sSFR, quenching and the evolution of galaxies across cosmic time

Antonio Pipino

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15/03/2012

Understanding galaxy formation

How is the gas accreted into (proto-)galaxies?

Cold vs. hot?

Smooth vs. clumpy accretion?

How fast is this gas turned into stars?

What determines the star formation timescale?

What regulates/halts the star formation?

When/where are chemical elements produced?

(specific) Star Formation history

Physics of gas inflows and outflows

sSFR = SFR / M_* **S.F.eff = SFR /M_{gas}**

Outline

- *Introduction*
  - *historical perspective*
- *Current knowledge (from "fossil" data)*
  - *abundance ratios in ellipticals (also mass-metallicity relation for both Es and star forming galaxies)*
  - *passive fraction (also color-bimodality)*
  - *mass function (now out to the epoch of S.F.)*
- *Suggested avenue for future progress*
  - *sSFR evolution + catching the galaxies when they form at high redshift*
- *Conclusions*

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ENTIRE POPULATION

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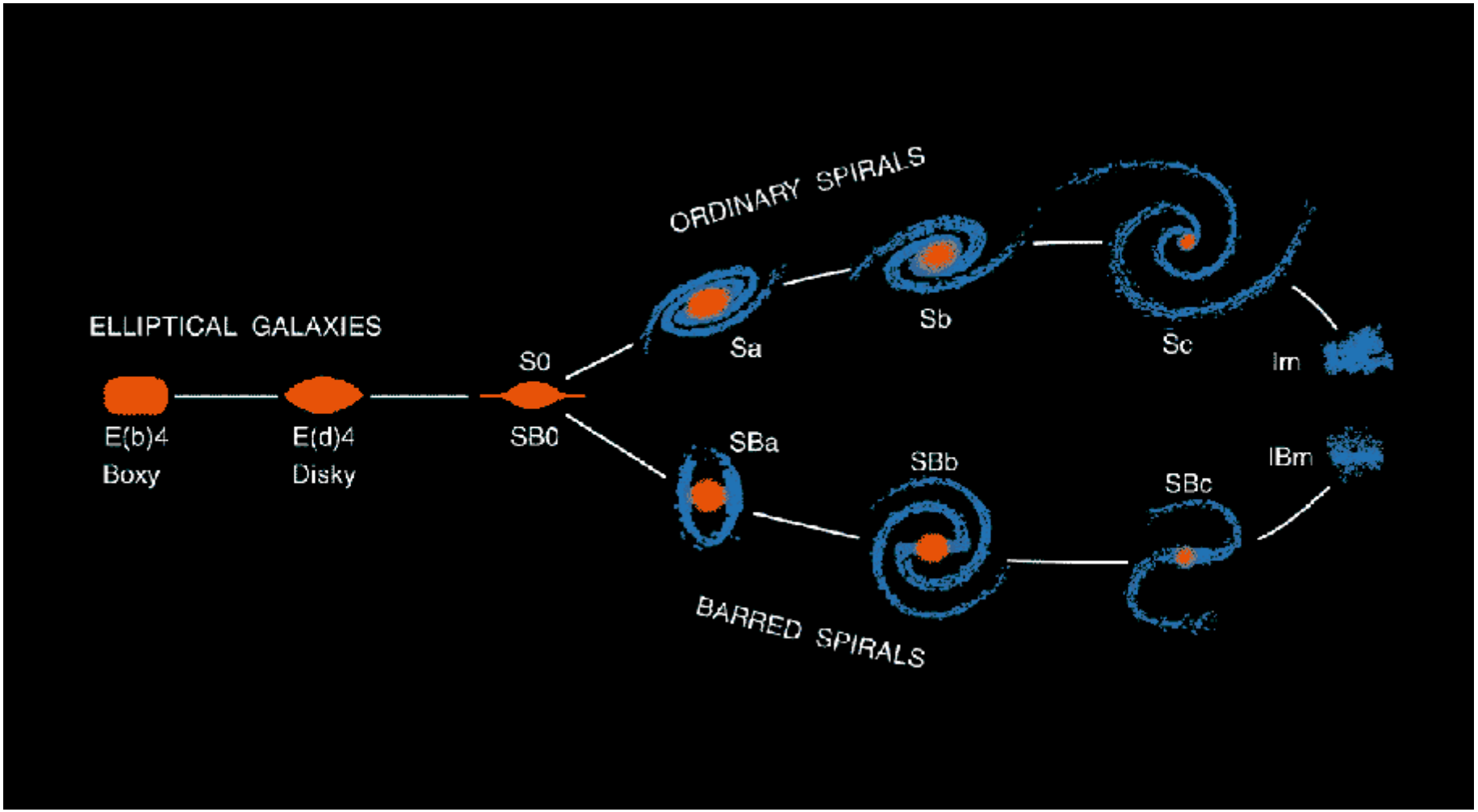
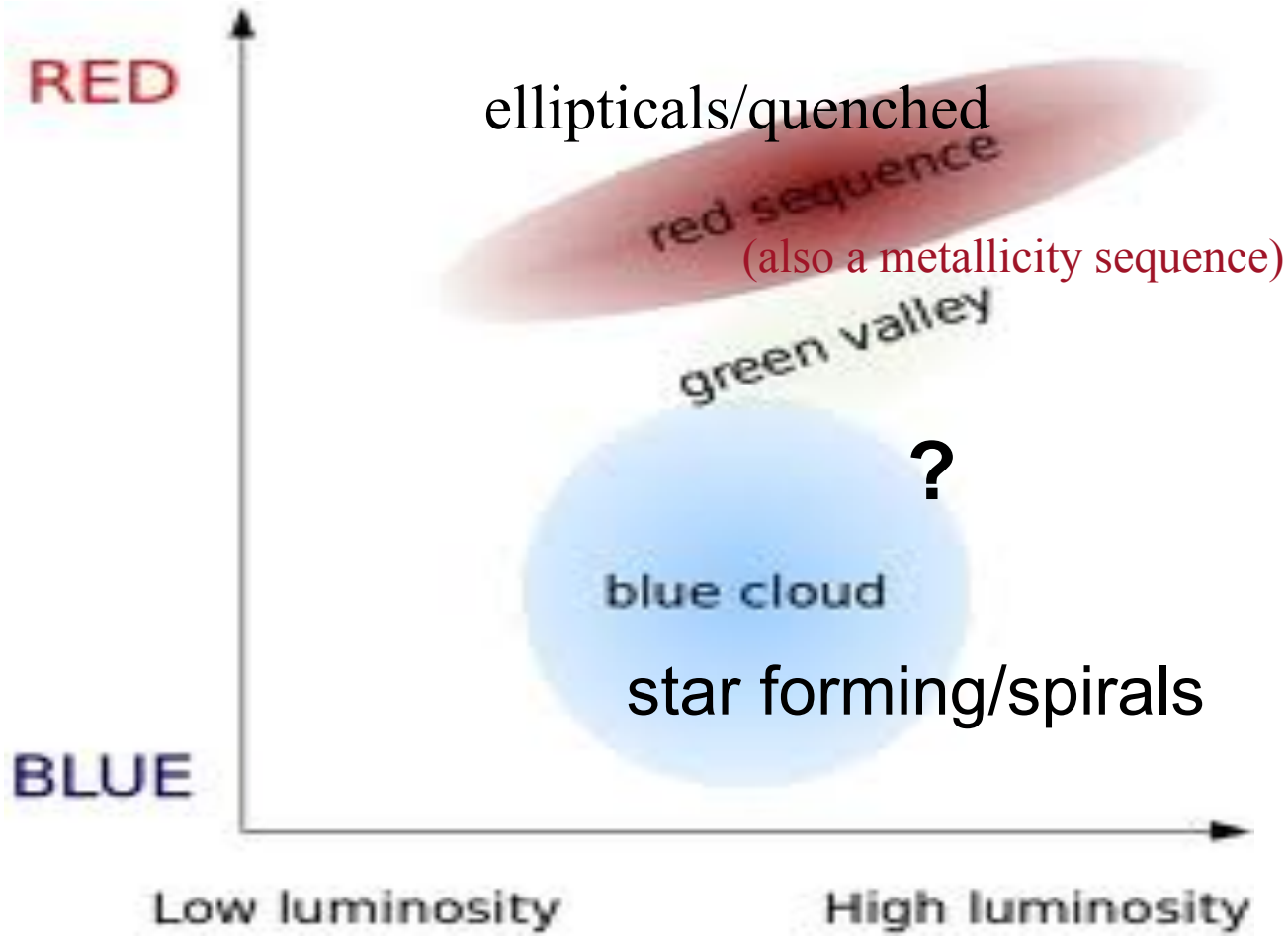
The Hubble Sequence



The Colour Sequence



Original "monolithic" approach:

Ellipticals: high sSFR, quenched by SN wind

Spirals: sSFR small, didn't change much in the last Gyrs.., SN self-regulate SF

Understanding galaxy formation

How is the gas accreted into (proto-)galaxies?

THEORY: *The growth of baryonic structures follows the Dark Matter (e.g. White & Rees, 1978, Fall & Efstathiou,1980), Mergers (wet/dry) AGN manteinance mode (e.g. Granato et al 2004) to prevent further accretion and keep galaxies red*

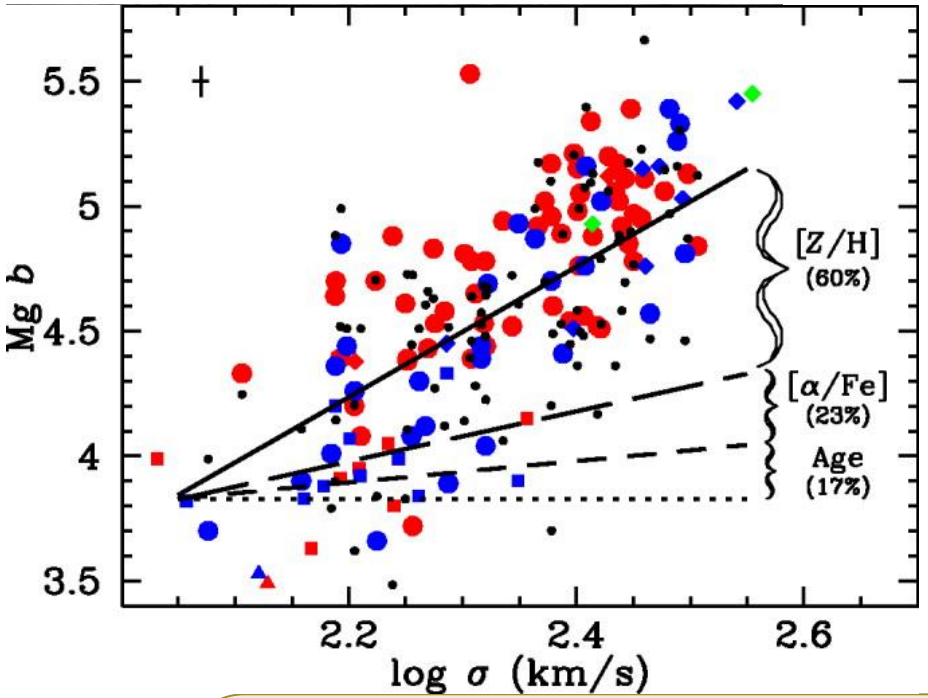
How fast is this gas turned into stars?

OBSERVATIONS: *more massive elliptical galaxies form faster (e.g. Thomas et al. 2005) , SFR-mass relation at z<2 (Daddi et al., 2007, Elbaz et al. 2010), sSFR evolution*

When/where are chemical elements produced?

OBSERVATIONS: *[Mg/Fe]-mass, the mass-metallicity relation (e.g. Tremonti et al., 2004, Maiolino et al. 2008, Mannucci et al. , 2010)*

What can we learn from the abundance ratios in ellipticals?



Fossil evidence in the metal content of the (unresolved) old stellar component from both spectroscopy and colours as a function of galactic mass

Thomas et al, 05, see also Thomas et al 2010, Graves et al. 2009 on SDSS…

Mg/Fe in ellipticals higher than solar
Mg/Fe - mass relation
+
Z-mass relation
Age-mass relation

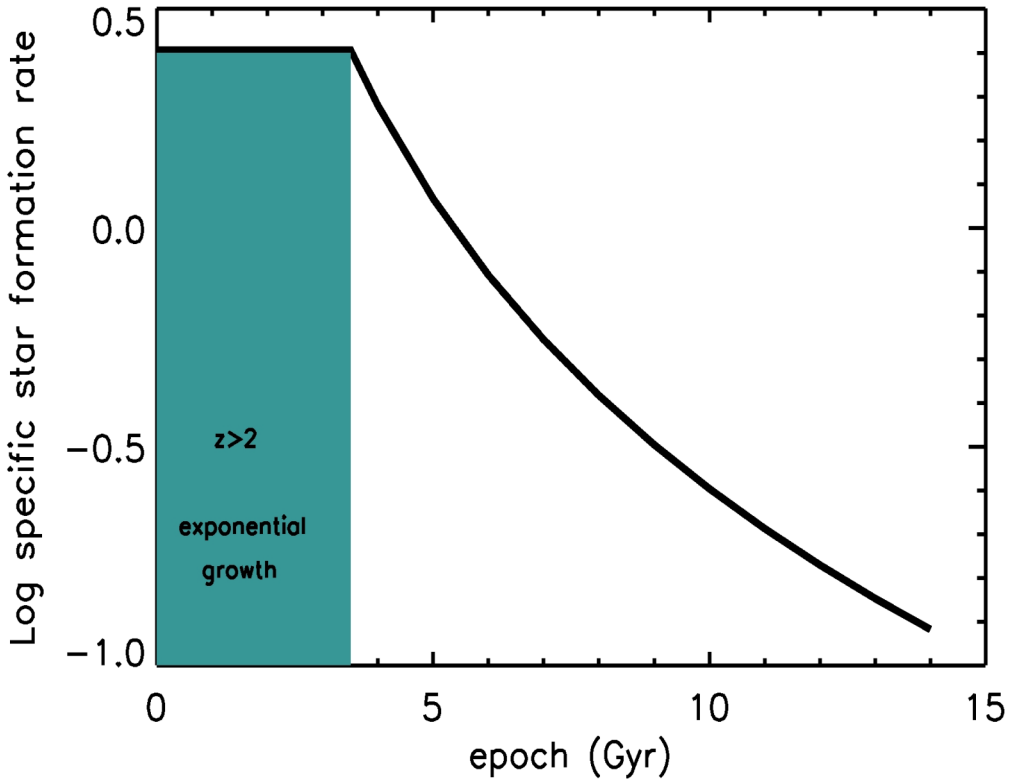
The observed sSFR evolution

Galaxies follow a M-SFR relation from z=2 (e.g. Daddi et al. 2007) to z=0 (Elbaz et al. 2007)

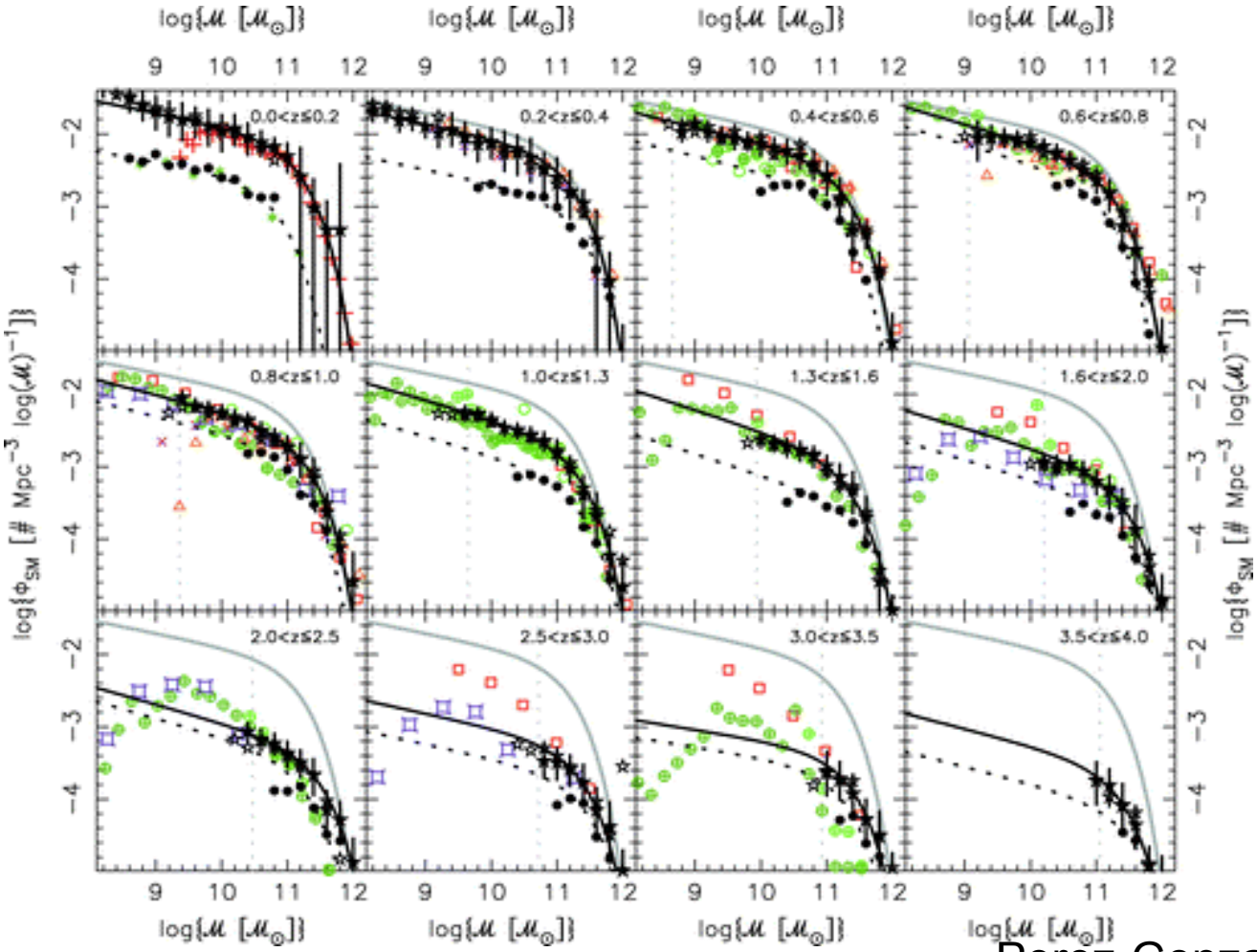
SSFR = SFR/M vs time (e.g. Gonzalez et al. 2010) captures the evolution of the S.F. 'main-sequence'

SSFR~const means

dM/M ~ const : exponential growth (Renzini, 2009)



The mass function evolution



Perez-Gonzalez et al. 2008,
see also Marchesini et al. 2009

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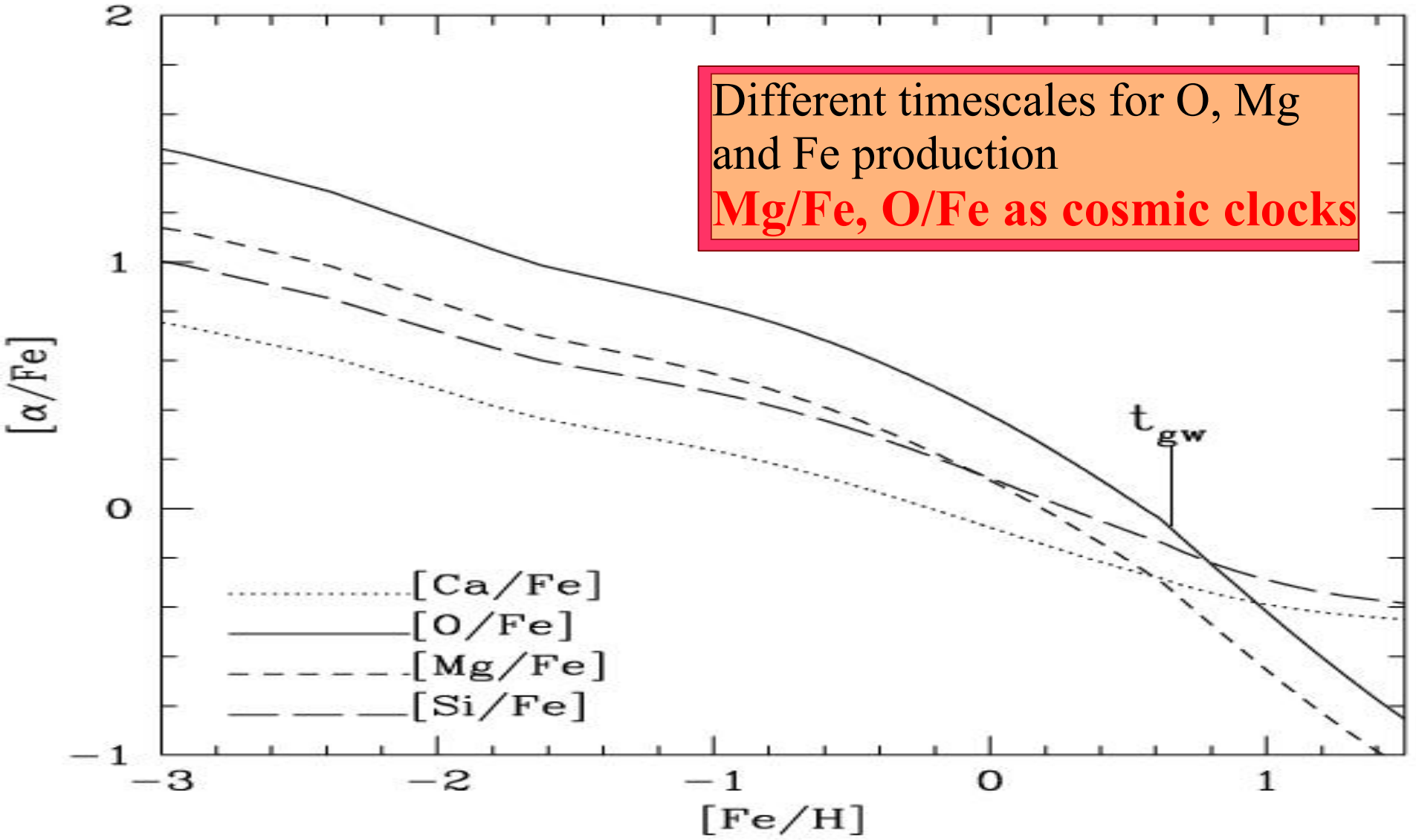
Effects of SNe on the abundance ratios in ellipticals:



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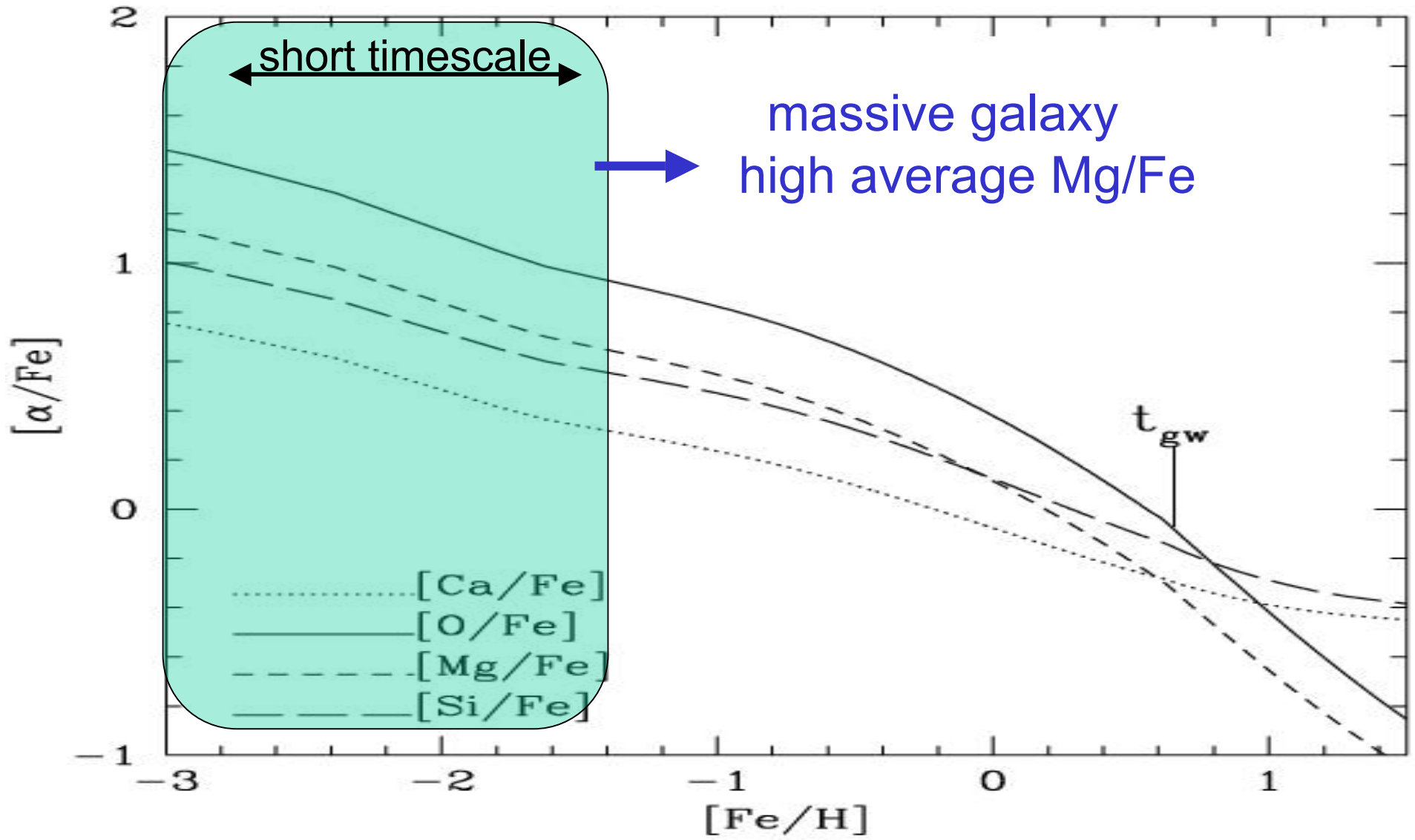

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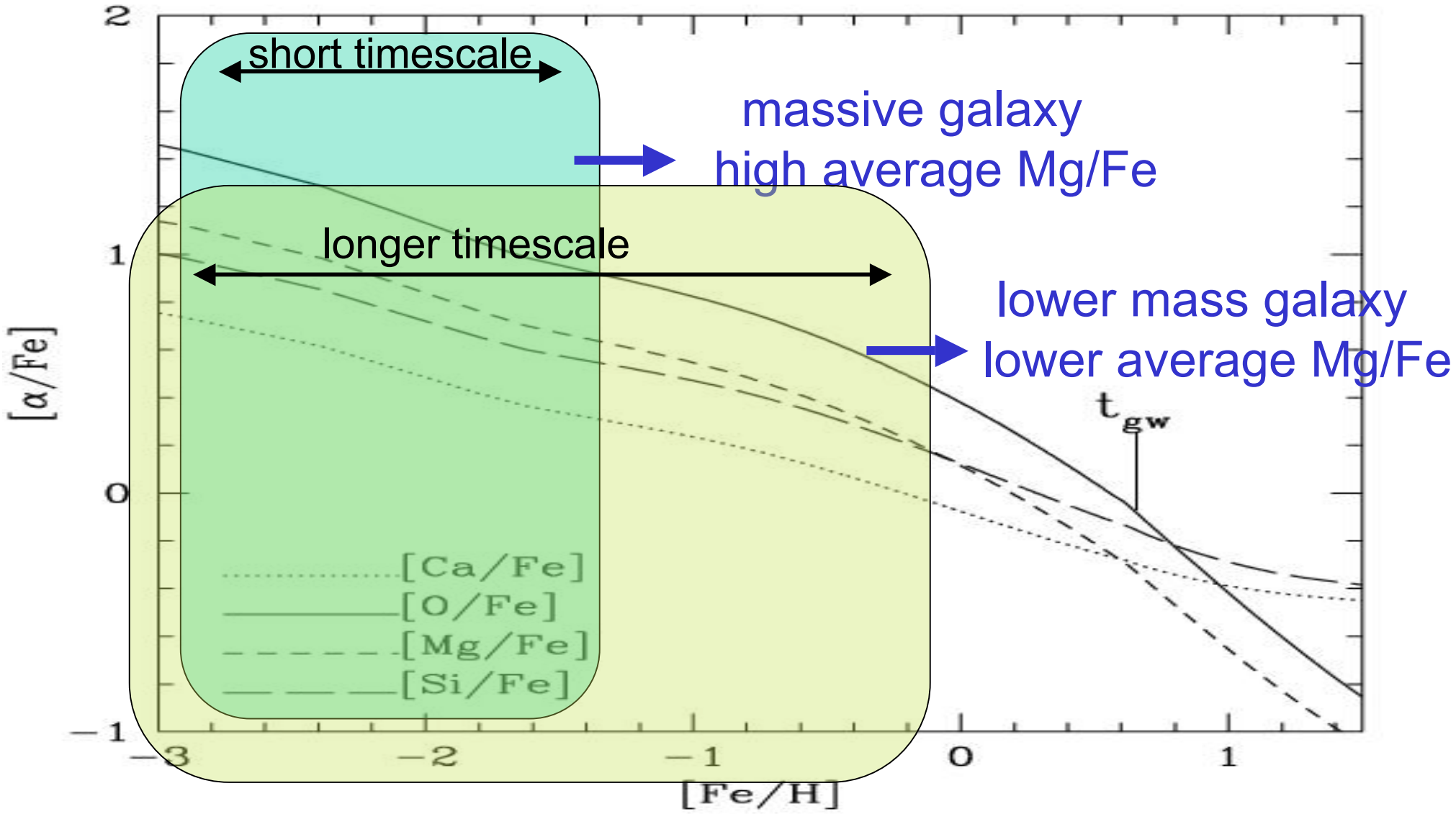

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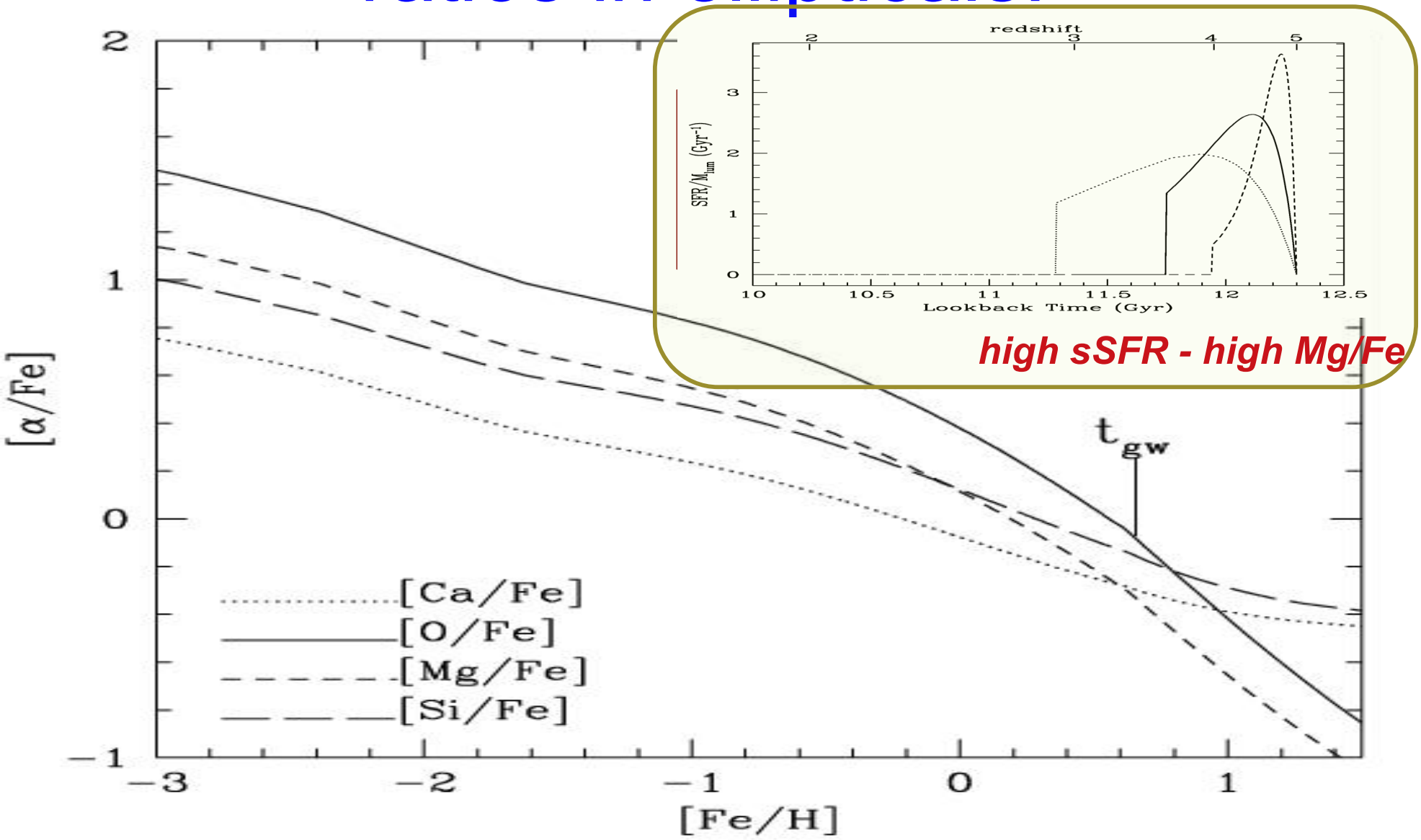
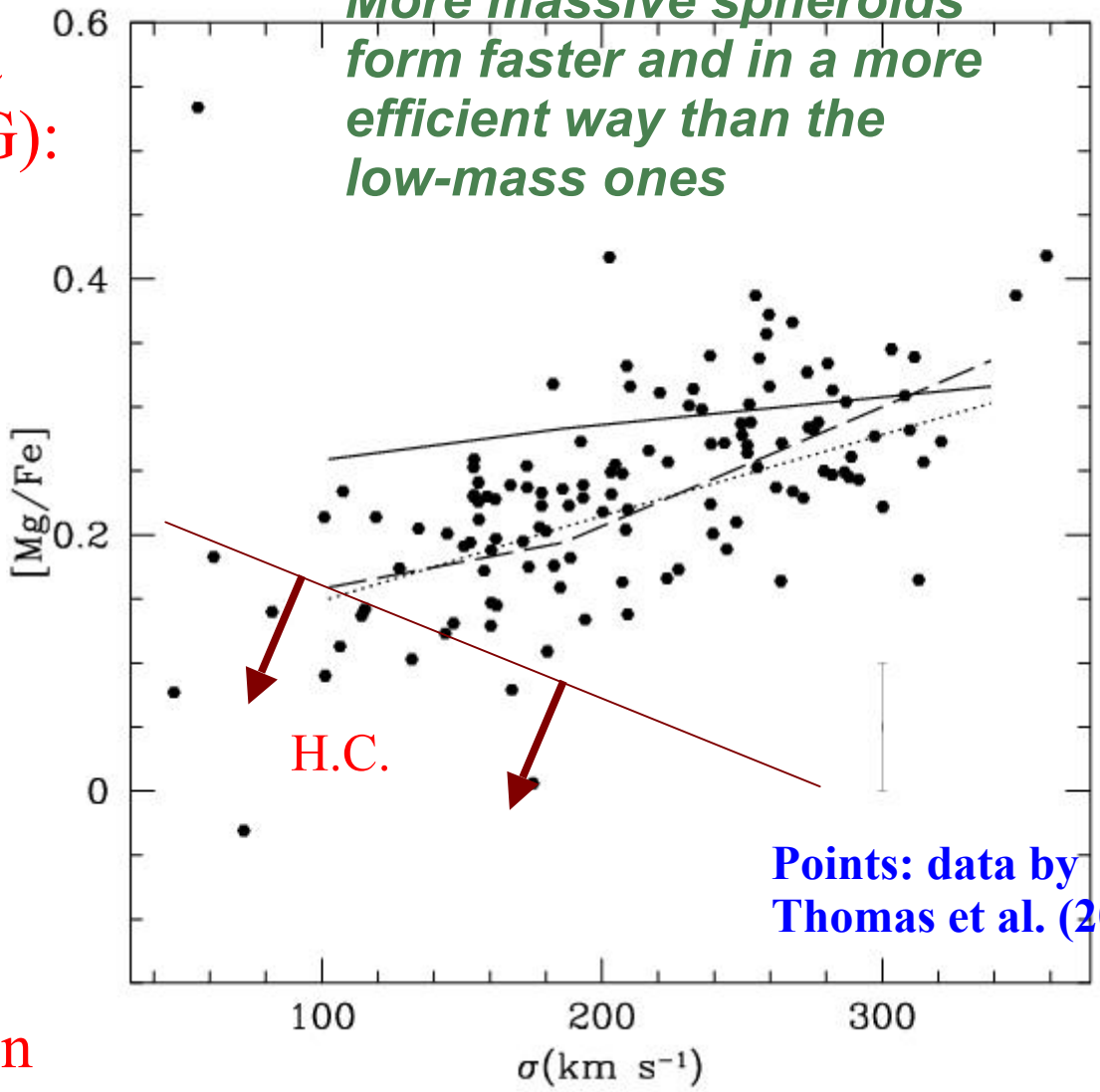


[Mg/Fe]-σ relation at z~0 - *stars*

Typical timescale to develop a galactic wind (=QUENCHING):
0.5 Gyr (high mass)
1.3 Gyr (low mass)
by means of
PM04 heuristic approach:
ν increases with Mass

Predictions from earlier models based on Hierarchical Clustering (H.C.) scenario:
at odds with the observations (Thomas et al. 1999). In fact:

Merger-induced starbursts worsen the agreement (Pipino & Matteucci 06)



[Mg/Fe]-σ relation at z~0 - *stars*

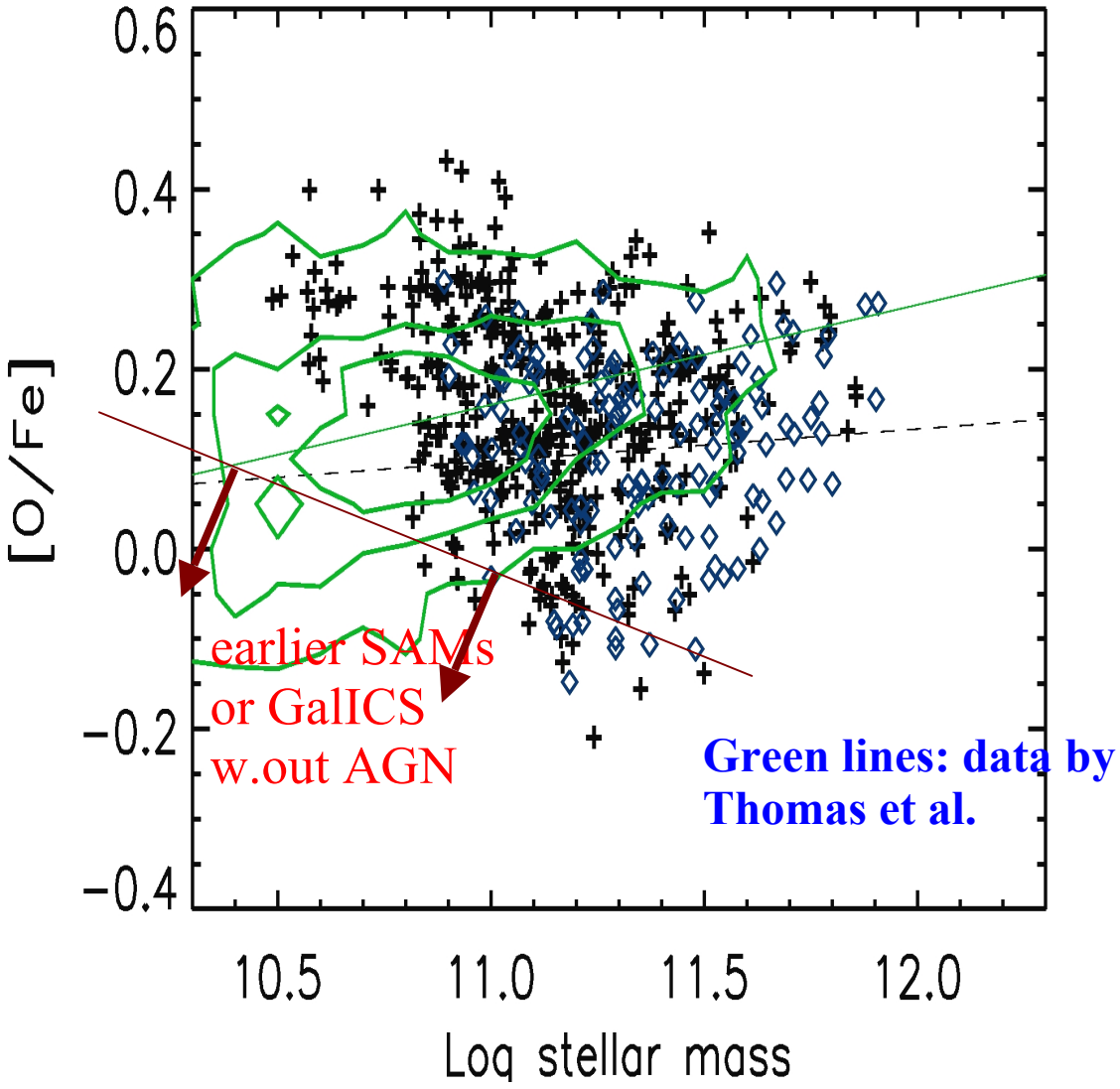
Pipino et al. 2009:

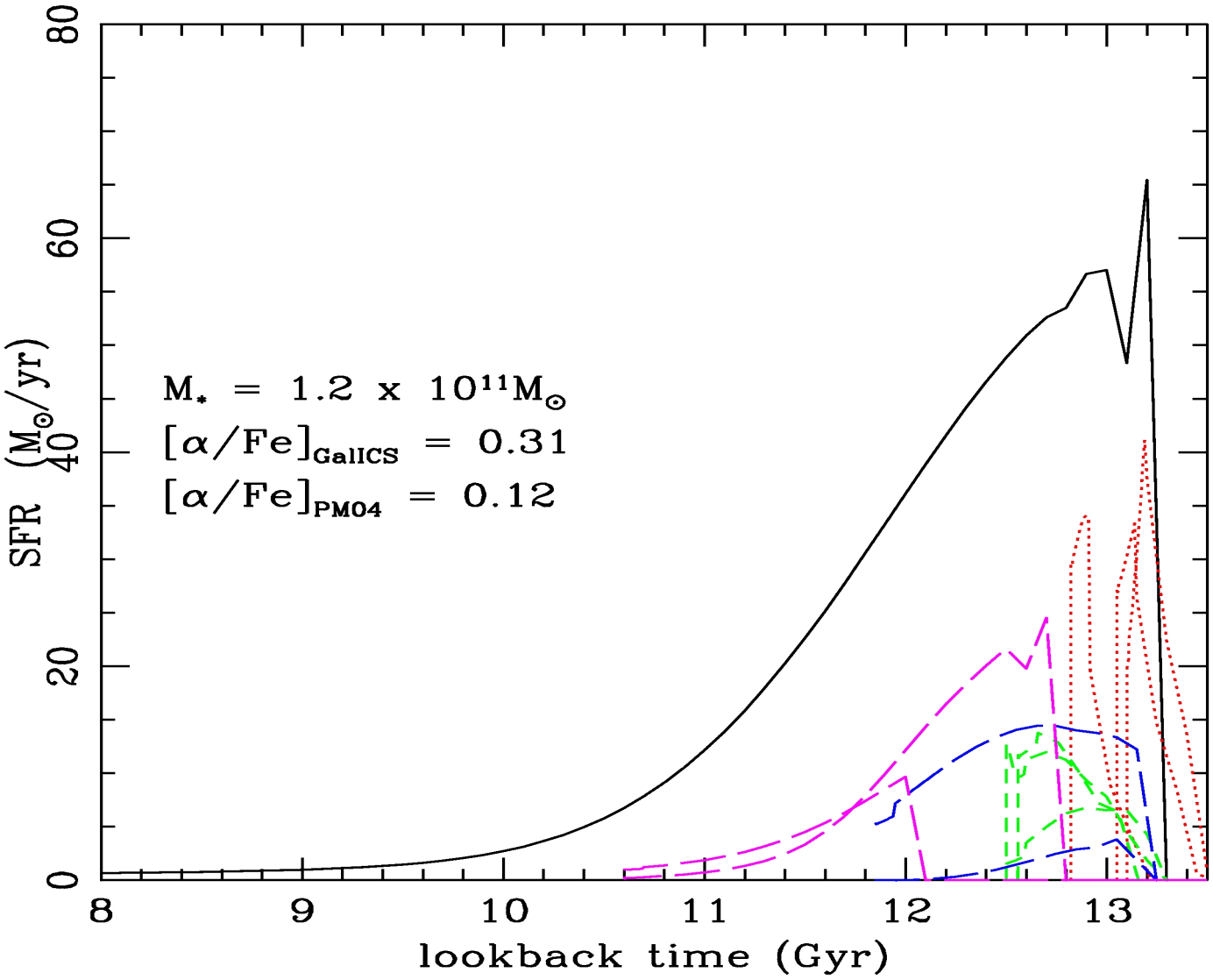
GalICS S.A.M. for gal. formation (Hatton et al 03)

plus self-consistent treatment of chemical evolution: (SNIa,IMF,yields..as in PM04)

- SF quenching is needed (AGN in this case)
- Slope >0 at high masses/centrals (it aims at downsizing and galaxy bimodality)

See also Calura&Menci 09,11
Arrigoni et al. 2010





Dry mergers help keeping alpha/Fe but they CANNOT create a slope with mass!!!

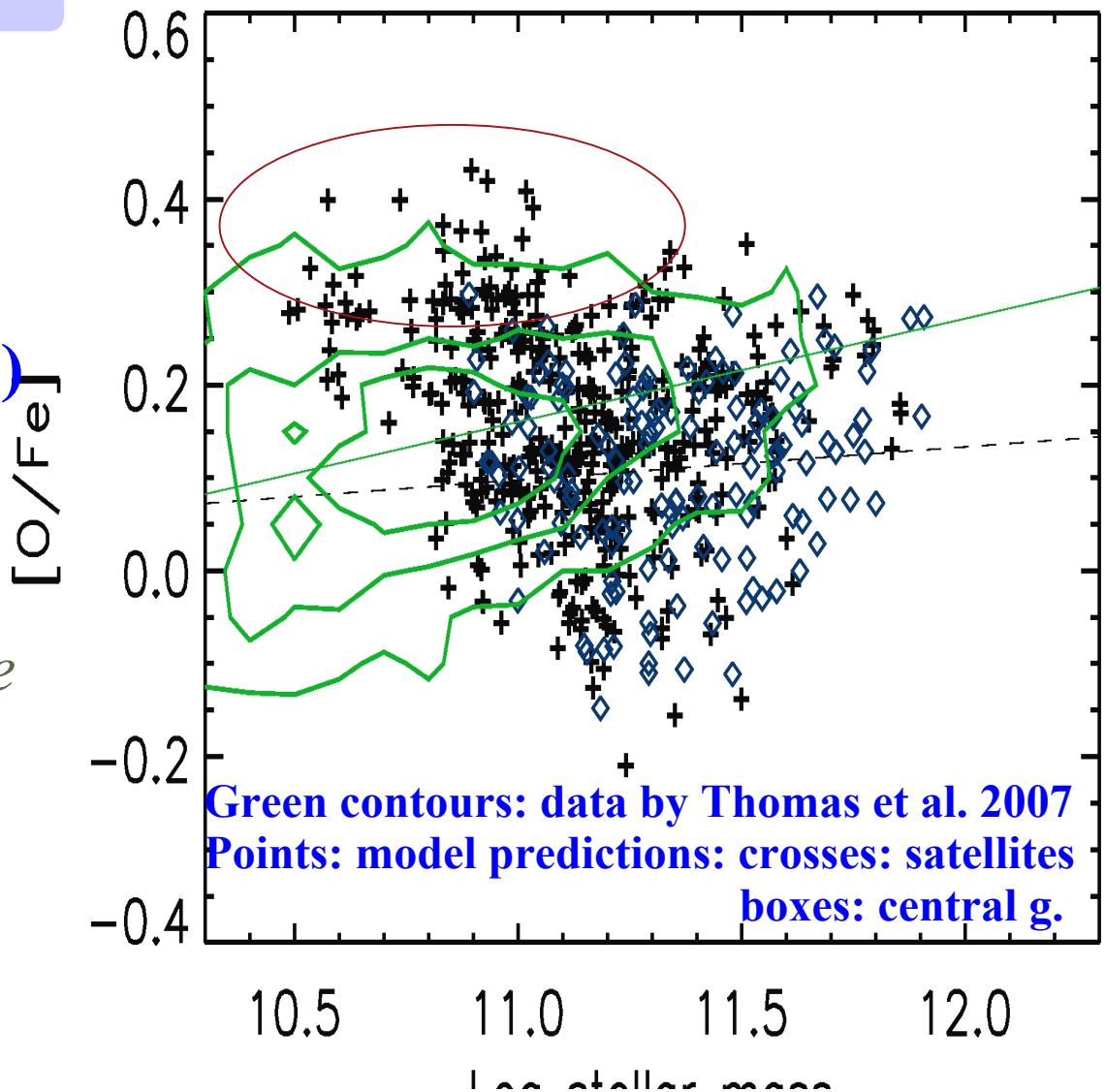
[Mg/Fe]-σ relation at z~0 - *stars*

Pipino et al. 2009:

GalICS S.A.M. for gal. formation (Hatton et al 03)

plus self-consistent treatment of chemical evolution: (SNIa,IMF,yields..as in PM04)

- Too many and too α-enhaced low mass galaxies needed in GalICS if we want to have slope and mean values OK at high masses



Mass-Z relation at z~0 - *stars*

…drawback for S.A.M.s

"accounting" for *downsizing*

(Pipino & Matteucci 2008):

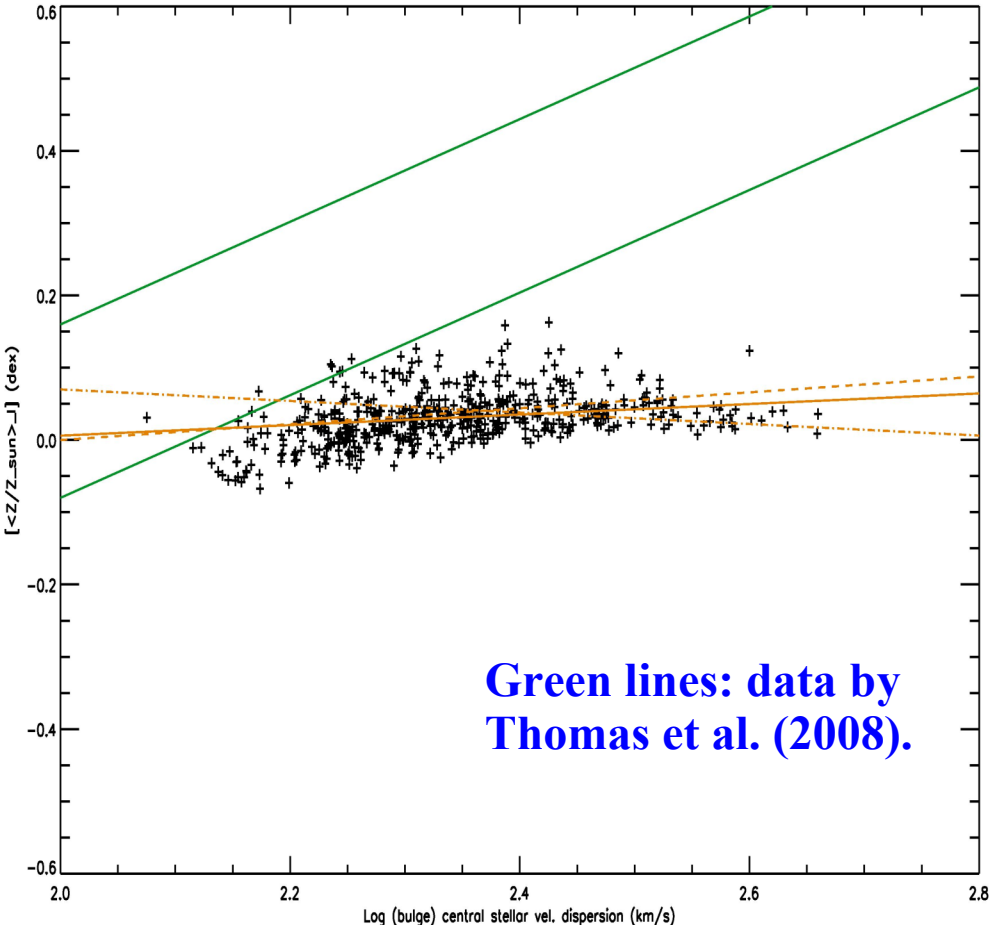
IF they reproduce the [Mg/Fe]-mass relation

THEN they fail in the mass-met.

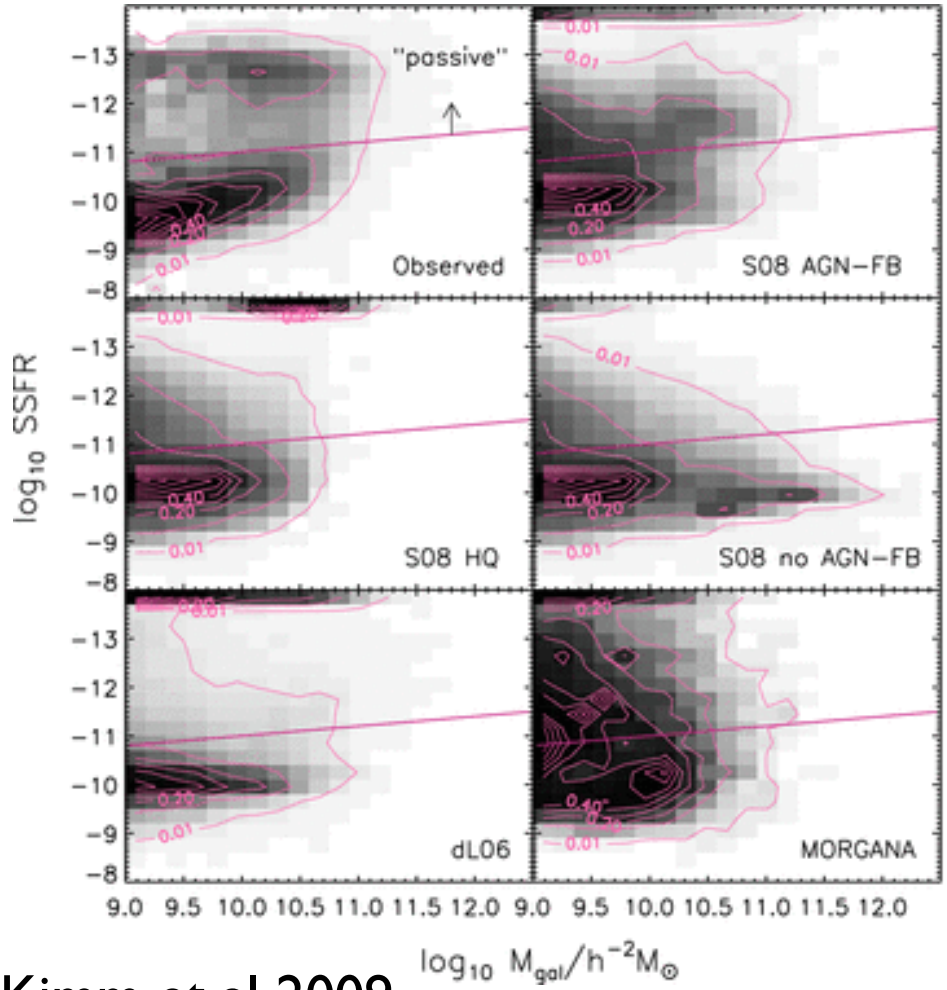
the opposite happened in earlier S.A.M

- Mass-Z and Mass-α/Fe act in opposite directions unless the galaxy assembly and the SF occur in the same place at the same time (as in monolithic models) !!!

Also, remember that GalICS does not resolve galaxies…but Es do have met. gradients!!!



Intermission - I



Kimm et al 2009

Current SAMs overpredict the galaxy passive fraction

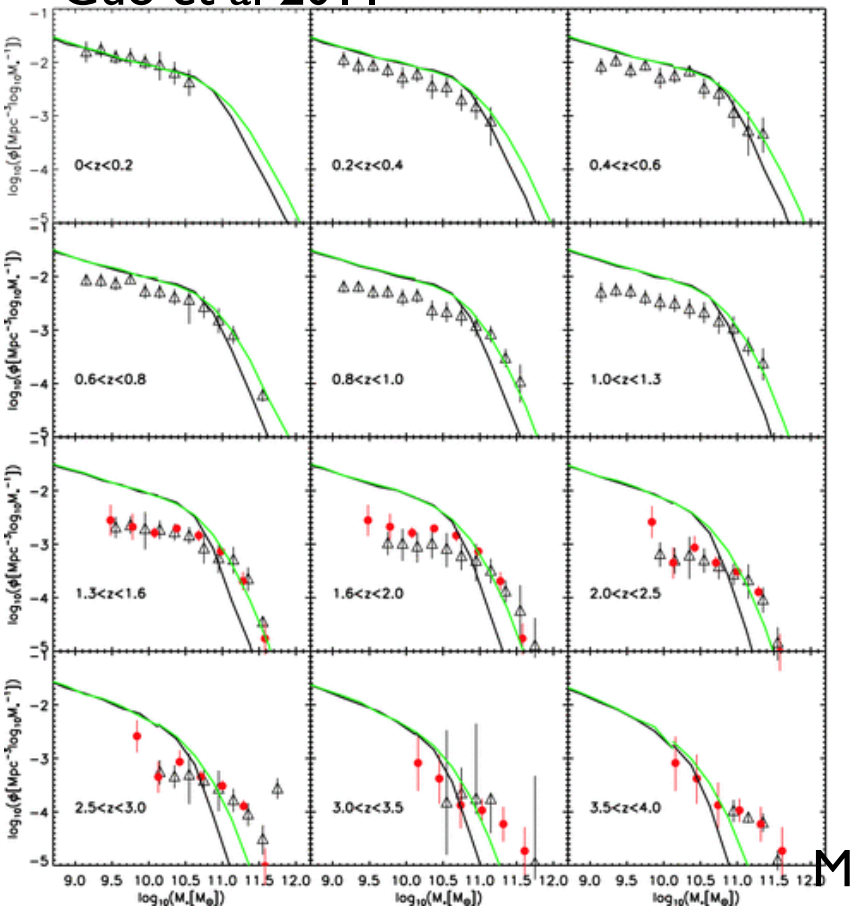
First noted for satellites

Led to a revision of the gas "stripping" as galaxies becomes satellites

(Font et al., 2008, Guo et al. 2011, Kimm et al., 2011)

Intermission - II

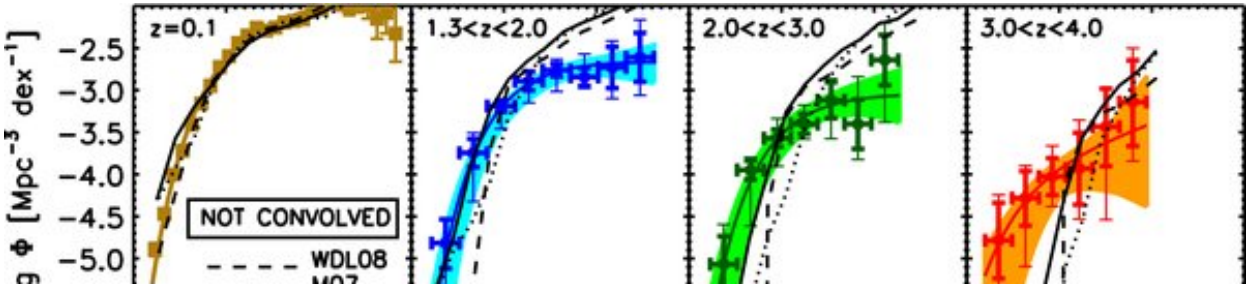
Guo et al 2011



State of the art SAMs do not reproduce the observed MF evolution at high z.

Predicted MF always steeper, with excess of "low mass" galaxies

Marchesini et al 2009, see also Fontanot et al. 2009



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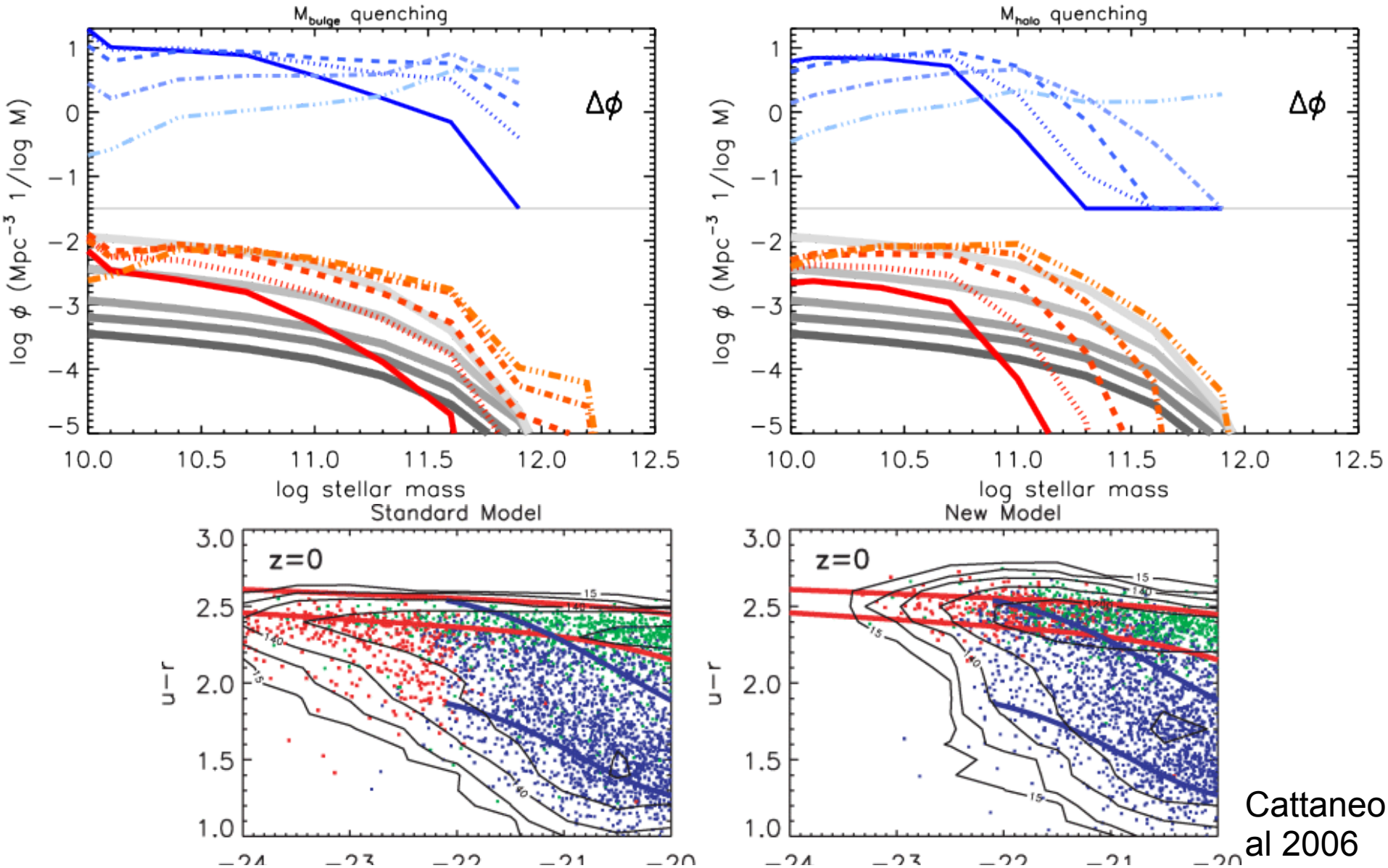
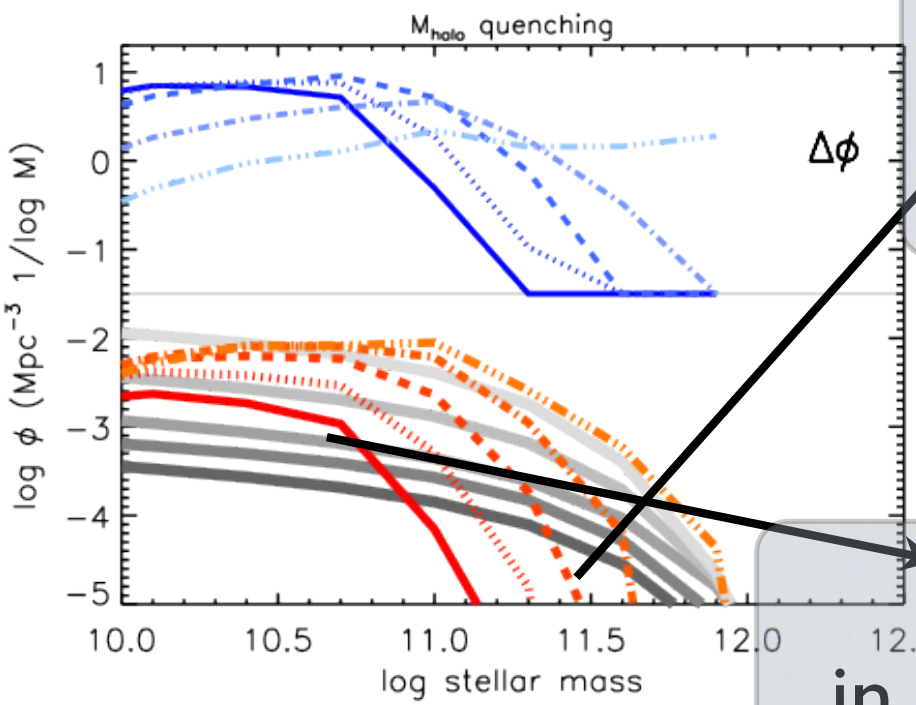
Basic model predictions



Cattaneo et al 2006

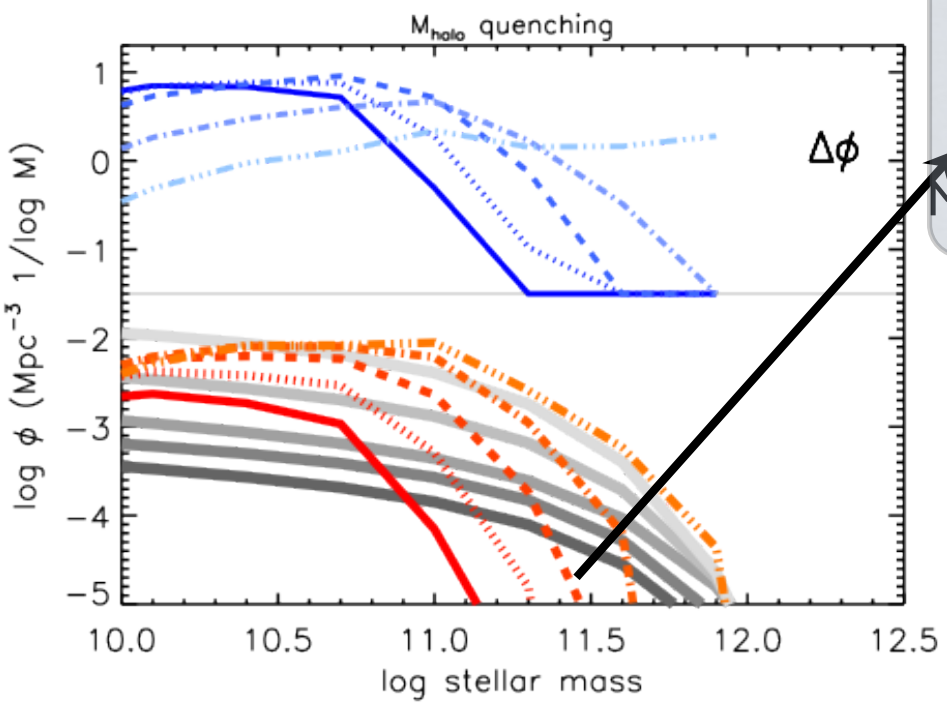
A closer look ...



Too strong evolution
at the high mass end
due to the hard limit
(30% of gals in haloes > 10^{12}
Msun at z=4, 40% at z=2, 61% at z=0)

Low mass galaxies
in excess of 1 dex at z=4

A closer look ...



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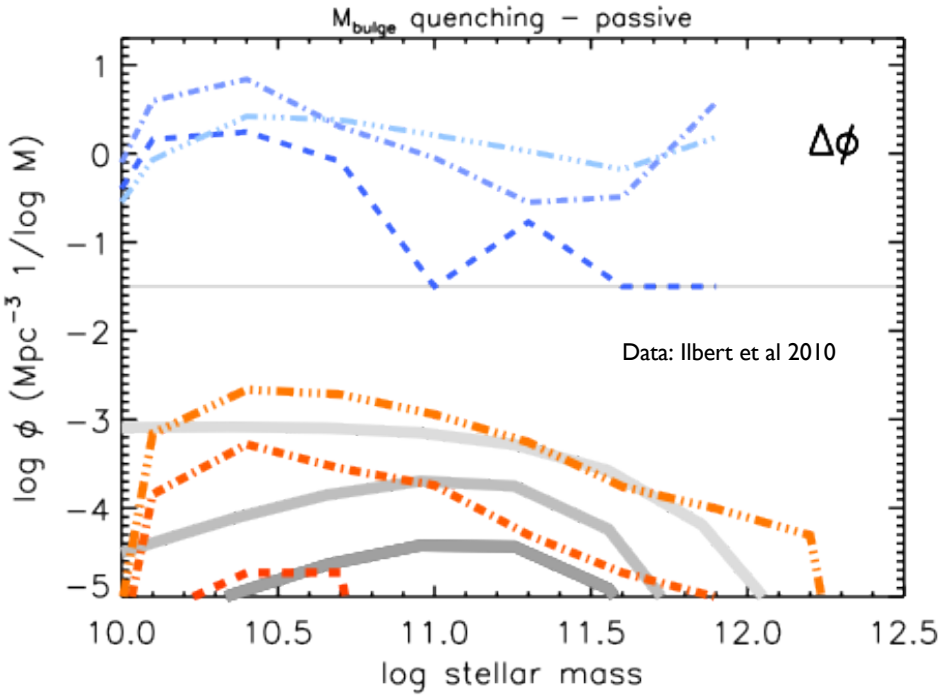
Msun at z=4, 40% at z=2, 61% at z=0)

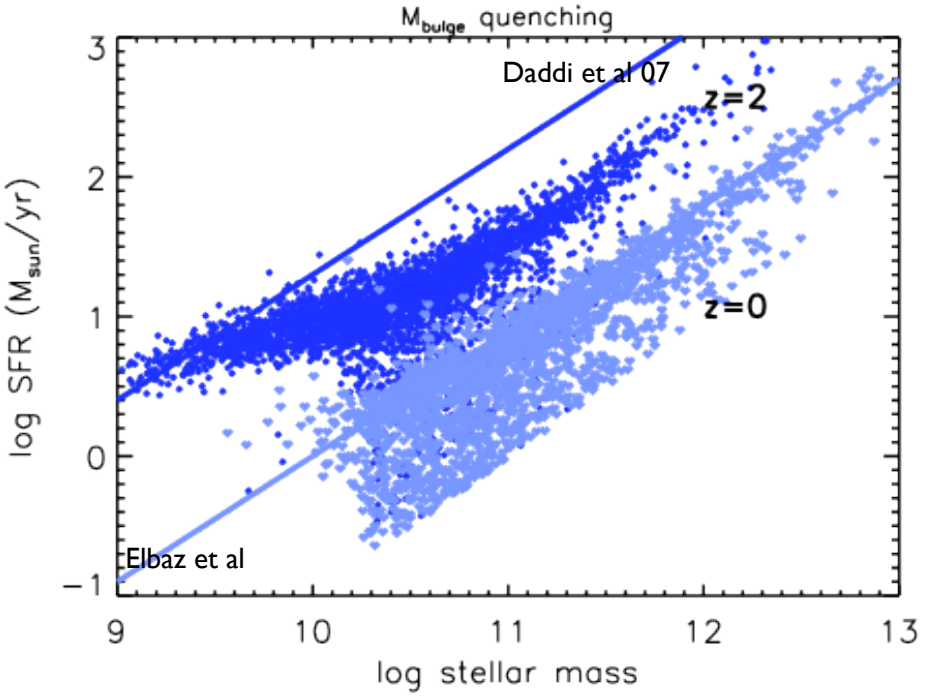
At z>>0 many galaxies are centrals,
perhaps satellites today:
the fact that they are overly efficient
in forming stars makes them red now..

…and not just an “environmental effect”

Low mass end



excess of low mass passive galaxies

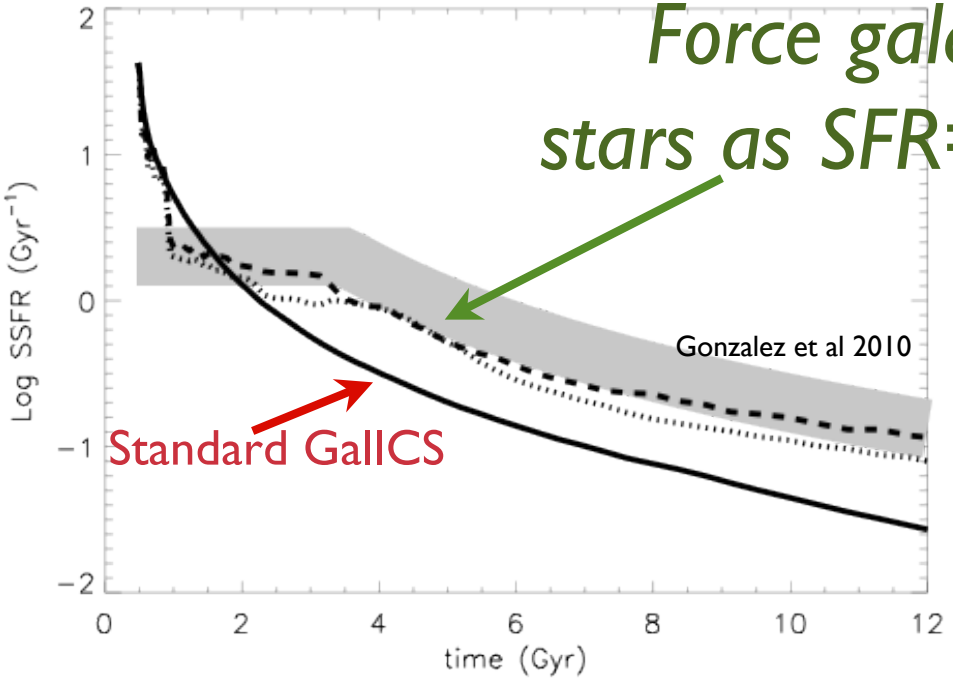


SFR-mass relation violated...because galaxies are too massive (not too low SFR)

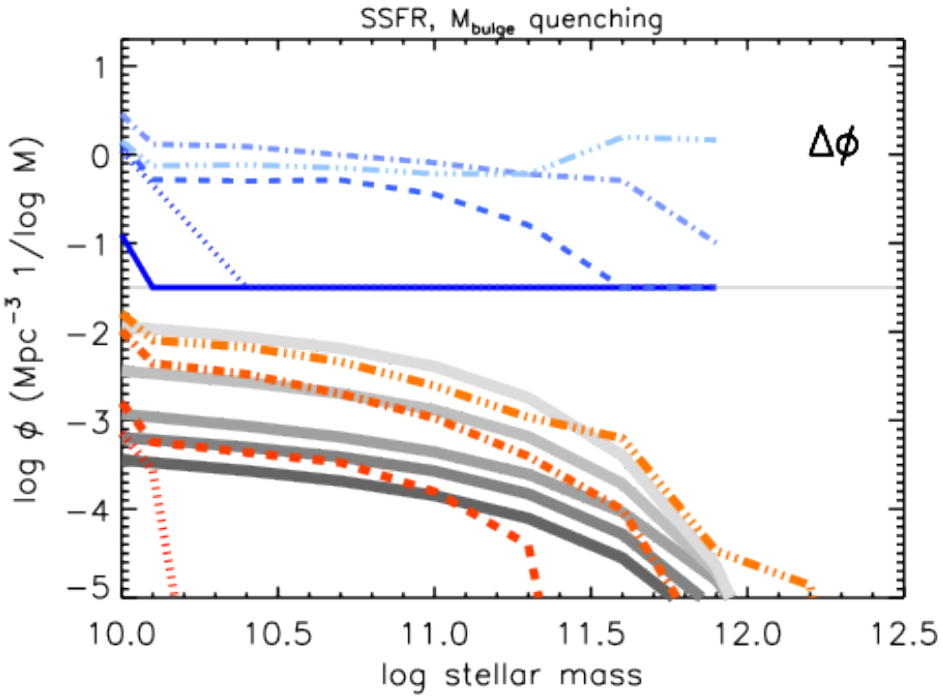
(some) open problems with S.A.M.

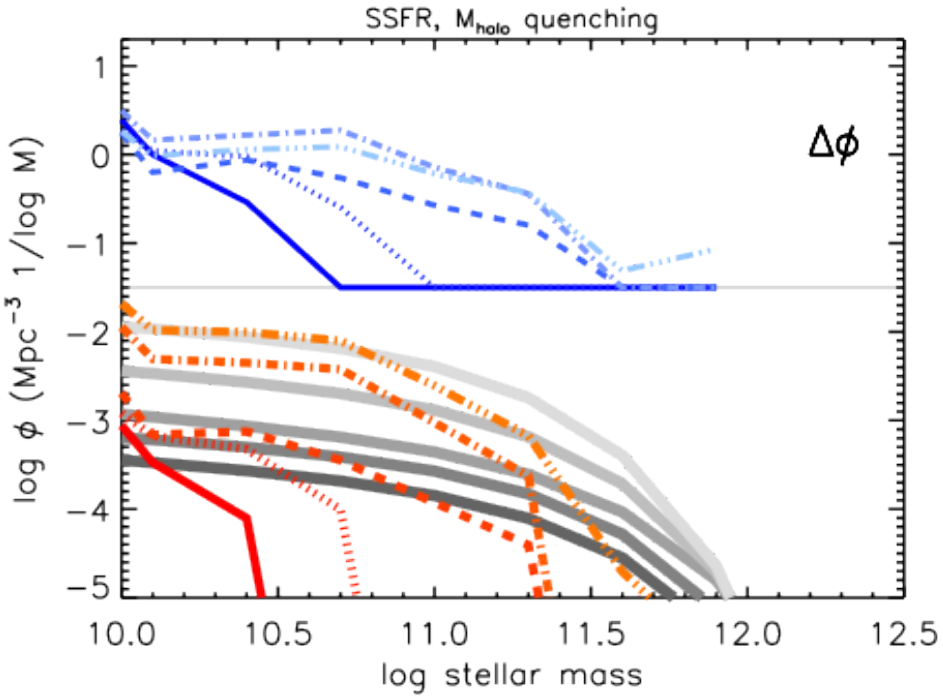
- **[alpha/Fe]-mass relation not satisfied despite the effort to comply with downsizing**
- **too many red satellites (Kimm et al., 2009, Font et al., 2008,…)**
- **too efficient formation of the central galaxy (Fontanot et al. 2009, Weinmann et al 09) + too many active central galaxies required by radio-mode**
- **excess of *preventive* feedback (Keres et al 2009) aimed at reproducing the downsizing**
- ***Shall we fix them by adding/adjusting, e.g., recipes for ram-pressure stripping/strangulation, AGN&stellar feedback linked to the galaxy and not only the halo, etc?***
- ***….or we change completely and find a new mode as a way to make "monolithic"-like galaxies in the hierarchical framework?***
- ***…let's start by looking at the sSFR, which sets the pace for the mass function evolution (Peng et al., 2010): it's probably matter of gas accretion and star formation!***

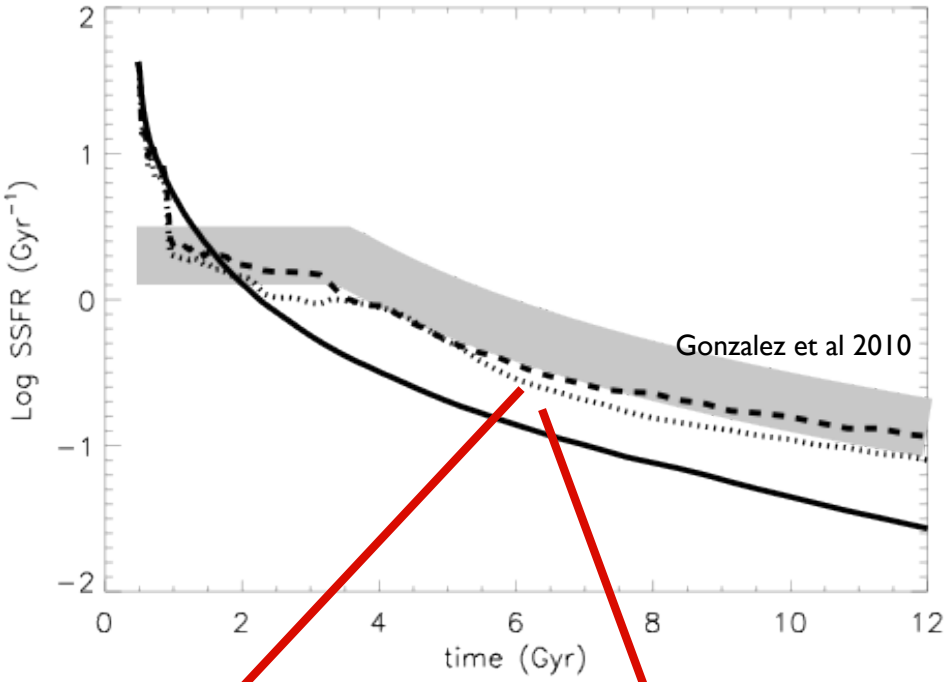
sSFR(z) difficult to reproduce with S.A.Ms (Weinmann et al. 11)



Force galaxies to form stars as SFR= M(t) x sSFR(t)

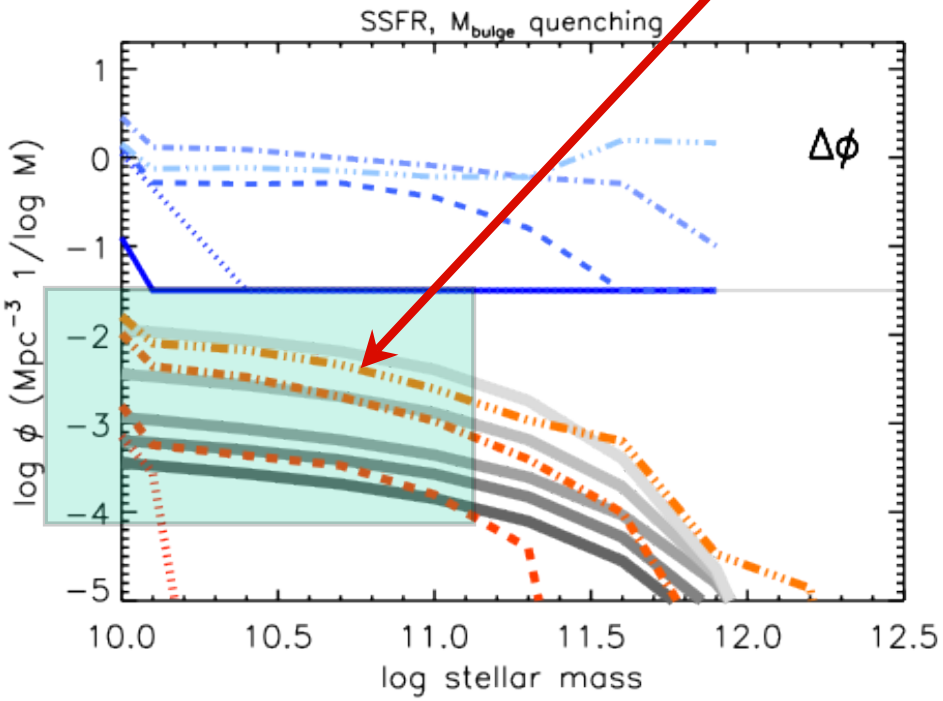


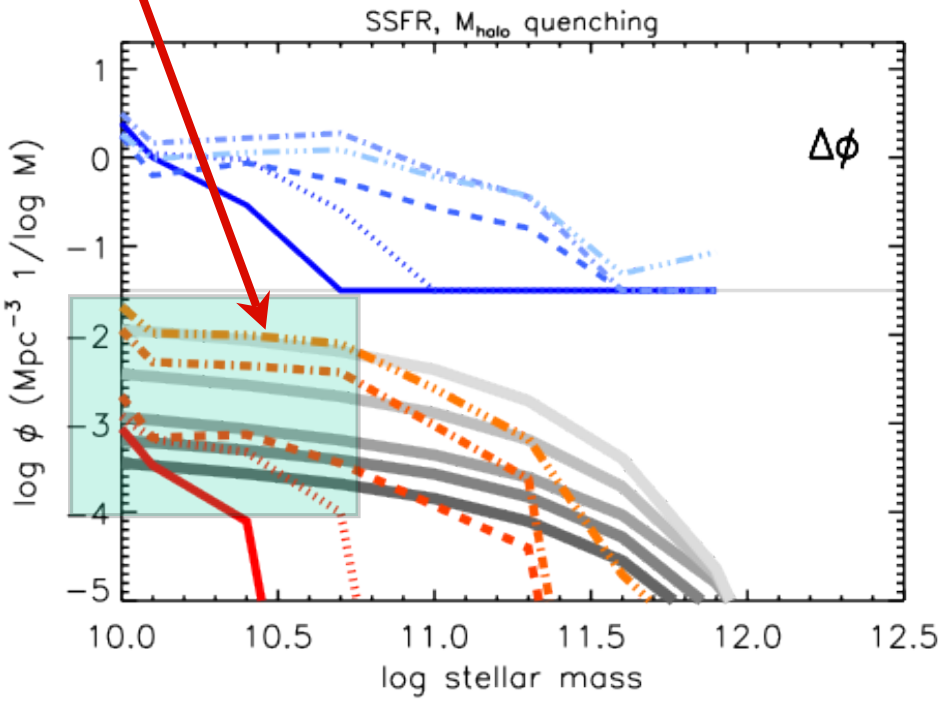


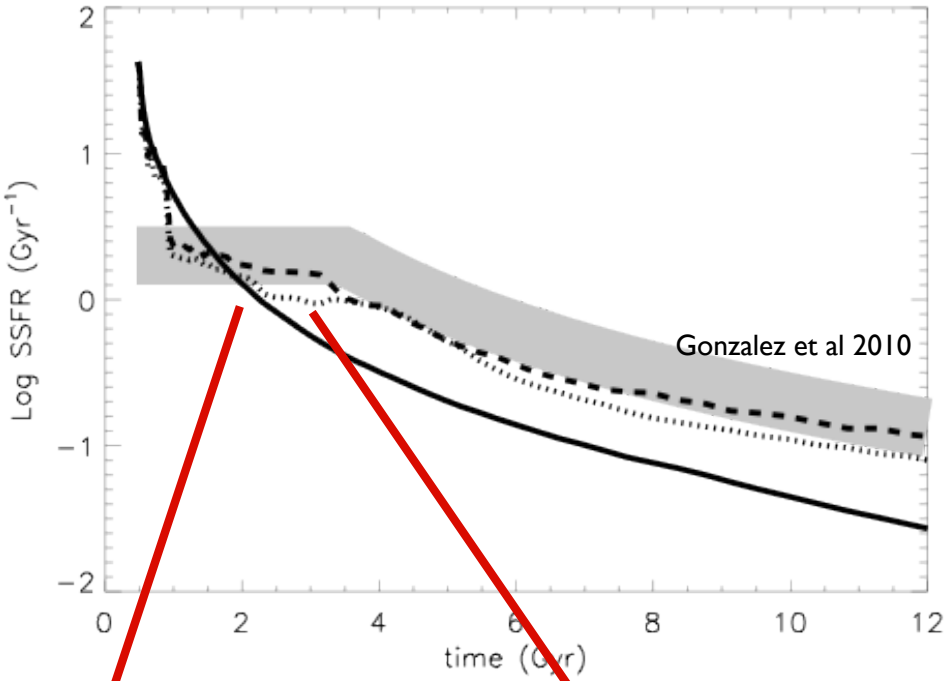


The evolution at low mass is now correct (bulge-q still better than halo-q.)

Present-day galaxies are however too gas rich!!! They used to form too efficiently because there's plenty of gas to begin with.. (see also Wang et al.12)

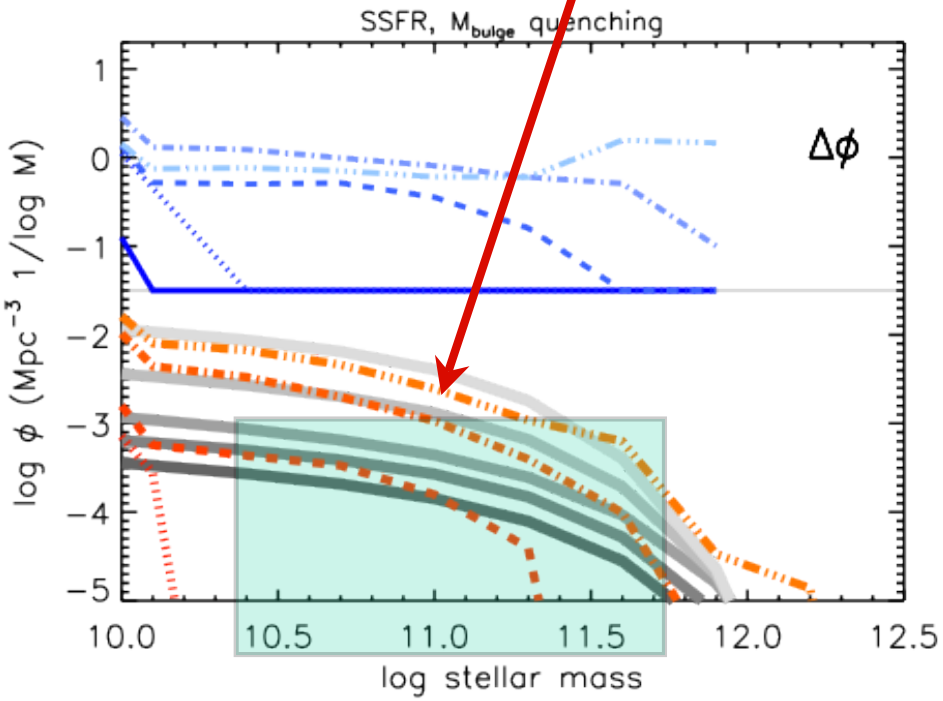


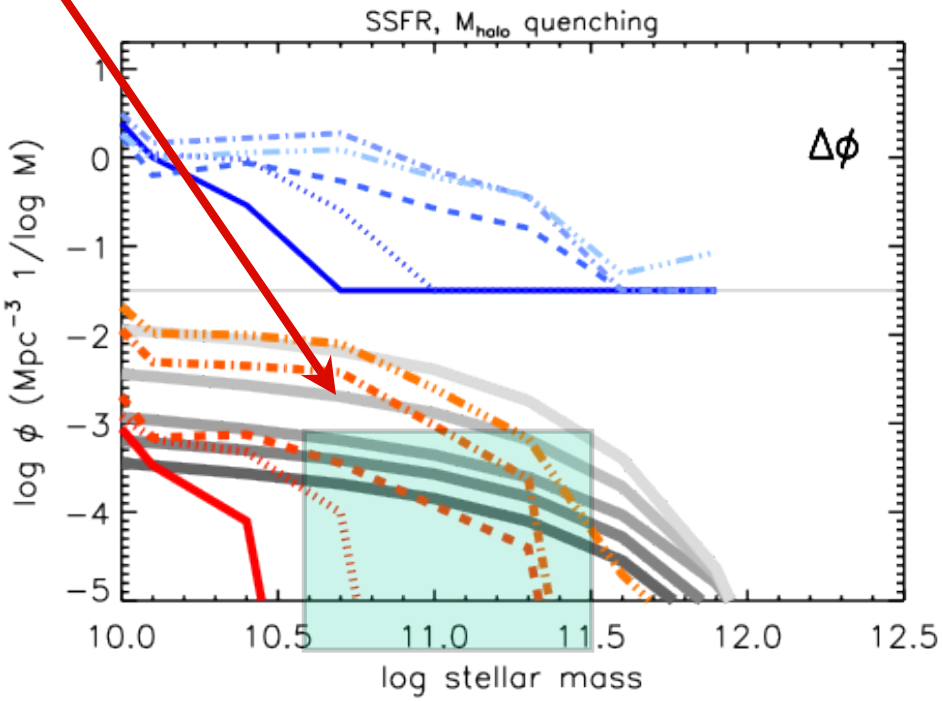




The existence of massive galaxies at z=4 and sSFR=2/Gyr at z>2 imply a substantial number of massive galaxies at z>4.

The lack of predicted ones highlight problems in the simulation set-up (resolution) and/or merger rate (Weinmann et al.11)

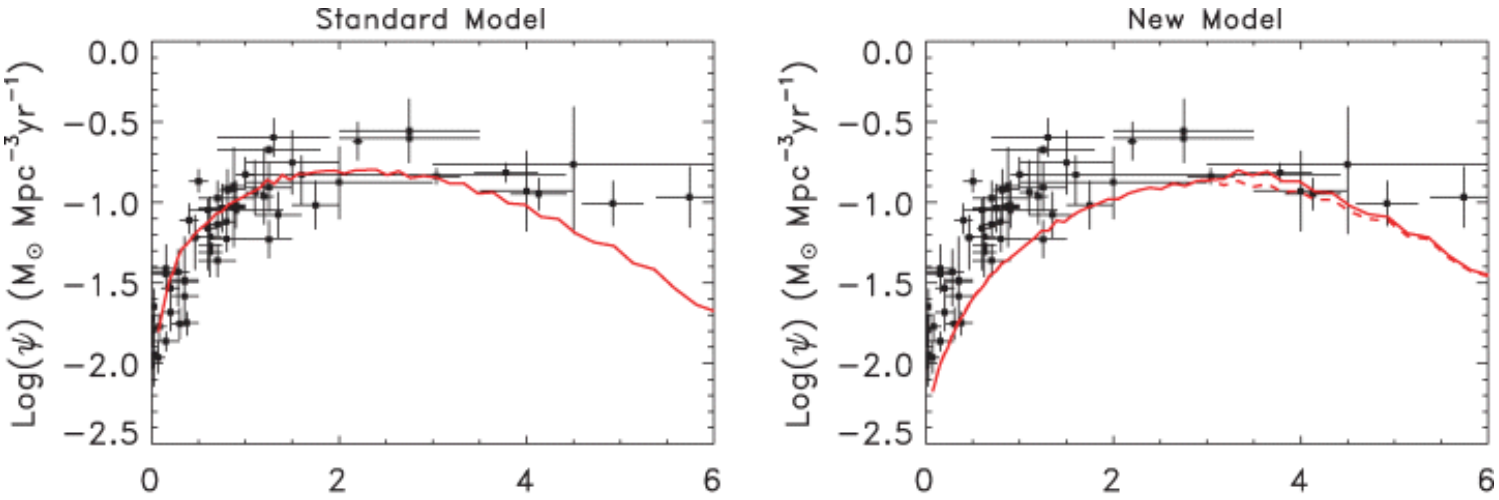


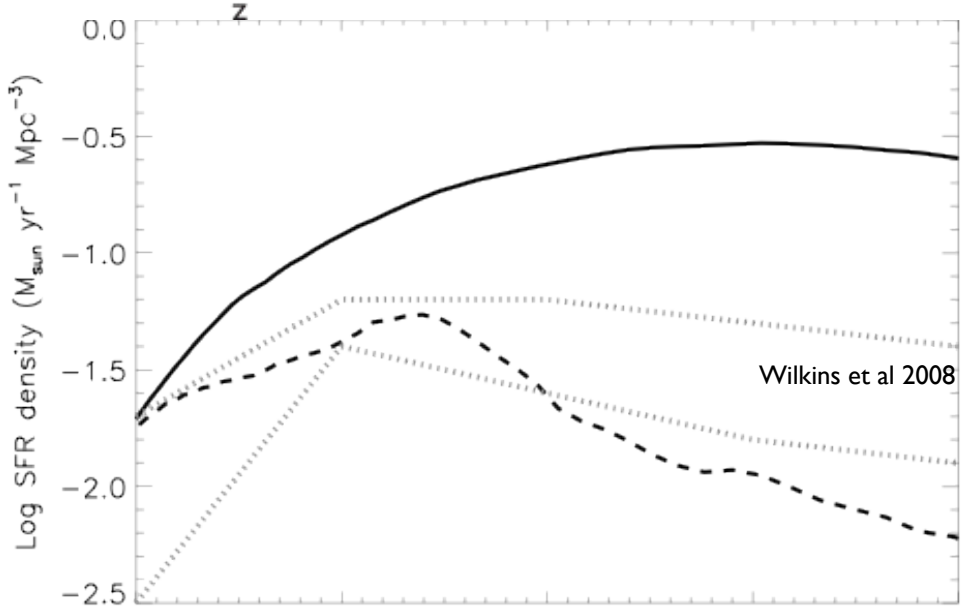


Conclusions

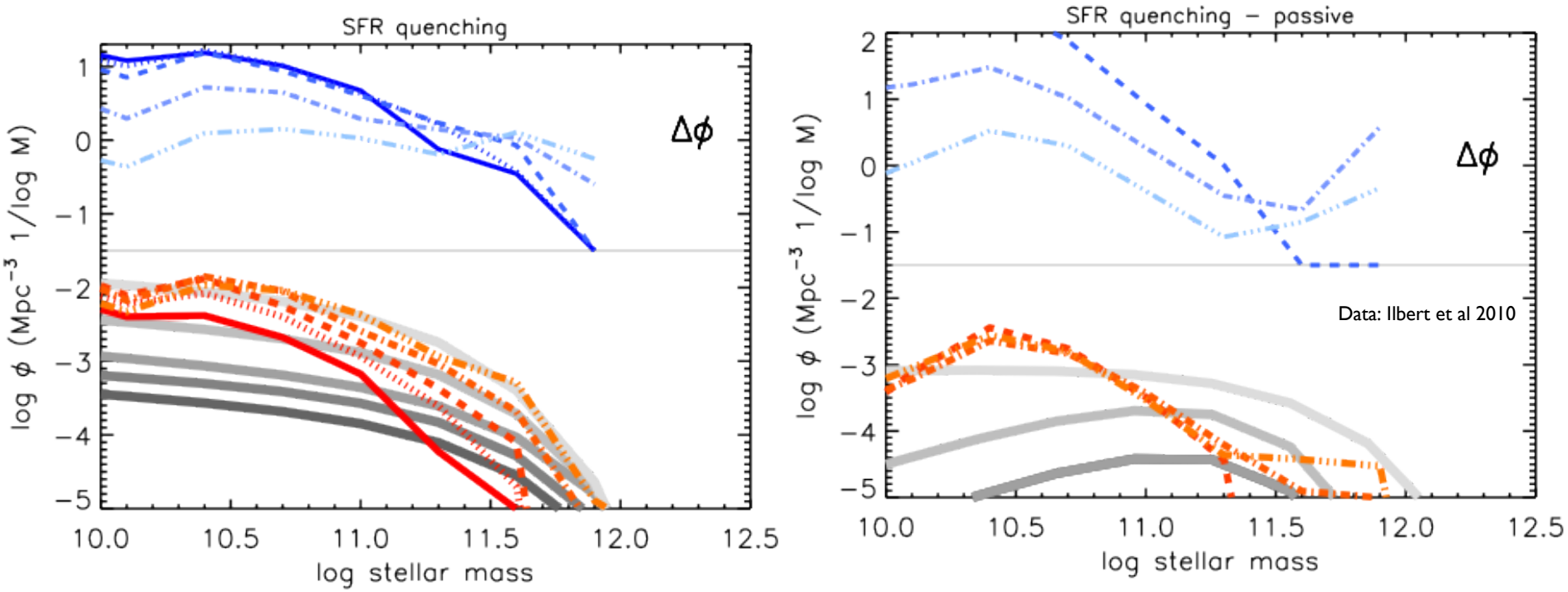
- **Tool: 'Monolithic' models. Successfully reproduce the vast majority of the photo-chemical properties & sSFR in ellipticals provided a suitable (sSFR)$_\nu$- mass relation**
- **GalICS + chemical evolution: huge leap forward in the agreement with the observed [Mg/Fe]-mass relation…**
- **…at the expenses of the Mass-Z relation**
- **…+ problems with MF, red fraction**
- **"sSFR evolution" offers a way out, but we need to understand the physical processes responsible for it**
- **A mass function at z~10 must be one of the initial conditions**
- **The gas accretion history has to be revised**
- **Mass-Z and Mass-[Mg/Fe] require galaxy assembly and star formation to occur simultaneously**

Why?


Standard Model
New Model
Log(ψ) (M⊙ Mpc⁻³yr⁻¹)
z
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0
2
4
6


Log SFR density (M_sun yr⁻¹ Mpc⁻³)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Wilkins et al 2008

High mass end



Problem can be cured by replacing
halo quenching with SFR-quenching (Peng et al 10)
...or having halo quenching only at z<2

[Mg/Fe]- and Z-Mass relations

…drawback for S.A.M.s

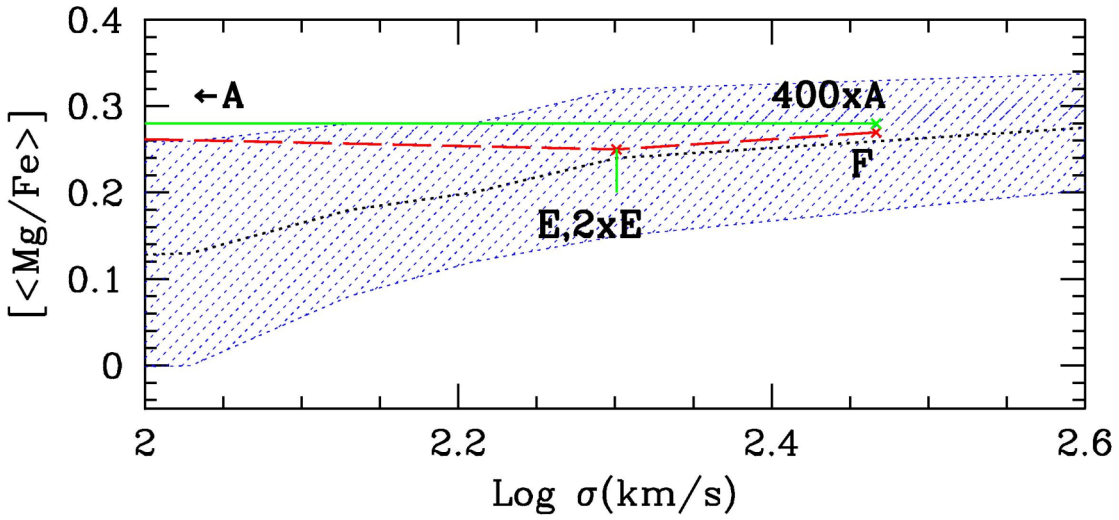
"accounting" for *downsizing*
by replacing the old-fashioned wet-mergers with the dry ones

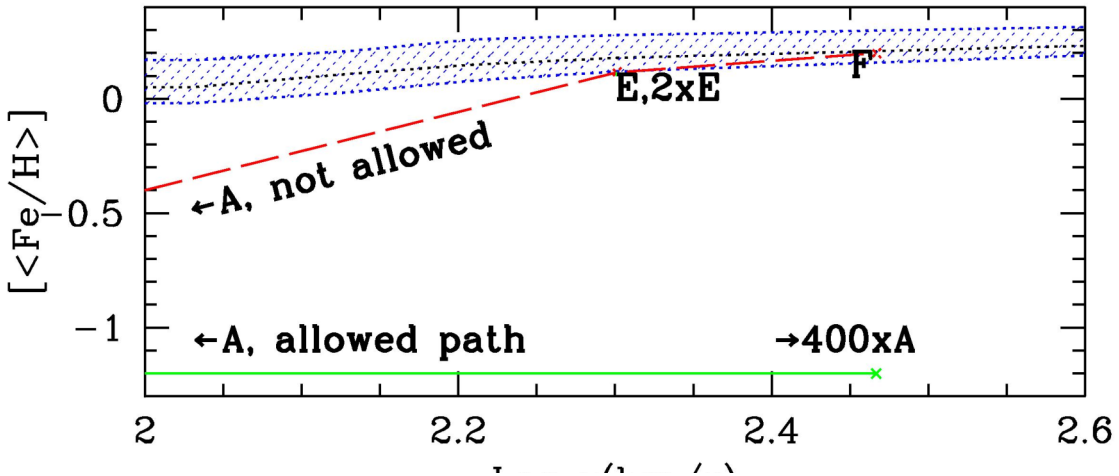
(Pipino & Matteucci 2008):

Simple (extreme) exercise:
Galaxy F formed either
- by a major dry merger E+E
- by 200 minor dry mergers of 400 progenitors w.same props.

NB: dissipationless mergers do not affect quantities like σ, colour, α-enhacement!!!

NB: the observed scatter allows 1-3 major mergers (consistent with merger rate estimates @ z<1)

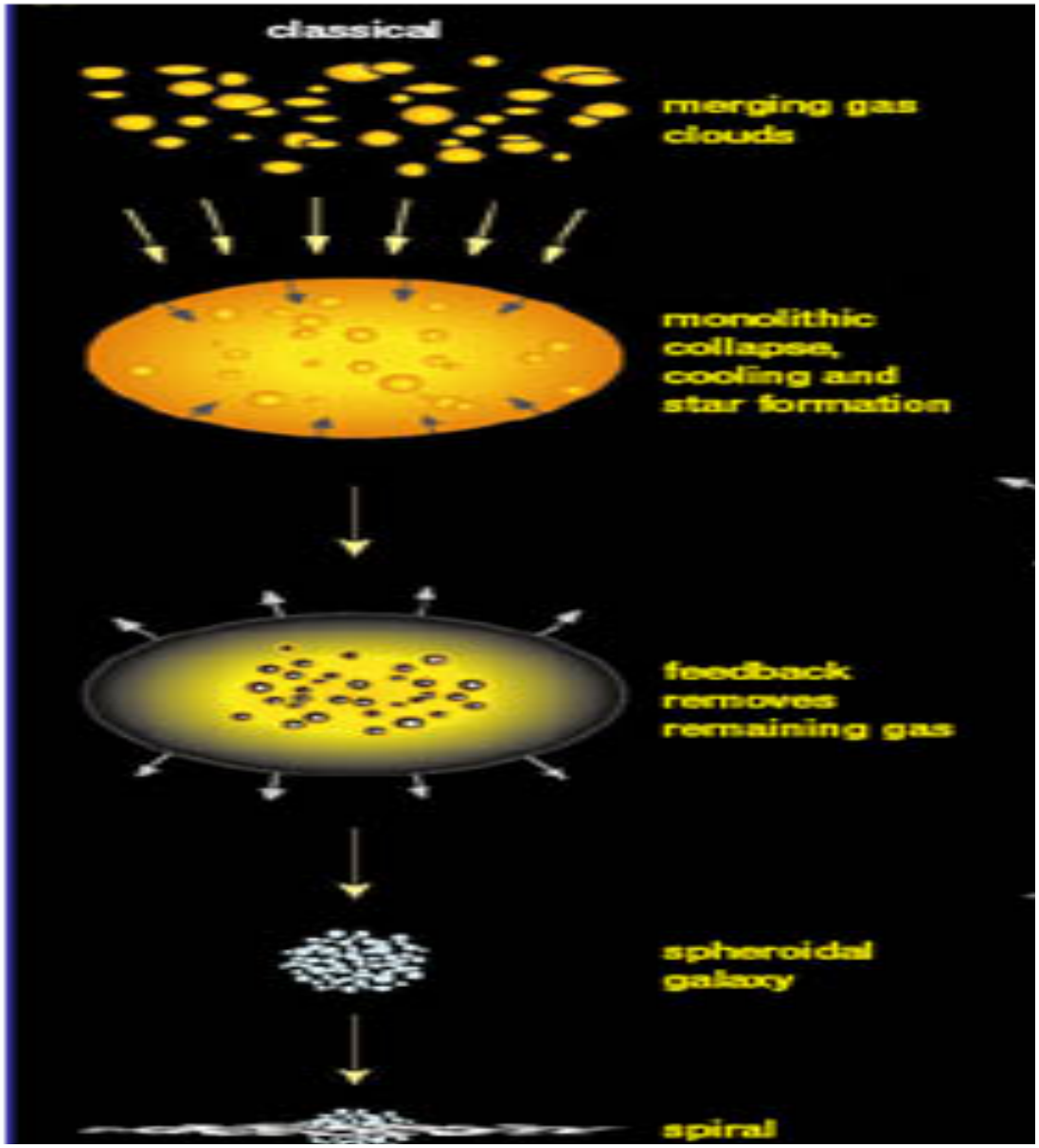




Two competing scenarios of galaxy formation (as they were originally put forward)

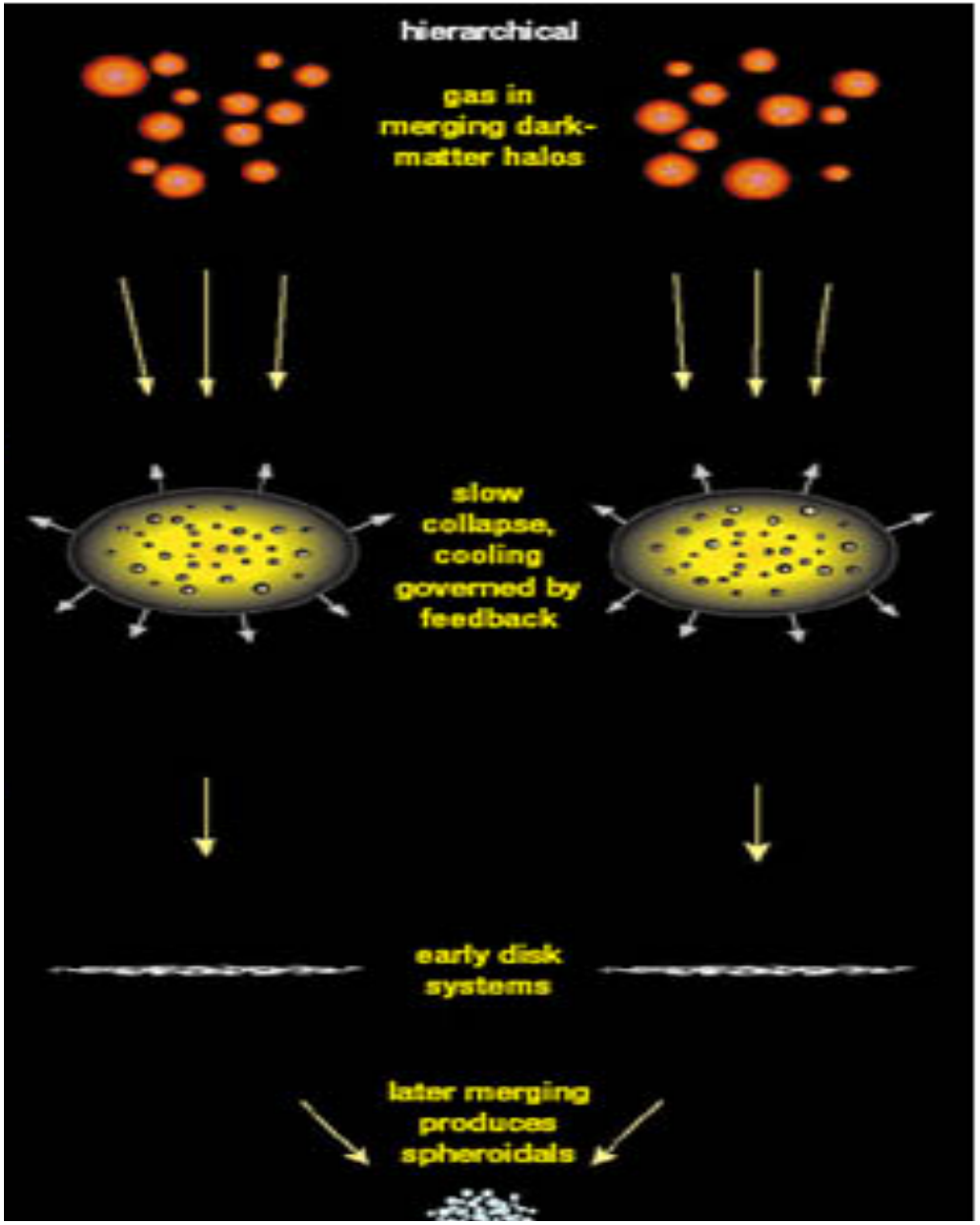
MONOLITHIC COLLAPSE vs HIERARCHICAL ASSEMBLY

- Formation only at high redshift
- Collapse of a gas cloud
- Strong initial burst of star formation
- Galactic wind powered by supernovae and then quiescent evolution



Two competing scenarios of galaxy formation (as they were originally put forward)

MONOLITHIC COLLAPSE vs HIERARCHICAL ASSEMBLY



- Galaxy assembly over a large time interval
- Baryonic matter follows the merger hierarchy of host haloes
- Small units merge and form bigger galaxies
- NOW: AGN quenching
- Galaxies “central” in their own halo, then become satellites:extra quenching from environment