Signatures of Strong Dark Matter Self-Interactions

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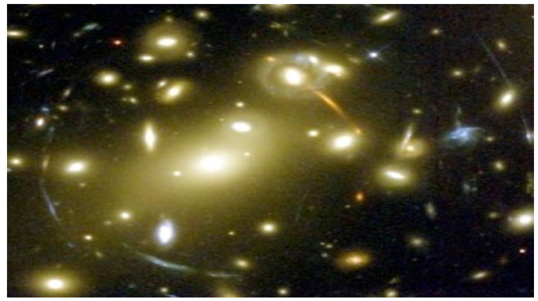
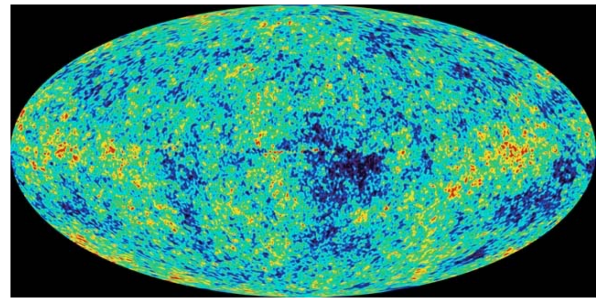
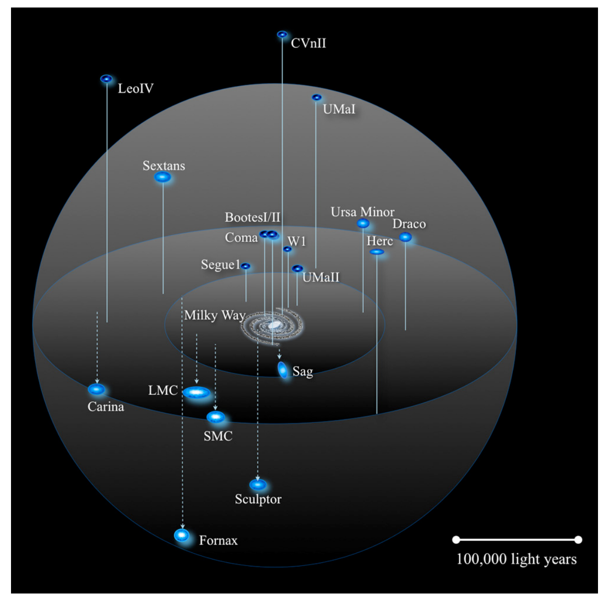
UCLA Dark Matter (March 30, 2023)

Cold Dark Matter (CDM)

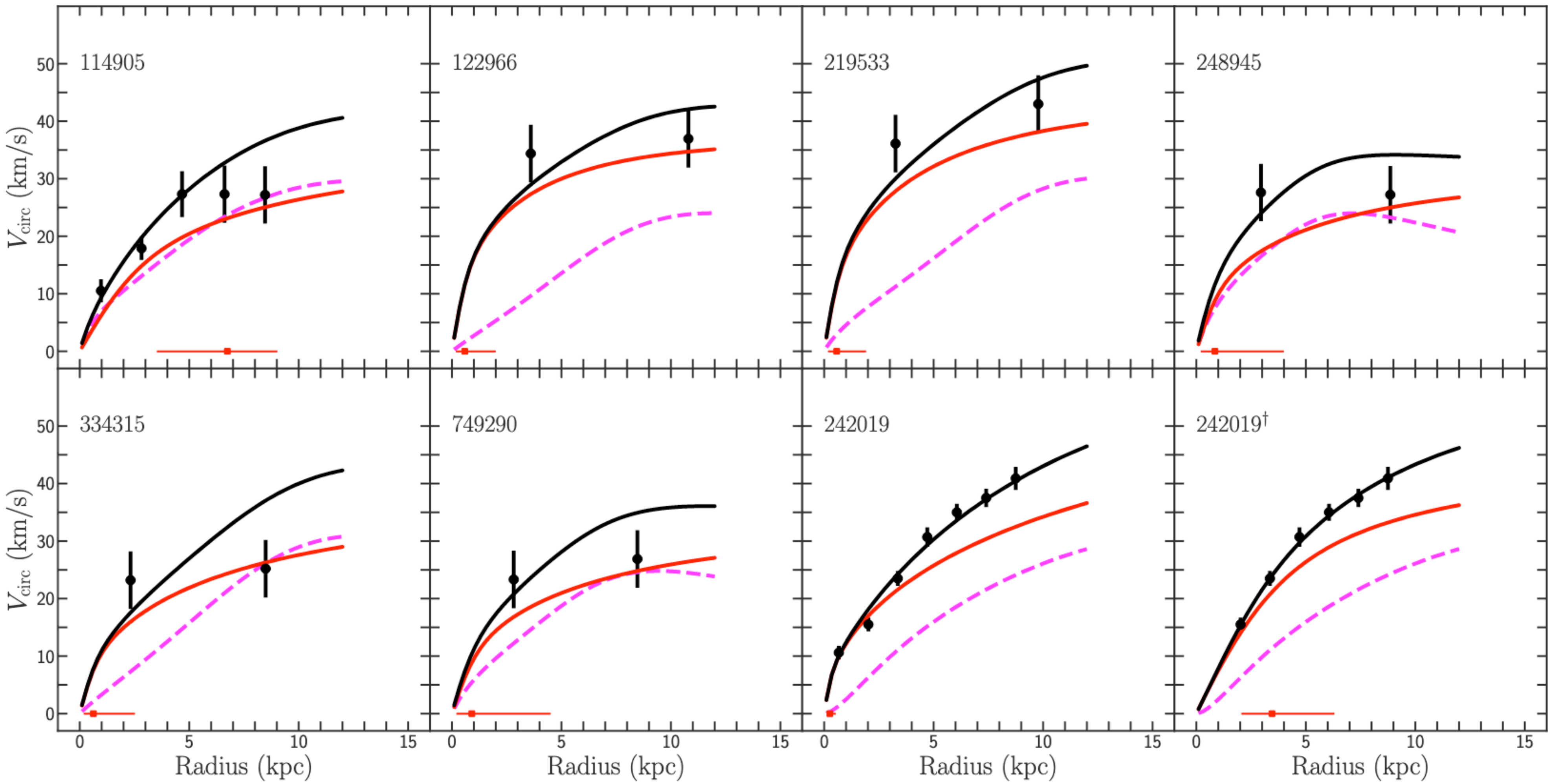
- Large scales: very well

- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
    - Core vs Cusp
    - Diversity
    - Too Big To Fail
    - “Cores” in clusters
    - Ultra-diffuse galaxies

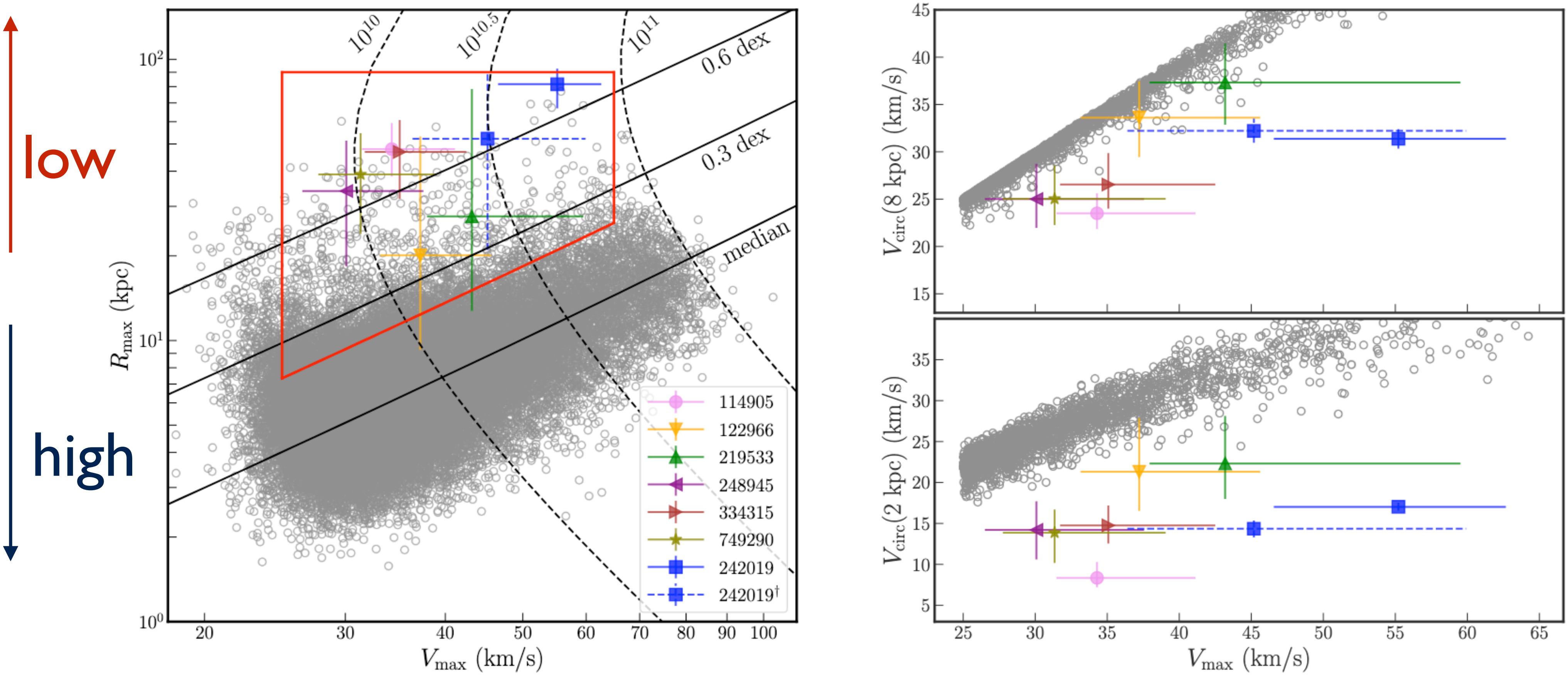
Ultra-diffuse Galaxies in the Field



- Red: dark matter halo; Magenta: baryons; Black: total
- These UDGs are extremely gas-rich, and largely baryon-dominated

Kong, Kaplinghat, HBY, Fraternali, Pina Mancera (ApJ 2022)

“Low-Concentration” Halos



- The gas-rich UDGs strongly favor low-concentration halos, “~5σ” lower than the median; this result is robust to the choice of halo density profiles
- These “low-concentration” halos can be found in the the IllustrisTNG dark matter-only simulations (gray)
- But the inner densities of the simulated halos are too high

Kong, Kaplinghat, HBY, Fraternali, Pina Mancera (ApJ 2022)

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]
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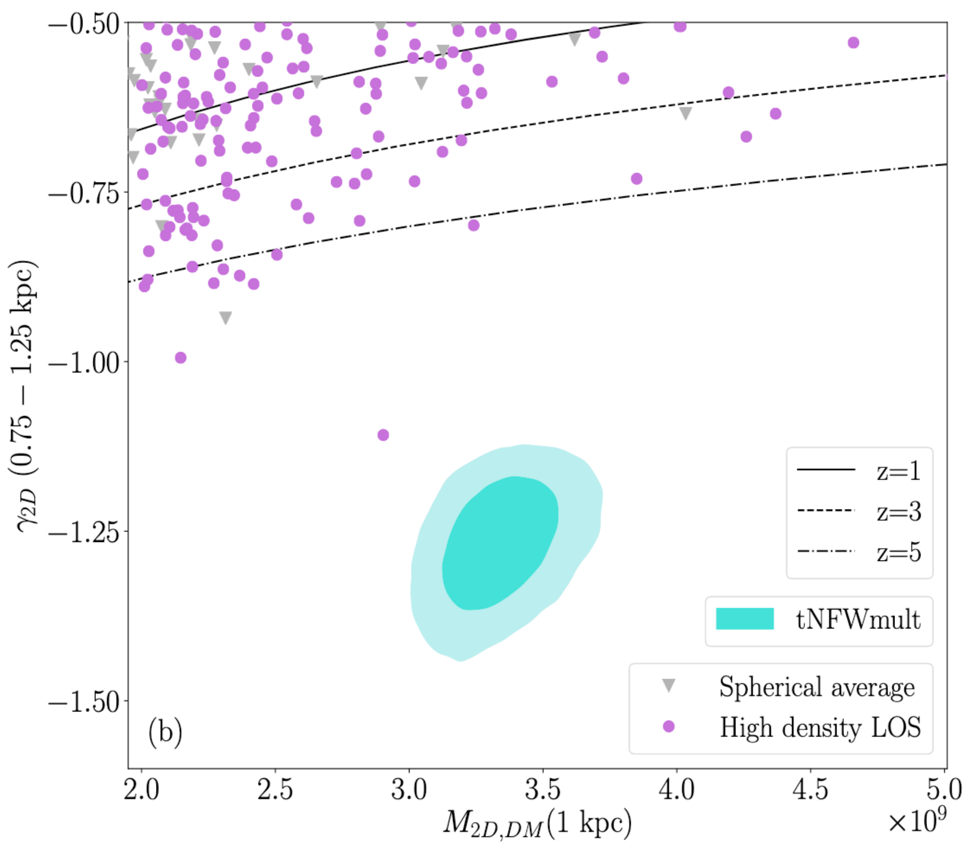
[2]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822-1897, USA
[3]Department of Physics, University of California, Santa Barbara, CA 93101, USA
[4]Institut d'Astrophysique de Paris, CNRS, UMR 7095, Universite Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France

(MNRAS 2010)

SDSSJ0946+1006 (the "Double Einstein Ring").

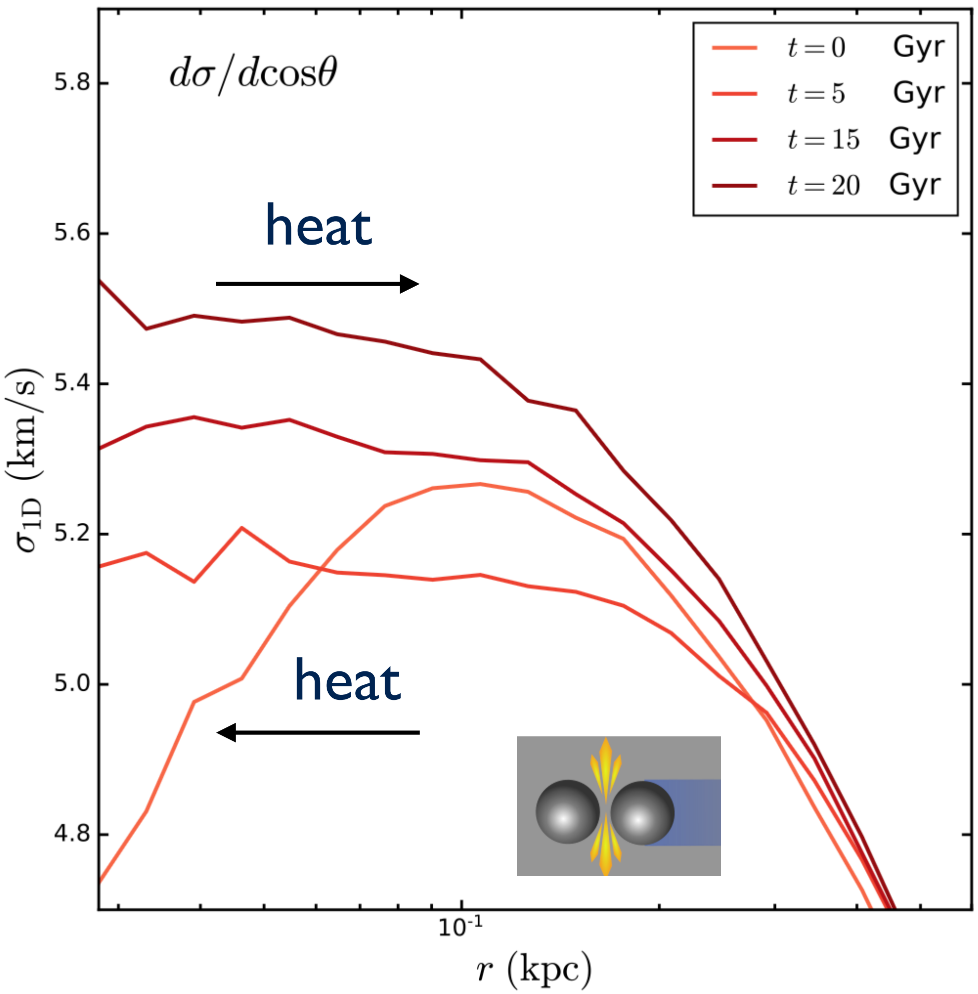


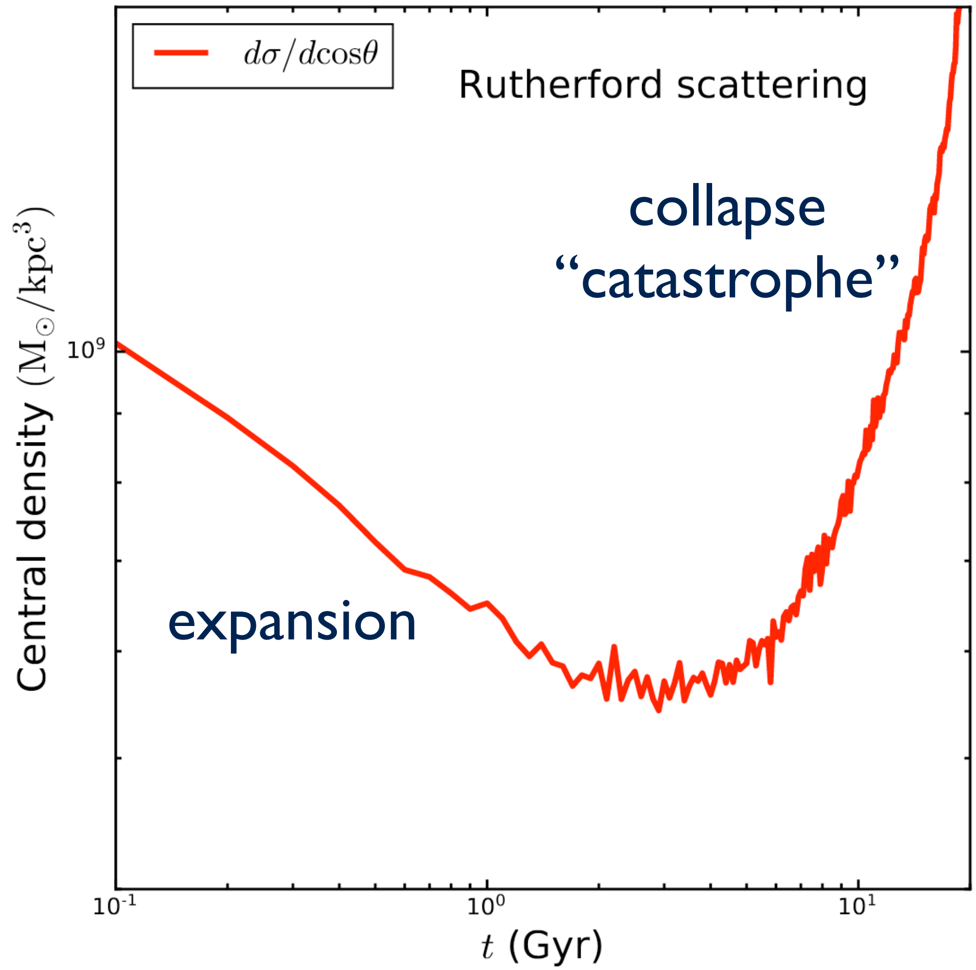
Minor, Kaplinghat, Vegetti (MNRAS, 2020)

- 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
- The substructure does not have a distinct stellar light signal; baryons cannot help

Conflict:
the UDGs vs the Substructure

Gravothermal Evolution





Yang, HBY (JCAP 2022)

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

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

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

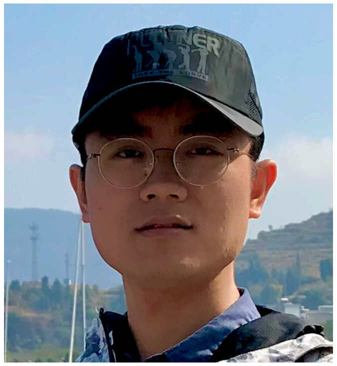
Balberg+(ApJ 2002)

Negative heat capacity!
⇒ gravothermal collapse

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

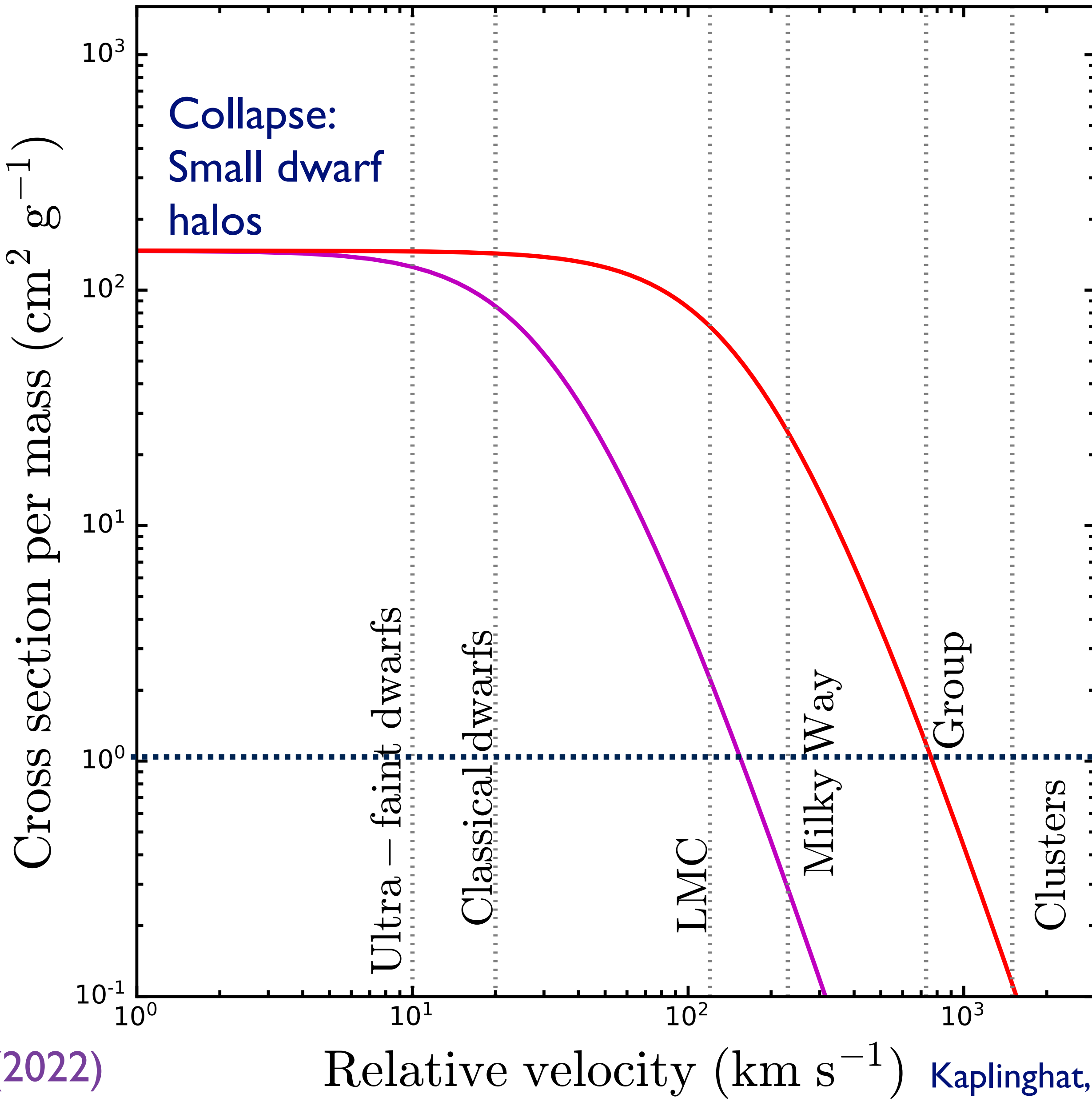
w/ Essig, McDermott, Zhong (PRL 2019)

Strong Dark Matter Self-Interactions



Daneng Yang (UCR)

Ethan Nadler (USC/Carnegie)



"conservative"

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

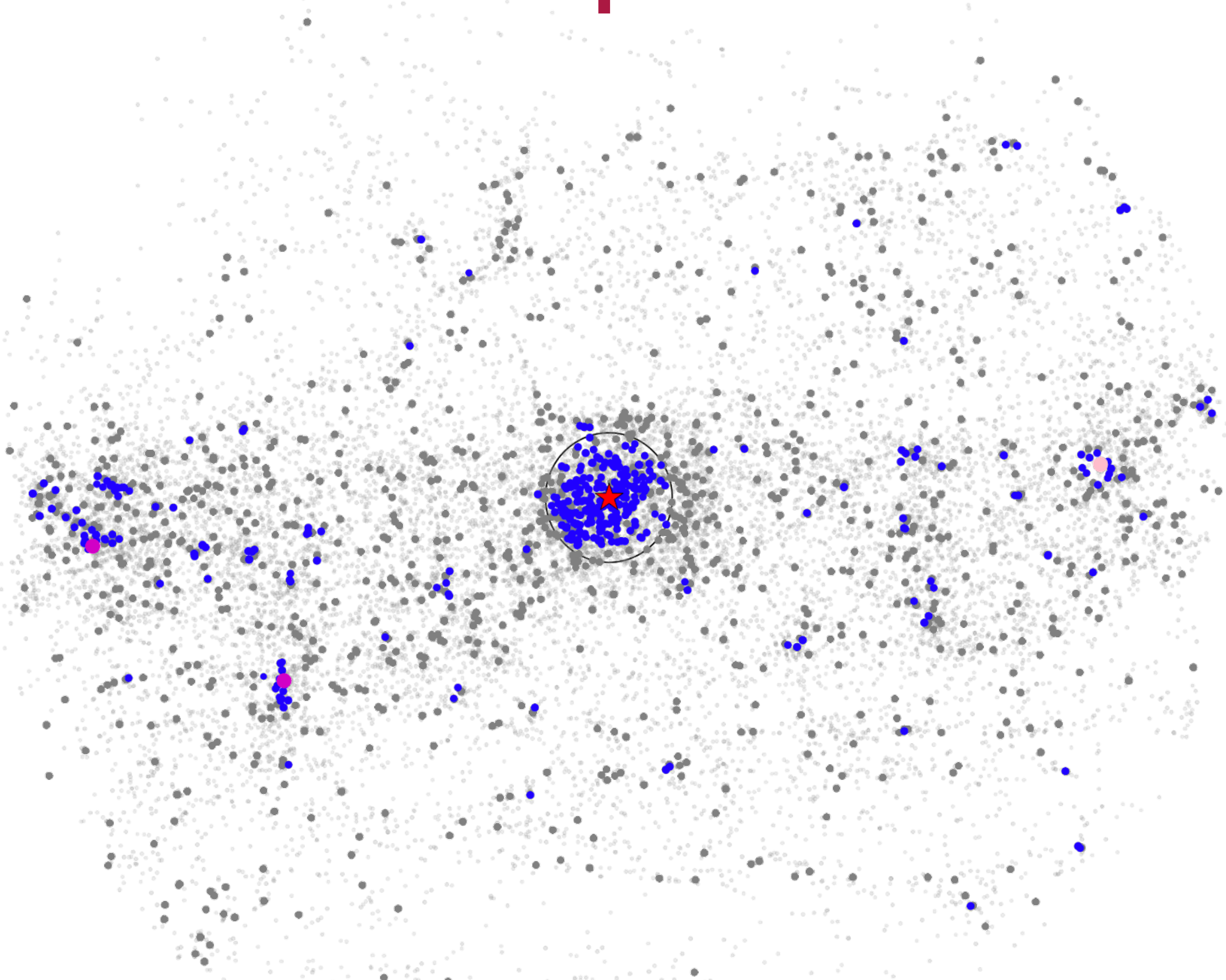
Kaplinghat, Tulin, HBY (PRL 2016)

Andrade+(MNRAS 2021)

Yang, Nadler, HBY (2022)

Nadler, Yang, HBY (in prep, 2023)

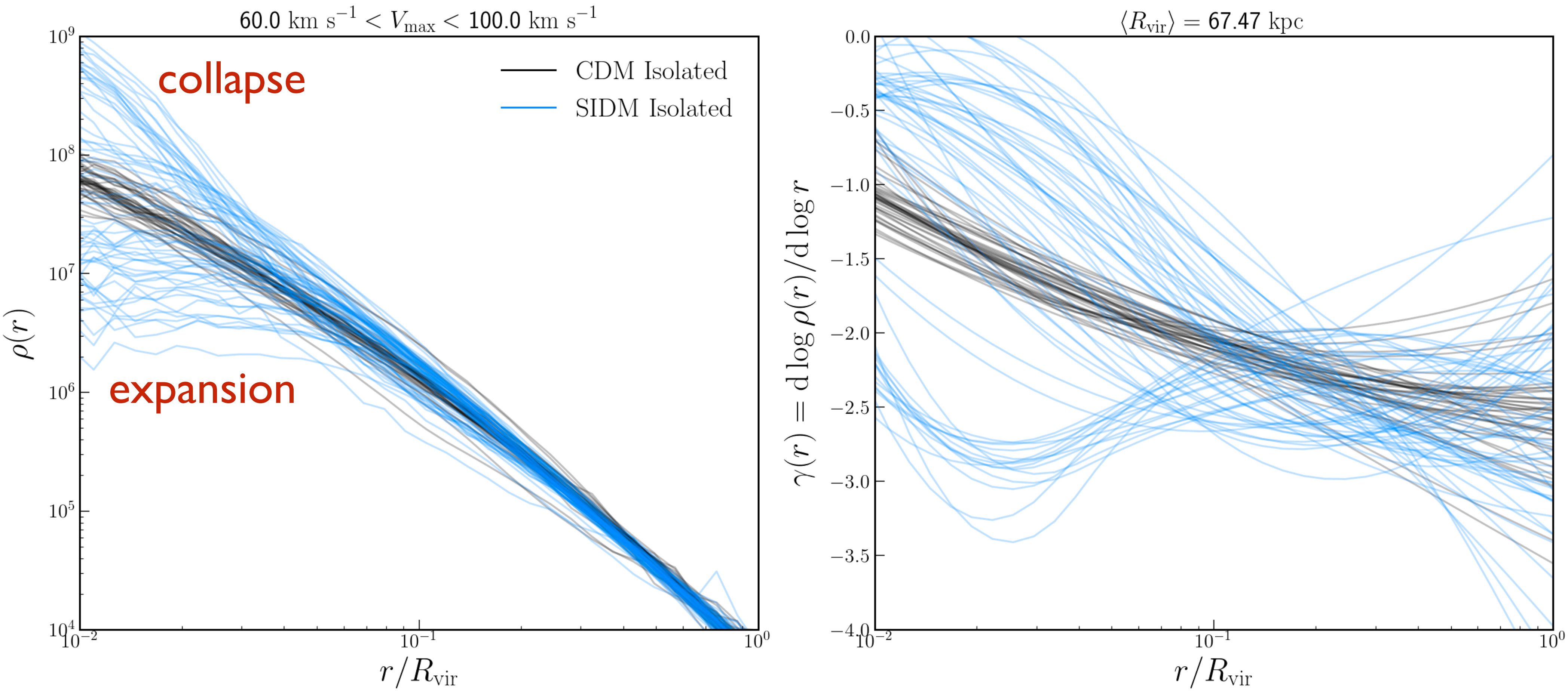
Group Scales



Nadler, Yang, HBY (in prep, 2023)

- High-resolution zoom-in cosmological simulations
- The main halo mass: 10^{13} $M_{\odot}$, containing a Milky Way-like halo: 9×10^{11} $M_{\odot}$
- The analysis is still going on; Some of the plots were made two weeks ago

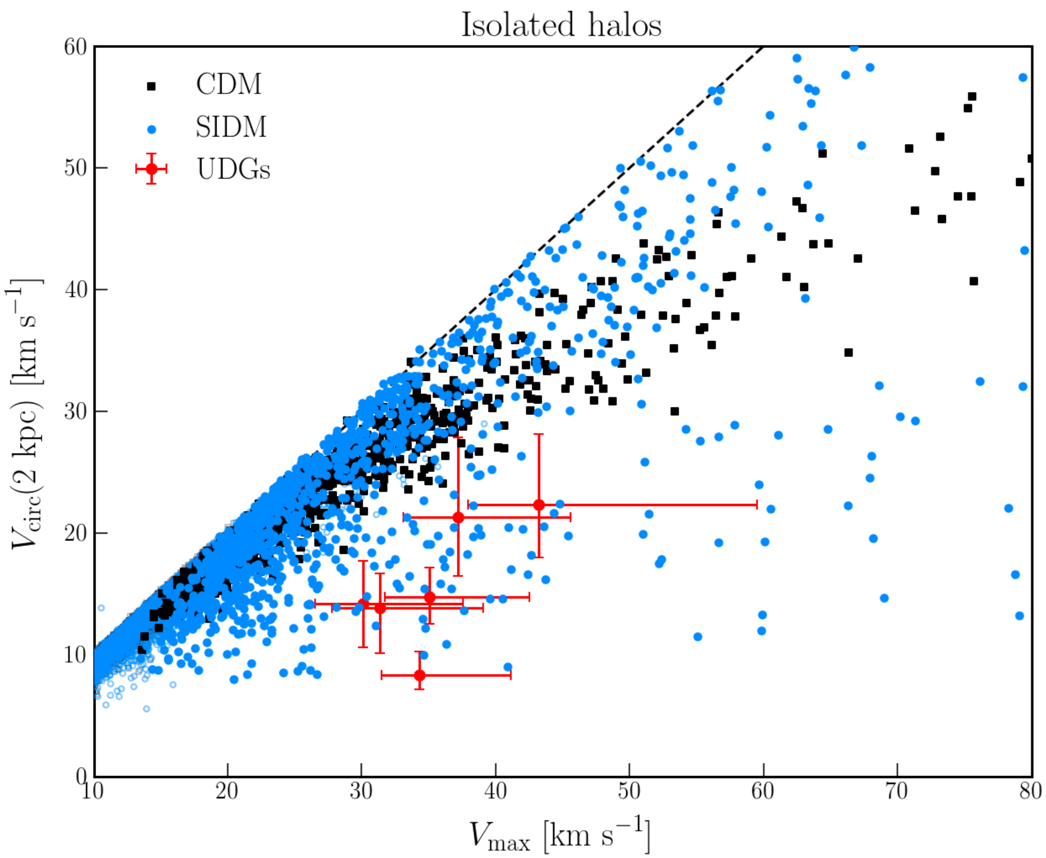
Isolated Field Halos

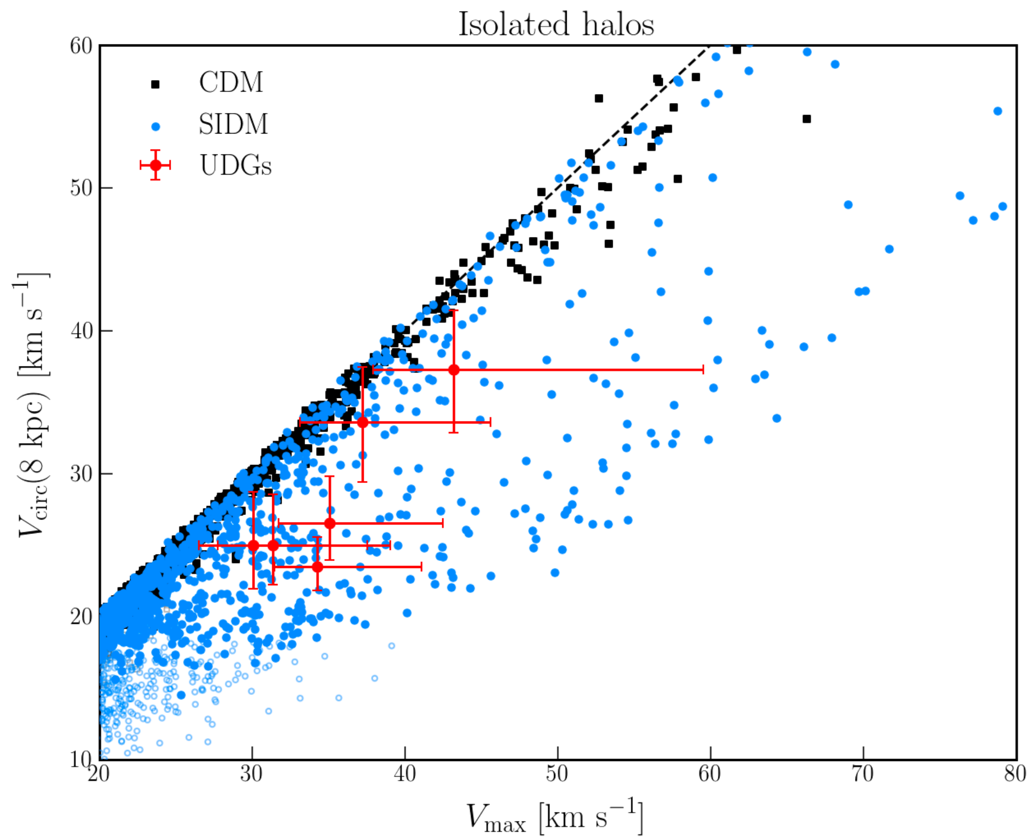


Nadler, Yang, HBY (in prep, 2023)

Strong dark matter self-interactions lead to large diversity in the inner halo density, due to core expansion and collapse

Ultra-Diffuse Galaxies in the Field



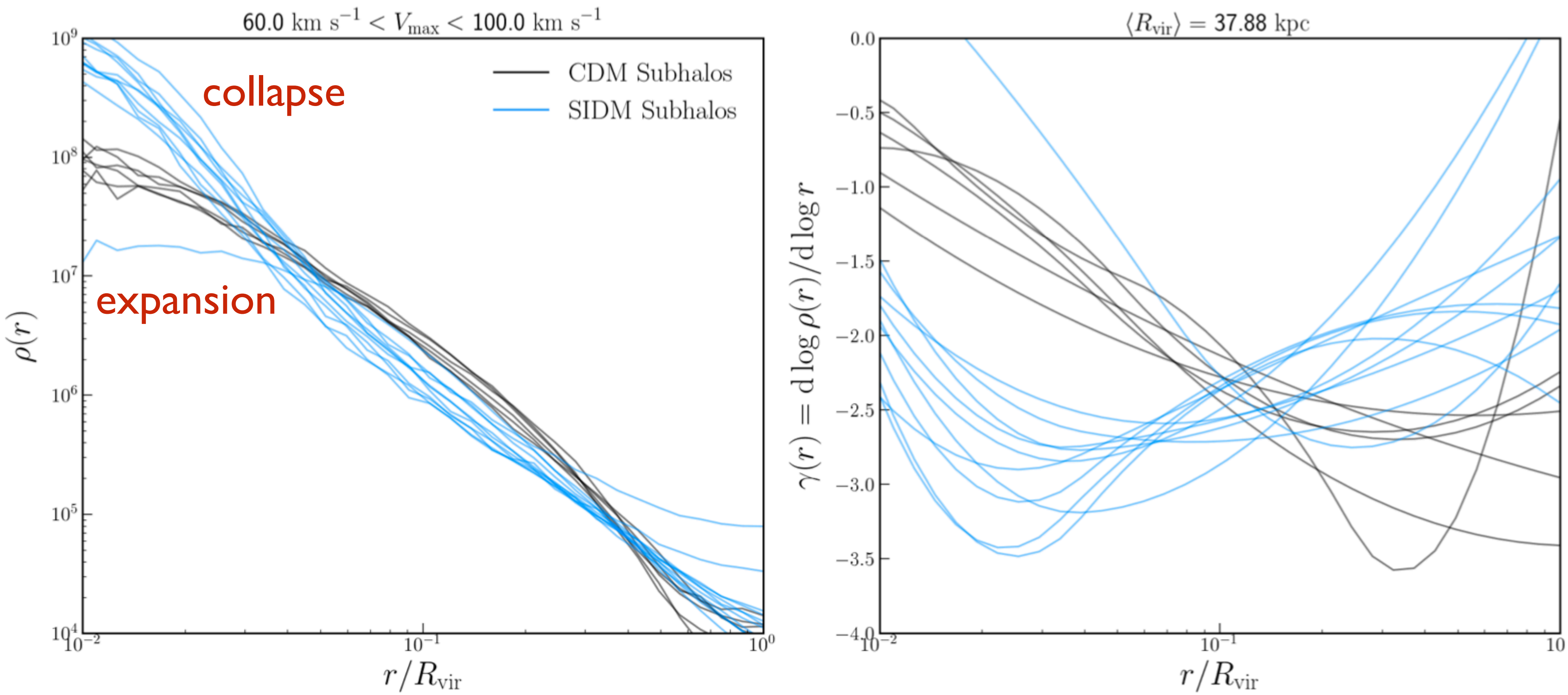


Nadler, Yang, HBY (in prep, 2023)

Red datapoints of the UDGs are from Kong+ (ApJ 2022)

These UDG galaxies are extremely gas-rich, and their halo properties are difficult to reproduce in CDM+feedback

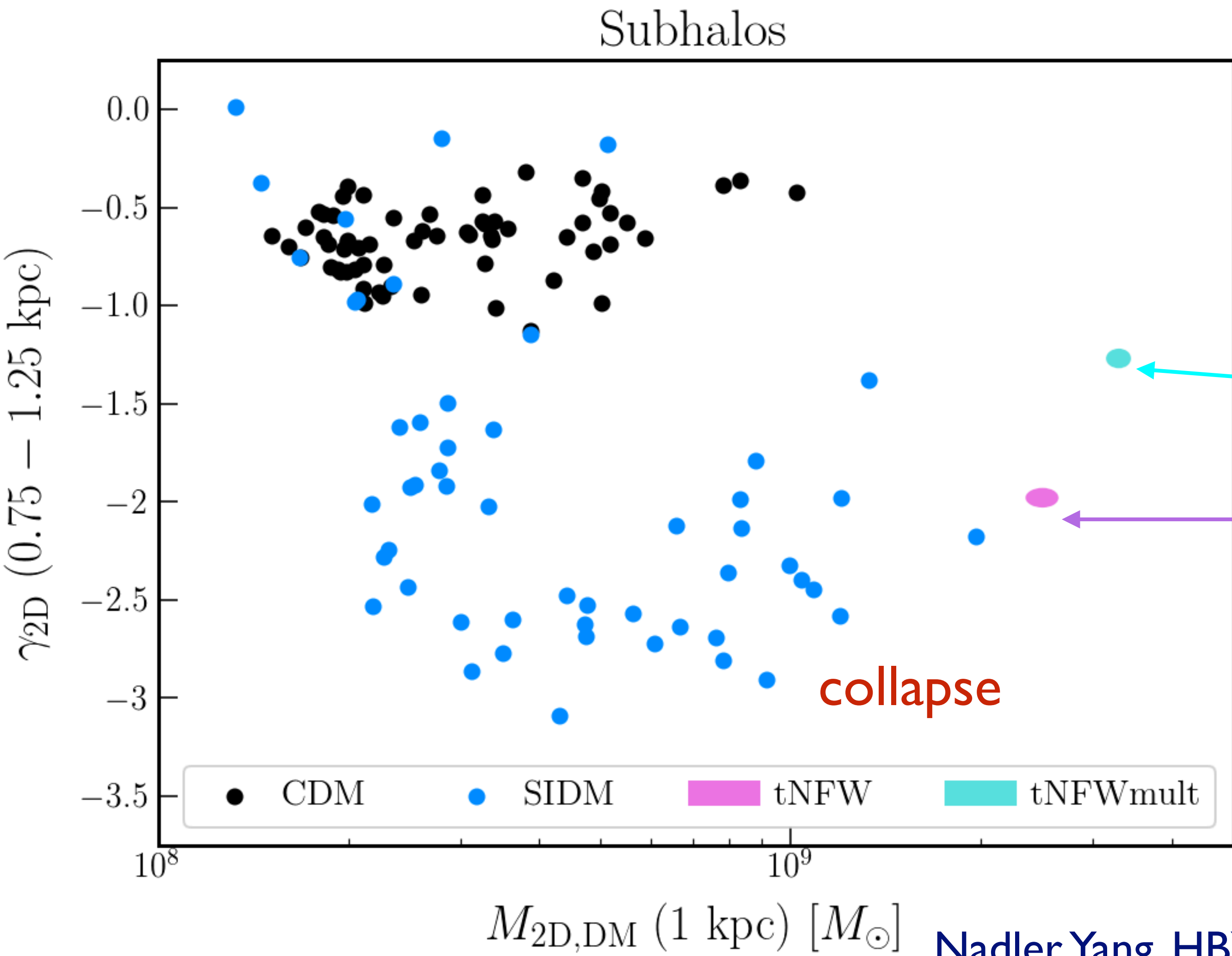
Subhalos in the Main Halo

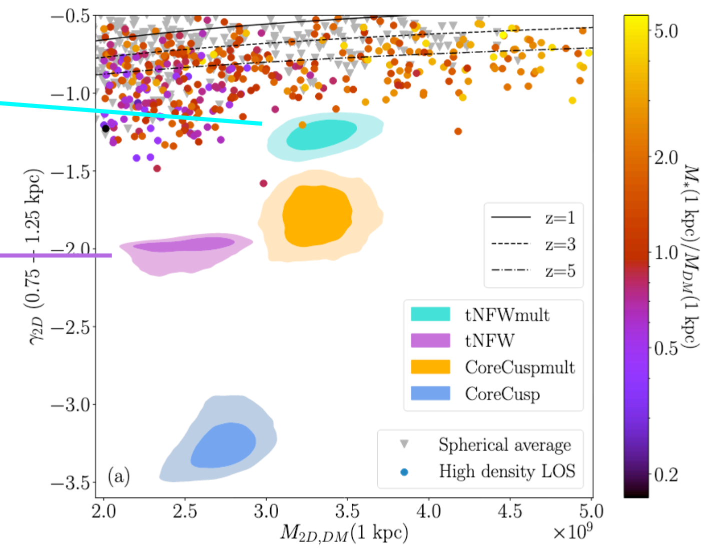


Nadler, Yang, HBY (in prep, 2023)

- Only one SIDM halo in the core-expansion phase survives
- More SIDM subhalos survive from tidal disruption than CDM ones
- Collapsed SIDM subhalos are more resilient to tidal disruption

Dense Dark Substructure





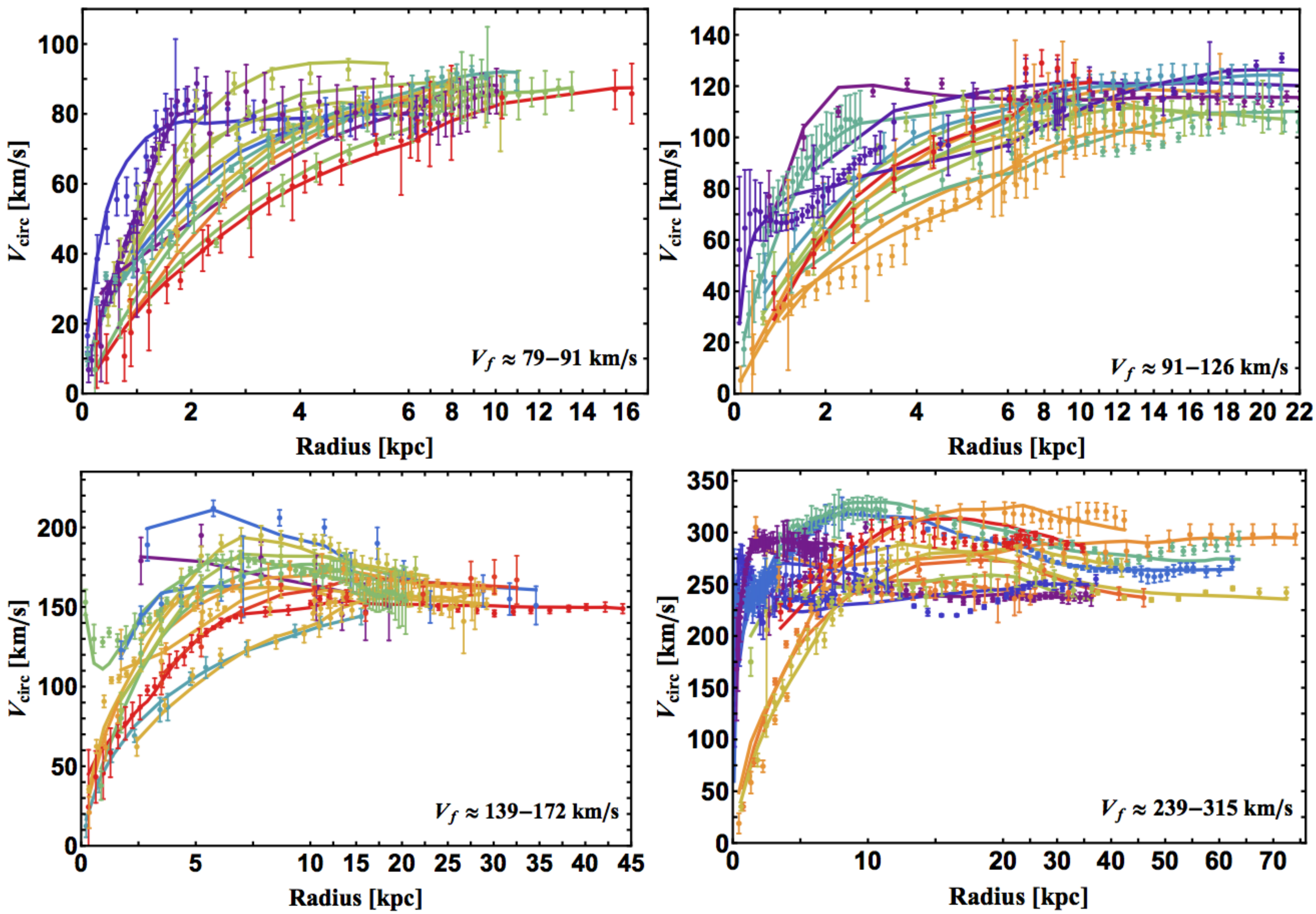
Minor+(2020)

Nadler, Yang, HBY (in prep, 2023)

There is a minor offset, as the simulated main halo mass 1.1×10^{13} $M_\odot$ is on the lower end of the mass range 10^{13}-6×10^{13} $M_\odot$ of the observed group halo

Testing SIDM collapse with strong lensing observations: Yang, HBY (2021); Gilman+(2022)

Diversity: Spiral Galaxies



DM/Baryon concentration

We analyzed 135 galaxies (3.6 μm band)!

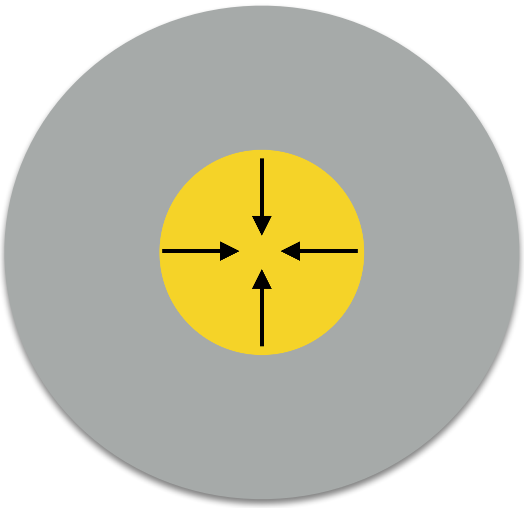
SPARC dataset, Lelli, McGaugh,Schombert (2016)

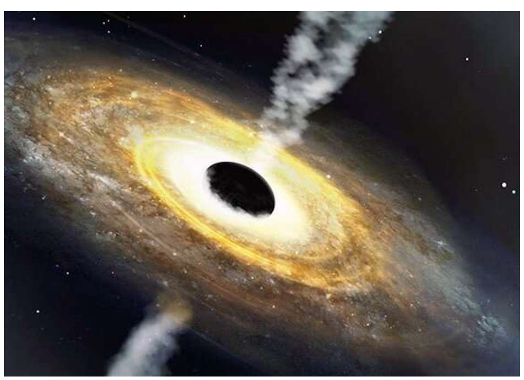
w/ Ren, Kwa, Kaplinghat (PRX 2018)

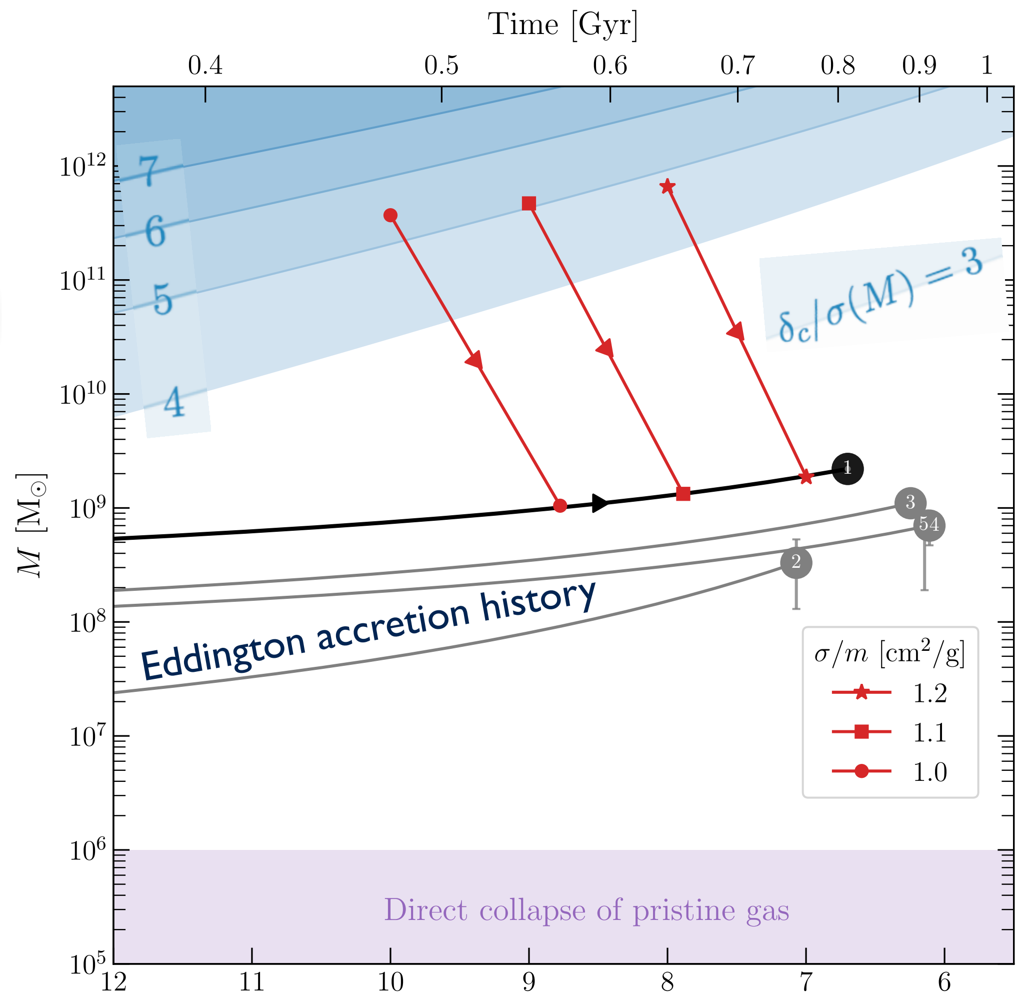
w/ Kamada, Kaplinghat, Pace (PRL 2017)

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

Seeding Supermassive Black Holes







Feng, HBY, Zhong (APJL, 2021; JCAP 2022)

The most challenging one, J1205-0000

Mass 2.2×10^9 $M_\odot$

z=6.7

f_{Edd}=0.16

Onoue et al. (2019)

~800 Myr after the Big Bang

- A conservative cross section is enough; the presence of baryons can speed the onset of collapse by a factor of 100
- The mechanism favors the existence of massive halos 10^{11}-10^{12} $M_\odot$ at z~8-10

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!

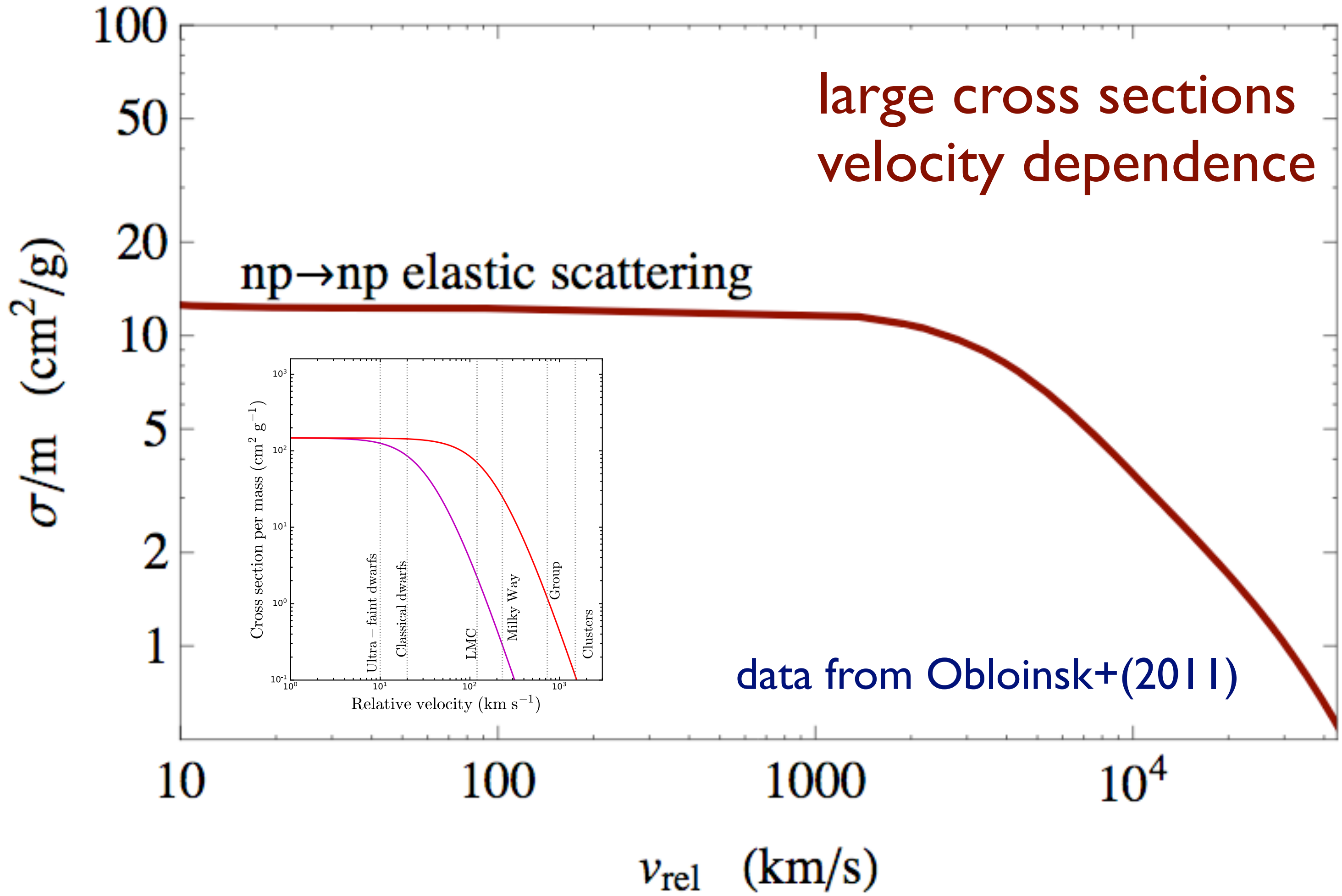
Abstract

Galaxies with stellar masses as high as ~ 10^{11} solar masses have been identified[1–3] out to redshifts z ~ 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 ≤ z ≤ 9.1, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of ~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 ~10^{11}-10^{12} $M_\odot$ at z~8

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

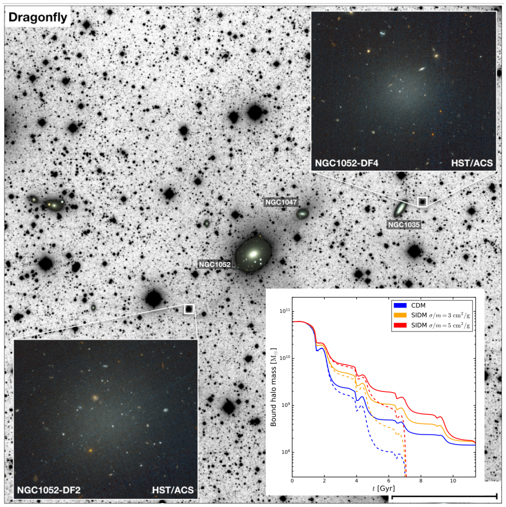
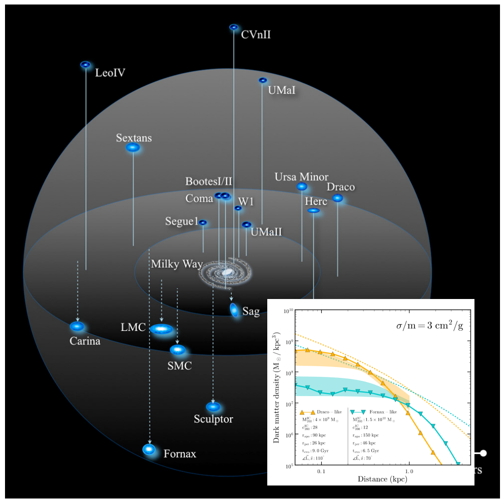
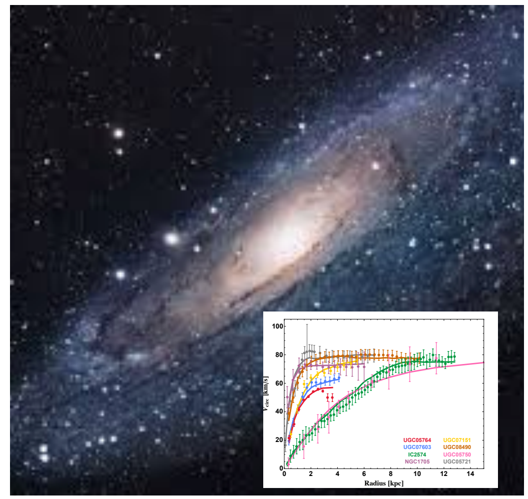
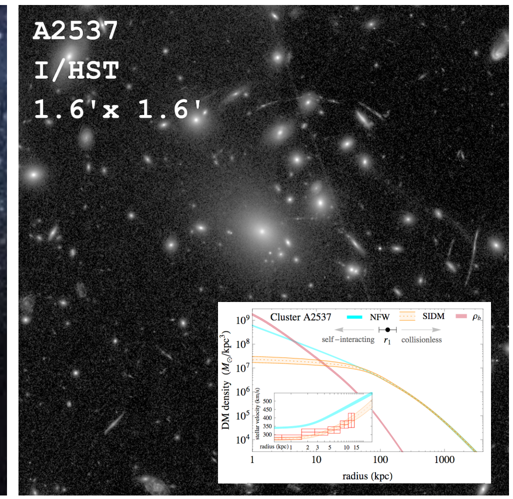
N-P vs. DM-DM Scatterings



Dark matter self-interactions occur at fundamental scales ~10^{-12} cm;
change the dark matter distribution at astro scales ~10^{22} cm

see reviews: Tulin & HBY (2017); Adhikari+(2022)

Conclusion

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 masses $\sim 10^8\text{-}10^{15}\ M_\odot$); bonus: seeding SMBHs

We may have detected strong dark matter self-interactions