Main successes and open problems of current galaxy formation models

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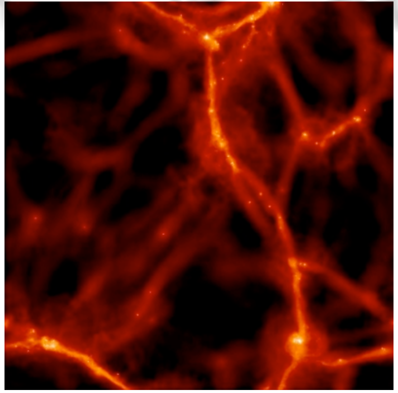
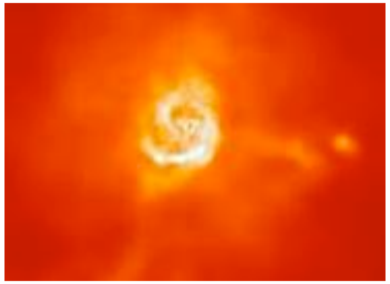
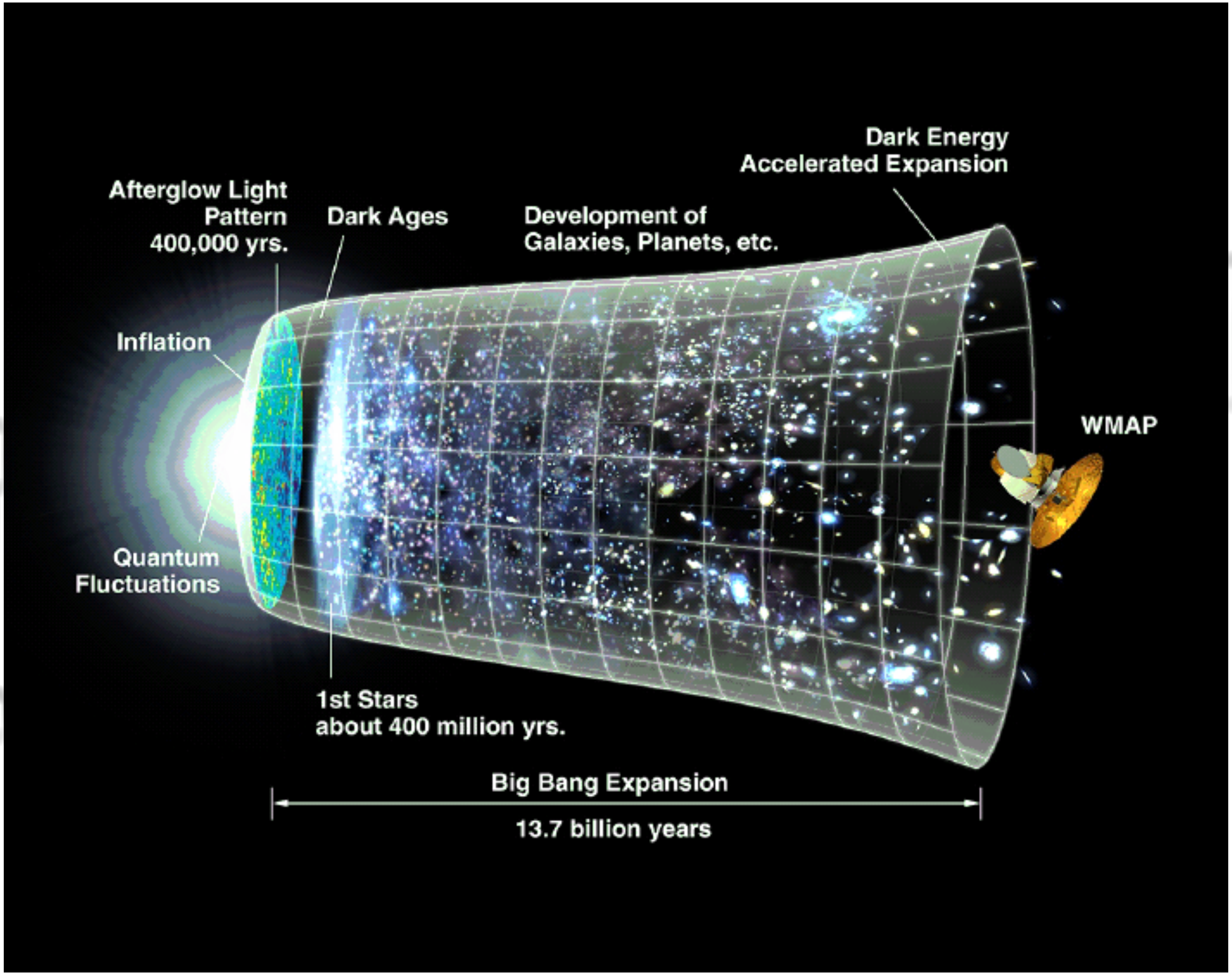
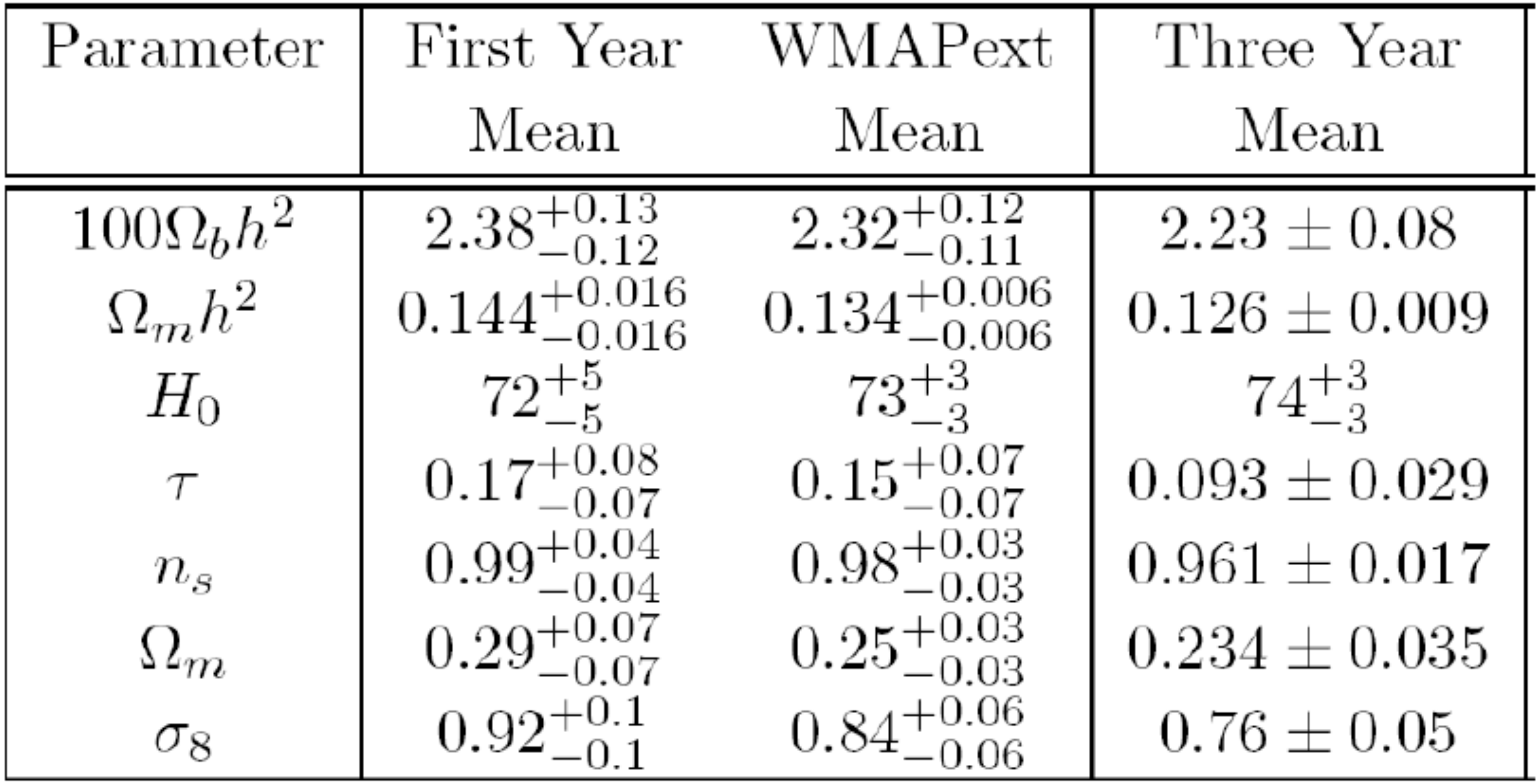


Granada 2009

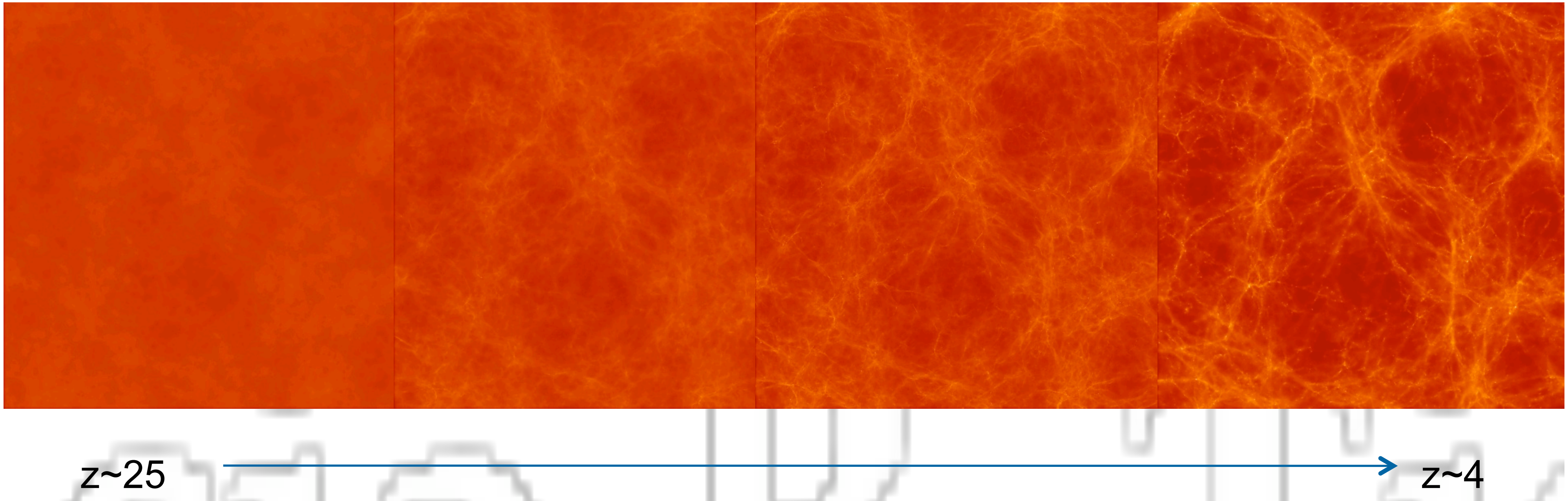


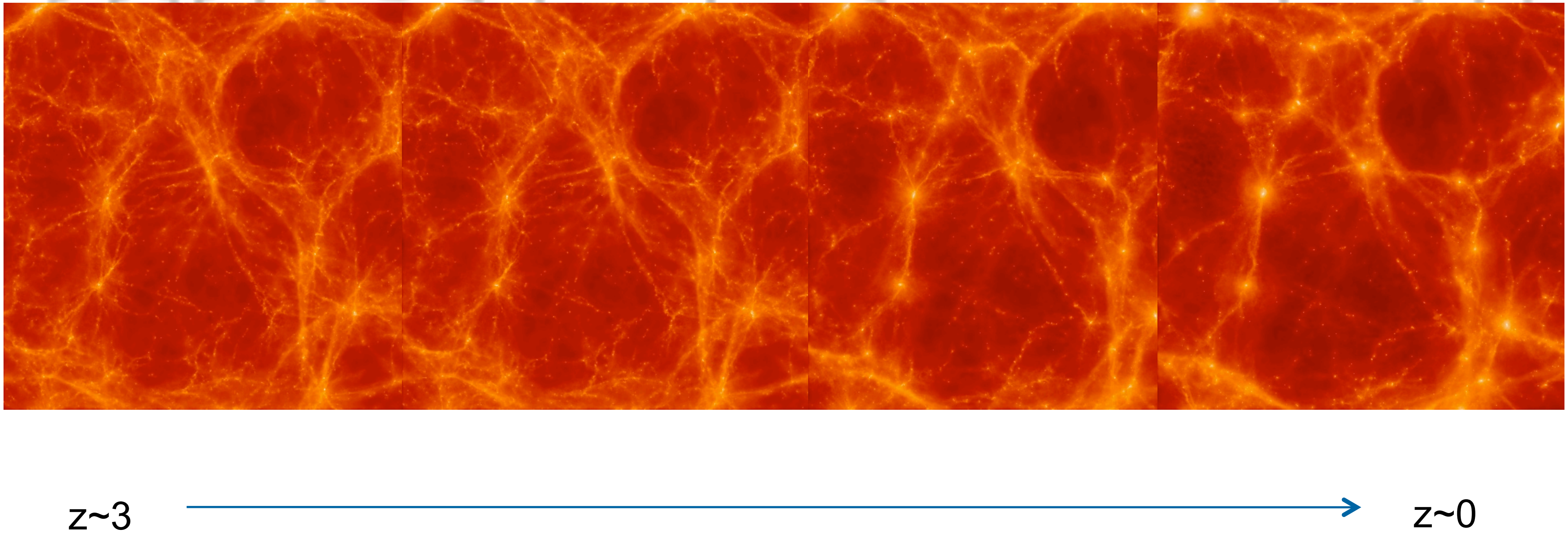

Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
Quantum Fluctuations
WMAP
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

WMAP3 team



Parameter	First Year Mean	WMAPext Mean	Three Year Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05


z~25
z~4


z~3
z~0

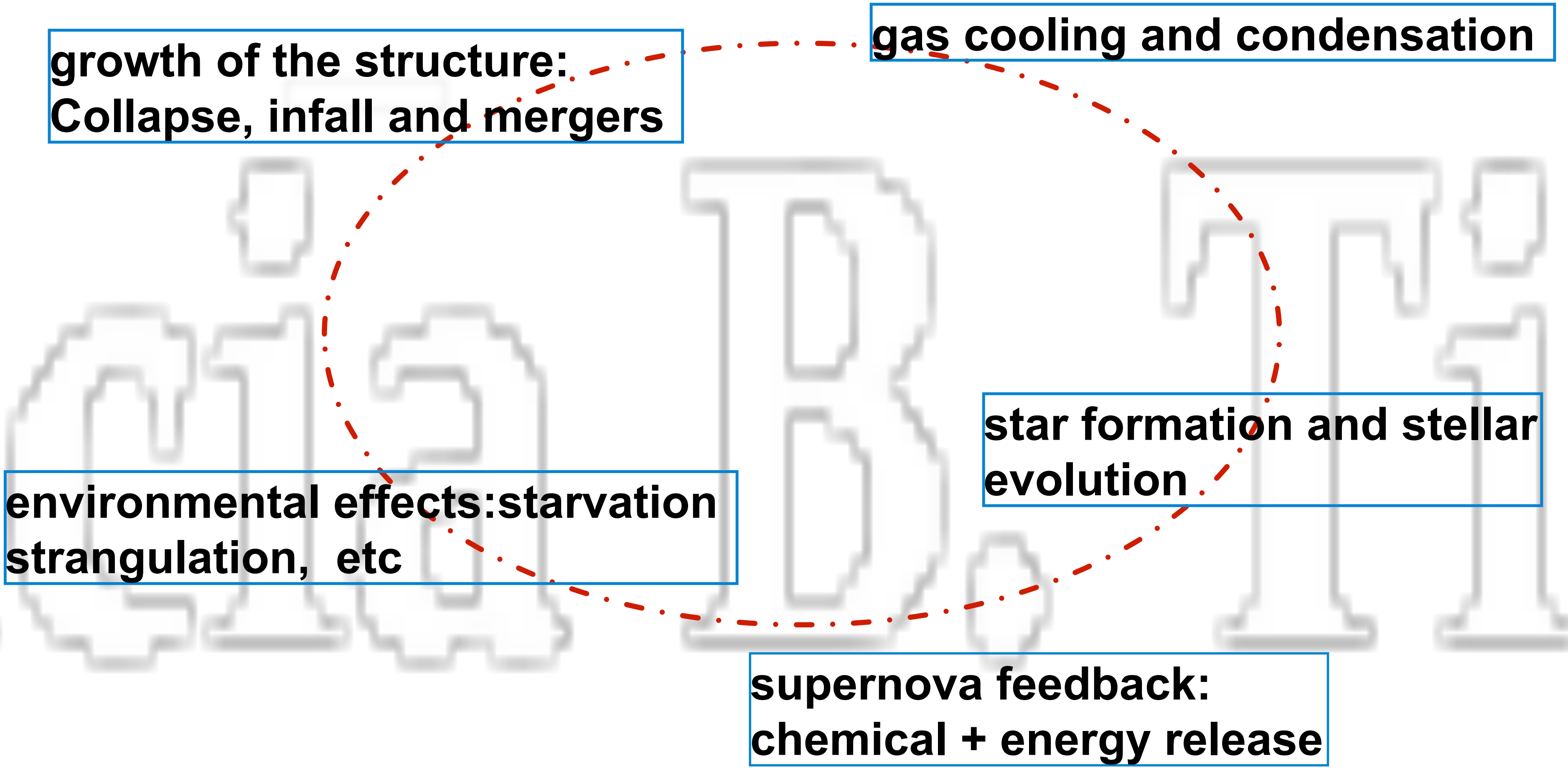
STRUCTURE FORMATION

- Dark matter is: ‘uniform’ on the largest scales,
  ‘filamentary’ on intermediate scales,
  ‘clumpy’ on small scales.

- Large-scale cosmic web grows by infall into and then flow along the filaments.

- Halos grow by inhomogeneous infall and merging at the nodes of the cosmic web.

GALAXY FORMATION



growth of the structure:
Collapse, infall and mergers

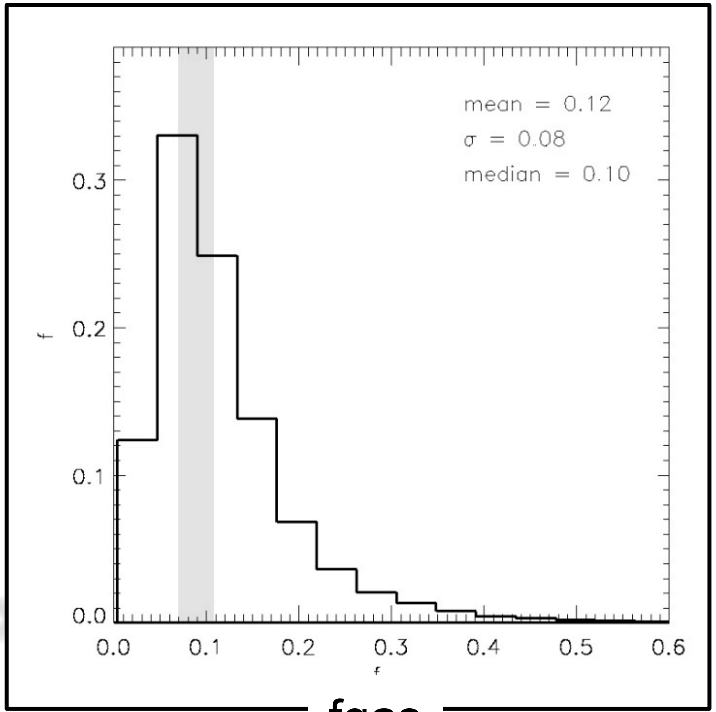
gas cooling and condensation

star formation and stellar evolution

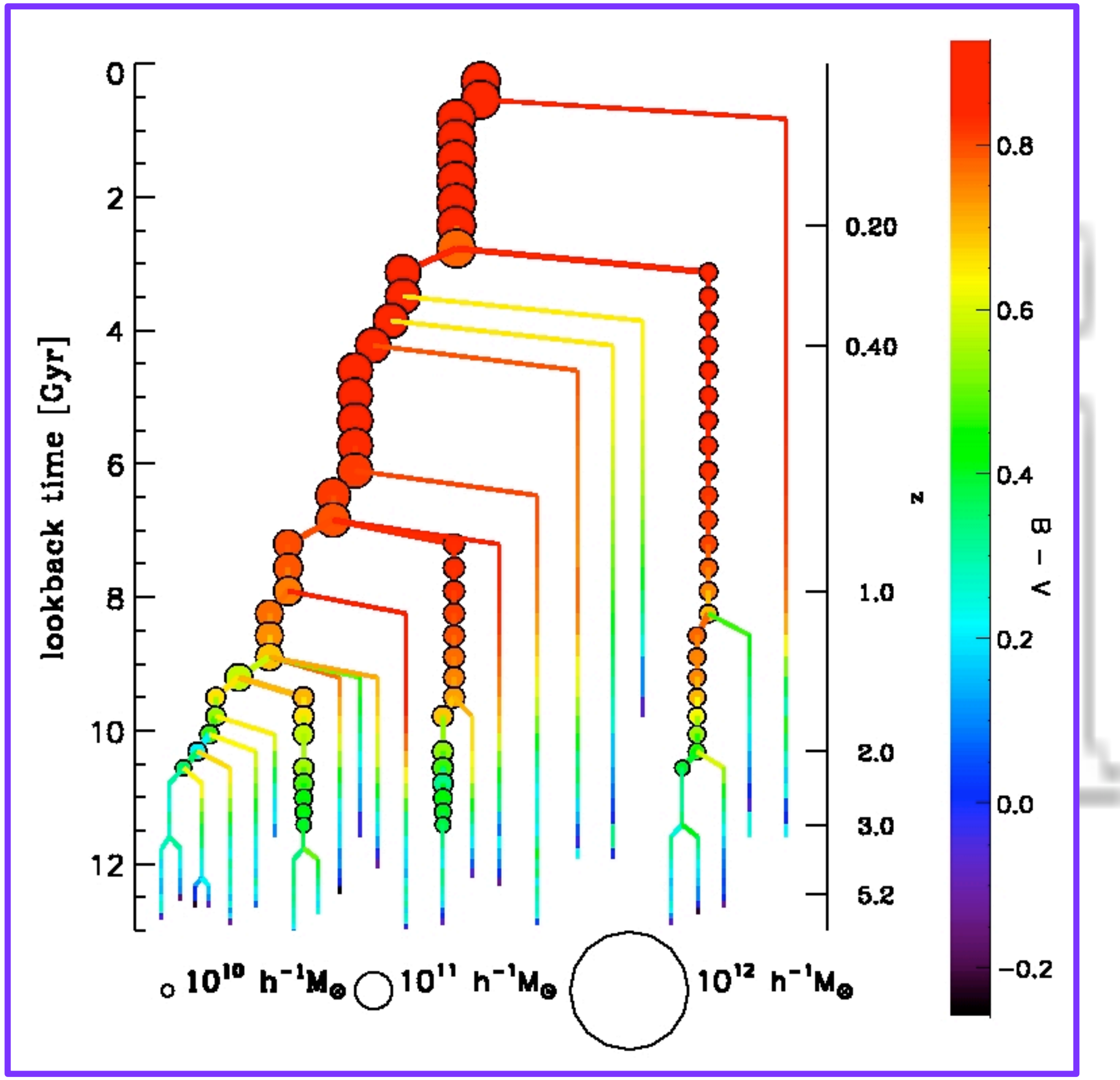
supernova feedback:
chemical + energy release

environmental effects:starvation
strangulation, etc

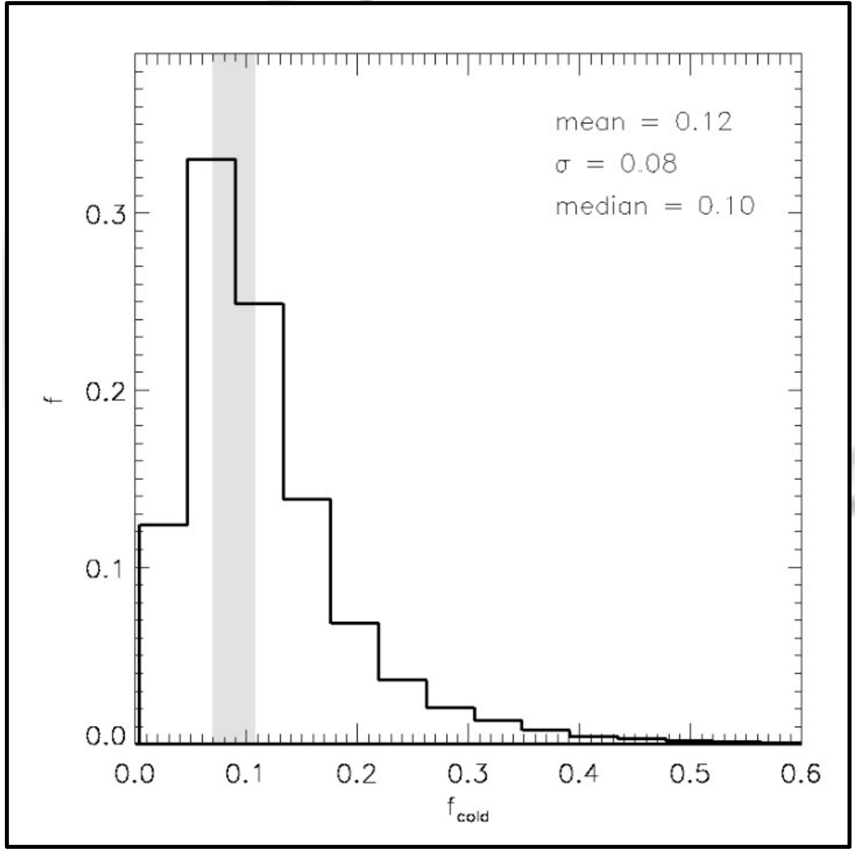
The hierarchical building up of the structure

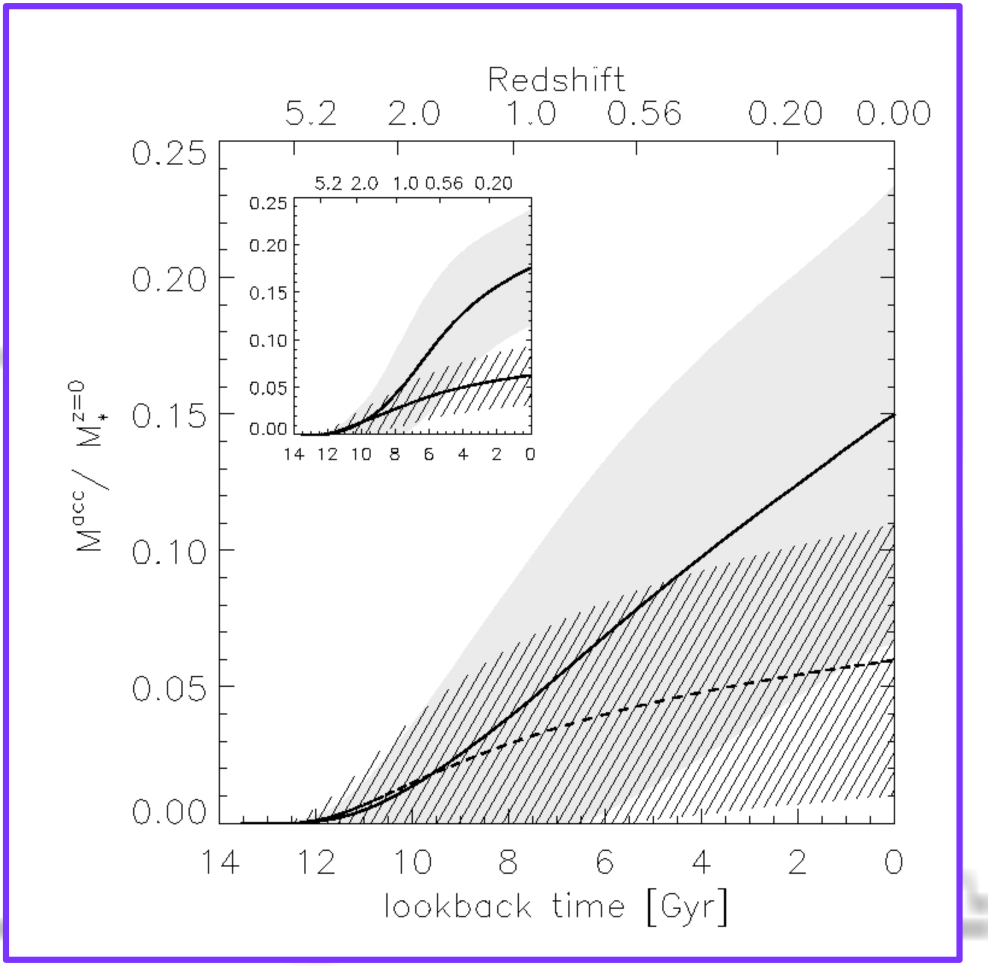


fgas



For a typical Milky Way galaxy there is an important spread in the accretion histories.





De Rossi et al. 2009

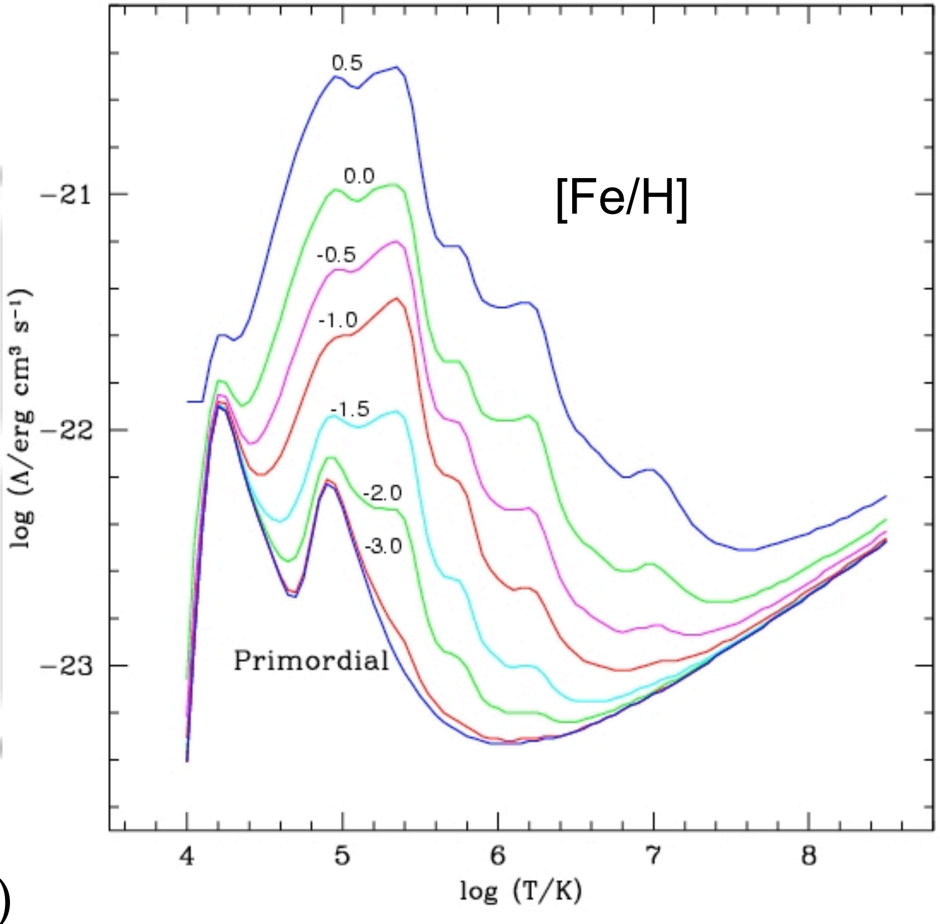
MAIN PHYSICAL PROCESS MODELLED IN COSMOLOGICAL SIMULATIONS

Gas cooling

- Gas cooling is modeled in a similar way by different authors, including AMR (e.g.Rassiera & Tyssier 2006) or Sph (e.g. Mosconi et al. 2001) codes.

- It depends on temperature and metallicity.

New codes follow the cooling of each elements (e.g. Wiersma, Schaye & Smith 2009)



Star formation

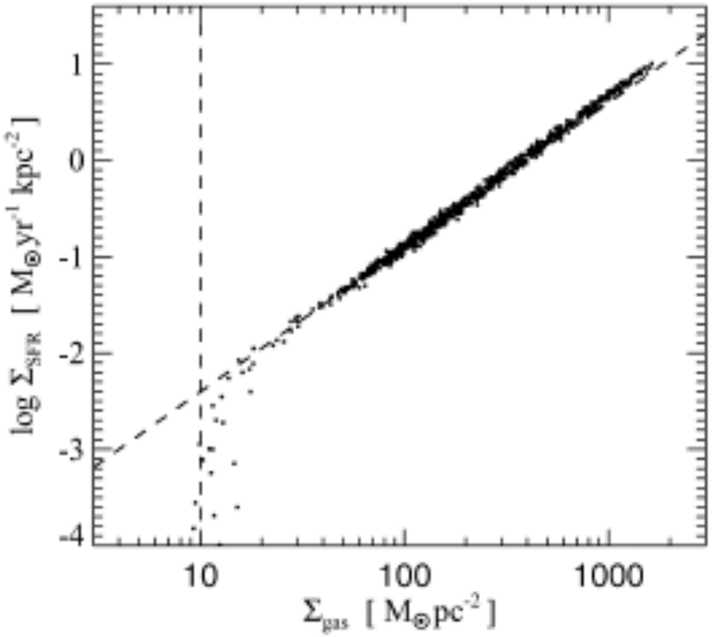
- Cold and dense gas in a collapsing cloud is considered to be suitable for star formation :
  - ★ $\rho > \rho_{crit}$ (assure that star formation takes place in substructure)
  - ★ nH > nmin =0.1cm ^{3}
  - ★ $t > t_{crit}$ (cold gas; ~15000K)
  - ★ convergent flow

The rate of SF is modeled to follow the Schmidt law (1959) such as

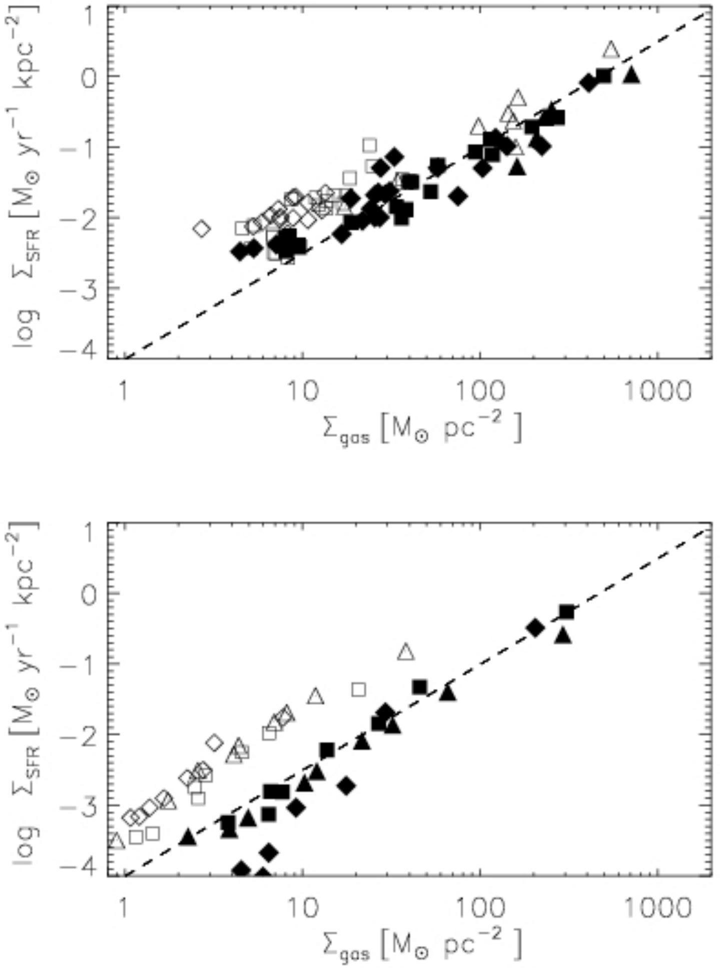
$$d\rho_{stars}/dt=\rho^{3/2}{}_{gas}$$

Star formation

$$\Sigma_{\mathrm{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\mathrm{gas}}}{1\,\mathrm{M_\odot\,pc^{-2}}} \right)^{1.4 \pm 0.15} \mathrm{M_\odot\,yr^{-1}\,kpc^{-2}}. \tag{12}$$

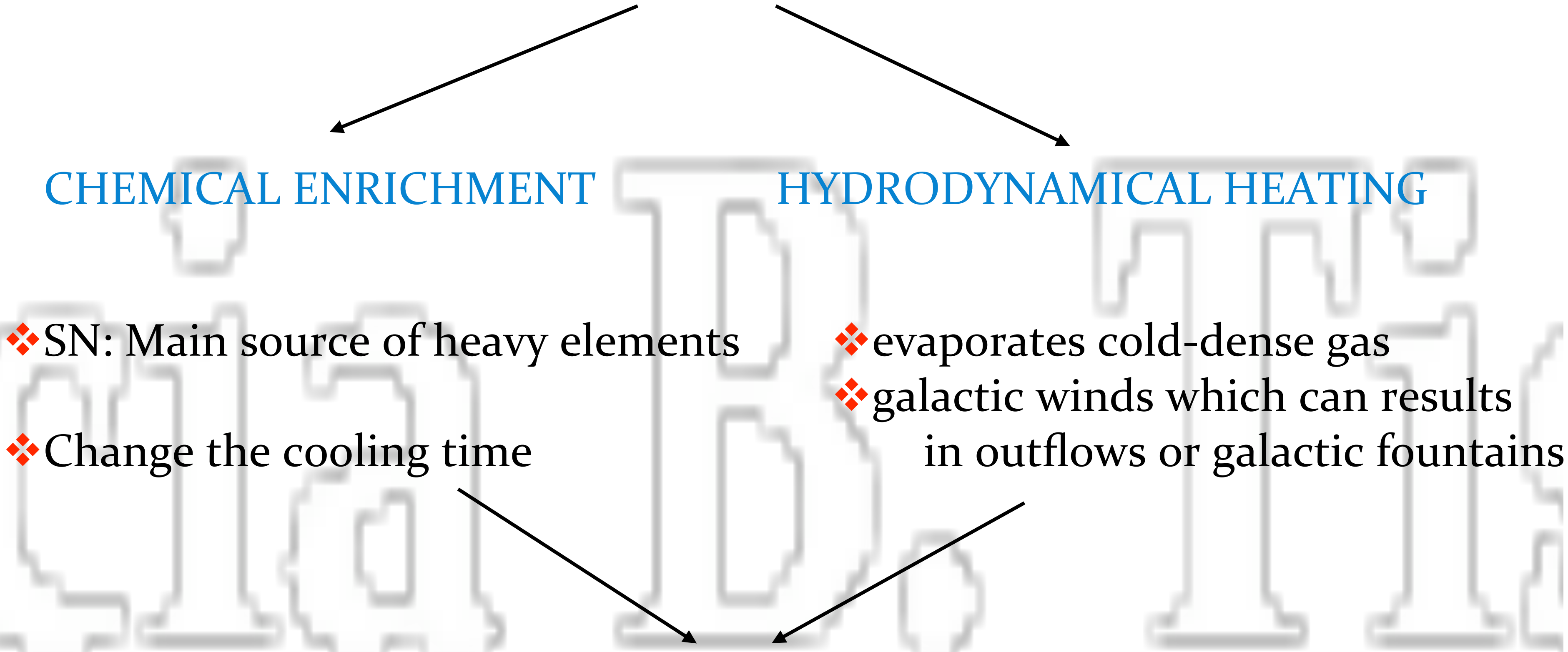


Springel & Hernquist 2003



Scannapieco et al. 2006

Supernova Feedback



CHEMICAL ENRICHMENT

HYDRODYNAMICAL HEATING

- SN: Main source of heavy elements
- Change the cooling time

- evaporates cold-dense gas
- galactic winds which can results in outflows or galactic fountains

Regulates the star formation activity and enriches the ISM and IGM
Affects the gas dynamics: disc formation

CHEMICAL FEEDBACK

First attempts to introduce chemical feedback in SPH simulations of MilkyWay type galaxies:

Steinmetz & Muller (1994)→ SNII; global metallicity Z
Raiteri et al. (1996; also Berczik 1999)→ SNII & SNIa; Fe & H

Mosconi, Tissera, Lambas & Cora. (2001): SNII & SNIa, Eth.
Lia, Portinari & Carraro (2002):detailed SE; diffusion
Kawata & Gibson (2003):SNII, SNIa,IS; Eth +Ekin
Springel & Hernquist (2003): Z + Twophases +Ekin
Kobayashi (2004; et al. 2006):detailedSE; Eth +Ekin
Scannapieco et al. 2005, 2006: SNII & SNIa + Multiphase+SNE
Okamoto et al. 2006: SNII+SNIa+Twophases+Ekin (+top heavy Imf)
Oppenhaimer & Dave 82006): SNII &SNIa + Twophases + Ekin
Stinson et al. (2006): SNII&SNIa + cooling off
Martinez-Serrano et al. (2008): detailedSE; diffusion

CHEMICAL FEEDBACK

Numerical space Physical space Need

Star particles ↔ Stellar populations

IMF:

SNe

long-lived stars

Type II Sne

M* > 8 Mo; typical life-times: ~ 10^6 yr

Produce most O, Si, Ca, etc

Type Ia Sne

Main source of iron (Fe)

Typical life-times: ~ Gyr

YIELDS

Intermediate mass stars

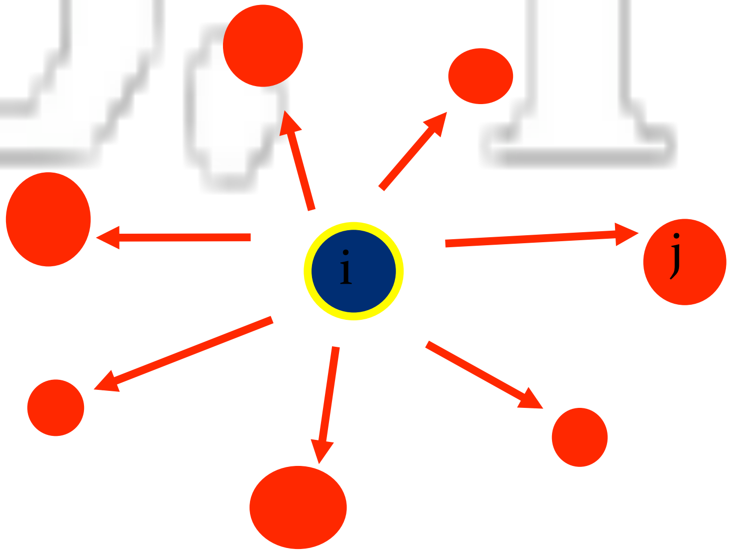
CHEMICAL FEEDBACK

When SN explosions take place, they distribute metals according to the SPH technique (Mosconi et al. 2001). For a given chemical element x at a particle i,

$$Mx_i = \sum_j m_{j/}\rho_j \, Mx_i \;\; W(r_{ij},h_{ij})$$

Each neigbhour will receive

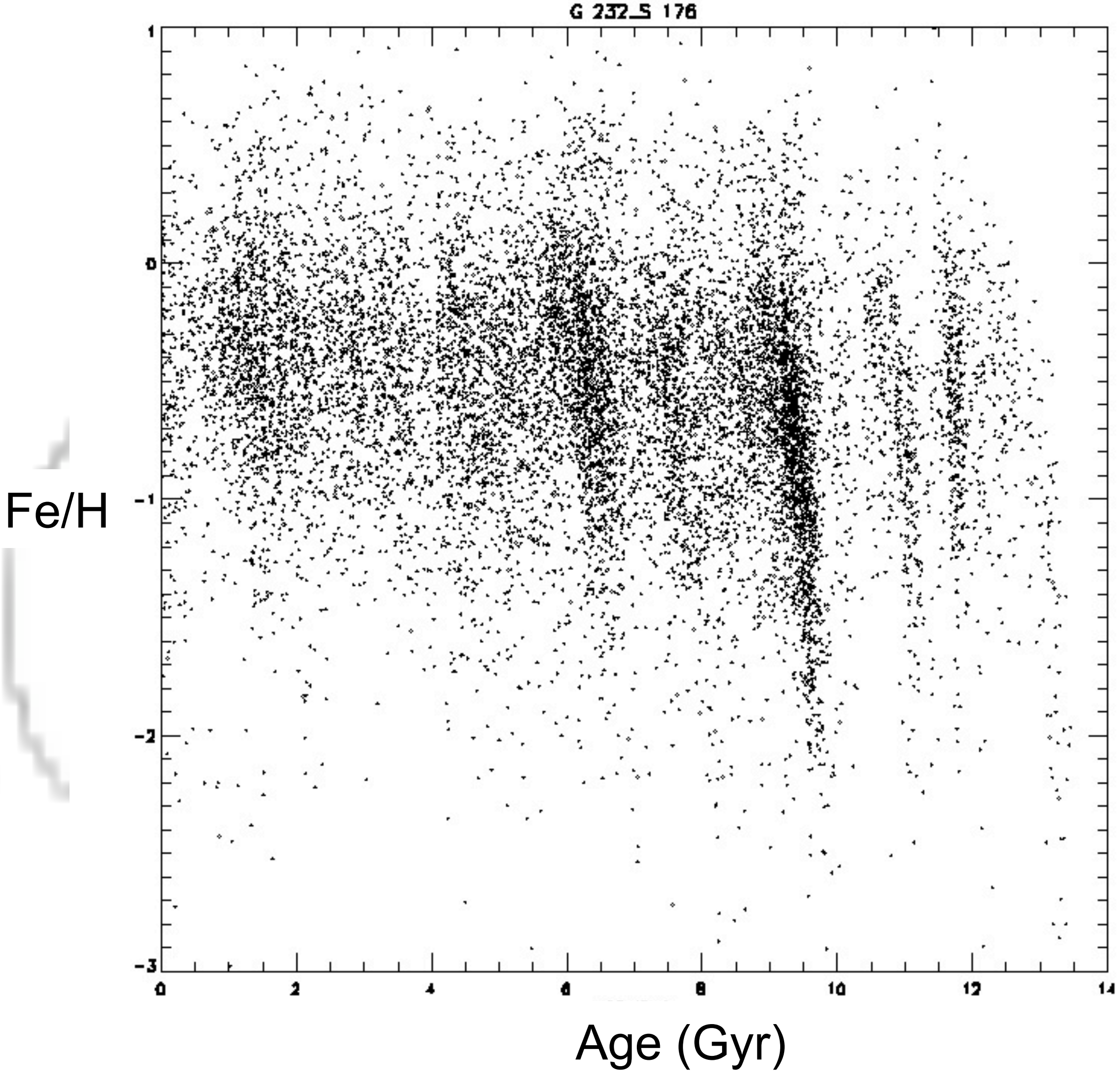
$$Mx_j = m_{j/}\rho_j \, Mx_i \;\; W(r_{ij},h_{ij})$$



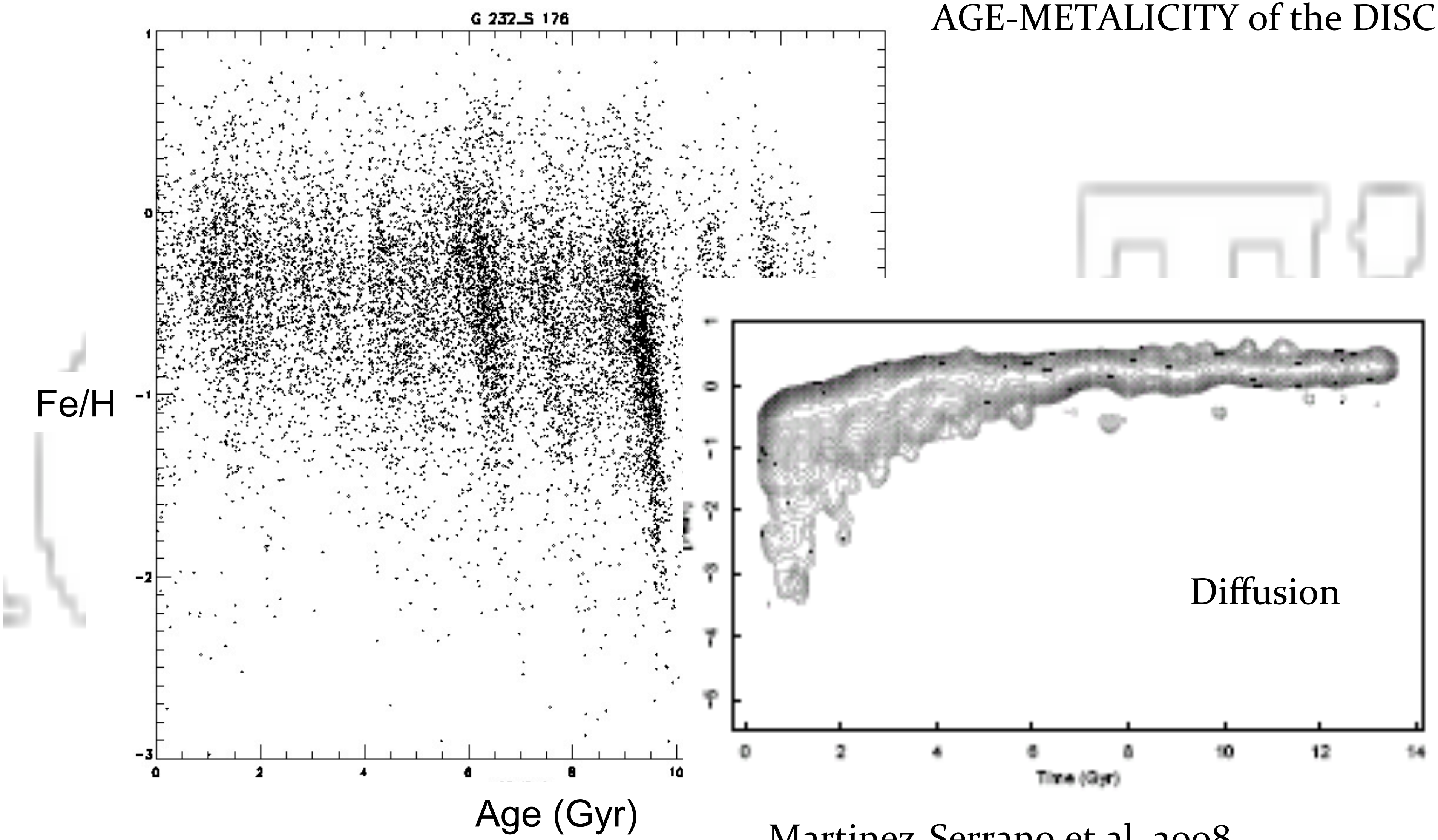
Exploding star particle

Gaseous neighbours

AGE-METALICITY of the DISC



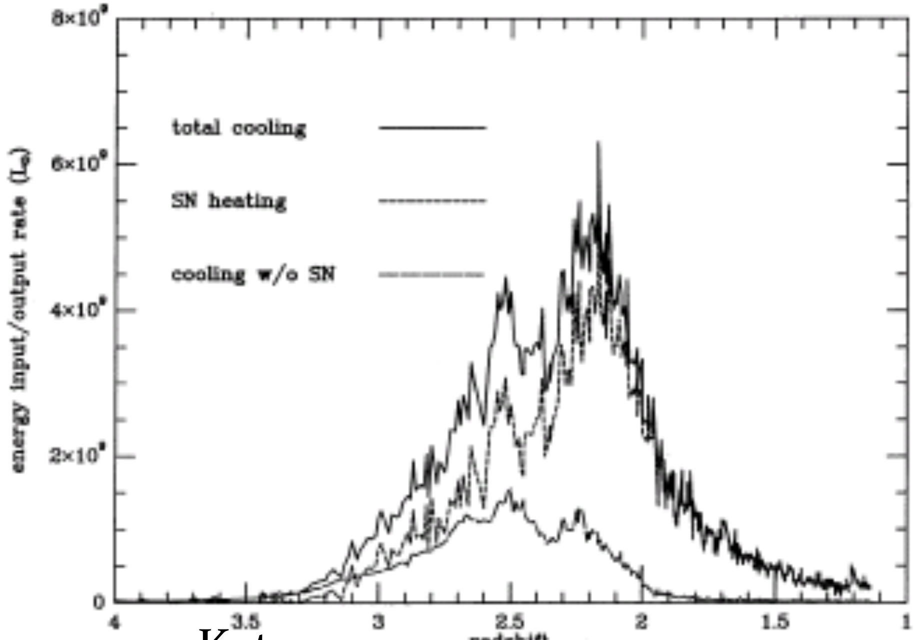
AGE-METALICITY of the DISC



Martinez-Serrano et al. 2008

ENERGY FEEDBACK

KATZ



Katz 1992

FIG. 6a

Thermal feedback:

Injection of SN energy directly into the ISM directly →

it is radiated away very efficiently

The energy is injected mainly in high density regions with short cooling times compared to the typical time step of integration:

There is no time for this energy to modify the dynamics.

ENERGY FEEDBACK

First ad hoc solution was kicking particles: a fraction of SN energy is dumped as thermal energy and the remaining one as kinetic energy as proposed by Navarro & White (1993).

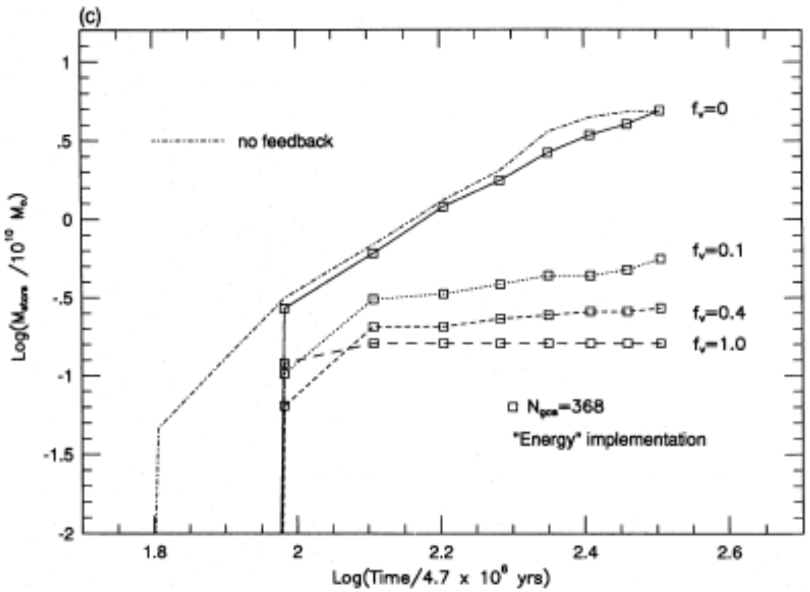


Figure 20 – *continued*

Mstar vs time

Kinetic feedback can produced strong changes .

Drawback: ad hoc parameters

A given direction and with a given velocity have to be adopted

Navarro & White 1993

ENERGY FEEDBACK

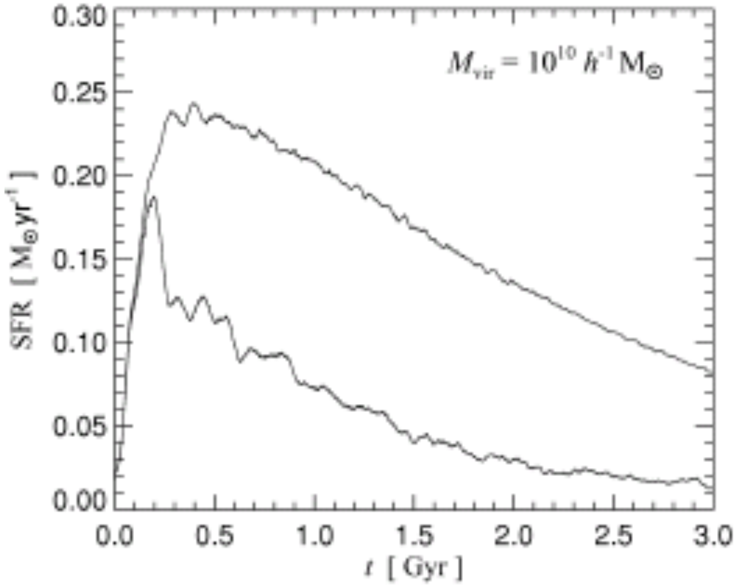
Solution: resolve the relevant scales to take into account the multiphase characters of the interstellar medium, where gas co-exists in a wide range of temperature and density states (e.g. Cox & Smith 1974; McKee & Ostriker 1977; Efstathiou 2000).

Instead **subgrid models** **are** designed to follow analytically the physics within a gas cloud represented by a particle and then, to mimic the effects it should have on larger resolved scales.

ENERGY FEEDBACK AND MULTIPHASE MODEL

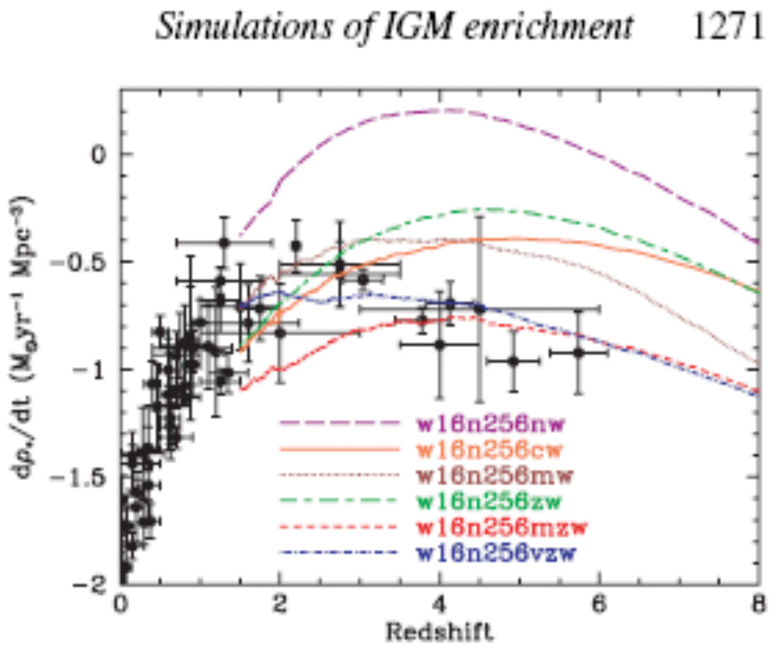
Based on Yepes et al. (1997), Springel & Hernquist (2003) developed a two-phase within SPH, so that each particle has two phases (cold and hot) within it.

SH03: regulates the star formation activity during quiescent phases of evolution BUT it could not drive galactic winds.



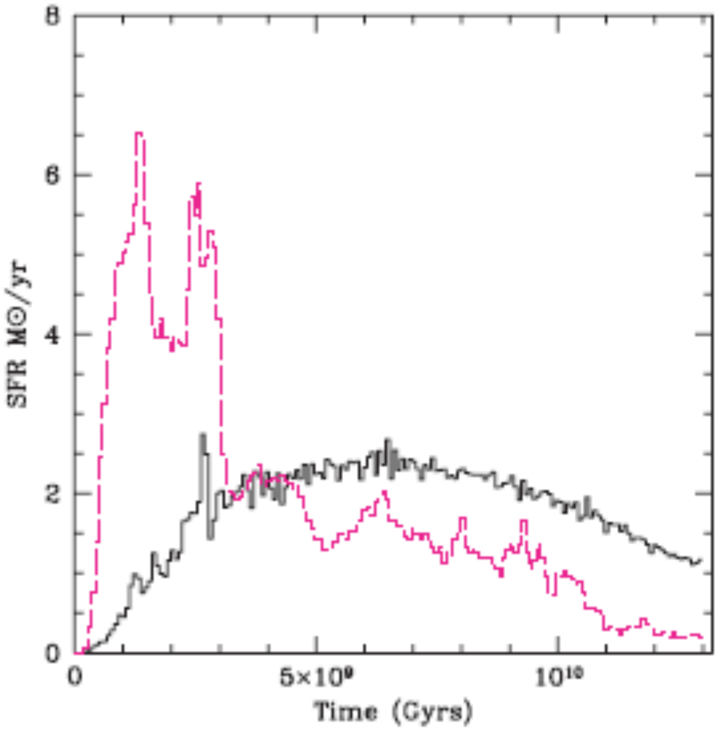
SH03 came back to the kinetic feedback and kicked particles (e.g. Navarro & White 1993).

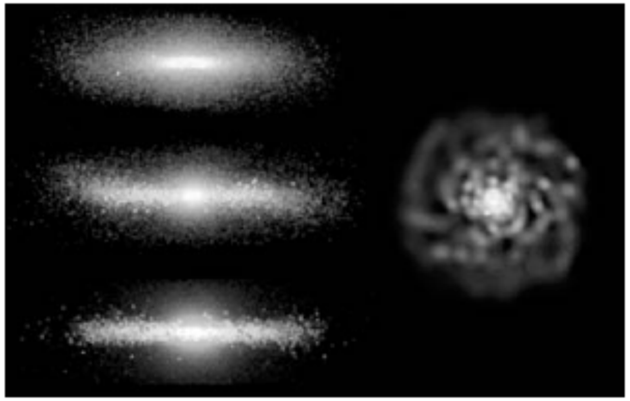
Important improvements have been made from this simple model of kinetic energy by trying to adjust the parameters using observationally motivated constrains (see also Okamoto et al. 2005; Kobayashi et al. 2006).



One important improvement is to add chemical evolution → metal loaded winds can be triggered.

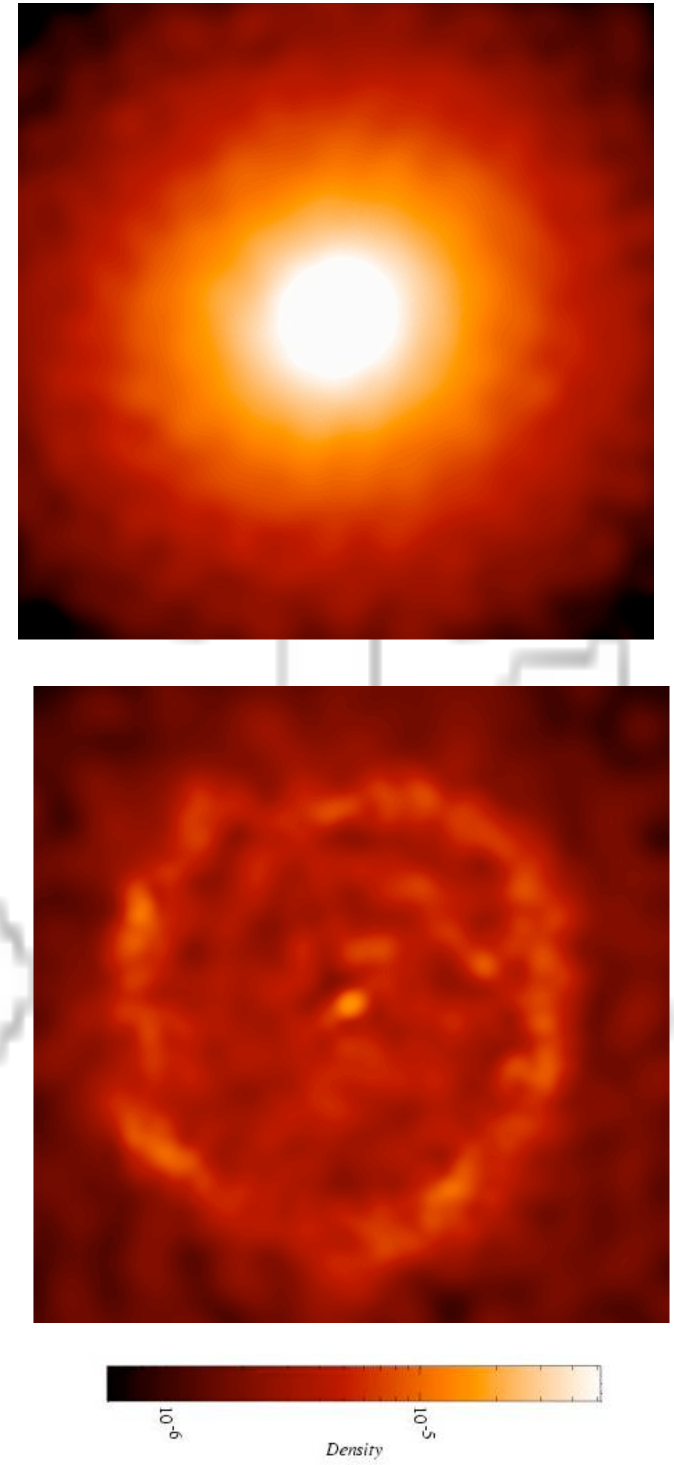
Stinson et al. (2006), followed this model and extended by using the blast wave solution of Chevalier (1974) and McKee & Ostriker (1977) to estimate the maximum radius and the time applied to turning off the cooling (Gerristsen 1997 and Thacker & Couchman 2000).





Multiphase Model + SN Feedback

Scannapieco, Tissera, White, Springel 2006



- ❖Multiphase medium described by an entropy based model.

- ❖A self-regulated feedback cycle between cold and dense environments and diffuse and hot environments.

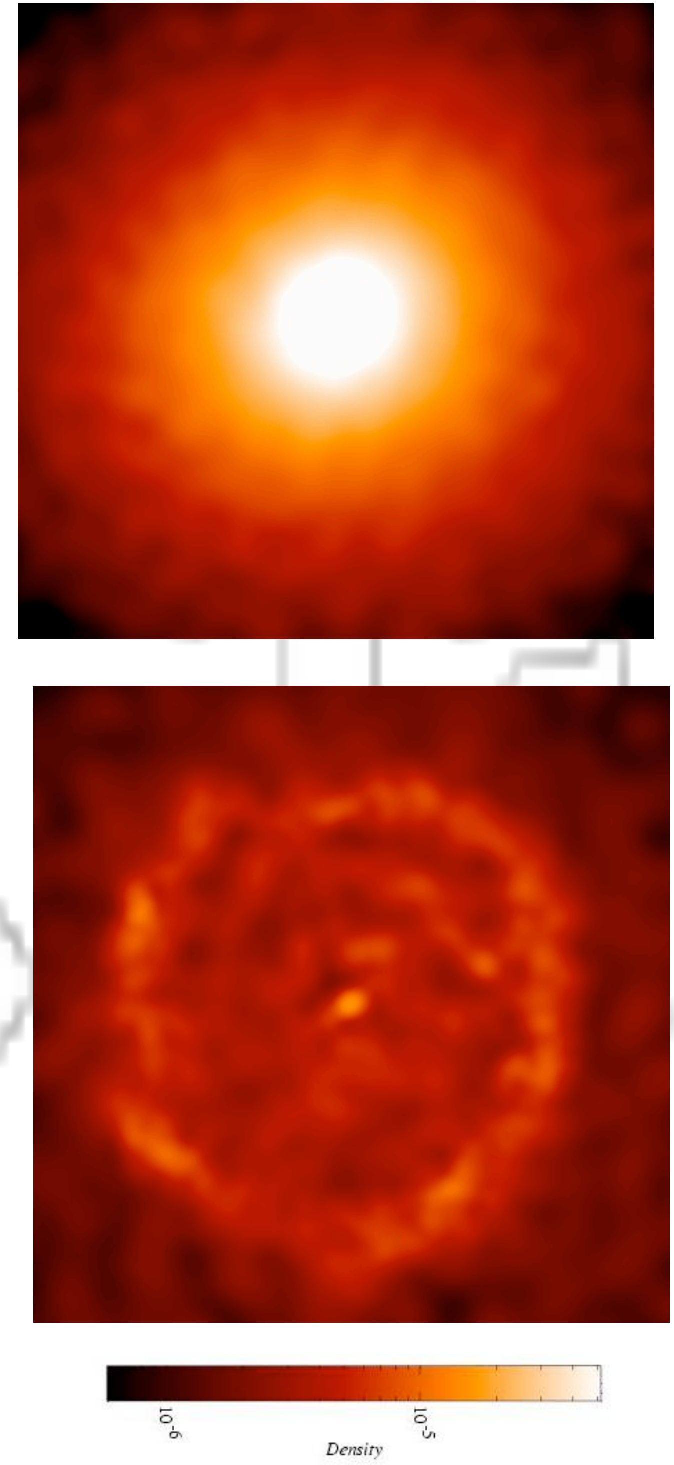
- ❖Galactic winds are naturally generated with a strength that reflects the potential well of the system.

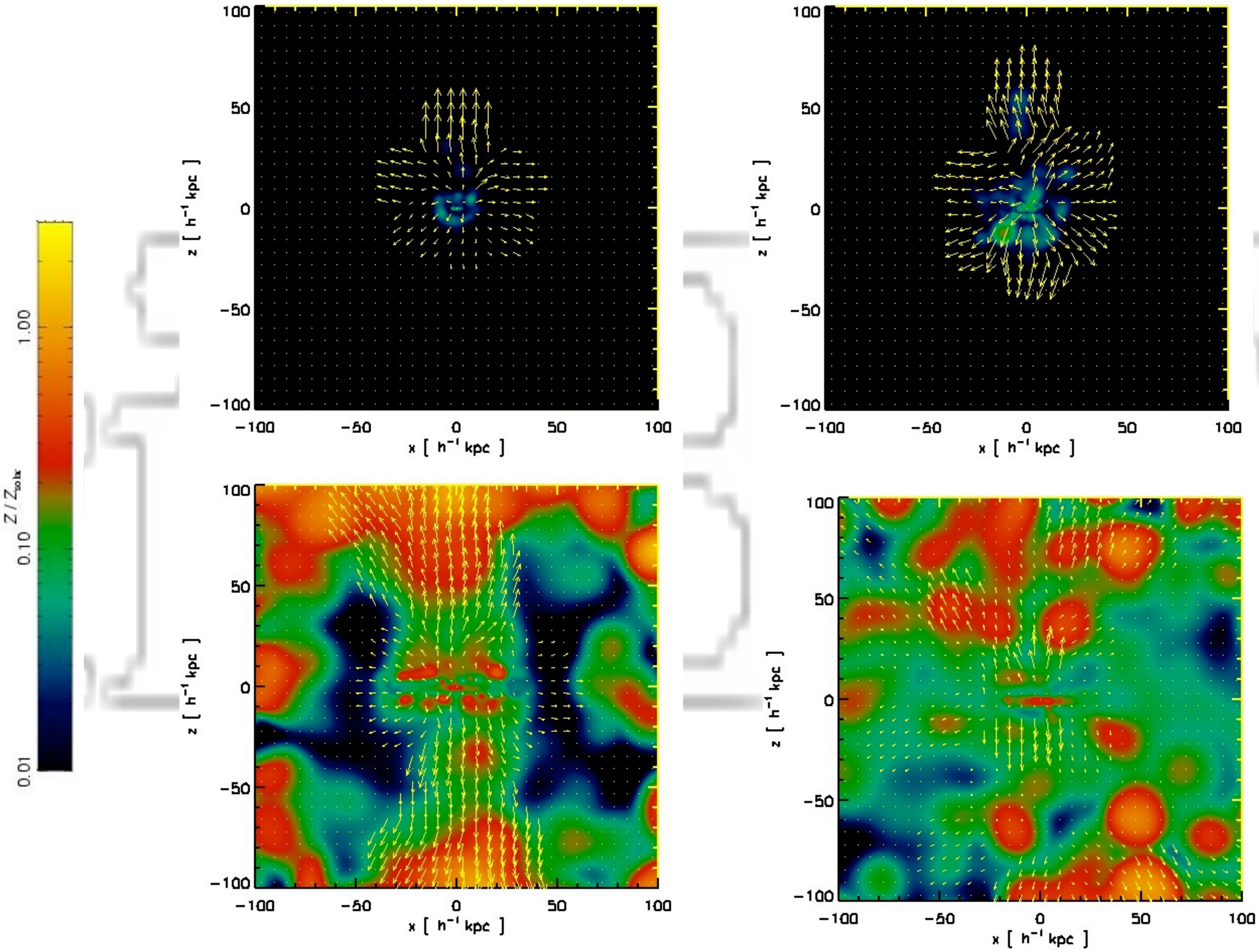
Multiphase Model + SN Feedback

There is a problem related to the SPH : limited ability to resolve steep density gradients (Shapiro et al. 1996; Pearce et al. 1999):

- **The evaporation of low mass clumps of dense gas artificially evaporates.**
- **The artificially enhancement of radiative cooling in the diffuse gas nearby dense ones.**

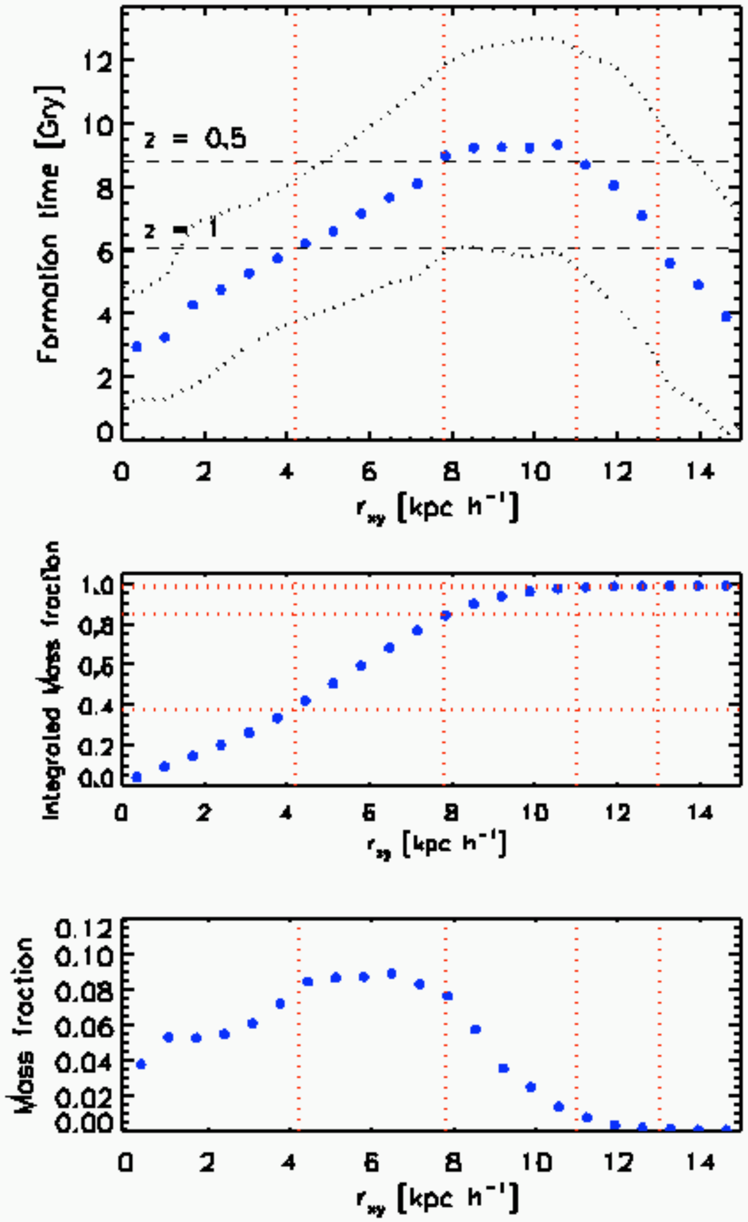
A self-regulated feedback cycle between cold and dense environments and diffuse and hot environments.



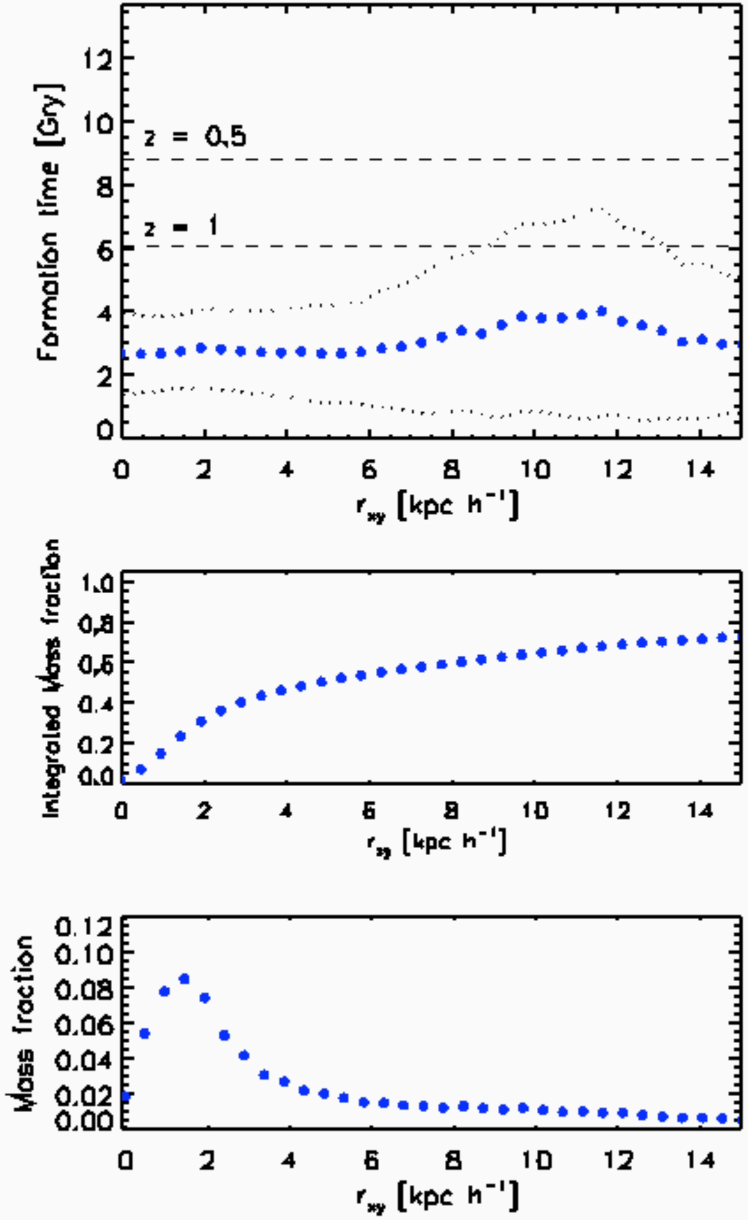


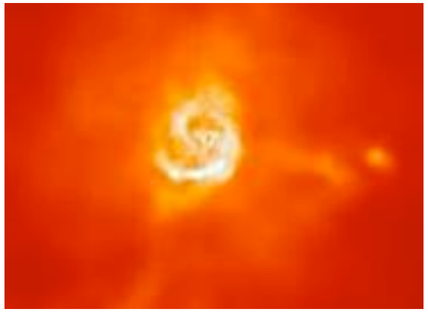
Scannapieco et al. 2006

disc component

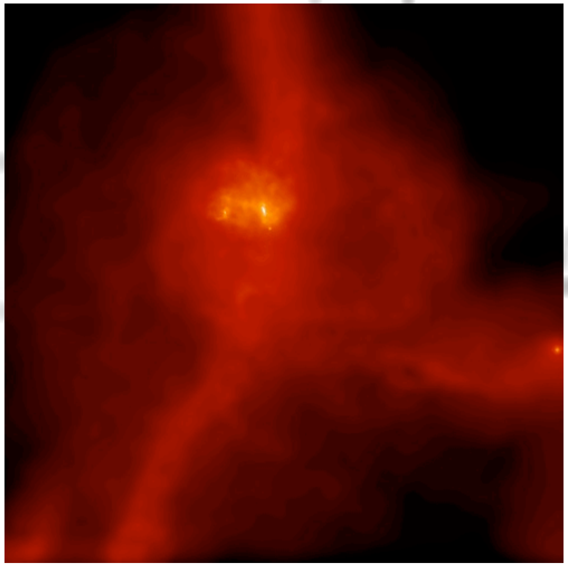


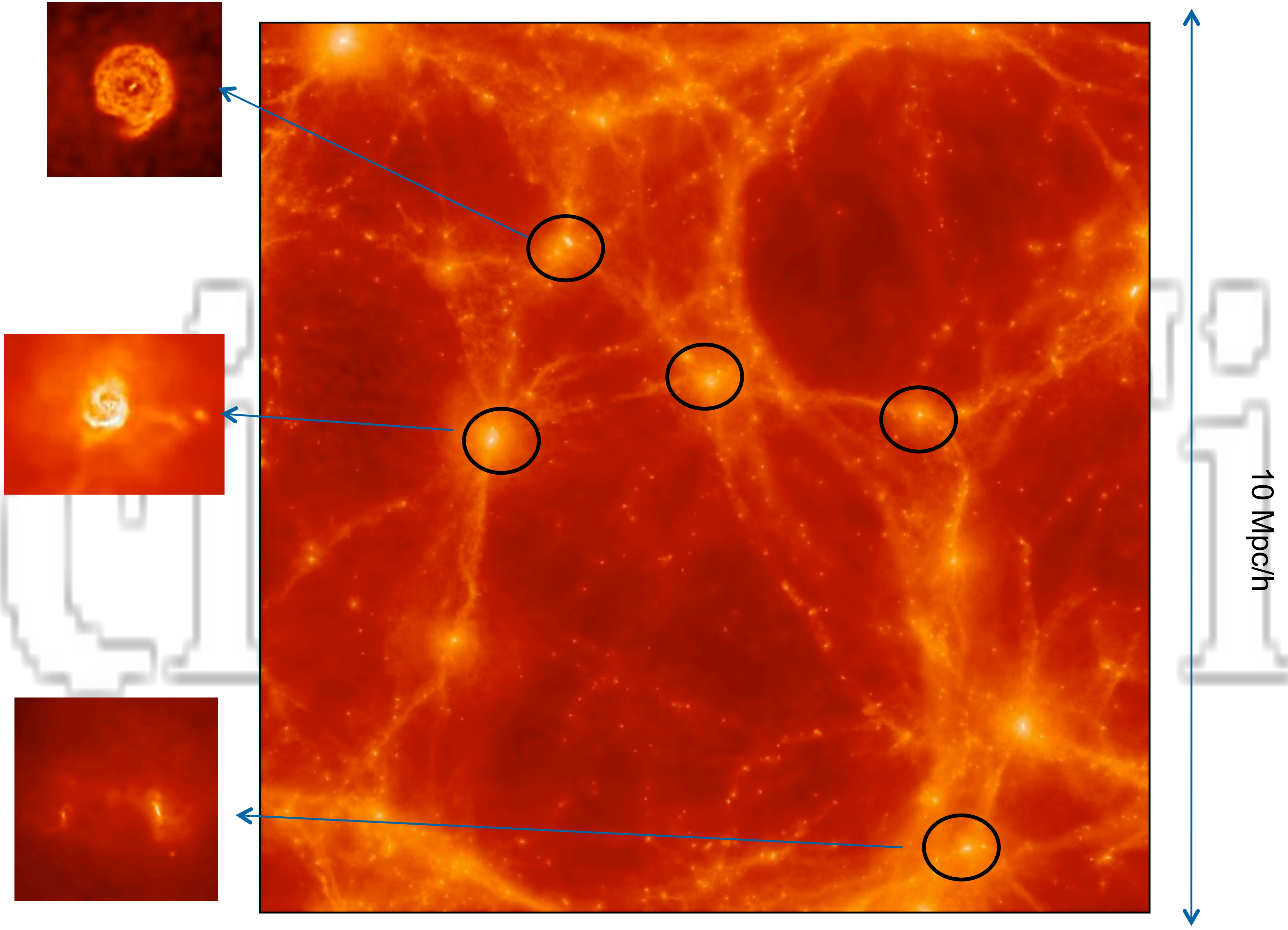
Spheroidal component





RESULTS




10 Mpc/h

Disc Formation

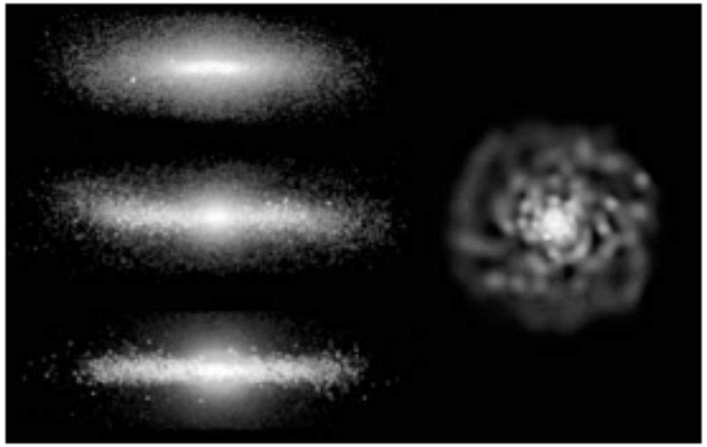
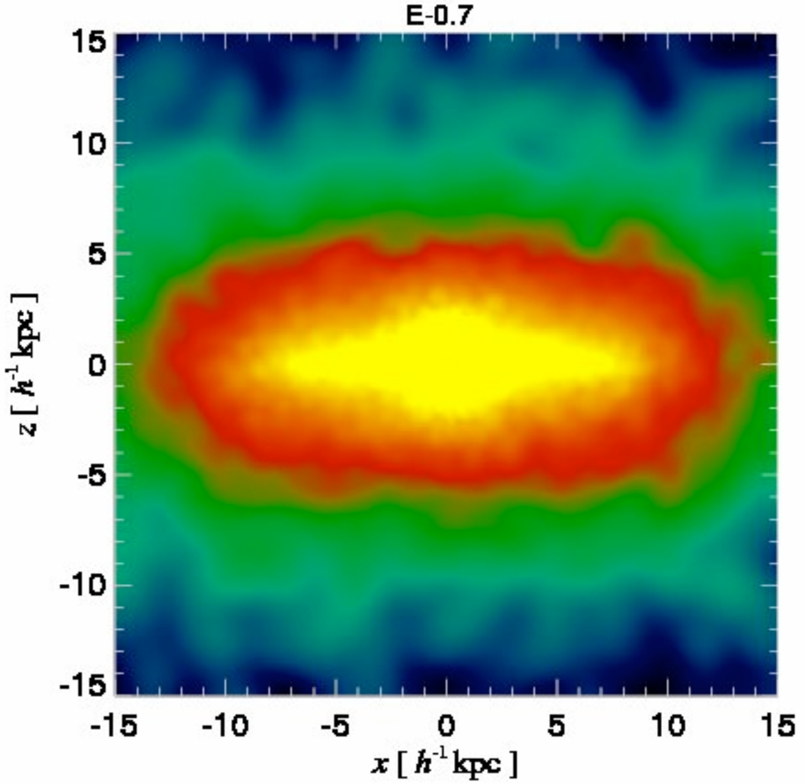


Figure 6. Left-hand panel: brightness maps of the edge-on discs of (from top to bottom) GAL1, MW1 and DWF1 at $z = 0$. Each star particle in the simulations has been weighted by its age-dependent bolometric luminosity. Right-hand panel: the face-on surface density of the gas for DWF1 at $z = 0$. Each frame is 30 kpc across.

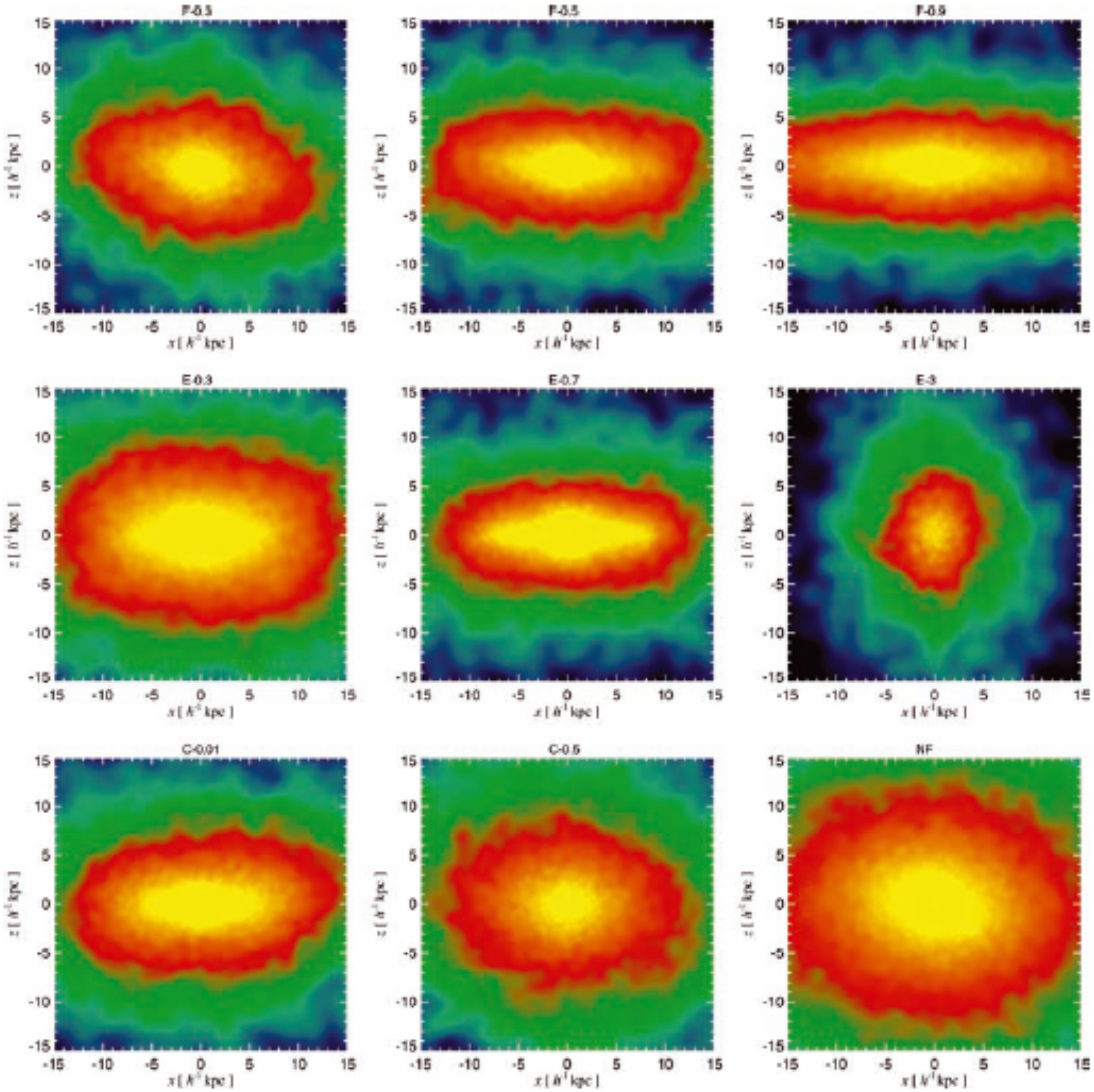
Governato et al. 2007



Scannapieco et al. 2008

Special selection of initial conditions: normally galaxies are chosen not to have a recent major merger

C. Scannapieco et al.



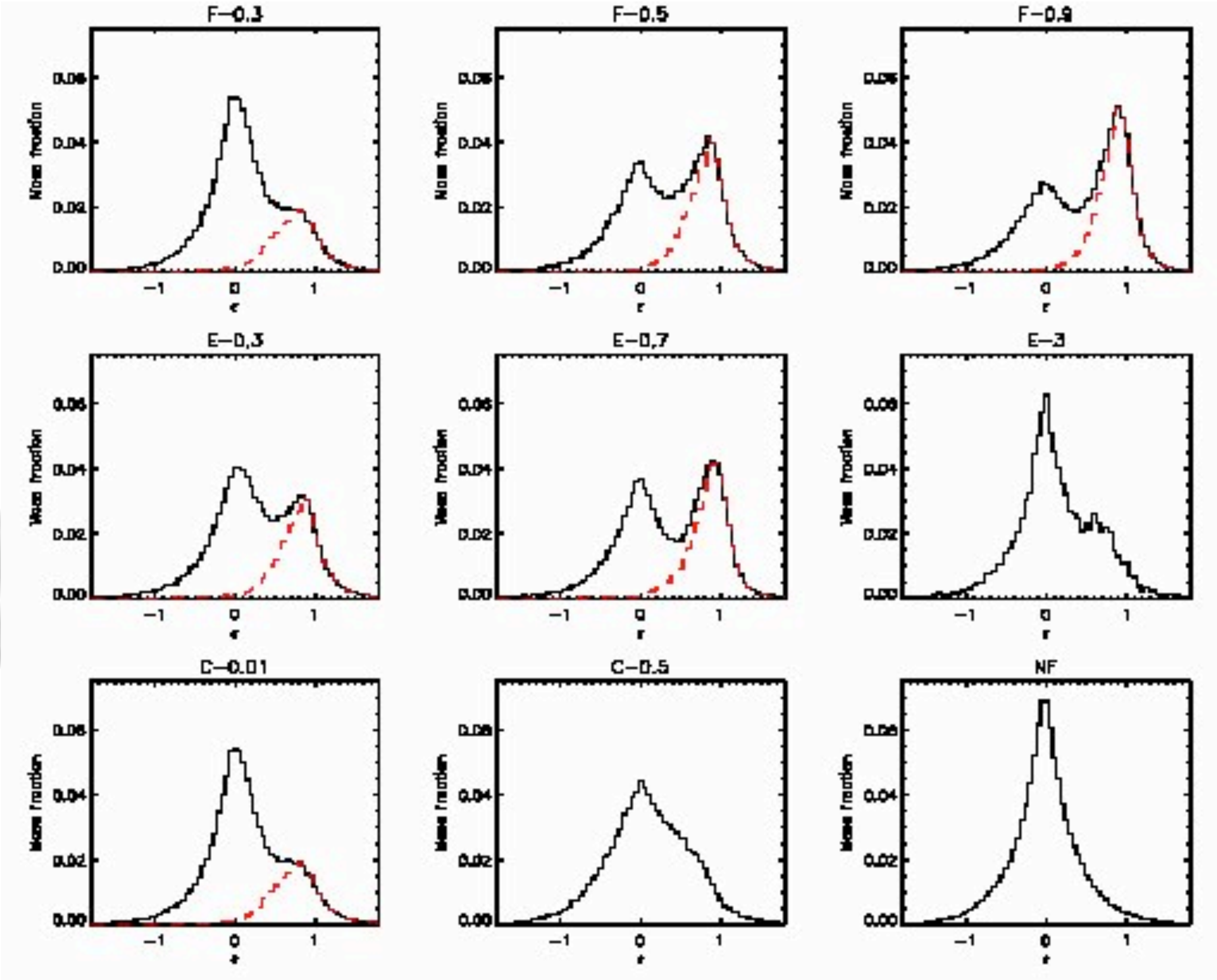
The same IC, different combination of SN and SF parameters

Scannapieco et al. 2008

The same IC, different combination of SN and SF parameters

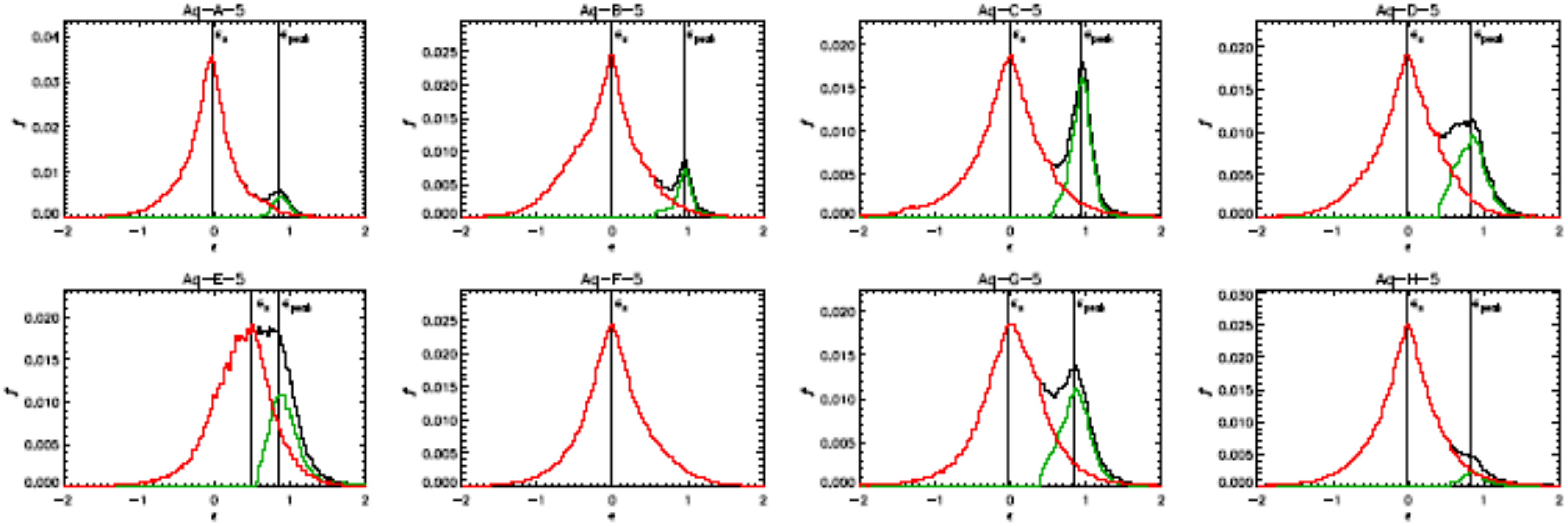
Є=Ji/Jcir

Disk → Є=1



Scannapieco et al. 2008

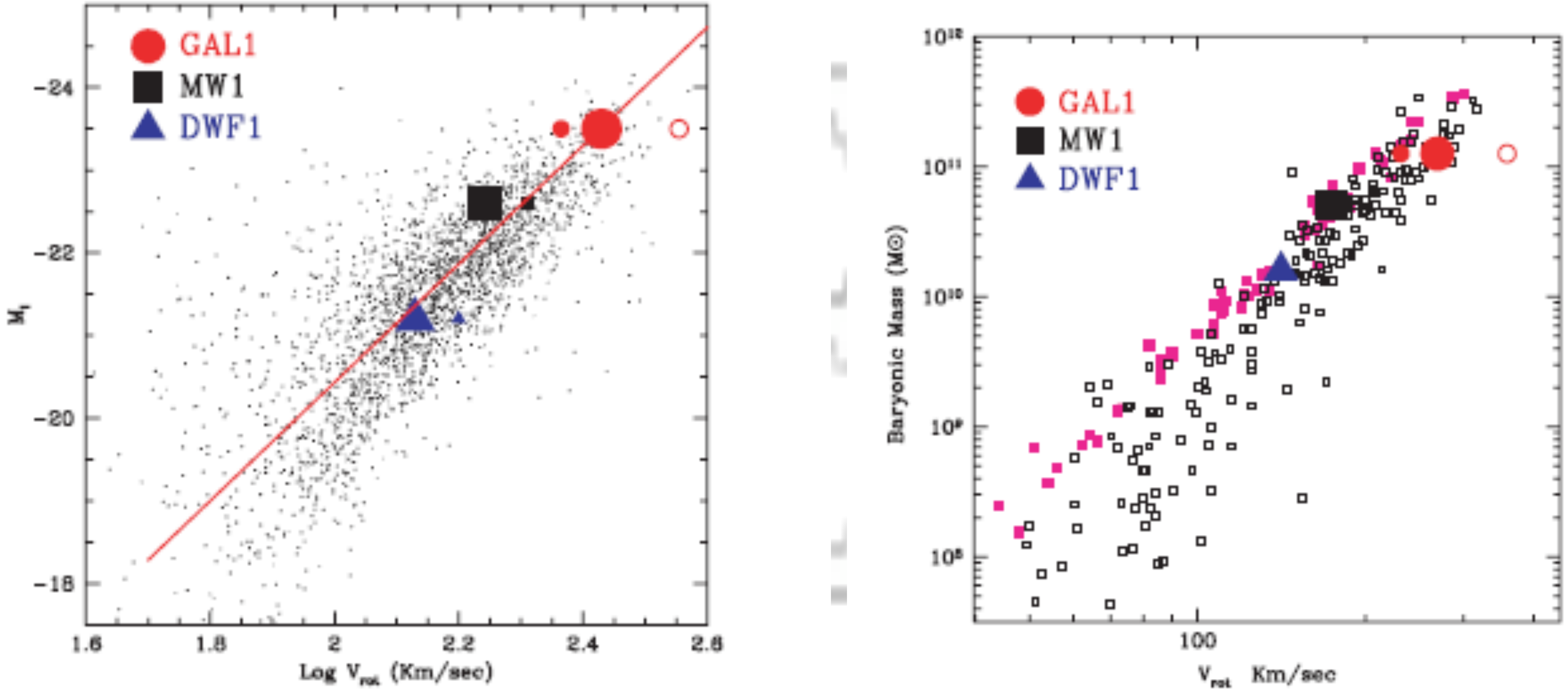
Aquarius project: Different initial conditions, similar SF and SN parameters



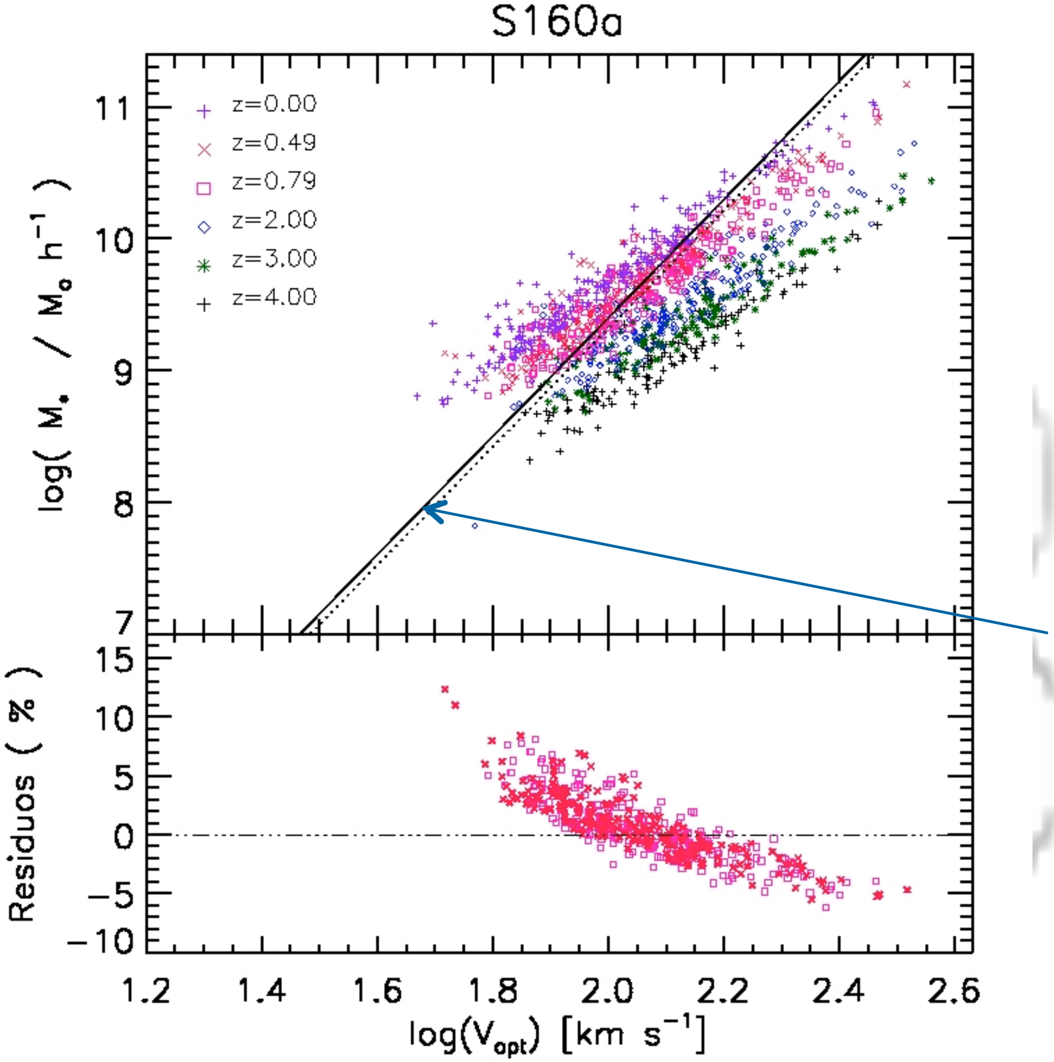
Scannapieco et al. 2009

THE COMPARISON WITH OBSERVATIONS WILL TELL WHICH IS THE BEST COMBINATION OF PARAMETERS.

Tully-Fisher relation



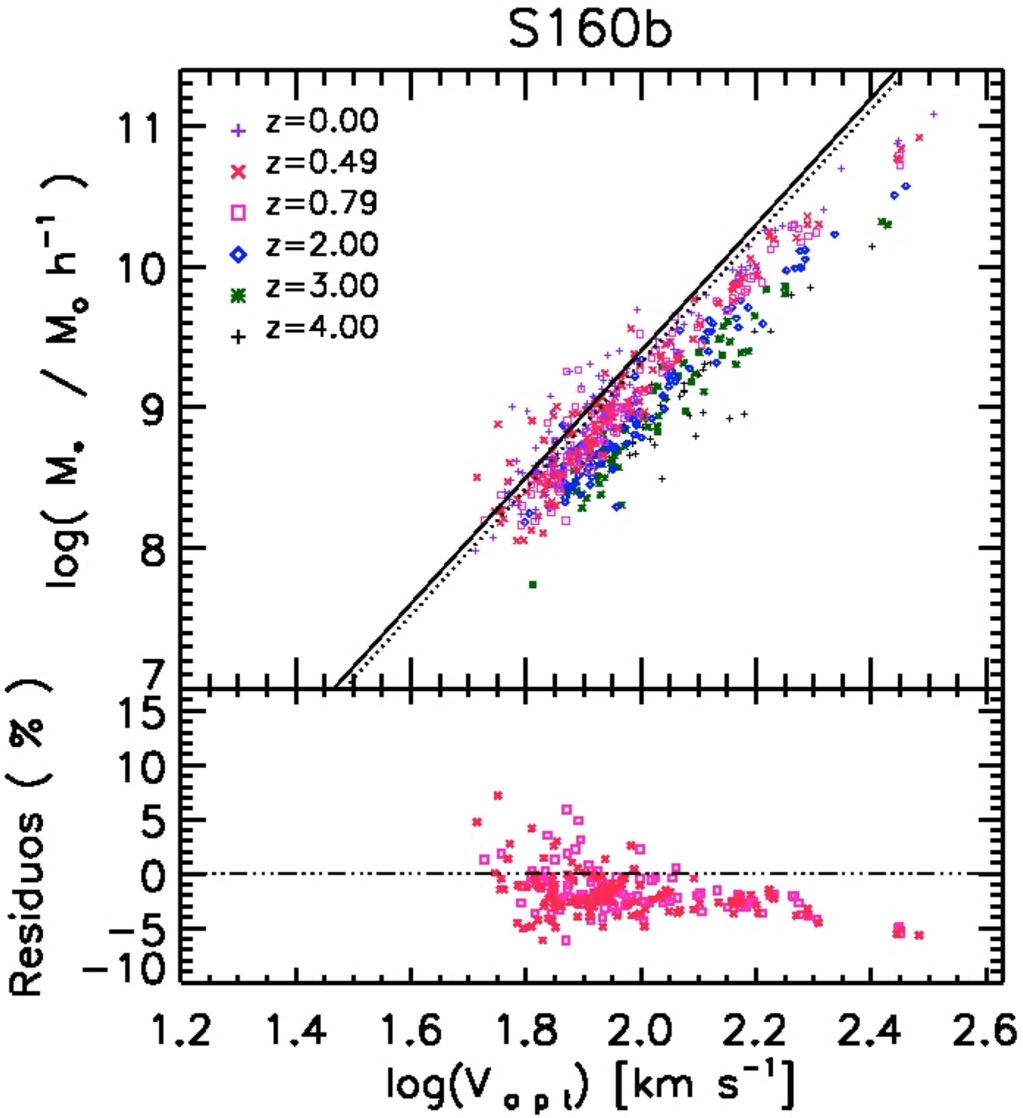
Governato et al. 2007



Simulations: Mstar ~ Vopt 3
As expected from the virial
Theorem.

Atkinson et al. 2007

De Rossi et al. 2009

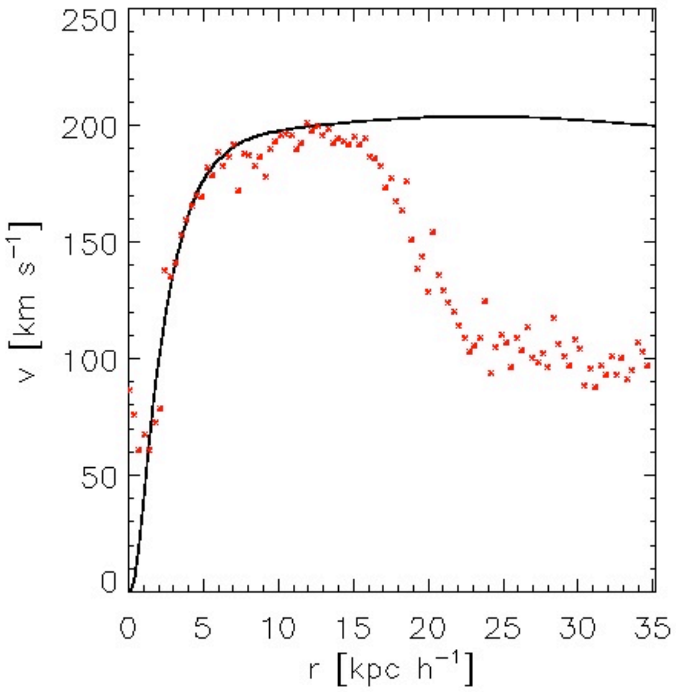


Simulations: De Rossi et al. 2009
Y=yo+ mx

z	yo	m
z=4	8.80(0.52)	3-65(0.19)
z=3	8.89 (0.42)	3.91 (0.12)
z=2	9.05 (0.21)	4.13 (0.07)
z=1	9.21 (0.17)	4.17 (0.06)
z=0.5	9.27 (0.18)	4.17 (0.06)
z=0	9.36(0.17)	4.12 (0.06)

Atkinson et al. 2007

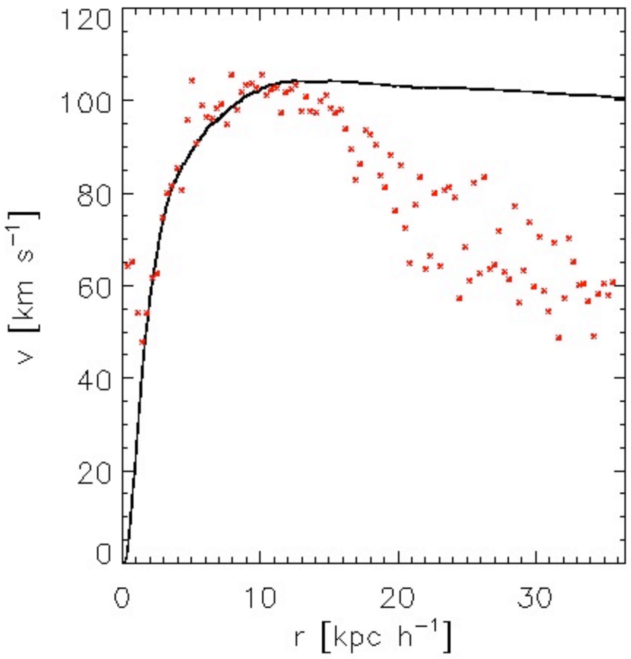
0.70-1.00	9.31	4.49
0.40-0.70	9.40	4.49



Nopt=91558

S/T_stars=0.39
D/T_stars=0.60

S/T_gas=0.15
D/T_gas=0.85

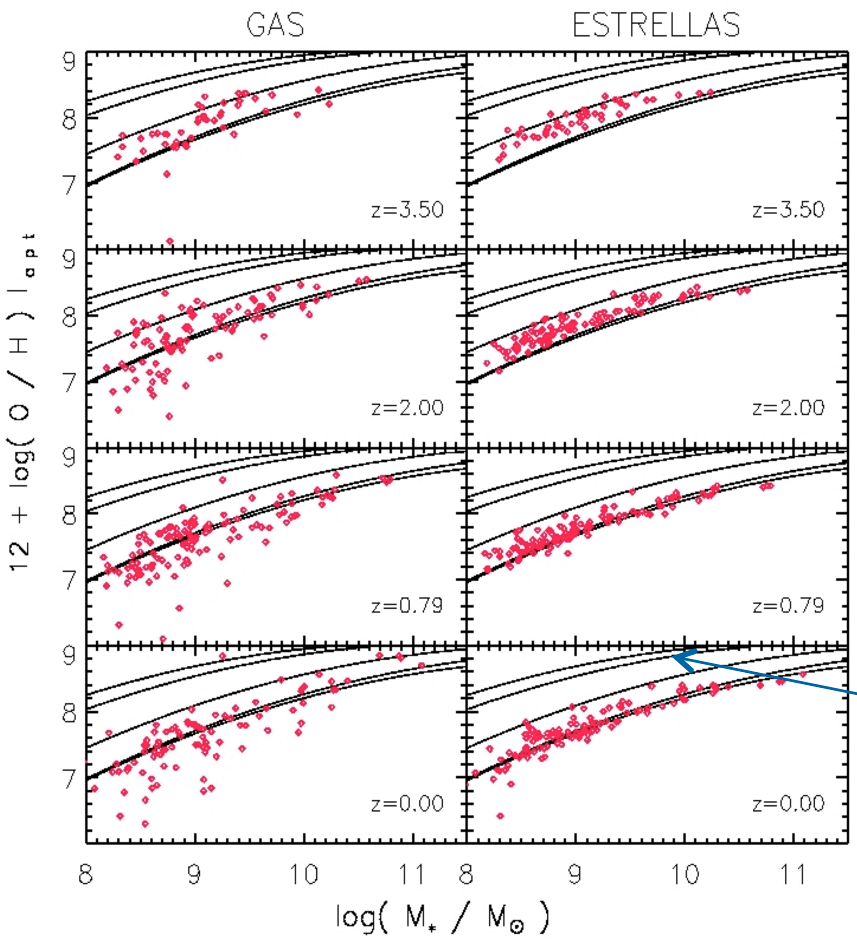


Nopt=13244

S/T_stars=0.49
D/T_stars=0.51

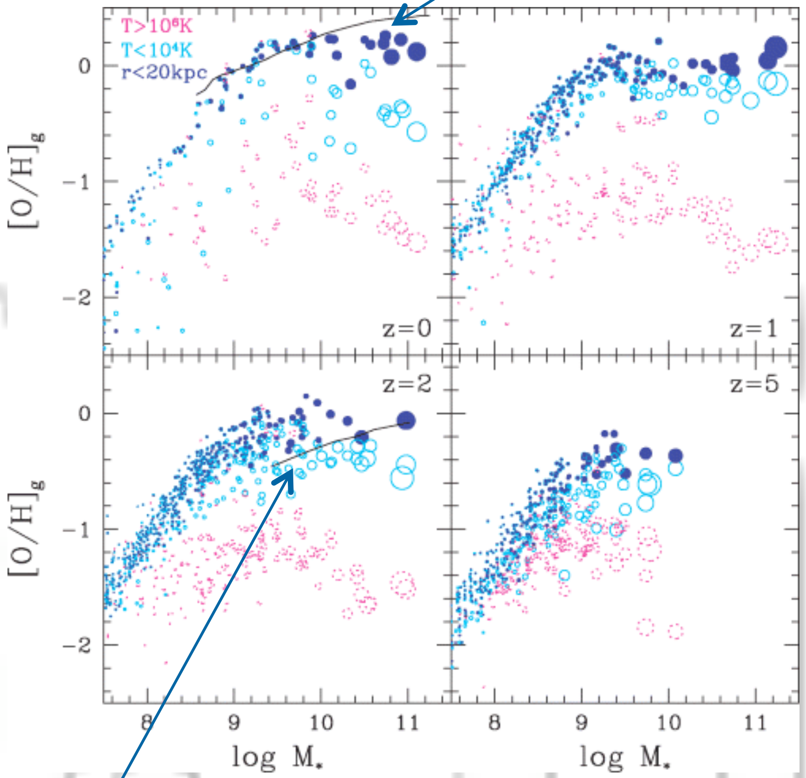
S/T_gas=0.15
D/T_gas=0.85

Mass-metallicity relation



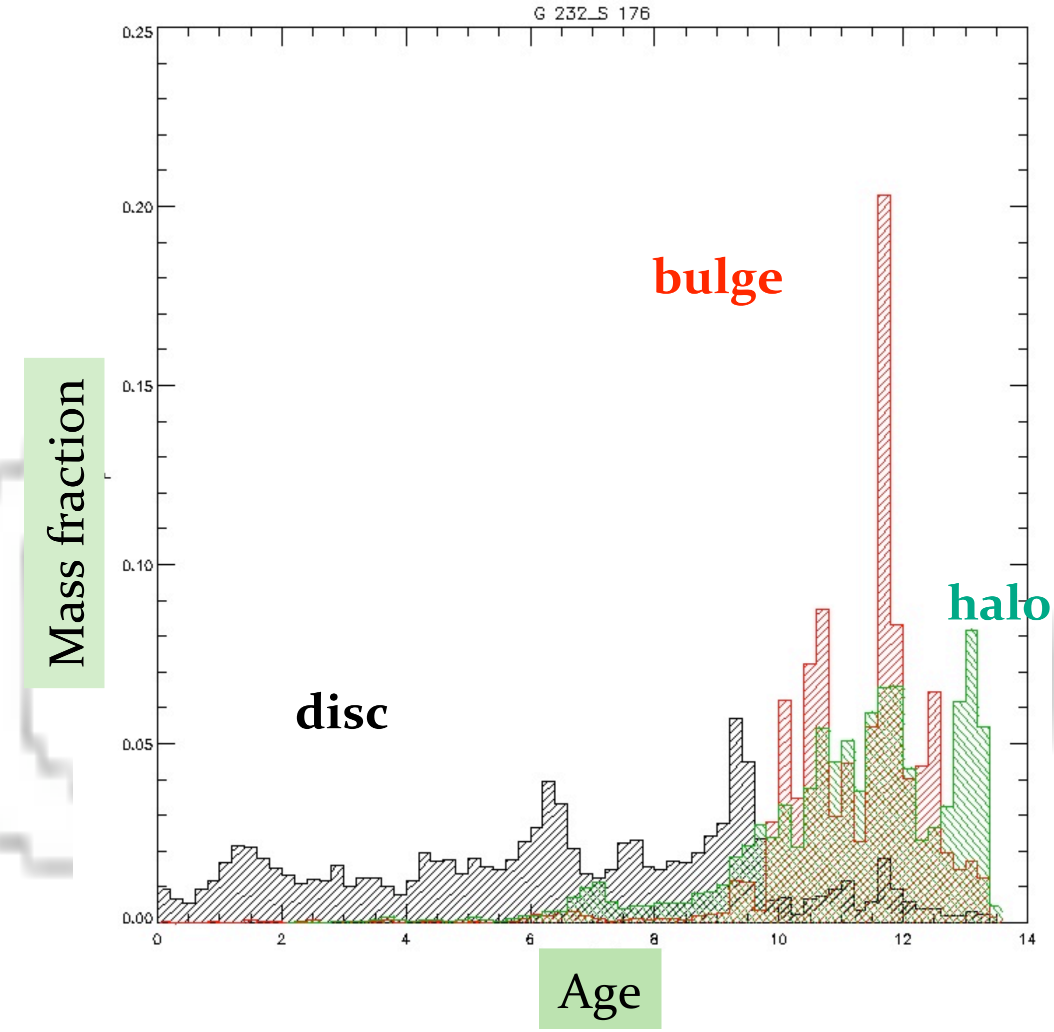
De Rossi et al. 2010

Tremonti et al



Erb et al. 2006

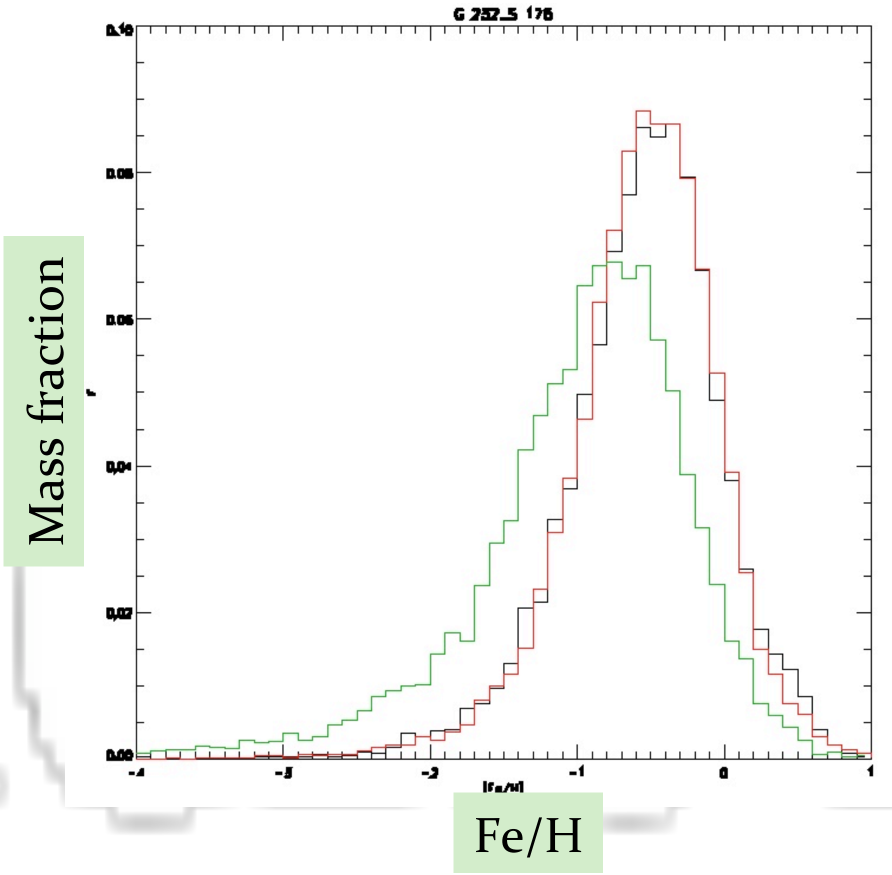
Kobayashi et al. 2007

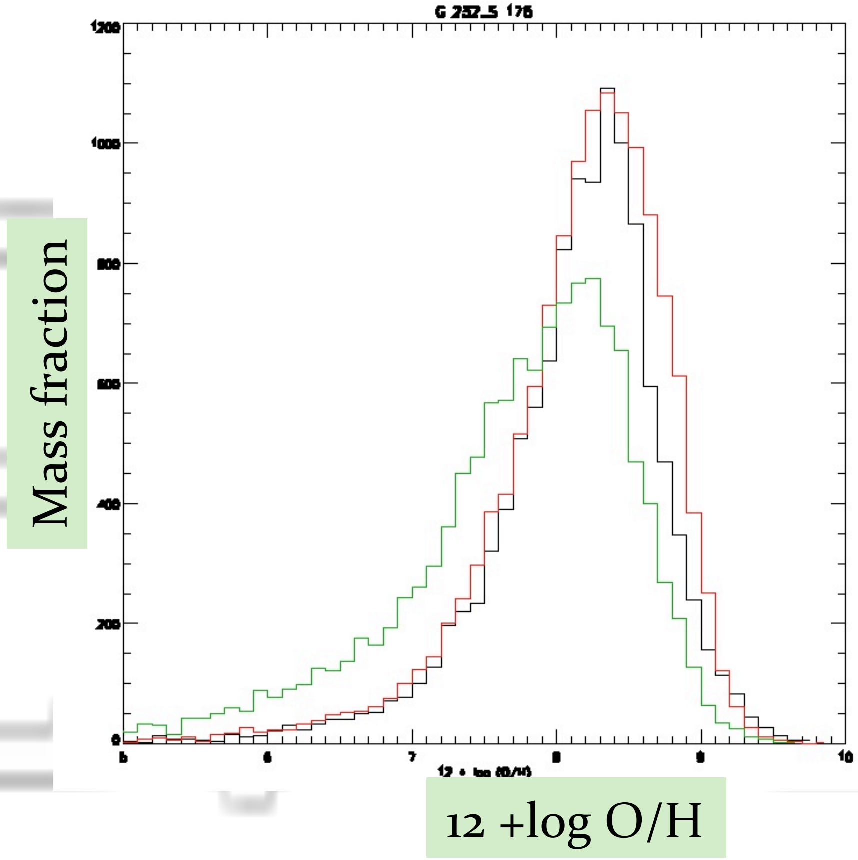


<disc> = 6 Gyr

<bulge> = 11.20 Gyr

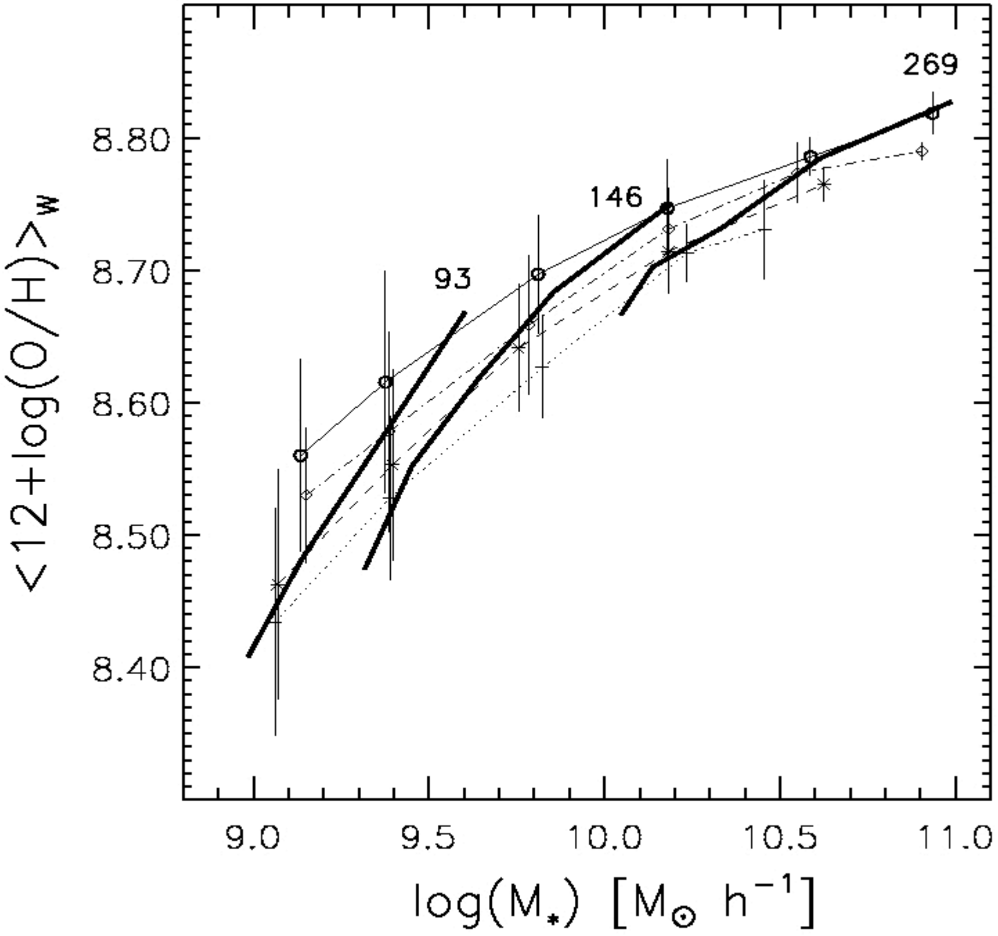
<halo> = 11.01 Gyr





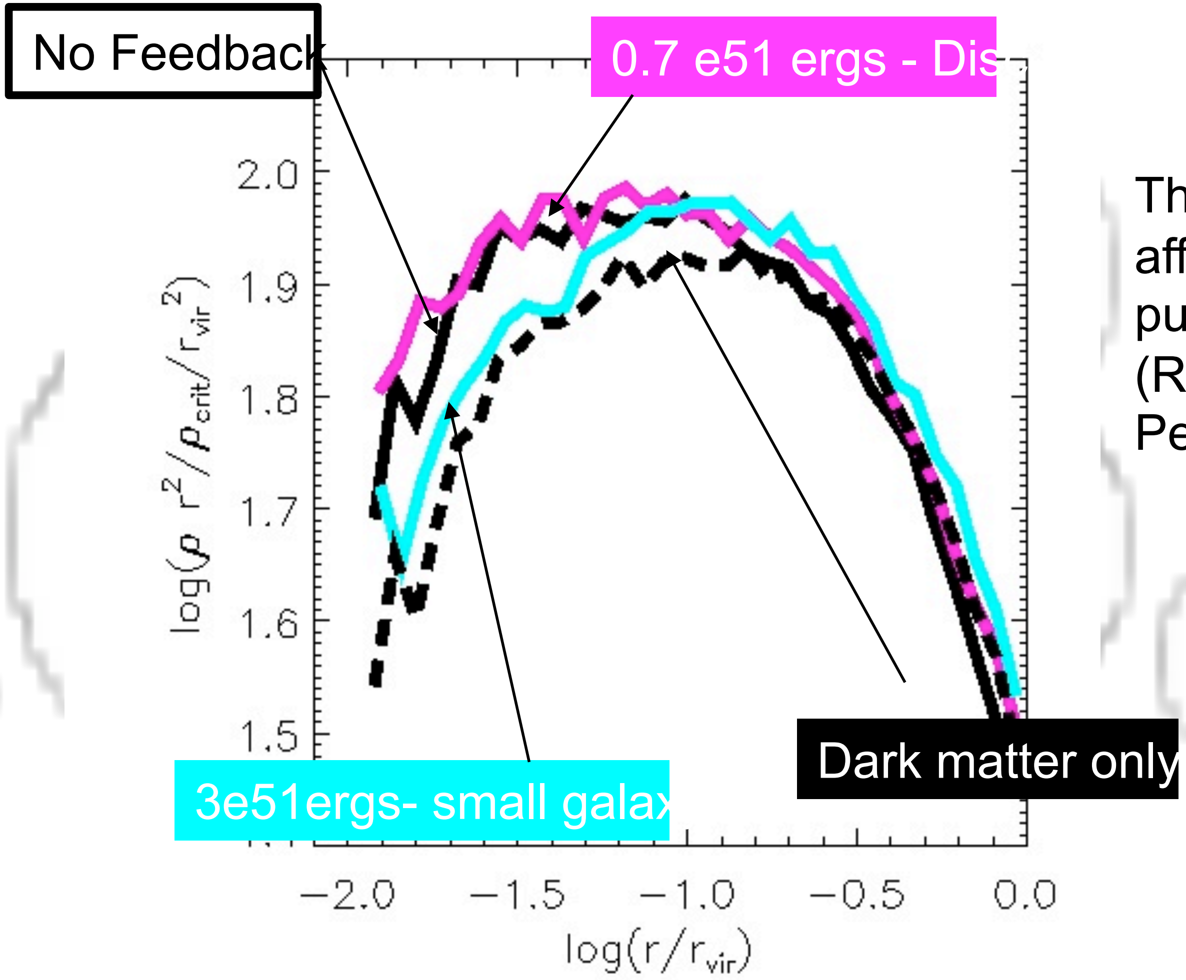
disc **bulge** **halo**

Mass-metallicity relation



De Rossi et al. 2007

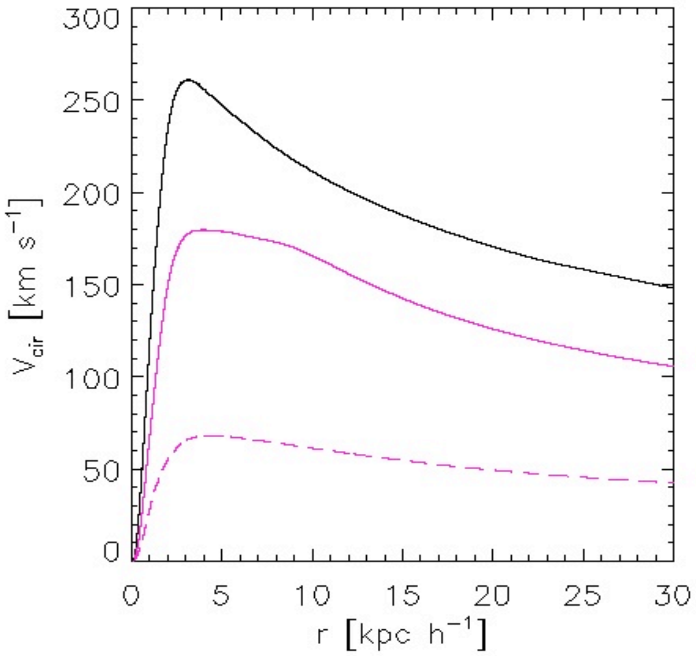
Impact of galaxy formation on the dark matter distribution



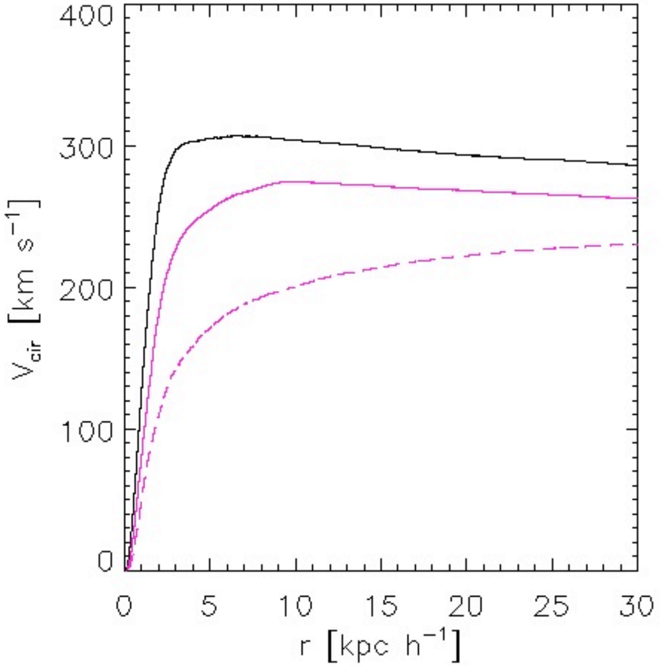
The dark matter distribution is affected by the way baryons are put together to form a galaxy (Romano-Diaz et al. 2008; Pedrosa et al. 2009)

Impact of galaxy formation on the dark matter distribution

Simulations provide a suitable tool tc study the effects of baryonic accumulation on the dark matter potential:



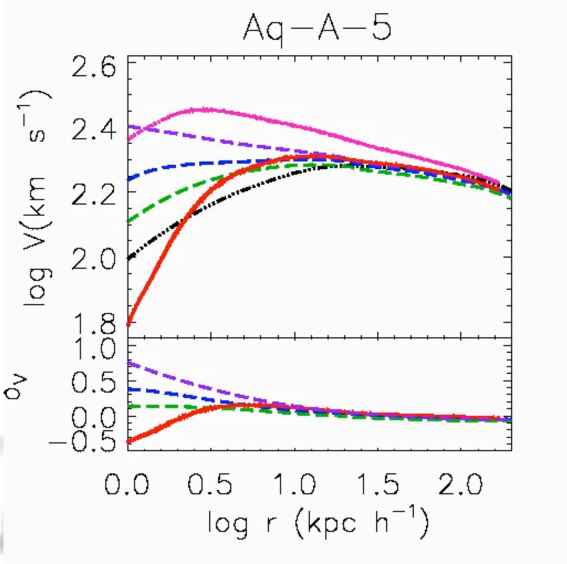
Baryons

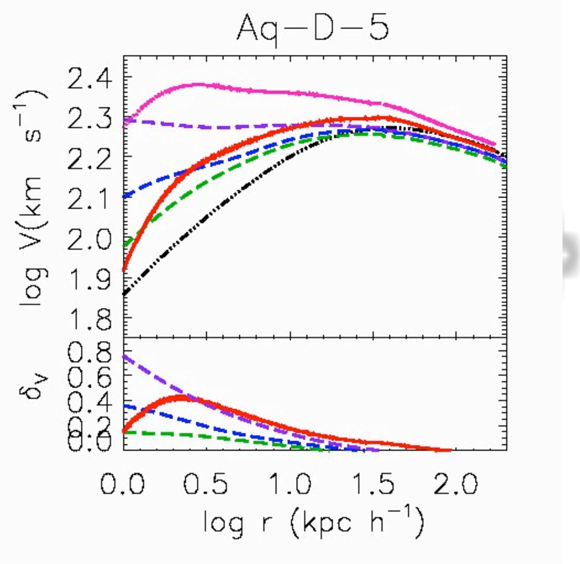


Total

Pedrosa et al. 2009

Impact of galaxy formation on the dark matter distribution





Tissera et al. 2009

The dark matter distribution is affected by the way baryons are put together to form a galaxy (Romano-Diaz et al. 2008; Pedrosa et al. 2009)

The Adiabatic contraction overestimates the effects of baryons.

Aquarius project : total

Aquarius project:DM

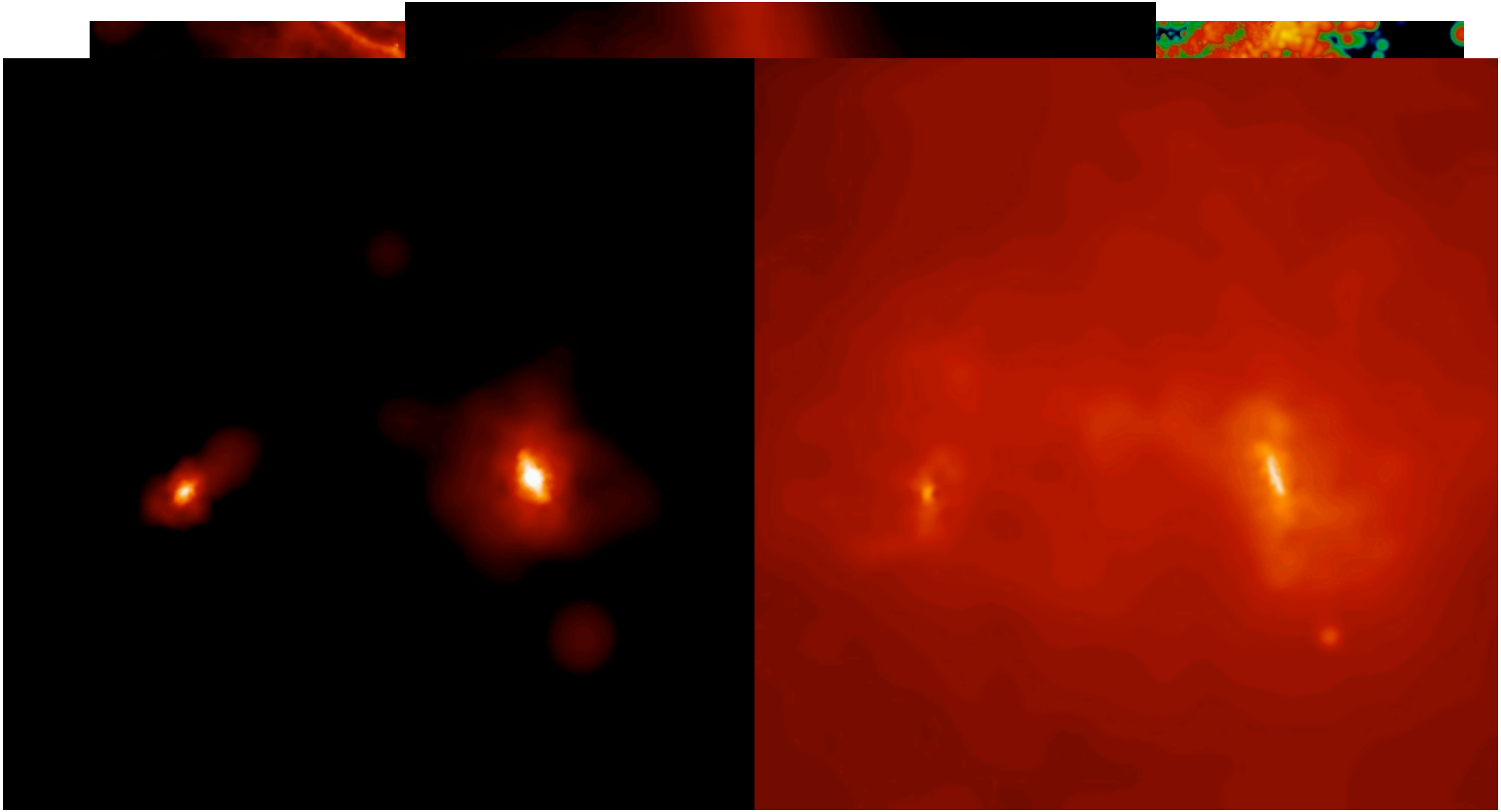
Dark matter only

Blumenthal et al. 1986

Gnedin et al. 2004

Abadi et al. 2009

Environmental effects



Environmental effects

Cosmological simulations provide for these effects naturally:

It is important to note that the comparison with observations is an open problem.

Some simulated quantities are not directly measure or even impossible to do so.

The observed large volumes are impossible to model with sufficient spatial and temporal resolution.

Environmental effects

Gas accretion is bimodal in temperature and metallicity

Cold gas: Metal-poor filaments

Metal-rich dense clumps

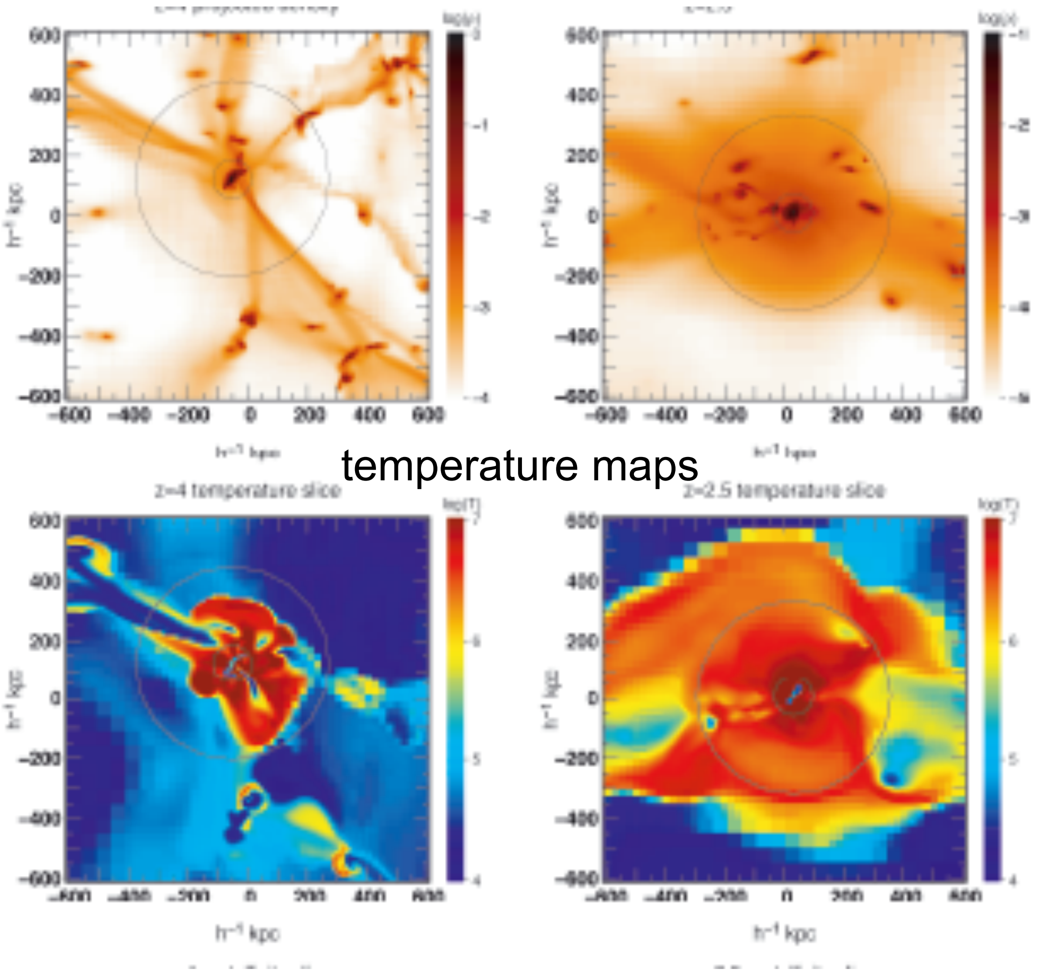
Hot gas: Chemical heterogeneity

Radius dependent metal.

$M_{\text{shock}\ \ v}=10^{11.6}$ Mo

z=4 Density maps z=2.5

temperature maps



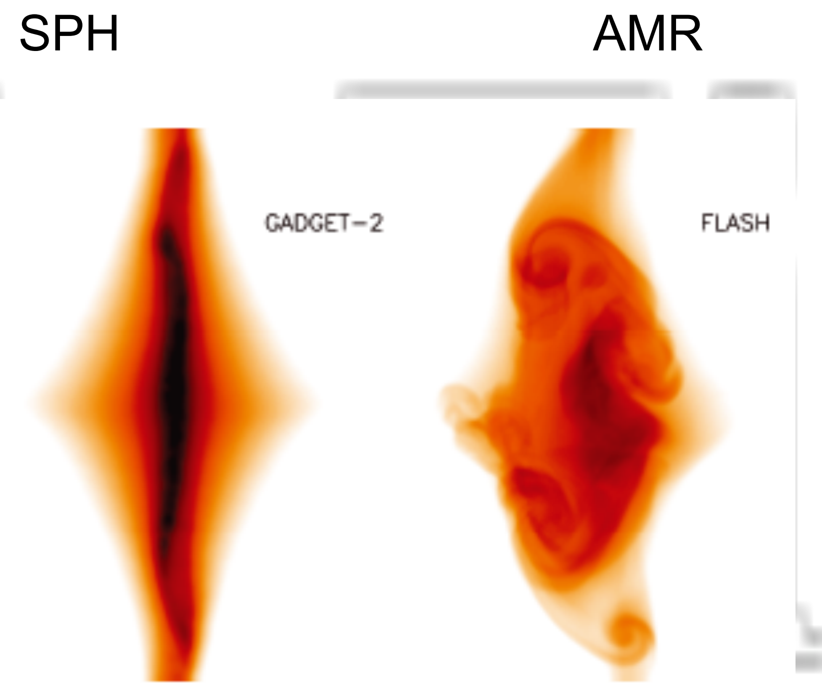
Ocvirk, Pichon & Teyssier (2008)

Environmental effects

Several aspects remain to be better resolved:

interface instability between cold and hot phases

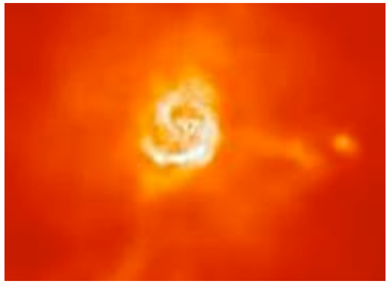
AREPO: Springel 2009
It has been designed to conserve the best characteristics of each method


SPH

AMR

Logarithm entropy maps

Mitchell et al. 2009



Conclusions

The global evolution of the structure is well described.

Gas cooling and collapse is described but we are just able to start understanding how the gas flows along the filamentary structure.

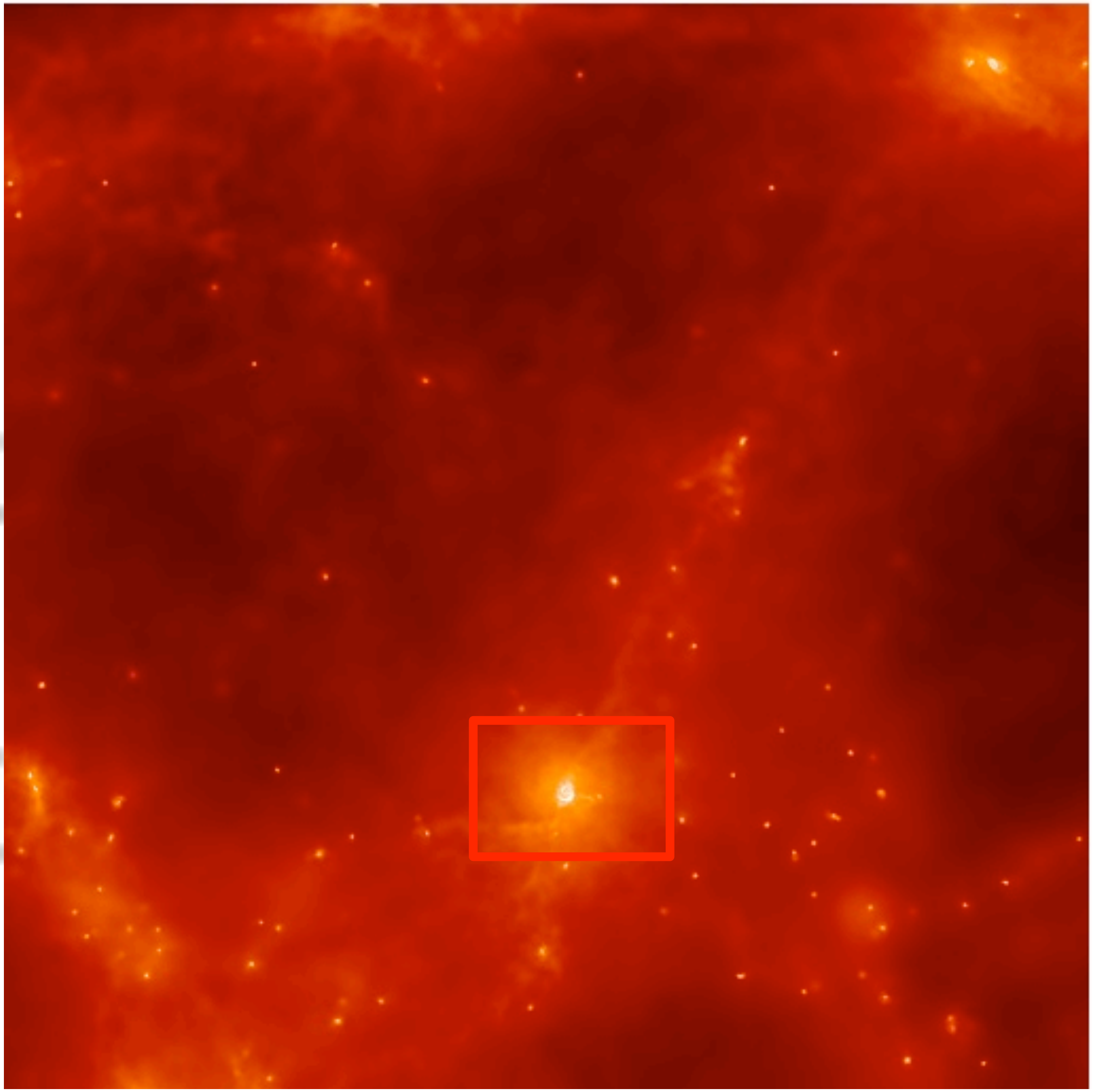
Star formation is still very simply modeled.

SN feedback is better described.

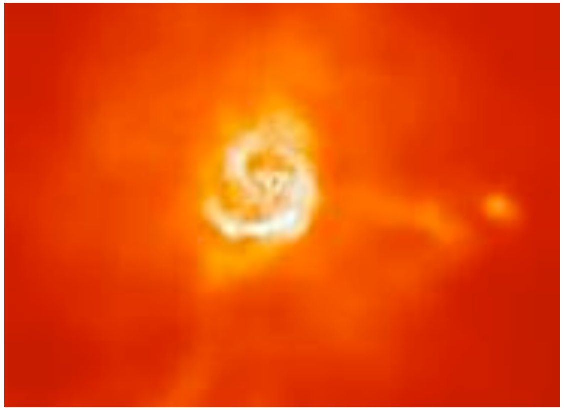
Chemical mixing is still not properly represented.

Other physical processes are still missing:
AGN activity (see this week paper by Sijacki , Springel & Haehnelt.)
High redshift physics, etc.

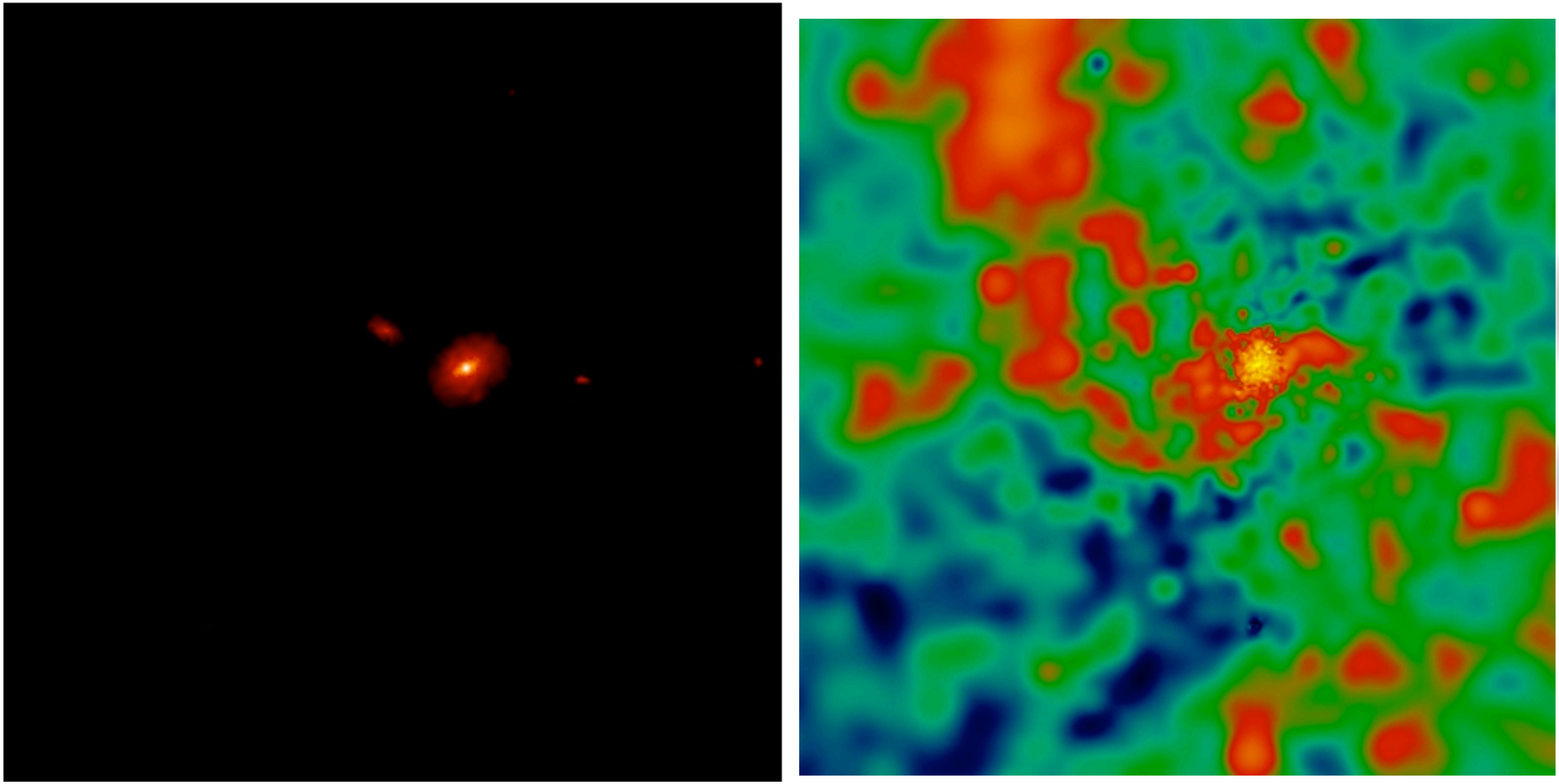
Numerical resolution is always an issue.

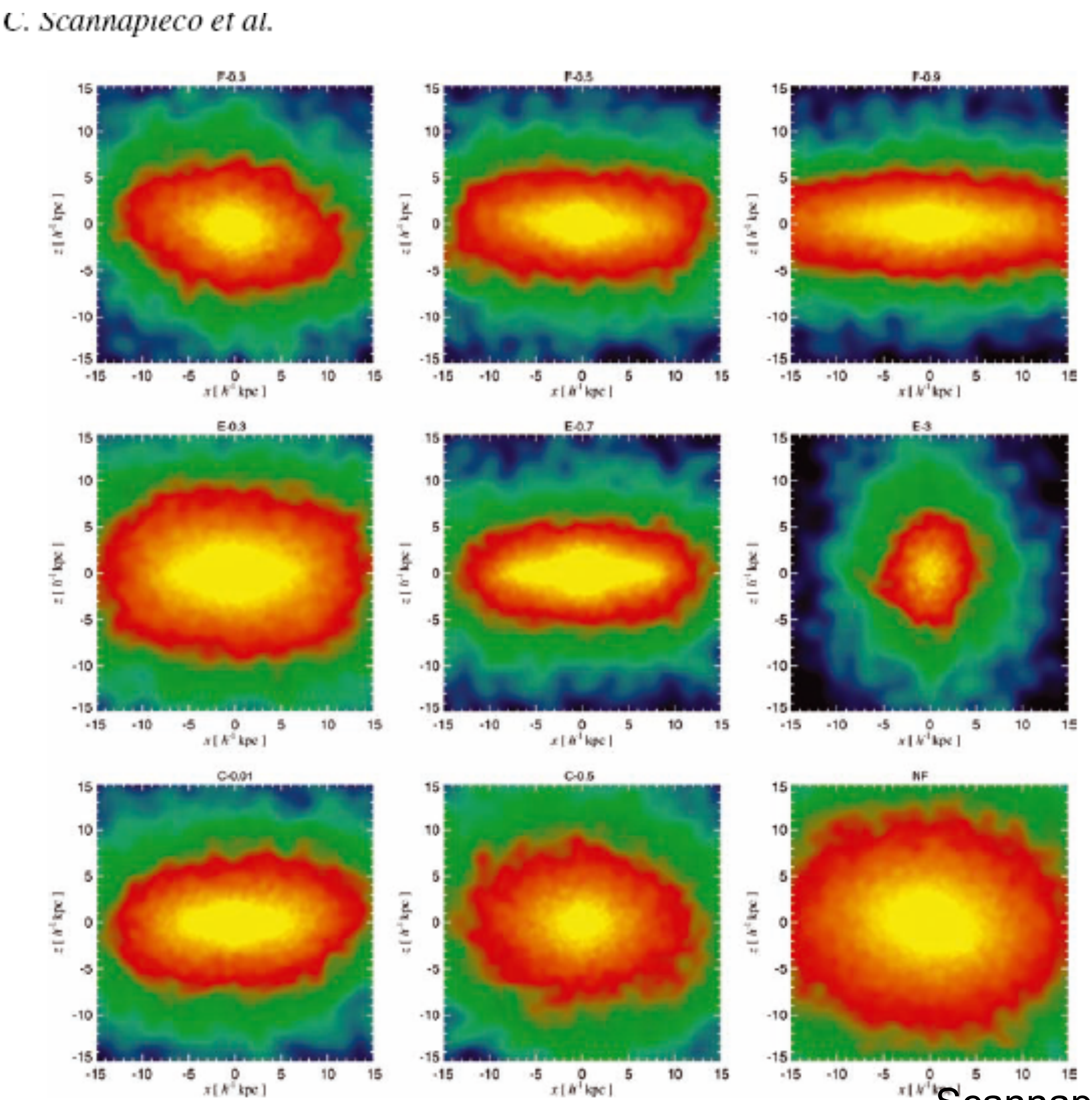


Thank you

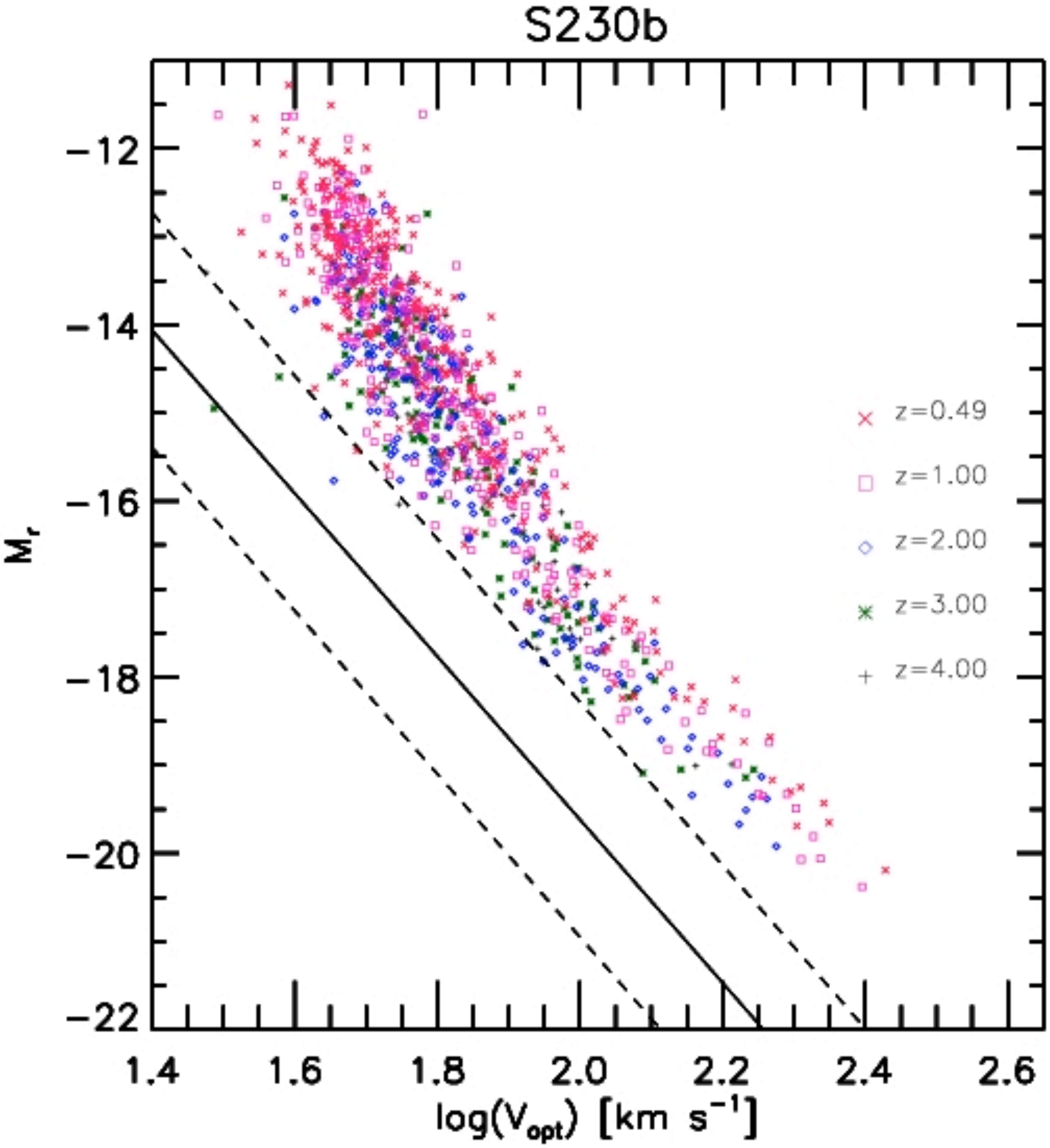


FUTURE WORK ....





Scannapieco et al. 2008


S230b
M_r
−12
−14
−16
−18
−20
−22
1.4
1.6
1.8
2.0
2.2
2.4
2.6
log(V_opt) [km s⁻¹]
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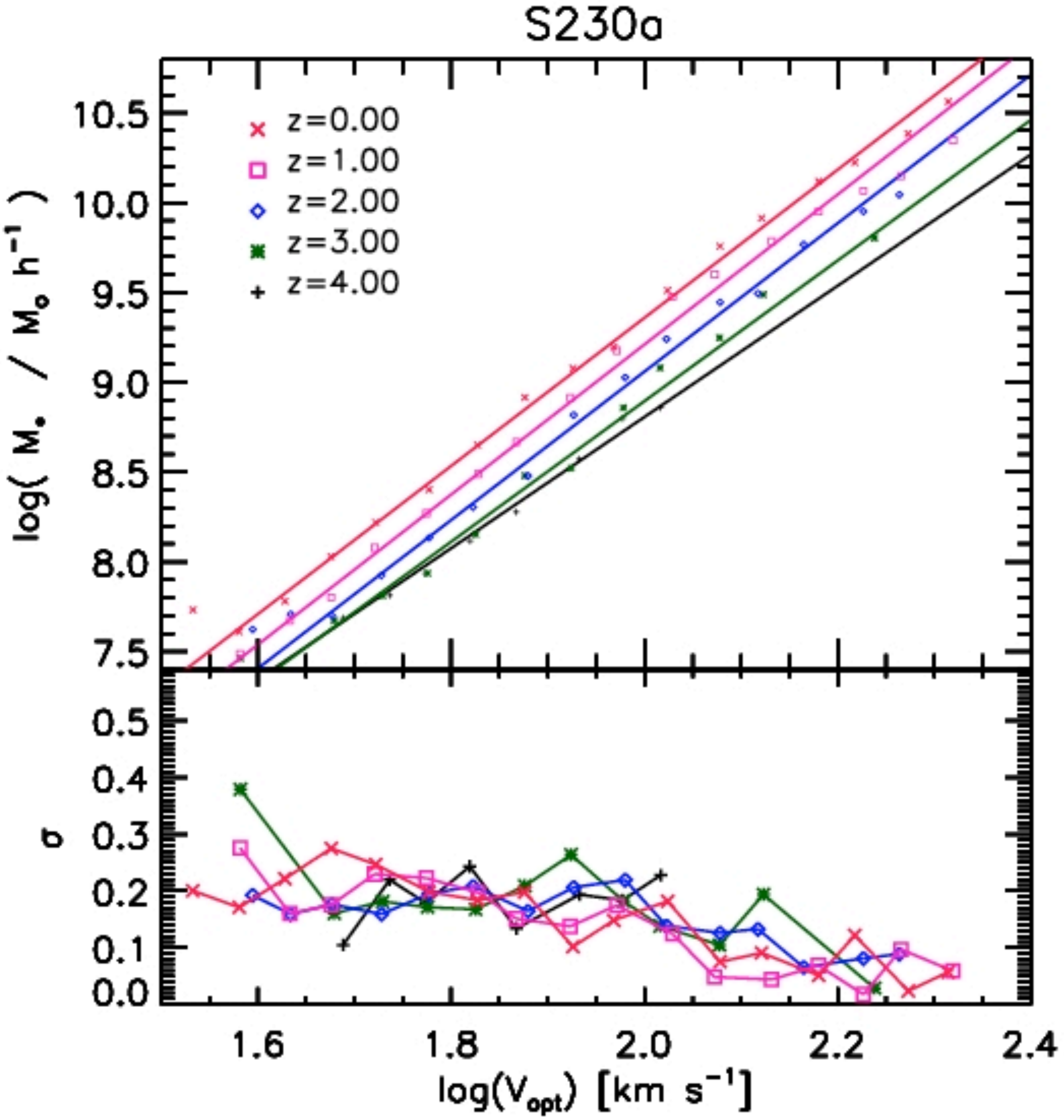
z=1.00
z=2.00
z=3.00
z=4.00

S230a
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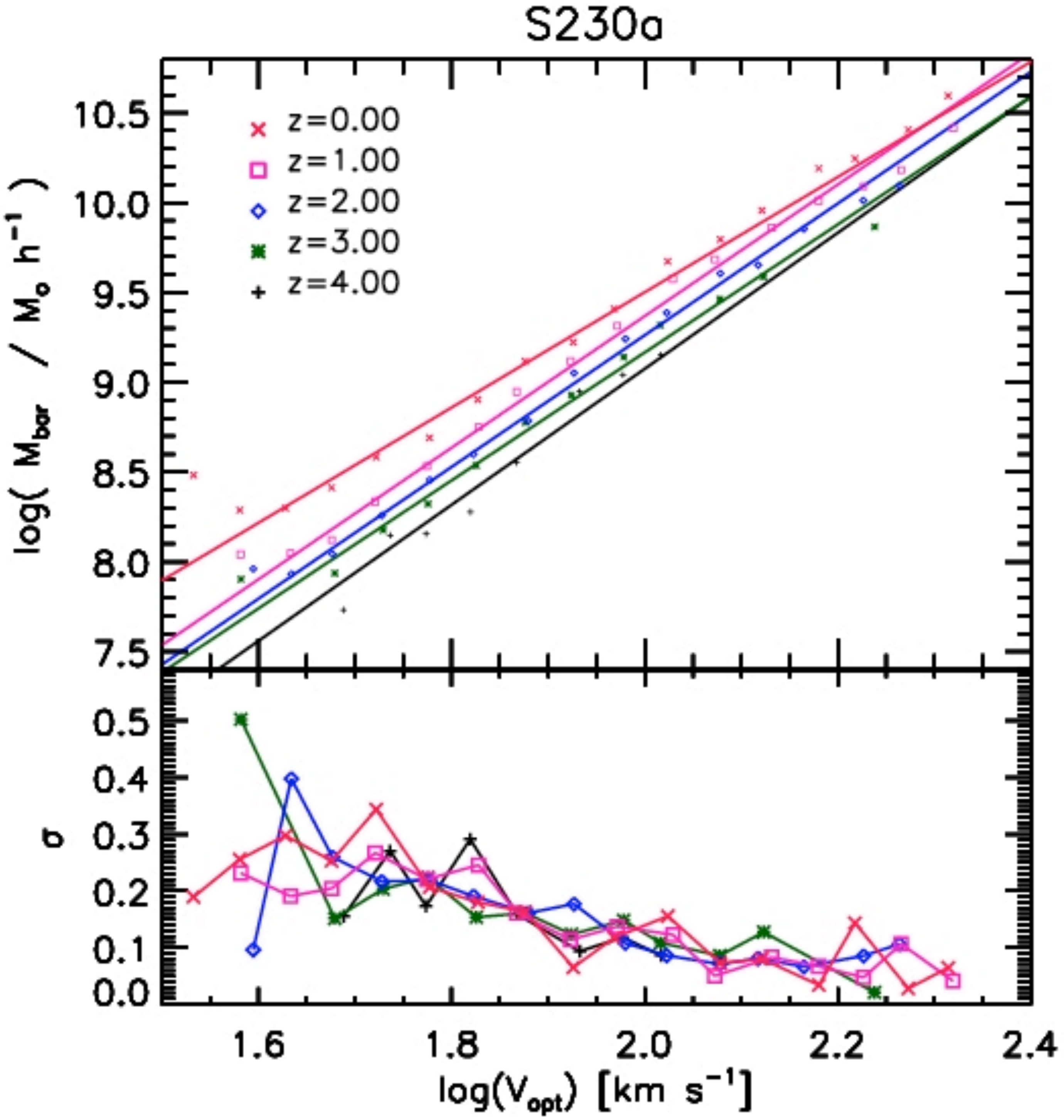
z=3.00
z=4.00
log(M* / Mo h⁻¹)
10.5
10.0
9.5
9.0
8.5
8.0
7.5
σ
0.5
0.4
0.3
0.2
0.1
0.0
1.6
1.8
2.0
2.2
2.4
log(Vopt) [km s⁻¹]


S230a
z=0.00
z=1.00
z=2.00
z=3.00
z=4.00
log(M_{bar} / $M_{\odot}$ h^{-1})
10.5
10.0
9.5
9.0
8.5
8.0
7.5
σ
0.5
0.4
0.3
0.2
0.1
0.0
1.6
1.8
2.0
2.2
2.4
log(V_{opt}) [km s^{-1}]