

Why Dark Matter May Have Self-Interactions

Hai-Bo Yu

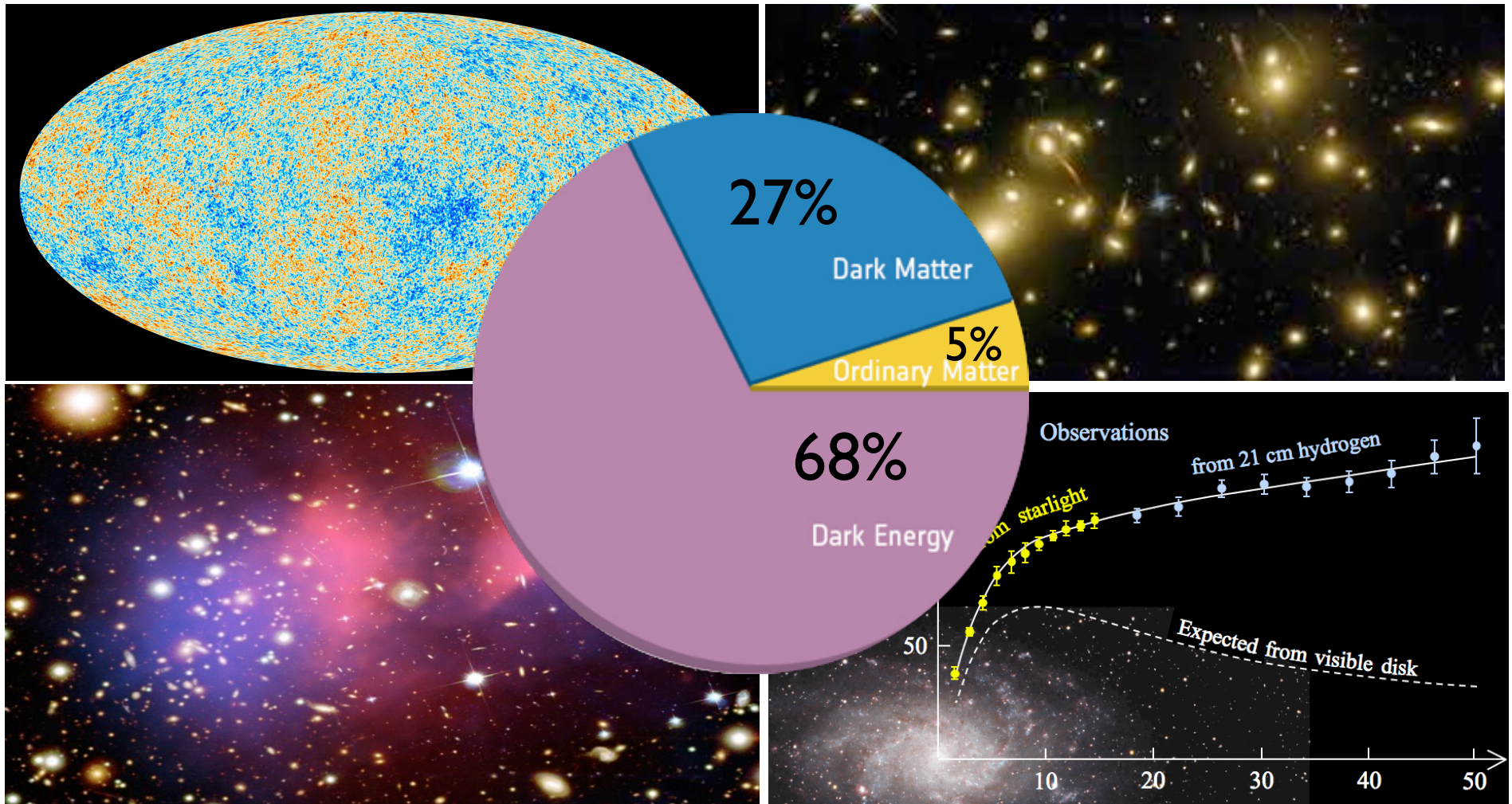
University of California, Riverside



2nd New Horizons for PSI Workshop
August 27, 2026, Beijing

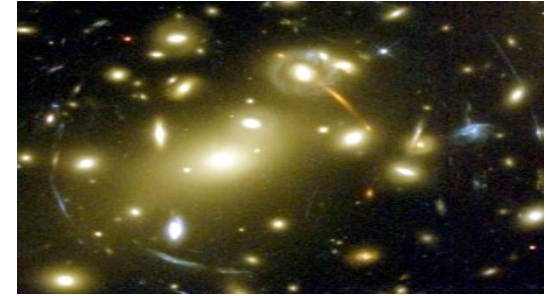
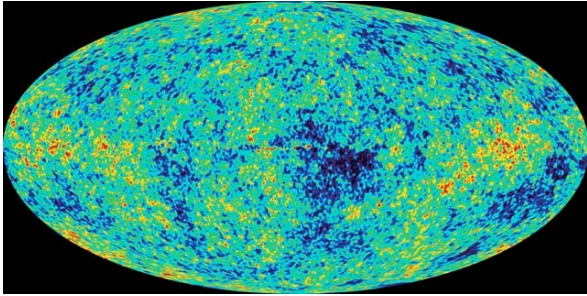


Dark Matter



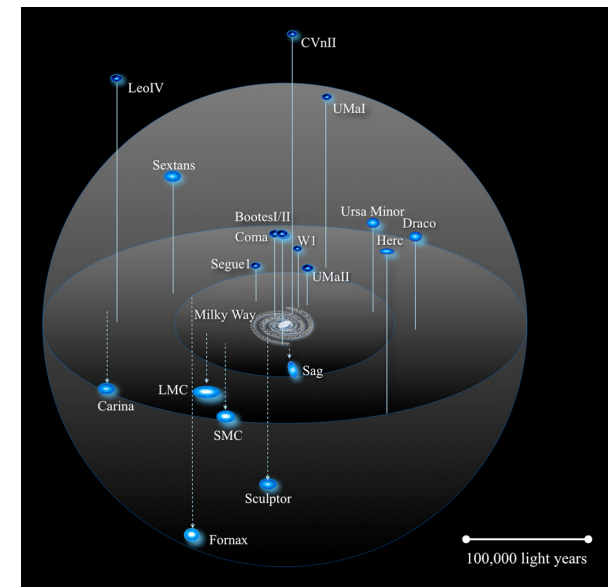
Cold Dark Matter (CDM)

- Large scales: very well

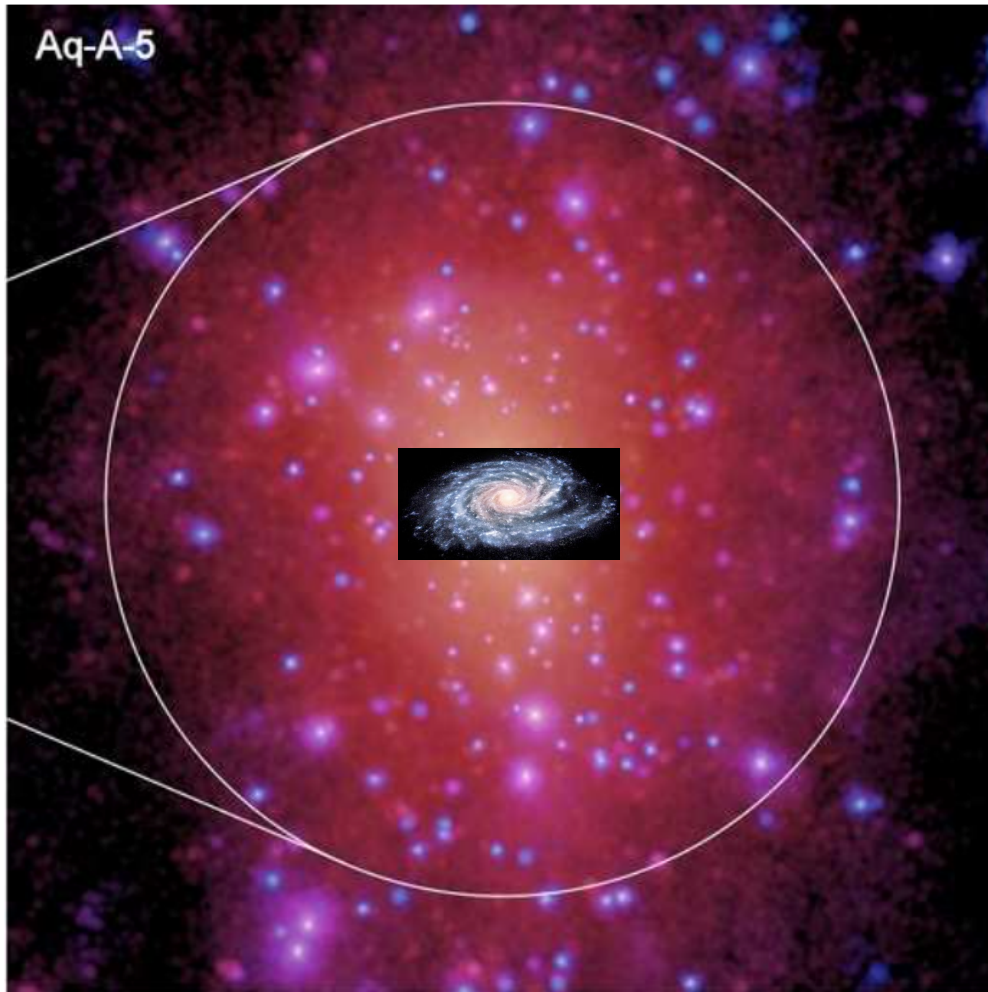


- Small scales (field/satellite dwarf galaxies, substructures)

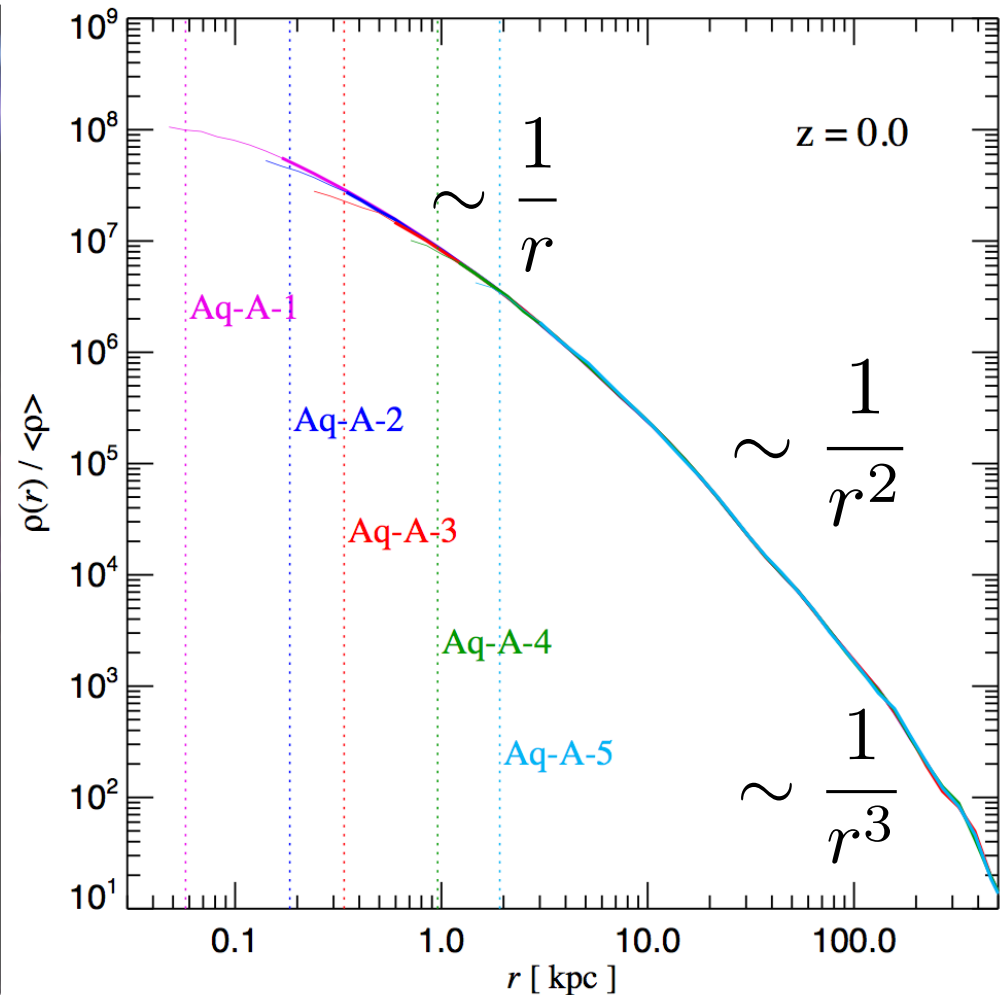
- Core vs Cusp
- Diversity
- Too Big To Fail
- Dense substructures
- Ultra-diffuse galaxies
- ...



CDM: Universal Density Profile

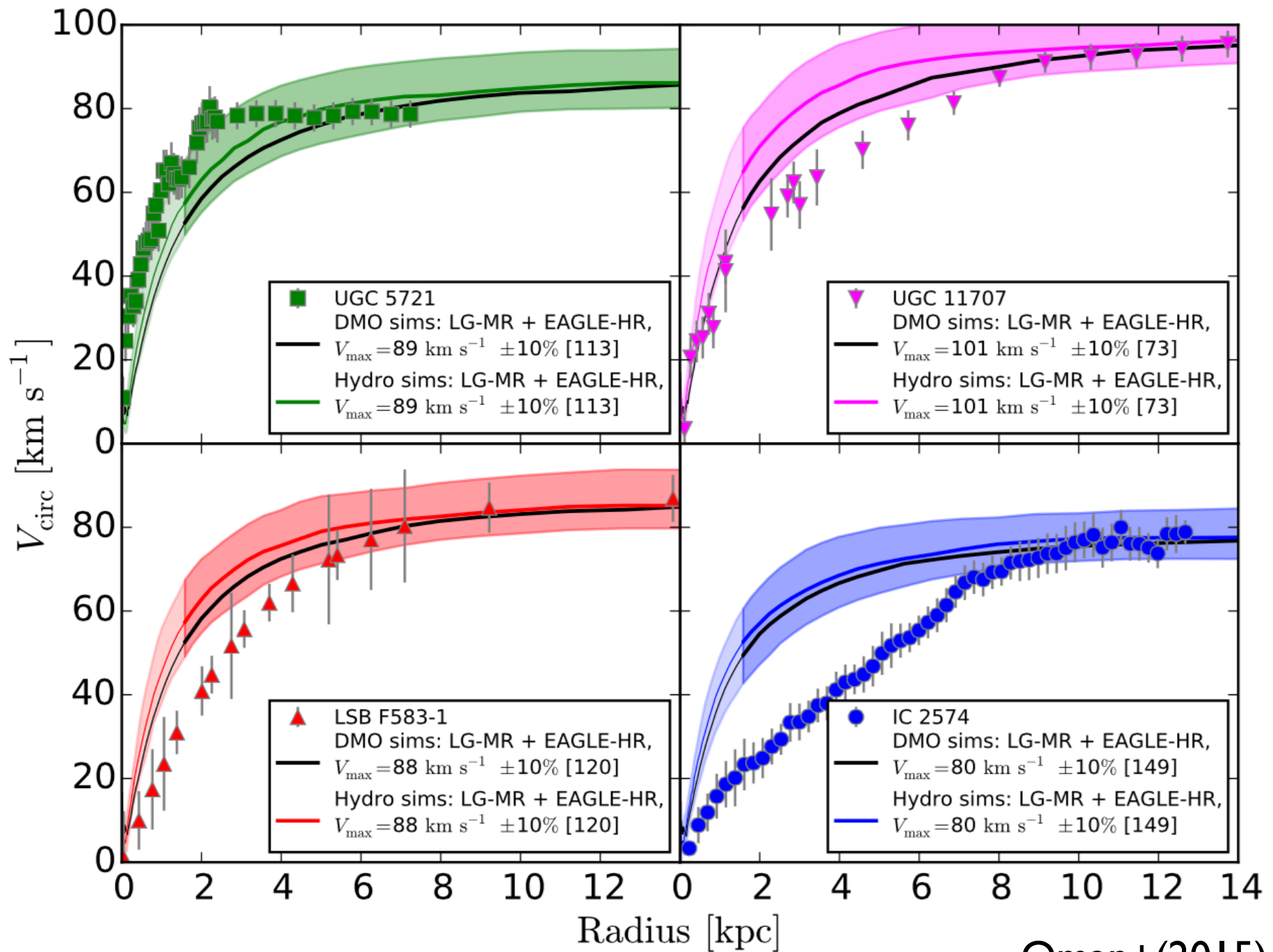


Aquarius Project, Springel+ (2008)



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

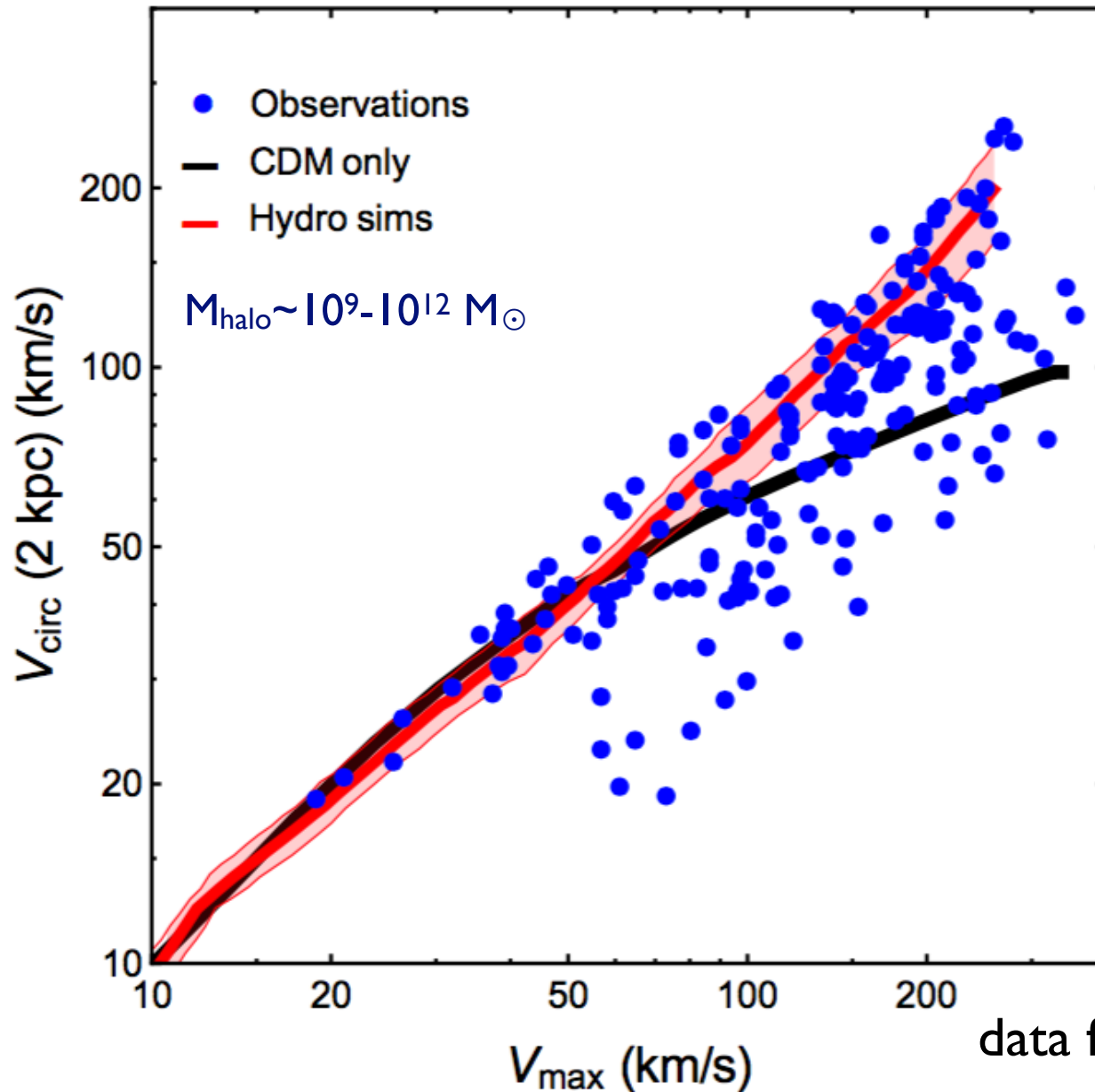
the Navarro-Frenk-White (NFW) profile (1996)



Oman+(2015)

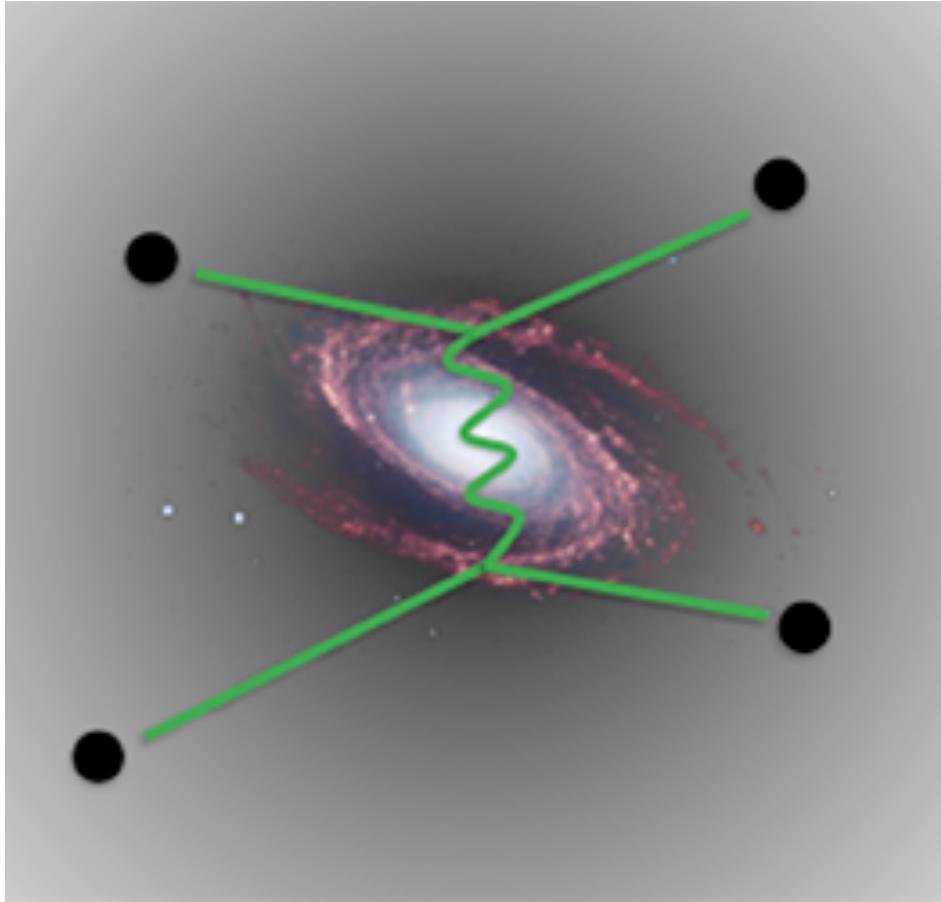
Rotation curves (matter distributions) are **diverse** in spiral galaxies

The Diversity Problem



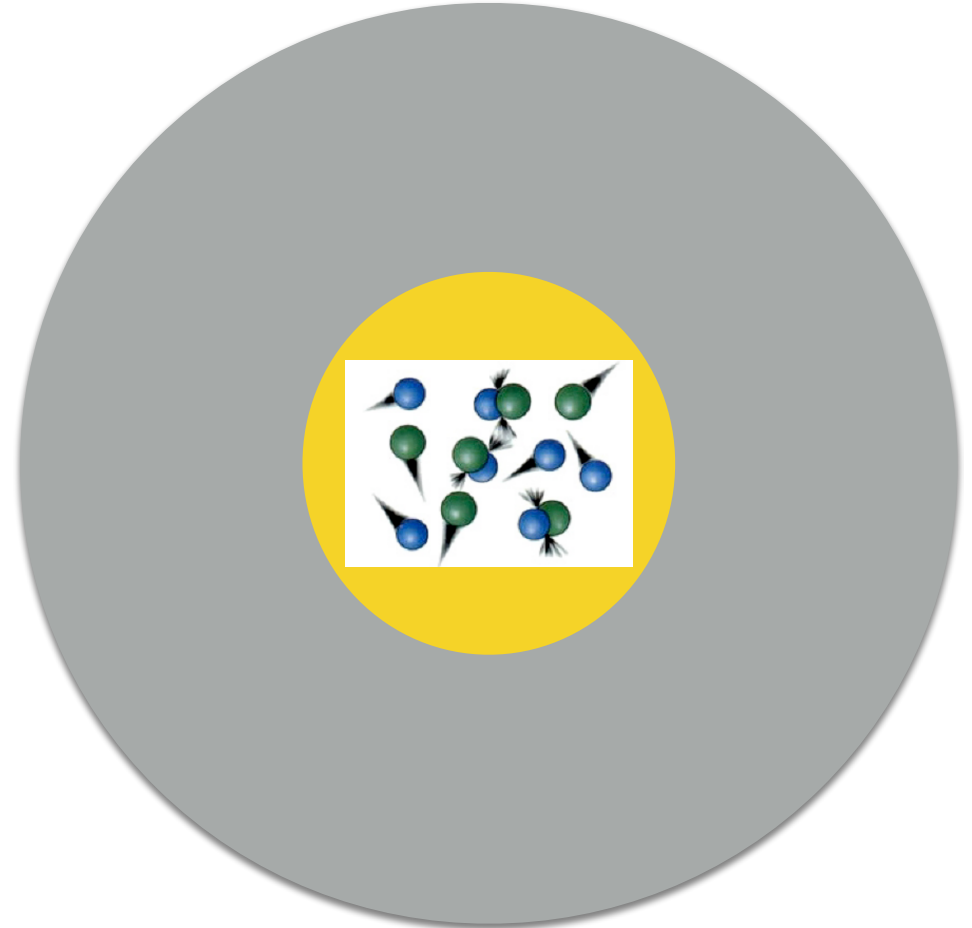
Rotation curves (matter distributions) are **diverse** in spiral galaxies

Dark Matter Self-Interactions



Self-interactions in the dark sector

Treat dark matter as ideal gas

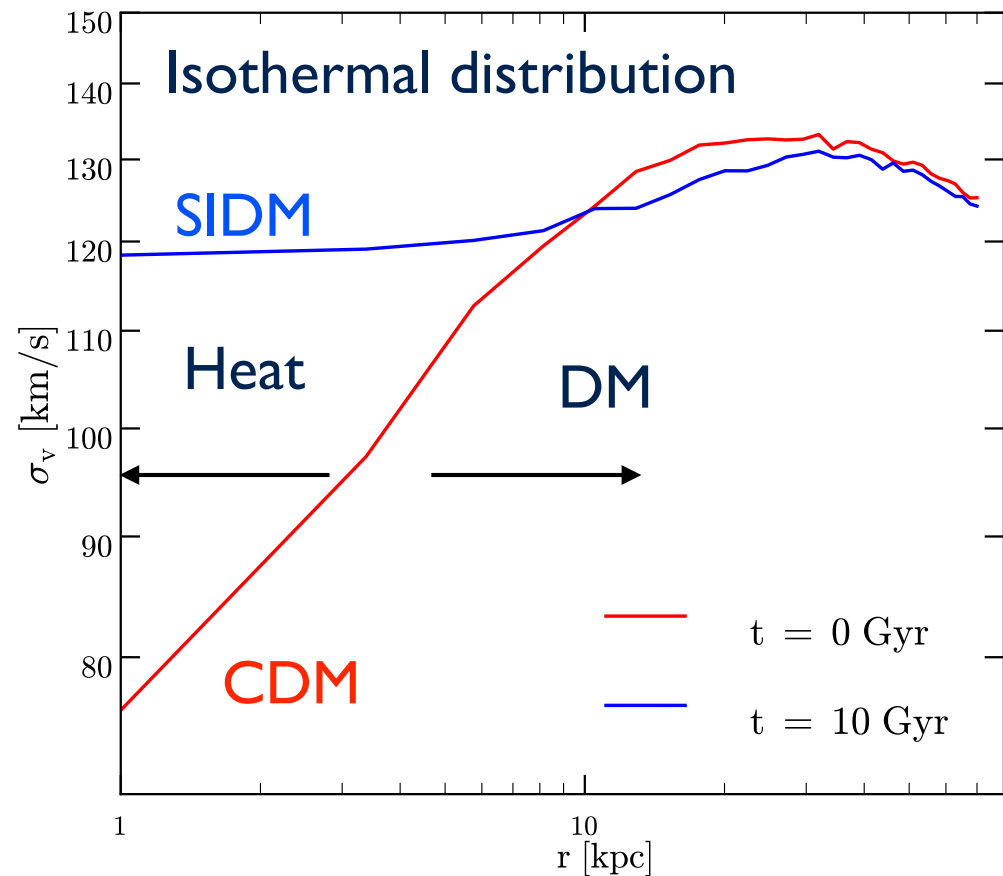
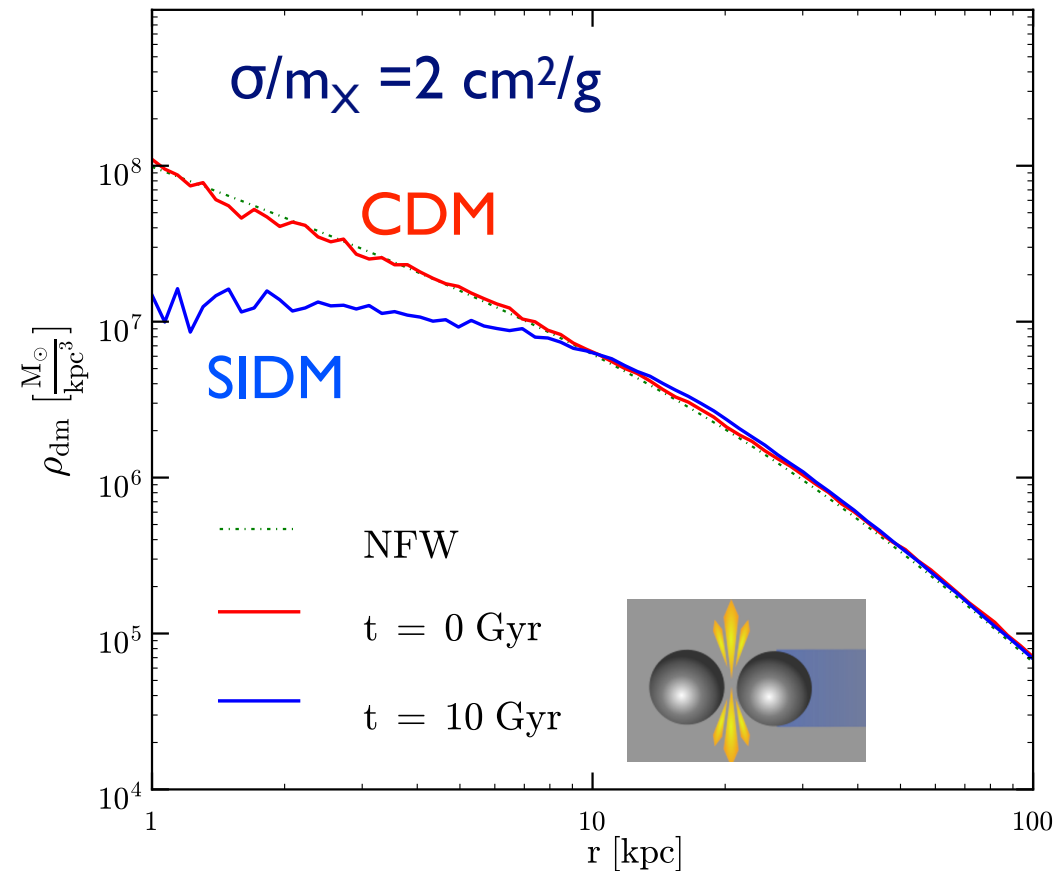


thermalization

$$PV=nRT$$

“takeaway message”

Self-Interacting Dark Matter



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

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

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

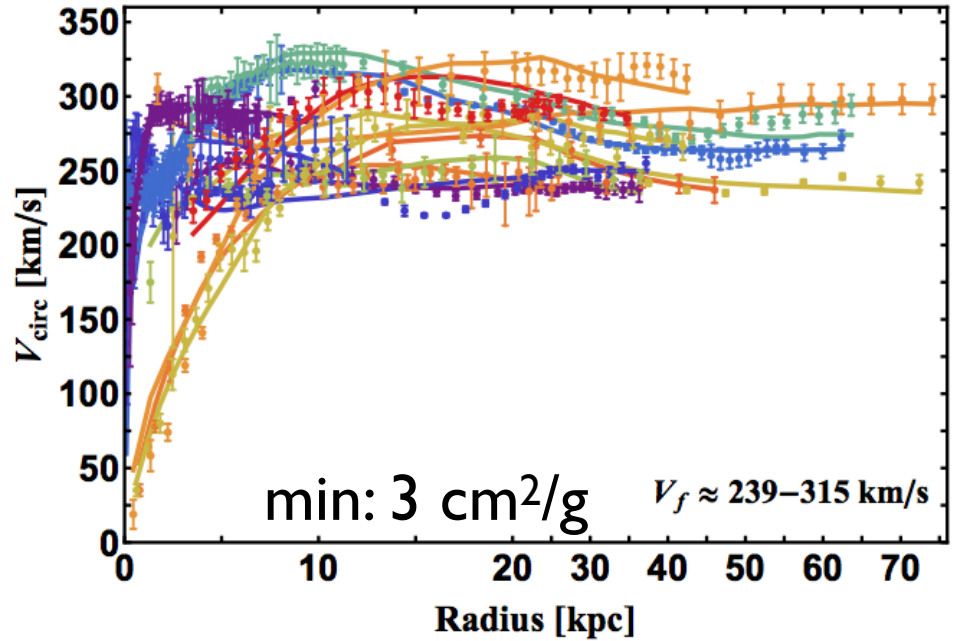
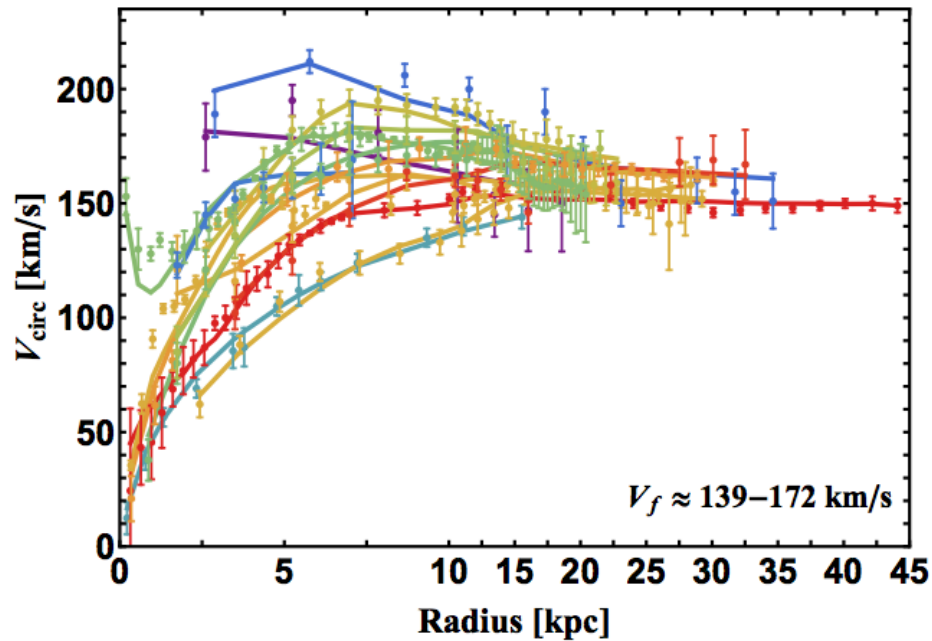
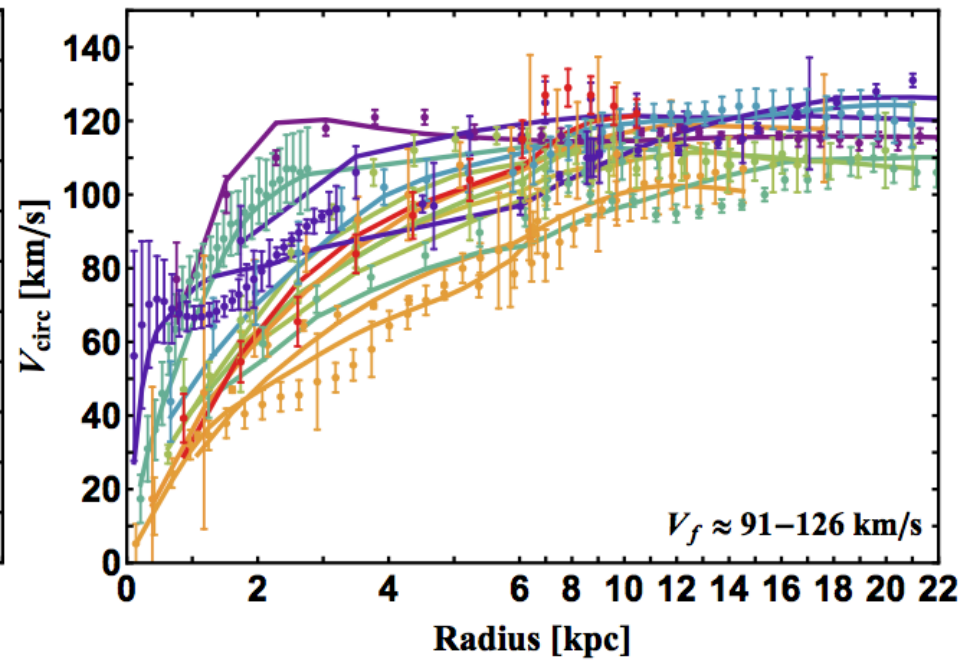
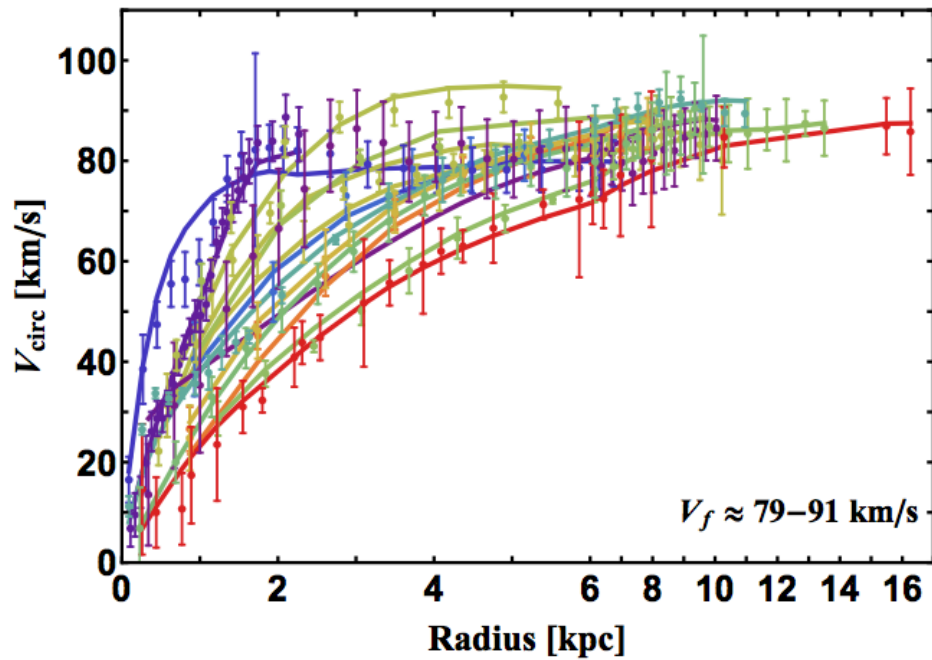
Review: Tulin, HBY (Physics Reports 2017)

with Kaplinghat, Keeley, Linden (PRL 2014)

with Kaplinghat, Linden (RPL 2015)

with Kaplinghat, Tulin (PRL 2016)

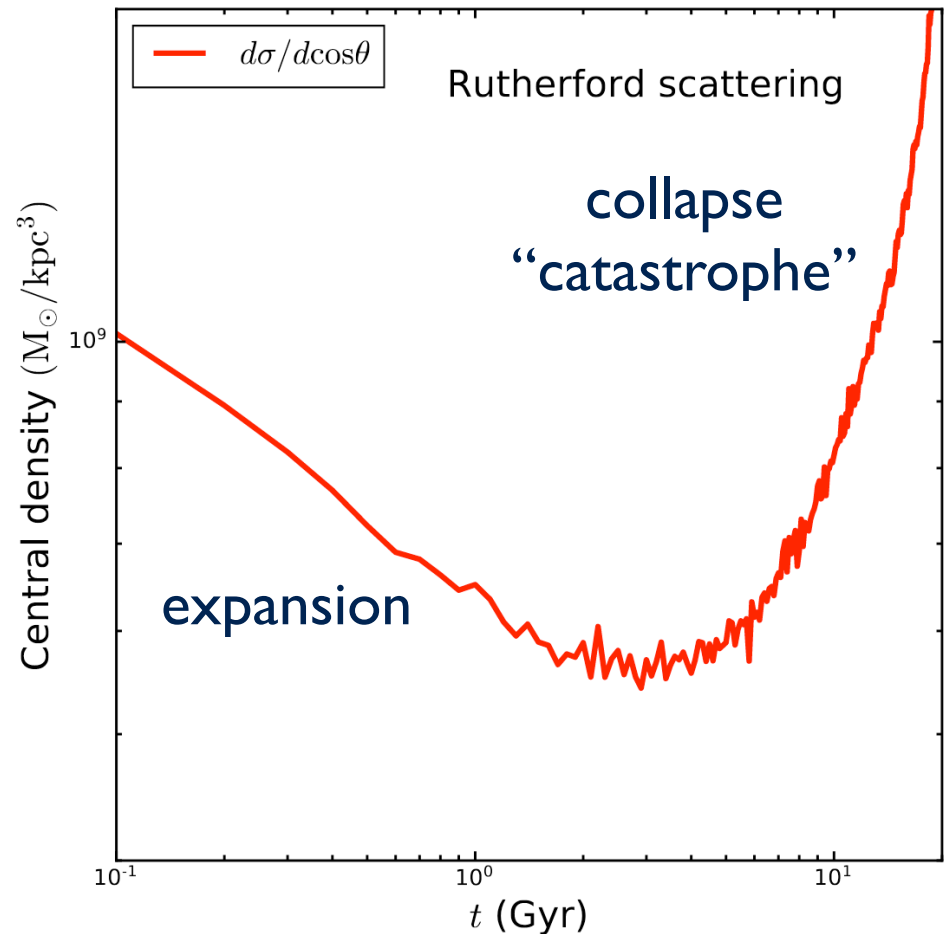
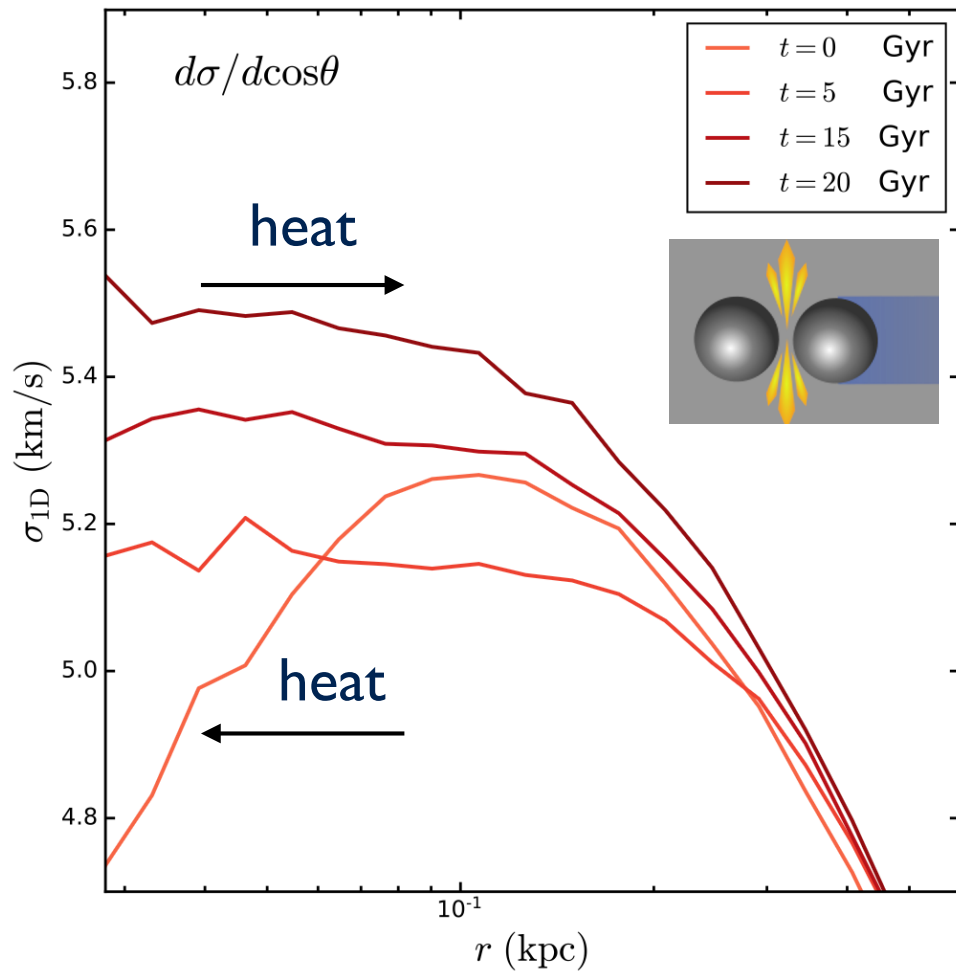
with Kamada, Kaplinghat, Pace (PRL 2017)



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



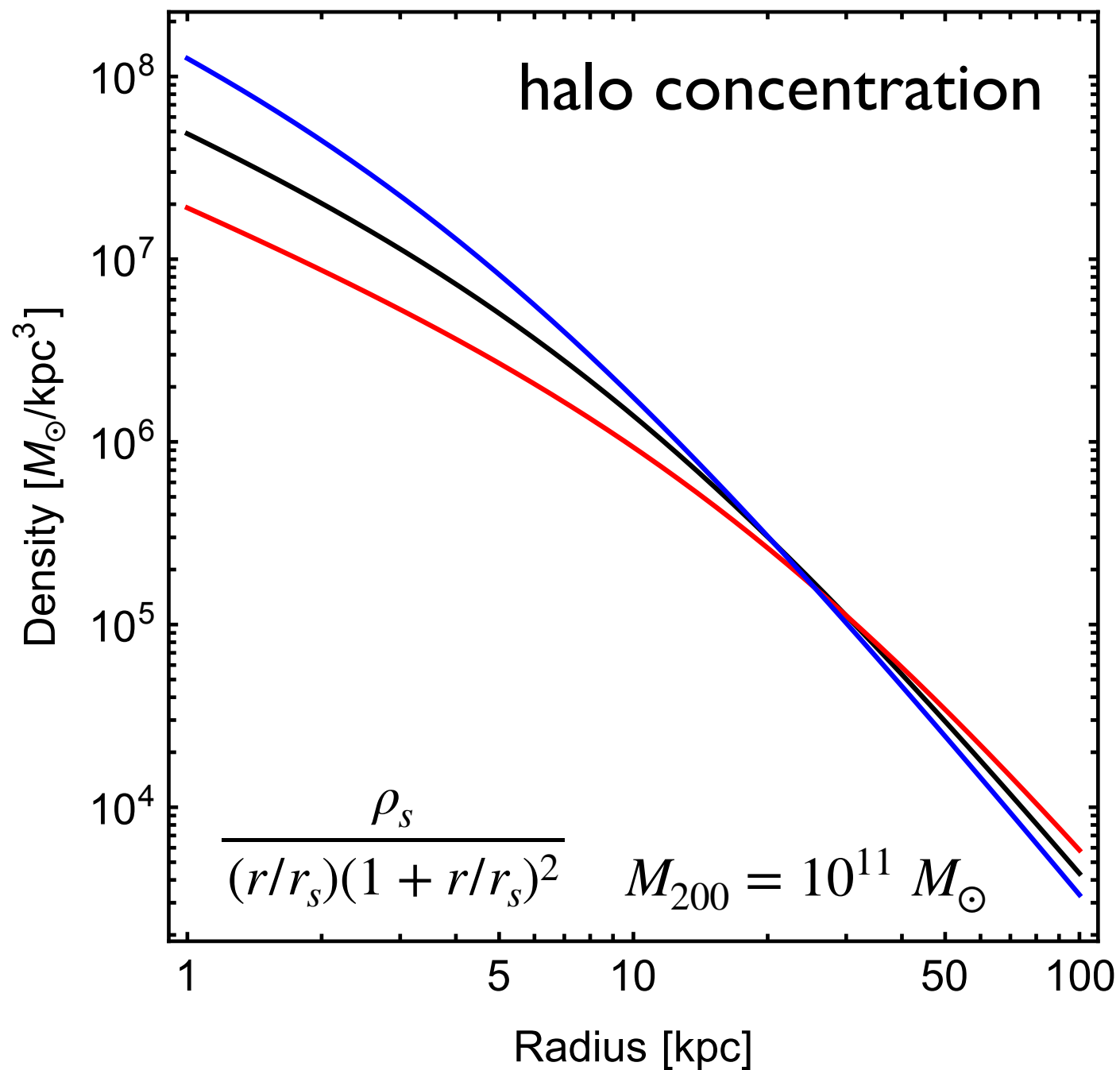
Yang, Yu (JCAP 2022)

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

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)

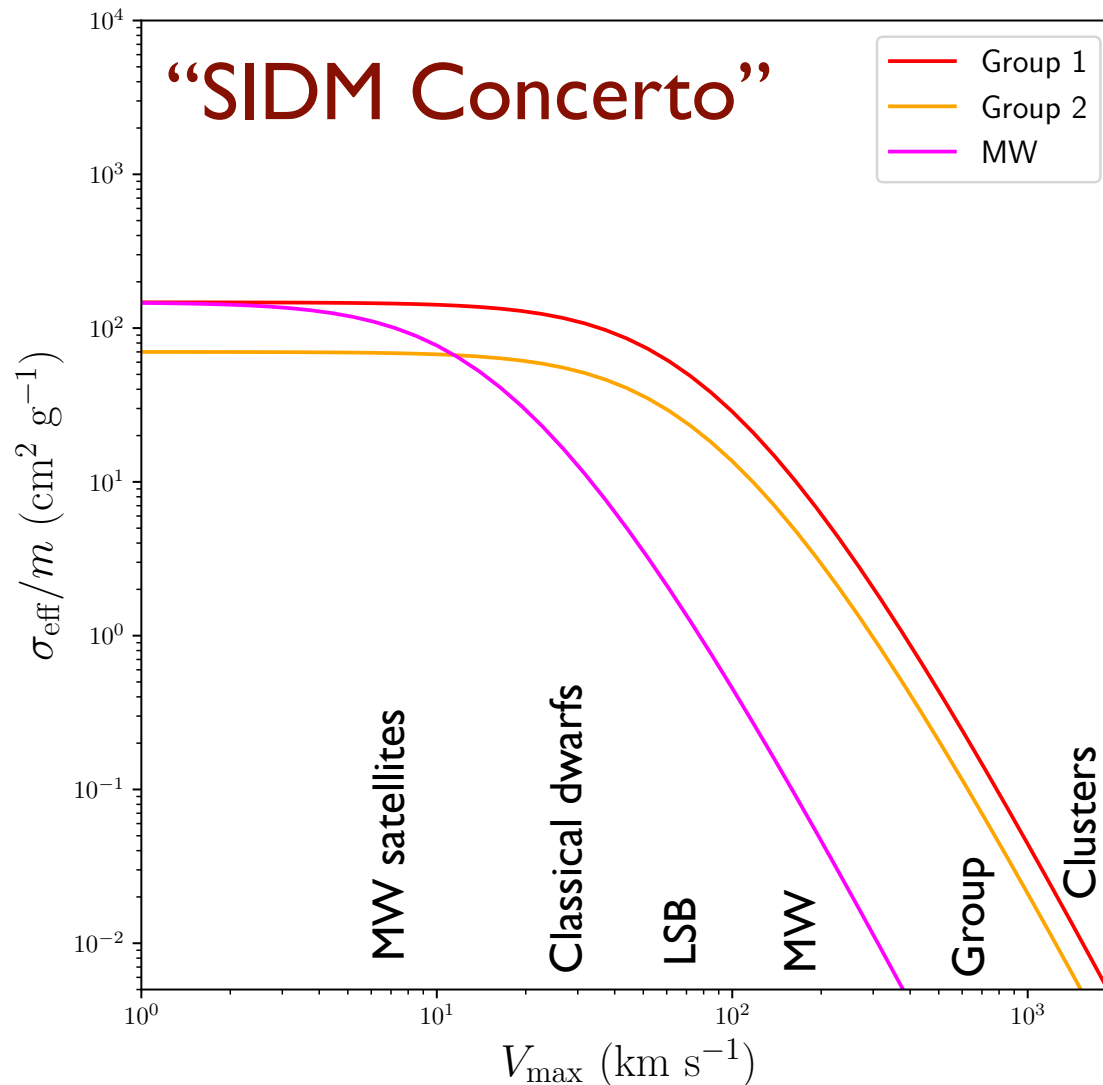
Cosmological Zoom-in Simulations



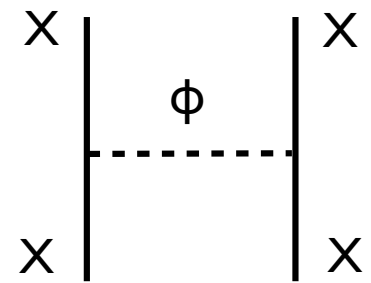
Ethan Nadler
(UCSD)



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

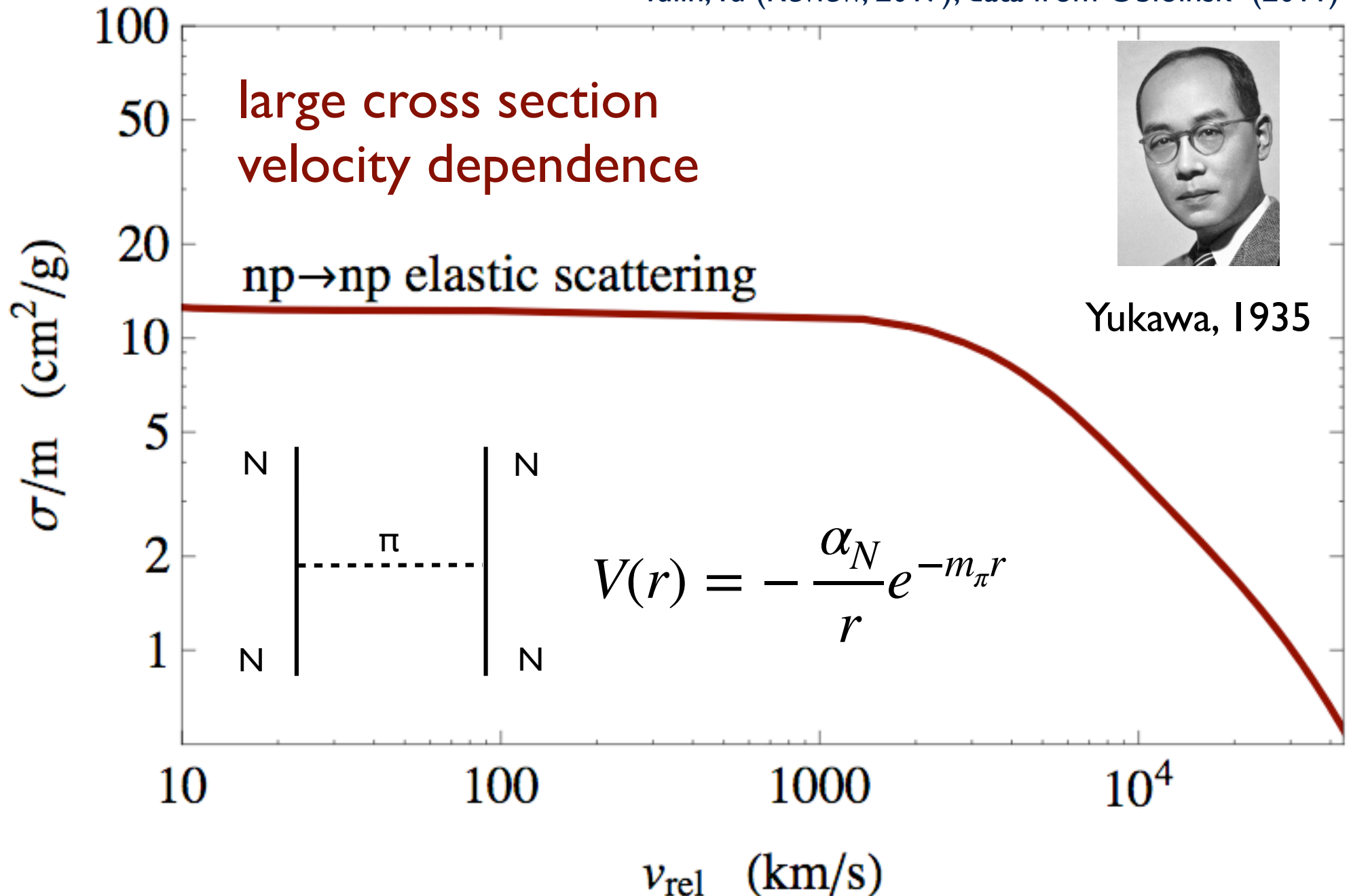


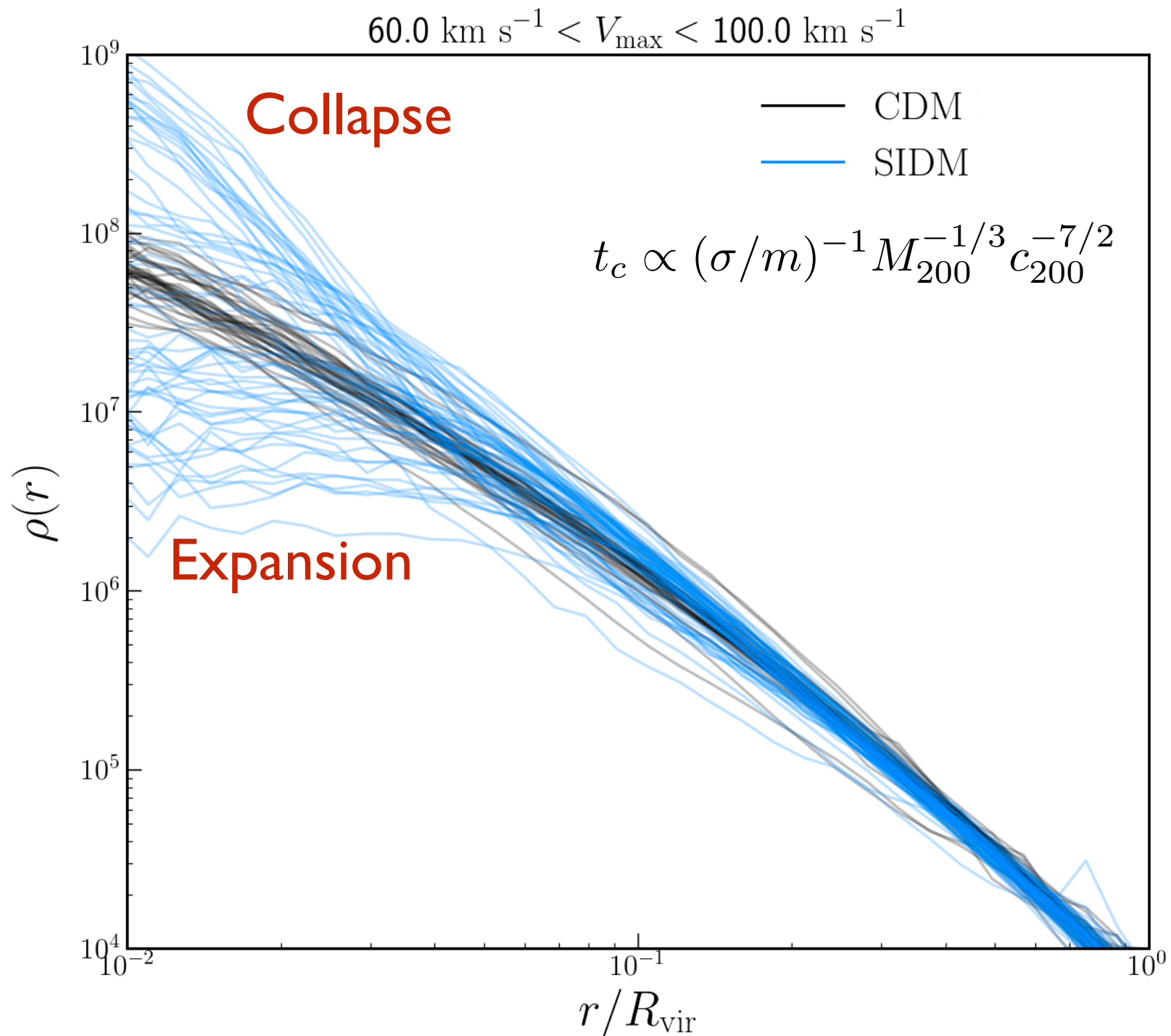
https://www.esa.int/ESA_Multimedia/Images/2007/07/The_Bullet_Cluster2

The cross section per mass should be less than a few times cm^2/g for the relative velocity: 2000–3000 km/s

Nuclear Interactions

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



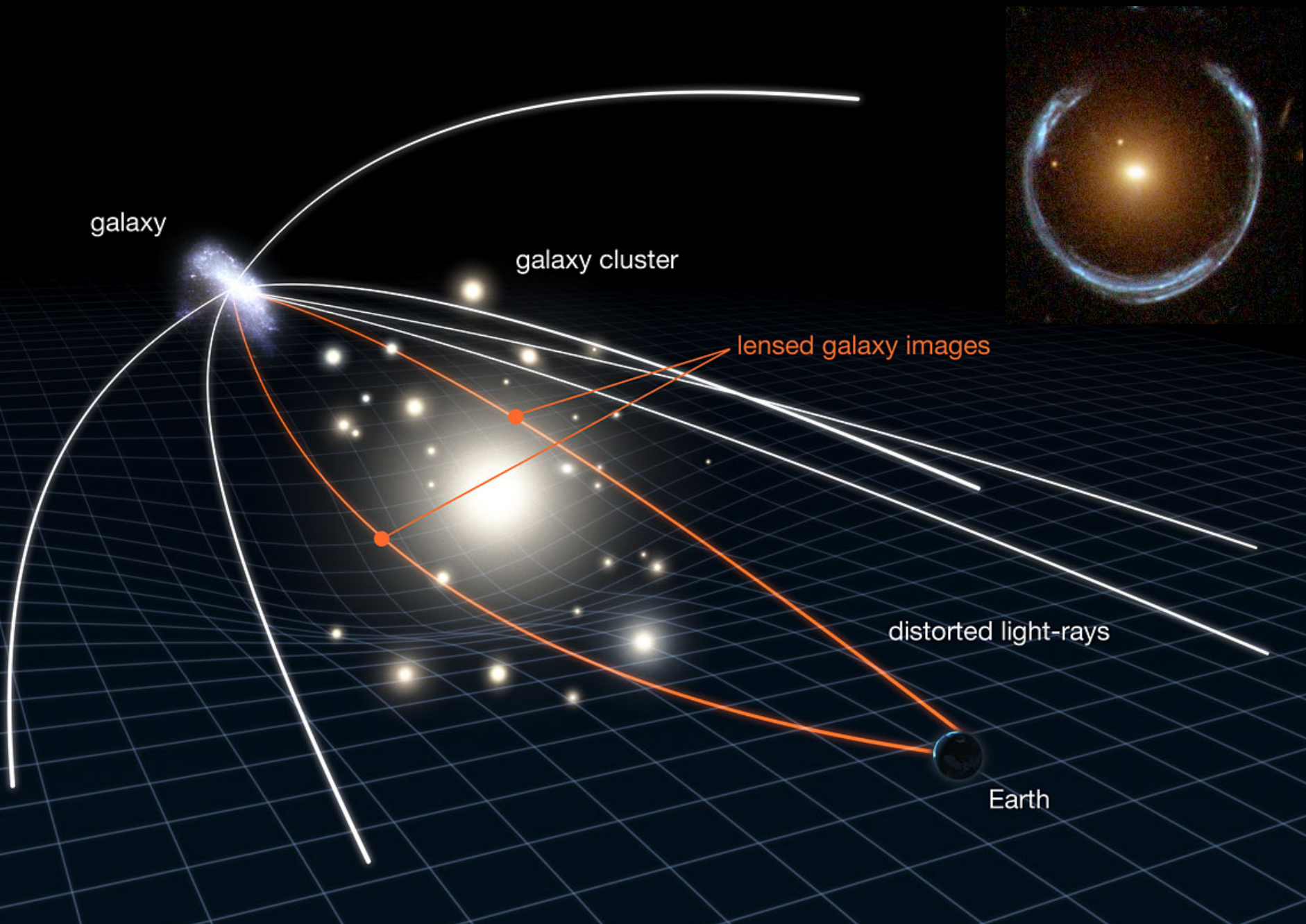


SIDM amplifies diversity encoded in the scatter of halo concentration

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*

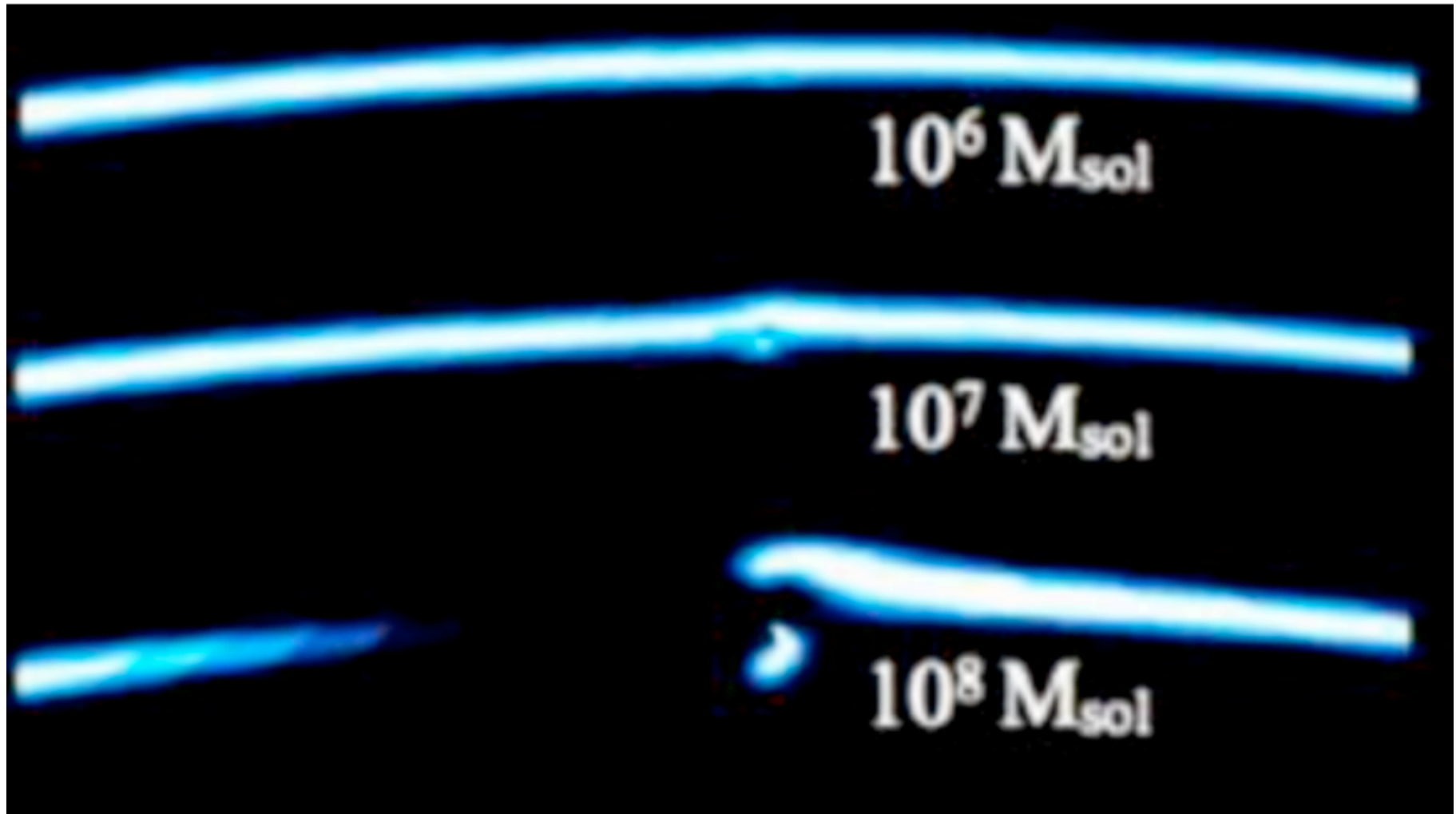
²*Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822-1897, USA*

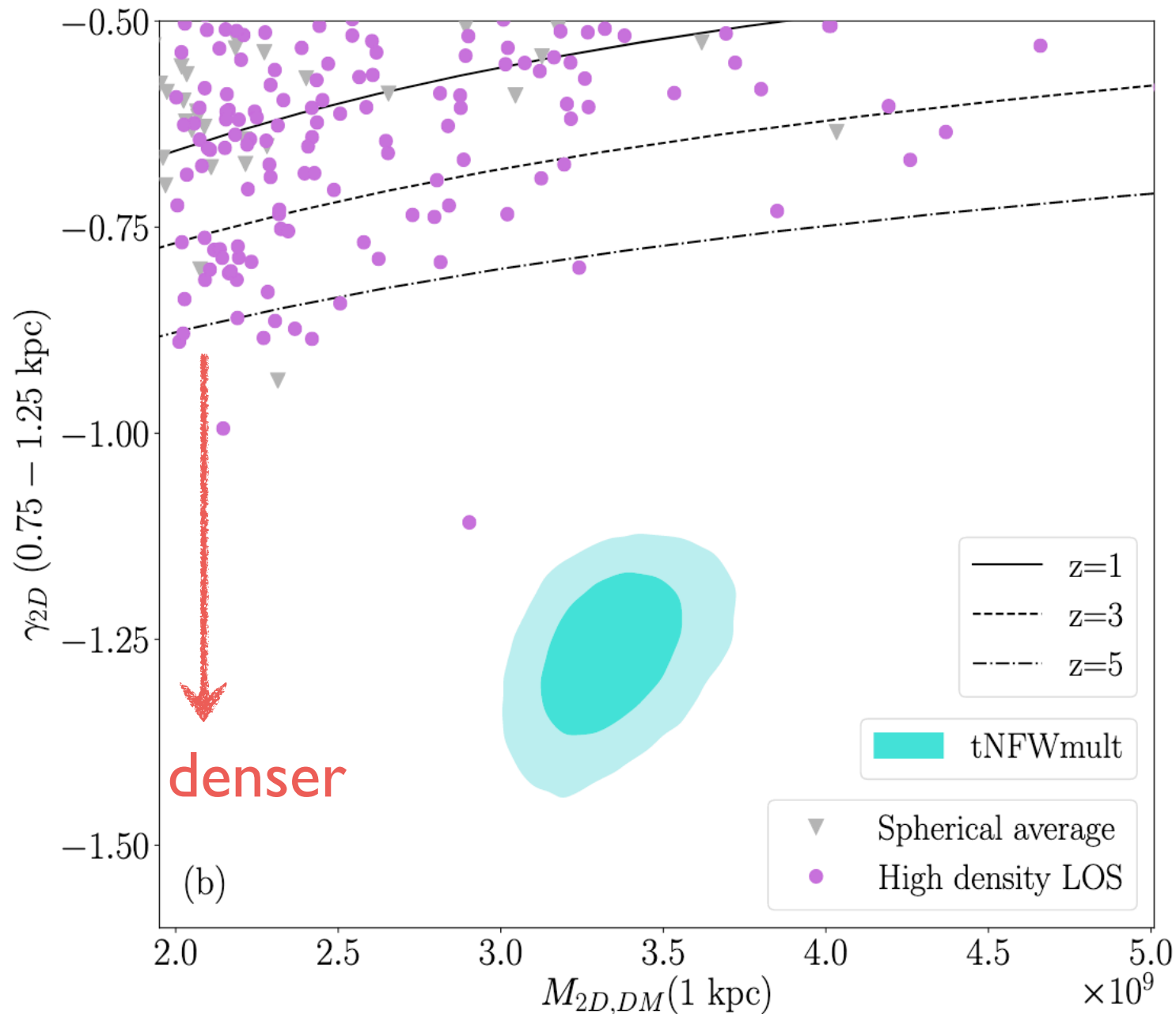
³*Department of Physics, University of California, Santa Barbara, CA 93101, USA*

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

(MNRAS 2010)

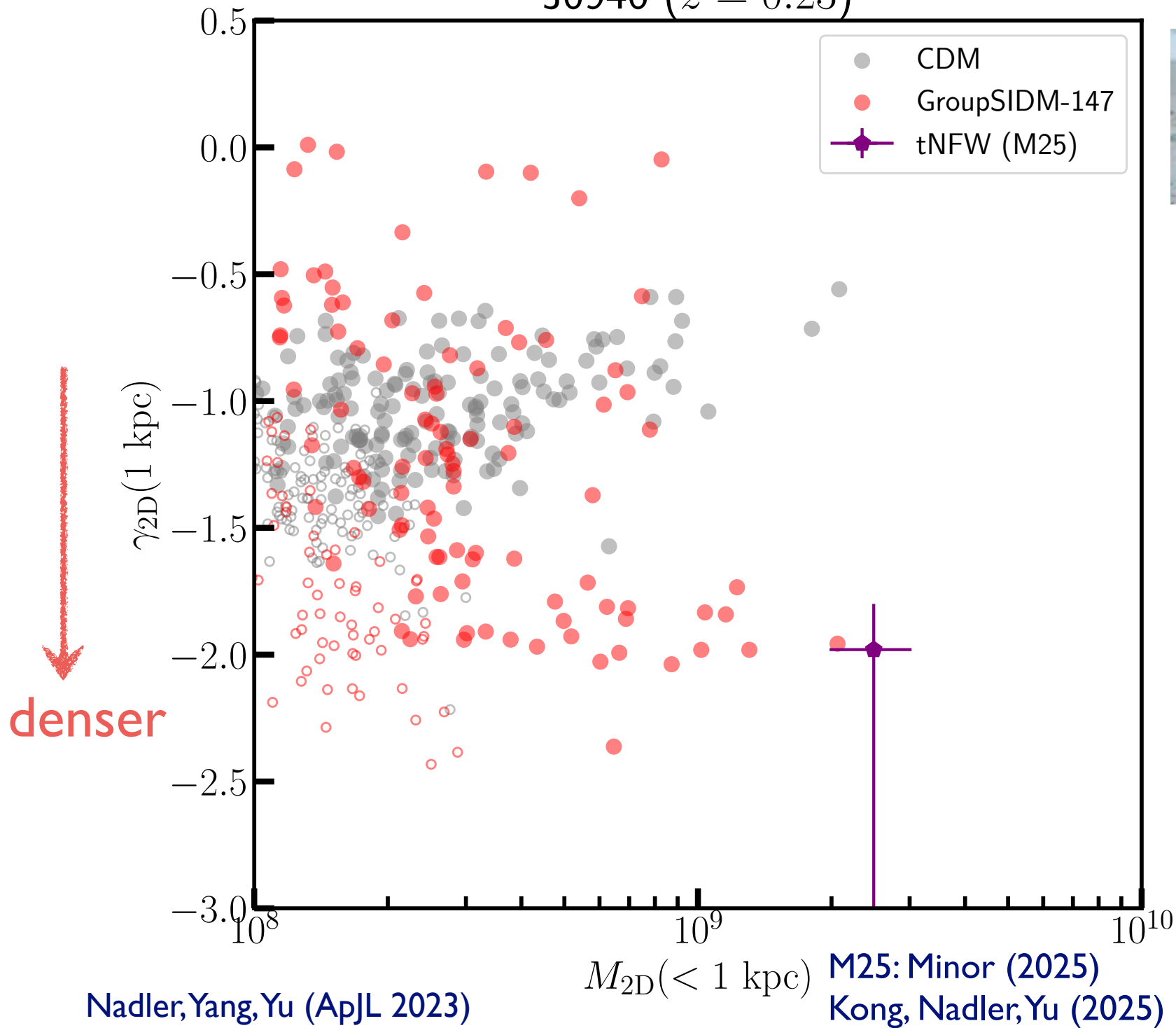
SDSSJ0946+1006 (the “Double Einstein Ring”).





- 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

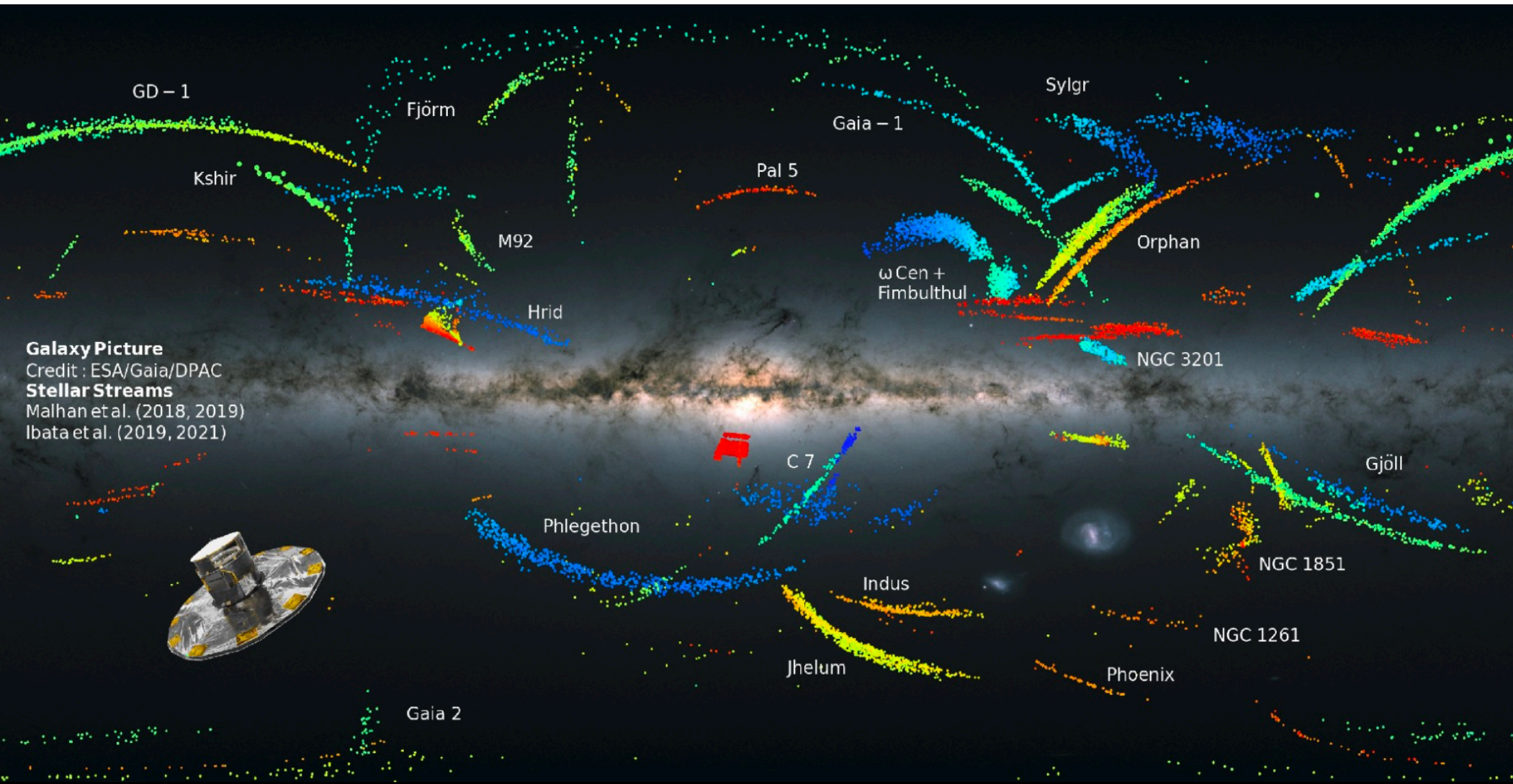
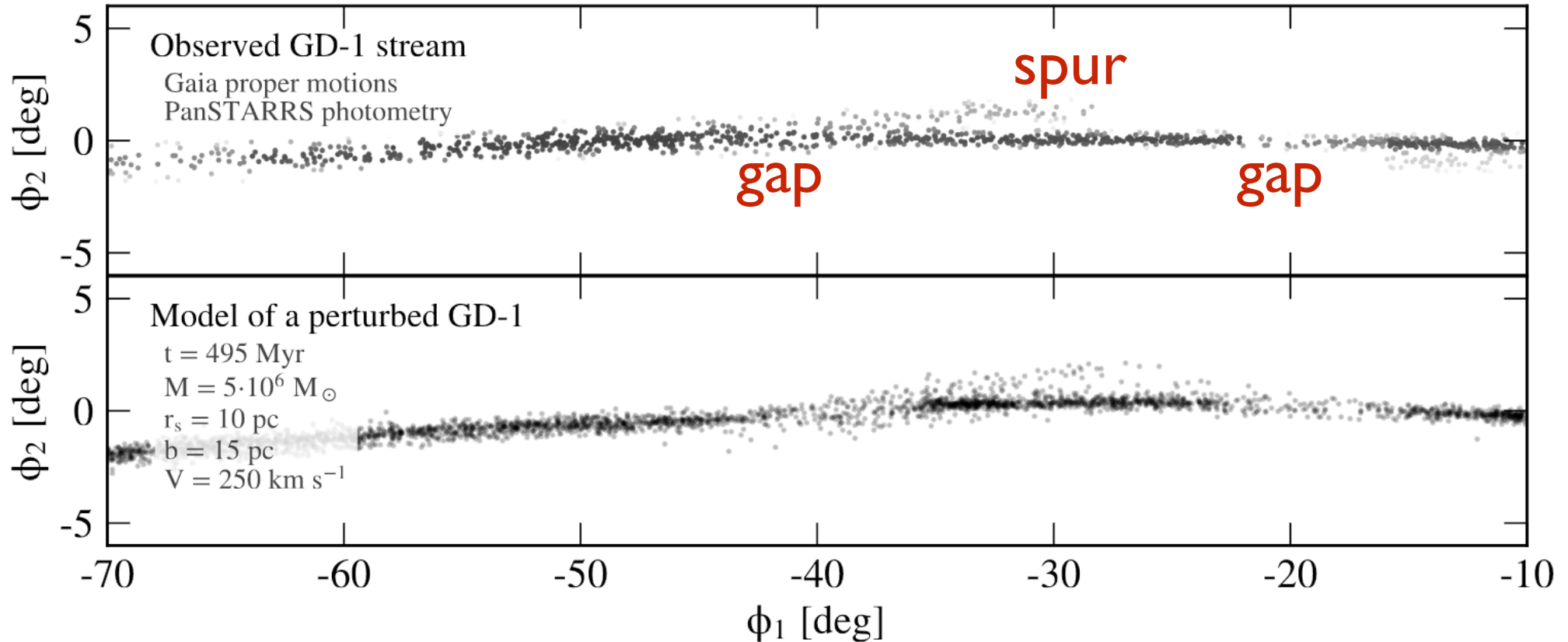


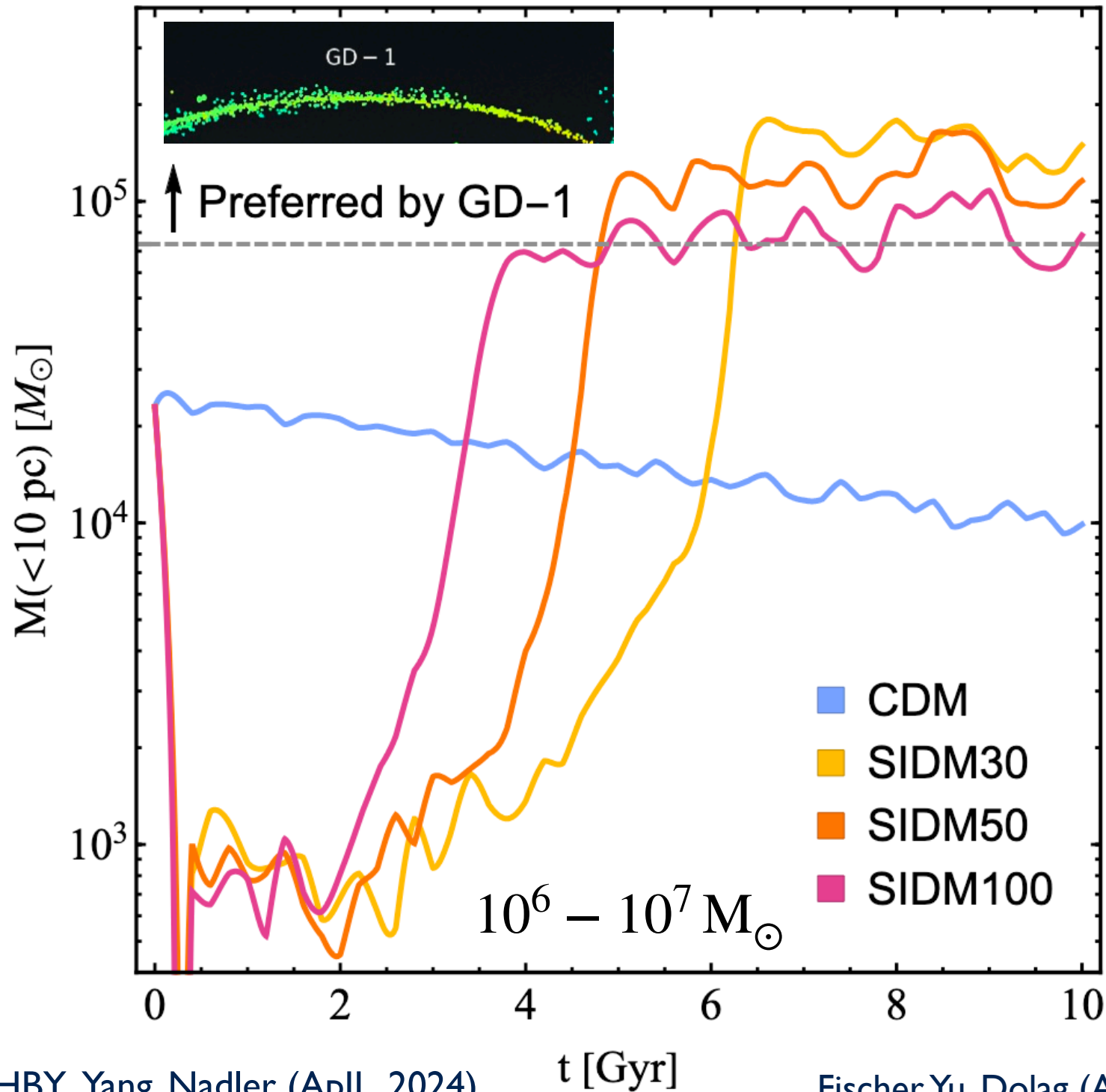
Figure: Khyati Malhan

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 GD-I 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)

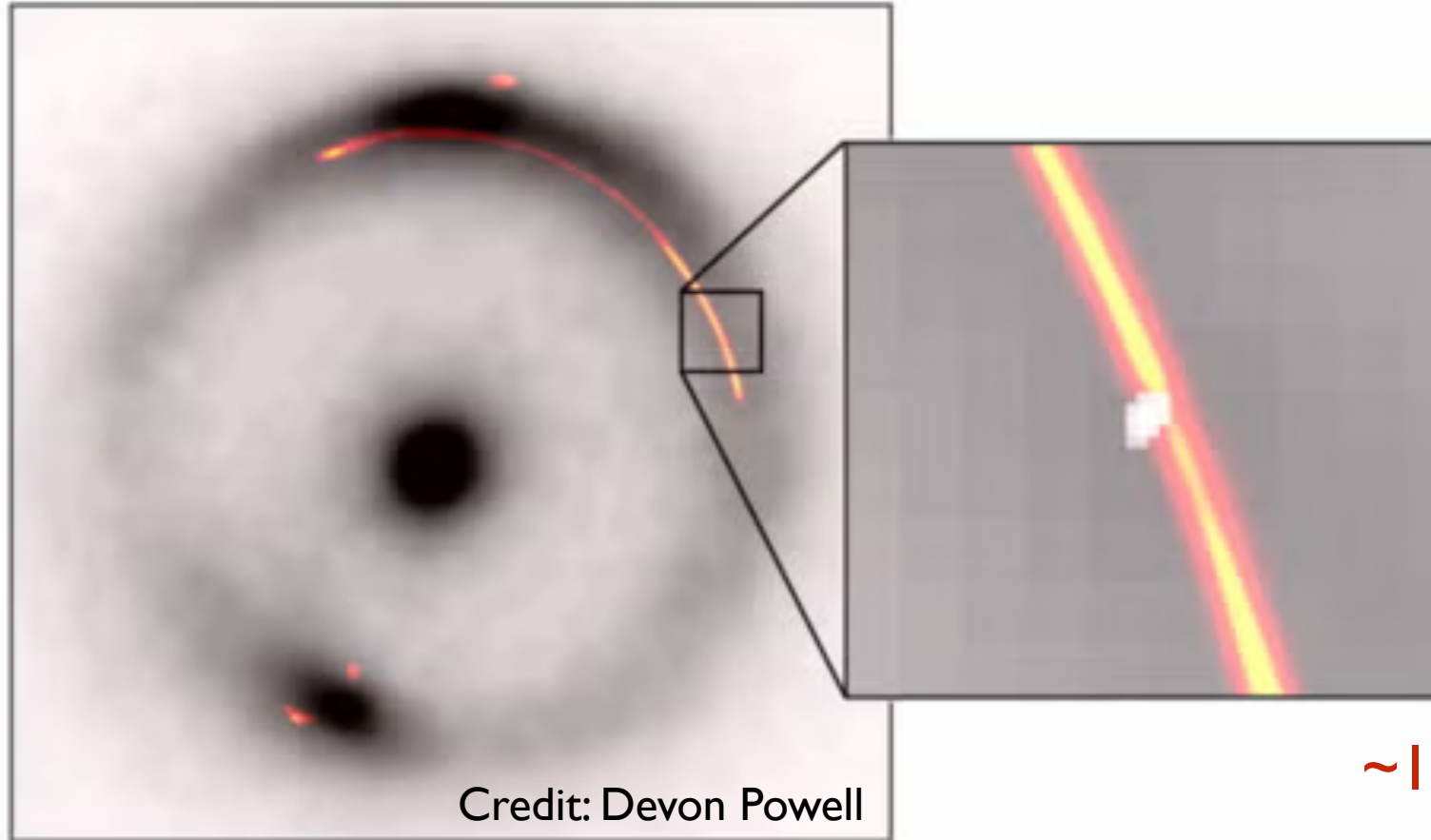


Moritz Fischer
(DIPC)

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

JVAS B1938+666

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



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

~10–20σ “outlier”

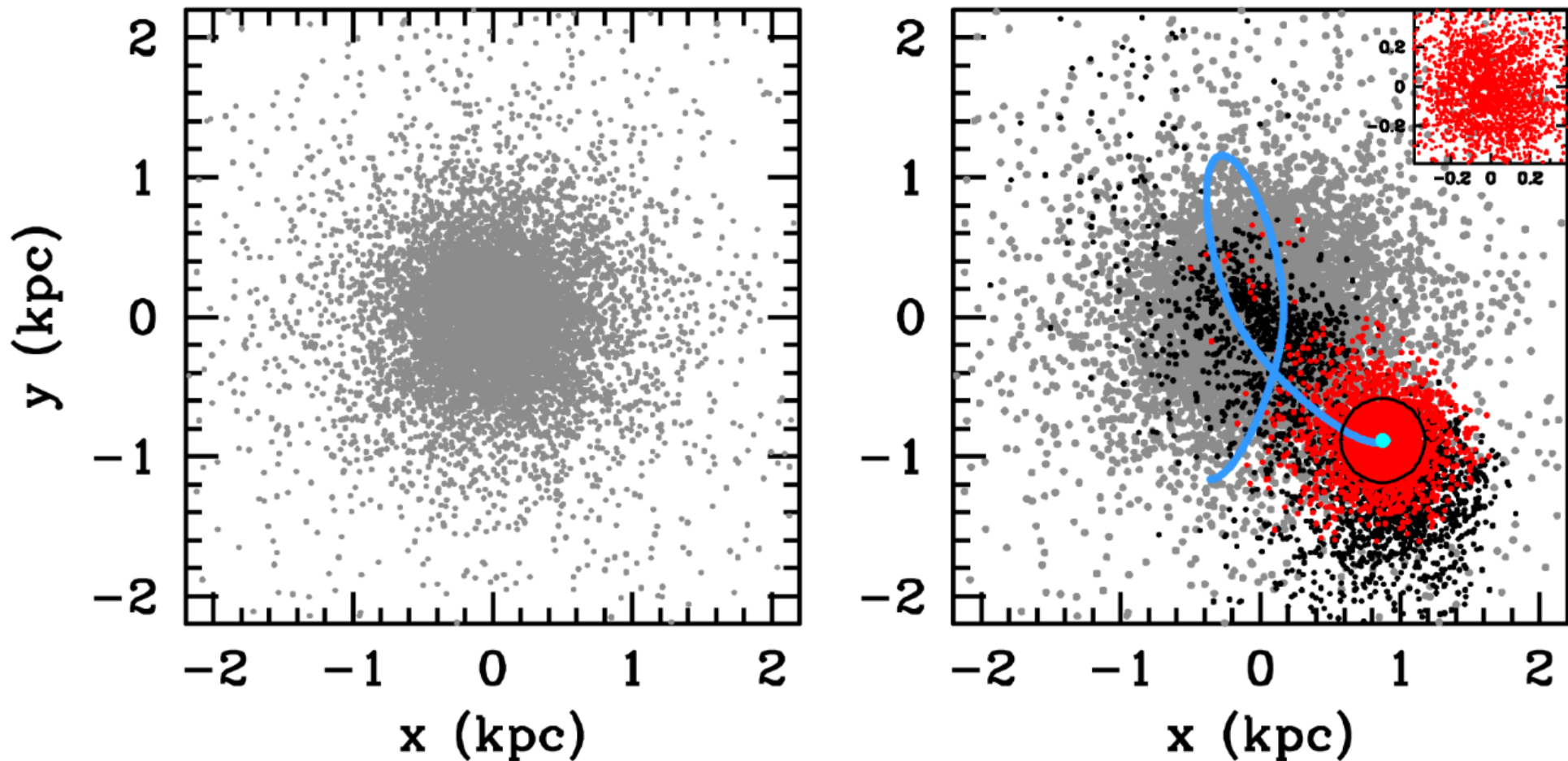
Credit: Devon Powell

The black ring and central dot: an infrared image of a distant galaxy distorted by gravitational lensing. The orange emission: radio waves from the same system. The inset highlights a small “pinch” in the image caused by an additional dense object (white blob), about a million times the mass of the Sun. **The object is extremely compact**

Capture of field stars by dark substructures

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

- field (t=0)
- currently bound
- previously bound



Fornax is a satellite galaxy of the Milky Way and it contains 6 globular star clusters. Fornax 6 is special, as the properties of its stars are similar to those of field stars, but drastically different from other star clusters

Hint: there is a dense substructure in Fornax

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

Core-Collapsed SIDM Halos as the Common Origin of Dense Perturbers in Lenses, Streams, and Satellites

[Hai-Bo Yu](#) *

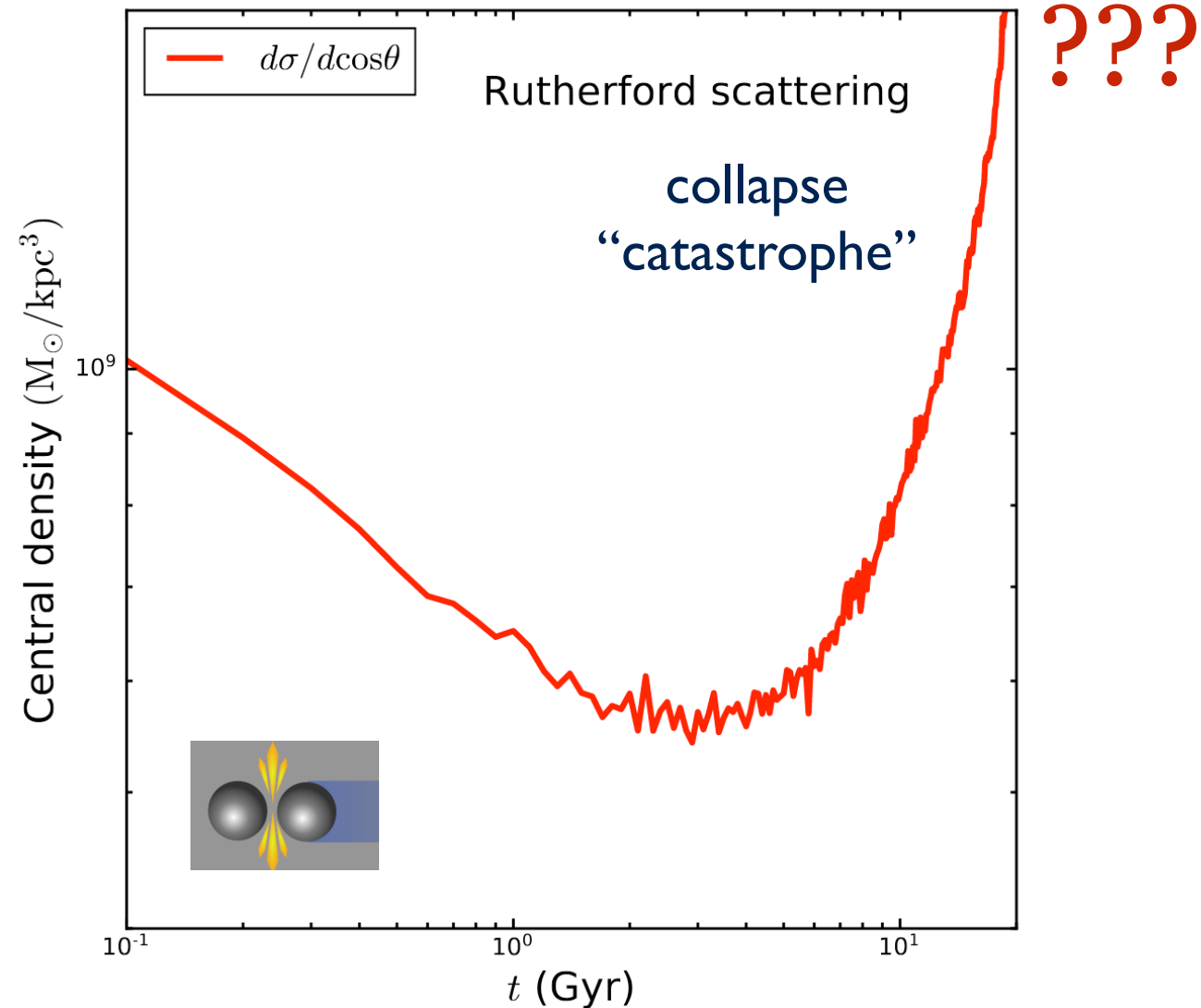
Phys. Rev. Lett. **136**, 141001 – Published 9 April, 2026

THREE BIRDS WITH ONE STONE



- Gravo-thermal collapse is an inevitable consequence of dark matter self-interactions
- Observational hints of compact, dense objects, which are outliers in the standard CDM paradigm, have emerged, with their remarkably high densities being consistent with predictions from SIDM

Gravothermal Evolution

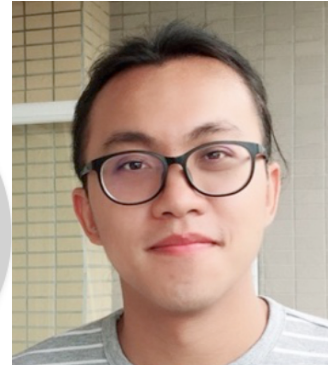
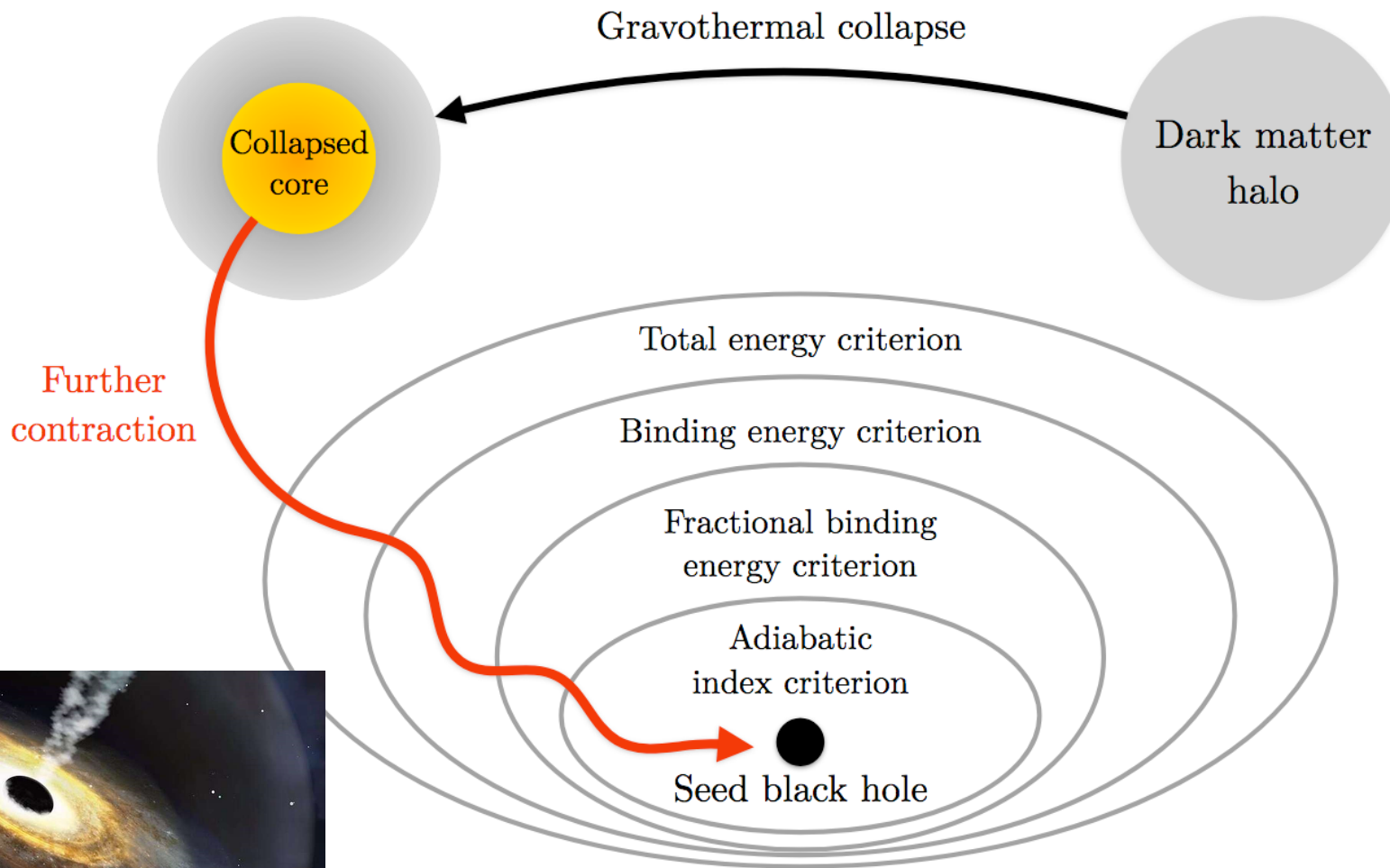


$$2K.E. + P.E. = 0$$

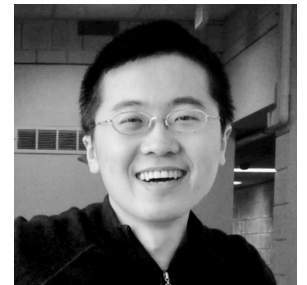
$$E_{\text{tot}} = -K.E. \quad \frac{E_{\text{tot}}}{T} < 0$$

Negative heat capacity!
 $\Rightarrow$ gravothermal collapse

Seeding Supermassive Black Holes



Wei-Xiang Feng
(Tsinghua)



Yi-Ming Zhong
(CityU, HK)

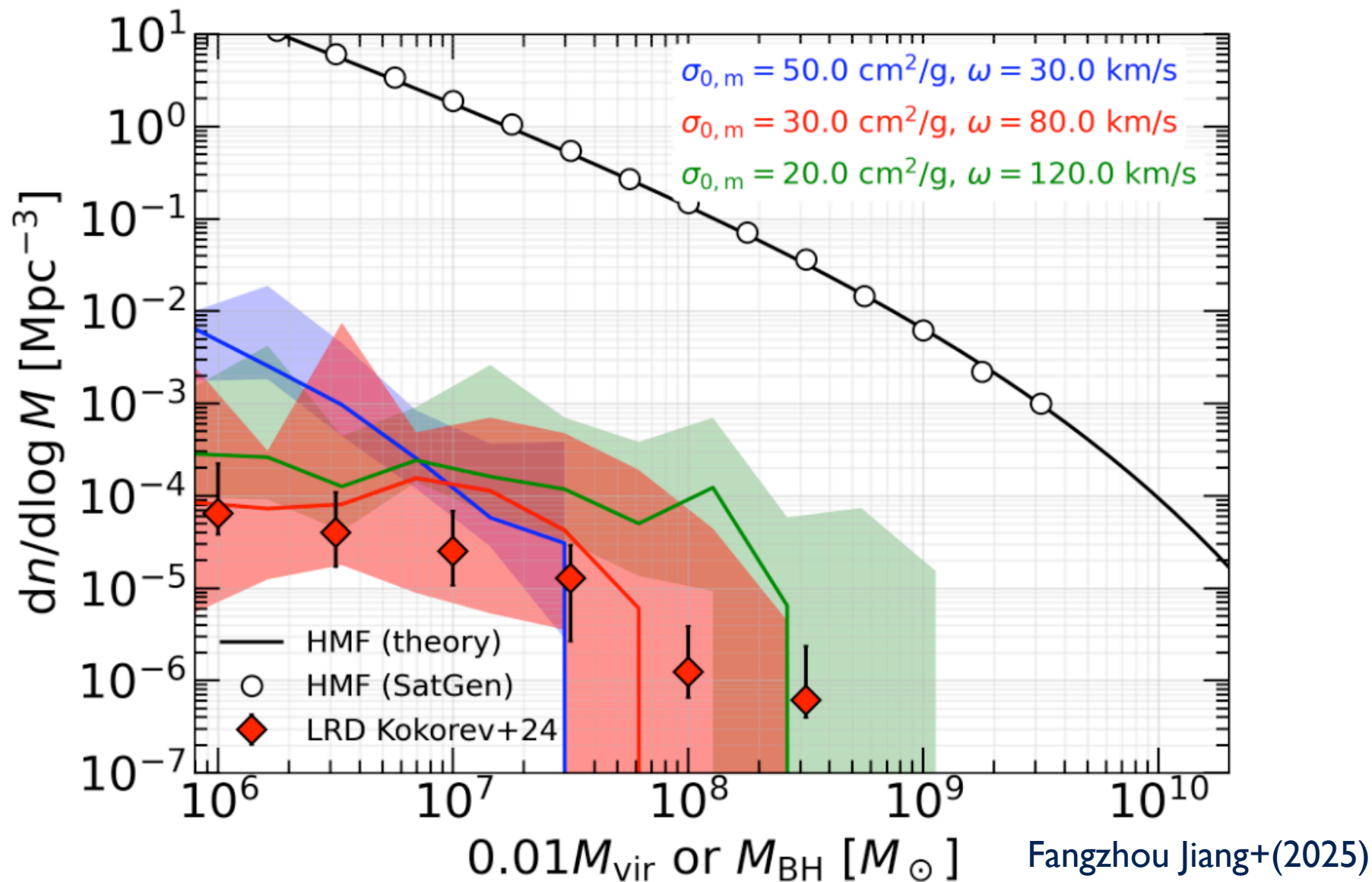


Balberg, Shapiro (PRL 2002)

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)

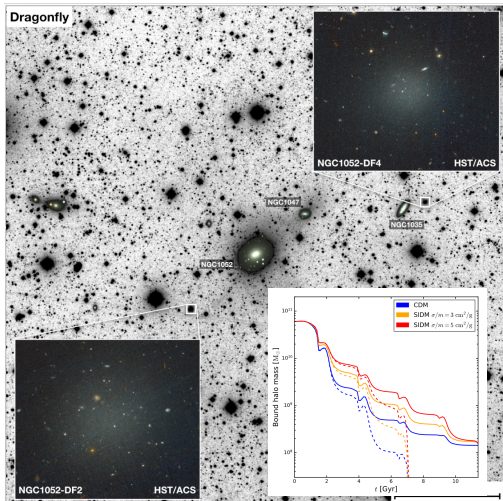
SIDM From Dwarf to Cluster Scales

Ultra-diffuse galaxies
(dark-matter-deficient)

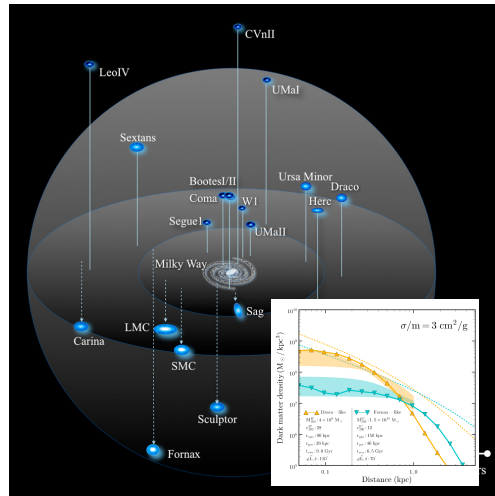
Milky Way satellites

Spiral galaxies

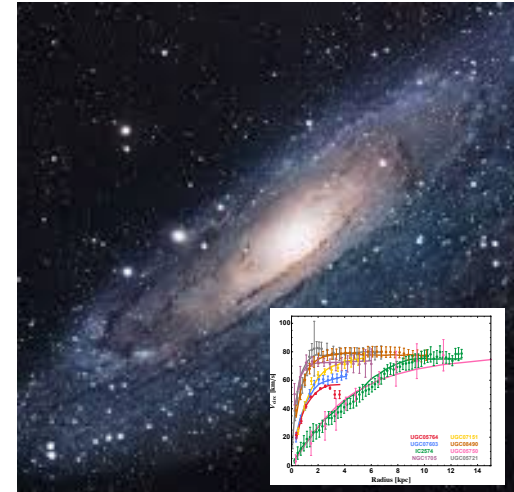
Galaxy clusters



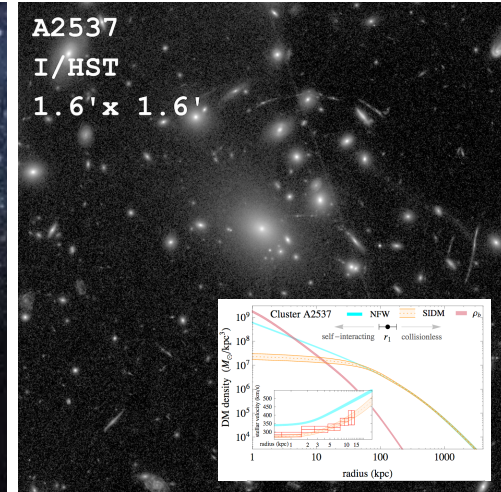
$$M_{\text{halo}} < \sim 10^8 M_{\odot}$$



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

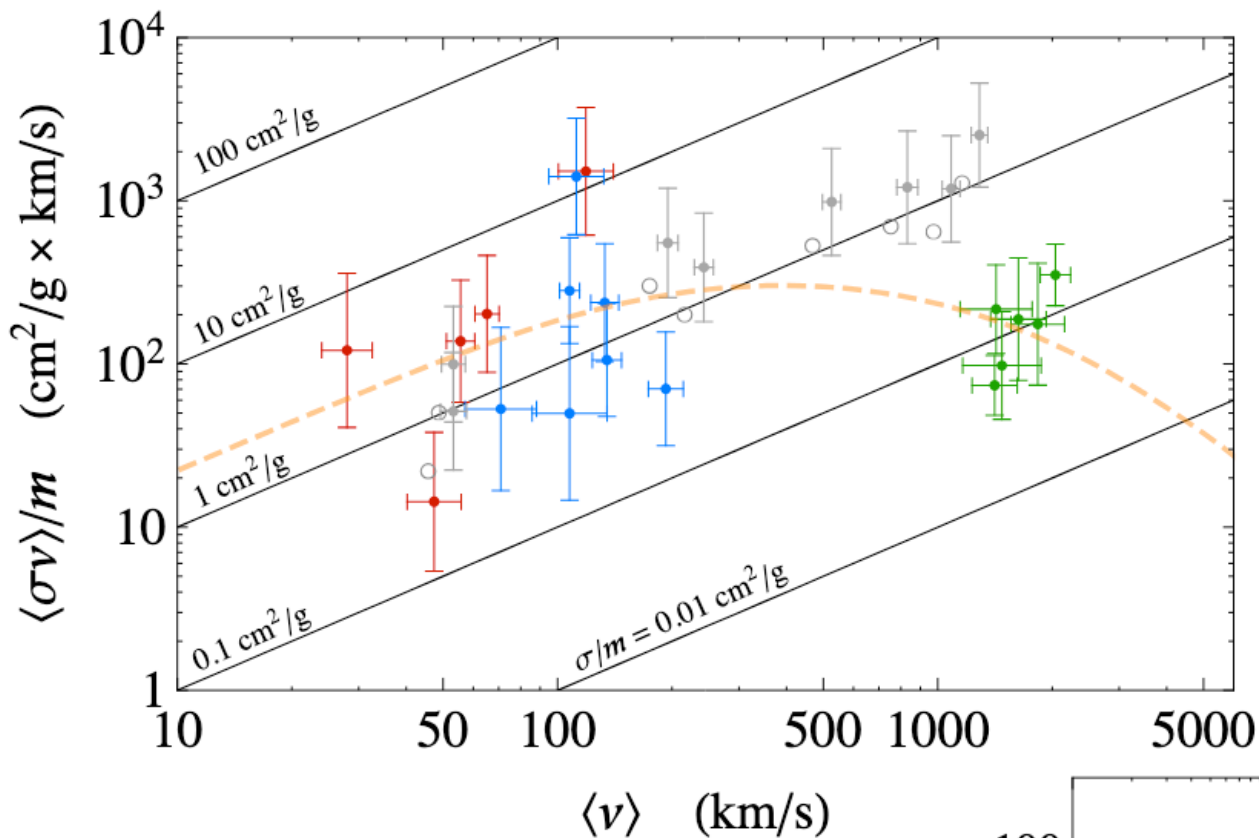


$$M_{\text{halo}} \sim 10^9 - 10^{13} M_{\odot}$$



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

- 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

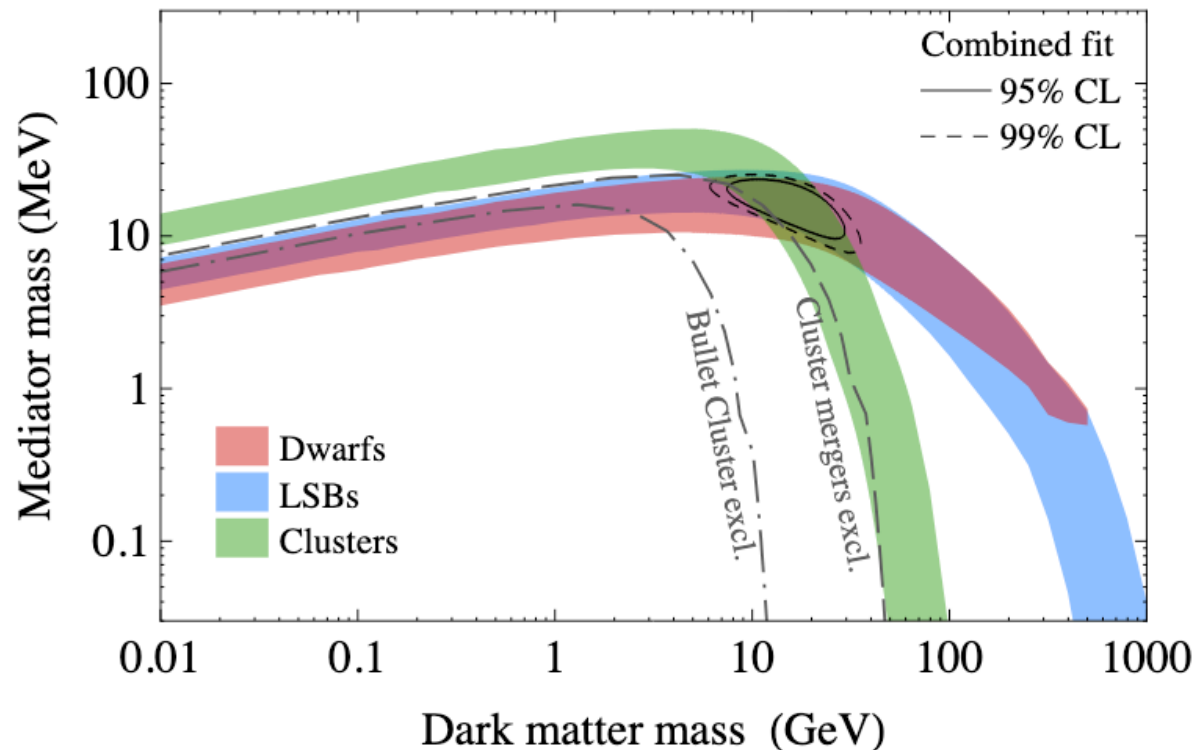


$$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

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

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

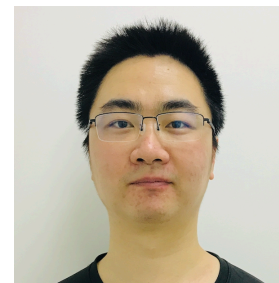
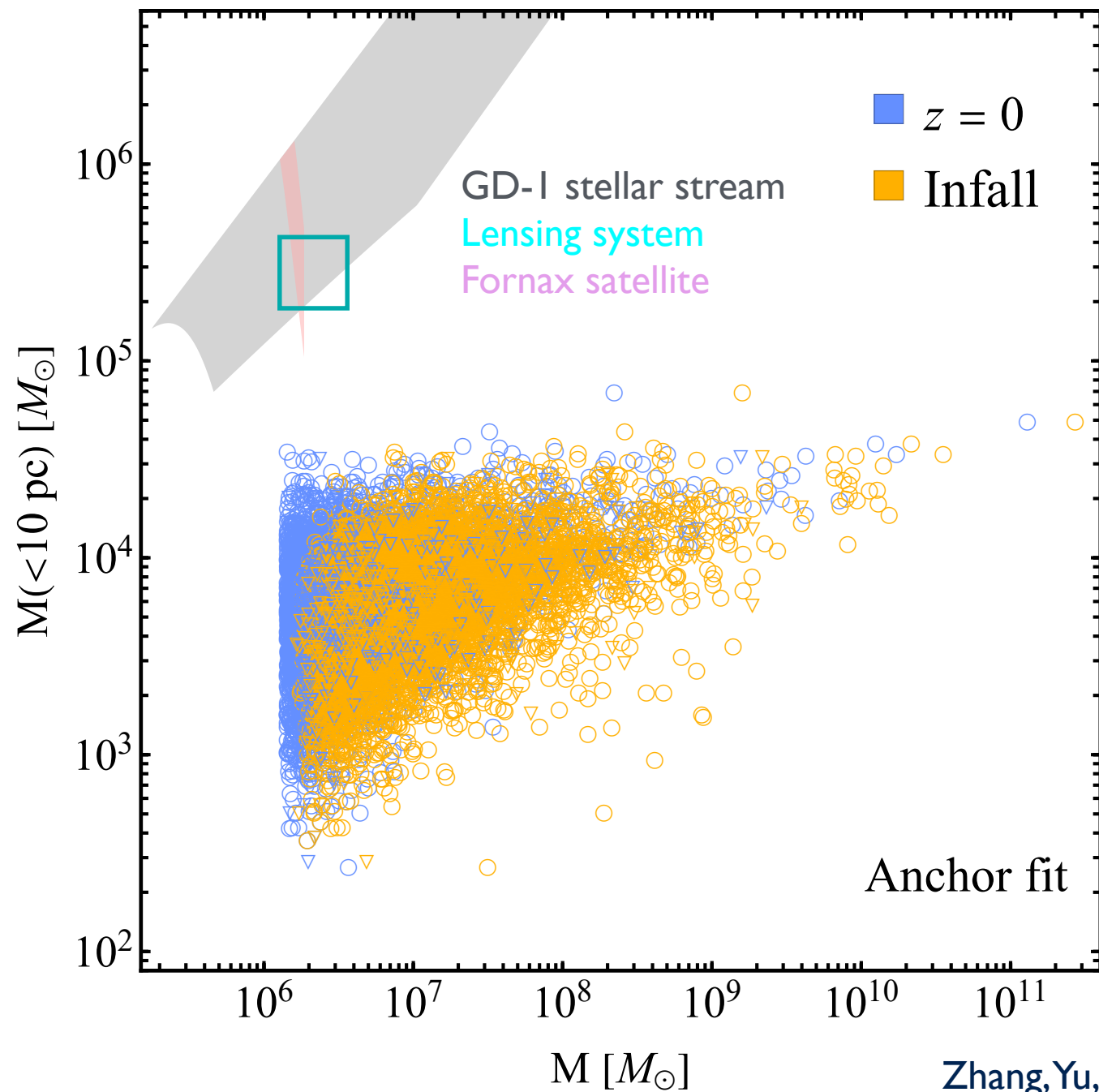
- Positive cross-section measurements on two different halo-mass scales
- Determine the dark matter particle mass and the mediator mass!



Kaplinghat, Tulin, Yu (PRL 2016)



THANK YOU!



Xingyu Zhang
(UCR)

Zhang, Yu, Kong, Nadler (in prep)

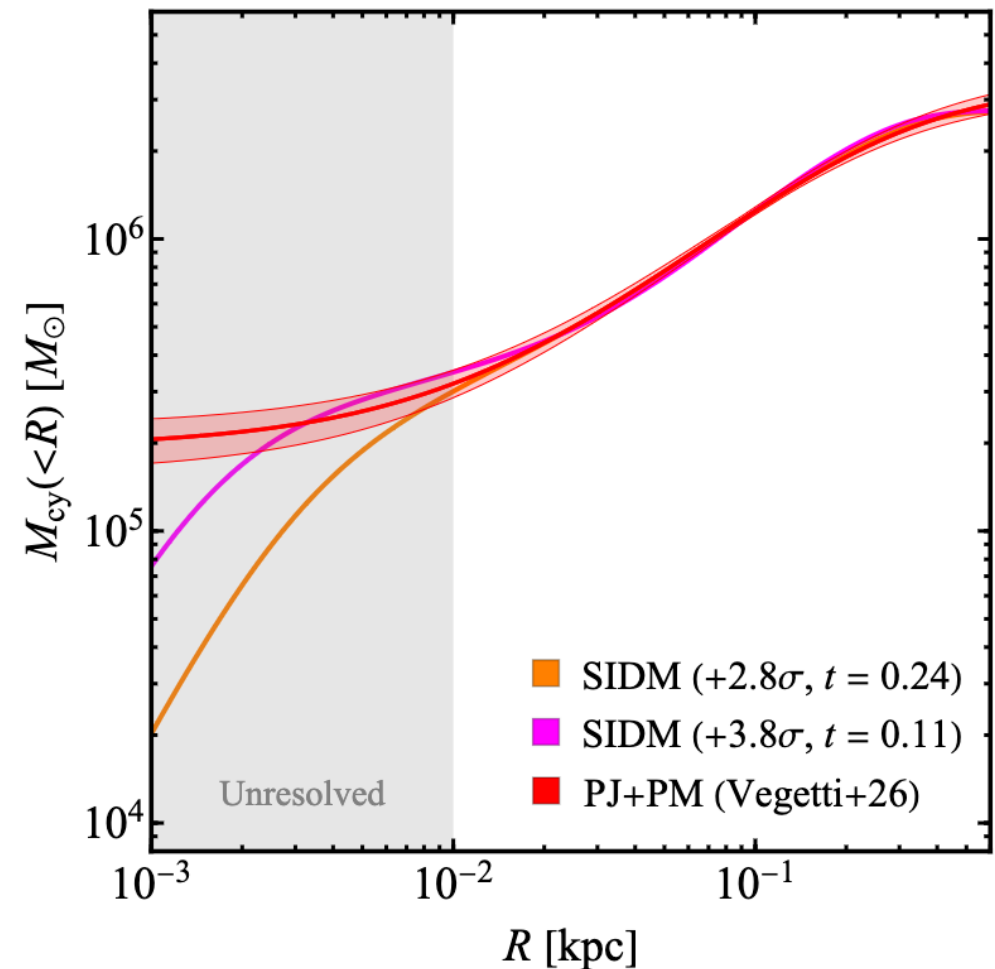
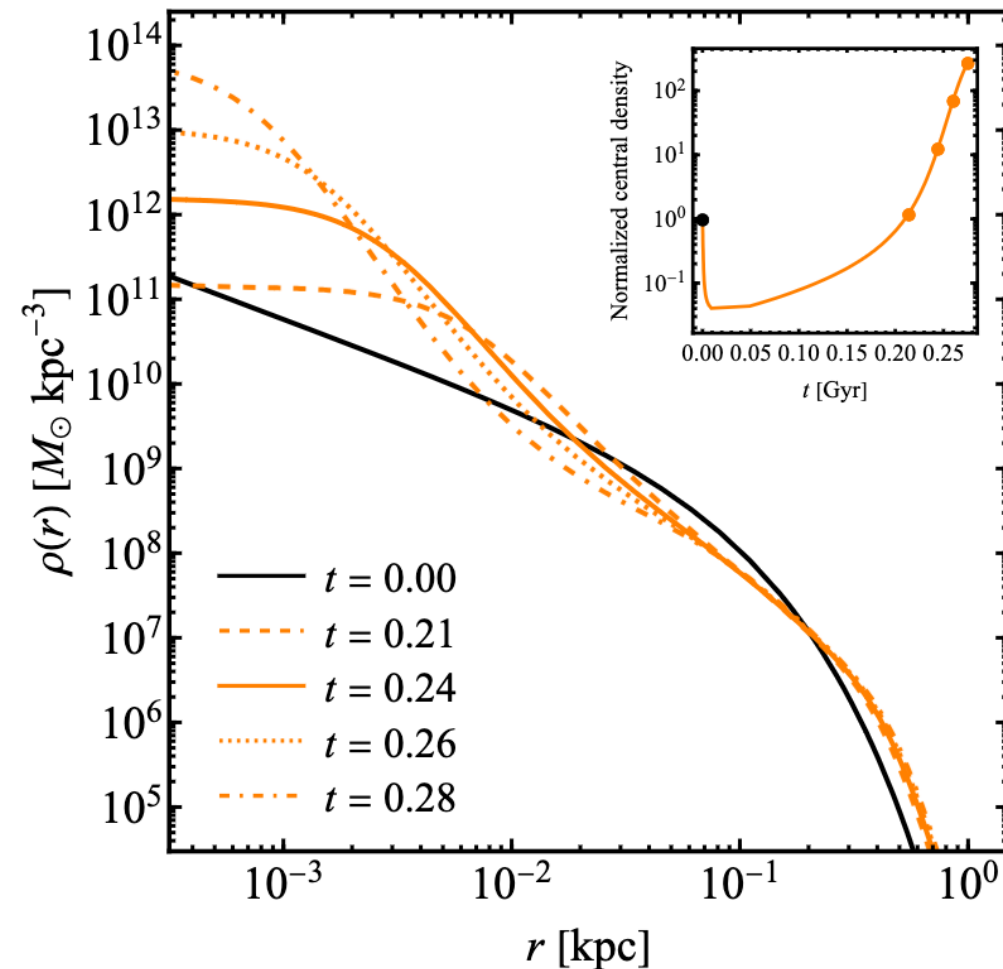
CDM subhalos are not dense enough!

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](#)

$\sim 20\sigma$ “outlier”!

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



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

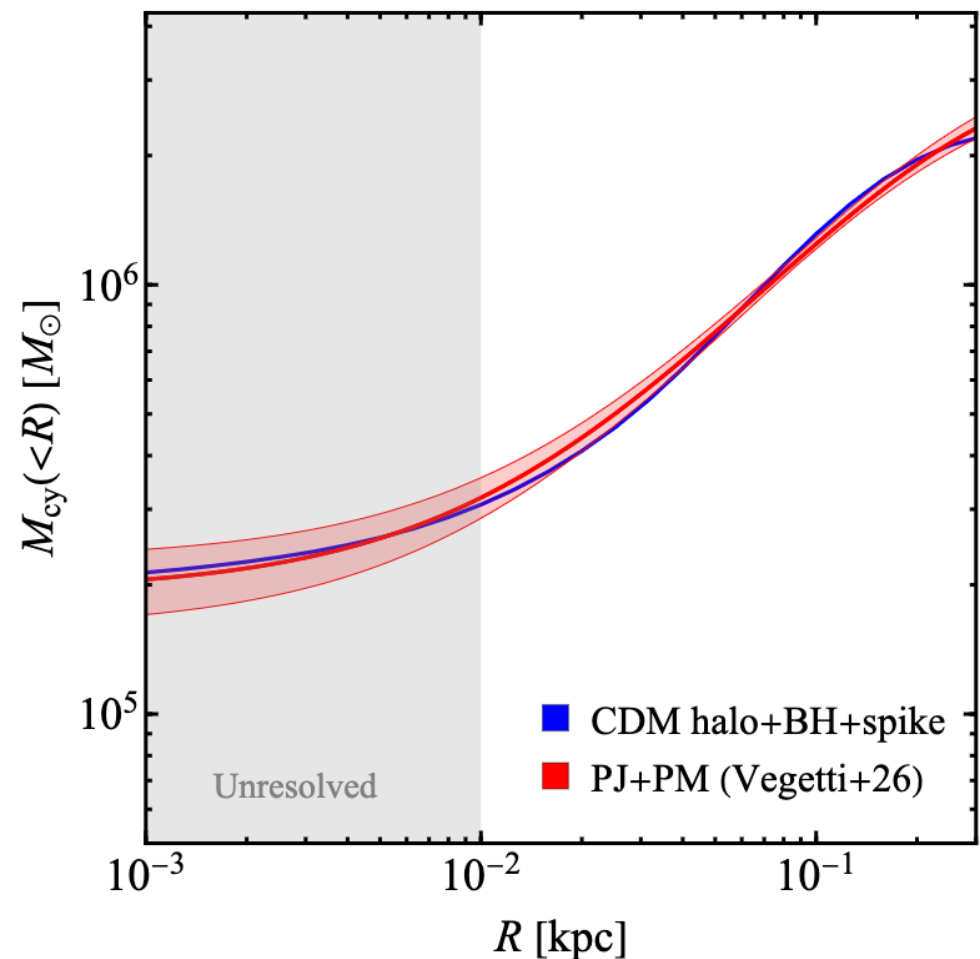
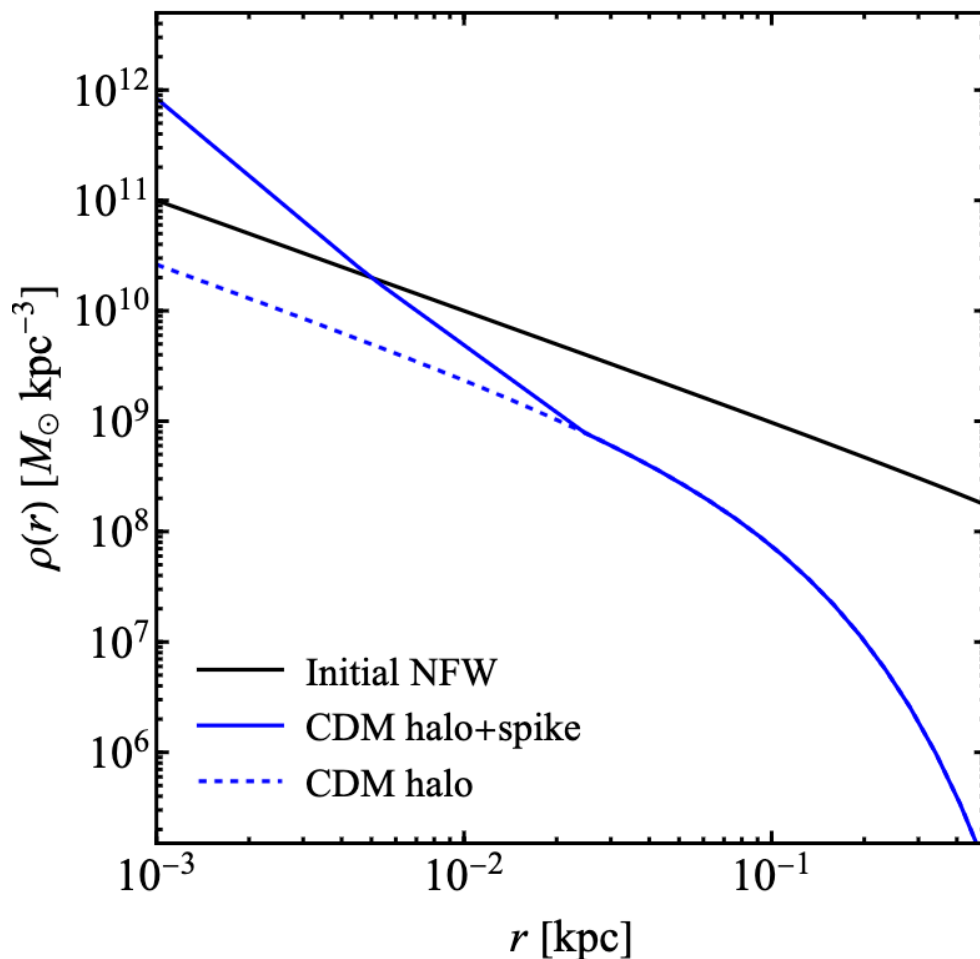
Zhang, Yu (2026)

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](#)

JVAS B1938+666-V

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)