Gravothermal collapse in dark matter halos

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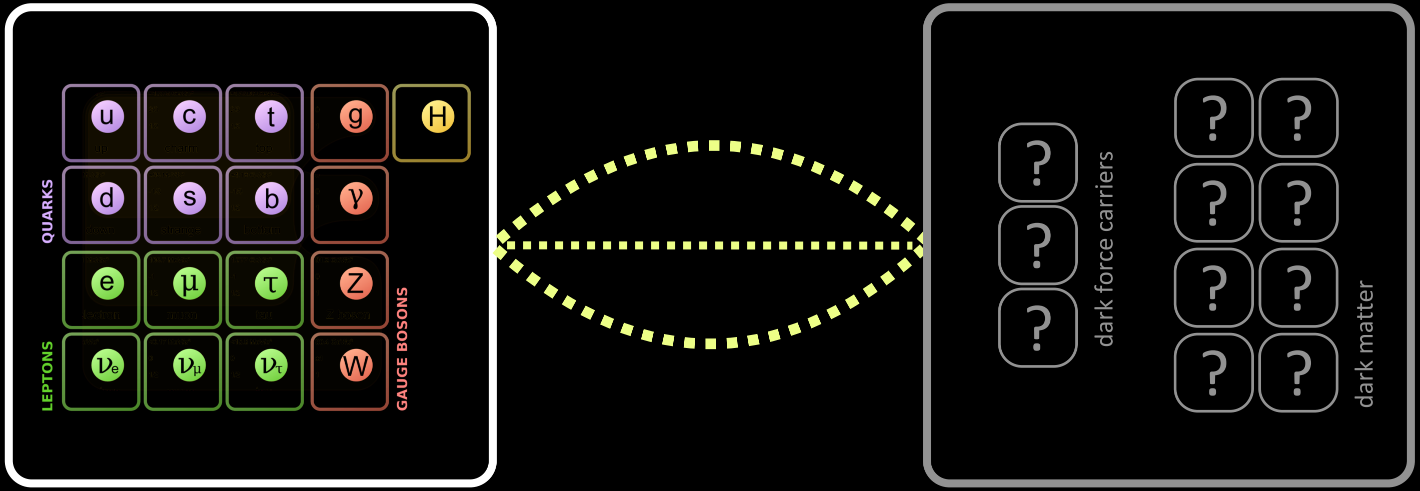
Dark sector dark matter



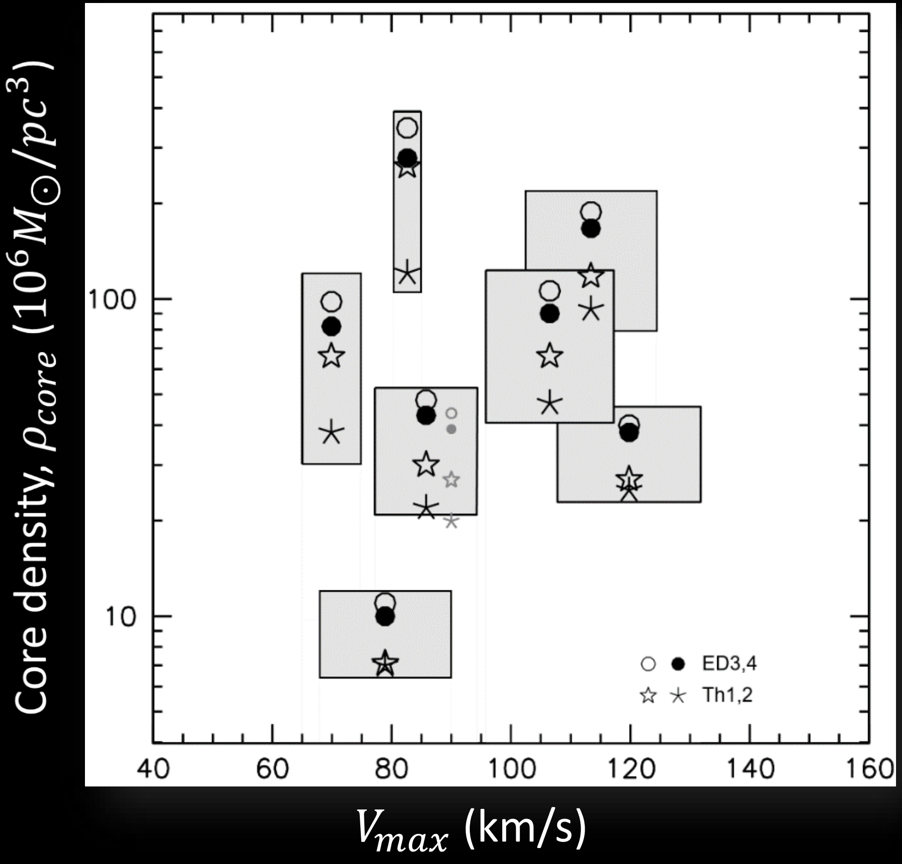
A new dark force that allows for dark matter self-interaction.

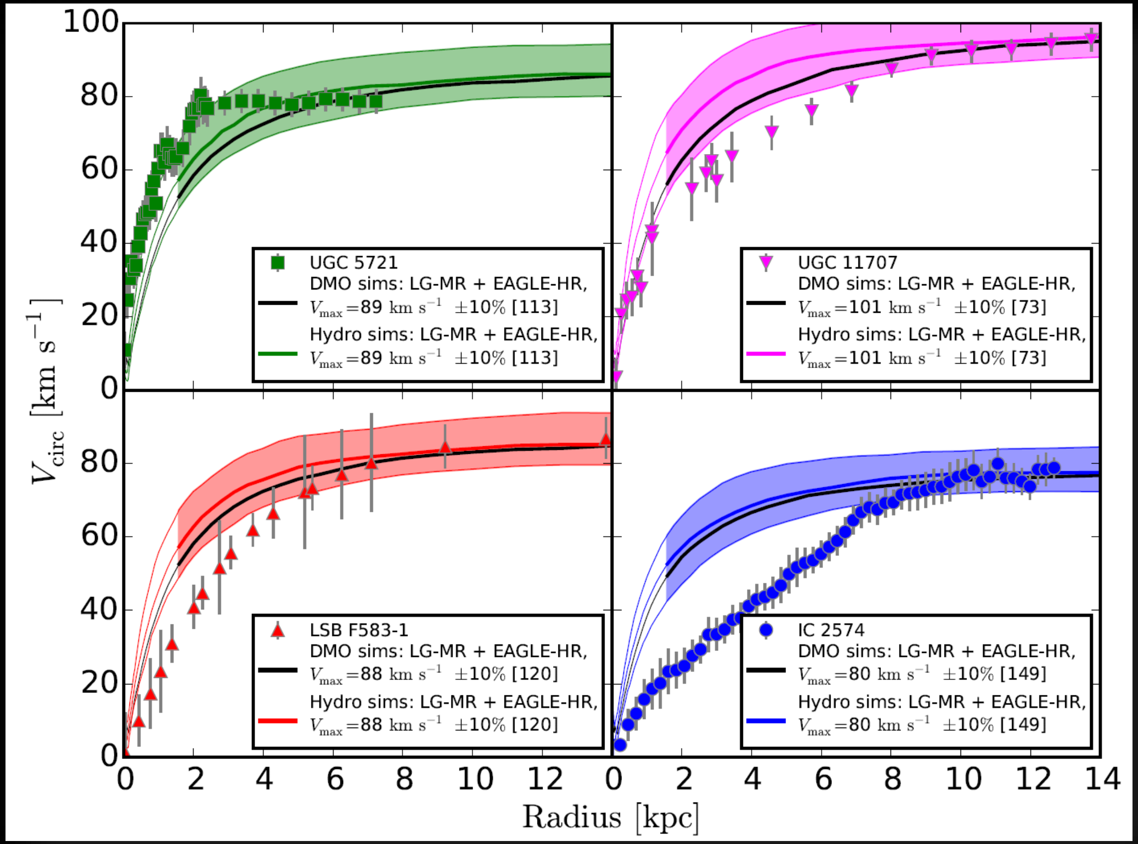
Only viable if cross section over mass, σ/m, is <u>enhanced</u> at small velocities and decreases with velocity.

Outline

- The diversity of field galaxies: focus on rapidly rising rotation curves
- Large σ/m → halos in the core collapse phase → solution to the diversity problem
- Need for gravothermal core collapse in small mass halos
- Tests of models with the large σ/m at low velocities and σ/m dropping sharply with velocity

The puzzling diversity in rotation curves



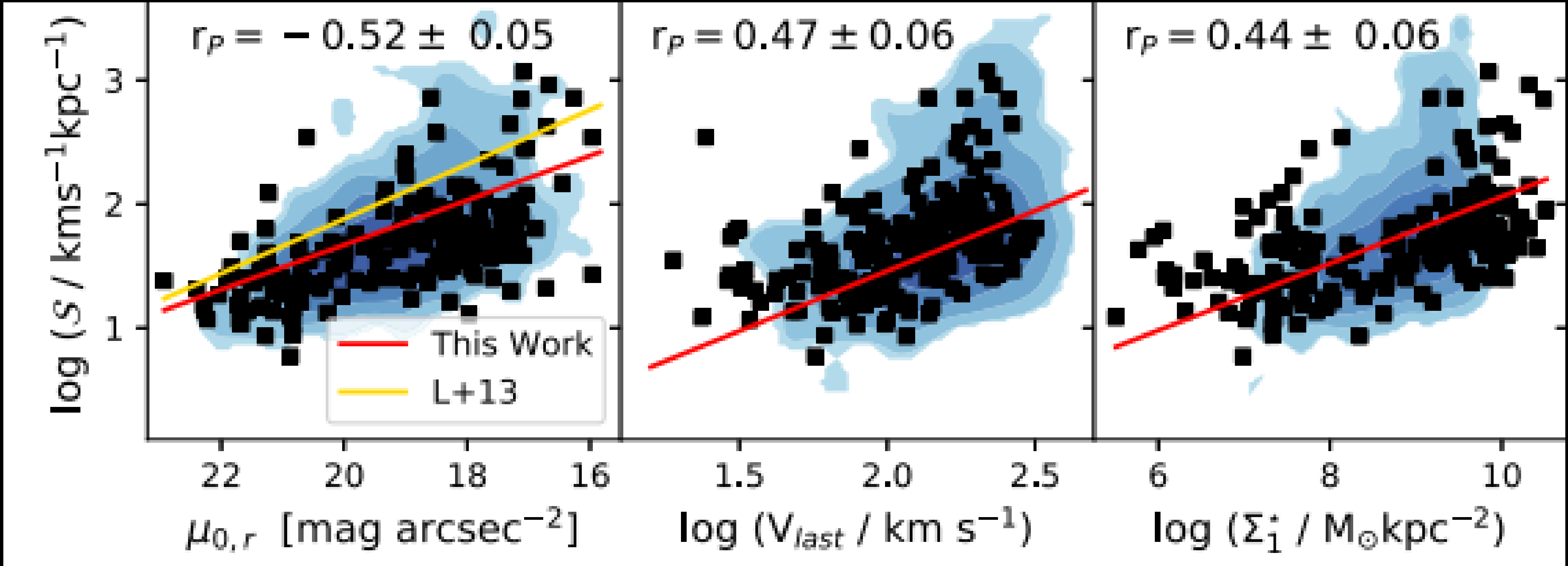


with Rachel Kuzio de Naray, Greg Martinez and James Bullock (2010)

Oman et al, 2015

Diversity in field galaxies

Stars and Dark Matter



Frosst et al 2021

Possible solutions (a simplified view)

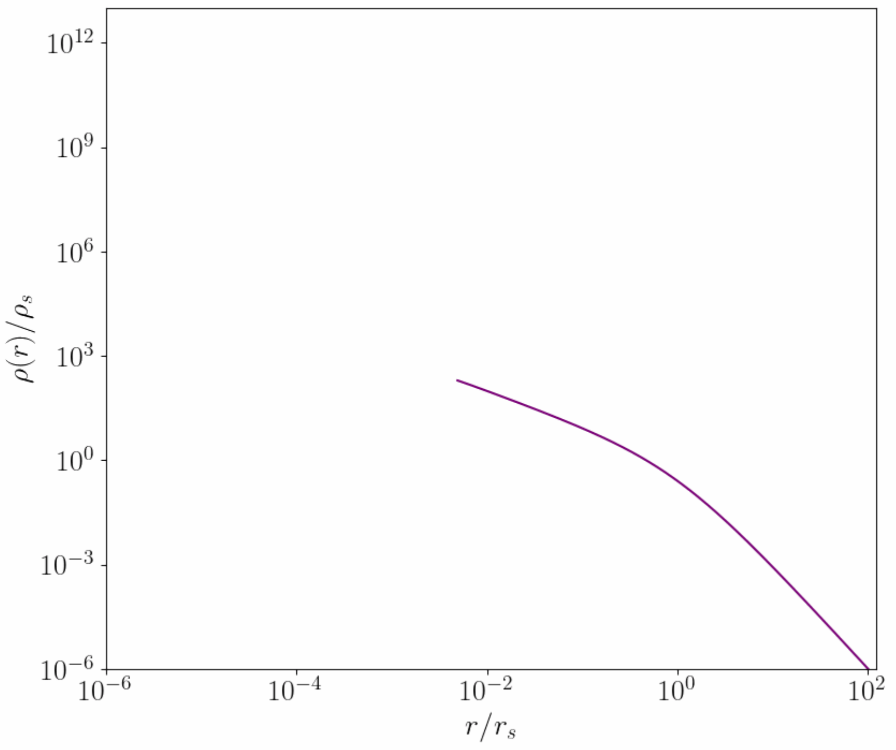
INTERPRETATION OF DATA IS WRONG (NON-ROTATIONAL SUPPORT, INCLINATION ERRORS); ALL HALOS ARE CUSPY

STRONG FEEDBACK

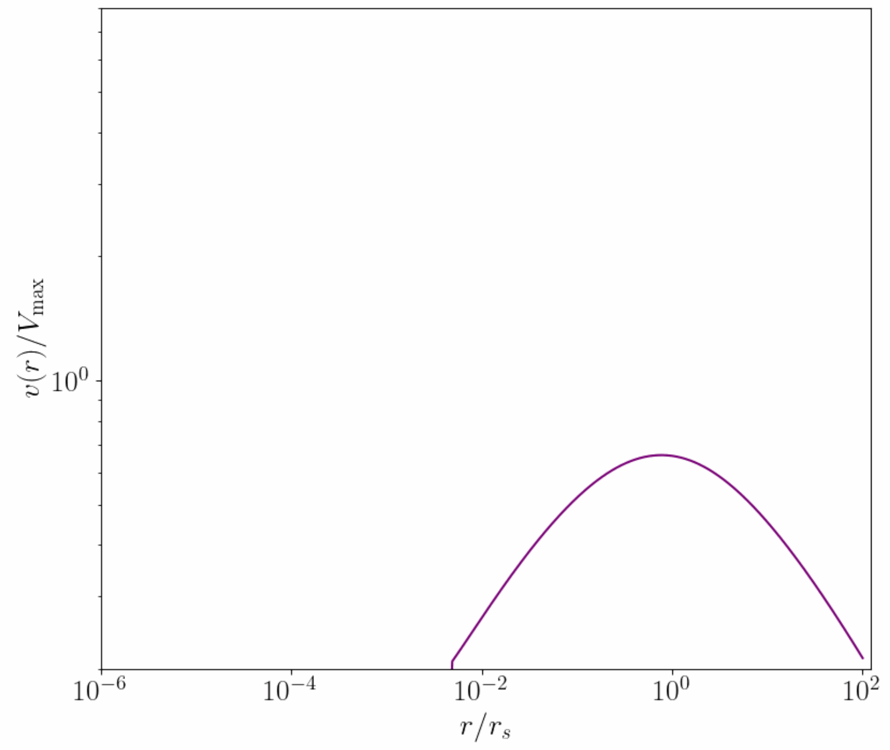
SELF-INTERACTING DARK MATTER

Gravothermal evolution of a SIDM halo

Density vs radius



Velocity dispersion vs radius



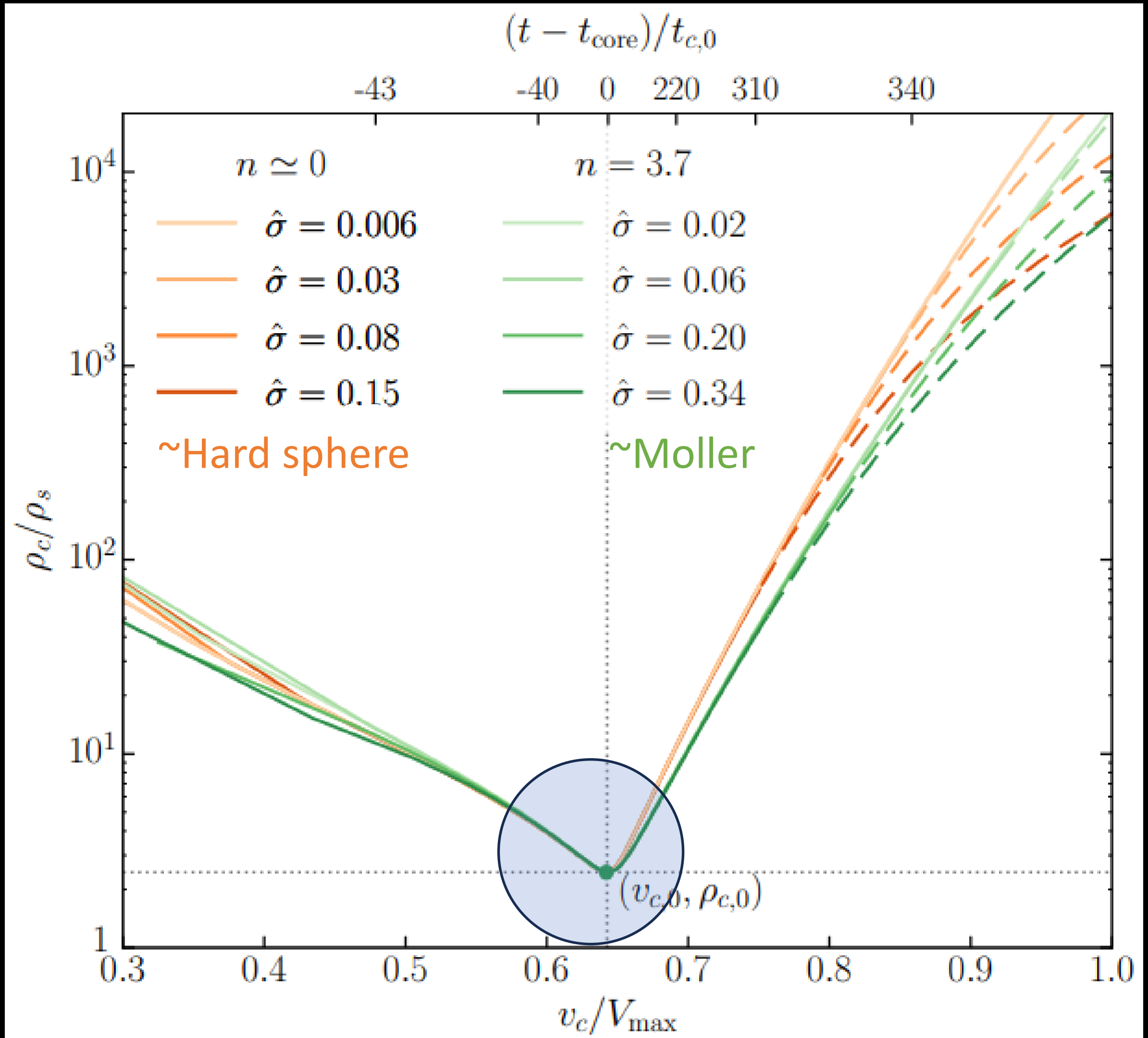
Animations of the temporal evolution of the halo density and velocity dispersion profiles

Gravothermal evolution of the core of SIDM halos

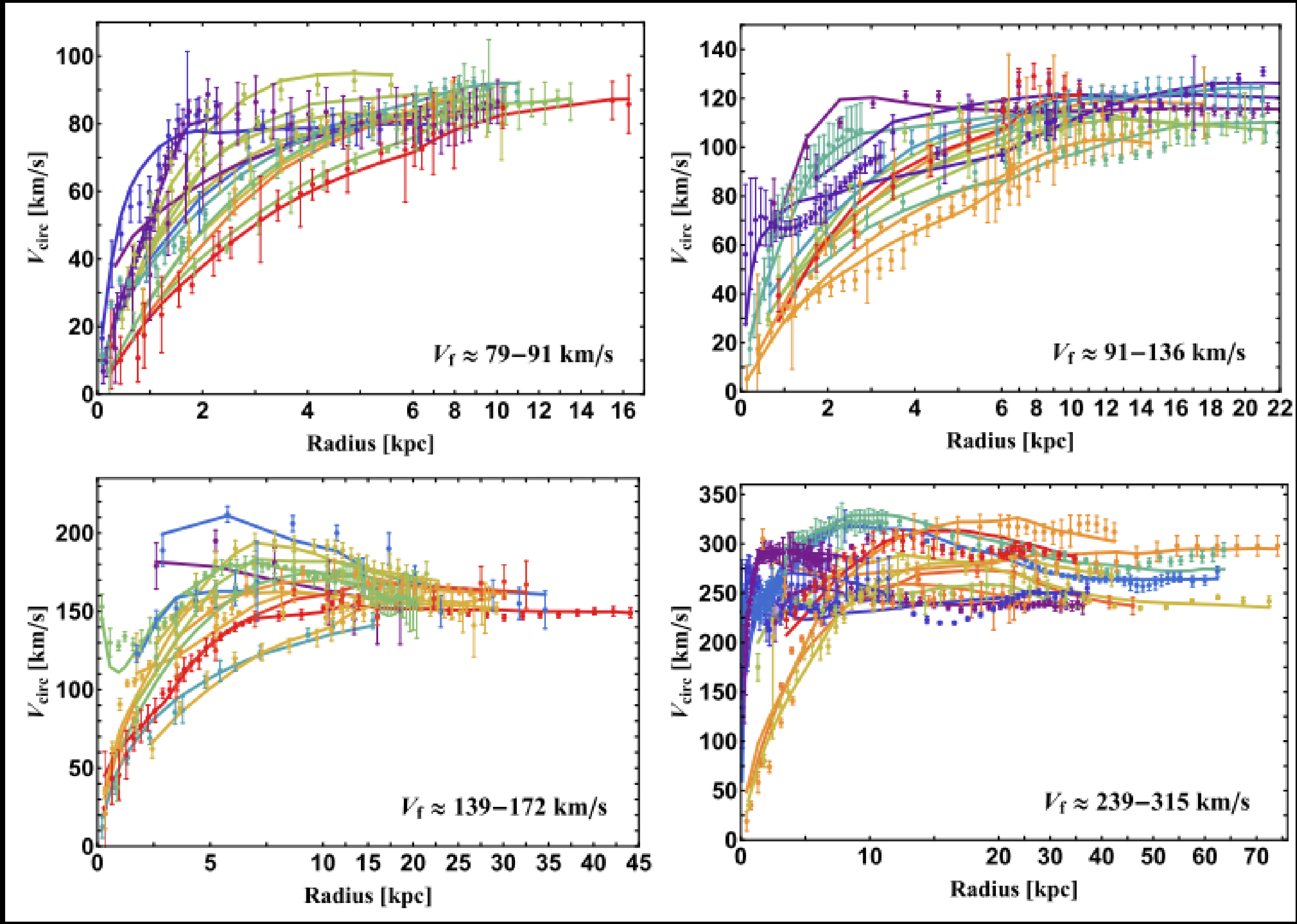
Universal gravothermal evolution → particle physics and halo properties can be scaled out in the long mean-free-path regime (solid part of the curves).

$$t_{c,0}^{-1} \propto \rho_{c,0} v_{c,0} \langle v^5 \sigma_{\text{viscosity}}/m \rangle / \langle v^5 \rangle$$

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



SIDM fits to the rotation curves (SPARC)

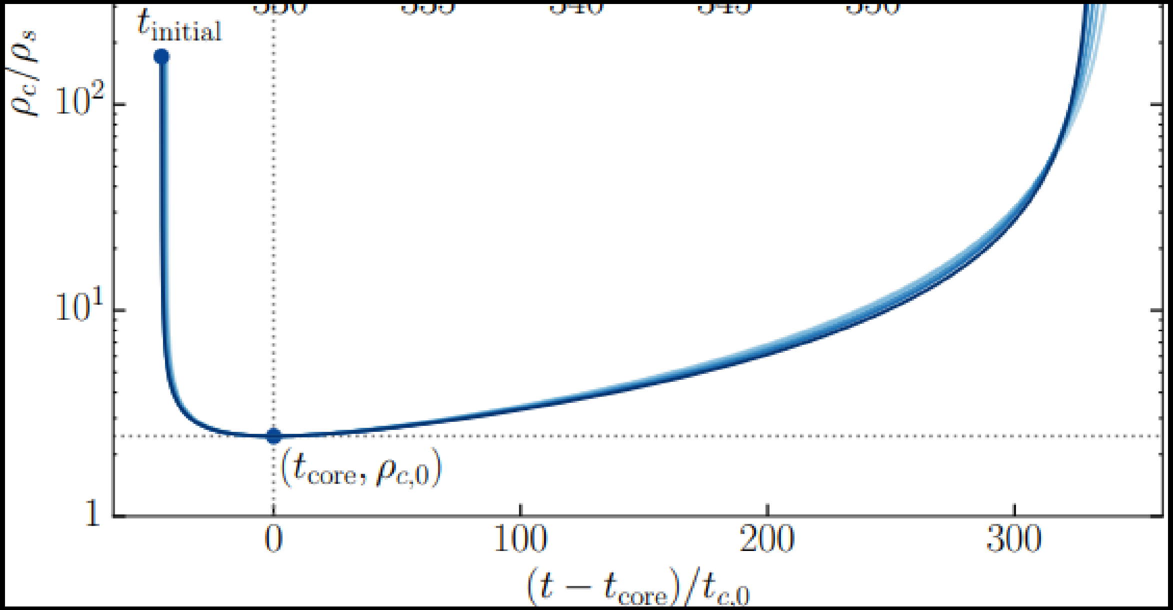


Diversity arises from (1) halo concentrations and (2) response of SIDM halo to the stellar distributions

σ/m set to 3 cm^2/g but overall fit quality is only mildly sensitive to it.

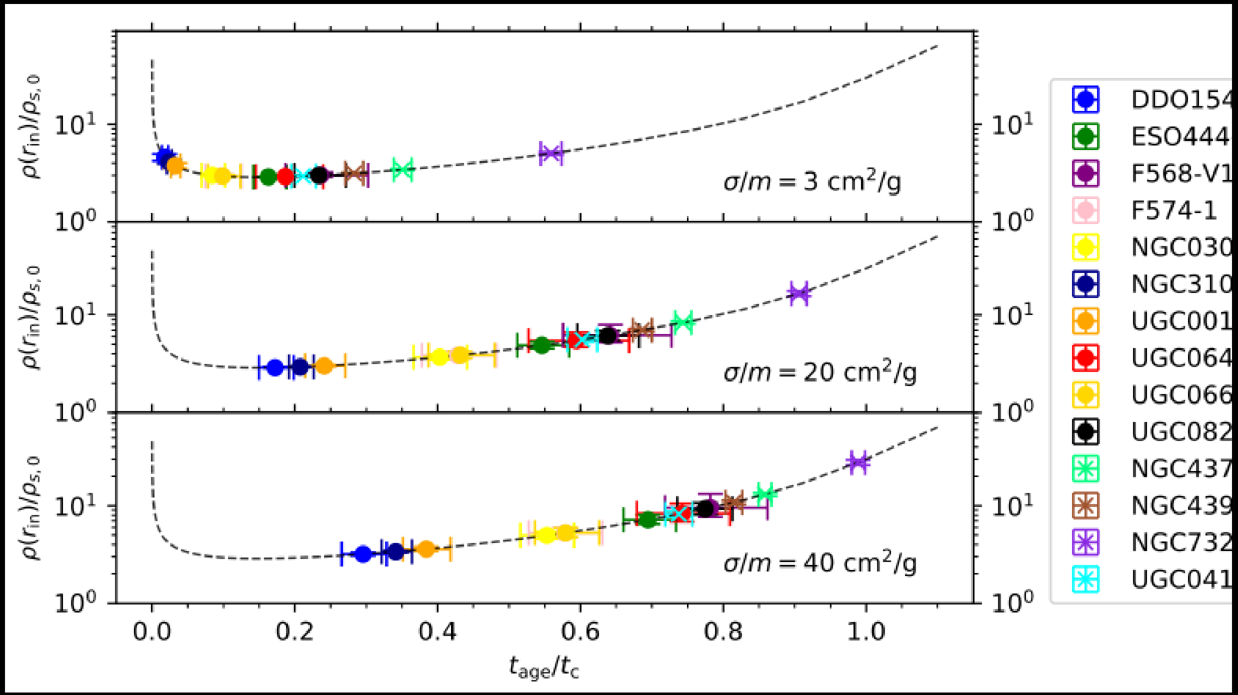
With Tao Ren, Anna Kwa and Hai-Bo Yu (2019)

We have neglected the possibility of very large σ/m in previous analyses.

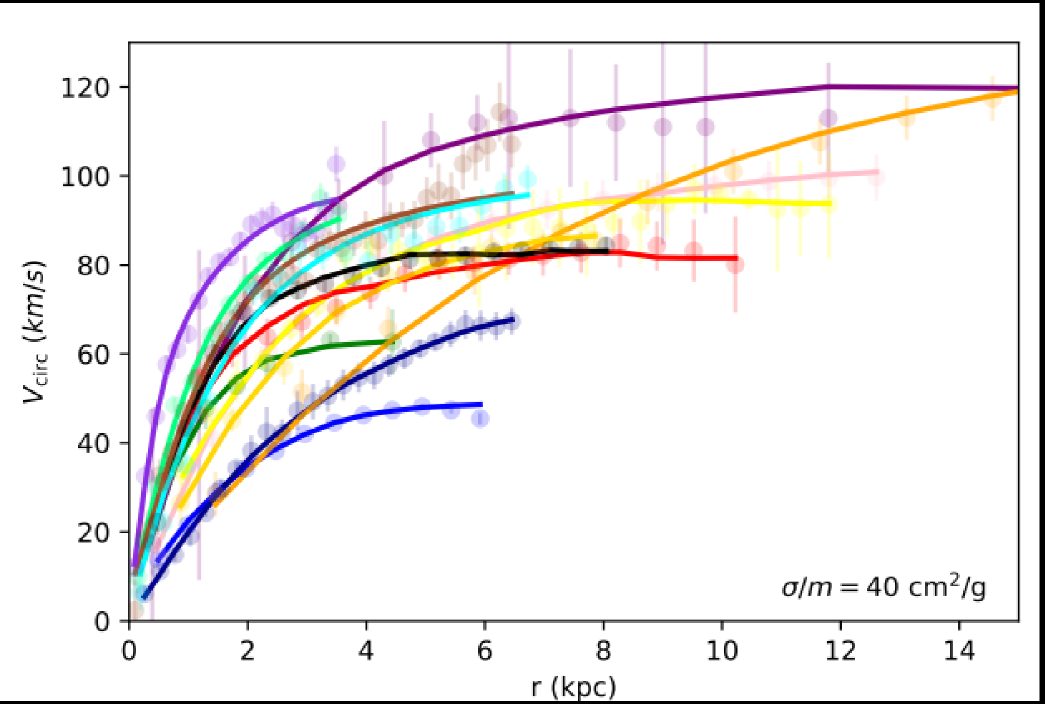


Moderate to large cross section

Large σ/m solution to the diversity problem



There are low-surface brightness galaxies that are dense (cusp-like)

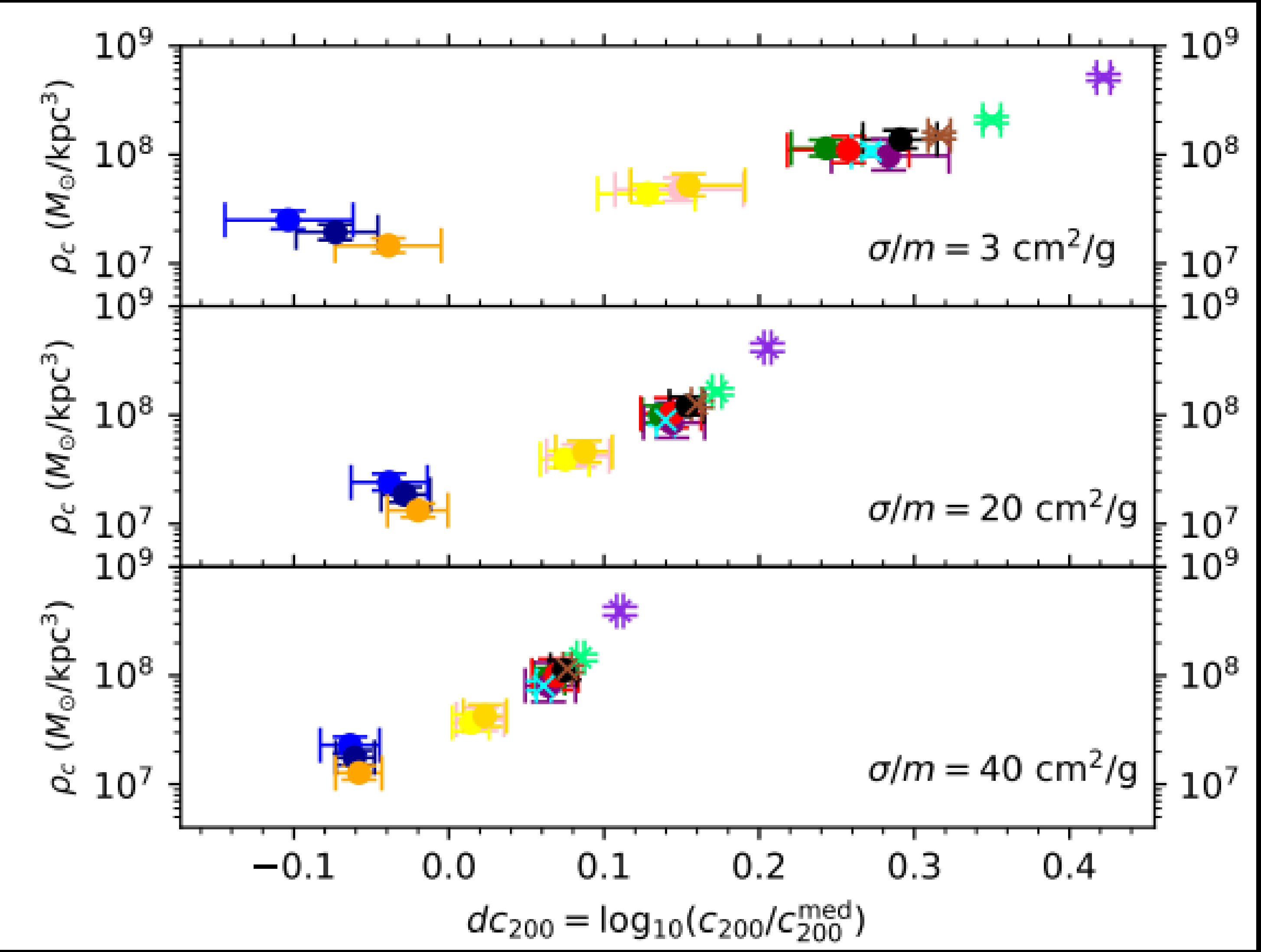


With Grant Roberts, Mauro Valli and Haibo Yu (will be posted soon)

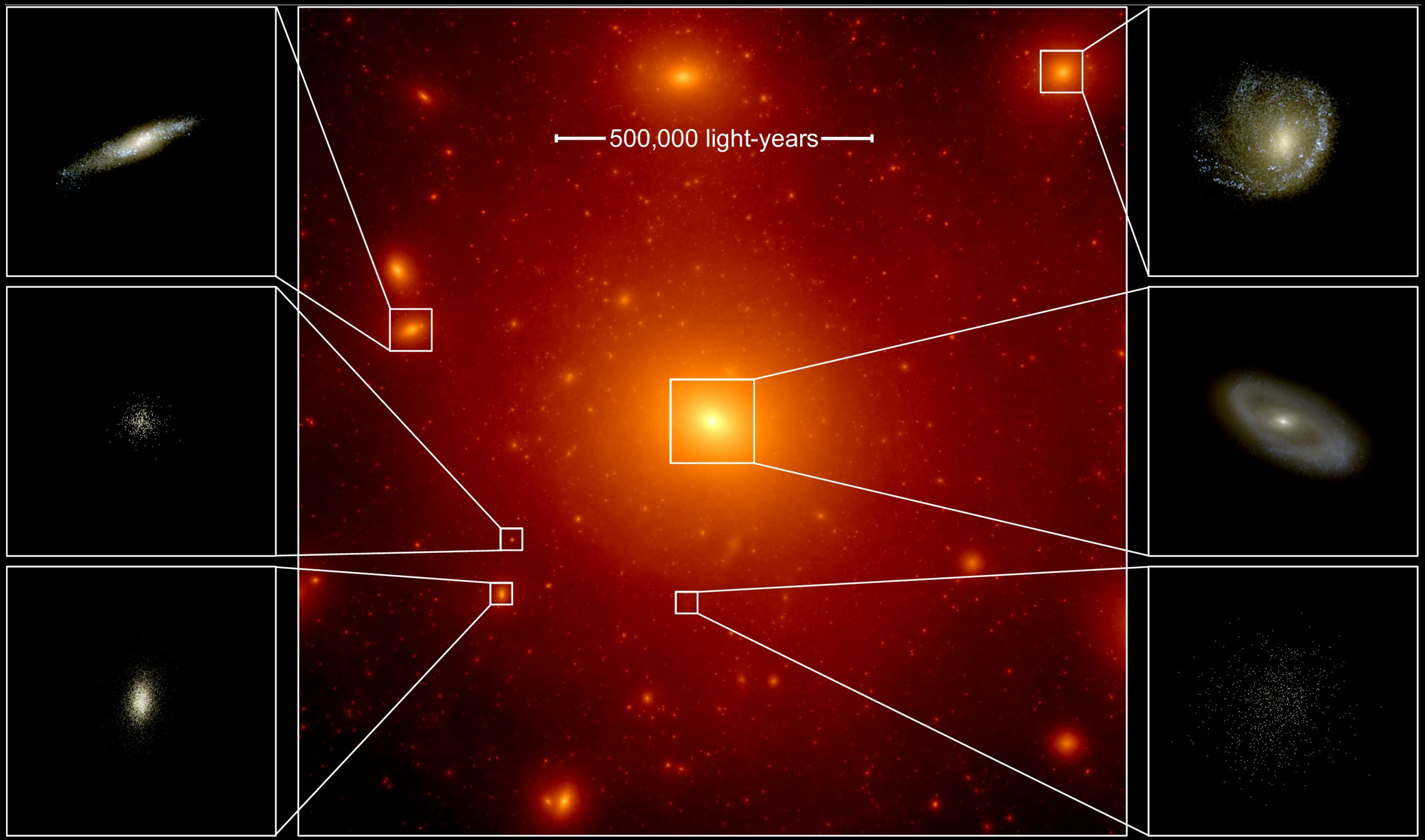
Large σ/m solution to the diversity problem: diversity from the halo concentration

The concentration distribution argues for a solution like that for 20 cm^2/g.

Much larger σ/m are likely to be ruled out using rotation curves (more work needed)

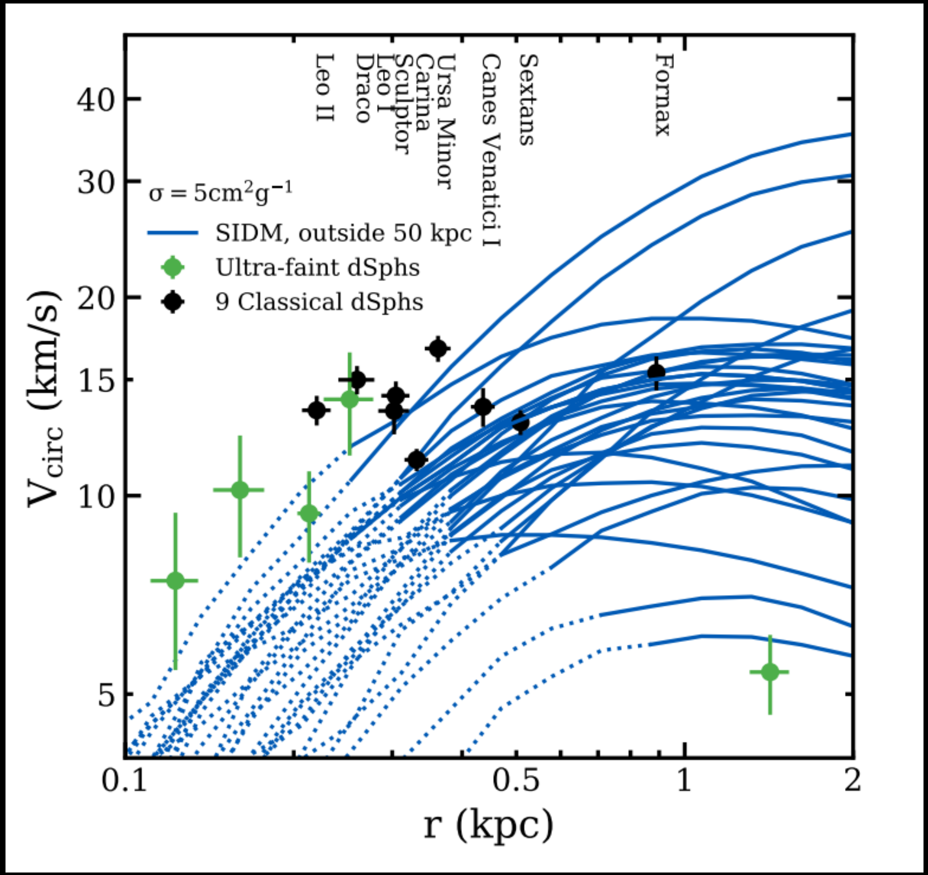


Milky Way satellites: test bed for models that explain the diversity of field galaxies

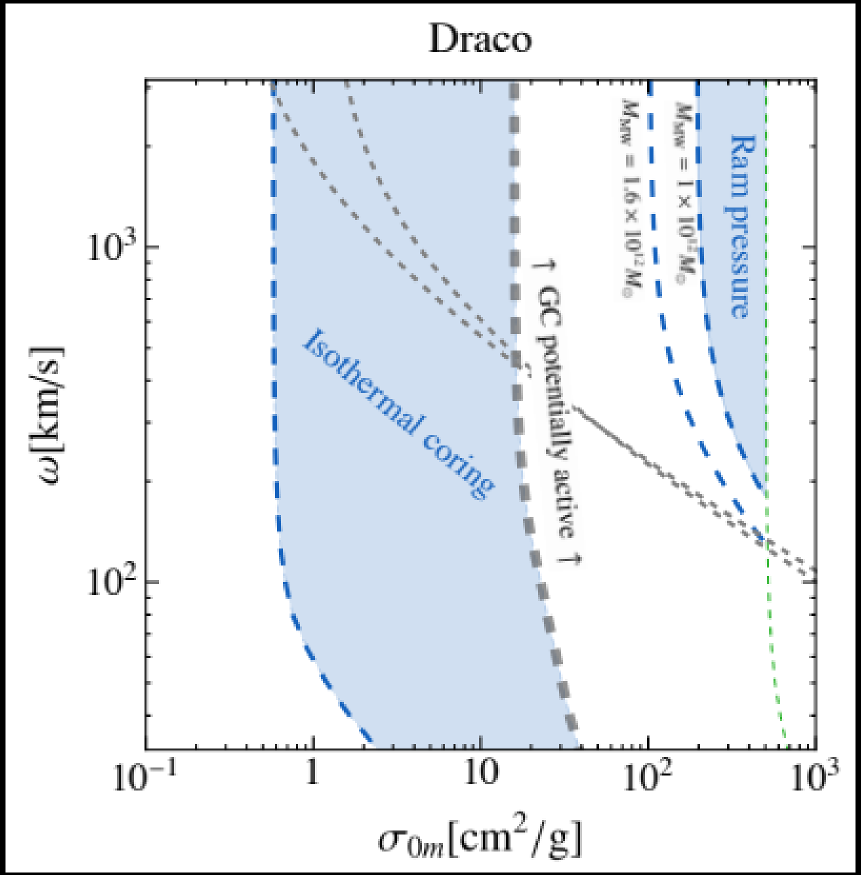


DC Justice League Simulations, Alyson Brooks et al. (2020)

SIDM solution: Moderate cross sections ($< 10~\mathrm{cm}^2/\mathrm{g}$) are in tension with MW satellite densities



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

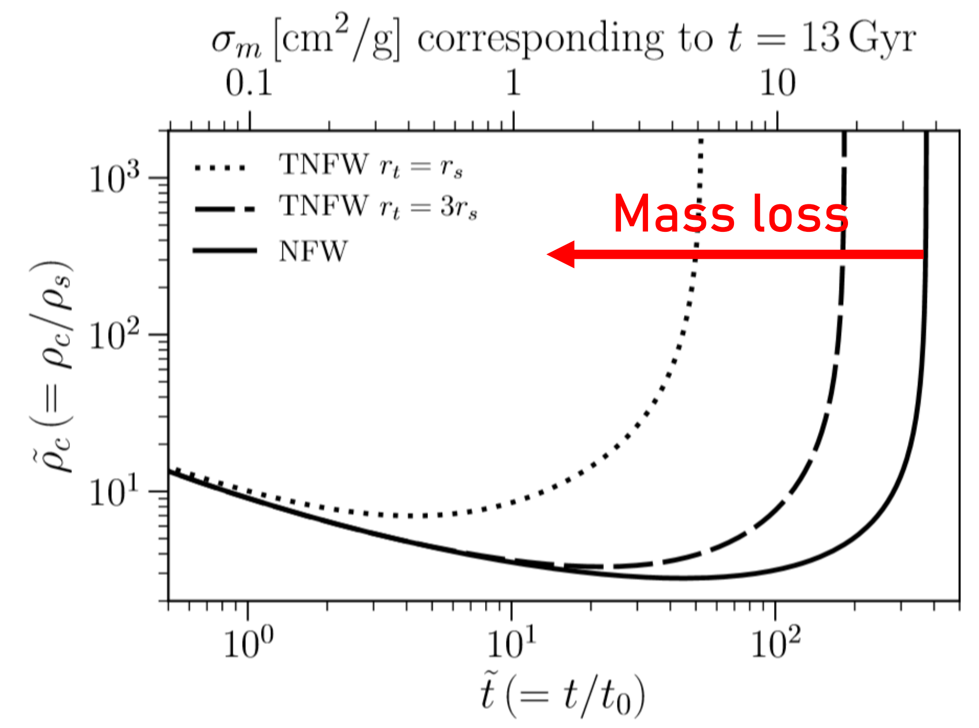


With Oren Slone, Fangzhou Jiang and Mariangela Lisanti (2021)

Test 1: Ultra-faint satellite galaxies of the Milky Way

Subhalo's orbit provides a new source of diversity in the DM density profiles (in addition to halo concentration)

Core density

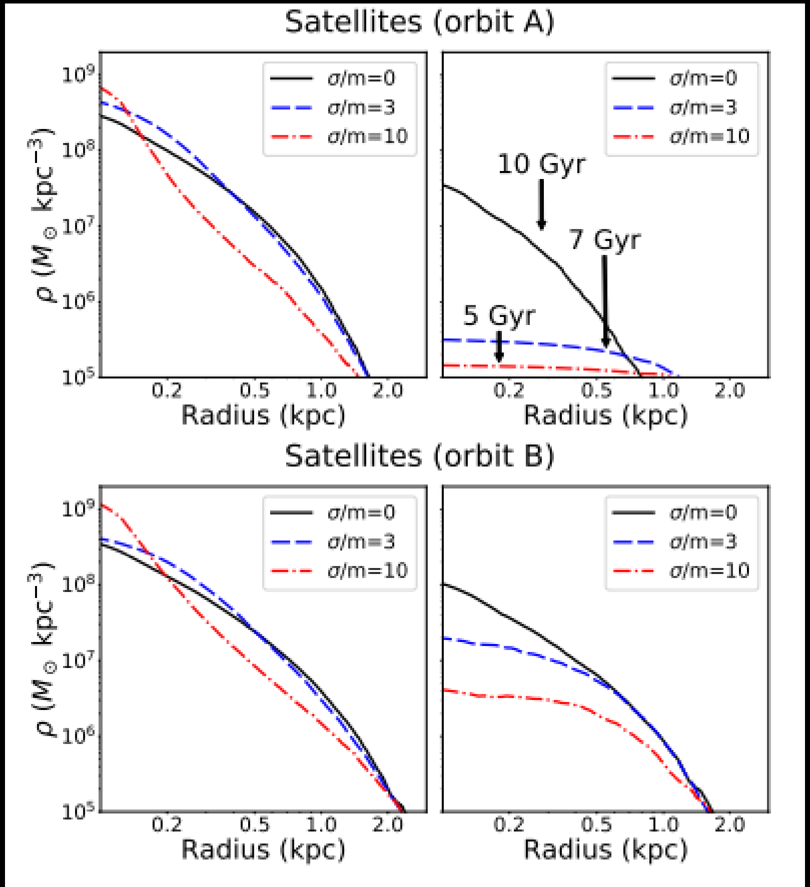


Age/(interaction time)

With Hiro Nishikawa and Kim Boddy (2019)

High concentration; formed early

Low concentration; formed late

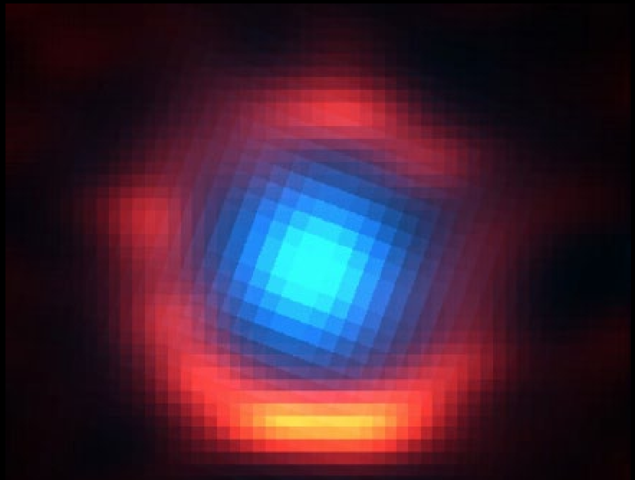


Comes close

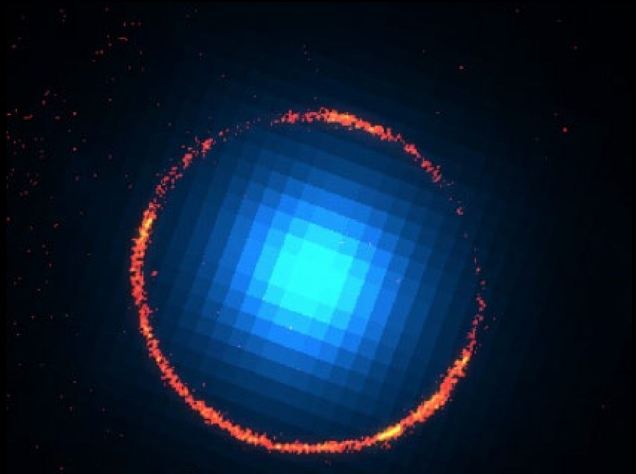
Stays far

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

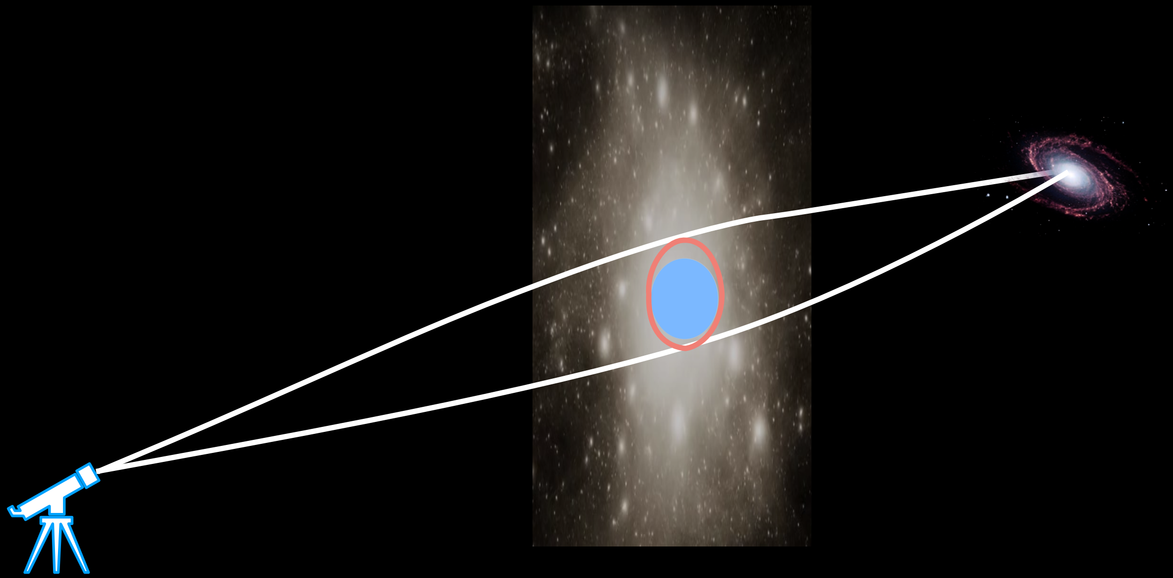
Test 2: Detecting Dark Subhalos with Strong Lensing



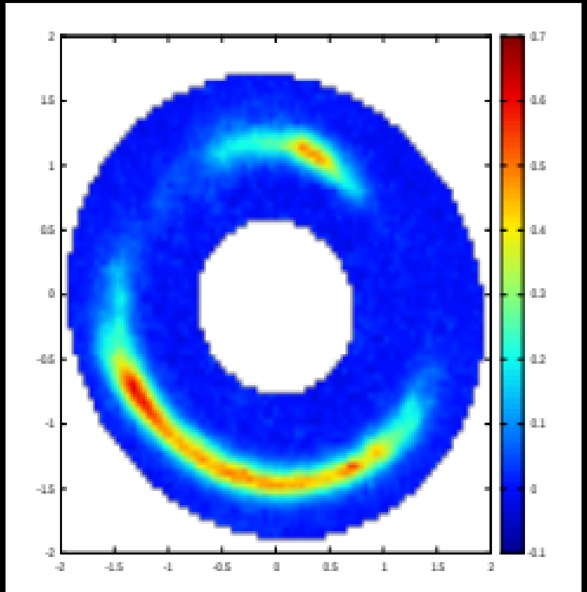
0.4 arcsec resolution (2013)



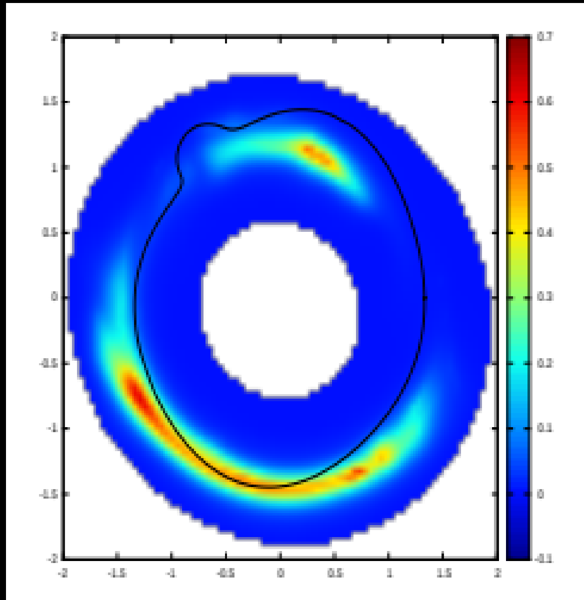
0.025 arcsec resolution (2018)



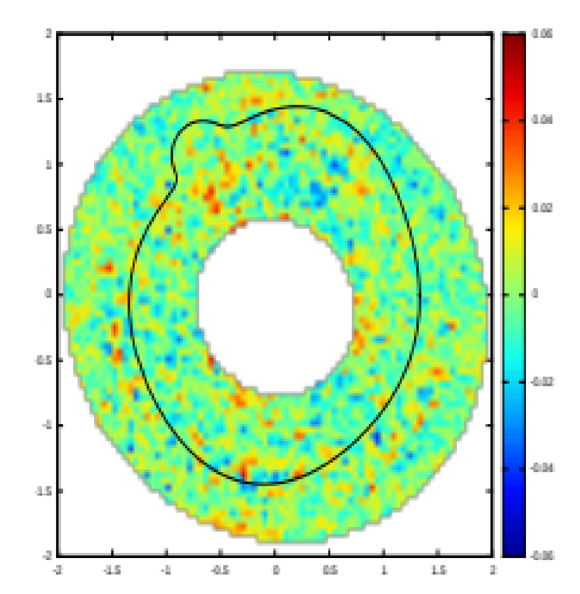
SDSSJ0946+1006 requires an unexpectedly high subhalo density



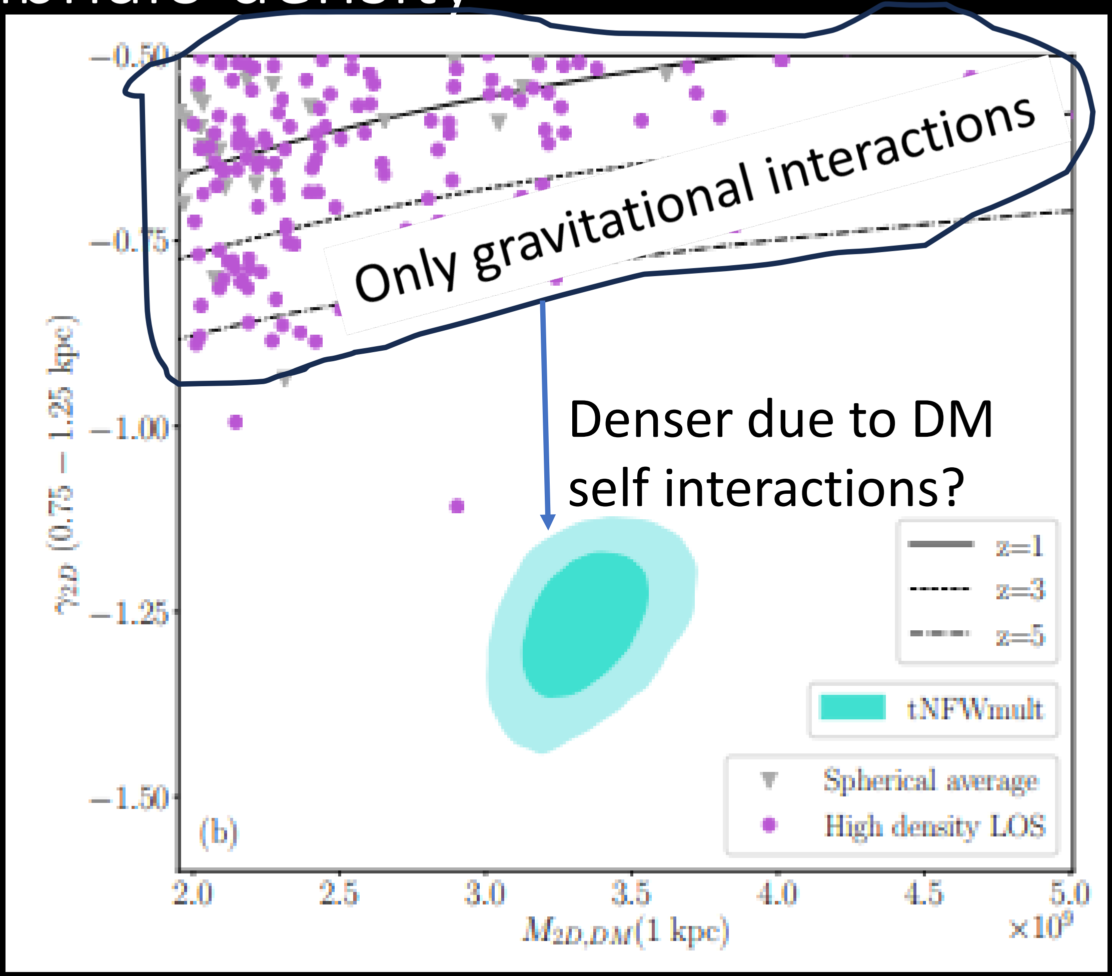
(a) masked HST image



(d) best-fit model, tNFWmult



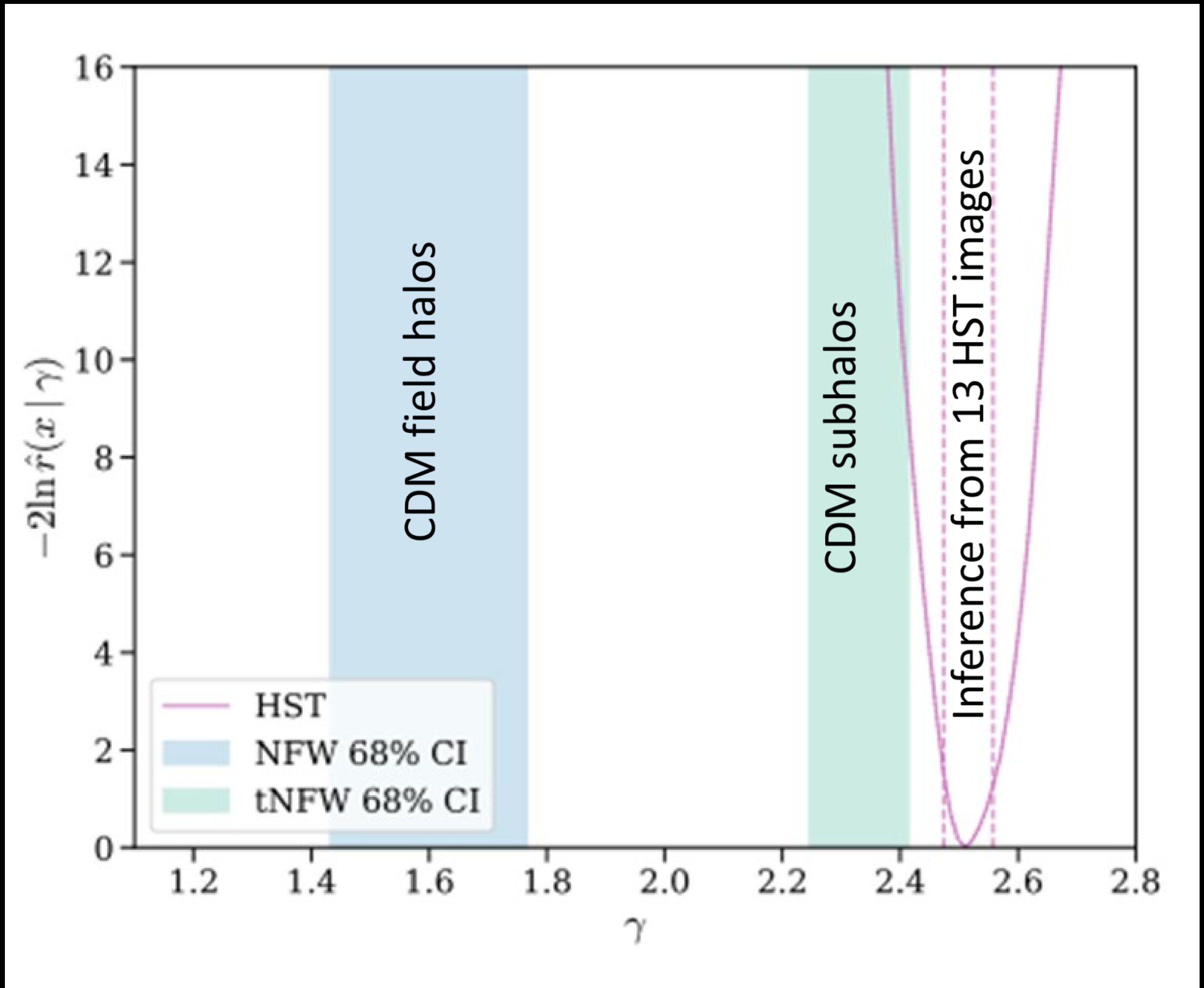
(e) residuals, tNFWmult



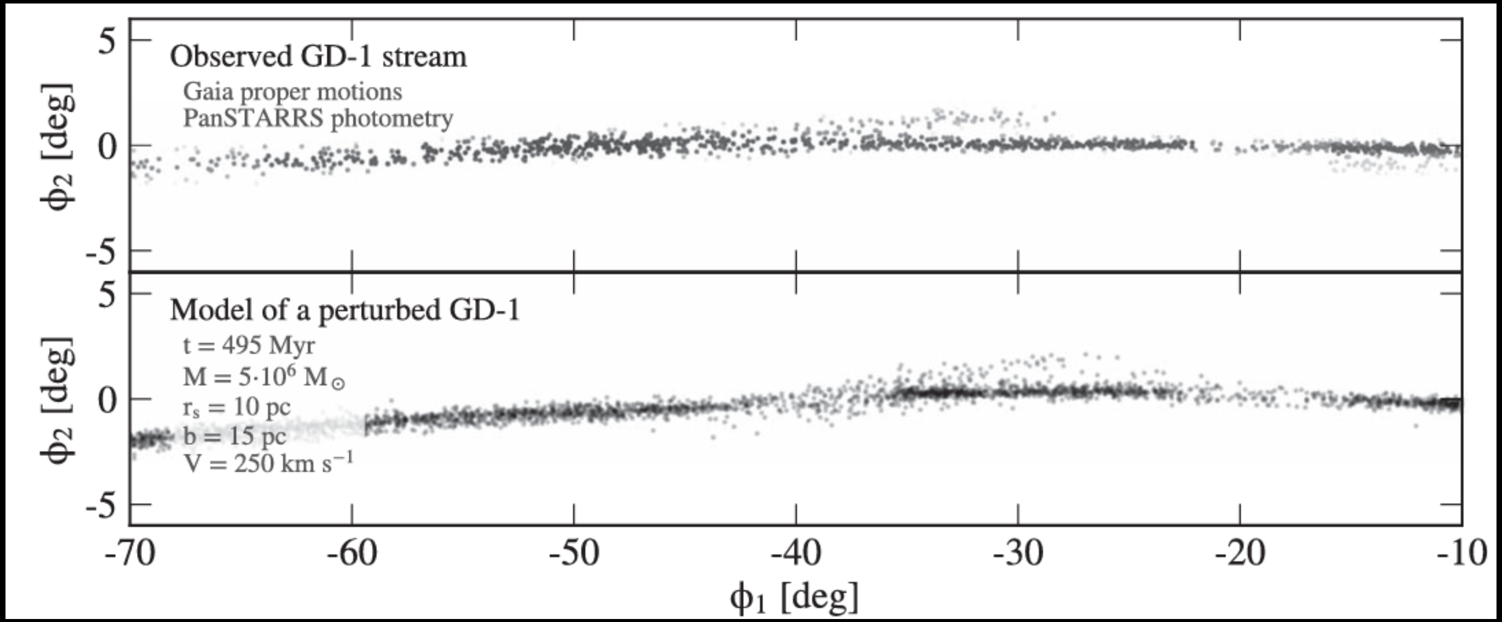
With Quinn Minor, Sophia Nasir and Simona Vegetti (2020)

Test 2: Detecting Dark Subhalos with Strong Lensing

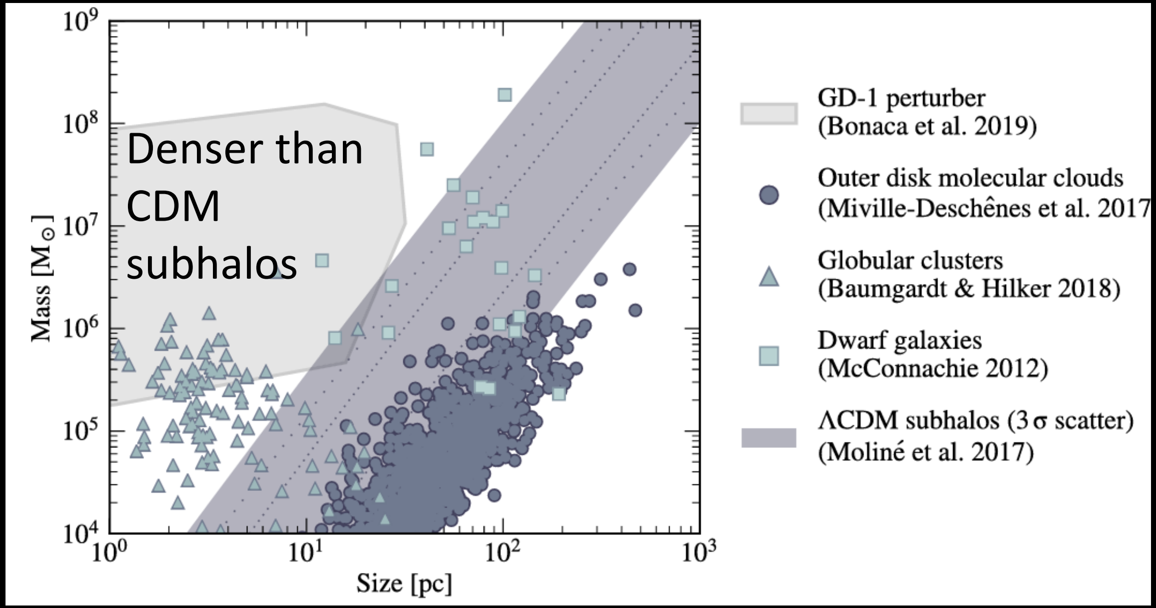
The promise of more data and new methods



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



Test 3: Gaps and spurs in stellar streams



Bonaca, Hogg, Price-Whelan, Conroy (2019)

Conclusions

Diversity of spiral galaxies and Milky Way satellites provide excellent motivations to consider large values for σ/m at velocities below 100 km/s. [Cross section must fall sharply with increasing velocity.]

A promising way to discover non-gravitational self-interactions is to look for objects that are denser than those predicted by CDM.

Substructure lensing, gaps and spurs in stellar streams and ultra-faint satellites of the Milky Way provide opportunities to do so.