The Mass –Radius Relationship of Early Type Galaxies

Cesare Chiosi

Emiliano Merlin

Lorenzo Piovan

Astronomy Department, University of Padova, Italy

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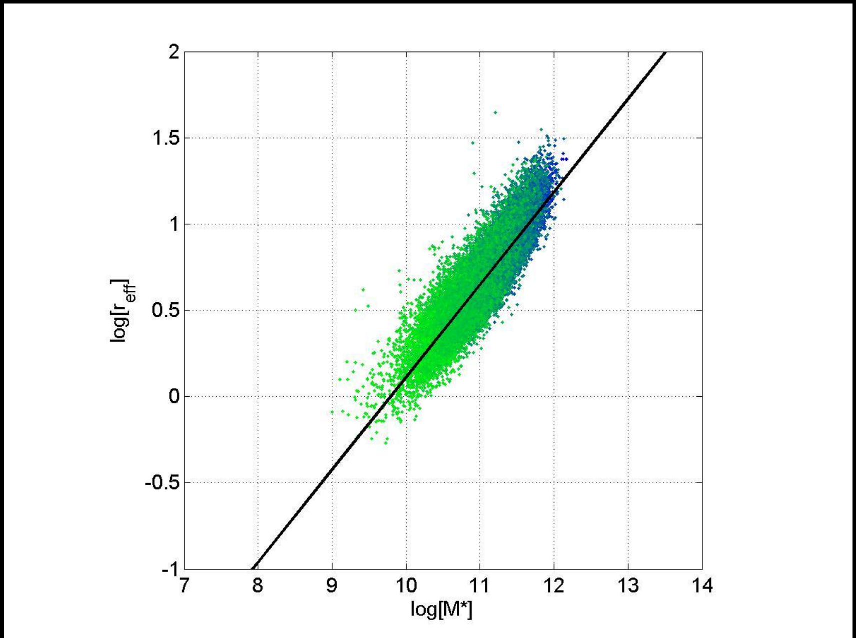
Observational MR
Normal ETGs

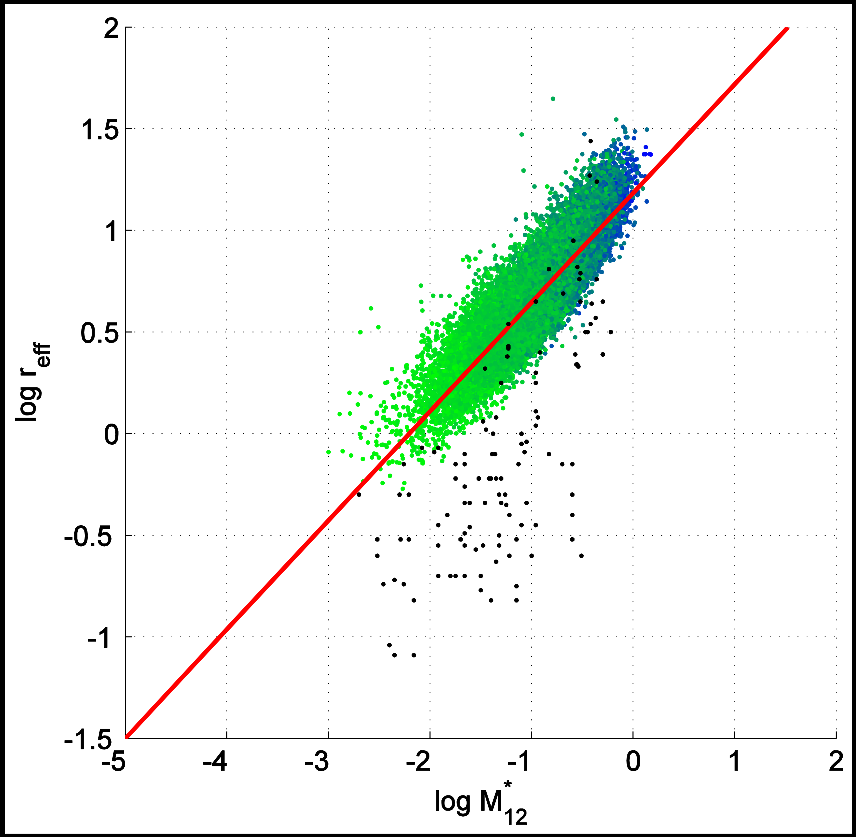


- Bernardi et al (2010)
  95,000 objects

- Best fit (sole SDSS data)

$$\log R_{1/2} = 0.53 \log M_{S,12} + 1.15$$

Observational MR: Compact Galaxies



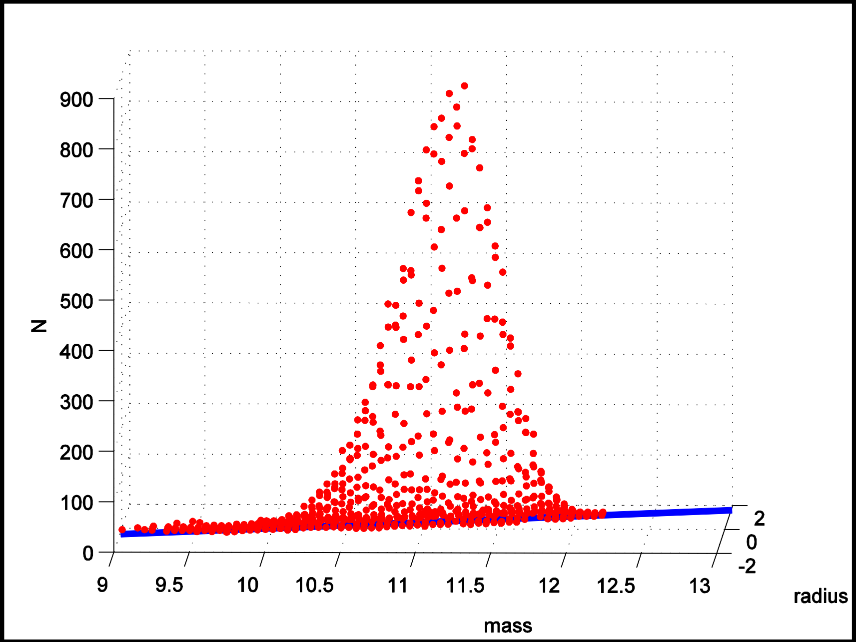
- For $\log M_S > 11$

$$\log R_{1/2} = 1.07 \log M_{S,12} - 11.95$$

- For $9 < \log M_s < 11$

$$\log R_{1/2} = 0.50 \log M_{S,12} - 4.9$$

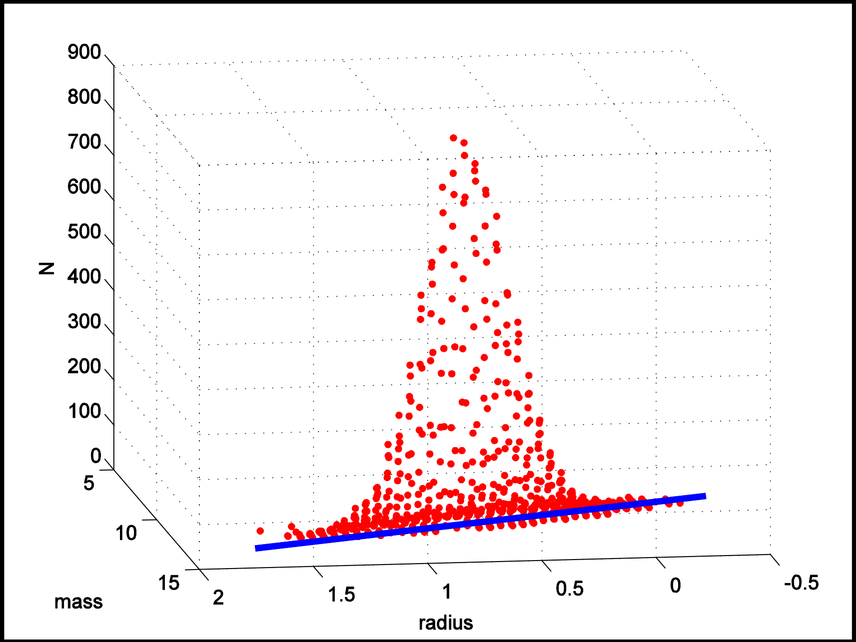
Observational data: distribution in mass



The blue line is the best fit of data on the MR projection

- No compacts included

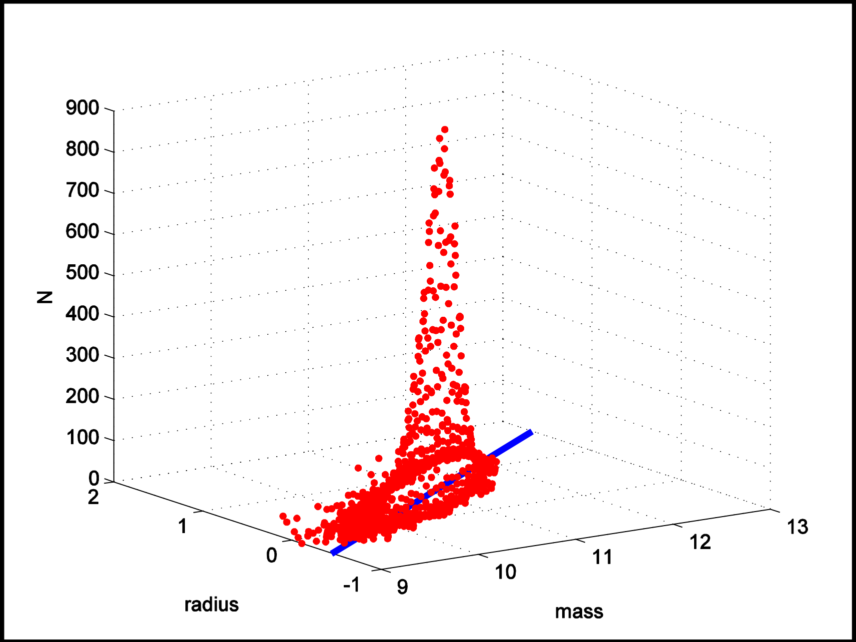
Observational data: distribution in radius



The blue line is the best fit of data on the MR projection

- No compacts included

Observational data: distribution along the best fit line



The blue line is the best fit of data on the MR projection

- No compacts included

Observational MR: Dwarf Galaxies

- In addition to the dwarf galaxies already included in the sample of Burstein et al (1997) we consider the study by Woo et al (2008) of the Dwarfs in the Local Group, from which we get

$$\log R_{1/2} = 0.3 \log M_{s,12} + 0.9$$

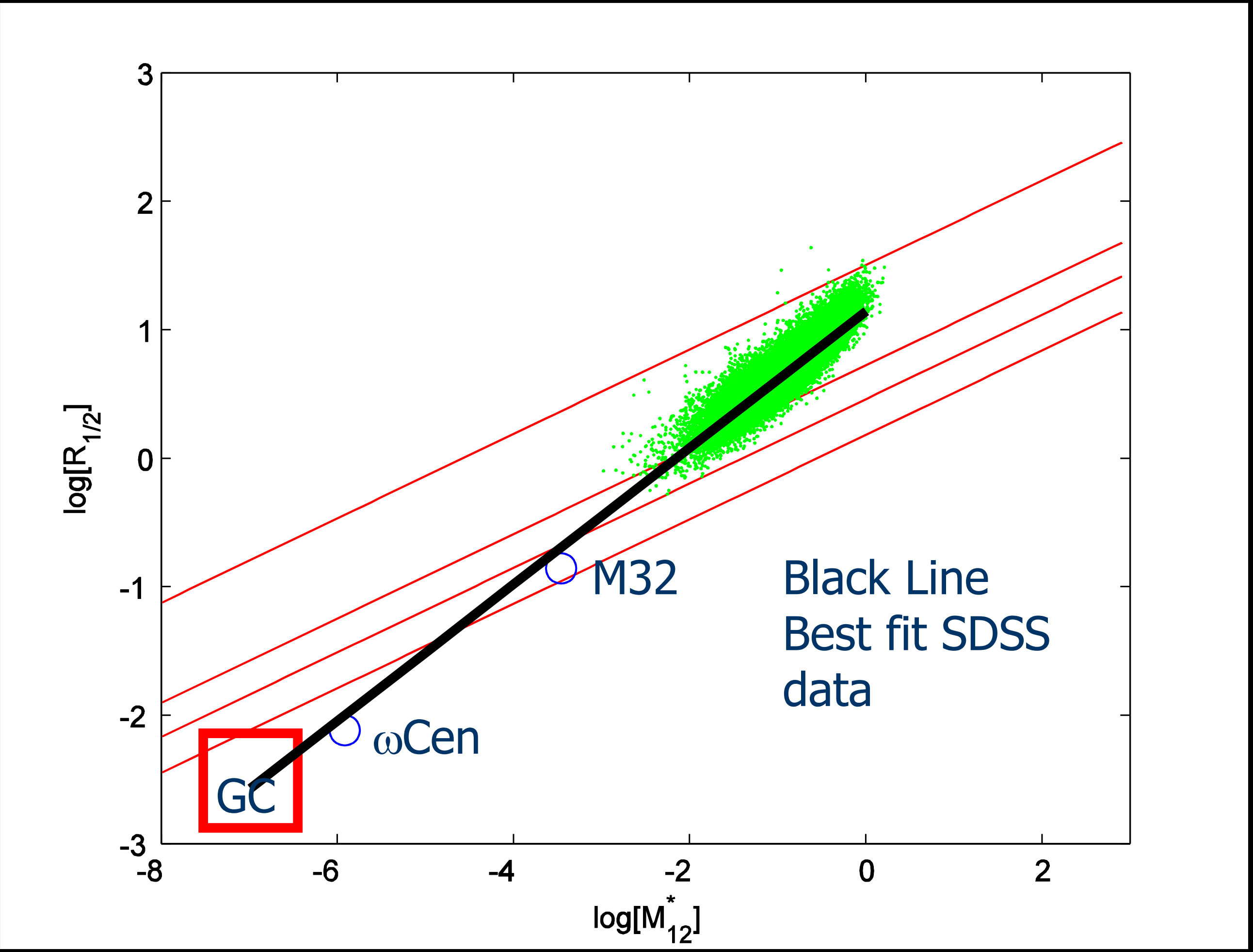
Observational MR: Globular Clusters, ωCen, M32

- Finally, we consider also the group of Galactic Globular Clusters and the two dwarf galaxies ωCen and M32. Data from Burstein et al (1997)

Observational data: Conclusions

- Tight mass-radius relation for massive galaxies (slope 0.53, about 1 at the top end)
- More dispersed for the dwarf galaxies (slope 0.2 to 0.3)
- Globular Clusters, ωCen, and M32 fall along the line of normal ETGs

Overall View of the MR-plane



NB-TSPH Models in a Nutshell

- For complete reports see Merlin et al (2011, 2010), Merlin & Chiosi (2006, 2007), Chiosi & Carraro (2002).
- Two groups of models
- Cosmological initial conditions (ΛCDM Universe)
- Local initial conditions
- For the present aims, they can be used together

Initial Over-density

- Each model starts from a given initial density contrast of the cosmological background, given total mass (DM + BM), and initial redshift

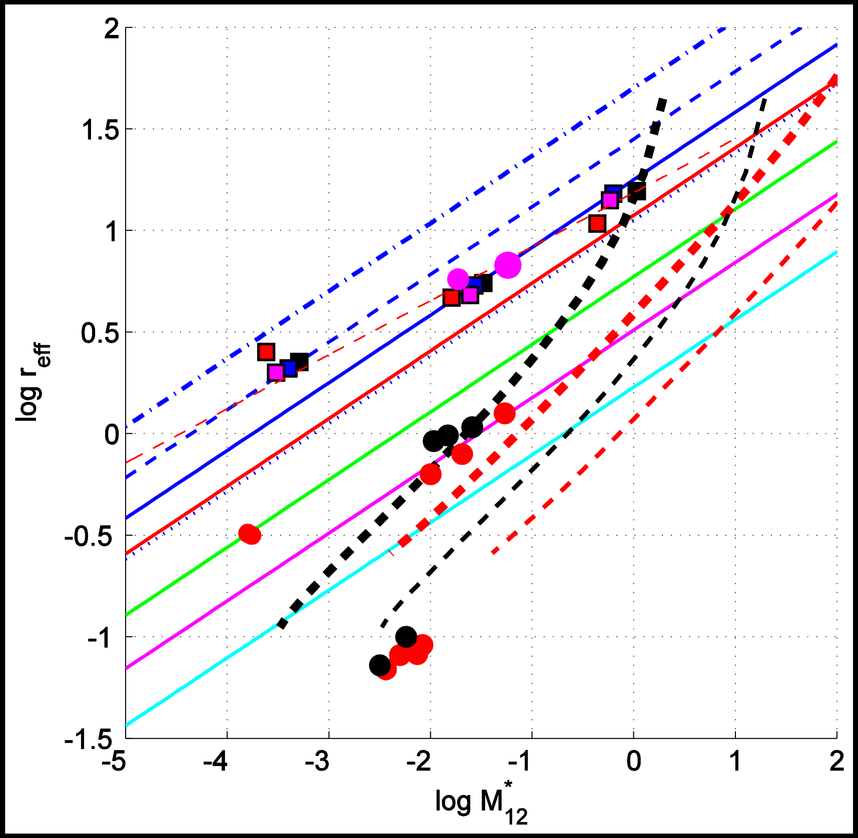
$$\frac{\delta\rho}{\rho} = \frac{\rho_p - \rho_{bg}(z)}{\rho_{bg}(z)} = \frac{<\rho_p>}{\rho_{bg}} - 1$$

- Star formation $d\rho_s/dt = \varepsilon_s \rho_g / t_{ff}$

Initial Over-density

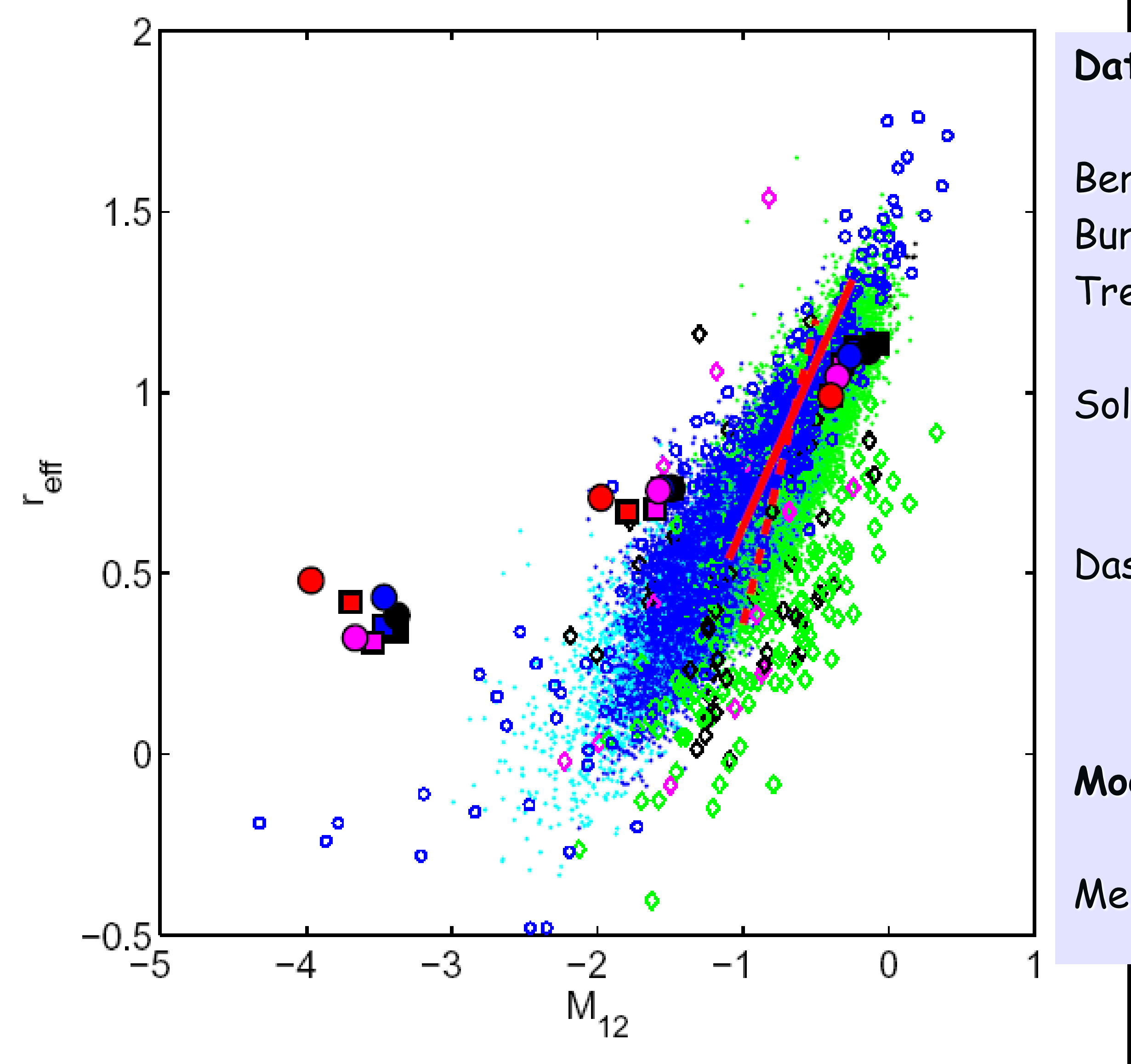
- Where ε varies from 1 (standard models) to 0.1 (ancillary models).
- This can allow us to evaluate the effect of local initial density……i.e. not due to cosmological fluctuactions (acting on DM) but cooling of BM (gas) inside the DM potential well.
- For each over-density (redshift) there is one MR along which collapsed objects of any mass are located. Each z has its own MR.

View of the MR plane for Selected Models



- Note the role of the overdensity and efficiency of star formation

Modern Models & Data



Data from

Bernardi et al (2010): small points

Burstein et al (1997): open circles

Treu et al (2005): diamonds

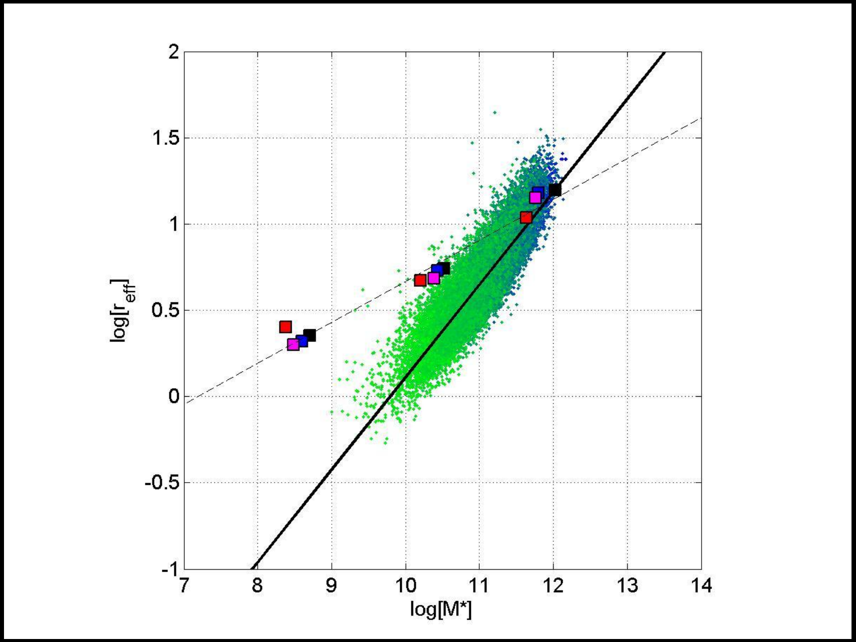
Solid red line: best fit of Guo et al. (2009)

Dashed red line: evolutionary path of van Dokkum et al. (2010).

Models from

Merlin et al. (2011)

Models + Data



- Given an initial density (redshift), the higher the mass the closer is the model to the observational MR.
- This holds at any redshift.
- Is the MR made only of galaxies falling close to the highest mass value?

Evolution at constant E_G/M

- The initial values of R_{200} and M_T of the models obey the relation

$$R_\lambda = 0.0962 \times \lambda^{-1/3} h^{-2/3} (1+z)^{-1} {M_T}^{1/3}$$

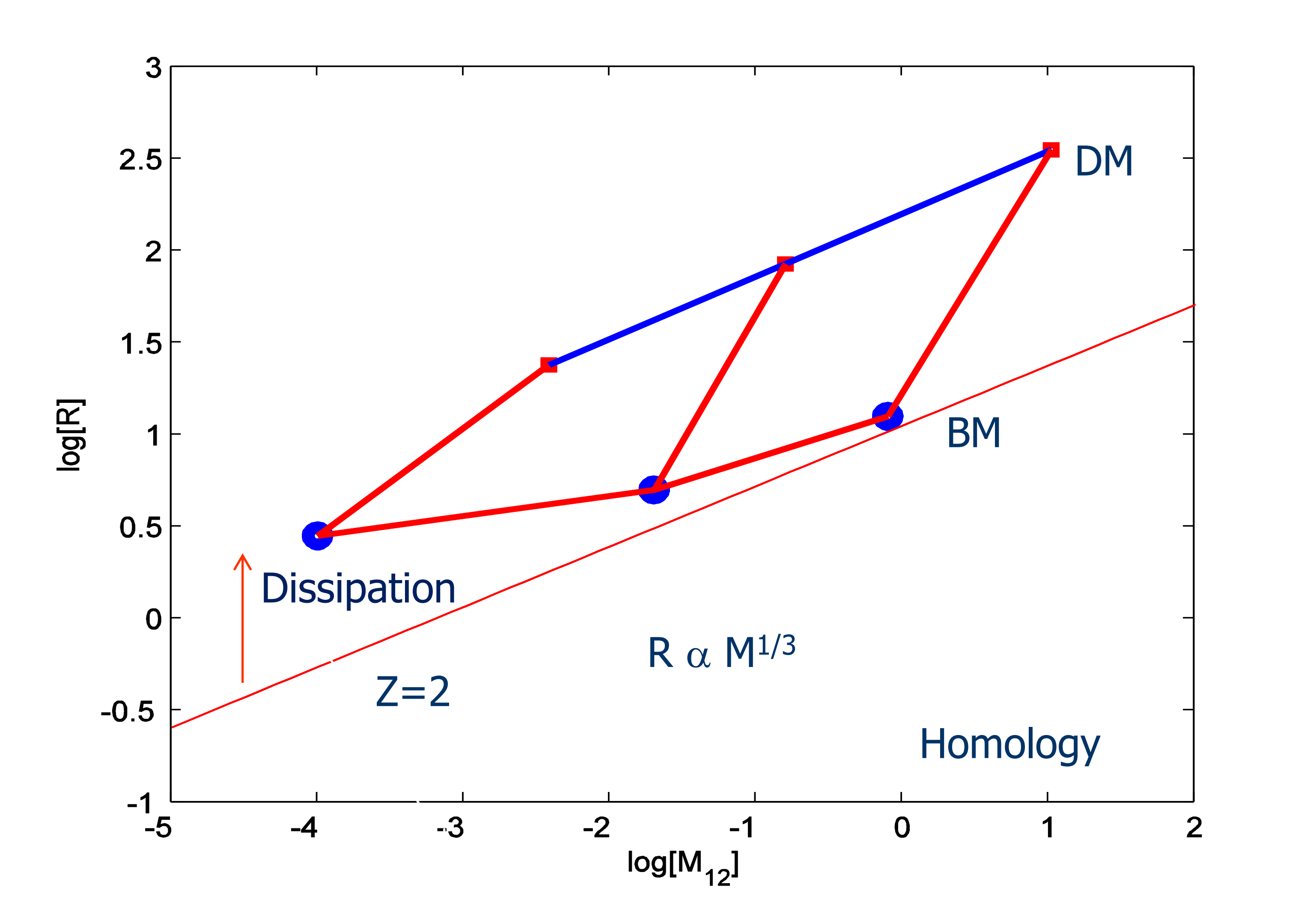
- The present day values of Re and Ms obey a similar relation so that we can evaluate the mean values of $\langle R_{200}/R_e \rangle$ and $\langle M_T/M_s \rangle$

- From which we derive that

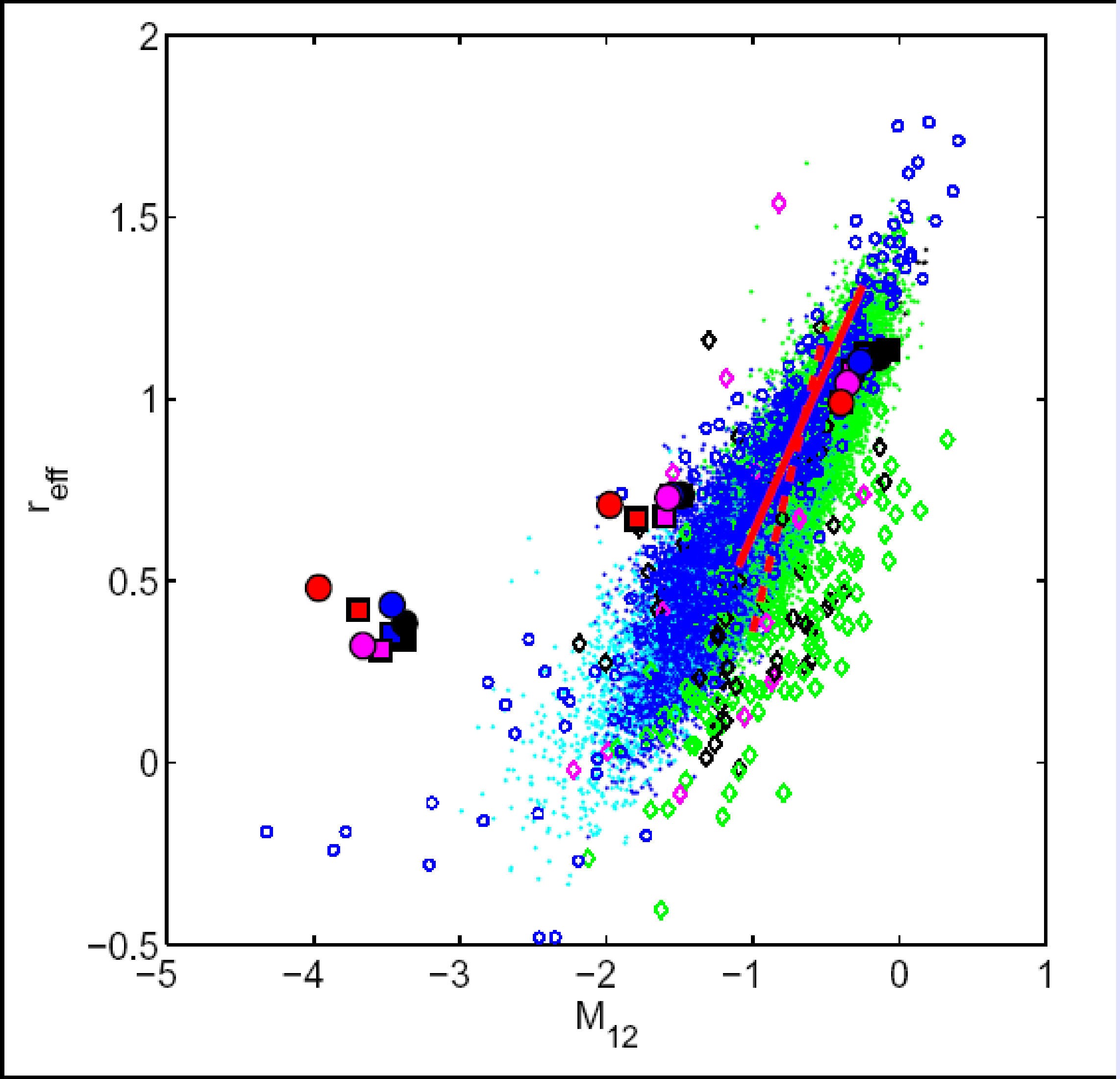
$$\langle \frac{M_s}{R_e} \rangle \cong \langle \frac{M_T}{R_{200}} \rangle$$

- The evolution occurs at constant gravitational energy per unit mass!

Evolution at constant E_G/M



Mass-Radius: Data + Models



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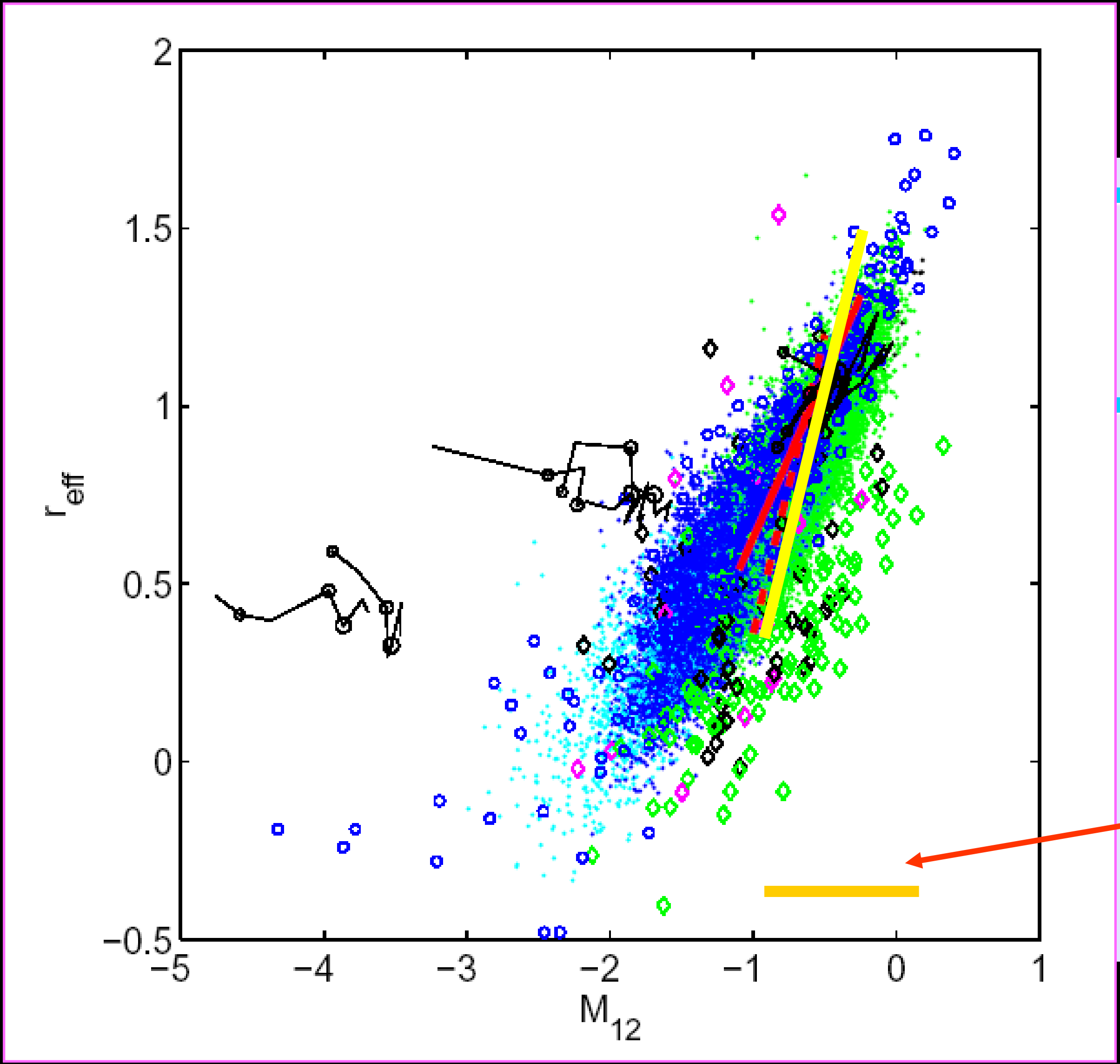
Models from

Merlin et al. (2011)

Mass-Radius: Path of Models



- Evolutionary path of models with different mass and initial density
- Yellow line the “evolutionary path” of van Dokkum et al (2010)

Re a M^2

Range of data

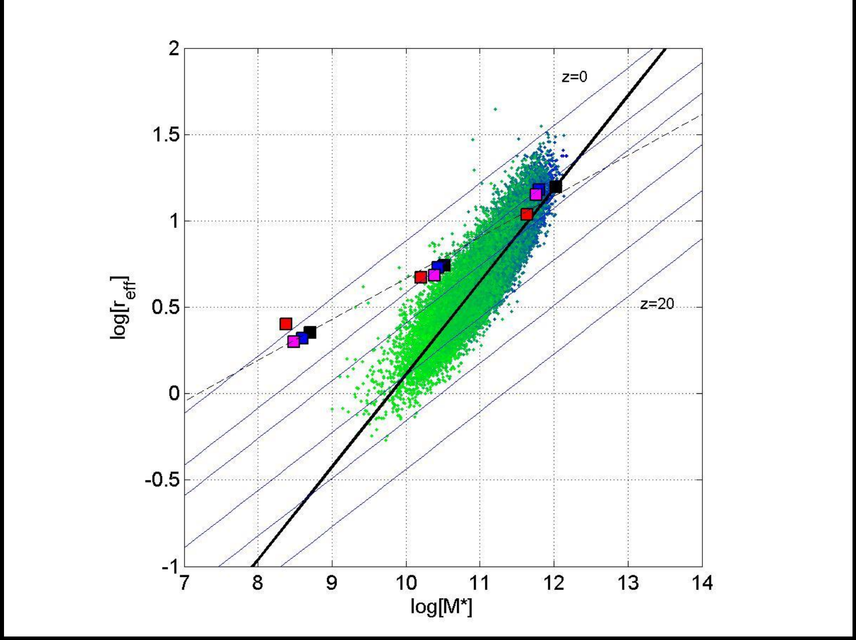
Mass-Radius: Comments on the Path

- Massive galaxies from the very initial stage and during the whole process of mass assembling (fully equivalent to a series of mergers) tend to remain near the place in which they are born. In any case, while assembling more mass, they tend to evolve at nearly constant radius. Only the most massive ones show some tendency to follow a law like R_e a M^b where b goes from 1 to 2.

- In any case with these models it is hard to interpret the "so-called evolutionary path" predicted by van Dokkum et al (2010) R_e a M^2 . But… →

The MR lines of Constant Initial over-density

$$R_{1/2} = 0.9\left(\frac{S_S(n)}{0.34}\right)\left(\frac{25}{m}\right)\left(\frac{1.5}{f_\sigma}\right)^2\left(\frac{M_{DM}}{10^{12}M_\odot}\right)^{1/3}\left(\frac{4}{(1+z_f}\right) \quad (4)$$



- Previous expression recast according to Fan et al (2010)

Maximum Extension of the MR-plane: Shepherd Line

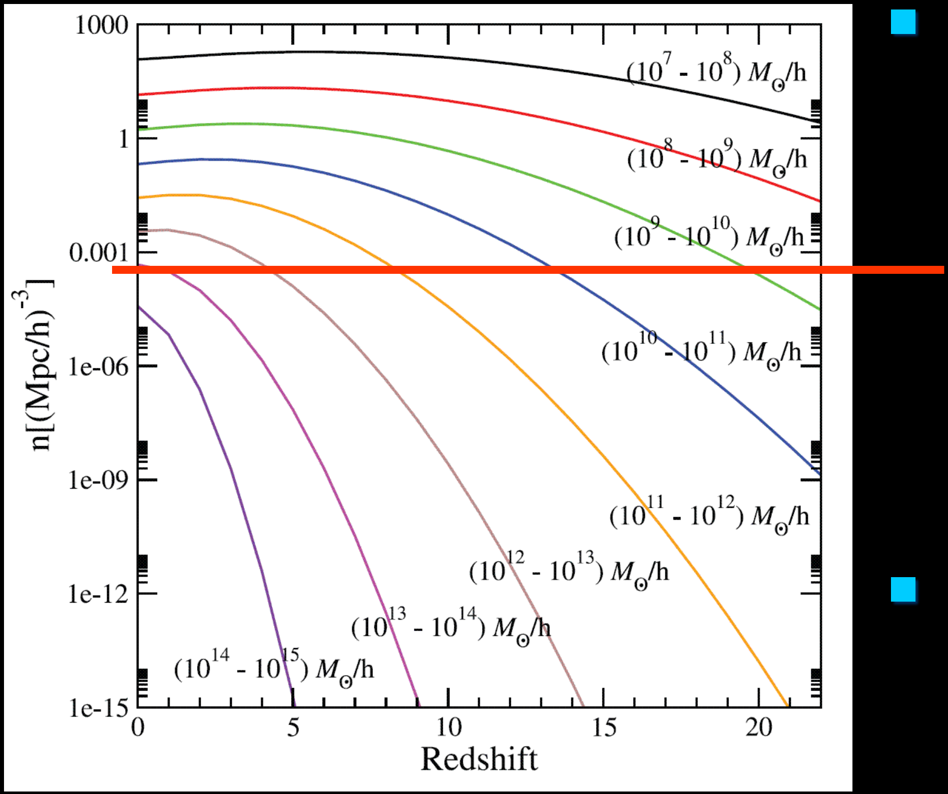
- Start from the study by Lukic et al (2007)

- Choose a scale factor, multiply by it the results by Lukic et al (2007), and for each value of the mass derive the redshft at the intersection →

- M_D and z to be inserted in the relation by Fan et al (2010) to derive the associated baryonic galaxy.

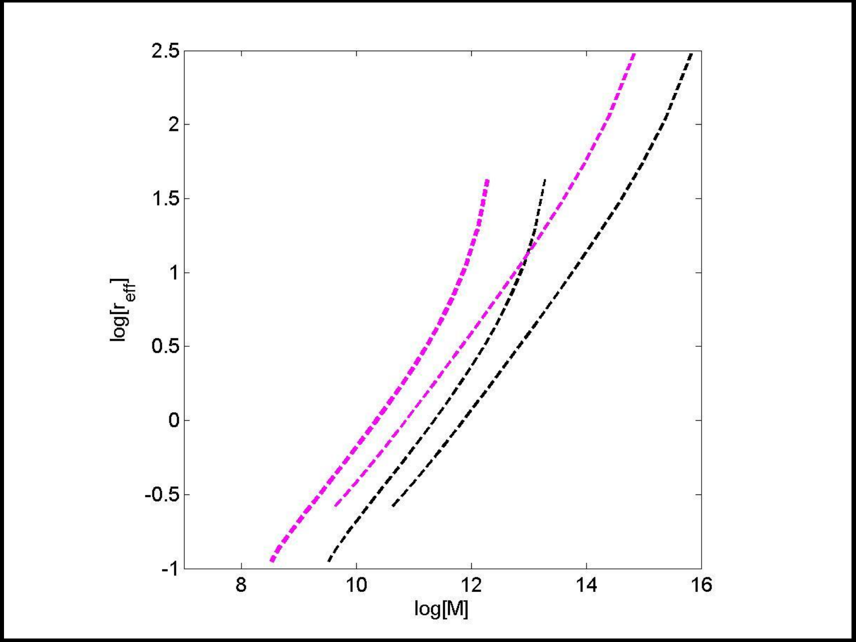
- This is the maximum extension of any MR relation at given redshift. Given an initial density (and other less important parameters), this intersection , named the shepherd line, delimits the maxium extension of the MR relation toward its high mass end.

Lukic et al (2007) plane



- Number density of halos per Mpc^3 as a function of the mass and redshift
- The underlying IMF is from Warren (2003), see also Press-Schechter et al

The line of maximum extension

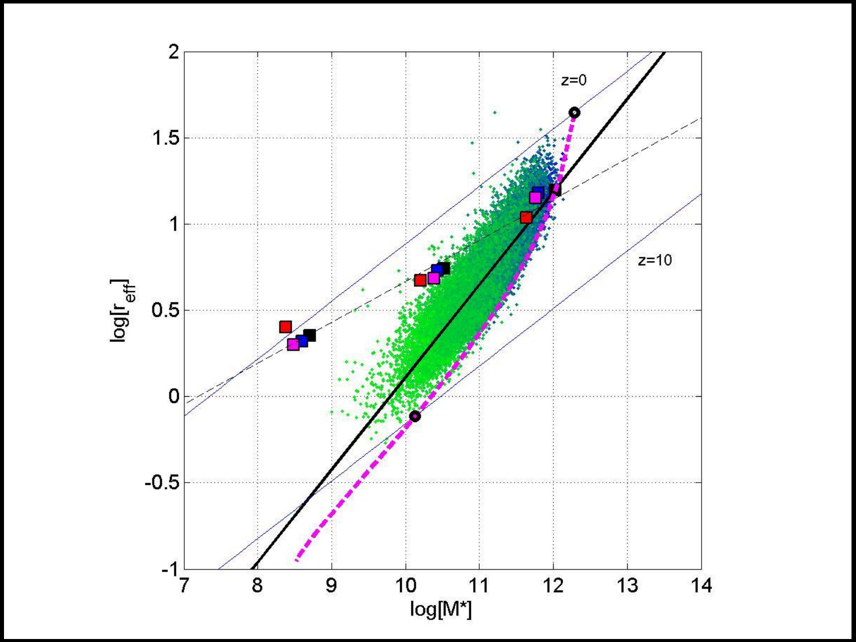


- Two different Norm factors
- Note the change in slope at increasing M. Very important!

BM (magenta)
&
DM (black)

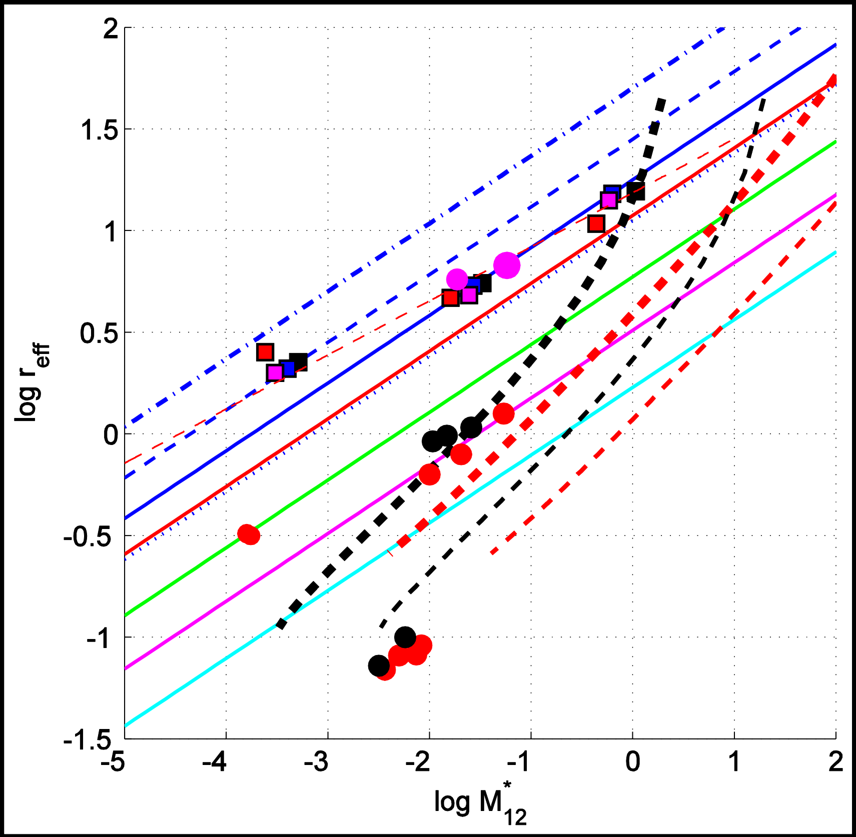
$$\log R_{1/2} = 0.007584(\log M_s)^3 - 0.1874(\log M_s)^2 + 1.908(\log M_s) - 9.027$$

Shepherd line + Data + Models



- The Key Diagram
- Convolution of iso-density lines whose high mass end is bounded by the line of maximum extension, named shepherd line.

Models at varying $\delta\rho/\rho$ and ε_s



- At increasing z, galaxies form at higher and higher initial densities ρ_{DM}.
- If ε_s is high, they soon start forming stars and freeze out their size.
- However, in galaxies born at the same inital density, if star formation is inhibited or delayed (small ε_s) their gas gas cools down and get denser before star formation begins. When this happens they have reached smaller dimensions.

Role of ρ_{DM} & ρ_g

But… What does drive the MR?

- (A) The simple theoretical view of the spherical dissipationless collapse (Gott & Rees 1975). Only the slope.

- (B) The Chiosi & Carraro (2002) view, hovever revised according to Lukic et al (2007) study. Slope, zero point, and thickness.

Case A: Dissiptionless collapse

- Gott & Rees 1975, Faber (1984) Burstein et al (1997).
- Given rms amplitude of primordial density perrtubations δ, where M is the mass at initial redshfìt and n the spectrum of the density fluctuations δ.
- After collapse the structure obeys the relations.
- Inserting n=-1.8 one gets.
- The slope fairly agrees with data from normal/giant galaxies down to Globular Clusters.

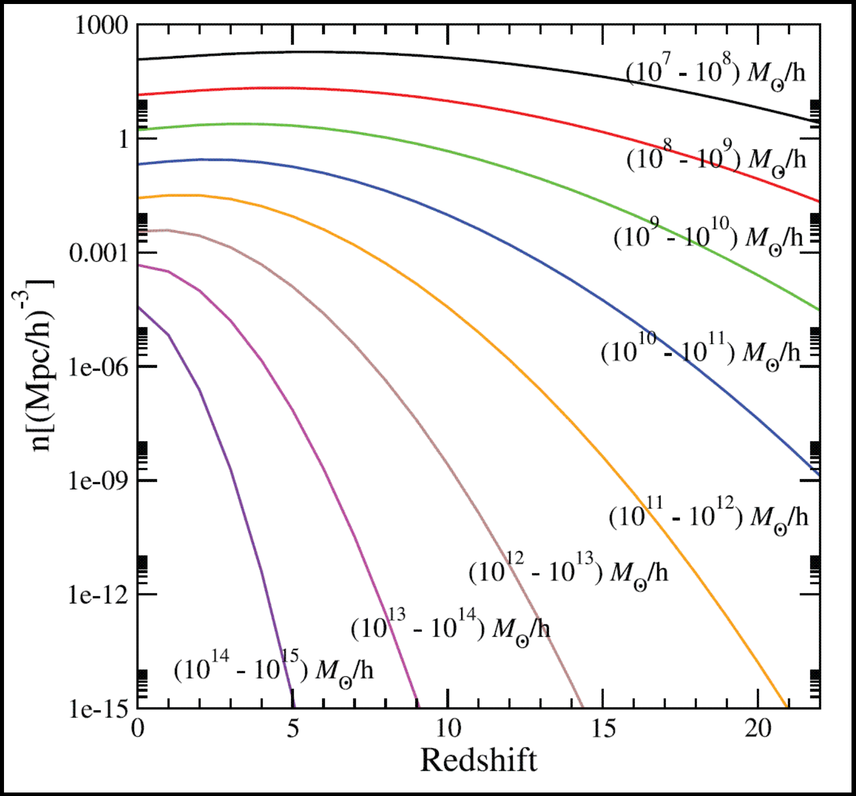
$$\delta \propto M^{-\frac{1}{2}-\frac{n}{6}}$$

$$R \propto \delta^{-1} M^{\frac{1}{3}}$$

$$R \propto M^{\frac{5+n}{6}}$$

$$R_{DM} \propto M_{DM}^{0.53}$$

Case B: Lukic et al. (2007) plane



- Number density of halos per Mpc^3 as a function of the mass and redshift
- The underlying IMF is from Warren et al (2003), see also Press-Schechter

Case B: Lukic et al. (2007) plane

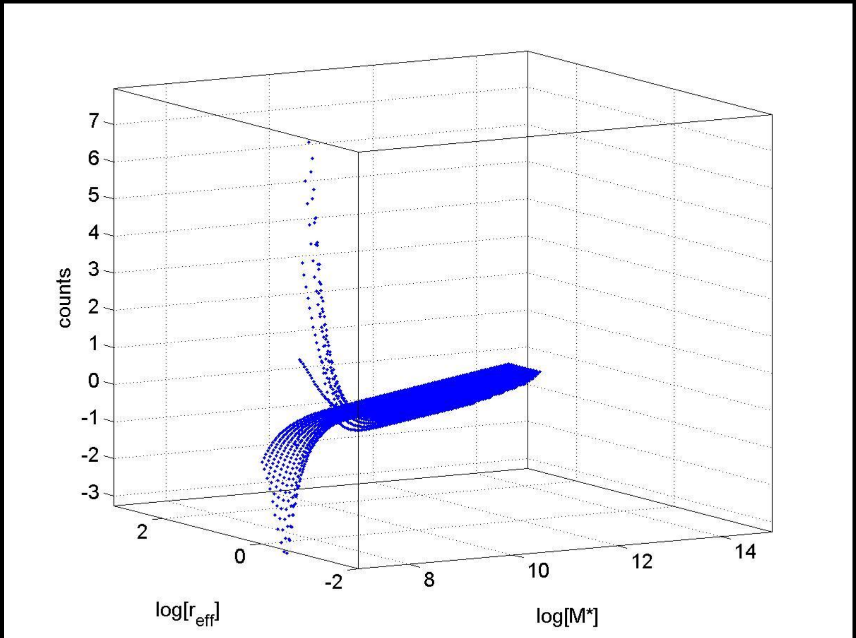
- Analytical fits of the Lukic et al (2007) relations $N(z, M_{DM}) = \sum_{0}^{4} A_n(M_{DM}) * z^n$

- Split the mass and redshift ranges in subintervals of appropriate spacing and explore the whole ranges of values.

- To each point (M_{DM}, z) point we associate a baryonic galaxy (M_s, $R_{1/2}$), by means of the Fan et al (2010) relation or NB-TSPH models ($m=M_{DM}/M_s$ and $f=\sigma_s/\sigma_{DM}$ are needed), and the corresponding dN(z), i.e. number of halos with mass MDM born between z ad z+dz.

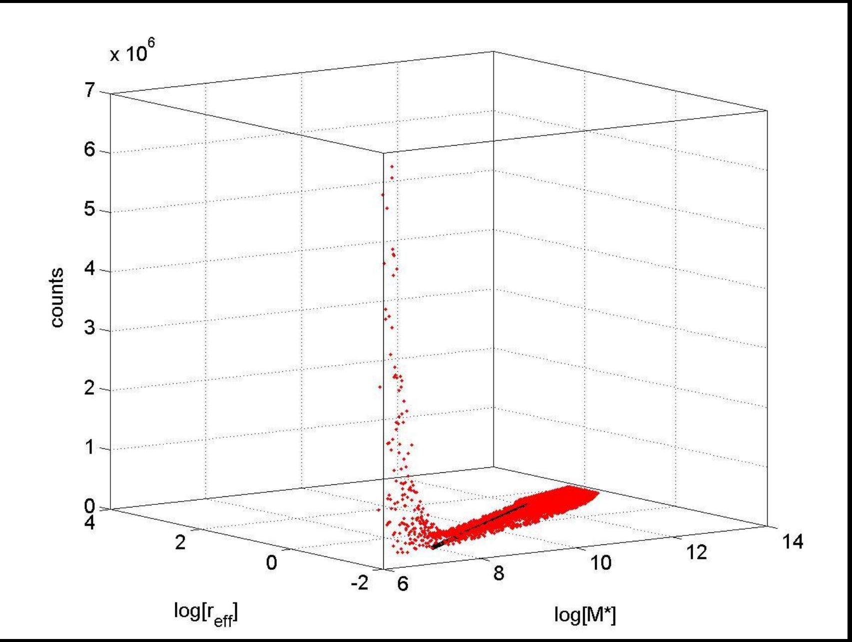
- Both positive and negative values of dN(z) are possible due to the varying slope of the Lukic et a(2007) curves. Positive slope → number of halos decreases with time (effect of mergers). See the three panels below.

Case B: The Number Densities $N(Z,M_{DM})$



- $N(Z,M_D)$ vs radius and mass

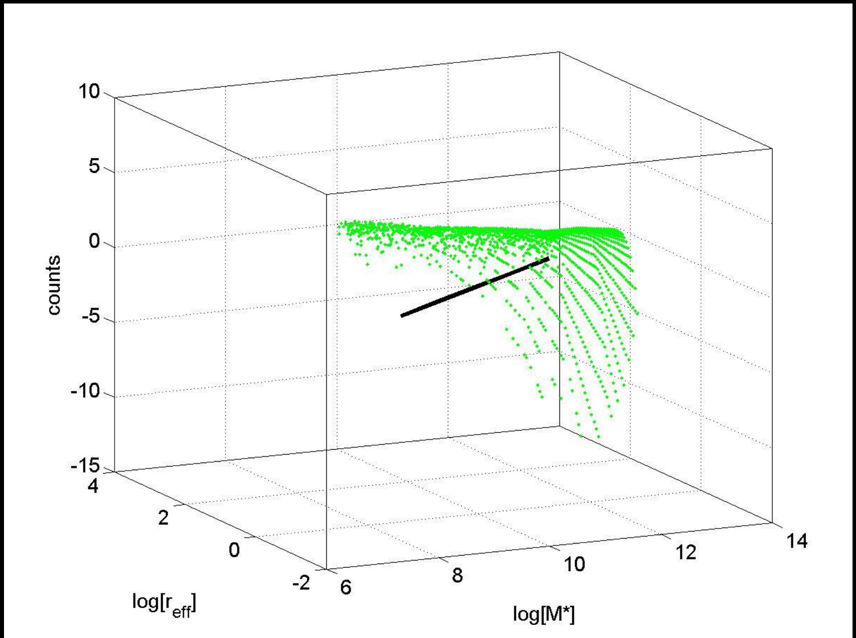
Case B: The Number Densities $N(Z,M_{DM})$



- $N(Z,M_D)$ vs radius and mass

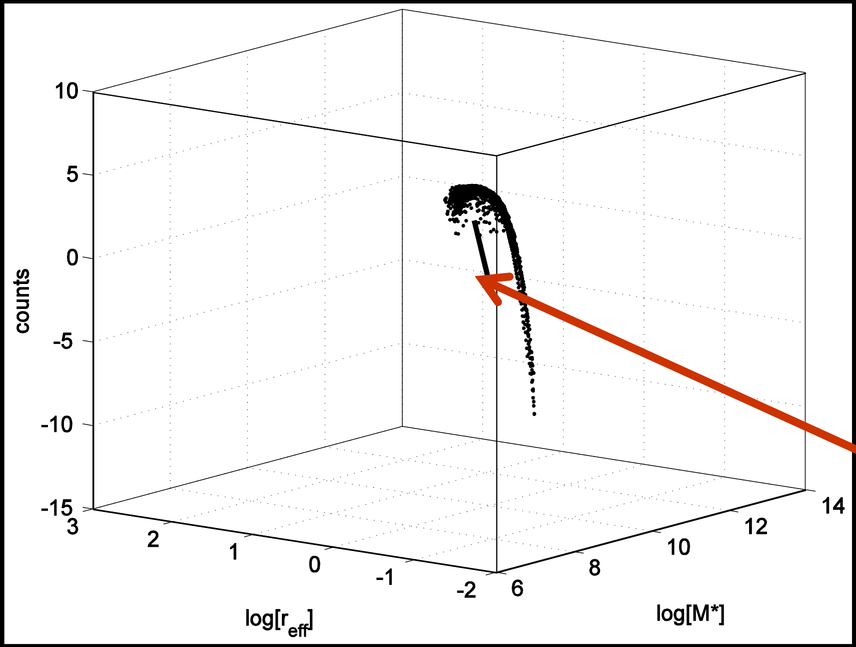
- After correcting for mergers

Case B: The Number Densities $N(Z,M_{DM})$



- Log $N(Z,M_D)$ vs radius and mass

Case B: The Number Densities $N(Z,M_{DM})$

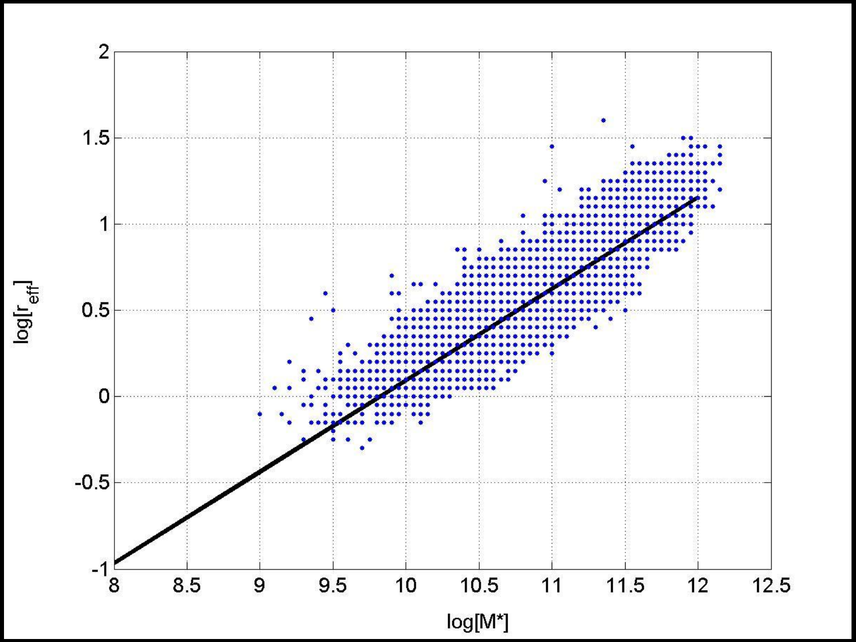


- Log $N(Z,M_D)$ vs radius and mass

Best fit line of the MR relation

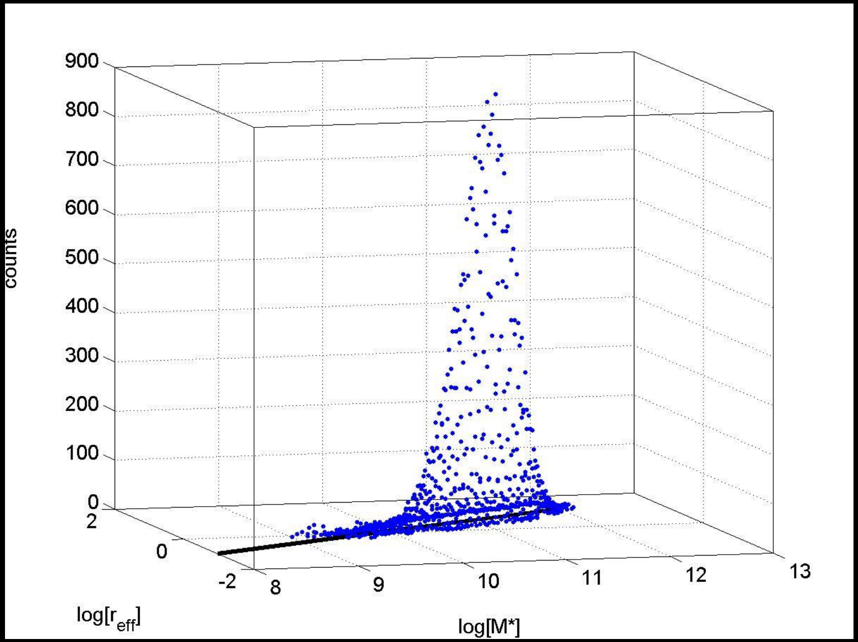
- Narrowness or theoretical thickness of the MR is accounted for

Theoretical MR Relation

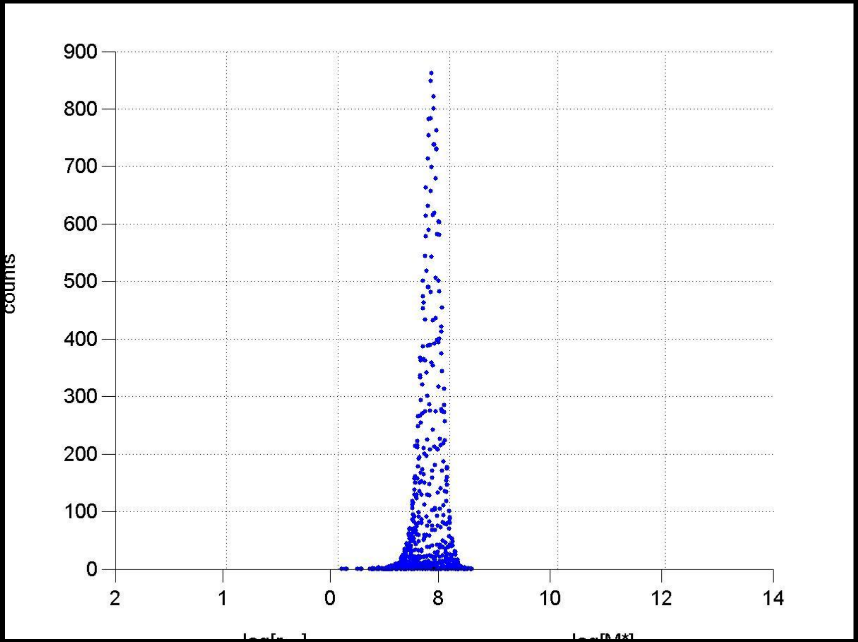


- Using the above results we get the MR relation to be compared with data

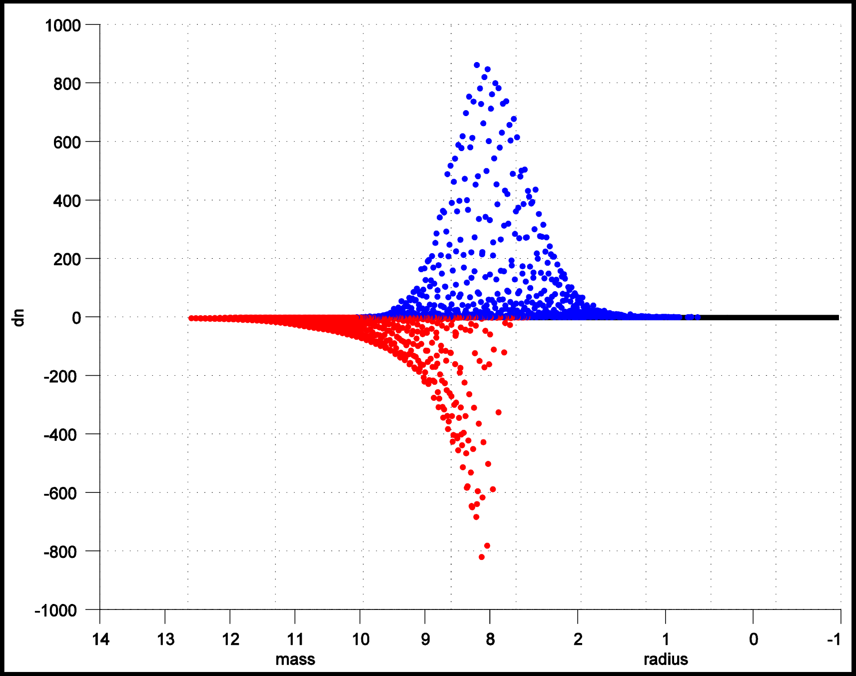
Theoretical MR Relation



Theoretical MR Relation



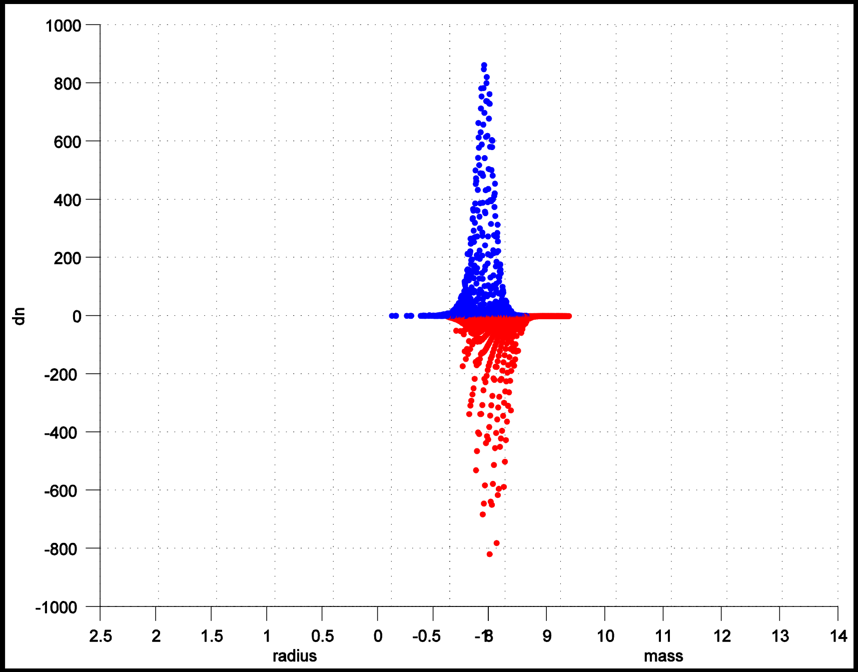
Theoretical vs Observational MR



- Blue dots: data
- Red dots: theory

- Excess of galaxies, it depends on the assumed normalization factor in the Lukic et al (2007) diagram
- and presence of too massive halos with mass more typical of a cluster of galaxies.
- It can be lowered.

Theoretical vs Observational MR



- Blue observational data
- Red theoretical results

The MR Plane: theory vs data

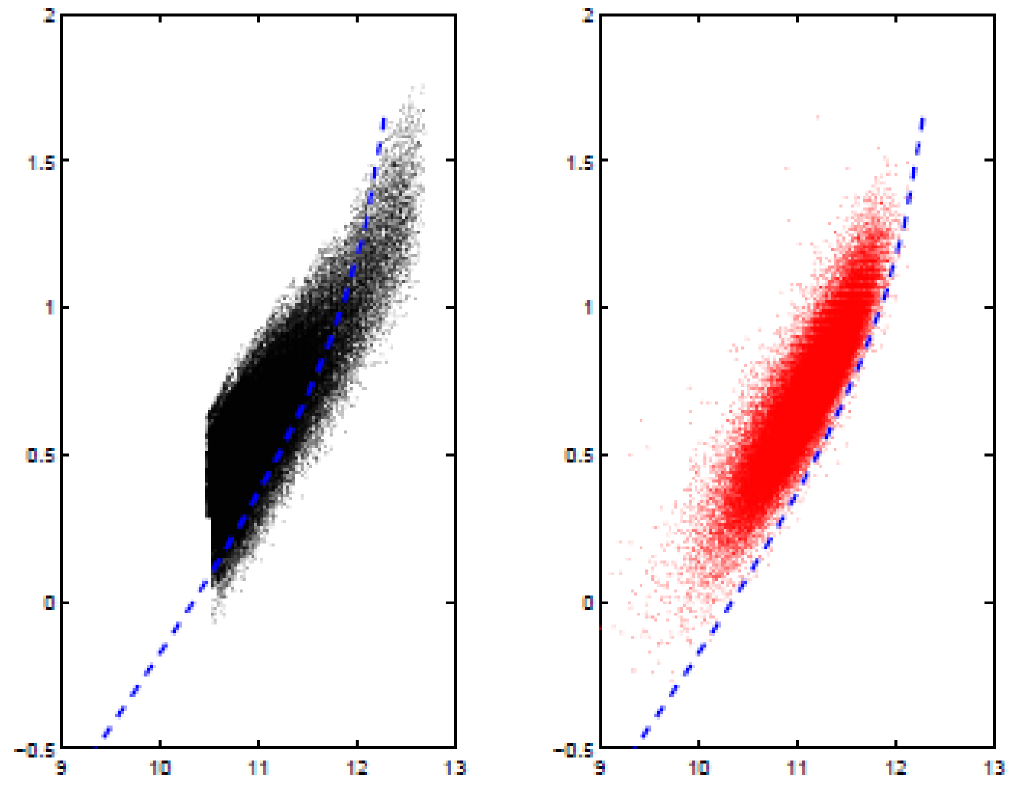


Fig. 7. Left panel: Predicted MR-relationship limited to galaxies more massive than $10^{10}\,M_{\odot}$. Right panel: The observational data of Bernardi et al. (2010b)

MonteCarlo Simulations
m=10, $f_{\sigma s}$=1, Norm=1e8

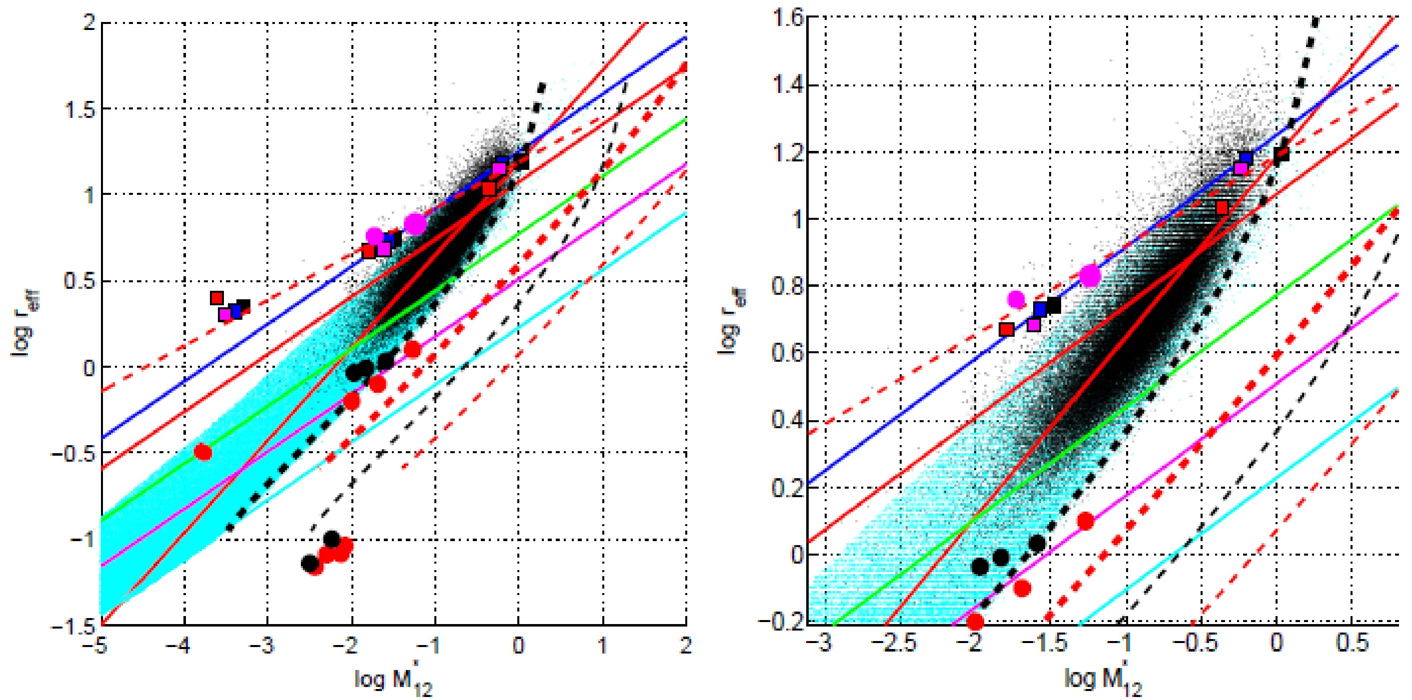
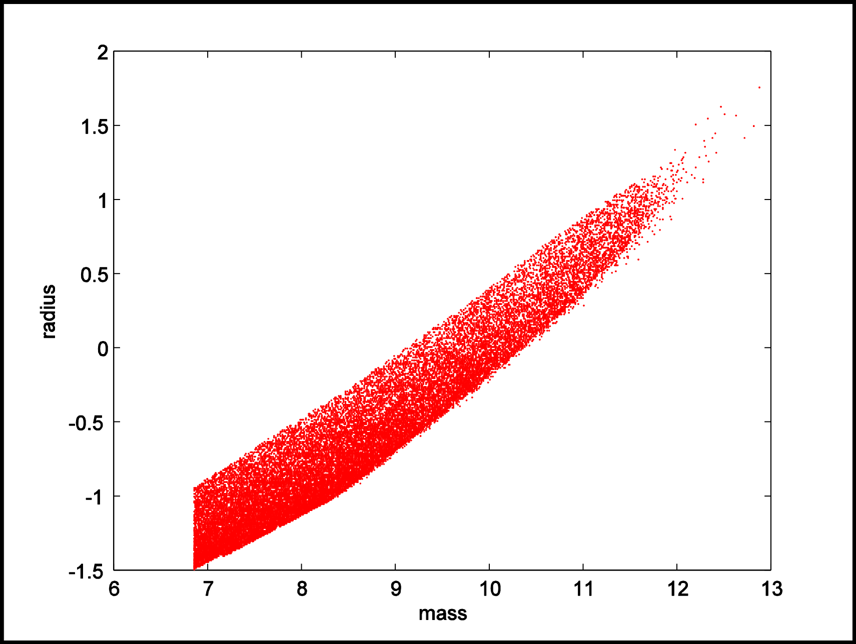
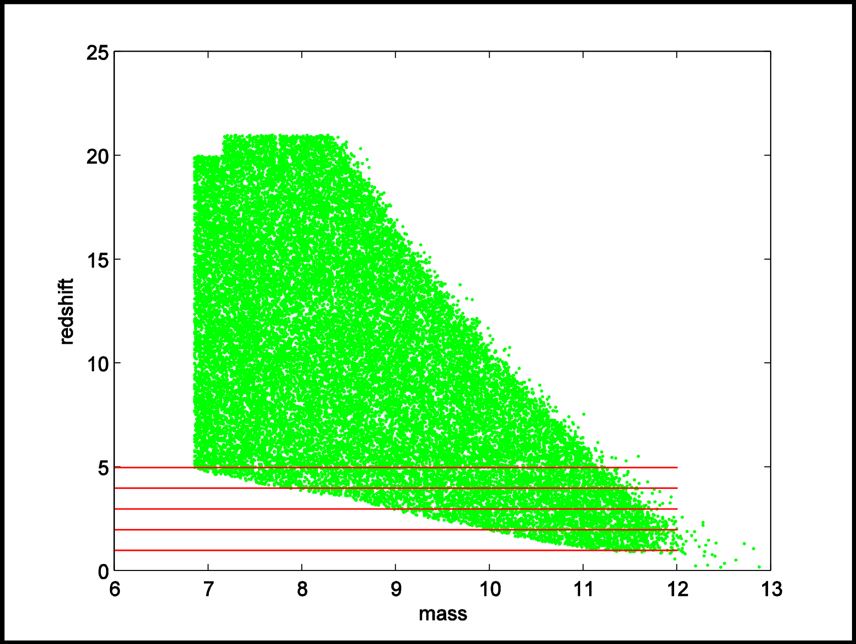


Fig. 8. Left panel: Comparison of the theoretical (cyan dots) with the observational (black dots) distributions of galaxies in the MR-plane $\log(R_{1/2})$ in kpc versus $\log M_{12}$ in units of $10^{12} M_{\odot}$. Superposed to it is the theoretical plane of Fig. 3. The observational data are from the HB sample of Bernardi et al. (2010b). Right panel; blow up of the upper right corner of the left panel to better show the agreement between data and theory for the most massive galaxies.

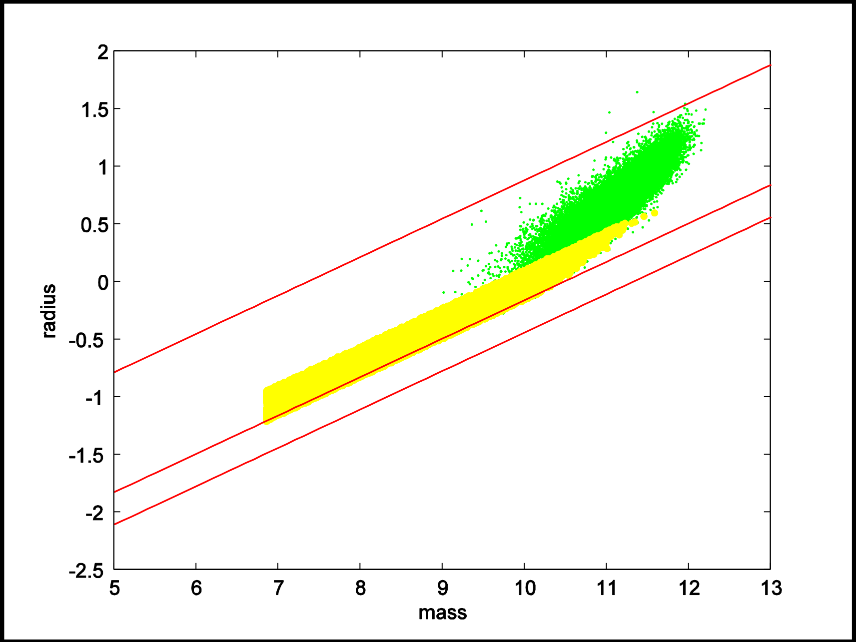
MonteCarlo Simulations $m=10$, $f_{\sigma s}=1$, Norm=1e8





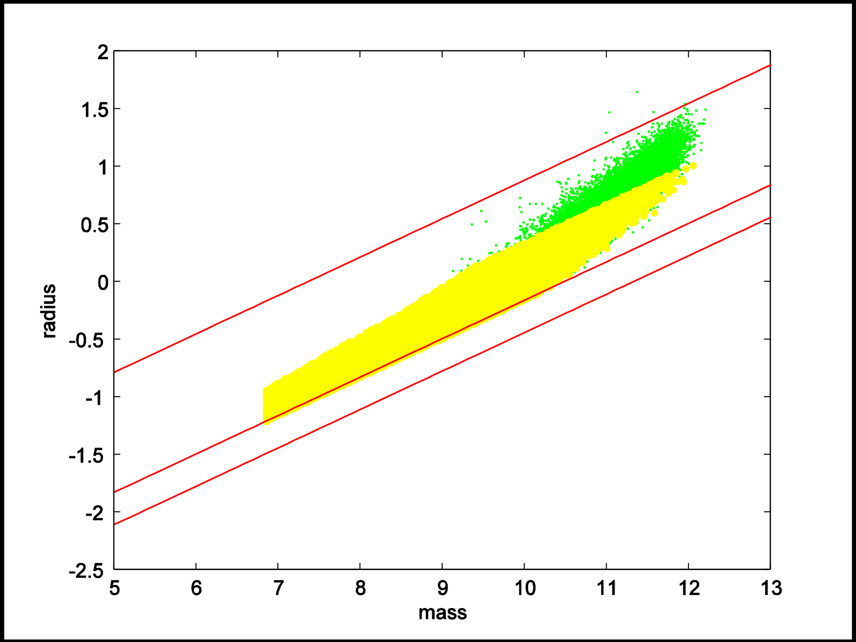
- Lines of constant z from 5 to 0.
- **Nearly all galaxies are formed before z=1 and vast majority before z=2**

MonteCarlo Simulations $m=10$, $f_{\sigma s}=1$, Norm=1e8



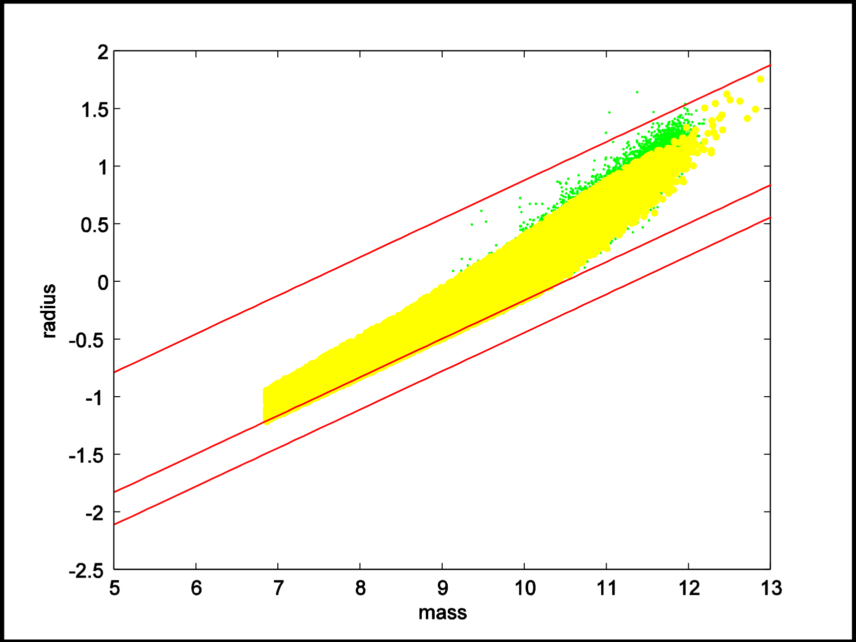
- Red lines: iso-density curves for z=20, z=10, and z=0, from bottom to top
- Green Dots: data
- Yellow dots: models for Z > 5

MonteCarlo Simulations
m=10, $f_{\sigma s}$=1, Norm=1e8



- Red lines: iso-density curves for z=20, z=10, and z=0, from bottom to top
- Green Dots: data
- Yellow dots: models for Z > 2.5

MonteCarlo Simulations
m=10, $f_{\sigma s}$=1, Norm=1e8



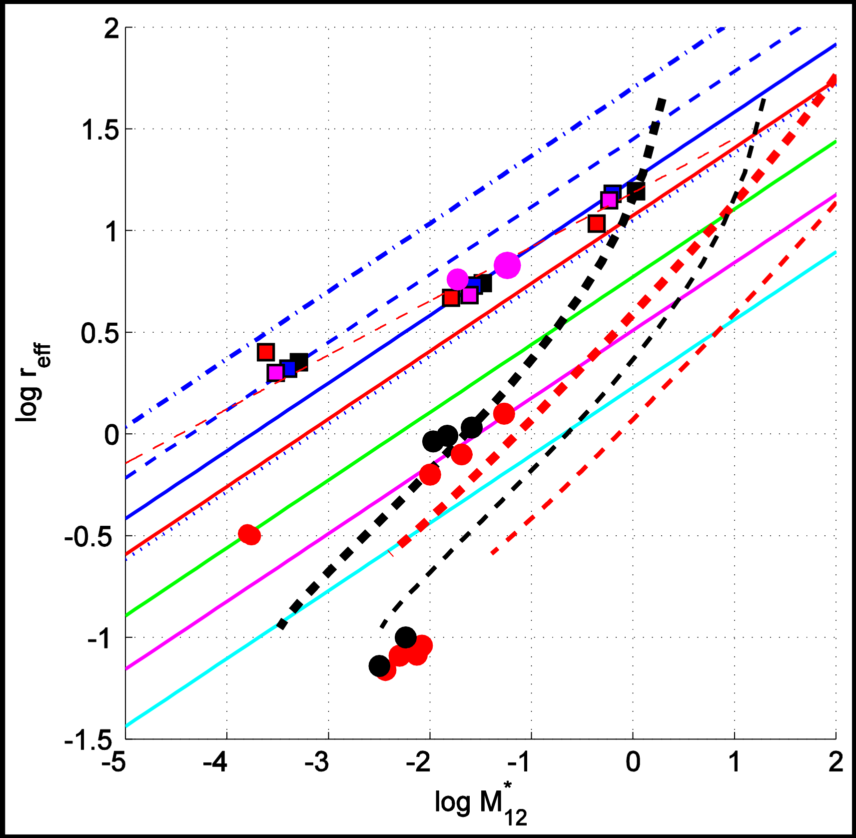
- Red lines: iso-density curves for z=20, z=10, and z=0, from bottom to top
- Green Dots: data
- Yellow dots: models for Z > 0.25

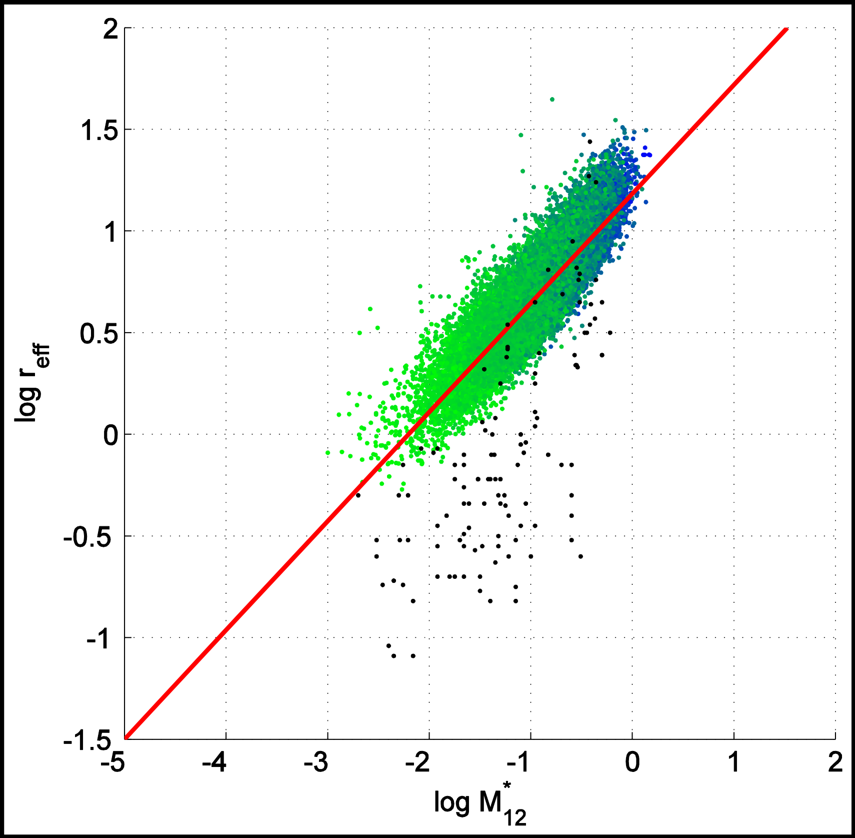
MonteCarlo Simulations

- Nearly all galaxies are formed before $z = 1$ and the vast majority before $z = 2$.

- The percentage of galaxies that undergo at least one merger with respect to those that proceed in isolation is about 1/3.

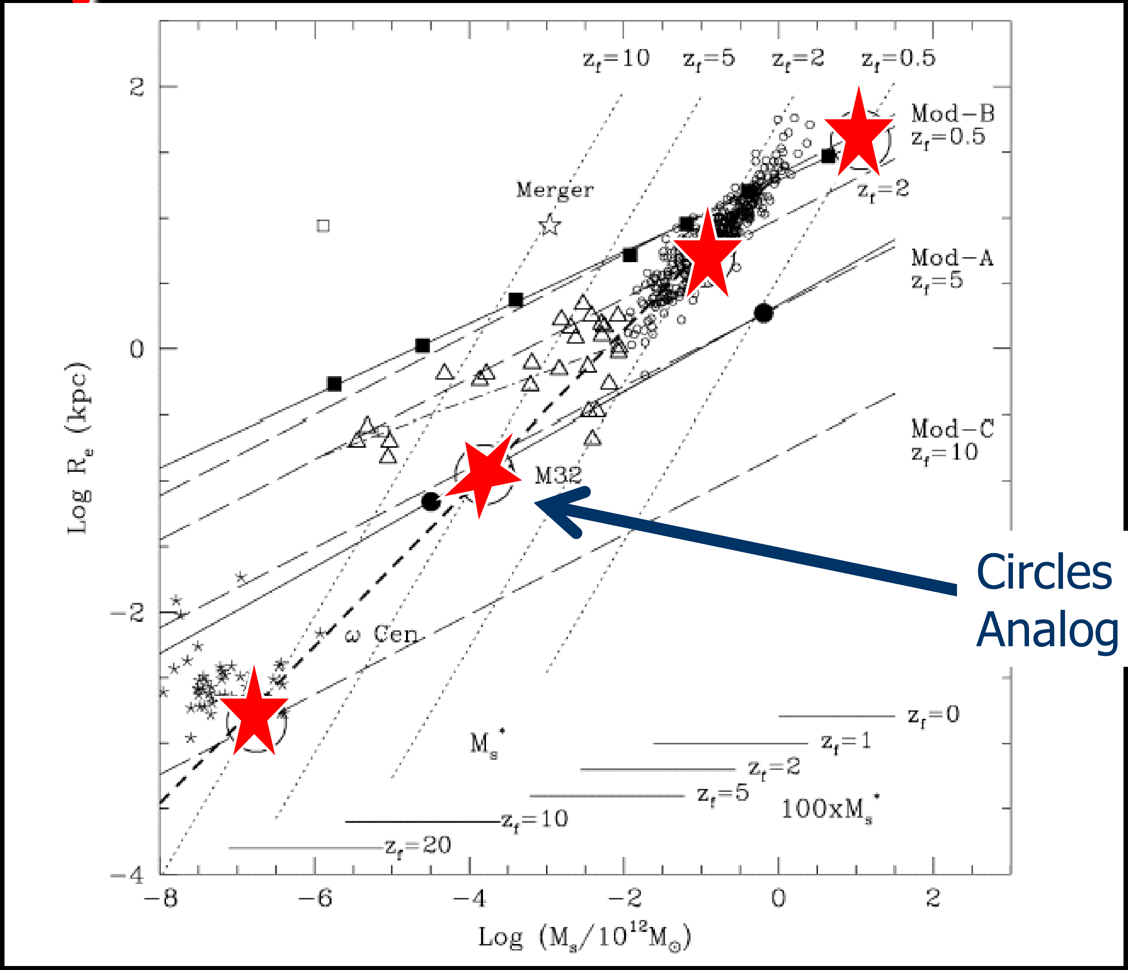
What about the compacts?





Compatible with density drop-outs

Repetita iuvant !



Circles and Red Stars: Analog of shepherd line

Chiosi & Carraro (2002, MNRAS, 335, 335)

Conclusions

- Convolution of iso-density lines bounded by the shepherd line over the history of the Universe.
- ETGs closely follow the MR of quasi dissipation-less collapse..
- The zero point and thichness of the MR depend on the cosmic evolution of the N(Z,MDM) function ultimately governed by the cosmic growth of pertubations and gravity.
- The percentage of mergers with respect to isolated growth and evolution of ETGs is about 1/3.

The End