CASPEN report

Andrew Robertson, hosted by Annika Peter at Ohio State University

Overview of visit

I visited OSU to work with Annika Peter on sections of a self-interacting dark matter (SIDM) review paper that is part of the Novel Probes of Cosmology initiative, as well as to discuss possible observational tests of SIDM on galaxy cluster scales that could be calibrated using the BAHAMAS-SIDM simulations that I have recently run. I was at OSU for five days, from Monday 11th to Friday 15th of February 2019, during which I presented some of my recent work at their weekly Galaxies Meeting, and had the chance to speak with a number of staff members and students/postdocs.

Annika and I spent a couple of hours discussing what was still to be done for the SIDM review paper, and decided that I should focus on finishing the section on how SIDM has been implemented within cosmological simulations, and the relative merits of different methods that have been employed. We discussed our thoughts on this topic, and I sketched an outline of what this section of the review would contain. We then spent the bulk of my visit, together with PhD student Stacy Kim, discussing new ways of exploiting the BAHAMAS-SIDM simulations to place robust constraints on DM self-interactions.

Tests of SIDM with galaxy clusters

Projected offsets between the brightest cluster members

In some previous work, Stacy and Annika had found that in idealised simulations of equal mass galaxy cluster mergers with SIDM, the brightest cluster galaxies (BCGs) from the two clusters that merged would oscillate about the centre of mass of the resulting (merged) cluster, with oscillations that could be long lived, and with amplitudes that increased with increasing SIDM cross-section. This inspired us to look for such a signal in my cosmological simulations, by looking at the separations between the two brightest galaxies within our simulated clusters.

An example simulated cluster (with our largest SIDM cross-section, though the maps looked similar with CDM) is shown in the left hand panel of Fig. 1. The brightest and second brightest galaxies within the cluster are marked with red and orange crosses, and in the right hand panel we show the distribution of 3D distances between the brightest and second brightest galaxies, $|\mathbf{r_1} - \mathbf{r_2}|$, for the 1000 most massive haloes in our $z = 0$ snapshot.[1] While there is a hint of a slightly larger tail of systems with large $|\mathbf{r_1} - \mathbf{r_2}|$ in SIDM, the distributions of offsets are fairly similar, and do not reflect the offsets (with sizes of order 100 kpc) seen in Stacy's work. This appears to be driven by the fact that BCGs are not as distinct as one might hope, and so the two brightest galaxies within a cluster are not necessarily the two BCGs from before the last major merger. Also, the signal predicted from idealised simulations was for equal mass mergers, and many systems will not have undergone a recent merger with a mass ratio of order unity. We investigated whether the signal was more distinct if the two brightest galaxies had similar stellar masses (potentially indicative of them coming from a merger of similar mass clusters), but this selection criteria had little effect on the distribution of $|\mathbf{r_1} - \mathbf{r_2}|$.

BCG velocity offsets

Deciding that the distribution of offsets between the two brightest galaxies in clusters was not a particularly sensitive probe of DM self-interactions, we instead looked at the offsets between the BCG and the cluster centre. The cluster centre is not especially well defined, but several definitions have been used in both observations and simulations. The projected offsets between the optical centre of the BCG, and the gravitational lensing inferred peak in the projected density had already been compared between the BAHAMAS-SIDM simulations and observational data, finding that the small offsets in the observations were consistent with CDM, and were in tension with our largest simulated cross-section. The size of these offsets are small, of order 10 kpc. However, BCG oscillations with such an amplitude at the centre of a cluster-scale DM halo would correspond to fairly large velocities. As such, line-of-sight velocities could be a more sensitive probe of the phenomenon of BCGs offset from the centre of their cluster DM haloes.

We therefore took our simulated systems and projected them along a random line of sight. We then took all galaxies within a cylinder oriented along the line of sight, with a radius of r_{200} and a length of $5\,r_{200}$, and found their velocities (peculiar + Hubble) along the line-of-sight, v, with respect to zero peculiar velocity at the location of the most bound particle. We cut out all galaxies with $|v| > 4000\,\mathrm{km\,s^{-1}}$, and then measured the mean, $\hat{v}$, and standard deviation, σ_c, of the remaining galaxy velocities. An example of the v distribution for a simulated cluster is shown in the left panel of

[1] Roughly all systems with $M_{200} > 2 \times 10^{14}\,\mathrm{M_\odot}$.

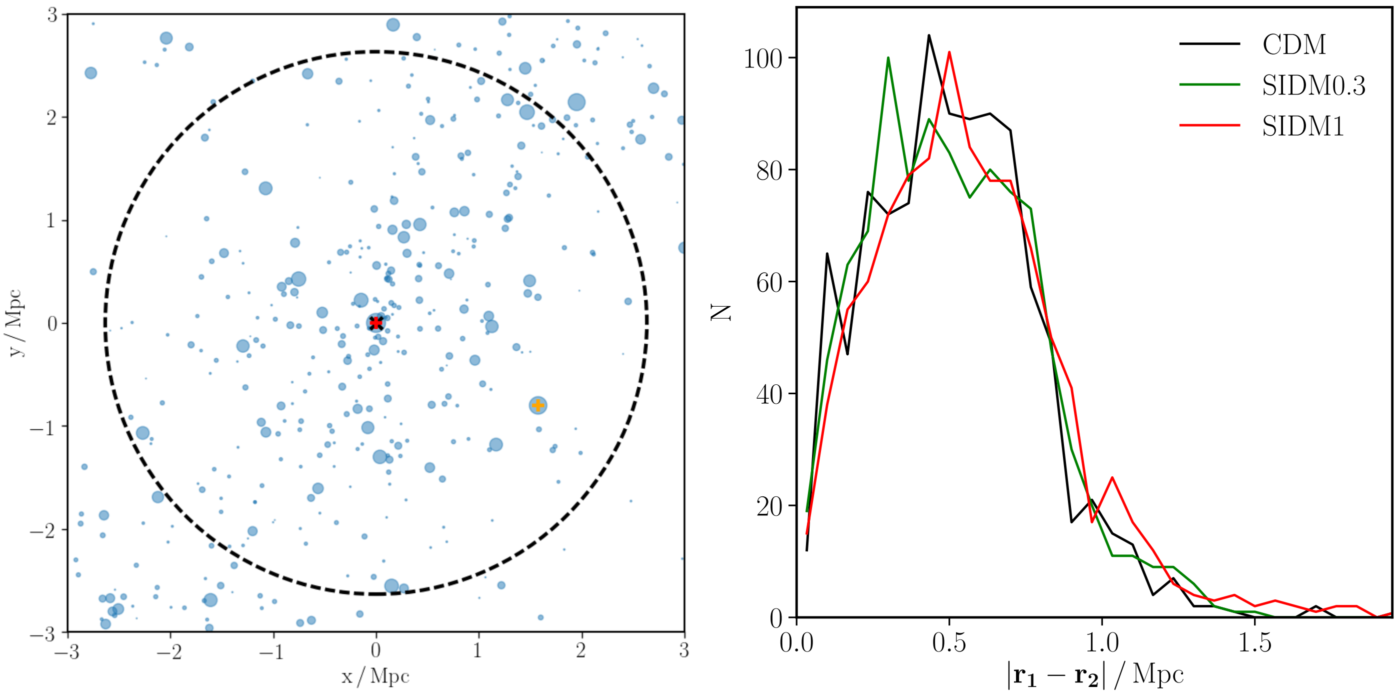

Figure 1: Left: an example of the galaxy distribution within a simulated galaxy cluster. Each blue circle is centred on the most gravitationally bound particle within a galaxy, with the area of the circle proportional to the stellar mass of the galaxy. The black cross indicates the location of the most bound particle within the cluster, with the red and orange crosses denoting the location of the most massive and second most massive galaxies respectively. Right: the distribution of 3D distances between the two brightest galaxies in the 1000 most massive clusters ($M_{200} \gtrsim 2 \times 10^{14}\,\mathrm{M_\odot}$) from simulations with different DM models .

Fig. 2. For each simulated system we measured the velocity separation between $\hat{v}$, and v of the brightest galaxy, ΔV_1. We then compared the distributions of $|\Delta V_1|/\sigma_\mathrm{c}$ to those from Lauer et al. 2014, which we show in the right panel of Fig. 2.

Similar to the projected offsets between the two brightest galaxies, different DM models do not have a particularly pronounced effect on the distribution of velocity offsets. That said, there does appear to be a monotonic relationship between increasing SIDM cross-section, and a decreasing fraction of systems with small offsets. To use a comparison between our simulated $|\Delta V_1|/\sigma_\mathrm{c}$ distributions and the observed one to place robust constraints on the SIDM cross-section would require that we match the selection of systems, and procedure for calculating $|\Delta V_1|/\sigma_\mathrm{c}$, more precisely to what was done observationally. It would also be good to investigate how the scale of changes induced by different choices for the subgrid physics implementation compare to the changes with DM model. This is possible with BAHAMAS due to having a variety of runs with different subgrid physics parameters, and something I hope to do in the future.

Summary

I thoroughly enjoyed my visit to OSU, and would like to thank CASPEN for funding the trip and Annika for hosting me. While we did not find a 'smoking gun' signature of SIDM in my simulated clusters, we did find a number of features that vary subtly with SIDM cross-section and could potentially be used to infer the properties of DM particles from a large number of observed clusters. We also had fruitful discussions about other lines of inquiry that could be pursued with my simulations in the future, and have continued to communicate since my visit.

This work was supported by a collaborative visit funded by the Cosmology and Astroparticle Student and Postdoc Exchange Network (CASPEN).

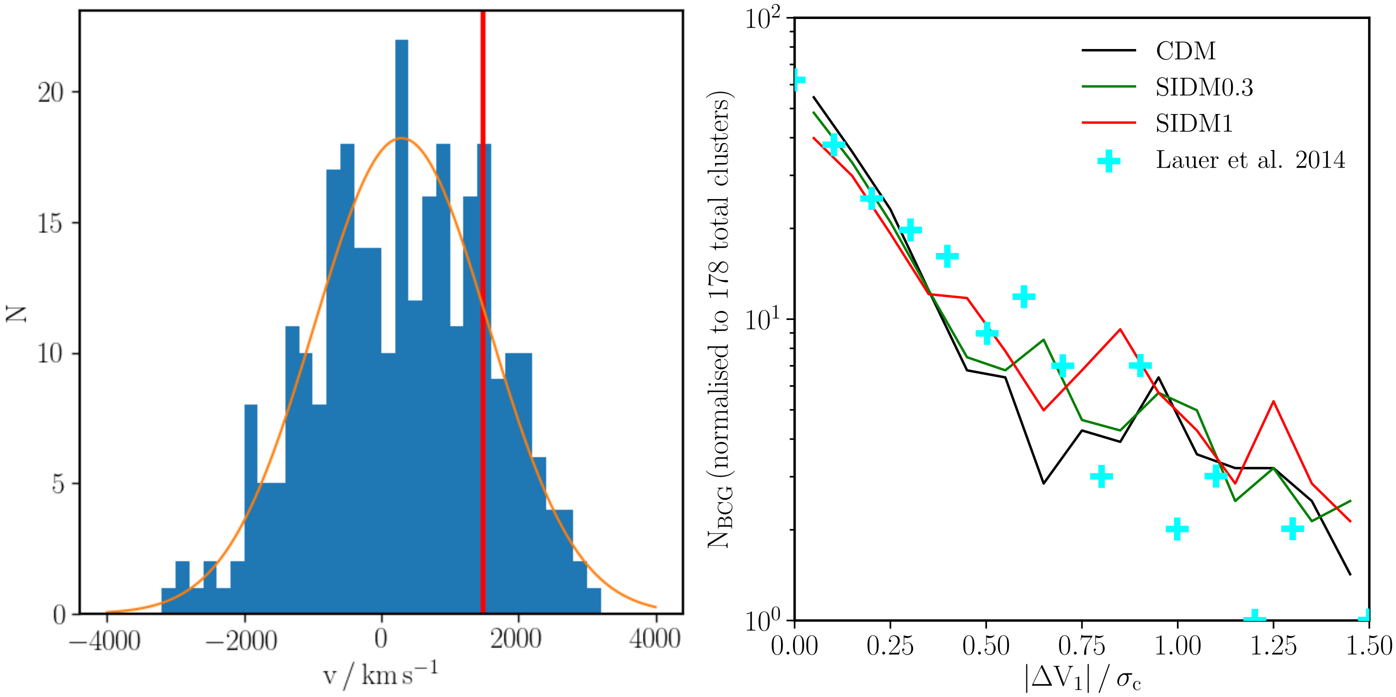

Figure 2: Left: an example of the galaxy line-of-sight velocity distribution within a simulated galaxy cluster. The blue histogram shows the distribution of all galaxy line-of-sight velocities, the orange normal distribution has the same mean and variance as the blue histogram and the red vertical line shows the line-of-sight velocity of the brightest galaxy in the cluster. The zero-point of the x-axis is fairly arbitrary, corresponding to zero peculiar velocity (in the simulation frame) at the location of the most bound particle in the cluster. Right: the distribution of velocity offsets between the mean line-of-sight velocity and the line-of-sight velocity of the BCG, normalised by the velocity dispersion (standard deviation) of line-of-sight galaxy velocities. The different lines correspond to different simulated DM models, while the data points are from Lauer et al. 2014. The simulation lines are from the 1000 most massive systems in the $z = 0$ snapshot for each DM model, but the y-axis has been renormalised to match the number of observed systems (178).