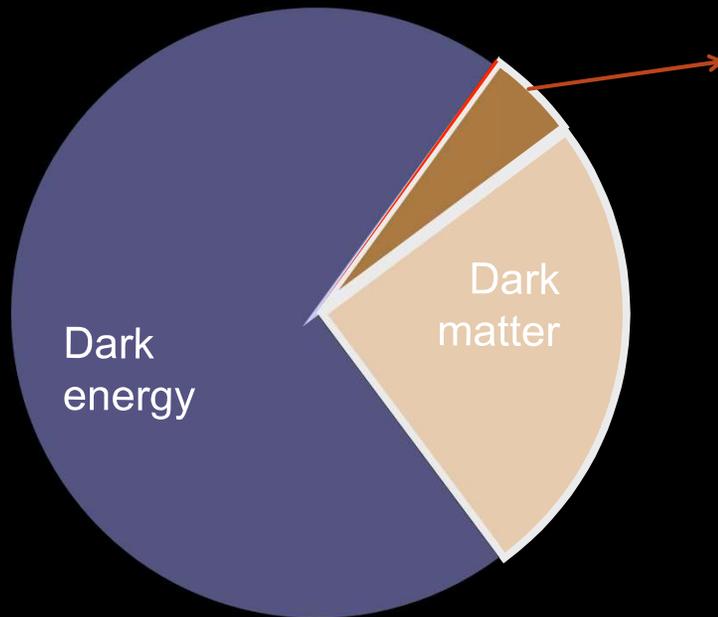


***Self-interacting  
dark matter (SIDM)***

Manoj Kaplinghat

The predictions of the  $\Lambda$ CDM model agree well with the observed large-scale structure of the Universe.



Periodic Table of the Elements

1																	18				
H Hydrogen 1.008																	He Helium 4.002				
2											10	11	12	13	14	15	16	17	18		
Li Lithium 6.941	Be Beryllium 9.012											B Boron 10.81	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180				
3	4											10	11	12	13	14	15	16	17	18	
Na Sodium 22.990	Mg Magnesium 24.305											Al Aluminum 26.982	Si Silicon 28.086	P Phosphorus 30.974	S Sulfur 32.06	Cl Chlorine 35.45	Ar Argon 39.948				
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38		
K Potassium 39.098	Ca Calcium 40.078	Sc Scandium 44.956	Ti Titanium 47.88	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.845	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.63	As Arsenic 74.922	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.80				
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56		
Rb Rubidium 85.468	Sr Strontium 87.62	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.94	Tc Technetium 98.906	Ru Ruthenium 101.07	Rh Rhodium 102.905	Pd Palladium 106.42	Ag Silver 107.868	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.757	Te Tellurium 127.6	I Iodine 126.905	Xe Xenon 131.29				
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88		
Cs Cesium 132.905	Ba Barium 137.327	Lanthanides					Hf Hafnium 178.49	Ta Tantalum 180.948	W Tungsten 183.85	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.222	Pt Platinum 195.084	Au Gold 196.967	Hg Mercury 200.59	Tl Thallium 204.384	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium 209	At Astatine 210	Rn Radon 222
87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120		
Fr Francium 223	Ra Radium 226	Actinides					Rf Rutherfordium 261	Db Dubnium 262	Sg Seaborgium 266	Bh Bohrium 264	Hs Hassium 265	Mt Meitnerium 268	Ds Darmstadtium 271	Rg Roentgenium 272	Cn Copernicium 285	Uut Ununtrium 288	Fl Flerovium 289	Uup Ununpentium 292	Lv Livermorium 293	Uus Ununseptium 294	Uuo Ununoctium 294
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108		
La Lanthanum 138.905	Ce Cerium 140.12	Pr Praseodymium 140.908	Nd Neodymium 144.24	Pm Promethium 144.913	Sm Samarium 150.36	Eu Europium 151.964	Gd Gadolinium 157.25	Tb Terbium 158.925	Dy Dysprosium 162.50	Ho Holmium 164.930	Er Erbium 167.259	Tm Thulium 168.934	Yb Ytterbium 173.054	Lu Lutetium 174.967							
99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118		
Ac Actinium 227	Th Thorium 232.038	Pa Protactinium 231.036	U Uranium 238.029	Np Neptunium 237.048	Pu Plutonium 244.064	Am Americium 243.061	Cm Curium 247.07	Bk Berkelium 247.07	Cf Californium 251.08	Es Einsteinium 252.083	Fm Fermium 257.10	Md Mendelevium 258.10	No Nobelium 259.10	Lr Lawrencium 262							

Alkali Metal Alkaline Earth Transition Metal Lanthanide Actinide Halogen Noble Gas

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

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

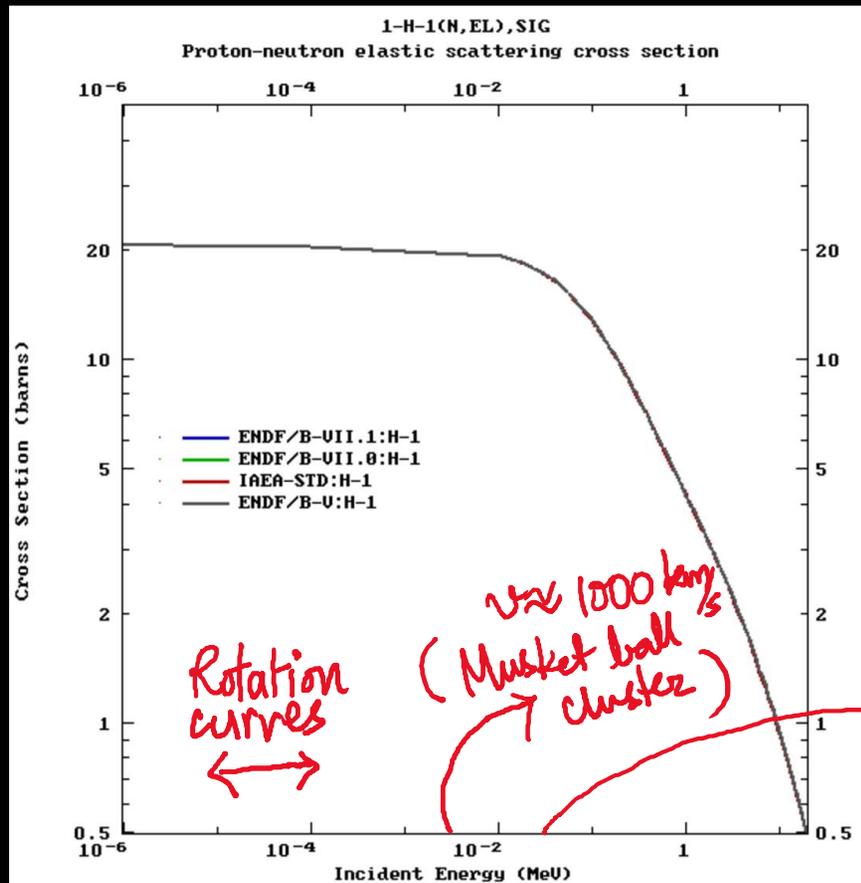
(in galaxies)

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  $v \sim 1000$  km/s.

# A motivating Standard Model example

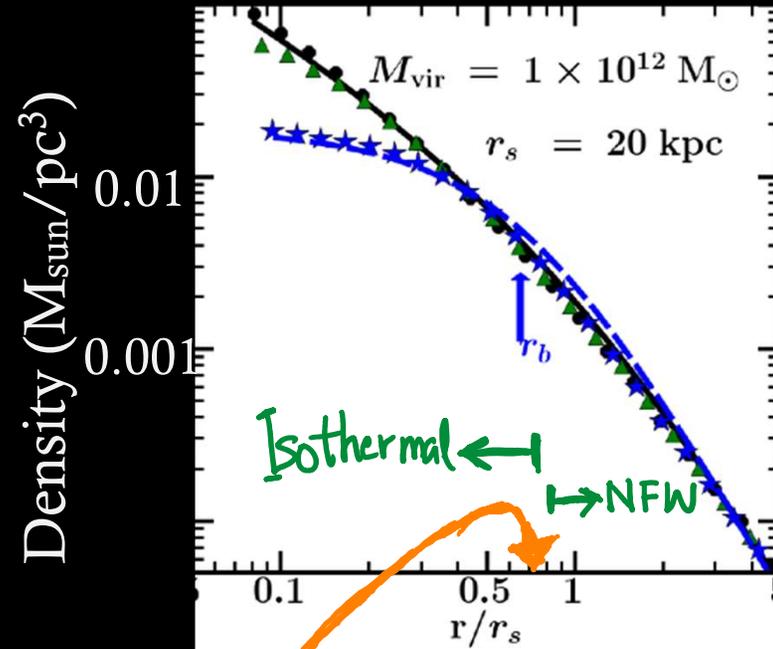
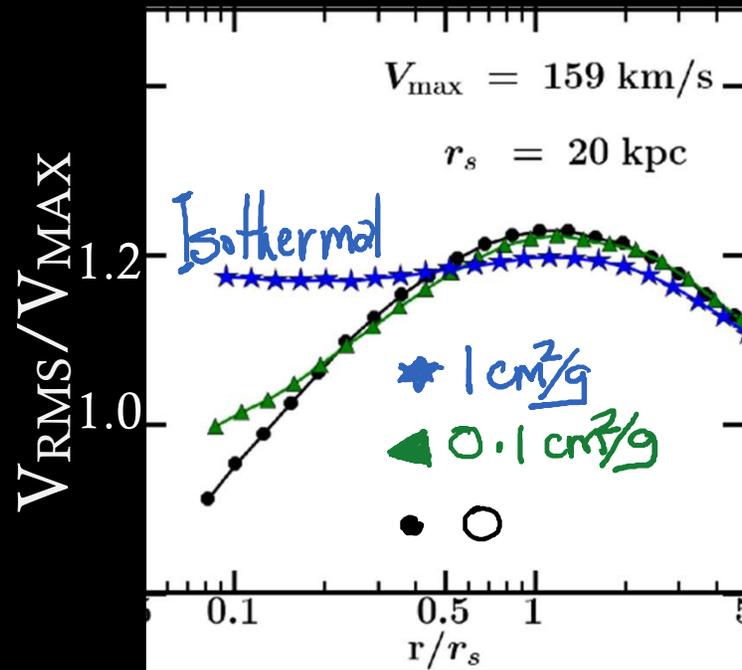


For velocity dependence, you need two scales, or one extra parameter in addition to the mass of the dark matter particle.

**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



$r_b$ : one interaction on average over age of halo

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

# SIDM halo profile for field galaxies

Inside  $r_1$ ,  $\rho_{\text{SIDM}}(r) = \rho_0 e^{-\Phi(r)/kT}$

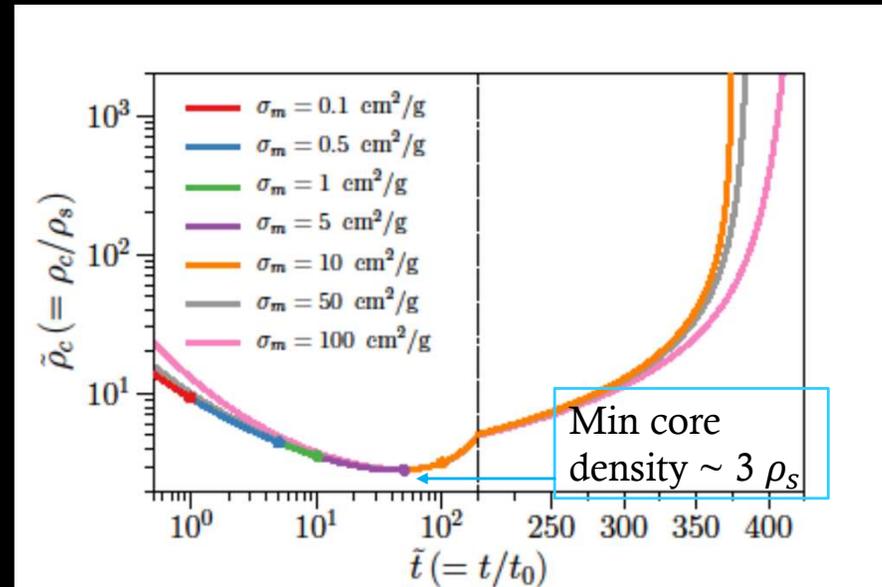
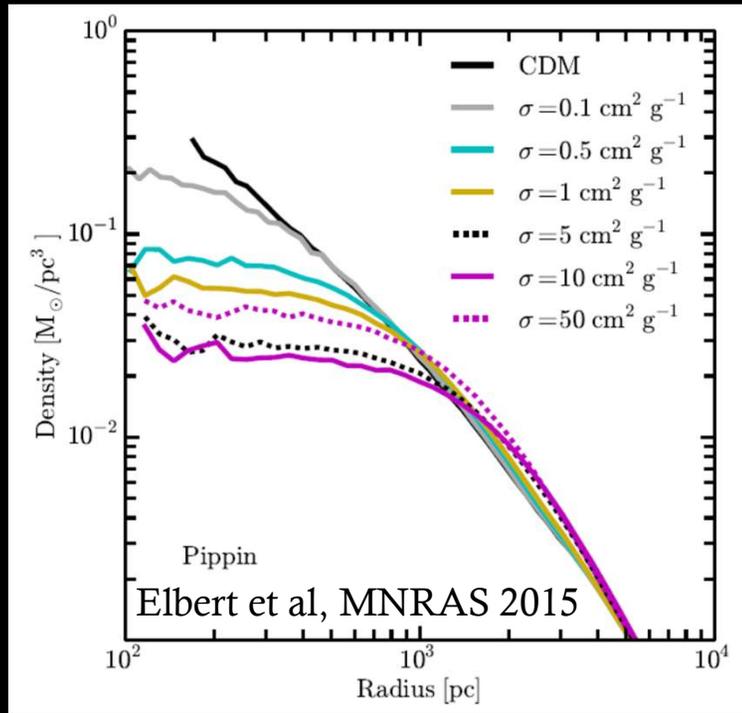
gravitational potential  
of dark matter and baryons

Outside  $r_1$ ,  $\rho_{\text{SIDM}} = \rho_{\text{CDM}}$

Match mass and density at  $r_1$   
to fix  $\rho_0$  and  $T$  in terms of  
CDM (NFW) halo  
parameters  $V_{\text{max}}$  and  $R_{\text{max}}$ .

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)

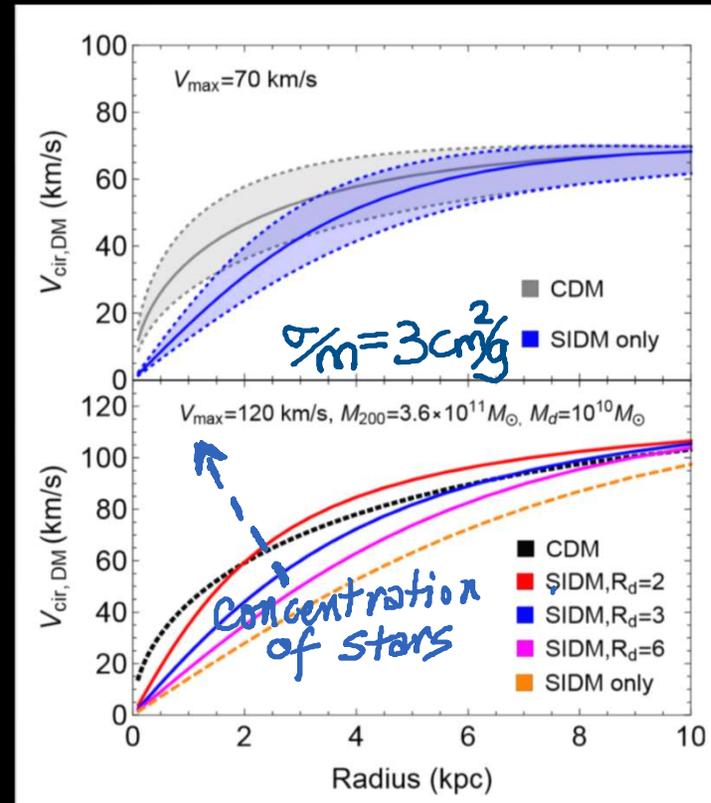
$$t_0 \propto \left( \rho_s v_{\text{max}} \frac{\sigma}{m} \right)^{-1}$$

# Rotation curves of field galaxies

# SIDM does not predict large cores in all galaxies

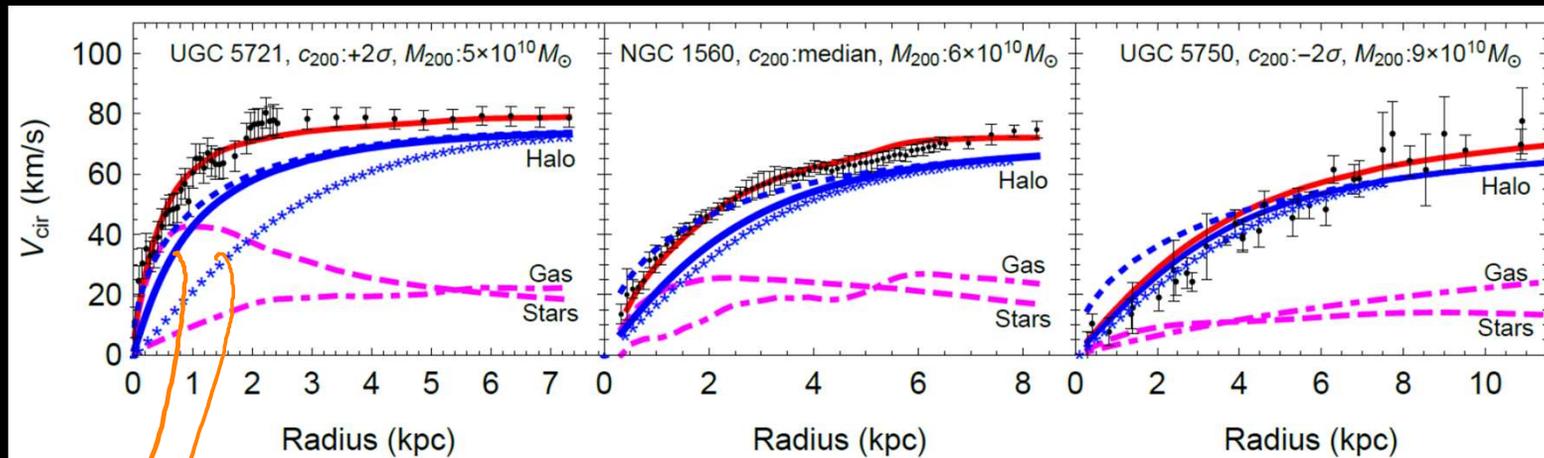
As stellar (and gas) density increases, cores become hard to discern (i.e., cuspy).

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

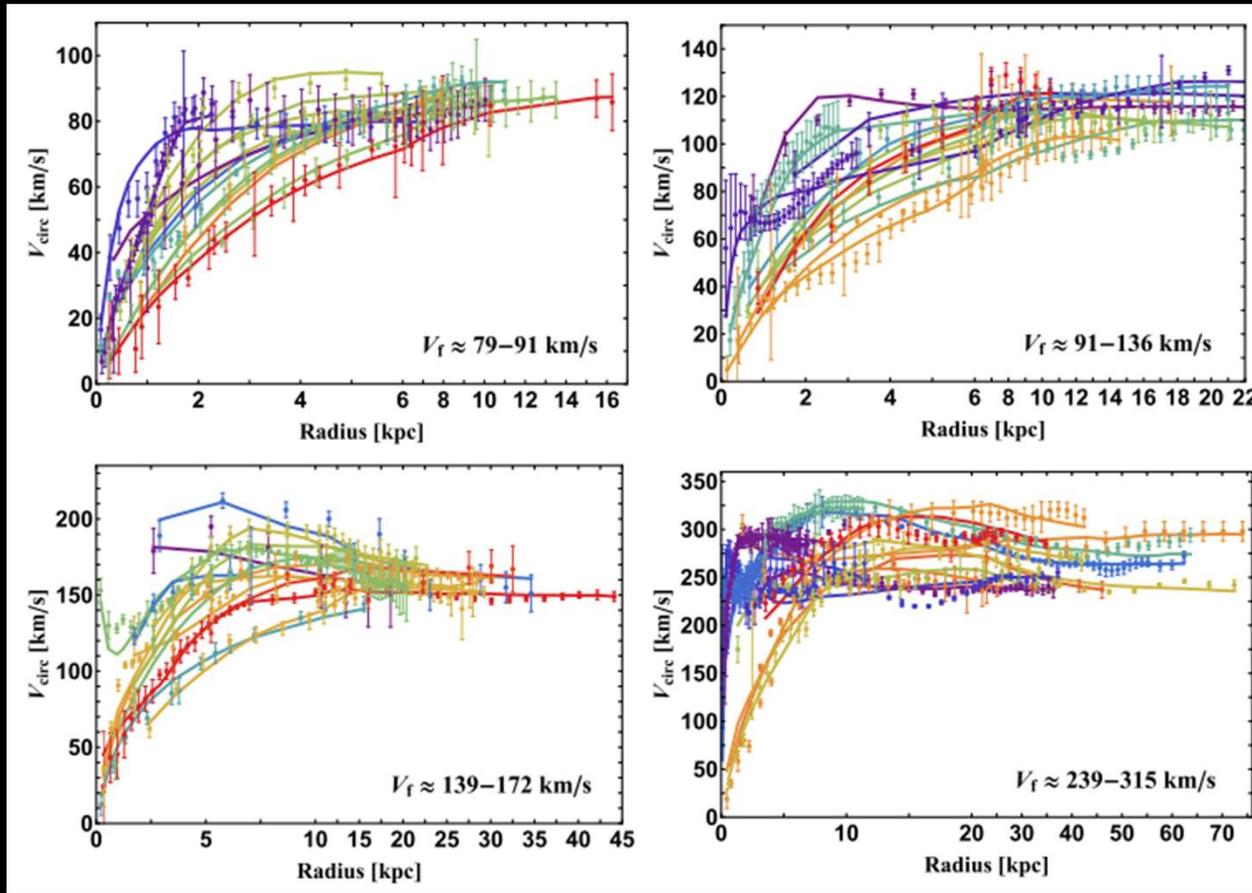
# How SIDM explains the diverse rotation curves



Without including the potential of stars  
correct SIDM density profile

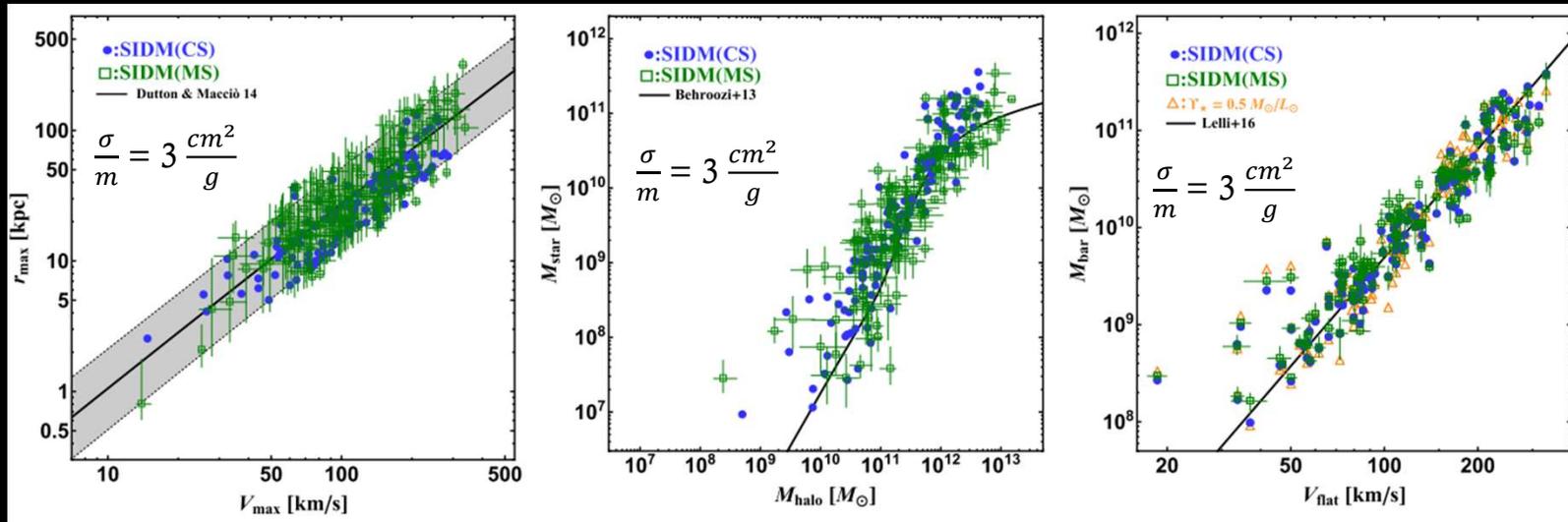
With Ayuki Kamada, Andrew Pace and Hai-Bo Yu, PRL 2017

# 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

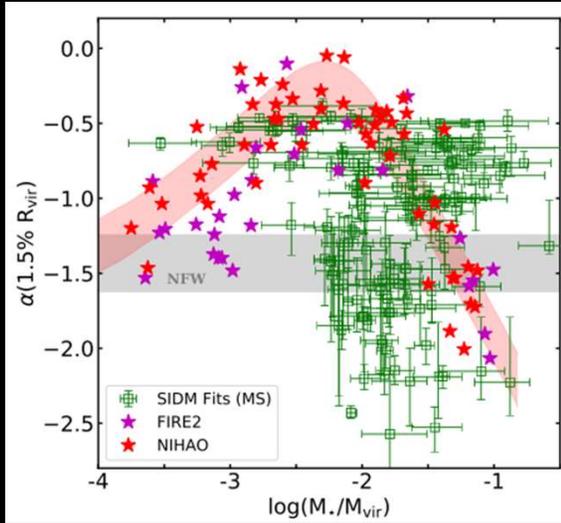
Baryonic Tully-Fisher

Free parameters per galaxy are  $M/L$  and two parameters to specify the halo ( $V_{\text{max}}$ ,  $R_{\text{max}}$ ) – same as CDM model.

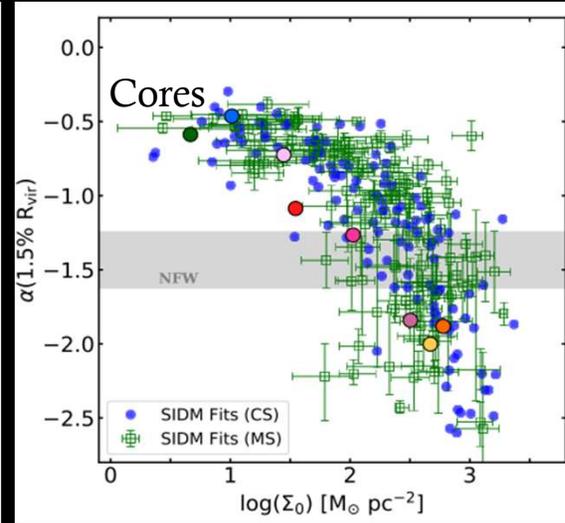
With Tao Ren, Anna Kwa and Hai-Bo Yu (2019)

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

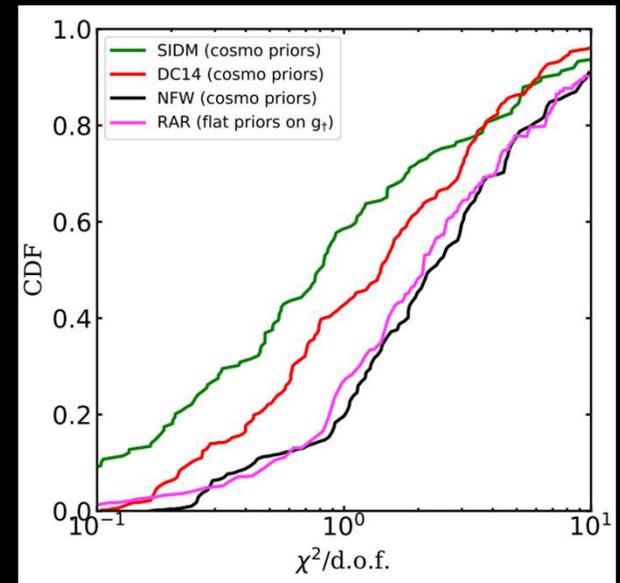
Slope at 1.5% of  $R_{vir}$



Stellar mass

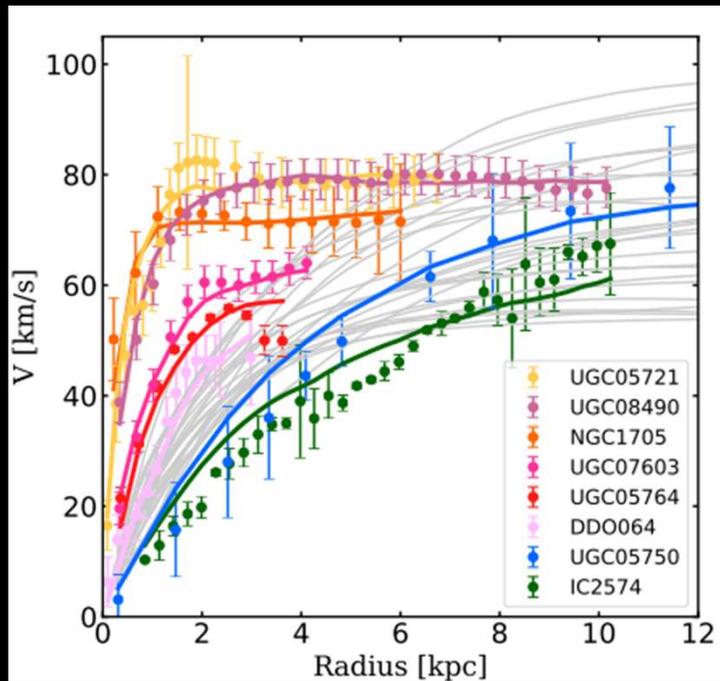


Stellar surface density



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

# Why current CDM models don't work



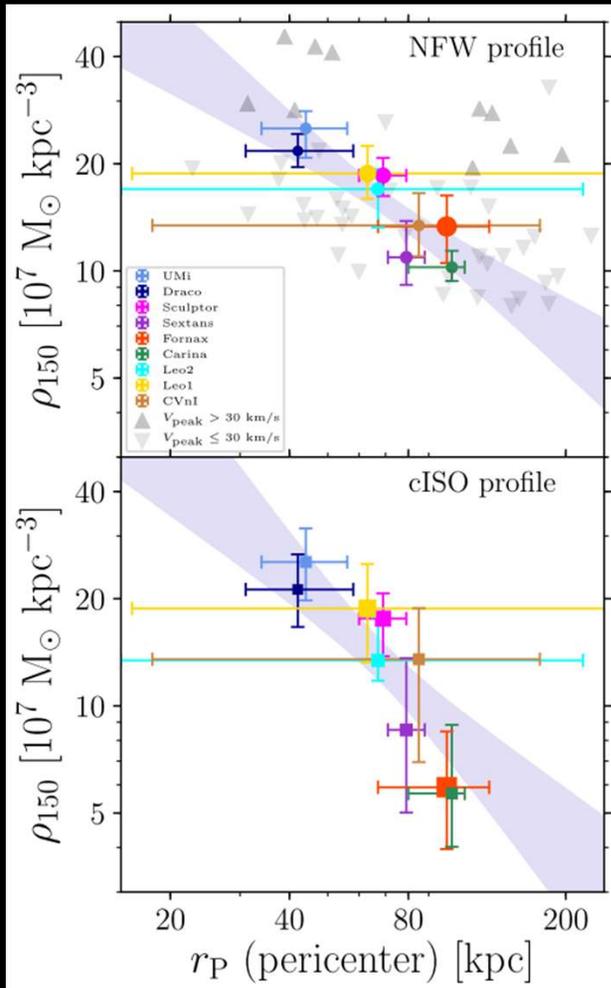
Grey curves from the NIHAO simulations.

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**

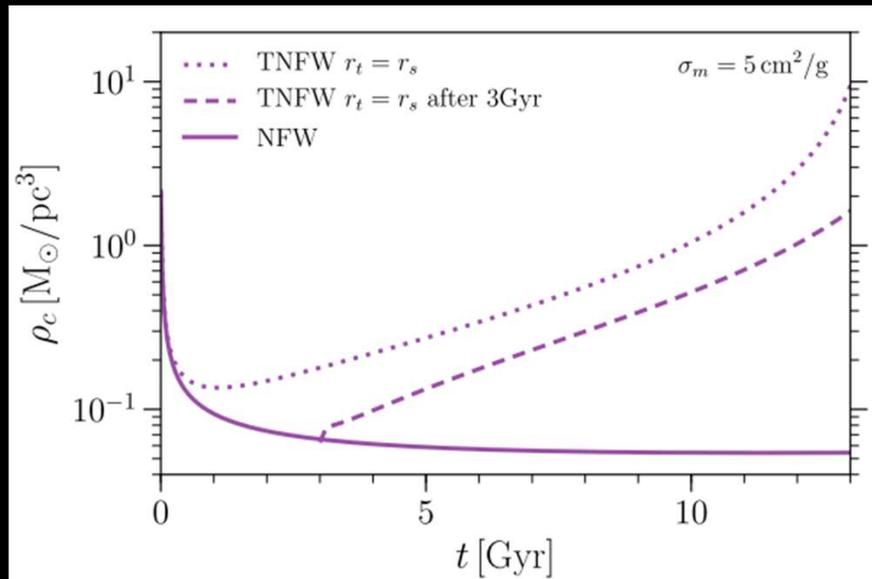
## The too-big-to-fail problem in light of GAIA data



Hard to see how this comes about in CDM simulations.

With Valli and Yu (2019)

## Accelerated evolution of SIDM subhalos!



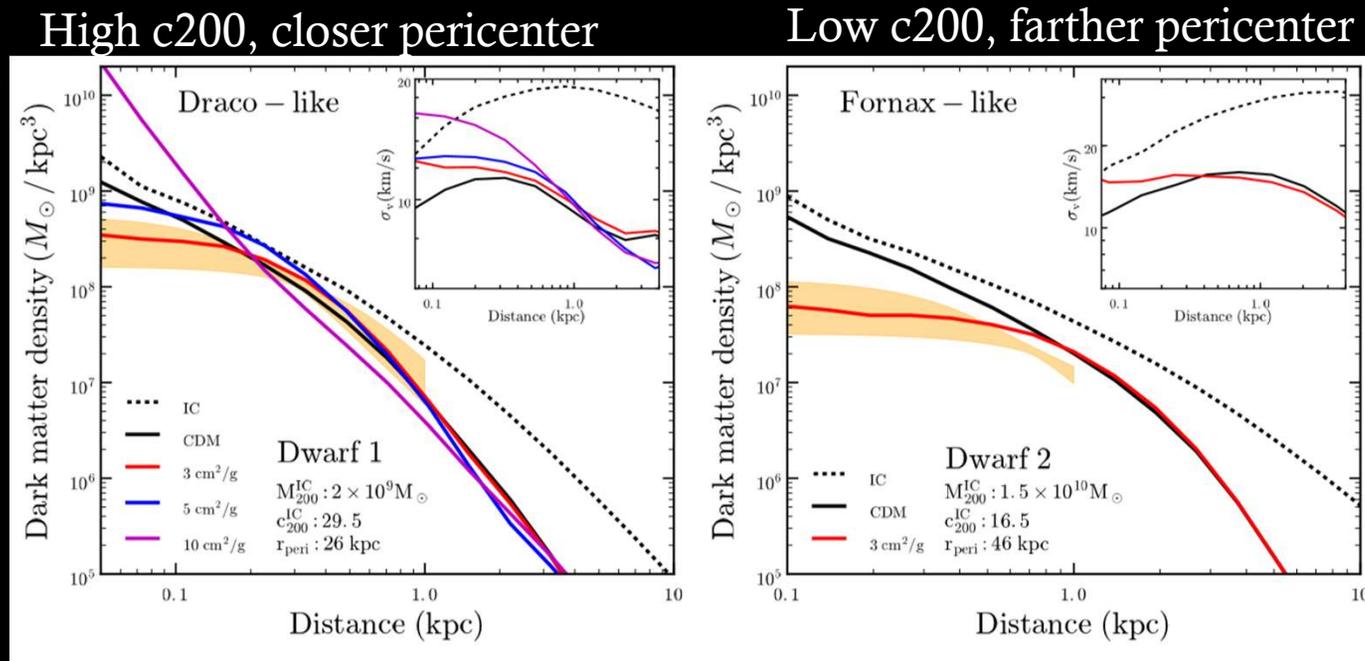
Core collapse is unique to SIDM and it provides a smoking gun for discovering dark matter self-interactions.

With Nishikawa and Boddy (2019)

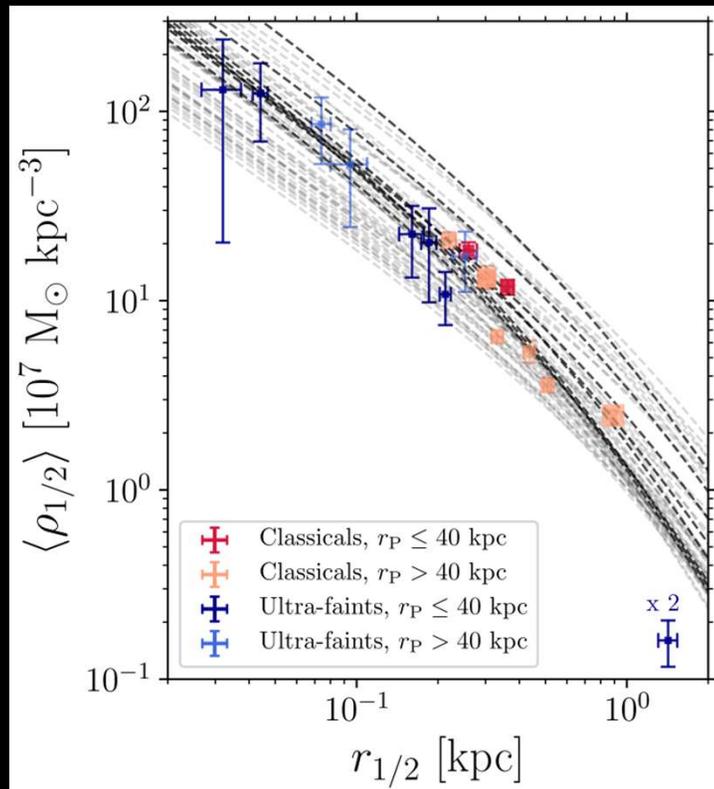


# Core collapse of SIDM subhalos: Draco and Fornax as examples to demonstrate how the pericenter correlation comes about

Dwarf-1 density increases with  $\sigma_m$  (core collapse)



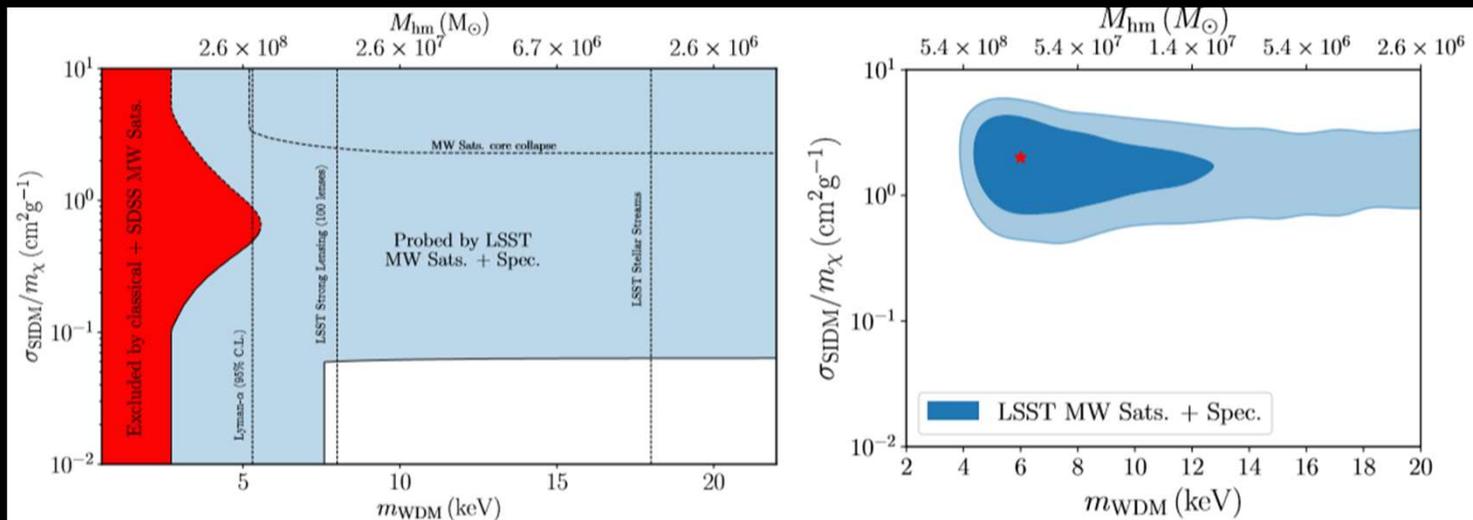
## Compact stellar distribution implies dense dark matter halo



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

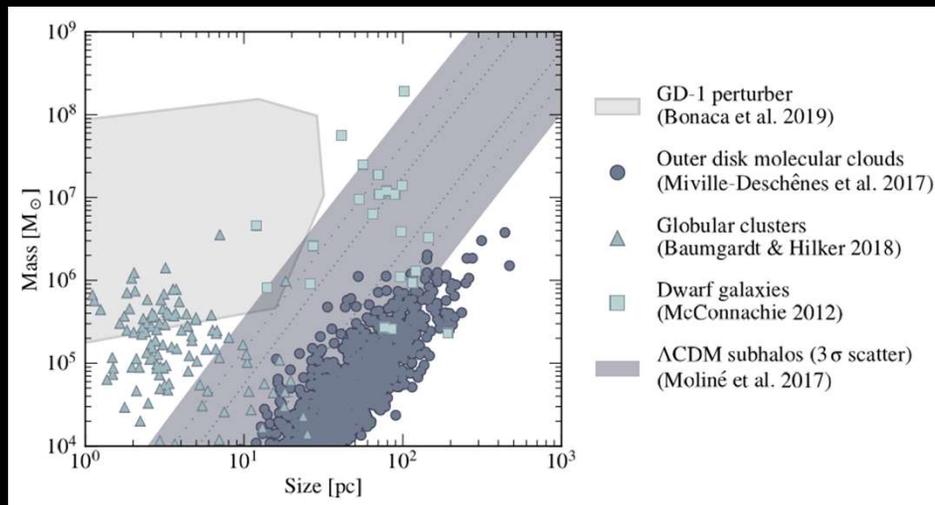
With Valli and Yu (2019)

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



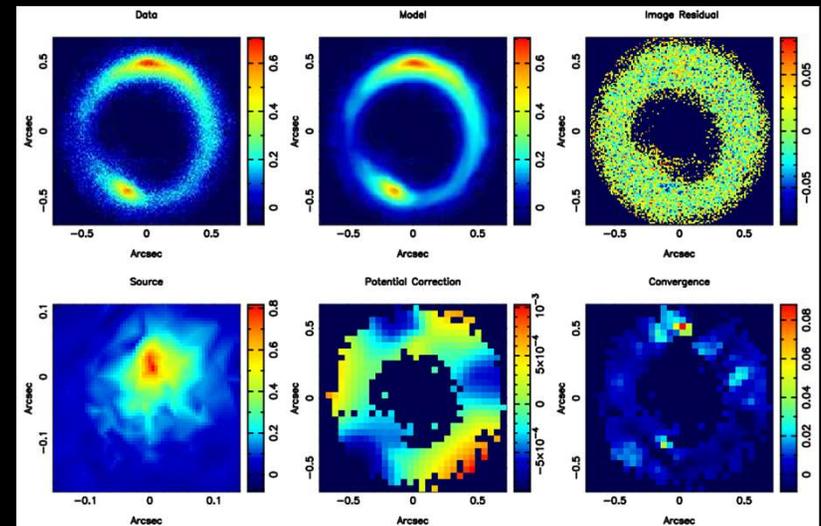
Keith Bechtol et al, LSST dark matter working group (2019)

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



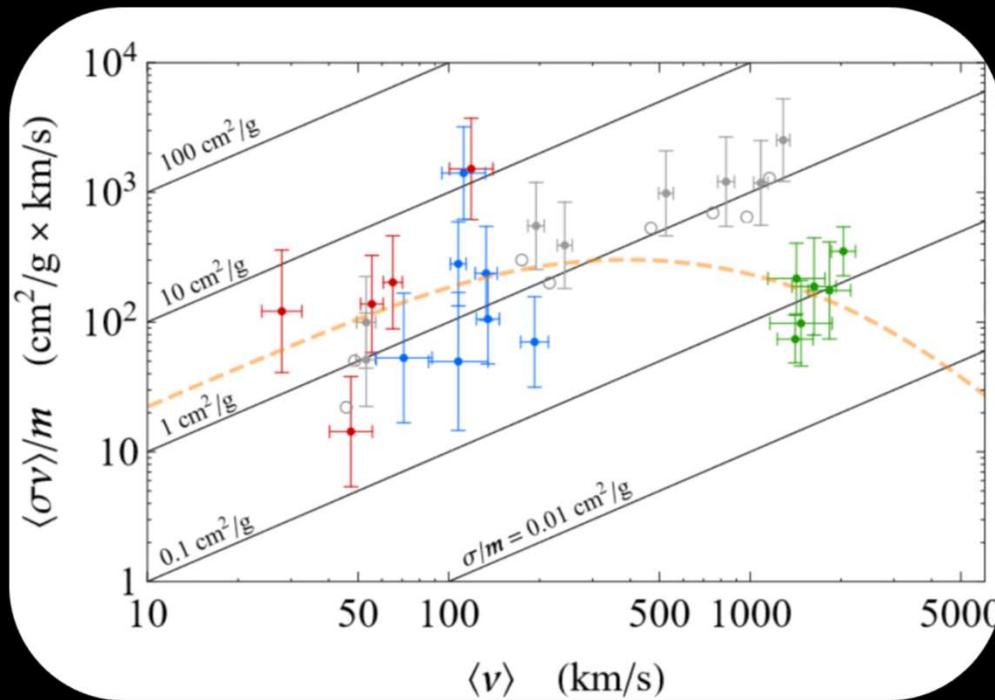
Ana Bonaca, David W. Hogg, Adrian M. Price-Whelan, Charlie Conroy, ApJ 2018

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



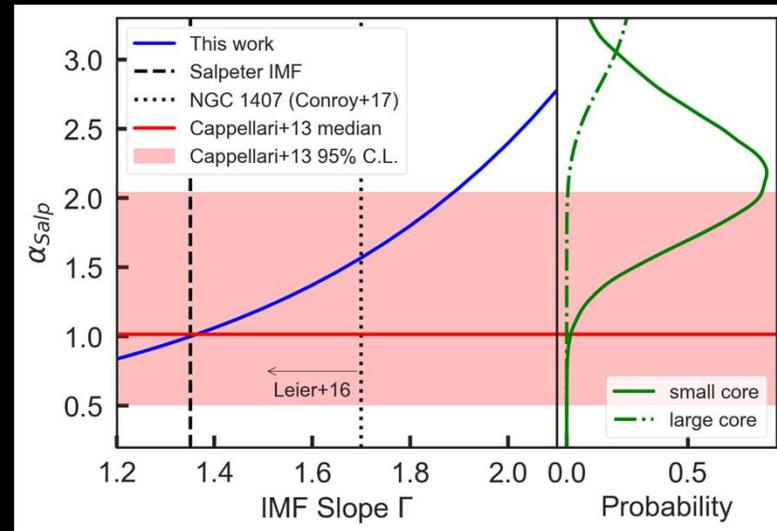
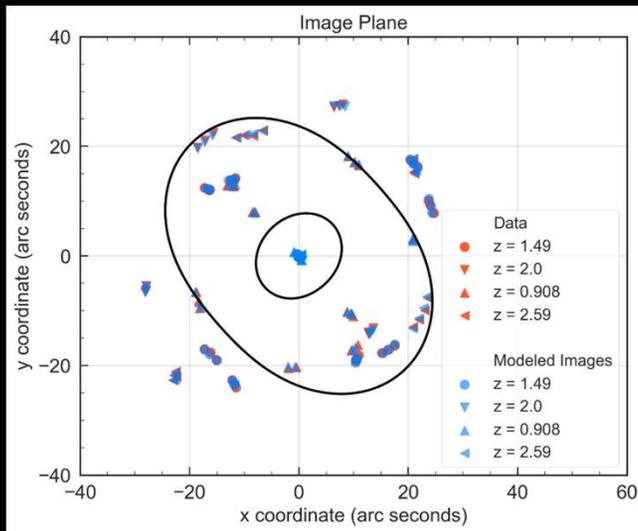
# Clusters of galaxies

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

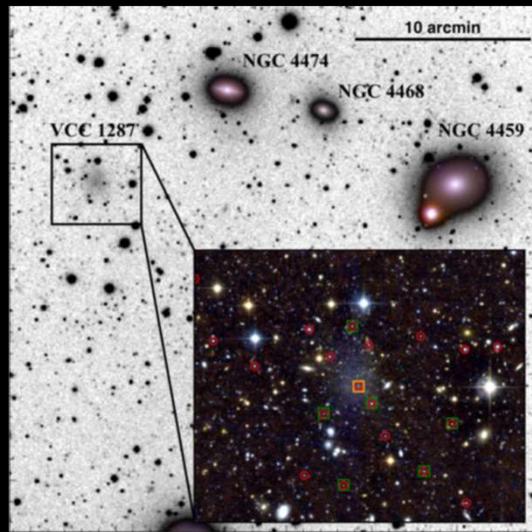


With Andrade, Minor, Nierenberg, MNRAS 2019

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.

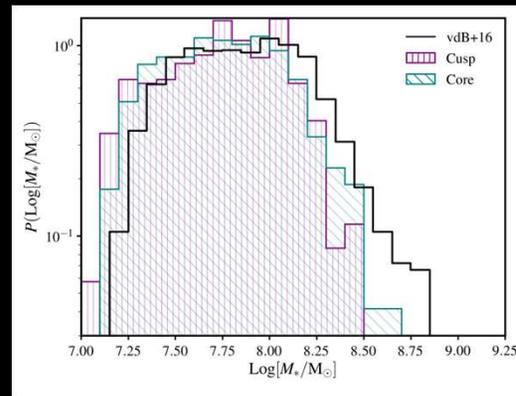
# Ultra-diffuse galaxies in clusters



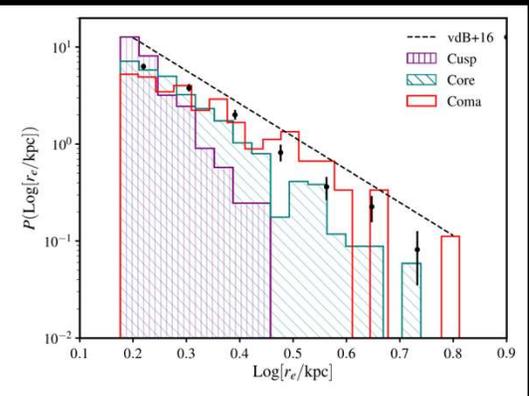
Beasley et al 2016

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

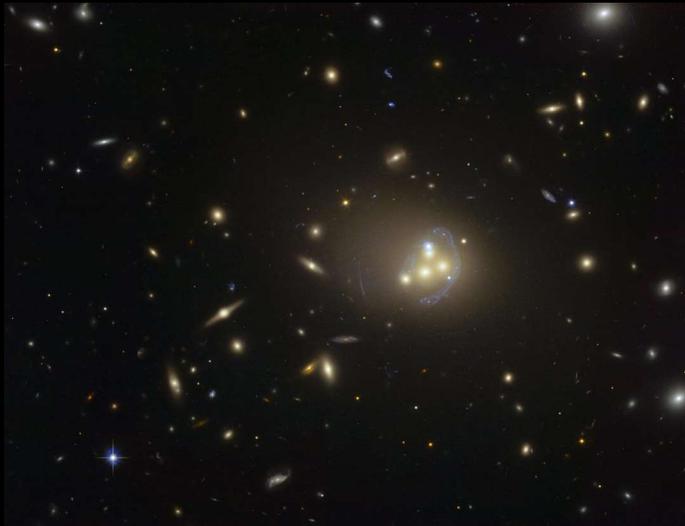
When dwarf galaxies with dark matter constant density cores fall into a cluster potential, the stars expand [Penarrubia et al 2010, Dooley et al 2016].



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]

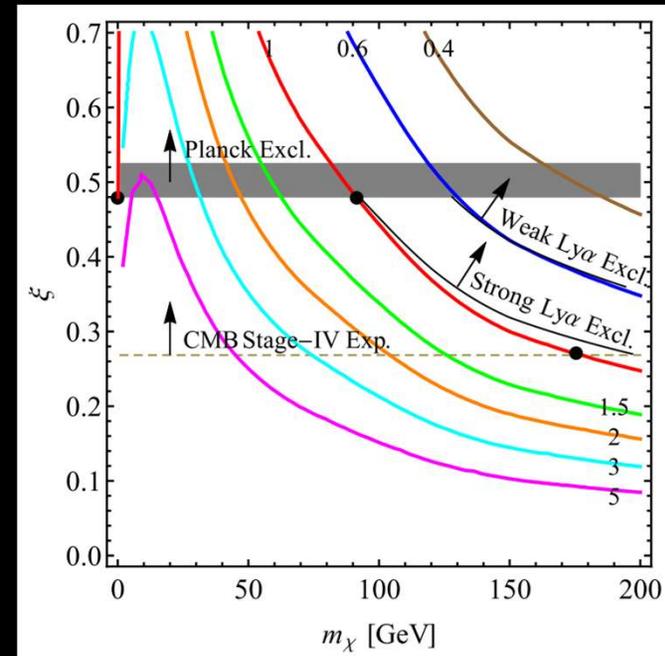
[With Kim Boddy, Anna Kwa and Annika Peter, PRD 2016]

--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.

<b>4</b>	<b>Theoretical considerations: from micro to macro</b>	<b>6</b>
4.1	What do we mean by “cross section?”	6
4.2	Modeling the Effective Macroscopic Phenomena Arising from Microscopic Interactions	8
<b>5</b>	<b>Physical Effects in Galaxies and Clusters</b>	<b>11</b>
5.1	SIDM Density Profile and its Shape	11
5.2	Lack of Dynamical Friction in Cored Halos	17
5.3	Enhanced Gravitational Tidal Stripping of Cored Subhalos	17
5.4	Drag Force and Mass Loss due to Self-Interactions ~ 2 pages	20
5.5	Large scale structure of SIDM models	22
5.6	Gravothermal collapse of SIDM haloes	24
5.7	Are these physical effects unique?	26
<b>6</b>	<b>Observations of SIDM</b>	<b>29</b>
6.1	Strong Gravitational Lensing in Clusters, Groups and Large Ellipticals	29
6.1.1	The total deflector mass distribution	29
6.1.2	Testing SIDM through perturbations to strong gravitational lenses	30
6.1.3	Strong gravitational lensing statistics of unresolved subhalos	31
6.2	X-ray and Weak Lensing Observations of Clusters, Groups and Large Ellipticals	32
6.3	Major and Minor Mergers in Groups and Clusters (and associated observables)	33
6.4	Incidence of Multiple BCGs, their Stellar Kinematics and their Spatial Separations	35
6.5	Rotation and Dispersion Measures of High Redshift Galaxies	36
6.6	Dwarf Galaxies in the Local Group and beyond	36
6.7	Rotation curves of spiral galaxies	38
6.8	Ultra-diffuse galaxies in clusters	40
<b>7</b>	<b>Beyond the simple SIDM framework</b>	<b>41</b>
7.1	SIDM with dissipation	42
7.2	Subcomponent SIDM	42
7.3	Phenomenology of light mediators	42
7.4	Connections to the Standard Model	43
<b>8</b>	<b>Future Prospects</b>	<b>43</b>

# 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/>