Metallicity evolution and star formation in the early Universe

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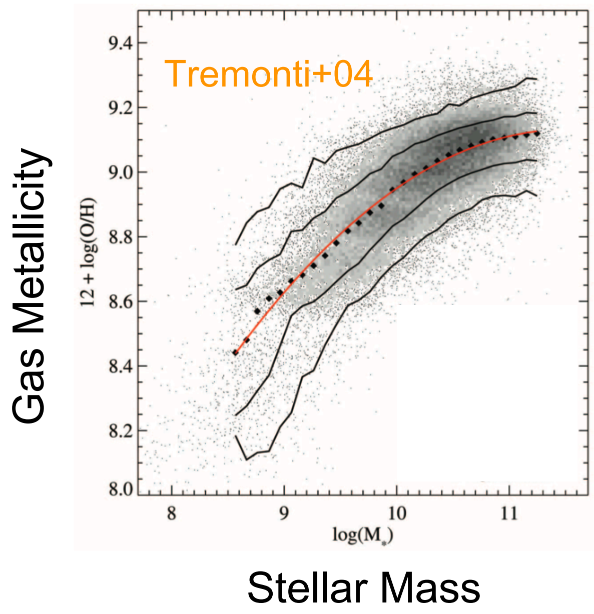
Metallicity and stellar mass provide information on the integrated star formation in galaxies, in contrast to ongoing star formation that may be affected by episodic events.

Stellar mass and metallicity together, i.e the mass-metallicity relation, and its redshift evolution, provide information on the role of:

- **outflows/inflows**
- **efficiency of star formation**

as a function of galaxy mass through the cosmic epochs.



z>3, tracing the formation of the first galaxies:

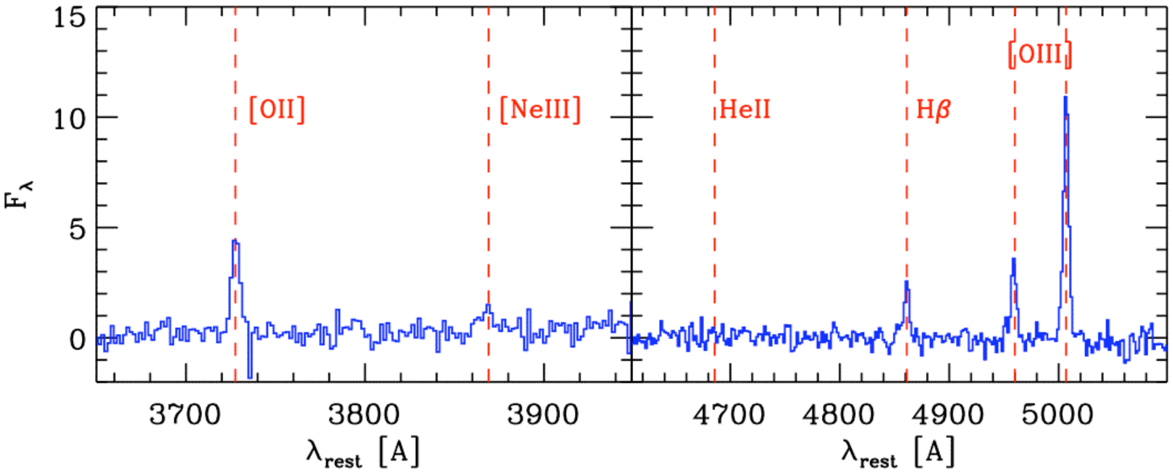
- **Before the peak of cosmic star formation**
- **Strong Evolution of the merger rate**
- **Formation of massive galaxies**

AMAZE ~~with~~ and LSD

250 hours near-IR Integral Field Spectroscopy with SINFONI@VLT
~ 40 LBGs at 3<z<5

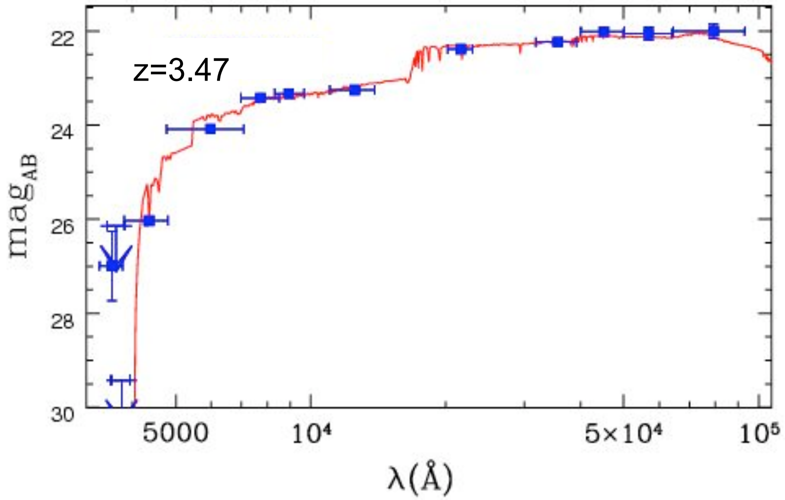
AMAZE (**A**ssessing the **M**ass-**A**bundance redshift(**Z**) **E**volution):
seeing limited, 180h (PI: Maiolino) Maiolino et al. 2008

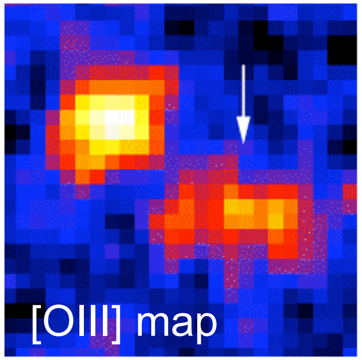
LSD (**L**yman-break galaxies **S**tellarpopulations and **D**ynamics):
diffraction limited with AO, 70h (PI: Mannucci) Mannucci et al. 2009



Gas metallicity from optical nebular lines (redshifted to H-K band)

Stellar mass from optical-to-Spitzer photometry

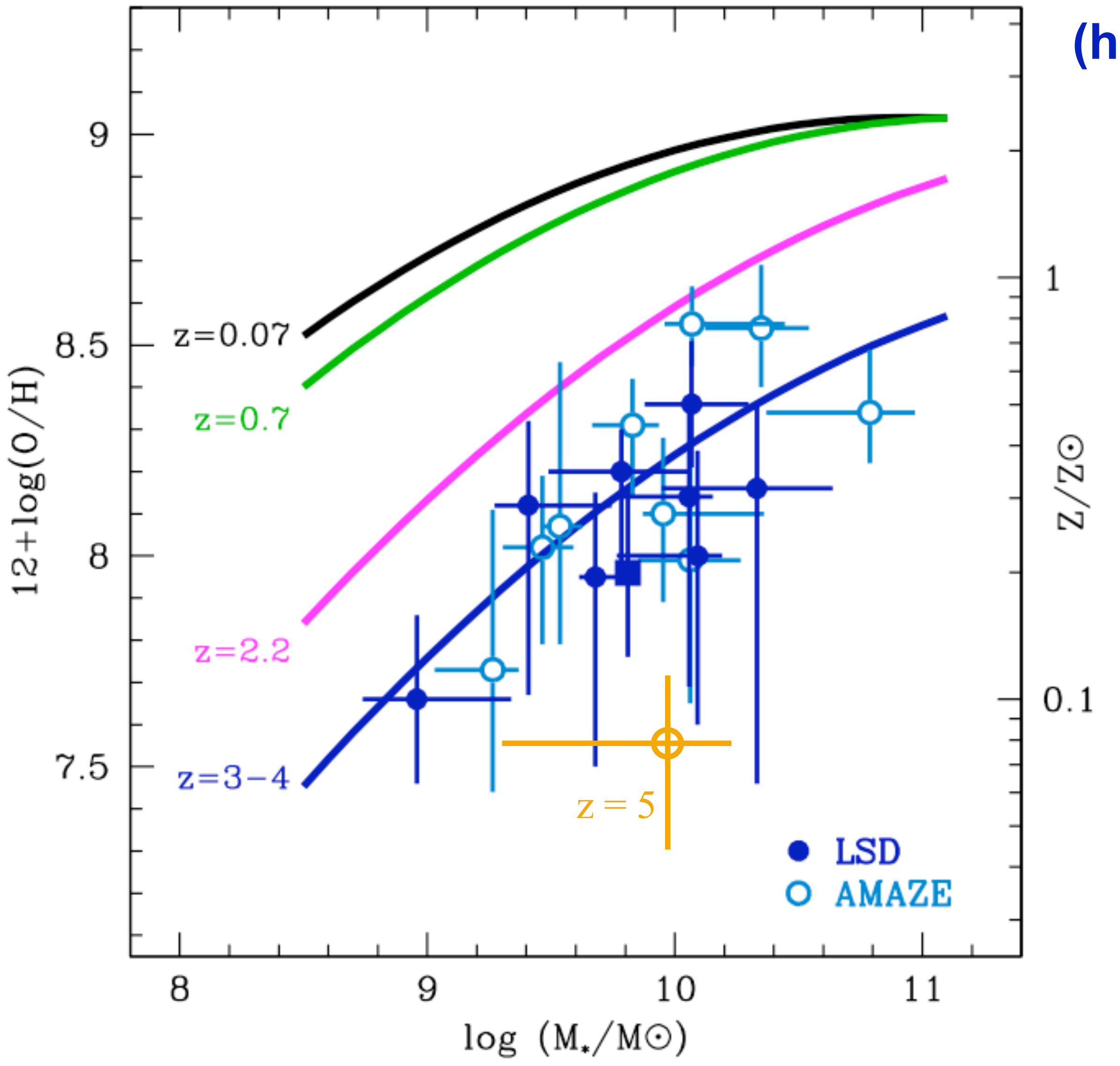




Spatially resolved spectroscopic information

Evolution of the mass-metallicity relation: results from AMAZE+LSD

(half of the final sample)



z~0.07 SDSS (Kewley&Ellison08)

z~0.7 GDSS+CFRS (Savaglio+05)

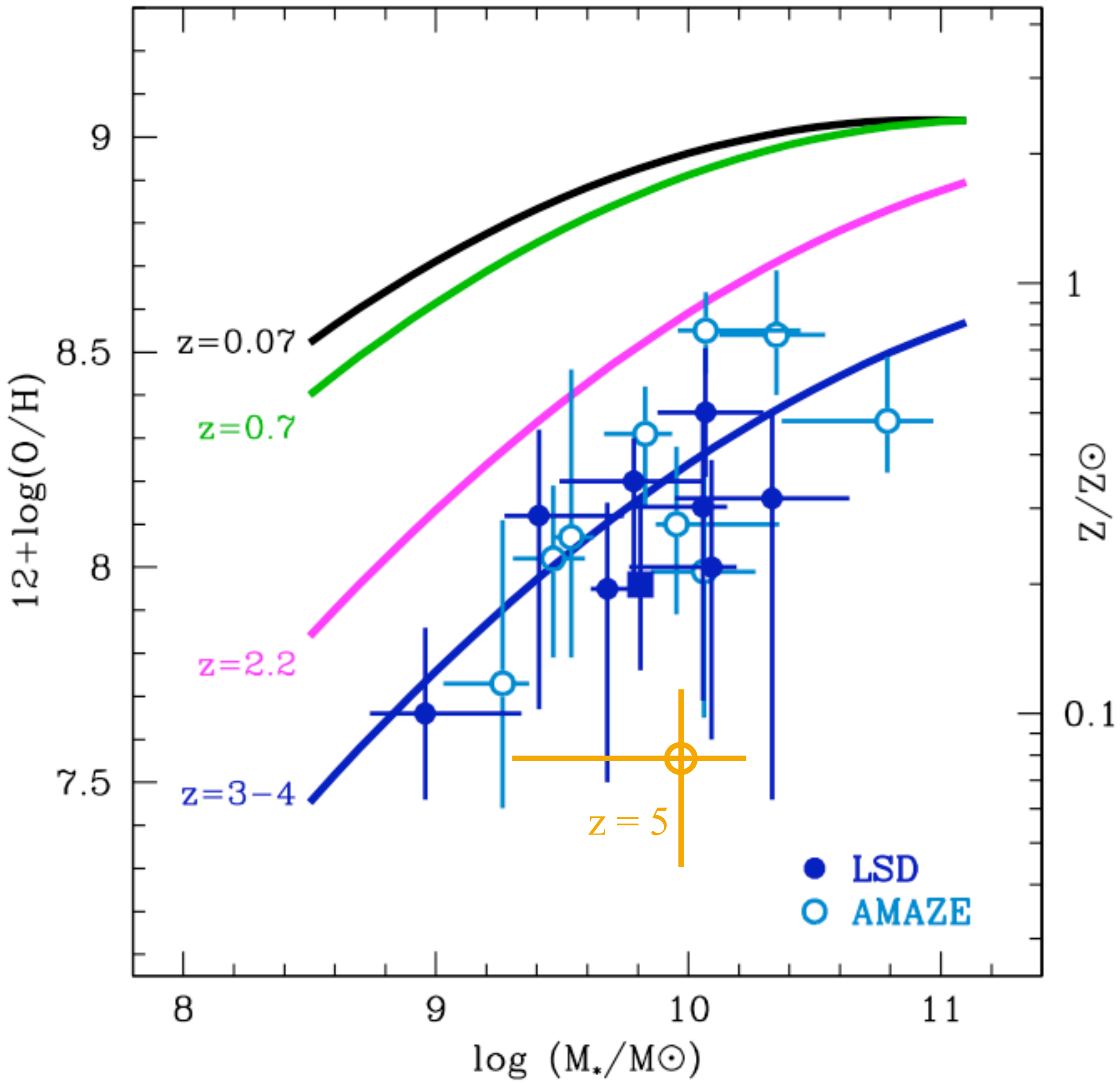
z~2.2 LBG (Erb+06)

z~3.3 ○ AMAZE (Maiolino+08)

● LSD (Mannucci +09)

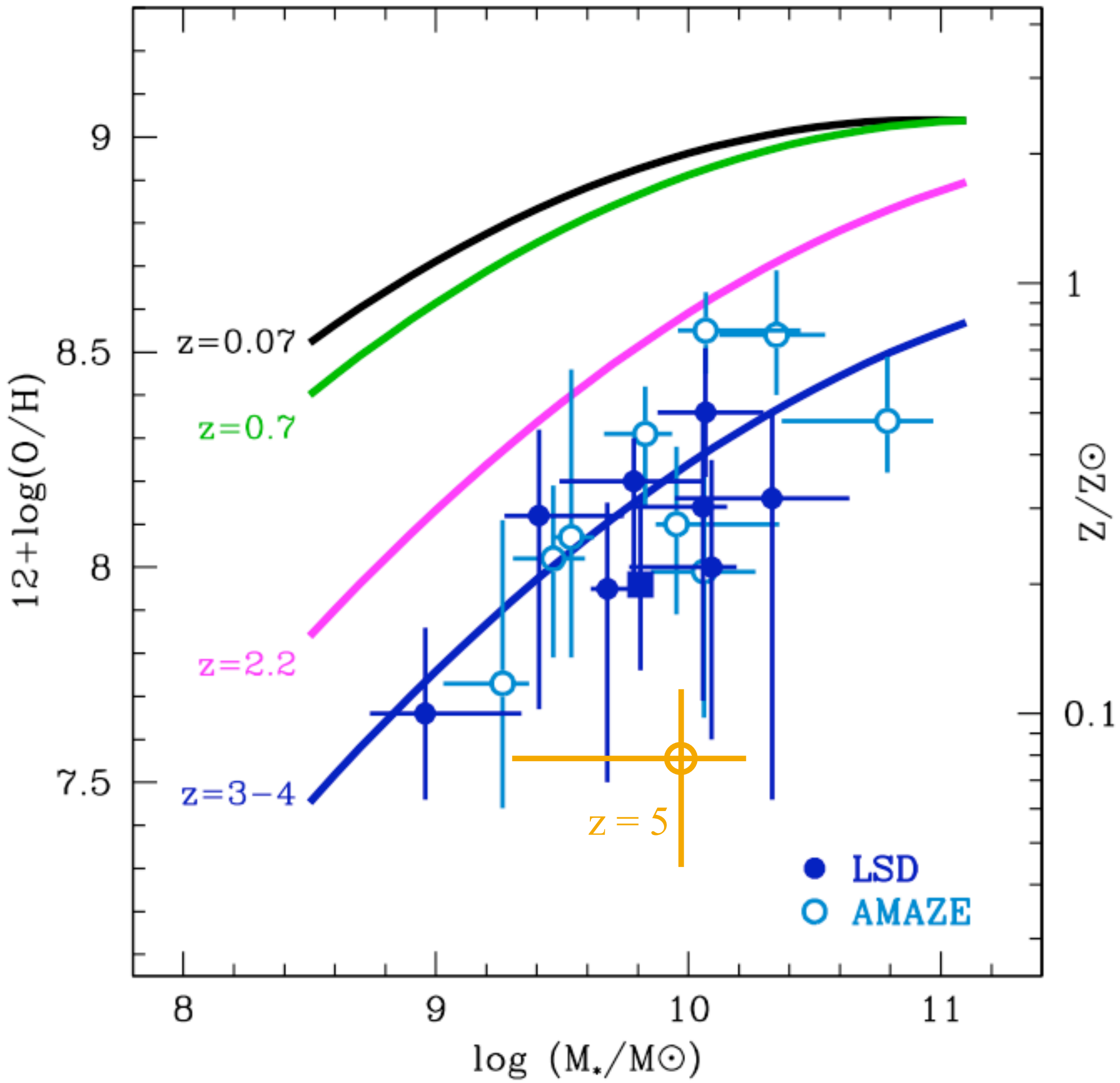
z~5 ○ AMAZE (Maiolino+09)

Evolution of the mass-metallicity relation: results from AMAZE+LSD



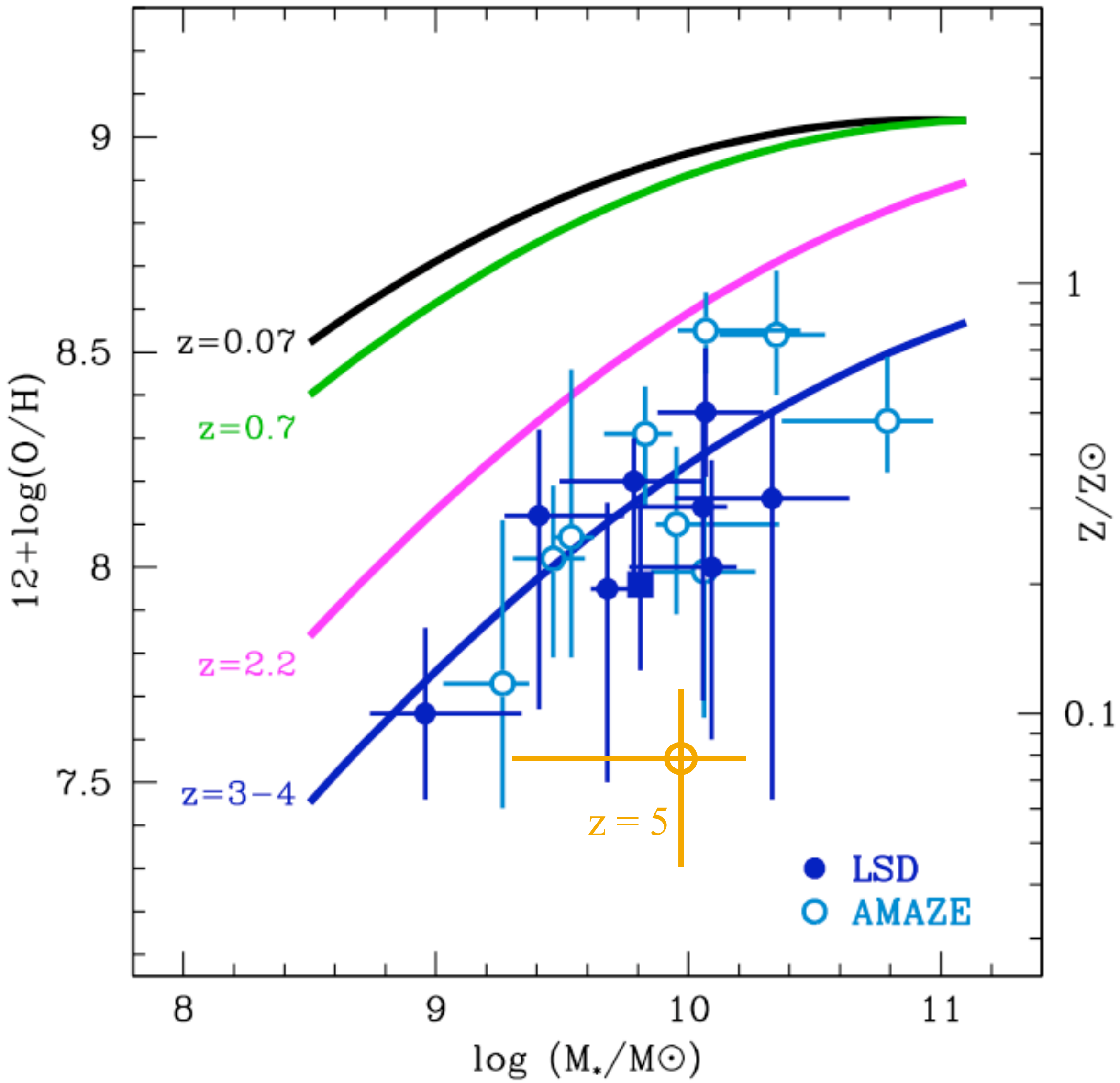
M-Z relation already in place at z~3.5

Evolution of the mass-metallicity relation: results from AMAZE+LSD



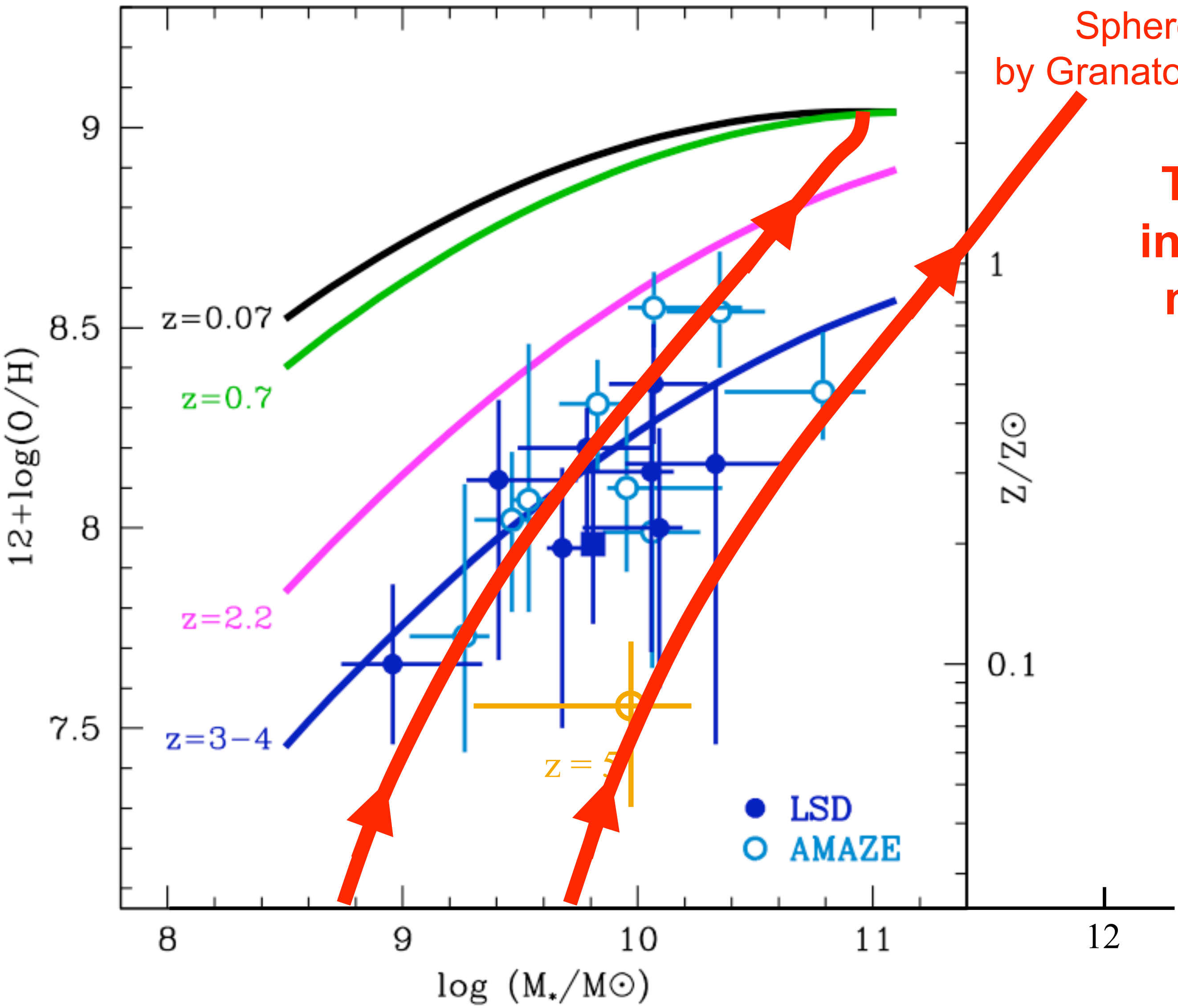
Strong evolution of the M-Z relation beyond z~2 (note: it's not tracing the evolution of individual galaxies)

Evolution of the mass-metallicity relation: results from AMAZE+LSD



The metallicity evolution of galaxies is clear only if differentiated by stellar mass... else nearly undetectable

Evolution of the mass-metallicity relation: results from AMAZE+LSD

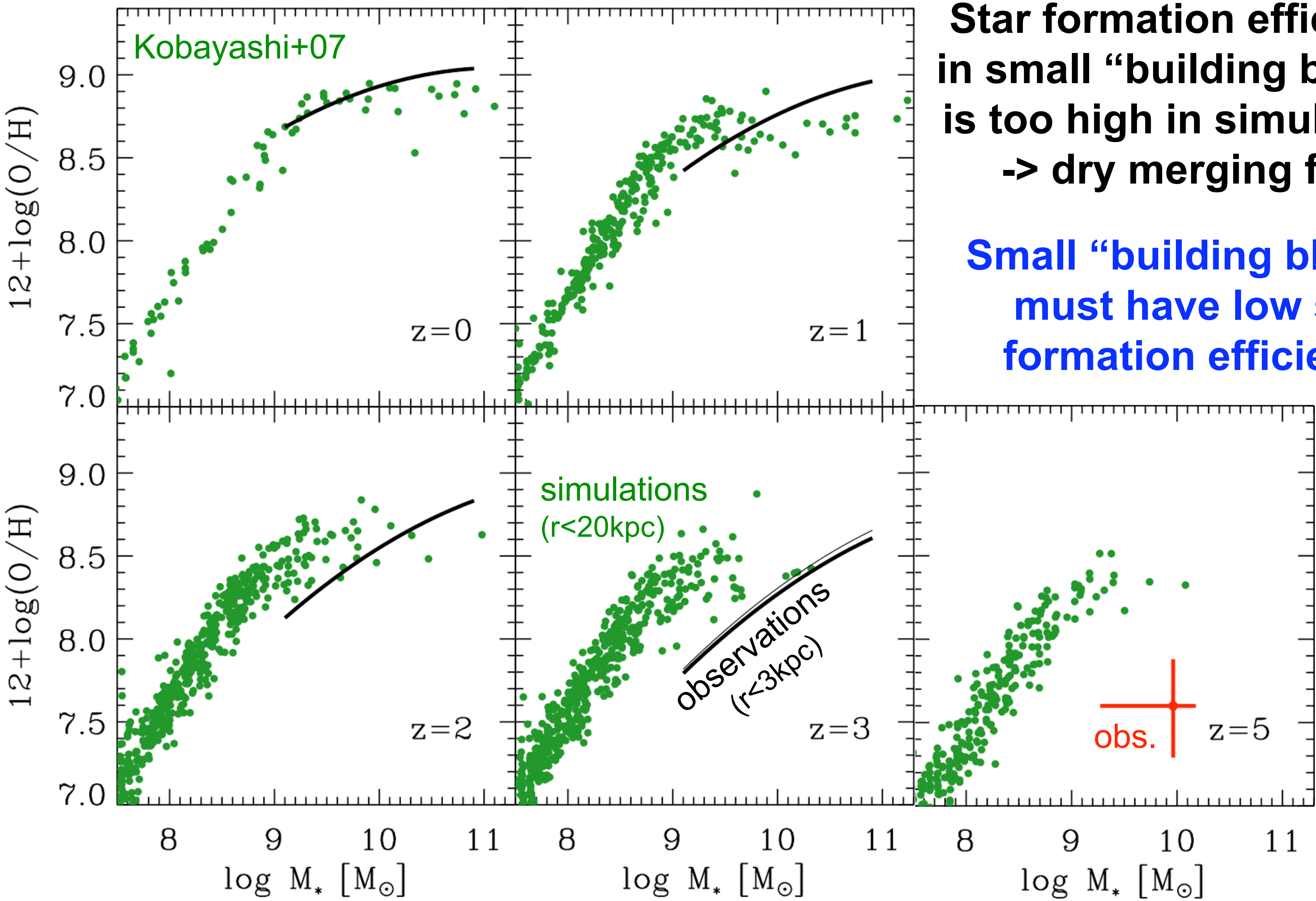


Spheroids evolutionary models
by Granato et al. 2004, Altieri et al. 2007

These must end up in local very massive metal rich galaxies

Metal poor massive galaxies at z~3

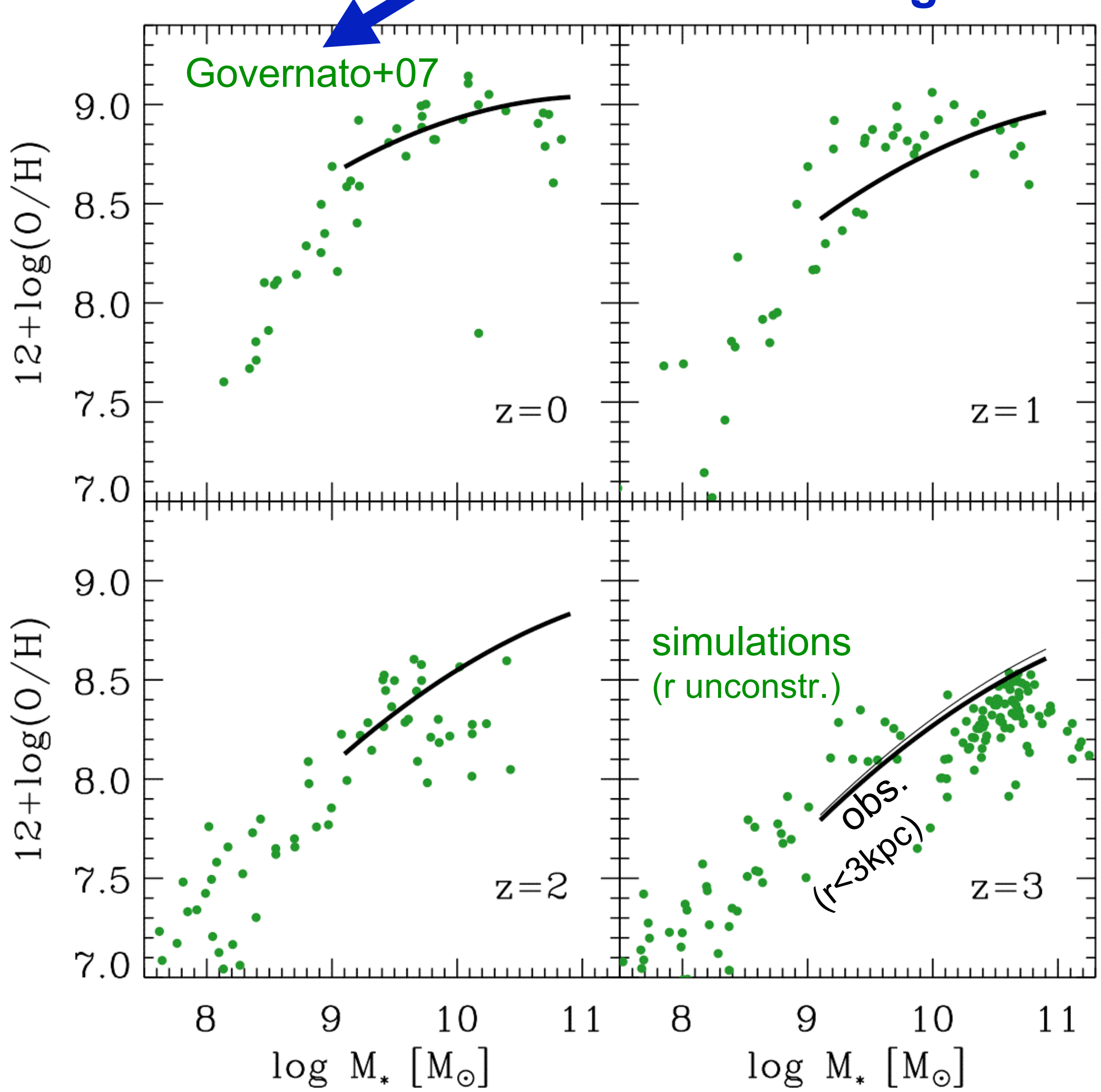
Several classical hierarchical models generally fail to reproduce the mass-metallicity relation at high-z



Star formation efficiency in small "building blocks" is too high in simulations -> dry merging fails

Small "building blocks" must have low star formation efficiency

Low star formation efficiency in "building blocks" either because below the density/mass threshold, or because of strong feedback

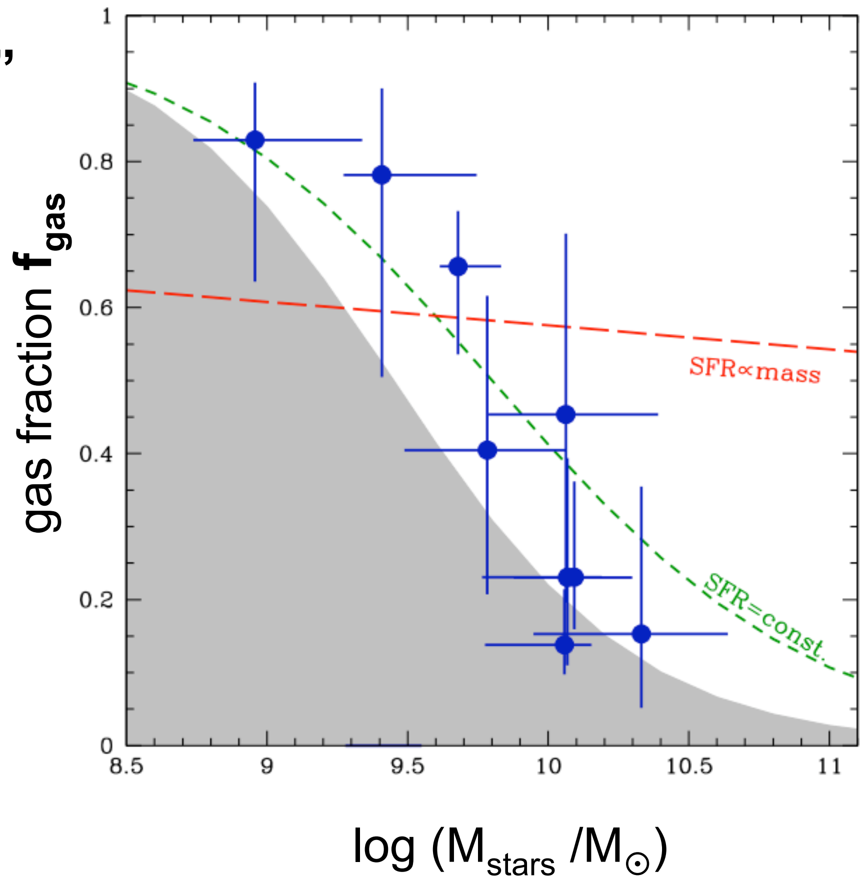


Most star formation after (gas) mass assembly

Investigating the inflow of un-evolved gas/galaxies through the "effective yield test"

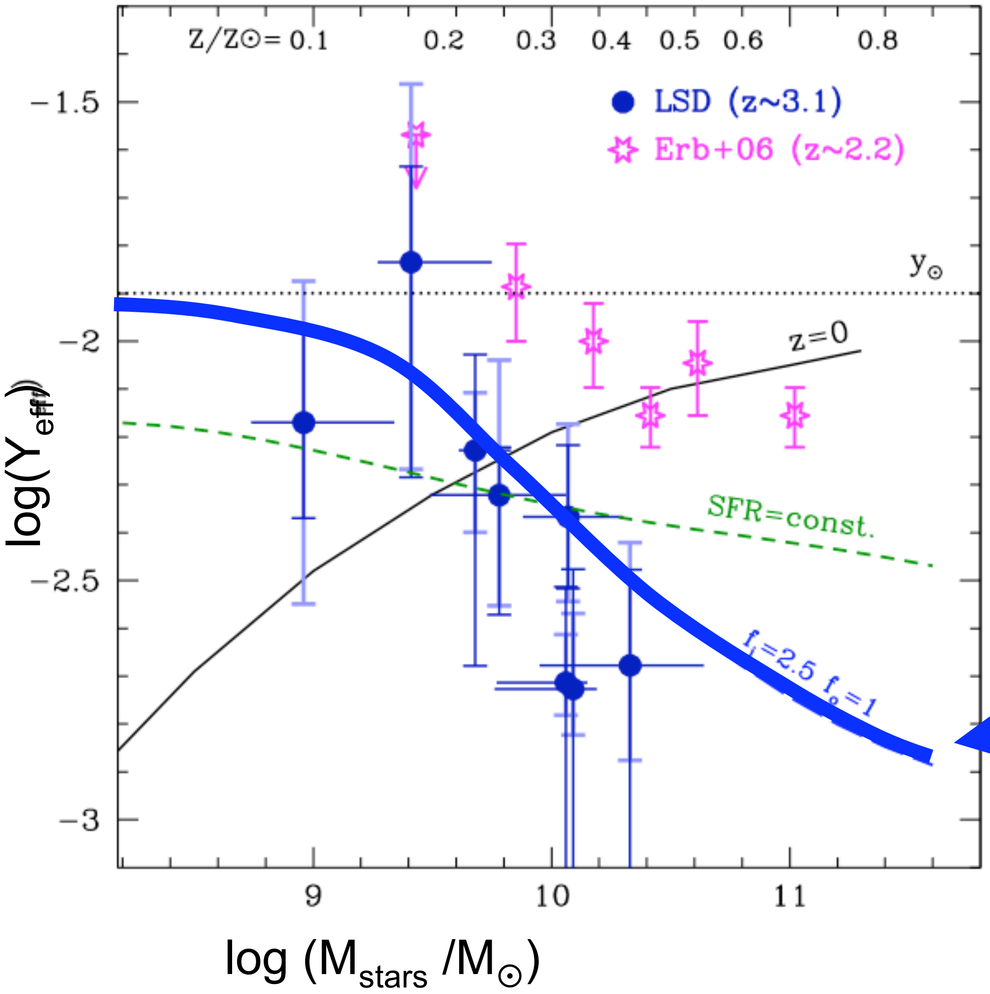
$Y_{eff} = Z / \ln(1/f_{gas})$ if $Y_{eff} < Y_0 \Rightarrow$ inflow/outflow

Gas fraction f_{gas} by "over-interpreting" the Schmidt law: SFR → Σ_{gas}



Mannucci et al. 2009

Investigating the inflow of un-evolved gas/galaxies through the "effective yield test"



pristine gas inflow rate = 2.5 x SFR

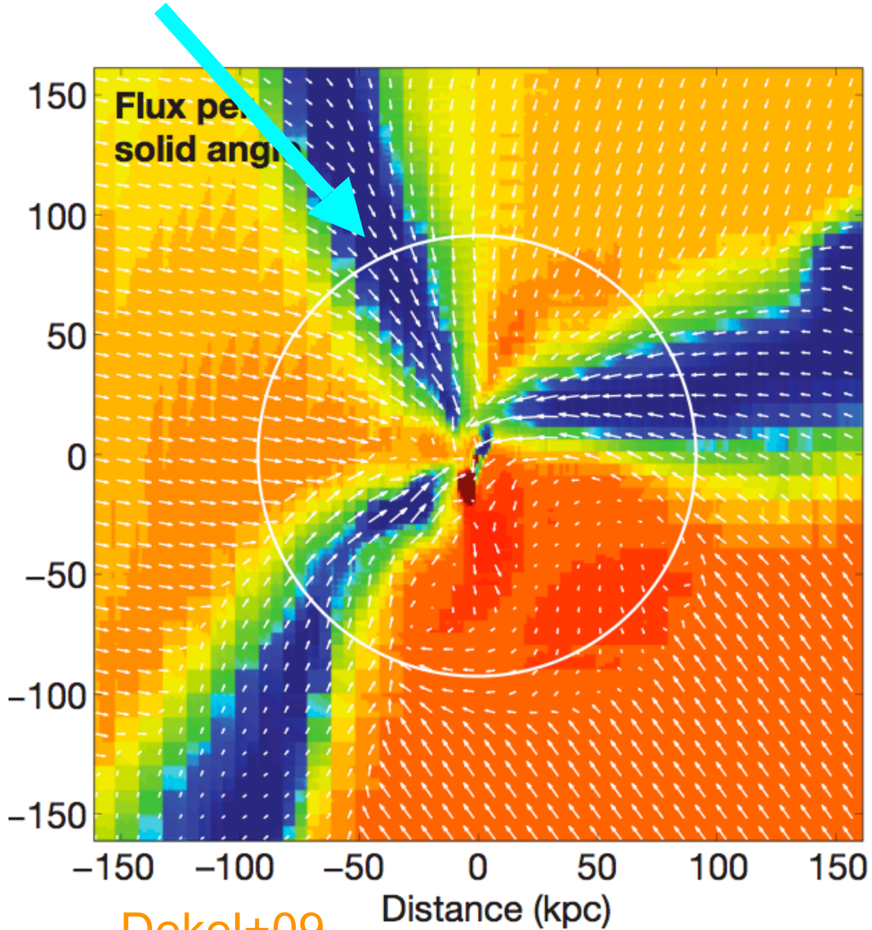
$$\frac{\mathbf{SFR}}{\dot{\mathbf{M}}_{\mathbf{inflow}}} = \mathbf{0.4}$$

Mannucci et al. 2009

What are the un-evolved “building blocks” making big galaxies?

Merging of un-evolved galaxies or cold flows of pristine gas?

Governato+07

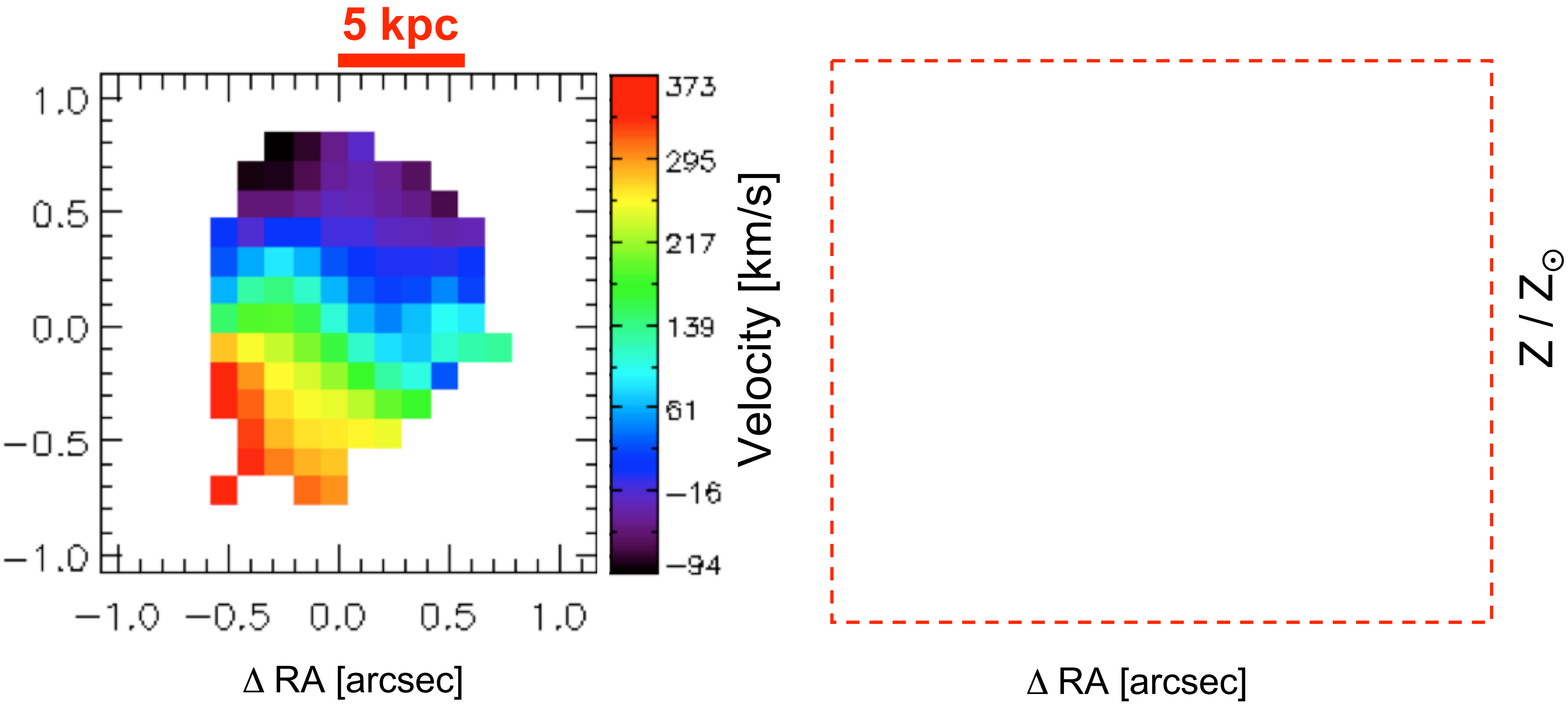


Dekel+09

We cannot distinguish based on the integrated metallicity

SSA-M38, z=3.3, SFR=120 $M_\odot$ yr^{-1}

No indication of significant merging: regular disk rotation pattern, and axysimmetric metallicity gradient

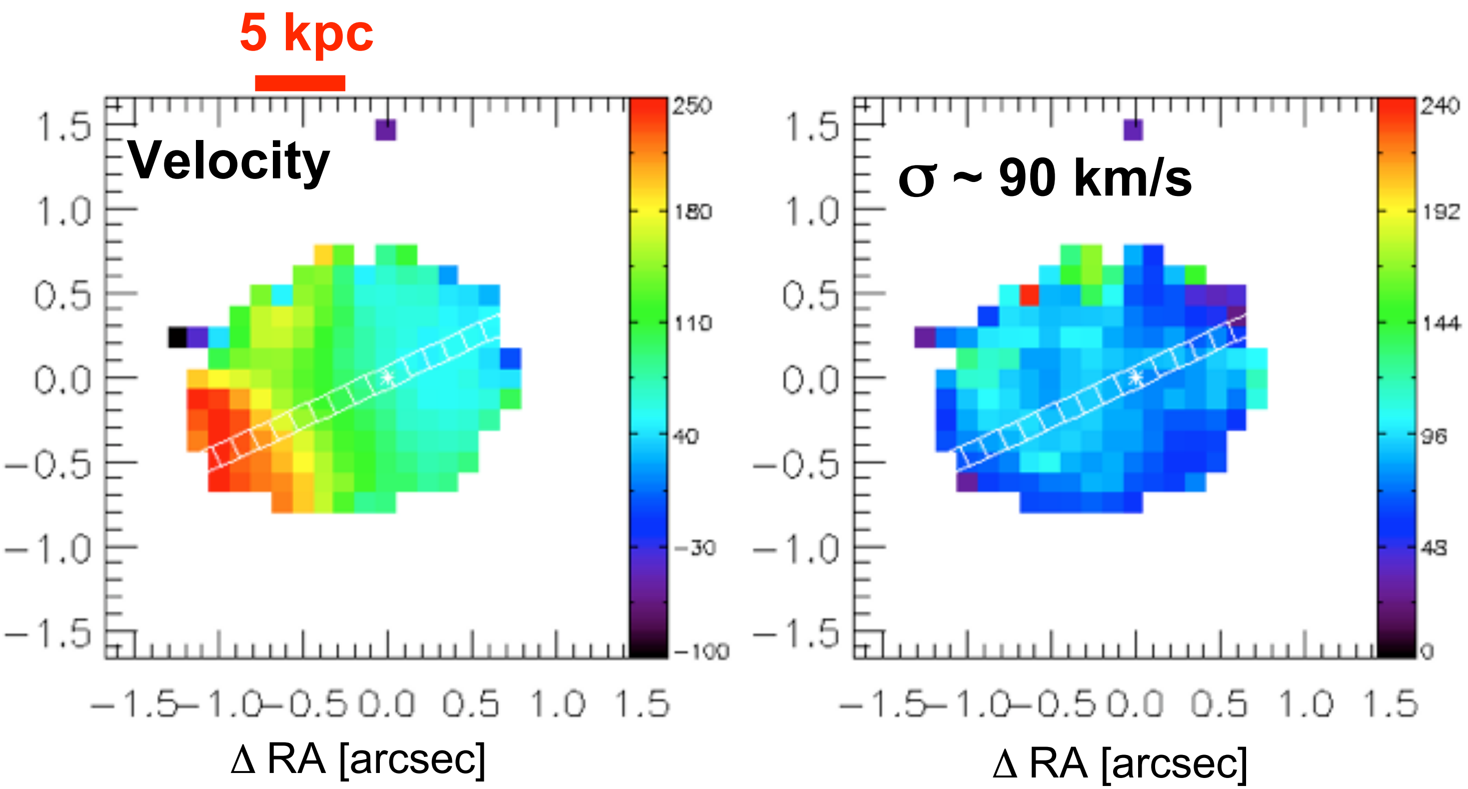


⇒ suggests secular evolution and high SFR driven by cold inflow of pristine gas

But not turbolent disk: σ ~ 25 km/s

SSA-C16, z=3.1, SFR=160 $M_{\odot}$ yr^{-1}

No indication of significant merging: regular disk rotation pattern, with large velocity dispersion



$$\frac{V}{\sigma} \sim 2.5$$

⇒ suggests secular evolution and high SFR driven by cold inflow of pristine gas

BUT 2/3 of the sample do show irregular kinematics -> (wet) merging ?

Future work

- **Mass metallicity relation at z~5**
- **Stellar metallicities (evolution of the M-Z_{star} relation)**
- **Dynamical Mass - Metallicity relation**
- **Metallicity gradients**

Conclusions

- **Mass-metallicity relation already in place at z~3.5**

- **Strong evolution of the mass-metallicity relation at z>3**

- **Comparison with models and Y_{eff} indicate that at z>3 galaxies were formed through merging of small galaxies or gas streams inflows characterized by low star formation efficiency.**
  -> Most of the star formation after (gas) mass assembly

- **Evidence for large disks at z>3 with high SFR with regular rotation patterns, smooth metallicity gradients**
  -> no evidence for significant merging;
  generally highly turbulent,
  but also cases with low velocity dispersion.

- **Yet, 2/3 of the sample with irregular kinematics**