The Dynamical Evolution of a Galaxy Cluster: The Local Effect of Dark Energy

Martina Donnari

Collaborators: M. Arca Sedda, M. Merafina

Frascati, November 27th, 2015

Outline

- Introduction
  - Local effect of Dark Energy
  - Look at the observations
- Simulations forecasted
- Data analysis and preliminary results
  - Trajectory of CoM
  - Hubble diagram
  - Merging
- Conclusions and what's next

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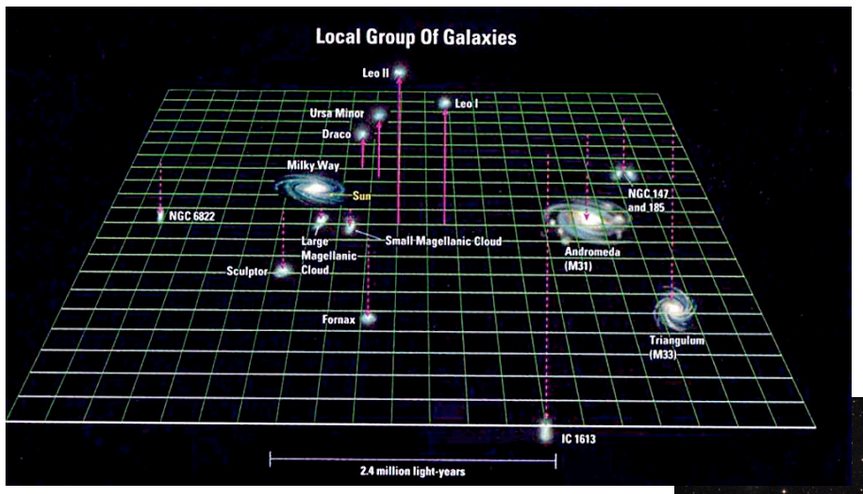
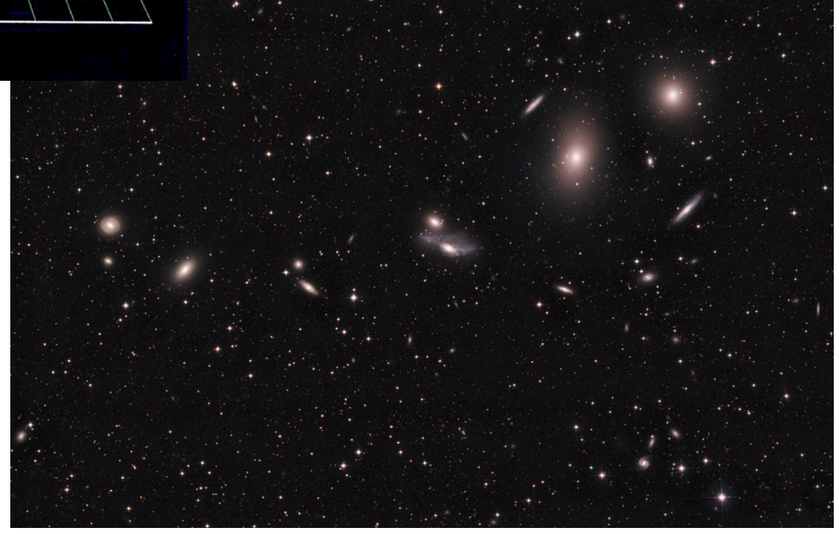
Scientific context

Very Local Hubble Flow: VLHF





Hubble-Sandage paradox

How the observed spatial non uniformity of the galaxy distribution in the local volume may be compatible with the observed regular linear velocity field?

Can the DE explain the LHF?

YES ☐ NO ☐

Chernin et al., **A&A 415, 19-25 (2004)**
Hoffmann et al., **MNRAS, 386, 390-396 (2008)**
Martinez-Vaquero et al., **MNRAS, 397, 2070-2080 (2009)**

Scientific context

Previous theoretical work

Interplay between DE and gravity

M. Merafina, G.S. Bisnovatiy-Kogan, M. Donnari
A&A 568, A93 (2014)

Two main ingredients

- Cosmological model: $\Lambda\mathrm{CDM}$

$$\Phi = -\frac{\Lambda c^2}{6} r^2$$

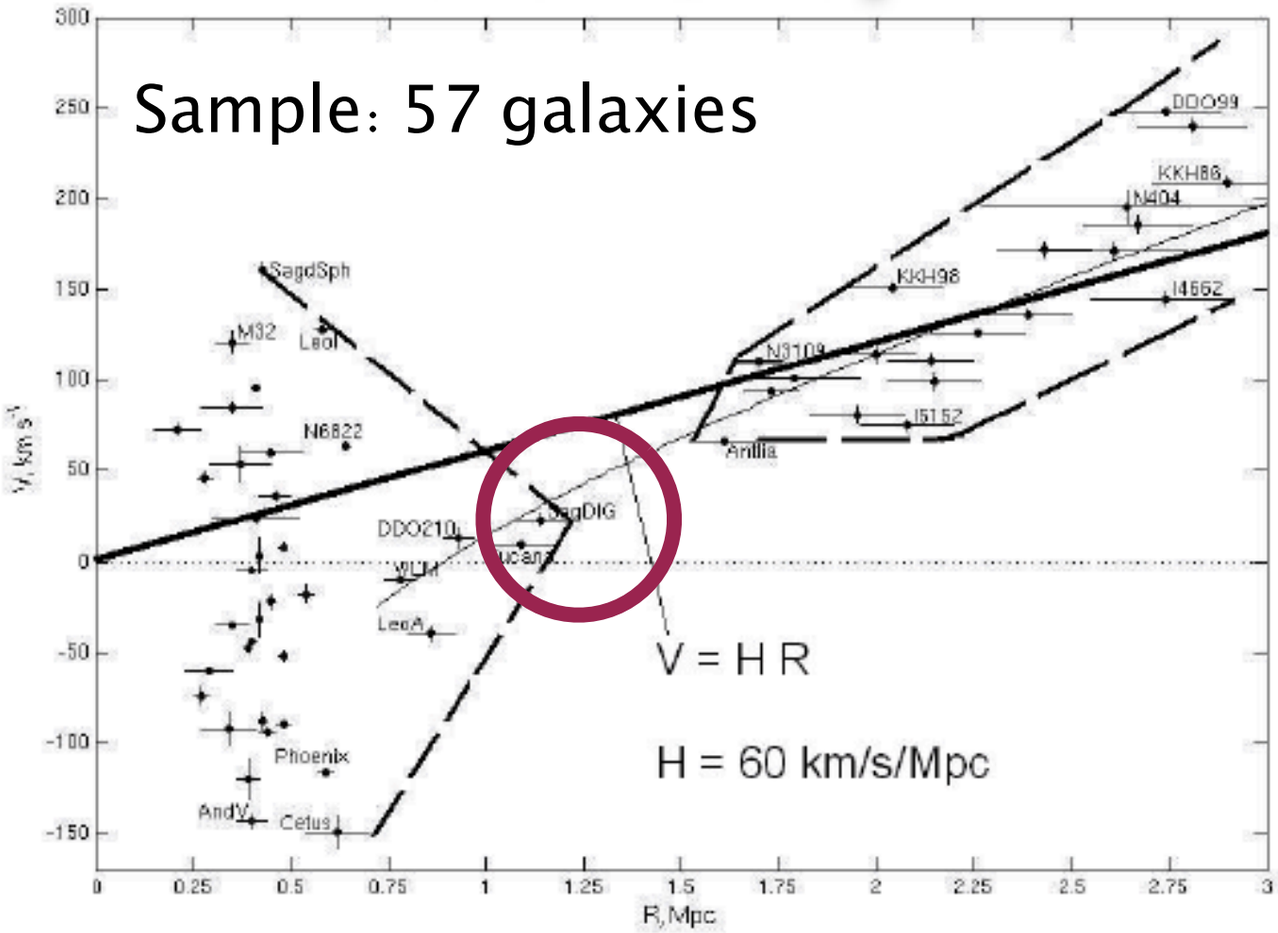
- Key parameter: Zero Gravity Radius

$$F_{tot} = F_G + F_\Lambda = 0$$

$$R_\Lambda = \left(\frac{3M}{8\pi\rho_\Lambda}\right)^{1/3} \simeq 11 \left(\frac{M}{10^{15} M_\odot}\right)^{1/3} \mathrm{Mpc}$$

Look at the observations

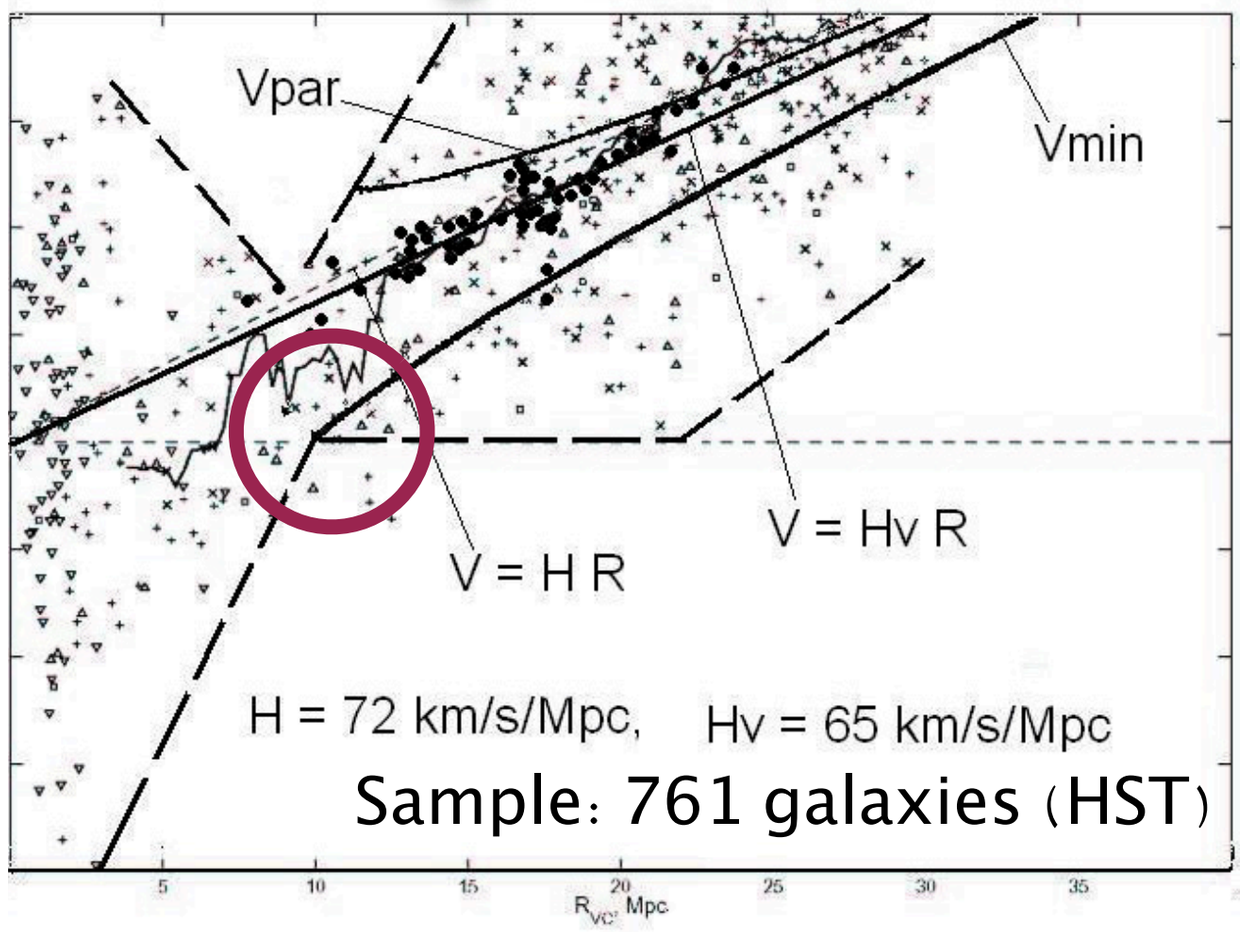
Local Group



Zero Gravity Radius

$$R_\Lambda = (1 - 1.3)\ \mathrm{Mpc}$$

Virgo Cluster



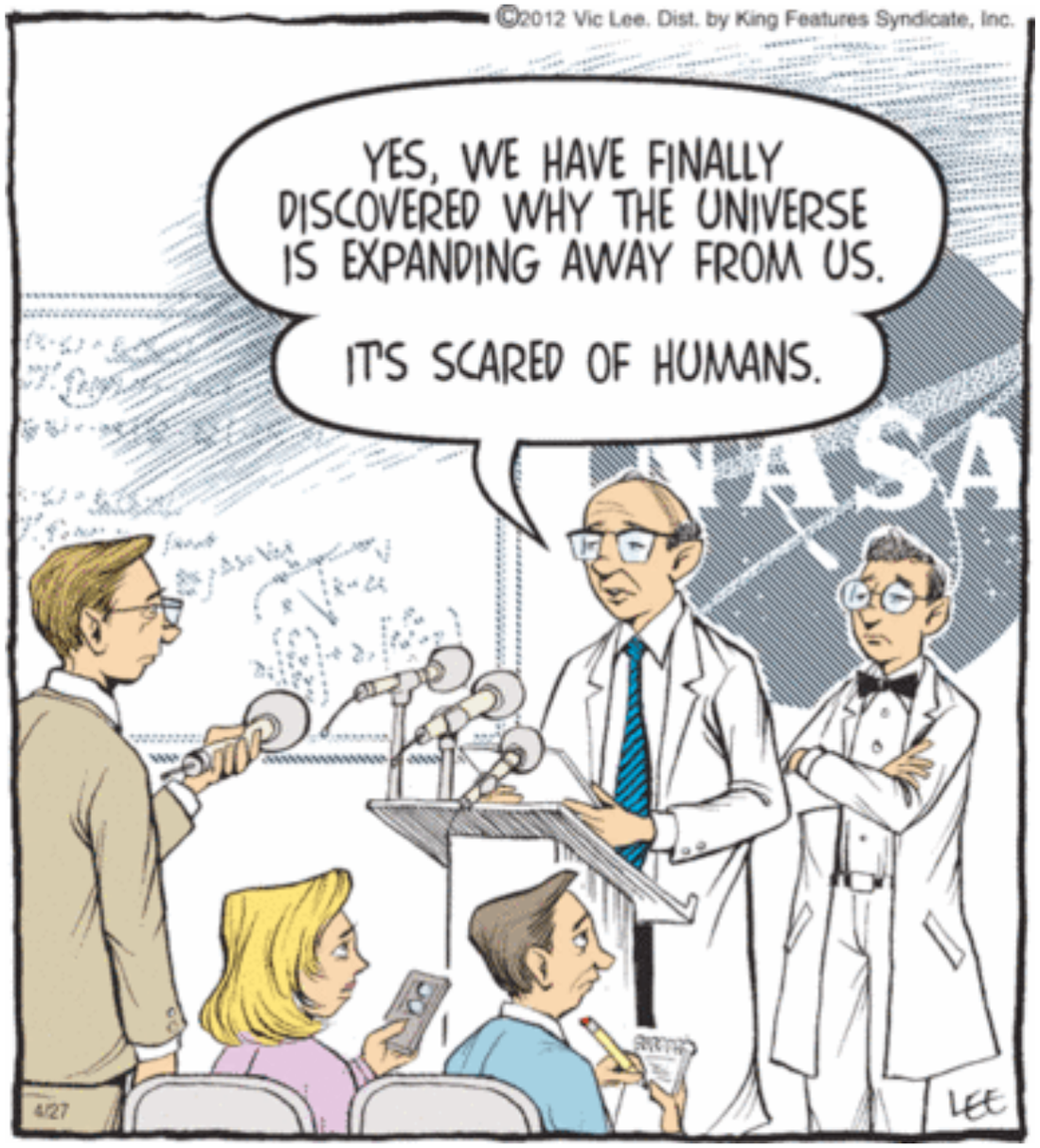
Zero Gravity Radius

$$R_\Lambda = (9 - 11)\ \mathrm{Mpc}$$

Karachentsev&Nasonova MNRAS 405, 1075 (2010)
Chernin et al. A&A 520, A104 (2010)

Local effect of Dark Energy

Can Dark Energy have dynamical effects on a single galaxy cluster, acting on the dynamics of its galaxies?



Look at the simulations…

- Introduction
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- **Simulations forecasted**
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Simulations forecasted

HiGPUs code

Hermite's N-body integrator running on Graphic Processing Units

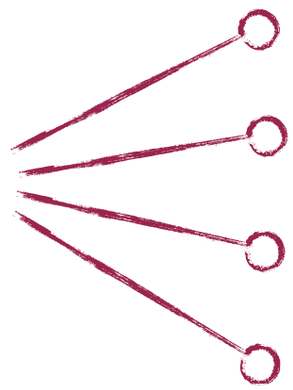
R. Capuzzo-Dolcetta et al. **JPC, 236, 580 (2013)**

✗ Cosmological simulation

✗ Hydrodynamical simulation

✓ Direct N-body simulation

4 simulations



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Isolated cluster: only gravitational interaction

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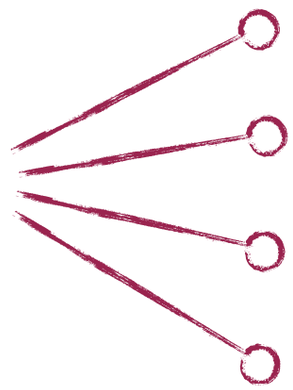

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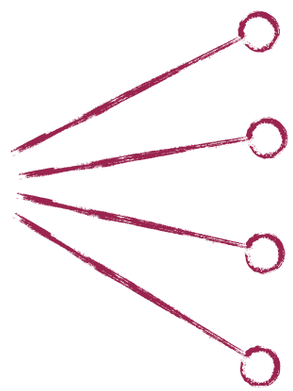

Isolated cluster: only gravitational interaction

Switch on DE: repulsive central force

Switch on DE 

Dark Energy $\rho_\Lambda = \frac{\Lambda c^2}{8\pi G}$

Simulations forecasted

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4 simulations

- Isolated cluster: only gravitational interaction
- Switch on DE: repulsive central force
- Switch on gas: additional central force

Switch on Gas

β model $\quad \rho_\beta(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$

A. Cavaliere, R. Fusco Femiano **A&A 49, 137 (1976)**

Simulations forecasted

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- Isolated cluster: only gravitational interaction
- Switch on DE: repulsive central force
- Switch on gas: additional central force
- Switch on both DE+Gas

Switch on DE

Dark Energy $\rho_\Lambda = \dfrac{\Lambda c^2}{8\pi G}$

Switch on Gas

β model $\rho_\beta(r) = \rho_0 \left[1 + \left(\dfrac{r}{r_c}\right)^2\right]^{-3\beta/2}$

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Simulations forecasted

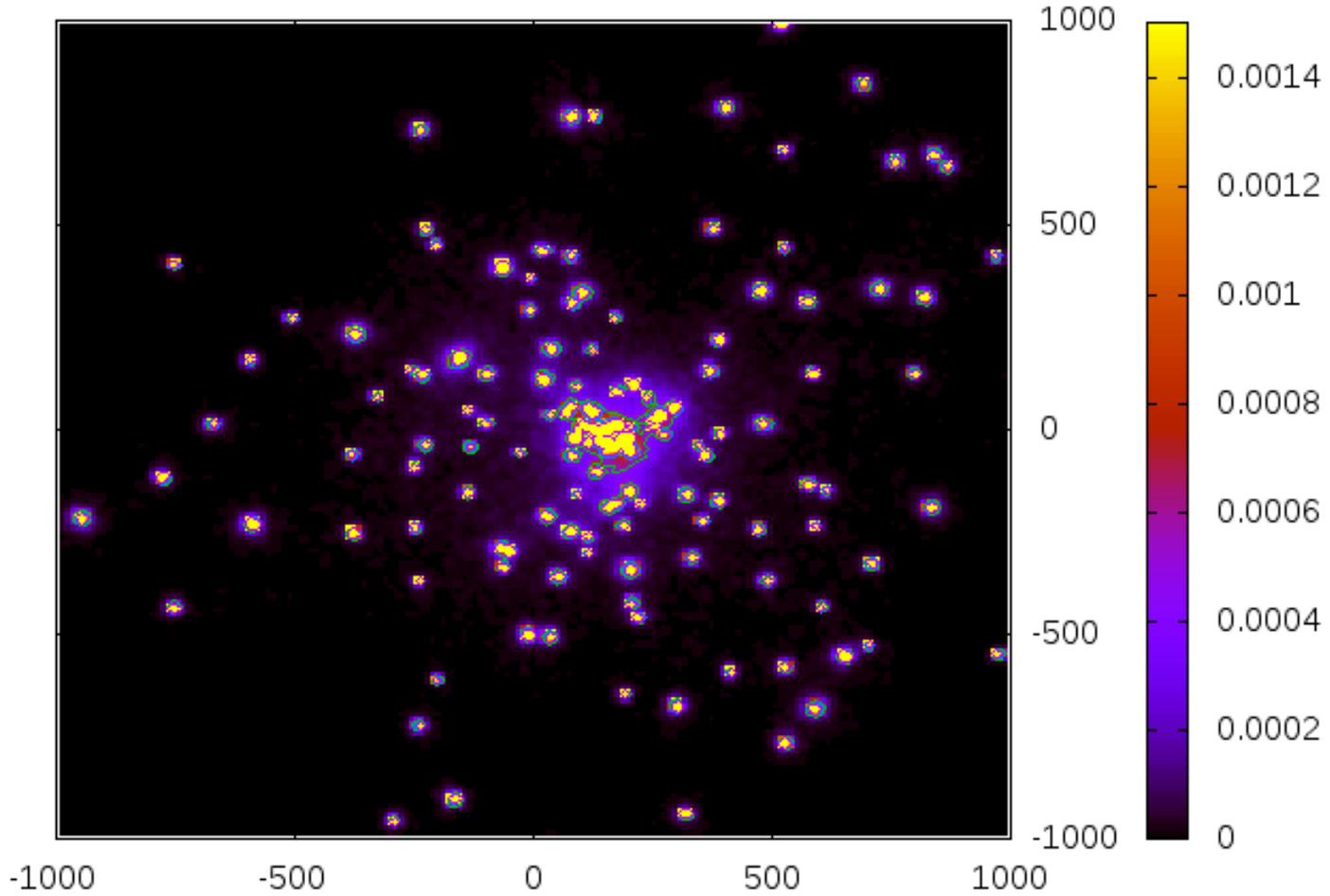
Cluster

$$M_{clus} = 9.2 \times 10^{13} M_{\odot}$$

$$r_c \simeq 100 kpc$$

$$R_{\Lambda} \simeq 4.8 Mpc$$

$$\rho_r^* = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-\alpha}$$



For simulations with gas $M_{gas} = 4.7 \times 10^{12} M_{\odot}$ ⇒ $\frac{M_{gas}}{M_{clus}} \simeq 5\%$

(*) M. Girardi et al., **ApJ 505, 74 (1998)**

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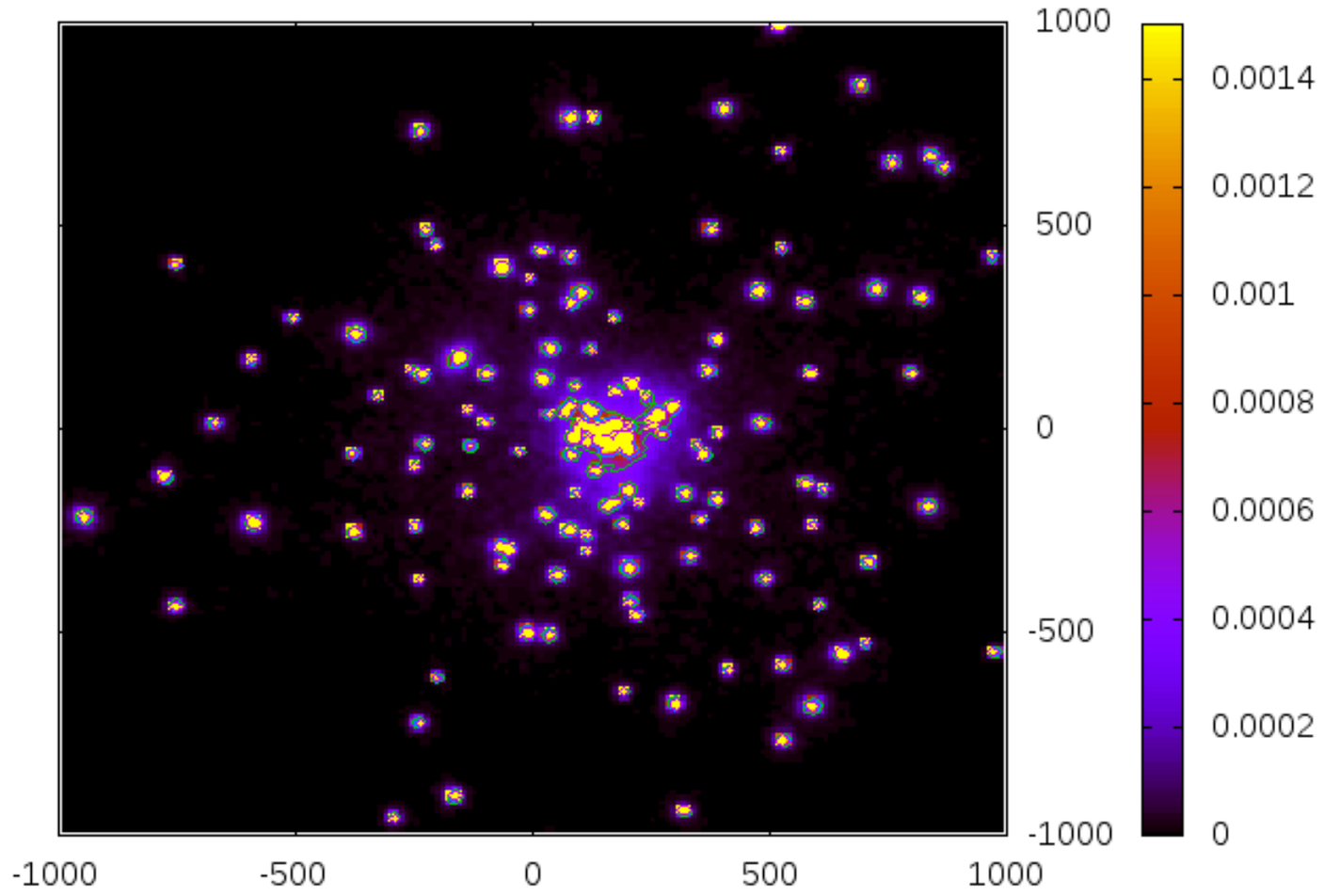


[...] This neglect is a good approximation for cluster where the mass fraction of the gas is only 5-20% of the total cluster mass [...]

$$\frac{M_{gas}}{M_{clus}} \simeq 5\%$$

(*) M. Girardi et al., **ApJ 505, 74 (1998)**

S. Schinlder, H. Bohringer, **A&A 269, 83 (1993)**

Galaxies

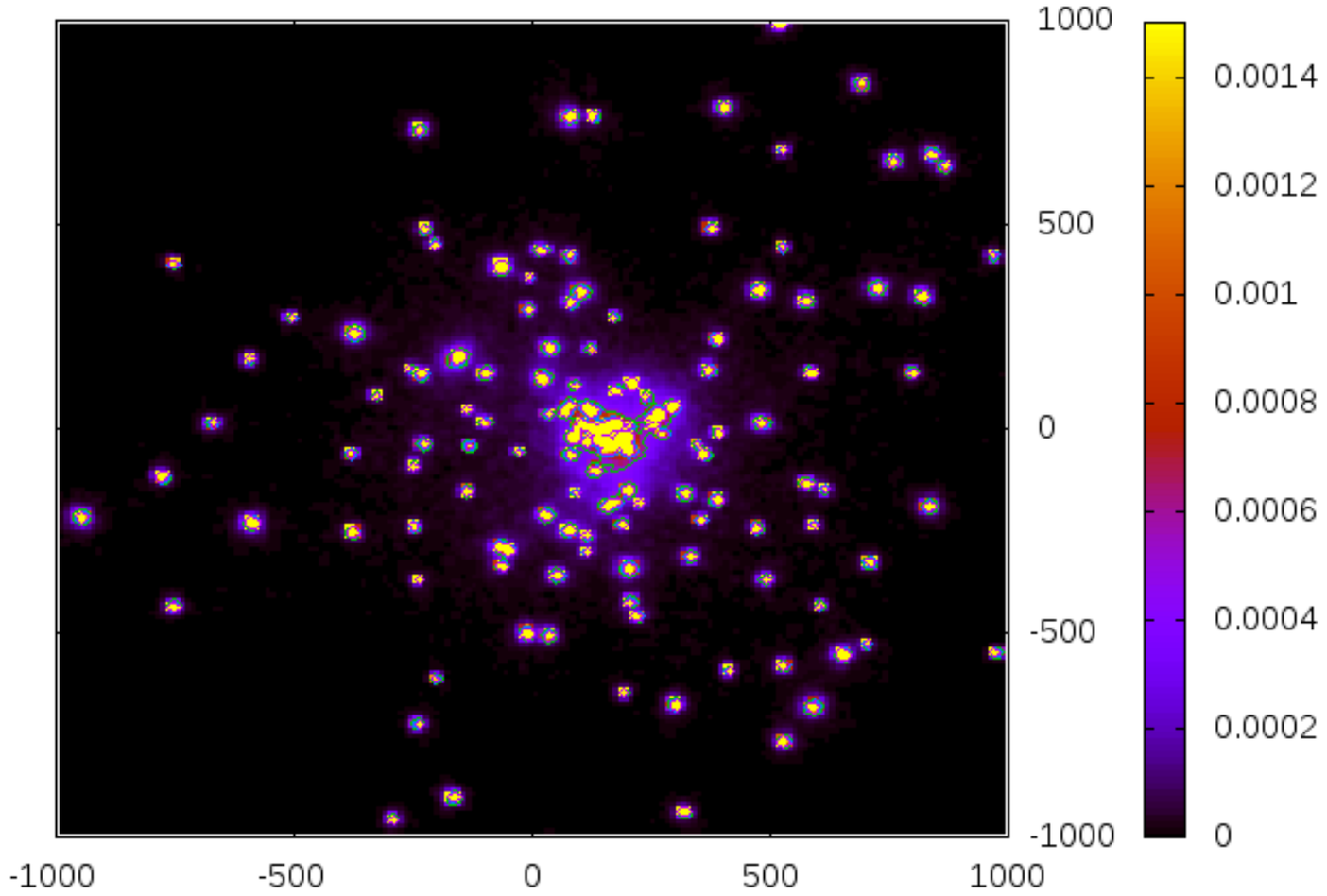
$$N_{gal} = 241$$

$$f(M_{gal}) \overset{*}{=} k\, M_{gal}^{-1}$$

$$9 \times 10^{10} < M_{gal}(M_\odot) < 10^{12}$$

$$\rho(r) = \rho_b \left(\frac{r}{r_b}\right)^{-\gamma} \left[1 + \frac{r}{r_b}\right]^{\gamma-4}$$

$$0.2 < \gamma < 1.74$$



$N_{stars} > 10^6$ ⇨ 70% of galaxies have N > 2500 stars

(*) A.V. Tutukov et al., **ARep 51, 435 (2007)**

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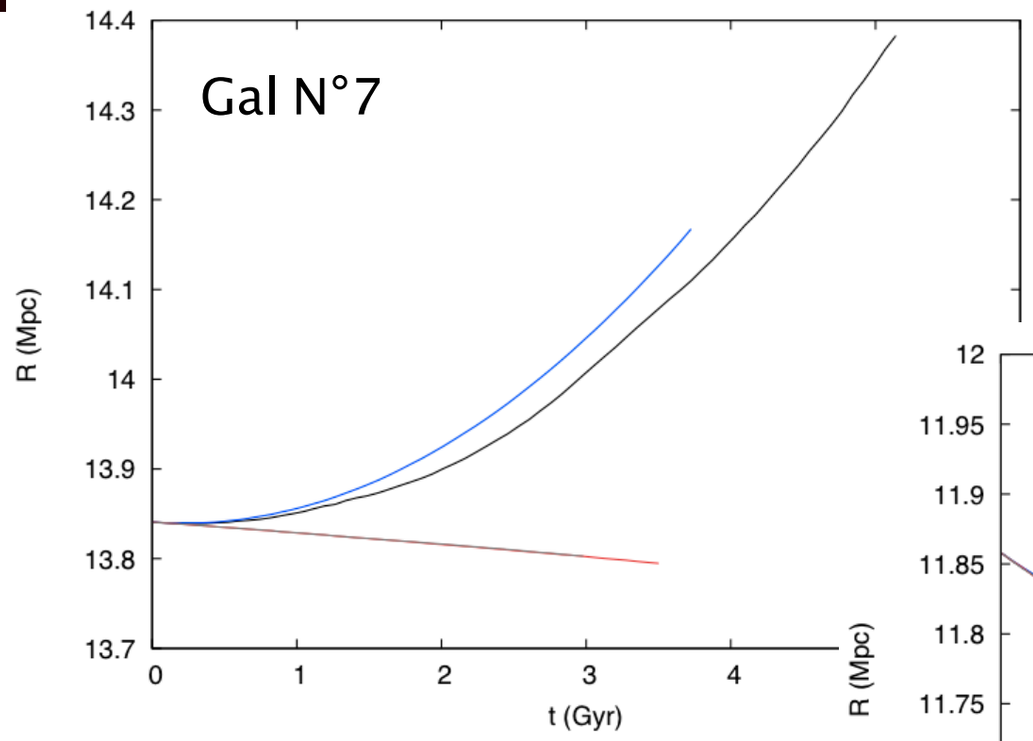
Trajectory of CoM

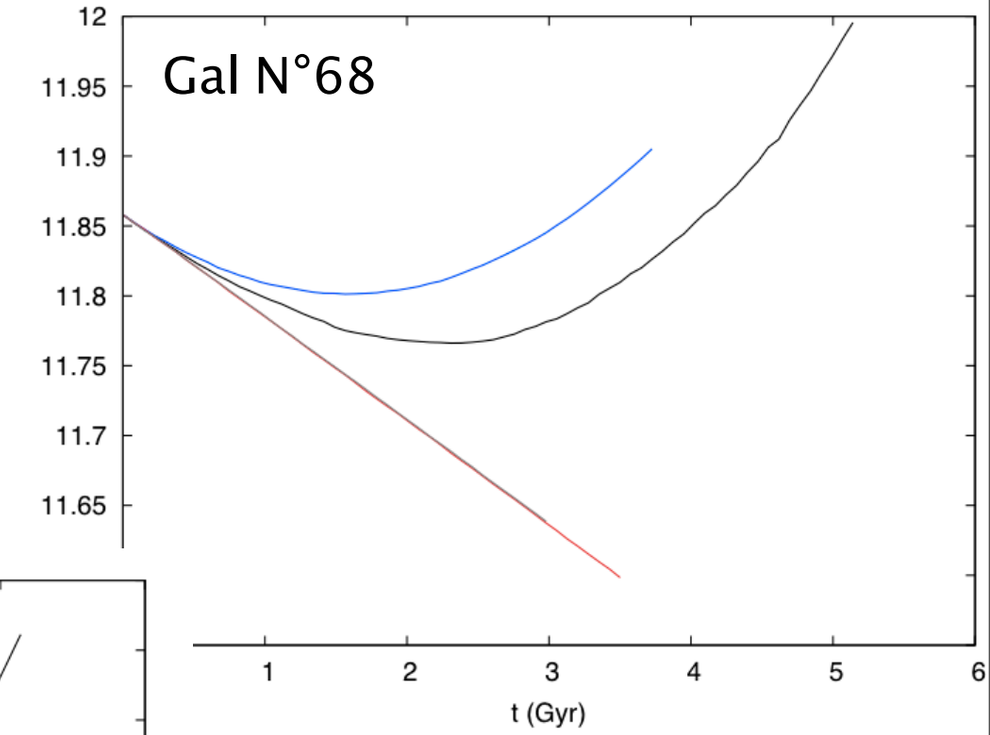
Dark
Dark+Gas
No-Dark
Gas

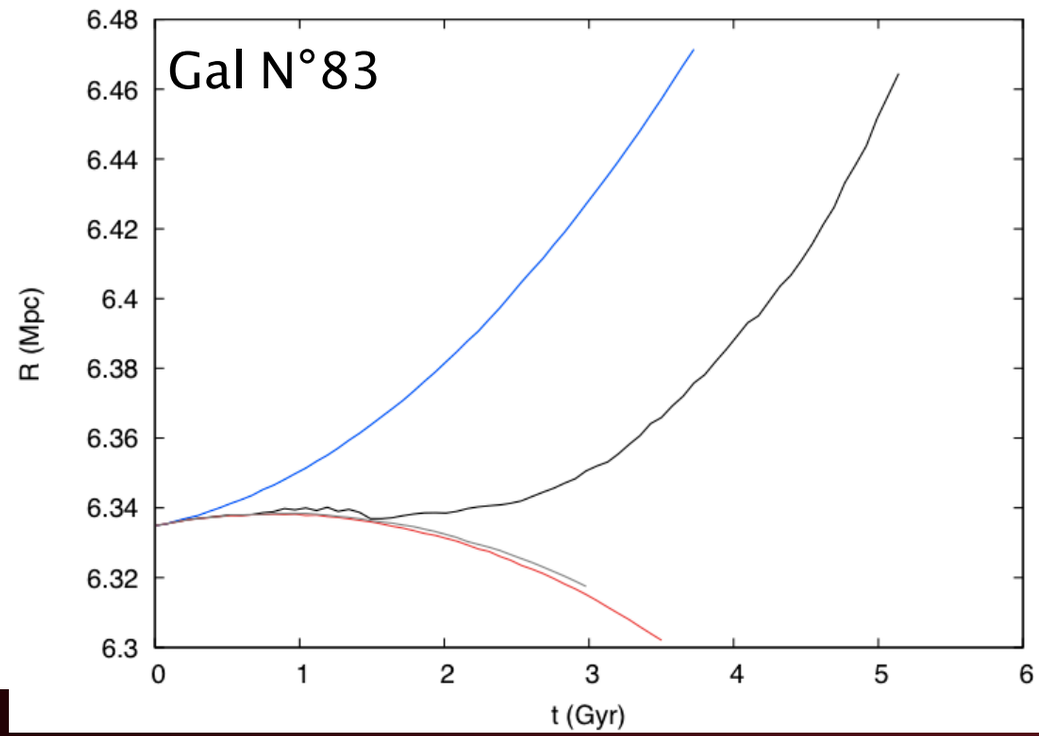
$$R_\Lambda \simeq 4.8 Mpc$$

- Visible VLHF for 3 galaxies out of ZGR (blu and black lines)

- Gas doesn't affect the external dynamics of the cluster (grey and red lines)







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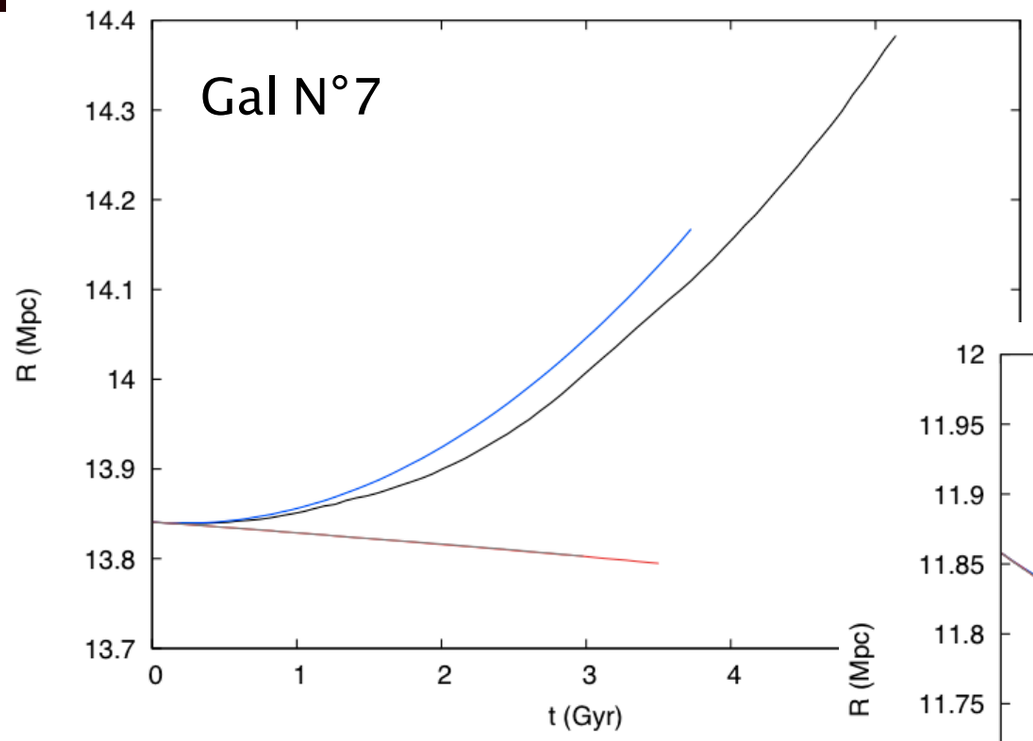
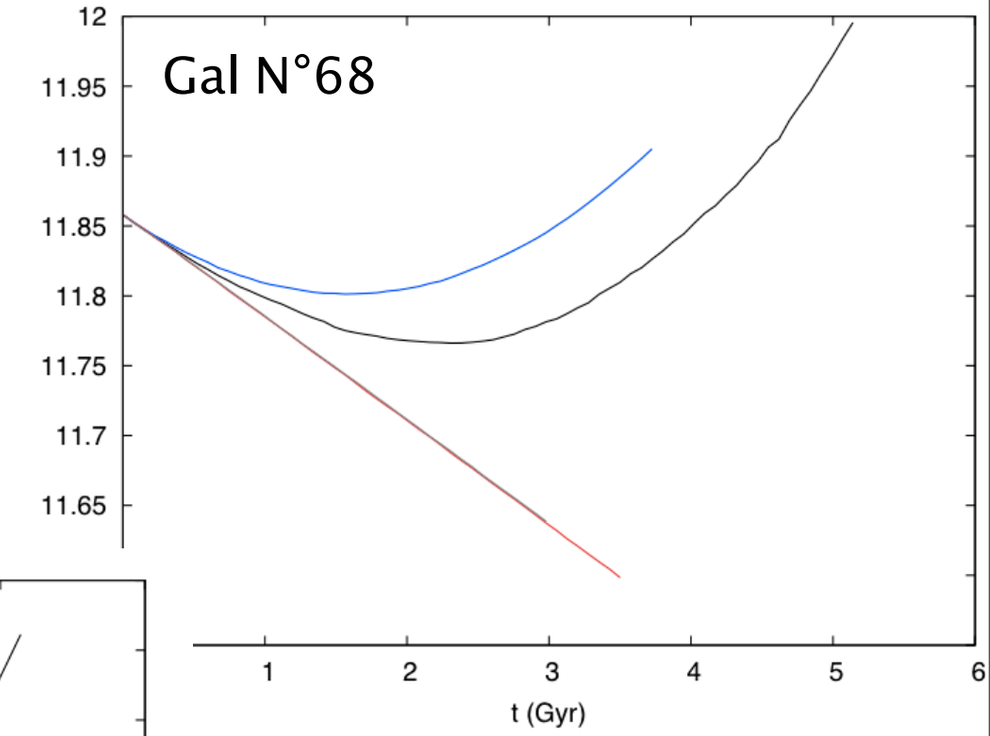
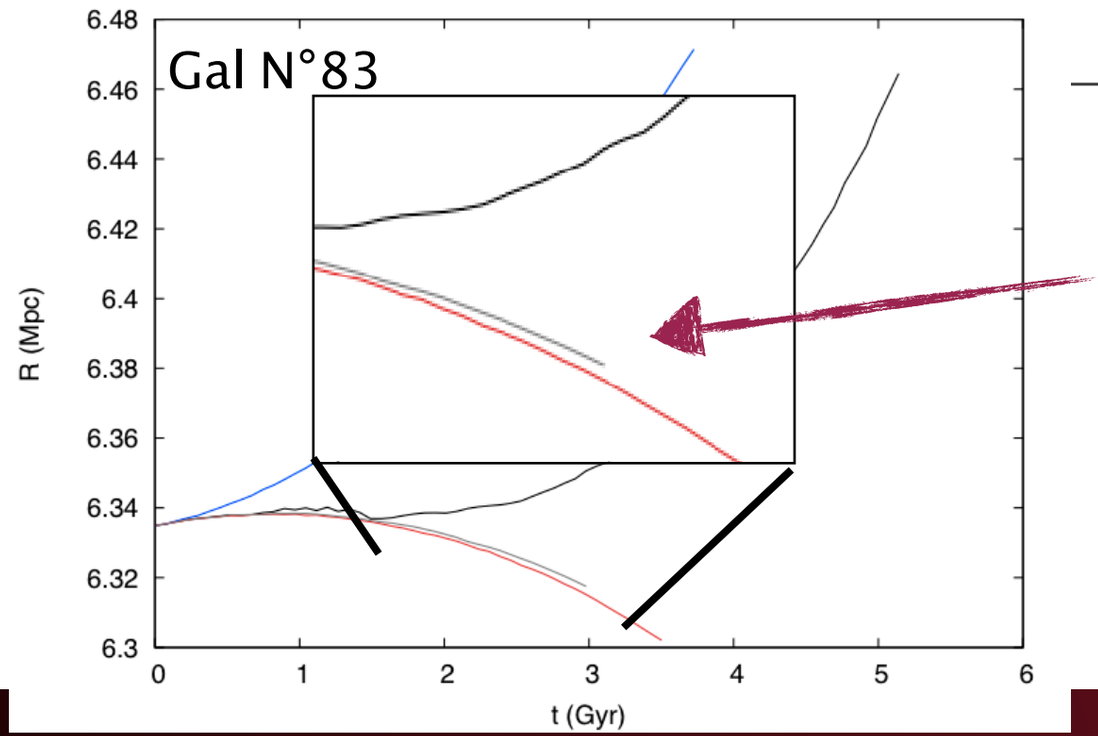






- Visible VLHF for 3 galaxies out of ZGR (blu and black lines)
- Gas doesn't affect the external dynamics of the cluster (grey and red lines)

Discrepancy visible only for the galaxies closer to the center of the cluster

Hubble diagrams

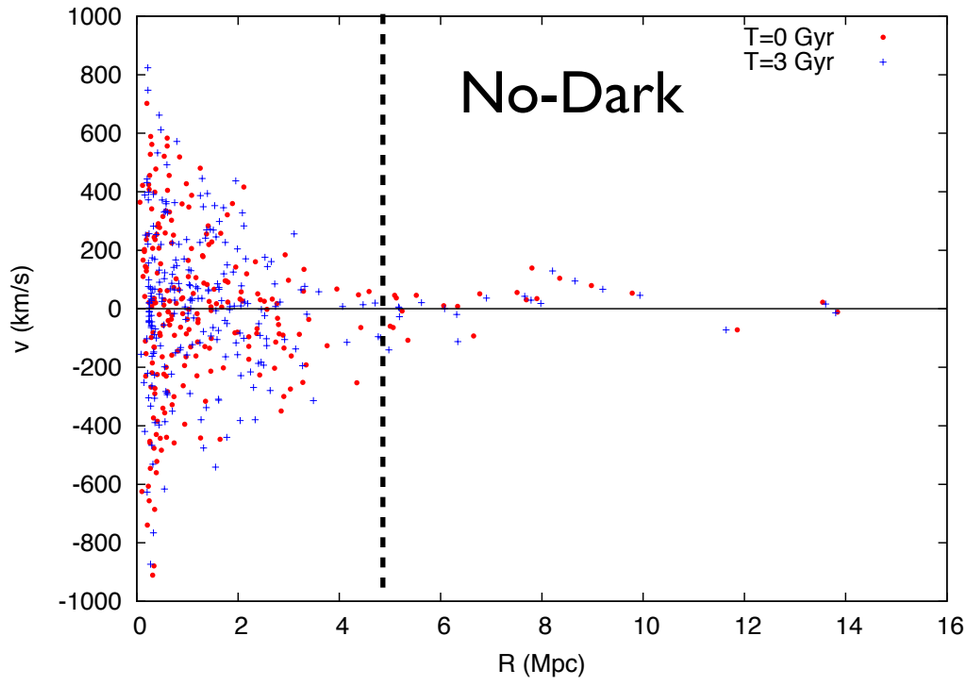
ZGR

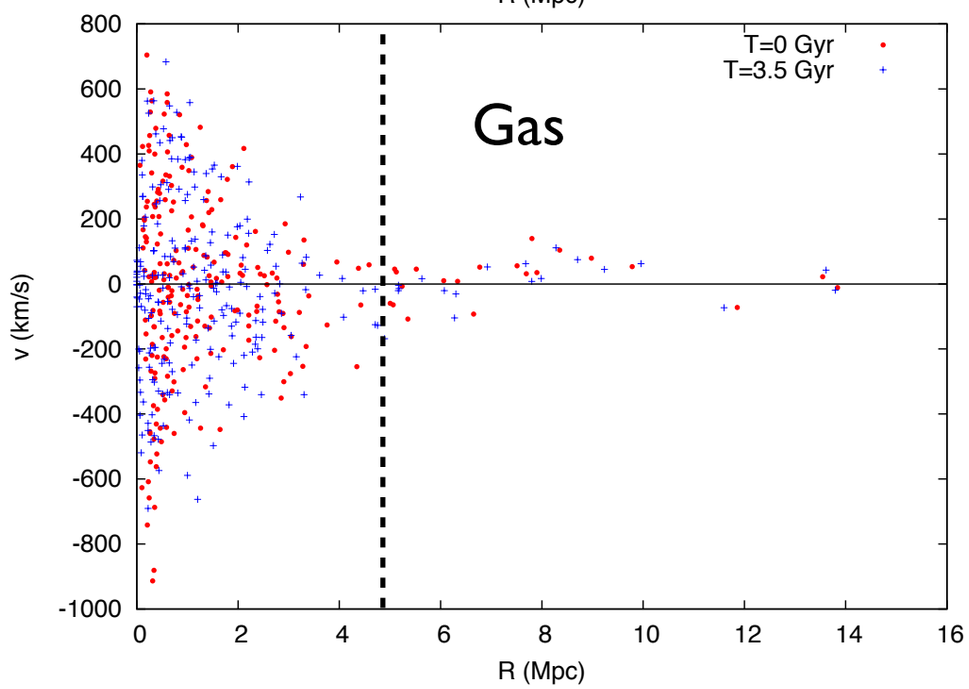
T=0 Gyr

T=3-3.5 Gyr

No-Dark & Gas

NO trend





Hubble diagrams

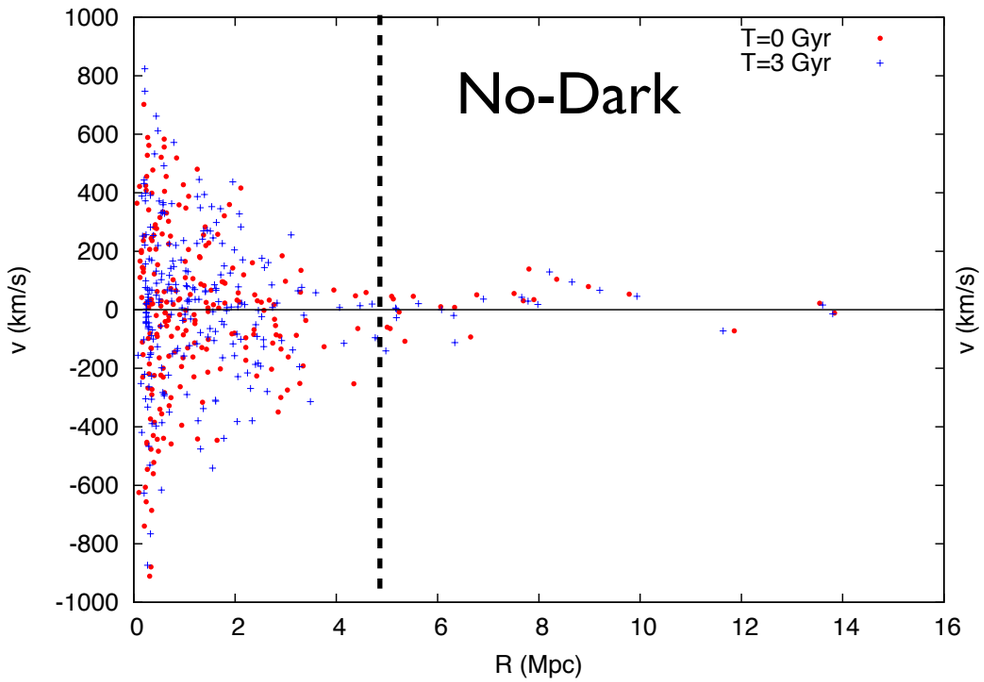
ZGR
T=0 Gyr
T=3-3.5 Gyr

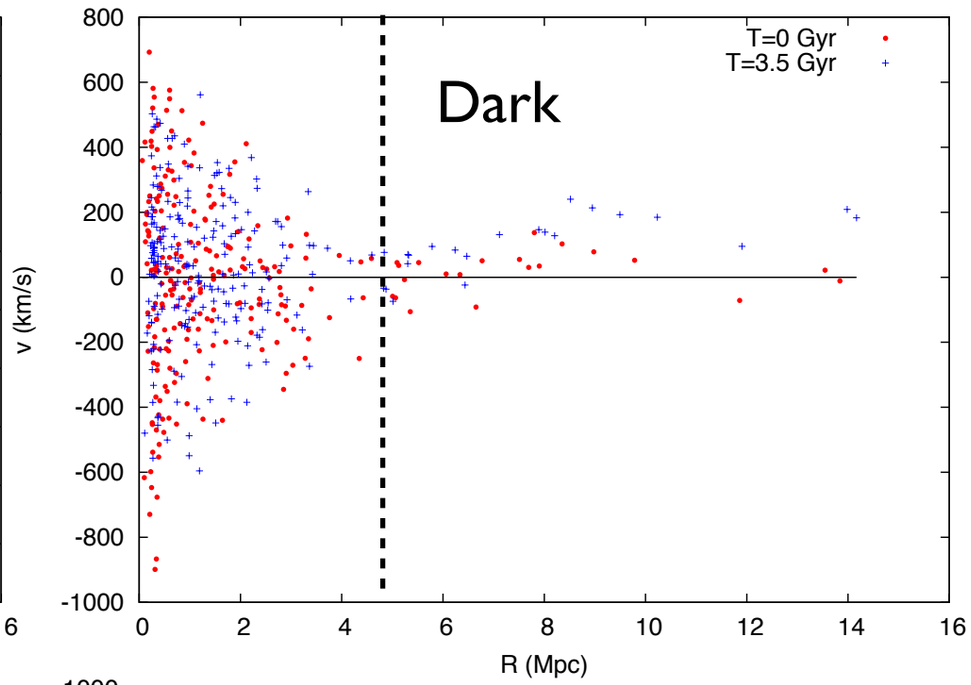
No-Dark & Gas

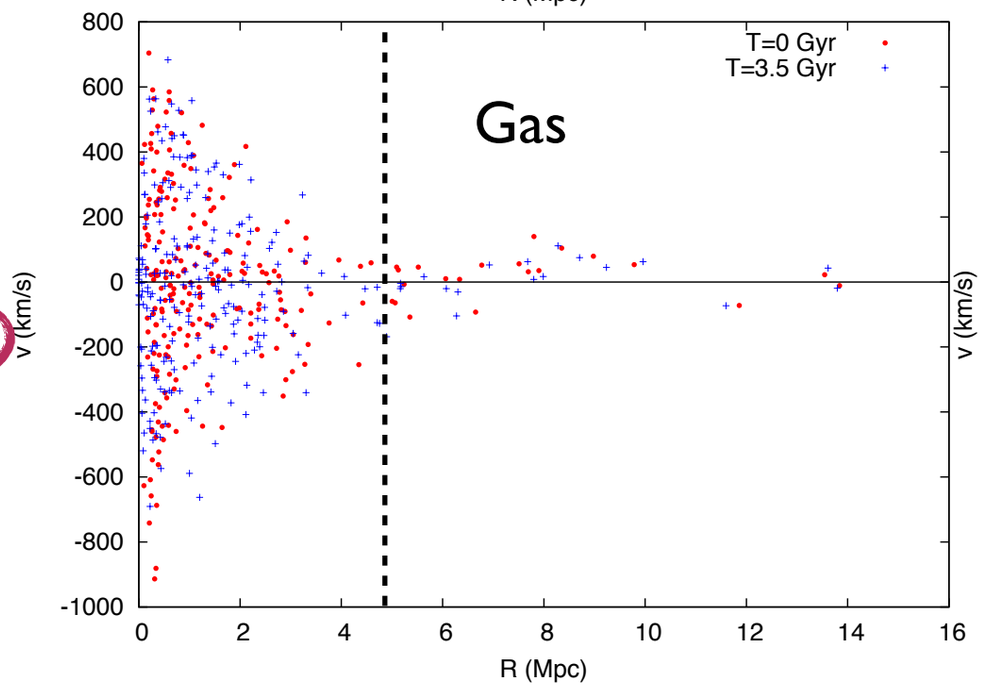
NO trend

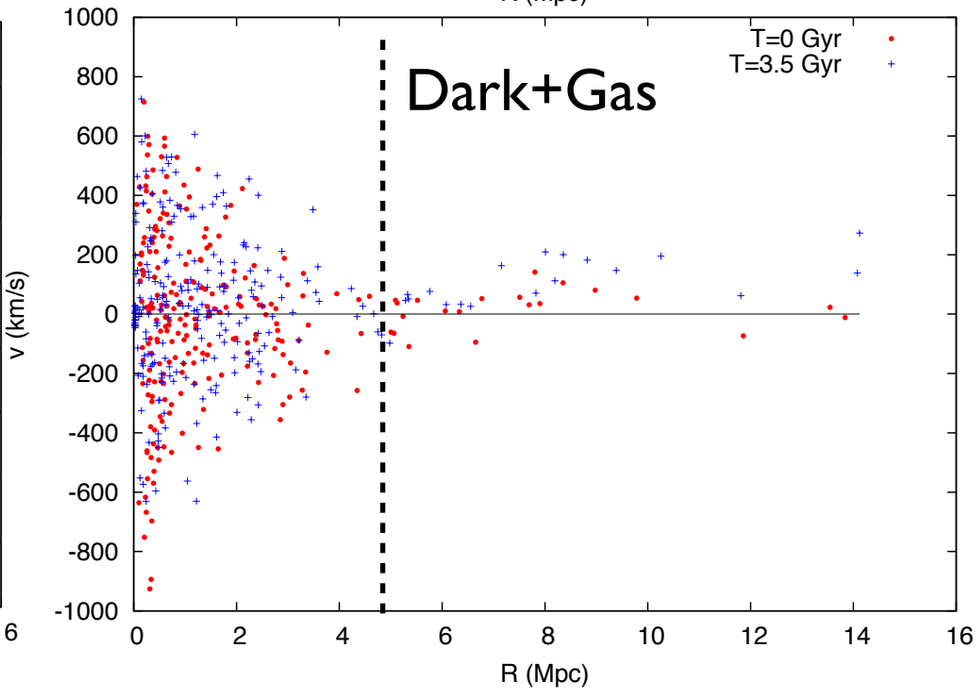
Dark & Dark+Gas

All the galaxies out of ZGR have an increasing radial velocity: VLHF



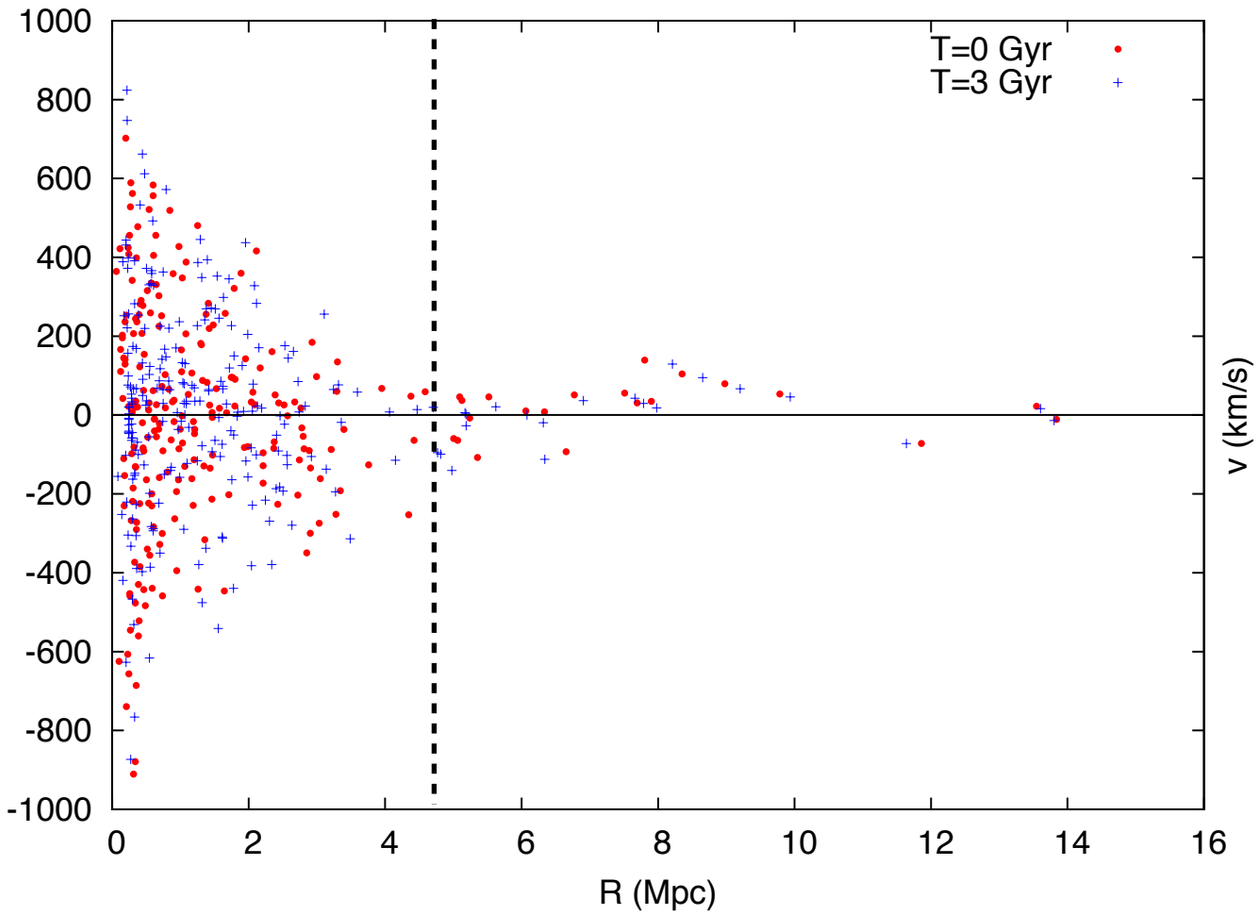




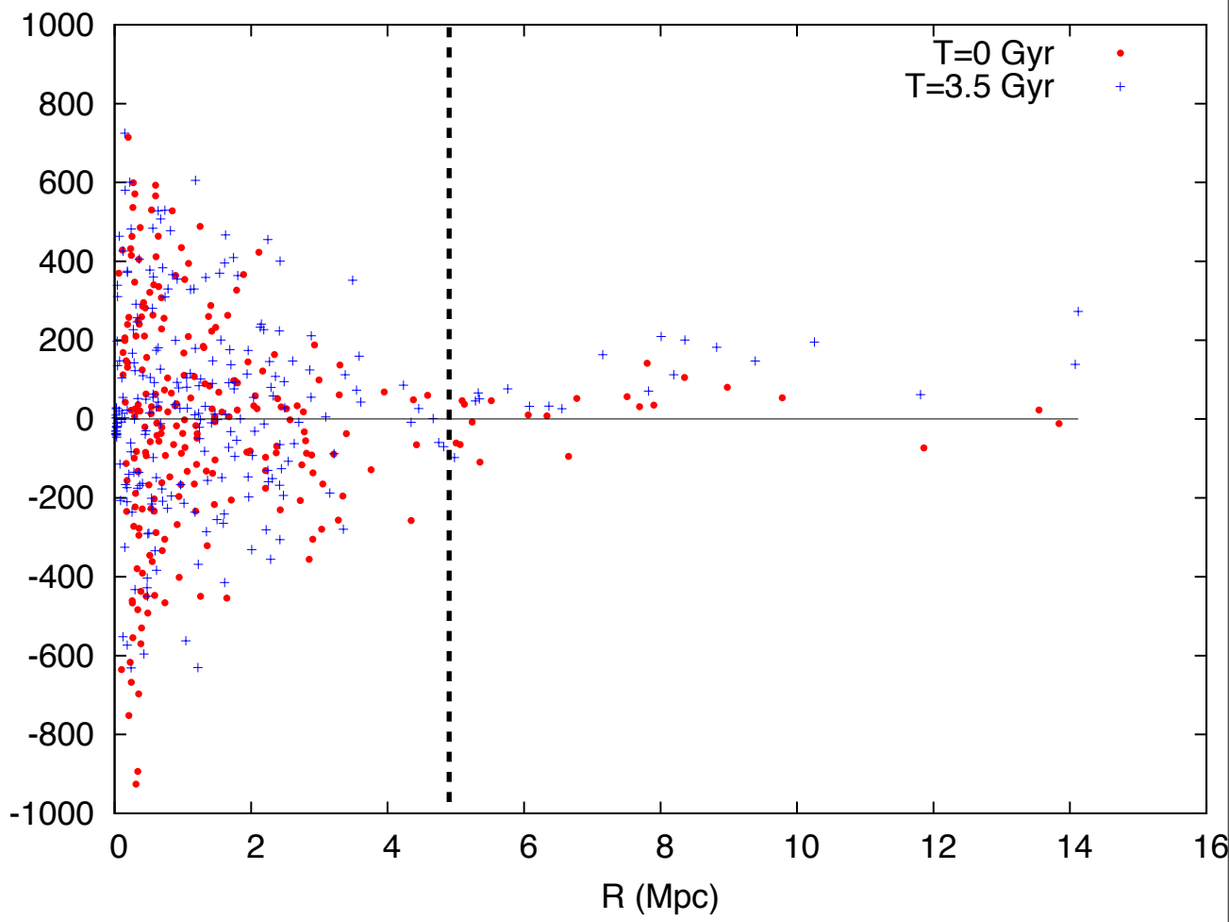


Hubble diagrams

No-Dark



Dark+Gas



Hubble diagrams

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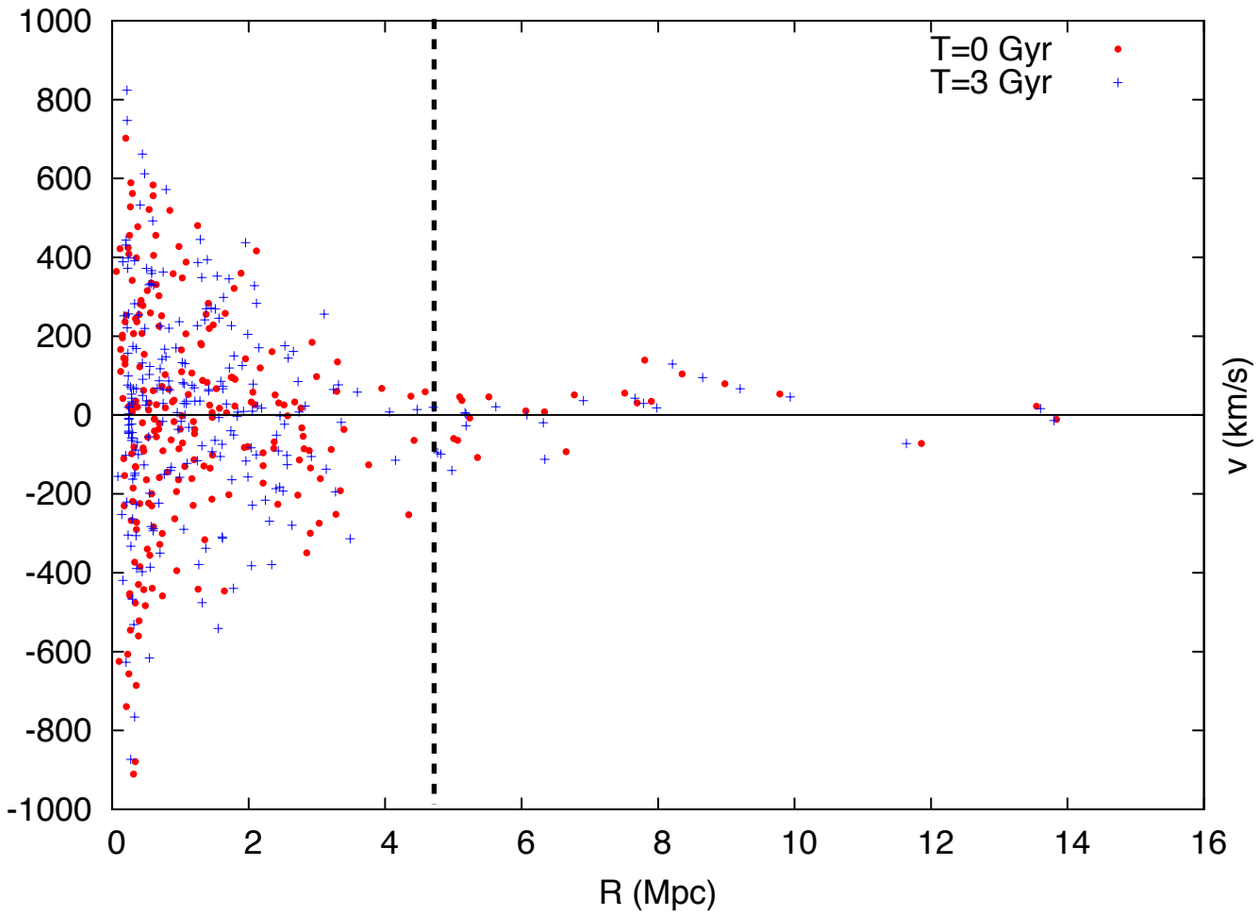

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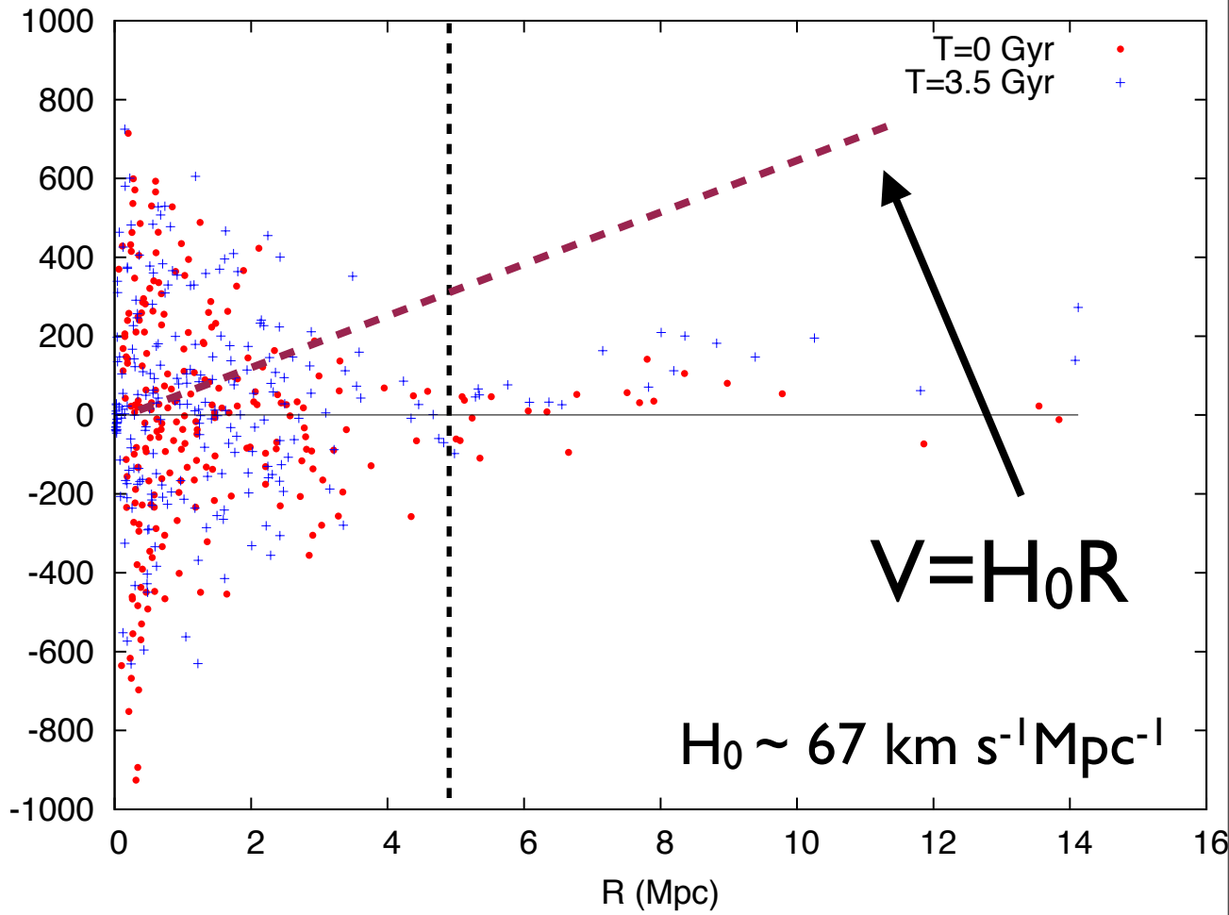

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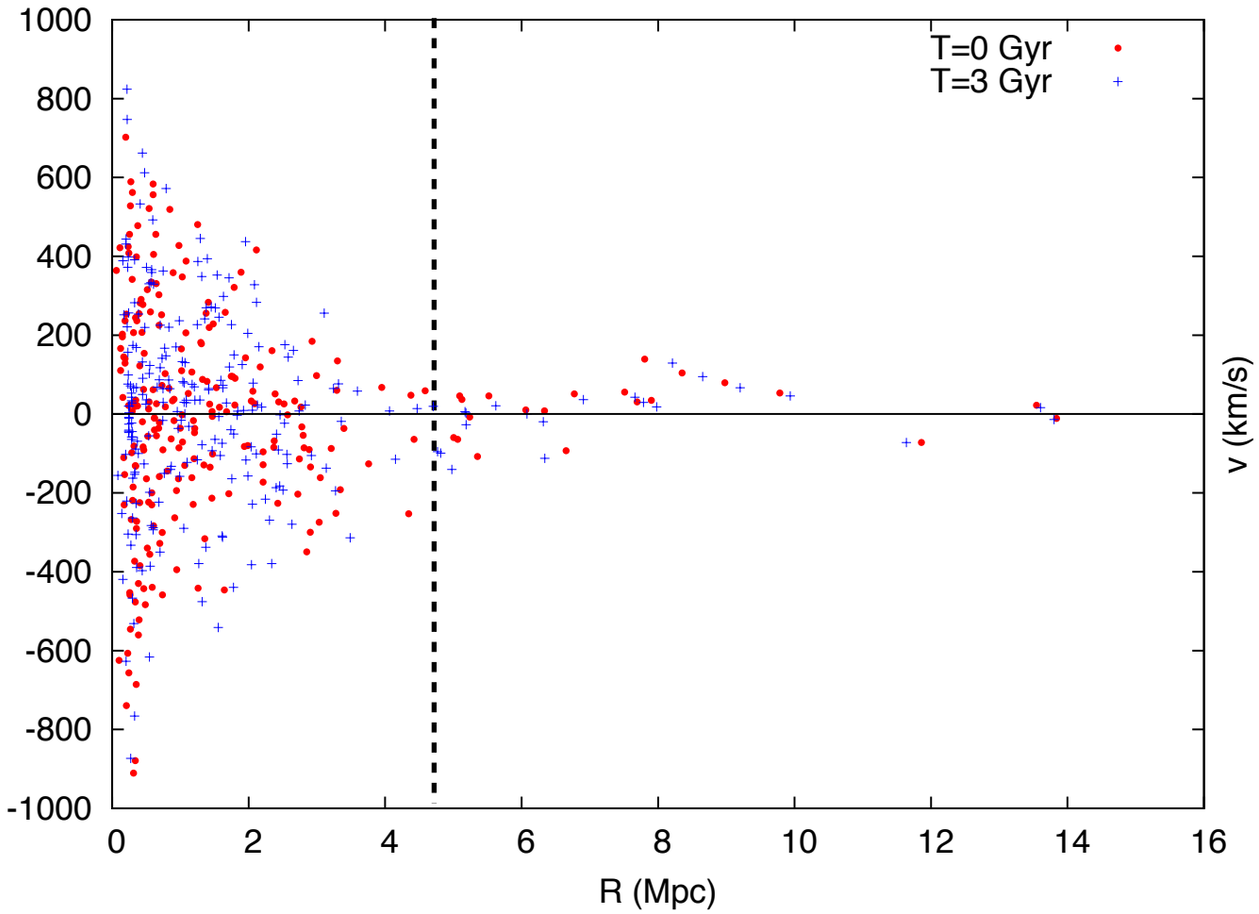

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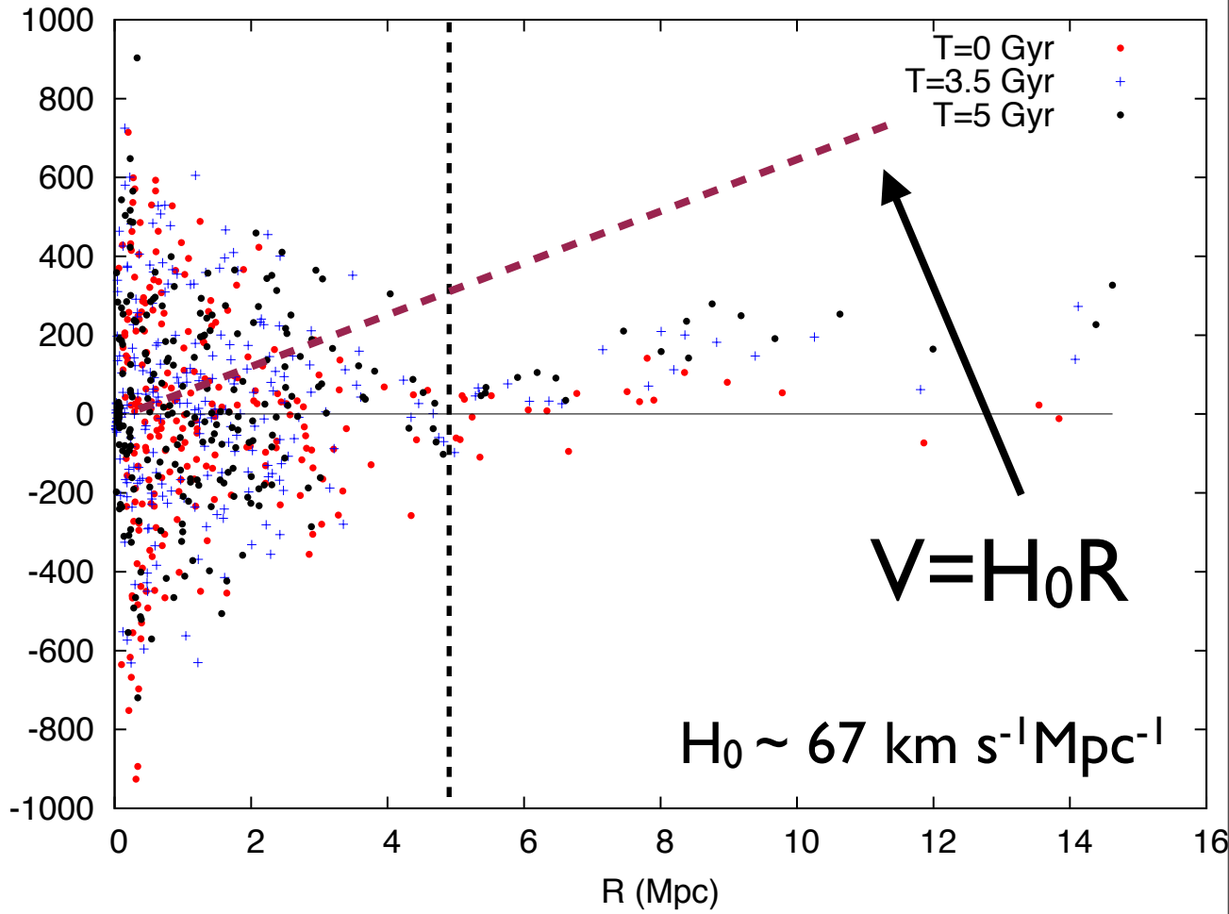

- After T=5 Gyr (black dots), around 8% of all the galaxies flow away → Not enough for the VLHF …

Hubble diagrams: single particle simulations

High resolution simulations → Several months to reach an Hubble time

Possible solution → Simulation with single particles

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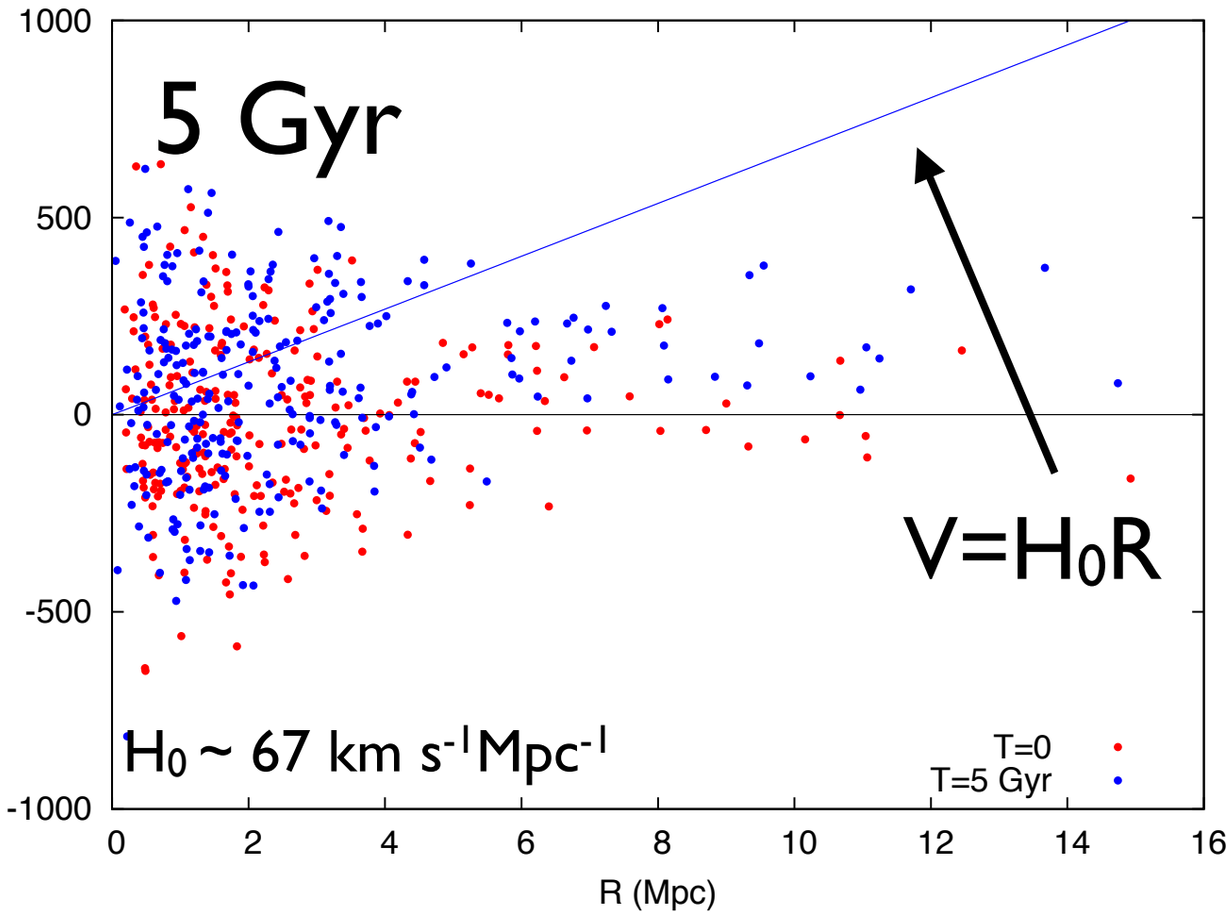

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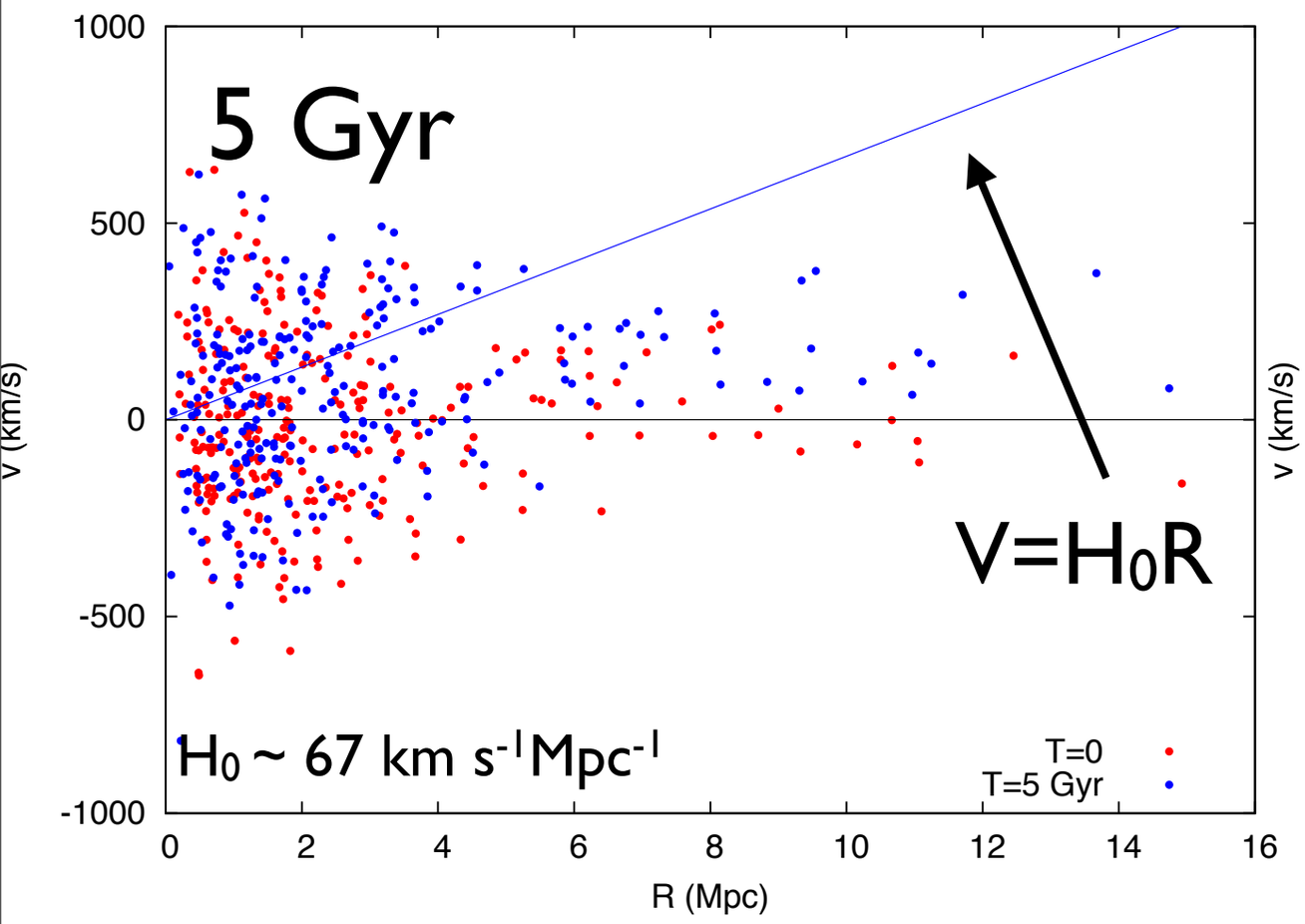

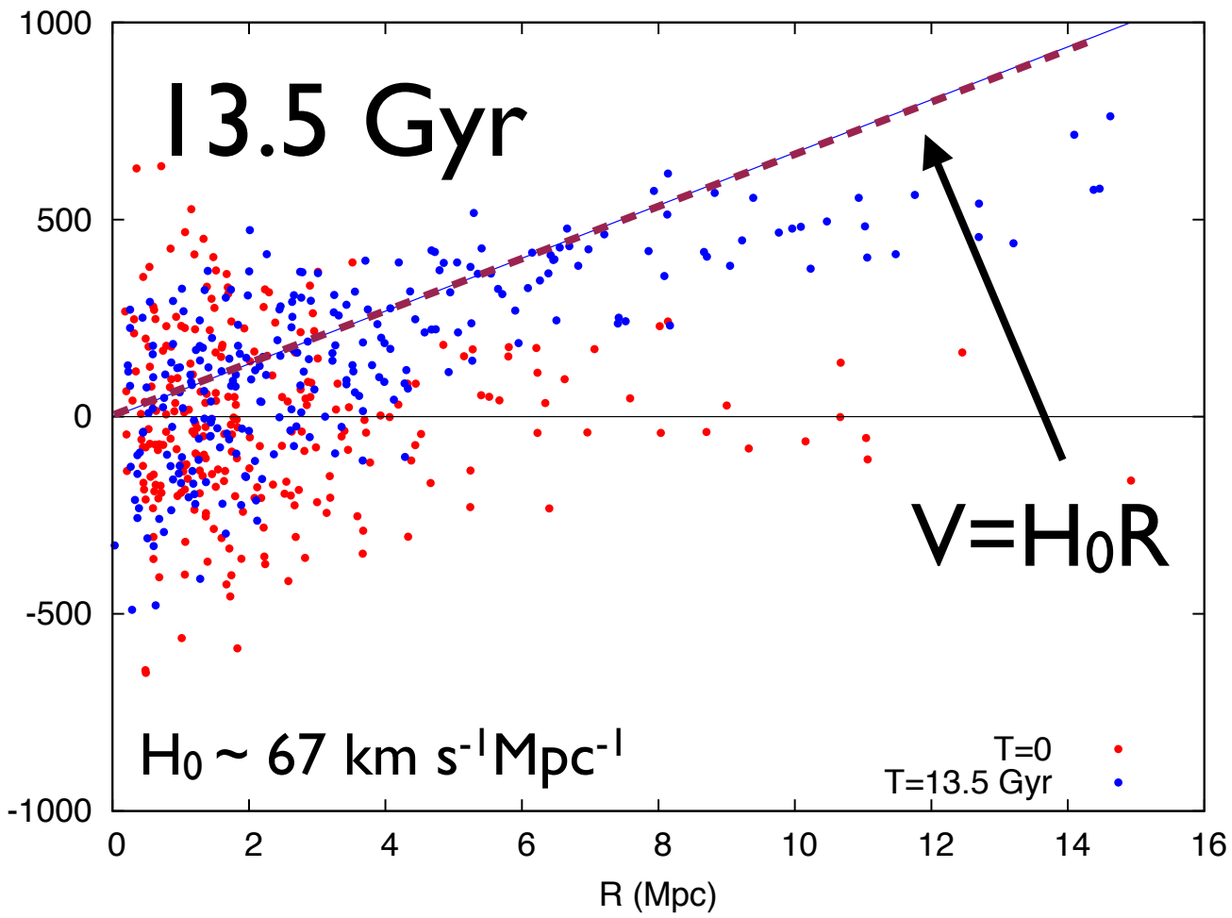

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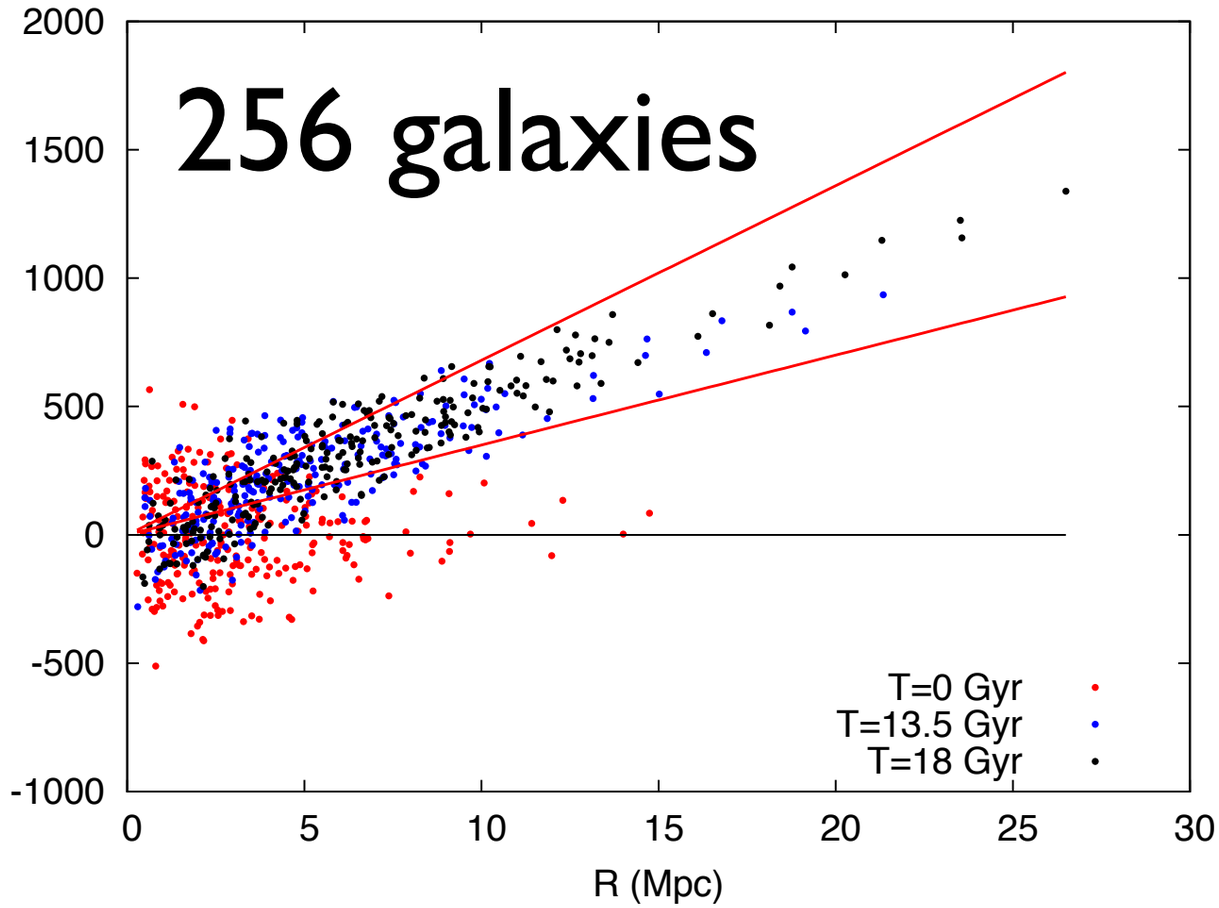


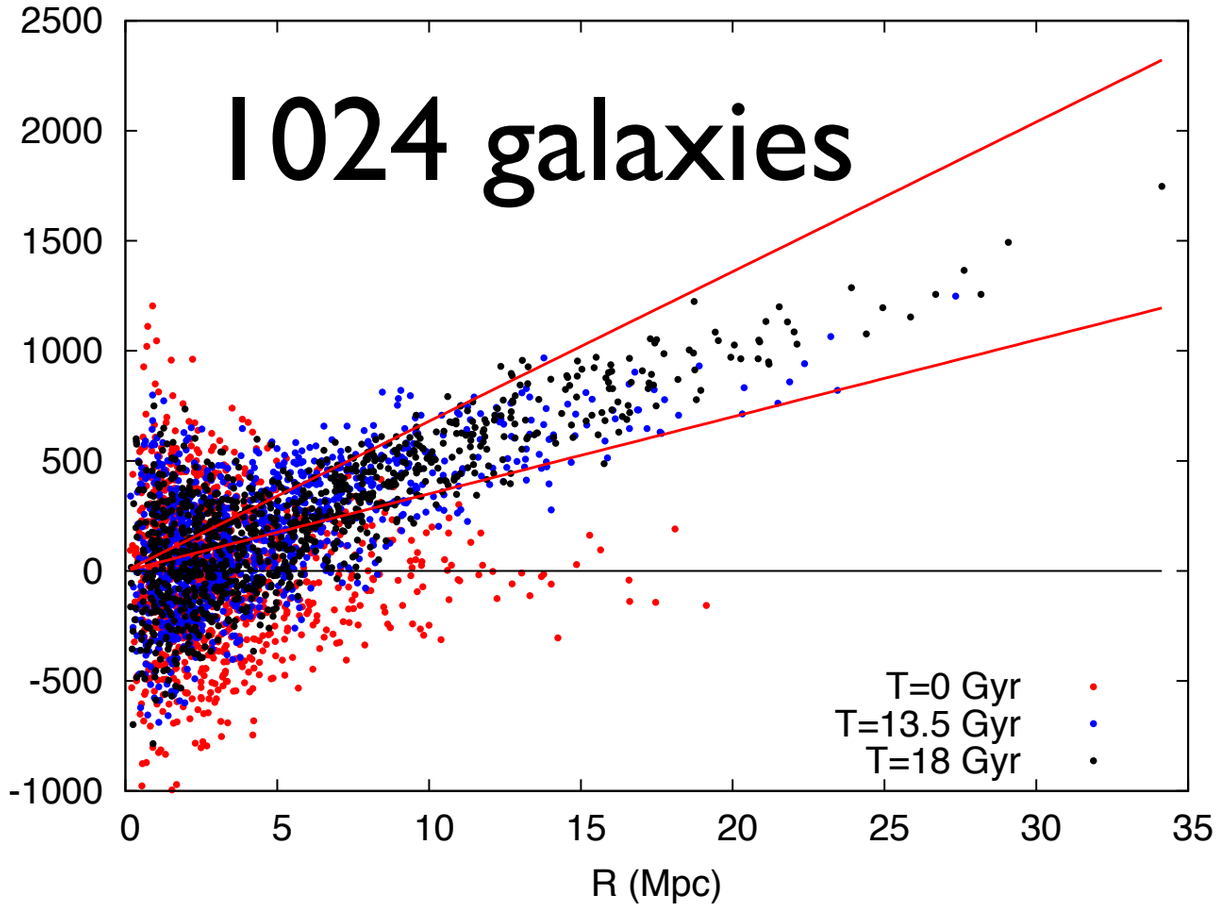
Best fit

T~13.5 Gyr H_{loc}~45 km/s/Mpc

T~18 Gyr H_{loc}~55 km/s/Mpc

30 < H_{loc} (km/s/Mpc) < 65

40 < H_{loc} (km/s/Mpc) < 60



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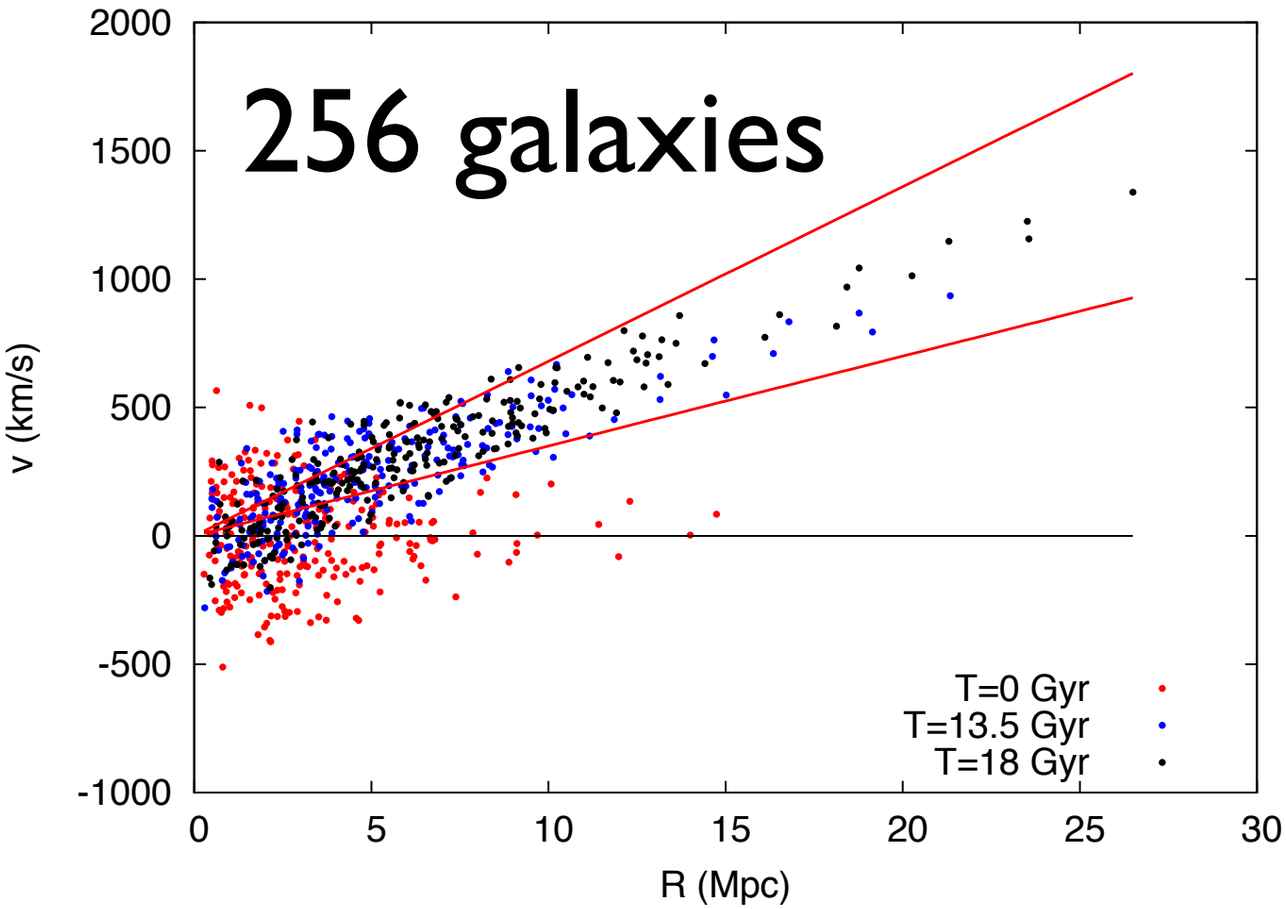

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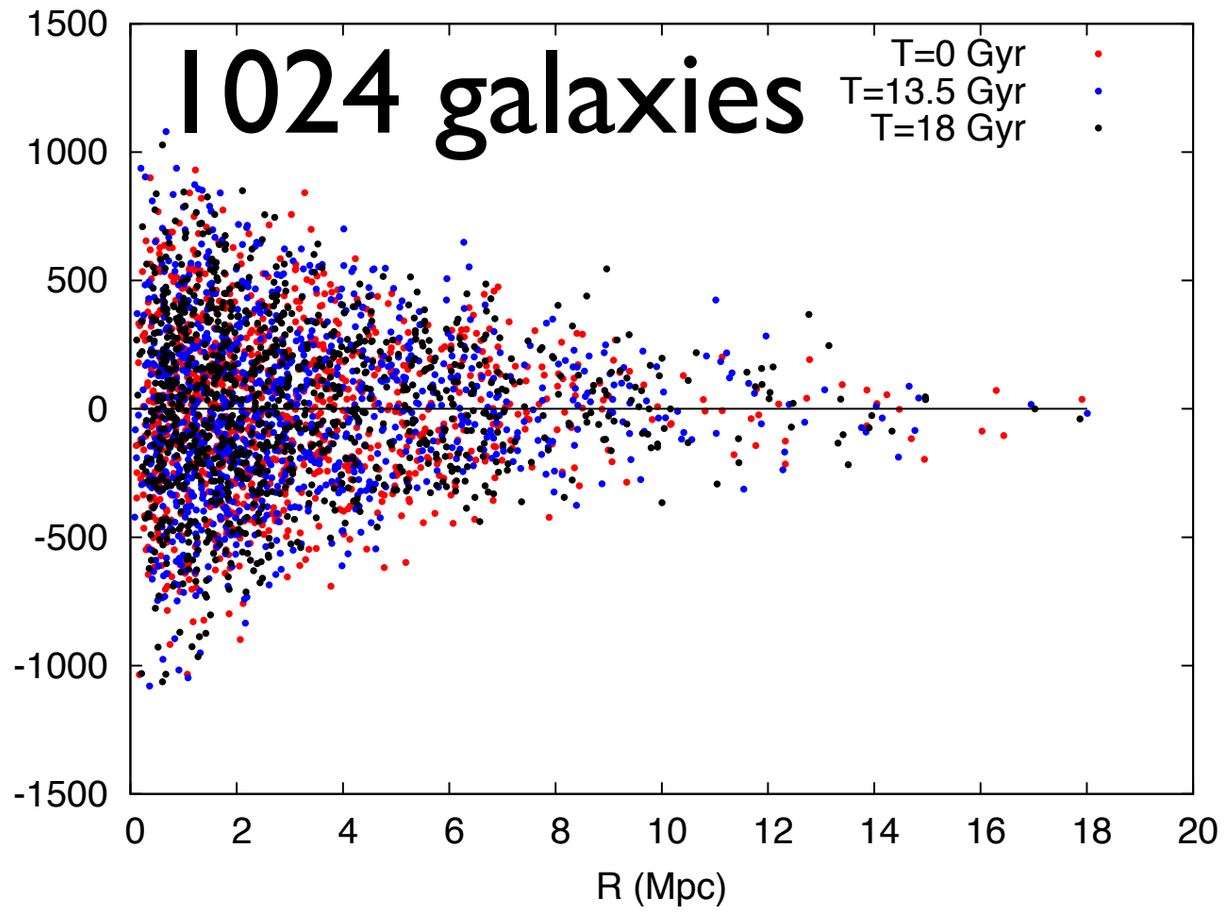
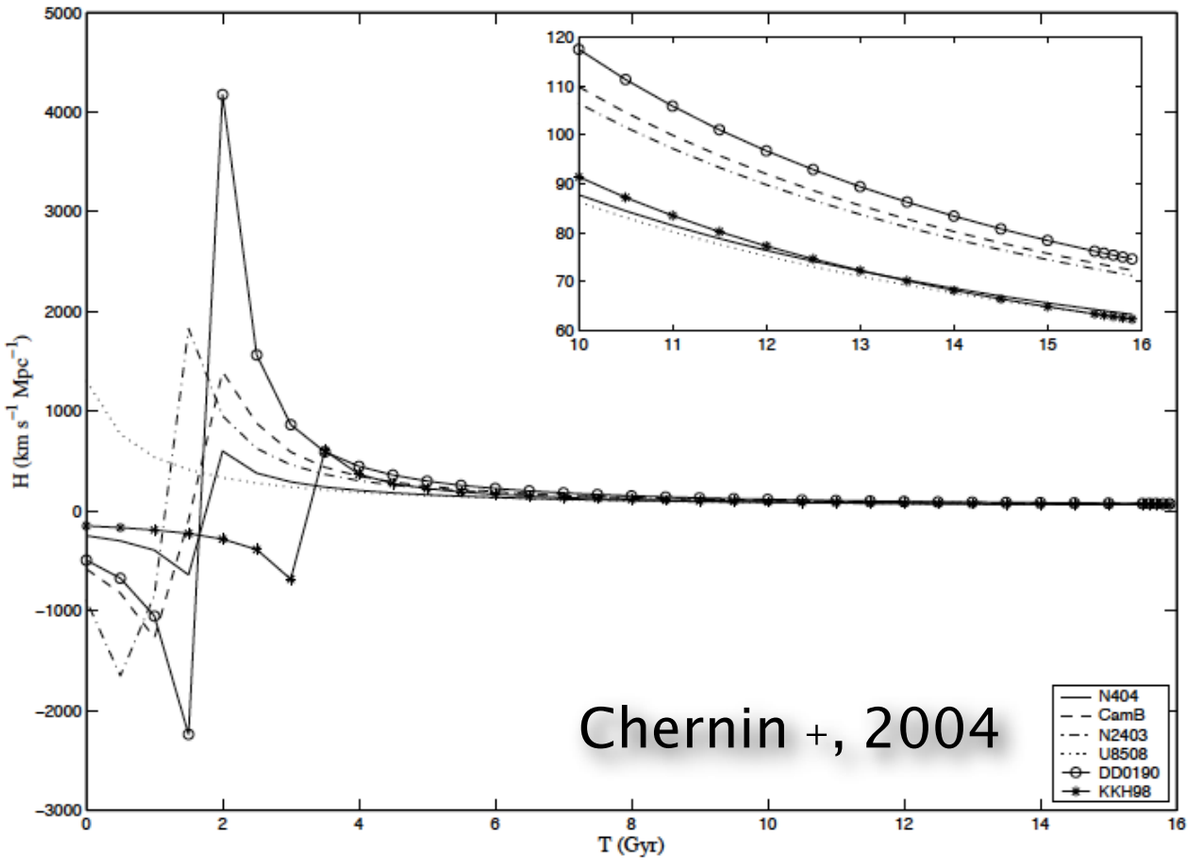


Hubble diagrams: single particle simulations



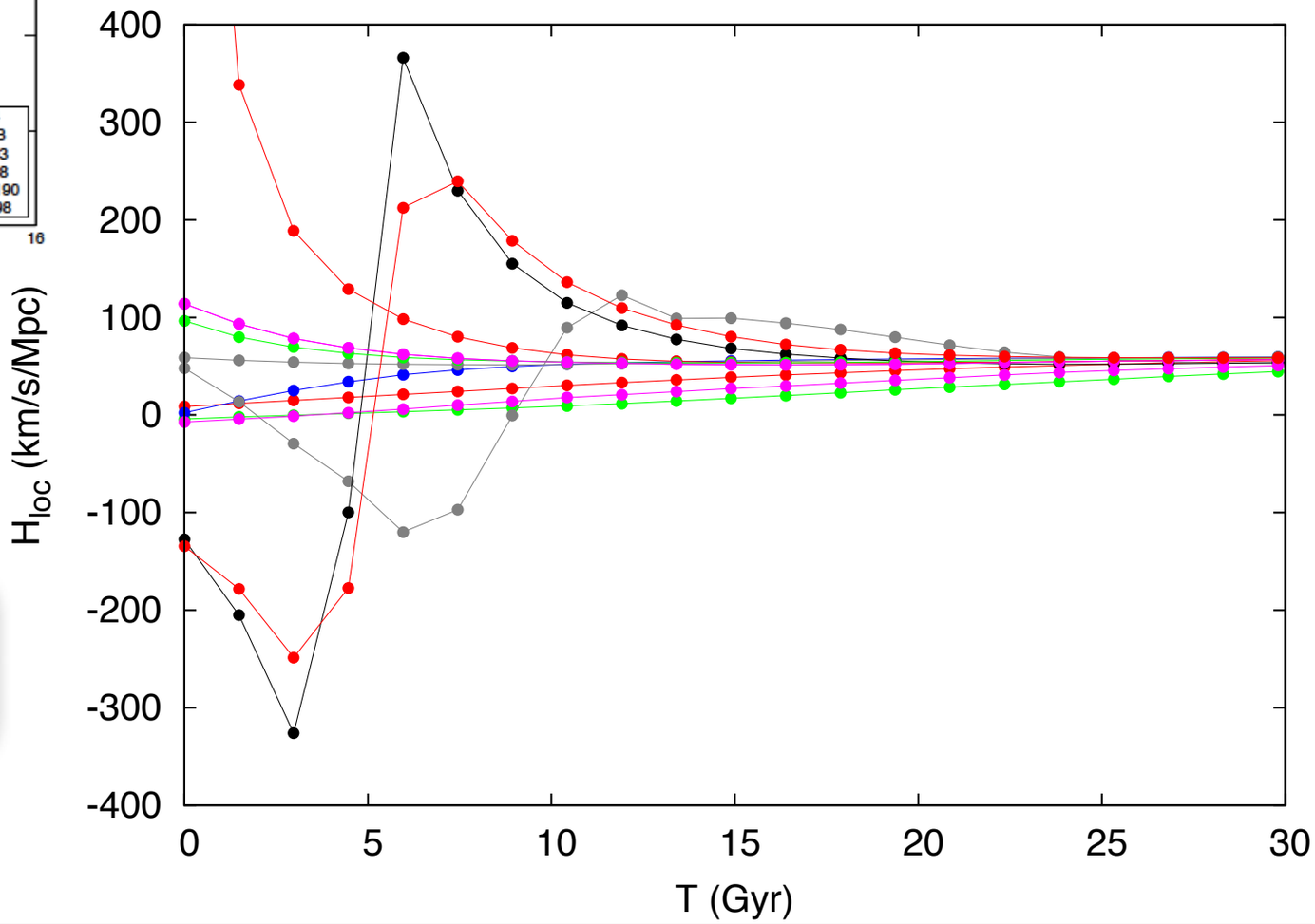
Chernin +, 2004

Simulations – T~30 Gyr

$55 < H_{loc}\ (km/s/Mpc) < 70$

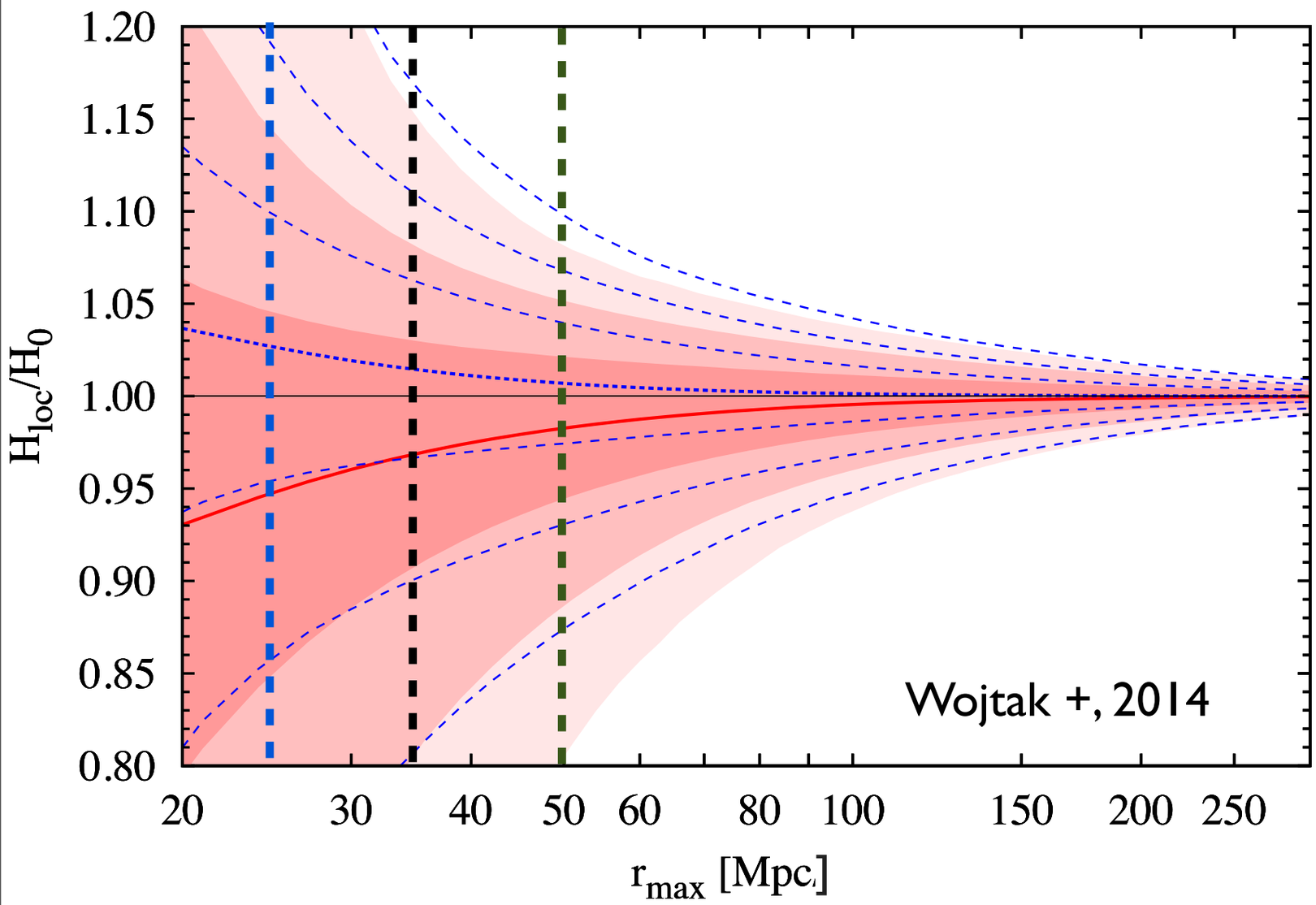
Local Group

$$H_{loc} = 72 \pm 15\ \mathrm{km\,s^{-1}Mpc^{-1}}$$



Hubble diagrams: single particle simulations

Planck 2013 ⟶ $H_0 \sim 67.3$ km/s/Mpc



T~13.5 Gyr R_{max}~25 Mpc

45% < H_{loc}/H_0 < 96 %

T~18 Gyr R_{max}~35 Mpc

59% < H_{loc}/H_0 < 89 %

T~30 Gyr R_{max}~50 Mpc

82% < H_{loc}/H_0 < 104 %

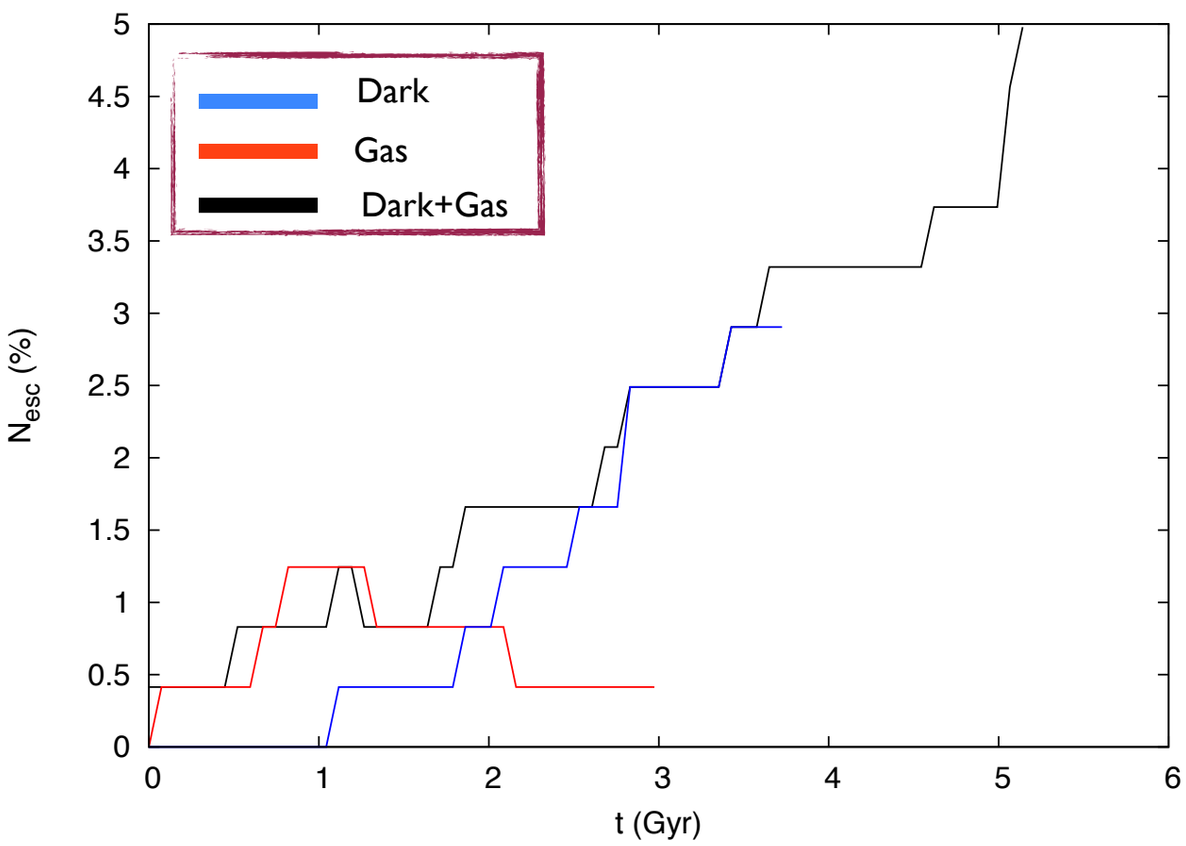
Escapers

All of these galaxies can be considered real escapers?

Criterion for the escapers →

- $R > R_\Lambda$
- $E_{N_{body}} = K + U > 0$

Escapers → Mass loss → Decreasing of ZGR



DG: 5% of escapers after 5 Gyr

$M_{esc} \sim 5\% M_{clus}$

↓

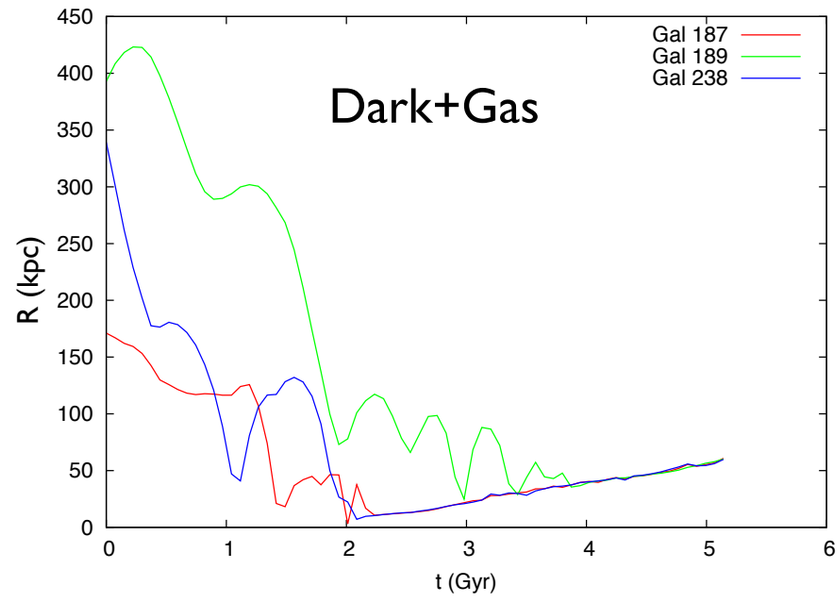
$R_\Lambda^{new} \simeq 98\% R_\Lambda^{old}$

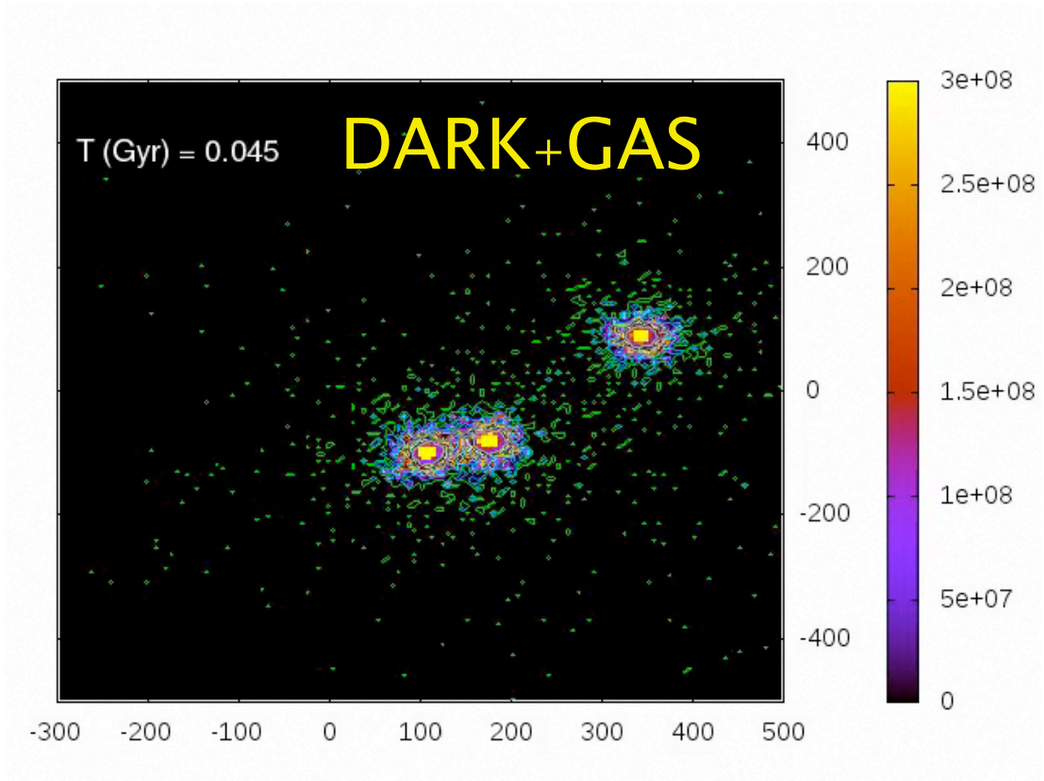
Some merging

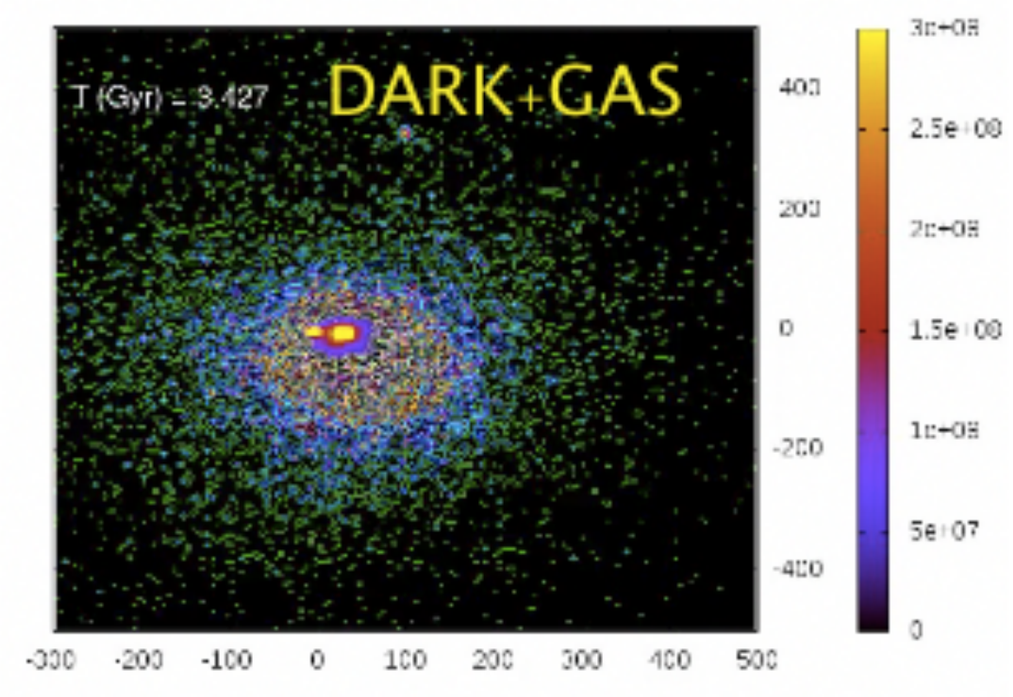
Could we follow the formation of a central massive structure?

R = (170-400) kpc

The merging among the 3 galaxies occurs in all the 4 simulations



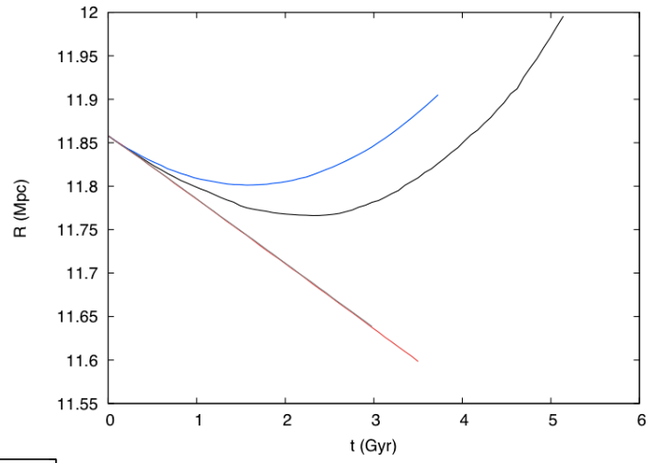




- Introduction
  - Local effect of Dark Energy
  - Look at the observations
- Simulations forecasted
- Data analysis and preliminary results
  - Trajectory of CoM
  - Hubble diagram
  - Merging
- Conclusions and what's next

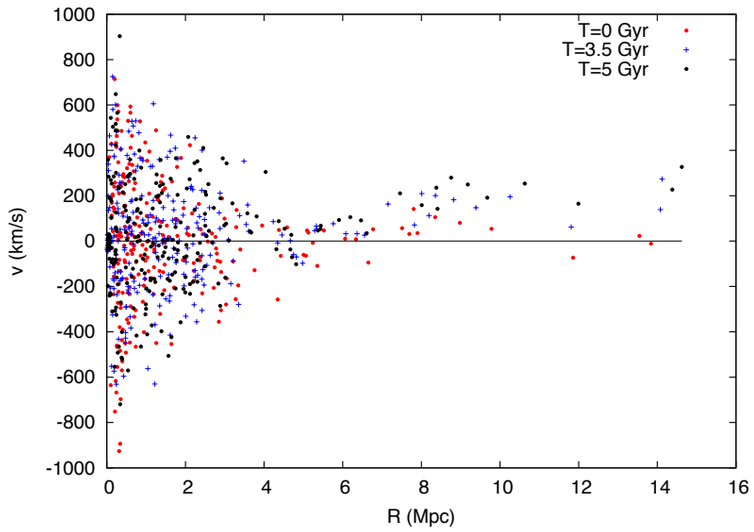
Conclusions

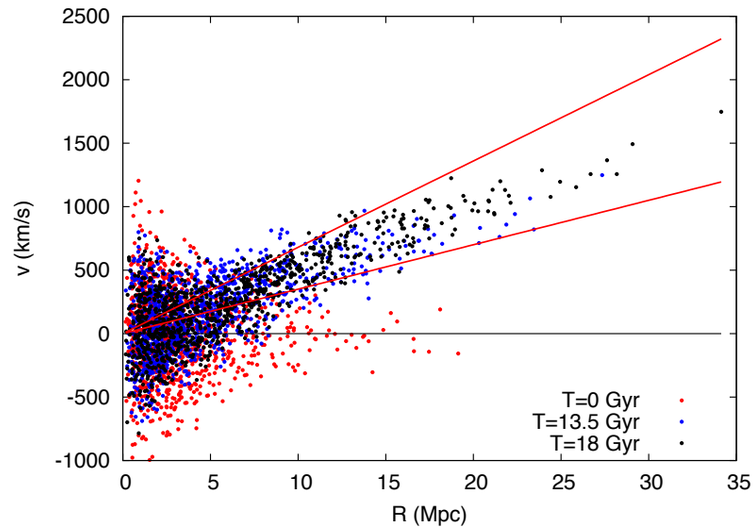
- Carried out 4 simulations of one cluster
- Studied the dynamics of inner and outer galaxies



We found relevant differences when the DE is considered

We reproduced the hubble flow





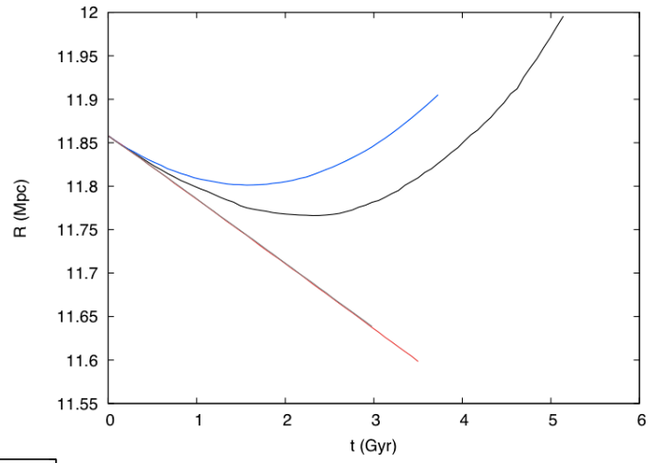
Can the DE explain the LHF?

YES ☐ NO ☐

Donnari et al., in preparation

Conclusions

- Carried out 4 simulations of one cluster
- Studied the dynamics of inner and outer galaxies



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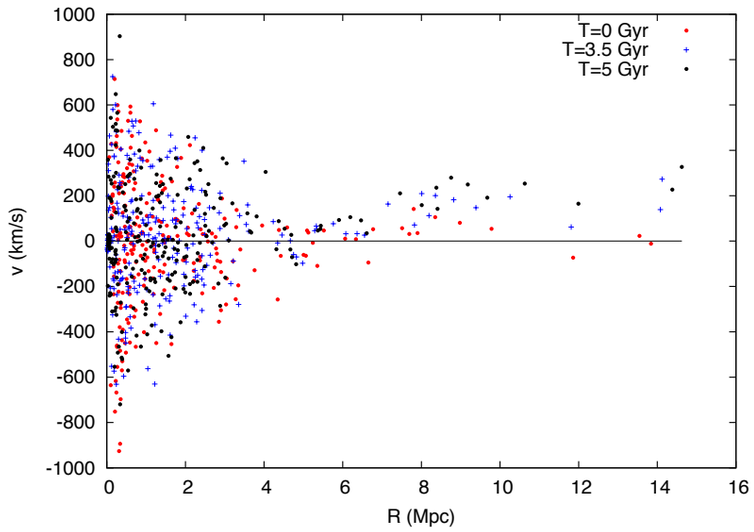
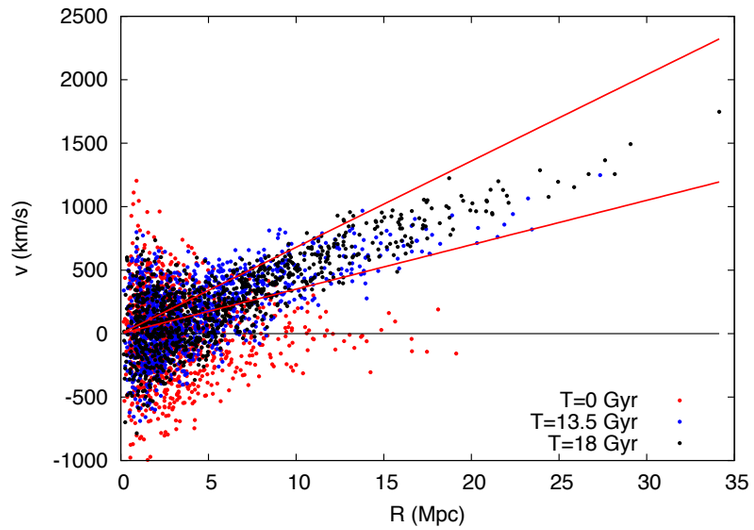




Can the DE explain the LHF?

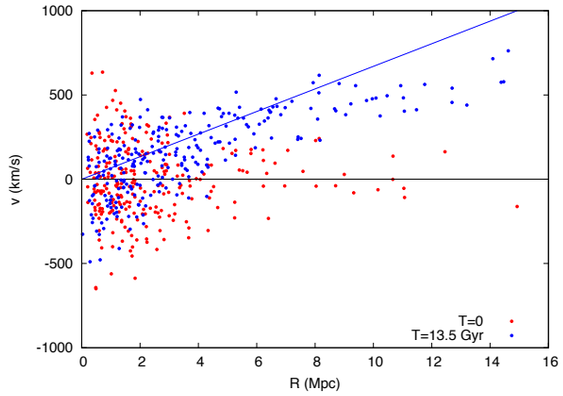
YES ☑ NO ☐

Donnari et al., in preparation

What's next

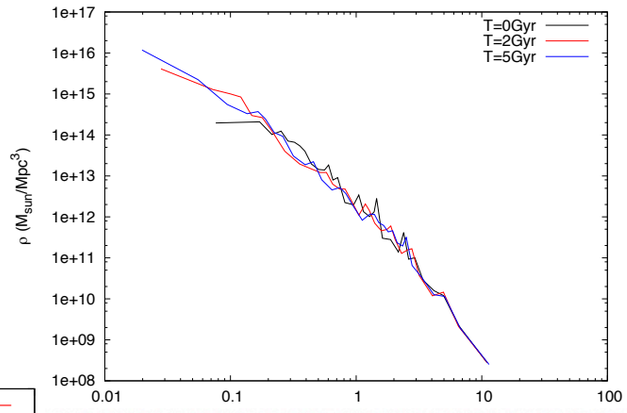
- Carry out these and other simulations over an Hubble time

  -) To build a reliable statistic with different IC of the clusters



- Study the global properties of the cluster

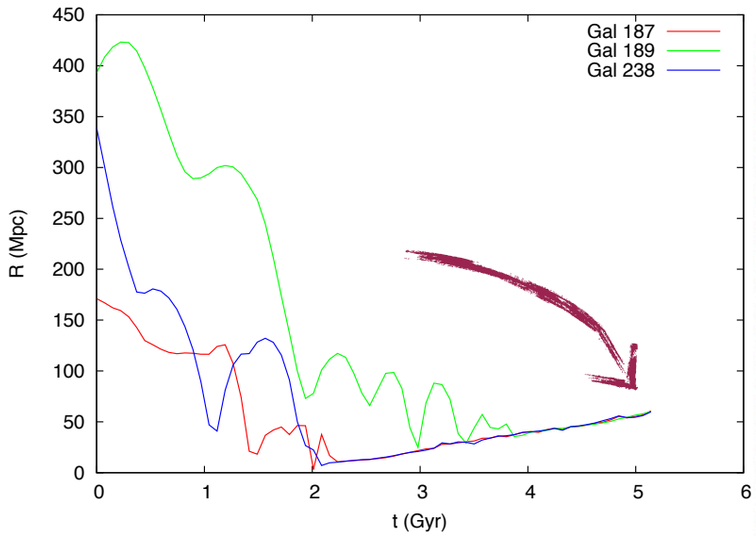
  -) Investigate density profile

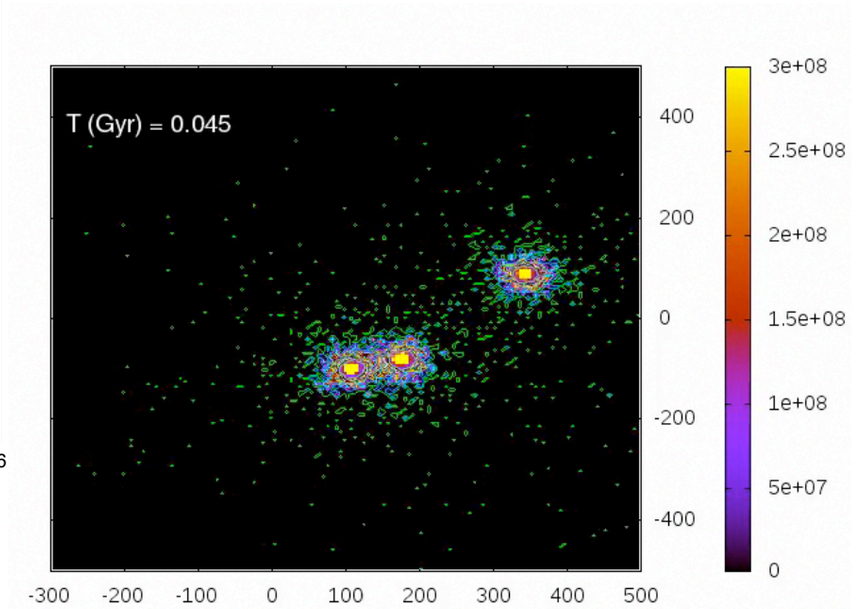


  -) How do Mass and ZGR change ?

- Possible merging

  properties of the merging products (mass, density profile)





Thank you for your attention