Colliding Clusters and Dark Matter Self-Interactions

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Based on arXiv:1308.3419 with Mads T. Frandsen, Subir Sarkar and Kai Schmidt-Hoberg

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Outline

- Introduction
- Constraints for self-interacting Dark Matter (DM)
- New constraints from colliding clusters
- The particle physics perspective
- Frequent self-interactions
- Rare self-interactions
- Conclusions

Motivation: Cosmology

- There are various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Cusp-vs-core problem
  - Too-big-to-fail problem
  - Missing-satellite problem
- DM self-interactions may solve these problems.

Moore (1994)
Flores, Primack: astro-ph/9402004

Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048

Klypin et al.: astro-ph/9901240
Moore et al.: astro-ph/9907411

Spergel & Steinhard: astro-ph/9909386

Self-interacting DM

- To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

$$\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns/GeV}$$

- The typical cross section of a WIMP is 15 orders of magnitude smaller!
- Evidence for DM self-interactions on astrophysical scales would rule out many popular models for DM, such as supersymmetric WIMPs and axions.

Motivation: Particle physics

- Large self-interactions are (more) natural in models with a complex dark sector, e.g.
  - Strongly interacting DM

    Kusenko, Steinhard: astro-ph/0106008
    Frandsen, Sarkar, Schmidt-Hoberg: 1103.4350

    See talks by Nuria Rius, Francesco Sannino, Michele Frigerio, Pedro Schwaller
  - Mirror DM

    Berezhiani, Dolgov, Mohapatra: hep-ph/9511221
    Mohapatra, Nussinov, Teplitz: hep-ph/0111381
  - Atomic DM

    Kaplan, Krnjaic, Rehermann, Wells: 0909.0753
    Cyr-Racine, Sigurdson: 1209.5752
- We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

Self-interactions: Constraints

- Various astrophysical observations give constraints on the DM self-interaction cross section:
  - Core density in clusters — Yoshida et al.: astro-ph/0006134
  - Core density in dwarfs — Dave et al.: astro-ph/0006218
  - Halo ellipticity — Miralda-Escude (2002)
  - Subhalo evaporation rate — Gnedin, Ostriker: astro-ph/0010436
- These constraints seem to be very strong, implying $\sigma/m_\chi < 0.1\ \mathrm{cm}^2/\mathrm{g}$, which is too small to give observable effects on small scales.

Self-interactions: New constraints

- However, recent numerical simulations indicate that the conventional bounds on DM self-interactions have been overstated.

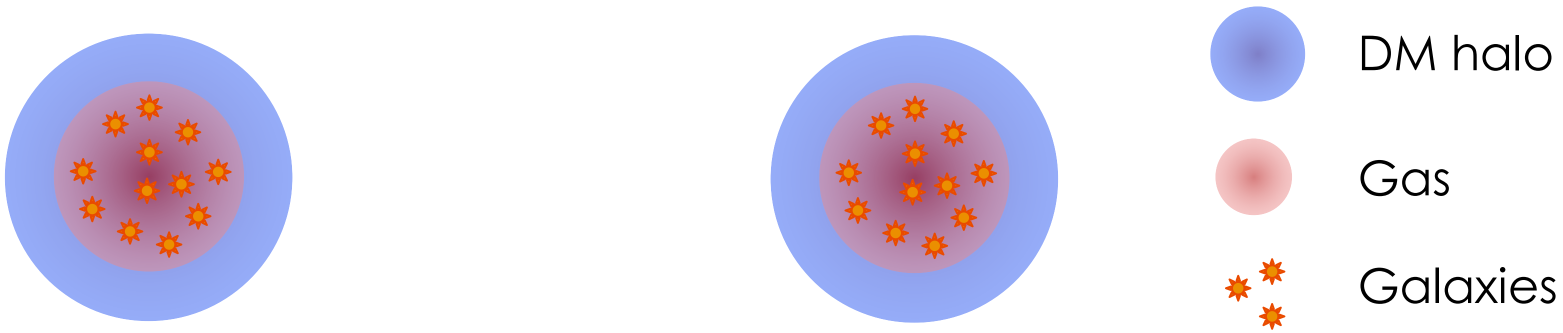
Vogelsberger, Zavalla, Loeb: 1201.5892
Rocha et al.: 1208.3025
Peter et al.: 1208.3026
Zavalla, Vogelsberger, Walker: 1211.6426

- Velocity-independent DM self-interactions with $\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g}$ may still be viable.

- We need to find new systems and develop new techniques to constrain or measure such interactions.

Colliding clusters

- In the absence of DM self-interactions, we expect the following picture:



- For simplicity: Neglect tidal forces and dynamical friction, which may induce an asymmetric tail in the DM distribution.

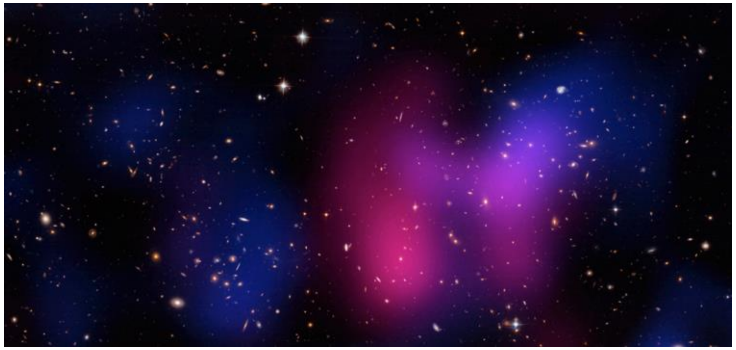
Colliding clusters

- This simple picture agrees well with observations:

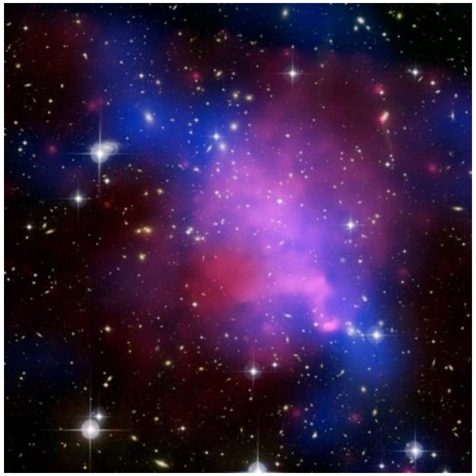
DM halo

Gas

Bullet Cluster: Clowe et al.: astro-ph/0608407



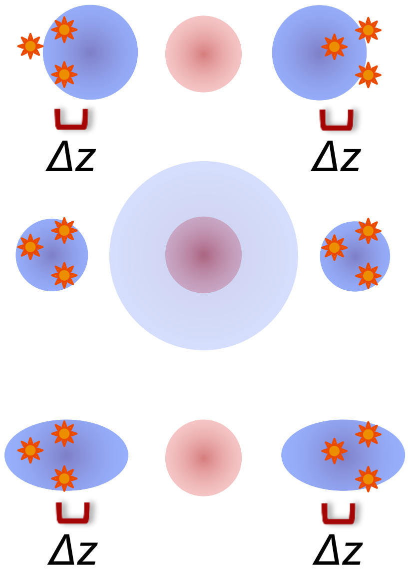
Musket Ball Cluster: Dawson et al.: 1110.4391



Abell 520: Mahdavi et al.: 0706.3048

Colliding clusters

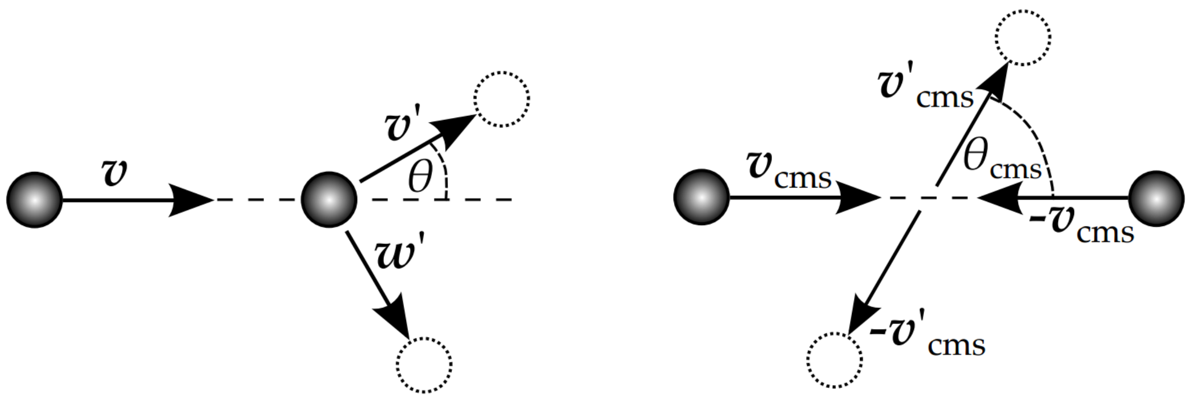
- We conclude that DM behaves differently from gas.
- However, before concluding that DM is actually collisionless, we need to understand how self-interactions would modify the picture:
  - Does the DM halo slow down?
    - Observables: Velocity offset **NEW**
  - Does the DM halo evaporate?
    - Observables: M/L ratio, dark core
  - Is the DM halo deformed?
    - Observables: Ellipticity, offset **NEW**



Observational constraints

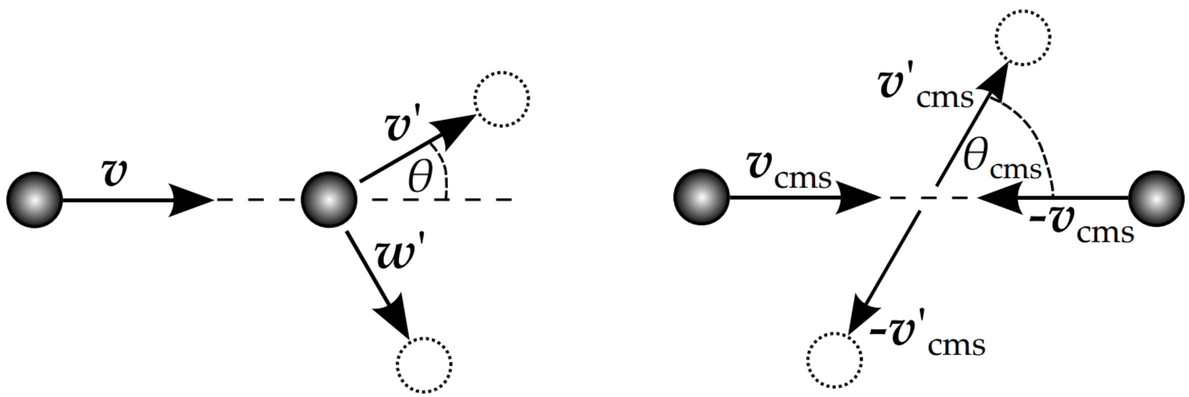
- Observations of the Bullet Cluster constrain the rate of halo evaporation and halo deceleration due to DM self-interactions.
  - $\sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$ (analytically) Markevitch et al.: astro-ph/0309303
  - $\sigma/m_\chi < 0.7\ \mathrm{cm}^2/\mathrm{g}$ (numerically) Randall et al.: 0704.0261
- Given existing bounds on DM self-interactions, can we hope for an observable separation?
- The answer to this question depends on the particle physics nature of DM self-interactions!

Particle physics perspective



- Since the relative velocity $\boldsymbol{v}_0$ between the two sub-clusters is large, we can approximate $\boldsymbol{v} \approx \boldsymbol{v}_0$ and $\boldsymbol{w} \approx 0$ (in the sub-cluster rest-frame).
- The collision of two DM particles leads to the evaporation of a DM particle if $v'^2 > v_{\rm esc}^2$ and $w'^2 = v^2 + w^2 - v'^2 > v_{\rm esc}^2$.

Particle physics perspective



- We find $v' = v_0 \cos\theta = v_0 \sqrt{(1+\cos\theta_{\mathrm{cms}})/2}$.
- Evaporation occurs if $\frac{2\, v_{\mathrm{esc}}^2}{v_0^2} - 1 < \cos\theta_{\mathrm{cms}} < 1 - \frac{2\, v_{\mathrm{esc}}^2}{v_0^2}$.
- Such collisions are referred to as expulsive.

Evaporation rate

- In this approximation, the evaporation rate is

$$R_{\mathrm{imd}} = \frac{\rho_2}{m_{\mathrm{DM}}} v_0 \int \mathrm{d}\phi_{\mathrm{cms}} \int_{2\, v_{\mathrm{esc},1}/v_0^2 - 1}^{1-2\, v_{\mathrm{esc},1}/v_0^2} \mathrm{d}\cos\theta_{\mathrm{cms}} \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\mathrm{cms}}}$$

- Defining the fraction of expulsive collisions

$$f = \frac{\int_{2\, v_{\mathrm{esc},1}/v_0^2 - 1}^{1-2\, v_{\mathrm{esc},1}/v_0^2} \mathrm{d}\Omega_{\mathrm{cms}} \; (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}{\int \mathrm{d}\Omega_{\mathrm{cms}} \; (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}$$

- The halo fraction lost to evaporation is

$$\frac{\Delta N_{\mathrm{imd}}}{N} = 1 - \exp\left[-\frac{\Sigma_2 \sigma f}{m_{\mathrm{DM}}}\right]$$

$\Sigma_2 = \int \rho_2(z)\,\mathrm{d}z$

DM surface density of main cluster

$\sigma \equiv \int \mathrm{d}\Omega_{\mathrm{cms}}\, \mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}}$

Total self-interaction cross section

Example: Bullet Cluster

- For v_esc = 1900 km/s and v_0 = 4500 km/s, we find

$$2\,v_\mathrm{esc}^2/v_0^2 \;\approx\; 0.4$$

- Consequently, immediate evaporation occurs for

$$50^\circ \lesssim \theta_\mathrm{cms} \lesssim 130^\circ$$

- For isotropic scattering, we find

$$f = 1 - \frac{2\,v_\mathrm{esc}^2}{v_0^2} \approx 0.6$$

Rare and frequent interactions

- Bullet Cluster: $\frac{\Delta N_{\mathrm{imd}}}{N} = 1 - \exp\left[-\frac{\Sigma_2\, \sigma\, f}{m_{\mathrm{DM}}}\right] < 30\%$
- For isotropic scattering, the fraction of expulsive collisions is large ($f \approx 1$). Consequently, scattering must be rare in order for the sub-cluster to survive:

$$\Sigma_2\, \sigma / m_\chi < 1$$

- An alternative way to satisfy this constraint is to have frequent self-interactions ($\Sigma_2\, \sigma / m_{\mathrm{DM}} \gg 1$) but a small fraction of expulsive collisions ($f \ll 1$).

Frequent interactions: Models

$$f = \frac{\int_{2\, v_{\mathrm{esc},1}/v_0^2 - 1}^{1 - 2\, v_{\mathrm{esc},1}/v_0^2} \mathrm{d}\Omega_{\mathrm{cms}} \; (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}{\int \mathrm{d}\Omega_{\mathrm{cms}} \; (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}$$

- In order to have $f \ll 1$, the overwhelming majority of collisions must have small momentum transfer, (i.e. small scattering angles).
- Consequently, we are interested in cross-sections, which diverge in the limit $\theta_{\mathrm{cms}} \to 0$ and $\theta_{\mathrm{cms}} \to \pi$.
- This requirement is for example satisfied by long-range interactions leading to Rutherford scattering (caveat: velocity suppression).

Rare and frequent interactions

- For the evaporation rate, rare self-interactions with $f \sim 1$ and frequent self-interactions with $f \ll 1$ are largely indistinguishable.
- What about other observables (such as the separation between DM halos and galaxies)?
- Because of the strong directionality of the problem, we expect that the angular distribution of the scattered DM particles influences the magnitude and the time-evolution of the separation.

Frequent interactions: Effects

- Frequent DM self-interactions lead to the deceleration of DM halos moving through a larger system:

$$R_{\mathrm{dec}} \equiv v_0^{-1}\,\mathrm{d}v_{\parallel}/\mathrm{d}t = \frac{\rho_2\, v_0\, \sigma_{\mathrm{T}}}{2\, m_{\mathrm{DM}}}$$

where the momentum transfer cross section is

$$\sigma_{\mathrm{T}} = 4\pi \int_0^1 \mathrm{d}\cos\theta_{\mathrm{cms}}\,(1-\cos\theta_{\mathrm{cms}})\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\mathrm{cms}}}$$

- This deceleration can be described in terms of an effective drag force

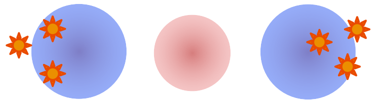
$$\frac{F_{\mathrm{drag}}}{m_{\mathrm{DM}}} = \frac{\tilde{\sigma}}{4\, m_{\mathrm{DM}}}\rho\, v_0^{2m}$$

m = -1 for long-range interactions

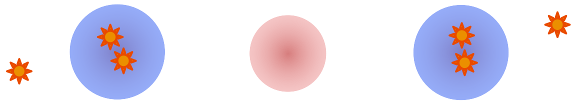
m = 1 for velocity-independent interactions

Frequent interactions: Predictions

- In a cluster collision, the DM halo will retain its shape, since the drag force affects all DM particles equally.
- In the decelerating frame of the DM halo, galaxies will experience a fictitious accelerating force.
- The resulting tilt in the effective potential will shift the distribution of galaxies relative to the DM halo.
- Moreover, some galaxies can escape and will end up travelling ahead of the DM halo.



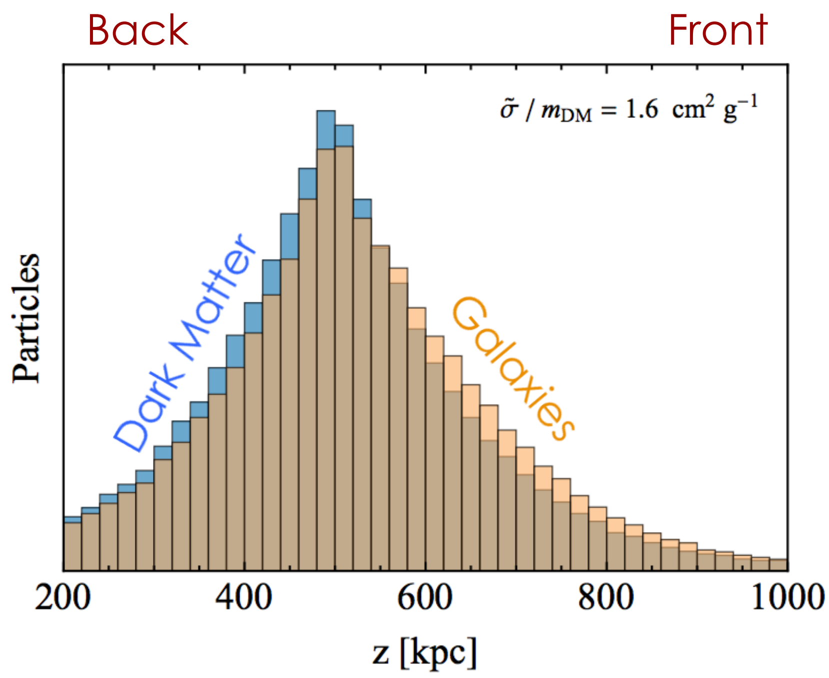
Just after the collision



At late times

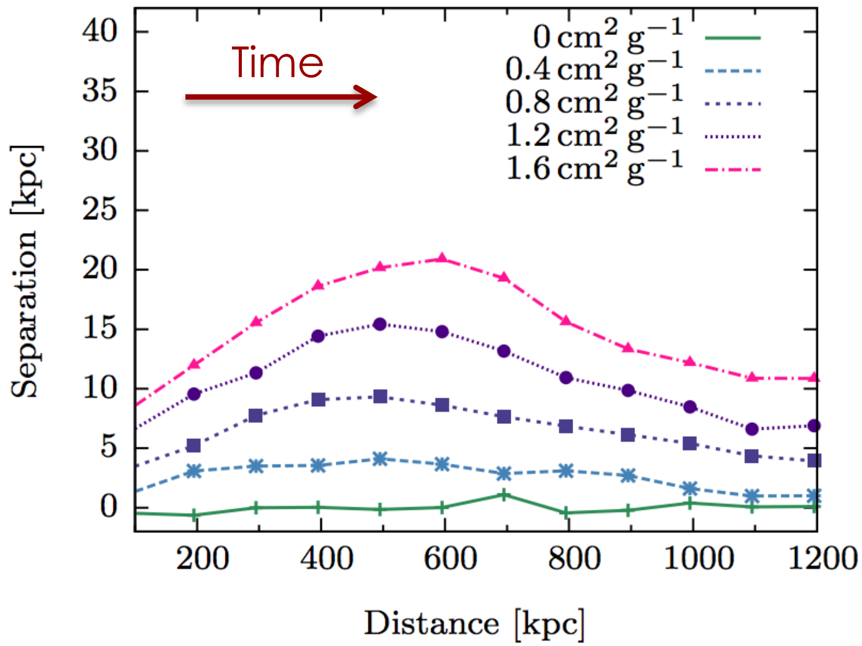
Numerical simulations

- Simplified numerical simulation: Trace the motion of a set of test particles (DM and galaxies) in a time-dependent gravitational potential.



1. The peaks of the two distributions always remain coincident.
2. The distribution of galaxies develops a tail in the forward direction.
3. The majority of the DM particles and galaxies remain bound to the same gravitational potential.

DM-galaxy separation



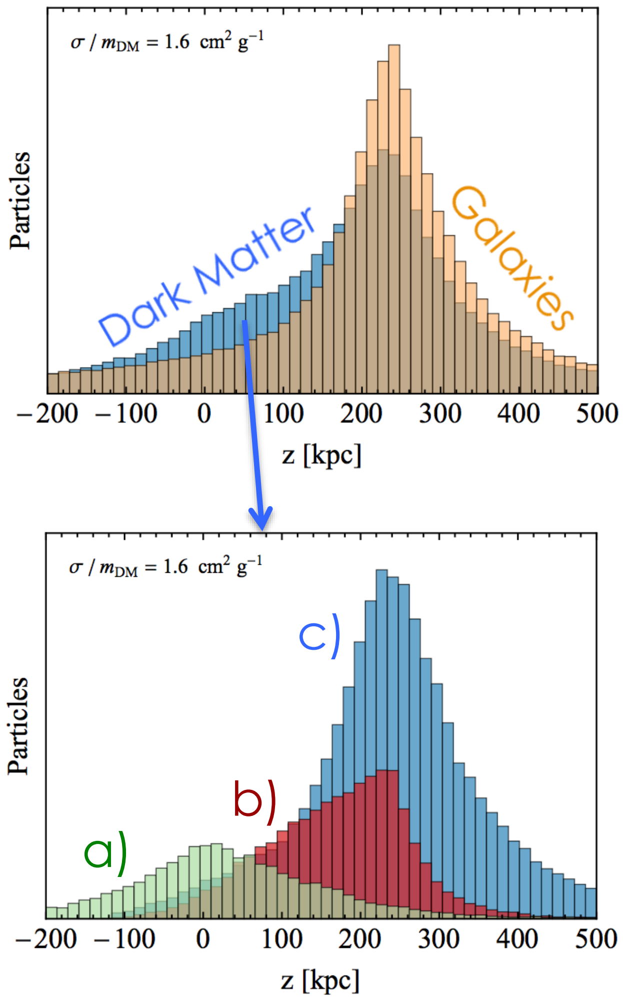
- Once the drag force decreases, bound galaxies return to their original position.
- Escaping galaxies are no longer considered part of the system, once they reach large distances.
- Consequently, the separation is largest shortly after the collision and then decreases.

- In contrast to the conventional expectation, the separation is harder to observe in more evolved systems.

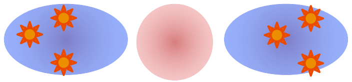
Rare self-interactions

- Rare self-interactions mean that in a cluster collision the probability for multiple scattering is negligible.
- Consequently, a typical DM particle will fall in one of three categories:
  a) The DM particle scatters once with high momentum transfer and escape from the sub-cluster.
  b) The DM particle scatters once with low momentum transfer and remains bound to the sub-cluster.
  c) The DM particle does not scatter at all.

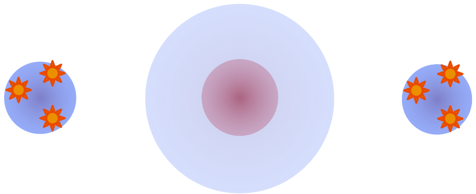
Numerical simulations



We can confirm our expectations by extending our numerical simulation to include scattering between individual DM particles.



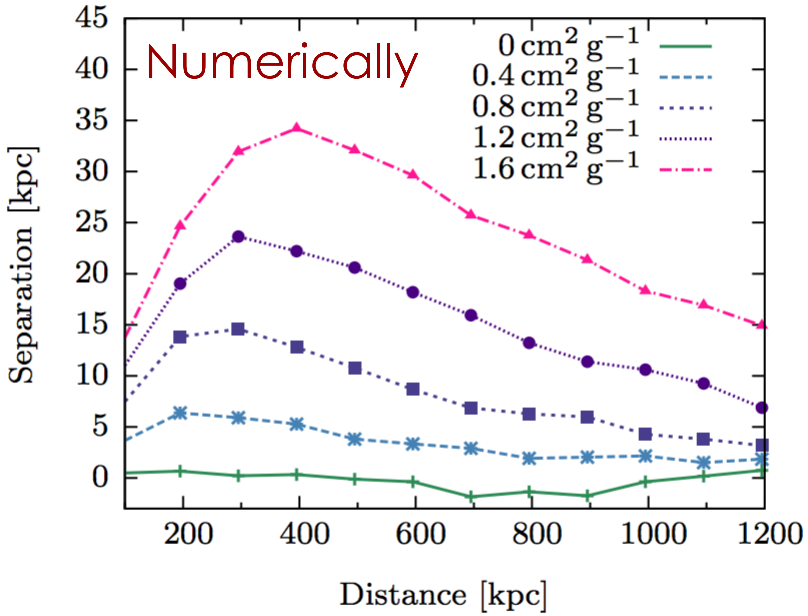
Just after the collision

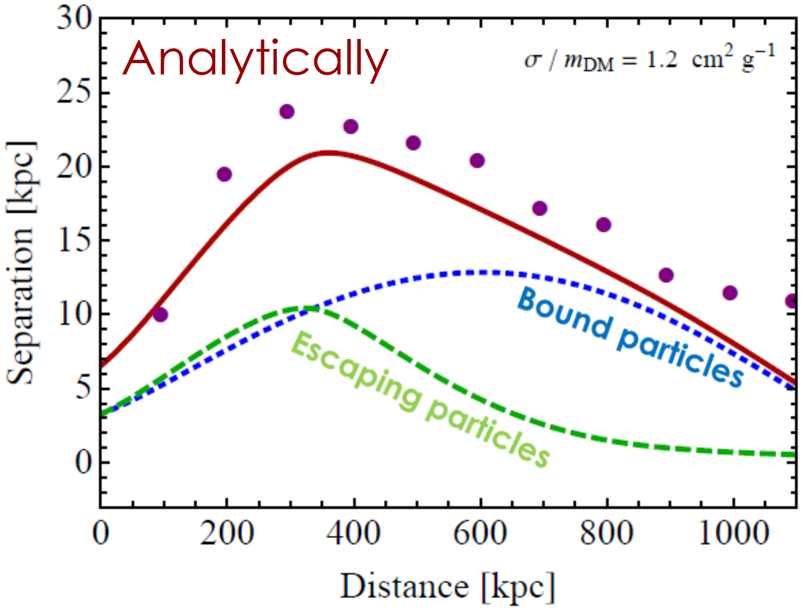


At late times

DM-galaxy separation

- At large distances, escaping particles are no longer associated to the sub-cluster.
- Particles that have scattered but remained bound only contribute to the separation for a short time.





Observational bounds

- For both rare and frequent self-interactions, the peak of the DM distribution remains coincident with the peak of the distribution of galaxies.
- The effect of self-interactions is never large enough to completely separate DM halo and galaxies.
- The predicted separation is small (10 – 40 kpc), below current bounds for the Bullet Cluster (Δz < 50 kpc).
- There are promising new strategies:

  1. Statistical analysis of a large number of mergers (or infalling sub-halos).

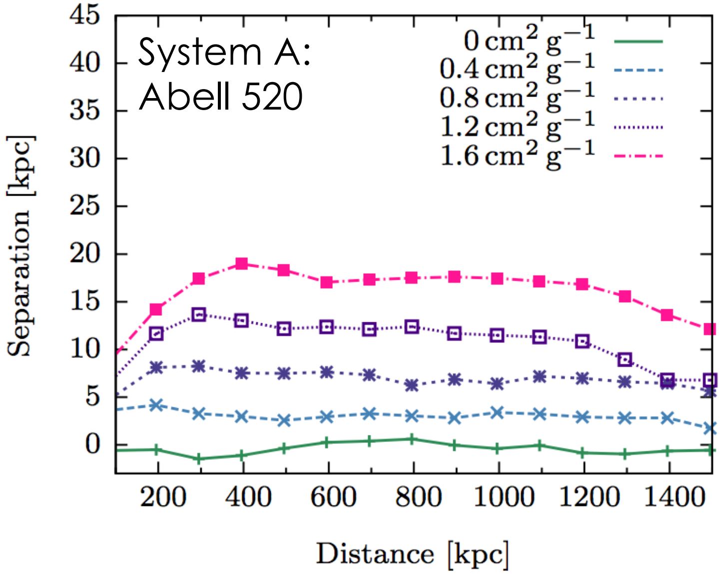
     Harvey et al.: 1310.1731

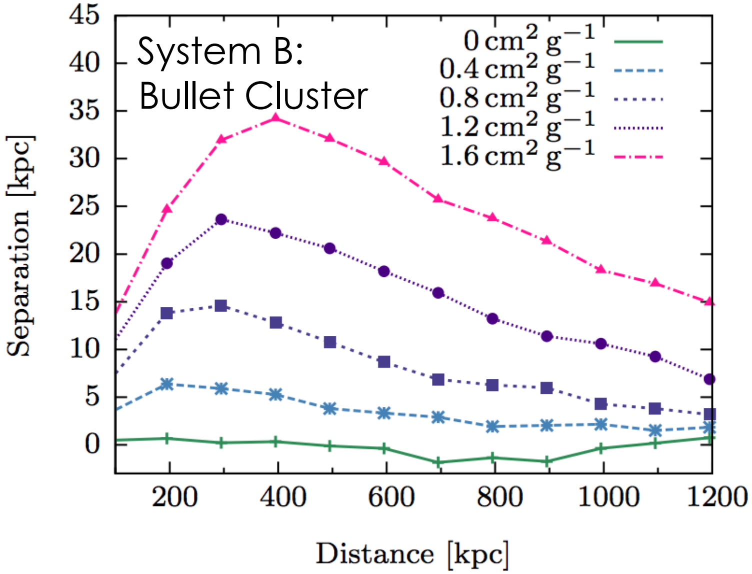
  2. Measurement of the shape of DM halos and the corresponding galaxy distributions.

Conclusions

- DM self-interactions can be frequent only if the fraction of expulsive collisions *f* is small. In this case DM self-interactions can be described by an effective drag force.
- When *f* is large, however, DM self-interactions must be rare and an effective description of collective effects is not possible.
- These two classes of DM self-interactions give qualitatively different predictions for the DM-galaxy separation in cluster collisions.
- In both cases, the expected separation between DM halo and galaxies is largest shortly after the collision but still below current observational bounds.

Considering different systems





- The main cluster in System B is much larger than the sub-cluster, so escaping particles are more likely to be associated with the main cluster.
- The sub-cluster in System B is more tightly bound and thus particles that have scattered but remained bound will quickly reach their maximum distance and return.

Velocity dependent interactions

- A possible solution could be velocity-dependent self-interactions, which would be enhanced in low-velocity systems such as dwarf satellites:

1. Long-range interactions via dark photons

Ackerman, Buckley, Carroll, Kamionkowski: 0810.5126

2. Yukawa interactions via light mediators

Feng, Kaplinghat, Yu: 0905.3039
Buckley, Fox: 0911.3898
Loeb, Weiner: 1011.6374

- For such interactions, no relevant constraints arise from high-velocity systems such as galaxy clusters.

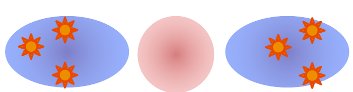
DM sub-populations

a) The DM particle scatters once with high momentum transfer and escape from the sub-cluster.
   - These particle will typically travel in the direction opposite to the direction of motion of the sub-cluster, leading to a DM tail in the backward direction.
   - This tail will exert a gravitational pull on the DM halo and the galaxies, slowing both of them down in exactly the same way.
   - Ultimately, these particles will end up far away from their original system, no longer contributing to the observable separation.

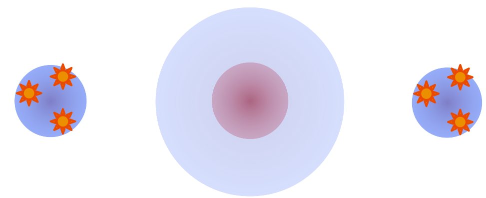
DM sub-populations

b) The DM particle scatter once with low momentum transfer and remain bound to the sub-cluster.
   - These particles will typically have elliptical orbits, which they retain for a very long time.
   - Before completing half an orbit, they will preferentially be found towards the back of the system.

c) The DM particle does not scatter at all.
   - These particles will behave exactly like galaxies.



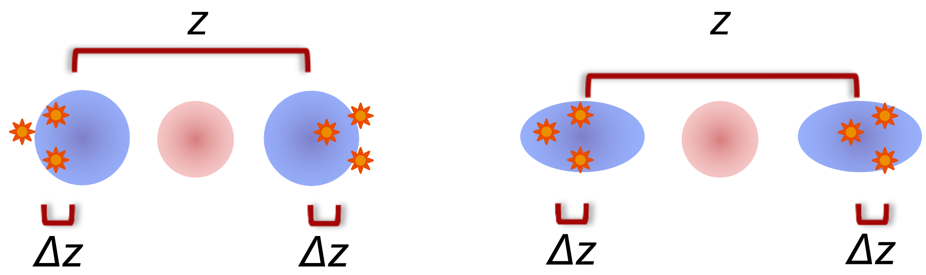
Just after the collision



At late times

DM-galaxy separation

- Here we will focus on the potential separation between DM halos and galaxies caused by self-interactions.



- The separation ***Δz*** is defined as the distance between the respective centroids of the DM halo and the distribution of galaxies.
- Given existing bounds on DM self-interactions, can we expect an observable separation?