THE IMPACT OF COSMOLOGICAL SIMULATIONS IN UNDERSTANDING THE EVOLUTION OF FOSSIL GROUPS

Ali Dariush

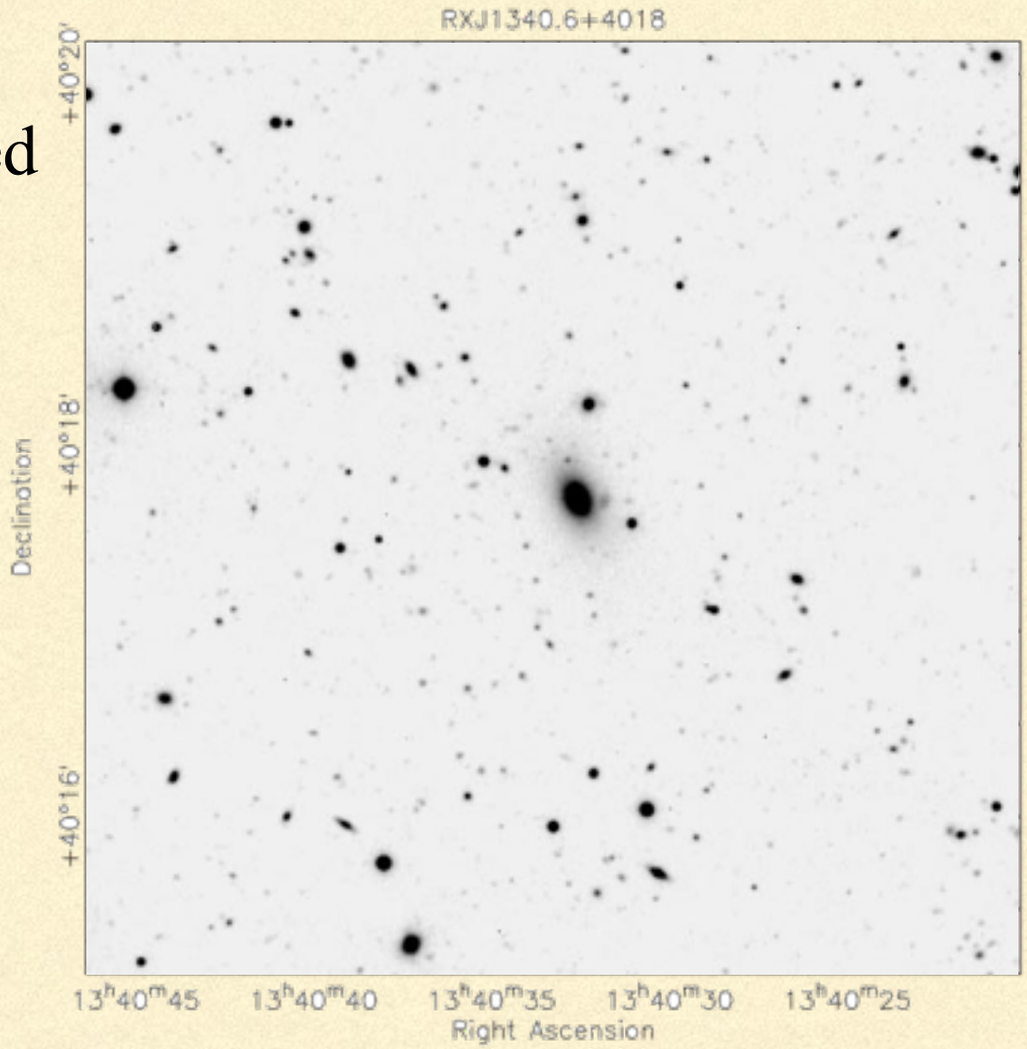
Institute of Astronomy, University of Cambridge

FOSSIL GALAXY SYSTEMS

Fossil galaxy systems are the final stage of evolution in groups, where L* galaxies merged to form the bright, central elliptical.
(Ponman et al., Nature, 1994 ; Jones et al., MNRAS, 2000)

According to the standard definition:
(Jones et al., MNRAS, 2003)

- (i) $\Delta m_{12} \geq 2.0\ mag\ (0.5\ R_{virial})$
- (ii) $L_x \geq 10^{42} h_{50}^{-2} erg/s$



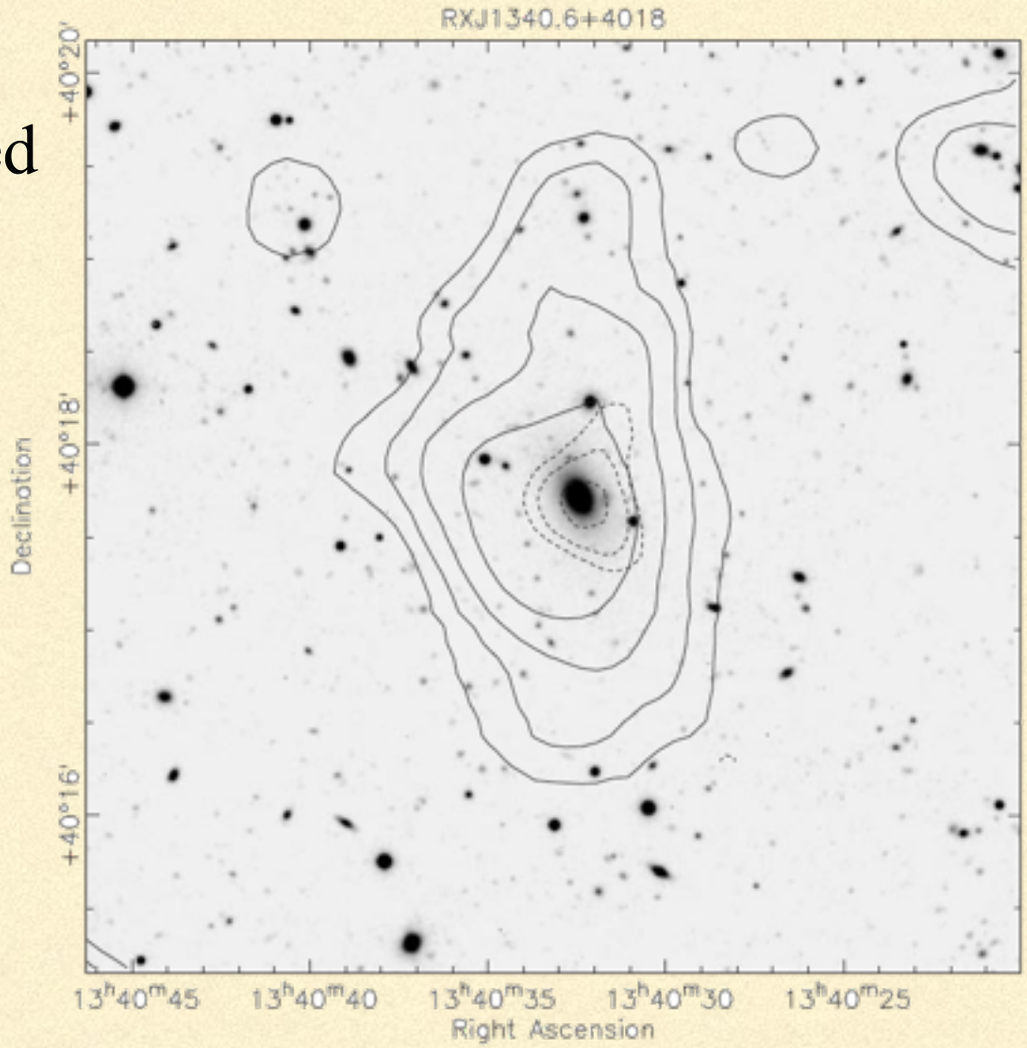
R-band CCD image and overlaid X-ray contours
(Jones et al., MNRAS, 2000)

FOSSIL GALAXY SYSTEMS

Fossil galaxy systems are the final stage of evolution in groups, where L* galaxies merged to form the bright, central elliptical.
(Ponman et al., Nature, 1994 ; Jones et al., MNRAS, 2000)

According to the standard definition:
(Jones et al., MNRAS, 2003)

- (i) $\Delta m_{12} \geq 2.0\ mag\ (0.5\ R_{virial})$
- (ii) $L_x \geq 10^{42} h_{50}^{-2} erg/s$



R-band CCD image and overlaid X-ray contours
(Jones et al., MNRAS, 2000)

FOSSIL GALAXY SYSTEMS

Motivation

(A) Do simulated galaxy systems, selected based on fossil definition, correspond to

(i) early-formed and

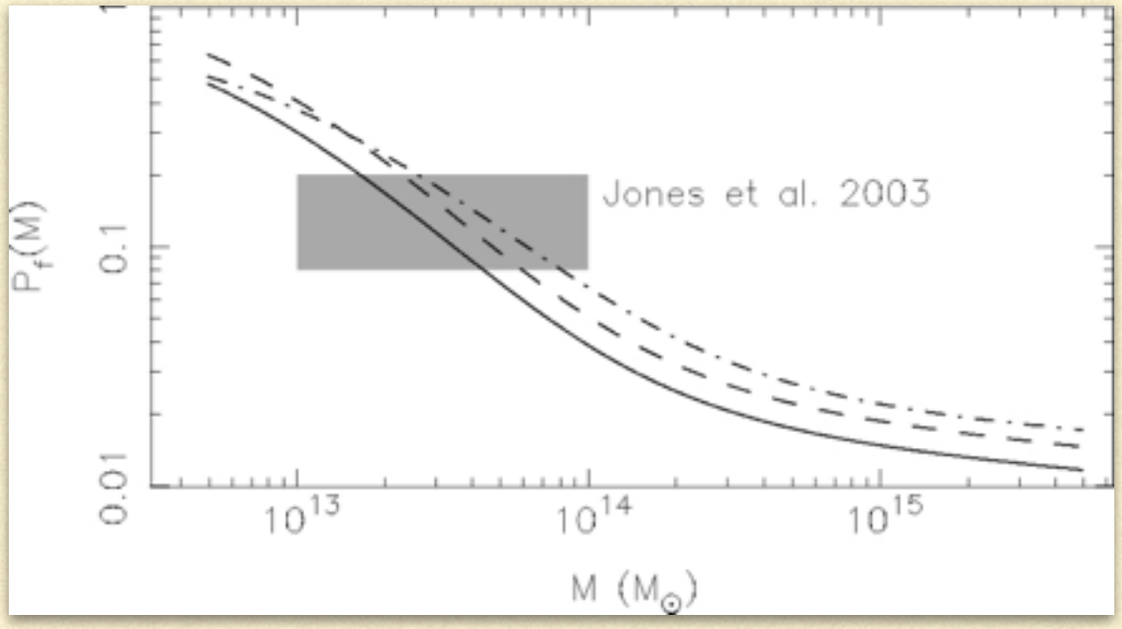
(ii) dynamically-relaxed systems ?

B) If so, do they show distinct characteristics ?

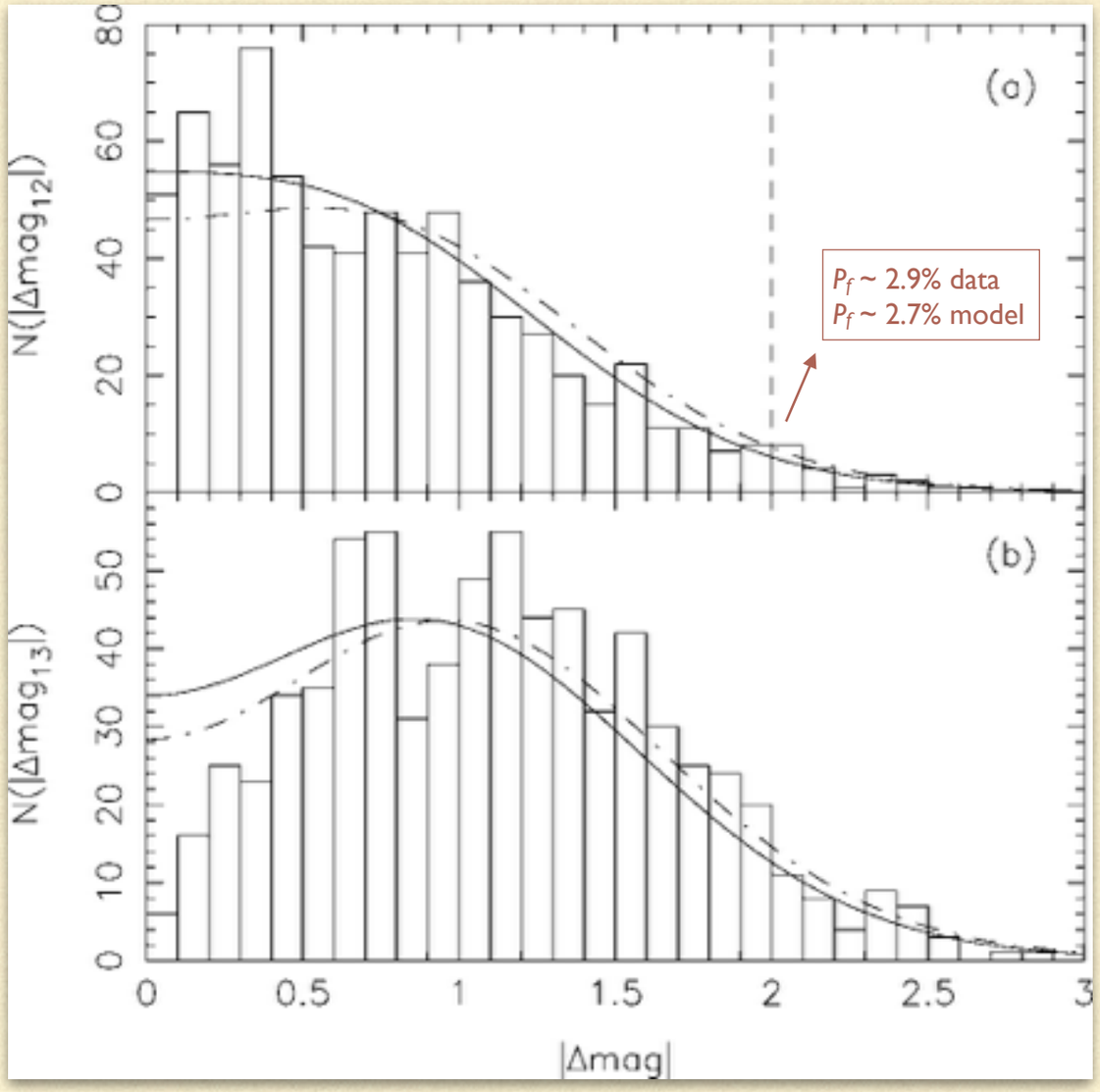
FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

Luminosity gap as an indicator of mass assembly history

THE LUMINOSITY GAP STATISTIC



Probability $P_f(M)$ that a halo of mass M contains a fossil system of galaxies (Milosavljevic et al., ApJL, 2006).



The *r*-band luminosity gap distribution from 730 clusters in the SDSS C4 Catalog (Miller et al., AJ, 2005). Lines are theoretical predictions (Milosavljevic et al., ApJL, 2006).

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

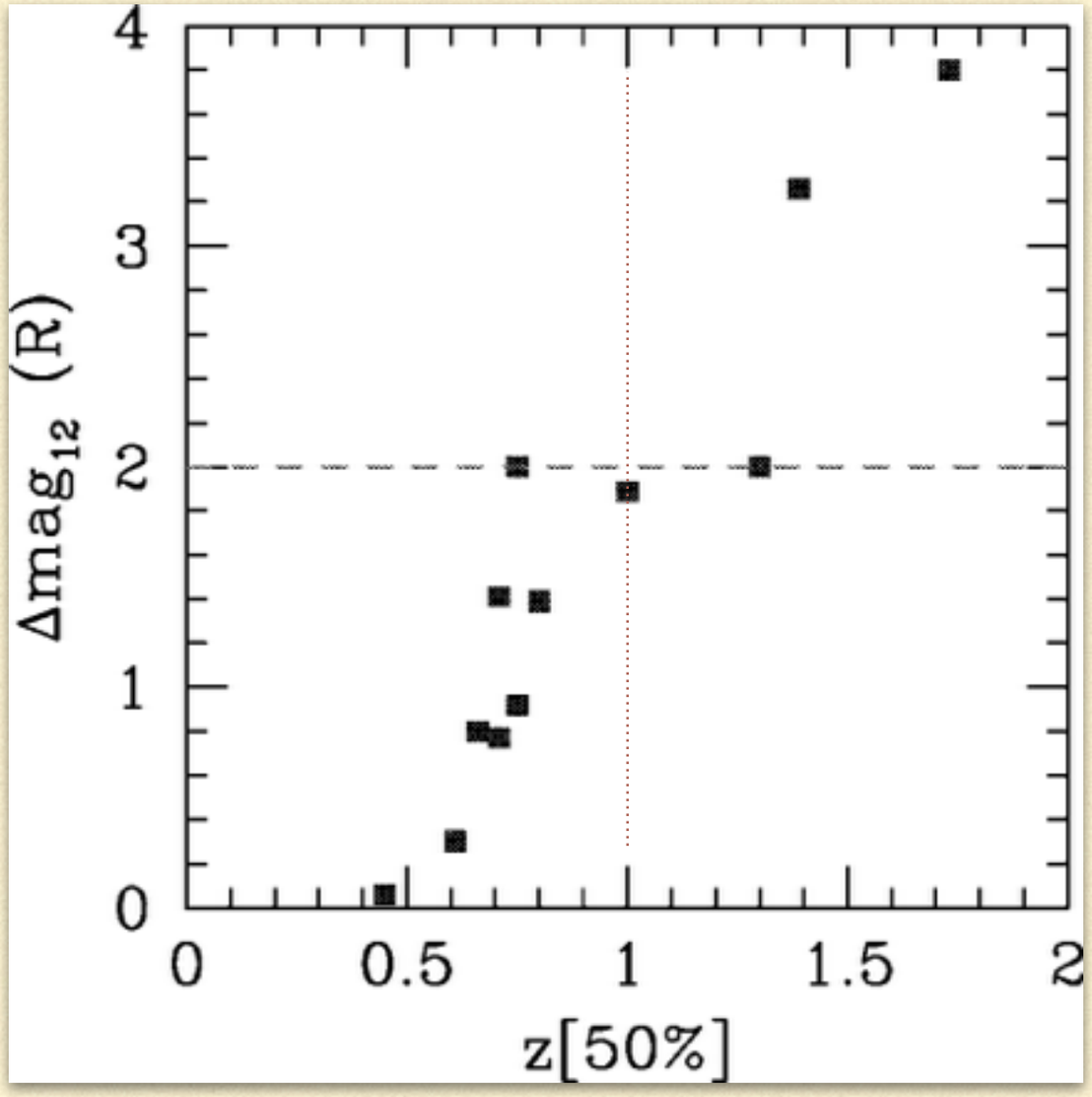
High-resolution N-body/hydrodynamical simulations of 12 galaxy group sized dark matter halos in the low-density ΛCDM cosmology (based on TreeSPH code ; D'Onghia et al., ApJL, 2005).

- 33± 16% of systems are FG (Observation ~ 10-20% ; Jones + 03)

- FGs are X-ray over-luminous (compared to non-FGs) for the same optical luminosity

$$FG \quad L_R = (1.28 \pm 0.06) \times 10^{11} L_\odot; \; L_X = (6.3 \pm 1.1) \times 10^{43} erg.s^{-1}$$
$$non-FG \quad L_R = (1.26 \pm 0.04) \times 10^{11} L_\odot; \; L_X = (1.7 \pm 0.6) \times 10^{43} erg.s^{-1}$$

- The earlier a galaxy group is assembled, the larger is the magnitude gap (dm12) in the R-band at z =0.



The luminosity gap of each simulated group as a function of formation time, i.e. the epoch in which the group assembled 50% of the system's final mass (D'Onghia et al., ApJL, 2005).

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

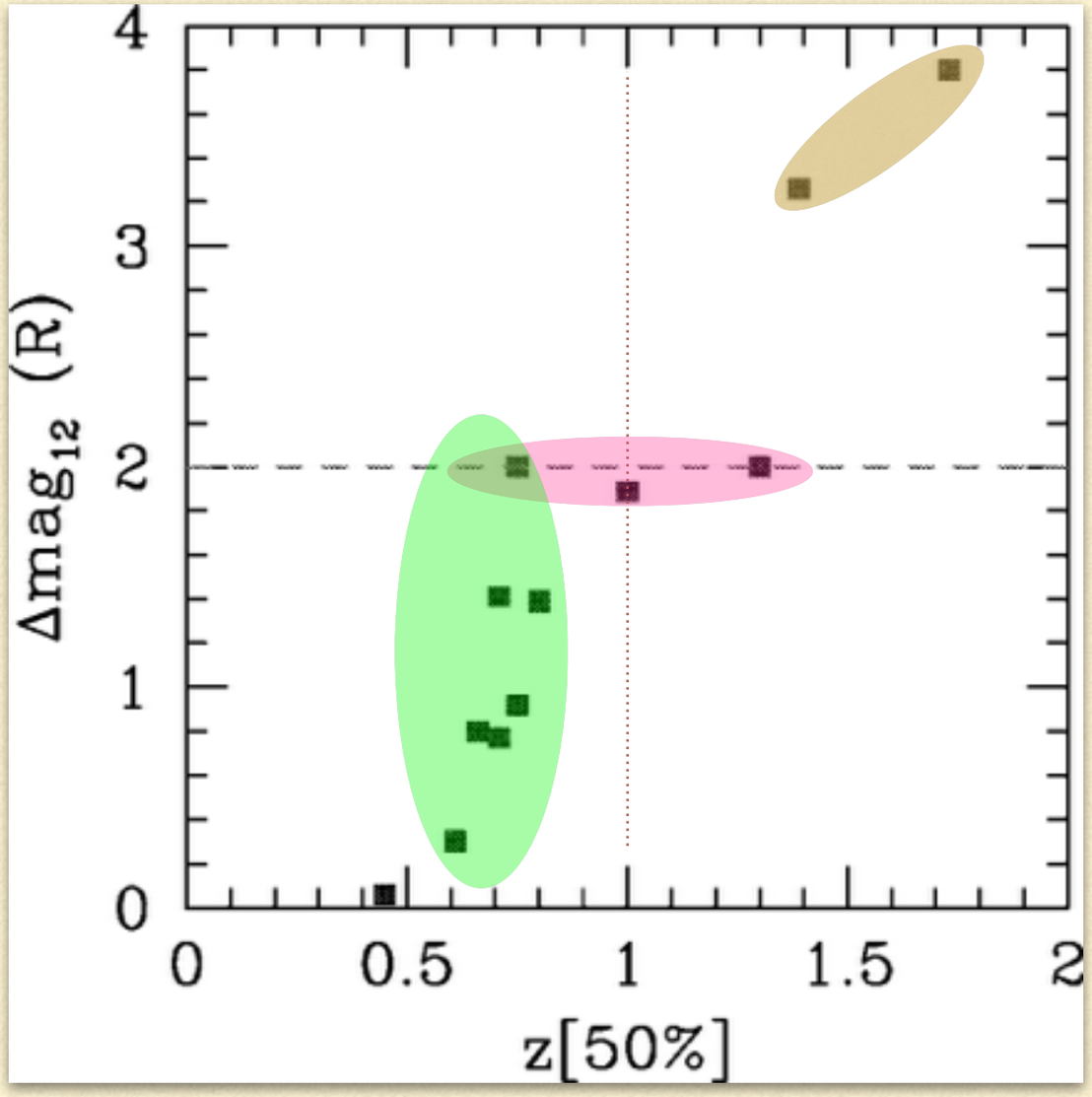
High-resolution N-body/hydrodynamical simulations of 12 galaxy group sized dark matter halos in the low-density ΛCDM cosmology (based on TreeSPH code ; D'Onghia et al., ApJL, 2005).

- 33± 16% of systems are FG (Observation ~ 10-20% ; Jones + 03)

- FGs are X-ray over-luminous (compared to non-FGs) for the same optical luminosity

$$FG \quad L_R = (1.28 \pm 0.06) \times 10^{11} L_\odot; \; L_X = (6.3 \pm 1.1) \times 10^{43} erg.s^{-1}$$
$$non-FG \quad L_R = (1.26 \pm 0.04) \times 10^{11} L_\odot; \; L_X = (1.7 \pm 0.6) \times 10^{43} erg.s^{-1}$$

- The earlier a galaxy group is assembled, the larger is the magnitude gap (dm12) in the R-band at z =0.



The luminosity gap of each simulated group as a function of formation time, i.e. the epoch in which the group assembled 50% of the system's final mass (D'Onghia et al., ApJL, 2005).

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

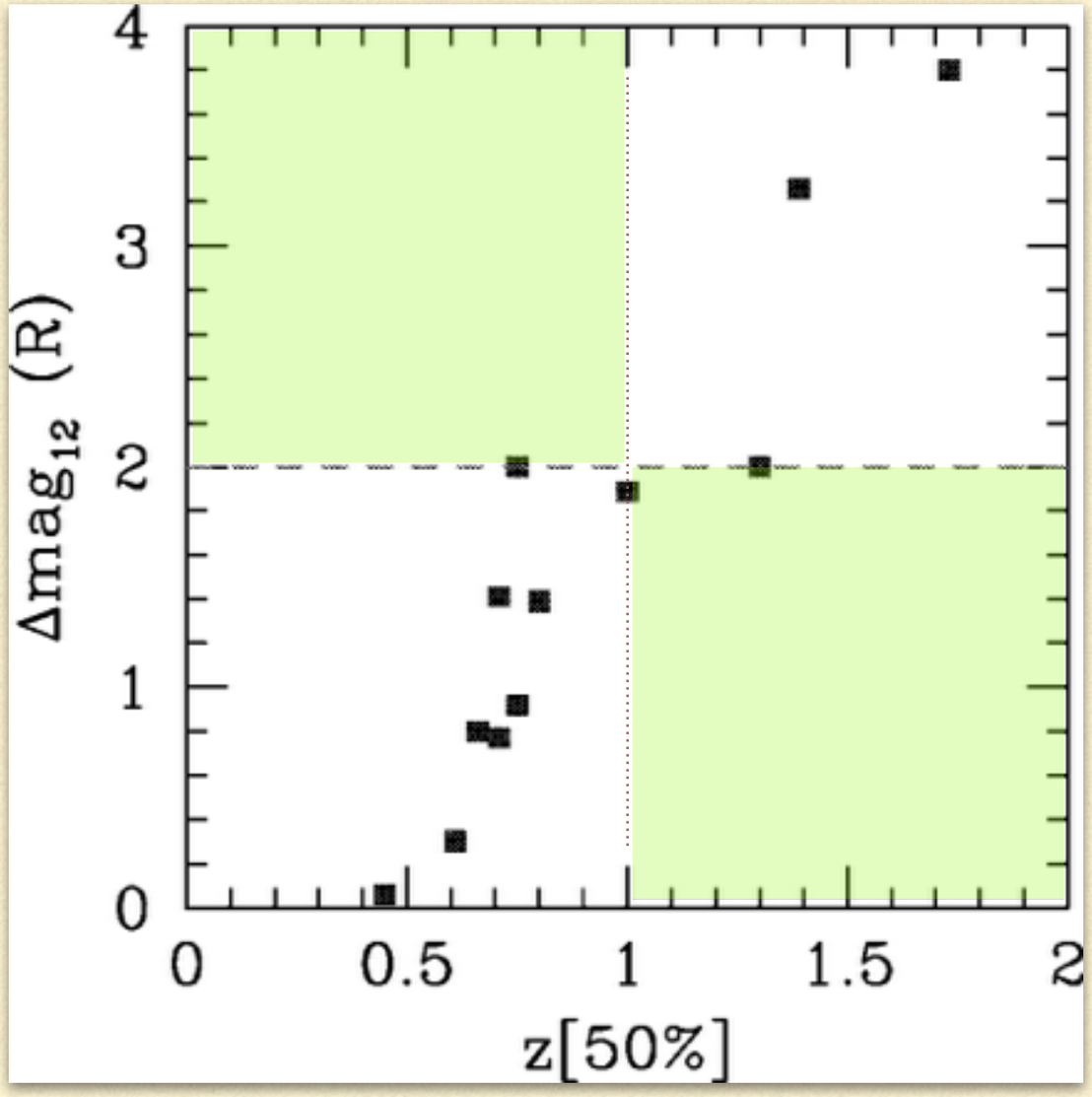
High-resolution N-body/hydrodynamical simulations of 12 galaxy group sized dark matter halos in the low-density ΛCDM cosmology (based on TreeSPH code ; D'Onghia et al., ApJL, 2005).

- 33± 16% of systems are FG (Observation ~ 10-20% ; Jones + 03)

- FGs are X-ray over-luminous (compared to non-FGs) for the same optical luminosity

$$FG \quad L_R = (1.28 \pm 0.06) \times 10^{11} L_\odot; \; L_X = (6.3 \pm 1.1) \times 10^{43} erg.s^{-1}$$
$$non-FG \quad L_R = (1.26 \pm 0.04) \times 10^{11} L_\odot; \; L_X = (1.7 \pm 0.6) \times 10^{43} erg.s^{-1}$$

- The earlier a galaxy group is assembled, the larger is the magnitude gap (dm12) in the R-band at z =0.



The luminosity gap of each simulated group as a function of formation time, i.e. the epoch in which the group assembled 50% of the system's final mass (D'Onghia et al., ApJL, 2005).

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

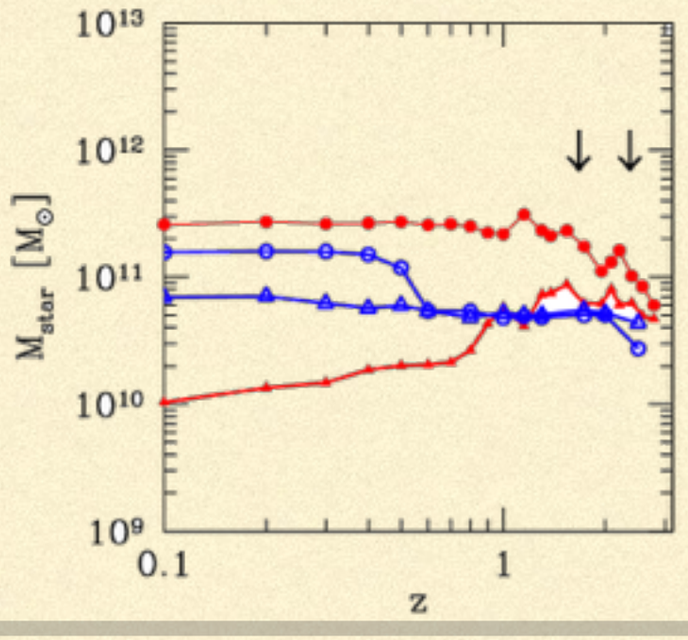
High-resolution N-body/hydrodynamical simulations of 12 galaxy group sized dark matter halos in the low-density ΛCDM cosmology (based on TreeSPH code ; D'Onghia et al., ApJL, 2005).

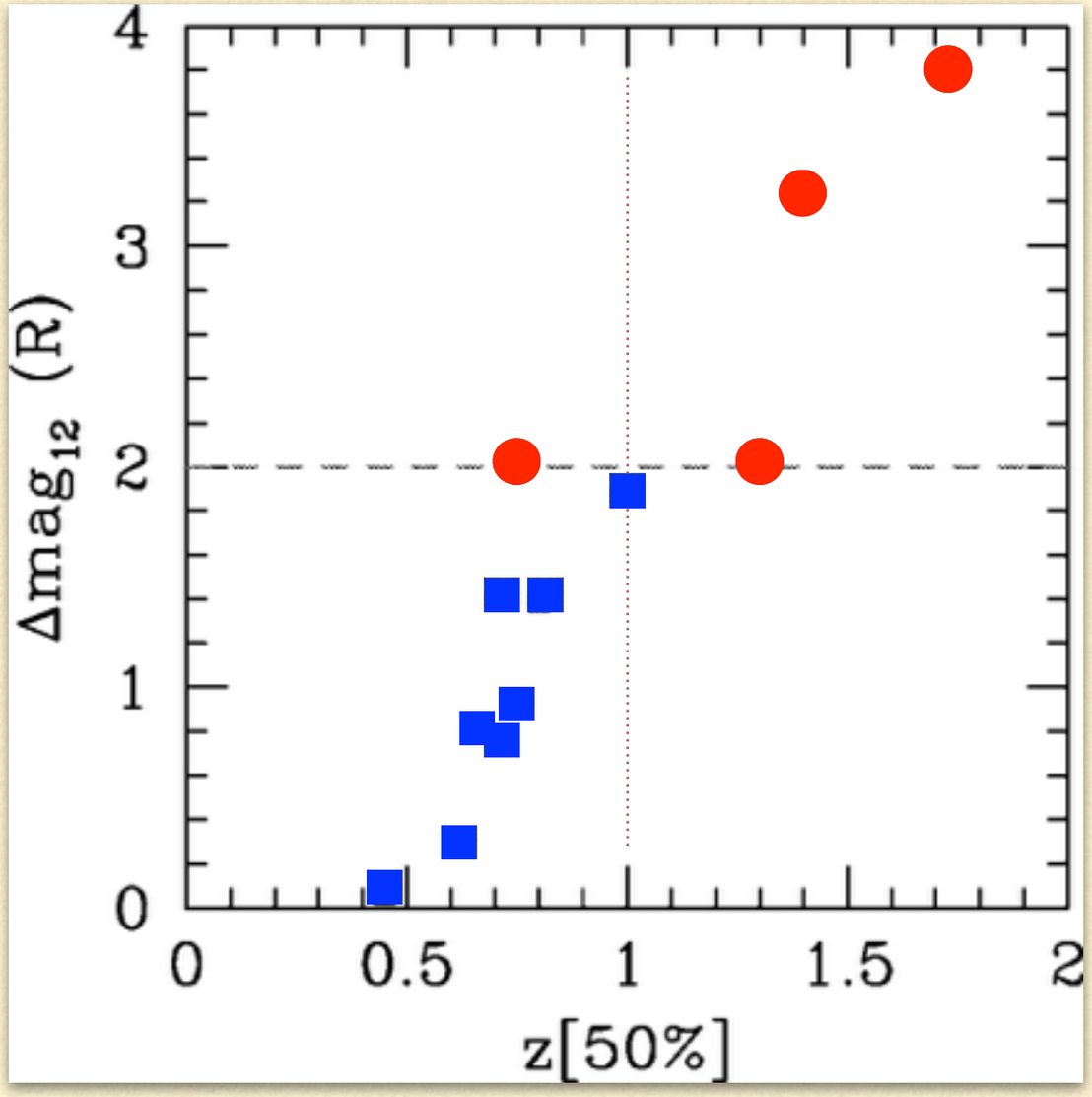
- 33± 16% of systems are FG (Observation ~ 10-20% ; Jones + 03)

- FGs are X-ray over-luminous (compared to non-FGs) for the same optical luminosity

$$FG \quad L_R = (1.28 \pm 0.06) \times 10^{11} L_\odot; \; L_X = (6.3 \pm 1.1) \times 10^{43} erg.s^{-1}$$
$$non-FG \quad L_R = (1.26 \pm 0.04) \times 10^{11} L_\odot; \; L_X = (1.7 \pm 0.6) \times 10^{43} erg.s^{-1}$$

- The earlier a galaxy group is assembled, the larger is the magnitude gap (dm12) in the R-band at z =0.





The luminosity gap of each simulated group as a function of formation time, i.e. the epoch in which the group assembled 50% of the system's final mass (D'Onghia et al., ApJL, 2005).

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

Millennium Simulation

The Millennium Run is one of the largest ever simulation of the formation of structure within the ΛCDM cosmology. It uses 10^{10} particles to follow the dark matter distribution in a cubic region $500h^{-1}$Mpc on a side (Springel V. et al., Nat., 2005).

Dark halo
(Springel + 05)

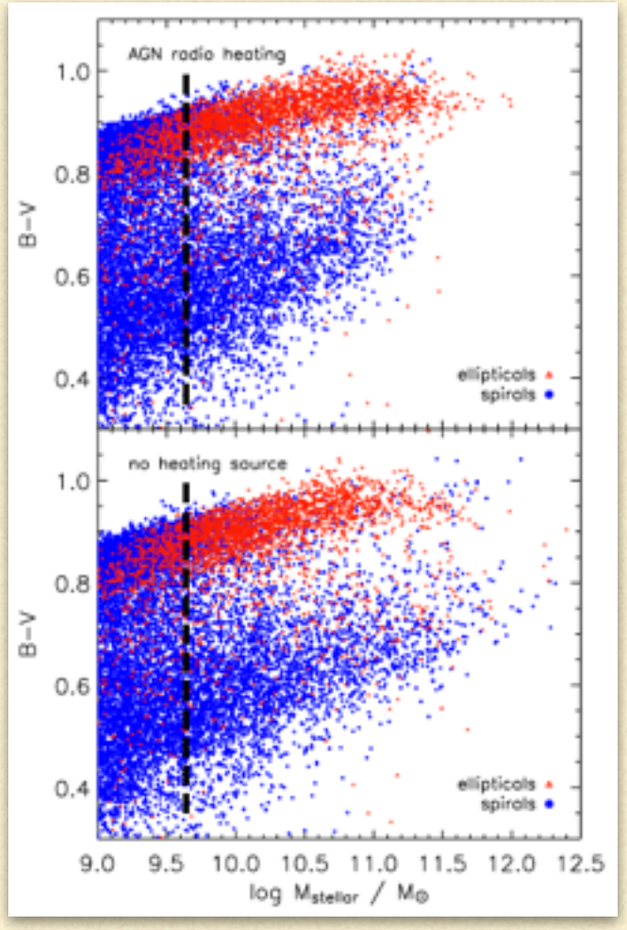
+

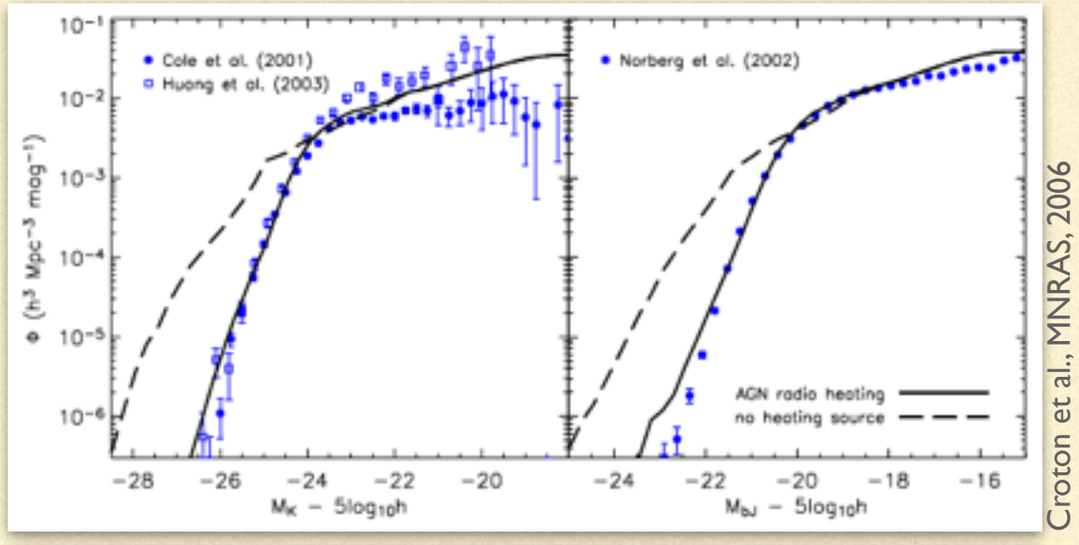
Galaxies
(Croton + 06)

+

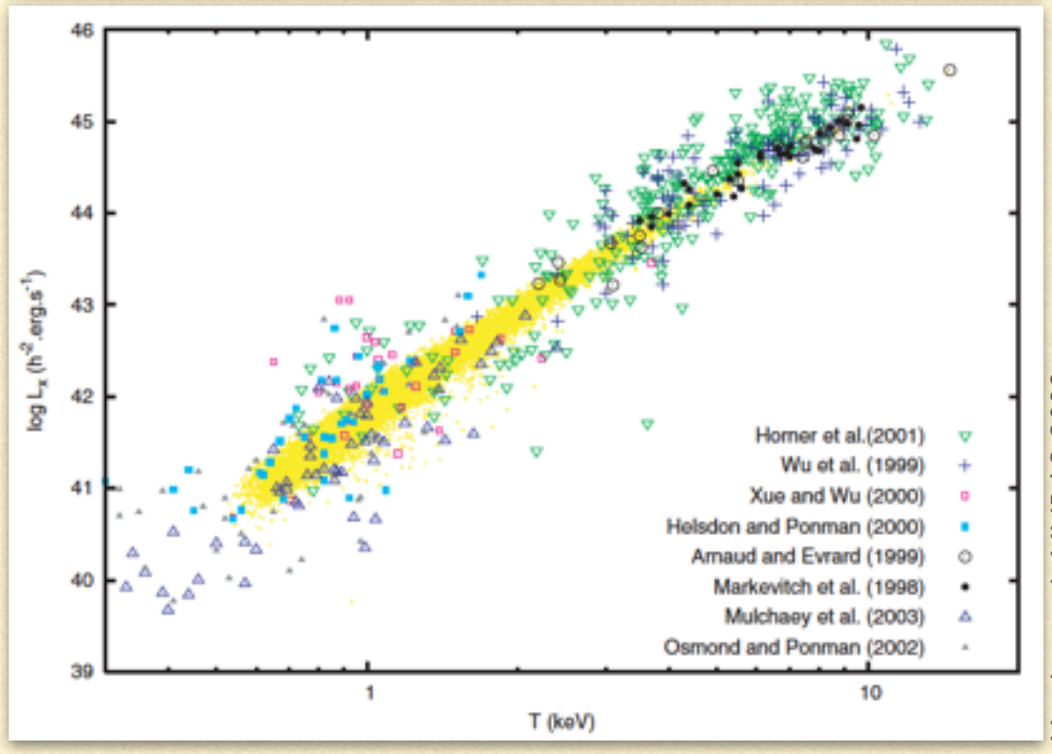
Hot gas (MGS)
(Hartley + 08)

Croton et al., MNRAS, 2006





Croton et al., MNRAS, 2006



Hartley et al., MNRAS, 2008

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

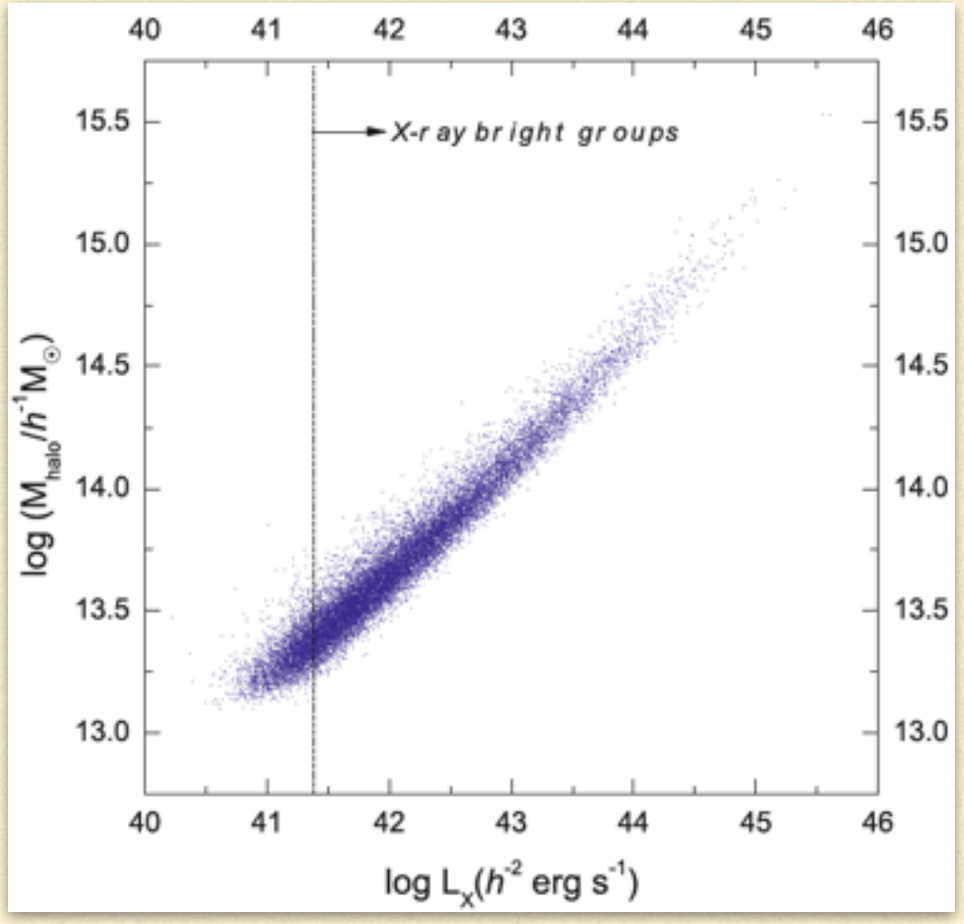
Fossils in Millennium Simulation

Role of the magnitude gap parameter

$$Control\ 1: \ 0.8 \leq \Delta m_{12} \leq 1.0$$

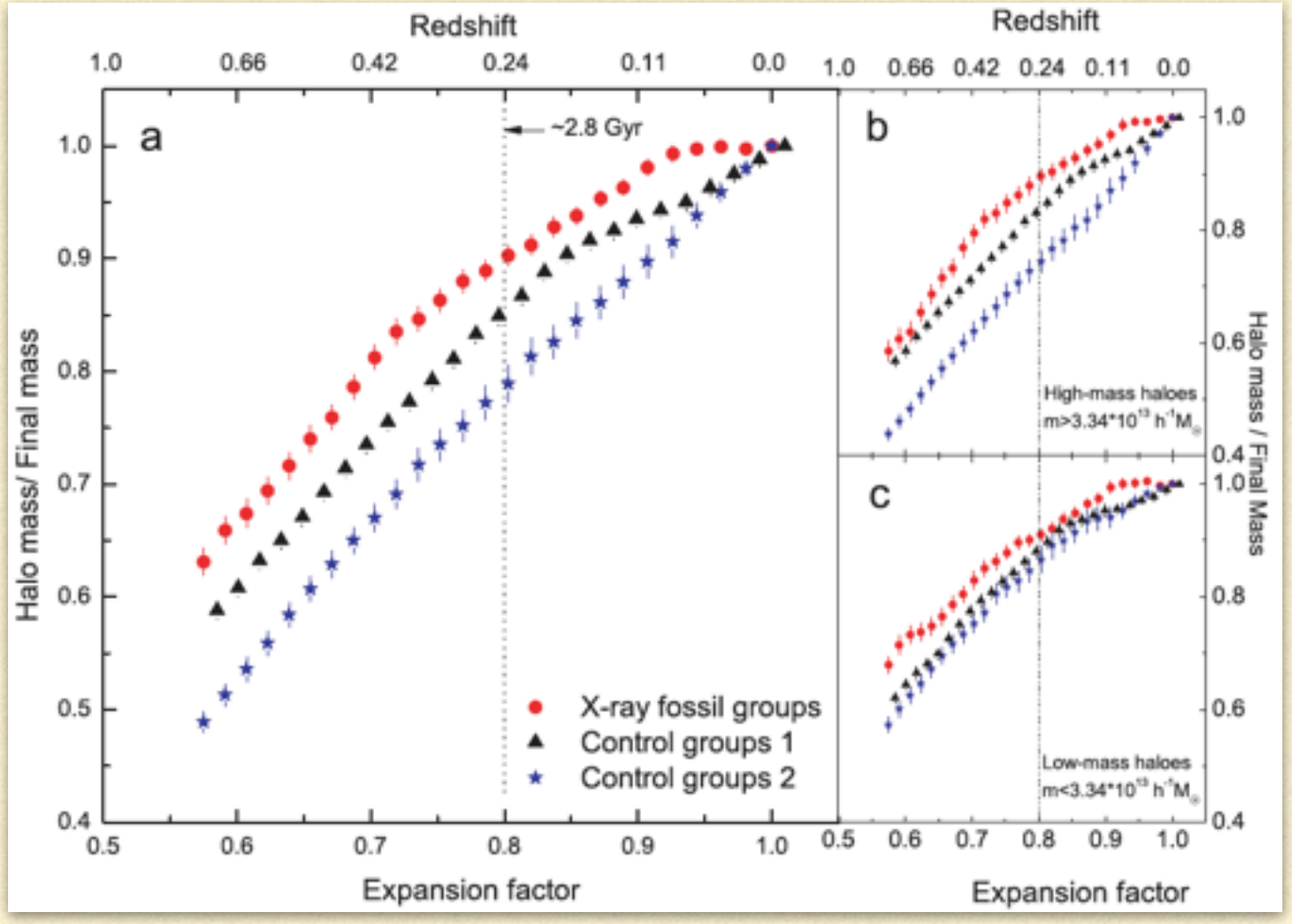
$$Control\ 2: \ 0.1 \leq \Delta m_{12} \leq 0.3$$

DM + MGC



Dariush et al., MNRAS, 2010

DM + SAM +MGC

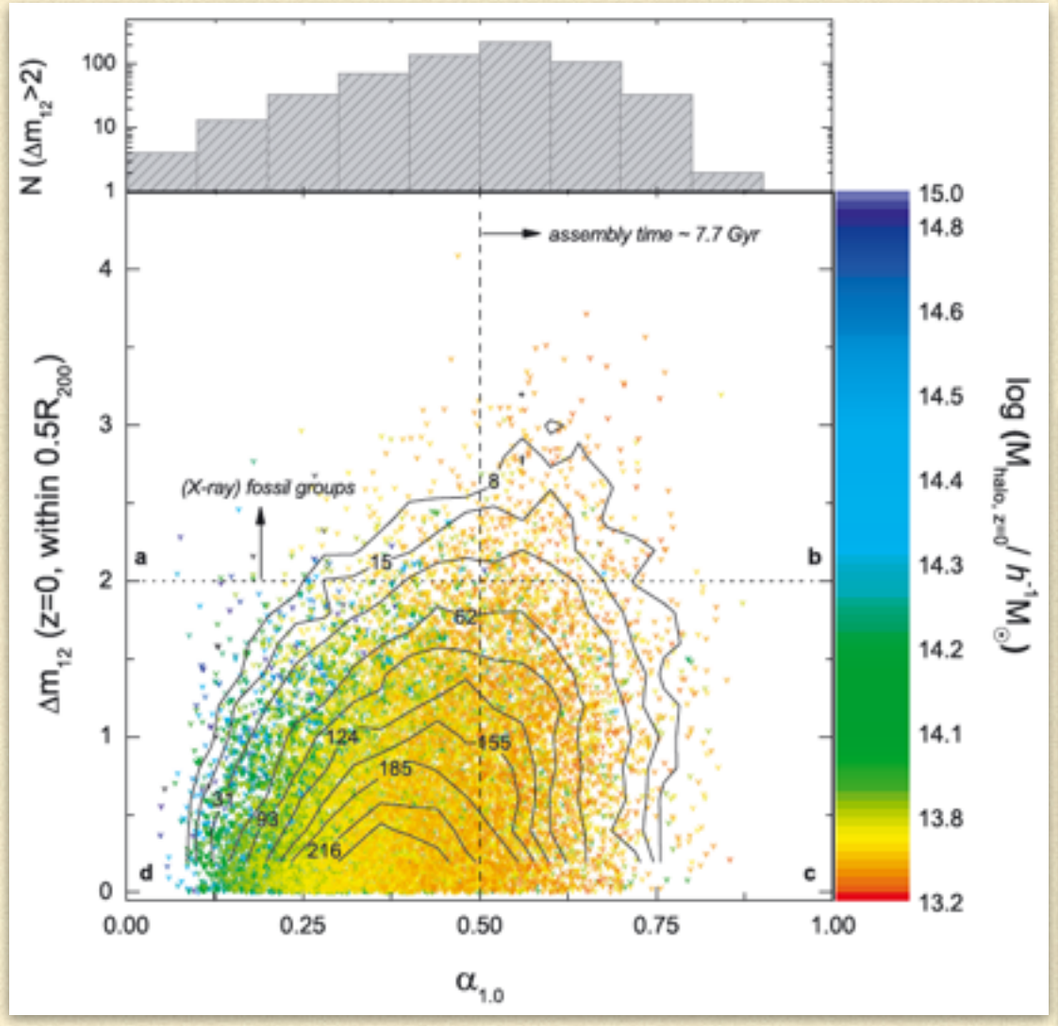


Dariush et al., MNRAS, 2007

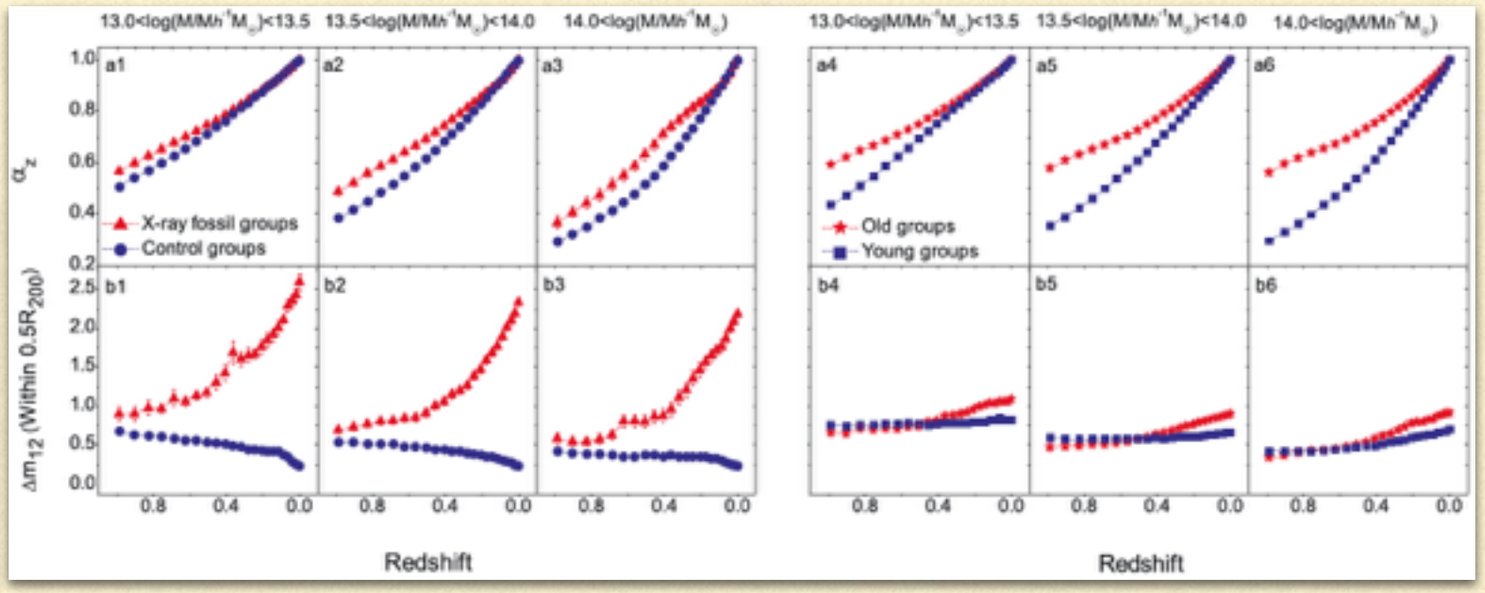
FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

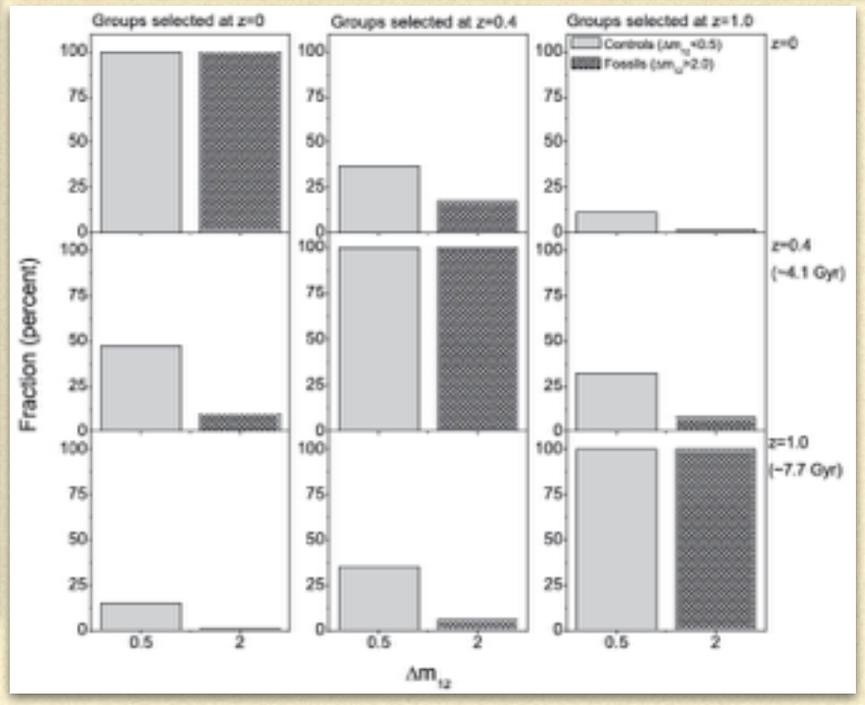
Fossils in Millennium Simulation

Role of the magnitude gap parameter



Dariush et al., MNRAS, 2010





$$\Delta m_{12} \geq 2.0\ mag$$

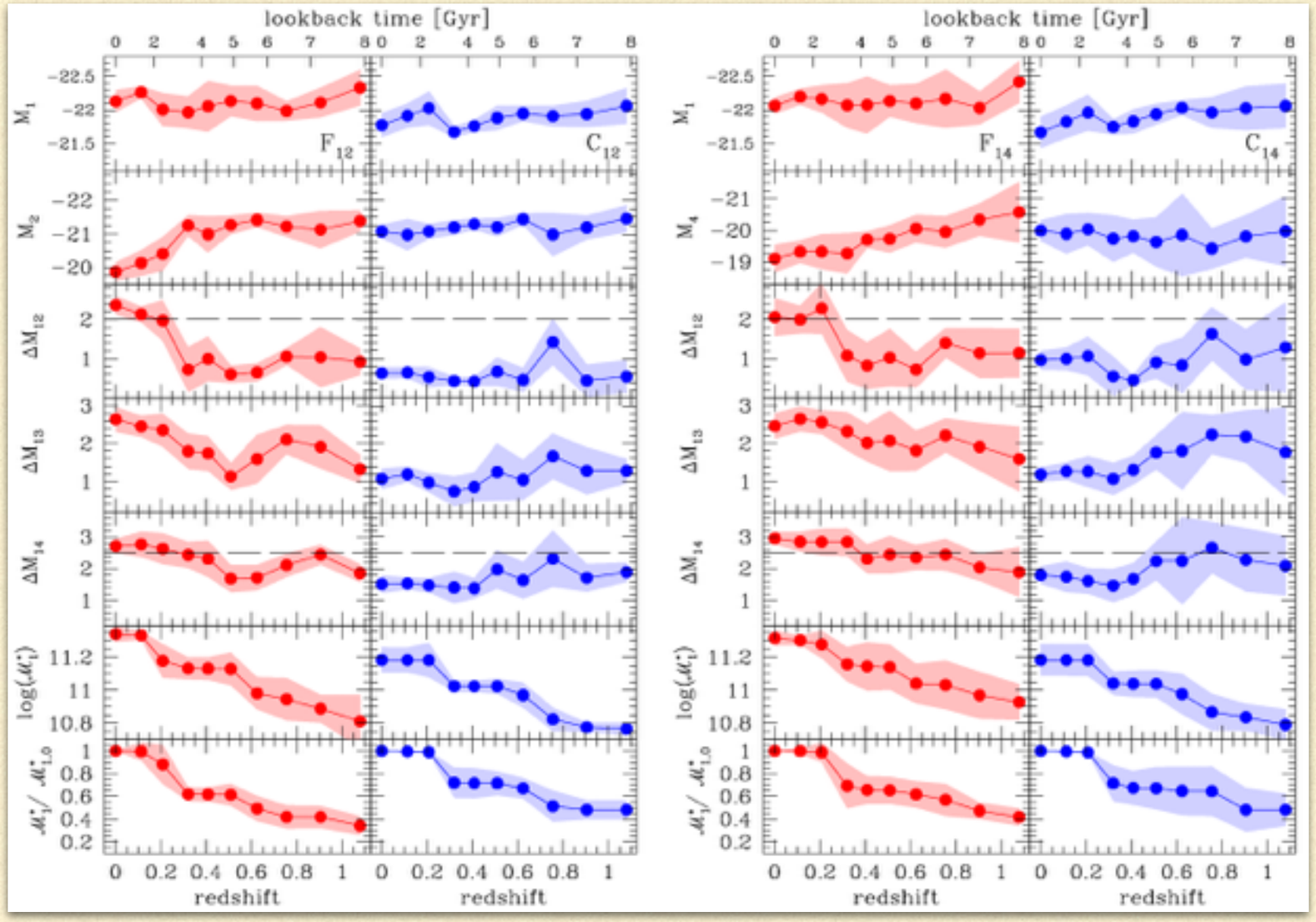
$$\Delta m_{14} \geq 2.5\ mag$$

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

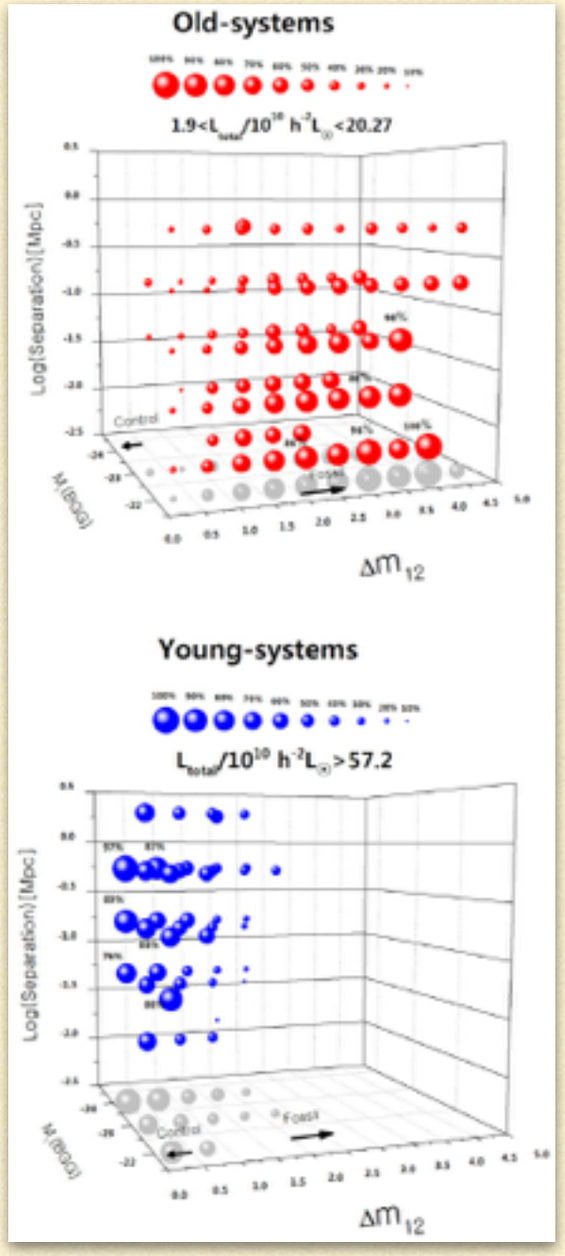
Fossils in Millennium Simulation

Role of the magnitude gap parameter

Guo et al. (2011) SAM



Kanagusuku et al., A&A, 2016 (Millennium run simulation II ; Boylan-Kolchin et al., MNRAS, 2009)

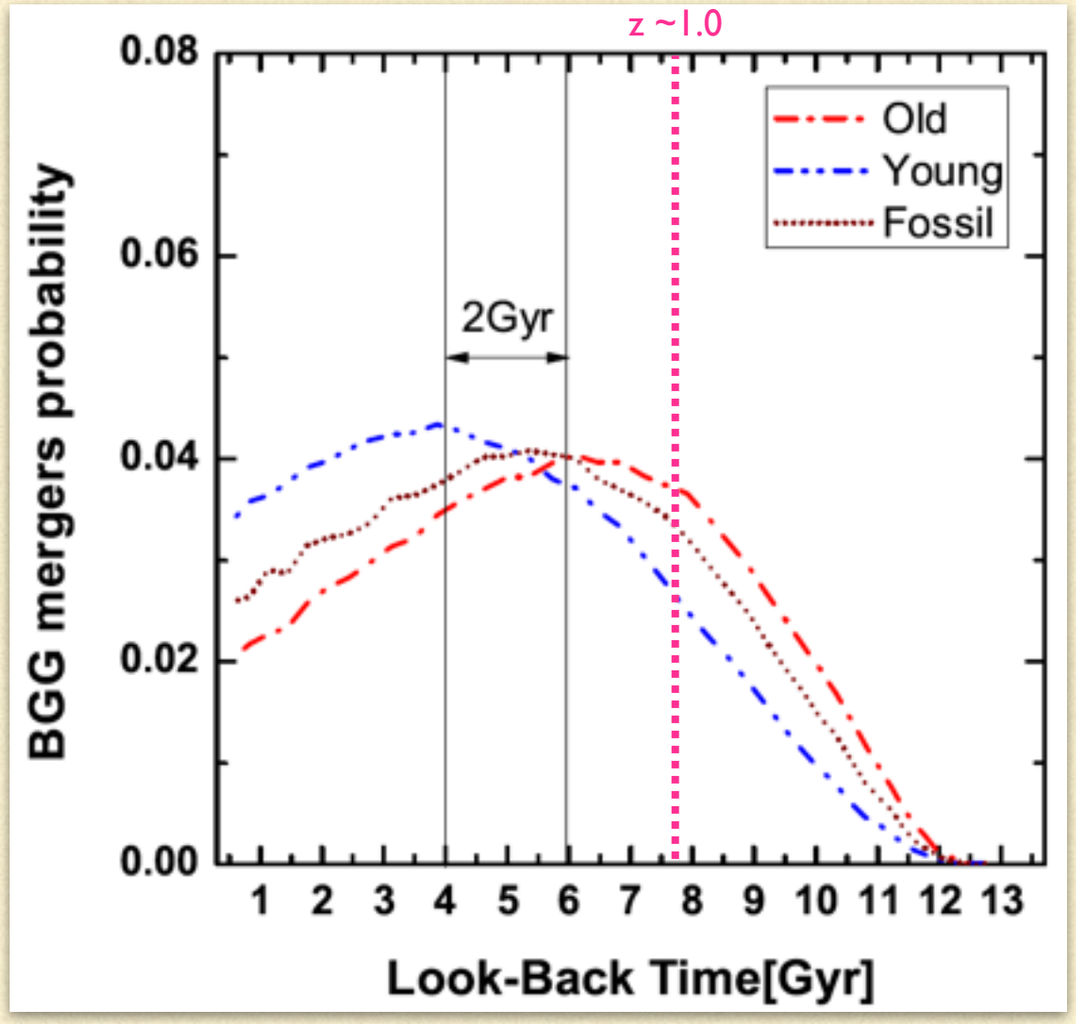


Raouf et al., MNRAS, 2014

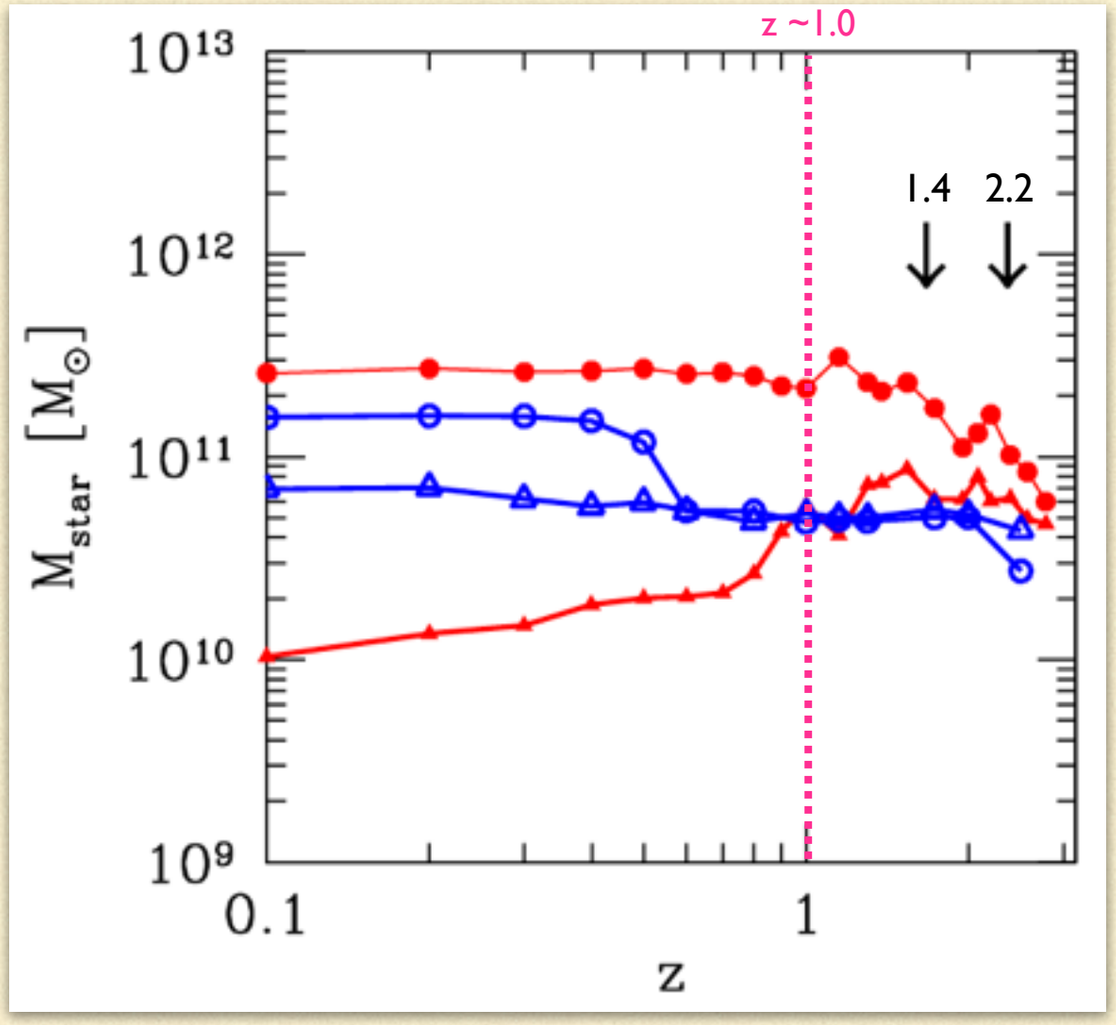
FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

Fossils in Millennium Simulation

Role of the magnitude gap parameter



Hashemizadeh et al. (*In preparation*)

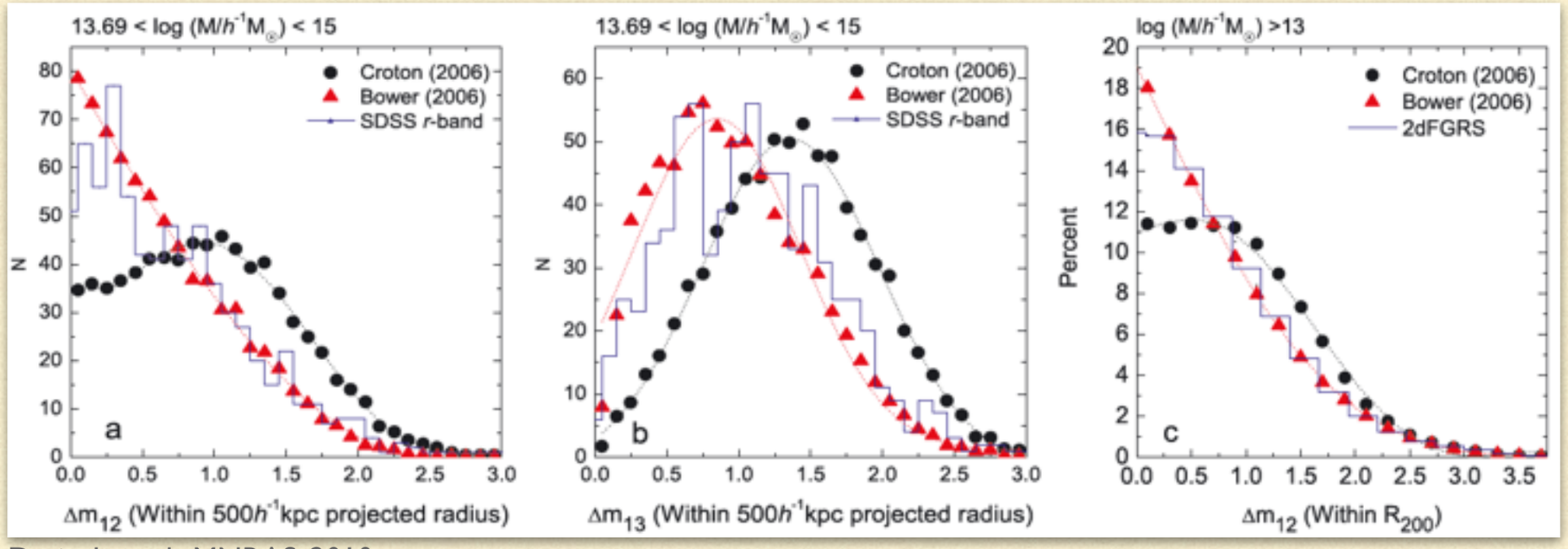


D'Onghia et al., ApJL, 2005

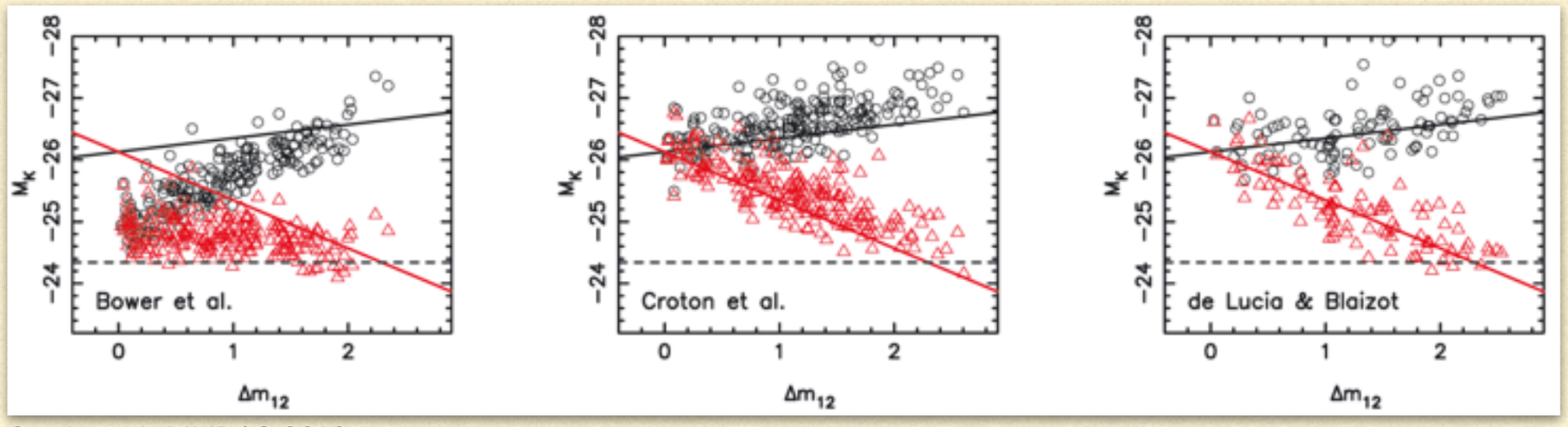
FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

Luminosity of bright galaxies
and
Fossil fraction:
SAM vs Observation vs Hydrodynamics

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

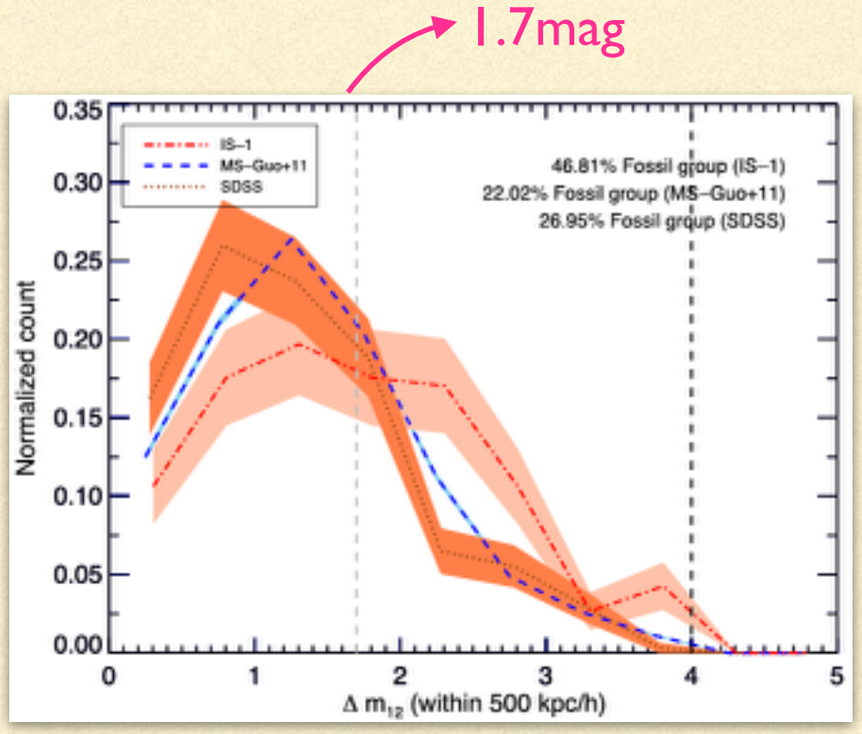


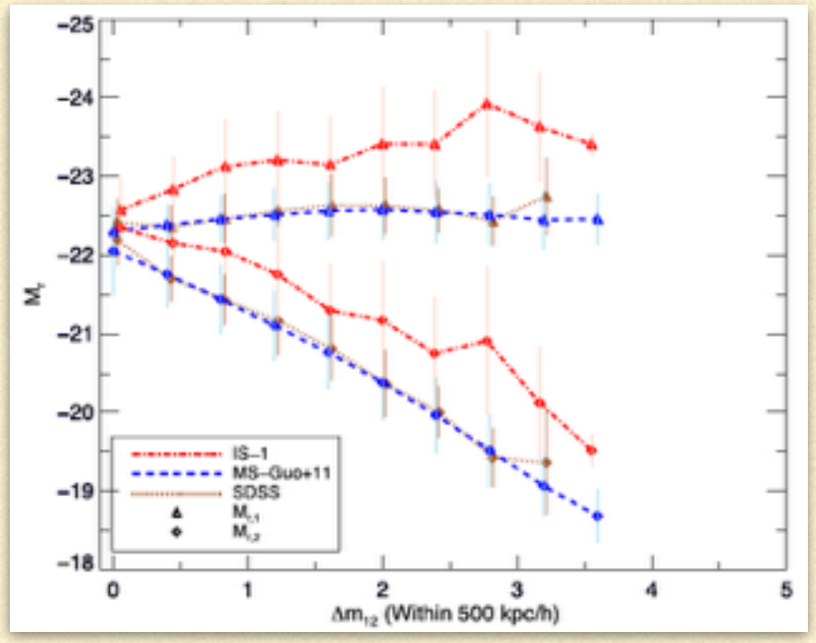
Dariush et al., MNRAS, 2010



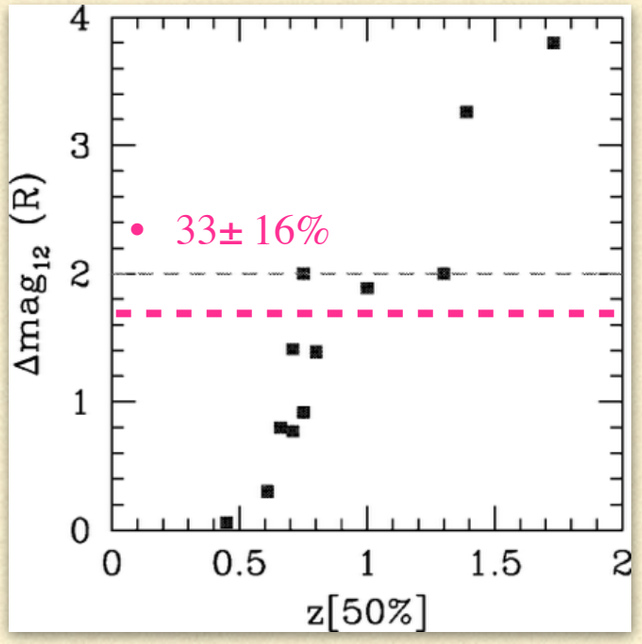
Smith et al., MNRAS, 2010

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS





Raouf et al., MNRAS, 2016 (based on Illustris-1 Simulation ;Vogelsberger et al., Nature, 2014)

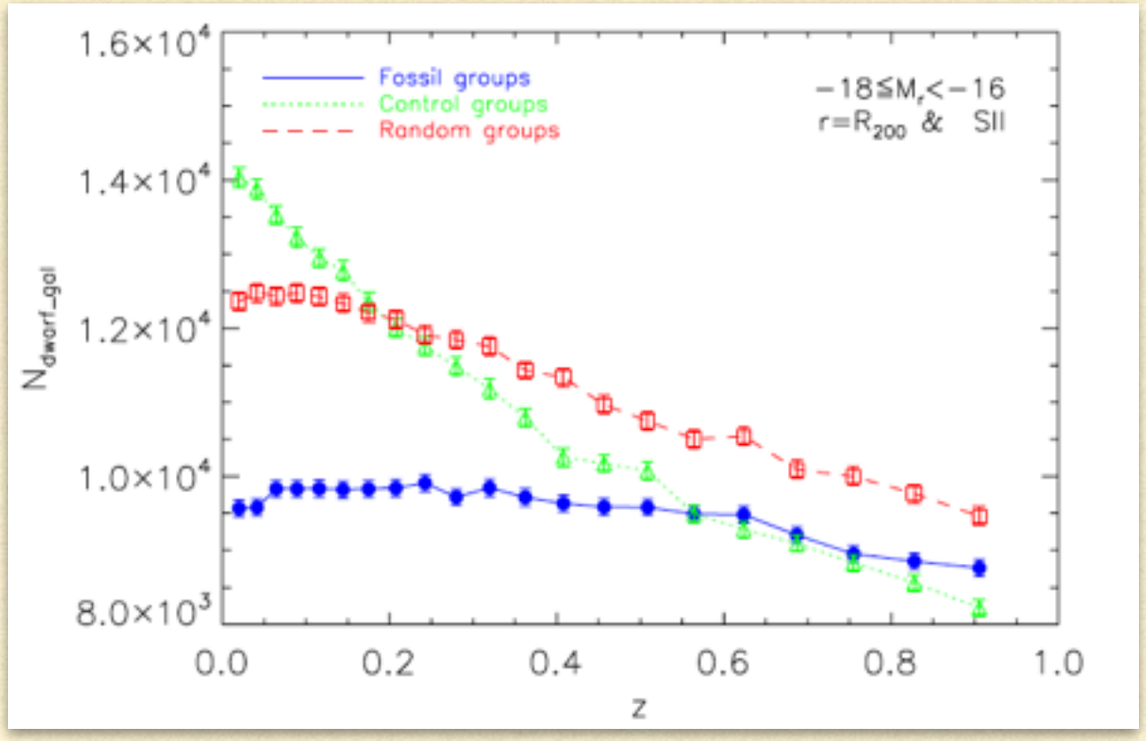


D'Onghia et al., ApJL, 2005

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

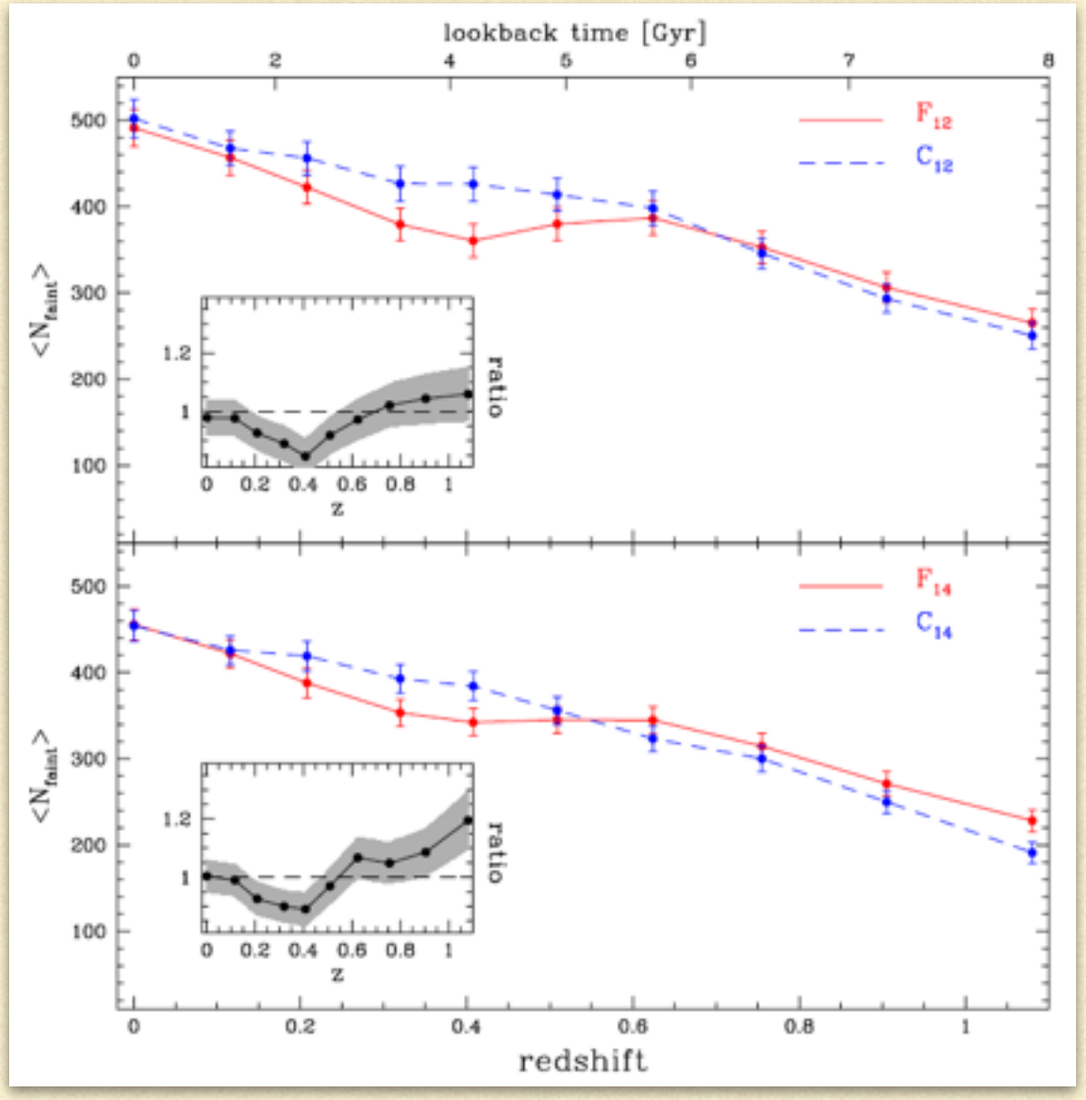
Luminosity function: infall of satellite galaxies

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS



Gozaliasl et al., A&A, 2014 (Millennium simulation I)

Guo et al. (2011) SAM

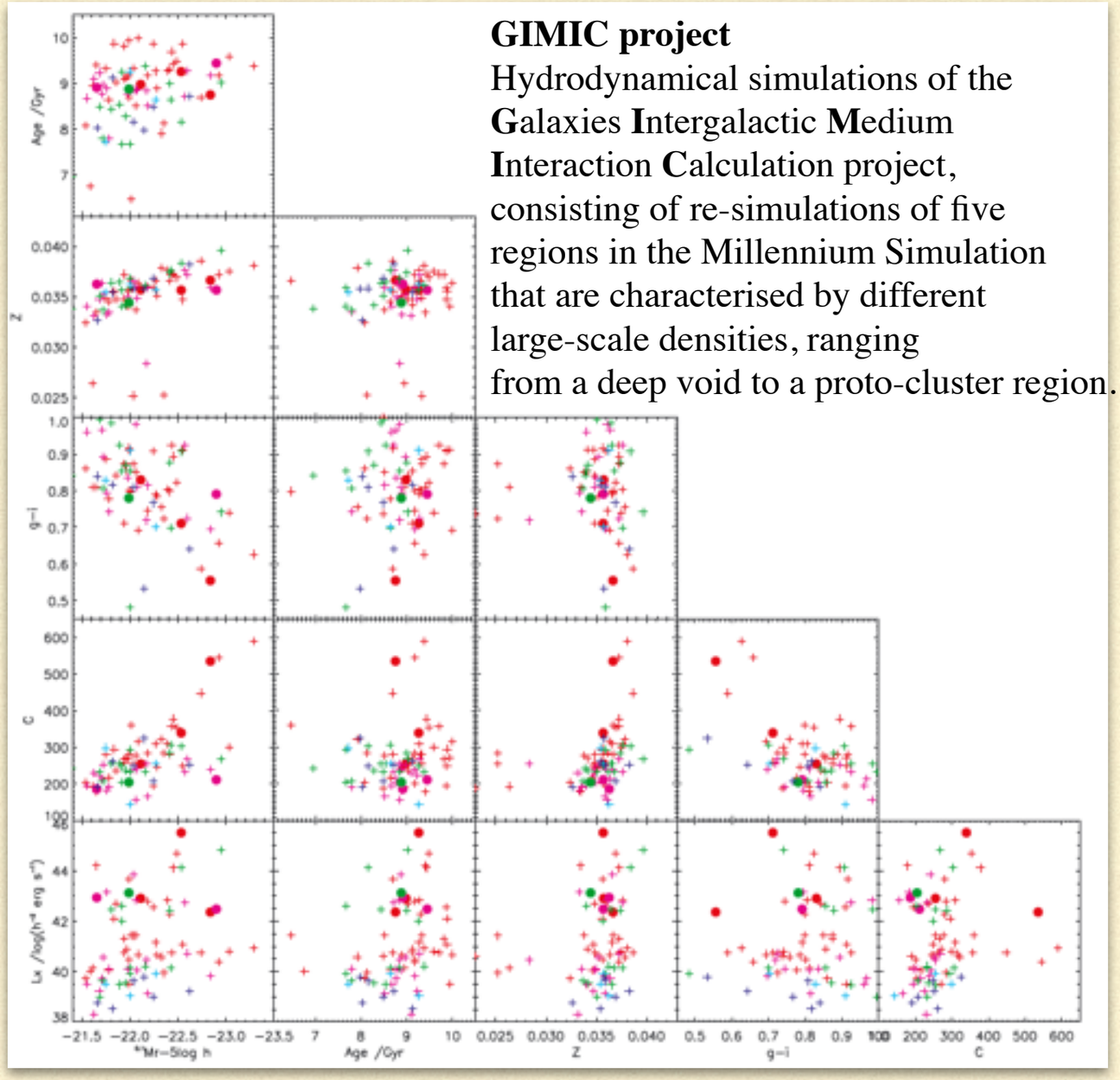


Kanagusuku et al., A&A, 2016 (Millennium run simulation II ; Boylan-Kolchin et al., MNRAS, 2009)

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS

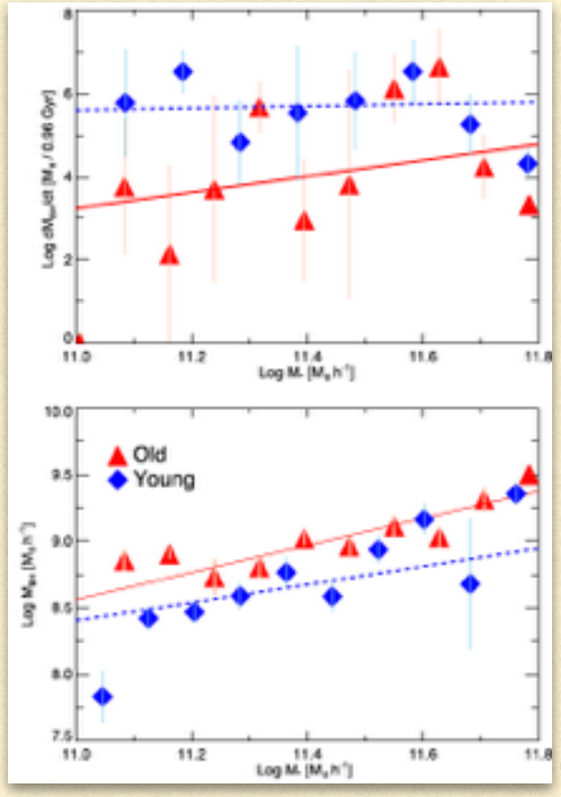
Physical properties of fossils

FOSSIL SYSTEMS IN COSMOLOGICAL SIMULATIONS



GIMIC project
Hydrodynamical simulations of the **G**alaxies **I**ntergalactic **M**edium **I**nteraction **C**alculation project, consisting of re-simulations of five regions in the Millennium Simulation that are characterised by different large-scale densities, ranging from a deep void to a proto-cluster region.

Cui et al., MNRAS, 2011 (GIMIC project, based on Millennium simulation I)



Black Hole Accretion Rate

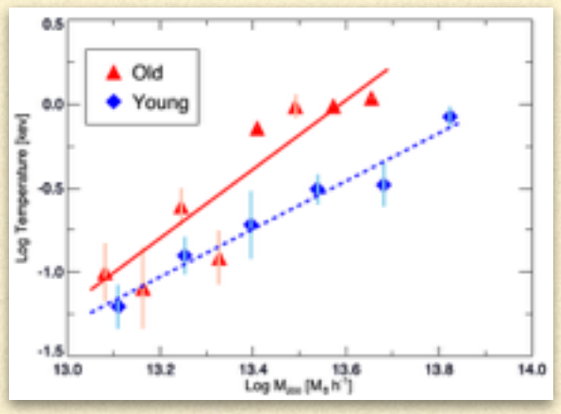
$$Old: \quad \frac{M_{200,z=1}}{M_{200,z=0}} \geq 0.5$$

$$Young: \quad \frac{M_{200,z=1}}{M_{200,z=0}} \leq 0.3$$

Black Hole Mass

Consistent with observation! e.g. Miraghaei et al., MNRAS, 2014

BGG Stellar Mass (M*)



IGM Temperature

Halo Mass (M_{200})

Raouf et al., MNRAS, 2016 (based on Illustris-1 Simulation)

SUMMARY

Motivation

(A) Do simulated galaxy systems, selected based on fossil definition, correspond to

(i) early-formed and

A small fraction of them !

There are far more early-formed systems with small luminosity gaps

(ii) dynamically-relaxed systems ? Not really !

e.g. fossil phase changes quickly

B) If so, do they show distinct characteristics ?

No solid evidence !

SUMMARY

The observational criteria to select FGs is simple, yet encompasses some of the most fundamental physics with regards to the cosmic evolution of galaxy systems. Having said that:

- The fossil criteria, as investigated in the Millennium Simulation (+ associated SAMs), is not a good proxy in order to identify early-formed galaxy systems. Moreover, there is a disagreement between the faction of systems with large luminosity gaps from Semi-analytic models and those estimated based on full-hydrodynamic simulations.

- Statistically, systems having larger magnitude gaps, are more likely to contain early-formed systems. But that does not led for such systems to show characteristics different from normal population of galaxy systems.

- However, simulated galaxy systems selected based on their evolution history, seem to have characteristics similar to those selected observationally and based on fossil definition! This is intriguing and need more investigation/validation (e.g. , SAMs, Illustrious, EAGLE etc.)