

Dark Matter (I): Overview

Hai-Bo Yu (郁海波)

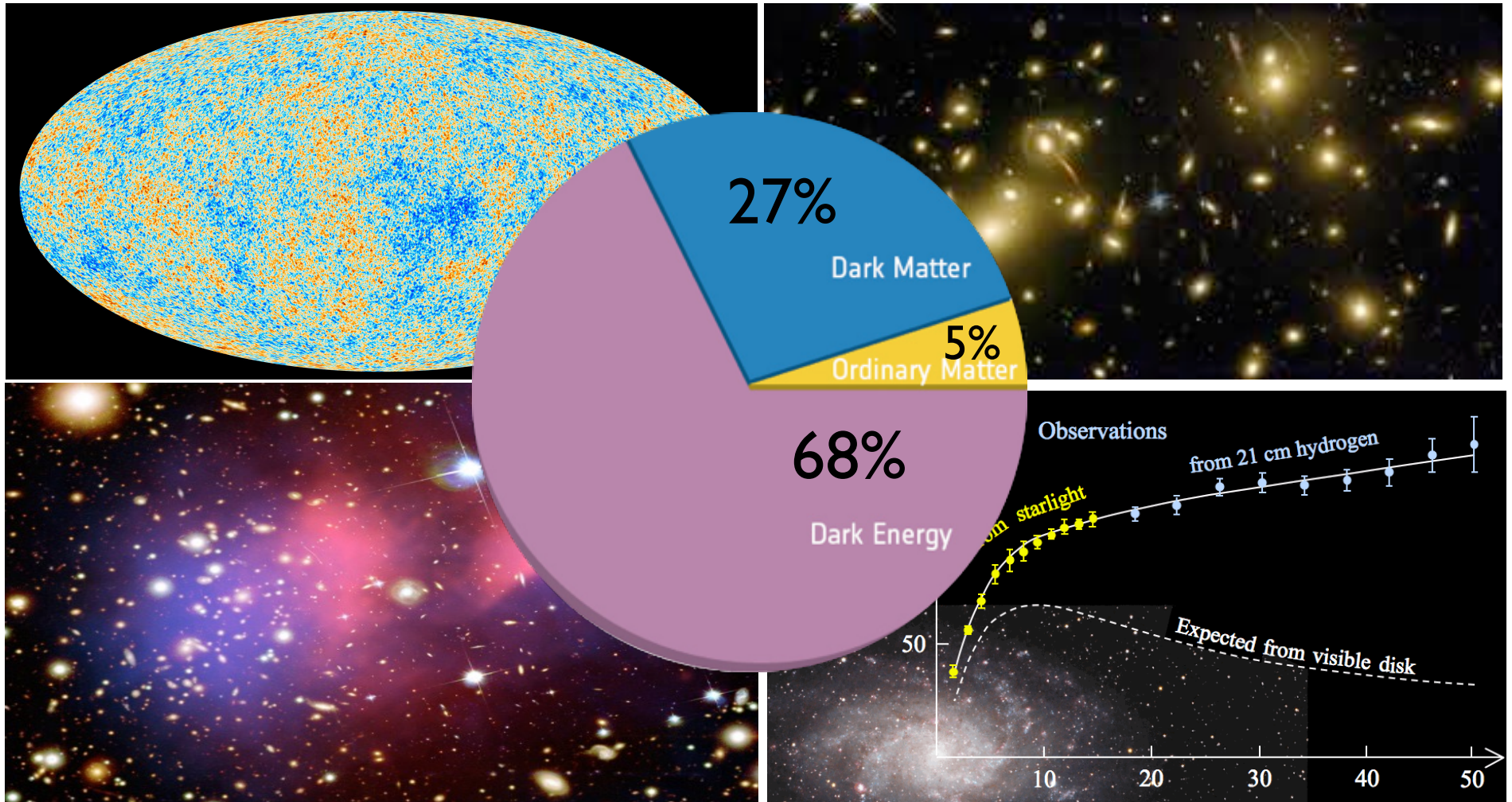
University of California, Riverside



**Fudan Particle Physics Summer
School 2026, August 19-21, 2026**



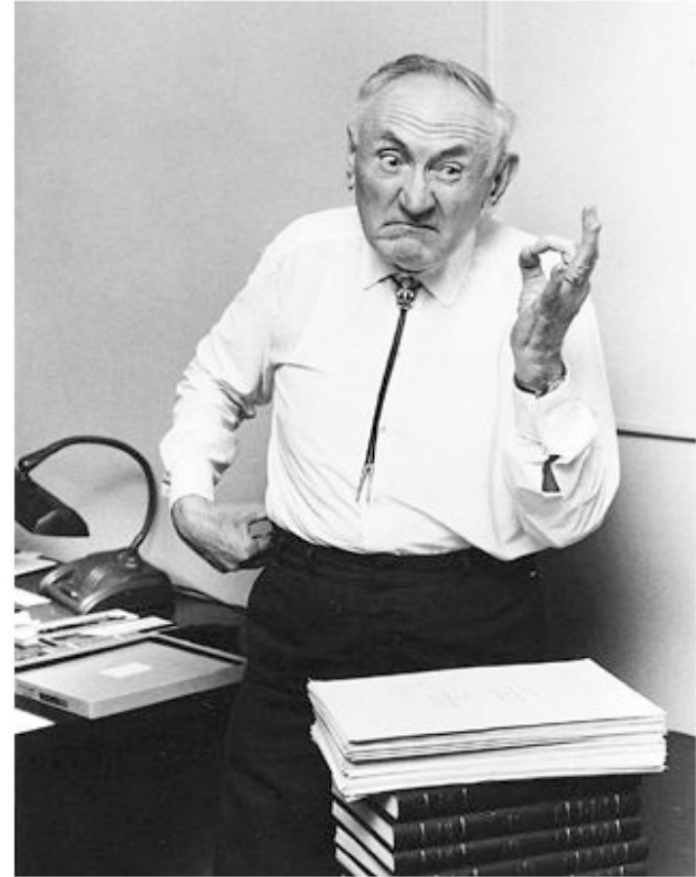
Dark Matter



Coma Cluster



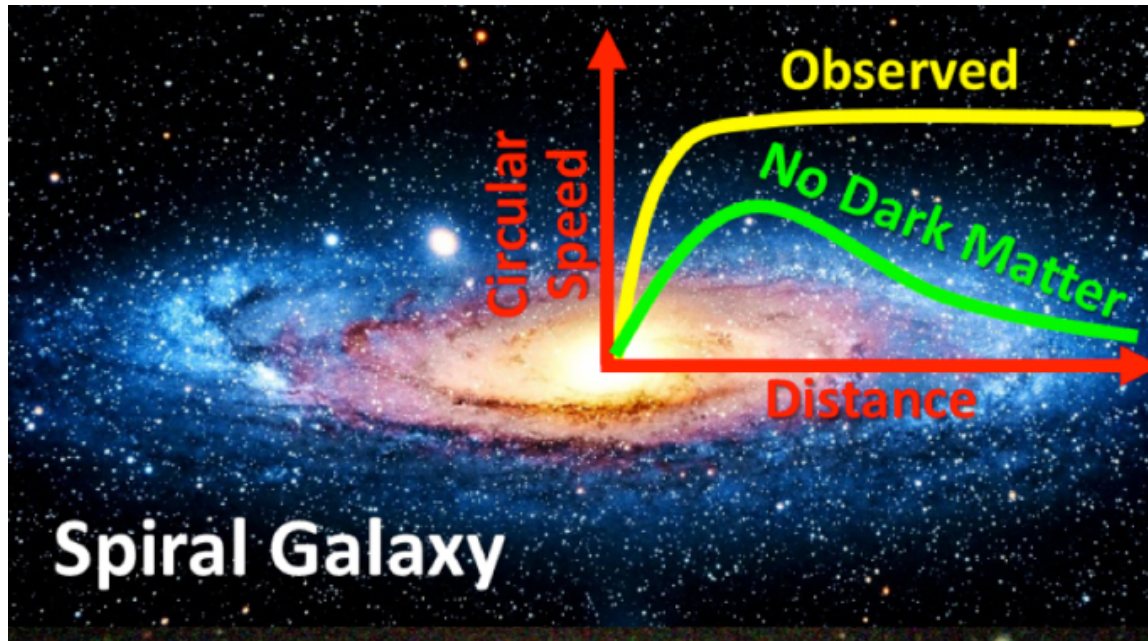
- The galaxies are moving too fast
- The galaxies must be held together by some unseen dark matter
- Based on virial theorem $2\langle T \rangle + \langle V \rangle = 0$



Fritz Zwicky

1930s

Galaxy Rotation Curves



Vera Rubin

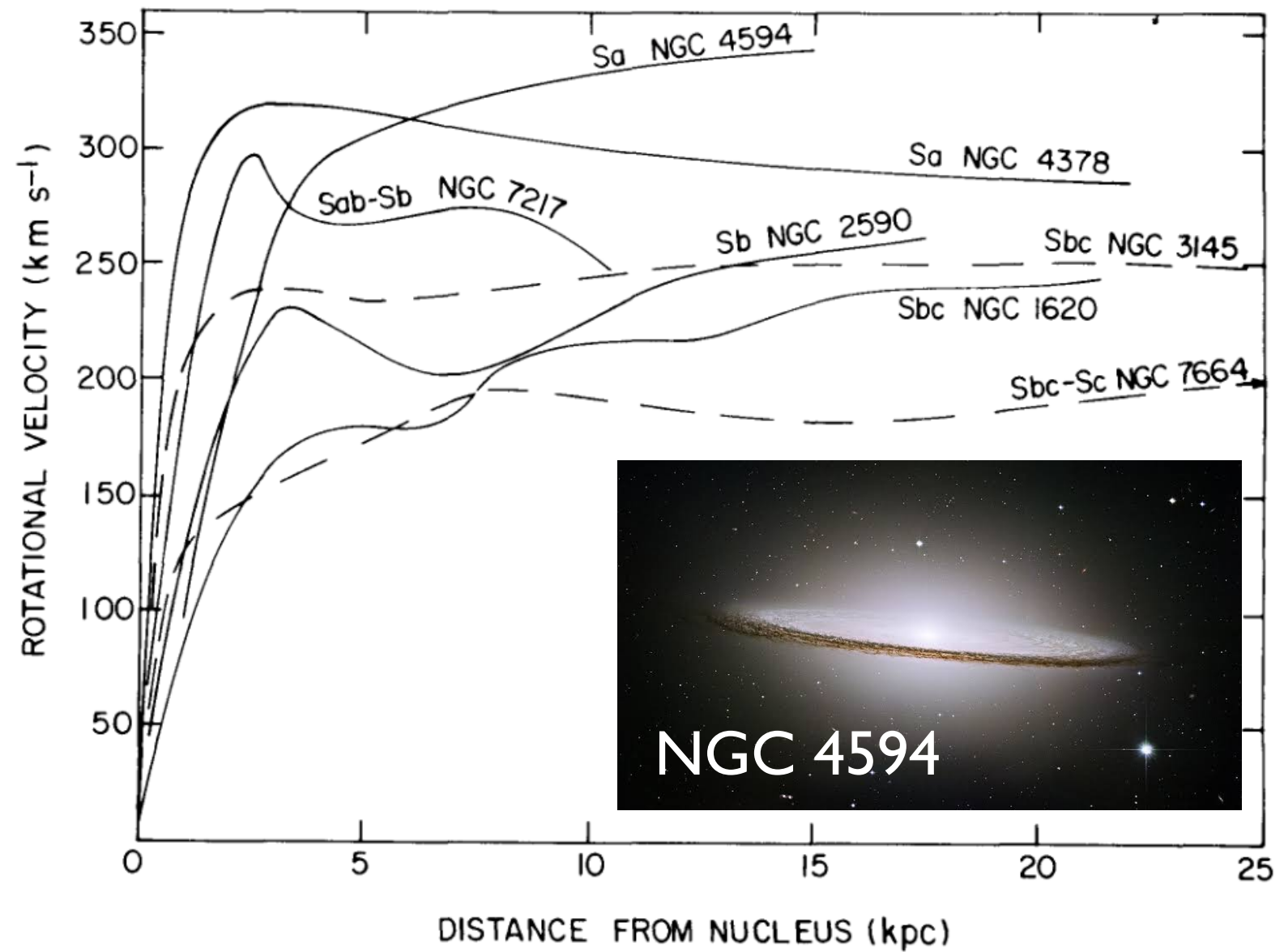
$$V(r) = \sqrt{\frac{GM(r)}{r}}$$

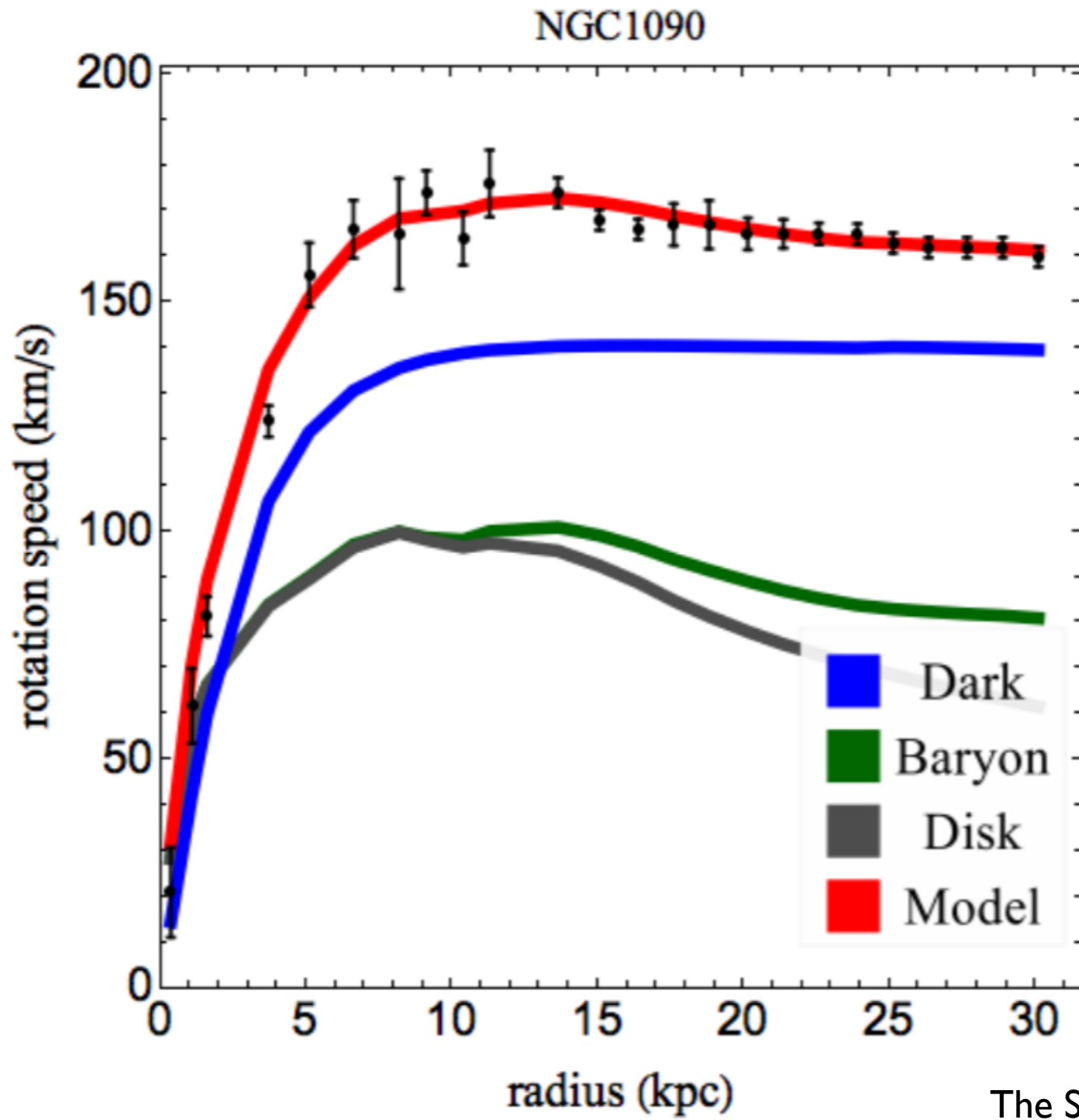
1970s



EXTENDED ROTATION CURVES OF HIGH-LUMINOSITY SPIRAL GALAXIES. IV.
SYSTEMATIC DYNAMICAL PROPERTIES, Sa→Sc

VERA C. RUBIN,*† W. KENT FORD, JR.,* AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1978 June 7; accepted 1978 July 18

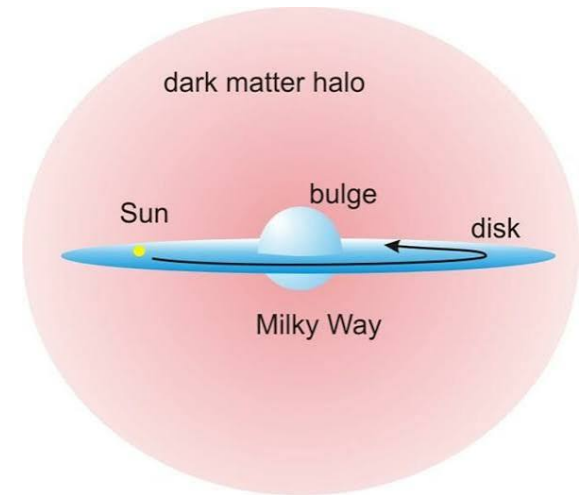
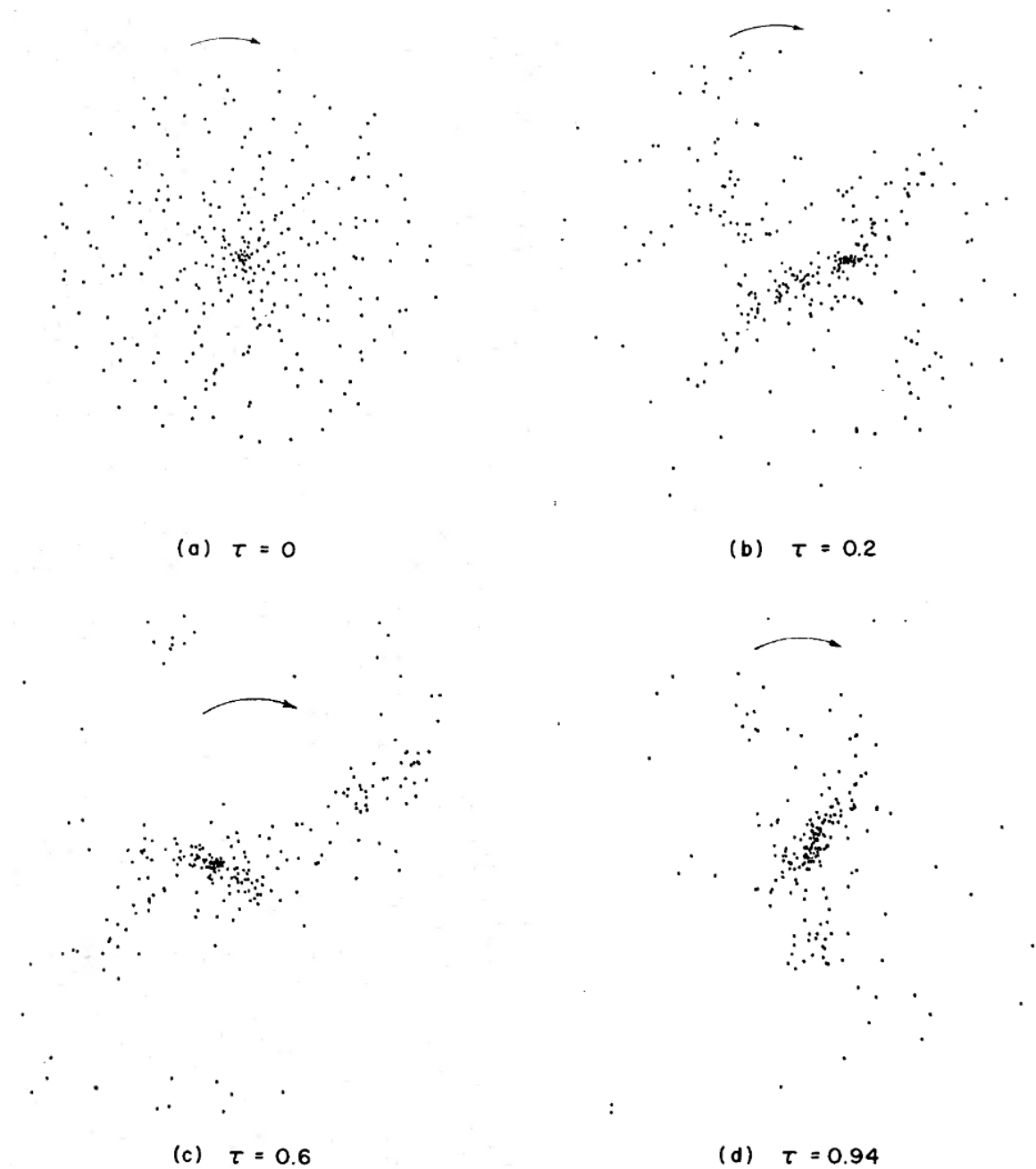




The SPARC database

$$V_{\text{circ}}^2(r) = V_{\text{halo}}^2(r) + V_{\text{gas}}^2(r) + \Upsilon_{\star, \text{disk}} V_{\text{disk}}^2(r)$$

Ren, Kwa, Kaplinghat, Yu (2018)

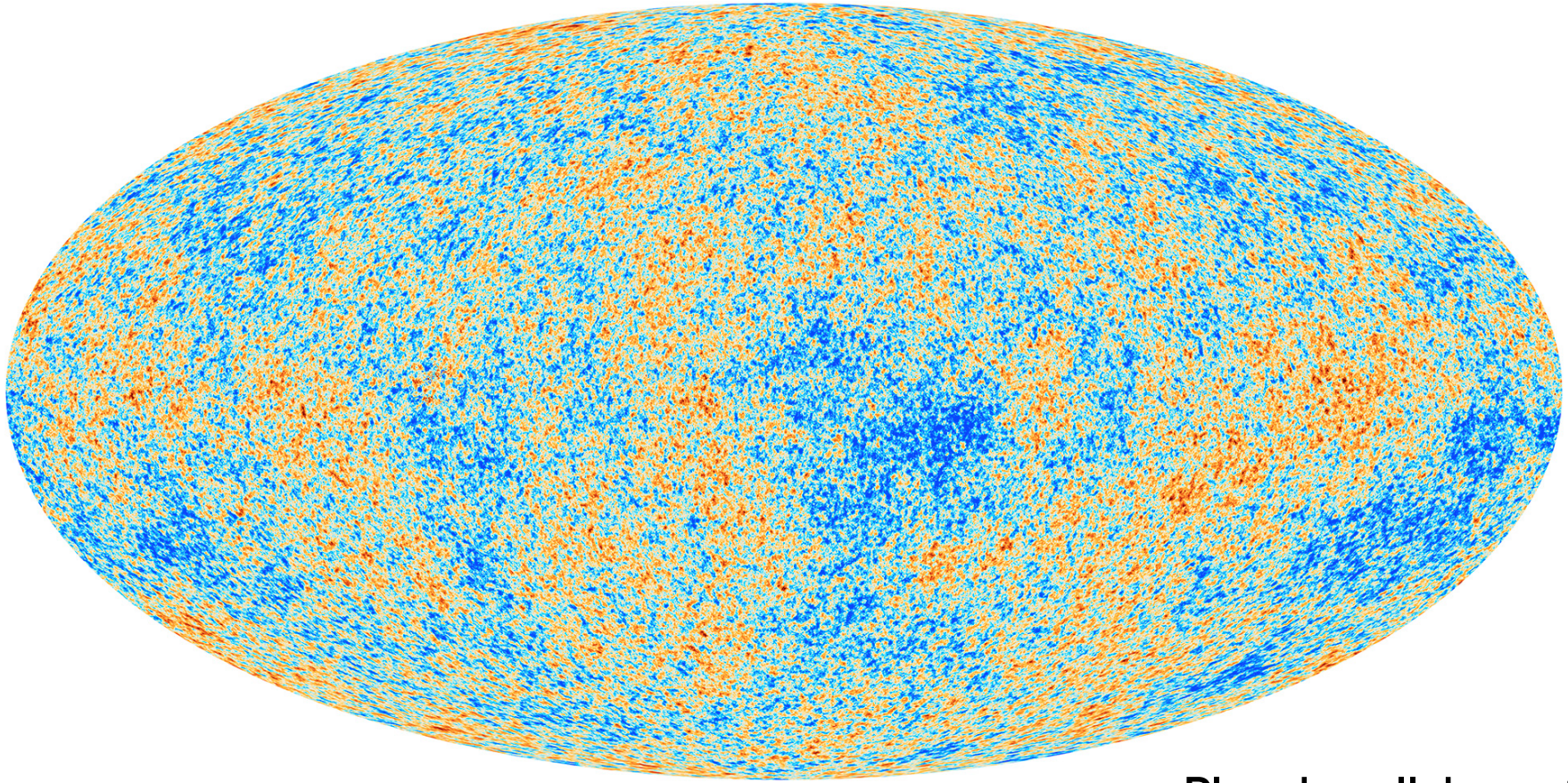


Ostriker, Peebles (1973)

Dynamical evidence:

Without a dark matter halo, a stellar disk is not stable

Cosmic Microwave Background



Planck collaboration

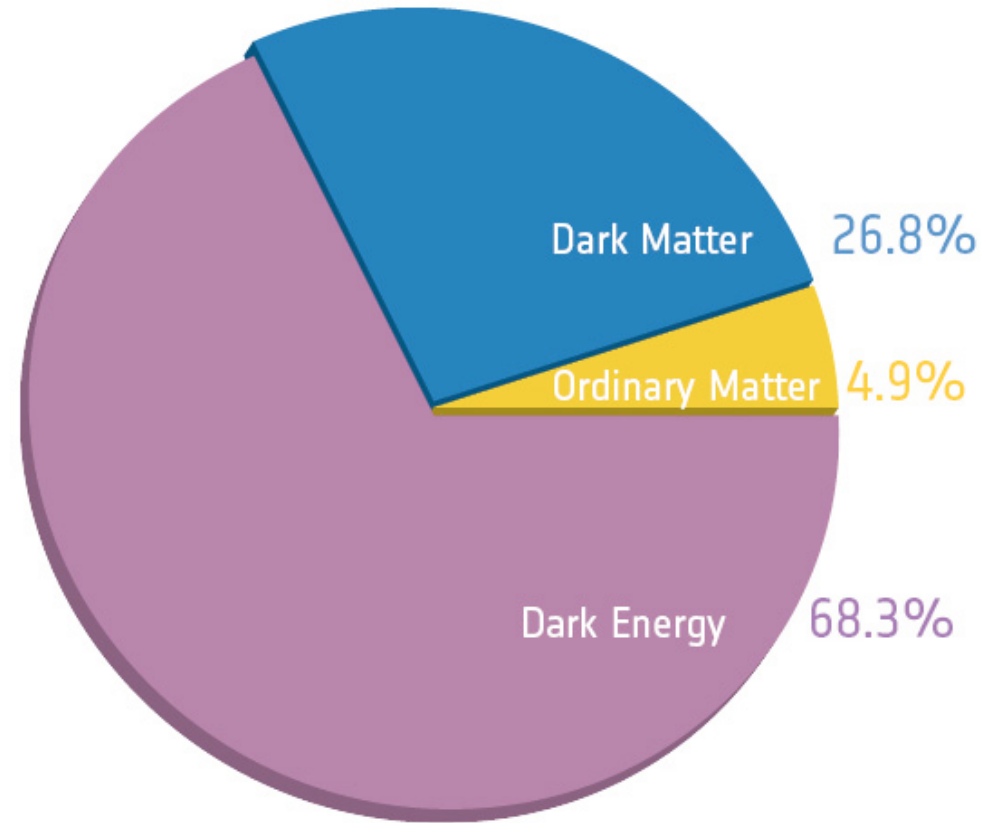
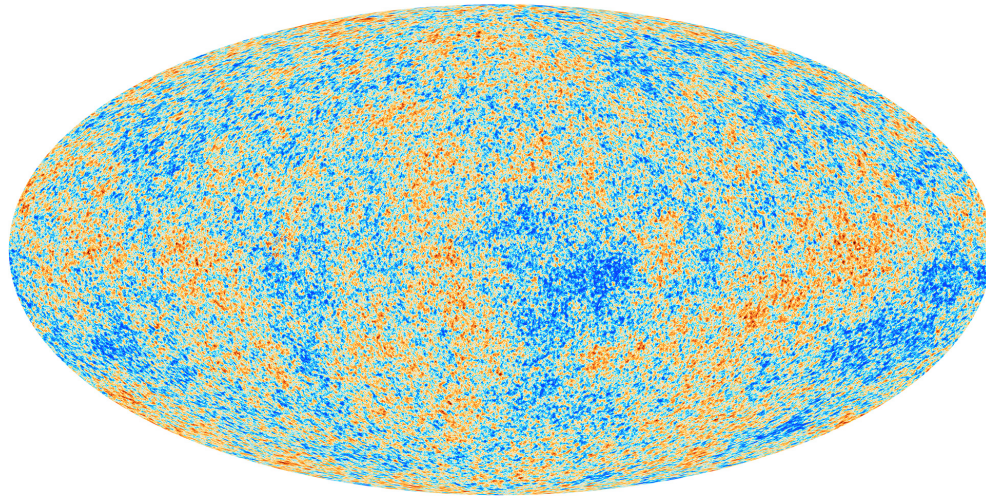
380,000 years after the Big Bang

Age of the Universe: 13.7 Gyr

$$\frac{T - \langle T \rangle}{\langle T \rangle} \sim 10^{-5}$$

1990s-2010s

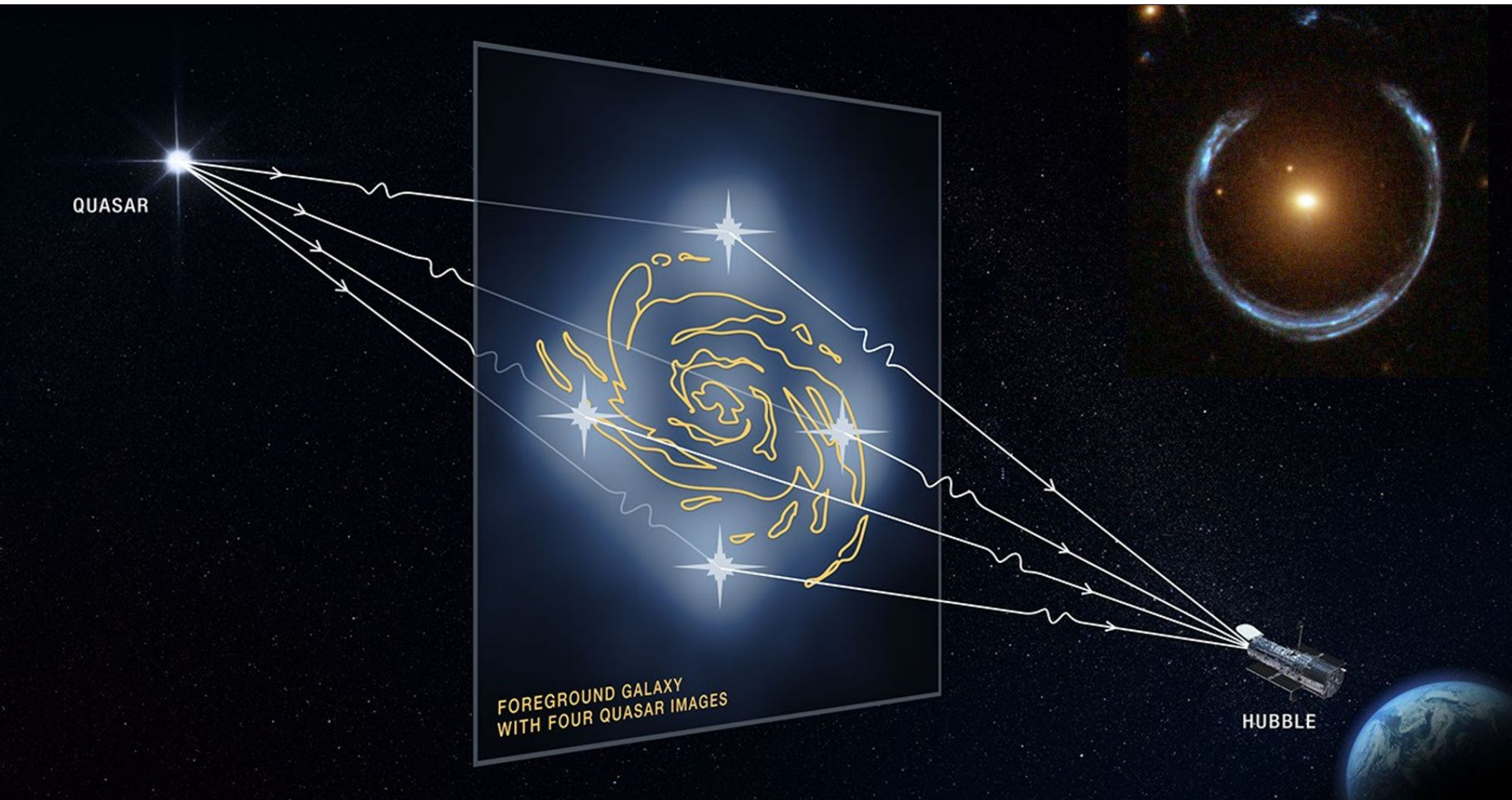
Components of the Universe



Cosmic scale:

Dark matter accounts for 27% of the total energy density of the Universe; 85% in mass

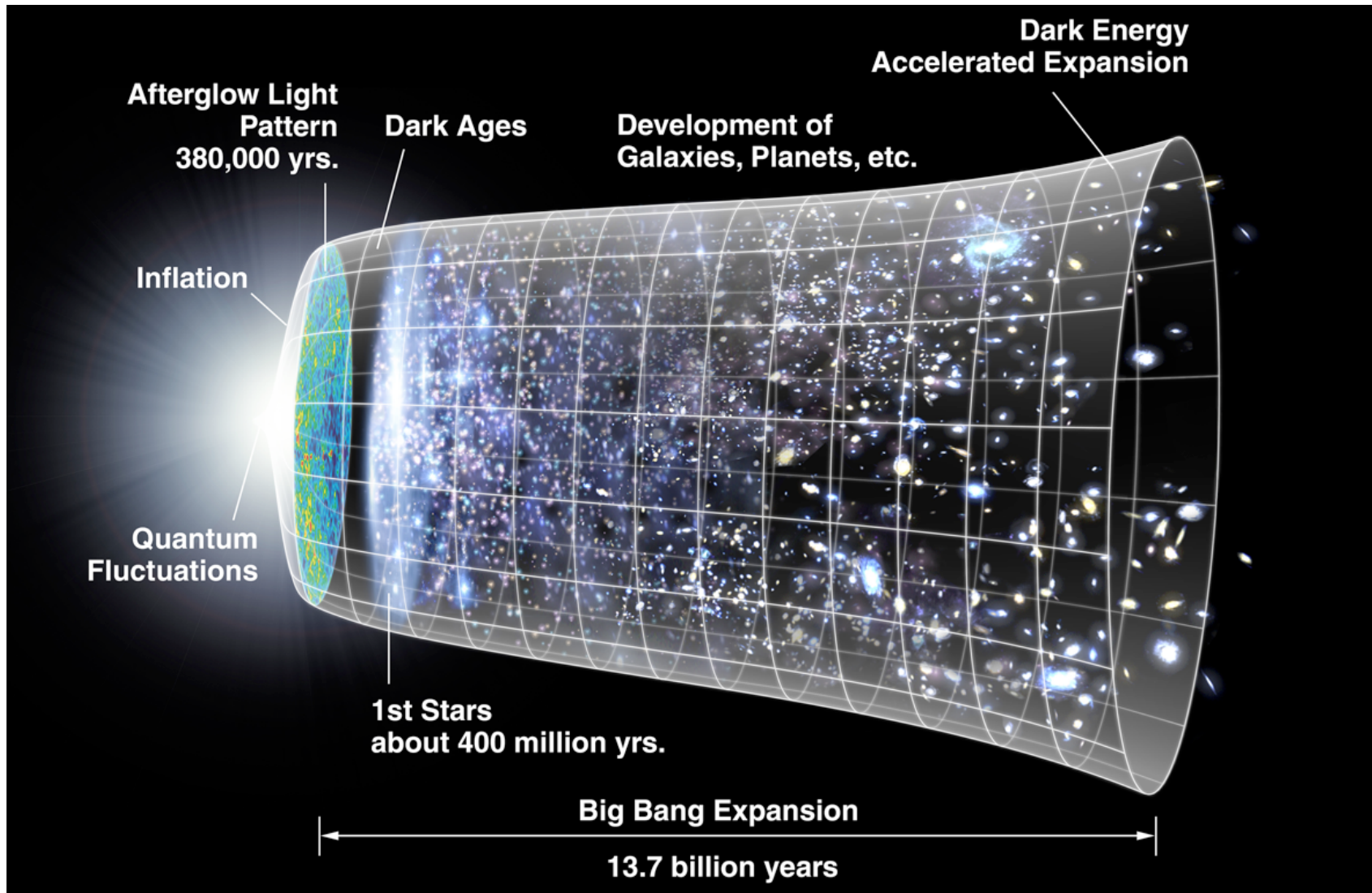
Gravitational Lensing



<https://science.nasa.gov/asset/hubble/illustration-of-strong-gravitational-lensing/>

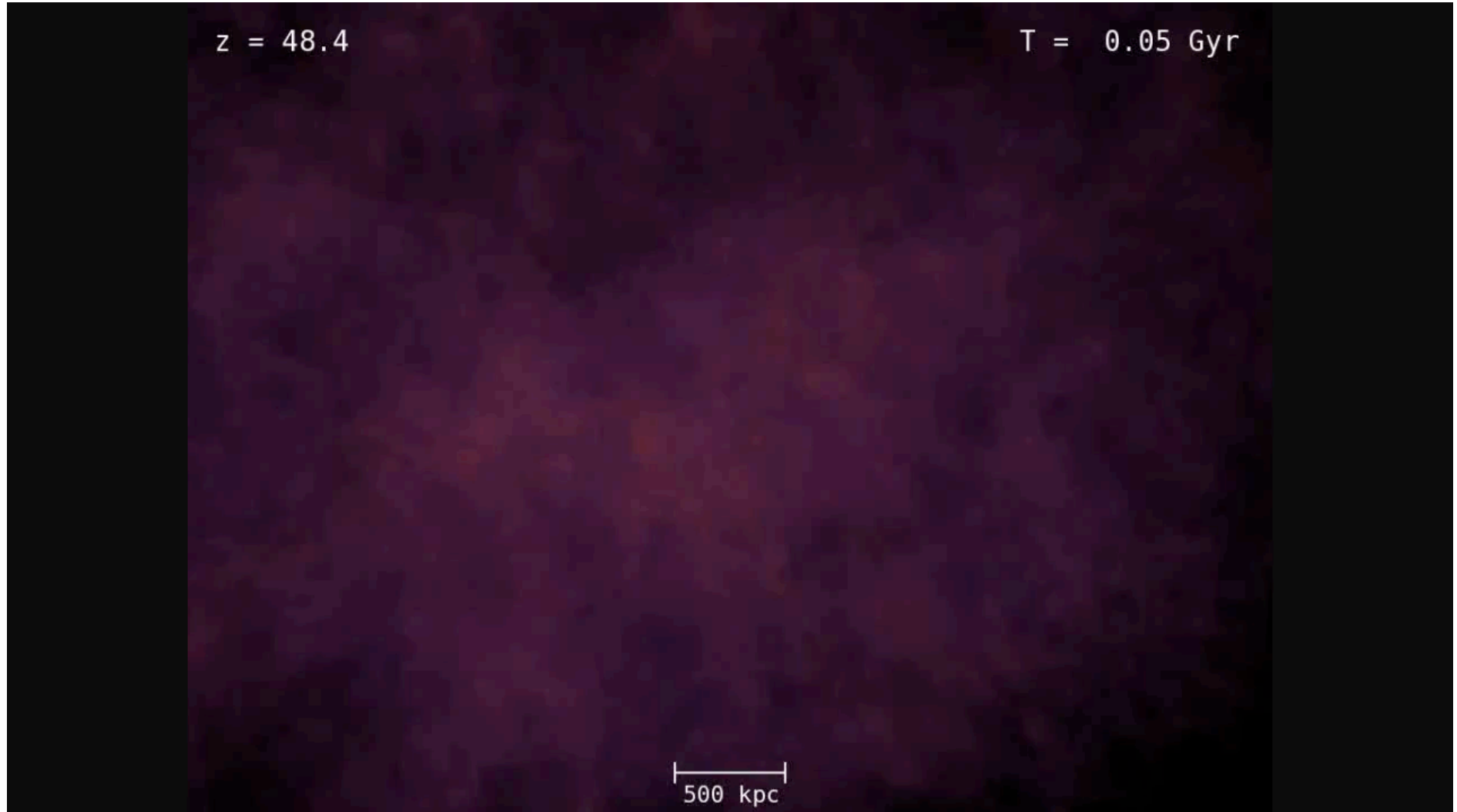
1990s-present

History of the Universe



Dark matter provides the seed for cosmic structure formation

Cosmic Structure Formation

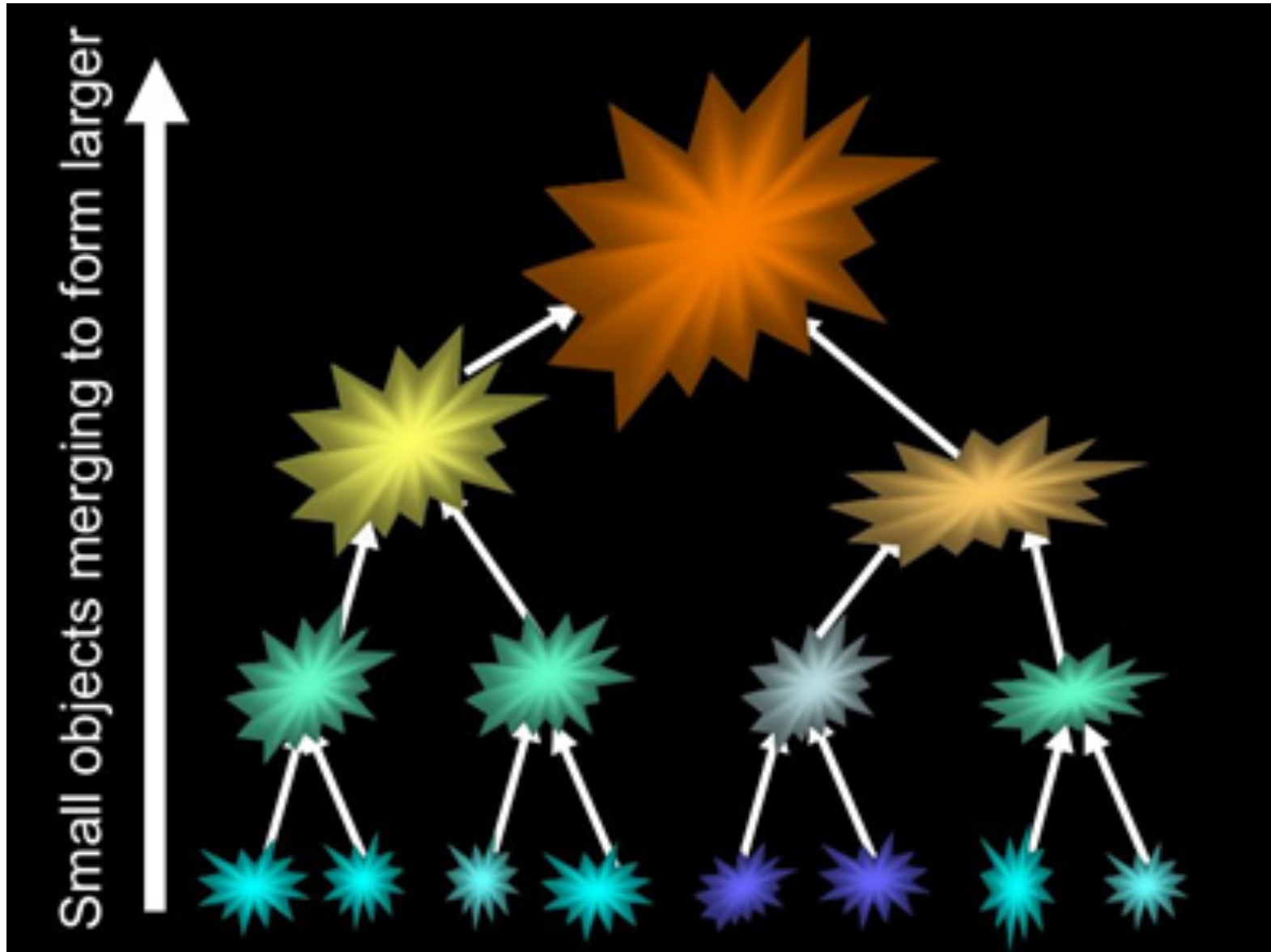


Aquarius Simulation

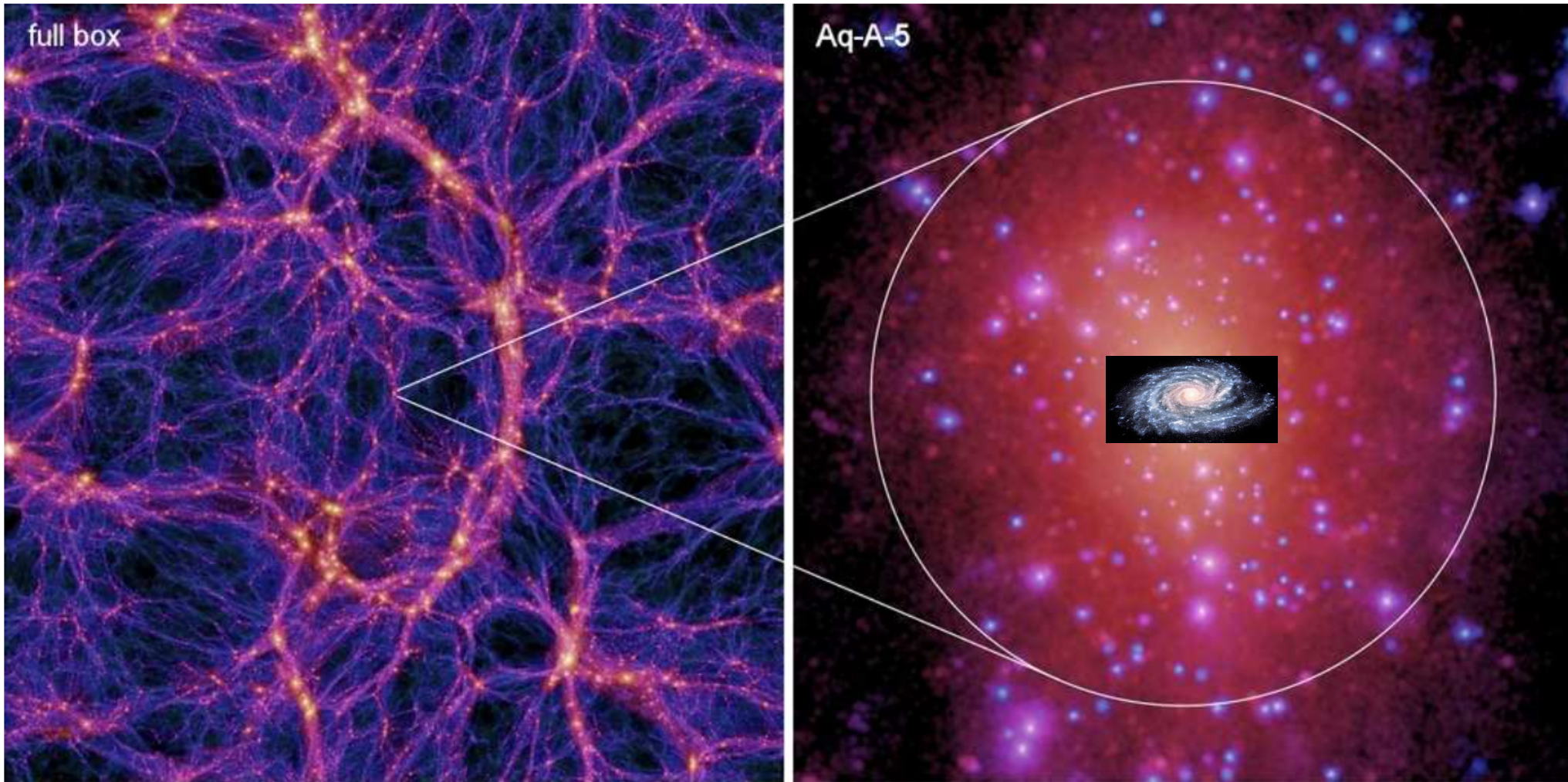
Springel et al. (2008)

1 parsec = 3.26 light years

Hierarchical Clustering



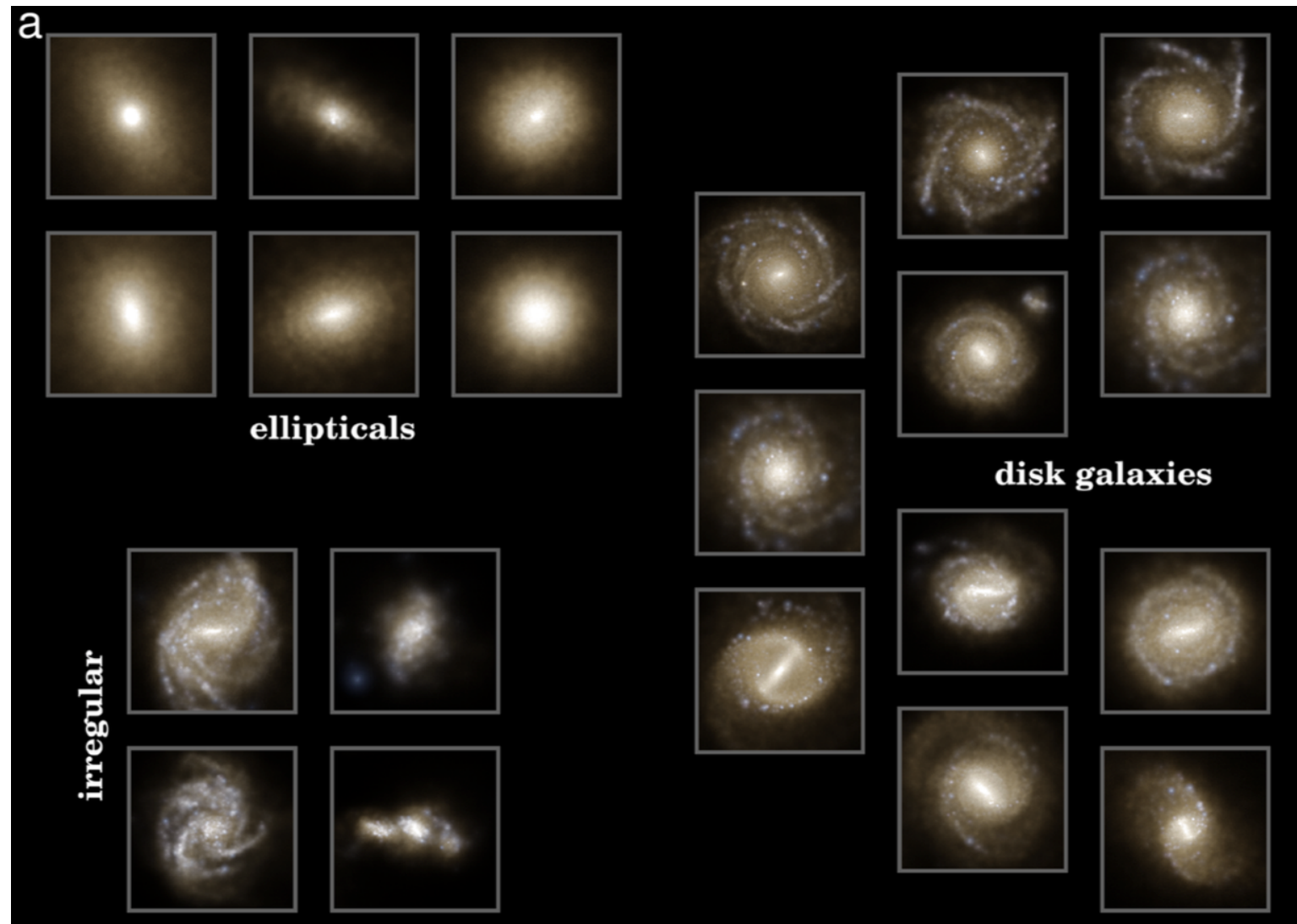
Dark Matter Halos: Hosting Galaxies



Aquarius Project, Springel+(2008)

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

Predictions on Galactic Scales



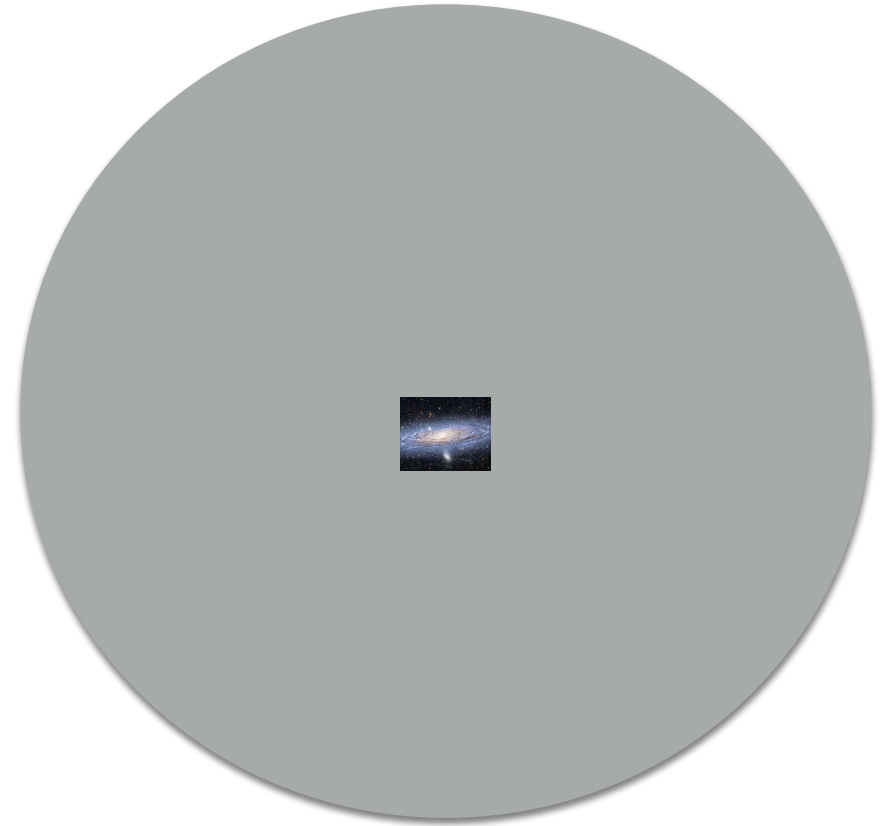
Illustris Project, Vogelsberger+ (Nature, 2014)

Produce a variety of galaxy types overall consistent with observations

The Milky Way



luminous component



dark matter halo

Total luminous matter: $\sim 7 \times 10^{10} M_{\odot}$; dark matter halo: $\sim 10^{12} M_{\odot}$

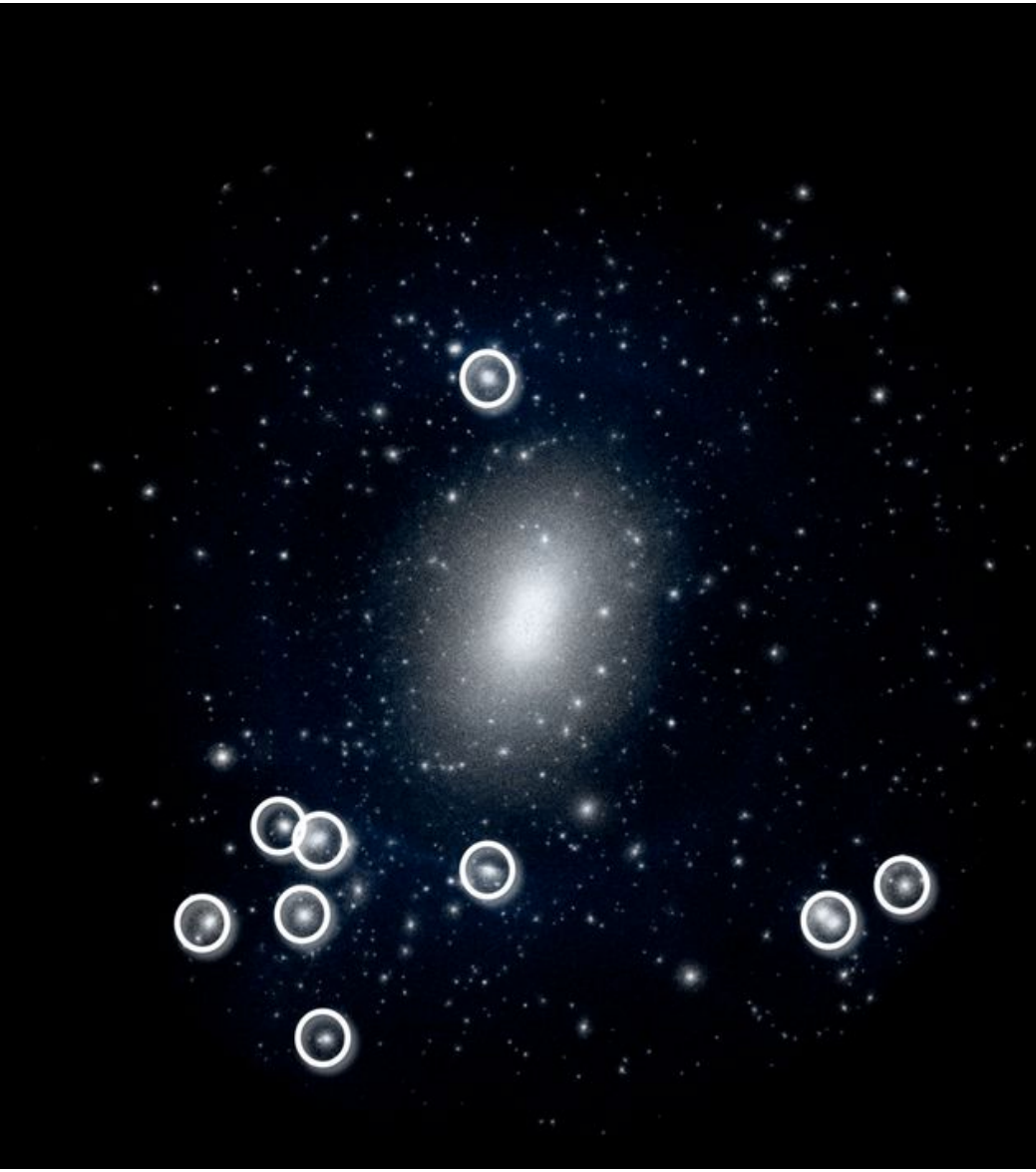
Luminous radius: 15 kpc; viral radius of the dark matter halo: 200-300 kpc

Near the solar system:

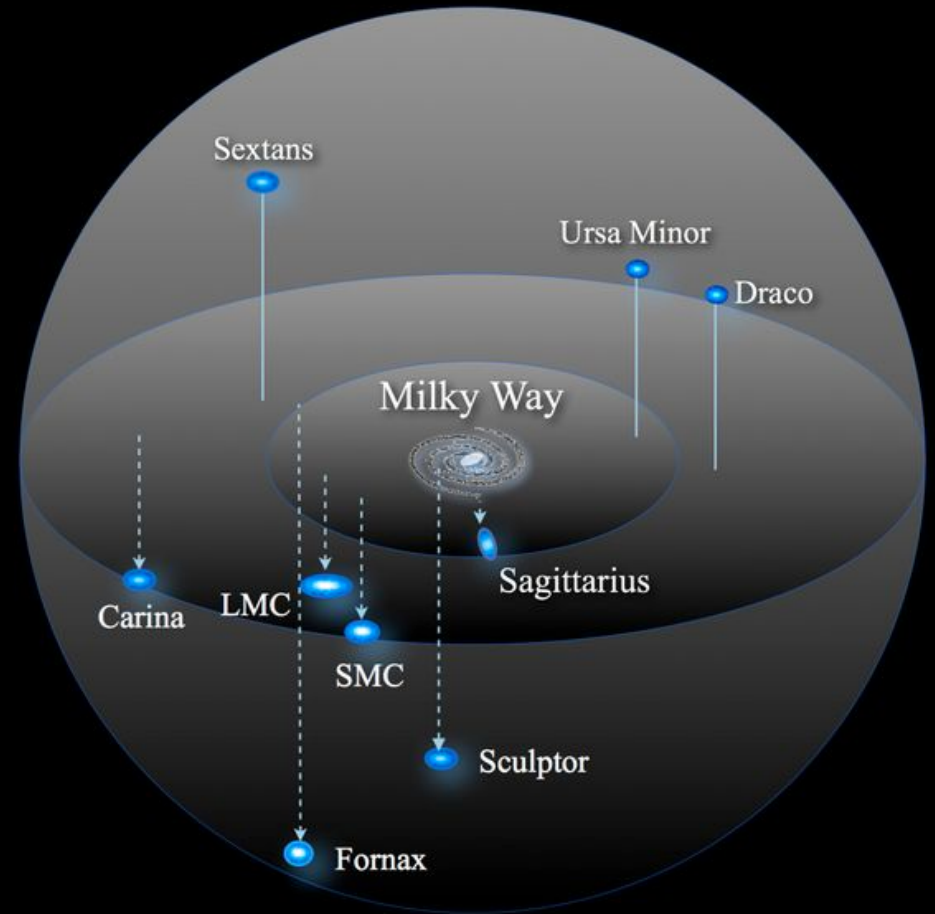
Density: about one particle per tea cup (if its mass is 100 times m_p)

Velocity: ~ 200 km/s

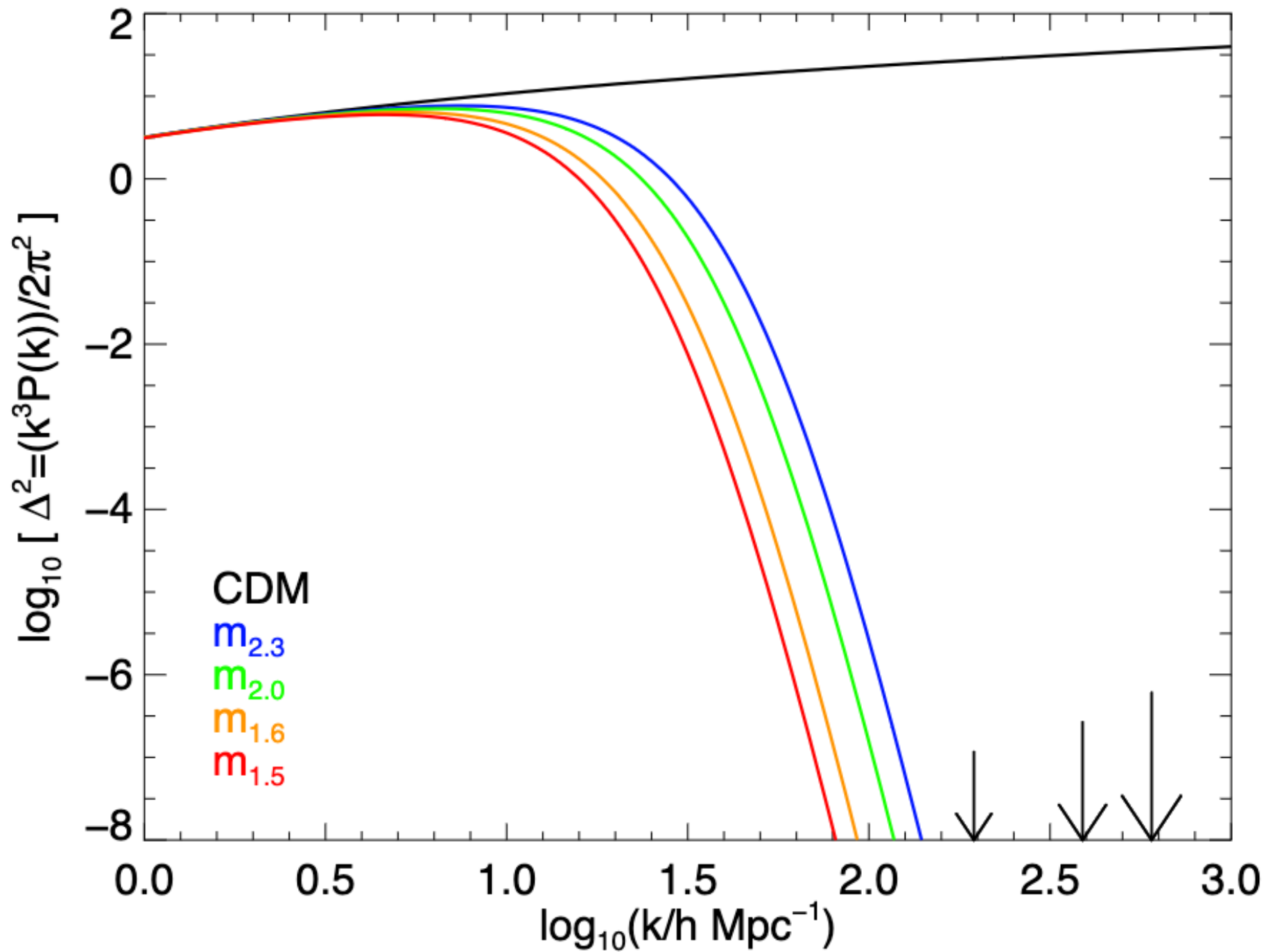
Simulations vs. Observations



Satellite dwarf halos in simulations



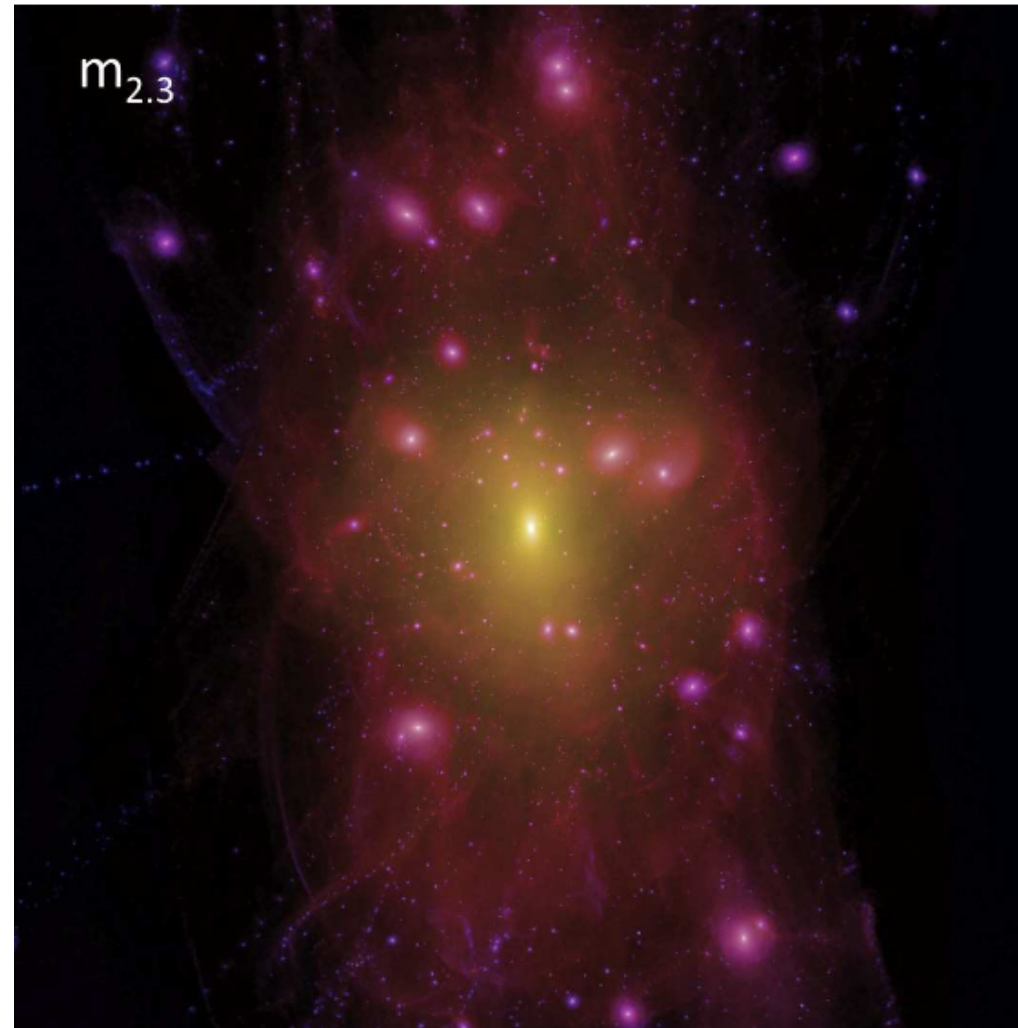
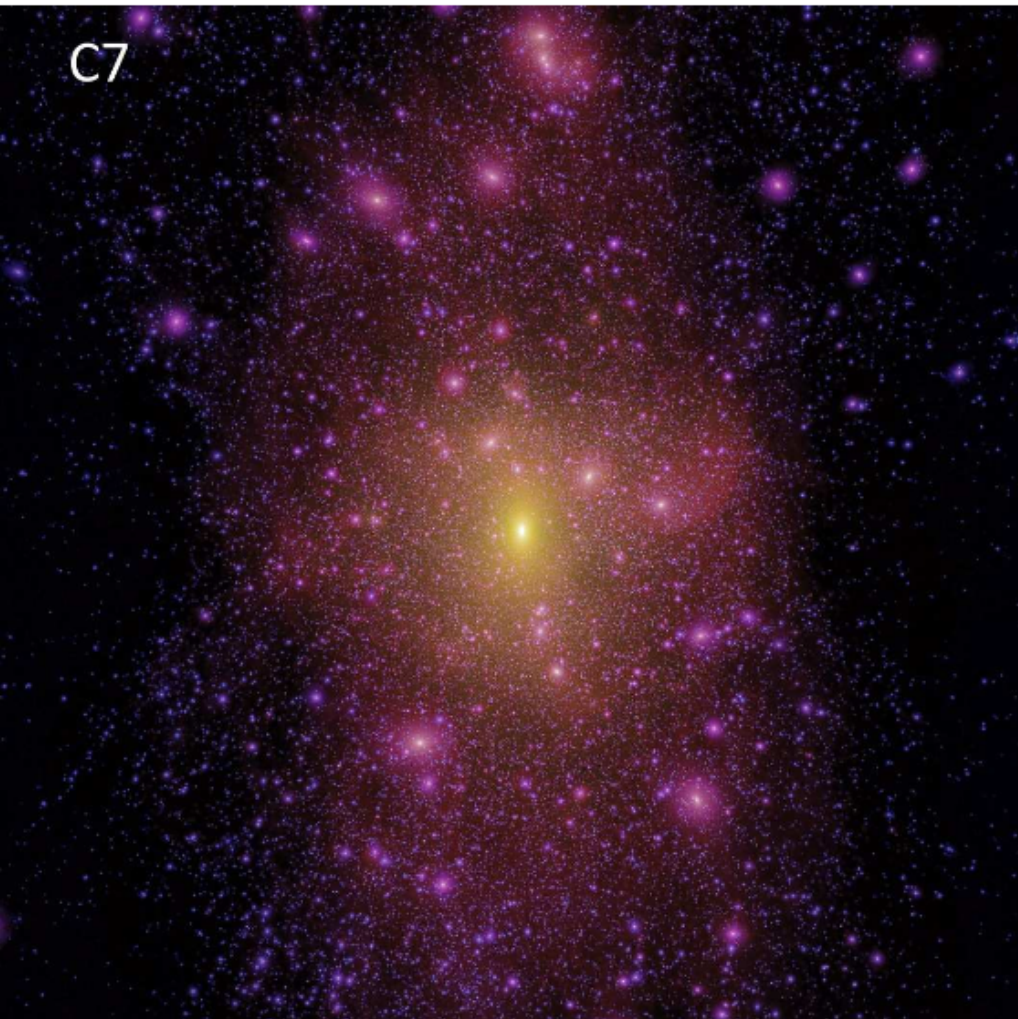
Satellite dwarf galaxies of the Milky Way
~60 small galaxies are associated the Milky Way



Cold Dark Matter vs Warm Dark Matter

Lovell+(2014)

CDM vs. WDM

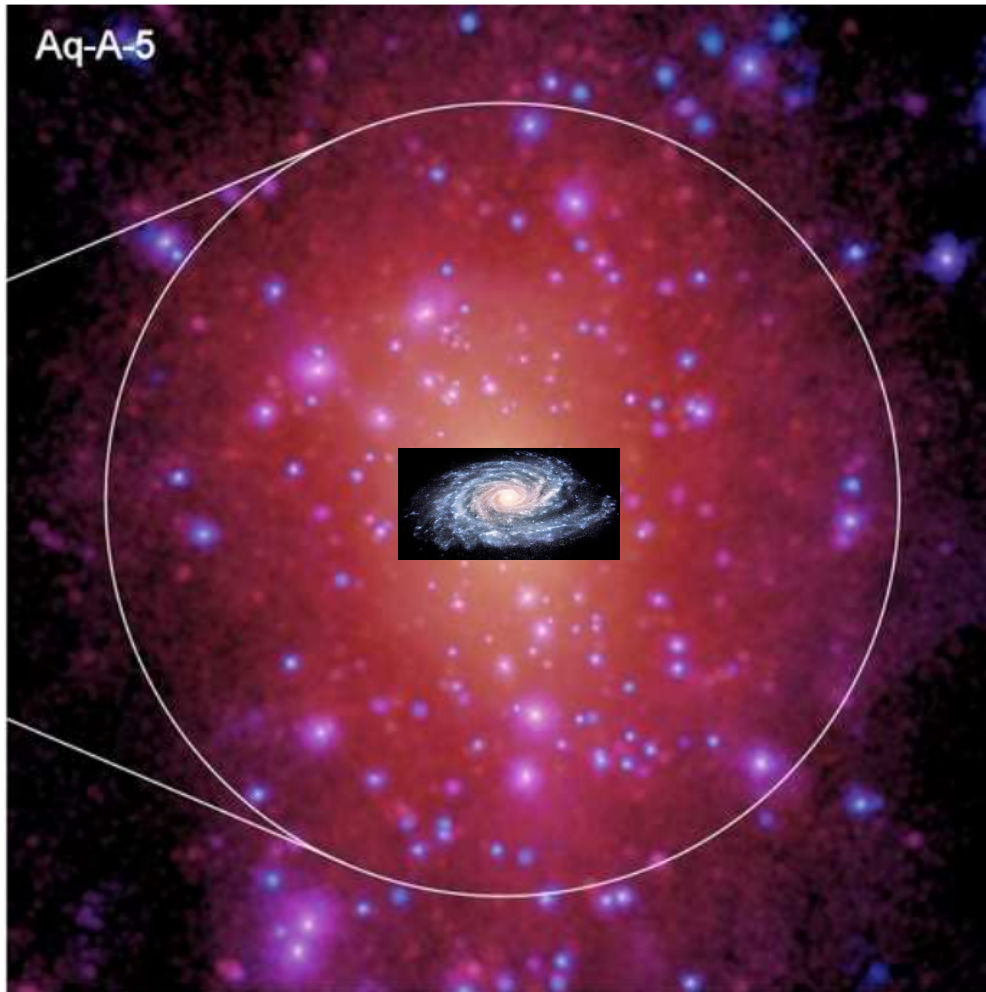


Lovell+(2014)

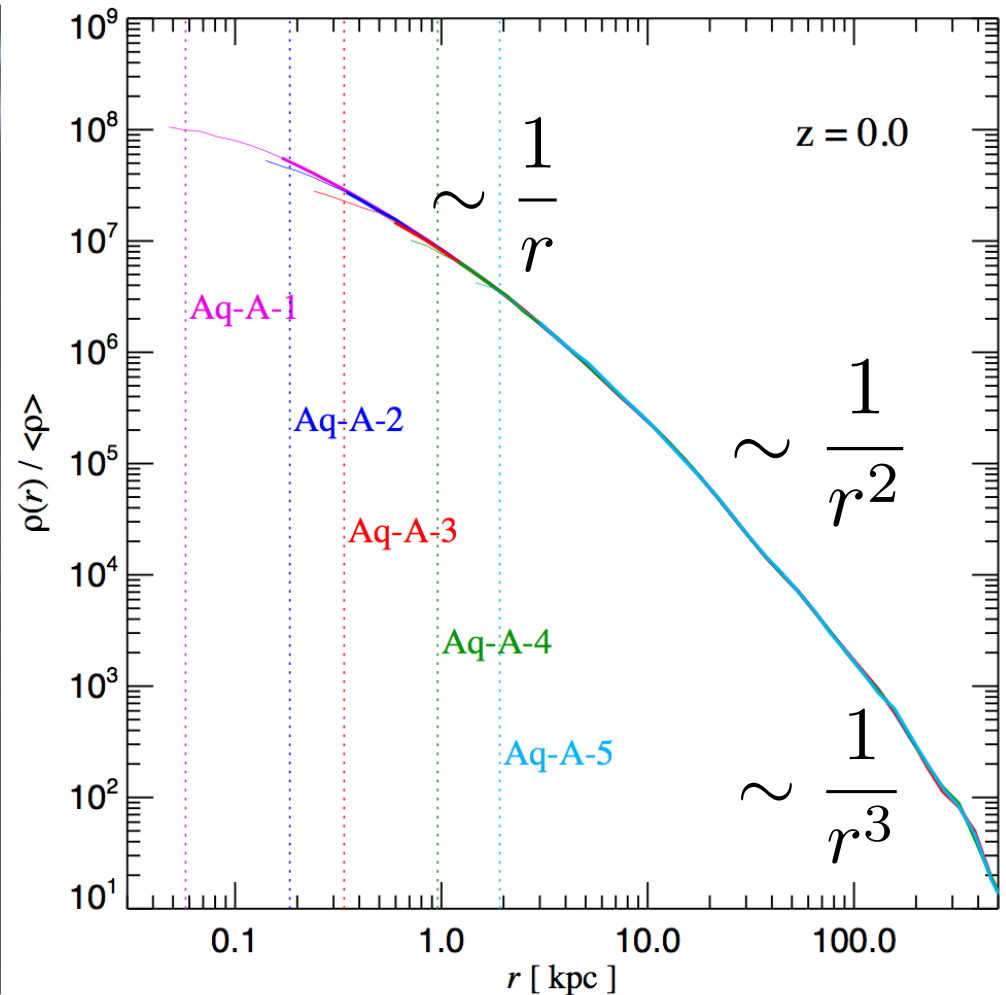
Current limit: the mass of thermal relic WDM must be larger than 6.6 keV

Tan, Dekker, Drlica-Wagner (2025)

CDM: Universal Density Profile

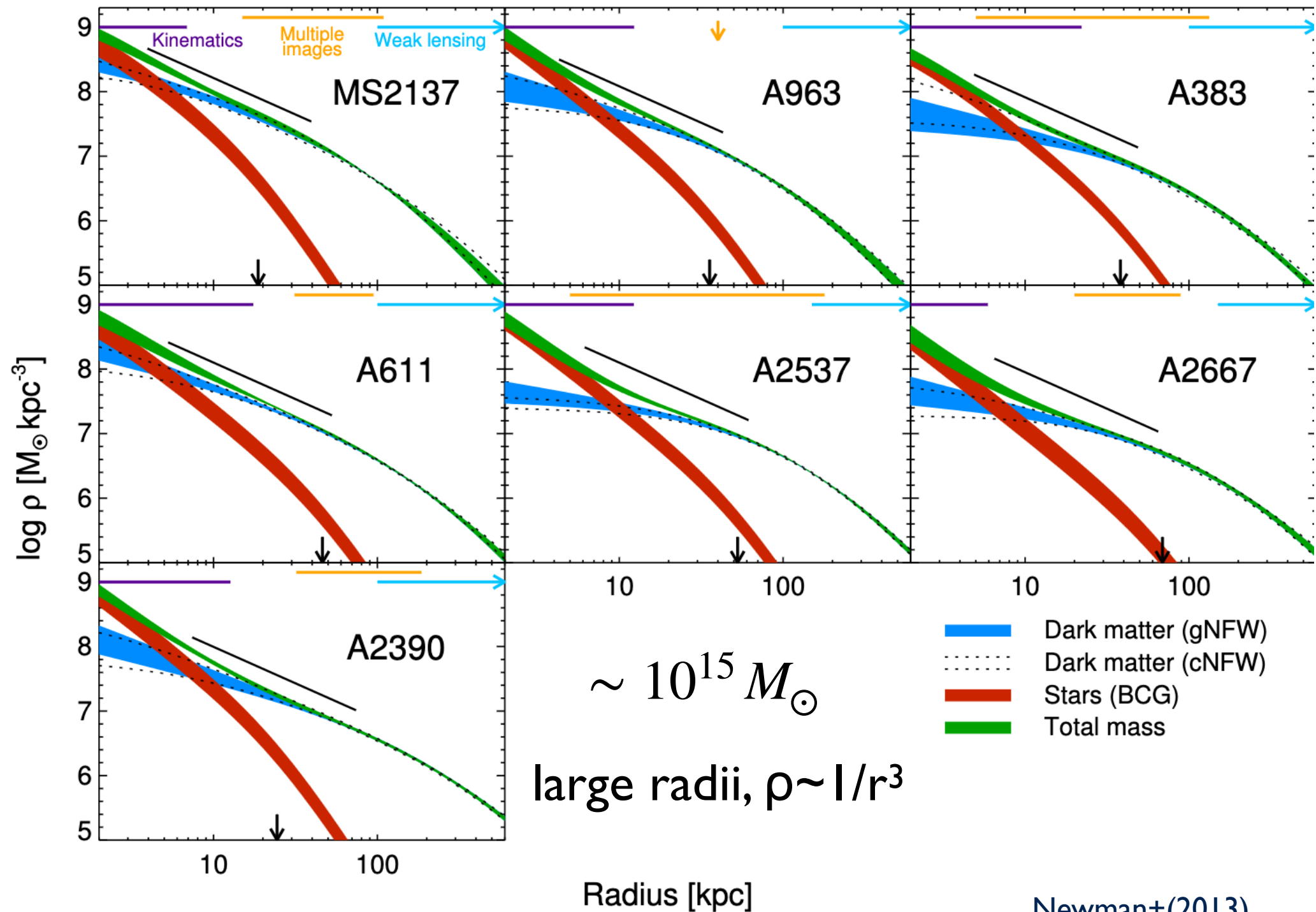


Aquarius Project, Springel+ (2008)



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

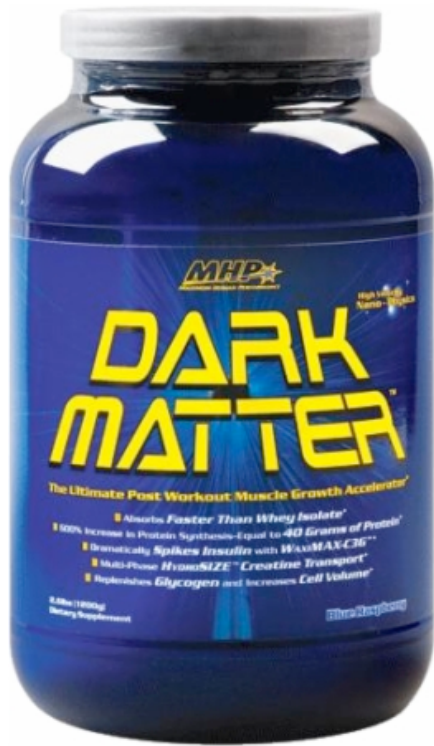
the Navarro-Frenk-White (NFW) profile (1996)



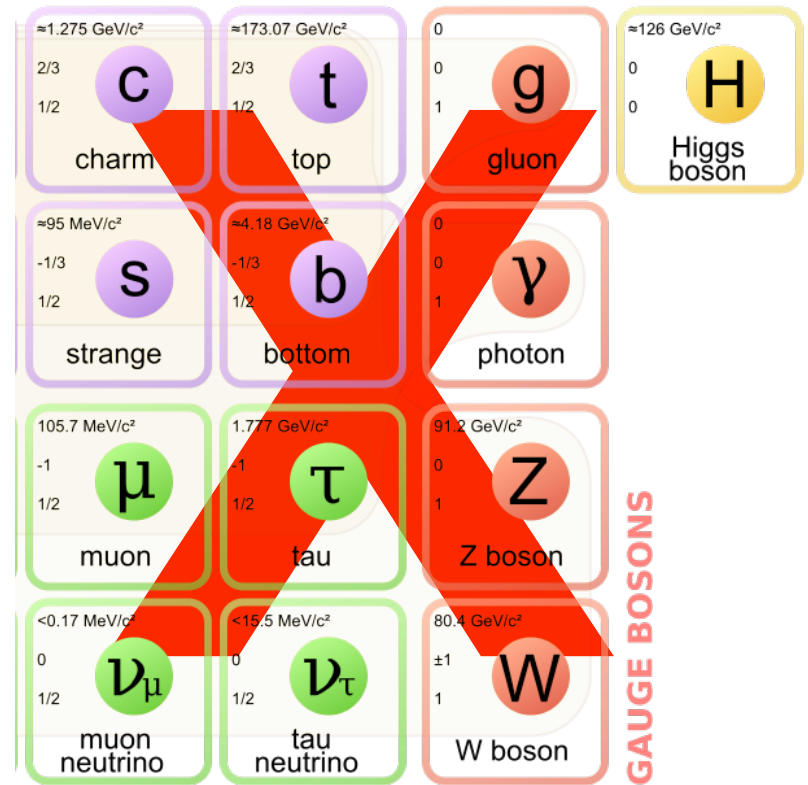
Newman+(2013)

Stellar kinematics, Multiple images, Weak lensing

Dark Matter Properties

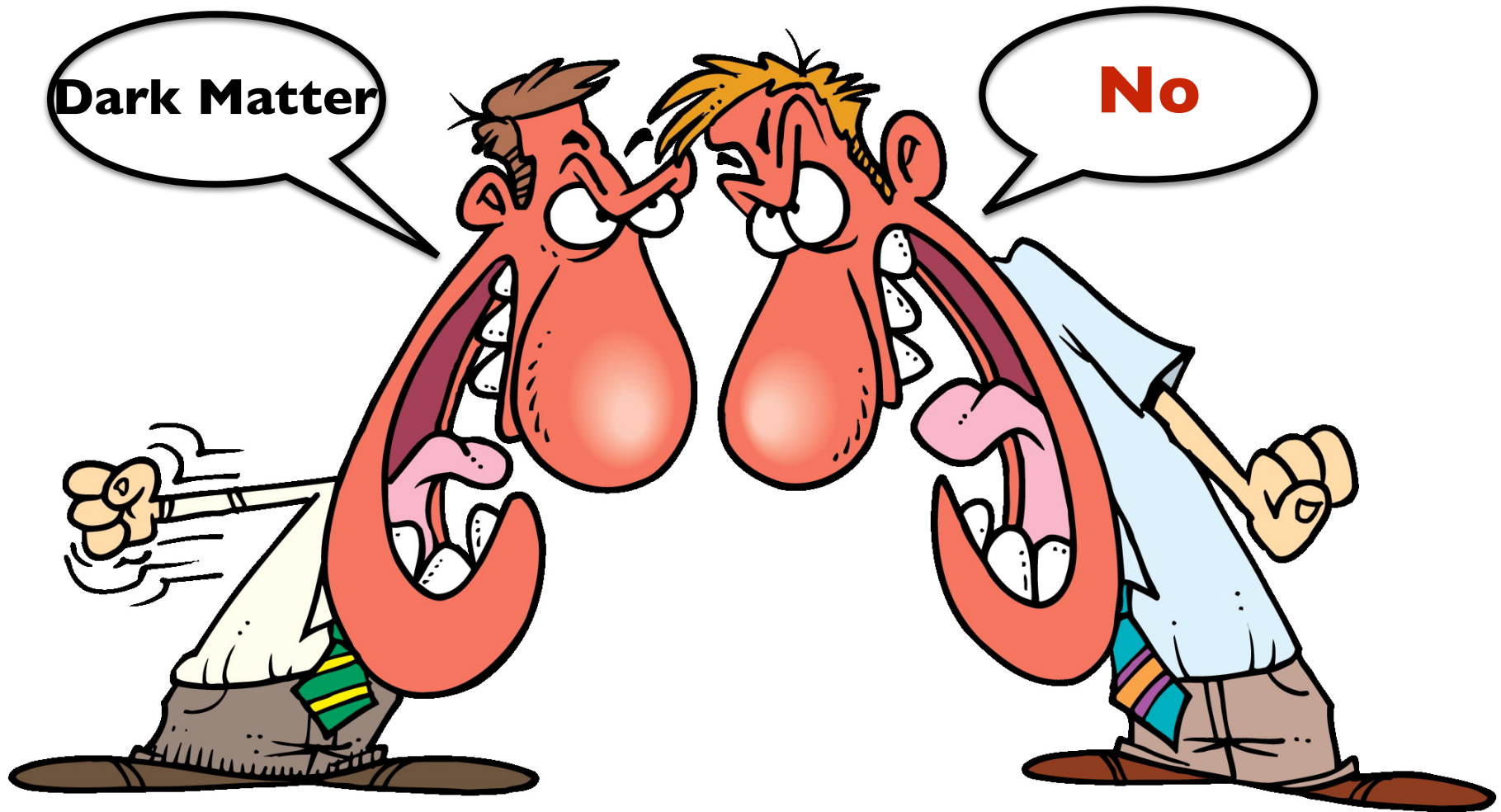


Dark
Stable
Cold



Neutrinos: carry the weak interaction, stable, but too light/hot

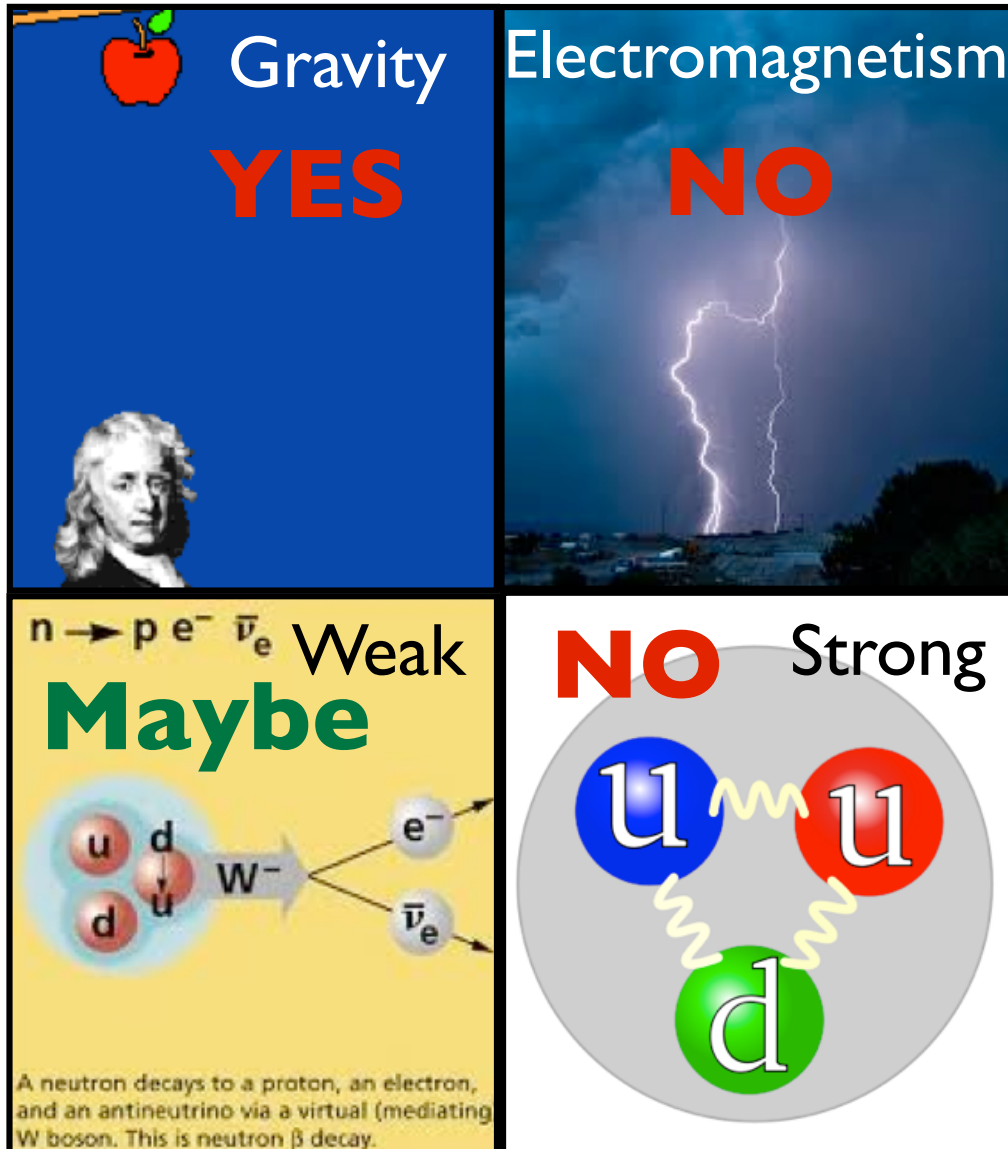
In the standard model of cosmology, dark matter is made of cold, **collisionless** new particles



the standard model of
cosmology

the standard model of
particle physics

The WIMP Paradigm



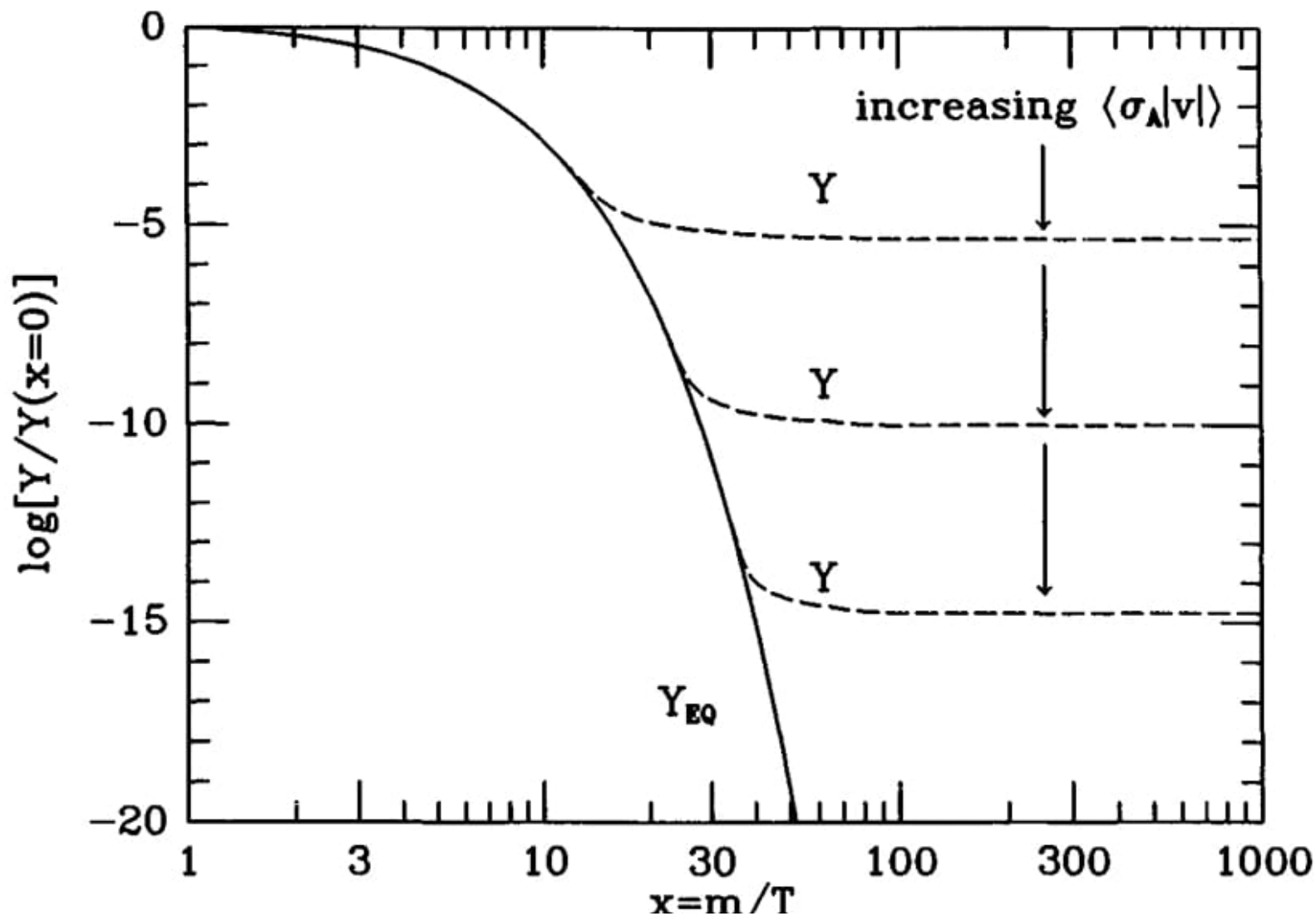
Dark matter candidate:

- Add a new massive particle X
- Interacts with us through the weak interaction

Weakly-Interacting Massive Particle (WIMP)

1970s — 2020s

Freezeout Mechanism



$$\Omega h^2 \simeq 0.1 \times \left(\frac{\langle\sigma v\rangle_{\text{freeze}}}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right)^{-1} \quad \text{The Early Universe, Kolb and Turner}$$

Searching for DM-SM Interactions



Direct detection (shake it)

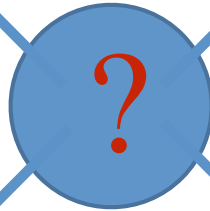


Collider Search (make it)



X

Ordinary
Matter



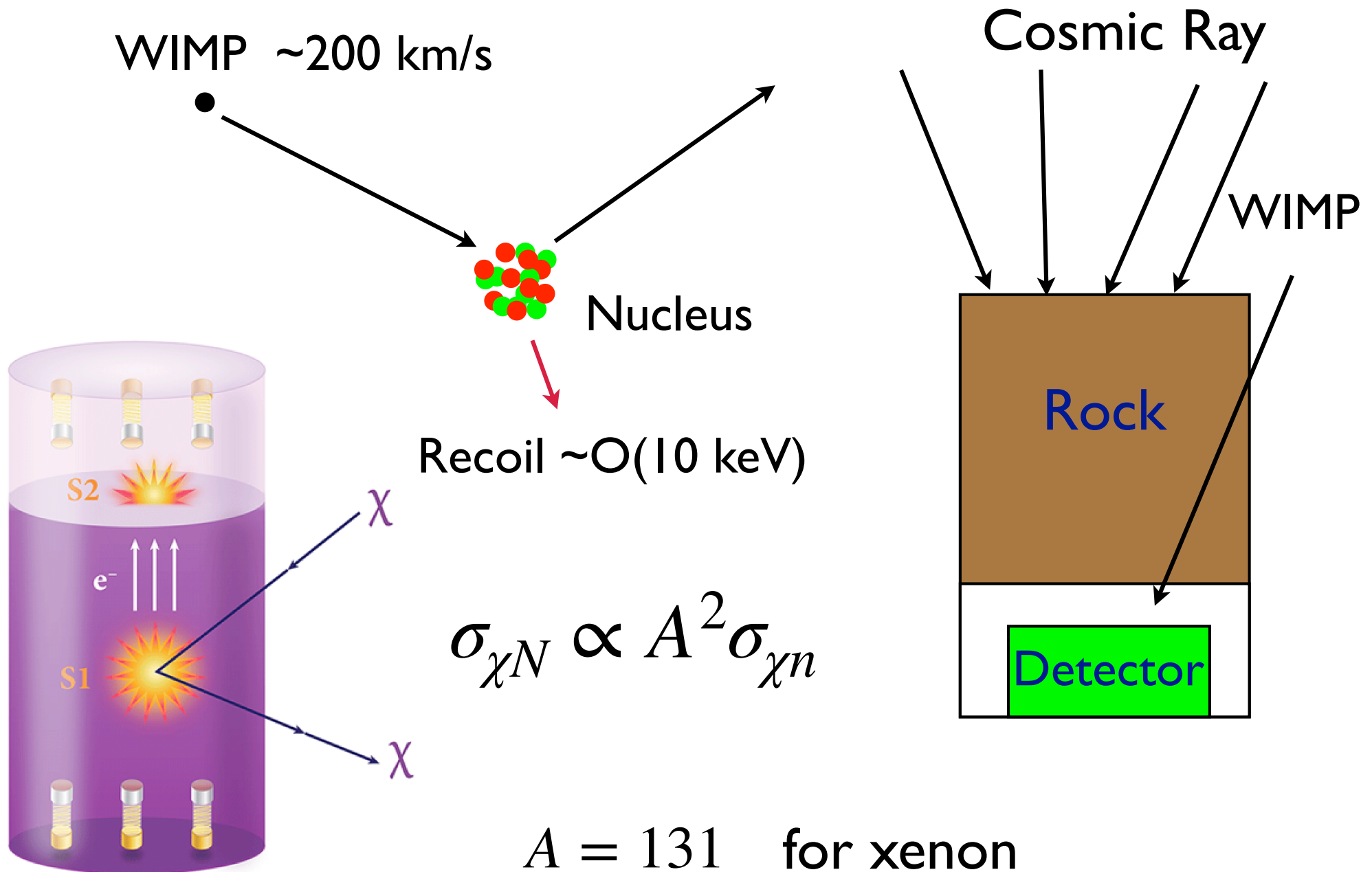
X

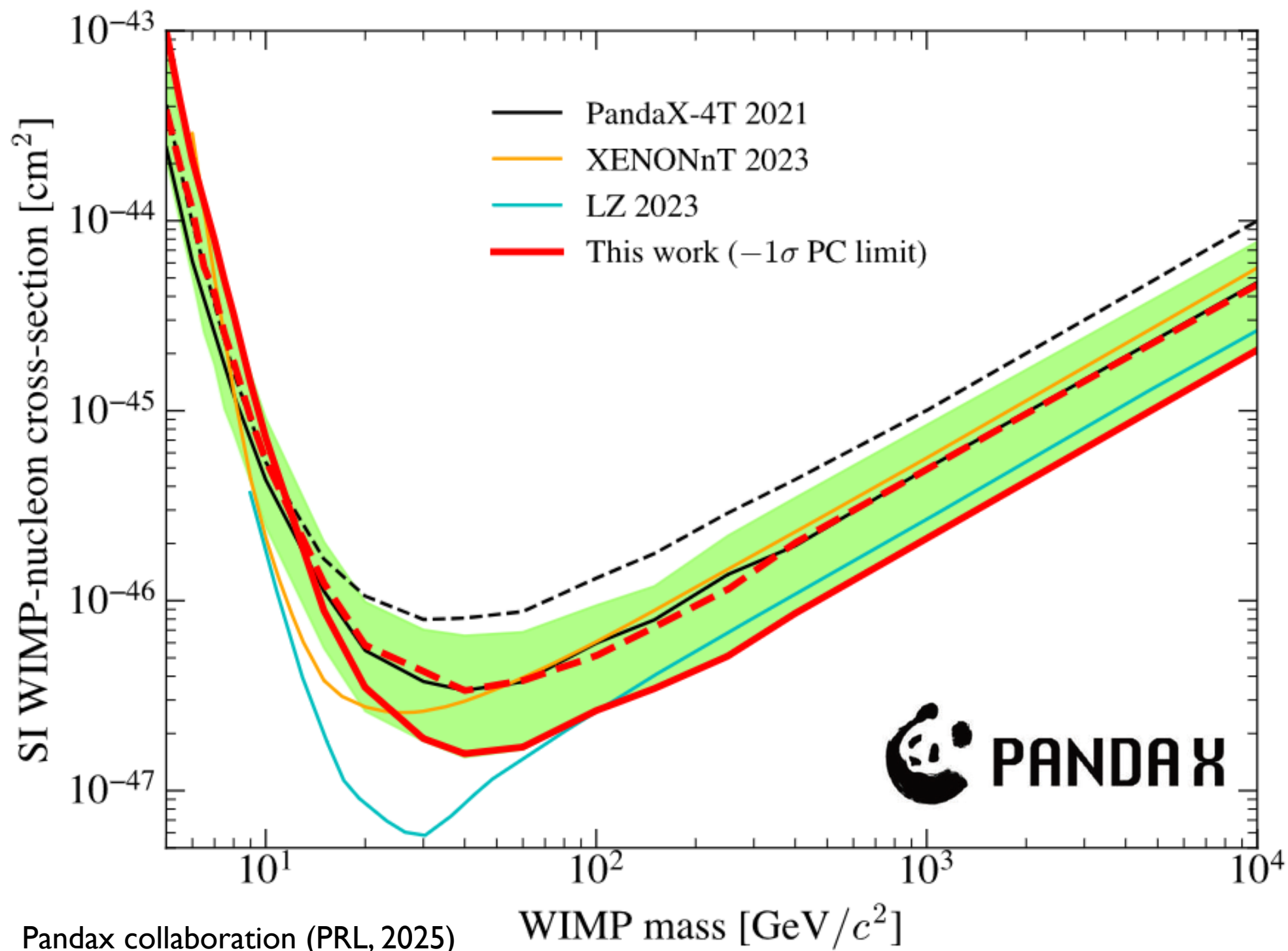
Ordinary
Matter

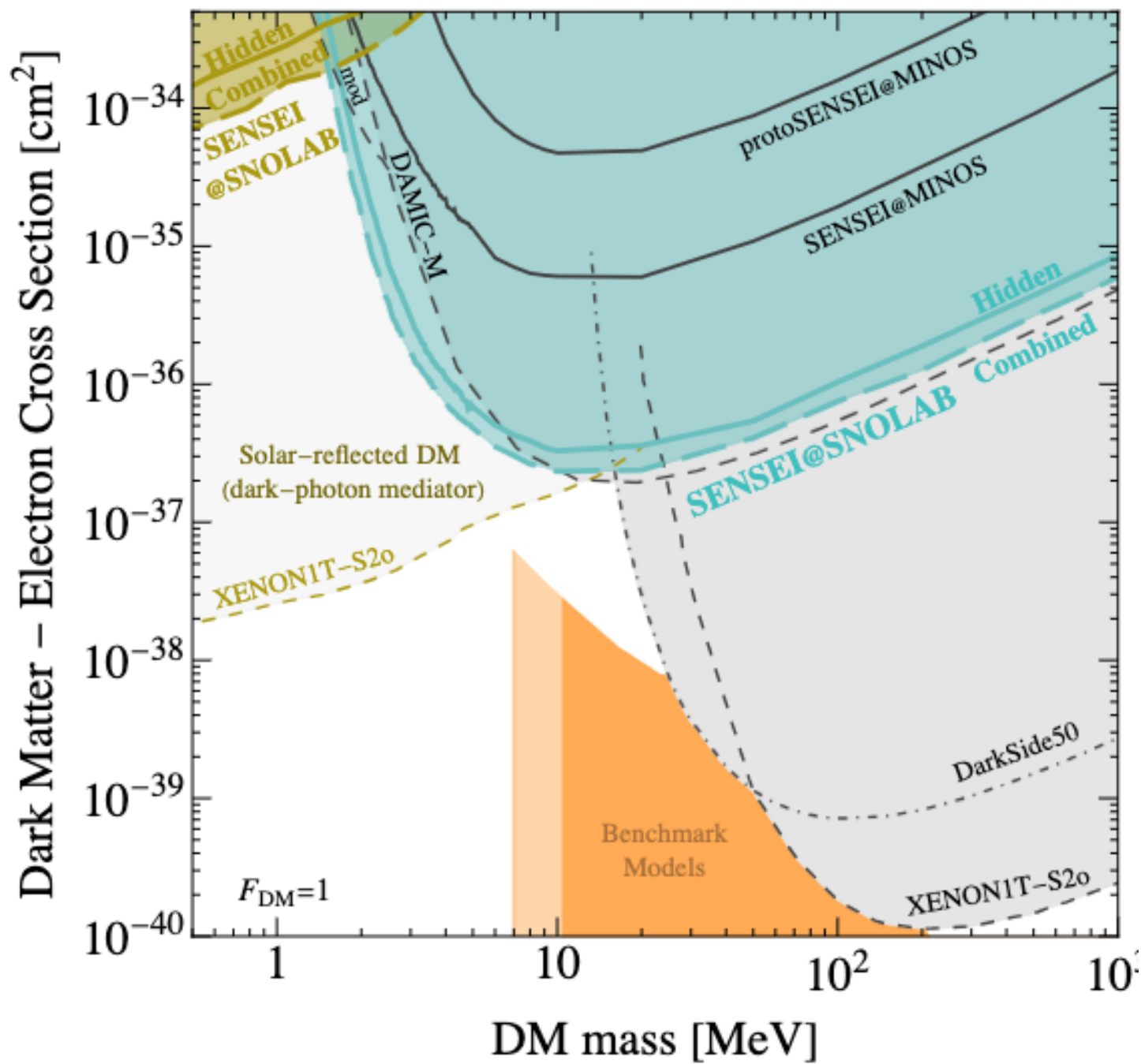
Indirect detection (break it)



Direct Detection

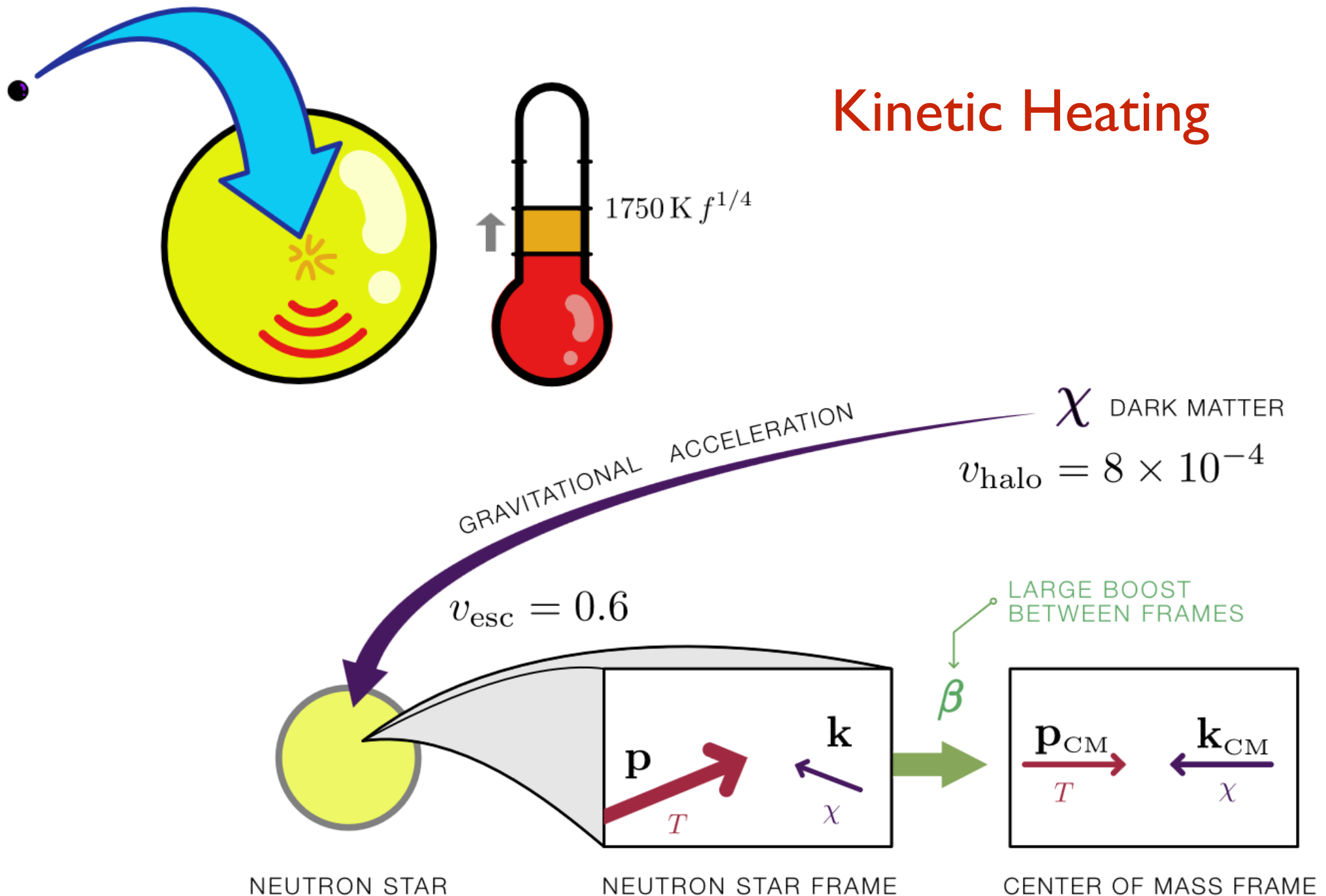




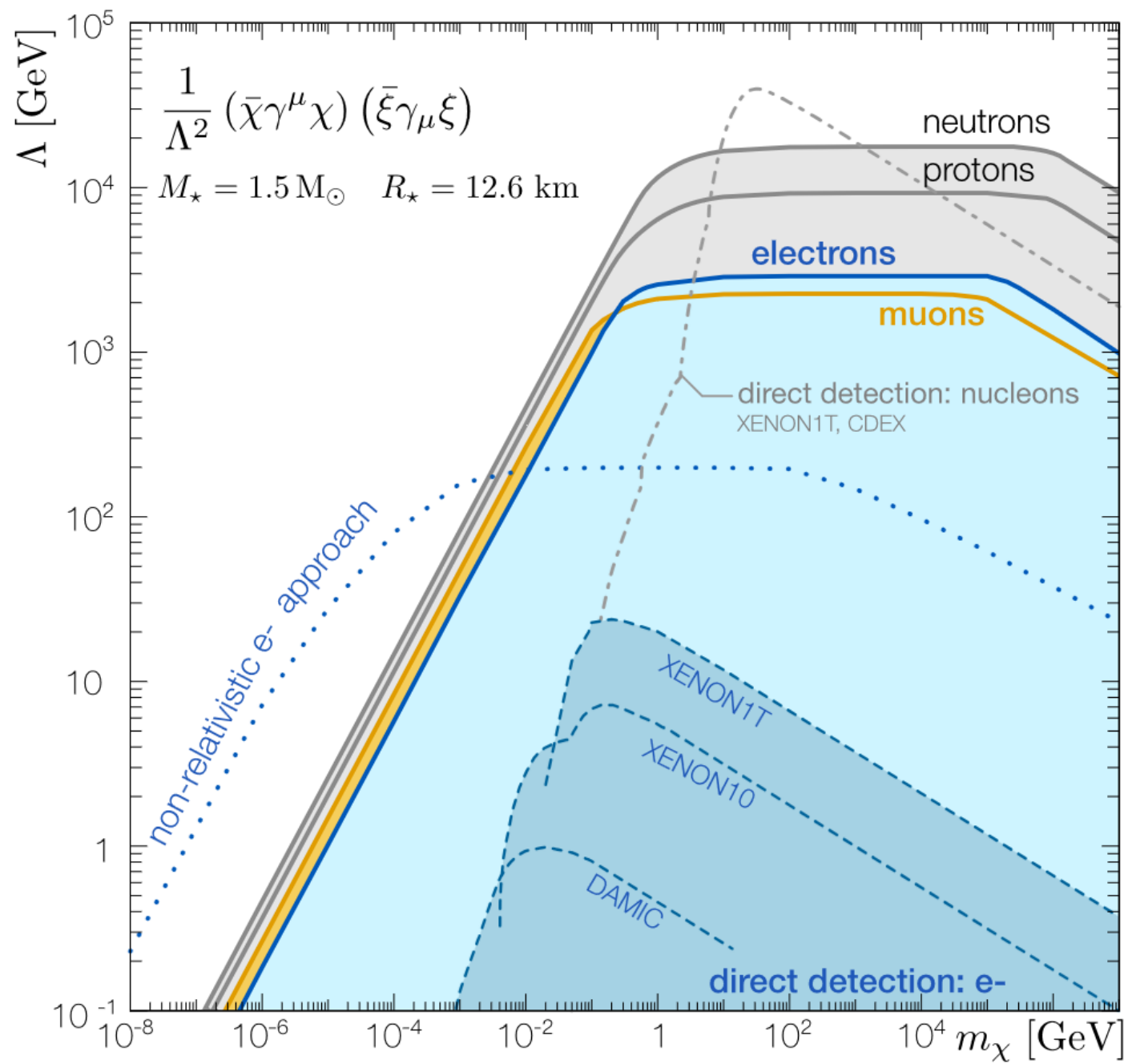


SENSEI Collaboration (PRL, 2025)

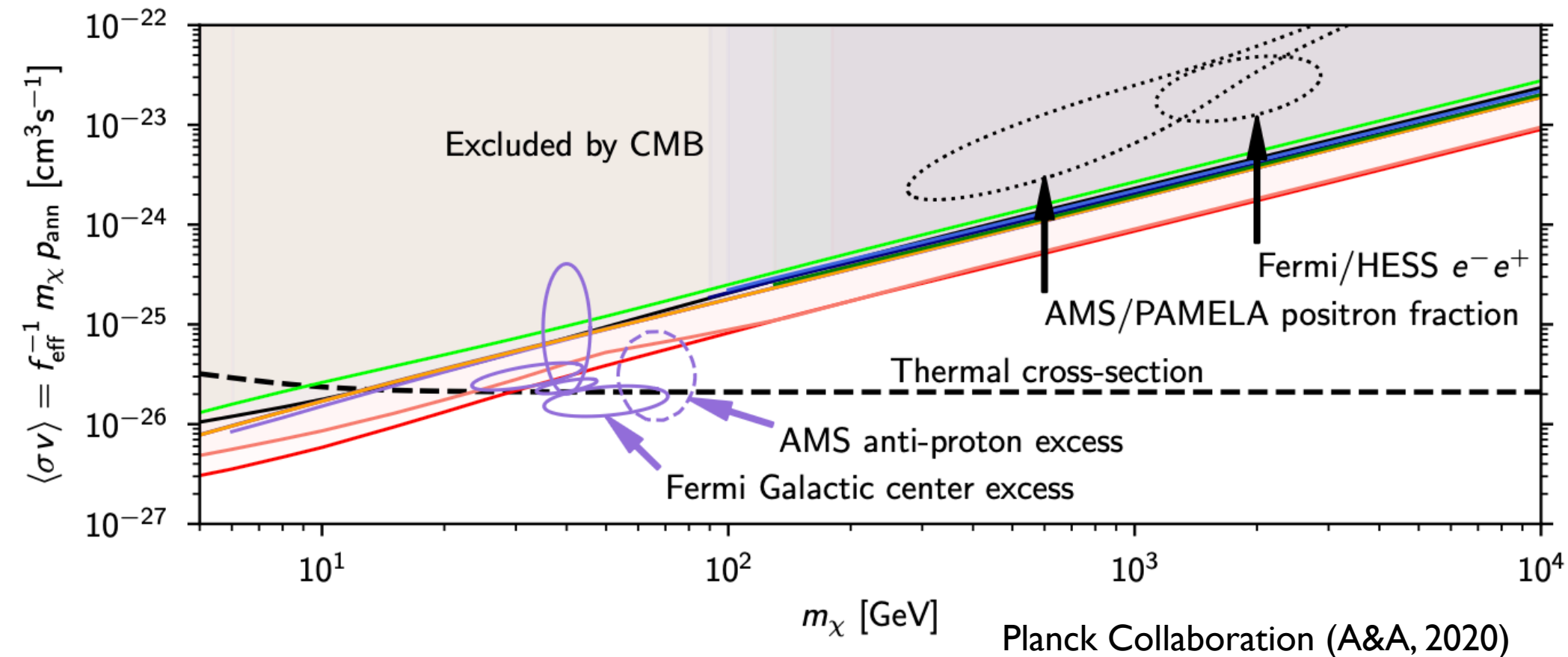
Kinetic Heating



Joglekar, Tanedo, Yu (PLB, PRD 2020); Raj, Tanedo, Yu (PRD 2018),
Baryakhtar, Bramante, Li, Linden, Raj (PRL 2017)



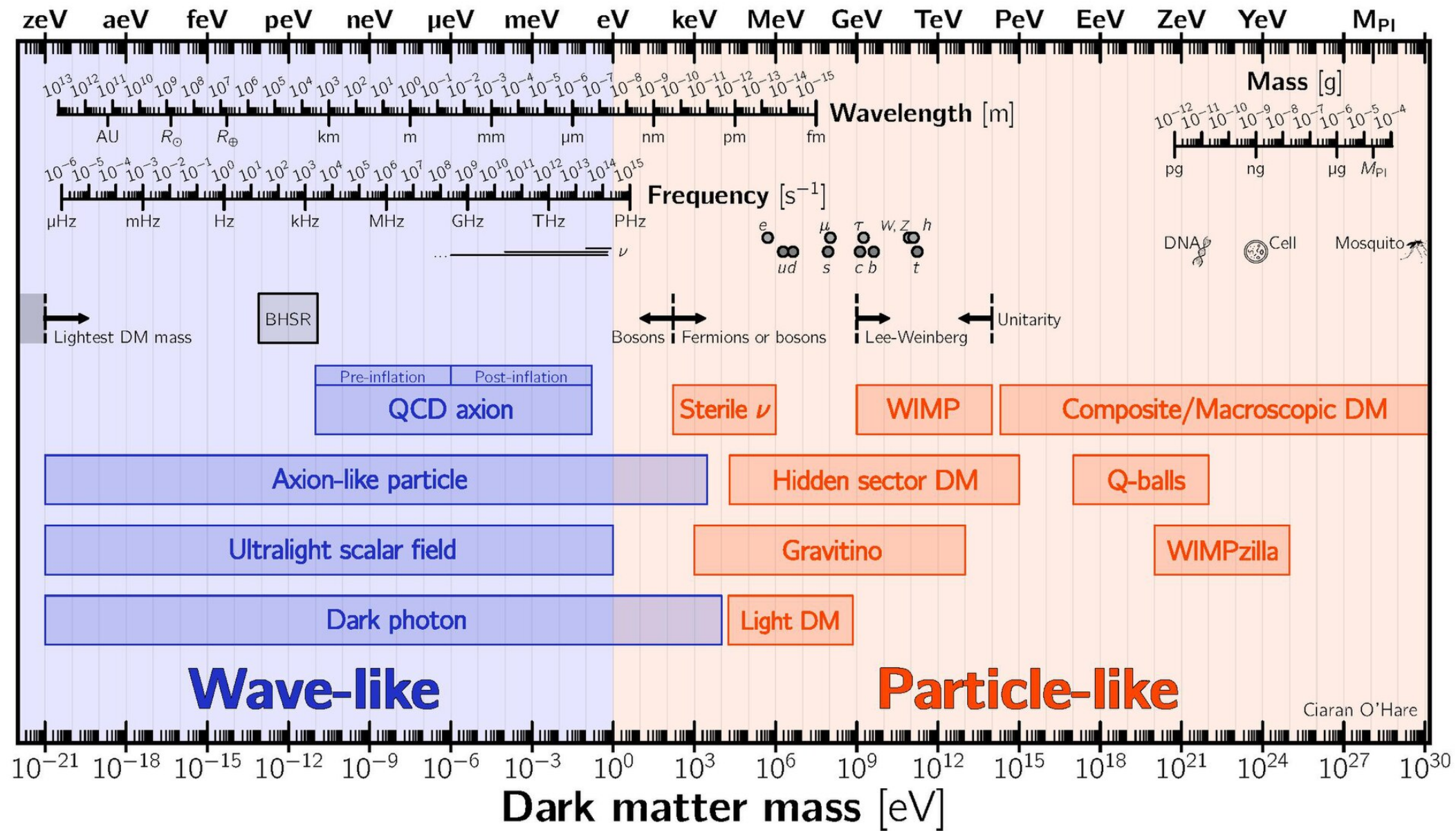
Constraints on Dark Matter Annihilation



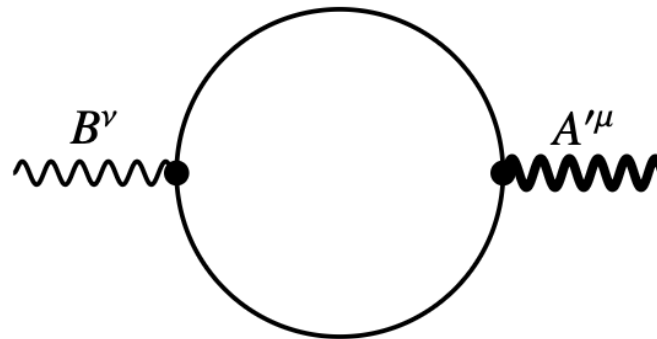
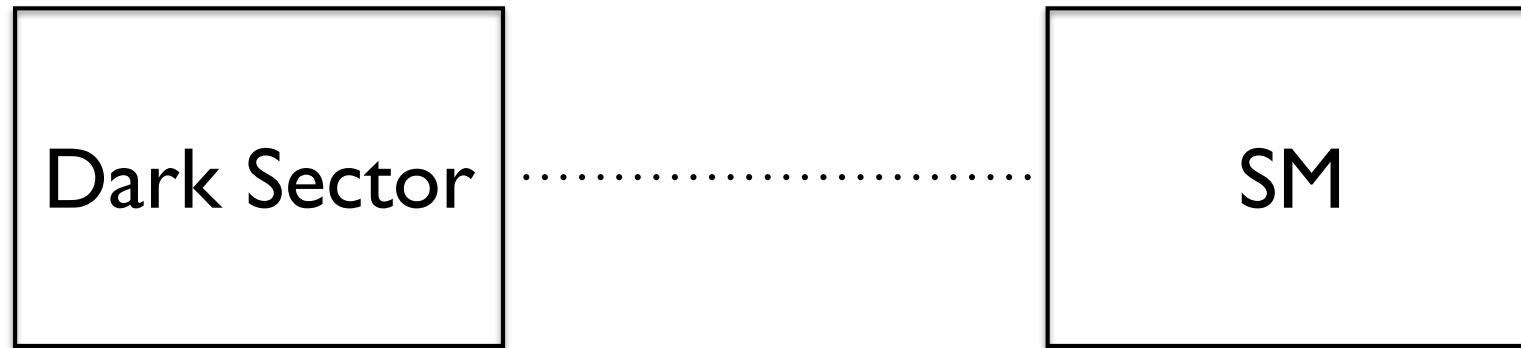
$$p_{\text{ann}} \equiv f_{\text{eff}} \frac{\langle\sigma v\rangle}{m_\chi}$$

f_{eff} is the fraction of the energy released by dark matter annihilation that is transferred to the intergalactic medium around the redshifts to which the CMB anisotropy data are most sensitive ($z \sim 600$)

Landscape of Dark Matter Candidates



Hidden/Dark-Sector Dark Matter



Holdom (PLB, 1986)

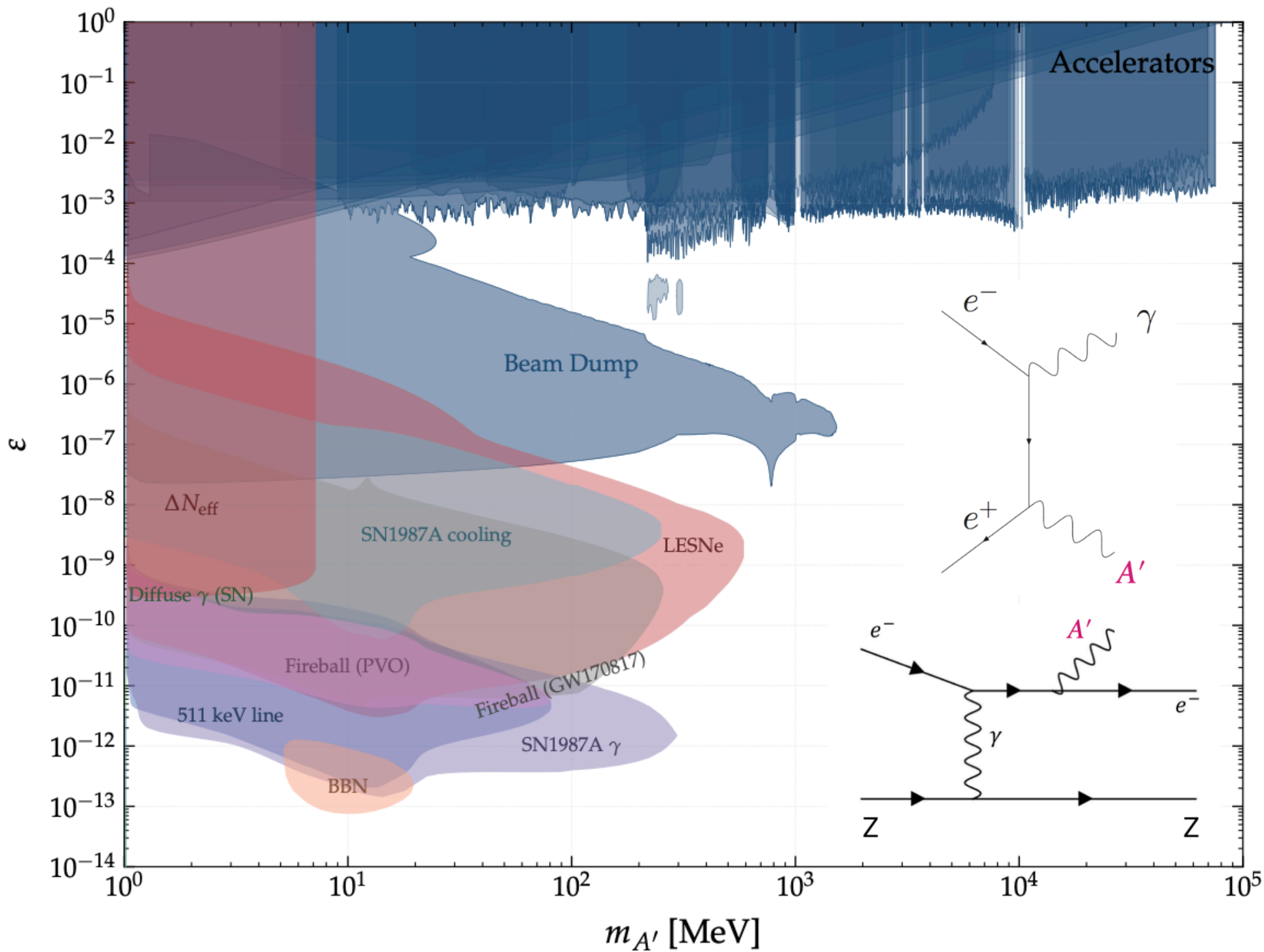
$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}Z^{\mu\nu}Z_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu})F'_{\mu\nu} + m_{A'}^2 A'^\mu A'_\mu$$

$$A_\mu \rightarrow A_\mu - \epsilon A'_\mu$$

$$A'_\mu \rightarrow A'_\mu + \epsilon \tan\theta_W Z_\mu$$

$$\mathcal{L}_{\text{EM,Z}} + \epsilon e A'_\mu J_{\text{EM}}^\mu + \mathcal{O}\left((m_{A'}/m_Z)^2\right) \epsilon A'_\mu J_Z^\mu$$

The Dark Photon: a 2026 Perspective: Caputo, Essig (2026); see references therein





“上穷碧落下黄泉，两处茫茫皆不见。”白居易《长恨歌》

“He exhausted all avenues in heaven and the nether world,
...he could not bring her existence to light.”

A Song of Immortal Regret, Bai Juyi (772-846)

Dark Matter (II): the Small-Scale Crisis of Λ CDM

Hai-Bo Yu

University of California, Riverside



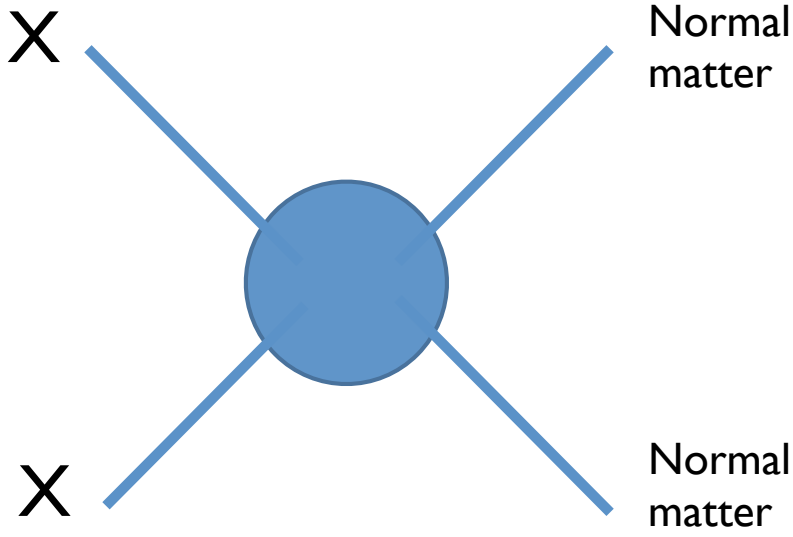
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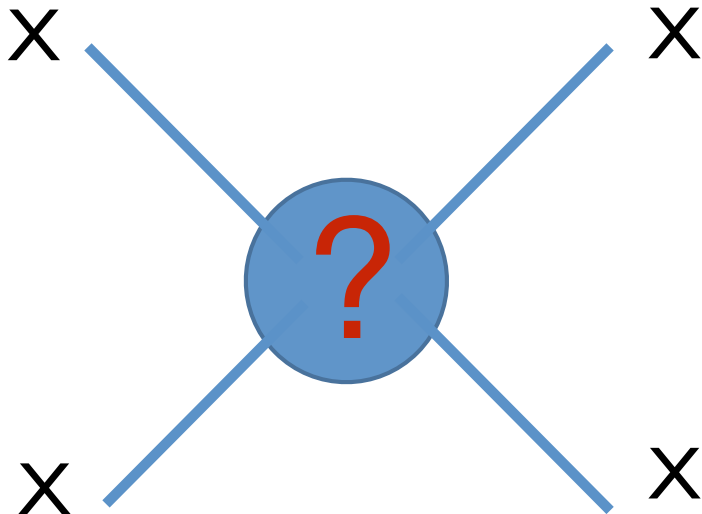
A Critical Rethinking

- Dark matter is light or superheavy, hidden from the existing searches
- **The nightmare scenario:** dark matter does not interact with the standard model particles, aside from gravity?
- Can we determine particle properties of dark matter via astrophysical observations?





Strong Constraints



Self-Interactions?

Most of the known particles have large self-interactions

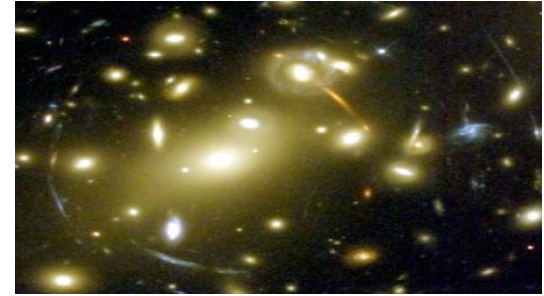
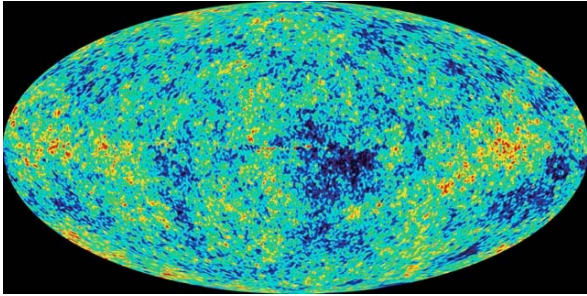
Standard Model of Elementary Particles

	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

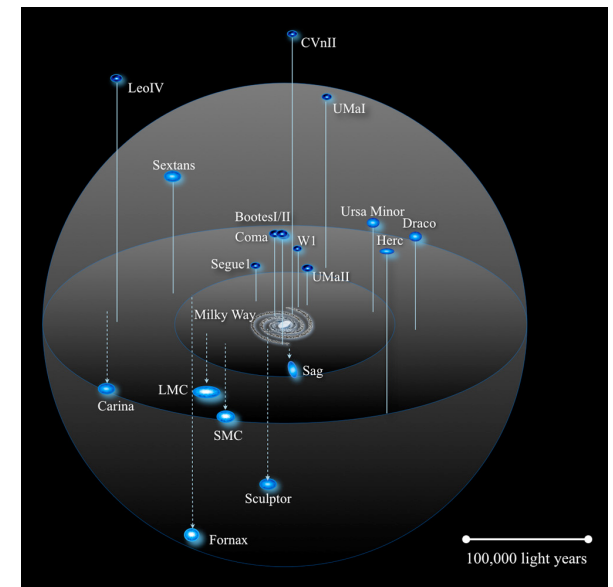
Cold Dark Matter (CDM)

- Large scales: very well

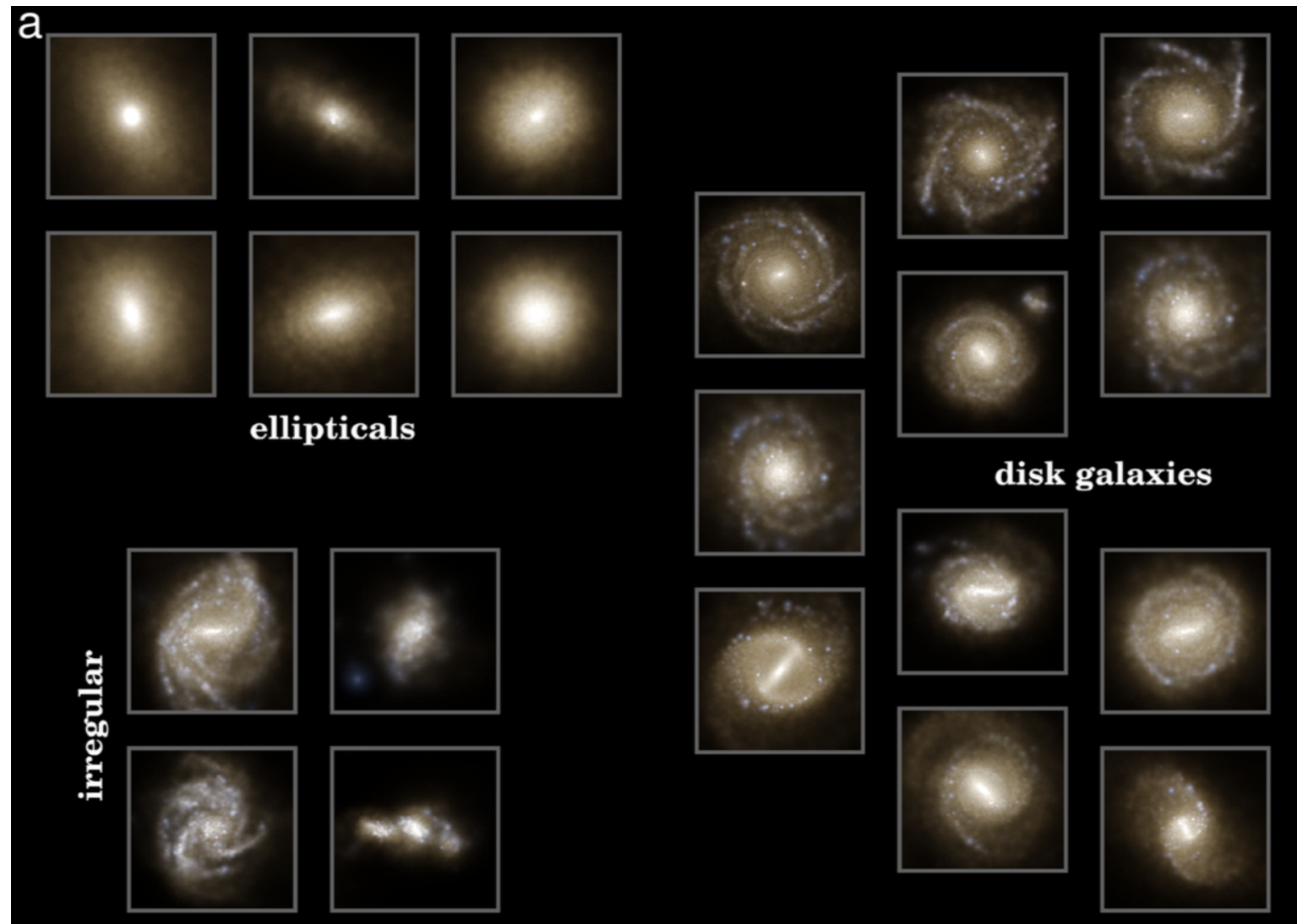


- Small scales (field/satellite dwarf galaxies, substructures)

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



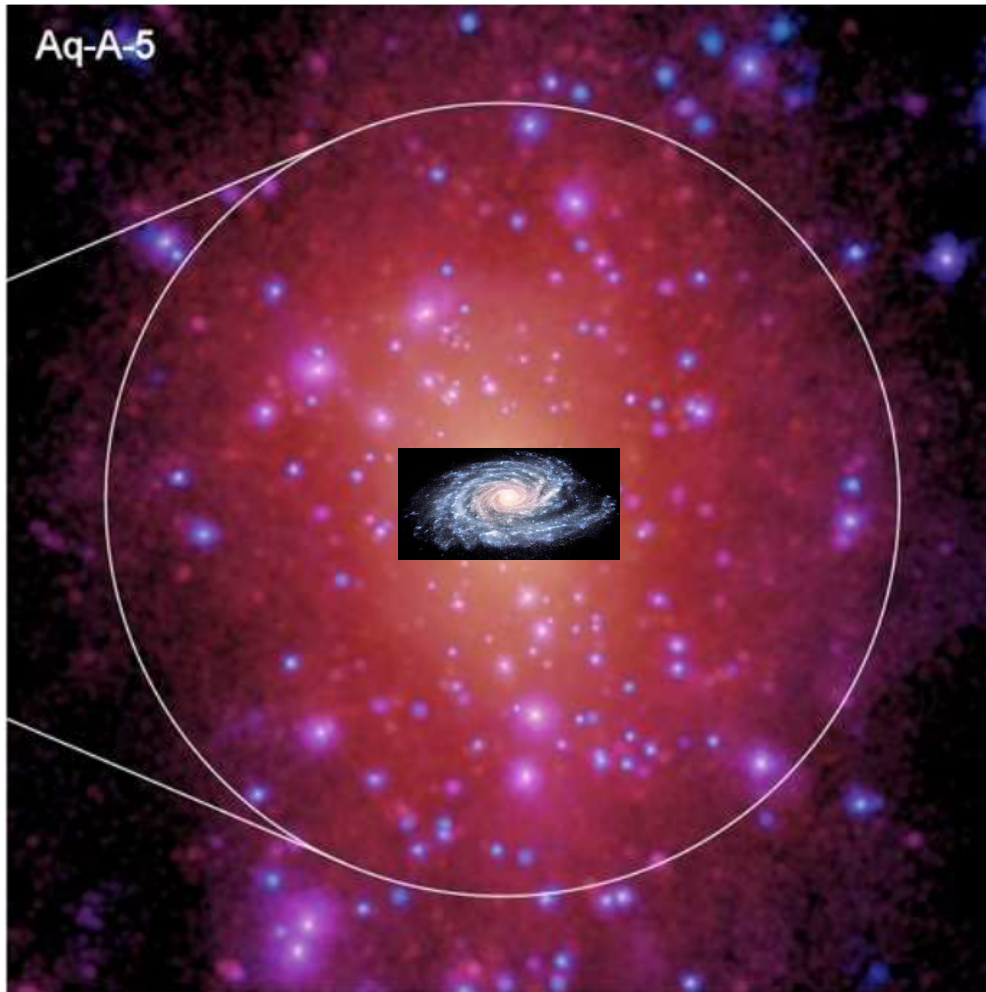
Predictions on Galactic Scales



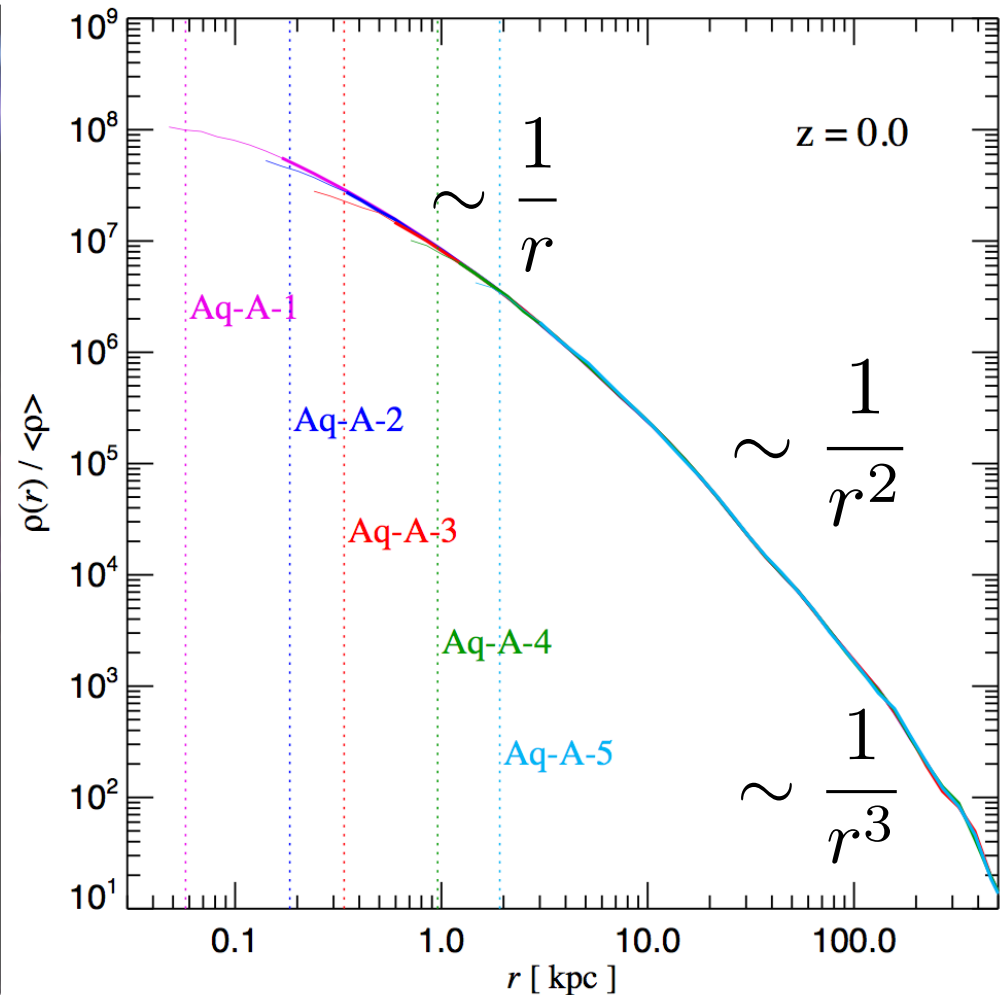
Illustris Project, Vogelsberger et al. (2014)

Produce a variety of galaxy types overall consistent with observations

CDM: Universal Density Profile



Aquarius Project, Springel+ (2008)

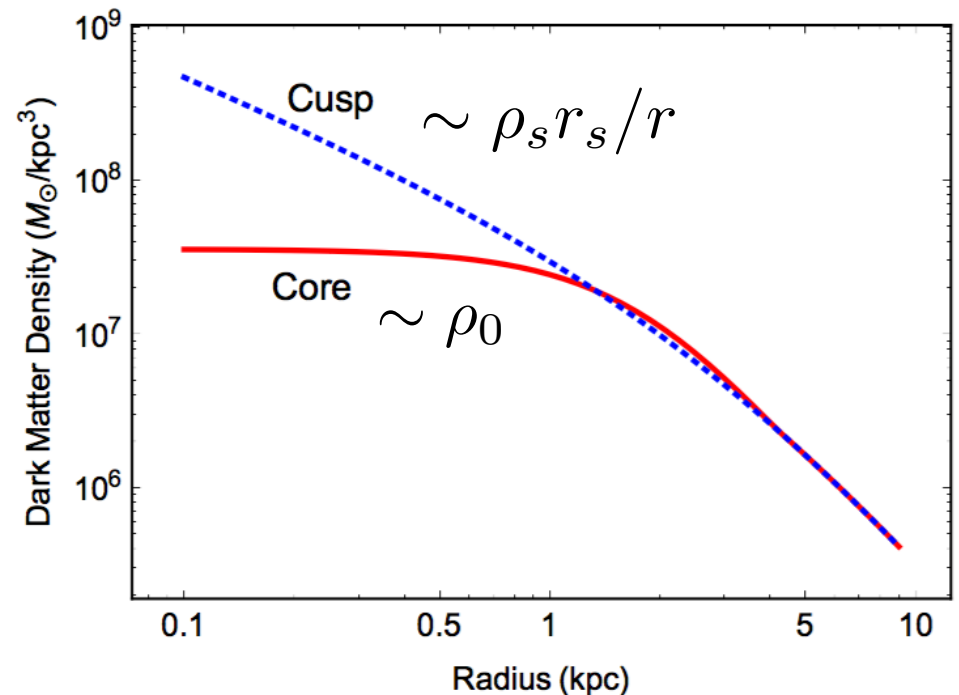
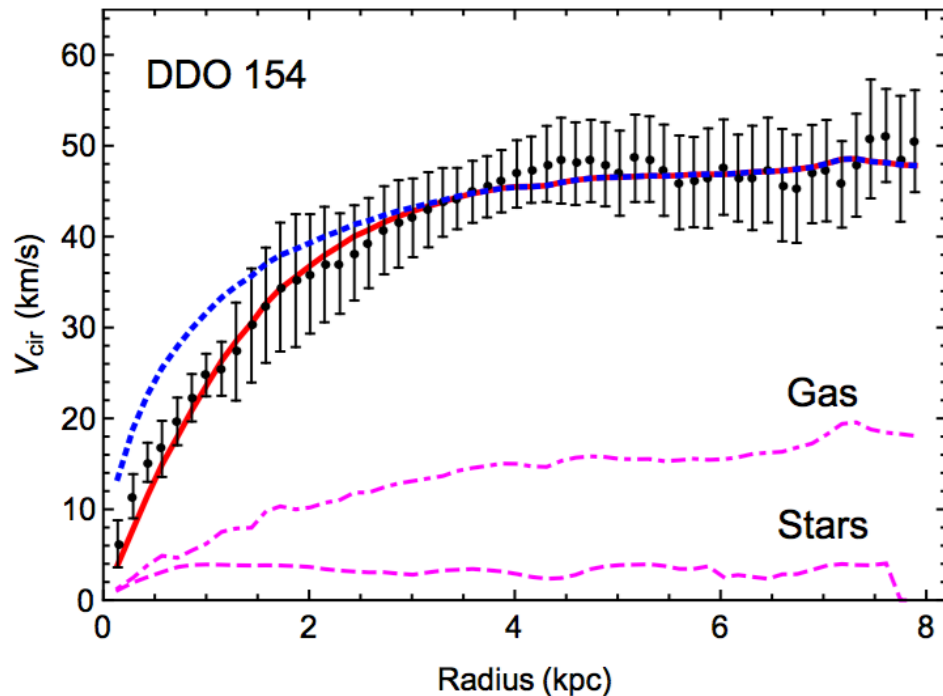


$$\frac{\rho_s}{r/r_s(1 + r/r_s)^2}$$

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

Core vs Cusp Problem

- Dark Matter-dominated systems (dwarfs, LSBs)



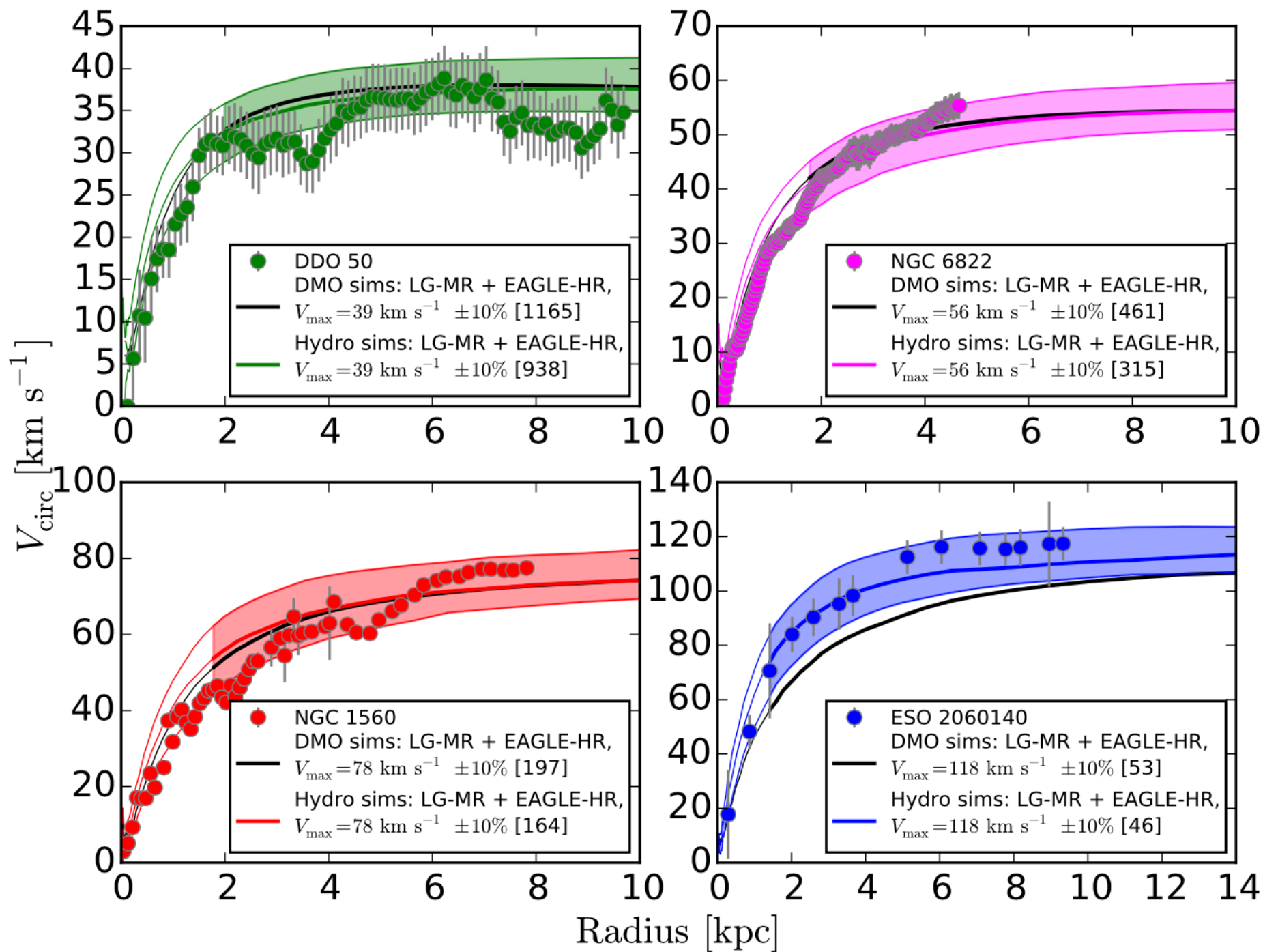
Tulin, HBY (Physics Reports 2017)

$$V_{\text{circ}}(r) = \sqrt{V_{\text{halo}}(r)^2 + \Upsilon_* V_{\text{star}}(r)^2 + V_{\text{gas}}(r)^2}$$

$$V_{\text{halo}}(r) = \sqrt{\frac{\rho_s}{r/r_s (1 + r/r_s)^2}}$$

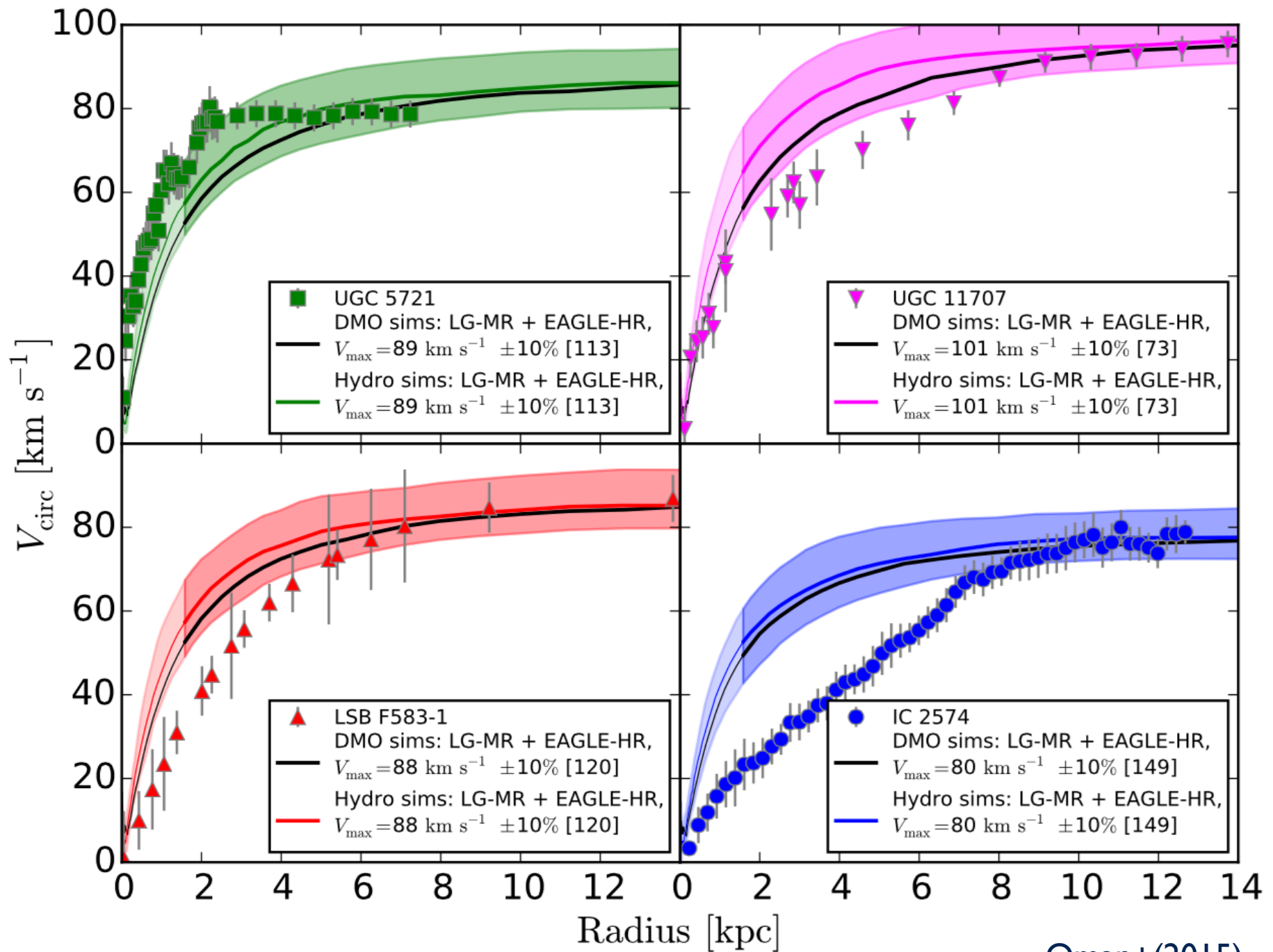
$$V_{\text{halo}}(r) = \sqrt{GM_{\text{halo}}(r)/r}$$

Flores, Primack (1994), Moore (1994)...



Colored bands: hydrodynamical simulations of CDM,
“smooth/weak” baryonic feedback

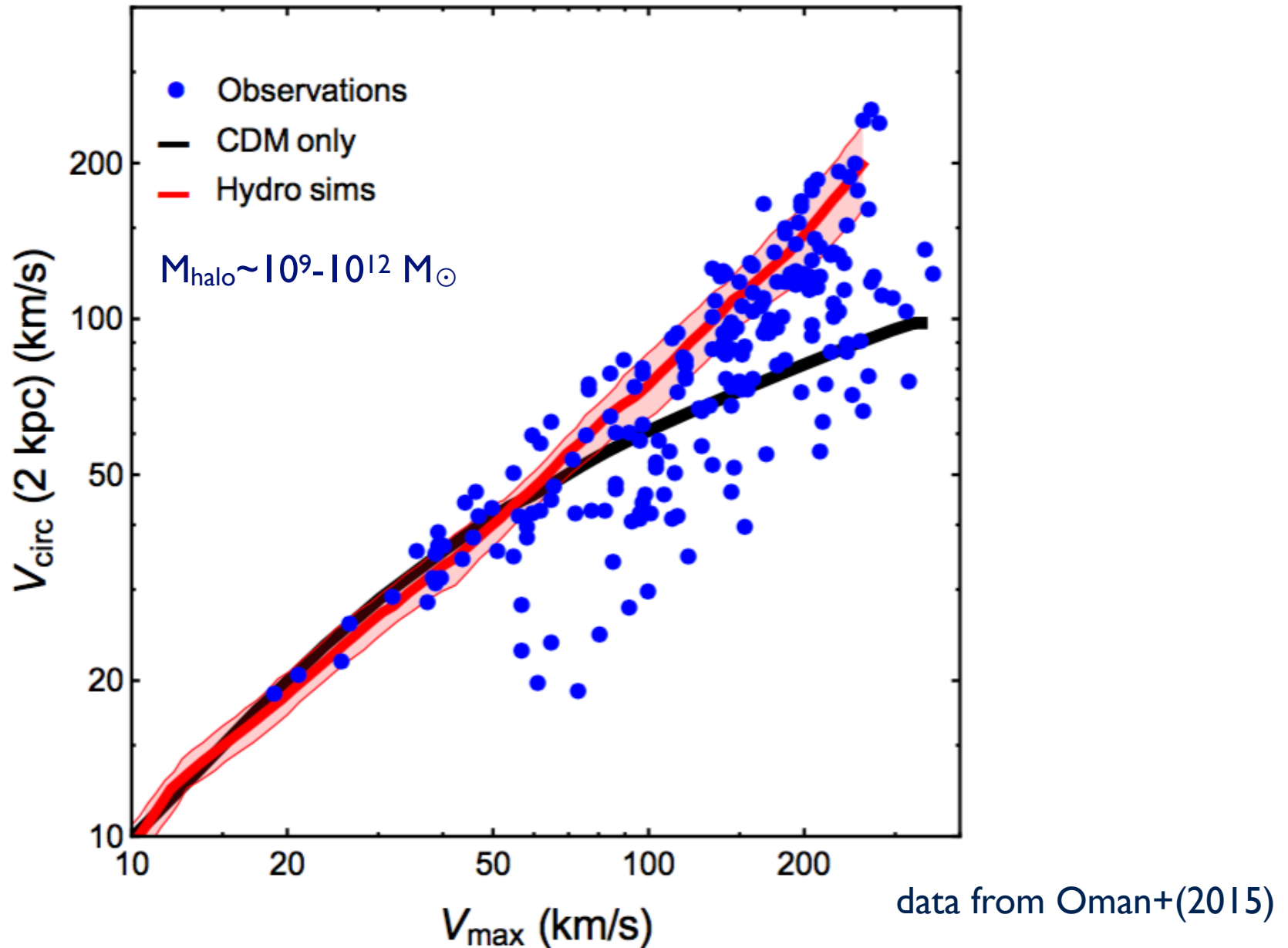
Oman+(2015)



Oman+(2015)

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

The Diversity Problem



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

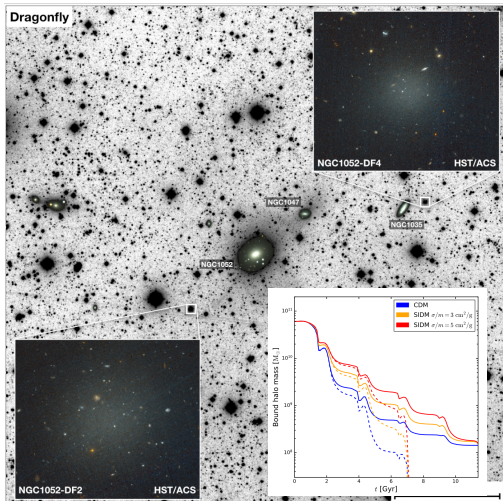
Diversity From Dwarf to Cluster Scales

Ultra-diffuse galaxies
(dark-matter-deficient)

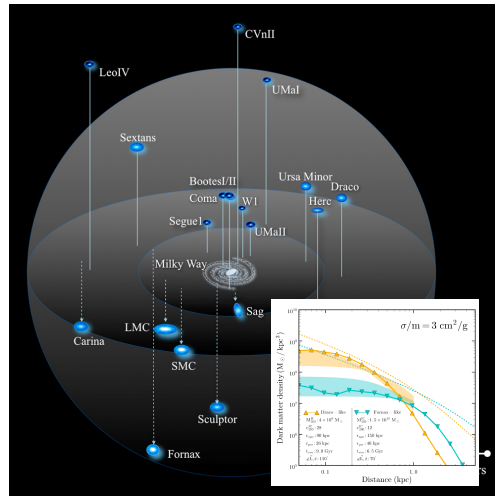
Milky Way satellites

Spiral galaxies

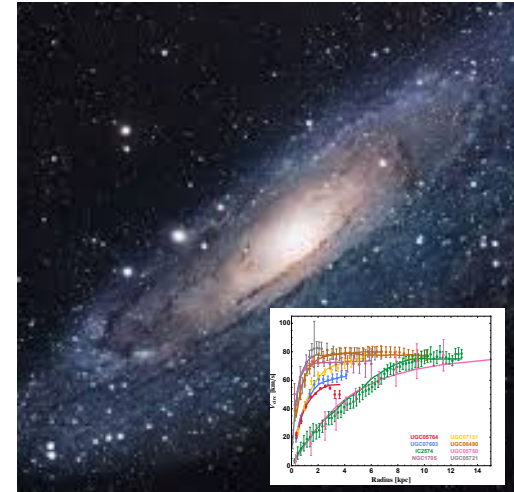
Galaxy clusters



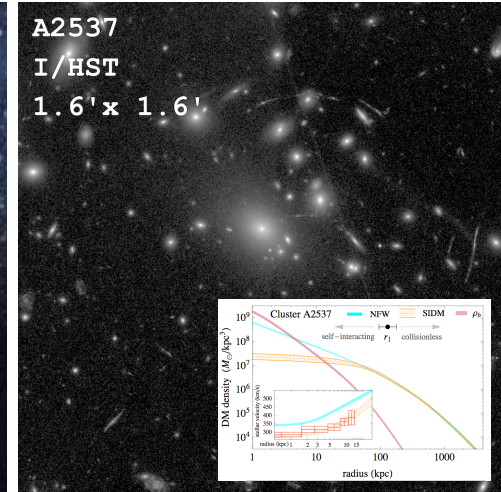
$$M_{\text{halo}} < \sim 10^8 M_{\odot}$$



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



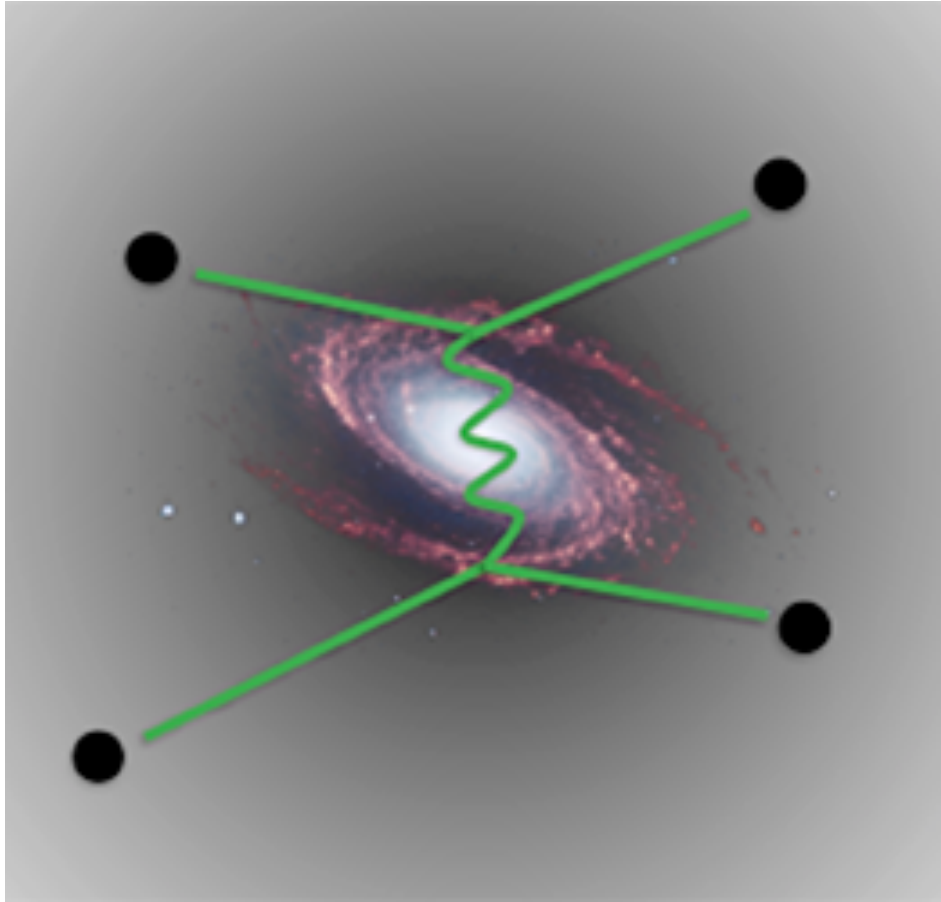
$$M_{\text{halo}} \sim 10^9 - 10^{13} M_{\odot}$$



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

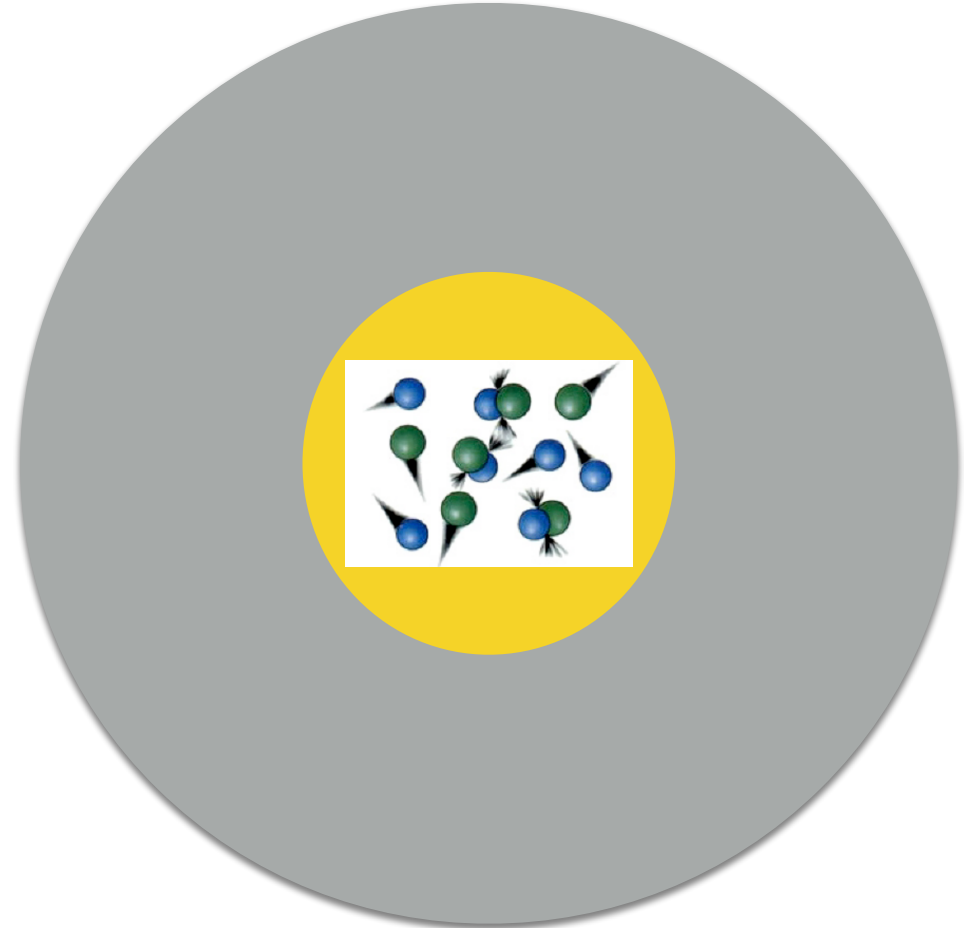
- The diversity problem is not limited to spiral galaxies
- Hydro CDM simulations show baryonic feedback could alleviate some of the tensions, but not all
- In simulations, the impact of baryonic feedback depends on the model adopted

Dark Matter Self-Interactions



self-interactions in the dark sector

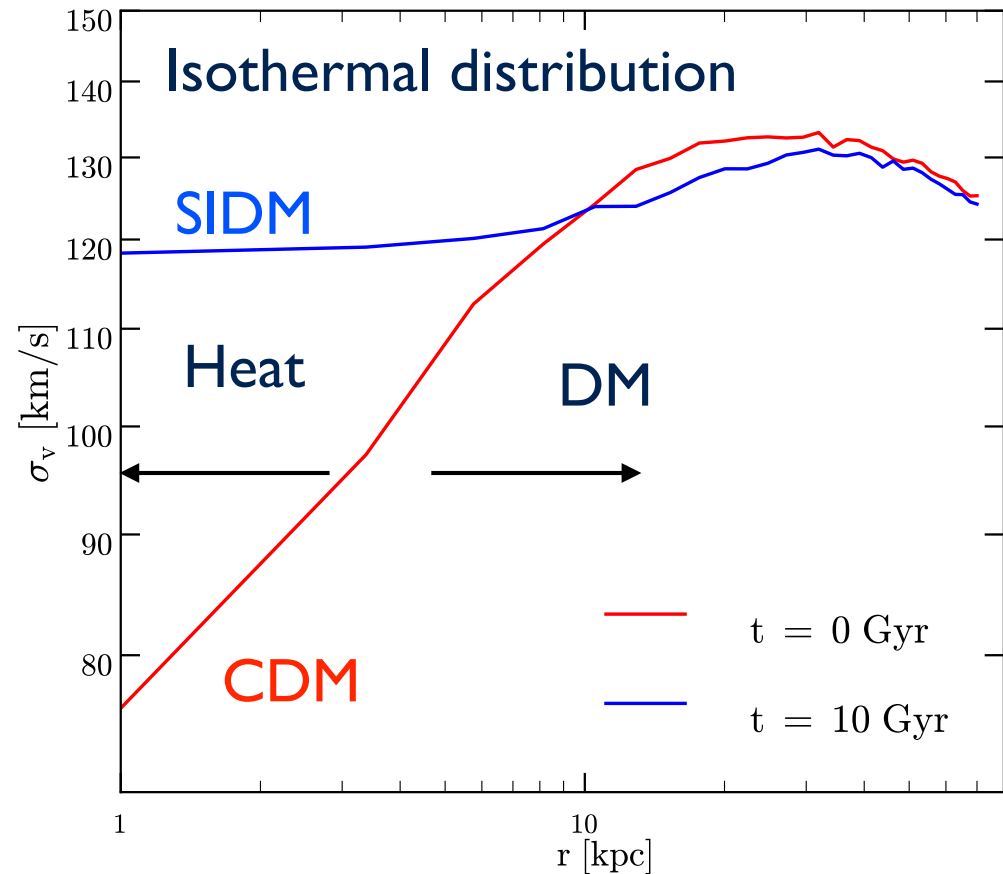
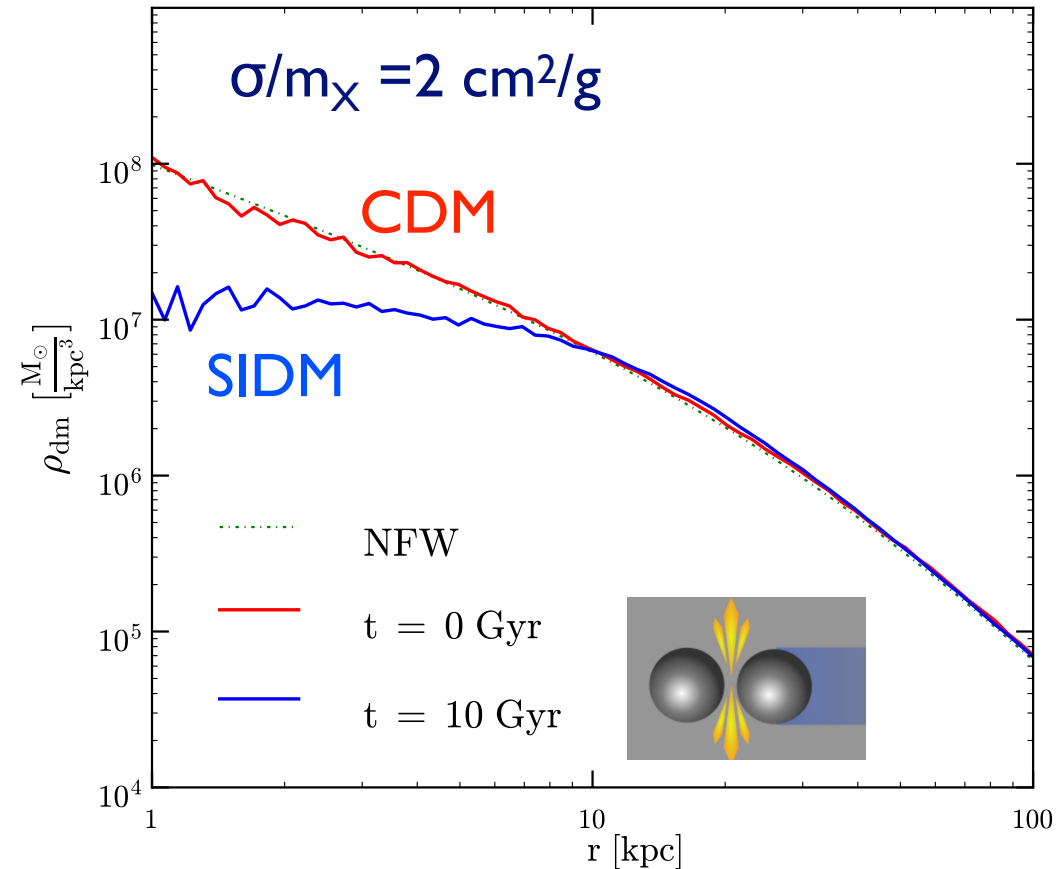
Treat dark matter as ideal gas



thermalization

$$PV=nRT$$

Self-Interacting Dark Matter



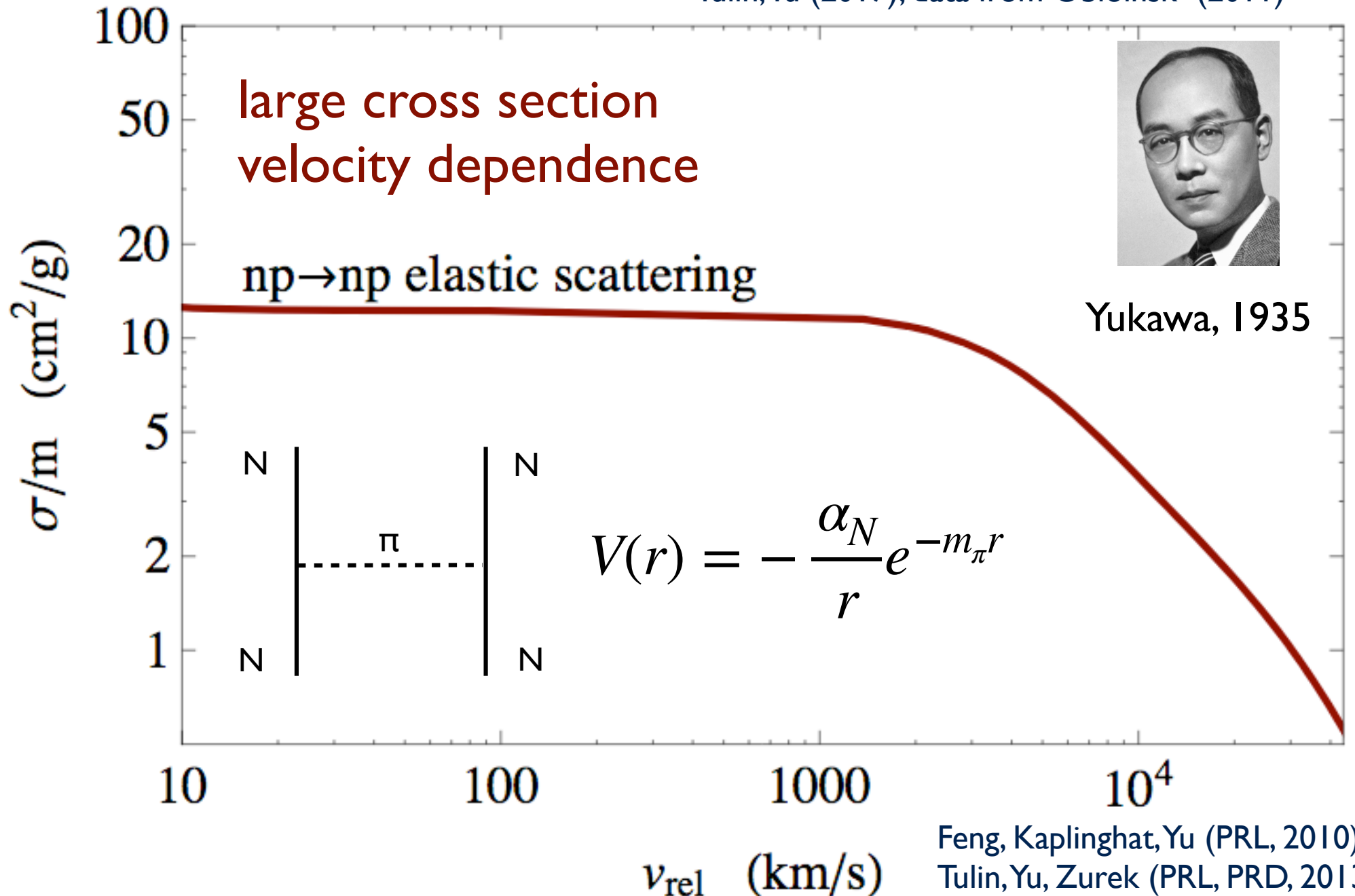
Review: Tulin, Yu (Physics Reports 2017)

$\sigma/m_X \sim 1-100 \text{ cm}^2/\text{g}$ (nuclear scale)

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

Nuclear Interactions

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



Modelling SIDM Halos

semi-analytical approach

Inner halo

Ideal gas: $PV=nRT$

isothermal distribution

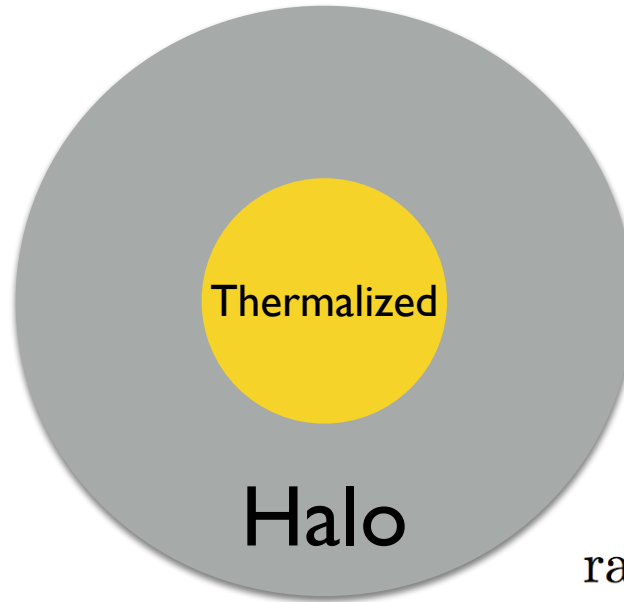
$$\rho_0 e^{-\Phi_{\text{tot}}/\sigma_0^2}$$

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

Known

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

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



Outer halo

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

The boundary is set by

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

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

The cosmology is embedded via
 the halo concentration-mass relation!



VS



More Specially...

$$\rho_{\text{iso}}(R, z) = \rho_0 \exp \left([\Phi_{\text{tot}}(0, 0) - \Phi_{\text{tot}}(R, z)] / \sigma_{\text{v}0}^2 \right)$$

$$\nabla^2 \Phi_{\text{tot}}(R, z) = 4\pi G [\rho_{\text{iso}}(R, z) + \rho_{\text{b}}(R, z)]$$

$$\rho_{\text{b}}(R, z) = \Sigma_0 \exp(-R/R_{\text{d}}) \delta(z)$$

Scale radius

Surface density of the stellar distribution

Numerical templates based on the two dimensionless parameters $a \equiv 8\pi G \rho_0 R_{\text{d}}^2 / (2\sigma_{\text{v}0}^2)$ and $b \equiv 8\pi G \Sigma_0 R_{\text{d}} / (2\sigma_{\text{v}0}^2)$

$$\rho_{\text{iso}}(r_1) = \rho_{\text{NFW}}(r_1)$$

$$M_{\text{iso}}(r_1) = M_{\text{NFW}}(r_1)$$

with Kamada, Kaplinghat, Pace (PRL 2016)

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

Andrew Robertson[★]¹, Richard Massey¹, Vincent Eke¹, Joop Schaye²
and Tom Theuns¹

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

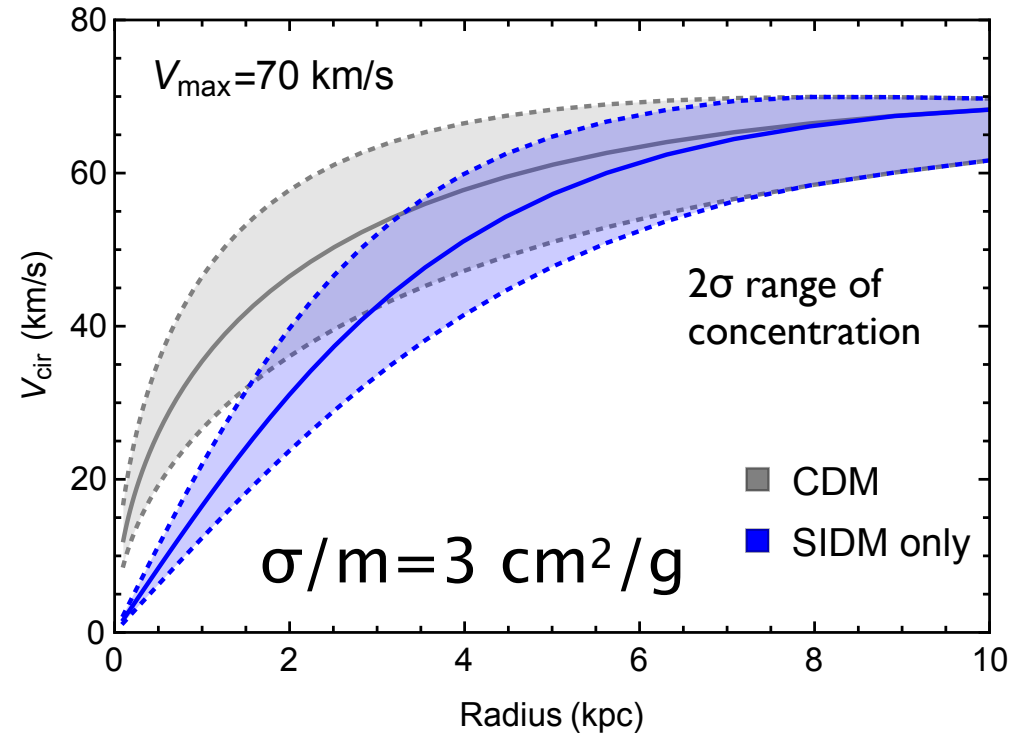
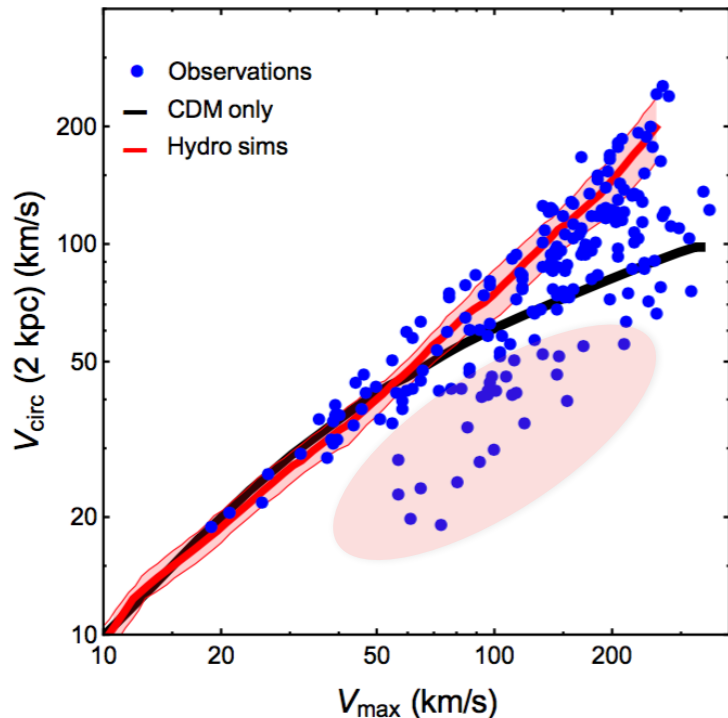
ABSTRACT

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 $3 \times 10^{15} M_{\odot}$. 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

Further improvement: Jiang+(2206.12425), Jia+(2601.17118)

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo



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

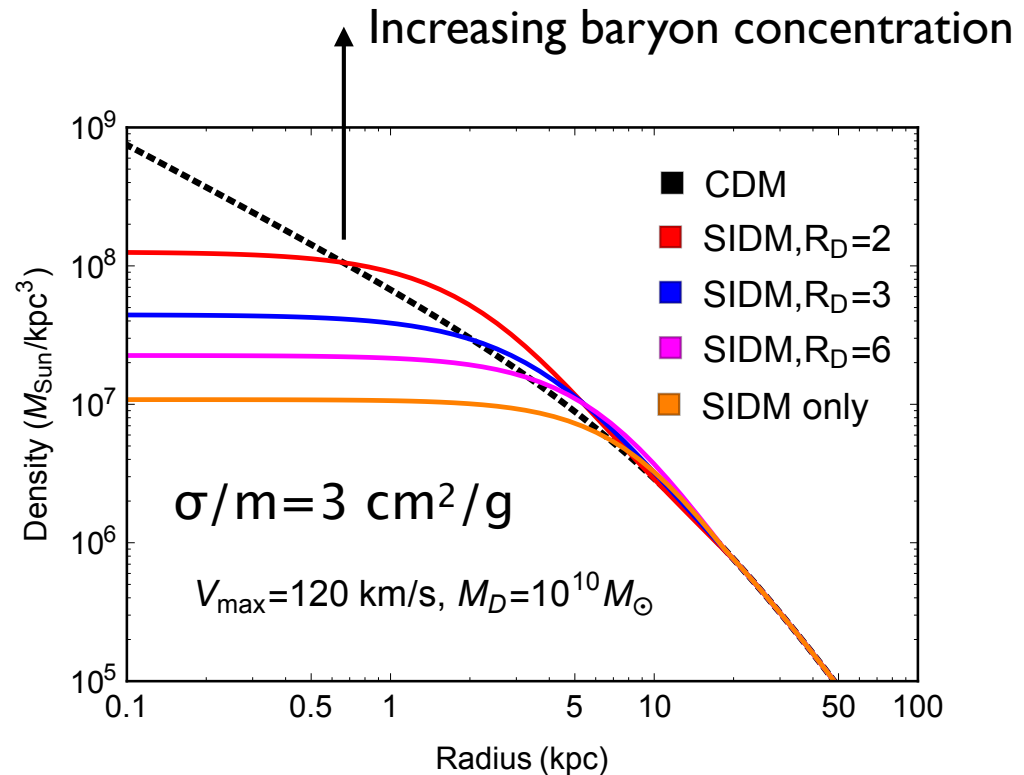
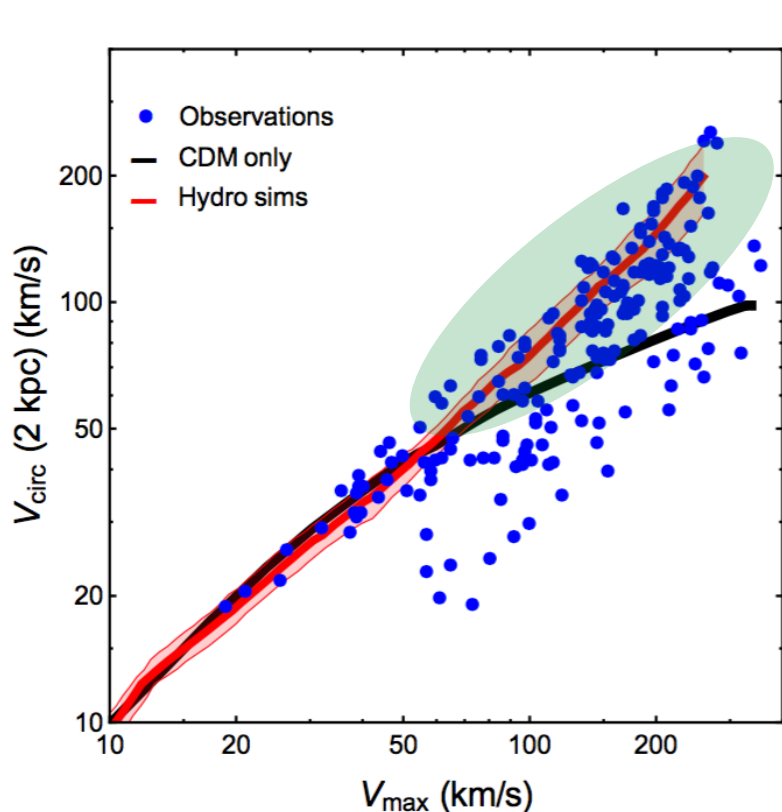
Isothermal
distribution

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

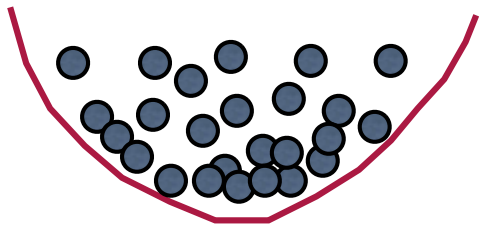
with Kamada, Kaplinghat, Pace (PRL 2016)

Addressing the Diversity Problem

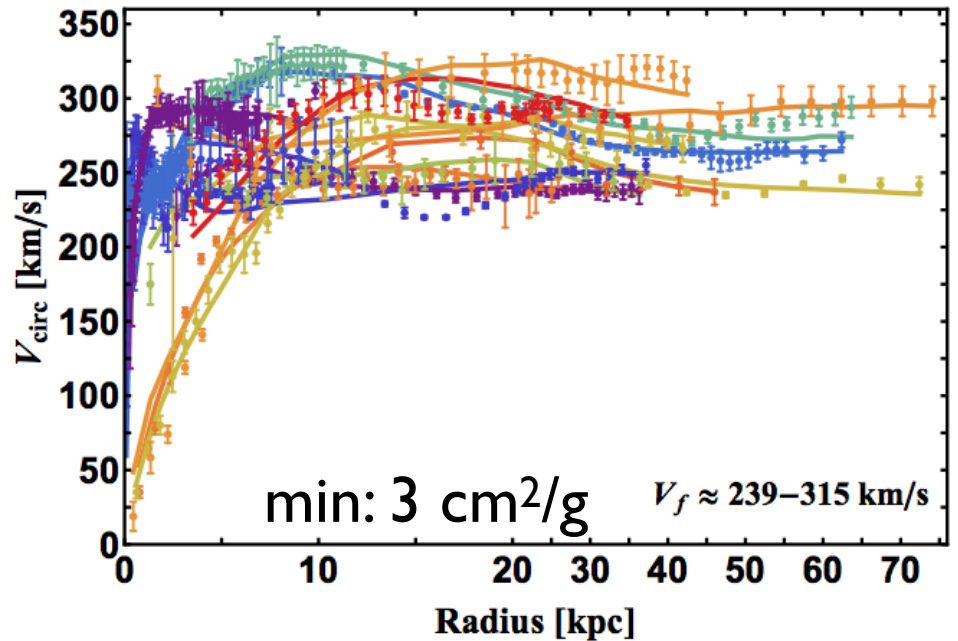
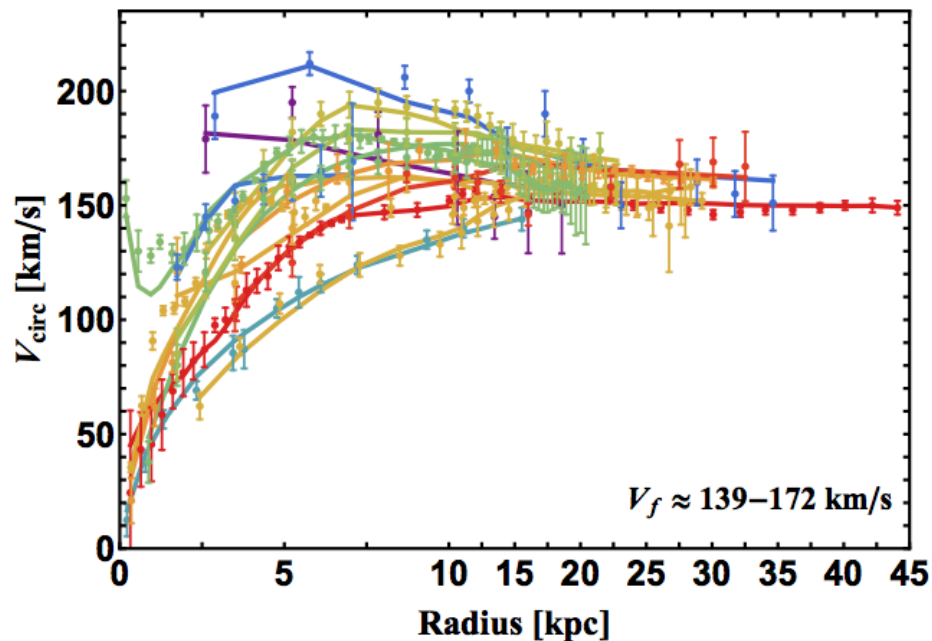
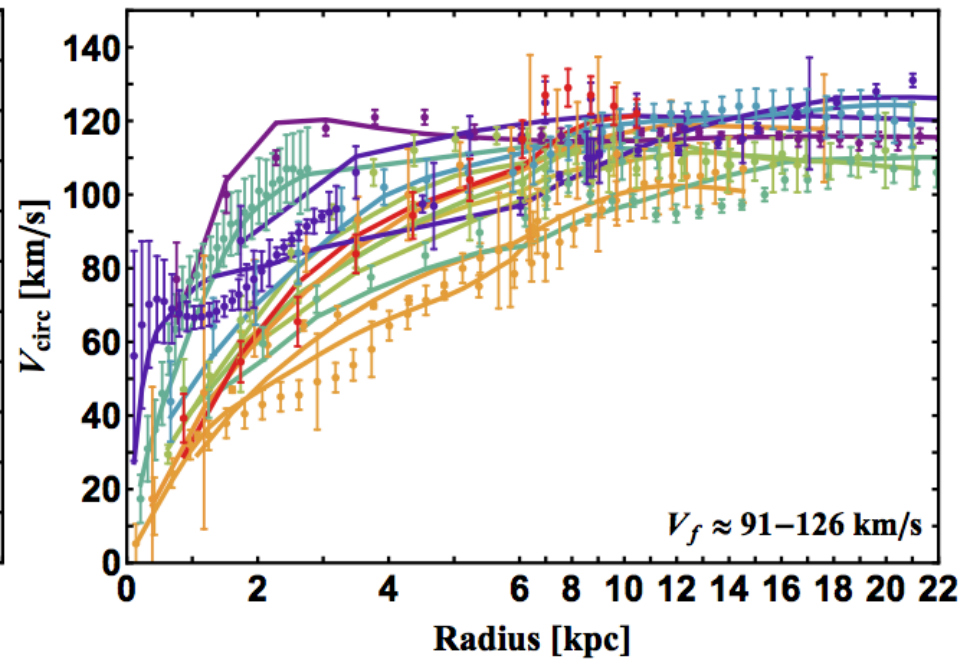
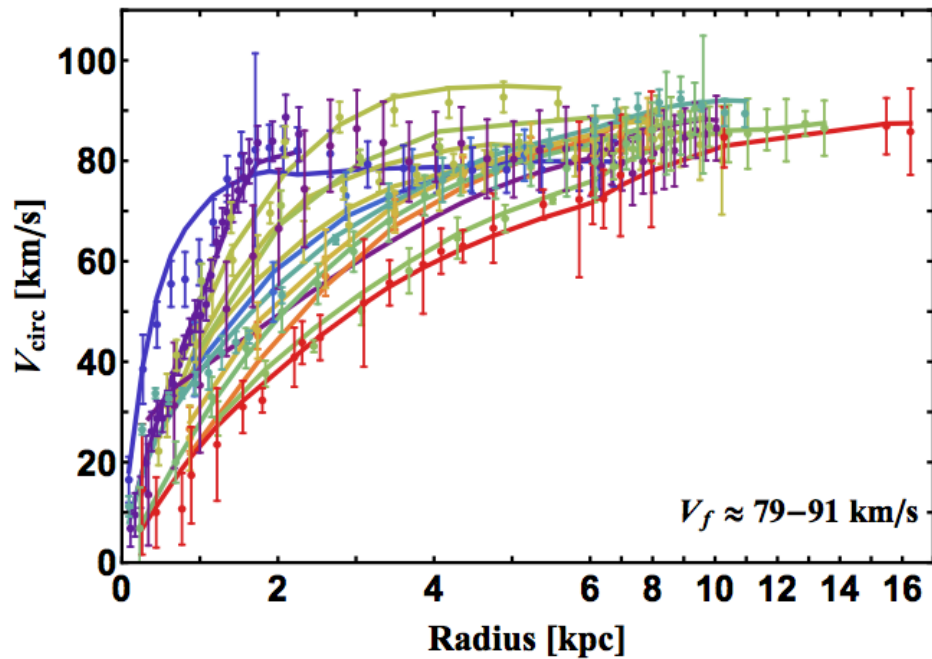
- DM self-interactions tie DM together with baryons



Thermalization leads to higher DM density due to the baryonic influence

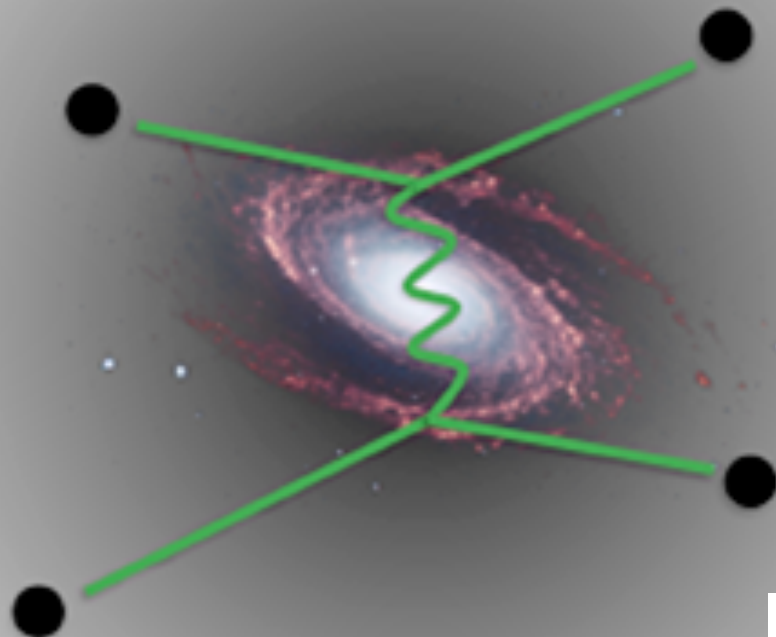


$$\rho_X \sim e^{-\Phi_{\text{tot}}/\sigma_0^2} \sim e^{-\Phi_B/\sigma_0^2}$$



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)...



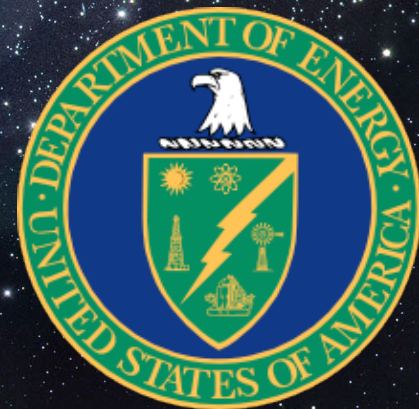
SIDM

CDM

Dark Matter (III): Self-Interacting Dark Matter

Hai-Bo Yu (郁海波)

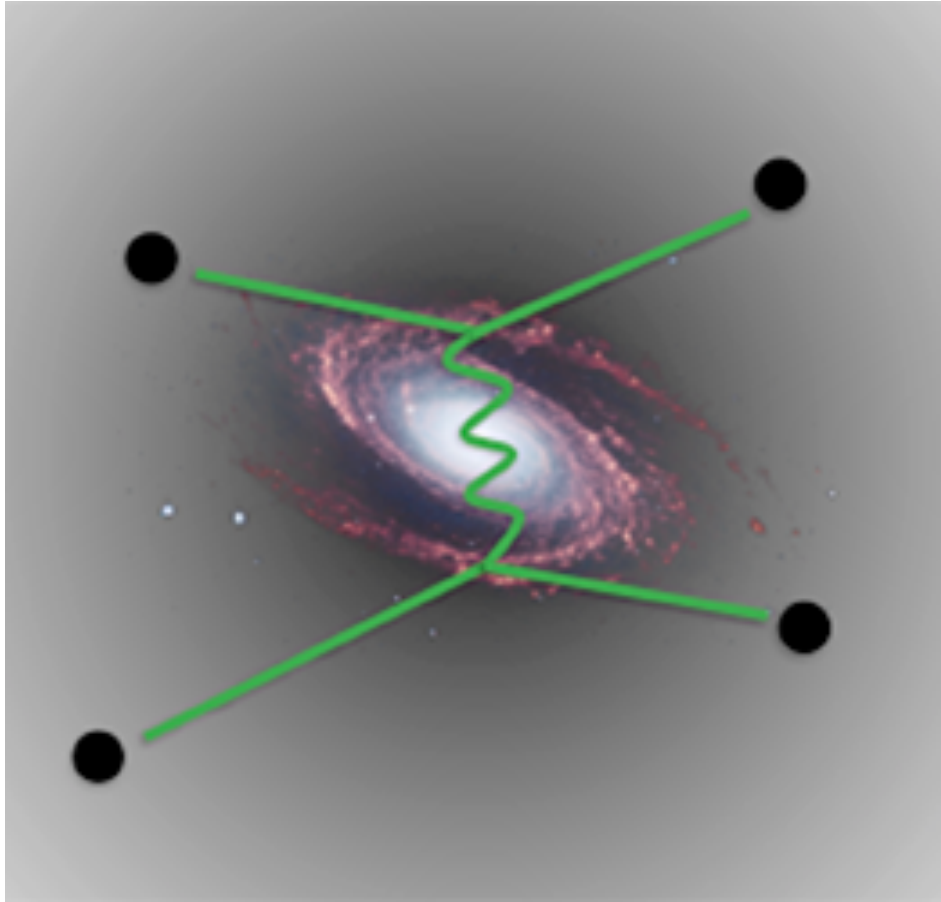
University of California, Riverside



**Fudan Particle Physics Summer
School 2026, August 19-21, 2026**

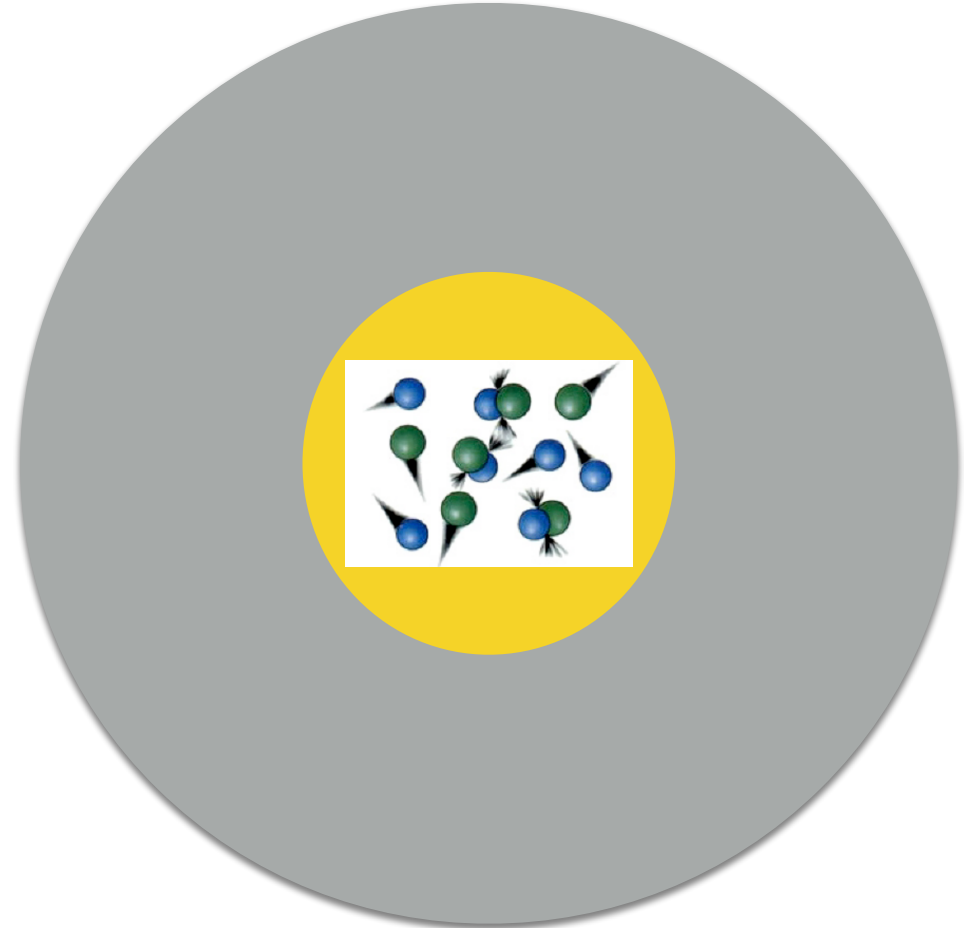


Dark Matter Self-Interactions



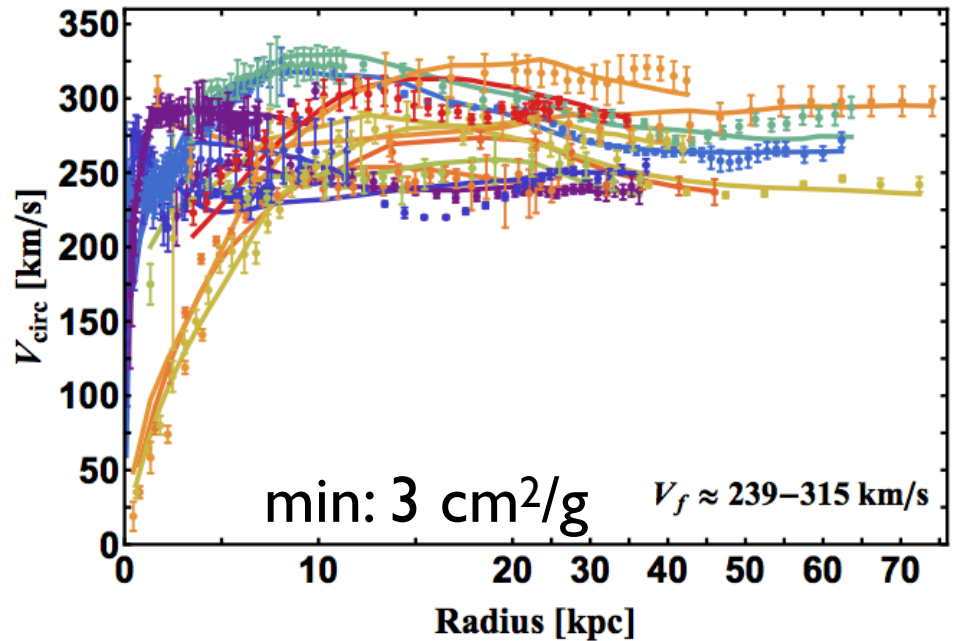
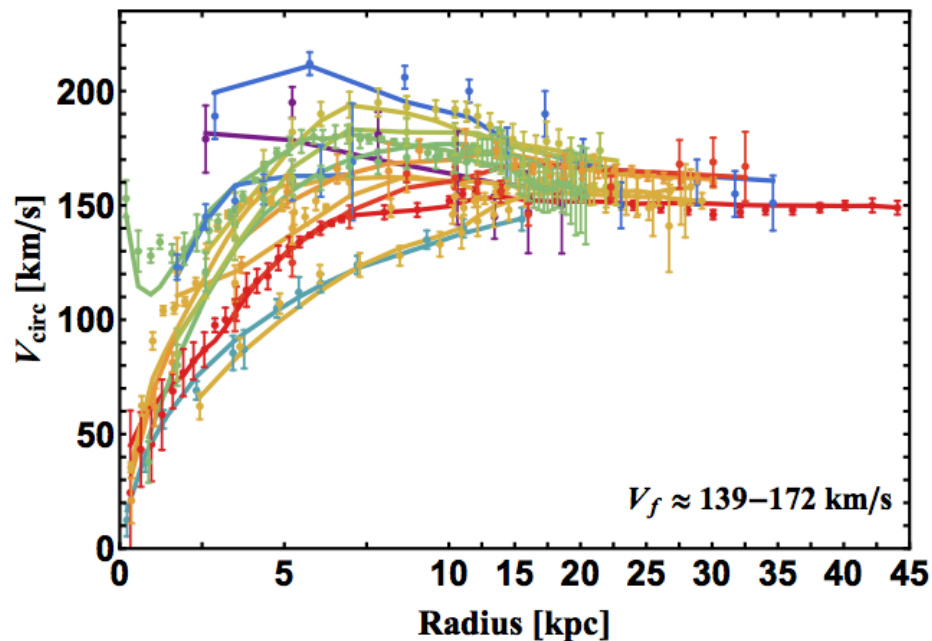
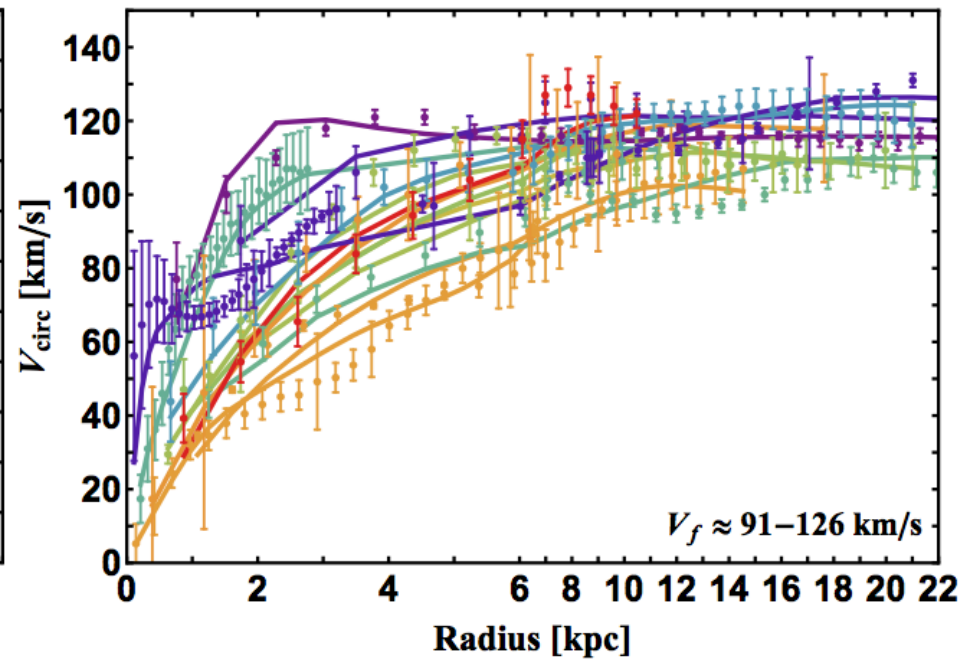
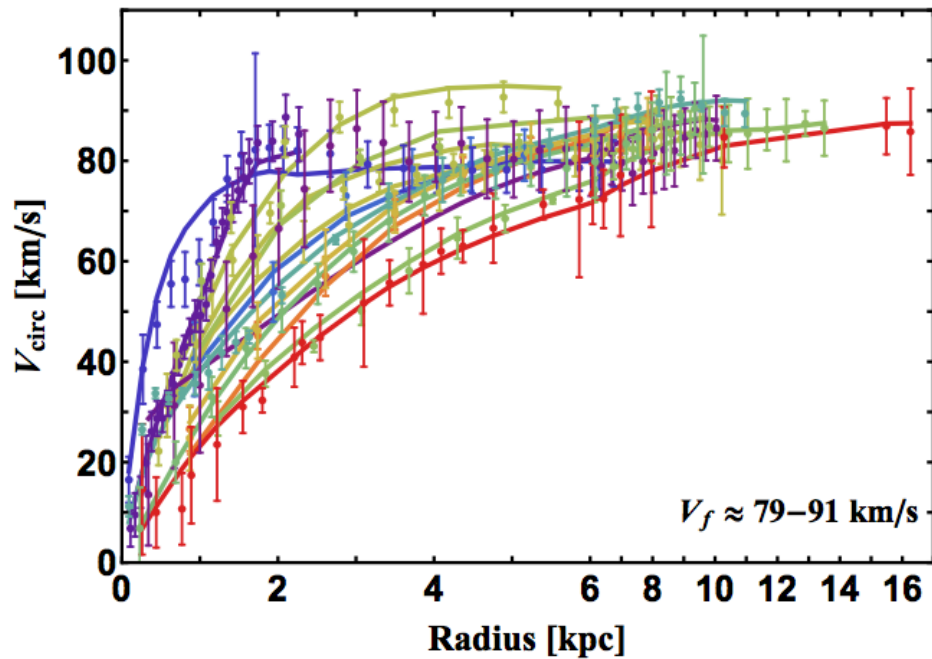
self-interactions in the dark sector

Treat dark matter as ideal gas



thermalization

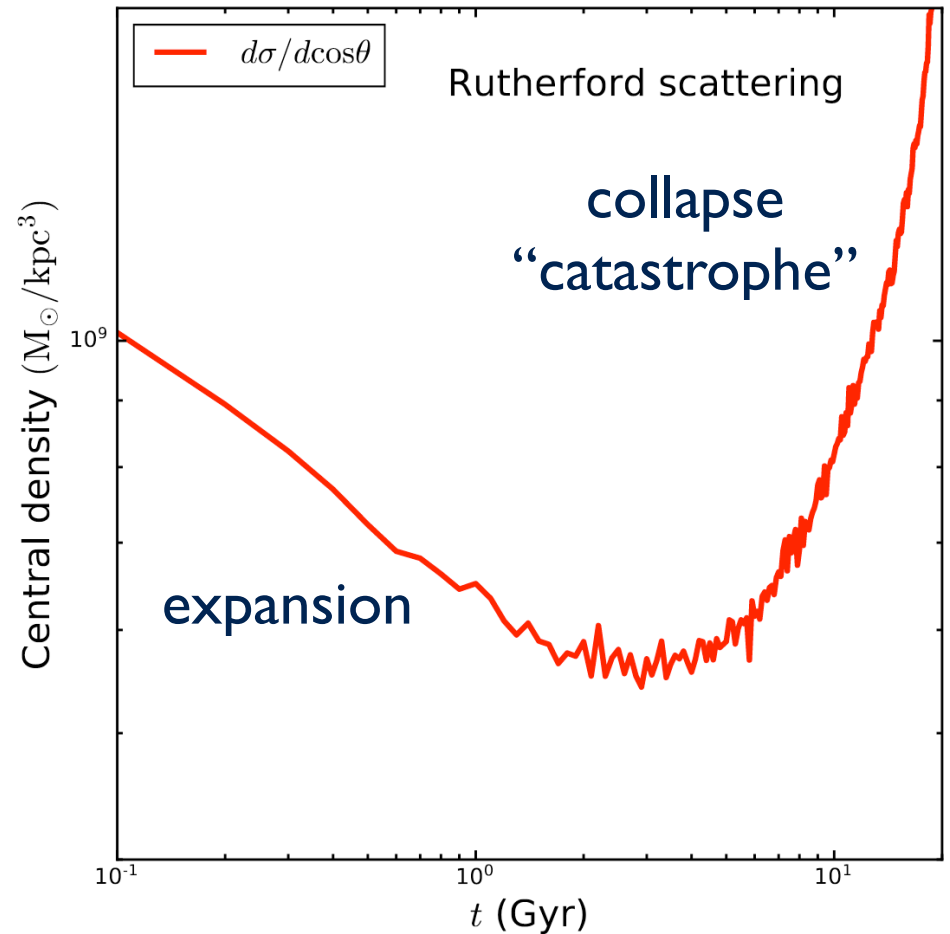
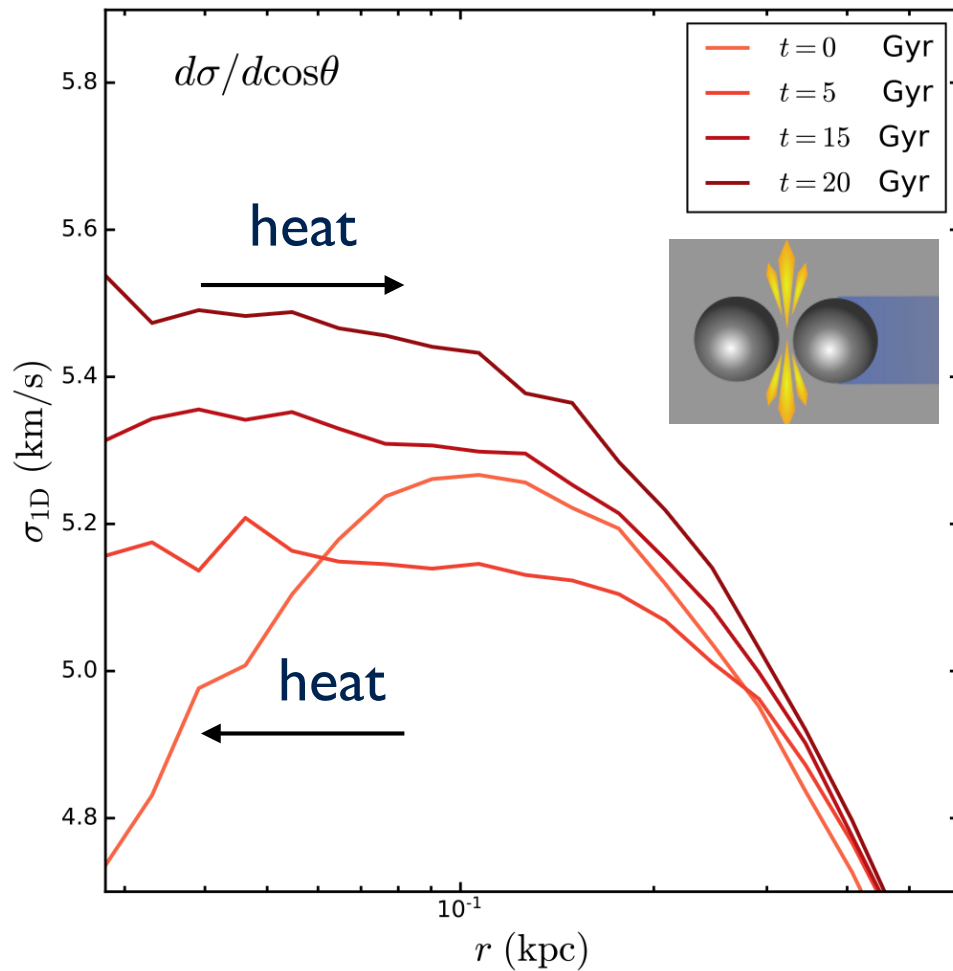
$$PV=nRT$$



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 Evolution



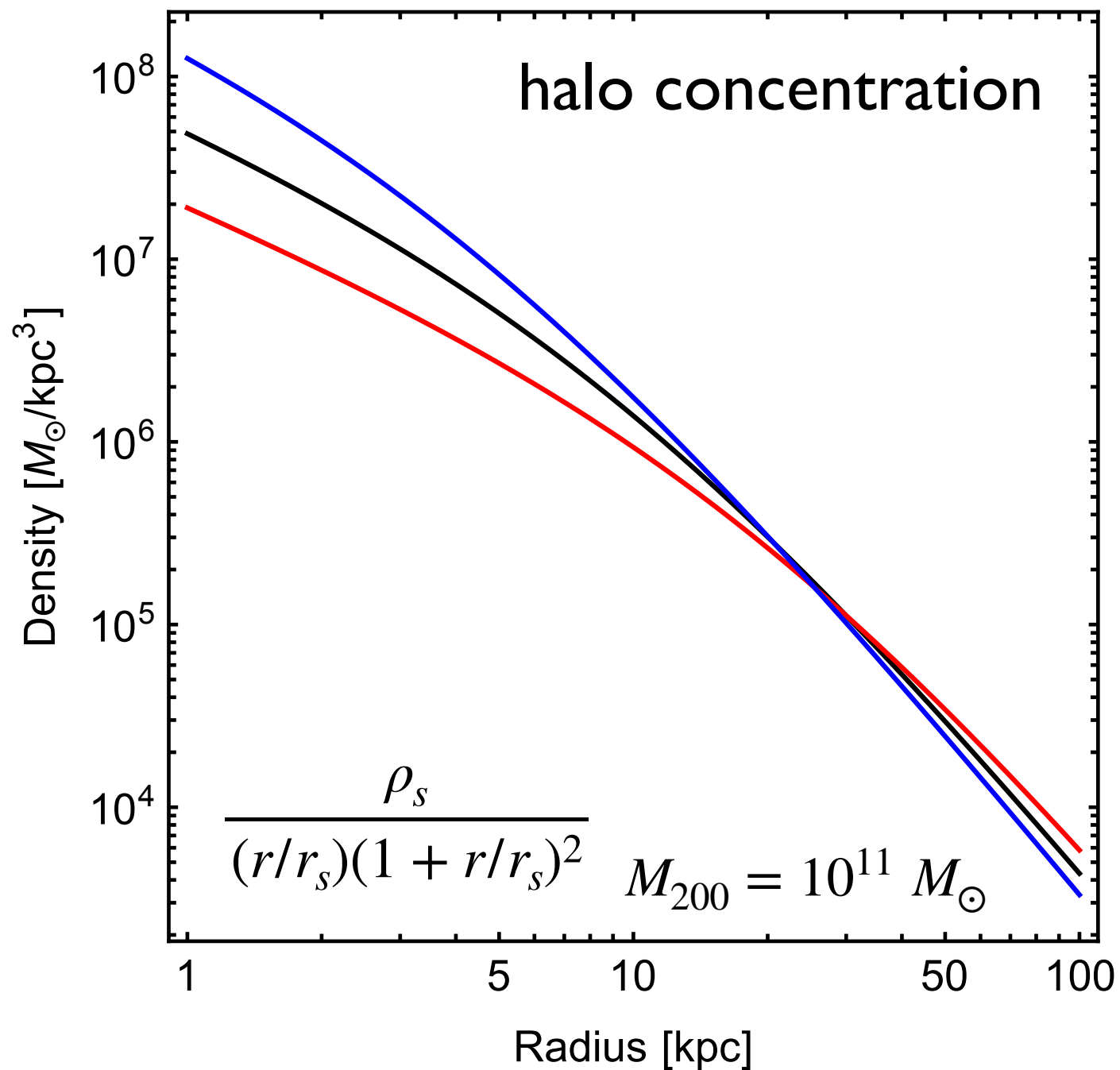
Yang, HBY (JCAP 2022)

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

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)

$$t_c = \frac{150}{C} \frac{1}{r_s \rho_s (\sigma_{\text{eff}}/m)} \frac{1}{\sqrt{4\pi G \rho_s}}$$

$$C = 0.75 \qquad \rho(r)_{\text{NFW}} = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

$$r_s = \left[\frac{3M_{200}}{(200\rho_{\text{crit}})4\pi c_{200}^3} \right]^{\frac{1}{3}}, \quad \rho_s = \frac{200\rho_{\text{crit}}c_{200}^3}{3f(c_{200})}$$

$$f(c_{200}) = \ln(c_{200} + 1) - \frac{c_{200}}{(c_{200} + 1)}$$

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

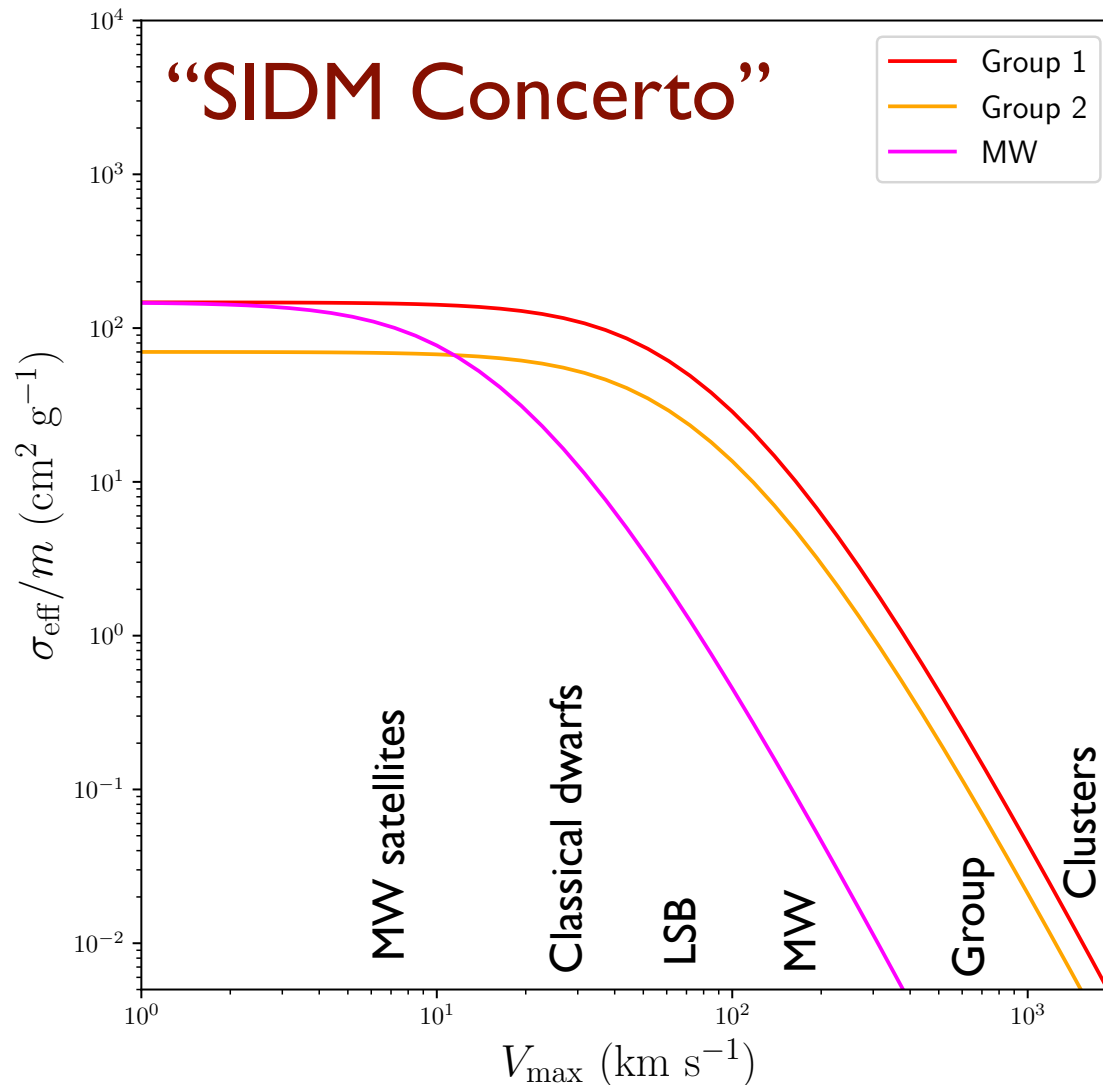
Cosmological Zoom-in Simulations



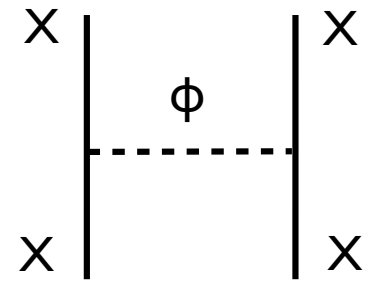
Ethan Nadler
(UCSD)



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 (2017); data from Obloinsk+(2011)

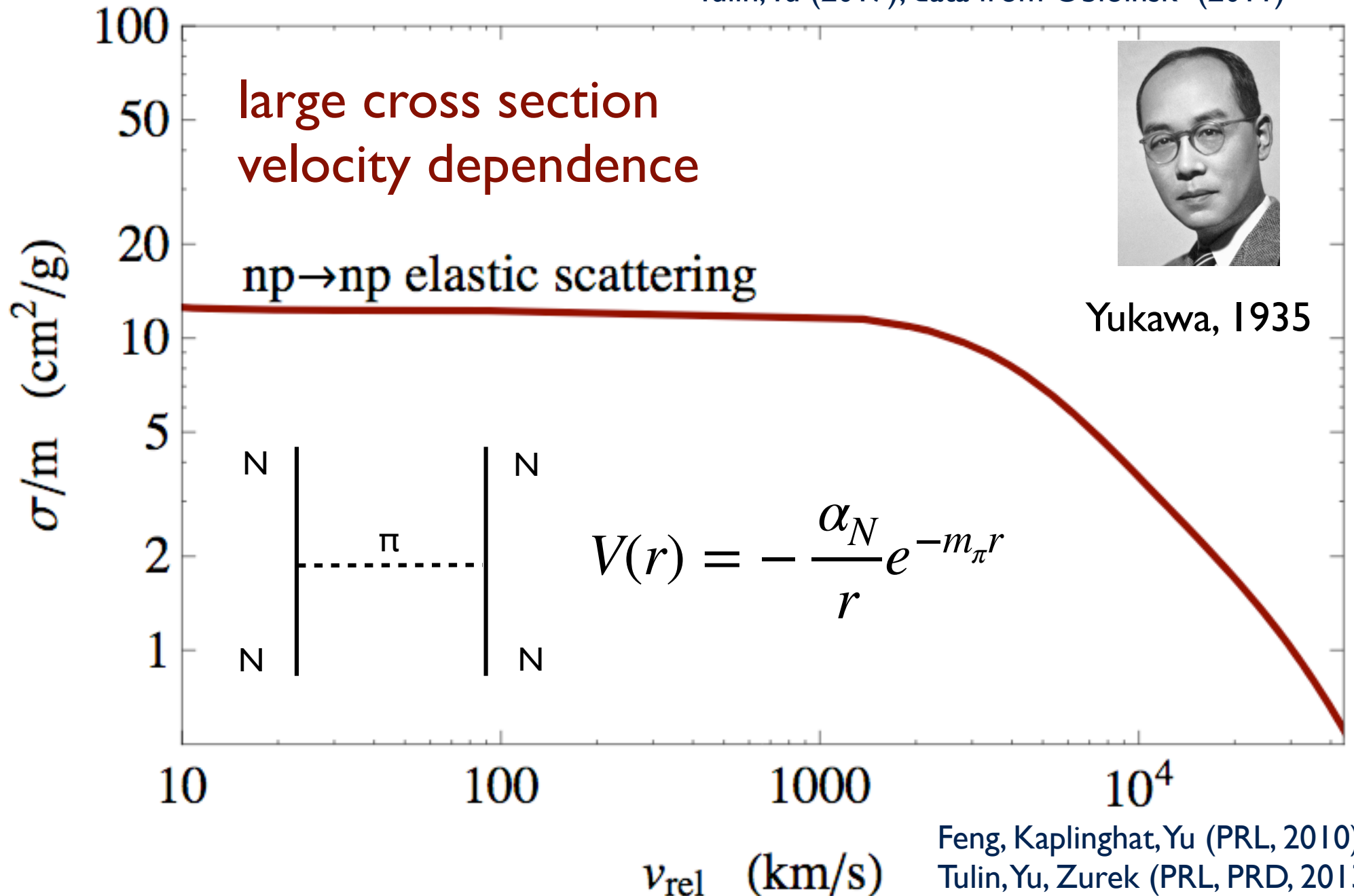
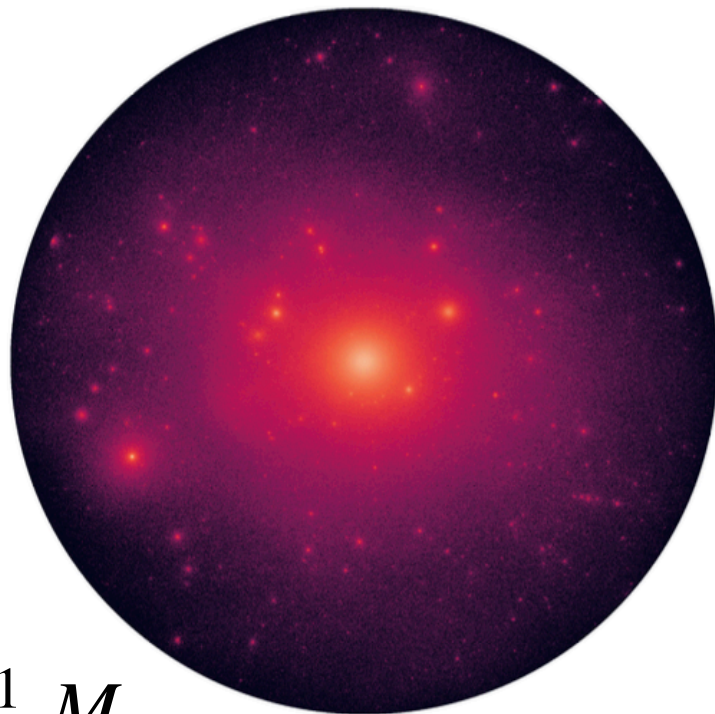


Table 1. Summary of SIDM Concerto Simulations.

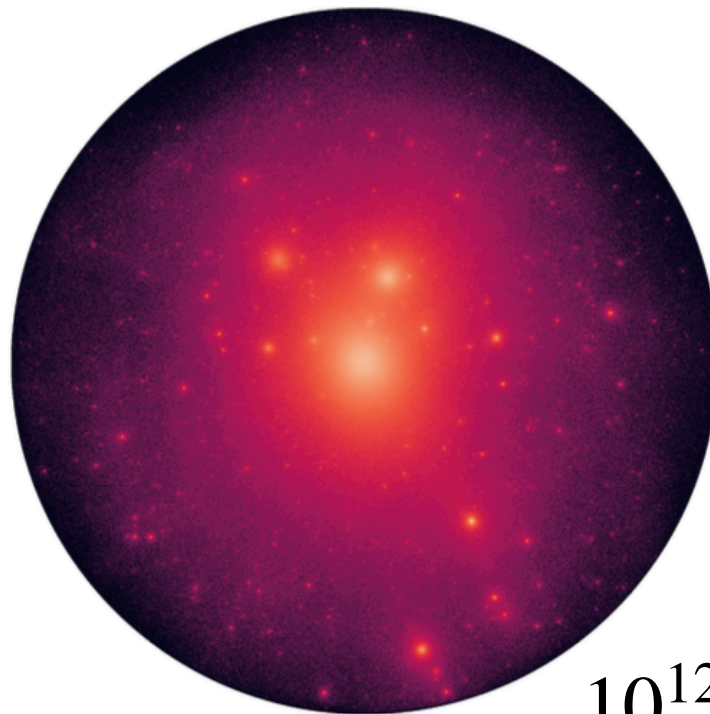
Suite	Host	Model	$\log(M_{\text{host}}/M_{\odot})$	R_{vir} [kpc]	m_{part} [$M_{\odot}$]	ϵ [$\text{pc } h^{-1}$]	Color and Linestyle
LMC	104	CDM	10.9	117.3	6.3×10^3	40	
LMC	104	GroupSIDM	10.9	115.5	6.3×10^3	40	—
MW	004	CDM	12.0	263.1	5.0×10^4	80	
MW	004	GroupSIDM	12.0	261.6	5.0×10^4	80	—
MW	004	MilkyWaySIDM	12.0	263.0	5.0×10^4	80	- - - - -
MW	416	CDM	12.2	307.2	5.0×10^4	80	
MW	416	MilkyWaySIDM	12.2	307.2	5.0×10^4	80	- - - - -
Group	352	CDM	13.1	609.5	4.0×10^5	170	
Group	352	GroupSIDM	13.1	608.3	4.0×10^5	170	—
Group	352	GroupSIDM-70	13.1	608.7	4.0×10^5	170	- - - - -
Group	962	CDM	13.5	818.4	4.0×10^5	170	
Group	962	GroupSIDM-70	13.5	815.9	4.0×10^5	170	- - - - -
L-Cluster	000	CDM	14.2	1379.5	2.7×10^7	600	
L-Cluster	000	GroupSIDM	14.2	1382.1	2.7×10^7	600	—

LMC



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

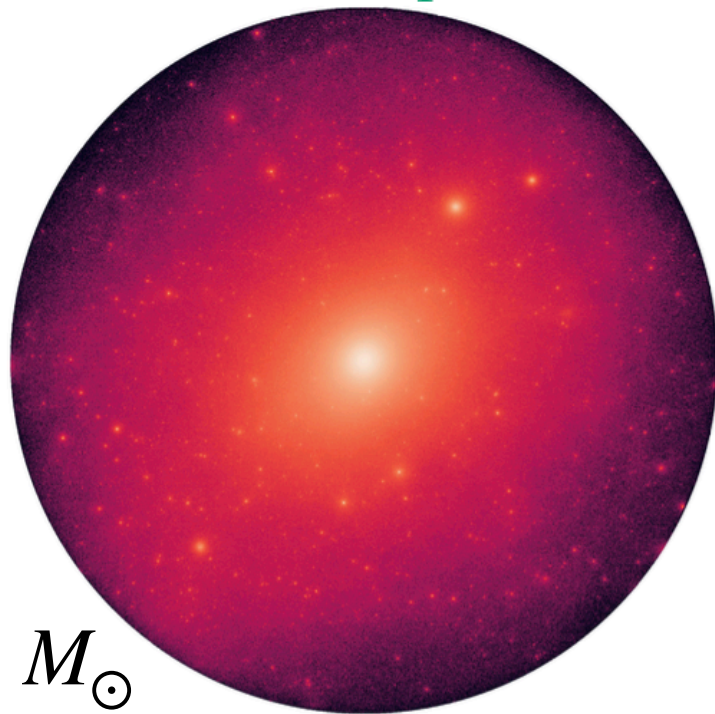
MW



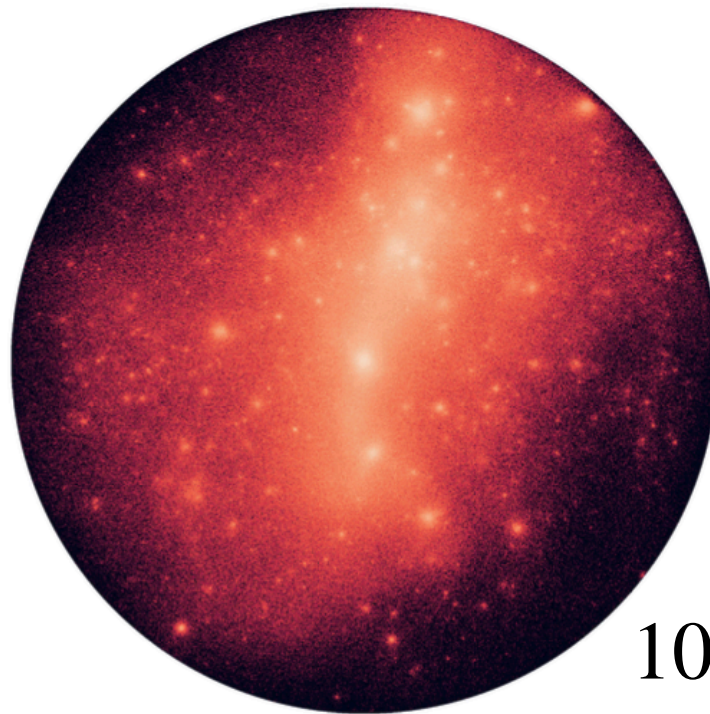
$10^{12} M_{\odot}$

Group

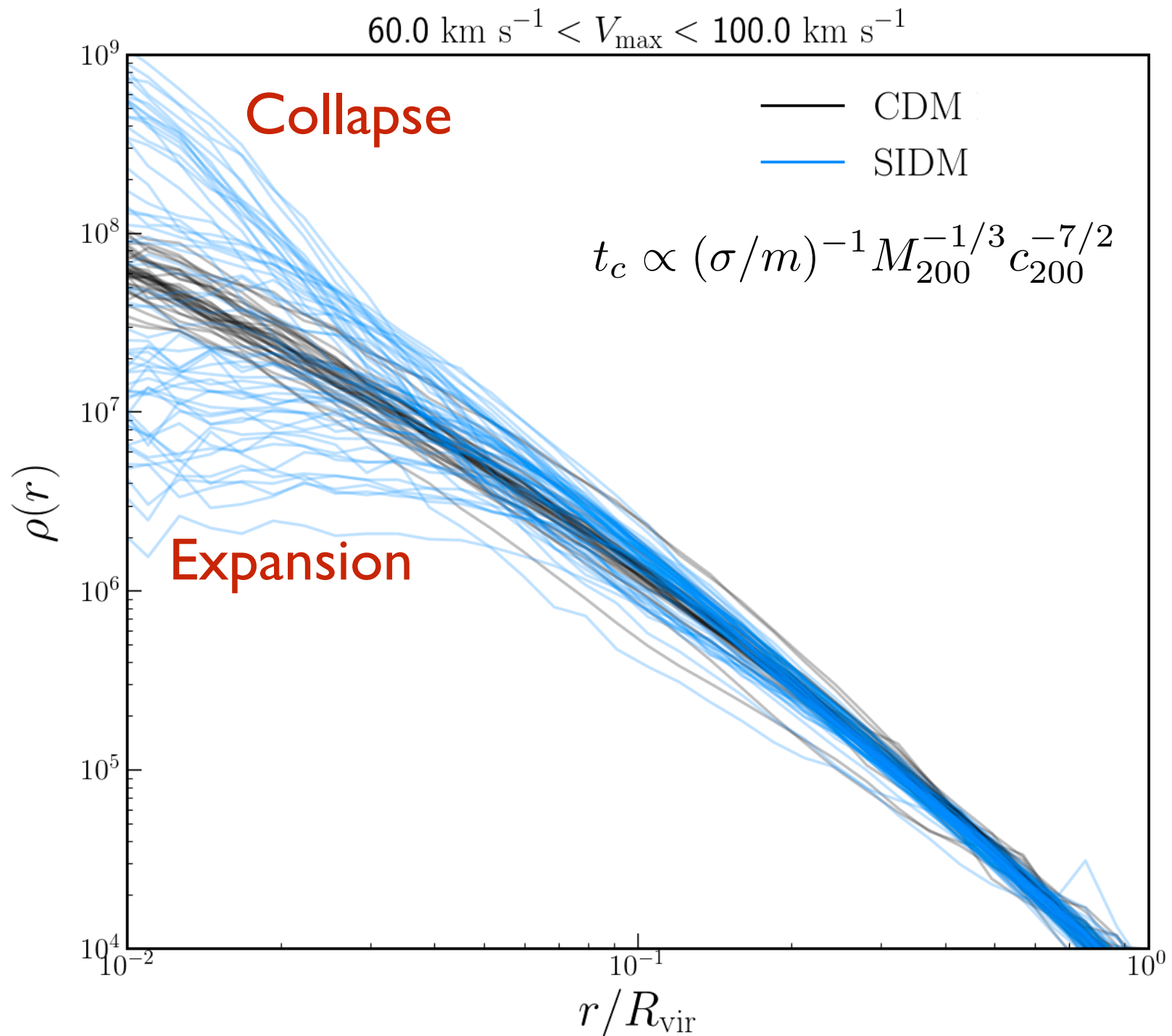
L-Cluster



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



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

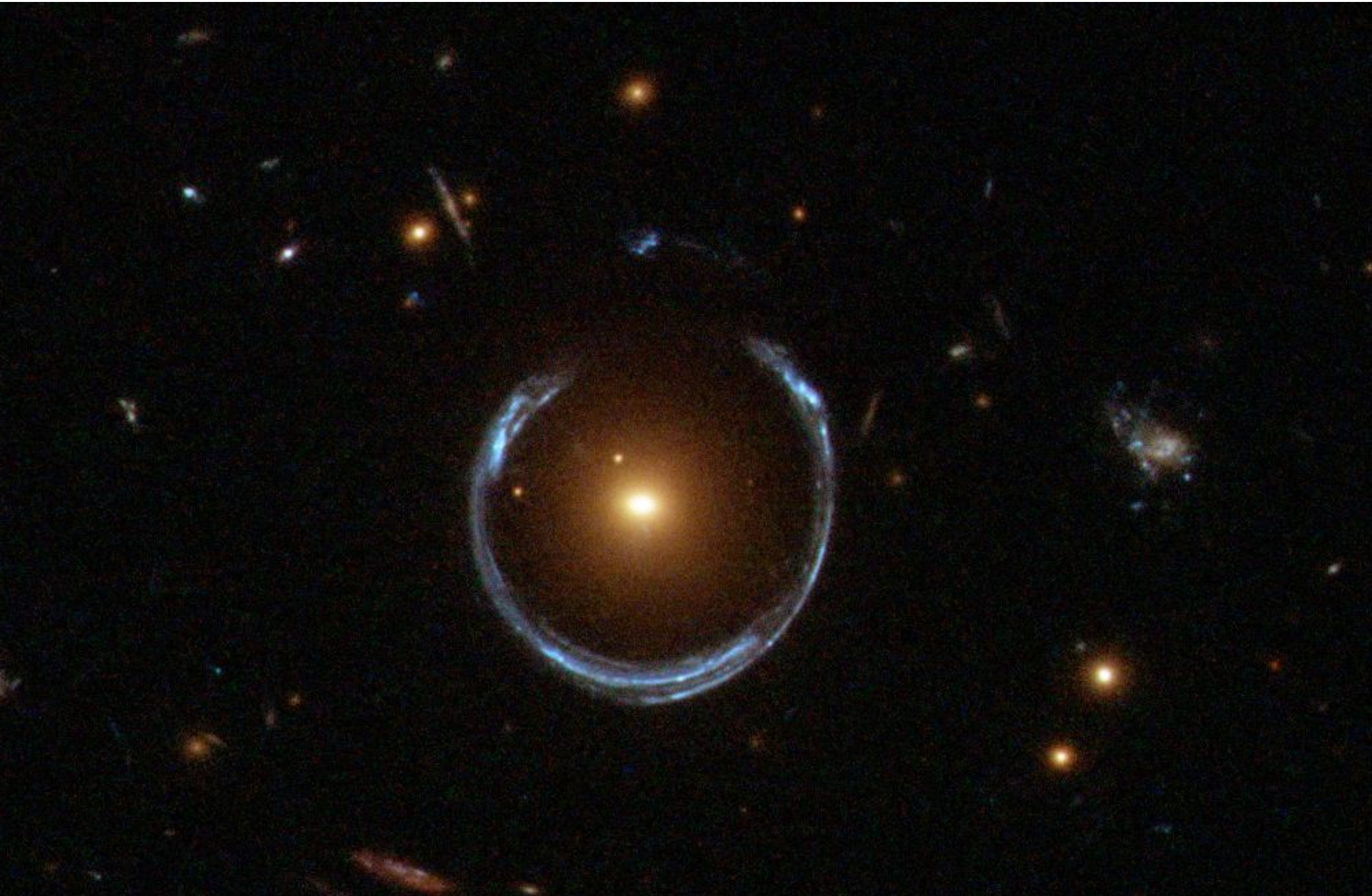


SIDM amplifies diversity encoded in the scatter of halo concentration

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*

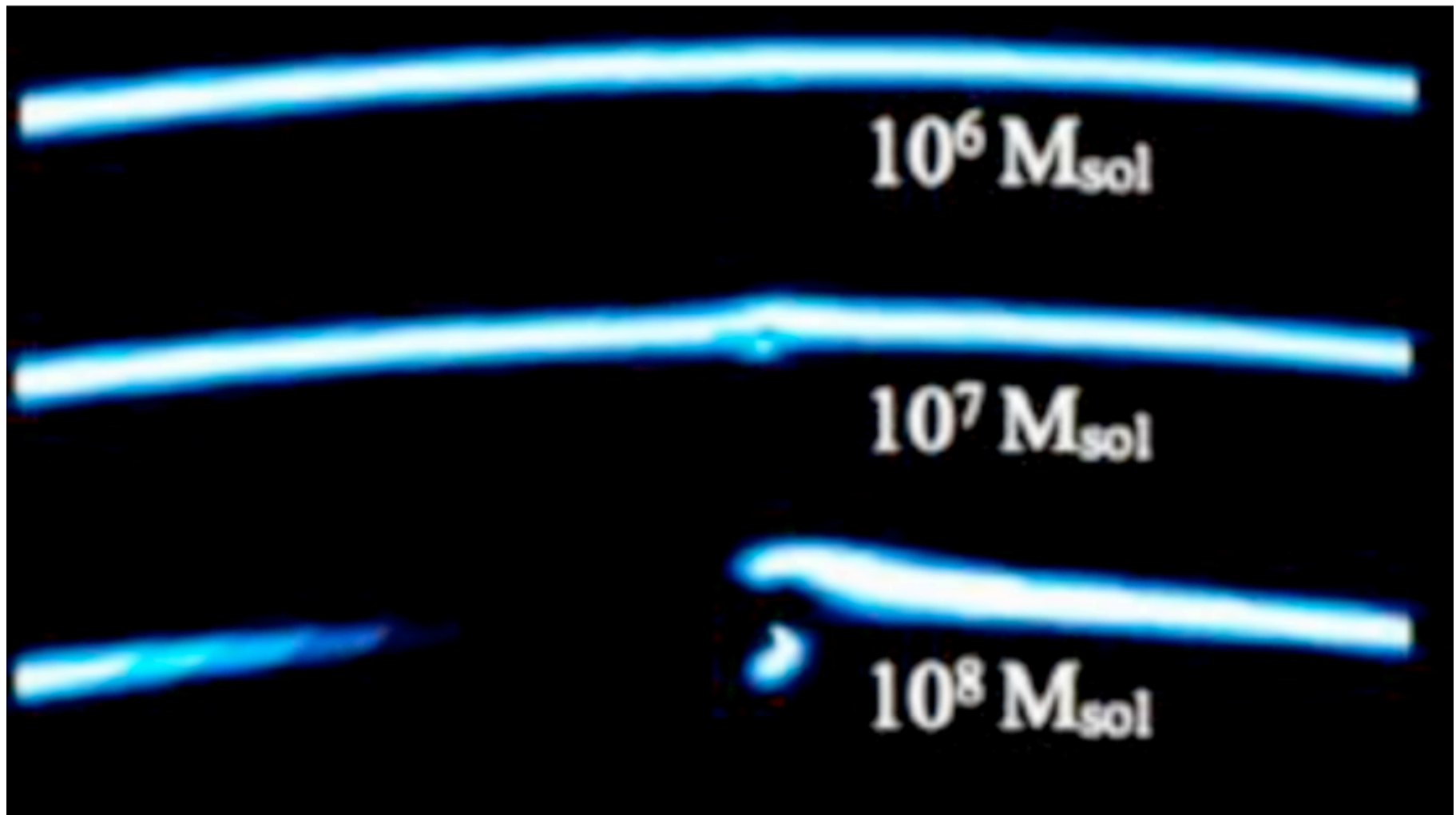
²*Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822-1897, USA*

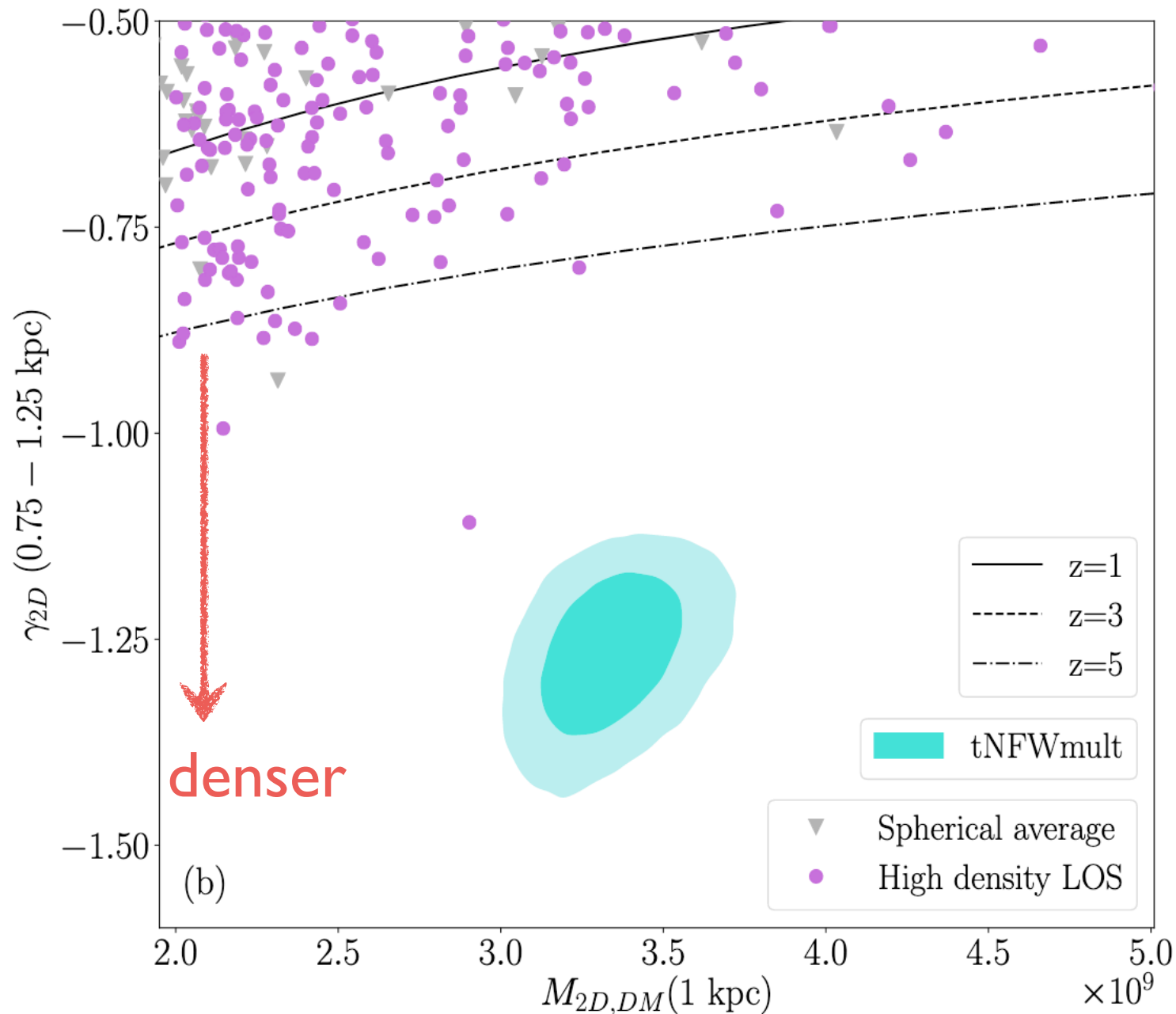
³*Department of Physics, University of California, Santa Barbara, CA 93101, USA*

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”).

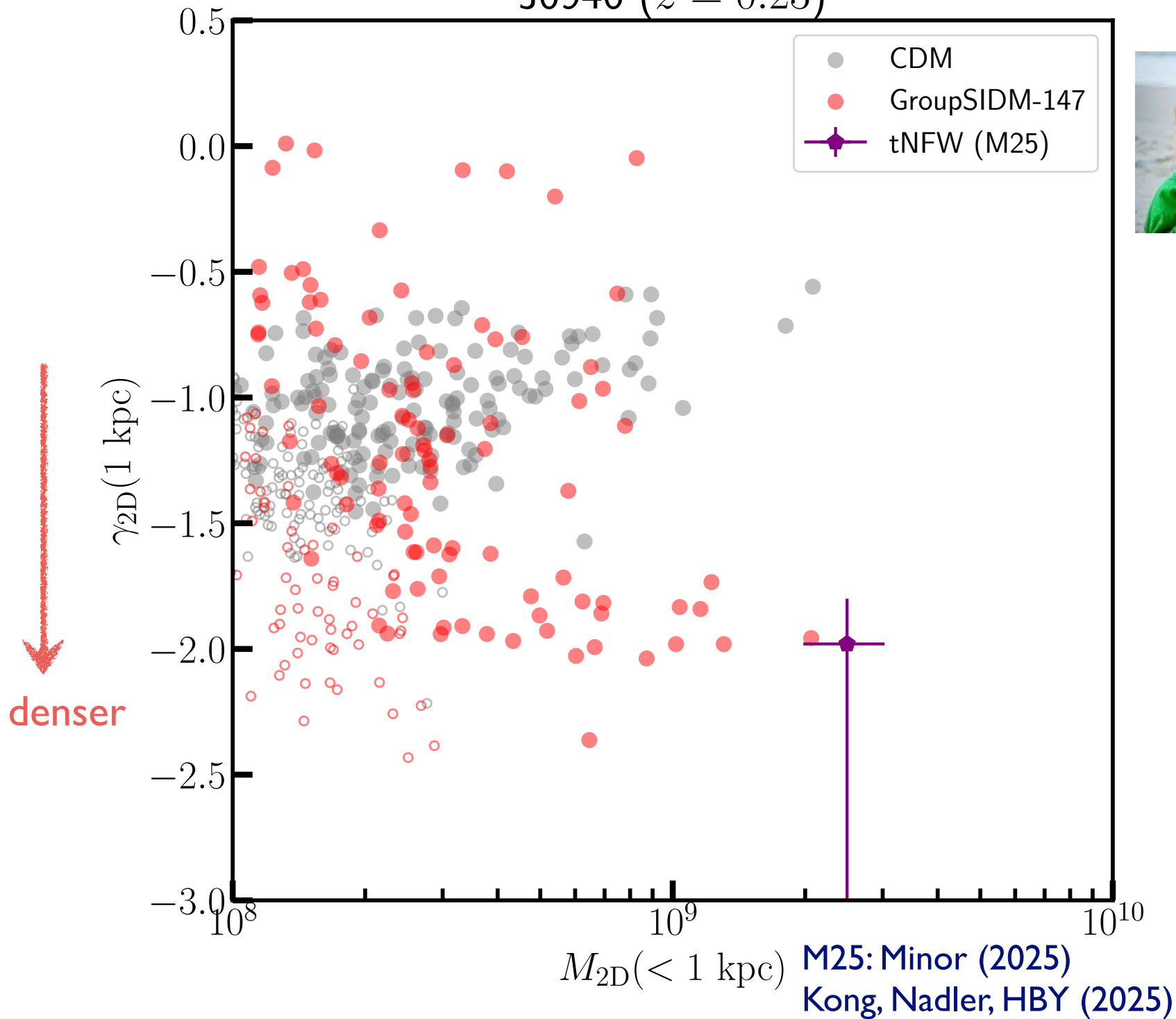




- The substructure is extremely dense
- Compared to the IllustrisTNG simulation, the tension with CDM is at the $> 99\%$ CL
- The substructure does not have a detectable luminous component

Minor+(MNRAS, 2020)

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-A

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

The core-collapse interpretation: Kong, Nadler, Yu (PRD 2025); Yu (PRL 2025)

Stellar Streams of the Milky Way

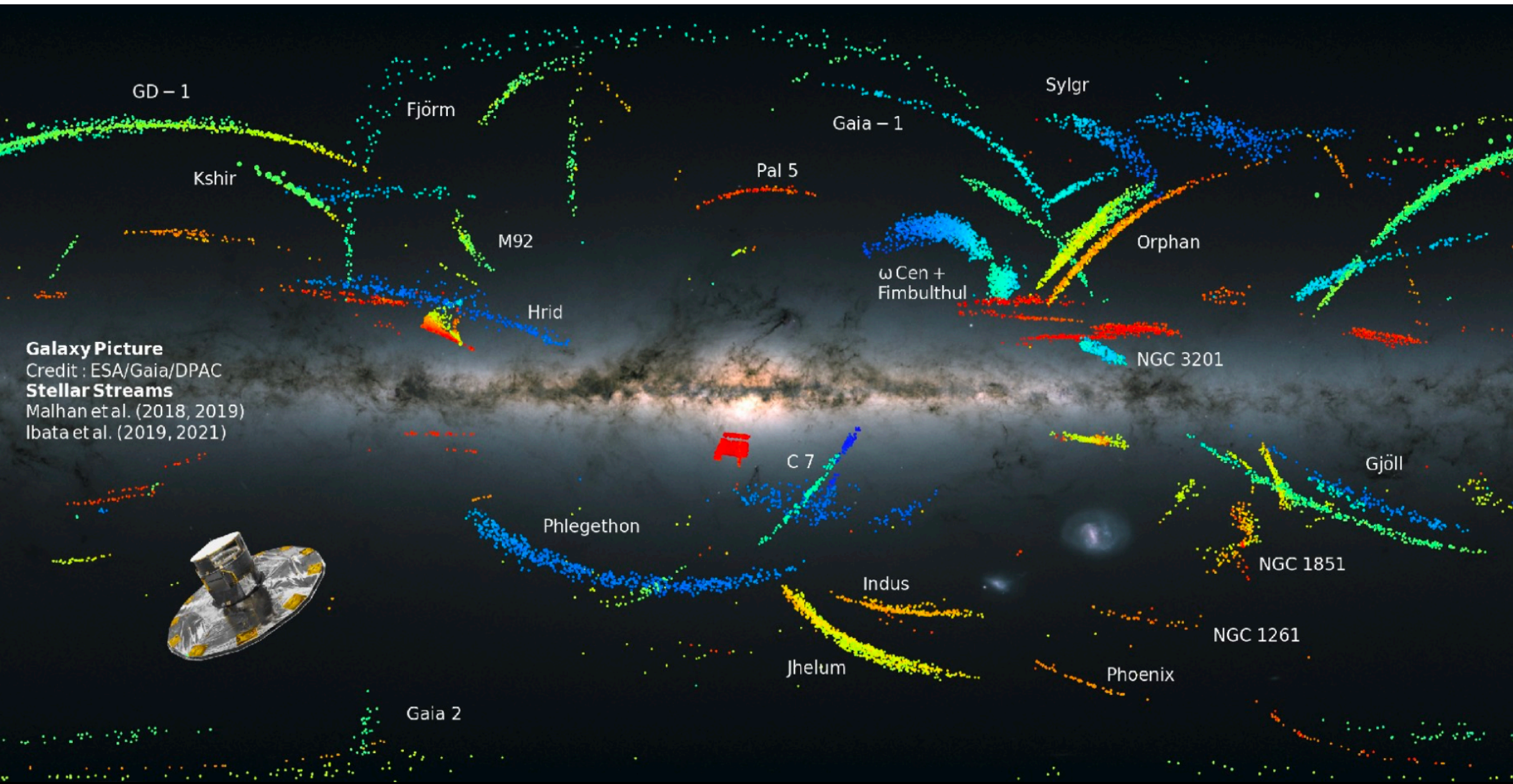
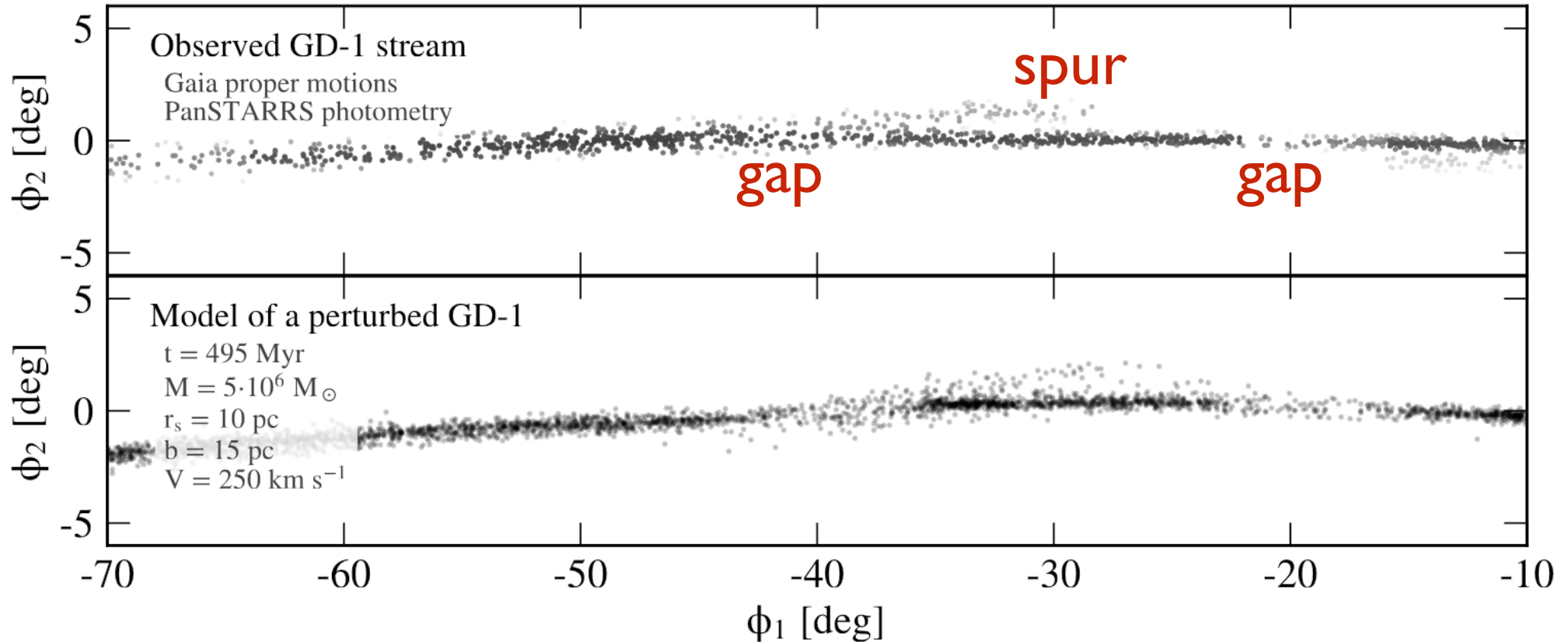


Figure: Khyati Malhan

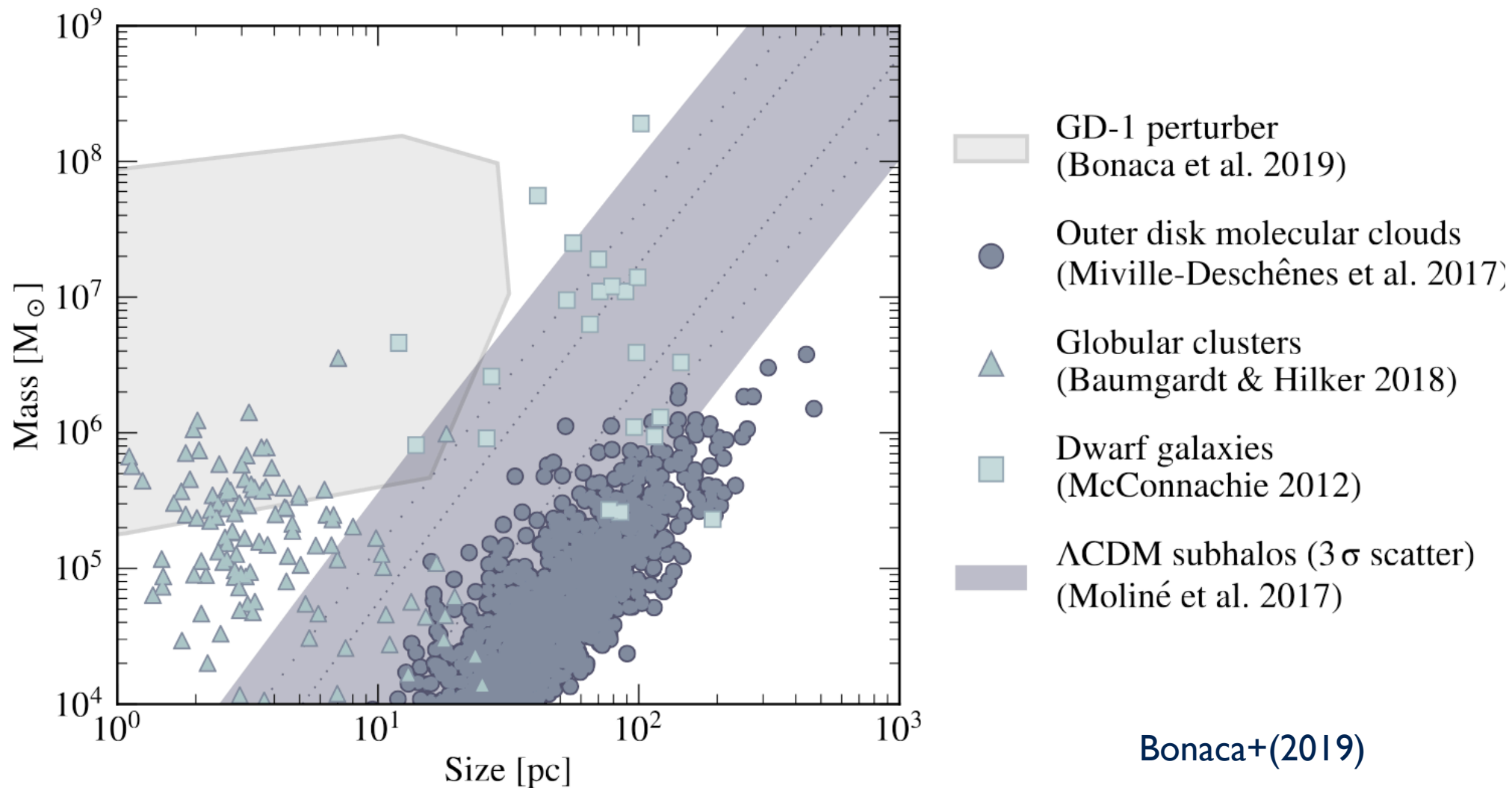


The Spur and the Gap in GD-1: Dynamical evidence for a dark substructure in the Milky Way halo

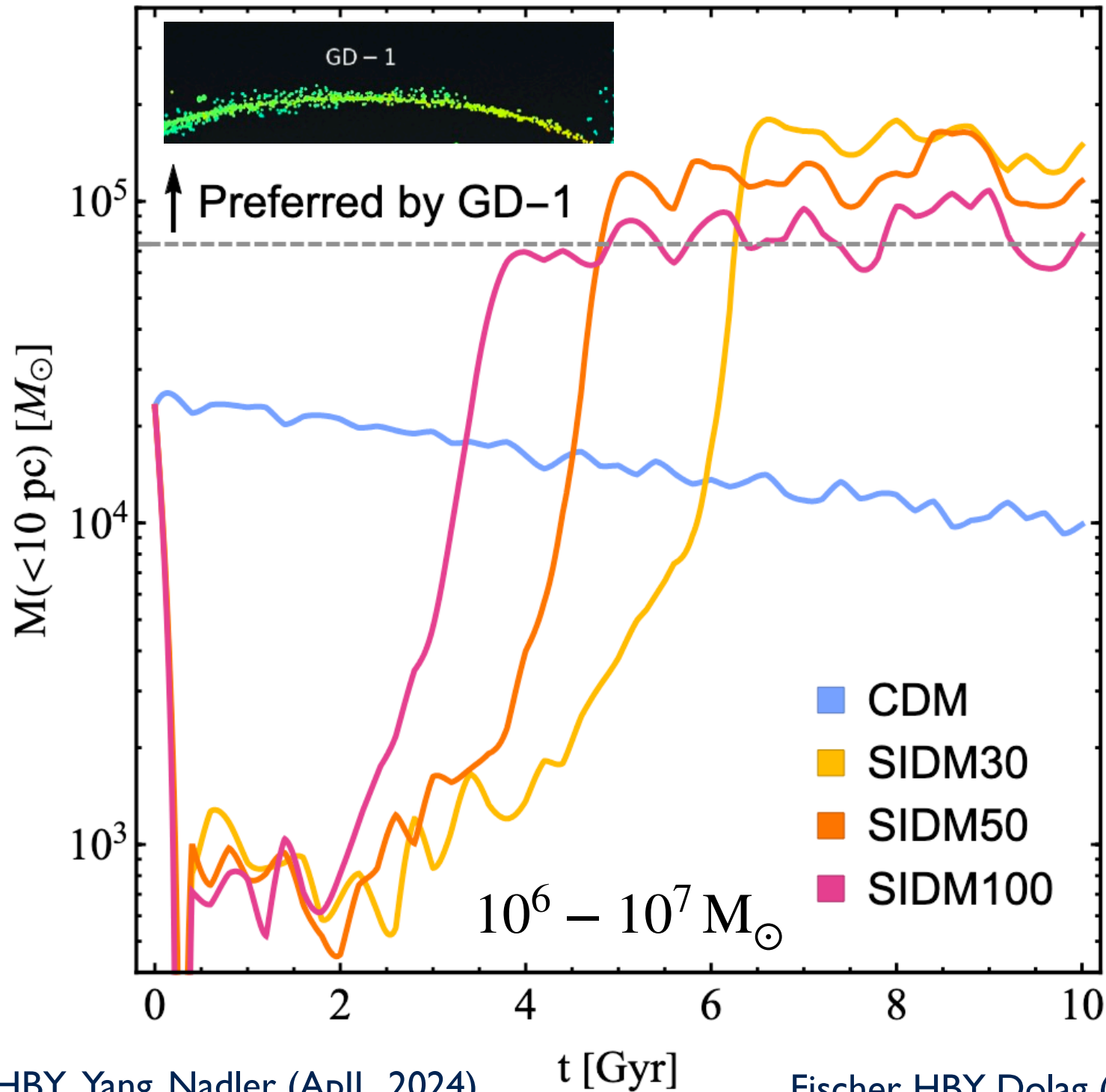
ANA BONACA,¹ DAVID W. HOGG,^{2, 3, 4, 5} ADRIAN M. PRICE-WHELAN,⁶ AND CHARLIE CONROY¹



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



- None of the known satellite galaxies and globular clusters of the Milky Way can be the perturber
- Overall, CDM subhalos are not dense enough



Xingyu Zhang
(UCR)

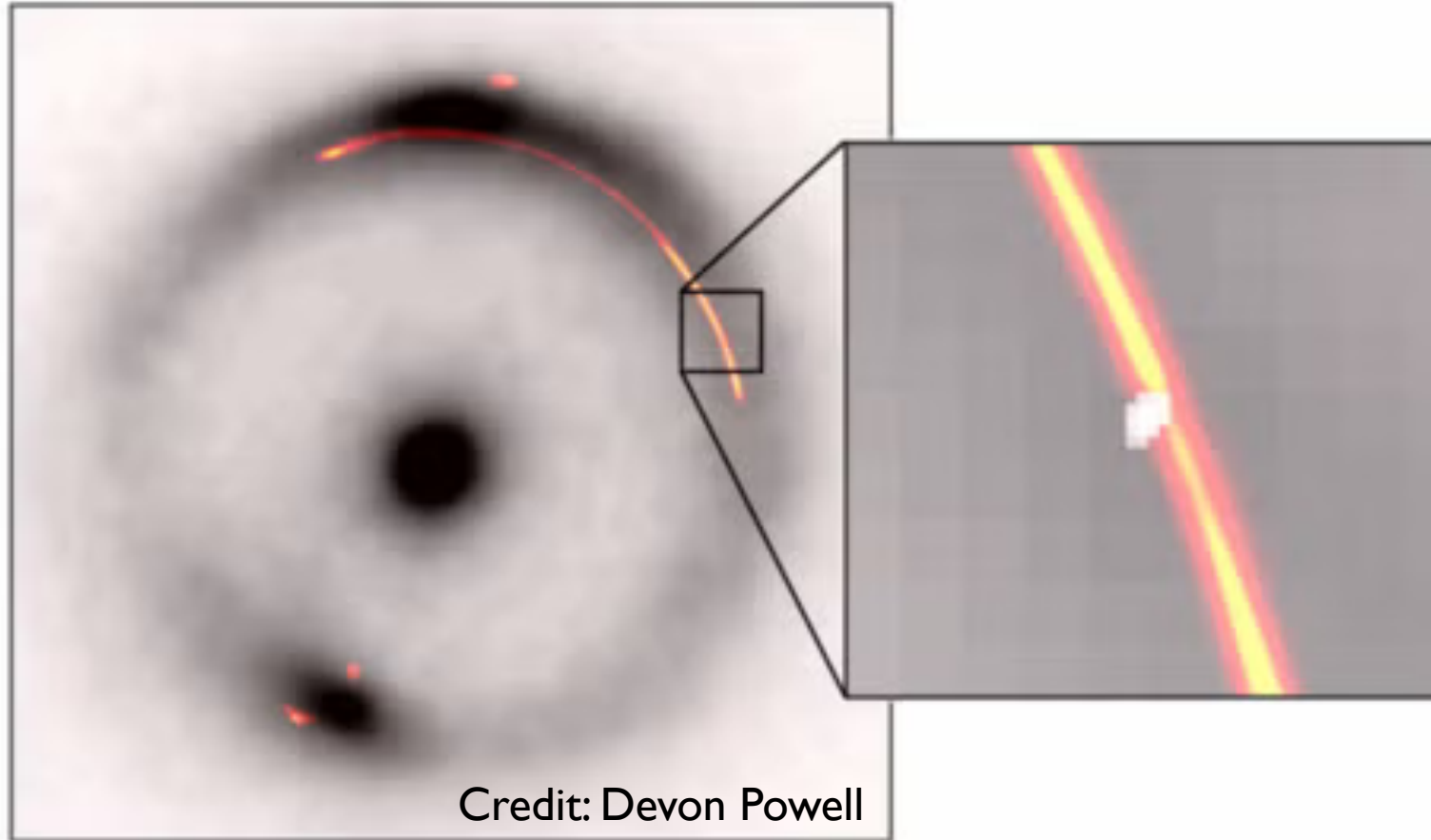


Moritz Fischer
(DIPC)

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](#)



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

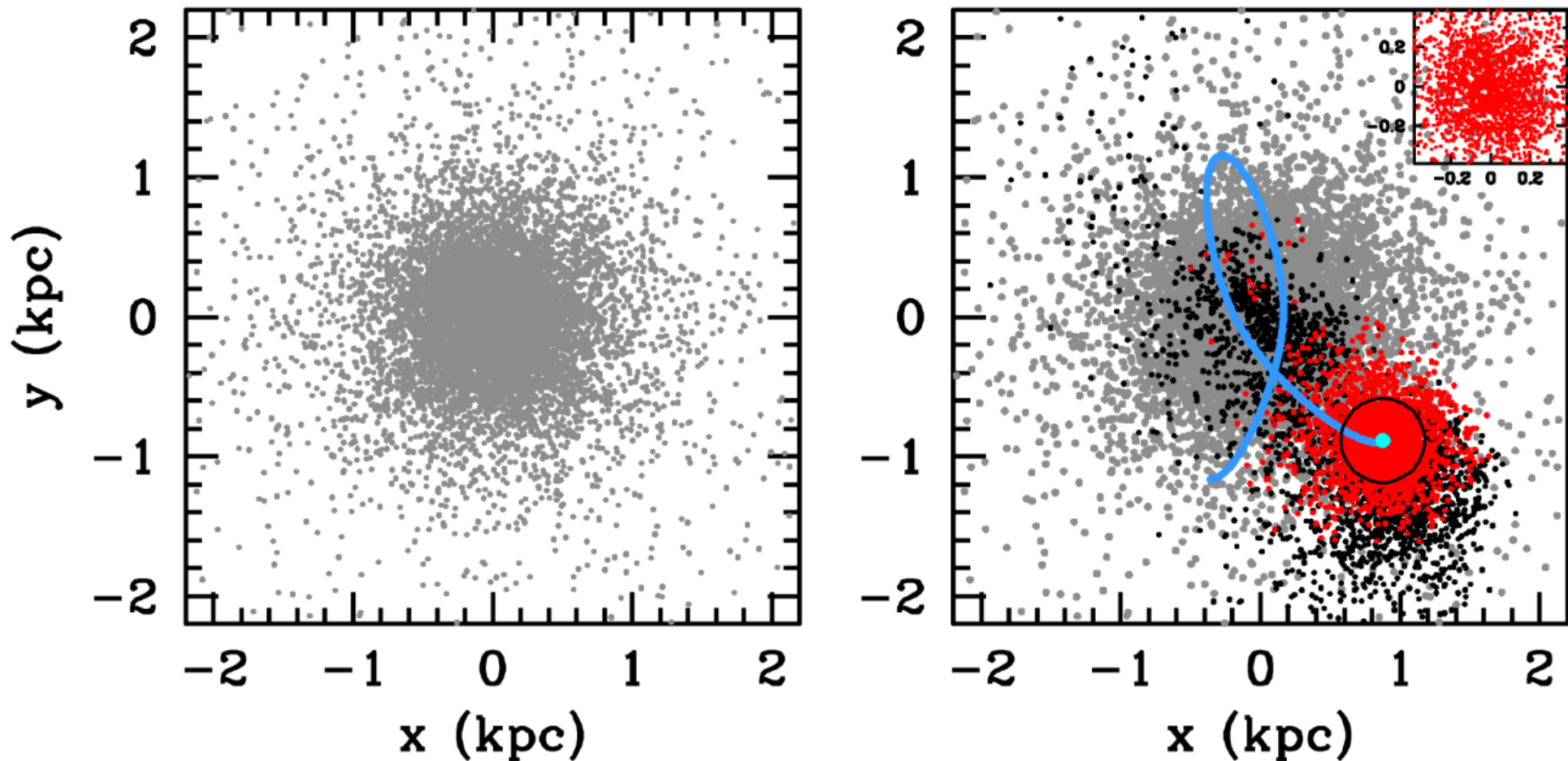
$\sim 10\sigma$ “outlier”

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

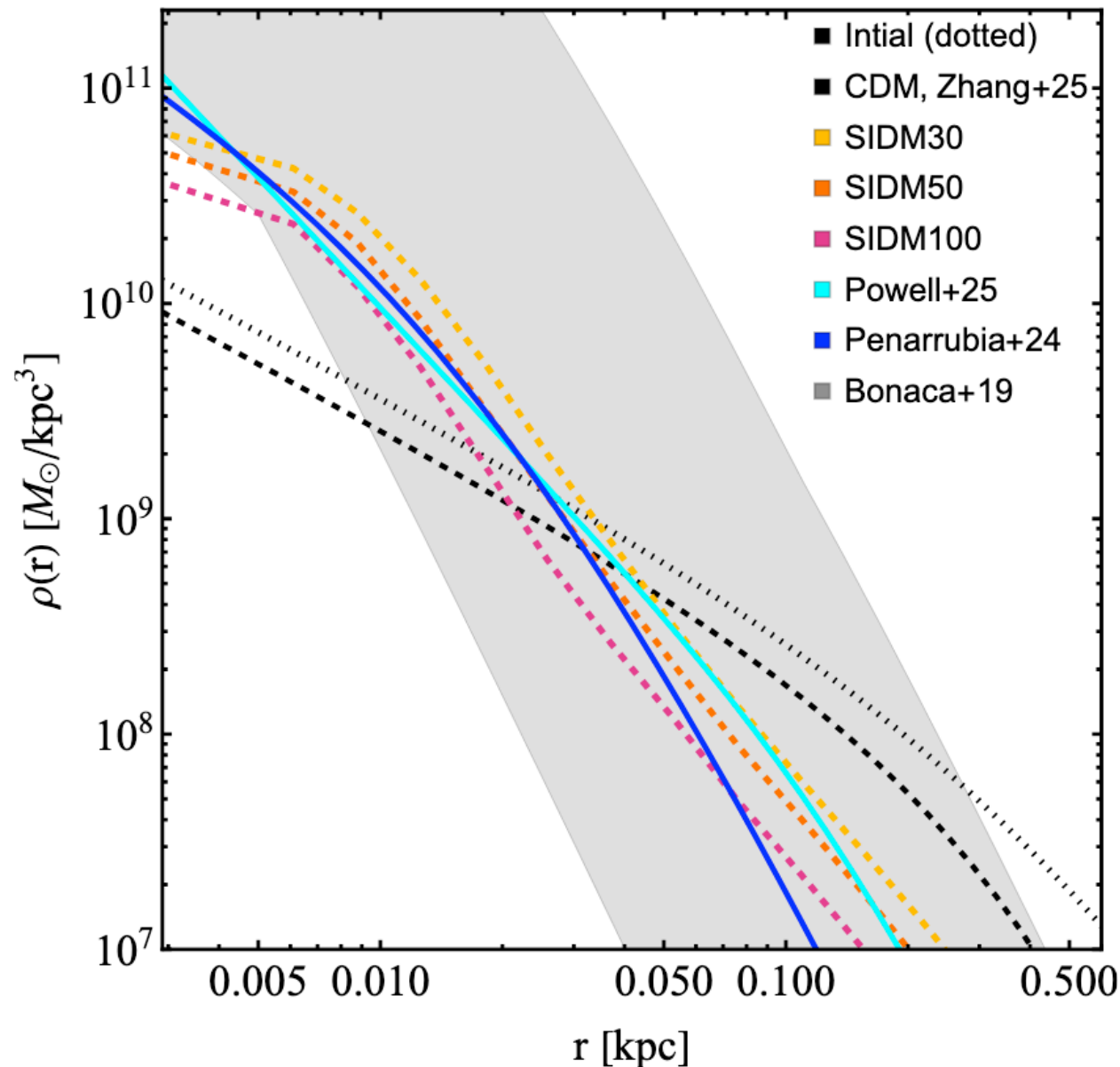
Hint: there is a dense substructure in Fornax

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

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

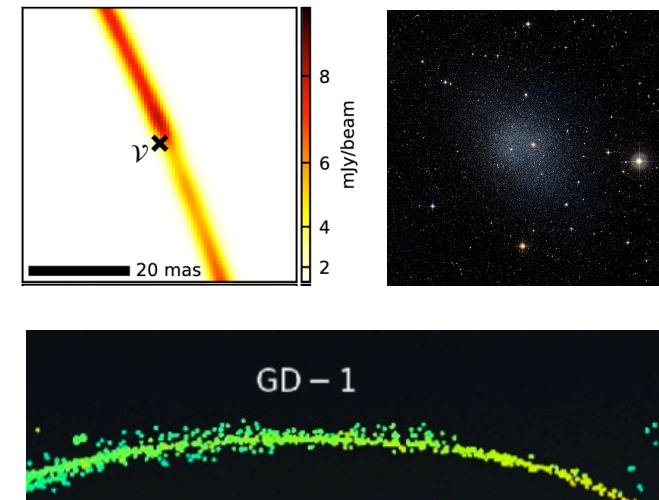


Different cosmic environments and epochs

Strong lensing system

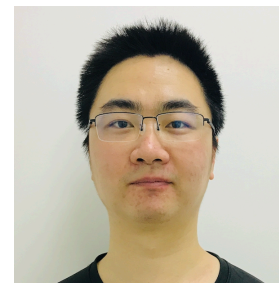
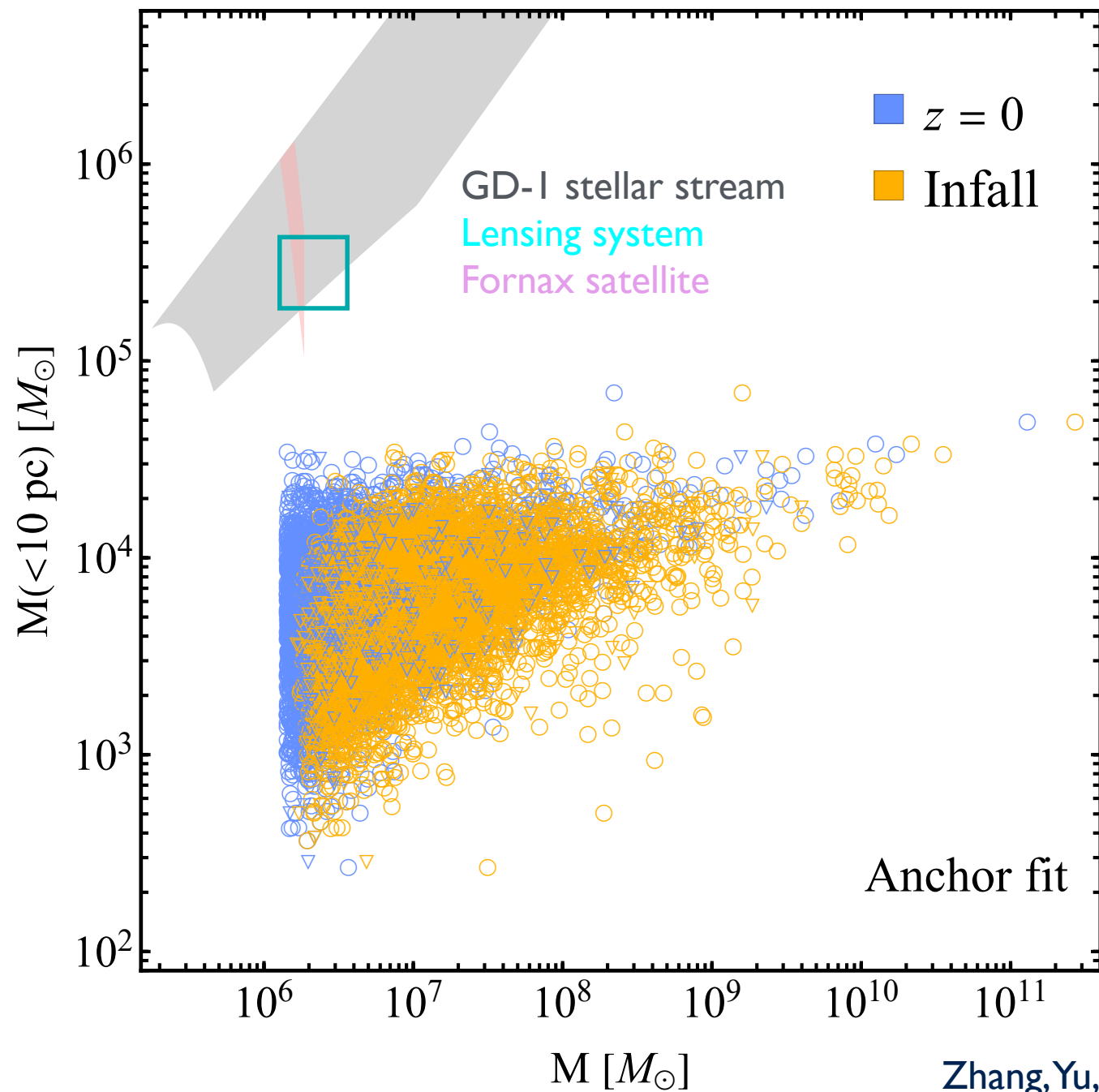
Fornax satellite

GD-I stellar stream



THREE BIRDS WITH ONE STONE





Xingyu Zhang
(UCR)

Zhang, Yu, Kong, Nadler (in prep)

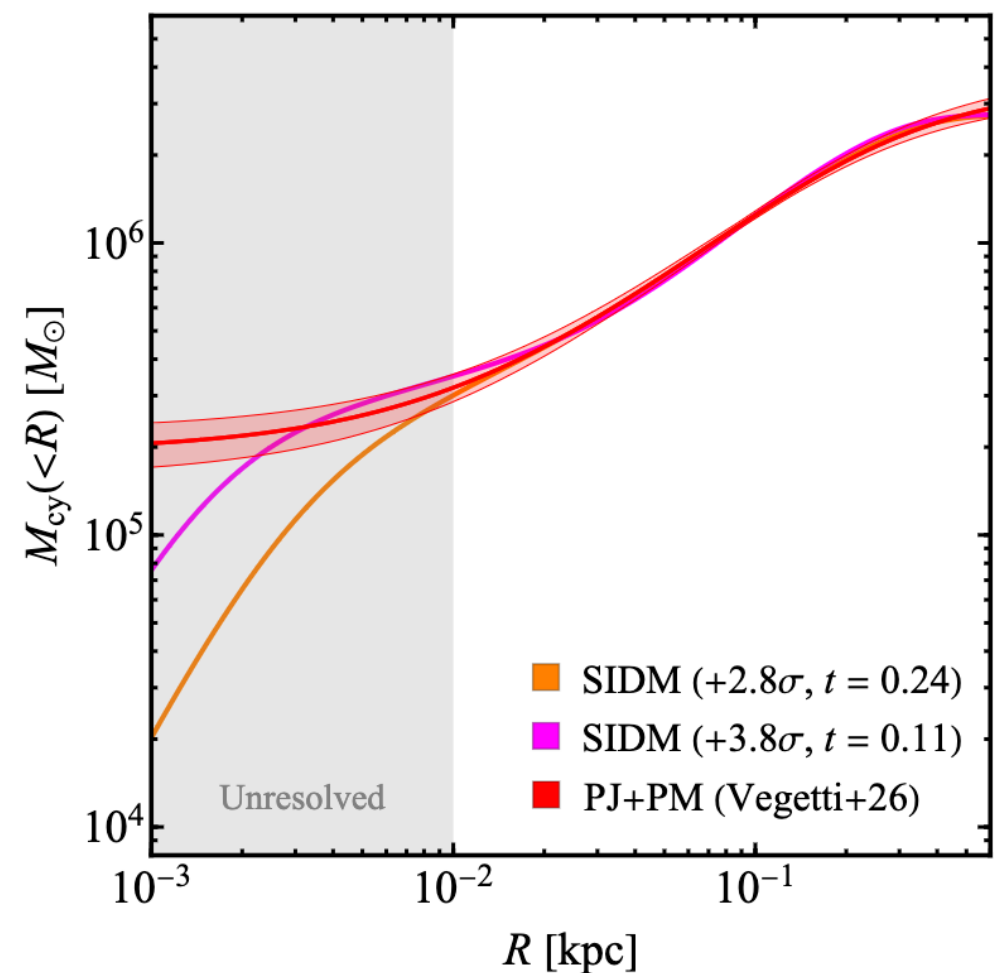
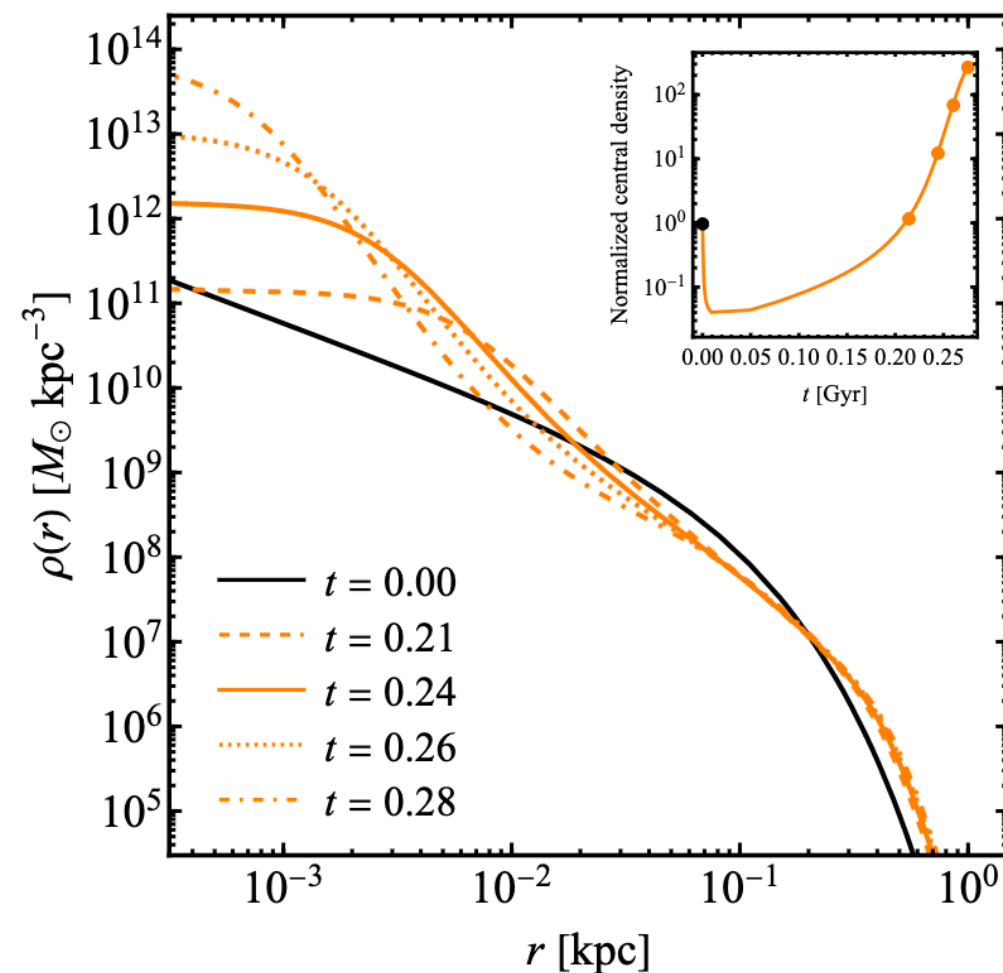
CDM subhalos are not dense enough!

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: $3 \times 10^5 M_\odot$

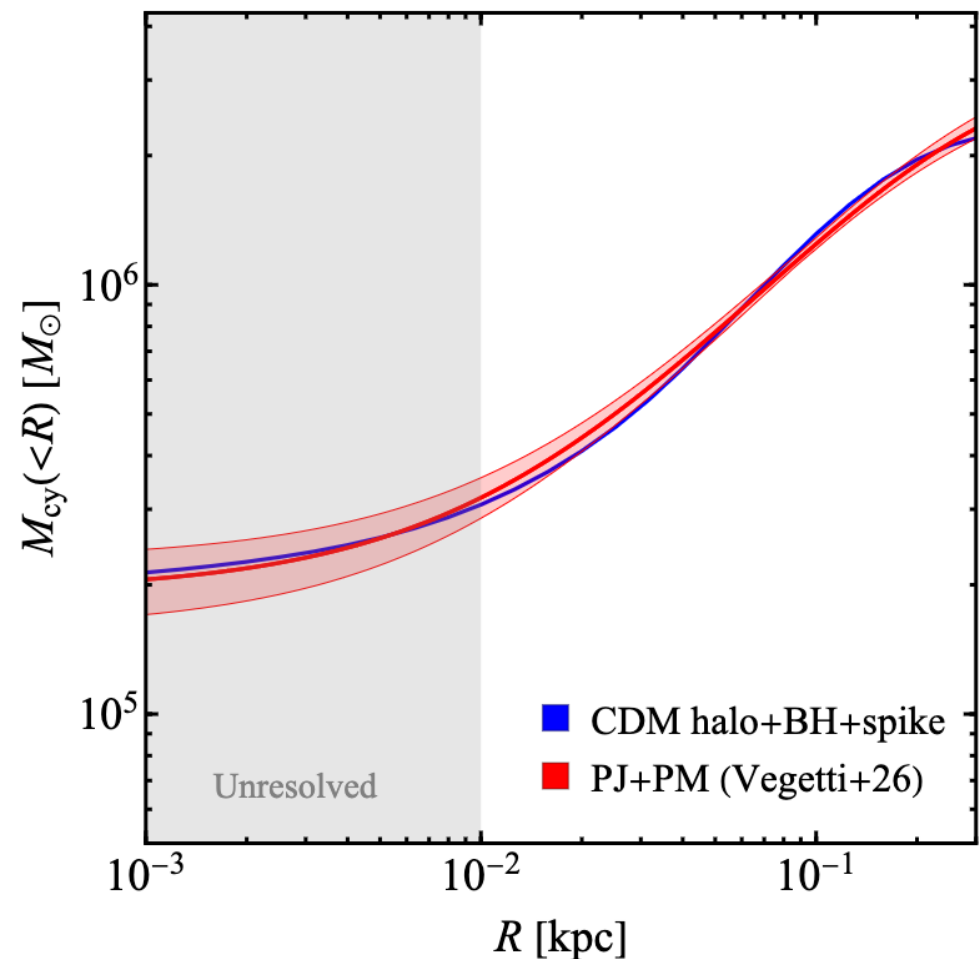
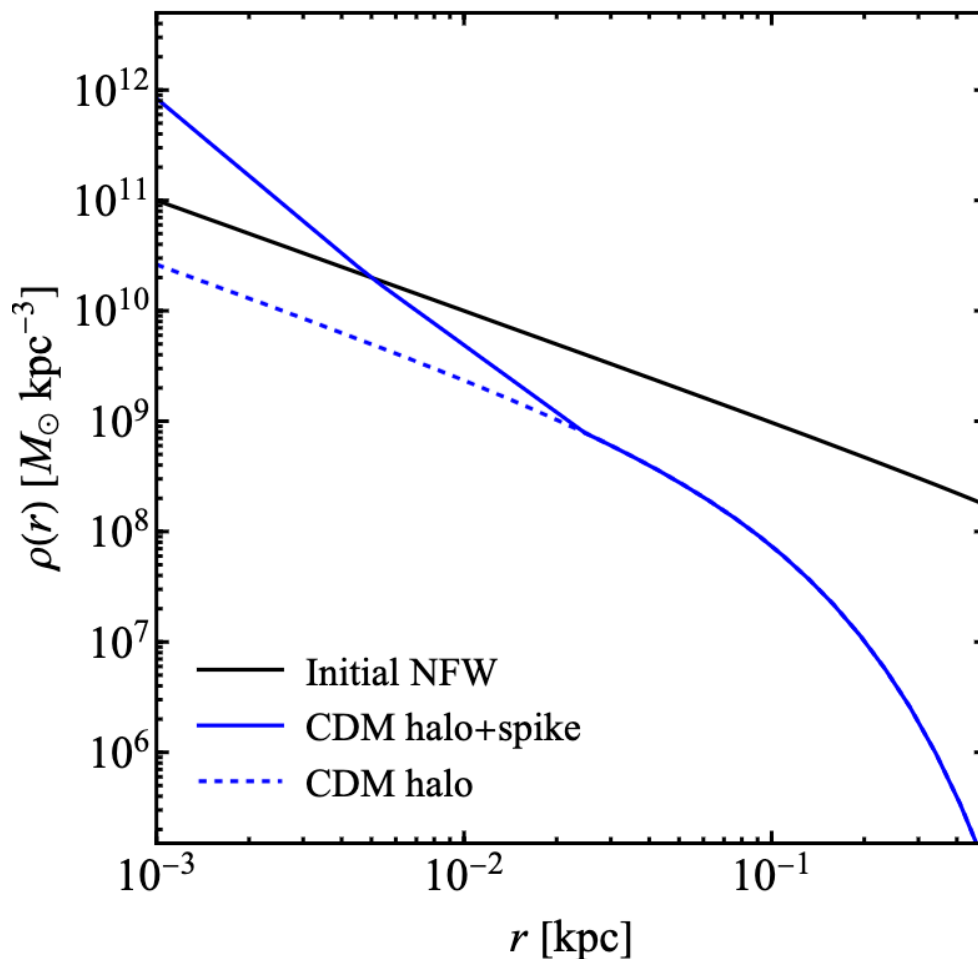
Zhang, Yu (2026)

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](#)

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)

THREE BIRDS WITH ONE STONE

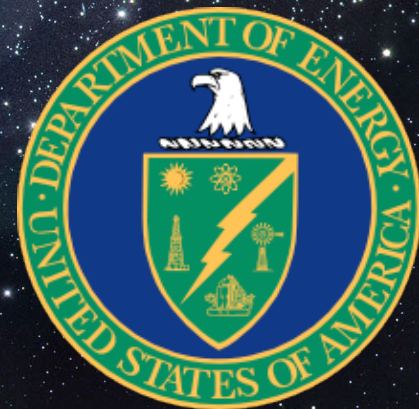


- Gravoothermal collapse is the unique prediction of SIDM
- Collapsed SIDM halos can explain high densities of compact objects identified in strong lensing, stellar stream, and dwarf galaxy observations

Dark Matter (IV): SIDM, Black Holes, Particle Physics

Hai-Bo Yu (郁海波)

University of California, Riverside



**Fudan Particle Physics Summer
School 2026, August 19-21, 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 Λ CDM paradigm, have emerged, with their remarkably high densities being consistent with predictions from SIDM

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

$$r_s = \left[\frac{3M_{200}}{(200\rho_{\text{crit}})4\pi c_{200}^3} \right]^{\frac{1}{3}}, \quad \rho_s = \frac{200\rho_{\text{crit}}c_{200}^3}{3f(c_{200})}$$

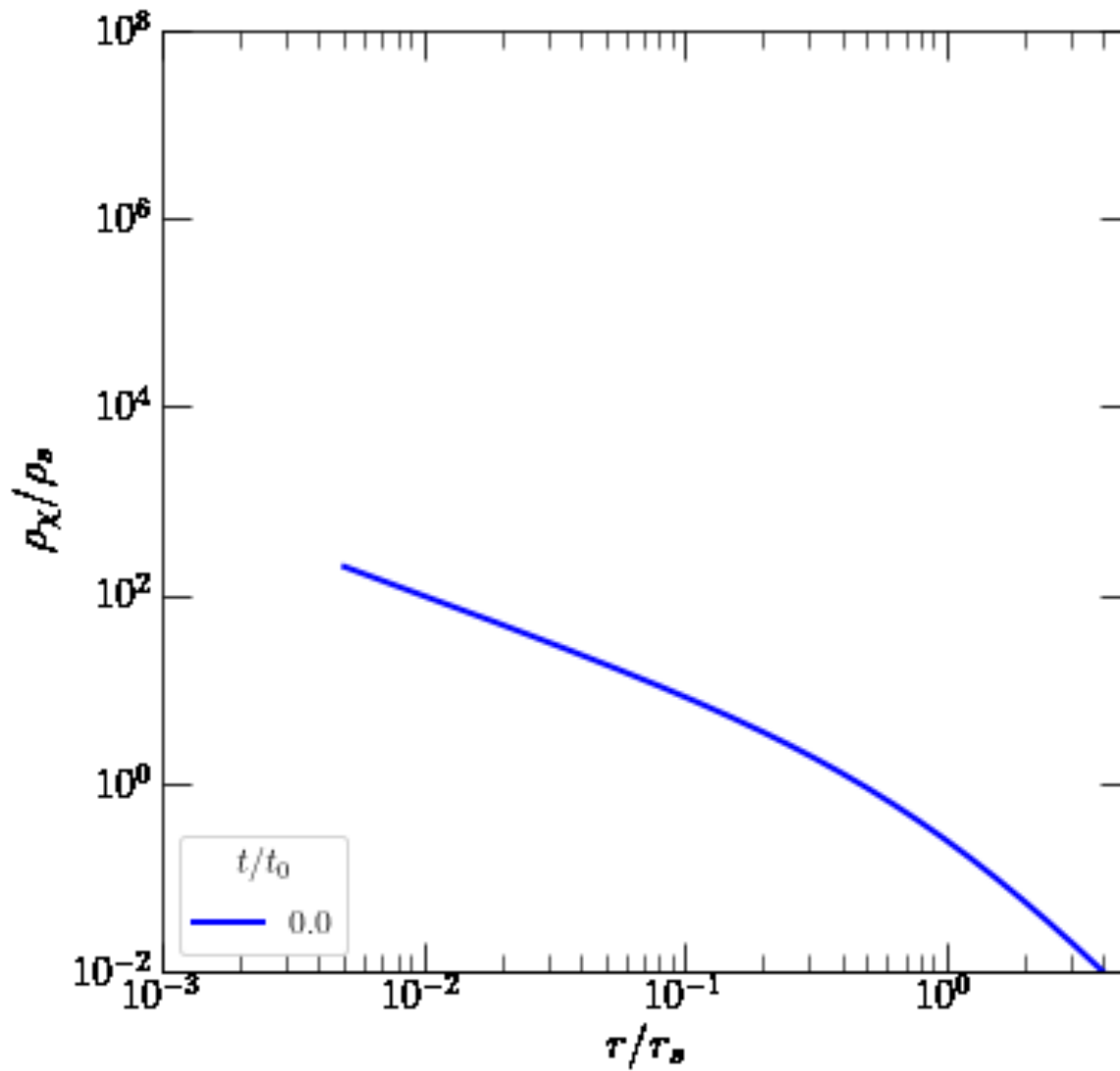
$$f(c_{200}) = \ln(c_{200} + 1) - \frac{c_{200}}{(c_{200} + 1)}$$

$$V_{\text{max}} = \sqrt{0.5823G\rho_s(2.163r_s)^2}, \quad r_{\text{max}} = 2.163r_s$$

To specify a CDM halo

$$(r_s, \rho_s) \leftrightarrow (M_{200}, c_{200}) \leftrightarrow (V_{\text{max}}, r_{\text{max}})$$

Gravothermal Evolution



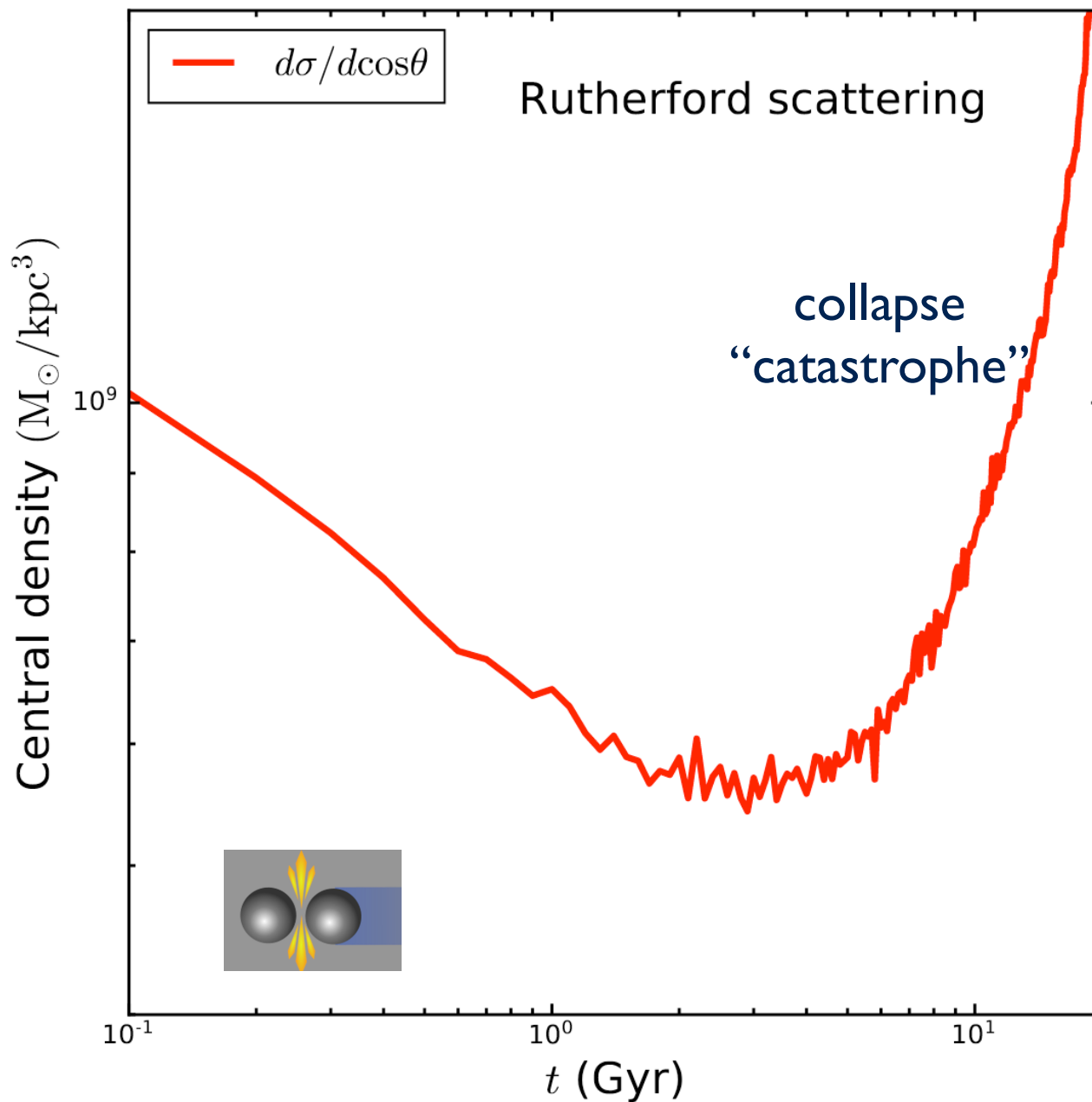
$$\frac{\partial}{\partial r} M = 4\pi r^2 \rho$$

$$\frac{\partial}{\partial r} (\rho v^2) = -\frac{GM\rho}{r^2}$$

$$\frac{\rho v^2}{\gamma - 1} \left(\frac{\partial}{\partial t} \right)_M \ln \frac{v^2}{\rho^{\gamma-1}} = -\frac{1}{4\pi r^2} \frac{\partial L}{\partial r}$$

$$m v^2 = k_B T$$

$$\gamma = 5/3$$

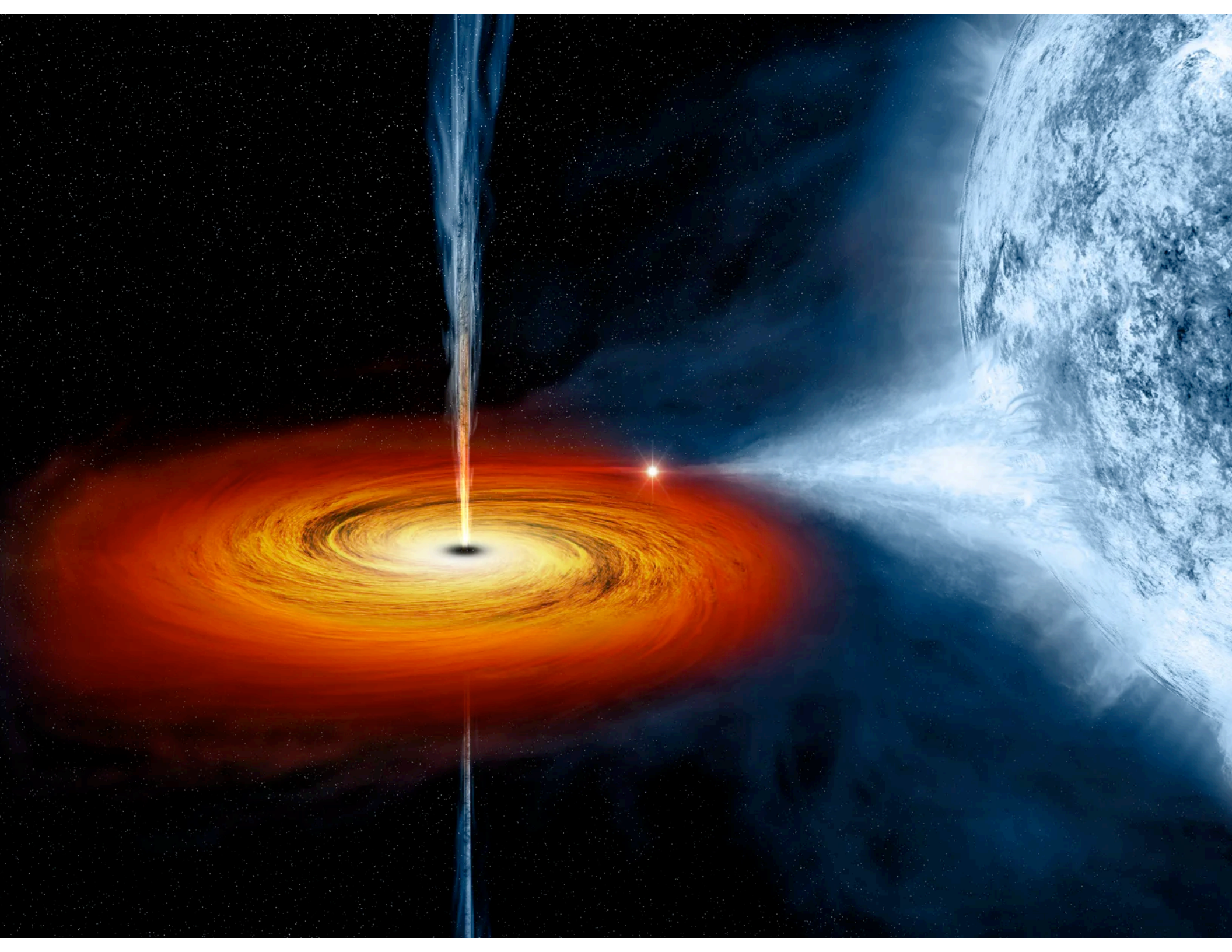


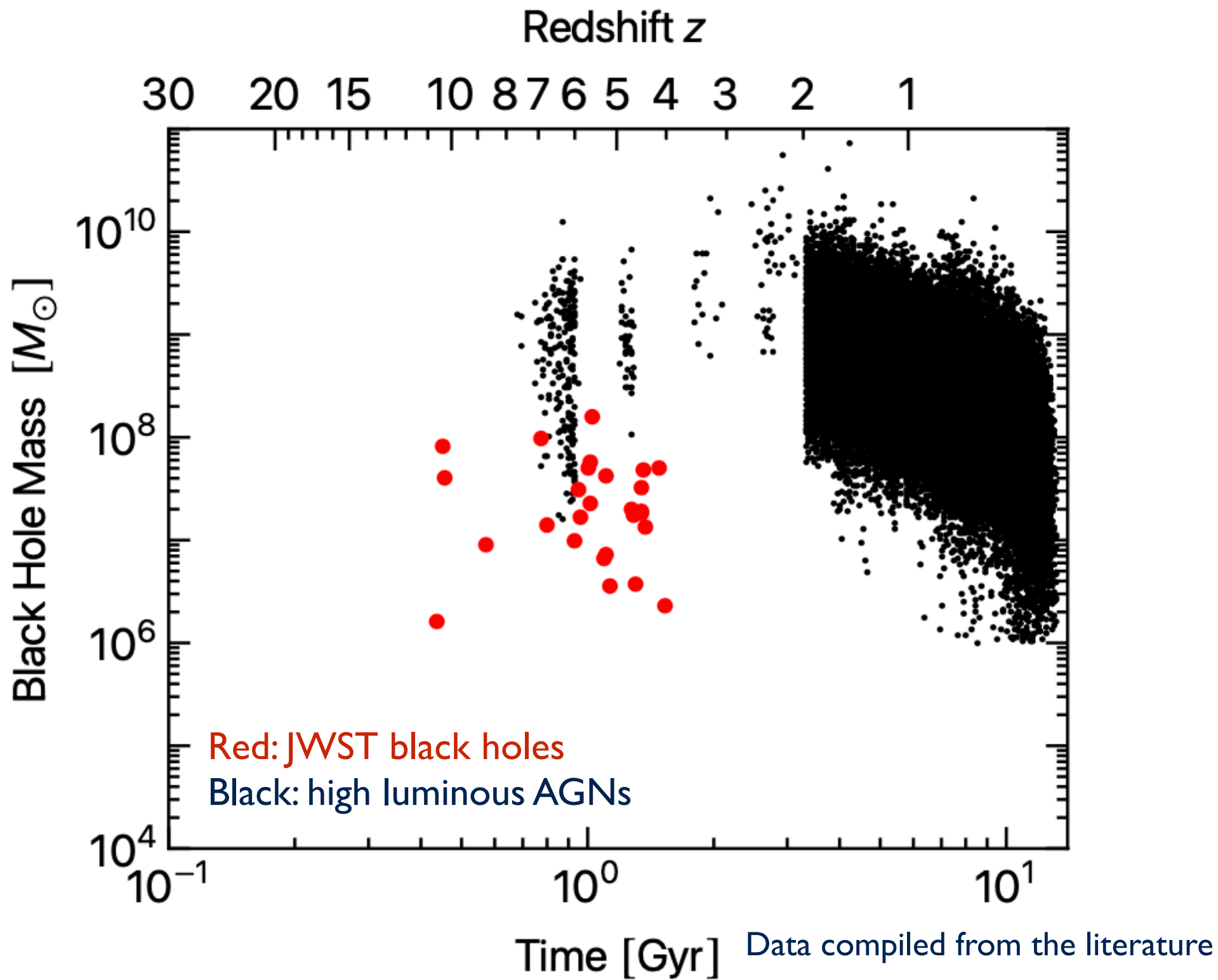
???

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

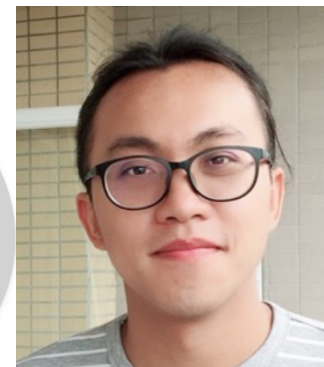
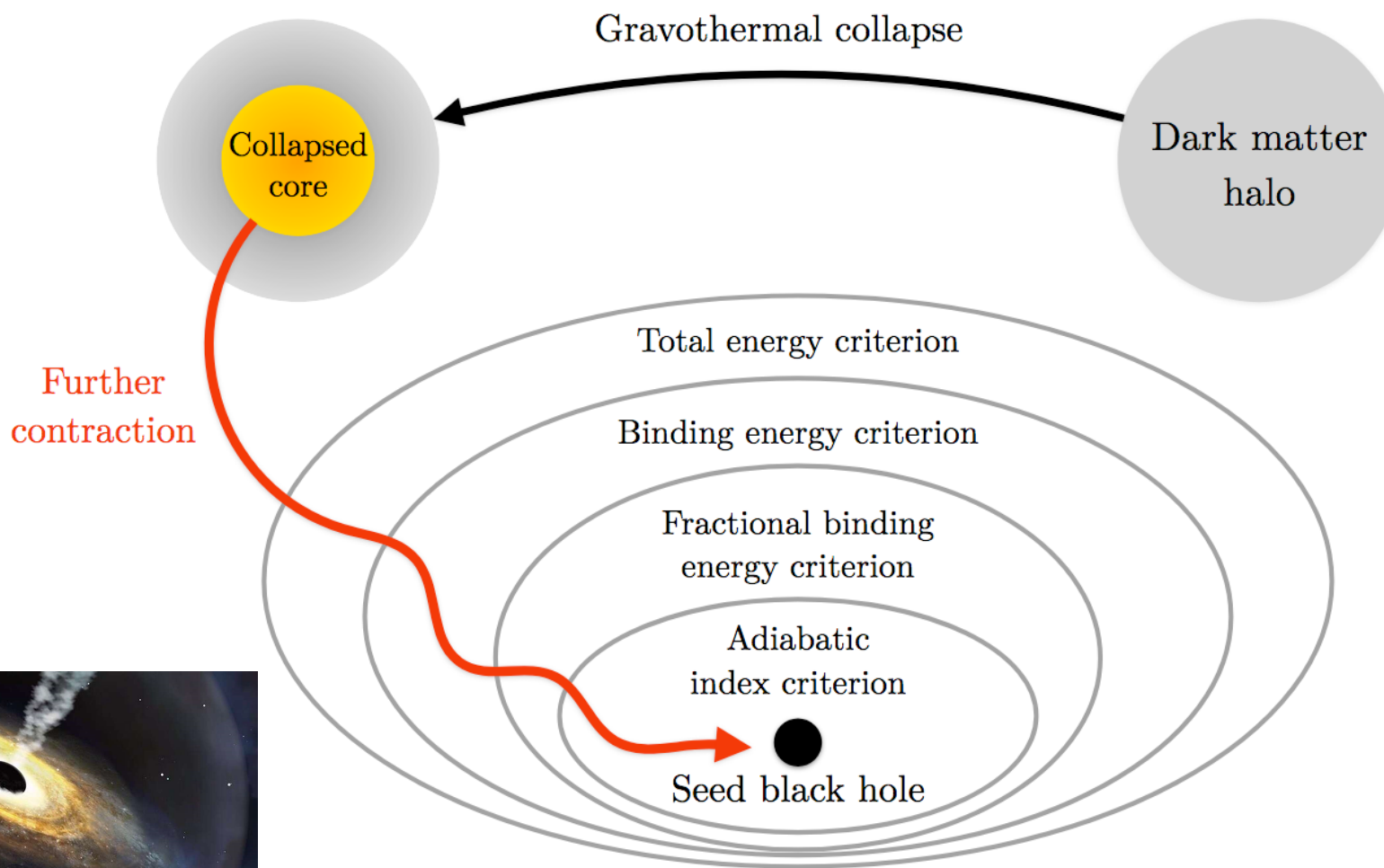
$$E_{\text{tot}} = -K.E. \quad \frac{E_{\text{tot}}}{T} < 0$$

Negative heat capacity!
 $\Rightarrow$ gravothermal collapse

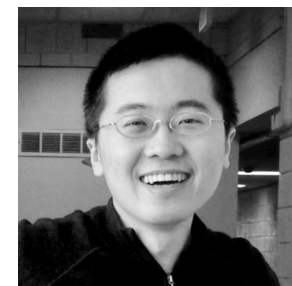




Seeding Supermassive Black Holes



Wei-Xiang Feng
(Tsinghua)

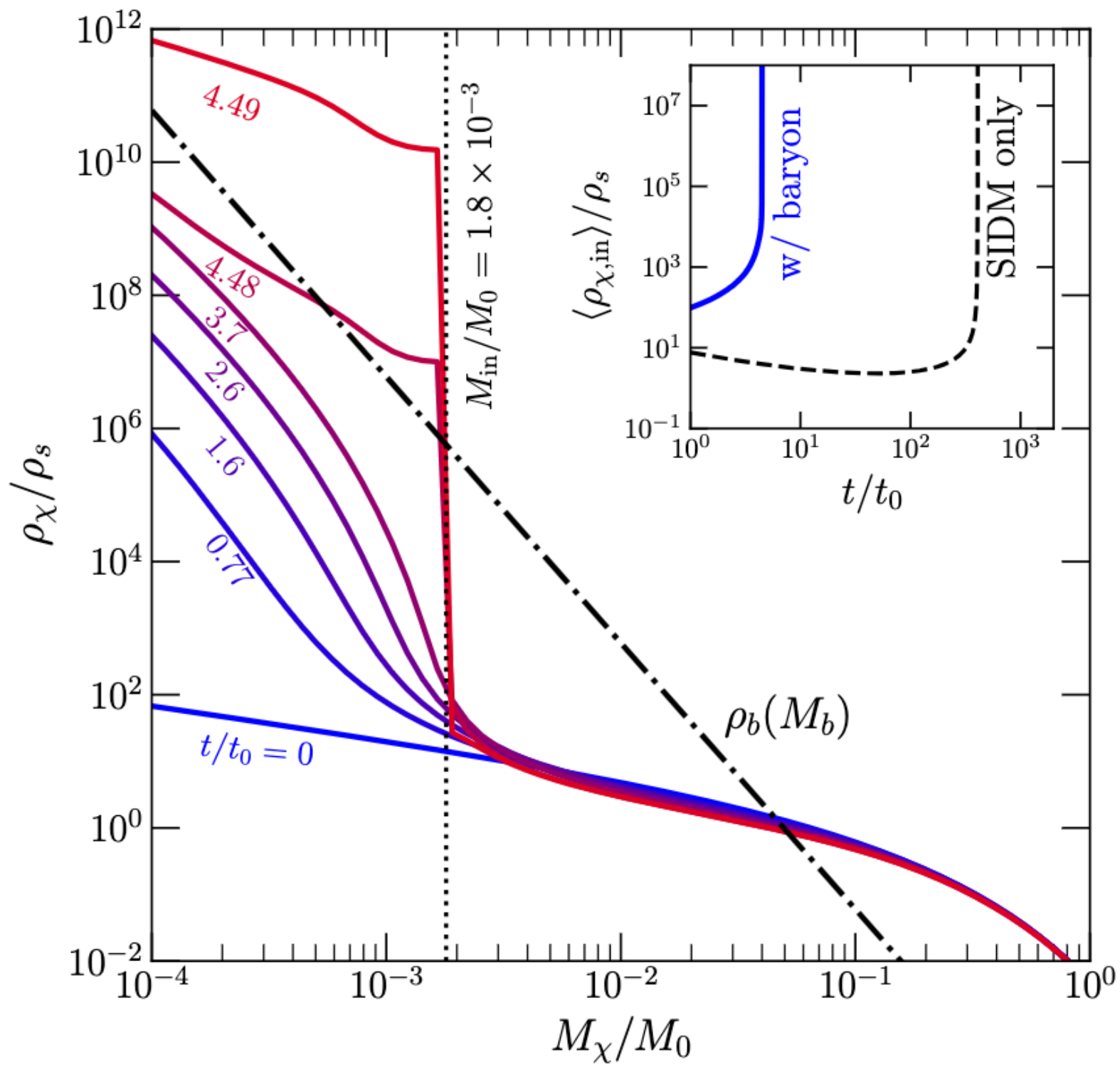


Yi-Ming Zhong
(CityU, HK)

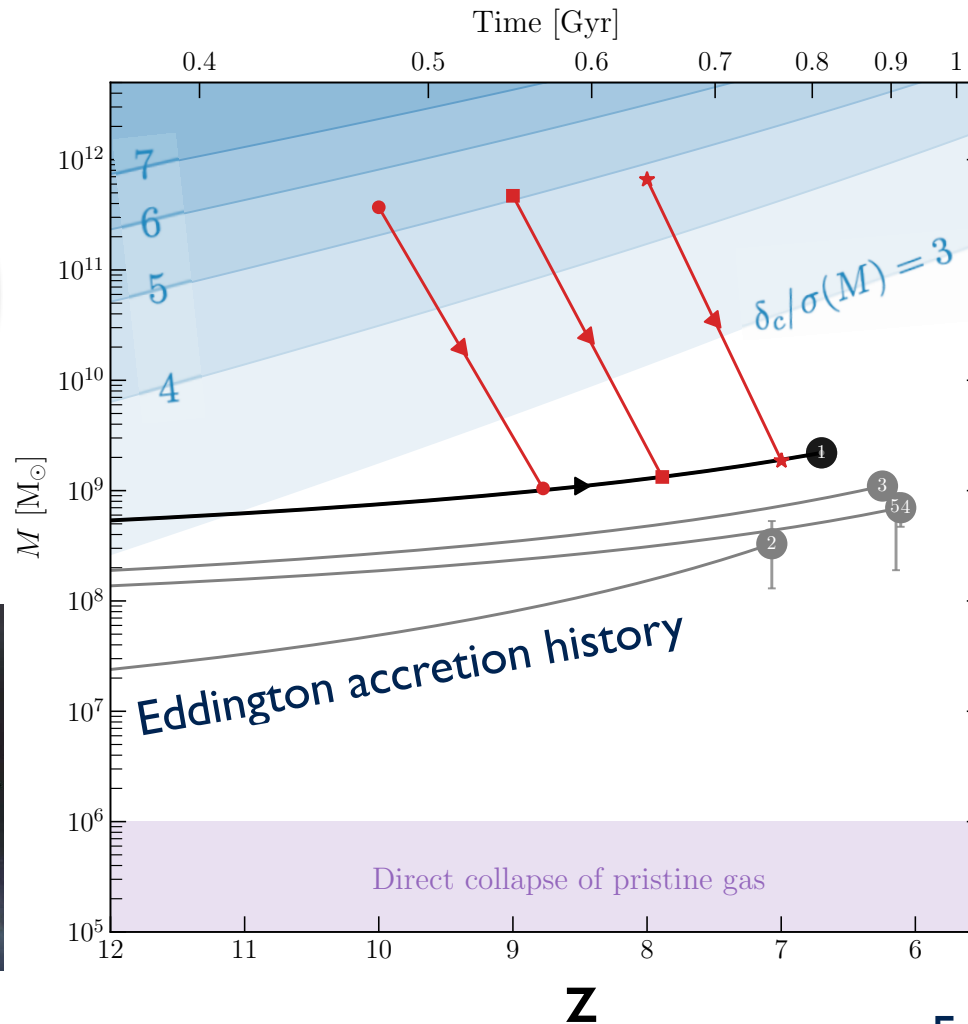
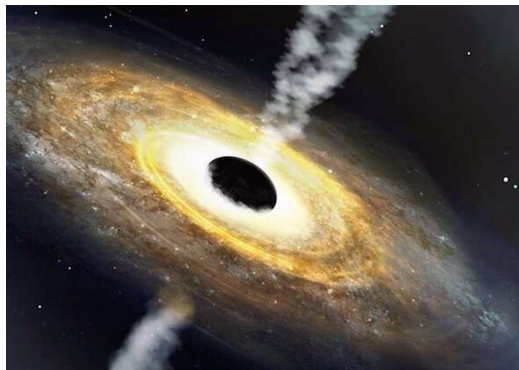
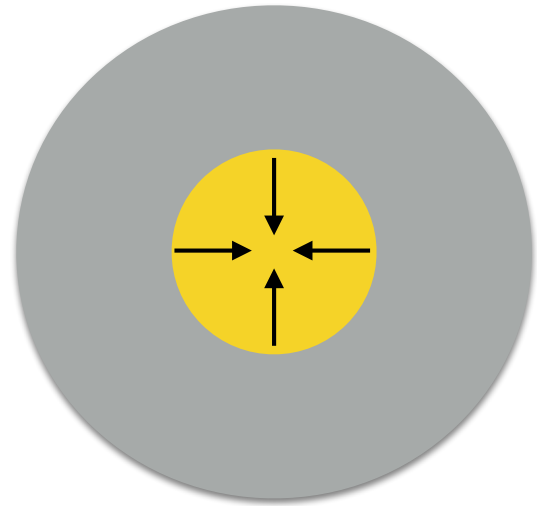


Balberg, Shapiro (PRL 2002)
Pollack, Spergel, Steinhardt (ApJ 2015)

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



Seeding Supermassive Black Holes



The most challenging one, J1205-0000

Mass $2.2 \times 10^9 M_{\odot}$

$z=6.7$

$f_{\text{Edd}}=0.16$

Onoue et al. (2019)

~ 800 Myr after the Big Bang

Feng, HBY, Zhong (APJL 2021)

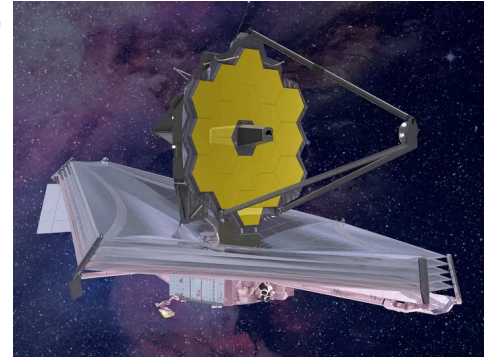
- The presence of baryons can speed the onset of collapse by a factor of 10–100!
- The mechanism requires the existence of massive halos at high redshifts

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 $z \sim 8$!

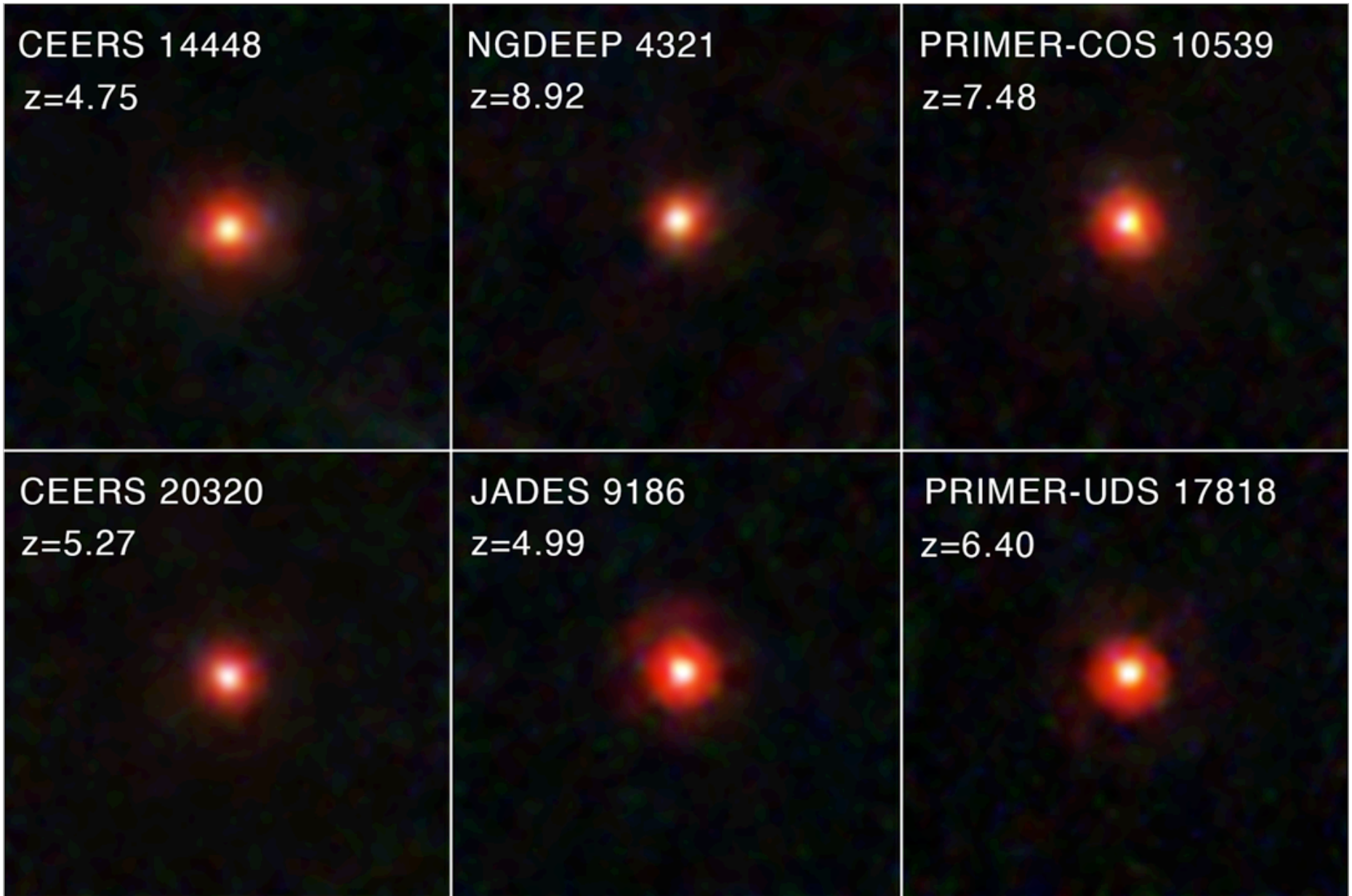
Abstract

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 $2.5 \mu\text{m}$. Here we make use of the $1\text{--}5 \mu\text{m}$ 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 $7.4 \leq z \leq 9.1$, 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 $\sim 10^{11}\text{--}10^{12} M_{\odot}$ at $z \sim 8$

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

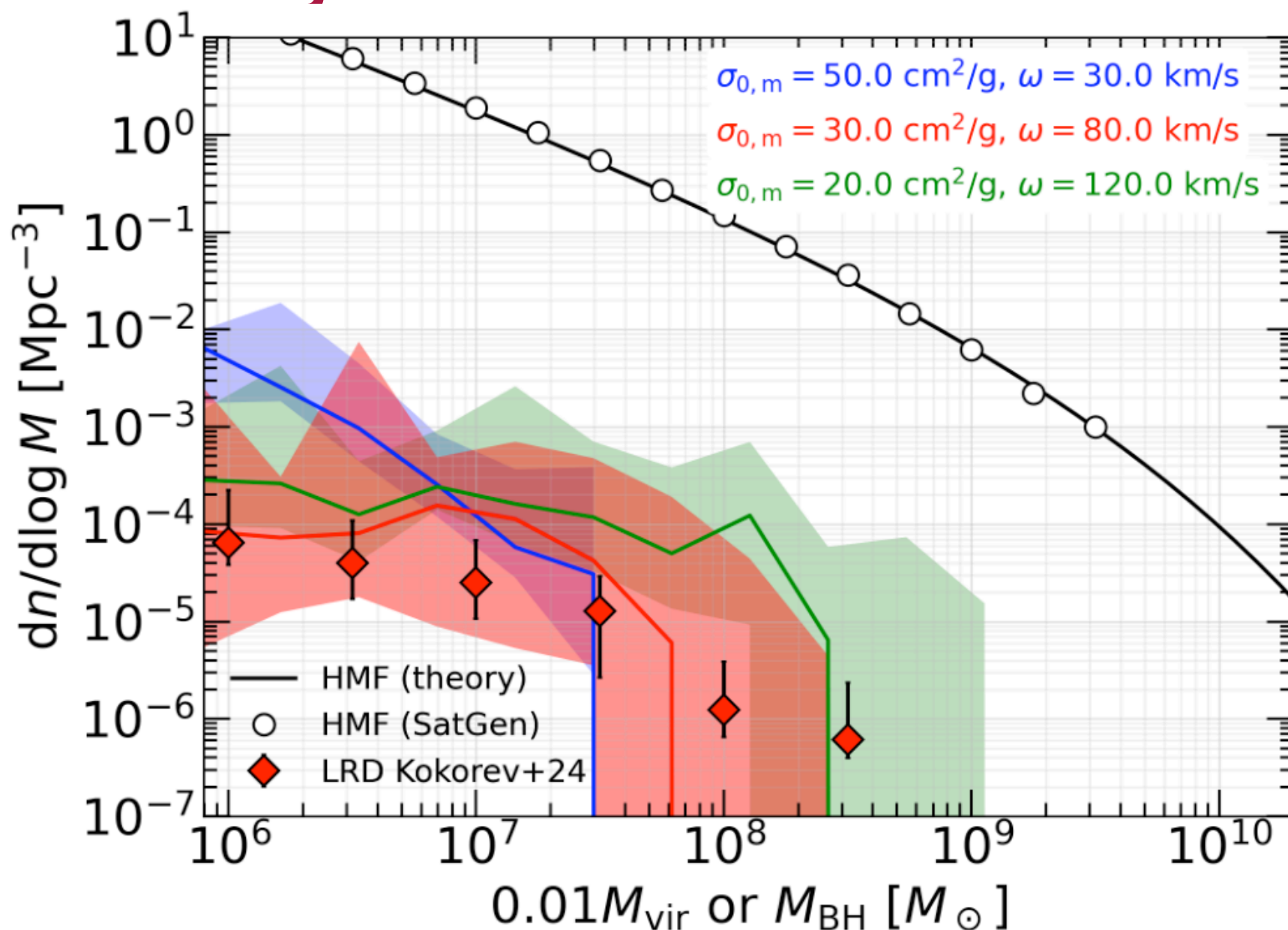
The JWST Little Red Dots



341 LRD galaxies have been identified

NASA, ESA, CSA, STScI, Dale Kocevski

JWST Little Red Dots



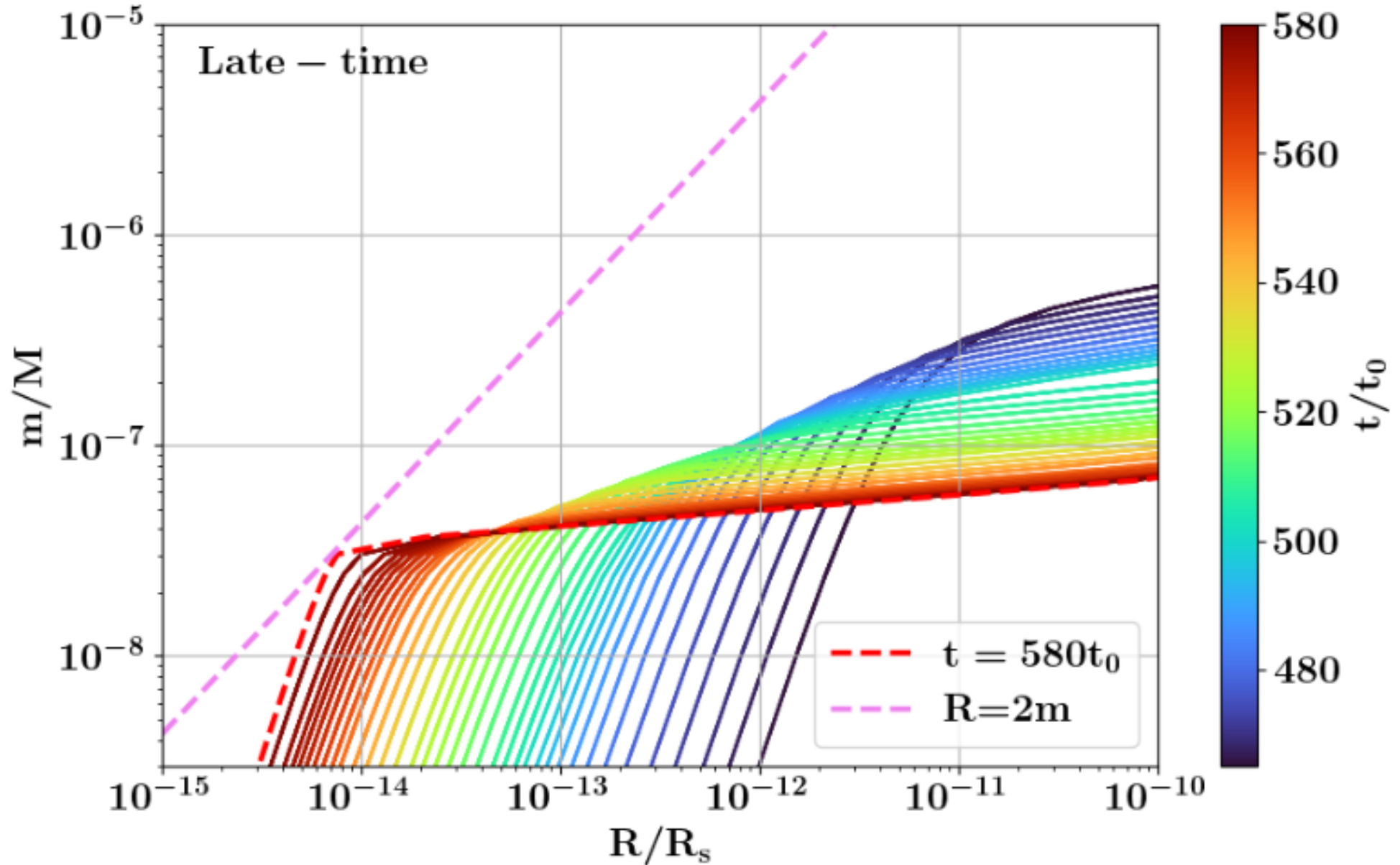
$\sim 10^9 M_{\odot}$ halos on the high-concentration tail at $z \sim 10-15$

Fangzhou Jiang+(2025), Feng, Yu, Zhong (2025), Gu+(2026)...

Non-Equilibrium Relativistic Core Collapse of Self-Interacting Dark Matter Halos – Limits On Seed Black Hole Mass

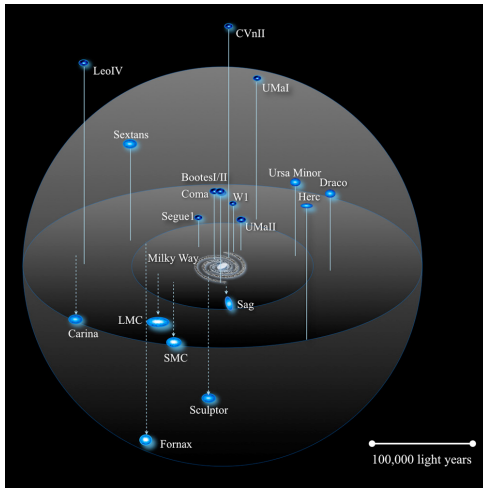
Hua-Peng Gu,^{1,2} Fangzhou Jiang,^{1,2,*} Xian Chen,^{1,2,†} and Ran Li^{3,4}

¹Department of Astronomy, School of Physics, Peking University, Beijing 100871, China



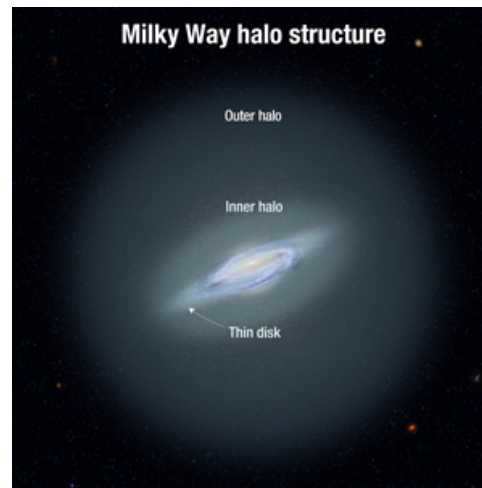
Dark Matter “Colliders”

Dwarf galaxies



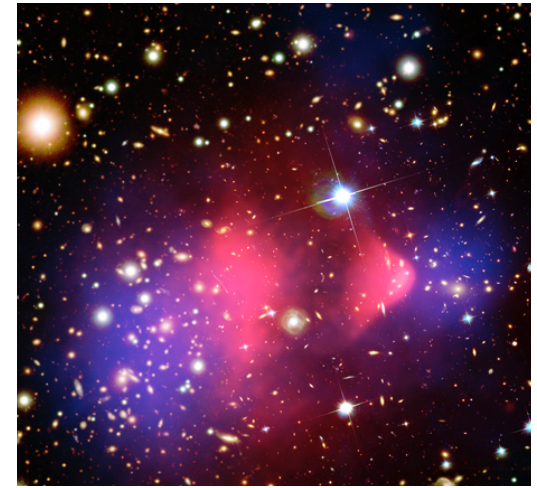
“B-factory” ($v \sim 30$ km/s)

MW-like galaxies



“LEP” ($v \sim 200$ km/s)

Clusters



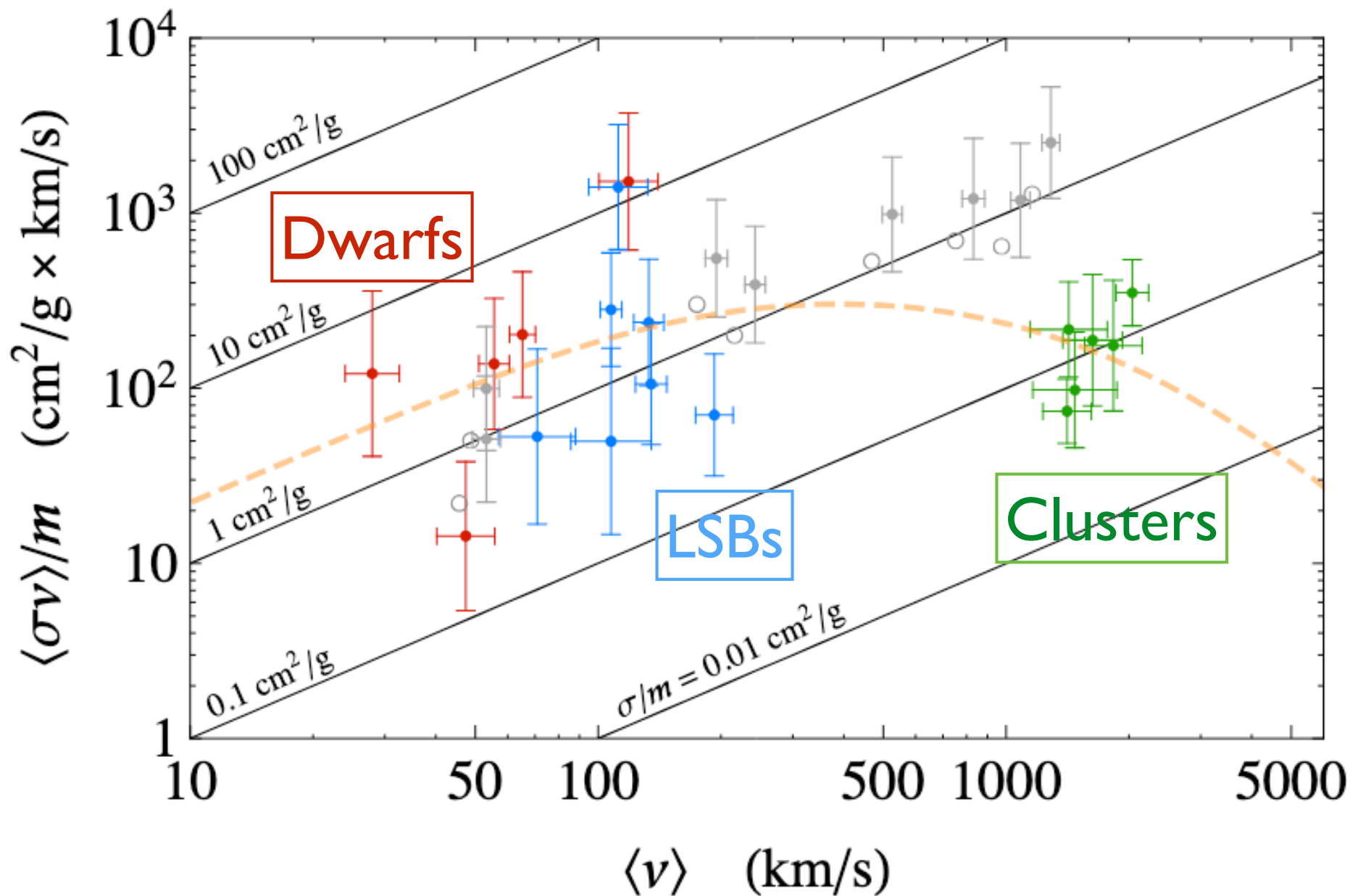
“LHC” ($v \sim 1000$ km/s)

Self-scattering
kinematics

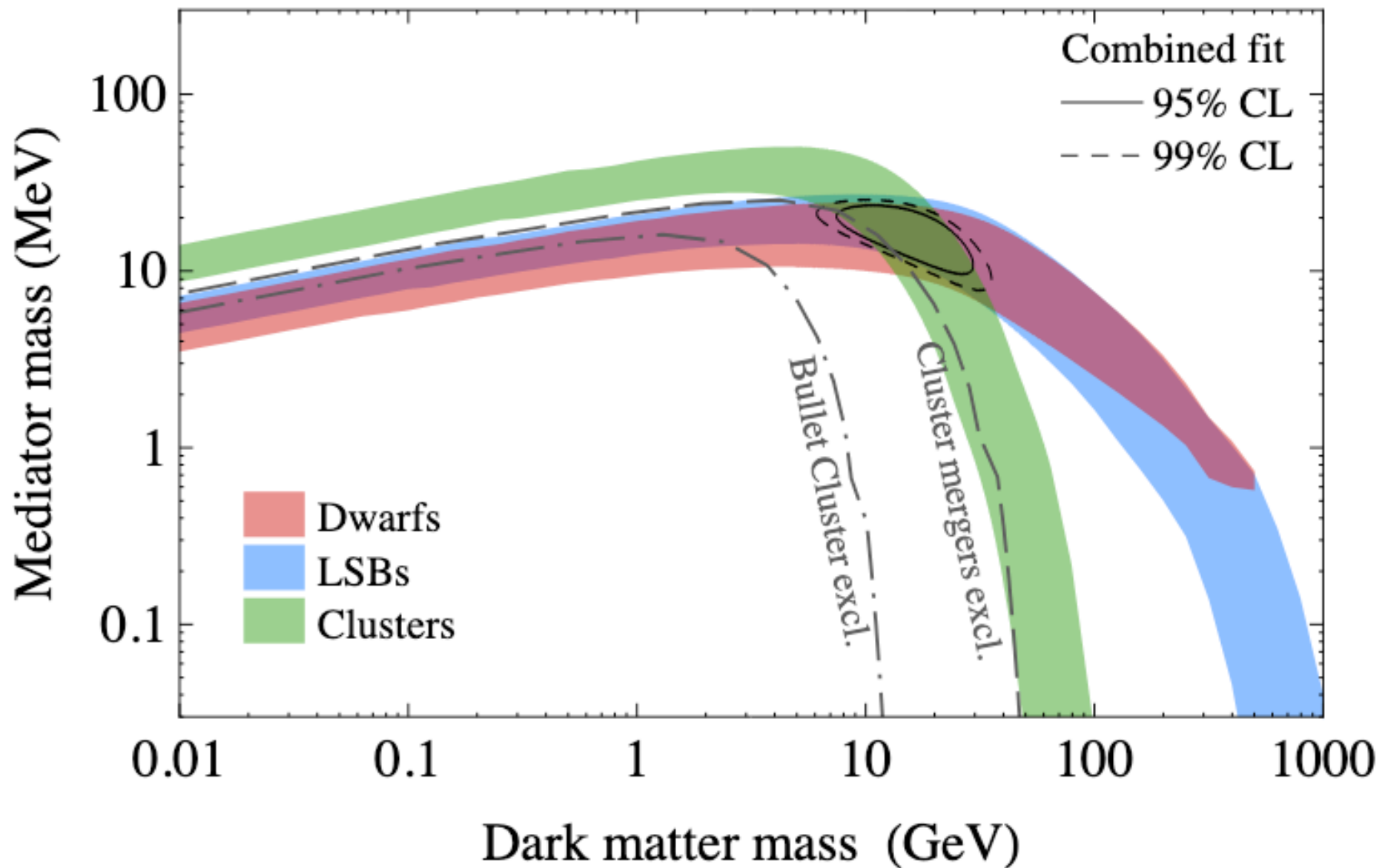


Observations
on all scales

Measure particle
physics parameters
 σ_X , m_X , m_ϕ



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

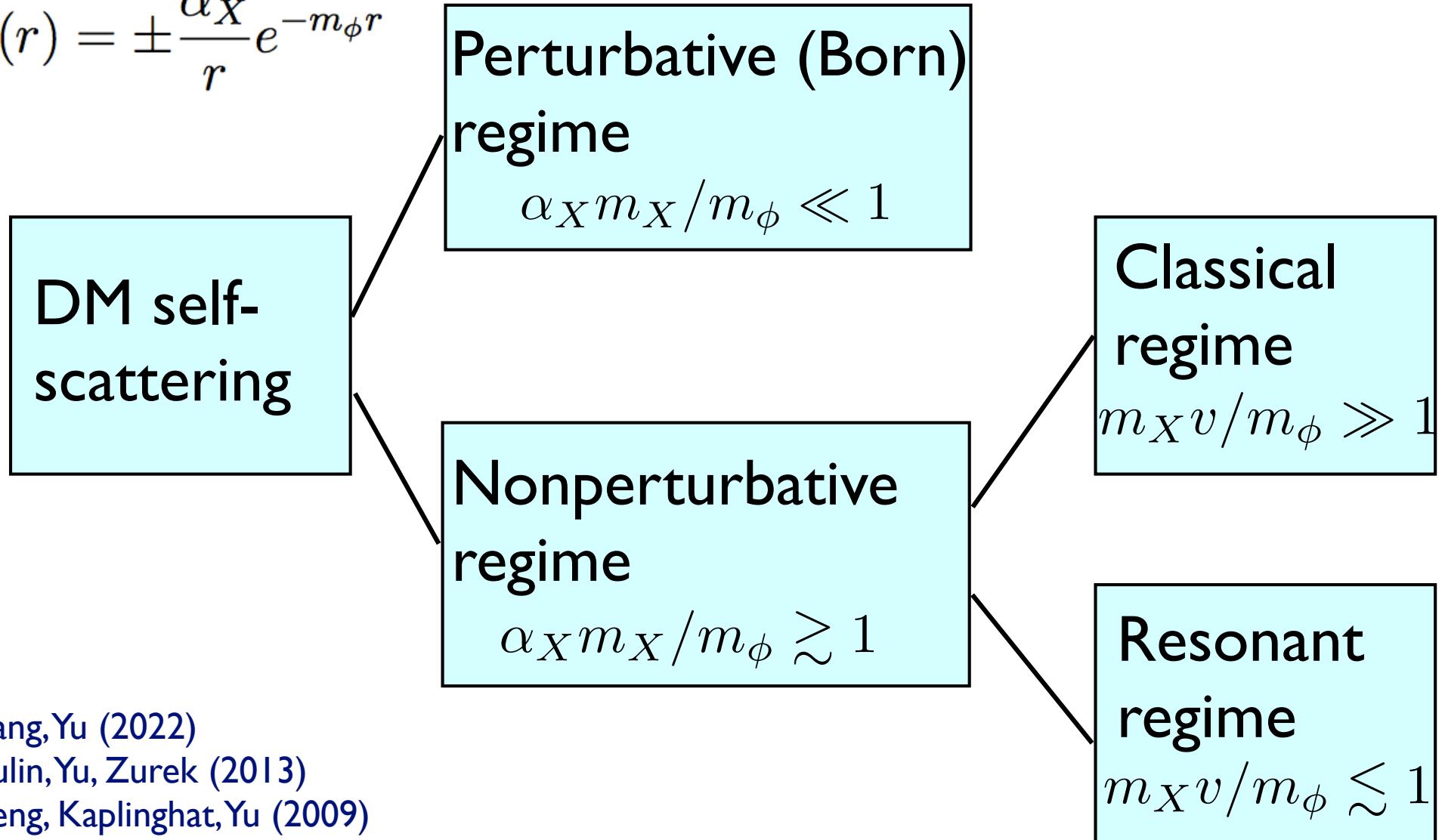


$$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r} \quad \alpha_\chi, m_\chi, m_\phi \quad \alpha_\chi = \alpha_{\text{EM}} = 1/137$$

Kaplinghat, Tulin, HBY (PRL, 2015)

Scattering with a Yukawa Potential

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



Yang, Yu (2022)

Tulin, Yu, Zurek (2013)

Feng, Kaplinghat, Yu (2009)

Numerical Approach

- Quantum mechanics 101-partial wave analysis

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dR_\ell}{dr} \right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r) \right) R_\ell = 0$$

- Transfer cross section

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left| \sum_{\ell=0}^{\infty} (2\ell+1) e^{i\delta_\ell} P_\ell(\cos\theta) \sin\delta_\ell \right|^2 \quad \sigma_T = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

$$\frac{\sigma_T k^2}{4\pi} = \sum_{\ell=0}^{\infty} [(2\ell+1) \sin^2 \delta_\ell - 2(\ell+1) \sin \delta_\ell \sin \delta_{\ell+1} \cos(\delta_{\ell+1} - \delta_\ell)]$$

Rearrange $\ell \rightarrow \ell+1$

$$\frac{\sigma_T k^2}{4\pi} = \sum_{\ell=0}^{\infty} (\ell+1) \sin^2(\delta_{\ell+1} - \delta_\ell) \quad \checkmark$$

Both formulas are identical in the limit of $\ell \rightarrow \infty$
 But the second one converges much faster

Numerical Approach

- Partial wave analysis

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{dR_\ell}{dr} \right) + \left(k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r) \right) R_\ell = 0$$

- Boundary conditions $r \rightarrow \infty$

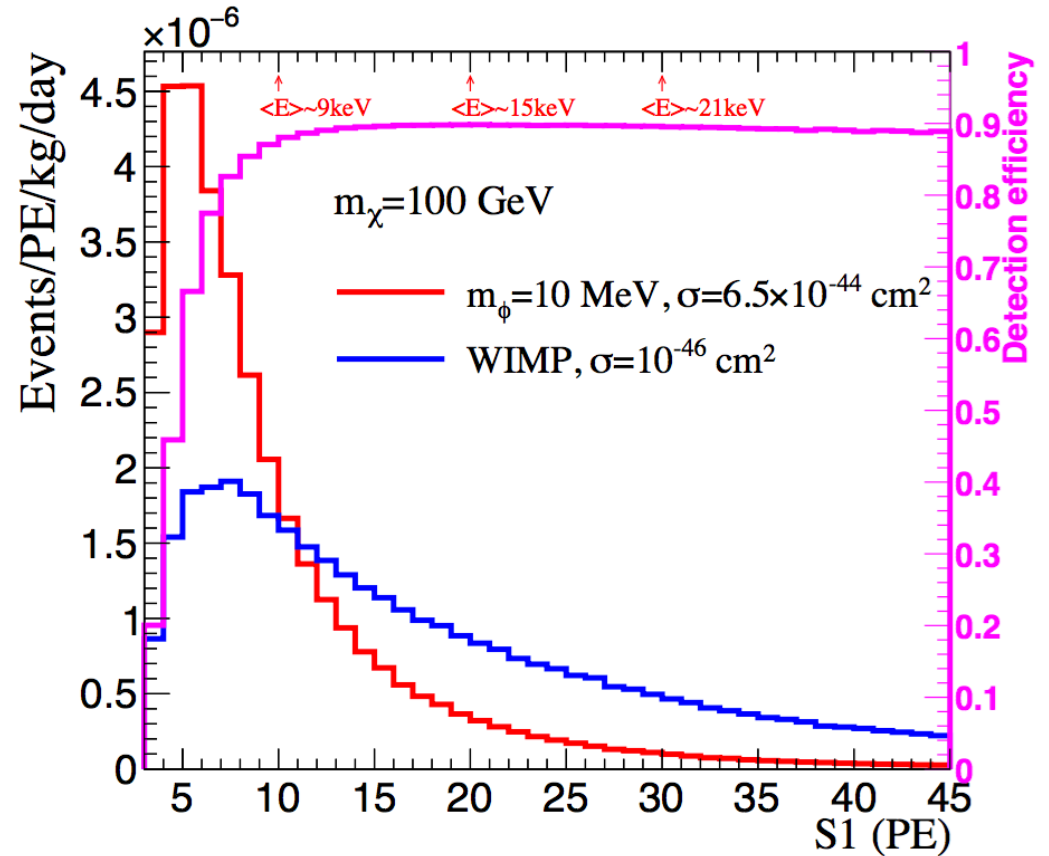
$$R_\ell(r) \rightarrow \sin(kr - \pi\ell/2 + \delta_\ell)/r$$

$$R_\ell(r) \rightarrow \cos \delta_\ell j_\ell(kr) - \sin \delta_\ell n_\ell(kr)$$



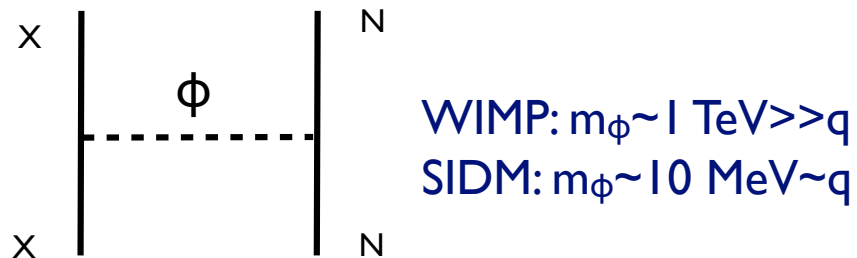
The second one is much more efficient

Direct Detection



Smoking-gun signature

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

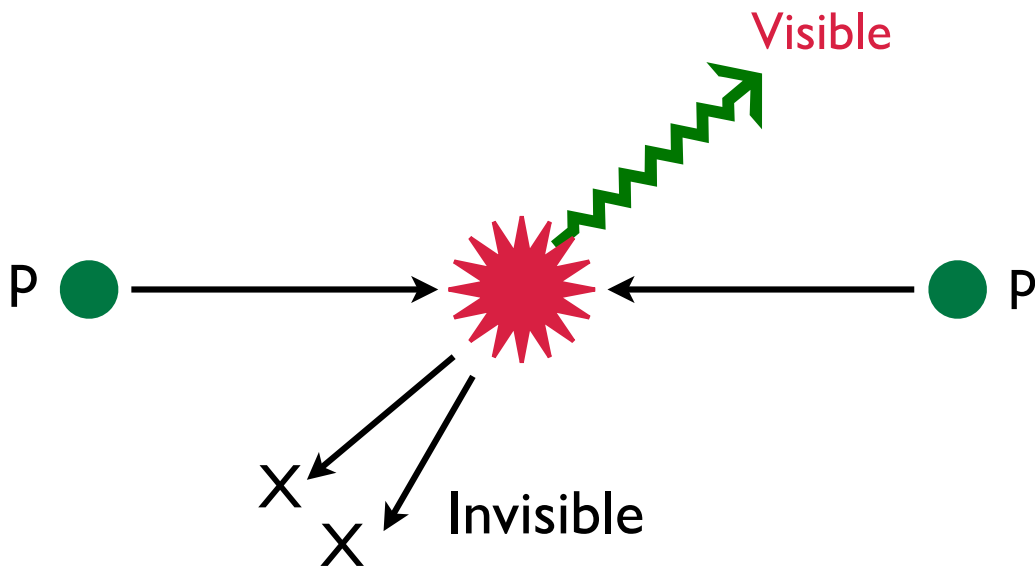


Strong upper limit: the kinetic mixing parameter $< 10^{-11} - 10^{-10}$

Collider Searches

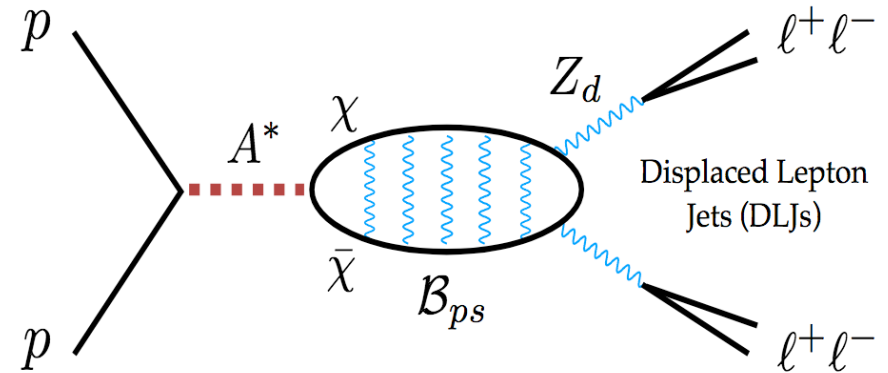
- Striking collider signals

WIMP



$pp \rightarrow \text{Monojet} + \text{Missing Energy}$

SIDM



$$L_{Z_d \rightarrow \ell^+ \ell^-} = \gamma_{Z_d} \left[\sum_{\ell} \frac{\alpha \epsilon_{Z_d}^2 m_{Z_d}}{3} \sqrt{1 - \frac{4m_{\ell}^2}{m_{Z_d}^2}} \left(1 + \frac{2m_{\ell}^2}{m_{Z_d}^2} \right) \right]^{-1}$$

$$\sim 1 \text{ m} \left(\frac{m_{\chi}}{10 \text{ GeV}} \right) \left(\frac{10 \text{ MeV}}{m_{Z_d}} \right)^2 \left(\frac{10^{-4}}{\epsilon_{Z_d}} \right)^2,$$

With Tsai, Xu (JHEP, 2018)

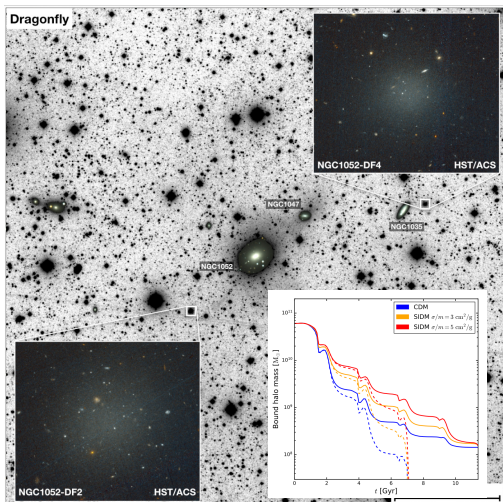
From Dwarf to Cluster Scales

Ultra-diffuse galaxies
(dark-matter-deficient)

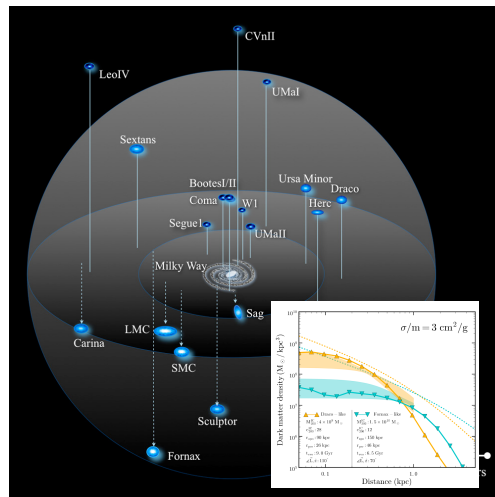
Milky Way satellites

Spiral galaxies

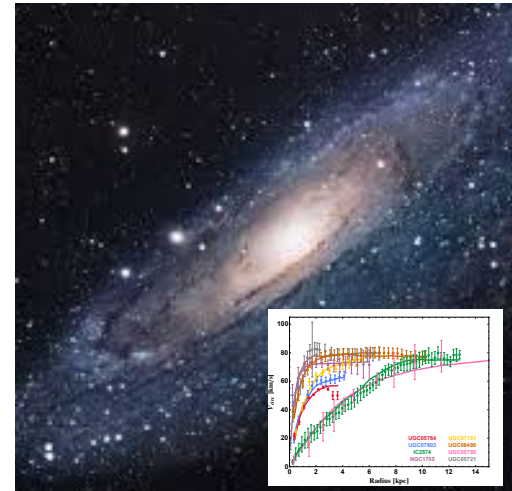
Galaxy clusters



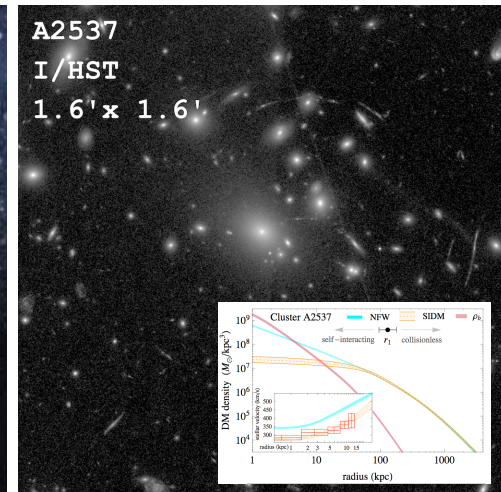
$$M_{\text{halo}} < \sim 10^8 M_{\odot}$$



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



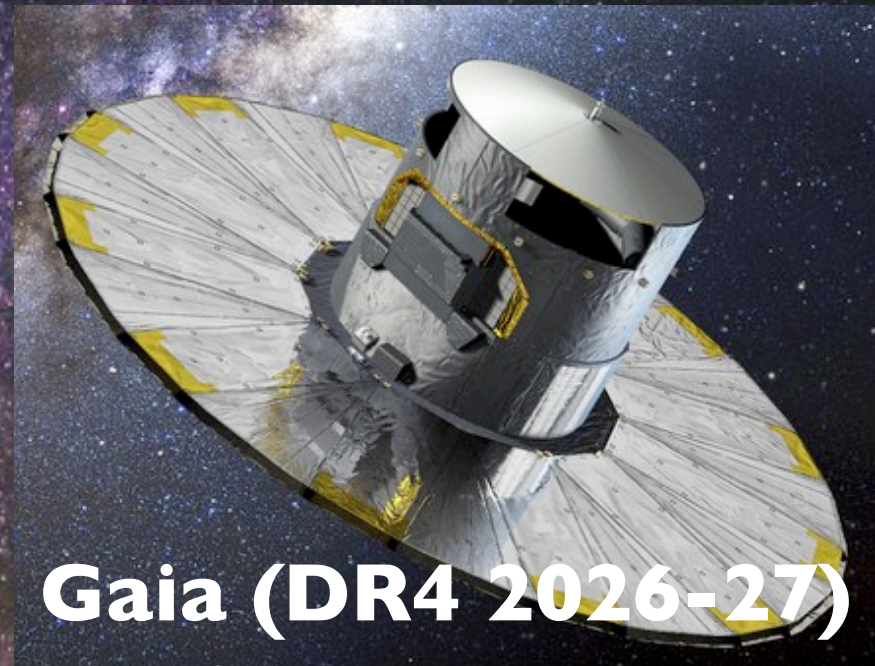
$$M_{\text{halo}} \sim 10^9 - 10^{13} M_{\odot}$$



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

- SIDM can explain **diverse** dark matter distributions over a wide range of galactic systems (halo masses $\sim 10^6 - 10^{15} M_{\odot}$)
- Some halos are denser than expected in CDM; Gravothermal collapse
- **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

JWST



Gaia (DR4 2026-27)

Rubin/LSST (2025)



VIA (2027)





THANK YOU!