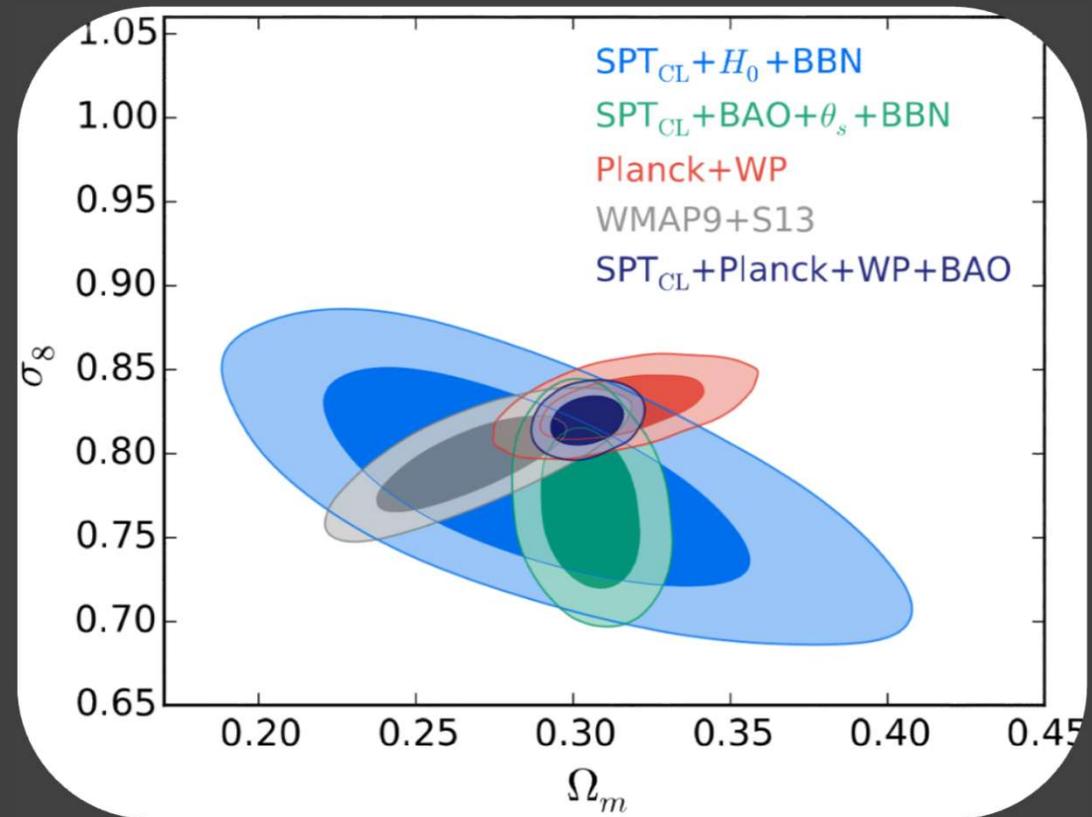


The Self-Interacting Dark Matter (SIDM) paradigm

MANOJ KAPLINGHAT

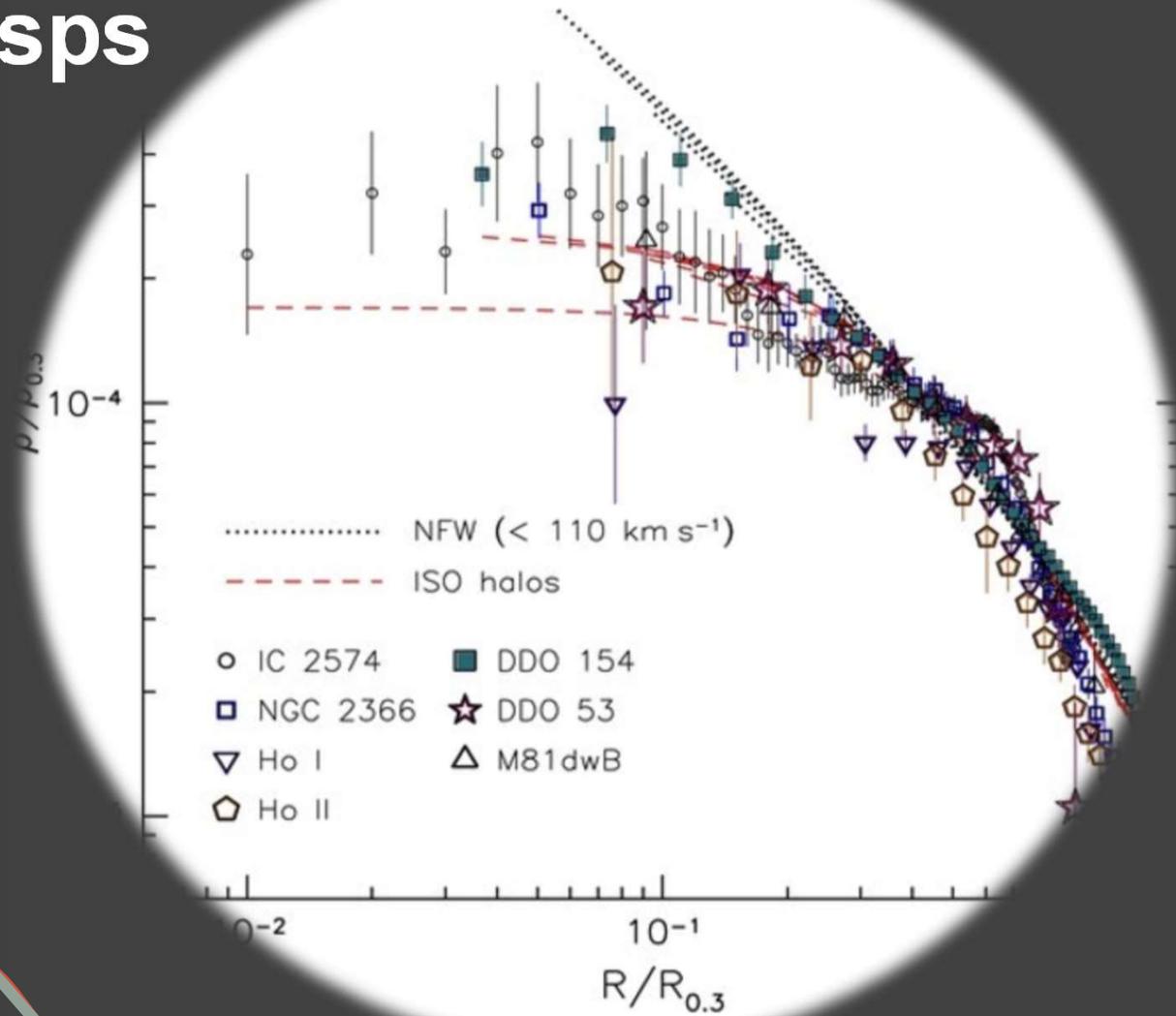
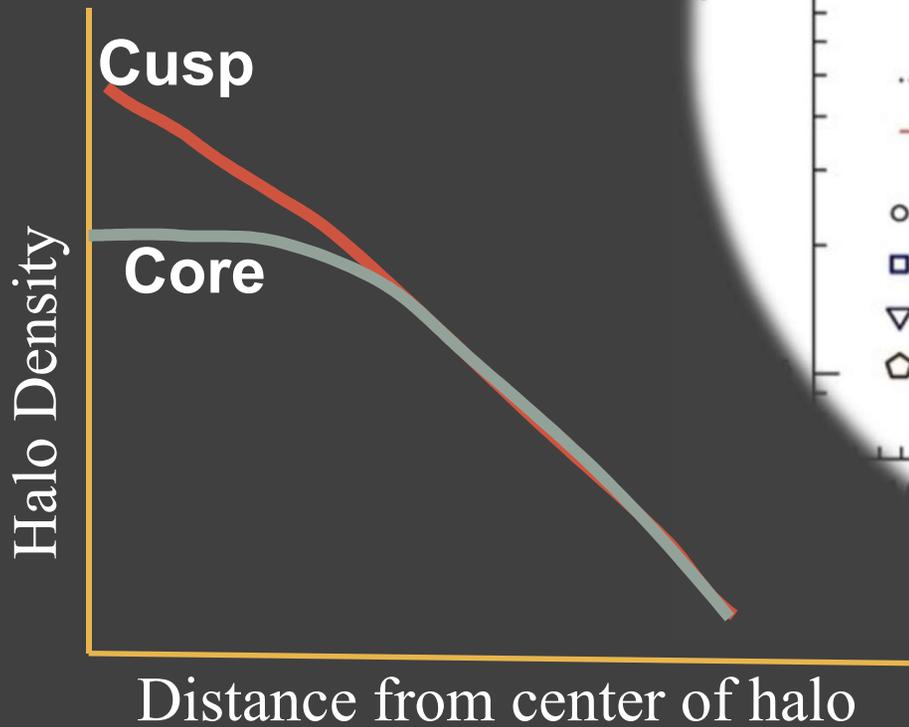
UNIVERSITY OF CALIFORNIA, IRVINE

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

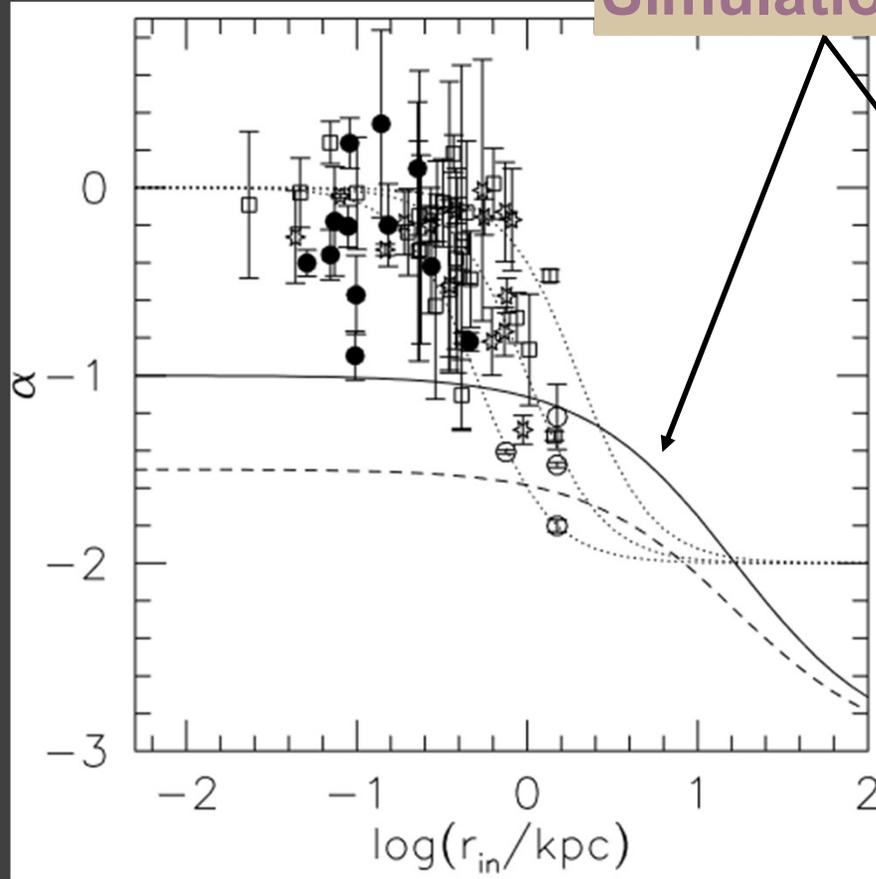


Oh et al 2015

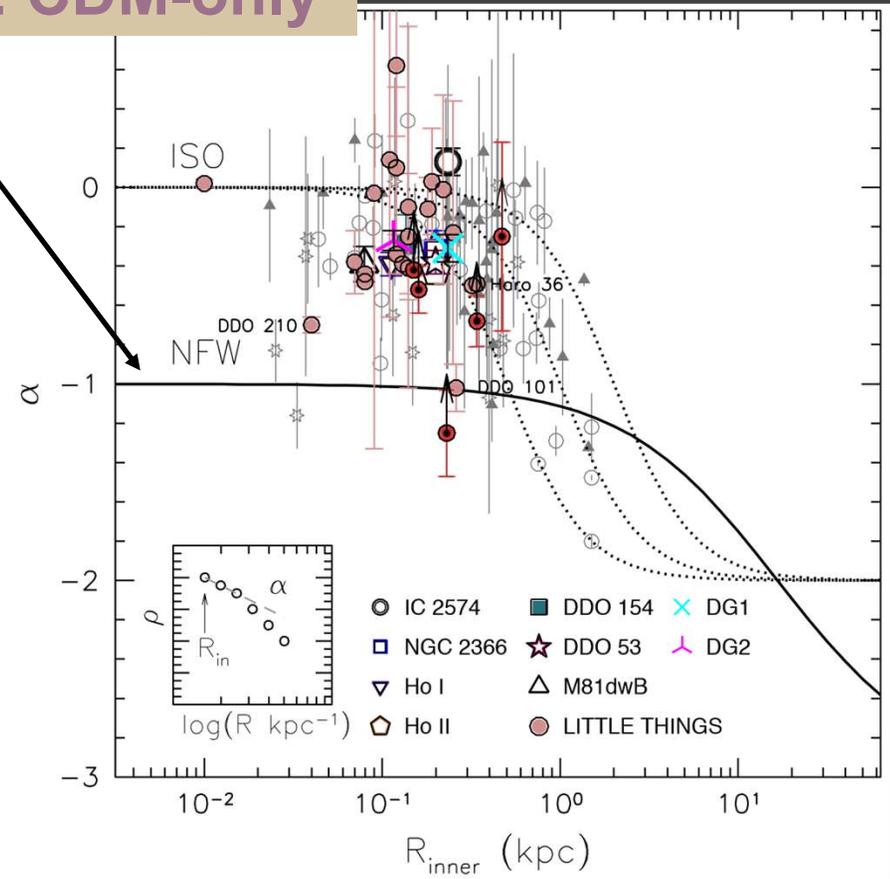
Cores and cusps: almost two decades old

Simulation: CDM-only

Slope of the DM density profile

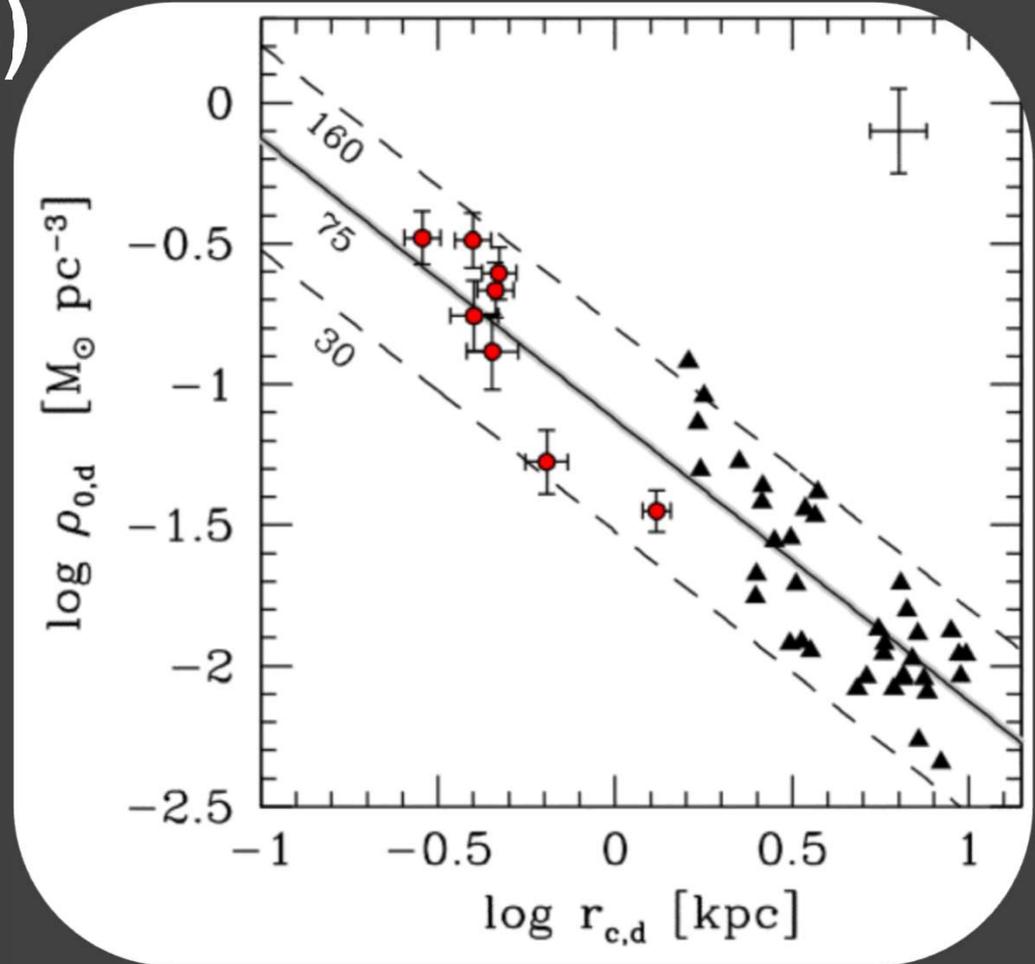
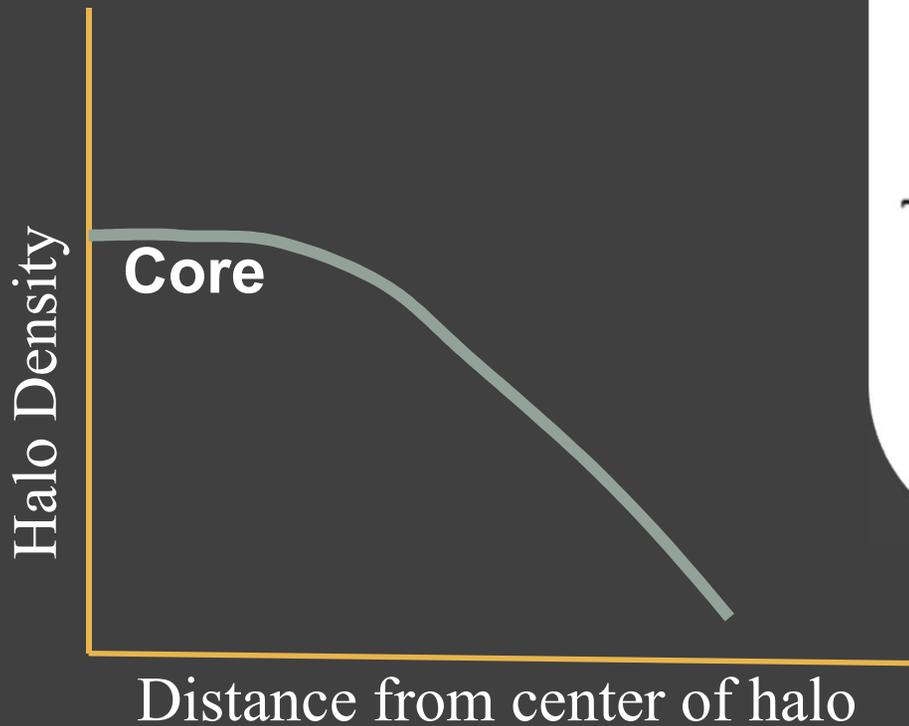


de Blok and Bosma, 2002



LITTLE THINGS, Oh et al 2015

Uniformity of cored profiles (in DM dominated galaxies)



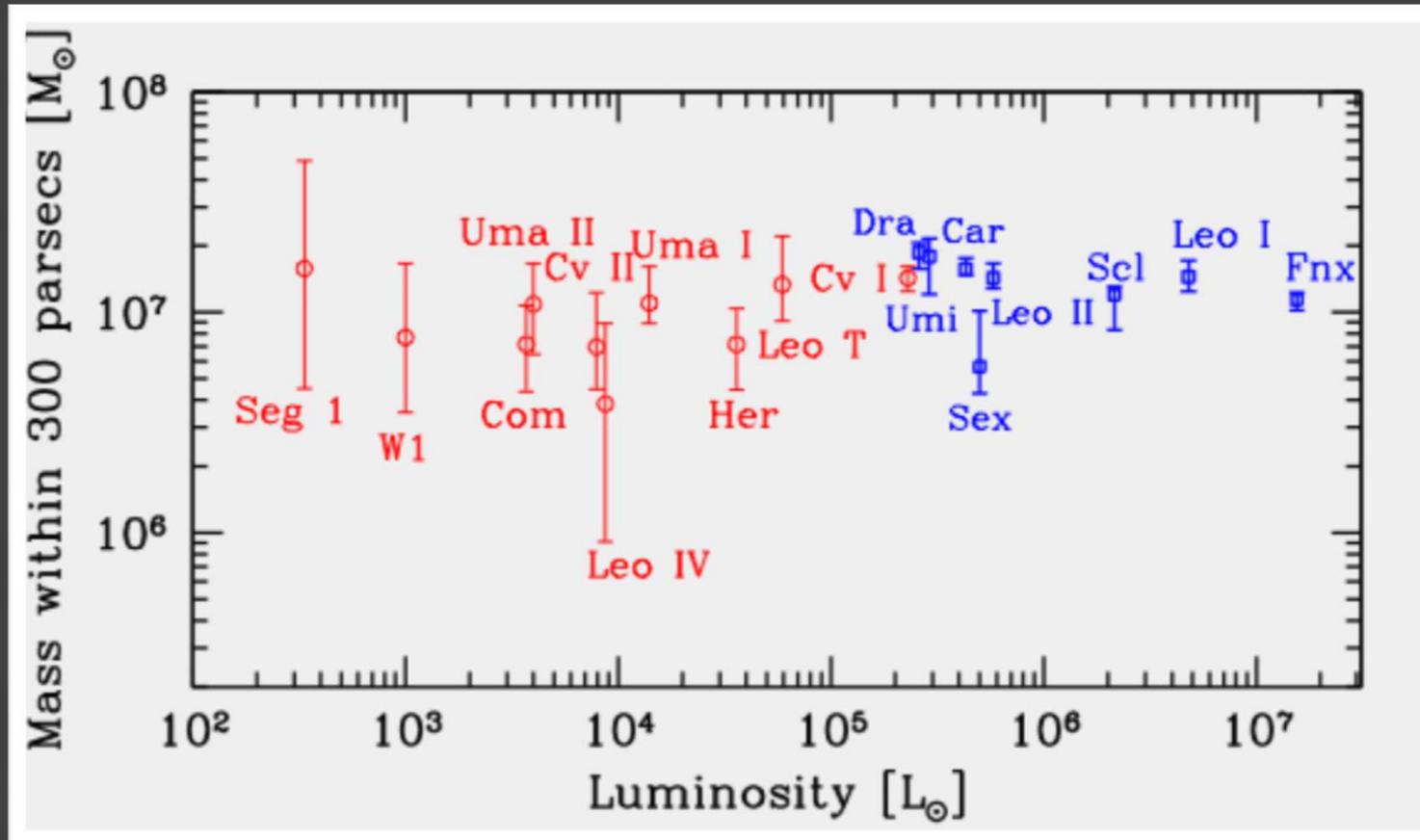
Burkert 2015

Donato et al 2009

Salucci, Wilkinson, et al 2012

Kormendy and Freeman 2014

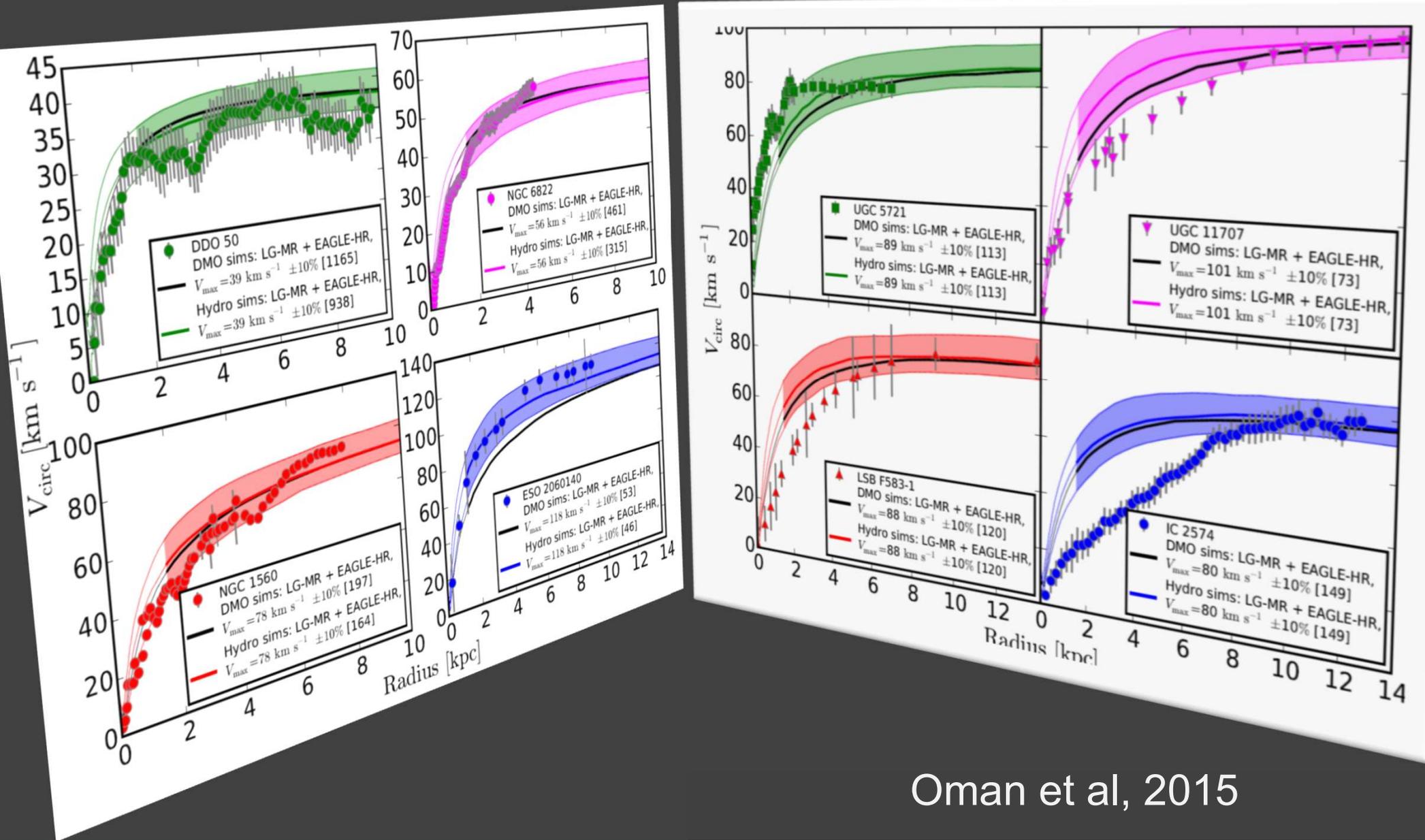
Satellite galaxies are a great laboratory to search for new physics



With Louis Strigari, James Bullock and collaborators (2008)

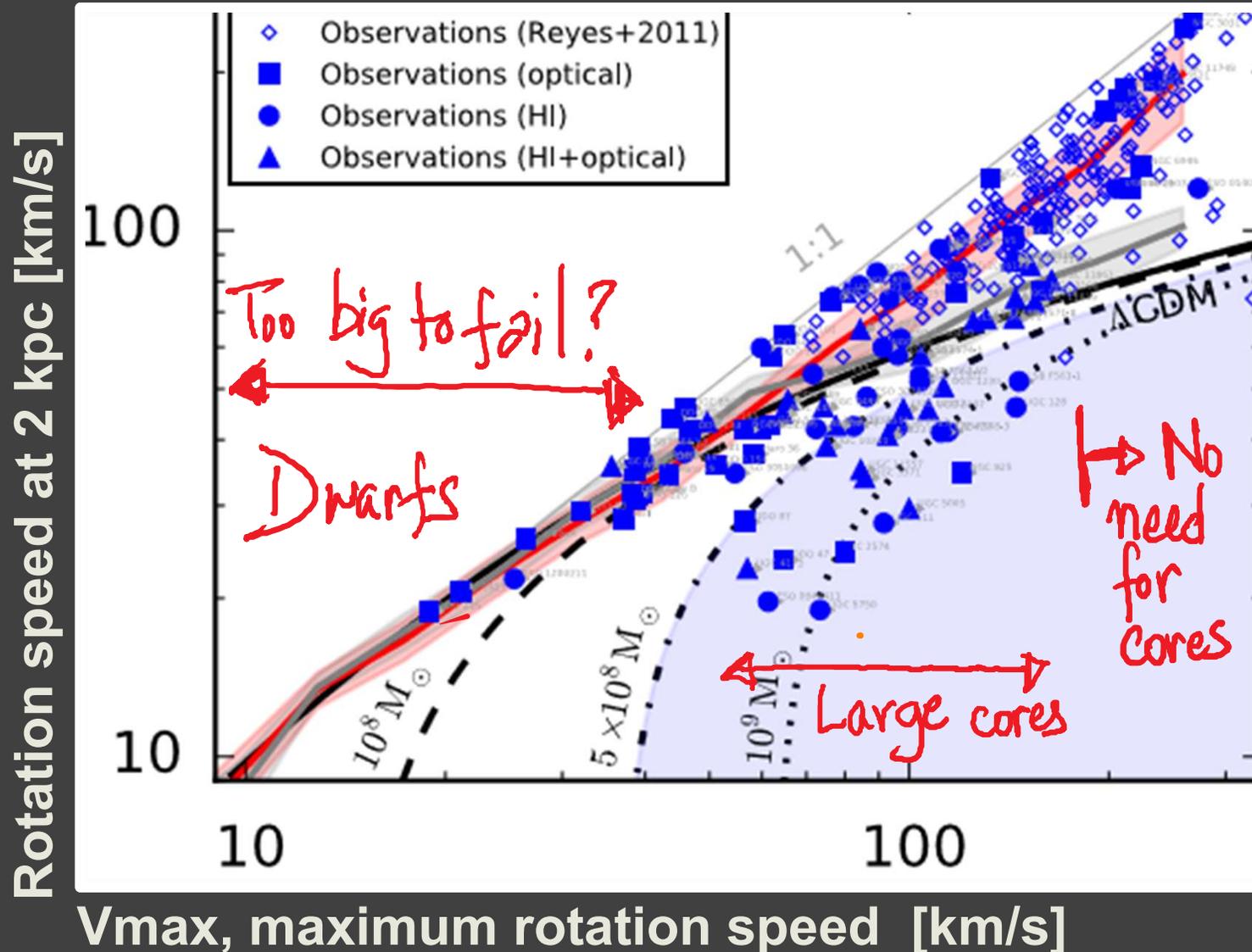
But I will disregard them until the end ...

Cores AND cusps



Oman et al, 2015

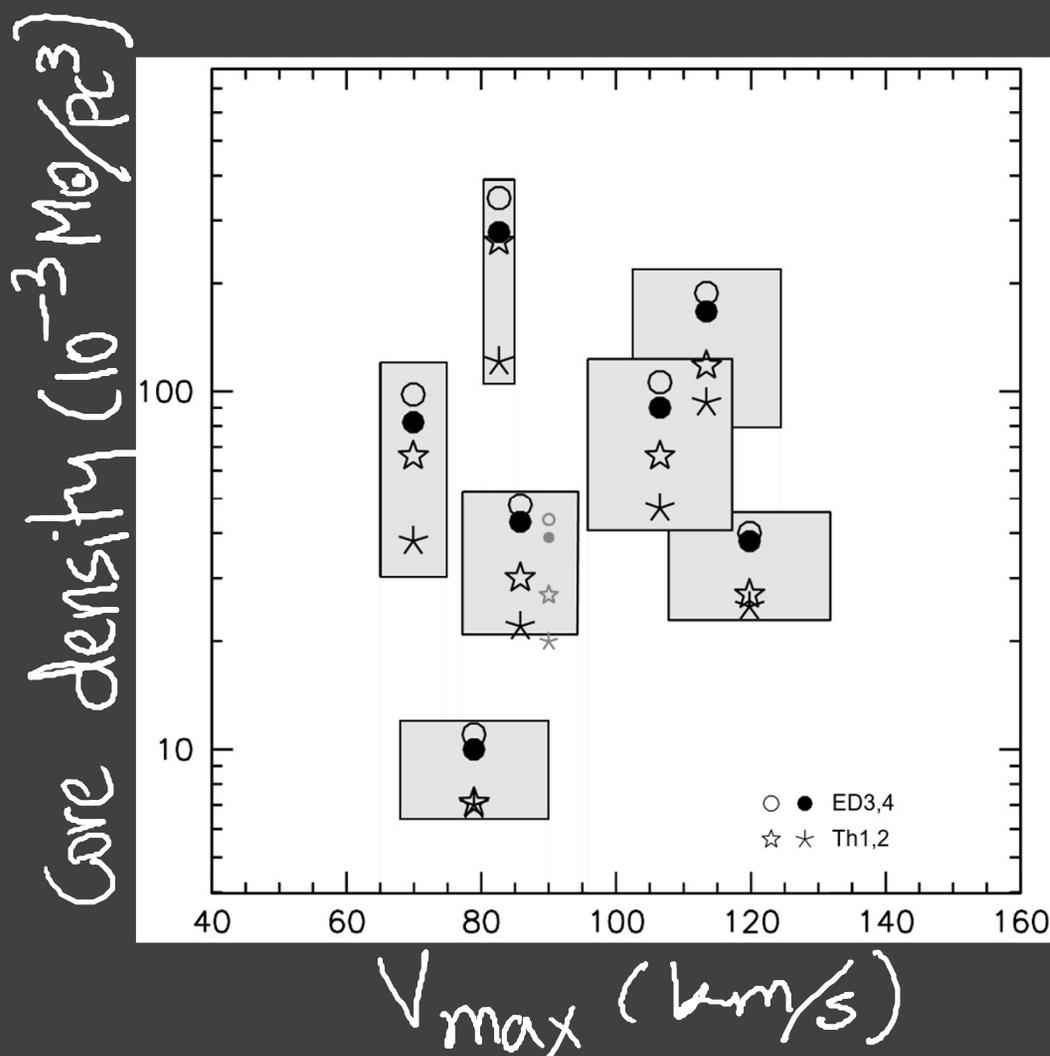
The puzzling diversity in rotation curves



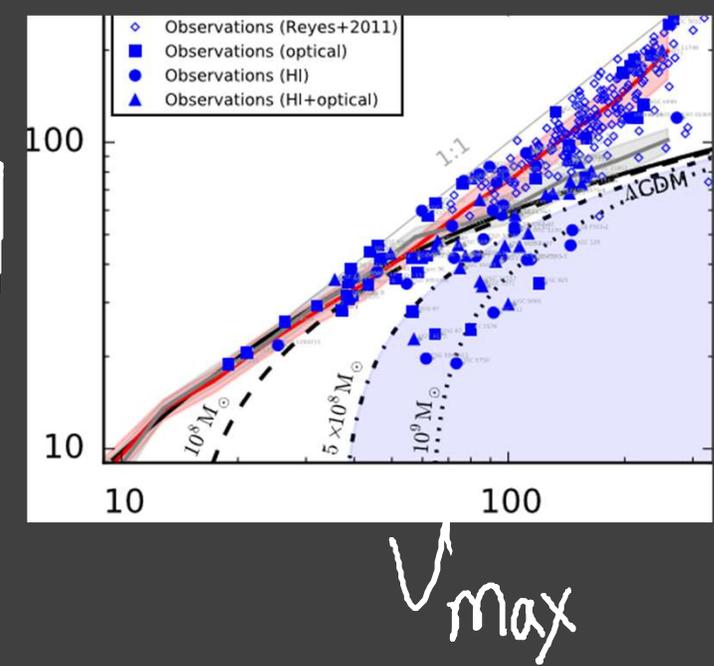
▶ Similar V_{max}
⇒ Similar halo masses
And
Similar total baryon masses

Oman et al, 2015

The puzzling diversity in rotation curves



$V(2kpc)$



Oman et al, 2015

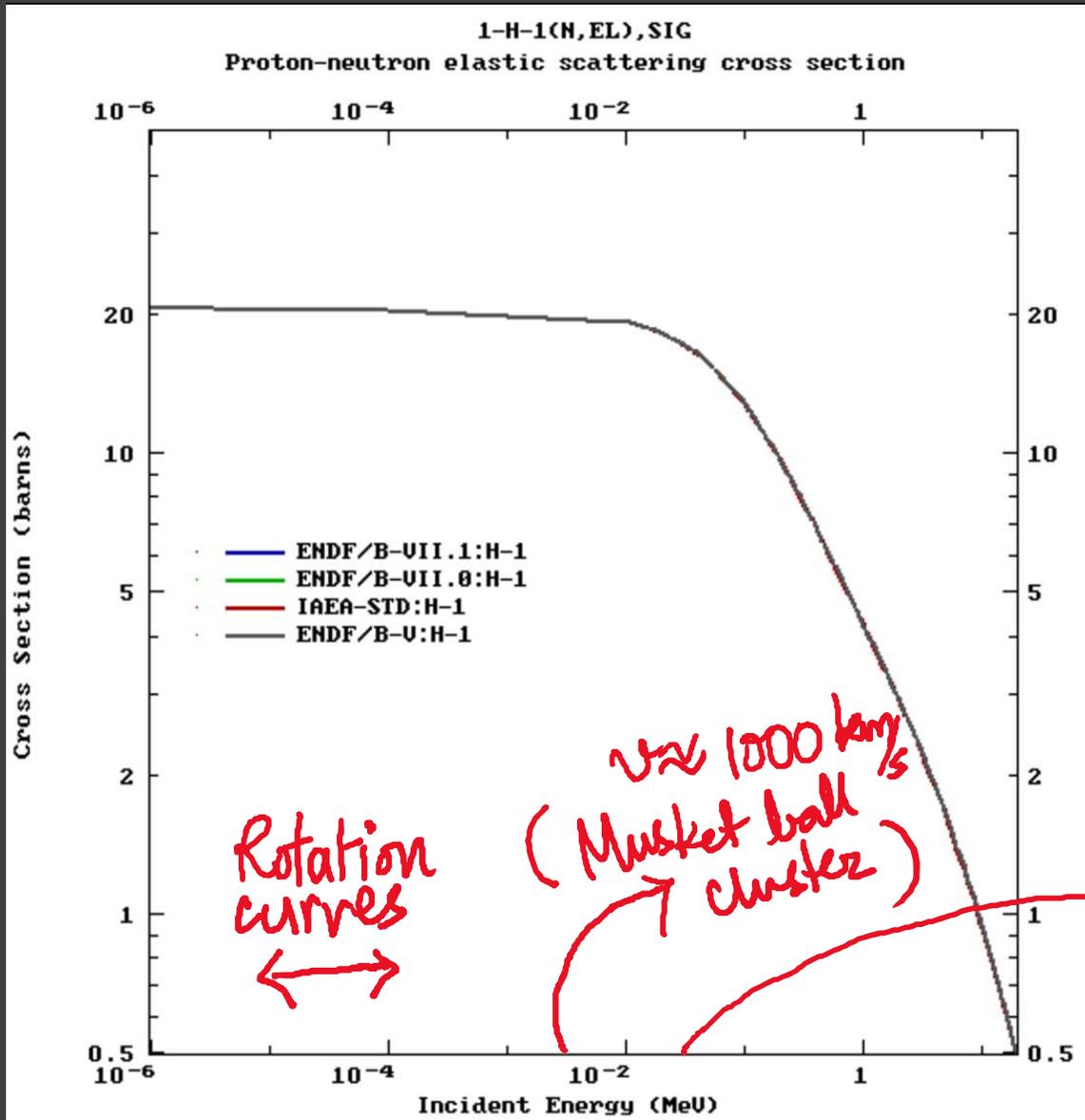
with Rachel Kuzio de Naray, Greg Martinez and James Bullock (2010)

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.

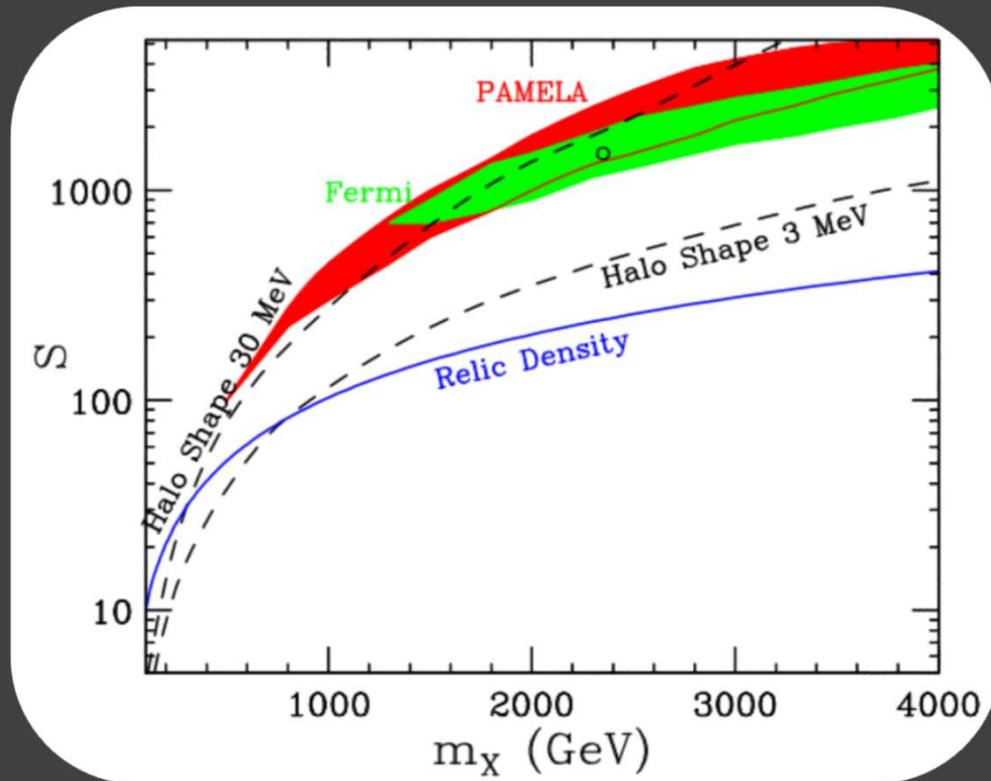
Require $\sigma/m \sim \text{few barns/GeV}$

A motivating Standard Model example



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

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

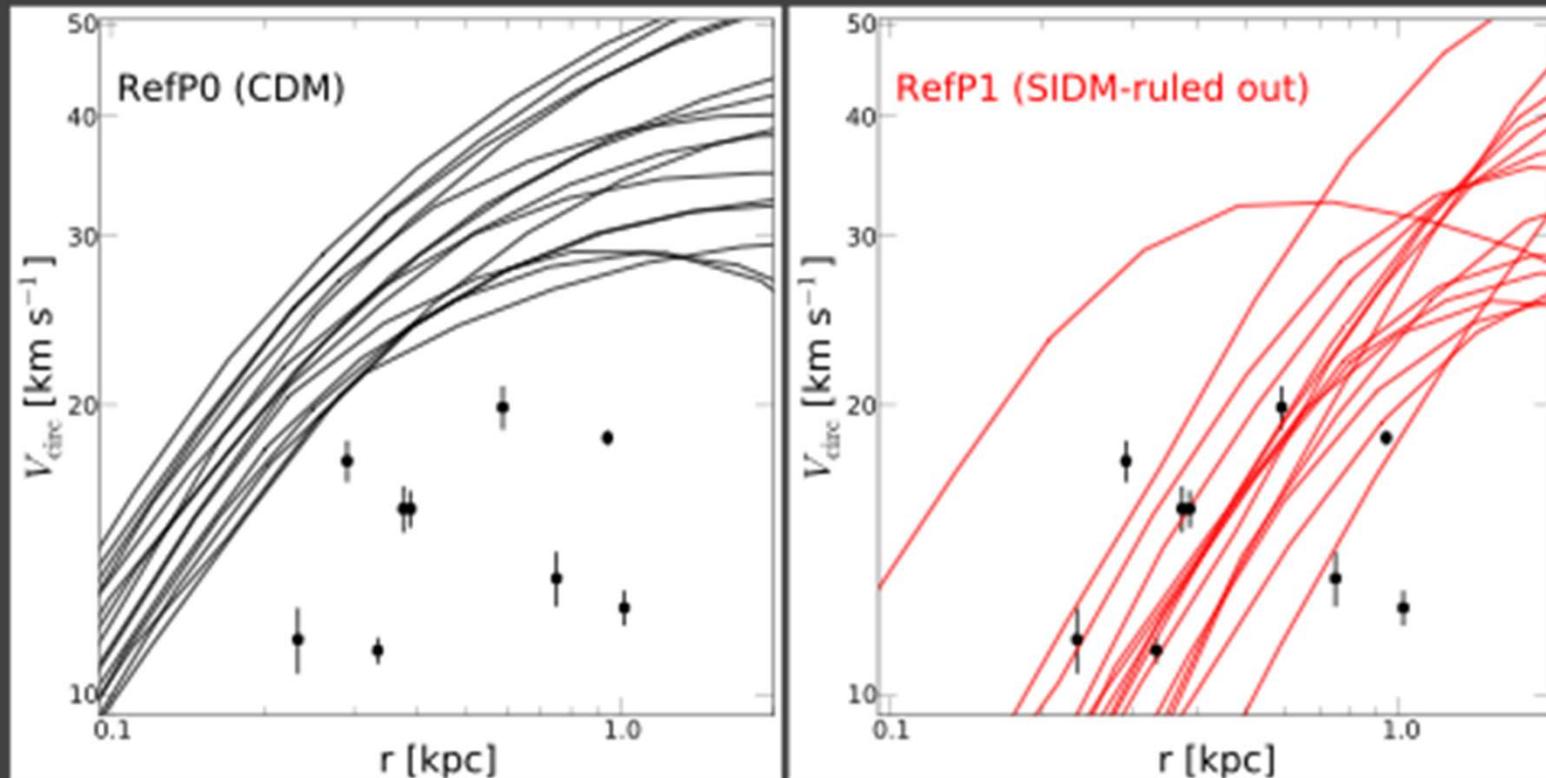
With Jonathan Feng, Haibo Yu, arXiv:0905.3039

With Jonathan Feng, Huitzu Tu, Haibo Yu, arXiv:0911.0422

Matt Buckley, Paddy Fox, arXiv:0911.3898

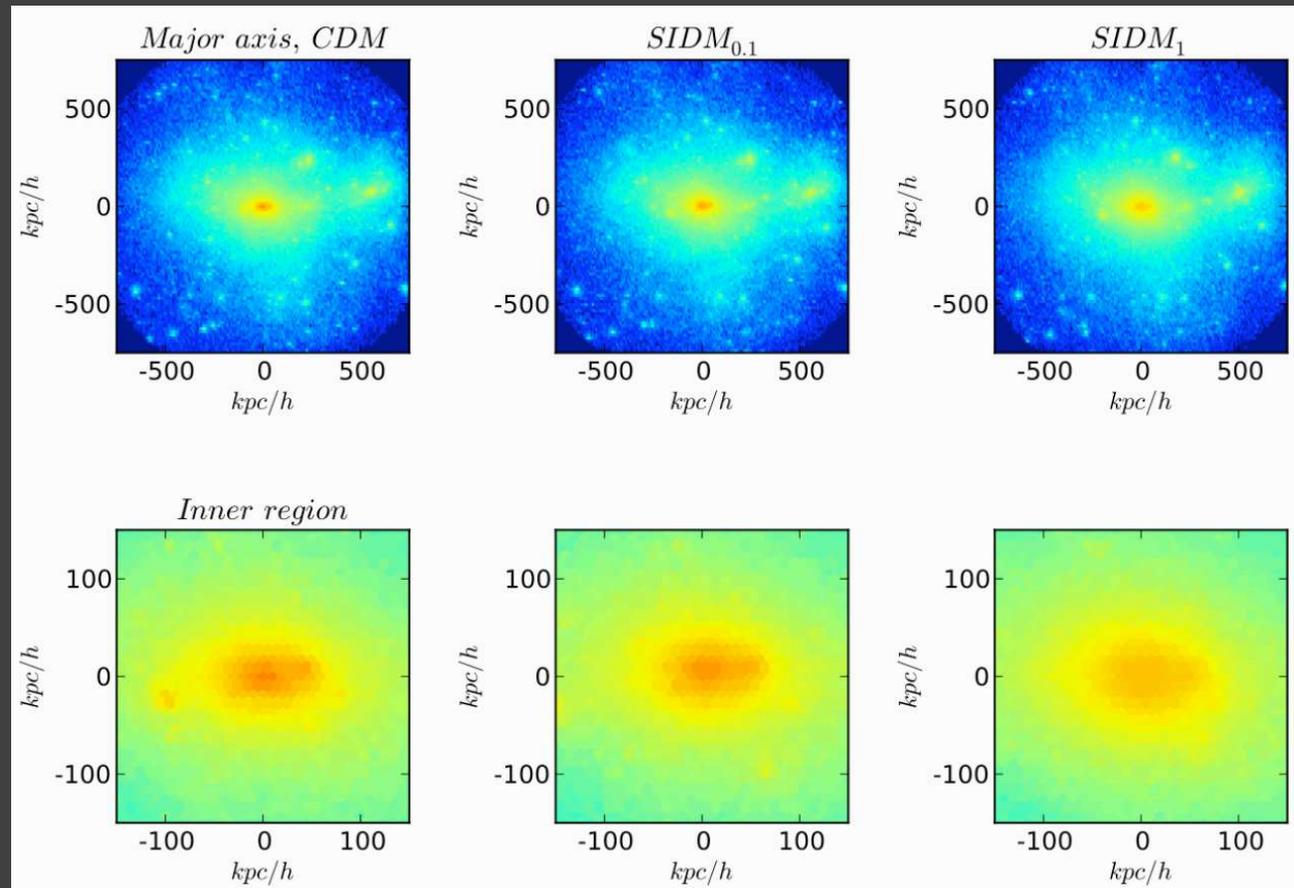
Avi Loeb, Neal Weiner, arXiv:1011.6374

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

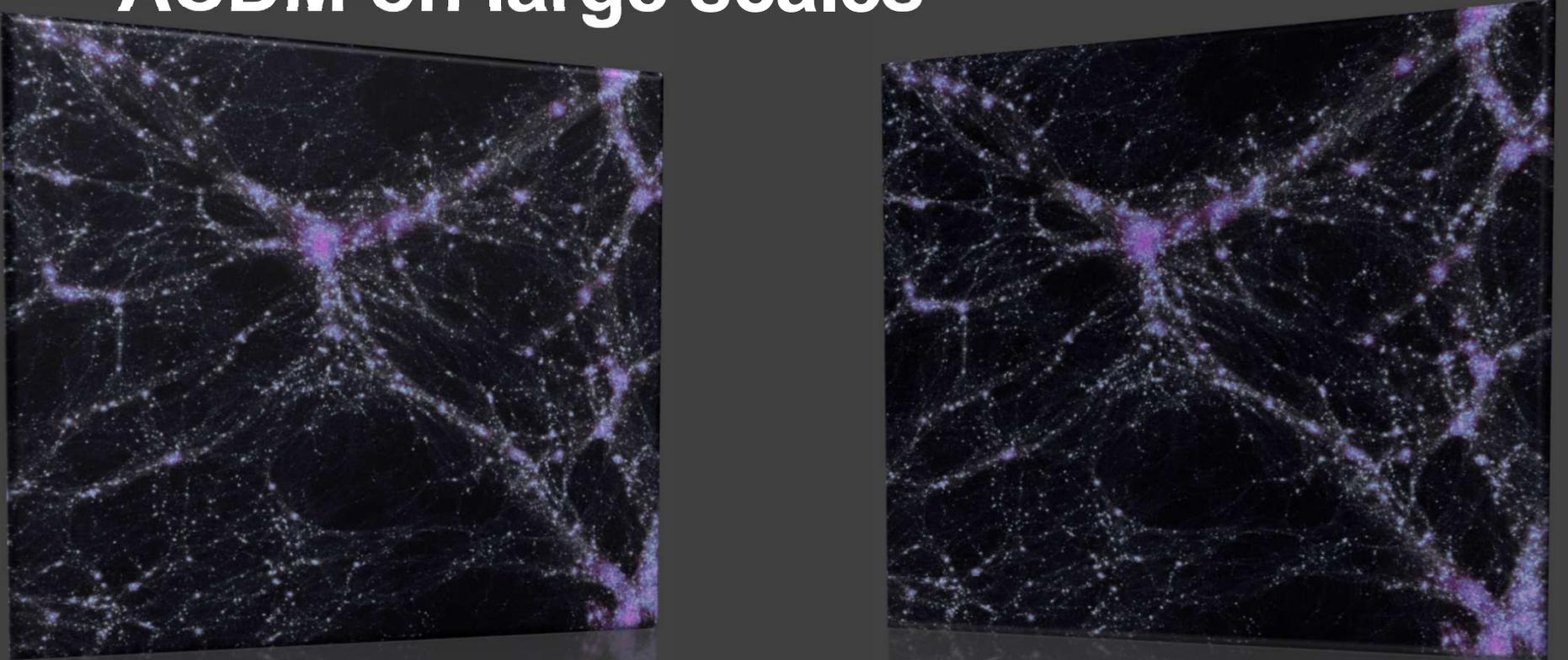


Constraints no better than $1 \text{ cm}^2/\text{g}$.

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

How SIDM works

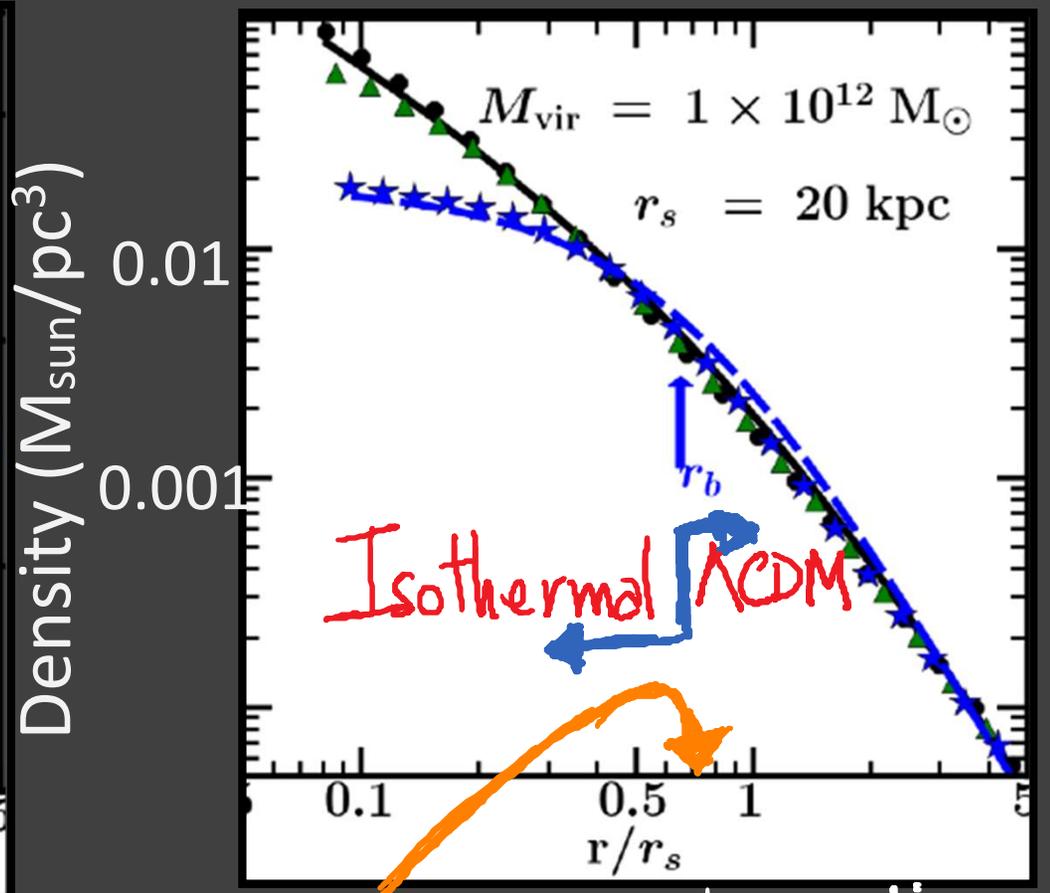
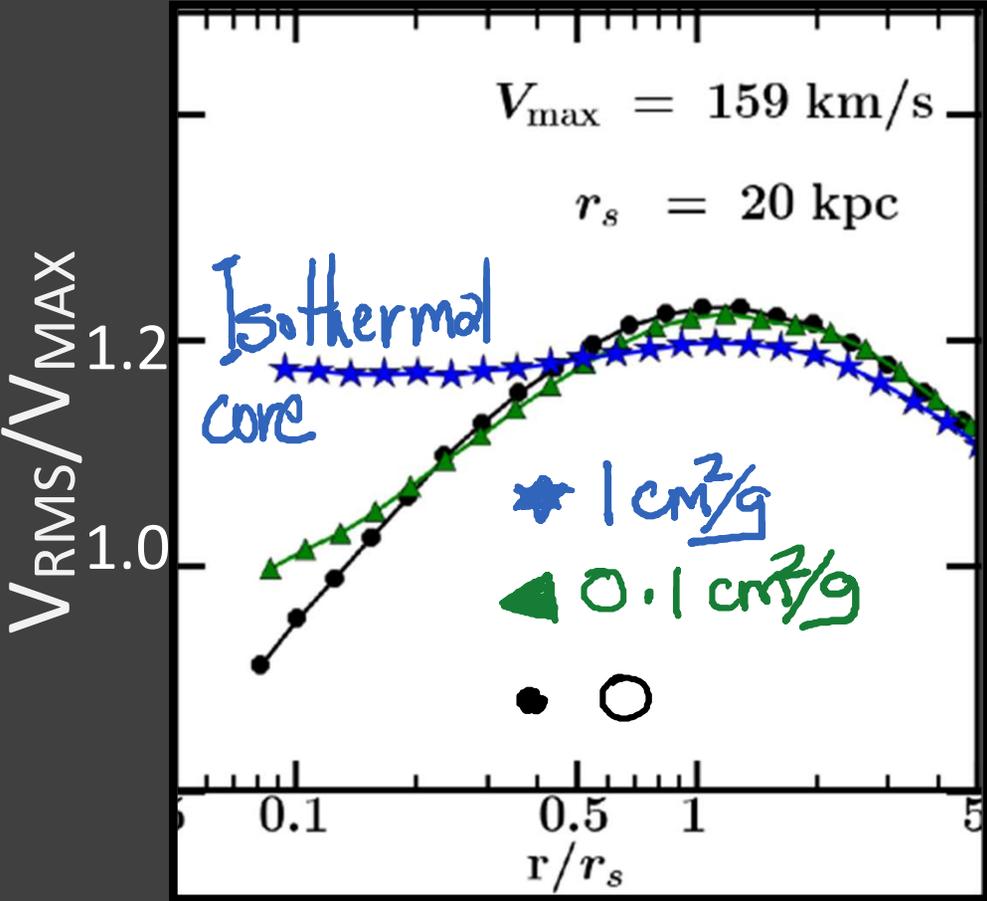
Λ SIDM inherits all the successes of Λ CDM on large scales



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



r_1 : one interaction on average over age of halo

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

Field galaxies: SIDM halo profile is almost uniquely determined

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

mass and density continuous at $r=r_1$

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

gravitational potential of dark matter and baryons

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

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

Field galaxies: both Cored and Cuspy

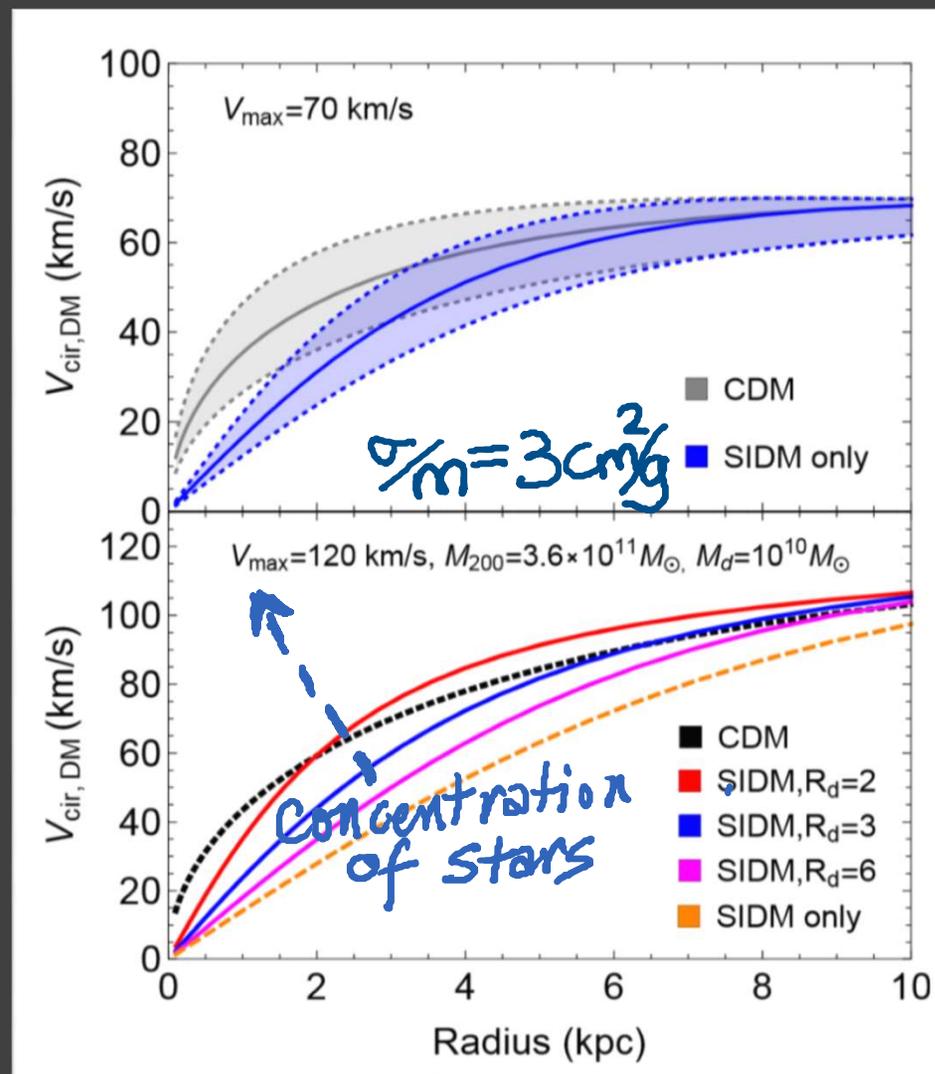
SIDM predicts large cores in all galaxies

↑ → cores hard to discern or even cuspy

$\rho_* + \rho_{\text{gas}}$

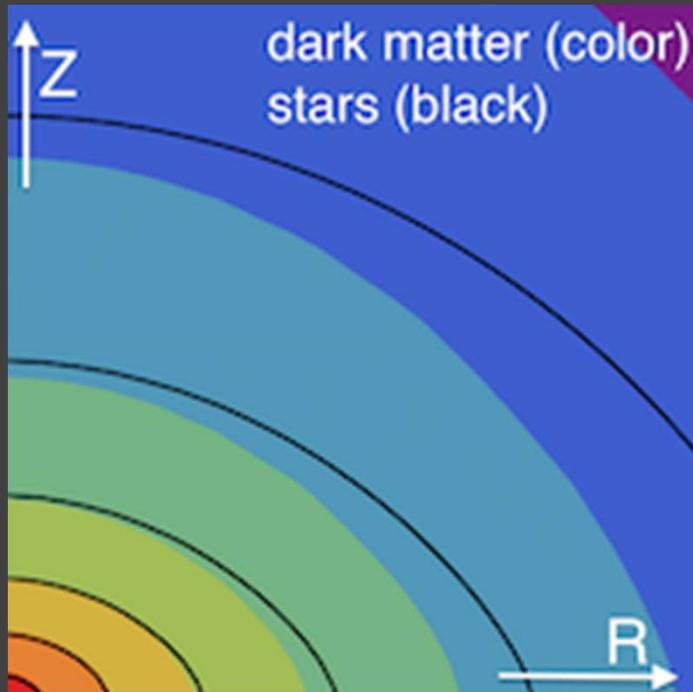
↓ → cores large & evident

Core $\sim r_1 \approx r_s$



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

Stars and dark matter tied in SIDM model

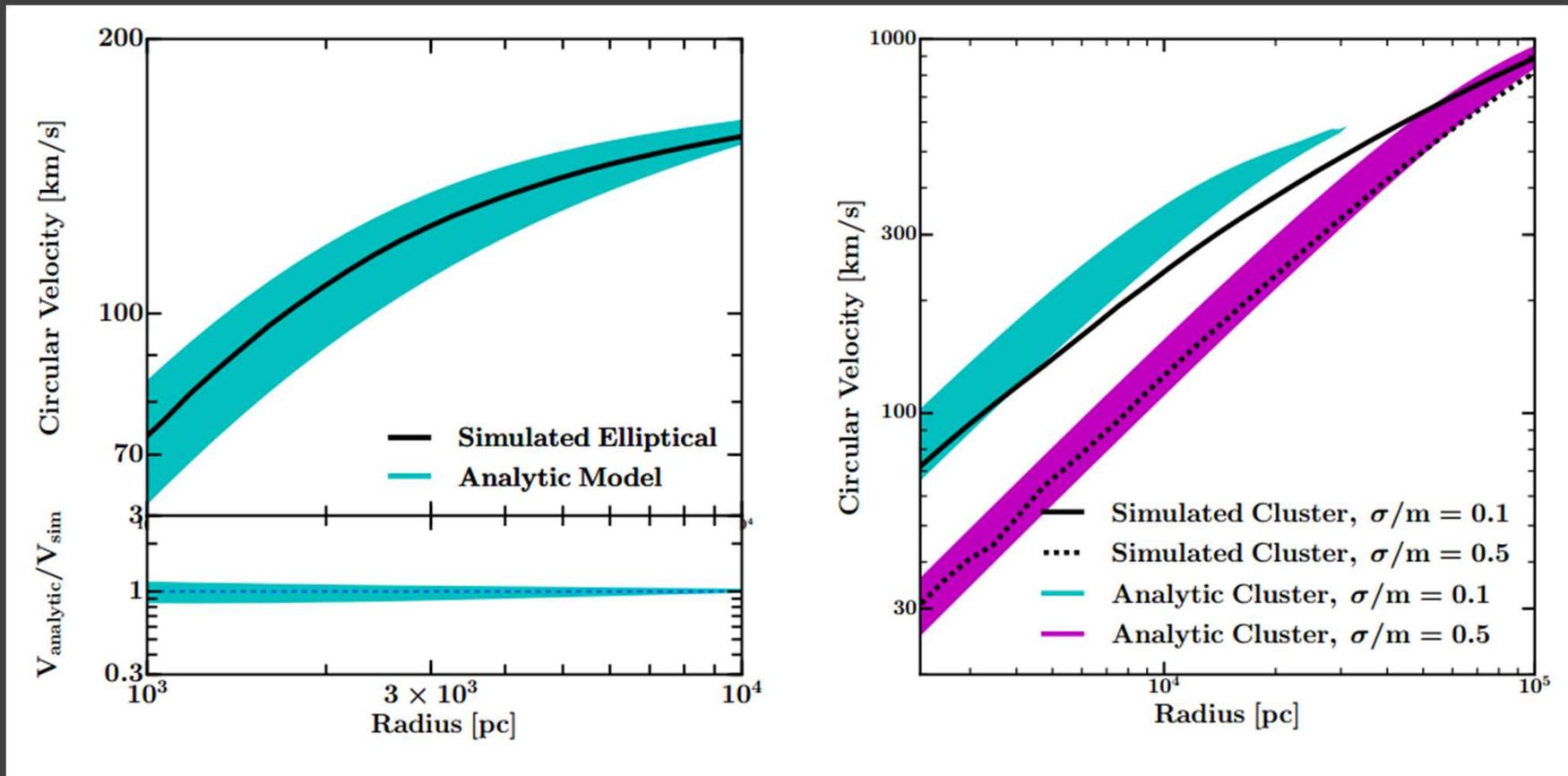


Isothermal => SIDM tracks the stellar potential, i.e., *dark and luminous matter are tied.*

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).

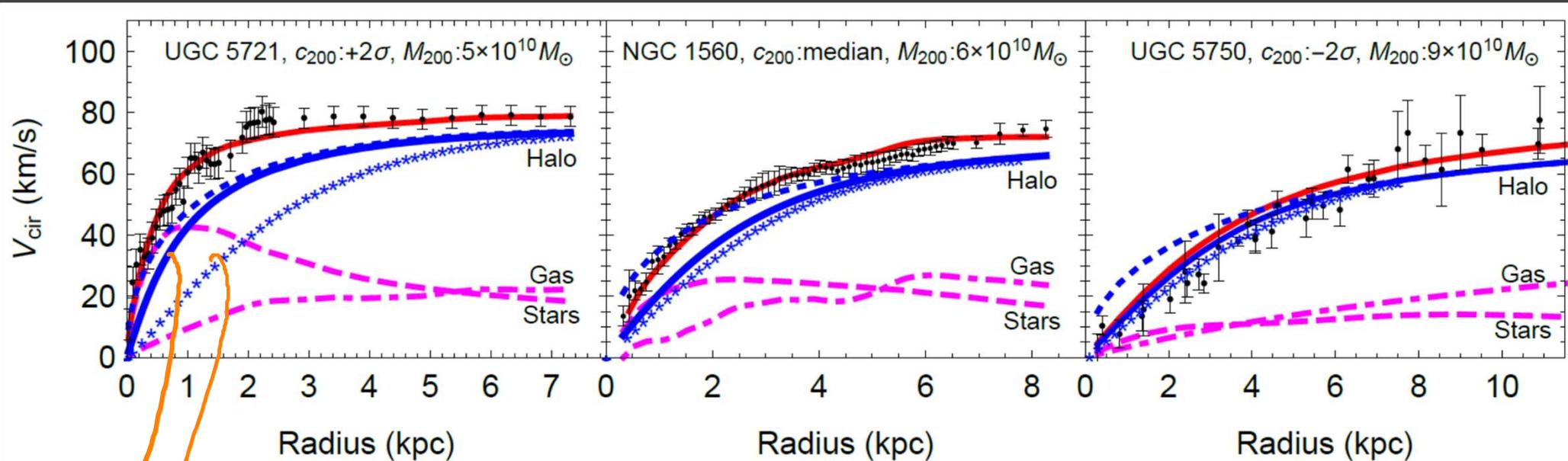
The SIDM halo profile in the presence of baryons: N-body simulations



With Oliver Elbert and James Bullock (2017)

The SIDM fits to galaxy rotation curves

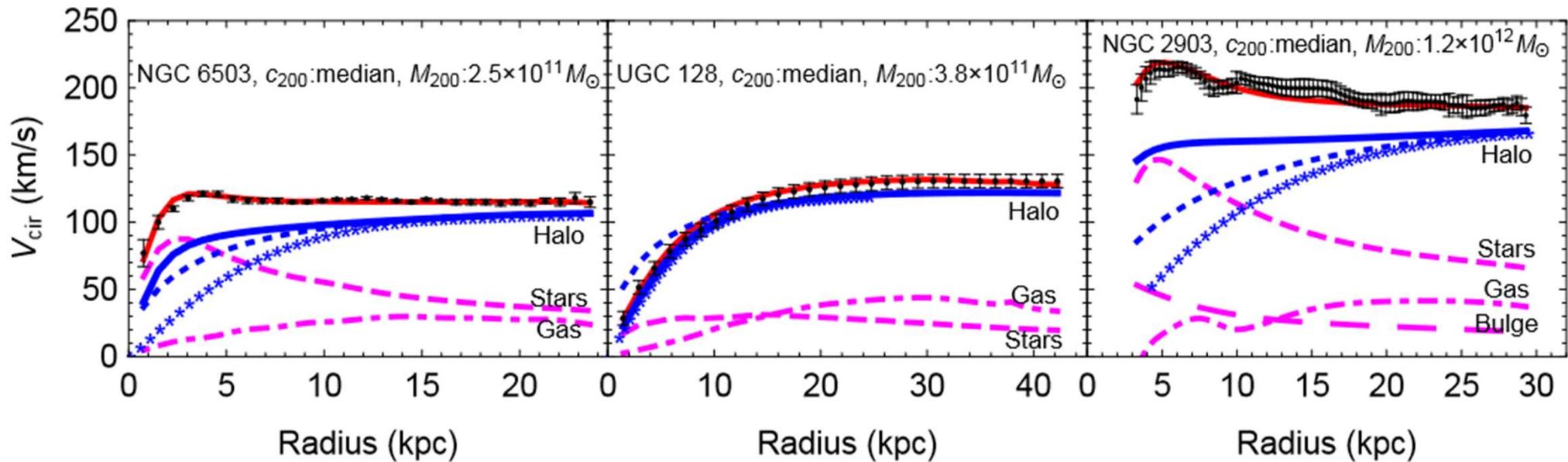
How SIDM explains the diverse rotation curves



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

→ without including the potential of stars
→ correct SIDM density profile

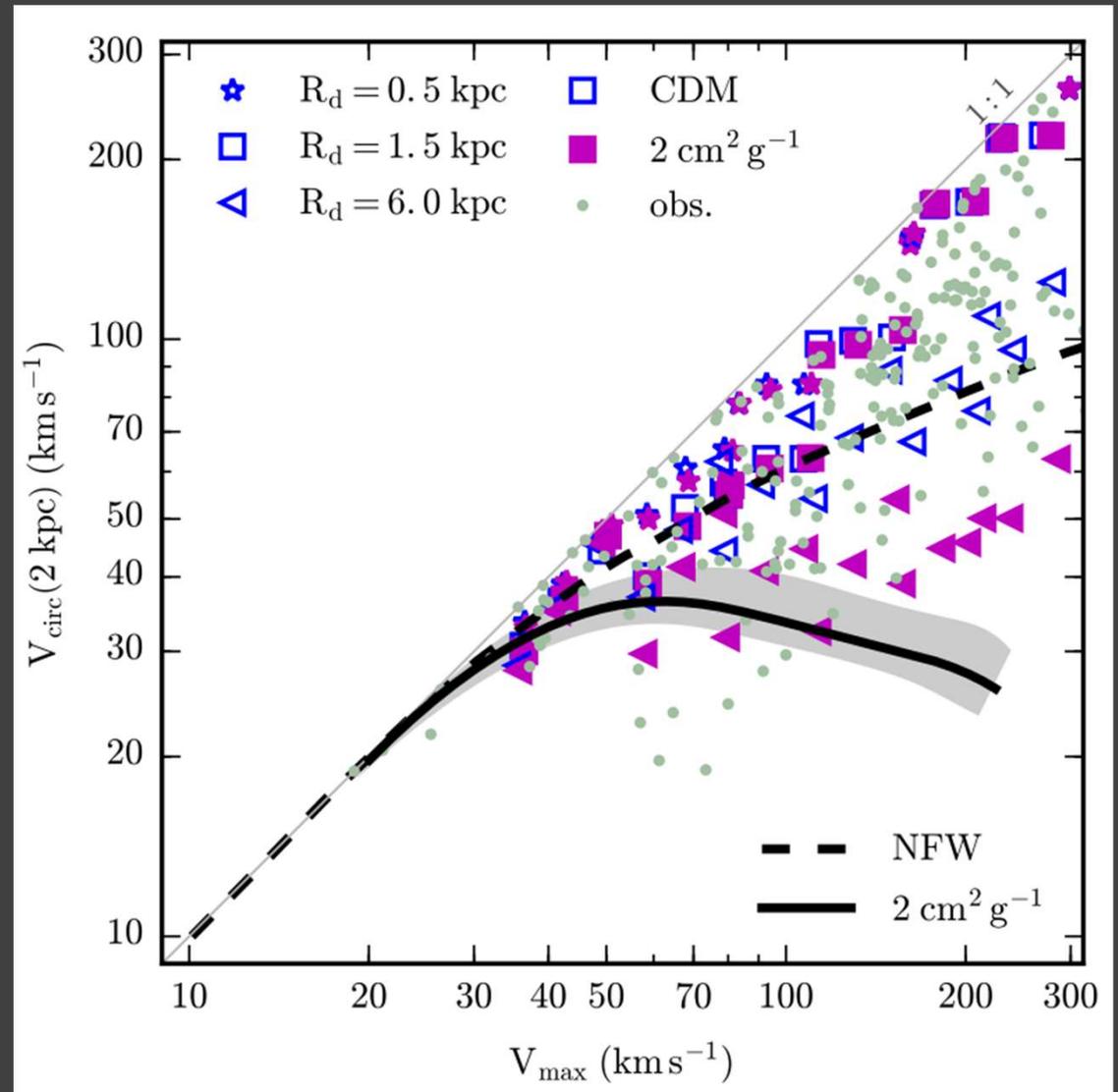
How SIDM explains the diverse rotation curves



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

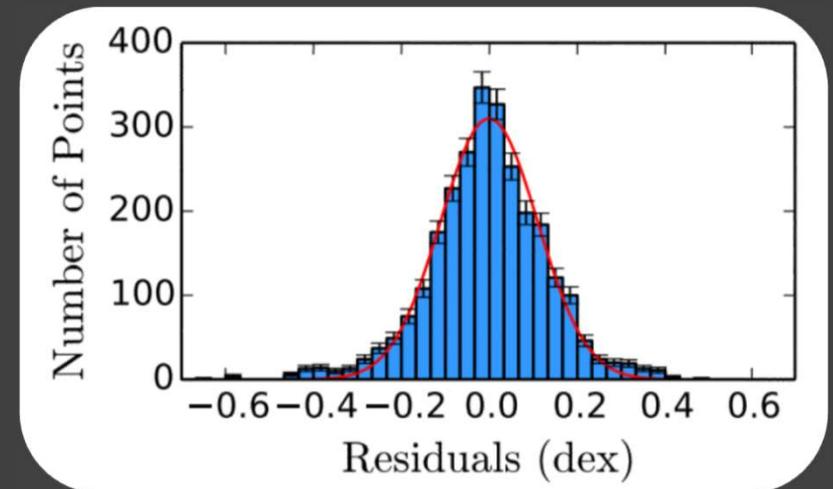
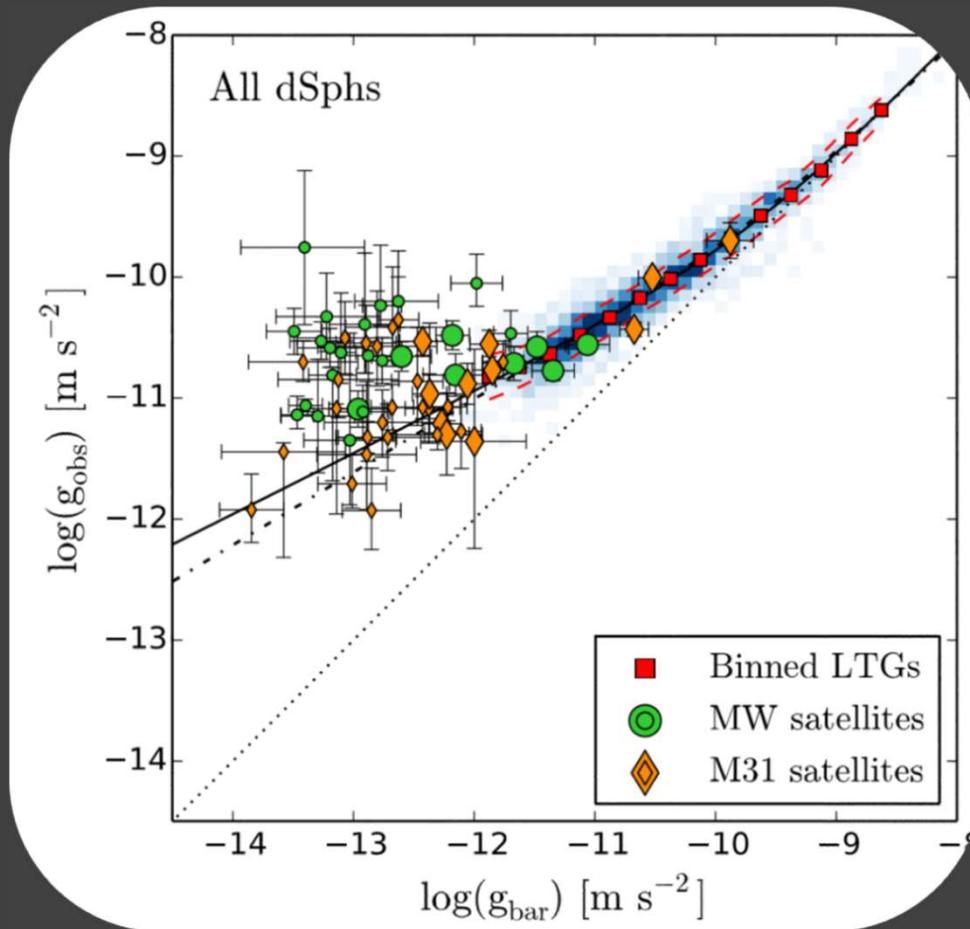
How SIDM explains the diverse rotation curves

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



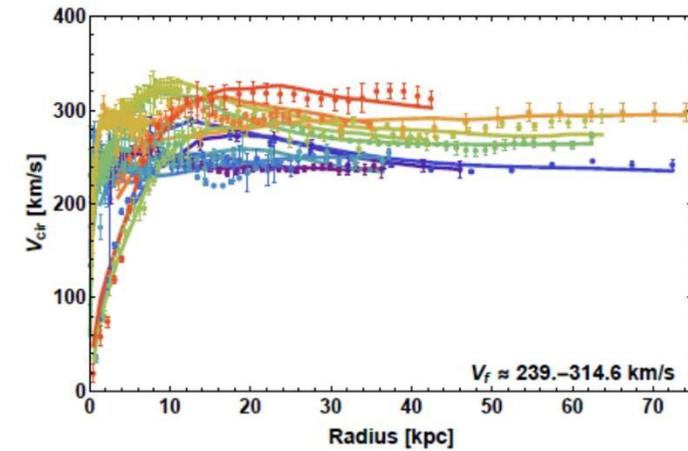
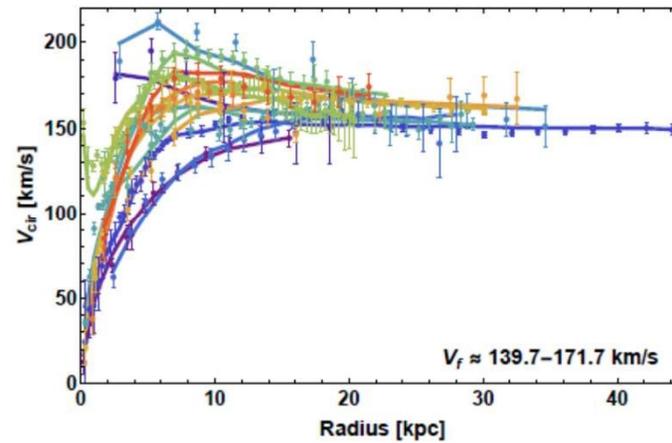
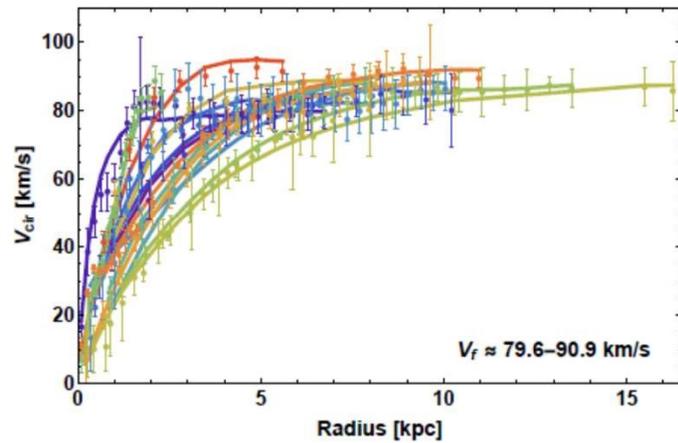
Uniformity in galactic rotation curves

The acceleration scale in galaxy formation



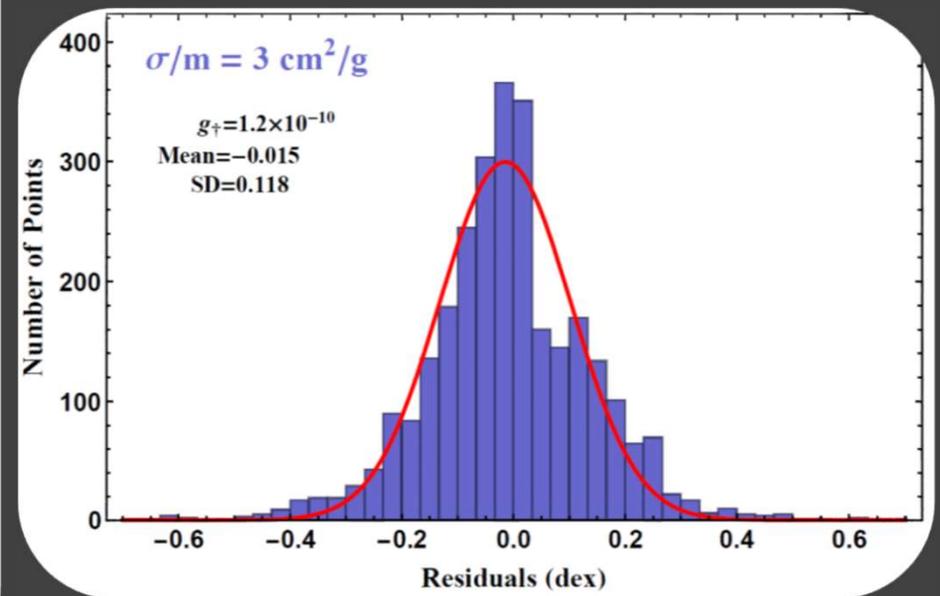
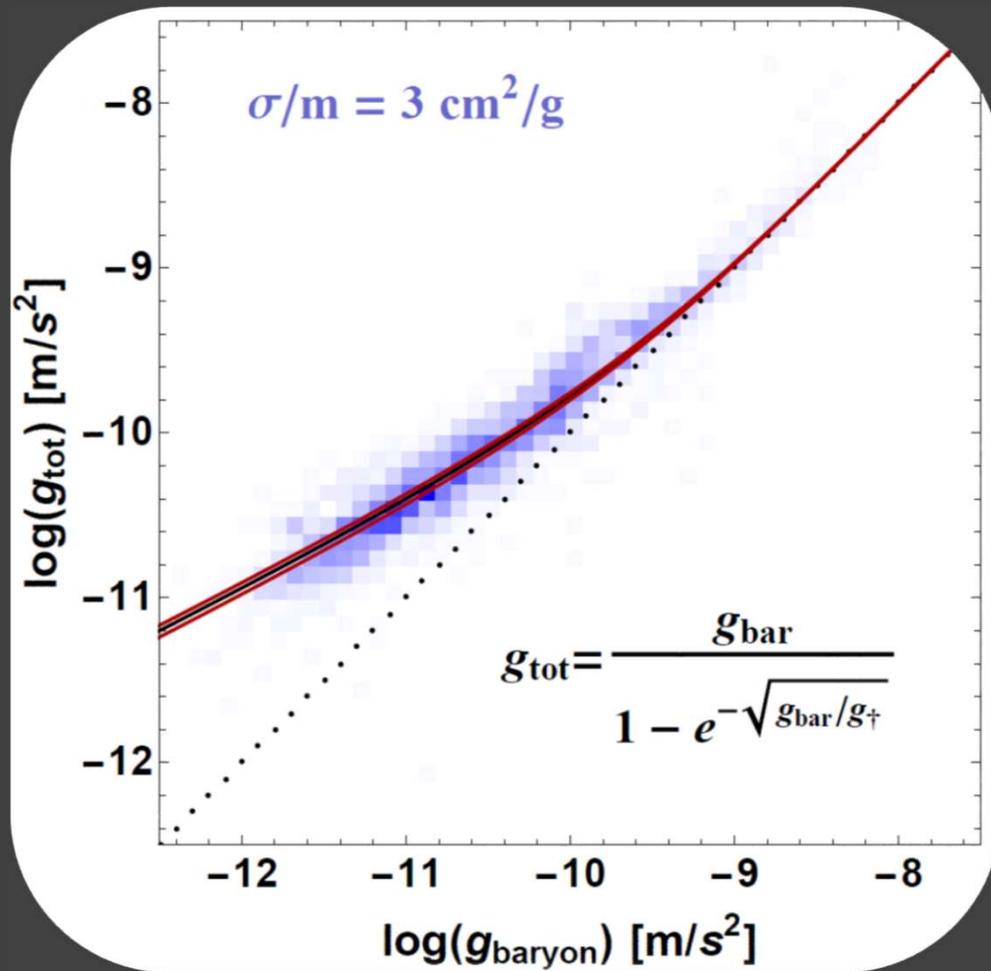
Lelli et al 2016

SIDM fits to the rotation curves in the SPARC sample



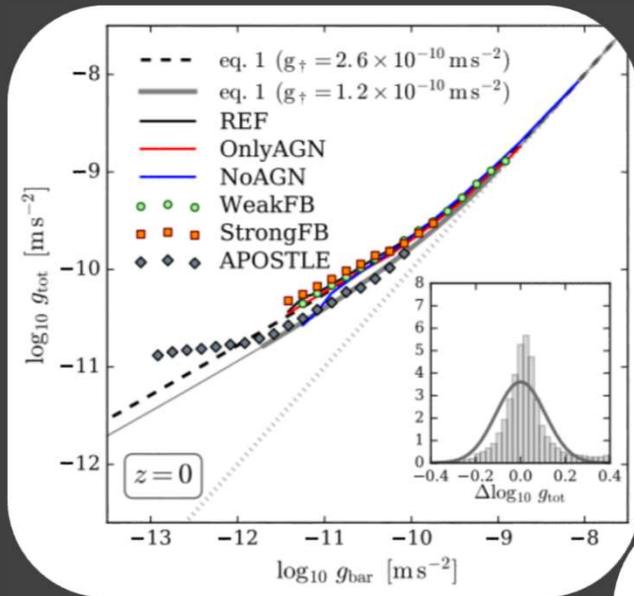
With Anna Kwa, Tao Ren and Hai-Bo Yu (in prep)

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

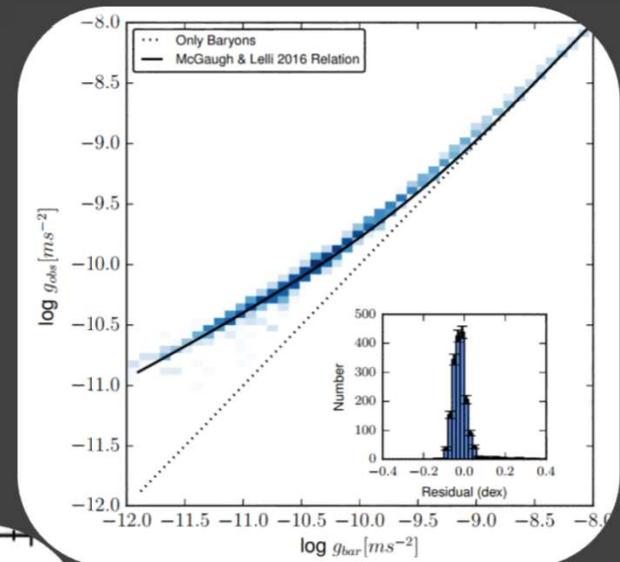


With Anna Kwa, Tao Ren and Hai-Bo Yu (in prep)

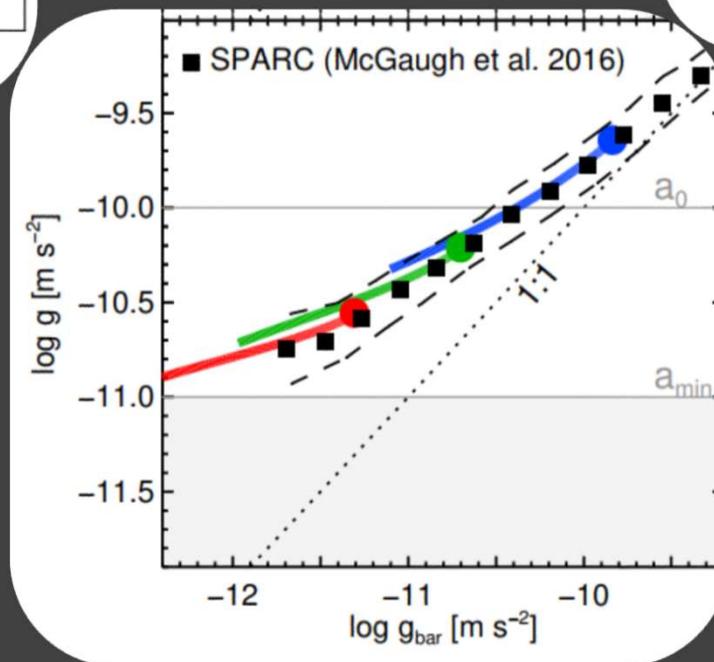
Acceleration-mass correlation in LCDM models



Ludlow et al, 2016



Keller and Wadsley, 2016



Navarro et al, 2016

Explanation for the acceleration scale in hierarchical structure formation models

$\sigma/m > \text{about } 1 \text{ cm}^2/\text{g}$

$r_{\text{core}} \sim O(1) r_s$

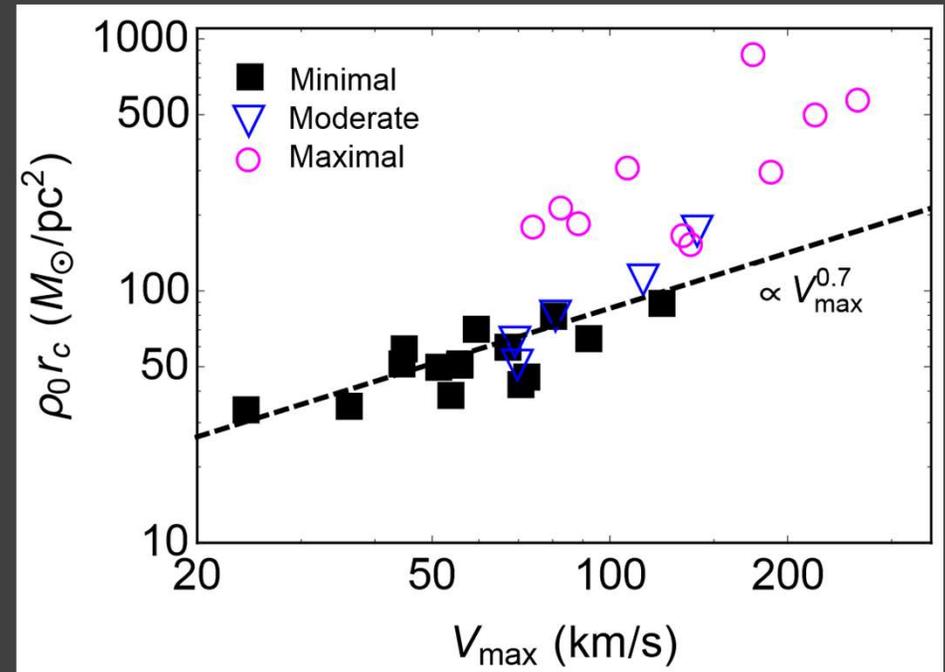
(No new scale in the problem)

Dimension analysis :

$$a = 2 V_{\text{max}}^2 / R_{\text{max}} \sim G \rho_{\text{core}} r_{\text{core}}$$
$$= 3 \times 10^{-11} \text{ m/s}^2 (V_{\text{max}}/100 \text{ km/s})^{0.7}$$

(using a LCDM $V_{\text{max}} R_{\text{max}}$ relation)

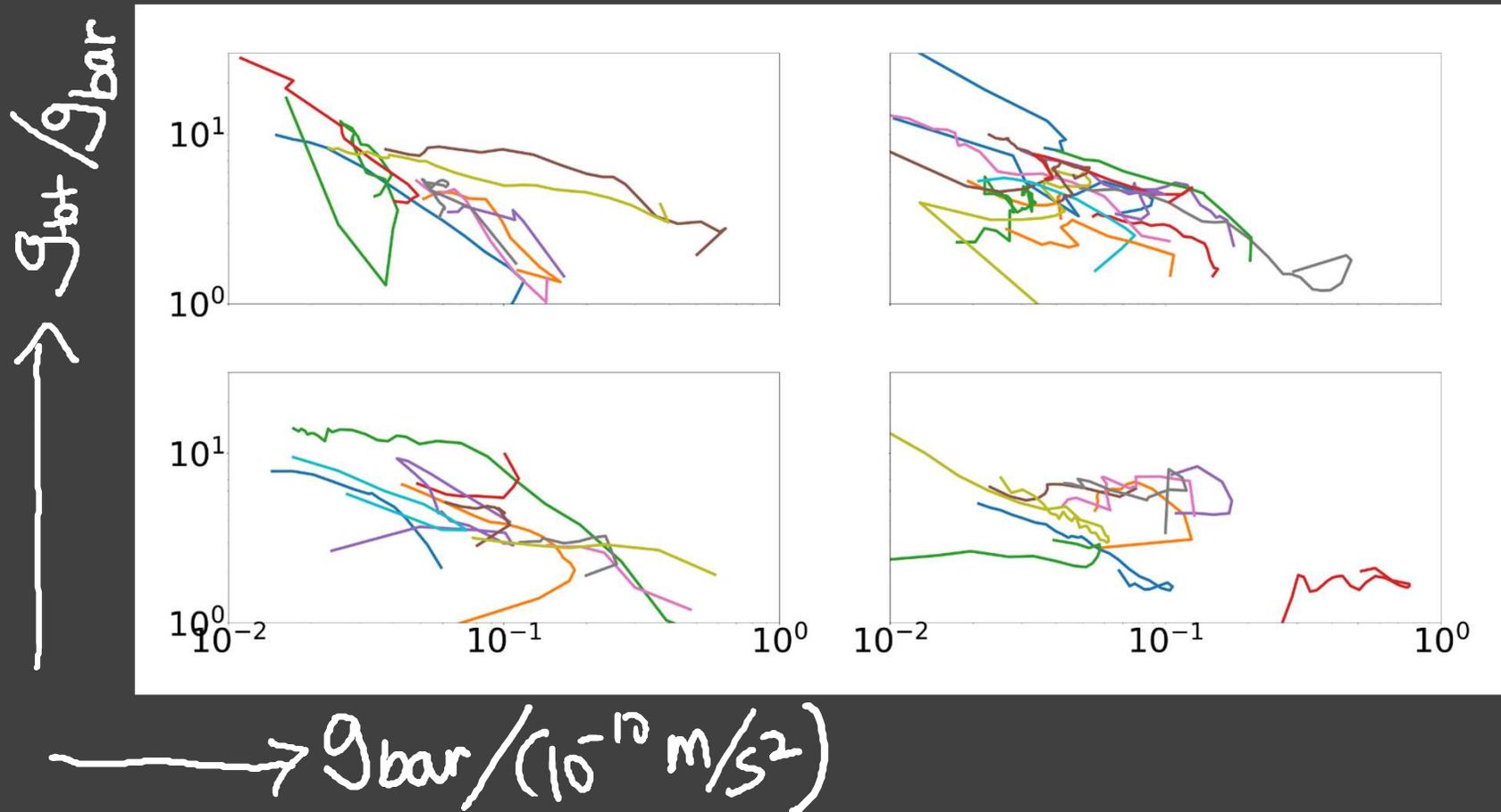
[See also Lin and Loeb (2016)]



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)]

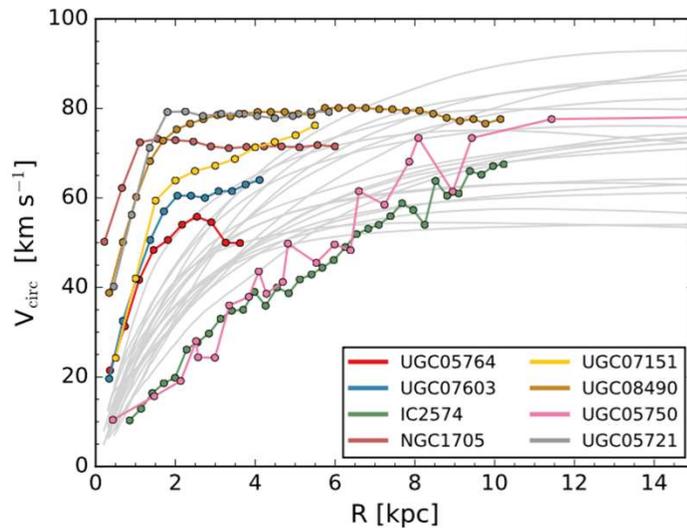
Discussion: one single relation for all galaxies?

$V_{\text{flat}} < 100$ 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.*



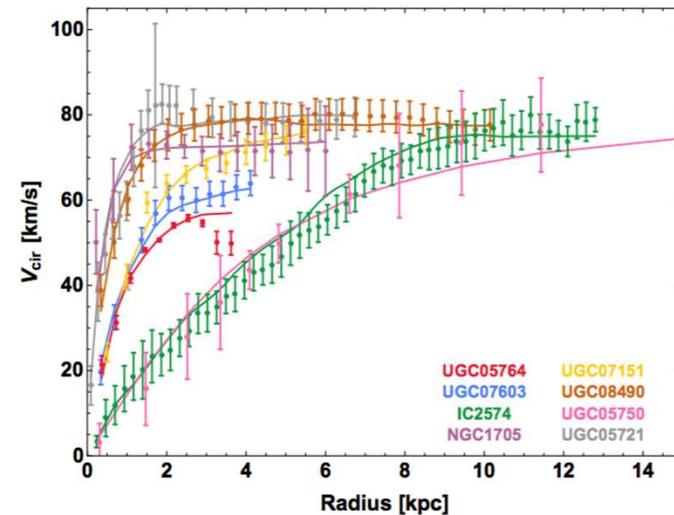
Discussion: could rotation curves distinguish LCDM and LSIDM?

Strong Feedback vs. SIDM



NIHAO simulations
strong feedback

Santos-Santos et al. (2017)



SIDM

with Kaplinghat, Kwa, Ren (in prep)

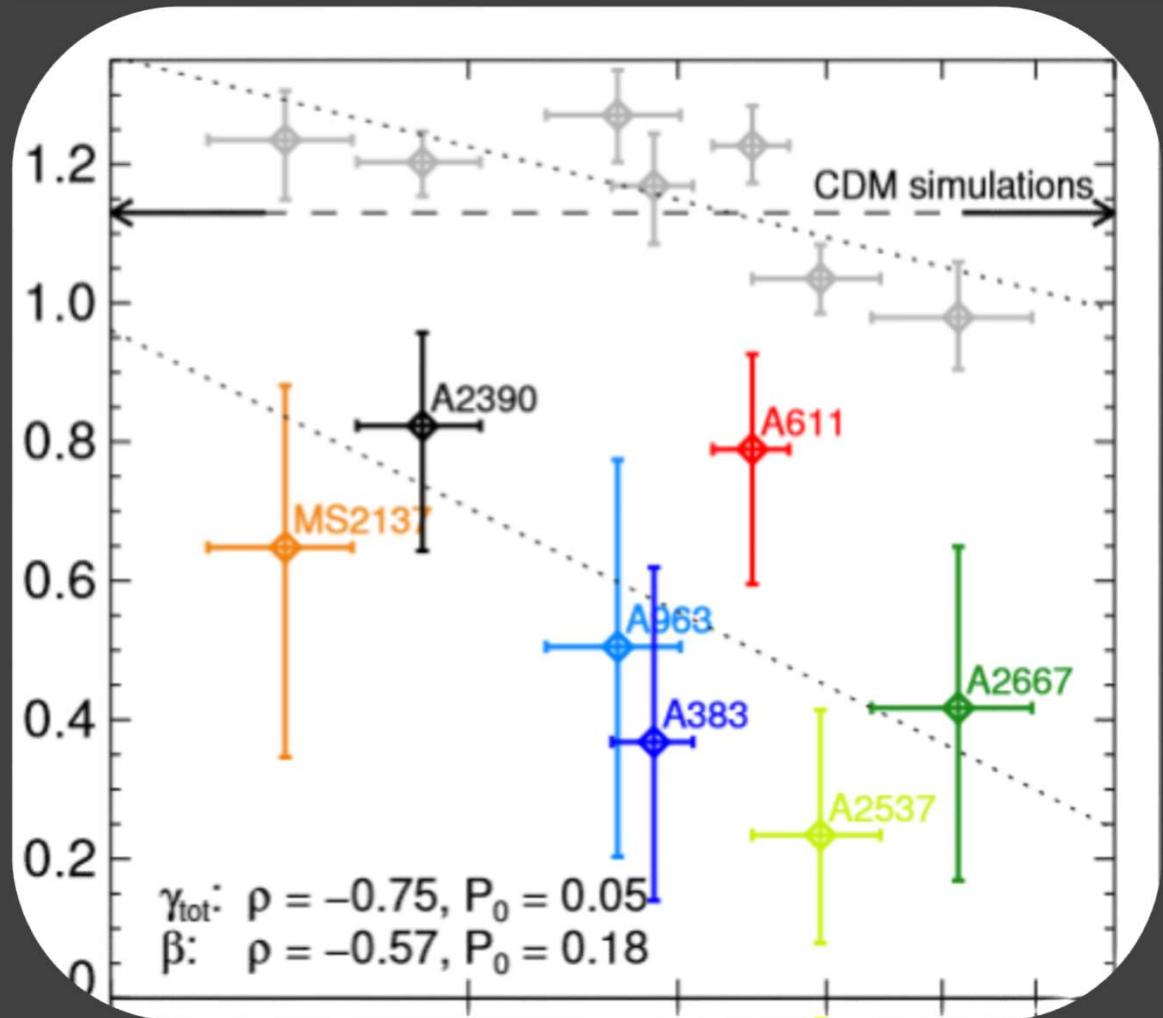
Slide from Hai-Bo Yu

Adding information from clusters of galaxies: SIDM particle properties

Cores in clusters of galaxies

weak lensing
strong lensing
stellar kinematics

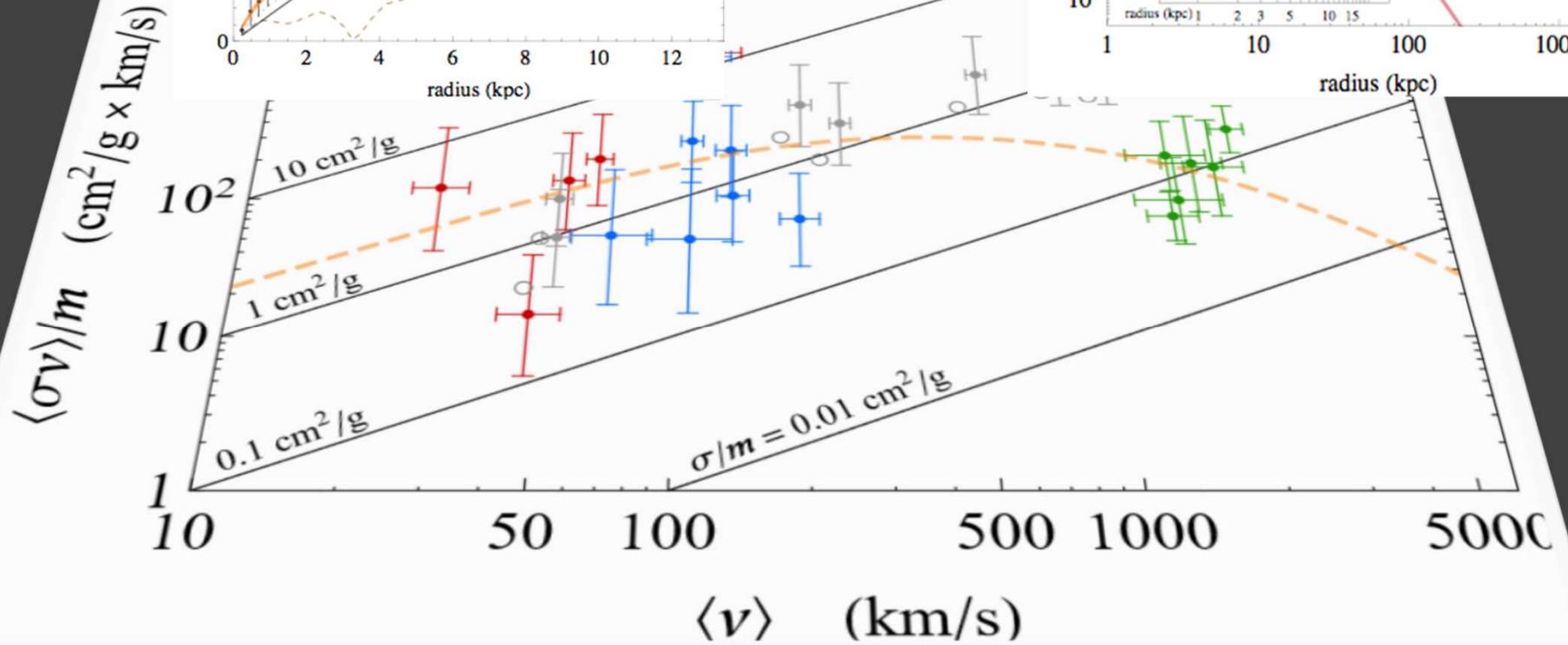
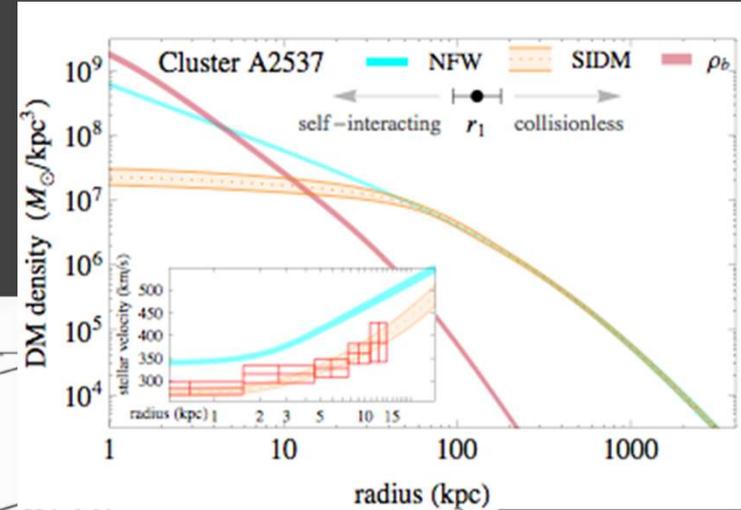
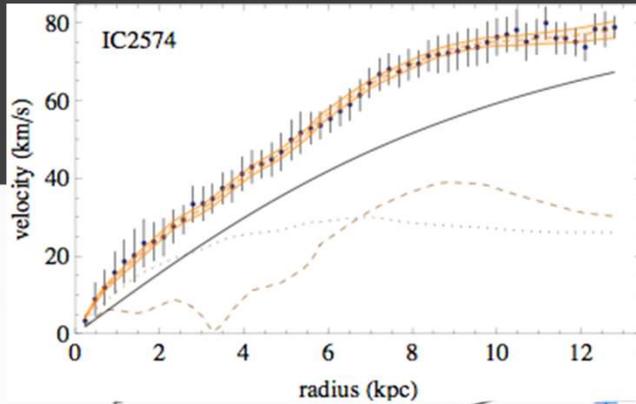
-(Slope of density profile)



Stellar extent

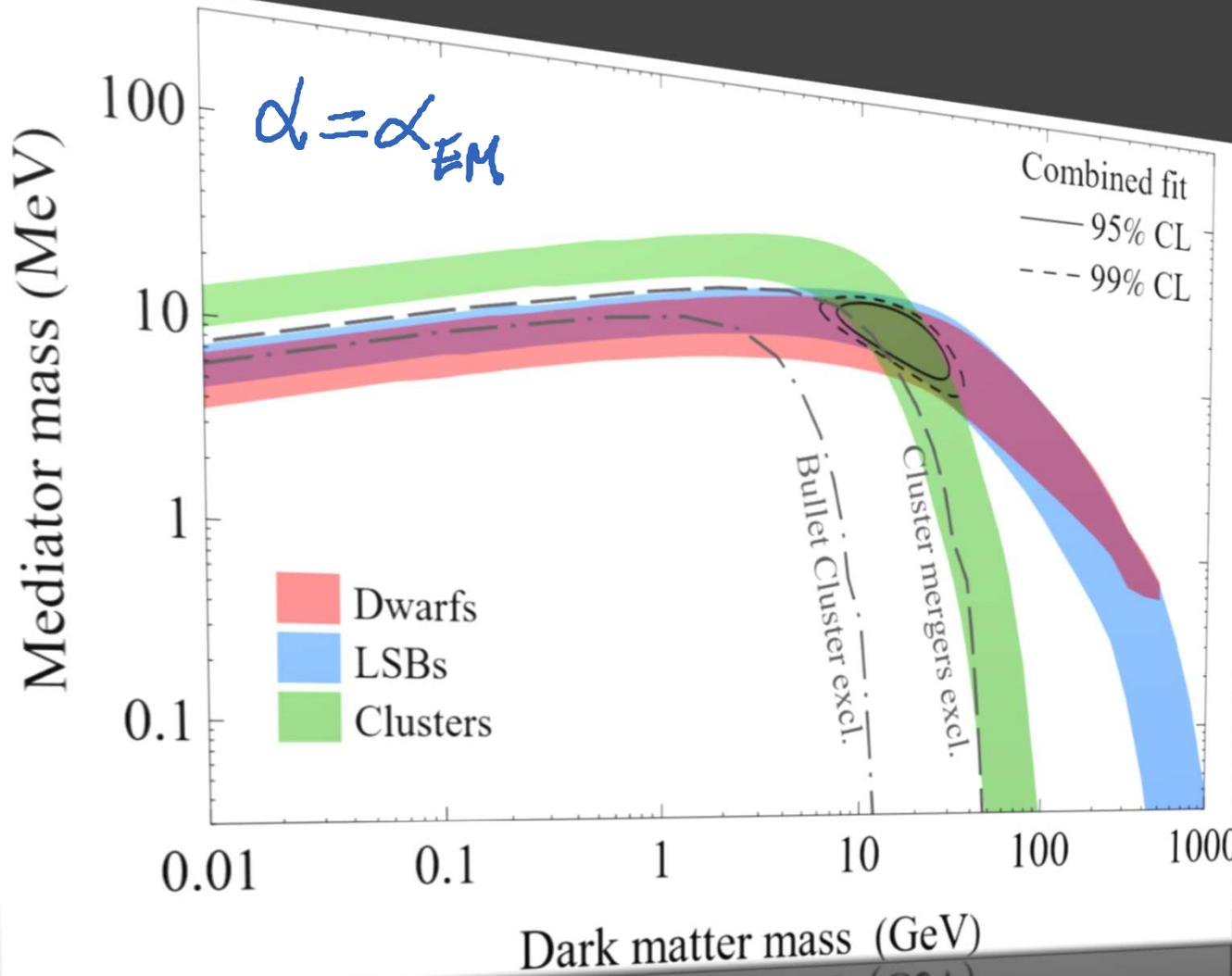
Newman et al 2012

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



With Sean Tulin and Hai-Bo Yu (2015)

SIDM particle properties: Yukawa interaction



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

Tulin, Yu, Zurek 2012

Non-abelian sector
 Boddy et al (2014)

With Sean Tulin and Hai-Bo Yu (2015)

Direct search constraints are strong

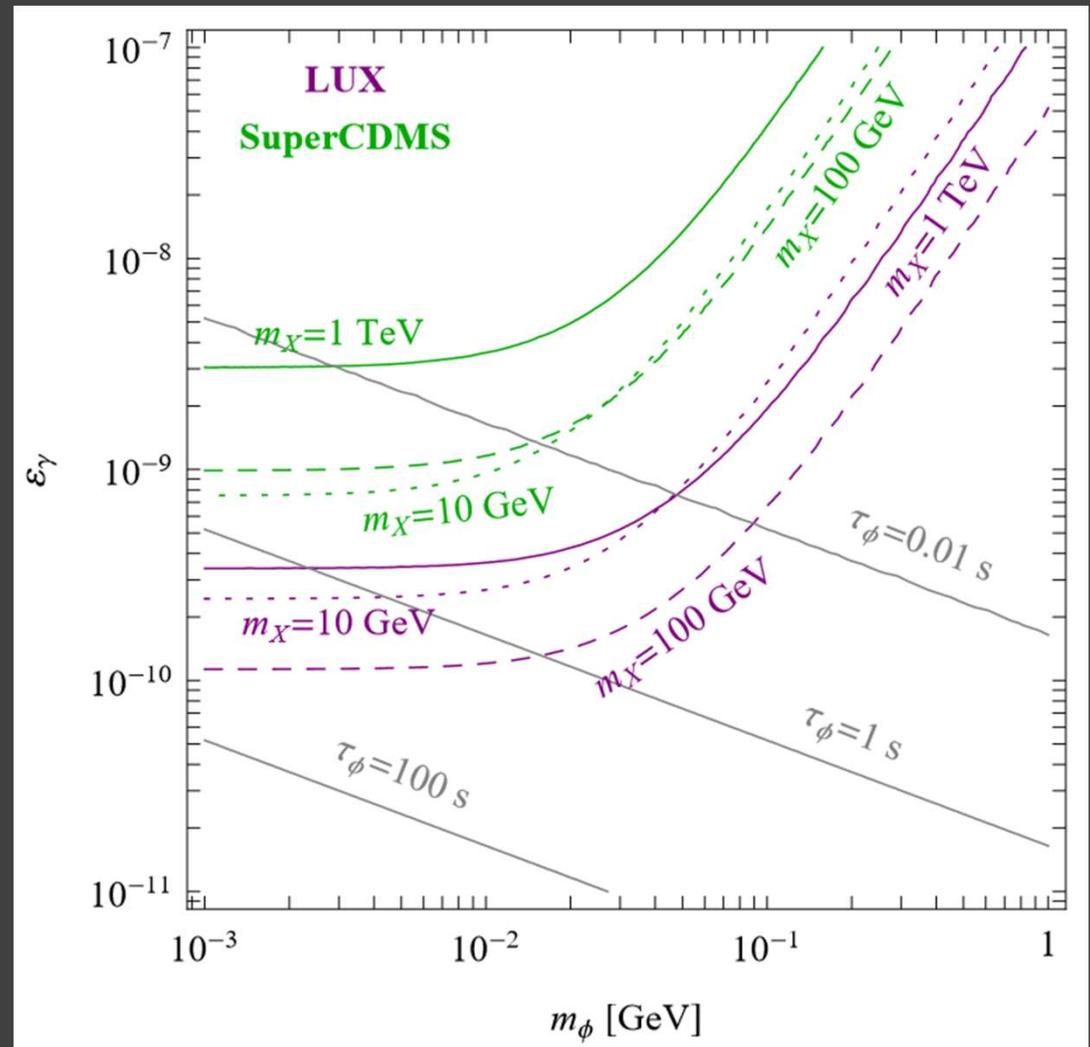
ϕ must decay!

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

↪ Direct Searches ↪

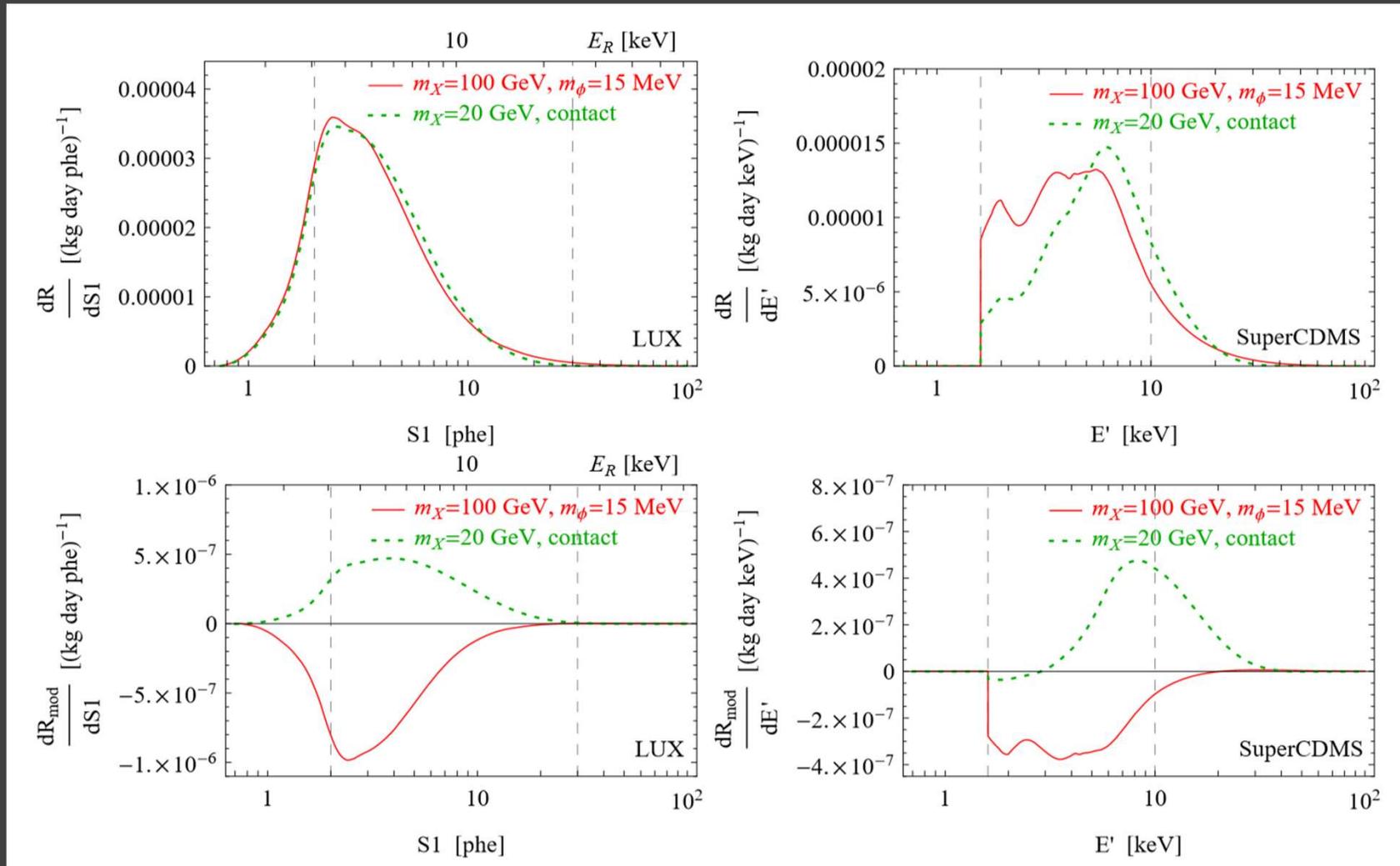
Momentum dependent scattering

Tulin, Yu and Kaplinghat (2013)



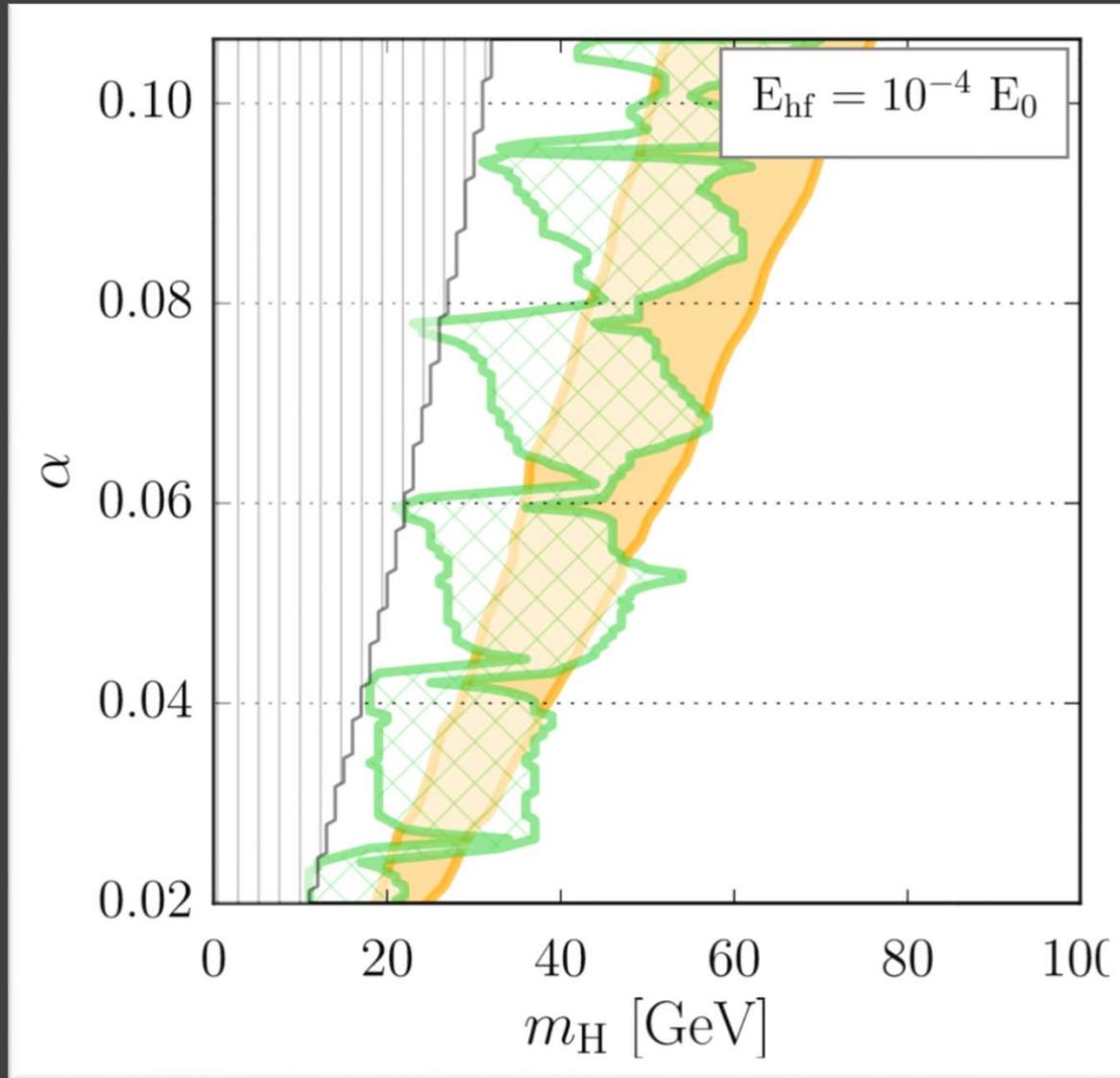
With Eugenio Del Nobile and Hai-Bo Yu (2015)

Different experiments will have different recoil and modulation spectra!



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

SIDM particle properties: Dark Hydrogen

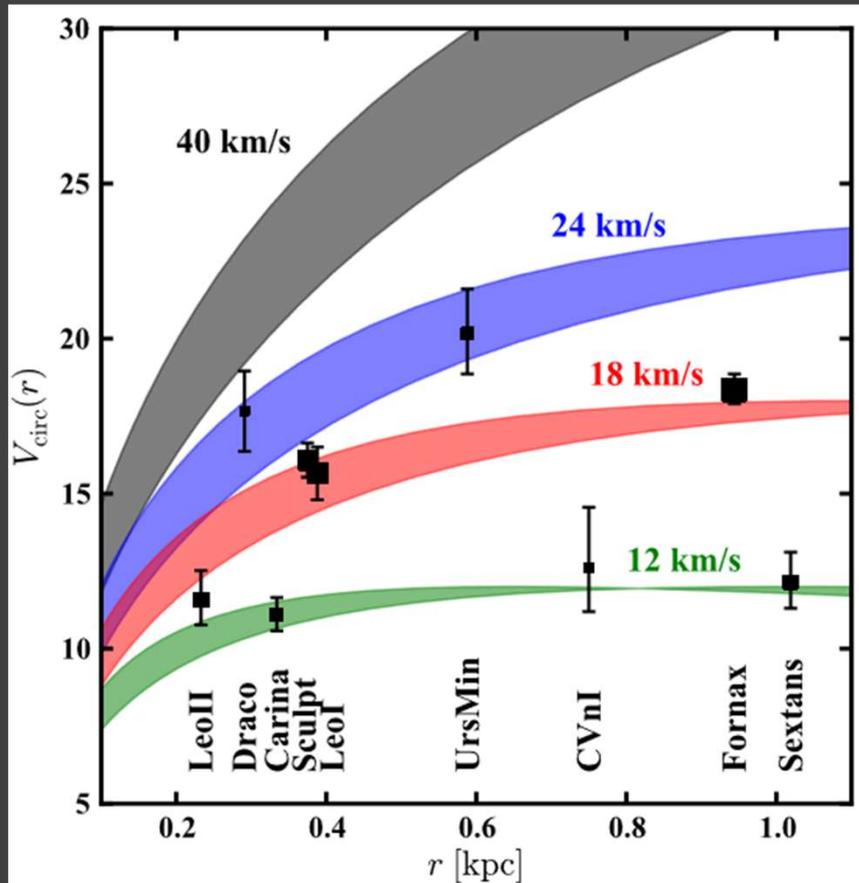


Inelastic collisions are important!

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

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

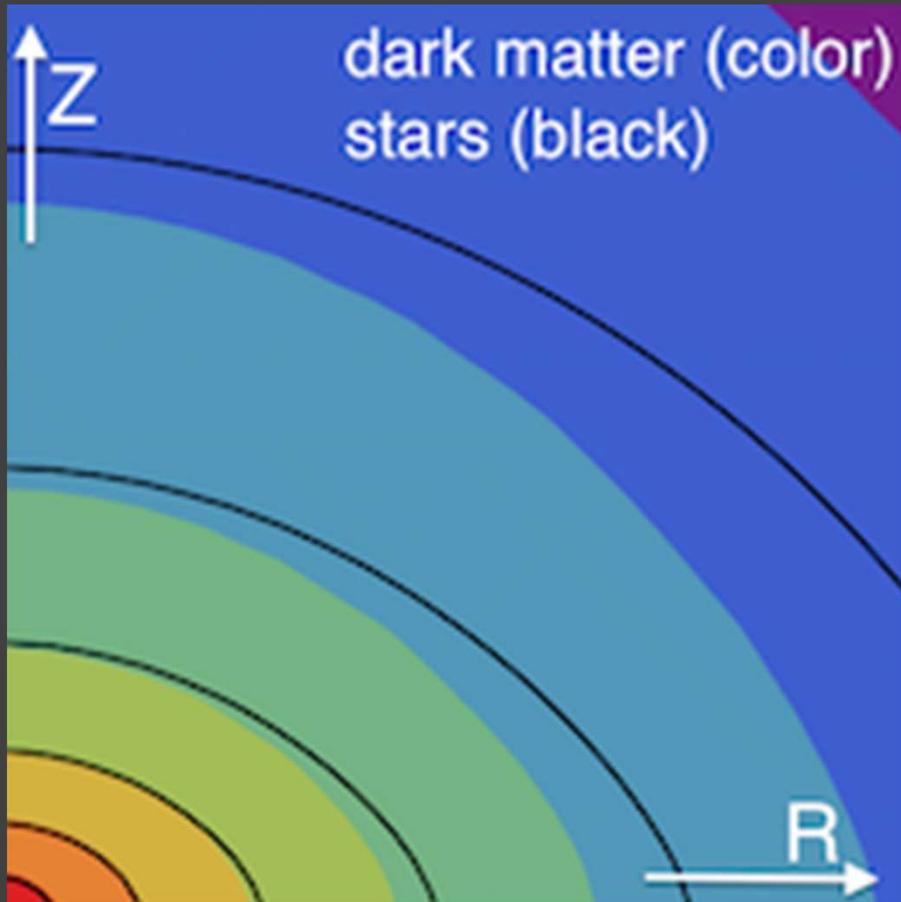
Model independent tests of the SIDM paradigm



SIDM predicts cores in satellite galaxies.

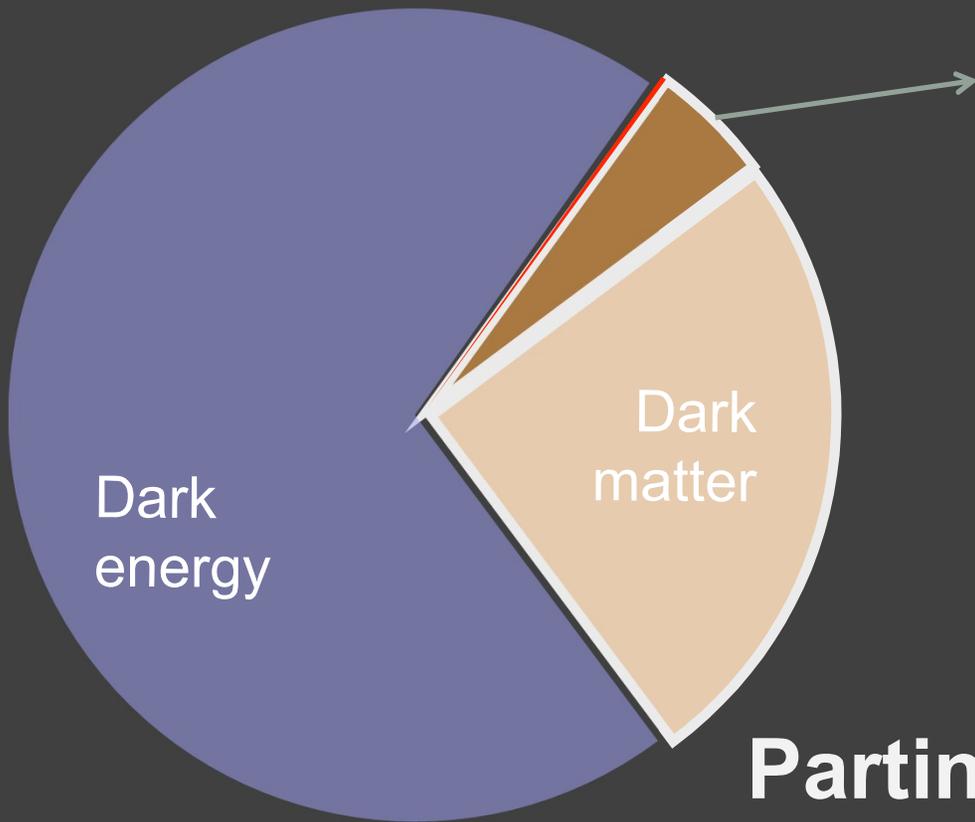
Multiple population chemodynamics in the MW satellites. [Walker and Penarrubia]

Model independent tests of the SIDM paradigm



SIDM tracks the stellar potential where stars dominate.

Strong lenses and elliptical galaxies in X-rays.



Periodic Table of the Elements

1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.93	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.73	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.09	35 Br Bromine 79.90	36 Kr Krypton 84.80
37 Rb Rubidium 84.49	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.20	83 Bi Bismuth 208.98	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.97	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97			
89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium [262]			

Legend: Alkali Metal, Alkaline Earth, Transition Metal, Basic Metal, Semimetal, Nonmetal, Halogen, Noble Gas, Lanthanide, Actinide

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