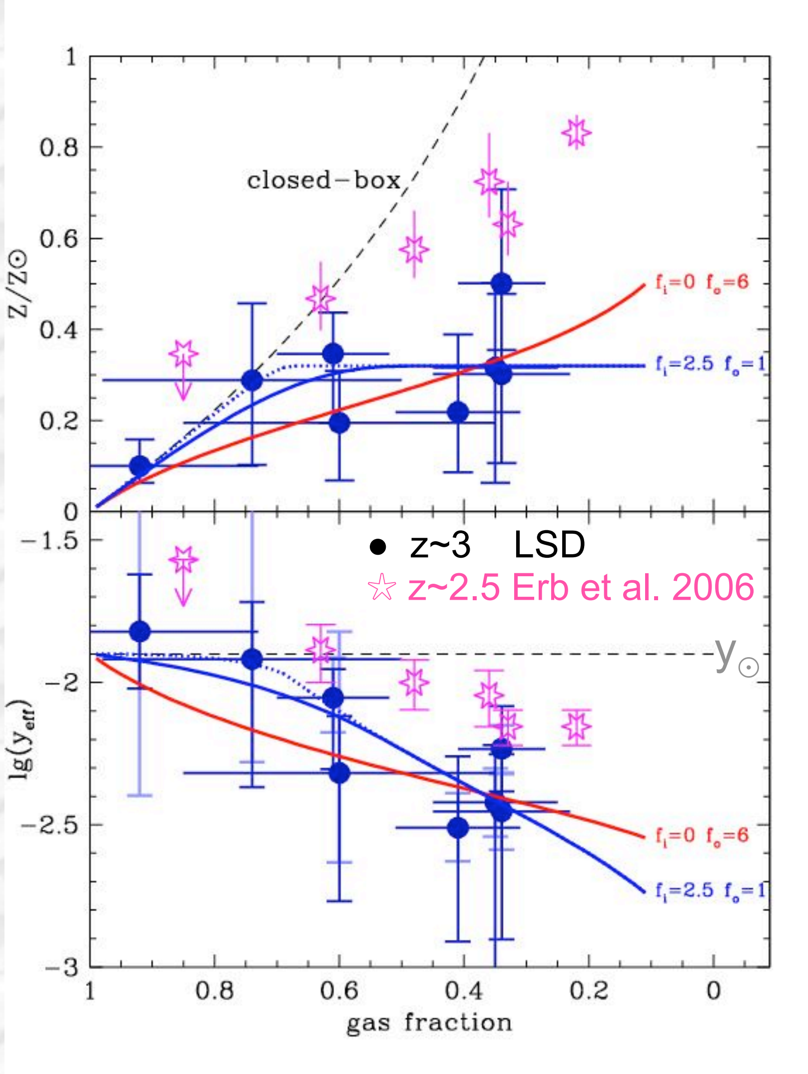
$$Z = y_{true} \cdot \ln(1/f_{gas})$$

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



Mannucci et al. 2009

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

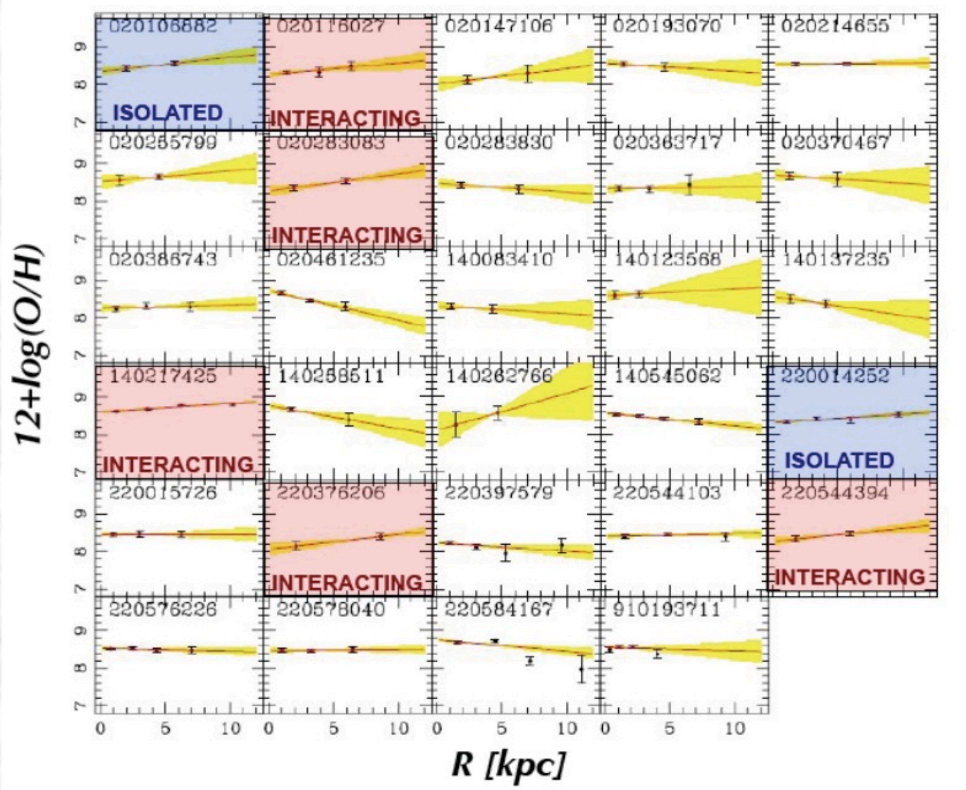
→ *Fingerprints of galaxy evolution!*

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

At higher redshift, steeper gradients measured in two gravitationally lensed galaxies at z~1.5 and z~2 with near-IR IFU spectra, supporting "inside-out formation"

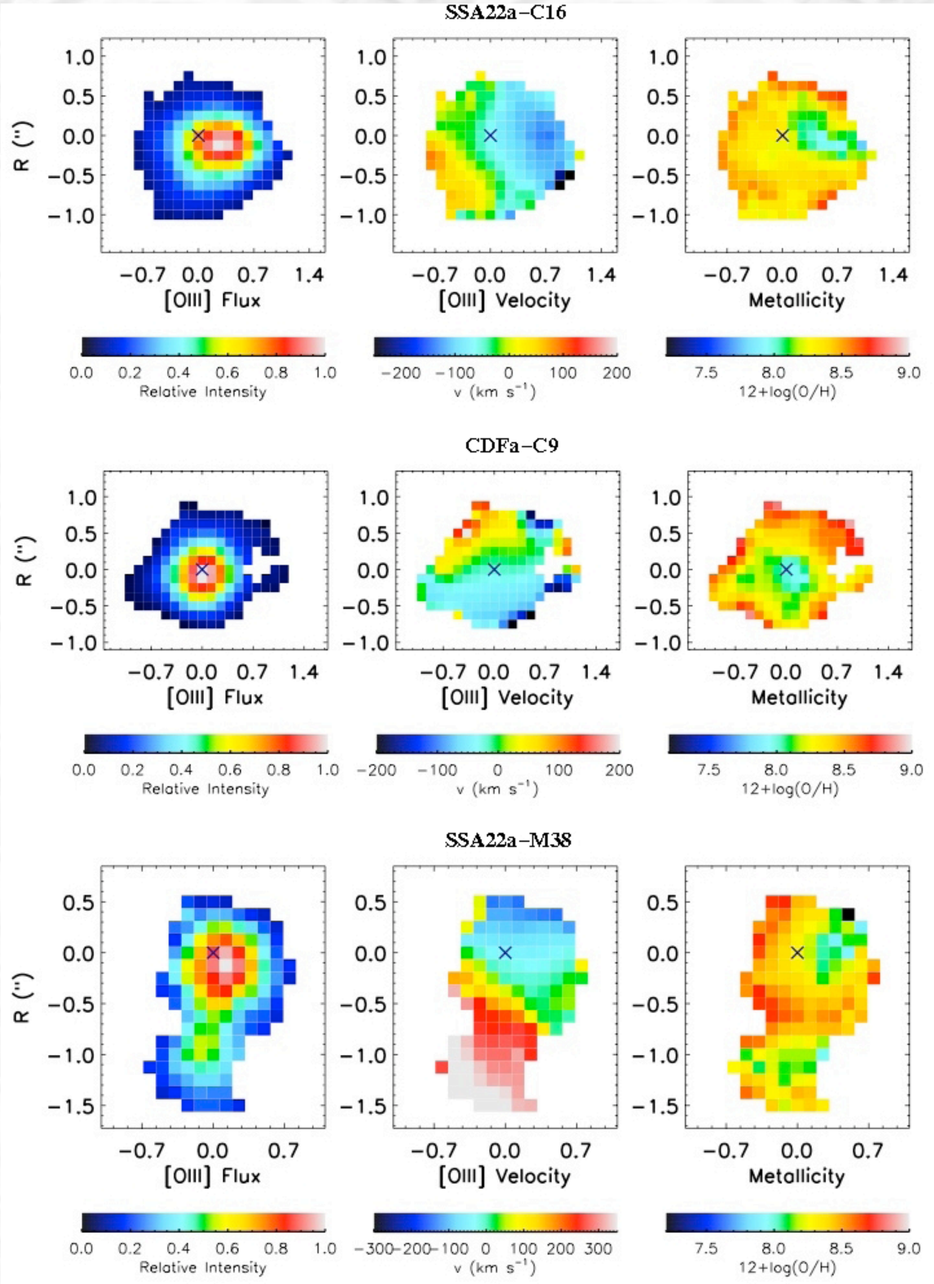
But more complex situation in larger samples: even positive "inverted" gradients at z~1.5 in MASSIV galaxies

(but see also Werk et al. 2010 at z=0)



Contini et al. 2011

Metallicity Gradients



Cresci et al. 2010, Nature

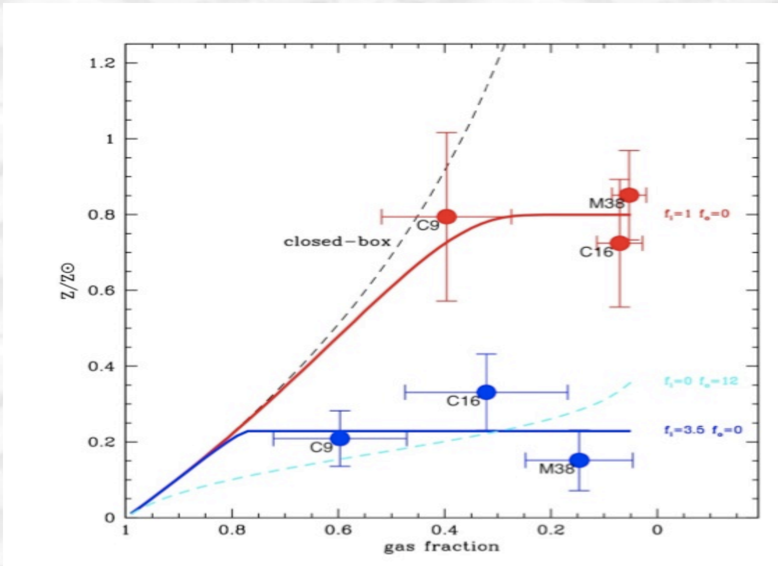
Thanks to the AMAZE/LSD data

First metallicity maps at z~3:

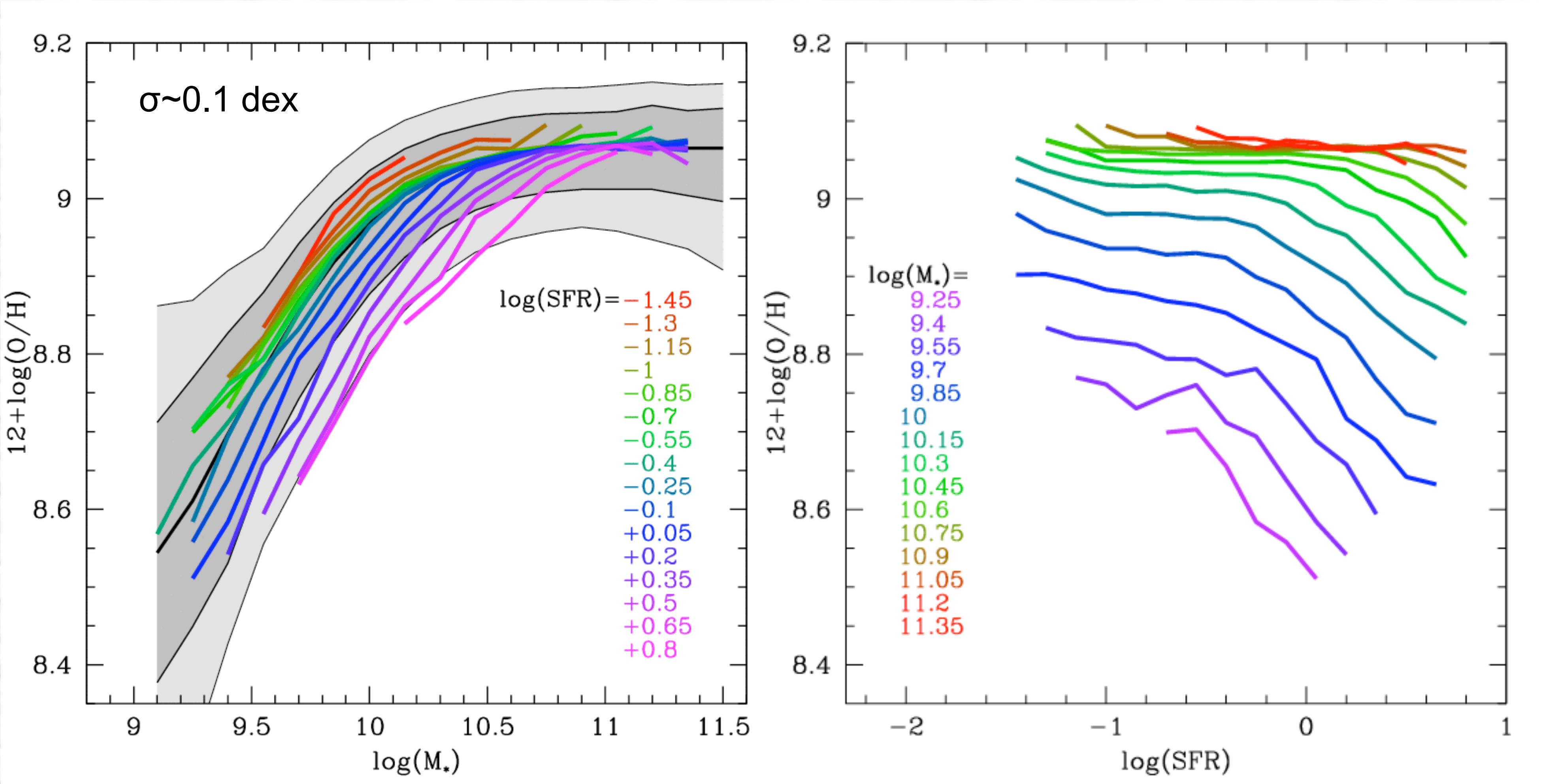
- Three undisturbed disks
- Well defined regions close to the SF peak are less metal enriched than the disk

⬇

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



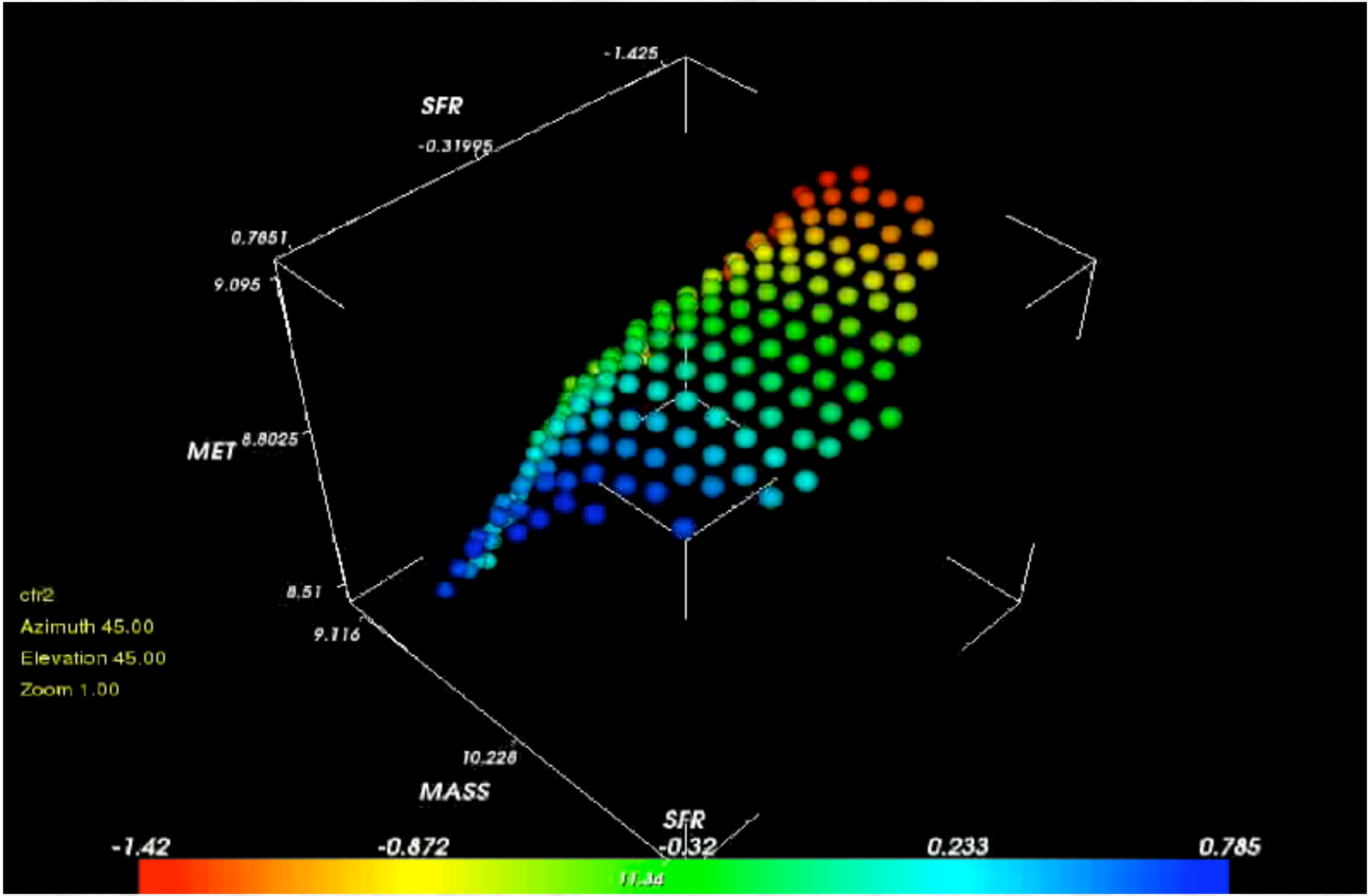
Is there a relation between metallicity, mass and SFR?



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

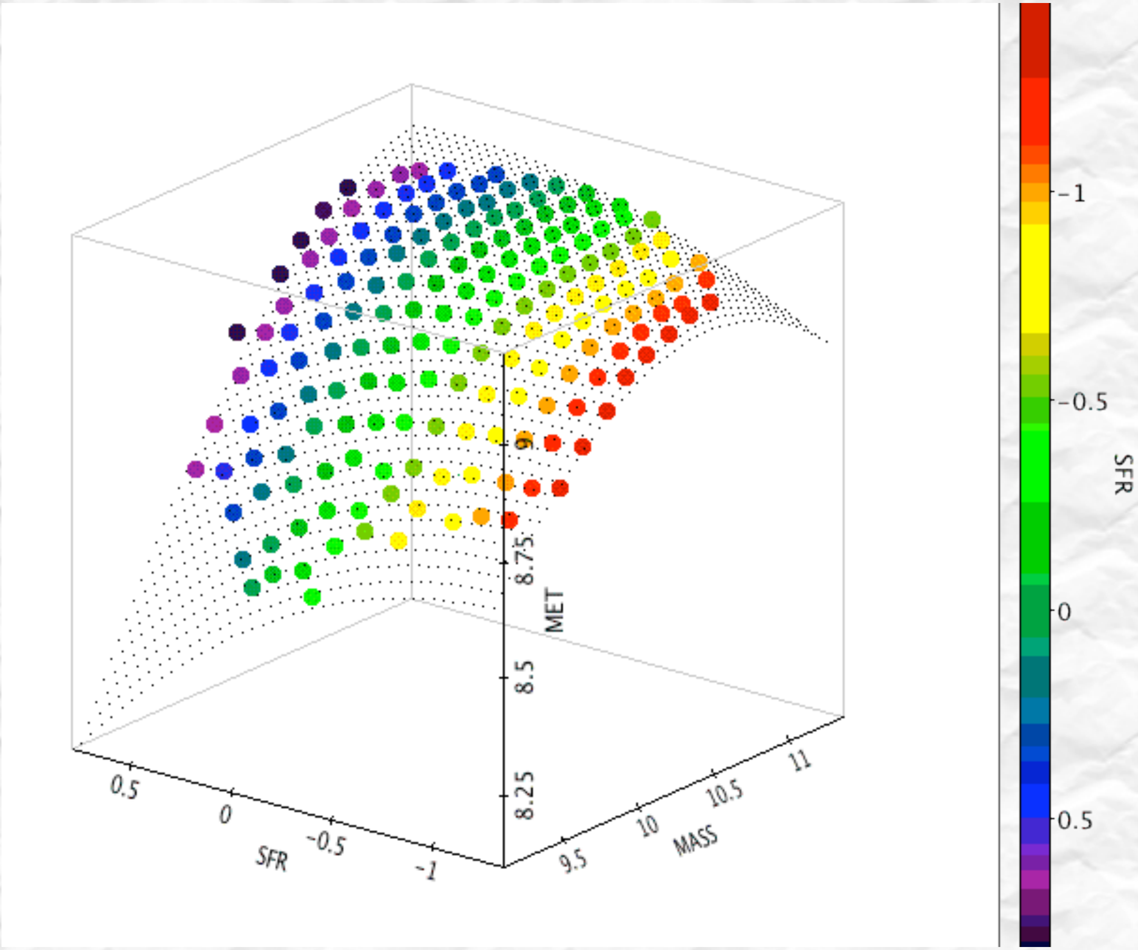
The Fundamental Metallicity Relation



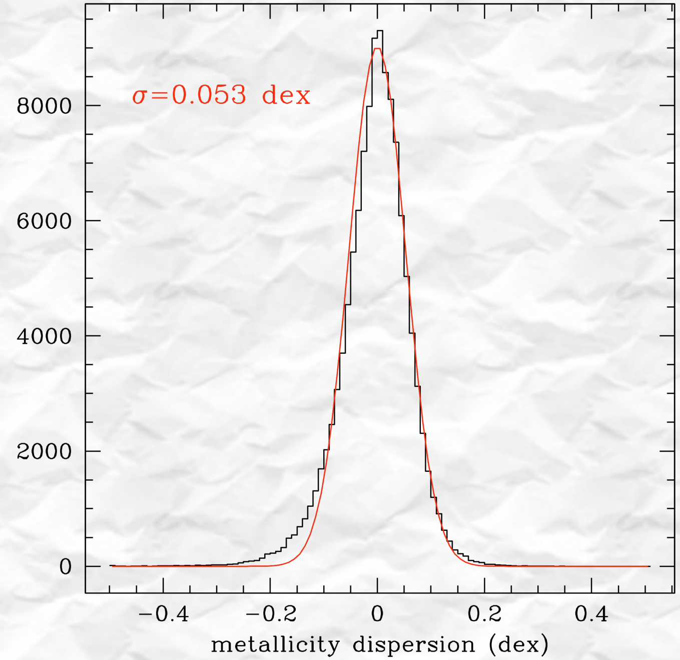
Mannucci, Cresci et al. 2010

The Fundamental Metallicity Relation

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

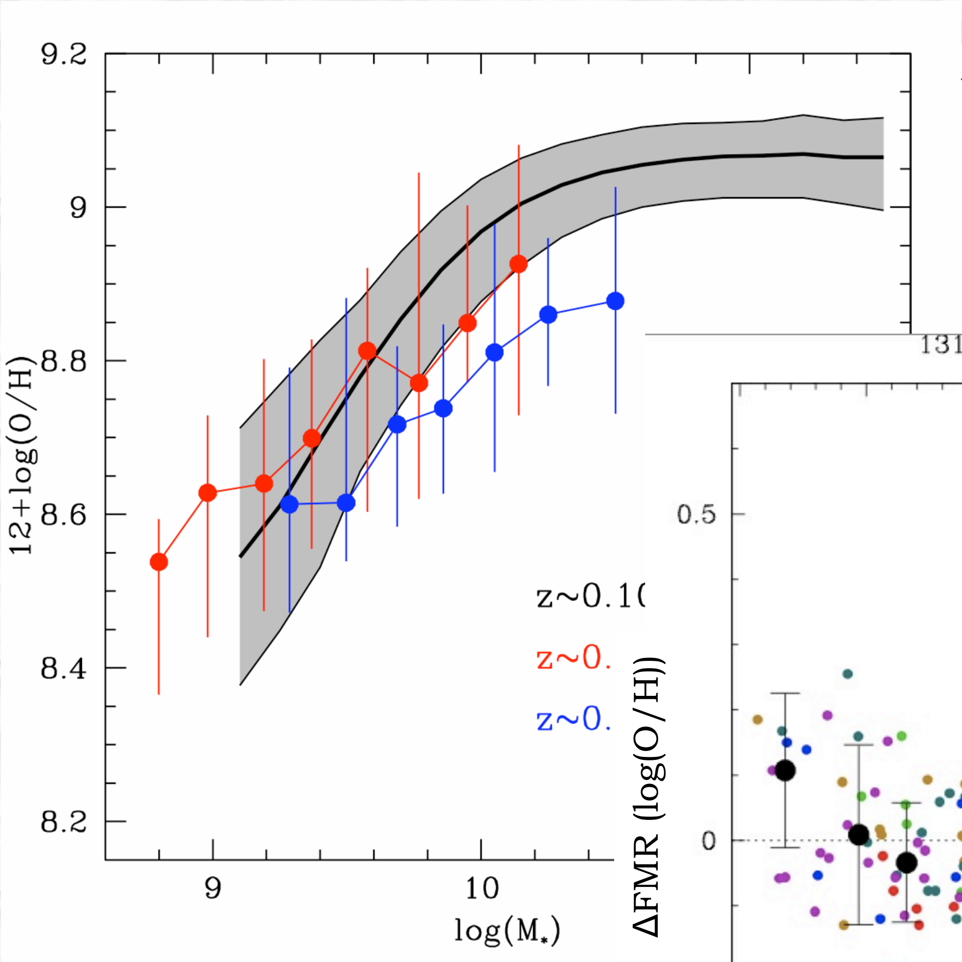


Dispersion of the original Mass-Met:
- half systematic (SFR)
- half intrinsic: ~12%



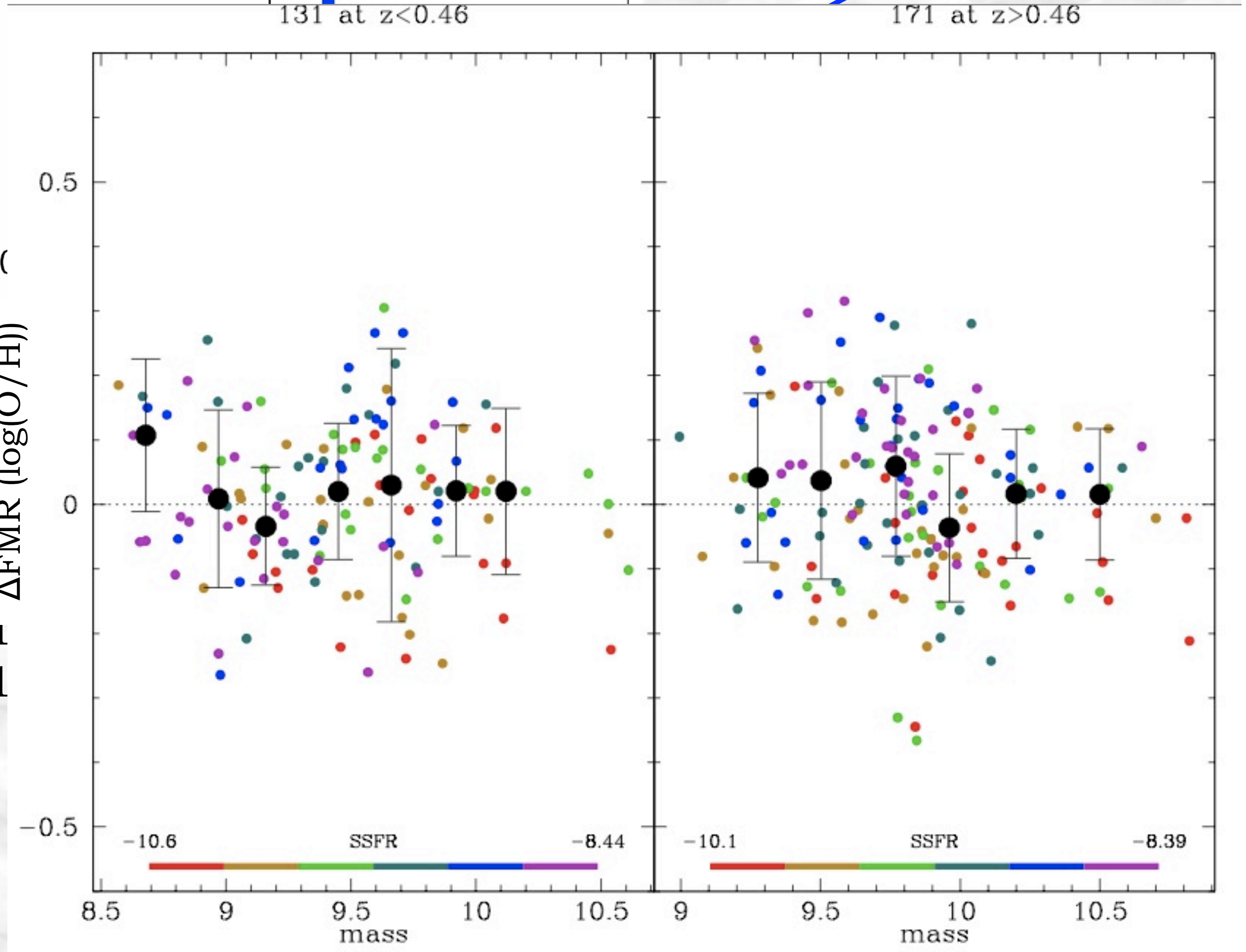
Mannucci, Cresci et al. 2010

Going to higher z with zCOSMOS



M-Z relation is evolving at z~0.62...

Using R_{23}
171 galaxies

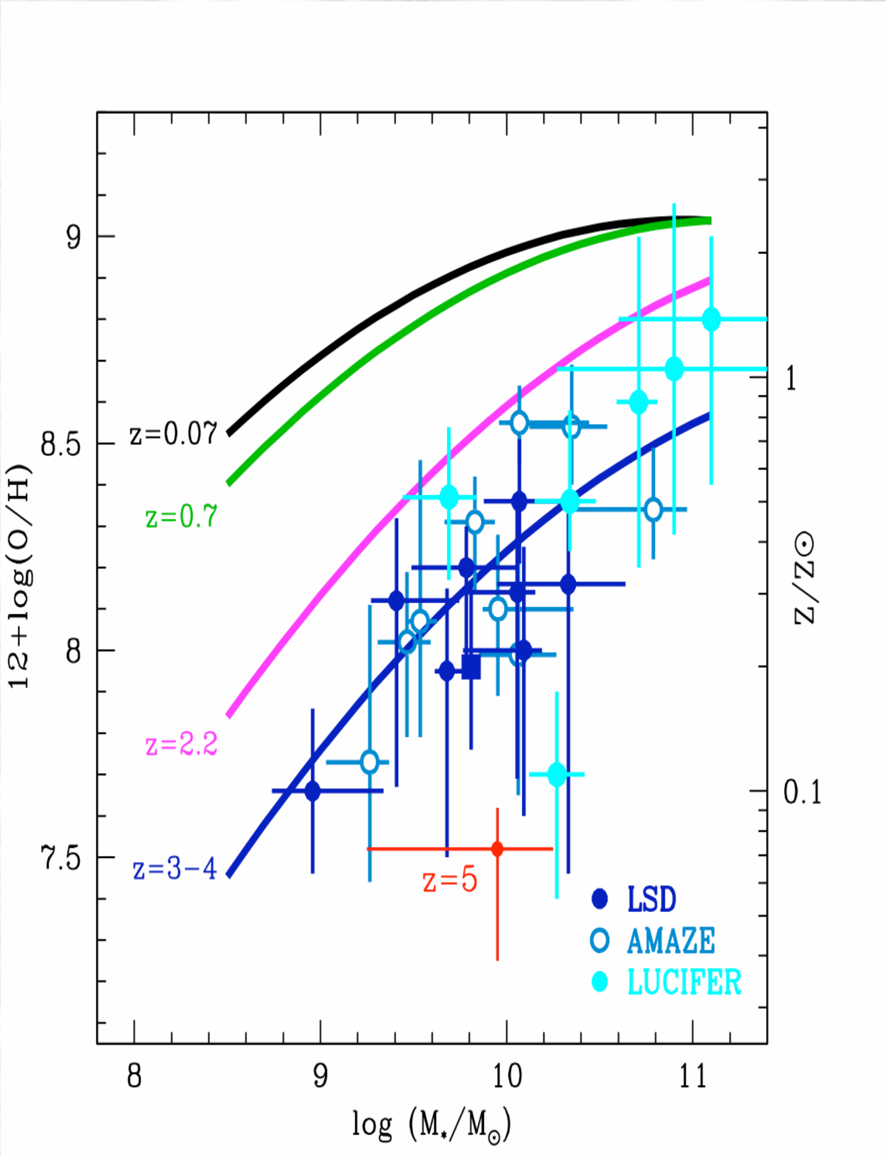


✓ S/N(Hα)>1
✓ S/N(Hβ)>1
✓ S/N>2 for

... but no evolution of the FMR

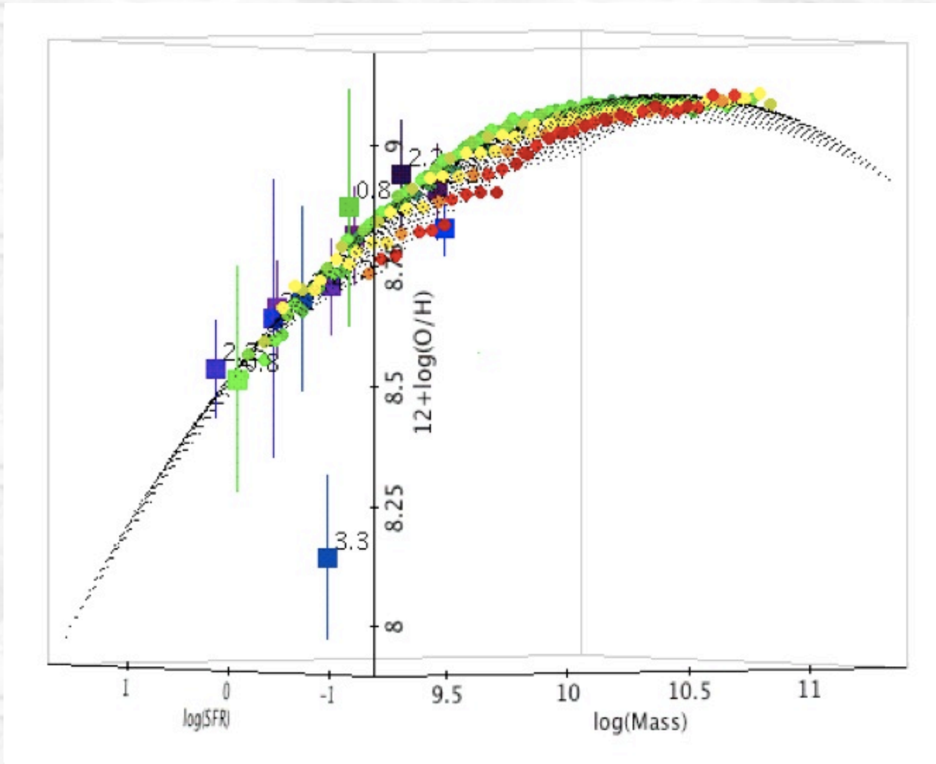
Cresci et al. 2011

Is the mass-metallicity really evolving?



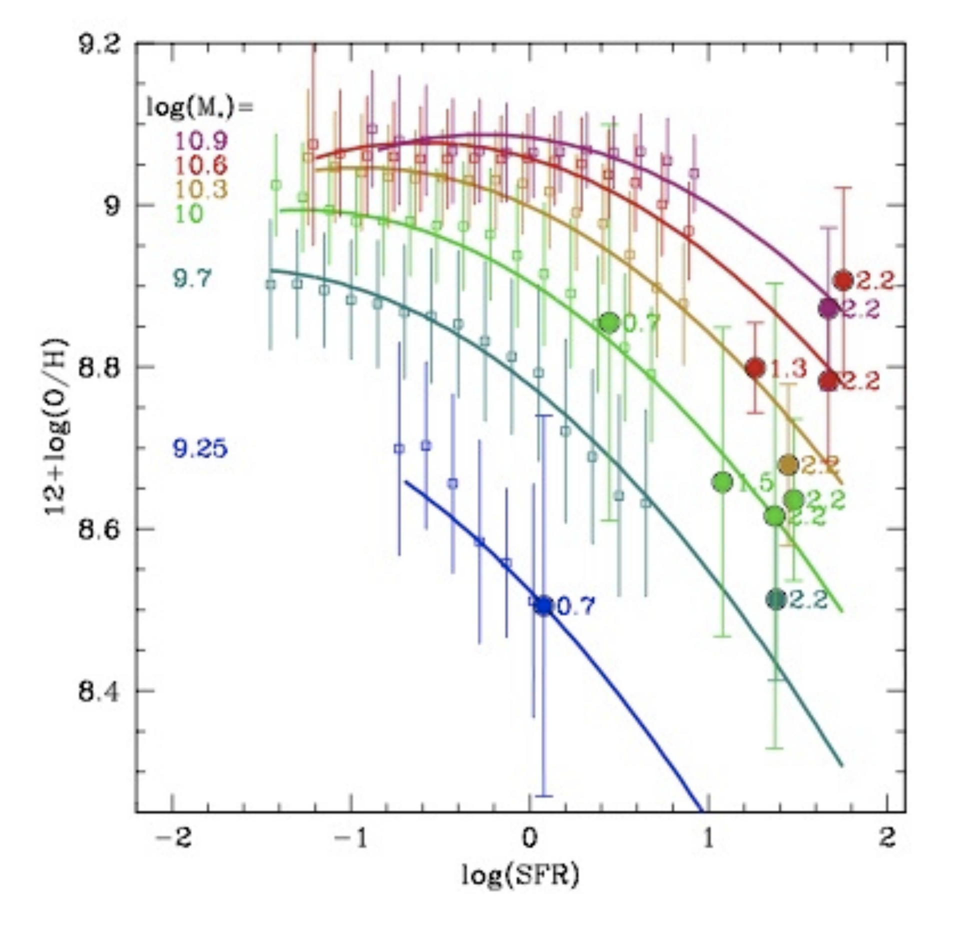
Adding distant Galaxies at: z=0.8 (*Savaglio et al. 2006*) z=1.4 (*Shapley et al. 2005, Liu et al. 2008, Wright et al. 2009, Epinat et al. 2009*) z=2.2 (*Erb et al. 2006, Law et al. 2008, Lehnert et al. 2009, Forster Schreiber et al. 2009*) z=3.3 (*Maiolino et al. 2008, Mannucci et al. 2009*)

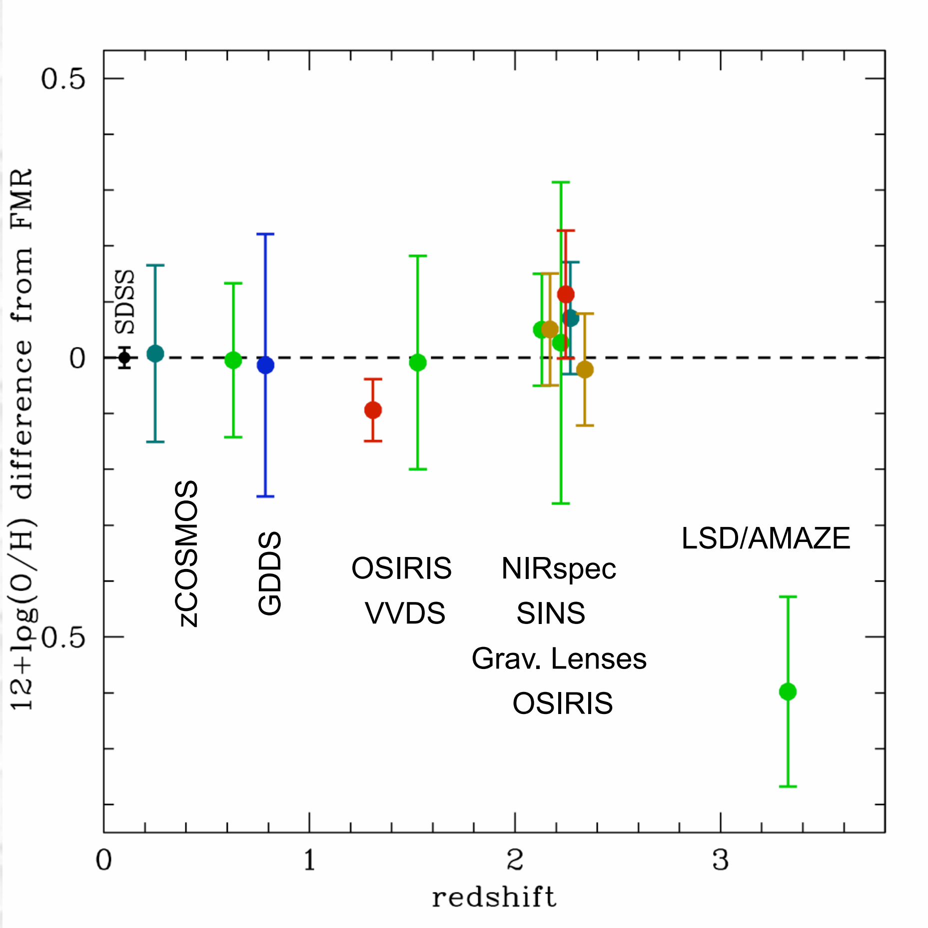
The Mass-Met evolution seems to be *only related to the increase of the SFR with z*, at least up to z~2



Mannucci, Cresci et al. 2010

Redshift evolution of the FMR



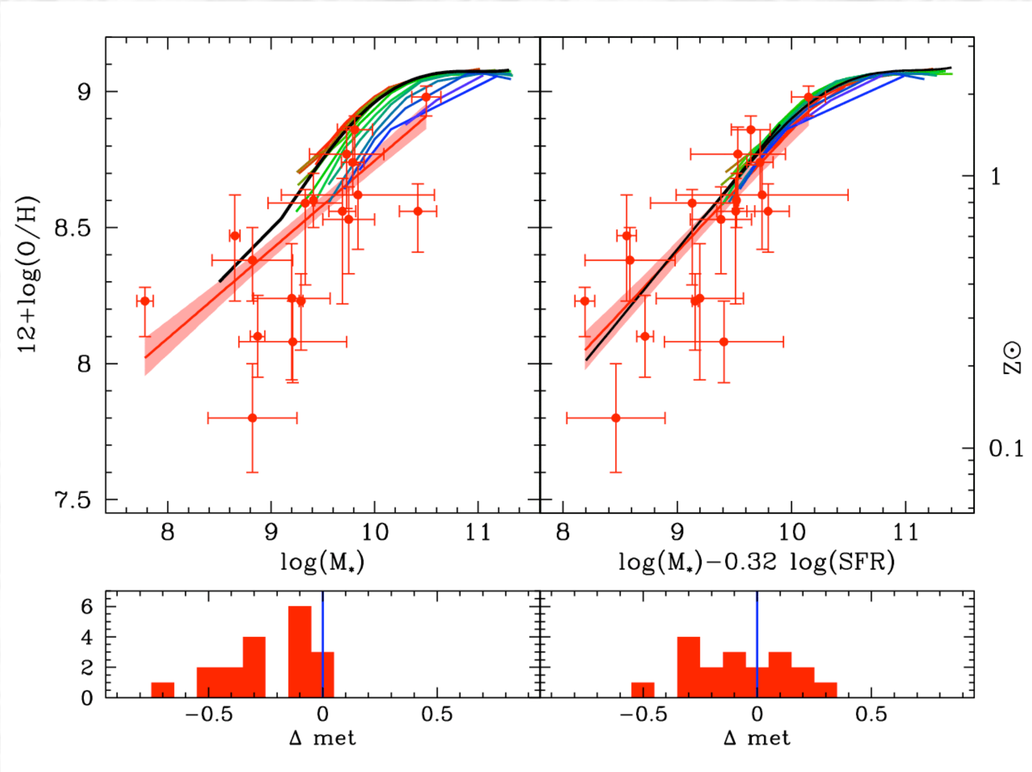


- **No evolution up to z=2.5**
- 0.6 dex of evolution at z=3.3? See Paulina's talk afterwards!
- To be tested with the larger and ubiased sample from LUCIFER

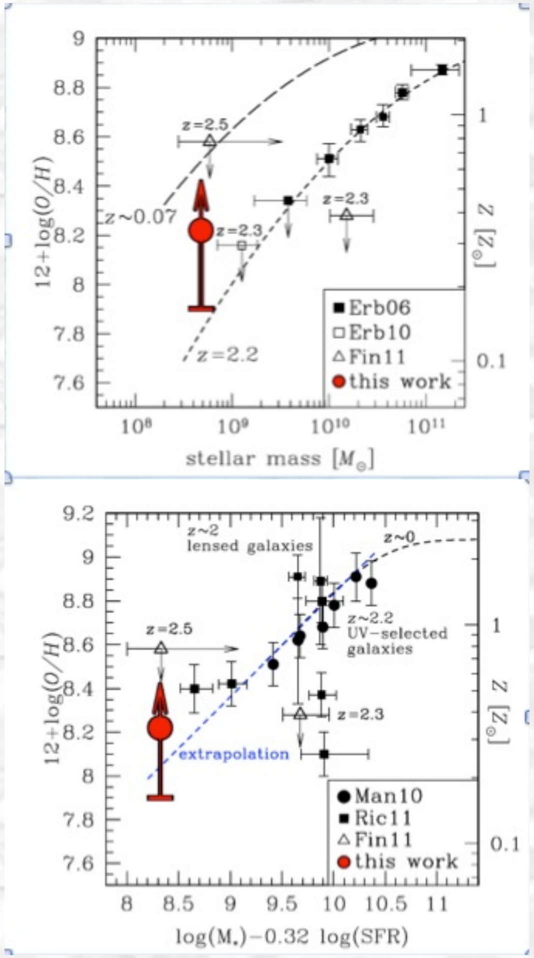
Mannucci et al. 2010, Cresci et al. 2011

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



Long GRB host galaxies
(Mannucci et al. 2011)

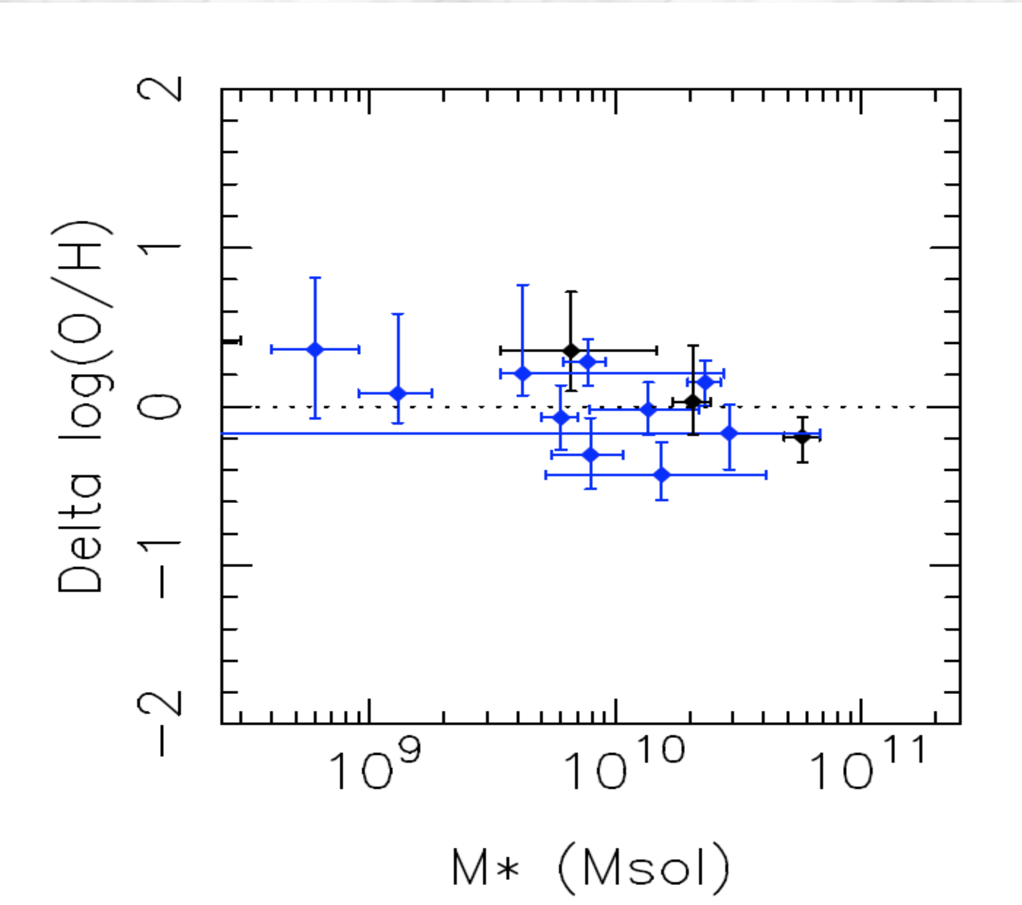


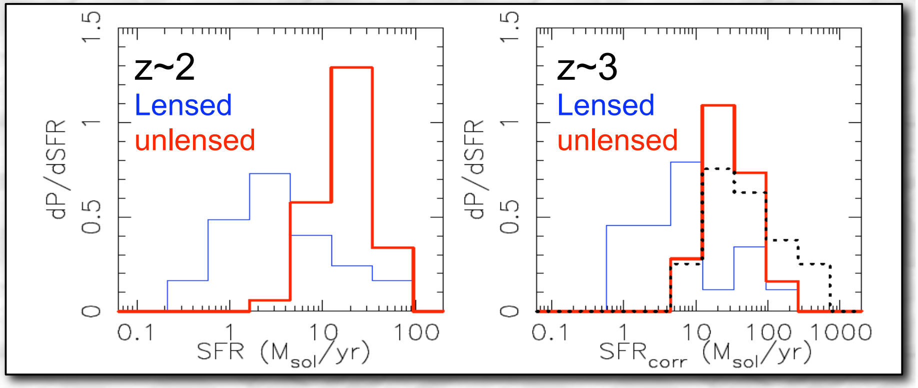
Stacked Ly α emitters at z=2.2 (Nakajina et al. 2011)

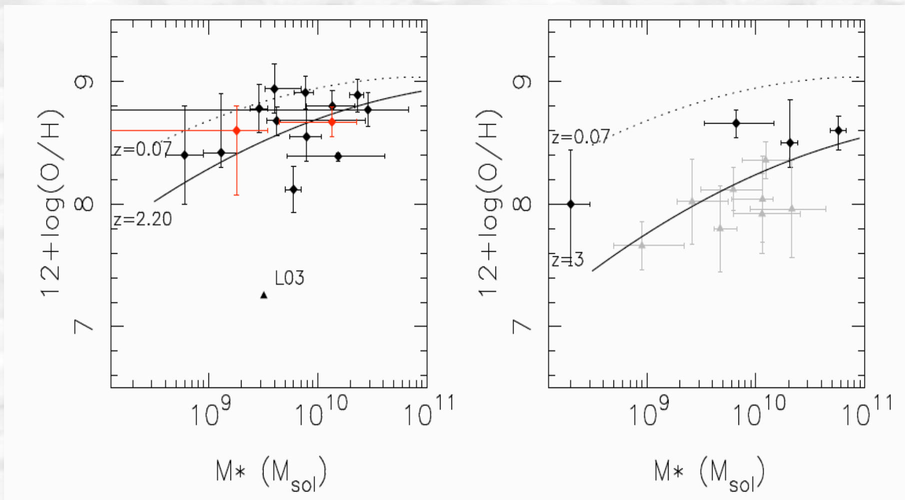
FMR works!

Richard+2010: Gravitationally Lensed galaxies at z~2.5

Sampling lower SFRs



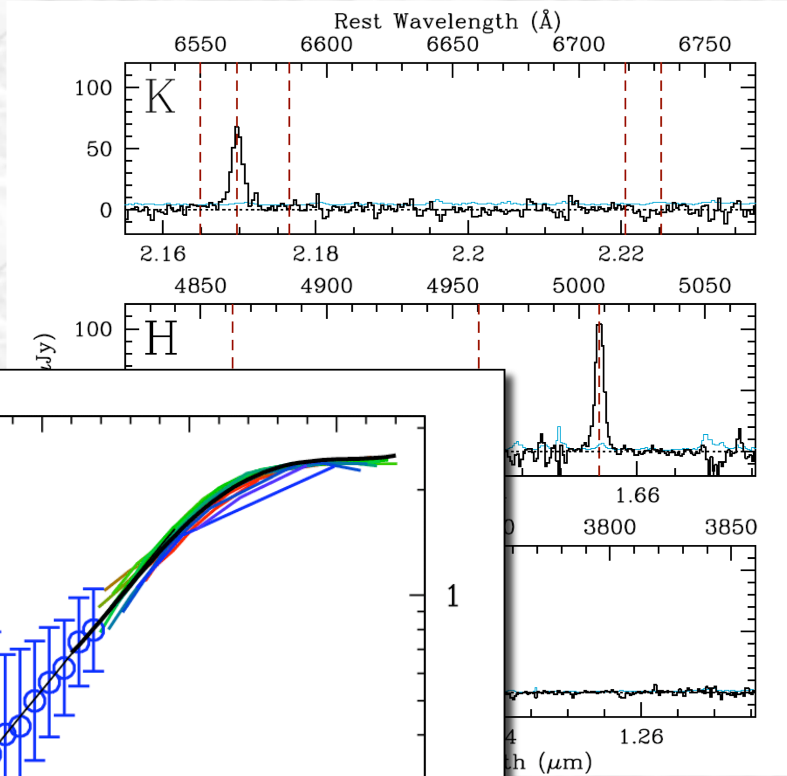


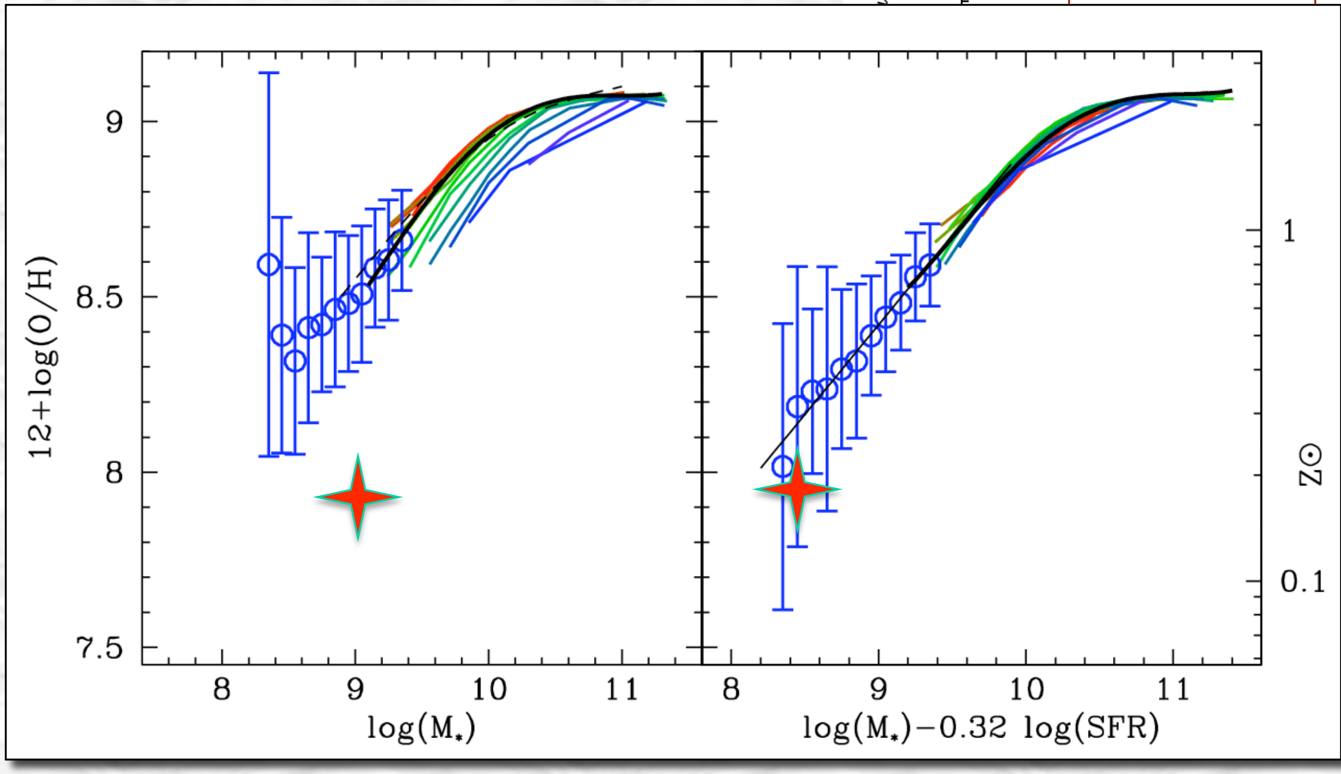


FMR works!

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





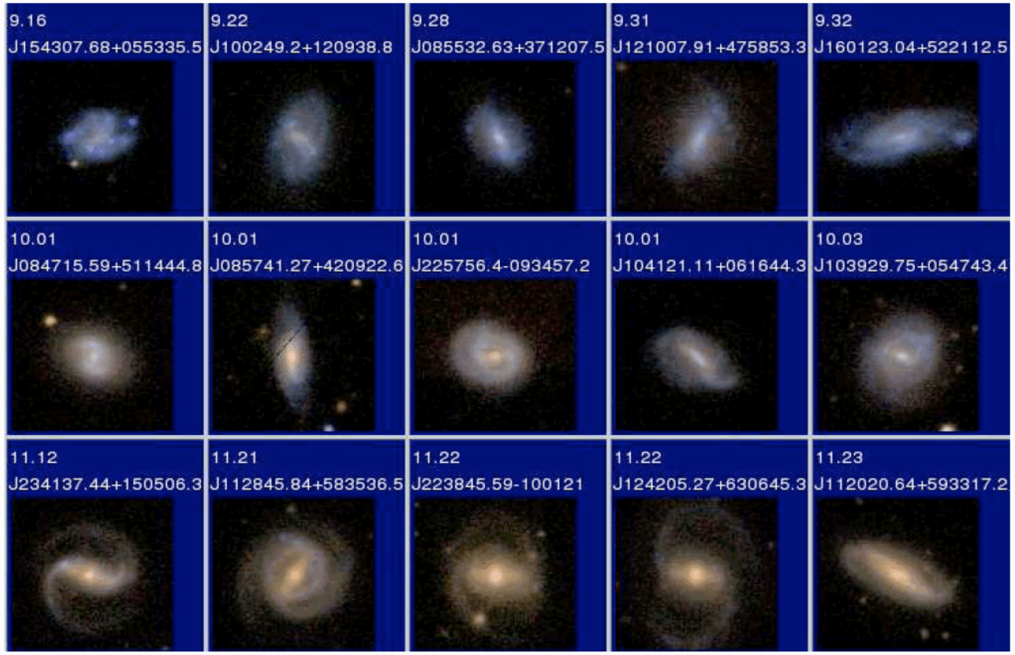
See also: Sara Ellison's Pairs, Thiago Goncalves LBAs, Contini et al. (2011) MASSIV galaxies …

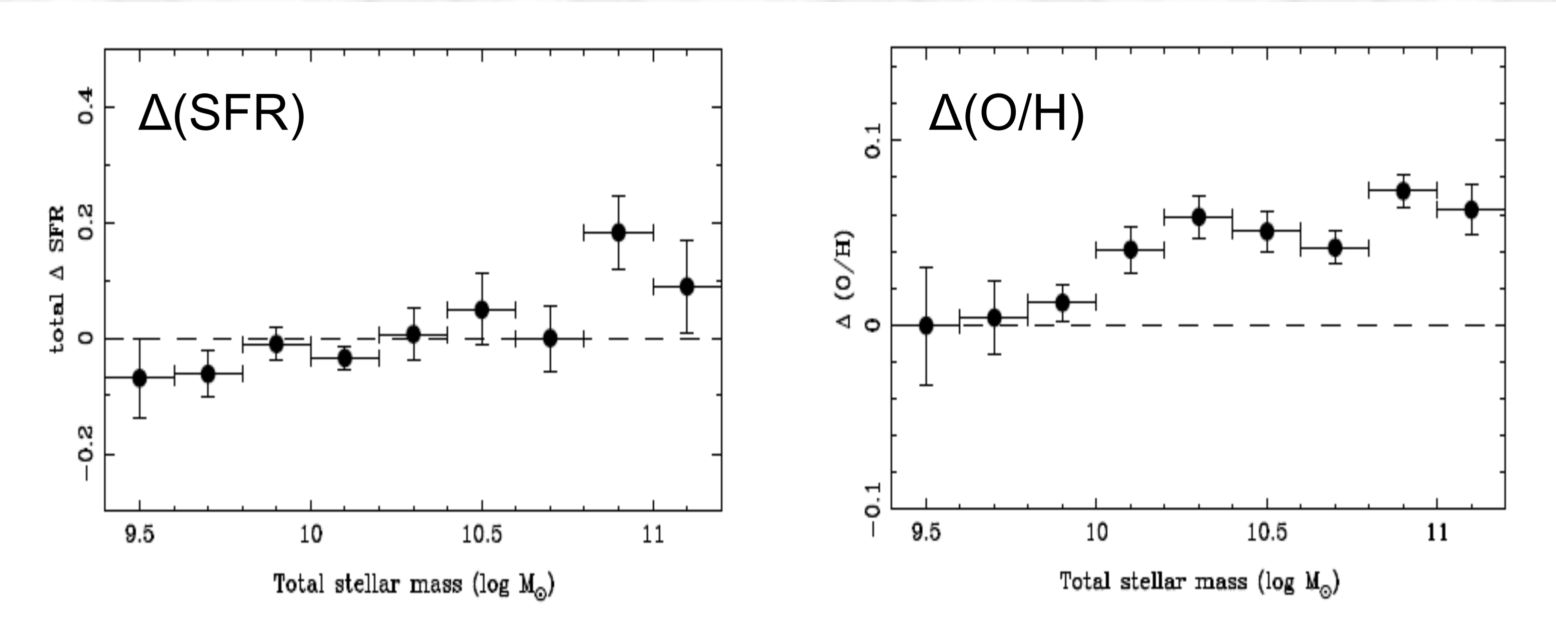
FMR outliers?

Barred galaxies at z<0.1

(Ellison et al. 2011)

SFR from enriched gas?

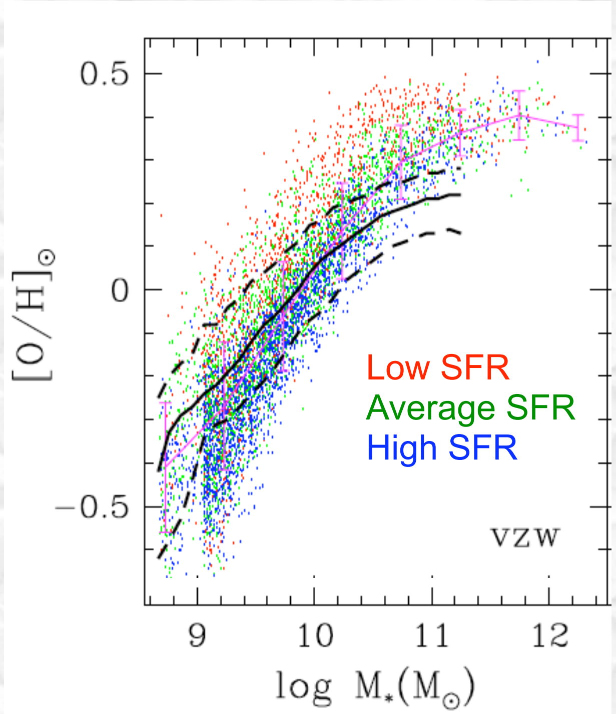




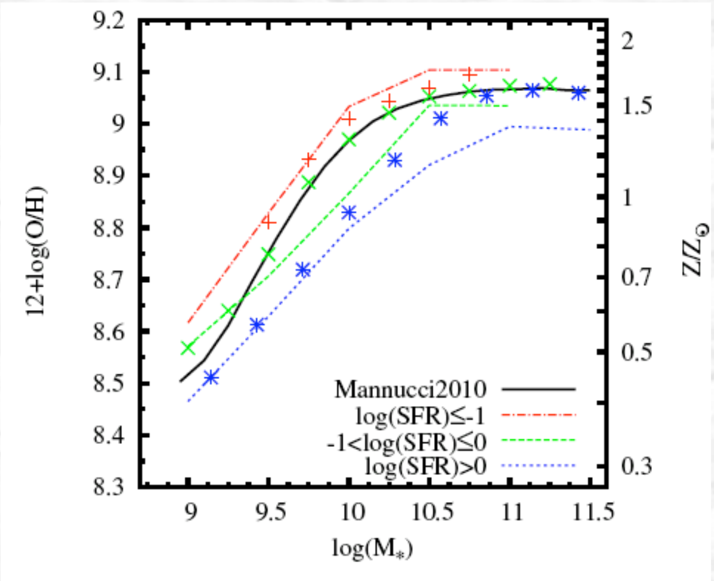
Models and FMR

Dave', Finlator & Oppenheimer (2011):
stable equilibrium against gas accretion and gas starvation: metallicity and SFR follows infall

Metallicity-dependent quenching of SF:
lower SFR in more metal poor galaxies (Dib et al. 2011, Krumholtz & Dekel 2011)



Dave', Finlator & Oppenheimer (2011)



Campisi et al. (2011)

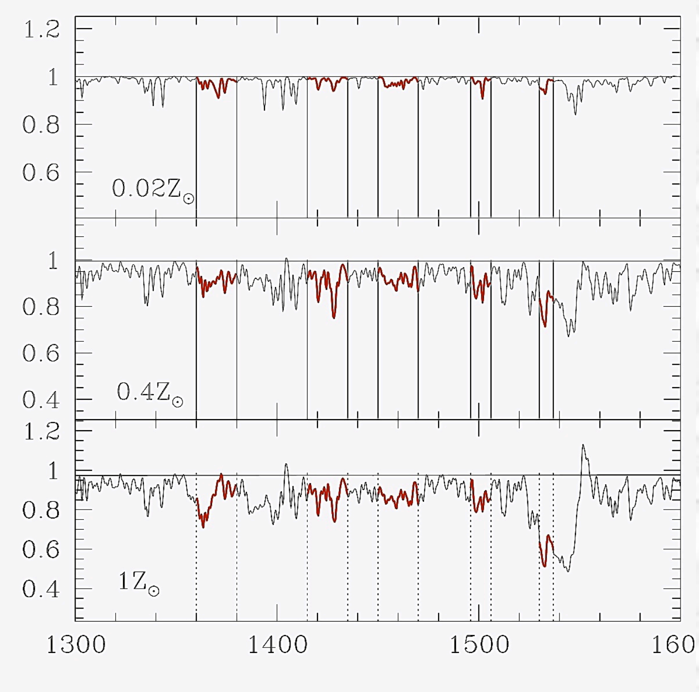
A Common feature in all models?

SAM models based on the Millennium (Croton 2006, De Lucia et al. 2007, Wang et al. 2008)

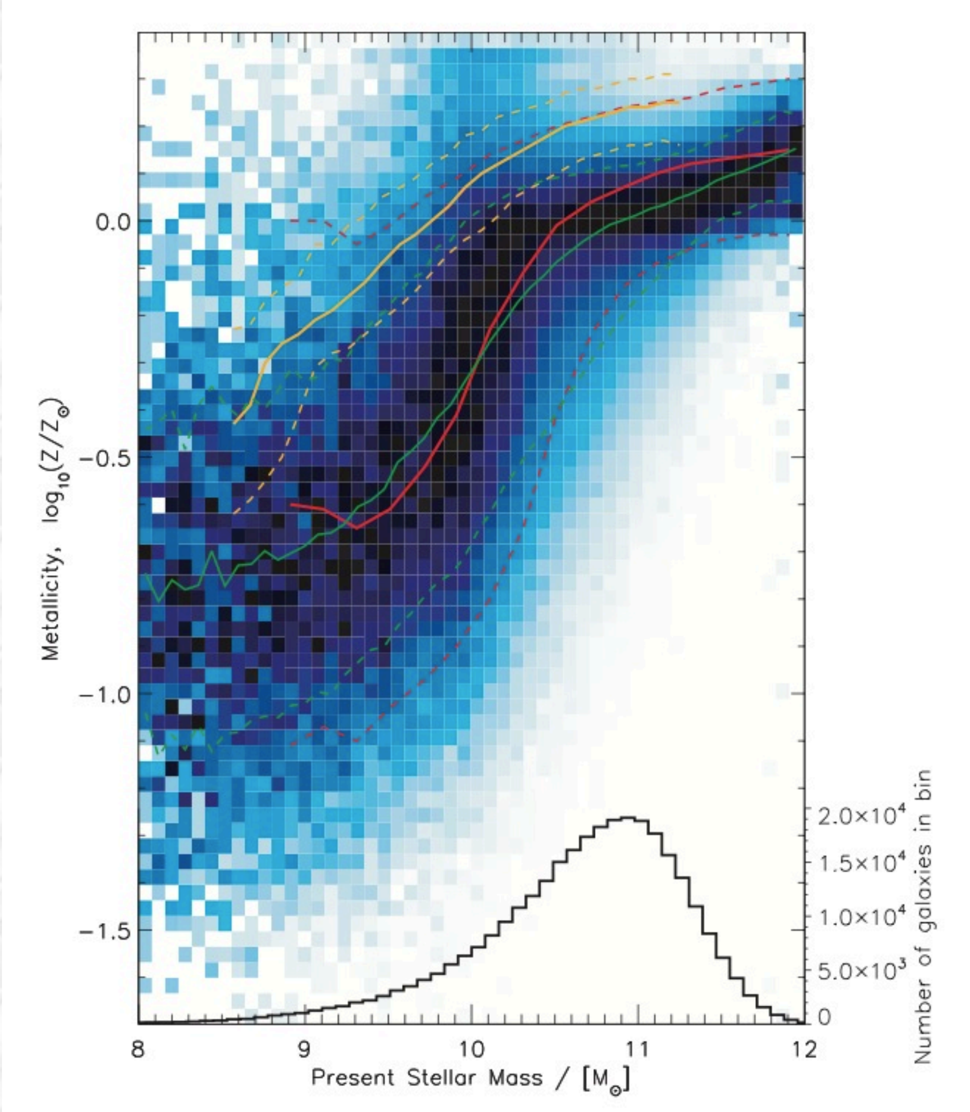
Stellar Metallicities

Stellar metallicities from optical Fe- and Mg- features in SDSS galaxies (Gallazzi et al. 2004, Panther et al. 2008): high S/N required, shifted to NIR at high-z

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



Sommariva et al. (2011)



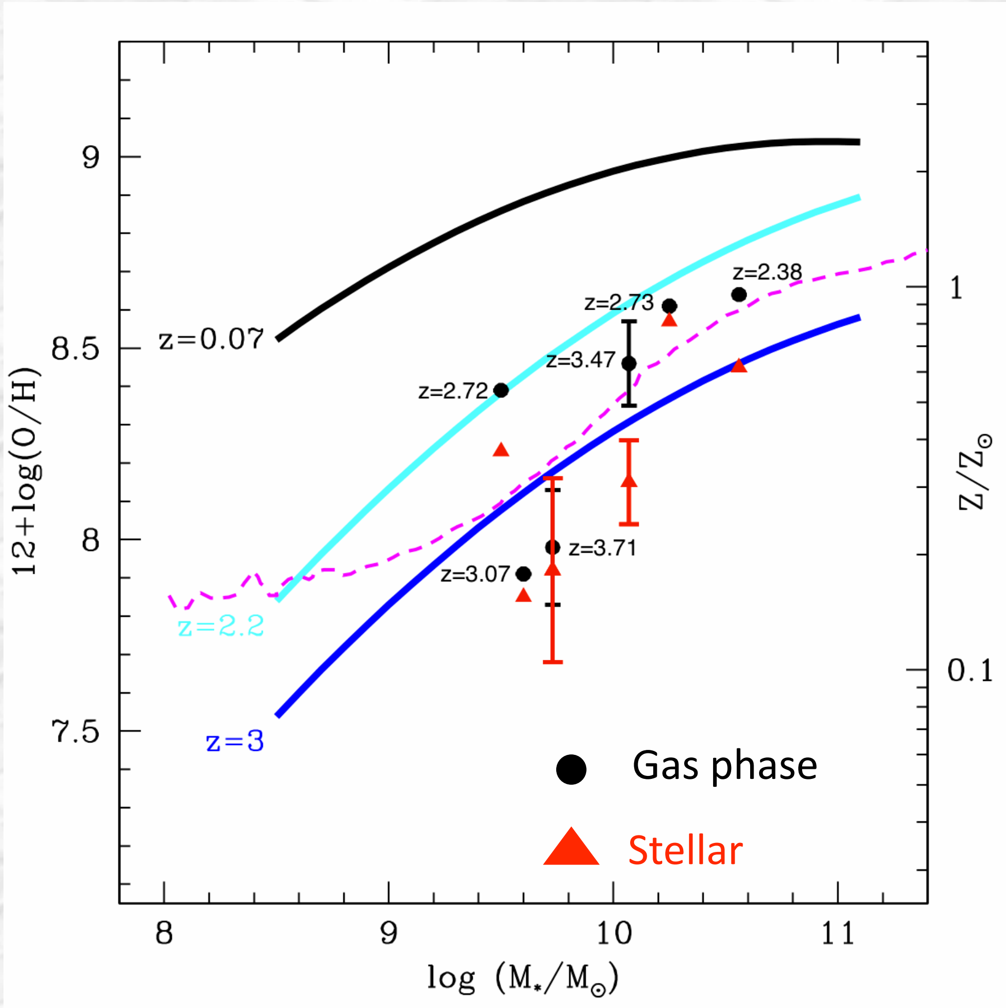
Panther et al. (2008)

Stellar Metallicities

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).

We obtained FORS optical spectra of 4 AMAZE galaxies (37 hours total) to measure for the first time stellar metallicities at z>3

Gas phase and **stellar metallicities** are comparable (as expected) in these star forming galaxies at high-z: remarkable agreement despite large uncertainties



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;

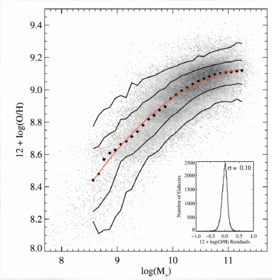
Resolved metallicity gradients provide evidence of pristine gas accretion in star forming disks at high redshift;

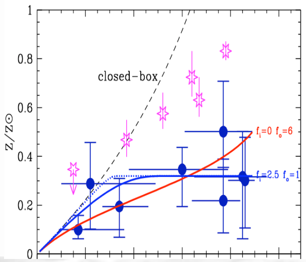
First measure of stellar metallicity in high-z star forming galaxies

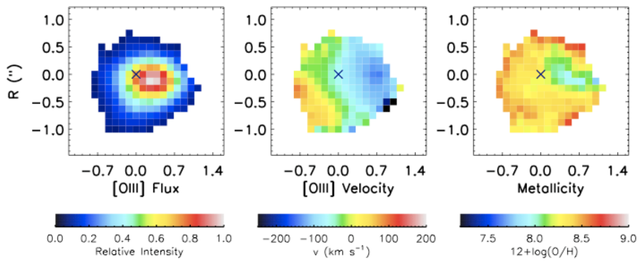
Fundamental Metallicity Relation:

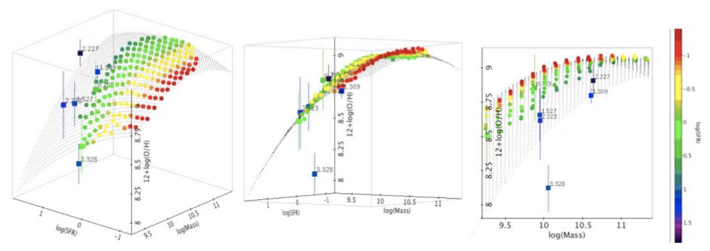
Local galaxies define a tight surface in this 3D space SFR-Met-M$_*$, which appear not to evolve up to z~2.5;

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)









Summary

➡ 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;

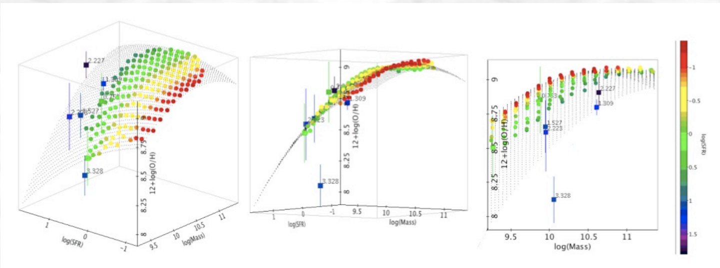
It has to be explained by the interplay of infall of pristine gas, outflow of enriched material and star formation history;

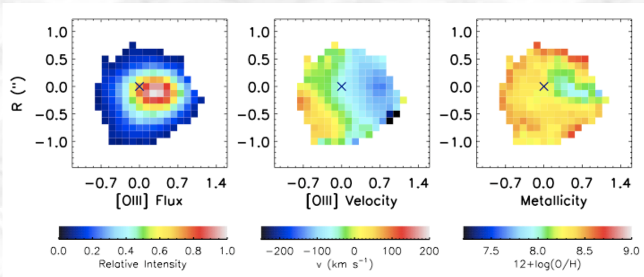
➡ Chemical evolution in high-z star-forming galaxy:

Evidence for significant inflows/outflows;

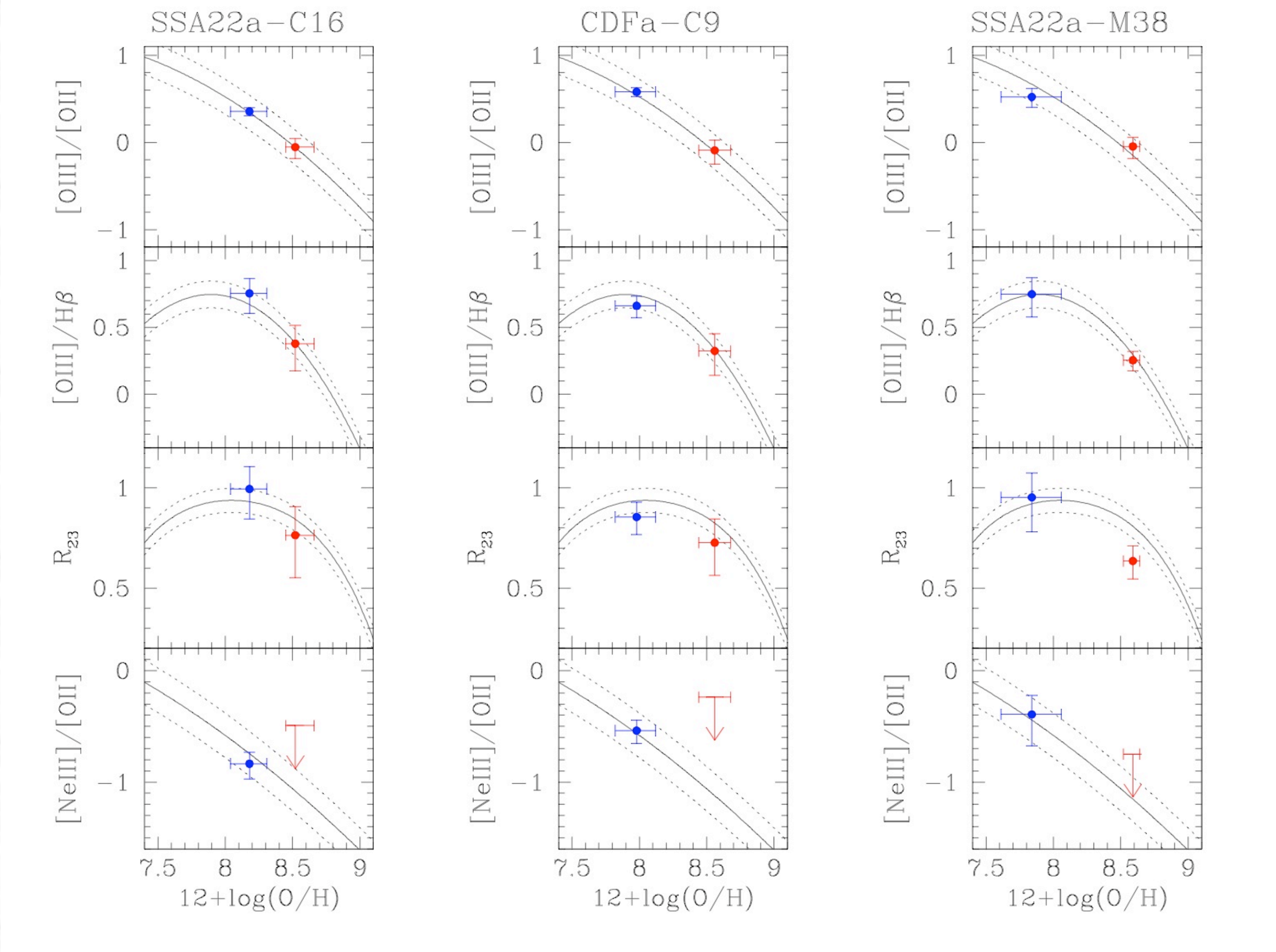
First resolved metallicity gradients at high z, direct evidence of pristine gas accretion in star forming disks at high redshift;

First measure of stellar metallicity in z>3 star forming galaxies

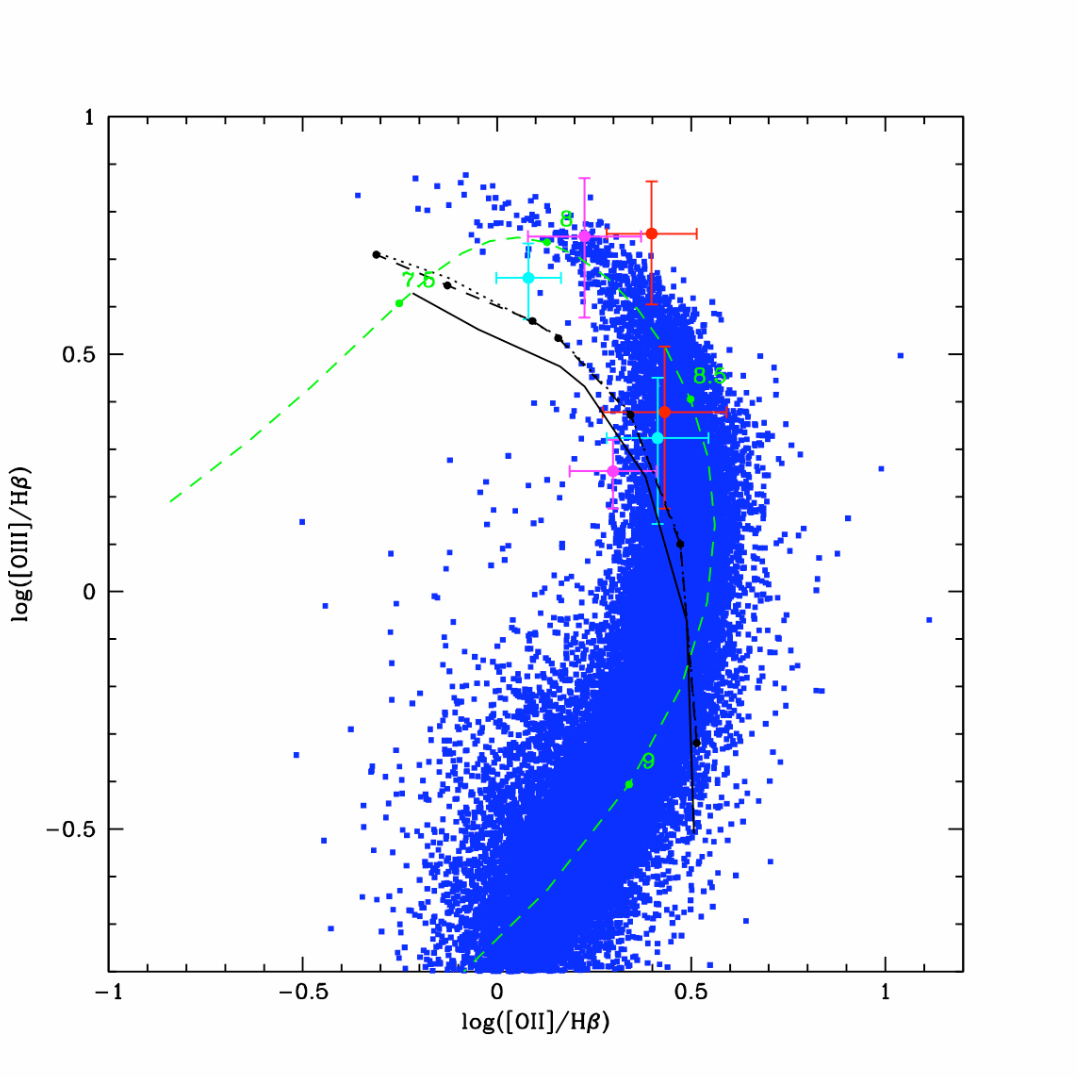




Measuring the gradients



Metallicity or U?

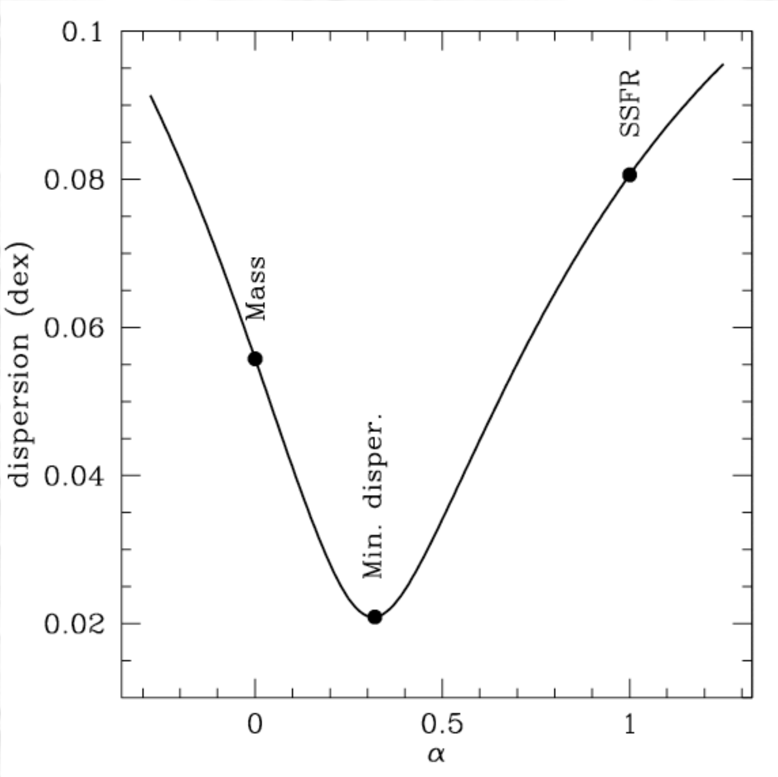


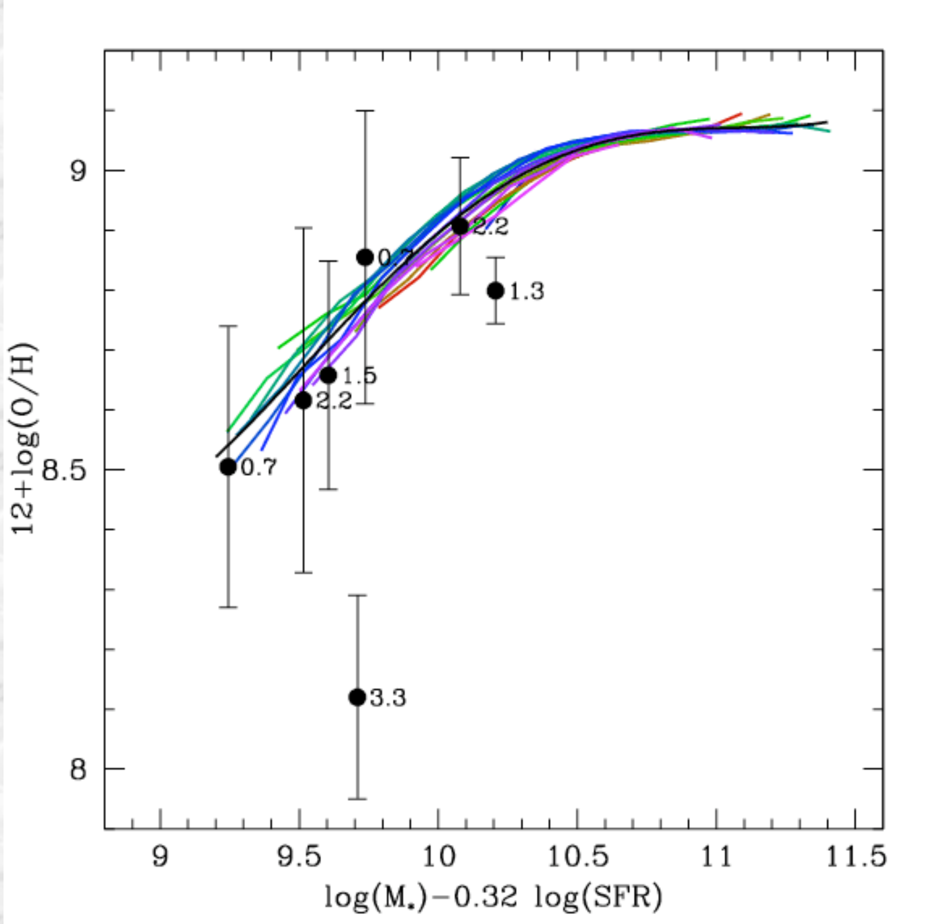
- It is well known that the ionization parameter U depends on metallicity (e.g. Nagao et al. 2006)
- The calibration are based on a large sample of local galaxies with different U, and its variation is included in the spread (Maiolino et al. 2008)
- Higher U are claimed at high-z (Brinchmann et al. 2008), but strong line metallicity diagnostics based on local galaxies are found to deviate at high-z not more than ~0.1 dex (Liu et al. 2008)

Anyway, according to the latest photoionization models (Martin-Manjon 2010, Levesque 2010, Dopita 2006), a strong variation of the ionization parameter U would scatter the points away from the local calibration: this is not observed in our galaxies

A projection

μ_α = log(M) – α log(SFR)





- No extrapolation
- Easy physical meaning?

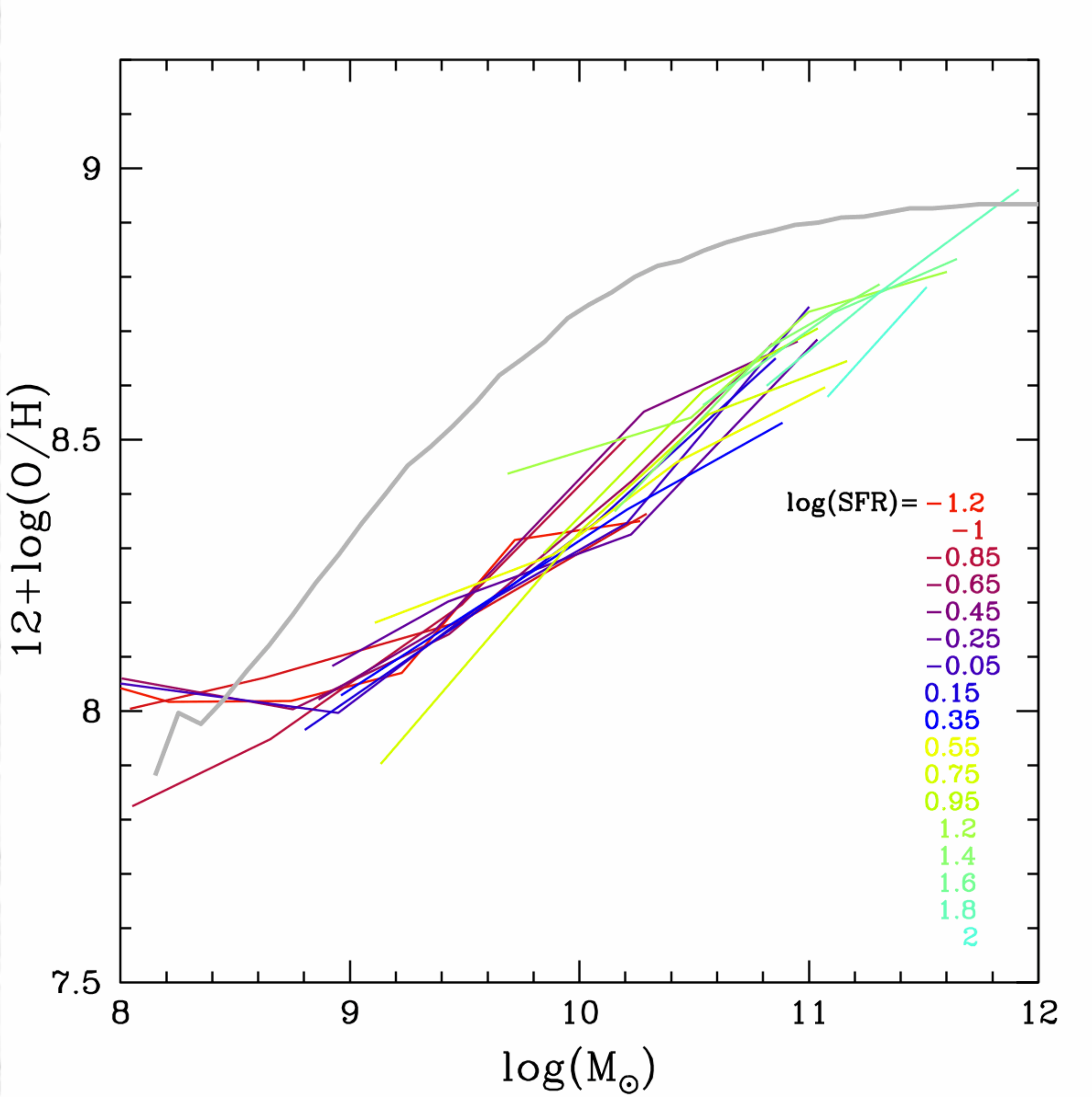
12 + log(O/H) =	$8.50 + 0.50\mu_{0.32}$	if $\mu_{0.32} < 10.2$
	9.05	if $\mu_{0.32} > 10.5$

in galaxies with any mass, SFR e redshift (<2.5)

Stellar FMR

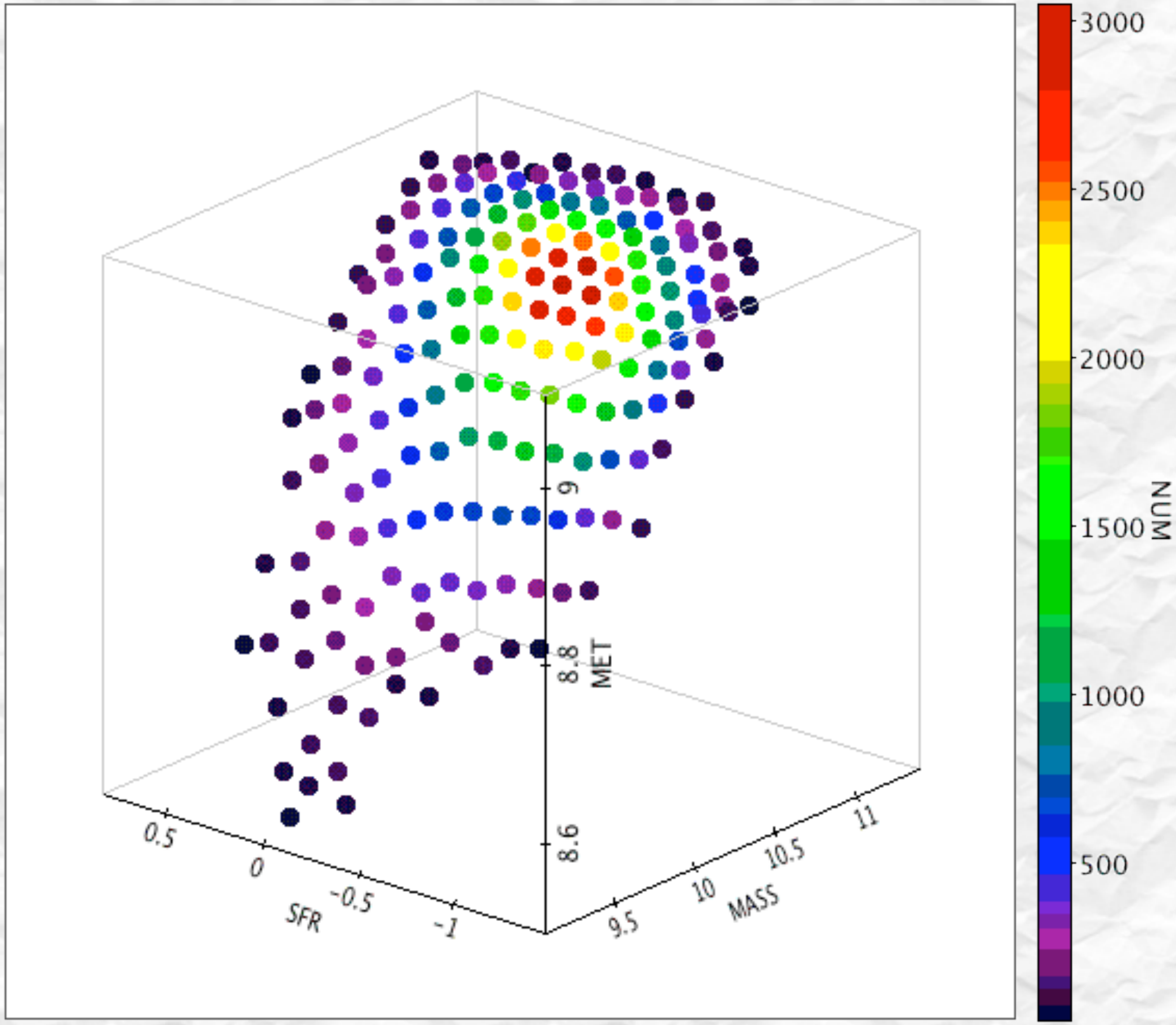
No dependence on SFR found in *stellar* M-Z relation:

the FMR is not dominated by stellar population age effects, but by the role of infalls and outflows

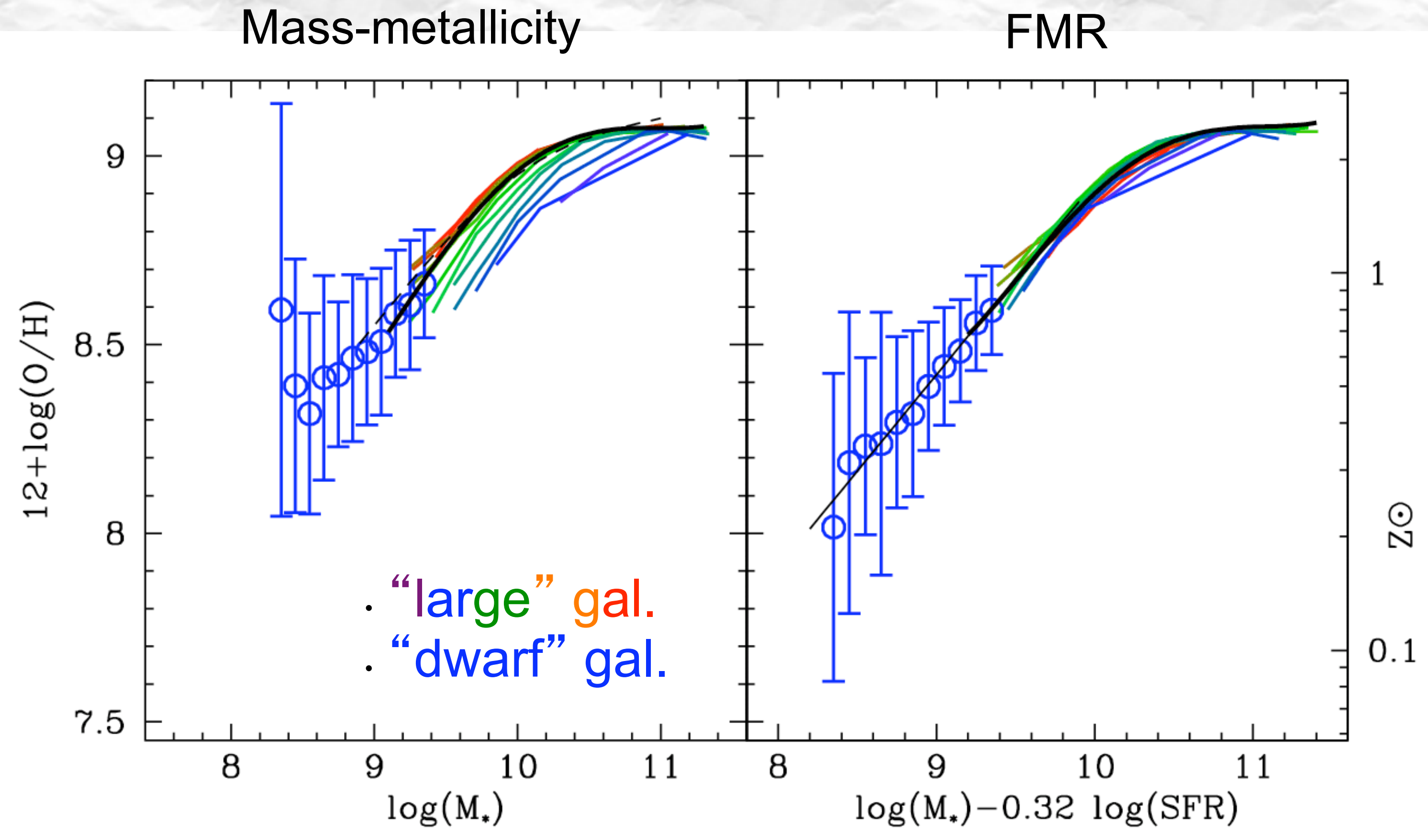


The SFR-M relation in the FMR

- FMR is not a mere consequence of the mass-met and mass-SFR relations
- The mass-SFR relation only defines as the FMR is populated, not its existence



Extension of the FMR toward low masses



Extension of the FMR toward lower masses ($M<10^{9.2}M_{\odot}$)

$\sim 10^4$ SDSS DR7 low-mass galaxies

Mannucci et al. (2011)

Physical interpretationç

Processes affecting metallicity

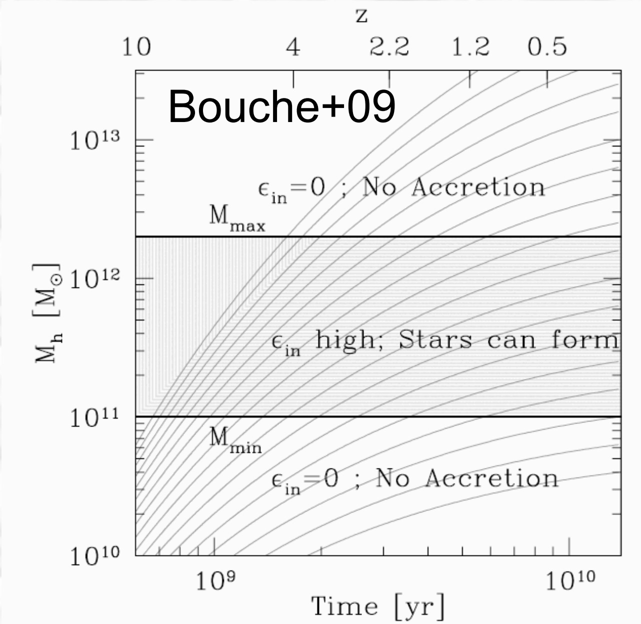
1. Infall (M$_{inf}$)
2. Star formation ($\Sigma_{SFR} = \alpha\Sigma^{n}_{gas} \sim M^{n}_{inf}$, n~1.4)
3. Outflow ?

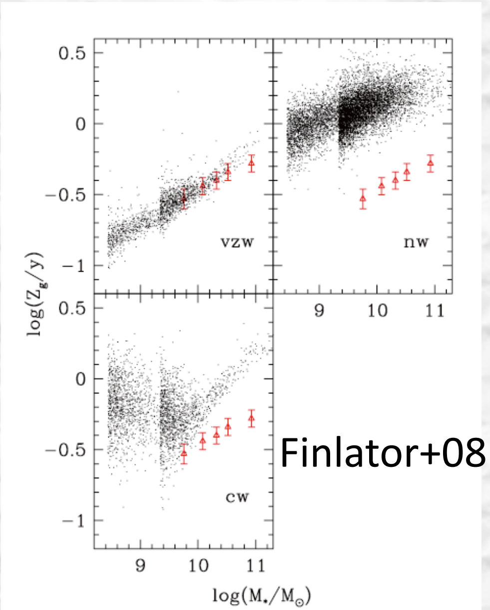
Infall: smooth?
merging dominated?
upper and lower mass thresholds? Bouche' +09

Outflows : Const. vel. Dekel+03
momentum driven Finlator+08
AGN Somerville+08

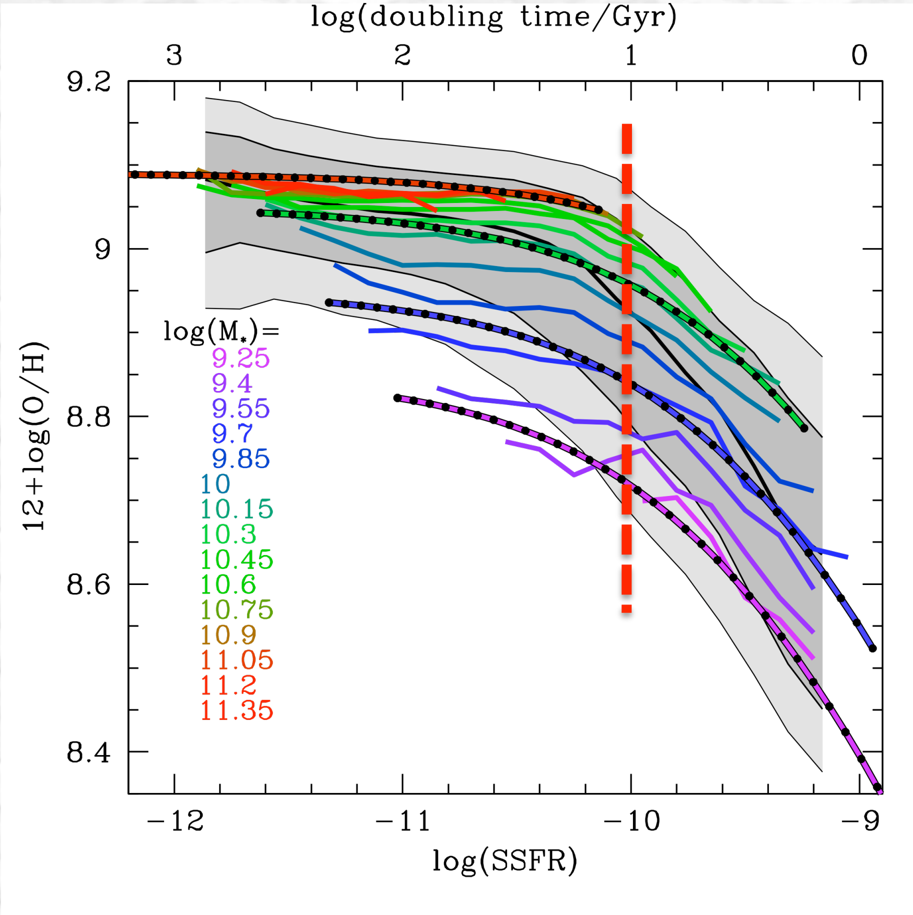
SF efficiency: downsizing de Rossi+07
outflow-regulated" SF Brooks+07

Different scaling relations with M and SFR





A Physical interpretationç



SSFR=SFR/Mass

F_g=0.3% $\log(M_{infall})$=5.5-7.5

Toy model:

- SFR related to infall by the Schmidt-Kennicutt law on the infalling gas
- timescales of chemical enrichment are longer than the dynamical ad infalling times
- metallicity before SF follows the mass-metallicity due to another effect (downsizing? outflows?)

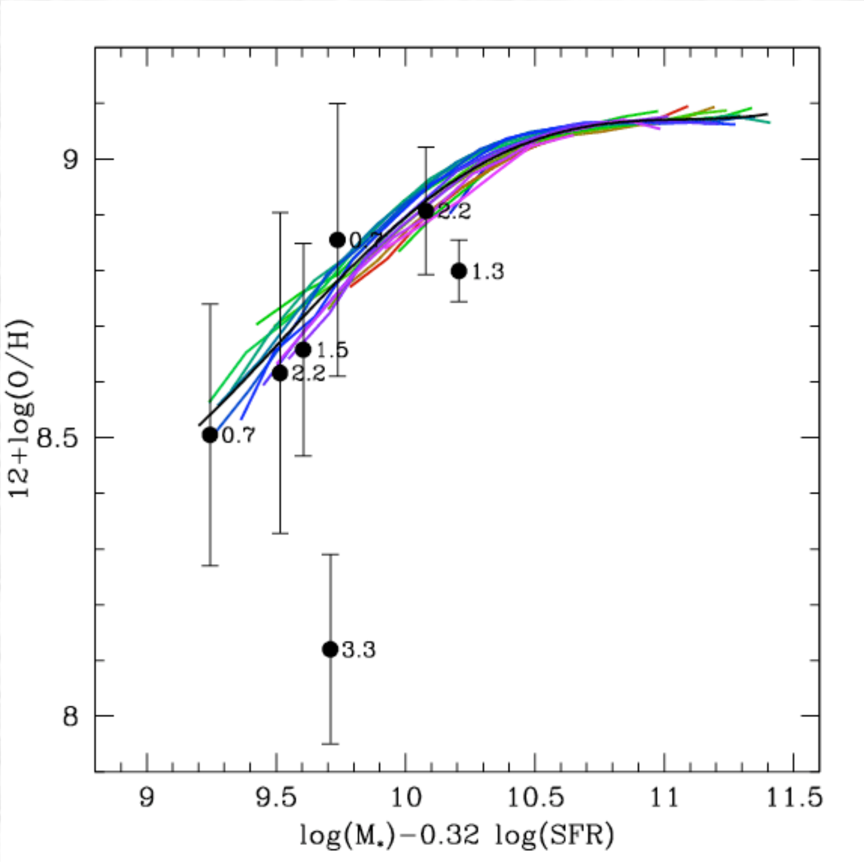
Scenario

Two effects are shaping the FMR: infall and (possibly) outflow

- Infall is related to SFR and dominates at high redshift
- outflow is related to mass and dominates in the local universe

Physical interpretation - 2

Chemical enrichment timescale *shorter* than the others:
quasi steady state



12+log(O/H) =log(M) – 0.32 log(SFR) ~
*~ log (SFR/M_{inf}*M_{out}) ~*
~ log [SFR/M_{inf}($SFR^s M_*^{-m}$)]*

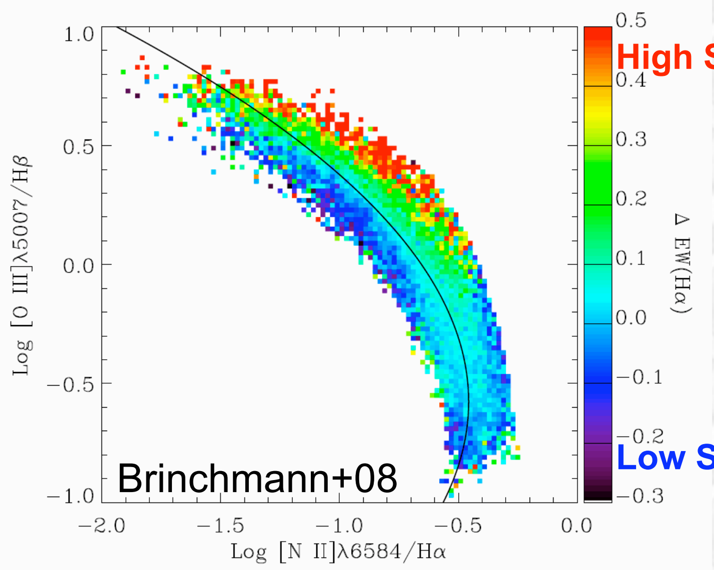
Infall cannot be the only effect:

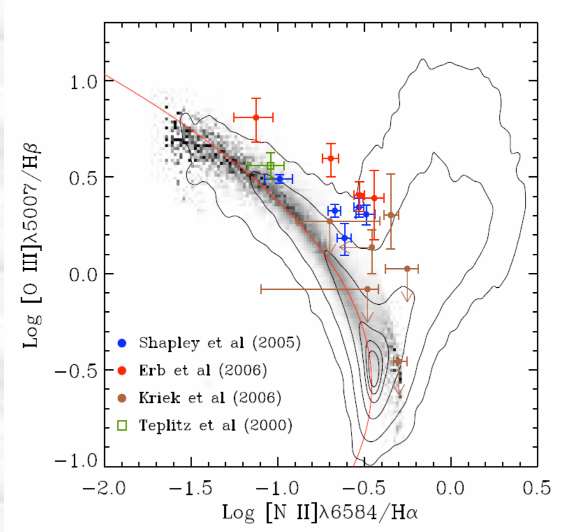
Many different types of outflows, showing different dependence on mass and SFR

Outflow ~ $SFR^s M_*^{-m}$
(m and s free param.)

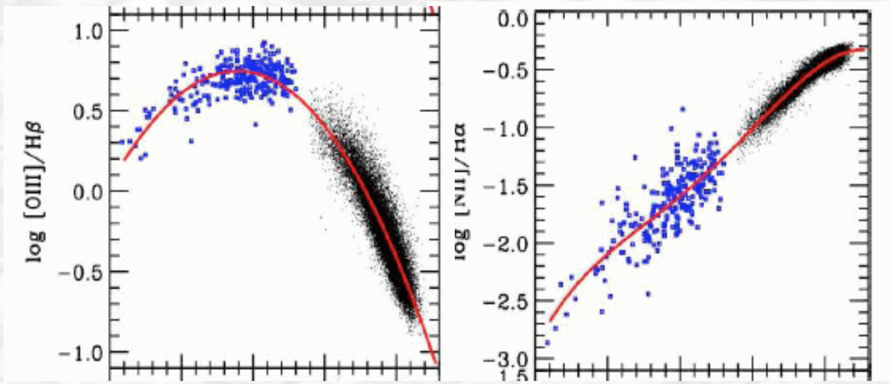
Using SK and comparing with $\mu_{0.32}$:
m=1
s=0.65
as in the momentum-driven outflows (Dave'+06, Oppeheimer+08)

Dependence of metallicity on SFR





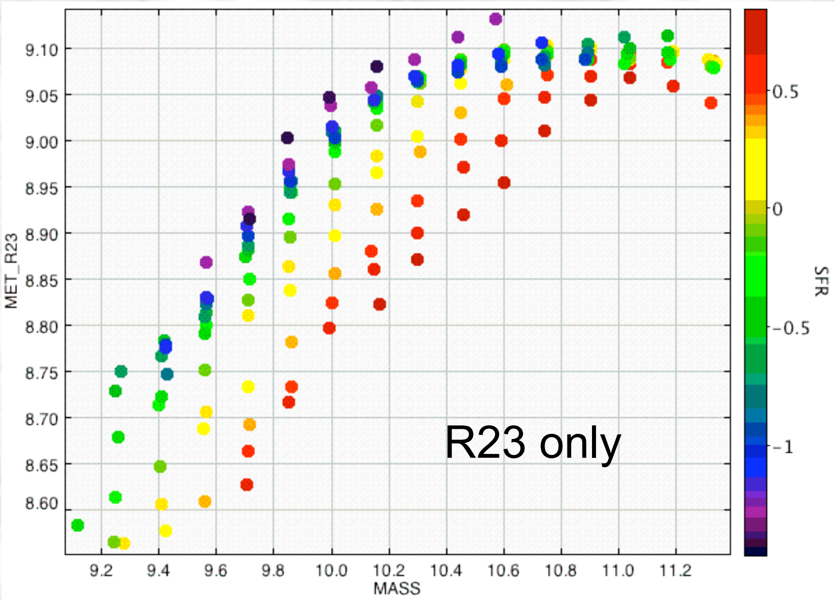
Brinchman et al 2008



Increasing SSFR:

1. met (NII/Ha): constant or increasing
2. met (R23): decreasing

Dependence of metallicity on SFR



Increasing SSFR:

1. met (NII/Ha): constant or increasing
2. met (R23): decreasing