The Self-Interacting Dark Matter (SIDM) paradigm

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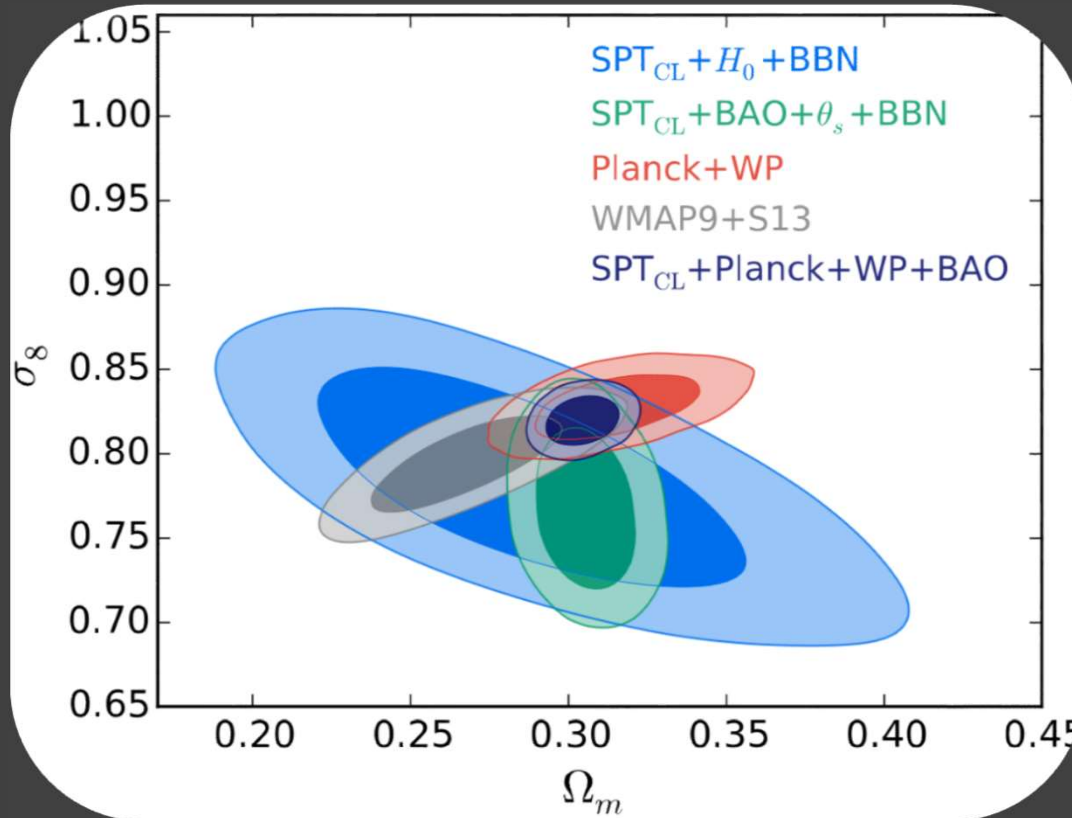
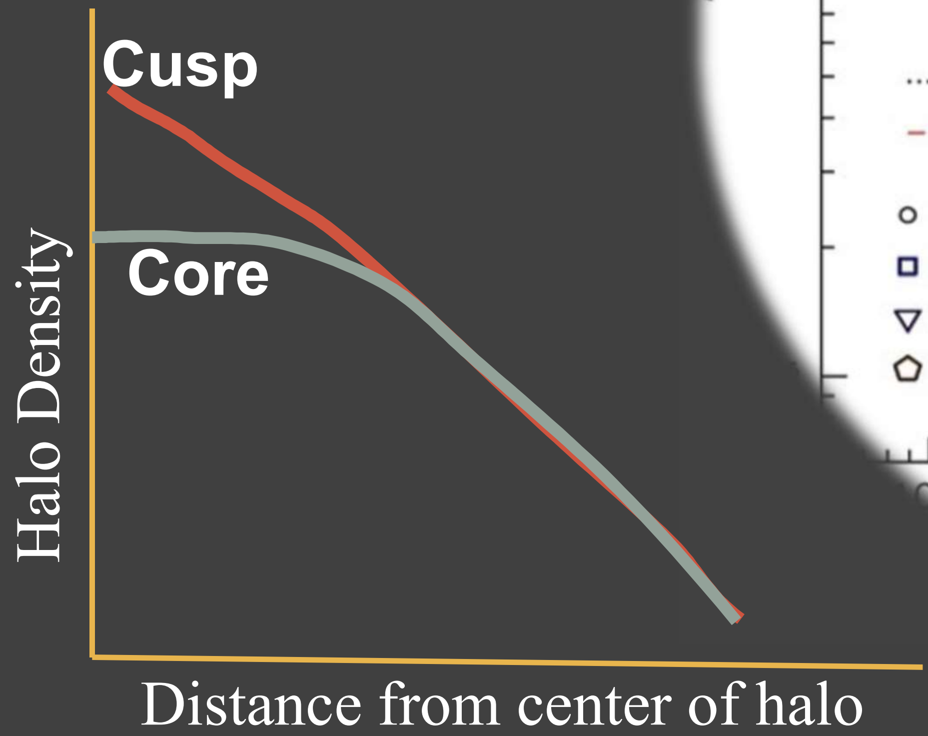
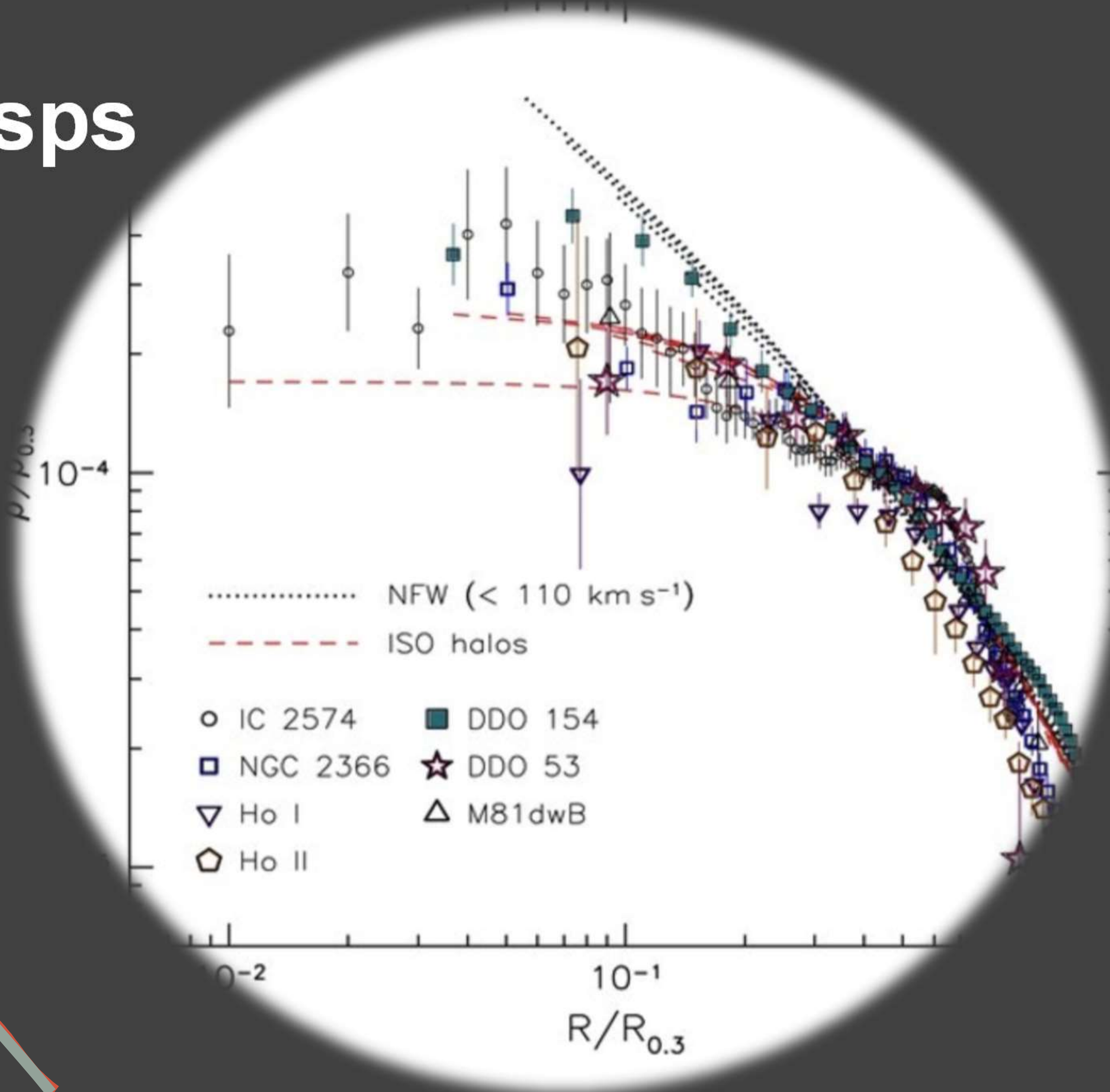
The predictions of the LCDM model agree well with the observed large-scale structure of the Universe.



However, there are unexplained puzzles.

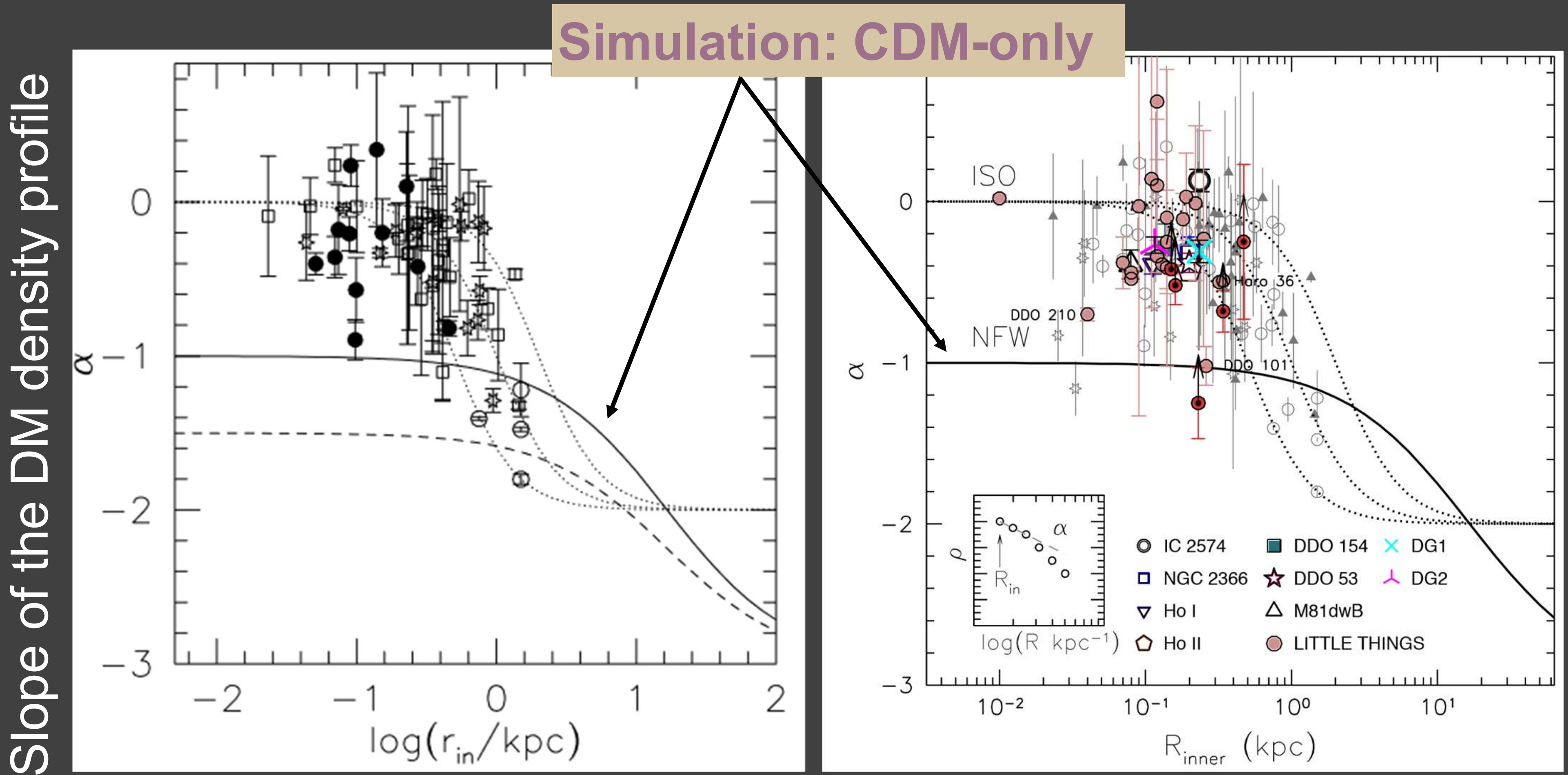
Cores AND cusps





Oh et al 2015

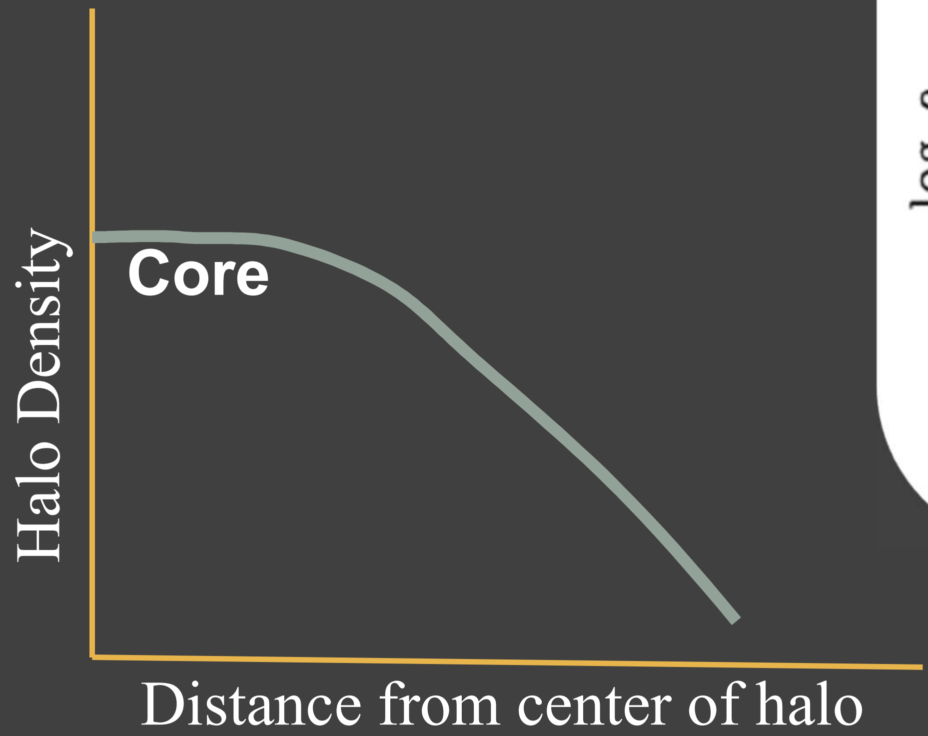
Cores and cusps: almost two decades old

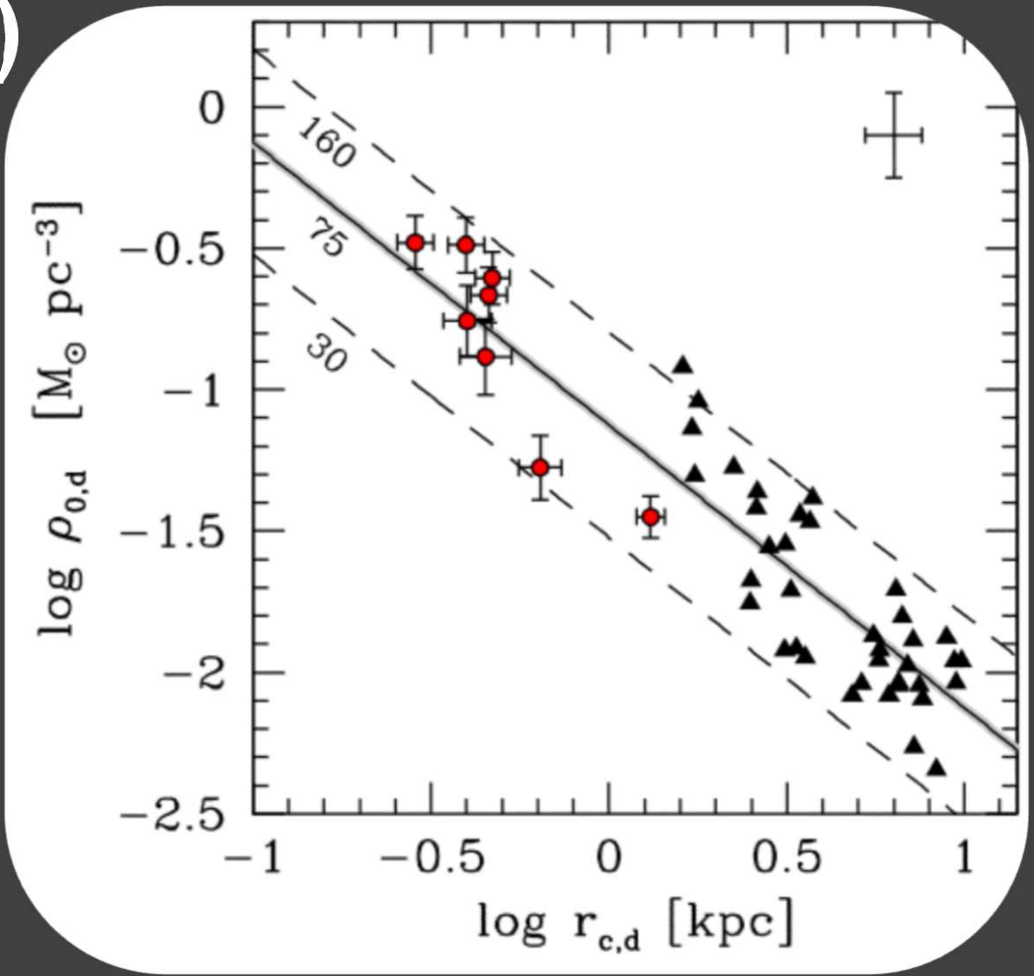


de Blok and Bosma, 2002

LITTLE THINGS, Oh et al 2015

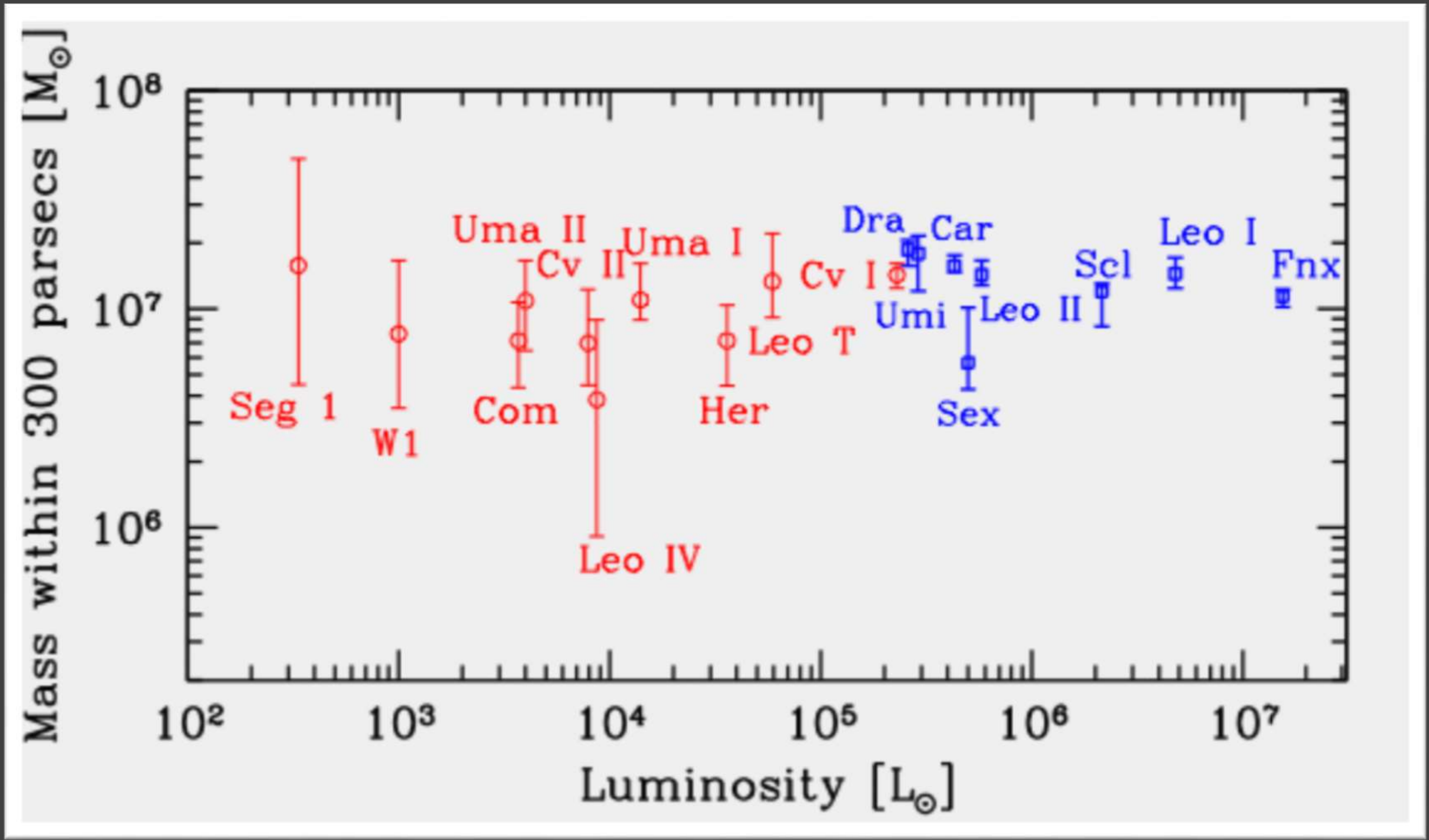
Uniformity of cored profiles (in DM dominated galaxies)





Burkert 2015
Donato et al 2009
Salucci, Wilkinson, et al 2012
Kormendy and Freeman 2014

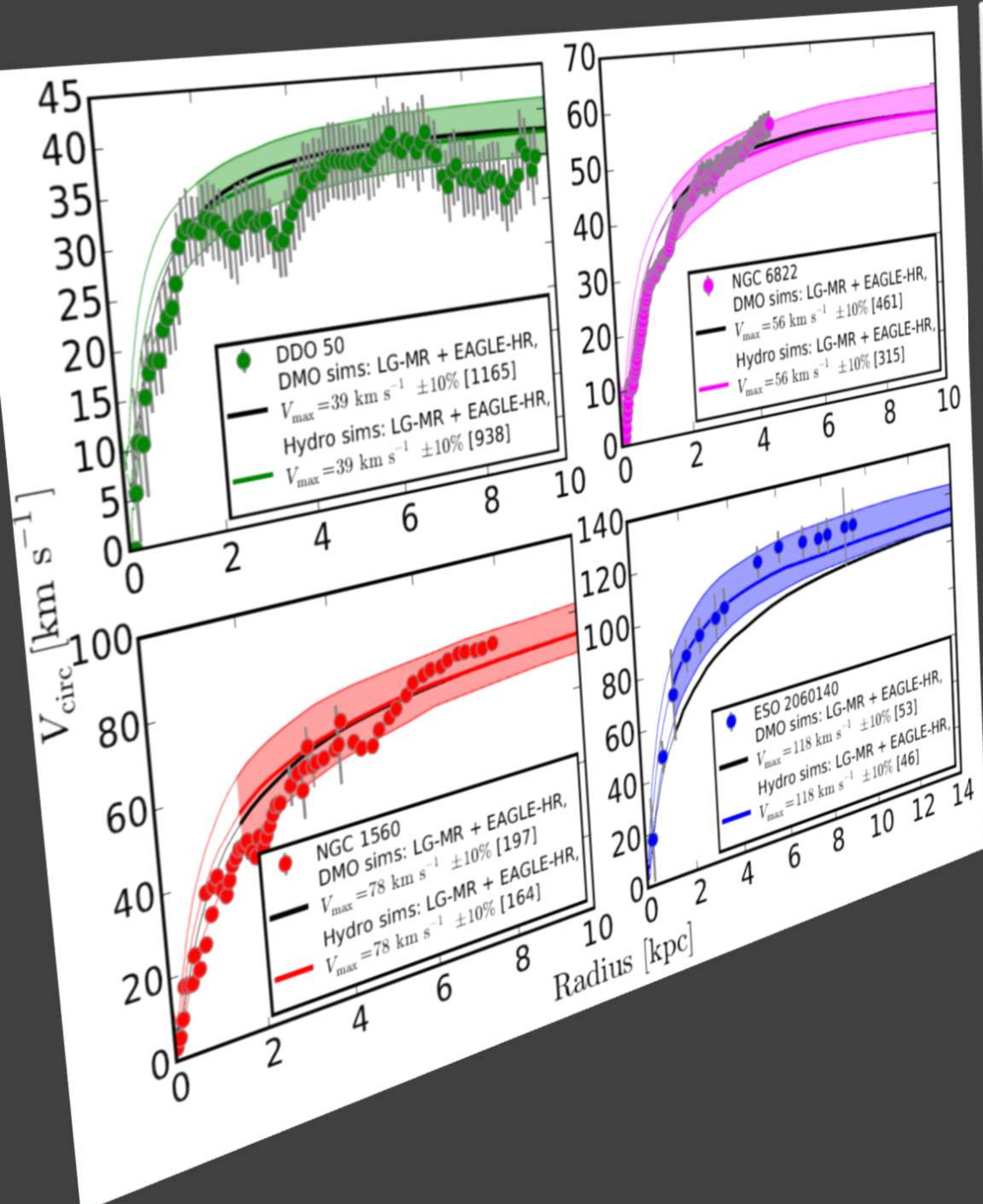
Satellite galaxies are a great laboratory to search for new physics

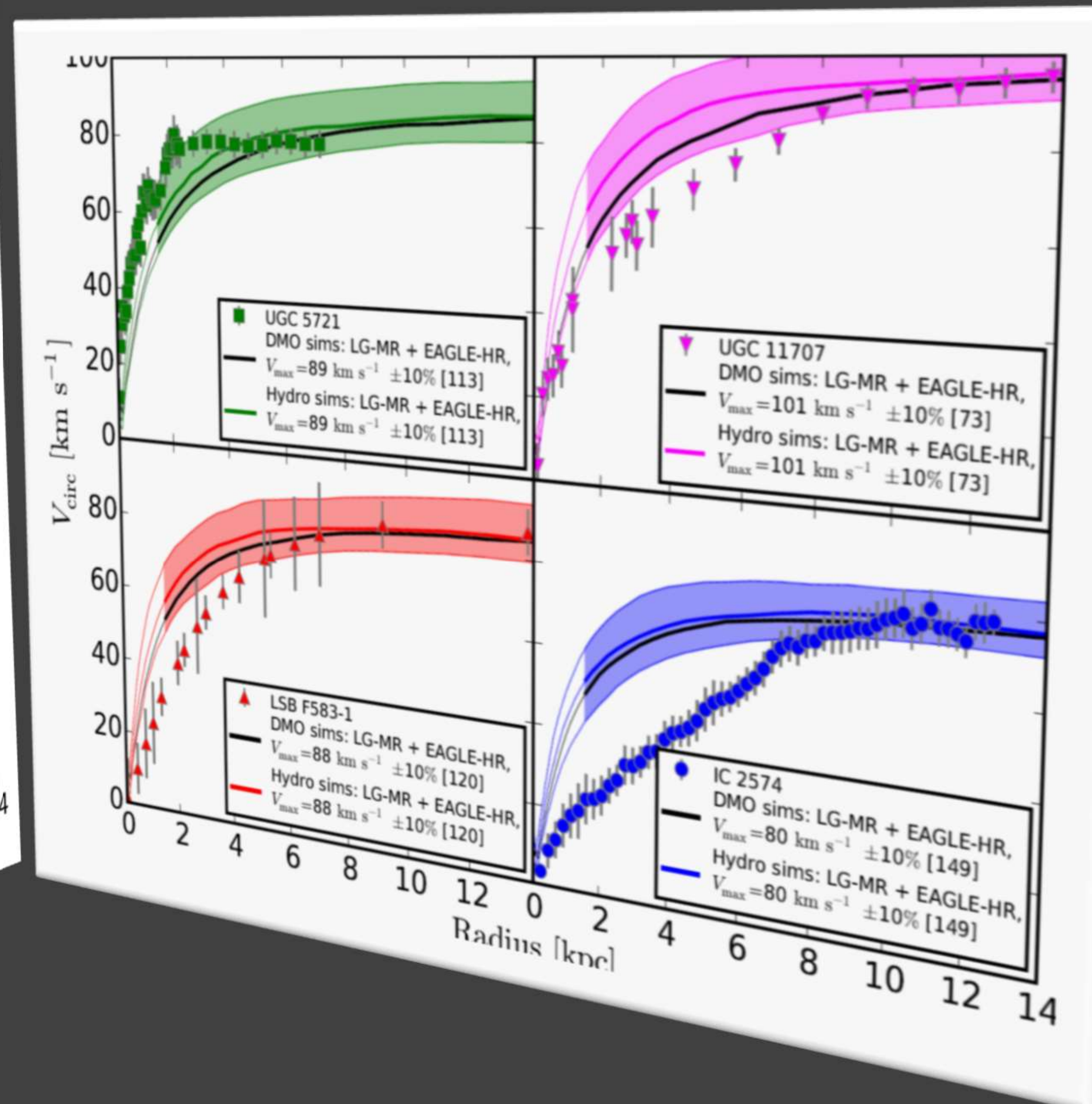


With Louis Strigari, James Bullock and collaborators (2008)

But I will disregard them until the end …

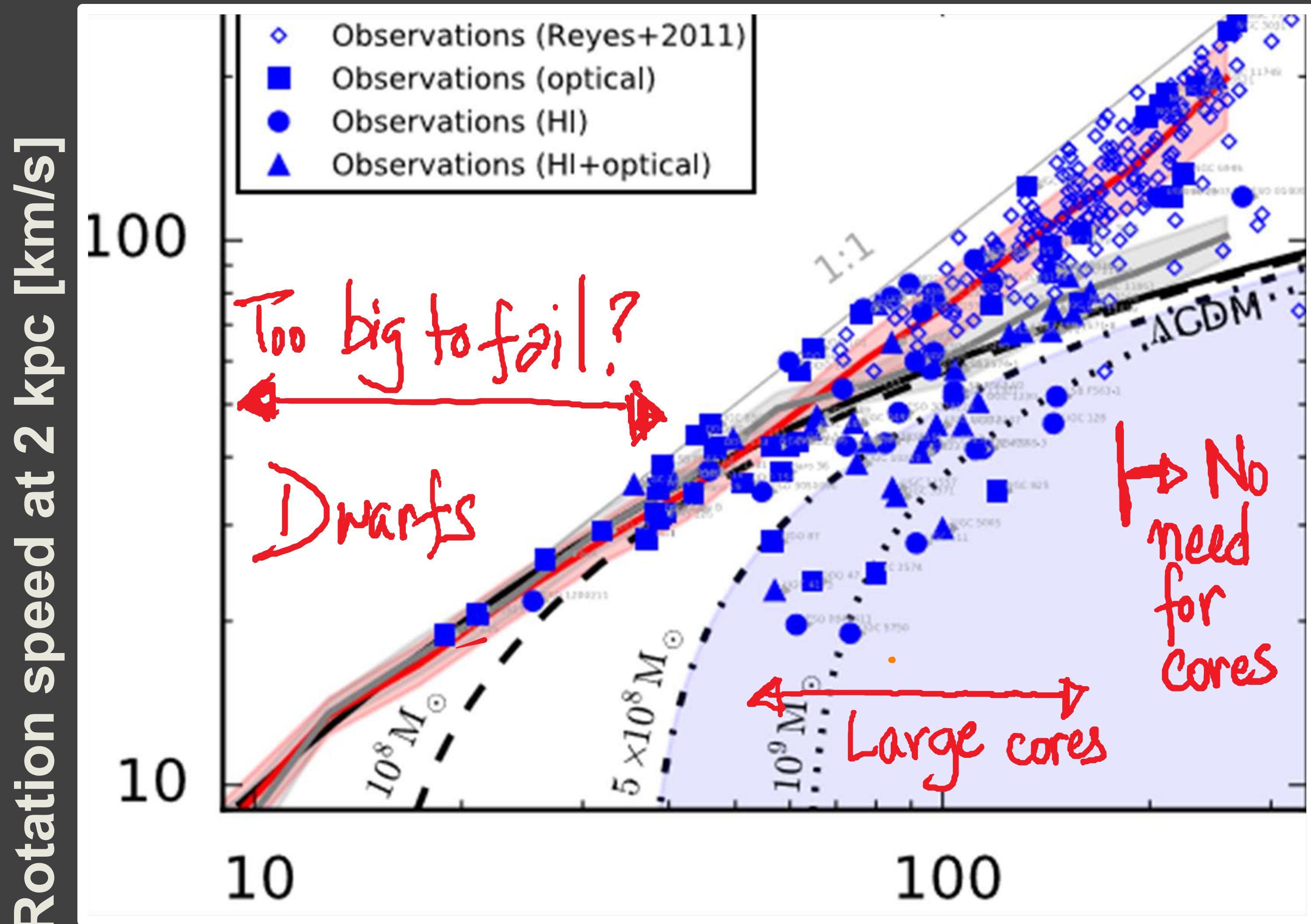
Cores AND cusps





Oman et al, 2015

The puzzling diversity in rotation curves

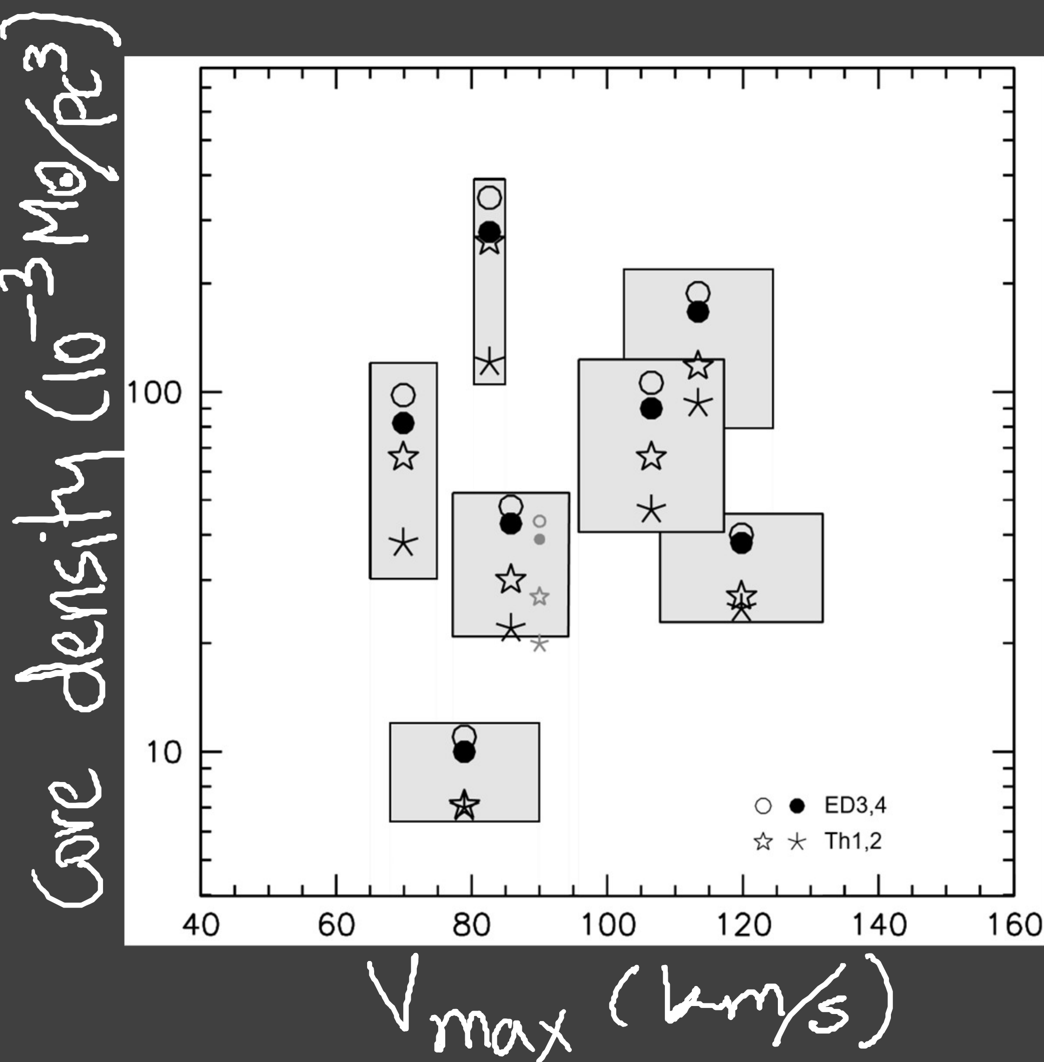


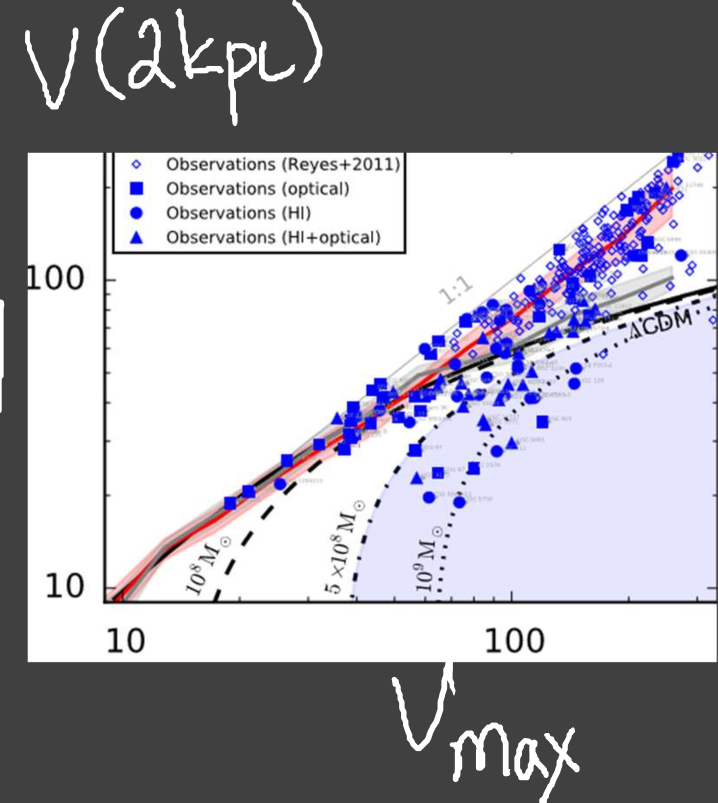
Vmax, maximum rotation speed [km/s]

Similar Vmax
⇒ Similar halo masses
And
Similar total baryon masses

Oman et al, 2015

The puzzling diversity in rotation curves





Oman et al, 2015

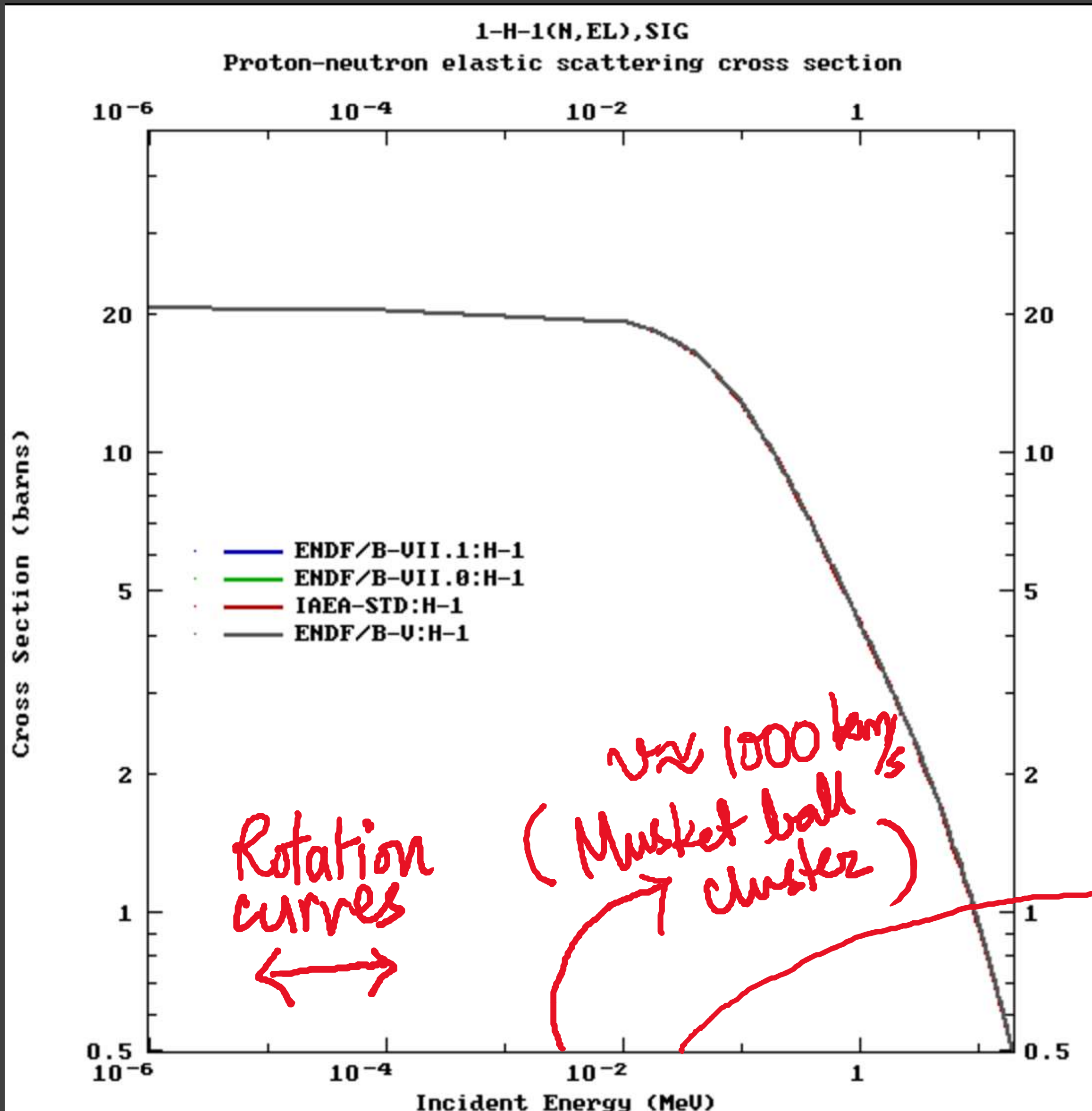
with Rachel Kuzio de Naray, Greg Martinez and James Bullock (2010)

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

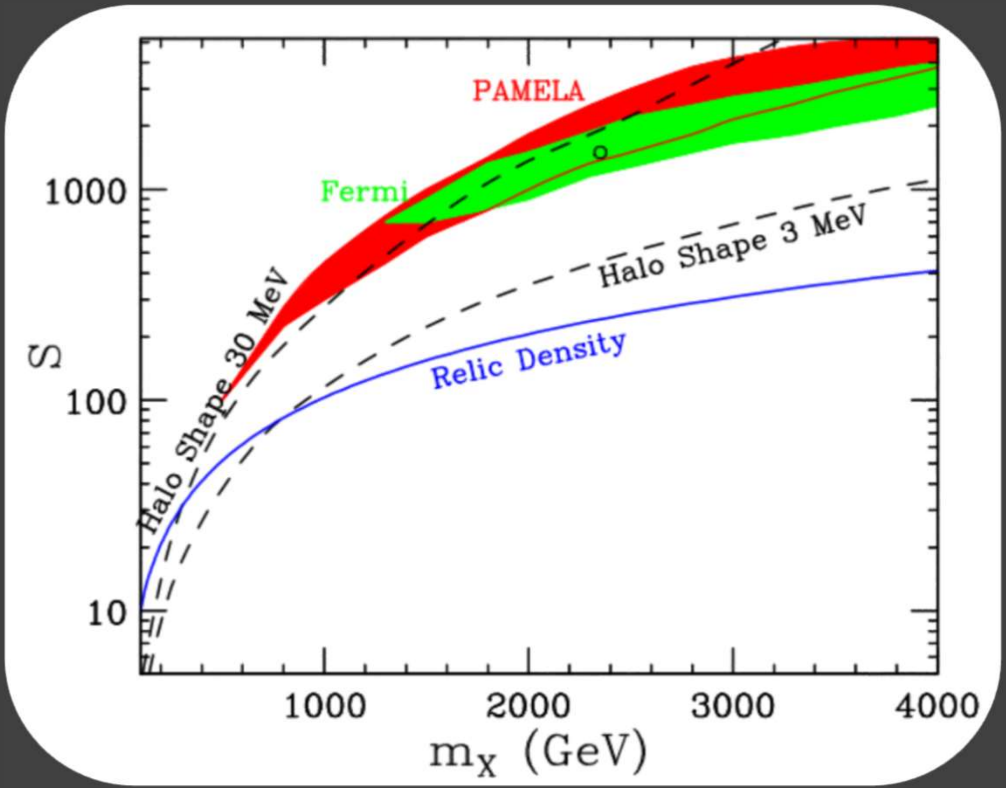
A motivating Standard Model example



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

v≈ 3000 km/s
(Bullet cluster)

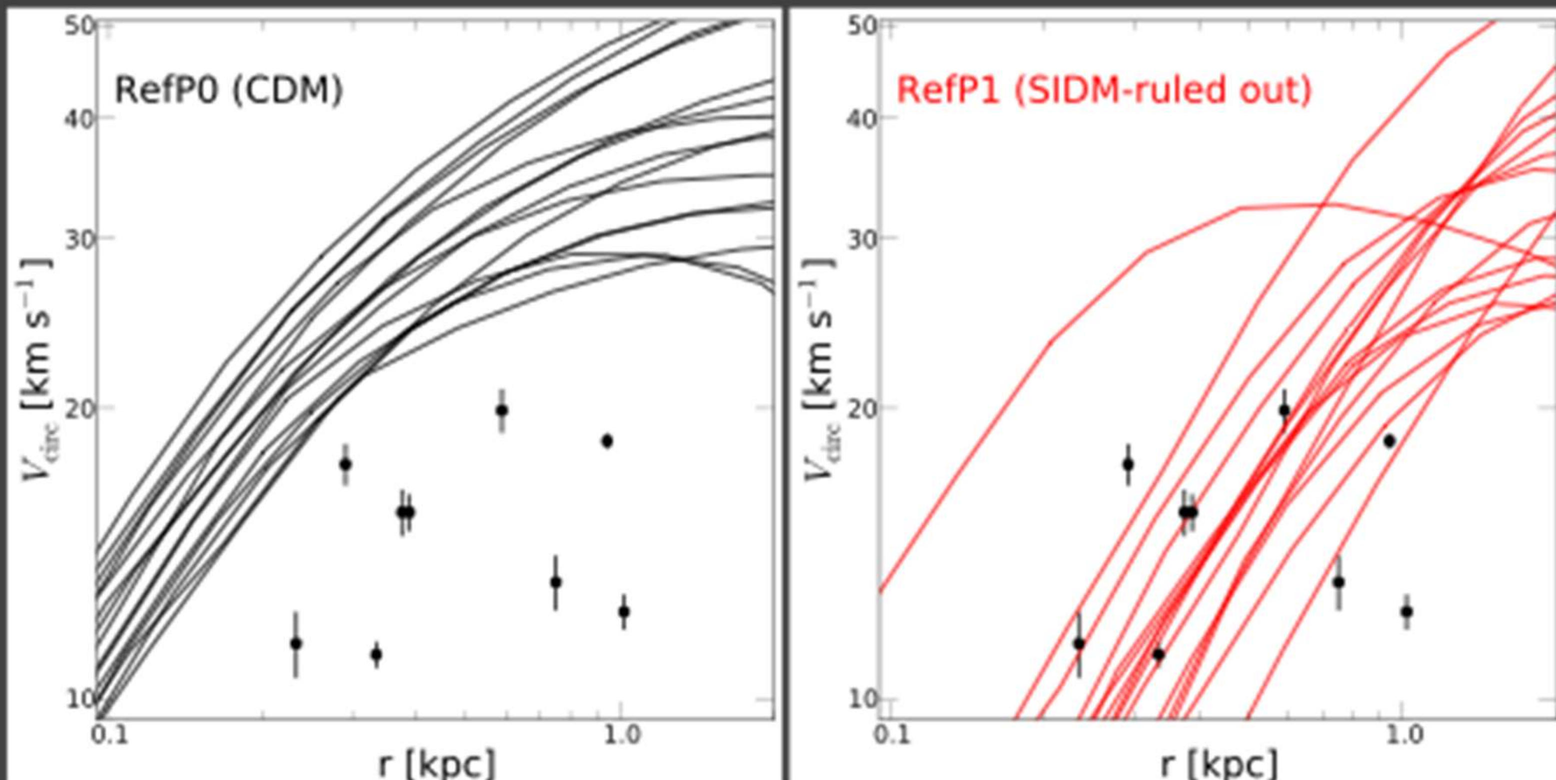
Revival of the SIDM idea



"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

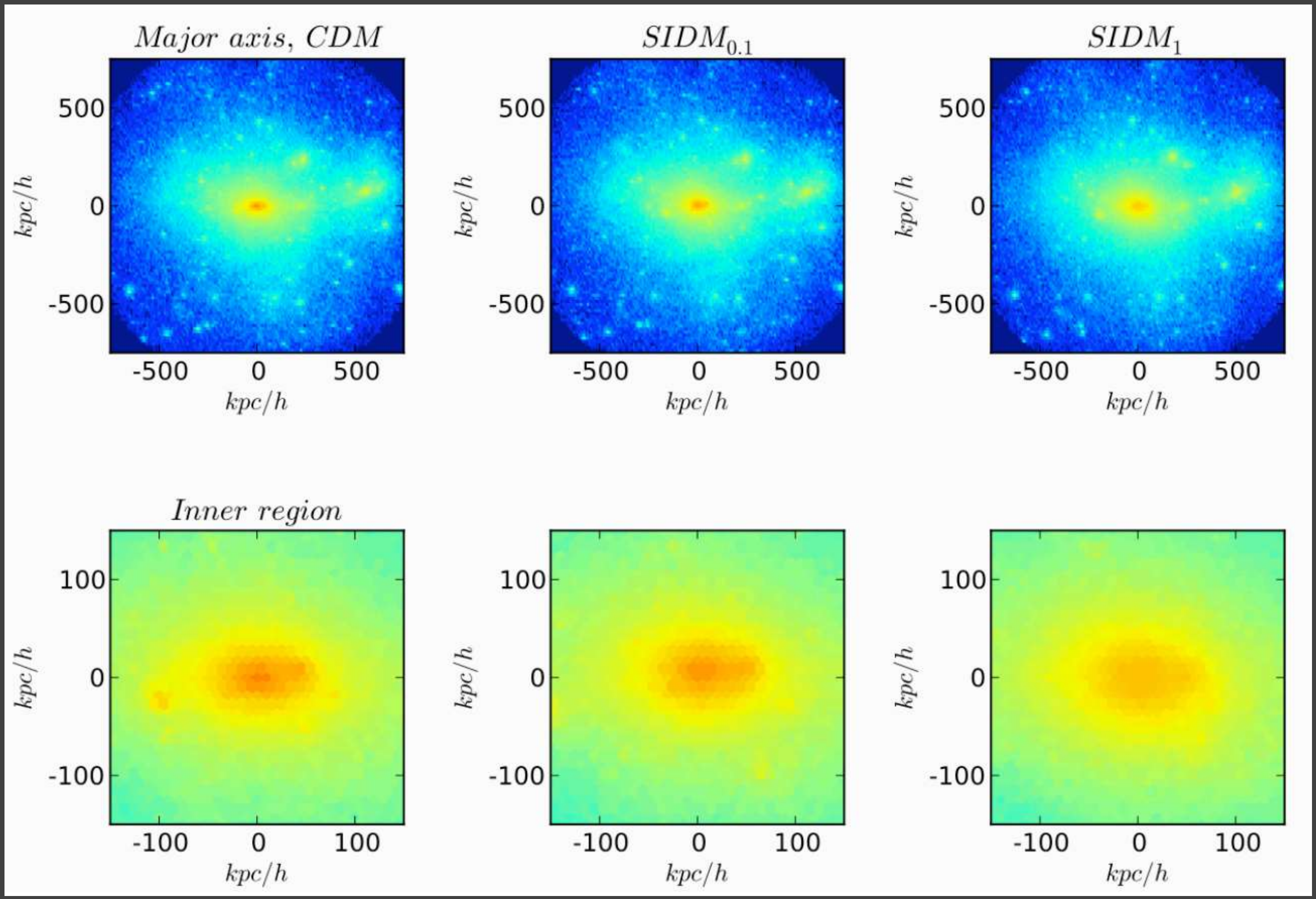
With Jonathan Feng, Haibo Yu, arXiv:0905.3039
With Jonathan Feng, Huitzu Tu, Haibo Yu, arXiv:0911.0422
Matt Buckley, Paddy Fox, arXiv:0911.3898
Avi Loeb, Neal Weiner, arXiv:1011.6374

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

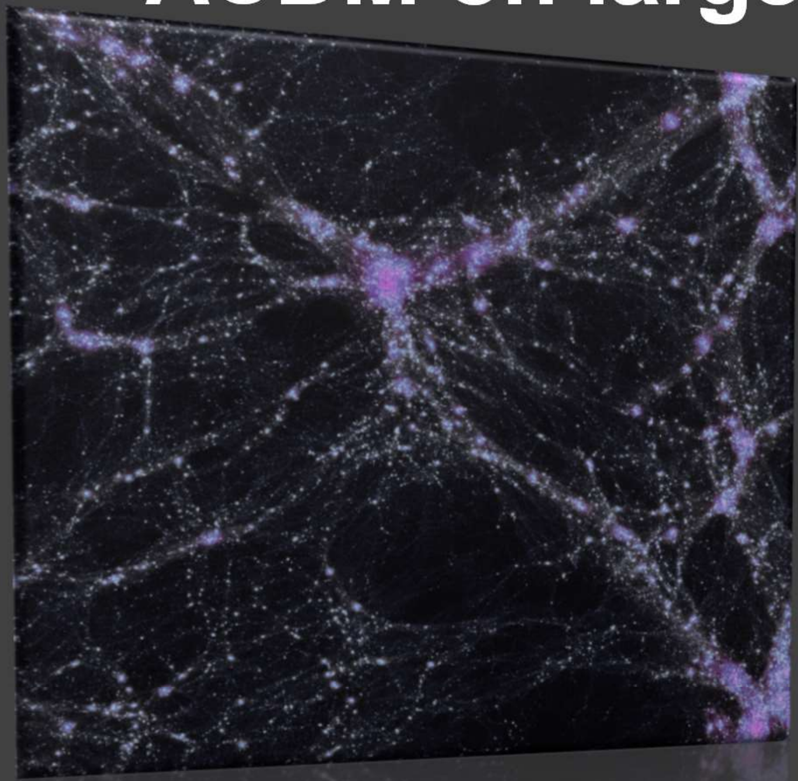
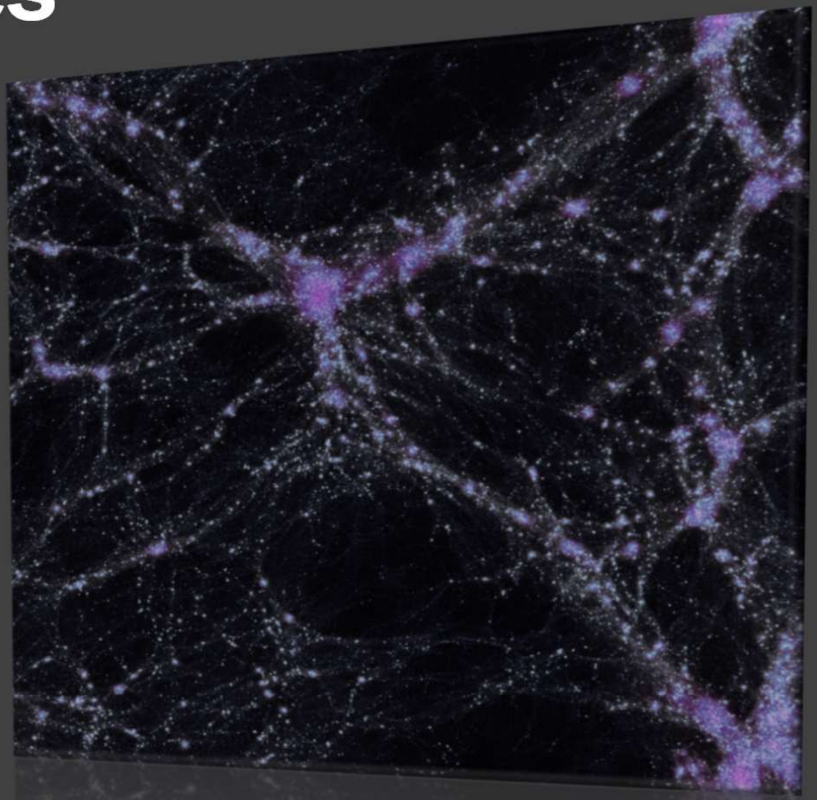


Constraints no better than 1 cm^2/g.

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

How SIDM works

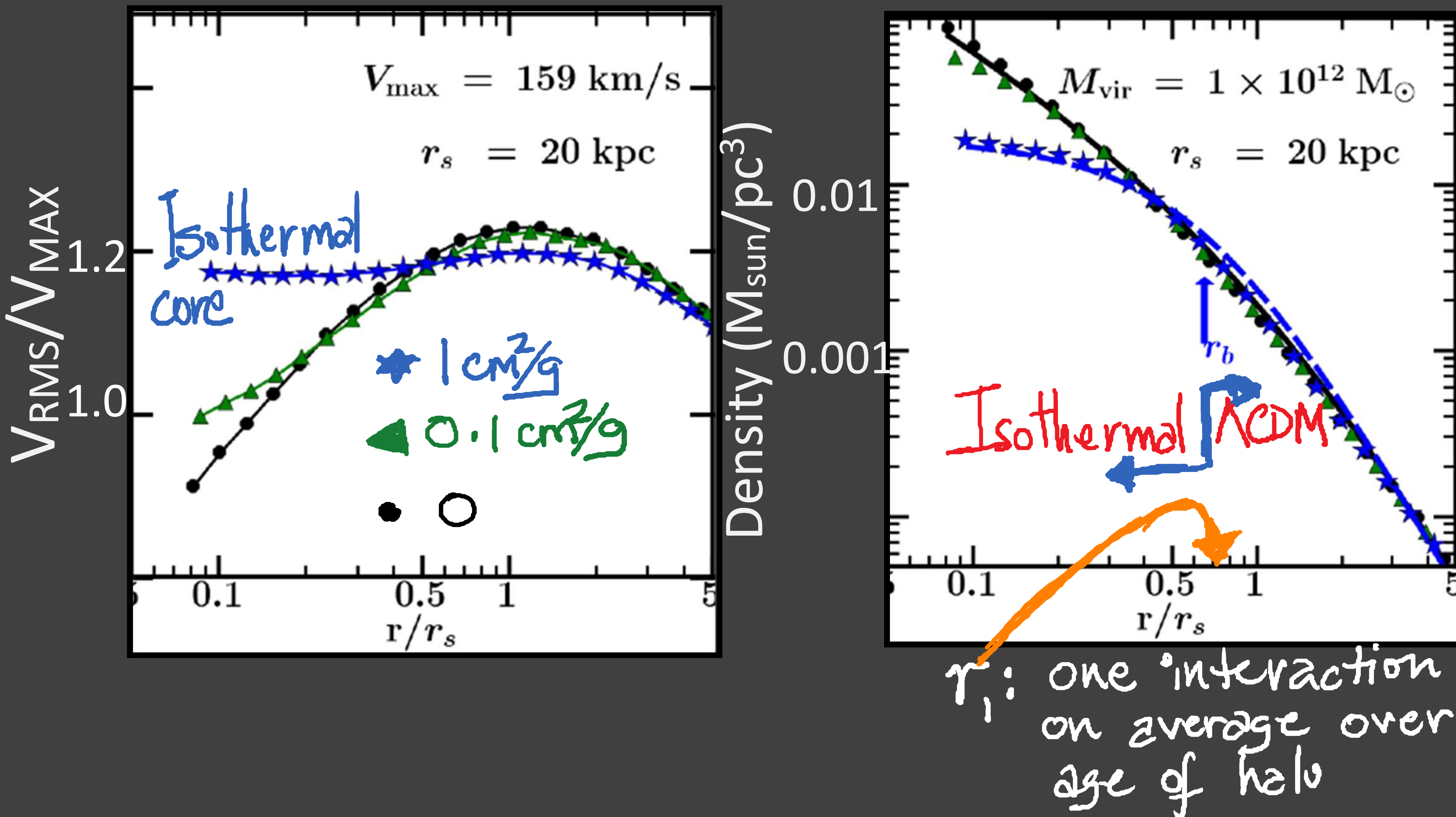
ΛSIDM inherits all the successes of ΛCDM on large scales

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

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

SIDM: thermalization of the inner halo



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

Field galaxies: SIDM halo profile is almost uniquely determined

$$\rho_{iso}(r) \propto e^{-\Phi(r)/kT}$$

gravitational potential of dark matter and baryons

$$\rho_{SIDM}(r) = \begin{cases} \rho_{iso}(r), & r < r_1 \\ \rho_{CDM}(r), & r > r_1 \end{cases}$$

mass and density continuous at $r = r_1$

$$\rho_{SIDM}(r_1) \frac{\sigma}{m} \overline{v_{rel}}\, t_{gal} = 1$$

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

Field galaxies: both Cored and Cuspy

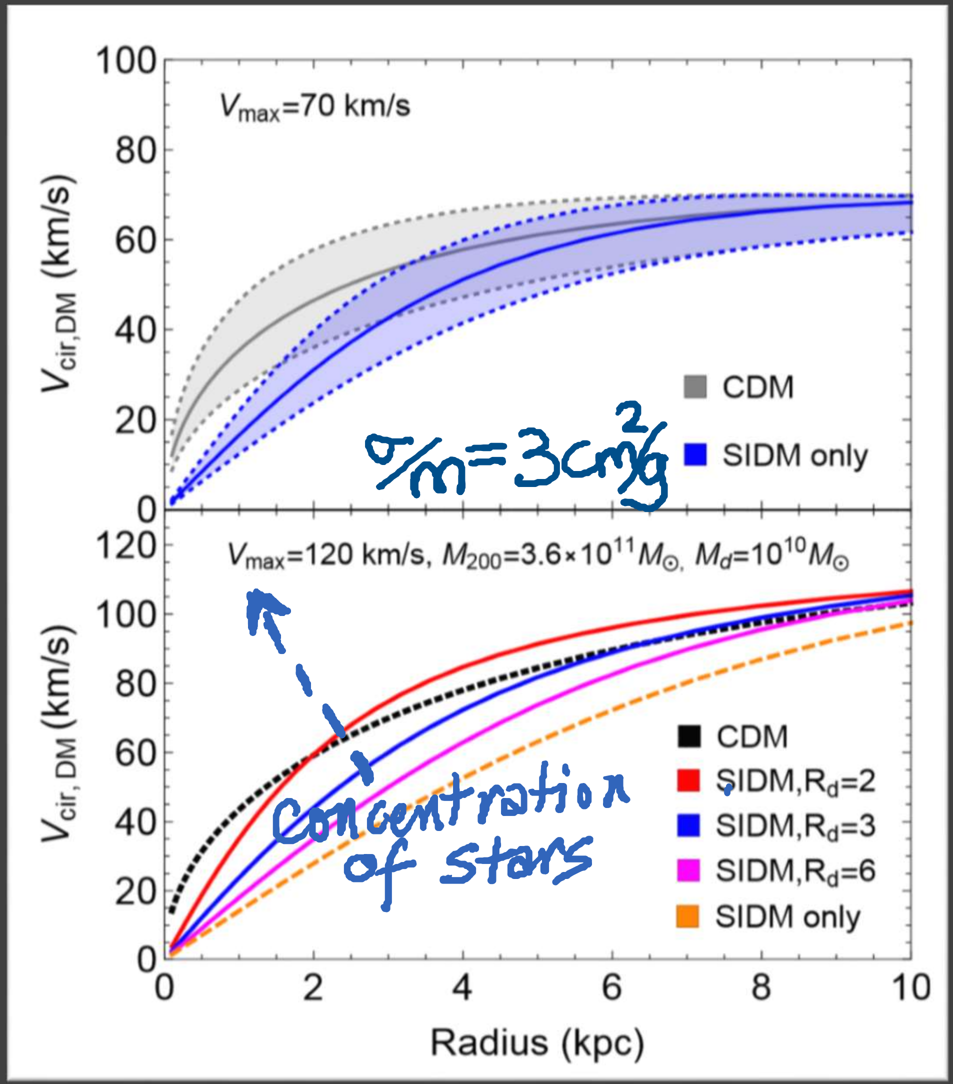
~~SIDM predicts large cores in all galaxies~~

↑ → cores hard to discern or even cuspy

$\rho_* + \rho_{gas}$

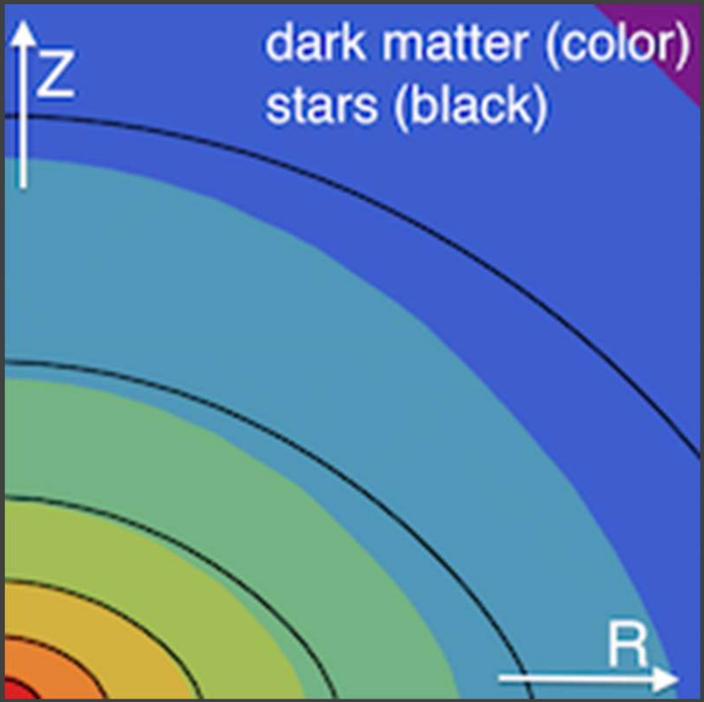
↓ → cores large & evident

Core ~ $r_1 \approx r_s$



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

Stars and dark matter tied in SIDM model

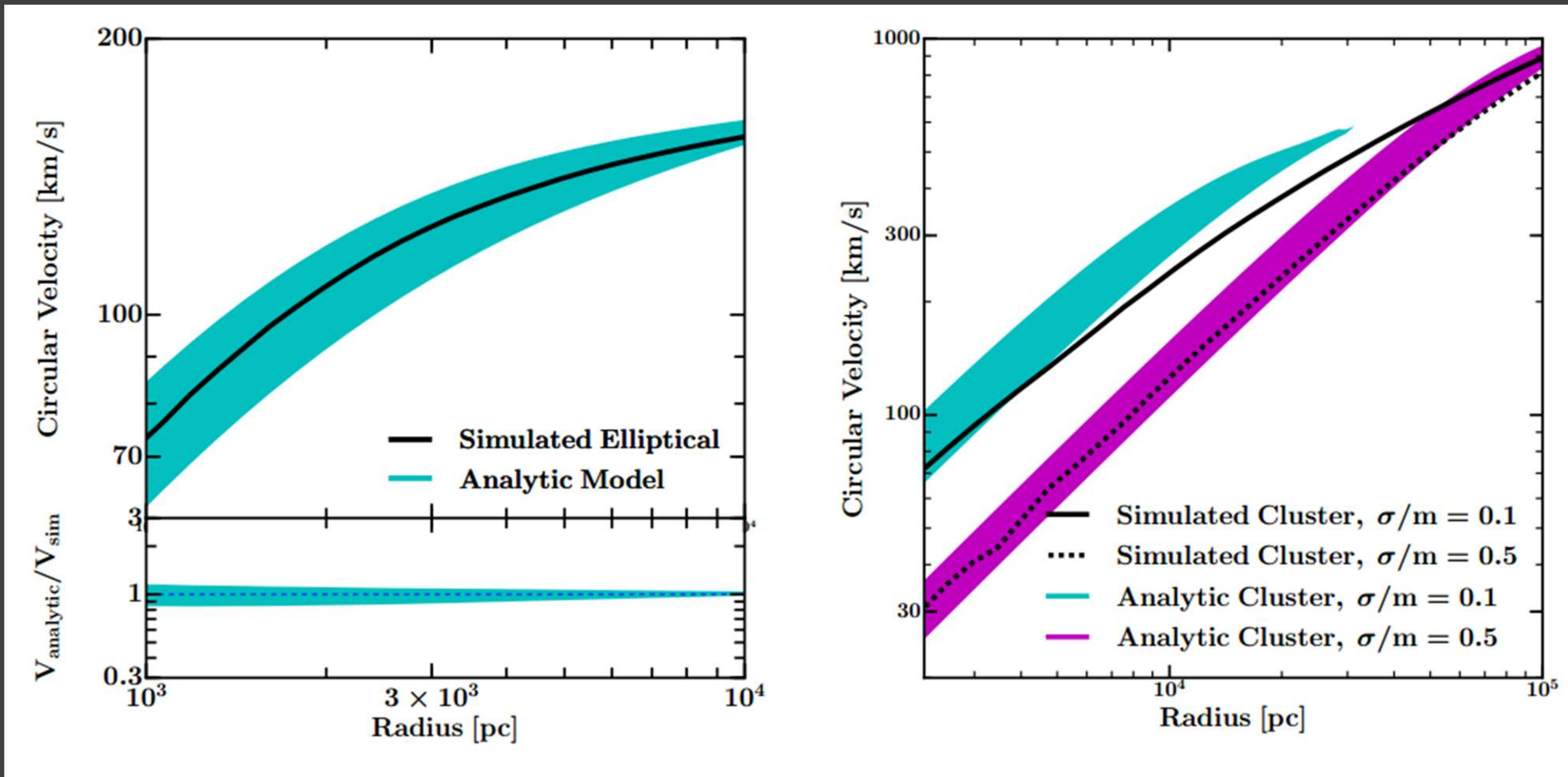


Isothermal => SIDM tracks the stellar potential, i.e., *dark and luminous matter are tied*.

When baryon density increases, dark matter density increases, cores get small and are set by the stellar distribution.

When DM dominates, stars follow the increasing core size of DM halos adiabatically (seen in sims by Vogelsberger, Zavala, Simpson and Jenkins 2014).

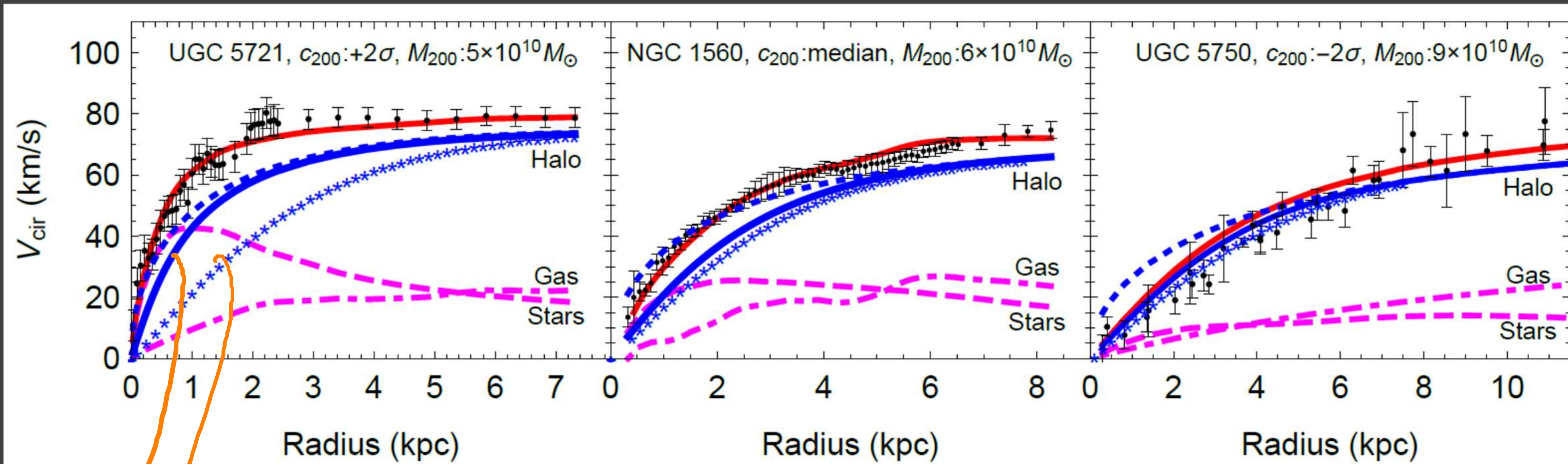
The SIDM halo profile in the presence of baryons: N-body simulations



With Oliver Elbert and James Bullock (2017)

The SIDM fits to galaxy rotation curves

How SIDM explains the diverse rotation curves

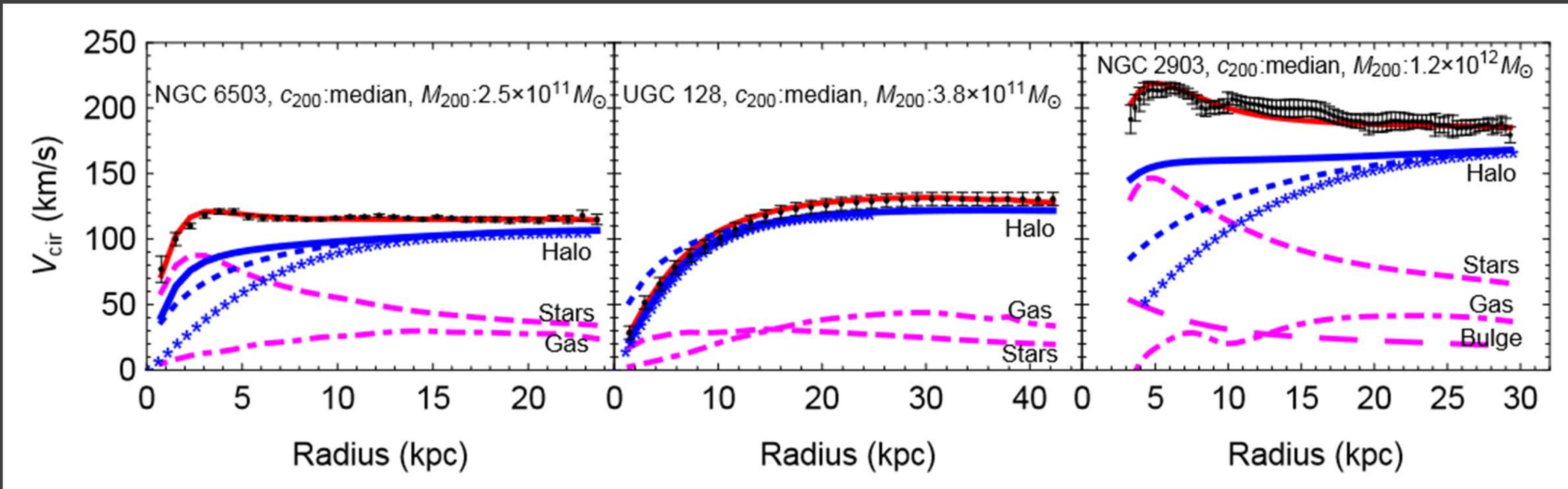


With Ayuki Kamada, Andrew Pace and Hai-Bo Yu (2017)

without including the potential of stars

correct SIDM density profile

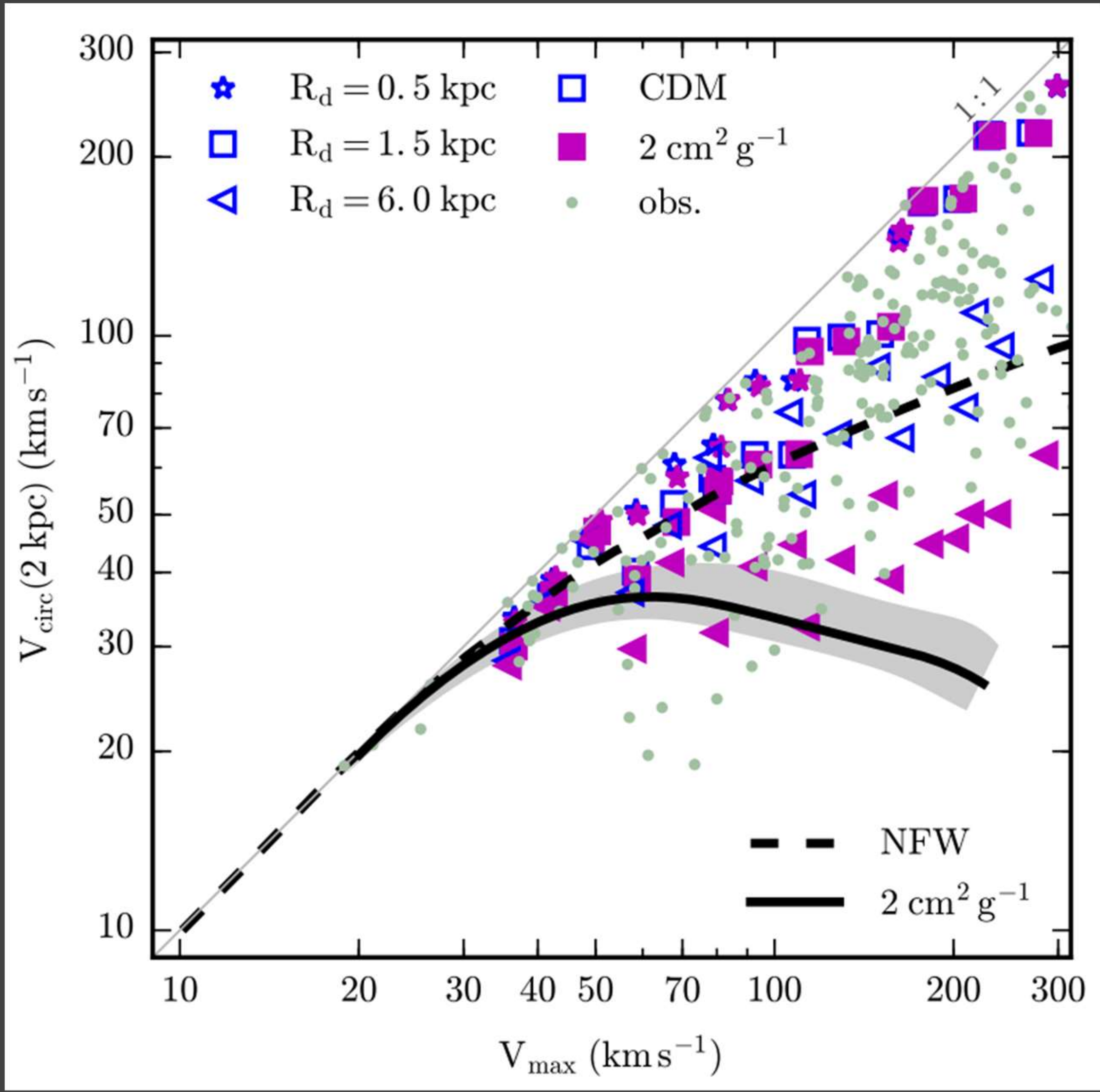
How SIDM explains the diverse rotation curves



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

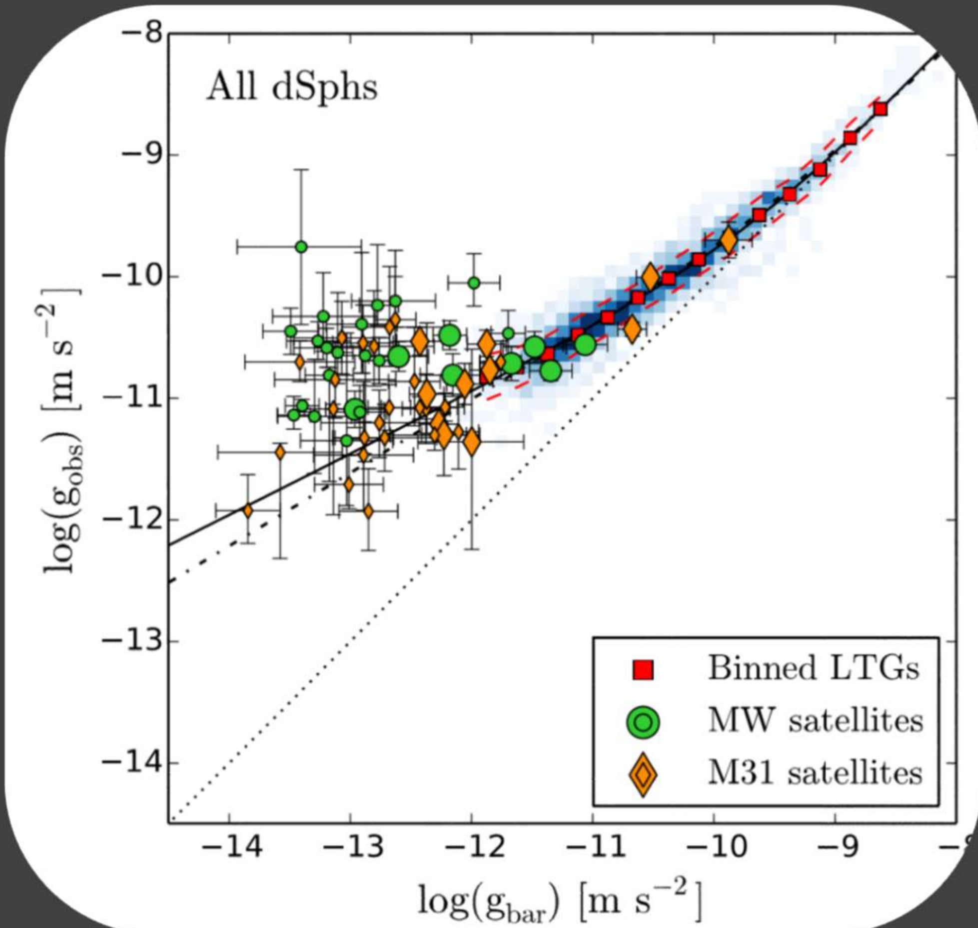
How SIDM explains the diverse rotation curves

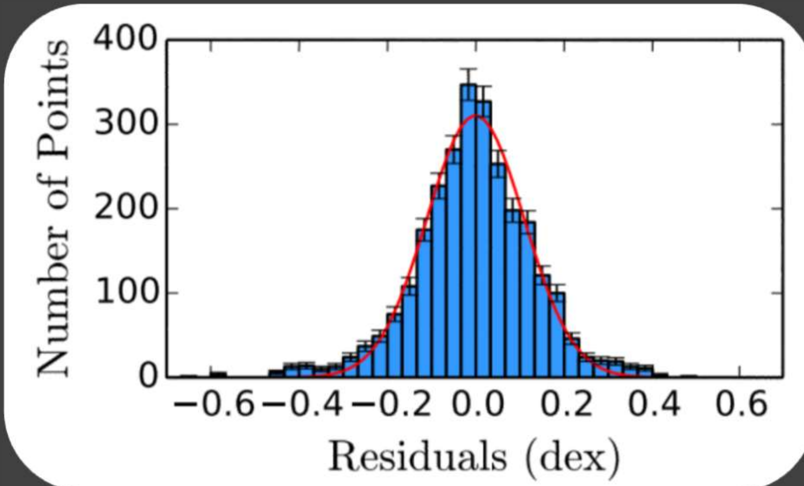
Verified in N-body simulations by Creasey et al (2017)



Uniformity in galactic rotation curves

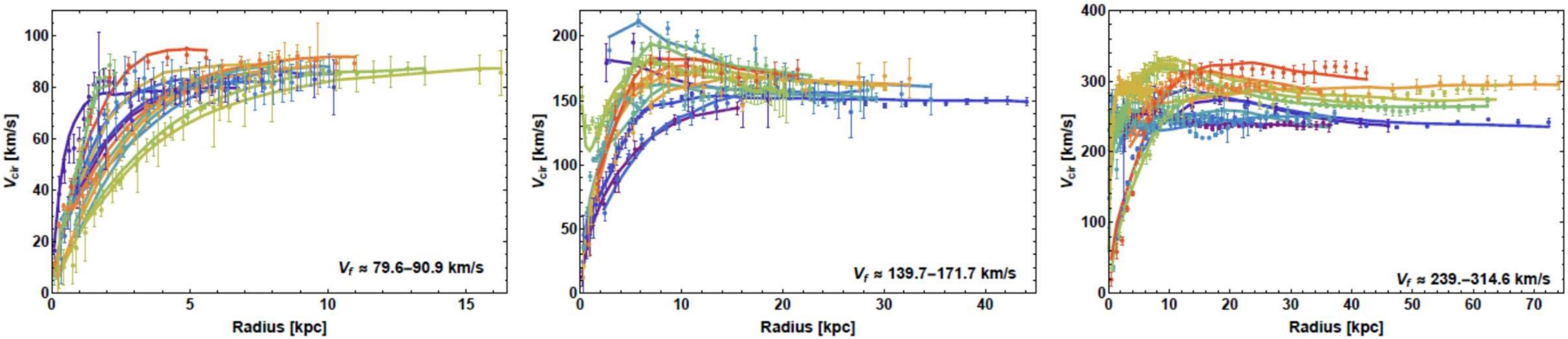
The acceleration scale in galaxy formation





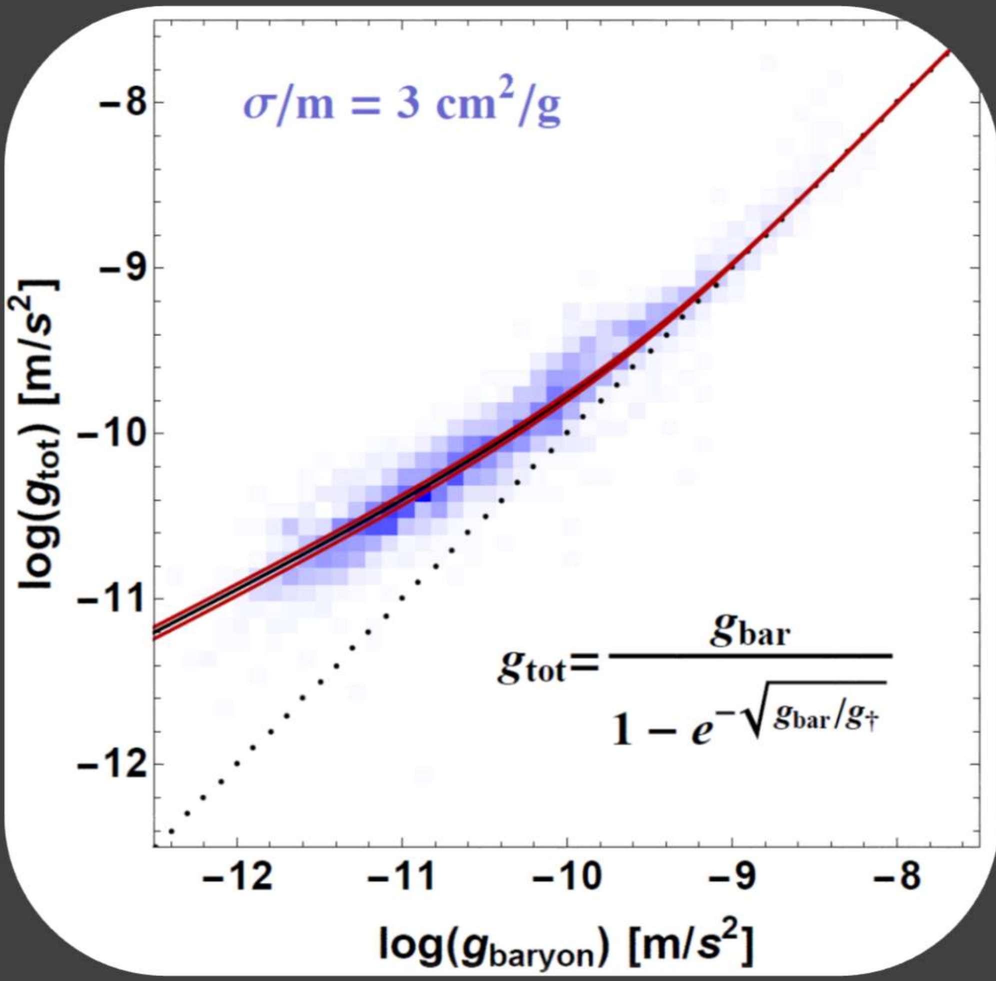
Lelli et al 2016

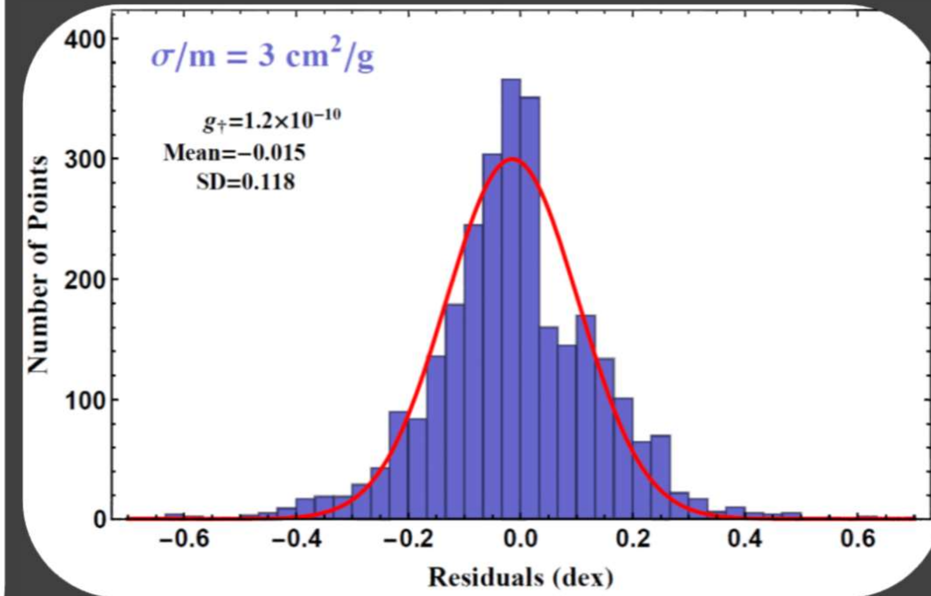
SIDM fits to the rotation curves in the SPARC sample



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

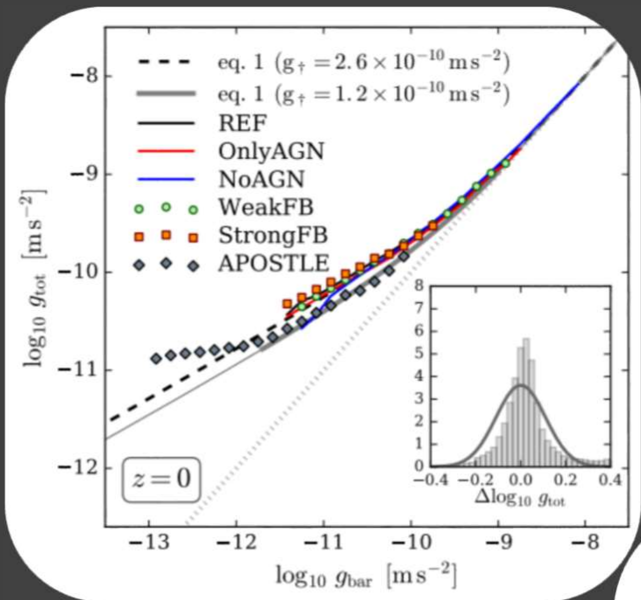
SIDM gives just as tight a correlation for the SPARC data set



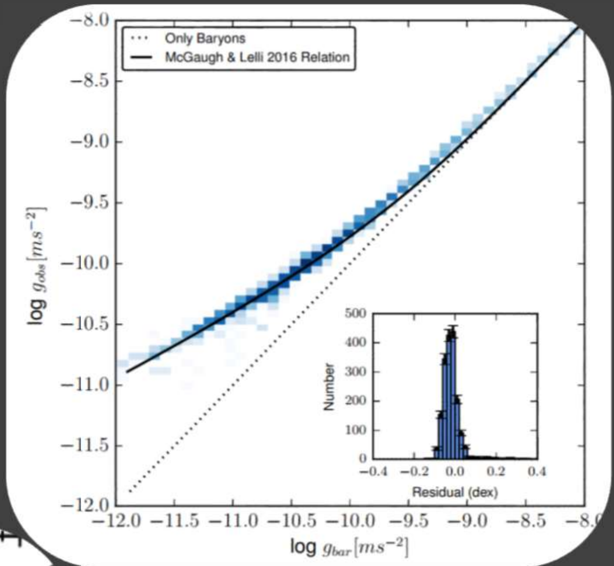


With Anna Kwa, Tao Ren and Hai-Bo Yu (in prep)

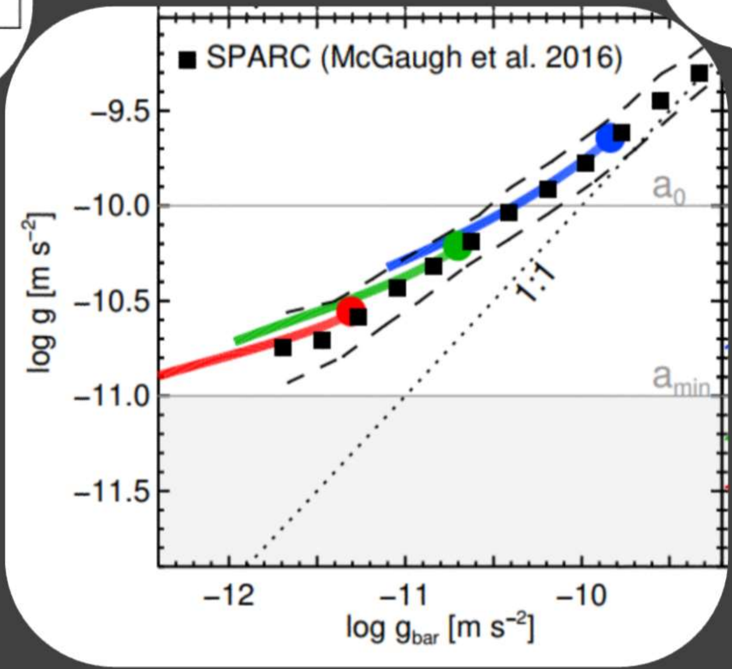
Acceleration-mass correlation in LCDM models



Ludlow et al, 2016



Keller and Wadsley, 2016

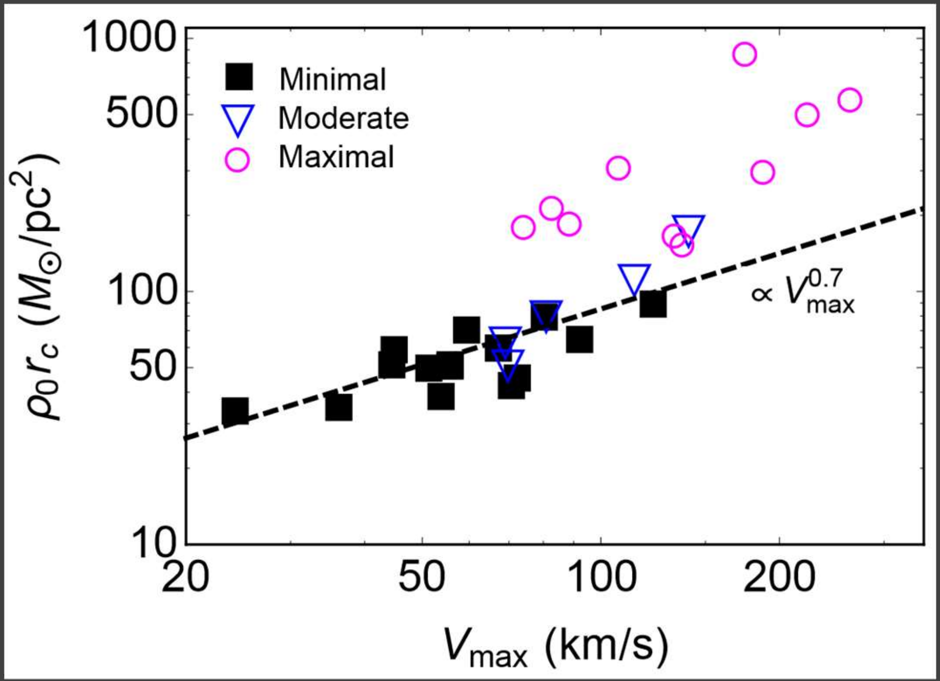


Navarro et al, 2016

Explanation for the acceleration scale in hierarchical structure formation models

σ/m > about 1 cm^2/g
$r_{core} \sim O(1)\ r_s$
(No new scale in the problem)

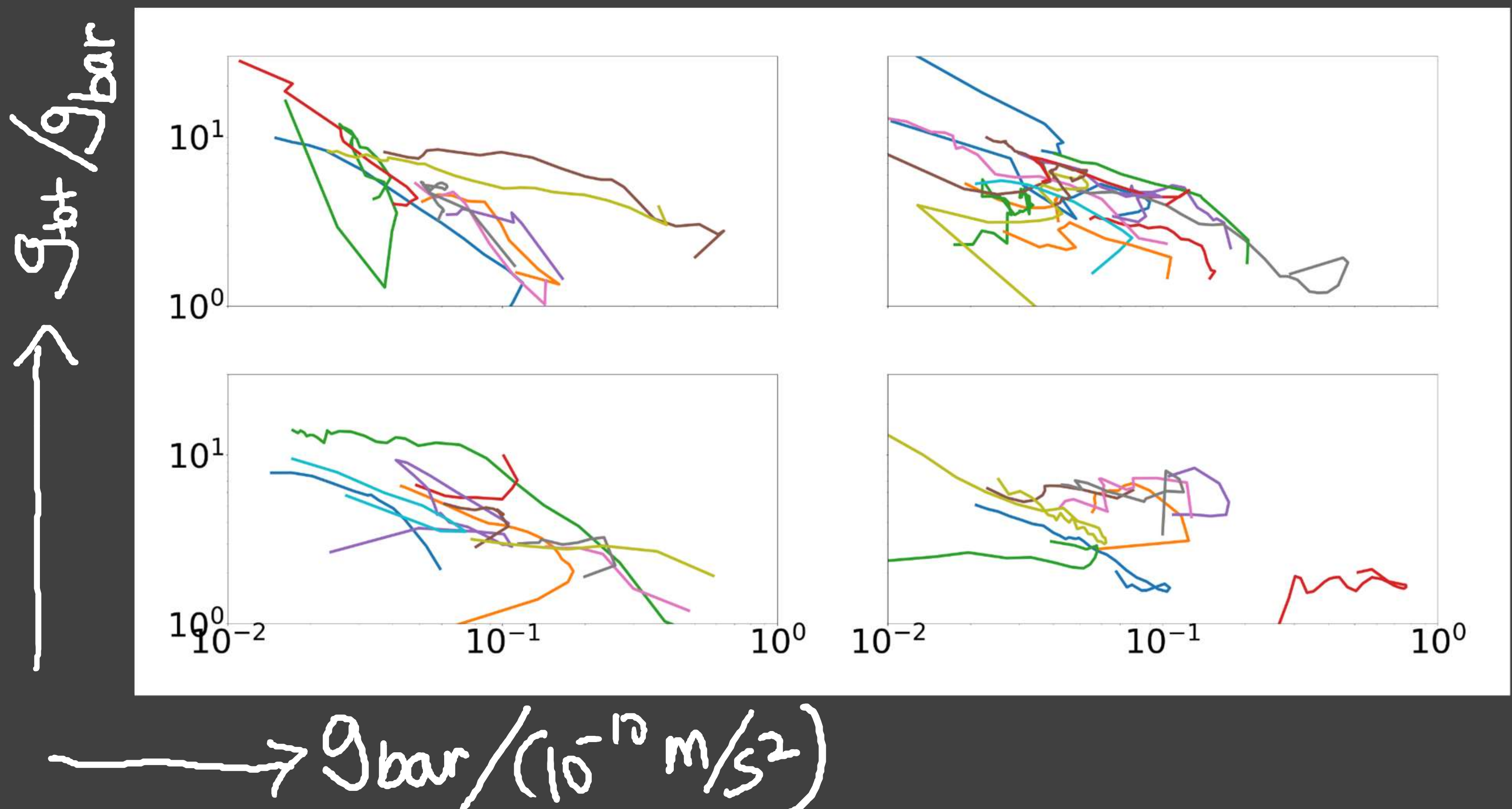
Dimension analysis :
$a = 2\ V_{max}^2/R_{max} \sim G\ \rho_{core}\ r_{core}$
$= 3 \times 10^{-11}\ m/s^2\ (V_{max}/100\ km/s)^{0.7}$
(using a LCDM V_{max} R_{max} relation)
[See also Lin and Loeb (2016)]



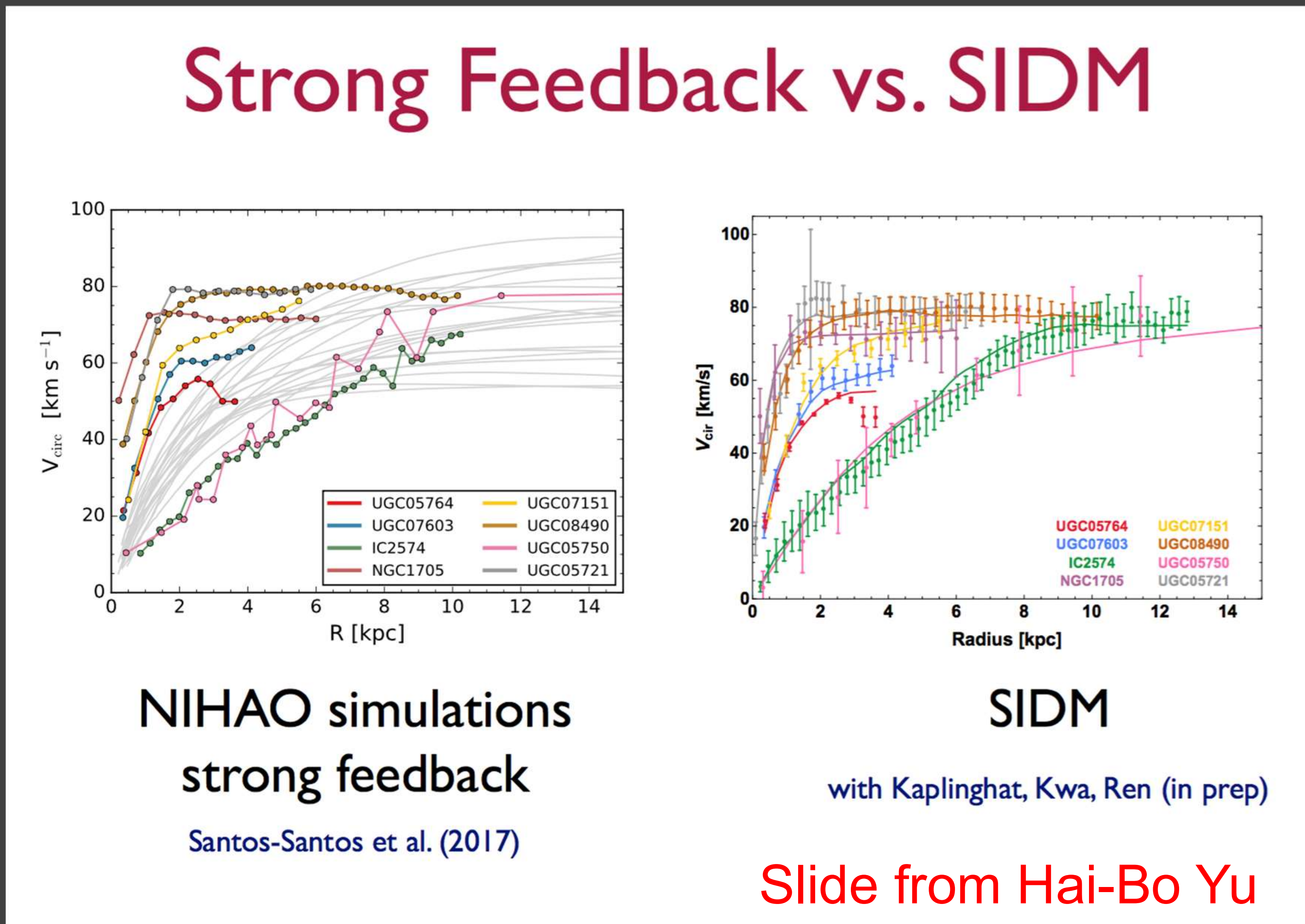
Acceleration scale in galaxies related to LCDM halo formation and angular momentum conservation [Kaplinghat and Turner (2002); see also van den Bosch and Dalcanton (1999)]

Discussion: one single relation for all galaxies?

Vflat < 100 km/s galaxies from SPARC sample plotted below. These galaxies show the largest diversity in the inner part. To keep things simple, galaxies included have no bulges. *The curves in this plane seem systematically different from each other.*



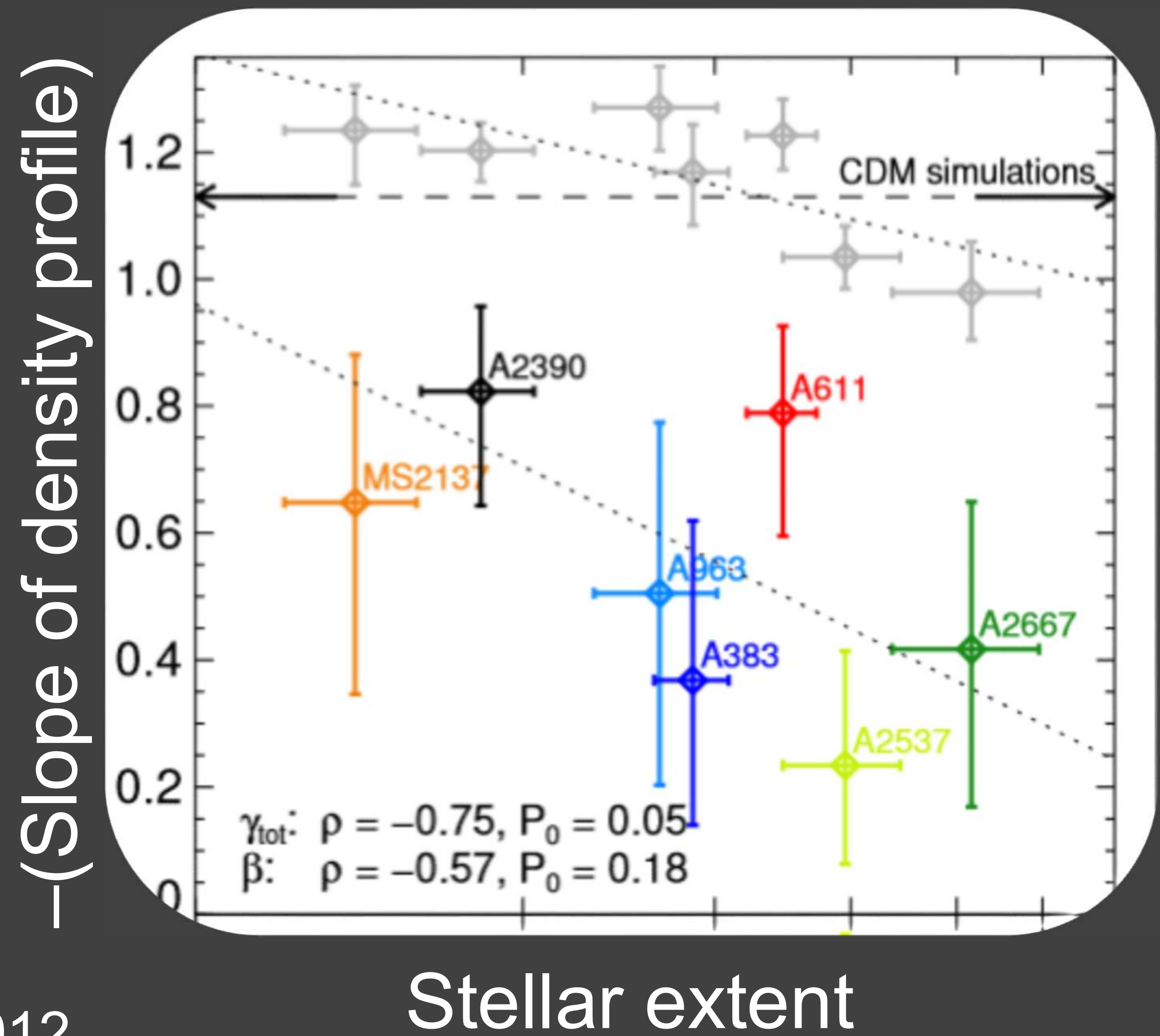
Discussion: could rotation curves distinguish LCDM and LSIDM?



Adding information from clusters of galaxies: SIDM particle properties

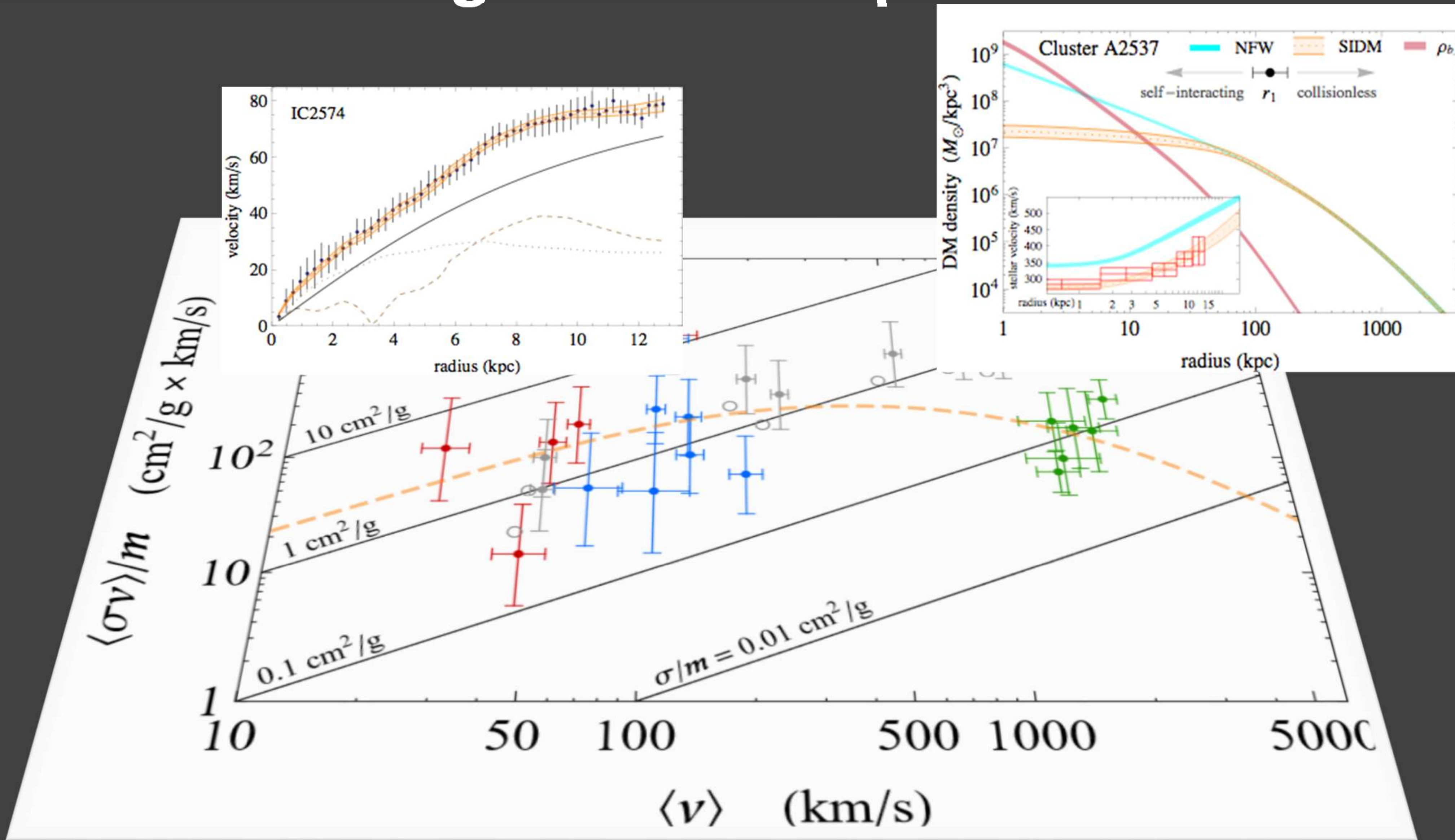
Cores in clusters of galaxies

weak lensing
strong lensing
stellar kinematics



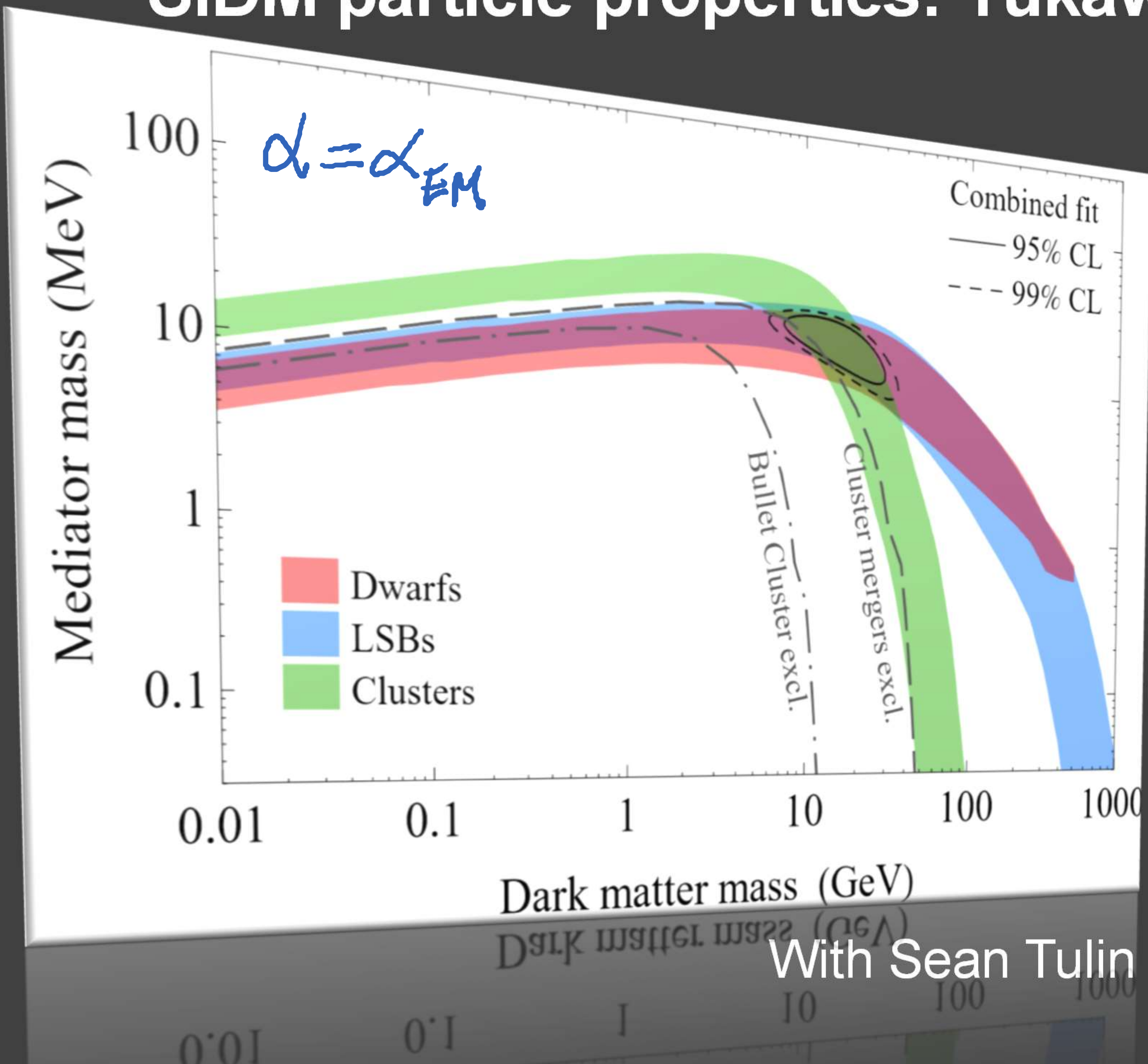
Newman et al 2012

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



With Sean Tulin and Hai-Bo Yu (2015)

SIDM particle properties: Yukawa interaction



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

Tulin, Yu, Zurek 2012

Non-abelian sector
Boddy et al (2014)

With Sean Tulin and Hai-Bo Yu (2015)

Direct search constraints are strong

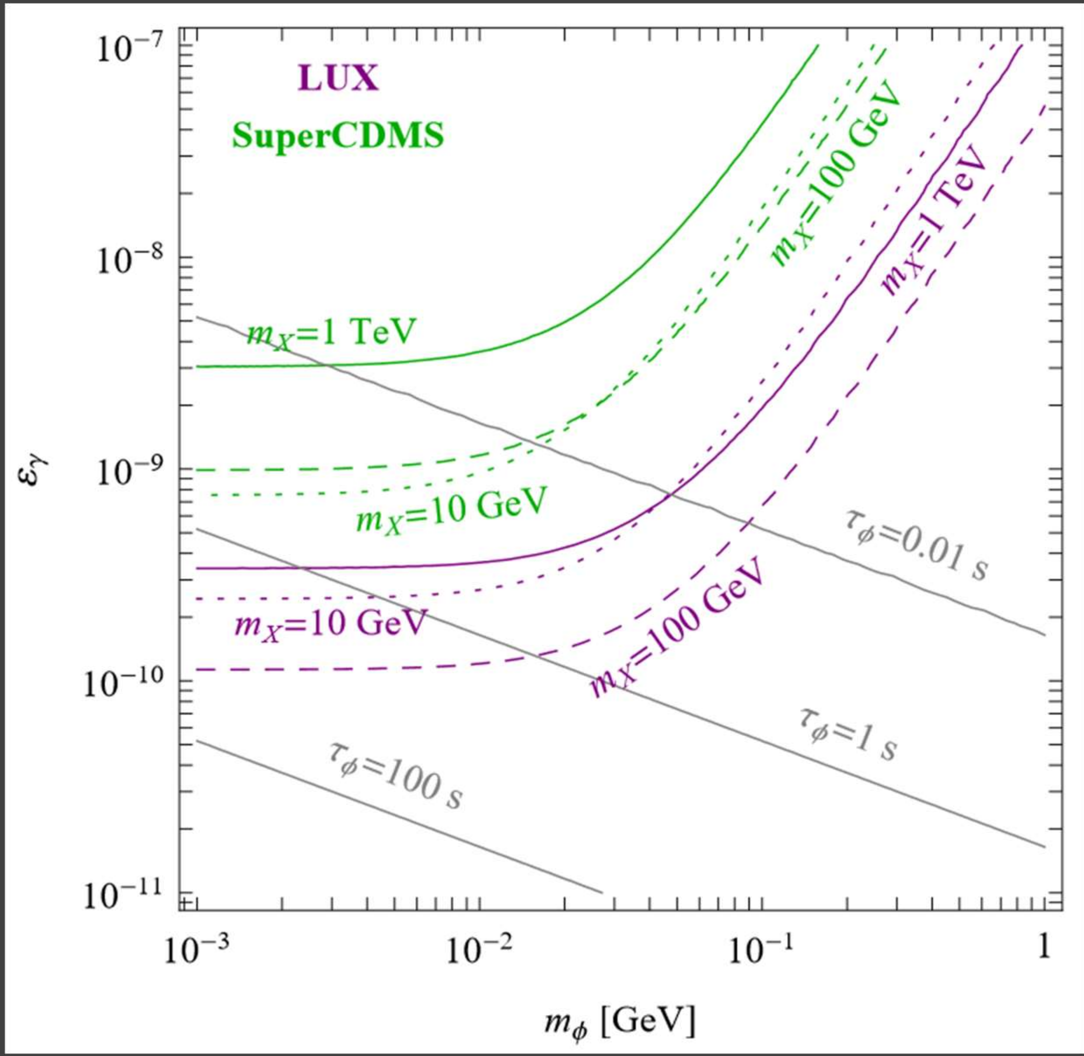
ϕ must decay!

$\mathcal{L} \supset \frac{\epsilon_\gamma}{2} F F_\phi$

$\hookrightarrow$ Direct searches $\rightarrow$

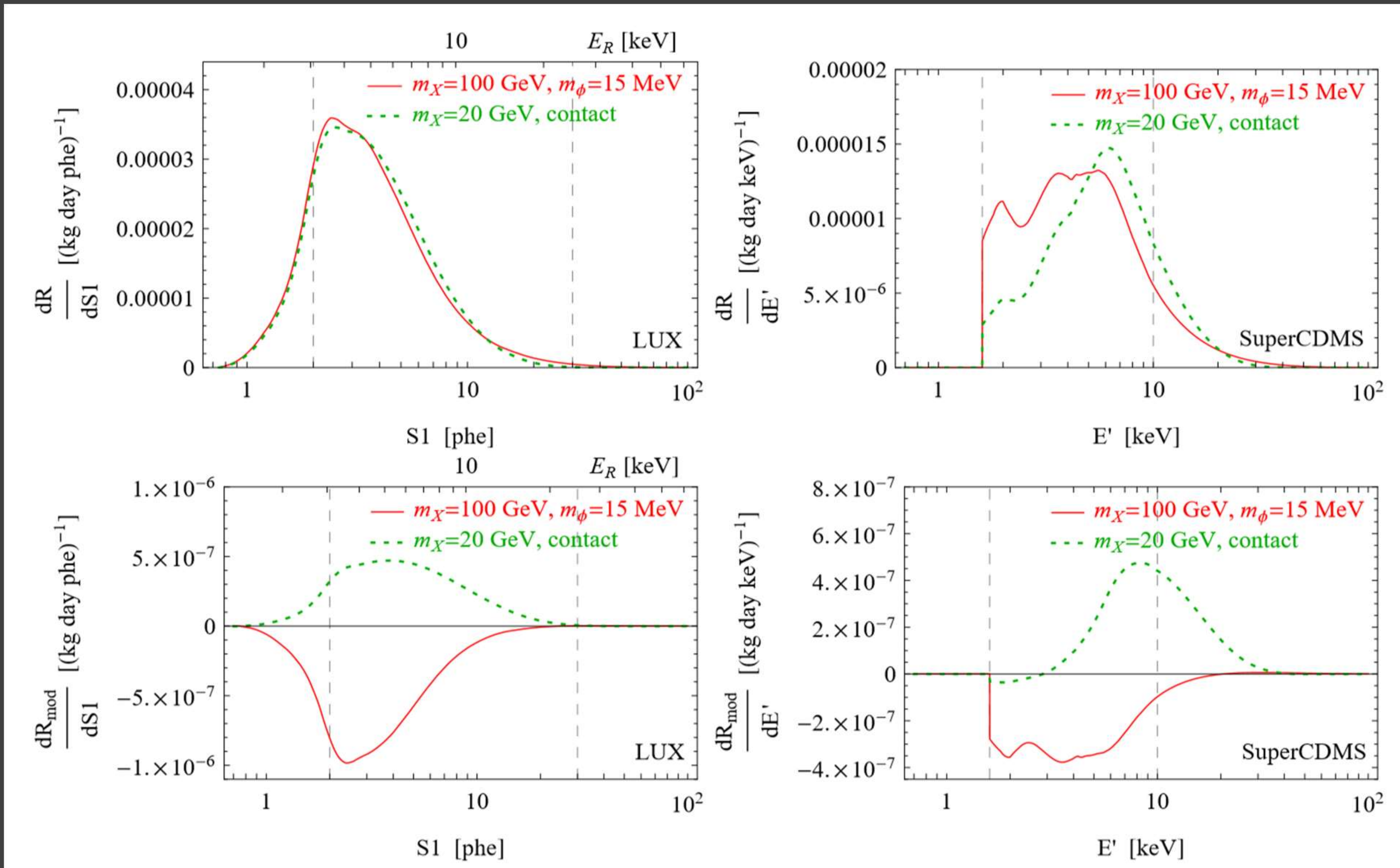
Momentum dependent scattering

Tulin, Yu and Kaplinghat (2013)



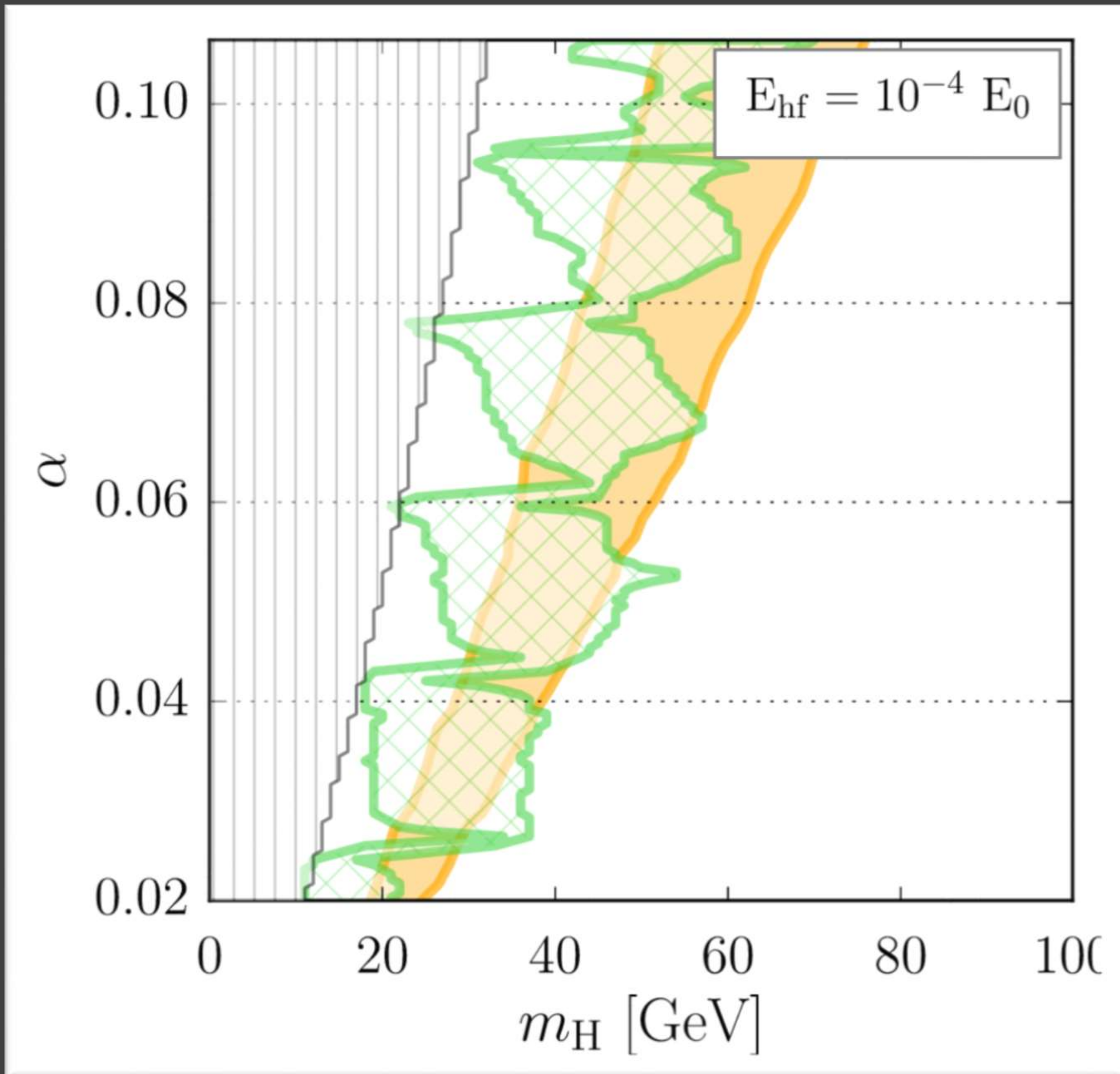
With Eugenio Del Nobile and Hai-Bo Yu (2015)

Different experiments will have different recoil and modulation spectra!



With Eugenio Del Nobile and Hai-Bo Yu (2015)

SIDM particle properties: Dark Hydrogen

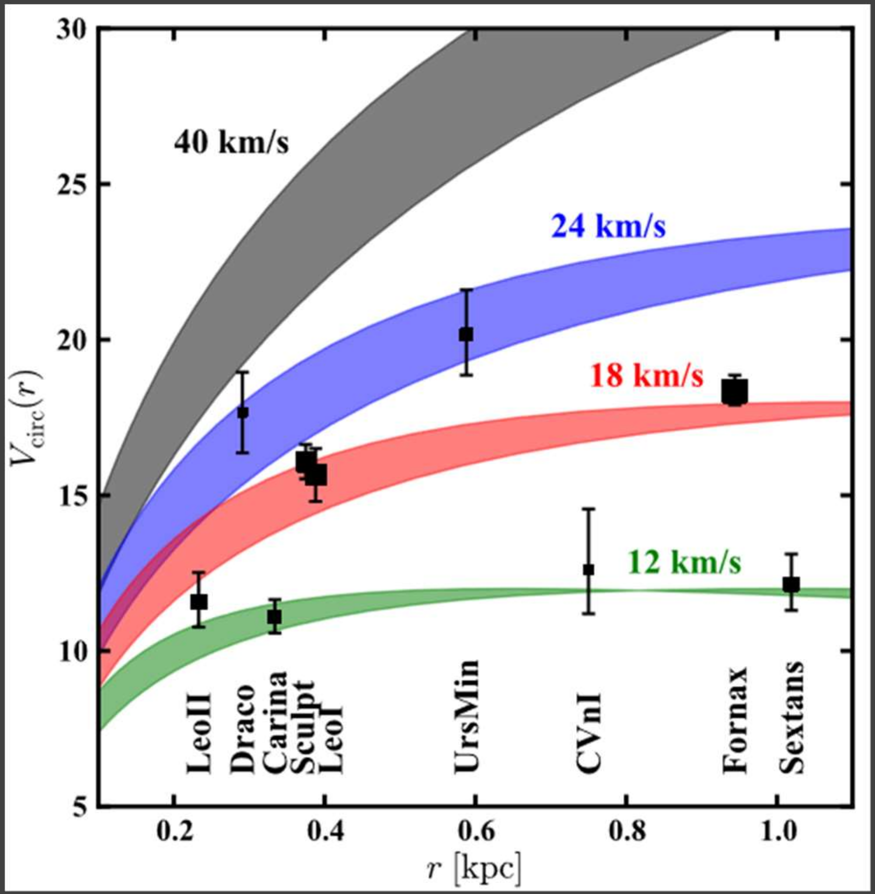


Inelastic collisions are important!

with Kim Boddy, Anna Kwa, Annika Peter (2016)

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

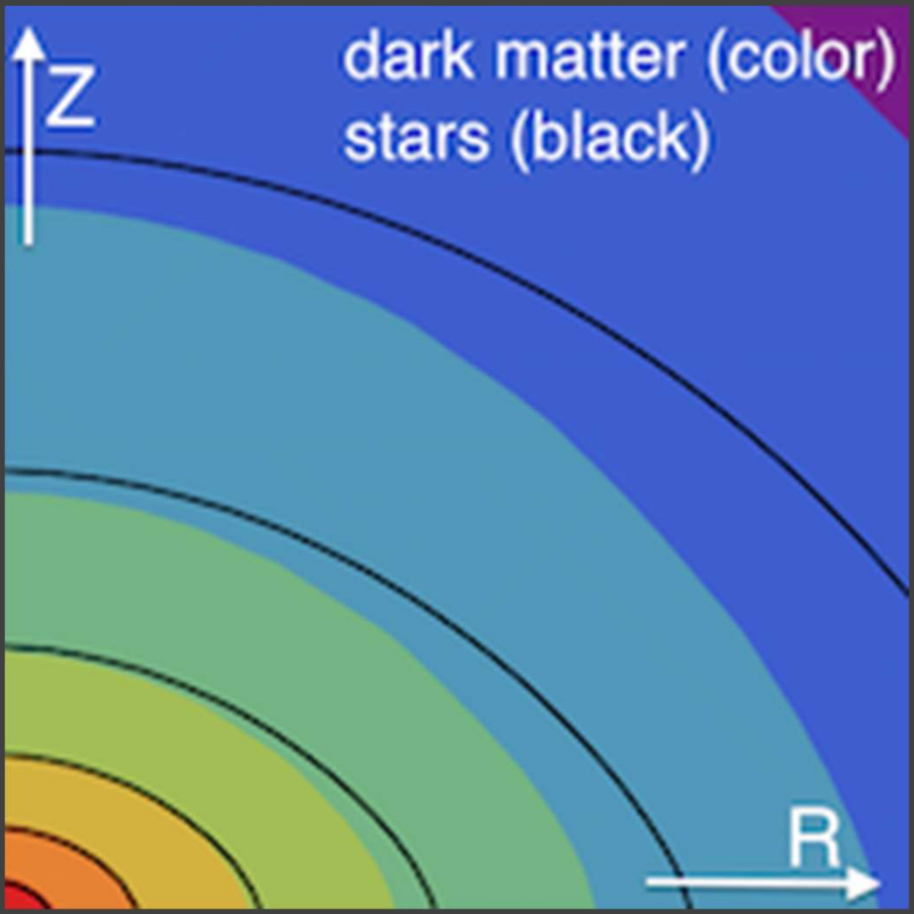
Model independent tests of the SIDM paradigm



SIDM predicts cores in satellite galaxies.

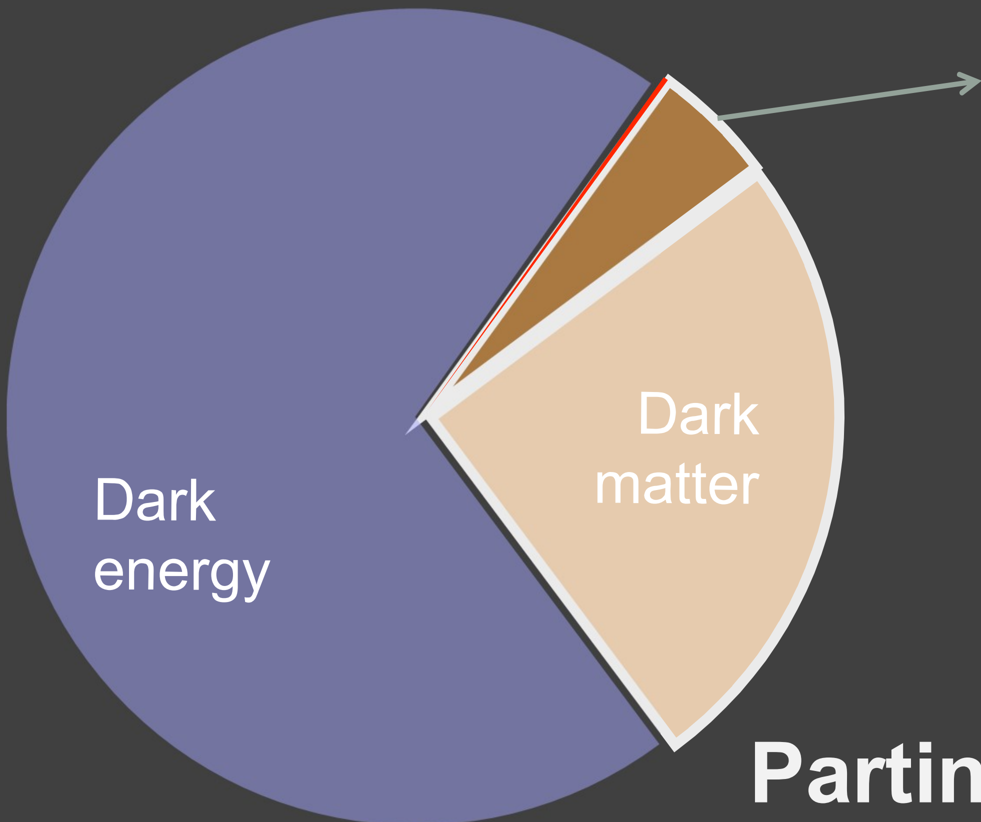
Multiple population chemo-dynamics in the MW satellites. [Walker and Penarrubia]

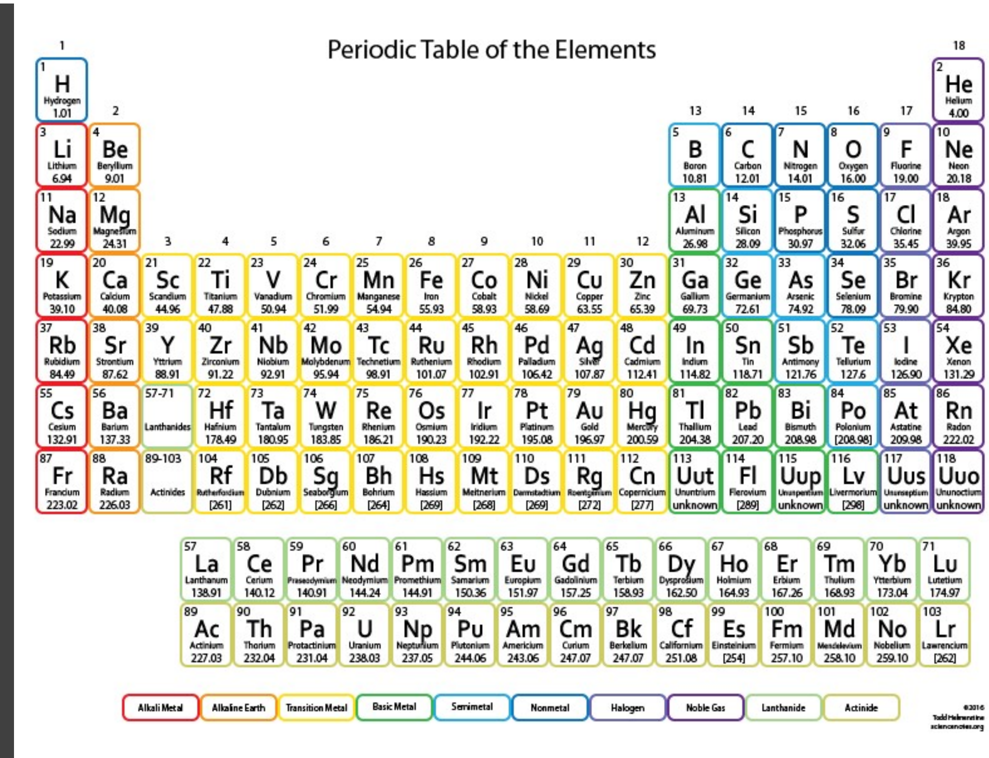
Model independent tests of the SIDM paradigm



SIDM tracks the stellar potential where stars dominate.

Strong lenses and elliptical galaxies in X-rays.





Parting thought: perhaps, the "dark sector" is richer than we have previously imagined.