Evidence for self-interacting dark matter from Abell 3827

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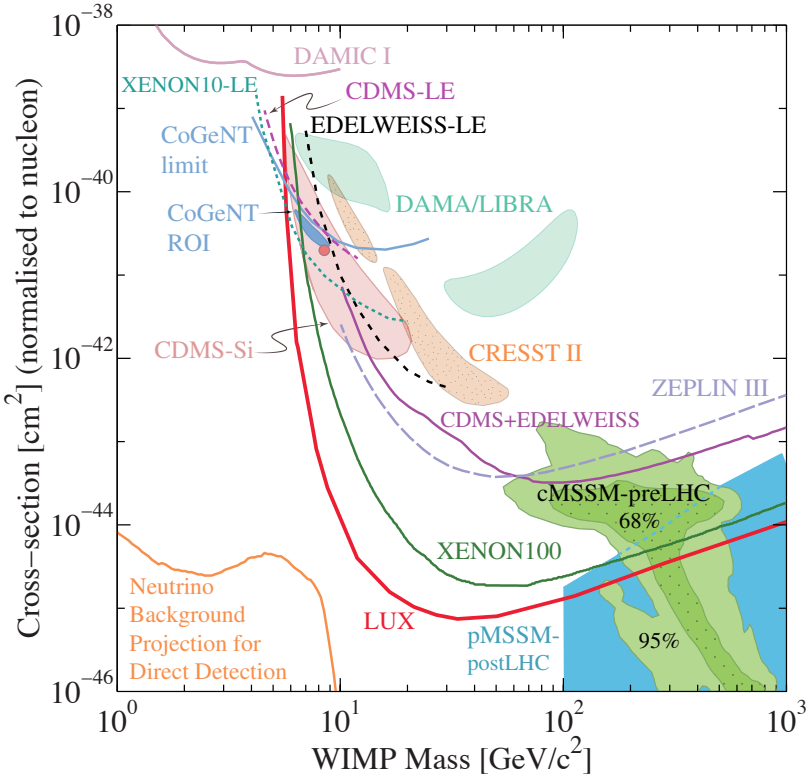
VIA lecture

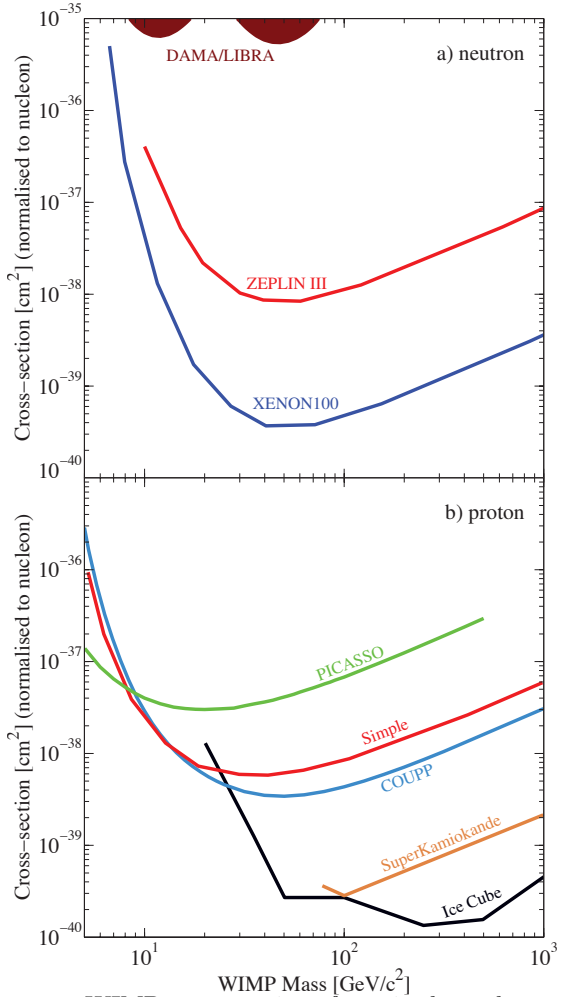
September 18, 2015

Dark matter properties??

Interactions through gravity.
No convincing evidence so far of DM interaction with nuclei, or DM annihilation.



spin-independent interactions with nuclei

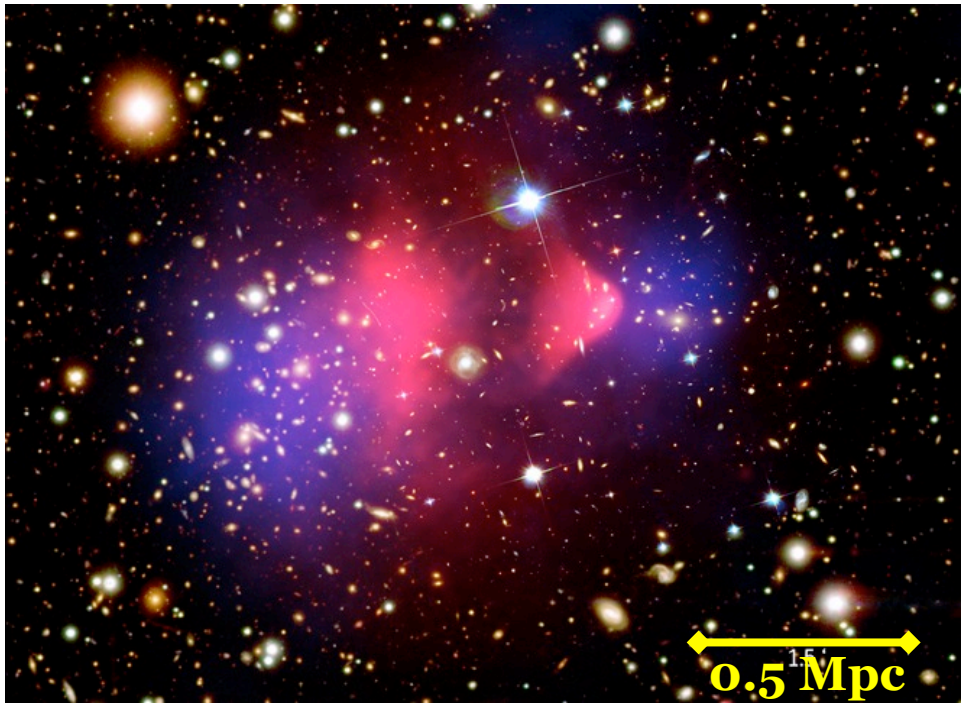


spin-dependent interactions

Review of Particle Physics
Particle Data Group
Olive+2014

Astrophysics may help: The Bullet Cluster

***Upper limit* on self-interaction:**



DM projected density detected using *weak lensing* (blue)

X-ray emitting hot gas (pink)

Offset between DM & galaxies is consistent with zero:

$$\sigma / m \leq 1.25 \quad \mathrm{cm}^2/\mathrm{g}$$

M/L of main cluster and subcluster are the same → scattering of DM negligible:

$$\sigma / m \leq 0.7 \quad \mathrm{cm}^2/\mathrm{g}$$

Need a better version of the Bullet Cluster and/or more examples of similar clusters

Clowe+2006

Outline

Part I

Detection of stars-DM offset (LLRW & Saha 2011; Massey, LLRW+2015)

interpretation? 1. gravitational effects, like dynamical friction
2. non-gravitational effects: DM self-scattering

Part II

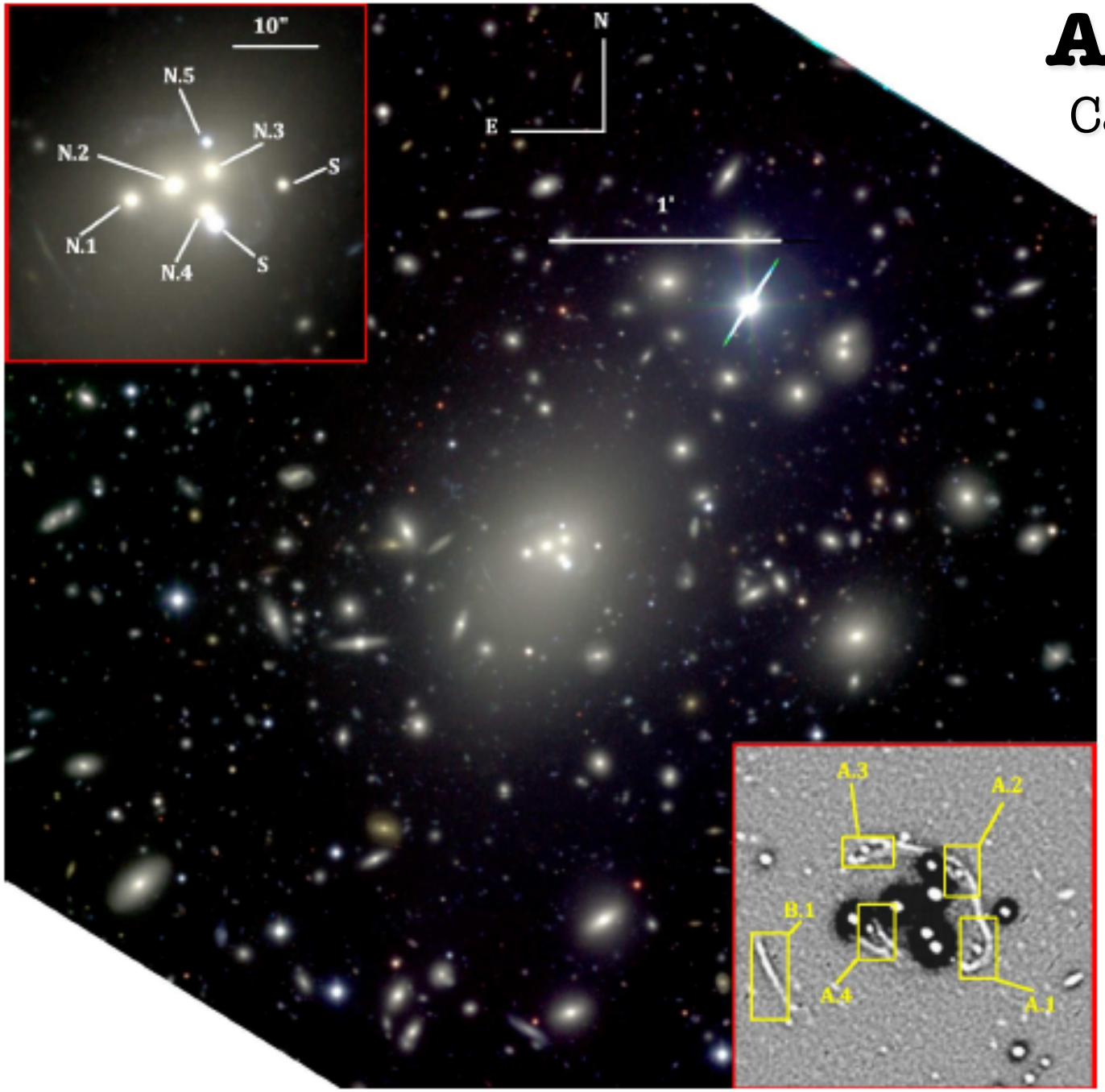
Self-interacting dark matter – invoked in astrophysics for 15 years because it can potentially solve CDM's small scale problems (missing satellites, core/cusp)

Part I

detection of an offset between galaxy' stars and nearest center of mass and possible interpretations

Abell 3827

Carrasco+ 2010



Cluster of galaxies—
end stage of a merger

4 massive elliptical
galaxies near
cluster center

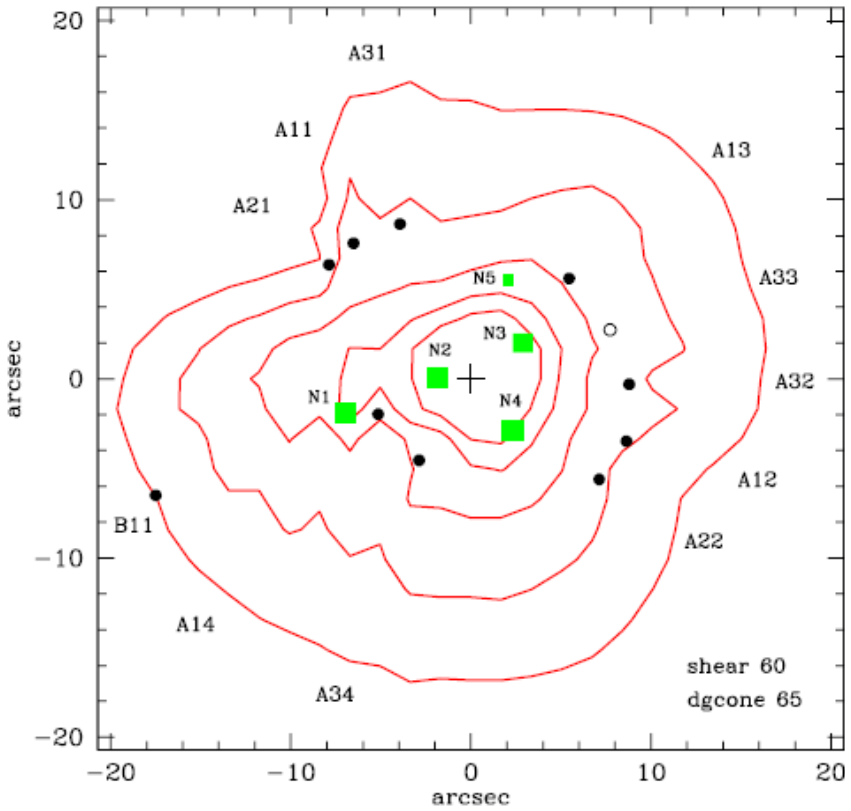
z of cluster = 0.1

1" → 1.9 kpc

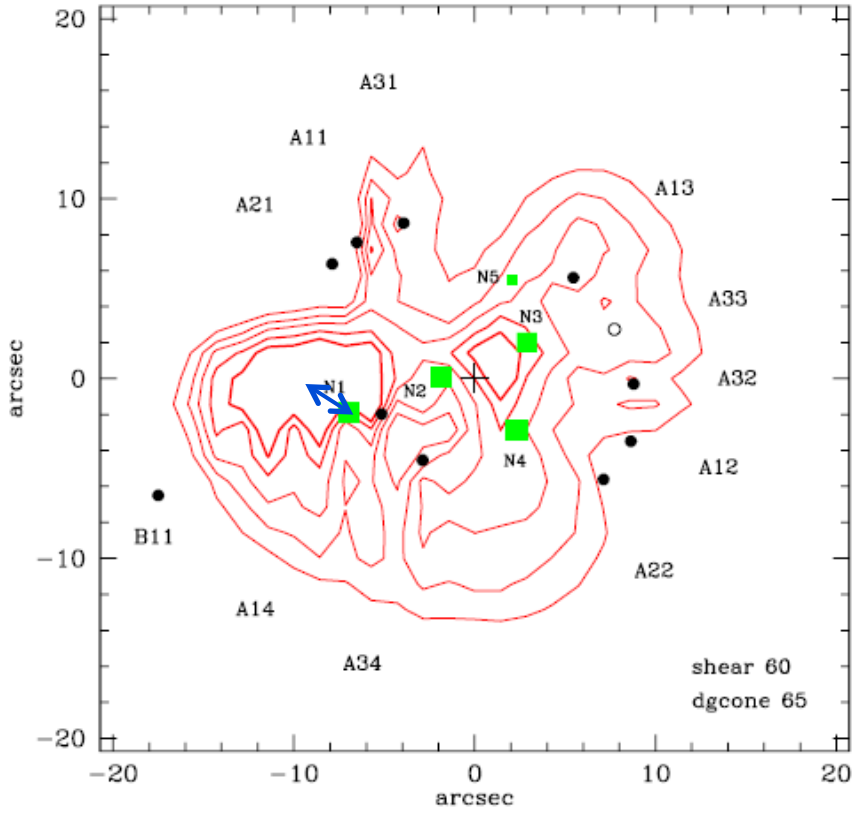
Mass reconstruction

Ground-based data
Free-form lensing inversion

Mass isodensity contours



Residuals after subtracting circularly symmetric power law density profile

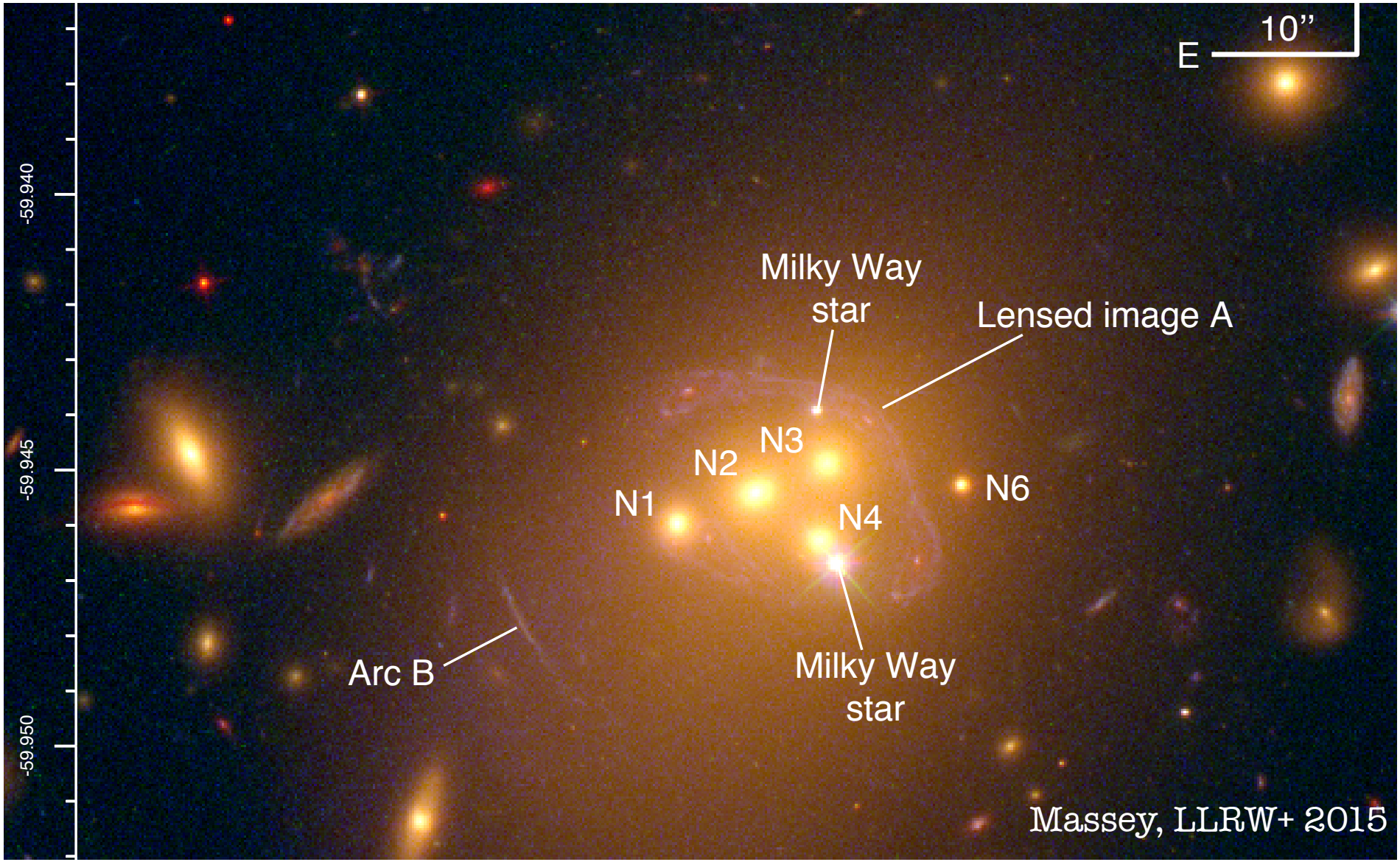


Mass-light offset 6 kpc
Clump mass $10^{11} M_{sun}$

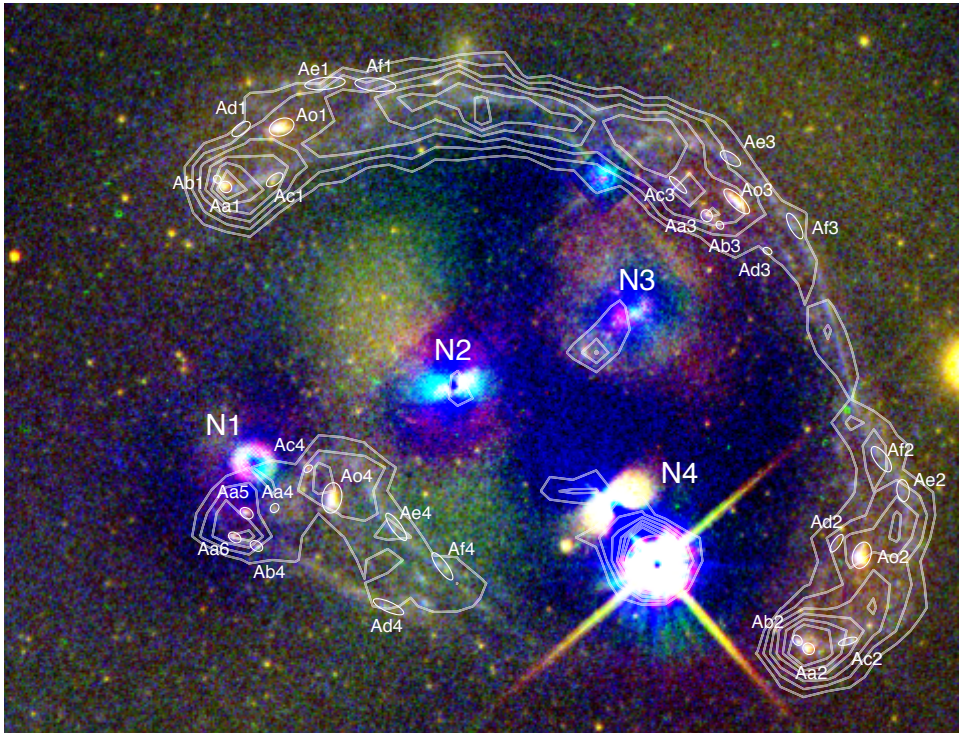
LLRW+Saha 2011

Abell 3827 with HST

1” → 1.9 kpc



Abell 3827 spectroscopy



Four old elliptical galaxies
Large stellar masses

Imaging & spectroscopy:
and still image identification
for a few images is
not completely certain

F814W (red), F606W (green) and F336W (blue)
line emission at 835.5 nm from *VLT / MUSE* integral field spectroscopy.

	RA	Dec	z	F814W band mag	F814W band M^* [$M_\odot$]	F606W band mag	F606W band M^* [$M_\odot$]	Hα flux [erg/s/cm^2]	SFR [$M_\odot$/yr]	σ_v^* [km/s]
N.1	330.47518	−59.945997	0.09891±0.00032	16.86	1.04×10^{11}	17.52	1.00×10^{11}	$< 6.04\times10^{-16}$	< 0.14	332
N.2	330.47233	−59.945439	0.09928±0.00017	15.74*	2.92×10^{11}	16.55	2.46×10^{11}	$< 2.59\times10^{-16}$	< 0.06	377
N.3	330.46978	−59.944903	0.09973±0.00016	15.69*	3.06×10^{11}	16.42*	2.77×10^{11}	$< 6.31\times10^{-16}$	< 0.14	326
N.4	330.46999	−59.946322	0.09636±0.00026	16.18	1.94×10^{11}	16.73	2.08×10^{11}	$< 1.57\times10^{-15}$	< 0.26	192

Mass recovery – Grale & Lenstool

Grale

Author: Jori Liesenborgs
Free-form, adaptive grid
Large parameter space: 100's - 1000's
is searched using a genetic algorithm
Input: image positions and shapes

Systematic errors in mass maps come from considering a range of methods

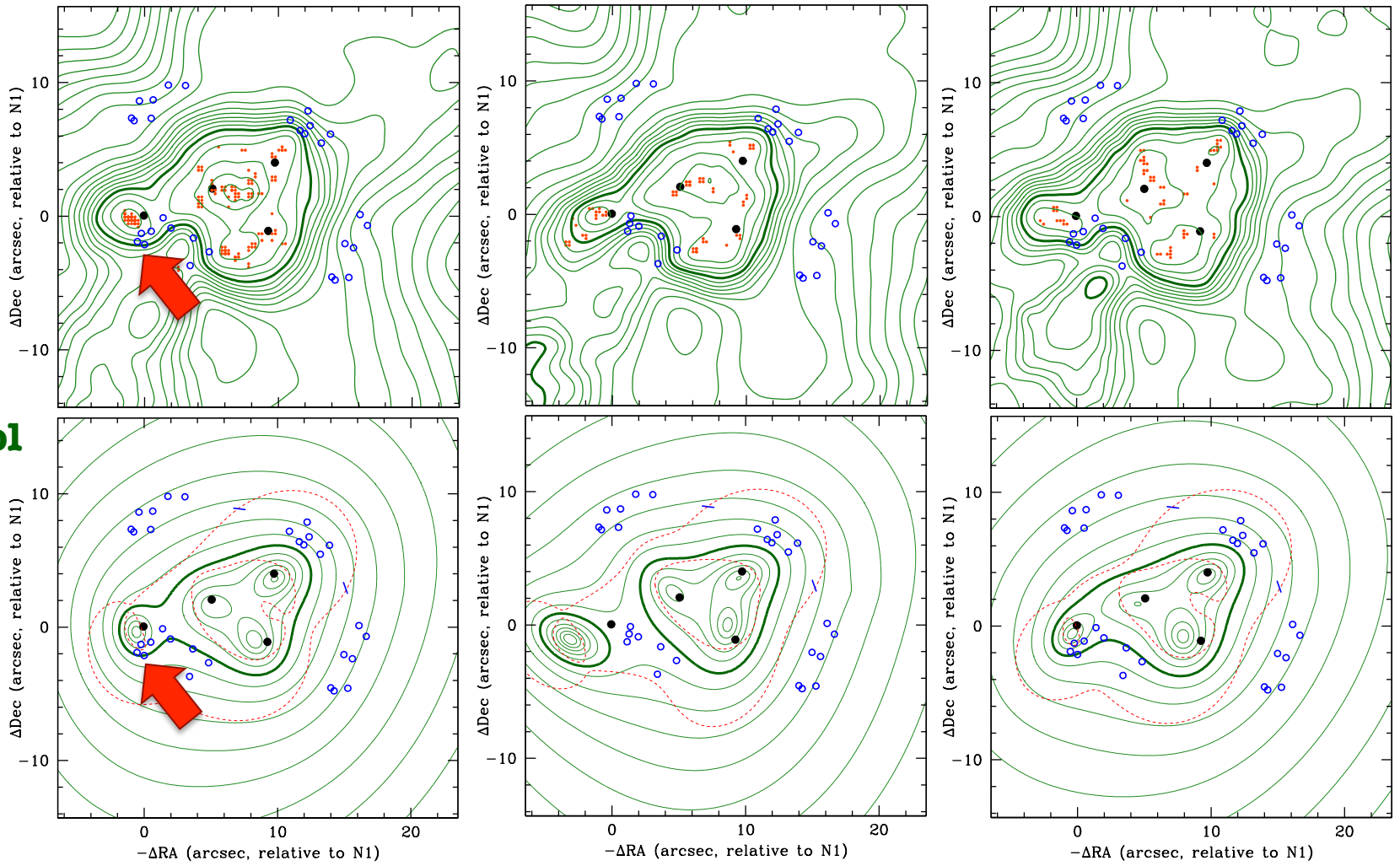
Lenstool

Authors: Jean-Paul Kneib and Eric Jullo
Parametric; mass distribution described by a handful of params
Usually, galaxies' mass center is fixed at the observed light center
Smooth isodensity contour are the result of strong priors
Input: image positions, shapes,
locations and luminosities of lensing galaxies

Mass recovery – Grale & Lenstool

Grale

Lenstool



Mass-light offset of the best constrained galaxy: $1.62^{+0.47}_{-0.49}$ kpc

Why the observed image distribution implies light/mass offset – an intuition-building simple model

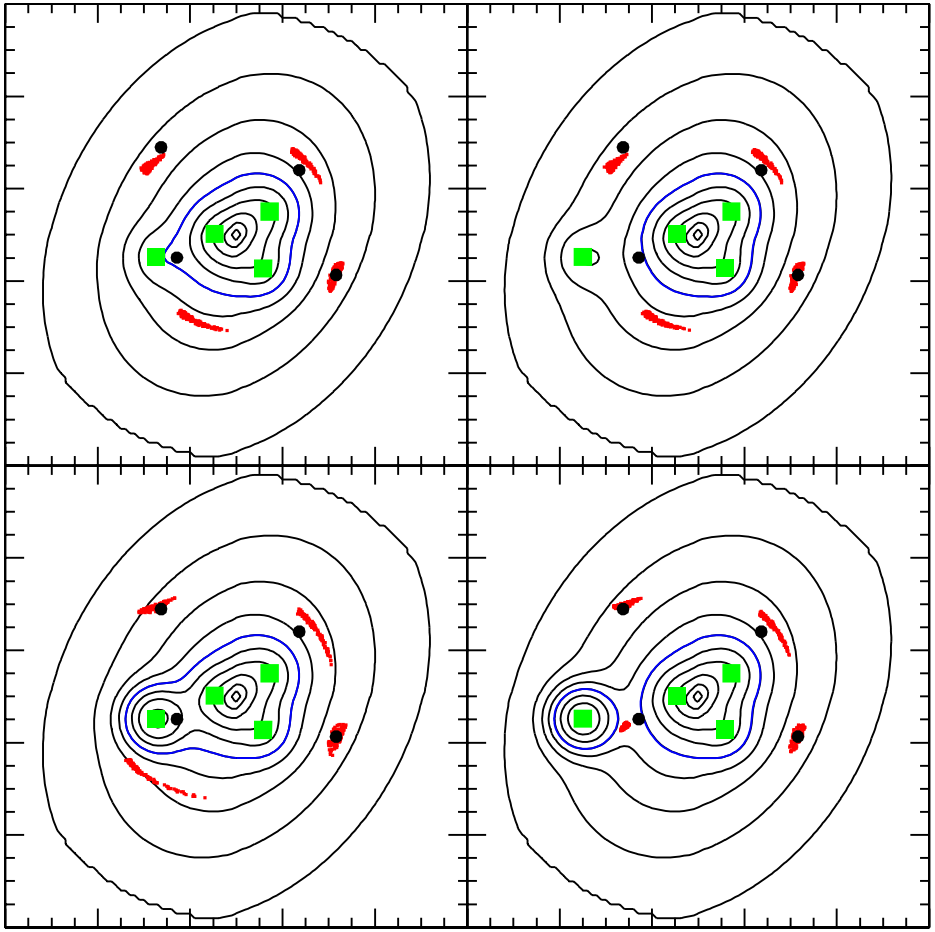
mass isodensity contours

4 synthetic clusters

Black dots:
observed images

Red dots:
images generated by the synthetic cluster

Green squares:
mass clumps



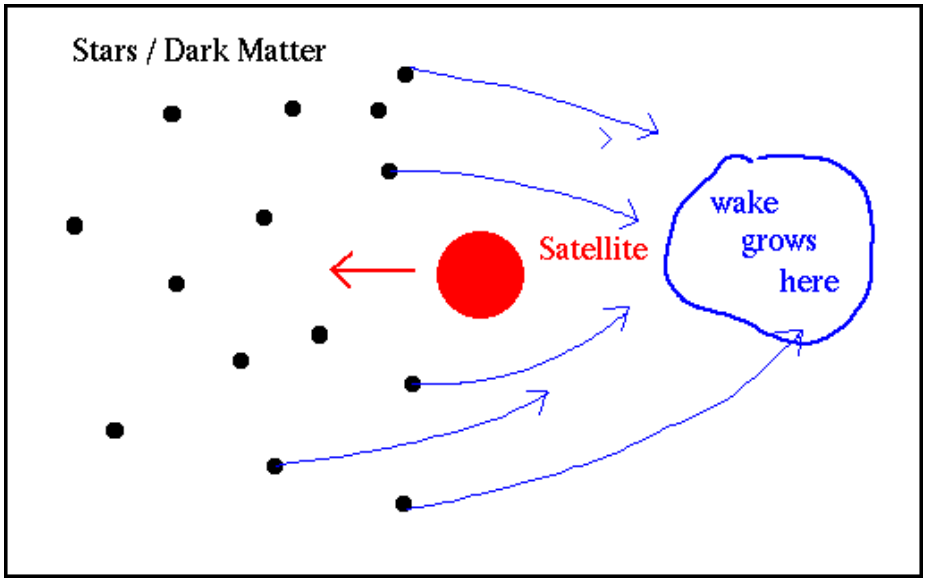
Only cluster #4 reproduces all observed images

Conclusion:
mass clump needs to be massive, and displaced from the nearest galaxy

LLRW+Saha 2011

Possible explanations

① Unrelated line of sight mass clump – no associated light; low prob. ✗
② Gas associated with the galaxy – no excess X-ray emission ✗
③ DM tidal tails of the galaxy – tidal tails are symmetric → no offset ✗
④ **DM self-scattering cross-section– maybe**
⑤ **Dynamical friction – maybe**

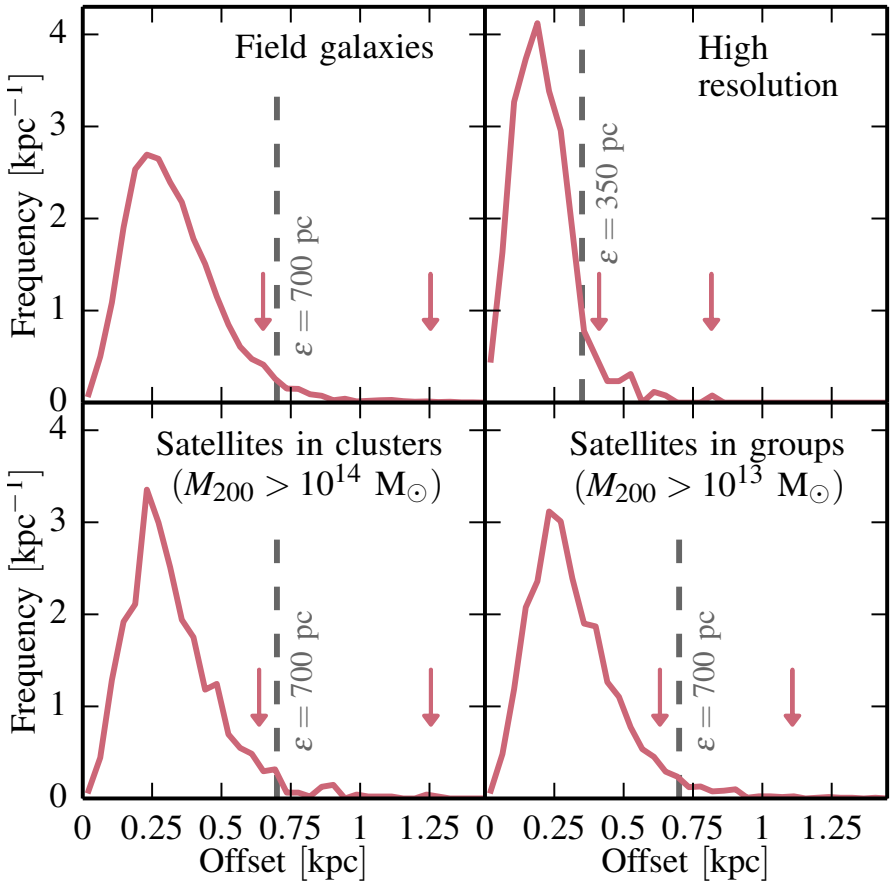


Dynamical friction is a Newtonian effect, so should be detected in simulations

Looking for offsets in simulations

EAGLE simulations: 1000's of galaxies with stellar mass $M_* > 10^9$ M$_\odot$

arrows indicate the position of the 95% and 99.7%



DM halo – stars offsets:
smaller in high resolution sims;
however offset does not go to zero:
for Milky Way mass galaxy
offset could be 0.3-0.4 kpc.

No offsets as large as observed in A3827 are found

Schaller+2015

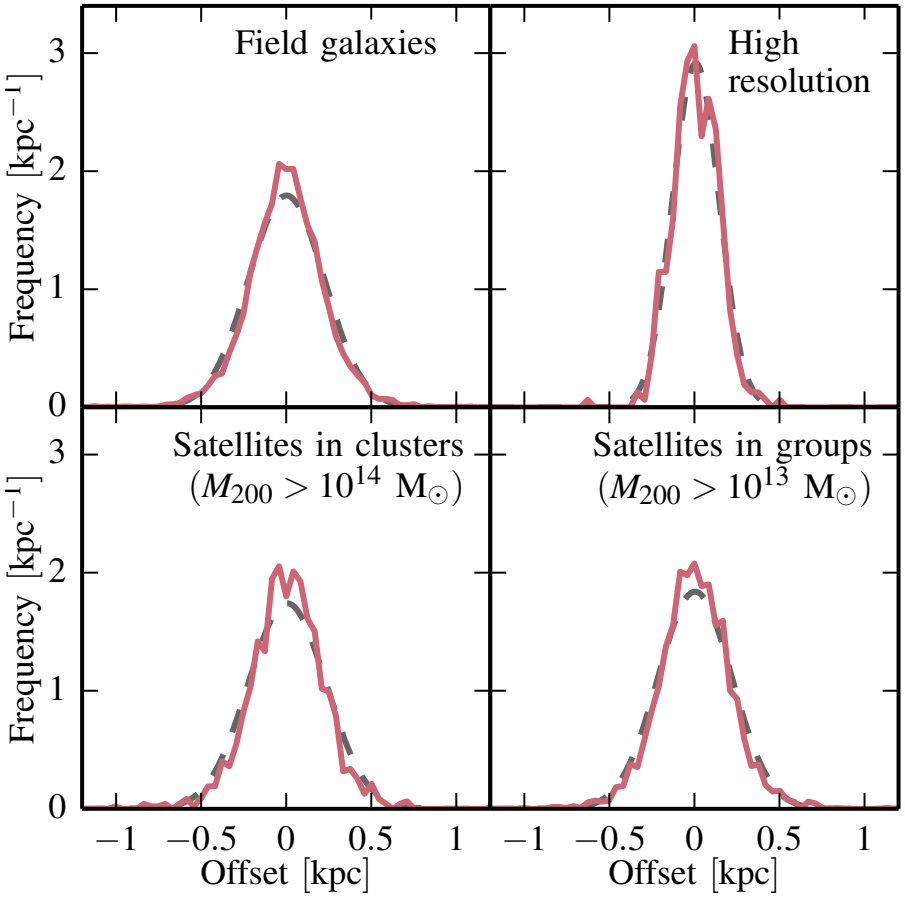
Simulations assume non-interacting cold DM

Looking for offsets in simulations

EAGLE simulations: 1000's of galaxies with stellar mass $M_* > 10^9$ M$_\odot$

Test of dynamical fraction:
Offset along the axis of motion of the stellar distribution?

No offsets as large as observed in A3827 are found



Schaller+2015

Simulations assume non-interacting cold DM

Interaction between a galaxy and the larger cluster

Suppose dark matter has some self-scattering cross-section

$$F_{dm} \sim \frac{GM_{co}M_{dm}}{r^2} \times \left[1 - \frac{M_{dm}\,\sigma/m}{\pi s^2}\right]$$

Stars are completely collisionless

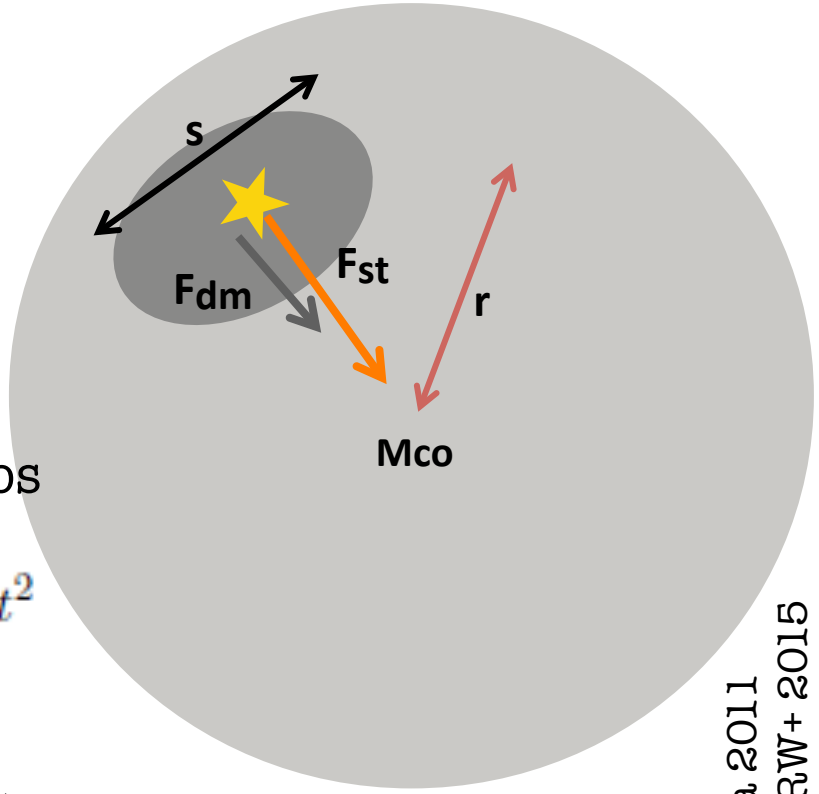
$$F_{st} \sim \frac{GM_{co}M_{st}}{r^2}$$

After time t, a separation between stars and DM halo of a galaxy develops

$$d \sim \left(\frac{F_{st}}{M_{st}} - \frac{F_{dm}}{M_{dm}}\right) t^2 = \frac{GM_{co}M_{dm}\,\sigma/m}{\pi r^2 s^2}\, t^2$$

DM self-interaction cross-section:

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



This analysis neglects the restoring force due to gravity between stars and DM halo

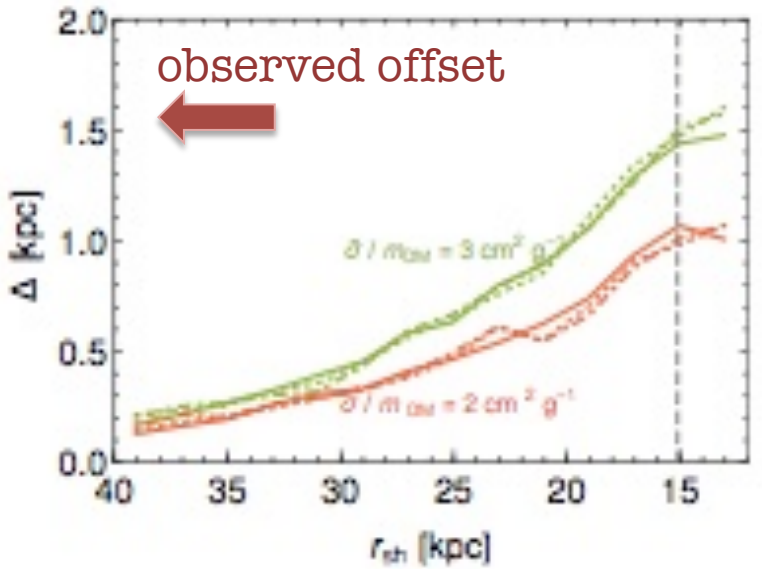
LLRW+Saha 2011
Massey, LLRW+ 2015

DM self-scattering cross-section implied by Abell 3827

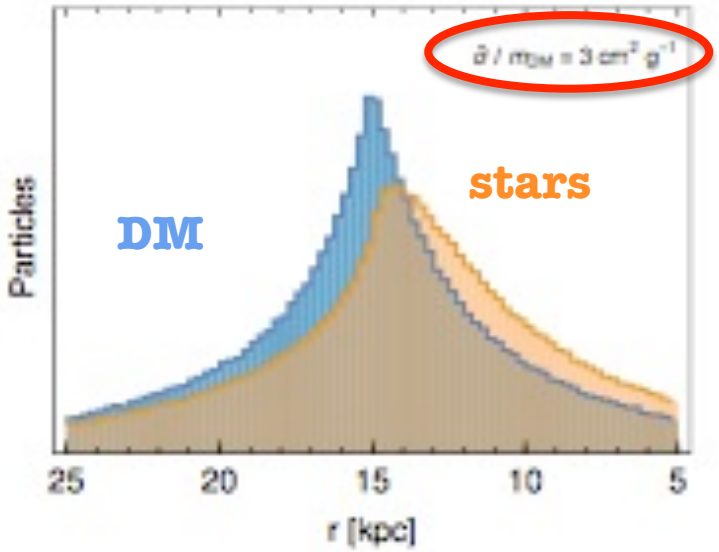
DM self-interaction vs. restoring force of gravity between DM halo and stars of the galaxy

If the interactions are numerous and weak, then DM particles of the galaxy experience a drag force; in effect, the stars of the galaxy move "ahead".

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



distance from cluster center



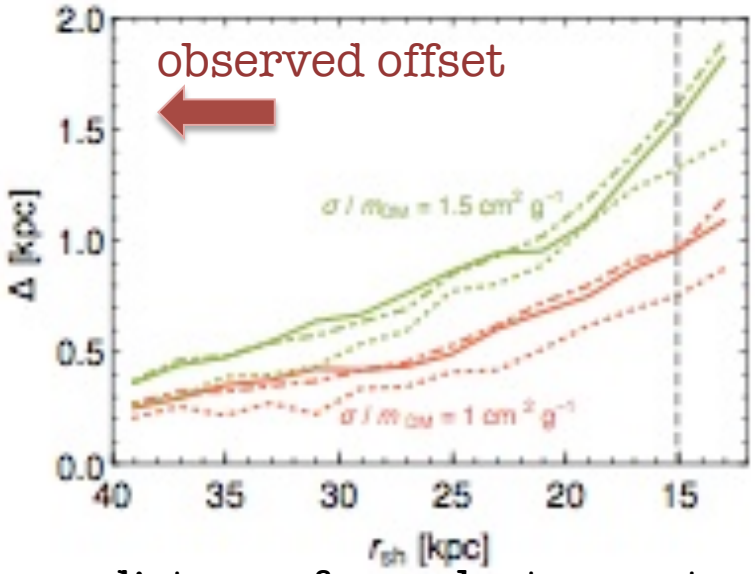
centroids of the star and DM distributions are offset

Kahlhoefer+2015

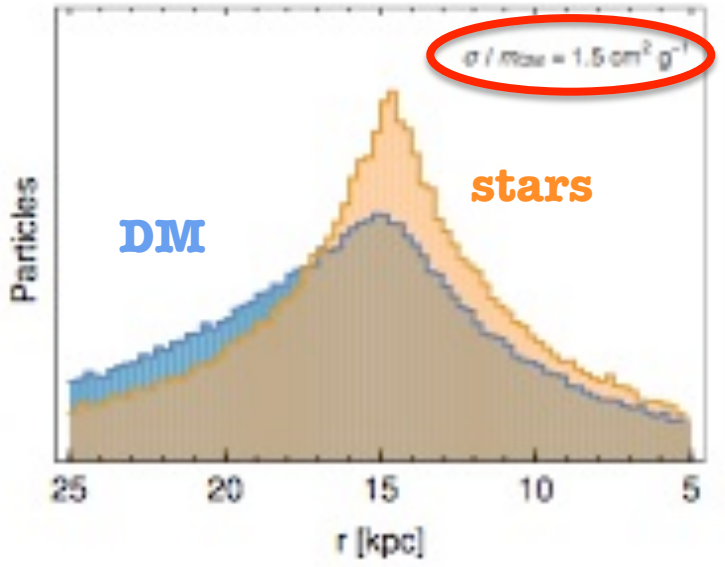
DM self-scattering cross-section implied by Abell 3827

DM self-interaction vs. restoring force of gravity between DM halo and stars of the galaxy

If DM particles experience rare contact interactions, then DM distribution of the galaxy develops a tail.



distance from cluster center



peaks of the star and DM distributions coincide

Kahlhoefer+2015

Part II

self-interacting dark matter

and how it could help explain observations on galaxy cluster and dwarf galaxy scales

Spergel & Stenhardt (2000) suggested that SIDM could solve the missing satellites problem identified in 1999.

How to simulate self-interacting DM?

CDM is simulated as a collisionless fluid.
SIDM is neither collisionless nor a fluid.

A given cross-section could imply
many weak scatterings → drag force (all/most particles remain bound)
few strong scatterings → evaporation (some particles become unbound)

Need to represent *microscopic* physics by *macroscopic* process in the code.

Introduce a collision term on the RHS of the Boltzmann equation
How to implement this differs between authors

For example, Burkert (2000):

$\sigma/m = 10 - 100\ \mathrm{cm}^2/\mathrm{g}$ produced flat cores in their simulated galaxies

Prob. of scattering in Δt,
$P = l/\lambda$
mean free path $\lambda = (\rho\sigma^*)^{-1}$
$l = v\Delta t$
(use energy, mom. conserv.)

Simulating self-scattering DM:

Rocha+ 2012

$$\frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} = \Gamma[f,\sigma]$$

Boltzmann equation with a scattering term

$$= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} |\mathbf{v}-\mathbf{v}_1| \left[f(\mathbf{x},\mathbf{v}',t) f(\mathbf{x},\mathbf{v}_1',t) - f(\mathbf{x},\mathbf{v},t) f(\mathbf{x},\mathbf{v}_1,t) \right]$$

after scattering — before scattering

Need to coarse grain (integrate above over small volume in phase space) and discretize this equation (convert from fluid to N-body particles)

$$\Gamma(i|j) = (\sigma/m) m_{\rm p} |\mathbf{v}_i - \mathbf{v}_j| g_{ji}$$

$$g_{ji} = \int_0^{h_{\rm si}} d^3\mathbf{x}' W(|\mathbf{x}'|, h_{\rm si}) W(|\delta\mathbf{x}_{ji} + \mathbf{x}'|, h_{\rm si})$$

comparable to inter-particle separation

If two N-body particles are close enough to interact (kernels W overlap)

- use Monte Carlo to find scattering direction;
- remove 2 particles from the pre-scatter locations in phase space
- introduce 2 particles into post-scatter locations in phase space

Simulating self-scattering DM:

Rocha+ 2012

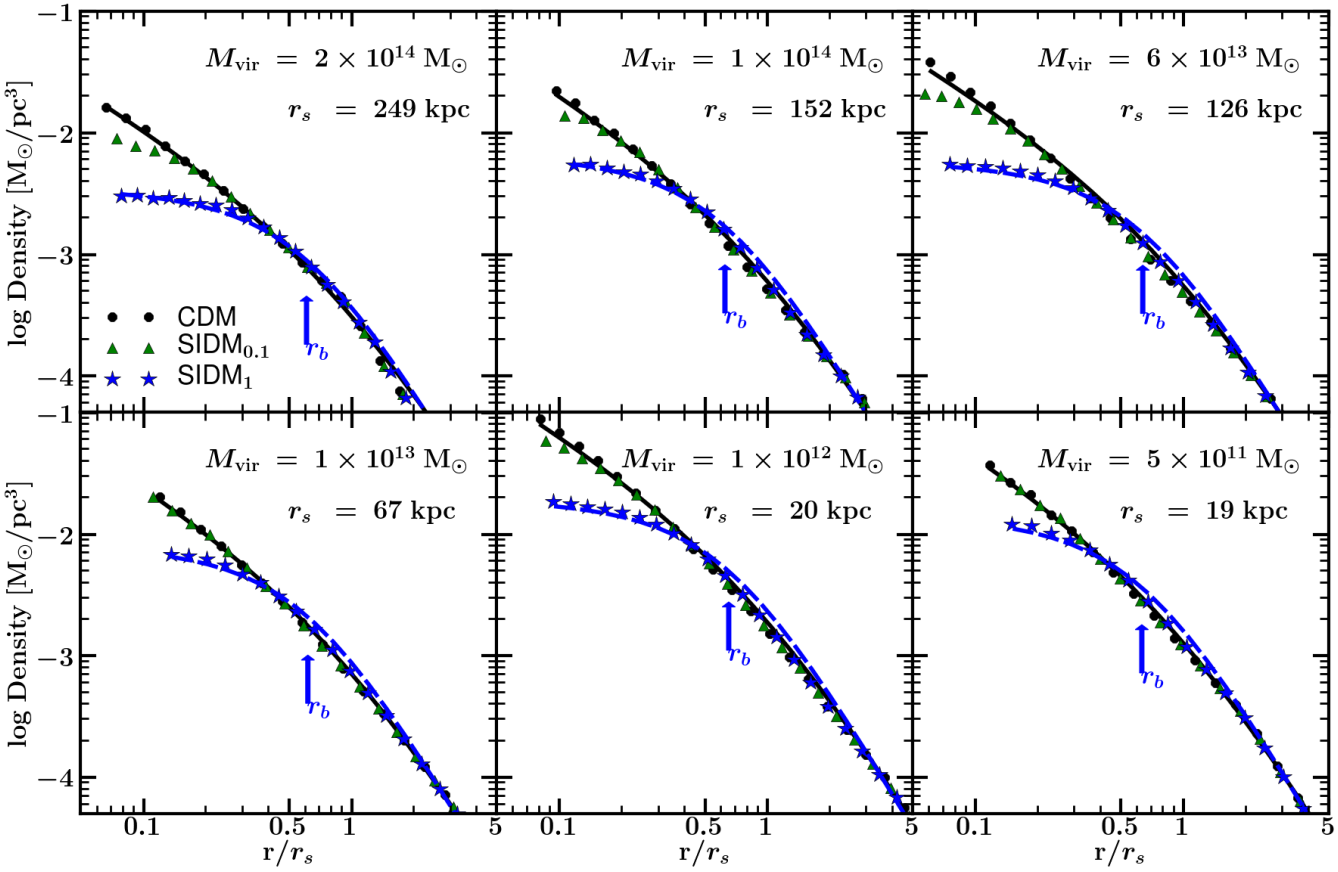
Density profiles: CDM vs. SIDM

— NFW profile

▲ $\sigma/m = 0.1\ \mathrm{cm}^2/\mathrm{g}$

★ $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

On large, cosmological scales, structure is same as in LCDM

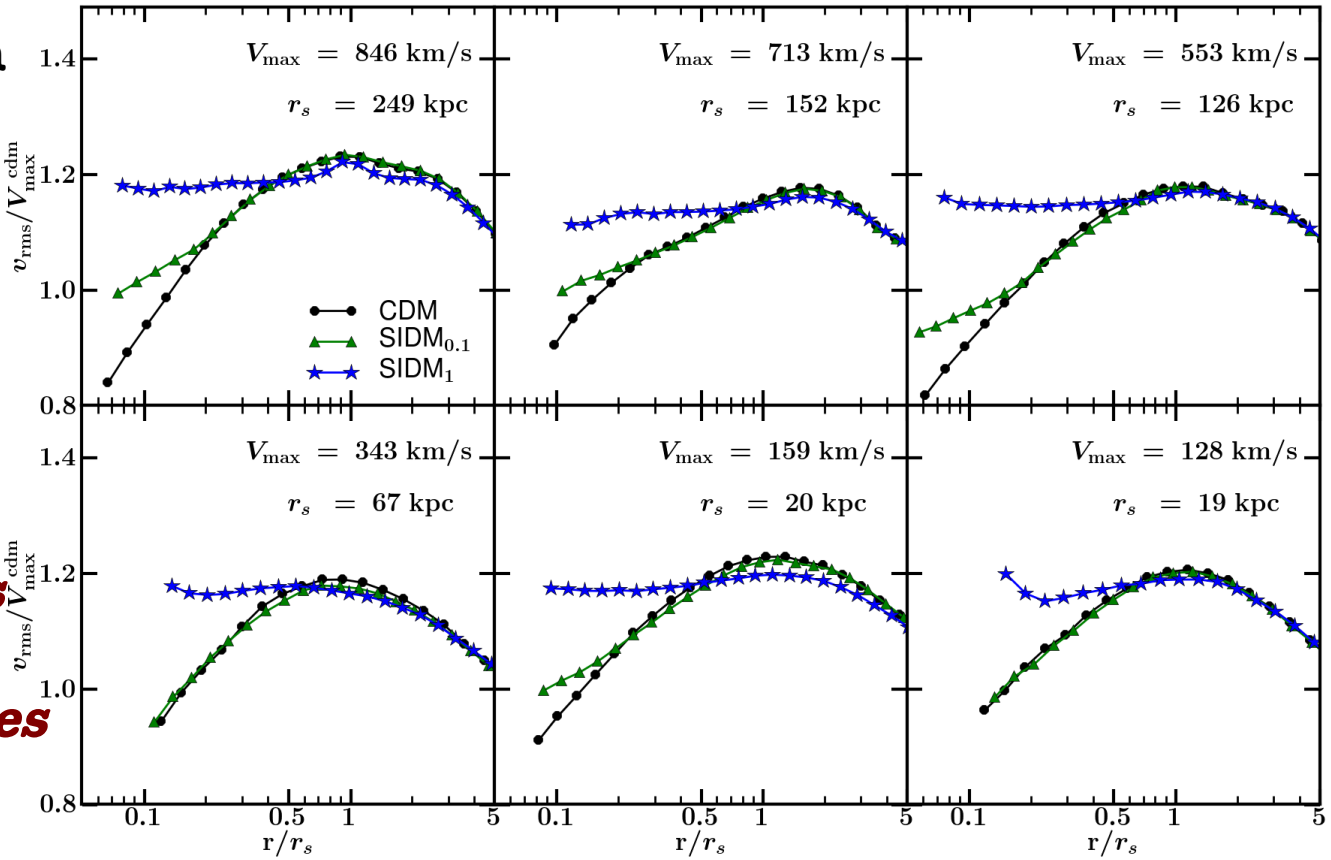


Flat density cores in dwarf galaxies are not resolved in their simulations; used scaling relations to extrapolate → cores consistent with observations

Simulating self-scattering DM:

Rocha+ 2012

Velocity dispersion profiles: CDM vs. SIDM



Core size of clusters and dwarfs are reproduced, but missing satellites count is unaffected

Central regions of CDM halos are cold (low velocity dispersion). Scattering transfers kinetic energy from outside to the central regions, and increased central velocity dispersion. From hydrostatic equilibrium eqn.

Reference guide to DM interaction cross-sections:

What we estimate from Abell 3827

$$\sigma/m \gtrsim 1.7 \pm 0.7 \times 10^{-4} \left(\frac{t_{\rm infall,yrs}}{10^9}\right)^{-2} \ {\rm cm}^2/{\rm g} \qquad \sigma \gtrsim 3.1 \times 10^{-26} \left(\frac{t_{\rm infall,yrs}}{10^9}\right)^{-2} \left(\frac{m}{100{\rm GeV}}\right) \ {\rm cm}^2$$

A more realistic estimate from Abell 3827

$$\sigma/m \gtrsim 2 \ {\rm cm}^2/{\rm g}$$ **lower limit** $$\sigma \gtrsim 3.62 \times 10^{-22} \left(\frac{m}{100{\rm GeV}}\right) \ {\rm cm}^2$$

From Bullet Cluster and similar

$$\sigma/m \lesssim 1 \ {\rm cm}^2/{\rm g}$$ **upper limit** $$\sigma \lesssim 1.82 \times 10^{-22} \left(\frac{m}{100{\rm GeV}}\right) \ {\rm cm}^2$$

Needed to solve core-cusp problem

$$\sigma/m \sim 0.1 - 10 \ {\rm cm}^2/{\rm g} \qquad \sigma \sim 0.182 - 18.2 \times 10^{-22} \left(\frac{m}{100{\rm GeV}}\right) \ {\rm cm}^2$$

Thermal annihilation estimate: $\sigma_{th.ann.}$ $10^{-33} \left(\frac{\langle v \rangle}{300{\rm km/s}}\right)^{-1} \left(\frac{\Omega_{DM} h^2}{0.1}\right)^{-1} \ {\rm cm}^2$

e.g., Modak 2015

Summary

Abell 3827: an interesting and (so far) unique case:
4 elliptical galaxies tightly packed in the cluster core,
& a well aligned background source → multiple images.

an offset between galaxy's stars and its DM halo: $1.62^{+0.47}_{-0.49}$ kpc

Interpretations:

Could be due to Newtonian effects, like dynamical friction.
A preliminary study of simulations with std DM do not see such offsets.

If offset is due to DM self-interaction, then, unlike Bullet Cluster,
A3827 is a detection, with implied cross section $\sigma/m \gtrsim 2\ \mathrm{cm}^2/\mathrm{g}$
similar to, or in mild conflict with the upper limit from Bullet Cluster;
both are considerably higher than expected from a thermal relic.

Prospects for the future:
Bullet Cluster, Musket Ball, Abell 3827.... need more of these
Need better modeling of various SIDM scenarios in simulations