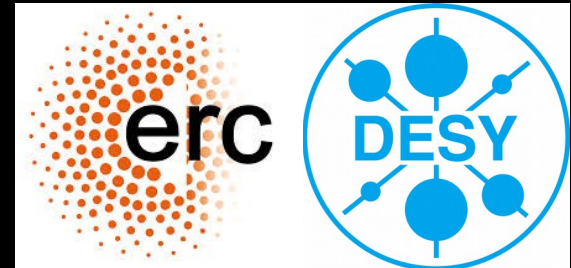


Dark matter self interactions and colliding galaxy clusters

Evidence for self interactions in Abell 3827?

Kai Schmidt-Hoberg

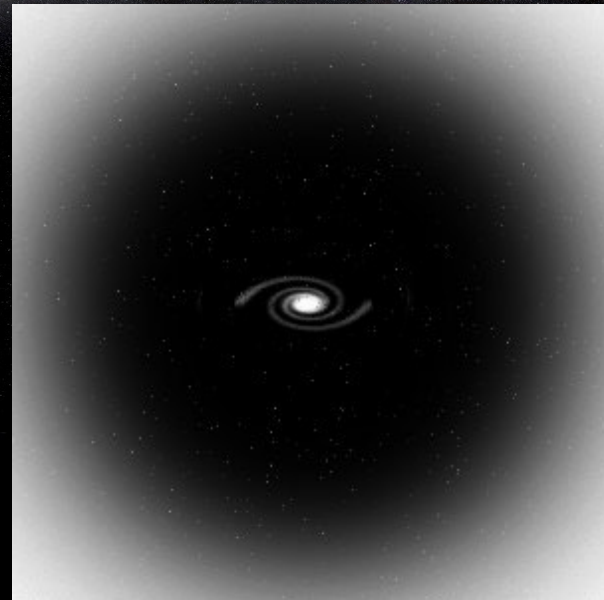
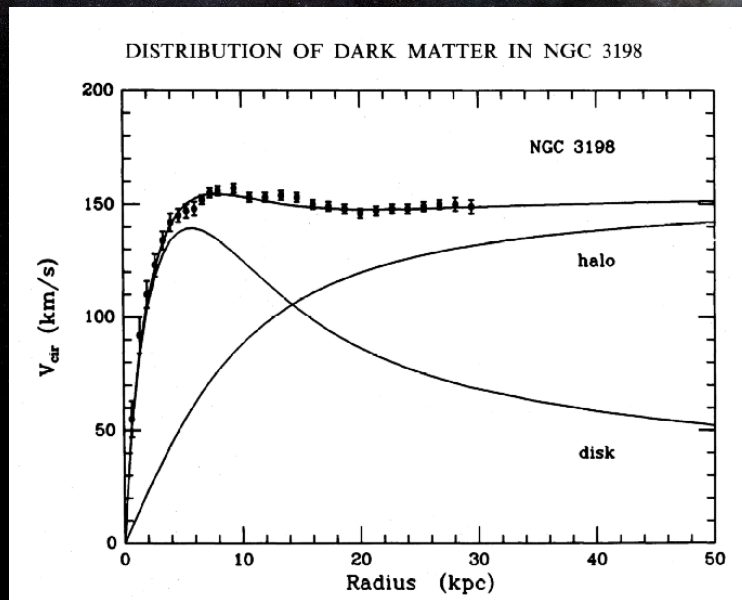
Based on 1504.06576 and 1308.3419
with F Kahlhoefer, J Kummer, M Frandsen and
S Sarkar



Evidence for dark matter

Compelling evidence for dark matter on all astrophysical scales:

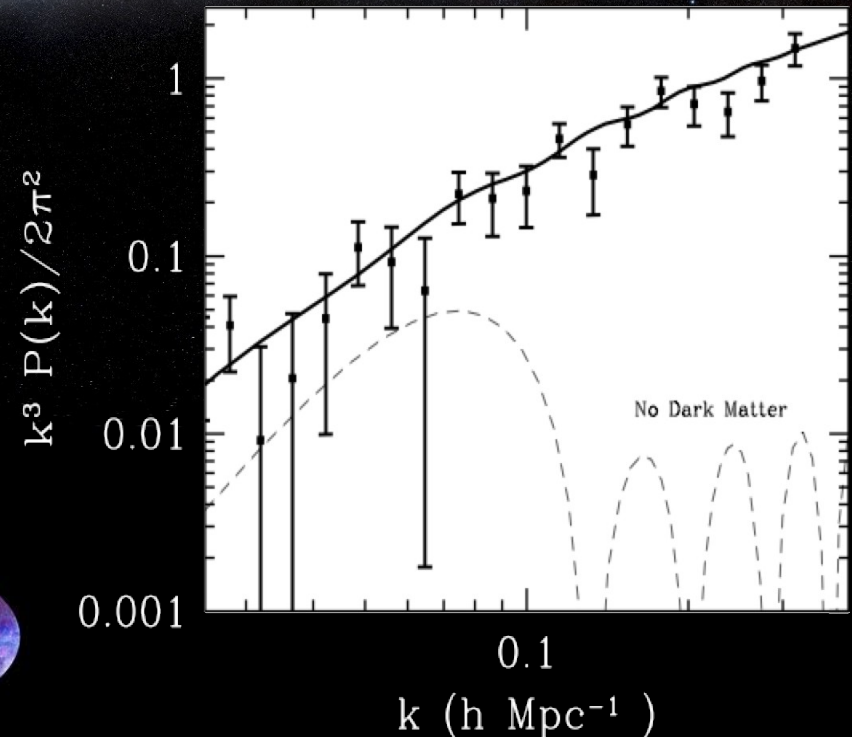
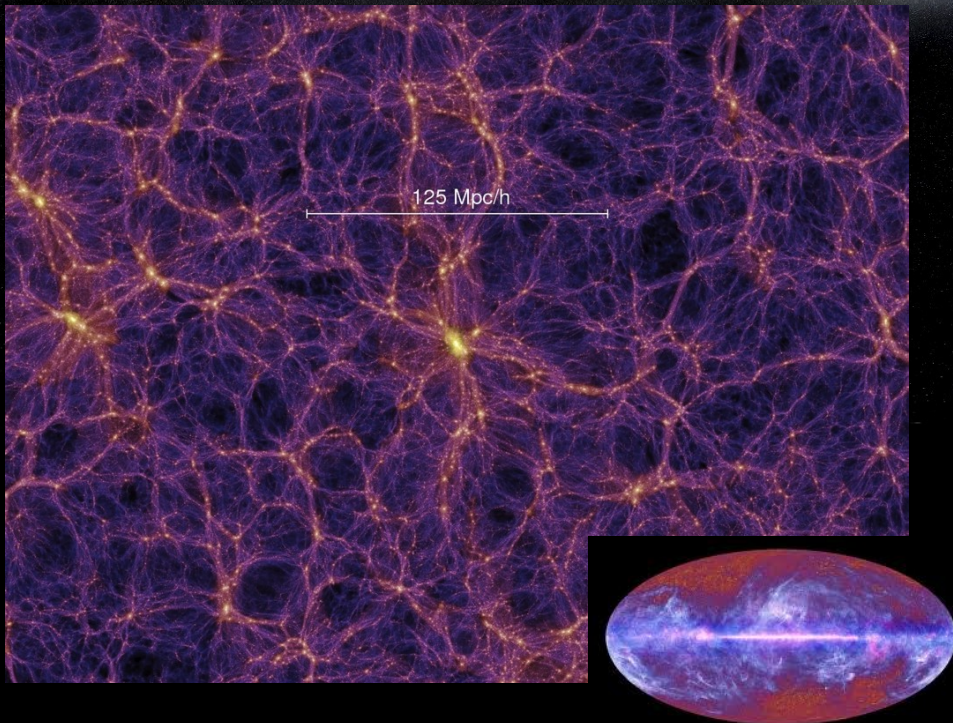
- Galactic scales: Rotation curves of Galaxies



Evidence for dark matter

Compelling evidence for dark matter on all astrophysical scales:

- Galactic scales: Rotation curves of Galaxies
- Cluster scales: Gravitational lensing
- Cosmological scales: Large scale structure (N body simulations) & CMB



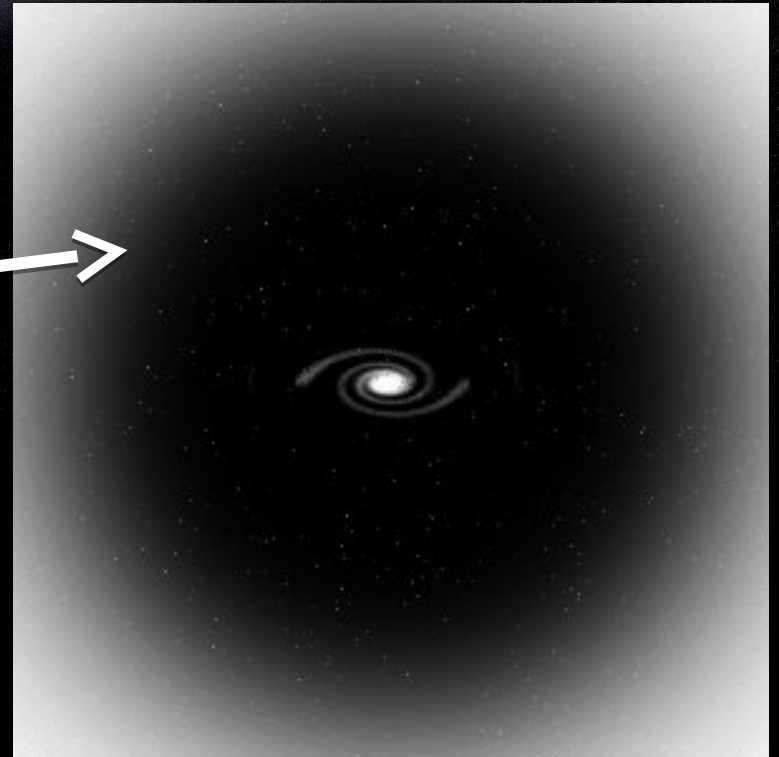
Evidence for dark matter

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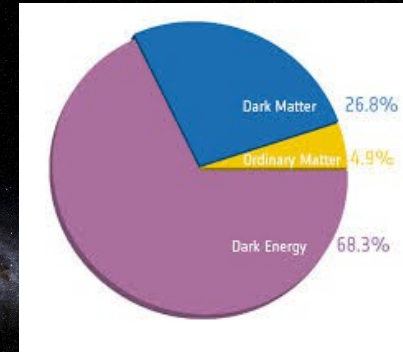
What is it ???

What do we know to start with?



What do we know?

- How much: $\Omega \approx 0.26$
- Very likely a particle
- **Dark:**
 - Electrically neutral - probably
 - Colour neutral - probably
- **Cold:** nonrelativistic during structure formation
- Sufficiently **long-lived**
- **Non-baryonic** (from BBN)



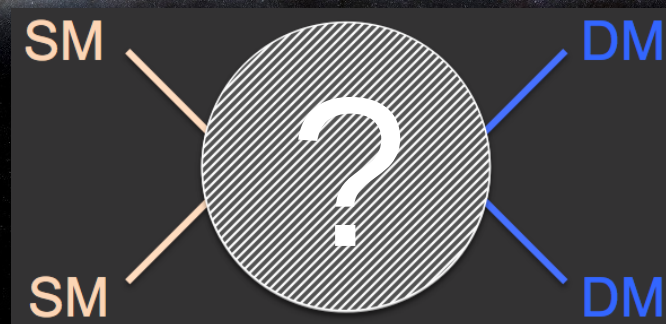
Candidate within the Standard Model of particle physics?

- Neutrinos
 - Correspond to hot DM
 - Cannot account for the observed dark matter density

Physics beyond the Standard Model !

Many candidates: WIMP, axion, gravitino, ...

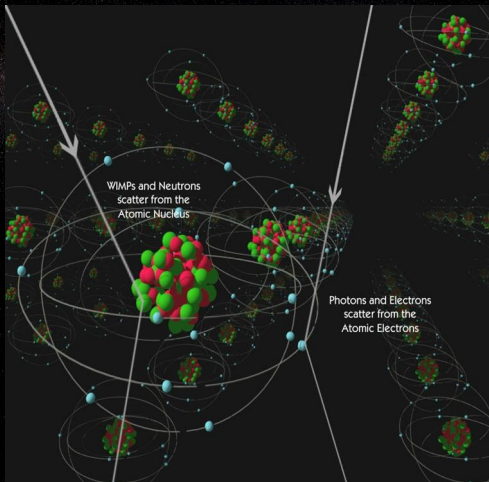
Dark matter – how to test it?



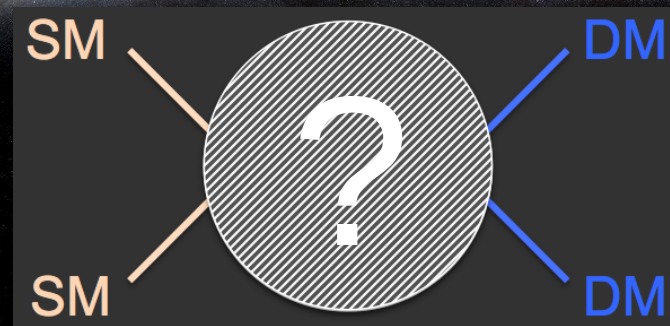
Dark matter – how to test it?



Collider searches



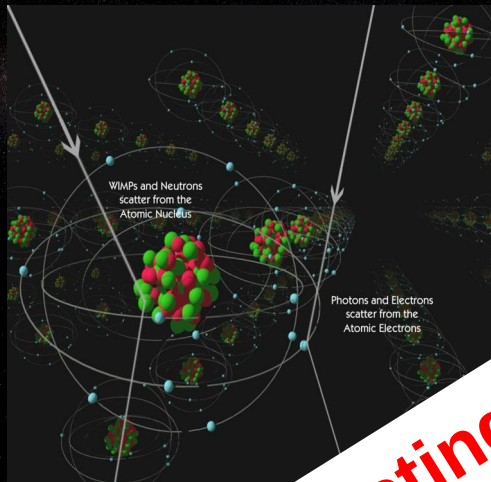
Direct detection



Indirect detection



Dark matter – how to test it?



Collider

Detection

SM

DM

SM

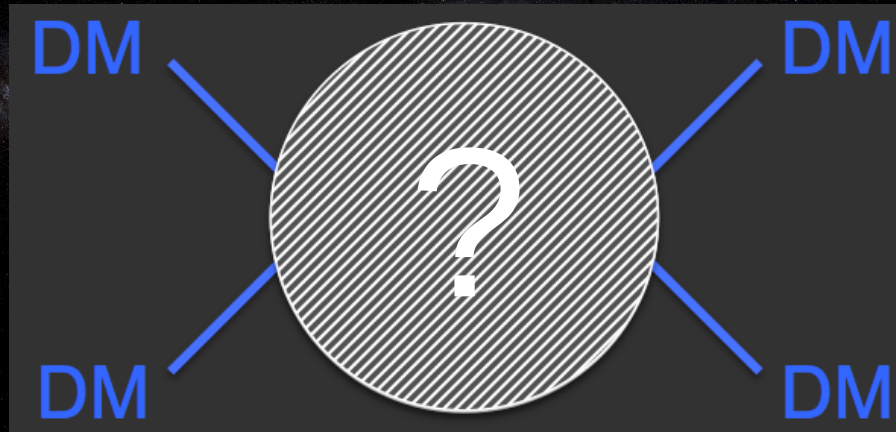
DM

Indirect detection

Very interesting – but not the topic for today



Self-Interactions?



Why is this interesting?

Motivation: Cosmology

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:

- Cusp-vs-core problem

Moore (1994)

Flores, Primack: astro-ph/9402004

- Too-big-to-fail problem

Boylan-Kolchin, Bullock, Kaplinghat:
1103.0007, 1111.2048

- Missing-satellite problem

Klypin et al.: astro-ph/9901240

Moore et al.: astro-ph/9907411

- DM self-interactions may solve these problems (but baryons...)

Spergel & Steinhard: astro-ph/9909386

Motivation: Particle physics

- Dark sector often assumed to be simple, mainly because we don't know much...
- Large self-interactions are natural in models with a complex dark sector, or light mediators, e.g.
 - Strongly interacting DM Kusenko, Steinhard: [astro-ph/0106008](#)
 - 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](#)
- Bonus: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.

How large a cross section?

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

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

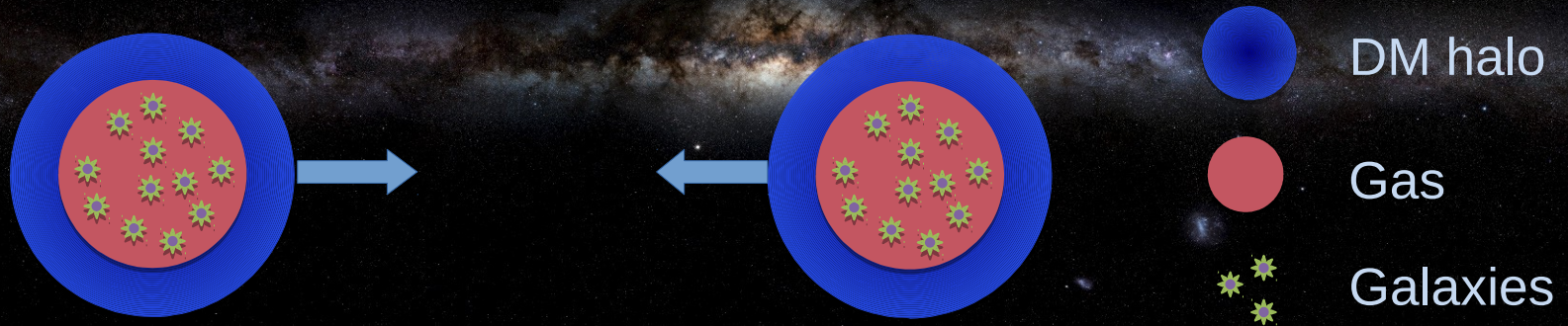
- The nucleon nucleon scattering cross section $\sim 20\text{b}$ at low energies
 - The typical cross section of a WIMP is 20 orders of magnitude smaller!
-
- Potential impact:
Evidence for DM self-interactions on astrophysical scales would rule out most popular models for DM, such as supersymmetric WIMPs, gravitinos, axions...

Self-interactions: Classic constraints

- Various astrophysical observations give constraints on the DM self-interaction cross section, e.g.
 - Subhalo evaporation rate Gnedin, Ostriker: astro-ph/0010436
 - Halo ellipticity Miralda-Escude (2002)
- These constraints seemed to be very strong, implying $\sigma/m_\chi < 0.1 \text{ cm}^2/\text{g}$, which is too small to give observable effects
- Note that the constraints apply for particular velocities and can be easily evaded by assuming a velocity dependence of the cross section
- In any case, recent numerical simulations indicate that the conventional bounds on DM self-interactions have been significantly overstated
- Velocity-independent DM self-interactions with $\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g}$ may still be viable.

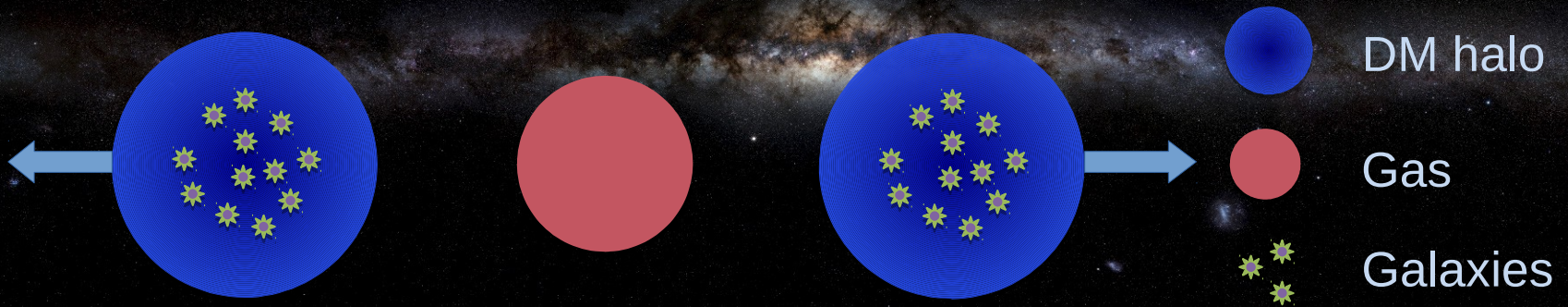
More recently: Colliding clusters

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



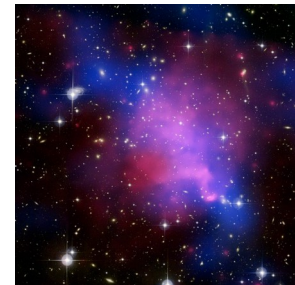
More recently: Colliding clusters

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



in rough agreement with observations: upper bounds on self interactions,

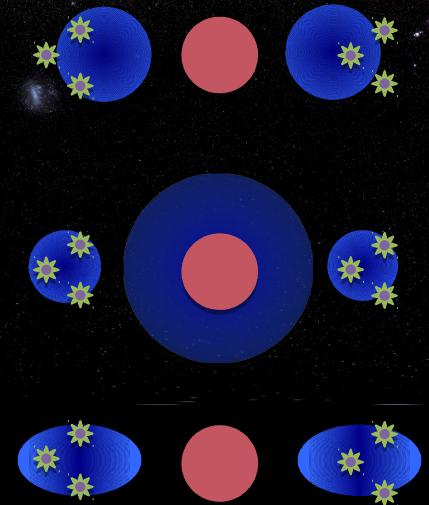
$$\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g}$$



Colliding clusters: possible effects

How would self-interactions modify the picture?

- Does the DM halo slow down?
 - Observables: Velocity, offset
- Does the DM halo evaporate?
 - Observables: M/L ratio, dark core
- Is the DM halo deformed?
 - Observables: Ellipticity, offset



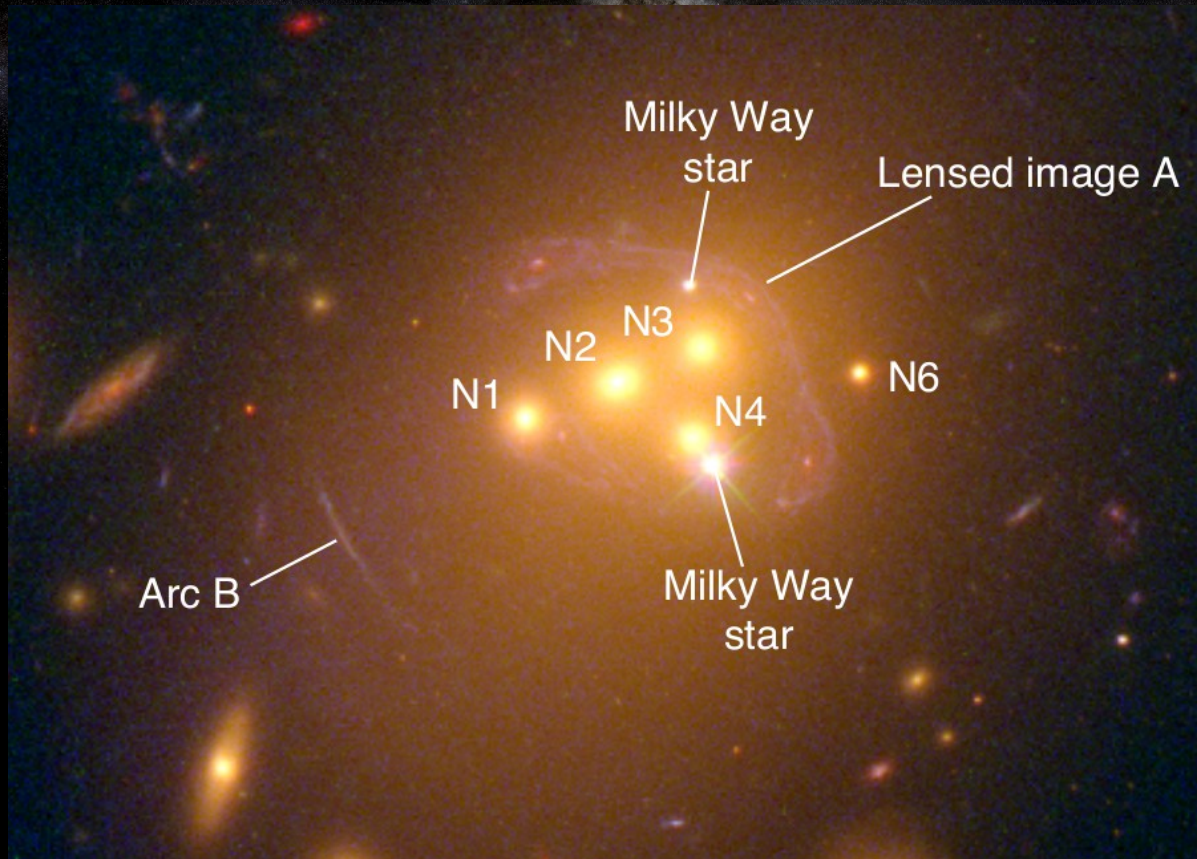
Potential smoking gun: offset

An even cleaner probe would be an infalling galaxy

Evidence in A3827?

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

Massey et al., arXiv:1504.03388



Evidence in A3827?

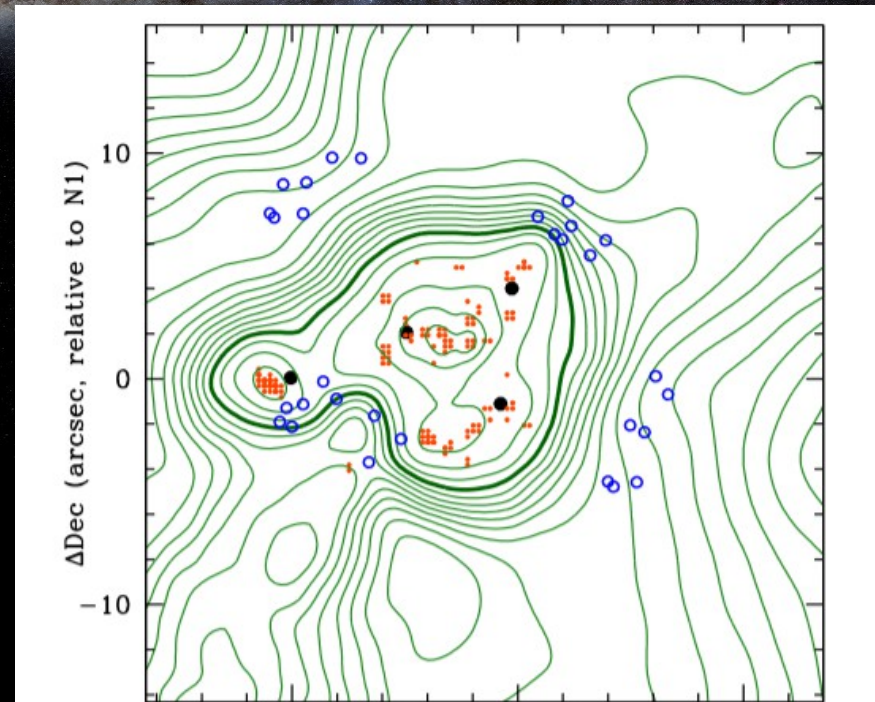
The behaviour of dark matter associated with 4 bright cluster galaxies in the 10kpc core of Abell 3827

Massey et al., arXiv:1504.03388

“The best-constrained offset is $1.62 \pm 0.48 \text{ kpc}$, 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

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\text{infall}}}{10^9 \text{ yrs}} \right)^{-2} \text{ cm}^2/\text{g}.$$

where t is the infall duration.”



Evidence in A3827?



The image shows a screenshot of the BBC News website, overlaid on a background of a starry night sky. The website's navigation bar includes the BBC logo, a 'Sign in' button, and links for News, Sport, Weather, and Shop. Below this is a red banner with the word 'NEWS' in white. A secondary navigation bar lists various sections: Home, Video, World, UK, Business, Tech, Science, Magazine, and Entertainment. The 'Science & Environment' section is highlighted with a red underline. The main headline reads 'Dark matter becomes less 'ghostly'', attributed to Paul Rincon, Science editor at BBC News. The article is dated 15 April 2015 and is categorized under 'Science & Environment'. To the left of the main article, a partial view of another article titled 'Dark matter is real: dark: Scientists' is visible, along with social media sharing icons for Facebook, Twitter, and Google+. To the right, a portion of a German newspaper, 'DIE WELT', is visible, featuring a headline about dark matter in German: 'Die volle Kraft der... Wissenschaft: Niemand weiß, woraus die... haben Forscher eine spektakuläre... erhellt.' and a photo of a man, identified as Norbert Lossau, Ressortleiter Wissenschaft.

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Science & Environment

Dark matter becomes less 'ghostly'

By Paul Rincon
Science editor, BBC News website

15 April 2015 | Science & Environment

Speaking of Science
Dark matter is real: dark: Scientists

By Rachel Feltman April 14

DIE WELT
Wissen Panorama Feuilleton ICON Reise PS WELT Regional
Die volle Kraft der...
Wissenschaft: Niemand weiß, woraus die...
haben Forscher eine spektakuläre...
s erhellt.
Von Norbert Lossau
Ressortleiter Wissenschaft

Evidence in A3827?

The quoted self-interaction cross section is several orders of magnitude smaller than any existing bound in the literature, 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:

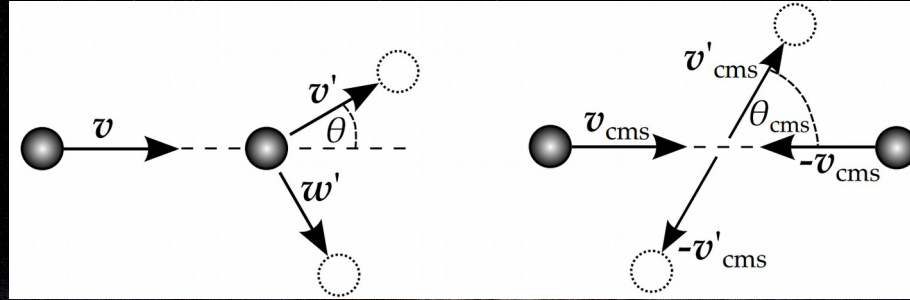
1. A3827 is strongly lensed, allowing for a much more precise measurement of the separation
2. The subhalo under consideration has been falling towards the centre of A3827 for a very long time ($1e8 - 1e9$ years), so self-interactions have had plenty of time to affect the trajectory of the subhalo (assuming the separation grows proportional to the infall time squared).

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.
 - This neglects the crucial fact that initially the stars are gravitationally bound to the DM subhalo and can only be separated from it 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 both on the velocity of the subhalo and the background DM density, both of which will vary along the trajectory of the subhalo.

The particle physics picture



The momentum transfer in a collision of two DM particles is completely fixed by the scattering angle. Averaging over many DM particles, the effective momentum transfer is given by

$$\sigma_T = 4\pi \int_0^1 d \cos \theta_{\text{cms}} (1 - \cos \theta_{\text{cms}}) \frac{d\sigma}{d\Omega_{\text{cms}}}$$

This is the quantity typically studied

However, this is not all that matters...

Can be obtained with **rare scatters and large momentum transfer** (e.g. isotropic scattering) or **frequent scatters with small momentum transfer** (e.g. long range interactions)

Assume frequent interactions

Frequent DM self-interactions imply many scatters for all particles and therefore lead to a deceleration of the overall DM halo.

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

$$\frac{F_{\text{drag}}}{m_{\text{DM}}} = \frac{\tilde{\sigma}}{4 m_{\text{DM}}} \rho v_0^{2m} \leftarrow \begin{cases} m = -1 & \text{for long-range interactions} \\ m = 1 & \text{for velocity-independent interactions} \end{cases}$$

Long range interactions which would give a sizable effect at $v \sim 1000$ km/s are strongly constrained by low-velocity systems (one could imagine a cutoff due to finite mediator mass though...)

Back-of-the envelope estimate

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

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

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

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

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

$$\frac{\tilde{\sigma}}{m_{\text{DM}}} \gtrsim 2 \text{ cm}^2 \text{ g}^{-1}$$

Refining the estimate

Realistic density profiles for the subhalo and the central cluster

Realistic trajectory for the infalling subhalo

Including these refinements requires a full three-dimensional simulation. Such a simulation was developed to study major mergers like the Bullet Cluster.

[arXiv:1308.3419](https://arxiv.org/abs/1308.3419)

We treat the gravitational potential of the cluster as time-independent, while for the subhalo 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 subhalo.

Expectations for frequent interactions

In the presence of a drag force, a DM subhalo falling into a galaxy cluster will retain its shape, since the drag force affects all DM particles equally.

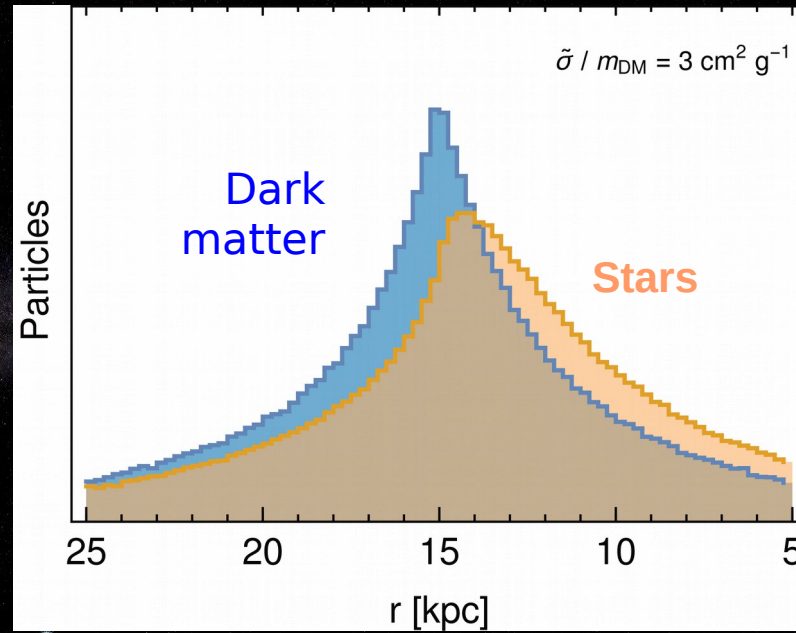
In the decelerating frame of the DM subhalo, stars will experience a fictitious accelerating force.

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

Moreover, some stars 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.

Results



As expected, the peaks of the two distributions are slightly shifted. The dark matter halo retains its form. However 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 subhalo.

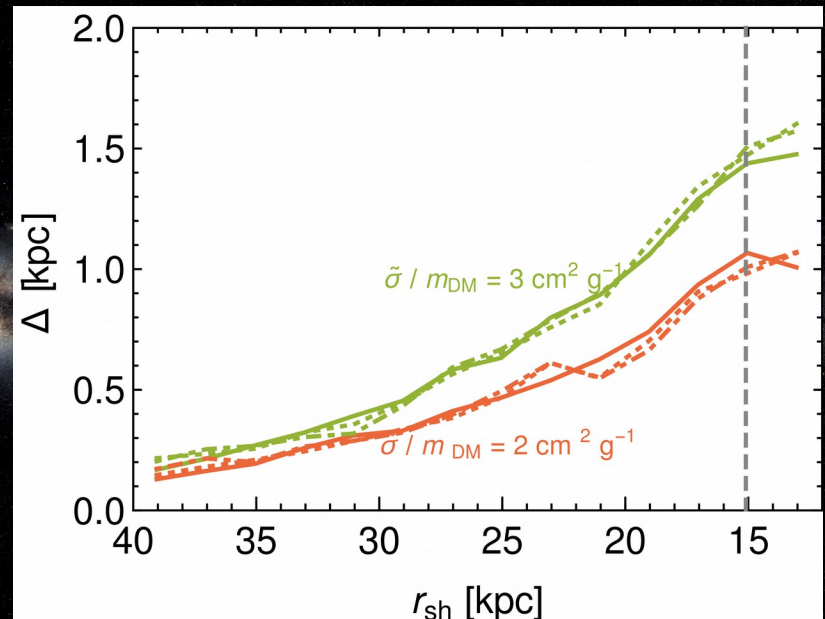
What is the observable separation?

There are some subtleties as to how to define the centroids

It is not sensible to just calculate the subhalo position including all initially bound particles, because particles that have escaped would strongly bias the centroid position.

It is also not sensible to just determine the peak position, which (for the DM distribution) cannot be obtained observationally.

For a realistic estimate we include only particles within the iso-density contour containing 20% of the total mass of the DM subhalo (corresponding roughly to the inner 4 kpc) and some alternatives



The cross section required to obtain a separation of 1.5 kpc is about

$$\sigma / m_{\chi} \sim 3 \text{ cm}^2 / \text{g}.$$

Rare self interactions

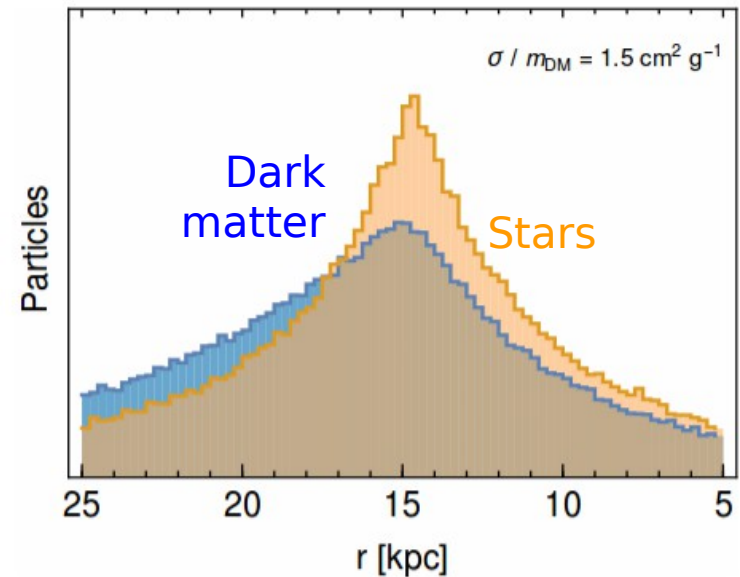
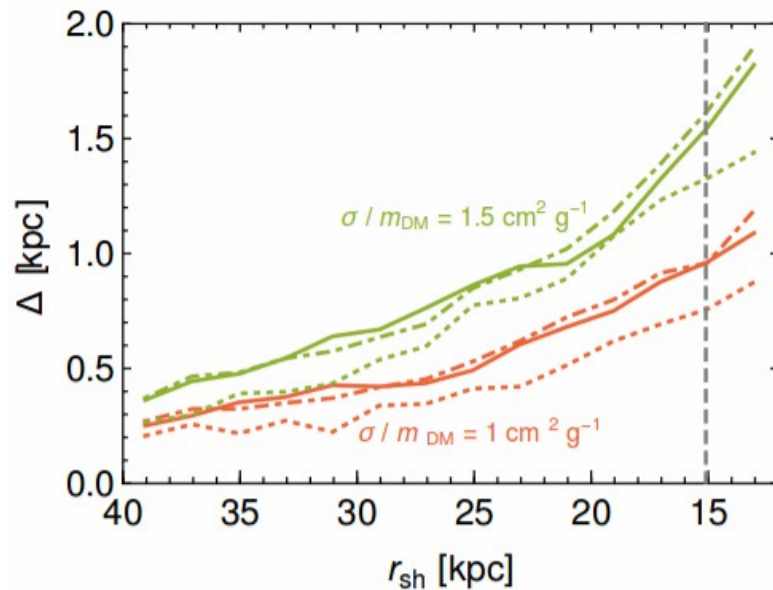
Rare self-interactions mean that for a typical DM particle the probability for multiple scattering is negligible.

- A significant fraction of DM particles will not experience any scattering at all and therefore behave just like (equally collisionless) stars.

On the other hand, whenever a DM scatters, it will often receive such a high momentum transfer, that it escapes from the subhalo.

A separation between the DM subhalo and stars can also occur in this case, but the separation is due to DM particles leaving the subhalo in the backward direction or being kicked into very elliptical orbits.

Rare self interactions



The cross section required to obtain a separation of 1.5 kpc is about $\sigma/m_\chi \sim 1.5 \text{ cm}^2/\text{g}$.

Note that the separation is mainly due to differences in the shapes of the two respective distributions, while the peaks of the distributions remain coincident.

What type of SIDM?

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 subhalo and the relative position of the peaks of the two distributions.

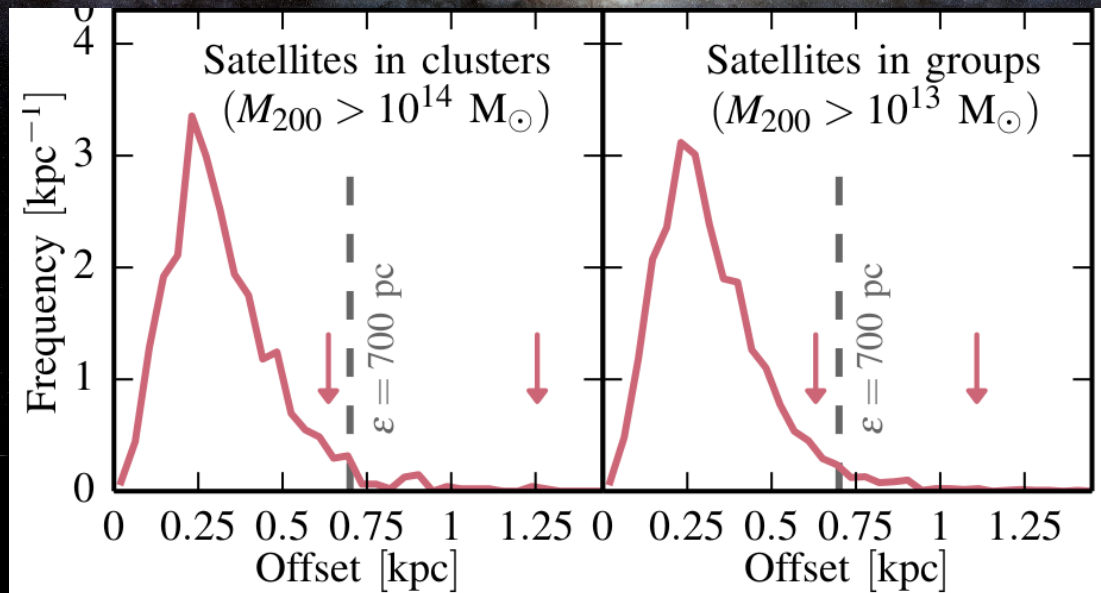
Contact interactions: the DM subhalo is expected to be deformed due to the scattered DM particles leaving the subhalo in the backward direction, such that the position of the centroid depends sensitively on the centroid definition.

Effective drag force: we expect the DM subhalo to retain its shape, while the distribution of stars will be both shifted and deformed.

Have we really seen DM self interactions

To answer this need to know how likely other astrophysical explanations are

Very recent hydrodynamical cosmological simulations to measure offsets between the centres of stellar and dark matter components of galaxies.



1505.05470

Offset > 1.5 kpc in less than 99.8%

The remaining 0.2% had recent mergers with other satellites

Conclusions

- Self interacting dark matter could solve some problems of the collisionless cold dark matter paradigm and can arise naturally in more complex dark sectors
- Orthogonal handle on properties of DM: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.
- Subhalos falling into galaxy clusters are a novel and interesting probe of DM self-interactions.
- Both effective drag forces (from frequent self-interactions) and rare self-interactions can lead to a separation between the DM subhalo and the stars.
- An explanation of the separation observed in A3827 requires DM self-interactions of $\sigma/m_\chi > 1 \text{ cm}^2/\text{g}$.
- Consequently, this interpretation is highly testable (if not already excluded) using other galaxy clusters.
- If true, WIMPs, axions, etc are excluded as DM candidates

A horizontal view of the Milky Way galaxy, showing a dense band of stars and dust stretching across the center of the frame. The background is a deep black space filled with numerous small, distant stars.

Thank you!