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And Yet There is Mass: How Projection Effects Can Solve the Apparent Lack of Mass in Substructures of Simulated Galaxy Clusters

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Abstract. Observed substructure masses in galaxy clusters have been reported to reach total masses much larger than predicted from simulations. Using the fully hydrodynamical cosmological simulation *Magneticum Pathfinder*, this discrepancy is shown to originate from projection effects, following up on the work presented by Kimmig et al. (2022): while simulations attribute mass to a substructure only if that mass is bound to it, in observations it is not possible to identify bound mass but rather all mass inside an aperture is allocated to the substructure. Albeit a contribution from the main halo is substracted, this method is found to still result in substructure mass increases of 2-3 times relative to the bound mass.

Key words. Cold dark matter – Galaxy clusters – Computational methods

1. Introduction

Strong and weak lensing observations of galaxy cluster Abell 2744 (Jauzac et al. 2016) report an astonishing number of very massive substructures, representing a test of the ΛCDM paradigm: at $z \approx 0.3$ it has 8 massive substructures of mass $> 5 \times 10^{13}\mathrm{M}_{\odot}$, challenging current simulation studies. However, one of the crucial differences between simulations and observations, namely that simulations have full 3D information while observations are limited to 2D projected quantities, is shown to be the most likely cause for this discrepancy, based on dark matter only simulations (Mao et al. 2018; Schwinn et al. 2018), and recently in a statistical manner from a cosmological hydrodynamical simulation (Kimmig et al. 2022).

In particular, Kimmig et al. (2022) showed that similarly massive substructures can be found in simulations as in observations when accounting for the effect of projection, as then large quantities of the underlying host halo are attributed to the substructures, while simulations usually only account for mass that is physically bound. Moreover, they presented a simulated counter-part for cluster Abell 2744, formed through one massive 1:1.4 and several smaller mergers with ratios >1:20. This counterpart matches the substructure masses as well as other observed properties caused by the merging processes (e.g., Owers et al. 2011).

This work focuses on the impact of projection on substructure masses, highlighting the issue presented by Kimmig et al. (2022). As done there, galaxy clus-

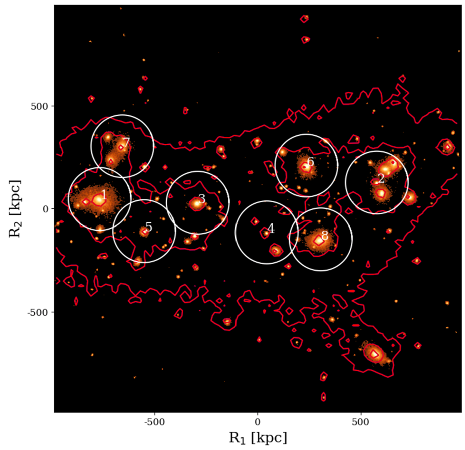

Fig. 1. The central region stellar mass map of an example galaxy cluster, with overlaid the total mass contours in red and apertures numbered by their mass in white.

ters are selected from *Magneticum Pathfinder* (*Box2b/hr*, (909 Mpc)^3) (Dolag et al. 2015, www.magneticum.org), in four mass bins with 29 galaxy clusters each. The most massive bin is termed *giants* and contains clusters with $M_{tot} > 1 \times 10^{15} M_\odot$. Of these galaxy clusters the highest mass reached is $M_{vir} = 2.8 \times 10^{15} M_\odot$, while the mean mass in the bin is $\bar{M}_{vir} \approx 1.3 \times 10^{15} M_\odot$. For the smaller three mass bins, the large volume of the simulation allows to select galaxy clusters such that their masses are tightly distributed about the chosen mean masses. They are termed *medium*, *small* and *tiny* with mean masses of $M_{vir} \approx 5, 2$ and $1 \times 10^{14} M_\odot$ respectively.

2. Measuring Substructure Masses

From simulations, all particles that are physically bound together are assigned to a subhalo via SubFind (Dolag et al. 2009). The fraction of mass contained in all subhalos within a cluster relative to the total mass of the cluster is termed f_{sub}. Subhalos can range in mass from galaxies to groups, depending on if they remain bound together after falling into the galaxy cluster potential. In contrast, when working in projection it can not be determined if a projected clustering of galaxies are gravitationally bound together or not. Instead, all mass within a cylinder of a given aperture radius is allocated to identified substructures, with an estimated contribution from the main halo being subtracted. The fraction of mass contained in all substructures relative to the mass of the galaxy cluster obtained in projection is termed f_{cyl}. Fig. 1 shows such apertures in white for a projection of the Abell 2744 counterpart from Kimmig et al. (2022). As can be seen, the identified substructures correspond to overdensities in the total mass as given by the red contours. From the stellar mass map it follows that these substructures can consist of either one (e.g., substructure 3) or multiple (e.g., substructure 2) massive individual galaxies.

Consequently, the determined total mass in projection of these substructures can be much larger than the summed bound mass within the individual galaxies that lie in the aperture. This is shown in the left panel of Fig. 2 which depicts the mass fractions in projection versus the bound mass fraction. We find that f_{cyl} are generally larger than f_{sub} by a factor of 2-3. This results from the contribution of the main halo that cannot be completely subtracted in projection, thus adding a mass increase as shown in the right panel of Fig. 2. Here the difference $f_{cyl} - f_{sub}$ is plotted as a function of f_{sub}, and the contours for all mass bins show no dependence on the amount of bound mass in subhalos f_{sub}.

We find a small trend with galaxy cluster mass, with the two more massive bins showing a higher increase in mass fraction in projected relative to bound mass. This may then be the result of a higher fraction of dynamically active galaxy clusters in the two more massive bins which exhibit complex main halo profiles. These are more difficult to separate from the substructures and consequently less easy to subtract, such that more mass may be contributed.

3. Conclusion

Projection has a significant impact when comparing masses from observations with those from simulations, both for the resulting individual substructures as well as total substructure mass fractions. Deviations are up to a fac-

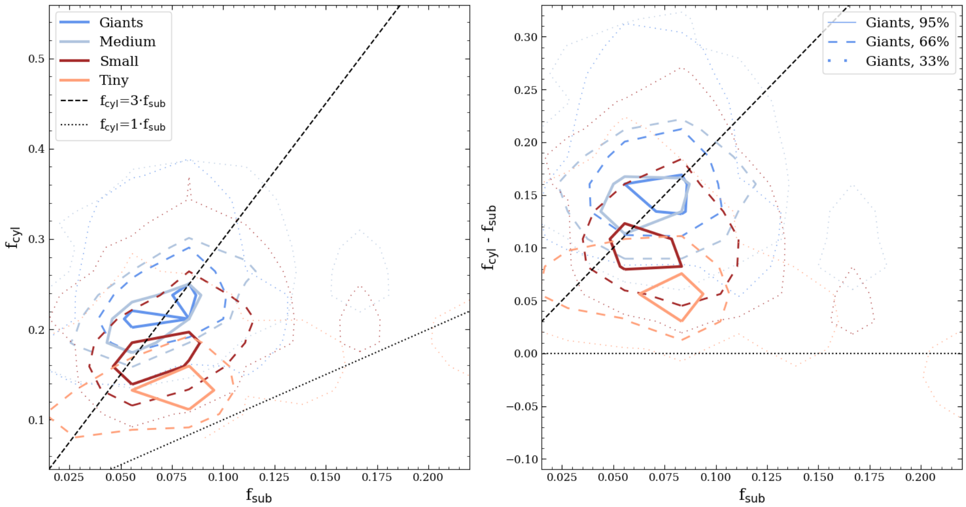

Fig. 2. The median substructure mass fraction in projection f_{cyl} (*left*) and difference of f_{cyl} to the bound subhalo mass fraction f_{sub} (*right*) as a function of f_{sub} for each galaxy cluster. Colors denote the different galaxy cluster mass bins.

tor 3, mostly originating from contributions of the main halo that are shown here to be independent of f_{sub}, extending the study by Kimmig et al. (2022). Thus, projection effects are an important factor to account for when determining masses. This holds true whenever masses within apertures are determined, irregardless of the considered main halo mass.

As substructure masses can be used as tracers for the dynamical state and thus assembly history of a galaxy cluster, this strongly impacts the conclusions drawn from observations. Higher observed substructure masses may not be indicative of a different or more rapid assembly process but are instead at least in part due to differences in methods as compared to simulations. Thus, taking projection effects into account is crucial when making such comparisons.

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