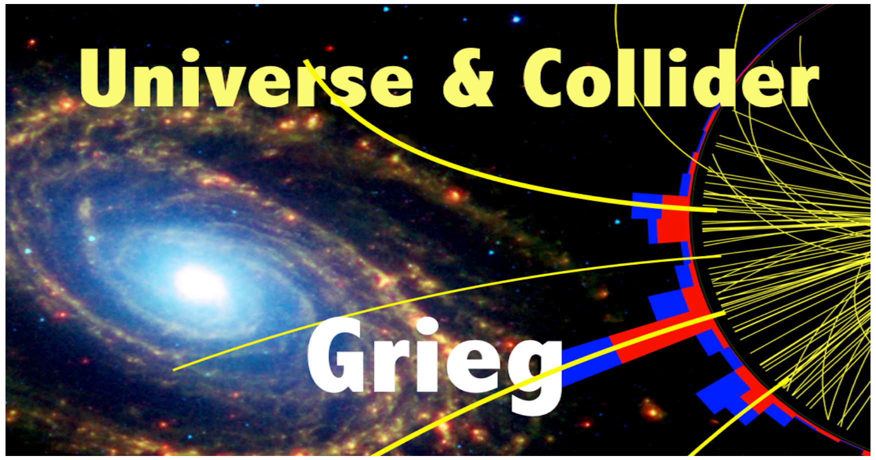
Evolution of Resonant Self-interacting Dark Matter Halos

Ayuki Kamada (University of Warsaw)



UNIVERSITY OF WARSAW

Based on
<u>AK</u> and Hee Jung Kim, arXiv:2304.12621

June 23, 2023 @ Pollica Summer Workshop

Contents

Resonant self-interacting dark matter (SIDM)

- sharp velocity dependence of self-scattering cross section
- are resonant SIDM halos similar to constant SIDM halos?

Evolution of resonant SIDM halos

- isothermal region does not evolve monotonically from inside to outside unlike constant SIDM
- formation, development and thermalization of density break

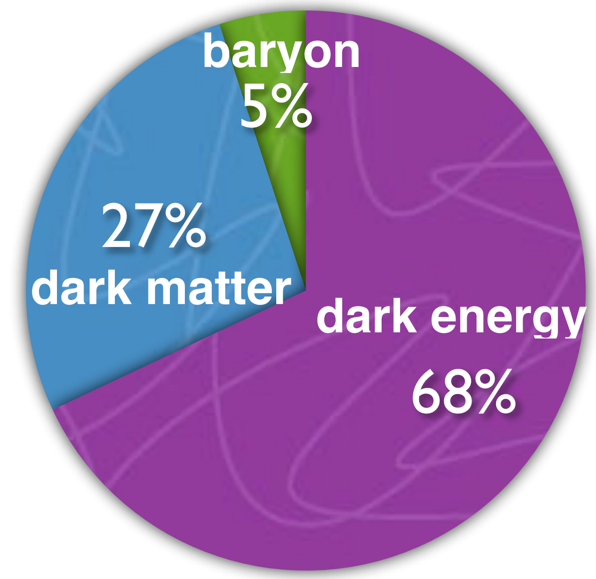
Possible imprints on observations

- density break in a certain mass range of halos
- change in stellar orbits by density break in the past

Dark matter

Dark matter

- 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

Gravitational probes

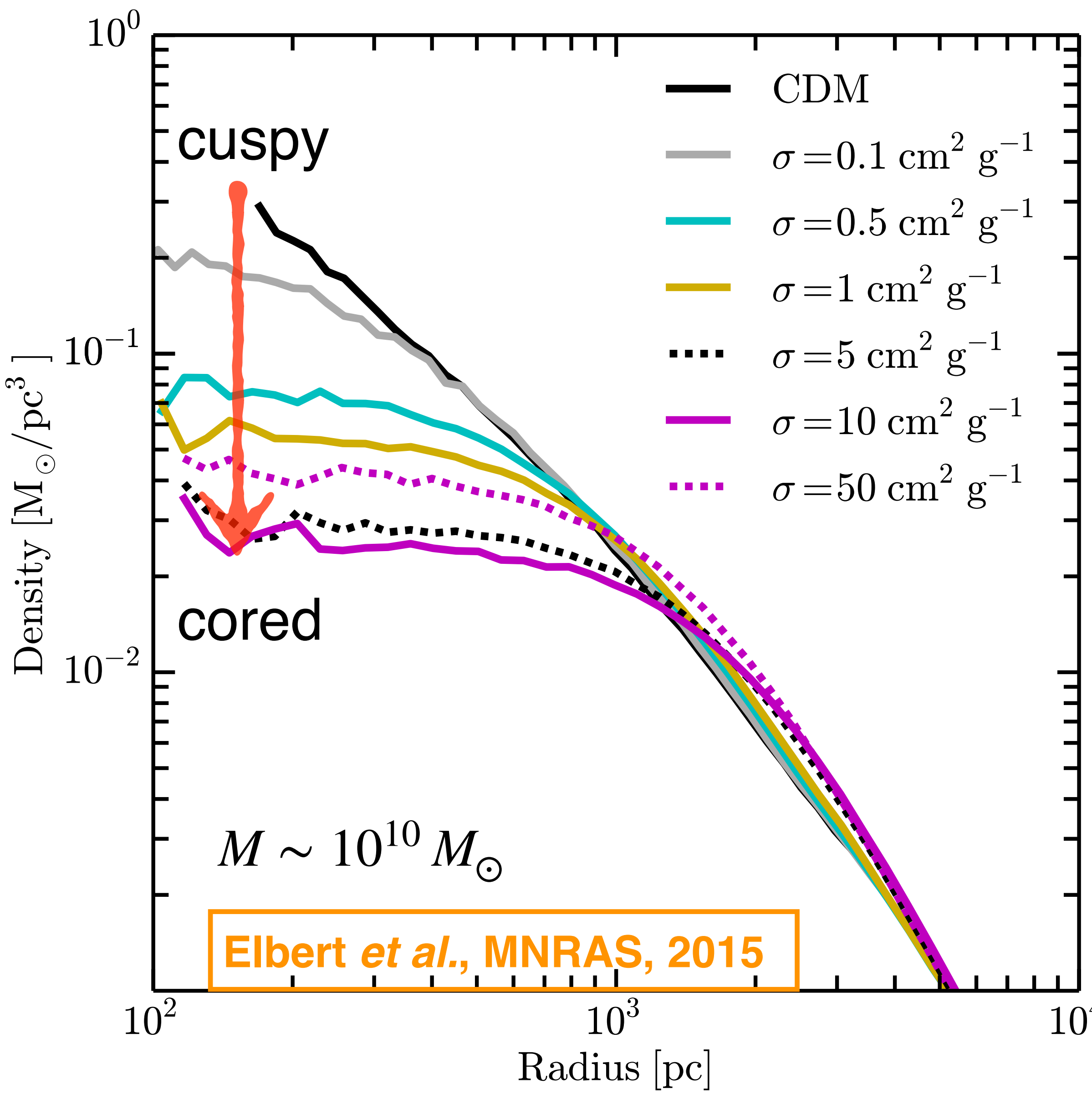
- complementary to direct, indirect and collider searches
- how the star distribution changes w/ properties of dark matter
  - all known properties of dark matter are derived in this way (including its existence; SM neutrinos are too hot to form galaxies)

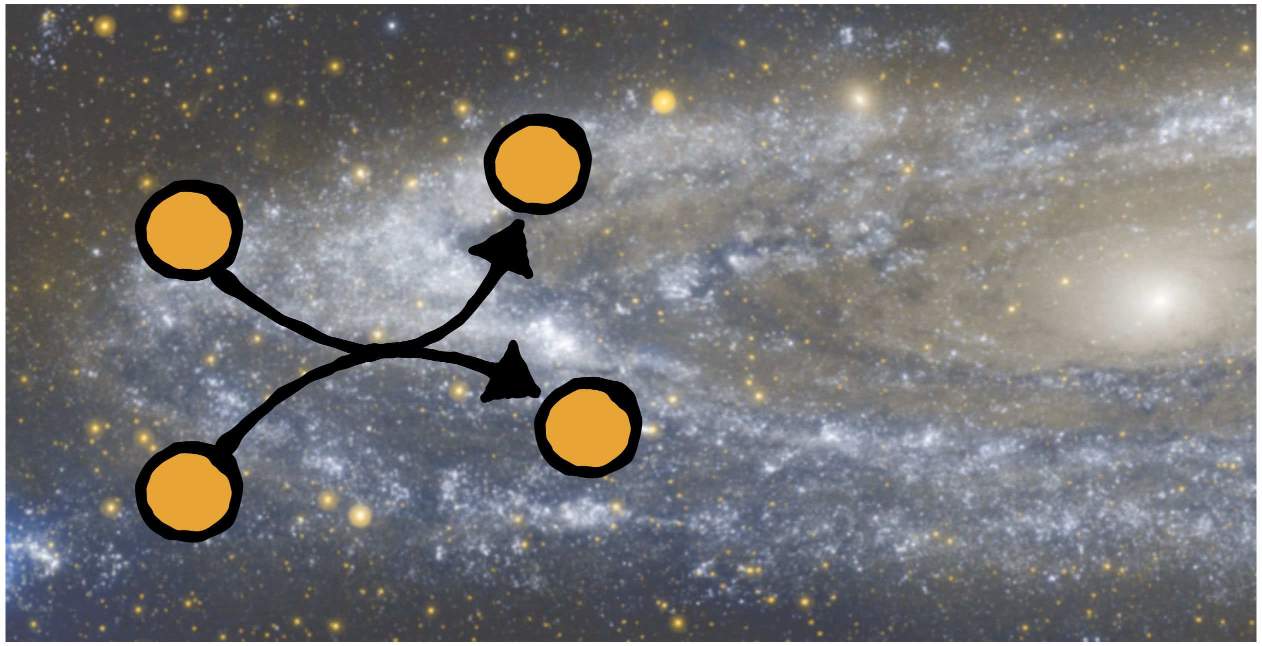
Dark matter

Self-interacting dark matter (SIDM)

- interactions among dark matter particles
    - hard to probe in other searches
    - dark matter density profile inside a halo turns from cuspy to cored
    - cored profile "appear to" provide better fit to astronomical data

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





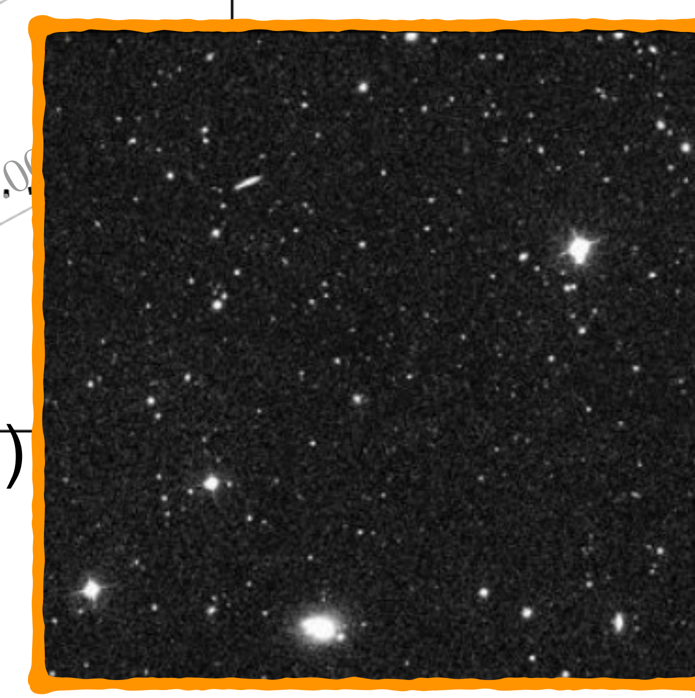
“Data” points

Overview

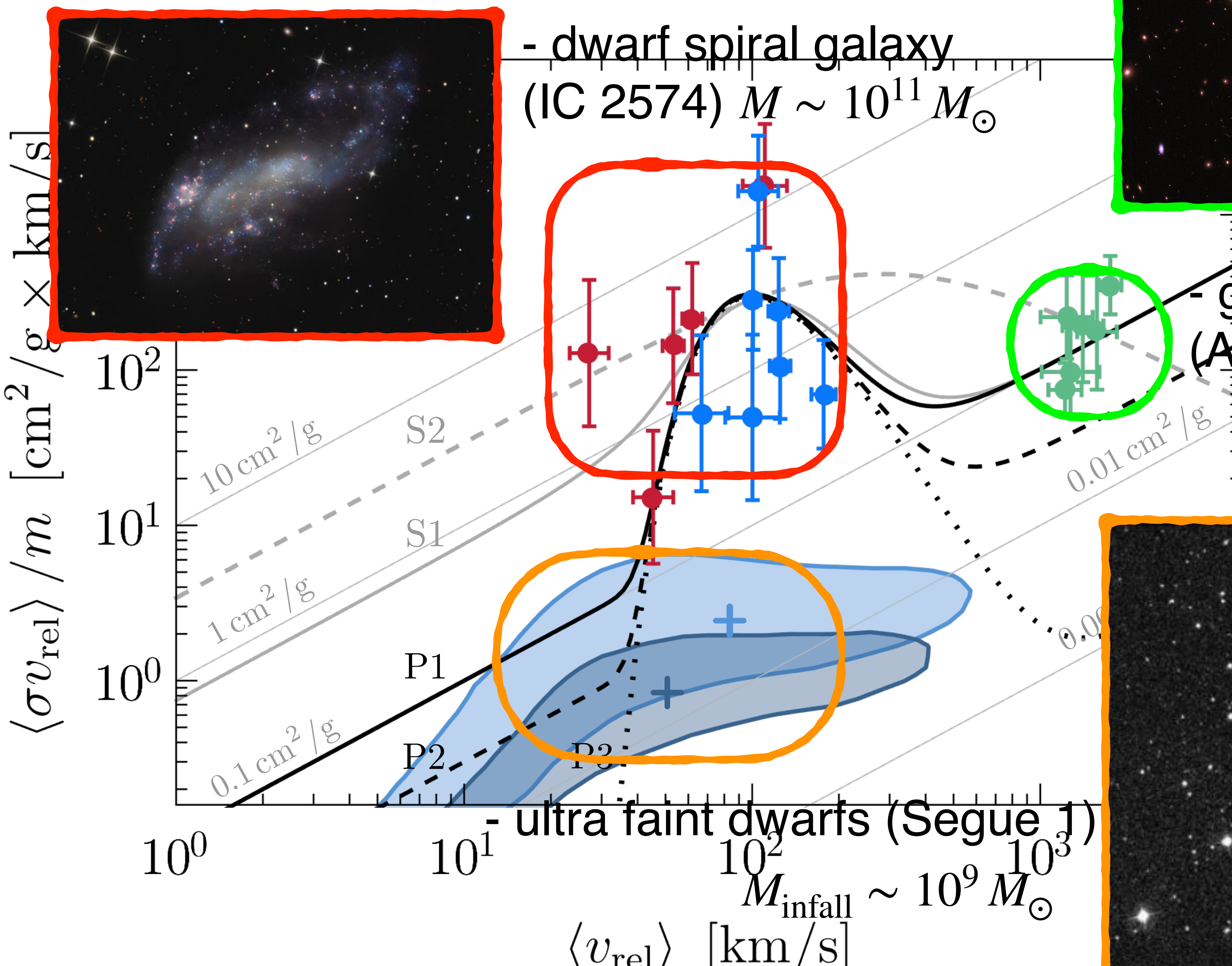
- cores in various-size halos may prefer sharp velocity dependence of self-scattering cross section

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

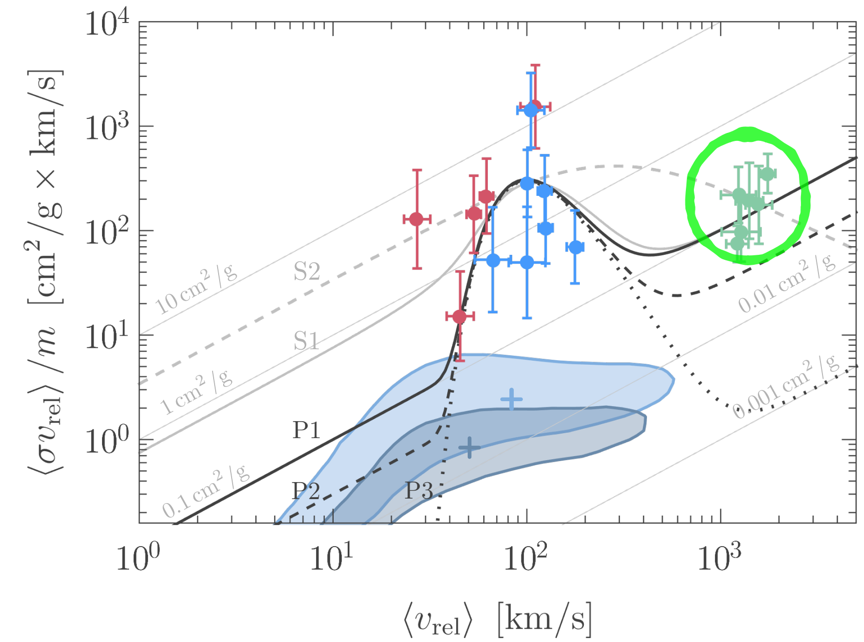


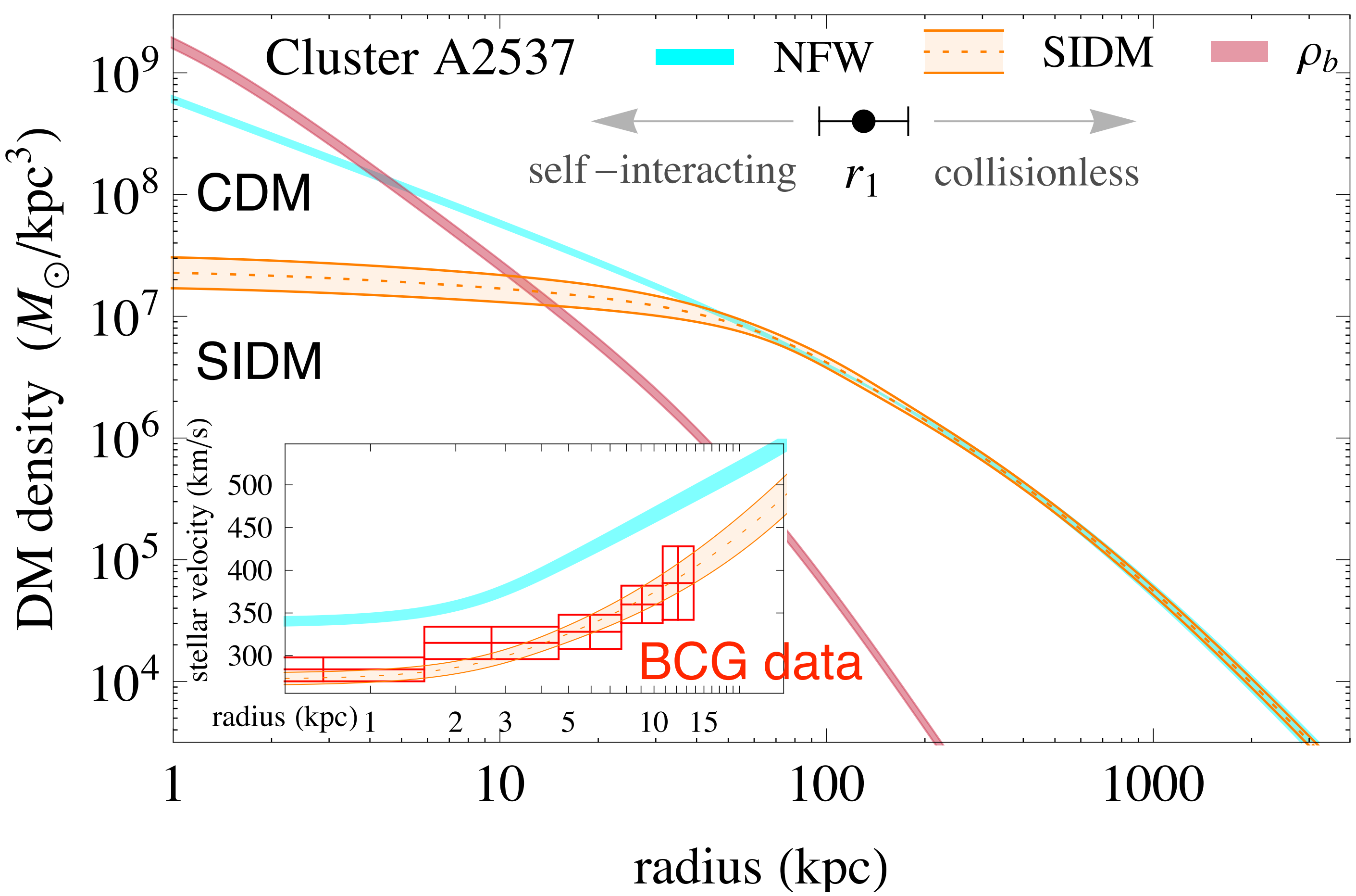
Data points

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





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

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

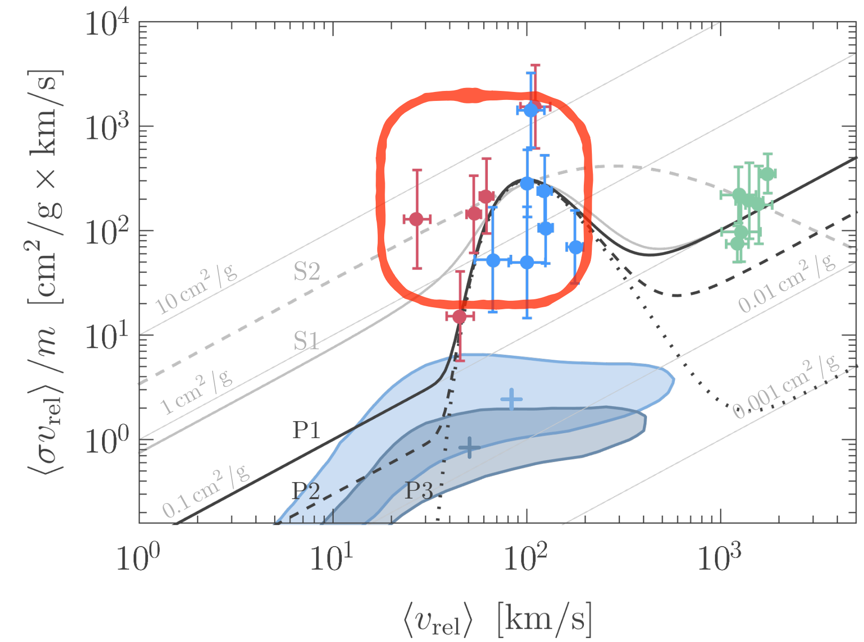
Kaplinghat, Tulin, and Yu, PRL, 2016

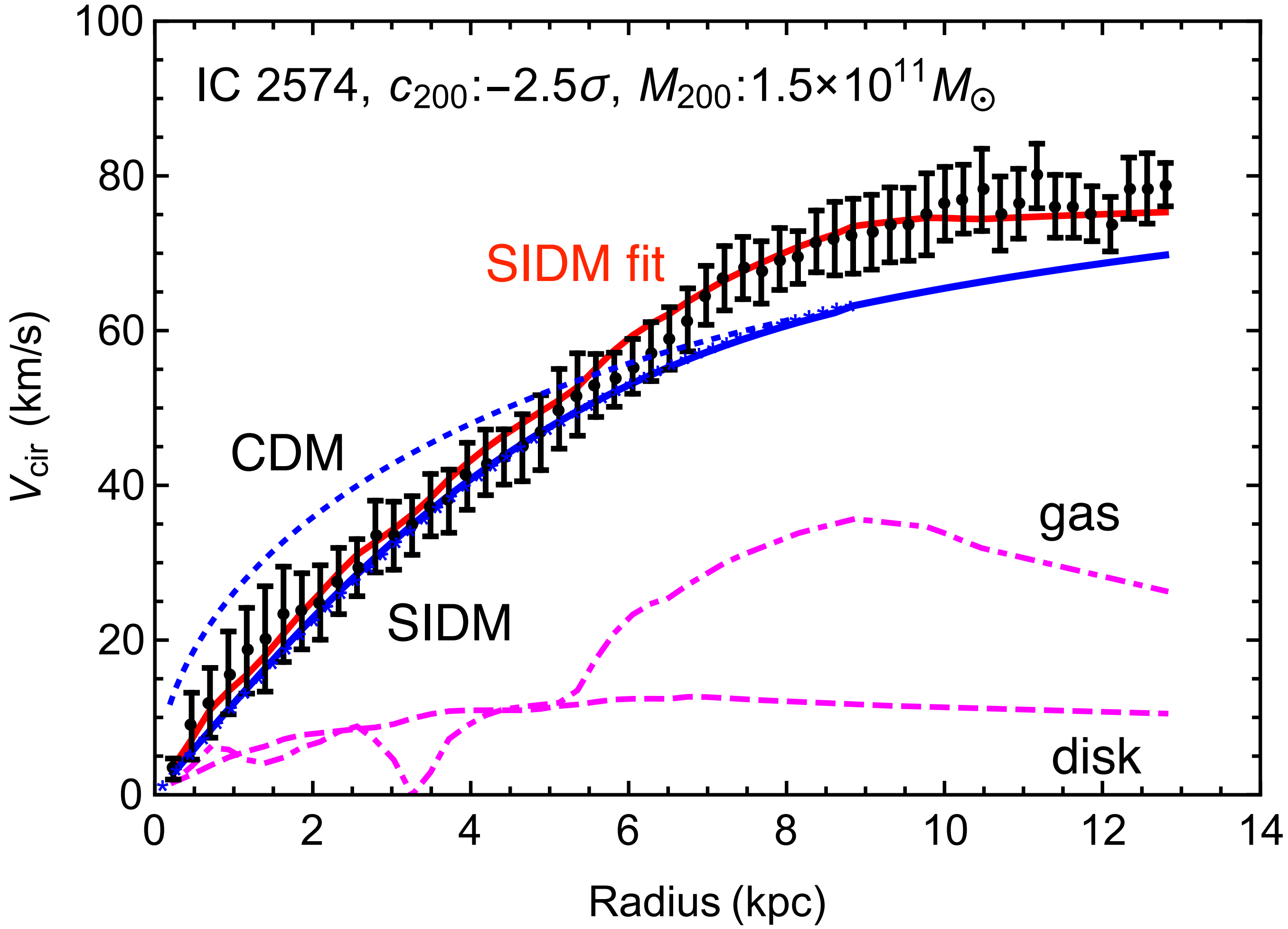
Data points

Dwarf spiral galaxies

- mass distribution is broadly determined by rotation curves

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





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

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

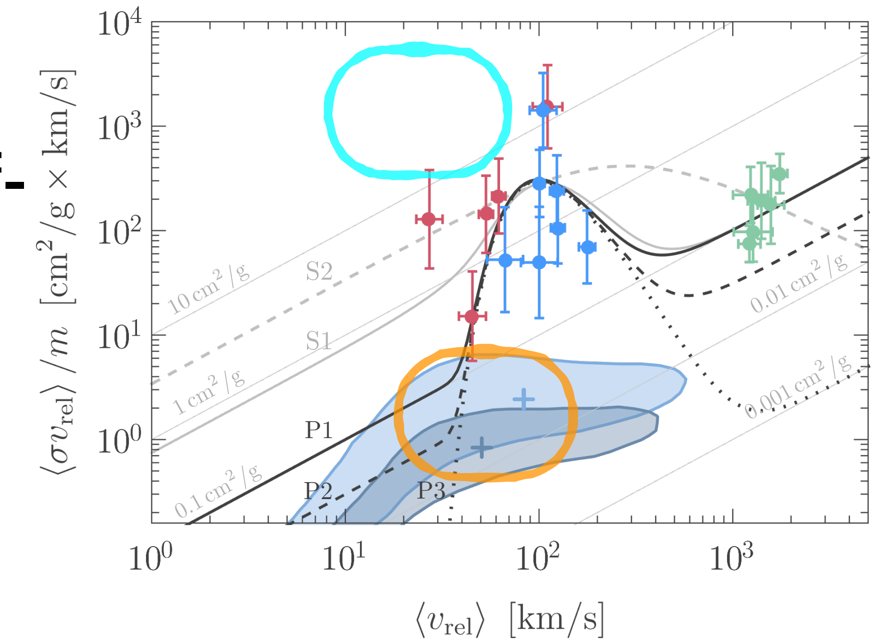
AK, Kaplinghat, Pace, and Yu, PRL, 2017

Data points

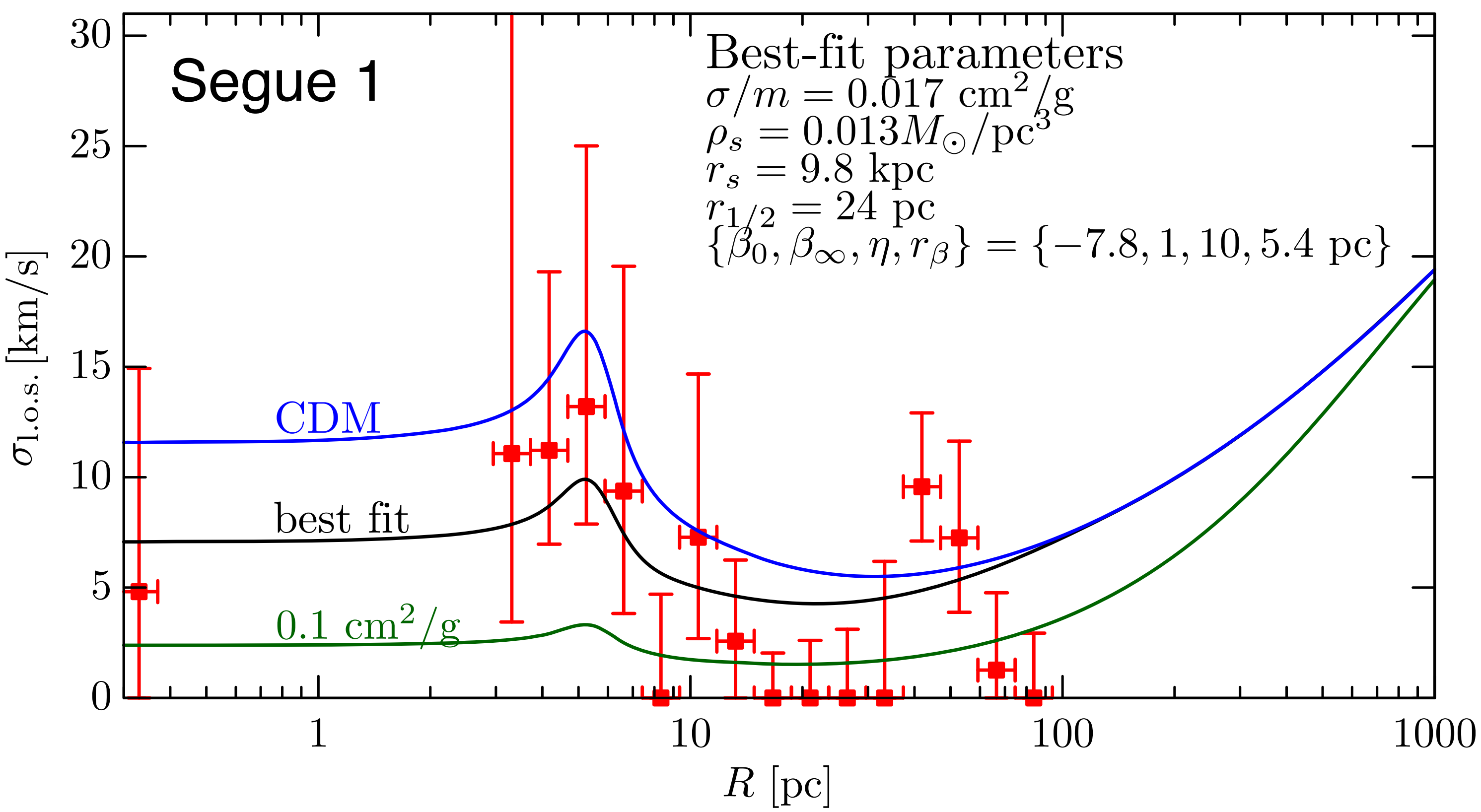
Ultra faint dwarf (UFD) galaxies

- 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



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

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

- gravothermal collapse?

Correa, MNRAS, 2021

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

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

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

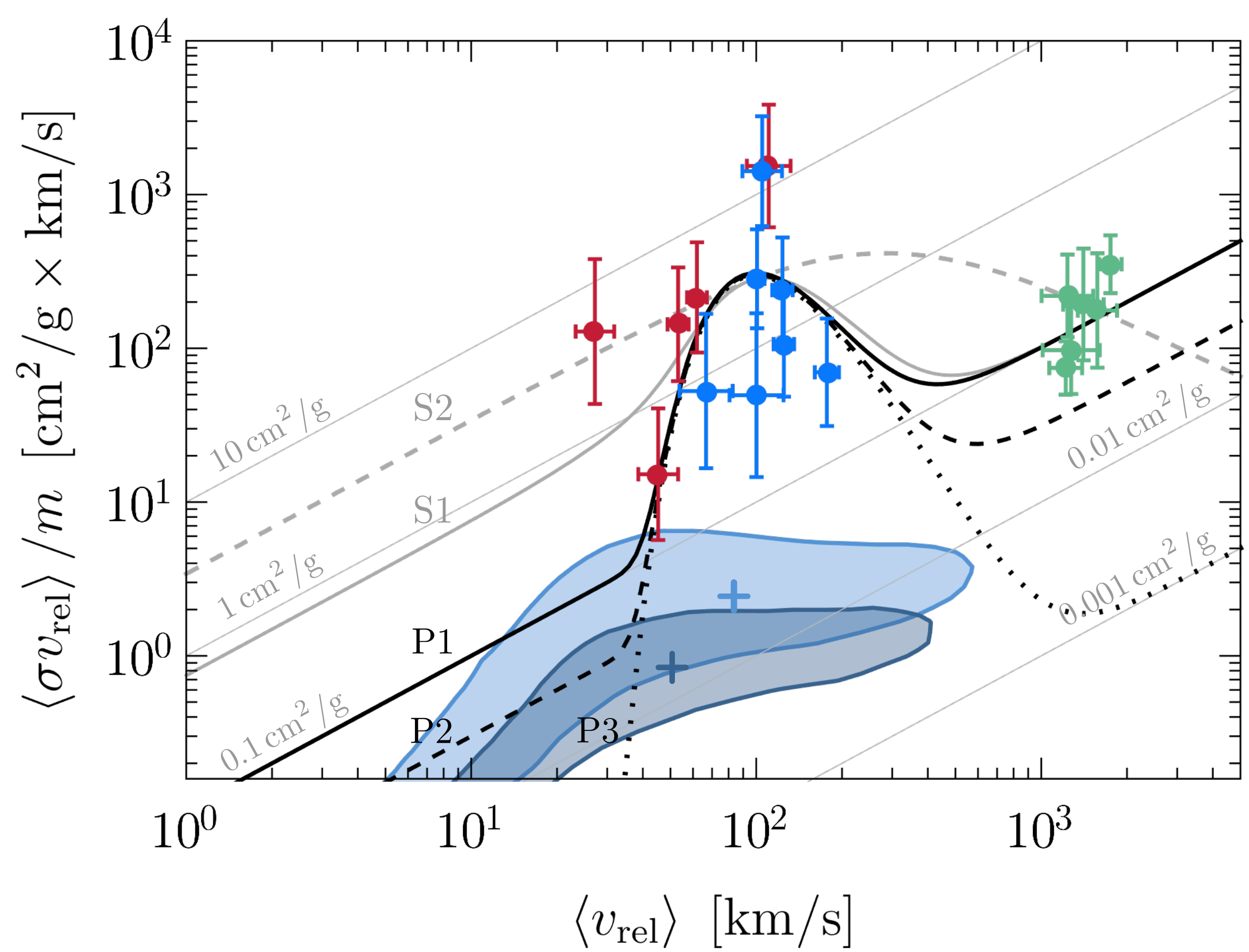
- s-wave benchmarks
  - S1 and S2

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

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

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

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



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

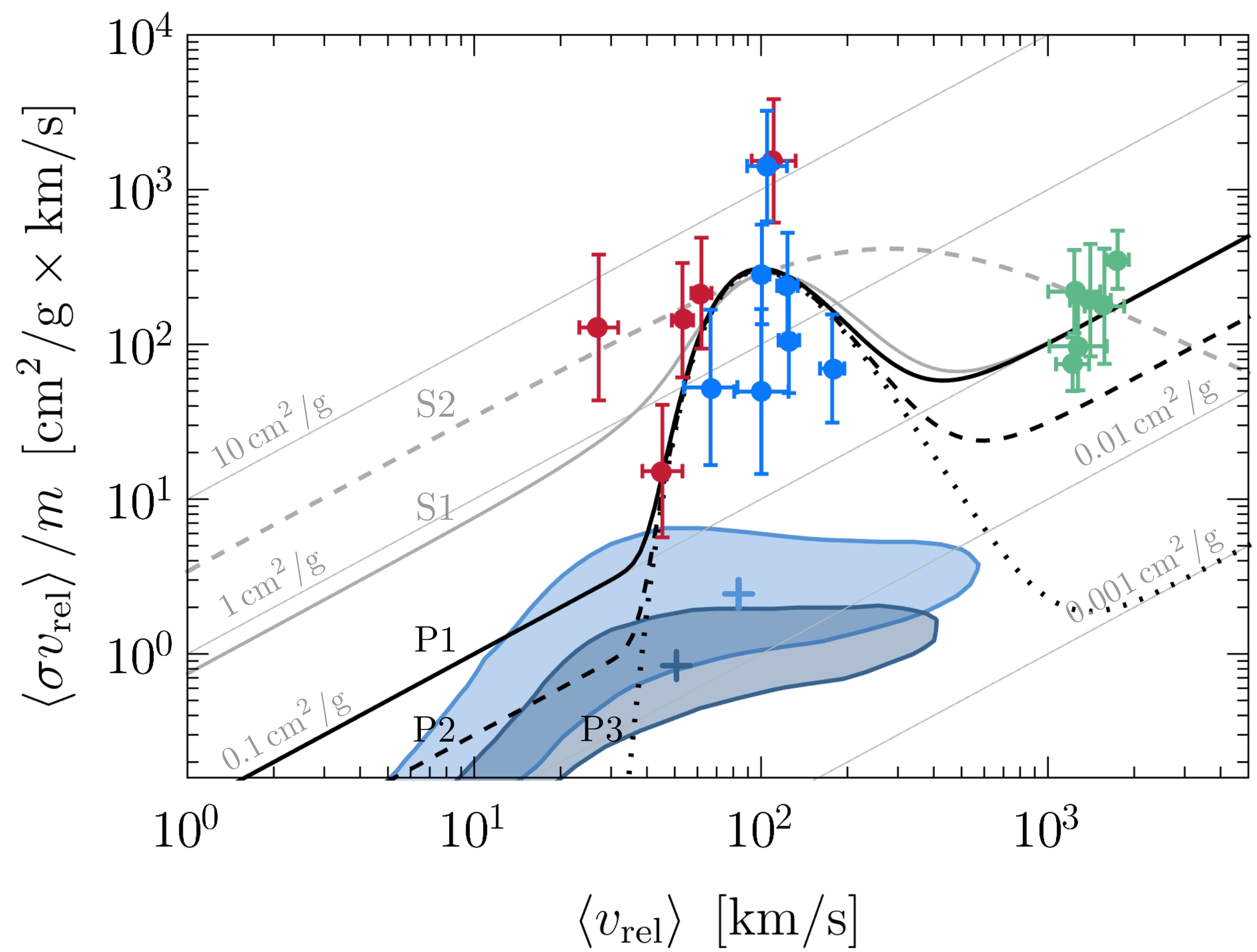
$$\gamma = 10^{-3} \qquad v_R = 108\,\mathrm{km/s}$$

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

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

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

  - consider P2 benchmark mainly in the following



Resonant SIDM

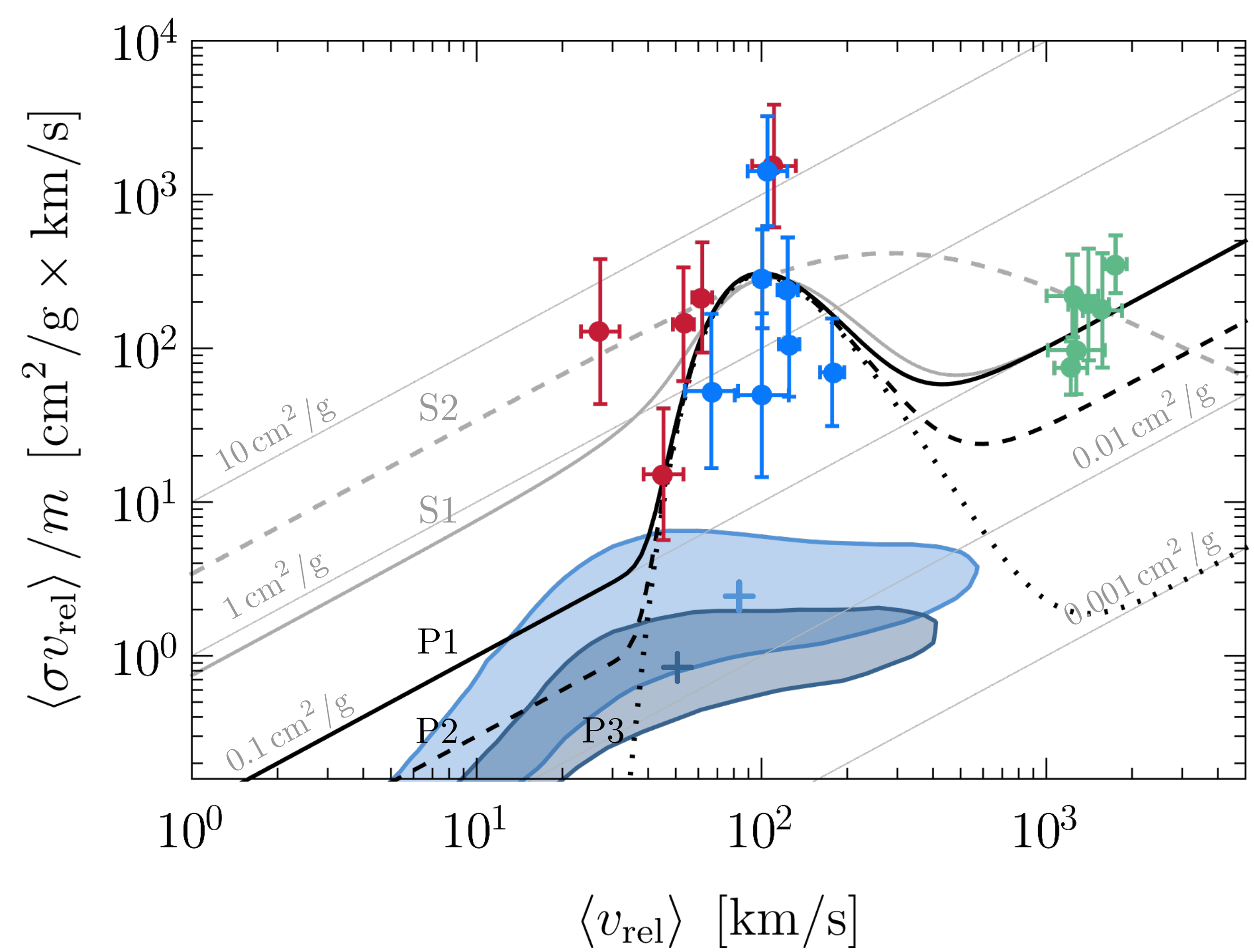
Question

- 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



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Possible imprints on observations

- density break in a certain mass range of halos
- change in stellar orbits by density break in the past

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

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

- heat conduction timescale

- naive interpolation between LMFP and SMFP regimes

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

- SMFP $\kappa_{\rm SMFP} = \frac{3}{2} b \frac{\nu}{\sigma_0 K_5(\nu)}$

$$b = \frac{25\sqrt{\pi}}{32} \simeq 1.38 \qquad K_p(\nu) = \frac{\langle \sigma v_{\rm rel}^p \rangle}{\sigma_0 \langle v_{\rm rel}^p \rangle}$$

Outmezguine *et al.*, MNRAS, 2023

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

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

$p = 5$? Yang *et al.*, ApJ, 2023

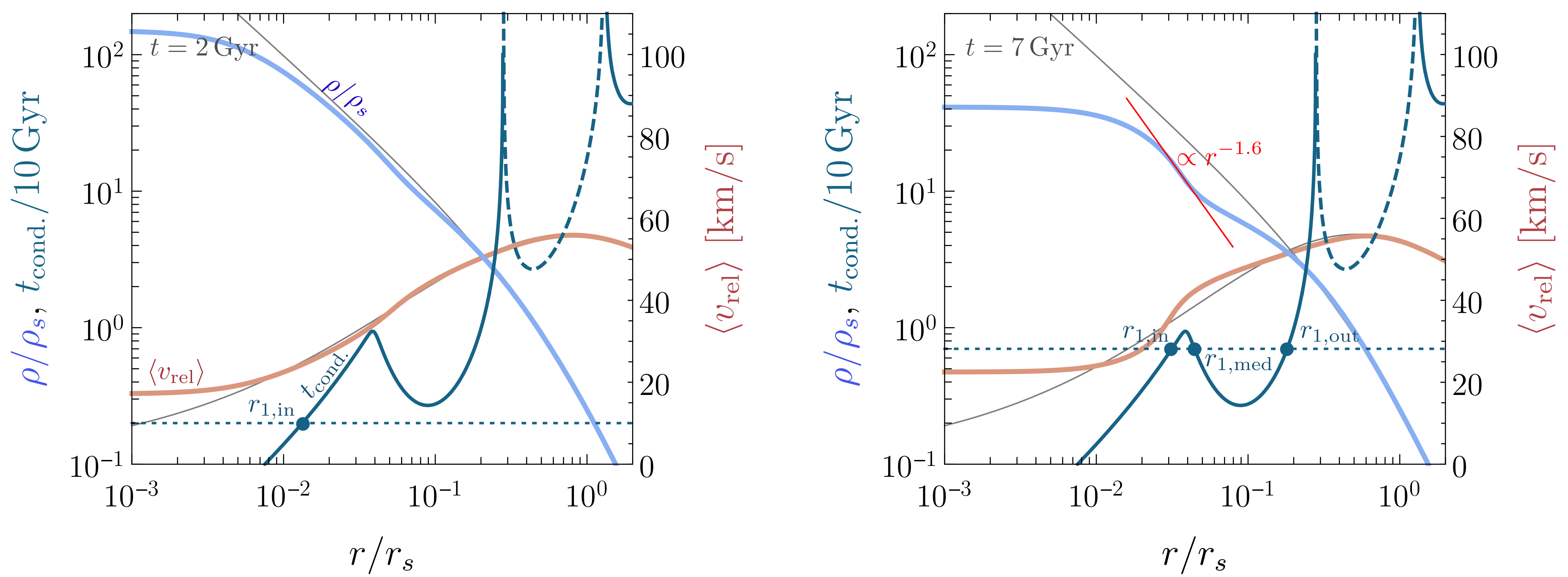
$C \simeq 0.75$ Koda and Shapiro, MNRAS, 2011

- start with NFW profile
  - mean c-M relation

Evolution of resonant SIDM halos

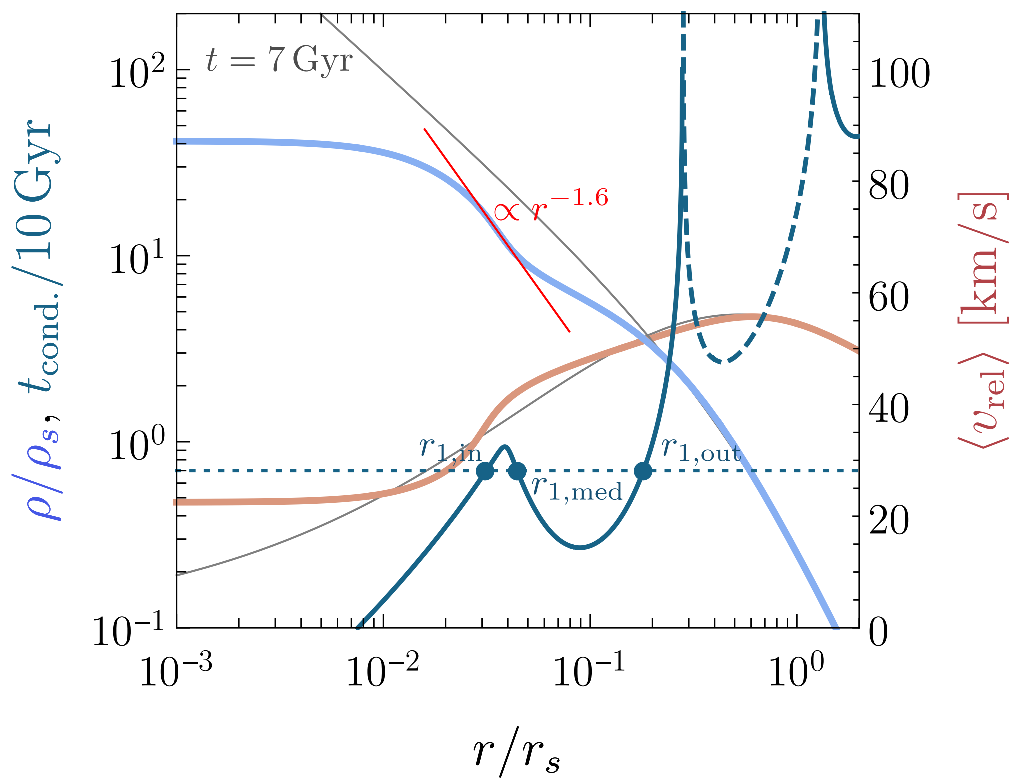
Formation of density break

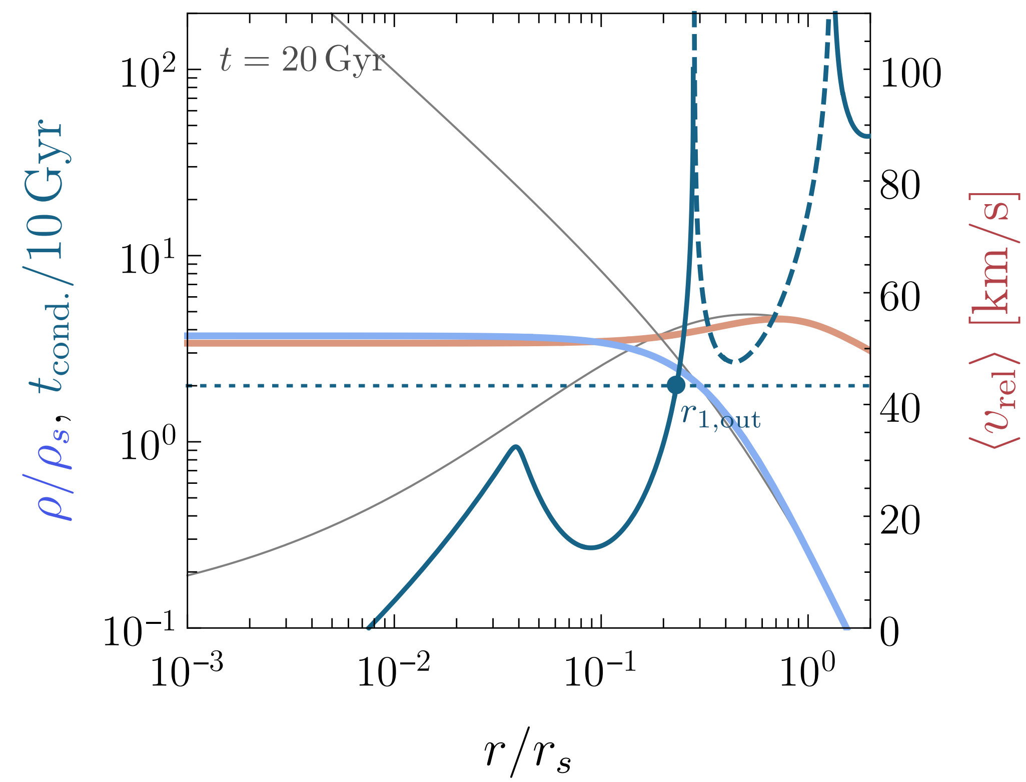
- profile of heat conduction timescale has a sharp peak $r/r_s \simeq 0.1$
- three r1's appear for $t > t_{\rm break}$ $\quad t_{\rm cond.}(r_1) = t$
- two isothermal regions appear $r < r_{1,\rm in}$ $\quad r_{1,\rm med} < r < r_{1,\rm out}$
- density break forms to connect the two isothermal regions



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

Evolution of resonant SIDM halos



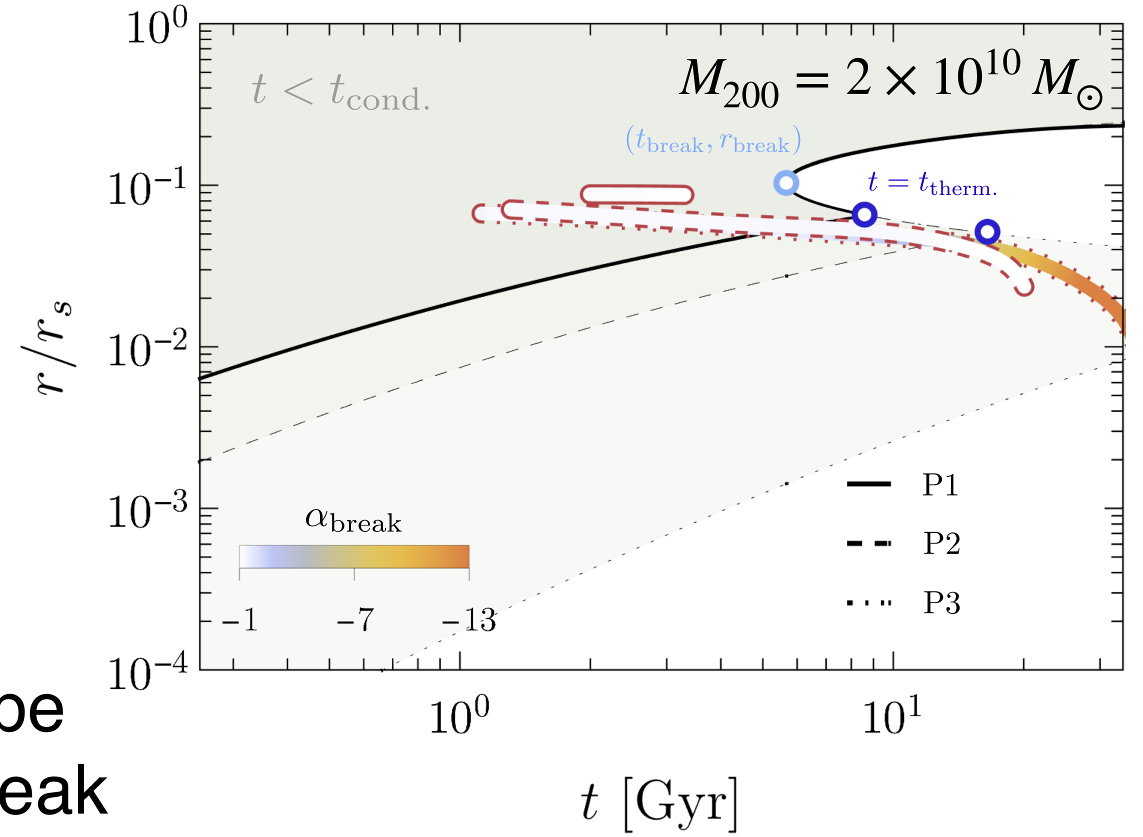


Development and thermalization of density break

- 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

Evolution of resonant SIDM halos

Benchmark / halo-size dependence

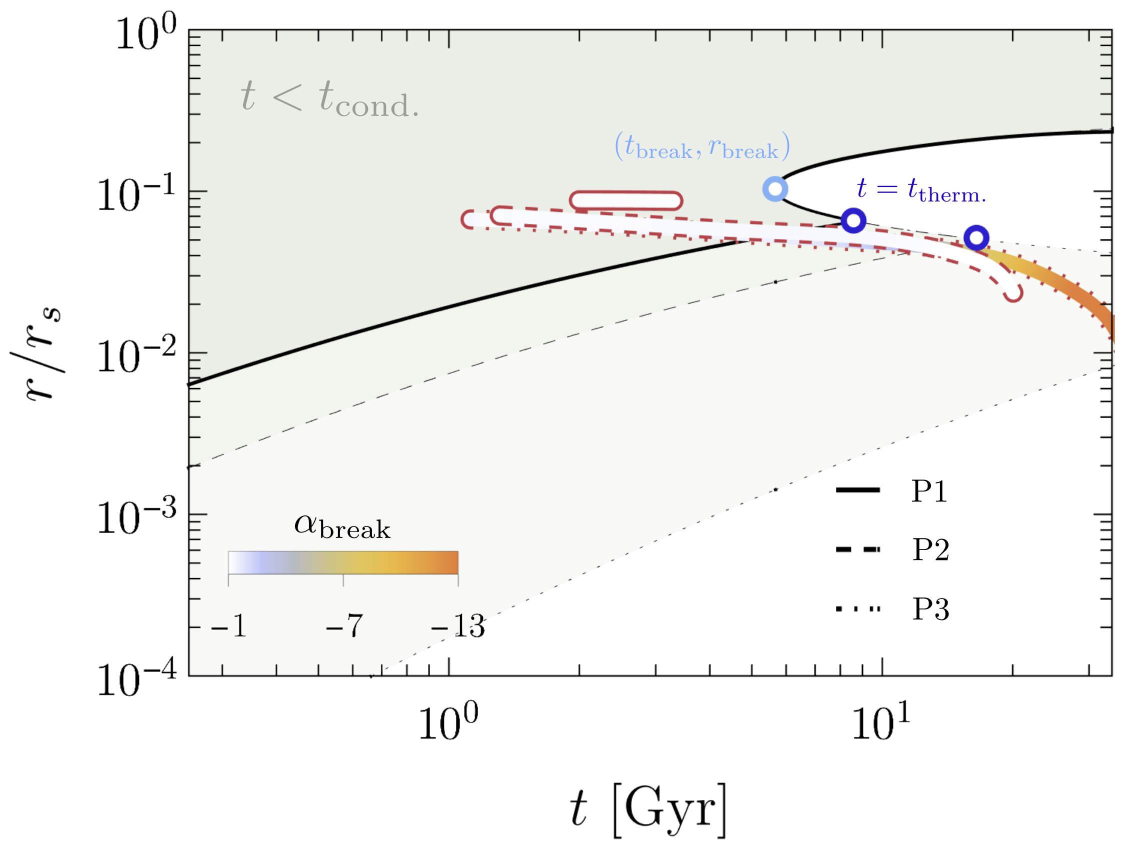
- density break propagates longer till thermalization and develops further, for larger separation between $r_{1,\mathrm{in}}$ and $r_{1,\mathrm{med}}$ at $t = t_{\mathrm{break}}$

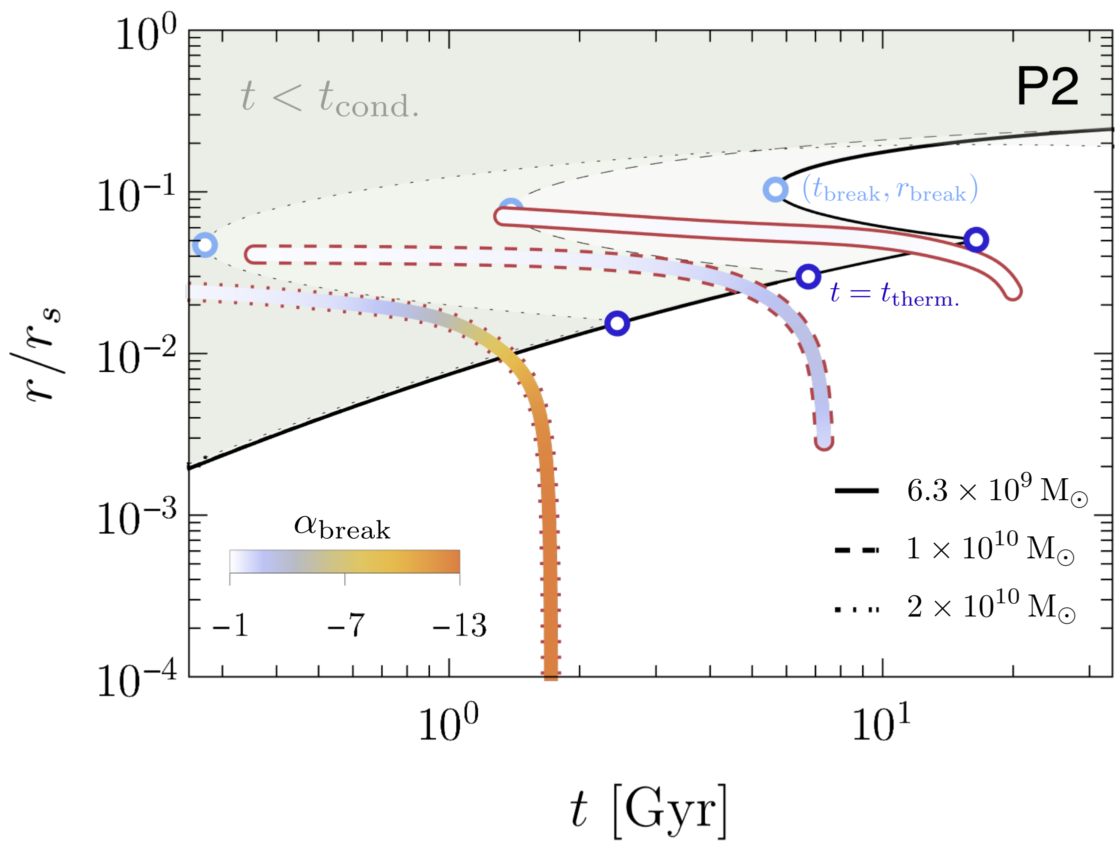
- smaller offset cross section (P3)

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

- larger halos

  - earlier formation (smaller t_{break})

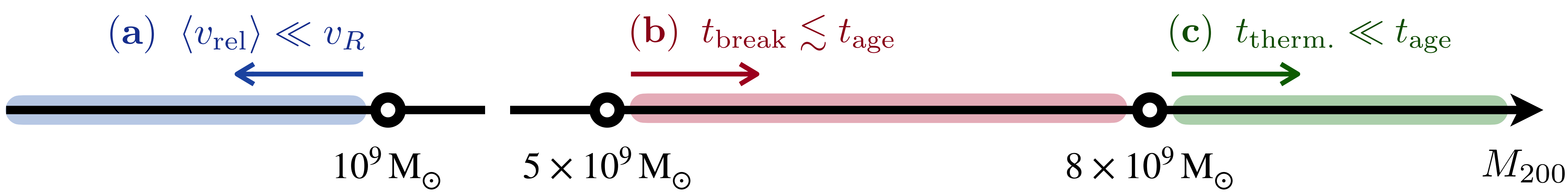


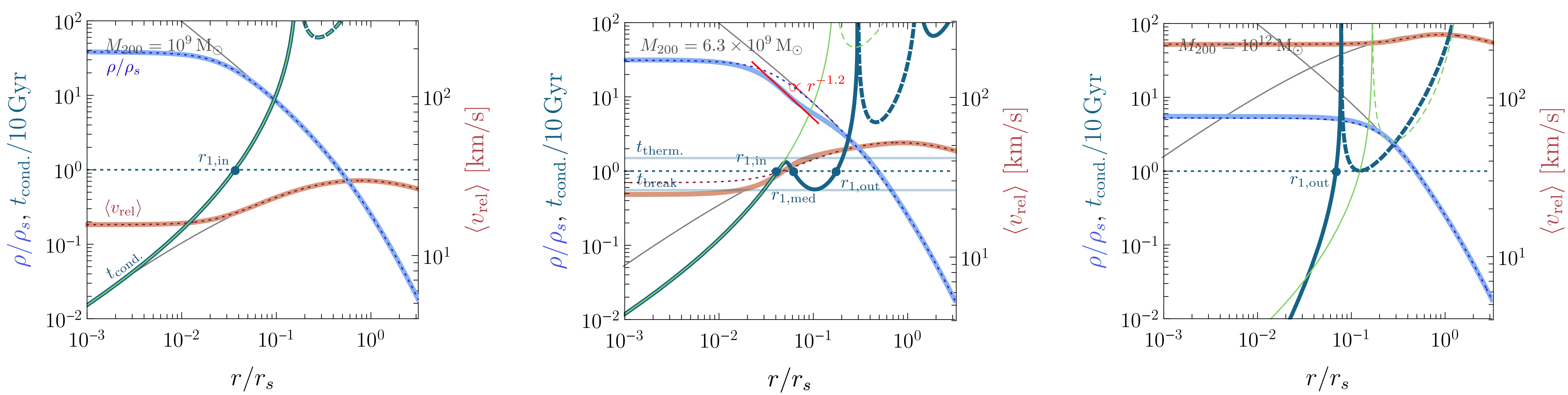


Resonant SIDM halos at present

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)



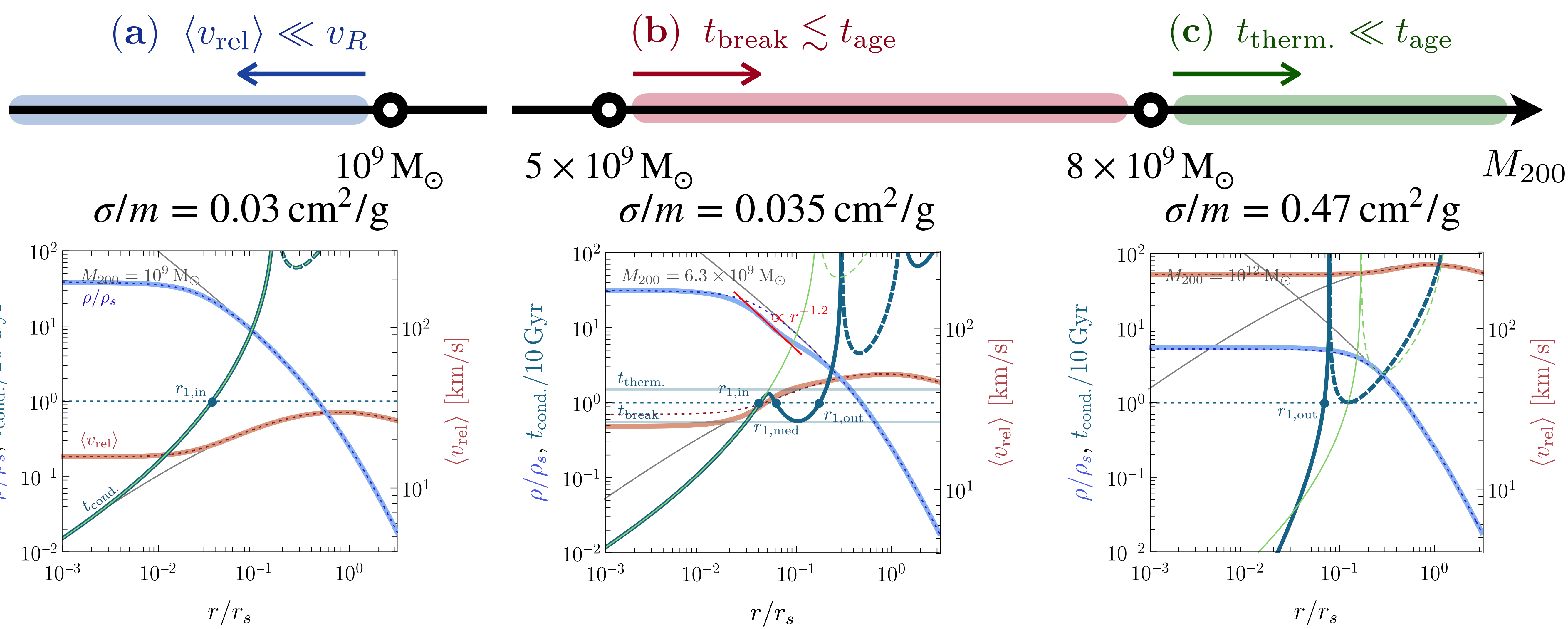


(a) - P2 benchmark (b) (c)

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?



(a) (b) (c)

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- density break in a certain mass range of halos

- change in stellar orbits by density break in the past

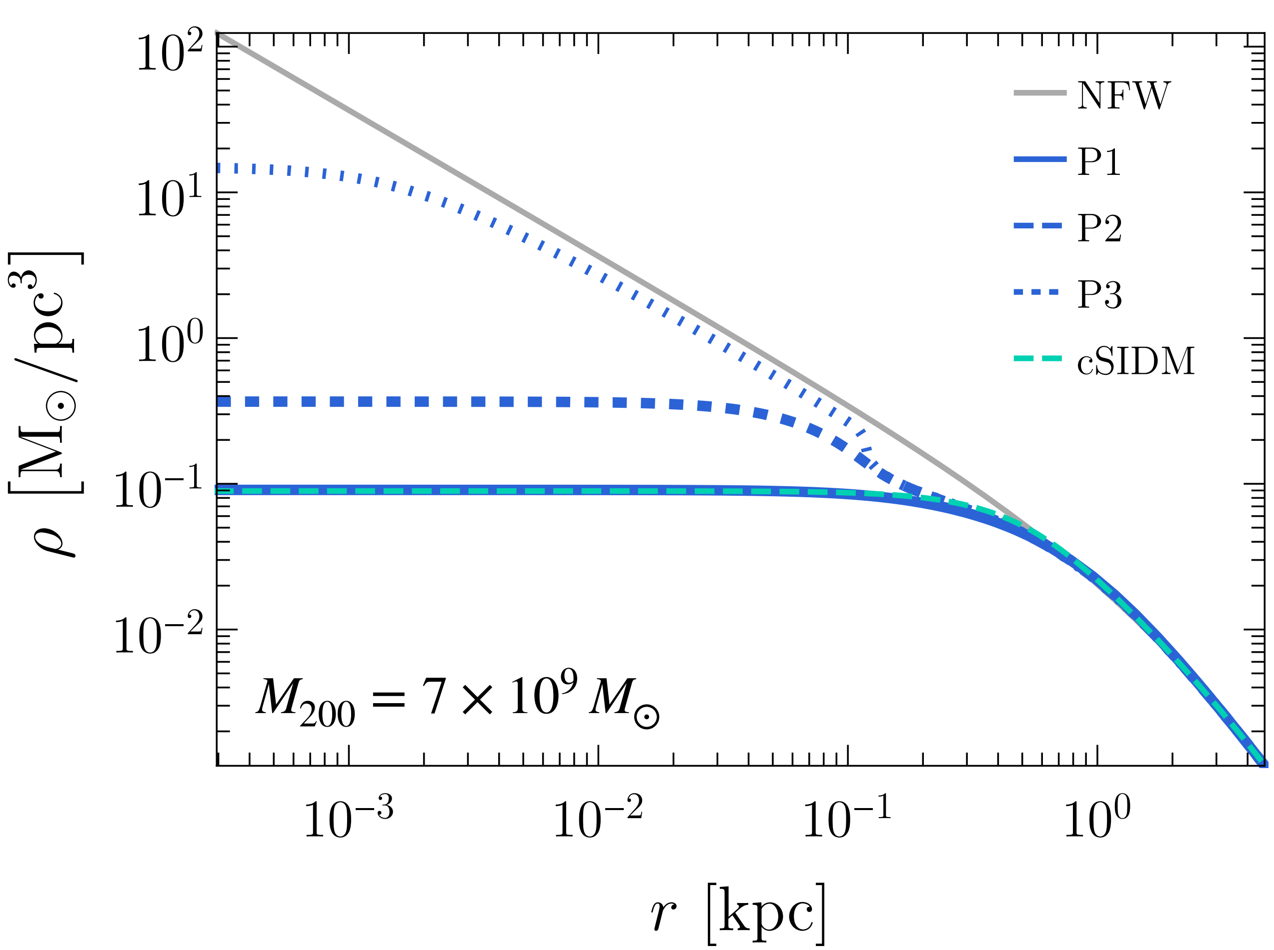
Density breaks at present

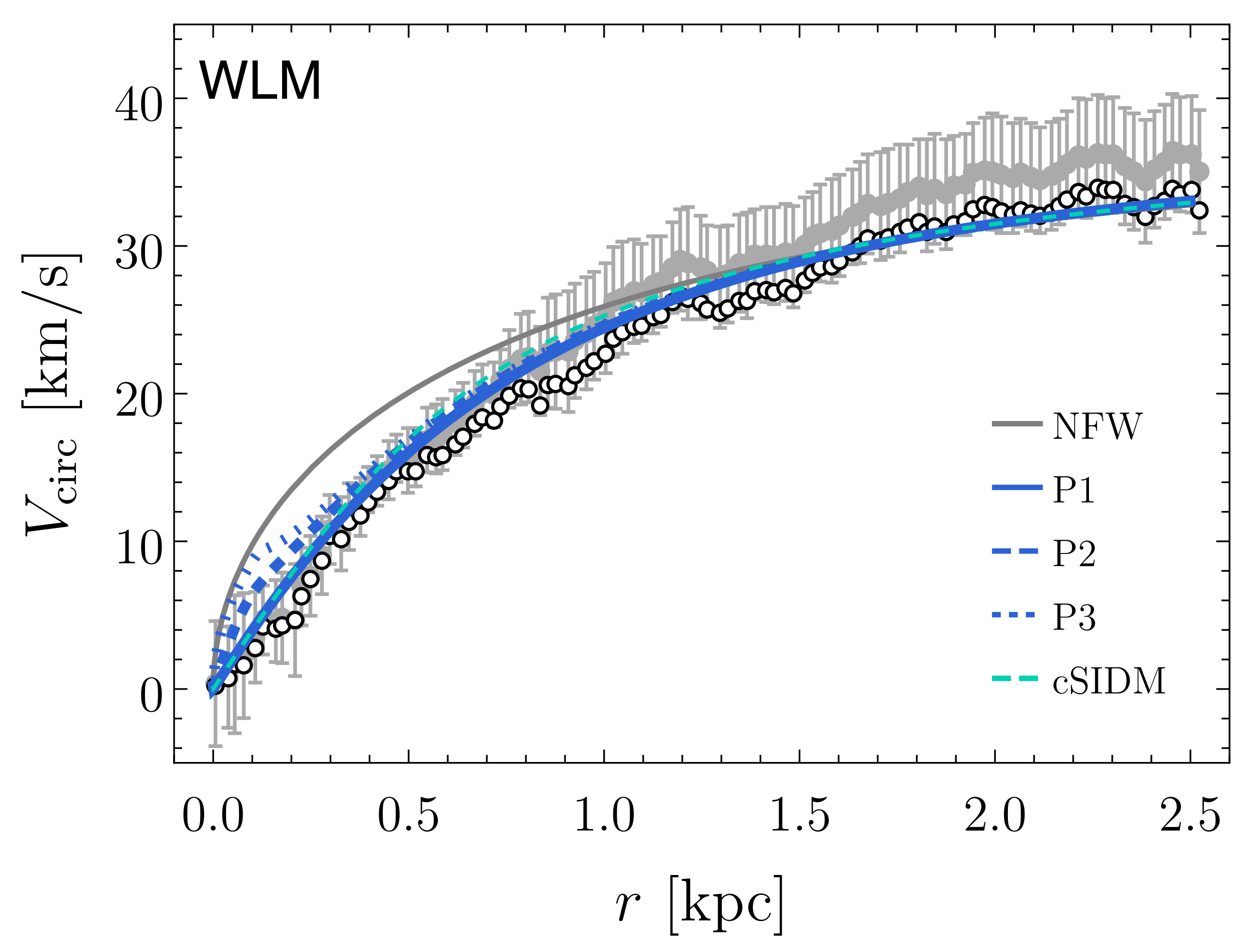
Rotation curve

- P1 benchmark halo is identical to constant SIDM halo $\sigma/m = 0.33\,\mathrm{cm}^2/\mathrm{g}$

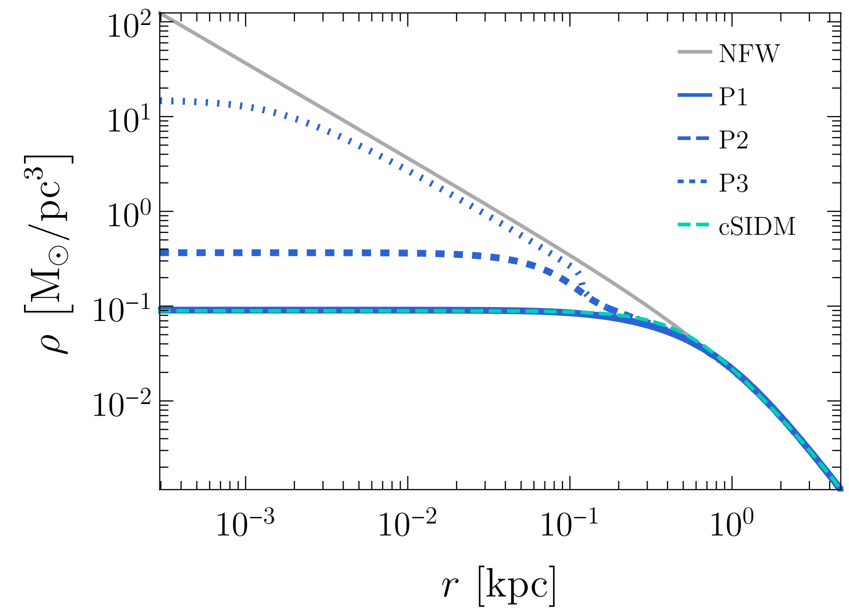
- P3 benchmark halo has a circular velocity profile transiting from constant SIDM to NFW around 0.1 kpc

    - may be a distinctive signature if observed by any chance





Density breaks at present

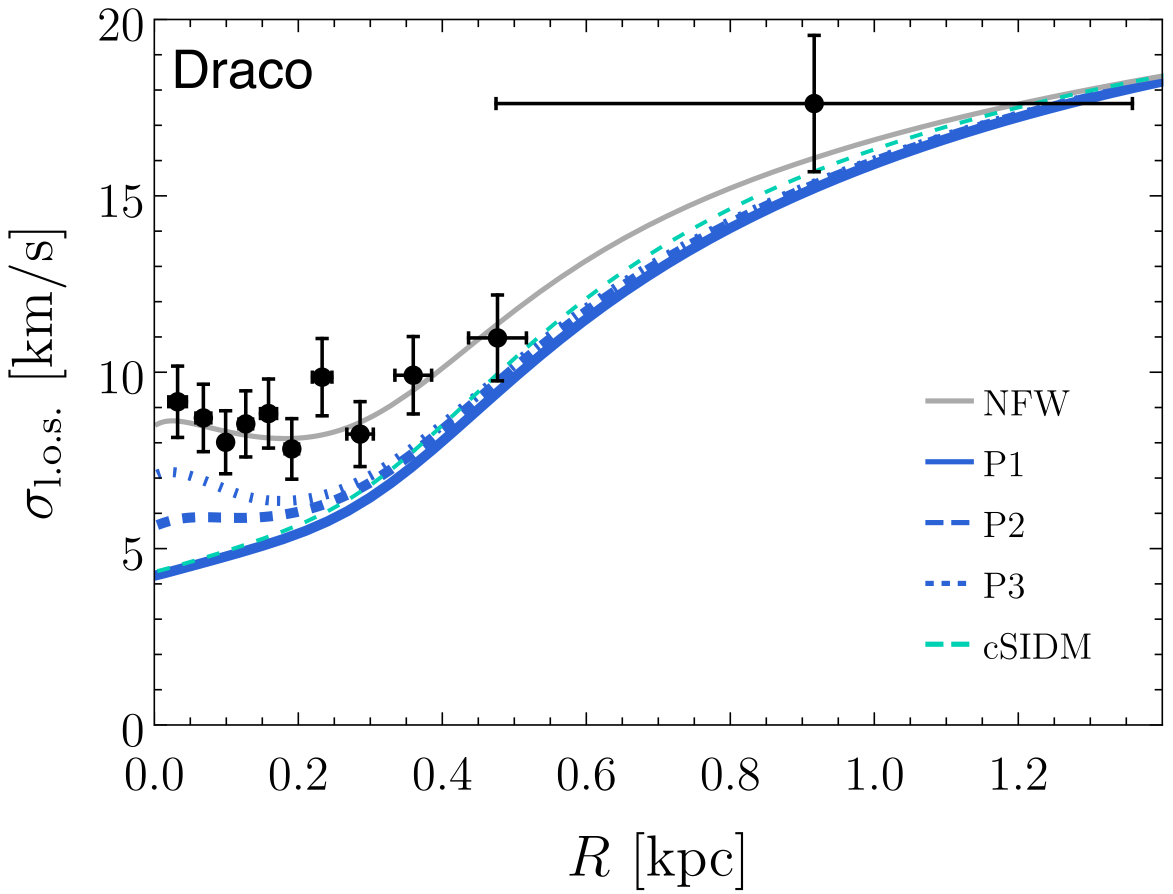


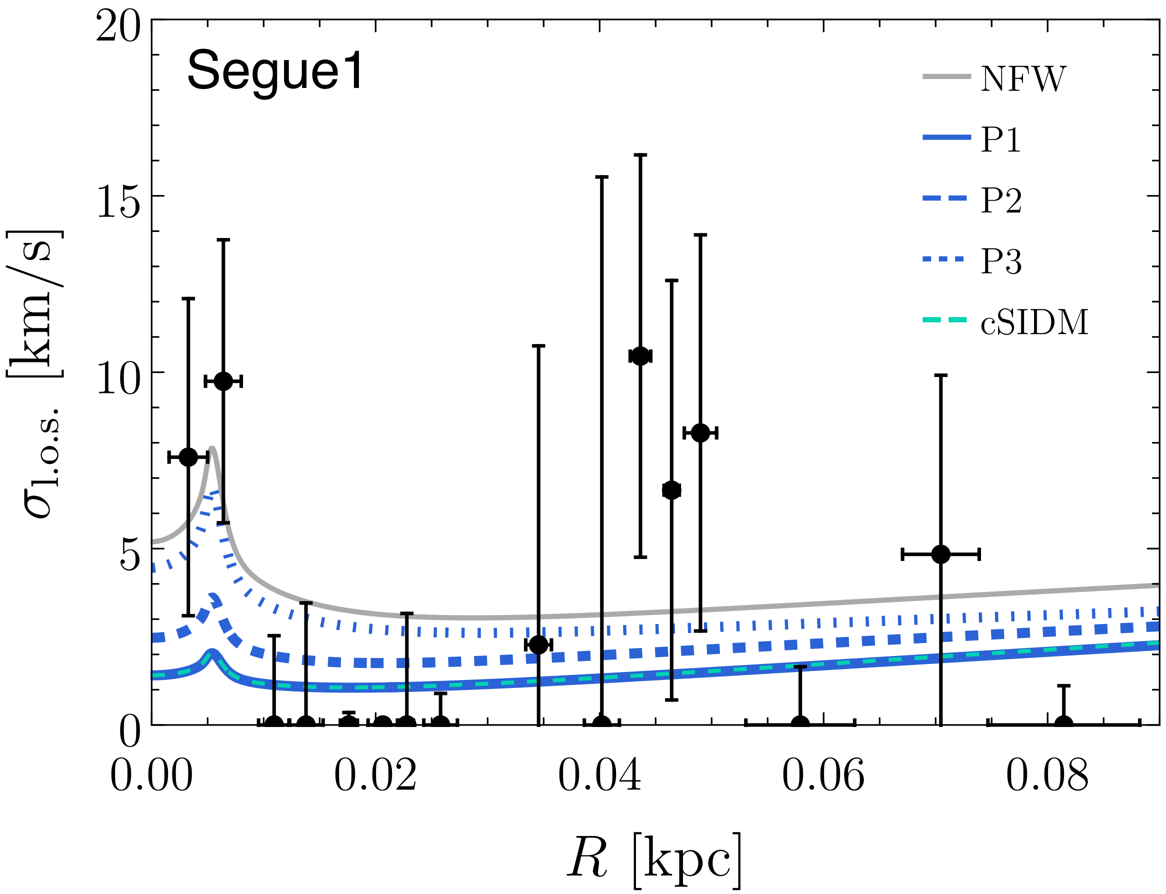
LOSVD profile of MW satellites

- 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





Density breaks in the past

Change in mean stellar orbits

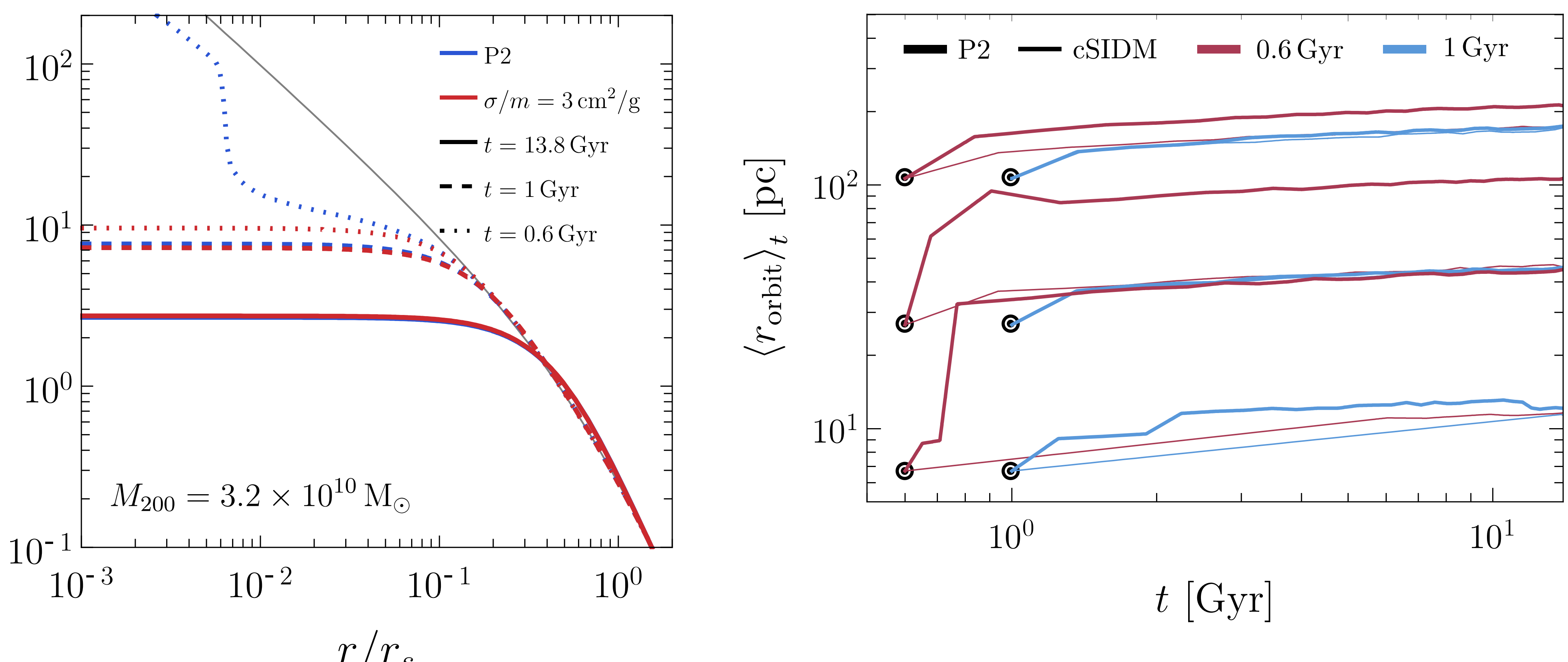
- energy in orbit distribution function is updated by the average change of potential at every orbital period

- 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



Summary

Resonant SIDM

- realizes sharp velocity dependence inferred by cores in various-size halos

Resonant SIDM halos

- density break forms, develops and is thermalized
    - should be confirmed by cosmological simulations (e.g., mergers, tidal stripping…)
- except for a certain mass range, one can find an identical constant SIDM halo
    - not clear how to find systematically

Possible imprints

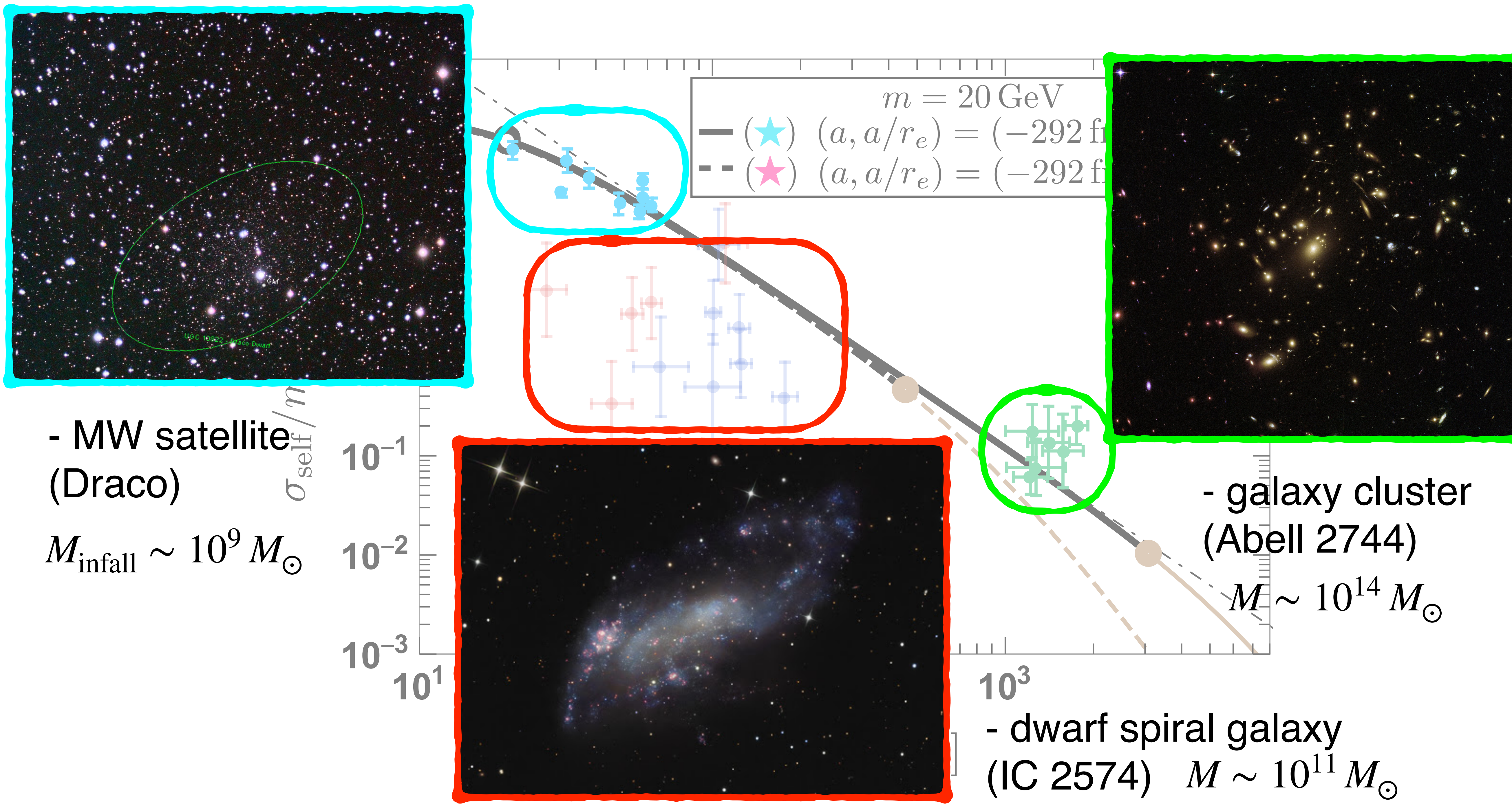
- density break at present may be seen in rotation curves and LOSVD profiles
- density break in the past differentiates orbits of stars forming before and after density break
    - should be studied further

Thank you

Data points

Overview

- cores in various-size halos



Another possible explanation

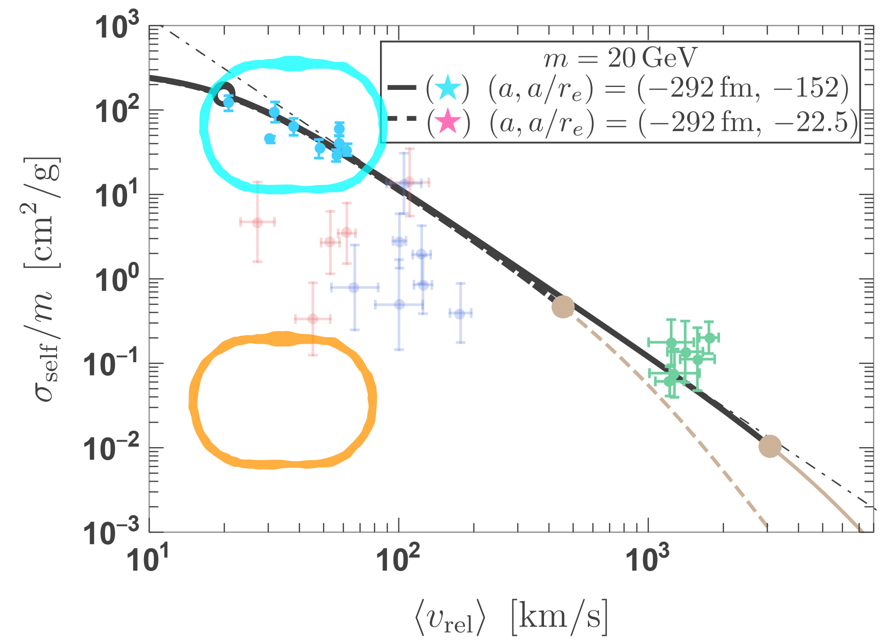
Gravothermal collapse

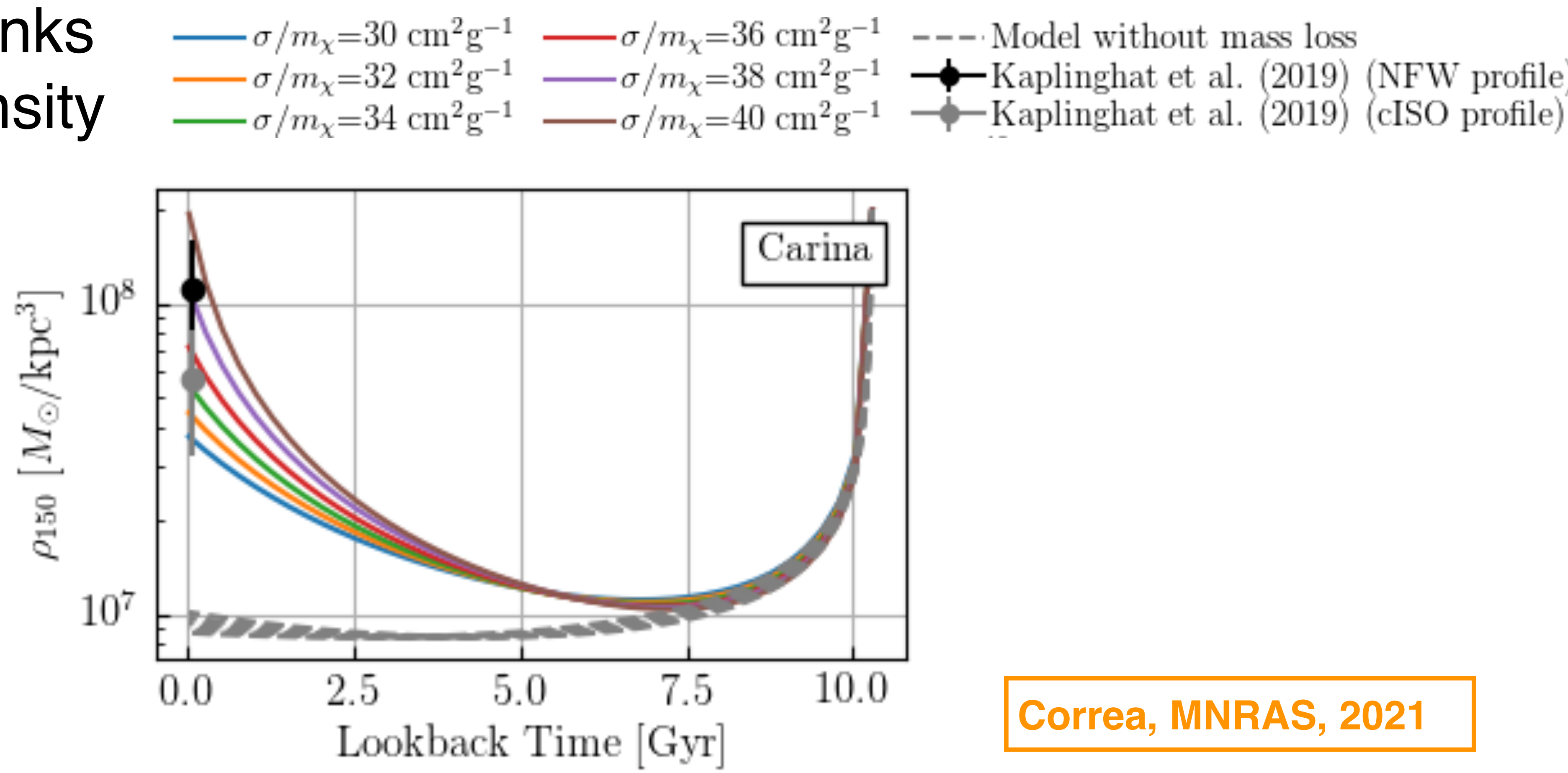
- another possibility is to take as a large cross section as $\sigma_{\rm self}/m \sim 40\,{\rm cm}^2/{\rm g}$

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

- first core expands and central density gets lower

- then core shrinks and central density gets higher





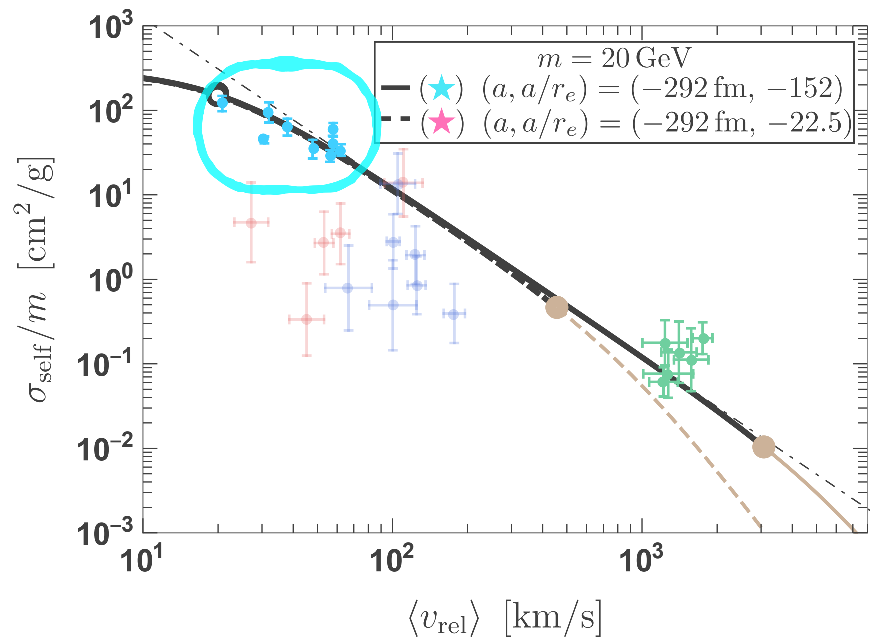
Correa, MNRAS, 2021

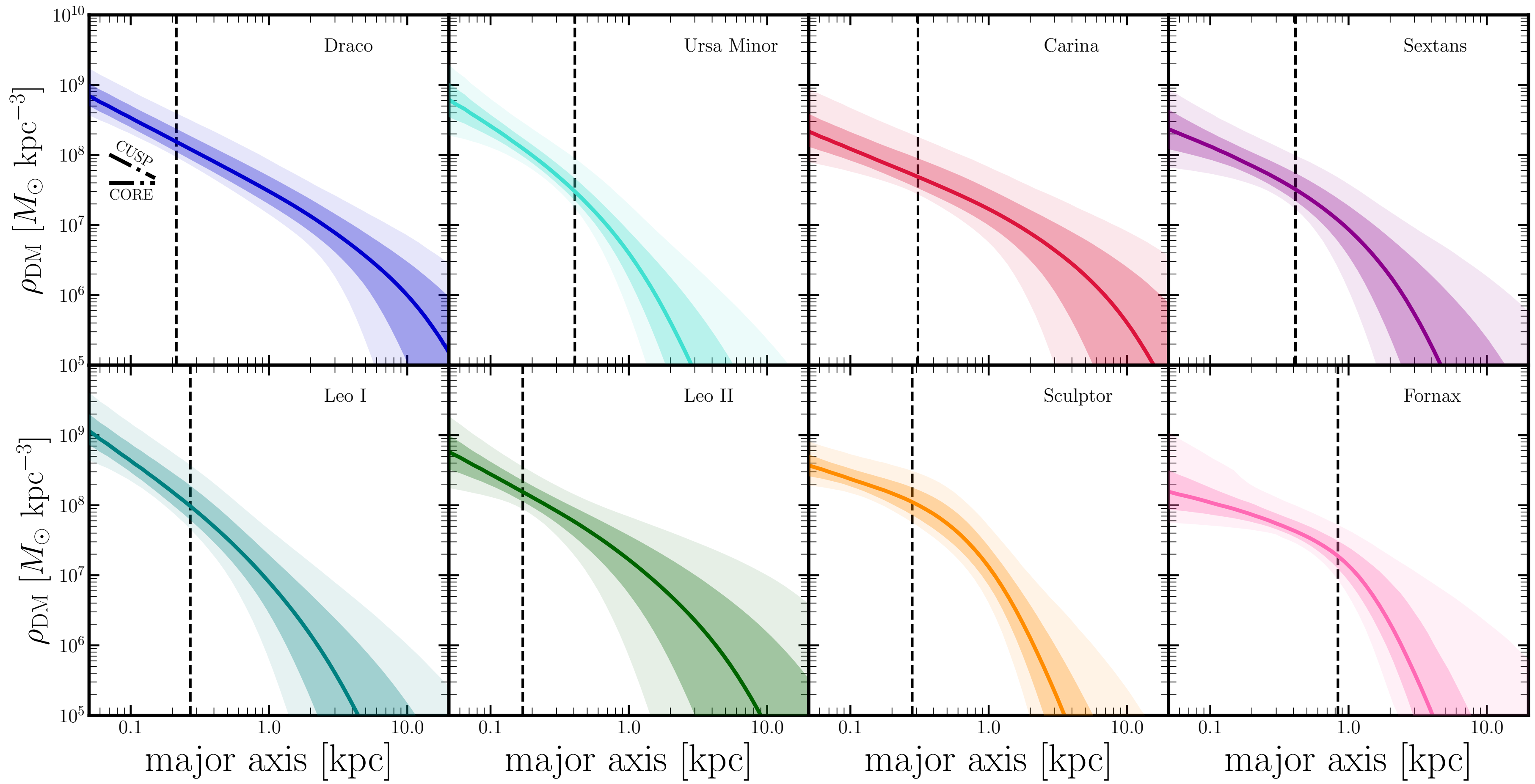
Data points

Classical dwarfs

- mass distribution is determined by stellar kinematics

- stellar kinematics in the central region (of some satellites) prefer cuspy CDM profile





Hayashi, Chiba, and Ishiyama, ApJ, 2020

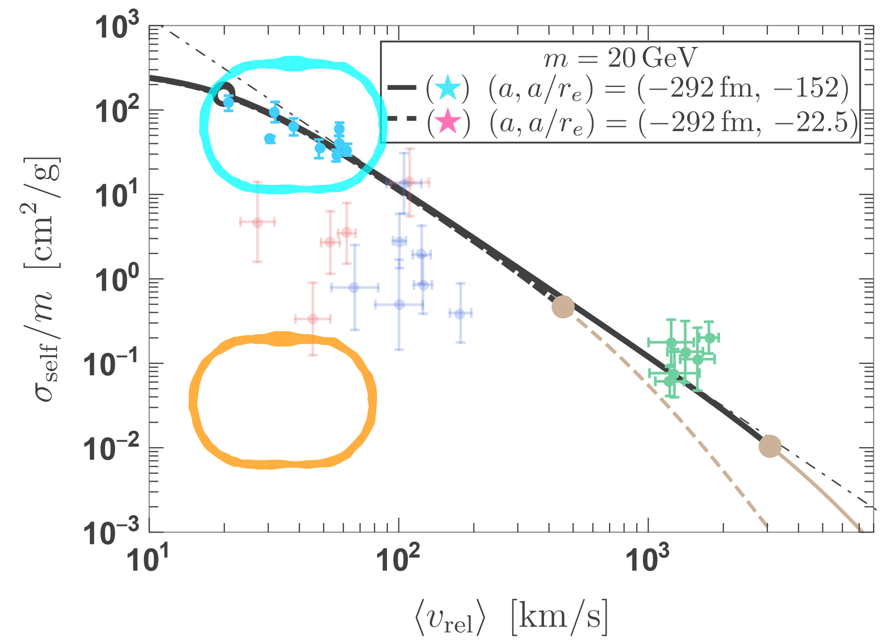
Data points

Classical dwarfs

- one possibility is to take as a tiny cross section as $\sigma_{\rm self}/m \simeq 0.01\,{\rm cm^2/g}$

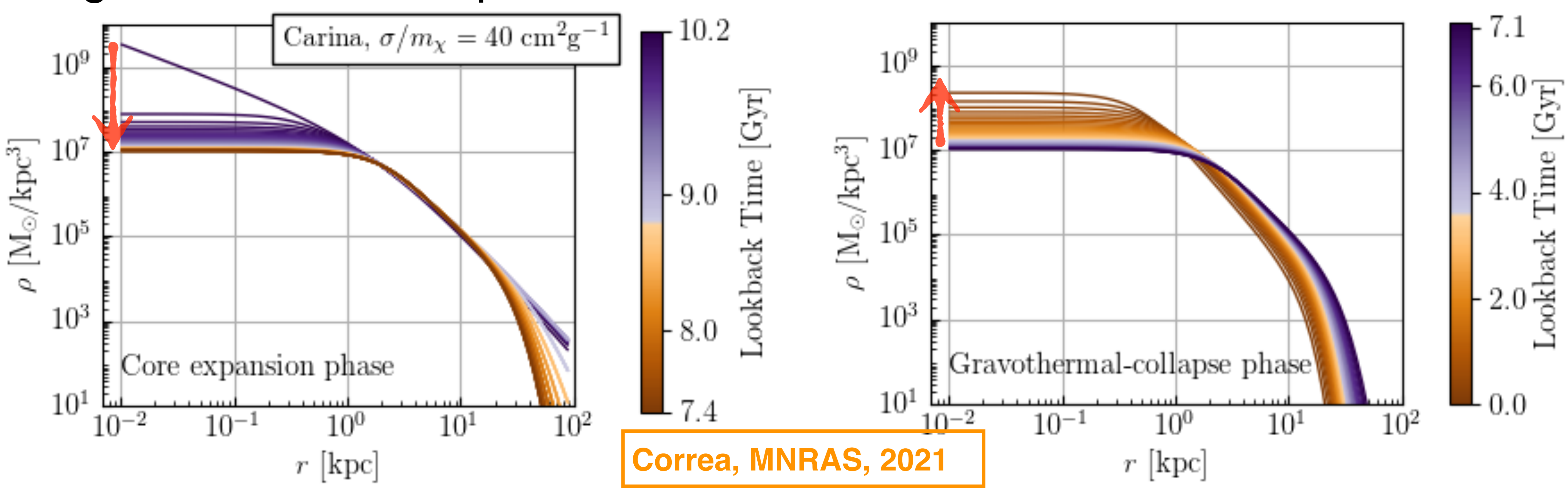
$$\langle v_{\rm rel} \rangle \sim 30\,{\rm km/s}$$

- resonance? **Chu, Garcia-Cely, and Murayama, PRL, 2019**



- another possibility is to take as a large cross section as $\sigma_{\rm self}/m \sim 40\,{\rm cm^2/g}$ $\langle v_{\rm rel} \rangle \sim 30\,{\rm km/s}$

- gravothermal collapse

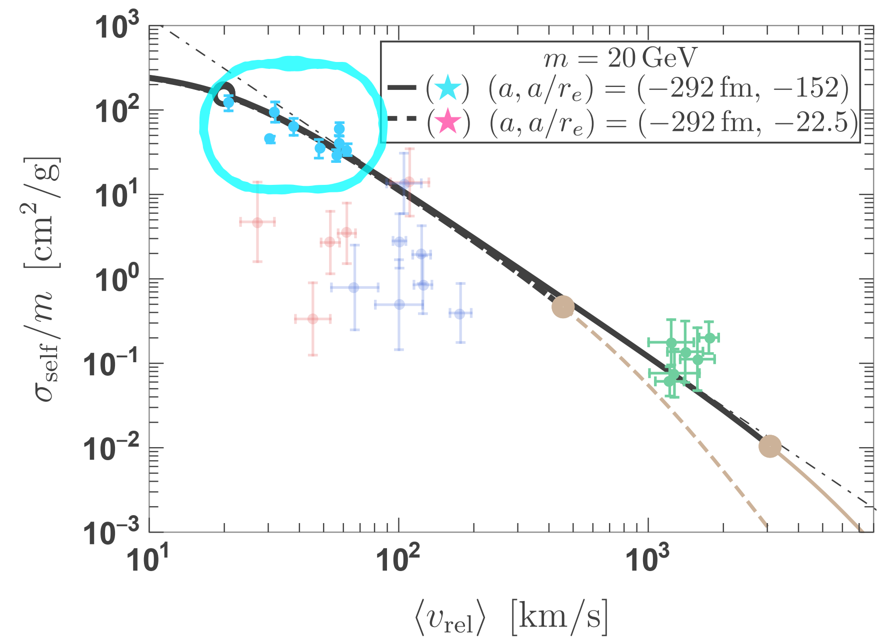


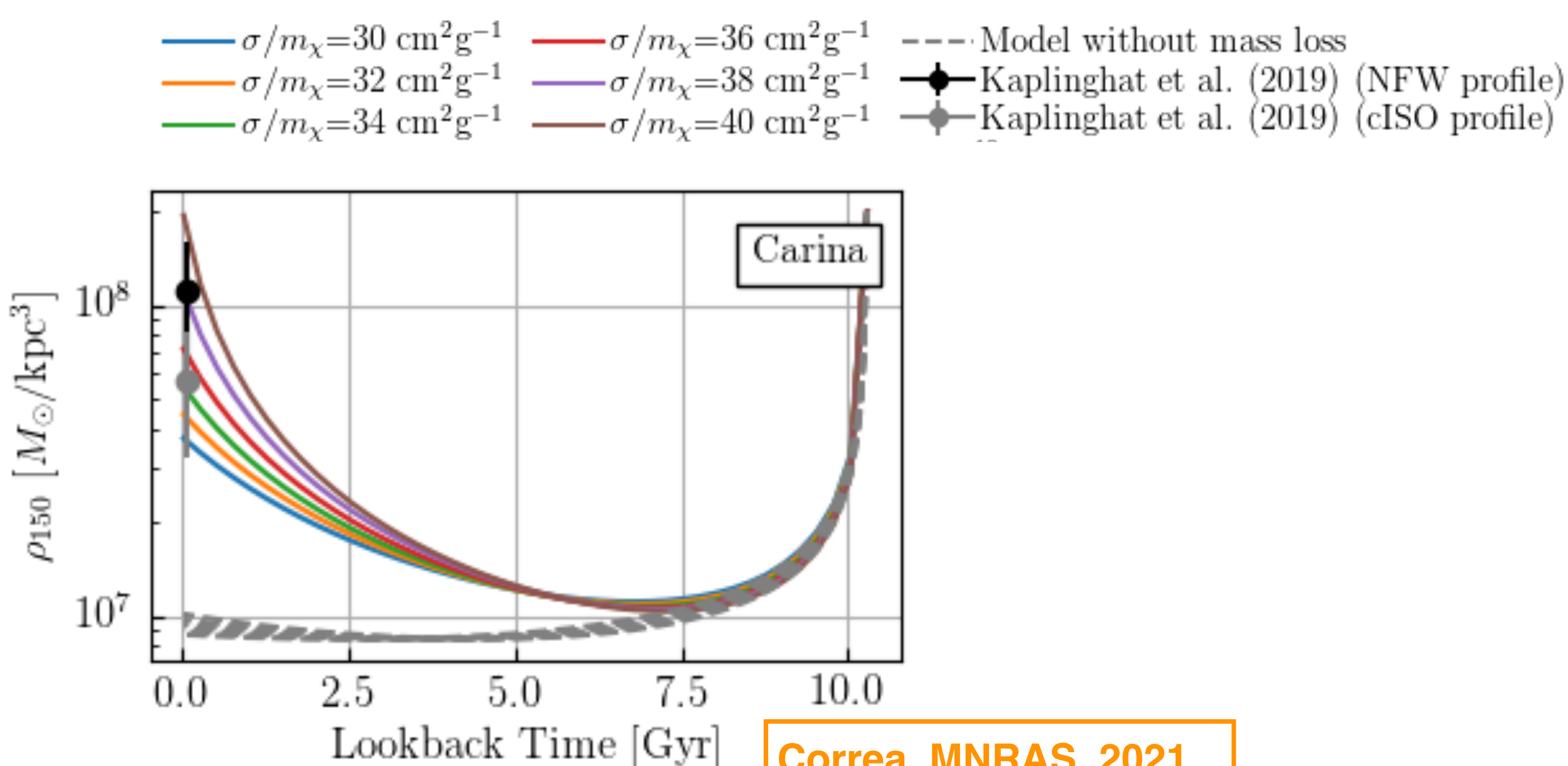
Correa, MNRAS, 2021

Data points

Classical dwarfs

- gravothermal collapse
    - core shrinks and central density gets higher
    - central density at present is very sensitive to the cross section

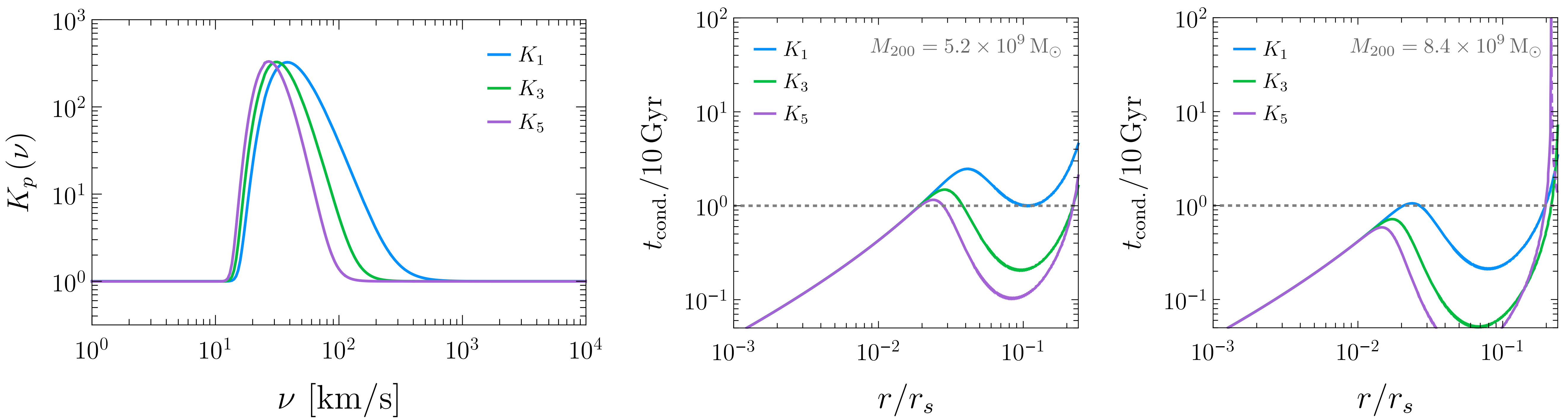




Correa, MNRAS, 2021

Gravothermal modeling

Dependence on distribution averaging



Evolution of resonant SIDM halos

Formation and thermalization time