Merging Systems Identification in Systems of Galaxies.

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Motivation:

- The nature of dark matter is still a great unsolved astrophysical problem (EoS of DM, GR in GG).
- Laboratory searches for the DM candidates succeeded in showing that any interaction between the dark and baryonic matter is vanishingly small (CDMS, XENON, PANDAX, etc).
- Despite their size, galaxy clusters have an average projected mass density of order $0{,}1 - 1 gcm^{-2}$, so they are no match for the laboratory experiments for constraining the DM-baryon interactions.
- However, clusters and galaxies may provide the best available laboratory for studying the DM self-interaction.

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Markevicht et al 2004:

- Studing the dinamics of merging clusters allow us determinate some properties of dark matter particles, since provide a diagnostic of large scale structure (LSS) formation.
- Provide empirical evidence favoring DM over modified gravity (Clowe et al. 2006).

Important for this work

provide constraints on the DM self-interaction cross-section in three different ways as follows:

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The Bullet Cluster

- Optical Image.
- X-ray emission of the ICM.
- Estimated mass using WL.

The most remarkable feature is a 23.ºffset between the subclusters DM centroid and the gas bullet, which is at least 2σ significant.

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The gas – Dark Matter offset:

- The offset between the subclusters DM centroid and the gas bullet, means that the scattering depth τ of the dark matter subcluster w.r.t. collisions with the flow of dark matter particles cannot be much greater than 1: $\tau_s = \frac{\sigma}{m}\Sigma_s$

where σ is the DM collision cross-section, m is its particle mass and Σ_s is the DM surface density of the subcluster. The surface density averaged over the face of the subcluster is $\Sigma \approx 0{,}2 gcm^{-2}$. Assuming spherical symmetry and requiring that $\tau_s < 1$, we obtain $\frac{\sigma}{m} < 5cm^2g^{-1}$. See also Merging Cluster Colaboration.

Cluster	$\frac{\sigma}{m}$
Bullet Cluster	$< 5cm^2/g$
Musket Ball	$< 7cm^2/g$
Baby Bullet	$< 4cm^2/g$

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The high velocity of the subcluster and its survival:

$$v - v_{ff} = \frac{\bar{p}}{m}\frac{\sigma}{m}\Sigma_m \quad (1)$$

$$v - v_{ff} < 1000 km/s \quad (2)$$

$$\frac{\sigma}{m} < 7 cm^2/g \quad (3)$$

Its possible to put an upper limit on the integrated mass loss and thereby on the collision cross-section:

$$\chi = 1 - 2\frac{v_{esc}^2}{v_0^2} \quad (4)$$

$$\chi\tau_m = \frac{\sigma}{m}\Sigma_m\left[1 - 2\frac{v_{esc}^2}{v_0^2}\right] \quad (5)$$

$$\chi\tau_m < 0{,}3 \quad (6)$$

$$\frac{\sigma}{m} < 1 cm^2/g \quad (7)$$

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A problem for the ΛCDM cosmological model?

- Several works indicate that is very difficult to observe a cluster colllision with similar velocity:
  - Hayashi et al. 2006
  - Farrar and Rosen 2007
  - Lee and Komatsu 2010
  - Forero-Romero et al. 2010
  - Thompson and Nagamine 2011
  - Watson et al. 2013
- Studies using hydrodinamical simulations.
  - Springel & Farrar. 2005
  - Milosavljevic et al. 2007
  - Mastropietro & Burket. 2008
  - Lage and Farrar. 2014
- It should be recalled that the ICs parameter space is very large.

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The Rise and Fall of a challenger by Thompson (2014).

- They investigate the probability of finding such a high-velocity pair in large-volume N-body simulations, particularly focusing on differences between halo finding algorithms.
- When employing the Rockstart (Behroozi et al 1013) halo finder that considers particle velocities, they find numerous Bullet-like pair candidates that closely match not only the high pairwise velocity, but also the mass, mass ratio, separation distance, and collision angle that have been shown to produce the Bullet Cluster.
- The probability of finding a massive, high pairwise velocity pair among halos with $M_{\rm halo} \geq 10^{14} M_{\odot}$ is $4{,}6 \times 10^{-4}$ using while it is $\approx 45\times$ lower using a friends-of-friends (FOF) based approach as in previous studies.

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High velocity tail of Bullet like pairs.

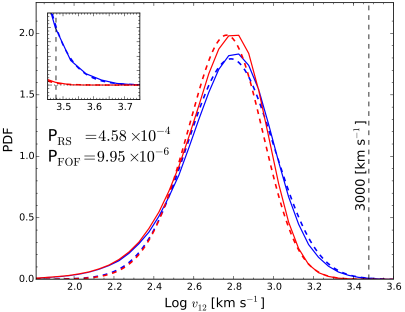

Figura : Probability distribution function of massive halo pairs ($M_{12} \geq 10^{14}$, $d_{12} \leq 10\mathrm{Mpc}$) in largest simulation (L4500) identified by FOF (Red solid line) and RS (Blue solid line).

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Simulación Millenium

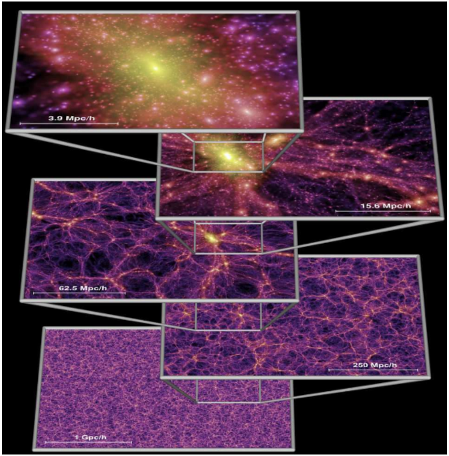

Figura : ΛCDM model (Ruiz et al 2012) + gadget3 + FoF/SubFind

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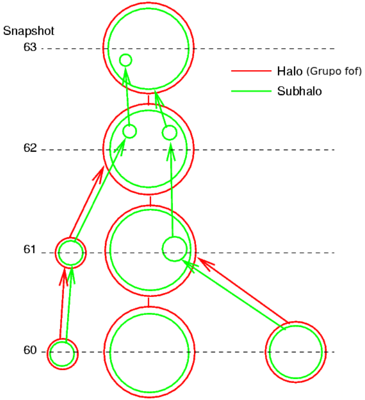
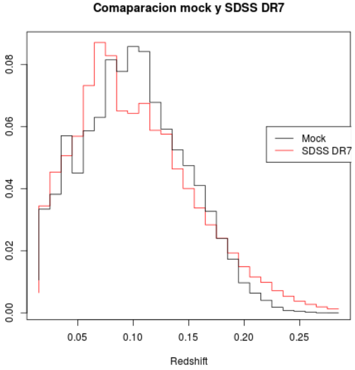
Using the Merging Trees Information.

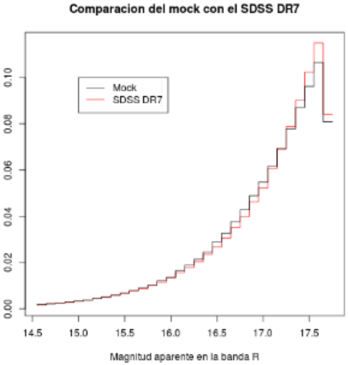
- Starting from the subhalos merging trees, we build up the FoF groups merging trees. but we are actually running new simulations and making its merging trees using consistent trees!



Buil up of mock catalogs:

We simulate the local SDSS universe (4π, $z < 0{,}12$) with SDSS-DR7 angular mask, replicating the MS box.





Dressler-Shectman Test (1988):

- Introducing the estimator:
  $\delta^2 = (\frac{11}{\sigma^2})[(v_{local} - v)^2 + (\sigma_{local} - \sigma)^2]$ where

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Dressler-Shectman Test (1988):

- Introducing the estimator: $\delta^2 = (\frac{11}{\sigma^2})[(v_{local} - v)^2 + (\sigma_{local} - \sigma)^2]$ where
- v: mean velocity of the cluster.
- v_{local}: mean local velocity. Computed using the 10 nearby neighbours.
- σ: cluster velocity dispersion.
- σ_{local}: local velocity dispersion.
- For systems just add: $\Delta = \Sigma\delta$.
- *Pinkney et al. (1996)*
    - Best test for substructures identification.
    - Low effectivity when the substructures yield along los and when the cluster occupacy is lower than 30 gx.
    - Recommended to be complemented with Skewness measurements of the distribution of radial velocities.
    - Can identify substructures 3 Gyr before the merger, equivalent to ten snapshots in the MS.

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- Since the underlying distribution of Δ is unknown, is neccesary run Monte Carlo realizations distribuying randomly the velocities, in order to .^{er}ase"the substructures but conserving the global velocity distribution.

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- Since the underlying distribution of Δ is unknown, is neccesary run Monte Carlo realizations distribuying randomly the velocities, in order to .^{er}ase"the substructures but conserving the global velocity distribution.
- computing the p value as:

$$p = \frac{N(\Delta_{MC} > \Delta)}{N_{MC}} \tag{8}$$

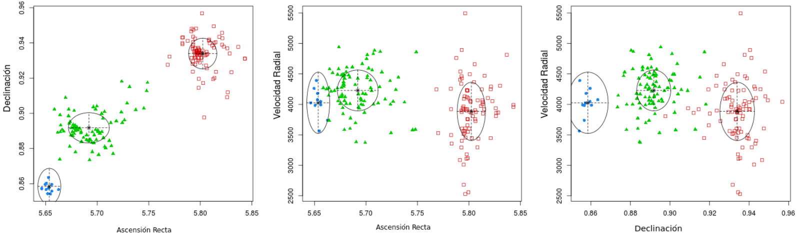
- we select galaxies with a high probability of membership to subhaloes.

Examples

Currently we turned to a machine learning methodology that select the galaxies in subhaloes based on a set of features, the most important ones are: δ, Δ, skewness of velocity distribution, color, magnitude and its correlations. Avoiding the systems catalog.

Mixture of Gaussians (*Mclust in R*)

Given that the application of the DS test leave us a subset of gaalxies with high probability of reside in substructures, we join them in order to define the substructures and its physical properties: barycenter, virial radius, velocity dispersion, occupacy etc.



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Aplication of the DS test in the simulated catalog

- We apply the test to 2854 clusters with mass over $10^{13} M_{\odot}$ and more than 30 members in the mock catalog.
- Finding that 1448 clusters present subestructures ($p < 0{,}15$), wich represent approximately over 50 % of the sample.
- If aditionally ask that the skewness of the distribution of radial velocities different of 0, the sample reduces to 715 clusters.

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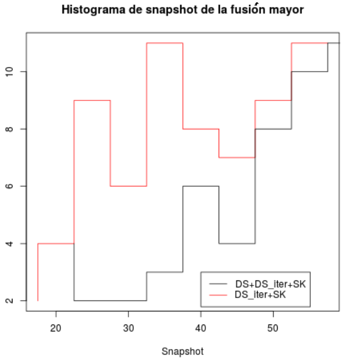
We also introduce a iterative DS test

- We apply the iterative DS test to the 2854 cluster sample and found only 119 where the test converge.
- Just 46 of this 119 systems of galaxies where detected using the traditional DS test complemented with the Skewnes test.



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Application of the mixture of Gaussians algorithm.

- Using *Mclust* on the galaxies with $\delta > 2$.
- leave 636 clusters, of 715 clusters, where inhabit 2 substructures with more than 5 members.
- In general one of this substructures correspond to the cluster core or the most massive component of the merger.
- Sometimes we found systems with problems in the groups parent catalog solved if we take into account the survey angular mask.
- After the substructure identification using Mclus, each one was associated with the corresponding halo using the galaxy members voting on the underlying halo catalog.

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Properties of the identified substructures:

- We compute the barycenter coordinates weigthed by luminosity in order to improve this determination.
- Resulting in good estimations of the geometrical centers of the subhalos using the galaxy members.
- After that we calculate the velocity dispersions and virial radius using:

$$
\begin{aligned}
R_{vir} &= \frac{\pi}{2} \frac{ngal(ngal-1)}{\sum_{i>j}^{ngal} R_{ij}^{-1}} \\
\sigma &= \frac{\sqrt{\pi}}{ngal(ngal-1)} \sum_{i=1}^{ngal-1} \omega_i g_i \\
\omega_i &= i(ngal-i) \\
g_i &= v_{i+1} - v_i
\end{aligned} \tag{9}
$$

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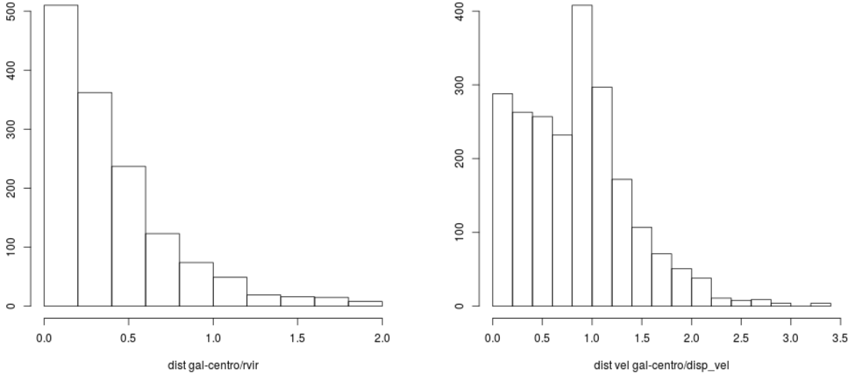
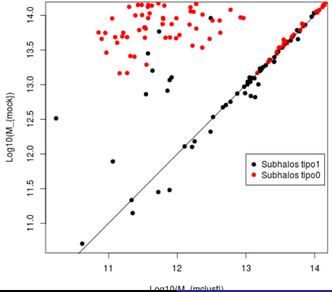
Angular and velocity normalized difference positions.



Properties of the identified substructures:

- The velocity dispersion determinations results comparable with the real halo values.
- If we consider as substructure members those galaxies with a projected angular distance below one virial radius r_{vir} and a radial velocity ofset lower than 2σ. The mass determinations improve specially for the substructures (halo types=1).



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Region where los projections introduce errors:

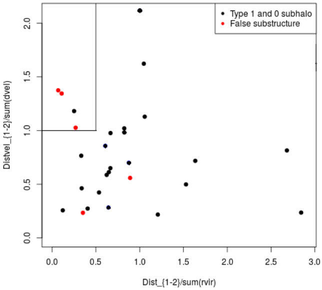

Figura : Projected distance between centers of groups identify with MG, normalized to the sum of the virial radius vs the difference in radial velocity normalized to the sum of the radial velocity dispersion. The black/red dots correspond to the clusters where we found the type 0 subhalo and a type 1 subhalo, and to the clusters where a false substructure is identified respectively.

Dawson (2013) Bayesian reconstruction techniques in order to recover the 3D merger configuration.

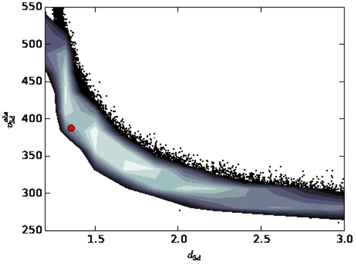

Figura : Distribution of posterior probability in the 3D distance (Mpc) and 3D velocity (Km/s) space for a simulated merging cluster, red dot indicates the real current values. Others kinematical parameters like Time since Collision or velocity at the merger time are also well recovered.

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Application to catalogs of systems of galaxies.

- Berlind et al (2008) include information on 8148 systems of galaxies, with 44554 galaxy members.
- We identify the substructures present in clusters applying MG over all galaxies with $\delta > 2$, we found 2 significant substructures in 15 clusters of the sample.
- Tempel et al (2012) include information in FoF 77858 clusters and groups of galaxies, with 576493 galaxy members.
- We found two significant substructures in 80 clusters of the sample.
- Eke et al 2PIGGS catalog include information on 28877 clusters and grups of galaxies, with 191440 galaxy members.
- We found two significant substructures in 38 clusters of the sample.

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Hidden compact groups in clusters of galaxies?

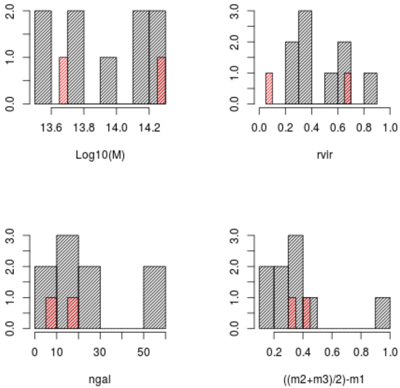

Figura : Mass, virial radius (Mpc), halo occupation, and magnitude gap distributions of subhaloes identified on mock catalogs, Two of this systems have a magnitude gap over 1 magnitude and virial radius

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Conclusions:

- We build up mock galaxy systems catalogs.
- We study different methods of substructures identification, including a new iterative DS test.
- Using the merging tres information we recover the merging systems and its properties using as input a catalog of a systems of galaxies.
- We identify the substructures present in merging clusters, finding its member galaxies and computing its more relevant physical properties.
- Using this information we succesfully apply Bayesian methods of merger reconstruction in selected systems.
- We apply our methodology to real galaxy catalogs and provide a sample of over 100 low redshift merging (relaxed) systems of galaxies in different stages of the merging process.

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Current Work:

- Develop a machine learning (LR, SVM, RF) subhalos identification algorithm using as training set the mock catalogs and K-Folds cross-validation.
- Calibrate the method developed using the new simulated catalogs in order to apply to intermediate/high redshift catalogs.
- Study the physical properties of the galaxies (sSFR, Metallicity, HI abundance, morphologies) in the merging clusters (relaxed) and its substructures.
- Recently Gastaldello (2014) reported the first bullet group in the Strong Lensing Legacy Survey (SL2S), therefore we eliminate the restriction of a minimum of 30 member galaxies in the parent catalog.
- Apply the astrophysical test over the merging cluster systems identified in order to determinate dark matter particles properties, including WL mass determinations information.

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