PUZZLES ON GALACTIC AND SUB-GALACTIC SCALES

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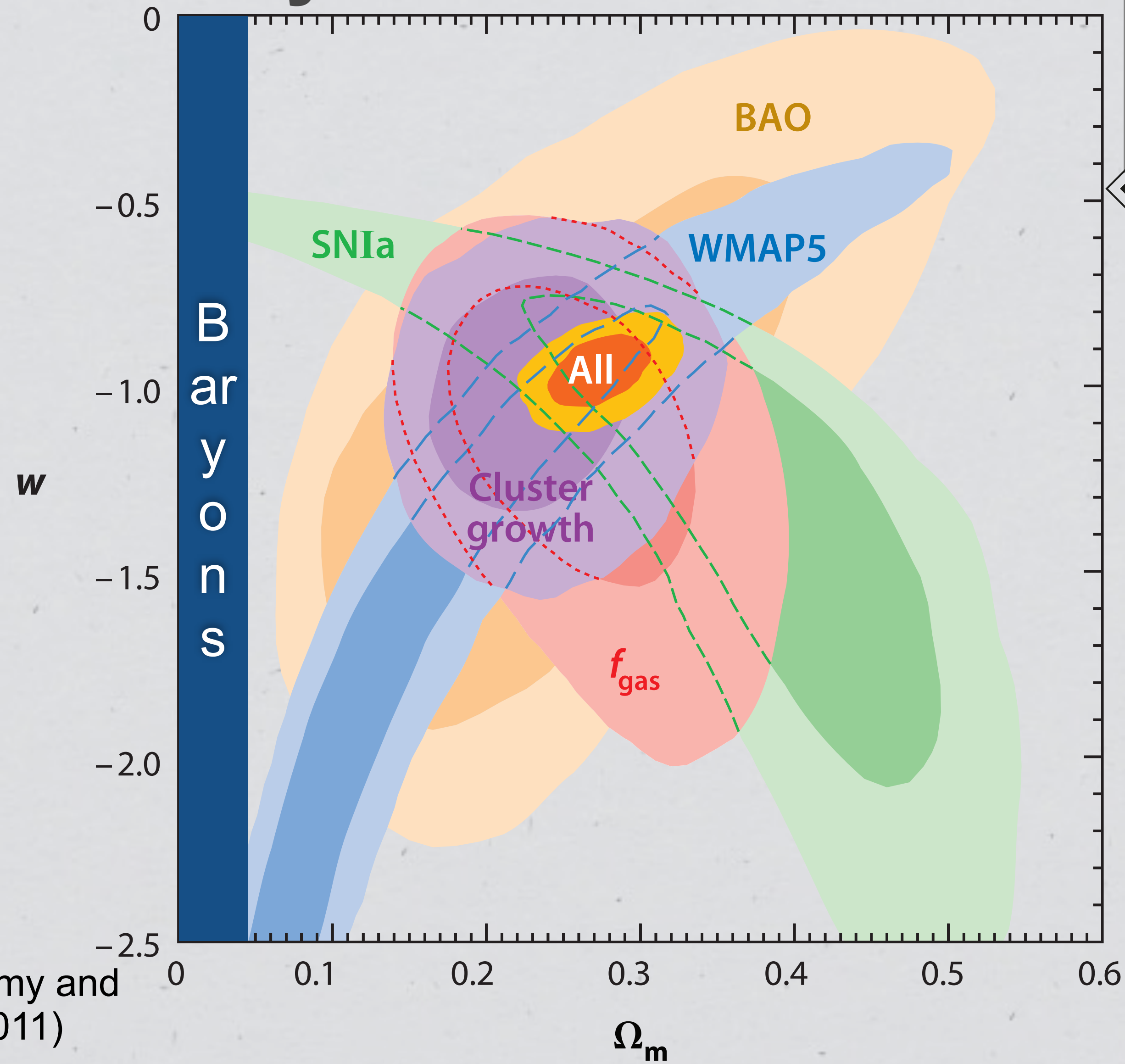
Dark matter has been **discovered** in multiple ways over the past 80 years through its gravitational influence.

It exists in the **smallest galaxies**, the **largest clusters of galaxies** and in all the structure seen out to the edges of the **observable universe**.

Cosmological density of the dark matter

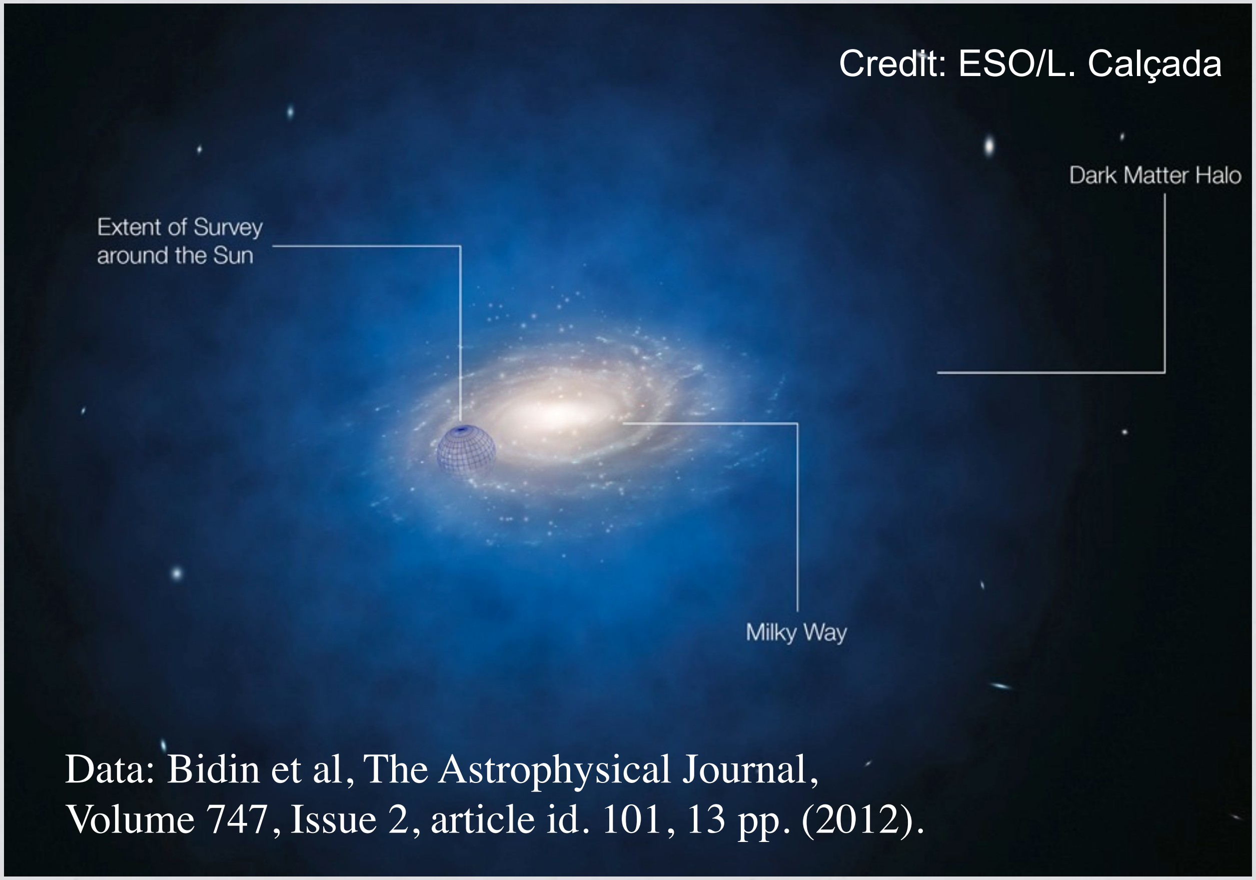
Different measures agree on a total matter density that is about 30% of the critical density of the Universe ~ 6 times the density in baryons.



Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

Local dark matter density

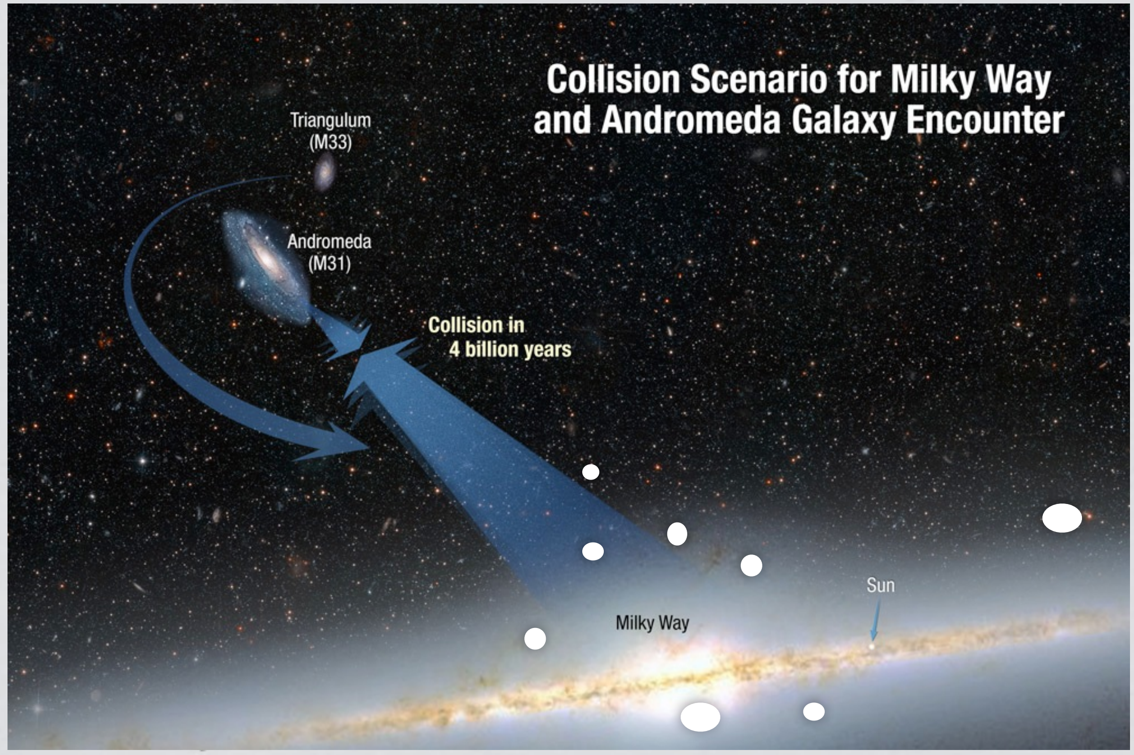


Motion of stars out of the plane of the disk to estimate the *total amount of matter* [Oort 1932]. Most recent estimate gets local dark matter density 0.3+/- 0.1 GeV/cc.

Bovy and Tremaine, ApJ 756, 89 (2012)

Dark matter in our galaxy

Relative motion of Andromeda and Milky Way gives their total mass [Kahn and Woltjer (1959)].



Credit: NASA; ESA; A. Feild and R. van der Marel, STScI

Recent measurements show sum of virial masses of Milky way and Andromeda is 3.2×10^{12} M_{sun} with 20% error. Stars and gas are roughly 10% of this mass.

Van der Marel et al, ApJ 753, 8 (2012)

Dark matter in satellite galaxies

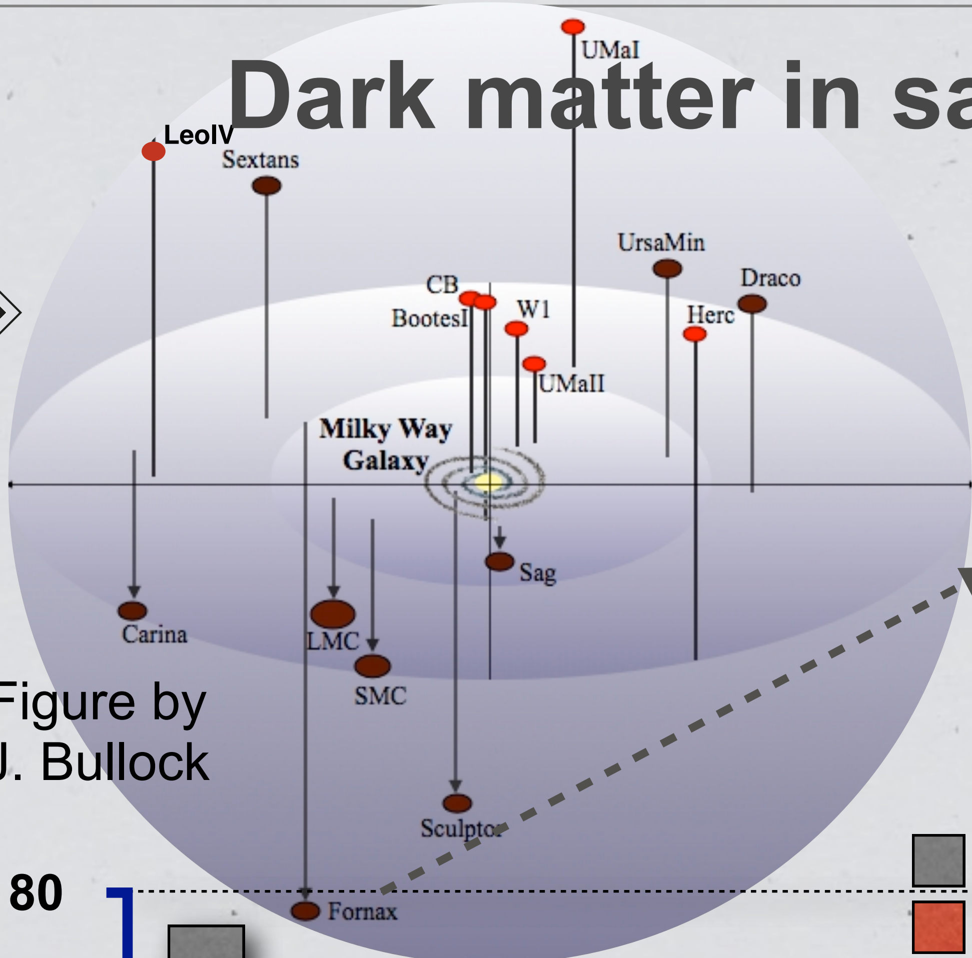
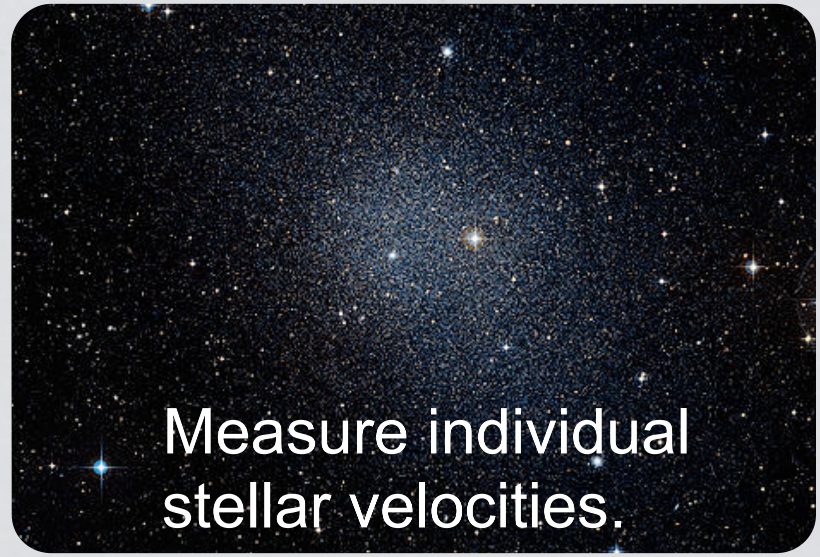
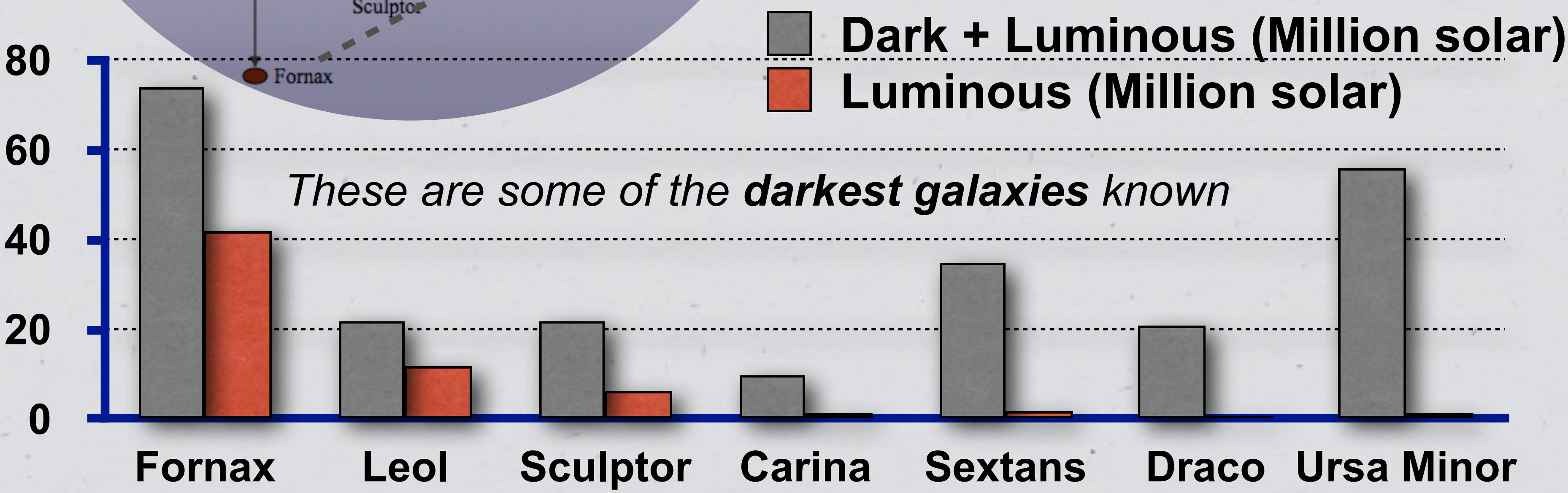


Figure by
J. Bullock



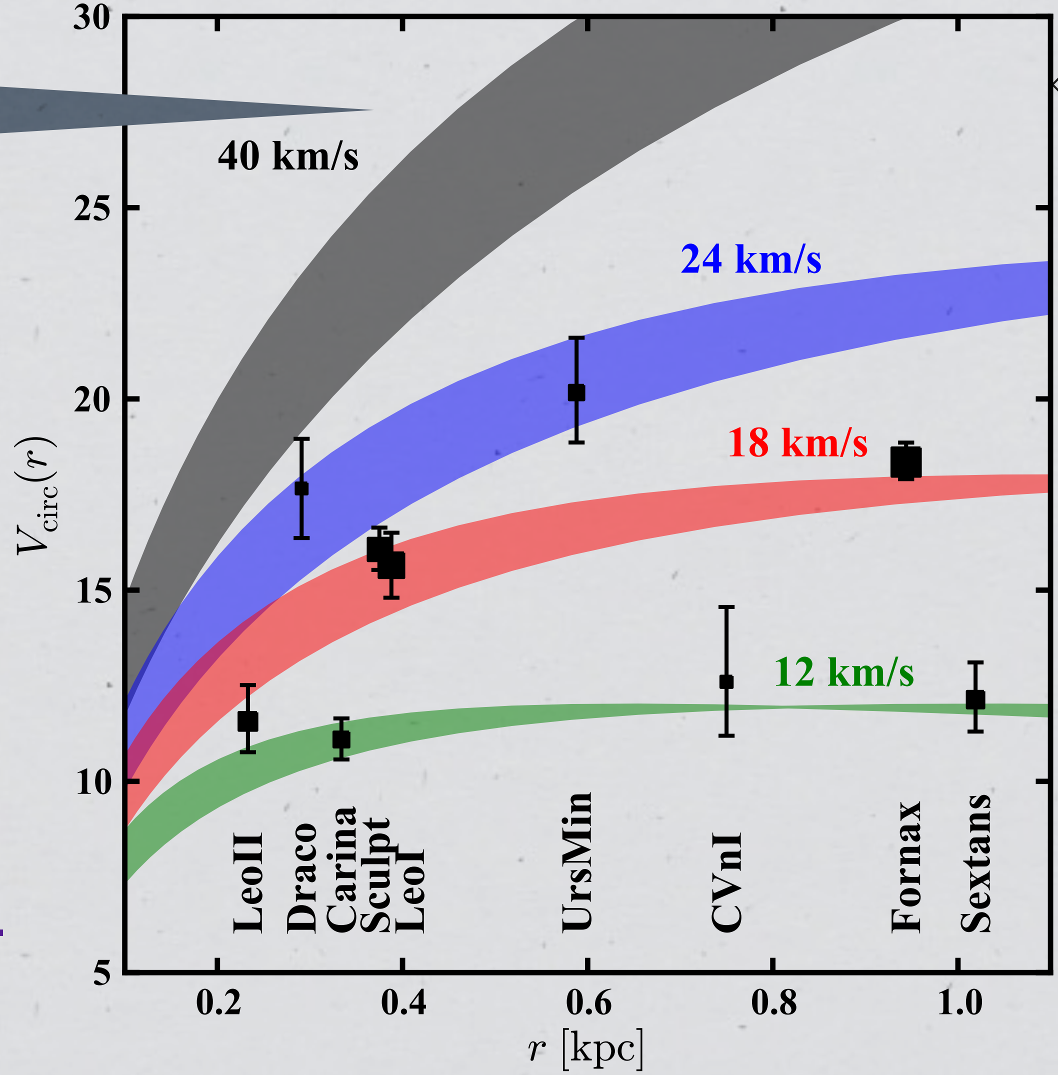


Too big to fail? The most massive apparently don't light up...

Predicted satellite galaxies not found!

This is a density issue: **too many dense (massive) satellite galaxies predicted** [Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012].

This problem also exists in Andromeda [Tollerud et al 2014].



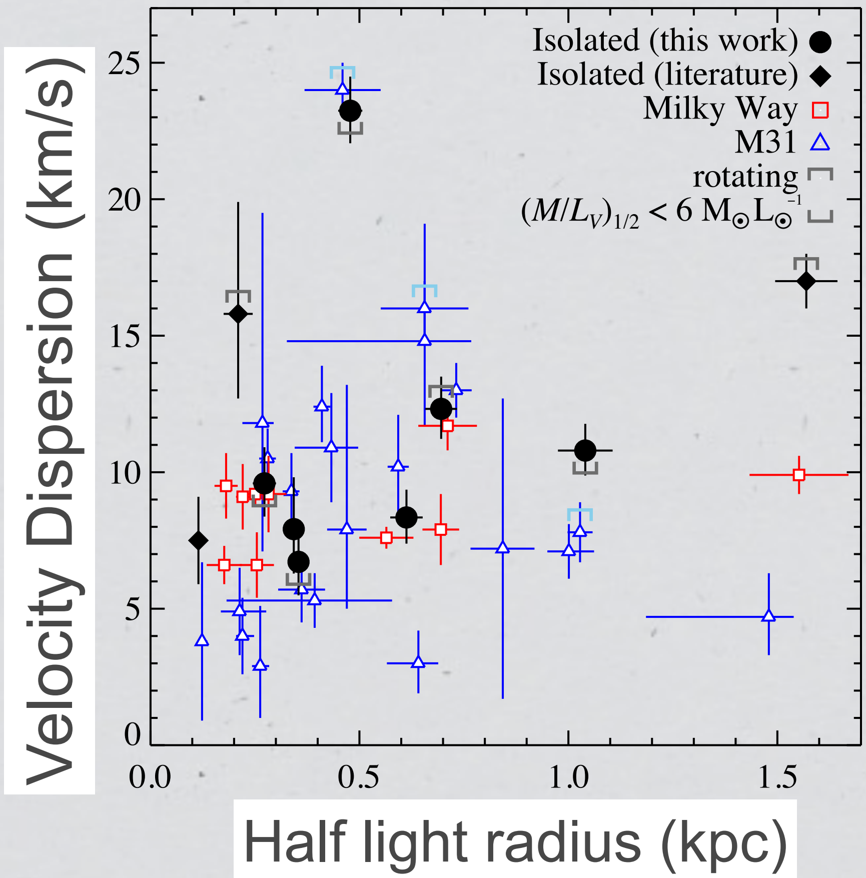
Dark matter densities in the inner regions of galaxies

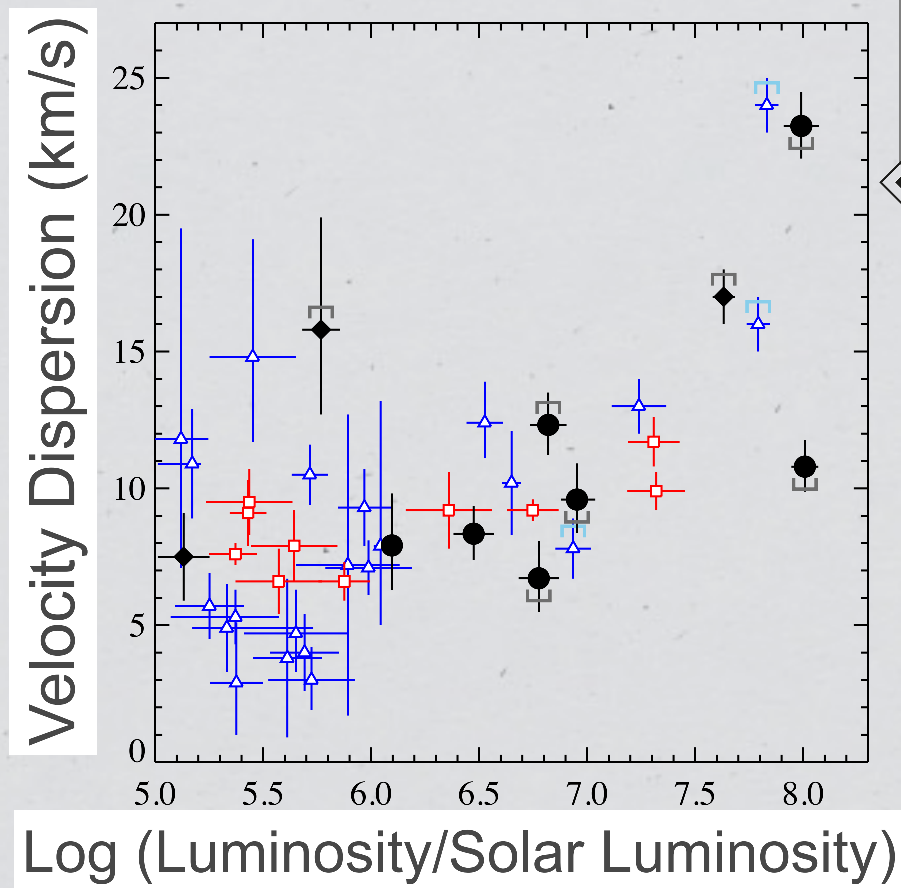
Dark matter halo mass of bound objects [Mass in solar masses]	Scales of interest (distance from center)	Core (region of roughly constant density)	Lower density than predicted by CDM-only simulations
Clusters of galaxies [1e14 to 1e15]	5-50 kpc	?	Y
Elliptical galaxies [1e12 to 1e13]	1-10 kpc	?	?
Dwarf galaxies; Low surface brightness galaxies [1e10 to 1e11]	0.5-5 kpc	Y	Y
Dwarf galaxies within the Milky Way (satellites) [~1e9]	0.3-1 kpc	?	Y

No consensus yet. See Walker and Penarrubia (2011) and Strigari, Frenk and White (2014).

TBTF

Inside or outside, there is a TBTF problem





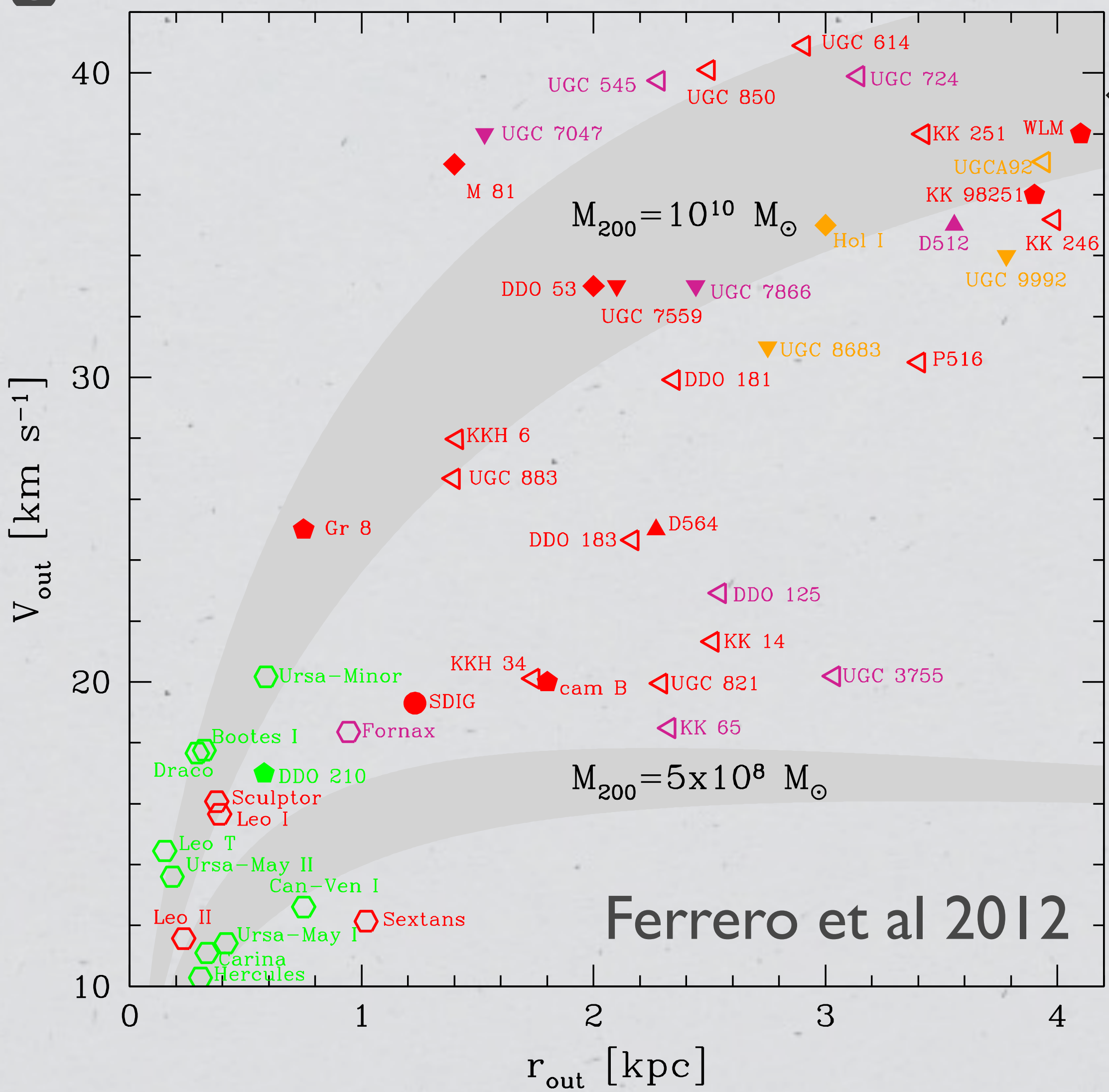
Comparison of the satellites of Andromeda and Milky Way to similar galaxies in the outskirt shows no systematic differences. This is an excellent way forward to disentangle the issues of the effect of environment.

Kirby et al, 2014

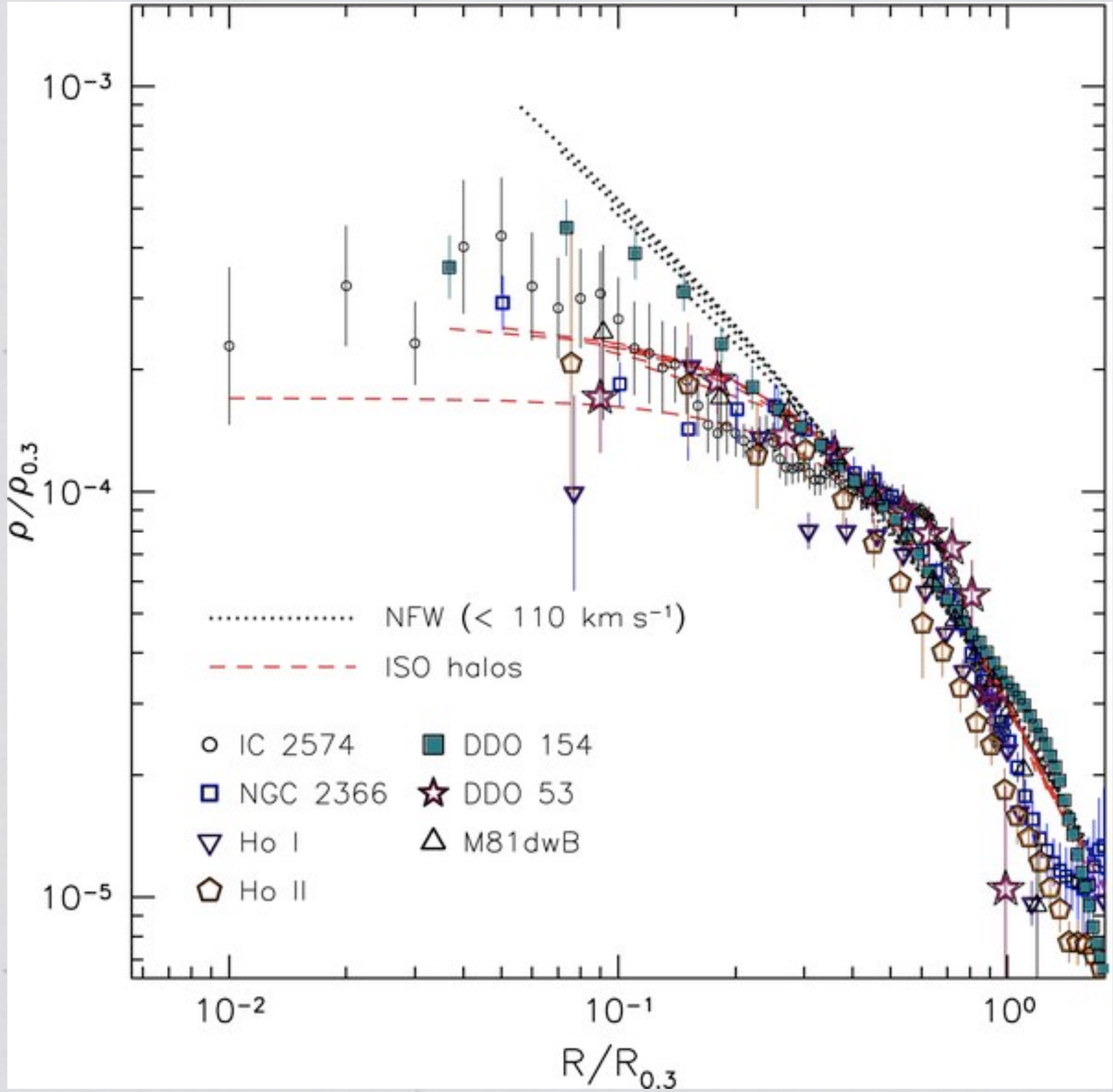
TBTF problem in nearby dwarf galaxies

- LCDM galaxy formation models predict these galaxies should be in halos with masses ~10^{10} Msun or larger.

- Almost all are in halos with masses ~10^{10} Msun or lower, i.e., **lower density than expected**.



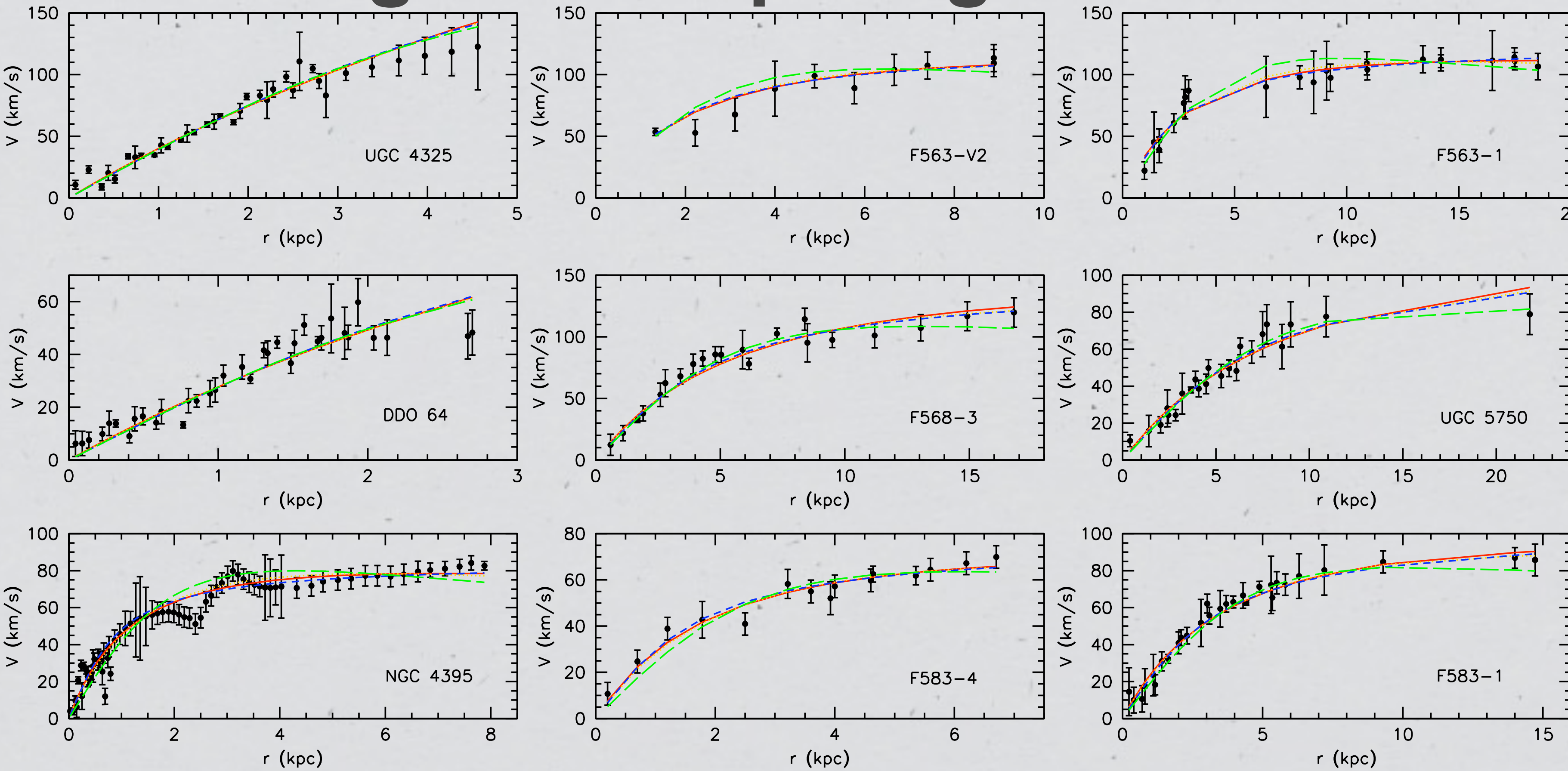
Constant density cores in dwarfs



THINGS: close-by dwarfs (<5 Mpc), DM dominated, low mass (V~30-100 km/s)

Oh et al 2011

Constant density cores in low surface brightness spiral galaxies



Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

Kuzio de Naray, McGaugh, de Blok, Bosma 2005, 2006

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

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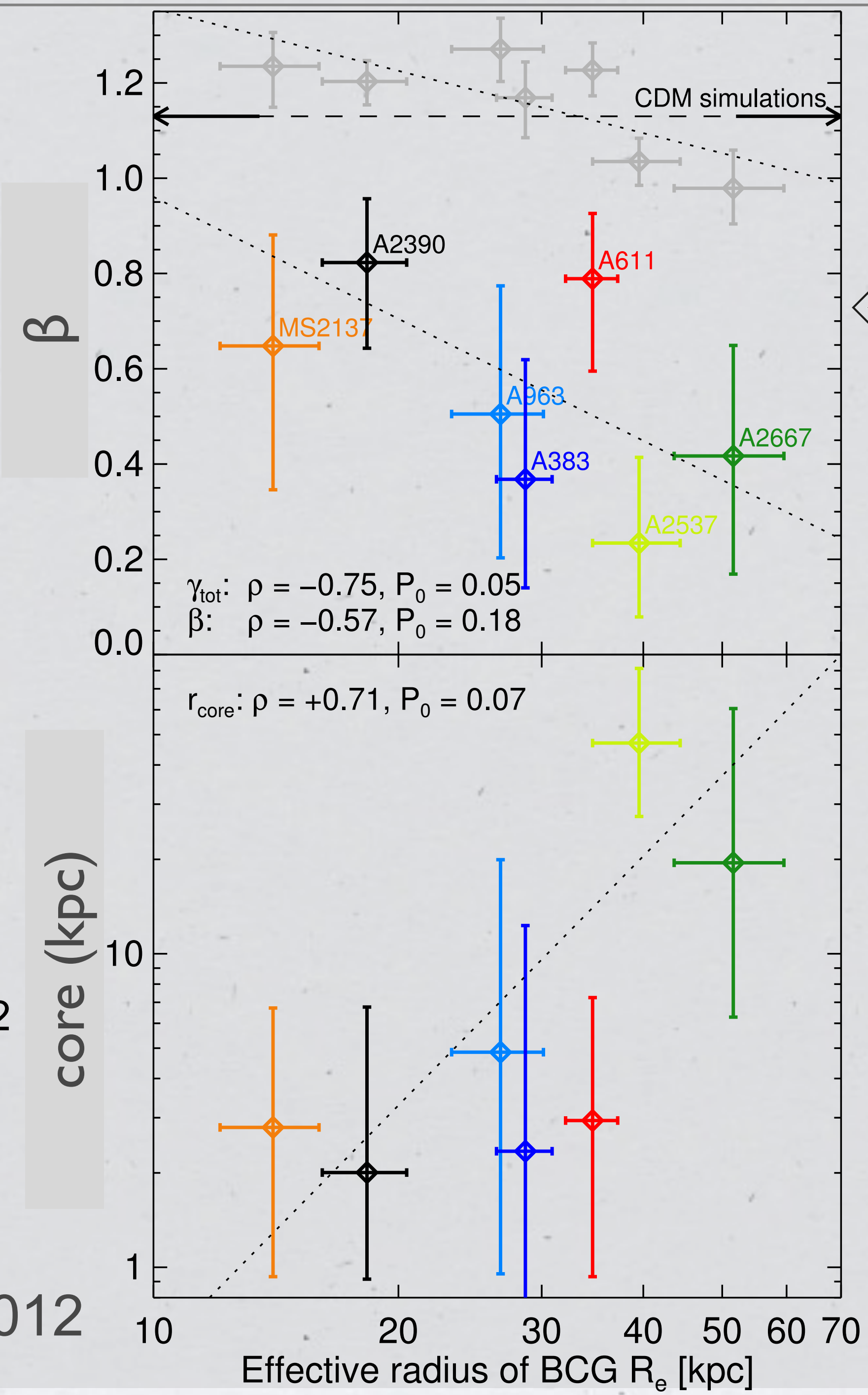
Cores of clusters of galaxies

Use weak lensing, strong lensing and kinematics of stars in the central galaxy to infer density profile of these clusters (with total masses around 10^{15} M_{sun}).

``gNFW" density $\propto 1/r^{\beta}(r_s+r)^{3-\beta}$

``cNFW" density $\propto 1/(r+\text{core})(r_s+r)^2$

Newman et al 2012



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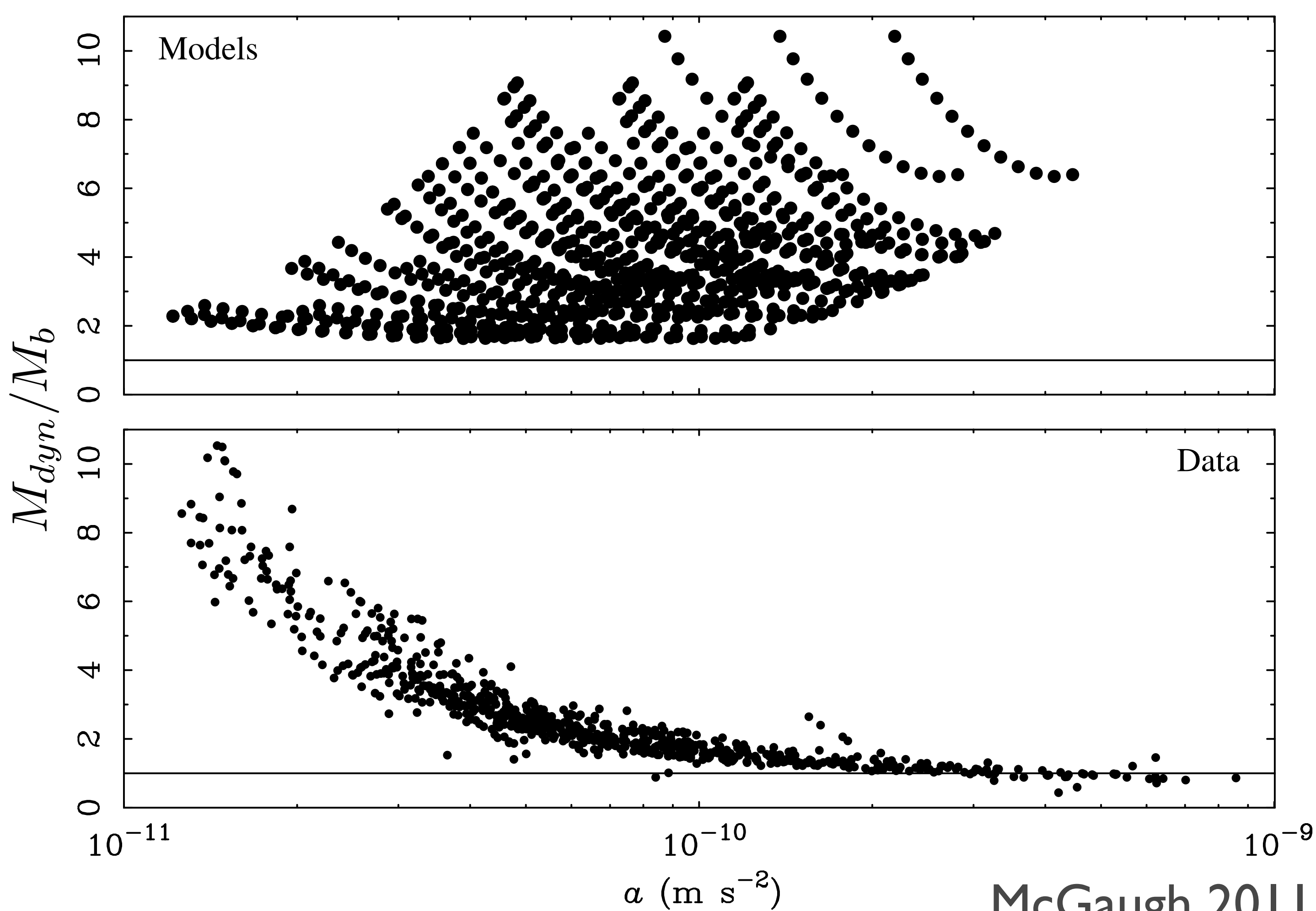
Correlations

The puzzles go far deeper than just the presence of cores or lowered densities. There are correlations between the luminous and dark components that have yet to be fully described in any model of galaxy formation.

The acceleration scale in galaxy formation

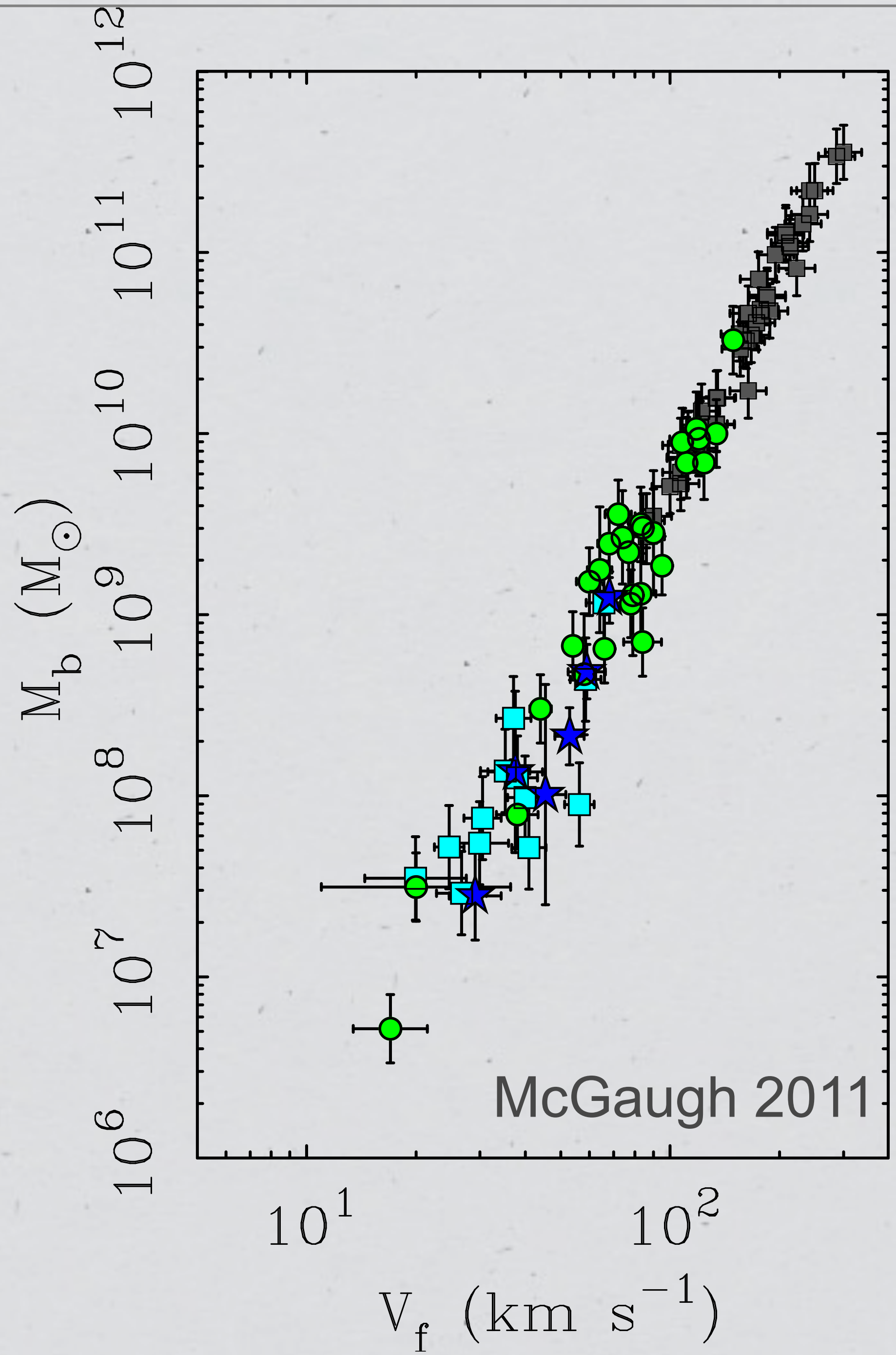


McGaugh 2011

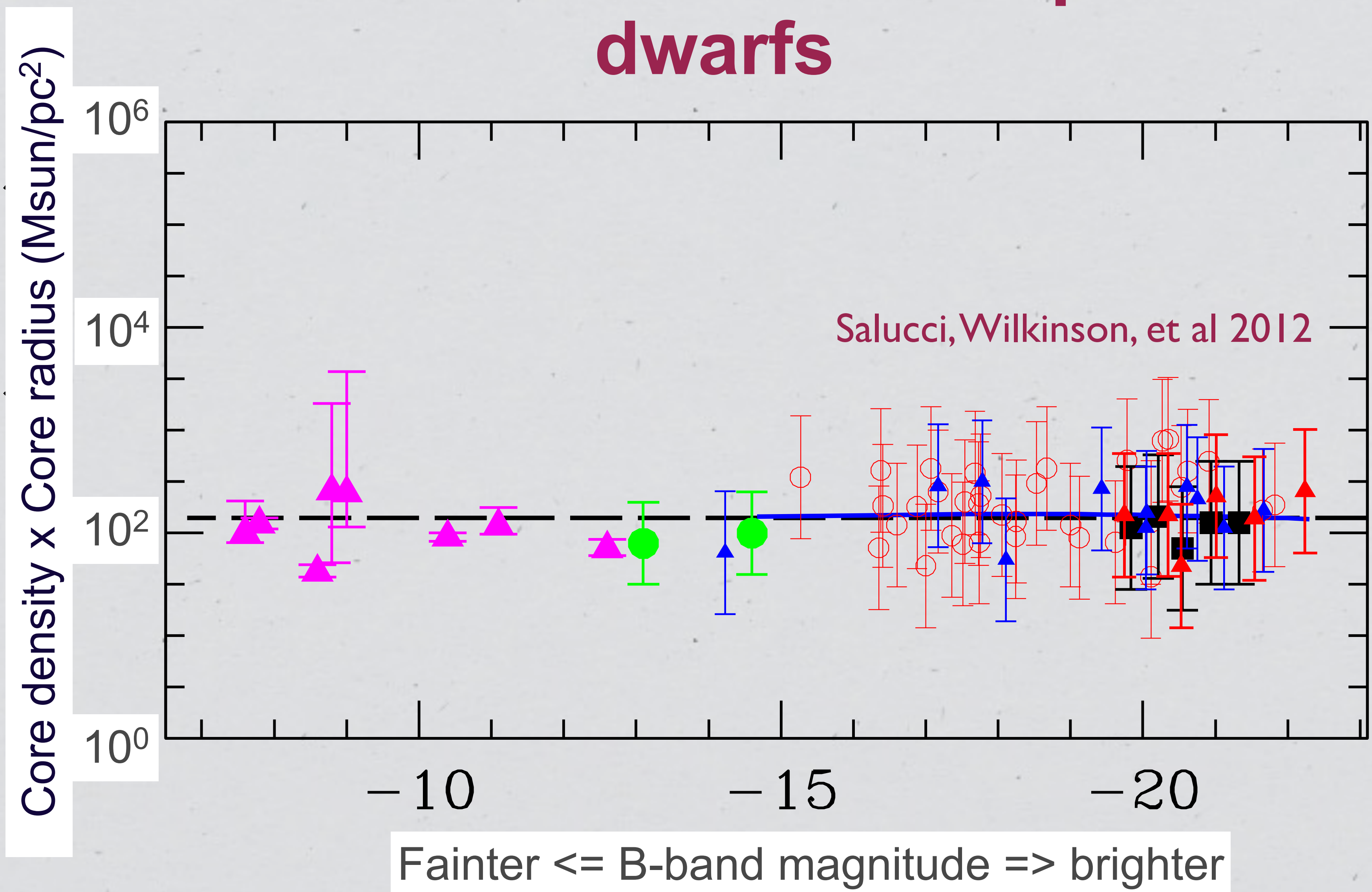
See also Kaplinghat and Turner 2002

Baryonic Tully-Fisher relation

No LCDM model explains this satisfactorily

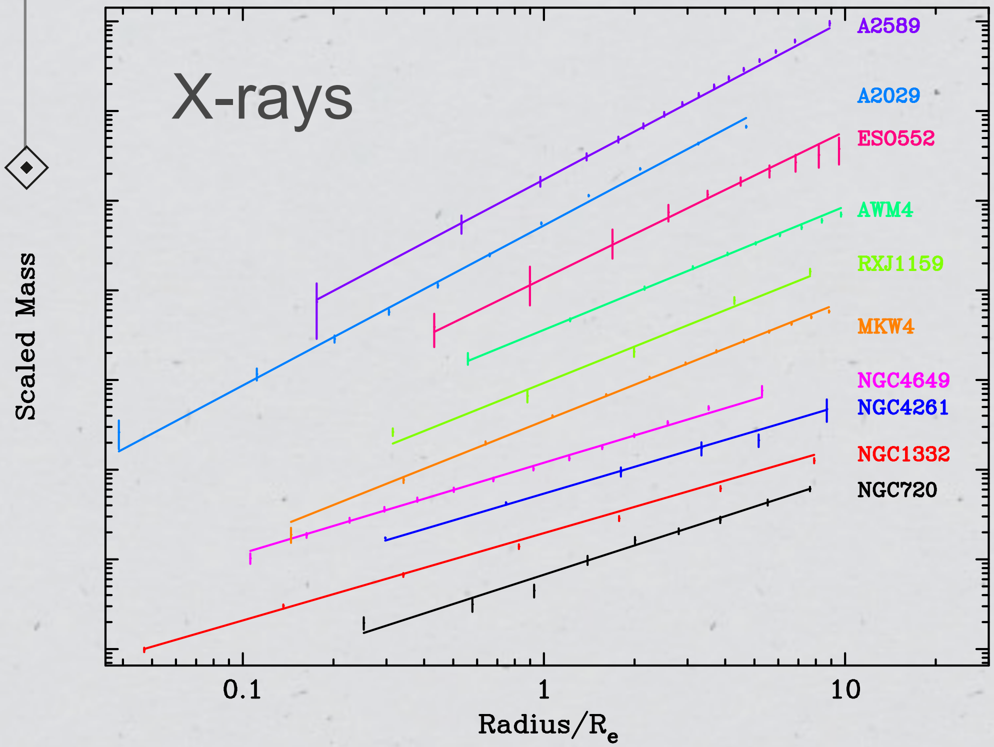


Core sizes and densities of spirals and dwarfs

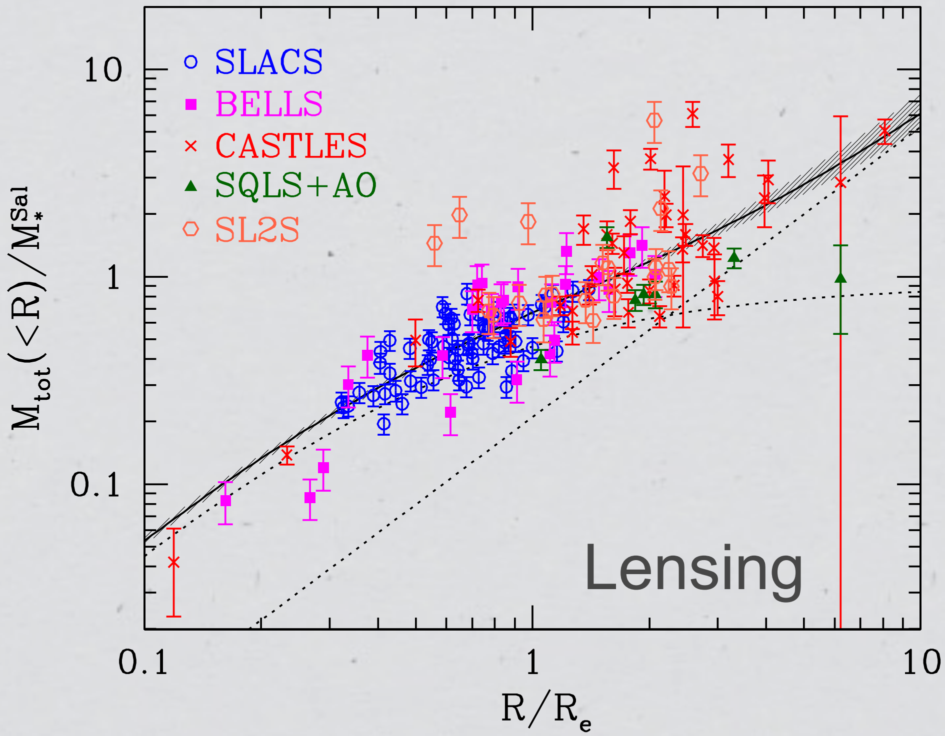


The observed correlations and the size of scatter need explanations.

Total matter in elliptical galaxies is featureless



Humphrey and Buote 2009



Oguri, Ruso, Falco 2014

Self-interacting dark matter (SIDM) solution to small-scale puzzles

Proposals motivated by small-scale issues [Spergel and Steinhardt 2000, Firmani et al 2000]. Lot of early and continued work on mirror dark matter [Mohapatra, Nussinov, Teplitz 2001; Foot, Volkas 2004].

Recent revival of large self-interaction strengths, many in terms of low-mass force carriers [Ackerman, Buckley, Carroll, Kamionkowski 2009, Feng, Kaplinghat, Yu, Tu 2009, Kaplan, Krnjaic, Rehermann, Wells 2009, Feng, Kaplinghat, Yu 2010, Buckley and Fox 2010, Loeb and Weiner 2011, R. Foot 2012, Cyr-Racine and Sigurdson 2012, Tulin, Yu and Zurek 2012, 2013, Fan, Katz, Randall, Reece 2013, Bellazzini, Cliche, Tanedo (2013)]

Relic density: thermal or asymmetric

What is SIDM?

We will define Self-Interacting Dark Matter (SIDM) as a form of Cold Dark Matter that has a significant elastic scattering cross section. In particular, the dark matter perturbation power spectrum is unchanged from the model without self-interaction [see Cyr-Racine and Sigurdson 2012] and there is no significant dissipation of energy [see Fan, Katz, Randall, Reece 2013].

In its simplest incarnation, SIDM has one extra parameter: scattering cross section over mass (σ/m) or mediator mass (for cross section that is not constant)

Doesn't the Bullet Cluster rule out SIDM?

Bullet cluster: $\sigma/m < 0.7\ cm^2/g$ for relative speed v~3000 km/s.

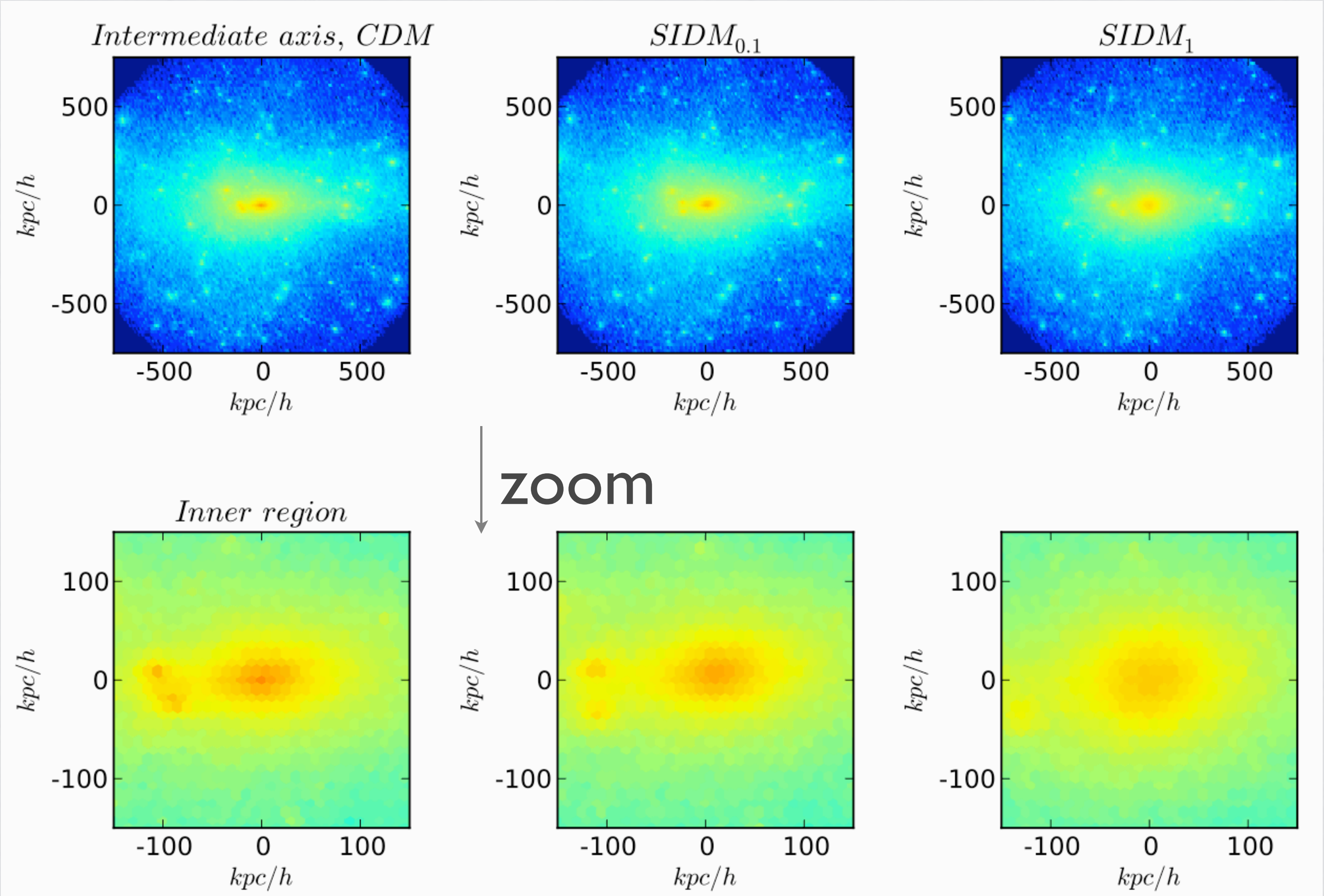
Generically, σ/m is v-dependent, making this a weak constraint on models.

Even for $\sigma/m < 0.7\ cm^2/g$, observable effects can be seen in dwarf galaxies.

However, even the $0.7\ cm^2/g$ limit has to reevaluated with self-consistent SIDM mergers.

Merging Cluster Collaboration (UC Davis, UC Irvine, Caltech/JPL, OSU)

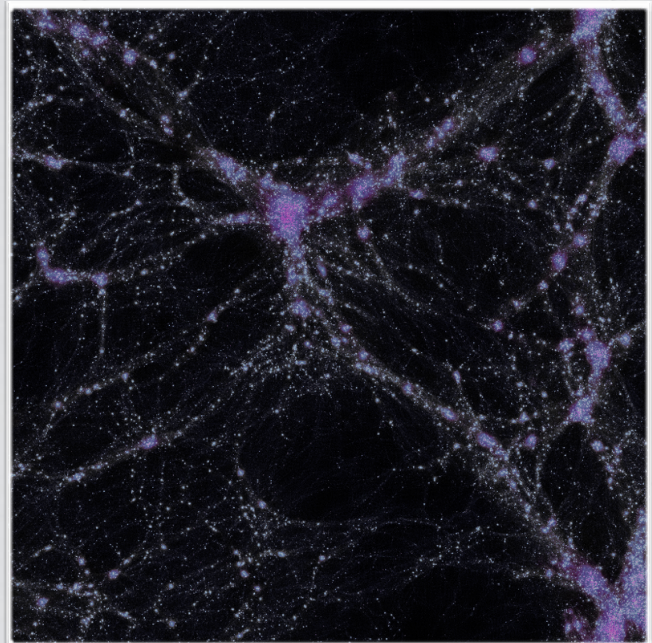
Don’t cluster halo shapes rule out SIDM?

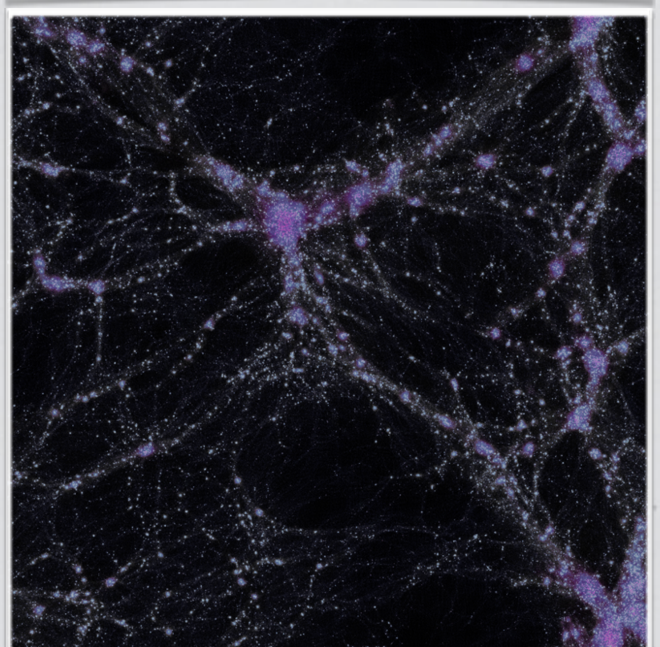


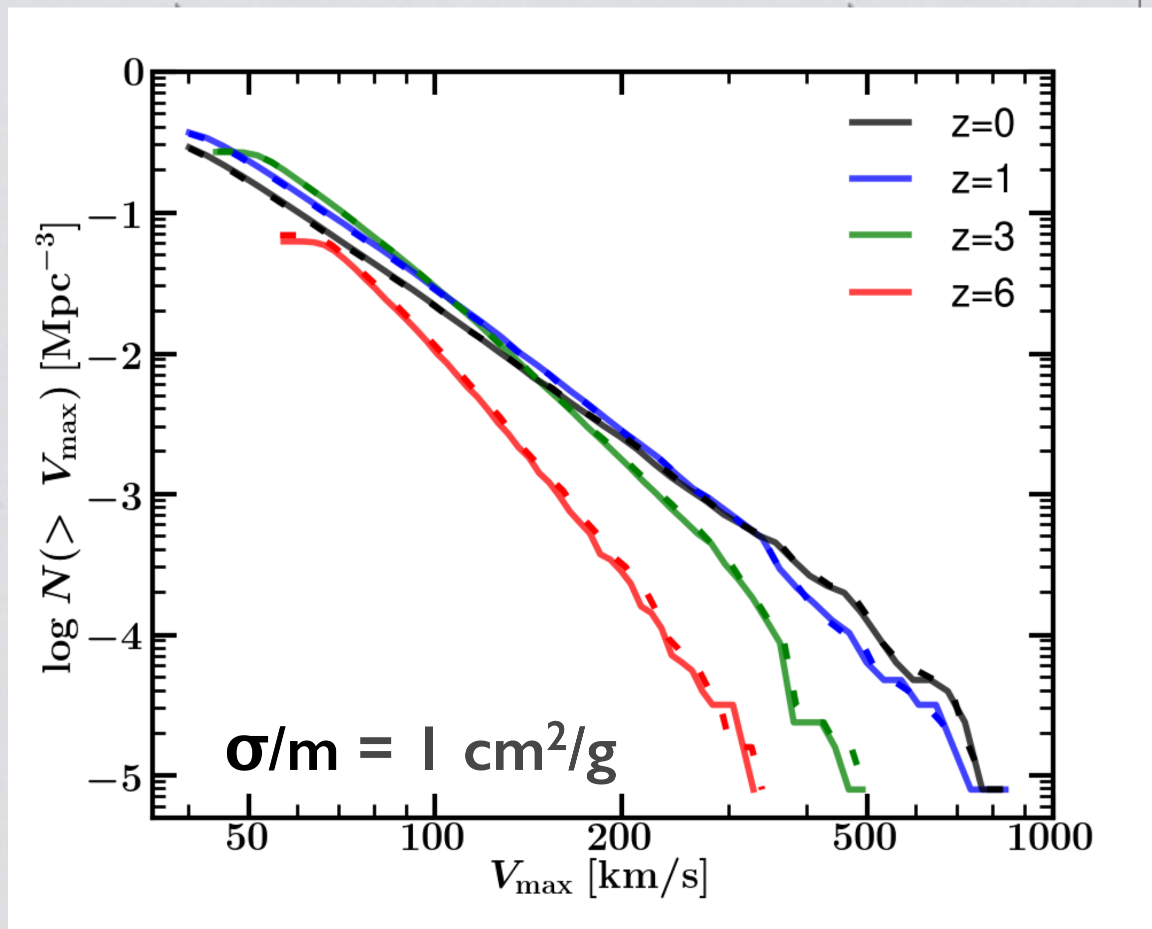
Constraints using shapes of LoCuSS clusters (Richards et al 2010) not better than about 1 cm^2/g.

Peter, Rocha, Bullock, Kaplinghat 2012

SIDM is the same as CDM on large scales

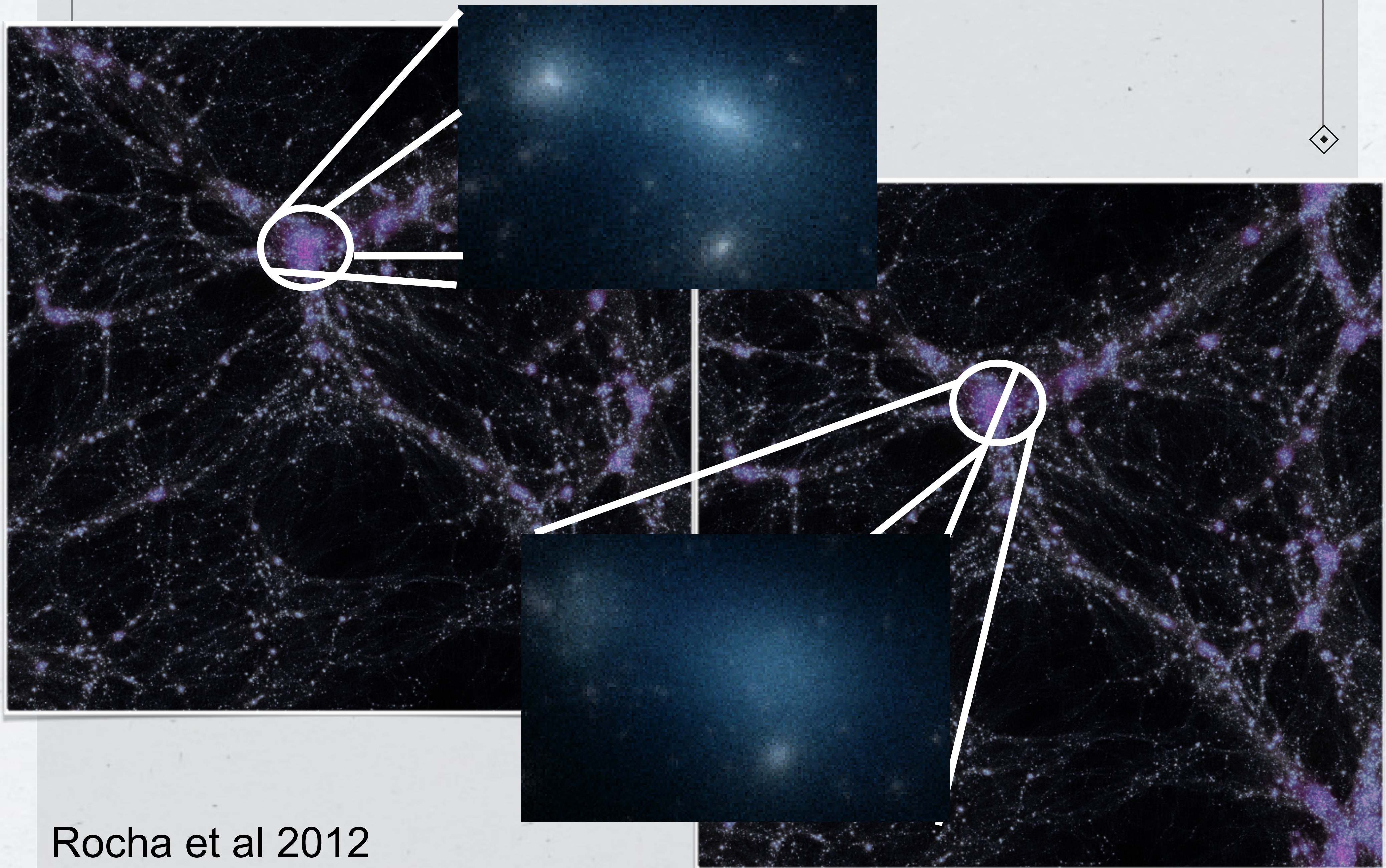






Rocha et al 2012

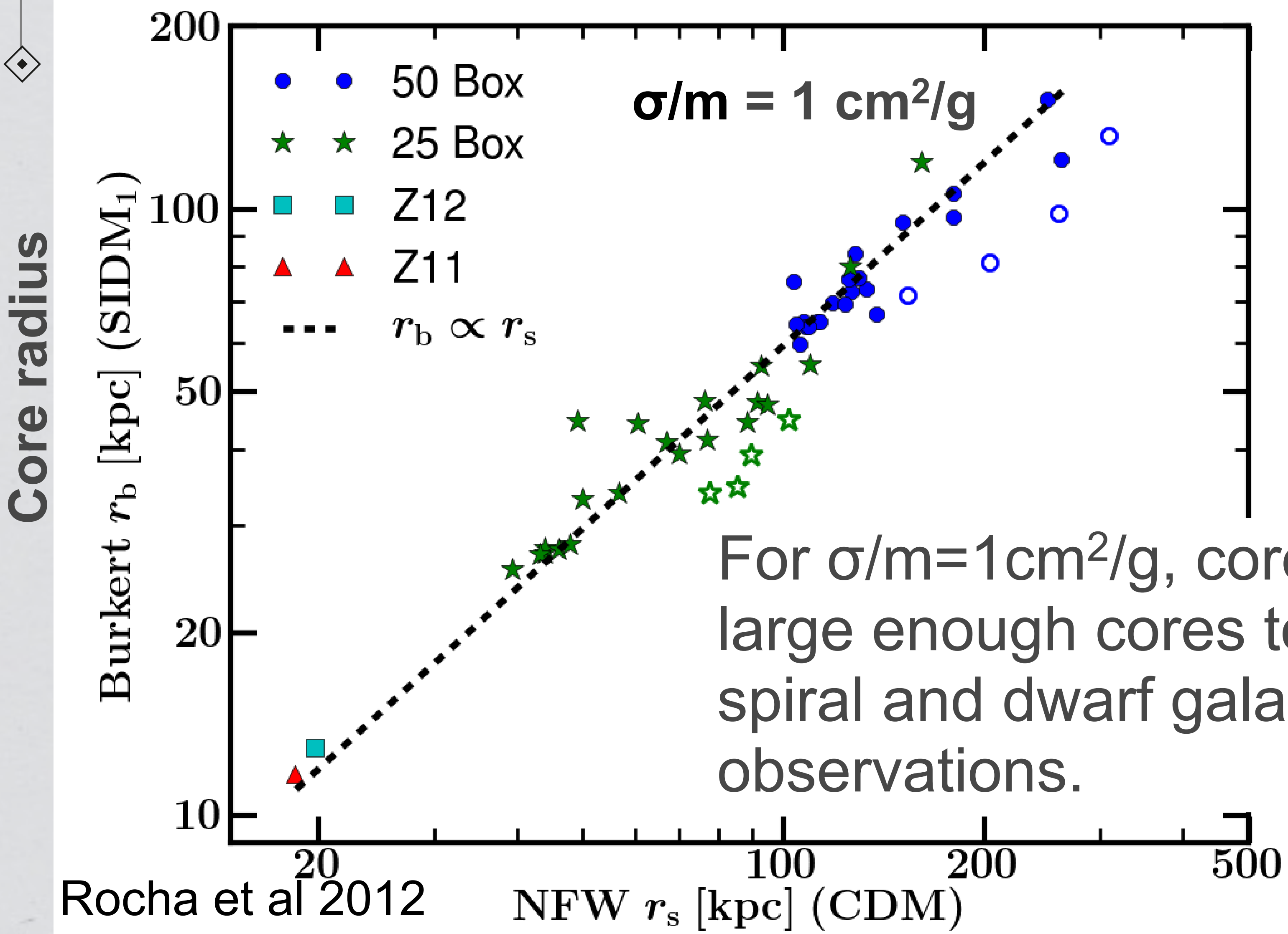
Differences only in the centers of galaxies



Rocha et al 2012

SIDM solution: core sizes

Outside this core radius, solution is CDM-like.



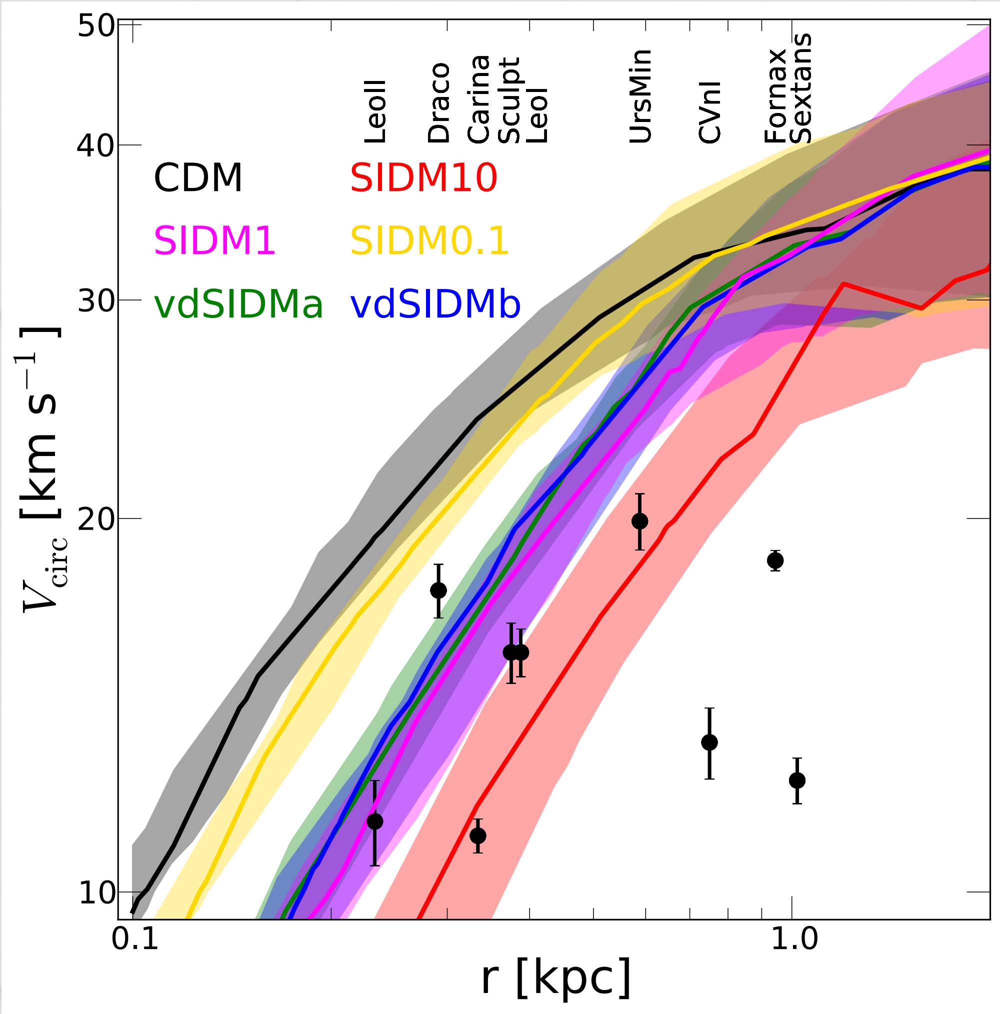
Rocha et al 2012

For σ/m=1cm^2/g, core ~ 0.7r$_S$: large enough cores to explain spiral and dwarf galaxy observations.

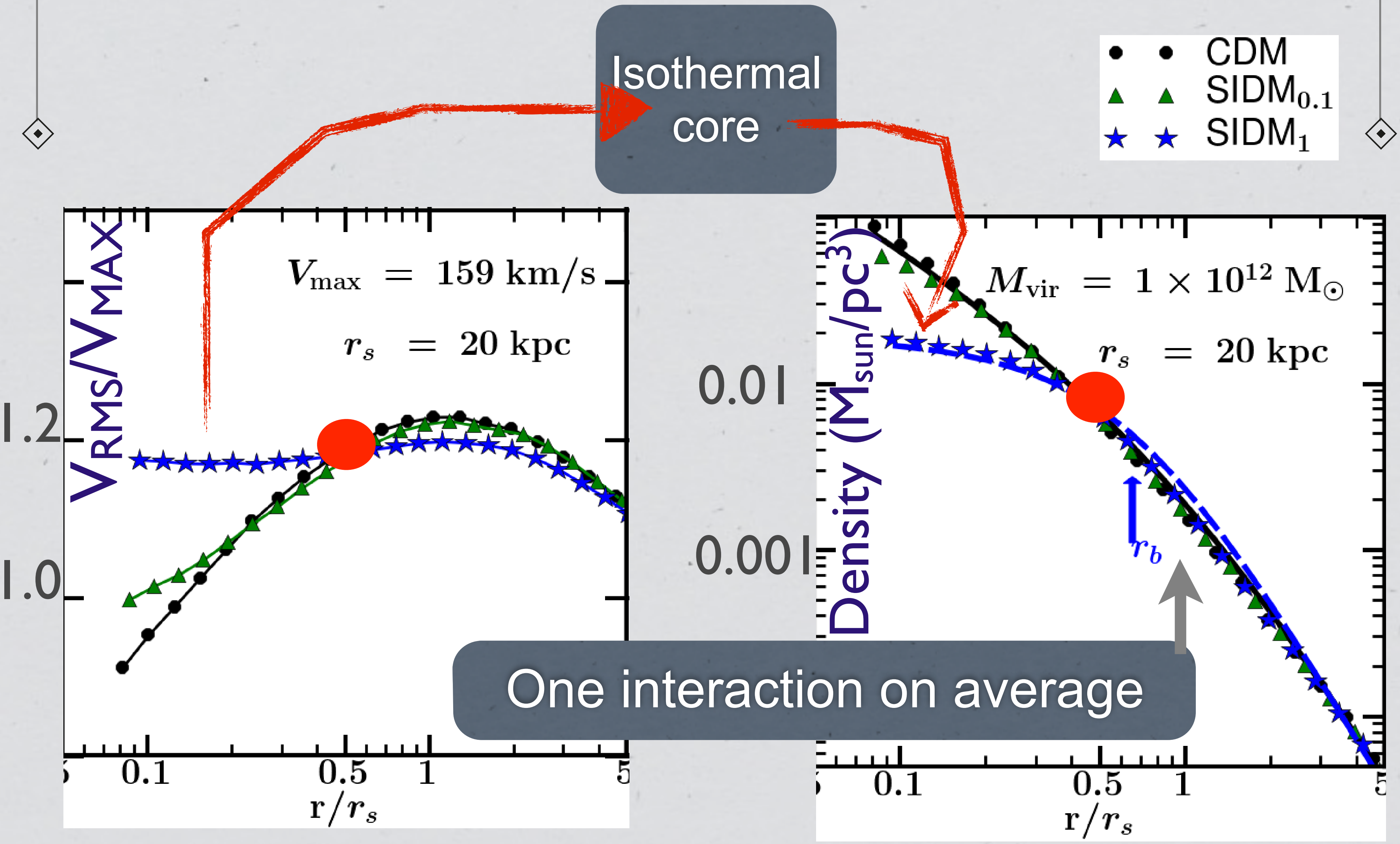
SIDM solution: Milky Way satellites

Milky Way bright satellite problem can be solved with the production of large cores [Vogelsberger, Zavala and Loeb 2012, Vogelsberger, Zavala and Walker 2012]

Includes velocity dependence of cross section that arises from broken U(1) [Feng, Kaplinghat and Yu 2010]

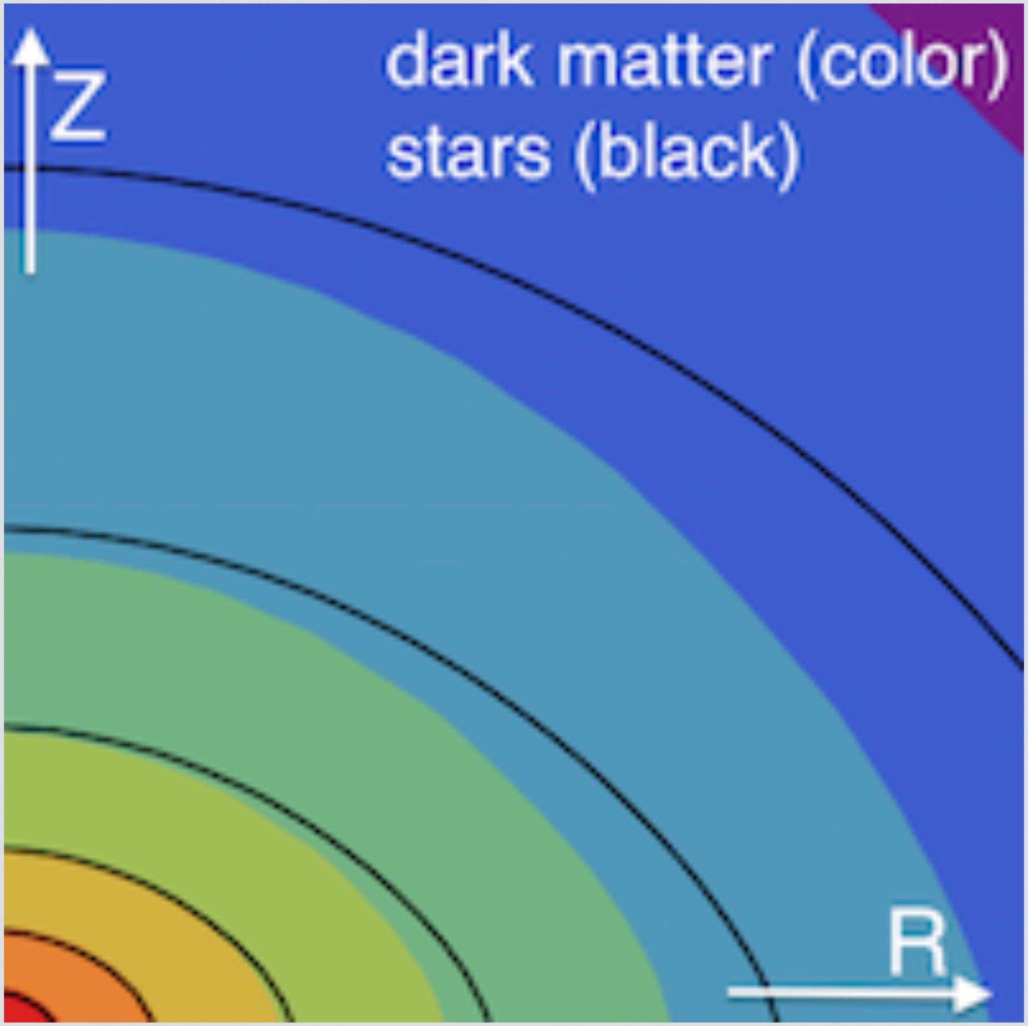


How does SIDM work?



Rocha et al 2012

Stars and dark matter tied in SIDM model



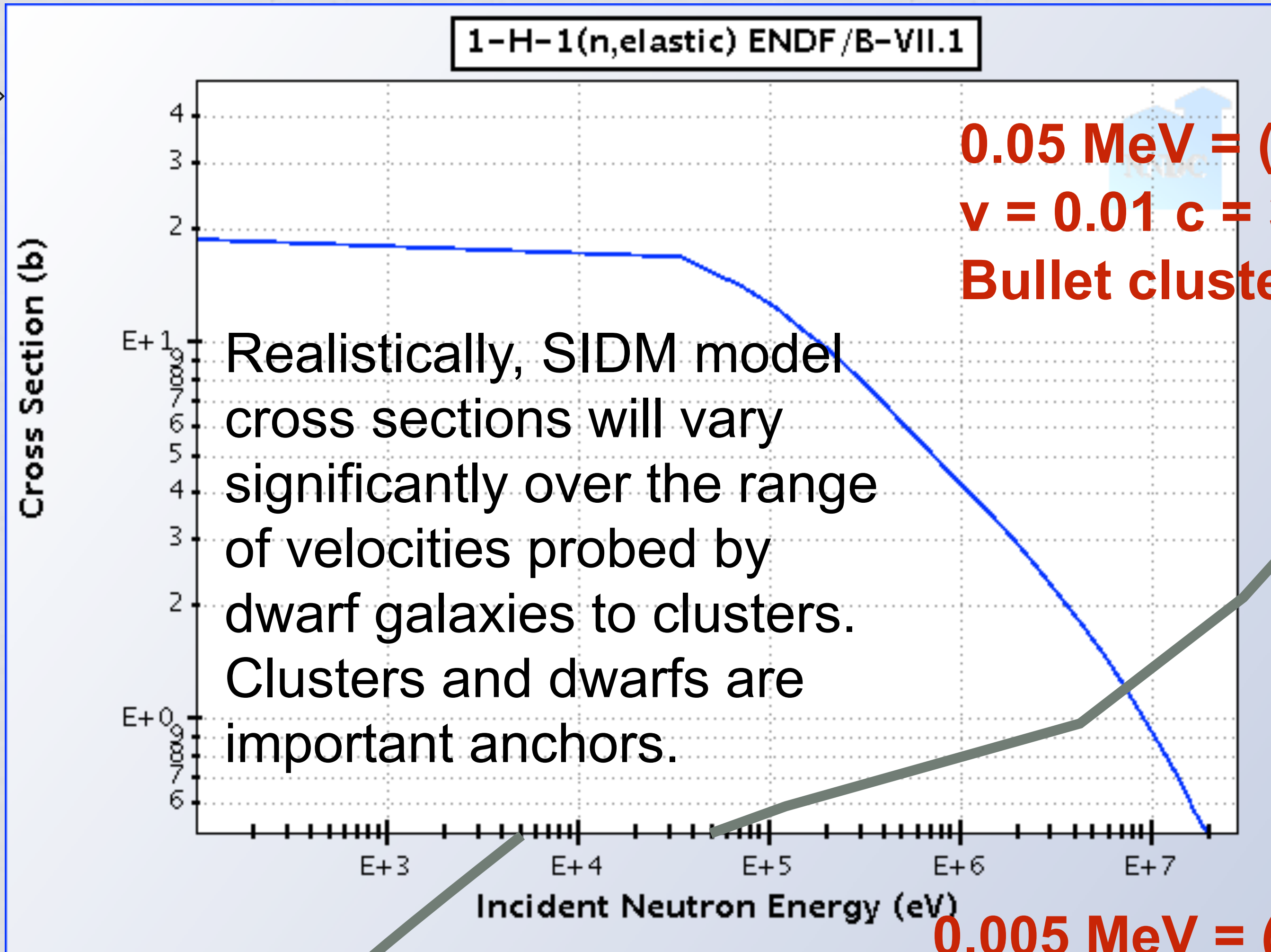
Kaplinghat, Keeley, Linden and Yu, PRL 2014

Dark matter tracks the stellar potential in the regions where stars dominate, i.e., dark and luminous matter are tied.

See also Vogelsberger, Zavala, Simpson and Jenkins 2014 for a related effect.

We will end this talk by considering a simple particle physics realization of SIDM with implications for direct and indirect searches.

SM example: neutron-proton scattering



Realistically, SIDM model cross sections will vary significantly over the range of velocities probed by dwarf galaxies to clusters. Clusters and dwarfs are important anchors.

0.05 MeV = (1/2) 1 GeV v^2
v = 0.01 c = 3000 km/s
Bullet cluster relative velocity

0.005 MeV = (1/2) 1 GeV v^2
v = 0.003 c ~ 1000 km/s
Musket Ball relative velocity

A simple SIDM model

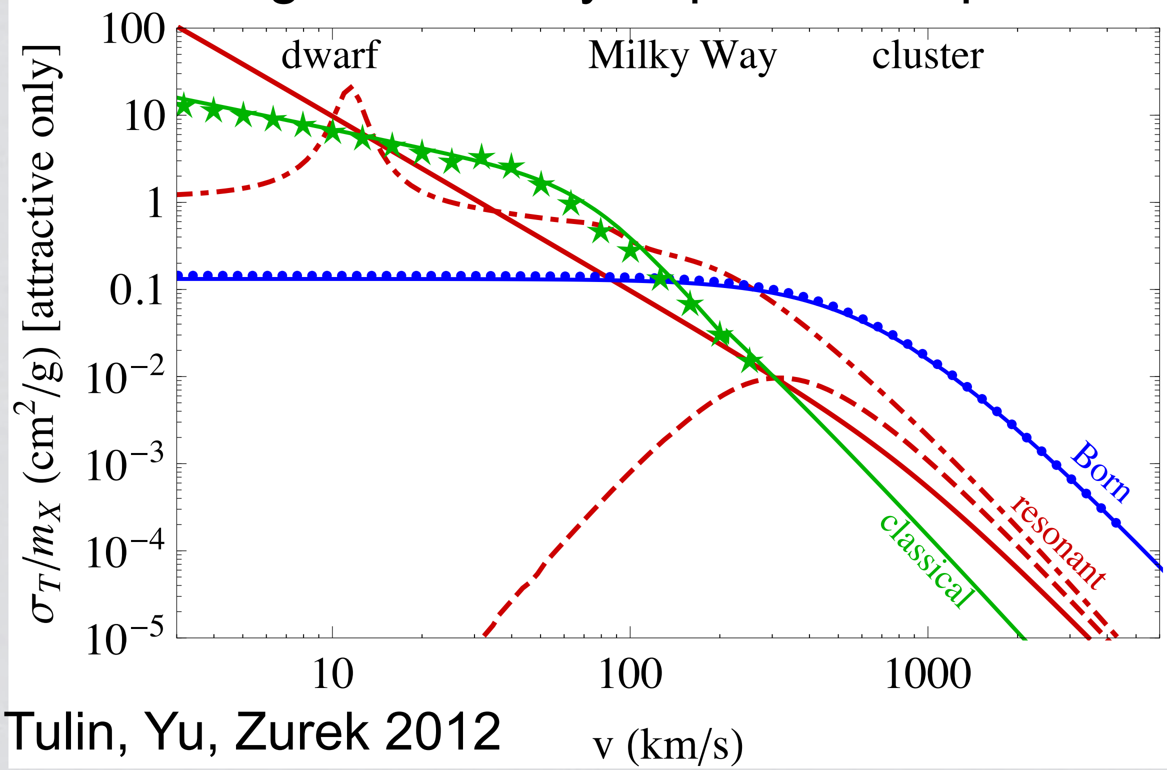
$$\mathcal{L} = g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + m_\chi \bar{\chi}\chi + m_\phi^2 \phi^\mu \phi_\mu$$

Symmetric: Relic density achieved through $\chi\bar{\chi} \to \phi\phi$

Asymmetric: cross section ($\chi\bar{\chi} \to \phi\phi$) > thermal relic cross section

$$V = \pm \frac{\alpha_x}{r} \exp\left(-m_\phi r\right)$$

A wide range of velocity dependence possible



Tulin, Yu, Zurek 2012

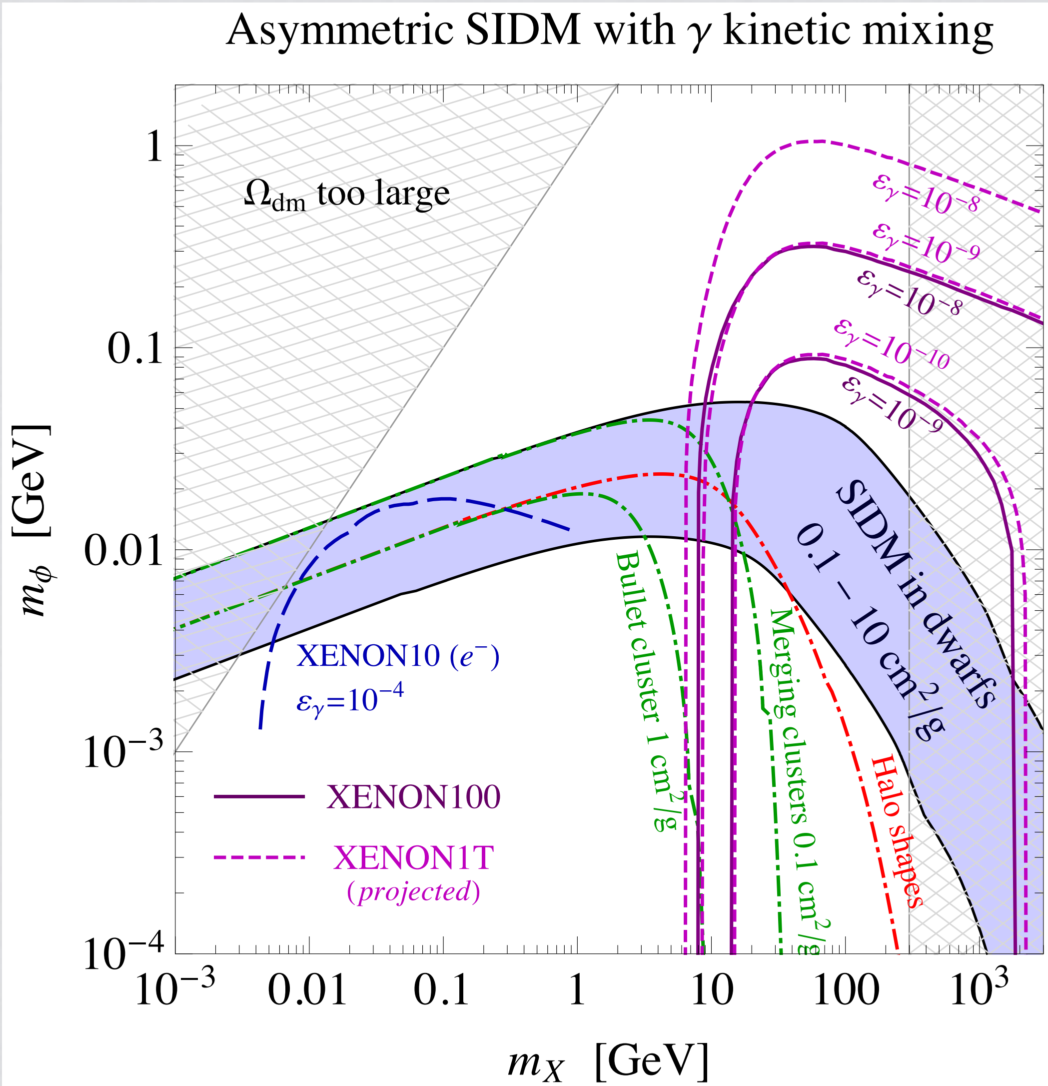
Similar SIDM phenomenology in SU(N) hidden sectors

[Boddy, Feng, Kaplinghat and Tait, 2014].

A simple SIDM model: direct detection

To be safe, make mediator decay before BBN. Unless there are other light particles in the hidden sector, this should happen through the coupling to SM fields. **Direct and indirect searches.**

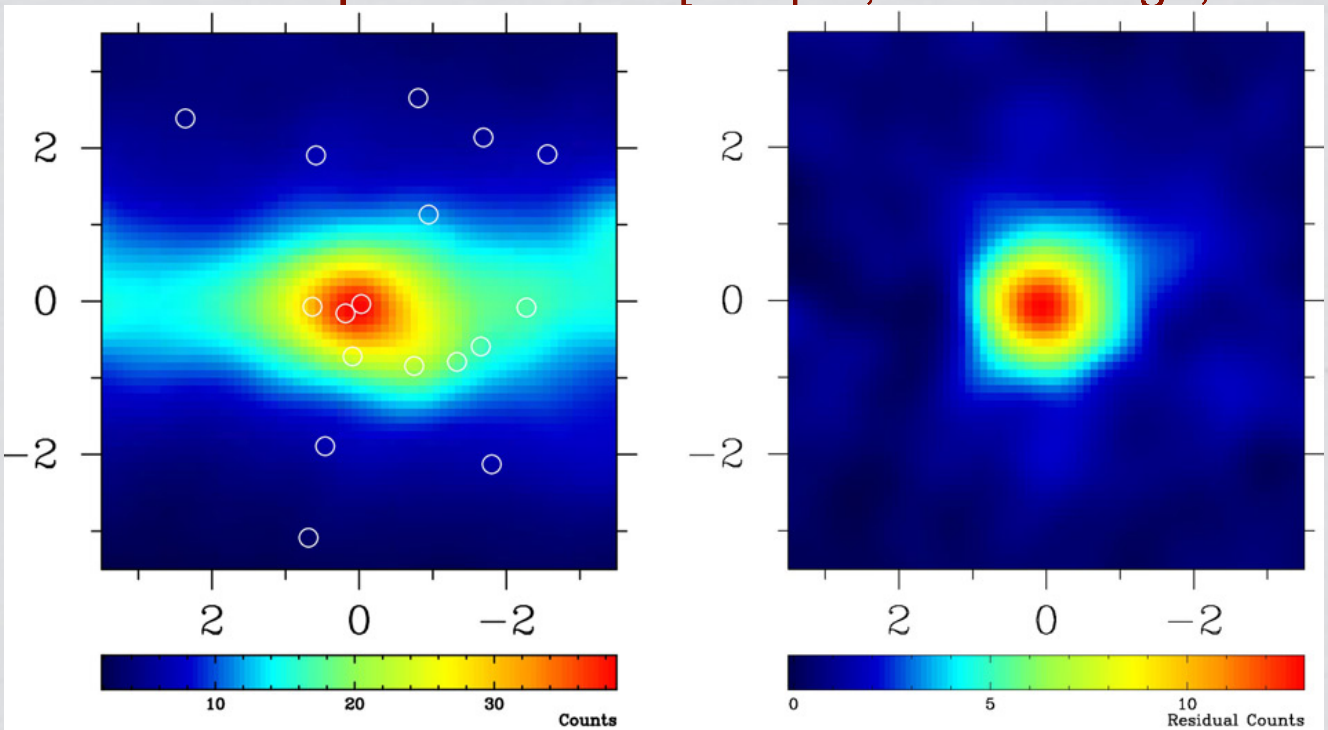
Direct: Momentum dependent form factor -- $q^4/(q^2+m_\varphi^2)^2$ -- no longer contact interaction!



Kaplinghat, Tulin, Yu, PRD 2013

A simple SIDM model: indirect detection

There is an extended source at the Galactic Center consistent with dark matter annihilation predictions. [Hooper, Goodenough; Hooper, Linden].



Abazajian, Kaplinghat 2012

For symmetric SIDM with γ kinetic mixing, annihilation produces e^+e^- and inverse Compton off of starlight produces gamma rays from Galactic Center. Is this symmetric SIDM explanation consistent with AMS-02?

Kaplinghat, Linden, Yu, in preparation

Summary

Observations capable of resolving the innermost regions of galaxies and clusters show that densities of dark matter are lower than dark-matter-only LCDM predictions. The dark and baryonic matter show strong correlations.

LSIDM is a promising explanation and it retains all the successes of LCDM on larger scales.

Like WIMPs, SIDM particle candidates could have direct and indirect signals.

The Galactic Center excess in gamma rays is consistent with the signal from annihilation of thermal relic dark matter, including SIDM candidates.