Observational Evidence of Strong Dark Matter Self-Interactions

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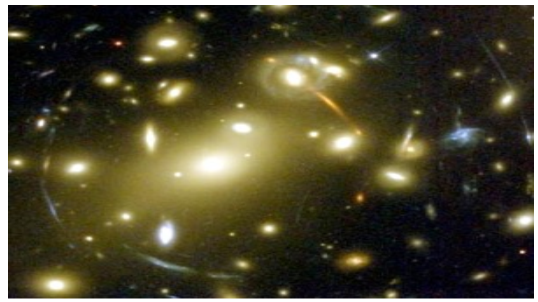
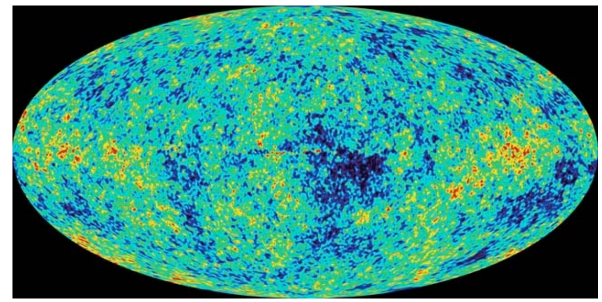
University of California, Riverside

IDM, L'Aquila, July 11, 2024

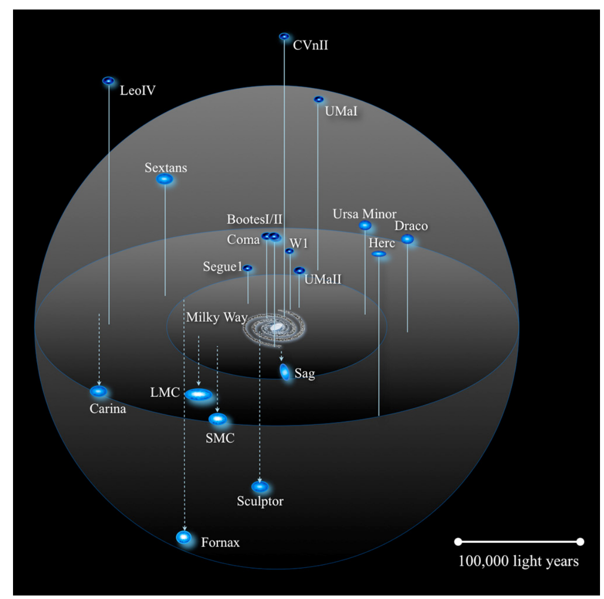
Cold Dark Matter (CDM)

- Large scales: very well

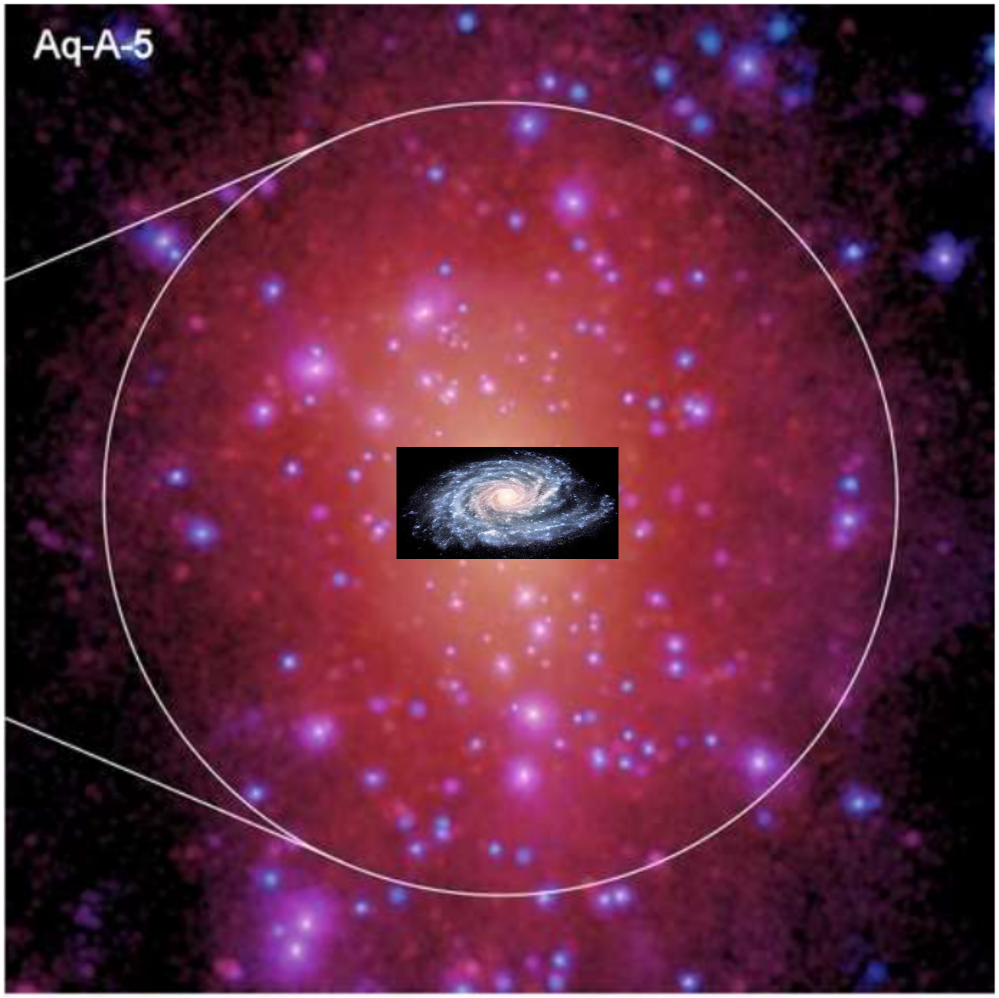




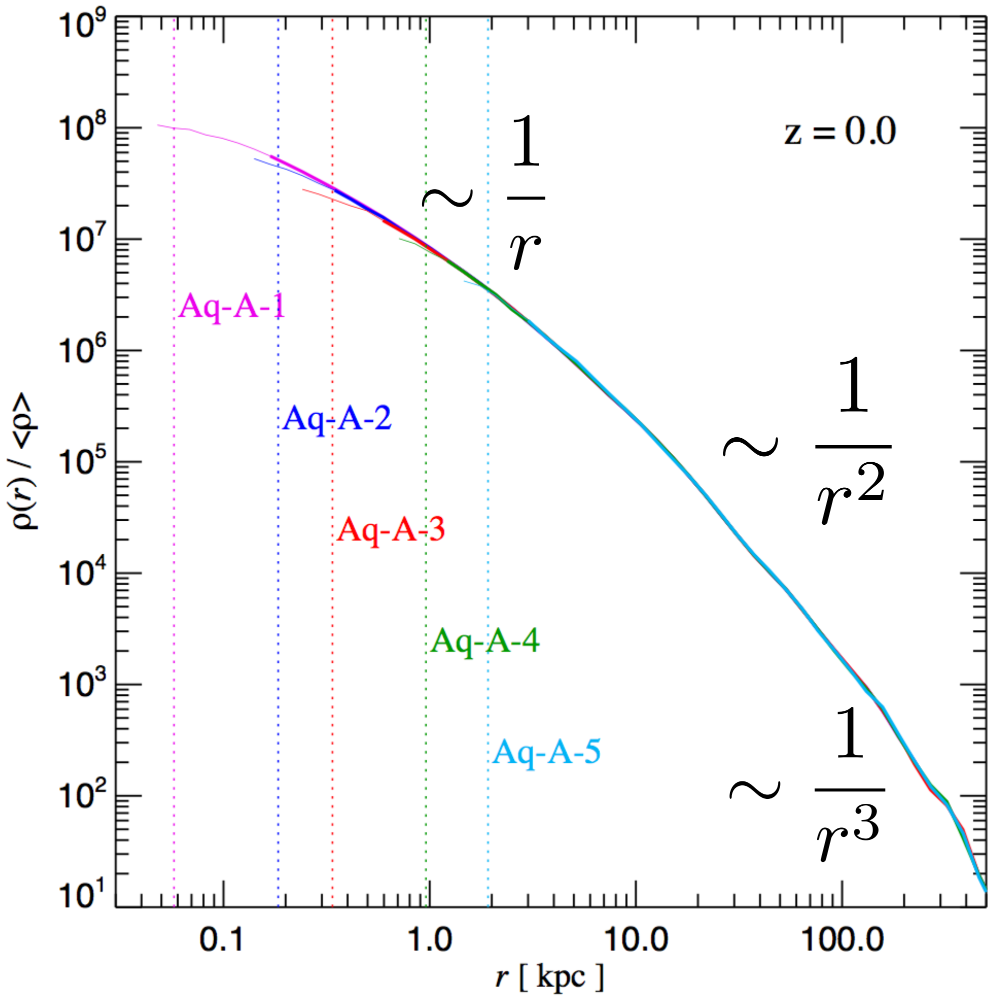
- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
    - Core vs Cusp
    - Diversity
    - Too Big To Fail
    - Ultra-diffuse galaxies
    - Dense lensing perturber
    - “Cores” in clusters



CDM: Universal Density Profile



Aquarius Project, Springel+ (2008)



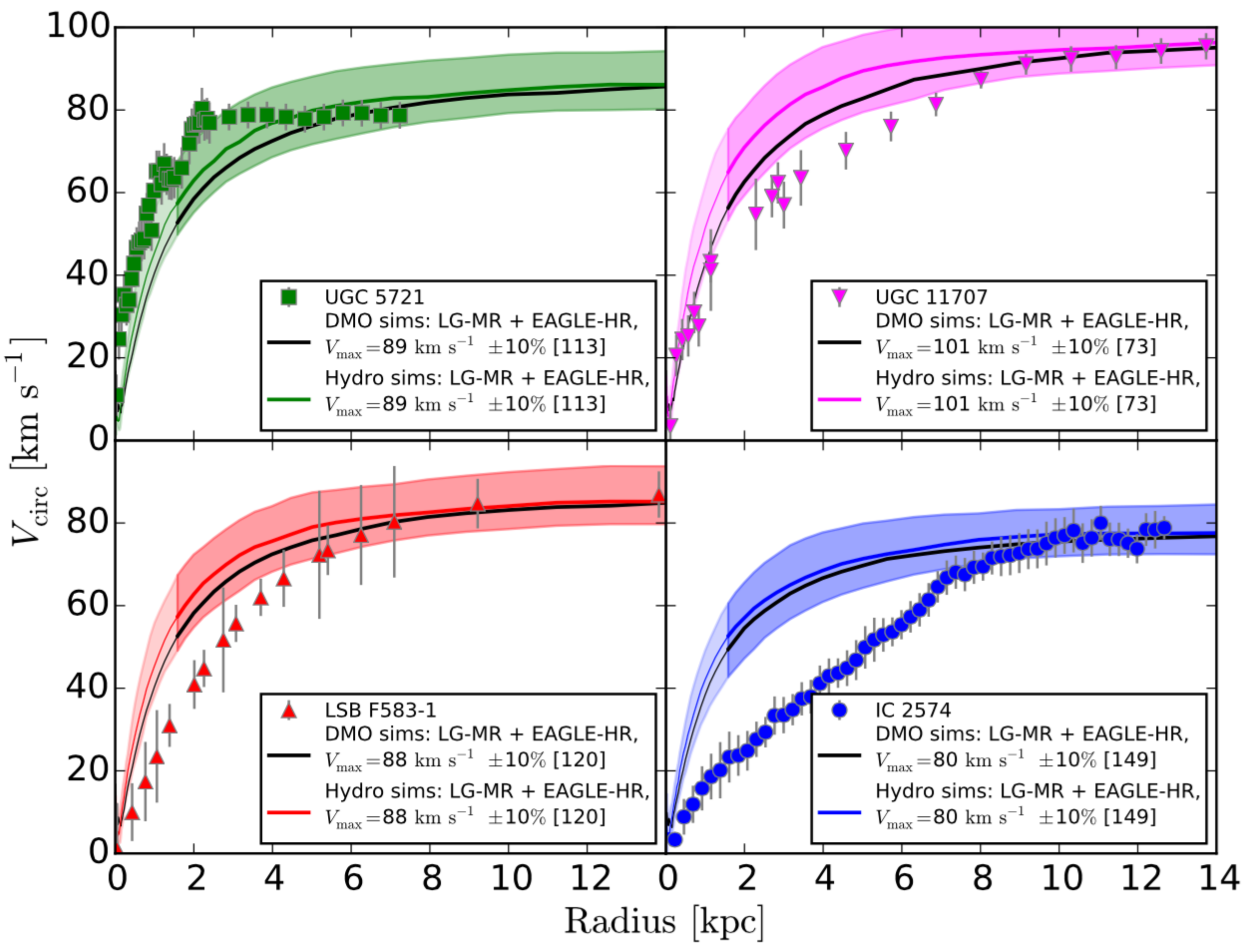
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

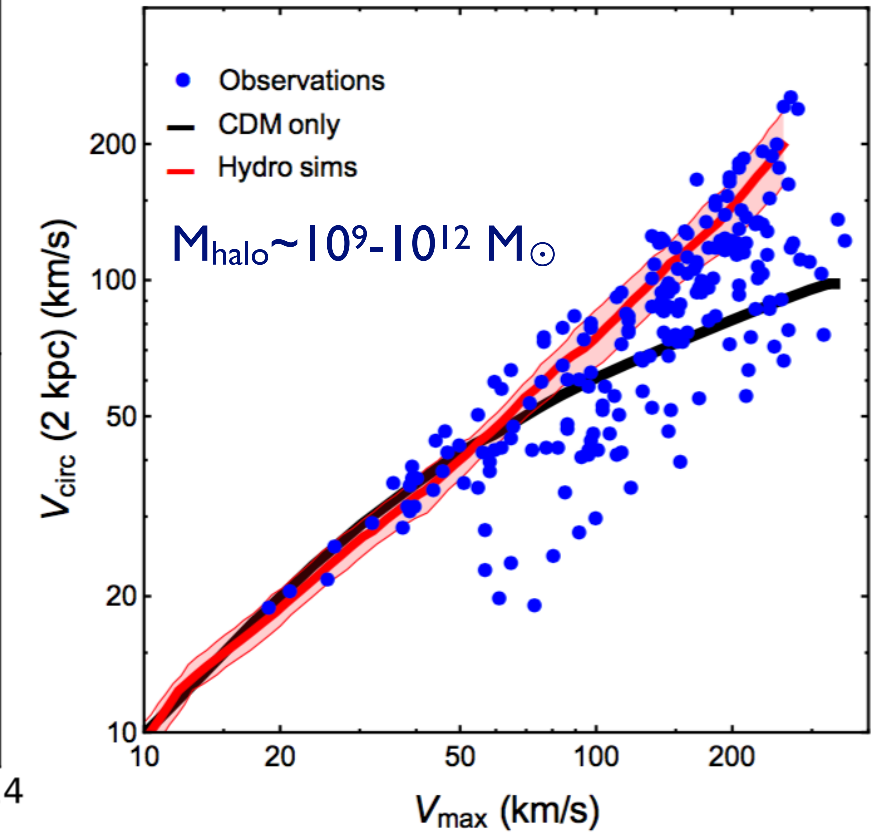
the Navarro-Frenk-White (NFW) profile (1996)

The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

1504.01437



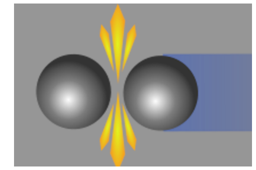


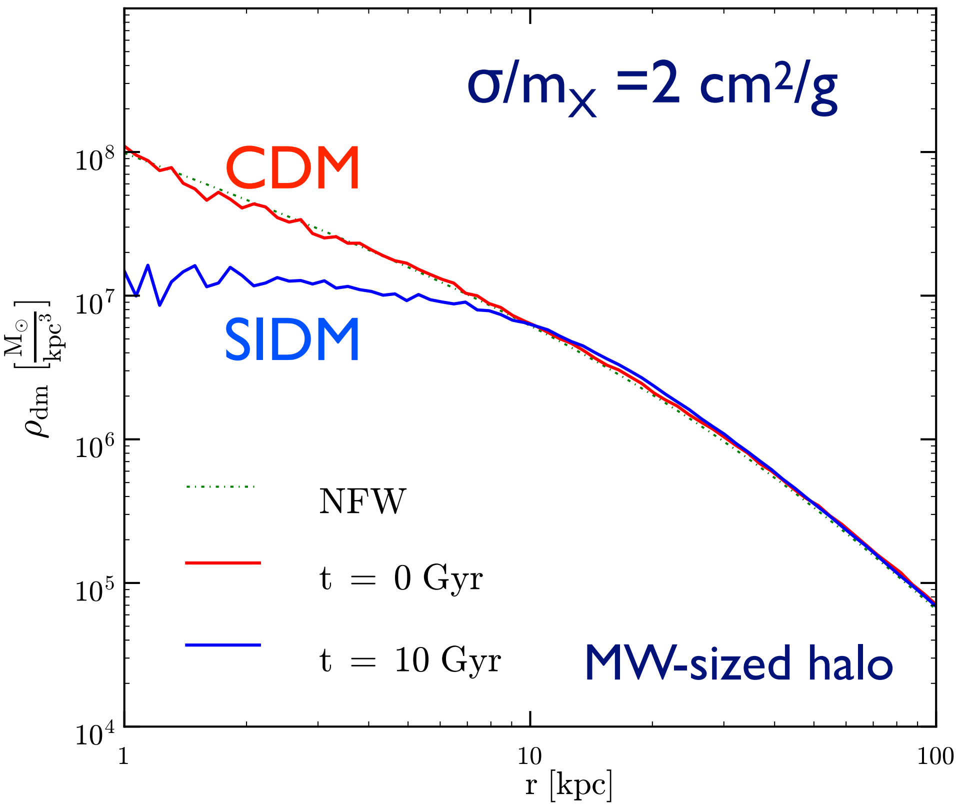
Colored bands: hydrodynamical simulations of CDM

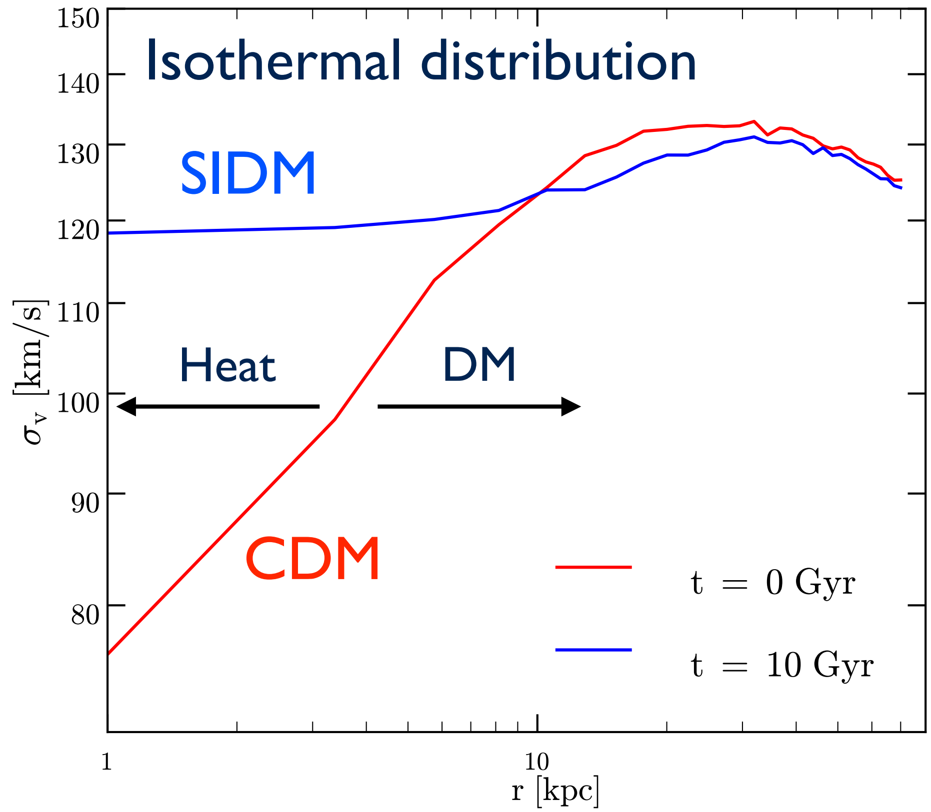
Rotation curves (matter distributions) are diverse in spiral galaxies

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo







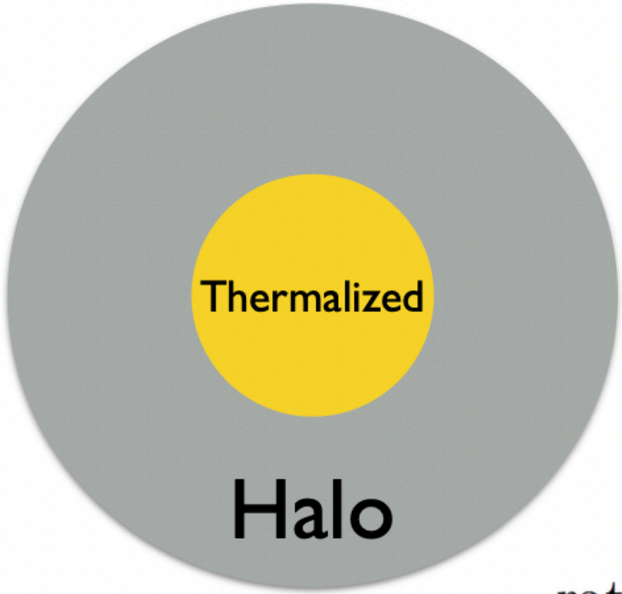
σ/m$_X$>O(1) cm²/g (nuclear scale)

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

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

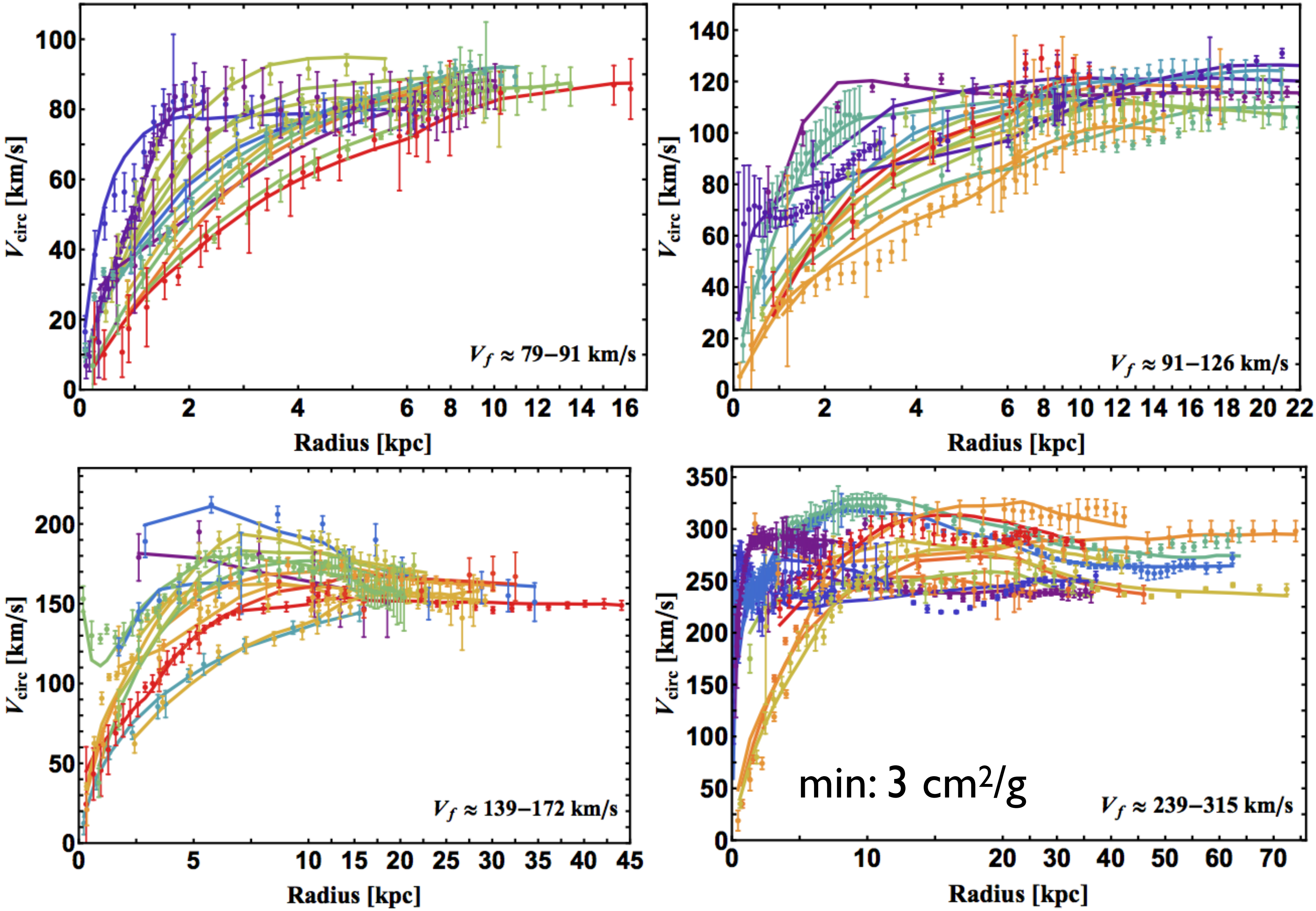
$$\text{rate} \times \text{time} \approx \frac{\langle\sigma v\rangle}{m}\rho(r_1)\,t_{\rm age} \approx 1$$

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

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

VS

Confirmed in hydro simulations: Robertson+(+HBY, MNRAS 2018), Robertson+(MNRAS 2021)

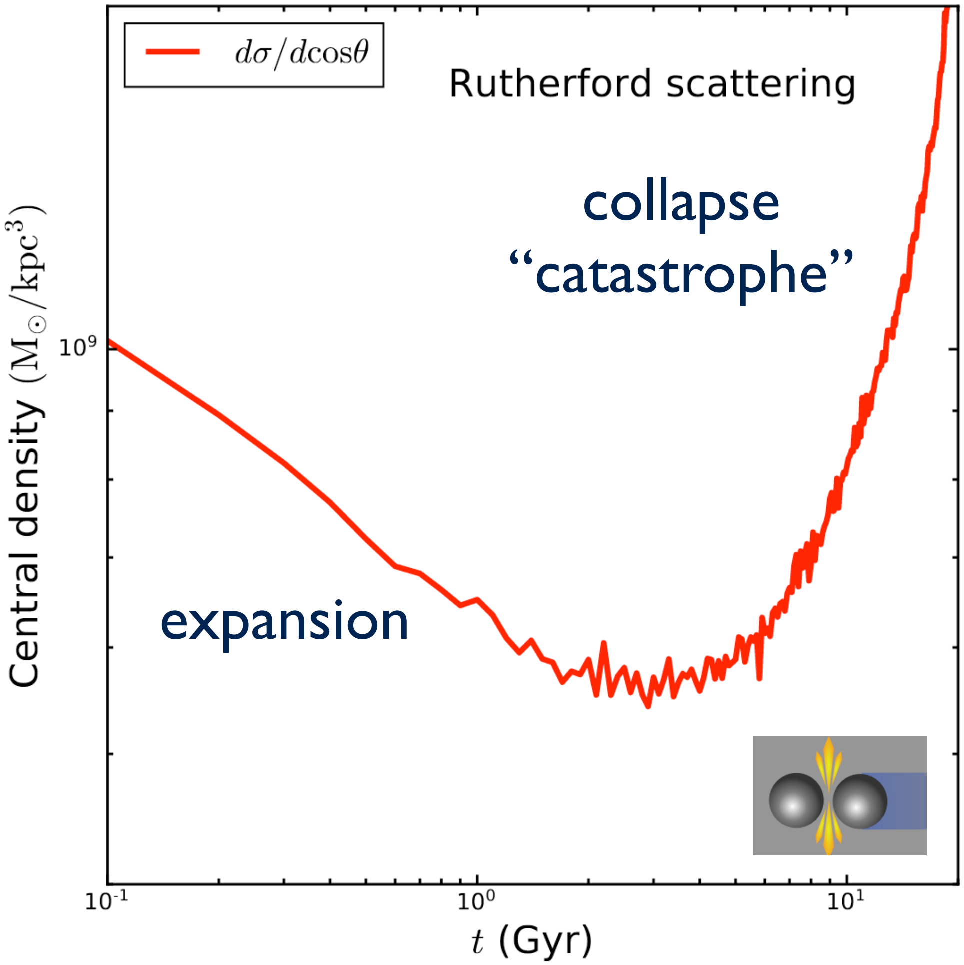


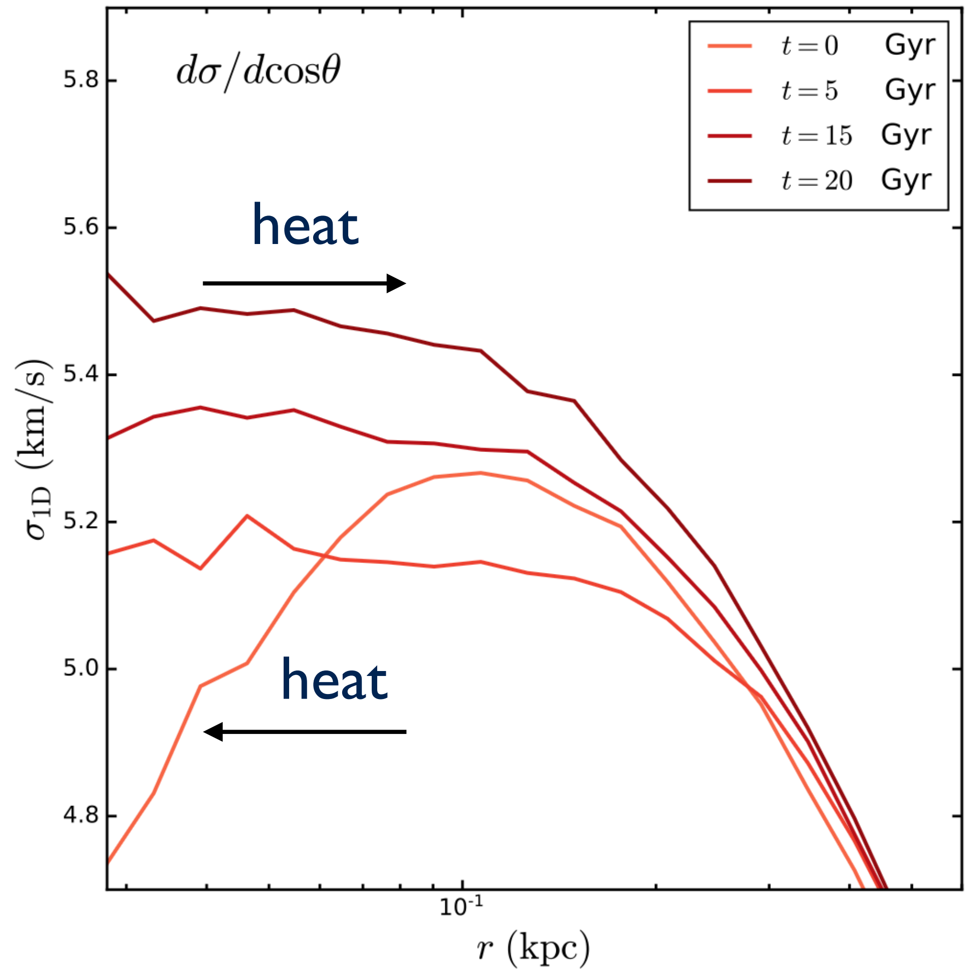
We analyzed 135 galaxies (3.6 μm band)

SPARC dataset, Lelli, McGaugh, Schombert (2016)

w/Ren, Kwa, Kaplinghat (PRX 2018)
w/Kamada, Kaplinghat, Pace (PRL 2017)
w/Creasey, Sameie, Sales+ (MNRAS 2017)
w/Roberts, Kaplinghat, Valli (in prep 2024)

Gravothermal Evolution





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

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

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

σ/m>10 cm²/g

Yang, HBY (JCAP 2022)

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

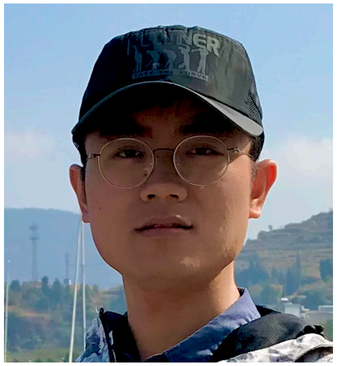
Negative heat capacity!

⇒ gravothermal collapse

Balberg+(ApJ, 2002)

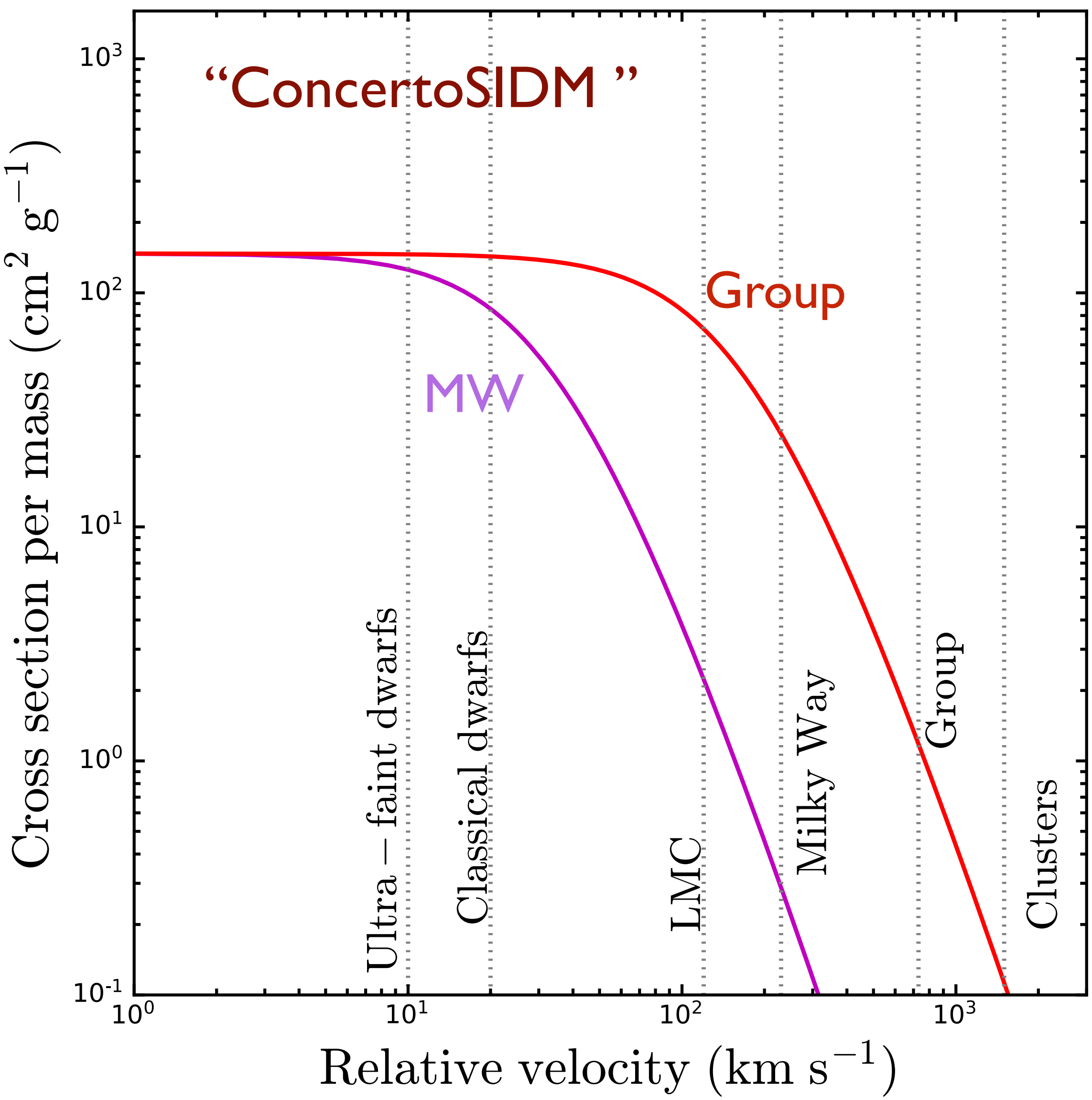
w/Essig, McDermott, Zhong (PRL 2019)

Zoom-in Cosmological Simulations



Daneng Yang (UCR)

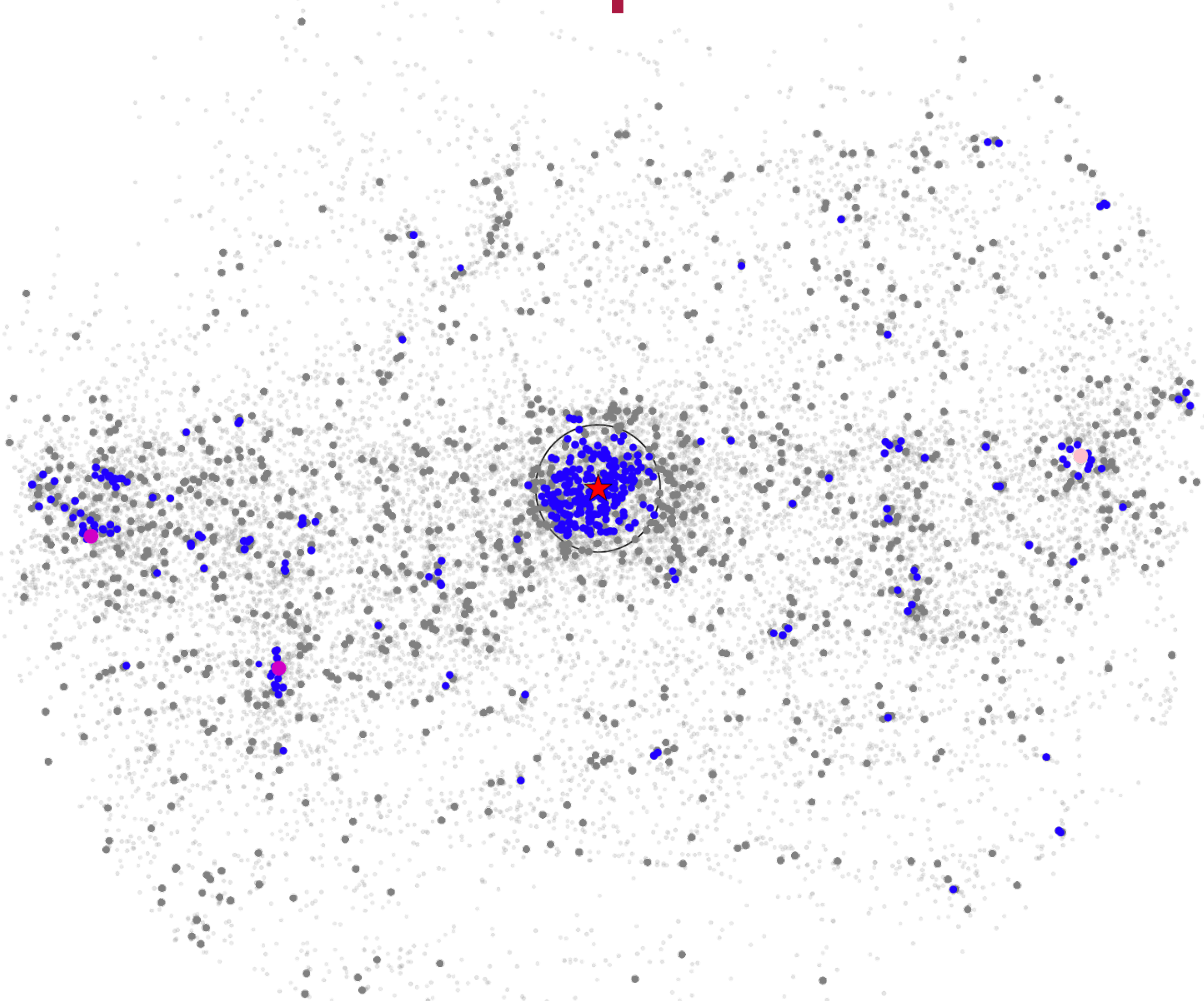
Ethan Nadler (USC/Carnegie)



MW: box with a Milky Way-like main halo; Yang, Nadler, HBY (ApJ 2022)

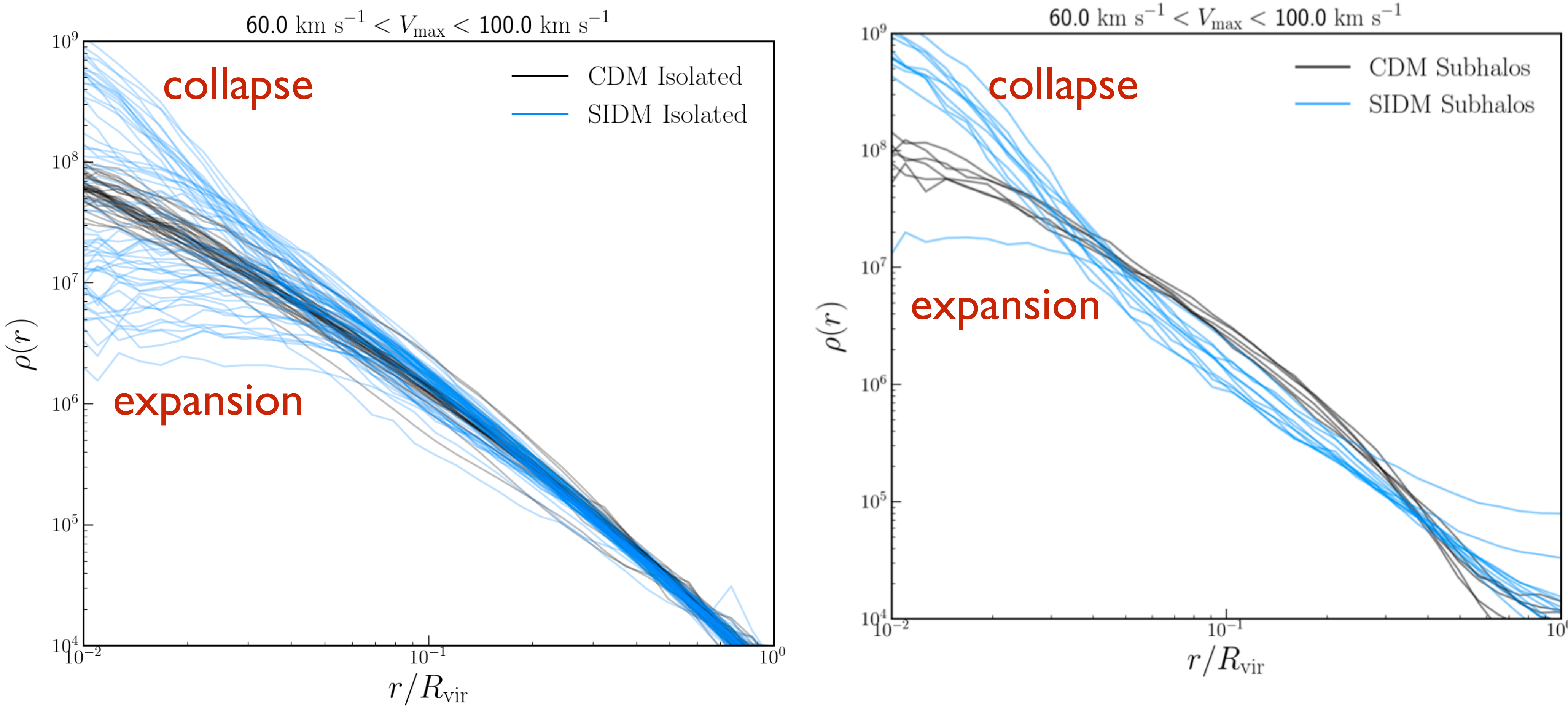
Group: box with a group-like main halo; Nadler, Yang, HBY (ApJL 2023)

Group Scale



- High-resolution zoom-in cosmological simulations; more than 30 million particles
- The main halo mass: ~10^{13} $M_\odot$, containing a Milky Way-like halo: ~9×10^{11} $M_\odot$

Isolated Halos and Subhalos



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

Nadler, Yang, HBY (ApJL 2023)

- Strong dark matter self-interactions further amplify the diversity encoded in the scatter of the concentration-mass relation
- Collapsed SIDM subhalos are resilient to tidal disruption
- Evidence of collapsed subhalos?

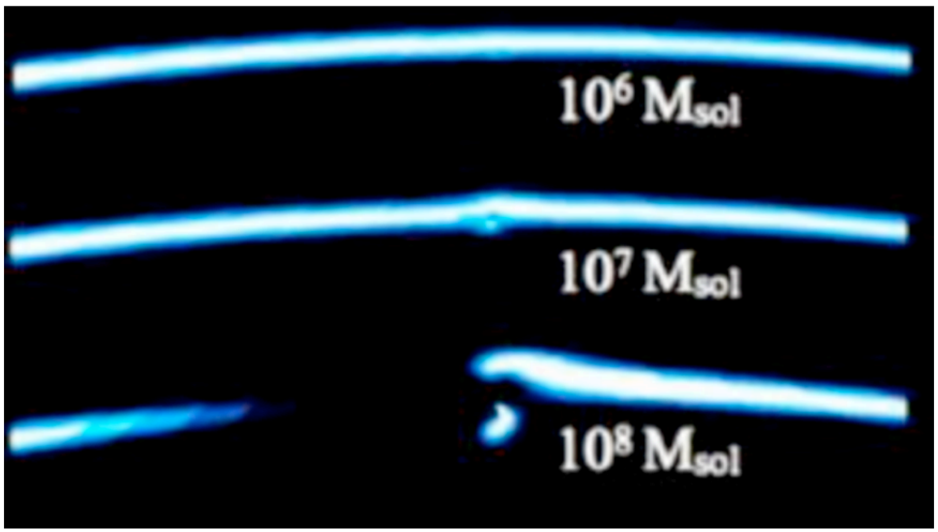
Detection of a Dark Substructure through Gravitational Imaging

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

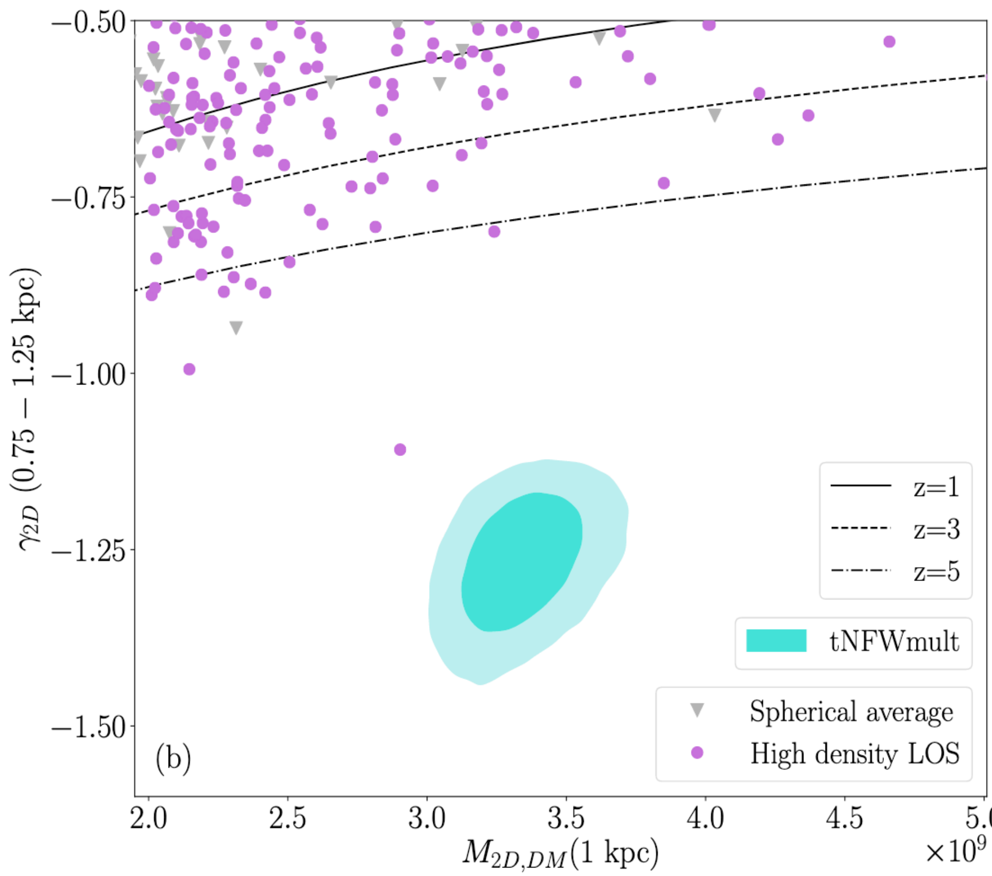
(MNRAS 2010)

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

JVAS B1938+666 as well



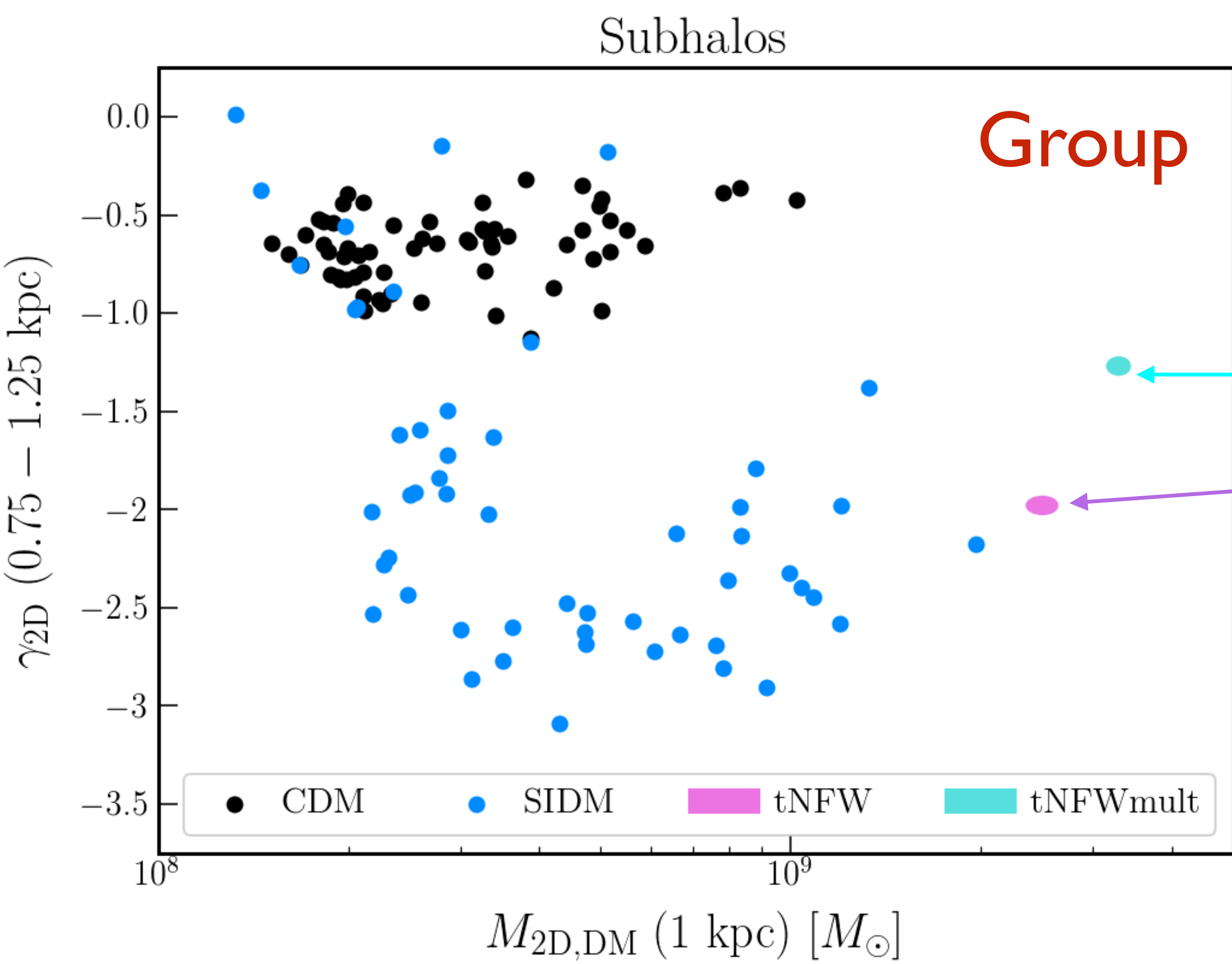
Perturber of a strong-lensing system

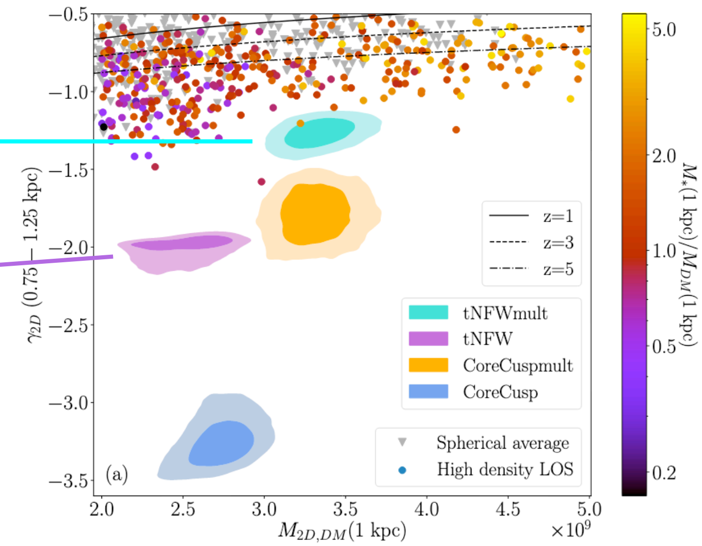


Minor+(MNRAS, 2020)

- The substructure is extremely dense
- Compared to the IllustrisTNG simulation, the tension with CDM is at the > 99% CL
- The substructure does not have a detectable luminous component

Dense Strong Lensing Perturber





Strong lensing perturber: Minor+(2020)

Nadler, Yang, HBY (ApJL 2023)

A slight offset in the subhalo mass: our main halo mass $10^{13}\ M_\odot$ is on the lower end of the favored range 10^{13}–$6\times10^{13}\ M_\odot$

Stellar Streams of the Milky Way

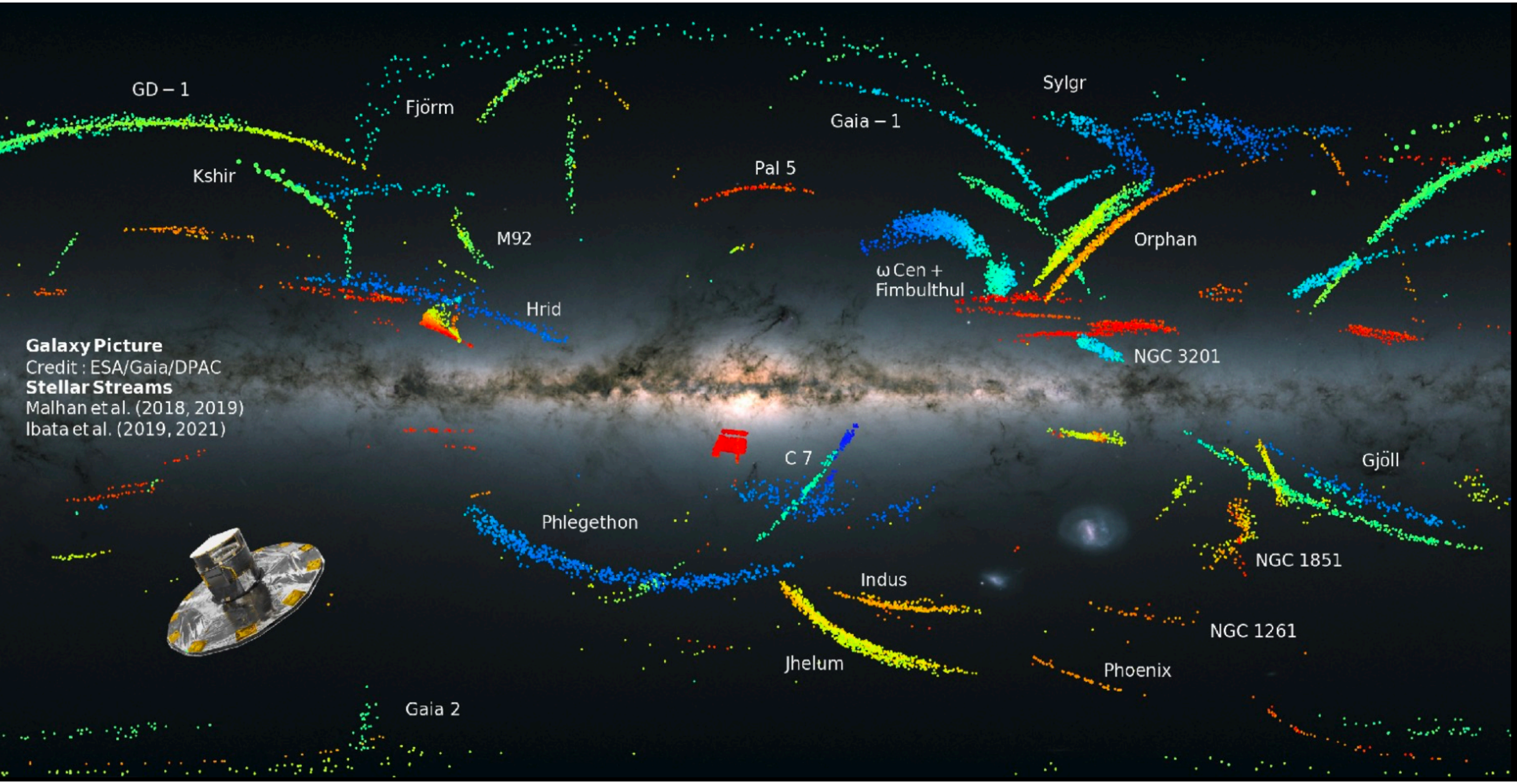
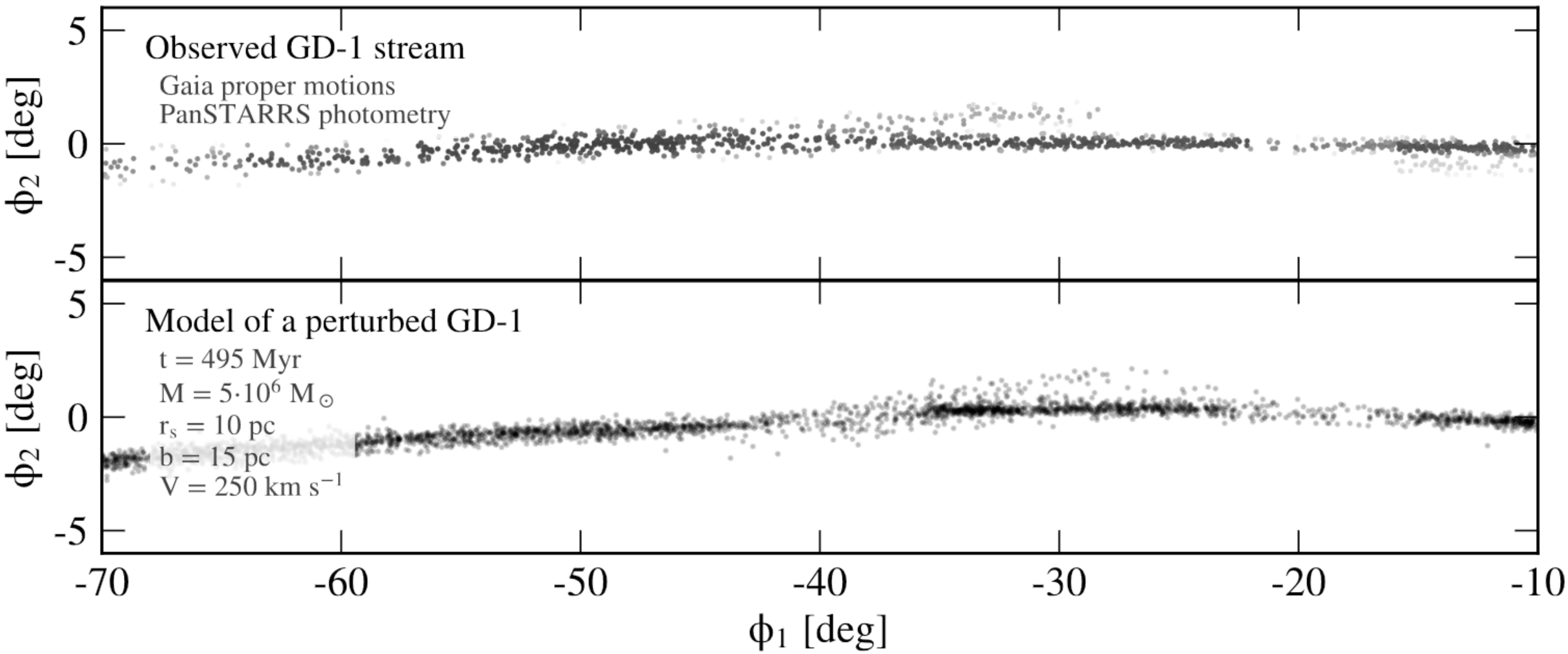


Figure: Khyati Malhan

2019

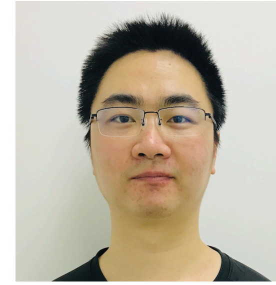
The Spur and the Gap in GD-1: Dynamical evidence for a dark substructure in the Milky Way halo

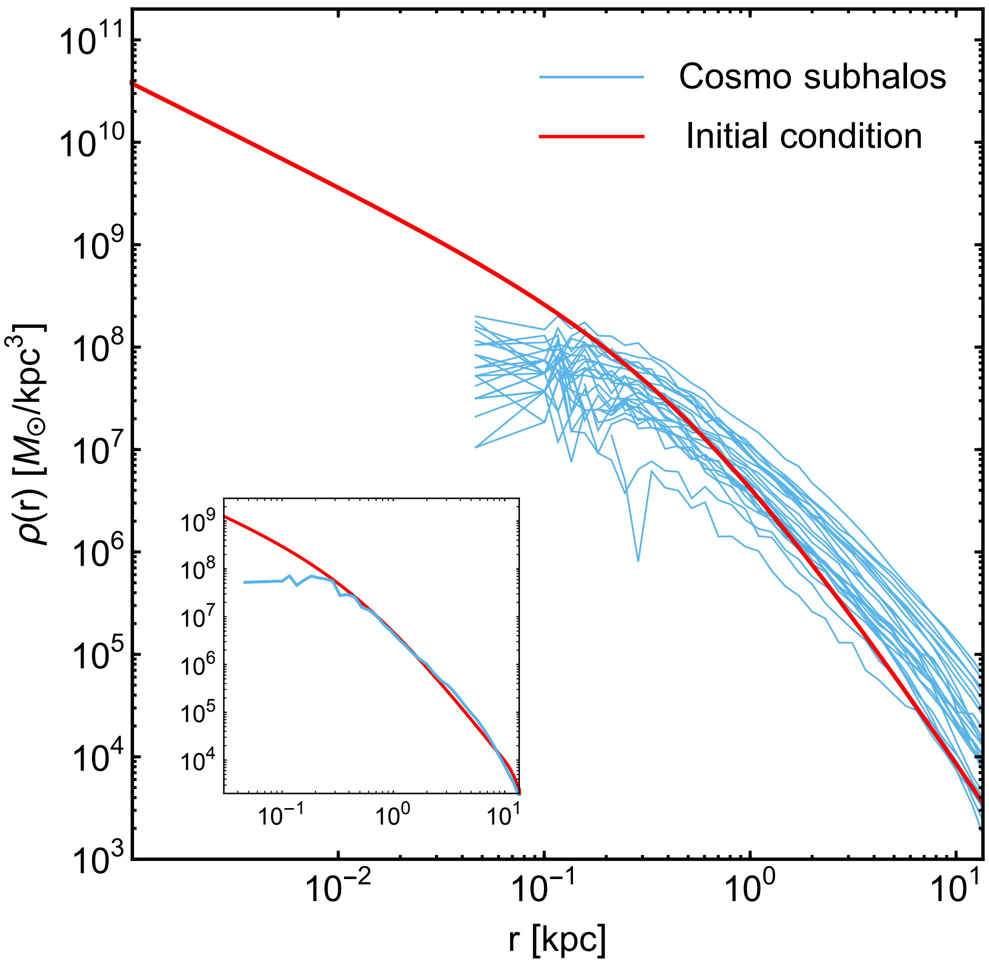
Ana Bonaca,[1] David W. Hogg,[2,3,4,5] Adrian M. Price-Whelan,[6] and Charlie Conroy[1]

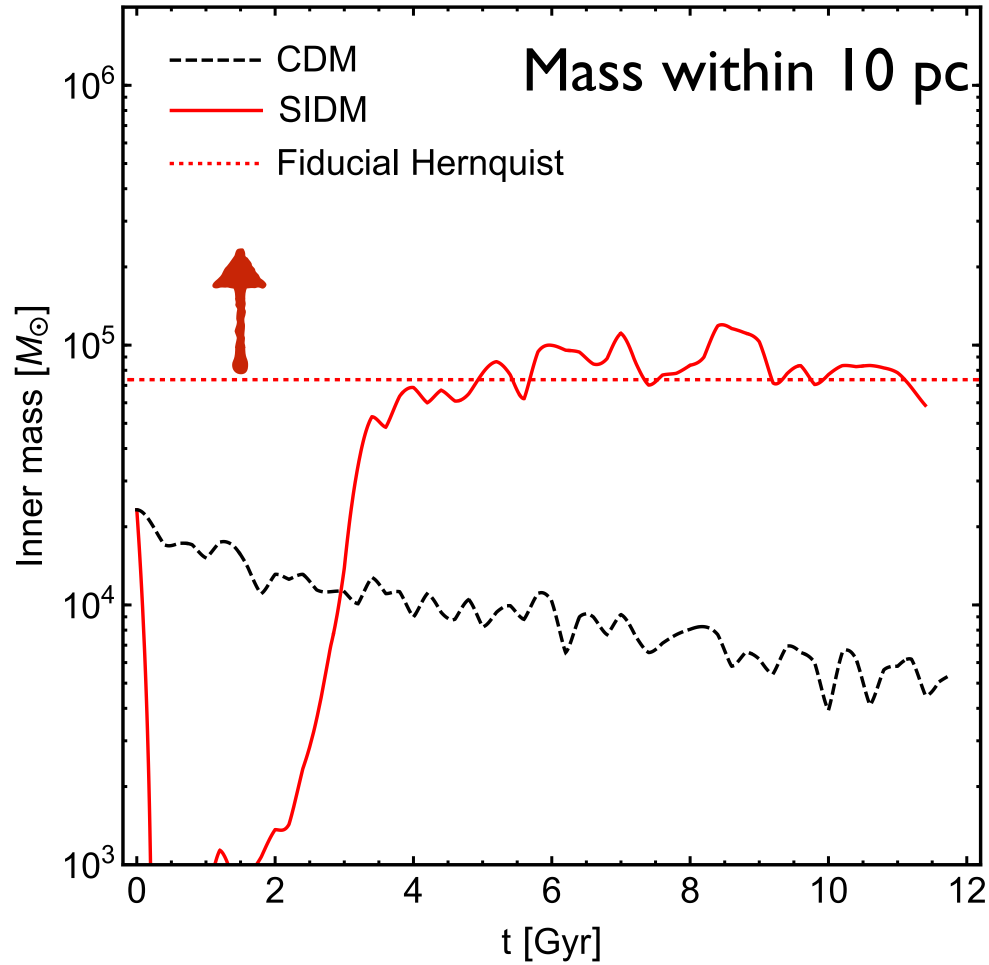


A CDM subhalo of the Milky Way is not dense enough to be a candidate for the GD-1 perturber

GD-1 Stellar Stream Perturber



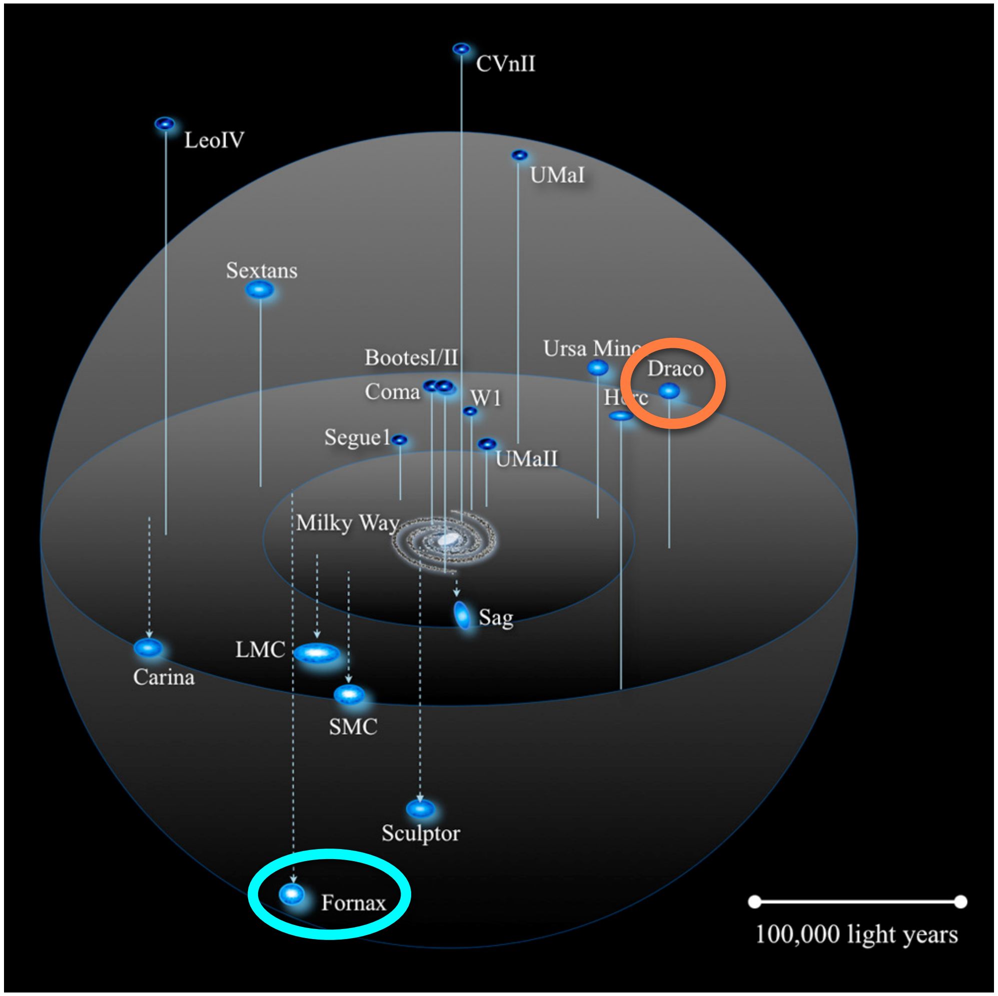




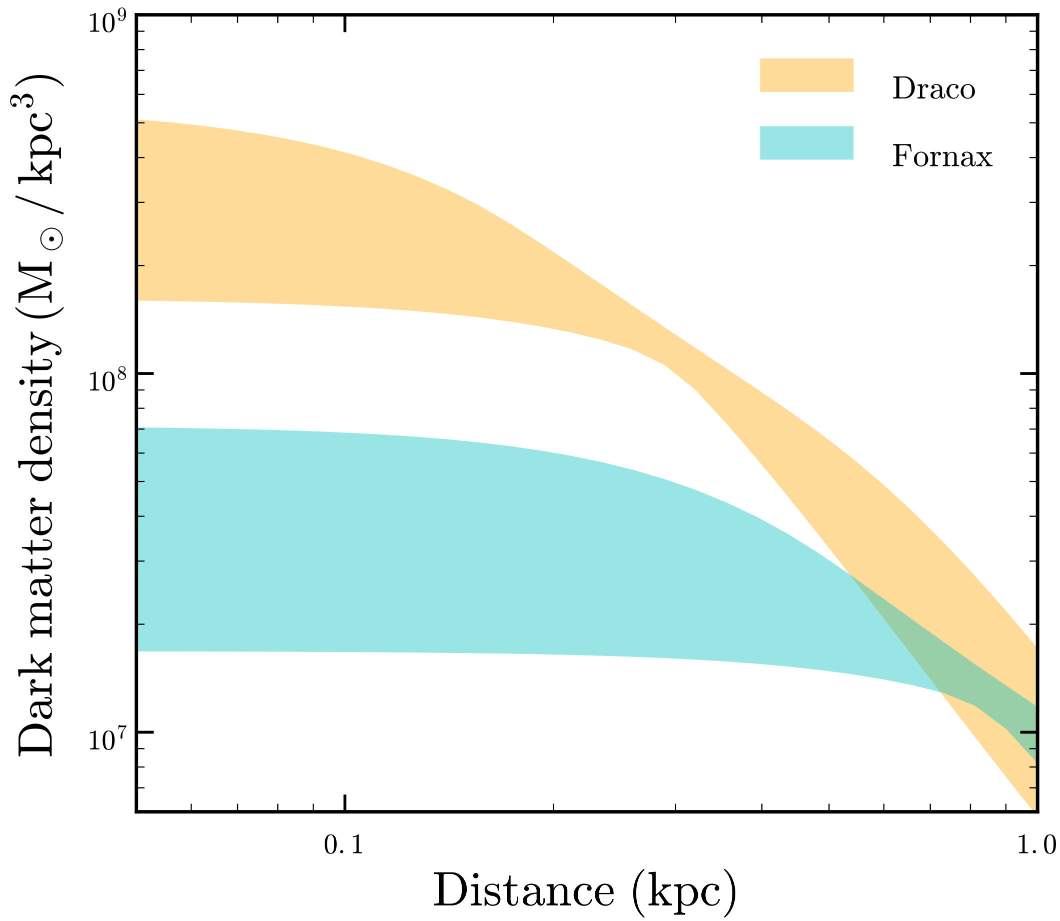
- Collapsed SIDM subhalo increases the mass within 10 pc, a factor of ~10
- The required cross section ~50-100 cm^2/g in the subhalos

w/Zhang+ (in prep 2024)

Diverse Satellite Galaxies



Observations



- Dark matter distributions are also diverse in the satellite galaxies
- Fornax: shallow density core; Draco: dense core/cusp

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

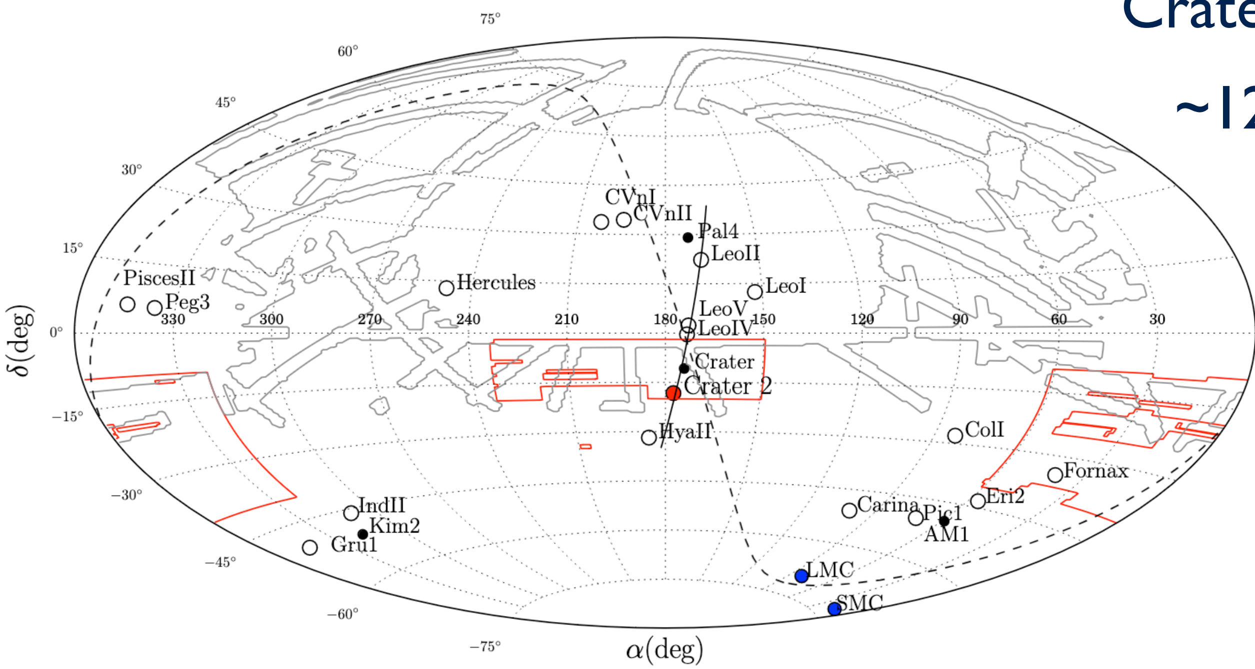
The feeble giant. Discovery of a large and diffuse Milky Way dwarf galaxy in the constellation of Crater*

G. Torrealba[1], S.E. Koposov[1], V. Belokurov[1] & M. Irwin[1]
[1] *Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA*

2 August 2016

Crater II satellite galaxy

~120 kpc from Sun

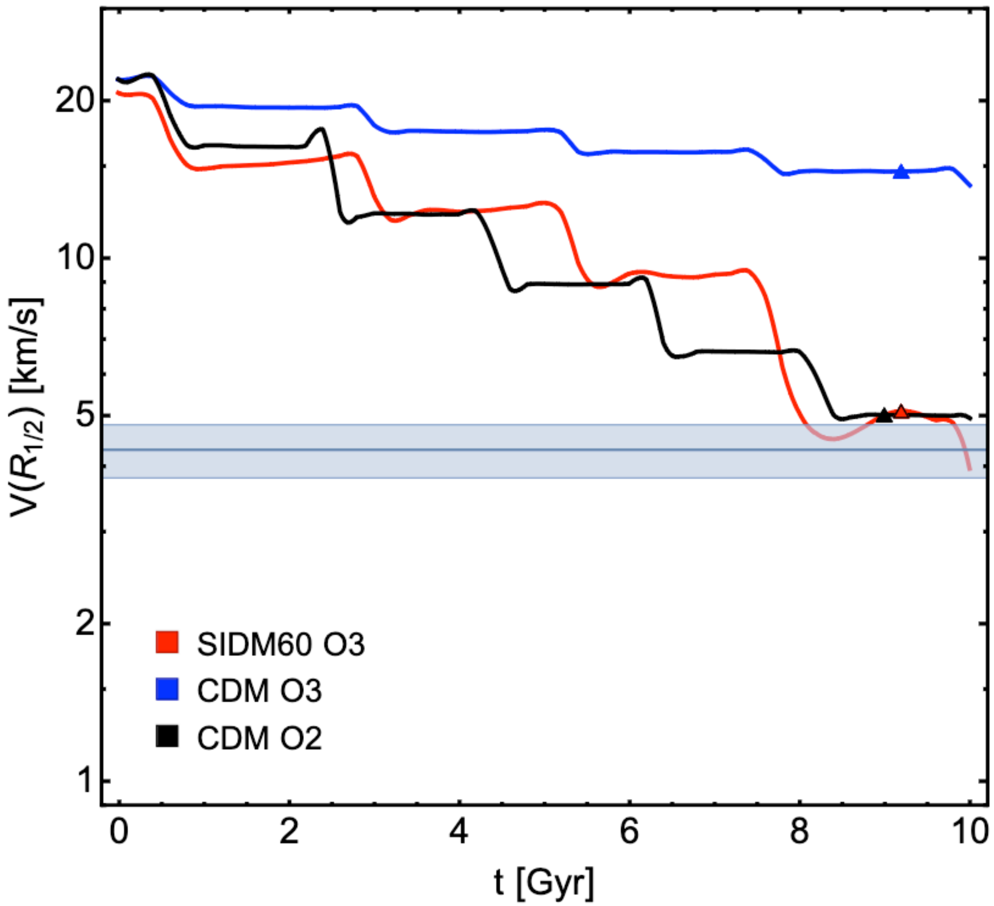


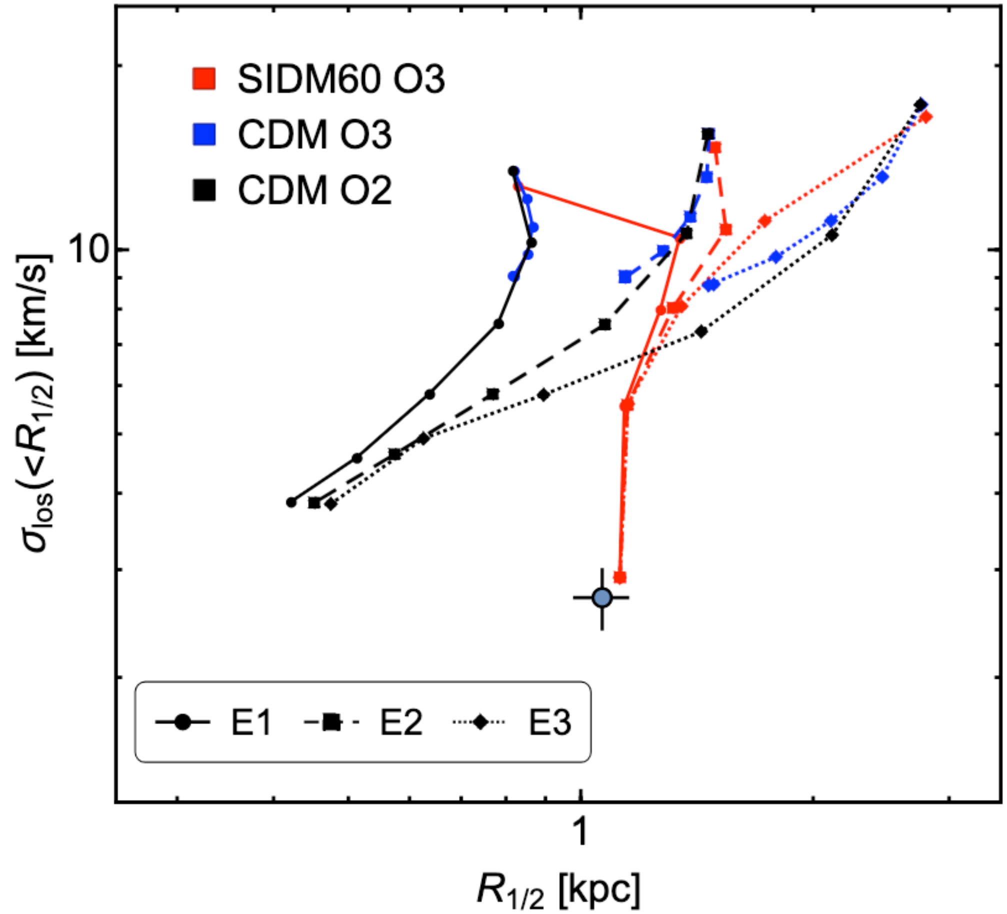
Extremely low dark matter density, and surprisingly large size in the stellar distribution

$$\sigma_{v_{\rm los}} = 2.7^{+0.3}_{-0.3}\ {\rm km\ s^{-1}} \qquad R_{\rm h} \sim 1\ {\rm kpc} \qquad r_{\rm p} \approx 37.7\ {\rm kpc}$$

Challenges in CDM, see e.g., Borukhovetskaya, Navarro, Errani, Fattahi (MNRAS, 2022)

Crater II: the Large, Cold Satellite

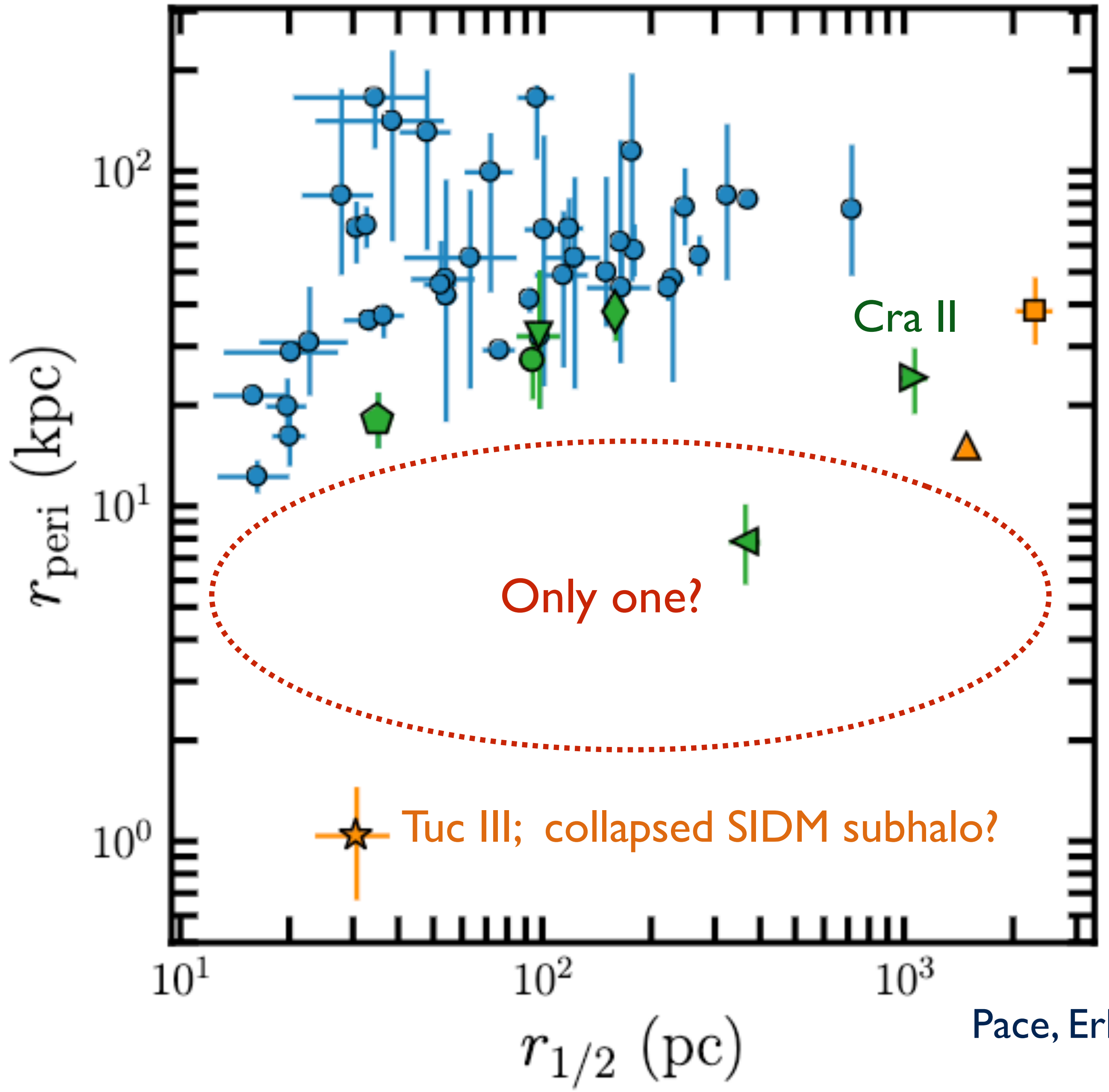




- O3 orbit is consistent with Gaia DR3
- The required cross section ~60 cm^2/g
- For CDM, it is difficult even if we are free to choose the orbit

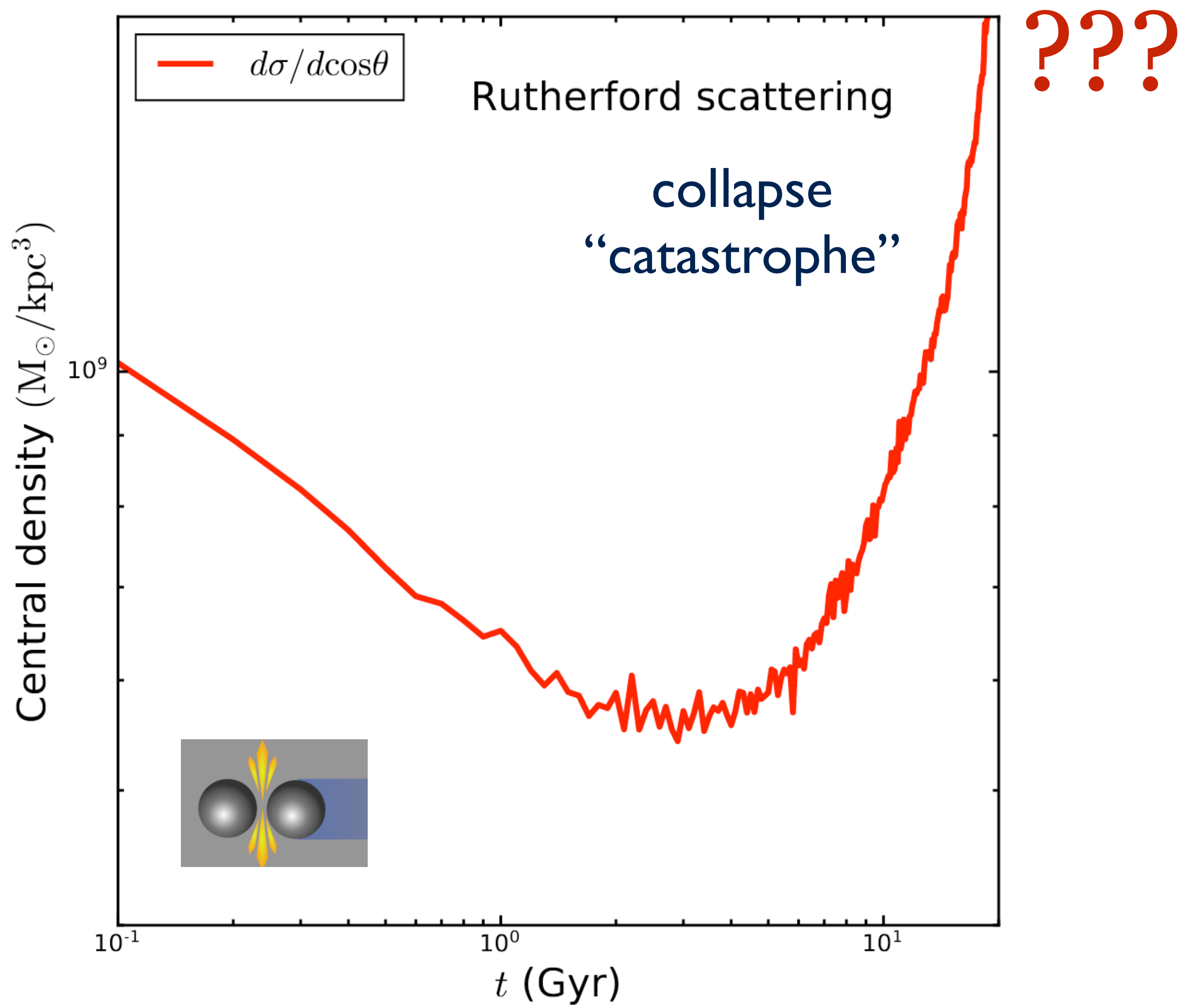
w/Zhang, Yang, An (ApJL, 2024)

More Fun with the MW Satellites



Pace, Erkal, Li (ApJ, 2022)

Gravothermal Collapse



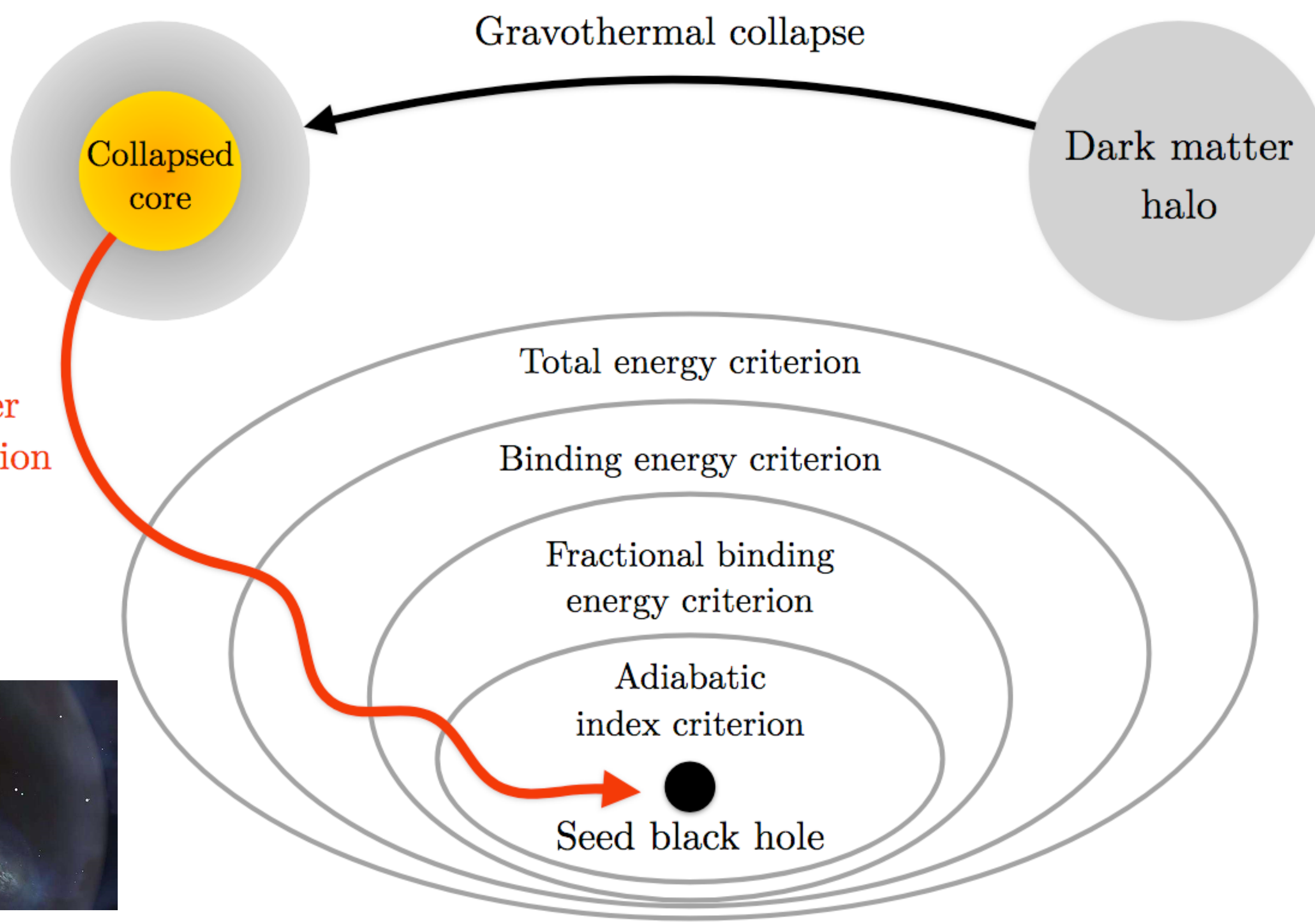
$$2K.E. + P.E. = 0$$

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

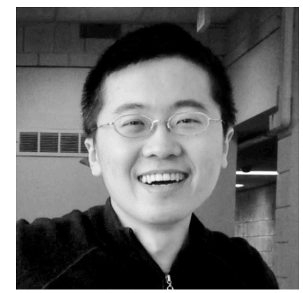
$$\frac{E_{\mathrm{tot}}}{T} < 0$$

Negative heat capacity!
⇒ gravothermal collapse

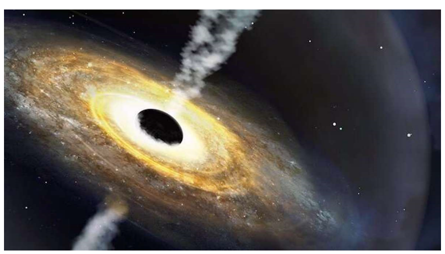
Seeding Black Holes



Wei-Xiang Feng



Yi-Ming Zhong



Truncated Maxwell-Boltzmann distribution

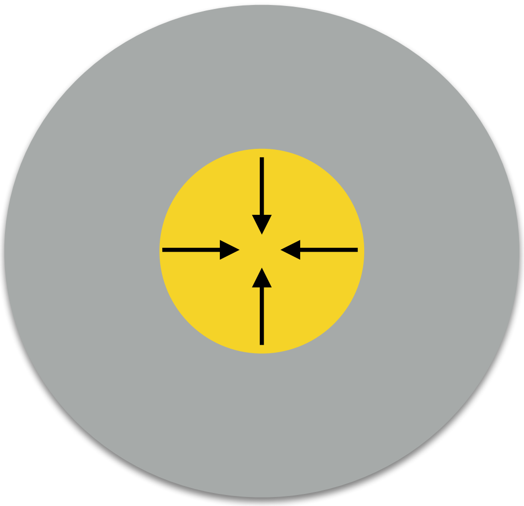
$$\begin{cases} (e^{-\epsilon/kT} - e^{-\epsilon_c/kT}) d^3p(\epsilon) & (\epsilon \leq \epsilon_c) \\ 0 \quad (\epsilon > \epsilon_c), \end{cases}$$

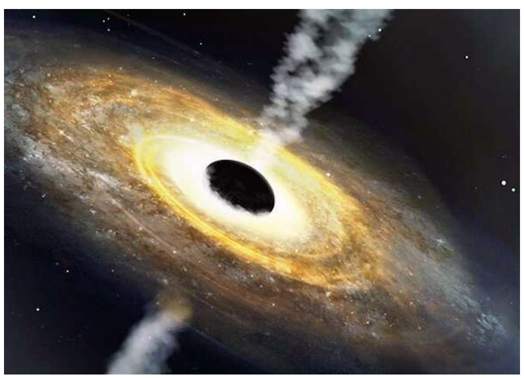
Central 3D velocity dispersion>0.57c

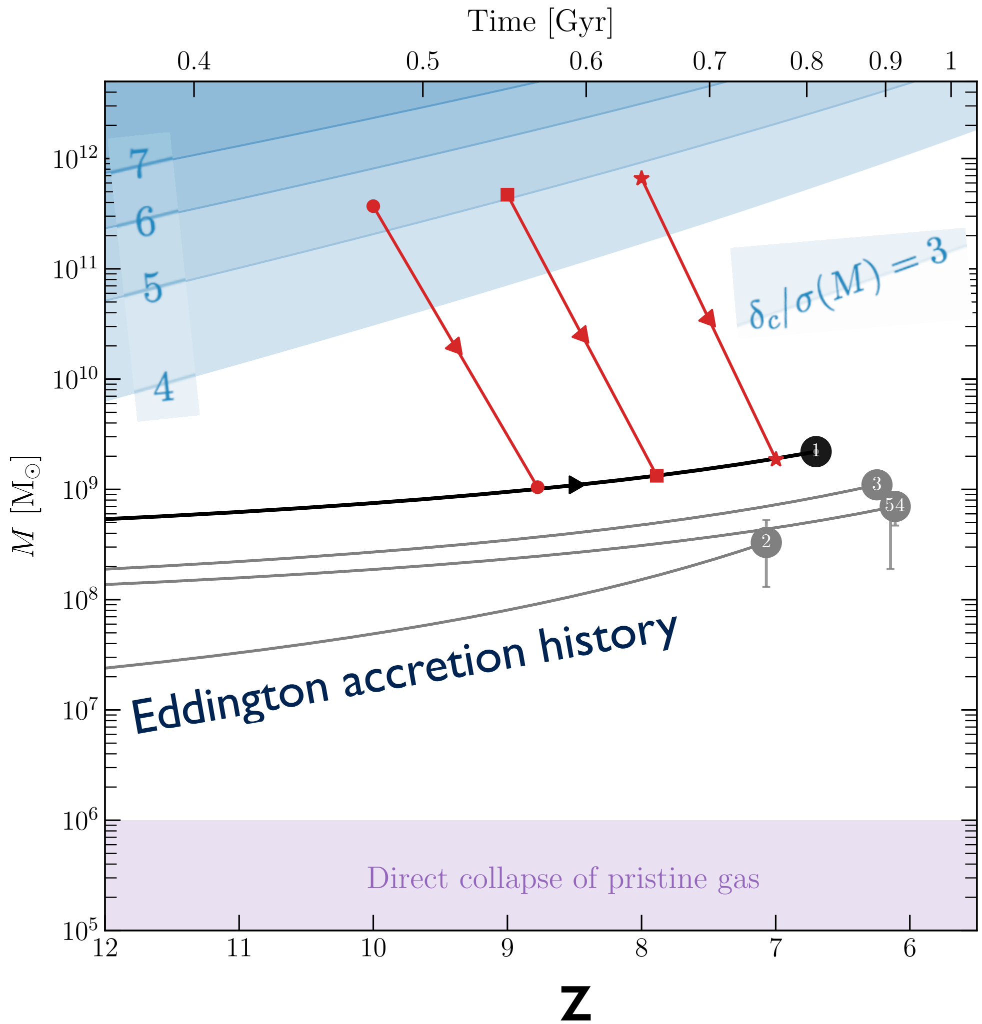
Find GR configurations using the TOV equation;
Check the GR instability condition

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

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)

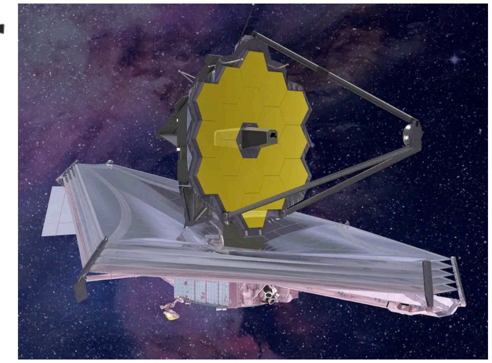
~800 Myr after the Big Bang

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

- The presence of baryons can speed the onset of collapse by a factor of 10–100!
- The mechanism requires the existence of massive halos at high redshift

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

45k Accesses | **3811** Altmetric | Metrics

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

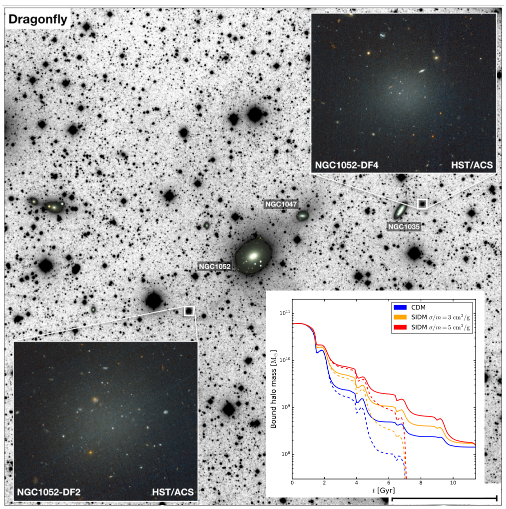
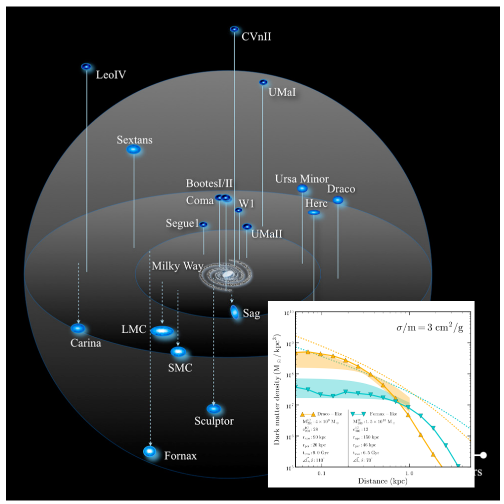
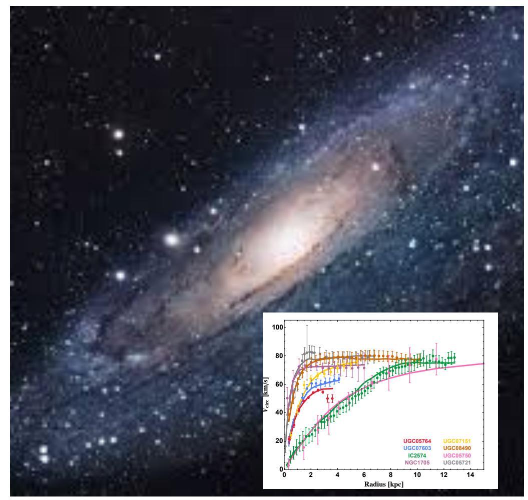
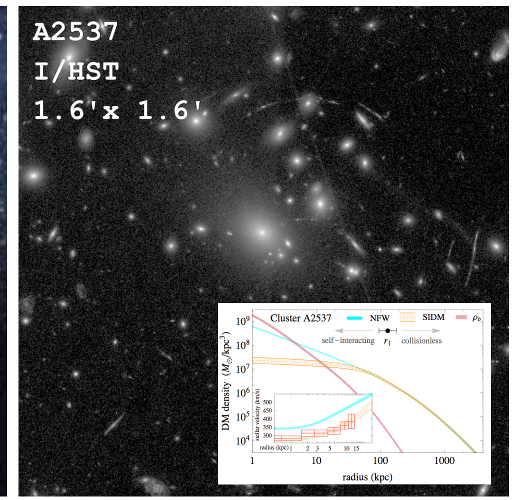
Abstract

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 $7.4 \le z \le 9.1$, 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} $M_\odot$ at z~8

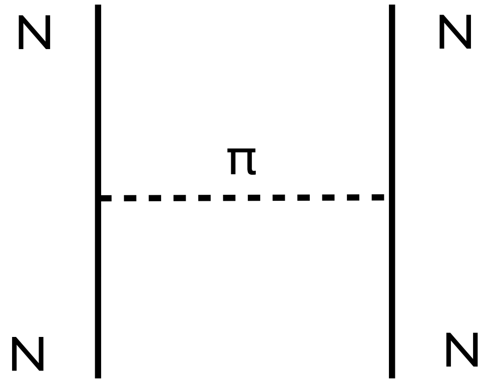
see, e.g., Boylan-Kolchin (2022); Nadler, Benson, Driskell, Du, Gluscevic (2022)

SIDM From Dwarf to Cluster Scales

Ultra-diffuse galaxies (dark-matter-deficient)	Milky Way satellites	Spiral galaxies	Galaxy clusters
			
$M_{halo} \lesssim 10^8\ M_\odot$	$M_{halo} \sim 10^8\ M_\odot$	$M_{halo} \sim 10^9$-$10^{13}\ M_\odot$	$M_{halo} \sim 10^{15}\ M_\odot$

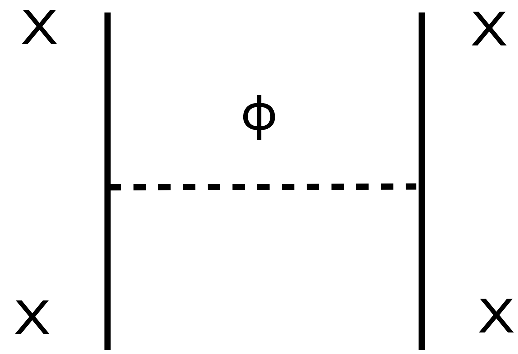
- SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo masses $\sim 10^8$–$10^{15}\ M_\odot$)
- Bonus: seeding SMBHs
- Fundamental scales $\sim 10^{-12}$ cm vs galactic scales $\sim 10^{22}$ cm
- Measuring particle properties of dark matter without detecting it directly

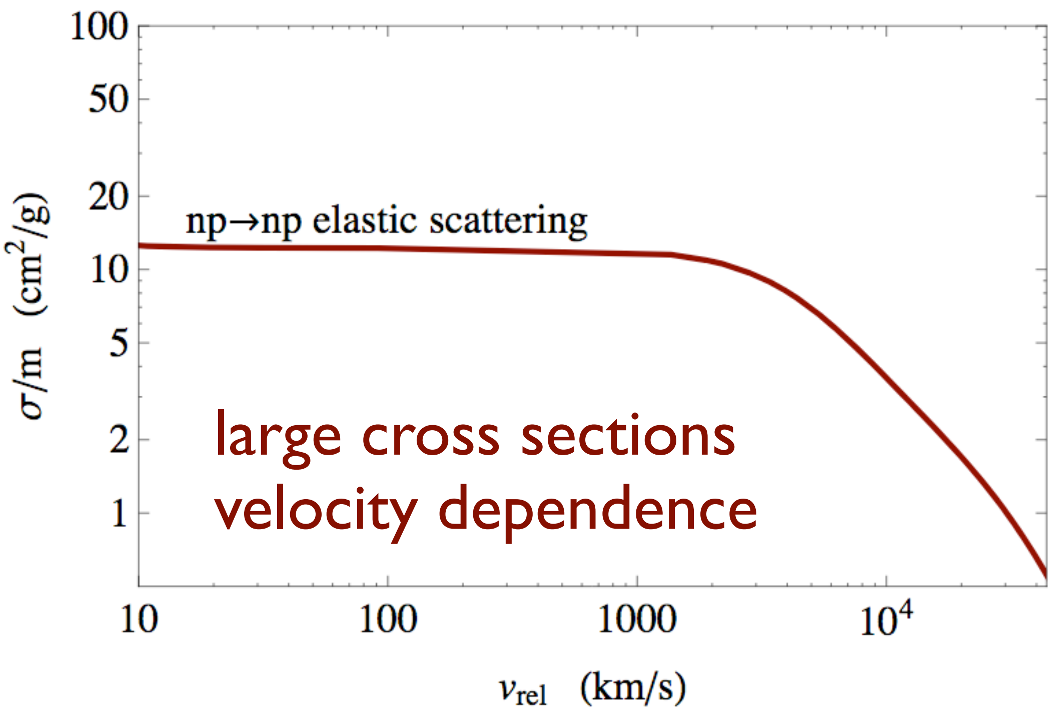
Yukawa Potential and SIDM



Yukawa, 1935

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





Application to model dark matter self-interactions

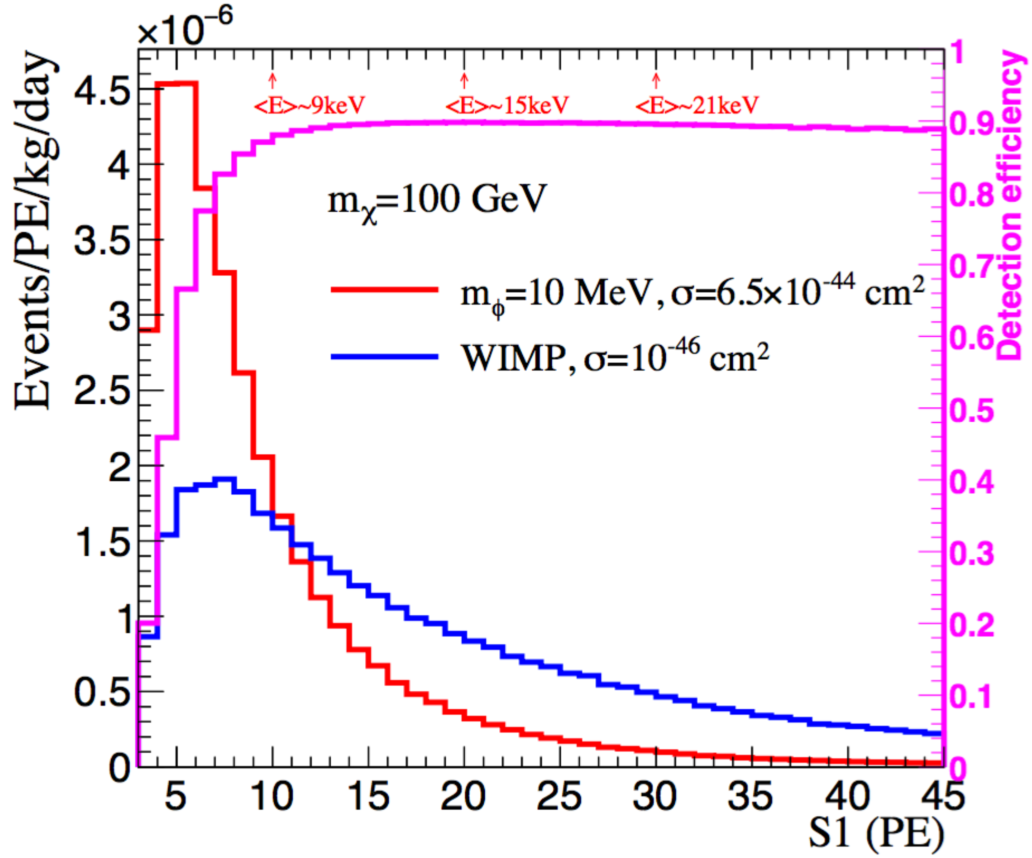
w/ Feng, Kaplinghat (PRL 2010)

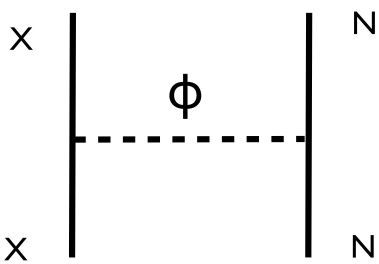
w/ Ibe (PRB 2010)

w/ Tulin, Zurek (PRL, PRD 2013)

...

SIDM Direct Detection





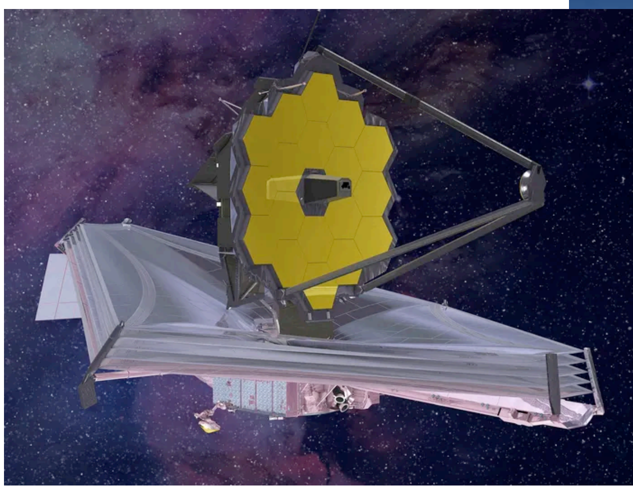
WIMP: m_ϕ~1 TeV>>q
SIDM: m_ϕ~10 MeV~q

Smoking-gun signature

PandaX collaboration+HBY (PRL, 2018; Sci. China, 2021; PRL, 2023)

Strong upper limit: the kinetic mixing parameter $<10^{-11}$–10^{-10}

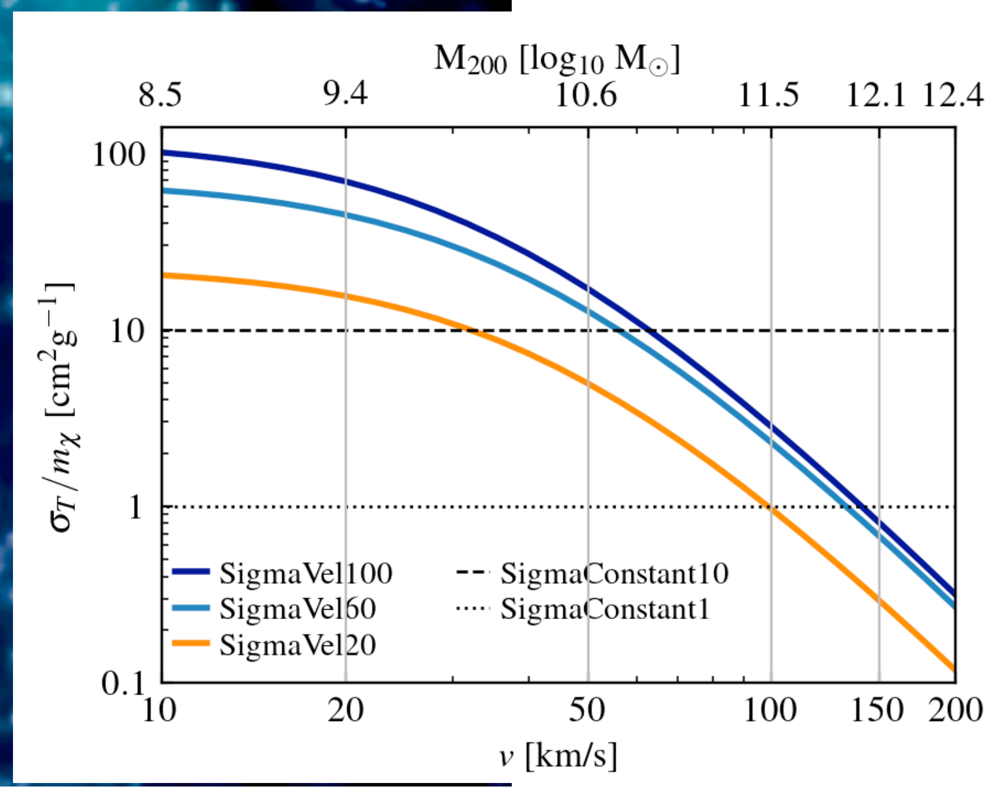
Looking Forward

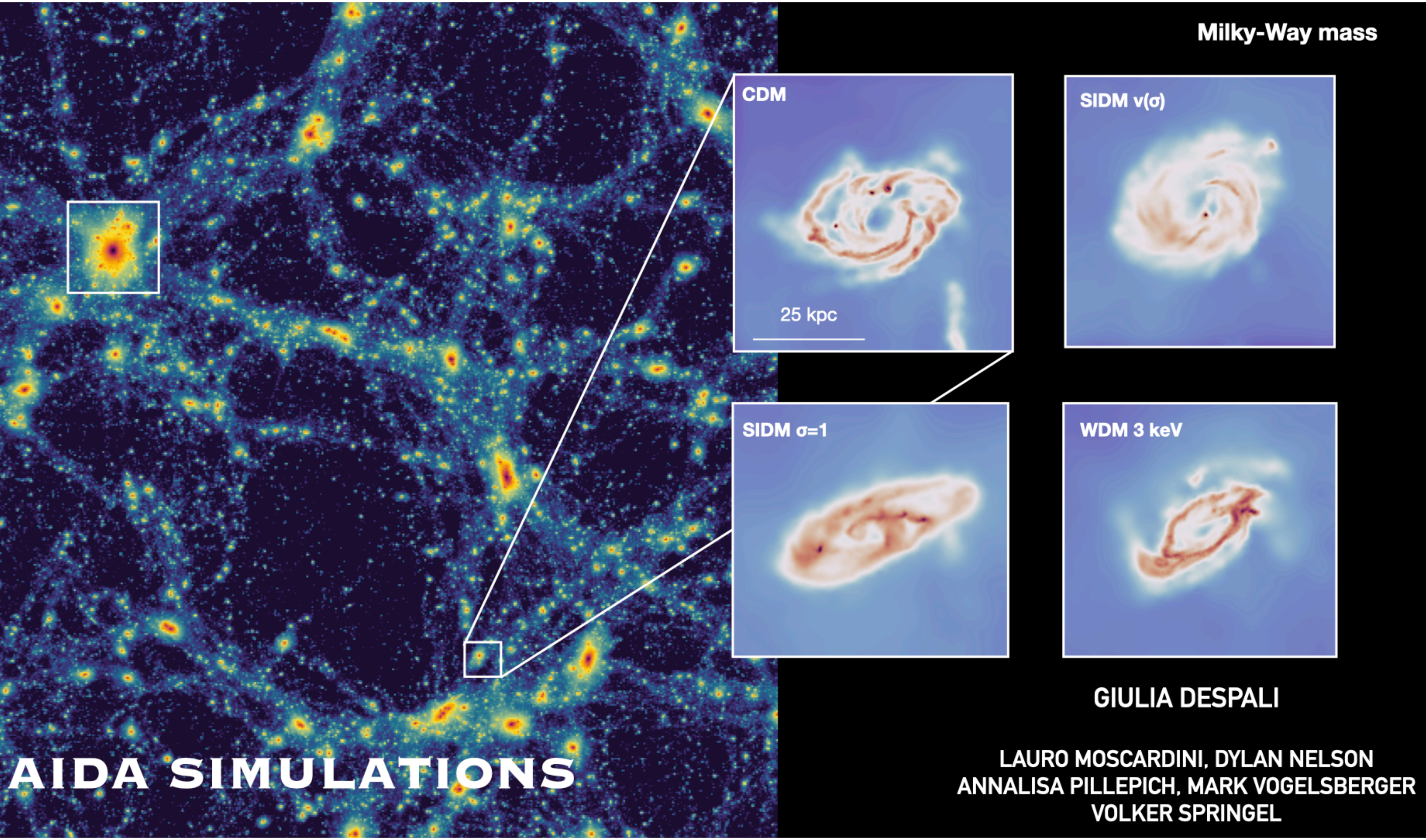


- Strong-lensing systems See Daniel Gilman's talk on Monday
- Satellite galaxies, and stellar streams of the Milky Way
- Better, dedicated modeling and simulations are required

TangoSIDM

Camila Correa
(Paris-Saclay)





Giulia Despali
(U of Bologna)

Baryon physics is based on IllustrisTNG
The results will be released soon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Thank You!