

Why Dark Matter May Have Self-Interactions

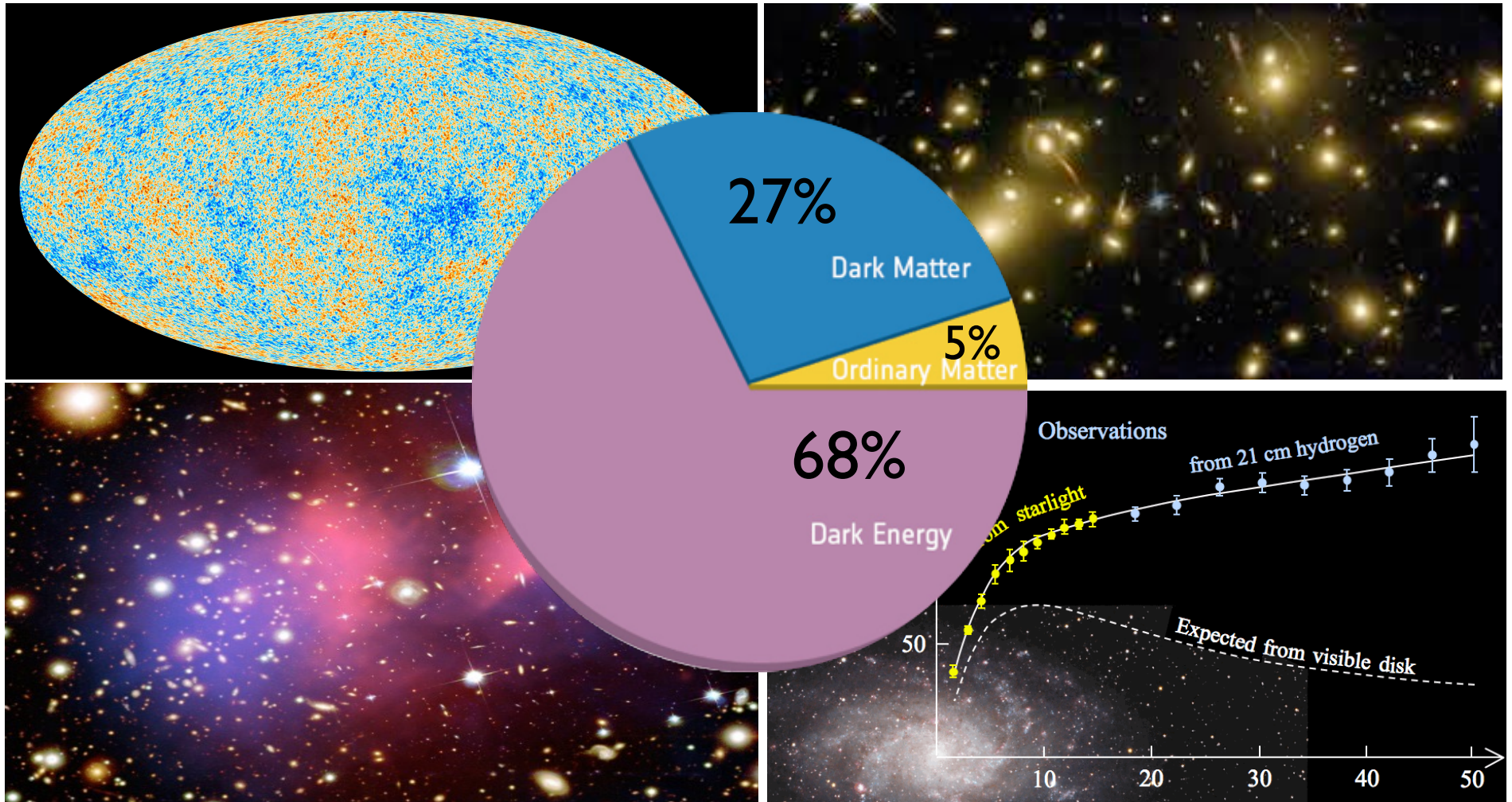
Hai-Bo Yu

University of California, Riverside

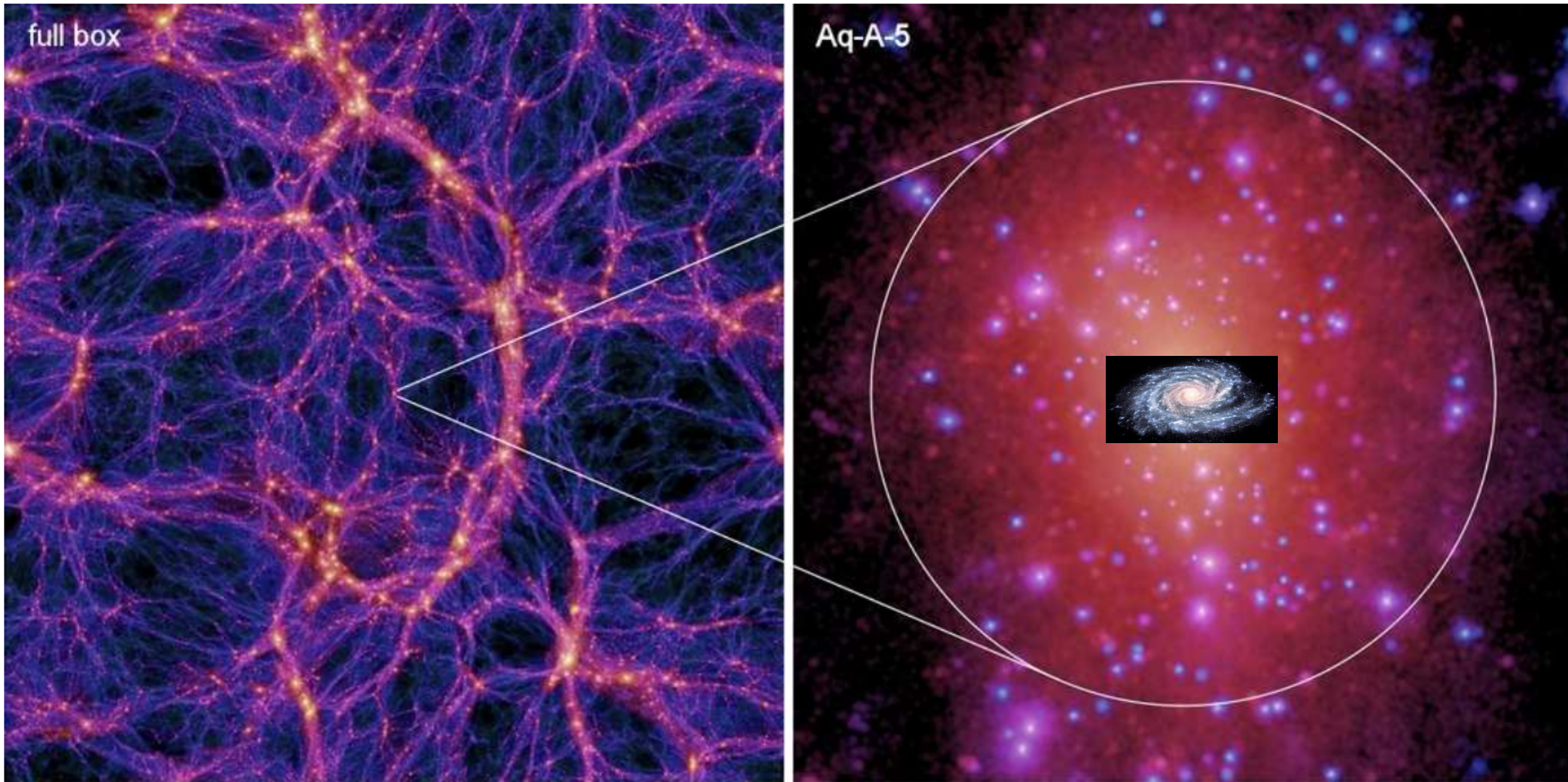
**30th International Summer Institute
on Phenomenology of Elementary
Particle Physics and Cosmology,
August 11, 2026, Fuji Calm**



Dark Matter

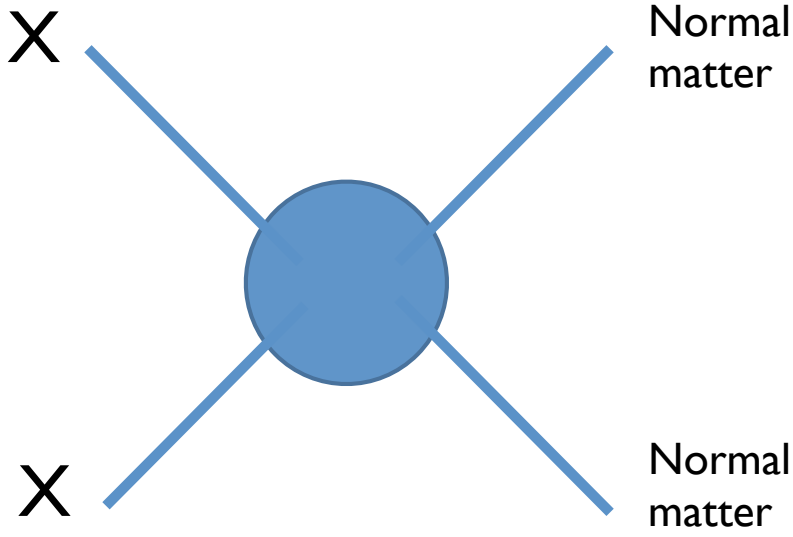


Dark Matter Halos: Hosting Galaxies

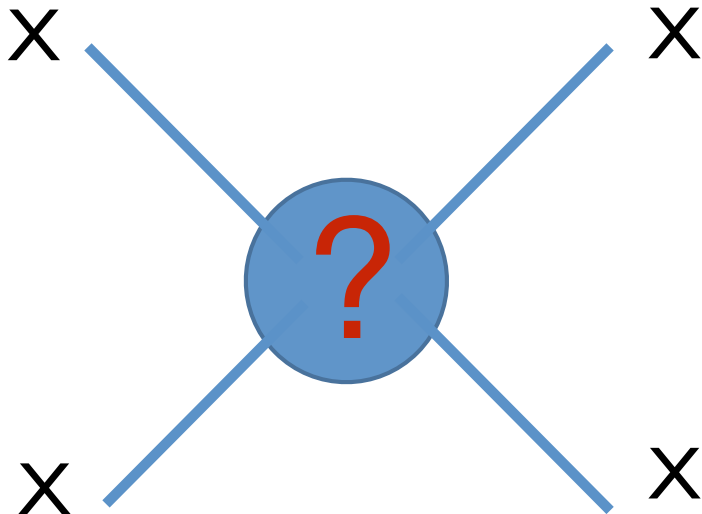


Aquarius Project, Springel+(2008)

Dark matter is essential for seeding the structure formation of the Universe



Strong Constraints



Self-Interactions?

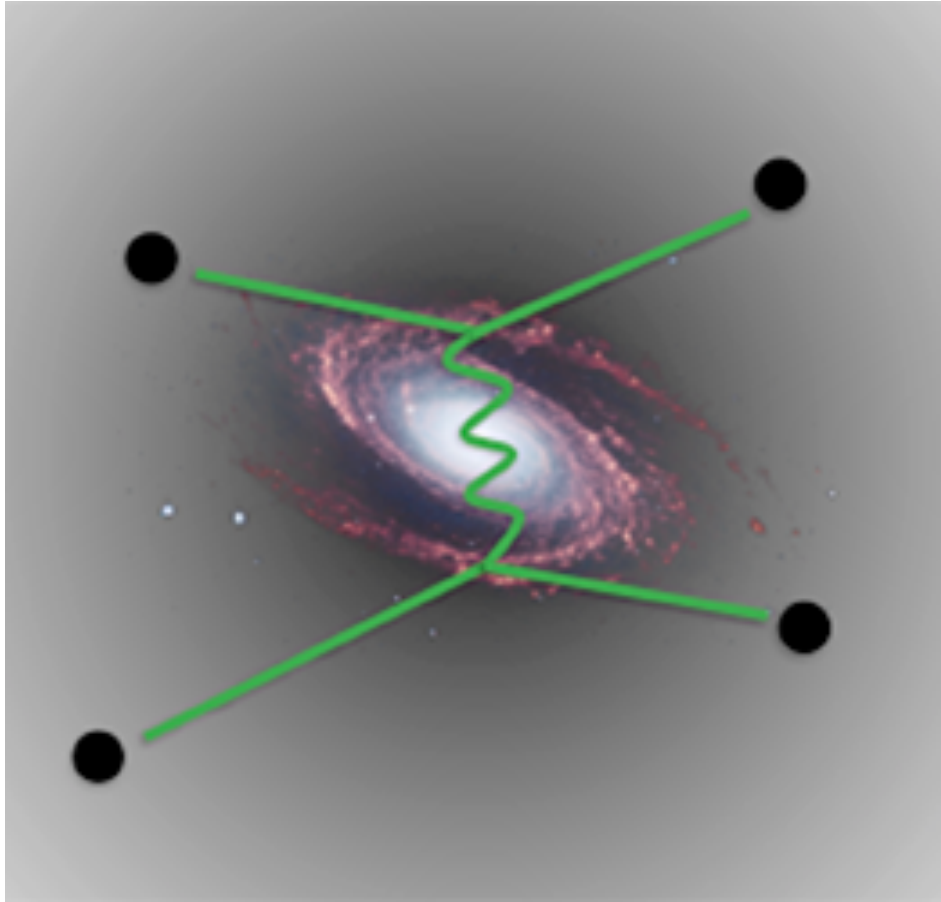
Most of the known particles have large self-interactions

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

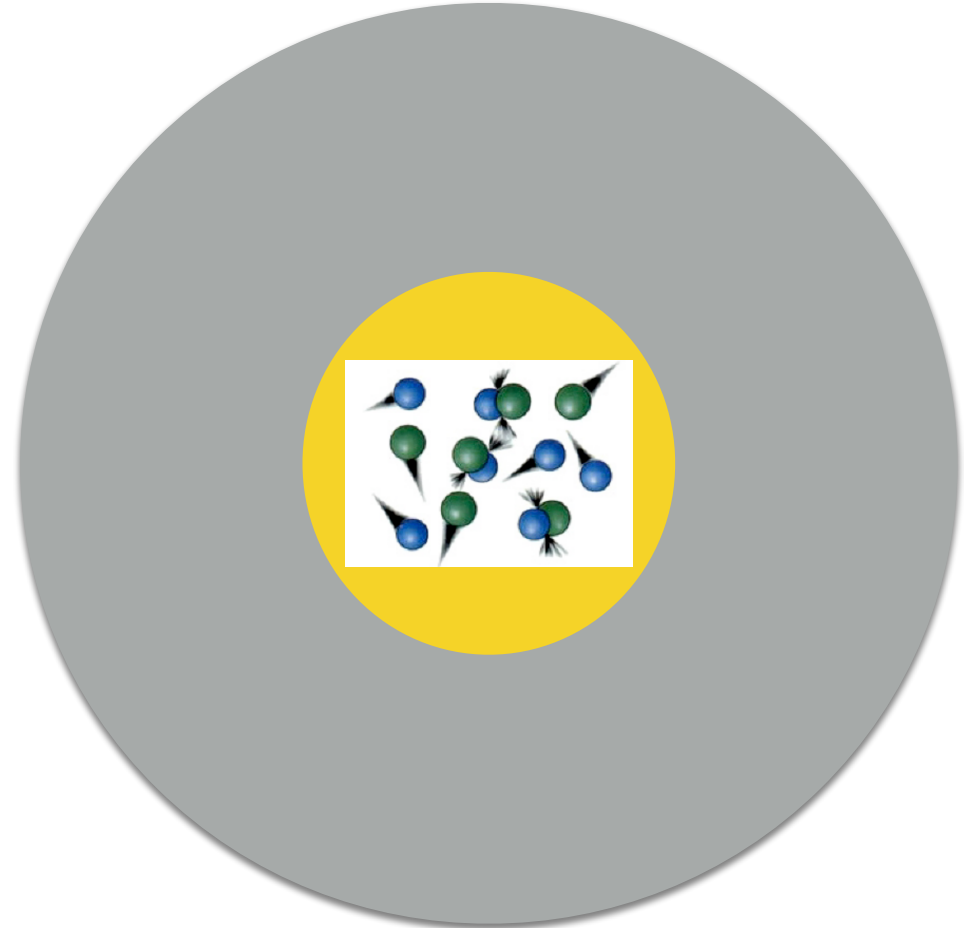
mass, charge, spin

Dark Matter Self-Interactions



Self-interactions in the dark sector

Treat dark matter as ideal gas



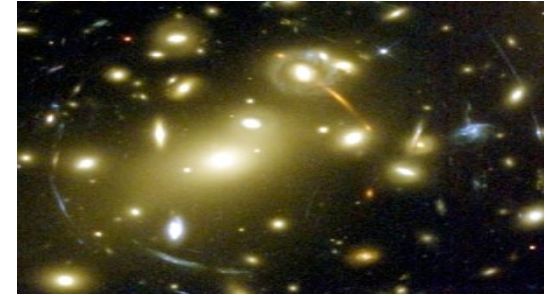
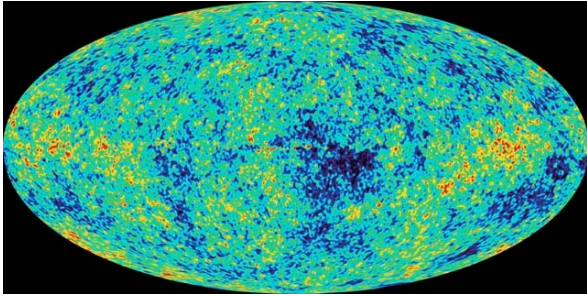
thermalization

$$PV=nRT$$

“takeaway message”

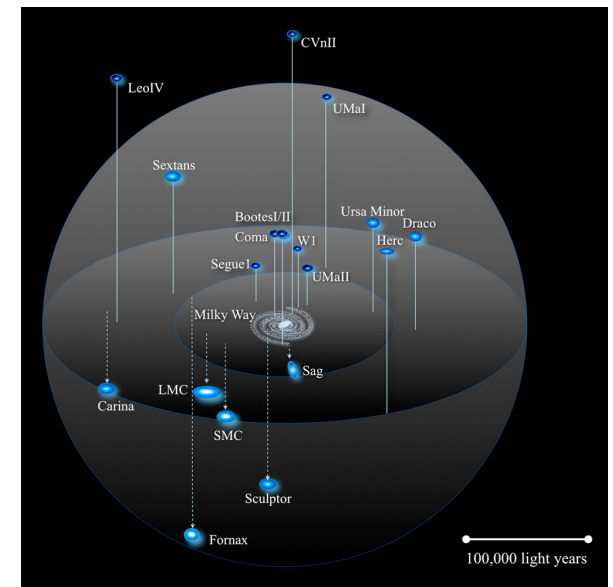
Cold Dark Matter (CDM)

- Large scales: very well

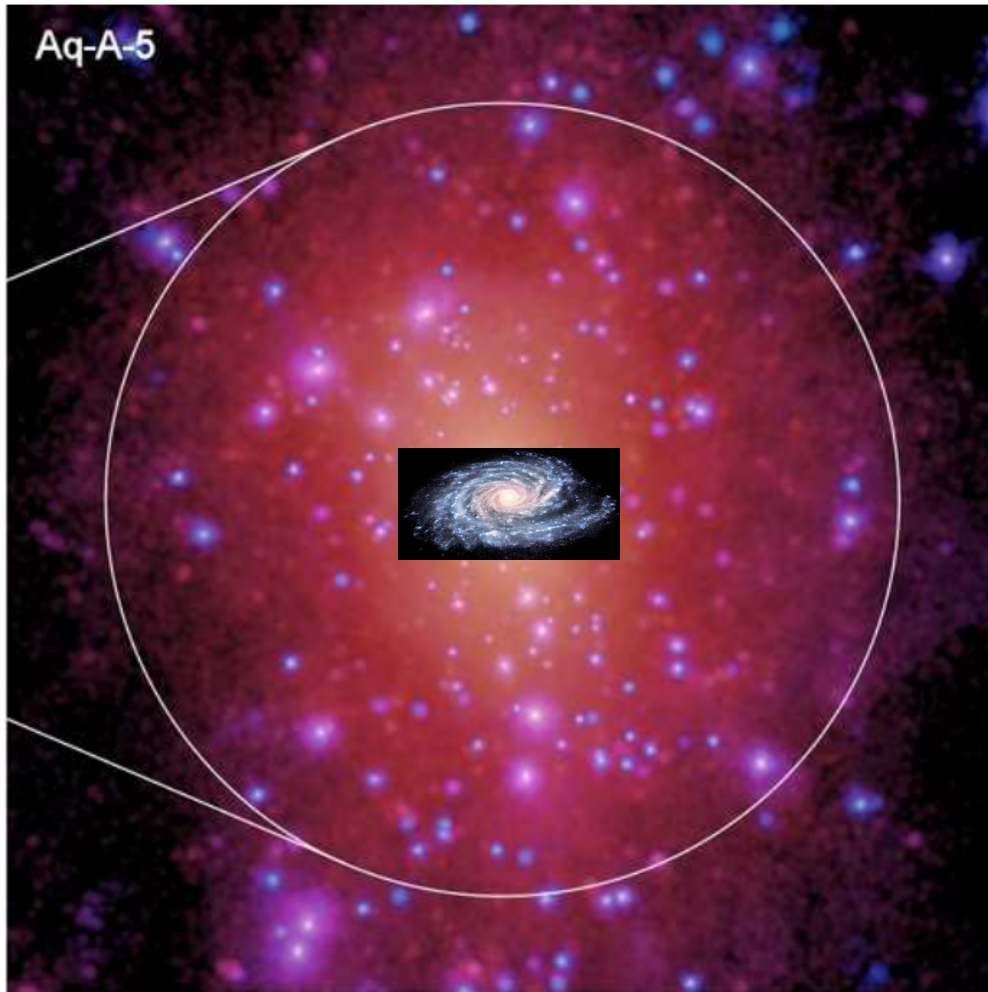


- Small scales (field/satellite dwarf galaxies, substructures)

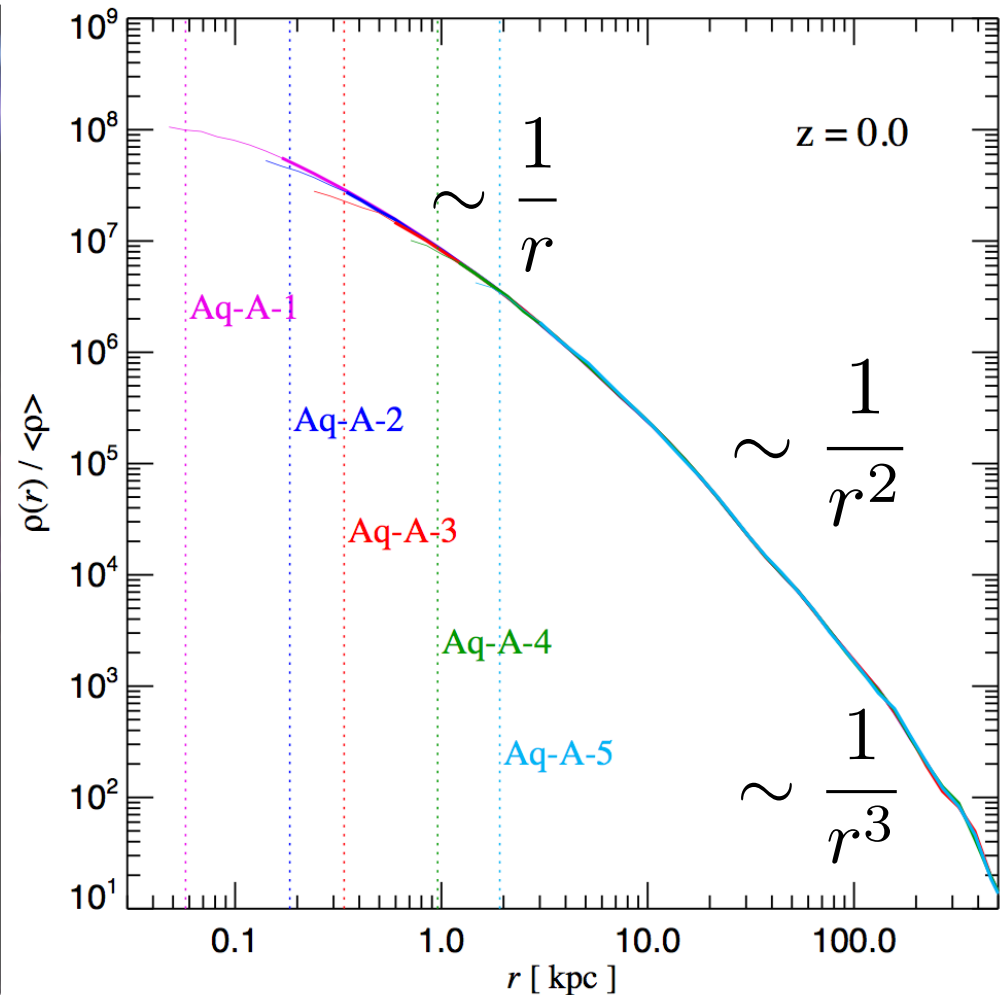
- Core vs Cusp
- Diversity
- Too Big To Fail
- Dense substructures
- Ultra-diffuse galaxies
- ...



CDM: Universal Density Profile

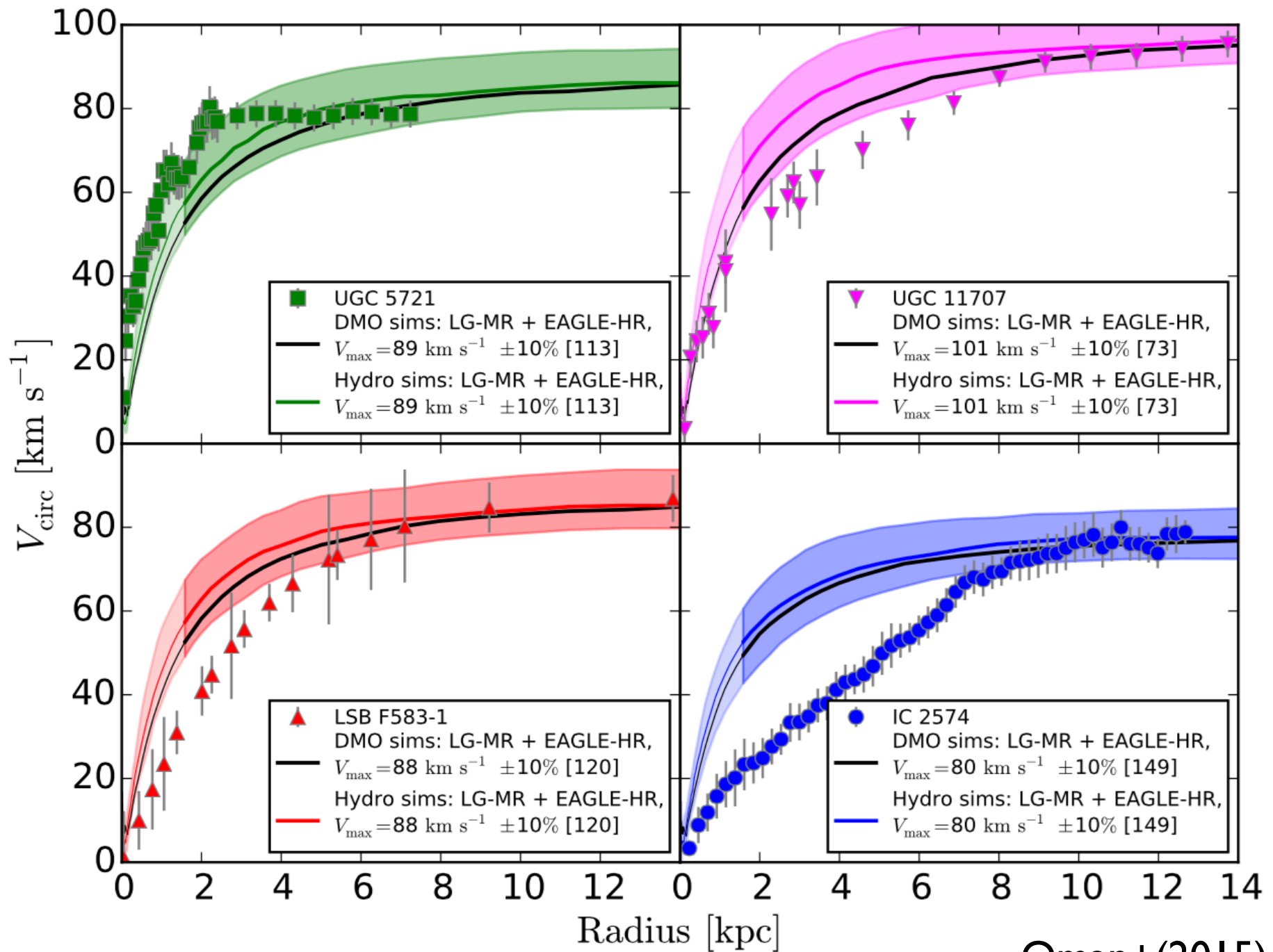


Aquarius Project, Springel+ (2008)



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

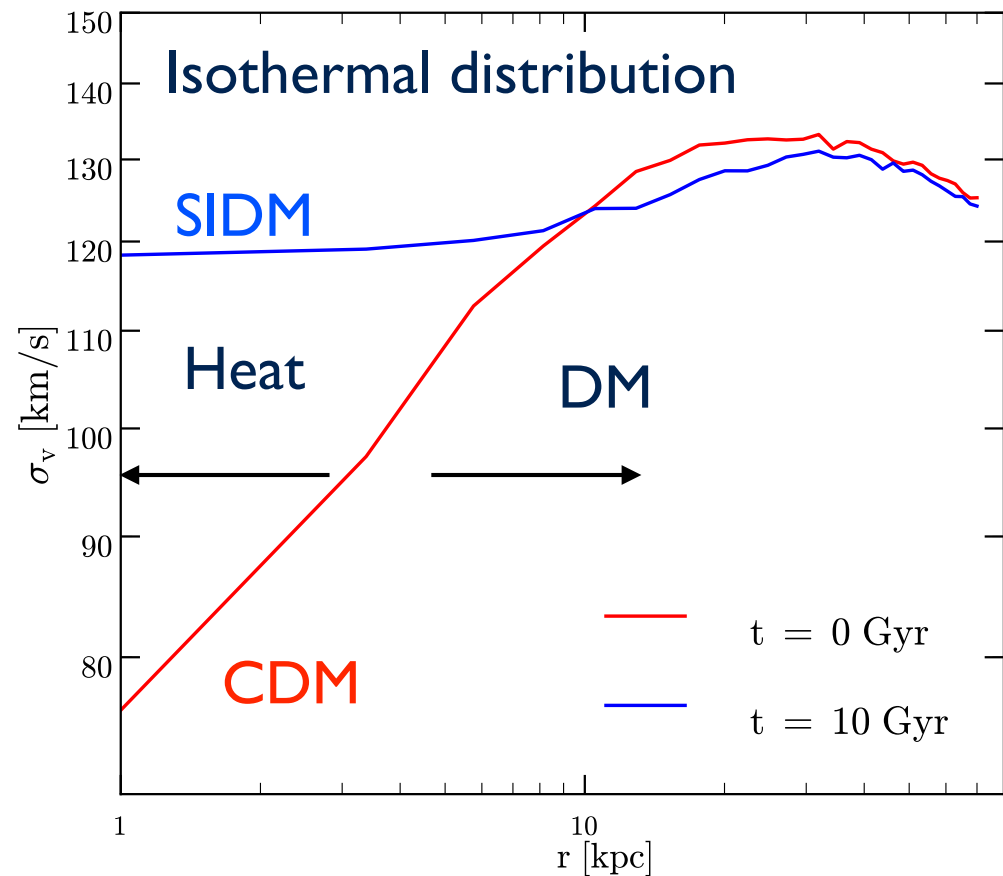
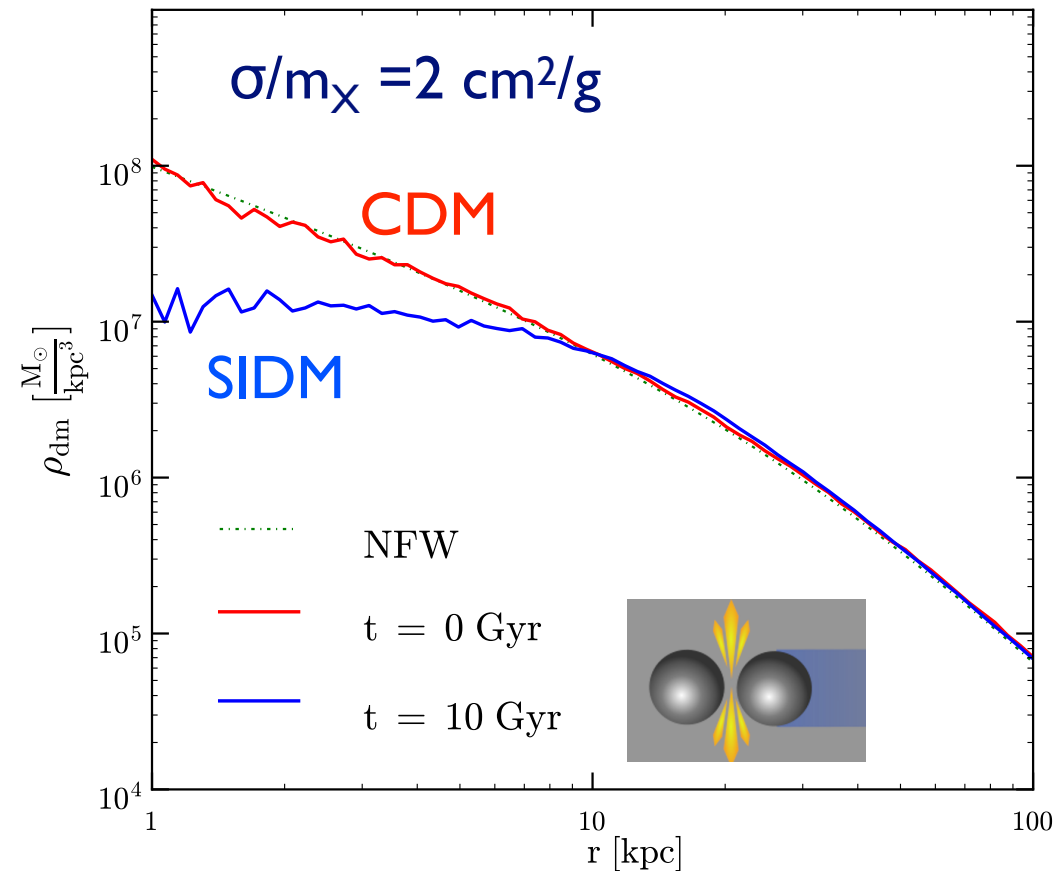
the Navarro-Frenk-White (NFW) profile (1996)



Oman+(2015)

Rotation curves (matter distributions) are **diverse** in spiral galaxies

Self-Interacting Dark Matter



$$\rho_{\text{dm}} = \rho_0 \exp \left[-\Phi_{\text{tot}} / \sigma_0^2 \right]$$

$$\Phi_{\text{tot}} = \Phi_{\text{dm}} + \Phi_b$$

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

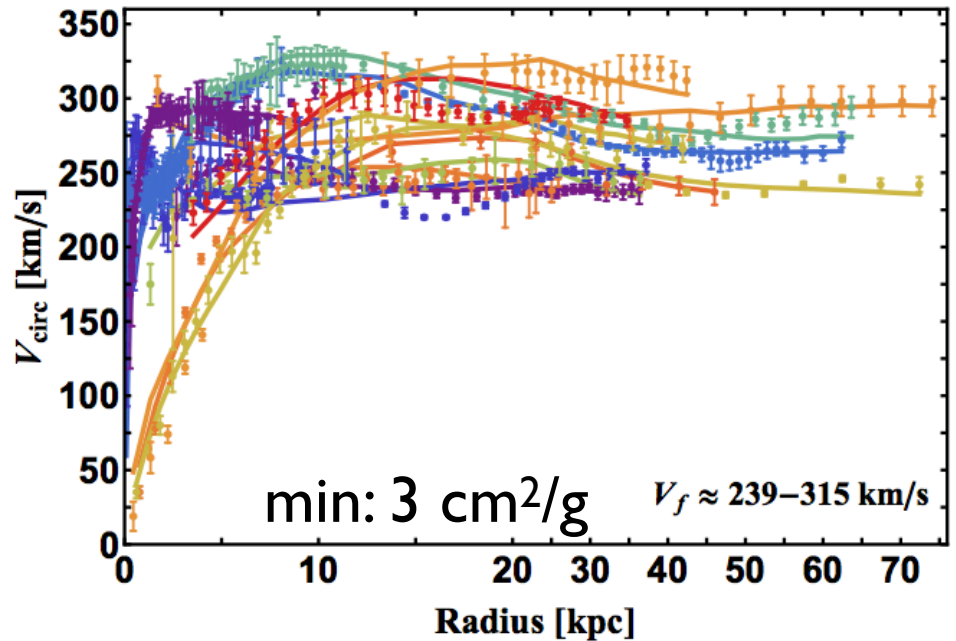
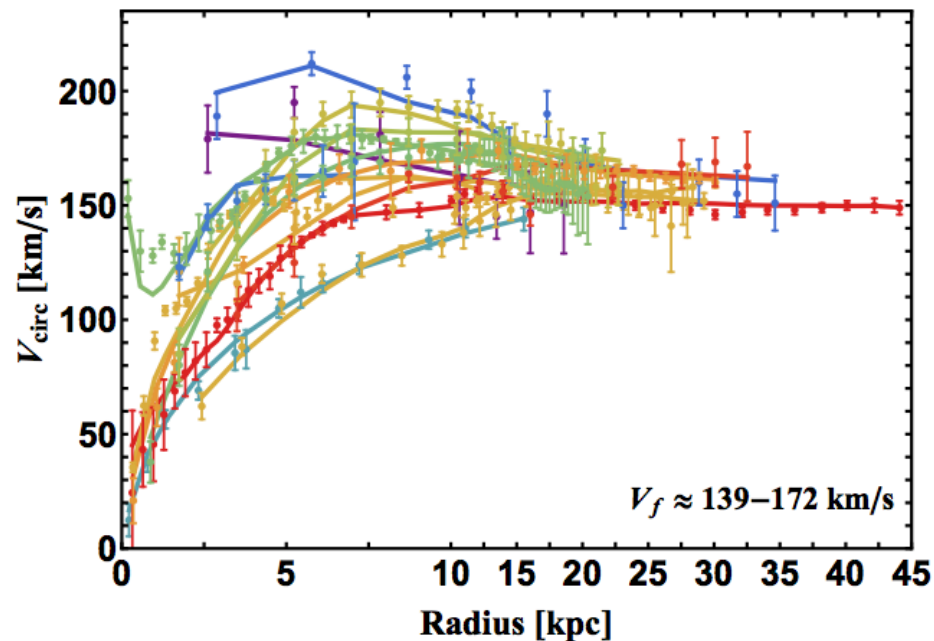
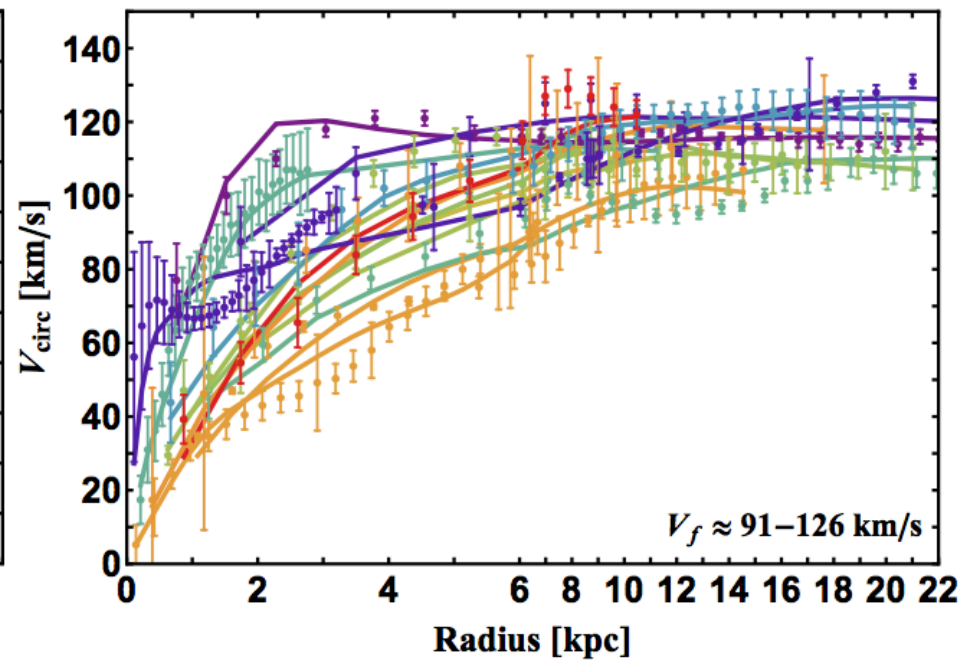
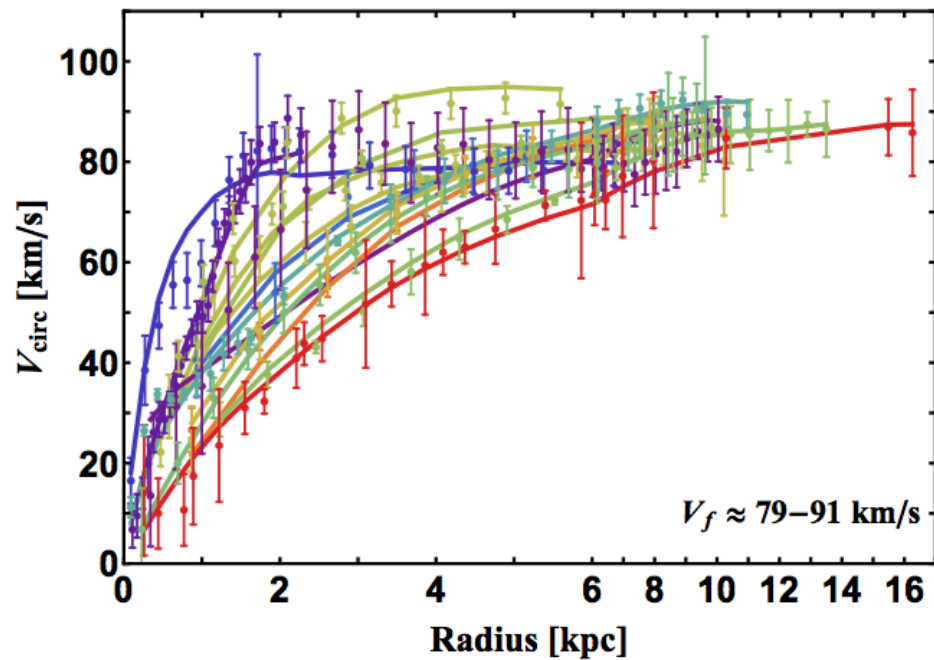
Review: Tulin, HBY (Physics Reports 2017)

with Kaplinghat, Keeley, Linden (PRL 2014)

with Kaplinghat, Linden (RPL 2015)

with Kaplinghat, Tulin (PRL 2016)

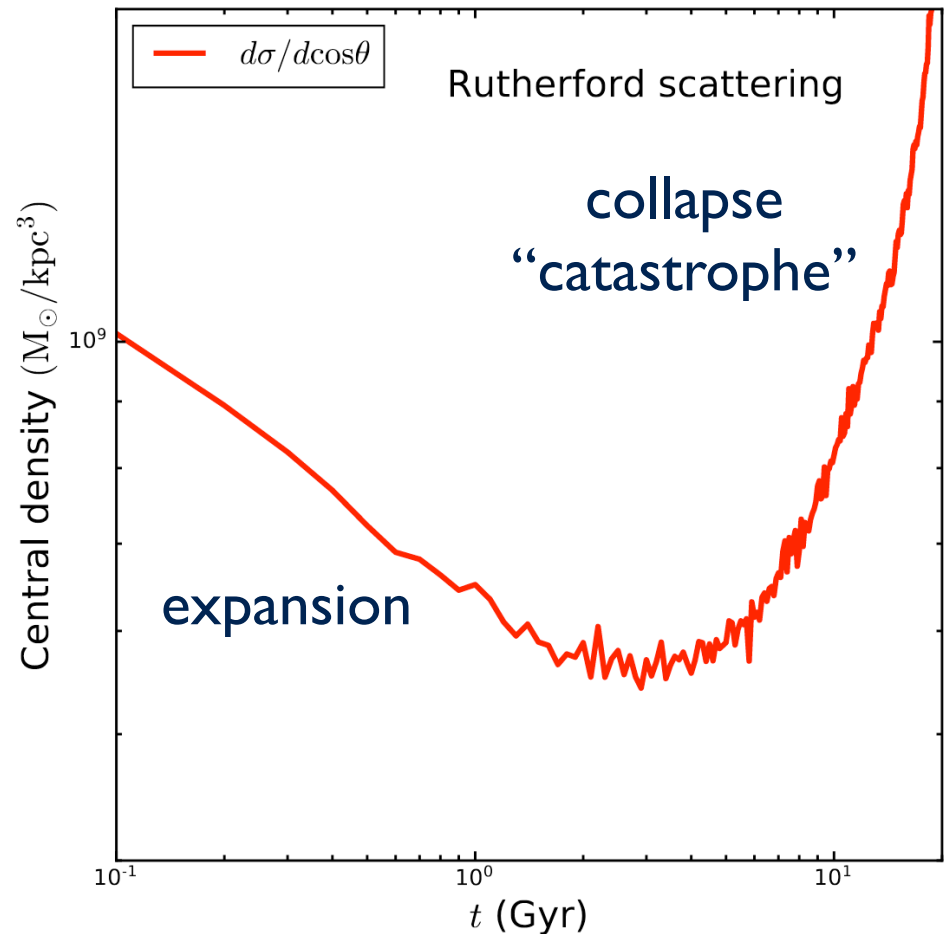
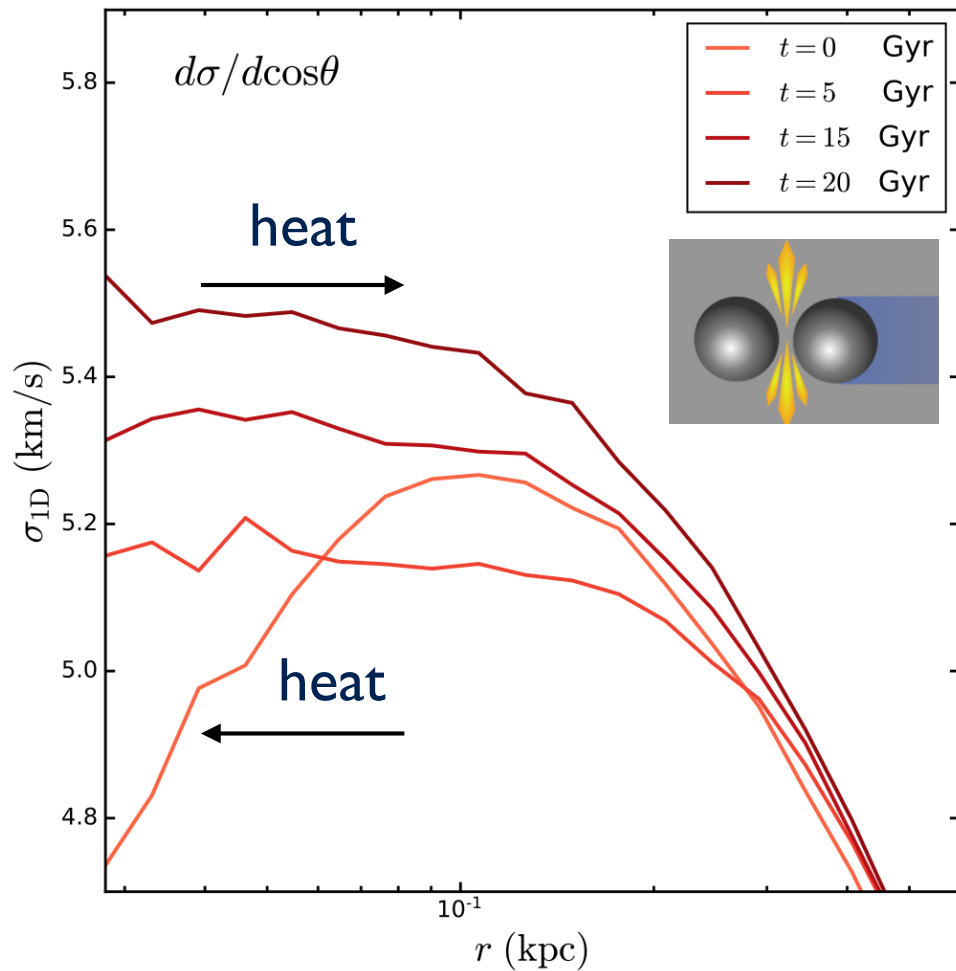
with Kamada, Kaplinghat, Pace (PRL 2017)



We analyzed 135 galaxies (3.6 μm band)
SPARC dataset, Lelli, McGaugh, Schombert (2016)

w/ Ren, Kwa, Kaplinghat (PRX 2018)
w/ Creasey, Sameie, Sales+ (MNRAS 2017)
Zentner+ (JCAP 2022)...

Gravothermal Collapse



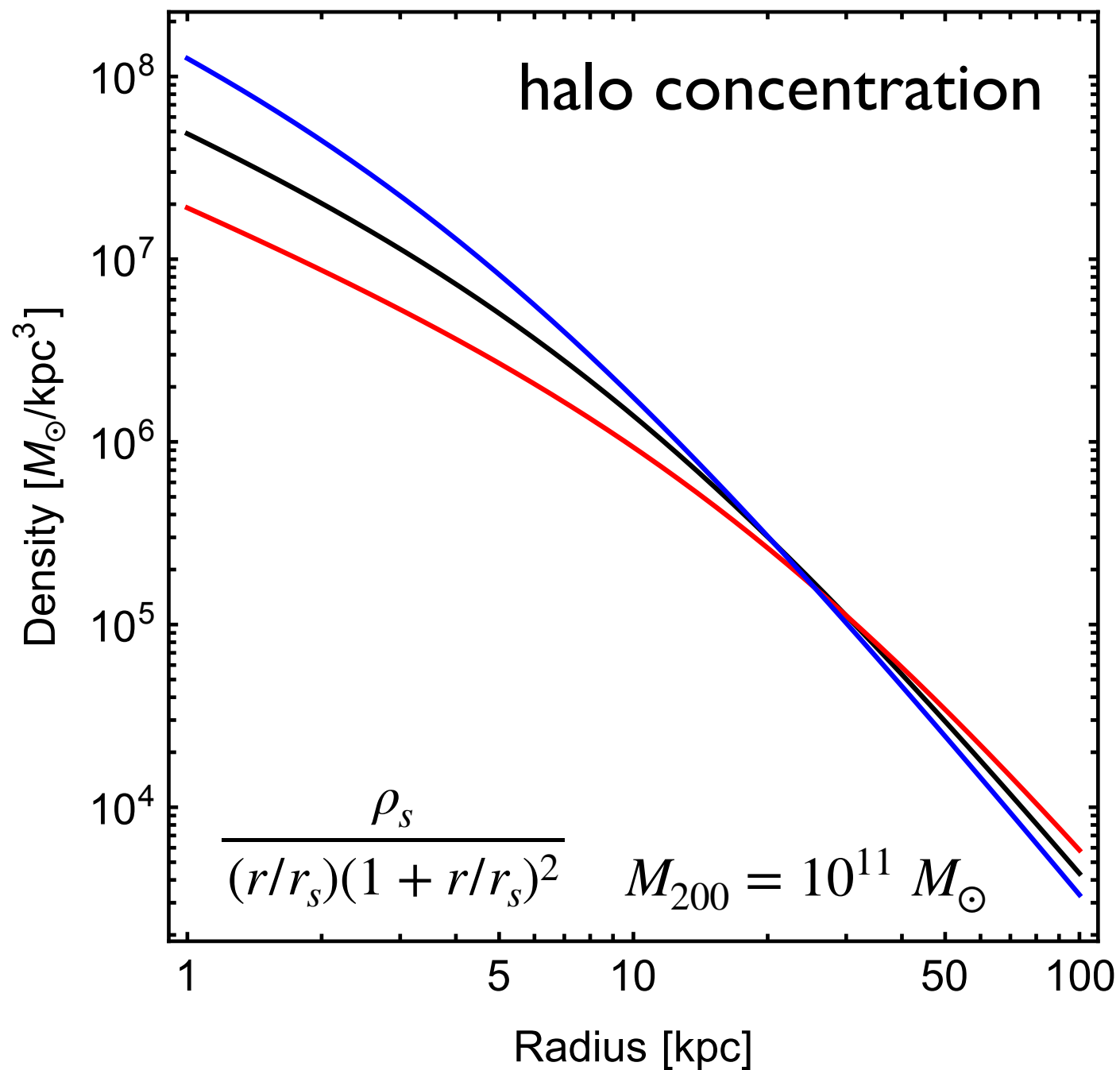
Yang, Yu (JCAP 2022)

$$\frac{E_{\text{tot}}}{T} < 0 \quad \text{Negative heat capacity!} \\ \Rightarrow \text{gravothermal collapse}$$

Balberg+(ApJ, 2002)...

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

w/ Essig, McDermott, Zhong (PRL 2019)



$c_{200} \equiv r_{200}/r_s = 23$ ($+3\sigma$, blue), 11 (median, black), 5 (-3σ , red)

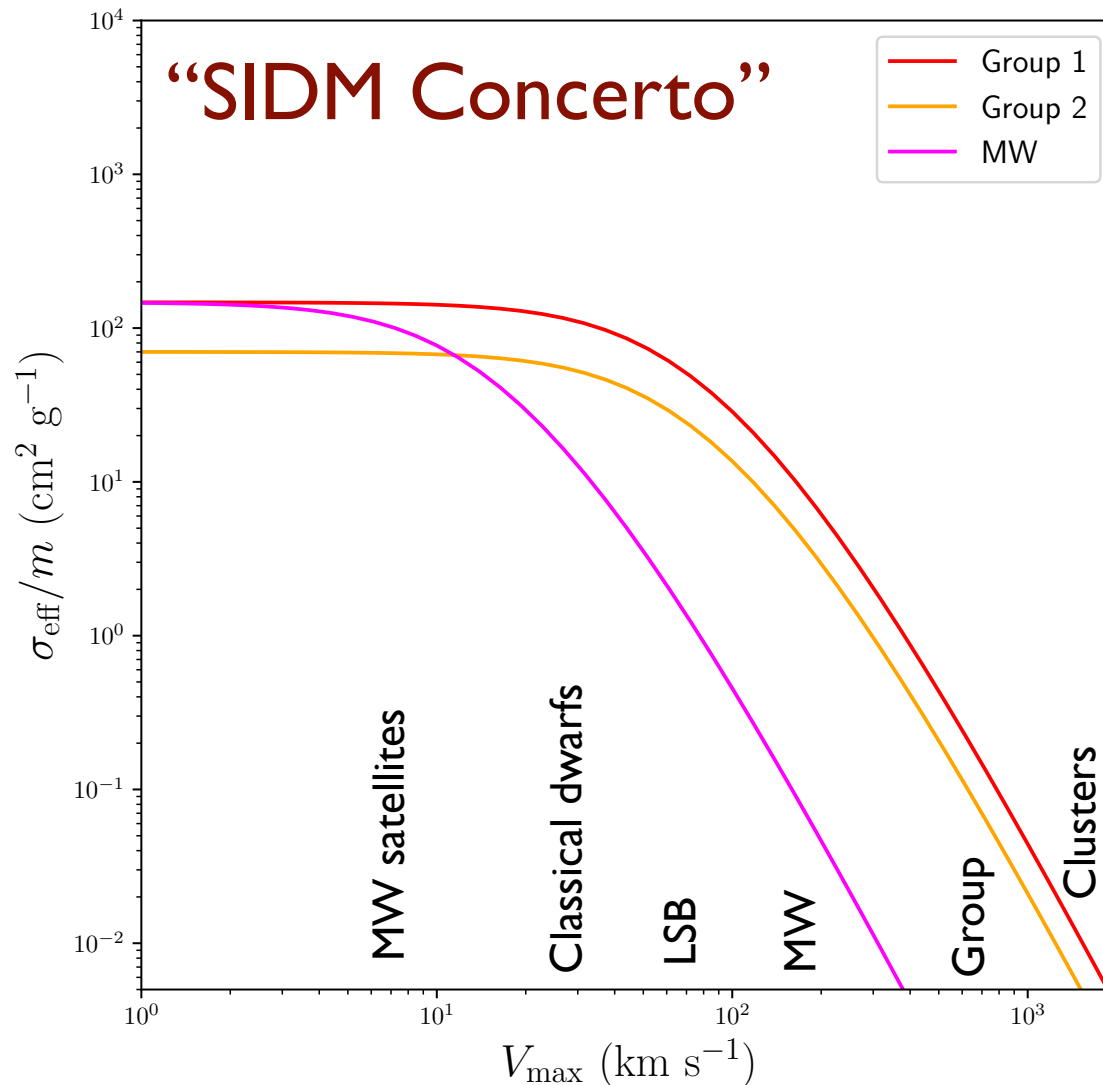
Cosmological Zoom-in Simulations



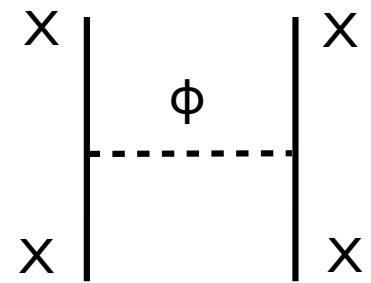
Ethan Nadler
(UCSD)



Daneng Yang
(Purple Mountain)



Demao Kong
(UCR)



$$V(r) = \frac{\alpha_{\chi}}{r} e^{-m_{\phi} r}$$

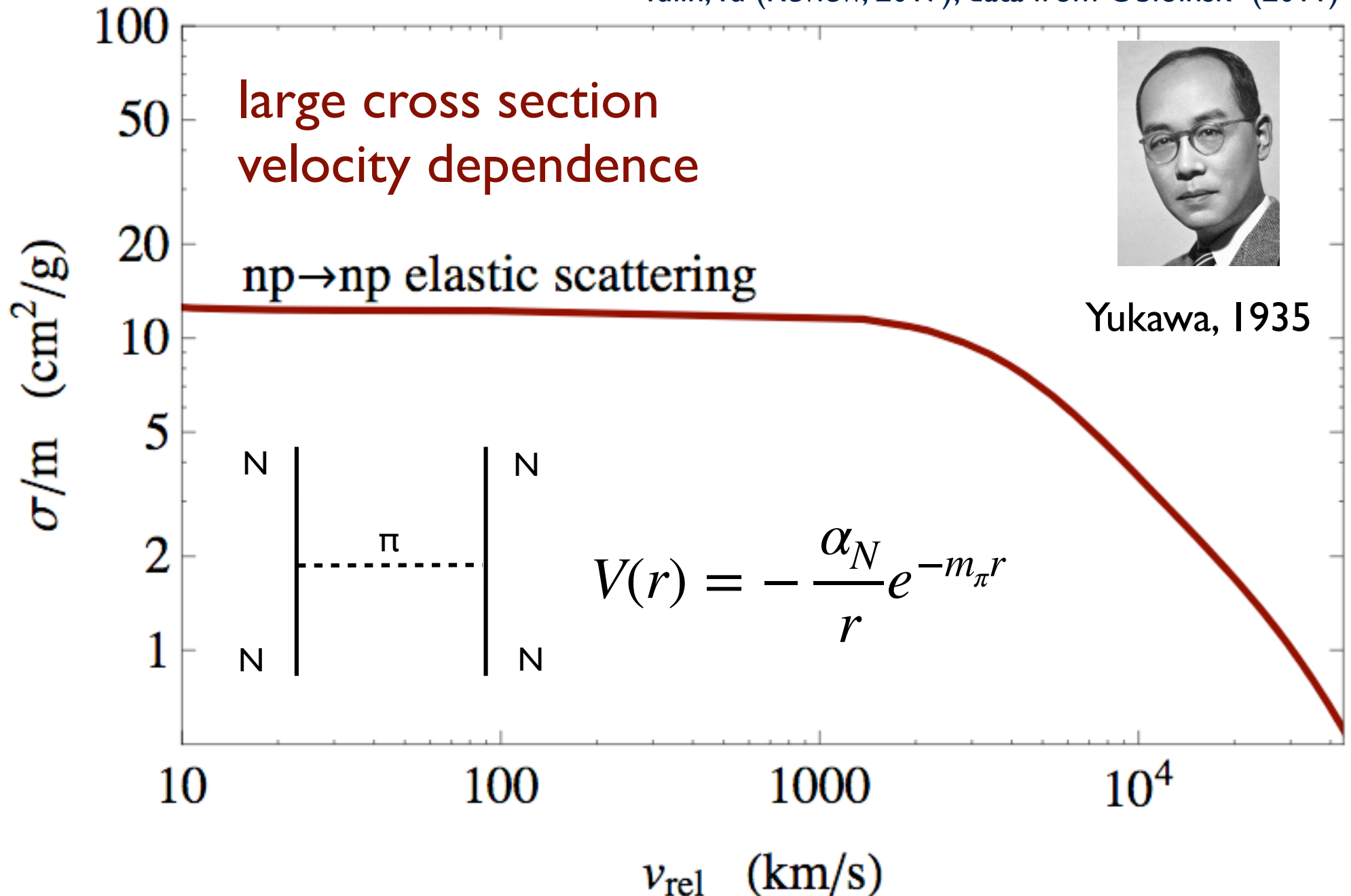
MW: box with a Milky Way-like main halo; Yang, Nadler, Yu (ApJ 2022)

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

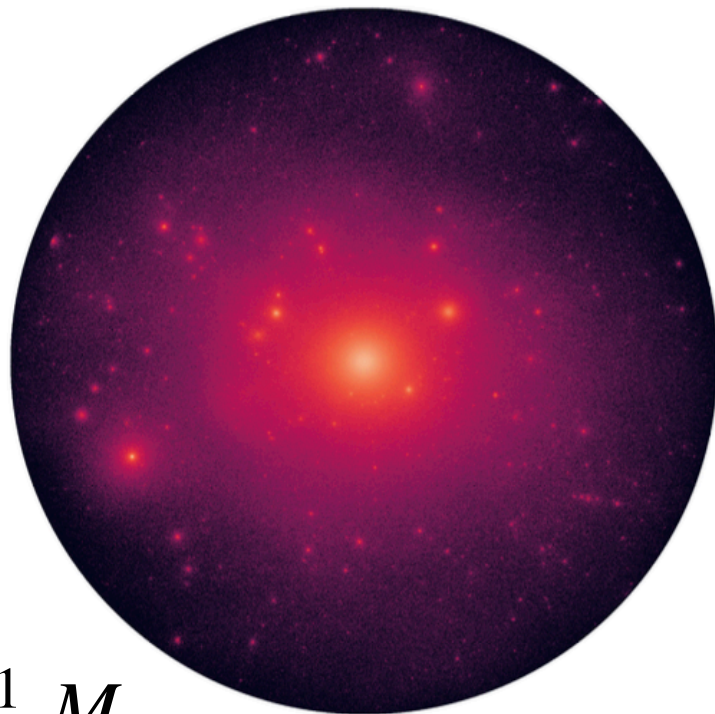
6 main halos with masses over LMC, MW, Group, Cluster scales; 14 simulations in total; the data is publicly available (~18 TB): Nadler, Kong, Yang, Yu (ApJ 2025); More than 4000 downloads

Nuclear Interactions

Tulin, Yu (Review, 2017); data from Obloinsk+(2011)

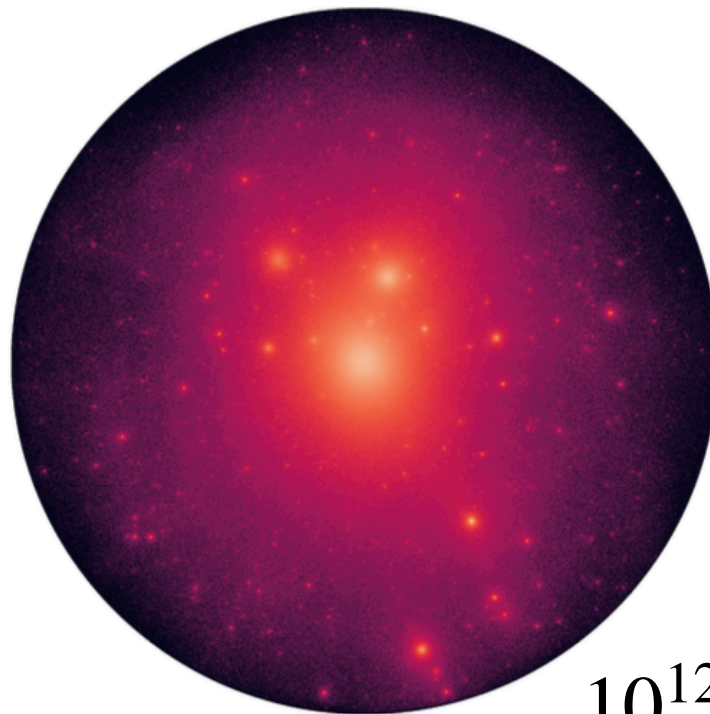


LMC



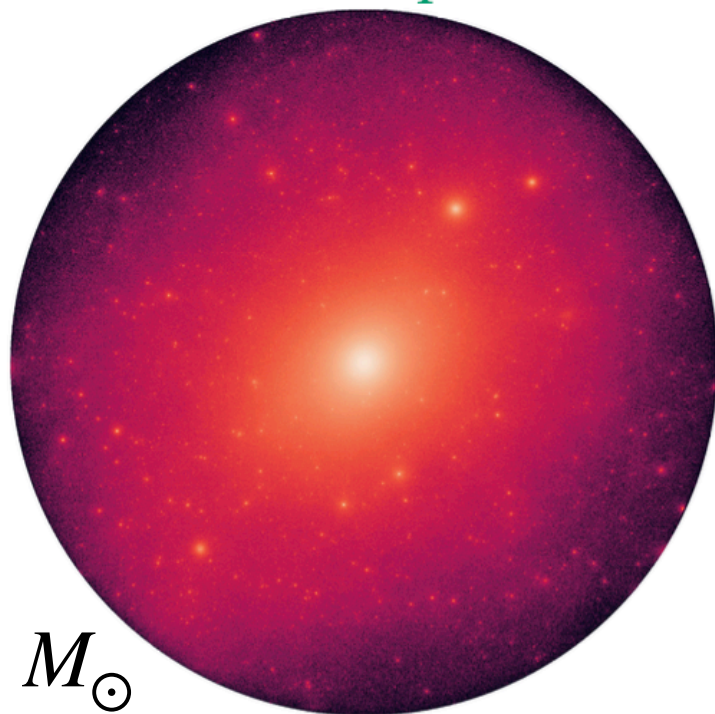
$10^{11} M_{\odot}$

MW



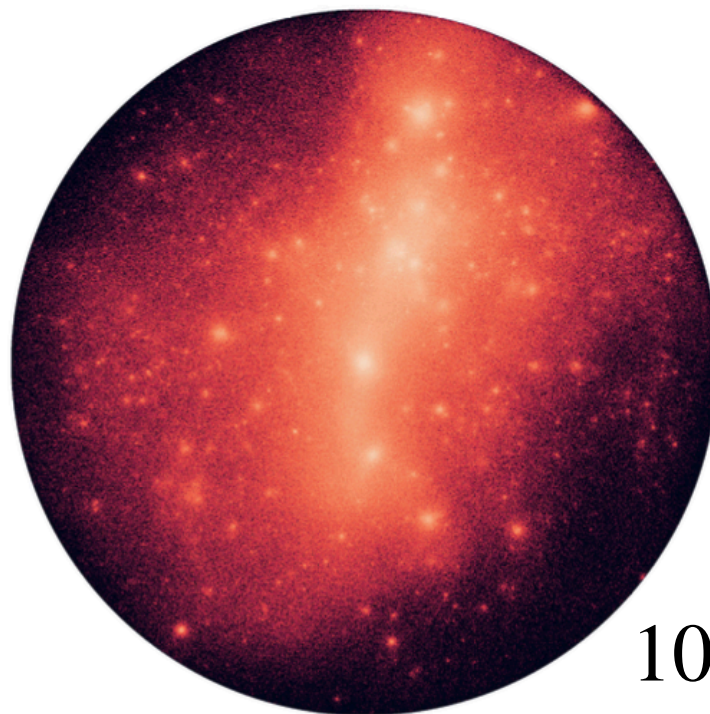
$10^{12} M_{\odot}$

Group

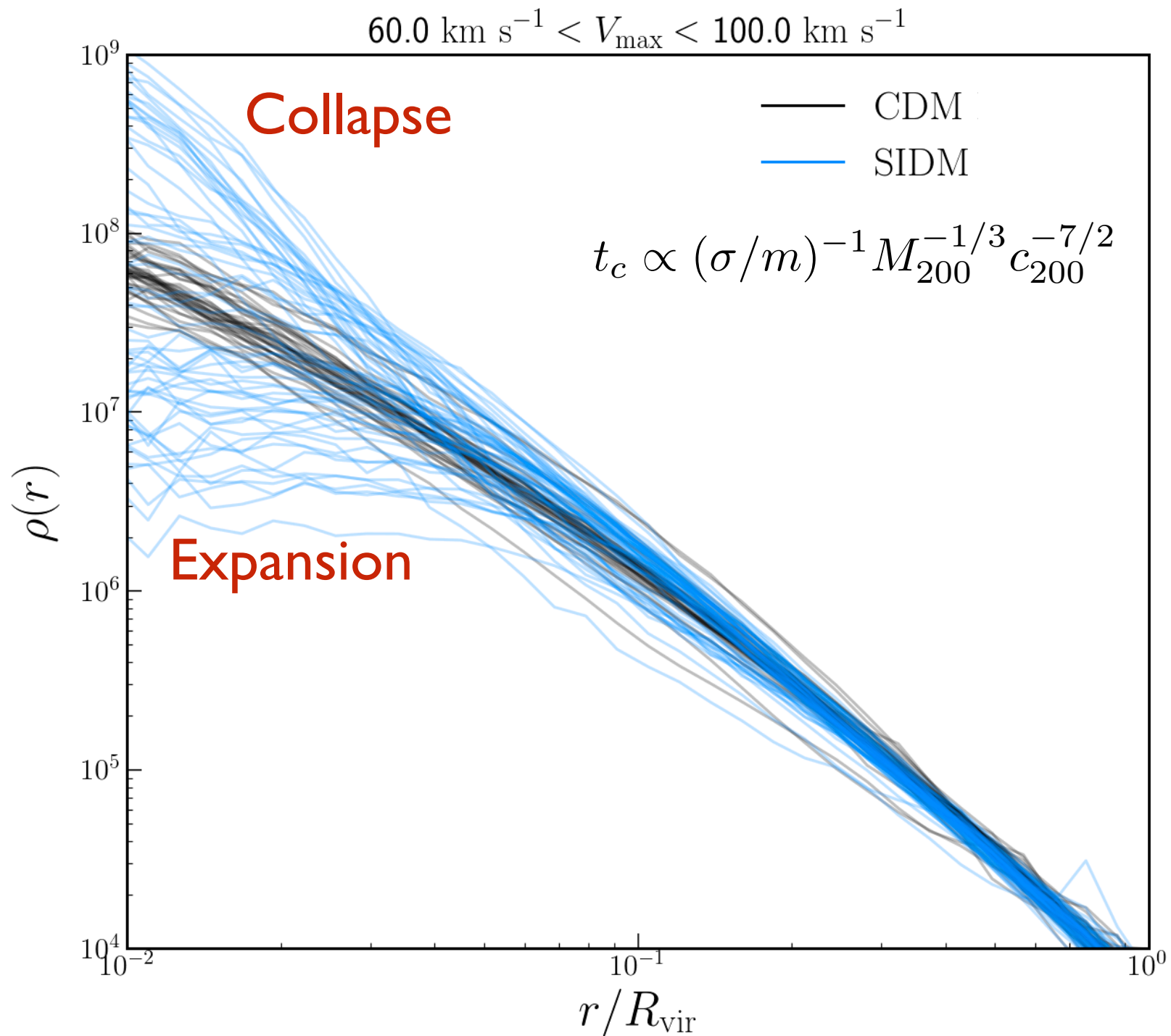


$10^{13} M_{\odot}$

L-Cluster



$10^{14} M_{\odot}$

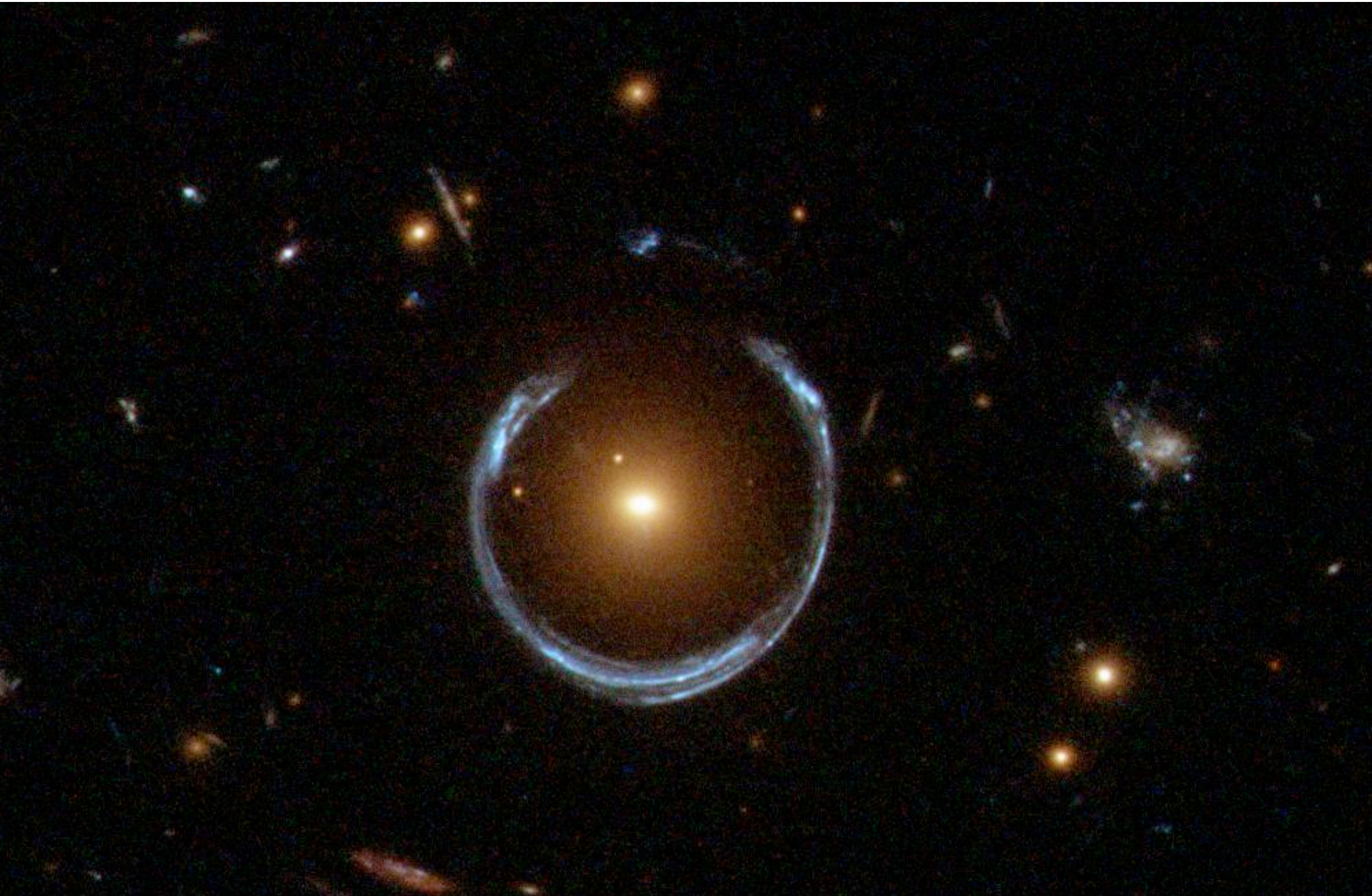


SIDM amplifies diversity encoded in the scatter of halo concentration

Any evidence for
core-collapsed halos?



Substructure by Strong Lensing



Detection of a Dark Substructure through Gravitational Imaging

S. Vegetti^{1★}, L.V.E. Koopmans¹, A. Bolton², T. Treu³ & R. Gavazzi⁴

¹*Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, the Netherlands*

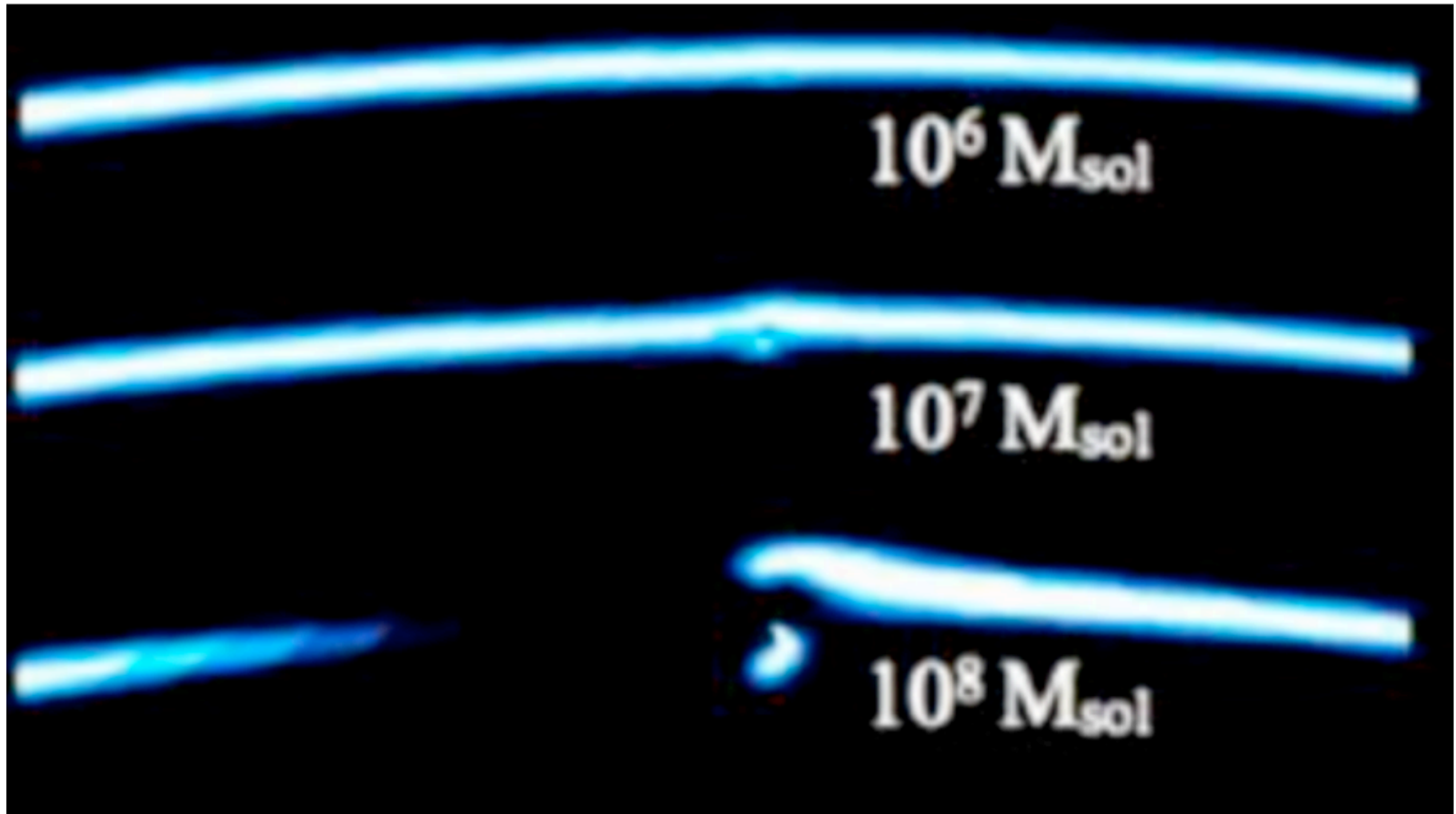
²*Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822-1897, USA*

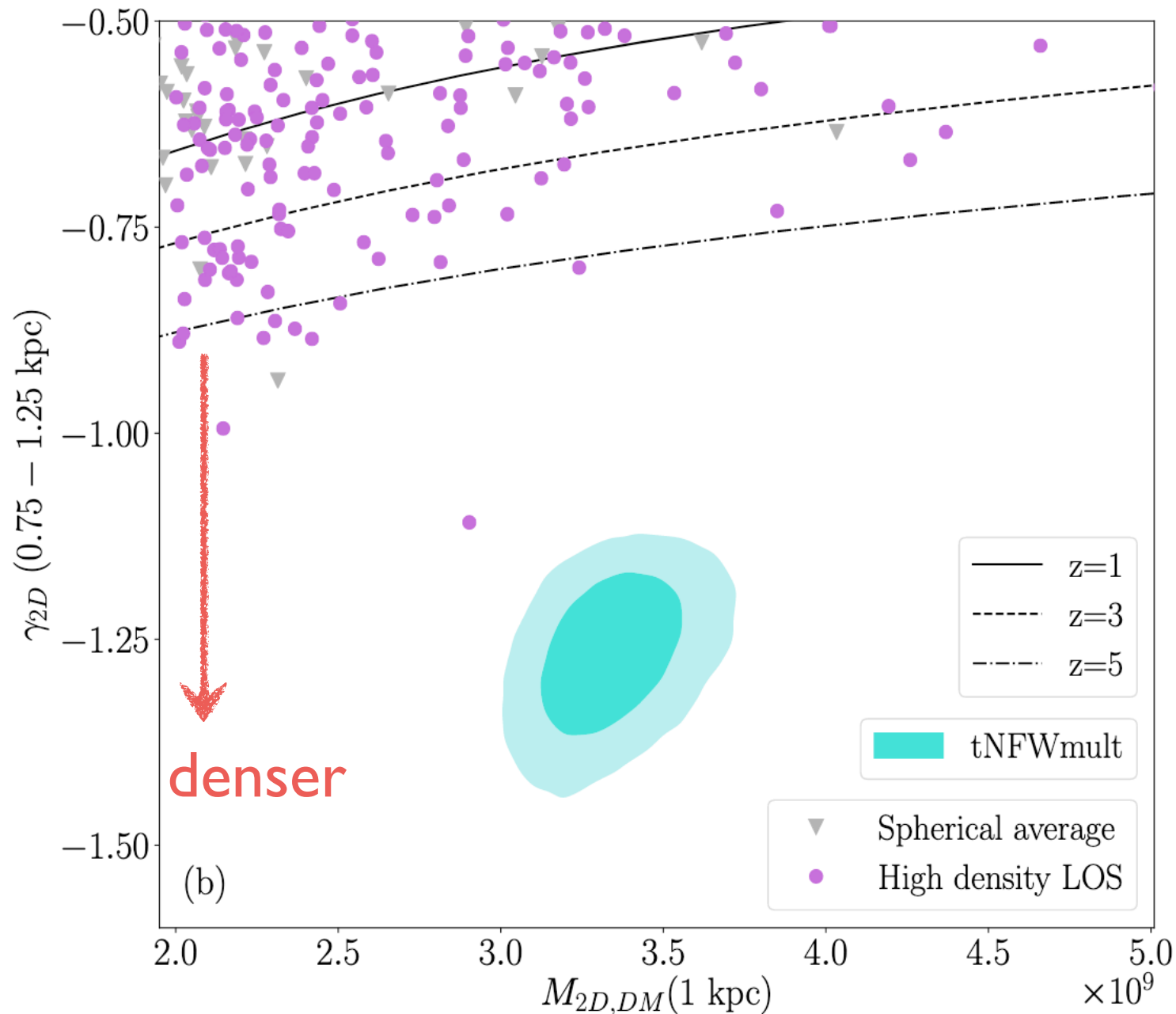
³*Department of Physics, University of California, Santa Barbara, CA 93101, USA*

⁴*Institut d'Astrophysique de Paris, CNRS, UMR 7095, Universite Pierre et Marie Curie, 98bis Bd Arago, 75014 Paris, France*

(MNRAS 2010)

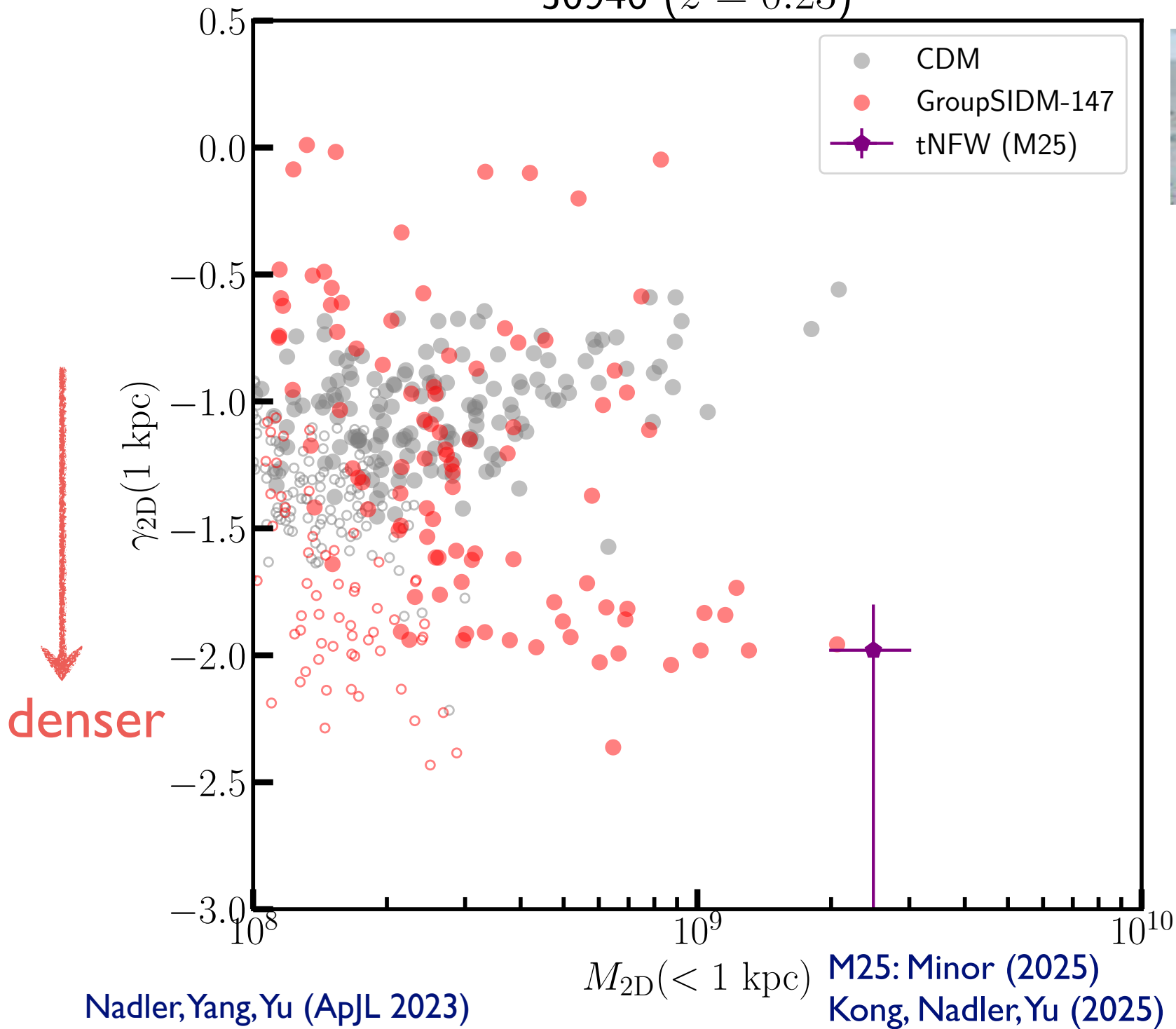
SDSSJ0946+1006 (the “Double Einstein Ring”).





- The substructure is extremely dense Minor+(MNRAS, 2020); Despali+(A&A, 2025)
- Compared to the IllustrisTNG simulation, the tension with CDM is at the $> 99\%$ CL
- The substructure does not have a detectable luminous component

J0946 ($z = 0.23$)



More Strong-Lensing Perturbers

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance

[S. Vegetti](#) , [D. J. Lagattuta](#), [J. P. McKean](#), [M. W. Auger](#), [C. D. Fassnacht](#) & [L. V. E. Koopmans](#)

[Nature](#) **481**, 341–343 (2012) | [Cite this article](#)

JVAS B1938+666

Updated analysis: Tajalli+(2025)

A million-solar-mass object detected at a cosmological distance using gravitational imaging

[D. M. Powell](#) , [J. P. McKean](#), [S. Vegetti](#) , [C. Spingola](#), [S. D. M. White](#) & [C. D. Fassnacht](#)

[Nature Astronomy](#) **9**, 1714–1722 (2025) | [Cite this article](#)

JVAS B1938+666-V

DETECTION OF LENSING SUBSTRUCTURE USING ALMA OBSERVATIONS OF THE DUSTY GALAXY SDP.81

Yashar D. Hezaveh, Neal Dalal, Daniel P. Marrone, Yao-Yuan Mao, Warren Morningstar, Di Wen, Roger D. Blandford, John E. Carlstrom, Christopher D. Fassnacht, Gilbert P. Holder

[▼ Show full author list](#)

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[The Astrophysical Journal](#), [Volume 823](#), [Number 1](#)

SDP.81

But see Stacey+ (2508.02776)

Galaxy Mass Modelling from Multi-Wavelength JWST Strong Lens Analysis: Dark Matter Substructure, Angular Mass Complexity, or Both?

Samuel C. Lange¹ , Aristeidis Amvrosiadis¹, James W. Nightingale^{3,1,2}, Qiuhan He¹, Carlos S. Frenk¹, Andrew Robertson⁴, Shaun Cole¹, Richard Massey^{1,2}, Xiaoyue Cao^{5,6}, Ran Li^{5,6}, Kaihao Wang^{5,6}

SPT2147-50

All consistent with the core-collapse SIDM scenario; Kong, Nadler, Yu (2025); Yu (PRL 2026)

Stellar Streams of the Milky Way

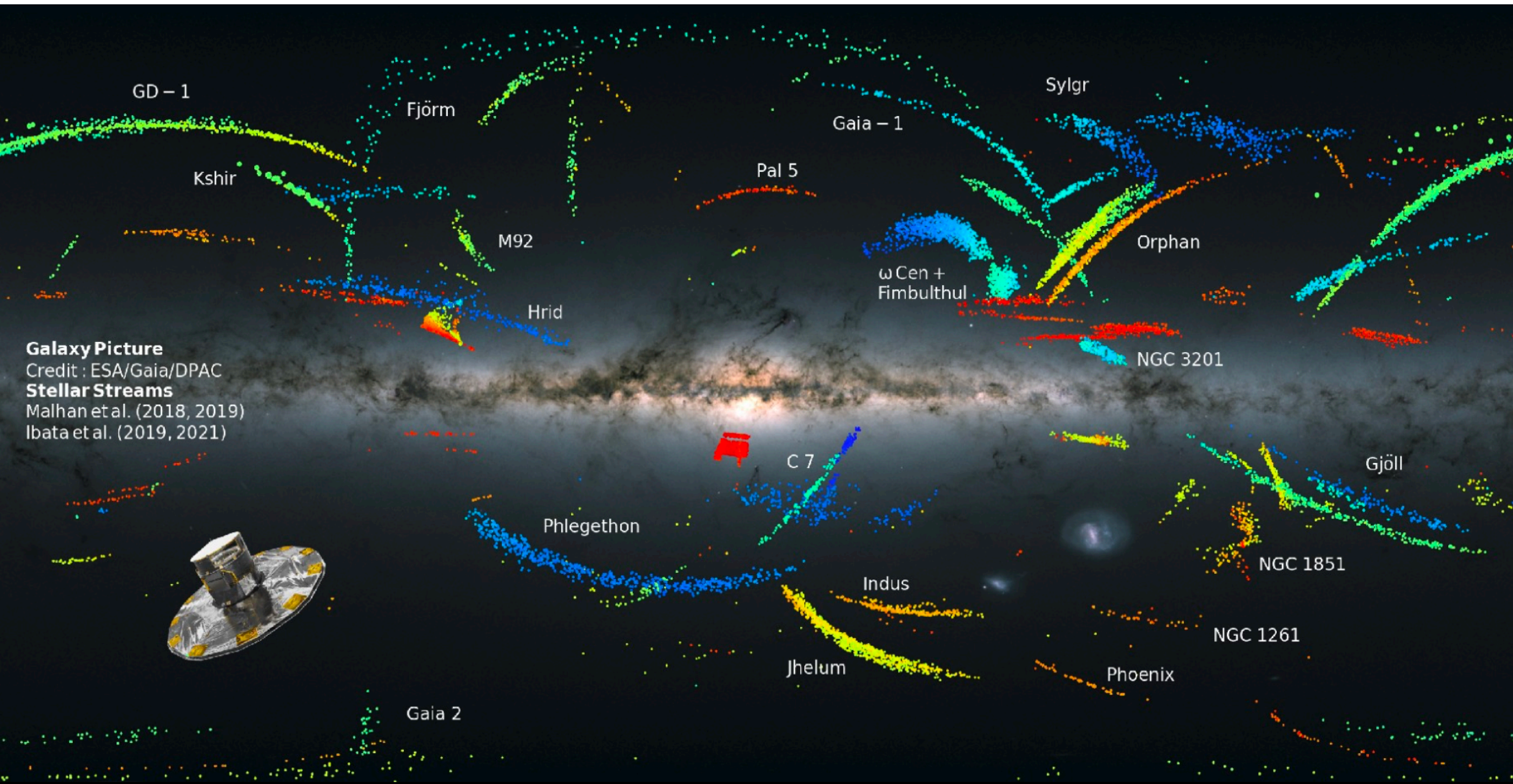
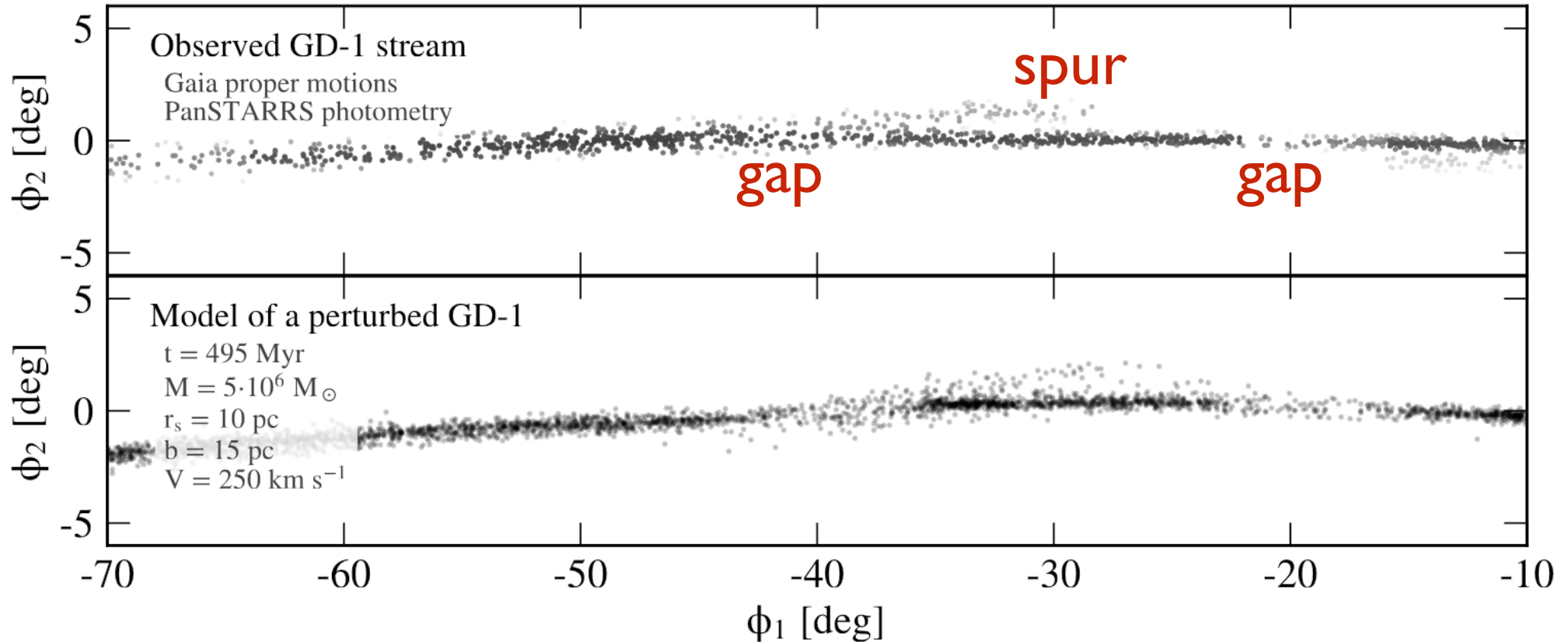


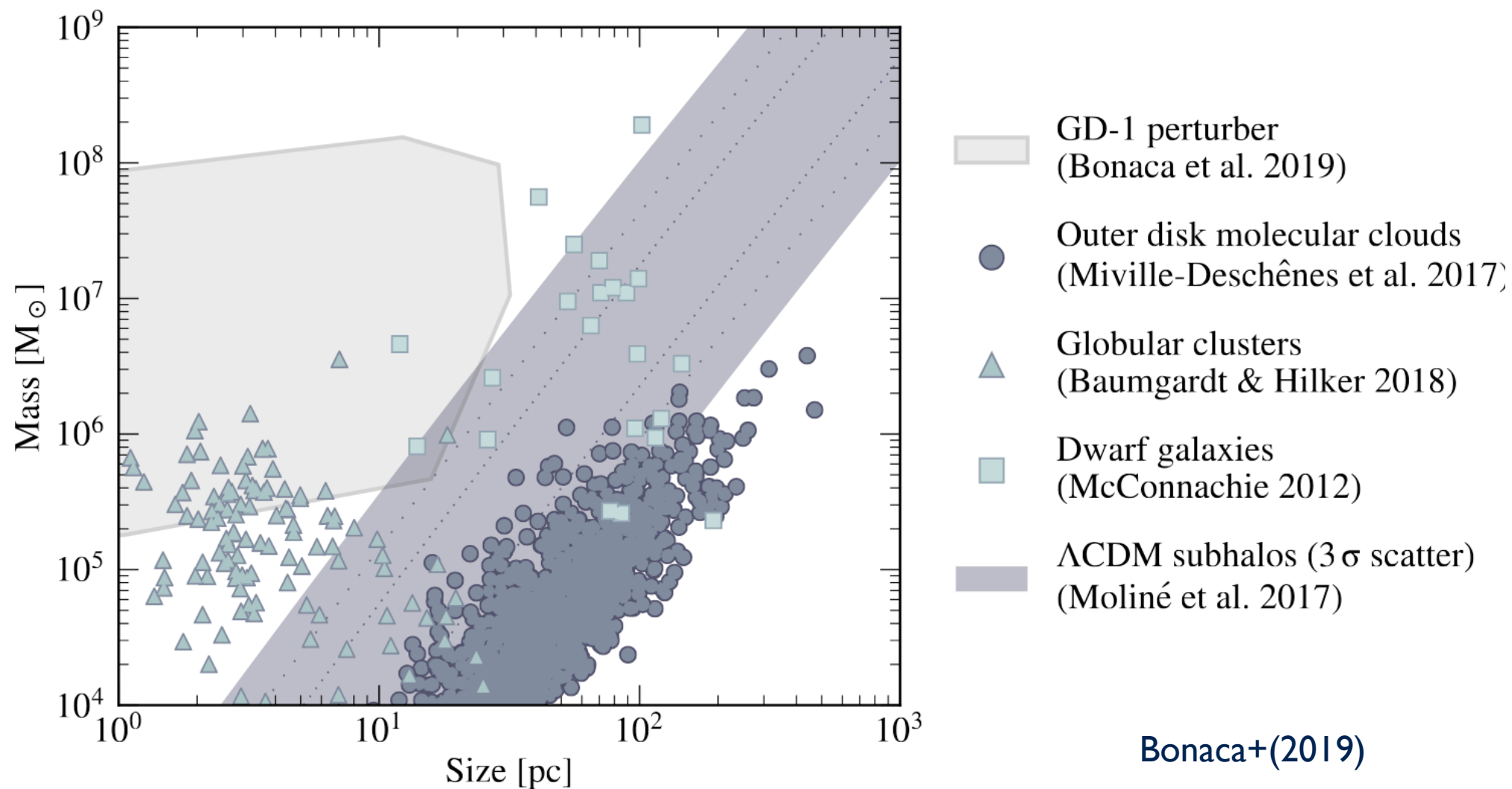
Figure: Khyati Malhan

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

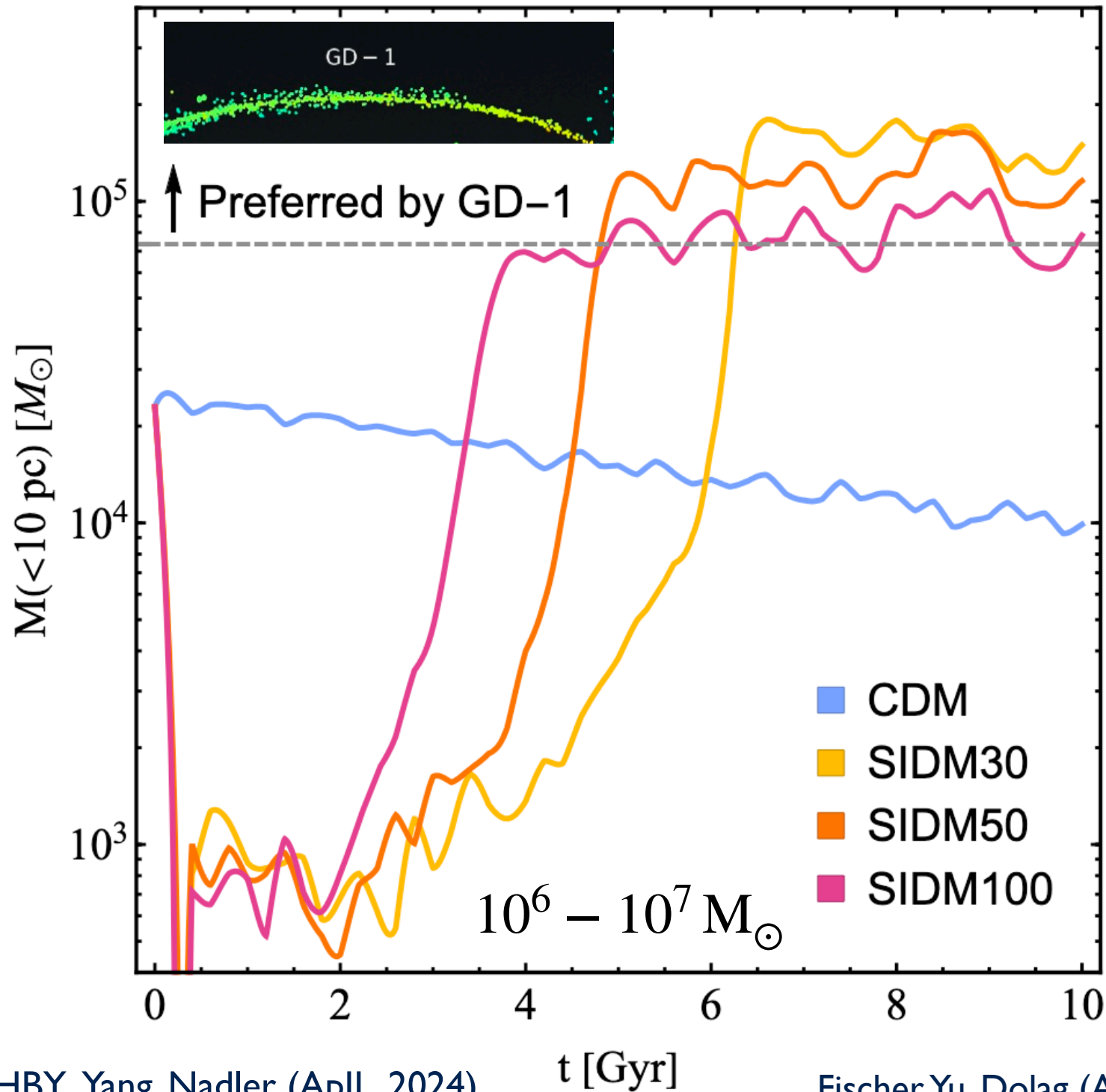
ANA BONACA,¹ DAVID W. HOGG,^{2, 3, 4, 5} ADRIAN M. PRICE-WHELAN,⁶ AND CHARLIE CONROY¹



The spur- and gap-like features can be produced if the GD-1 stellar stream had a recent encounter with a dense object/perturber gravitationally



- The Milky Way satellite galaxies and globular clusters do not match the orbit
- CDM subhalos are not dense enough ($\sim 3\sigma$)



Xingyu Zhang
(UCR)



Moritz Fischer
(DIPC)

A million-solar-mass object detected at a cosmological distance using gravitational imaging

JVAS B1938+666-V

[D. M. Powell](#) , [J. P. McKean](#), [S. Vegetti](#) , [C. Spingola](#), [S. D. M. White](#) & [C. D. Fassnacht](#)

[Nature Astronomy](#) **9**, 1714–1722 (2025) | [Cite this article](#)

A dense strong-lensing perturber detected with radio observations

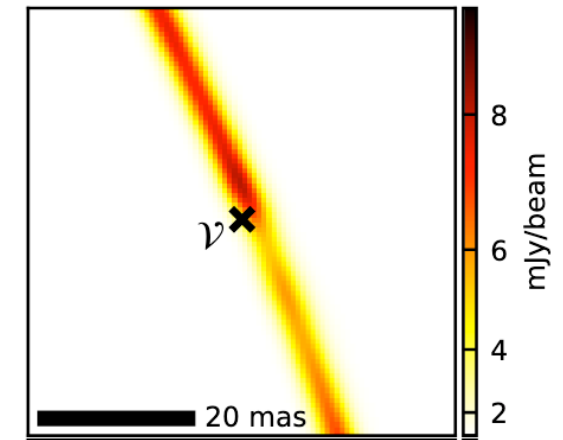
MNRAS **533**, 3263–3282 (2024)

Advance Access publication 2024 August 13

Capture of field stars by dark substructures

Jorge Peñarrubia,^{1,2}  Raphaël Errani,^{3,4} Matthew G. Walker ,³ Mark Gieles ,^{5,6} and Tjarda C. N. Boekholt ,^{7,8}

Observational hint: there is a dense substructure in the Fornax satellite galaxy of the Milky Way

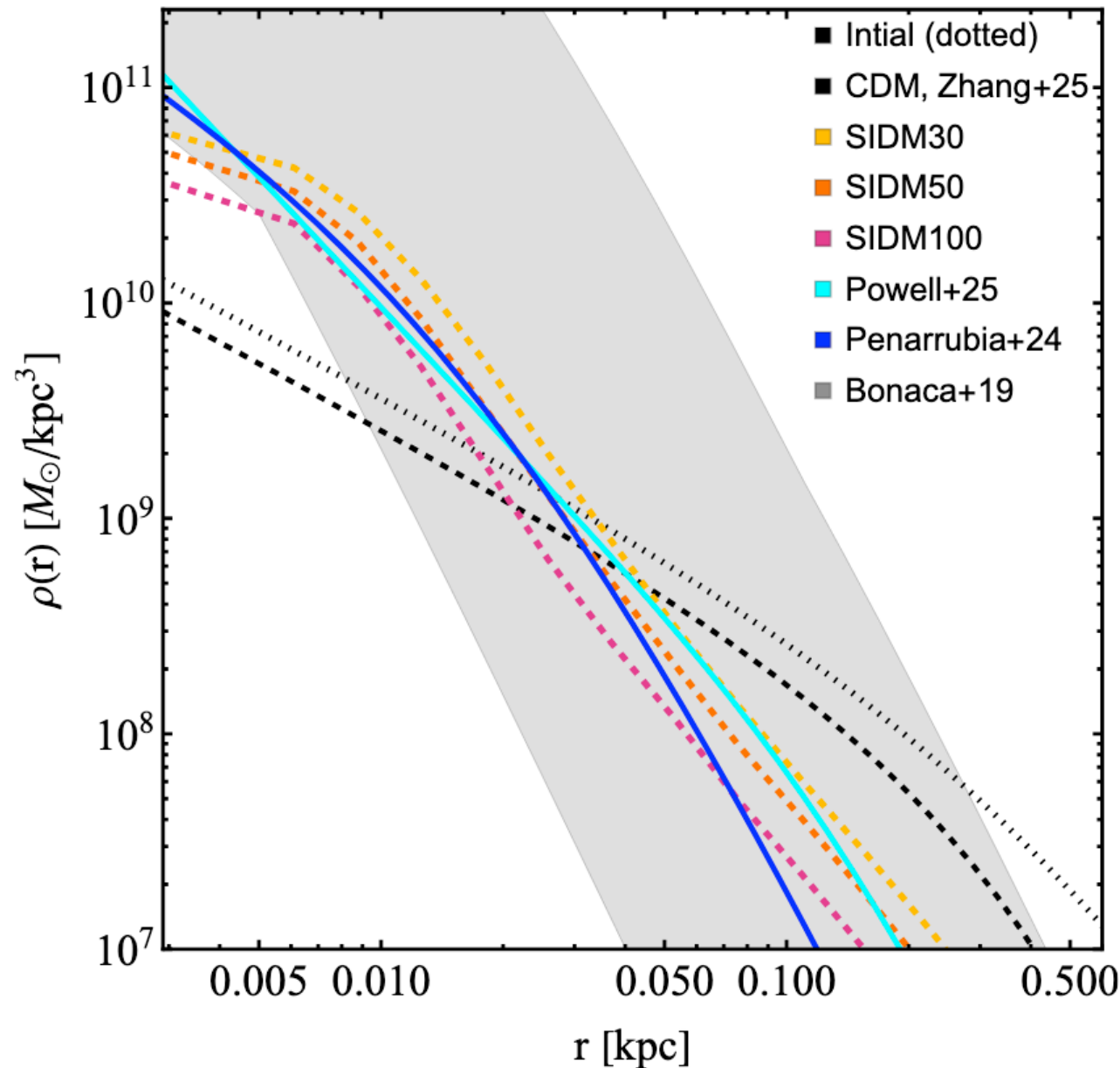


$10^6 - 10^7 M_{\odot}$

Three Birds with One Stone: Core-Collapsed SIDM Halos as the Common Origin of Dense Perturbers in Lenses, Streams, and Satellites

2510.11006

HAI-BO YU¹

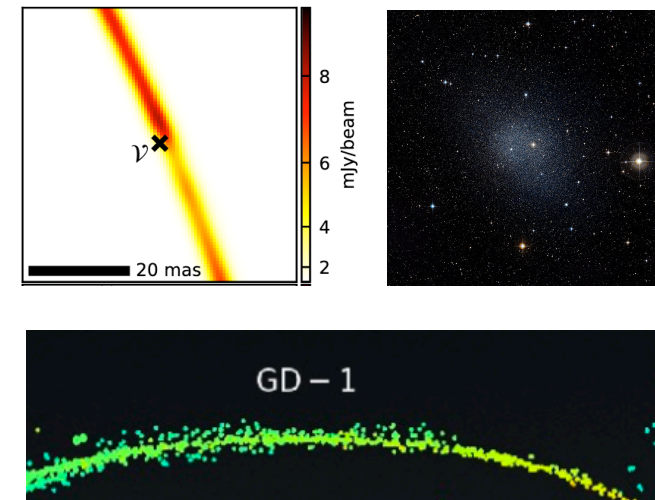


Different cosmic environments and epochs

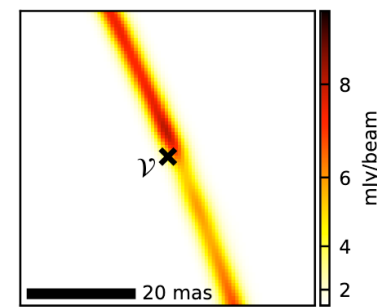
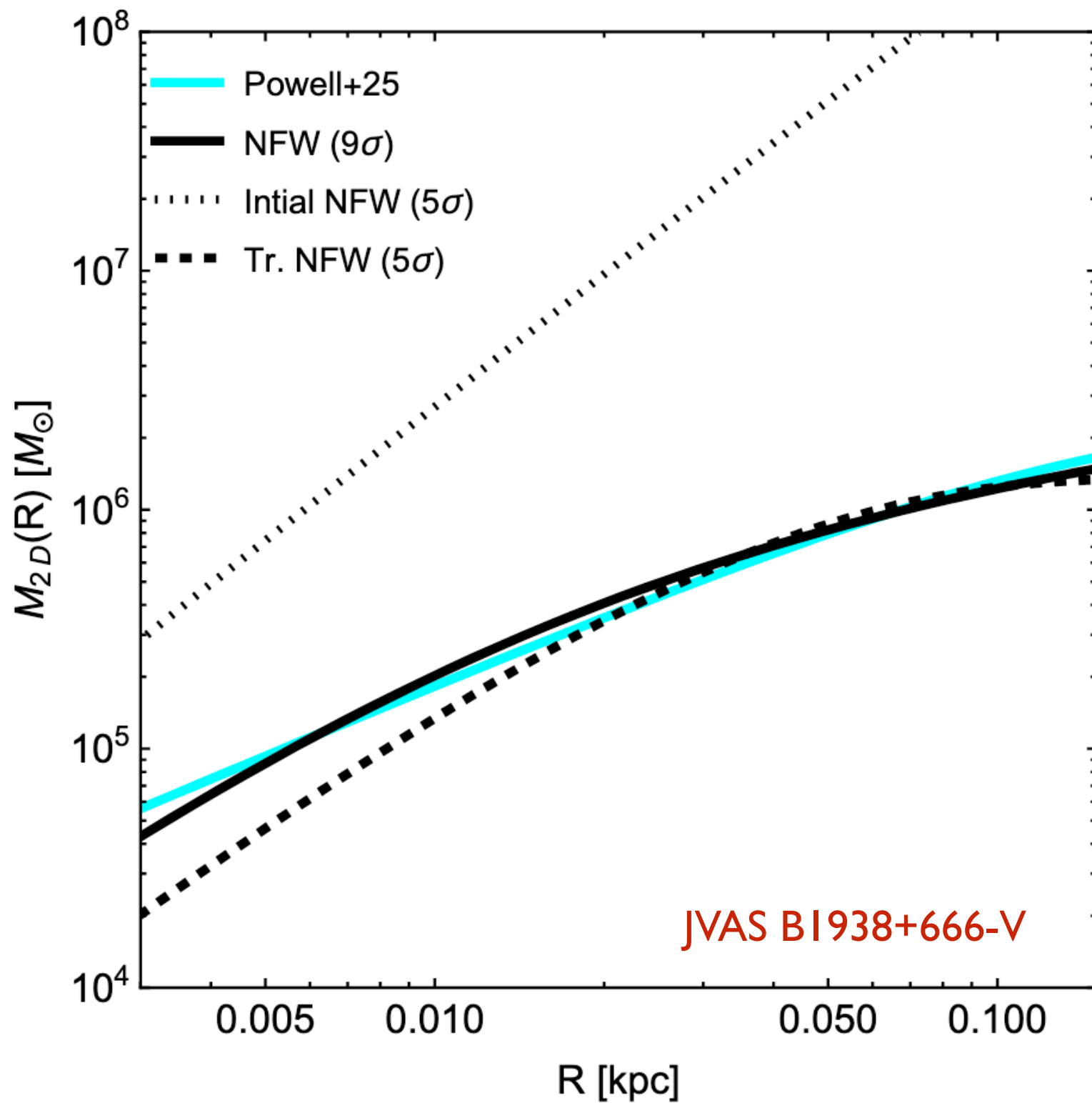
Strong lensing system

Fornax satellite

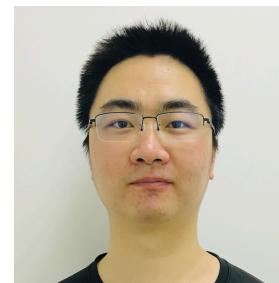
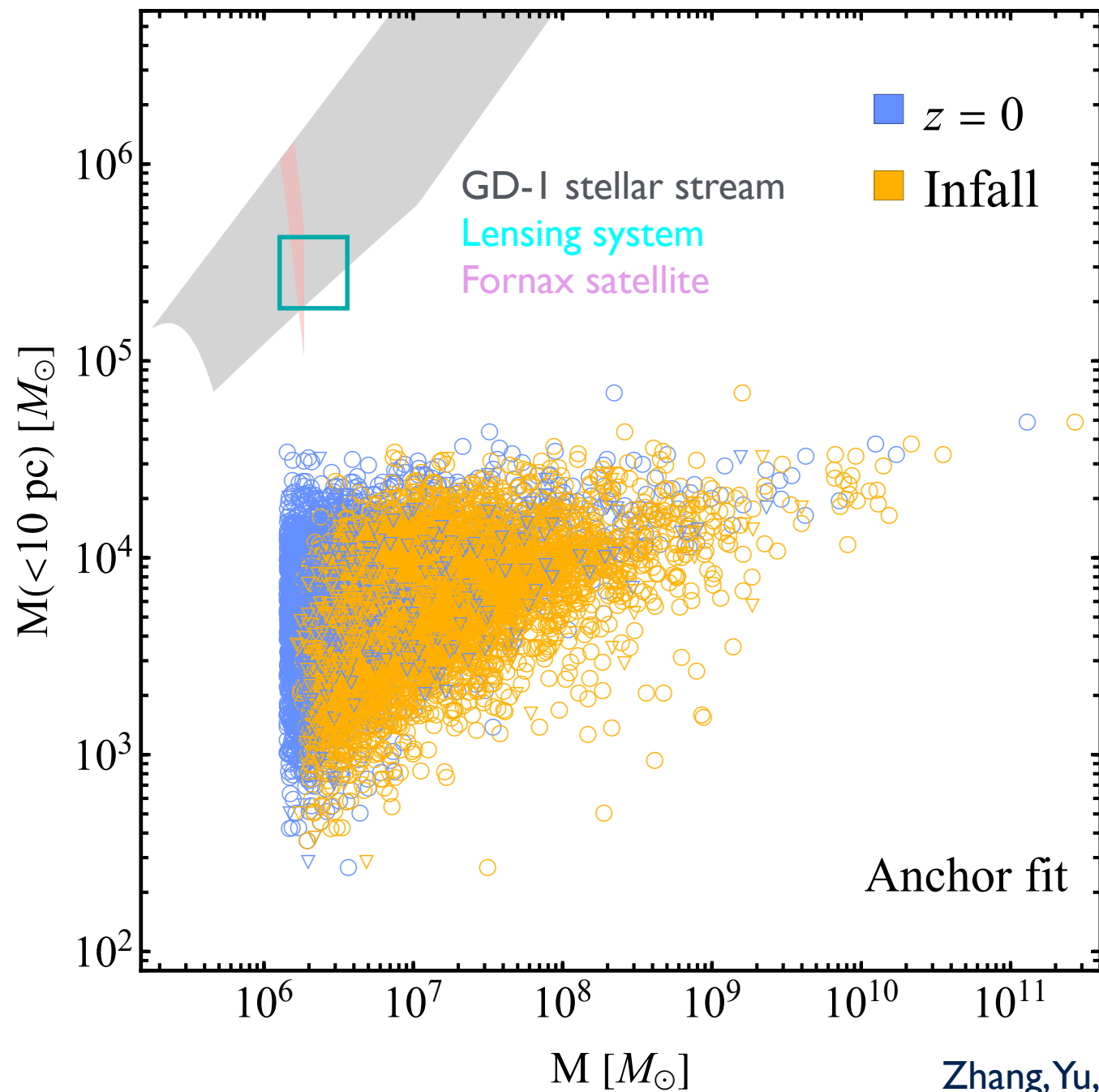
GD-I stellar stream



Yu (PRL 2026)



Yu (PRL 2026)



Xingyu Zhang
(UCR)

Zhang, Yu, Kong, Nadler (in prep)

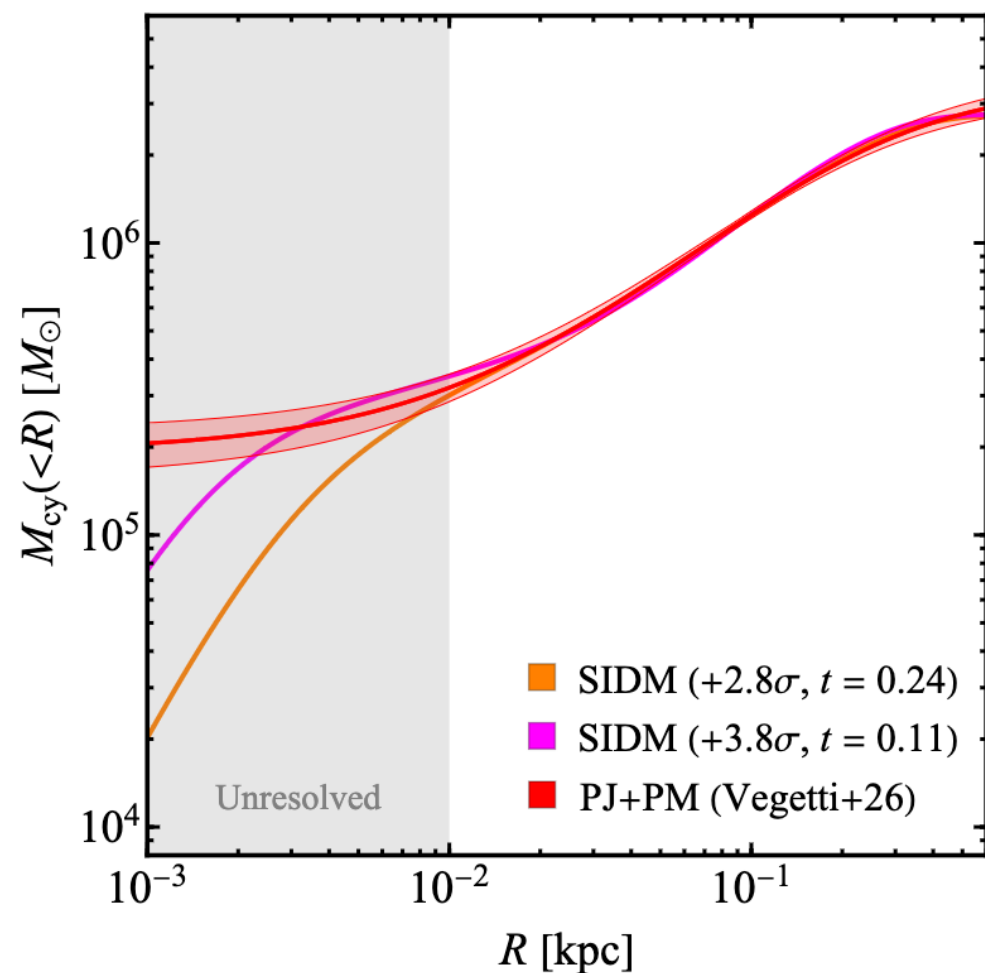
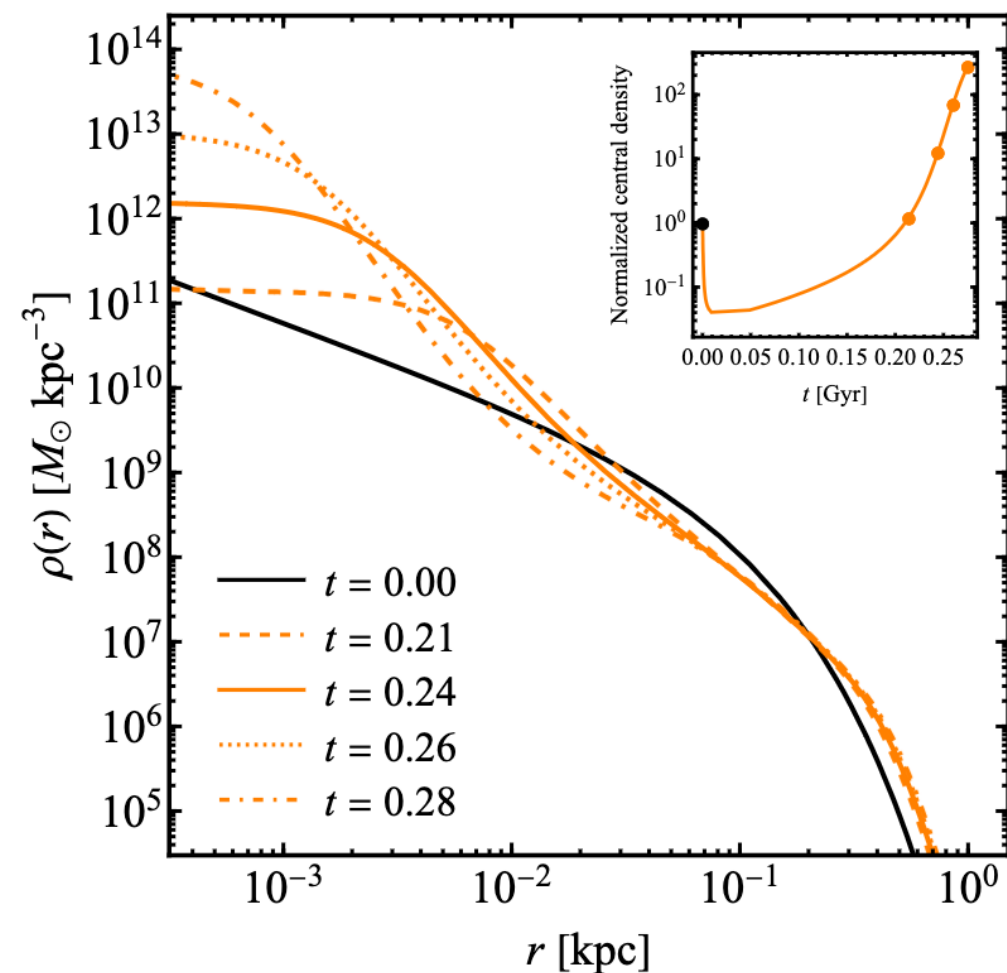
CDM subhalos are not dense enough!

A possible challenge for cold and warm dark matter

[Simona Vegetti](#) , [Simon D. M. White](#), [John P. McKean](#), [Devon M. Powell](#), [Cristiana Spingola](#), [Davide Massari](#), [Giulia Despali](#) & [Christopher D. Fassnacht](#)

JVAS B1938+666-V

The perturber: an unresolved point-mass within 10 pc+an extended distribution



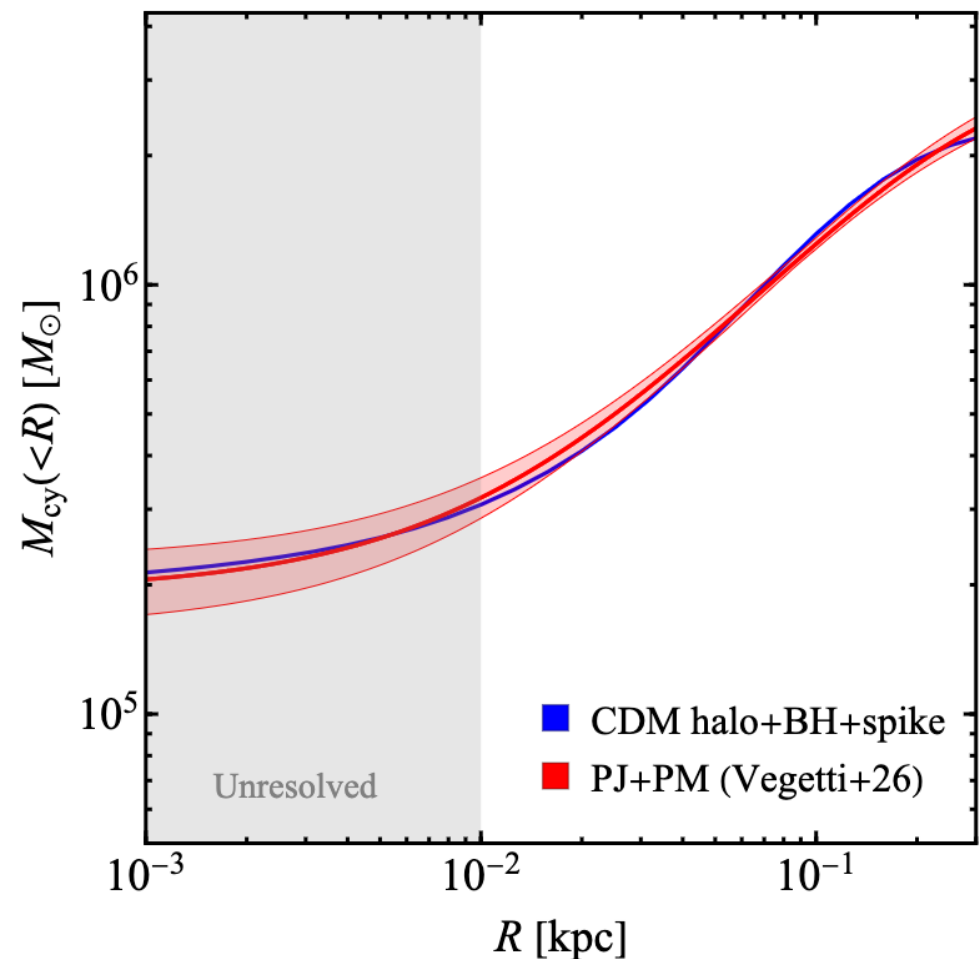
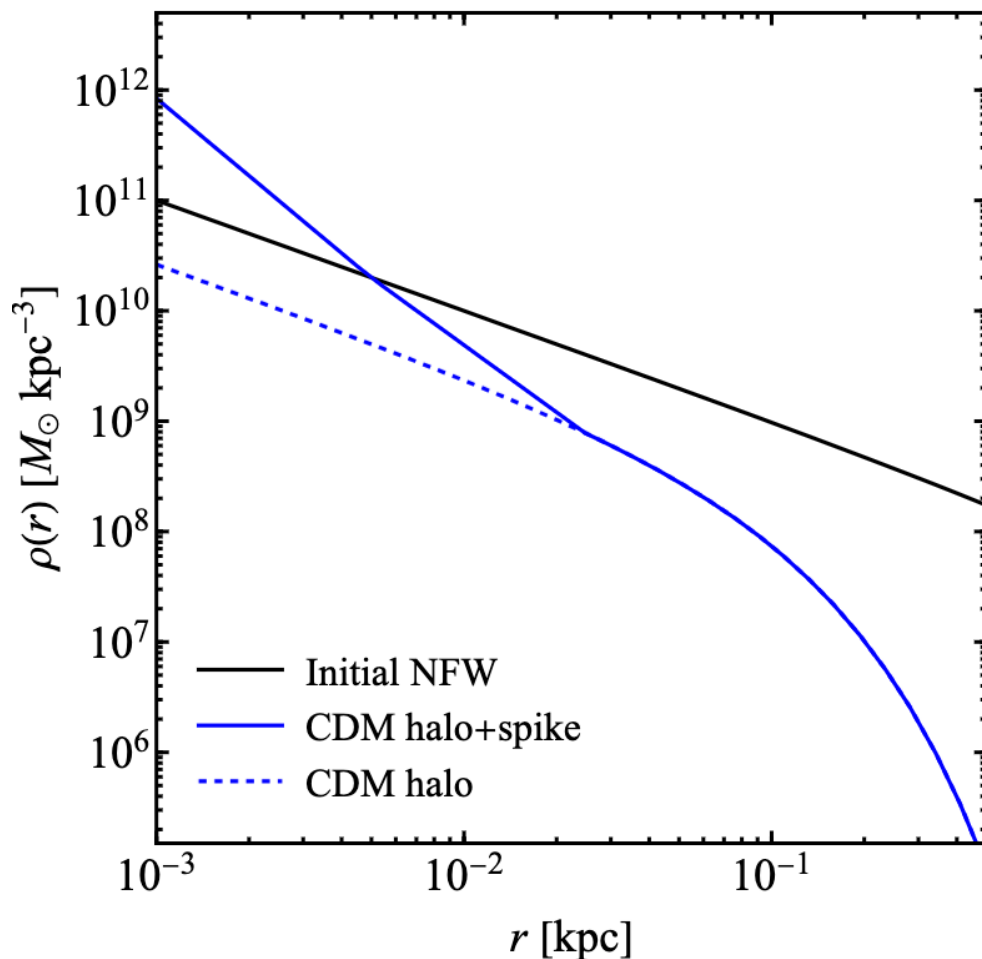
Mass within the SMFP region: $3 \times 10^5 M_\odot$

Zhang, Yu (2026)

A possible challenge for cold and warm dark matter

[Simona Vegetti](#) , [Simon D. M. White](#), [John P. McKean](#), [Devon M. Powell](#), [Cristiana Spingola](#), [Davide Massari](#), [Giulia Despali](#) & [Christopher D. Fassnacht](#)

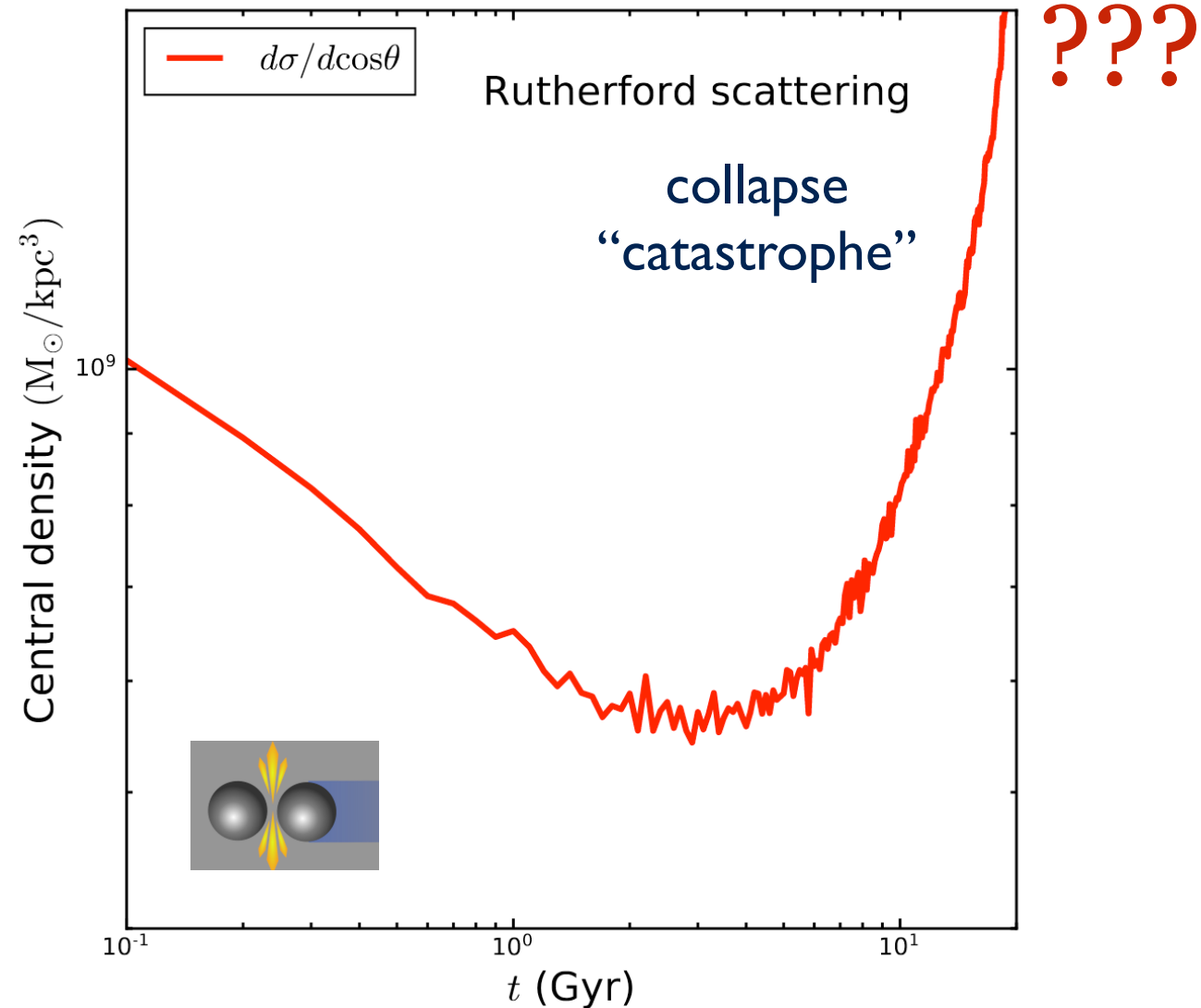
The perturber: an unresolved point-mass within 10 pc+an extended distribution



Challenge: the progenitor loses five orders of magnitude in mass

Zhang, Yu (2026)

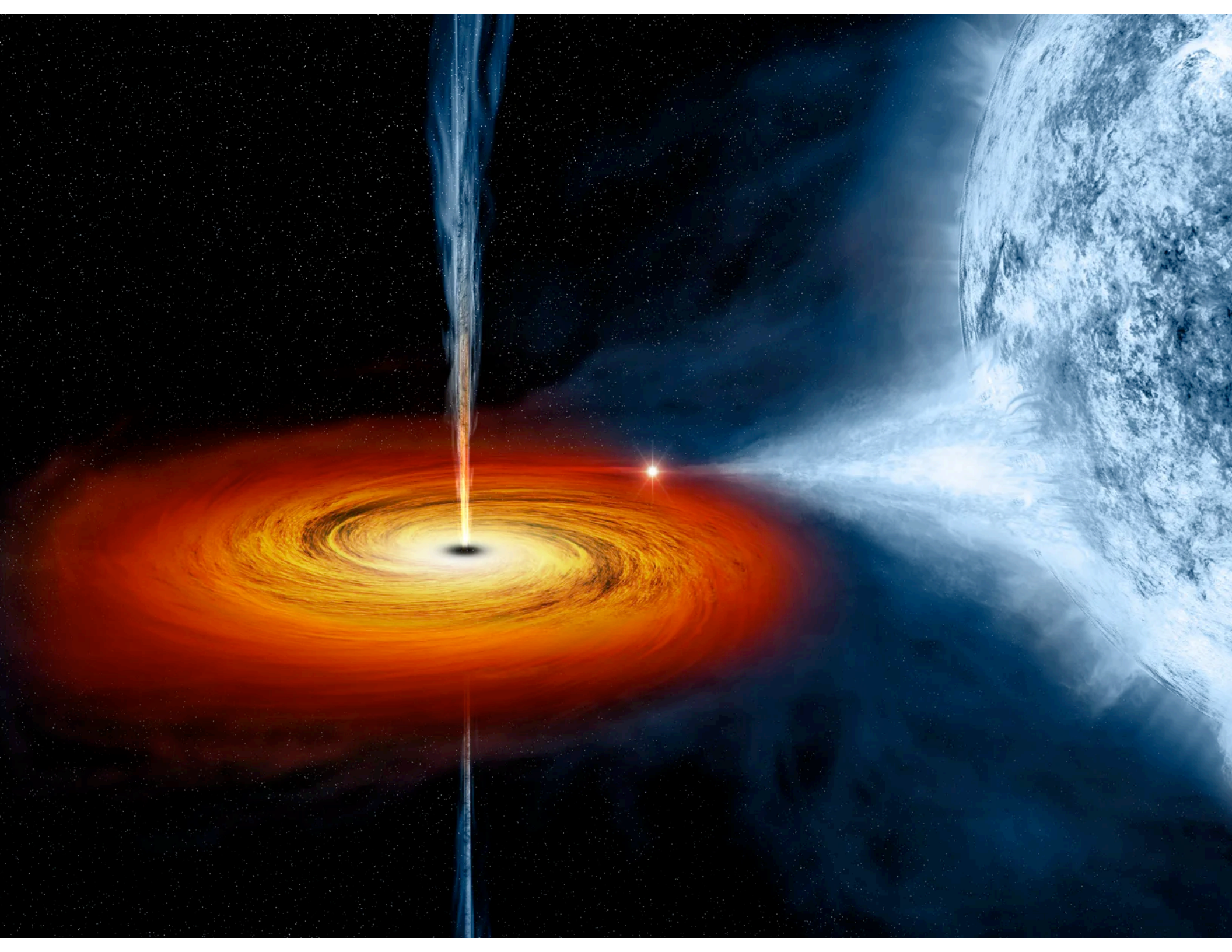
Gravothermal Evolution

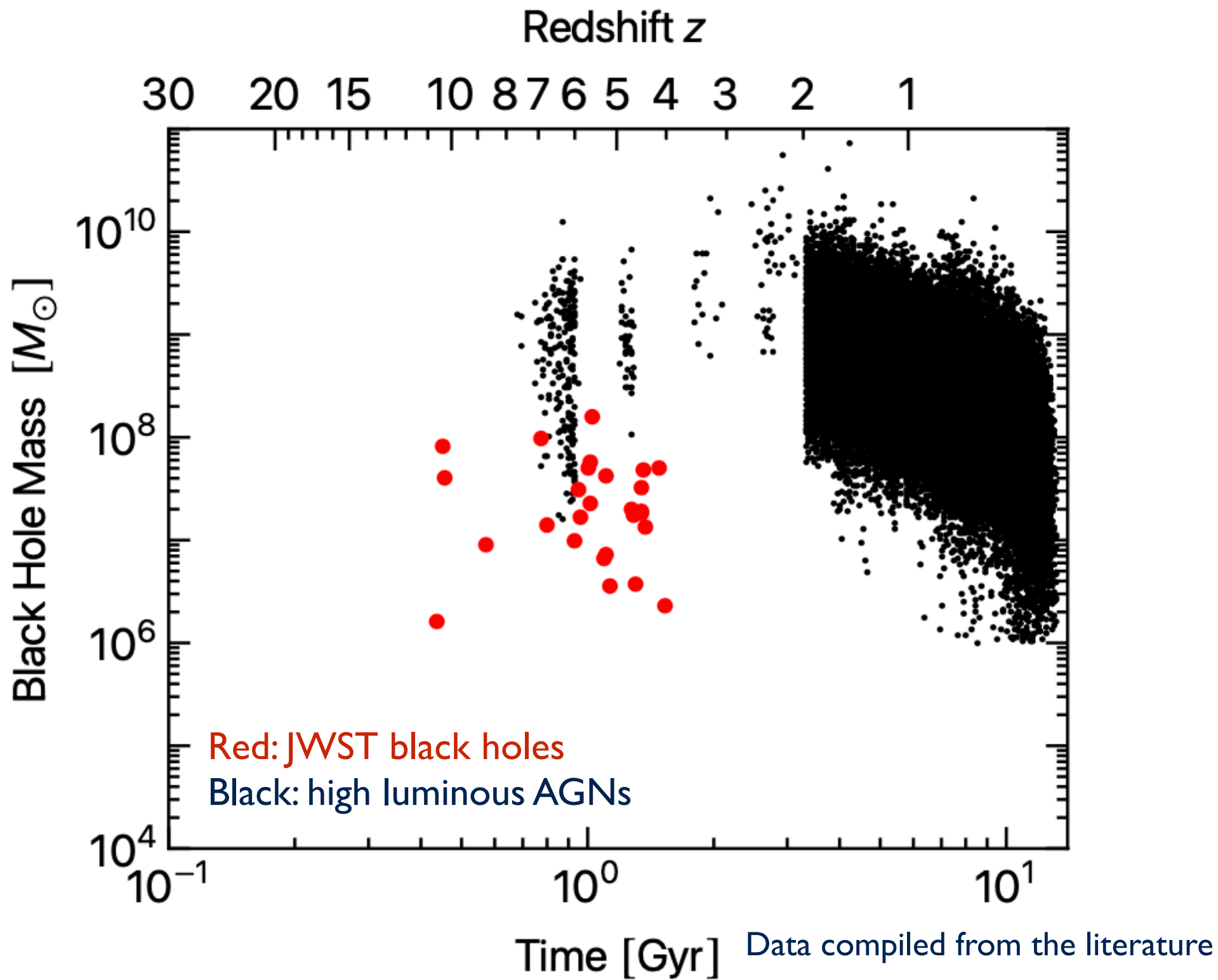


$$2K.E. + P.E. = 0$$

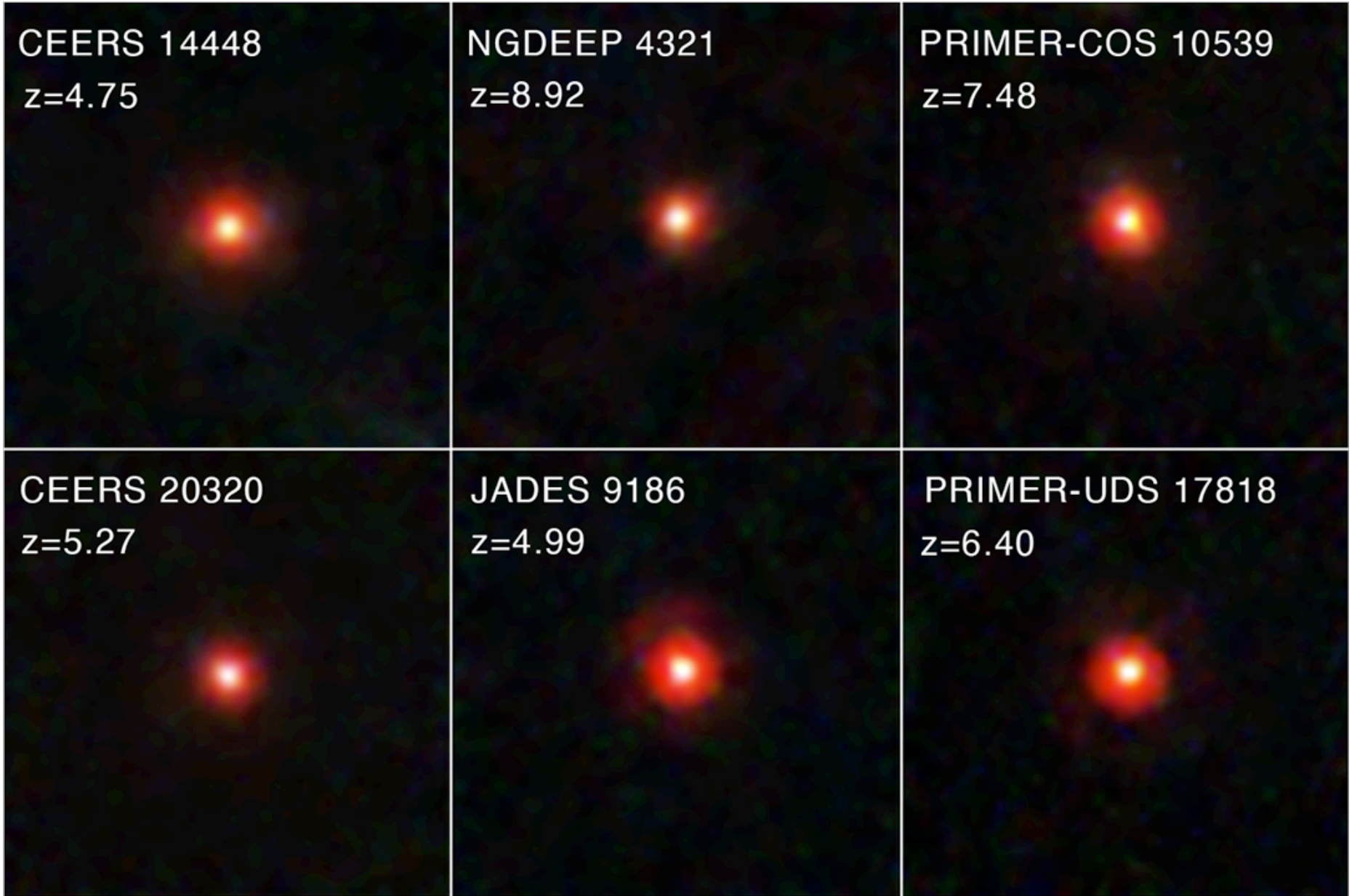
$$E_{\text{tot}} = -K.E. \quad \frac{E_{\text{tot}}}{T} < 0$$

Negative heat capacity!
 $\Rightarrow$ gravothermal collapse





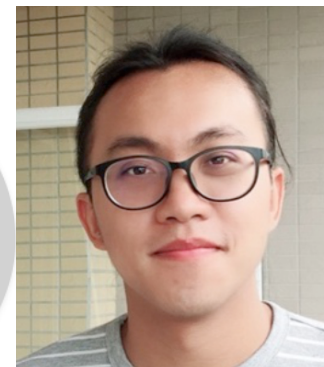
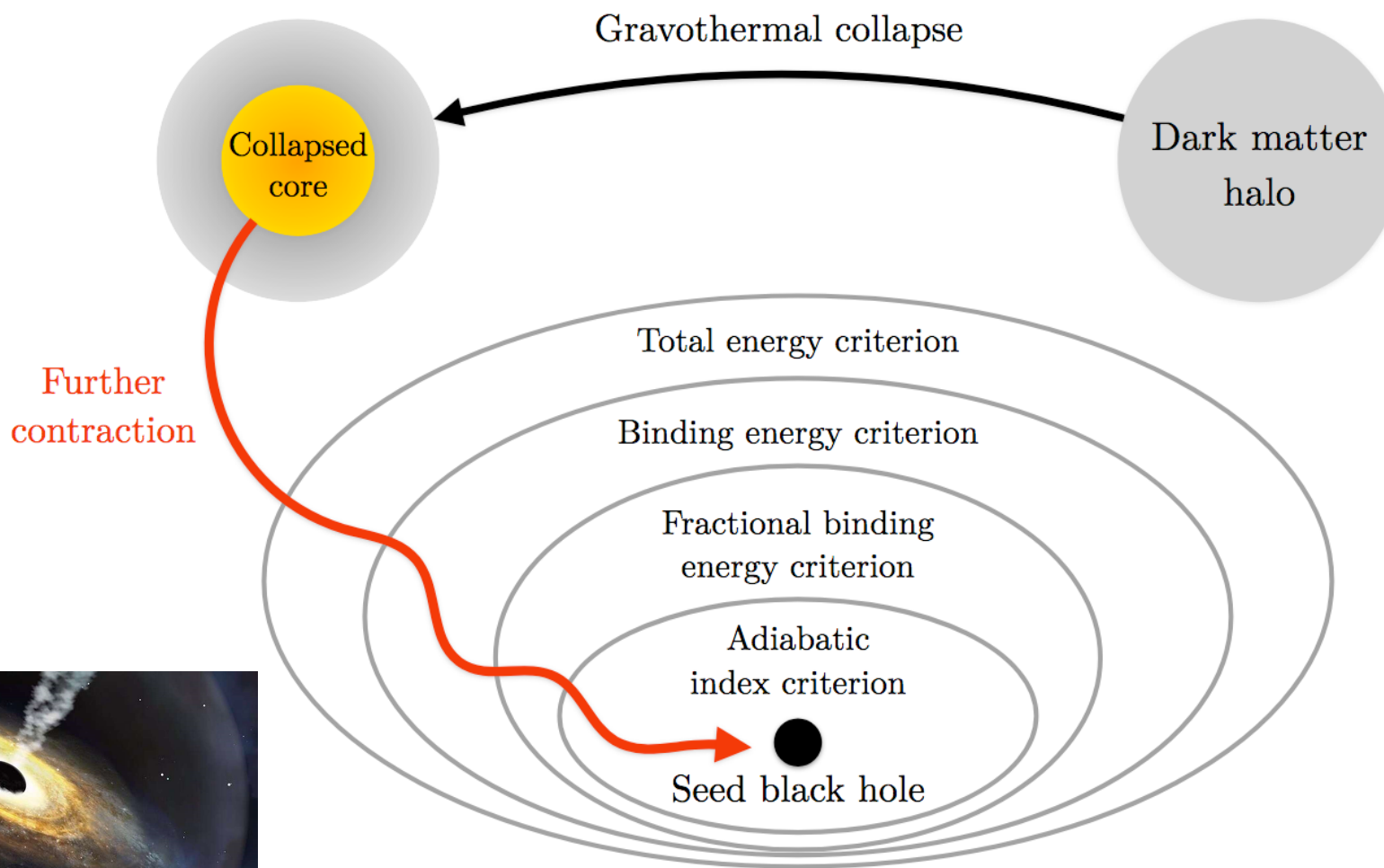
The JWST Little Red Dots



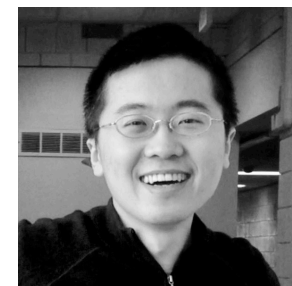
341 LRD galaxies have been identified

NASA, ESA, CSA, STScI, Dale Kocevski

Seeding Supermassive Black Holes



Wei-Xiang Feng
(Tsinghua)



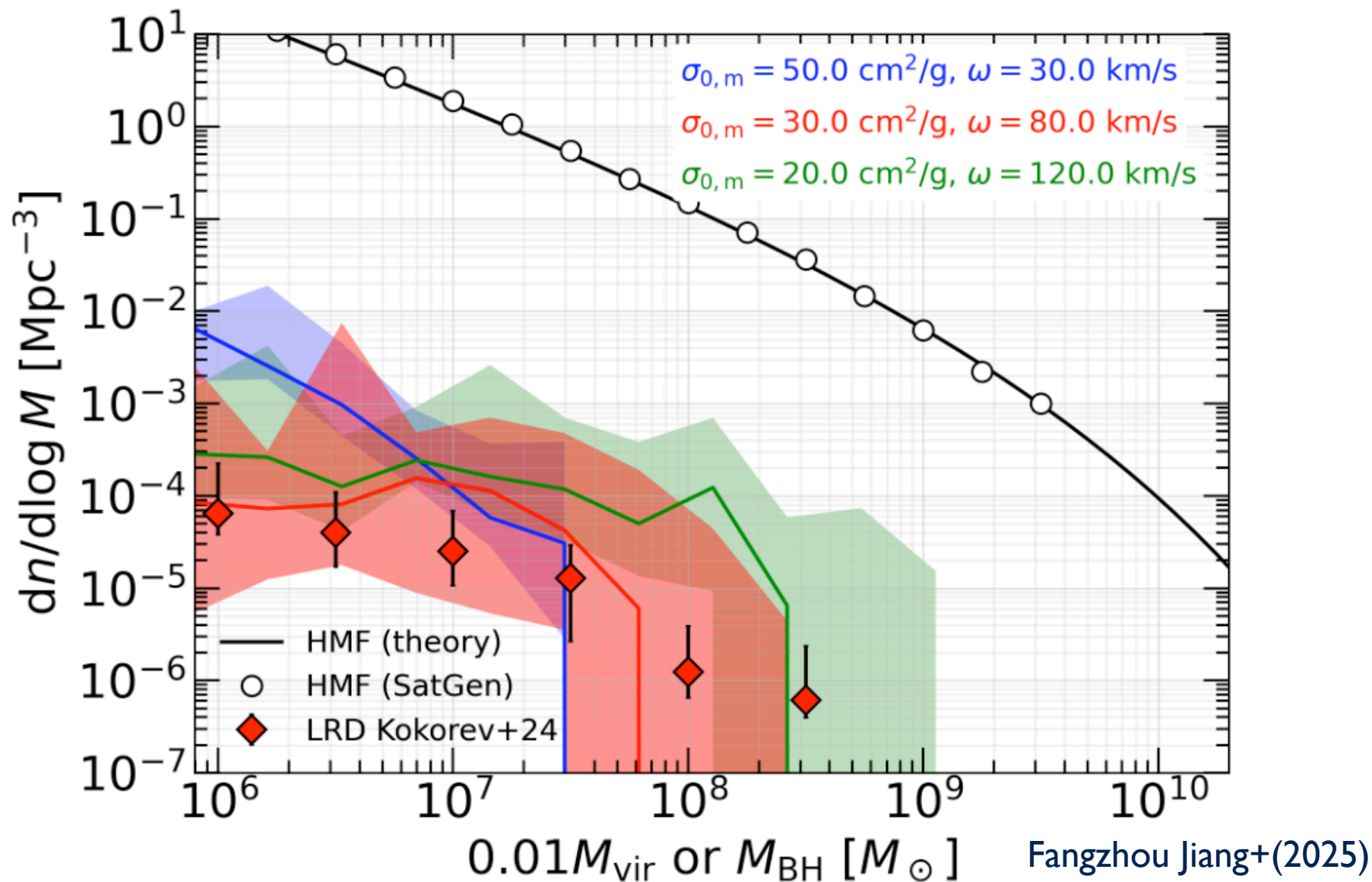
Yi-Ming Zhong
(CityU, HK)



Balberg, Shapiro (PRL 2002)
Pollack, Spergel, Steinhardt (ApJ 2015)

Feng, HBY, Zhong (ApJL 2021, JCAP 2022, 2025)

JWST Little Red Dots



$\sim 10^9 M_{\odot}$ halos on the high-concentration tail at $z \sim 10-15$

Jiang+(2025); Feng, HBY, Zhong (2025); Roberts+(2025); Gu+(2026)

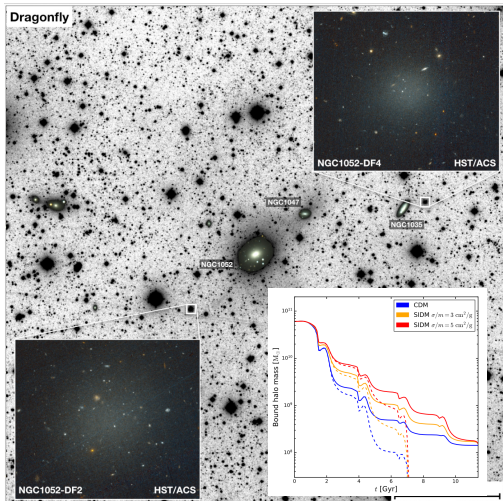
SIDM From Dwarf to Cluster Scales

Ultra-diffuse galaxies
(dark-matter-deficient)

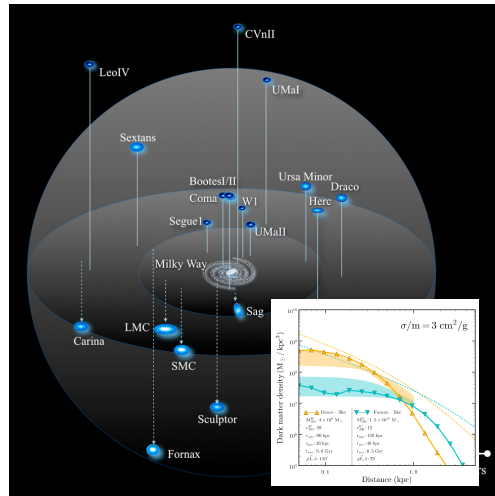
Milky Way satellites

Spiral galaxies

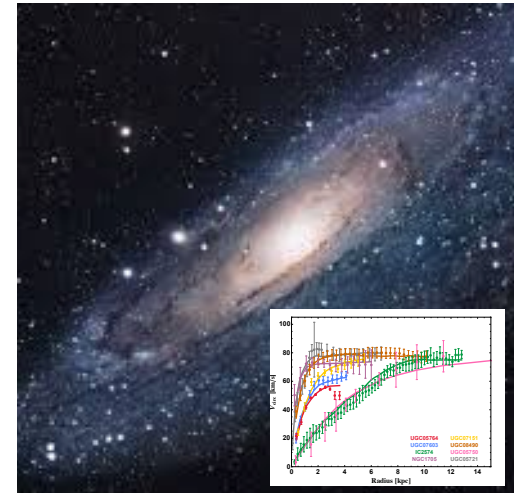
Galaxy clusters



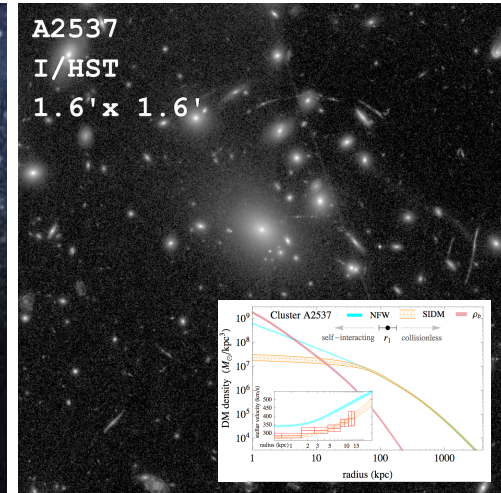
$$M_{\text{halo}} < \sim 10^8 M_{\odot}$$



$$M_{\text{halo}} \sim 10^8 M_{\odot}$$

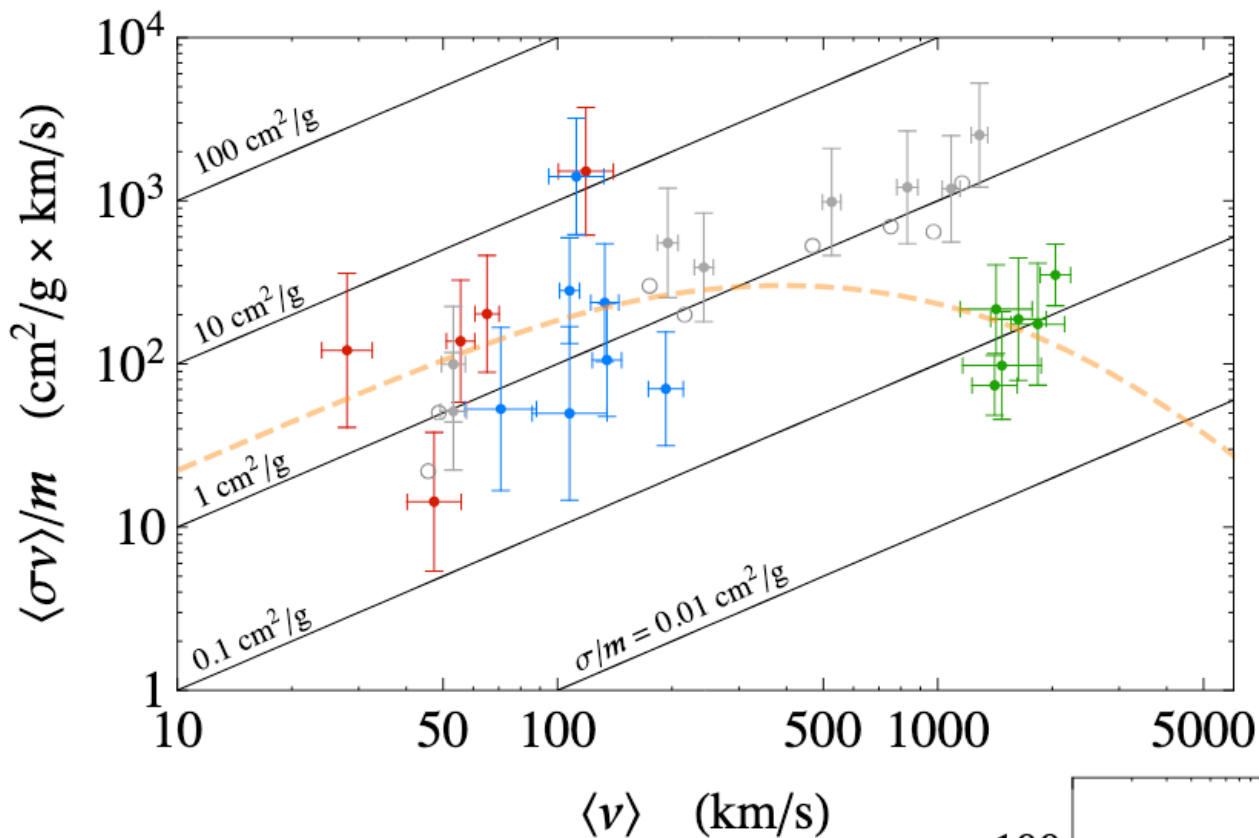


$$M_{\text{halo}} \sim 10^9 - 10^{13} M_{\odot}$$



$$M_{\text{halo}} \sim 10^{15} M_{\odot}$$

- SIDM can explain **diverse** dark matter distributions over a wide range of galactic systems (halo masses $\sim 10^6 - 10^{15} M_{\odot}$)
- Gravo-thermal collapse: Some halos are denser than expected in CDM
- **Bonus**: seeding SMBHs
- Fundamental scales $\sim 10^{-12} \text{ cm}$ vs galactic scales $\sim 10^{22} \text{ cm}$
- Measuring particle properties of dark matter **without** detecting it directly



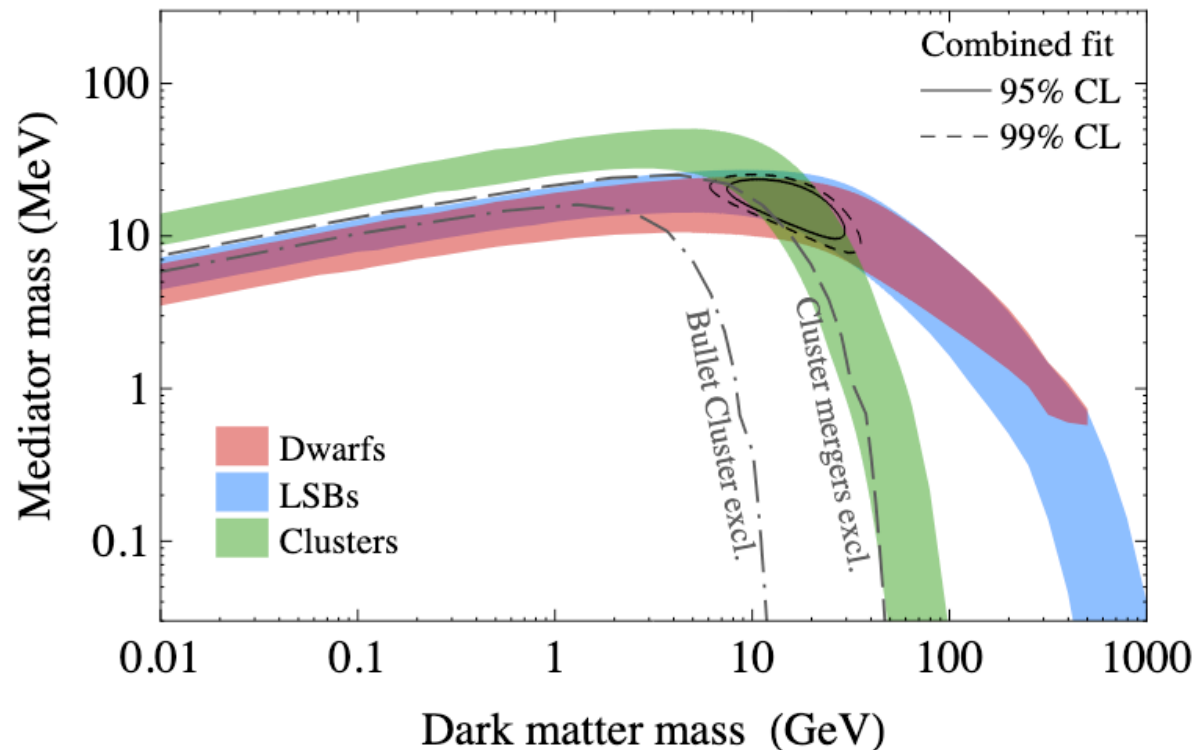
$$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

$$\alpha_\chi, m_\chi, m_\phi$$

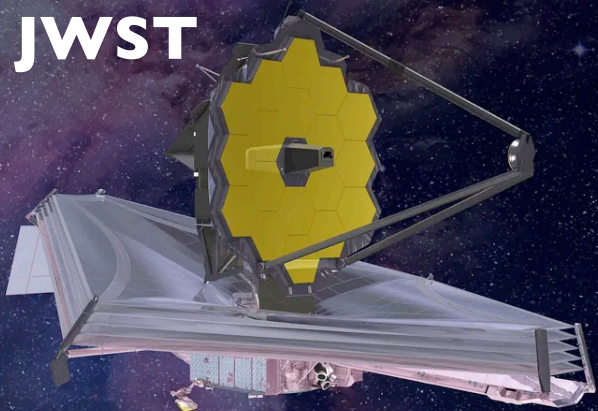
$$\alpha_\chi = \alpha_{\text{EM}} = 1/137$$

- Positive cross-section measurements on two different halo-mass scales
- Determine the dark matter particle mass and the mediator mass!

Kaplinghat, Tulin, Yu (PRL 2016)



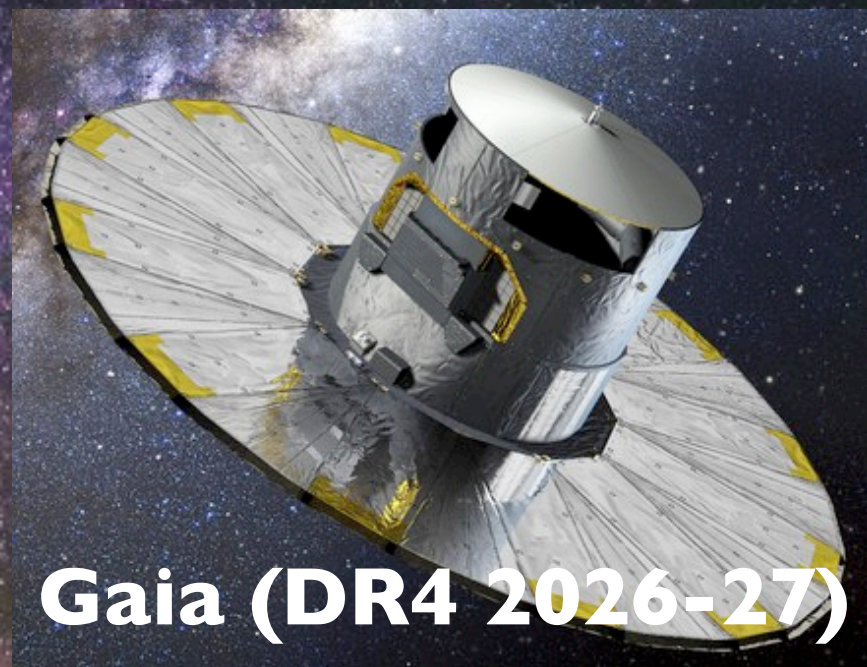
JWST



Euclid



Gaia (DR4 2026-27)



Rubin/LSST (2026)



VIA (2027)



THANK YOU!

