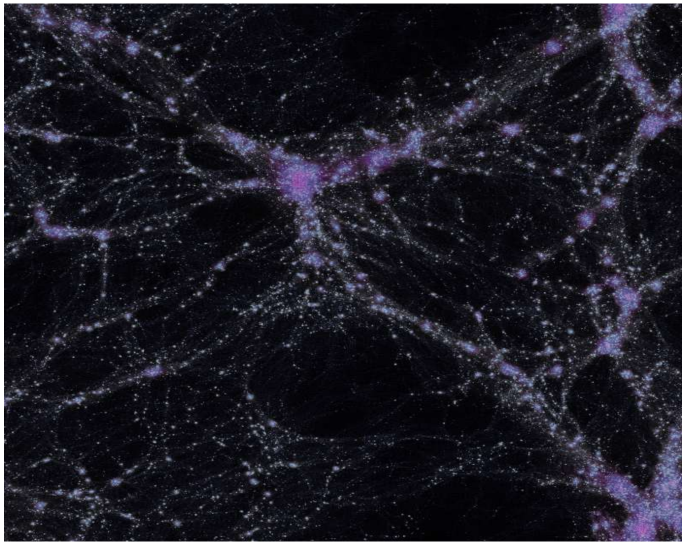
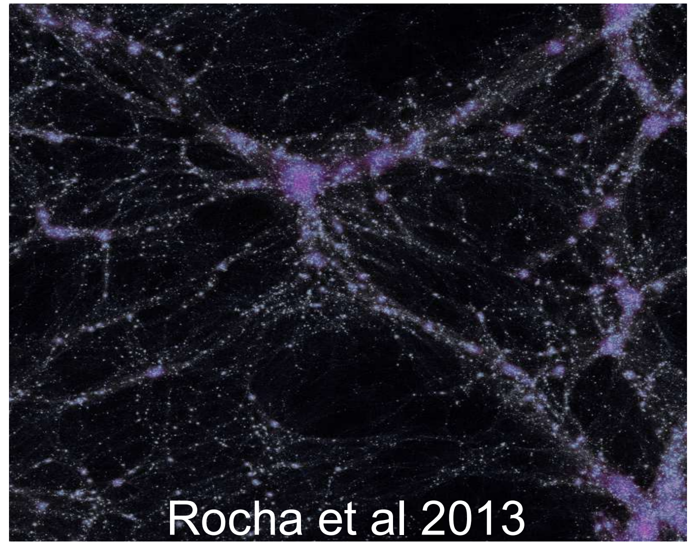
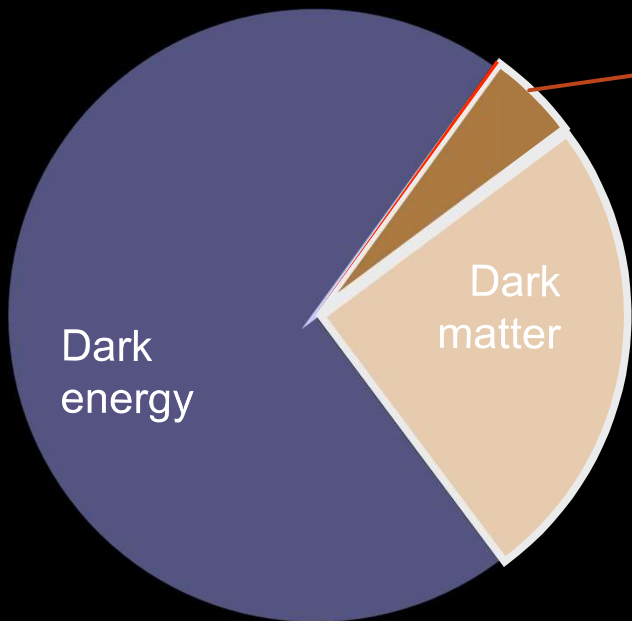


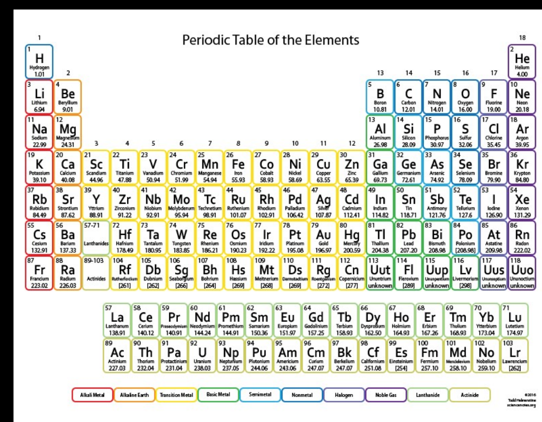


Self-interacting dark matter (SIDM)

Manoj Kaplinghat

The predictions of the ΛCDM model agree well with the observed large-scale structure of the Universe.





Visible sector particles interact with each other.
Why shouldn't dark sector particles?

SIDM phenomenology motivated by rotation curves

Originally proposed by Spergel and Steinhardt, PRL 2000.
Version below by MK, Sean Tulin and Hai-Bo Yu, PRL 2016

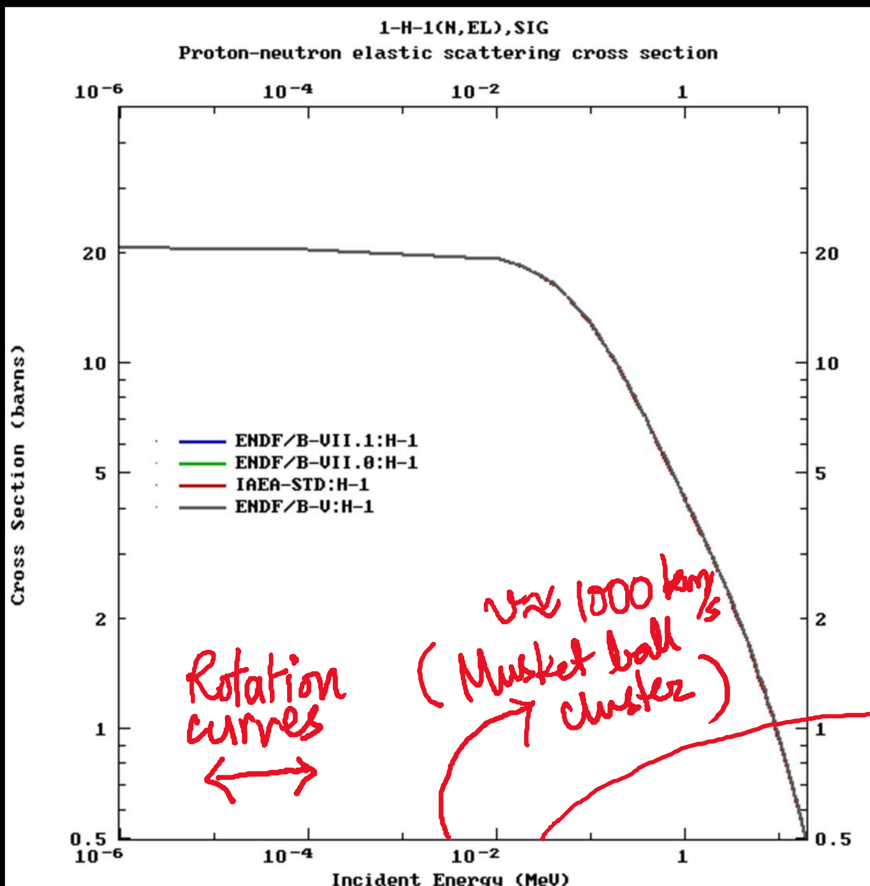
$$\frac{\sigma}{m} = \text{few } \frac{\text{cm}^2}{\text{g}}$$

(in galaxies)

Why?
-- Fits spiral galaxy rotation curves well
-- DM halo becomes insensitive to star formation history because self-interactions push system towards equilibrium quickly enough.

Cross section must be significantly smaller at v ~ 1000 km/s.

A motivating Standard Model example



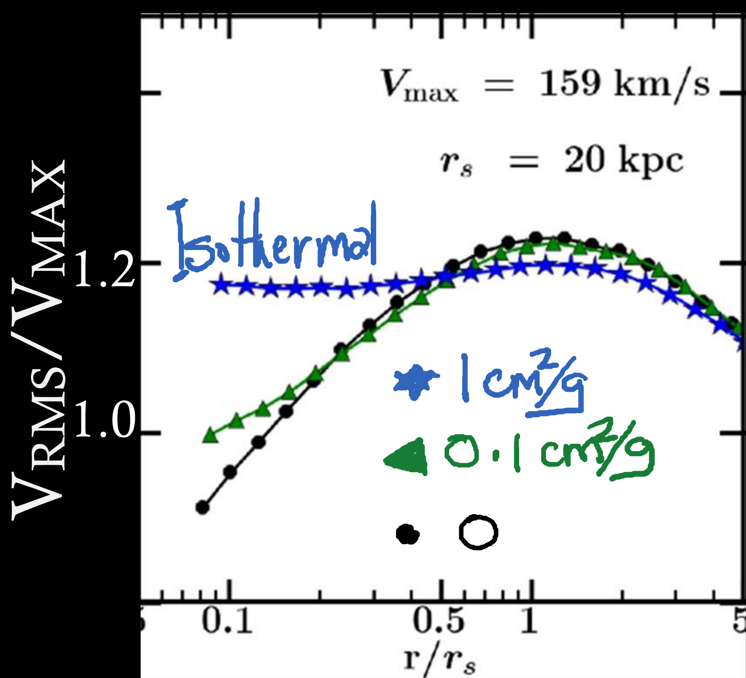
For velocity dependence, you need two scales, or one extra parameter in addition to the mass of the dark matter particle.

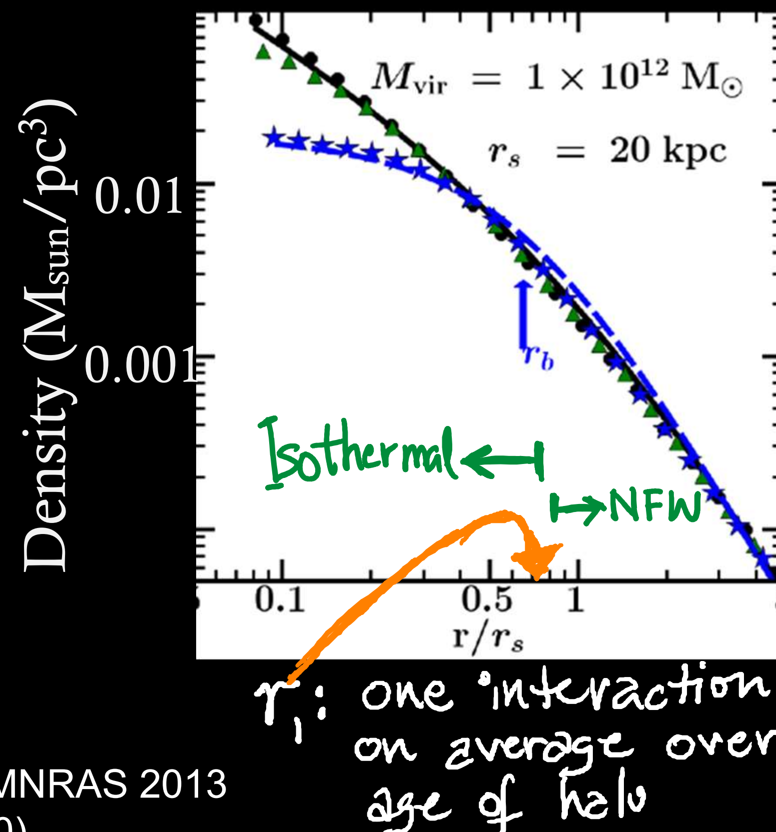
v ≈ 3000 km/s (Bullet cluster)

Focus of this talk will be on two ways to get information about dark matter self-interactions.

- **Stellar and dark matter densities in the field galaxies (core-cusp and related issues)**
- **Stellar and dark matter densities of satellite galaxies (too-big-to-fail and related issues).**
- **Briefly mention the implications for galaxy clusters and cosmology.**

Key physics in galaxies: thermalization of the inner halo





With James Bullock, Miguel Rocha, Annika Peter, MNRAS 2013
Builds on Dave, Spergel, Steinhardt, Wandelt (2000)

SIDM halo profile for field galaxies

Inside r1, $\rho_{\mathrm{SIDM}}(r) = \rho_0\, e^{-\Phi\,(r)/kT}$

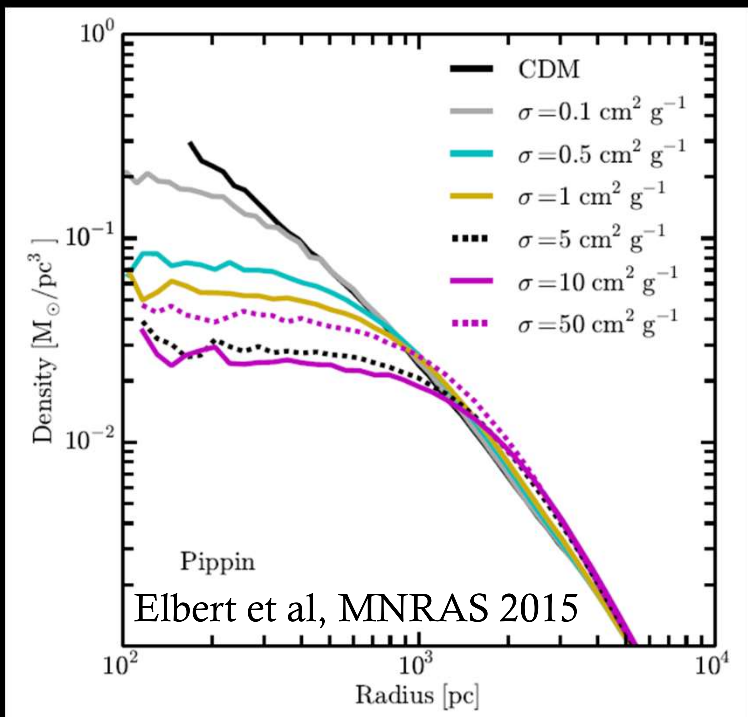
gravitational potential
of dark matter and baryons

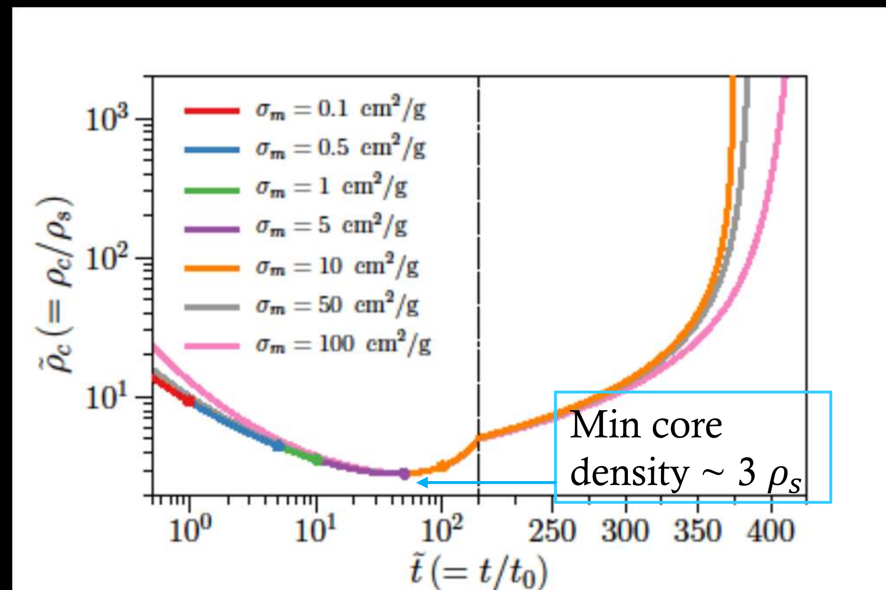
Outside r1, $\rho_{\mathrm{SIDM}} = \rho_{\mathrm{CDM}}$

Match mass and density at r1 to fix ρ_0 and T in terms of CDM (NFW) halo parameters Vmax and Rmax.

With Ryan Keeley, Tim Linden and Hai-Bo Yu, PRL 2014

Common evolution of a SIDM halo: core expansion and then core collapse





With Nishikawa and Boddy (2019)

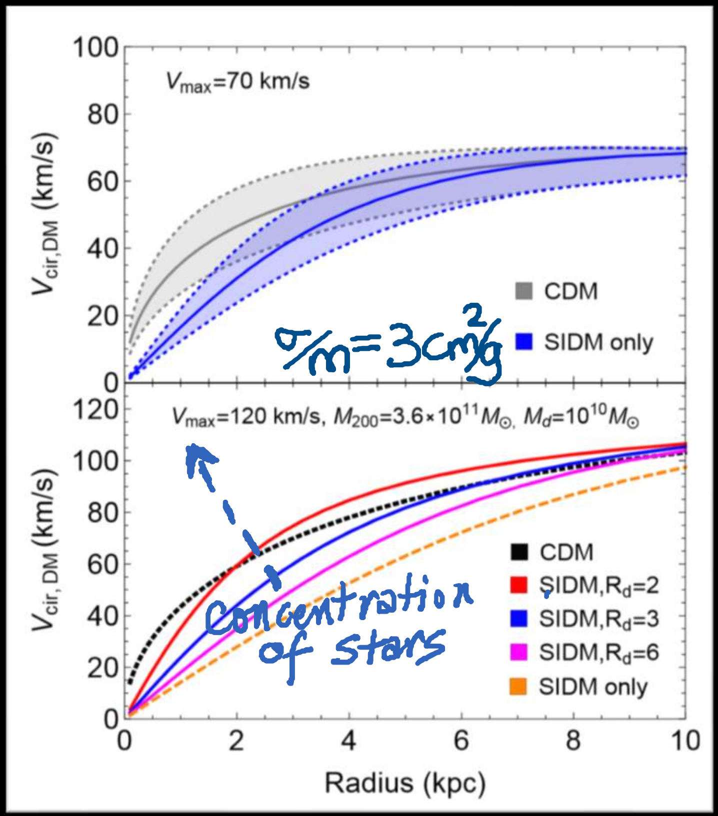
$$t_0 \propto \left(\rho_s V_{max} \frac{\sigma}{m} \right)^{-1}$$

Rotation curves of field galaxies

SIDM does not predict large cores in all galaxies

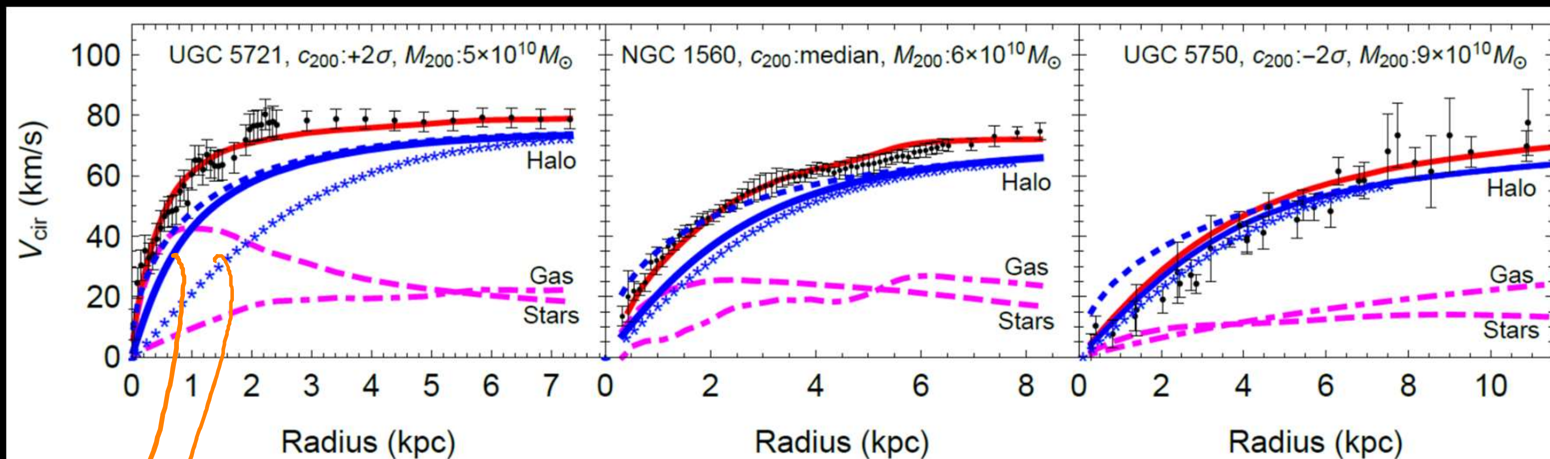
As stellar (and gas) density increases, cores become hard to discern (i.e., cuspy).

For low-surface brightness galaxies, core size is comparable to NFW scale radius (easily observable)



With Ayuki Kamada, Andrew Pace and Hai-Bo Yu, PRL 2017

How SIDM explains the diverse rotation curves

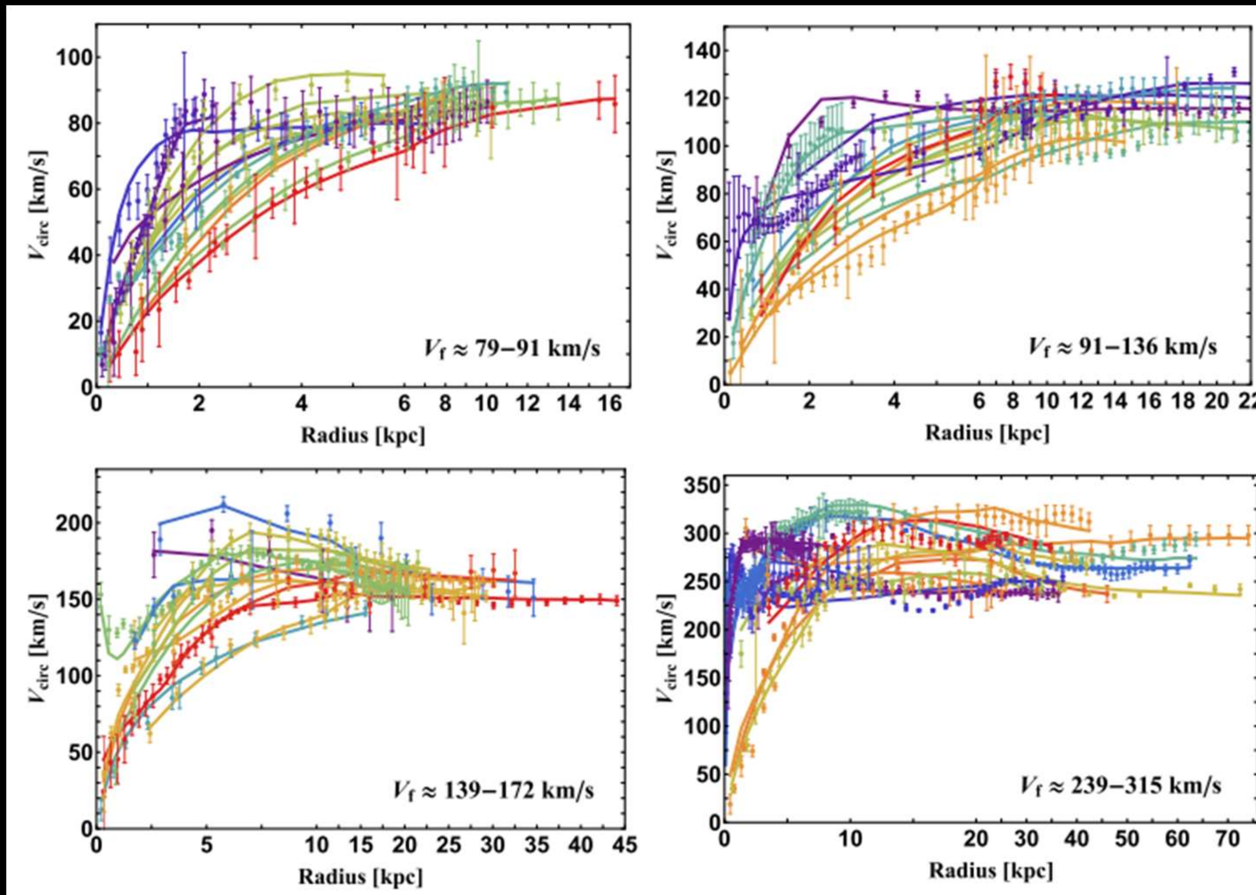


without including the potential of stars

correct SIDM density profile

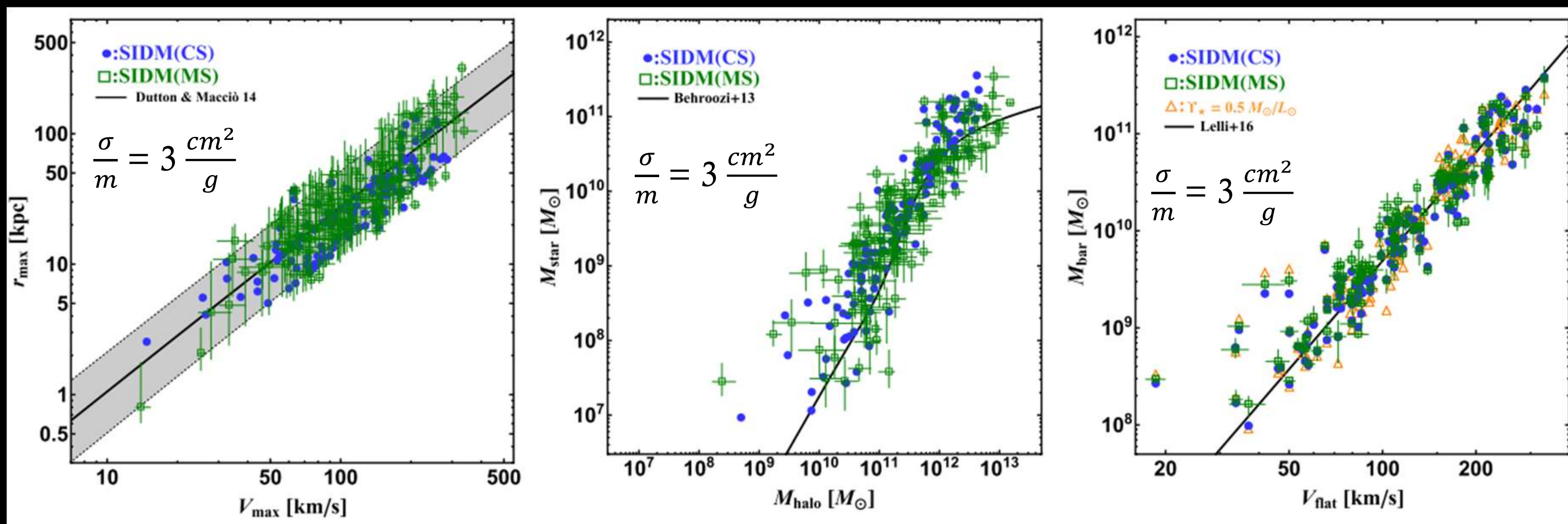
With Ayuki Kamada, Andrew Pace and Hai-Bo Yu, PRL 2017

SIDM fits to rotation curves in the SPARC sample



With Tao Ren, Anna Kwa and Hai-Bo Yu, PRX 2019

SIDM fits are fully consistent with LCDM halo models



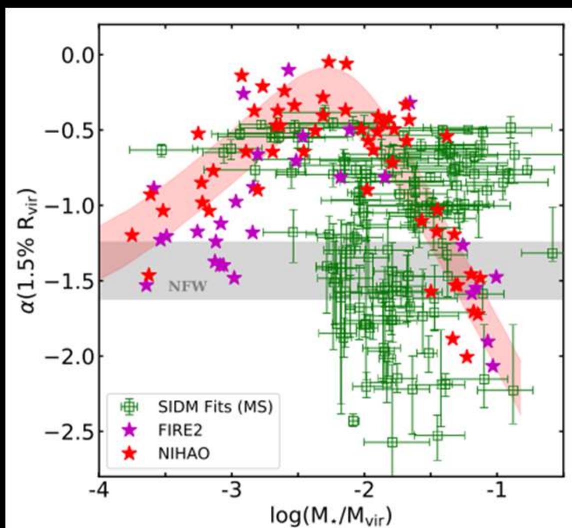
Halo parameters | Stellar mass – halo mass | Baryonic Tully-Fisher

Free parameters per galaxy are M/L and two parameters to specify the halo (Vmax, Rmax) – same as CDM model.

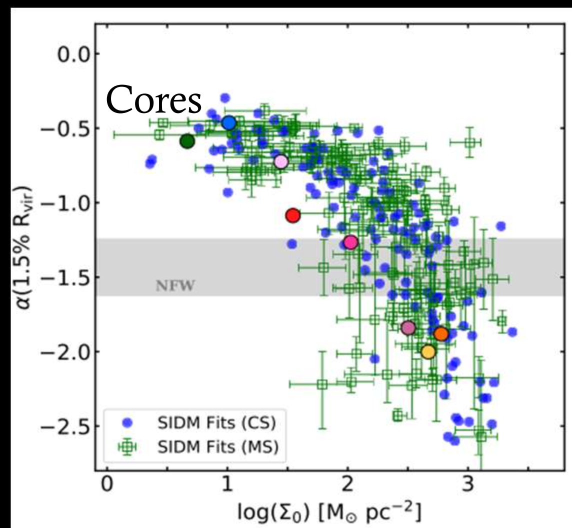
With Tao Ren, Anna Kwa and Hai-Bo Yu (2019)

Comparing SIDM and CDM fits (NIHAO, FIRE-2)

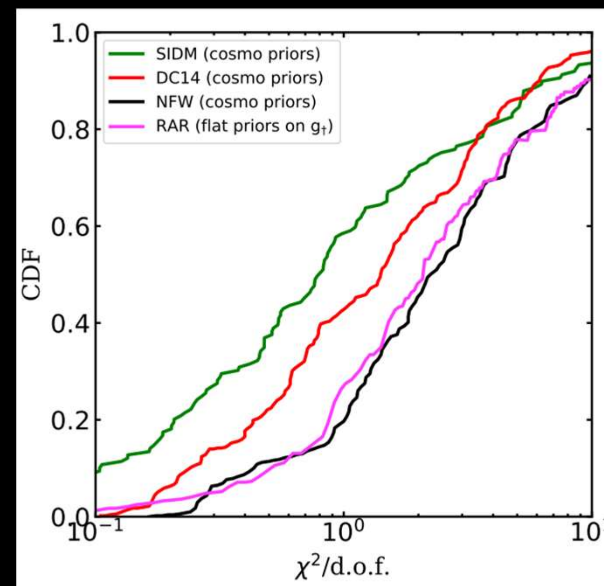
Slope at 1.5% of Rvir



Stellar mass

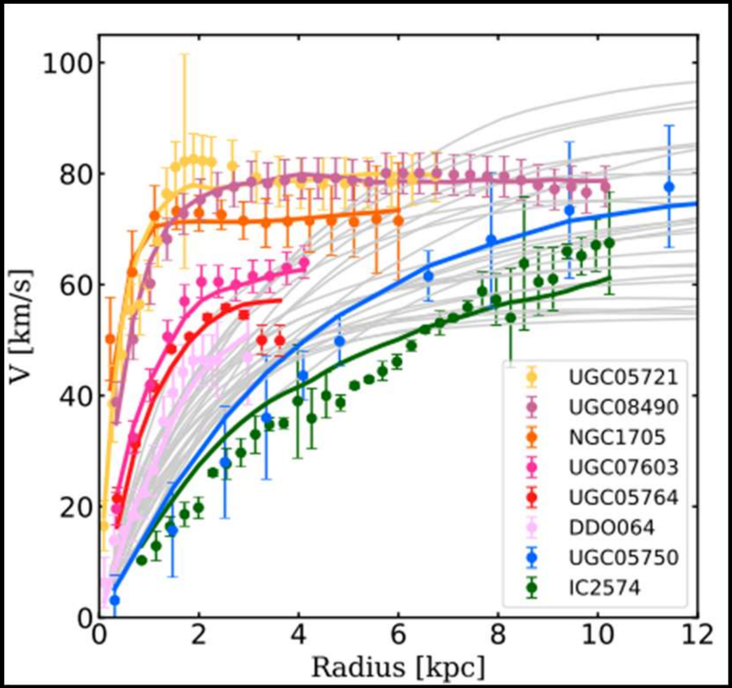


Stellar surface density



With Tao Ren and Hai-Bo Yu (to be posted)

Why current CDM models don’t work

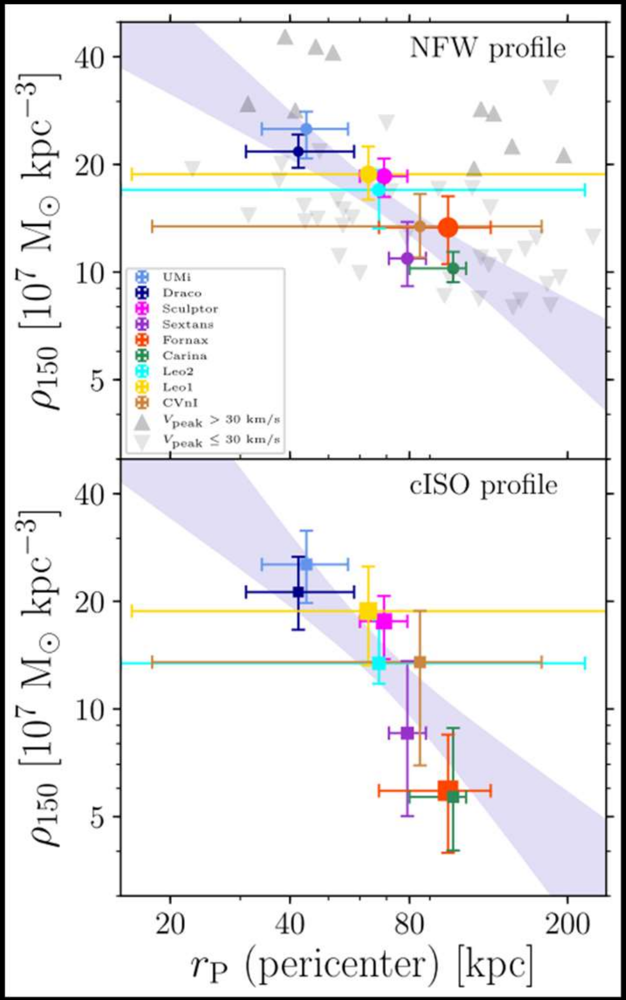


Grey curves from the NIHAO simulations.

Note the lack of high surface brightness galaxies!

With Tao Ren and Hai-Bo Yu (to be posted)

Local Group satellite galaxies:
too-big-to-fail and related issues

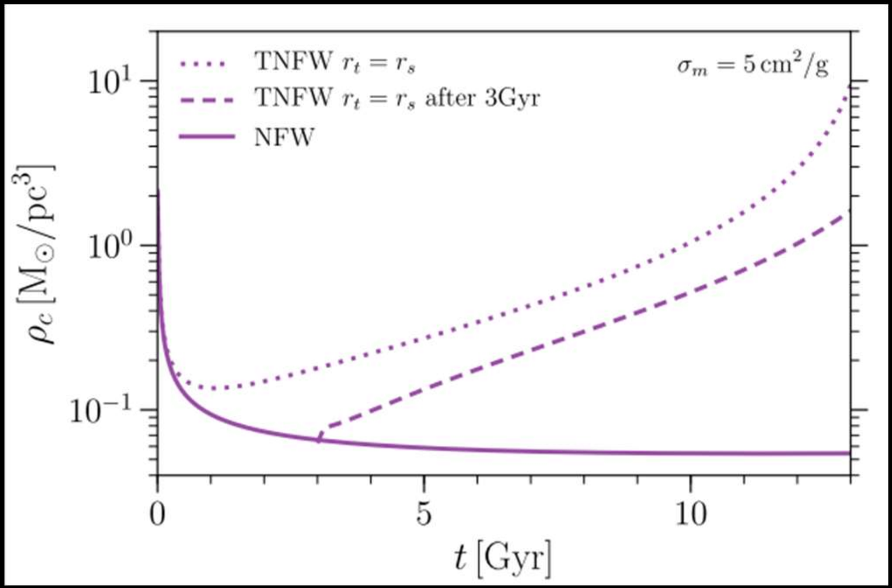


The too-big-to-fail problem in light of GAIA data

Hard to see how this comes about in CDM simulations.

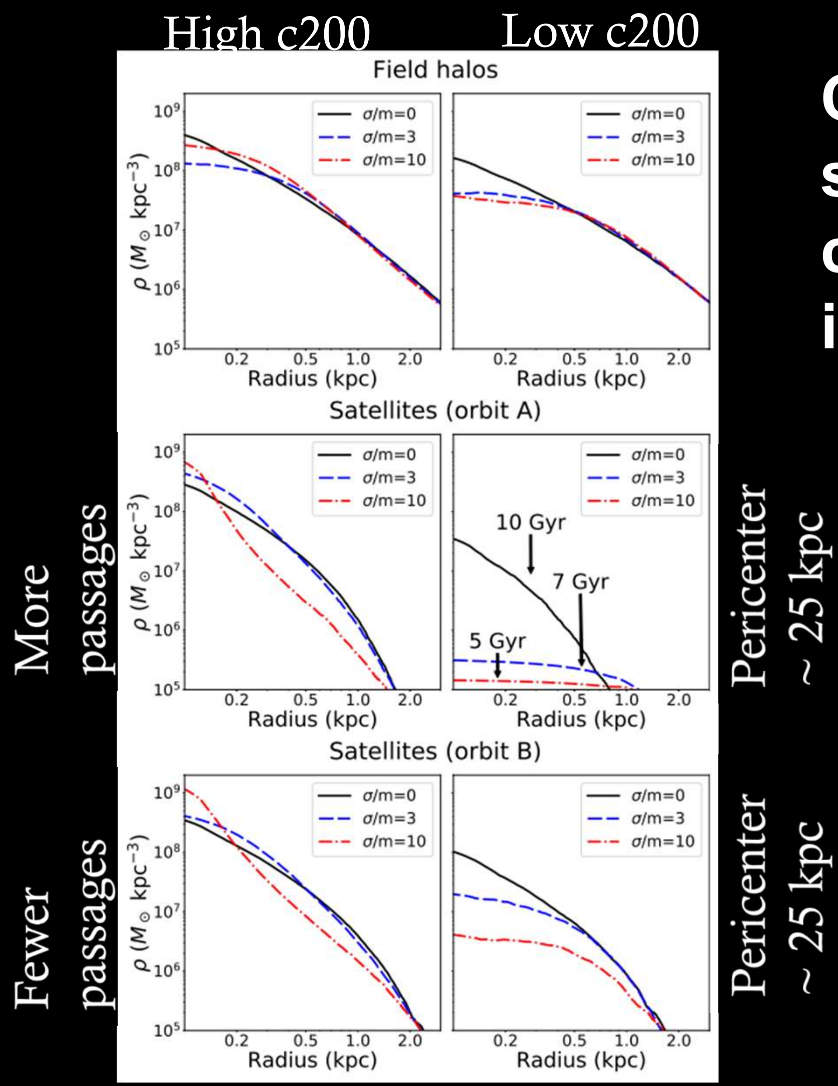
With Valli and Yu (2019)

Accelerated evolution of SIDM subhalos!



Core collapse is unique to SIDM and it provides a smoking gun for discovering dark matter self-interactions.

With Nishikawa and Boddy (2019)



Core collapse of SIDM subhalos: importance of halo concentration and pericenter in increasing diversity

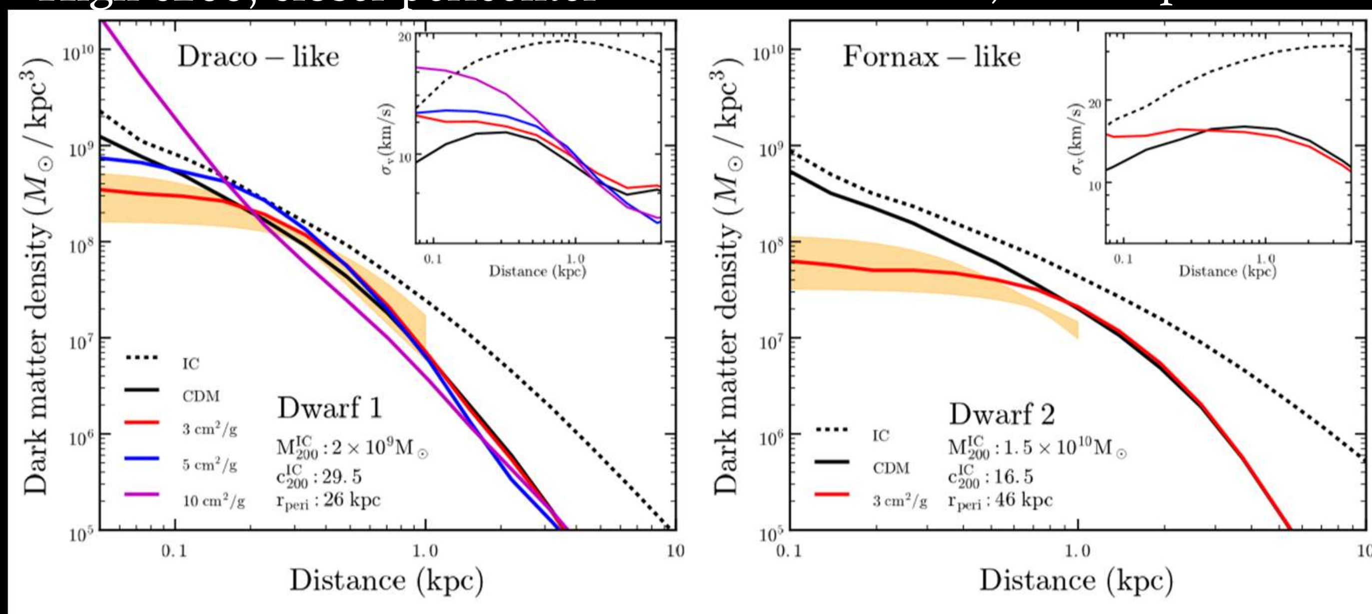
With Felix Kahlhoefer, Tracy Slatyer and Chih-Liang Wu (2019)

Core collapse of SIDM subhalos: Draco and Fornax as examples to demonstrate how the pericenter correlation comes about

Dwarf-1 density increases with $\frac{\sigma}{m}$ (core collapse)

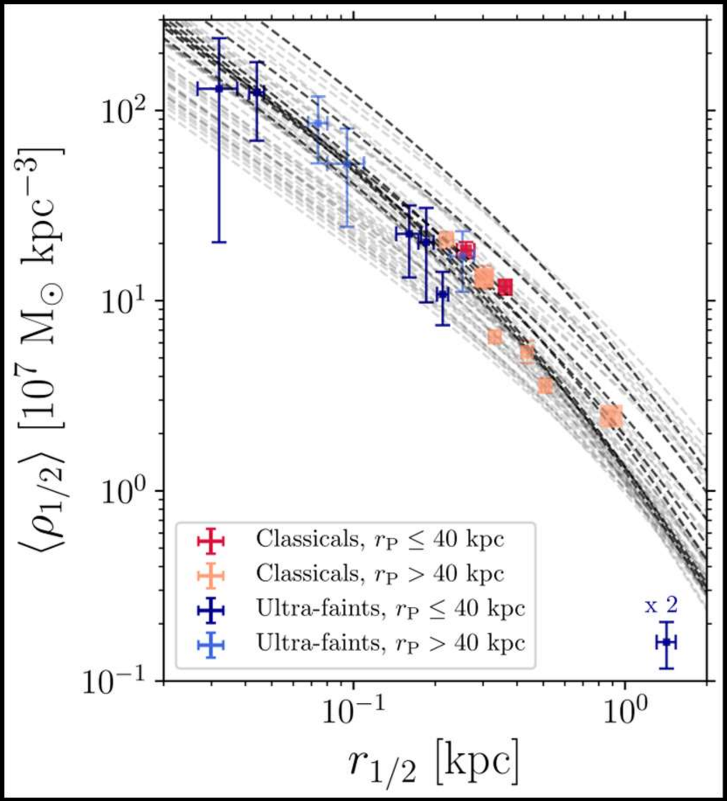
High c200, closer pericenter

Low c200, farther pericenter



Sameie, Yu, Sales, Vogelsberger, Zavala 2019

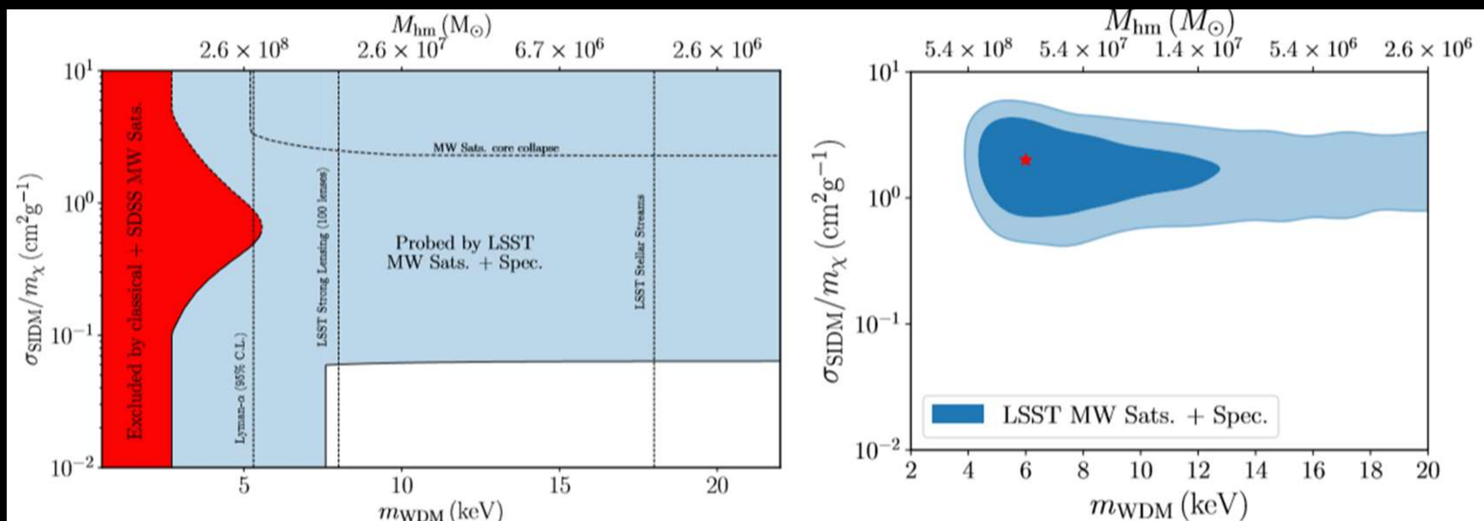
Compact stellar distribution implies dense dark matter halo



SIDM model seems to be the only way to explain the diversity of stellar and dark matter densities of Local Group satellites.

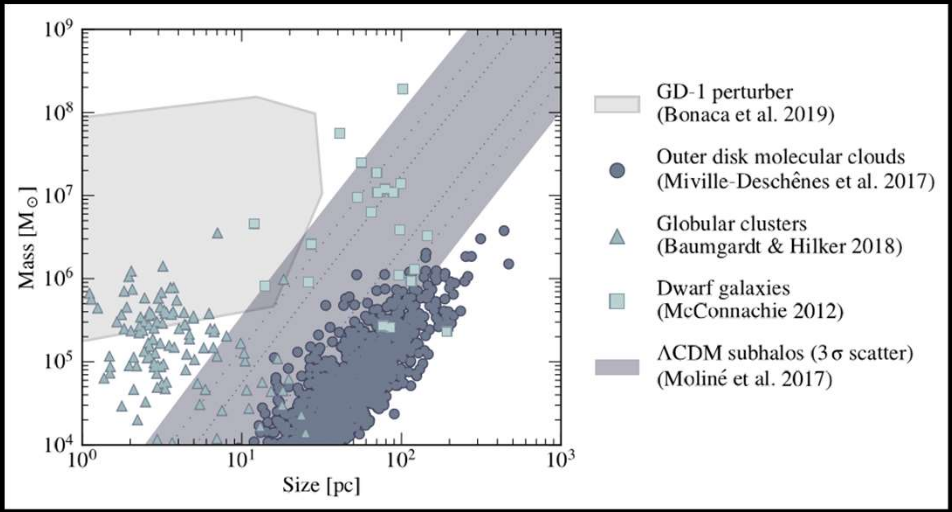
With Valli and Yu (2019)

Ultrafaint satellites of the Milky provide an exciting future test of dark matter self-interactions



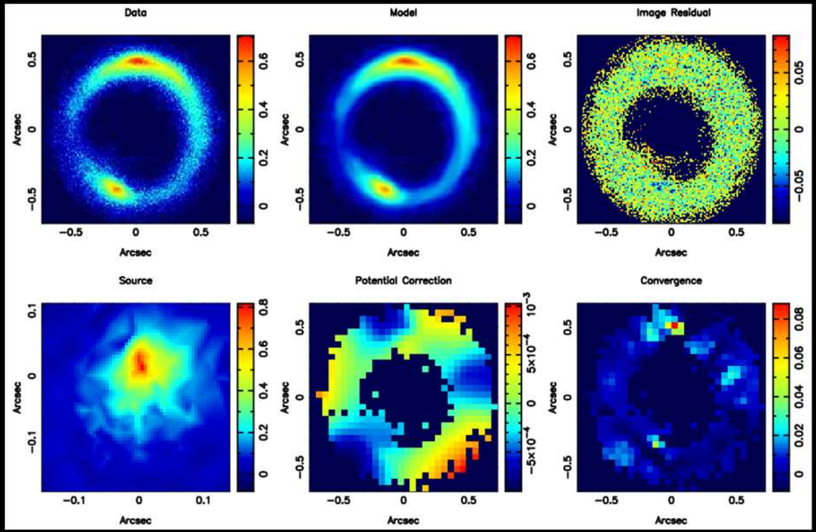
Keith Bechtol et al, LSST dark matter working group (2019)

Subhalo detection could be the way to discover dark matter self-interactions



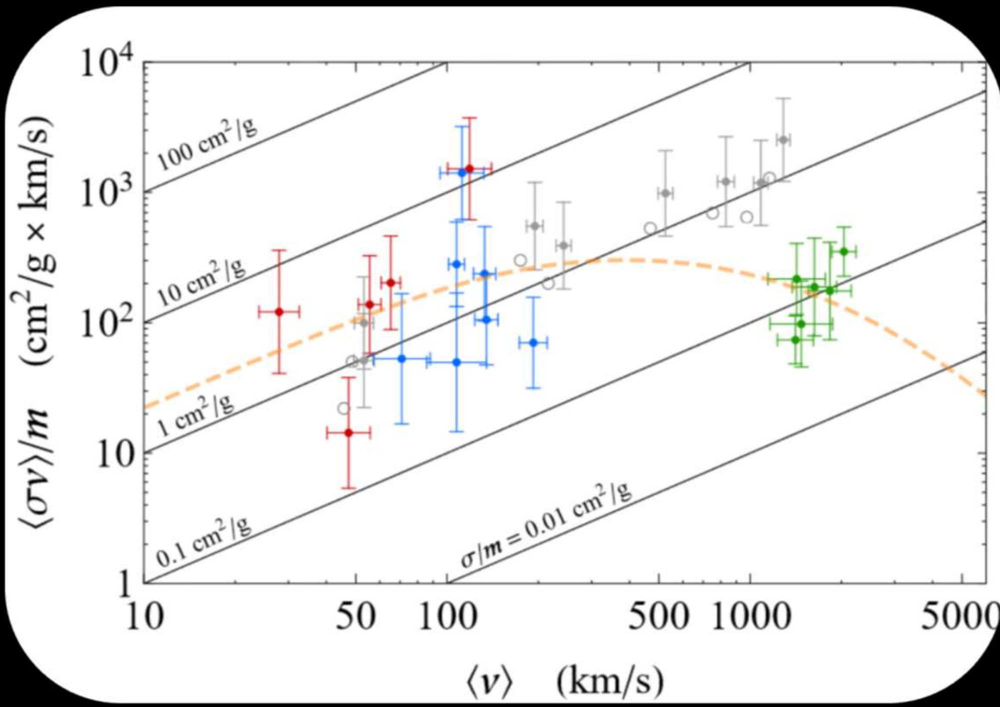
Ana Bonaca, David W. Hogg, Adrian M. Price-Whelan, Charlie Conroy, ApJ 2018

S. Vegetti, L. V. E. Koopmans, A. Bolton, T. Treu, R. Gavazzi, MNRAS 2009



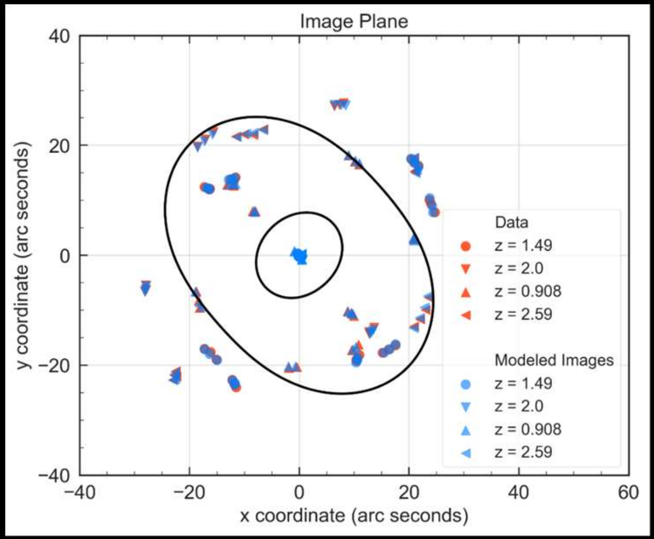
Clusters of galaxies

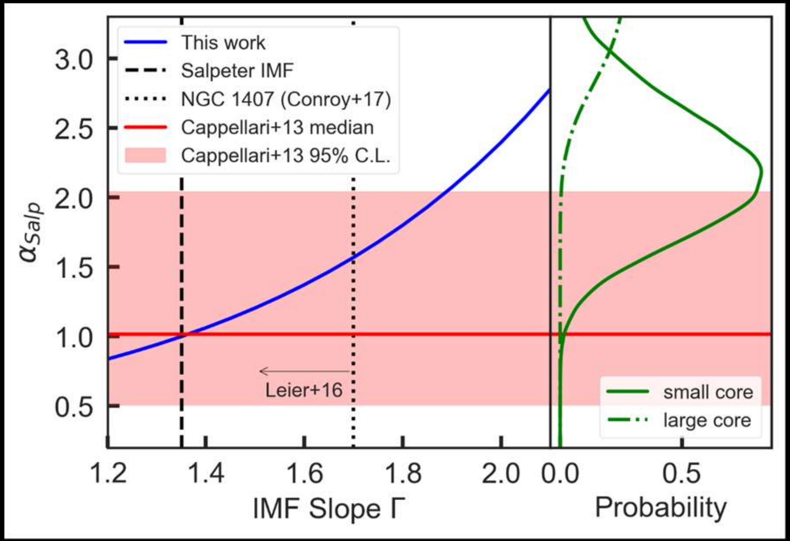
The self-interaction cross section must decrease at high collision speeds. Need more data points and reanalysis of existing data to robustly constrain the self-interaction mechanism.



With Sean Tulin and Hai-Bo Yu, PRL 2016

Cores and cusps in galaxy centers with strong lensing only: Abell 611



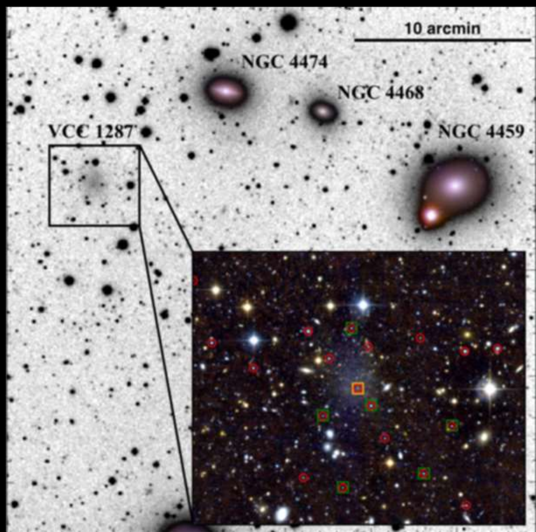


With Andrade, Minor, Nierenberg, MNRAS 2019

Large core solution requires unreasonable M/L values. Small core solution implies roughly $\frac{\sigma}{m} < 0.1\,\frac{cm^2}{g}$.

Stay tuned for an update with more clusters.

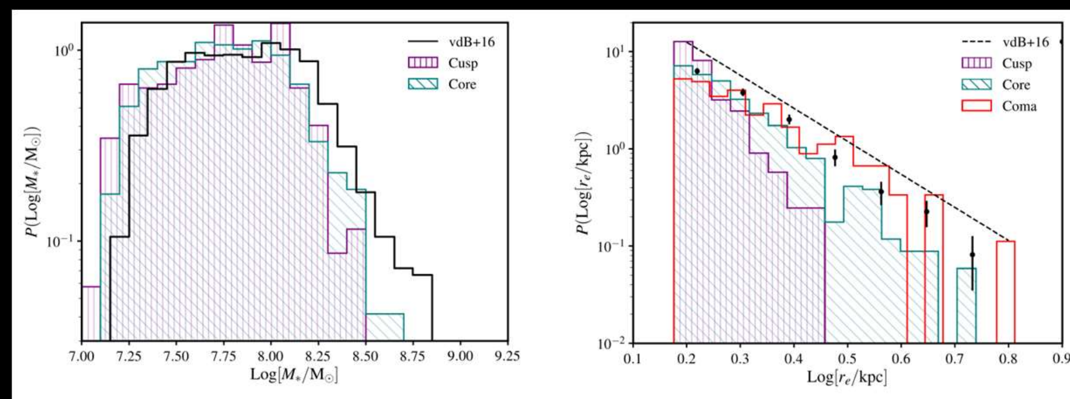
Ultra-diffuse galaxies in clusters



Beasley et al 2016

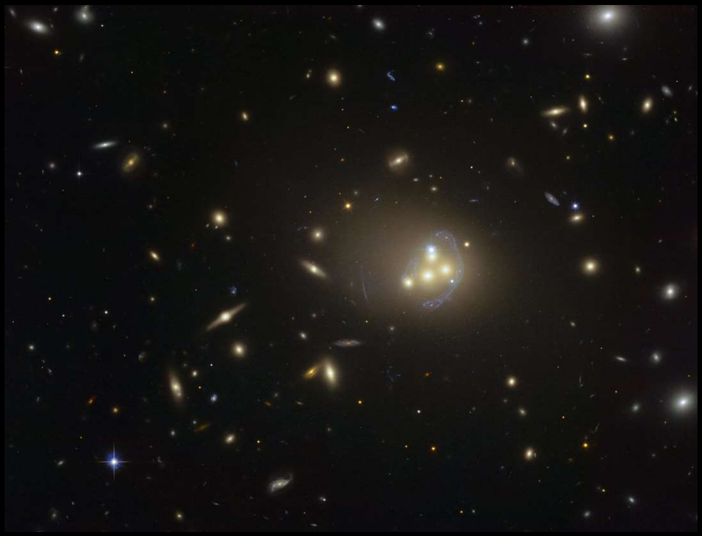
This can explain the numbers, radial distribution and scaling with host mass for UDGs

When dwarf galaxies with dark matter constant density cores fall into a cluster potential, the stars expand [Penarrubia et al 2010, Dooley et al 2016].



Carleton et al, MNRAS 2019

BCG sloshing: multiple bright cluster galaxies



Abell 3827, Massey et al (2015)

In the cores of the clusters, BCGs slosh around [Kim, Peter and Wittman, MNRAS 2016].

Likely related to decreased dynamical friction (GCs in Fornax: Cole, Dehnen, Read and Wilkinson, MNRAS 2012).

Cosmology

Cosmological consequences in simple SIDM models

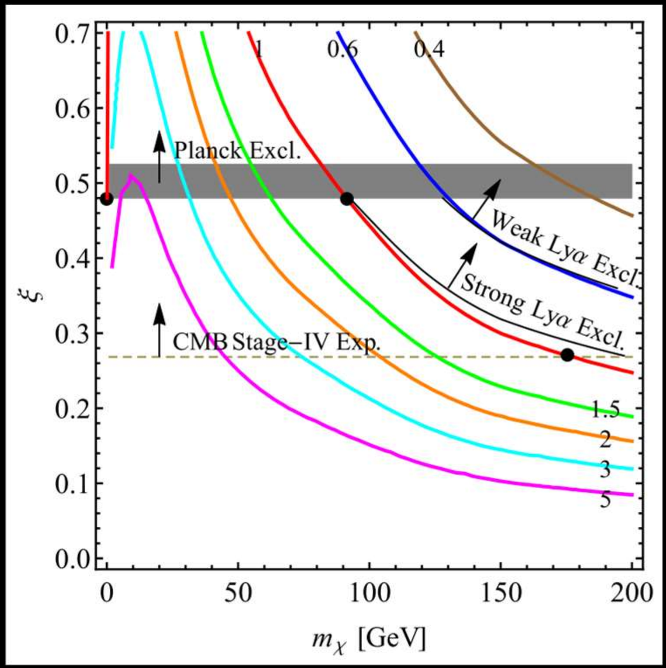
Production mechanisms.

--Thermal production strongly constrained in simple models.
[Torsten Bringmann, Felix Kahlhoefer, Kai Schmidt-Hoberg and Parampreet Walia, PRL 2016]
[With Kim Boddy, Anna Kwa and Annika Peter, PRD 2016]
--Asymmetric DM, freeze-in, SIMPs, etc. This is a wide-open area.

Implications for cosmology.

-- ETHOS [Cyr-Racine et al, PRD 2016 and Bose et al, PRD 2018]

Existence of SIDM implies at least one hidden sector of particles.



With Ran Huo and Hai-Bo Yu, PLB 2018.
Also, Laura G. van den Aarssen, Torsten Bringmann, Christoph Pfrommer, PRL 2012.

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Novel Probes of Dark Matter Self-Interaction

Will be a living review (along with the completed review on modified gravity) at https://www.novelprobes.org/