SELF-INTERACTING DARK MATTER MOTIVATED BY PUZZLES ON GALACTIC AND SUB-GALACTIC SCALES

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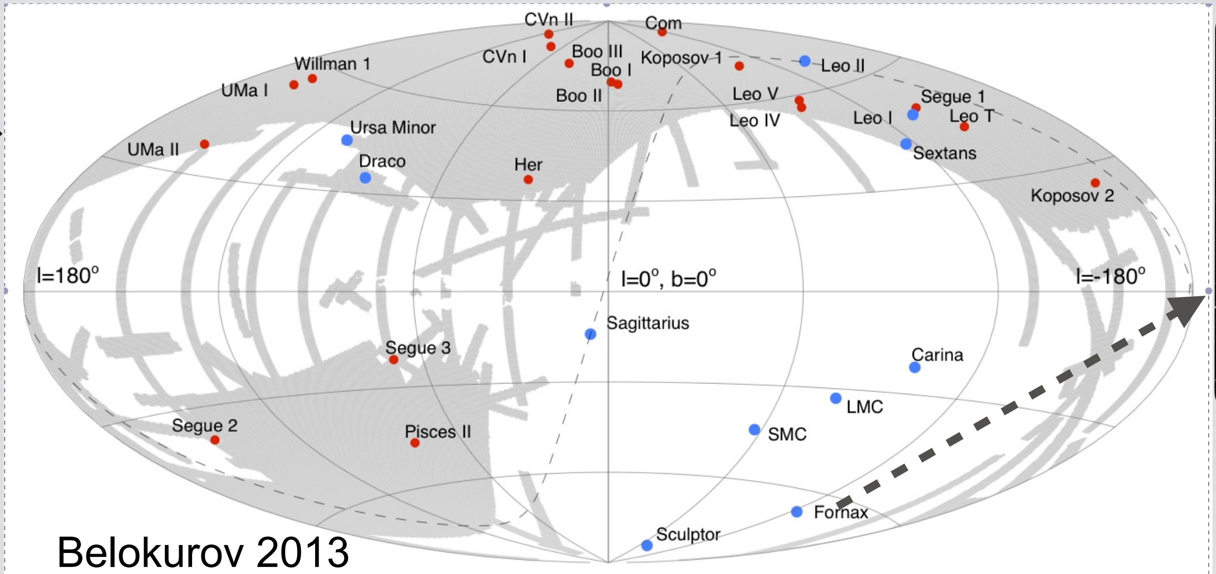
Manoj Kaplinghat, University of California, Irvine, USA

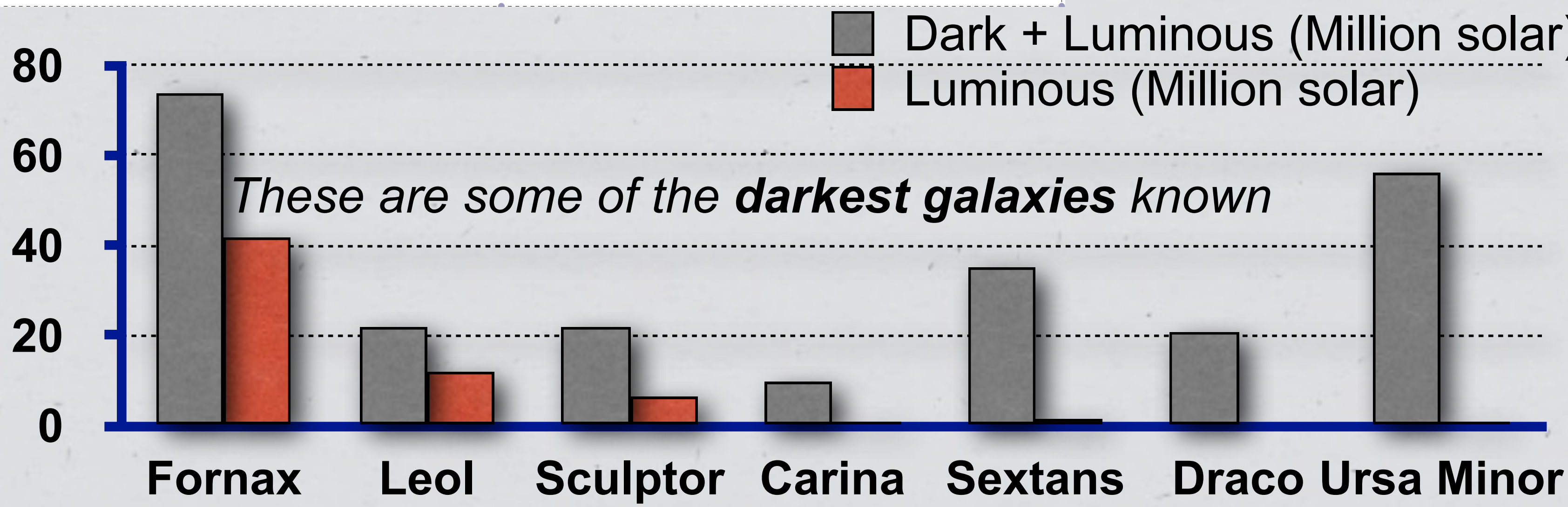
Plan for the talk:

Argue that estimates of the dark matter density are systematically **lower than expected for low-mass galaxies** and that the **dark and luminous matter are correlated** in ways that have yet to be understood.

Explore self-interacting dark matter as a solution.

Dark matter in satellite galaxies





Dark matter densities in the inner regions of galaxies

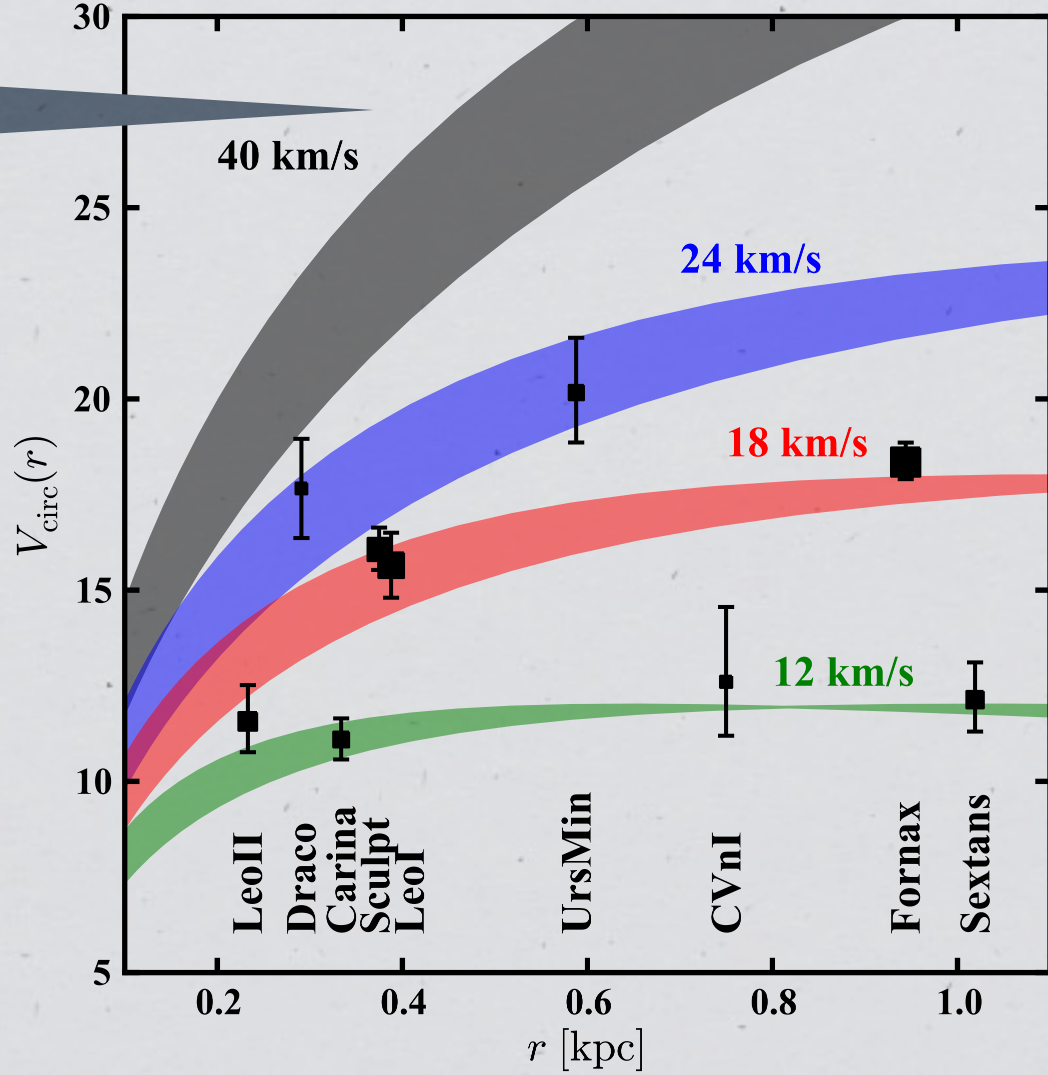
Dark matter halo mass of bound objects [Mass in solar masses]	Scales of interest (distance from center)	Core (region of roughly constant density)	Lower density than predicted by CDM-only simulations
Clusters of galaxies [1e14 to 1e15]	5-50 kpc	?	Y
Elliptical galaxies [1e12 to 1e13]	1-10 kpc	?	?
Dwarf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

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

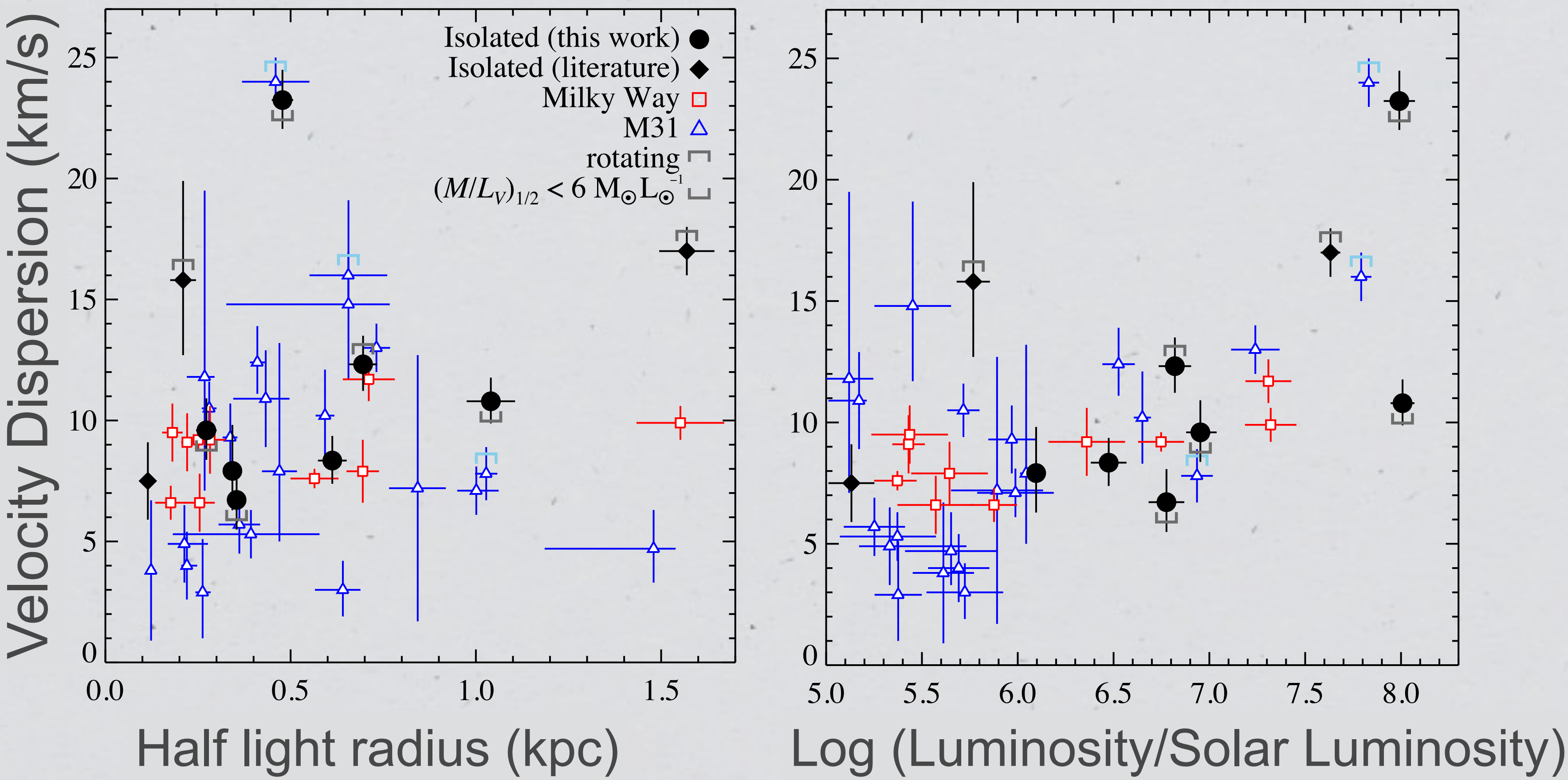
Predicted satellite galaxies not found!

Predicted satellites are denser [Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012]. No statement about core/cusp. Not a counting issue.

This problem also exists in Andromeda [Tollerud et al 2014] and in between MW and And.



Inside or outside (the Milky Way), there is a TBTF problem



No explicit environmental differences between local group dSphs.

Kirby et al, 2014

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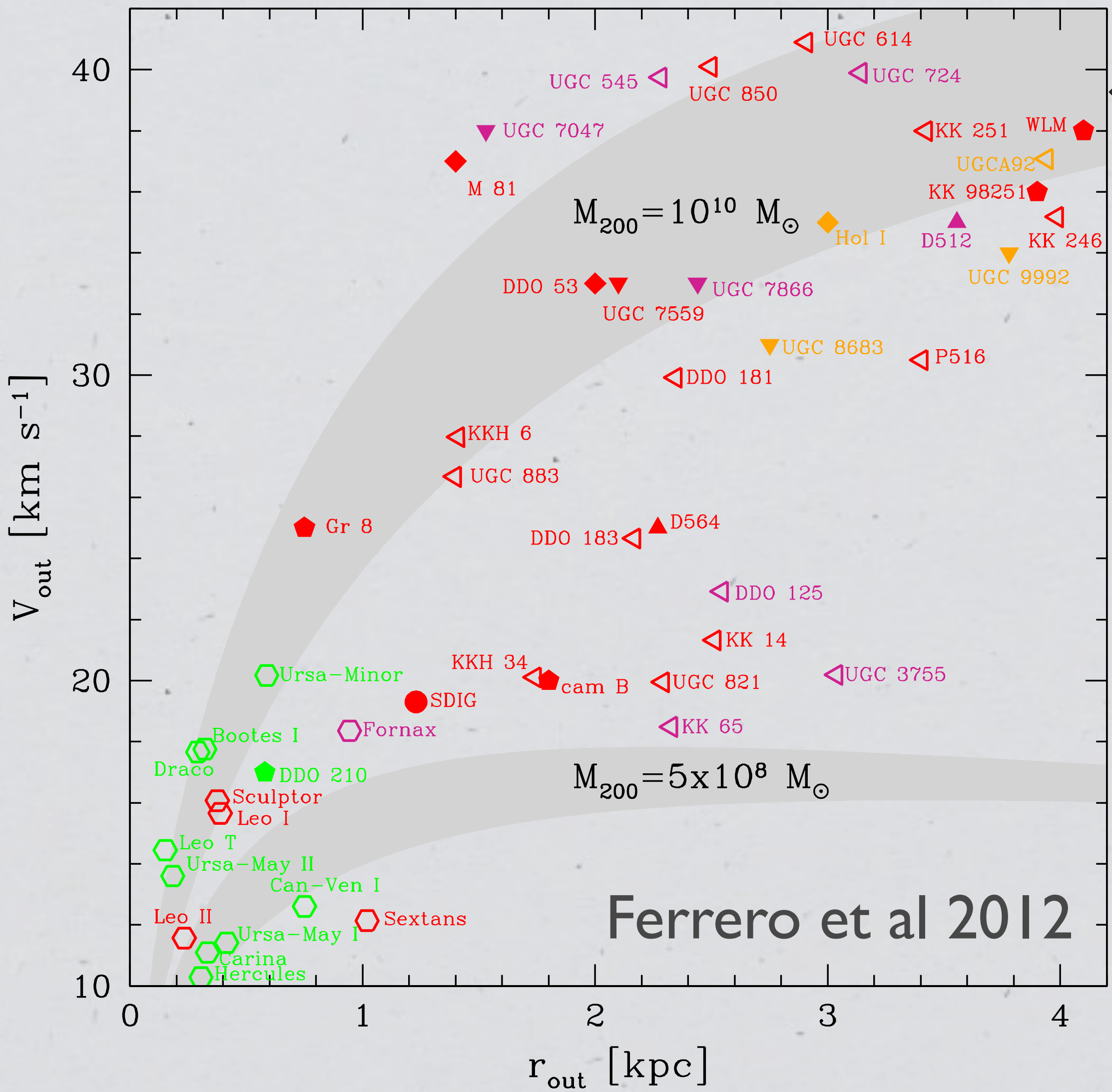
No consensus yet. See Walker and Penarrubia (2011) and Strigari, Frenk and White (2014).

TBTF

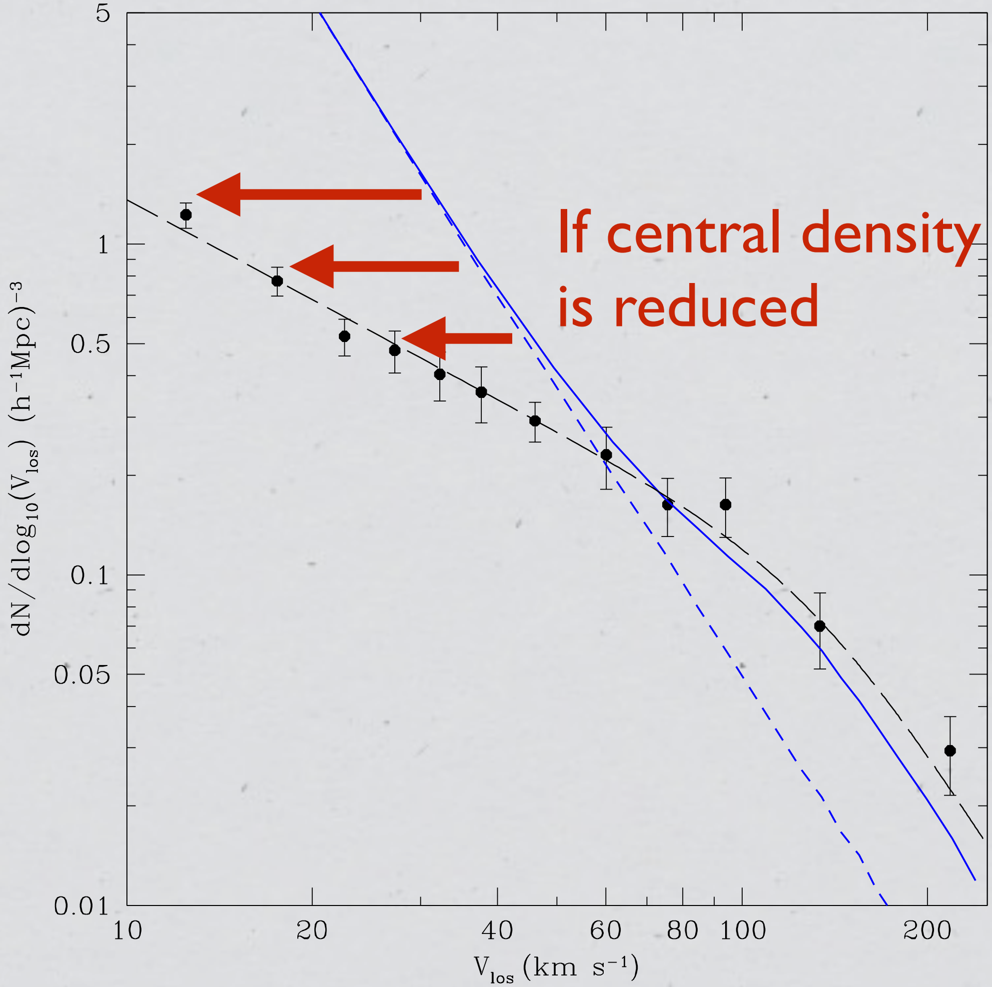
Nearby dwarf galaxies are under-dense

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**.



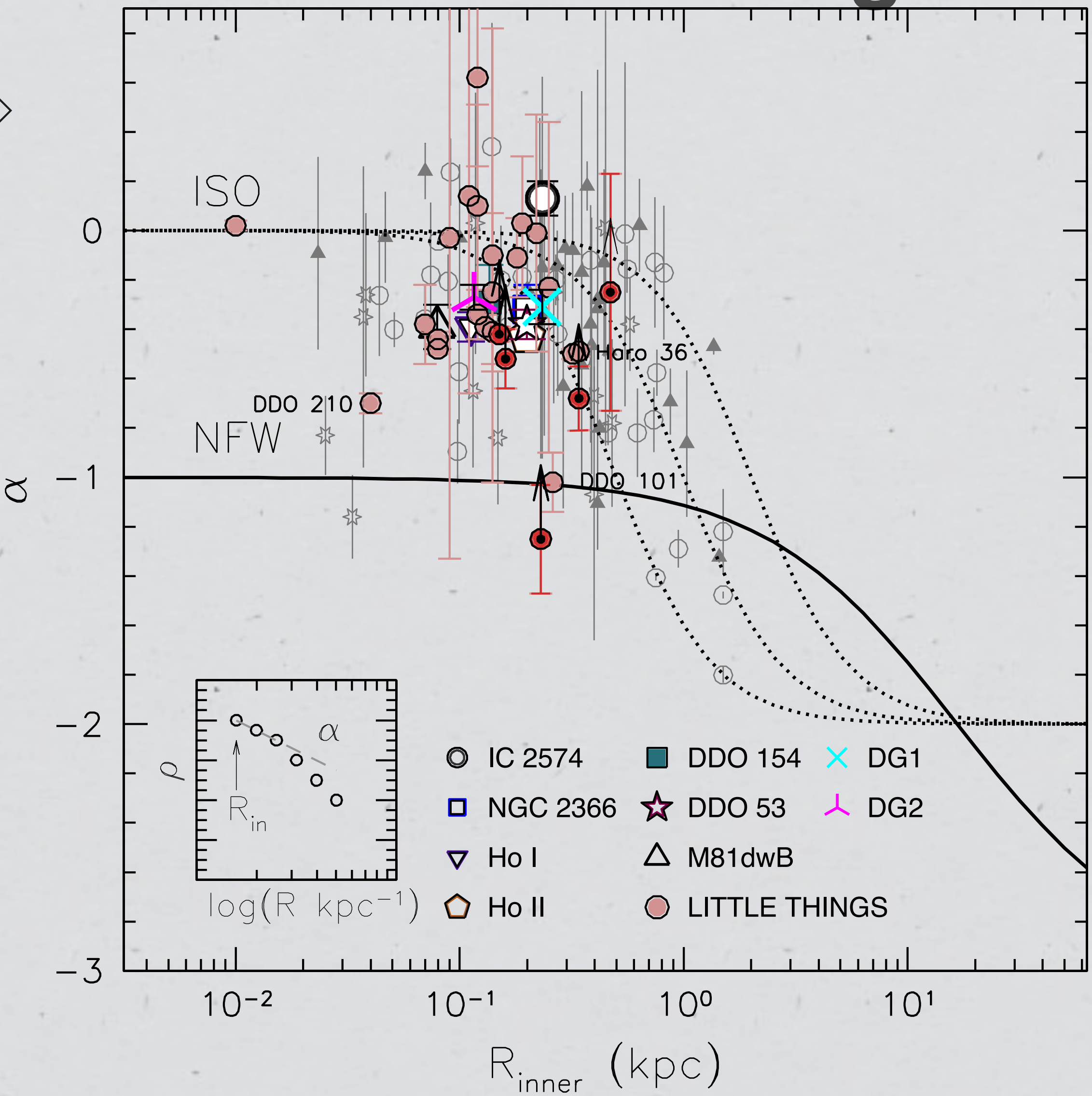
Abundance of Local Volume Galaxies



LCDM prediction:
blue solid curve

Klypin et al (2014)

Constant density cores in nearby dwarf galaxies



THINGS and LITTLE THINGS: close-by dwarfs (<10 Mpc), DM dominated, low mass (V~30-100 km/s)

Oh et al 2015

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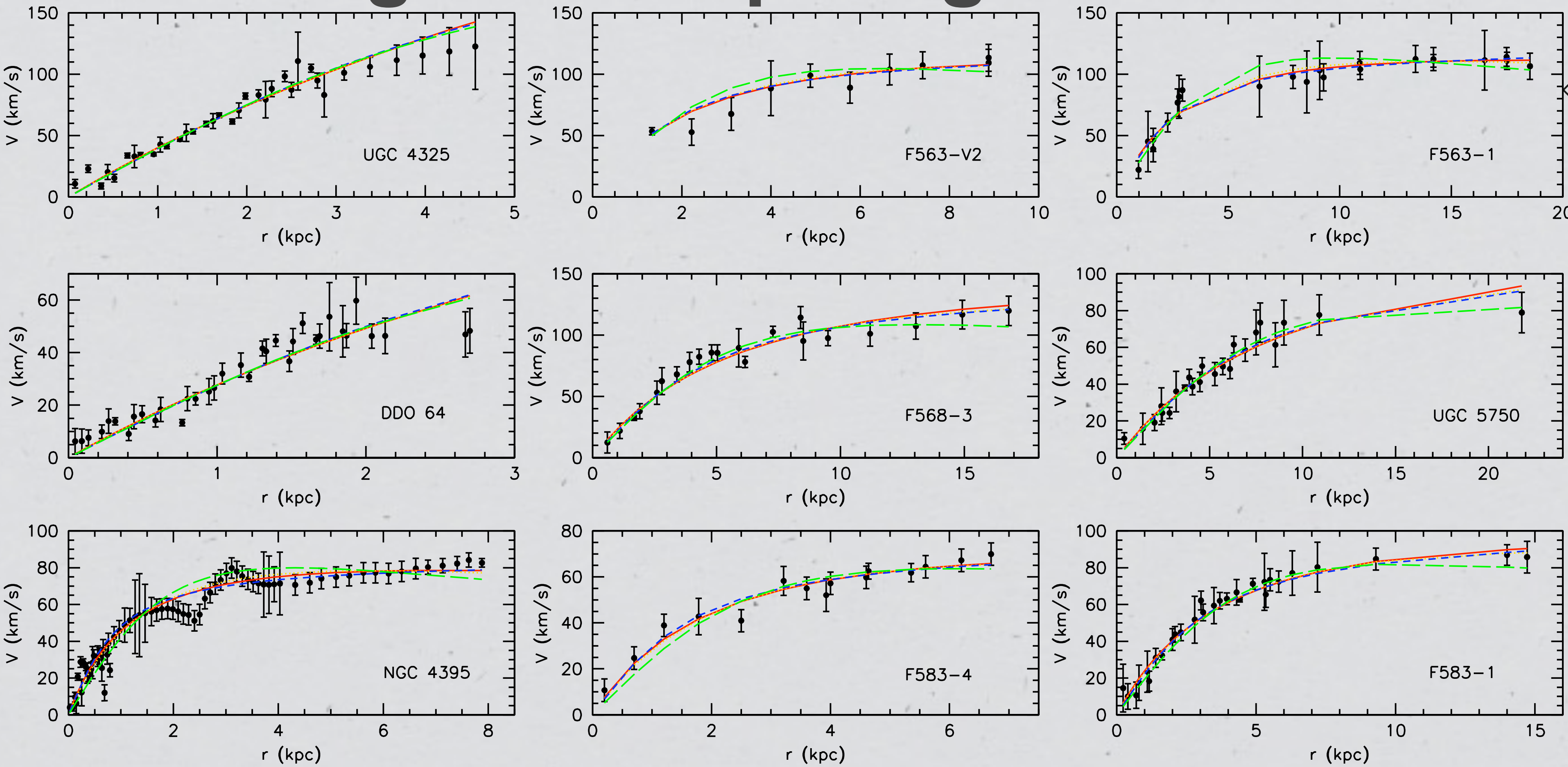
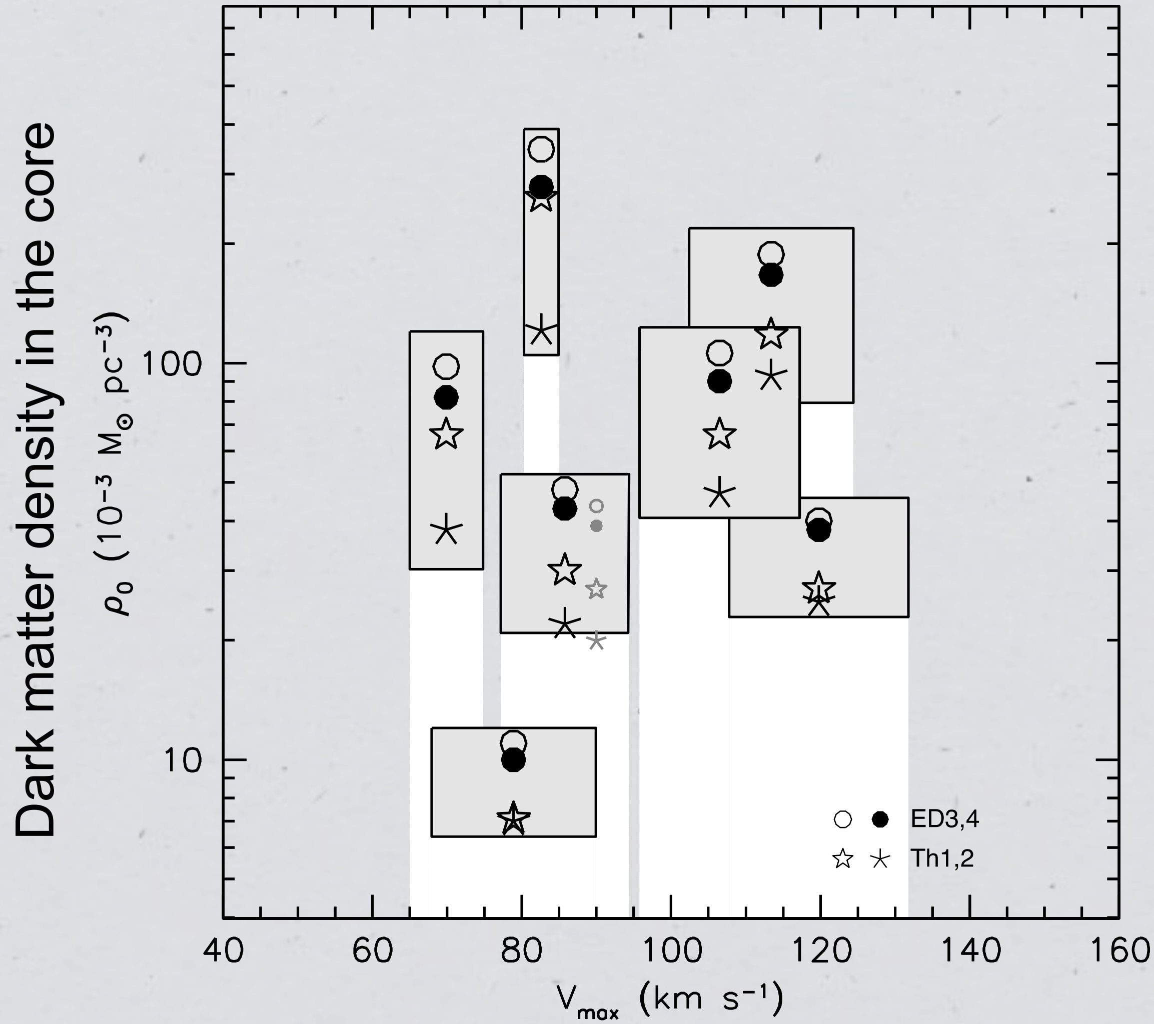
Constant density cores in low surface brightness spiral galaxies



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

There is a large scatter in core densities



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

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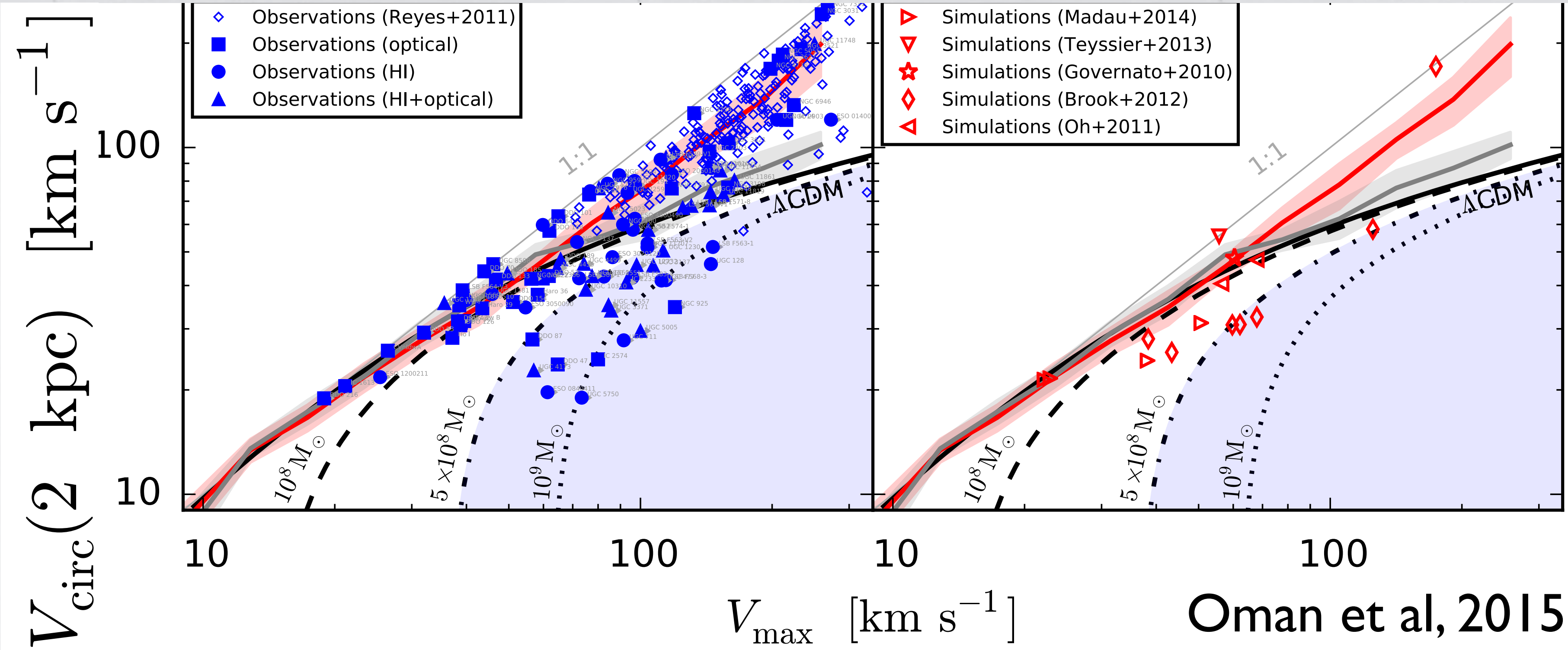

Oman et al, 2015

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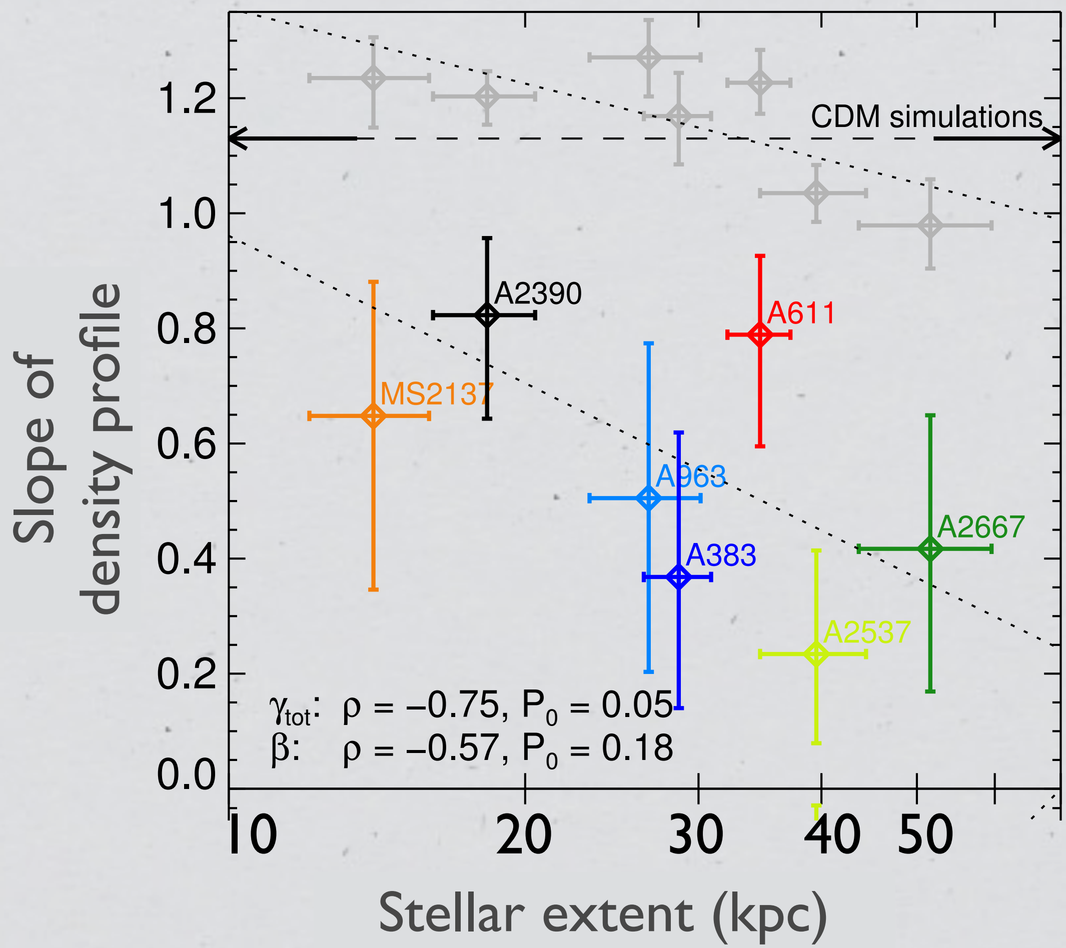
Cores of clusters of galaxies

Weak lensing, strong lensing and kinematics of stars used.

Cluster masses ~ 10^{15} M_{sun}.

Newman et al 2012



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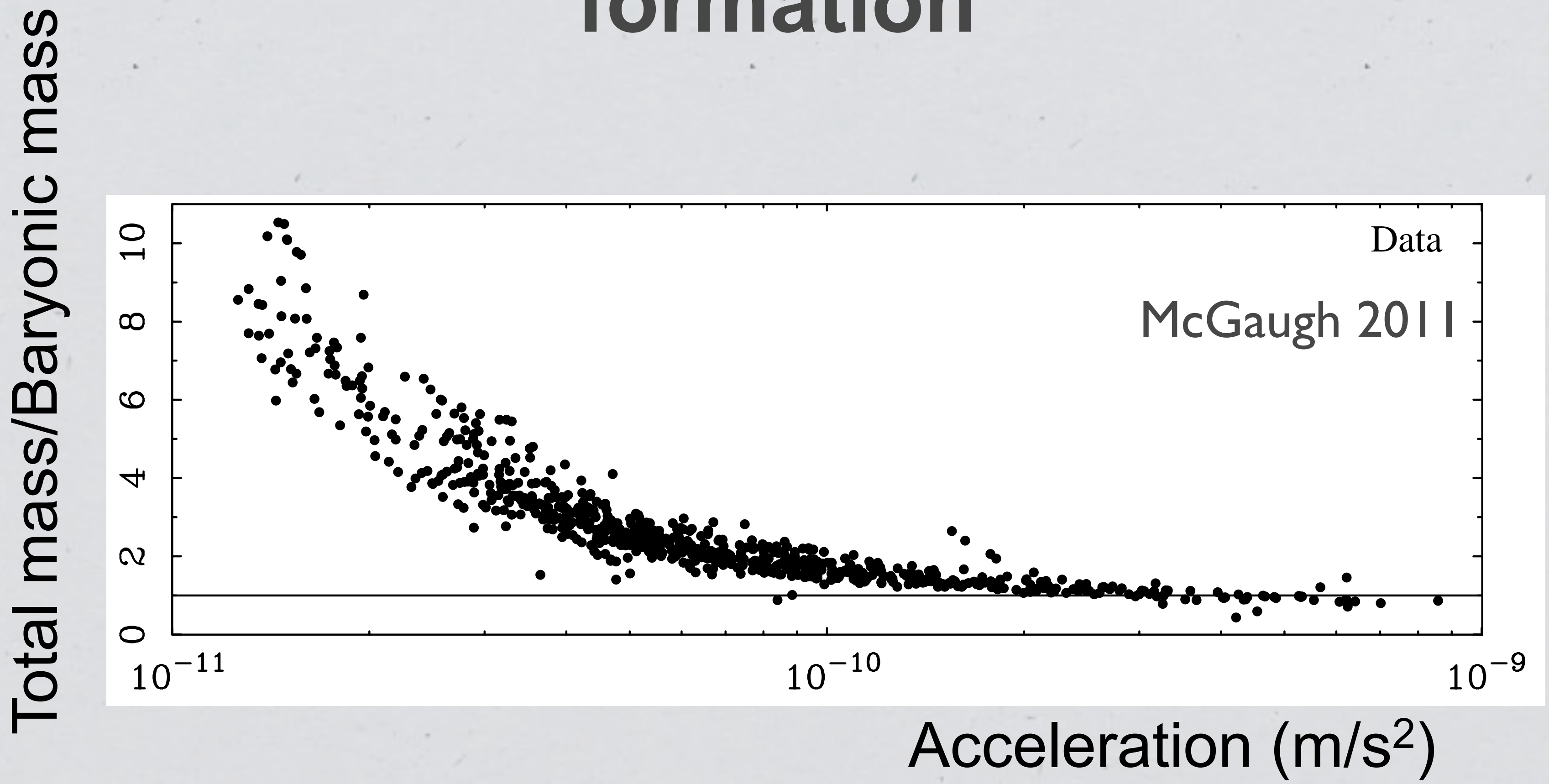
Correlations

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

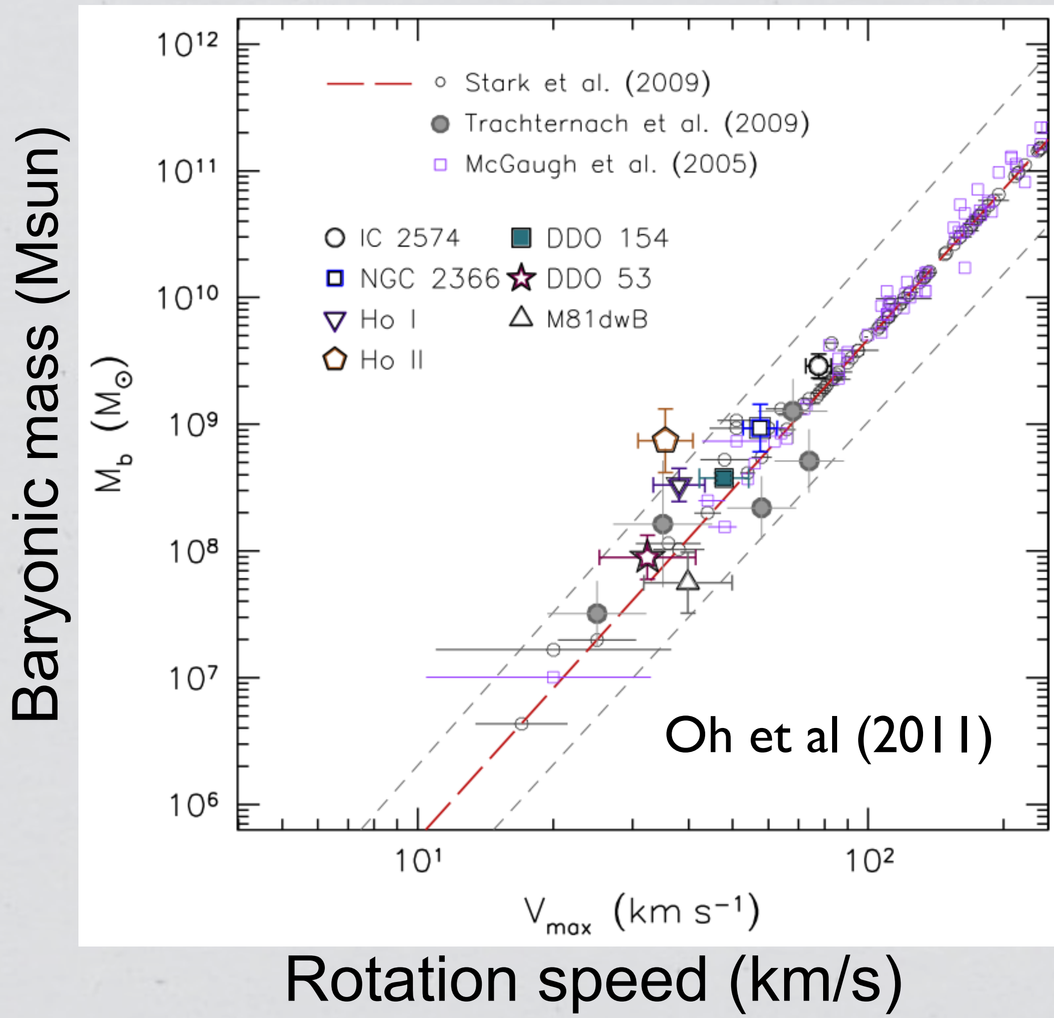
The acceleration scale in galaxy formation



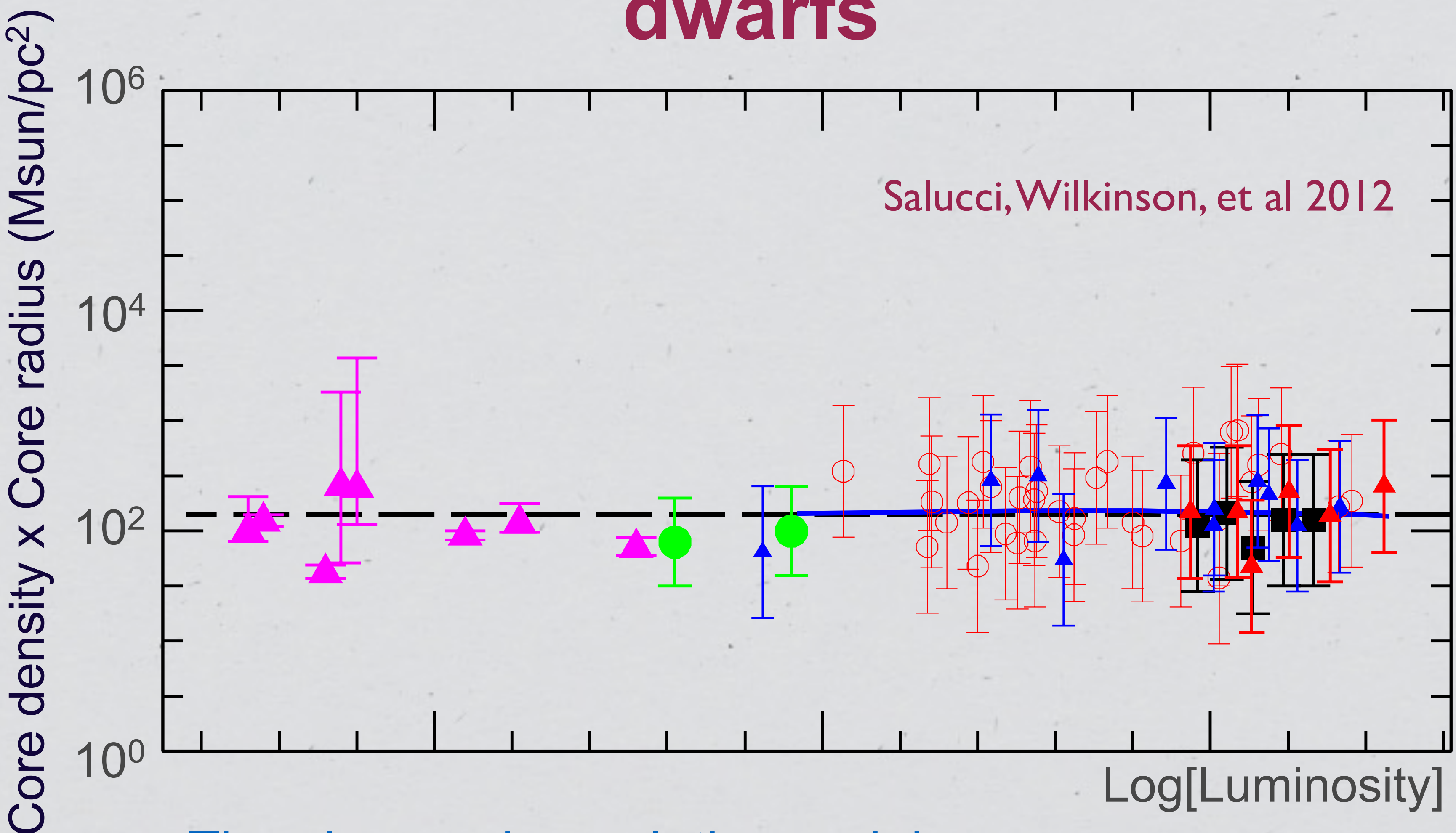
See Kaplinghat and Turner 2002 for an early attempt in the context of CDM

Baryonic Tully-Fisher relation

No LCDM model explains this satisfactorily, yet.

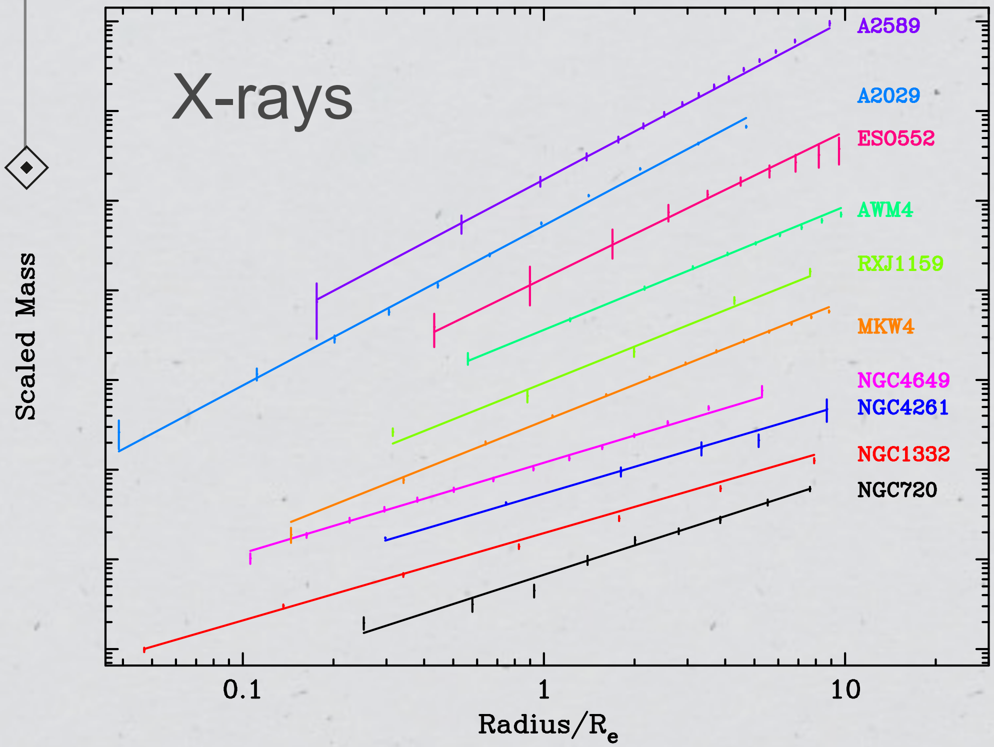


Core sizes and densities of spirals and dwarfs

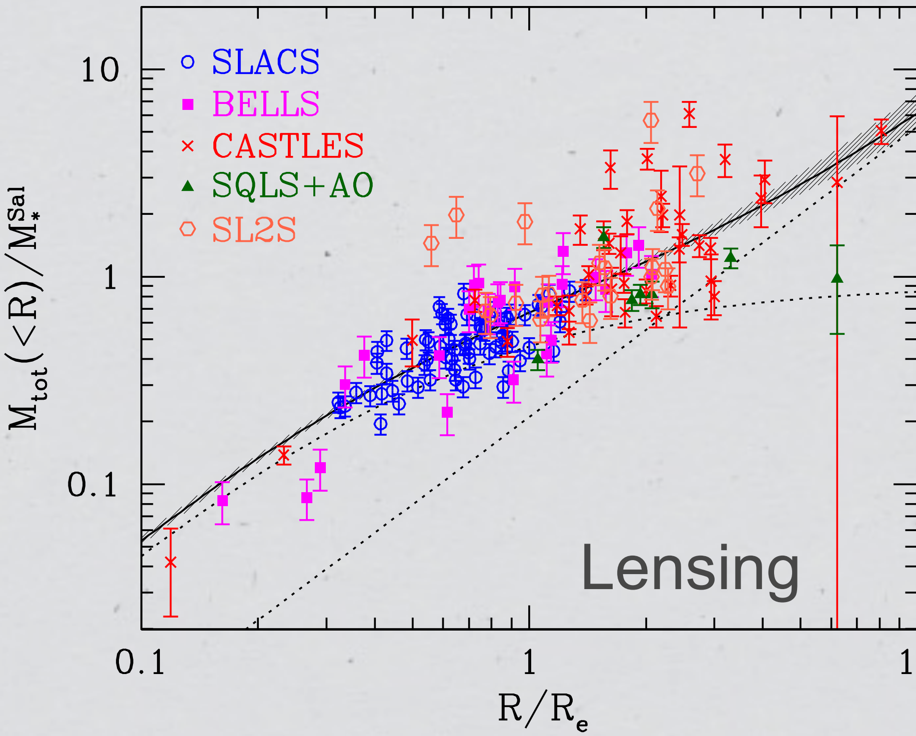


The observed correlation and the size of scatter need explanations.

Total matter in elliptical galaxies is featureless



Humphrey and Buote 2009



Oguri, Ruso, Falco 2014

Solutions

Perhaps cold dark matter with appropriate feedback can solve these problems. Here I will ask if self-interacting dark matter (without feedback for now) can solve all the small-scale puzzles and, if so, what are the correlated signatures.

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 [but see Cyr-Racine and Sigurdson 2012]. There is no significant dissipation of energy [but 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)

Brief history of SIDM

Proposals motivated by small-scale issues [Spergel and Steinhardt 2000, Firmani et al 2000]. Related early work on mirror dark matter [Mohapatra, Nussinov, Teplitz 2001; Foot, Volkas 2004]. See also Carlson, Machacek and Hall (1992).

Recent revival of large self-interaction strengths motivated first by model building [Ackerman, Buckley, Carroll, Kamionkowski (2008), 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 (WIMP/SIMP miracle), Asymmetric

Doesn't the Bullet Cluster rule out SIDM?

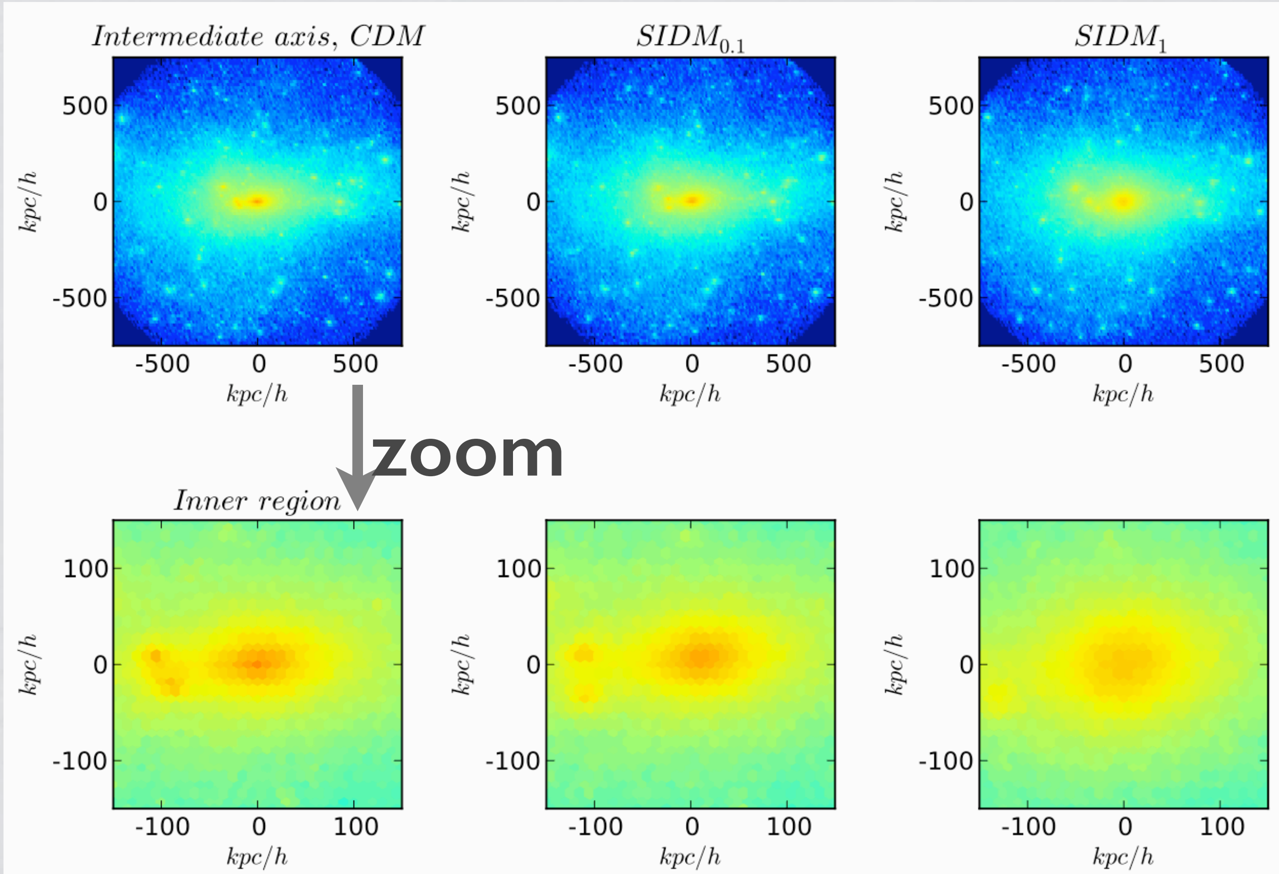
No.

Bullet cluster: $\sigma/m < \sim 1$ cm^2/g for relative speed v~3000 km/s.

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

Merging Cluster Collaboration (MC^2)

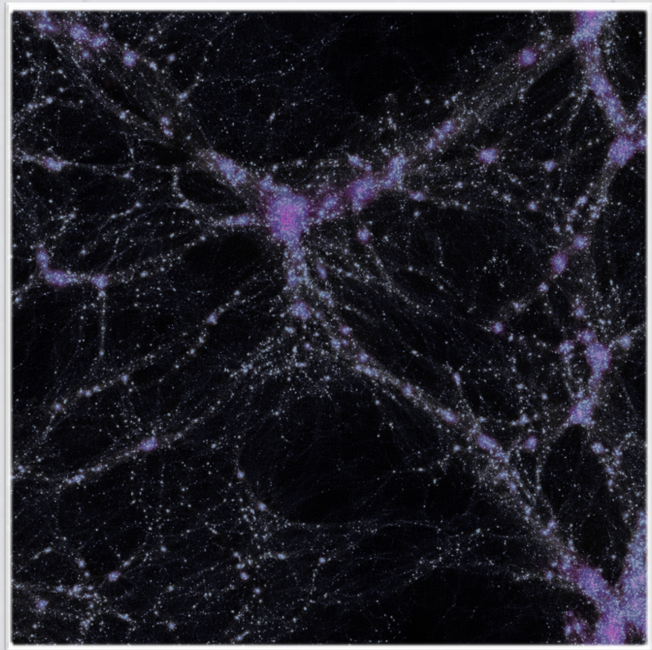
Don't cluster halo shapes rule out SIDM?

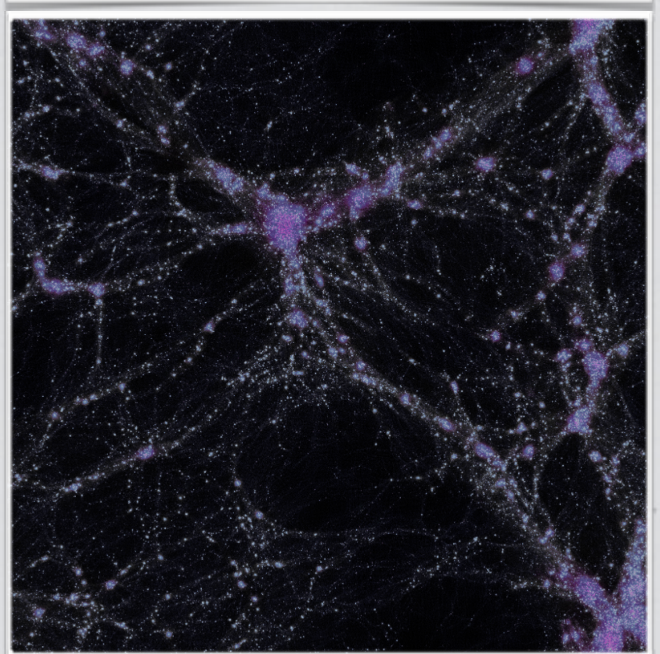


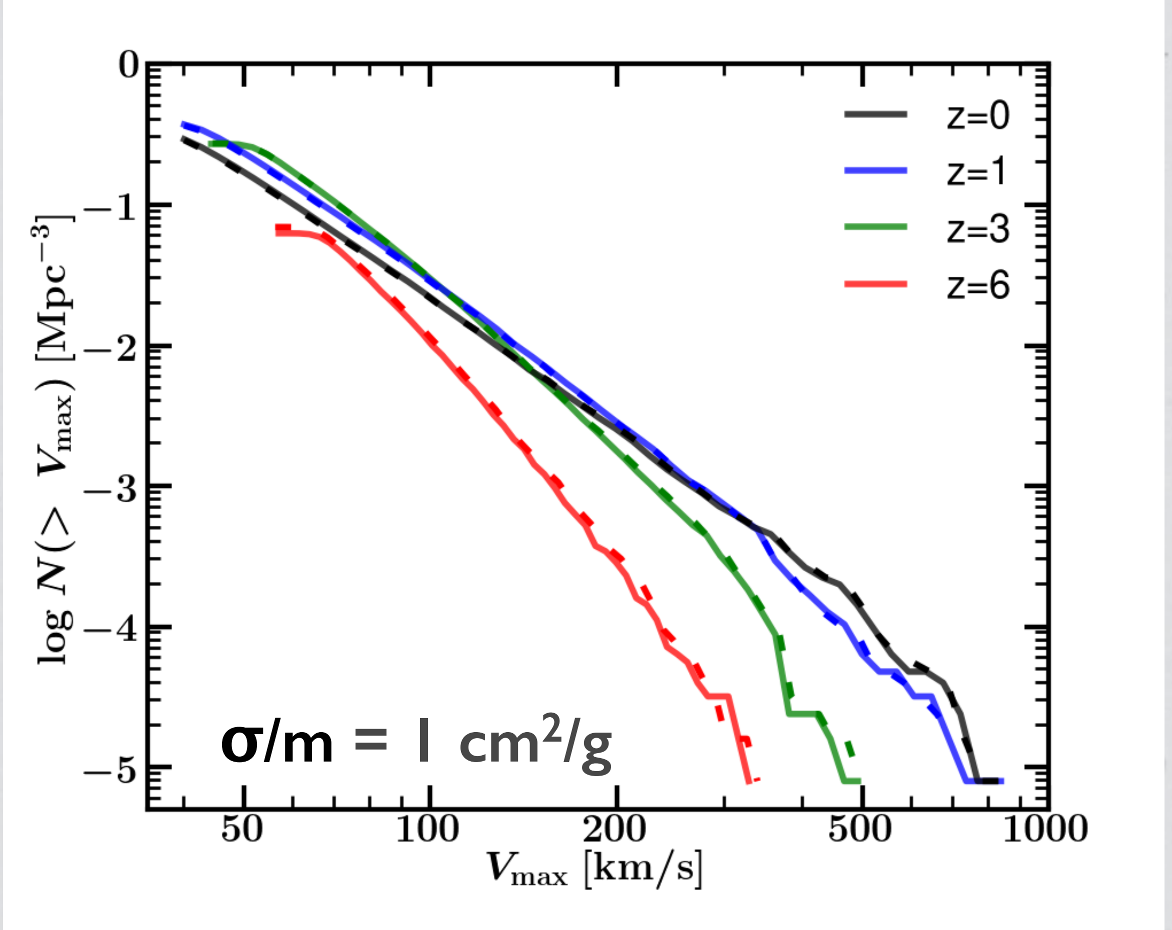
Constraints using shapes of LoCuSS clusters (Richards et al 2010) not better than about 1 cm^2/g.

Peter, Rocha, Bullock, Kaplinghat 2012

SIDM is the same as CDM on large scales

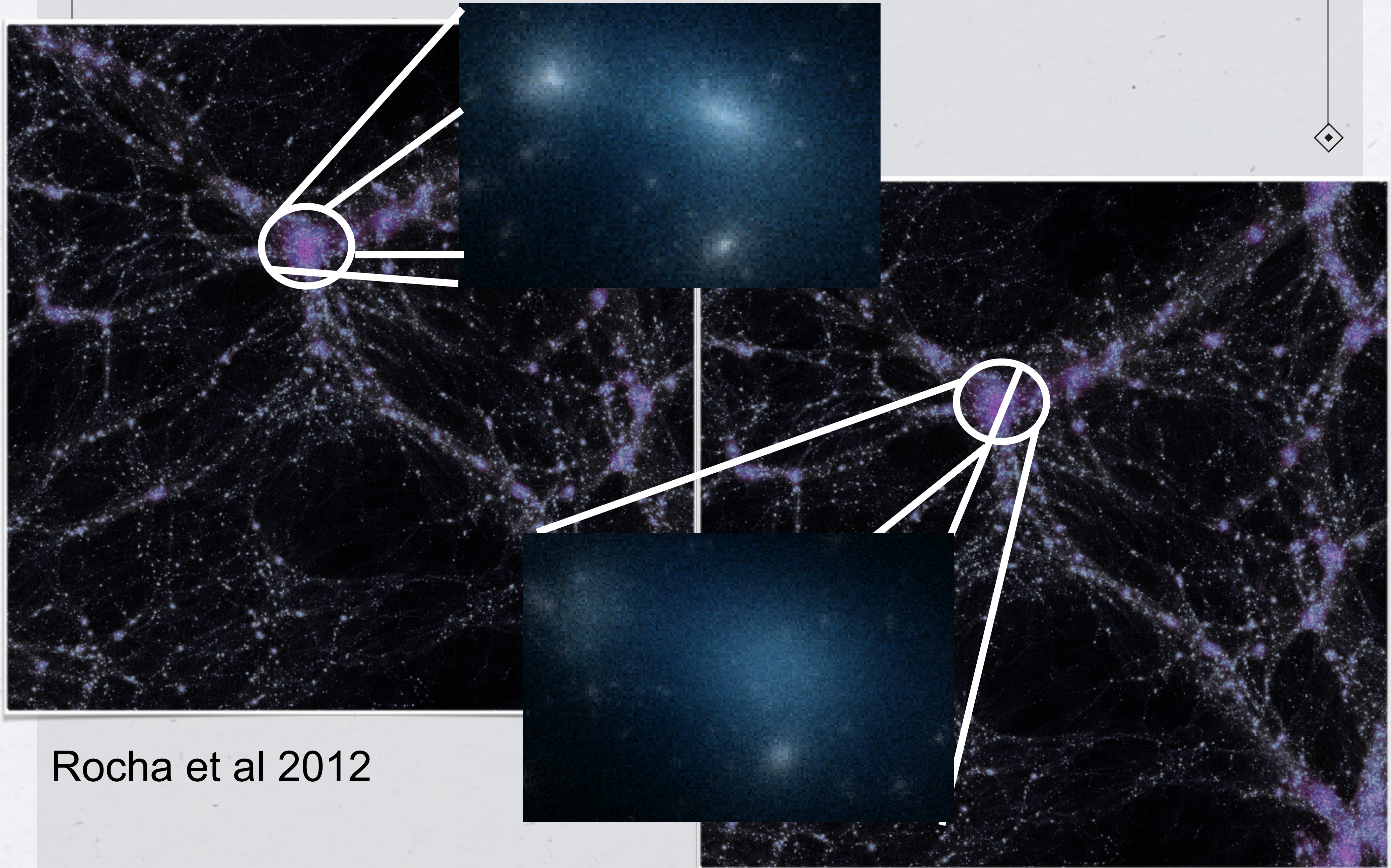






Rocha et al 2012

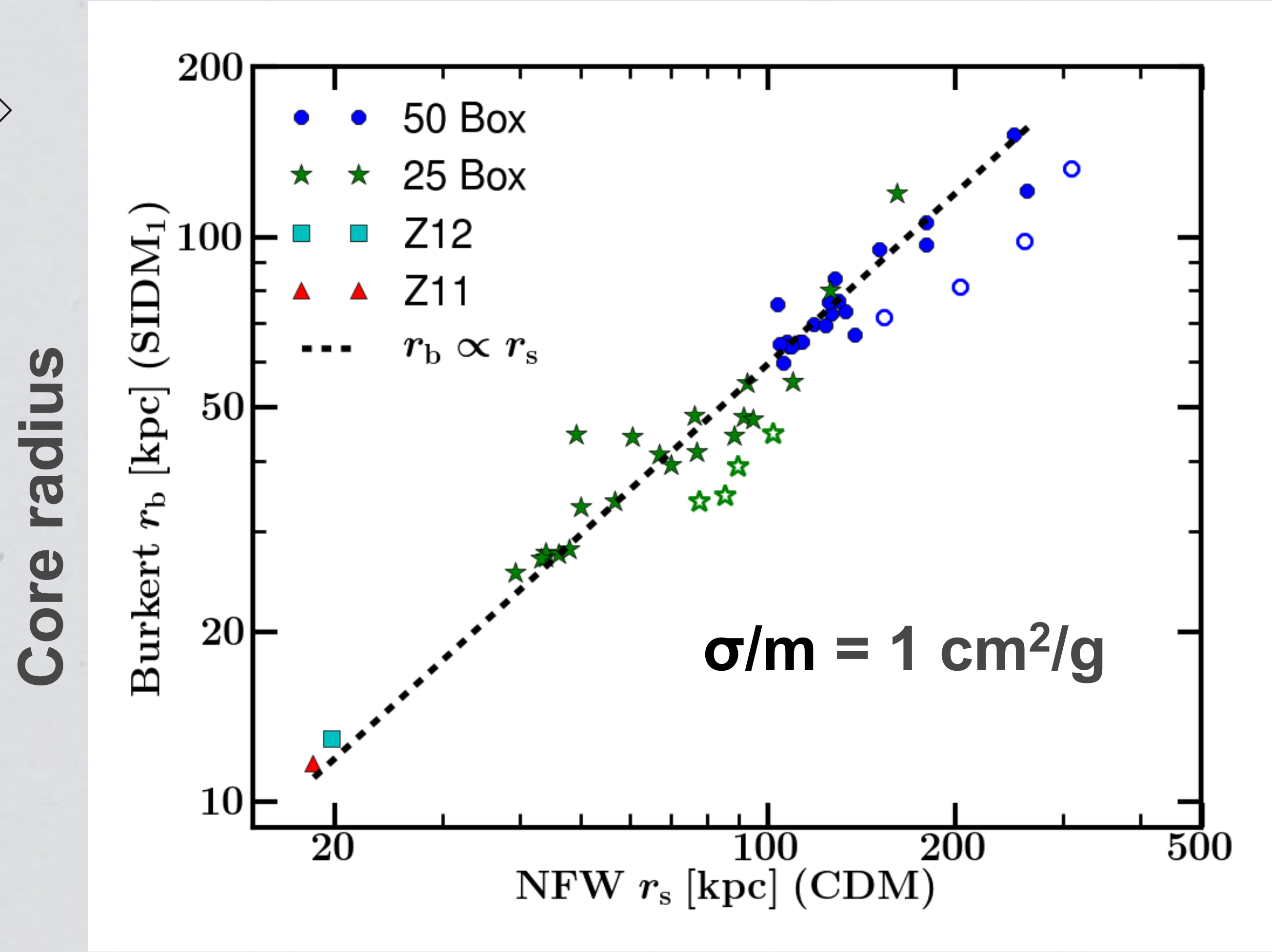
Differences only in the centers of galaxies



Rocha et al 2012

SIDM solution: core sizes

Outside this core radius, solution is CDM-like.



Core size ~ 0.7r$_S$, potentially large enough to explain spiral and dwarf galaxy observations.

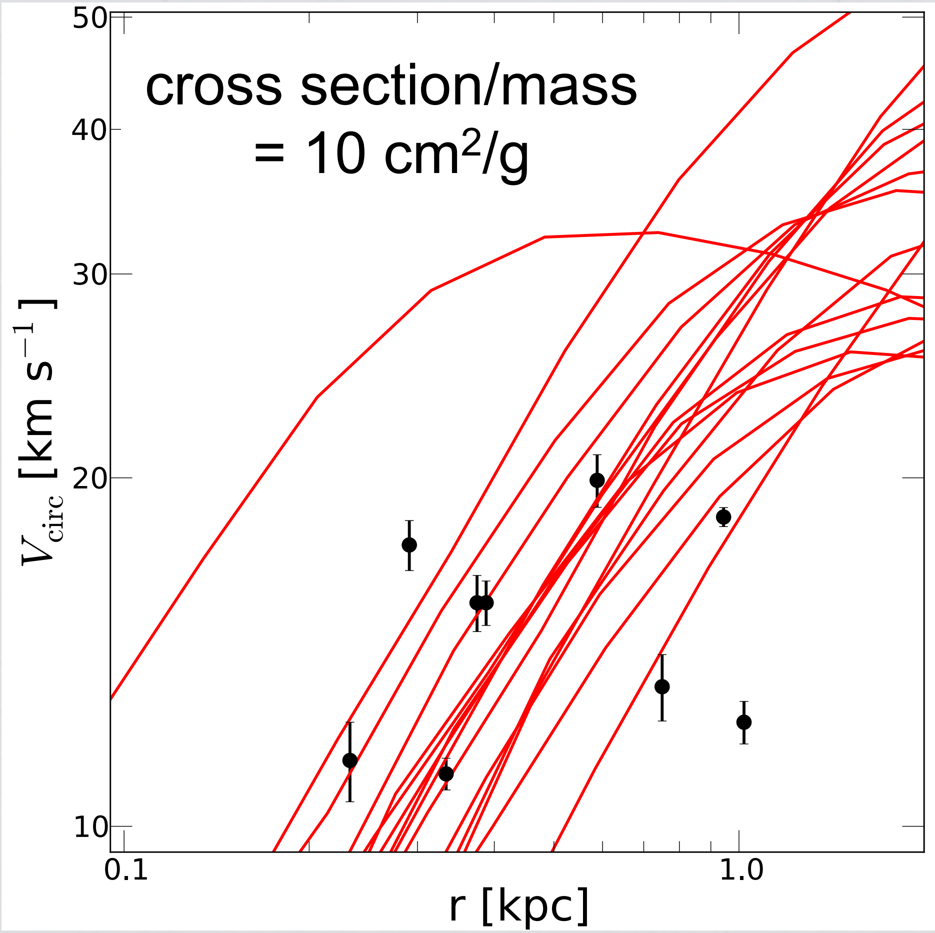
Rocha et al (2012)

Similar results from Fry et al (2015)

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]

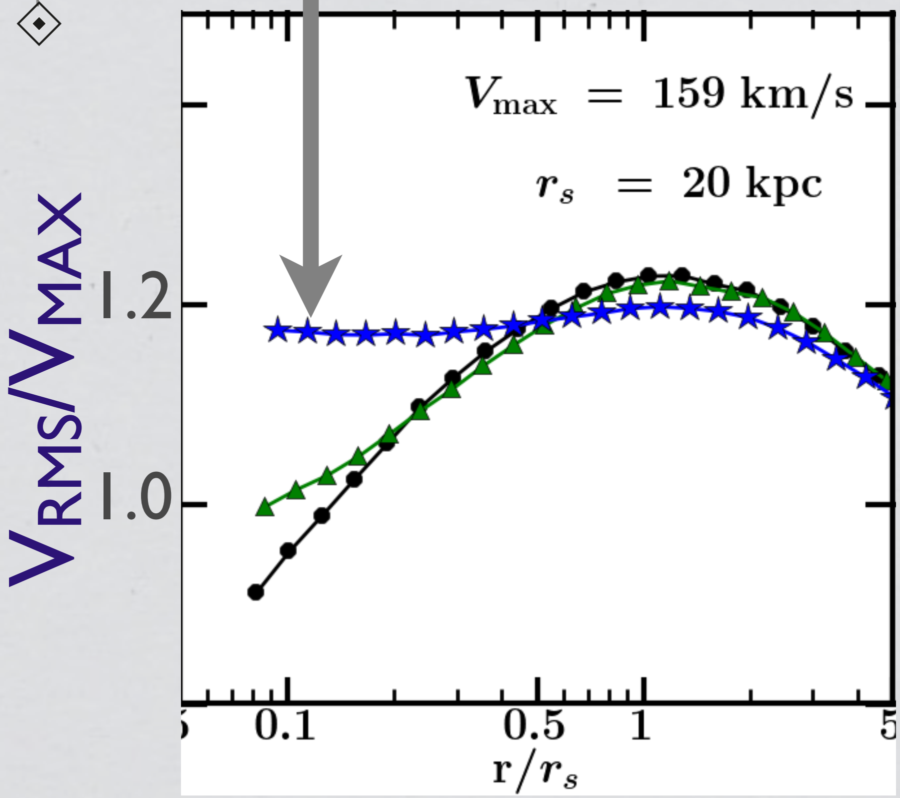
Includes velocity dependence of cross section that arises from broken U(1) [Feng, Kaplinghat and Yu (2010), Loeb and Weiner (2011)]

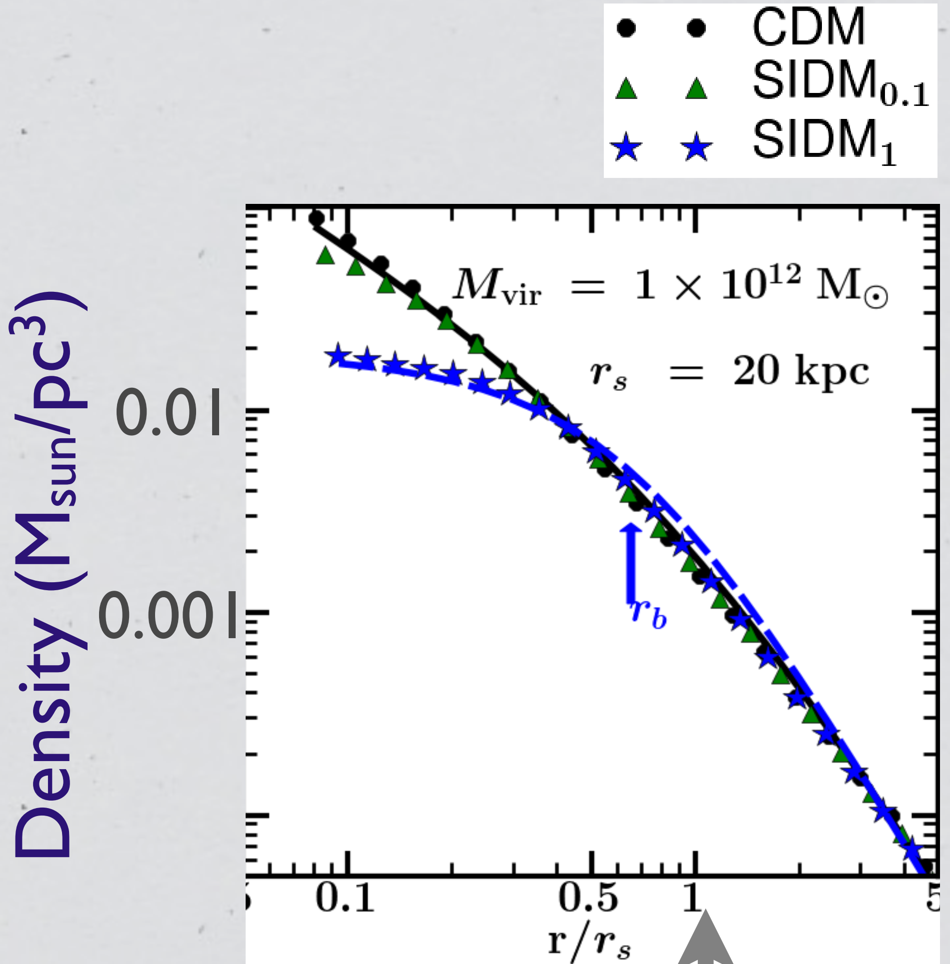


Vogelsberger, Zavala and Loeb 2012

How does SIDM work?

Isothermal

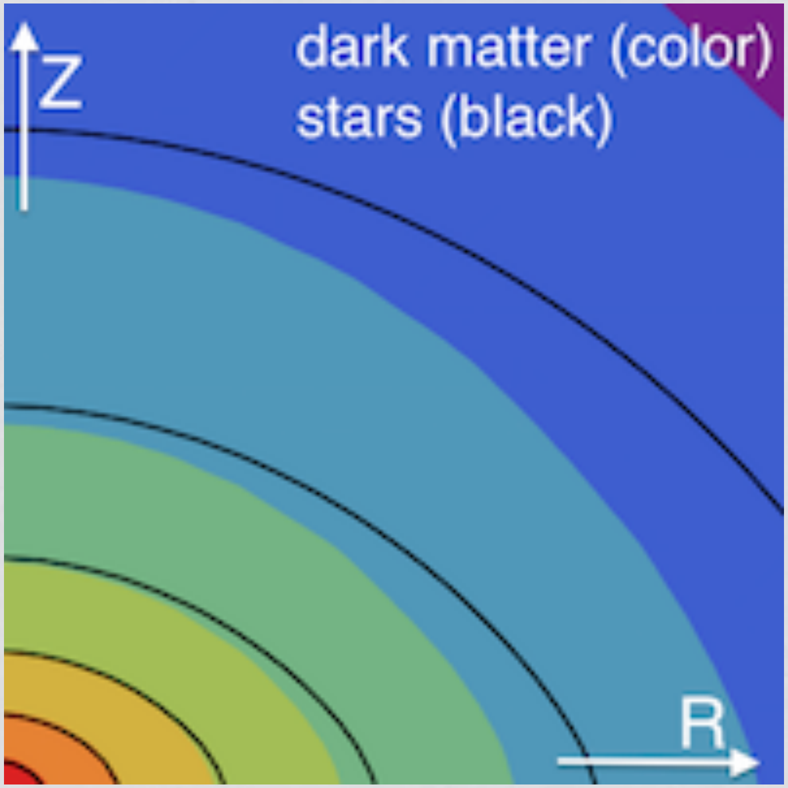




Rocha et al 2012

One interaction on average over halo age

Stars and dark matter tied in SIDM model



Isothermal => SIDM tracks the stellar potential in the regions where stars dominate, i.e., dark and luminous matter are tied.

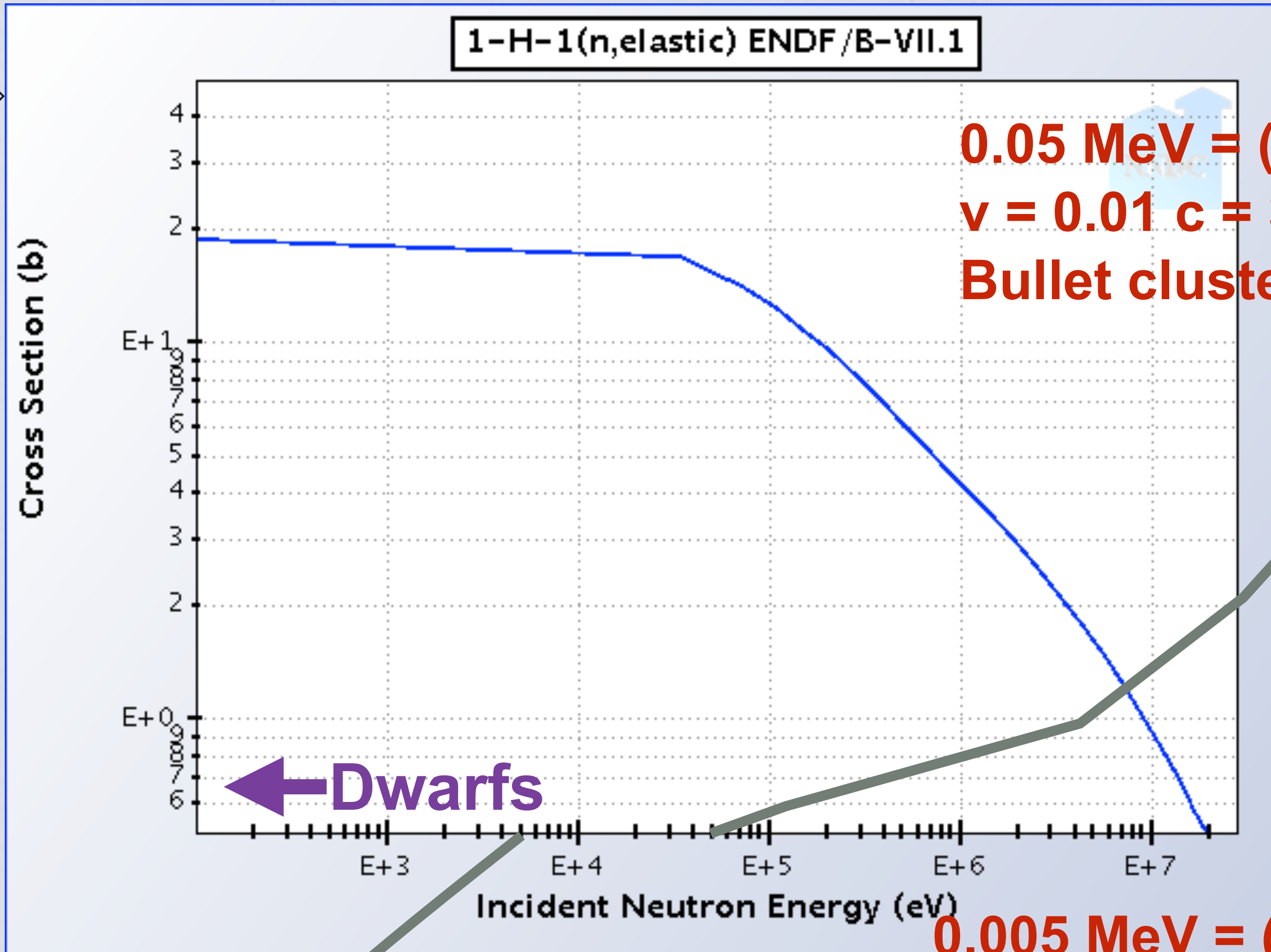
When baryons dominate, dark matter cores become small!

Kaplinghat, Keeley, Linden and Yu, PRL 2014

See Vogelsberger, Zavala, Simpson and Jenkins 2014 for an effect in the opposite regime.

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



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

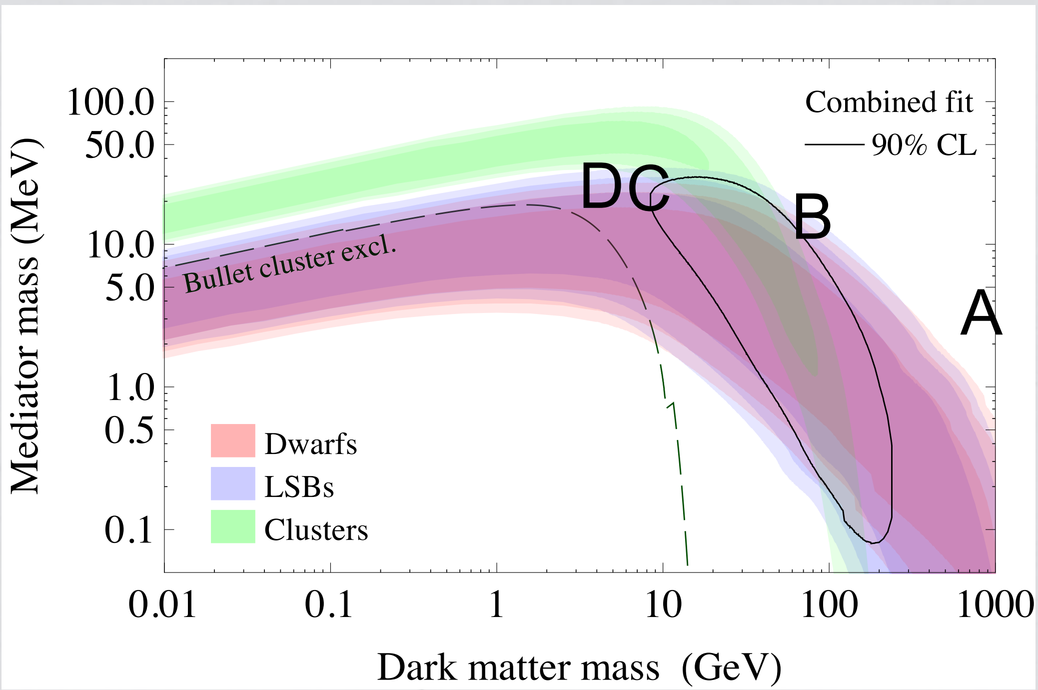
$$V = \pm \frac{\alpha_x}{r} \exp\left(-m_\phi r\right)$$

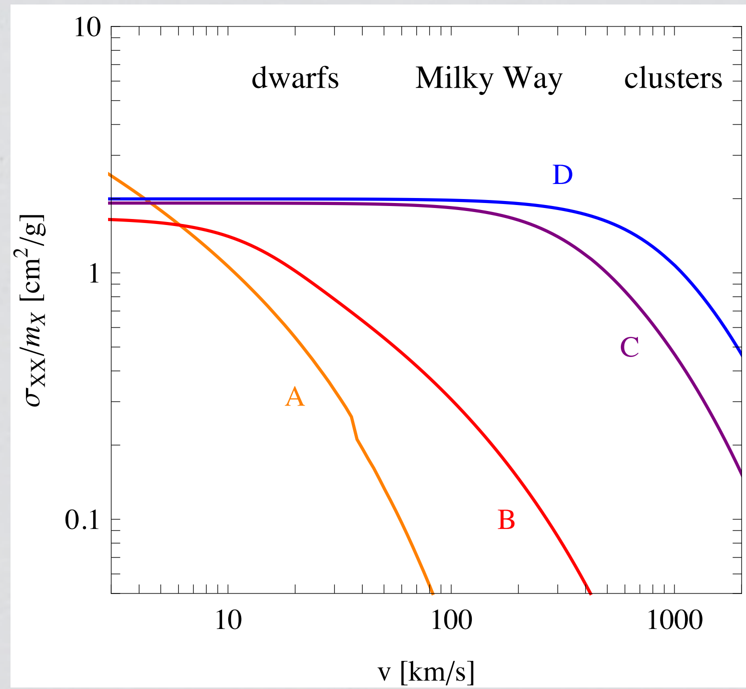
A wide range of velocity dependence possible.
Tulin, Yu, Zurek 2012

Similar SIDM phenomenology in non-abelian hidden sectors.
Boddy, Feng, Kaplinghat and Tait (2014)

Model with 2->2 and 3->2 scattering (SIMP miracle). Hochberg, Kuflik, Volansky and Wacker (2014)

Astrophysics can fix the mediator and dark matter masses!





Kaplinghat, Tulin and Yu, in prep

A simple SIDM model

The light mediator must decay or it will over-close the universe. 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.**

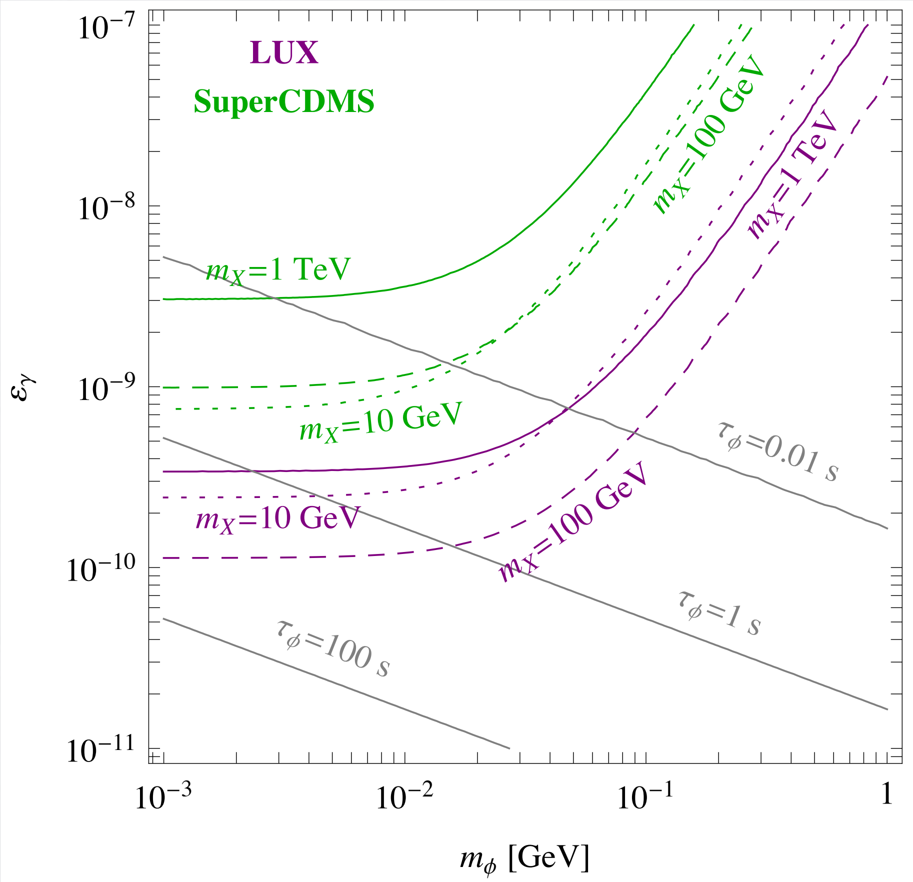
Direct: Momentum dependent form factor -- $1/(q^2+m_\varphi{}^2)^2$ -- no longer contact interaction!

Kaplinghat, Tulin, Yu, PRD 2013

Indirect: annihilation products are elections, positrons, photons and neutrinos.

Kaplinghat, Linden, Yu (2015)

Simple model already constrained



Del Nobile, Kaplinghat and Yu, in prep

Region above colored lines ruled out.

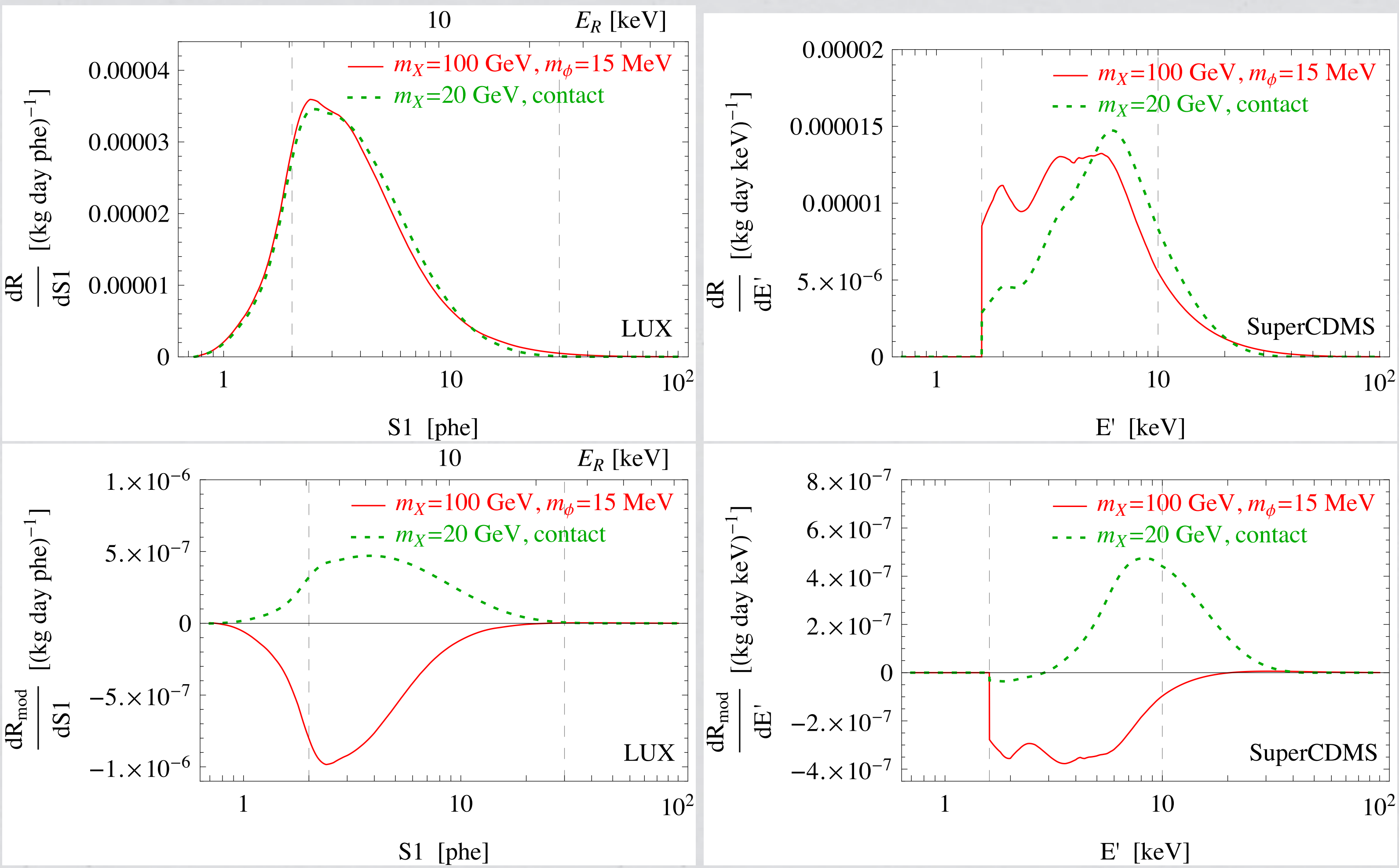
Magenta: LUX
Green: SuperCDMS

Dotted: DM mass = 10 GeV
Dashed: DM mass = 100 GeV
Solid: DM mass = 1 TeV

Distinguishing WIMP from SIDM in direct detection experiments

Del Nobile, Kaplinghat and Yu, in prep

Multiple targets and annual modulation crucial



del Nobile, Kaplinghat and Yu, in prep

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 with a large scatter. 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 have direct and indirect signals.