The Self-Interacting Dark Matter (SIDM) model

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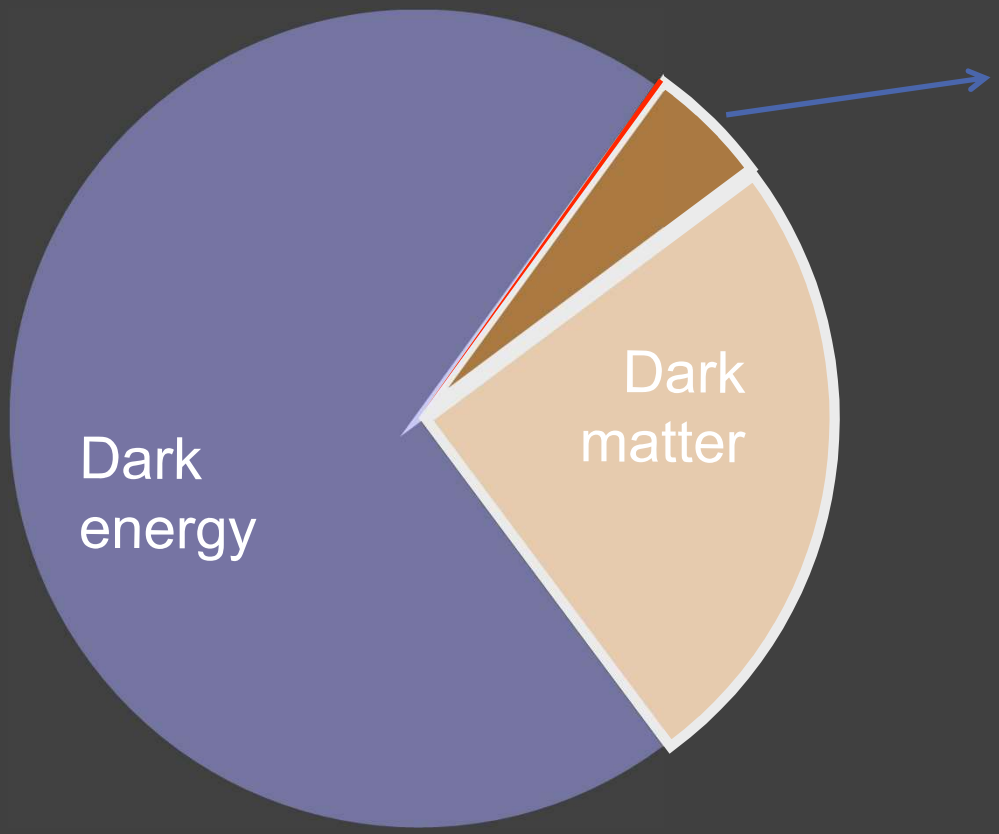
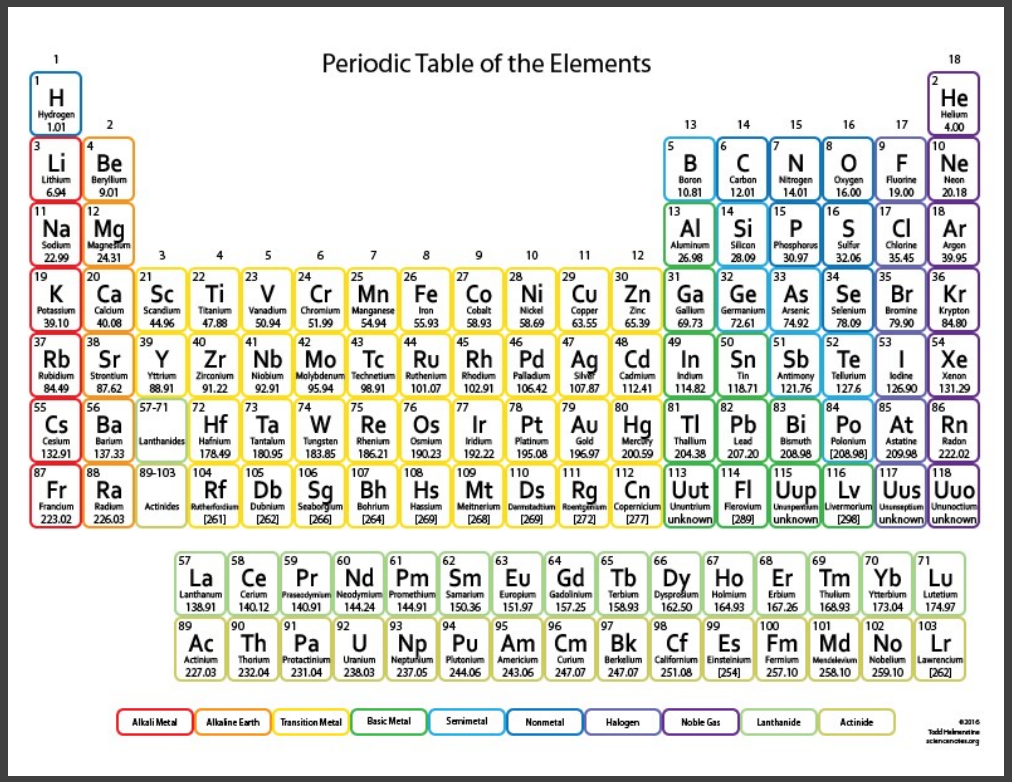
The predictions of the ΛCDM model agree well with the observed large-scale structure of the Universe.





Visible sector particles interact with each other. Why not dark sector particles?

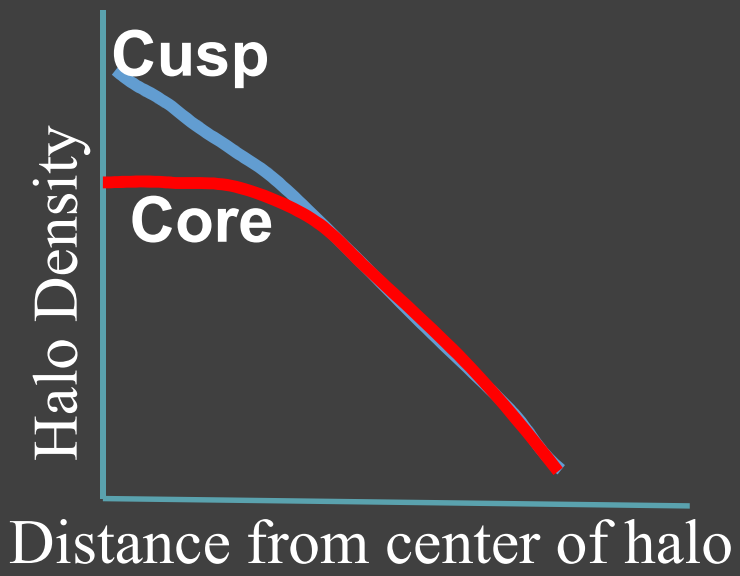
-- Clues: galactic rotation curves

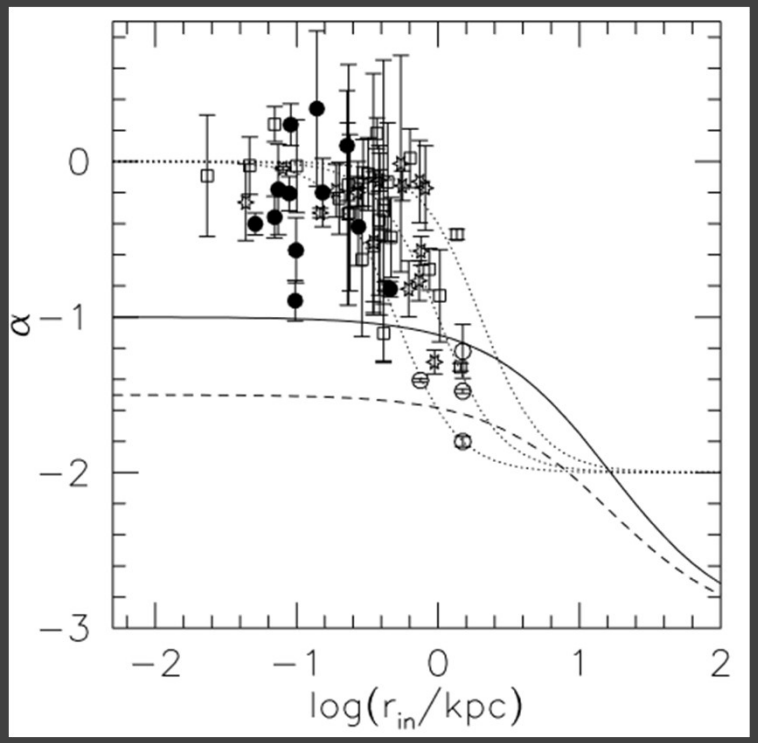
-- A SIDM model

-- Success: SPARC sample of rotation curves

-- Tests for the coming decade

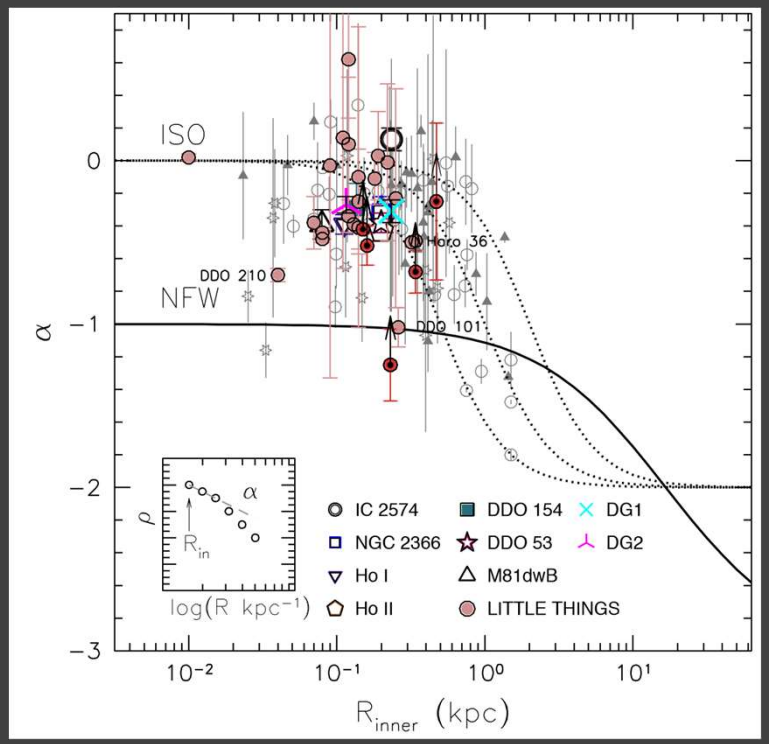
Cores AND cusps





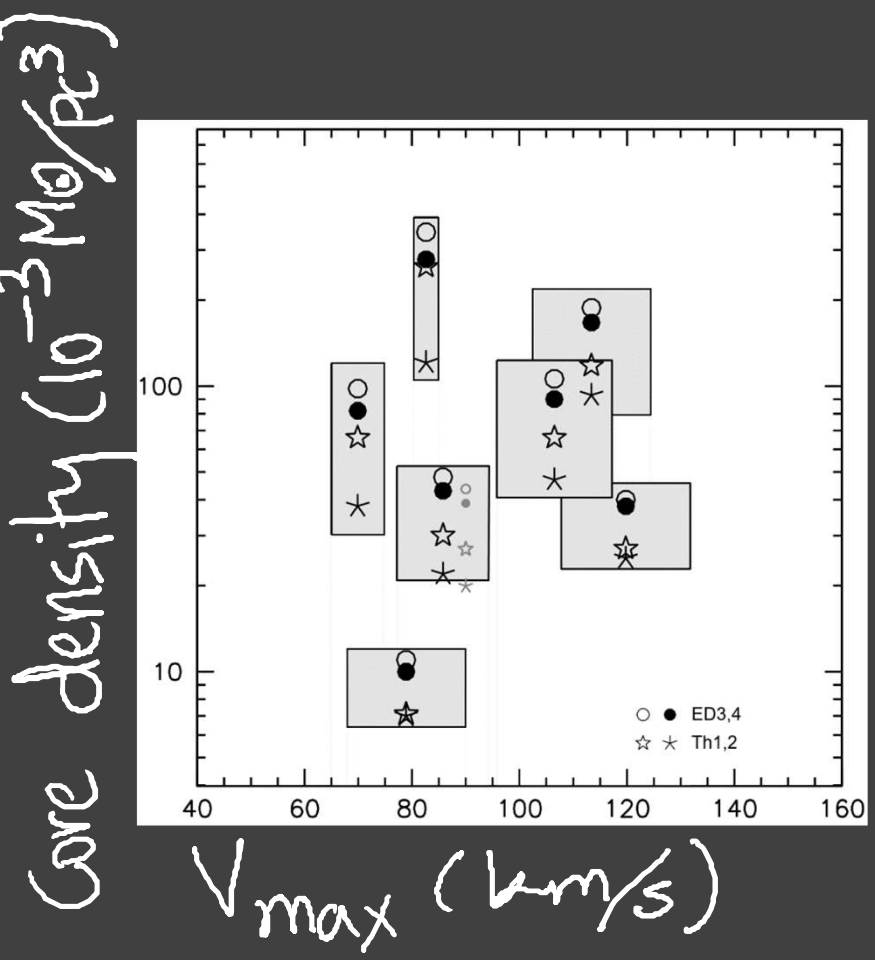
de Blok and Bosma, 2002

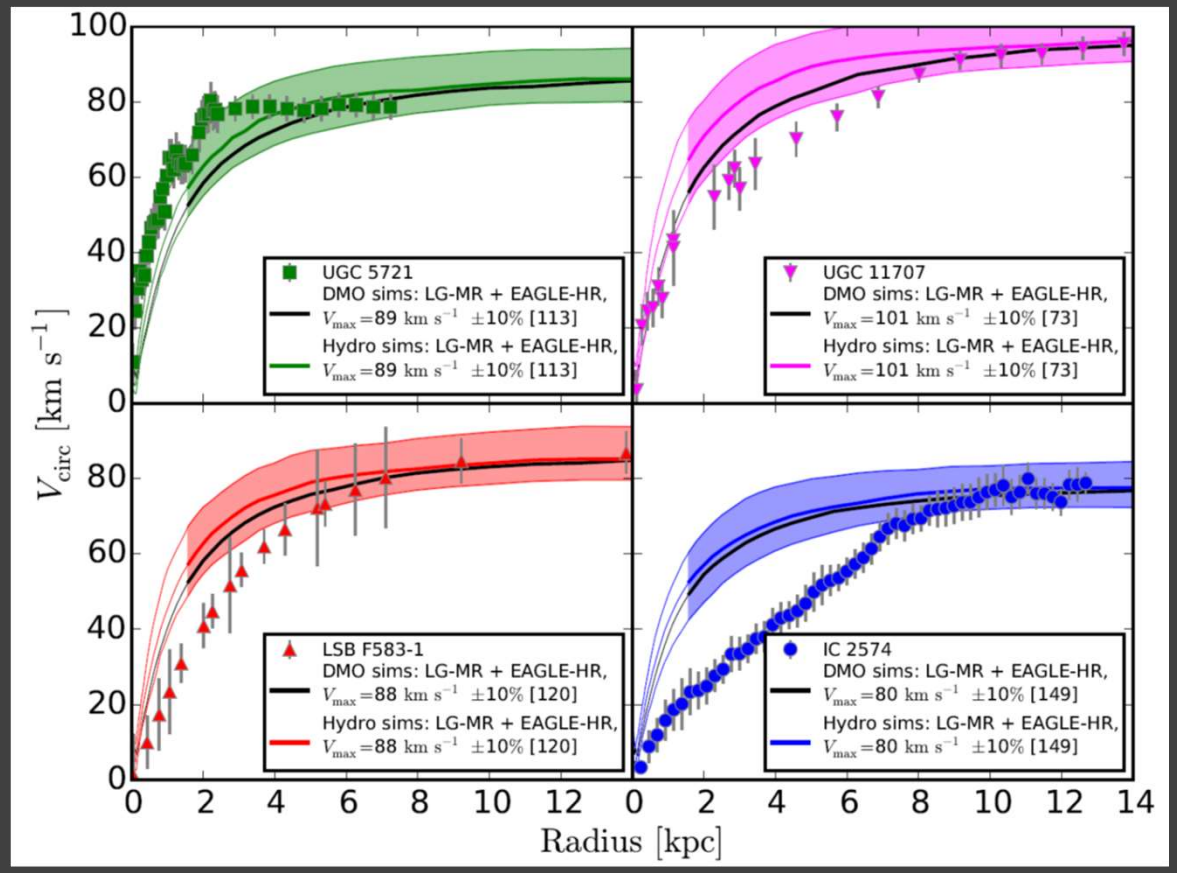
Slope of the DM density profile



LITTLE THINGS, Oh et al 2015

The puzzling diversity in rotation curves





Oman et al, 2015

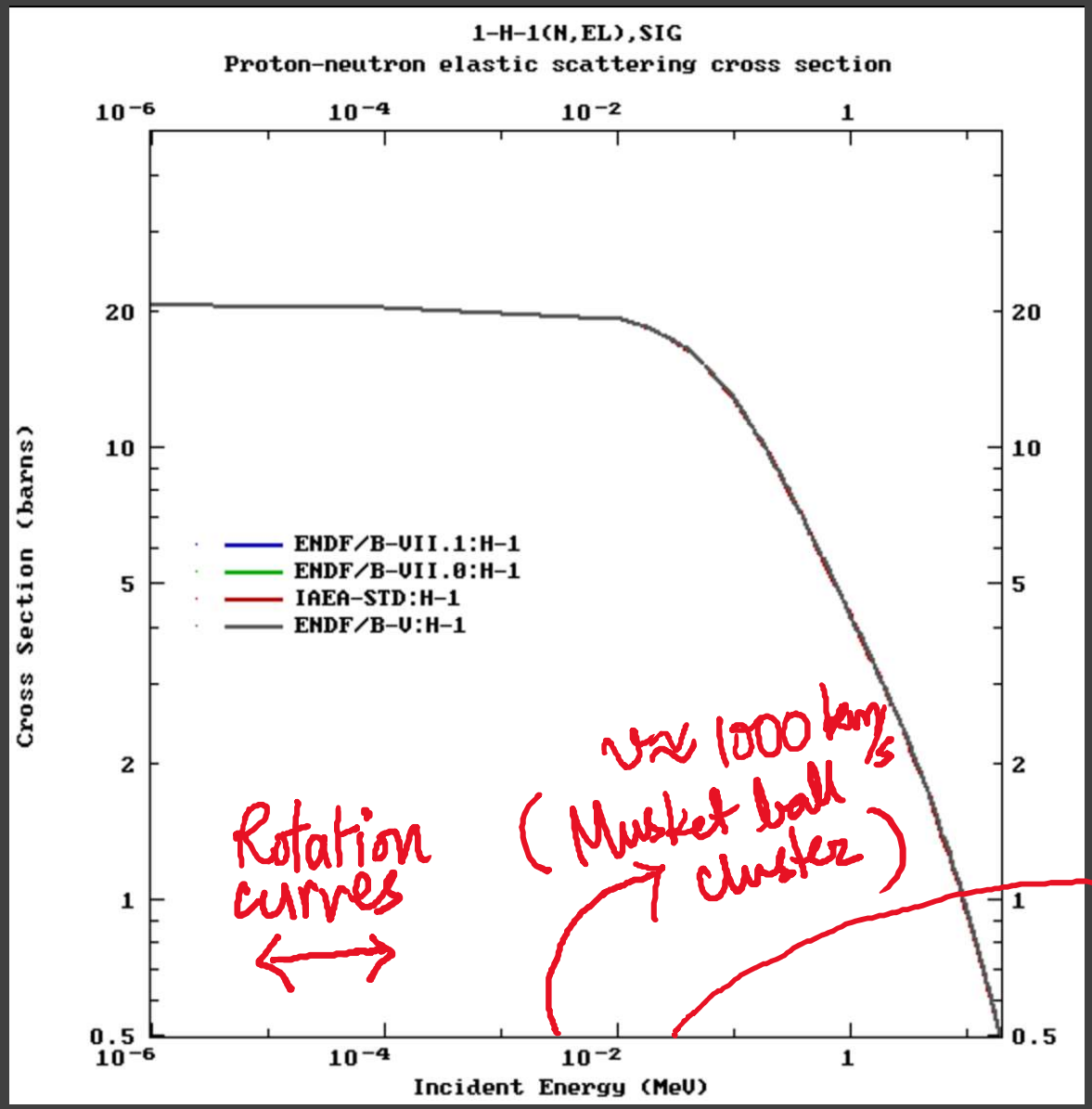
with Rachel Kuzio de Naray, Greg Martinez and James Bullock (2010)

The SIDM solution to the small scale puzzles

Particle dark matter with a large elastic self-scattering cross section explains the diverse inner rotation curves.

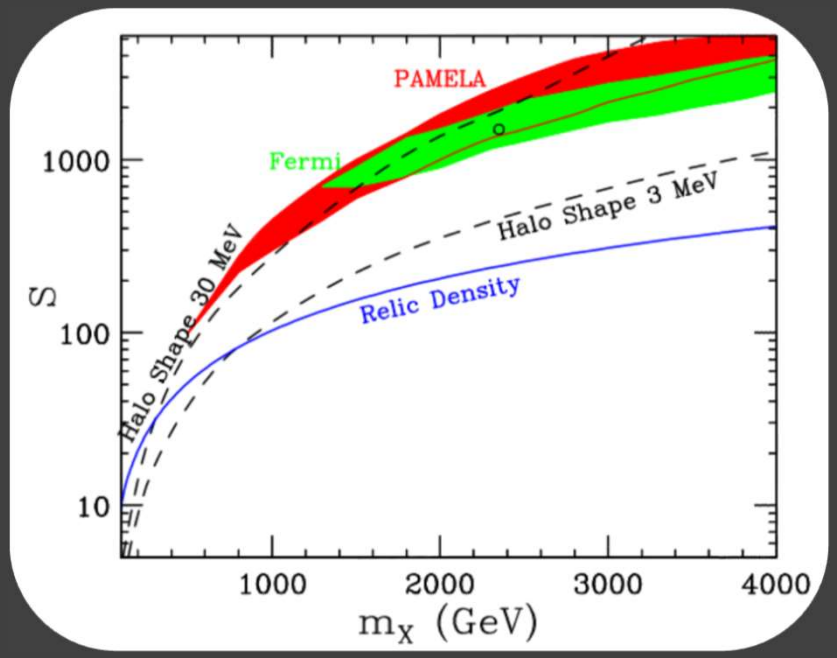
Require $\sigma/m \sim$ few barns/GeV

A motivating Standard Model example



To get velocity dependence, you need two scales. Hence, minimal LSIDM model has one more parameter than LCDM.

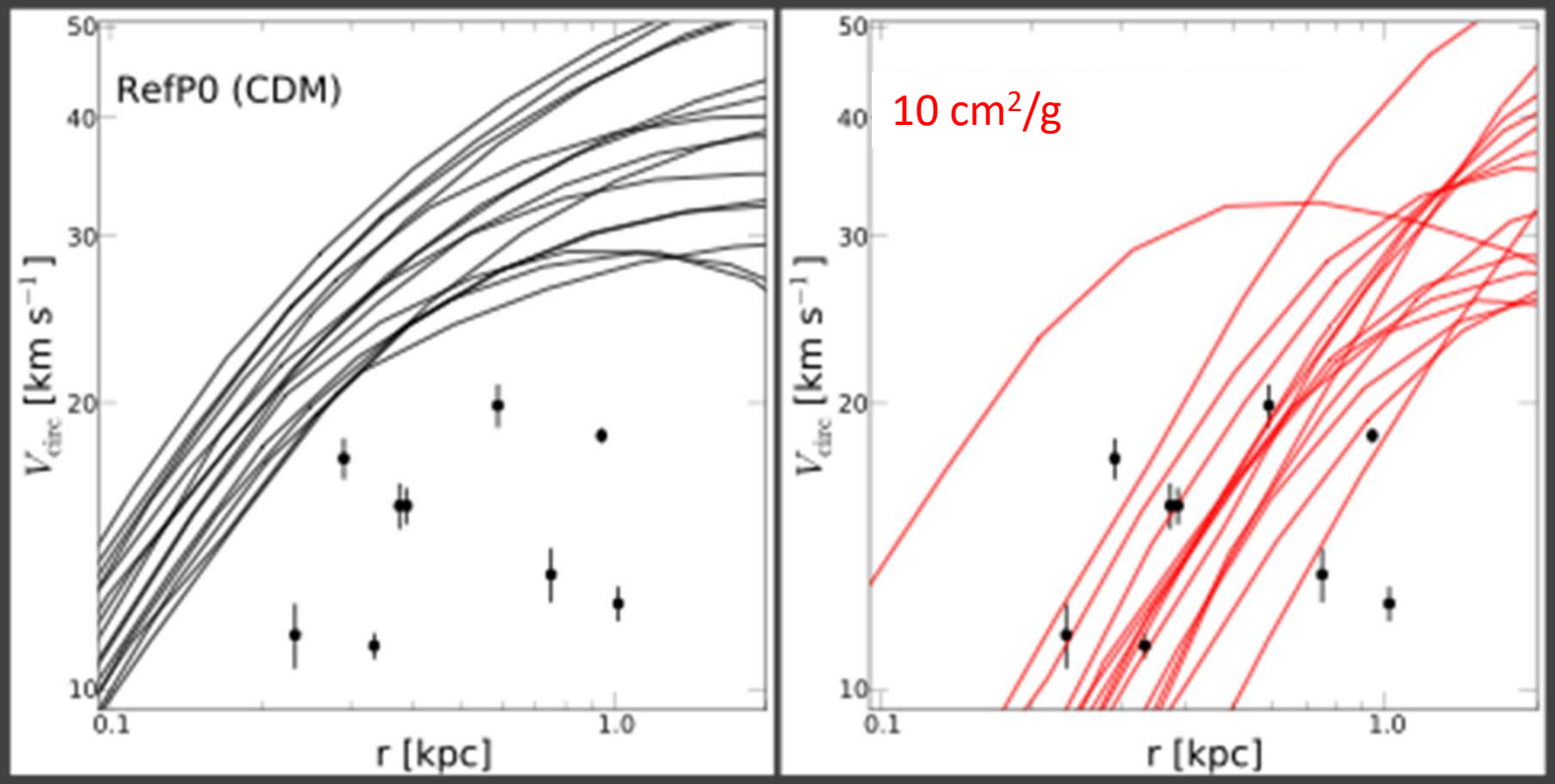
Revival of the SIDM idea



"Interestingly, viable models with moderate Sommerfeld enhancements, although unable to explain the positron data, may predict constant density spherical cores in small galactic halos and other departures from the standard cold dark matter paradigm that are consistent with current data."
arXiv:0911.0422

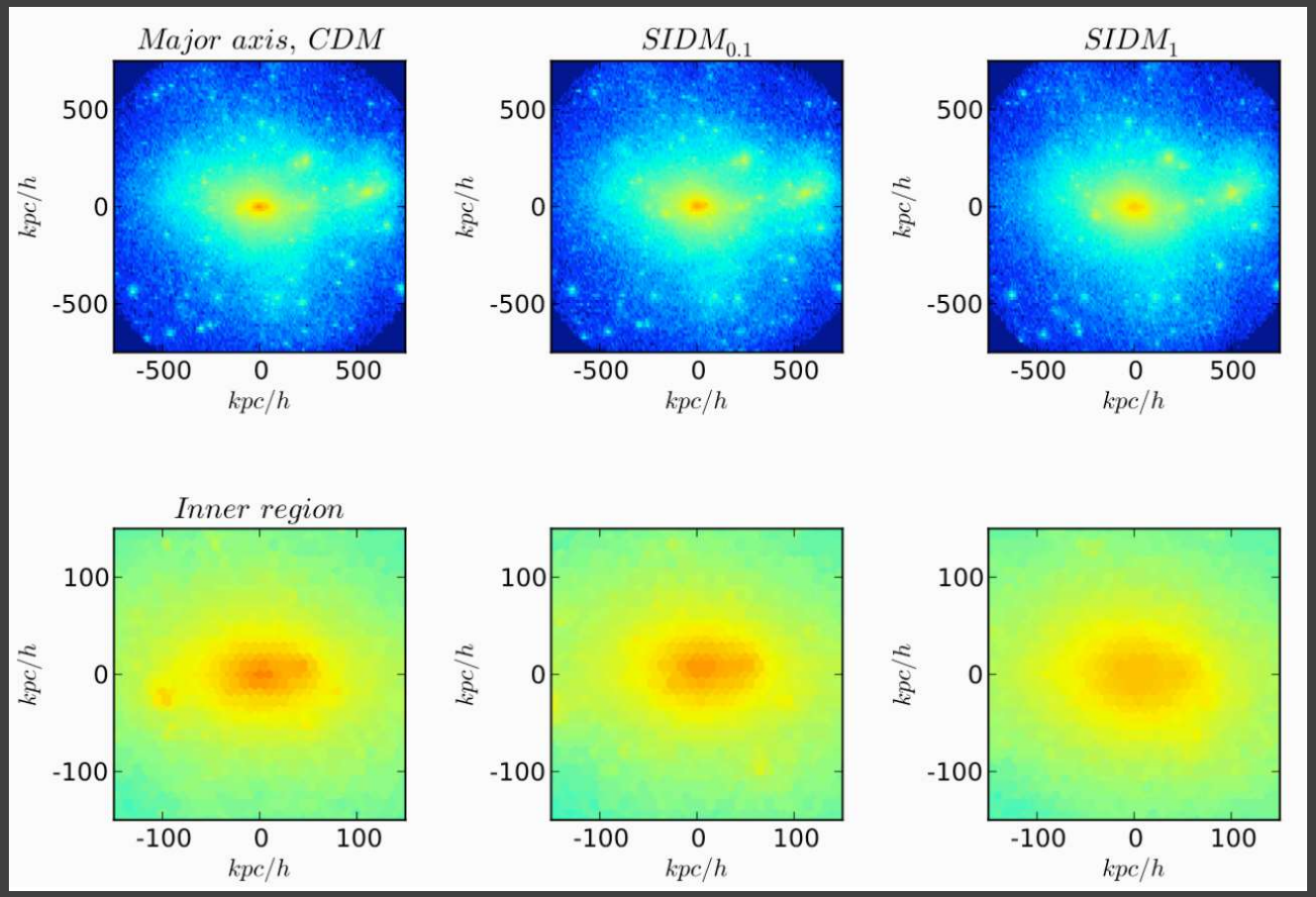
With Jonathan Feng, Haibo Yu, arXiv:0905.3039
With Jonathan Feng, Huitzu Tu, Haibo Yu, arXiv:0911.0422
Matt Buckley, Paddy Fox, arXiv:0911.3898
Avi Loeb, Neal Weiner, arXiv:1011.6374

Revival of the SIDM idea: cores in dwarfs and the too-big-to-fail problem



Vogelsberger, Zavala and Loeb (2012)
Vogelsberger, Zavala and Walker (2012)

Revival of the SIDM idea: astrophysical constraints reevaluated

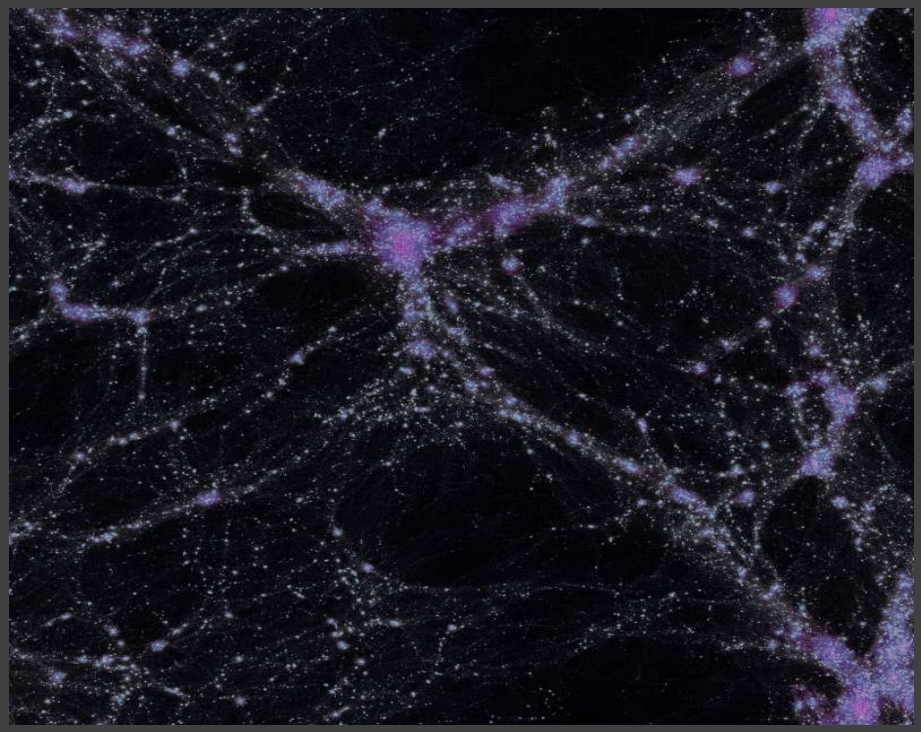


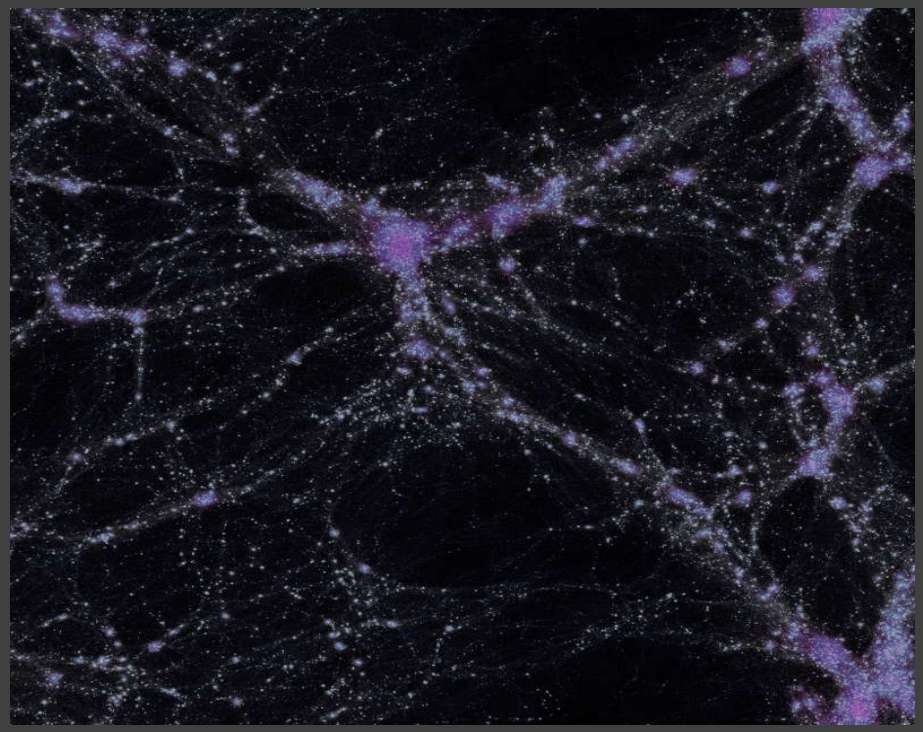
Many previous constraints were wrong.

With Annika Peter, Miguel Rocha, James Bullock, arXiv:1208.3026

How SIDM works

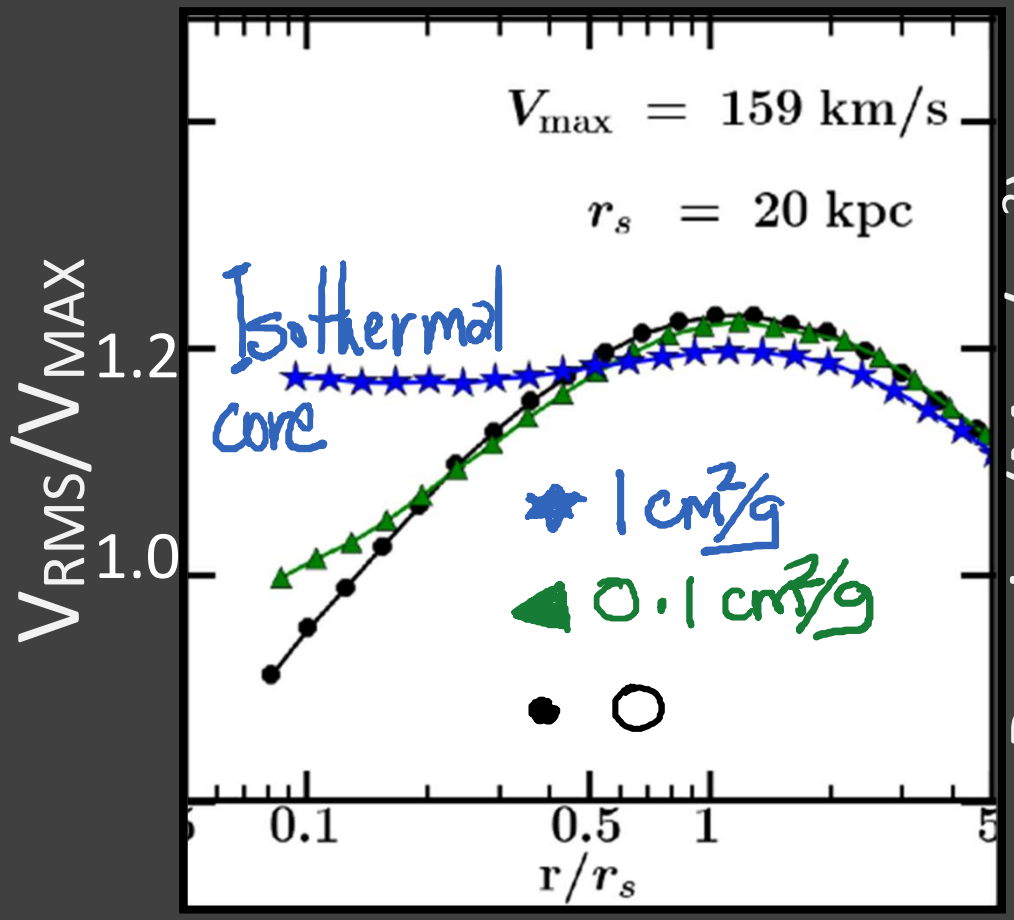
SIDM and CDM predictions deviate in the inner part of galaxies. Spergel and Steinhardt (2000)

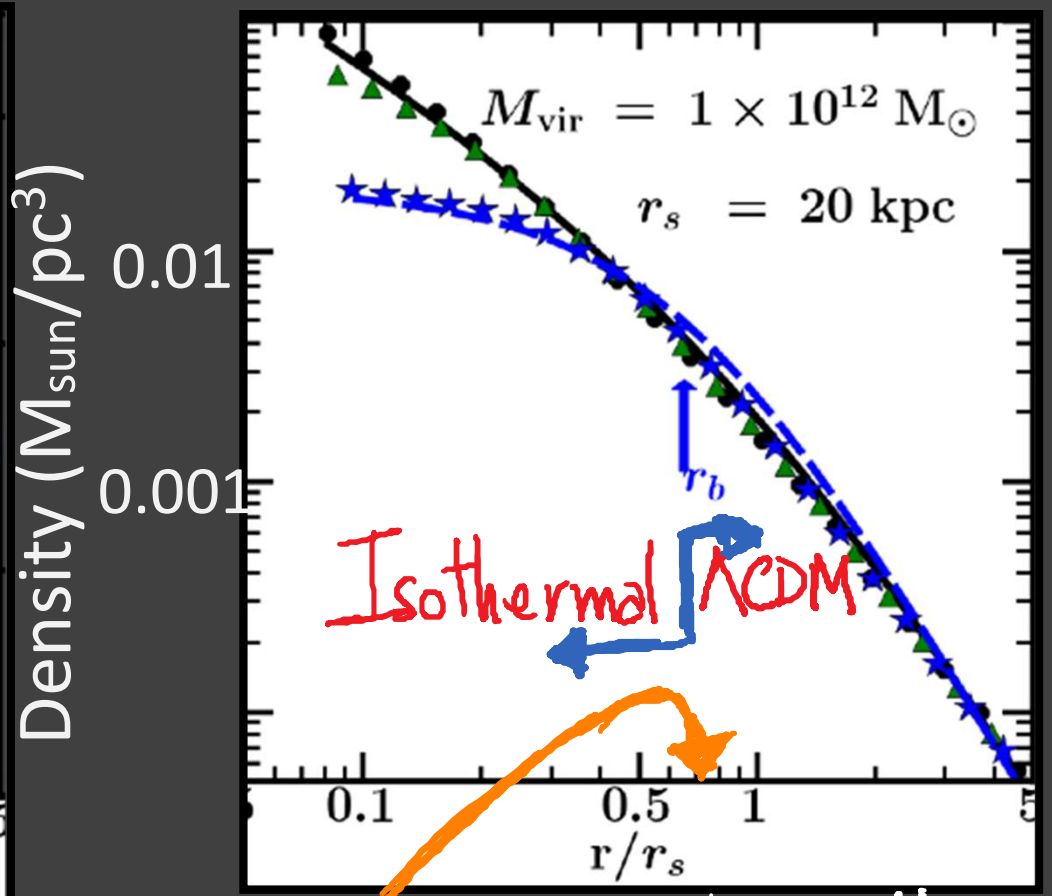




With James Bullock, Miguel Rocha, Annika Peter (2013)

SIDM: thermalization of the inner halo





r_1: one interaction on average over age of halo

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

Field galaxies: SIDM halo profile is almost uniquely determined

$$\rho_{SIDM}(r) \propto e^{-\Phi_{total}(r)/kT} \quad \text{for } r < r_1$$

- $r > r_1$: $\rho_{SIDM} \approx \rho_{CDM}$
- Interaction rate $\approx \frac{1}{\text{age}}$ at r_1
- $kT \approx \frac{V_{rms}}{\sqrt{3}} \approx \frac{1.1\, V_{max}}{\sqrt{3}}$

With Ryan Keeley, Tim Linden and Hai-Bo Yu (2014)
With Oliver Elbert and James Bullock (2017)

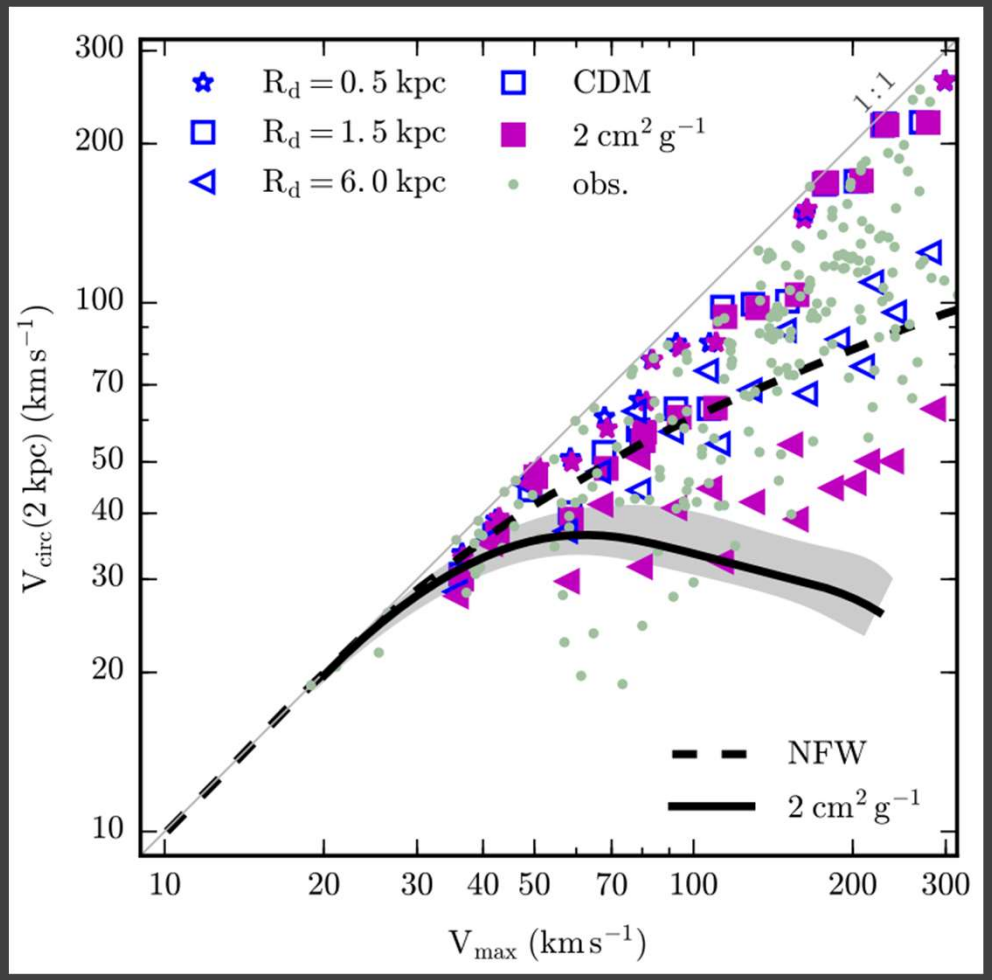
Field galaxies: both Cored and Cuspy

- SIDM does not predict large cores in all galaxies

↑ cores small / cuspy

$\rho_* + \rho_{gas}$

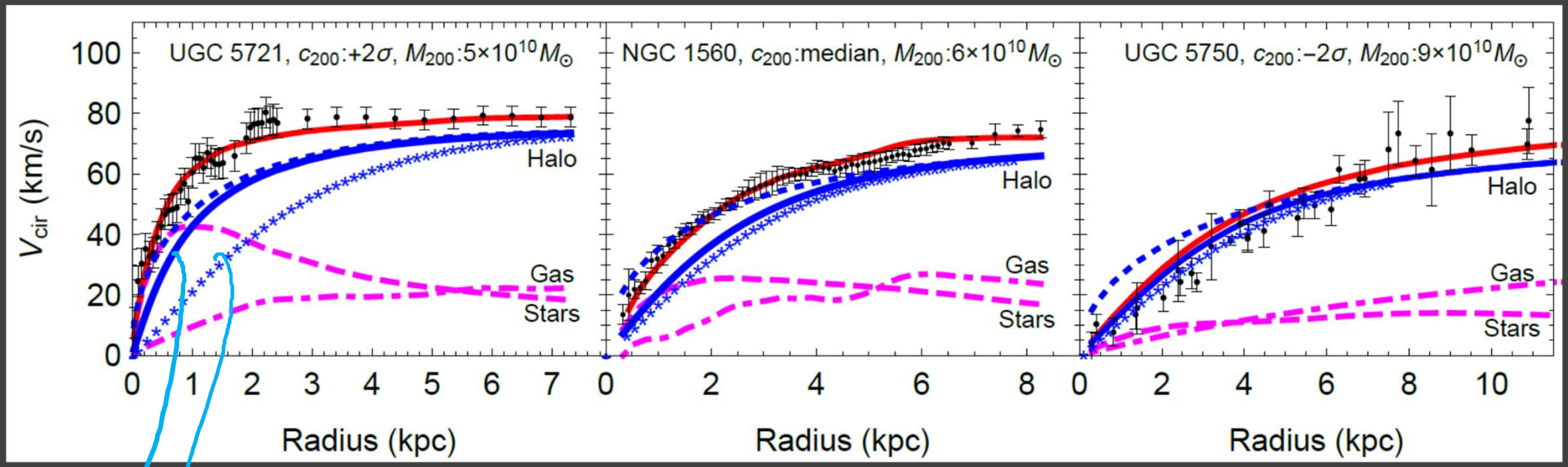
↓ core size ~ r_s (large!)



Creasey et al (2017)

SIDM model fits to galactic rotation curves

How SIDM explains the diverse rotation curves: importance of LCDM concentration-mass relation



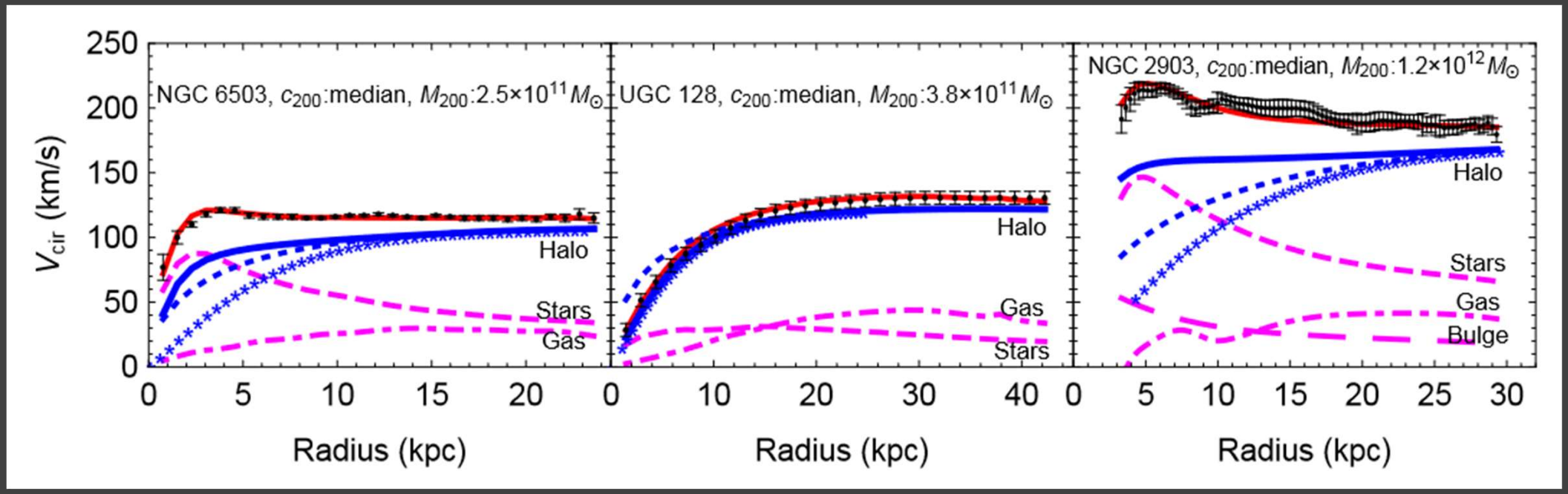
With Ayuki Kamada, Andrew Pace and Hai-Bo Yu (2017)

without including the potential of stars

correct SIDM density profile

Lower the stellar SB, lower density of dark matter required.

How SIDM explains the diverse rotation curves: impact of the baryonic potential



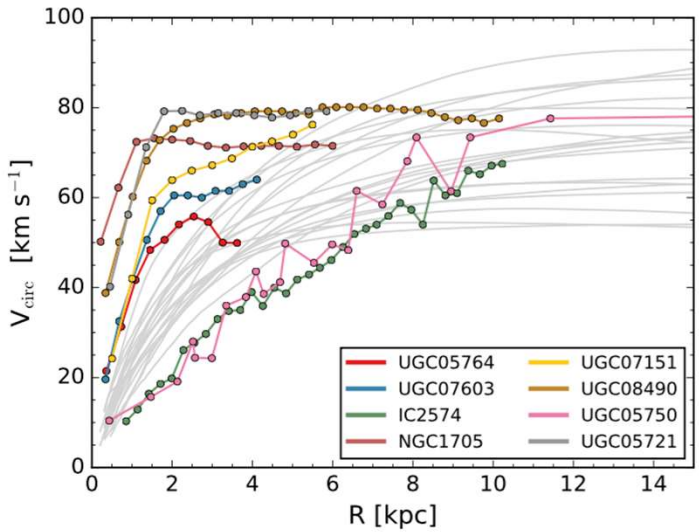
-- No need for cores in massive galaxies.

-- Roughly $1/r^2$ density profile for total mass profile.

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

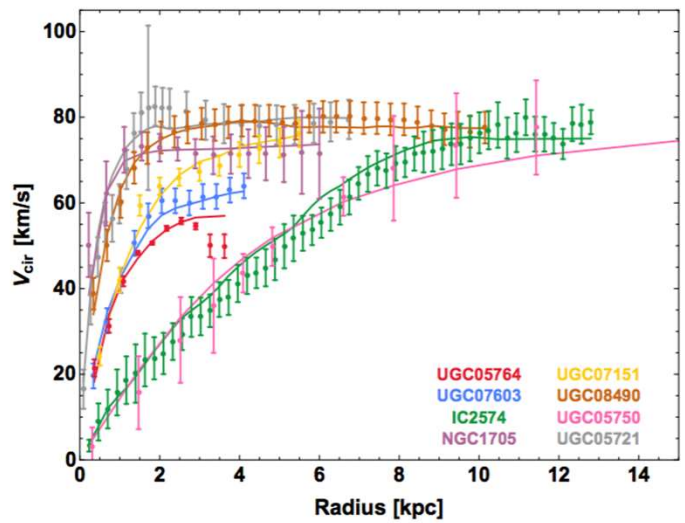
Could rotation curves distinguish LCDM and LSIDM?

Strong Feedback vs. SIDM



NIHAO simulations
strong feedback

Santos-Santos et al. (2017)

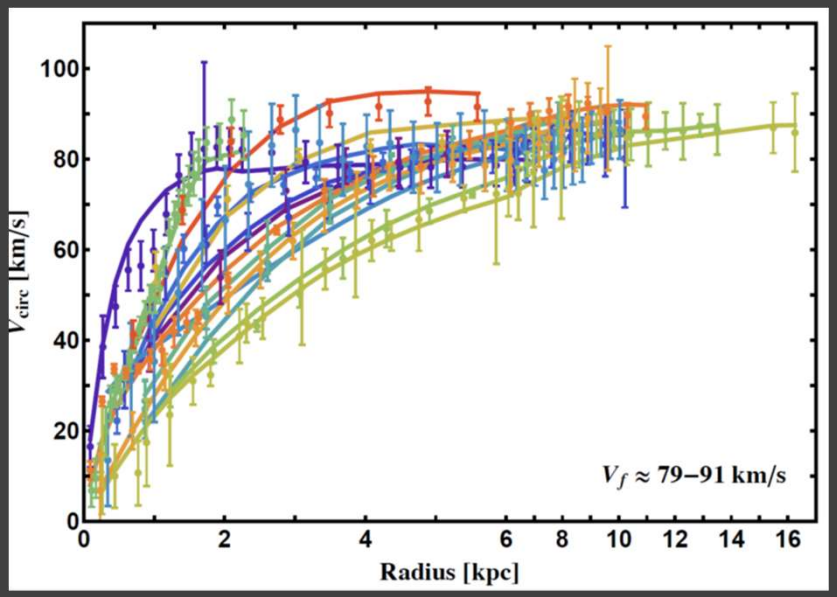


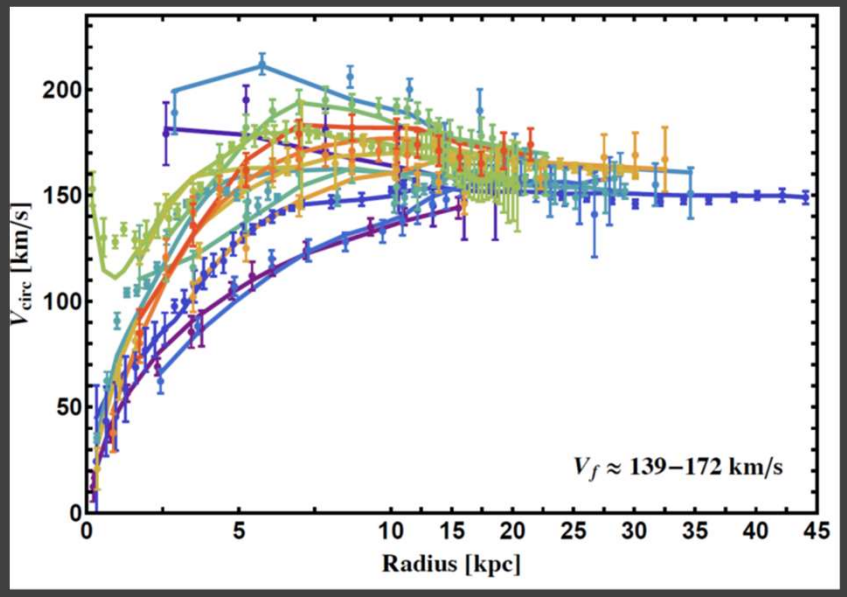
SIDM

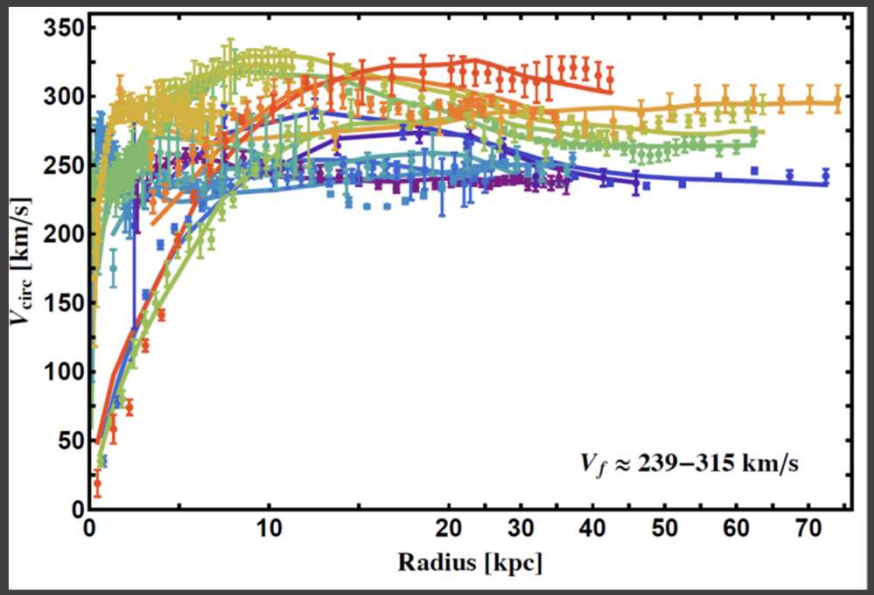
with Kaplinghat, Kwa, Ren (in prep)

Slide from Hai-Bo Yu

SIDM fits to the rotation curves in the SPARC sample

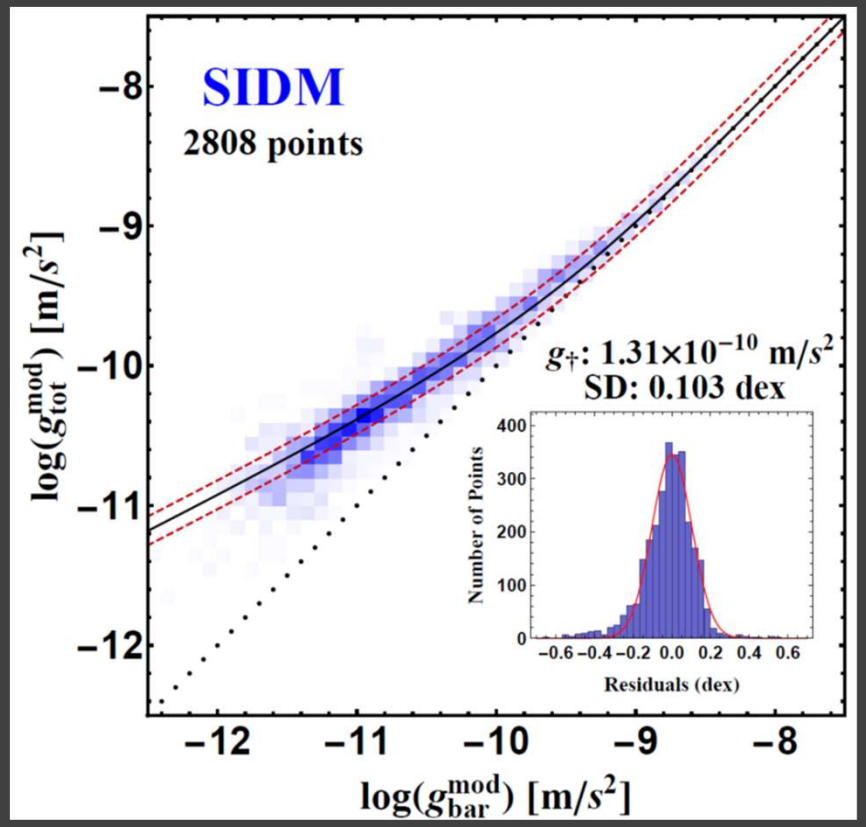


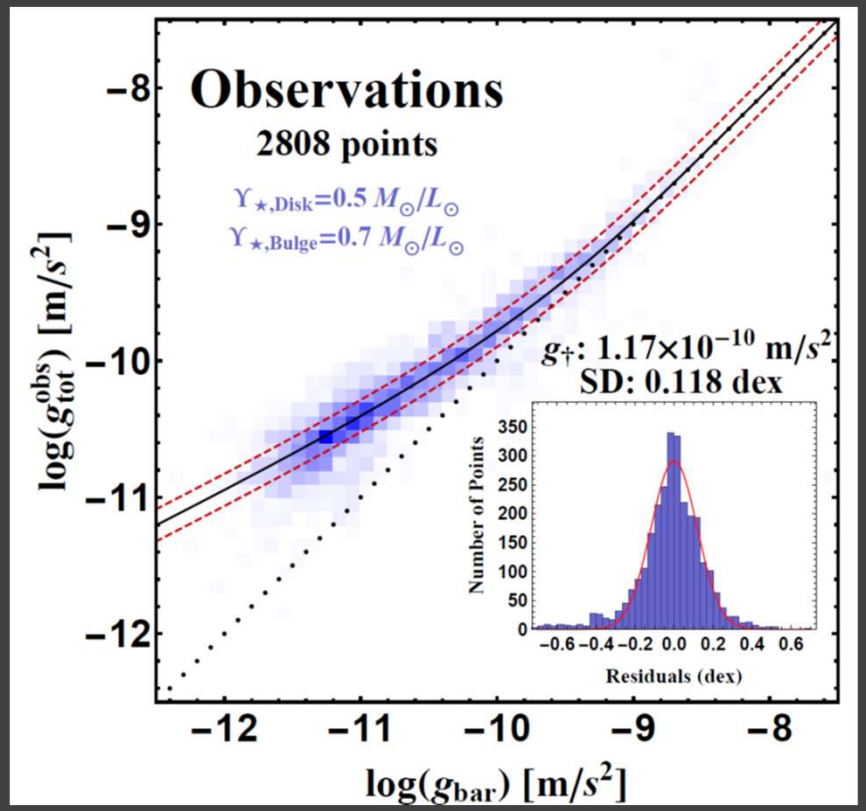




With Anna Kwa, Tao Ren and Hai-Bo Yu (to be posted soon)

The radial acceleration relation in the SPARC sample

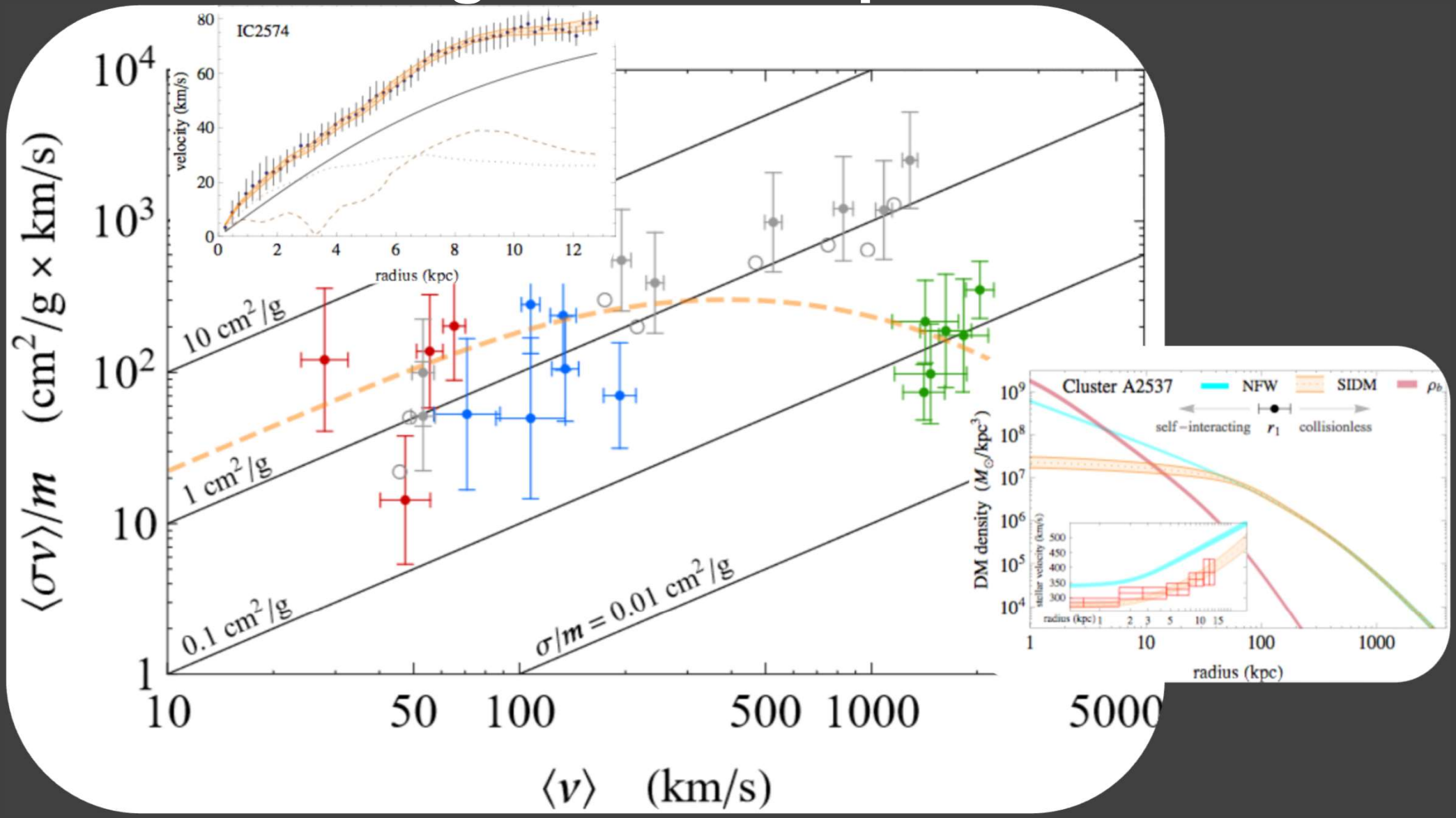




With Anna Kwa, Tao Ren and Hai-Bo Yu (to be posted soon)

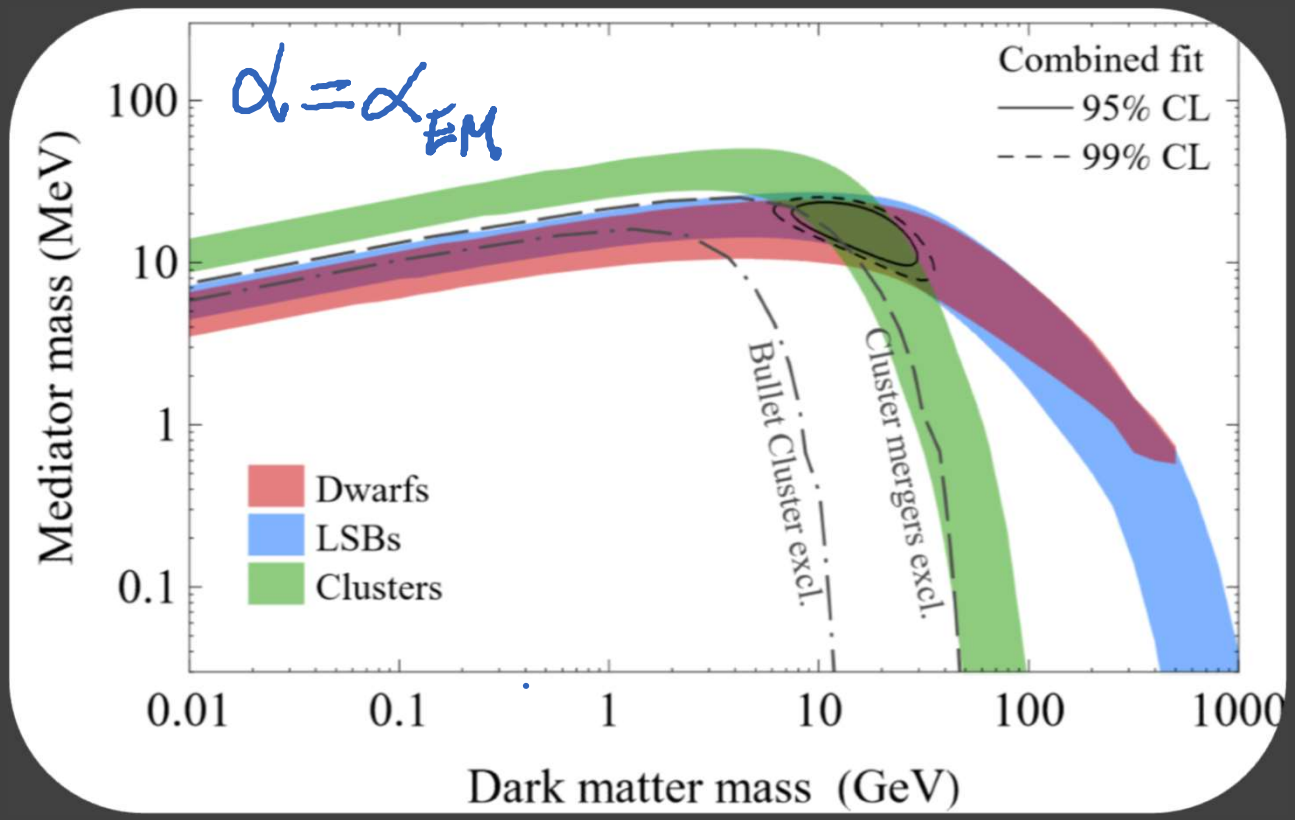
Adding information from clusters of galaxies: SIDM particle properties

The self-interaction cross section must decrease at high collision speeds



With Sean Tulin and Hai-Bo Yu (2015)

Measuring particle masses using astrophysics



$$V = \pm \frac{\alpha}{r} e^{-m_\phi r}$$

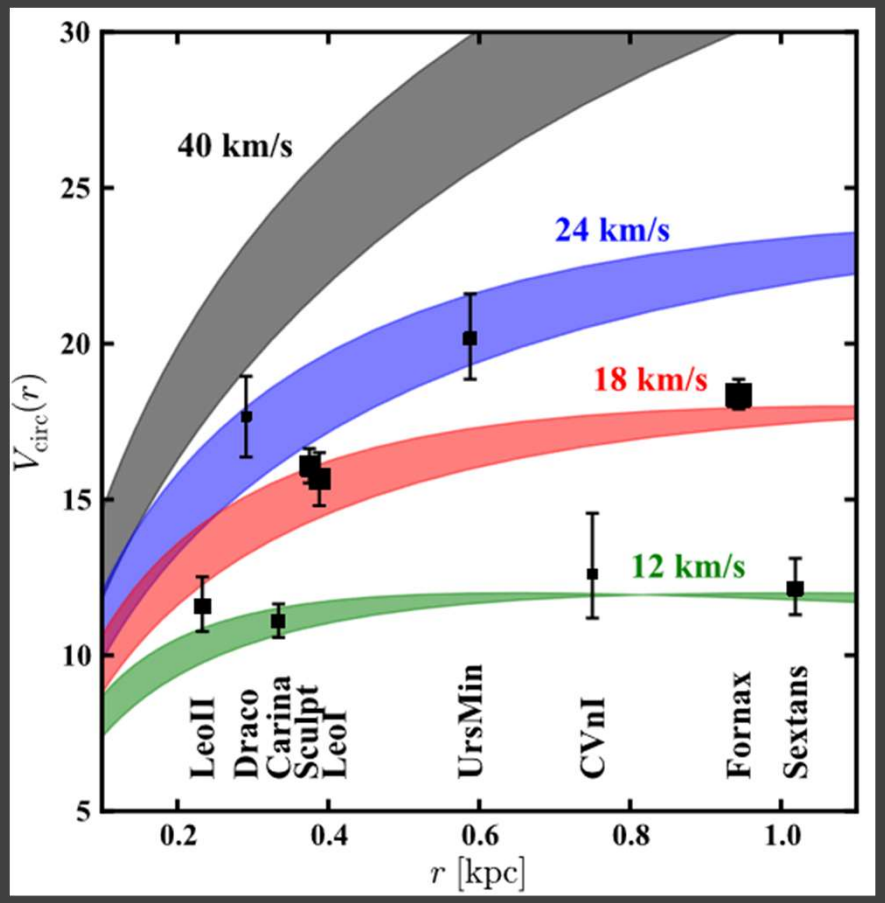
Tulin, Yu, Zurek 2012

Non-abelian sector
Boddy et al (2014)

With Sean Tulin and Hai-Bo Yu (2015)

Tests of LSIDM that don’t depend on specifics of the SIDM models.

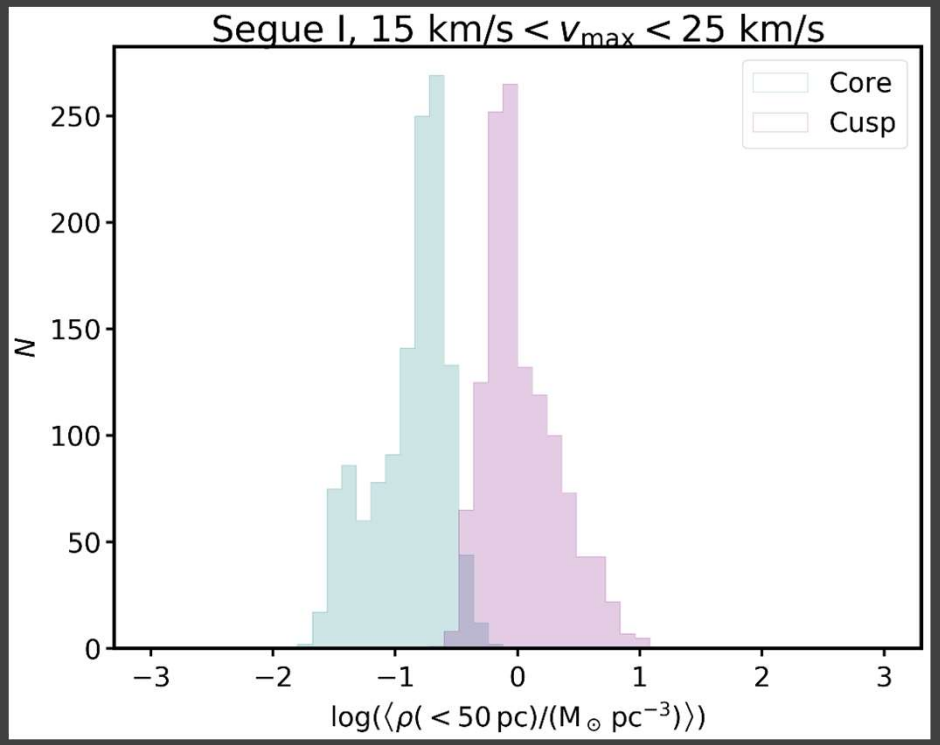
Cores in satellites



SIDM predicts cores in satellite galaxies.

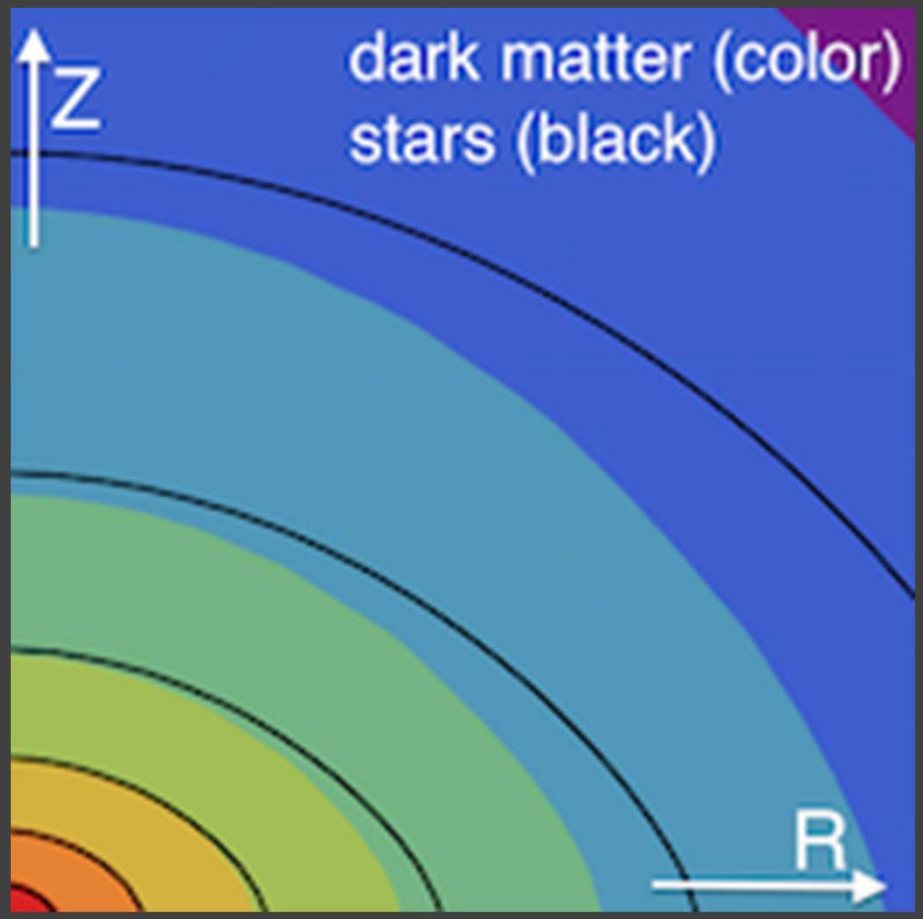
Multiple population chemo-dynamics in the MW satellites (Walker and Penarrubia 2011).

Lower densities in ultra-faint satellites



SIDM densities within 50-100 pc will be significantly smaller than CDM predictions (with Sheldon Campbell and Tim Carleton, in prep)

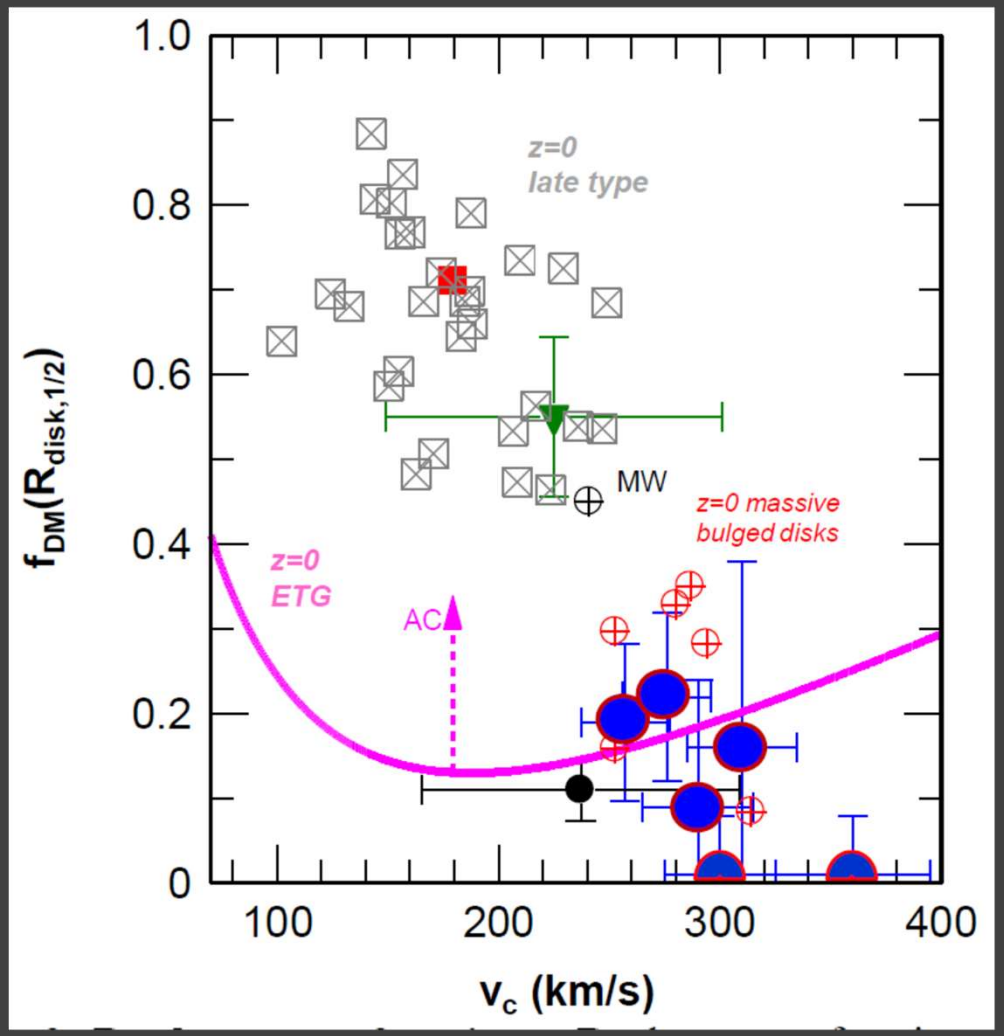
SIDM halo shape is not spherical



SIDM tracks the stellar potential where stars dominate.

Strong lenses and elliptical galaxies in X-rays.

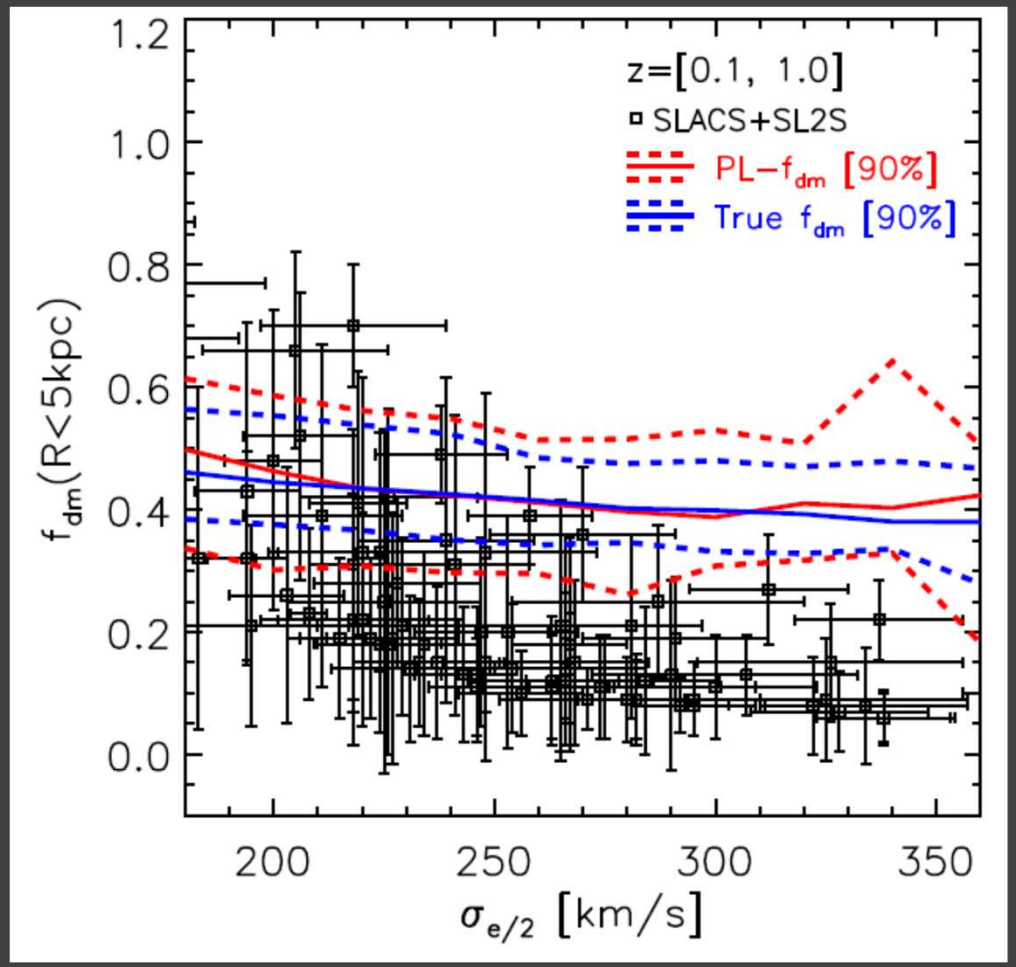
Growth of SIDM cores



Genzel et al 2017

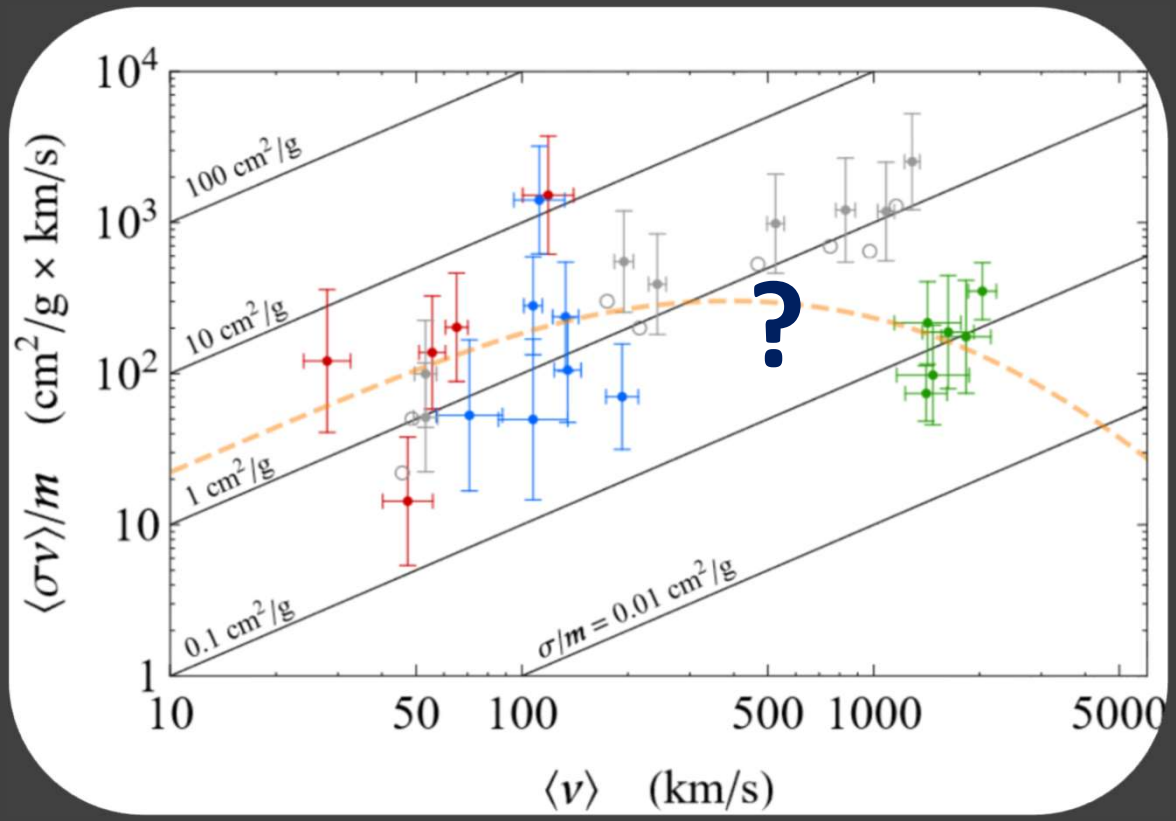
Early evolution of halos in LCDM and LSIDM should be different. This may be observable!

Dark matter halos of ellipticals

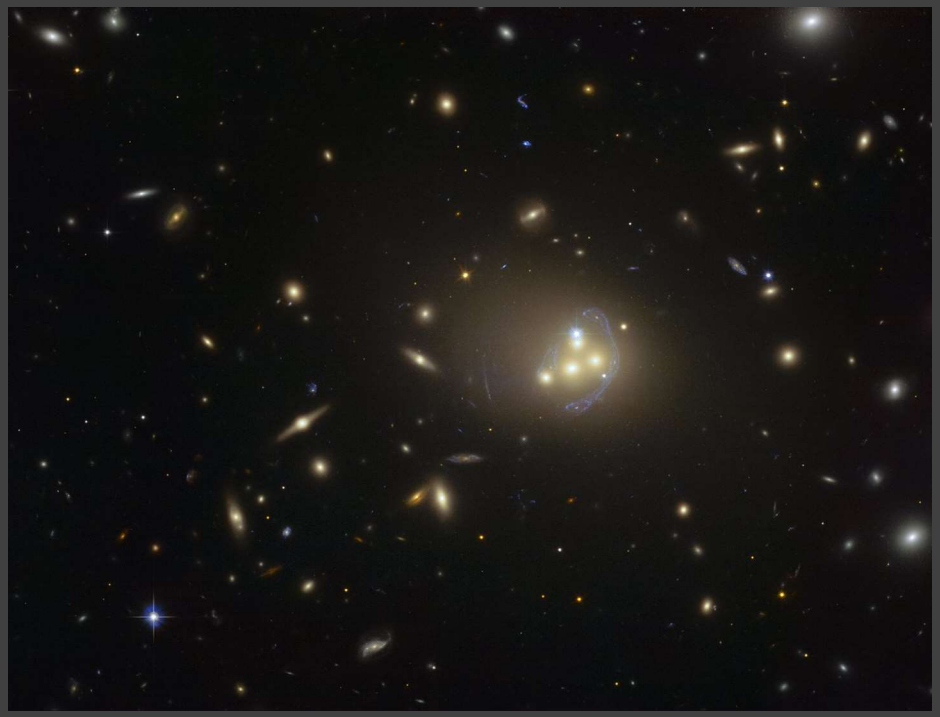


Xu et al 2016 (using Illustris)

Dark matter halos of groups



BCG offsets

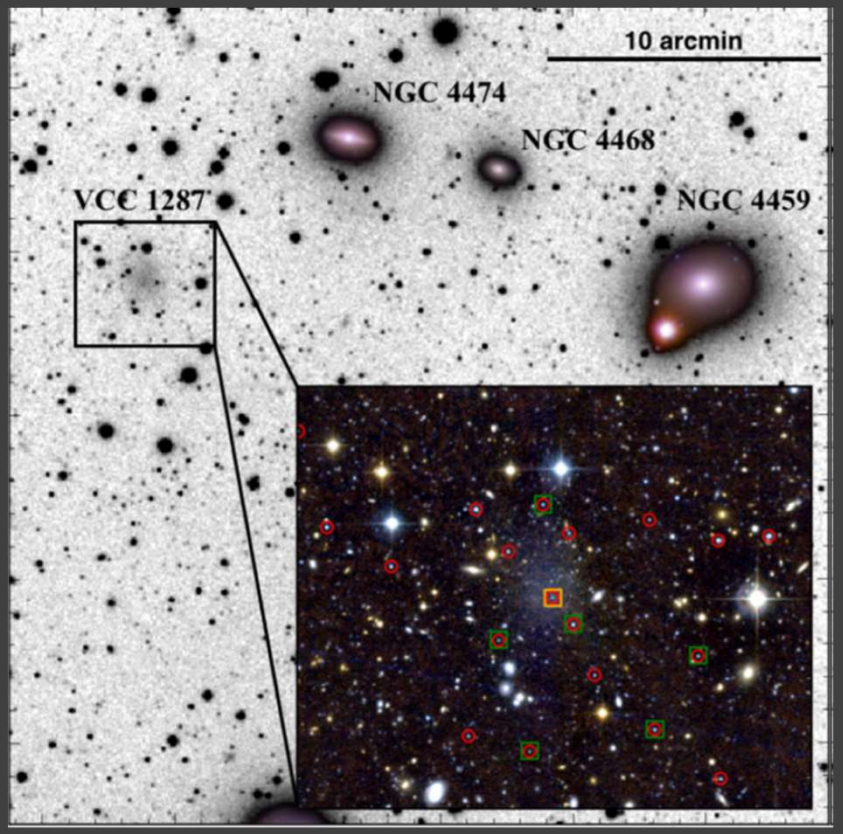


Abell 3827, Massey et al (2015)

In the cores of the clusters, BCGs slosh around (Kim, Peter, Wittman 2016).

Related to decreased dynamical friction (GCs in Fornax: Cole, Dehnen, Read, Wilkinson 2012).

Ultra-diffuse satellite galaxies



Beasley et al 2016

Infalling halos have cores in SIDM (with size dictated by stellar surface brightness).

Stars in cored halos expand due to tides (Penarrubia et al 2010).

Can this lead to the right number, radial distribution and scaling with host mass for UDGs? (Carleton et al, in prep).

There is a simple way to preserve all the successes of the ΛCDM and explain the distribution of dark matter in the inner parts of galaxies: *allow for thermalization of dark matter.*

This idea is testable in the next decade.