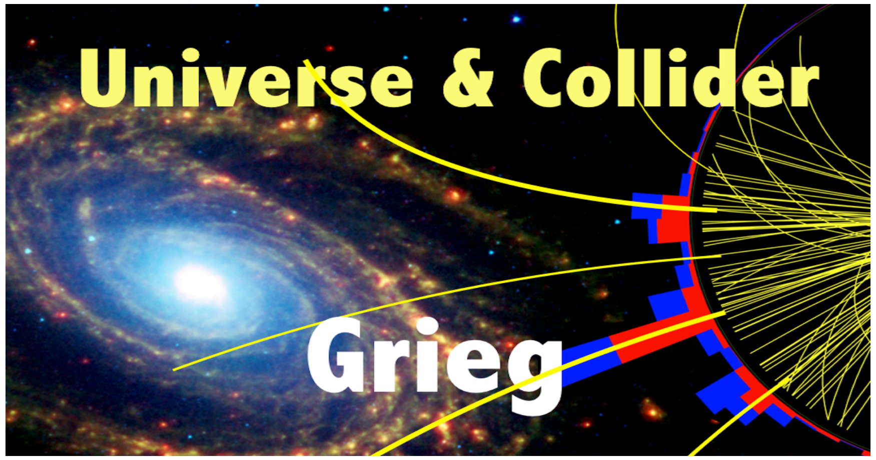
Current status of self-interacting dark matter

Ayuki Kamada (University of Warsaw)



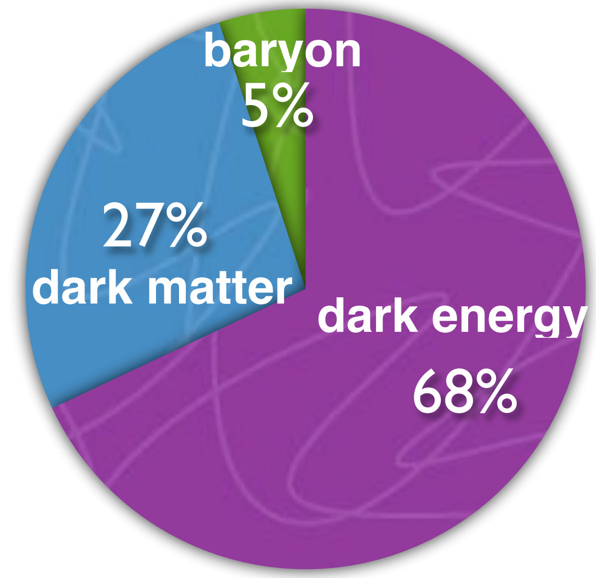
UNIVERSITY OF WARSAW

May 6, 2026 @ IJCLab

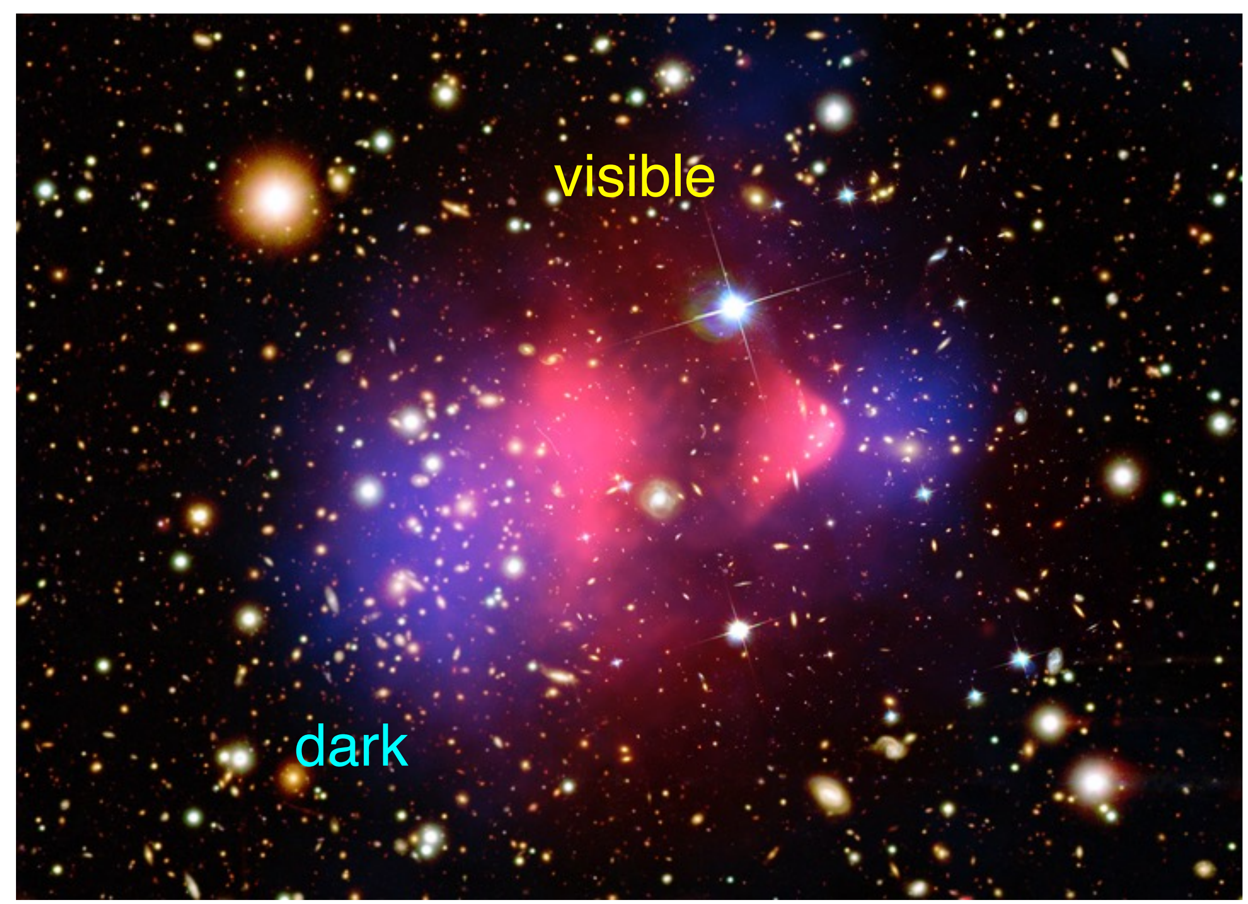
Dark matter

DM (or missing mass)

- evident from cosmological observations
    - cosmic microwave background (CMB)…
- essential to form galaxies in the Universe
- one of the biggest mysteries
    - astronomy, cosmology, particle physics…



cosmic energy budget



bullet cluster

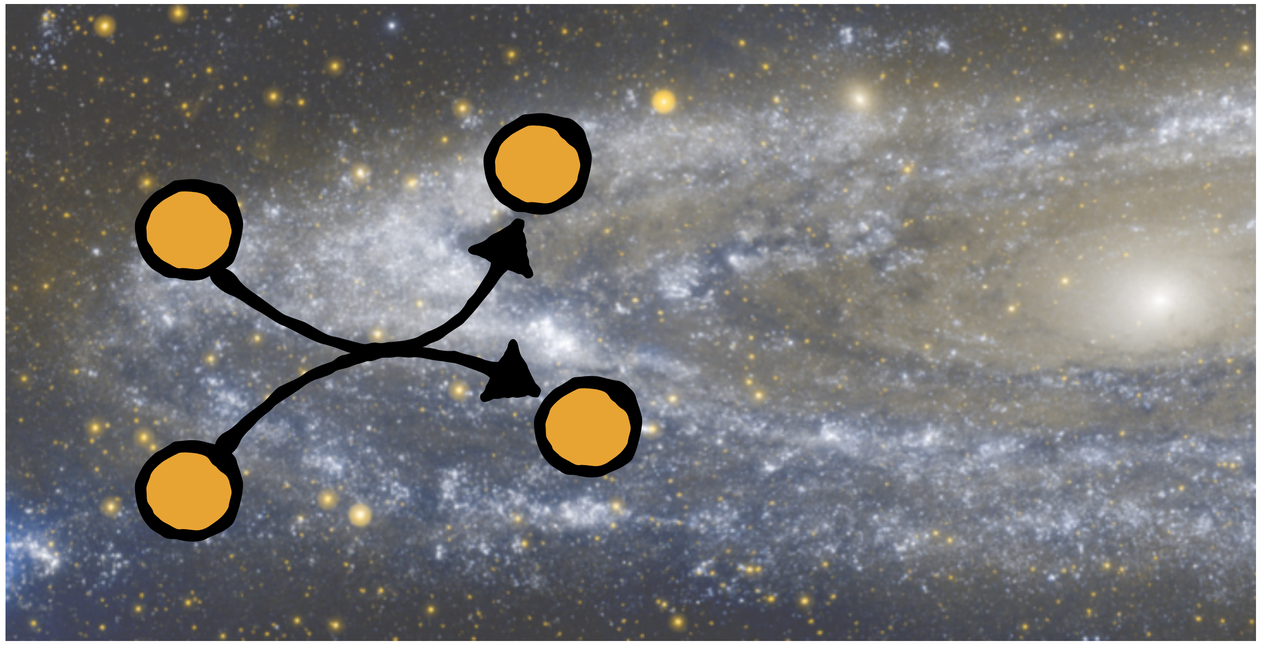
(Old but) new approach

Gravitational probes

- complementary to direct, indirect and collider searches
- how visible matter distribution changes w/ DM properties
- all known properties are derived in this way (including its existence; standard model (SM) neutrinos are too hot to form galaxies)

Self-interacting dark matter (SIDM)

- interactions among dark matter particles
  - hard to probe in other searches

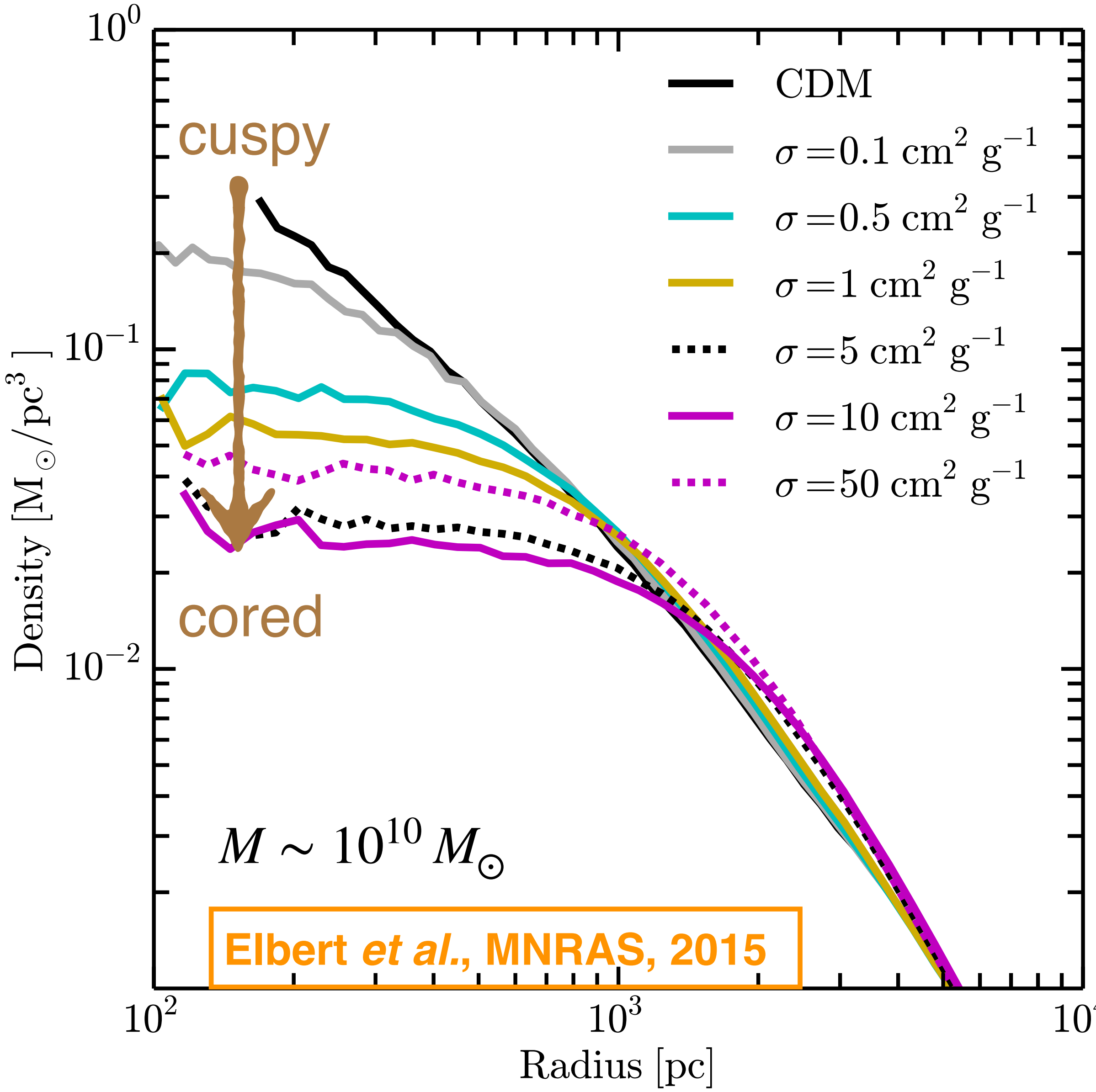


Self-interacting dark matter

Self-interacting dark matter (SIDM)

- dark matter density profile inside a halo turns from cuspy to cored
  - cored profile "appear to" provide better fit to astronomical data
  - though, stellar feedback should be taken into account

$$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g} \sim 1\,\mathrm{barn}/\mathrm{GeV}$$



Contents

Brief introduction of SIDM

- core vs cusp problem
- velocity-dependent cross section

Frontier of SIDM

- diversity problems: dwarf spiral galaxies and satellite galaxies
- strong self-interaction and gravothermal collapse

Contents

Brief history of SIDM

Dark Matter Self-interactions and Small Scale Structure

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(Dated: May 9, 2017)

Abstract

We review theories of dark matter (DM) beyond the collisionless paradigm, known as self-interacting dark matter (SIDM), and their observable implications for astrophysical structure in the Universe. Self-interactions are motivated, in part, due to the potential to explain long-standing (and more recent) small scale structure observations that are in tension with collisionless cold DM (CDM) predictions. Simple particle physics models for SIDM can provide a universal explanation for these observations across a wide range of mass scales spanning dwarf galaxies, low and high surface brightness spiral galaxies, and clusters of galaxies. At the same time, SIDM leaves intact the success of ΛCDM cosmology on large scales. This report covers the following topics: *(1) small scale structure issues*, including the core-cusp problem, the diversity problem for rotation curves, the missing satellites problem, and the too-big-to-fail problem, as well as recent progress in hydrodynamical simulations of galaxy formation; *(2) N-body simulations for SIDM*, including implications for density profiles, halo shapes, substructure, and the interplay between baryons and self-interactions; *(3) semi-analytic Jeans-based methods* that provide a complementary approach for connecting particle models with observations; *(4) constraints from mergers*, such as cluster mergers (e.g., the Bullet Cluster) and minor infalls, along with recent simulation results for mergers; *(5) particle physics models*, including light mediator models and composite DM models; and *(6) complementary probes for SIDM*, including indirect and direct detection experiments, particle collider searches, and cosmological observations. We provide a summary and critical look for all current constraints on DM self-interactions and an outline for future directions.

Astrophysical Tests of Dark Matter Self-Interactions

Susmita Adhikari[1,2*], Arka Banerjee[1], Kimberly K. Boddy[3], Francis-Yan Cyr-Racine[4], Harry Desmond[5,6,7†], Cora Dvorkin[8], Bhuvnesh Jain[9], Felix Kahlhoefer[10], Manoj Kaplinghat[11], Anna Nierenberg[12], Annika H. G. Peter[13], Andrew Robertson[14], Jeremy Sakstein[8,15], Jesús Zavala[16]

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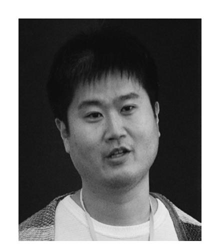
**EUREKA

銀河のダークハロー構造の多様性：
自己相互作用するダークマターの観点から



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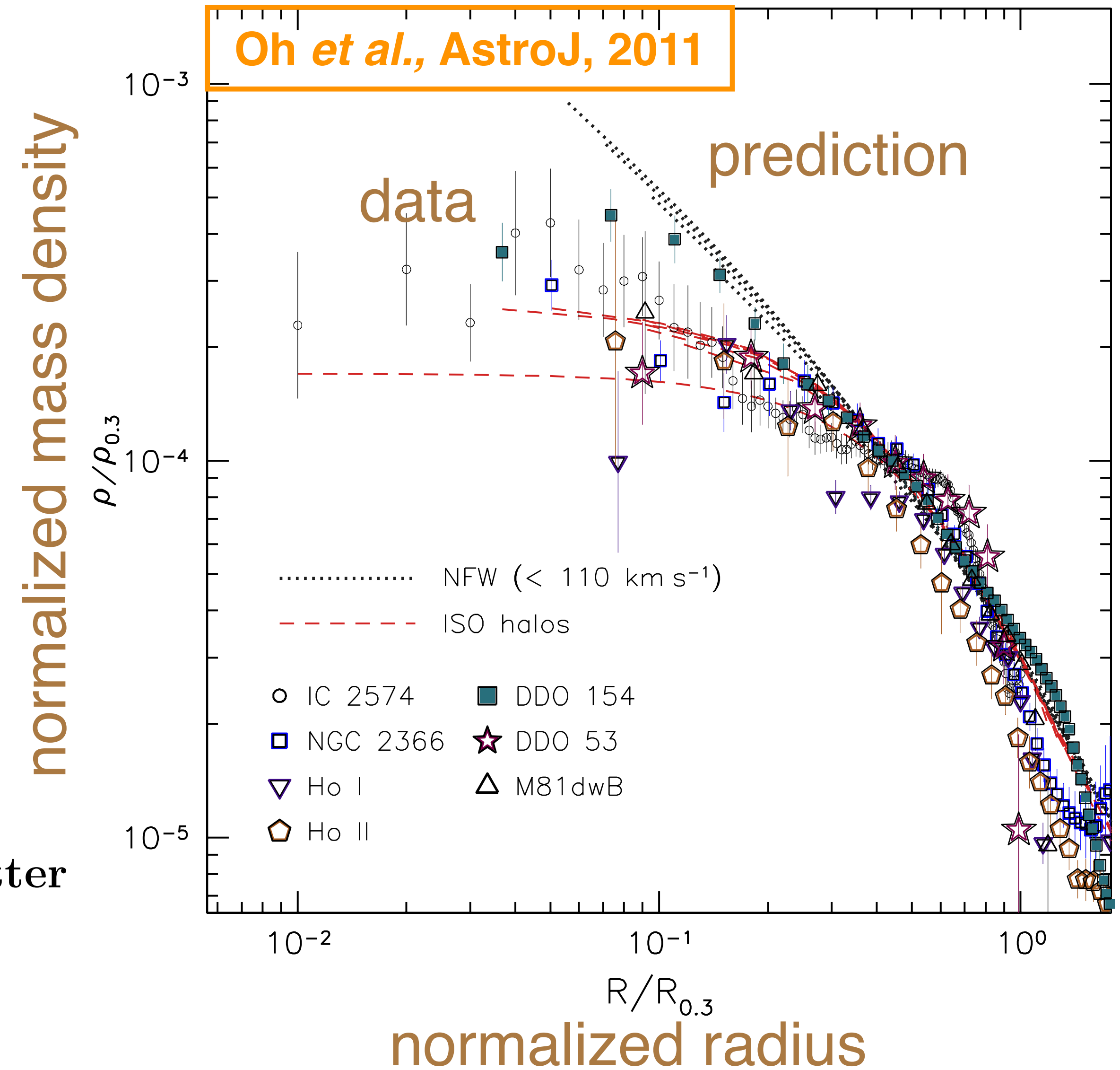
1st stage of SIDM

Core vs cusp problem (1994)

- dwarf galaxies appear to prefer a cored profile



SIDM as an explanation (1999)

Observational evidence for self-interacting cold dark matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton NJ 08544 USA

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross-section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

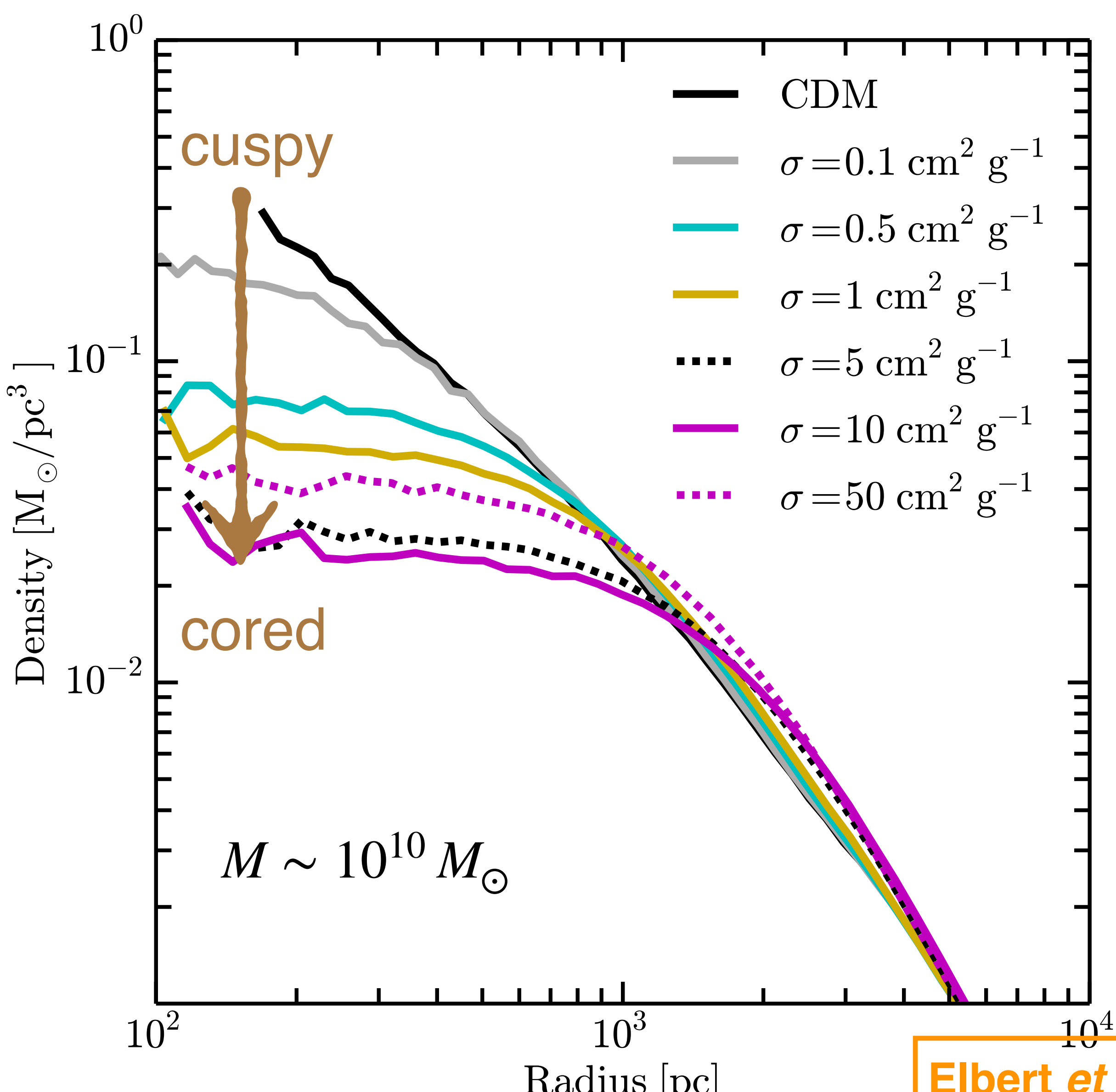
To summarize, our estimated range of σ/m for the dark matter is between 0.45-450 cm^2/g or, equivalently, $8 \times 10^{-(25-22)}$ cm^2/GeV. Numerical calculations are es-

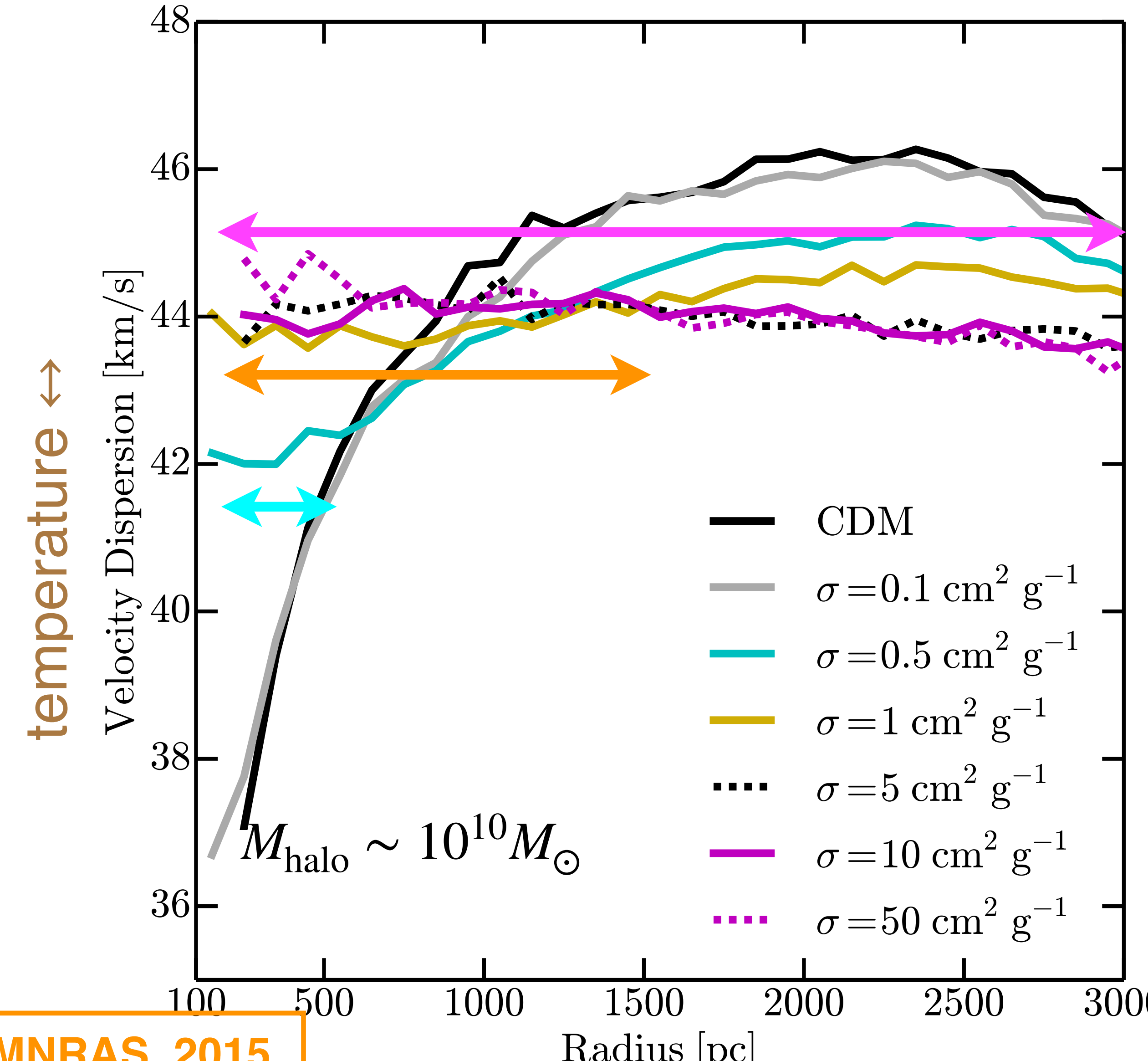
Underlying physics of SIDM

How a core forms

- heat transfer inside a halo

- iso-thermal (equal temperature) region forms



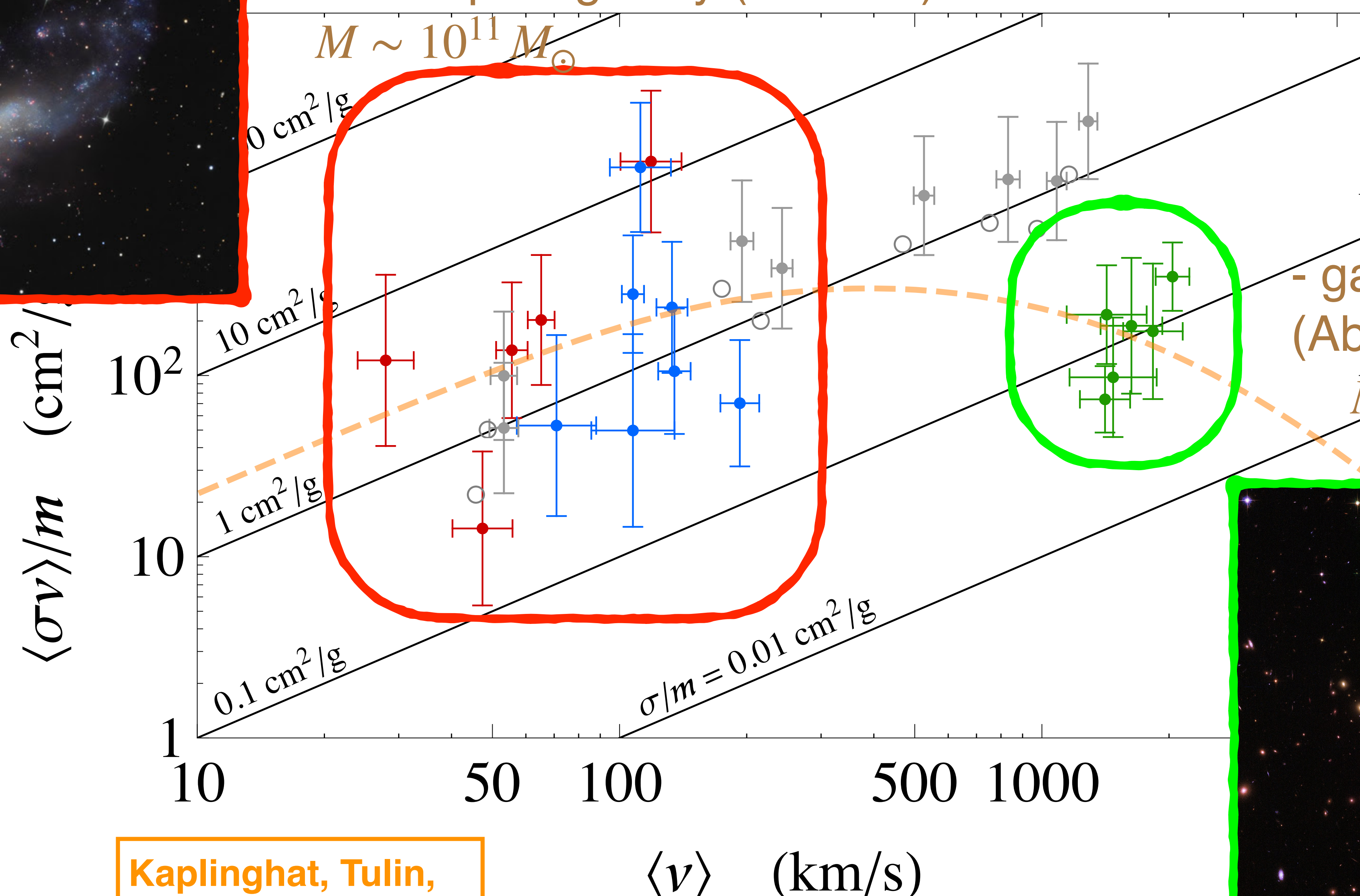


Elbert *et al.*, MNRAS, 2015

“Data” points

Overview

- cores in various-size halos may prefer velocity dependence of self-scattering cross section



Kaplinghat, Tulin, and Yu, PRL, 2016

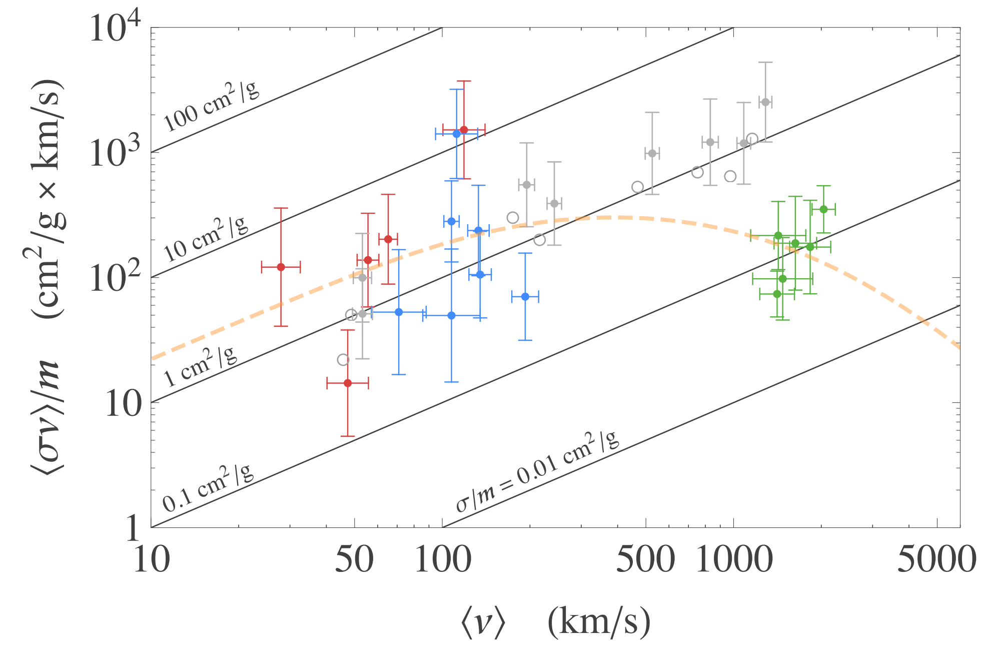
Data points

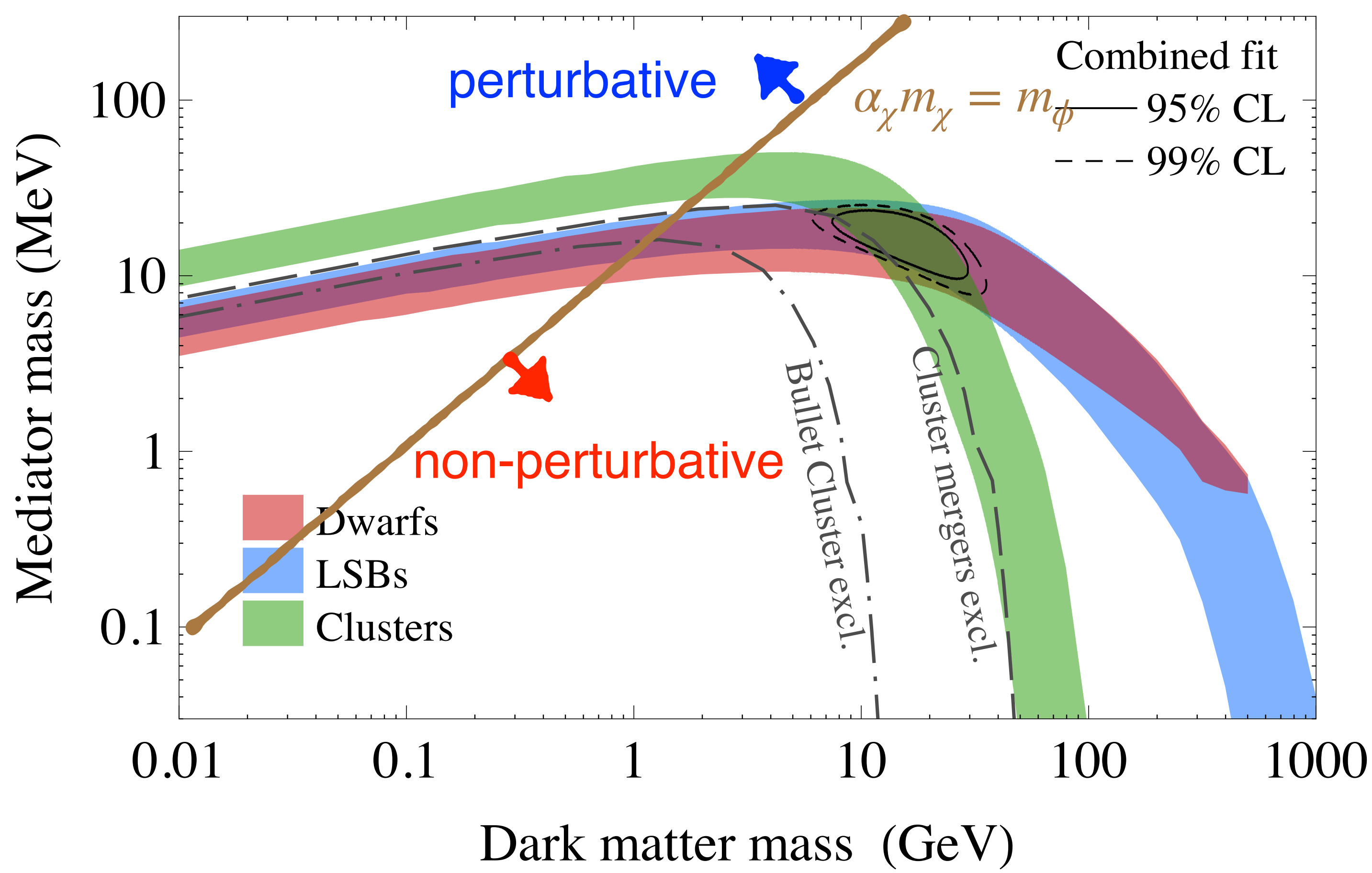
Light mediator fit to data

- DM and mediator masses are pinned down $m_\chi \sim 10\,\mathrm{GeV}$ $m_\phi \sim 10\,\mathrm{MeV}$

    - repulsive Yukawa (for simplicity)

$$\alpha_\chi = \alpha_{\mathrm{em}}$$





- perturbative: Born (tree-level) approximation is good

- non-perturbative: need to solve Schrödinger equation (resummation of ladder diagrams)

Tulin, Yu, and Zurek, PRD, 2013

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Frontier of SIDM

- diversity problems: dwarf spiral galaxies and satellite galaxies

- strong self-interaction and gravothermal collapse

Diversity in dwarf spiral galaxies

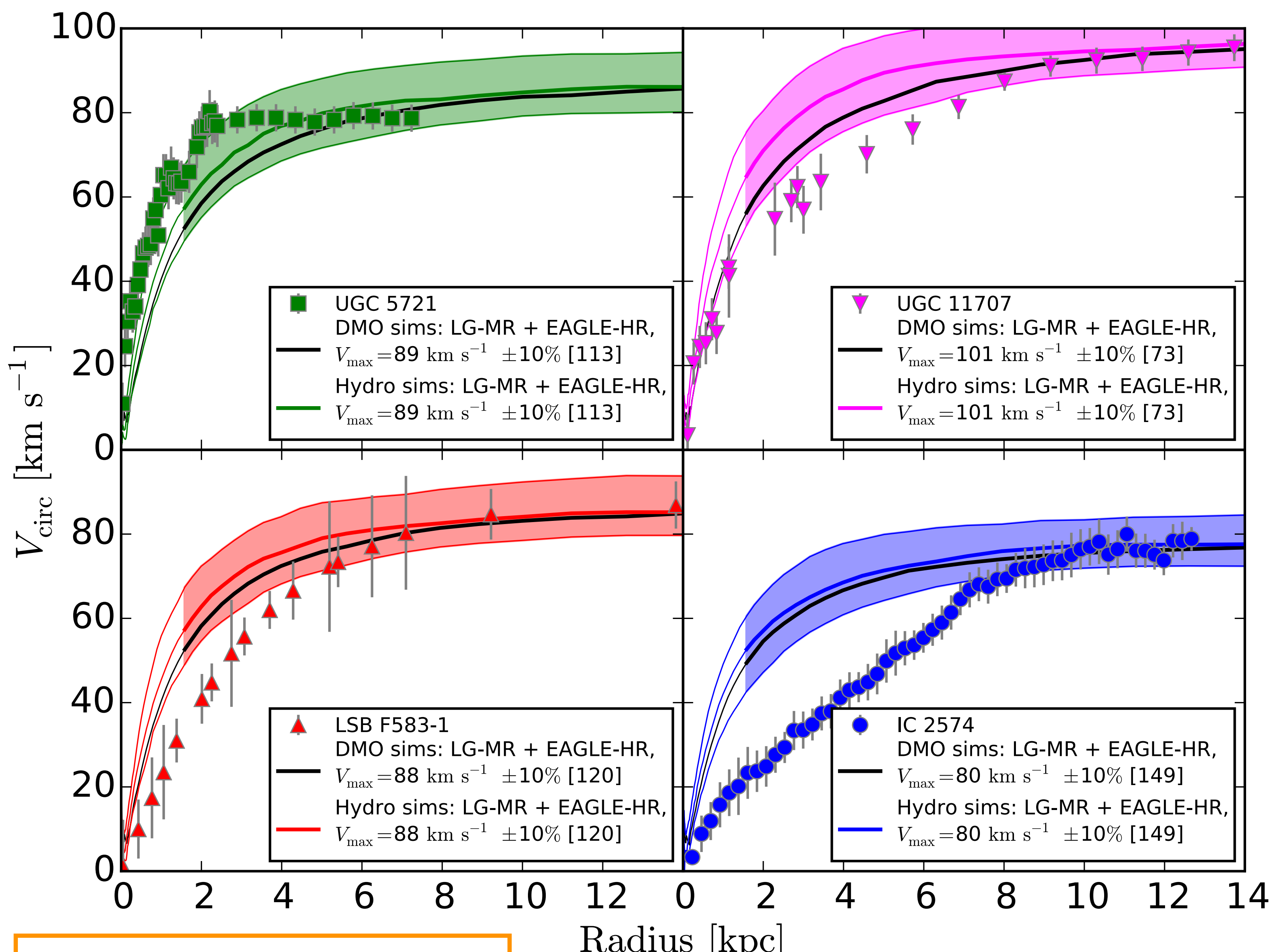
Rotation curves

- simulation: inner circular velocity is almost uniquely determined by outer circular velocity

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

- ρ_s and r_s are not independent (concentration-mass relation)

- observation: diverse inner circular velocity



Oman *et al.*, MNRAS, 2015

Can SIDM explain it?

Naively, no

- SIDM has a universal impact

The unexpected diversity of dwarf galaxy rotation curves

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

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[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

4.5 The challenge to alternative dark matter models

Finally, we note that the diversity of rotation curves illustrated in Fig. 5 disfavours solutions that rely on modifying the physical nature of the dark matter. Cores can indeed be produced if the dark matter is SIDM or WDM but, in this case, we would expect *all* galaxies to have cores and, in particular, galaxies of similar mass or velocity to have cores of similar size. This is in disagreement with rotation curve data and suggests that a mechanism unrelated to the nature of the dark matter must be invoked to explain the rotation curve shapes.

Really? But galactic disks show diversity

- different disk sizes in different halos
- SIDM profile is exponentially sensitive to baryon distribution

$$\rho_{\rm DM}(\vec{x}) = \rho^0_{\rm DM}\exp(-\phi(\vec{x})/\sigma^2)$$

$$\Delta\phi = 4\pi G(\rho_{\rm DM} + \rho_{\rm baryon})$$

- iso-thermal region forms through self-interaction

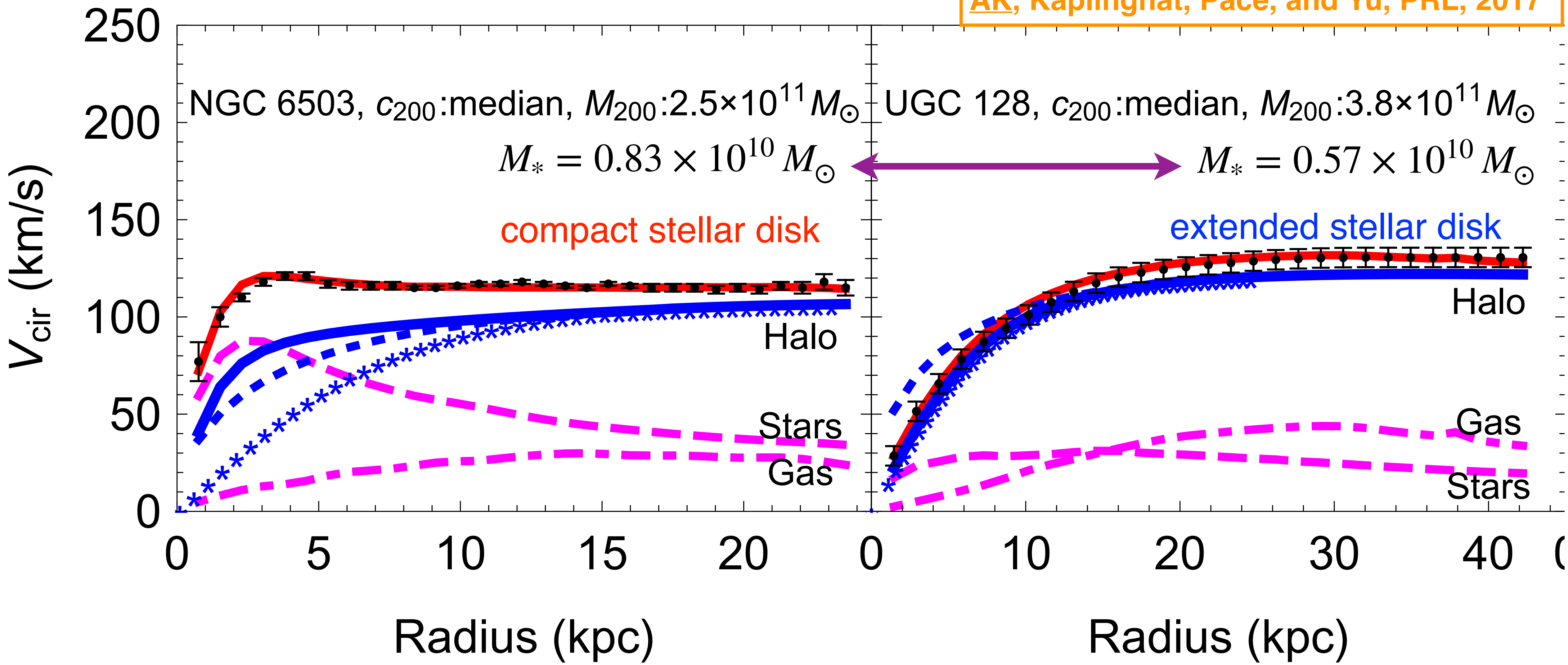
SIDM explanation

SIDM reproduces diversity (unlike a naive expectation)

- compact disk→ redistribute SIDM significantly
- extended disk→ unchange SIDM distribution

$\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$

AK, Kaplinghat, Pace, and Yu, PRL, 2017



Diversity in MW satellites

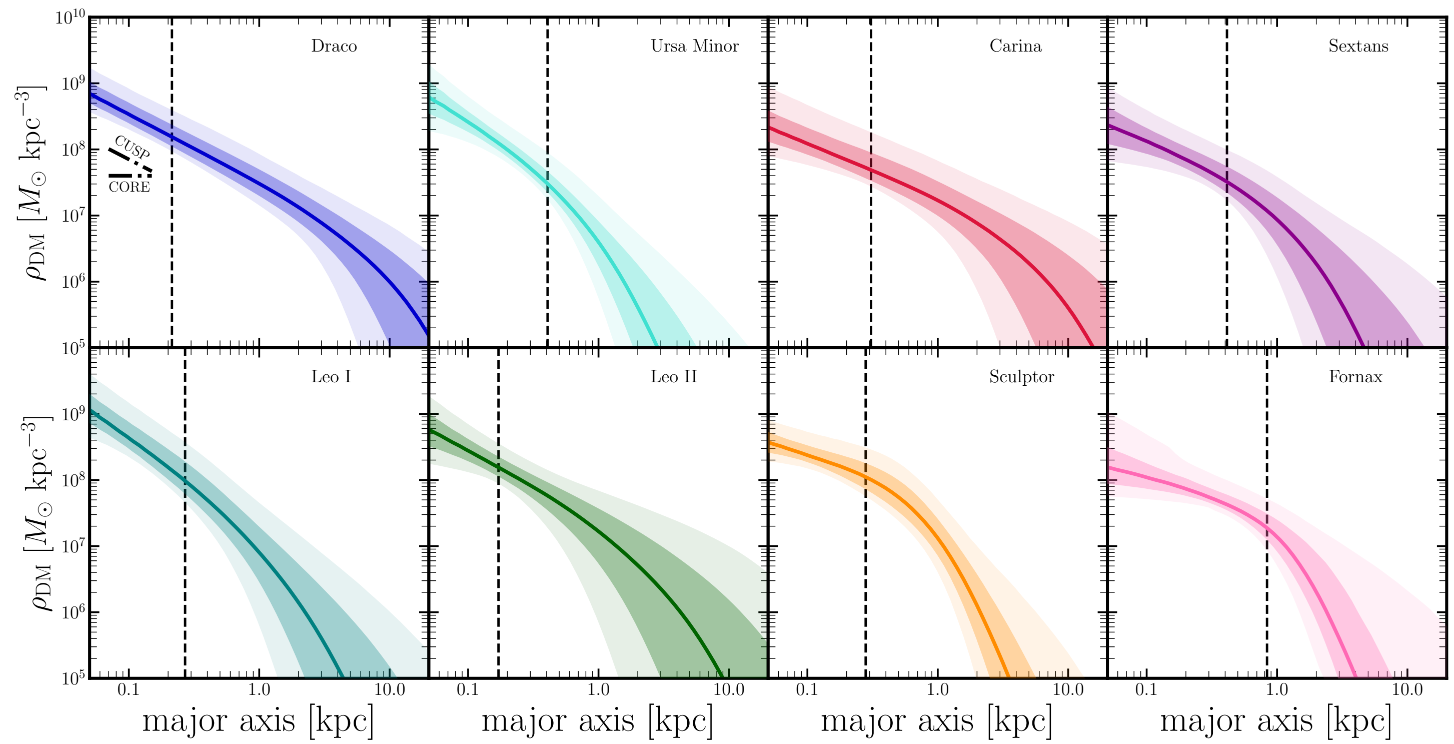
MW satellites (classical)

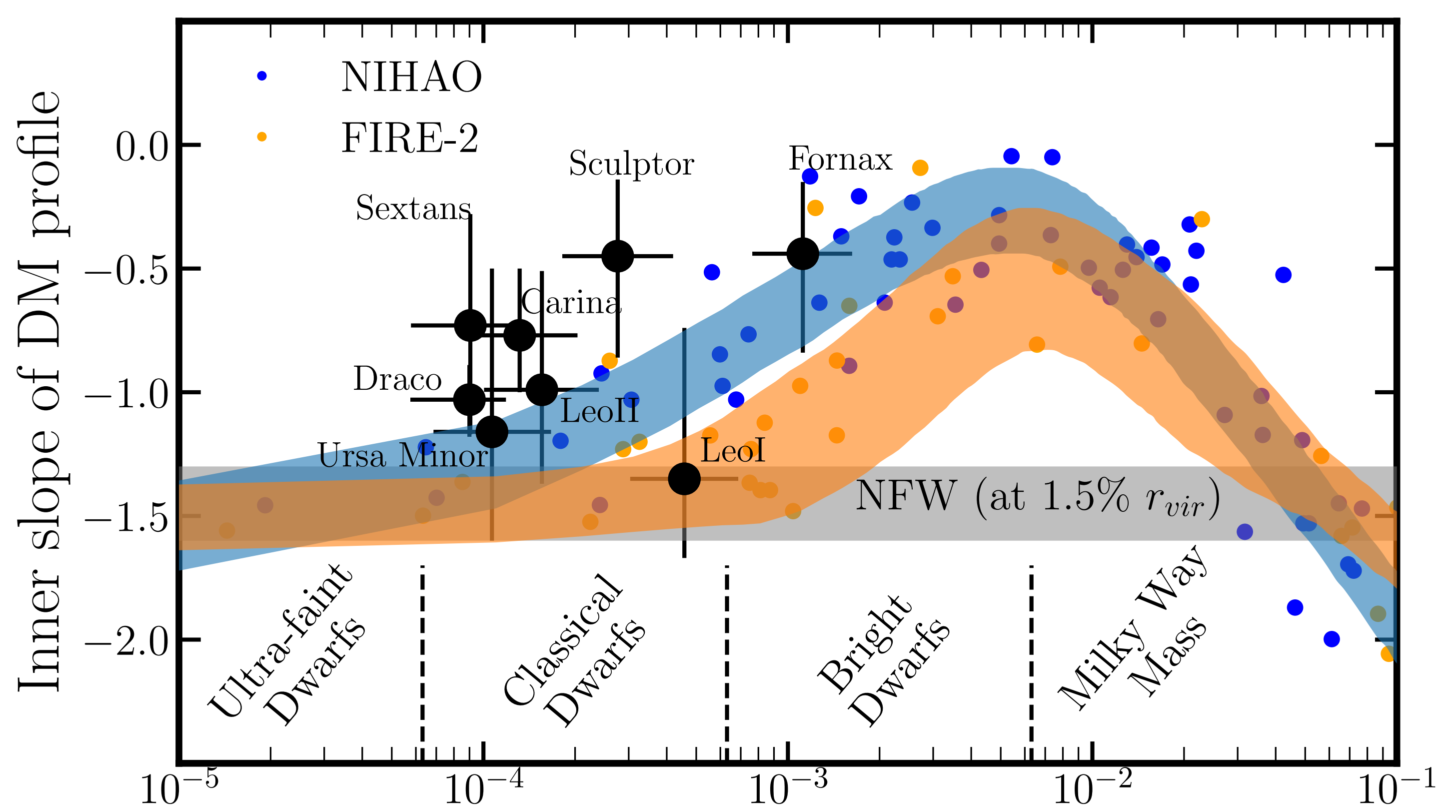
- mass distribution is determined by line-of-sight velocity dispersion (LOSVD) profile

- shows diversity in inner slope and density, though uncertainty is still large

SIDM again? Naively, no

- satellite galaxies have only negligible amount of baryons





Hayashi, Chiba, and Ishiyama, ApJ, 2020

SIDM explanation

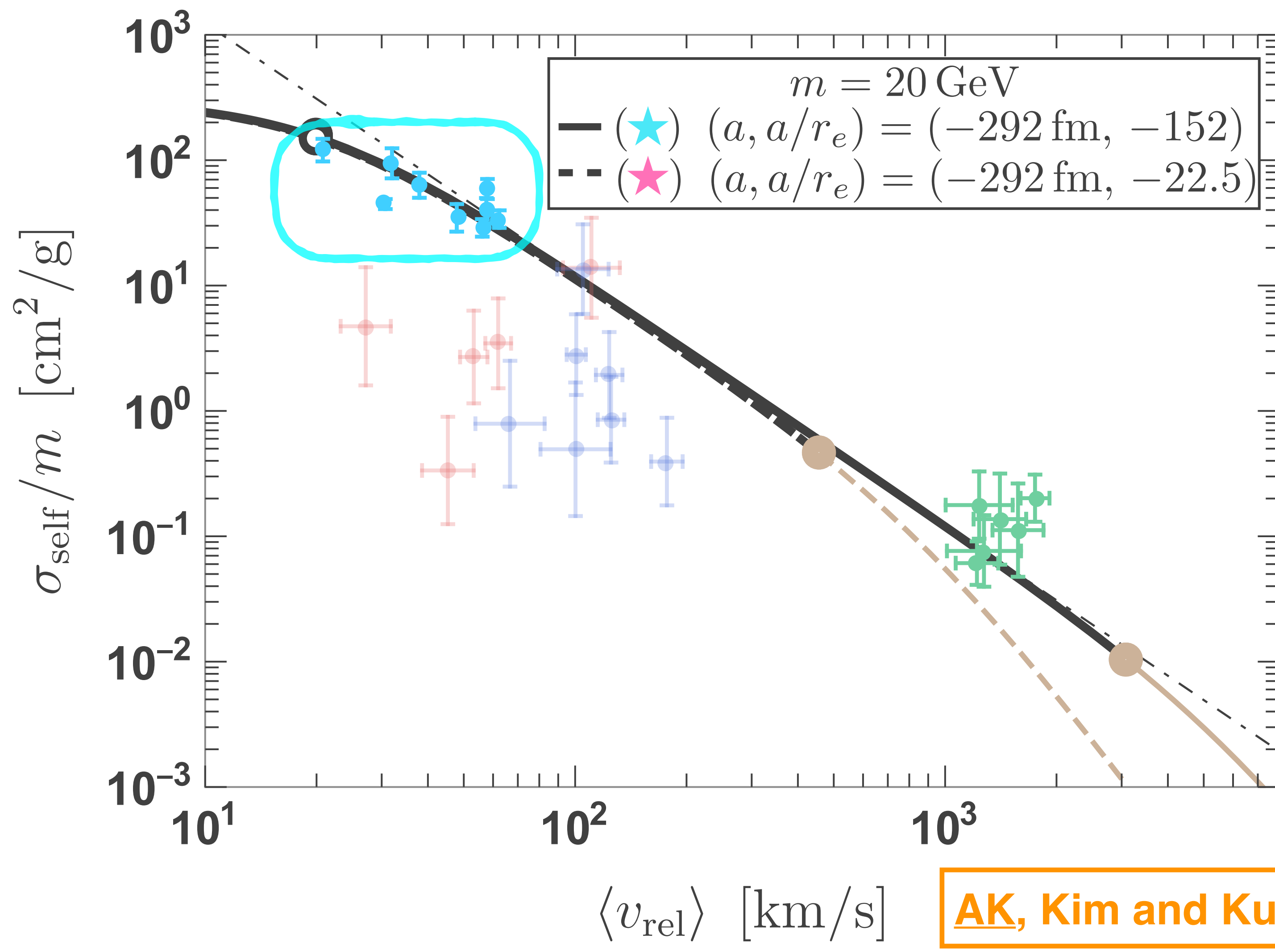
Strong SIDM

Correa, MNRAS, 2021

- explain diversity by taking a much larger cross section at low velocity

$$\sigma/m \sim 40\,\mathrm{cm}^2/\mathrm{g}$$

- gravothermal collapse is sensitive to initial profiles and orbits in MW

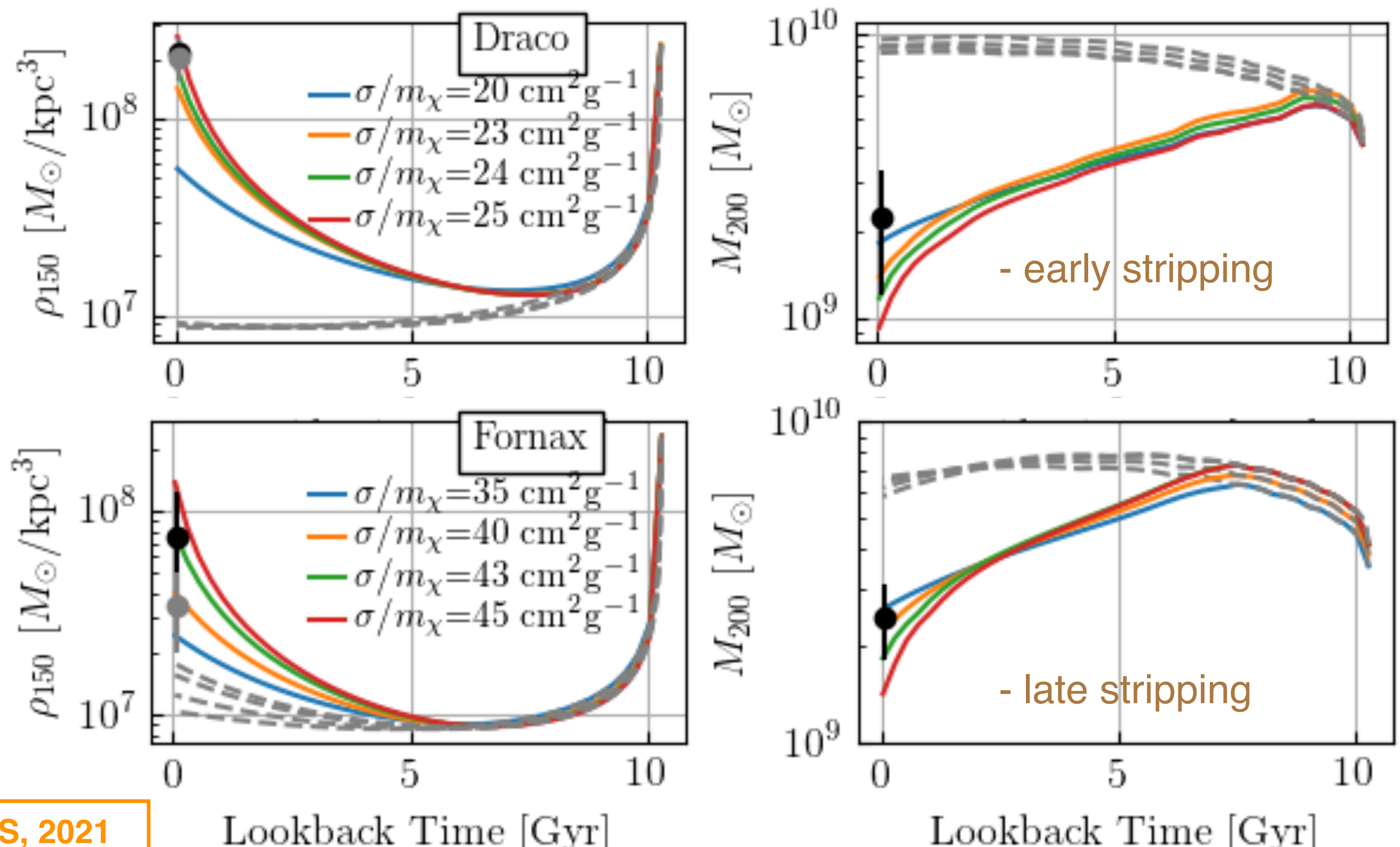


AK, Kim and Kuwahara, JHEP, 2020

Strong SIDM

Gravothermal collapse

- tidal stripping: different orbits in MW → different “initial” profiles
- stepped profile sees accelerated gravothermal collapse



Correa, MNRAS, 2021

On-going efforts

More precise prediction

- isolated halo + tidal stripping through gravothermal-fluid modeling
- cosmological simulations (time-consuming) are limited so far

How to examine?

- collapsed halos
    - through perturbations of strong-lensed systems

A possible challenge for cold and warm dark matter

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Check for updates

Simona Vegetti[1], Simon D. M. White[1], John P. McKean[2,3,4], Devon M. Powell[1], Cristiana Spingola[5], Davide Massari[6], Giulia Despali[6,7,8] & Christopher D. Fassnacht[9]

Measuring the density profile and mass concentration of dark-matter haloes is a key test of the standard cold dark matter paradigm. Such objects are dark and thus challenging to characterize, but they can be studied via gravitational lensing. Recently, a million-solar-mass object was discovered superposed on an extended and extremely thin gravitational arc. Here we report on extensive tests of various assumptions for the mass density profile and redshift of this object. We find that models that best describe the data have two components: an unresolved point mass of radius ≤10 pc centred on an extended mass distribution with an almost constant surface density out to a truncation radius of 139 pc. These properties do not resemble any known astronomical object. However, if the object is dark matter dominated, its structure is incompatible with cold dark matter models but may be compatible with a self-interacting dark-matter halo where the central region has collapsed to form a black hole. This detection could thus carry substantial implications for our current understanding of dark matter.

Summary

Self-interacting dark matter

- turns a density profile from core to cusp

Velocity dependence

- inferred by combining observations of different size halos
- larger cross section for smaller velocity is preferred

Frontier

- explain diversity of rotation curves through diversity in galactic disks

$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

- Strong SIDM: explain diversity of inner density through gravothermal collapse and diversity in initial profiles and orbits in MW

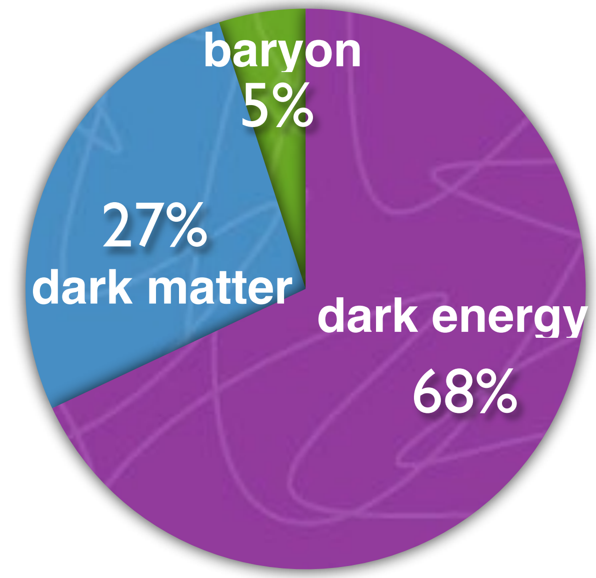
$\sigma/m \sim 40\,\mathrm{cm}^2/\mathrm{g}$

Thank you

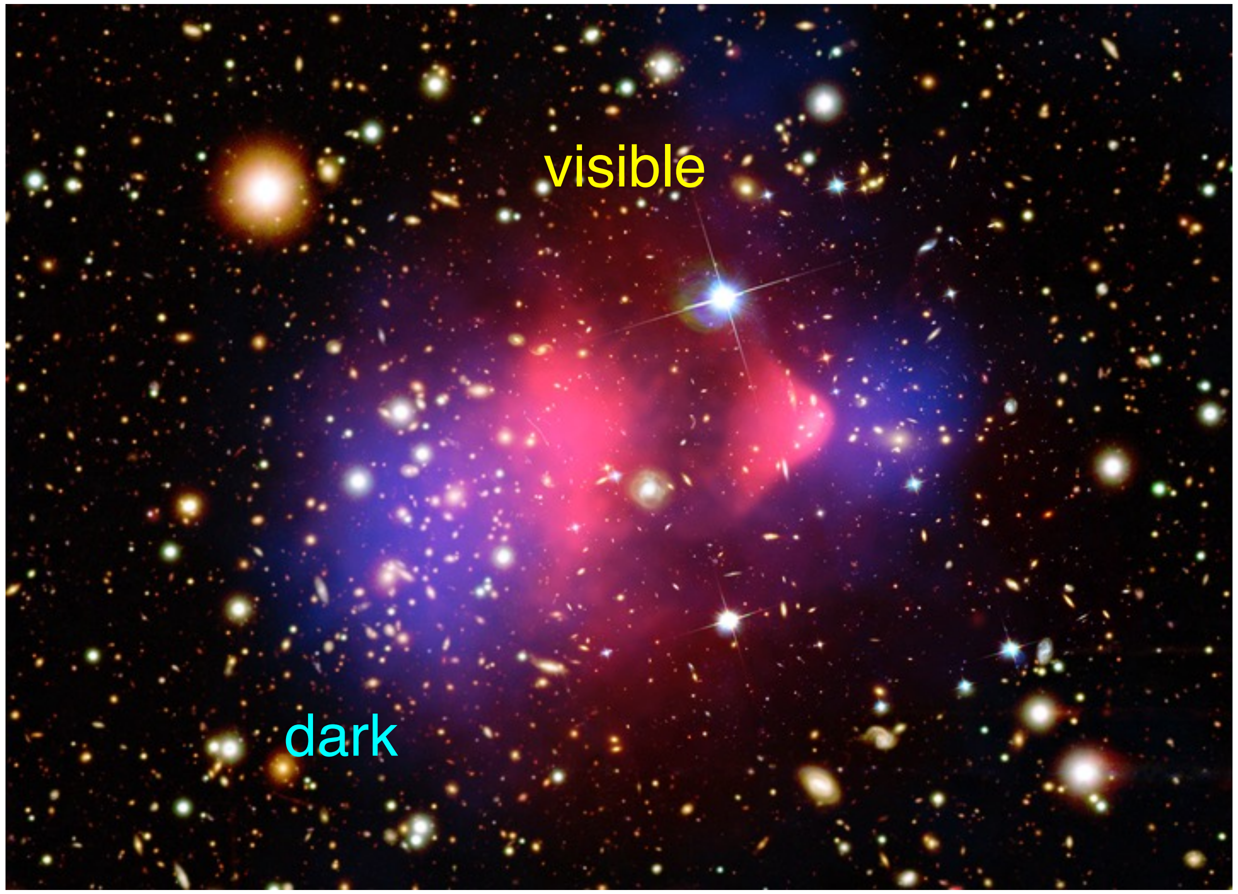
Dark matter

DM (or missing mass)

- evident from cosmological observations
  - cosmic microwave background (CMB)…
- essential to form galaxies in the Universe
- one of the biggest mysteries
  - astronomy, cosmology, particle physics…



cosmic energy budget



bullet cluster

WIMP dark matter

Attractive features

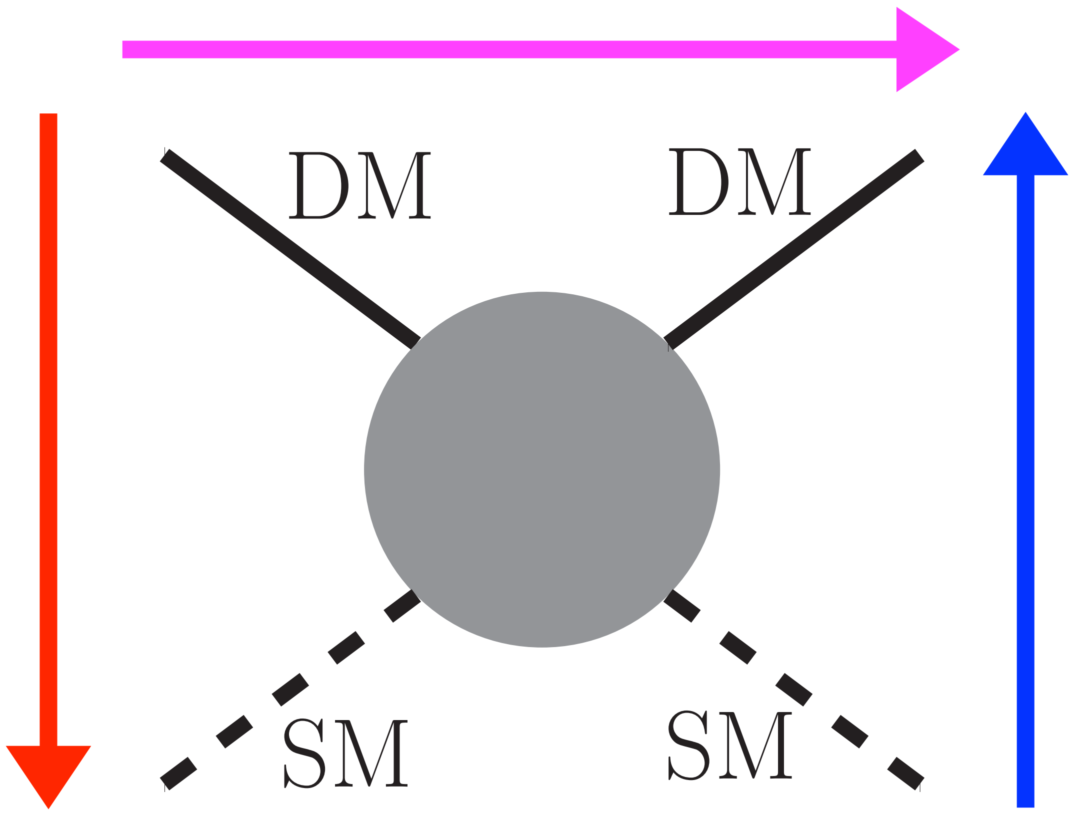
- thermal freeze-out (annihilation in the early Universe)

$$\Omega h^2 = 0.1 \times \frac{3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

- weak-scale annihilation cross section $\langle \sigma_{\mathrm{ann}} v \rangle \simeq 1\,\mathrm{pb} \times c$

- well motivated by hierarchy problem and TeV-scale new physics

- various search strategies
    - direct detection
    - indirect detection
    - collider



Current status of WIMPs

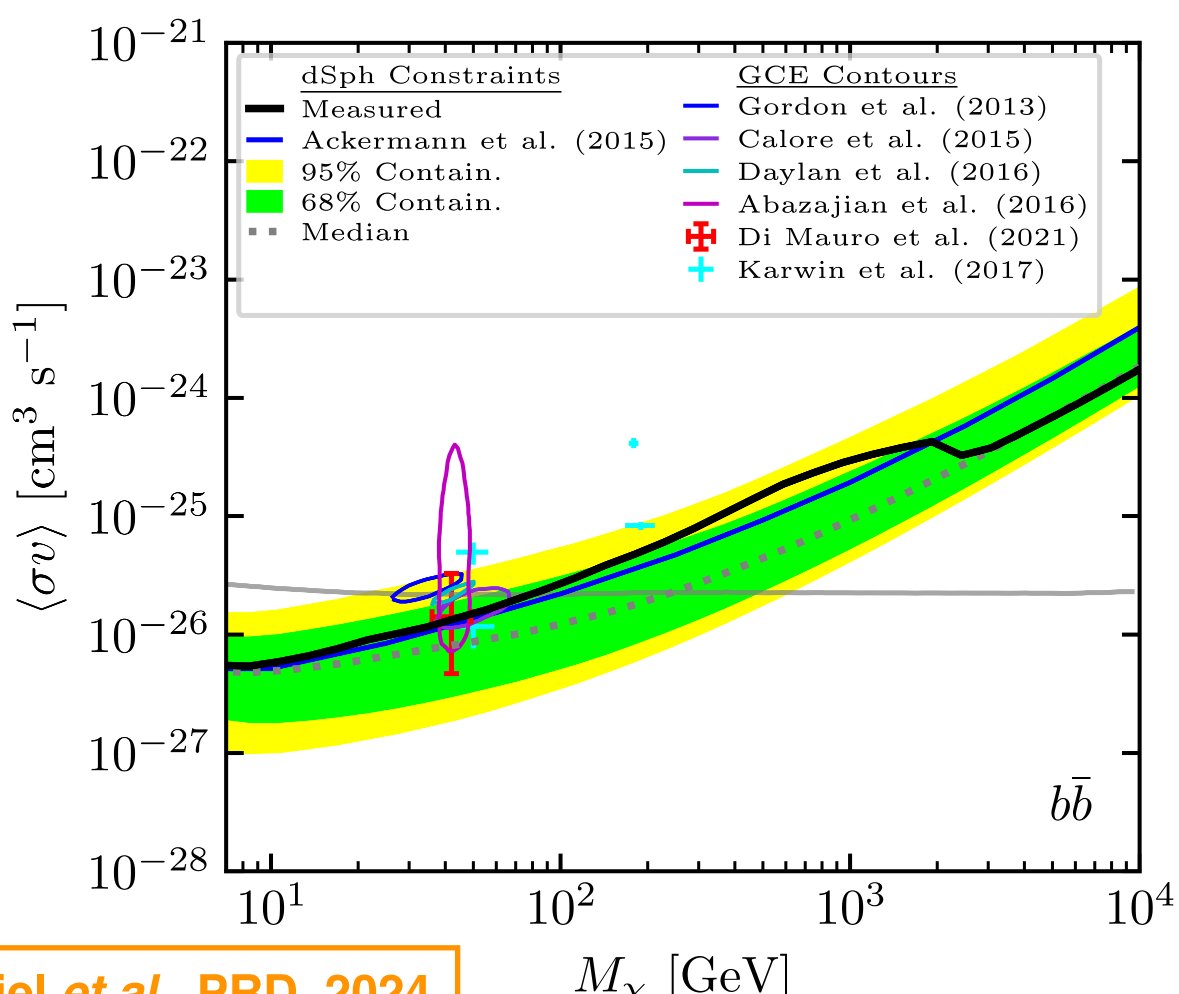
Snowmass 2021, arXiv:2203.08084

Still attractive?

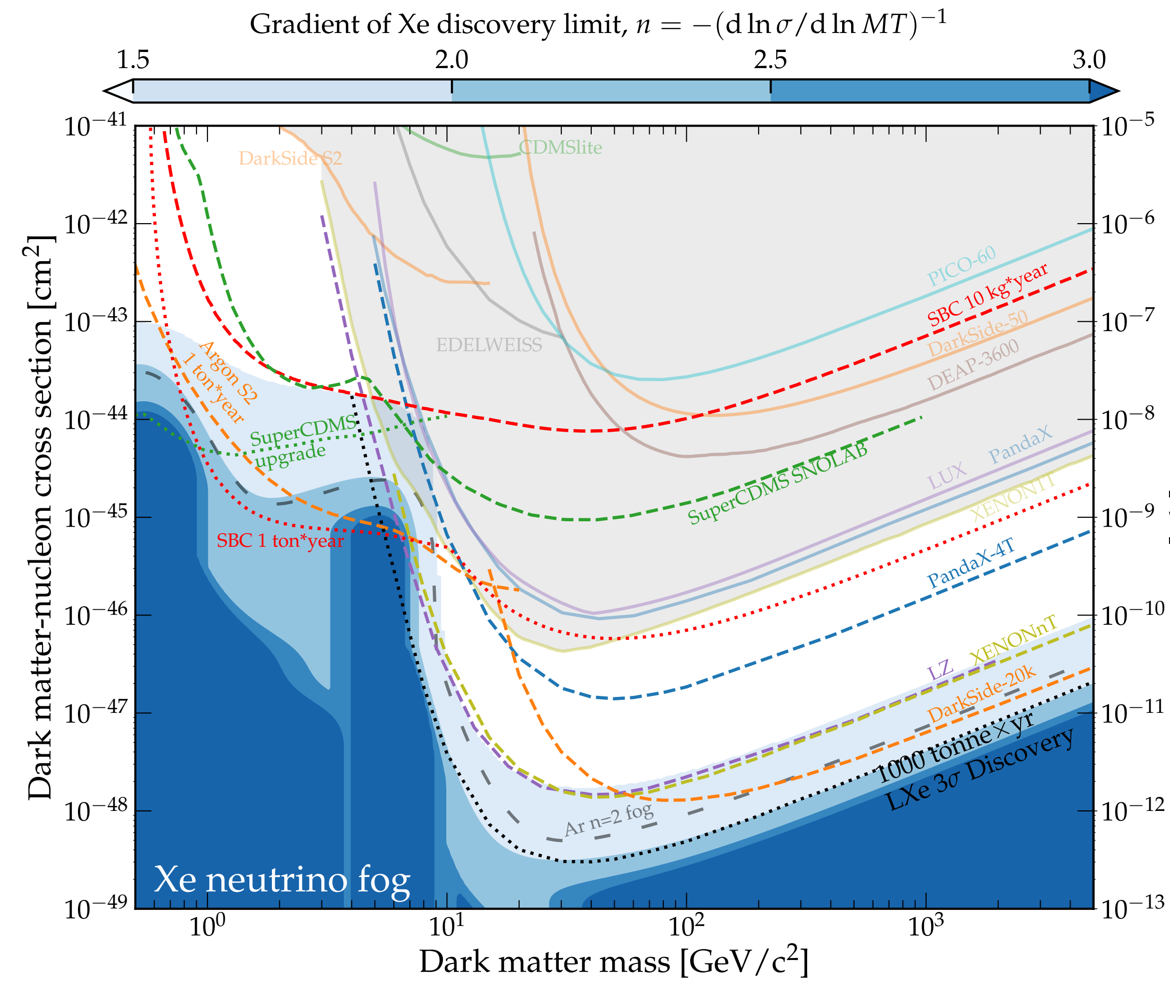
- no TeV-scale new physics at Large Hadron Collider (LHC)

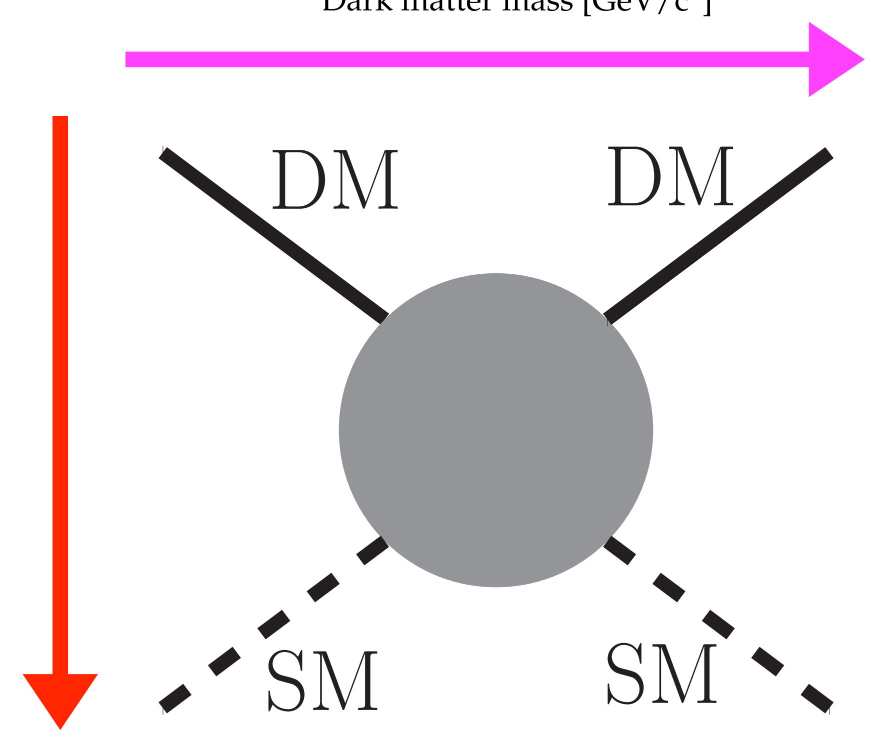
- no convincing signals in conventional searches

- (though we should wait)



McDaniel *et al.*, PRD, 2024

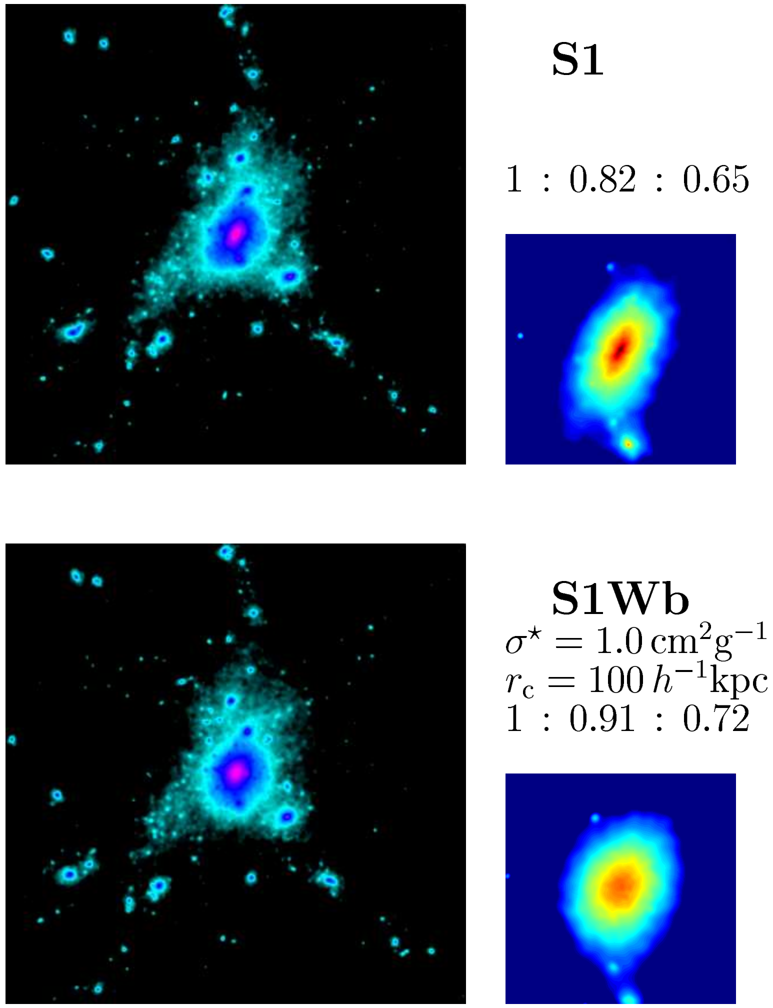




End of the 1st stage

Spherical halo

- self-interaction turns a halo shape from elliptical into spherical in an iso-thermal region



Yoshida *et al.*, ApJL, 2000

Galaxy-cluster halo shape (2000)

- inferred from strong lensing

A TEST OF THE COLLISIONAL DARK MATTER HYPOTHESIS FROM CLUSTER LENSING

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Received 2000 February 8; accepted 2001 August 29

at $z_s = 1$. Assuming also a cluster velocity dispersion $\sigma = 1000$ km s^{-1} (roughly the minimum value required given the Einstein radius of the cluster), and a cluster age $t_c = 5 \times 10^9$ years, we obtain the upper limit

$$\frac{s_x}{m_x} < \frac{1}{\rho 2^{1/2} \sigma t_c} \simeq 10^{-25.5}\,\frac{\mathrm{cm}^2}{m_p} \simeq 0.02\,\frac{\mathrm{cm}^2}{\mathrm{g}}\,. \qquad (14)$$

- not consistent?

To summarize, our estimated range of σ/m for the dark matter is between 0.45-450 cm^2/g or, equivalently, $8 \times 10^{-(25-22)}$ cm^2/GeV. Numerical calculations are es-

Dormant decade

Velocity dependence (self-interaction)

- typical collision velocity in a galaxy cluster $\langle v_{\rm rel} \rangle \sim 10^3\,{\rm km/s}$
is 10 times higher than that in a dwarf galaxy $\langle v_{\rm rel} \rangle \sim 10^2\,{\rm km/s}$

- but SIDM was not considered for a decade after that

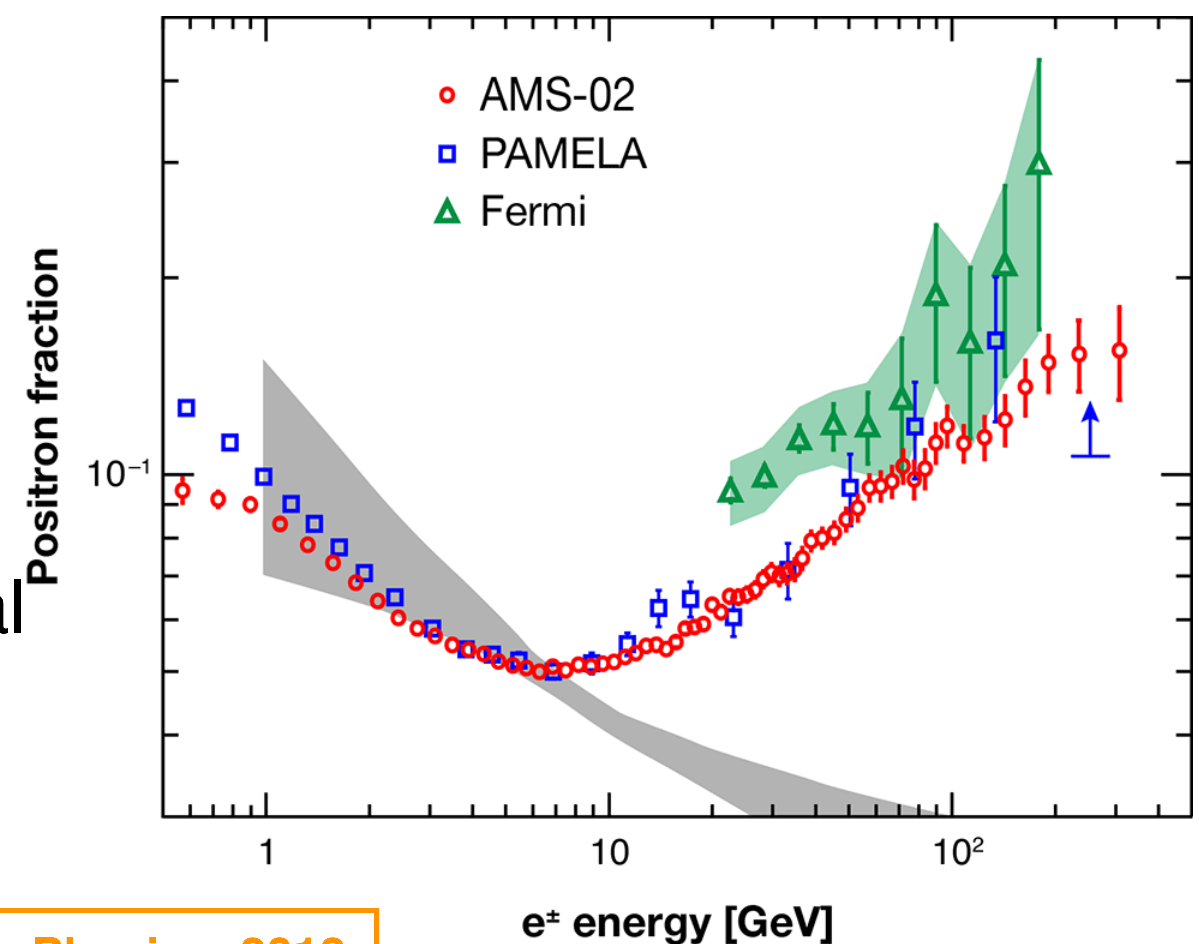
    - maybe not well motivated to consider a "complication" (velocity dependence)

Cosmic-ray anomalies (2008)

- Pamela, ATIC… reports an excess in electron/positron flux

- requires 100 times larger cross section (boost factor) than canonical value for correct relic abundance

$$\Omega h^2 = 0.1 \times \frac{3 \times 10^{-26}\,{\rm cm^3/s}}{\langle \sigma_{\rm ann} v \rangle}$$



Coutu, Physics, 2013

Dark force and light mediator

Velocity dependence (annihilation)

- typical collision velocity around the freeze-out $\langle v_{\rm rel} \rangle \simeq 1.5 \times 10^5\,{\rm km/s}$ is much higher than that in our MW galaxy $\langle v_{\rm rel} \rangle \sim 10^2\,{\rm km/s}$

Dark force and light mediator as an explanation (2009)

- dark matter may have its own "long-range" force $V = -\dfrac{\alpha_\chi}{r} e^{-m_\phi r}$
- non-minimal dark sector

- Yukawa potential

A theory of dark matter

Nima Arkani-Hamed,[1] Douglas P. Finkbeiner,[2] Tracy R. Slatyer,[3] and Neal Weiner[4]
[1]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
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[4]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003, USA*
(Received 31 October 2008; published 27 January 2009)

We propose a comprehensive theory of dark matter that explains the recent proliferation of unexpected observations in high-energy astrophysics. Cosmic ray spectra from ATIC and PAMELA require a WIMP (weakly interacting massive particle). with mass $M_\chi \sim 500$–800 GeV that annihilates into leptons at a level well above that expected from a thermal relic. Signals from WMAP and EGRET reinforce this interpretation. Limits on $\bar{p}$ and π^0-γ's constrain the hadronic channels allowed for dark matter. Taken together, we argue these facts imply the presence of a new force in the dark sector, with a Compton wavelength $m_\phi^{-1} \gtrsim 1\ {\rm GeV}^{-1}$. The long range allows a Sommerfeld enhancement to boost the annihilation cross section as required, without altering the weak-scale annihilation cross section during dark matter freeze-out in the early universe. If the dark matter annihilates into the new force carrier ϕ, its low mass

Scattering in quantum mechanics

Schrödinger equation

Weinberg, "Lectures on Quantum Mechanics"

$$\left[-\frac{1}{2\mu}\nabla^2 + V(r)\right]\psi_k(\vec{x}) = E\psi_k(\vec{x}) \qquad E = \frac{k^2}{2\mu} \qquad k = \mu v_{\rm rel}$$

- potential from long-range force

- reduced mass ($\mu = m/2$ for identical particle)

- scattering state (energy-eigenstate of Schrödinger equation)

$$\psi_k(\vec{x}) \to e^{ikz} + f(k,\theta)\frac{e^{ikr}}{r} \qquad r \to \infty$$

- (in-coming) plane wave

- scattering amplitude

- out-going spherical wave

Partial-wave decomposition

$$e^{ikz} = \sum_{\ell=0}^{\infty} \frac{1}{2ikr}(2\ell+1)R_{k,\ell}(r)P_\ell(\cos\theta)\left(e^{ikr} - e^{-i(kr-\ell\pi)}\right)$$

$$\psi_k(\vec{x}) = \sum_{\ell=0}^{\infty}\frac{1}{k}e^{i\left(\frac{1}{2}\ell\pi + \delta_\ell\right)}(2\ell+1)R_{k,\ell}(r)P_\ell(\cos\theta)$$

- radial Schrödinger equation

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

Scattering in quantum mechanics

Scattering phase

- radial wave function at infinity

$$R_{k,\ell}(r) \to \frac{\sin(kr - \frac{1}{2}\ell\pi + \delta_\ell)}{r} \quad r \to \infty$$

$$f(k,\theta) = \sum_{\ell=0}^{\infty}(2\ell+1)f_\ell(k)P_\ell(\cos\theta) \quad f_\ell(k) = \frac{e^{2i\delta_\ell}-1}{2ik}$$

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

- diagonalized S-matrix $S_\ell = e^{2i\delta_\ell}$

Sommerfeld enhancement

Iengo, JHEP, 2009 | Cassel, J.Phys.G, 2010

- radial wave function around the origin

- annihilation through the contact interaction (delta function potential)

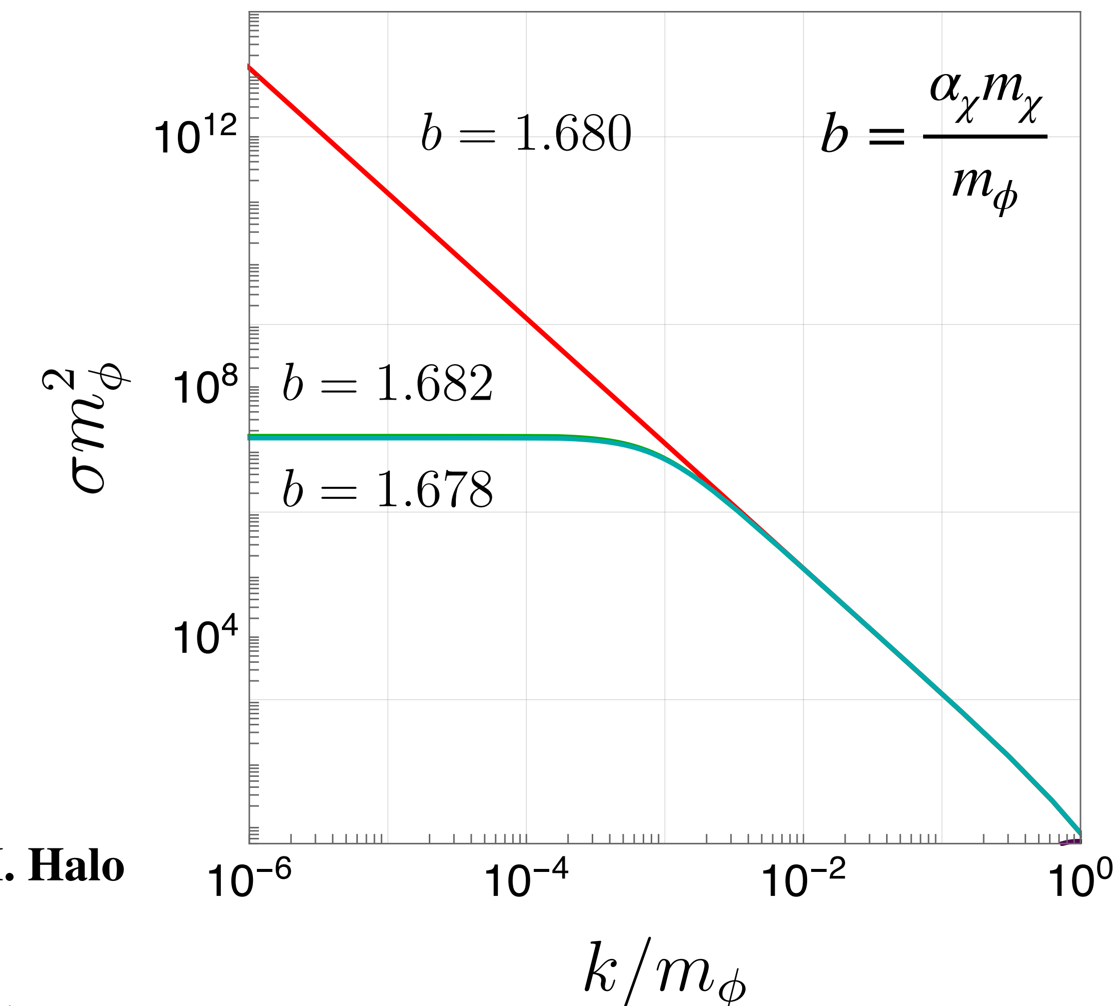
$$S_{k,\ell} = \left|\frac{R_{k,\ell}(r)}{R^{(0)}_{k,\ell}(r)}\right|^2 \quad r \to 0$$

- without potential

2nd stage of SIDM

Dark force also introduces velocity dependence in self-interaction

- people "re"-started to study SIDM



AK, Kuwahara and Patel, JHEP, 2023

Re-assessment of galaxy-cluster halo shape (2014)

Cosmological simulations with self-interacting dark matter – II. Halo shapes versus observations

Annika H. G. Peter,★ Miguel Rocha, James S. Bullock and Manoj Kaplinghat

Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA

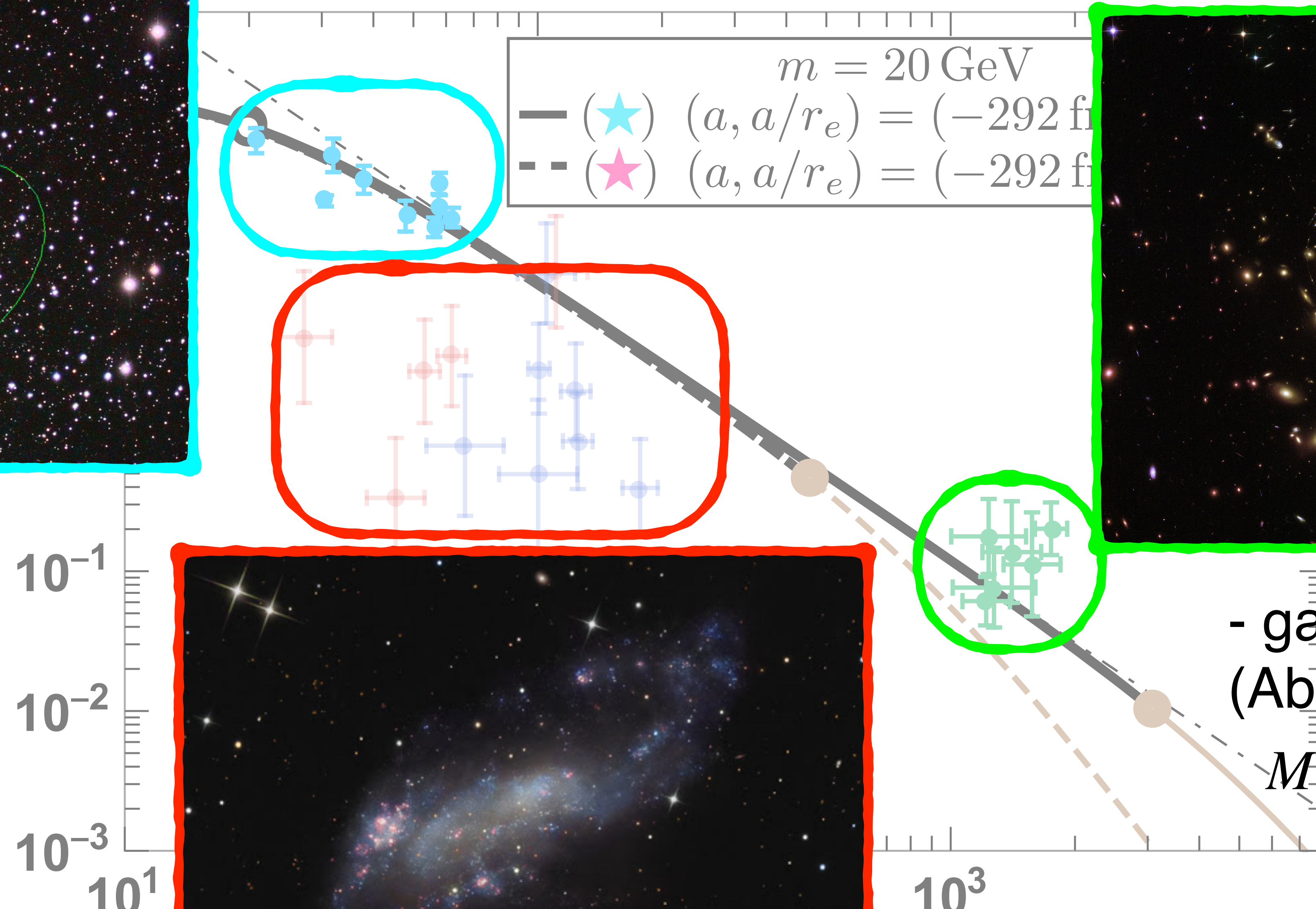
these constraints were off by more than an order of magnitude because (a) they did not properly account for the fact that the observed ellipticity gets contributions from the triaxial mass distribution outside the core set by scatterings, (b) the scatter in axis ratios is large and (c) the core region retains more of its triaxial nature than estimated before. Including these effects properly shows that the same observations now allow dark matter self-interaction cross-sections at least as large as $\sigma/m = 0.1\ \mathrm{cm^2\,g^{-1}}$. We show that constraints on self-interacting

To summarize, our estimated range of σ/m for the dark matter is between 0.45-450 cm^2/g or, equivalently, $8 \times 10^{-(25-22)}$ $\mathrm{cm}^2/\mathrm{GeV}$. Numerical calculations are es-

Data points

Overview

- cores in various-size halos



- MW satellite (Draco)

$M_{\rm infall} \sim 10^9\, M_\odot$

- galaxy cluster (Abell 2744)

$M \sim 10^{14}\, M_\odot$

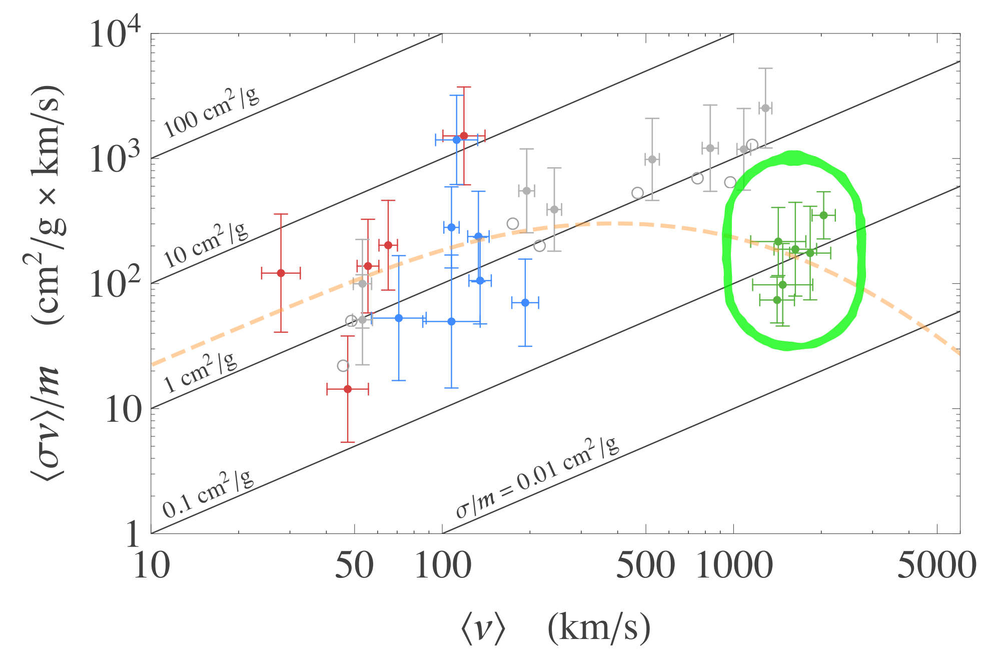
- dwarf spiral galaxy (IC 2574) $M \sim 10^{11}\, M_\odot$

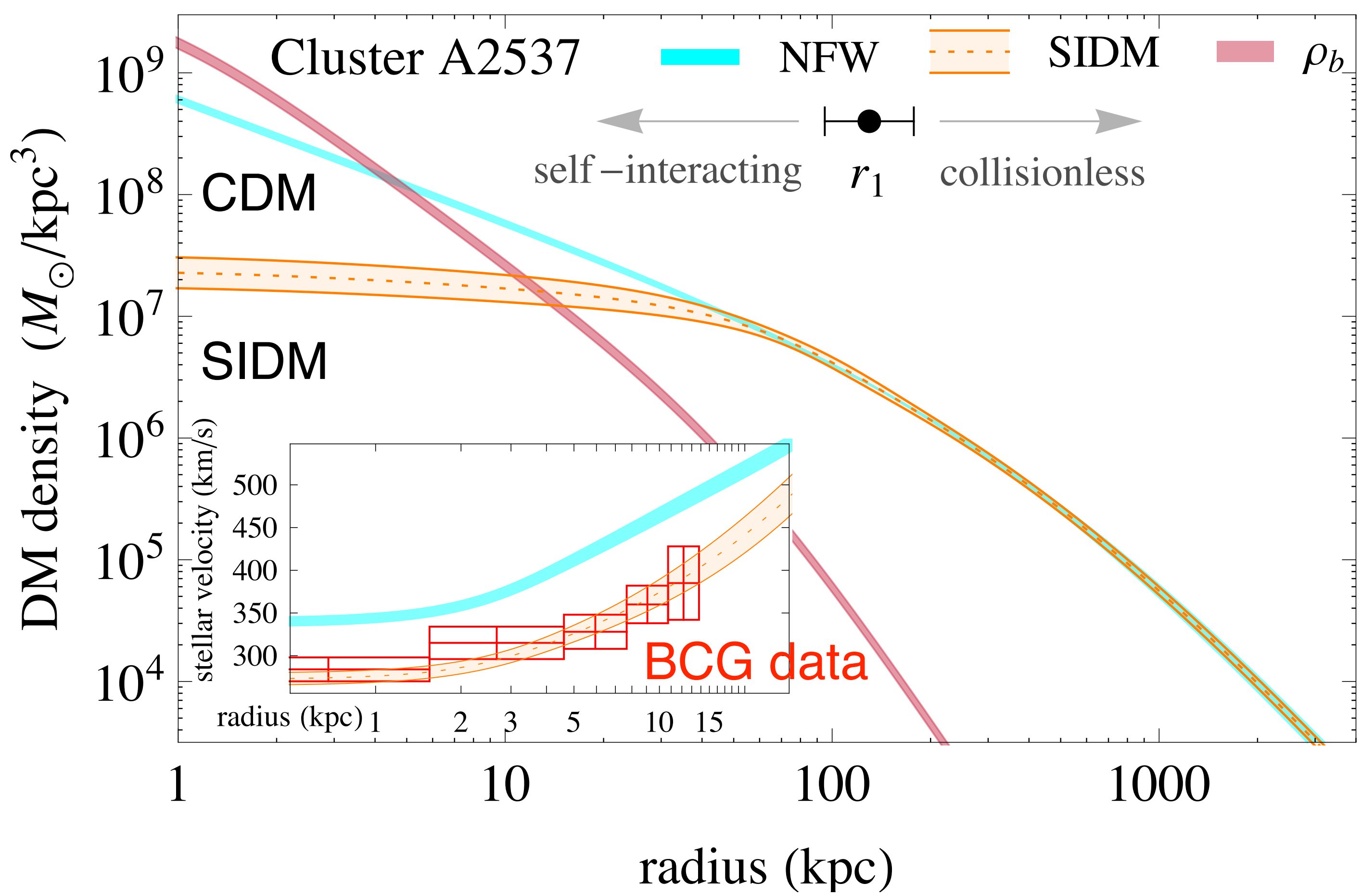
Data points

Galaxy clusters (GCs)

- mass distribution in the outer region is determined by strong/weak gravitational lensing

- stellar kinematics in the central region (brightest cluster galaxies) prefer cored SIDM profile





$$\sigma/m \sim 0.1\,\mathrm{cm}^2/\mathrm{g}$$

$$\langle v_{\mathrm{rel}} \rangle \sim 10^3\,\mathrm{km/s}$$

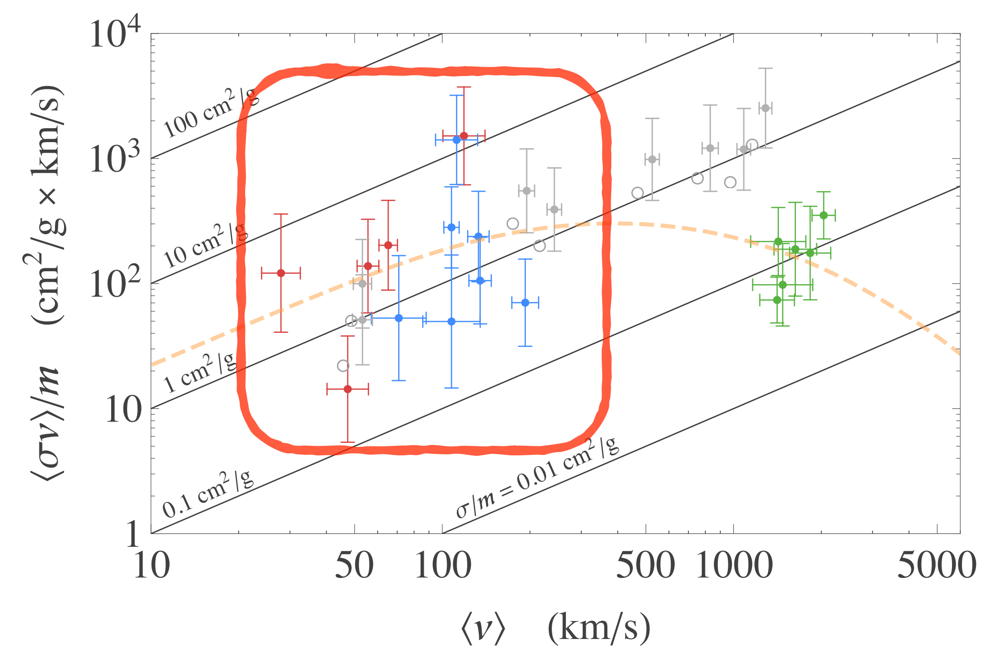
Kaplinghat, Tulin, and Yu, PRL, 2016

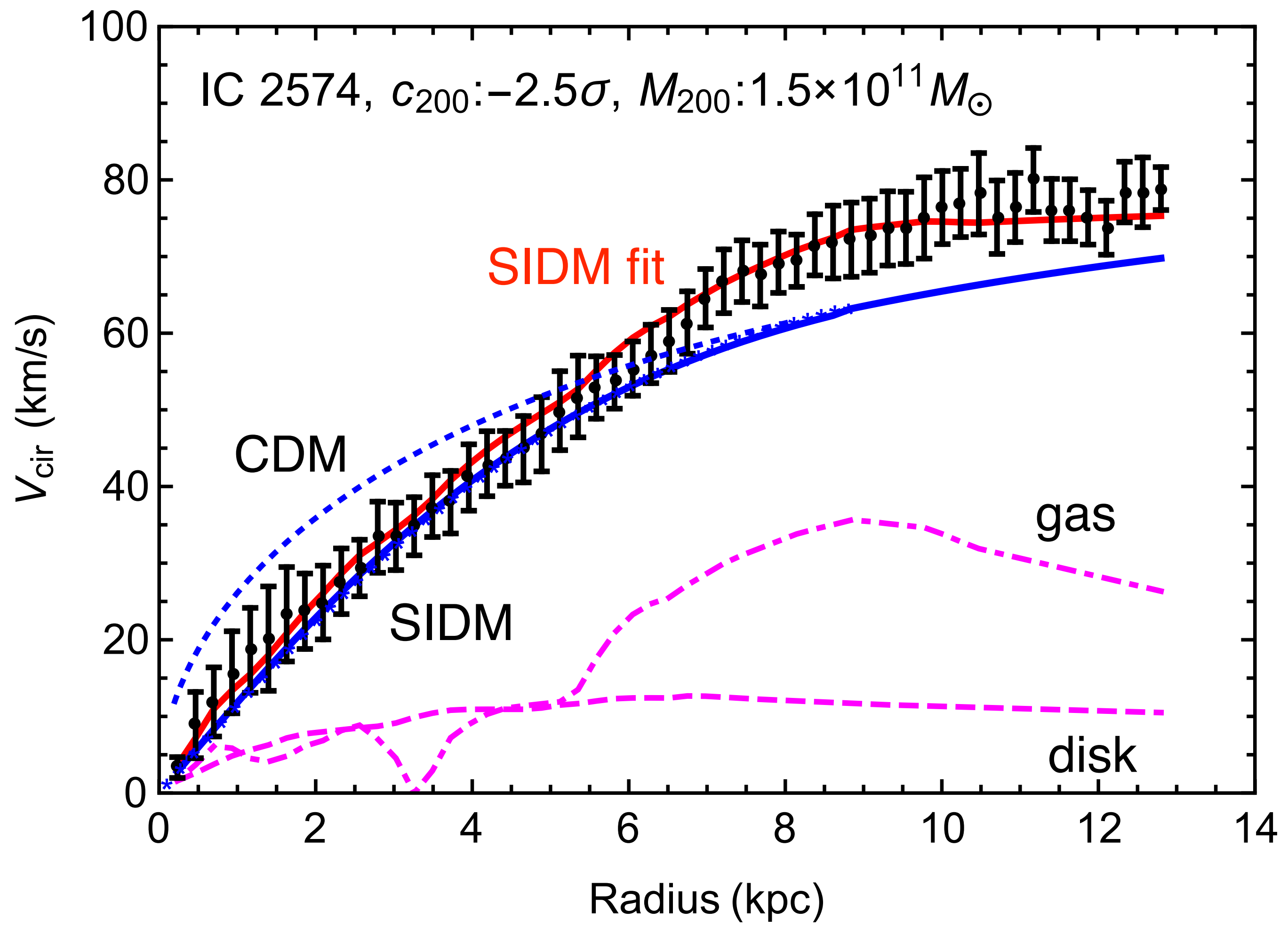
Data points

Dwarf spiral galaxies

- mass distribution is broadly determined by rotation curves

- rotation velocity in central region (of some galaxies) prefer cored SIDM profile





$$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

$$\langle v_{\rm rel}\rangle \sim 10^2\,\mathrm{km/s}$$

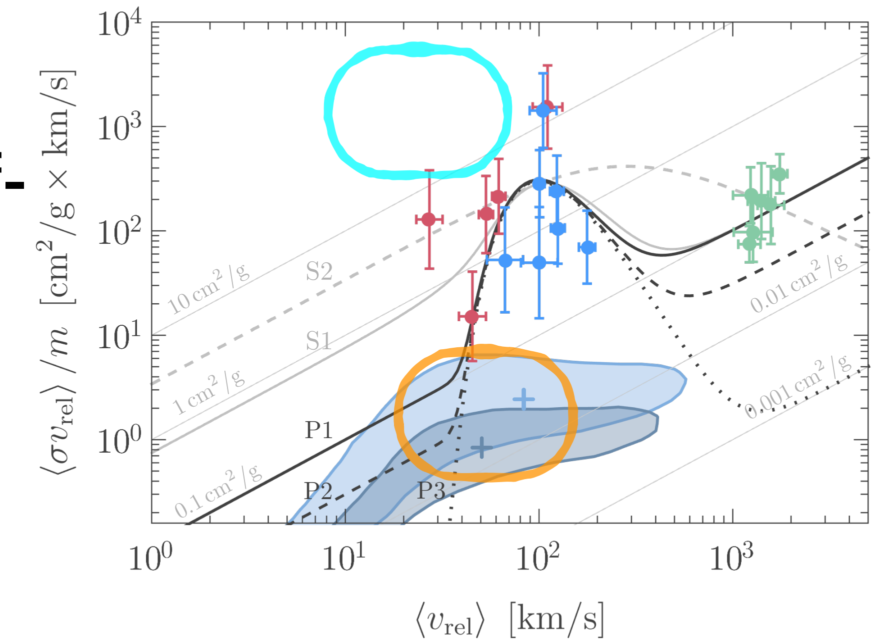
AK, Kaplinghat, Pace, and Yu, PRL, 2017

Data points

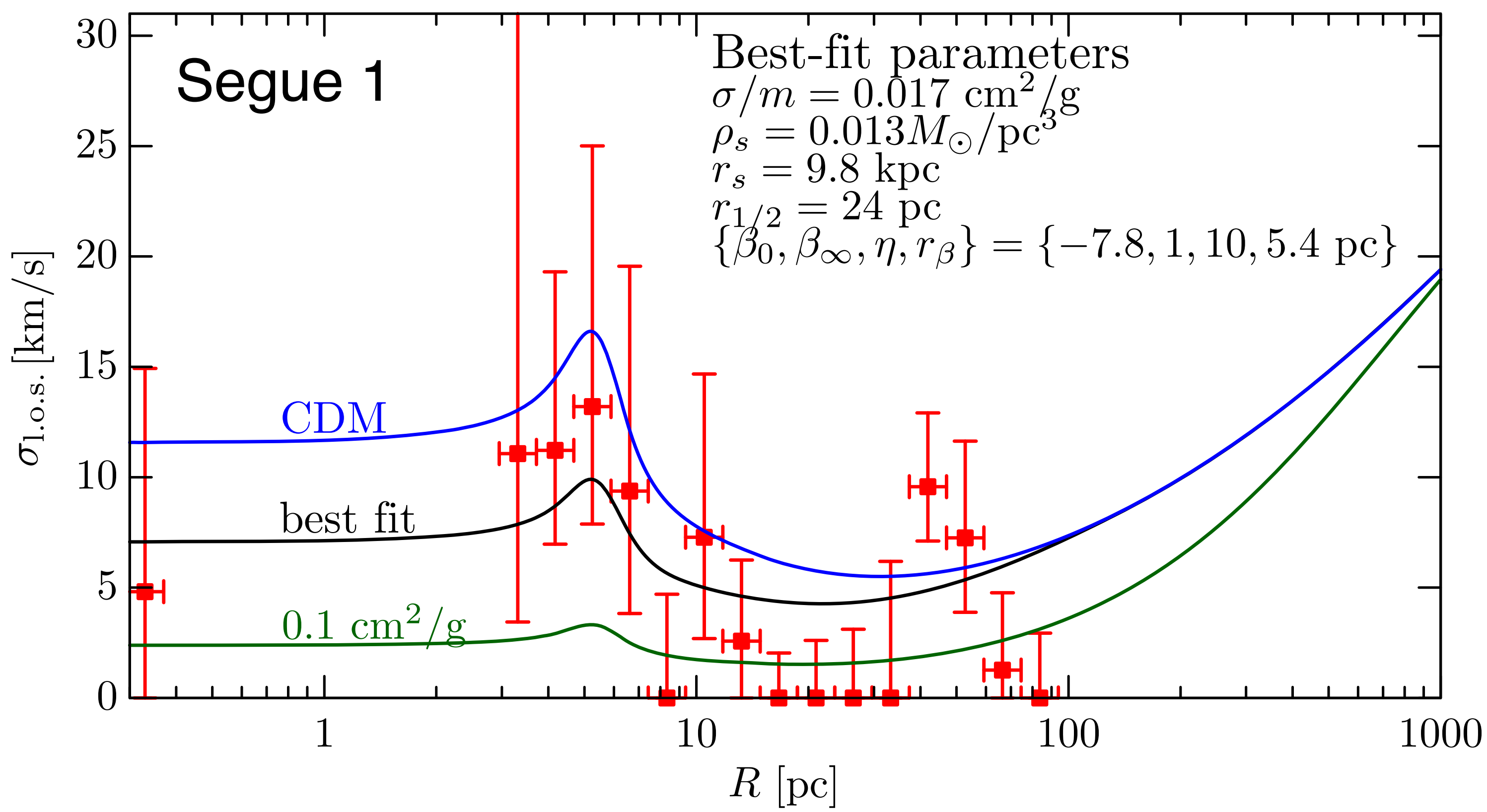
Ultra faint dwarf (UFD) galaxies

- mass distribution is determined by line-of-sight velocity dispersion (LOSVD) profile

- LOSVD in the central region (of some UFDs) prefer cuspy CDM profile



Hayashi *et al.*, PRD, 2021



$\sigma/m < 0.1\,{\rm cm}^2/{\rm g}$

$\langle v_{\rm rel} \rangle \sim 30\,{\rm km/s}$

- gravothermal collapse?

Correa, MNRAS, 2021

Diversity in MW satellites

***EUREKA

銀河のダークハロー構造の多様性：
銀河系矮小楕円体銀河の観点から

林　　航平
〈東北大学大学院理学研究科天文学専攻　〒980–8578 仙台市青葉区荒巻字青葉 6–3〉
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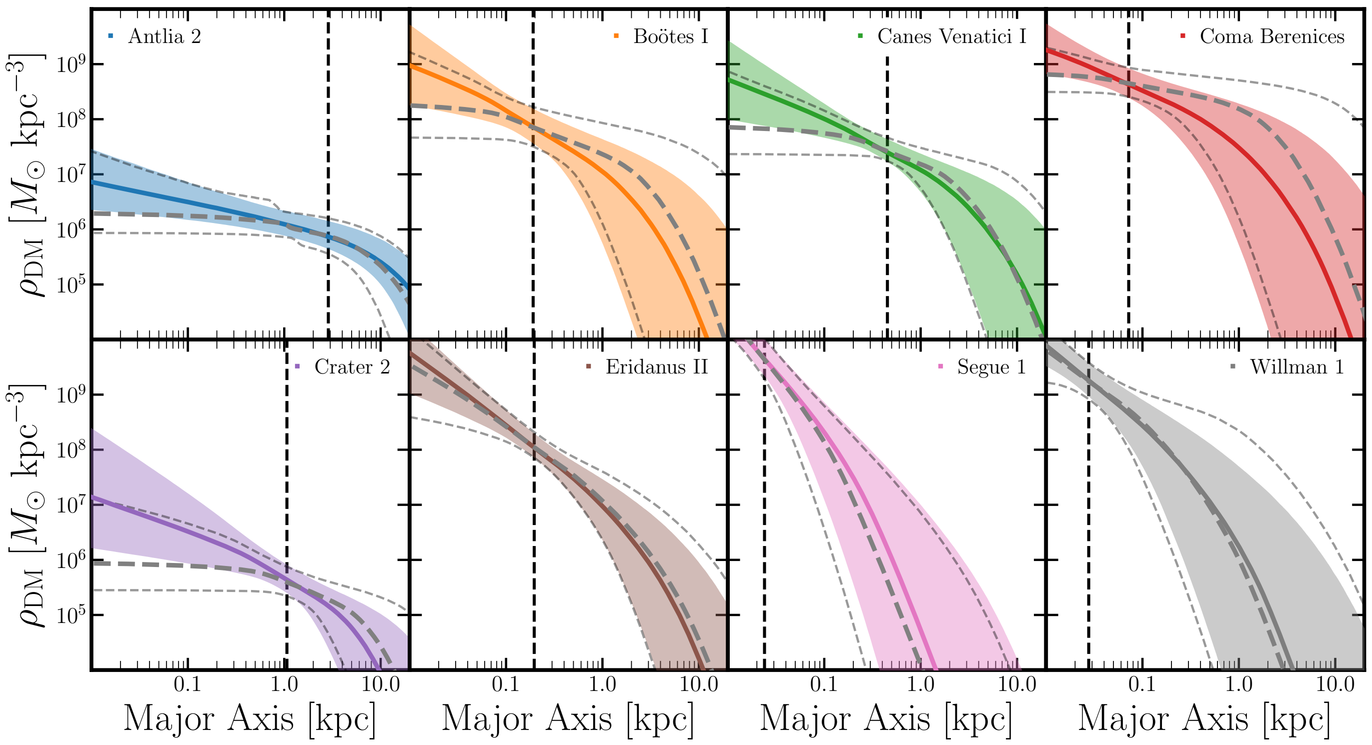
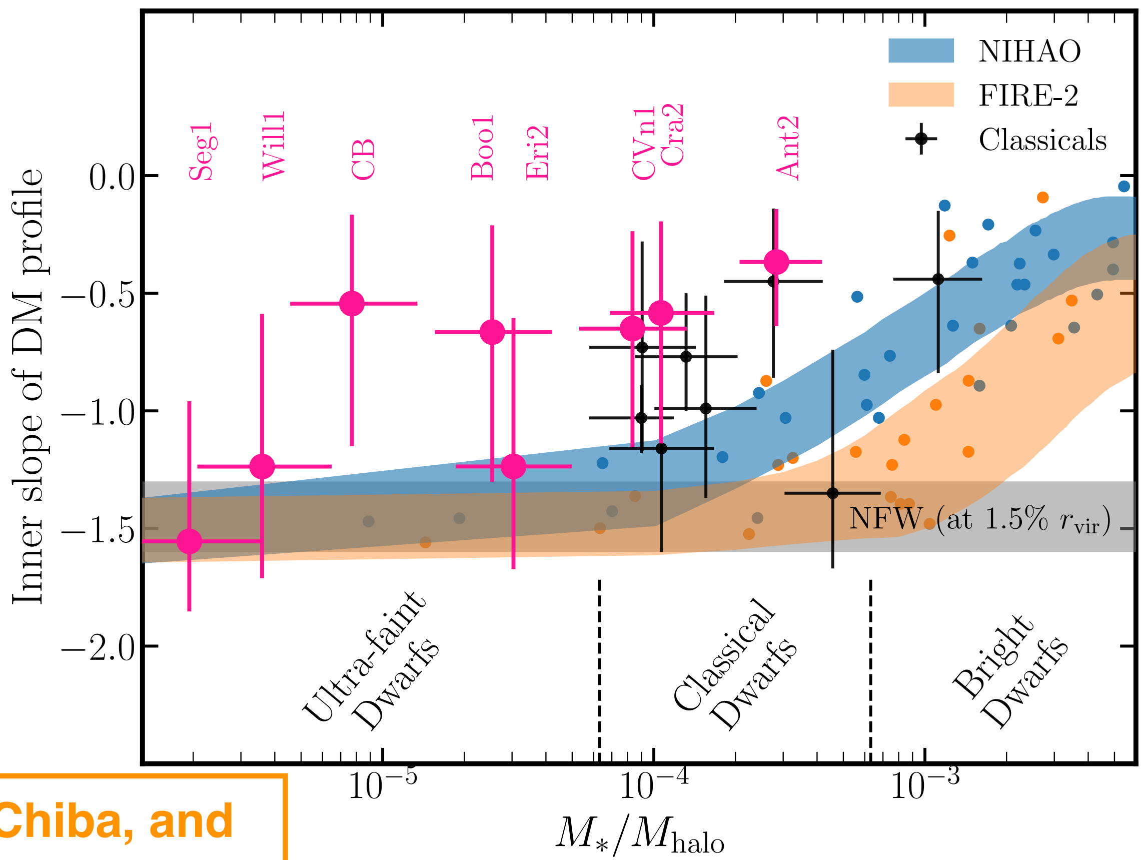
MW satellites (ultra-faint)





Hayashi, Hirai, Chiba, and Ishiyama, ApJ, 2023

Resonant enhancement

Maximally self-interacting dark matter

- s -wave Unitarity

$$\sigma^{\rm el} = \sigma^{\rm el,max}_{\ell=0} = \frac{16\pi}{m^2 v_{\rm rel}^2}$$

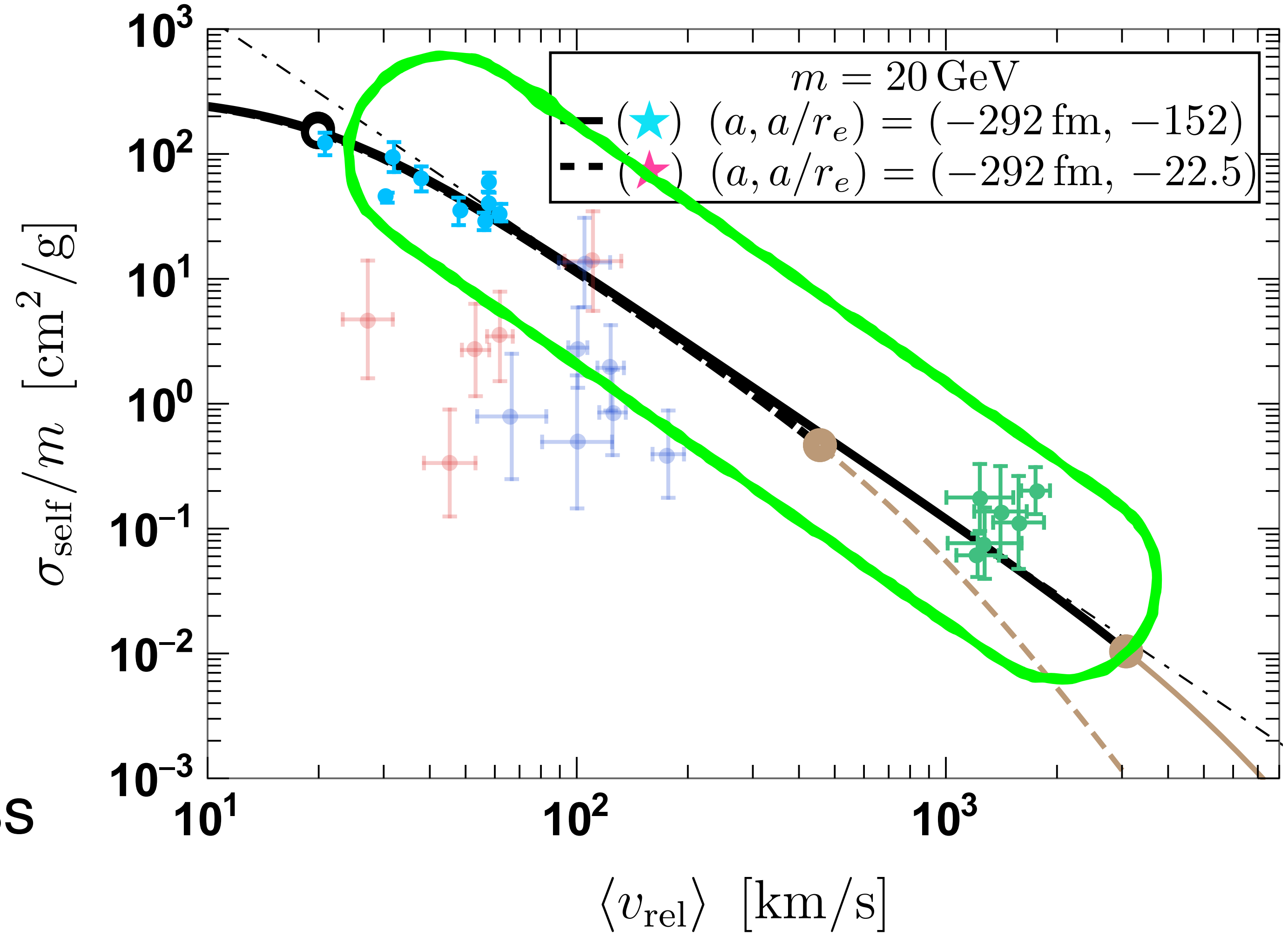
- comparison with “data”

  - $\sigma^{\rm el,max}_{\ell} \propto 1/v_{\rm rel}^2$ is in good agreement with data

  - depends solely on DM mass

    $m \simeq 20\,{\rm GeV}$

  - large $|a/r_{\rm e}|$ in effective range theory



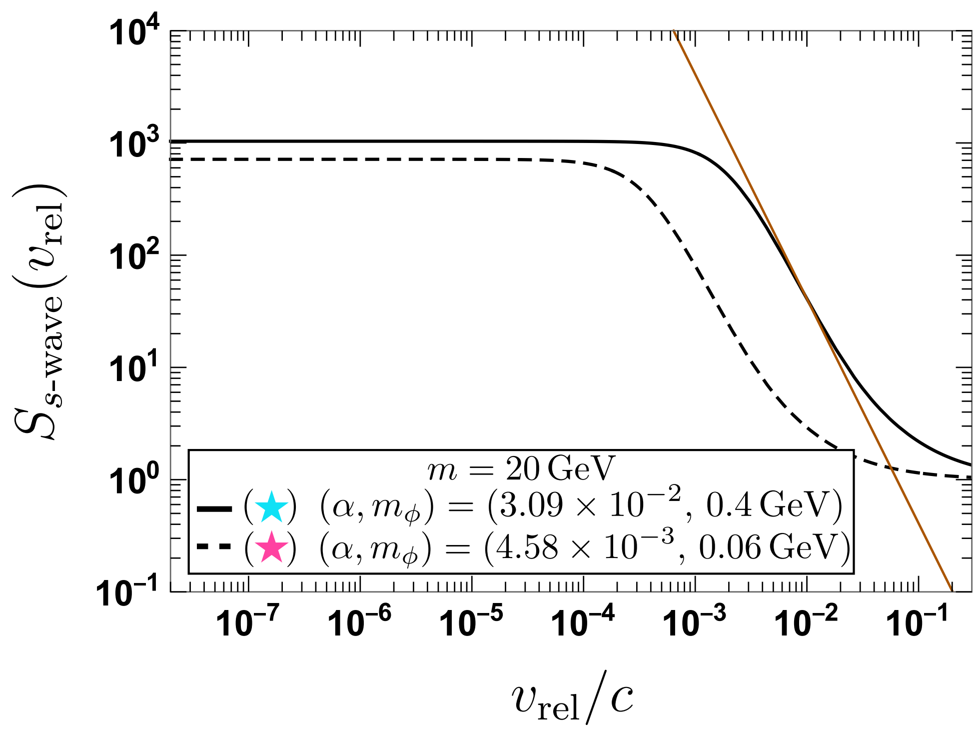
AK, Kim, and Kuwahara, JHEP, 2020

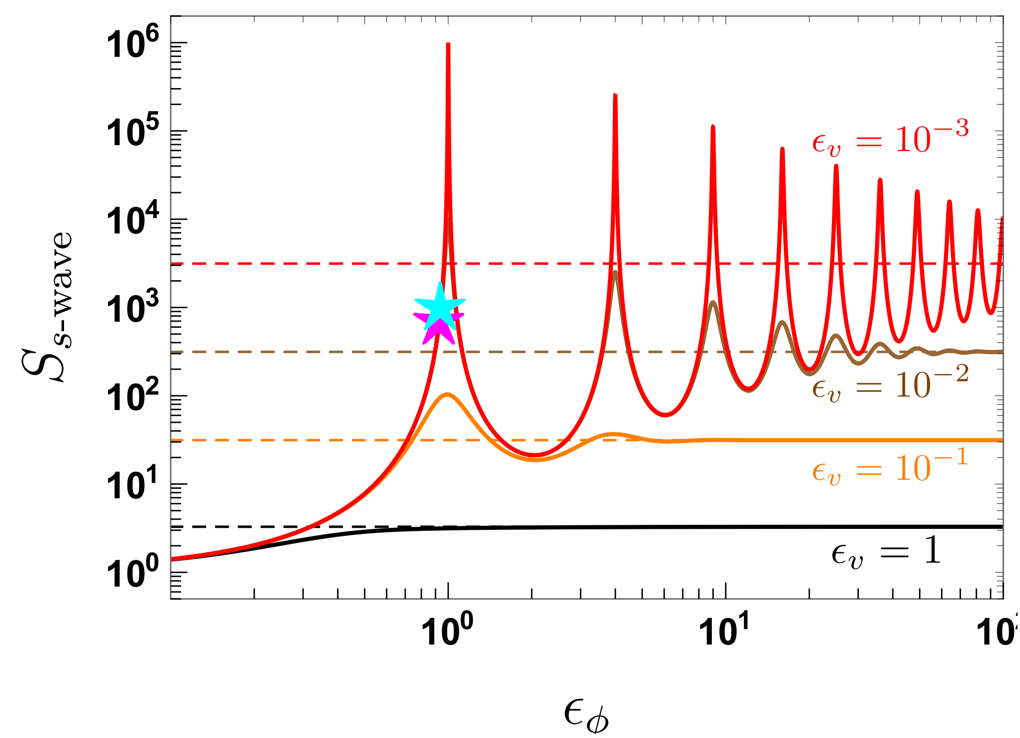
Maximally SIDM

Annihilation (Sommerfeld enhancement)

- almost zero-energy virtual level/bound state also enhances annihilation

$$(\sigma_{\rm ann} v_{\rm rel})_{\rm w/potential} = S(\sigma_{\rm ann} v_{\rm rel})_{\rm w/o}$$



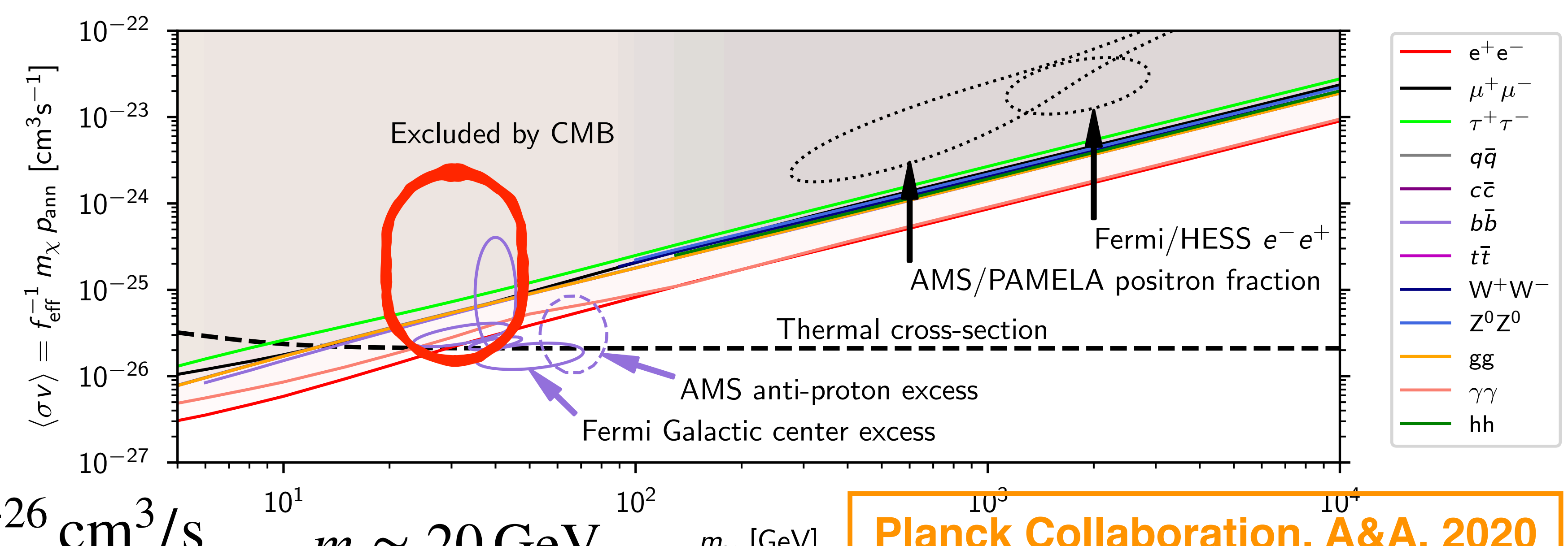


$$\epsilon_v = \frac{v_{\rm rel}}{2\alpha}$$

$$\epsilon_\phi = \frac{\alpha m}{\delta}$$

$$\delta = \zeta(2) m_\phi$$

- cosmological constraint is crucial for s-wave freeze-out DM



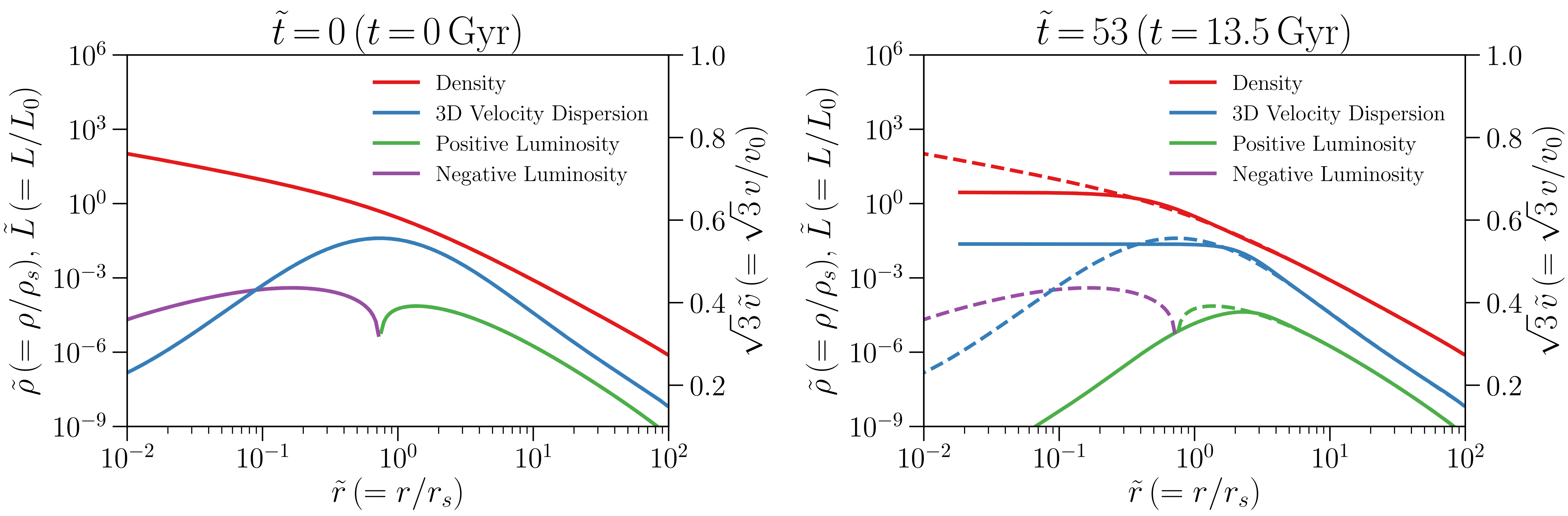
$(\sigma_{\rm ann} v_{\rm rel})_{\rm w/o} \simeq 3 \times 10^{-26}\,{\rm cm}^3/{\rm s}$ $\quad m \simeq 20\,{\rm GeV}$

Planck Collaboration, A&A, 2020

SIDM halo evolution

Core formation

- core expansion lasts till the temperature profile gets flat (thermalization)



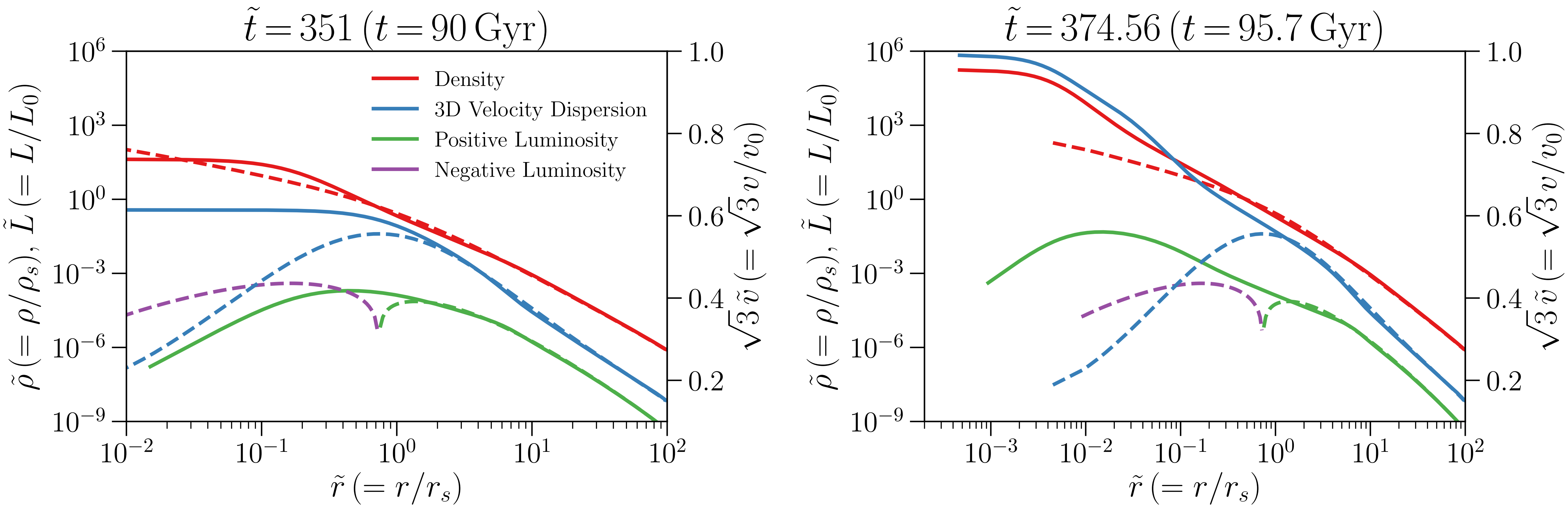
Nishikawa, Boddy, and Kaplinghat, PRD, 2020

SIDM halo evolution SIDM

Core collapse

- core collapse proceeds by depositing heat to the outer region

  - heat deposit → lower energy but higher temperature (negative heat capacity)



Nishikawa, Boddy, and Kaplinghat, PRD, 2020

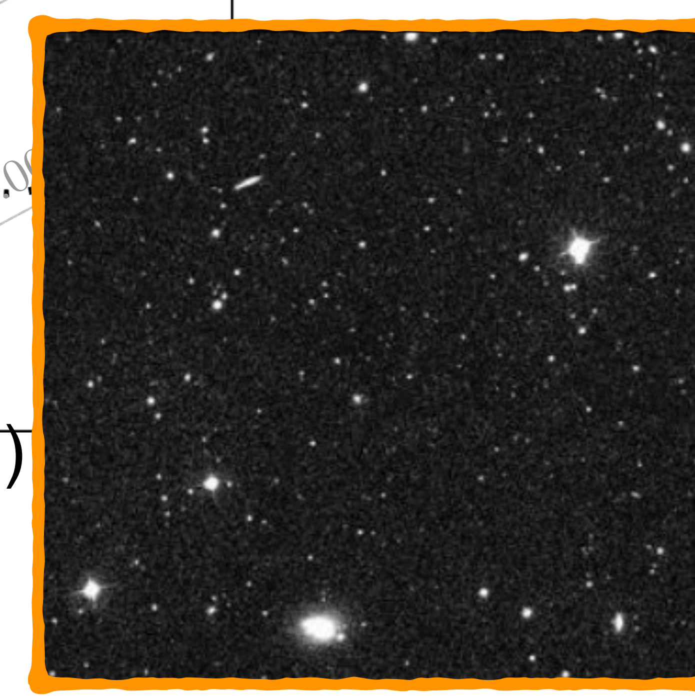
“Data” points

Overview

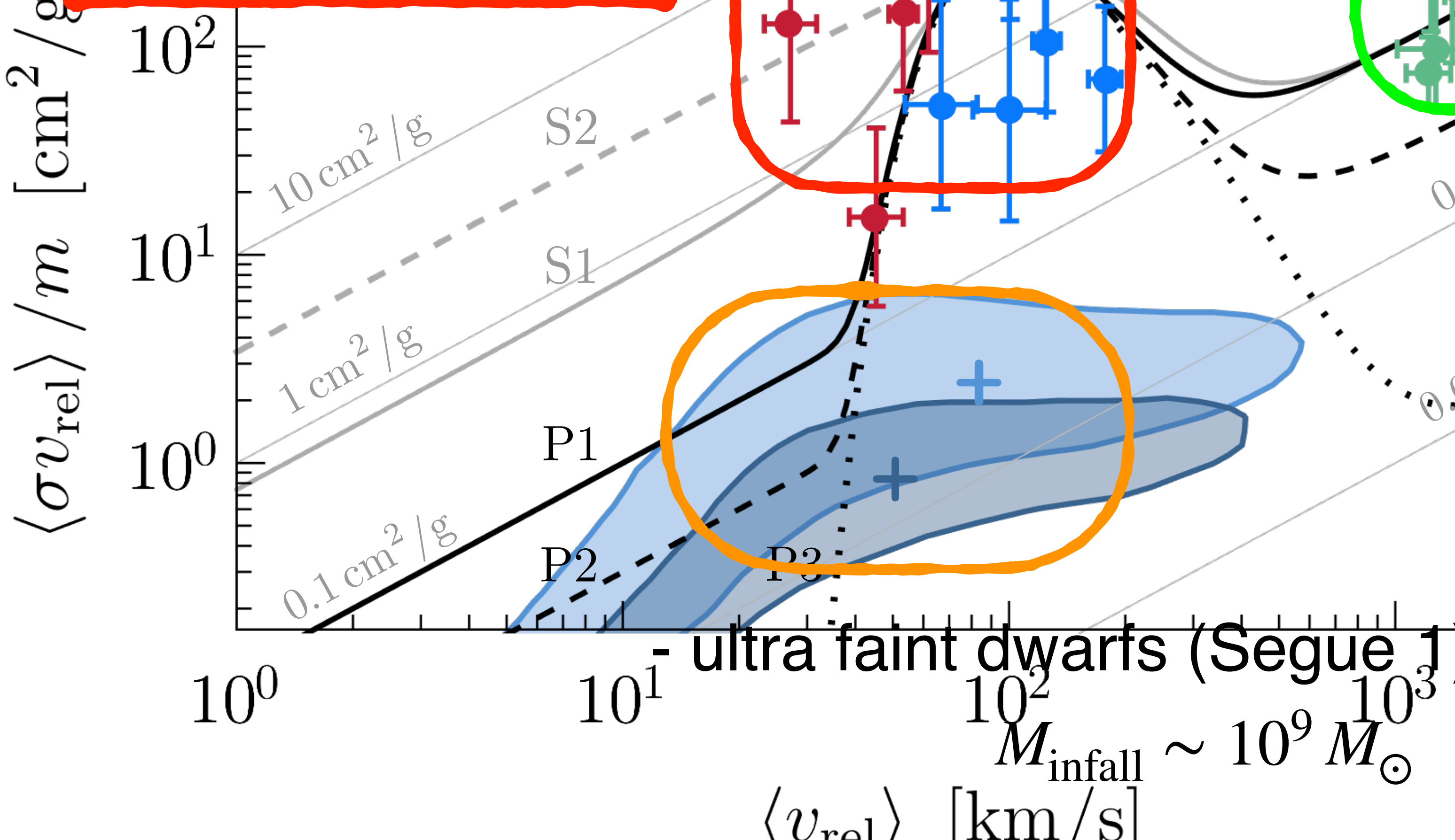
- cores in various-size halos may prefer sharp velocity dependence of self-scattering cross section

- dwarf spiral galaxy (IC 2574) $M \sim 10^{11}\, M_\odot$

- galaxy cluster (Abell 2744) $M \sim 10^{14}\, M_\odot$



- ultra faint dwarfs (Segue 1) $M_{\rm infall} \sim 10^{9}\, M_\odot$



Possible explanations

Resonant SIDM

Chu, Garcia-Cely, and Murayama, PRL, 2019

- resonance + constant offset

$$\frac{\sigma}{m} = \frac{4\pi S}{m^2 E(v_{\rm rel})} \frac{\Gamma(v_{\rm rel})^2/4}{[E(v_{\rm rel}) - E(v_R)]^2 + \Gamma(v_{\rm rel})^2/4} + \frac{\sigma_0}{m}$$

$$S = (2s_R + 1)/(2s_{\rm dm} + 1)^2$$

$$E(v_{\rm rel}) = (m/2)v_{\rm rel}^2/2$$

$$E(v_R) = m_R - 2m$$

$$\Gamma(v_{\rm rel}) = m_R \gamma^2 v_{\rm rel}^{2\ell+1}$$

- running width

- thermal average

$$f(v_{\rm rel};\nu) = \frac{v_{\rm rel}^2}{\sqrt{4\pi\nu^3}} \exp\left(-\frac{v_{\rm rel}^2}{4\nu^2}\right)$$

$$\langle v_{\rm rel}\rangle = (4/\sqrt{\pi})\nu$$

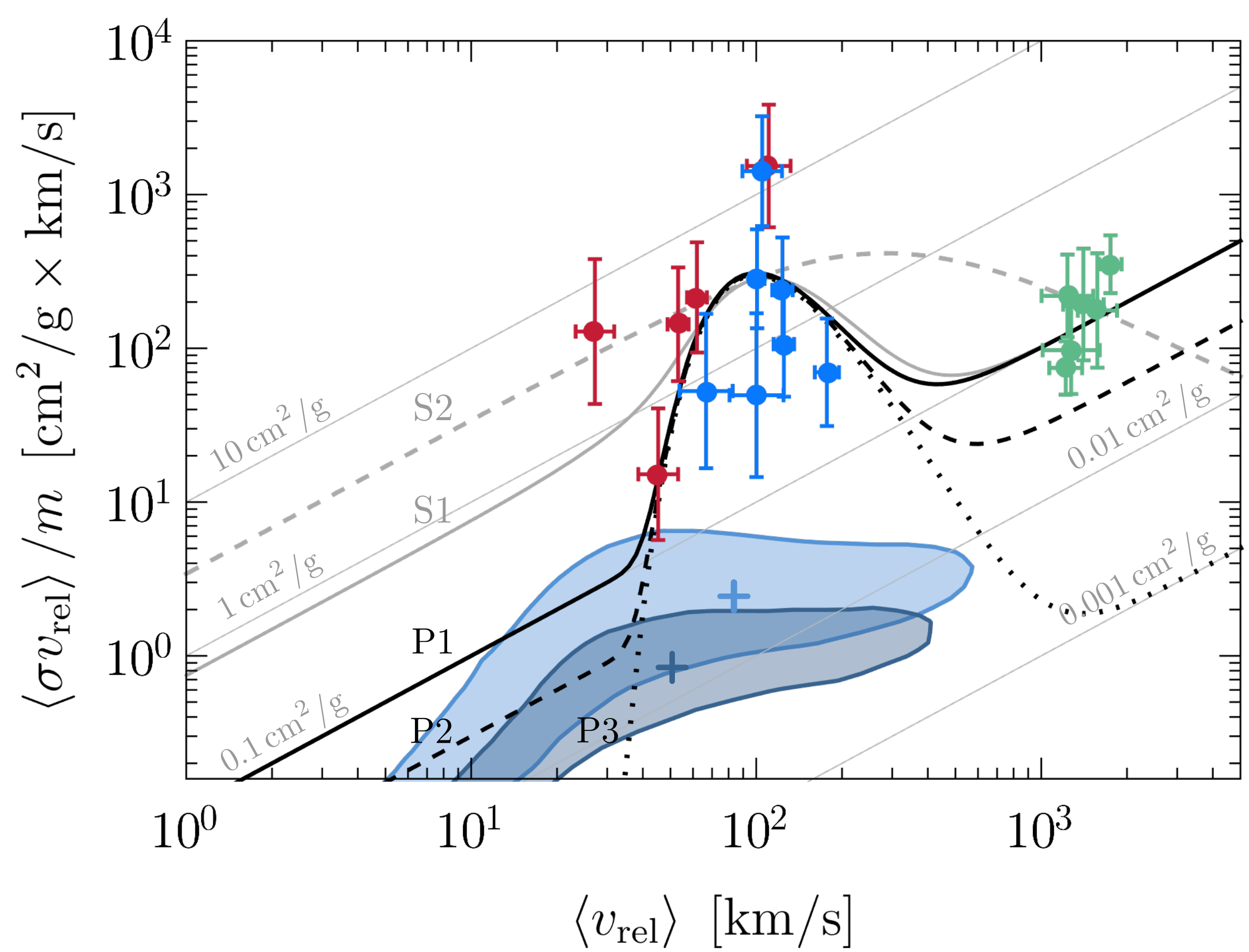
- s-wave benchmarks
  - S1 and S2

$$\gamma = 10^{-4.5}, 10^{-1.1}$$

$$v_R = 120\,{\rm km/s}, 5035\,{\rm km/s}$$

$$m/S^{1/3} = 22\,{\rm GeV}, 16\,{\rm GeV}$$

$$\sigma_0/m = 0.1\,{\rm cm^2/g}, \ll 0.1\,{\rm cm^2/g}$$



Possible explanation

Resonant SIDM

- s-wave benchmarks

  - S1 and S2 do not satisfy the UFD constraints

  - one need to take $\gamma \lesssim 10^{-7}(m/\mathrm{GeV})^{3/2}[v_R/(100\,\mathrm{km/s})]^2$ for s-wave

- p-wave benchmarks

  - P1, P2 and P3

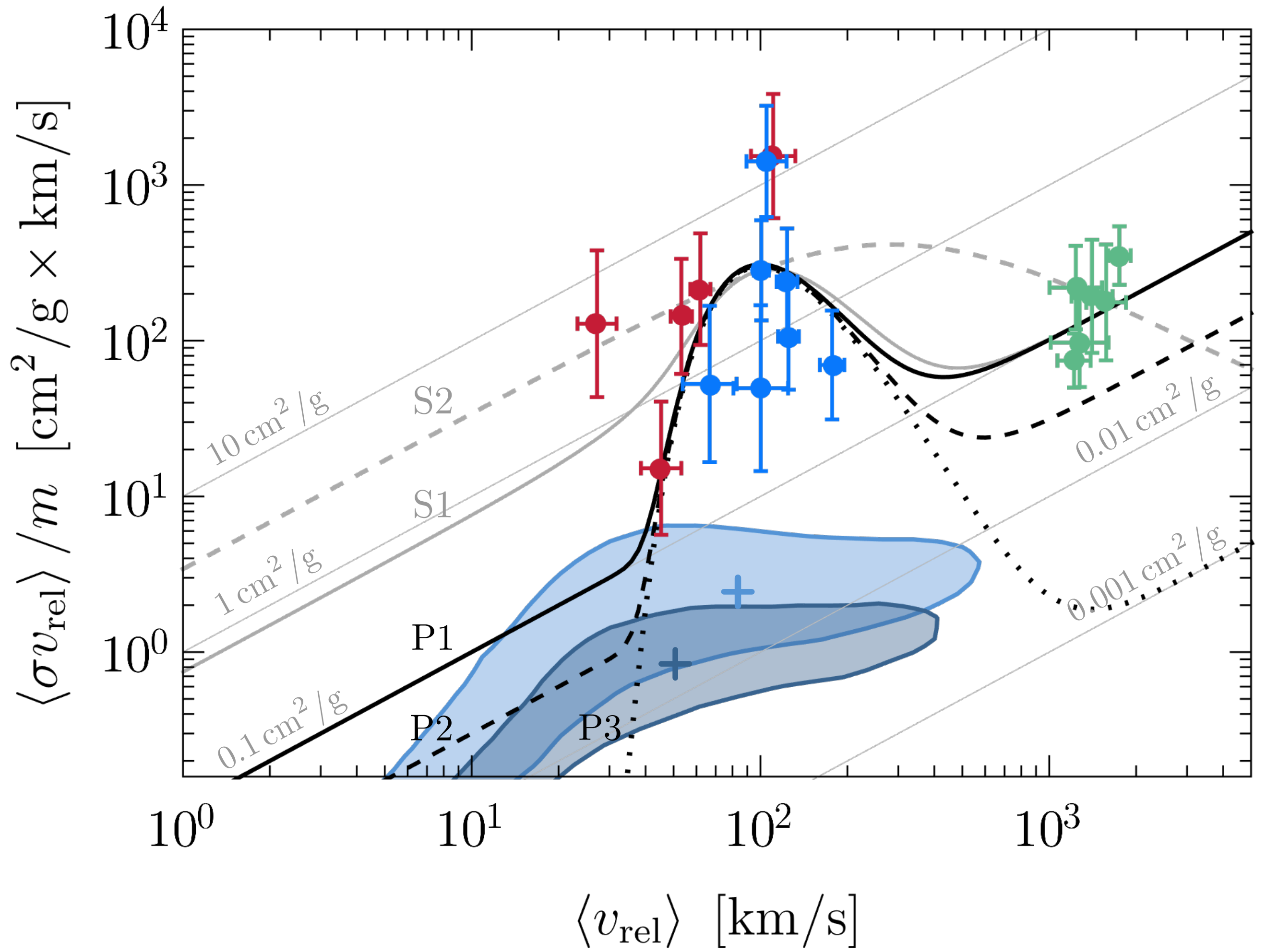
$$\gamma = 10^{-3} \qquad v_R = 108\,\mathrm{km/s}$$

$$m/S^{1/3} = 0.4\,\mathrm{GeV}$$

$$\sigma_0/m = 0.1\,\mathrm{cm^2/g}, 0.03\,\mathrm{cm^2/g}$$

$$0.001\,\mathrm{cm^2/g}$$

  - consider P2 benchmark mainly in the following



Resonant SIDM

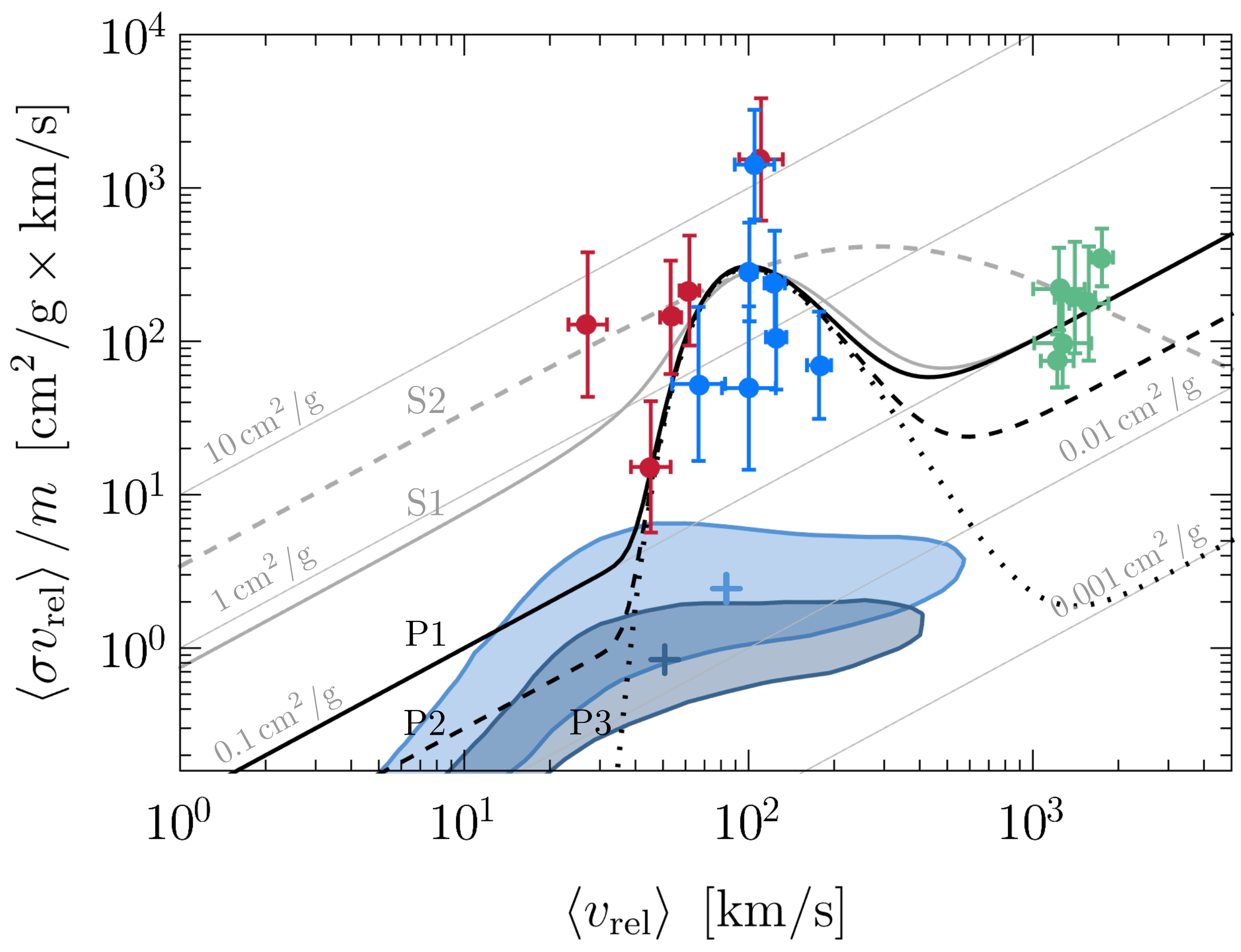
Question

- data are obtained by r1-procedure
  - switching Navarro-Frenk-White (NFW) profile to isotherm profile inside r1
  - assuming efficient heat conduction inside r1
  - valid for constant SIDM

$$\rho_{\mathrm{NFW}}(r_1)\frac{\langle \sigma v\rangle_{\mathrm{NFW}}(r_1)}{m}t = 1$$

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

- **Is a resonant SIDM halo similar to constant SIDM halo?**
  - mapping between resonant SIDM and constant SIDM



Evolution of resonant SIDM halos

Gravothermal modeling of isolated halo

- assuming hydrostatic equilibrium in the course of evolution

$$\frac{\partial}{\partial r}(\rho v^2) = -\rho \frac{GM}{r^2} \qquad \frac{\partial}{\partial r}M = 4\pi r^2 \rho$$

- self-scattering leads to heat conduction

$$\frac{D}{Dt}\ln\left(\frac{\nu^3}{\rho}\right) = -\frac{1}{4\pi r^2 \rho \nu^2}\frac{\partial L}{\partial r} = \frac{1}{3t_{\mathrm{cond.}}} \qquad \frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r}$$

- heat conduction timescale

- naive interpolation between LMFP and SMFP regimes

$$\kappa^{-1} = \kappa_{\mathrm{LMFP}}^{-1} + \kappa_{\mathrm{SMFP}}^{-1}$$

- SMFP $\quad \kappa_{\mathrm{SMFP}} = \frac{3}{2} b \frac{\nu}{\sigma_0 K_5(\nu)}$ $\quad b = \frac{25\sqrt{\pi}}{32} \simeq 1.38$ $\quad K_p(\nu) = \frac{\langle \sigma v_{\mathrm{rel}}^p \rangle}{\sigma_0 \langle v_{\mathrm{rel}}^p \rangle}$

Outmezguine *et al.*, MNRAS, 2023

- LMFP $\quad \kappa_{\mathrm{LMFP}} = \frac{3C}{2\pi^{3/2}} \frac{\rho \nu^3 \sigma_0 K_1(\nu)}{G m^2}$

$p = 3?$ — Outmezguine *et al.*, MNRAS, 2023

$p = 5?$ — Yang *et al.*, ApJ, 2023

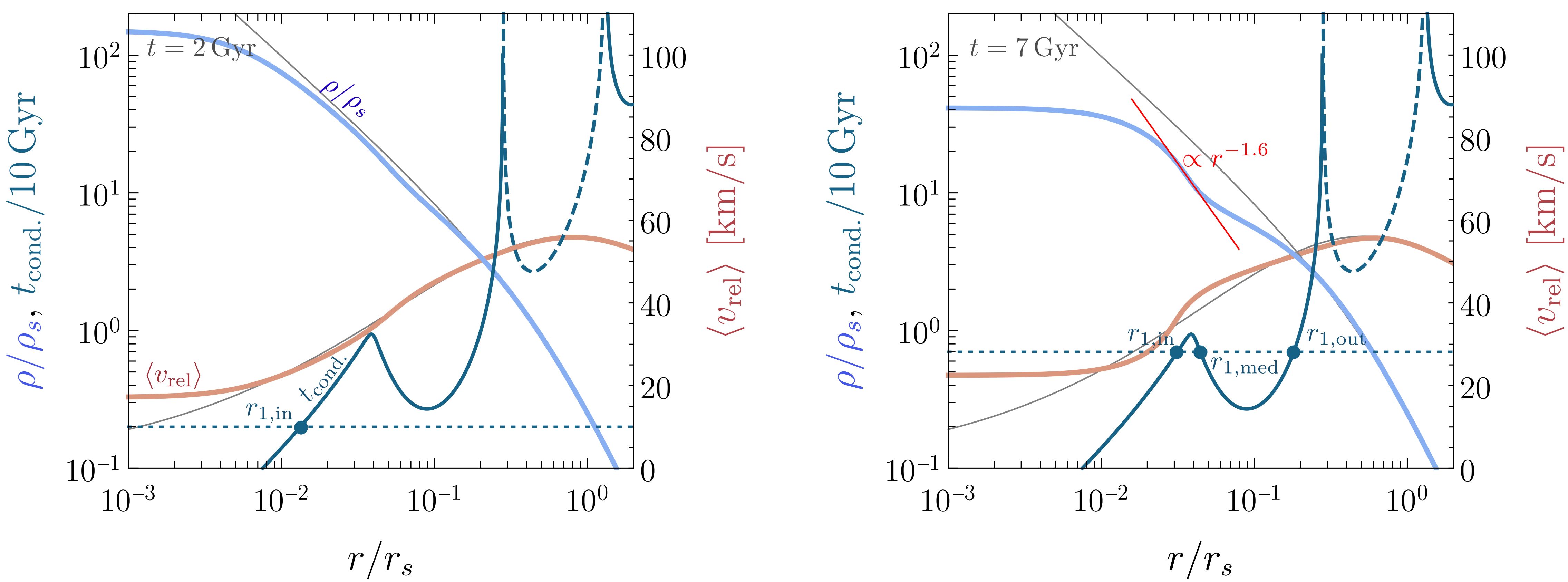
$C \simeq 0.75$ — Koda and Shapiro, MNRAS, 2011

- start with NFW profile
  - mean c-M relation

Evolution of resonant SIDM halos

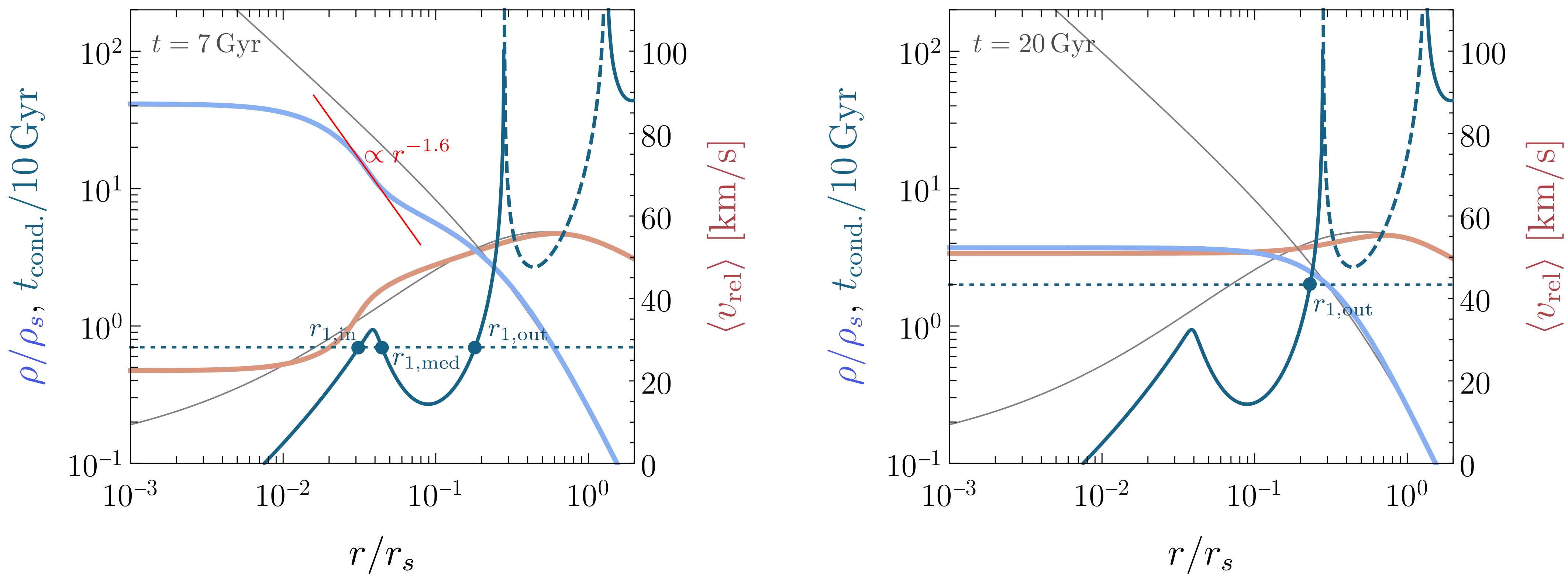
Formation of density break

- profile of heat conduction timescale has a sharp peak $r/r_s \simeq 0.1$
- three r1's appear for $t > t_{\rm break}$ $\quad t_{\rm cond.}(r_1) = t$
- two isothermal regions appear $r < r_{1,\rm in}$ $\quad r_{1,\rm med} < r < r_{1,\rm out}$
- density break forms to connect the two isothermal regions



- $M_{200} = 8 \times 10^9\, M_\odot$

Evolution of resonant SIDM halos

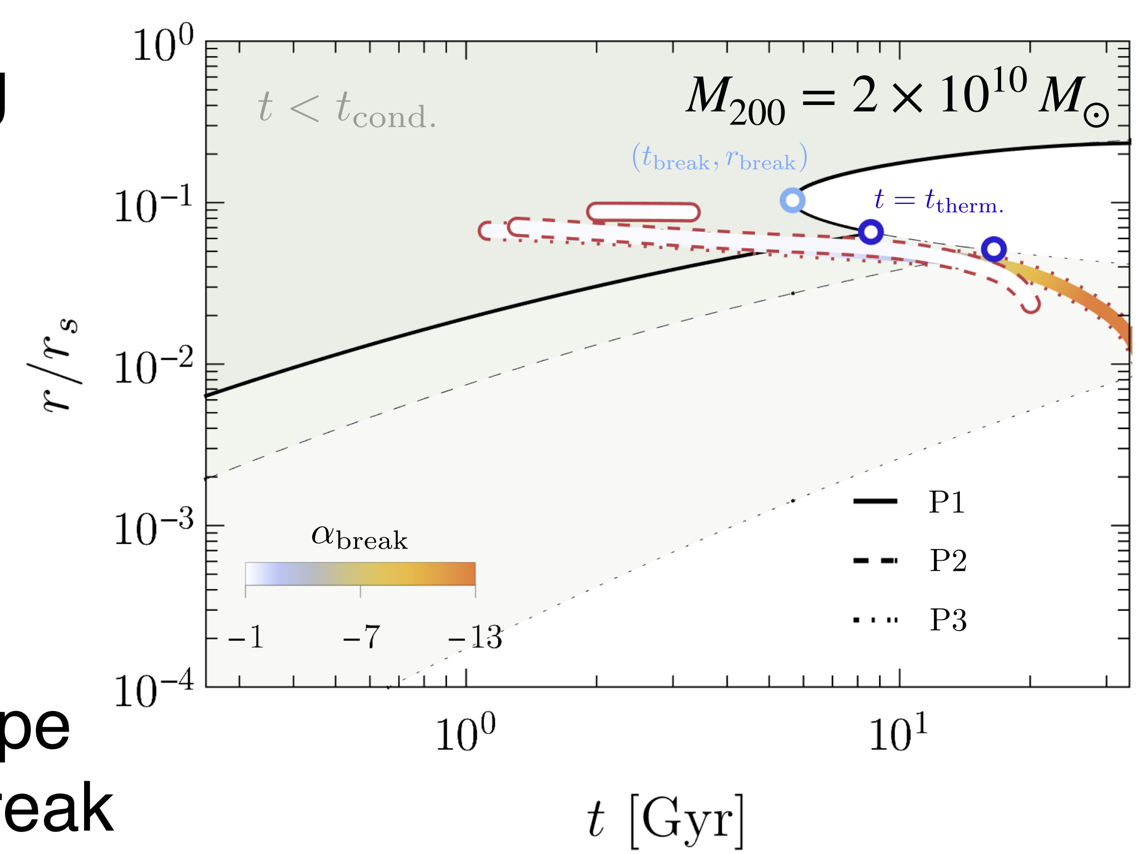


Development and thermalization of density break

- propagates inwards, while expanding the outer isothermal region

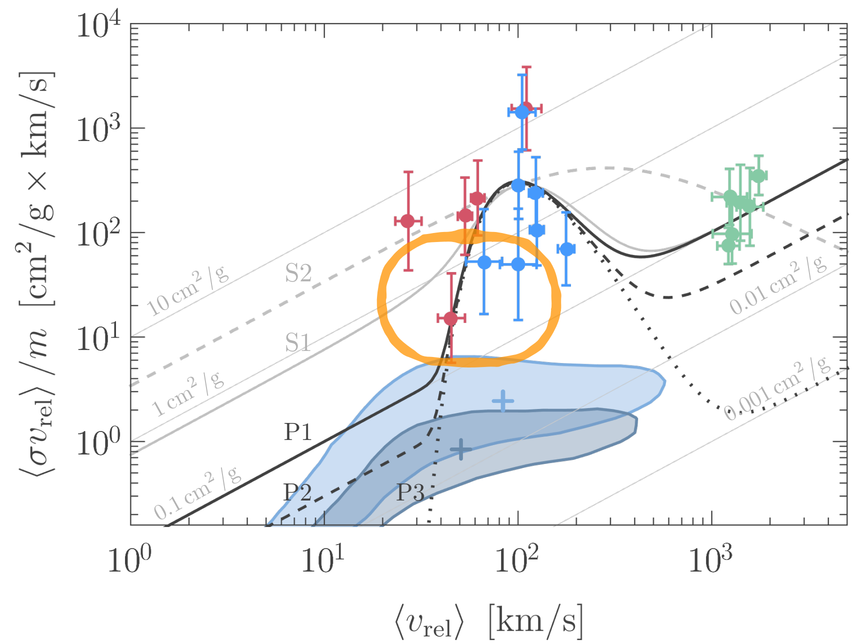
- during propagation, slope of density break gets sharper

- reaches the inner isothermal region and is thermalized to disappear



- position of steepest slope defines that of density break

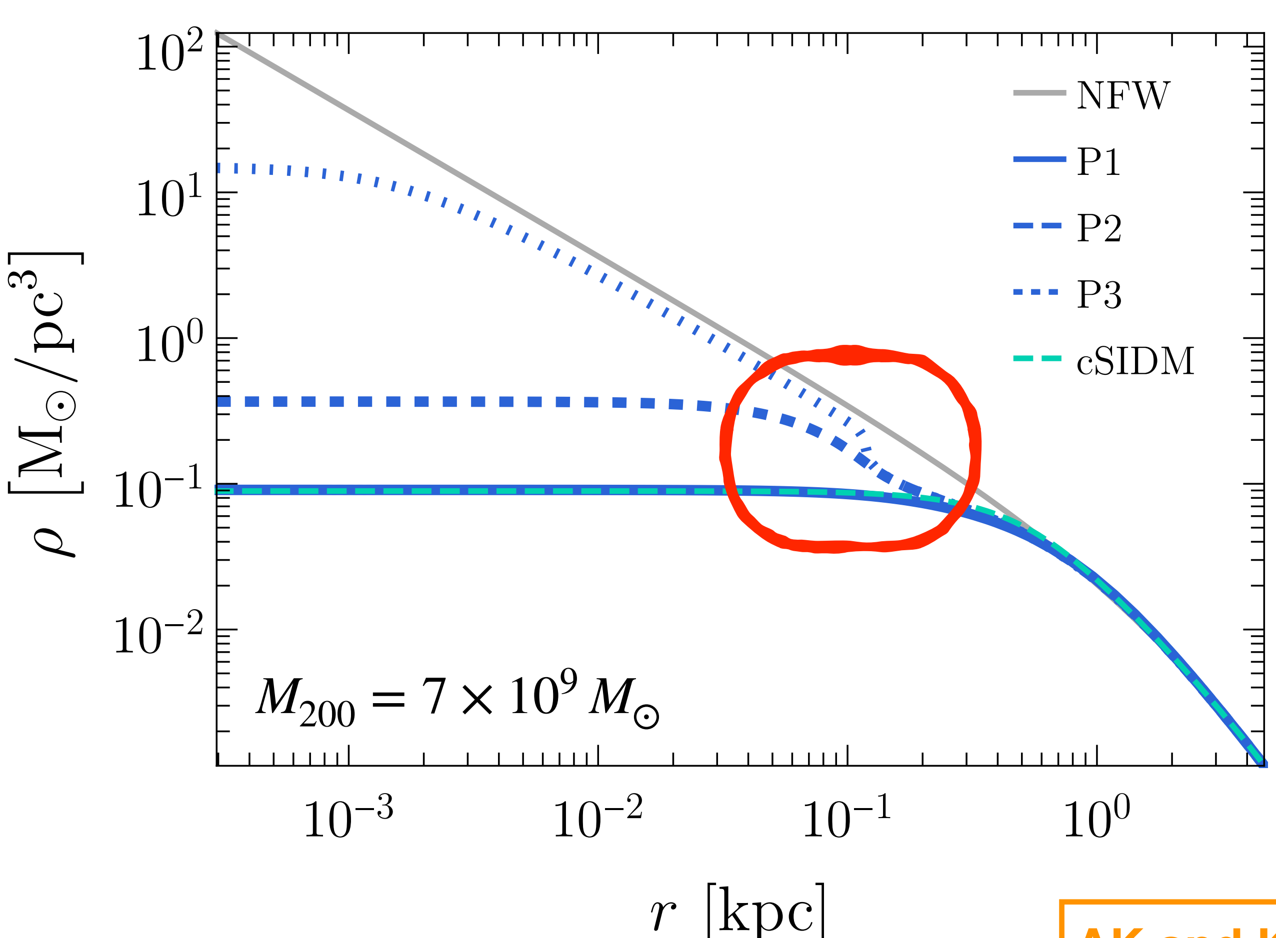
Resonant SIDM

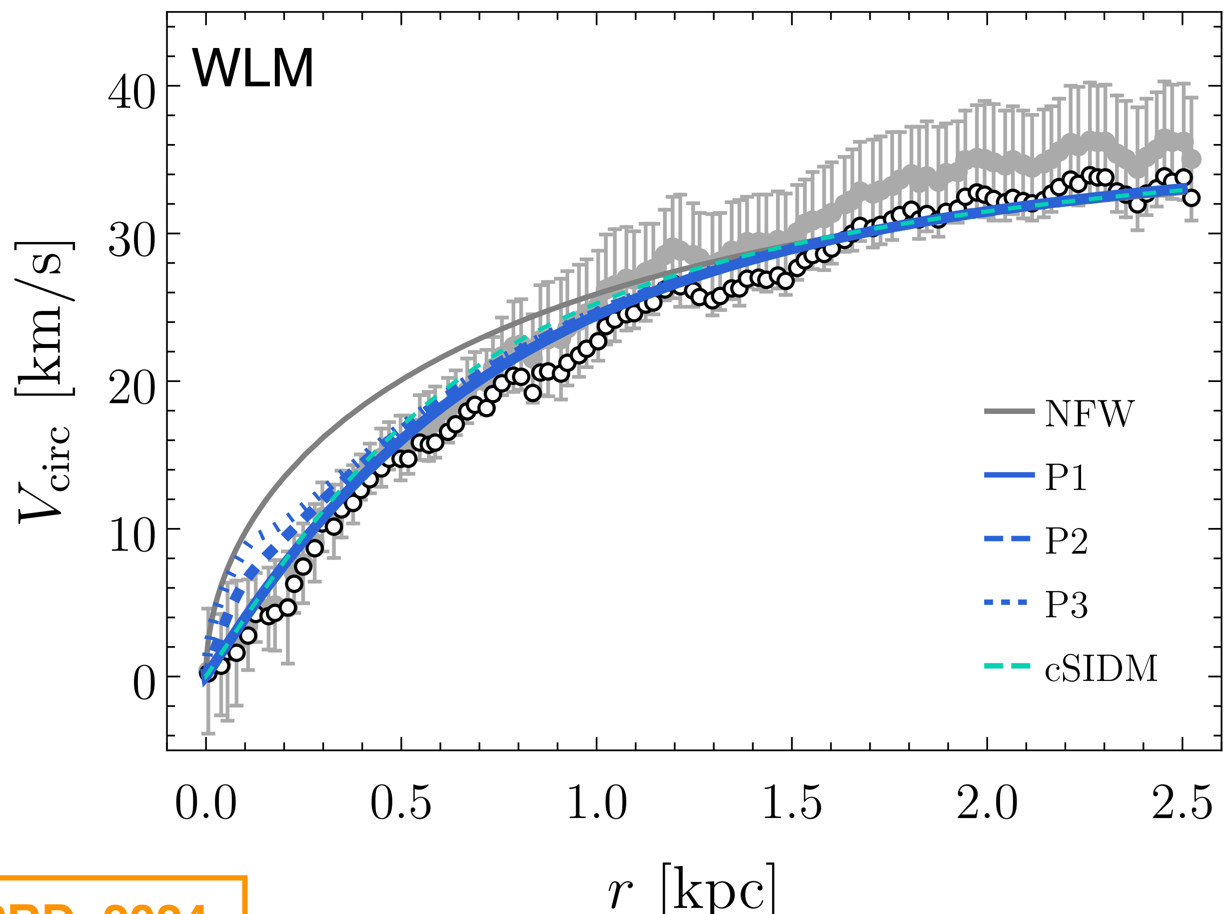


Density break

- formation, development and thermalization of density break in Resonant SIDM halo

- P3 benchmark halo has a circular velocity profile transiting from constant SIDM to NFW around 0.1 kpc
    - may be a distinctive signature if observed by any chance





AK and Kim, PRD, 2024

Evolution of resonant SIDM halos

Benchmark / halo-size dependence

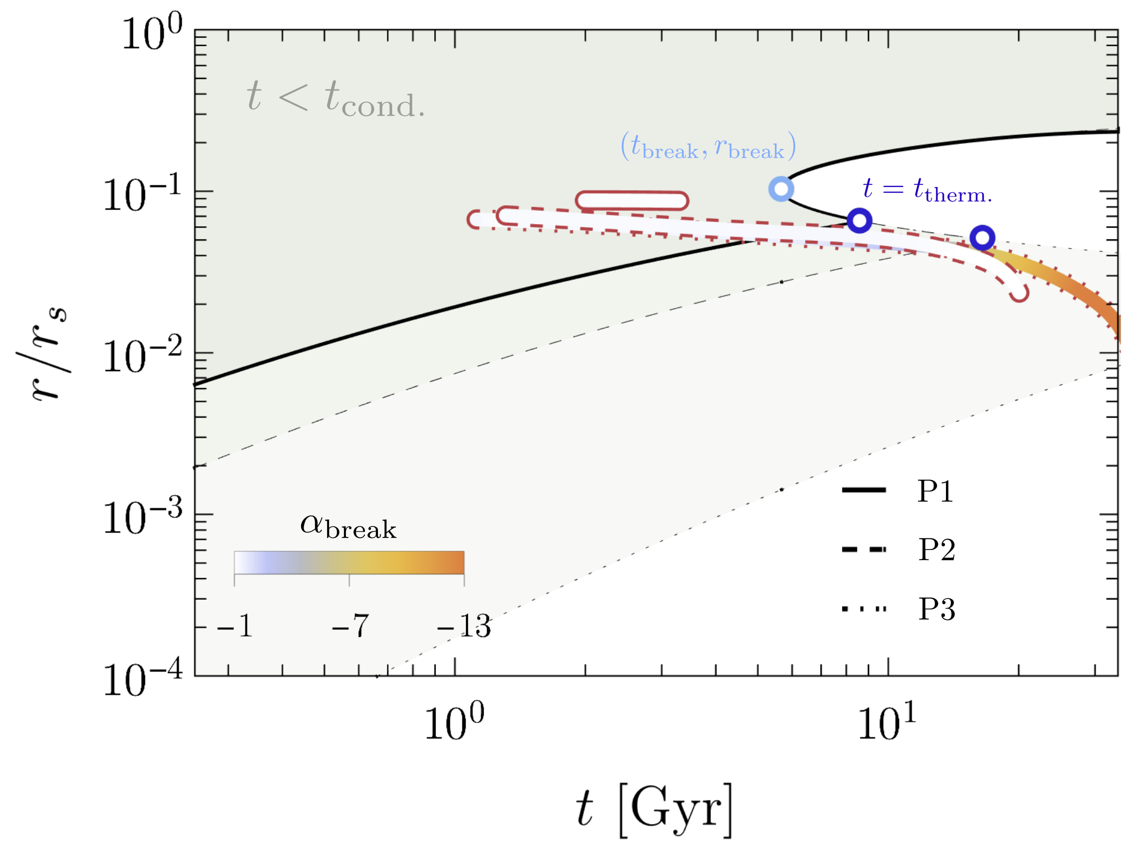
- density break propagates longer till thermalization and develops further, for larger separation between $r_{1,\text{in}}$ and $r_{1,\text{med}}$ at $t = t_{\text{break}}$

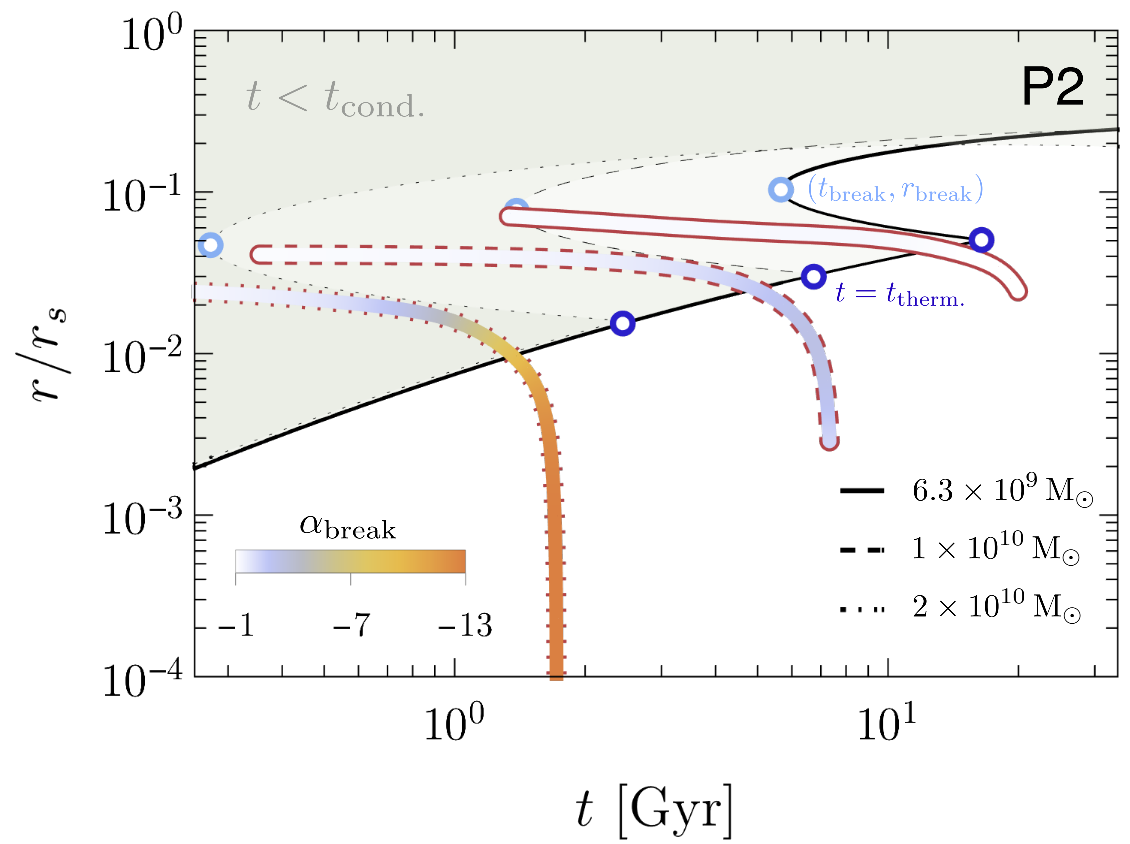
- smaller offset cross section (P3)

  - smaller $r_{1,\text{in}}$ $t = t_{\text{break}}$

- larger halos

  - earlier formation (smaller t_{break})

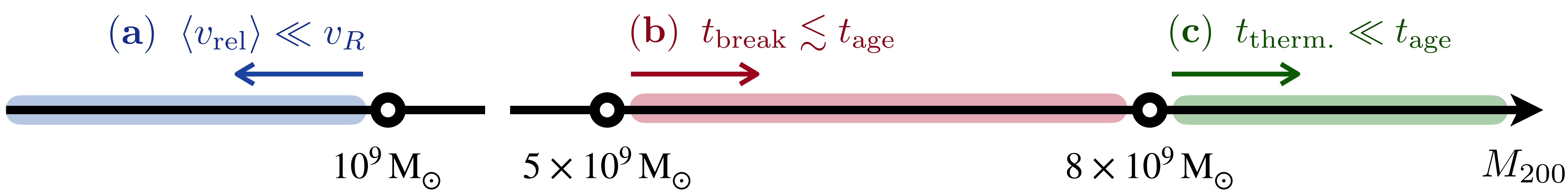


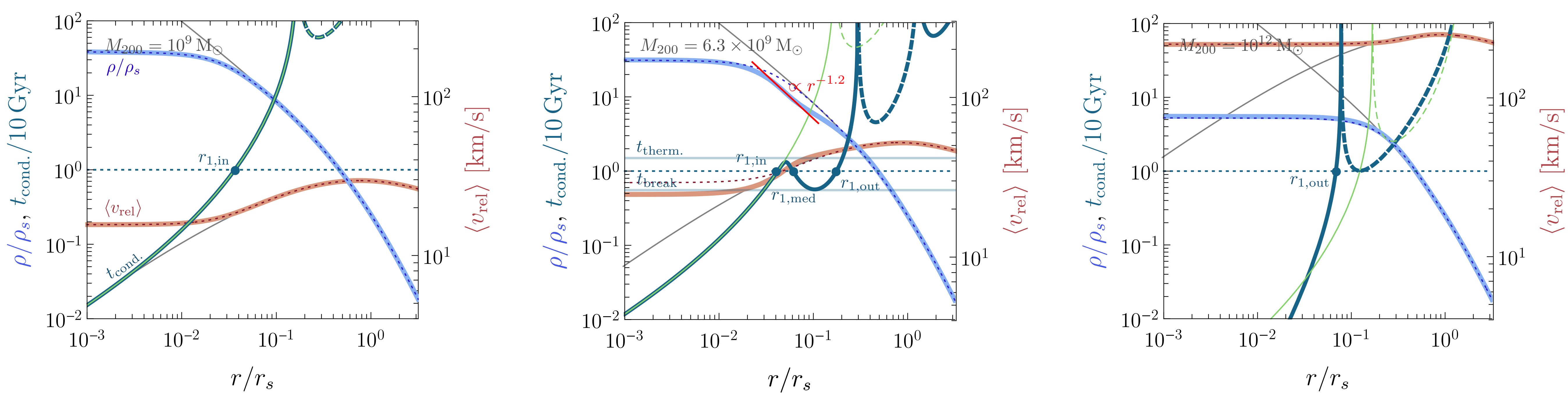


Resonant SIDM halos at present

Halo dependence

- no resonant scattering in too small halos (a)
- density break develops at present in a certain mass range (b)
- density break developed and is already thermalized in larger halos (c)



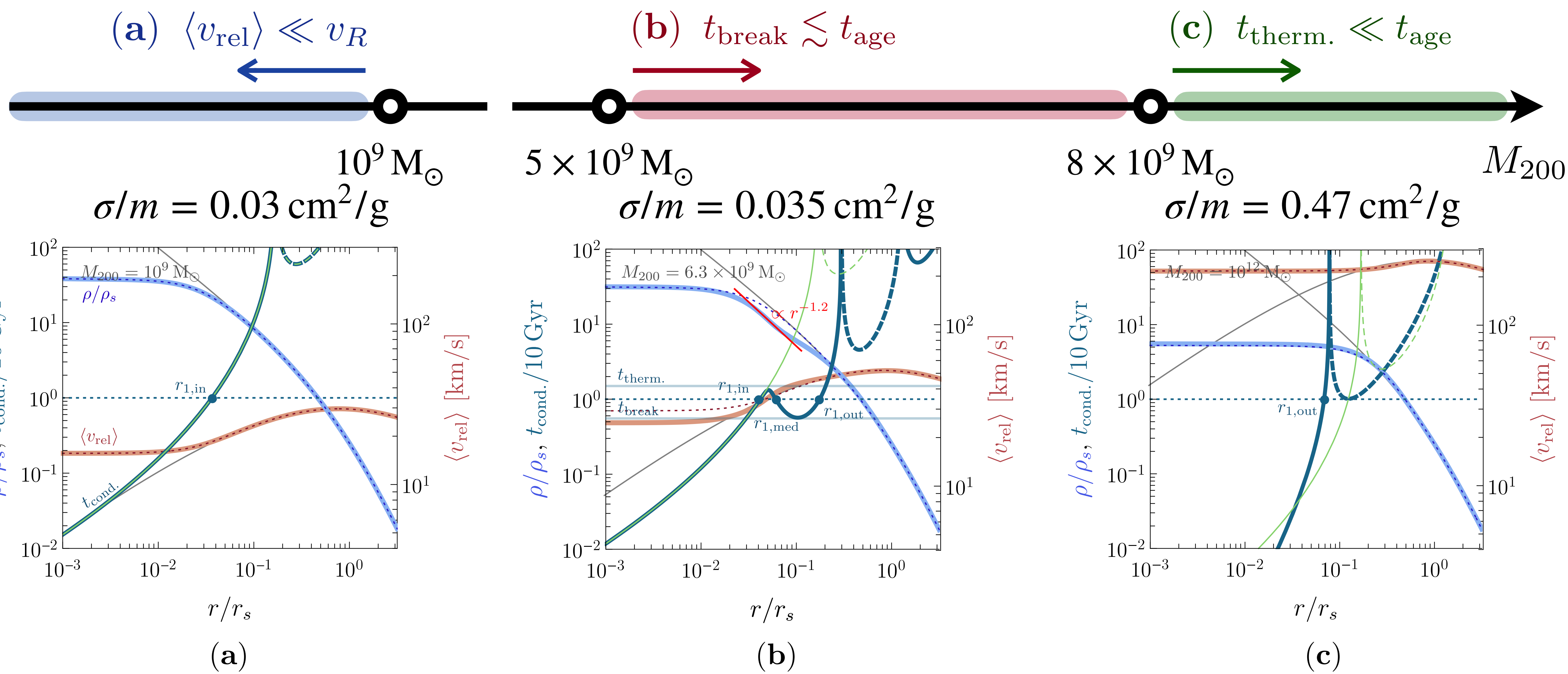


(a) - P2 benchmark (b) (c)

Resonant SIDM halos at present

Similarity to constant SIDM halos

- one can find an identical constant SIDM halo except for a certain mass range (b)
    - systematic mapping?

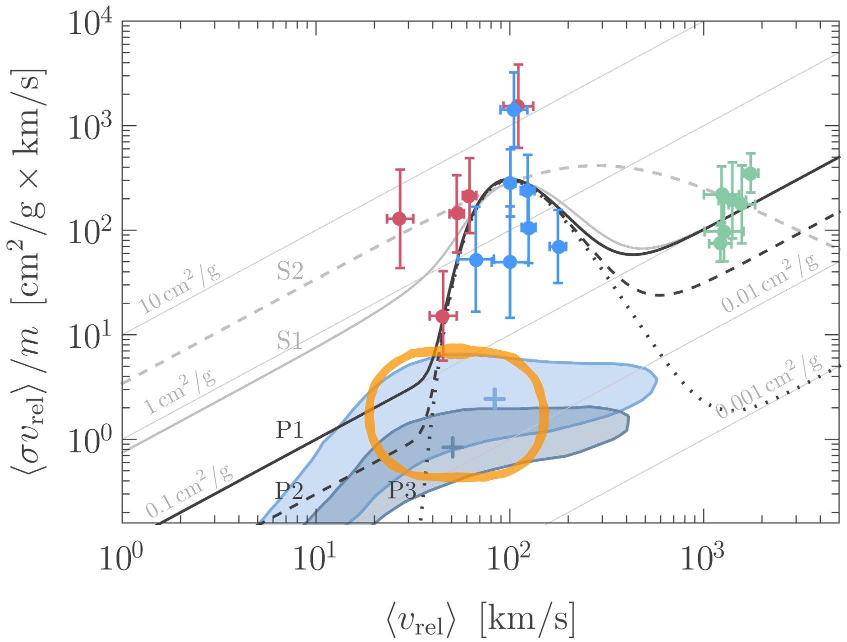


Resonant SIDM

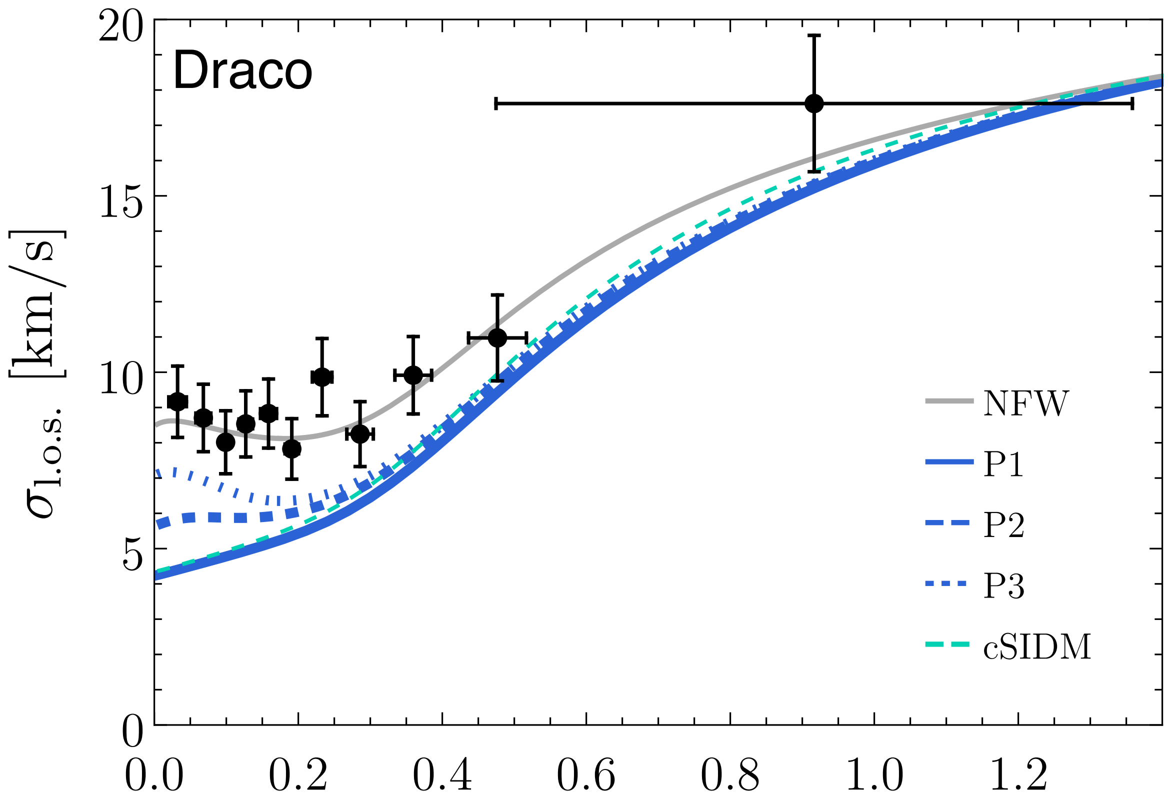
LOSVD profile of MW satellites

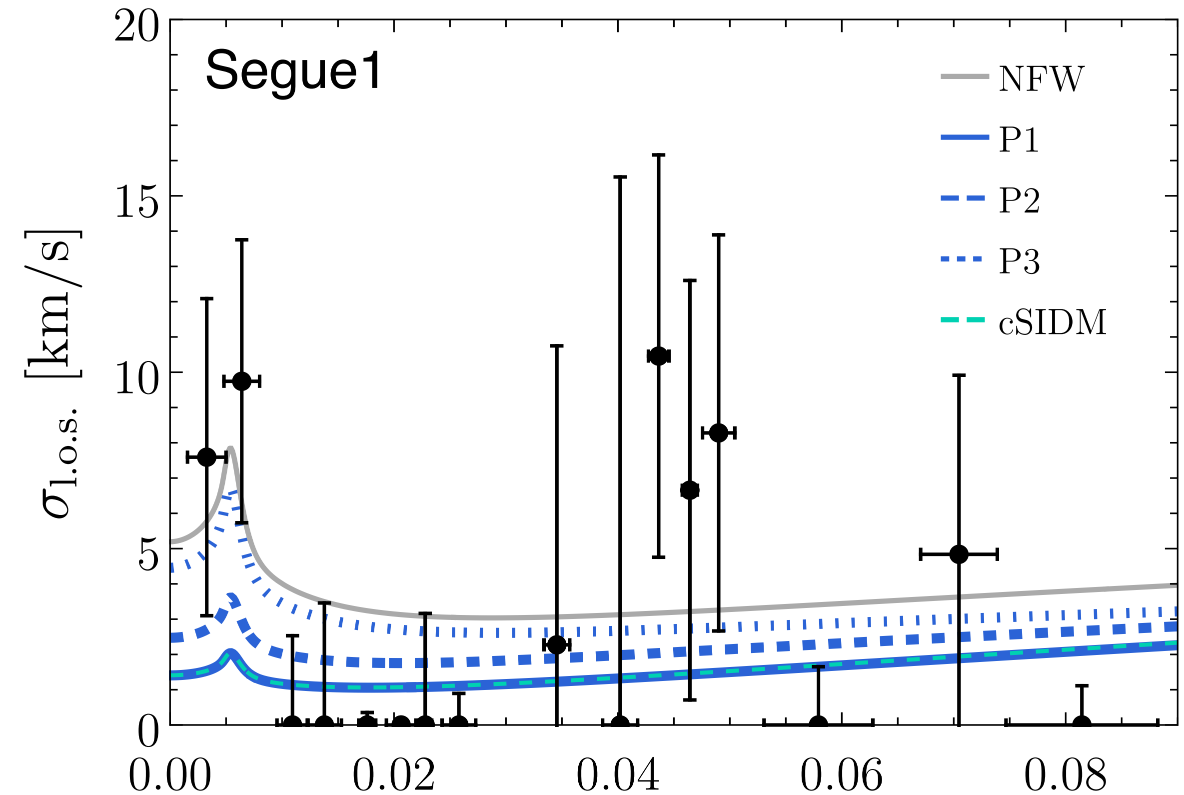
- stellar kinematic parameters are fixed to best fit values for NFW profile

Hayashi *et al.*, PRD, 2021



- P3 benchmark halo shows a transition from constant SIDM to NFW around 0.1 kpc
  - may fit the data better than constant SIDM





AK and Kim, PRD, 2024

Density breaks in the past

Change in mean stellar orbits

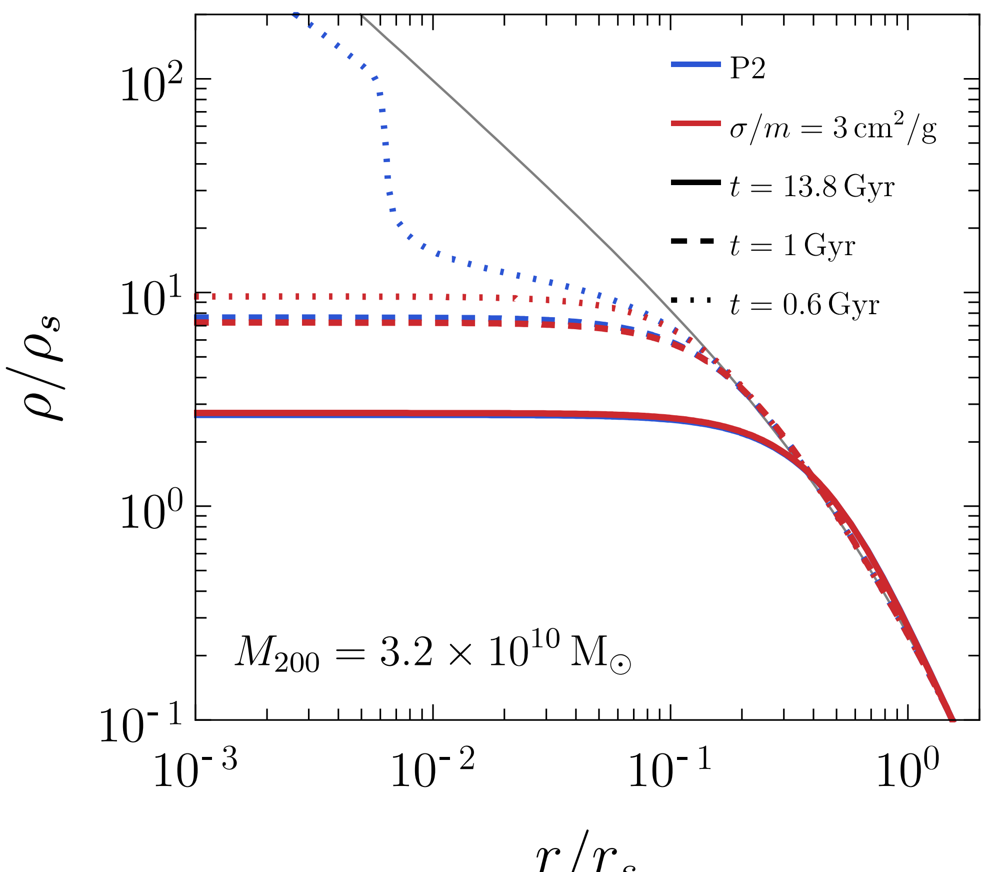
- energy in orbit distribution function is updated by the average change of potential at every orbital period

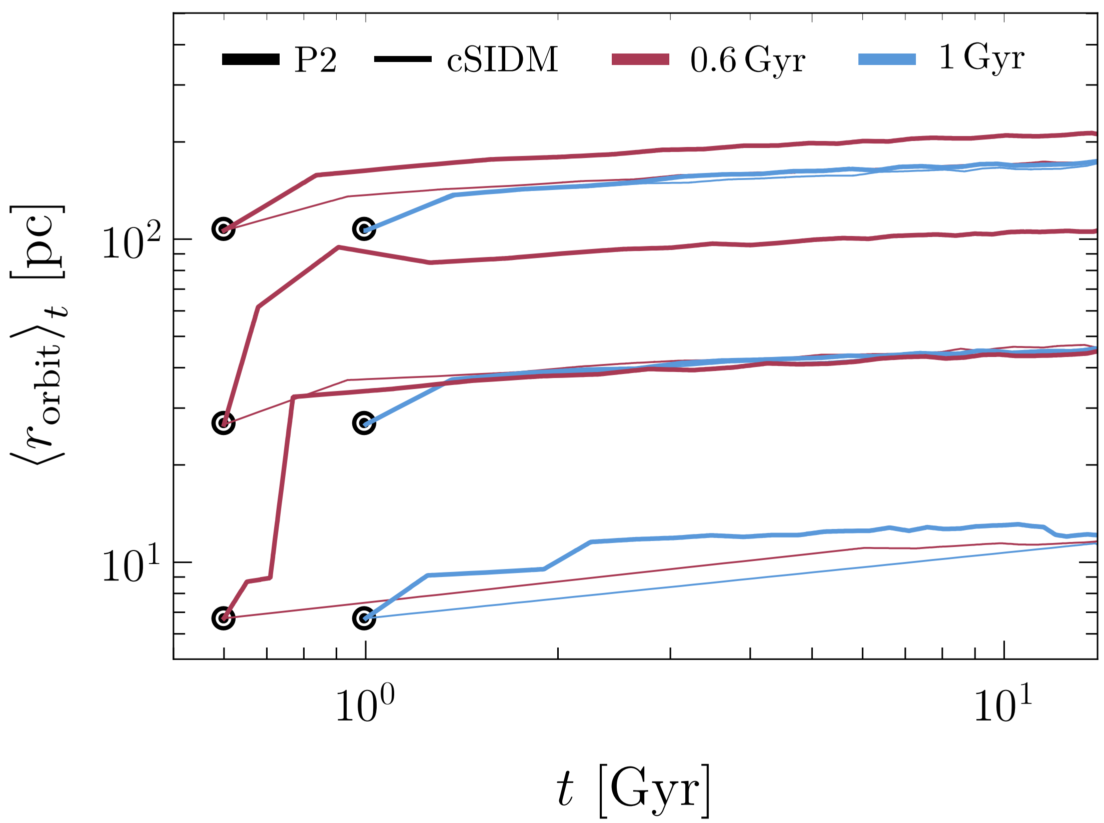
- orbits of stars are different depending on which they form before or after the development of density break

$$p(r,t;E,j) \propto \frac{1}{\sqrt{E(t) - V(r,t;j)}}$$

$$\langle \Delta E \rangle_t = \langle \Delta V \rangle_t$$

Pontzen and Governato, MNRAS, 2012





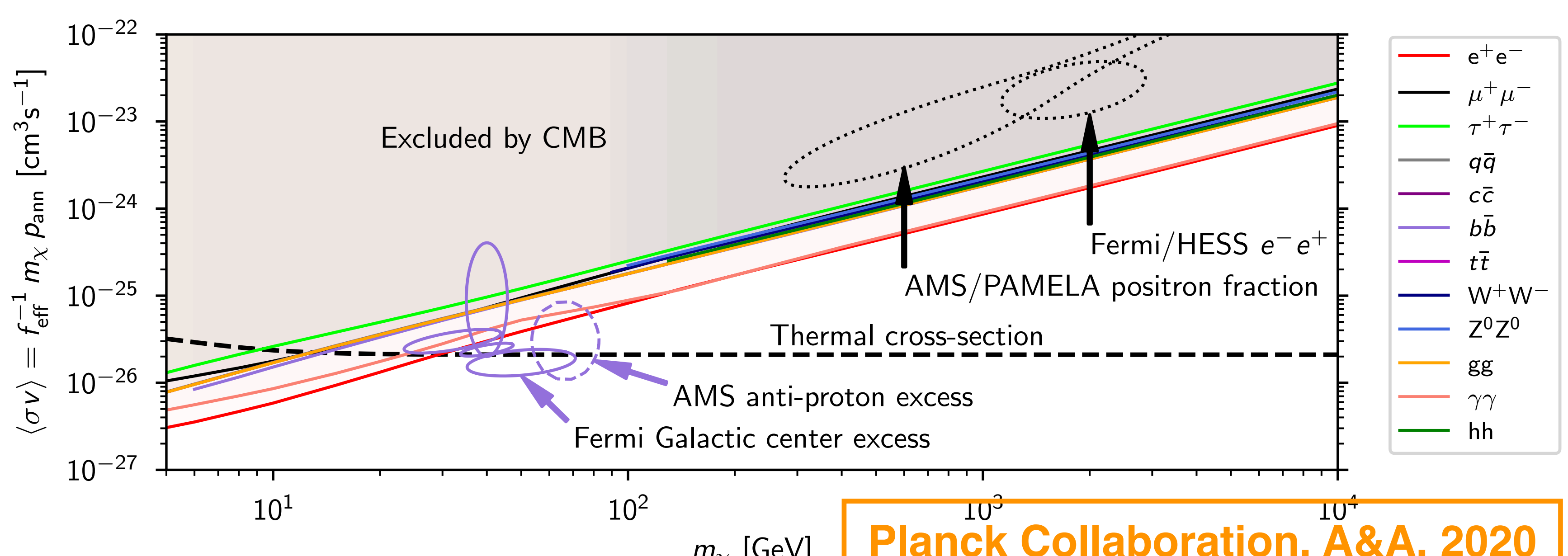
What should be concerned?

Light mediator

- naively overcloses the Universe
- decay or efficient annihilation

Enhanced annihilation

- large Sommerfeld enhancement by long-range force
- CMB constraints are relevant
  - energy deposit around the last scattering

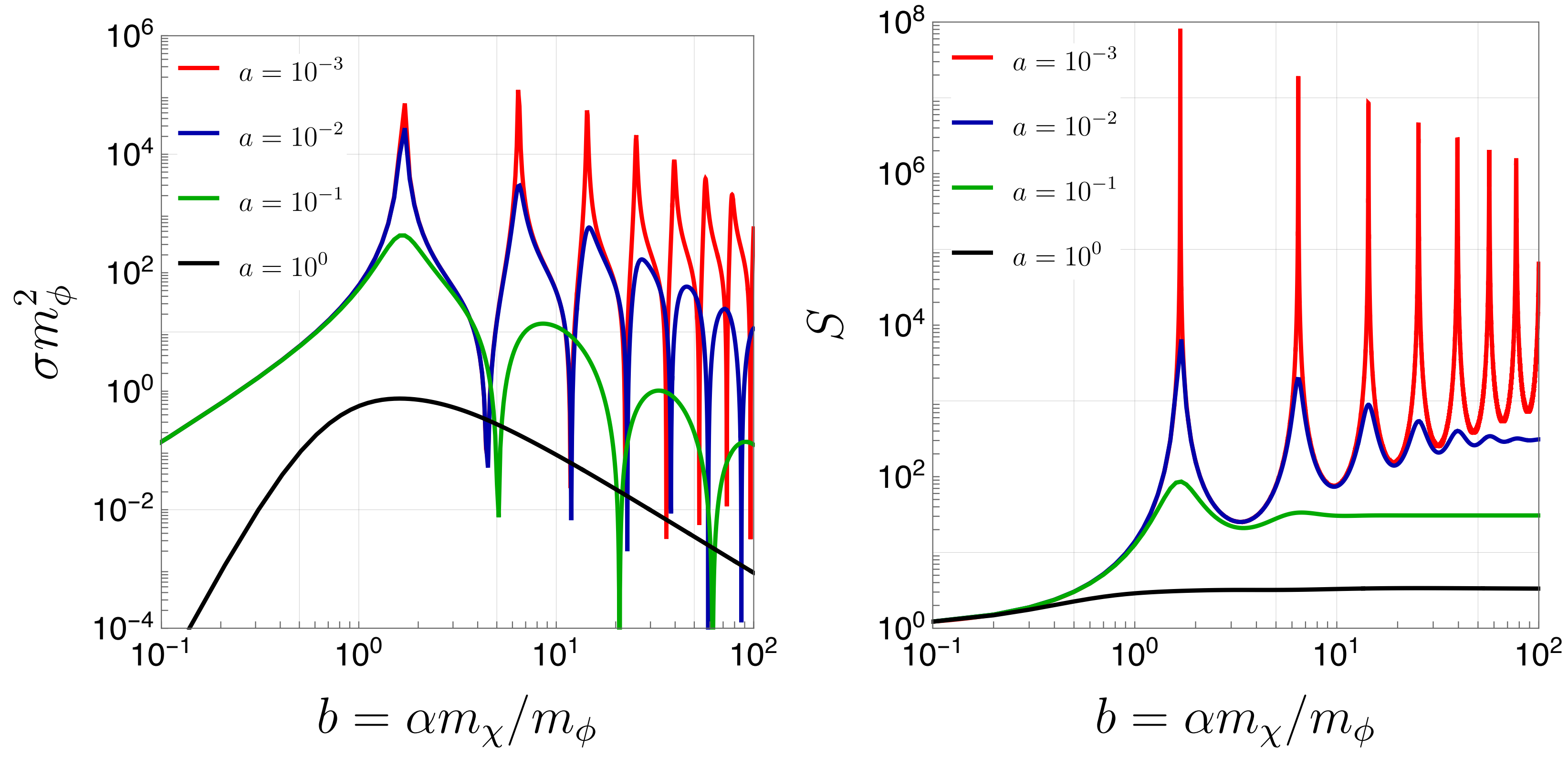


Planck Collaboration, A&A, 2020

Enhanced annihilation

Sommerfeld enhancement and self-scattering

- tightly correlated
    - resonant enhancement occurs at the same parameter point



- annihilation amplitude and scattering phase are related by Watson theorem
    - model-independent

$$\Gamma_\ell(k^2 + i\epsilon) = e^{2i\delta_\ell}\Gamma_\ell(k^2 + i\epsilon)^*$$

AK, Kuwahara and Patel, JHEP, 2023

Possible ways to go

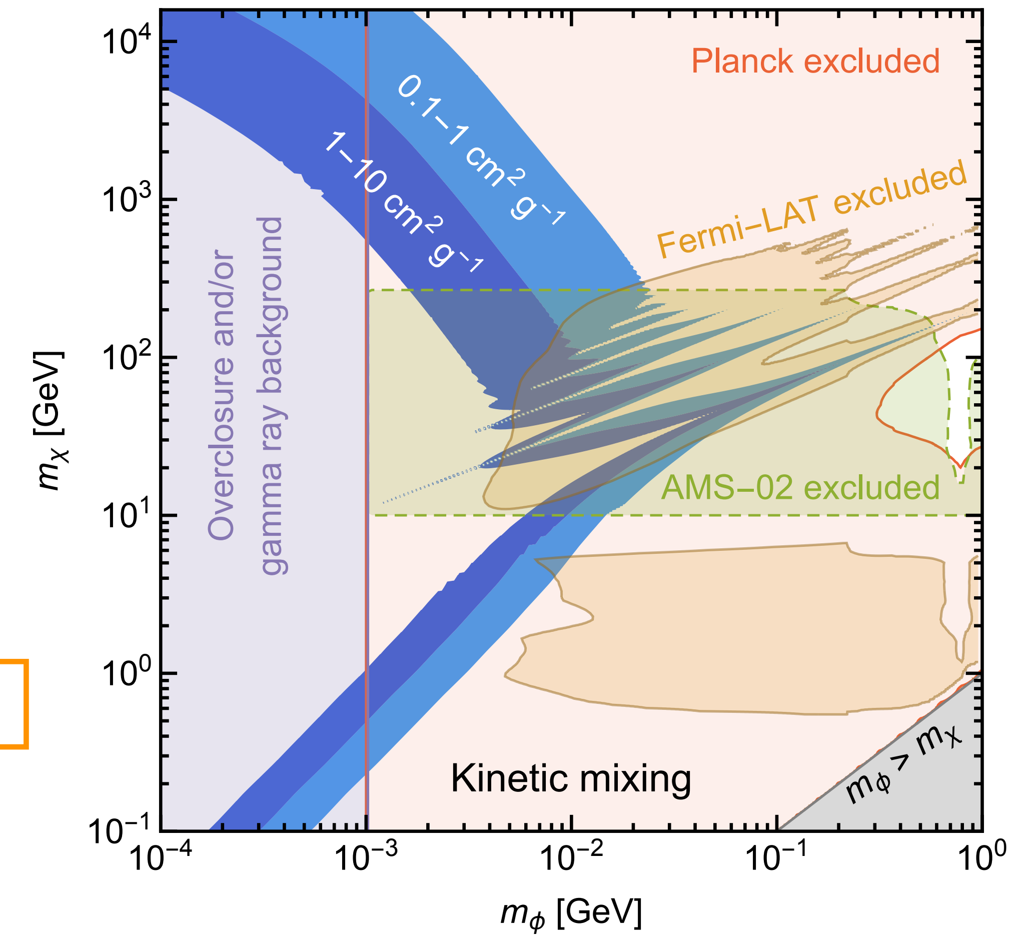
Evade constraints

- s-wave annihilation into electromagnetic energy is disfavored

- p-wave annihilation, annihilation into neutrinos

  - $L_\mu - L_\tau$ model (muon g-2)

  AK, Kaneta, Yanagi, and Yu, JHEP, 2018



Bringmann, Kahlhoefer, Schmidt-Hoberg and Walia, JHEP, 2020

- asymmetric dark matter

  - almost no late-time annihilation

  - dark baryon dark matter (naturally explain large cross section)

Ibe, AK, Kobayashi, and Nakano, JHEP, 2018