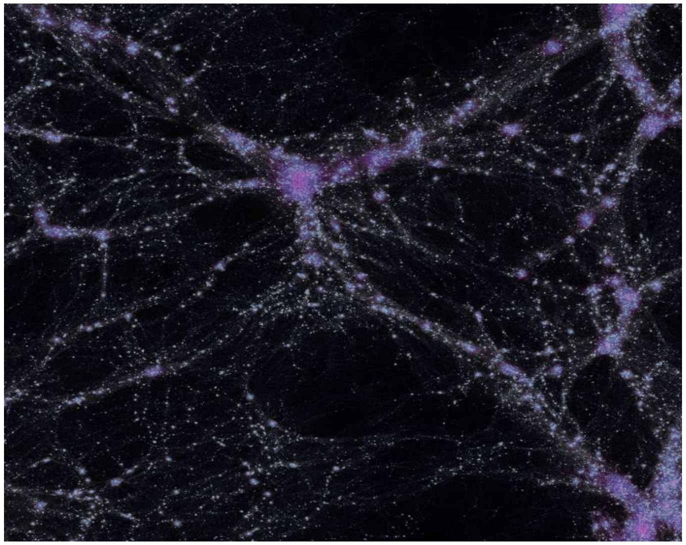
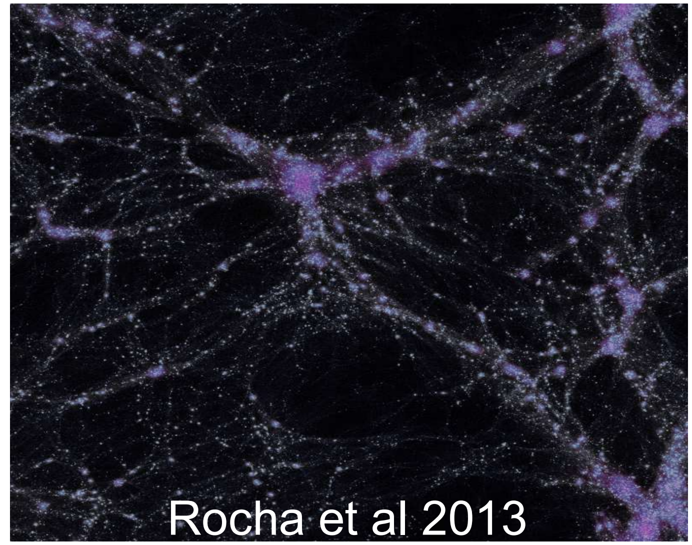


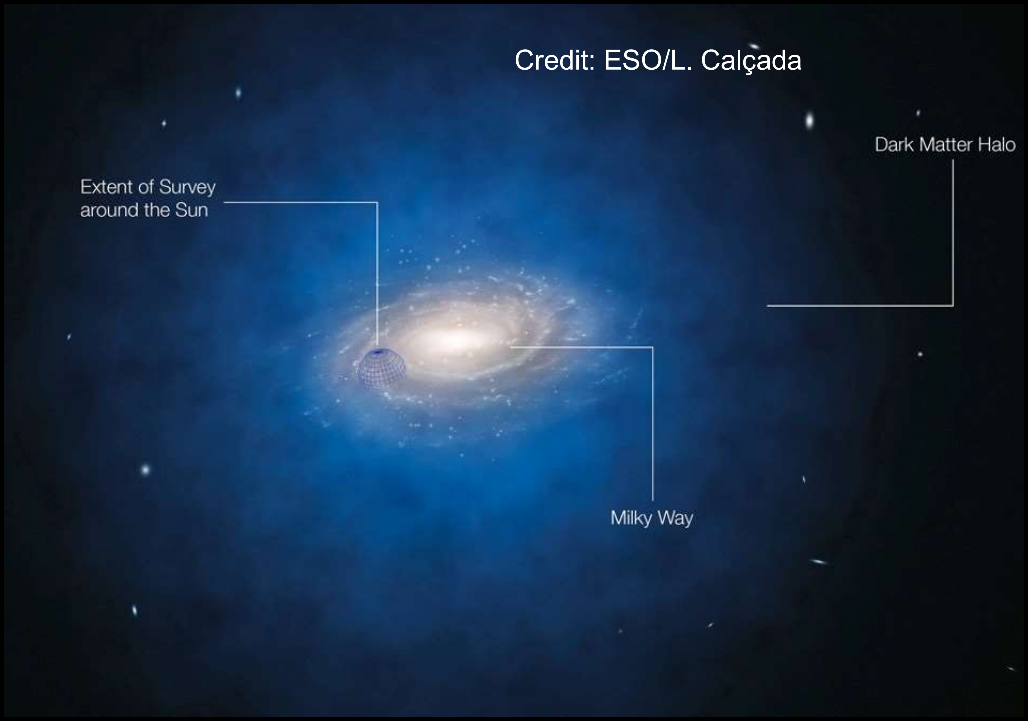


Self-interacting dark matter (SIDM)

Manoj Kaplinghat
UC Irvine

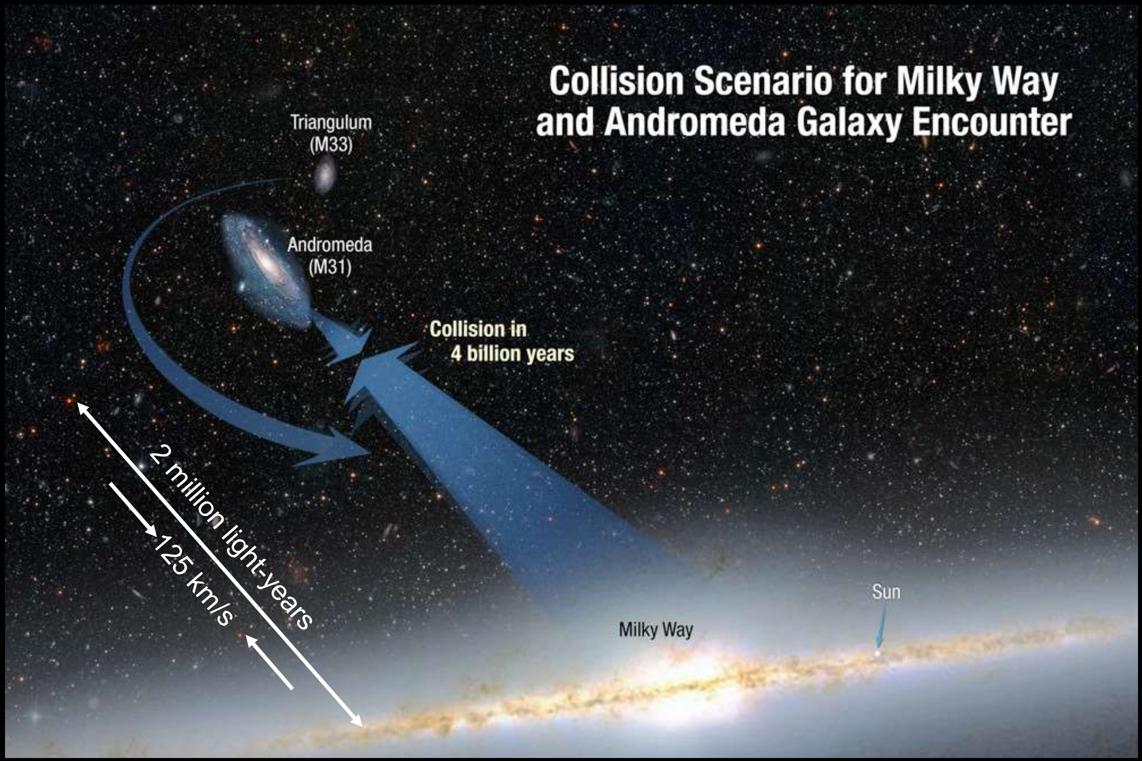
Dark matter is inferred from the solar neighborhood to the largest cosmological scales

In our backyard



0.3 GeV per cc in dark matter.

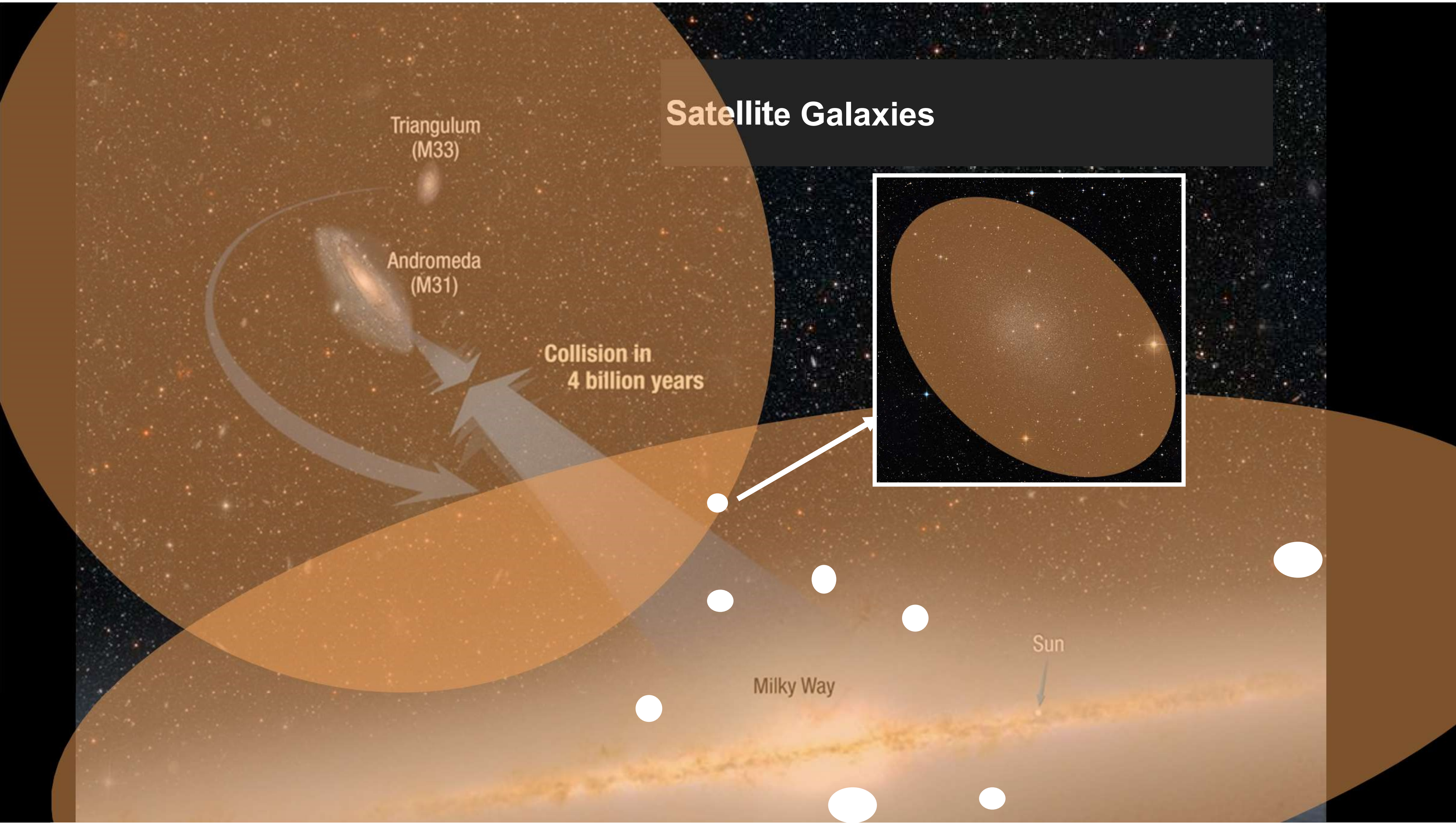
Fully consistent with ΛCDM.



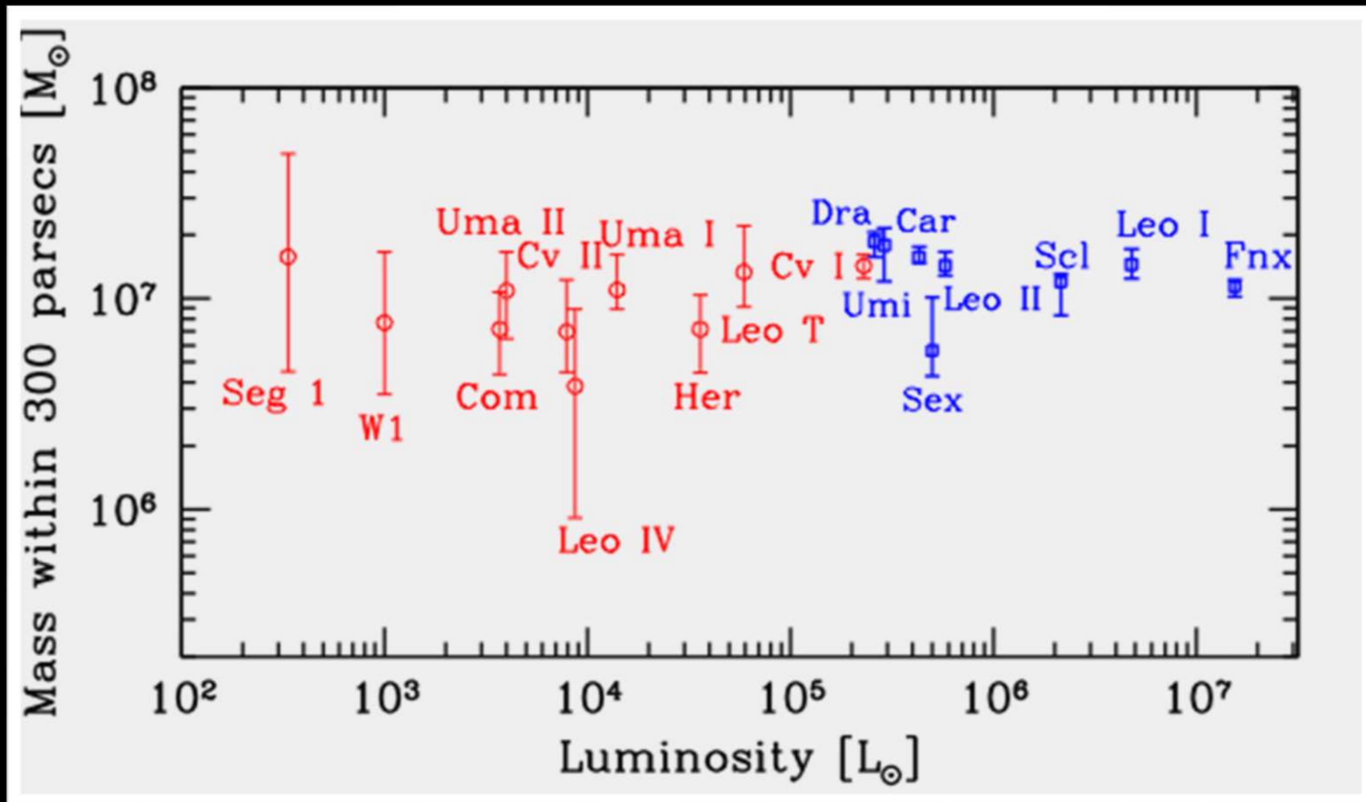
$$\mathrm{MW} + \mathrm{And} = 3 \times 10^{12} \mathrm{M}_{\odot}$$

DM is more than 10 times the mass in all the stars and gas.

Satellite Galaxies

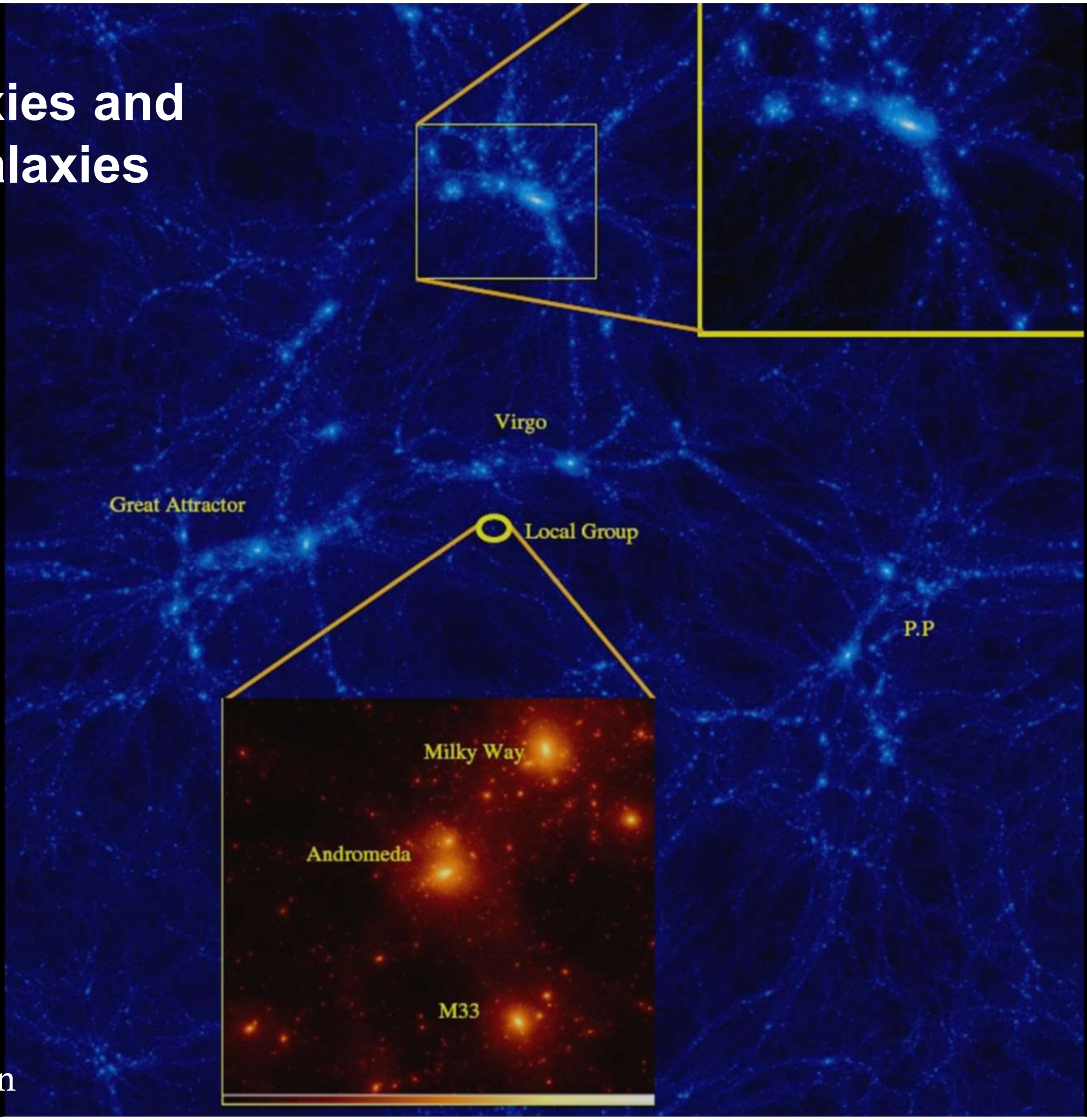


Satellite galaxies are mostly dark matter



Strigari et al Nature (2008)

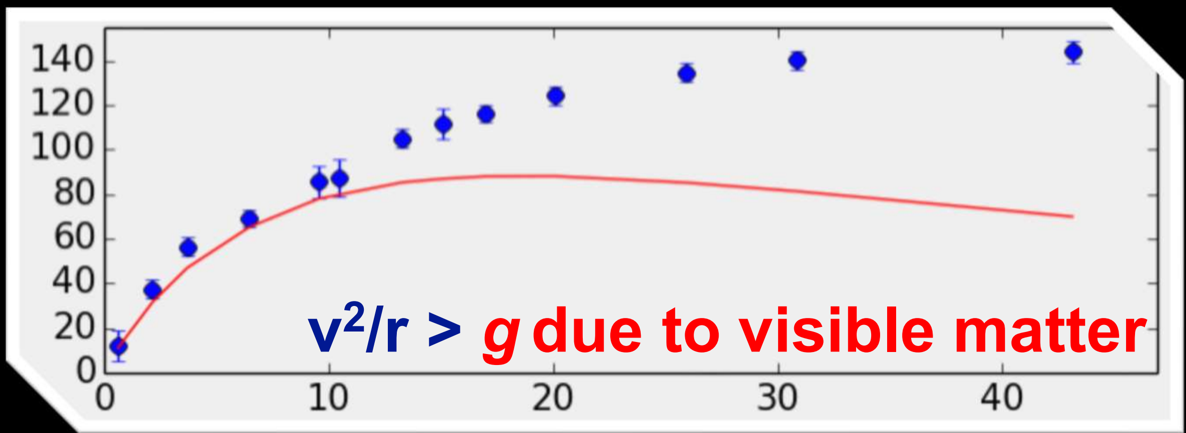
In other galaxies and clusters of galaxies



CLUES collaboration

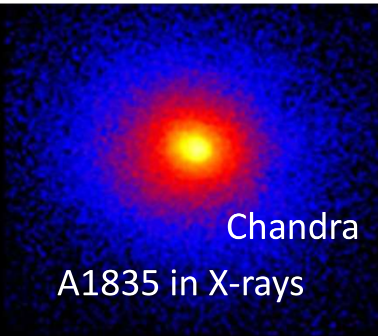
All spiral galaxies (not just our own) show evidence for dark matter

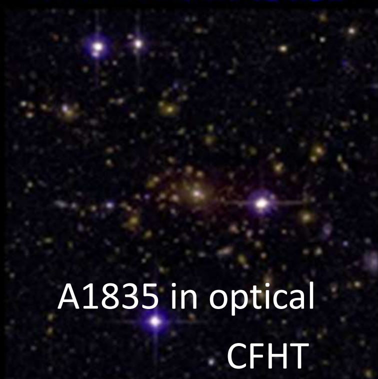
Rotation speed, **v** [km/s]

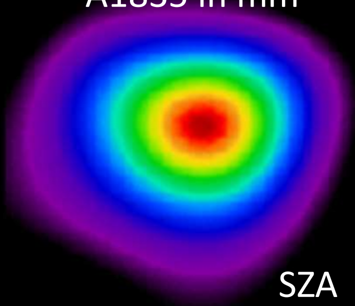


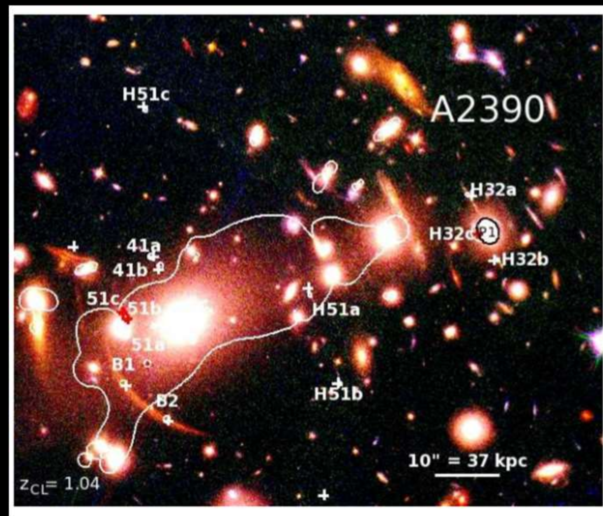
Distance from center, **r** [klyr]

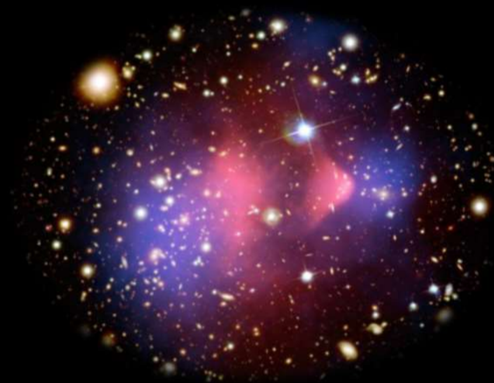
Dark matter in clusters of galaxies





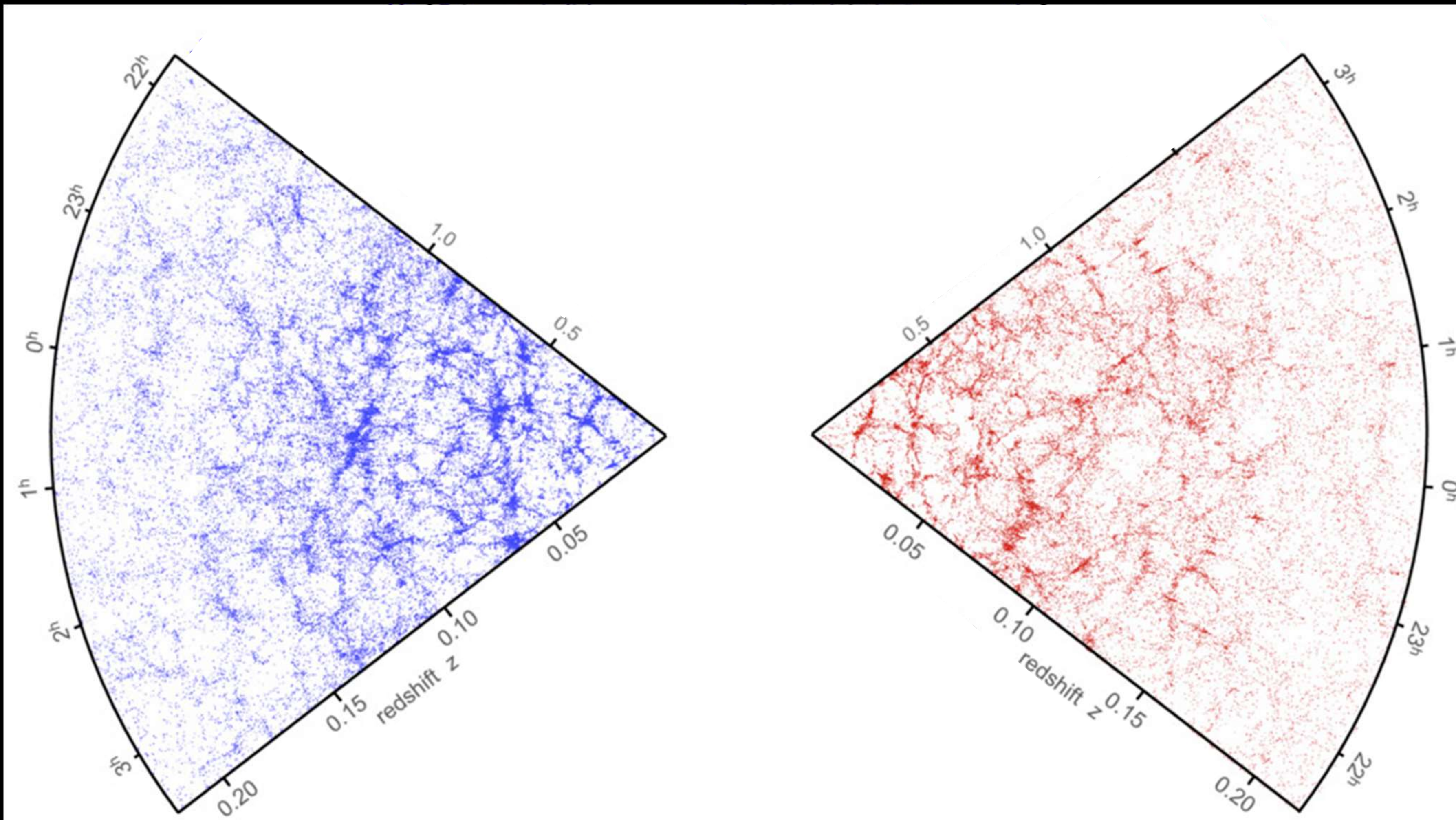




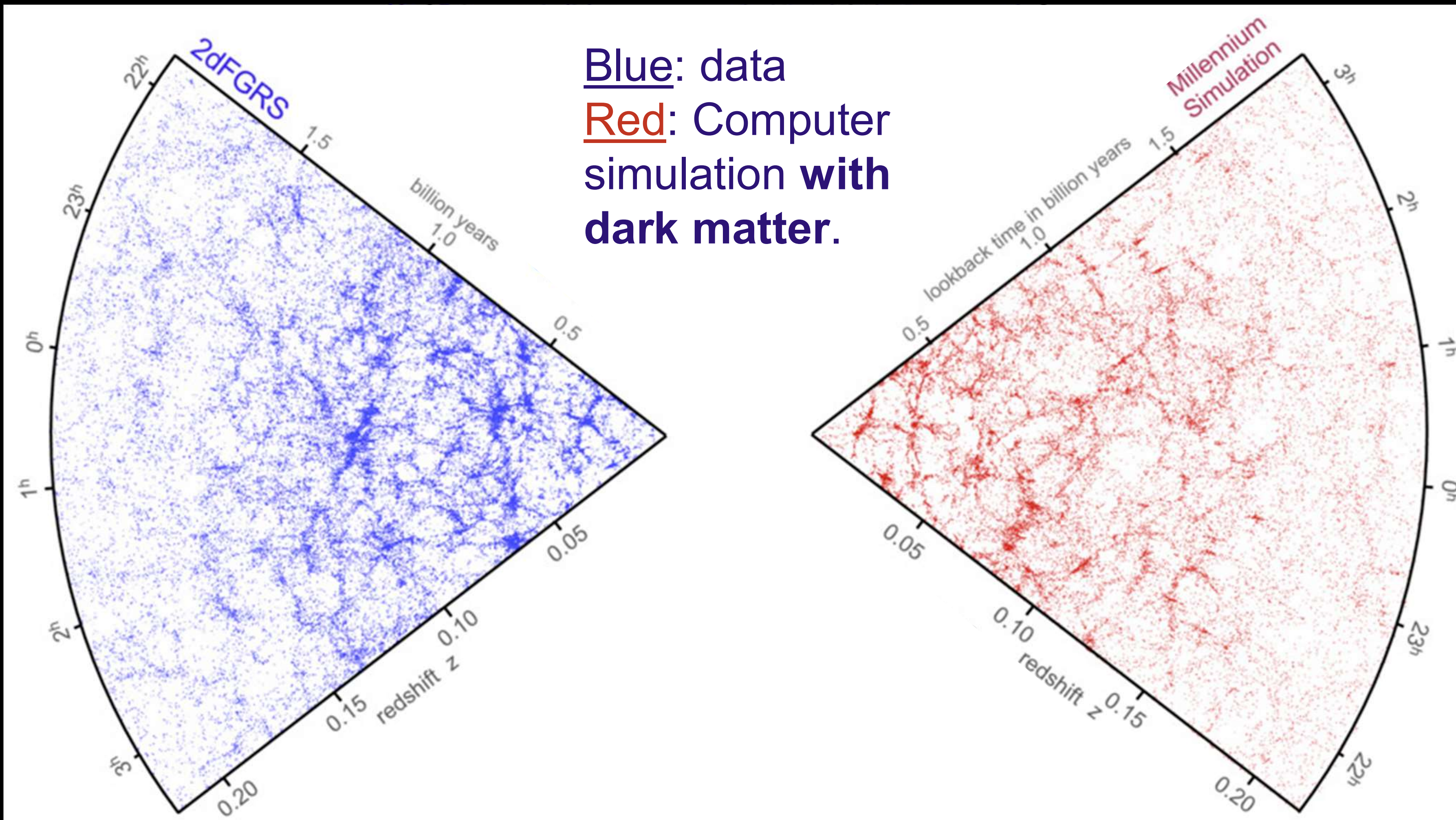


About 80% of the matter in clusters of galaxies is dark matter.

Distribution of galaxies on the largest scales

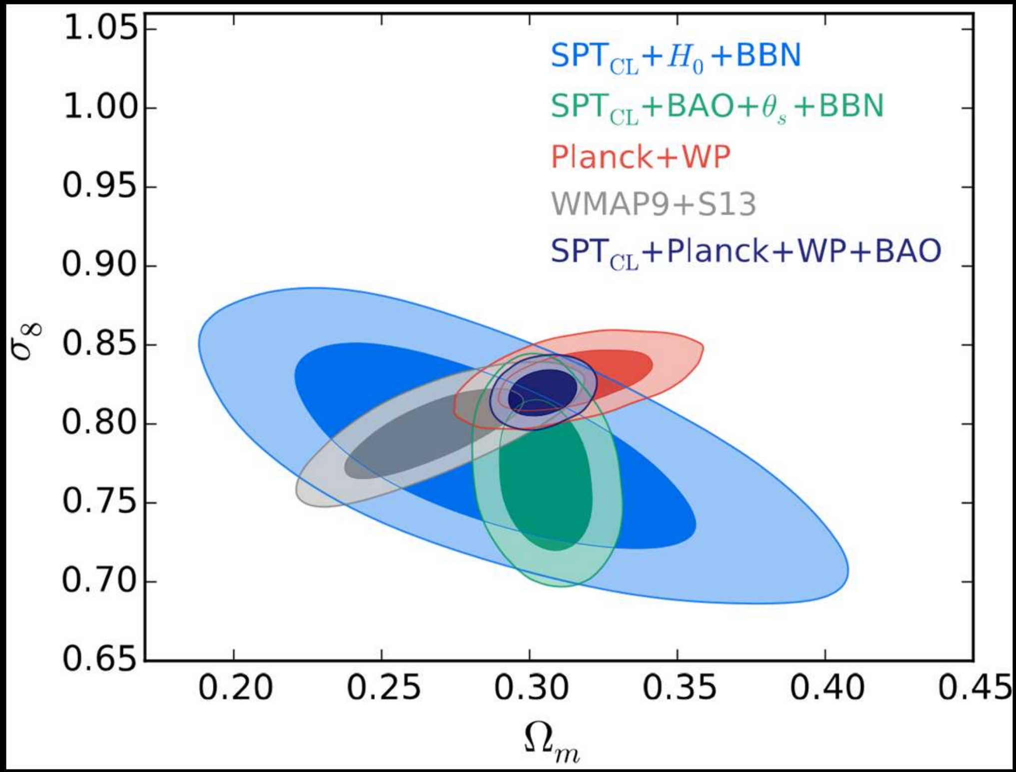


= Distribution predicted with dark matter



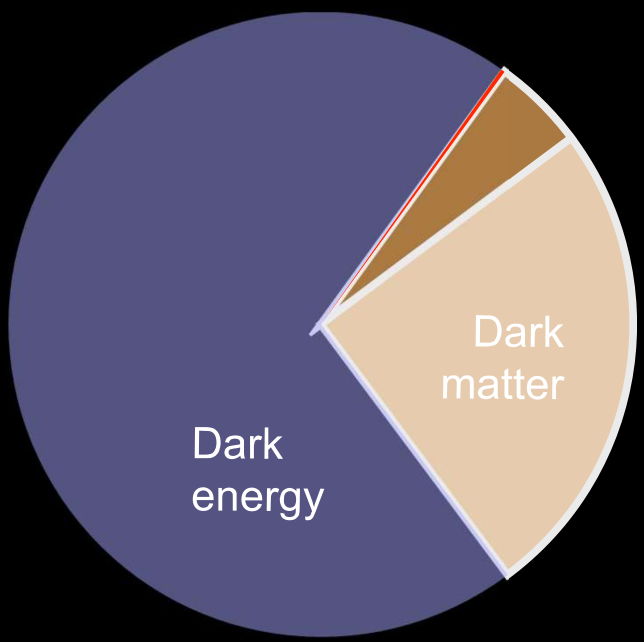
Blue: data
Red: Computer simulation **with dark matter**.

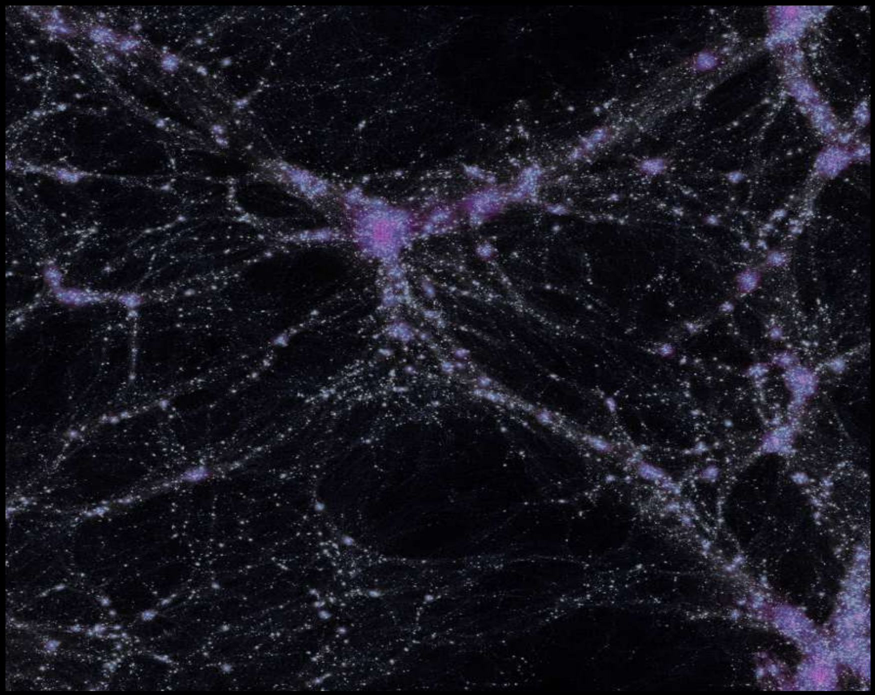
Consistency of different cosmological measures of the matter density



South Pole Telescope collaboration (2016)

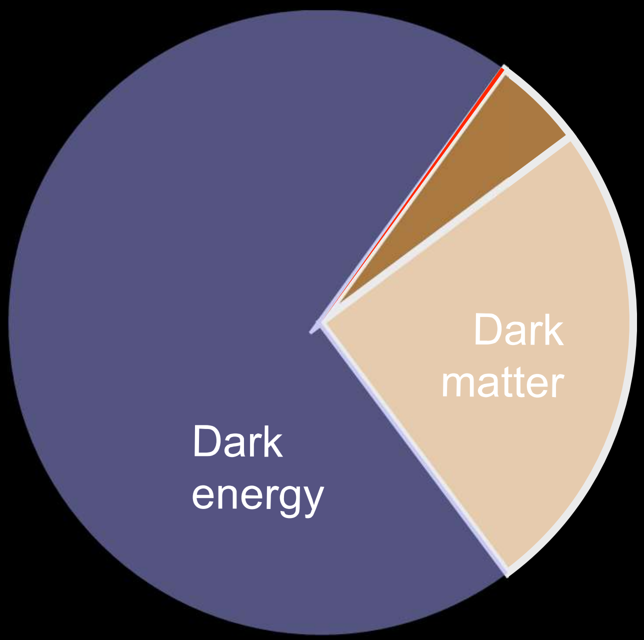
ΛCDM agrees well with the observed large-scale structure.

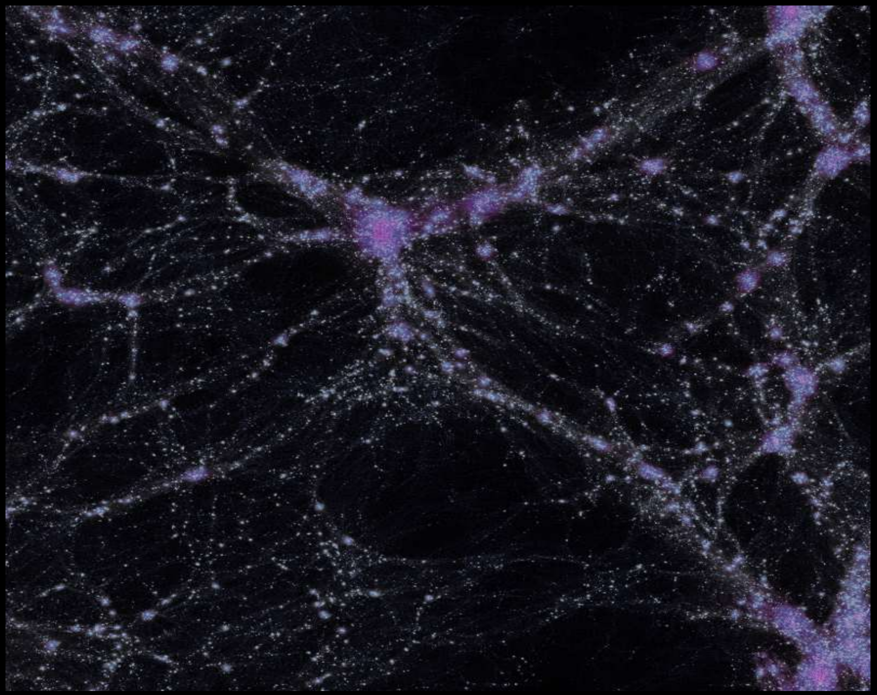




On large scales, cold dark matter (CDM) is the right description.

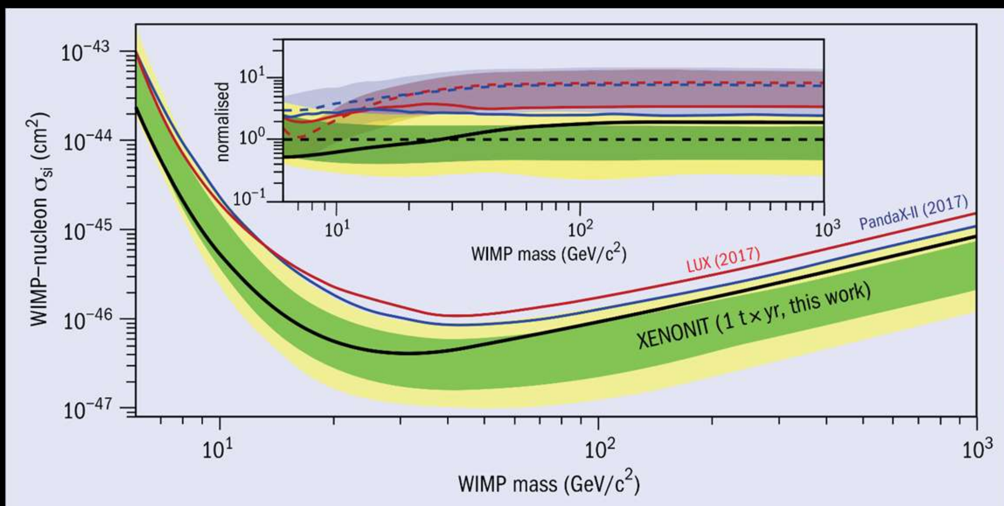
ΛCDM agrees well with the observed large-scale structure.



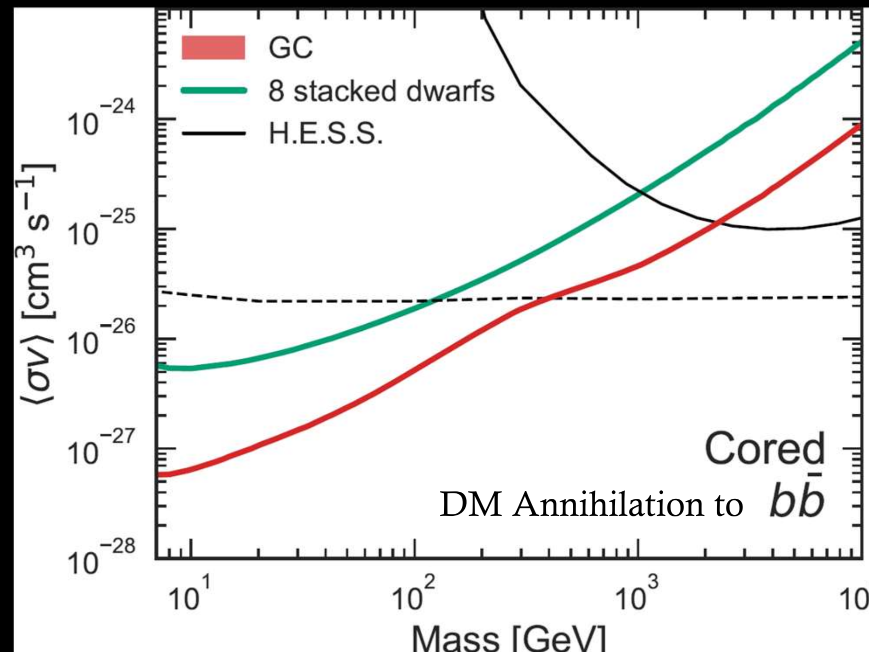


However, that doesn't tell us what the dark matter particle is.

Standard WIMP scenarios are under siege

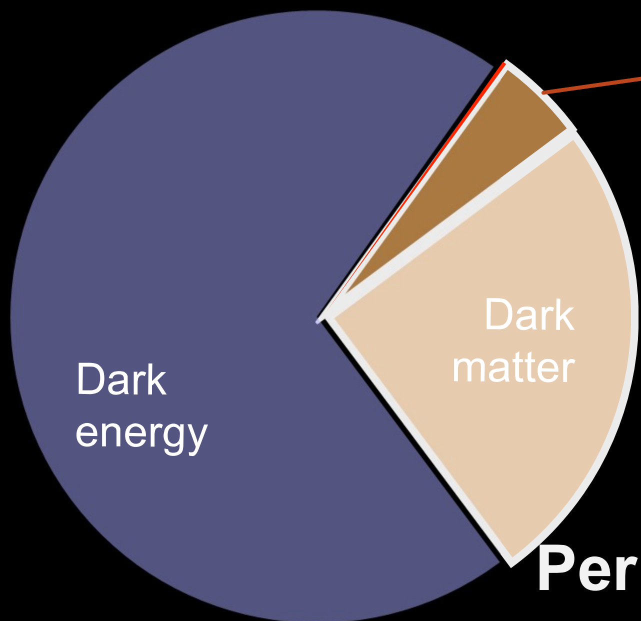


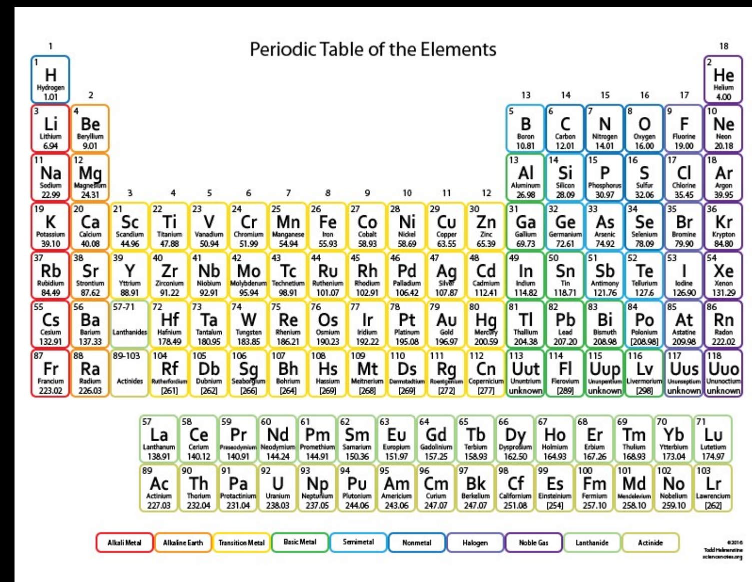
Xenon1T collaboration (2018)



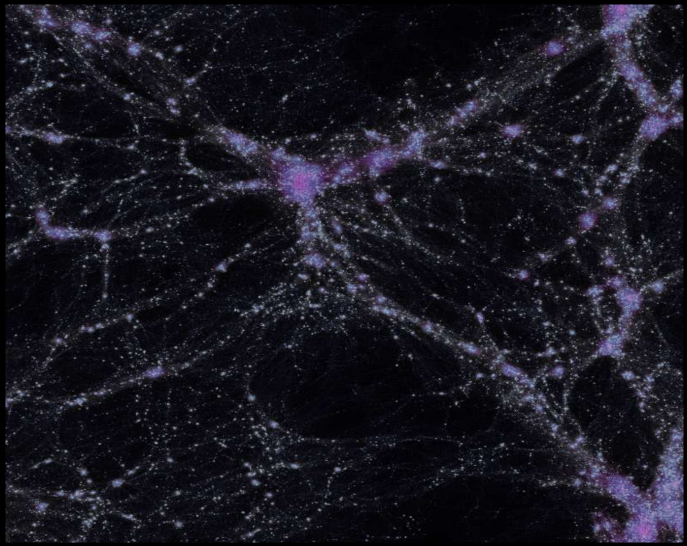
With Abazajian, Horiuchi, Keeley and Macias, PRD (2020)

These results motivate looking for lower mass dark matter and associated dark sectors.





Perhaps, the “dark sector” is richer than we have previously imagined.



Dark sector particles can interact with each other, like visible sector particles. This generic idea of self-interacting dark matter (SIDM) has been around for a while.

For the purposes of this talk, SIDM = CDM on large scales.

SIDM phenomenology motivated by rotation curves

Originally proposed by Spergel and Steinhardt, PRL 2000
Version below by Kaplinghat, Tulin and Yu, PRL 2016

Fits spiral galaxy rotation curves well

DM halo becomes insensitive to star formation history because self-interactions achieve equilibrium quickly.

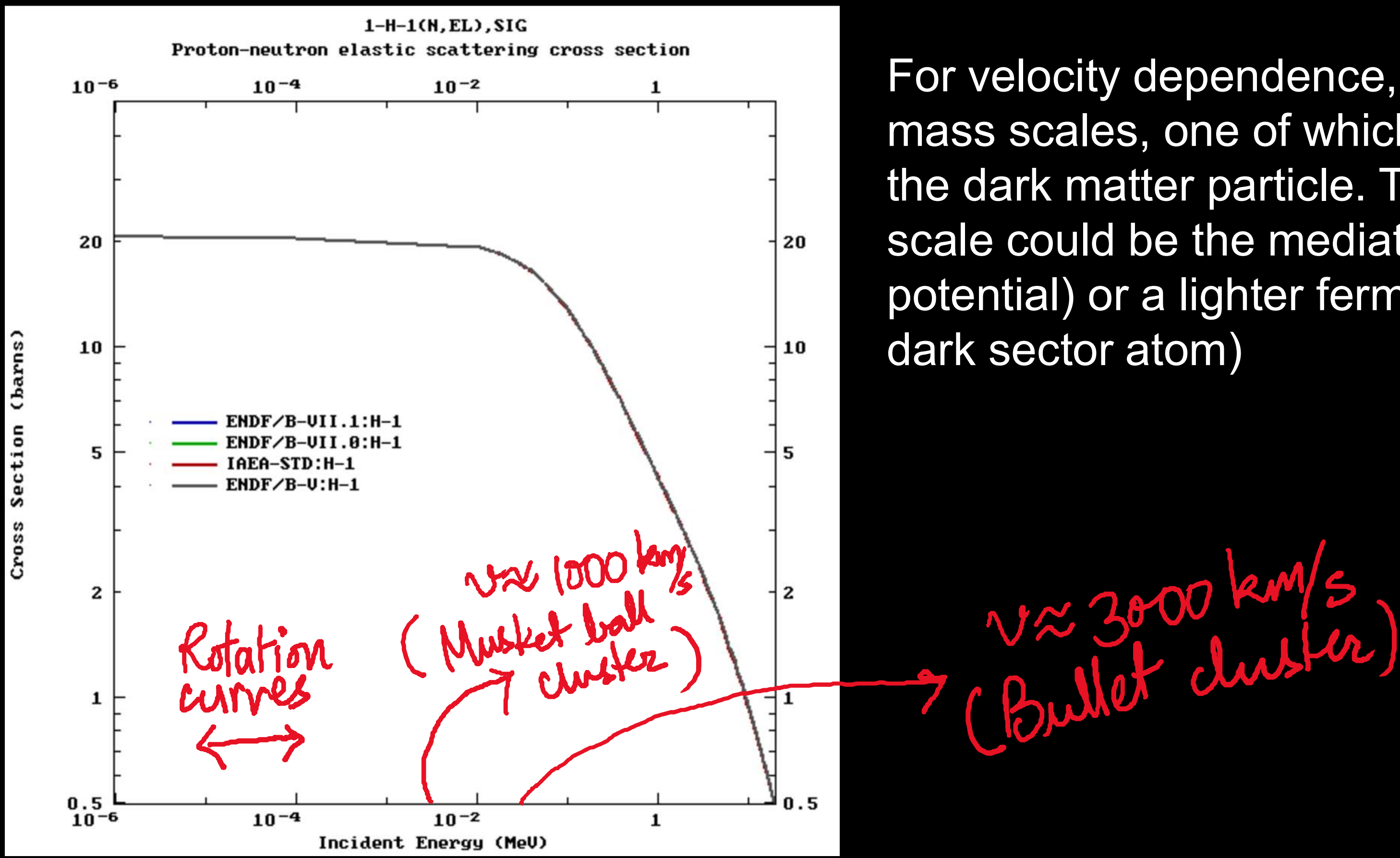
$\frac{\sigma}{m} = \text{few}\ \frac{\text{cm}^2}{\text{g}}$

(in galaxies)

But, cross section at low velocities could be much larger.

Cross section must fall with velocity and be close to 0.1 cm^2/g *at* $v \sim$ 1000 km/s.

Standard Model example for SIDM



For velocity dependence, you need two mass scales, one of which is the mass of the dark matter particle. The smaller mass scale could be the mediator mass (Yukawa potential) or a lighter fermion mass (e.g., dark sector atom)

SIDM phenomenology motivated by rotation curves

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

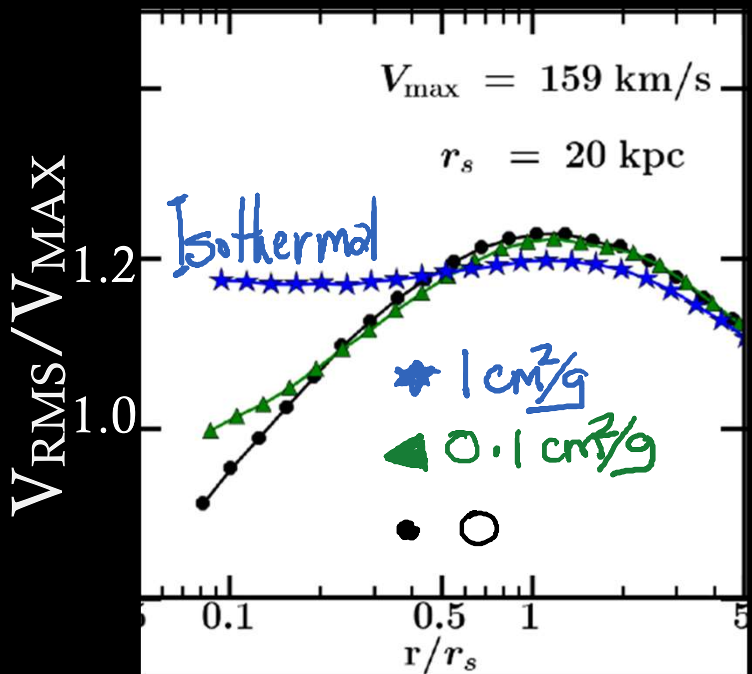
(in galaxies)

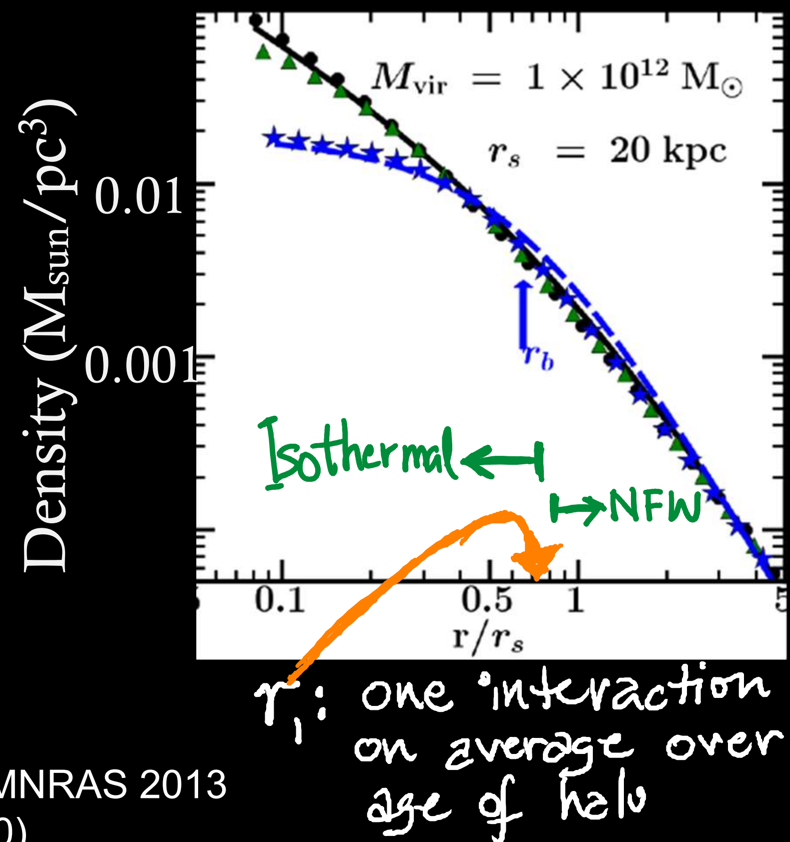
Required DM self-interaction cross section over mass at low velocities – O(10) barns/GeV – is similar in magnitude to nuclear cross sections.

Is this a clue to a QCD-like structure in the dark sector?

Impact of self-interactions on galactic halos

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)

Galaxy halo density profiles

Navarro–Frenk–White profile

From Wikipedia, the free encyclopedia

The **Navarro–Frenk–White (NFW) profile** is a spatial mass distribution of dark matter fitted to dark matter halos identified in N-body simulations by Julio Navarro, Carlos Frenk and Simon White.[1] The NFW profile is one of the most commonly used model profiles for dark matter halos.[2]

Contents [hide]

Density distribution [edit]

In the NFW profile, the density of dark matter as a function of radius is given by:

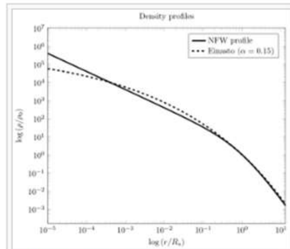
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

where ρ_0 and the "scale radius", R_s, are parameters which vary from halo to halo.

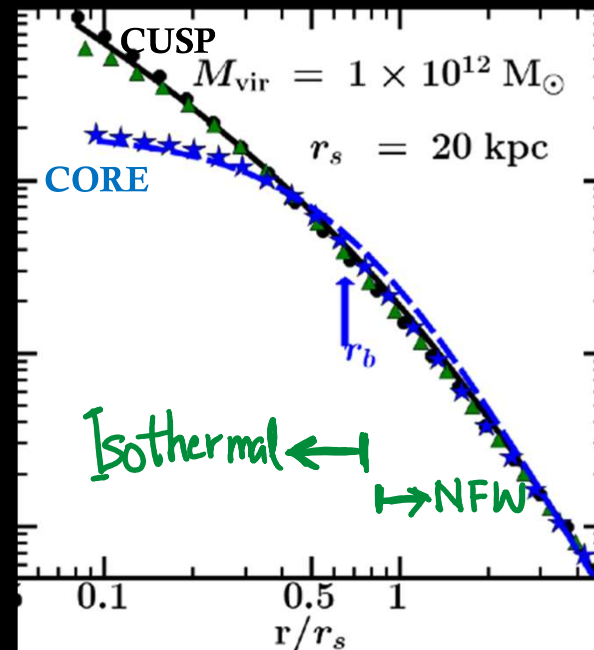
The integrated mass within some radius $R_{\max}$ is

$$M = \int_0^{R_{\max}} 4\pi r^2 \rho(r)\, dr = 4\pi\rho_0 R_s^3 \left[\ln\left(\frac{R_s + R_{\max}}{R_s}\right) + \frac{R_s}{R_s + R_{\max}} - 1\right]$$

The total mass is divergent, but it is often useful to take the edge of the halo to be the virial radius, $R_{\rm vir}$, which is related to the "concentration parameter", c, and scale radius via



Plot of the NFW and Einasto profiles



SIDM halo profile for field galaxies

Inside r_1, $\rho_{\mathrm{SIDM}}(r) = \rho_{core} e^{-\Phi\,(r)/kT}$

gravitational potential
of dark matter and baryons

Match mass and density at r_1 to fix ρ_{core} and *T* in terms of CDM (NFW) halo parameters.

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

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

SIDM halo profile (where the stars are)

Depends on the outer halo profile

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

gravitational potential of dark matter and baryons

High-surface brightness galaxies are “cuspy”

Low surface brightness galaxies are “cored”

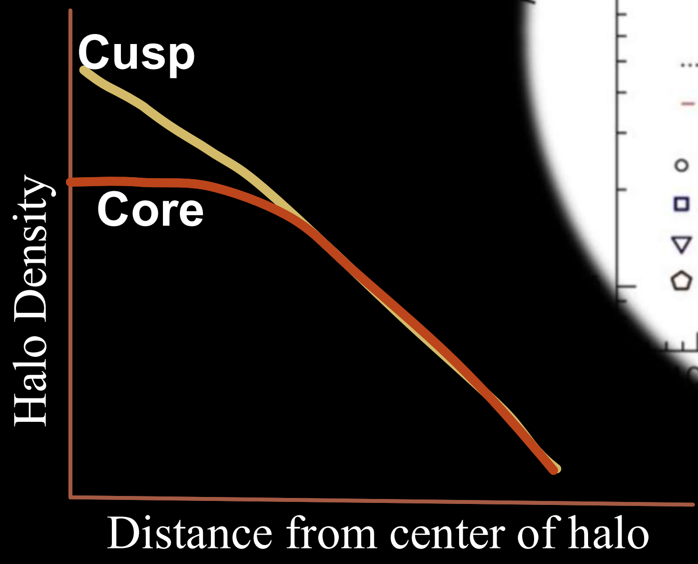
With Ryan Keeley, Tim Linden and Hai-Bo Yu, PRL 2014

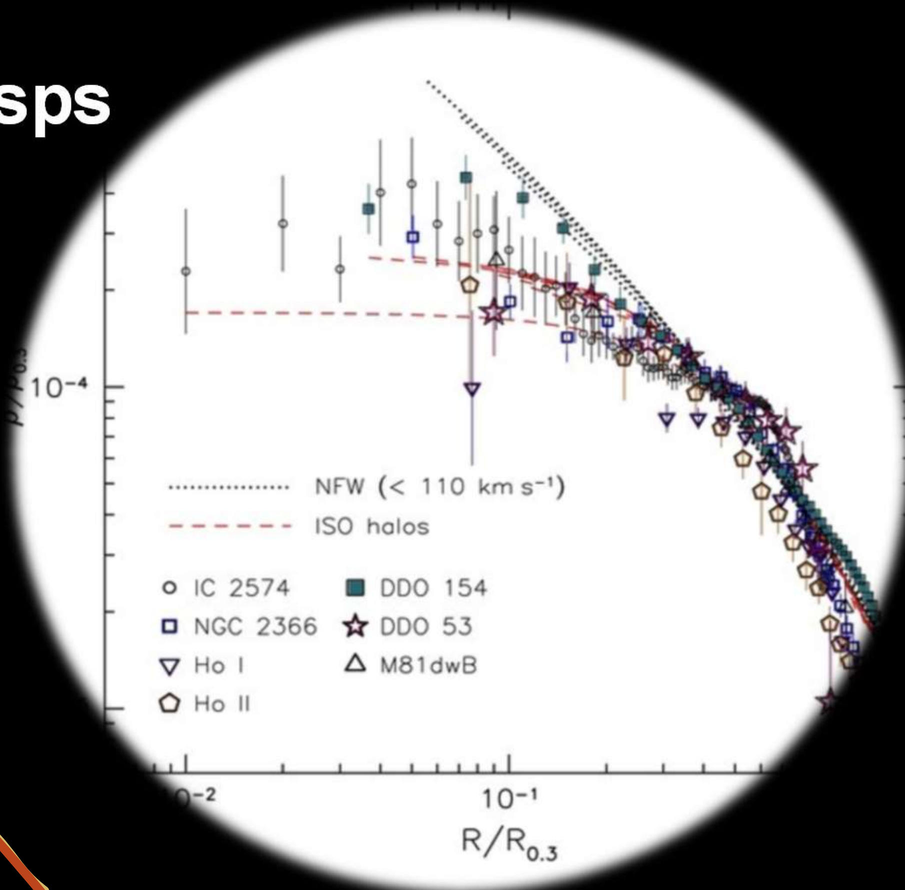
Can we discover that DM has self-interactions?

A promising strategy is to use field galaxies to constrain SIDM parameter space and then use satellite galaxies and dark subhalos to test.

Rotation curves of field galaxies

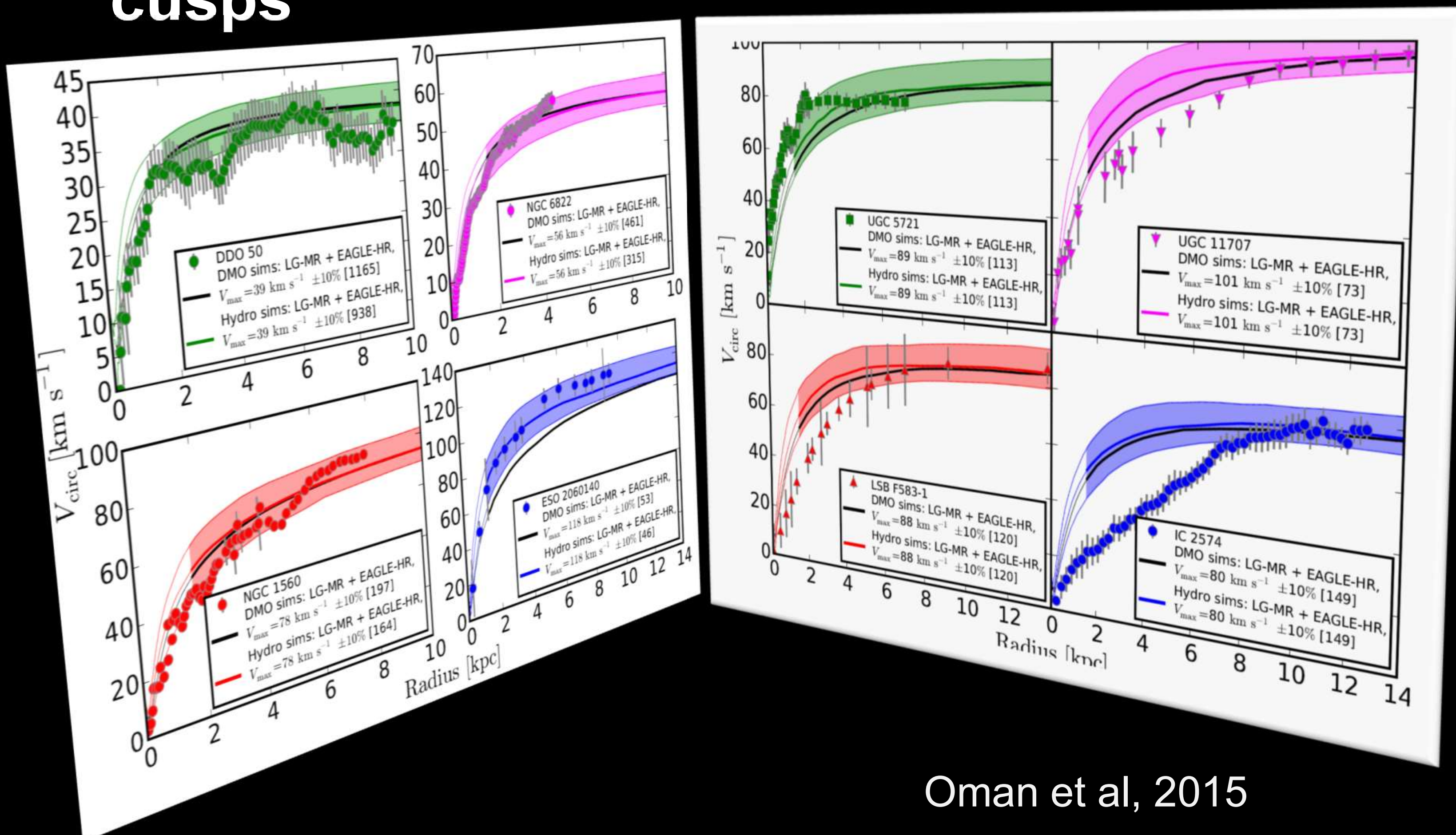
Cores AND cusps





Oh et al 2015

Diversity of rotation curves: Cores AND cusps

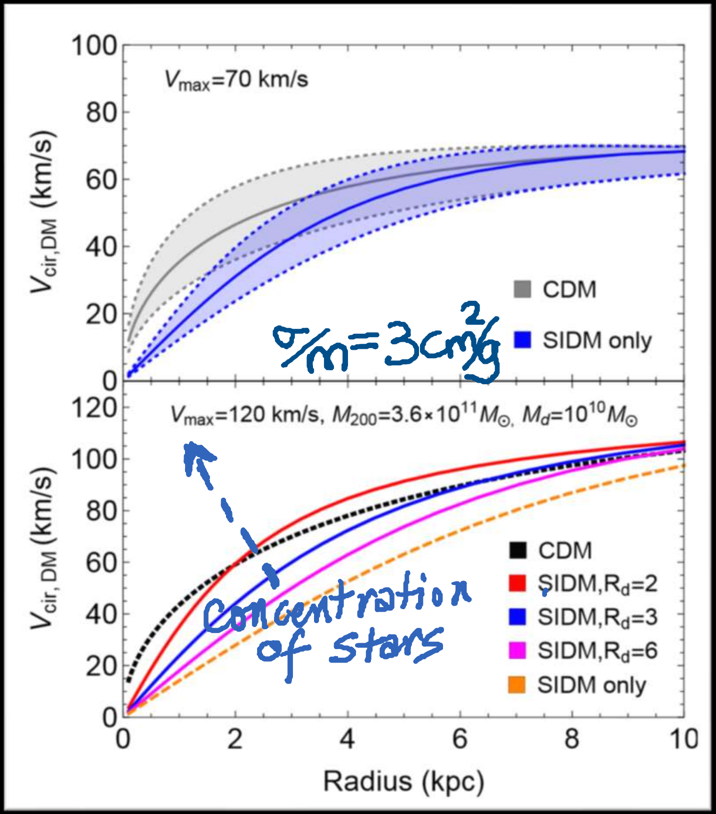


Oman et al, 2015

SIDM does not predict large cores in all galaxies

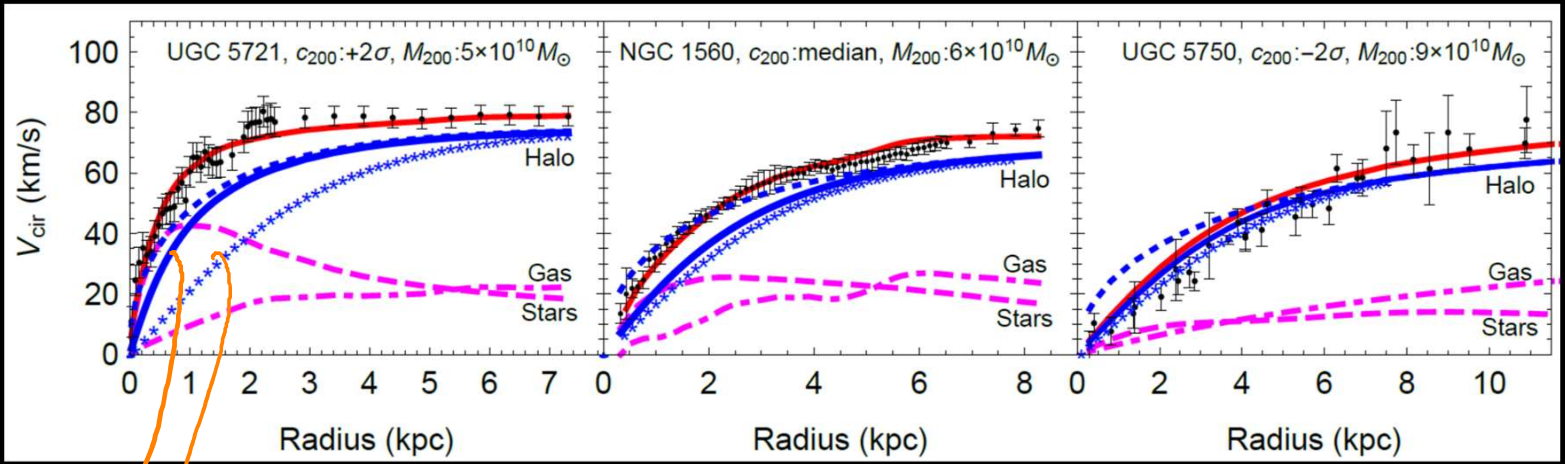
As stellar density increases, cores become hard to discern (i.e., cuspy).

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

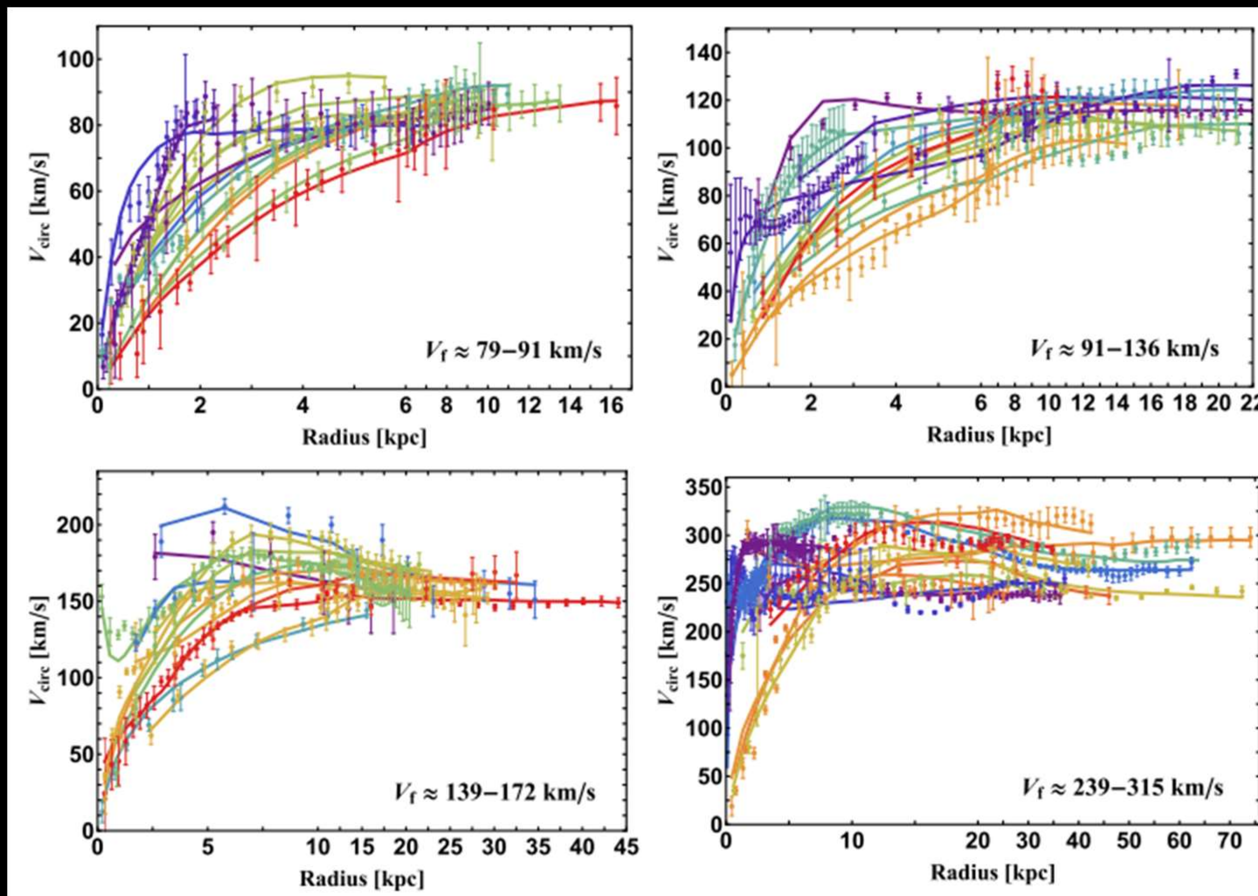
How SIDM explains the diverse rotation curves



without including the potential of stars
correct SIDM density profile

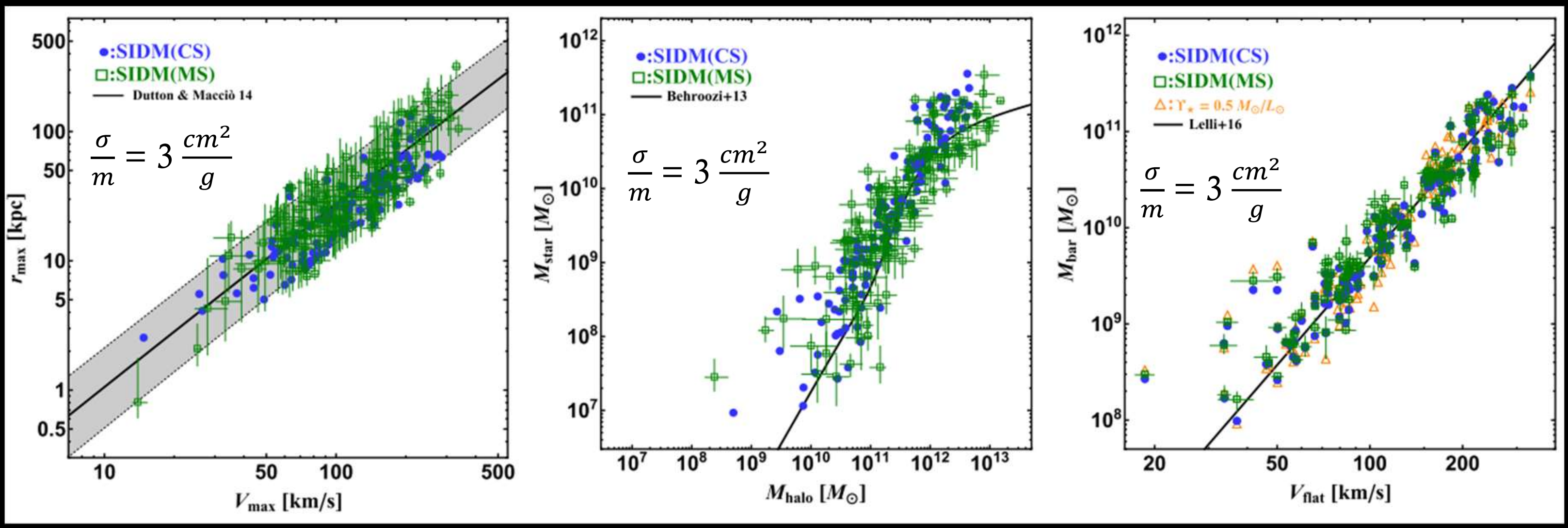
With Ayuki Kamada, Andrew Pace and Hai-Bo Yu, PRL 2017

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

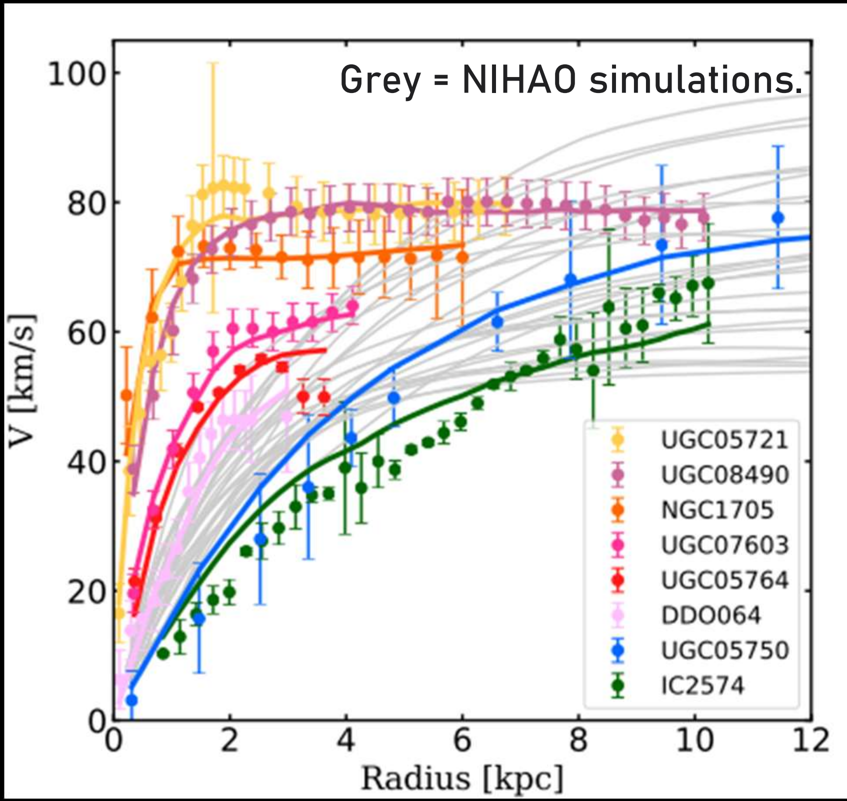


Halo parameters Stellar mass – halo mass Baryonic Tully-Fisher

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, PRX 2019

Current feedback models cannot be final word

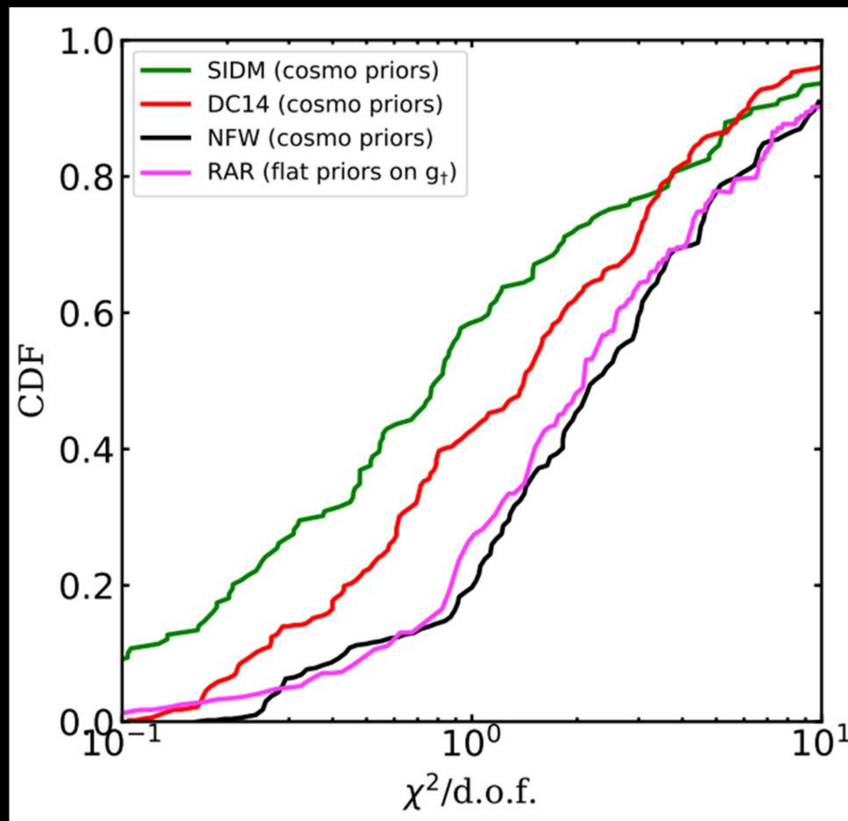


What you do to DM, you do to stars.

Strong feedback does not make high-surface brightness (compact) galaxies.

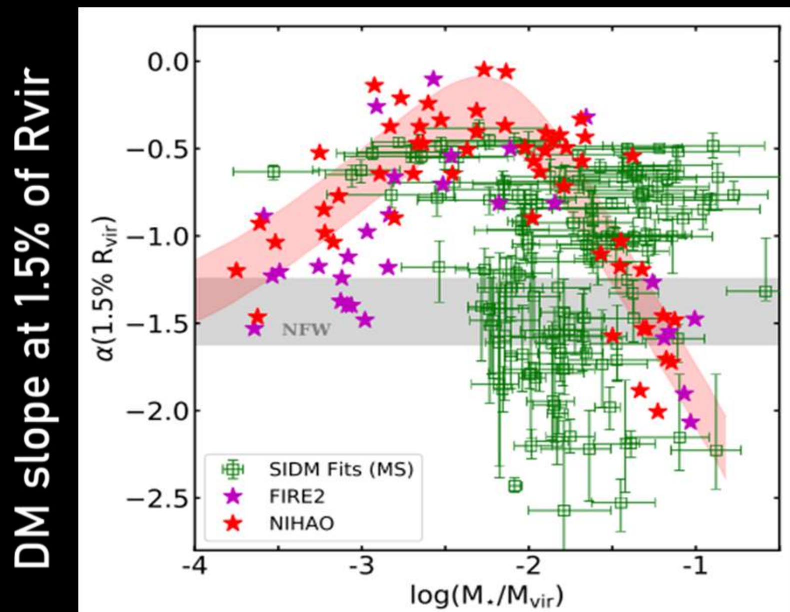
With Tao Ren and Hai-Bo Yu (2019)

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



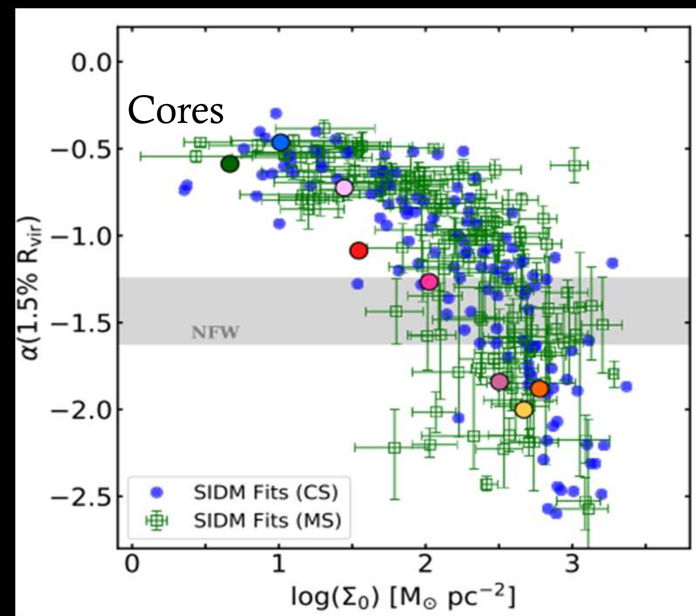
With Tao Ren and Hai-Bo Yu (2019)

Why does SIDM get the rotation curves right?



Stellar mass

CDM: slope correlated with stellar-to-halo mass



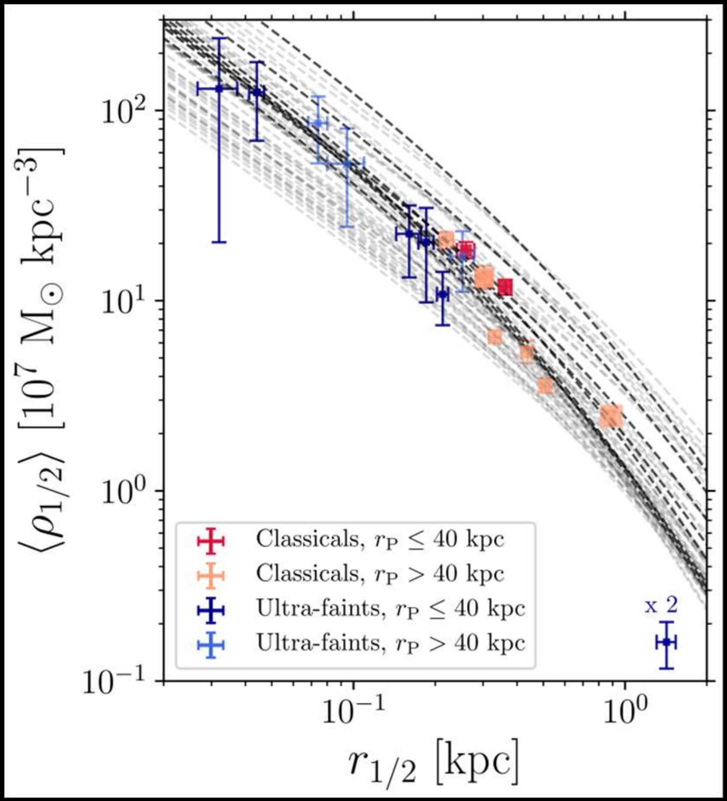
Stellar surface density

SIDM: slope correlated with stellar surface density

With Tao Ren and Hai-Bo Yu (2019)

Satellite galaxies

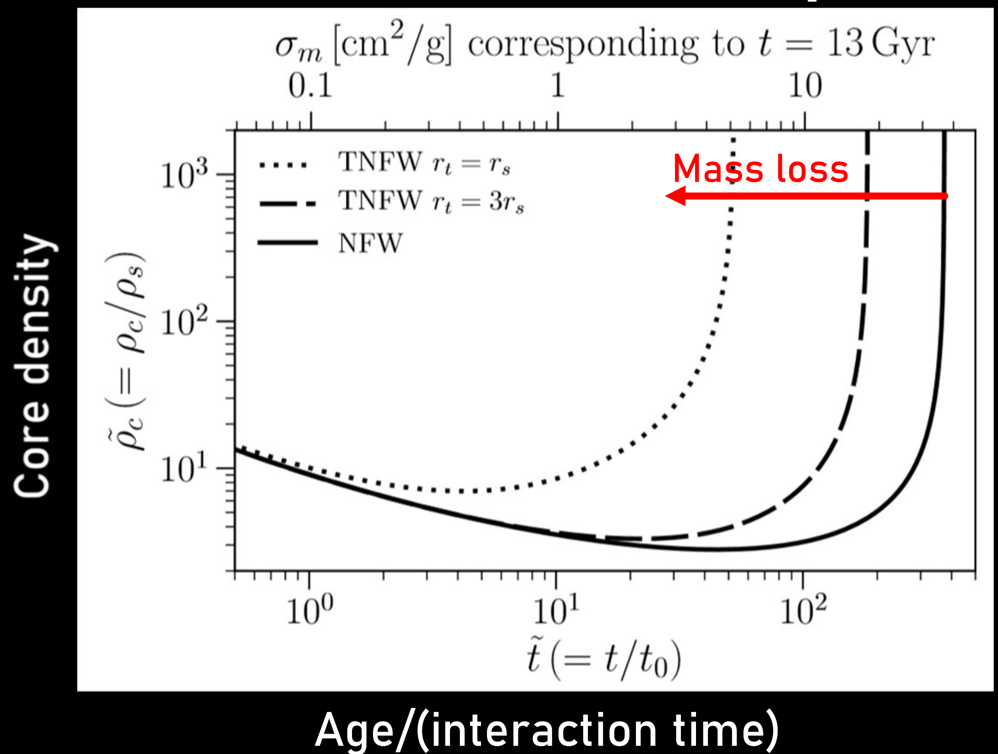
Diversity of satellite galaxies (+ too-big-to-fail problem)



Which dark matter model can explain the densities of satellites in a self-consistent way?

With Mauro Valli and Hai-Bo Yu (2019)

New SIDM phenomenology relevant for satellites: core collapse

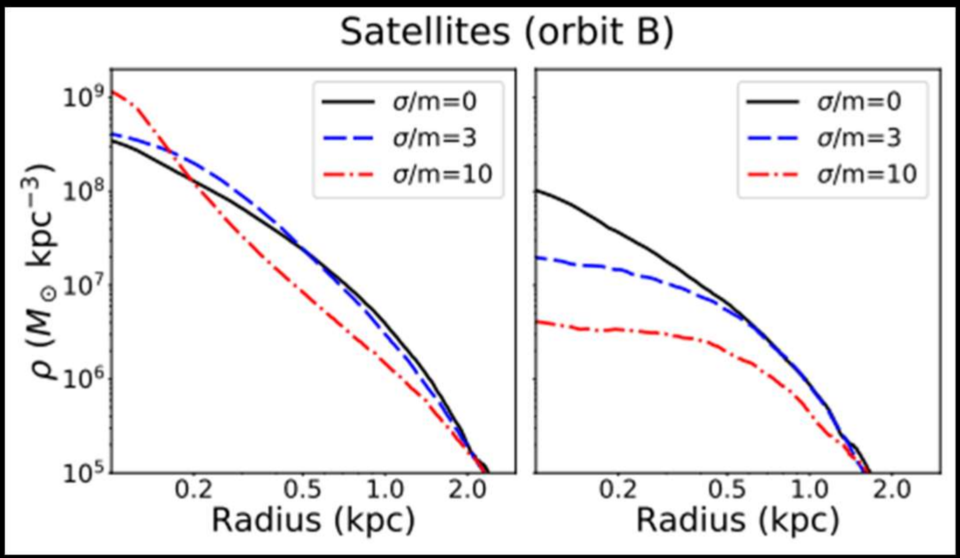


Core collapse is unique to SIDM and it could provide a smoking gun for discovering dark matter self-interactions.

With Nishikawa and Boddy (2019)

Satellite started out with **high** DM **concentration**

Satellite started out with **low** DM **concentration**

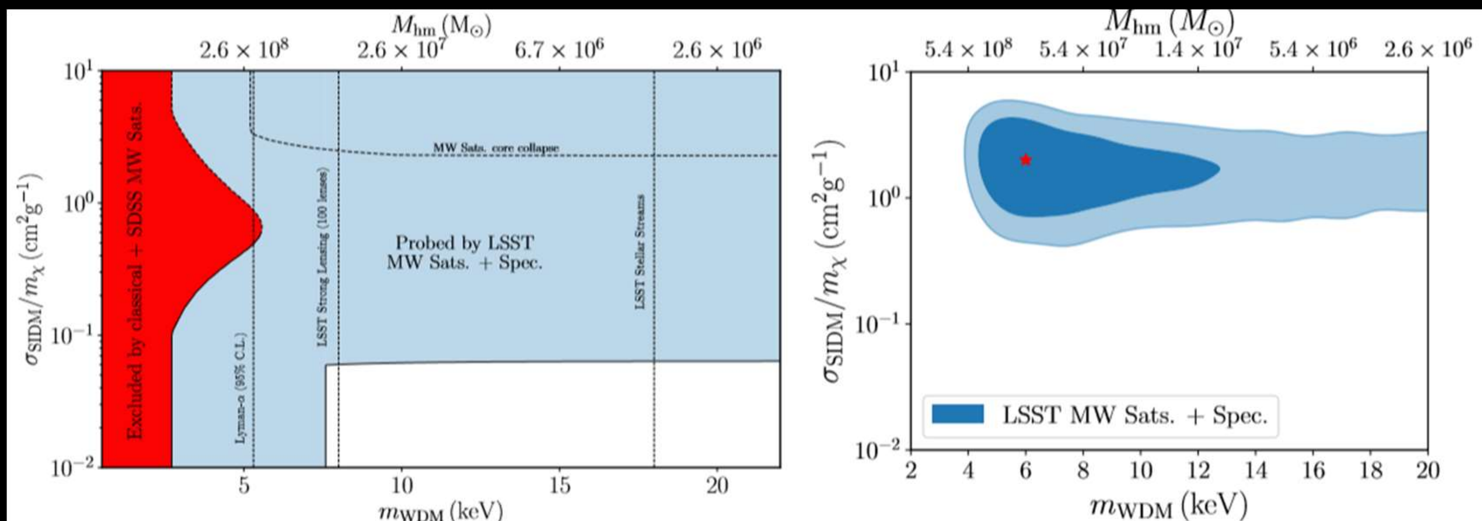


Example of satellite that has an orbit with a small pericenter distance

SIDM subhalos that survive close passages can be denser than CDM because of core collapse.

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

The simple model I have presented provides an excellent description of DM halos of galaxies and is consistent with all known observations.

It explains phenomena that cannot be currently explained within the CDM model and provides concrete avenues for falsification.