

# Are the nearby groups of galaxies gravitationally bound objects?

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# Scientific Background

- Small groups of galaxies are the most common type of galaxy association in the universe.
- Density fluctuations between galaxies and clusters of galaxies may provide important clues to galaxy formation.
- Groups of galaxies are important cosmological indicators of the distribution and properties of the dark matter in the universe.
- Virialization of a group is assumed when e.g. the mass of a group is estimated from observations.

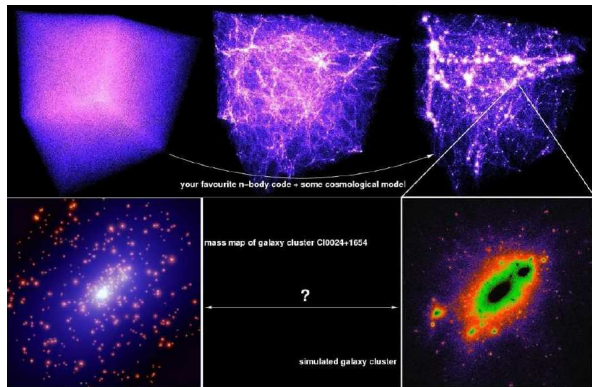
## Background

- Simulation data is produced with cosmological N-body simulation code AMIGA (Adaptive Mesh Investigations of Galaxy Assembly) (former version MLAPM by Knebe et al. 2001).
- Comparison of simulations with observational data is done with statistics.
- Study of virialization of groups of galaxies has been done sparingly and with different methods (e.g. constrained simulations and mock catalogues).
- The main purpose was to study if groups of galaxies found by the Friends-of-Friends (FOF) algorithm are bound or spurious.

# Cosmological N-body Simulations

- Are inevitable, as gravitation is fundamentally nonlinear.
- First simulations from the late 1960s with few hundred particles.
- Basic assumptions:
  - The universe is made up mainly of dark matter.
  - Gravitation is the only notable force in large scales.
  - Every particle in a simulation represents several 'real' particles.
  - Initial and periodic boundary conditions.
- Over the last two decades cosmological simulations have proved to be an invaluable tool in testing theoretical models in the nonlinear regime.

# Cosmological N-body Simulations



**Figure:** The standard approach is to assume a cosmological model and to use the appropriate power spectrum of the primordial perturbations to construct a random realisation of the density field within a given simulation volume. The evolution of the initial density field is then followed by using a choice of N-body simulation codes (illustration by Knebe 2005).

## Details of Our Simulations

- Four simulations with different values of cosmological constant  $\Lambda$  were done.
- For all simulations  $N_{partc} = 256^3$ ,  $h = 1.0$ ,  $\Omega_{total} = 1.0$  and  $\sigma_8 = 0.83$  were adopted.

| $\Lambda$ | $L$ | $N_{partc}$ | $z_i$   | $m_{res}$          | $F_{res}$ | $N_{haloes}$ |
|-----------|-----|-------------|---------|--------------------|-----------|--------------|
| 0.00      | 80  | $256^3$     | 72.8767 | $8.47 \times 10^9$ | 3.7       | 7919         |
| 0.73      | 80  | $256^3$     | 38.7099 | $2.29 \times 10^9$ | 7.3       | 8730         |
| 0.90      | 80  | $256^3$     | 31.7858 | $0.85 \times 10^9$ | 7.3       | 4937         |

where  $L$  is the size of the simulation box in one dimension in  $h^{-1}\text{Mpc}$ ,  $z_i$  is the initial redshift,  $m_{res}$  is the mass resolution in  $h^{-1}M_{\odot}$ ,  $F_{res}$  is the force resolution in  $h^{-1}\text{kpc}$ .

# Group-Finding Algorithm

- Given a set of galaxies with position on the sky and redshifts, the task of the group-finder is to return sets of galaxies that are most likely to represent the true gravitationally bound structures that are being traced by the observed galaxies.
- Huchra & Geller (1982) (hereafter HG82) developed an algorithm for identifying groups of galaxies: Friends-of-Friends (FOF).
- The FOF algorithm is nowadays a standard approach to identifying groups of galaxies in redshift surveys.
- Several other group-finders with optimised parameters/algorithms are based on the original FOF.
- In general, it is thought that FOF produces groups that are gravitationally bound objects.

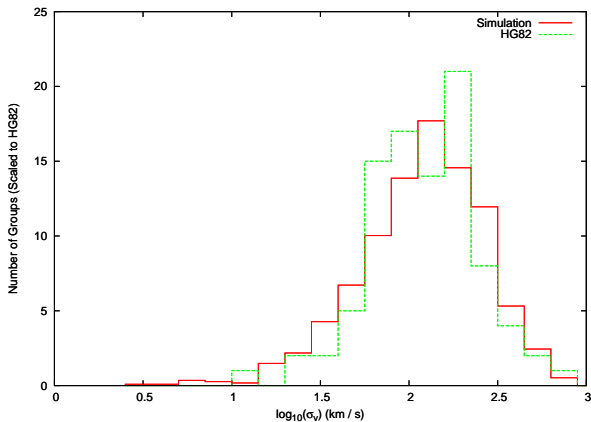
# Friends-of-Friends Algorithm

- FOF can be summed up into two criteria: projected separation and velocity difference.
- When linked objects are identified, the surroundings of each companion are then searched.
- The process is repeated until no further members are found.
- FOF does not assume any predetermined shape for a group.

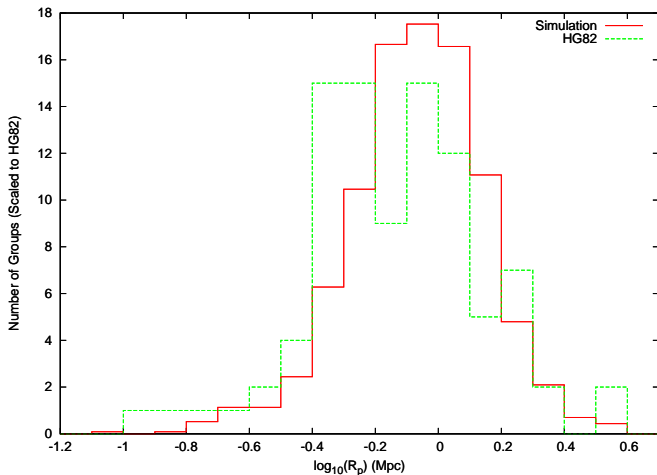
## Selection of the Groups

- Total of ten catalogues were generated, corresponding to 10 different 'observers', for each simulation, and with different apparent magnitude limits.
- All the observation points were chosen with the following criteria:
  - ① observation point is  $> 15$  Mpc from the edge of the simulation box
  - ② a massive ( $\sim 5 \times 10^{14} M_{\odot}$ ) halo (Virgo -type) is located within a distance of  $\sim 20$  Mpc.
- The local  $< 10$  Mpc environment of the observation points were not restricted with any criteria.

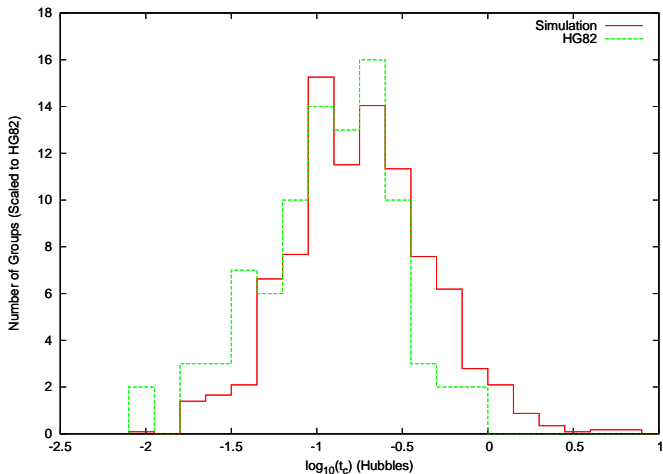
# Comparison with Observations



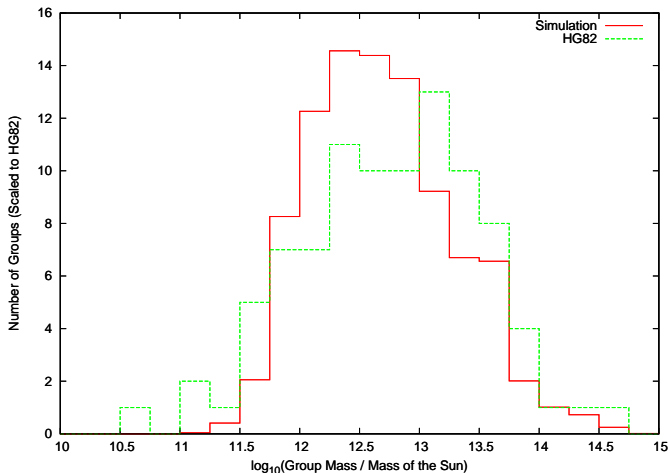
**Figure:** The velocity dispersion  $\sigma_v$  of the groups found from simulations and observations (HG82). The simulation data is from the low resolution  $\Lambda$ CDM simulation. The number of groups are scaled to the number of groups of galaxies found in HG82.



**Figure:** The mean pairwise separation  $R_p$  of the groups found from simulations and observations (HG82). The simulation data is from the low resolution  $\Lambda$ CDM simulation. The number of groups is scaled to the number of groups of galaxies found in HG82.



**Figure:** Crossing time  $t_c$  (in Hubbles) of the groups found from simulations and observations (HG82). The simulation data is from the low resolution  $\Lambda$ CDM simulation. The number of groups is scaled to the number of groups of galaxies found in HG82.



**Figure:** Mass distribution of the groups found from simulations (with  $m_{lim} = 20.0$ ) and observations (HG82). The simulation data is from the low resolution  $\Lambda$ CDM simulation. The number of groups is scaled to the number of groups of galaxies found in HG82.

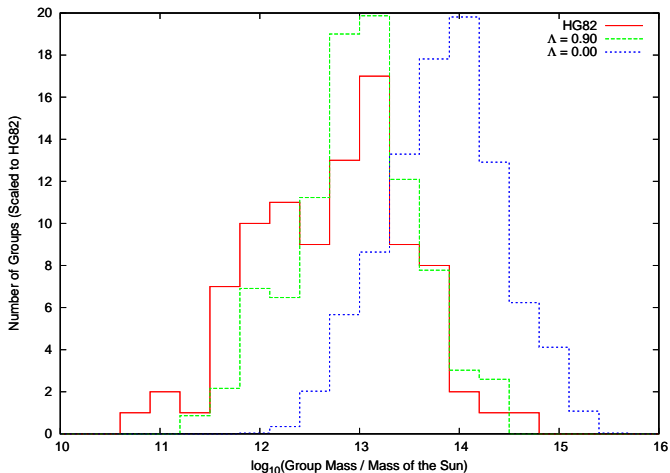
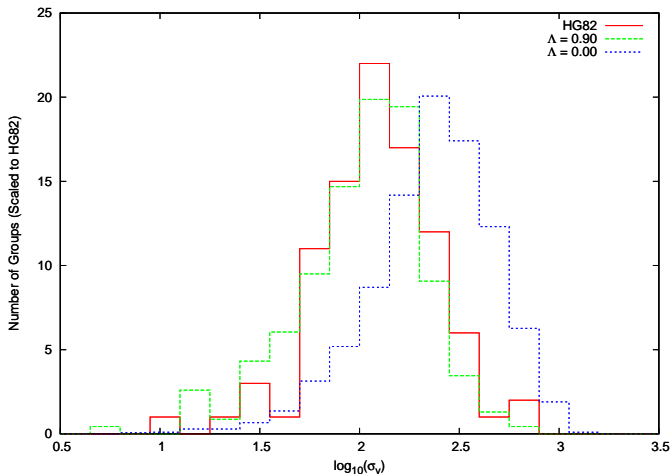


Figure: The mass distribution of groups from two different simulations with two different values of cosmological constant  $\Lambda$  when the apparent magnitude limit of  $m_{lim} = 13.2$  has been adopted. For comparison, also the observational data from HG82 has been plotted.



**Figure:** Velocity dispersion  $\sigma_v$  of groups from two different simulations with two different values of cosmological constant  $\Lambda$  when the apparent magnitude limit of  $m_{lim} = 13.2$  has been adopted. For comparison, also the observational data from HG82 has been plotted.

# Virial Theorem

- Groups of galaxies contain more than two members, general method is needed (see Chernin & Mikkola 1991).
- Kinetic energy:

$$T = \frac{1}{2M} \sum_{i < j} m_i m_j (\mathbf{v}_i - \mathbf{v}_j)^2 \quad . \quad (1)$$

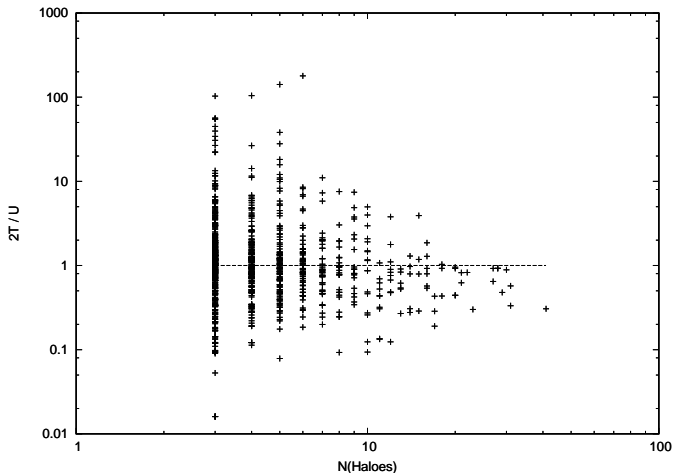
- Potential energy:

$$U = G \sum_{i < j} \frac{m_i m_j}{R_{i,j}} \quad . \quad (2)$$

- If a group does not fulfil the criterion:

$$\frac{2T}{U} \leq 1.0$$

it is considered spurious.



**Figure:** The number of members in a group ( $N(\text{Haloes})$ ) versus virialization ( $\frac{2T}{U}$ ). Groups with more than 10 members are more often virialized than 'poorer' groups with three to five members. Data is from the low resolution  $\Lambda$ CDM simulation when the apparent magnitude limit of 13.2 was adopted.

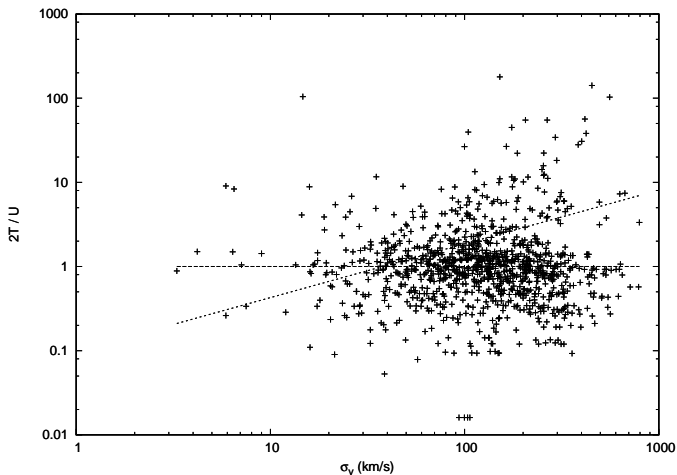
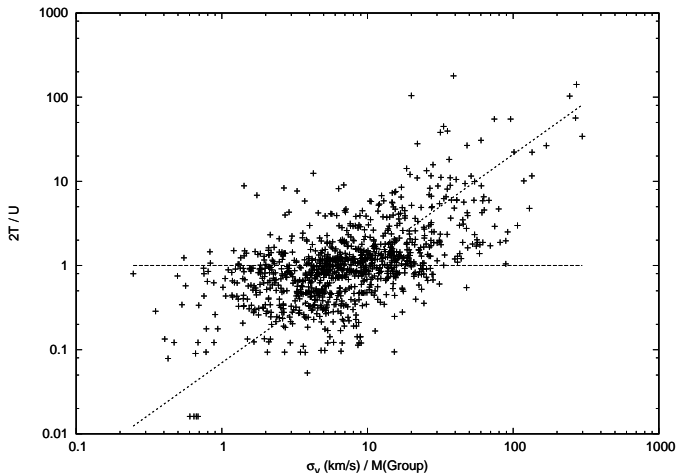


Figure: The velocity dispersion of groups ( $\sigma_v$ ) versus virialization ( $\frac{2T}{U}$ ). Straight line has been fitted to the data. Data is from the low resolution  $\Lambda$ CDM simulation when the apparent magnitude limit of 13.2 was adopted.

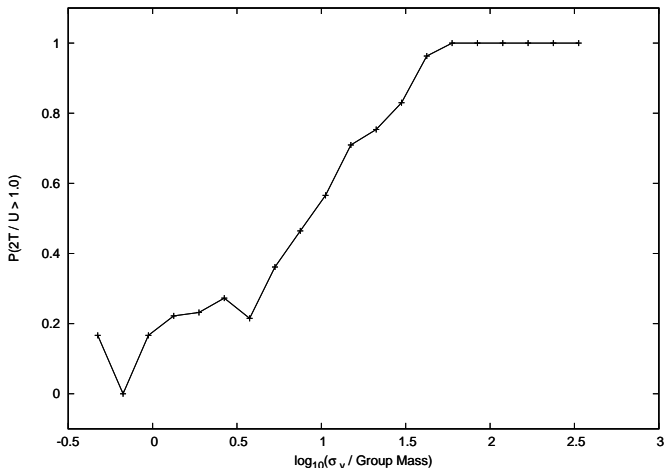


**Figure:** The velocity dispersion of groups ( $\sigma_v$ ) versus virialization ( $\frac{2T}{U}$ ) when the velocity dispersion of groups has been scaled with the total mass of a group ( $M(\text{Group})$  in  $M_\odot$ ) and a term  $10^{12}$ . Straight line has been fitted to the data. Data is from the low resolution  $\Lambda$ CDM simulation when the apparent magnitude limit of 13.2 was adopted.

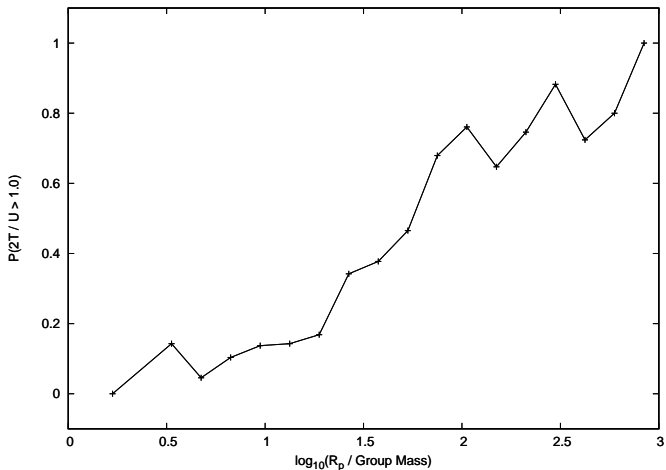
| $\Lambda$ | $m_{lim}$ | $N_{groups}$ | $Vir_{1.0}$ (%) | $Vir_{1.2}$ (%) | isolated (%) |
|-----------|-----------|--------------|-----------------|-----------------|--------------|
| 0.00      | 13.2      | 2907         | <b>55.6</b>     | 65.6            | <b>26.9</b>  |
| 0.00      | 20.0      | 6004         | 50.7            | 60.4            | 38.6         |
| 0.73      | 13.2      | 1055         | <b>52.4</b>     | 63.7            | <b>43.2</b>  |
| 0.73      | 20.0      | 6715         | 39.1            | 46.8            | 42.1         |
| 0.90      | 13.2      | 213          | <b>51.2</b>     | 63.4            | <b>54.3</b>  |
| 0.90      | 20.0      | 3660         | 40.0            | 45.5            | 37.2         |

| $m_{lim}$ | $N_{haloes}$ | $N_{groups}$ | $Vir_{1.0}$ (%) | $Vir_{1.2}$ (%) |
|-----------|--------------|--------------|-----------------|-----------------|
| 13.2      | $\in [3, 4]$ | 677          | 47.6            | 59.2            |
| 13.2      | $> 4$        | 378          | 61.1            | 71.7            |
| 20.0      | $\in [3, 4]$ | 4154         | 31.1            | 38.6            |
| 20.0      | $> 4$        | 2561         | 51.9            | 60.0            |

Is there a way to predict if a group of galaxies is gravitationally bound object?



**Figure:** Nonvirialization probability ( $P(2T/U > 1.0)$ ) versus velocity dispersion ( $\sigma_v$ ) of a group when  $\Lambda$ CDM cosmology, the apparent magnitude limit of  $m_{lim} = 13.2$  and a bin length of 0.15 was adopted. Logarithmic velocity dispersion  $\sigma_v$  axis has been scaled with a term  $10^{12}$ .



**Figure:** Nonvirialization probability ( $P(2T/U > 1.0)$ ) versus mean pairwise separation ( $R_p$ ) when  $\Lambda$ CDM cosmology, the apparent magnitude limit of  $m_{lim} = 13.2$  and a bin length of 0.15 was adopted. Logarithmic mean pairwise separation  $R_p$  axis has been scaled with a term  $10^{15}$ .

# Summary and Conclusions

- $\Lambda$ CDM cosmology can produce groups of dark matter haloes comparable to observations when the FOF algorithm is applied.
- About half of the groups of dark matter haloes generated by the FOF algorithm are spurious.
- When the value of cosmological constant  $\Lambda$  was varied, virialization fractions changed only slightly.