The great collider in the sky

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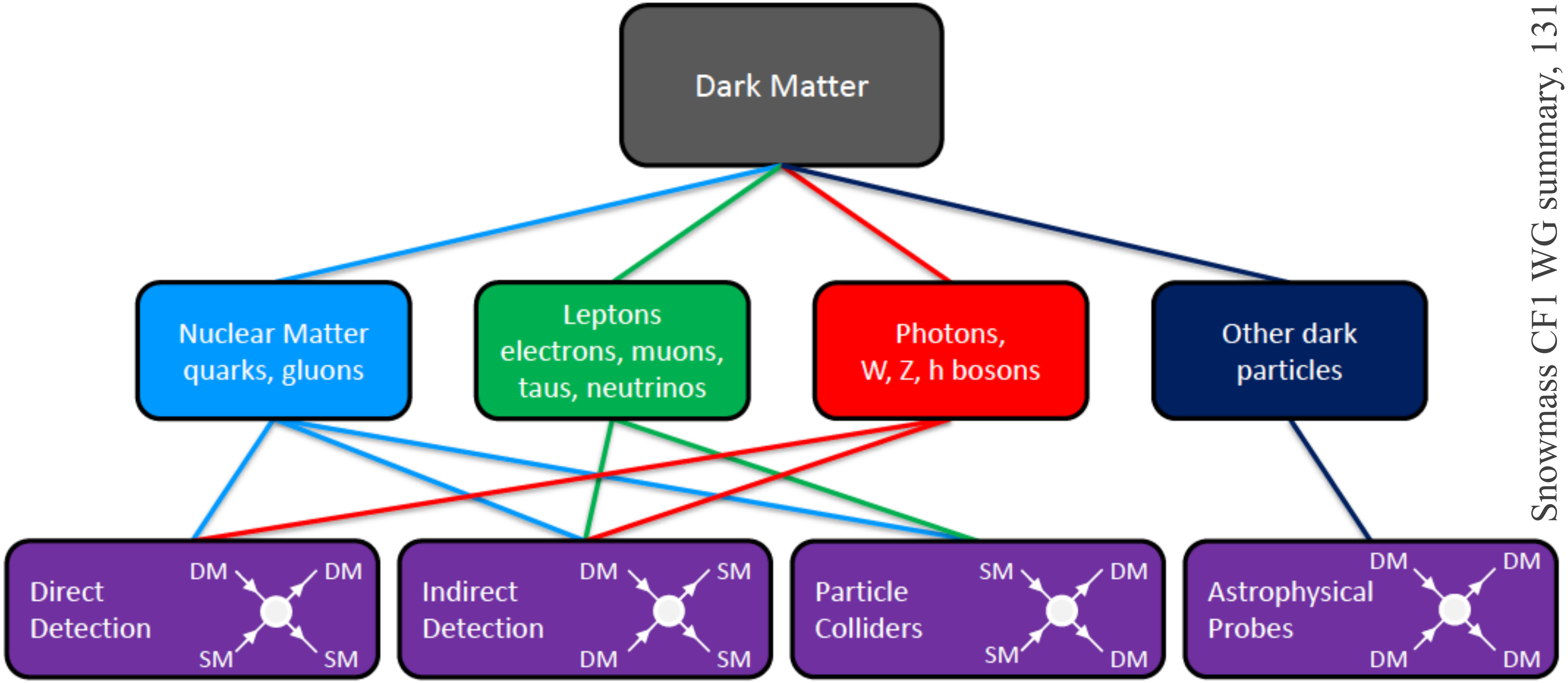
Based on work done with:

Felix Kahloefer, Mads Frandsen, Kai Schmidt-Hoberg, MNRAS **437**:2865,2014 [1308.3419]

Felix Kahloefer, Janis Kummer, Kai Schmidt-Hoberg, arXiv:1504.06576

2015: The Spacetime Odyssey Continues, Stockholm, 2-5 June 2015

Detecting dark matter particles



How do we compare results from recoil expts. having different thresholds, without making (uncertain) assumptions about the DM vel. distribution?

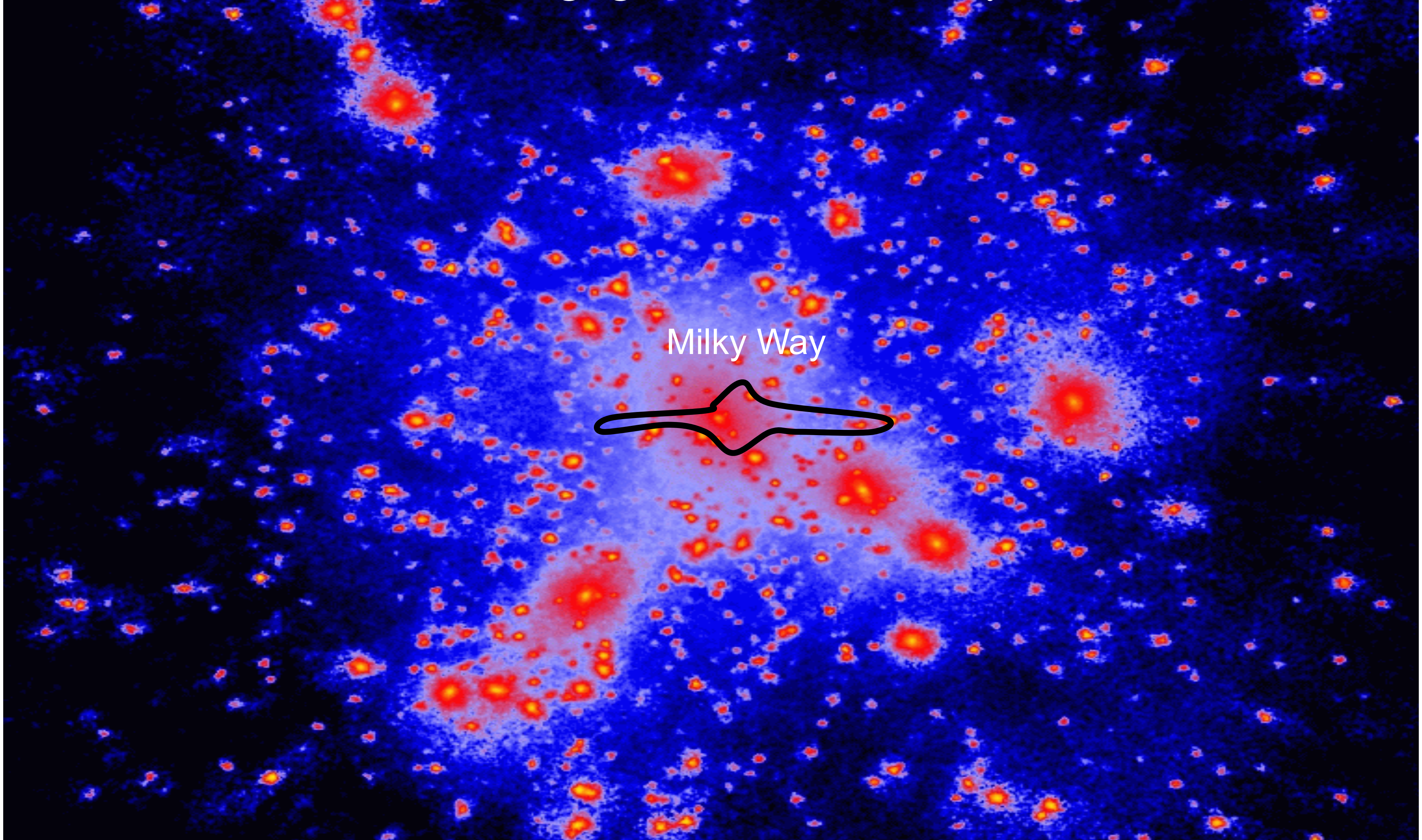
Can we probe down to the thermal relic #-secn by searching for annihilating DM in the Galactic Centre or in dwarf spheroidal galaxies?

When looking for generic BSM physics associated with DM, is reach (in energy) more important than sensitivity through higher luminosity?

Can we measure DM self-interactions through offsets between luminous & DM (reconstructed by gravitational lensing) in colliding clusters?

Snowmass CF1 WG summary, 1310.8327

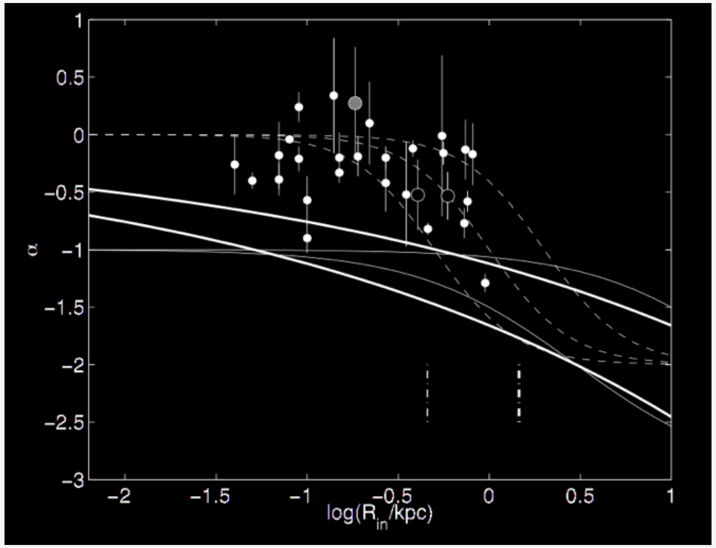
We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**



A galaxy such as ours is supposed to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation *etc* over billions of years

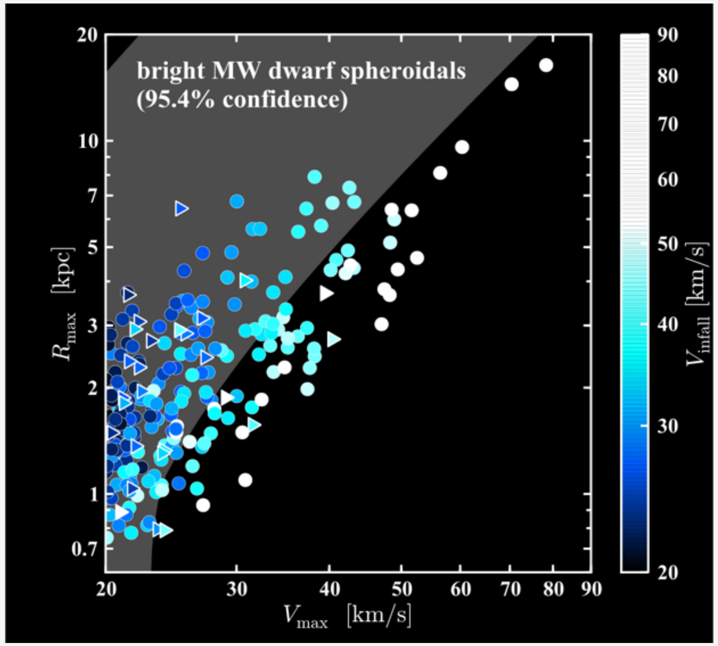
There are well-publicised discrepancies between N-body simulations of *collisionless* cold DM and astrophysical observations on galactic scales:

- Cusp-versus-core problem
- Too-big-to-fail problem
- Missing-satellite problem
- …



Zackrisson *et al.*, astro-ph/0603523

There may be astrophysical explanations (e.g. 'baryonic feedback' for the Cusp-vs-core problem) … simulations are only now beginning to be able to address these complex issues



Boylan-Kochlin *et al*, 1103.0007

or …

DM self-interactions may solve these problems (Spergel & Steinhardt, astro-ph/9909386)

Self-interacting DM

- To have observable effects on astrophysical scales, self-interaction #-sections must be large, typically: $\sigma/m_\chi \sim 1\ \text{cm}^2/\text{g} \sim 2$ barns/GeV

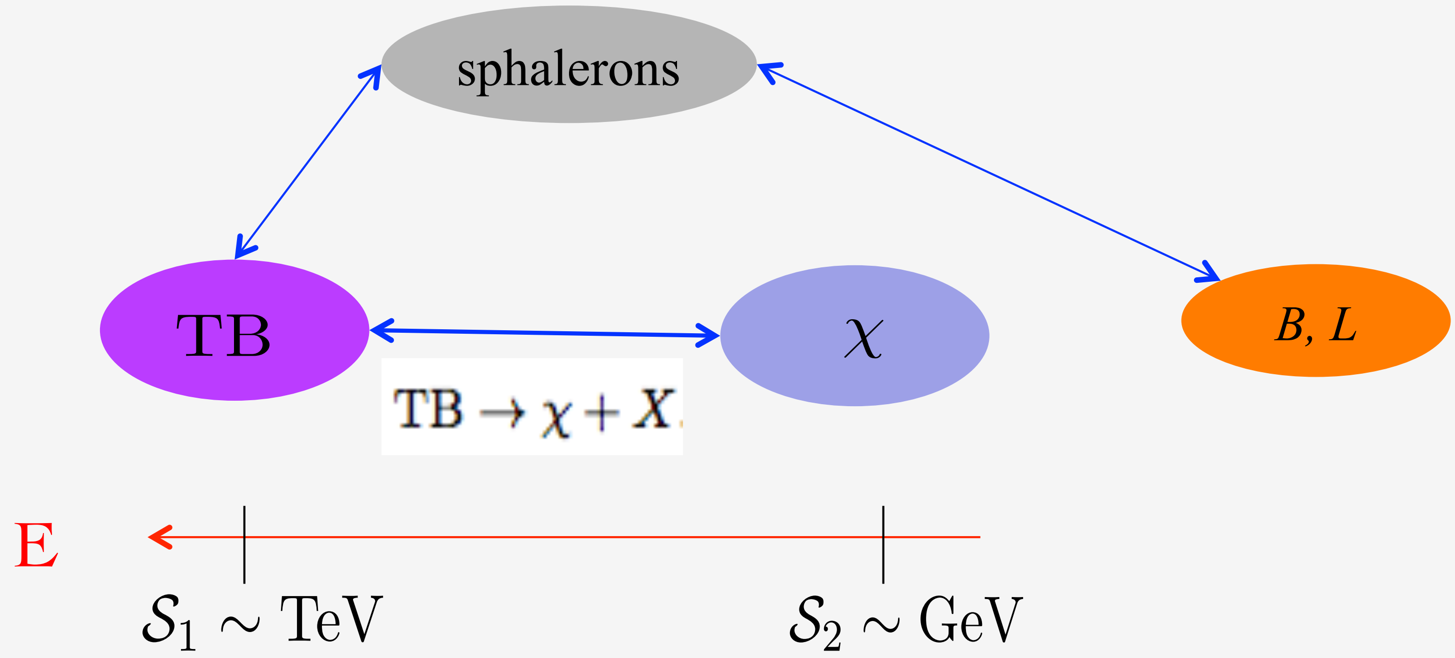
- The typical self-interaction #-section of a WIMP is smaller by $>10^{15}$ … hence astrophysical evidence for DM self-interactions would rule out popular particle candidates such as axions, neutralinos, axions etc

- However large self-interactions are natural in models such as:
  - Strongly interacting DM — Kusenko & Steinhard: astro-ph/0106008; Frandsen, Sarkar & Schmidt-Hoberg: 1103.4350; …
  - 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; …

- Using *astrophysical* colliders we can study the 'dark sector' even if DM has highly suppressed couplings to the Standard Model

Why have we not seen these particles yet?

Frandsen, Sarkar & Schmidt-Hoberg, 1103.4350



S_1 States (constituents) carry weak charges and are connected to sphalerons

S_2 States are SM singlets (in a hidden sector/hidden valley) but directly connected to the S_1 sector (with scale separation – TeV ➛ GeV – because of different *β*-function)

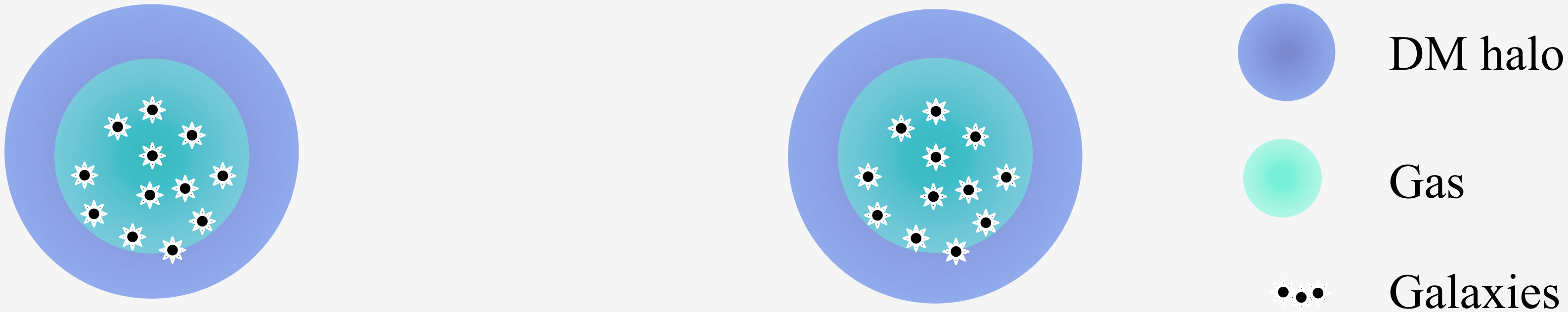
$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\mathrm{sph}}$, then χ decouples and becomes DM

The S_1 states do couple to the SM (so ***ought to show up*** at LHC Run II)

There are other such (viable) models … *falsifiable* through experiment

Observational constraints

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



… in agreement with observations

Such colliding clusters should however be rare – only ~0.1 systems like the Bullet Cluster should be seen up to $z \sim 0.3$ (Kraljic & Sarkar, 1412.7719) … however many more have actually been seen!

http://www.mergingclustercollaboration.org/

Observations of the **Bullet Cluster** (Clowe *et al,* astro-ph/0608407) constrain the rate of halo *evaporation* and halo *deceleration* due to DM self-interactions:

- $\sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$ (analytic)
- $\sigma/m_\chi < 0.7\ \mathrm{cm}^2/\mathrm{g}$ (numerical)

Markevitch *et al*, astro-ph/0309303
Randall *et al*, arXiv:0704.0261

Observational constraints

- Various other astrophysical observations constrain 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, astro-ph/0002050
  - Subhalo evaporation rate — Gnedin & Ostriker, astro-ph/0010436

- Nevertheless, velocity-*independent* DM self-interactions with $\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g}$ is still viable

Vogelsberger, Zavalla & Loeb, 1201.5892
Rocha *et al*, 1208.3025
Peter *et al*, 1208.3026
Zavalla, Vogelsberger & Walker, 1211.6426

A new approach

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

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

where the momentum transfer cross section is

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

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

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

m = -1 for long-range interactions

m = 1 for velocity-independent interactions

Predictions

- In the presence of such a drag force, a DM sub-halo falling into a galaxy cluster will retain its shape, since the drag force affects all DM particles *equally*

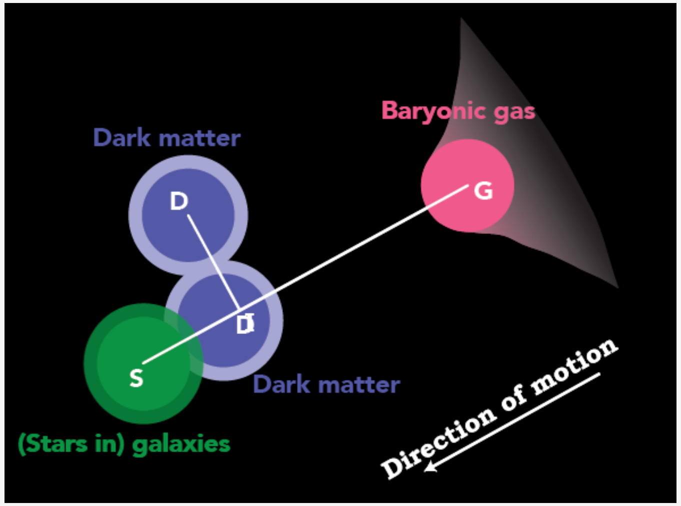
- In the decelerating frame of the DM subhalo, stars will experience a fictitious *accelerating* force

- The resulting tilt in the effective potential will shift the *distribution* of stars relative to the DM halo

- Moreover, some galaxies can escape and will end up travelling *ahead* of the DM halo

- Both of these effects can lead to a *separation* between the peak of the distribution of stars and the centroid of the DM halo

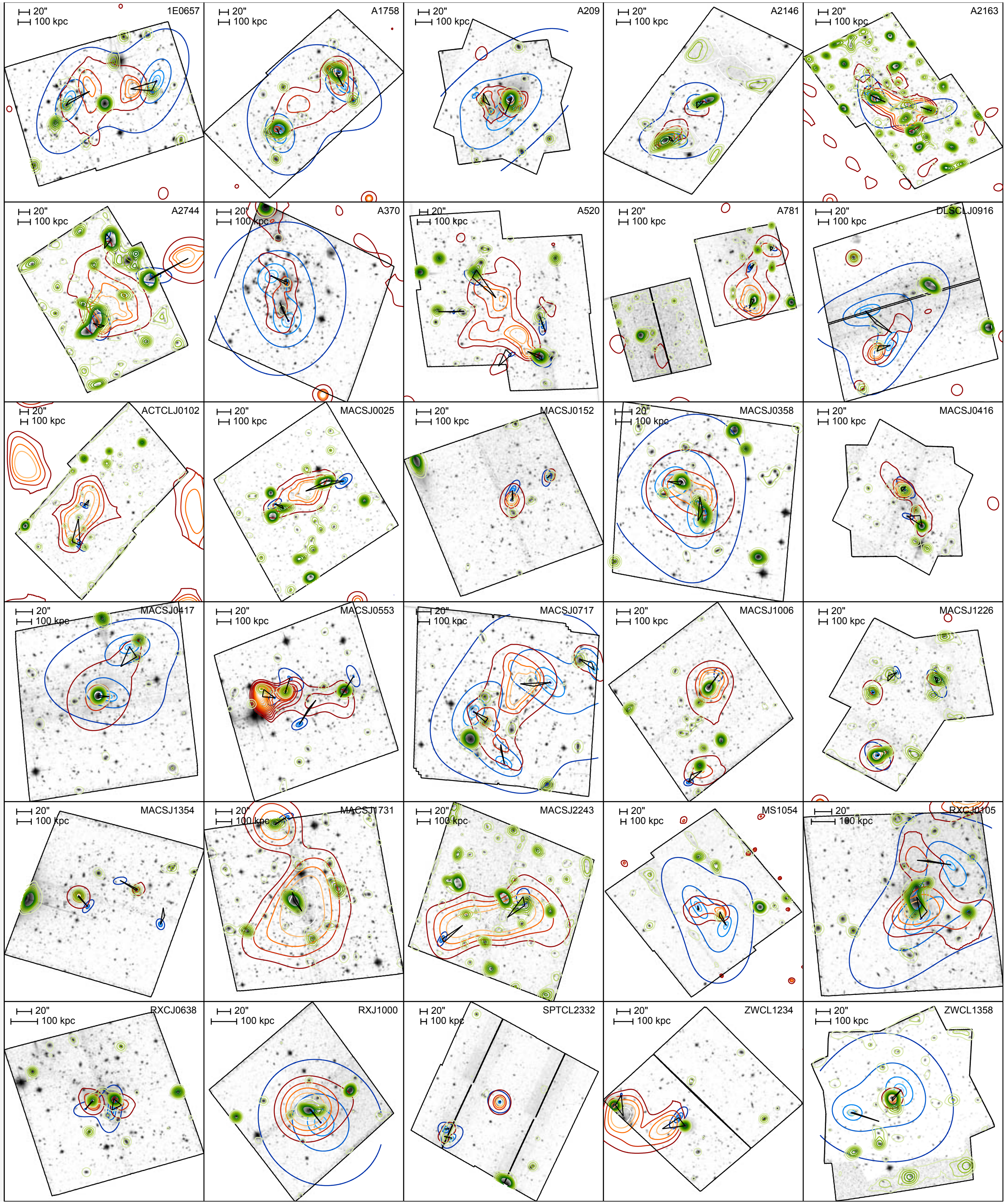
Infalling subhalos



Through statistical analysis of a large number of infalling sub-halos in clusters, the DM self-interaction is bounded as:

$$\sigma/m_\chi < 0.5 \text{ cm}^2/\text{g}$$

Massey *et al*, 1007.1924; Harvey *et al*, 1305.2117, 1310.1731, 1503.07675

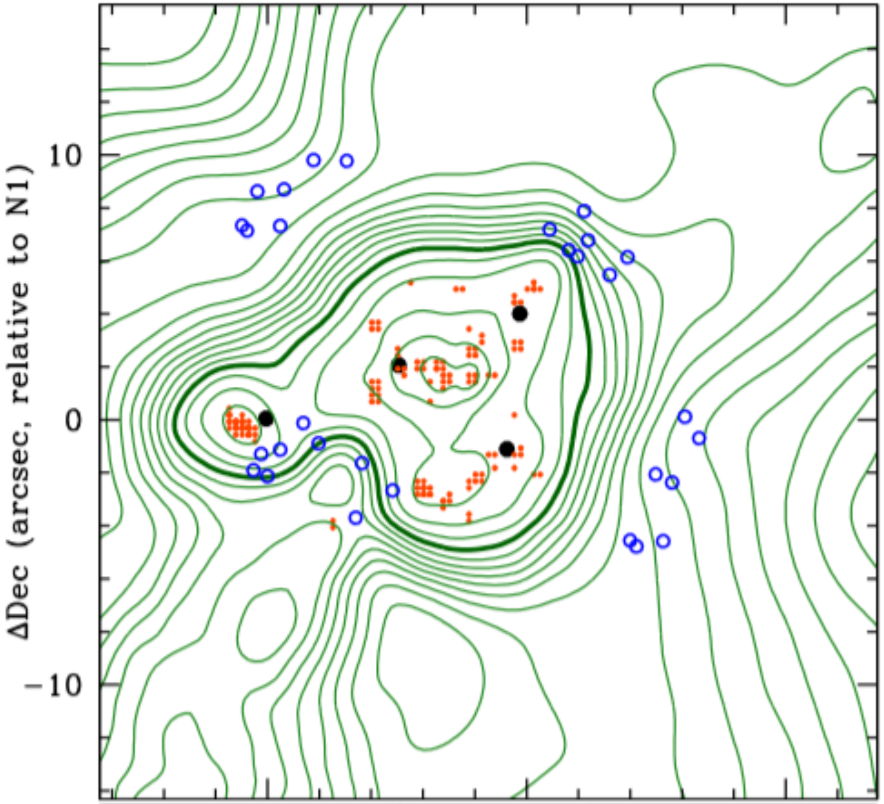


Evidence in A3827?

The behaviour of dark matter associated with 4 bright cluster galaxies in the 10 kpc core of Abell 3827

Massey *et al.*, 1504.03388

"The best-constrained offset is 1.62±0.48 kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. […]
With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but **if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section $\sigma/m=(1.7\pm0.7)\ \mathrm{x}10^{-4}\ \mathrm{cm}^2/\mathrm{g}\ (t/10^9\mathrm{yr})^{-2}$ where *t* is the infall duration**."



Evidence in A3827?

- The quoted self-interaction cross section is orders of magnitude *smaller* than any existing bound, making it seemingly impossible to confirm or rule out this claim using other astrophysical systems

- Massey *et al* give two reasons for this unique sensitivity:

  - A3827 is strongly lensed, allowing for a much more precise measurement of the separation

  - The subhalo under consideration has been falling towards the centre of A3827 for a very long time ($10^8 – 10^9$ yr), so self-interactions have had plenty of time to affect the trajectory of the subhalo (assuming the separation grows proportional to the infall time *squared*)

Williams & Saha, arXiv:1102.3943

Evidence in A3827?

This conclusion is based on two *incorrect* assumptions:

- The stars and the DM subhalo are assumed to develop completely *independently*, i.e. even a tiny difference in the acceleration can lead to sizeable differences in their trajectories.
  - But initially the stars are *gravitationally bound* to the DM subhalo so can be separated from it only if external forces are comparable to the gravitational attraction within the system

- The effective drag force on the DM subhalo is assumed to be *constant* throughout the evolution of the system.
  - However the rate of DM self-interactions depends on the velocity of the subhalo and the background DM density, both of which will *vary* along the trajectory of the subhalo.

Back-of-the-envelope estimate

$$\frac{F_{\rm sh}}{m_{\rm star}} = \frac{G_{\rm N}\, M_{\rm sh}(\Delta)}{\Delta^2}$$

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{1}{4}\,\frac{\tilde{\sigma}}{m_{\rm DM}}\, v^2\, \rho$$

$$F_{\rm sh}/m_{\rm star} < F_{\rm drag}/m_{\rm DM}$$

$$\frac{\tilde{\sigma}}{m_{\rm DM}} > \frac{4}{v^2\,\rho}\,\frac{G_{\rm N}\, M_{\rm sh}\,\Delta}{a_{\rm sh}^3}$$

$$\rho \sim 4\,{\rm GeV\,cm^{-3}} \;\; {\rm and} \;\; v \sim 1500\,{\rm km\,s^{-1}}$$

=> $$\frac{\tilde{\sigma}}{m_{\rm DM}} \gtrsim 2\,{\rm cm^2\,g^{-1}}$$

Refining the estimate

- Realistic density profiles for the subhalo and the central cluster

- Realistic trajectory for the infalling subhalo

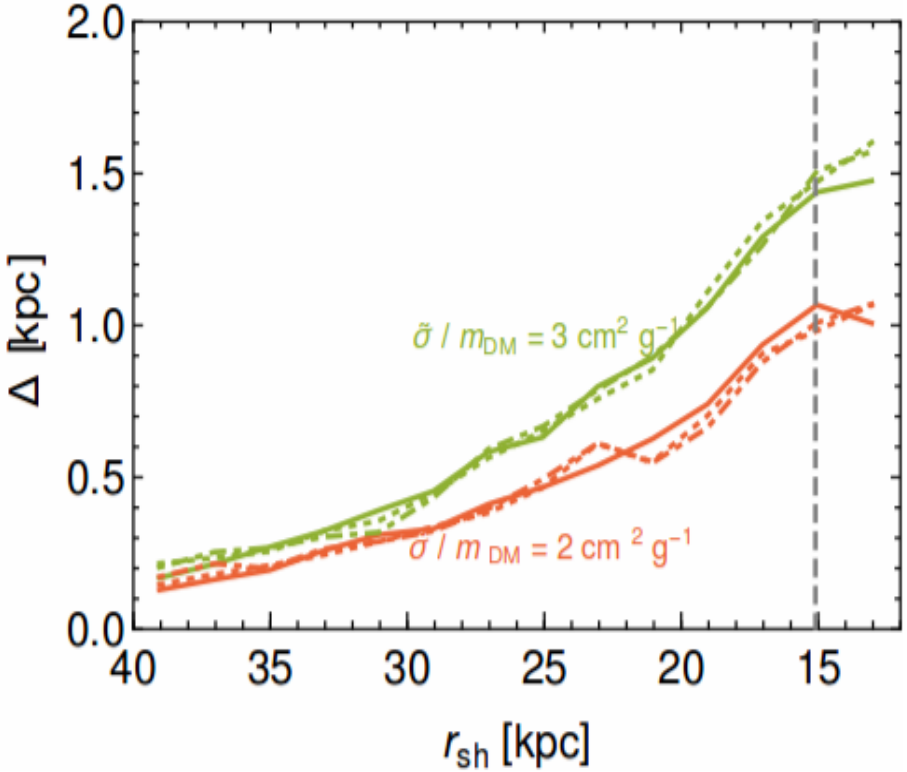
To include these refinements requires a full three-dimensional simulation … which we had developed already to study the Bullet Cluster

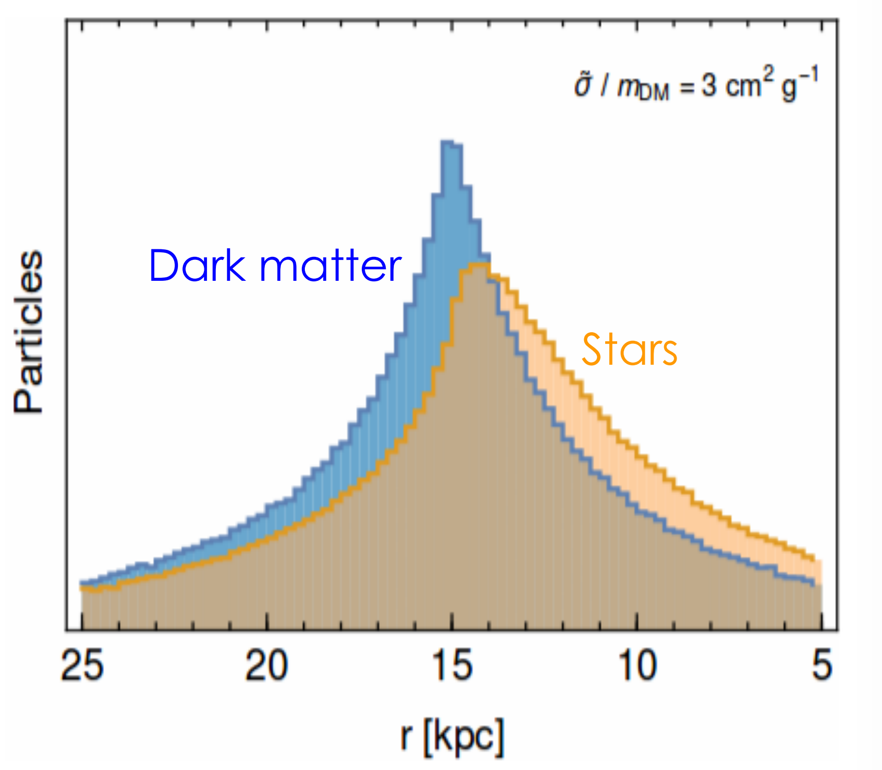
Kahlhoefer *et al*, 1308.3419

- We treat the gravitational potential of the cluster as time-independent, while for the sub-halo the profile is allowed to vary with time and is determined self-consistently from the simulation.

- Assuming an initial density profile, the simulation chooses a representative set of particles and then calculates their motion in the combined gravitational potential of cluster and sub-halo.

Results





- As expected, the peaks of the two distributions are slightly shifted
- Furthermore the tail of the distribution of stars is enhanced in the forward direction due to stars that have escaped from the gravitational potential of the sub-halo
- The #-section needed to get a separation of 1.5 kpc is $\sigma/m_\chi \sim 3\ \mathrm{cm}^2/\mathrm{g}$

The particle physics perspective

- In order to obtain an effective drag force, we have assumed that each DM particle participates in a large number of scattering processes
- This is possible only if in each scattering process the momentum transfer is small (i.e. scattering is peaked in the forward direction)
- The easiest way to obtain such an angular dependence is from long-range interactions
- However, long-range interactions also imply that scattering is suppressed for large velocities proportional to v^{-4}, so that *no* observable effects would be expected in galaxy clusters

But what if DM self-interactions are not so frequent?

Rare self-interactions

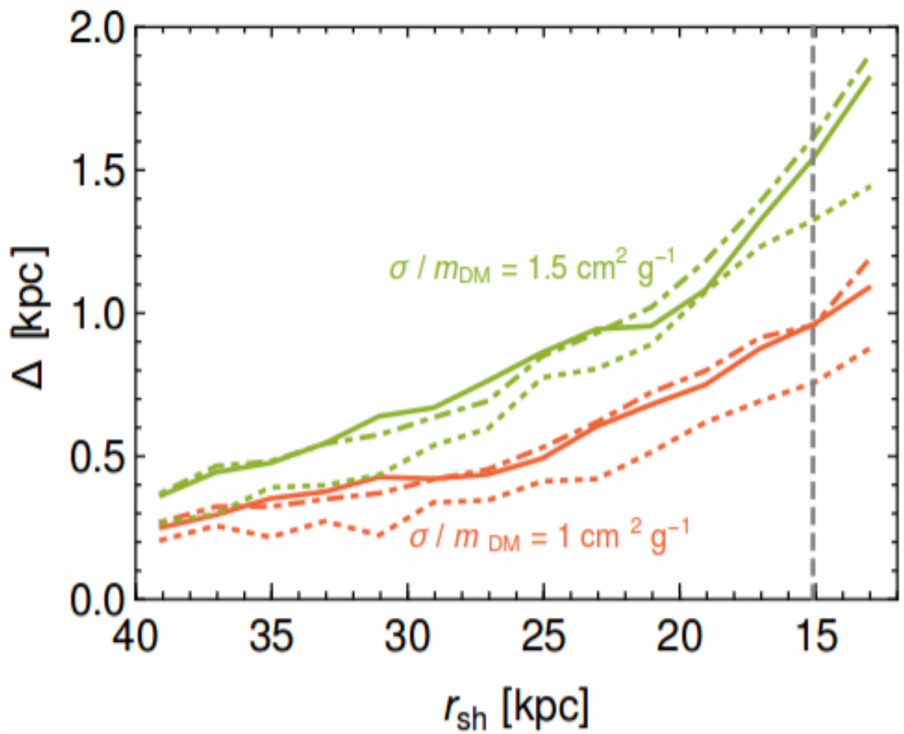
- Rare self-interactions mean that for a typical DM particle the probability for multiple scattering is *negligible*

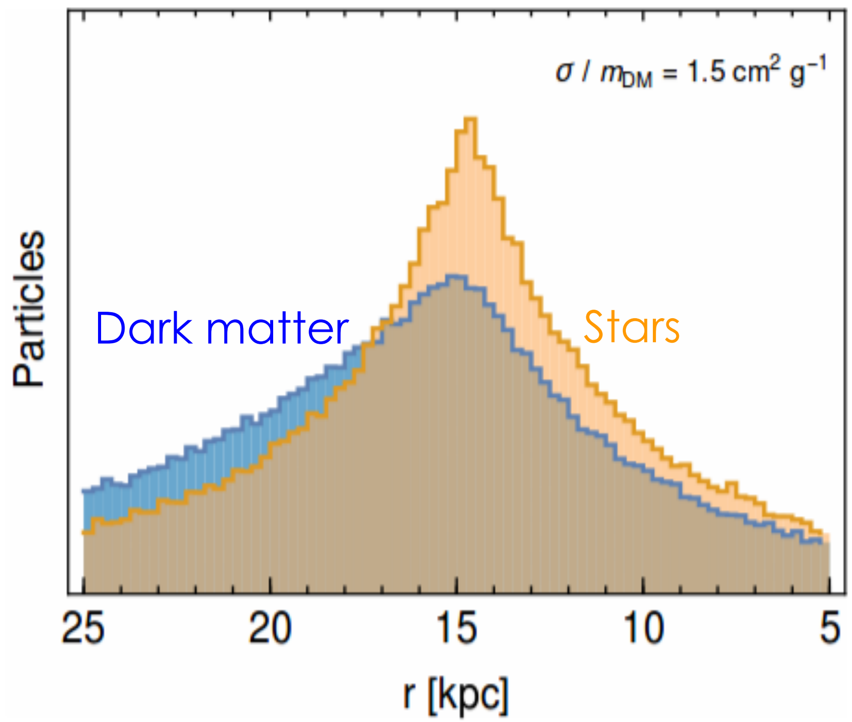
- A significant fraction of DM particles will not experience any scattering and behave just like the (collisionless) stars

- However whenever a DM particle scatters, it will typically receive such a high momentum transfer that it *escapes* from the sub-halo

- A separation between the DM sub-halo and stars can also occur in this case, but the separation is due to DM particles leaving the subhalo in the *backward* direction

Rare self-interactions





- The cross section required to obtain a separation of 1.5 kpc is now: $\sigma/m_\chi \sim 1.5\ \mathrm{cm}^2/\mathrm{g}$
- NB: the separation is mainly due to differences in the *shapes* of the two respective distributions, while the peaks of the distributions remain coincident

Rare self-interactions

- The case of contact interactions can potentially be distinguished from the case of an effective drag force by studying in detail the shape of the DM sub-halo and the relative position of the peaks of the two distributions.

- **Contact interactions:** The DM sub-halo is deformed due to the scattered DM particles leaving the sub-halo in the backward direction, such that the position of the centroid depends sensitively on the definition of the centroid

- **Effective drag force:** The DM sub-halo is expected to retain its shape, while the distribution of stars will be both shifted and deformed

Conclusions

- Sub-halos falling into galaxy clusters are a novel and interesting probe of DM self-interactions

- Both an effective drag force from frequent self-interactions, and rare self-interactions, can lead to a separation between the DM sub-halo and the stars

- The separation only grows close to the centre of the cluster and is therefore largely *insensitive* to the total in-fall time

- The separation observed in A3827 *if* due to DM self-interactions requires: $\sigma/m_\chi > 1\ \mathrm{cm^2/g}$

- This interpretation is thus *testable* using gravitational lensing of other galaxy clusters!