SIDM : Motivations and Viable Signatures

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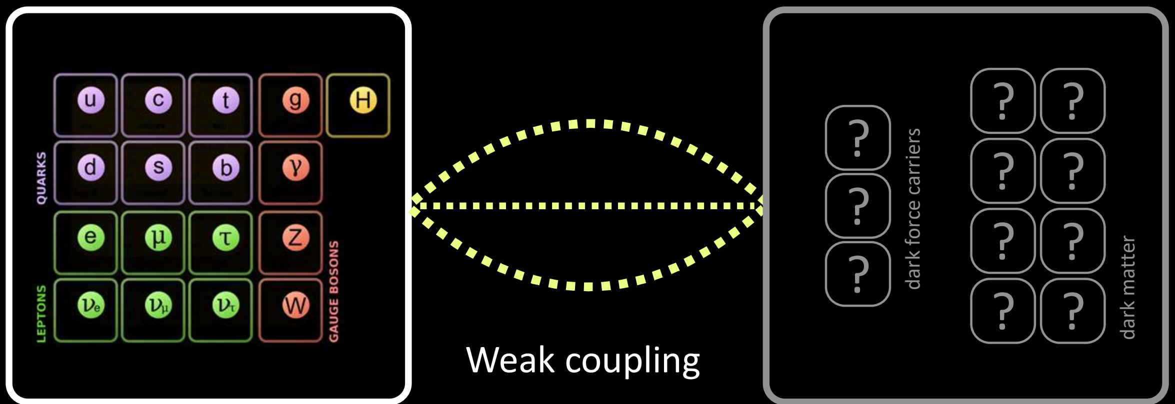
Outline

Motivations for self-interacting dark matter

Motivations for a large cross section at small velocities that allow for gravothermal collapse in some halos

Tests of the large cross section models

Dark sector dark matter

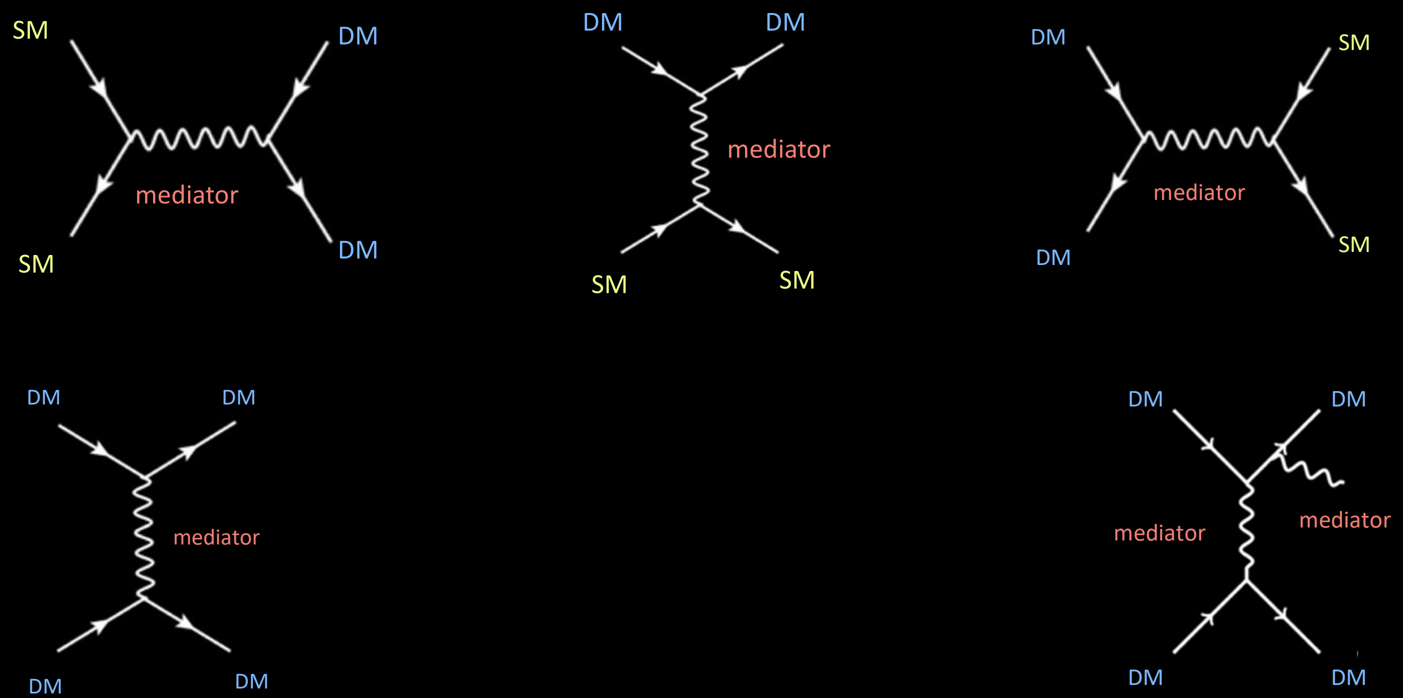


To impact structure formation in galaxies, elastic cross section over mass $\sigma/m > 1$ barn/GeV.

Only be viable if σ/m is enhanced at small velocities and decreases with velocity.

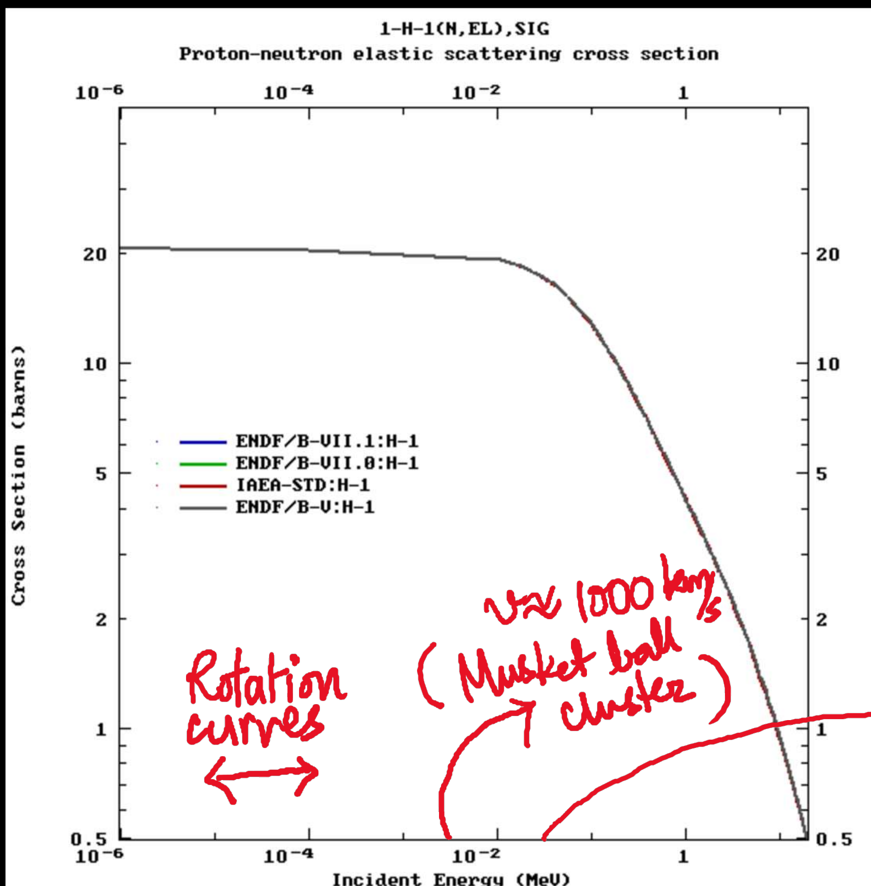
New mechanisms for creating dark matter (e.g., freeze-in, 3->2 processes)

From Theory Space to Phenomenology



Range of possibilities is large, and interplay between different phenomena is highly non-trivial

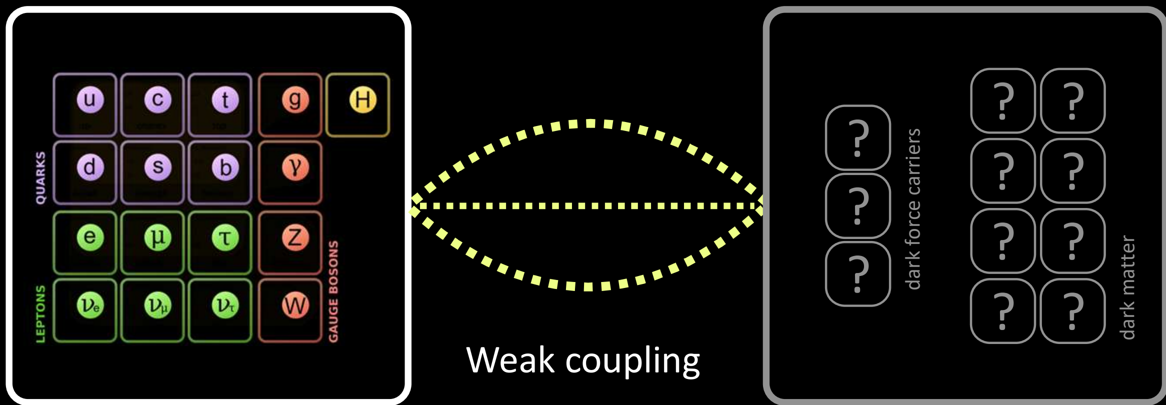
Standard Model example (for SIDM model)



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)

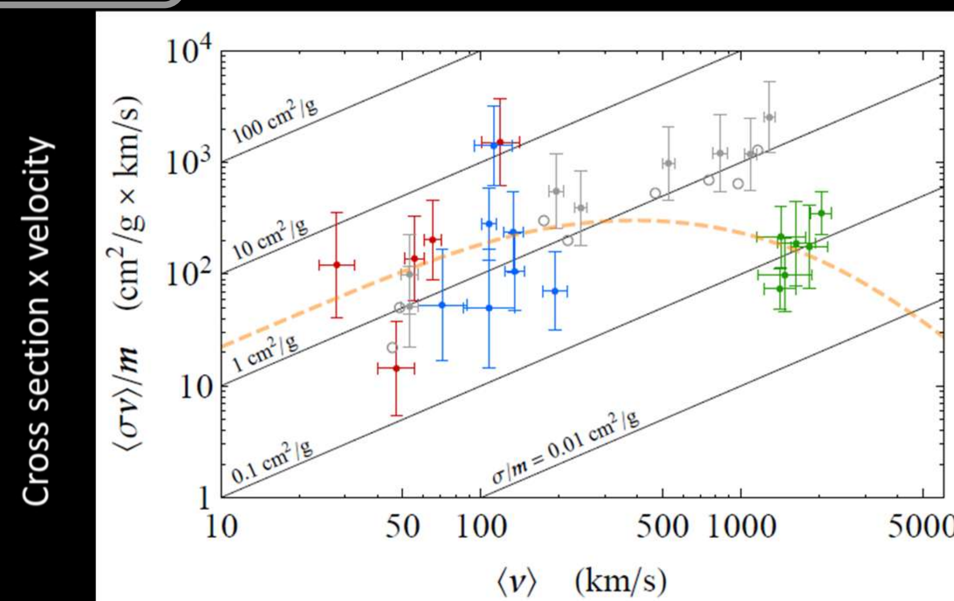
v ≈ 3000 km/s (Bullet cluster)

Dark sector dark matter



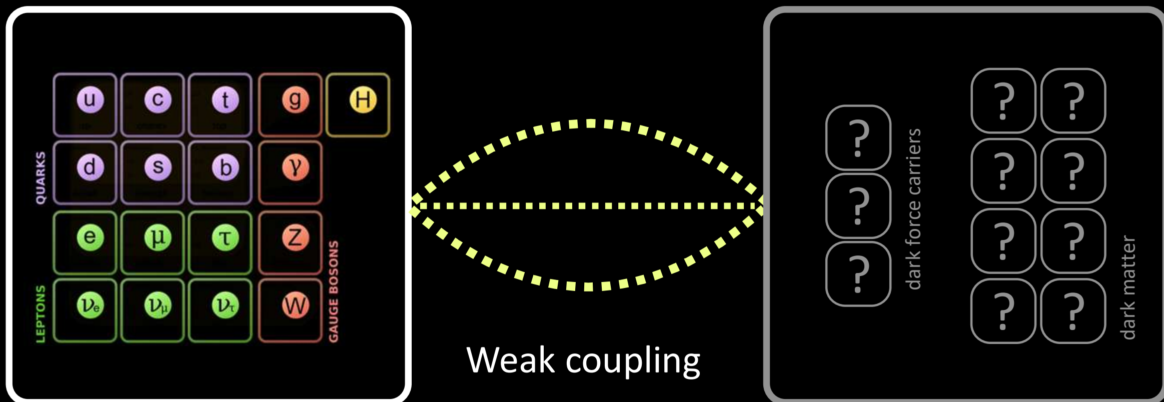
Dark sector particles can interact with each other like in the visible sector

with Sean Tulin and Hai-Bo Yu (2015)



Only be viable if σ/m is enhanced at small velocities and decreases with velocity.

Dark sector dark matter

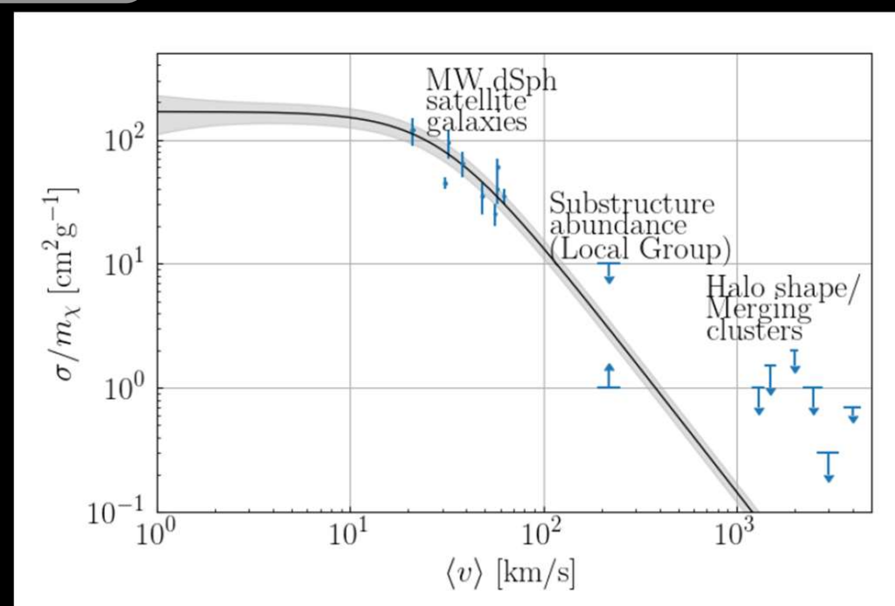


Dark sector particles can interact with each other like in the visible sector

Correa (2021)

Only be viable if σ/m is enhanced at small velocities and decreases with velocity.

Cross section



Dark sector dark matter

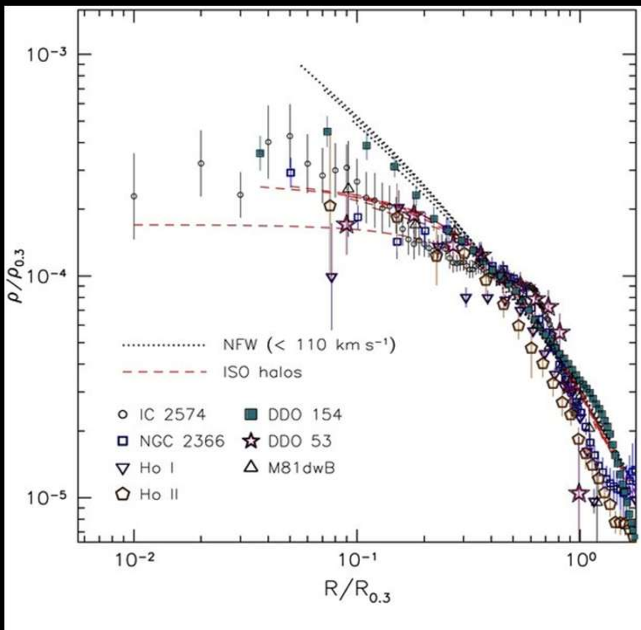
Large parameter space! Many ways to proceed.

I will focus on the parameter space in which elastic scattering between DM particles can impact galaxies in an observable way, and aim to use small-scale structure puzzles as **lampposts**:

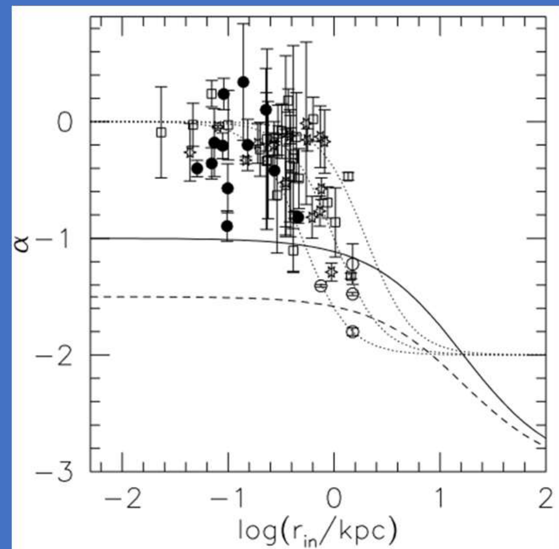
Diversity problem for field galaxies

Too big to fail problem

Cores AND cusps

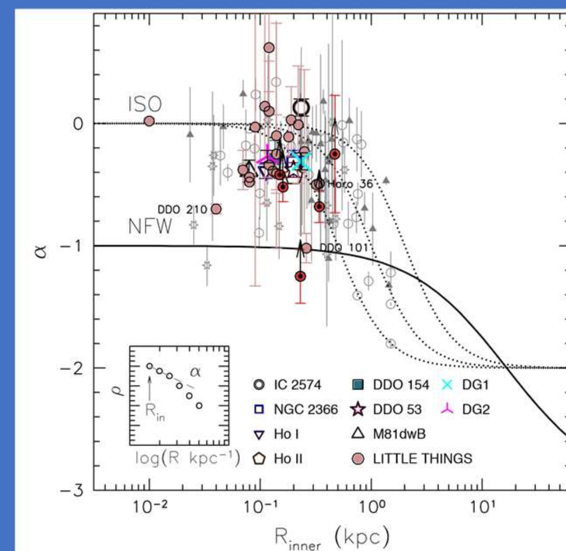


LITTLE THINGS, Oh et al 2015



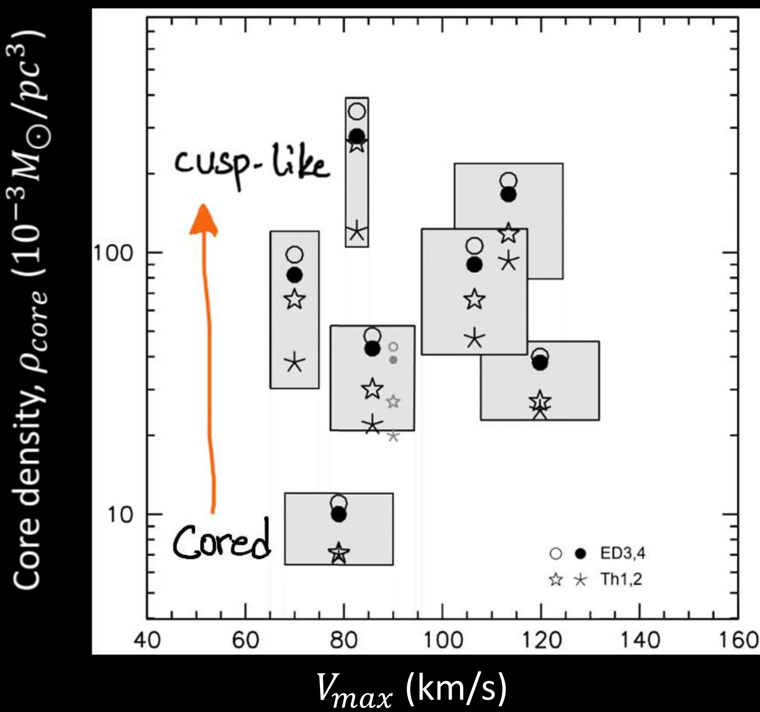
de Blok and Bosma, 2002

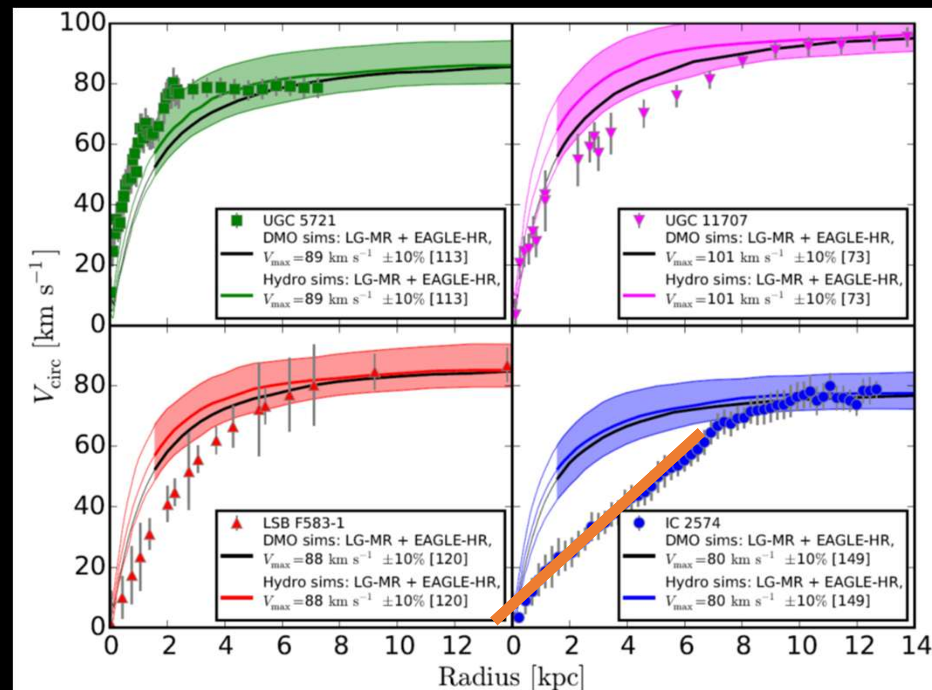
Slope of the DM density profile



LITTLE THINGS, Oh et al 2015

The puzzling diversity in rotation curves

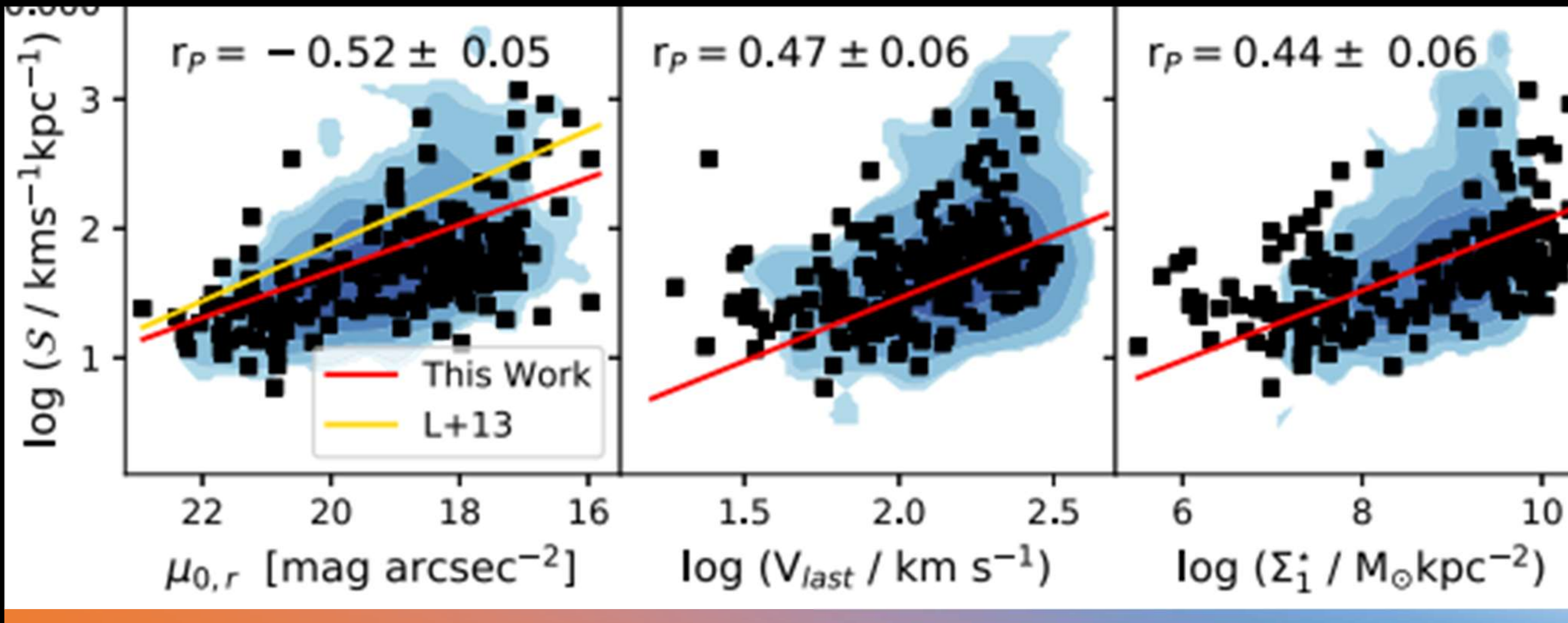




with Rachel Kuzio de Naray, Greg Martinez and James Bullock (2010)

Oman et al, 2015

Slope, $S \propto (G\rho_{core})^{1/2}$



Frosst et al 2021

Probes datasets

Diversity in field galaxies

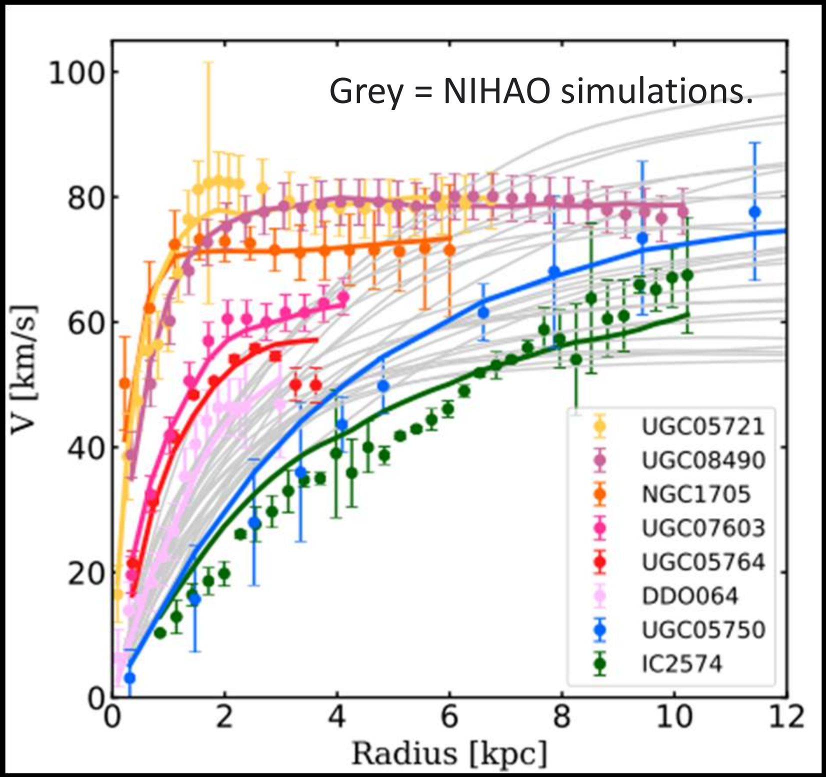
Possible solutions (a simplified view)

Interpretation of data is wrong (non-rotational support, inclination errors) and there are no cored halos

Strong feedback

Self-interacting dark matter

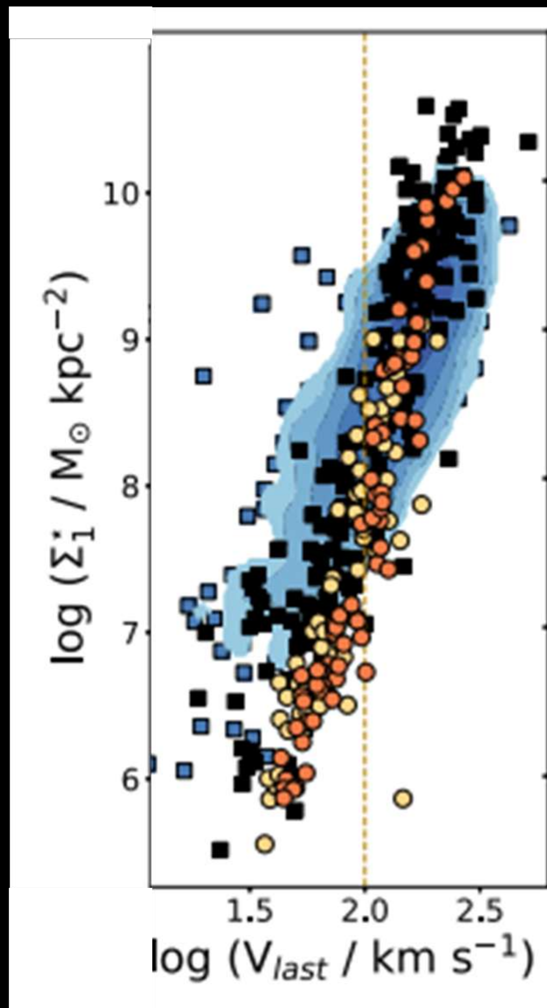
What you do to the dark matter, you do to the stars

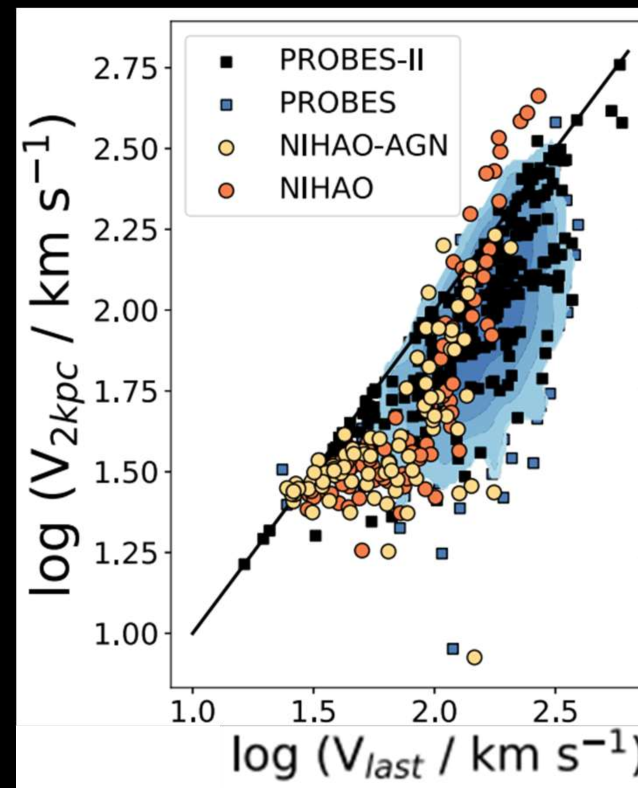


With Tao Ren and Hai-Bo Yu (2019)

Strong feedback has difficulty making galaxies that are compact enough in their stellar content.

Strong feedback in NIHAO





Frosst et al 2021

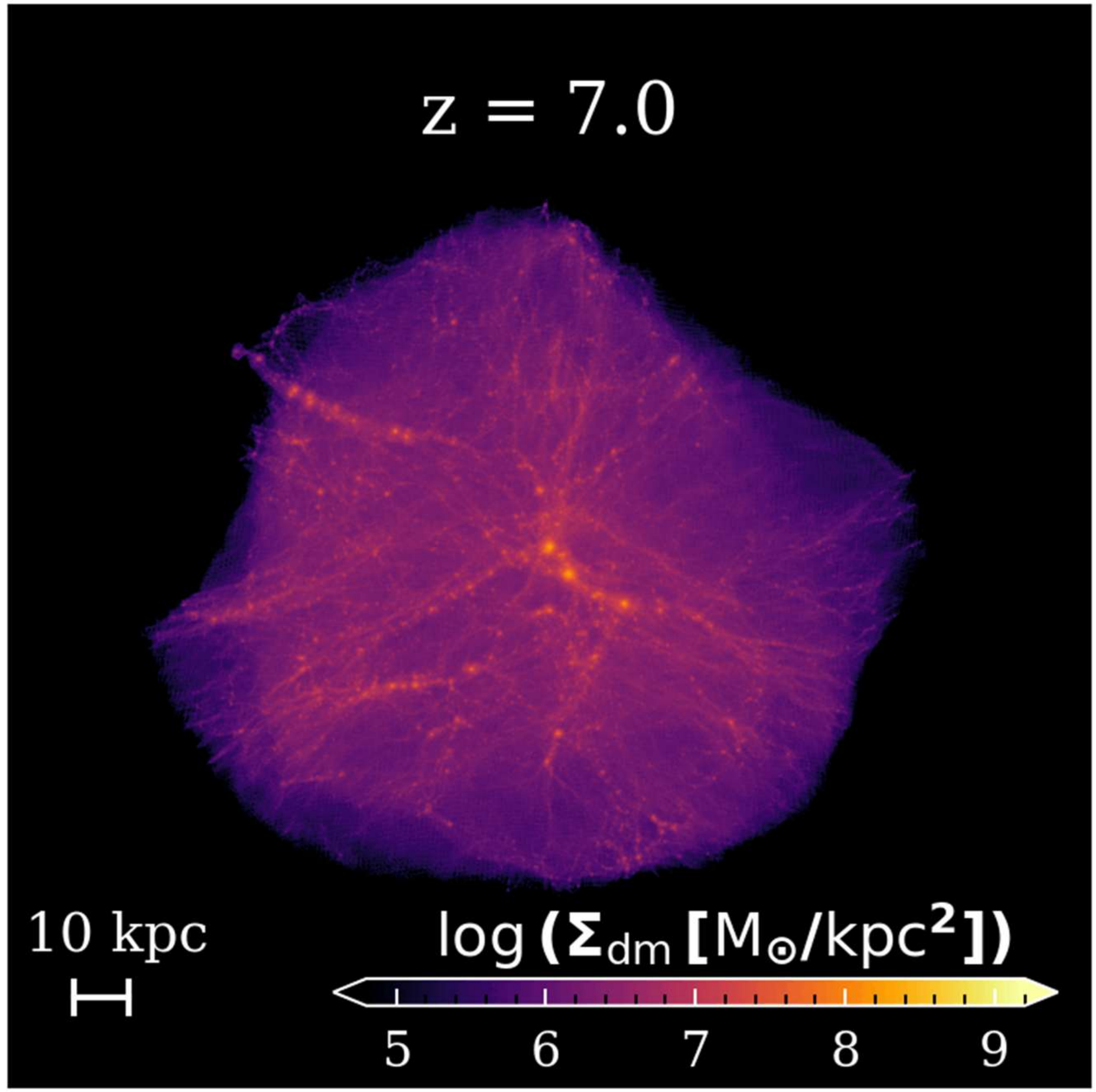
Possible solutions (a simplified view)

We will look at the simplest elastic SIDM models in this talk.

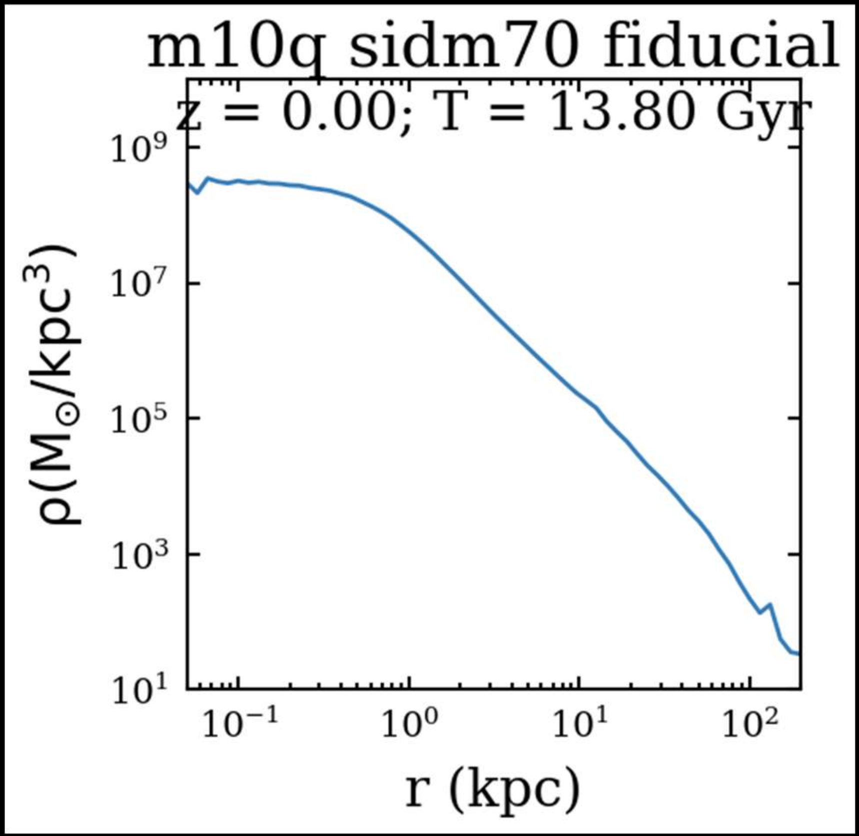
First, we need to understand how interactions impact galaxies.

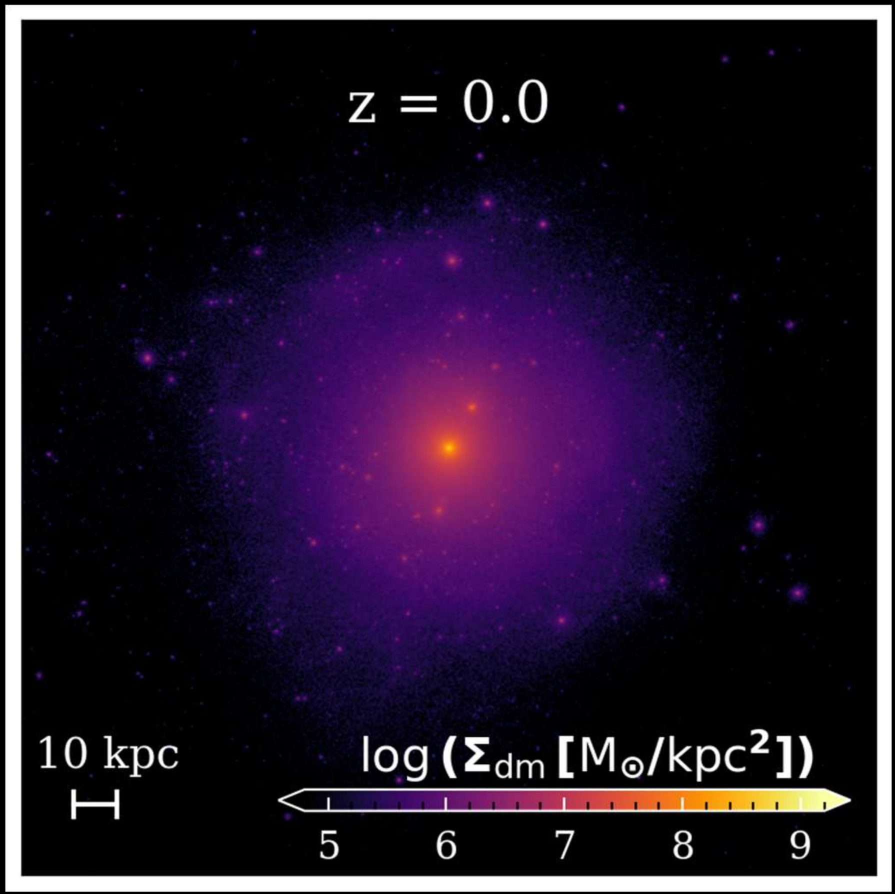
Interactions change the central parts of the halo but otherwise look like a CDM halo. Simulation on the right has cross section of 70 sq-cm/g.

m10b, In prep, Silverman et al 2025



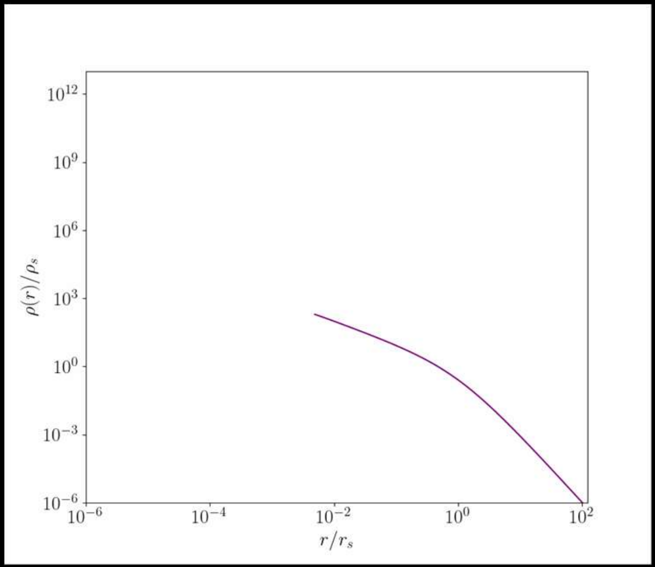
Evolution of the SIDM halo density profile

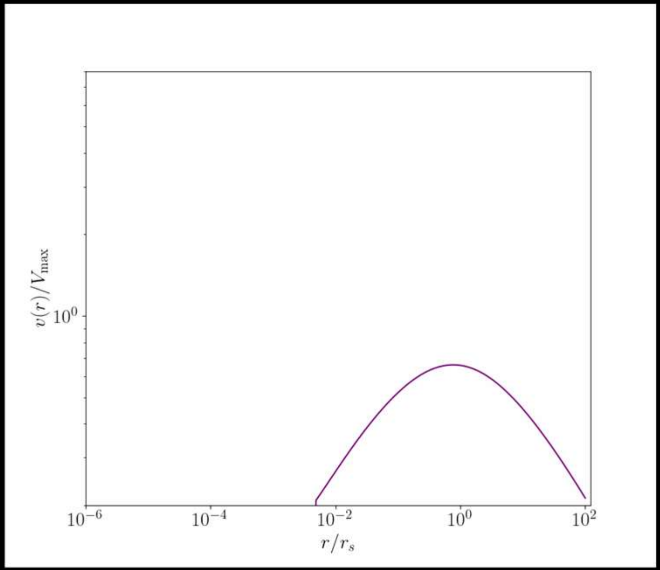


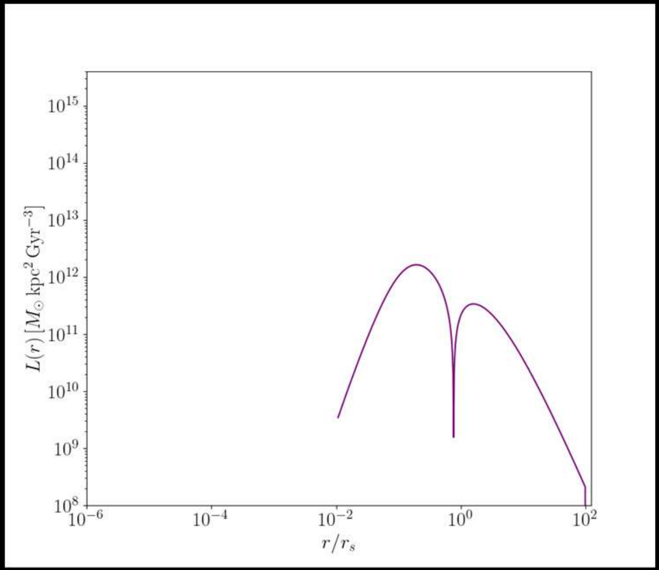


m10b, In prep, Silverman et al 2025

Temporal evolution of an isolated SIDM halo using gravothermal equations (~Moller scattering)







With Sophia Nasr, Nadav Outmezguine, Kim Boddy and Laura Sagunski (2023)

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho \ , \quad \frac{\partial(\rho v^2)}{\partial r} = -\frac{GM\rho}{r^2} \ , \quad \frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r} \ ,$$

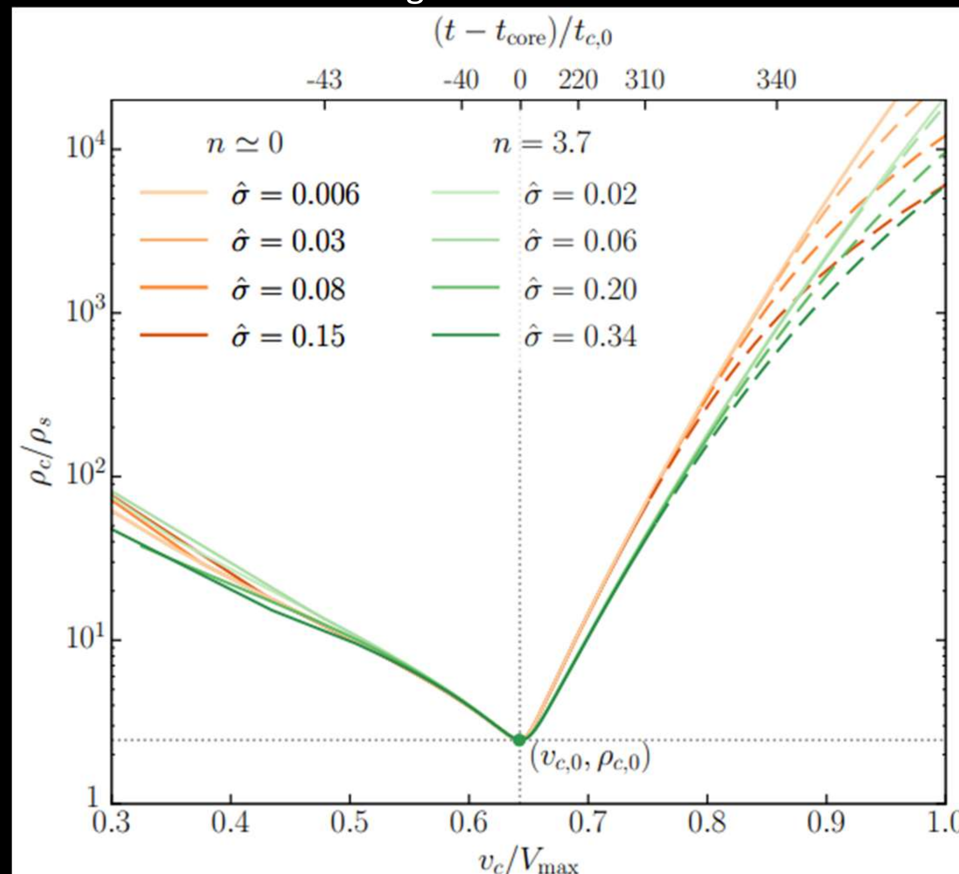
$$\frac{\partial L}{\partial r} = -4\pi r^2 \rho v^2 \left(\frac{\partial}{\partial t}\right)_M \log\left(\frac{v^3}{\rho}\right),$$

Evolution of a SIDM halo

Solid → Dashed
Long → short mean free path

Time in units of scattering time scale

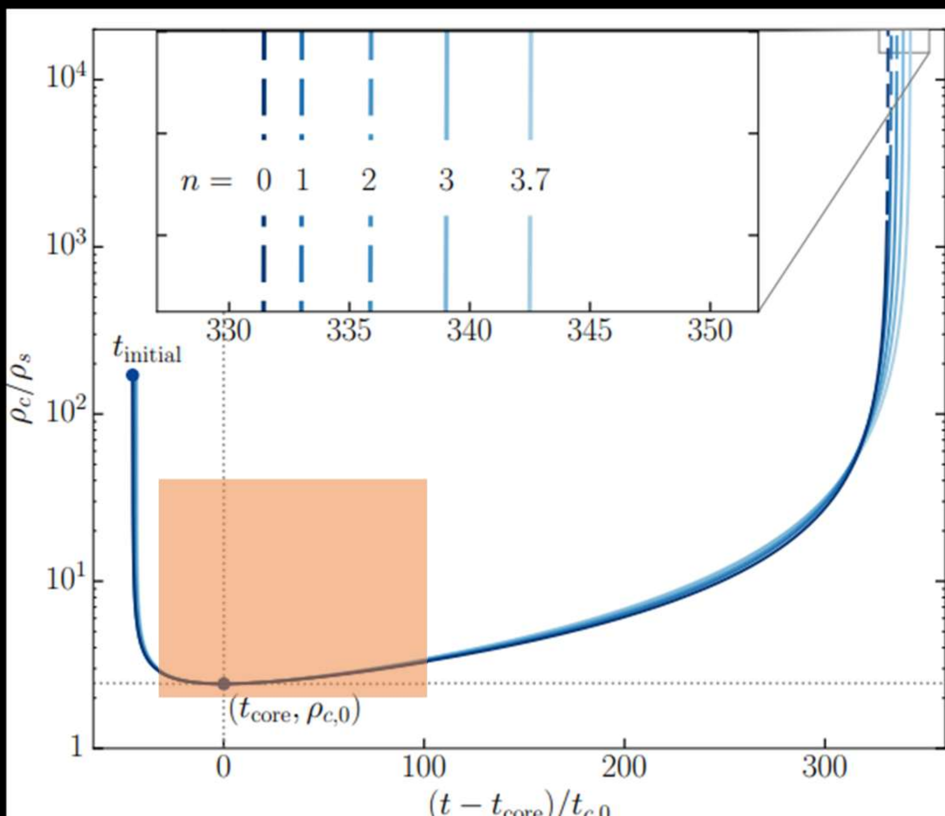
Central density (normalized)



Central velocity dispersion over Vmax

With Nadav Outmezguine, Sophia Nasr, Kim Boddy and Laura Sagunski (2022)

Temporal evolution of the core density



$$t_{c,0}^{-1} \propto \rho_{c,0} v_{c,0} \frac{\langle \sigma(v) v^5 \rangle}{\langle v^5 \rangle}$$

Approximate universality

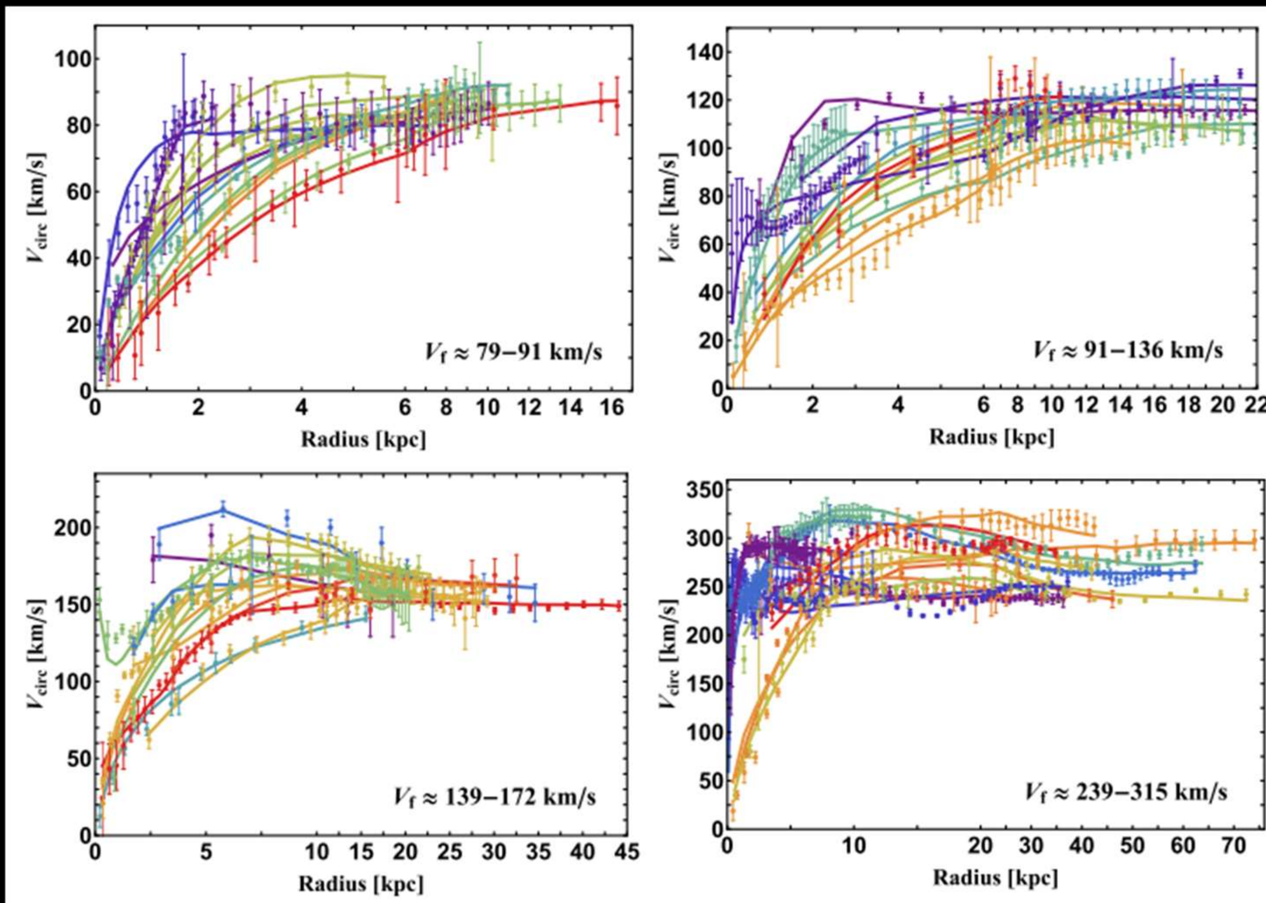
Core density only mildly dependent on cross section in the orange shaded region

Excellent analytic model for the density profile validated by hydro simulations

Both factors make this a highly predictive model space, and eventually rules it out

With Nadav Outmezguine, Sophia Nasr, Kim Boddy and Laura Sagunski (2022)

Moderate cross section SIDM fits to the SPARC sample



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

$$\frac{\sigma}{m} = 3\,\frac{cm^2}{g}$$

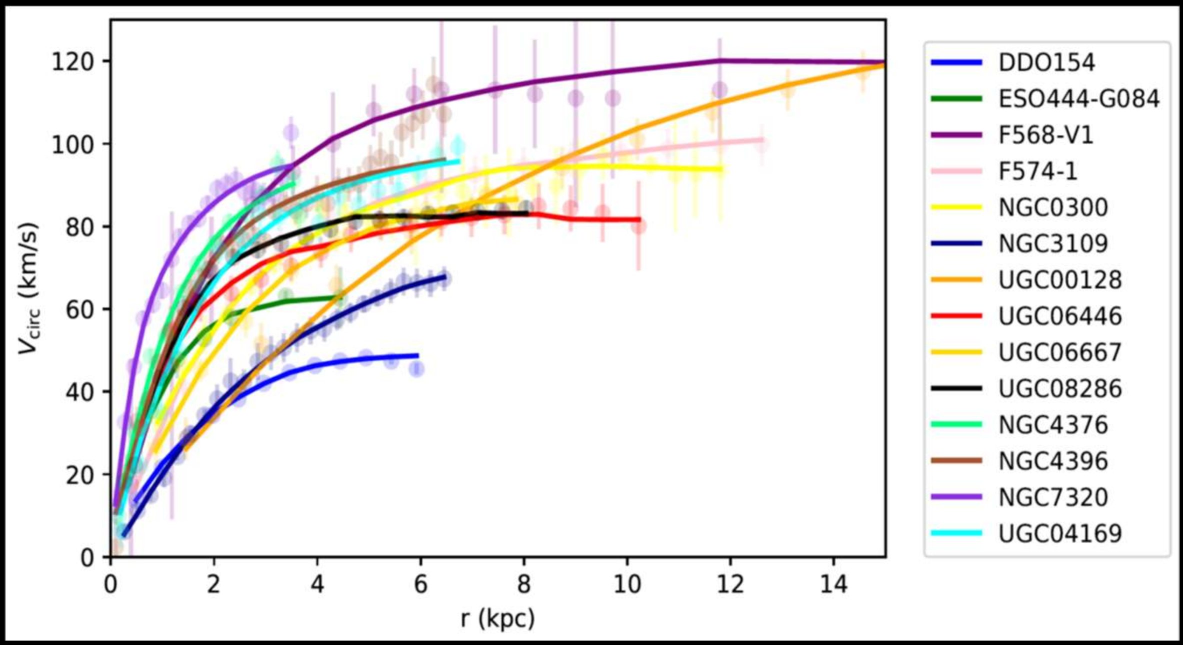
The results are the same for cross sections below about 10 sq-cm/g

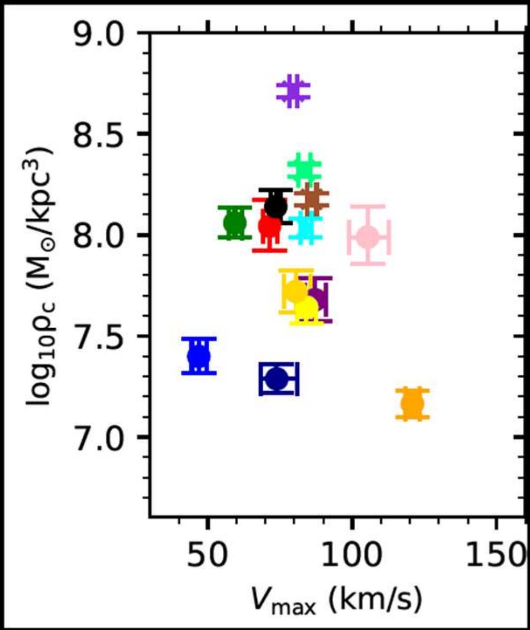
Diversity comes from:

1. Halo concentration (correlated with formation time of the halo)
2. Stellar distribution

Pick out a selection of the lowest surface brightness systems for a closer look

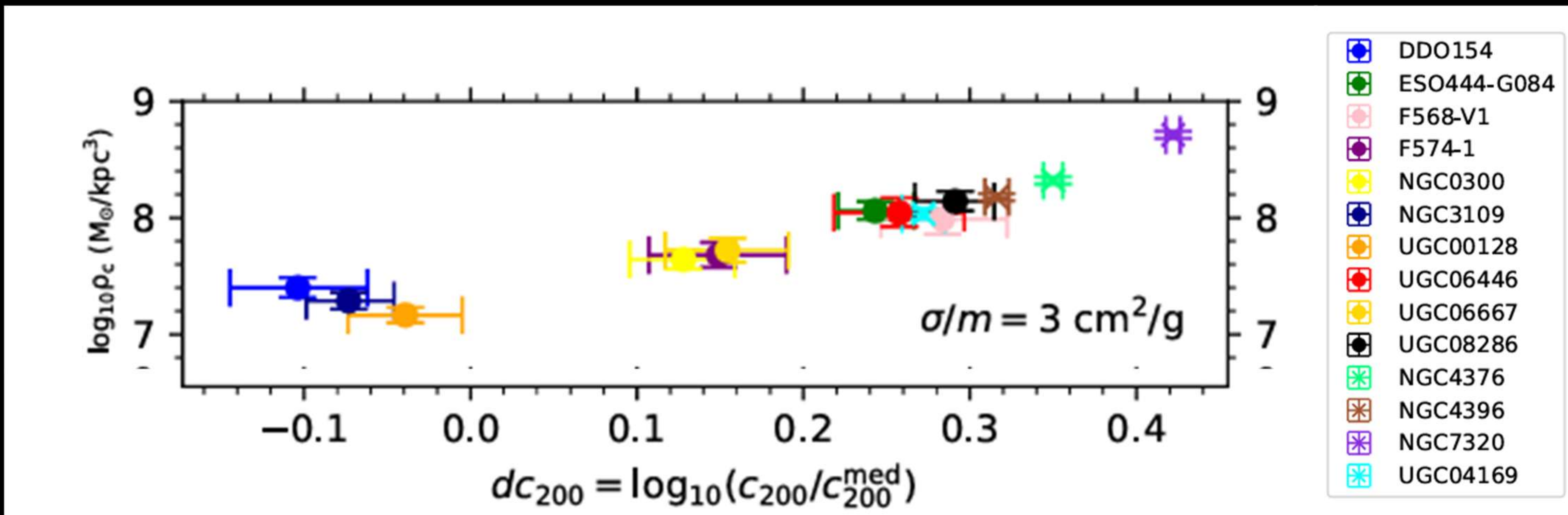
With Grant Roberts, Mauro Valli and Hai-Bo Yu (2024)





All galaxies picked out here (some from SPARC and others are newer data) have very low stellar densities but a large range of central dark matter densities. These have not had a good explanation in any scenario. [Kuzio de Naray 2010, Santos-Santos et al. 2019]

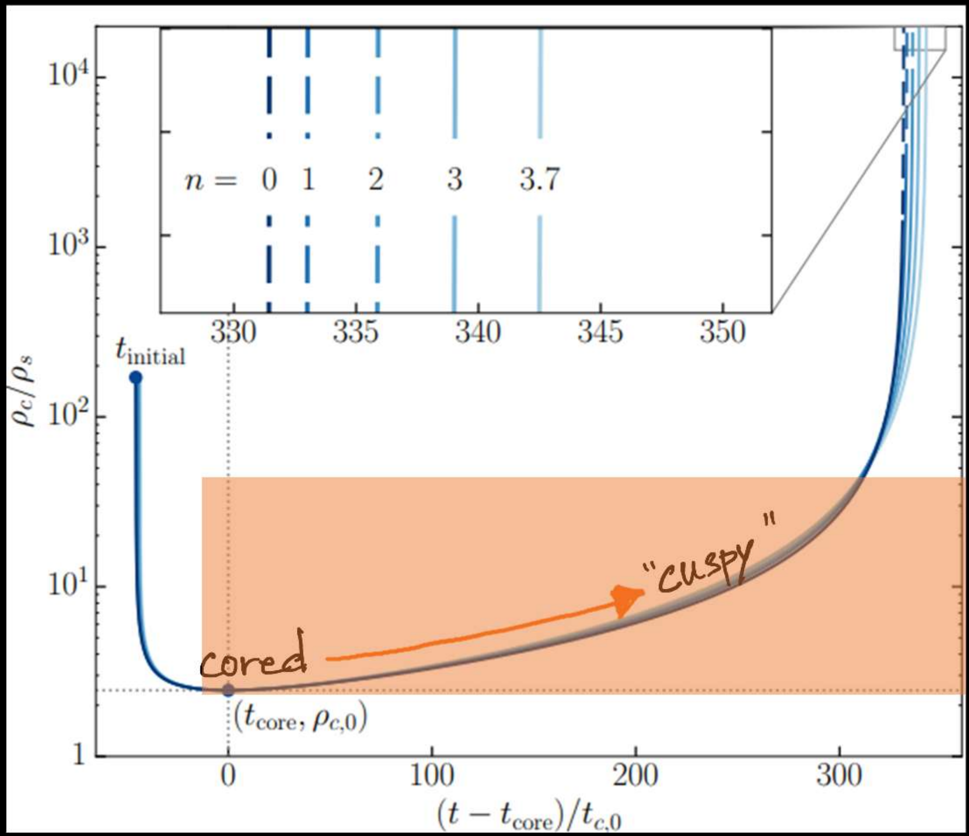
Moderate cross section ($< 10\ \mathrm{cm}^2/\mathrm{g}$) SIDM fits rely on these LSB galaxies sampling the high concentration tail

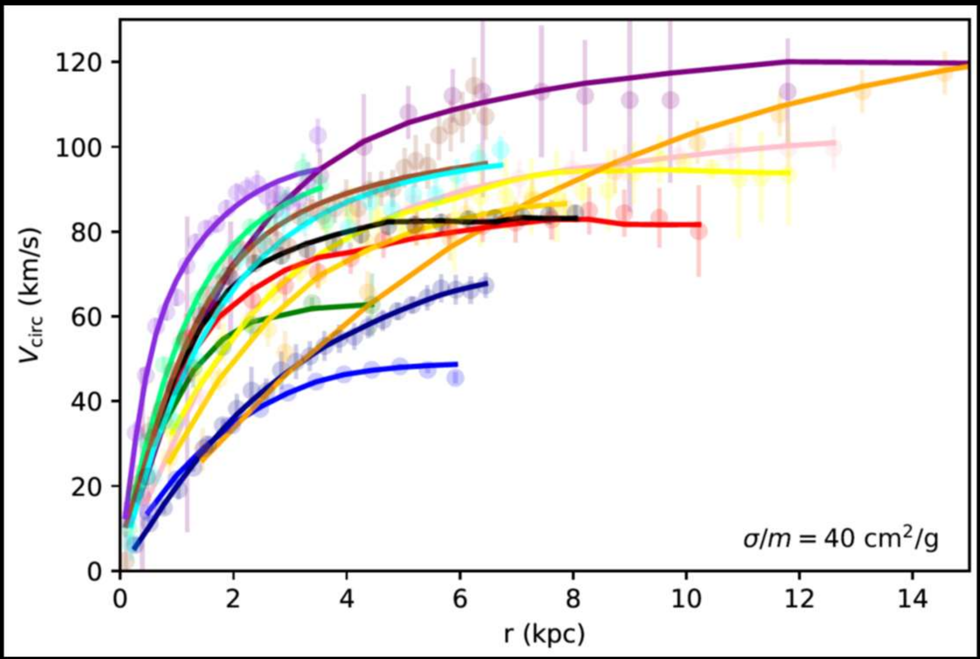


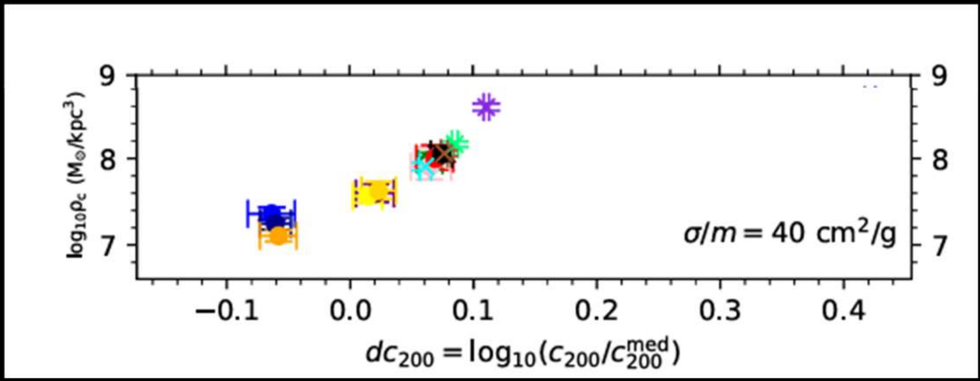
With Grant Roberts, Mauro Valli and Hai-Bo Yu (2024)

What's the alternative?

We have neglected the possibility of very large cross sections in our analysis before – i.e., galaxies being on the right side of this plot.





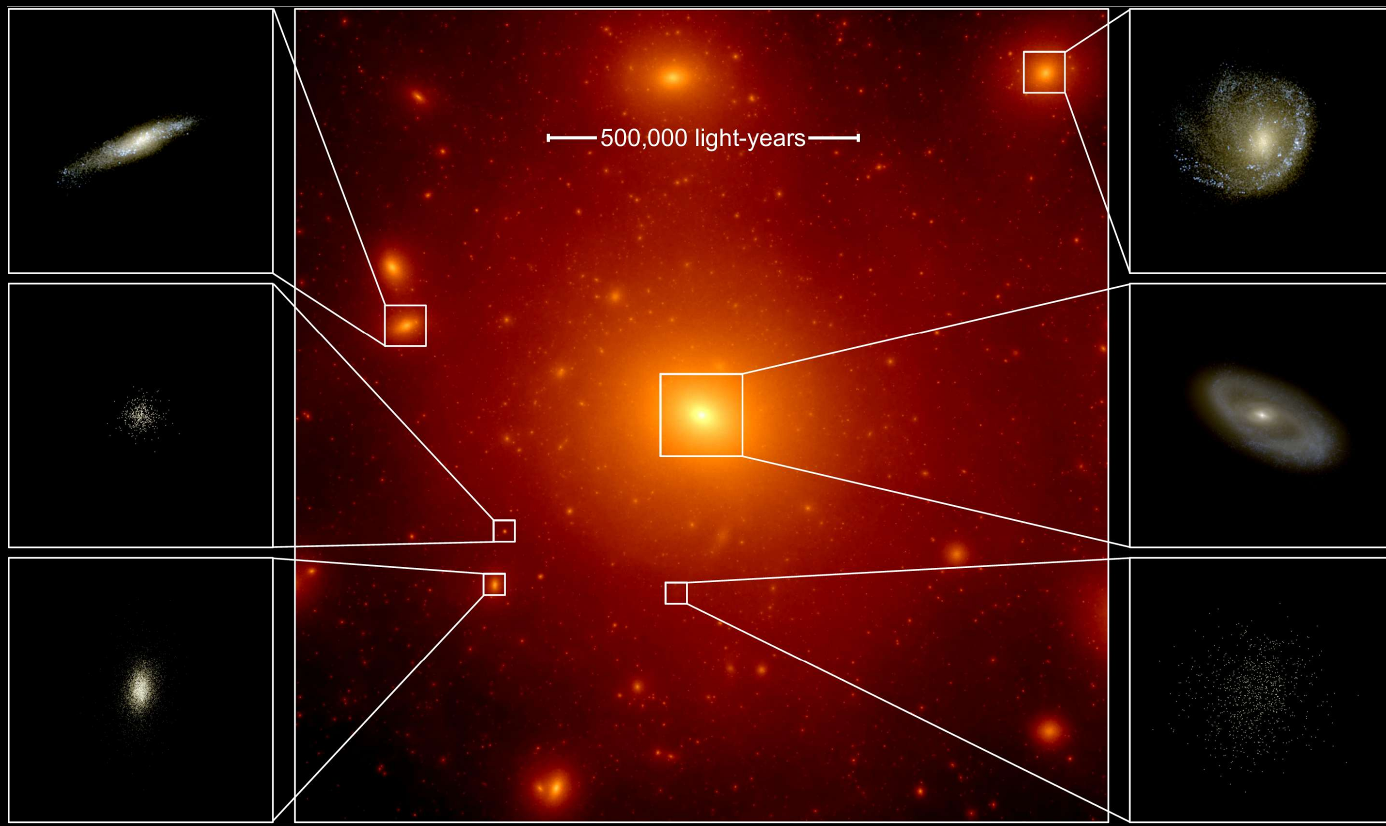


With Grant Roberts, Mauro Valli and Hai-Bo Yu (2024)

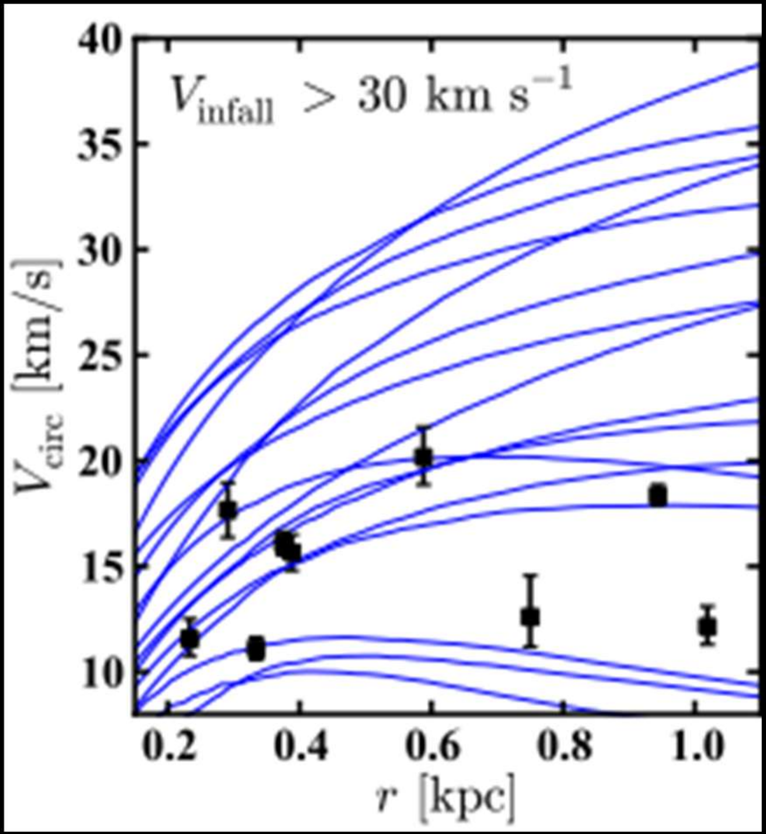
Fits with a large cross section are very good

They recover the success of the moderate cross section fits and no more outliers!

Milky Way satellites: test bed for models that have the potential to explain the diversity of field galaxies



DC Justice League Simulations, Alyson Brooks et al. (2020)

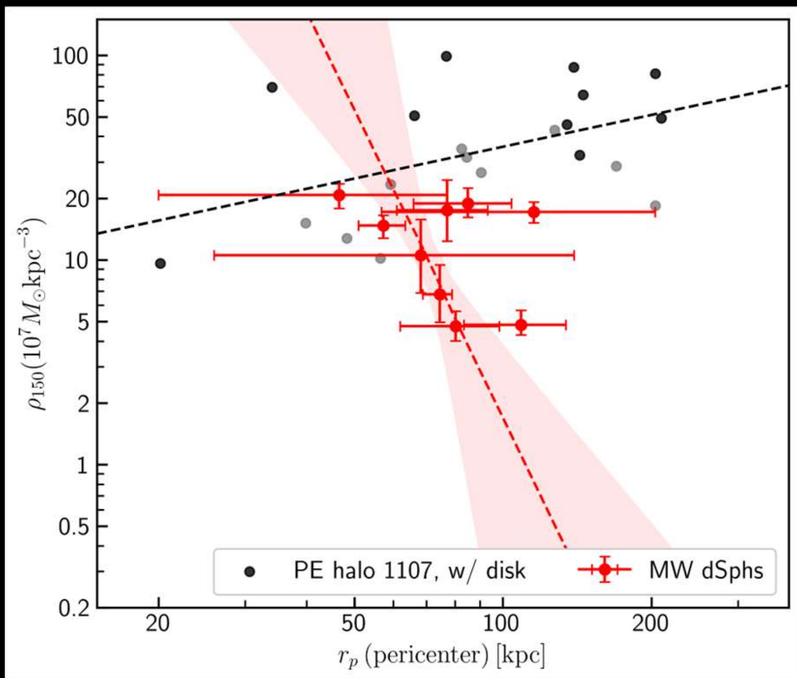


With Mike Boylan-Kolchin and James Bullock (2011)

Too big to fail?

Solutions proposed
Disk
Disk + Strong feedback
SIDM

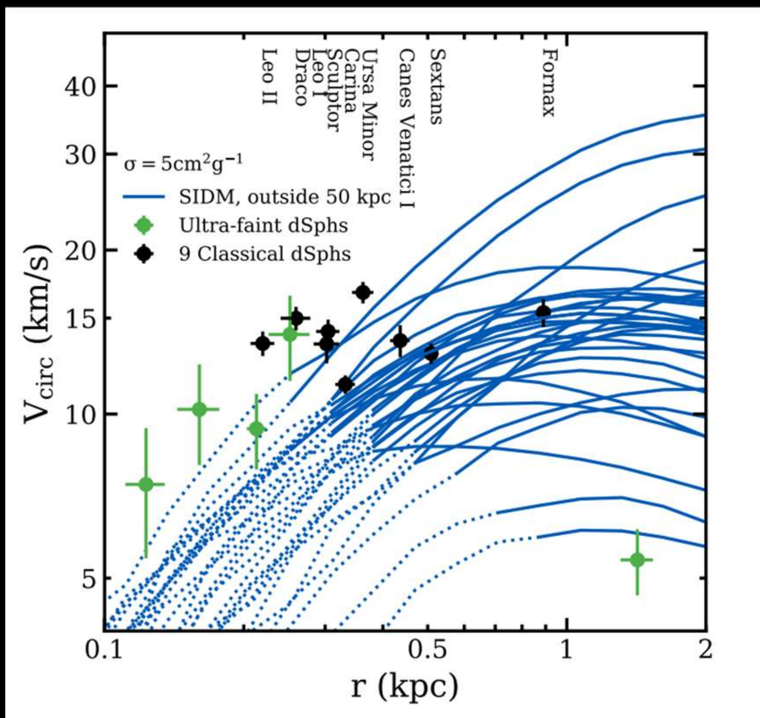
Too big to fail and Gaia data on satellite orbits



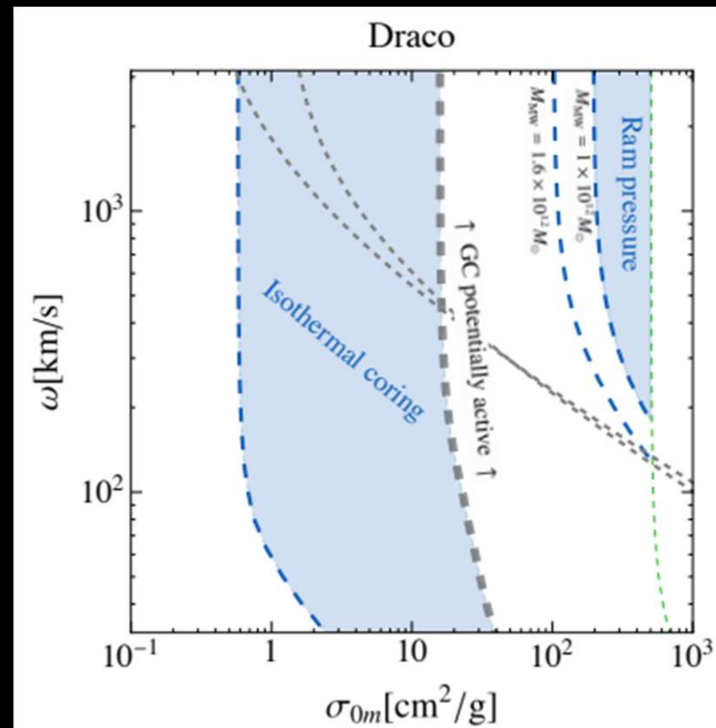
Data is on average less dense and more clustered in pericenter distances

With Mauro Valli and Hai-Bo Yu (2019)
With Kevin Andrade and Mauro Valli (2023)

SIDM solution: Moderate cross sections ($< 10\ \mathrm{cm}^2/\mathrm{g}$) are not going to work for MW satellites



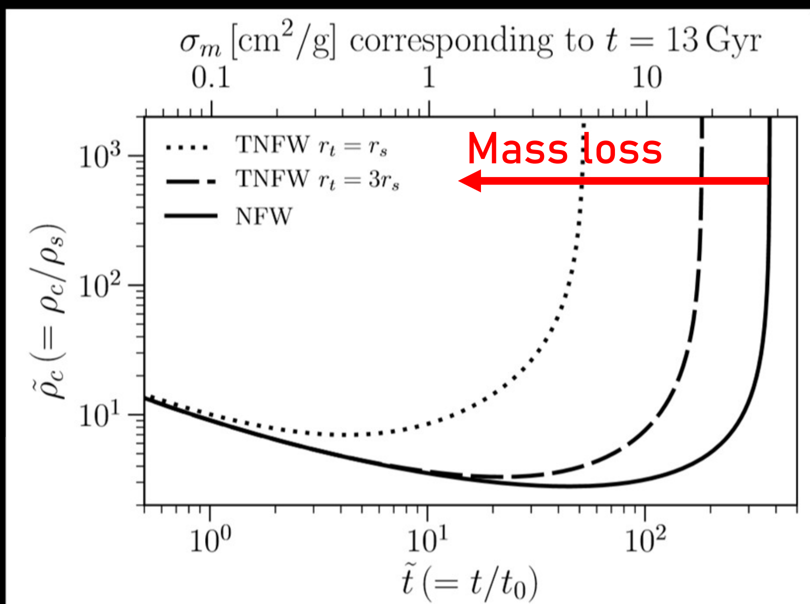
With Maya Silverman, James Bullock, Victor Robles and Mauro Valli (2022)



With Oren Slone, Fangzhou Jiang and Mariangela Lisanti (2021)

Gravothermal collapse in subhalos: new sources of diversity in the predicted DM density profiles for large cross section models

Core density

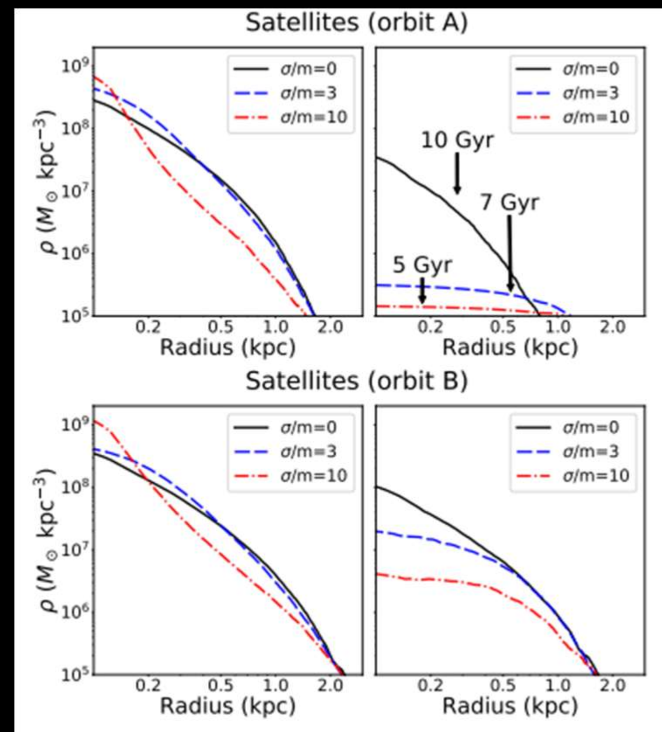


Age/(interaction time)

With Hiro Nishikawa and Kim Boddy (2019)

High concentration; formed early

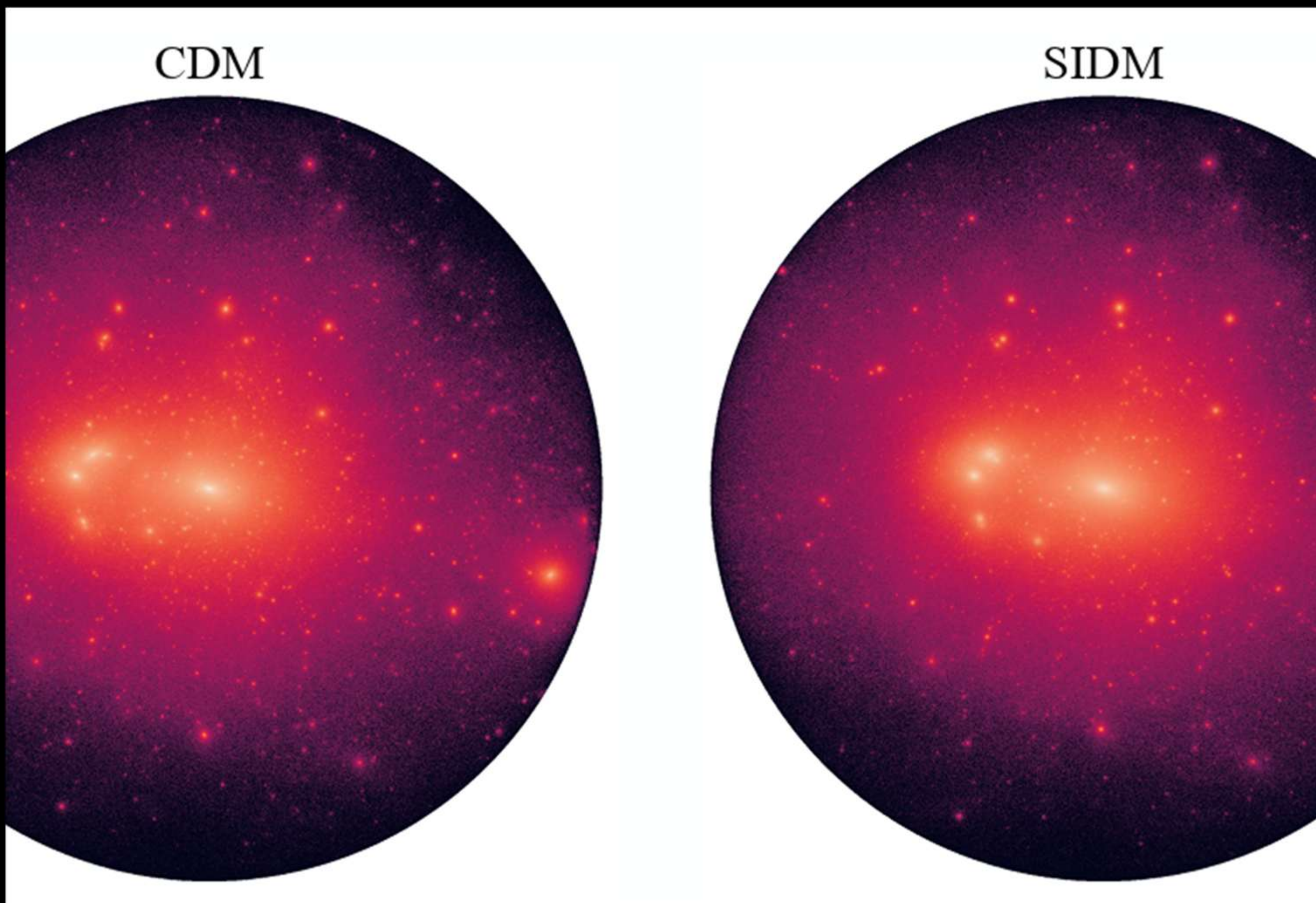
Low concentration; formed late



Comes close

Stays far

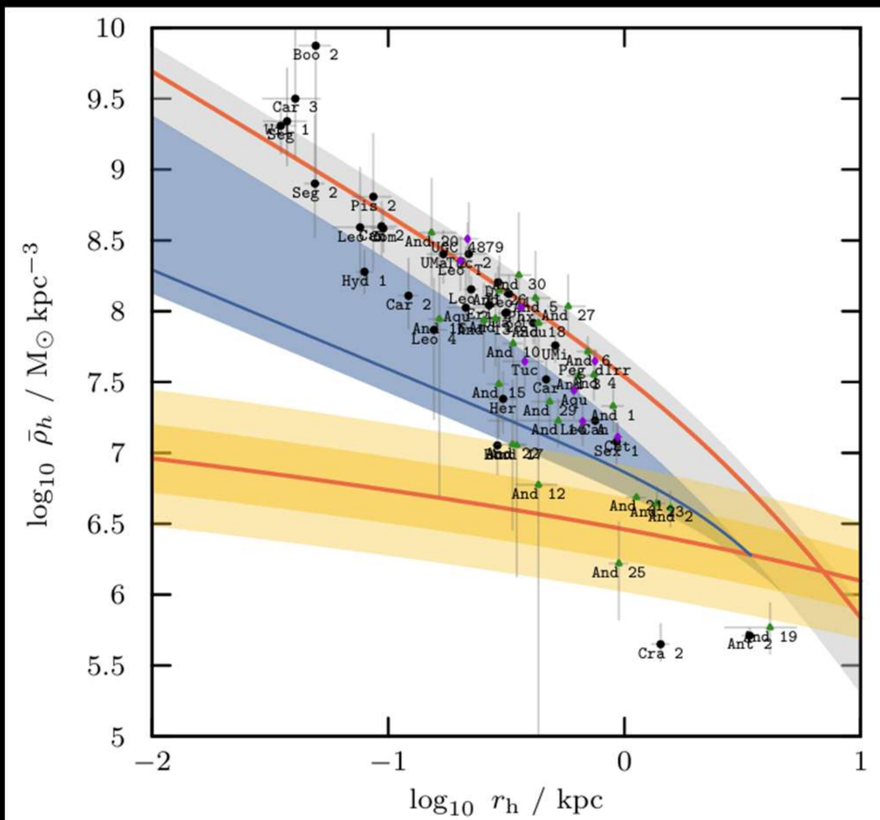
With Felix Kahlhoefer, Tracy Slatyer and Chih-Liang Wu (2019)



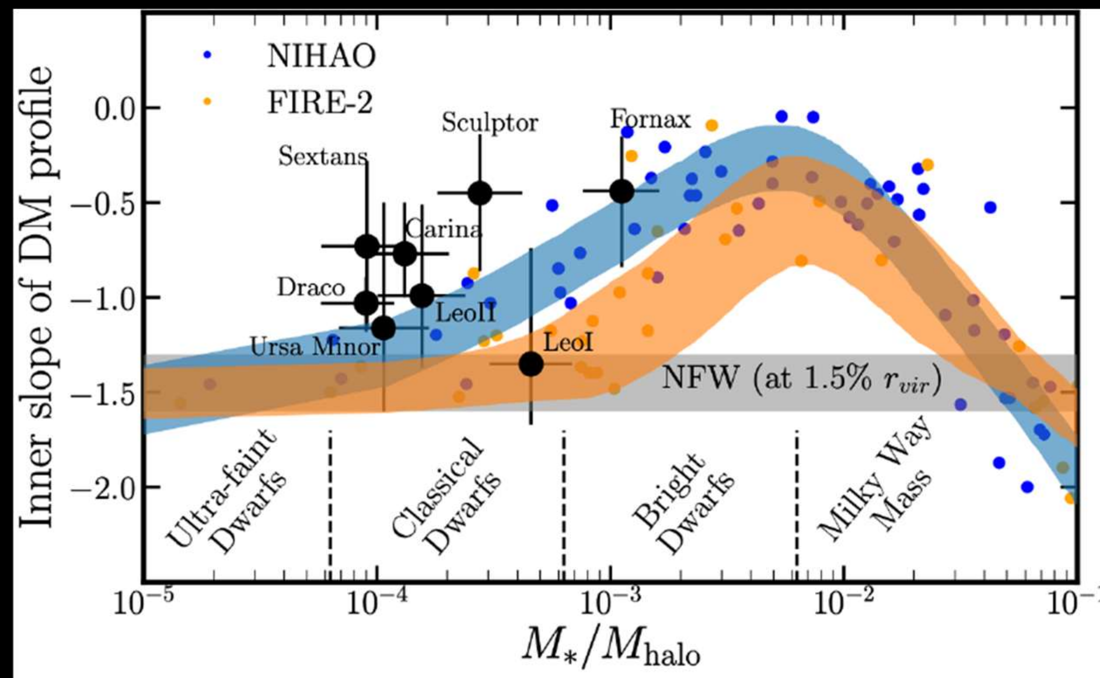
Yang, Nadler and Yu (2023)

Test 1 of the large cross section solution: The population of the faintest satellite galaxies in the Milky Way

Errani et al. 2022 (2111.05866)

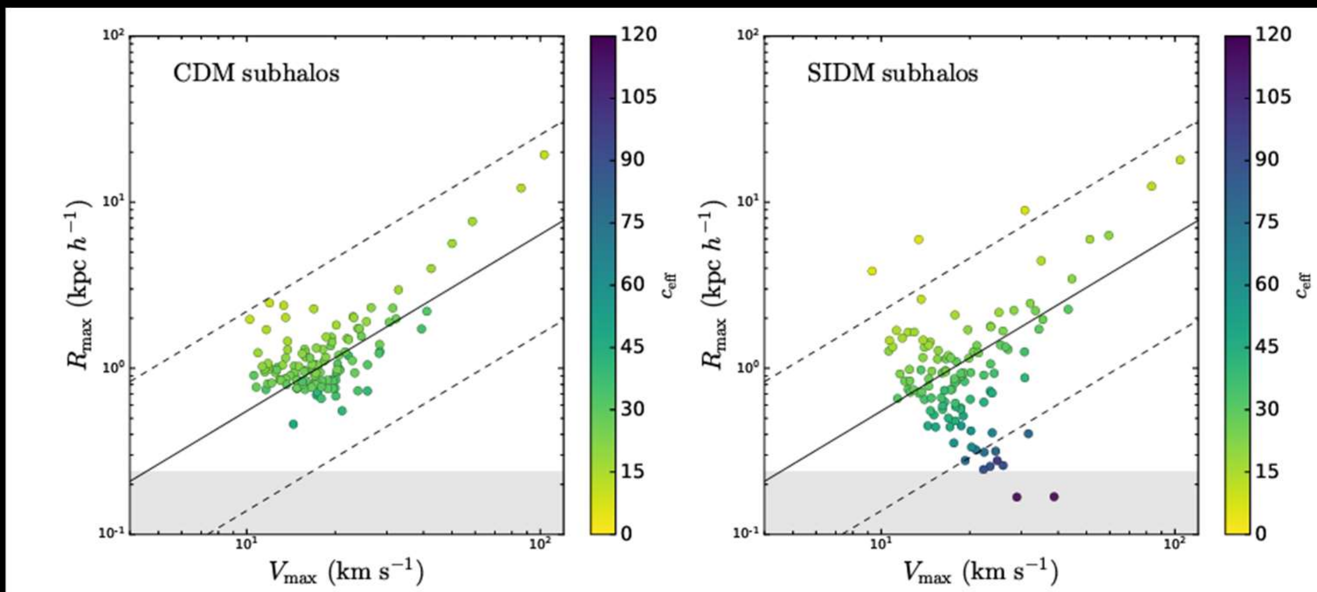


Using densities as a test of the viability of models



MW satellites: Density within half-light radius vs half-light radius

Hayashi et al. 2020 (2007.13780)



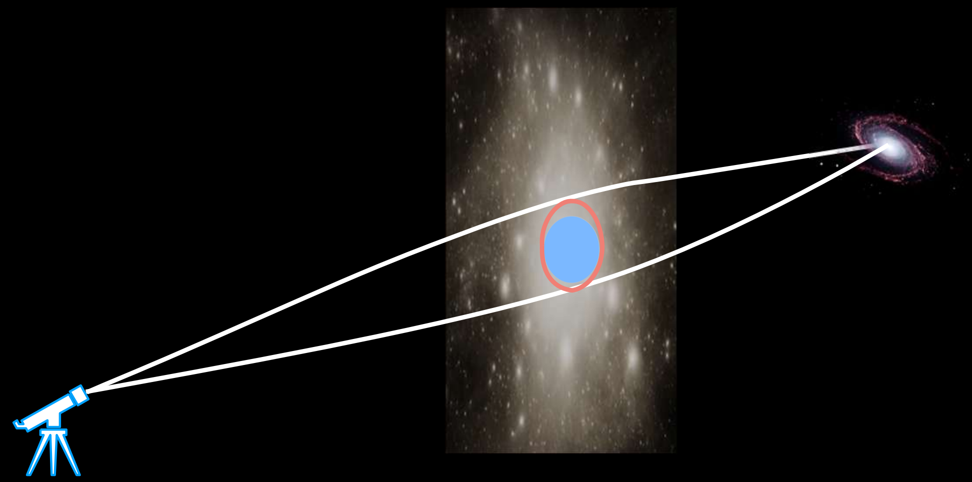
Yang, Nadler and Yu (2023)

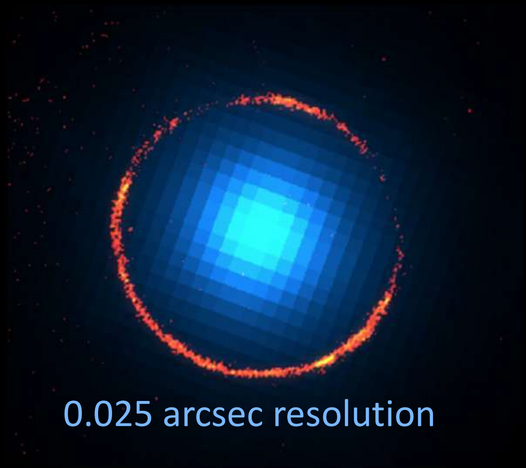
The diversity in halo structural parameters in CDM and large cross section SIDM models:

This figure suggests larger spread around CDM expectation for large cross section SIDM models

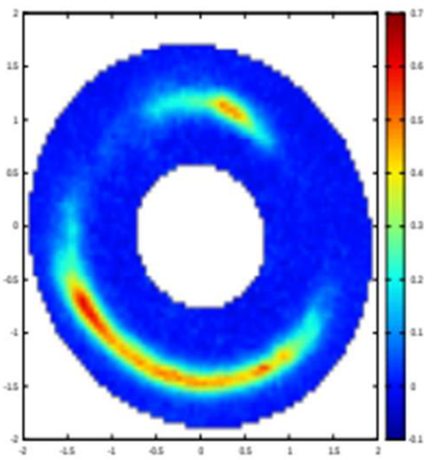
Stay tuned for work in this area in the next few years

Test 2: Detecting Dark Subhalos with Strong Lensing

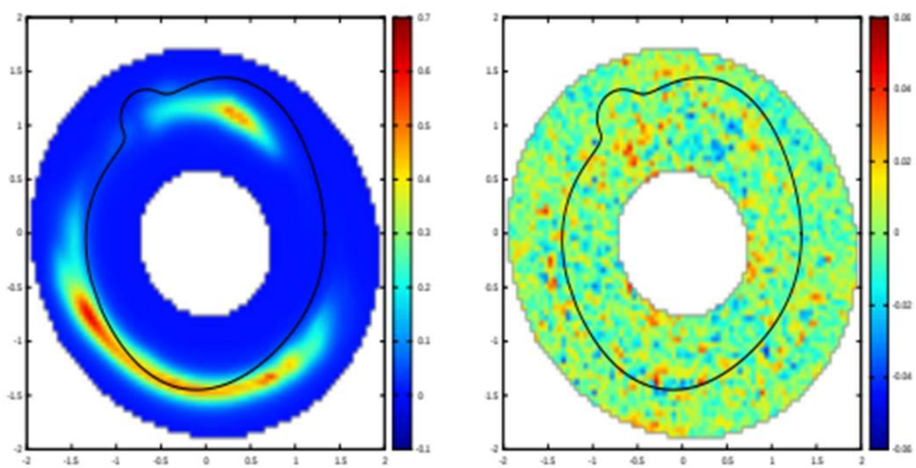




SDSSJ0946+1006 requires an unexpectedly high subhalo density



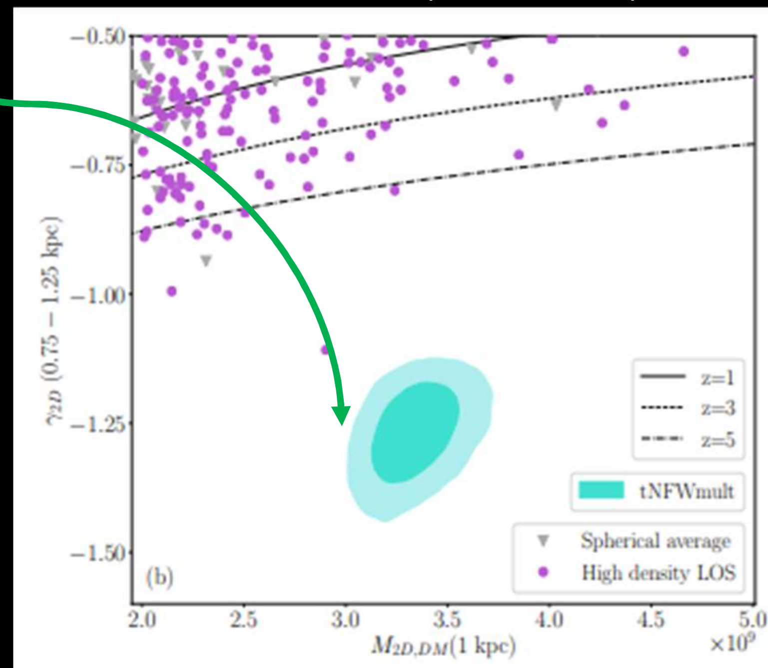
(a) masked HST image



(d) best-fit model, tNFWmult

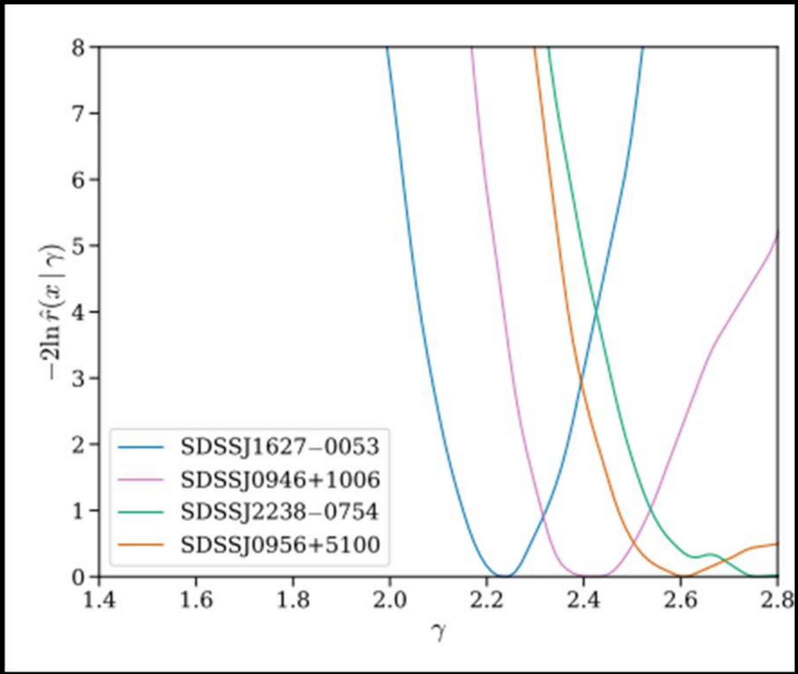
(e) residuals, tNFWmult

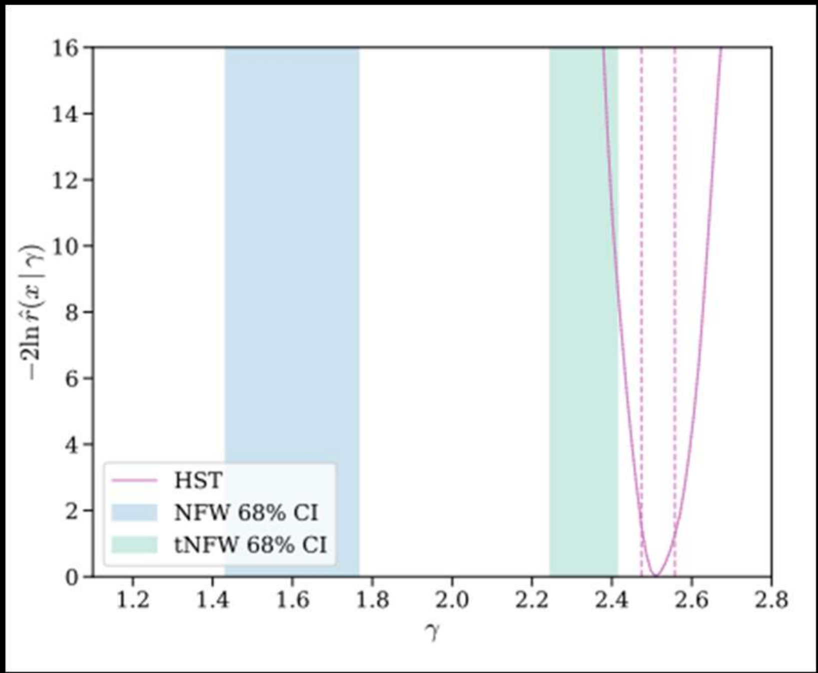
Purple points are those with the highest possible densities in cold dark matter simulations (Illustris TNG)



With Quinn Minor, Sophia Nasir and Simona Vegetti (2020)

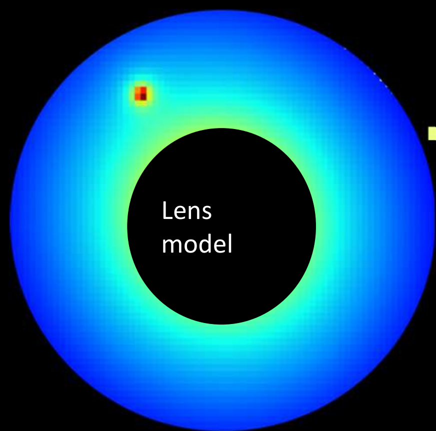
The promise of more data and new methods

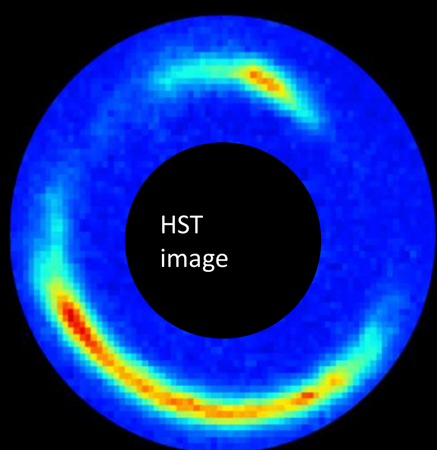




G. Zhang, A. Sengul, C. Dvorkin (2023)

A Possible Discovery Mode





Inferred subhalo density anomalously high, as predicted in some dark-sector theories

Dark force with MeV-scale mediators

Terrestrial experiments!