Self-Interacting Dark Matter

Hai-Bo Yu
University of California, Riverside

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DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA
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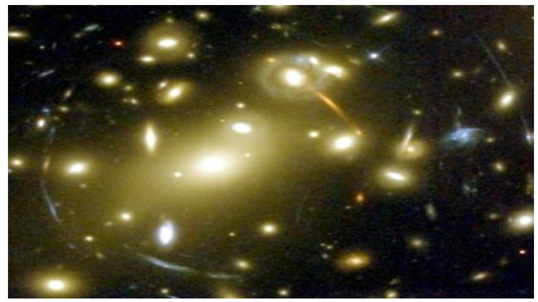
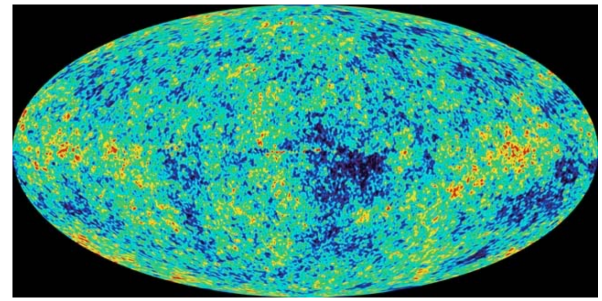
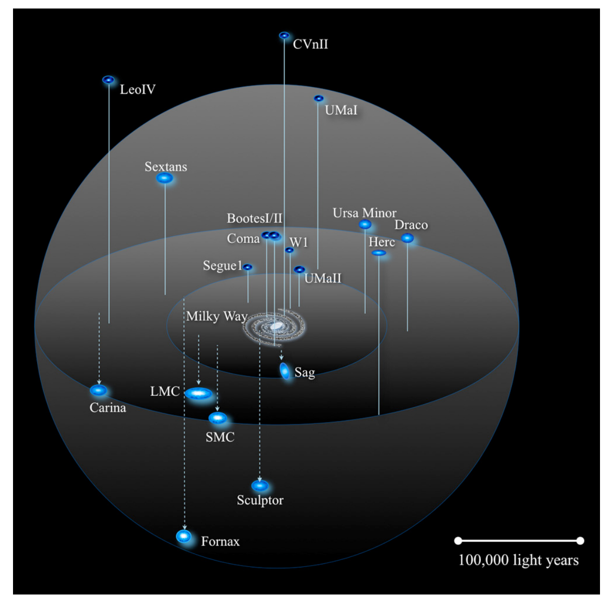
Cold Dark Matter (CDM)

- Large scales: very well

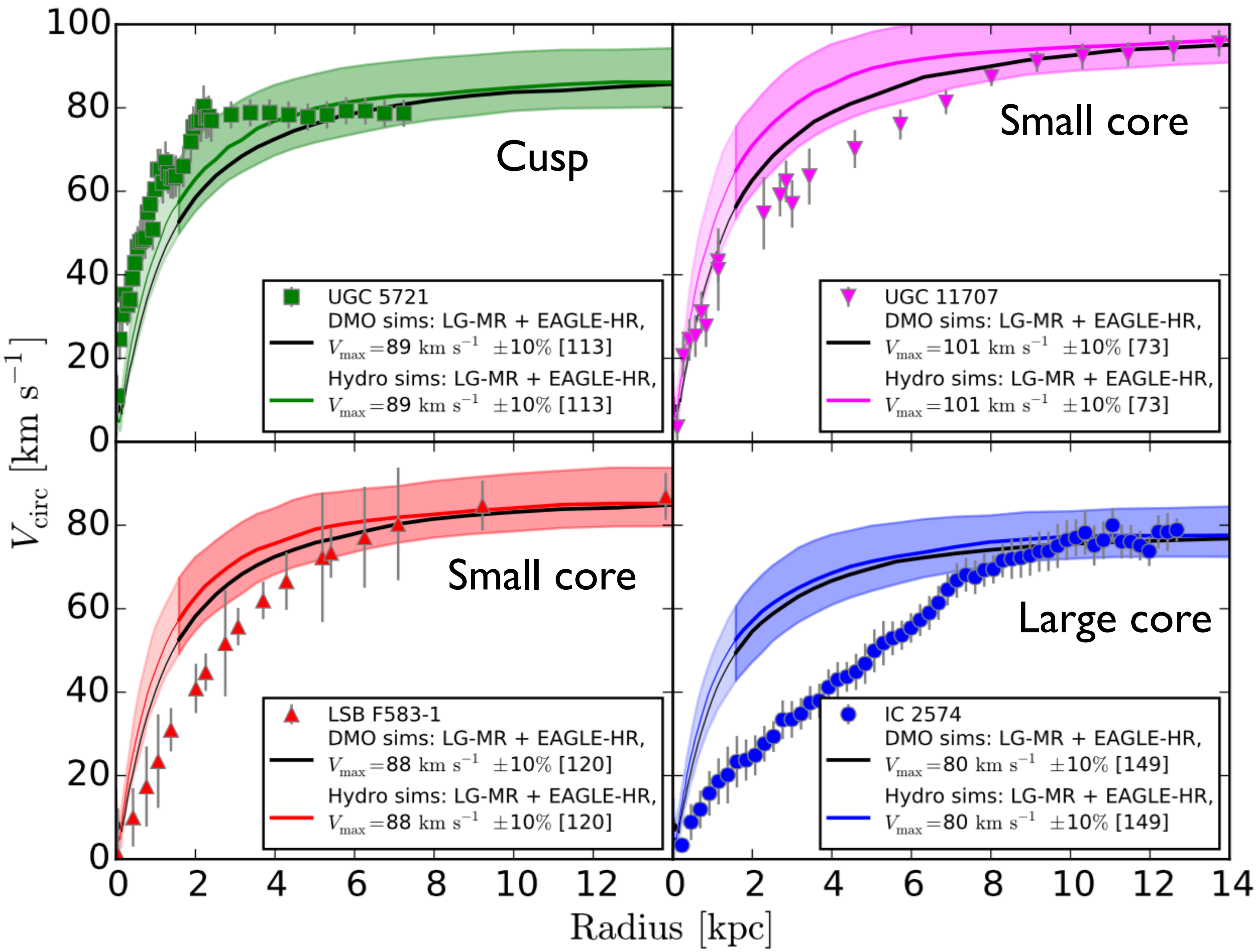




- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
  - Core vs Cusp
  - Diversity
  - Too big to fail
  - “Cores” in clusters
  - Ultra-diffuse galaxies



The Diversity Problem



All galaxies have the same observed Vmax!

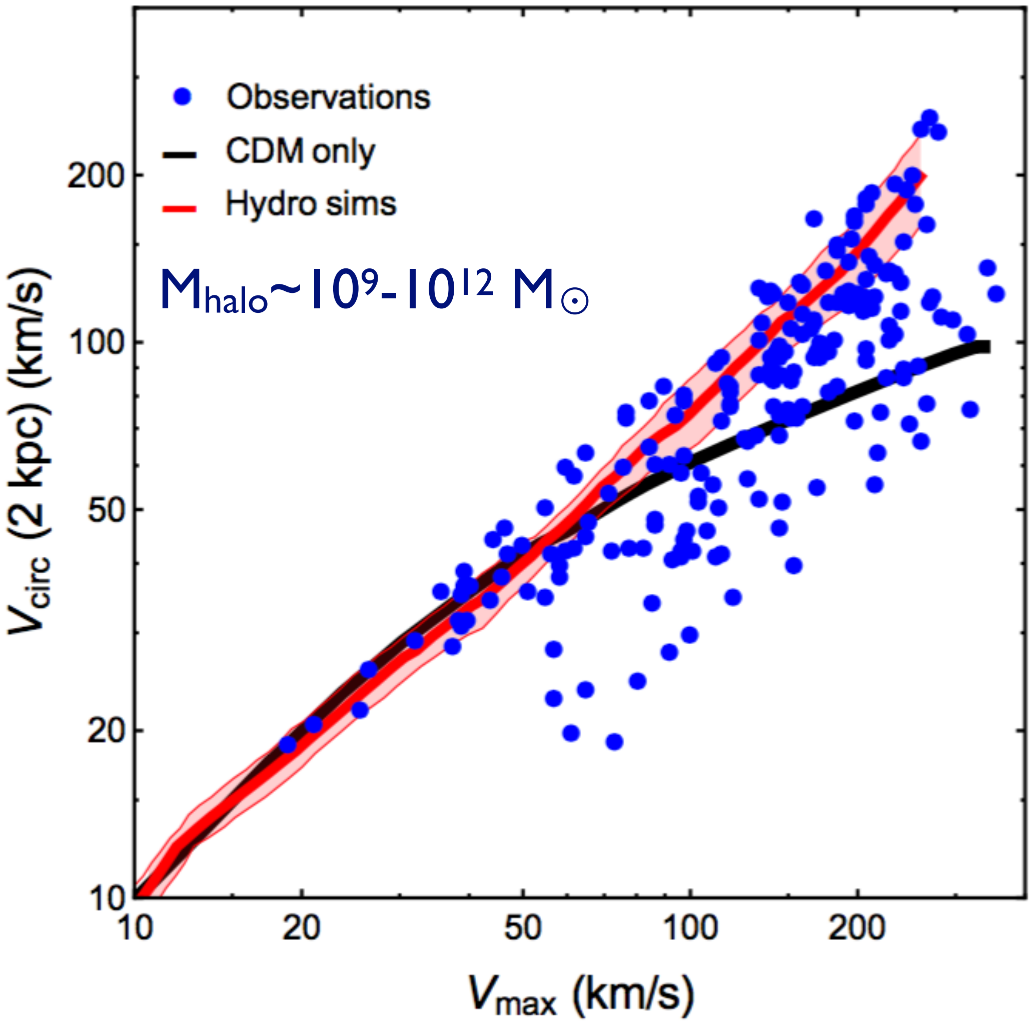
$$V \sim \sqrt{GM/r}$$

Oman+(2015)

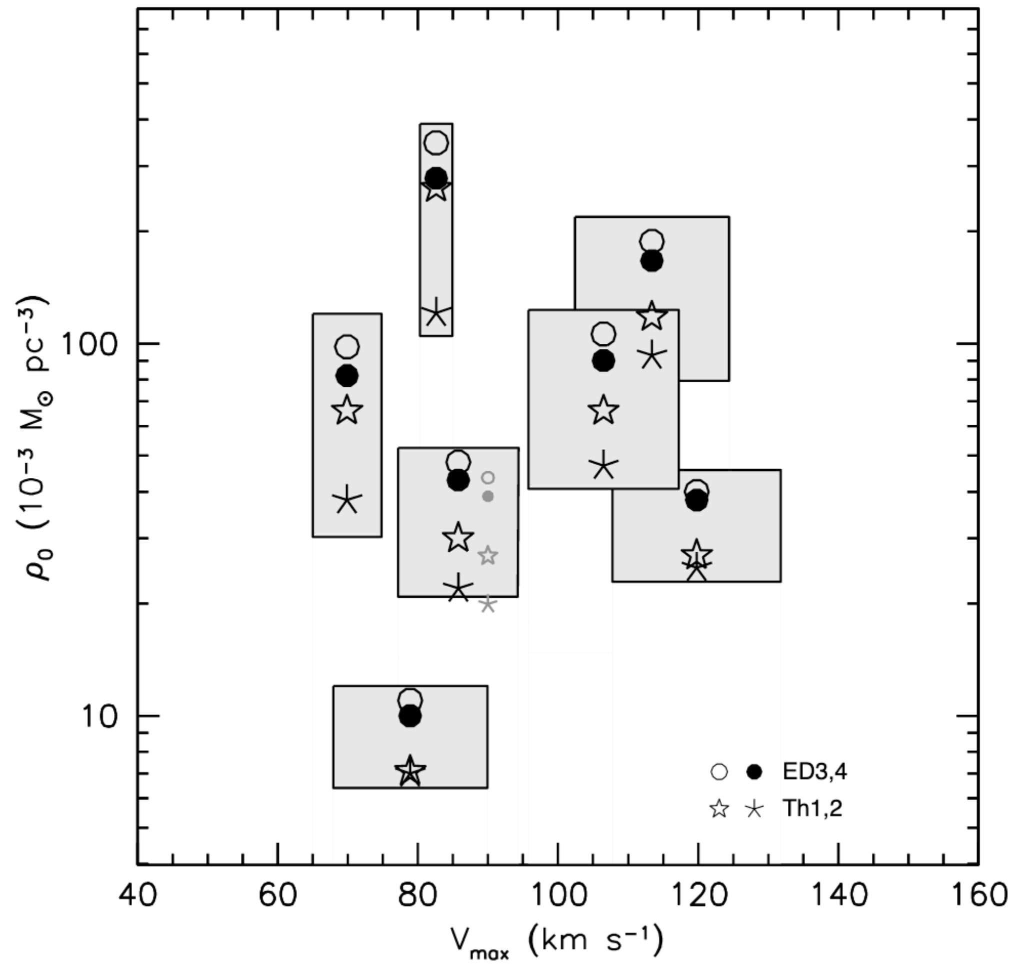
Colored bands: hydrodynamical simulations of CDM

Baryon/Dark matter distributions are diverse in spiral galaxies

Diversity: A Big Challenge



the data compiled in Oman+(2015)

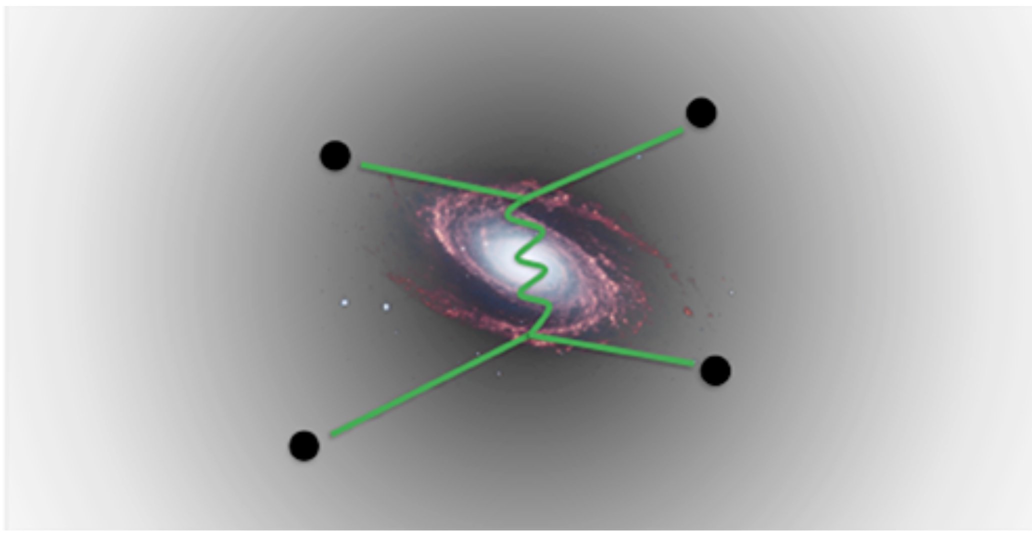


Kuzio de Naray, Martinez, Bullock, Kaplinghat (2010)

Dark matter distributions are diverse in spiral galaxies

The unexpected diversity of dwarf galaxy rotation curves

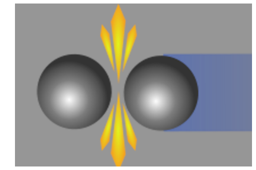
Kyle A. Oman,[1★] Julio F. Navarro,[1†] Azadeh Fattahi,[1] Carlos S. Frenk,[2] Till Sawala,[2] Simon D. M. White,[3] Richard Bower,[2] Robert A. Crain,[4] Michelle Furlong,[2] Matthieu Schaller,[2] Joop Schaye[5] and Tom Theuns[2]
[1]*Department of Physics & Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2]*Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[3]*Max-Planck Institute for Astrophysics, D-85748 Garching, Germany*
[4]*Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK*
[5]*Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

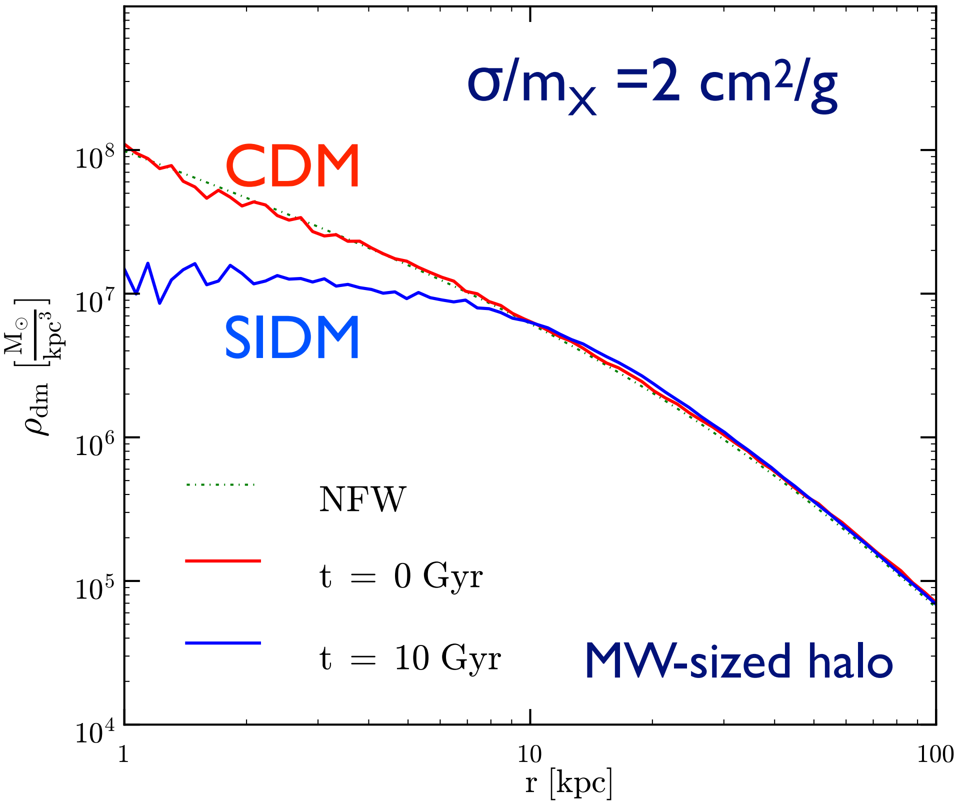


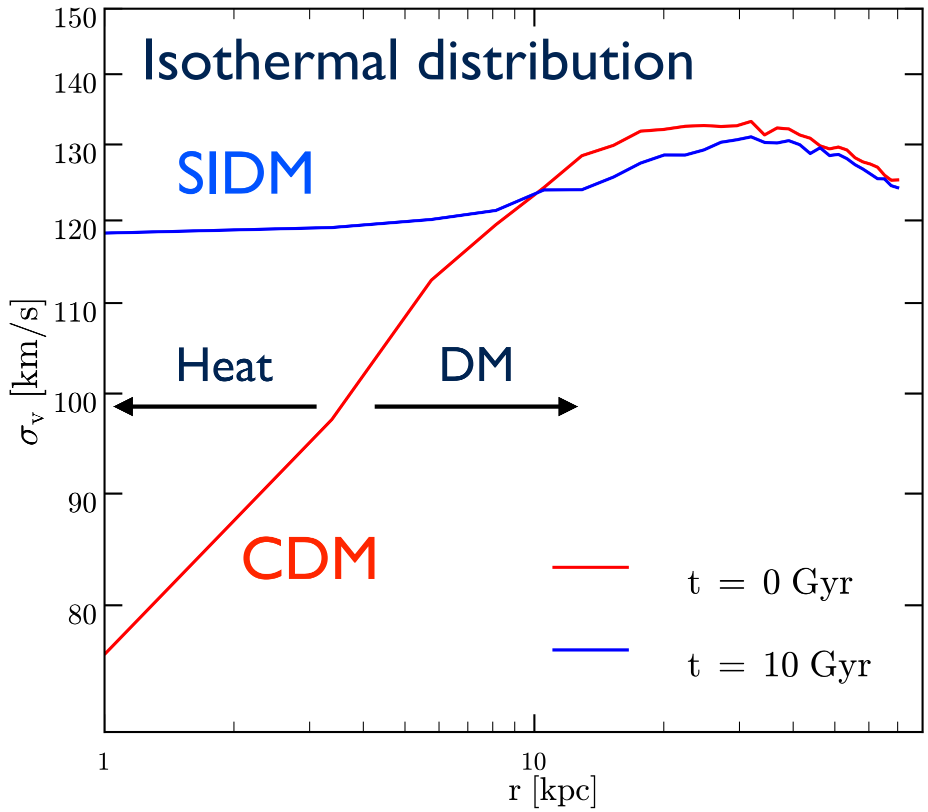
The diversity can be explained if dark matter has strong self-interactions

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo







σ/m$_X$ ~1 cm²/g (nuclear scale)

$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Review: Tulin, HBY (Physics Reports 2017)

Modelling SIDM Halos

semi-analytical approach

Inner halo

Ideal gas: PV=nRT

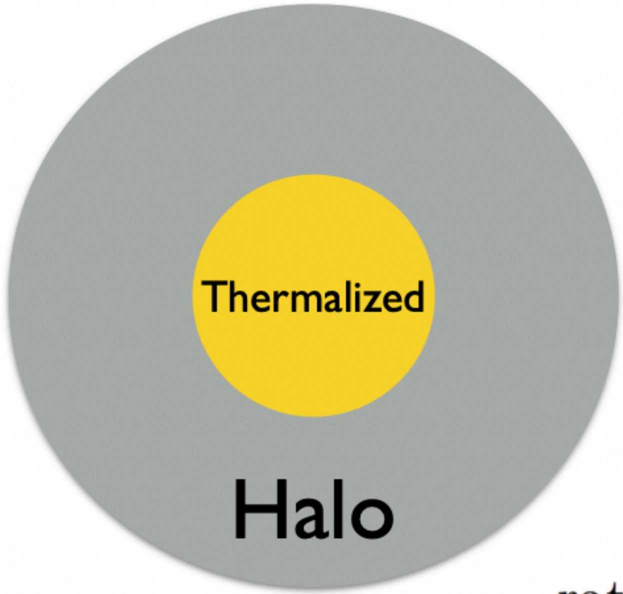
isothermal distribution

$$\rho_0 e^{-\Phi_{\rm tot}/\sigma_0^2}$$

$$\Phi_{\rm tot} = \Phi_{\rm dm} + \underline{\Phi_b}$$

Known

$$\nabla^2 \Phi_{\rm tot} = 4\pi G(\rho_{\rm dm} + \underline{\rho_b})$$



Outer halo

$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

The boundary is set by

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1$$

$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s) \leftrightarrow (V_{\rm max}, r_{\rm max})$$

with Kaplinghat, Keeley, Linden (PRL 2014)
with Kaplinghat, Linden (RPL 2015)
with Kaplinghat, Tulin (PRL 2016)
with Kamada, Kaplinghat, Pace (PRL 2017)

VS

The surprising accuracy of isothermal Jeans modelling of self-interacting dark matter density profiles

Andrew Robertson*[1], Richard Massey[1], Vincent Eke[1], Joop Schaye[2] and Tom Theuns[1]

[1] *Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK*
[2] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

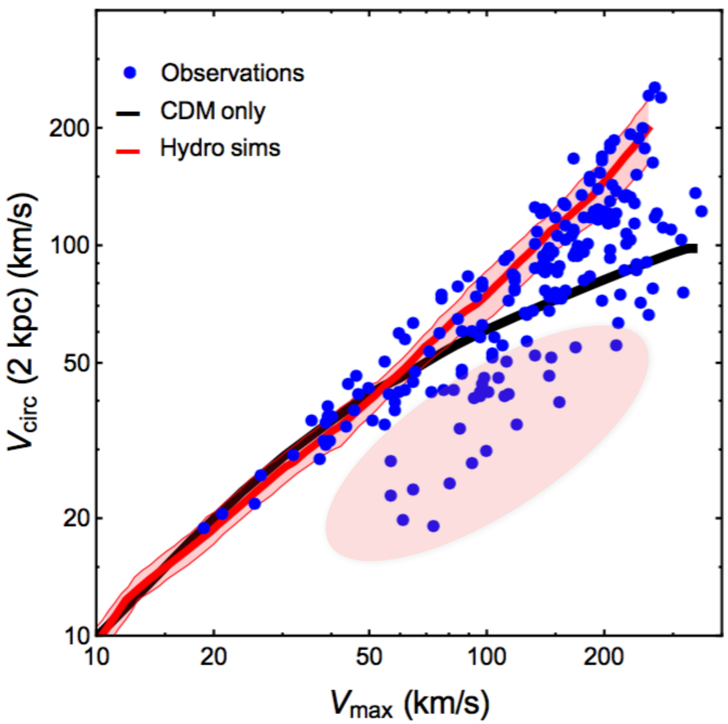
1 February 2021

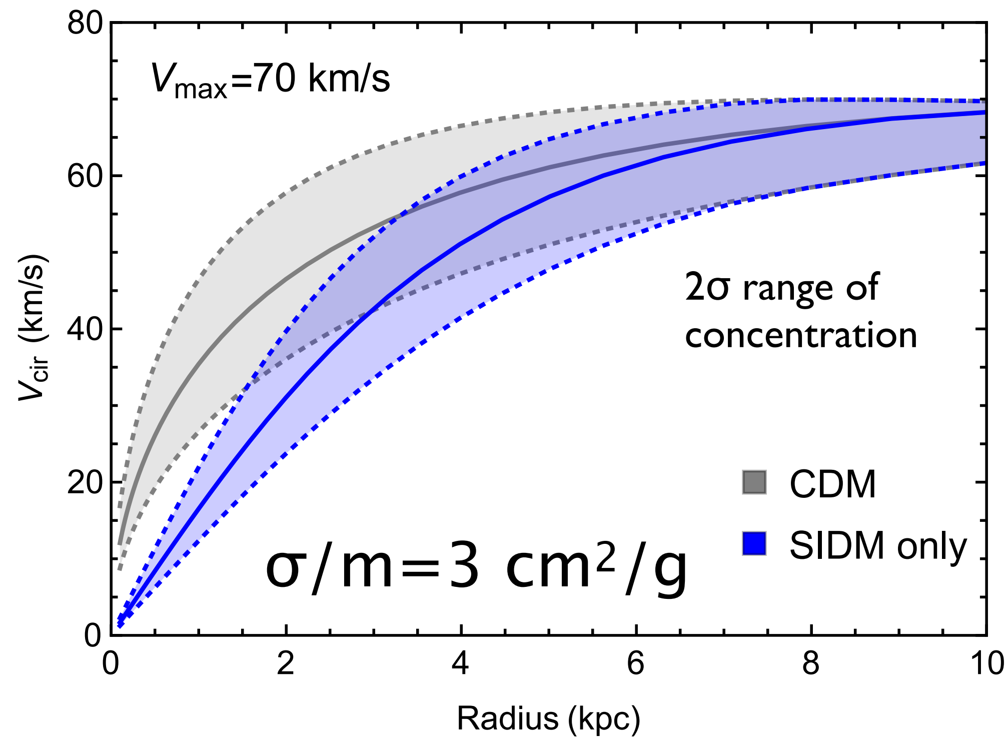
ABSTRACT

Recent claims of observational evidence for self-interacting dark matter (SIDM) have relied on a semi-analytic method for predicting the density profiles of galaxies and galaxy clusters containing SIDM. We present a thorough description of this method, known as isothermal Jeans modelling, and then test it with a large ensemble of haloes taken from cosmological simulations. Our simulations were run with cold and collisionless dark matter (CDM) as well as two different SIDM models, all with dark matter only variants as well as versions including baryons and relevant galaxy formation physics. Using a mix of different box sizes and resolutions, we study haloes with masses ranging from 3×10^{10} to 3×10^{15} $M_{\odot}$. Overall, we find that the isothermal Jeans model provides as accurate a description of simulated SIDM density profiles as the Navarro-Frenk-White profile does of CDM halos. We can use the model predictions, compared with the simulated density profiles, to determine the input DM-DM scattering cross-sections used to run the simulations. This works especially well for large cross-sections, while with CDM our results tend to favour non-zero (albeit fairly small) cross-sections, driven by a bias against small cross-sections inherent to our adopted method of sampling the model parameter space. The model works across the whole halo mass range we study, although including baryons leads to DM profiles of intermediate-mass ($10^{12} - 10^{13}$ $M_{\odot}$) haloes that do not depend strongly on the SIDM

Low Surface Brightness Galaxies

- DM self-interactions thermalize the inner halo





DM-dominated galaxies: Lower the central density and the circular velocity

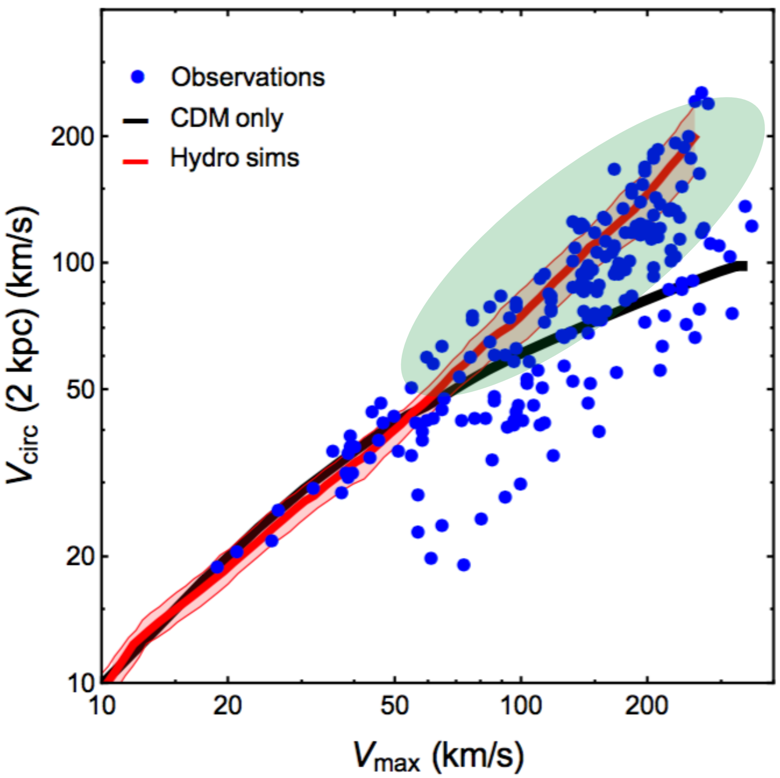
Isothermal distribution

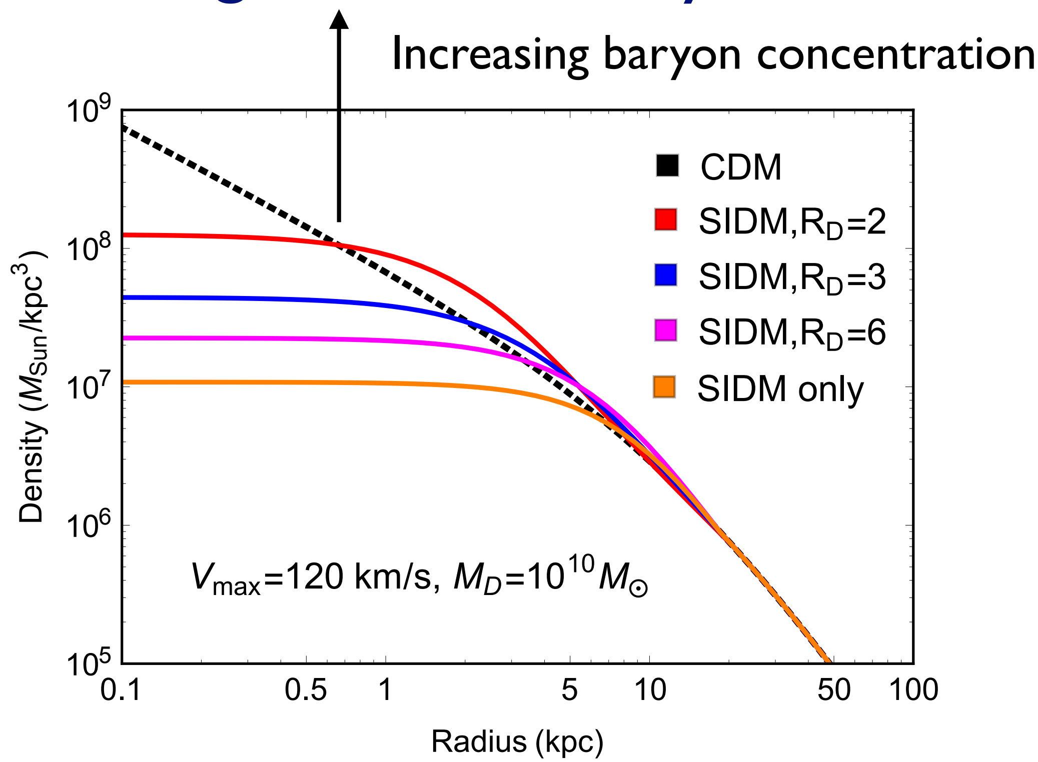
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

Most of them, but not all…

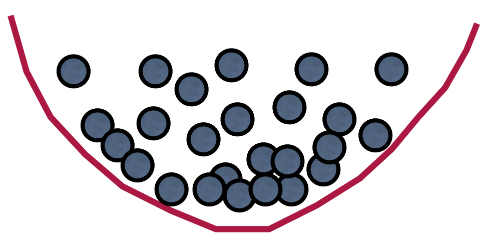
High Surface Brightness Galaxies

- DM self-interactions tie DM together with baryons



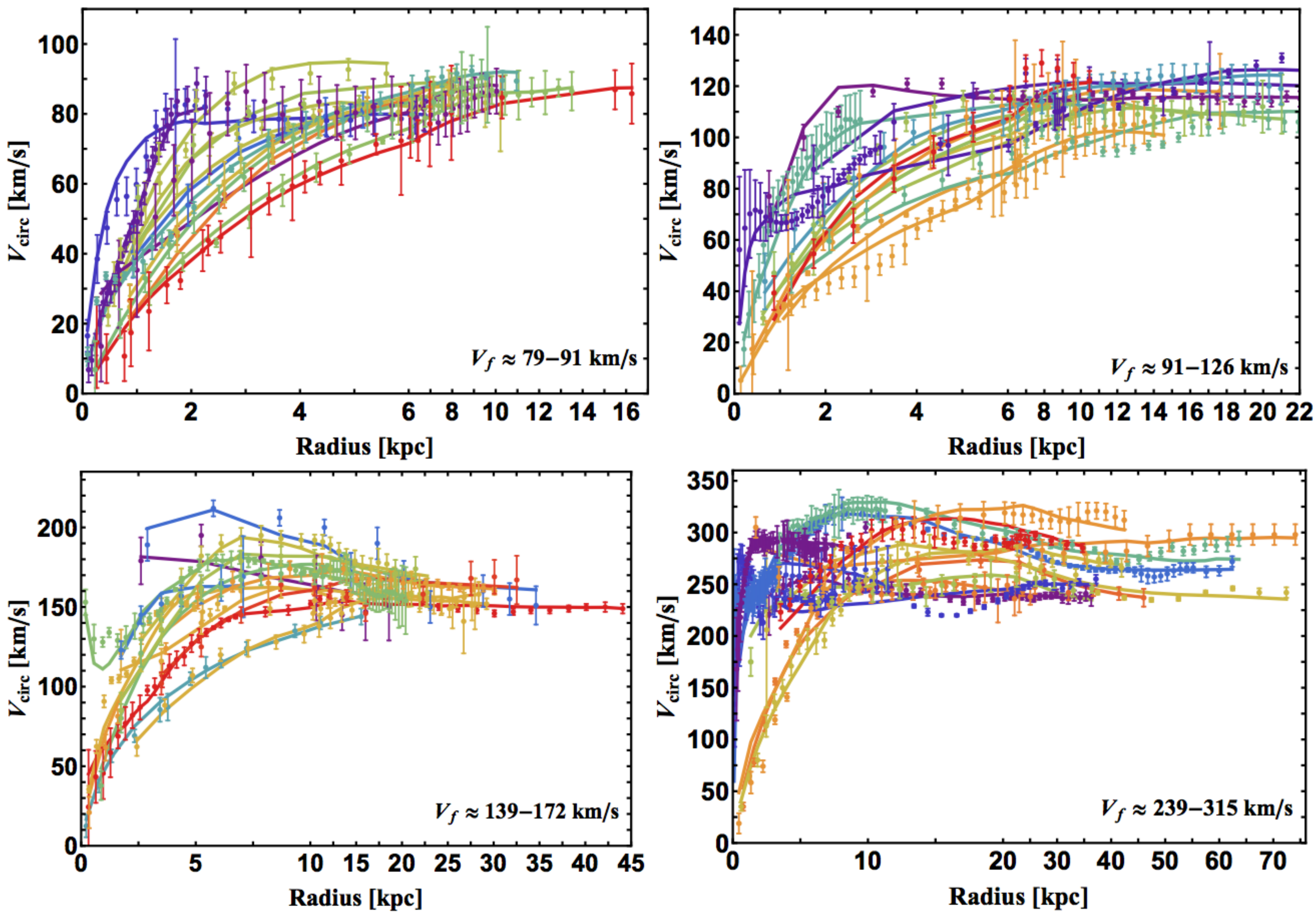


Thermalization leads to higher DM density due to the baryonic influence



$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_{\rm B}/\sigma_0^2}$$

Addressing the Diversity Problem



$\sigma/\mathrm{m} = 3\ \mathrm{cm}^2/\mathrm{g}$

DM/Baryon concentration

We analyzed 135 galaxies (3.6 μm band)!

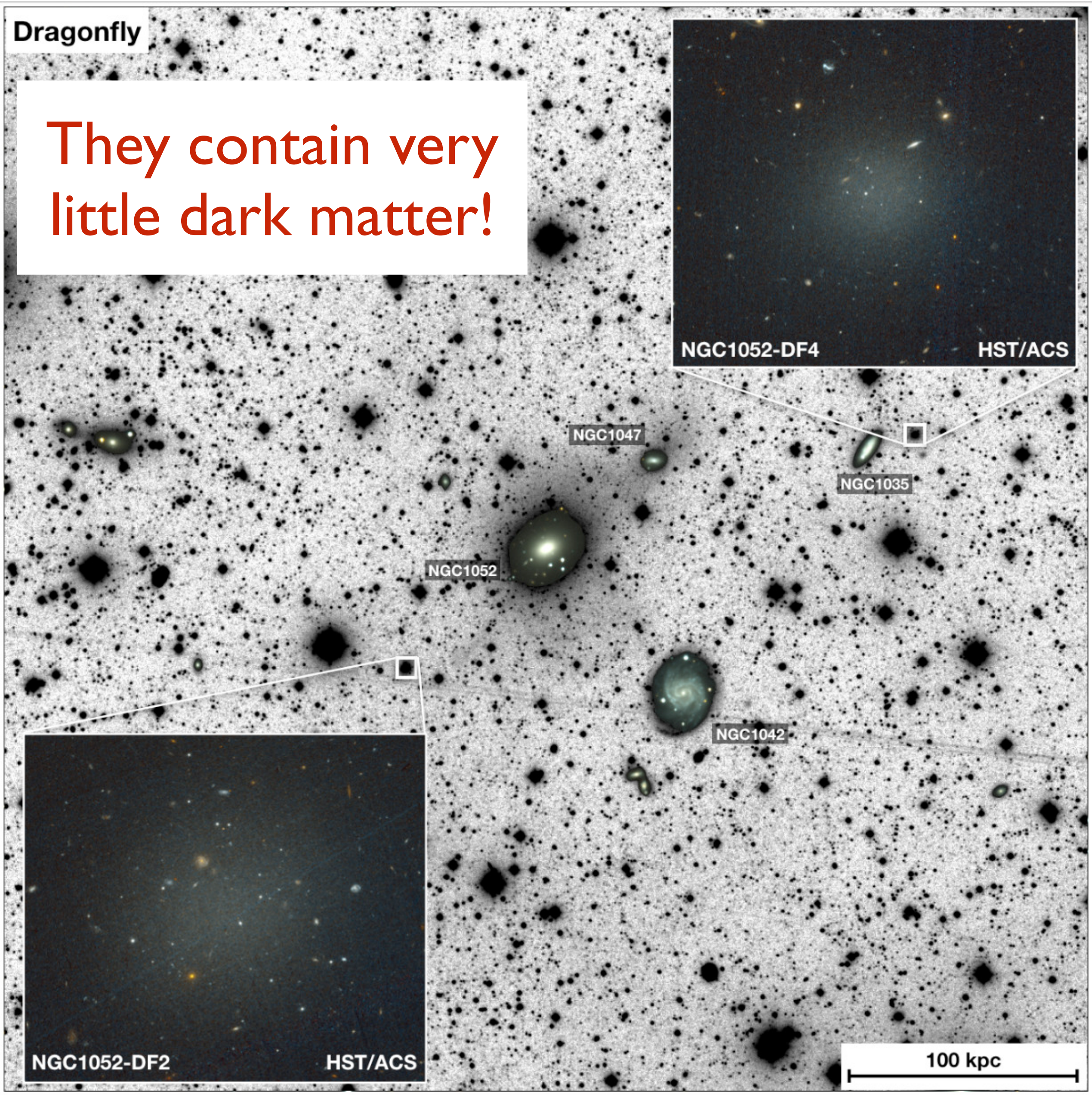
SPARC dataset, Lelli, McGaugh,Schombert (2016)

w/Ren, Kwa, Kaplinghat (PRX 2018)

w/Kamada, Kaplinghat, Pace (PRL 2017)

w/Creasey, Sameie, Sales+(MNRAS 2017)

Ultra-Diffuse Galaxies



Dragonfly team, van Dokkum+ (Nature 2018, APJL 2019)

Milky Way

$$M_{\rm DM}/M_{\rm star} \approx 30$$

DF2 and DF4

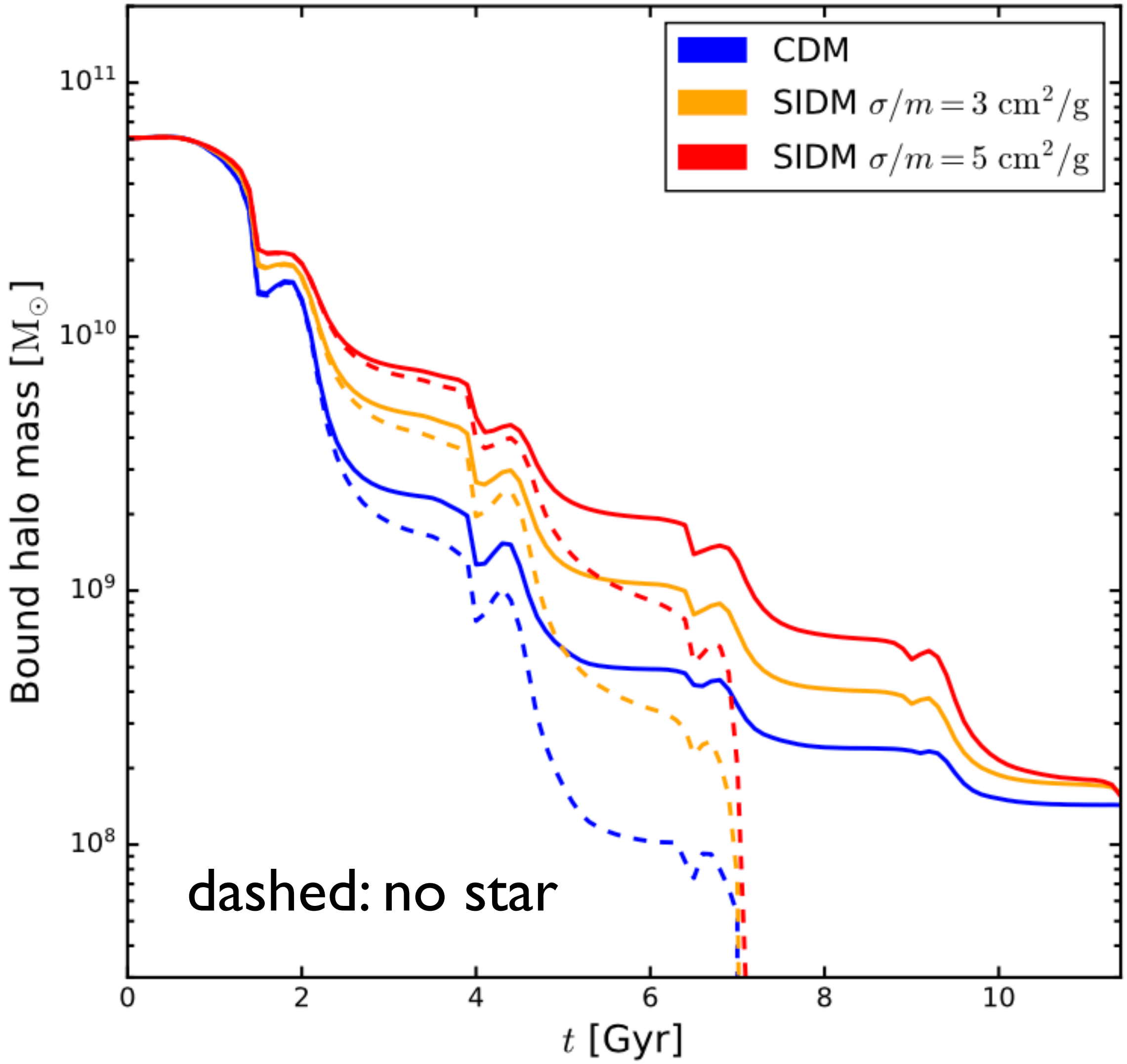
$$M_{\rm star} \approx 10^8\ {\rm M}_\odot$$

Expected

$$M_{\rm DM}/M_{\rm star} \sim 200$$

Observed

$$M_{\rm DM}/M_{\rm star} \lesssim 1$$



Halo concentration c_{200}

CDM: 4 (-4σ)

SIDM3: 7 (-1.8σ)

SIDM5: 10 (-0.4σ)

Initial, t=0 Gyr

$$M_{200} = 6 \times 10^{10}\ \mathrm{M_\odot}$$

$$M_* = 3.2 \times 10^{8}\ \mathrm{M_\odot}$$

$$M_{200}/M_* \approx 188$$

Final, t=11 Gyr

$$M_{\mathrm{DM}} = 1.5 \times 10^{8}\ \mathrm{M_\odot}$$

$$M_{\mathrm{star}} = 1.3 \times 10^{8}\ \mathrm{M_\odot}$$

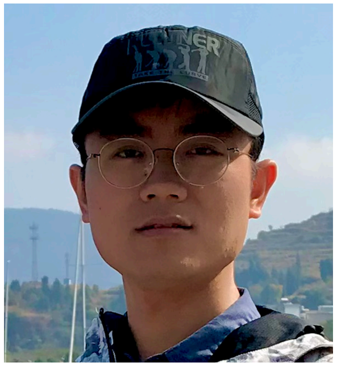
$$M_{\mathrm{DM}}/M_{\mathrm{star}} \approx 1$$

SIDM leads to core formation, boosting tidal mass loss

w/Yang, An (PRL 2020)

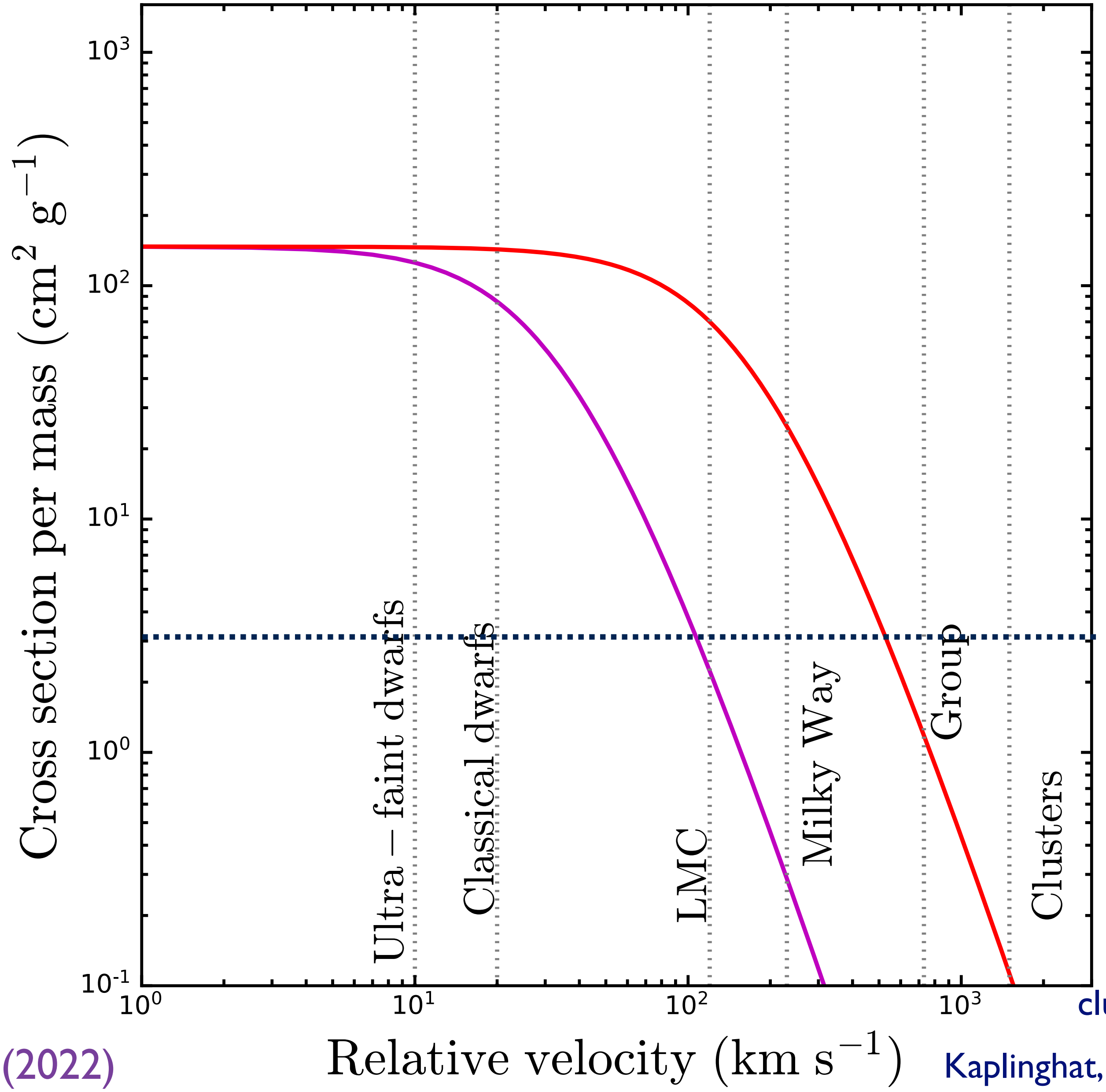
CDM FIRE2: Moreno+(Nature Astronomy, 2022)

Even Stronger DM Self-Interactions



Daneng Yang (UCR)

Ethan Nadler
(USC/Carnegie)



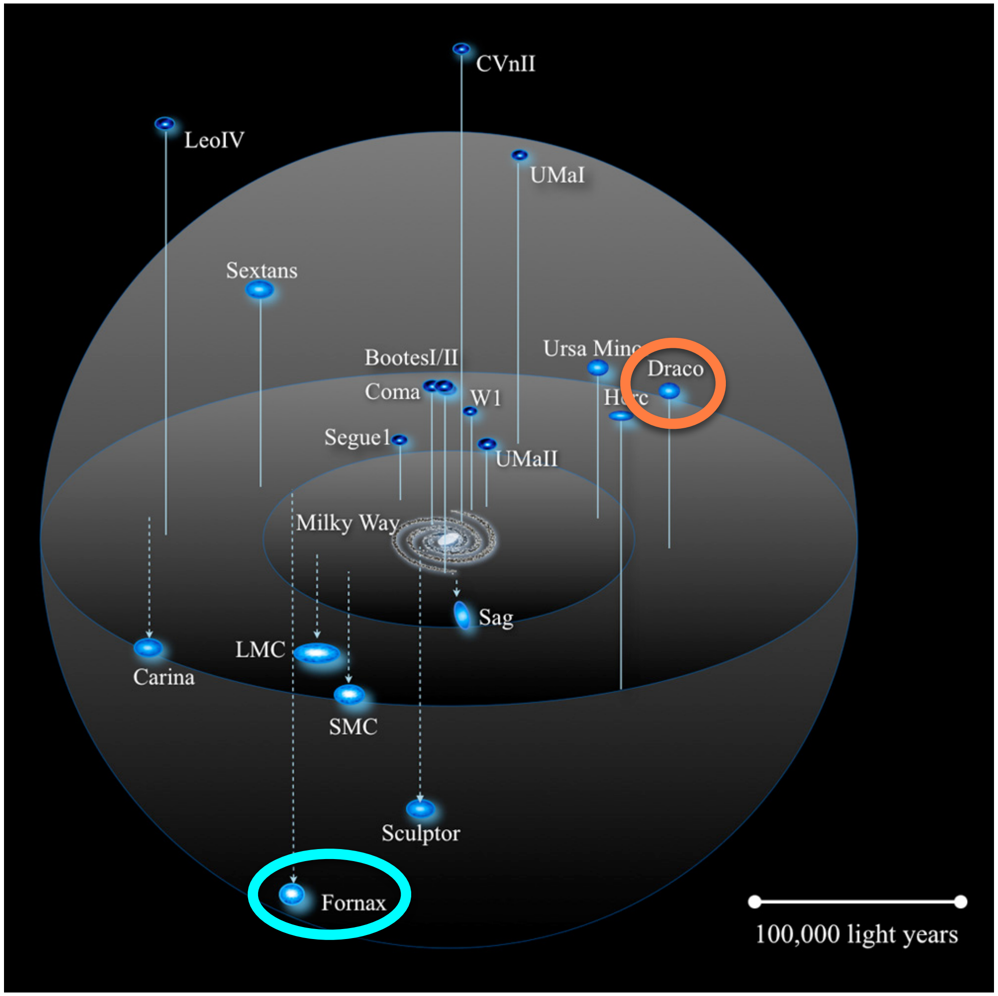
"conservative"

Saturate the limit on cluster scales ~0.1 cm²/g

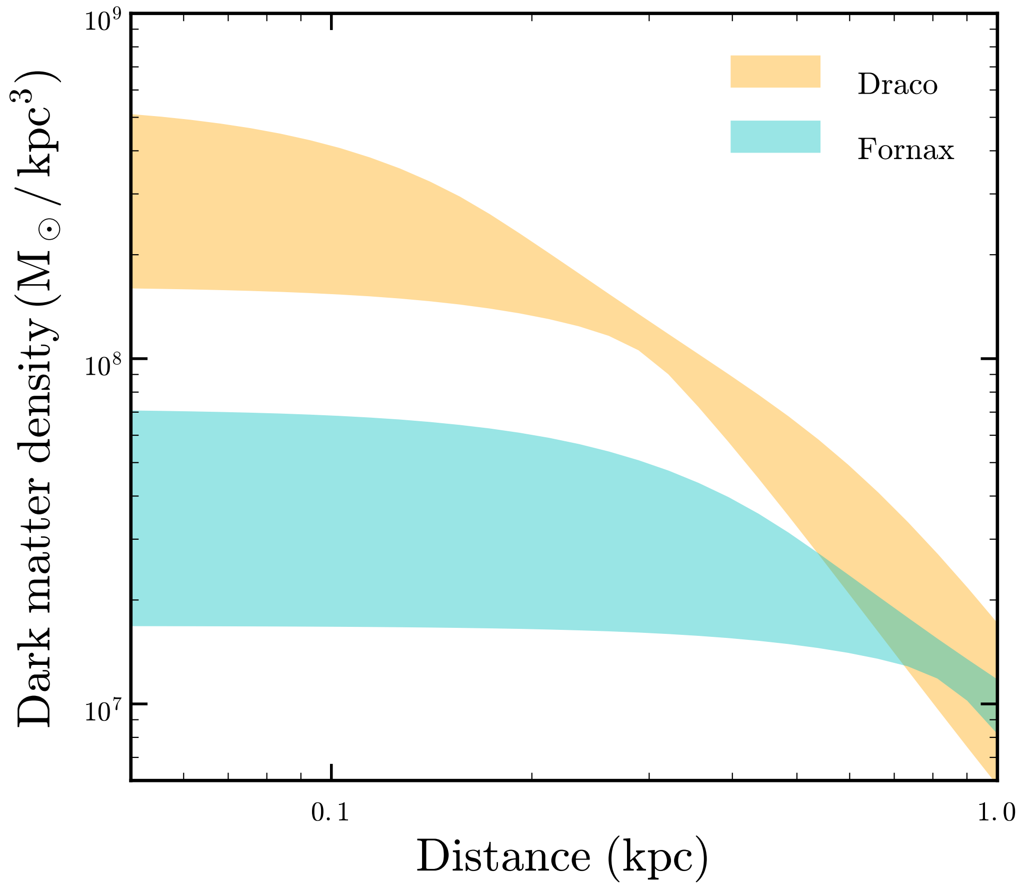
Yang, Nadler, HBY (2022)
Nadler, Yang, HBY (2023)

Kaplinghat, Tulin, HBY (PRL 2016)
Andrade+(MNRAS 2021)

Milky-Way Satellite Galaxies



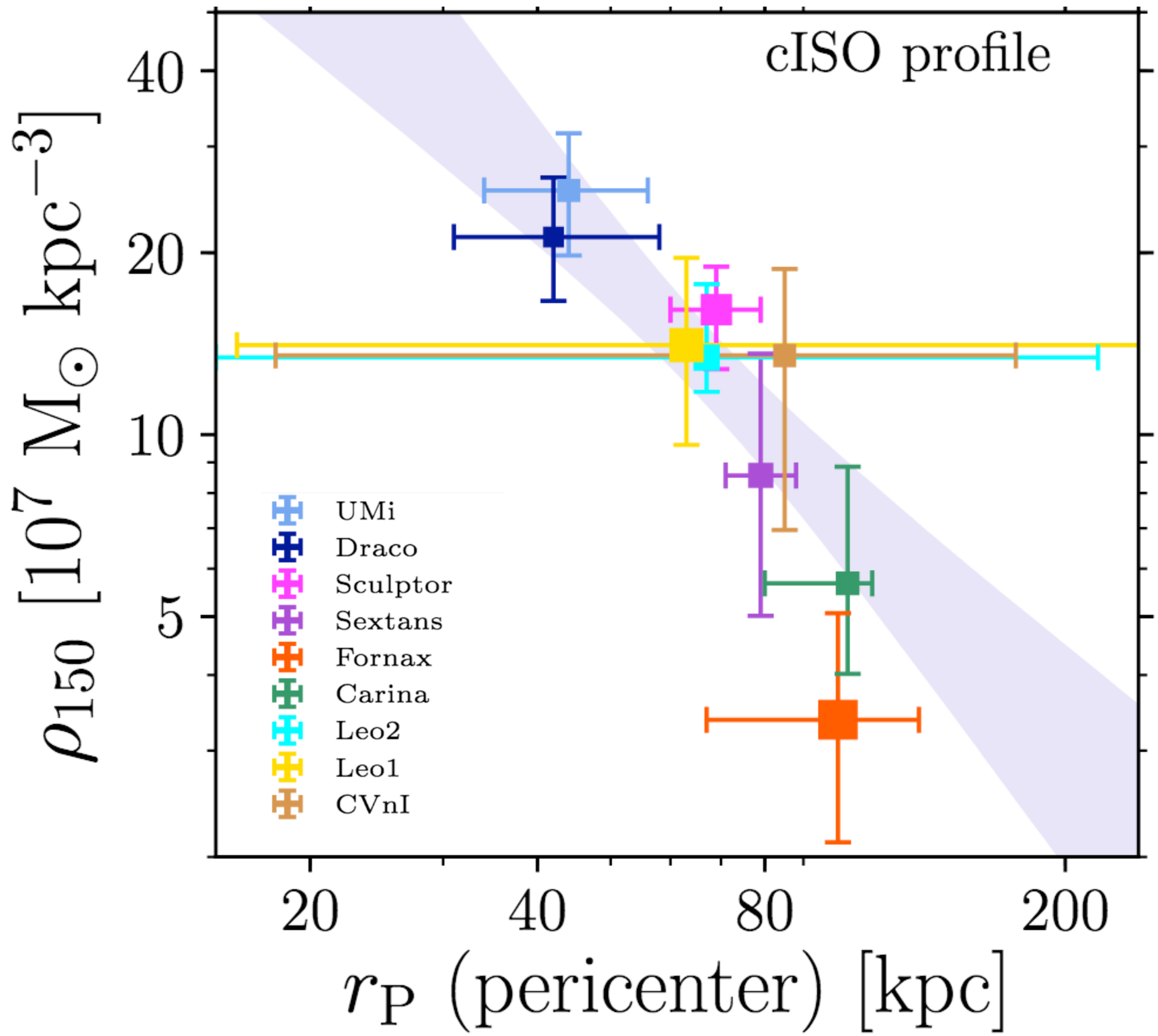
Observations



- Dark matter distributions are also diverse in the satellite galaxies
- Naively, we would get σ/m_X ~30 cm^2/g for Fornax, but σ/m_X <0.3 cm^2/g for Draco

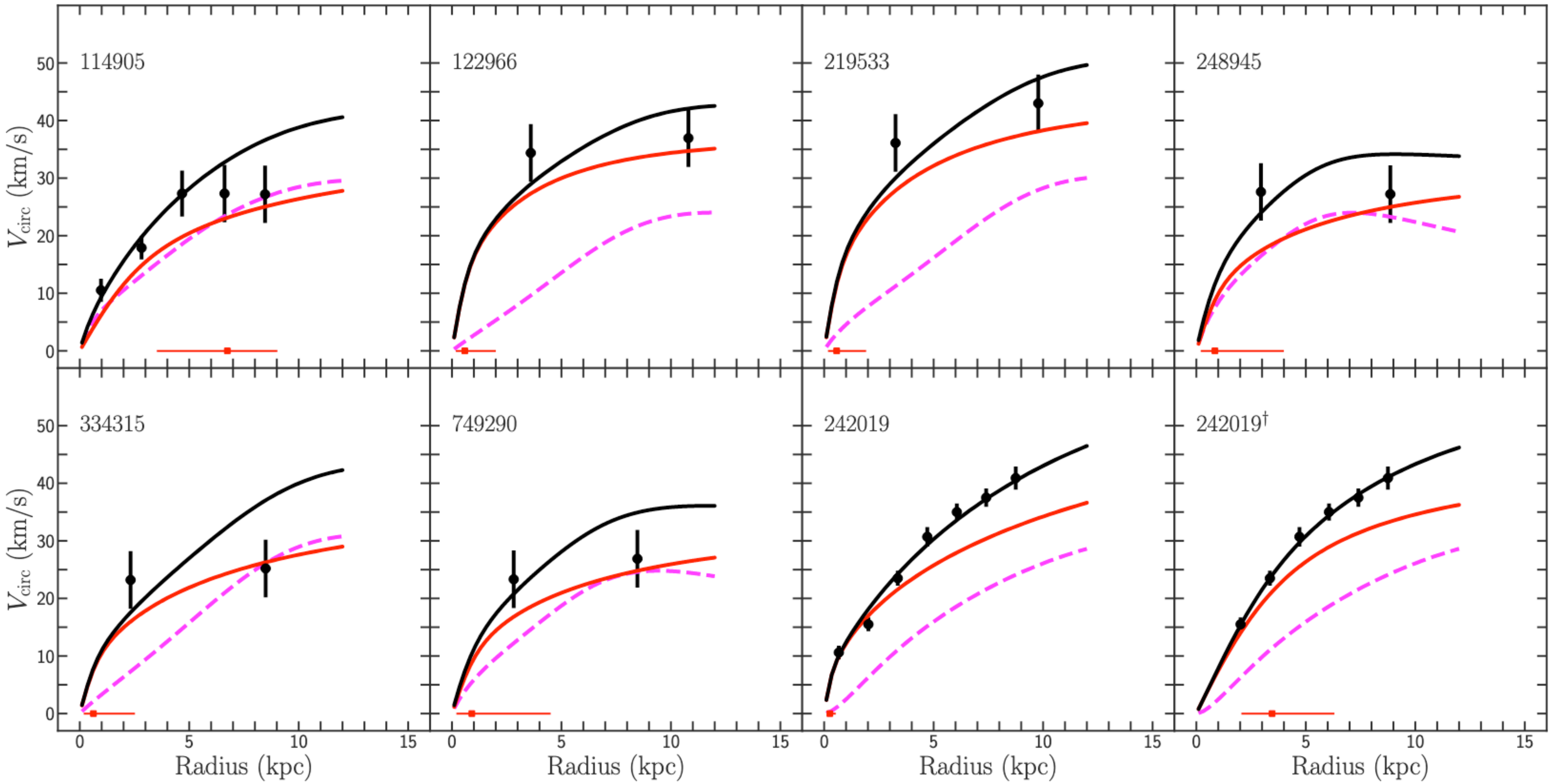
w/ Valli (Nature Astronomy 2018); Read+(2018); w/Kaplinghat, Valli (MNRAS, 2019); w/Sameie et al. (PRL 2019); Zavala+(PRD, 2019); Correa (MNRAS 2020); Turner+(MNRAS 2020); Nishikawa+(PRD, 2020); Silverman+(MNRAS, 2022); Slone+(PRD, 2023)

Anti-Correlation



Kaplinghat, Valli, HBY (MNRAS, 2019)

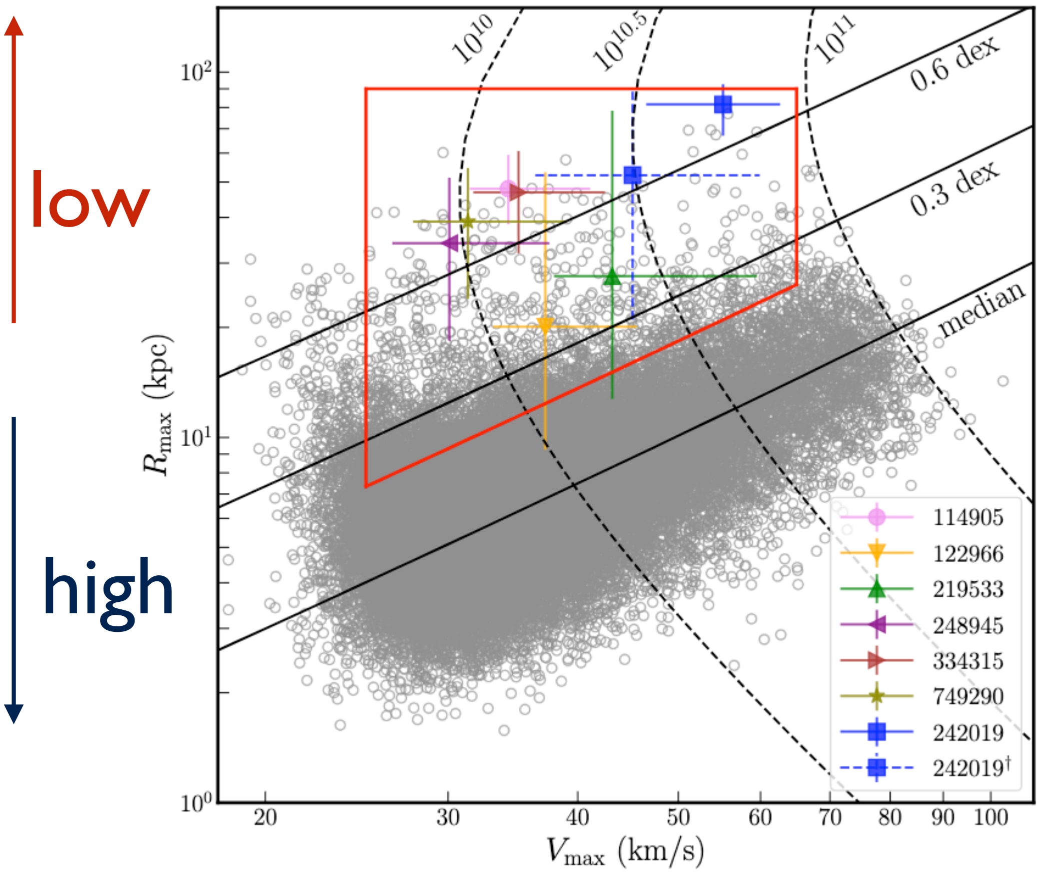
Ultra-diffuse Galaxies in the Field

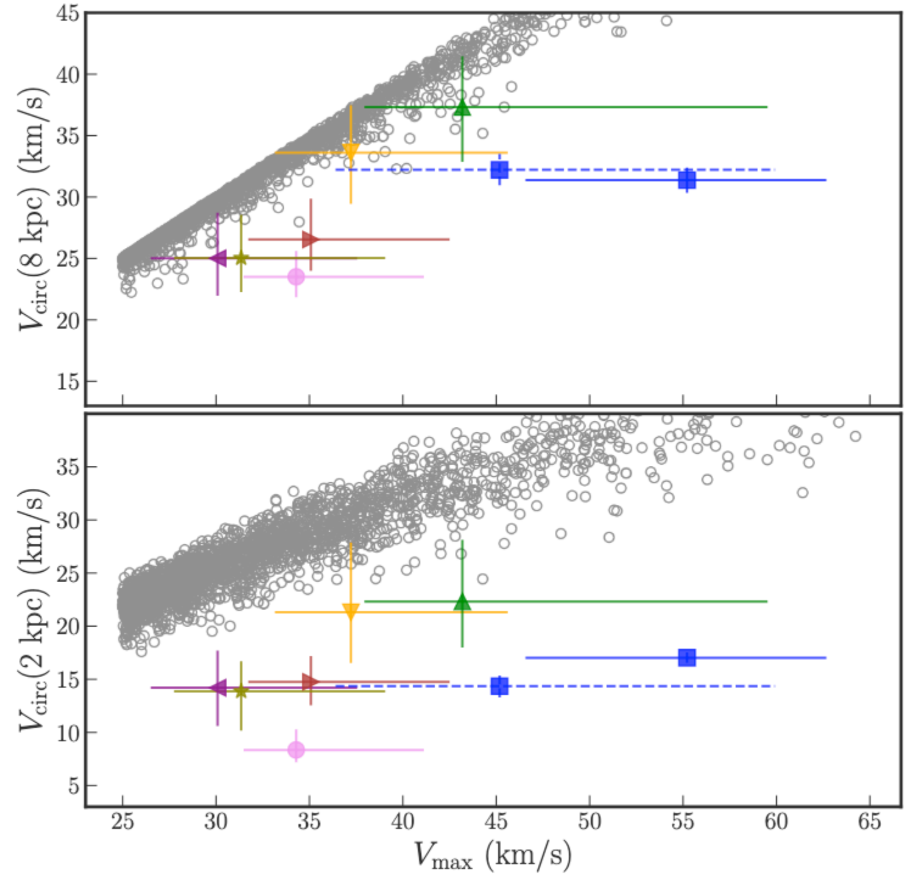


w/Kong, Kaplinghat, Fraternali, Mancera Piña (ApJ 2022)

- Red: dark matter halo; Magenta: baryons; Black: total
- These UDGs are extremely gas-rich, and largely baryon-dominated
- The UDG halo properties are inconsistent with CDM predictions

“Low-concentration” Halos





Kong+(ApJ 2022)

- The gas-rich UDGs strongly favor low-concentration halos, “~5σ” below the median
- These “low-concentration” halos can be found in the IllustrisTNG simulations!
- But the inner densities of the simulated halos are too high
- SIDM with a few cm^2/g would not work as the concentration is too low!

Detection of a Dark Substructure through Gravitational Imaging

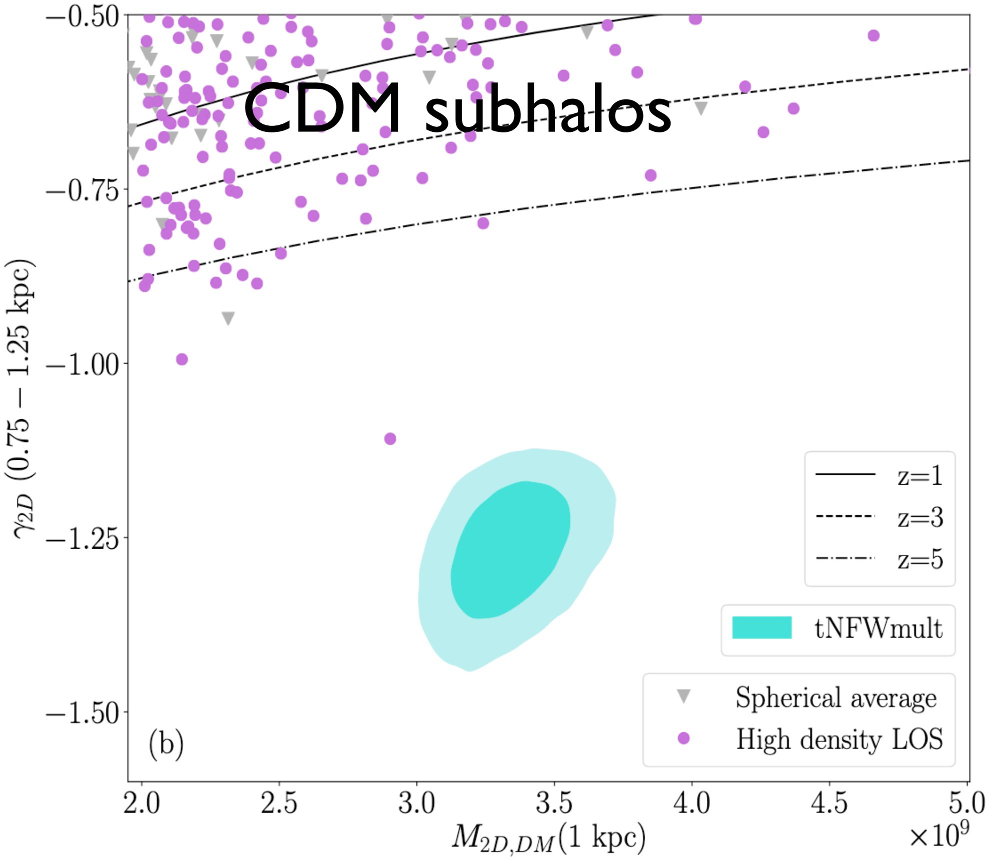
S. Vegetti[1★], L.V.E. Koopmans[1], A. Bolton[2], T. Treu[3] & R. Gavazzi[4]

[1] *Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, the Netherlands*
[2] *Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822-1897, USA*
[3] *Department of Physics, University of California, Santa Barbara, CA 93101, USA*
[4] *Institut d'Astrophysique de Paris, CNRS, UMR 7095, Universite Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France*

(MNRAS 2010)

SDSSJ0946+1006 (the "Double Einstein Ring")

JVAS B1938+666 as well

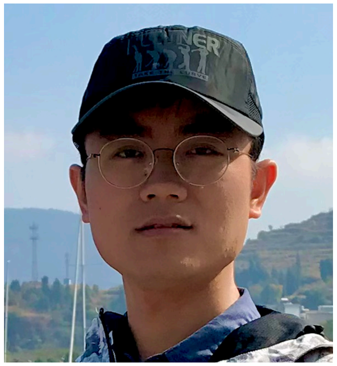


Minor, Kaplinghat, Vegetti (MNRAS, 2020)

- The substructure is extremely dense
- CDM subhalos are not dense enough
- Compared to the IllustrisTNG simulations, the tension with CDM is at the > 99% confidence level; no core!
- The substructure does not have a detectable luminous component

Opposite extremes:
the UDGs and cored spirals vs the substructure

Even Stronger DM Self-Interactions



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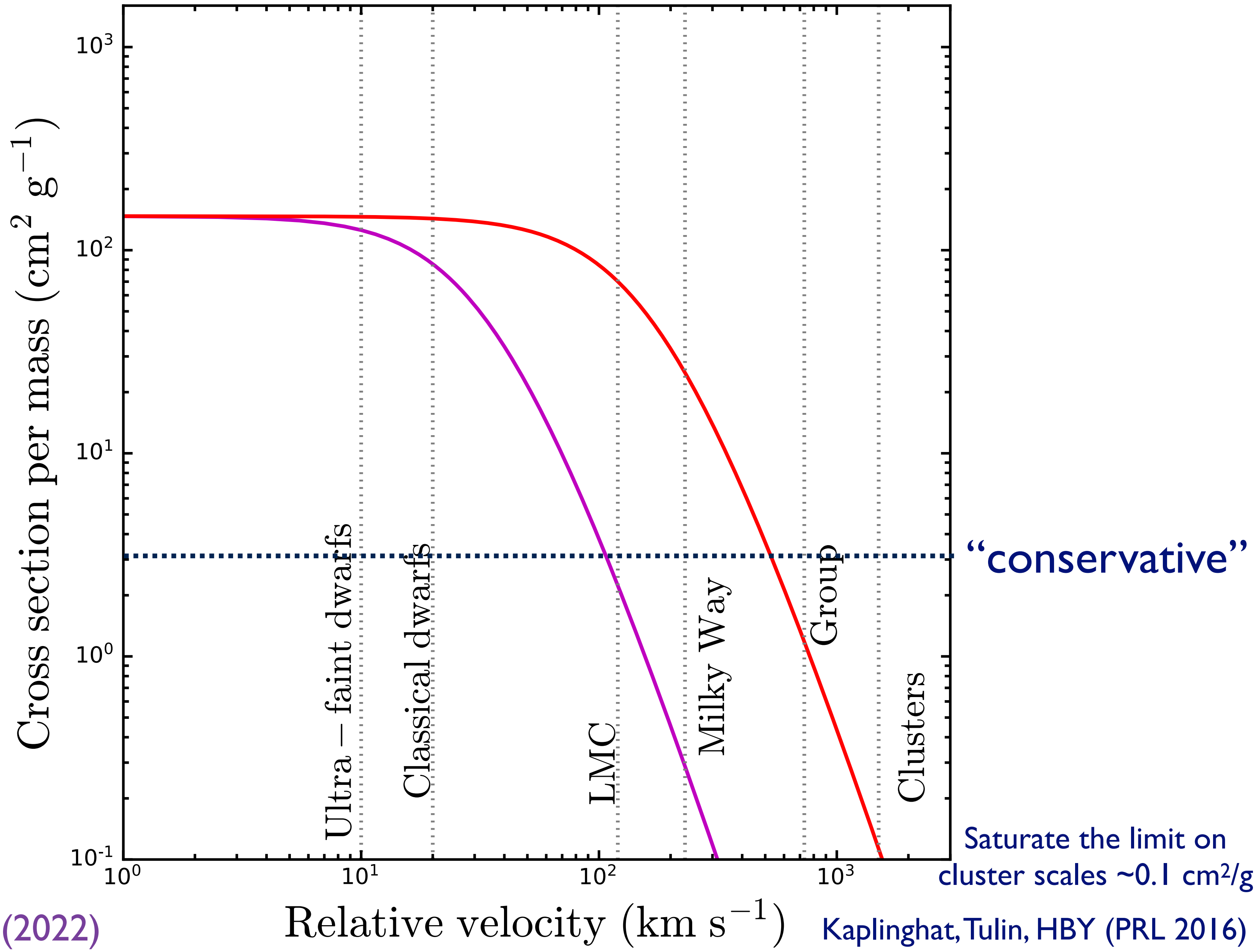


Saturate the limit on cluster scales ~0.1 cm^2/g

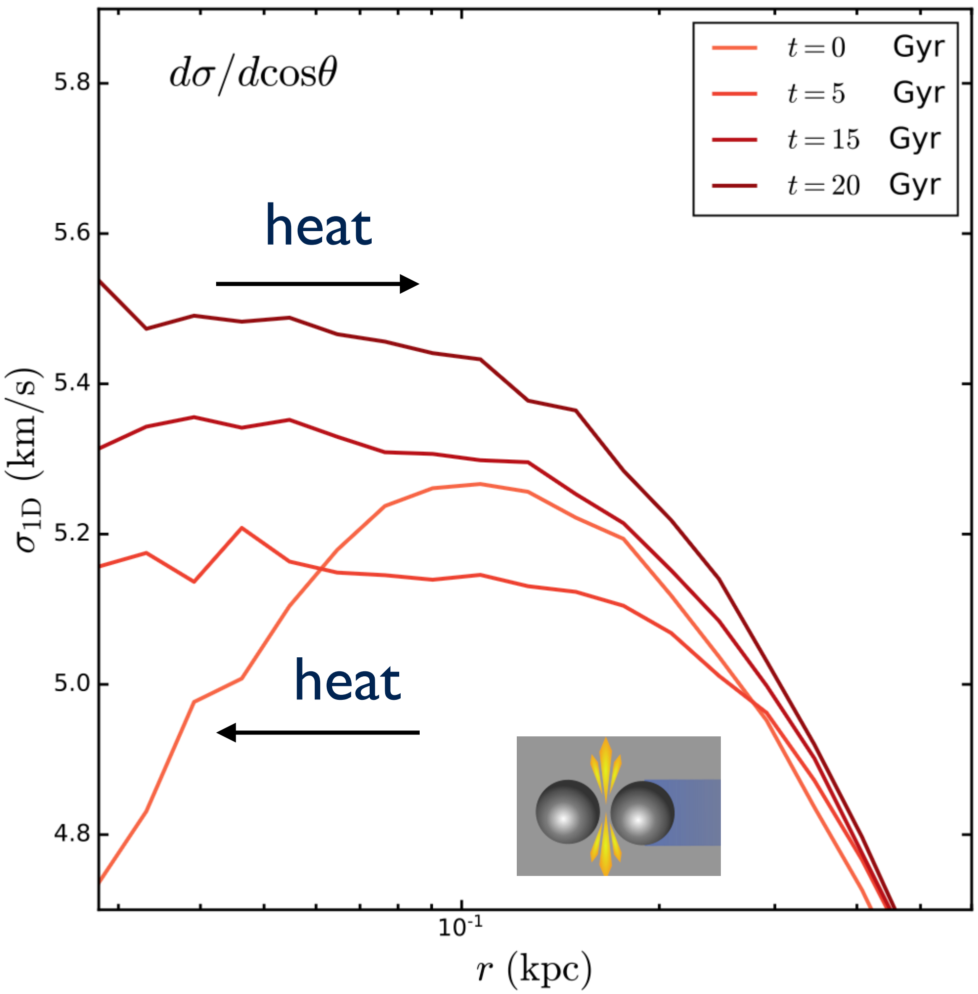
Yang, Nadler, HBY (2022)

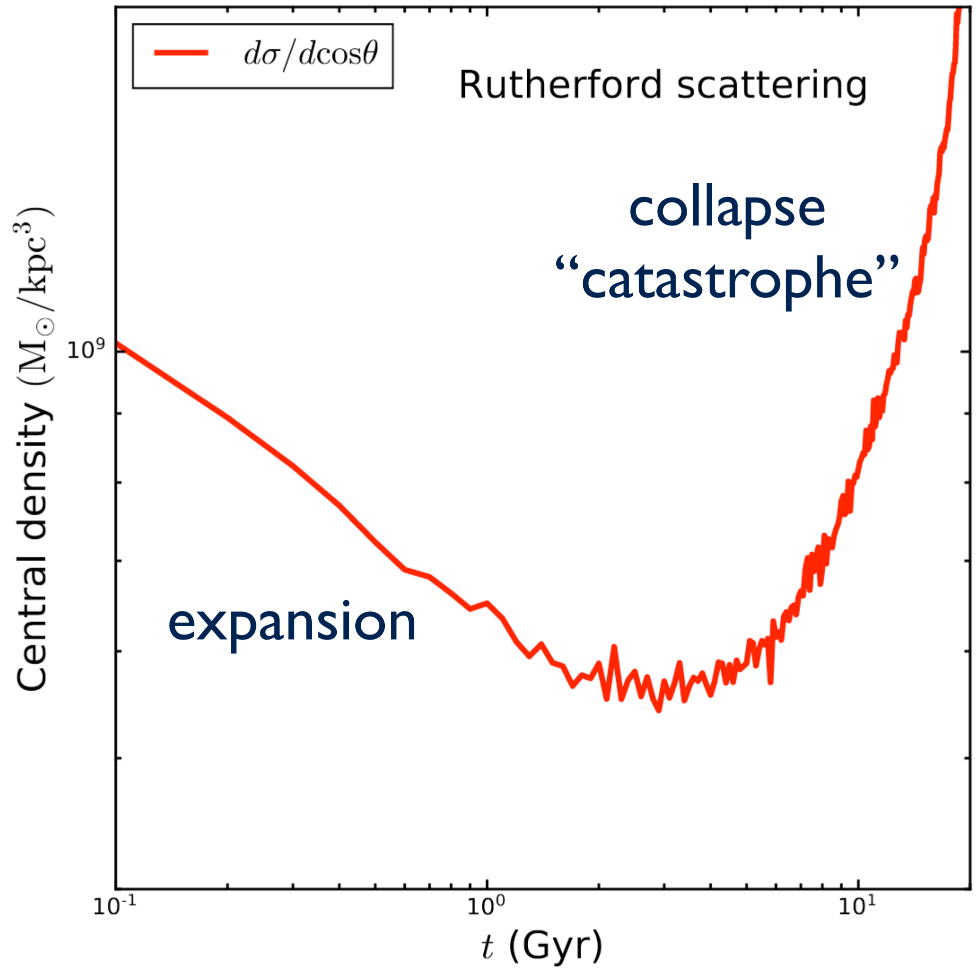
Nadler, Yang, HBY (2023)

Kaplinghat, Tulin, HBY (PRL 2016)

Andrade+(MNRAS 2021)

Gravothermal Evolution





Yang, HBY (JCAP 2022)

$$2K.E. + P.E. = 0$$

$$E_{tot} = -K.E.$$

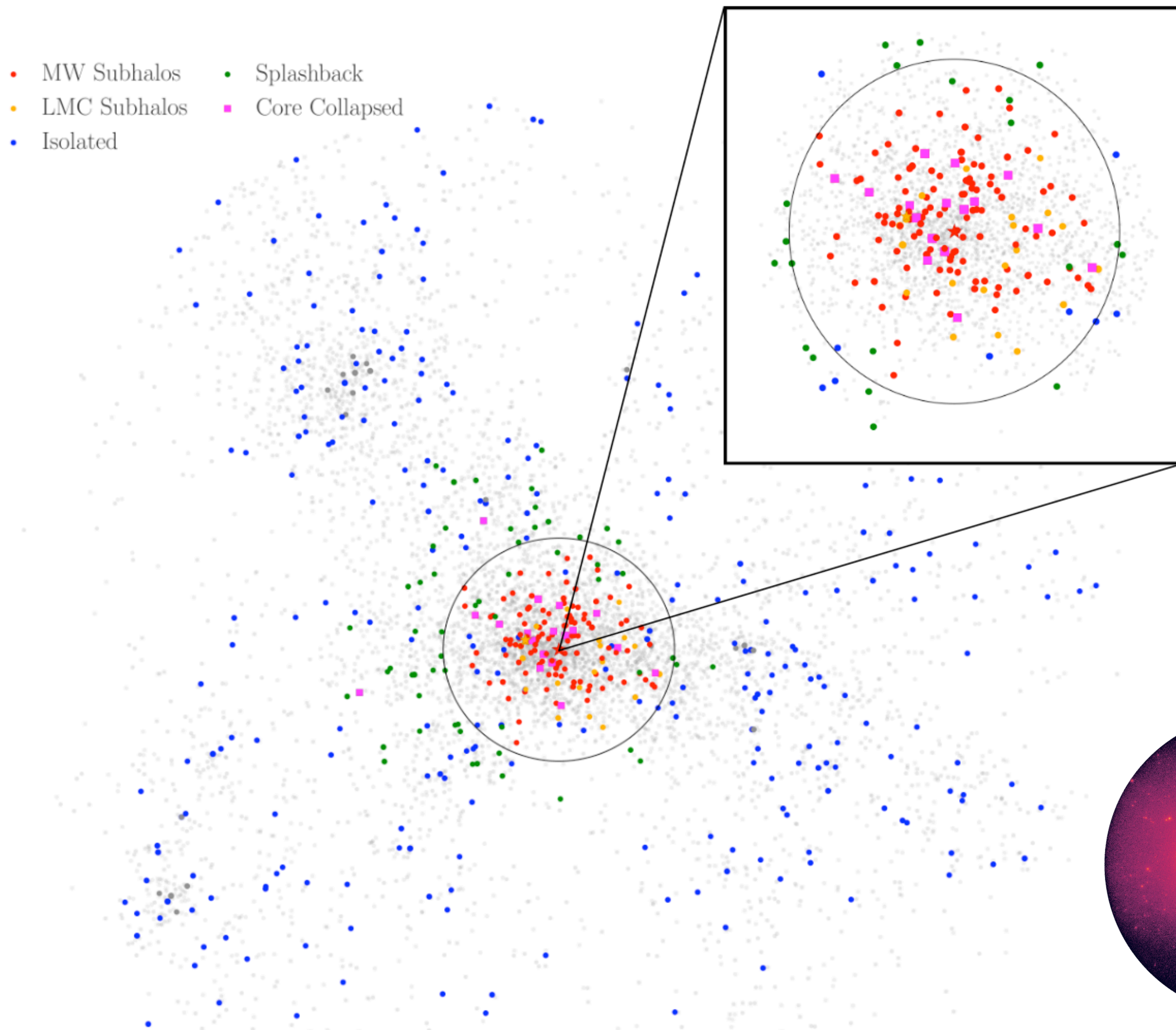
$$\frac{E_{tot}}{T} < 0$$

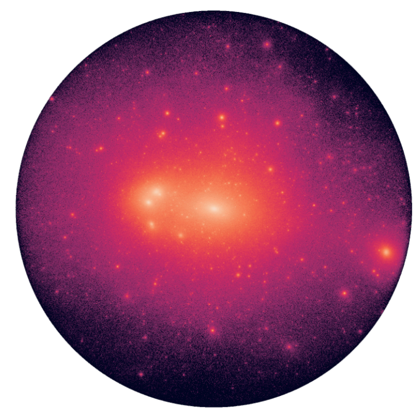
$$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$$

Balberg+(ApJ 2002)

Negative heat capacity!
⇒ gravothermal collapse

w/Essig, McDermott, Zhong (PRL 2019)



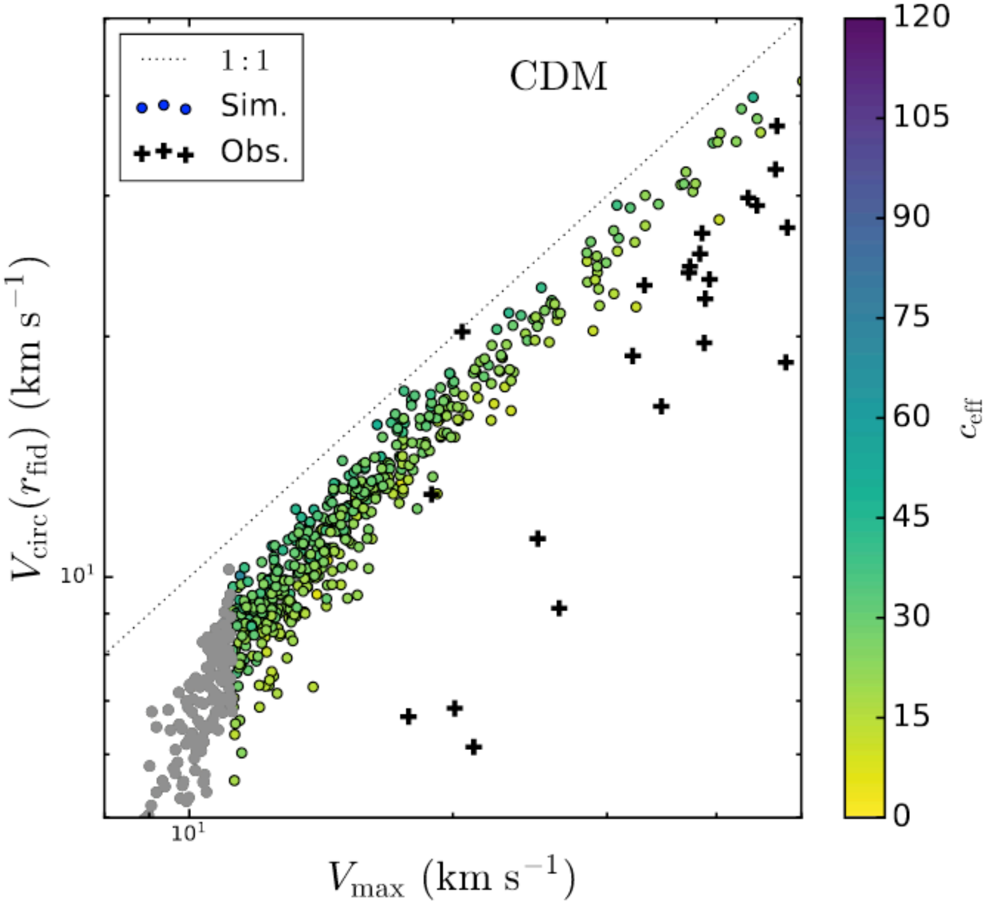


High-resolution zoom-in cosmological N-body simulations

Yang, Nadler, HBY (2022)

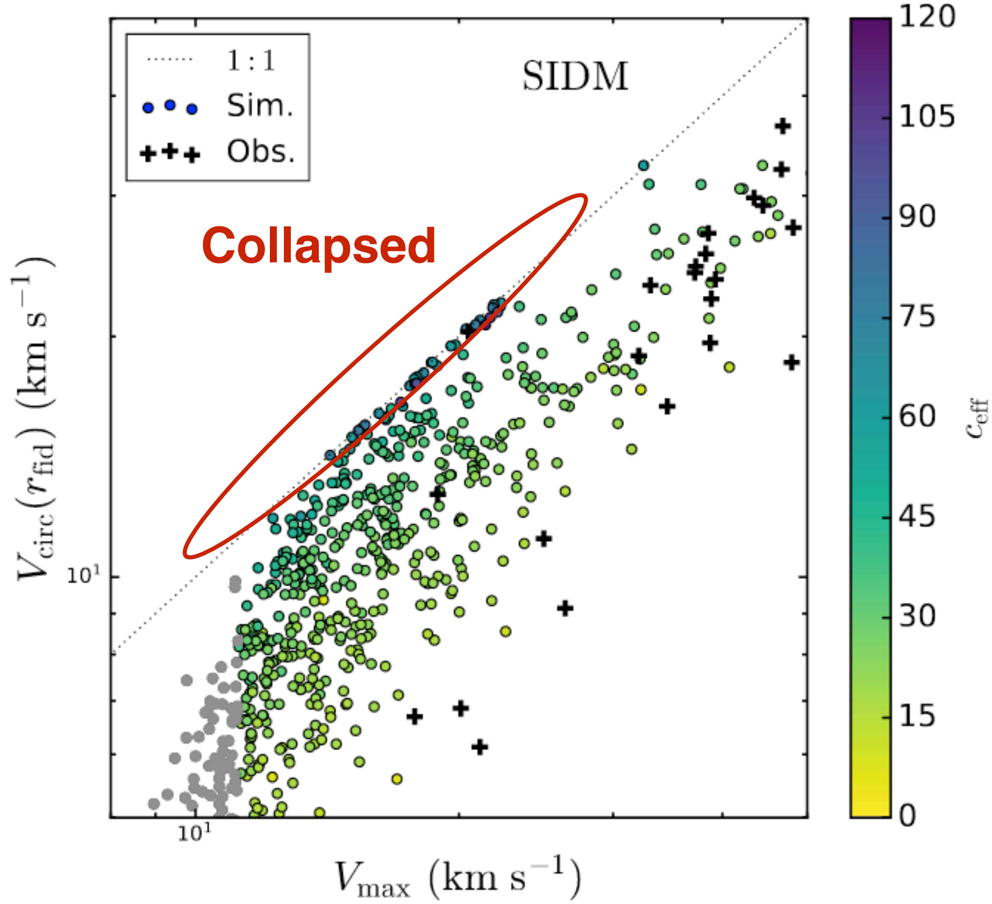
Even Larger Diversity

Isolated halos



$r_{fid} \equiv 2V_{max}/(70\,\mathrm{km/s})\,\mathrm{kpc}$

Isolated halos



$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$

- Stronger dark matter self-interactions produce larger diversity
- A constant cross section ~3 cm^2/g is conservative

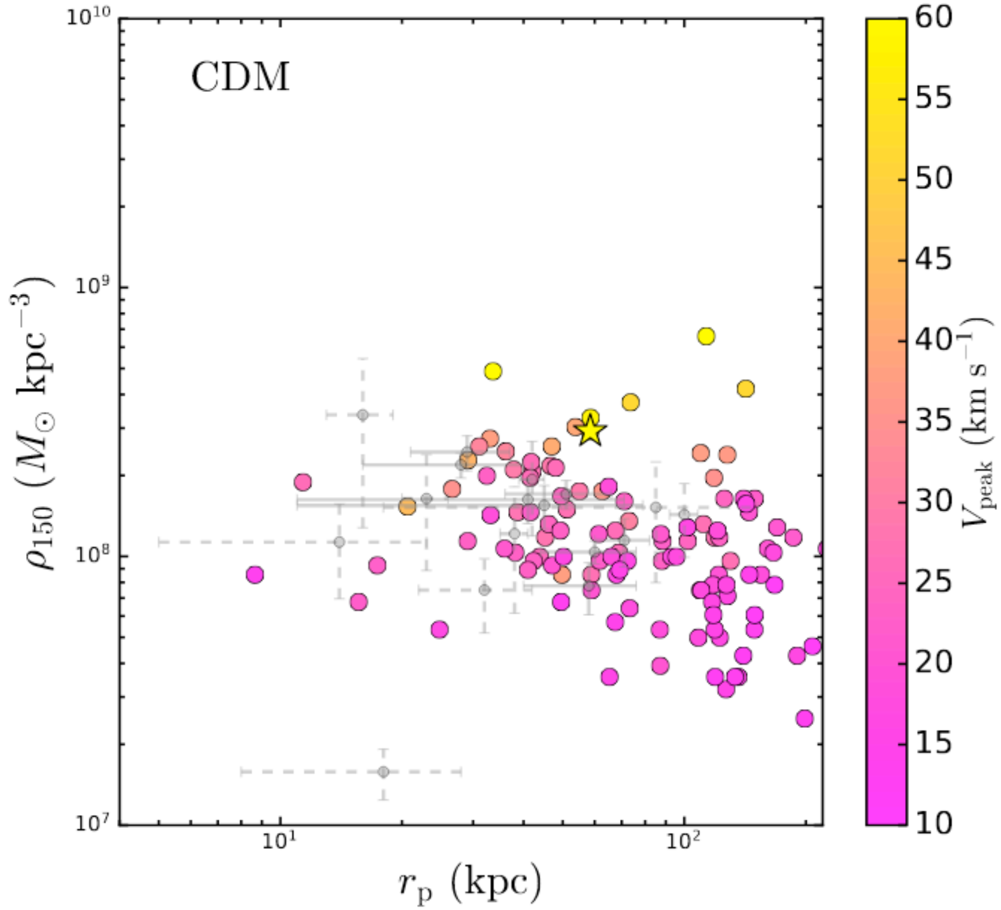
MW scale

"+" from Santos-Santos+(2022)

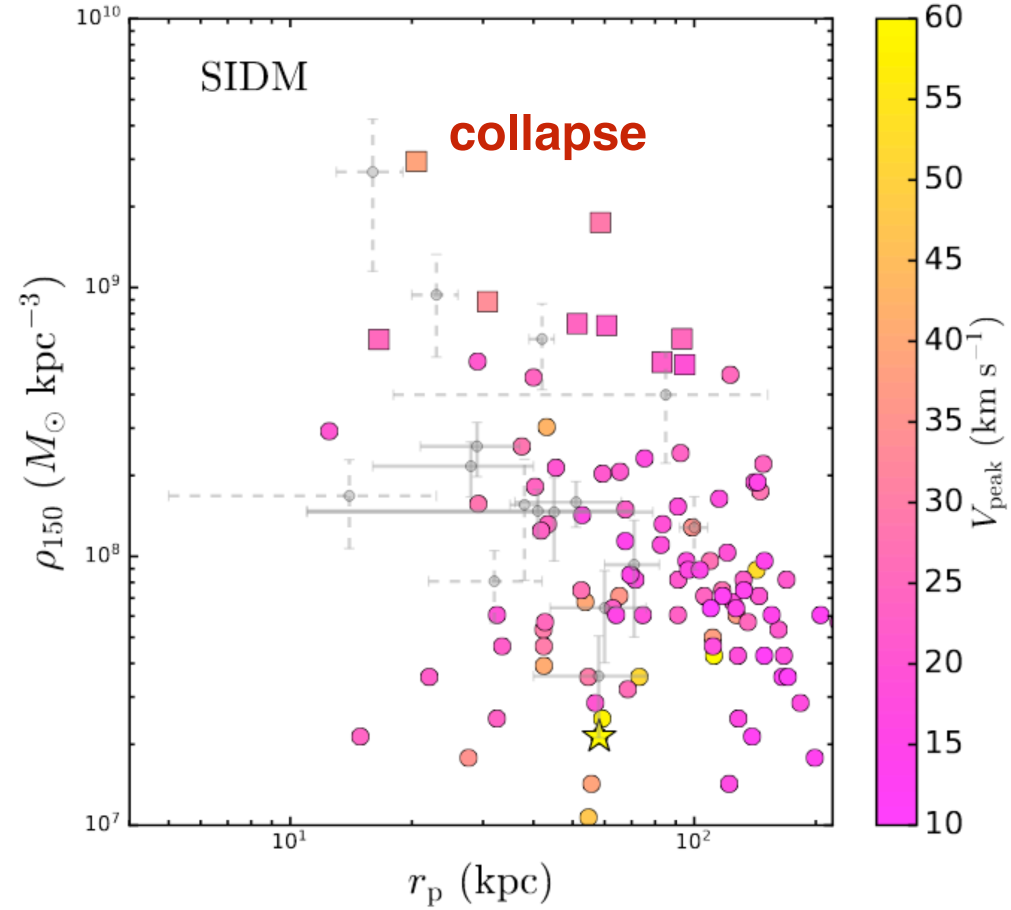
Yang, Nadler, HBY (2022)

Central Density vs Pericenter

Subhalos



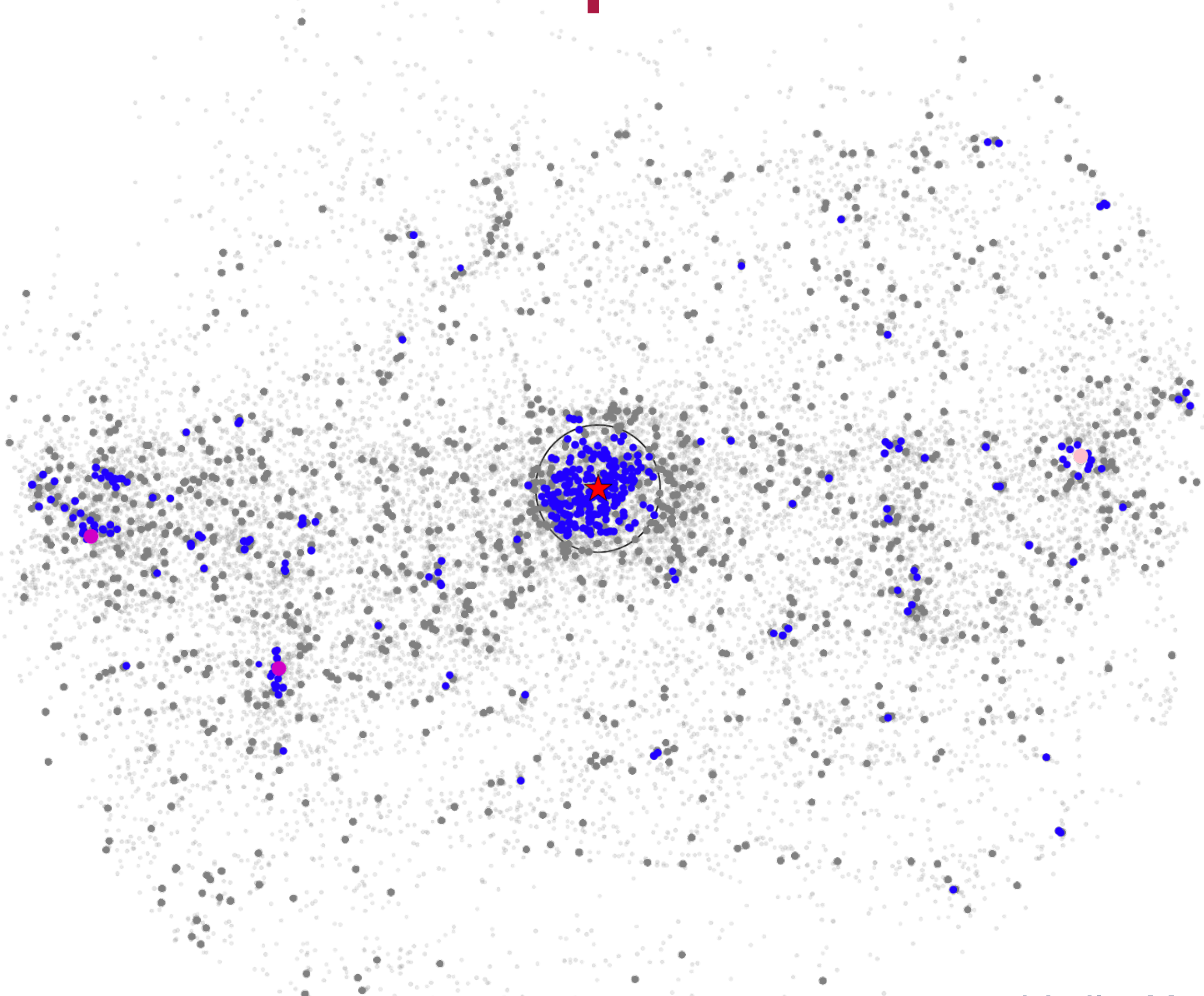
Subhalos



- Strong dark matter self-interactions increase the spread and amplify anti-correlation
- For the most ~15 massive subhalos, the CDM simulation does not show the anti-correlation trend
- The stellar disk would "destroy" the subhalos near the bottom

MW scale

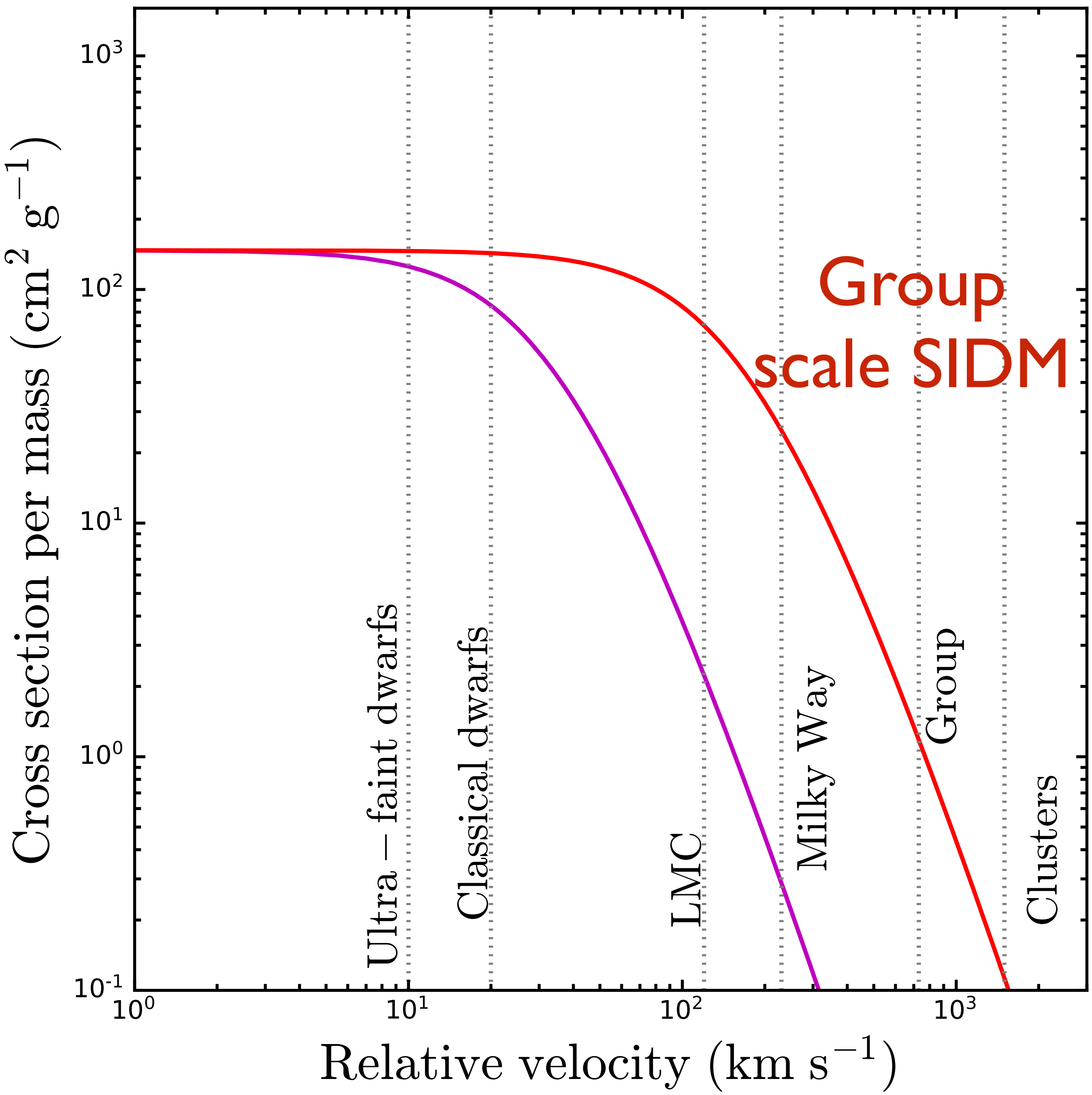
Group Scales



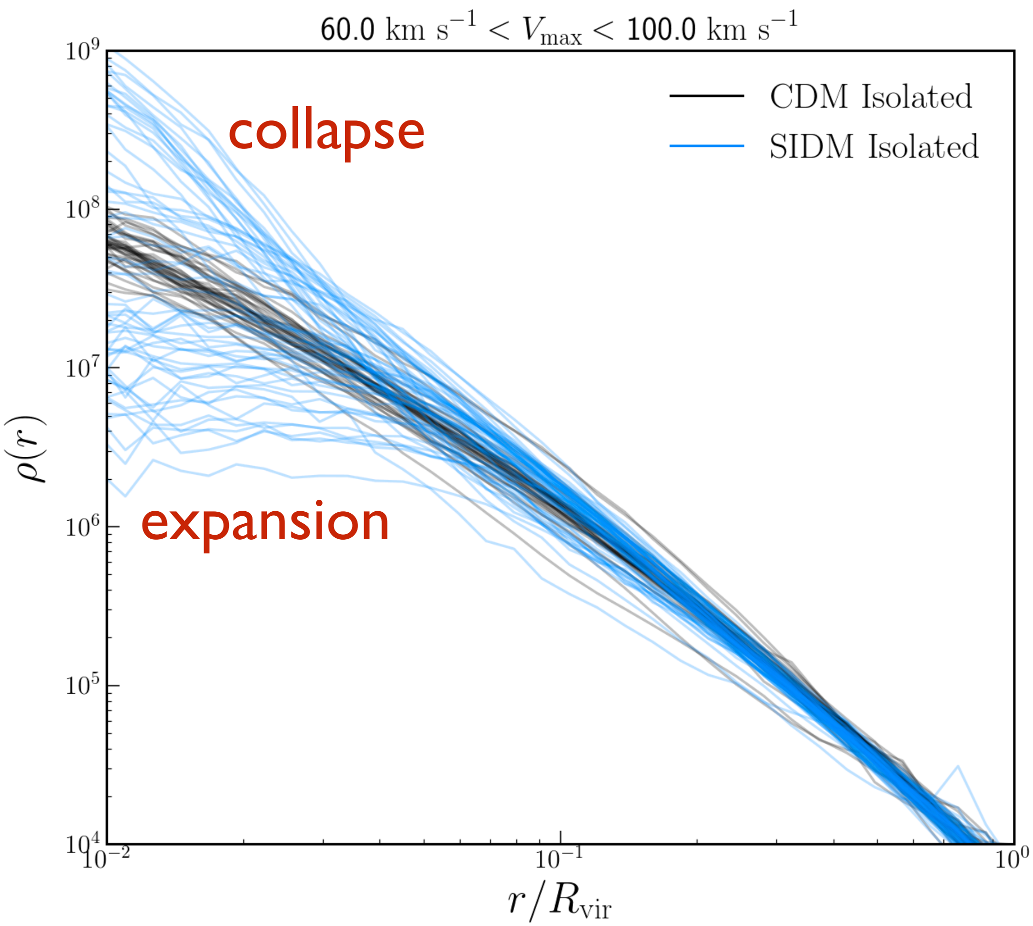
Nadler, Yang, HBY (2023)

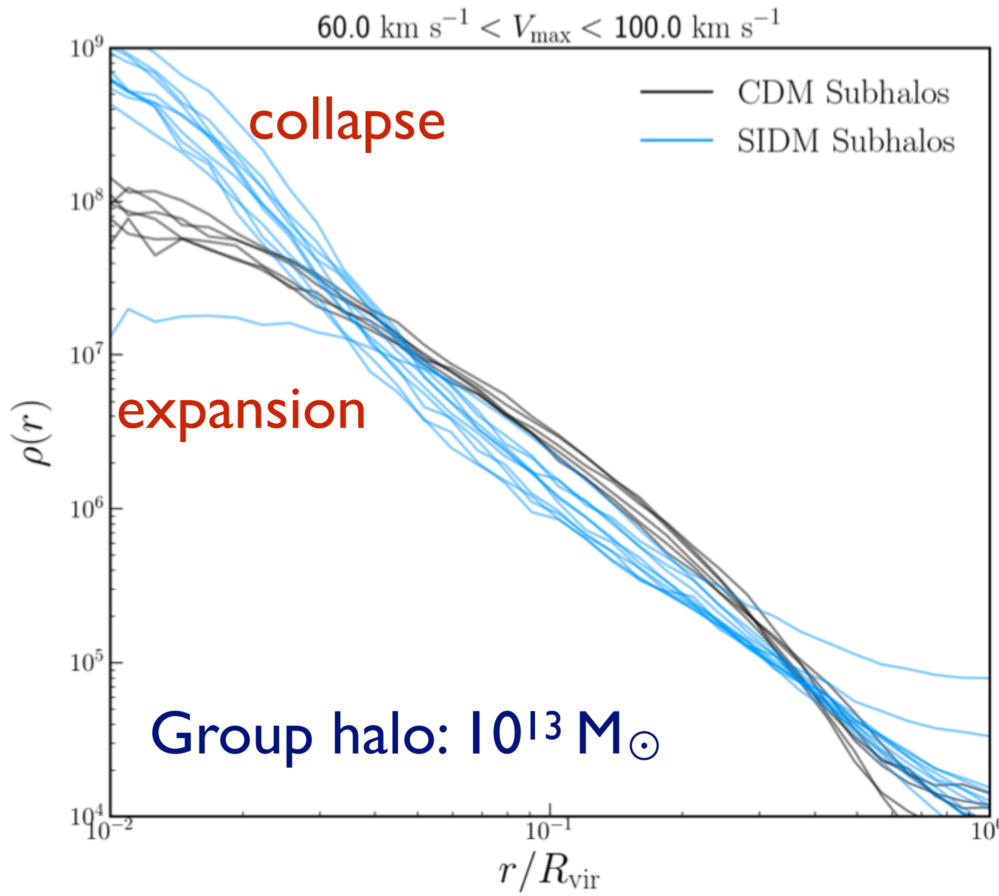
- High-resolution zoom-in cosmological simulations
- The main halo mass: $\sim 10^{13}\ M_{\odot}$, containing a Milky Way-like halo: $\sim 9\times 10^{11}\ M_{\odot}$

More Spicy


Group
scale SIDM
Cross section per mass (cm^2 g^{-1})
Relative velocity (km s^{-1})
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Ultra − faint dwarfs
Classical dwarfs
LMC
Milky Way
Group
Clusters

SIDM Isolated Halos and Subhalos



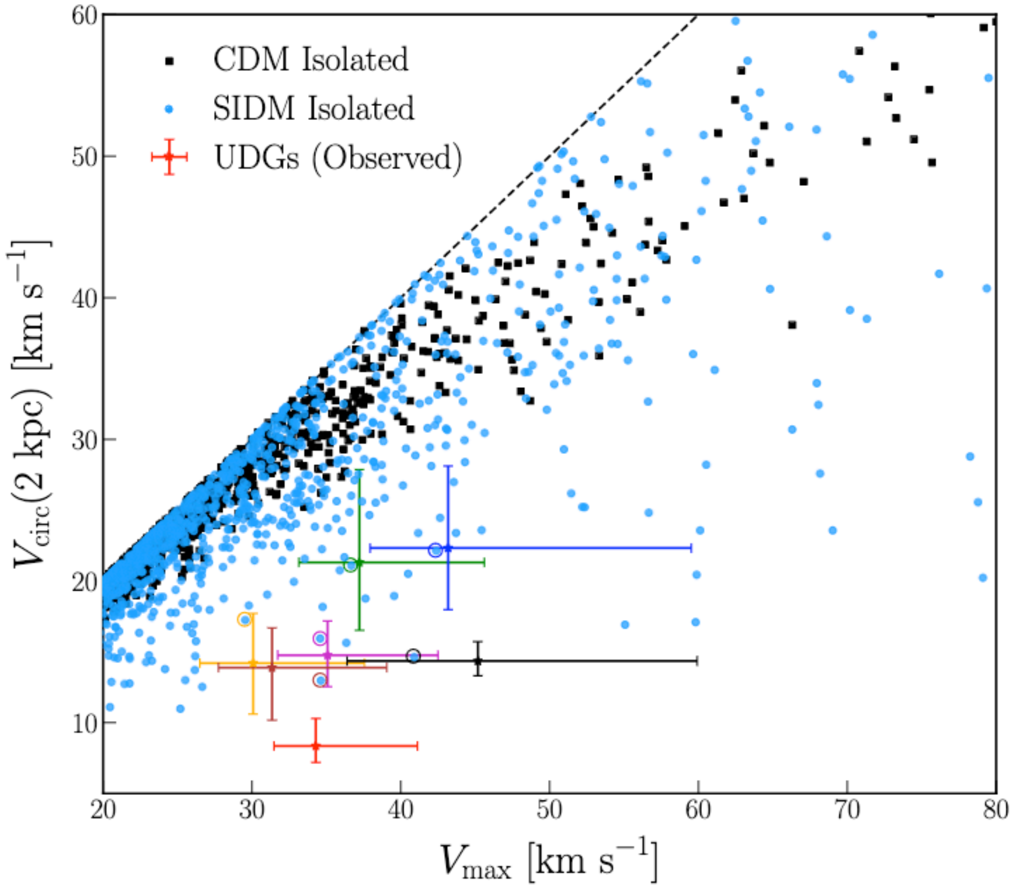


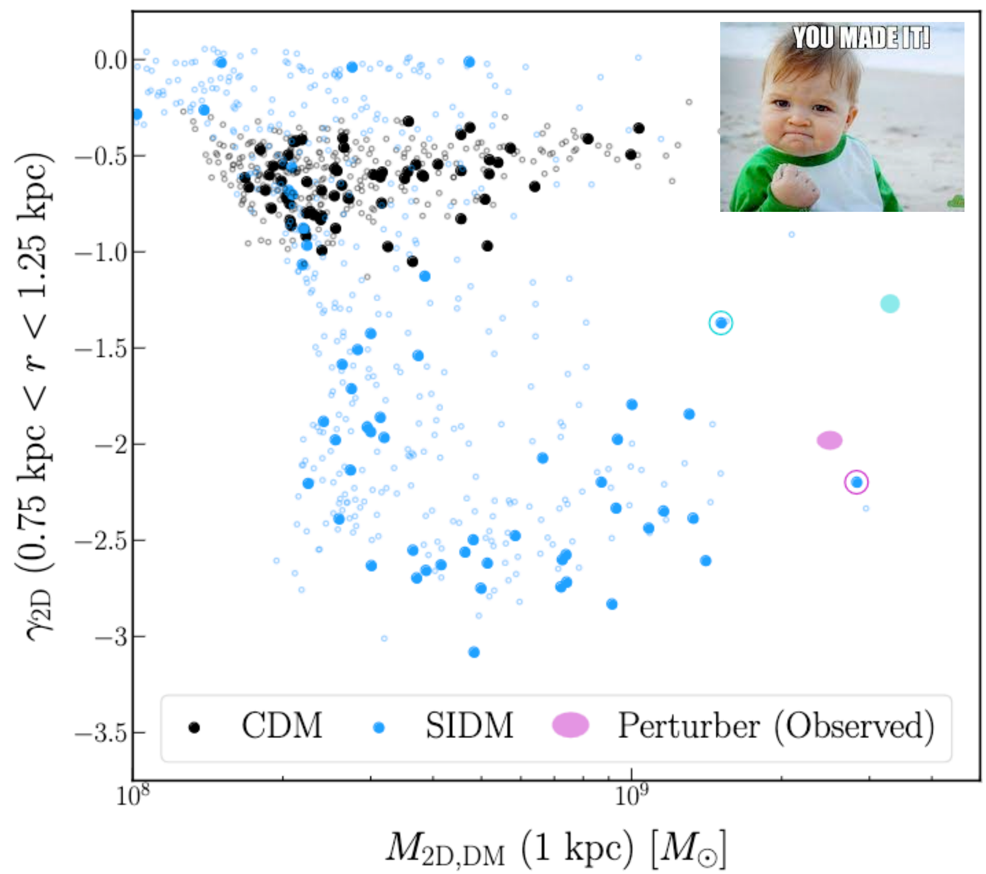
$$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$$

Group scale

- Strong dark matter self-interactions can greatly diversify the inner halo density, due to core expansion and collapse
- Amplify the scatter in the concentration-mass relation

Reconciling UDGs & Lens Perturber



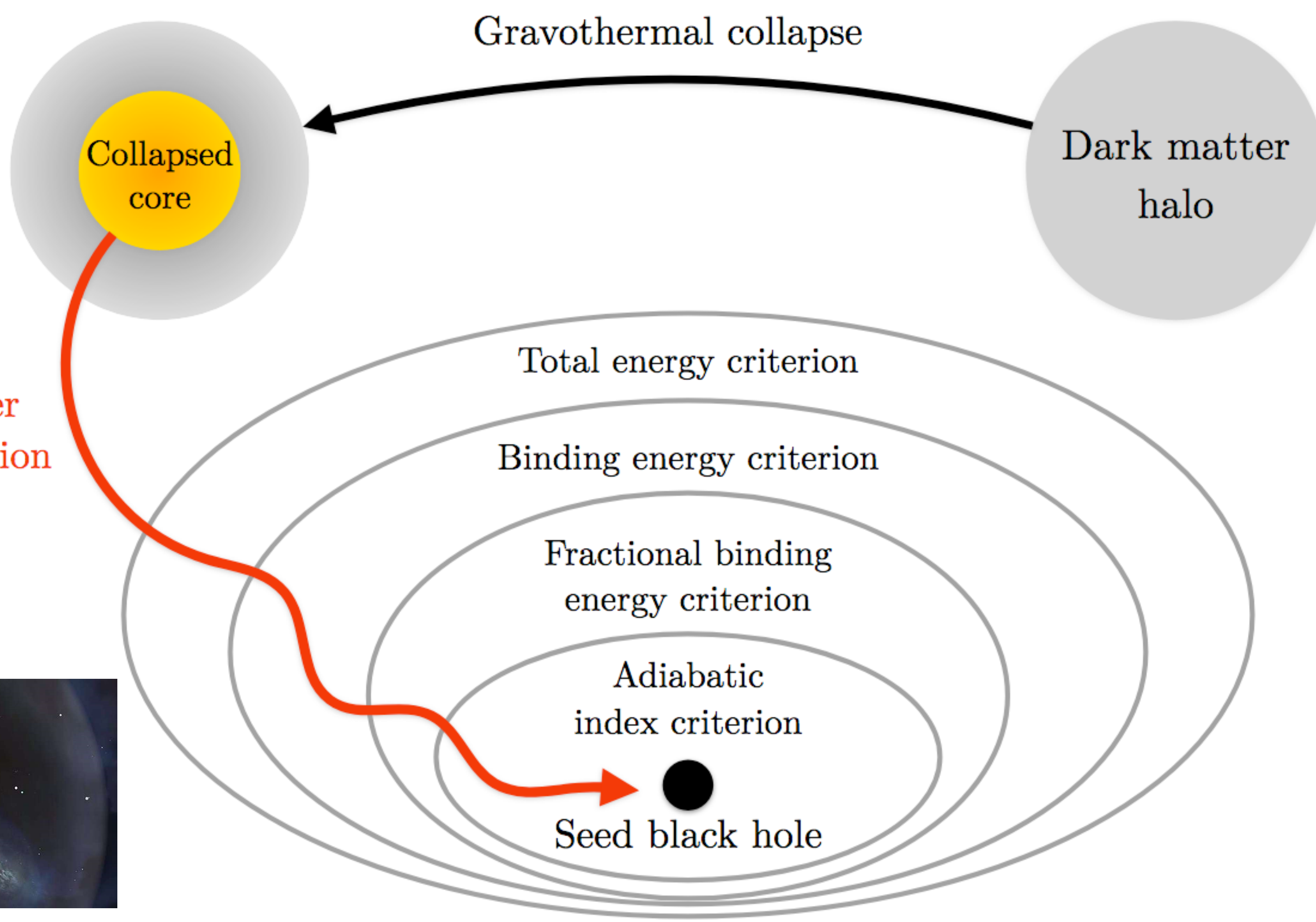


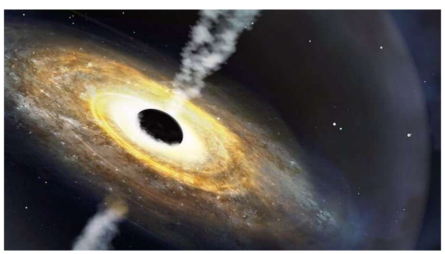
Group scale

For the lens perturber, there is a slight offset in mass, as the main halo mass is 10^{13} $M_\odot$ on the lower end of the favored range ~10^{13}-6×10^{13} $M_\odot$

Nadler, Yang, HBY (2023)

Collapsing into a Black Hole





Wei-Xiang Feng

Truncated Maxwell-Boltzmann distribution

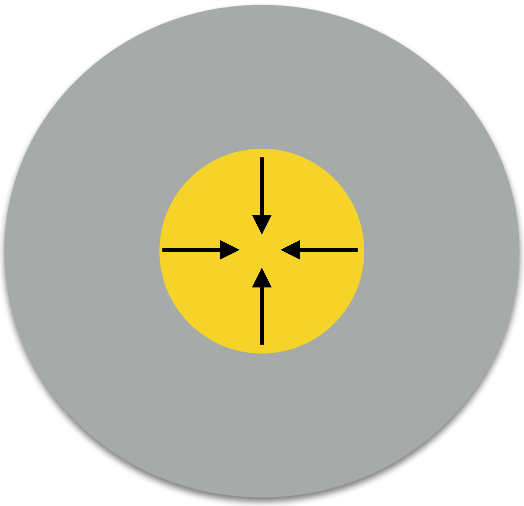
Central 3D velocity dispersion>0.57c

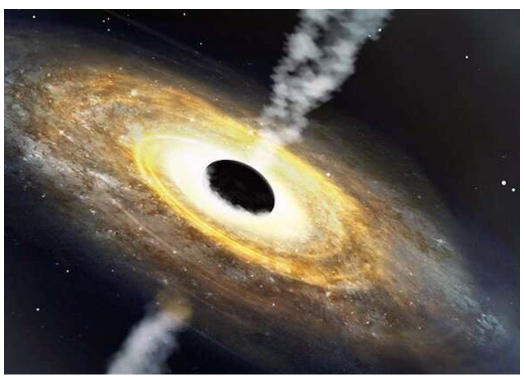
$$\begin{cases} (e^{-\epsilon/kT} - e^{-\epsilon_c/kT}) d^3p(\epsilon) & (\epsilon \leq \epsilon_c) \\ 0 \quad (\epsilon > \epsilon_c), \end{cases}$$

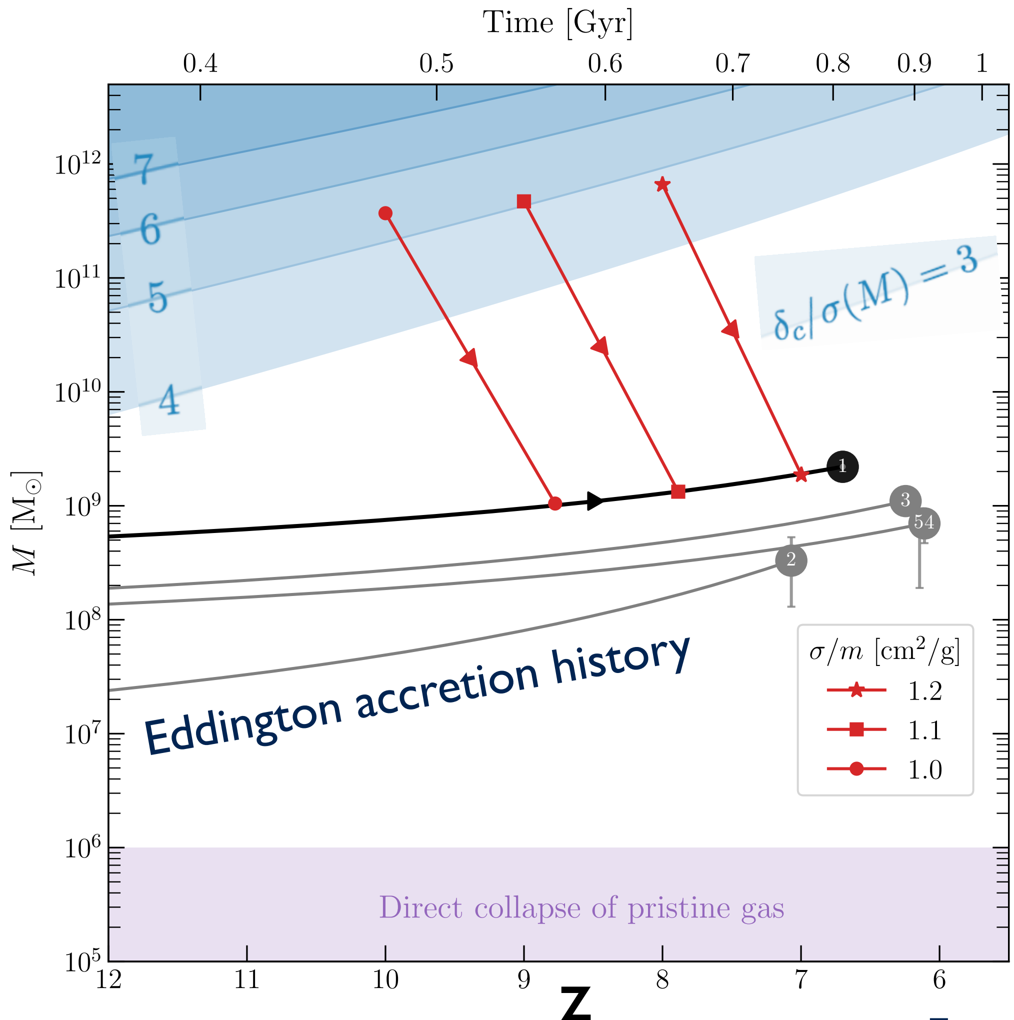
Find GR configurations using the Tolman-Oppenheimer-Volkov (TOV) equation; Check GR instability criteria

Feng, HBY, Zhong (ApJL 2021, JCAP 2022)

Bonus: Seeding Supermassive Black Holes







The most challenging one, J1205-0000

Mass $2.2\times10^9\ M_\odot$

z=6.7

f_{Edd}=0.16

Onoue et al. (2019)

~800 Myr after the Big Bang

Feng, HBY, Zhong (APJL, 2020)

- A conservative cross section is enough; the presence of baryons can speed the onset of collapse by a factor of 100!
- The mechanism predicts massive halos at high redshifts

Article | Published: 22 February 2023

A population of red candidate massive galaxies ~600 Myr after the Big Bang

Ivo Labbé, Pieter van Dokkum, Erica Nelson, Rachel Bezanson, Katherine A. Suess, Joel Leja, Gabriel Brammer, Katherine Whitaker, Elijah Mathews, Mauro Stefanon & Bingjie Wang

Nature (2023) | Cite this article

Massive galaxies exist in the early Universe at z~8!

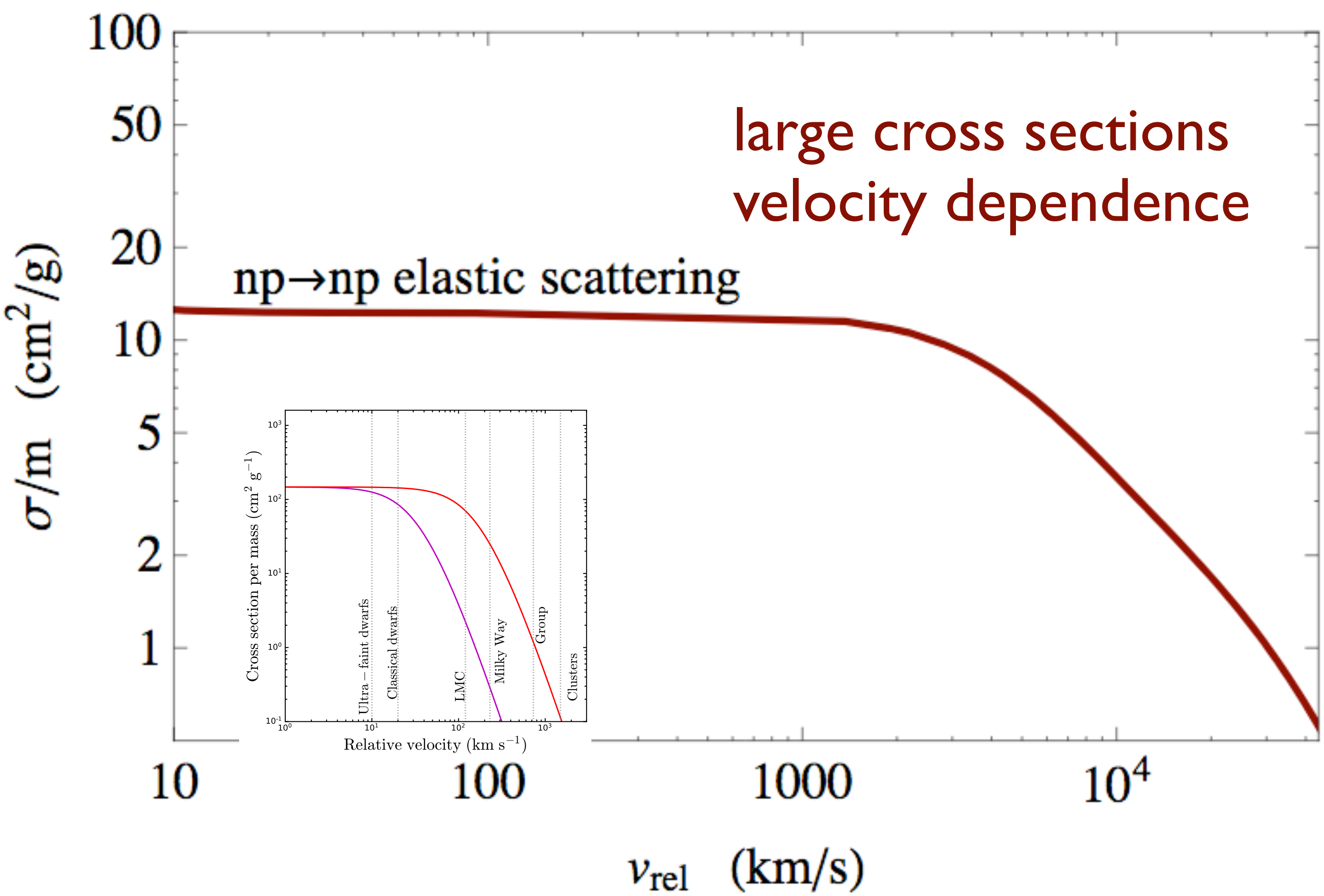
Abstract

Galaxies with stellar masses as high as $\sim 10^{11}$ solar masses have been identified[1–3] out to redshifts $z \sim 6$, approximately one billion years after the Big Bang. It has been difficult to find massive galaxies at even earlier times, as the Balmer break region, which is needed for accurate mass estimates, is redshifted to wavelengths beyond 2.5 μm. Here we make use of the 1-5 μm coverage of the *JWST* early release observations to search for intrinsically red galaxies in the first ≈ 750 million years of cosmic history. In the survey area, we find six candidate massive galaxies (stellar mass $> 10^{10}$ solar masses) at $7.4 \le z \le 9.1$, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of $\sim 10^{11}$ solar masses. If verified with spectroscopy, the stellar mass density in massive galaxies would be much higher than anticipated from previous studies based on rest-frame ultraviolet-selected samples.

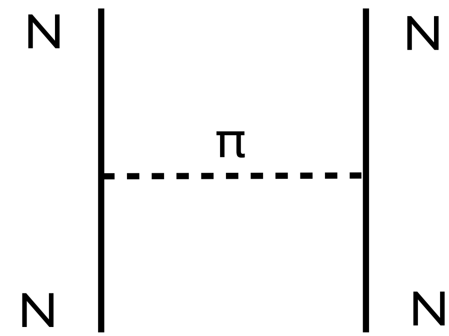
The expected halo mass $\sim 10^{11}$-$10^{12}\,M_\odot$ at z~8

see, e.g., Boylan-Kolchin (2022); Nadler, Benson, Driskell, Du, Gluscevic (2022)

N-P vs. DM-DM Scatterings

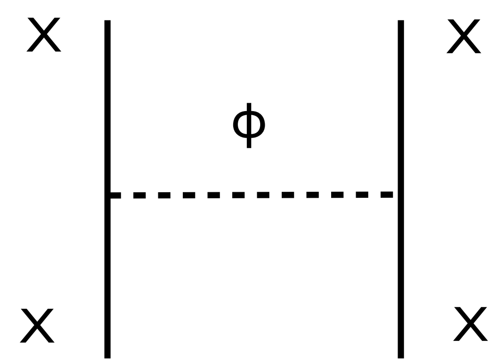


Tulin, HBY (2017); data from Obloinsk+(2011)



$$V(r) = -\frac{g^2}{4\pi}\,\frac{1}{r}\,e^{-\mu r}$$

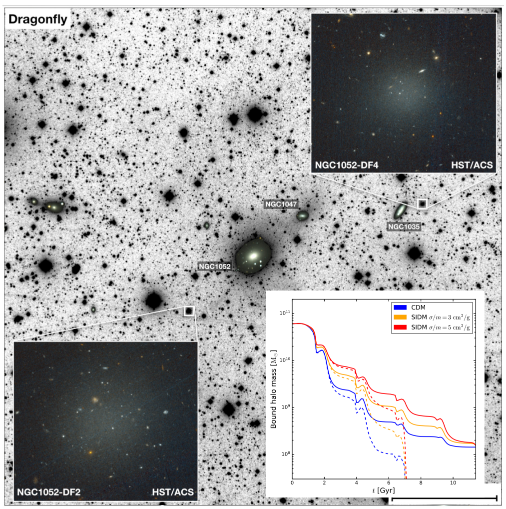
Yukawa (1935)

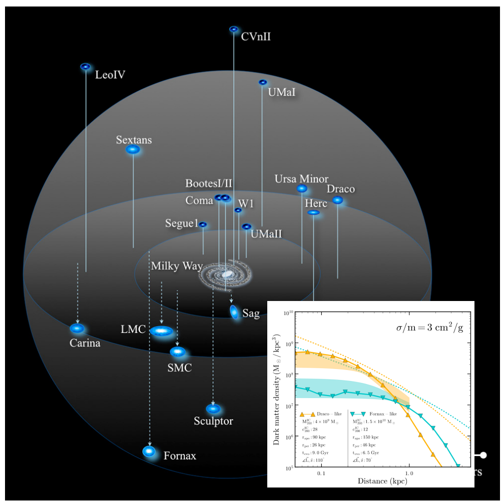


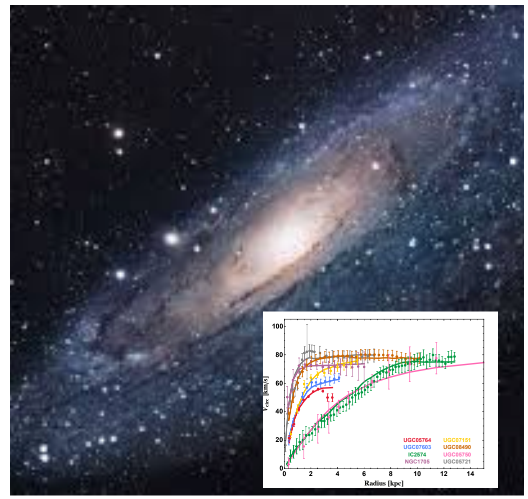
w/Feng, Kaplinghat (PRL, 2010)…

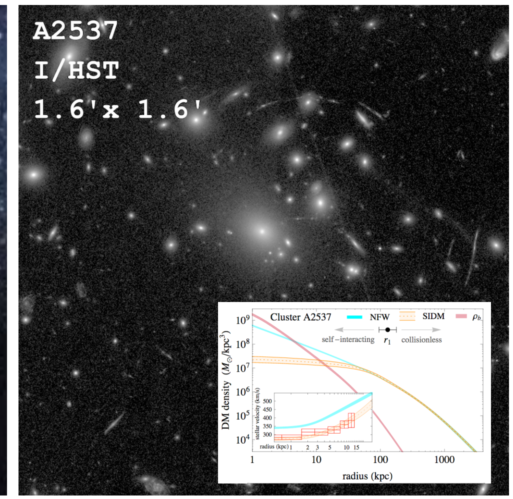
SIDM from Dwarfs to Clusters

Ultra-diffuse galaxies (dark-matter-deficient)	Milky Way satellites	Spiral galaxies	Galaxy clusters









$M_{halo} <\sim 10^8\ M_\odot$ | $M_{halo} \sim 10^8\ M_\odot$ | $M_{halo} \sim 10^9\text{-}10^{13}\ M_\odot$ | $M_{halo} \sim 10^{15}\ M_\odot$

- SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo mass $\sim 10^8\text{-}10^{15}\ M_\odot$); bonus: seeding SMBHs
- Dark matter self-interactions occur at fundamental scales $\sim 10^{-12}$ cm; change the dark matter distribution at astro scales $\sim 10^{22}$ cm, which can be detected!
- We may have detected strong dark matter self-interactions


Thank You!