Evolution of the metallicity-mass relations from cosmological-SPH simulations of galaxy clusters and groups

Alessio D. Romeo

Collaborators

J. Sommer-Larsen (NBI Copenhagen)

N.R. Napolitano (INAF Napoli)

V. Antonuccio-Delogu (INAF Catania)

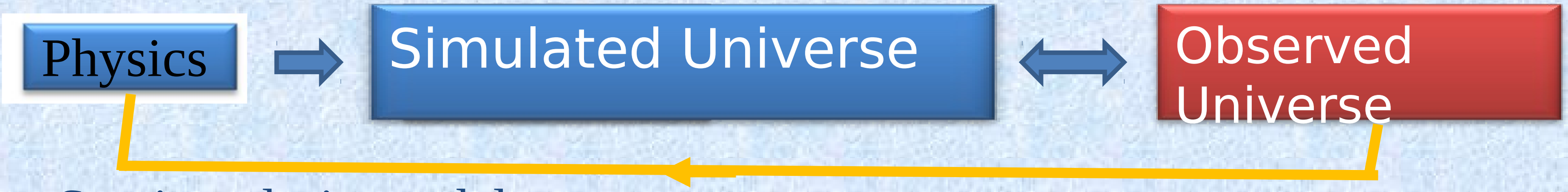
I. Gavignaud (UNAB Santiago de Ch.)

C. Tortora (Universitat Zurich)

S. Cielo (MPI Heidelberg)

SIM & SAM

Simulations can give an answer to a major question: what are the physical ingredients which lead to the galaxies we observe today?



Semi-analytic models

- Merger trees can trace particles in time
- Rely on a set of assumptions and approximations
- Fast when the simulation parameters are changed
- High resolution DM only + synthesis colours (e.g.)

Hydrodynamic simulations

- Full hydrodynamic description of physical phenomena
- Fewer simplifying assumptions
- Restricted on smaller scales (namely, galactic) in order to maintain a high resolution

Cosmological & hydrodynamic simulation (by *rezooming*)

- The formation is followed *ab initio* within a wide cosmological volume => role of environment
- Lower resolution
- Allows to study the mutual cycle between inter-galactic medium, star formation and stellar feedback

Rezoomed cosmological simulations

Gas hydrodynamics

⟷

coupled "self-consistently" with the stellar component:

Star formation

↓

stellar feedback

↓

energy & metals outflow: galactic winds

- radiative metal-dependent cooling
- star formation: Salpeter or Arimoto-Yoshii (top-heavier) IMF
- SN-II & Ia feedback
- stochastic chemical evolution: *not-instantaneous recycling* of H, He, C, N, O, Mg, Si, S, Ca, Fe

Simulation setup

ΛCDM "standard model" N-body code (*Fly*, Catania):
$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $z_i = 40$, $f_b = 0.12$

+

TreeSPH (Lagrangian) hydro-dynamical code
(Copenhagen)

mass resolution $m_{DM} = 18\ (2.3)\ x10^8\ h^{-1}\ M_{sun}$
$m_{SPH} = m_* = 2.5\ (0.3)\ x10^8\ h^{-1}\ M_{sun}$

- completeness limit: $M_V = -17\ /-15$, $M_K = -20\ /-17.5$
- softening length: 1.4-2.8 (stars) and 2.7-5.4 (DM) h^{-1} kpc

Simulation targets

"**Coma**" : 1x10^6 particles, 12.4x10^{14} $M_☼$, 6 keV

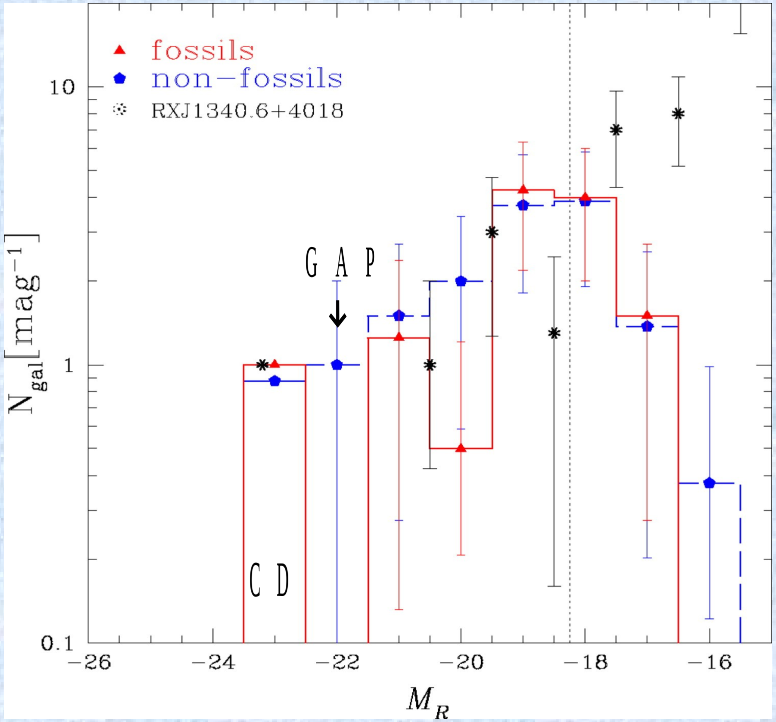
"**Virgo**" : 3x10^5 (2.2x10^6) particles, 3x10^{14} $M_☼$, 3 keV

12 **groups** : 3x10^5 (1.5x10^6) particles, 1x10^{14} $M_☼$, 1.5 keV

4 stacked samples:

- cluster cores (R <1/3 R_{vir})
- cluster outskirts
- NG
- FG

fossils →



Simulation models

- *Standard scheme* (**SW**): 70% of energy feedback from SNII
  ➜ continuous gal. super-winds

- *Other runs*: - weak feedback (only early starbursts);
  - strong feedback (SWx2/x4: "AGN");
  - "adiabatic" (no cooling/s.f.)

- *Optionals on top*: - pre-heating at z=3 $\approx$1 keV, 50 keVcm^2
  - thermal conduction

Simulation recipe

Top-heavy IMF (AY)
+
Strong feedback
(70% SN II → galactic "super" winds)

reproduces ICM properties: L_X-T, S(r), f_{cold}, Z_{Fe}(r), ICMLR

by removing low-S, over-X-ray emitting central gas

& spreading more efficiently metals up in the ICM

(Romeo et al. 2006)

⬇

but also => deficiency of bright (M*+2) galaxies

(Suggestion: no unique model for both gas and galaxies

solution: AGN feedback ?)

ICM

Simulating galaxy clusters – I. Thermal and chemical properties of the intracluster medium

A. D. Romeo,[1,2,3★] J. Sommer-Larsen,[1,4★] L. Portinari[1,5★] and V. Antonuccio-Delogu[3★]

Galaxy LF

Simulating galaxy clusters – II. Global star formation histories and the galaxy populations

Alessio D. Romeo,[1,2,3★] Laura Portinari[1,4★] and Jesper Sommer-Larsen[1,3,5★]

RS

The evolution of the galaxy red sequence in simulated clusters and groups

A. D. Romeo,[1,2★] N. R. Napolitano,[1] G. Covone,[1,3] J. Sommer-Larsen,[4,5] V. Antonuccio-Delogu[2,6]† and M. Capaccioli[3]

gradients

Stellar population gradients from cosmological simulations: dependence on mass and environment in local galaxies

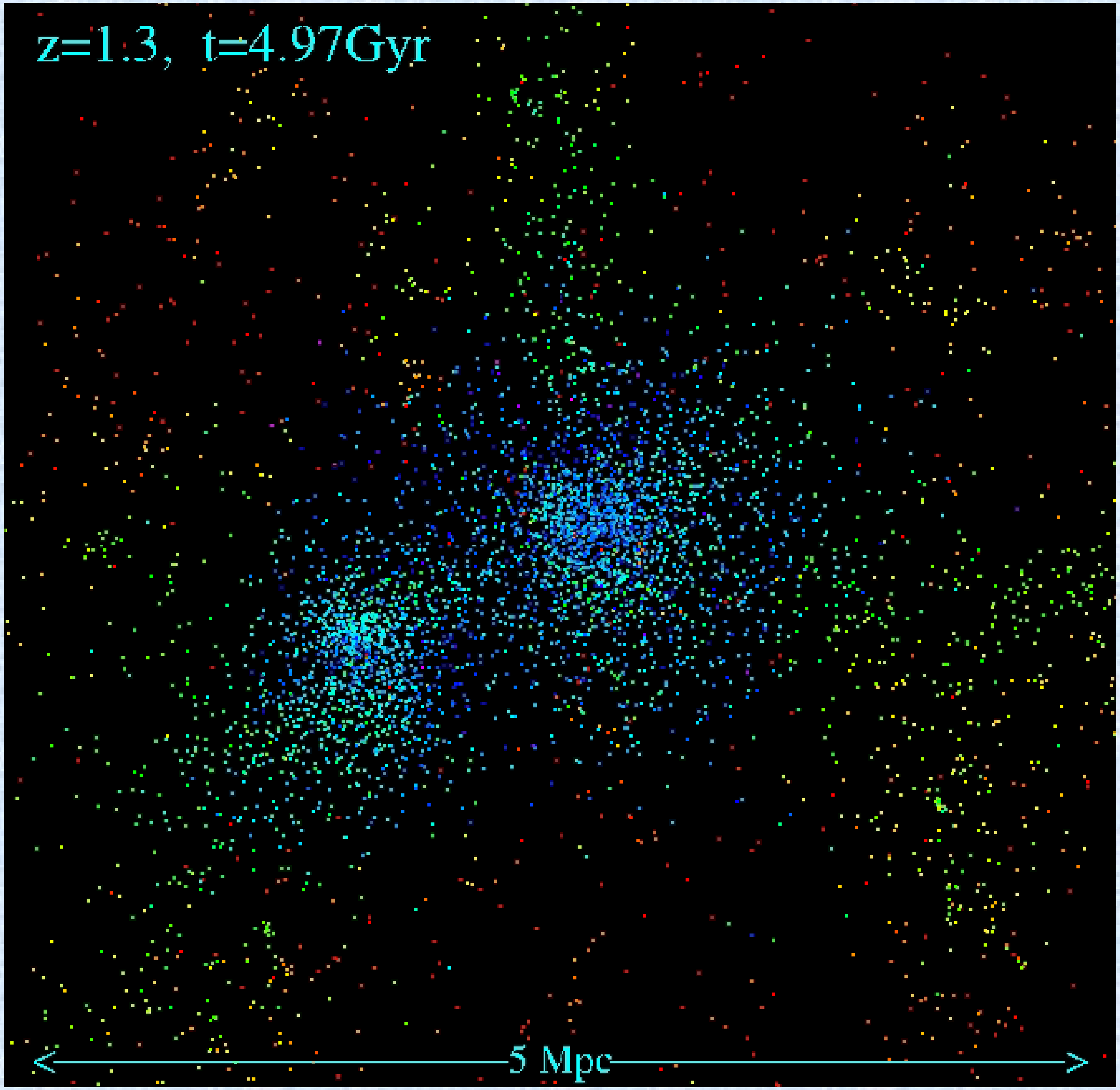
C. Tortora[1★], A.D. Romeo[2], N.R. Napolitano[3], V. Antonuccio-Delogu[4,5], A. Meza[2] J. Sommer-Larsen[6,7], M. Capaccioli [8,9]

ZM
(2013, accepted)

EVOLUTION OF THE MASS-METALLICITY RELATIONS IN PASSIVE AND STAR-FORMING GALAXIES FROM SPH-COSMOLOGICAL SIMULATIONS

A.D. Romeo Velonà[1], N.R. Napolitano[2], J. Sommer-Larsen[5,6,7], V. Antonuccio-Delogu[3], S. Cielo [4], I. Gavignaud[1], A. Meza[1]

1) The ICM

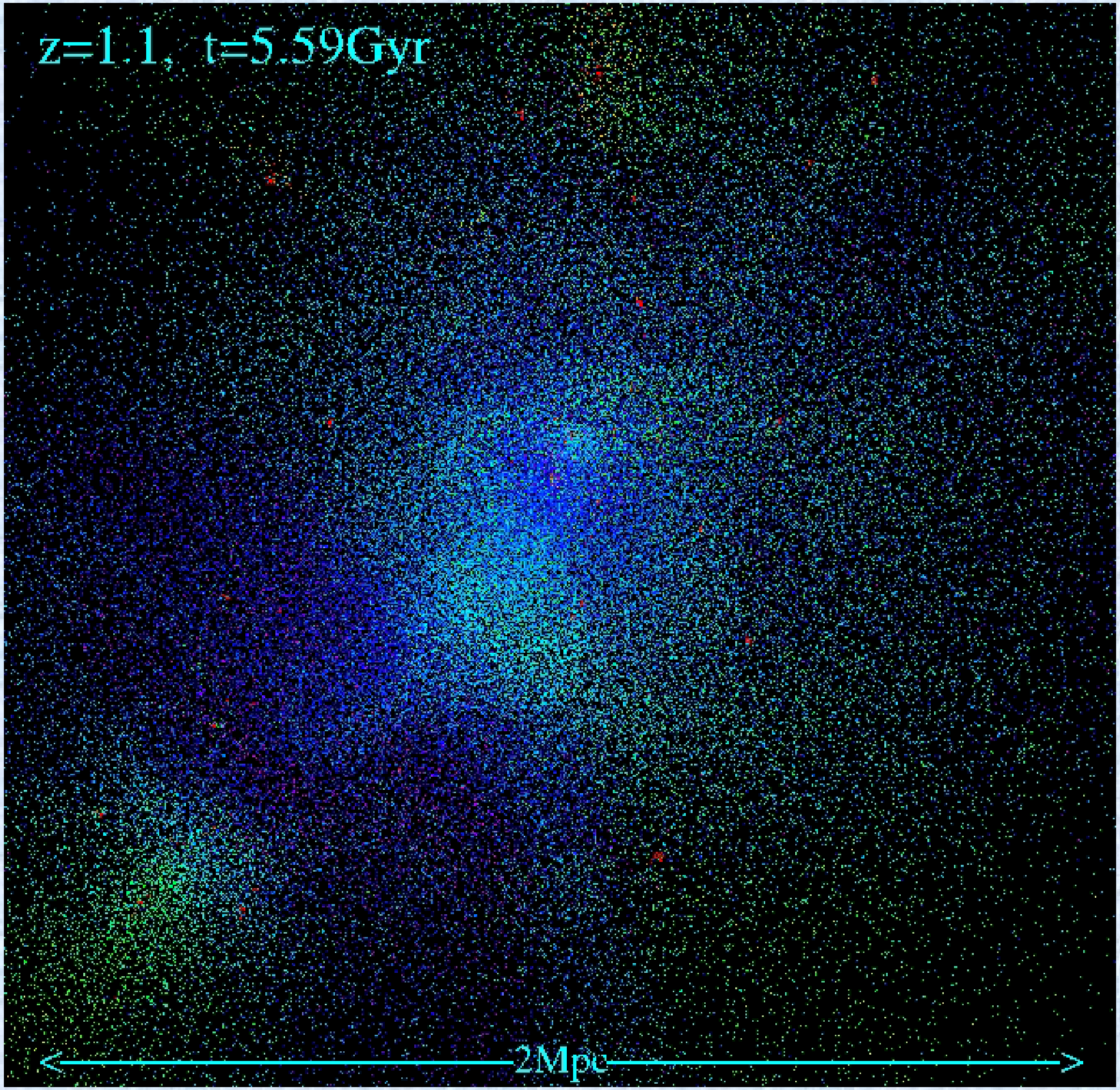


z~1 : shock

z~0.5: virialization

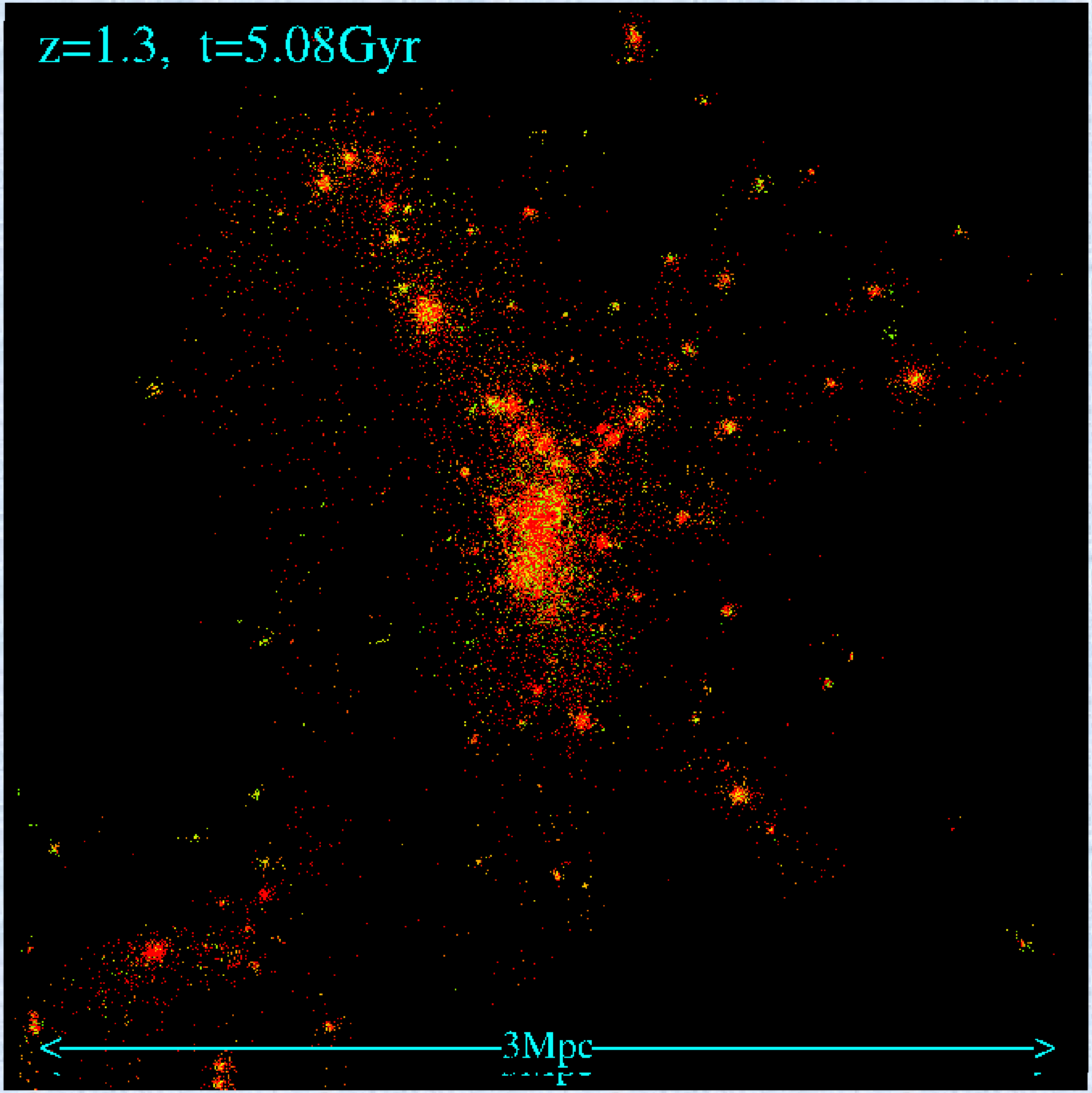
SPH (gas) particles by temperature – "Coma" low resolution

1) The ICM



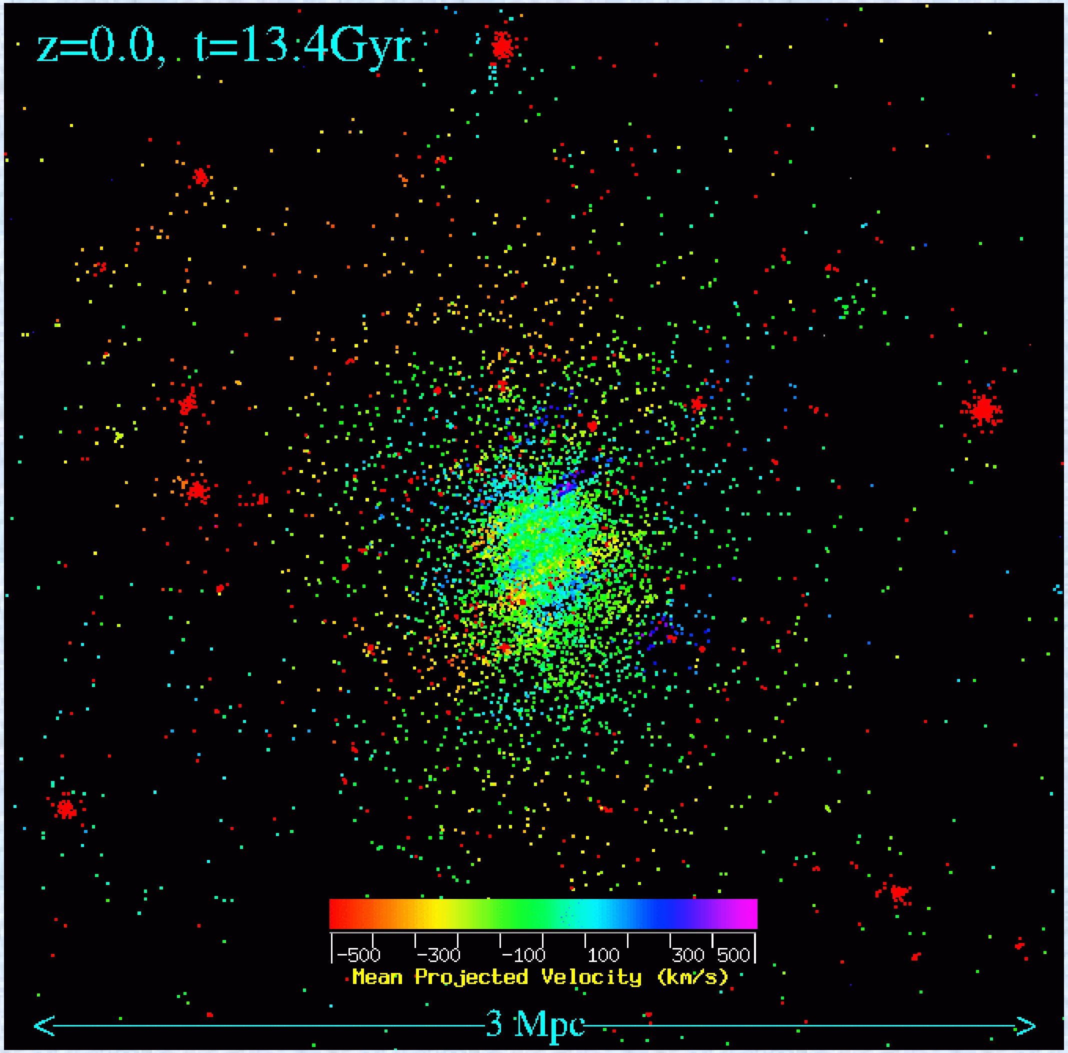
Same at 64x higher resolution

2) The galaxies



Star particles by formation redshift

3) The IC stars

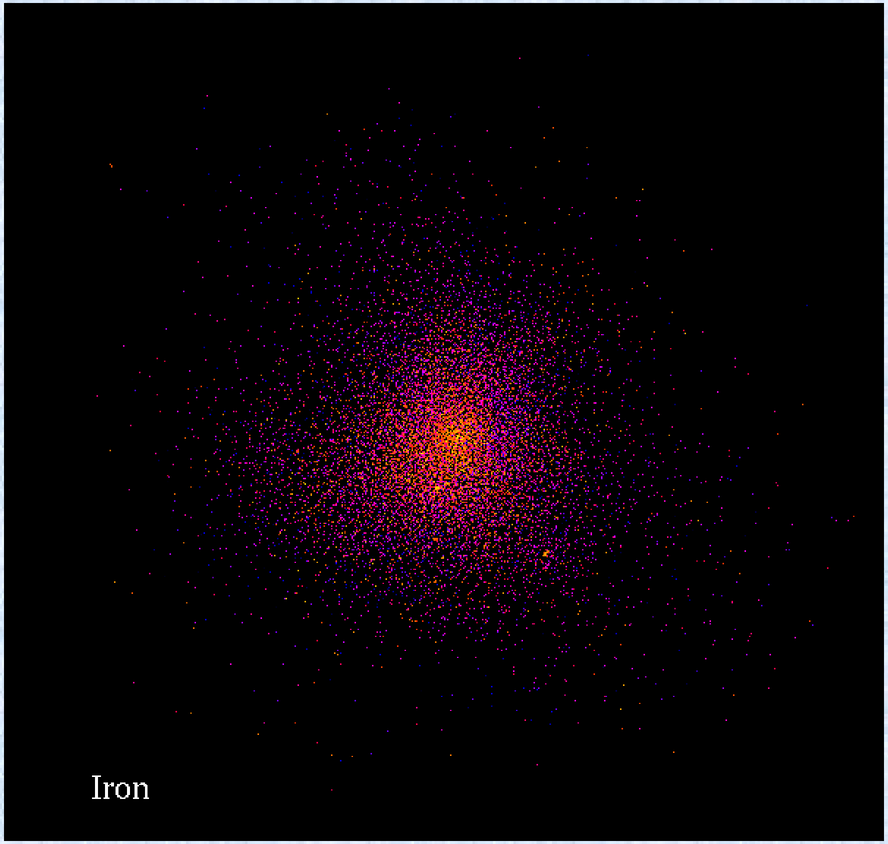


CD envelope (by vel.disp.)

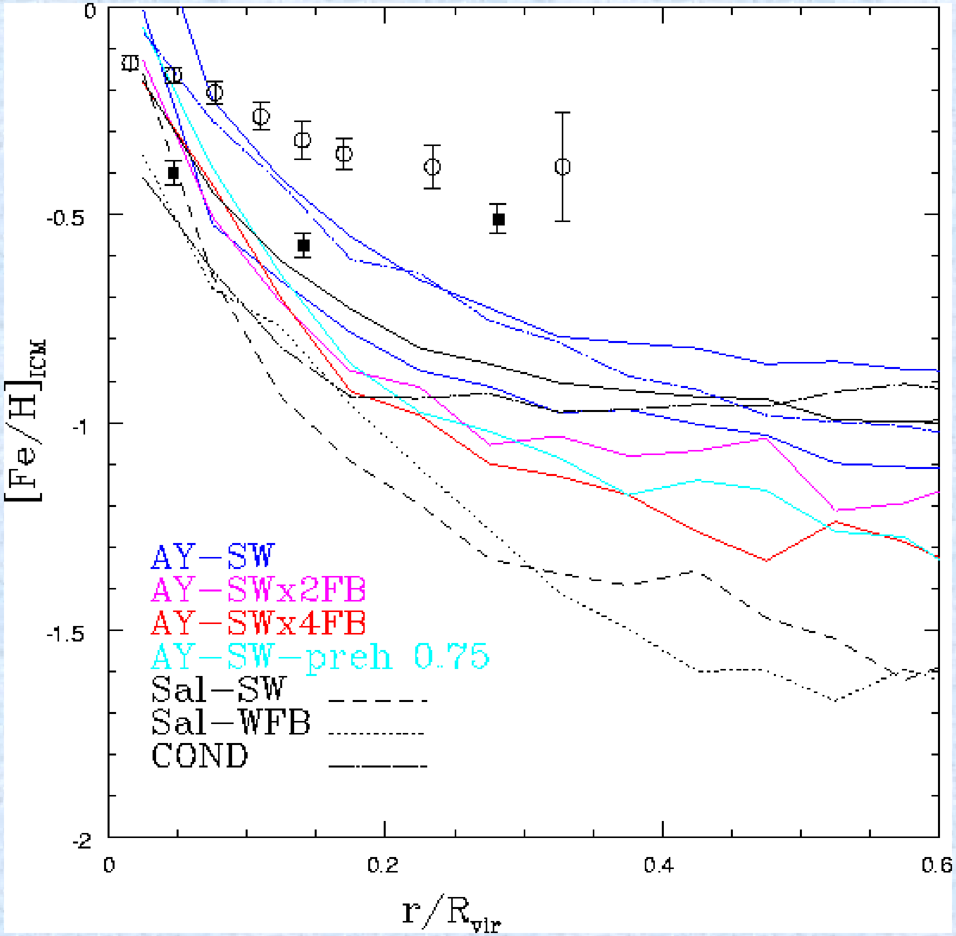
Metal-enrichment of ICM

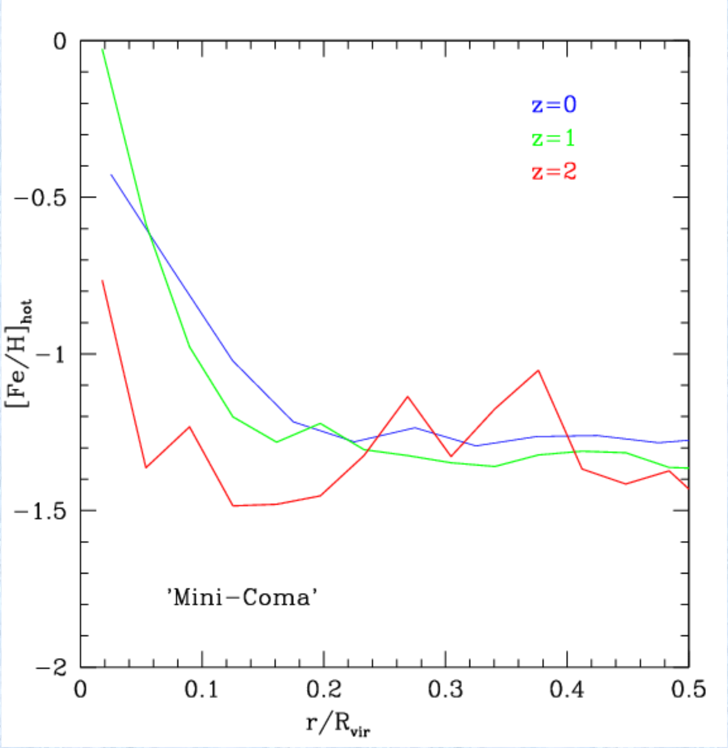
Observational facts:

- Iron: $Z_{Fe} \sim 1/3 \ Z_{Fe,sun}$
  decreasing radial profile:
- Steeper Z and T in "cold-core" clusters
- *alpha* elements (Si, O, Mg):
  supersolar abundance,
  increasing [α/Fe] radial profile:
  80% from SNII
- Evolution: enrichment completed before $z \sim 1.2$



Metals in the ICM ...





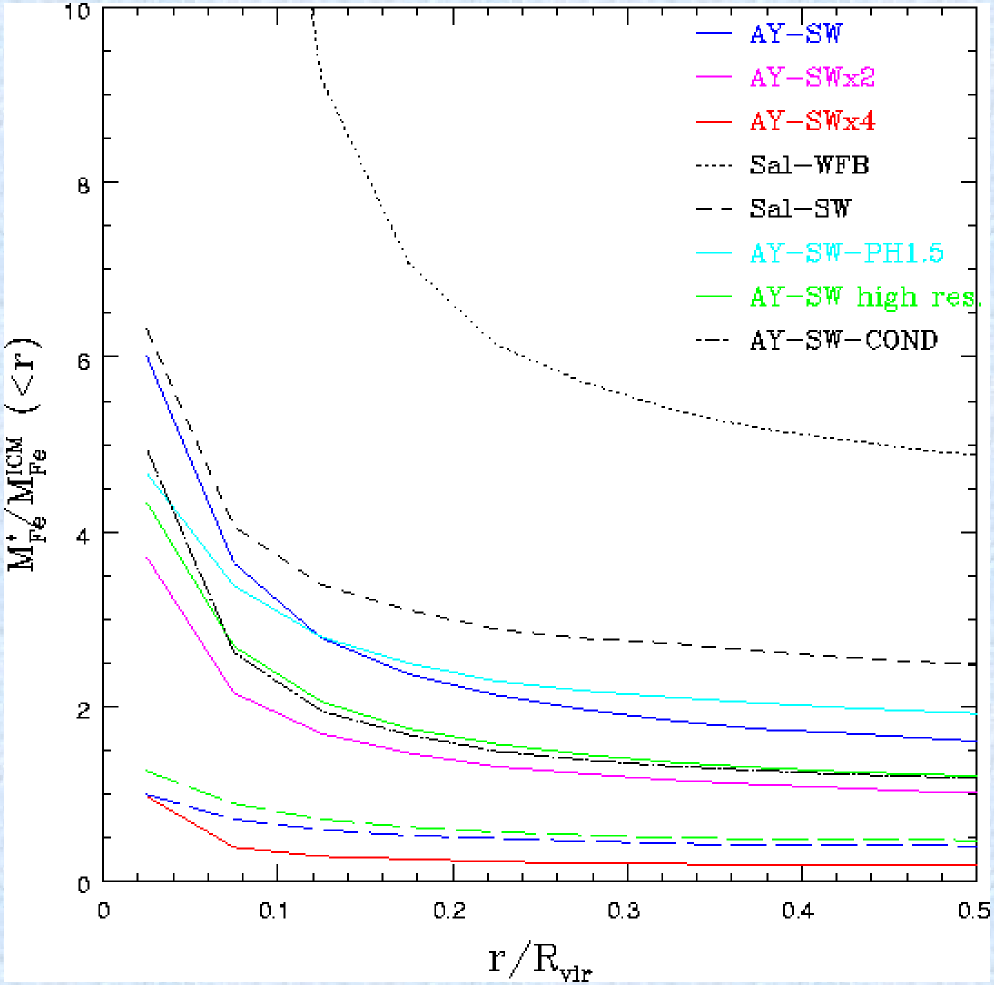
Metals already in place at *z*=1

--but still locked in stars

Need more efficient metal enrichment of ICM

...and metals in stars

Metal partition between stars and ICM: large overall amount kept locked into stars



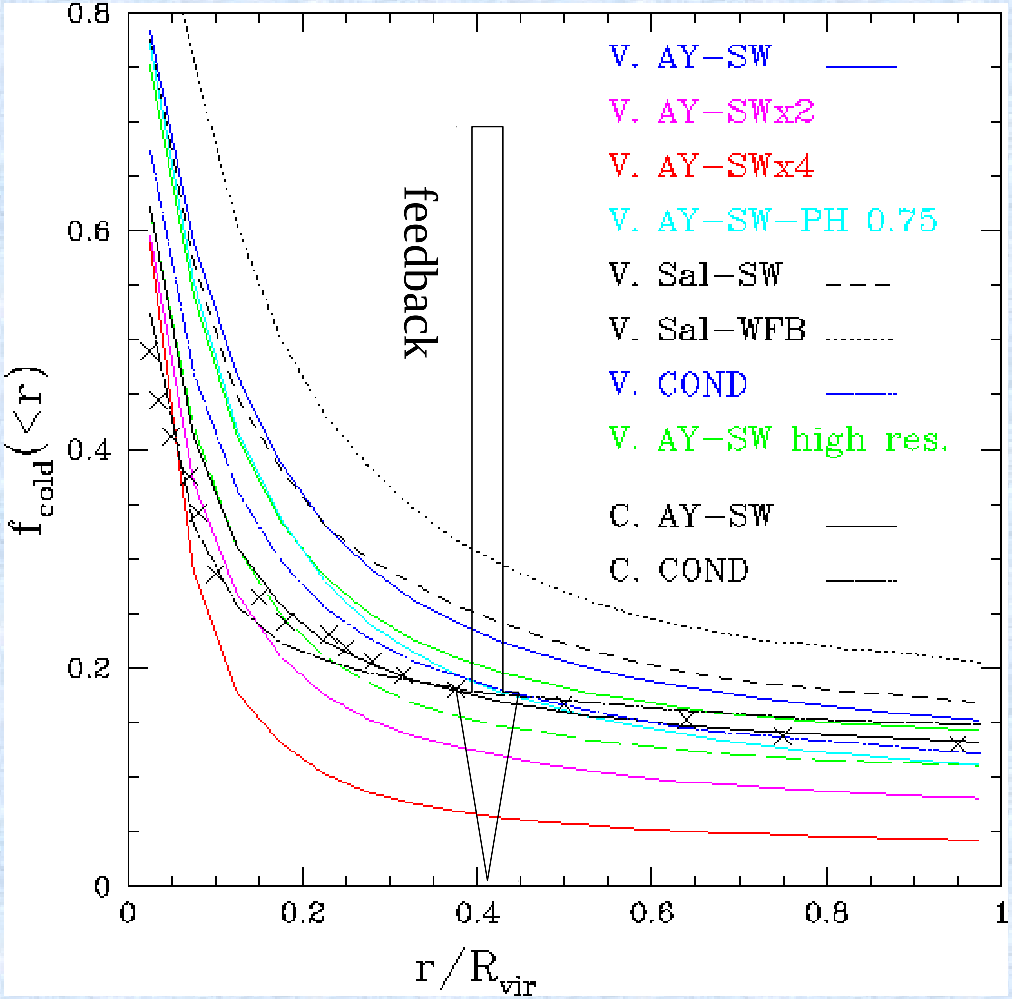
Enhancing feedback

"Equipartition"
(but also s.f. hampered …)

However: *consider IC stars as well !!*

COLD FRACTION PROFILES

f_{cold}=$(M_*+M_{coldgas})/M_b \approx (1 + M_{ICM}/M_*)^{-1}$

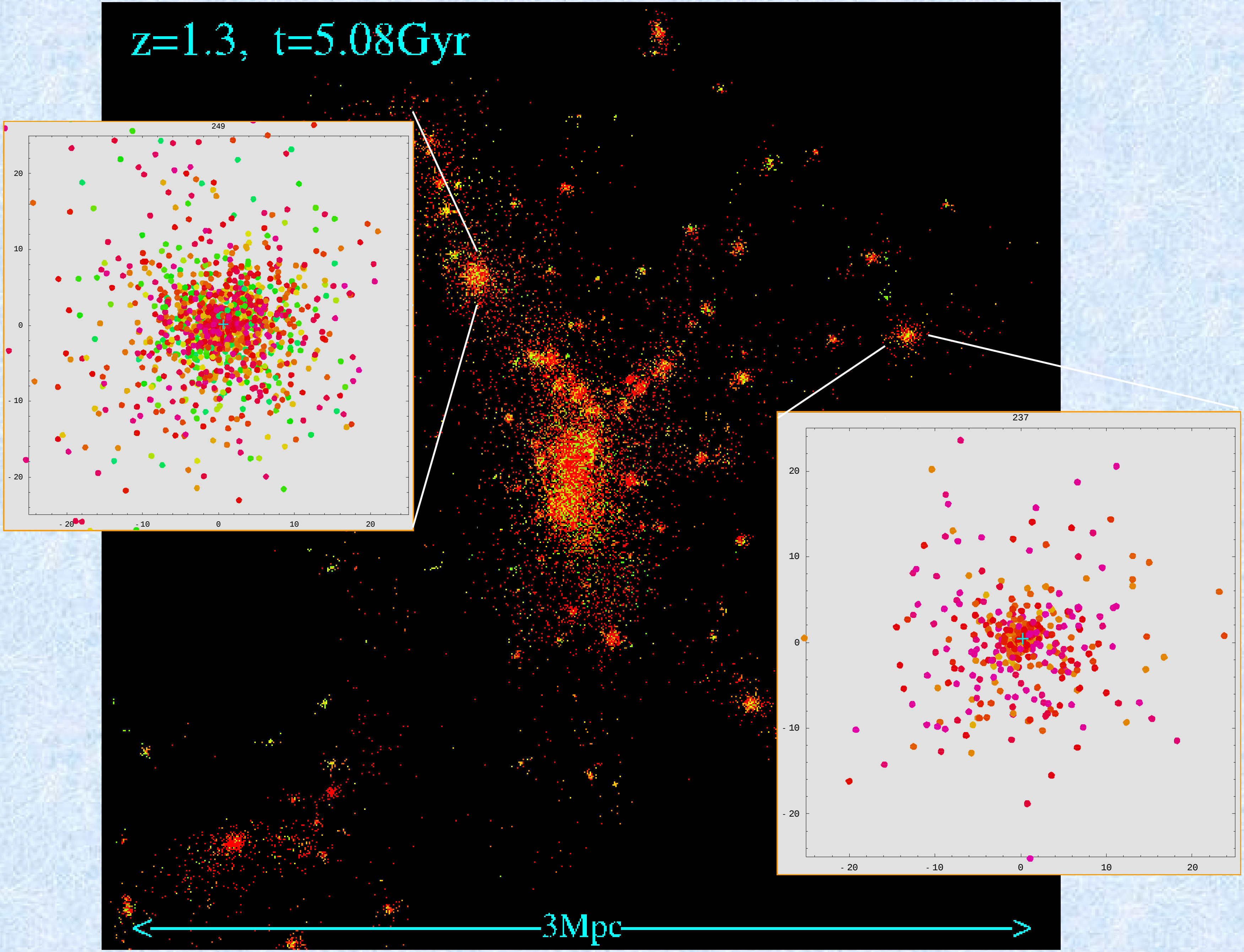


Historically, all "cooled" simulations → too large f_{cold} !

Salpeter IMF: too high M_* (→ small M/L_{opt})

High res. + c.f. correction

GALAXIES


z=1.3, t=5.08Gyr
249
237
3Mpc

Photometry of simulated galaxies

- 1 “Star” = 1 SSP (same τ & Z) = $3x10^8$ /4 $x10^7$ $M_☼$ corrected for the returned fraction back into gas → L_{SSP}(age,Z):

  $L = \int SF(t) \times L_{SSP}\, dt$ → multiband U, B, V, R, I, J, H, K

- Resolution limit: $M_V \leq -17$ /-15, $M_K \leq -20$ /-17.5

- BCG: 1) correction for excess of young central stars
  in the cold core (< 5 kpc)

- BCG: 2) correction for aperture effect (< 20 kpc)

Outline of results/diagnostics:

1. The LF
2. The Red Sequence
3. Mass-Metallicity relation
4. Luminous-to-faint ratio
5. Blue fraction
6. Cold gas fraction
7. Internal gradients (*Z*, age)

Stellar populations in Ellipticals

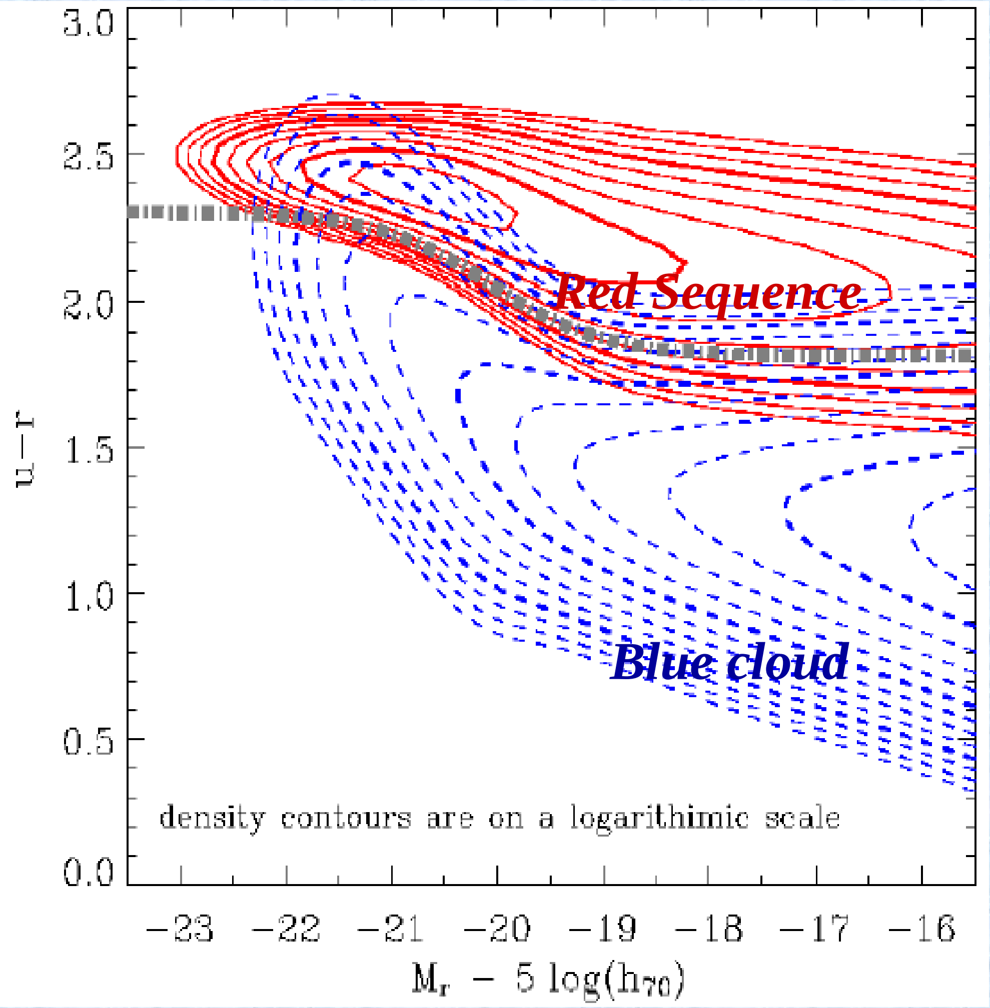
- Homogeneous old stellar populations dominated by red giant stars
- Spectra: metal absorption lines + molecules ⇒ typic of cold stars
- Metal rich stars ⇒ different generations of SF

COLOUR-LUMINOSITY RELATION

bright ⇔ red **faint ⇔ blue**

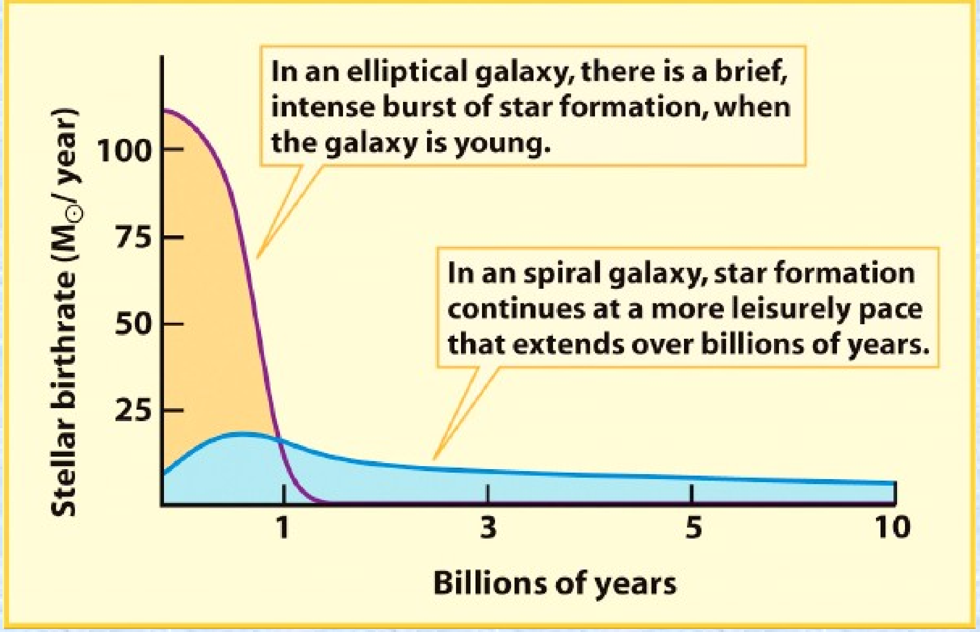
older **(?)** **younger**

- Colour = degenerate function of age **&** metallicity



SDSS *(Baldry et al. 2004)*

RS → constrains epoch (*slope*) and duration (*scatter*) of star formation activity



DOWNSIZING

More massive ellipticals are the last to get assembled...

but their stellar populations are the oldest !!!

Modelling the Red Sequence

The early-type CMR is a useful discriminant between the two competing theories of elliptical galaxy evolution:

1) Passive evolution/Monolithic collapse at high redshift:
tight, constant slope CM up to high *z* consistent with a synchronous starburst and then passive evolution = slow ageing & reddening (Kodama et al. 1998)

2) Dynamic evolution/Hierarchical merging :
RS slope flattens with *z* because more massive Ell. form from the (selective) mergers of more massive (metal rich) discs (Kauffmann & Charlot 1998)

The Red Sequence at *z*=0

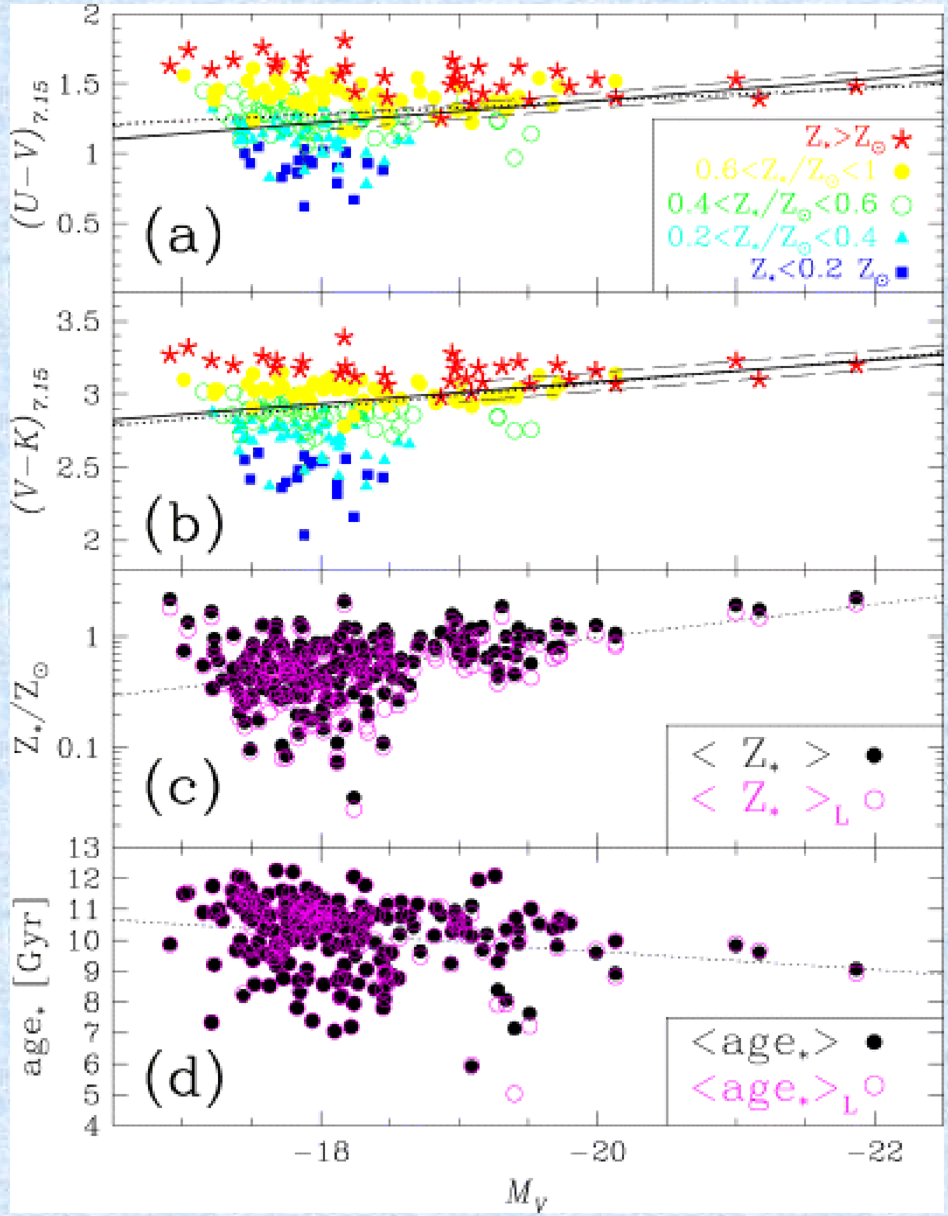
Colour-Magnitude

Metallicity-Mass

(cfr. Bower et al. 1992, Terlevich et al. 2001)

fainter metal-poorer

But Metallicity alone does not shape the RS as a peculiar locus in the CM plane



(Romeo et al., 2005, MNRAS 361, 983)

Two Sequences

- **Red Sequence**: early-type selection from σ_v – colour plane, with 2-sigma clipping (operative definition)

- "**Dead sequence**" (**DS**): all and only the galaxies with "no" SF over the last Gyr --> redshift-dependent threshold in terms of sSFR

Star formation efficiency

- SFR $=\varepsilon\, M_{gas}^{\alpha=1}$ (Schmidt-Kennicutt)
- sSFR$=\varepsilon\, f_{gas} \propto 1/\tau$ (time to form M_* at rate =SFR)

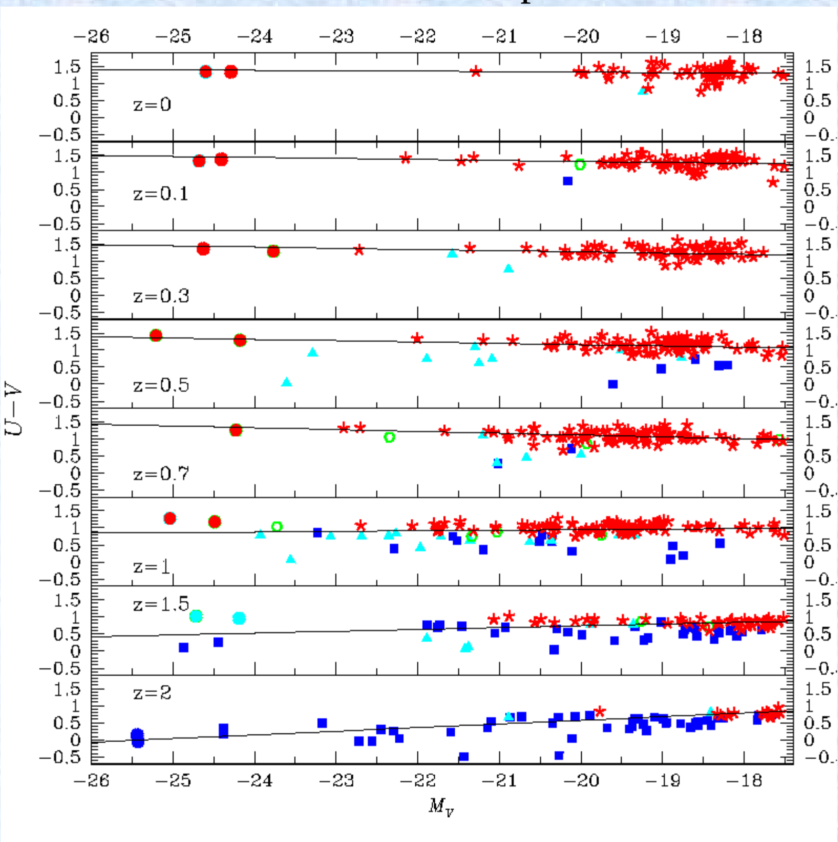
If $\tau << t_H$ -> starburst galaxy

sSFR decreases with mass: downsizing driven by s.f. efficiency (see Elbaz/Daddi+ 2007, Maiolino+ 2008)

SSFR as main driver of RS build-up

- Since $z\sim1$, most of s.f. occurs in less massive galaxies (*downsizing !)*

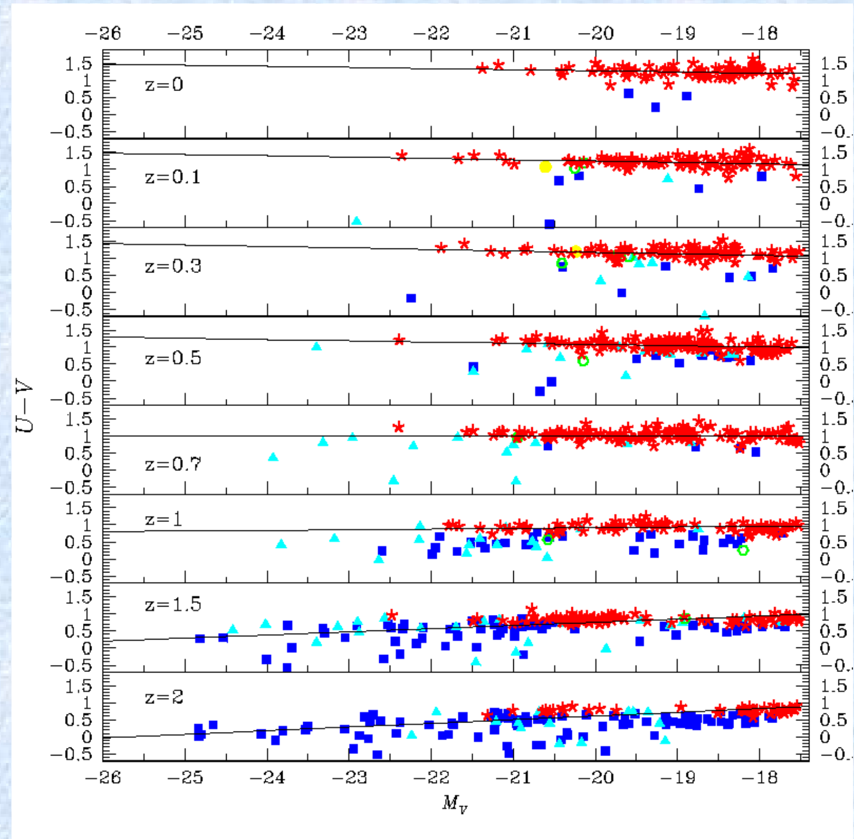
  and all star-forming galaxies lie below the RS fits
- Cluster cores complete the RS first



CORE

SFR/M$_*$
(Gyr^{-1})

> 1.5
1-1.5
0.5-1
0.1-0.5
< 0.1

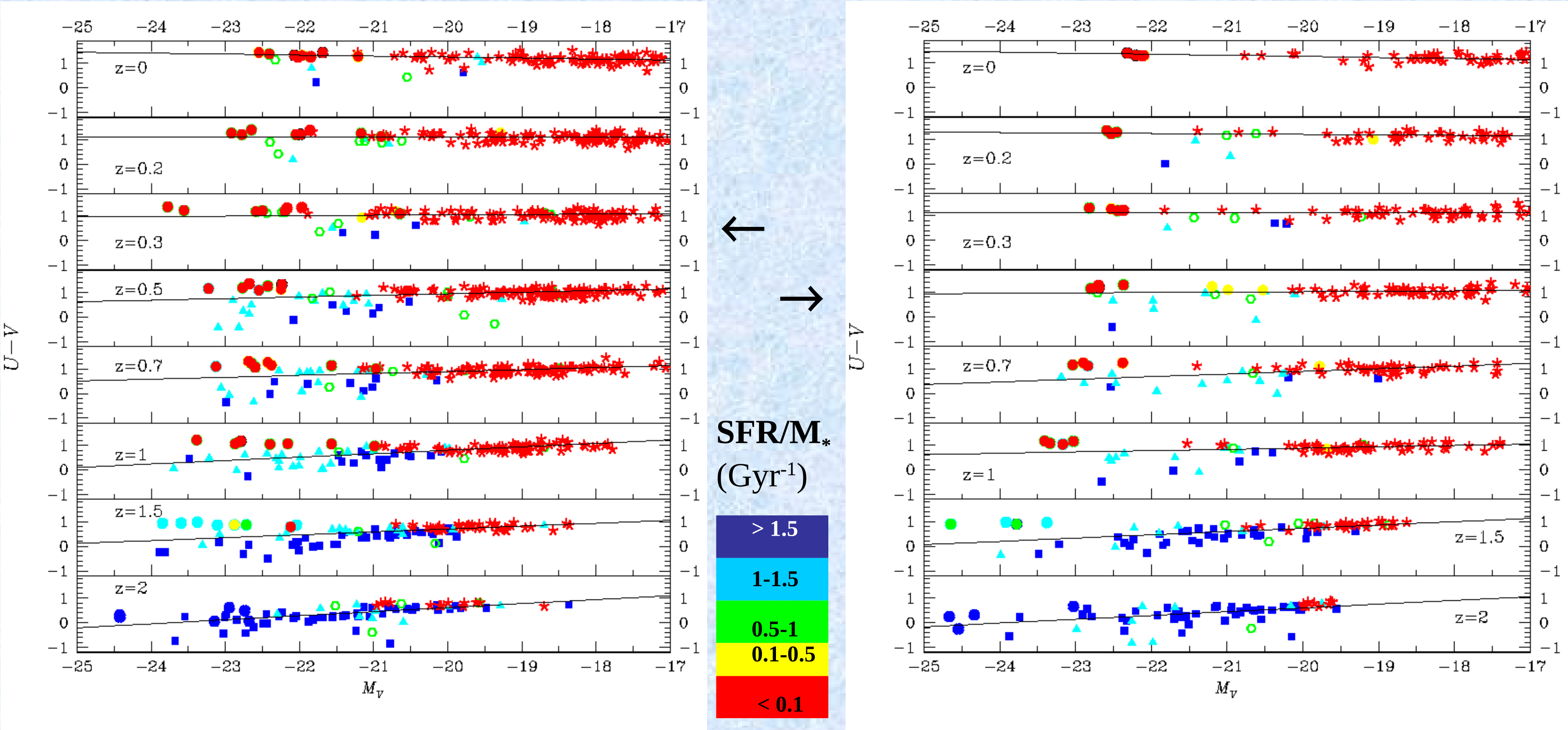


OUT

"Transfusion" from blue cloud to red peak :
Star formation moves towards less-massive galaxies

Environmental sequence in building the RS

- Normal groups: s.f. activity lasts down to z=0



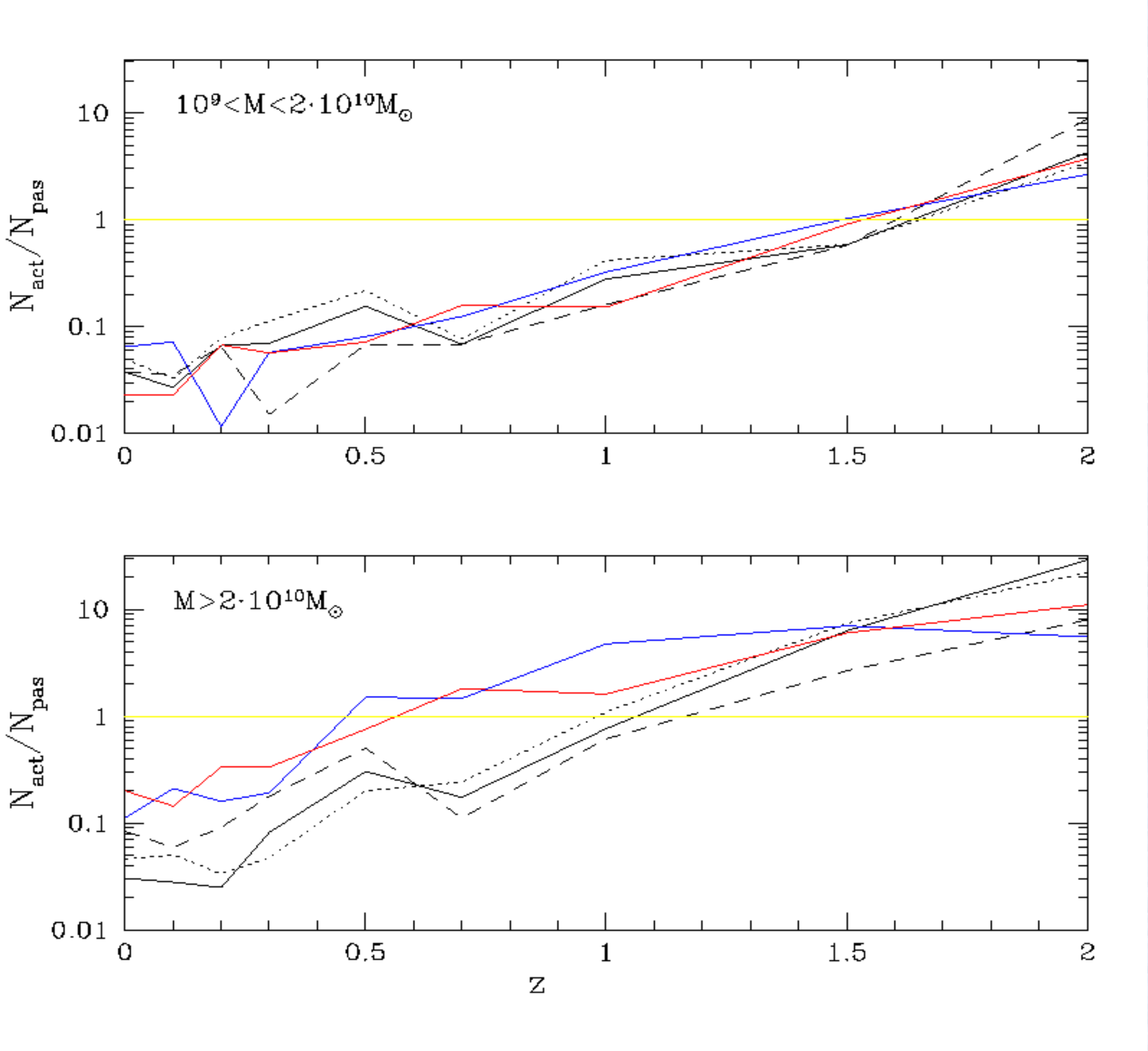
NORMAL GROUPS **FOSSIL GROUPS**

"Transfusion" from blue cloud to red peak :

Star formation moves towards less-massive galaxies (slower in groups)

The RS active to passive ratio

cl. IN
cl. OUT
cl. tot.
NG
FG



Less massive:

universal turnaround at z ~1.5

More massive:

environmental sequence

- $z \approx 1$ (clusters) → 0.5 (groups) : transition epoch between active and quiescent regimes

Environment dependency of the transition redshift

	$\alpha = \alpha_{DS}$	$N_{act}=N_{pas}$	N_{act}= 50% N_{pas}	
cluster cores	0.9	1.1	0.85	redshift
cluster outskirts	0.7	1	0.8	
Fossil Groups	0.4	0.6	0.4	
Normal Groups	0.2	0.4	0.3	

$M > 2x10^{10}M_{\odot}$

Environment dependency of the transition redshift

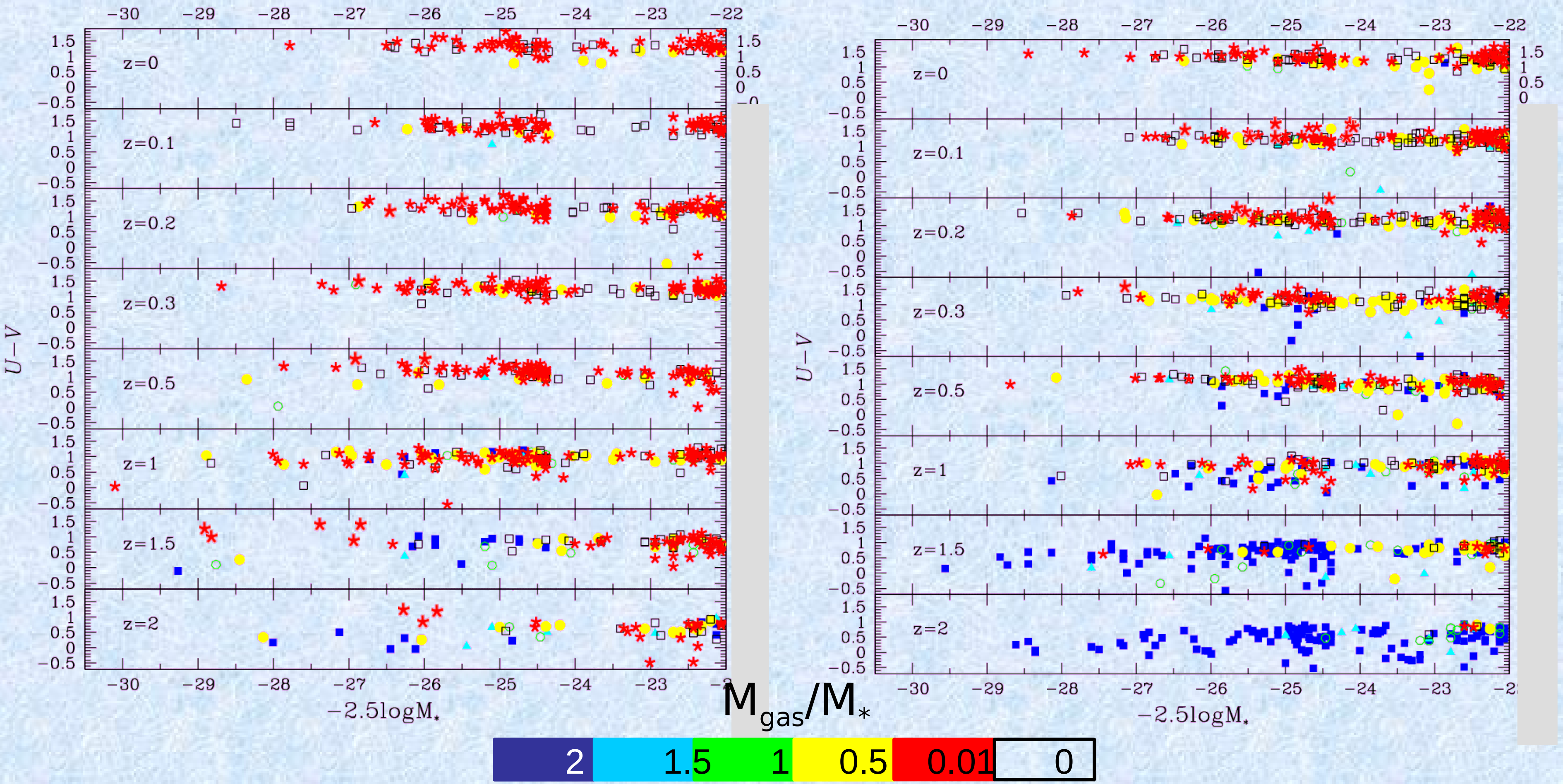
	$\alpha = \alpha_{DS}$	$N_{act}=N_{pas}$	$N_{act}=$ 50% N_{pas}	
cluster cores	0.9	1.1	0.85	redshift
cluster outskirts	0.7	1	0.8	
Fossil Groups	0.4	0.6	0.4	
Normal Groups	0.2	0.4	0.3	

Arnouts et al. 2007

transition redshift ⇔ epoch when RS approaches DS

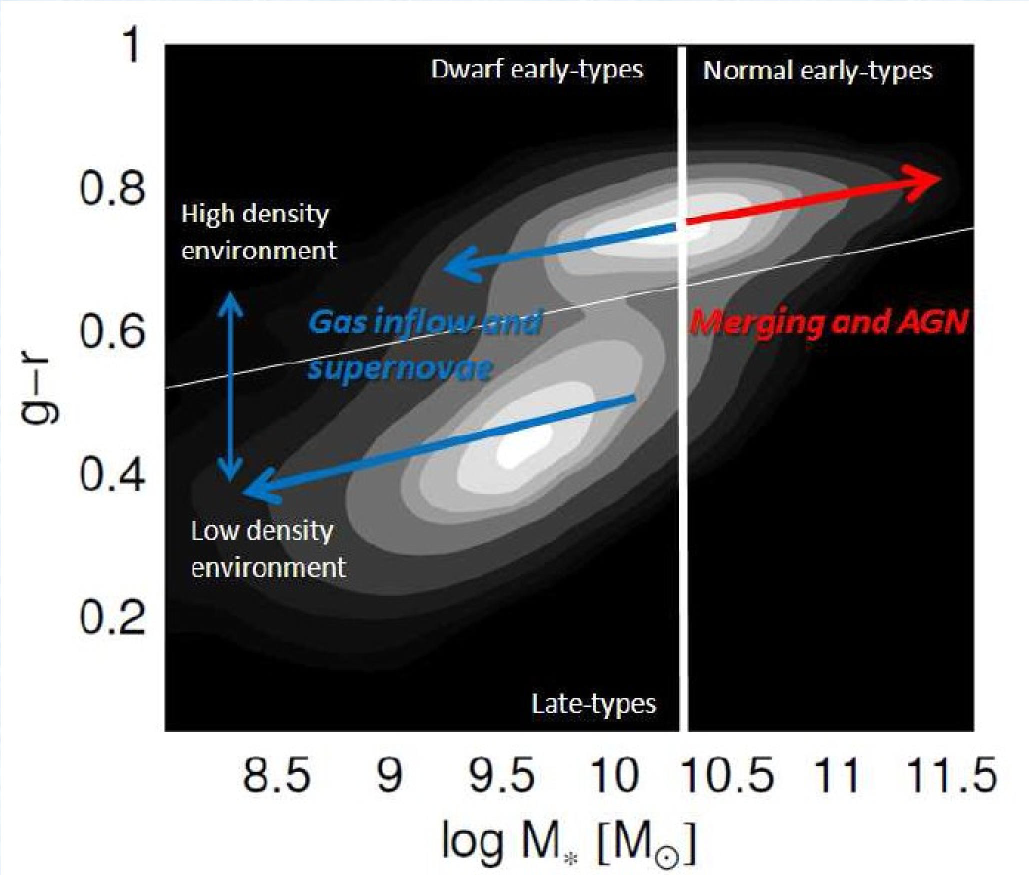
RS and (cold) gas fraction

Cluster cores | Outskirts



Quenching of star formation due to lack of cold gas, especially in cluster cores

Physical scenario: the RS



SDSS sample of ETGs and LTGs

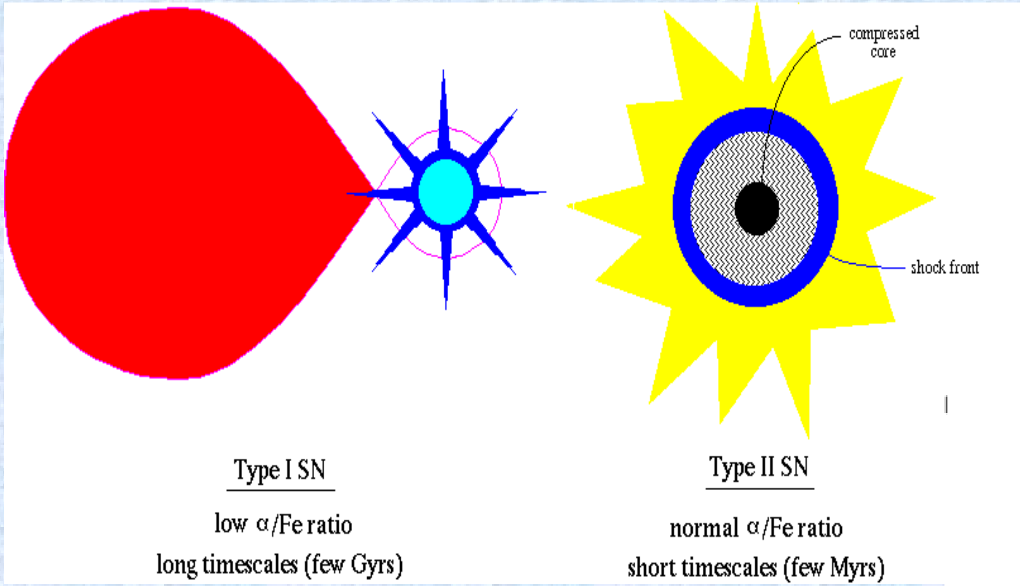
(Tortora et al. 2010, MNRAS, 407, 144)

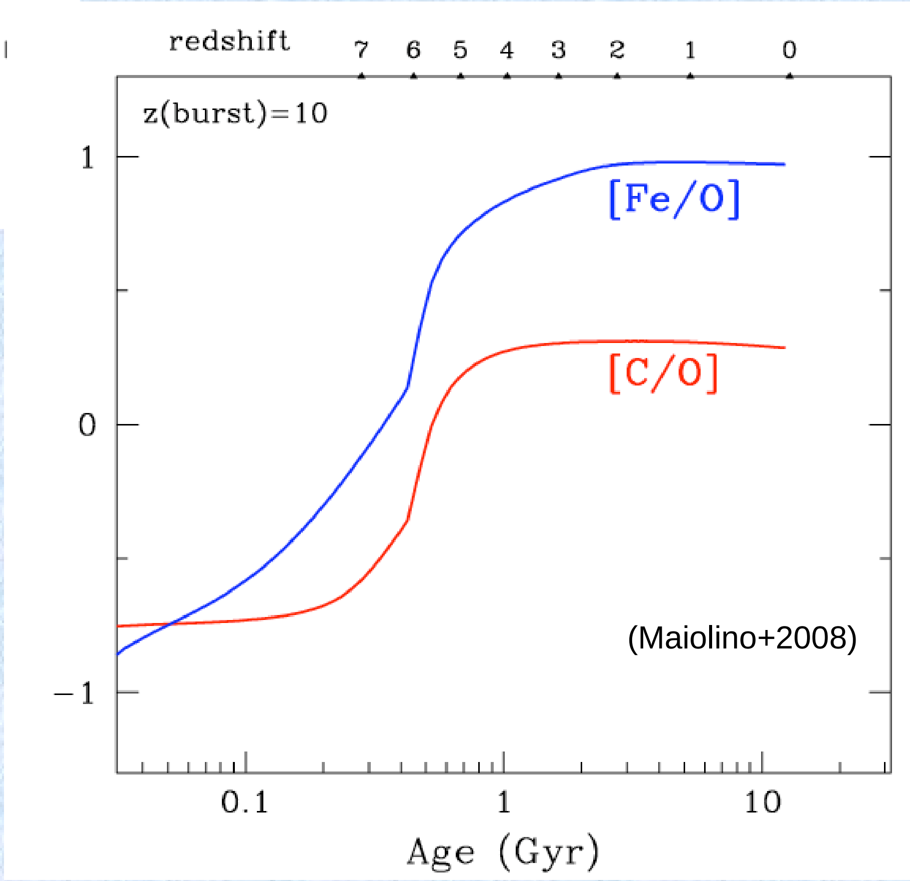
Deductions from the RS

- Evolution of stellar populations in galaxies is mostly passive (age reddening) at least since *z* ~1, except from (dry) merging on to the BCG
- **SSFR** (more than Z or age) drives the RS evolution within the CM plane
- **DS** is the asymptotic, universal locus of “final rest” of galaxies once inactive
- Transition epoch at *z*~1 from active to passive regimes<-->slope change
- It does exist an environmental sequence in building the RS:
    - Cluster cores complete the RS first
    - Normal groups: s.f. activity lasts longer
    - FG: more quiescent, earlier assembled: “fossilness” (gap) widens at *z*~0.7
- Needed proper model of AGN negative feedback at low z to quench cold cores

METALLICITY-MASS-(S)SFR RELATIONS

Metal production and chemical enrichment from SN FEEDBACK





Abundance ratios of elements with different timescales provide a clock of S.F.:
Shorter S.F. duration
=> higher α-enhancement
at least in a *closed-box* approx.
(*Chemo-archaeological downsizing*)

Estimation of metallicities

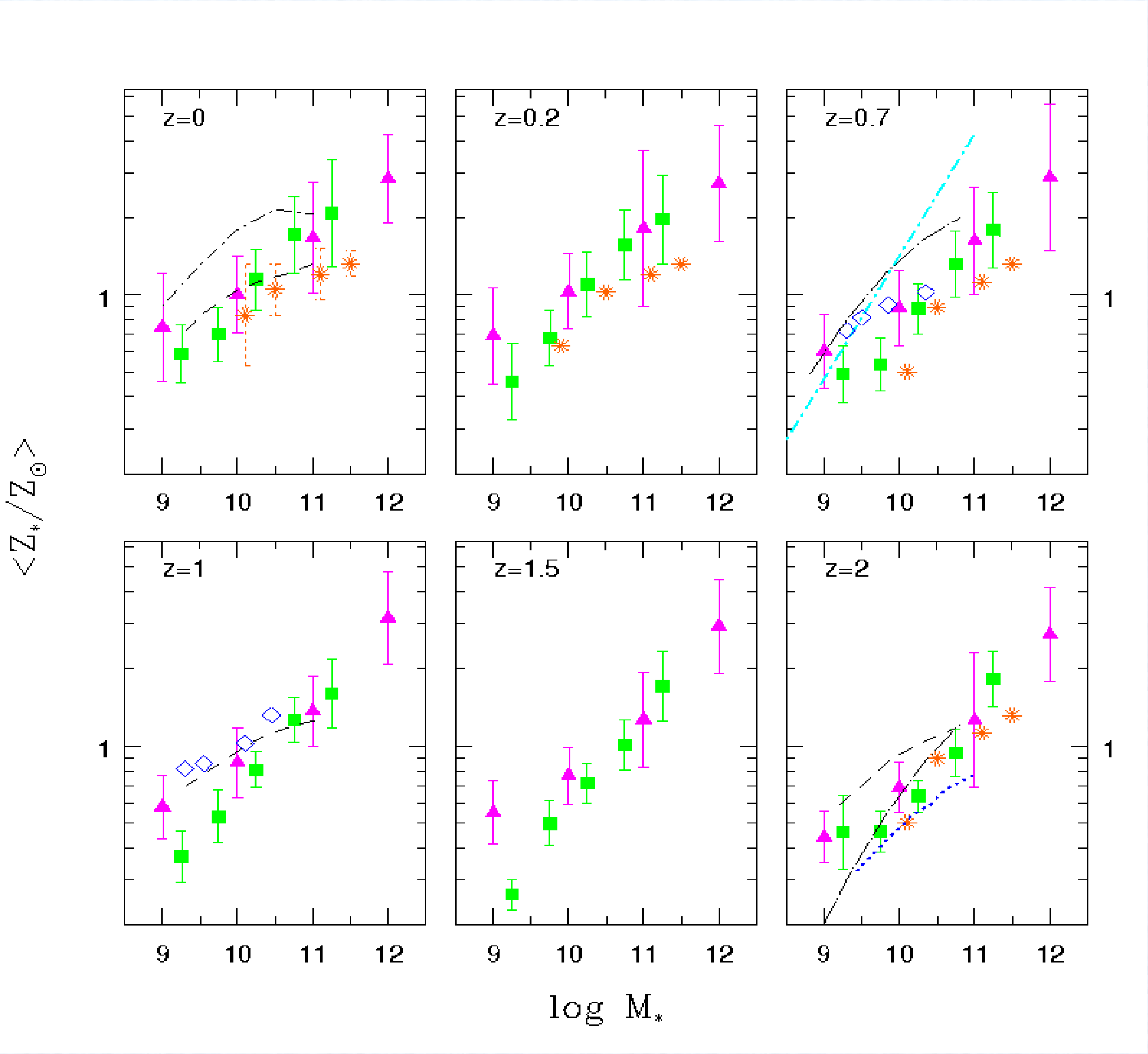
1) Stellar lum./mass weighted Z_* from SSP synthesis models

→ mainly for local Ell (f.ex. Thomas+ 2007, 2010)

2) Gaseous [O/H] from ISM nebular emission lines (f.ex. OIII) in HII regions of star-forming or gas-rich galaxies => skewed towards UV from young (OB) stars

Abundance indicators come from flux ratios of strong lines => problem of *calibration* (see talk by S.Cora)

The stellar Z-mass relation



Ellison+2009 (SDSS)

Savaglio+2005

Perez-Montero+2009

Erb+2006 (z=2)

Maiolino+2008

Tissera+2005 (SIM NO FB!)

Vale Asari+2009 (SAM)

Clusters Groups

Origin of the ZM relation

- Outflows more effective at enriching the ICM in less massive galaxies:
  Mass-selective inflows of pristine gas + outflows of enriched gas
  => lower galaxy Z by dilution => slope variation

- Gas reservoir exhausted in more massive galaxies => higher past conversion gas to stars => more metals produced

- Mass-dependent IMF:
  SFR-variable integrated IMF depending on the maximum mass of star clusters:
  higher SFR => more massive star clusters => more massive stars *in* clusters => more SNII (Koeppen, Weidner & Kroupa 2007)

Origin of the [α/Fe]-mass relation

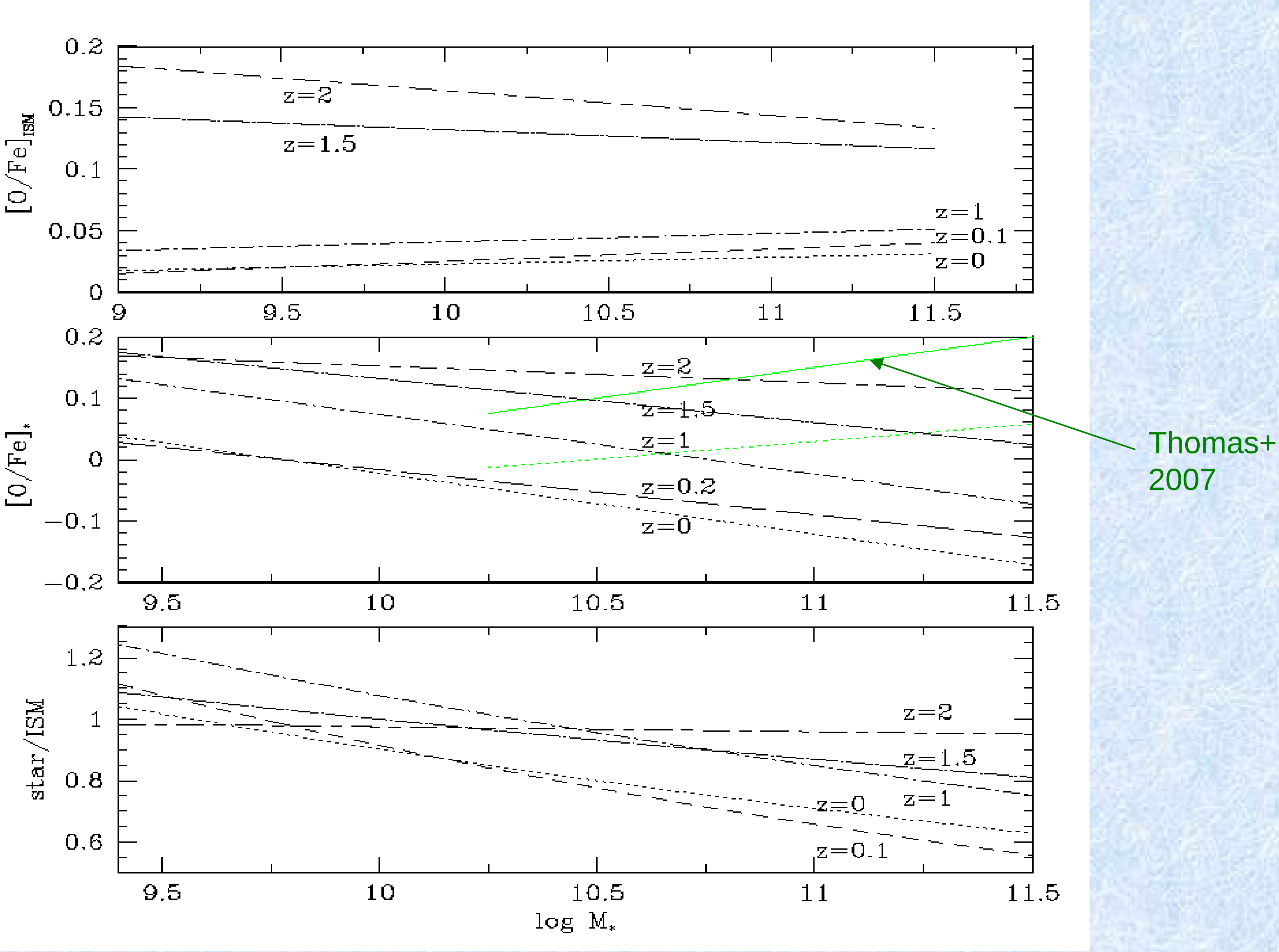
Increasing trend from:

- SF efficiency as increasing function of M_* (Matteucci 1994)
- Mass-dependent IMF: top-heavier in more massive galaxies (Arrigoni+2010)
- AGN late quenching of S.F. (Calura & Menci 2011)

Pipino+2009: It is impossible to simultaneously reproduce both the ZM and [α/Fe] for massive Ell, formed through a series of dry mergers (=>no changes in metals)

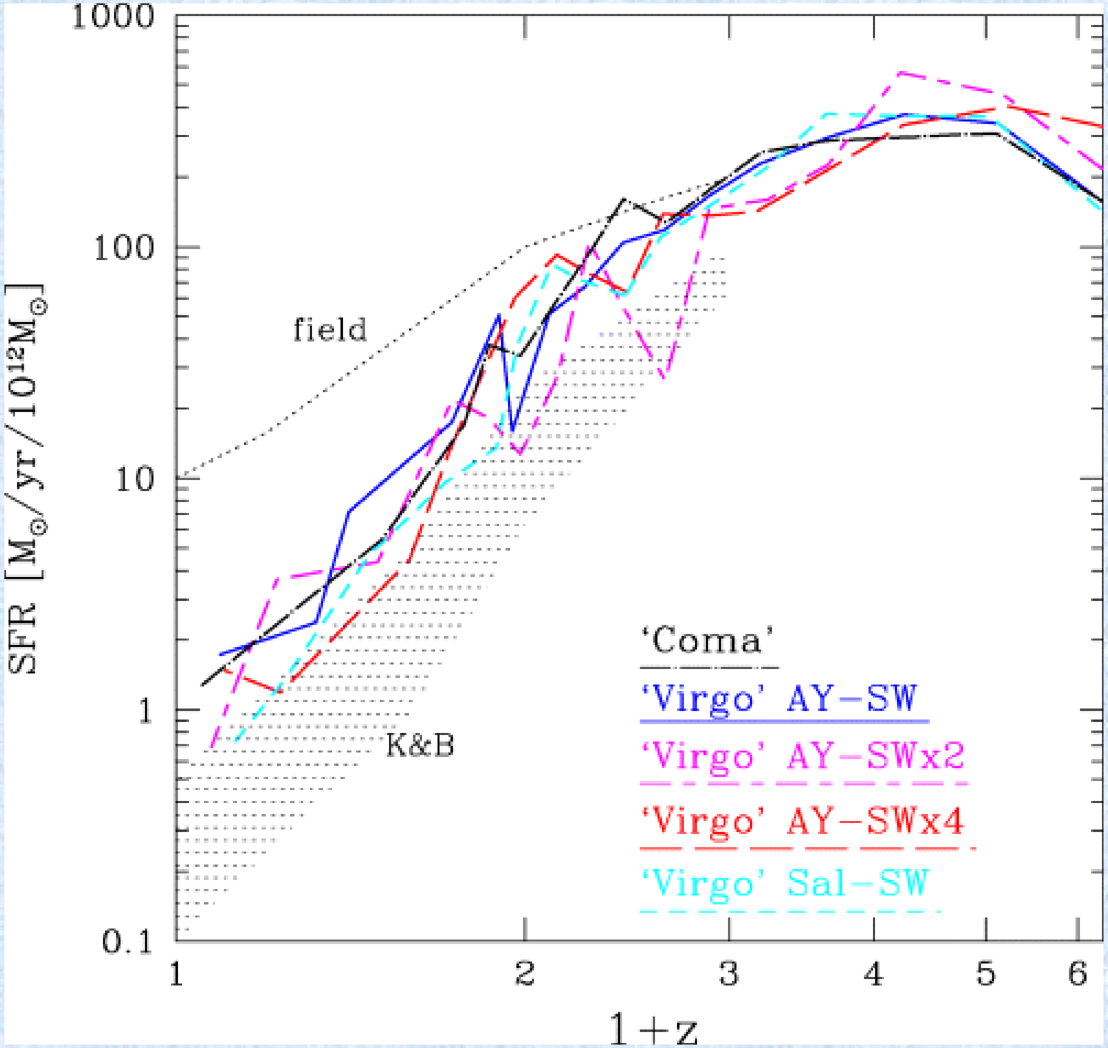
AGN feedback required to increase the slope of [α/Fe]-mass
BUT at the same time => flat ZM !
Problem: excess of dwarf α-enhanced satellites.

The alpha/Fe – mass relation



The level of [α/Fe] at given mass decreases with time

Star formation history



rich cluster gal.:

Kodama & Bower (2001)

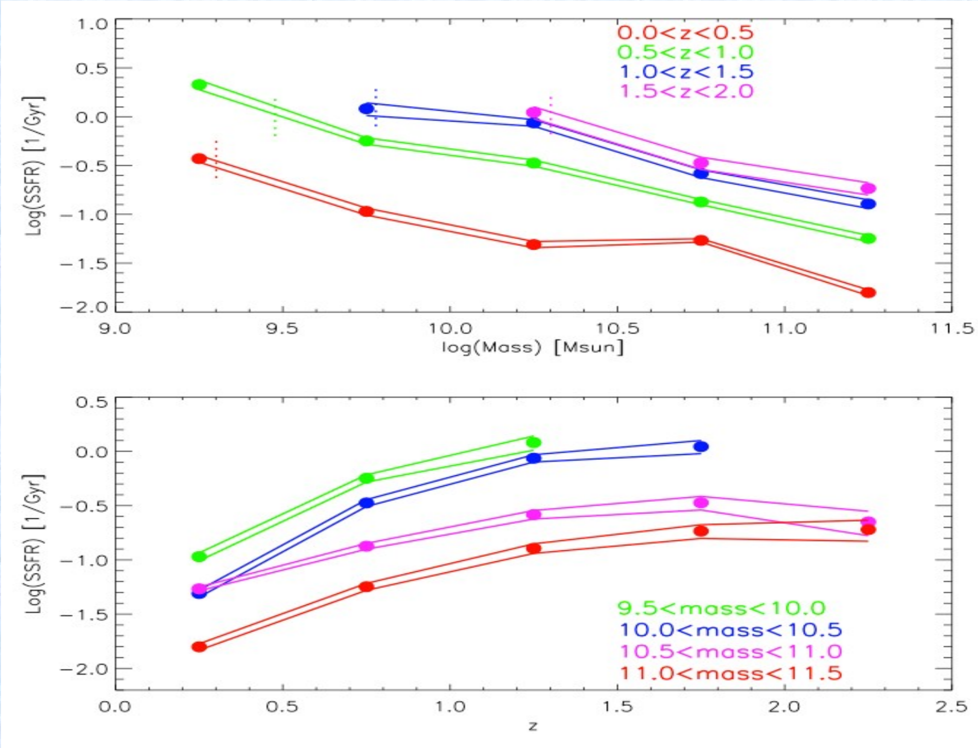
Field:

Madau et al. (1998)

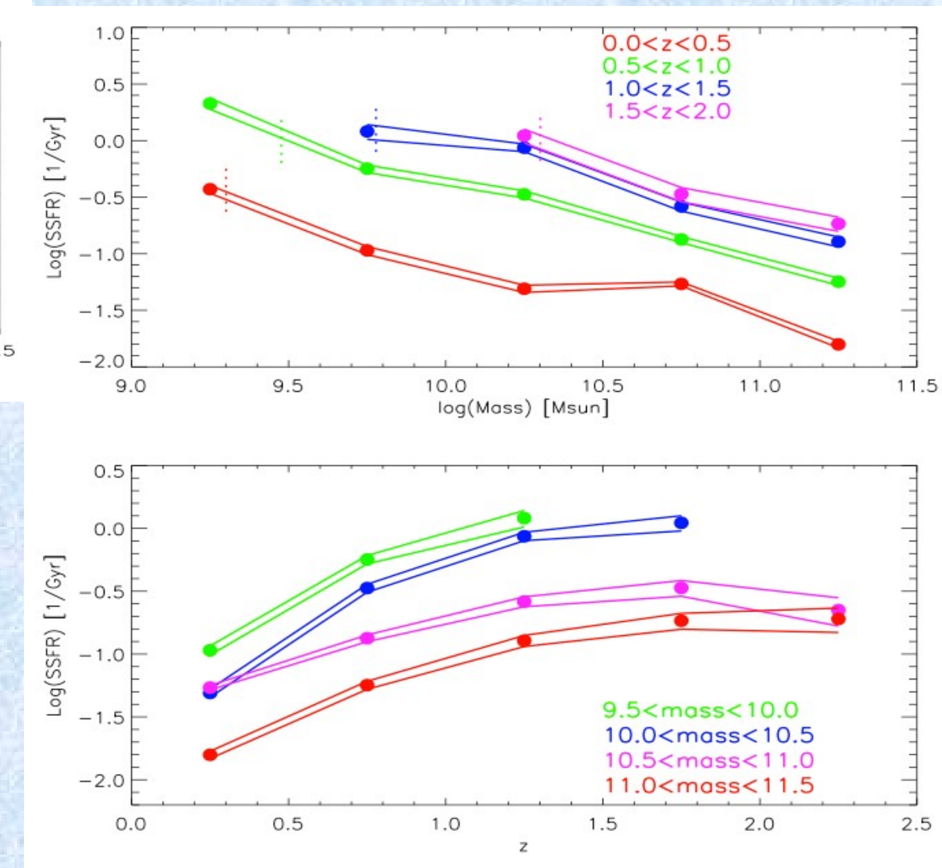
Cluster denser environment --> earlier s.f. than field --> fast drop (z<1)

(peak at z~3-4)

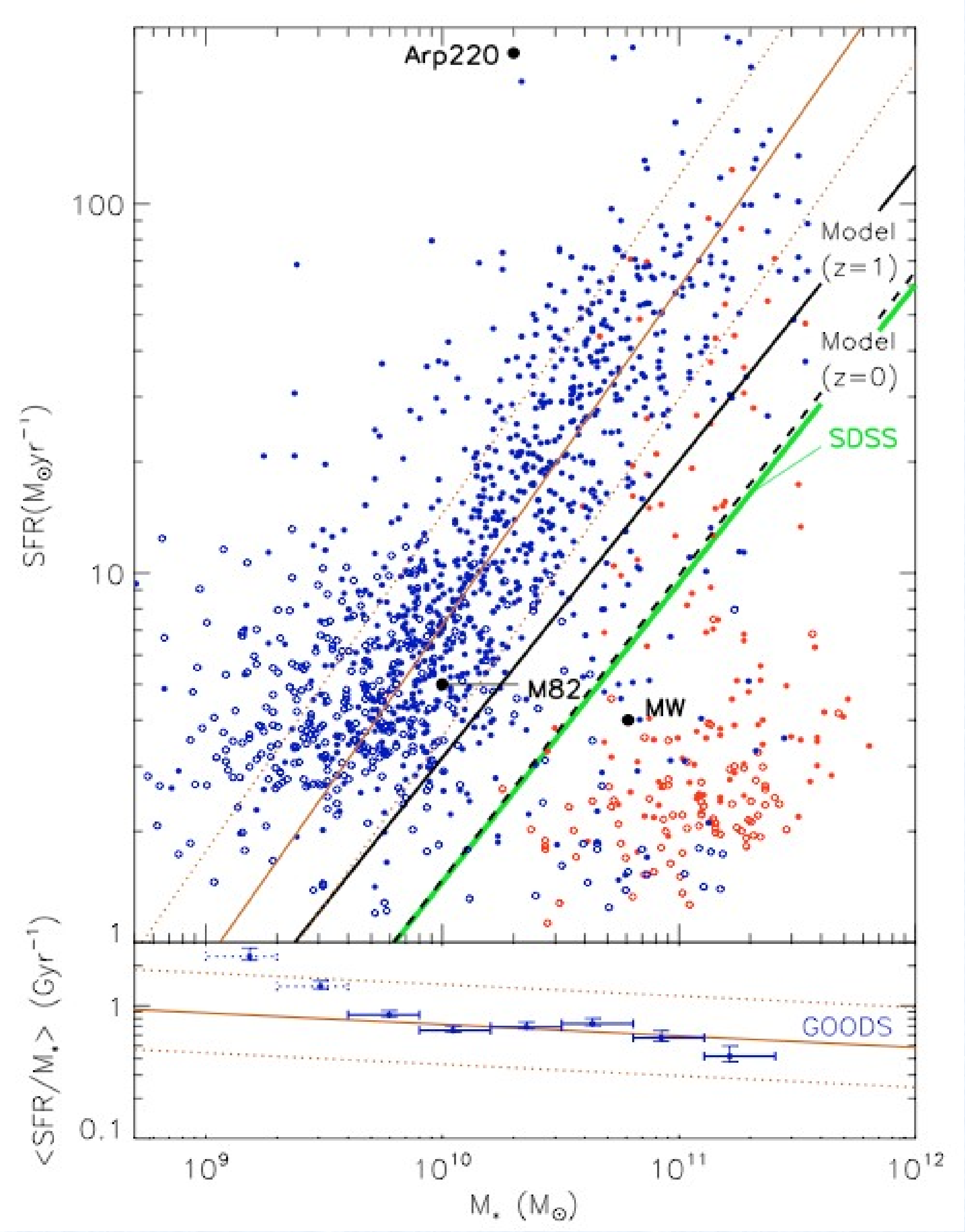
SFR and SSFR trends with mass



(Rodighiero+2010)



SFR and SSFR trends with mass

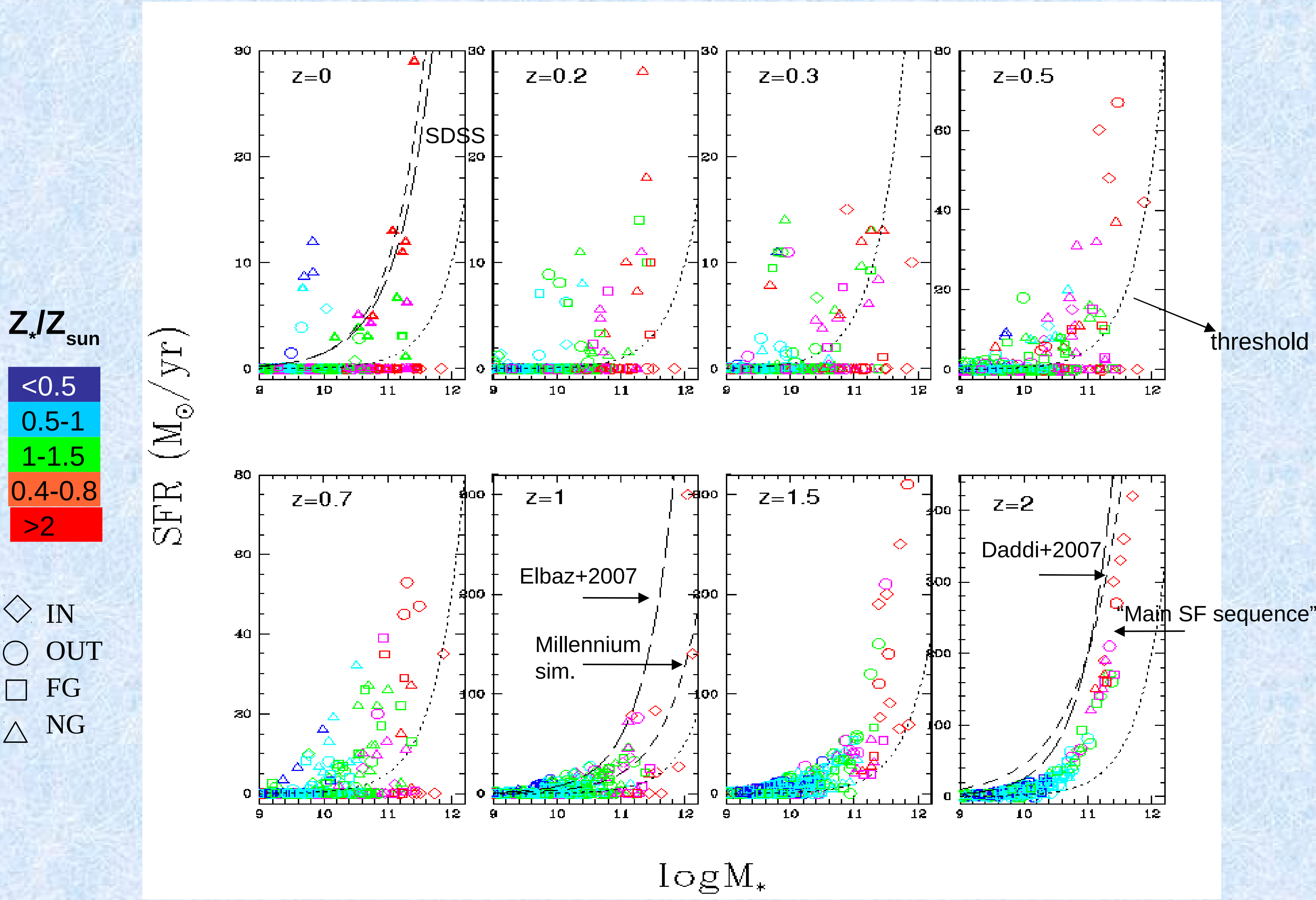


SFR ↑

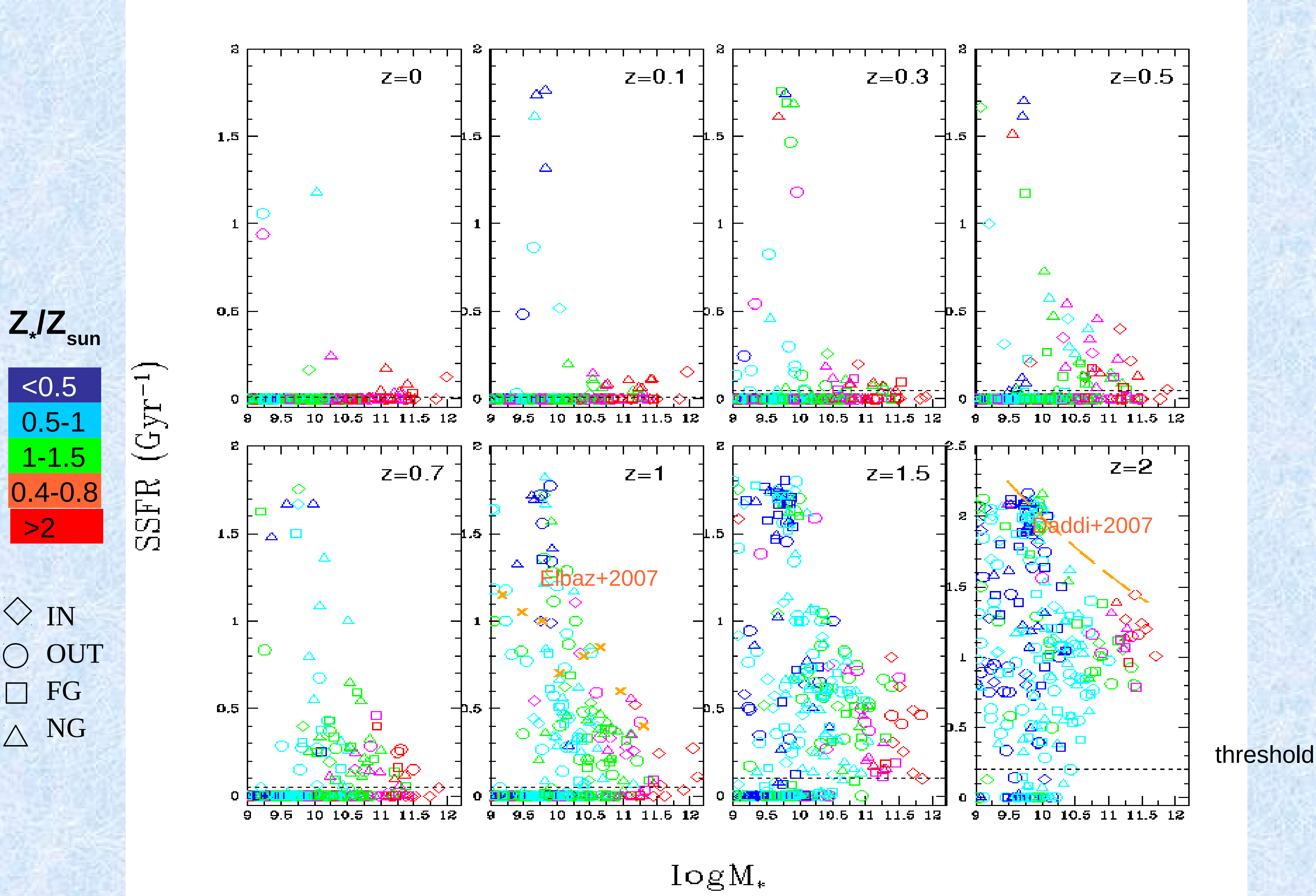
SSFR ↓

(Daddi+2007, Elbaz+2007)

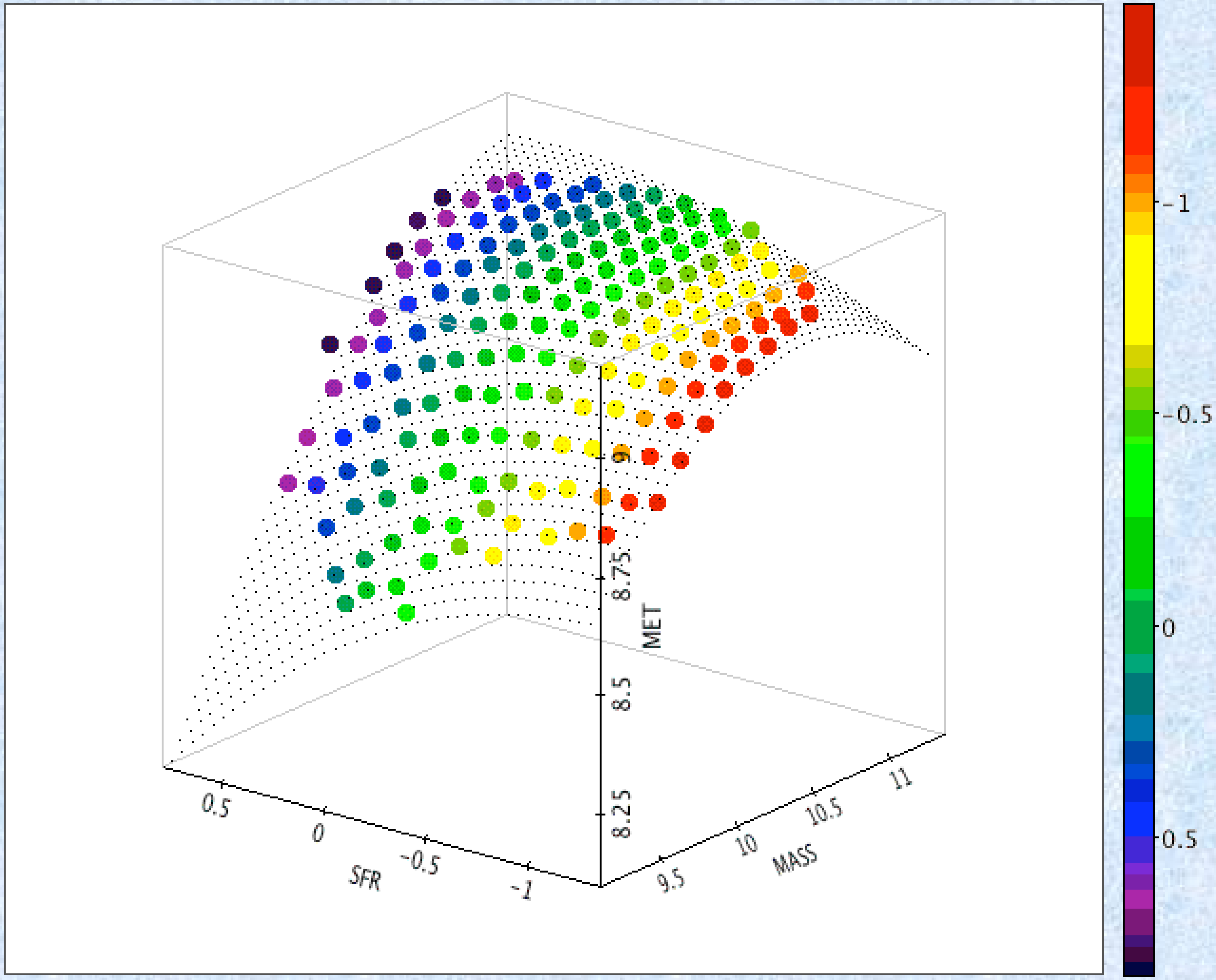
The SFR-stellar mass relation



The SSFR-stellar mass relation

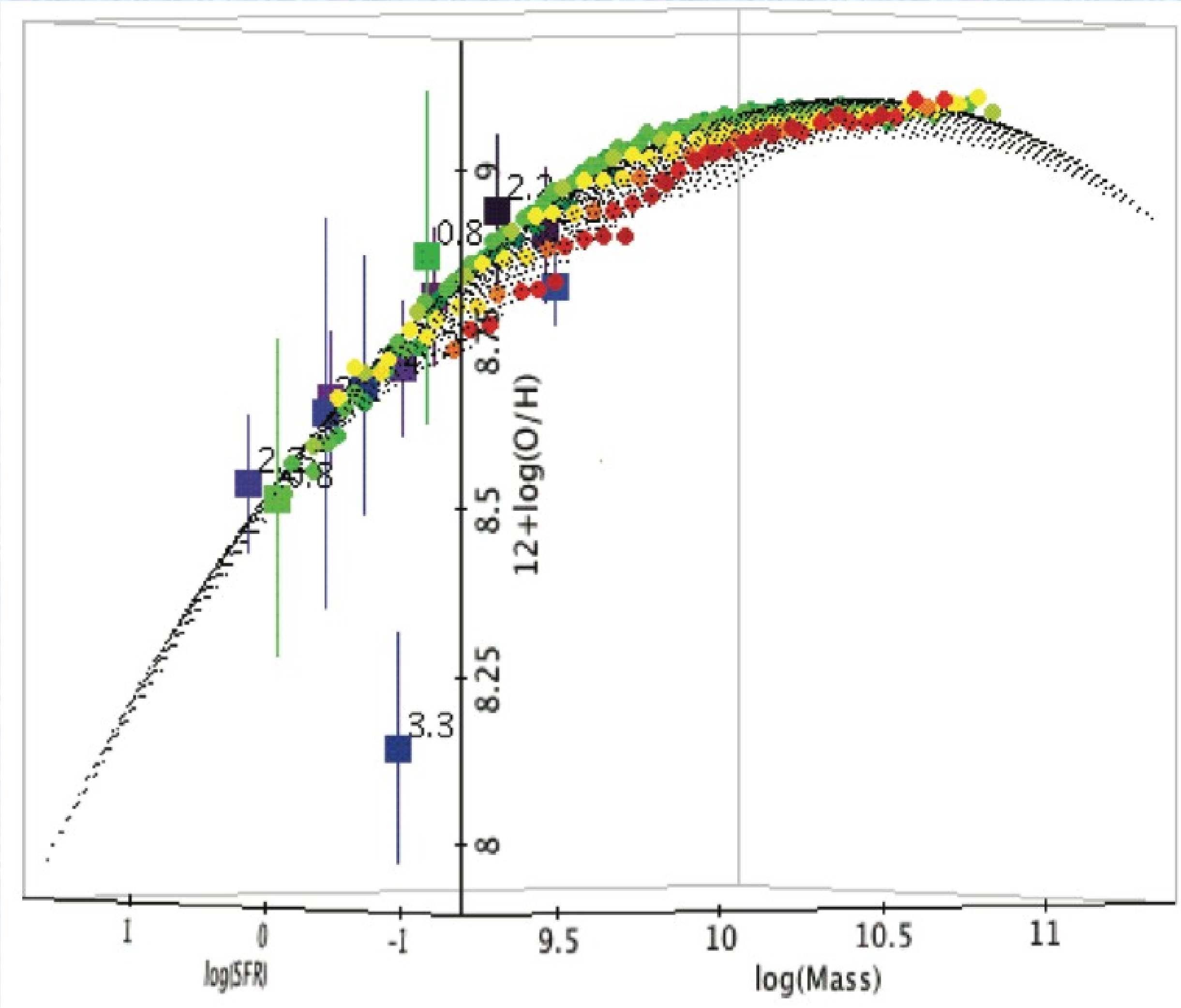


A fundamental Z-M-SFR 3D surface (Maiolino-Mannucci 2010)



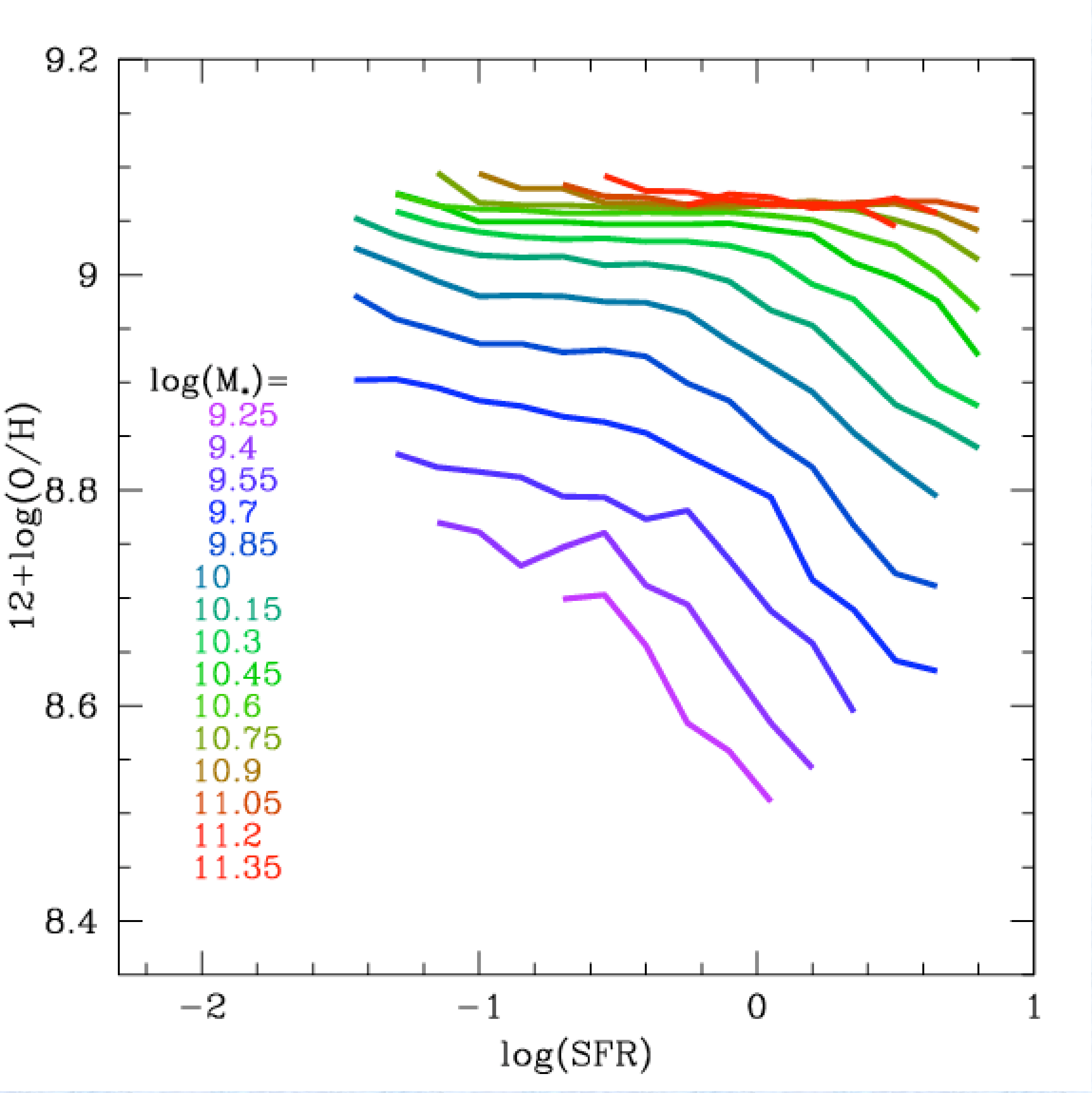
z=0

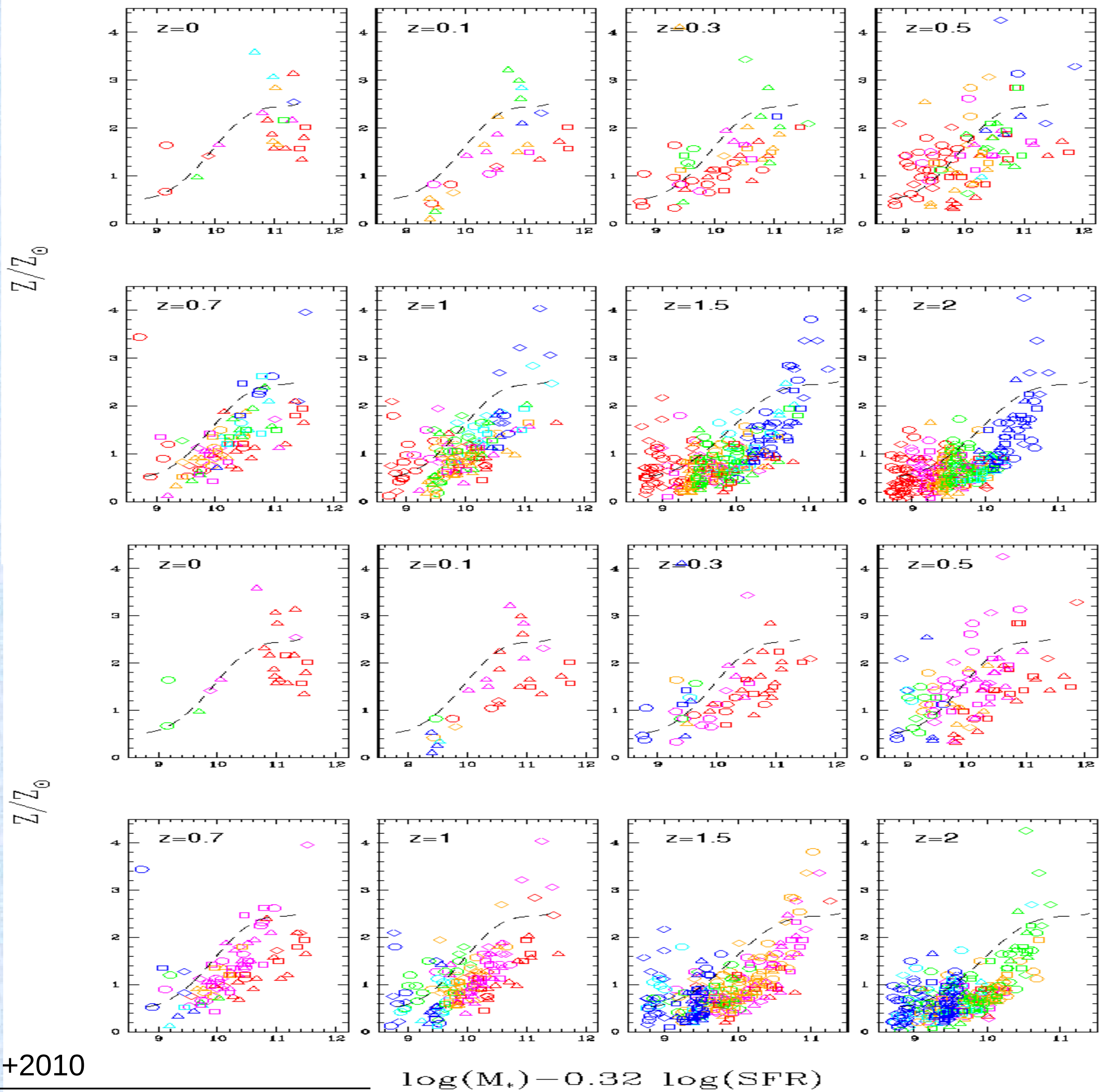
A fundamental Z-M-SFR 3D surface (Maiolino-Mannucci 2010)



No evolution up to z=2.5 !!

Z-SFR relation
(Mannucci+2010)





SFR
(M_{sun}/yr)

>30
20-30
10-20
5-10
2-5
<2

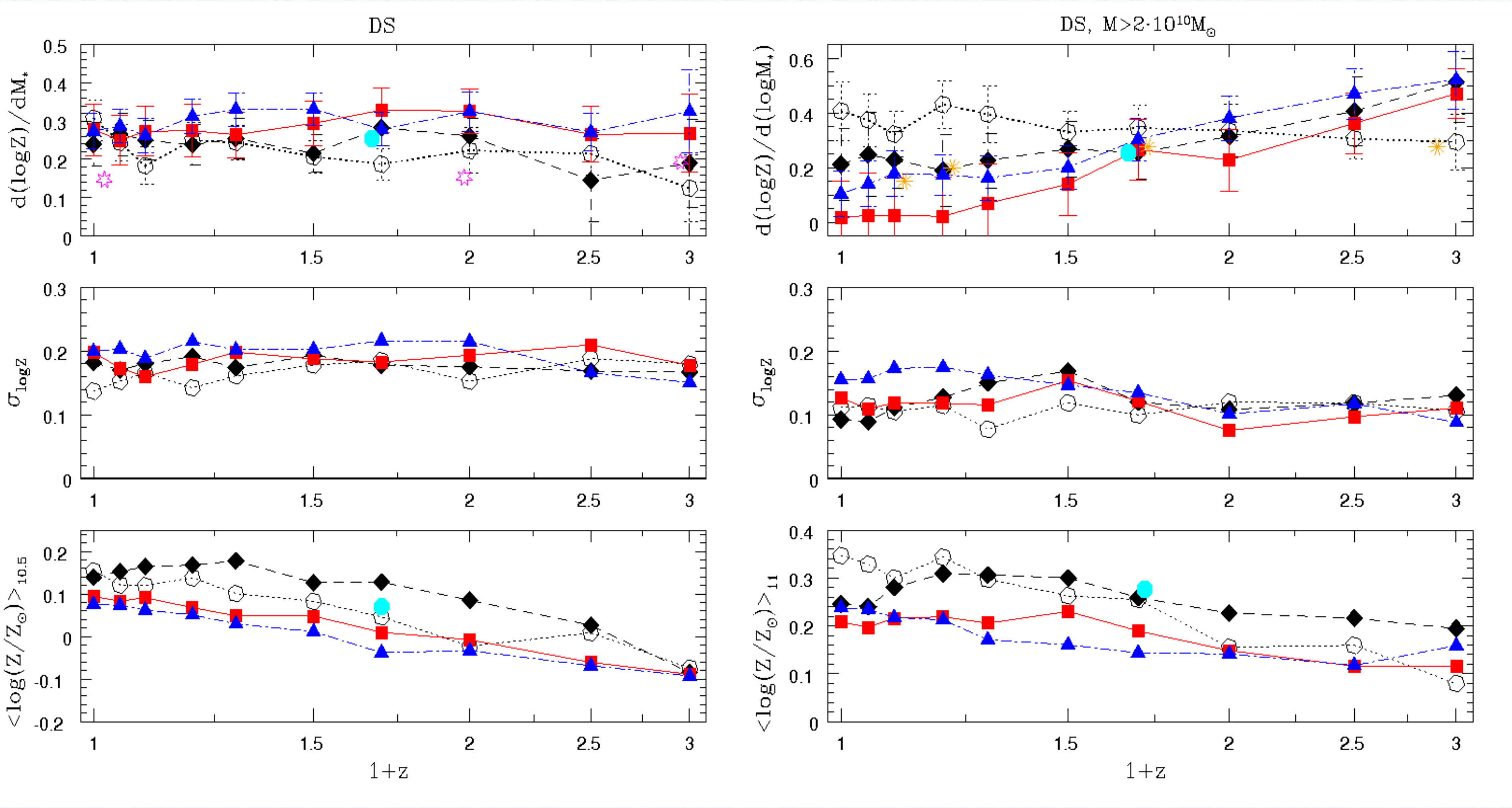
SSFR
(Gyr^{-1})

>1.5
1.2-1.5
0.8-1.2
0.4-0.8
0.1-0.4
<0.1

Only star-forming

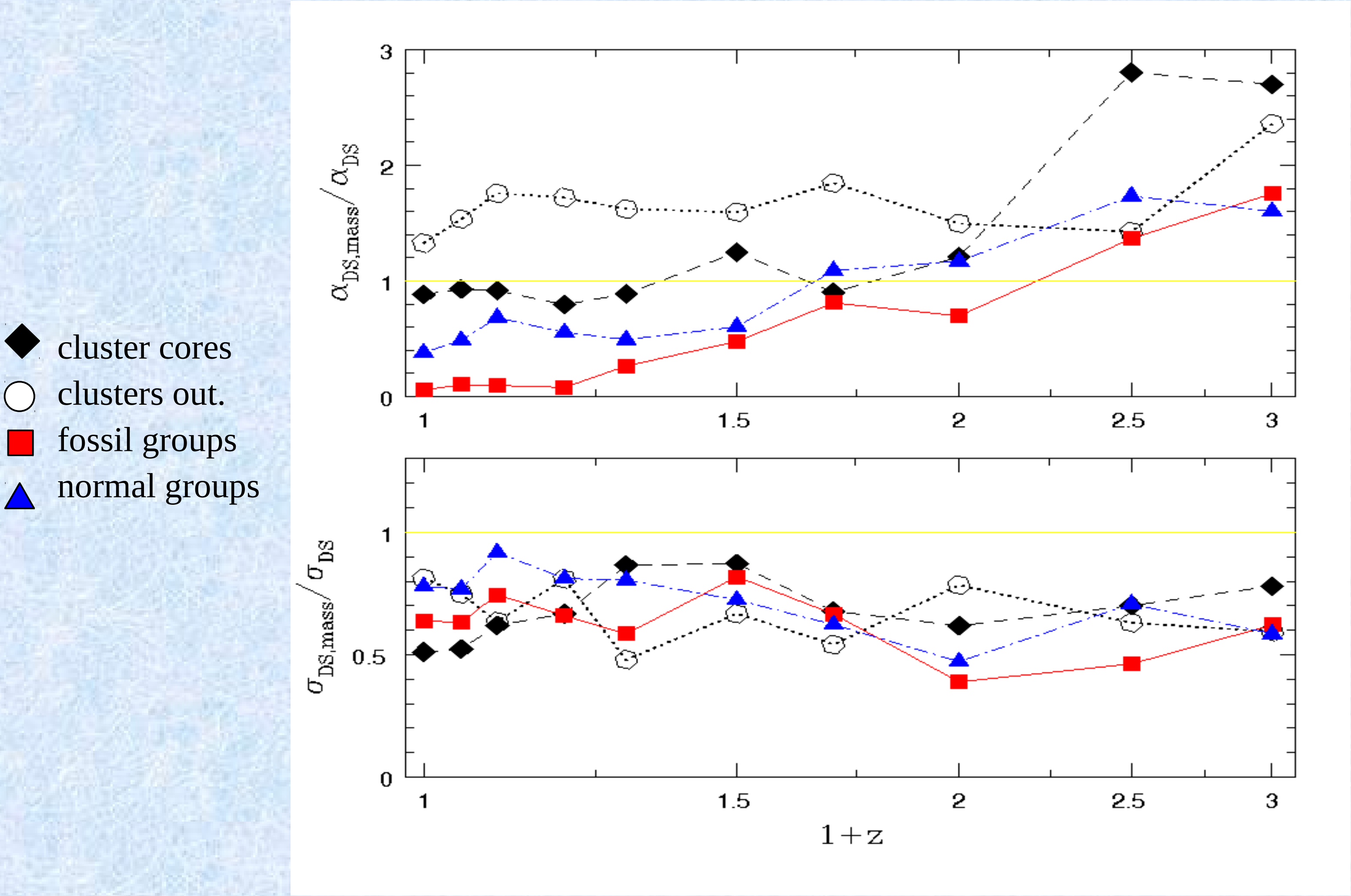
μ from Mannucci+2010

Slope and scatter of the ZM relation in the DS

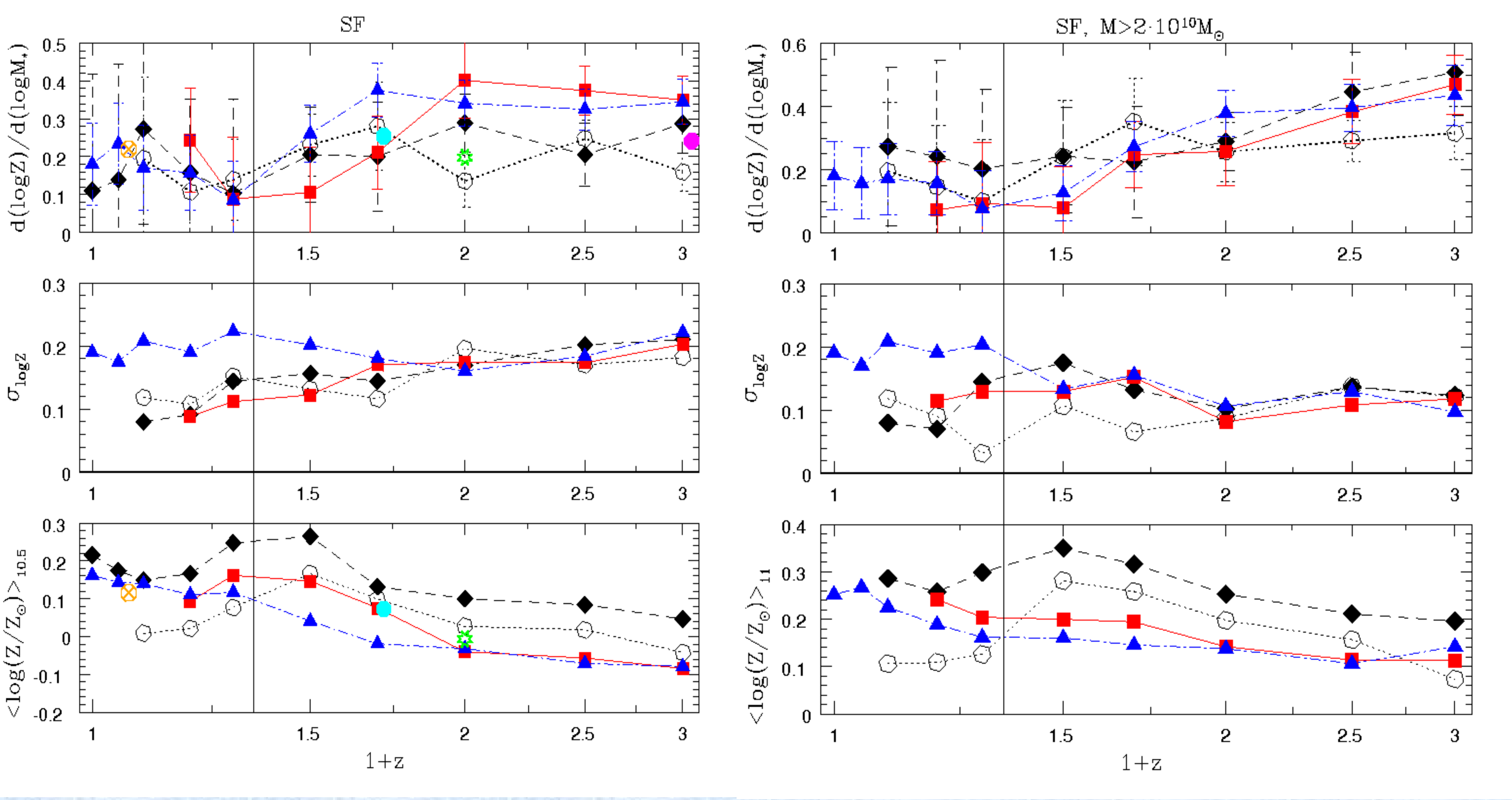


De Rossi+2007 Savaglio+2005 Vale Asari+2009

Slope and scatter of the ZM relation in the DS: ratio of massive to total

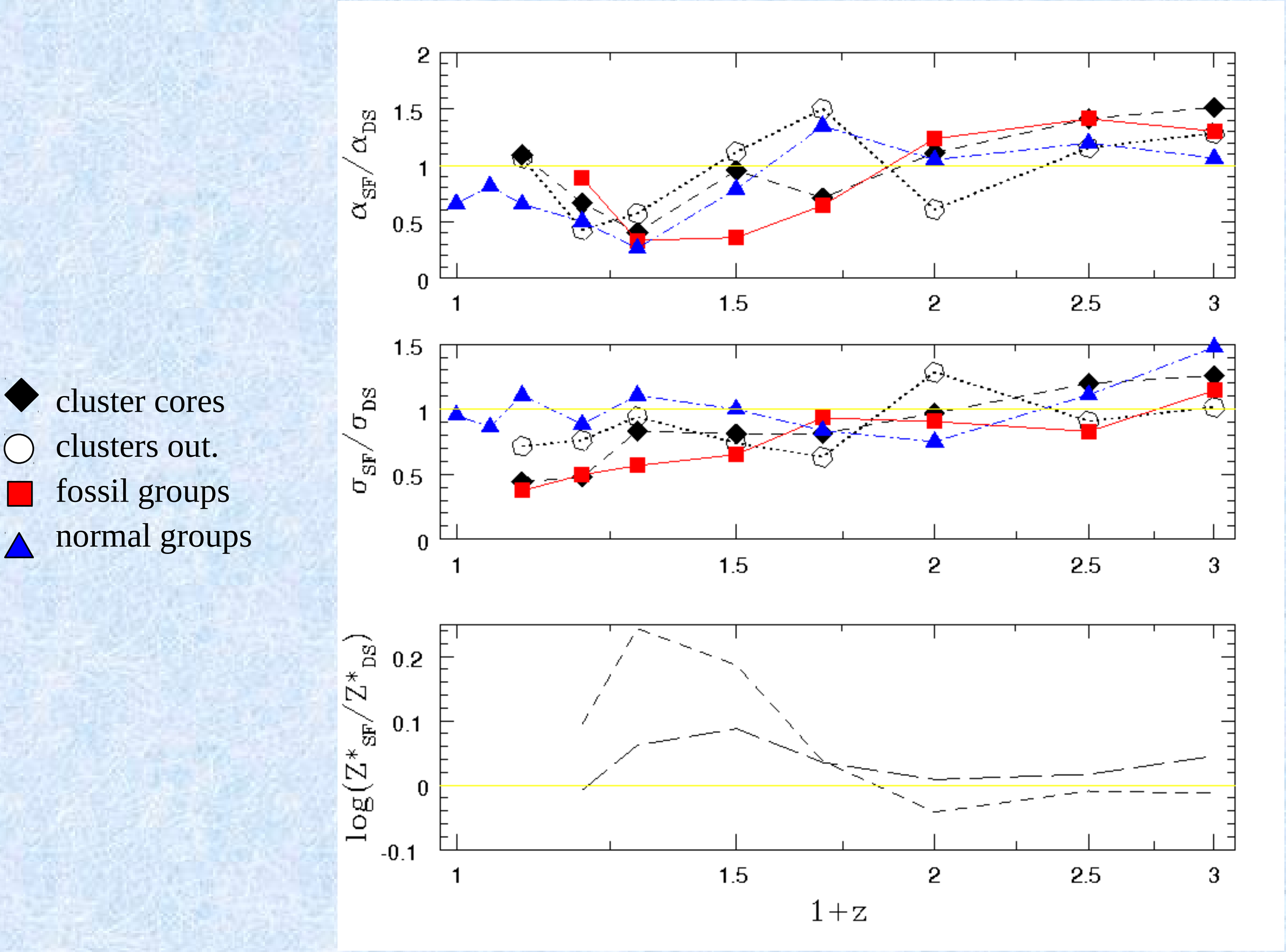


Slope and scatter of the ZM relation in the SF

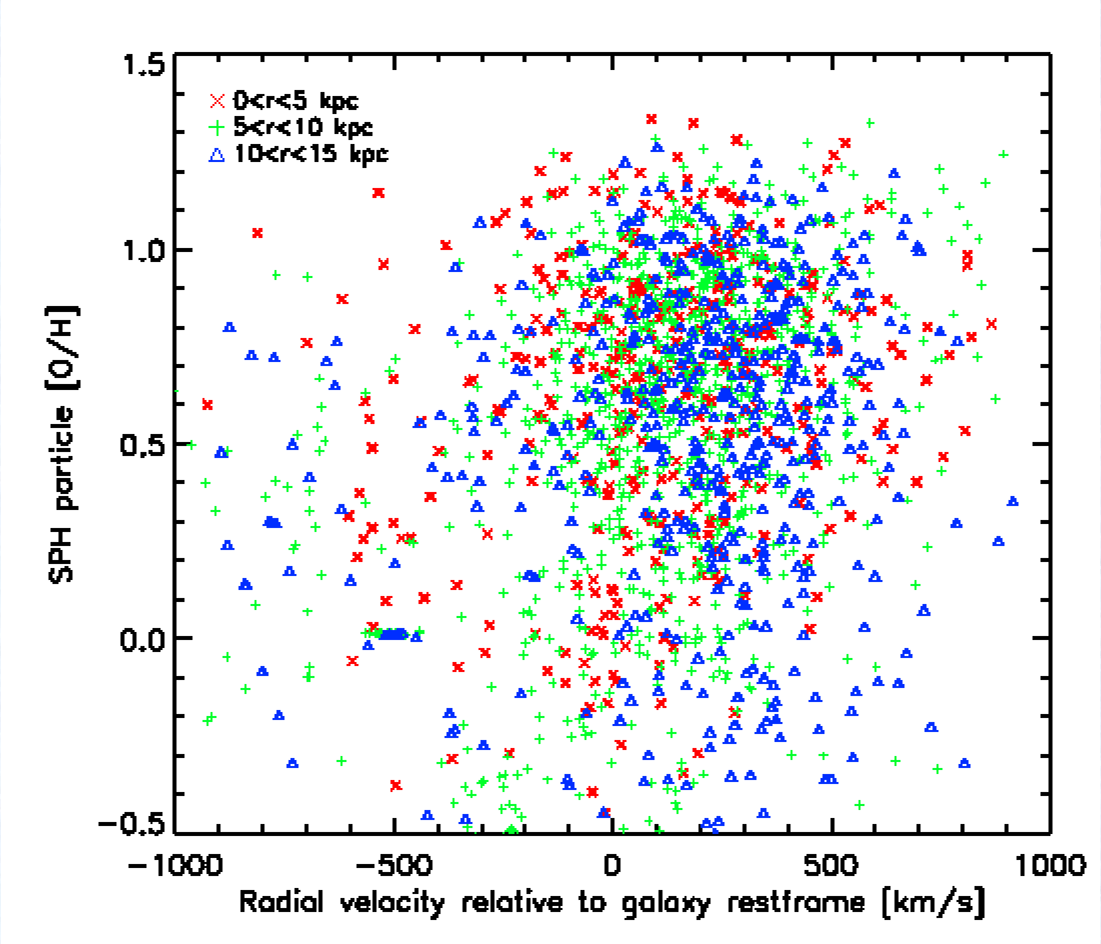


Perez-Montero+2009 Erb+2006 Kewley & Ellison 2008 Savaglio+2005

Ratio between SF and DS



The role of galactic super-winds



Starburst-driven asymmetric outflow at *z*~3:
Hot gas particles gone with the wind are metal-richer than cold s.f. gas left behind and also than star particles.

Conclusions

- Tight sequence of SF galaxies in the *SFR*-M_* plane at high *z*: its scatter increases in time alongside to the opposite build up of the DS
- Anti-correlation *sSFR* -M_* *(downsizing)*
- Anti-correlation *sSFR* - Z_*
- Correlation *SFR* - Z_*
- *sSFR* as main driver of the ZM relation as tracer of the s.f. efficiency

- ZM slope in DS: higher in groups;
  almost constant in time, but increasing with *z* for the more massive
- ZM slope in SF: stronger evolution than in DS
- ZM scatter: almost constant in DS, increasing with *z* in SF
- Feedback driven outflows/winds are a powerful means of reducing *Z* in the galaxy