Gravothermal Evolution of Galactic Dark Matter Halos with Velocity Dependent Self-interactions

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In collaboration with
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Work in progress

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Outline

- Introduction
- Time scales in gravothermal evolution
  - Avoiding core collapse (gravothermal catastrophe)
  - Forming super massive black hole (SMBH)
- Summary

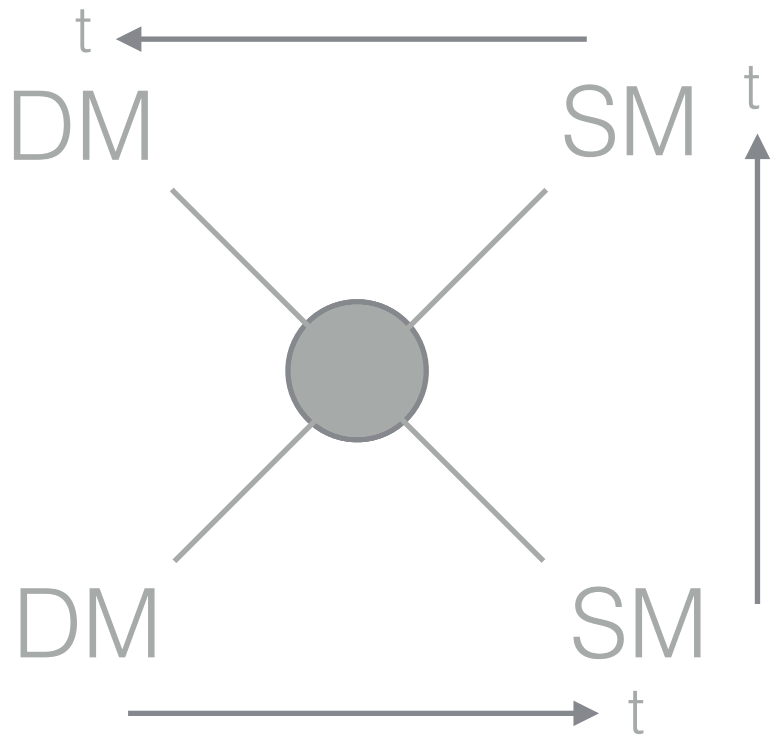
Self-interacting dark matter (SIDM)

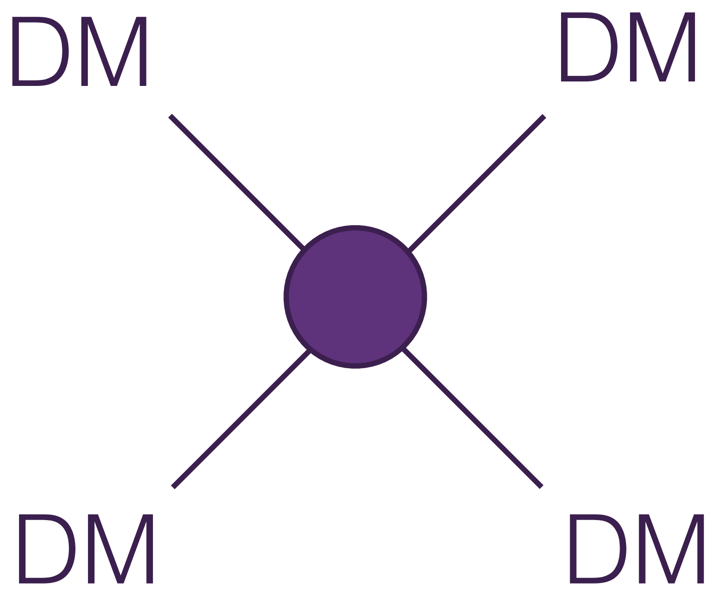
- Cold collisionless dark matter (CDM) is an ingredient of ΛCDM. Works great at large scales; meets challenges at small scales

- SIDM was originally proposed as a solution

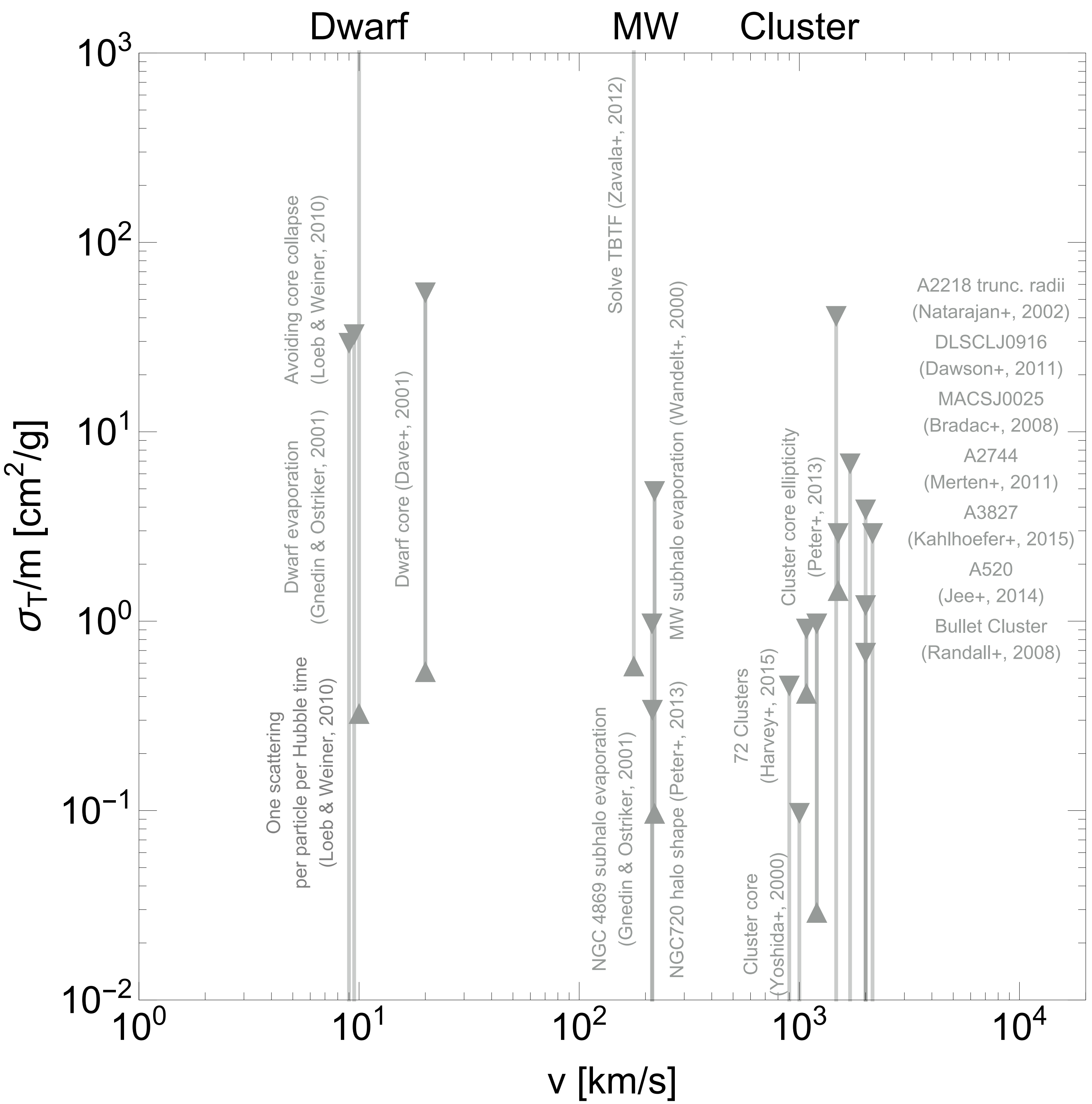
Spergel & Steinhardt, ’00

- More generally, DM self-interaction points to a new direction for DM study.





Strength of DM self-interaction



SIDM is studied at clusters, MW galaxies, dwarfs scales.

Upper range: merges, core shapes…

Lower range: significant self-interaction rate to explain some anomalies

Preferred value:
$\sigma/m \sim O(0.1)$ cm^2/g

1 cm^2/g ≈ 2 barn/GeV

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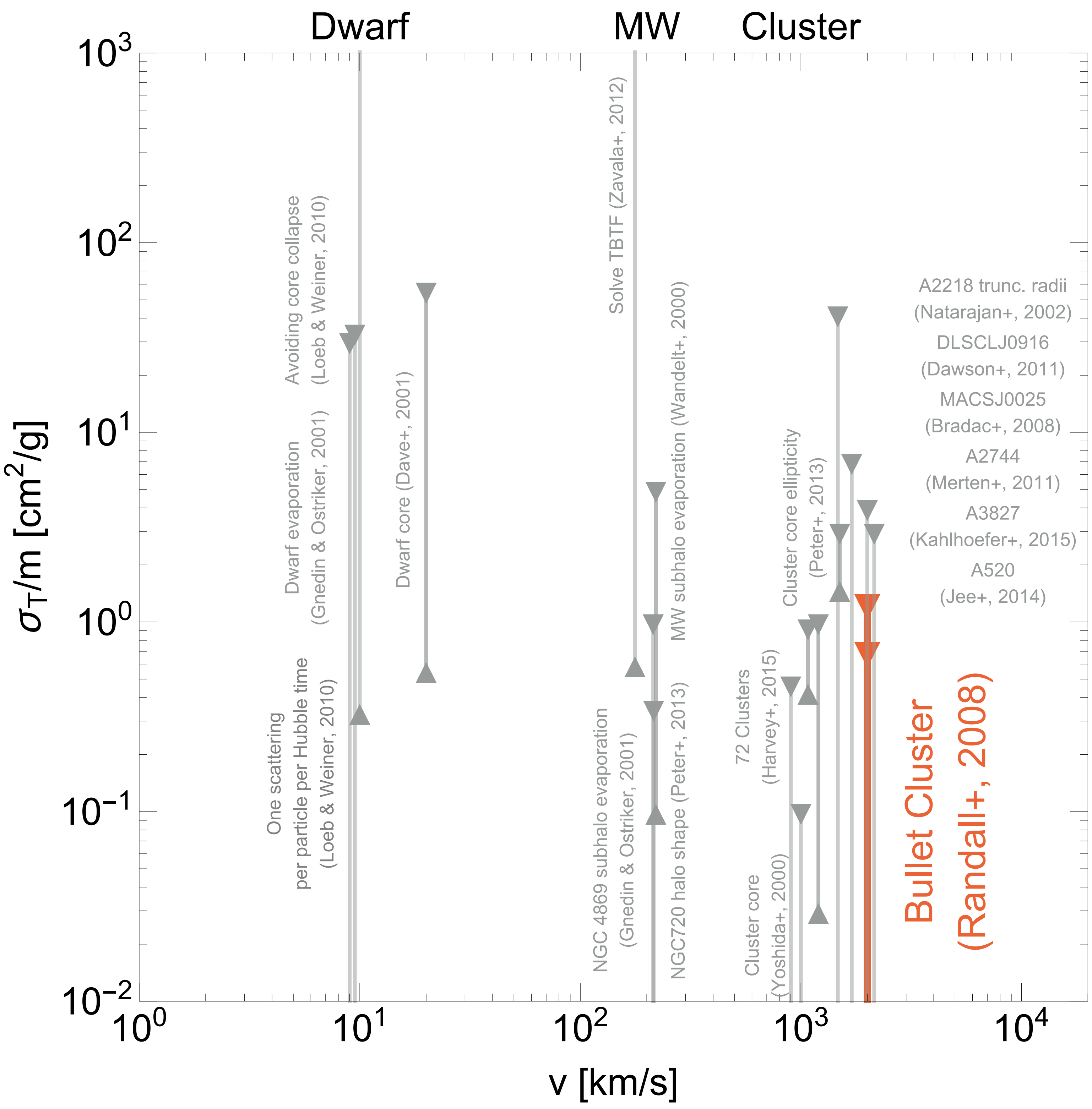

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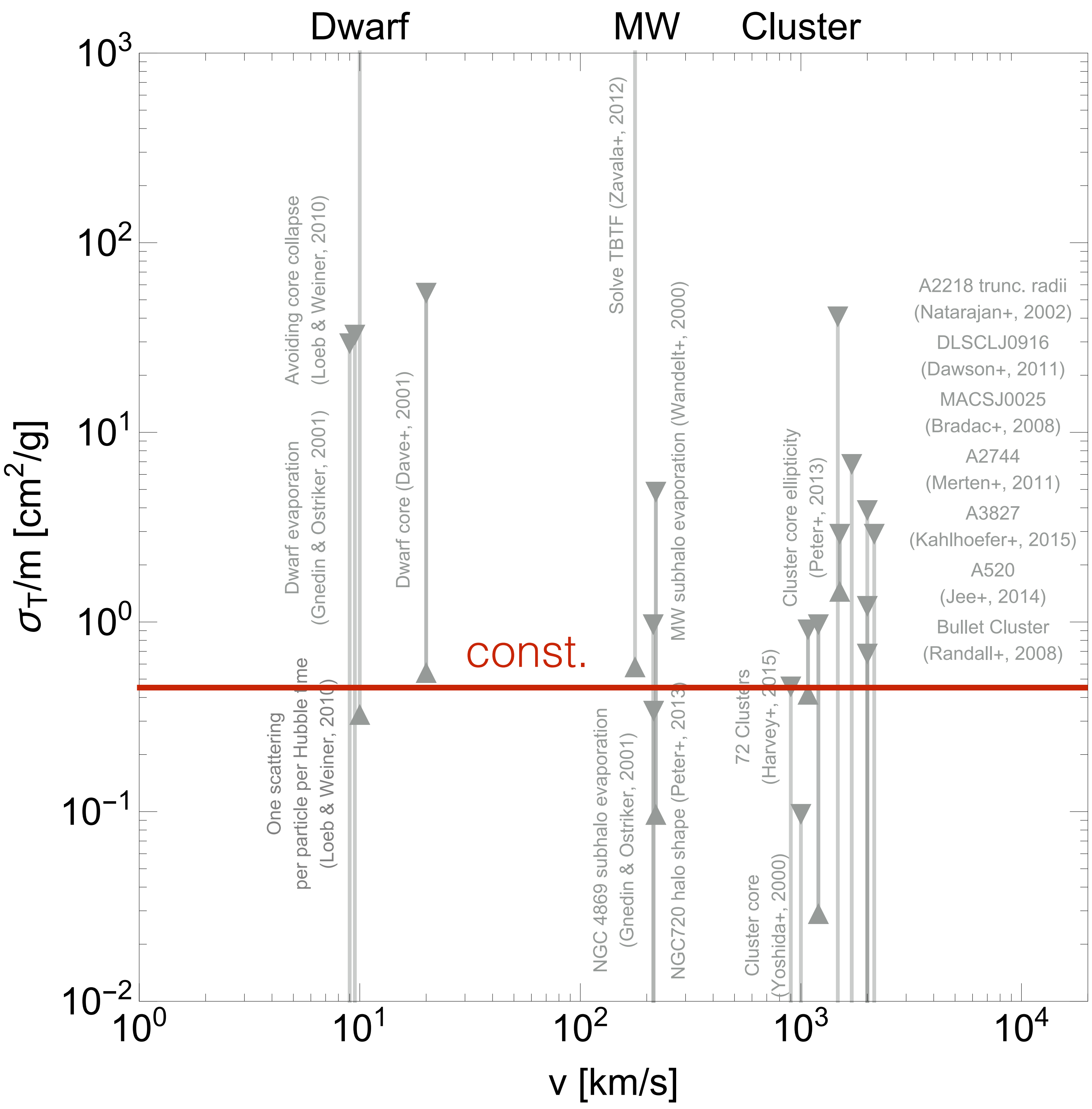

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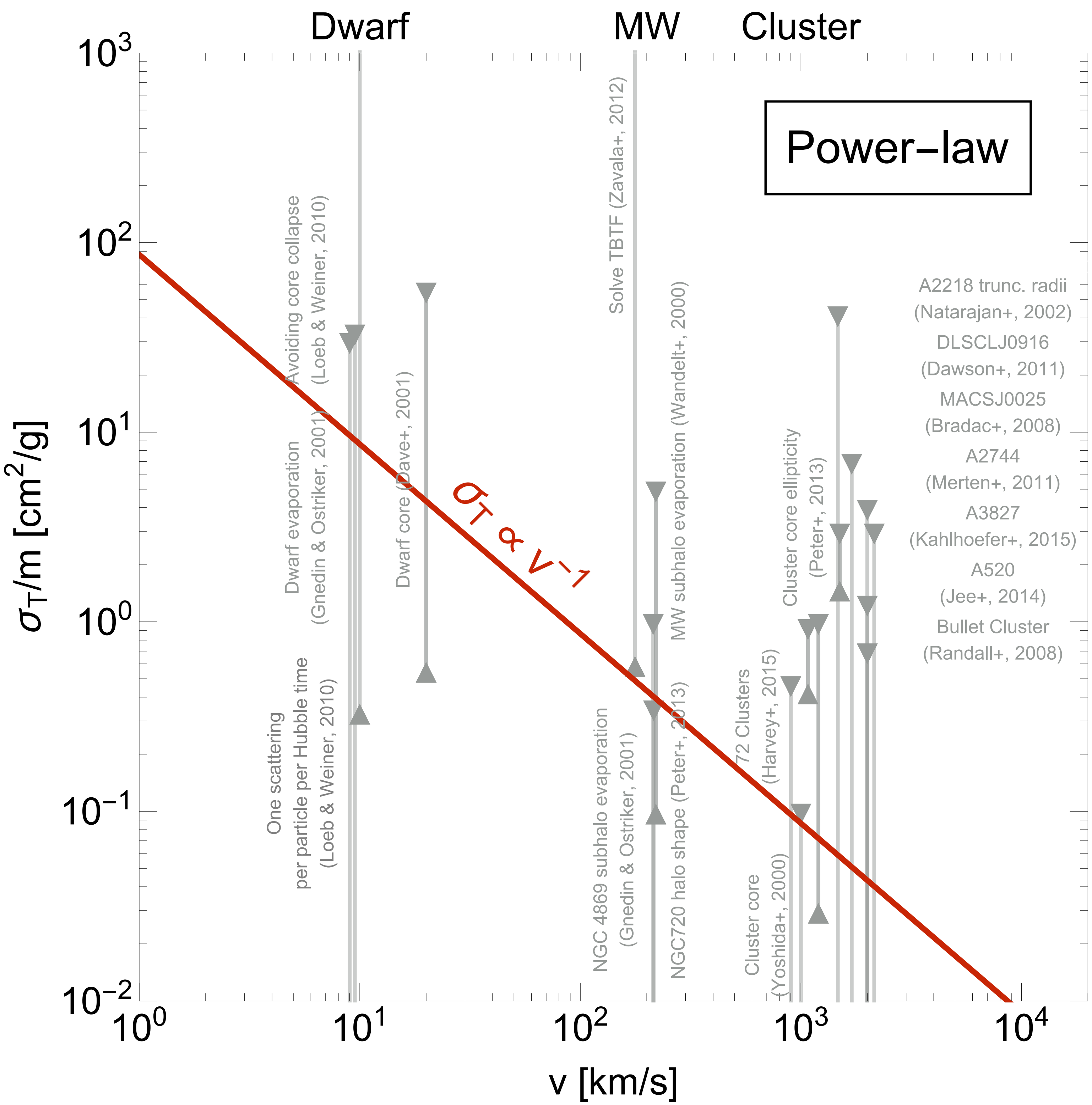
Velocity-dependent SIDM (vdSIDM)



DM self-interaction may be non-trivial

light mediators
⇒ vdSIDM

e.g. Ackerman et al ’08,
Buckly & Fox ’09, Feng et al ’09
Loeb & Weiner ’10, Tulin et al ’10

Easier to satisfy bounds at all scales
(e.g. power-law vd)

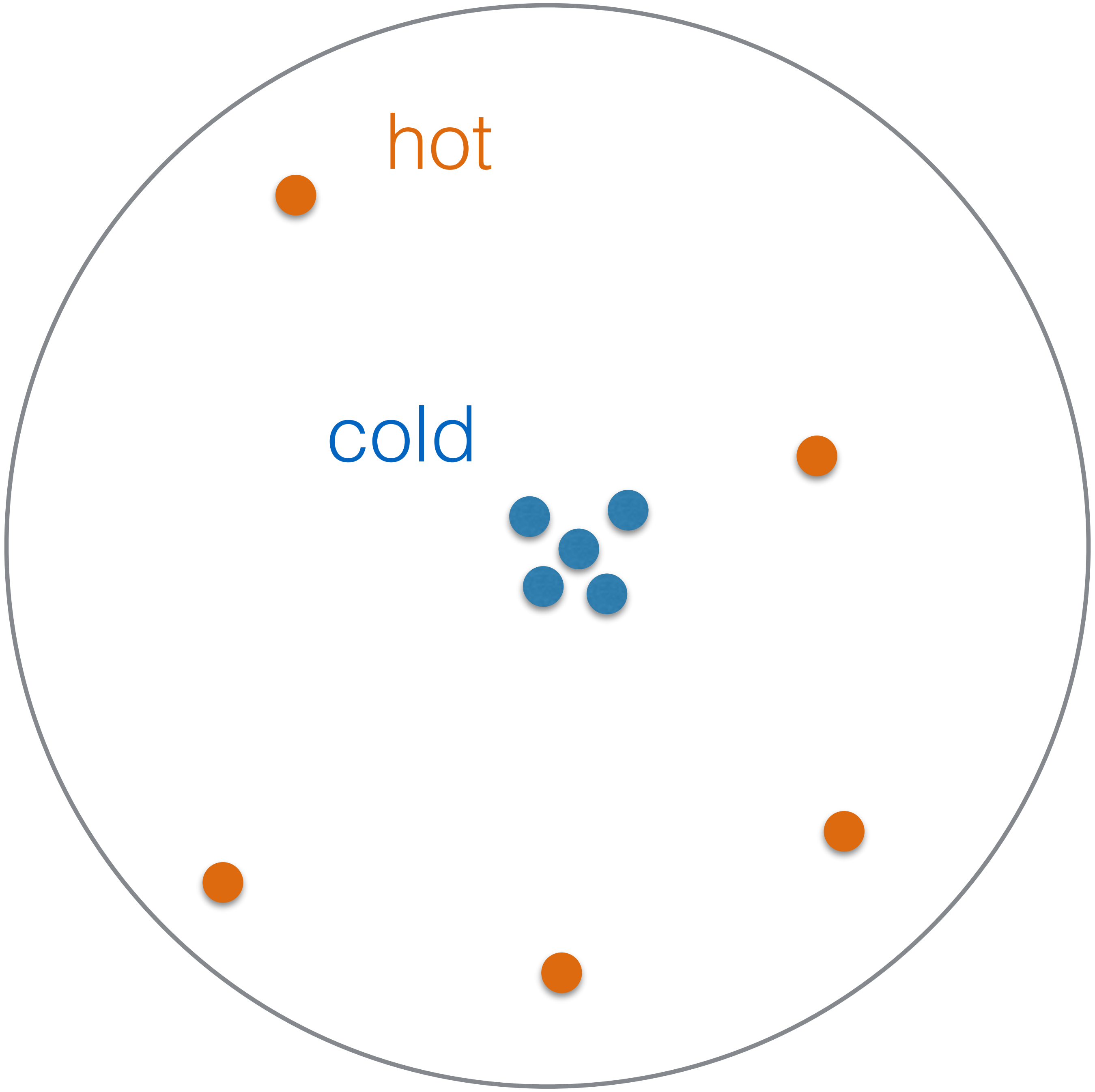
Gravothermal evolution

- DM self-interaction allows for kinetic heat flow
- DM halo experiences gravothermal evolution: first core develops, then core collapses
- Can calculate various constraints/preferred values on σ/m. e.g. time scale of the beginning/end of core collapse
- Earlier studies on time scales focus on velocity independent SIDM (viSIDM) evolution

Balberg & Shapiro, ’02, Balberg et al ’02, Koda & Shapiro, ’11, Pollack et al, ’15

A brief history of SIDM halo

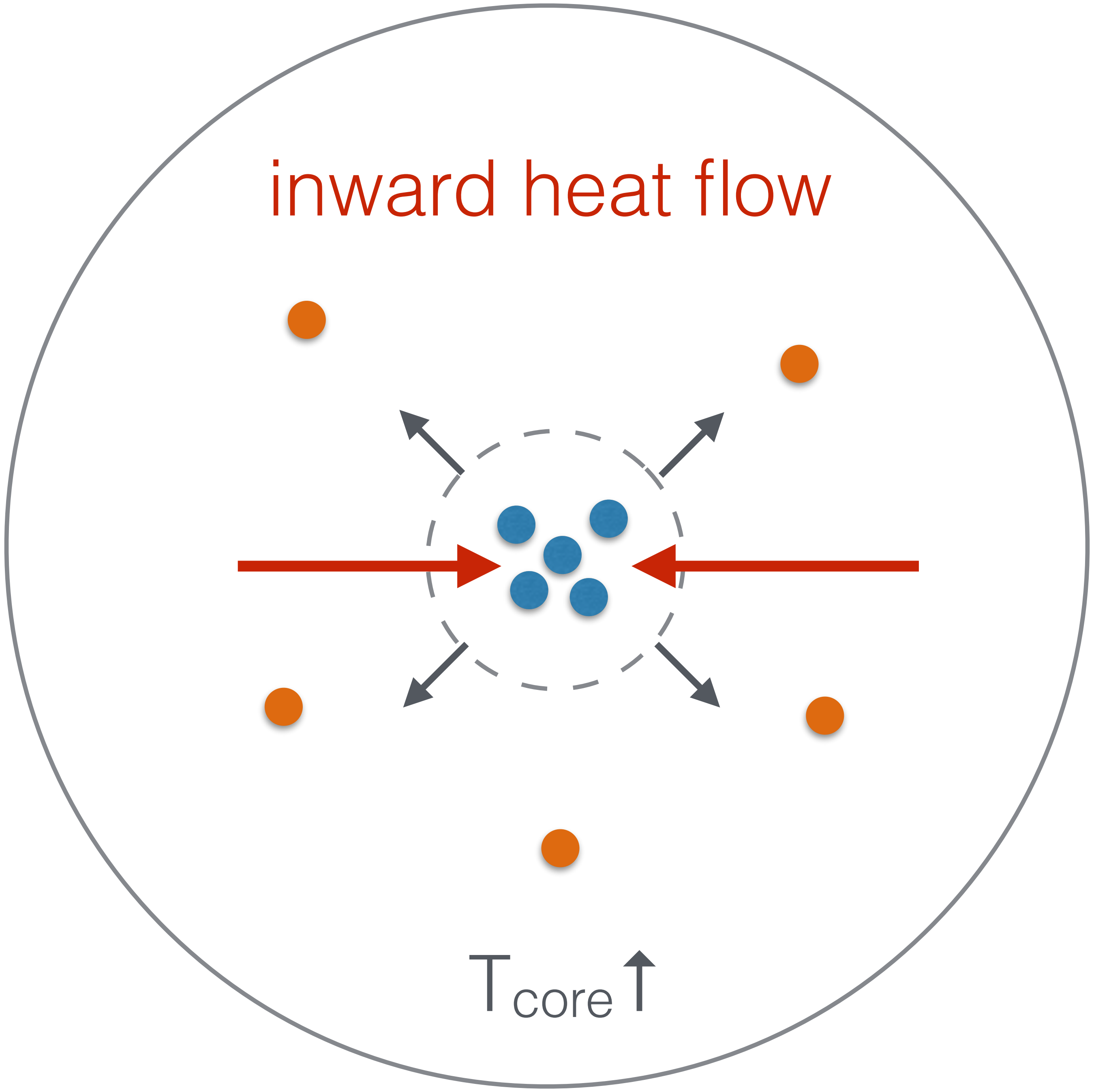
I. NFW profile



A brief history of SIDM halo

I. NFW

II. Core develops

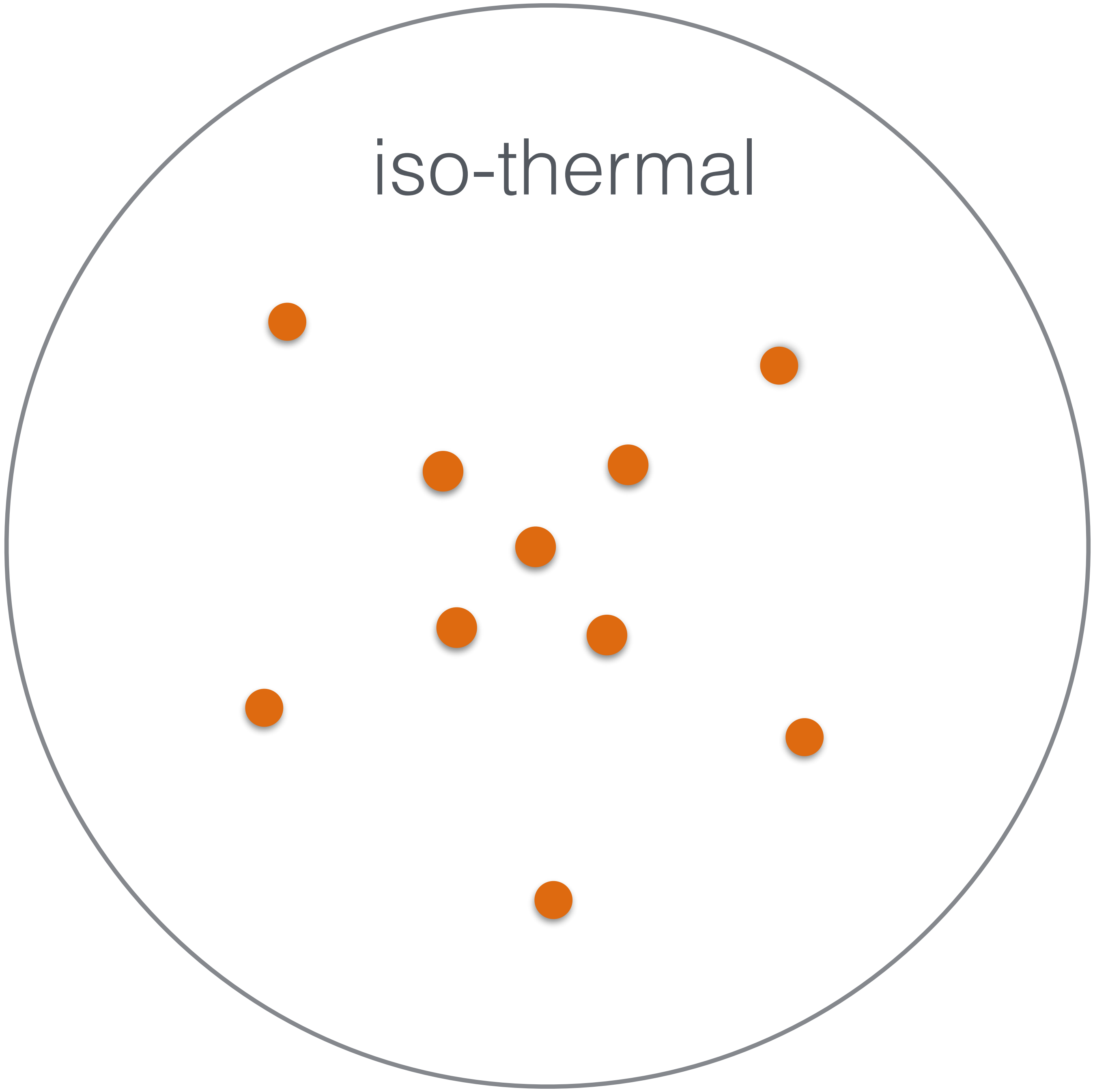


A brief history of SIDM halo

I. NFW

II. Core develops

III. Core profile



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I. NFW

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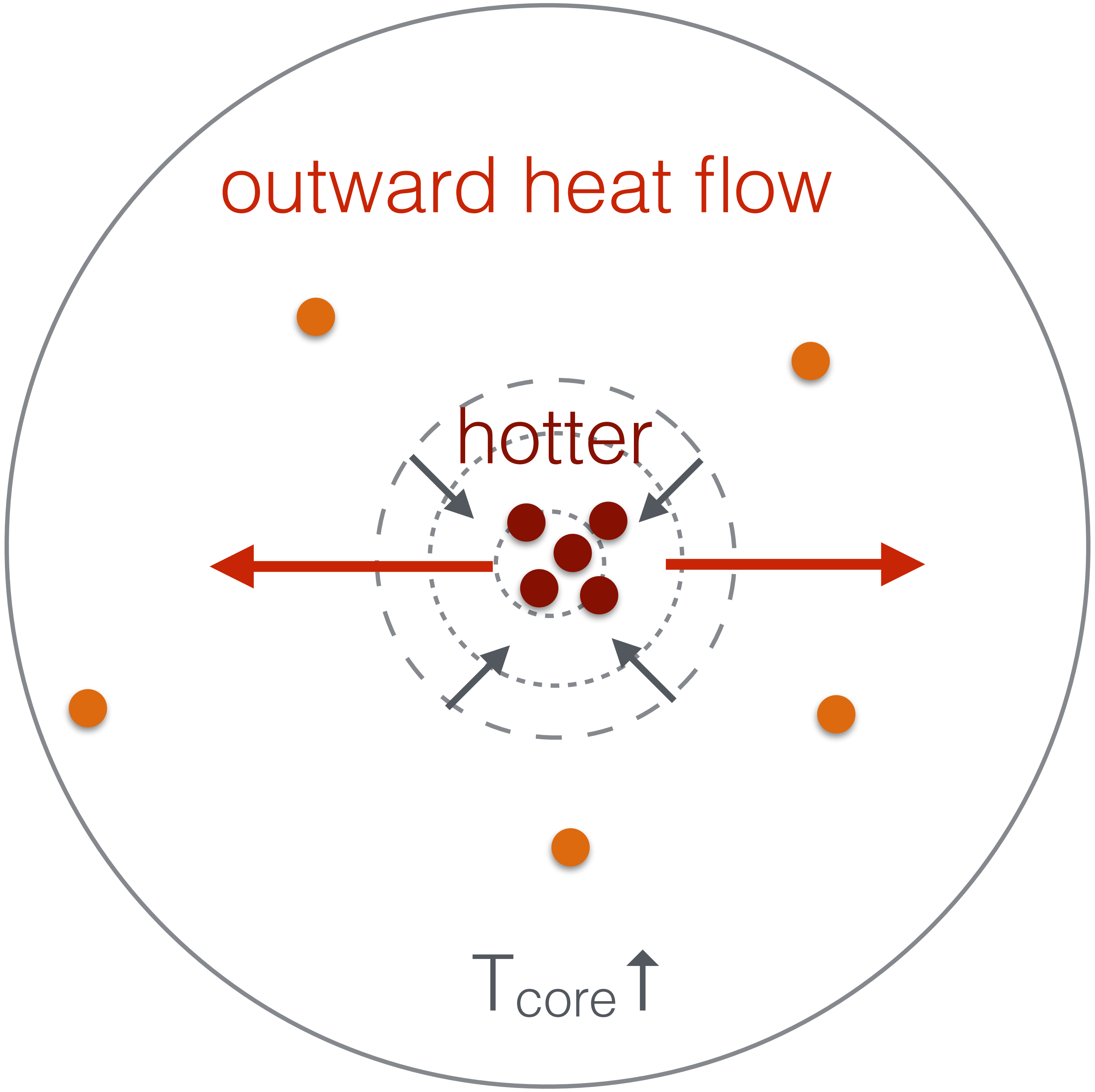
IV. Core collapses



Method

- Use conducting gas/fluid model to study an isolated spherical DM halo

Globular cluster: Hachisu et al ’78,
Lynden-Bell & Eggleton, ’80;
DM halo: Balberg et al, ’00

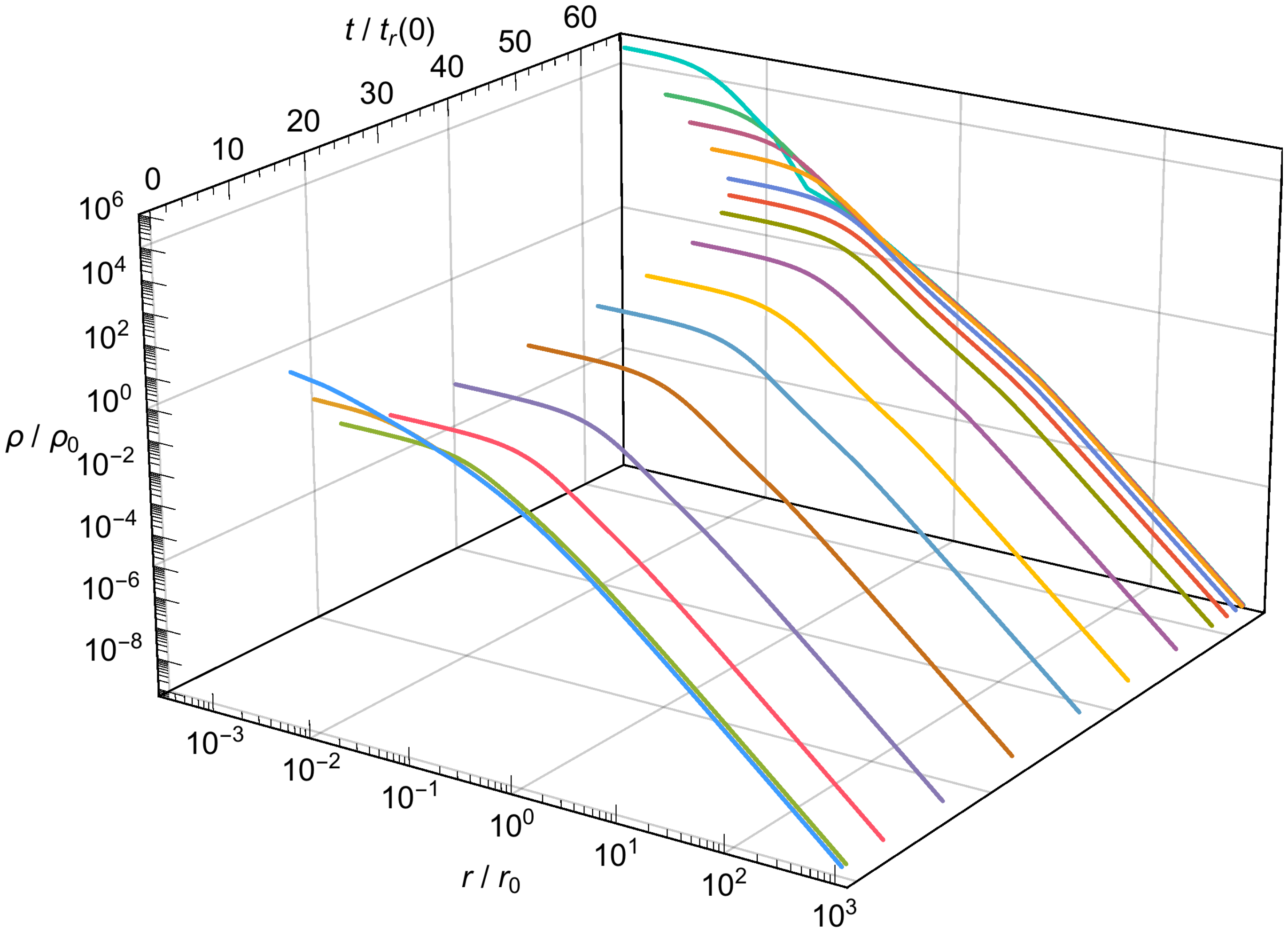
- Agrees with N-body simulations reasonably well (for viSIDM, after calibrating conductivity coefficient); profiles resolve deeply; easy to compute

Koda & Shapiro, ’11

- Few N-body simulation study on time-scales for vdSIDM case available. We simply adopt conductivity coefficients from transport theory.

N-body simulation study on vdSIDM: Zavala et al, ’12,
Vogelsberger et al ’12 ’14, Buckley et al ’14, Robertson et al ’15…

Result



Evolution of the density profile
(n = 1)

- Initial profile NFW

$$\rho = \frac{\rho_0}{(r/r_0)(1+r/r_0)^2}$$

- Self-interaction

$$\sigma/m = (\sigma/m)_p \, (v_p/v_{\rm rel})^n$$

$$v_p = \nu_0 \equiv \sqrt{4\pi G\rho_0 r_0^2}$$

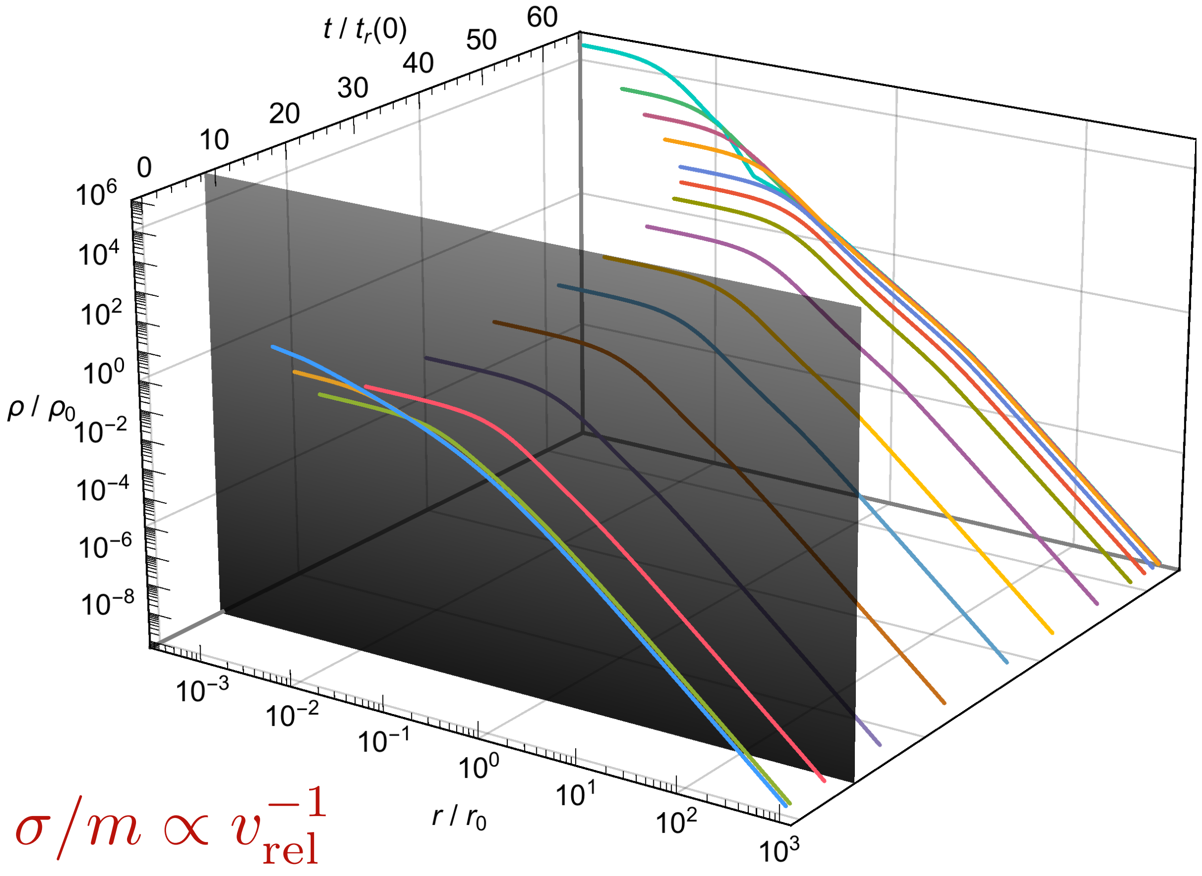
- Unit time

$$t_r(0) \equiv \frac{1}{a_n\rho_0(\sigma/m)_p(\nu_0/\nu_{\substack{t=0\\r=r_0}})^n\nu_0}$$

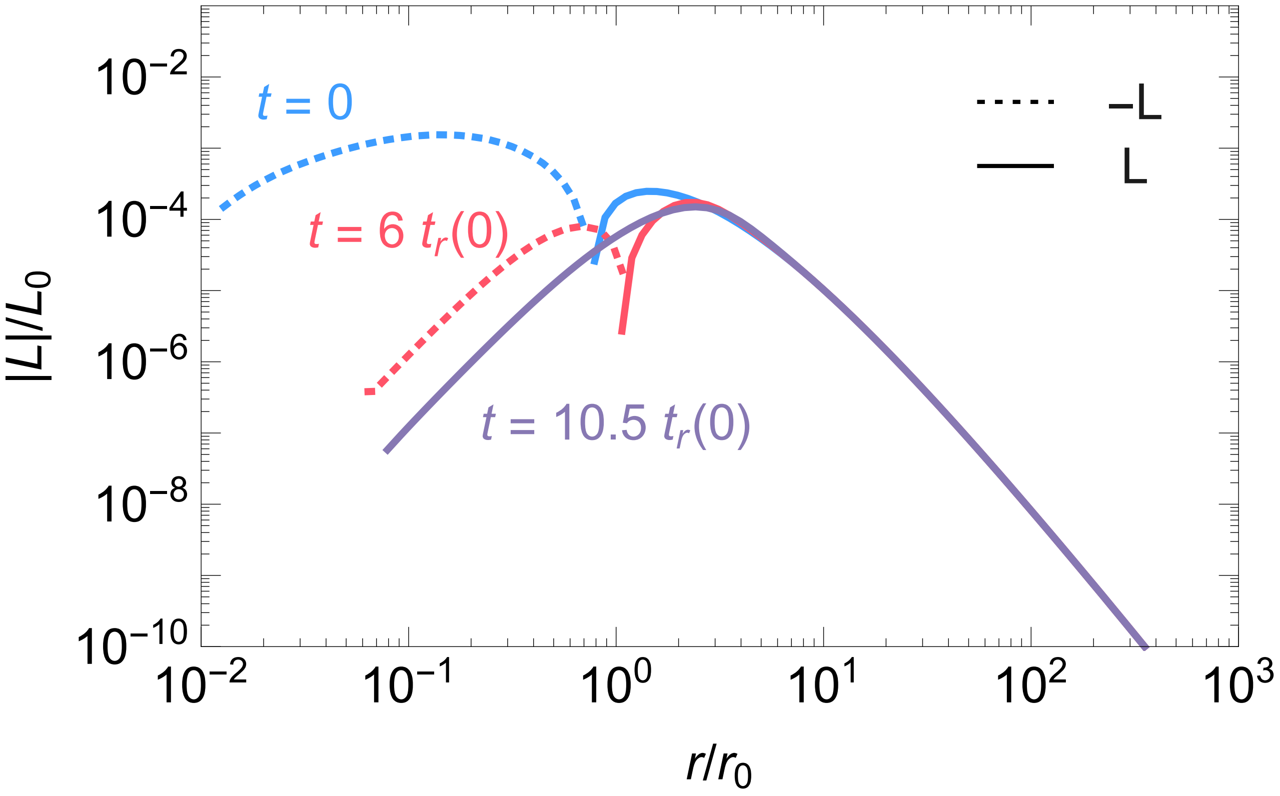
$$a_n \sim \mathcal{O}(1)$$

not relaxation time

1. Core develops

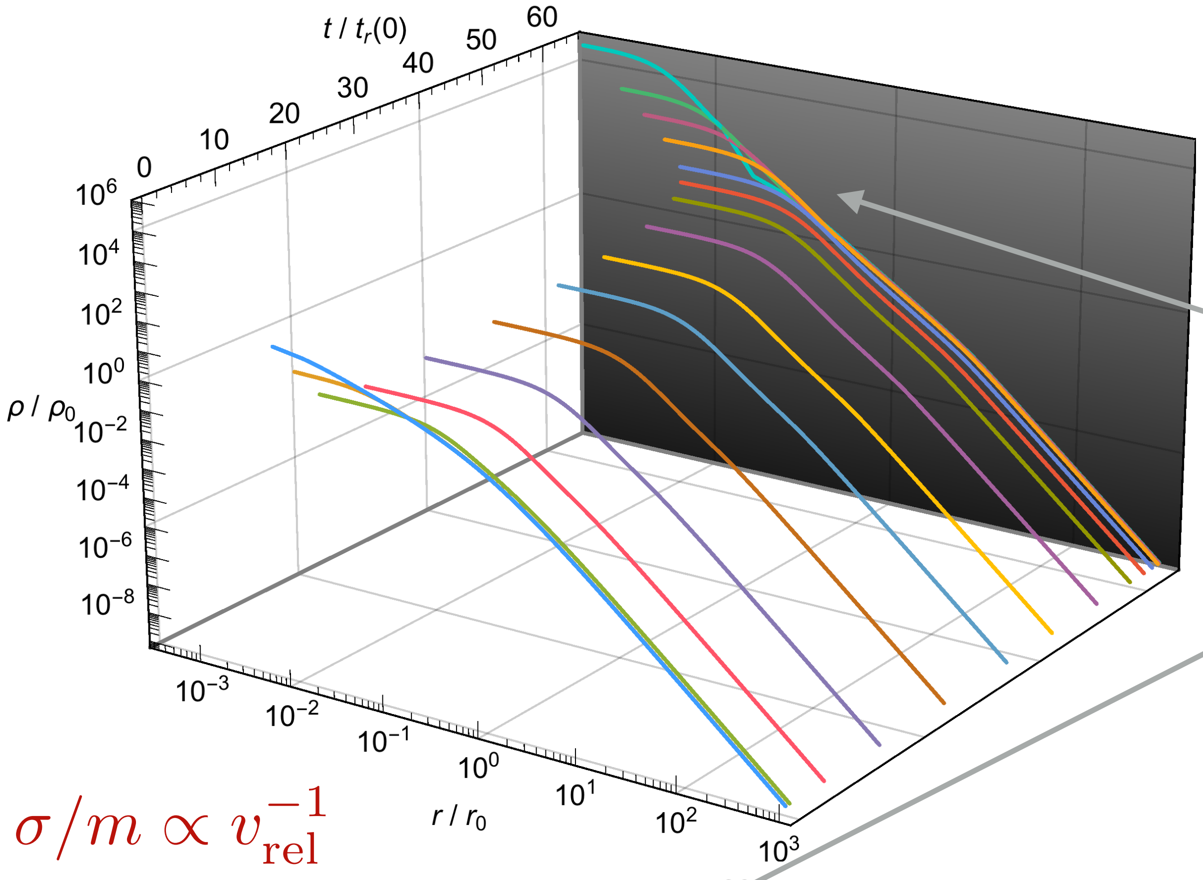


$\sigma/m \propto v_{\rm rel}^{-1}$



- Central density drops; cuspy quickly resolve to core
- Luminosity switches from negative to positive and finally becomes everywhere positive

2. Core collapse



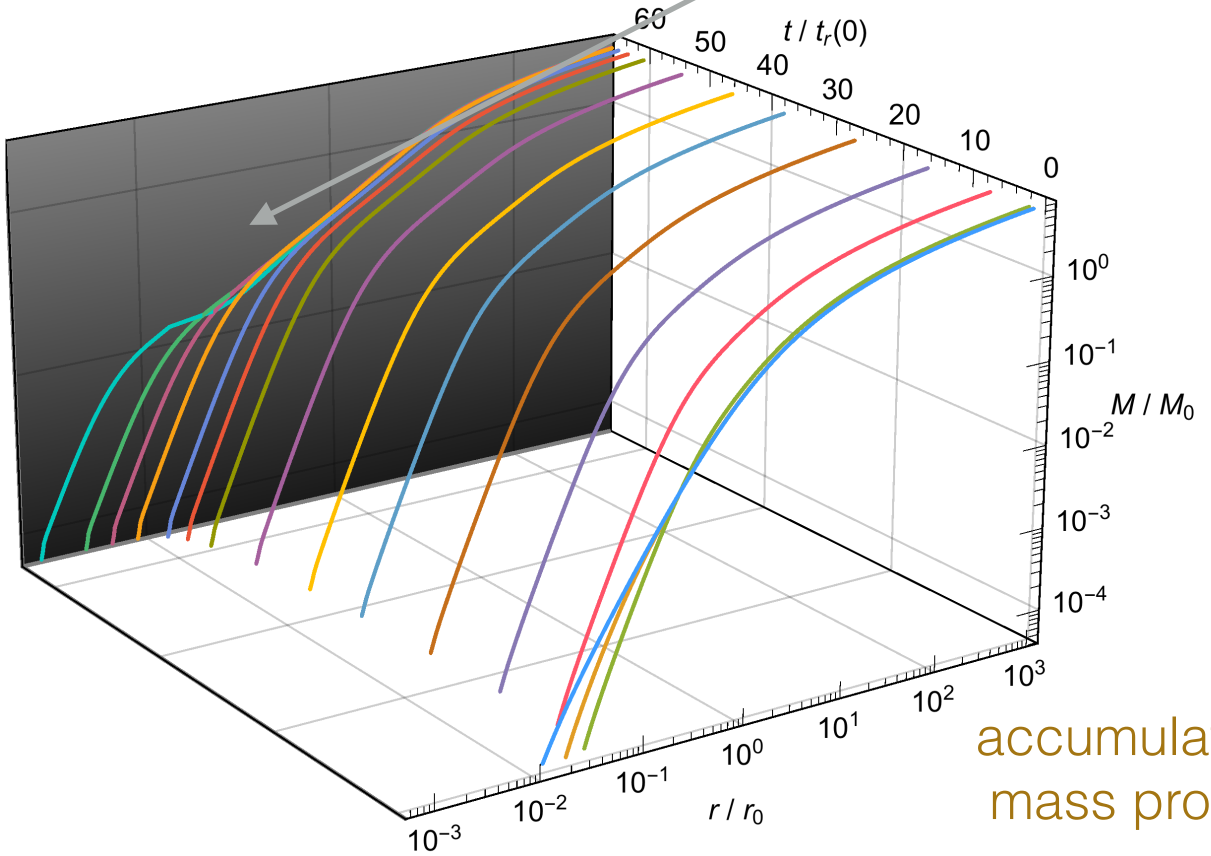
$\sigma/m \propto v_{\rm rel}^{-1}$

- Central density increases; First self-similar collapse (slope –2.2) then a secondary core develops (similar to viSIDM case)

Balberg et al ’02, Koda & Shapiro, ’11, Pollack et al, ’15

- Secondary core has a fixed mass portion as size shrinks

- Evolution ends in a singular state; may form a black hole



accumulative mass profile

Time scales

- Time for collapse to start

	$n=0$	$n=1$	$n=2$	$n=4$
$t_{\text{coll. start}}/t_r(0)$	65	9.5	2.8	1.1

viSIDM vdSIDM

- Time for collapse to end

	$n=0$	$n=1$	$n=2$	$n=4$
$t_{\text{coll. end}}/t_r(0)$	4.4×10^2	65	19	8.0

viSIDM vdSIDM

- Evolution speeds up for vdSIDM

Avoiding core collapse

- Collapsing halo has a special density profile (slope –2.2). Null observation of such halo would imply

$$t_{\text{collapse start}} \gtrsim t_{\text{Hubble}}$$

- e.g. n=1, $t_{\text{coll. start}} = 9.5\, t_r(0)$

$$\frac{\sigma/m}{1\,\mathrm{cm}^2/\mathrm{g}} \lesssim 0.46 \left(\frac{\rho_0}{10^{-24}\,\mathrm{g/cm}^3}\right)^{-1} \left(\frac{v_{\text{rel}}}{200\,\mathrm{km/s}}\right)^{-1}$$

SMBH formation

- Collapsed halo can form (seed) black hole for SMBH. Assume SMBH is entirely from the secondary core implies

Pollack et al, ’15

$$t_{\text{collapse end}} = t_{\text{observed}} - t_{\text{halo formation}}$$

- If all of DM is self-interacting, the remaining density profile of the collapsed halo does not fit observations

- If only subdominant component of DM are self-interacting (mass fraction f«1), then can evade all SIDM constraints

- Collapse slowed by 1/f: $t_r(0) \to t_r^f(0) = \frac{1}{f} t_r(0)$

Preferred values from SMBH formation

- e.g., take SMBH ULAS J1120+0641

Pollack et al, '15

$$M_{\Delta}^{\mathrm{Halo}} = 10^{12} M_{\odot}, z = 15 \rightarrow M^{\mathrm{SMBH}} = 2 \times 10^{9} M_{\odot}, z = 7.085$$

- n=1, $t_{\mathrm{coll.\ end}} = 65\, t_r^f(0)$

$$\frac{\sigma/m}{1\,\mathrm{cm}^2/\mathrm{g}} \simeq 0.66 \left(\frac{\rho_0}{10^{-21}\,\mathrm{g/cm}^3}\right)^{-1} \left(\frac{v_{\mathrm{rel}}}{200\,\mathrm{km/s}}\right)^{-1} \left(\frac{f}{0.1}\right)^{-1}$$

Summary

- DM self-interactions cause gravothermal evolution of DM halo: can provide interesting bounds.
- vdSIDM can speed up evolution.
- Results need further calibration. N-body simulation studies on time scales are encouraged.
- Future look: time scales in the evolution of double-disk dark matter halos. The presence of cooling may speed up the collapse further

Backup

Conducting gas/fluid model

- Isolated halo through the evolution
- The halo has complete spherical symmetry. Spatially all profiles depend on radius, *r*, only.
- The evolution is determined by

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{\partial}{\partial r}\left(\rho\nu^2\right) = -\frac{4\pi G}{r^2}\int_0^r dr' r'^2 \rho(r')$$

Heat flux

$$\frac{L}{4\pi r^2} = -\kappa\frac{\partial}{\partial r}\left(\frac{m\nu^2}{k_B}\right)$$

1st law of thermodynamics

$$\frac{1}{4\pi r^2}\frac{\partial L}{\partial r} = -\rho\nu^2\left(\frac{\partial}{\partial t}\right)_M \ln\frac{\nu^3}{\rho}$$

Balberg-Shapiro-Inagaki conductivity

- Conductivity $\kappa = (\kappa_{\rm thick}^{-1} + \kappa_{\rm thin}^{-1})^{-1}$

$$\kappa_{\rm thick} = \frac{3k_B}{2m}\frac{b}{a}\rho\frac{\lambda^2}{t_r}, \quad \kappa_{\rm thin} = \frac{3k_B}{2m}c\rho\frac{H^2}{t_r}$$

Balberg et al, ’00
Lynden-Bell & Eggleton, ’80

where $\lambda \equiv m/\rho\sigma, H \equiv \sqrt{\nu^2/4\pi G\rho}, t_r = m/\rho\langle\sigma v_{rel}\rangle$

- Optical thin region, larger σ/m, larger conductivity;
  Optical thick region, smaller σ/m, larger conductivity;

- low velocity at early time⇒ larger σ/m

  ⇒ larger conductivity

  ⇒ faster evolution

  (similar for optical thick period in end)