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

Yi-Ming Zhong
C.N.Yang Institute for Theoretical Physics, Stony Brook University

In collaboration with
R. Essig and S. McDermott

Work in progress

Brookhaven Forum, 10/08/2015

Outline

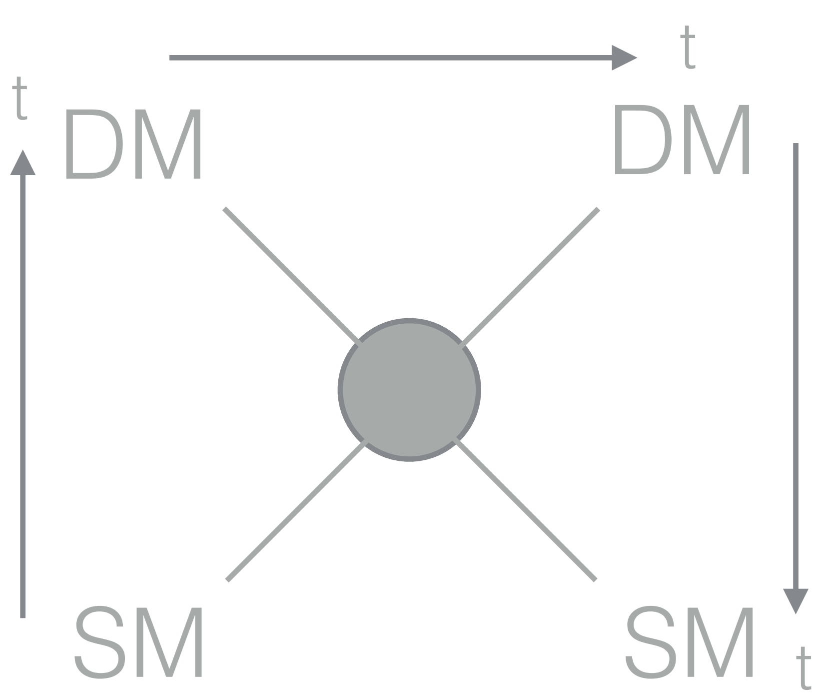
- Introduction
- Physical implications of gravothermal evolution
  - Avoiding core collapse (gravothermal catastrophe)
  - Forming super massive black hole (SMBH)
- Summary

Self-interacting dark matter (SIDM)

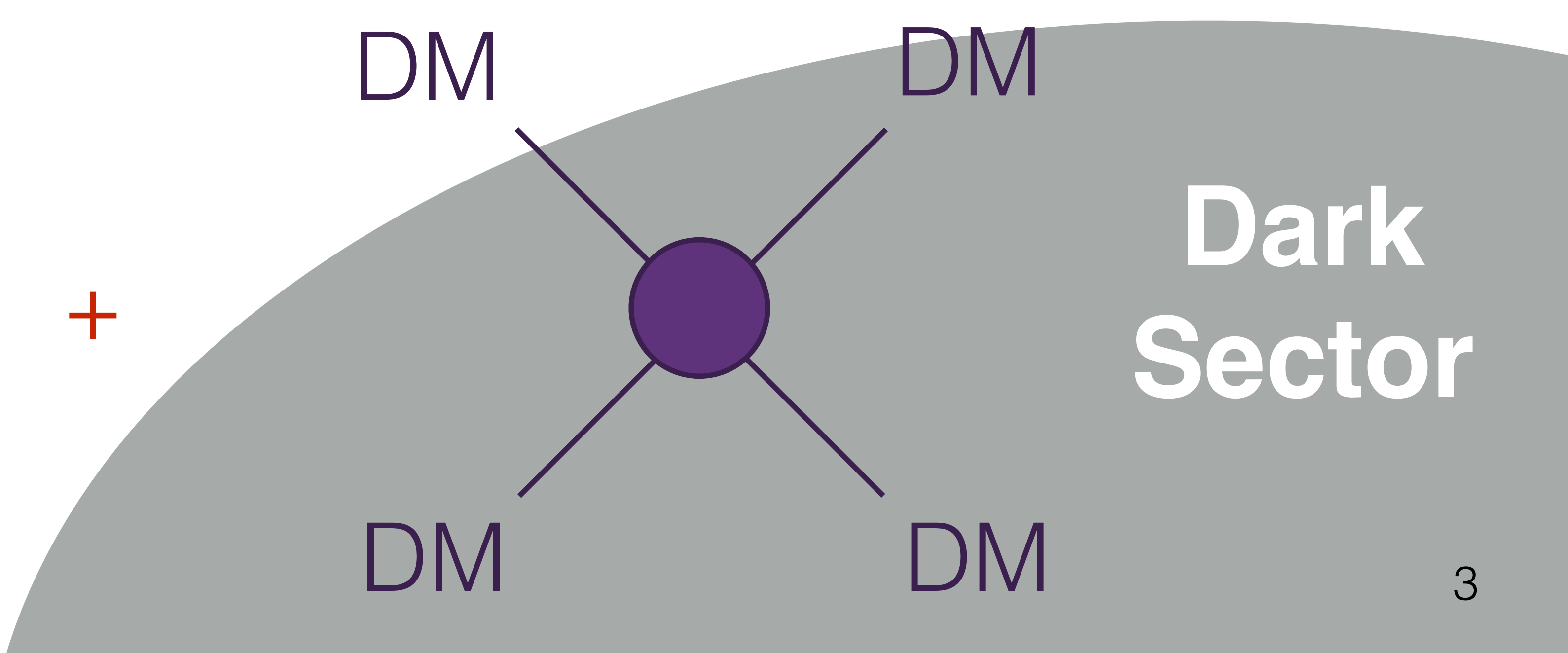
- Cold collisionless dark matter is an ingredient of ΛCDM. Works great at large scales; meets crisis at small scales
- SIDM was originally proposed as a solution

Spergel & Steinhardt, '00

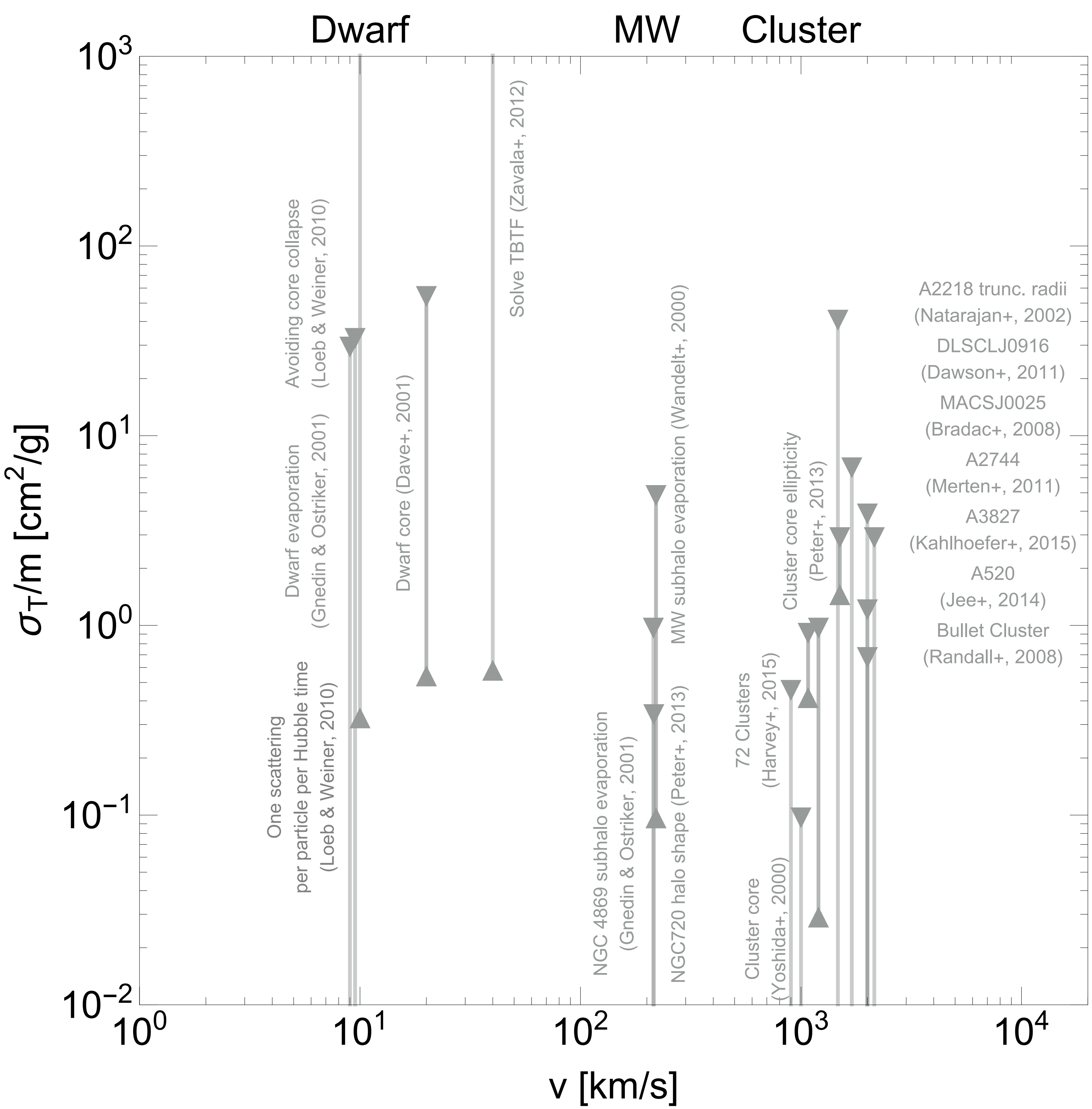
- **DM self-interaction itself is interesting!** (could even be a subdominant component)



+



Strength of DM self-interaction



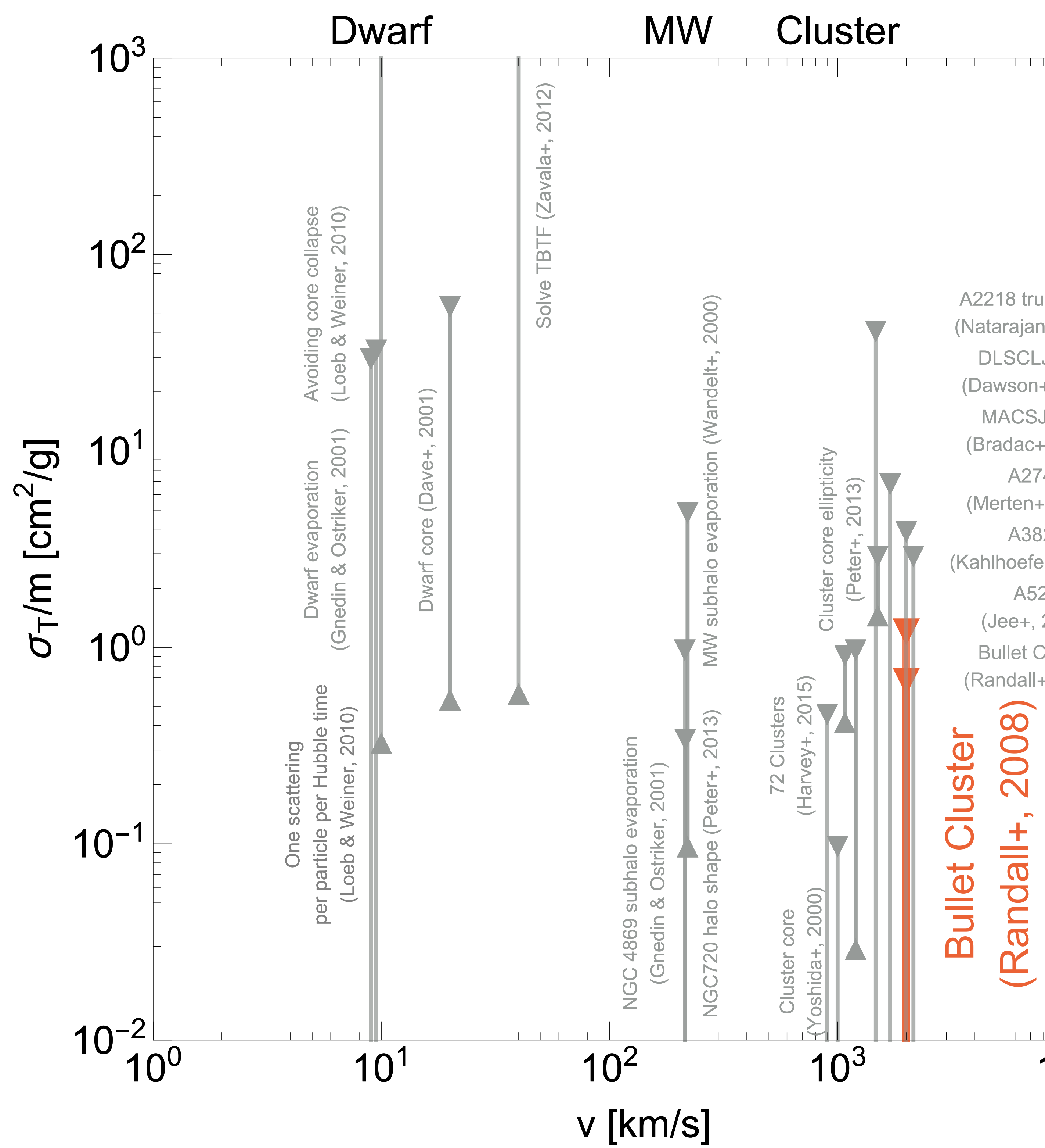
SIDM is studied at clusters, MW galaxies, dwarfs scales.

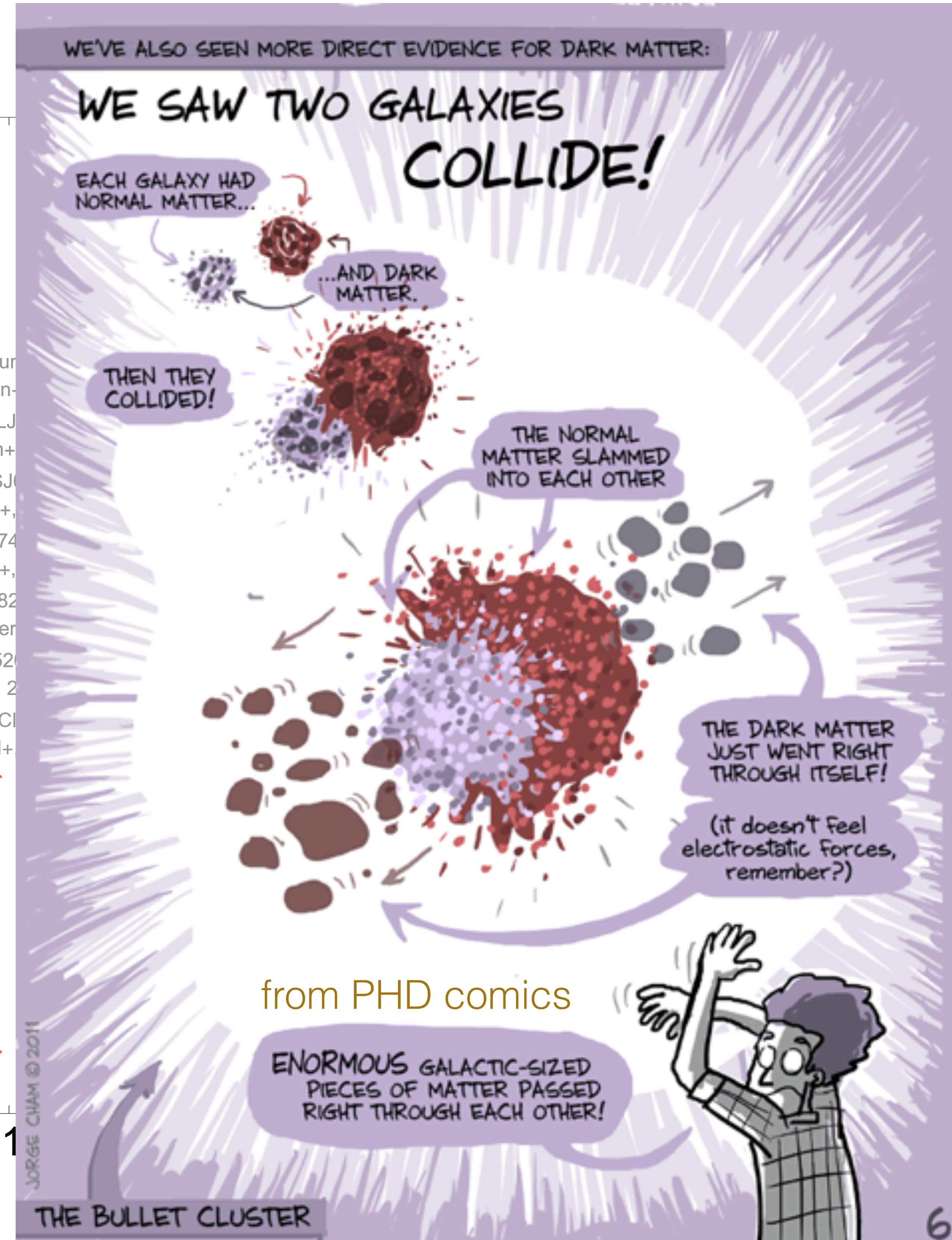
Upper range: merges, core shapes…

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

1 cm^2/g ≈ 2 barn/GeV

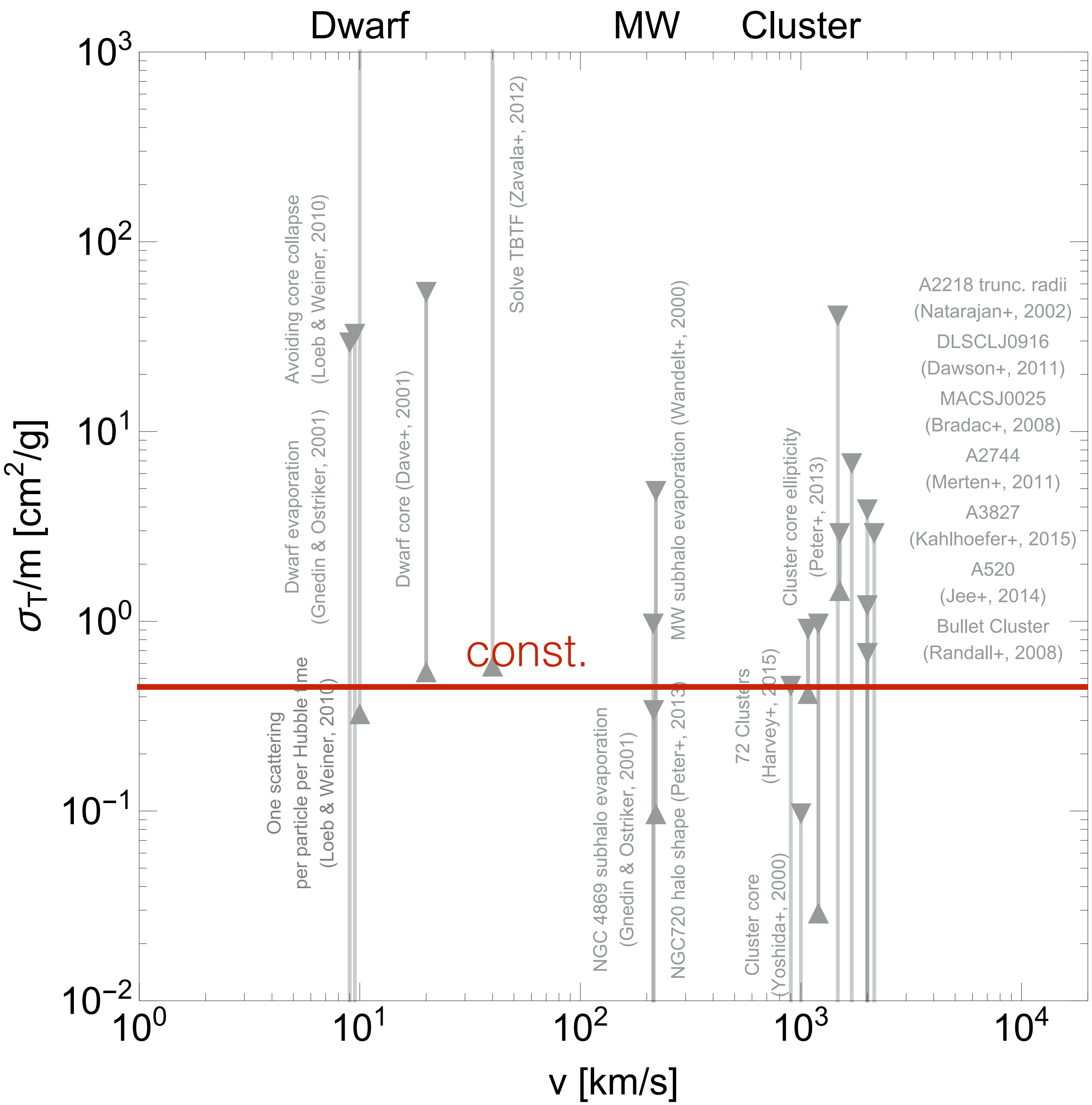
Strength of DM self-interaction





from PHD comics

Strength of DM self-interaction



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

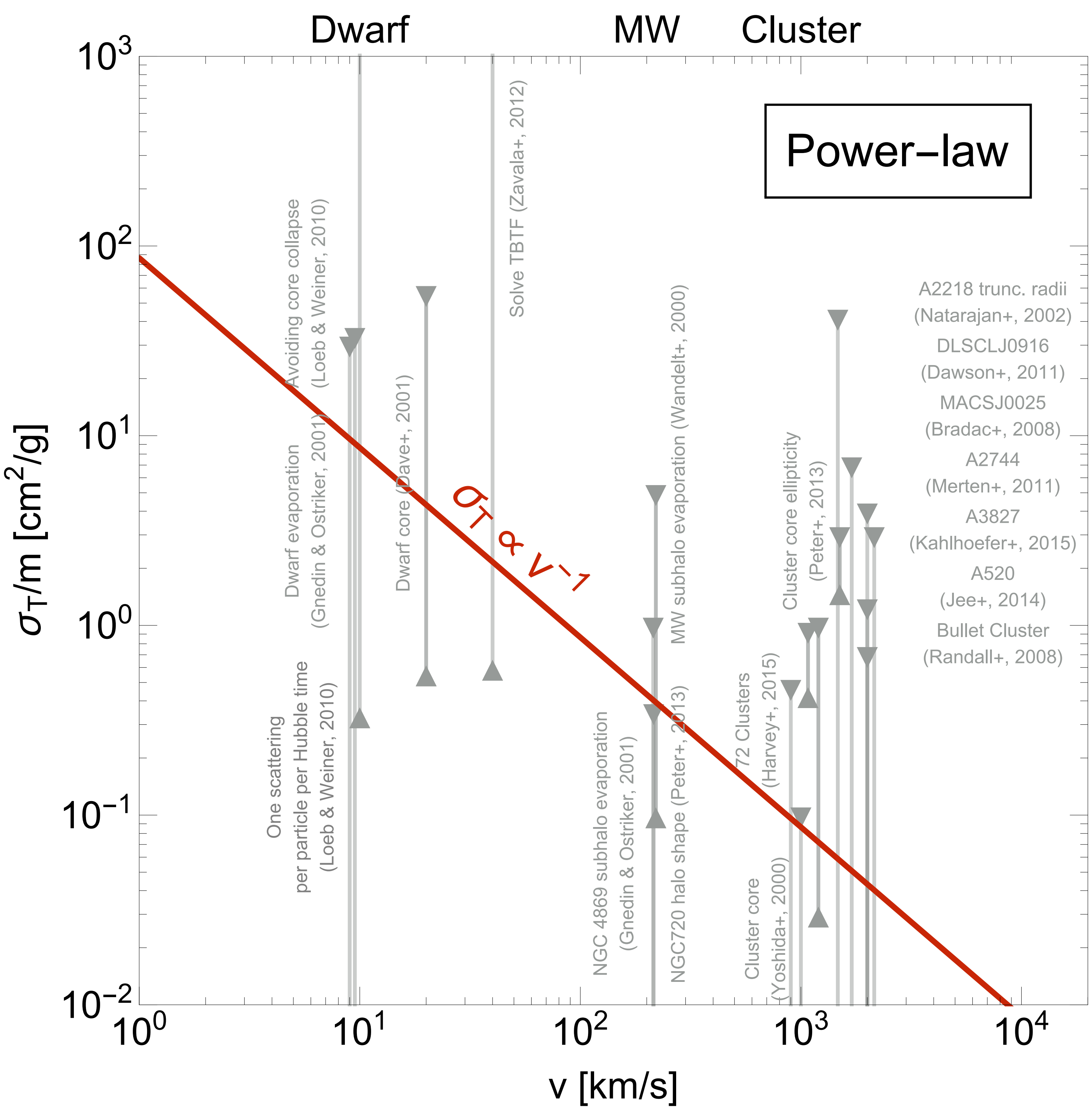
Upper range: merges, core shapes…

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

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

$1\ \mathrm{cm^2/g} \approx 2\ \mathrm{barn/GeV}$

Velocity-dependent SIDM (vdSIDM)



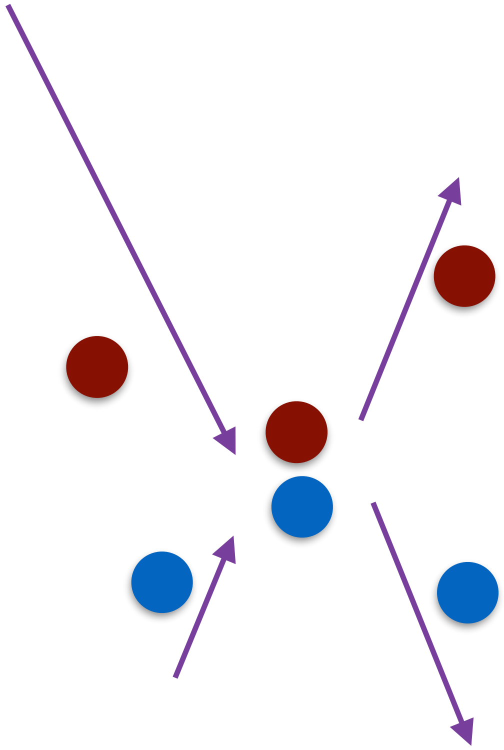
DM self-interaction may be non-trivial

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 velocity dep.)

Gravothermal evolution

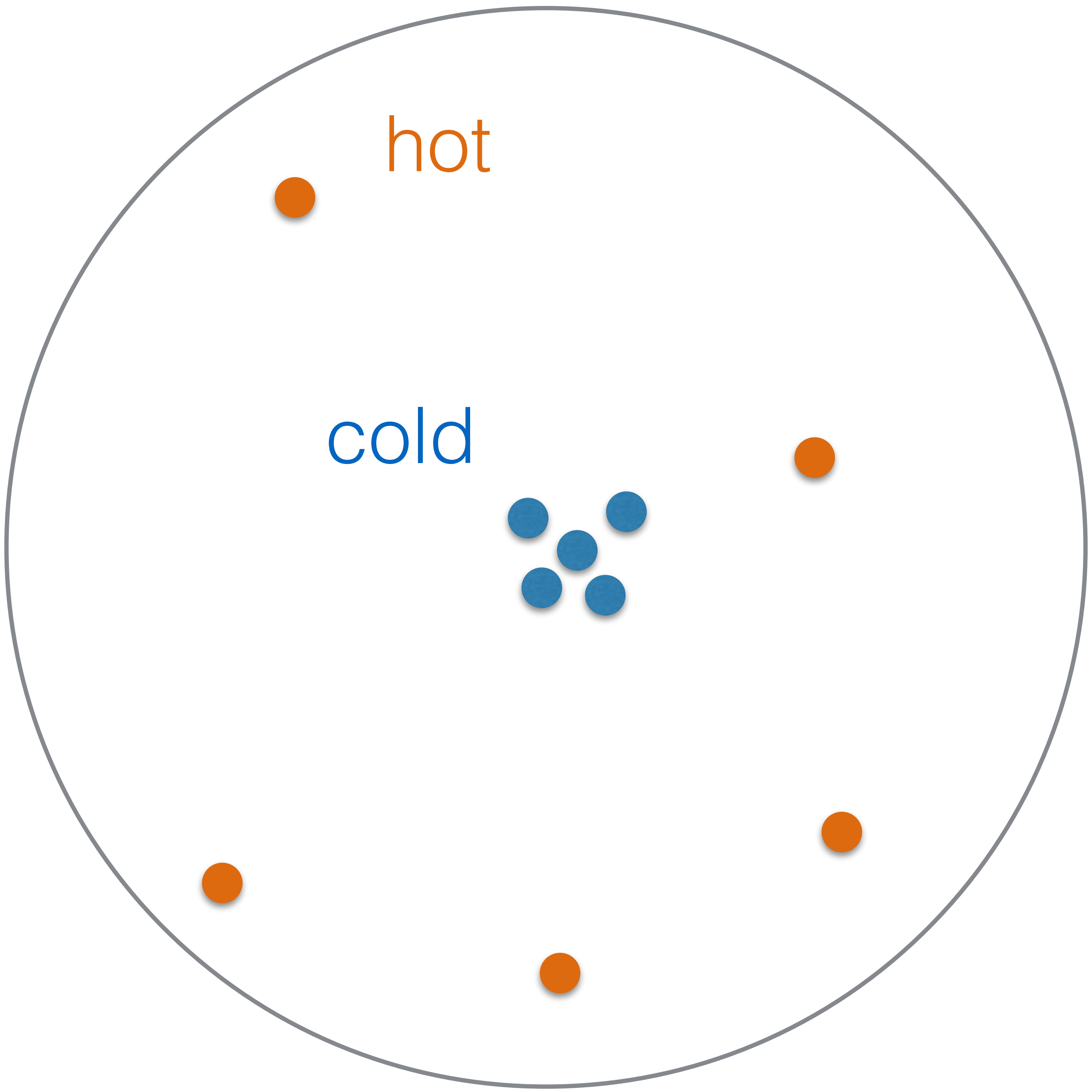


- DM self-interaction allows for kinetic heat flow
- DM halo experiences gravothermal evolution: first core develops, then core collapses
- Can calculate various constraints/preferred values on σ/m. e.g. time scale of the beginning/end of core collapse
- Earlier studies on time scales focus on velocity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

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

A brief history of SIDM halo

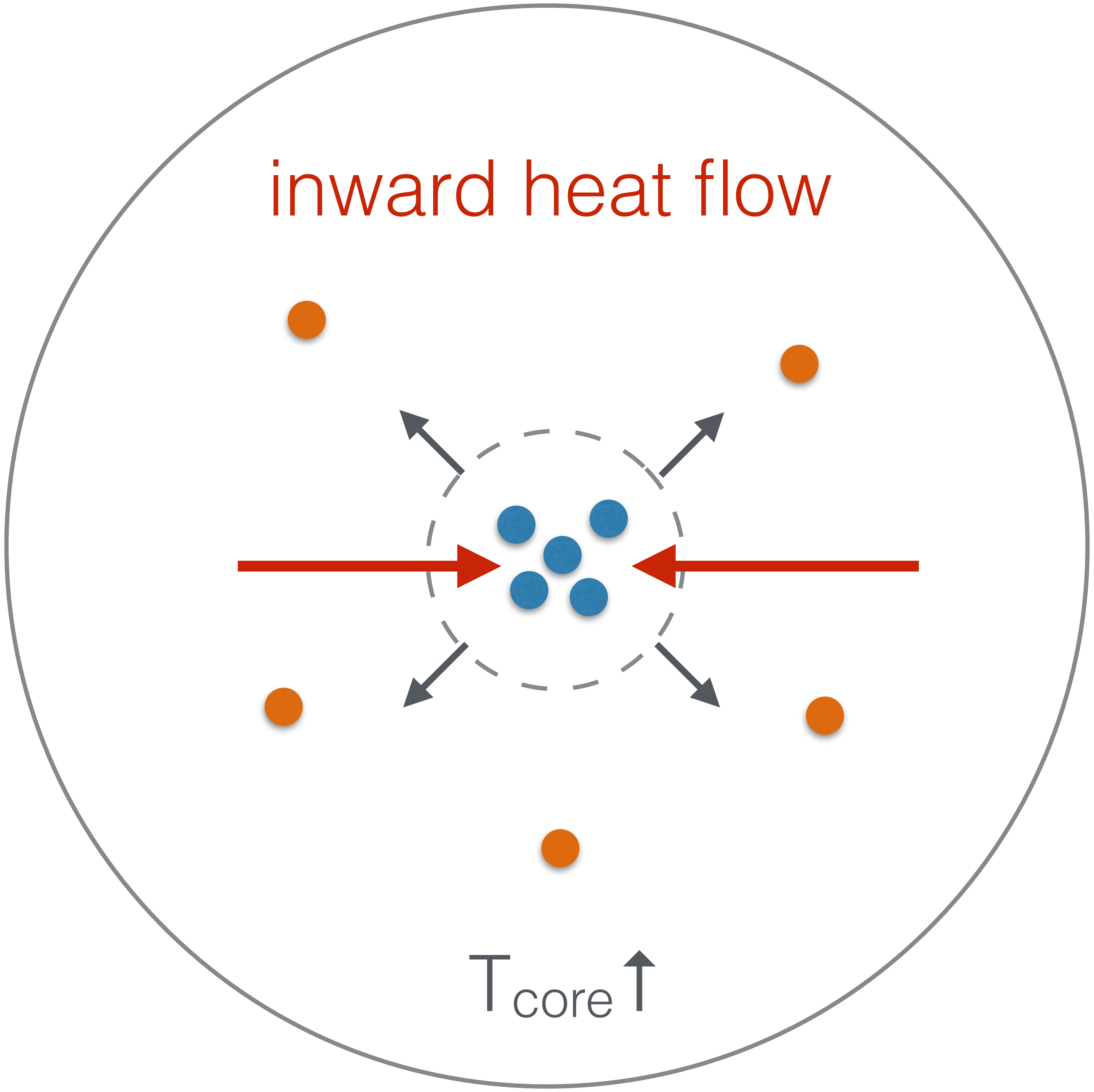
I. NFW profile



A brief history of SIDM halo

I. NFW profile

II. Core develops

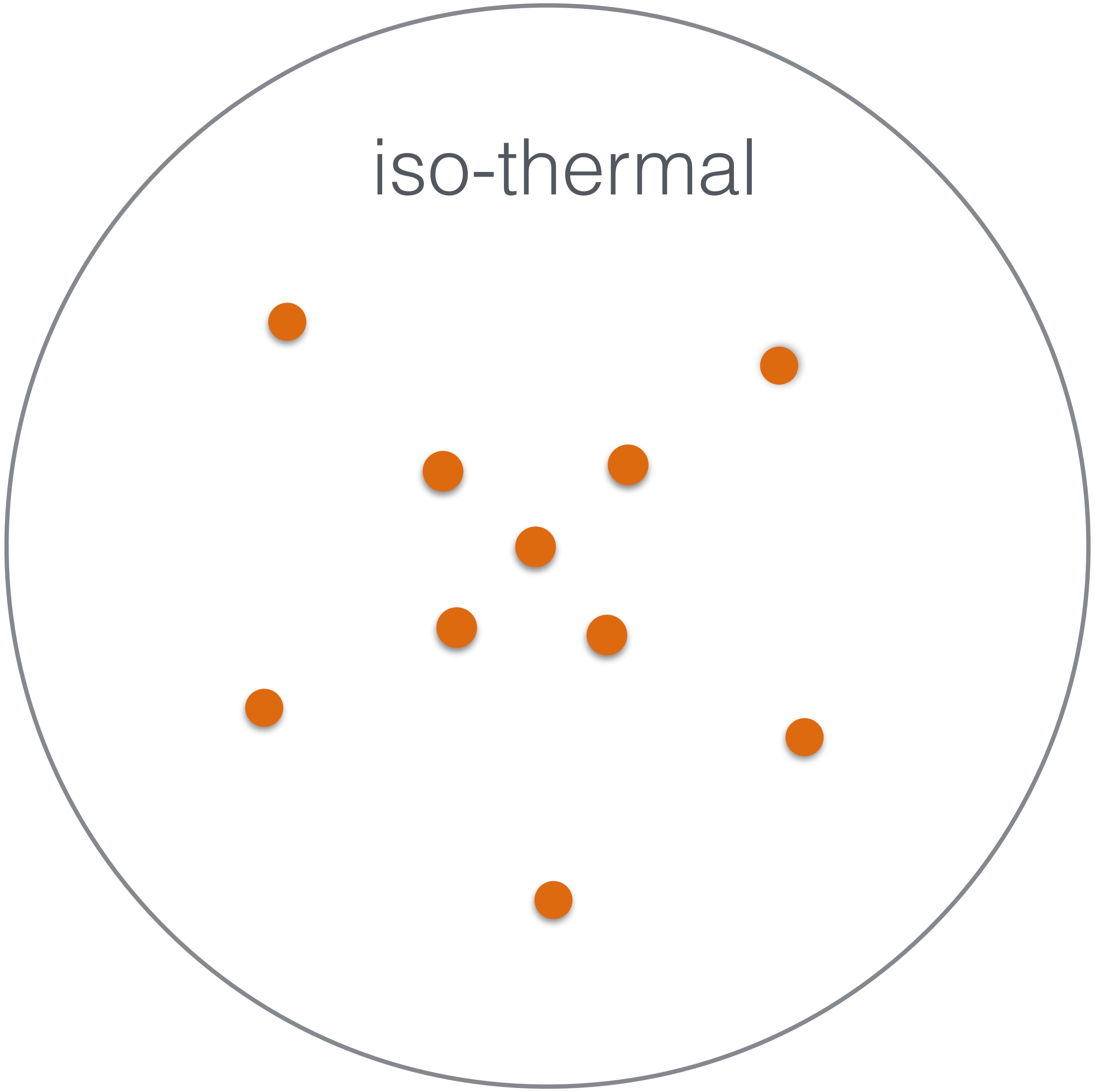


A brief history of SIDM halo

I. NFW profile

II. Core develops

III. Core profile



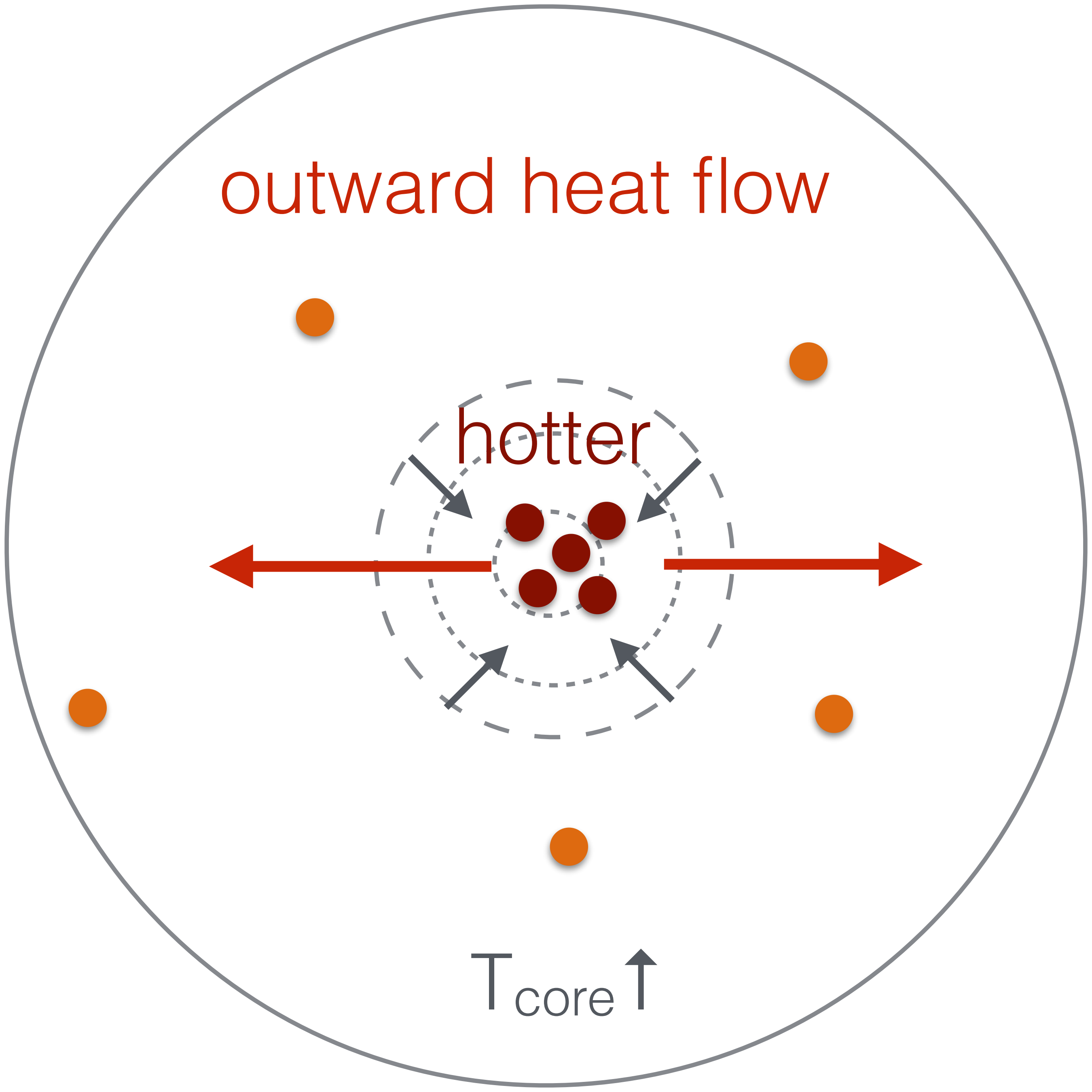
A brief history of SIDM halo

I. NFW profile

II. Core develops

III. Core profile

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

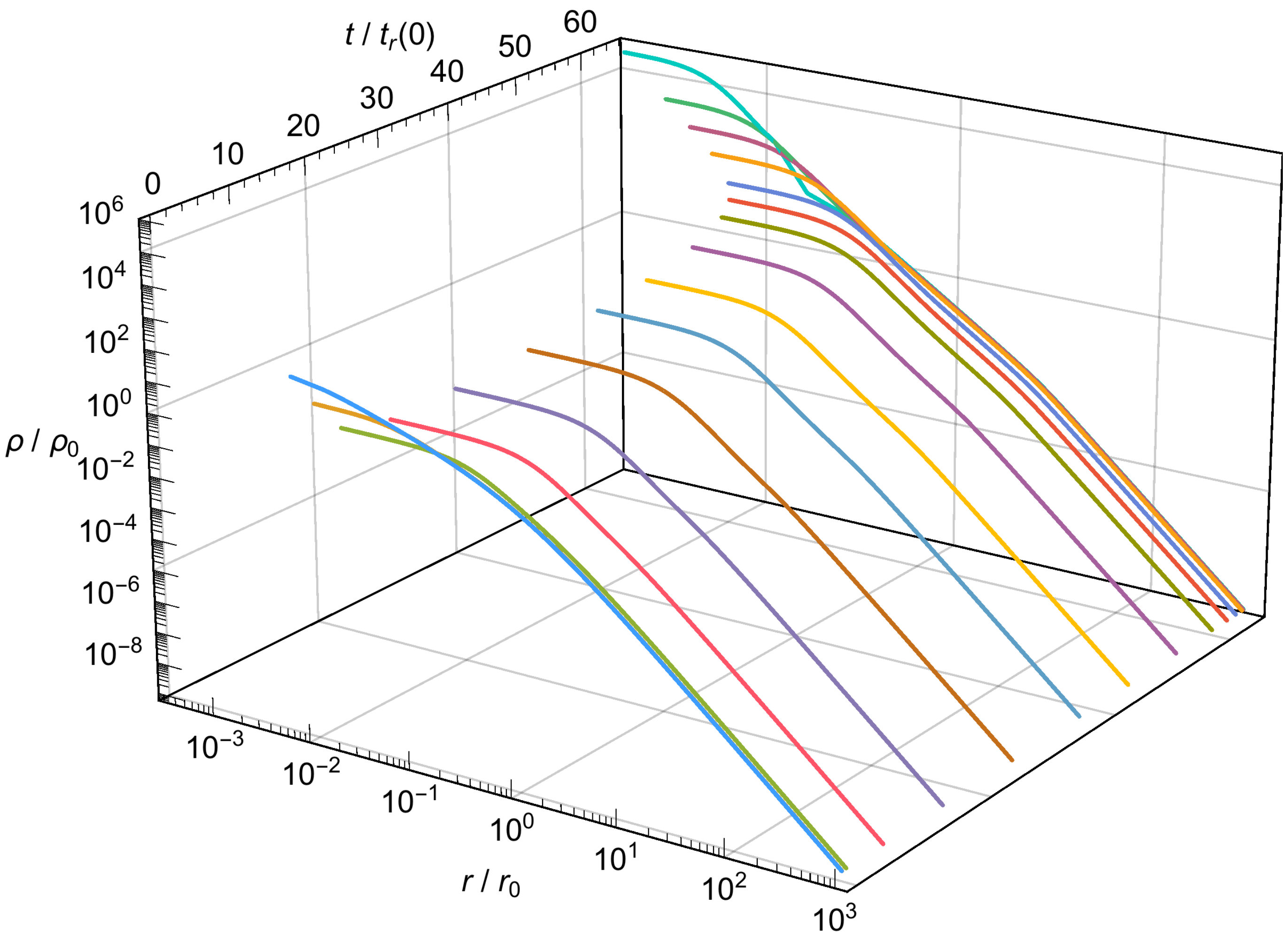
- Agrees with N-body simulations reasonably well (for viSIDM, after calibrating conductivity coefficient); profiles resolve deeply; easy to compute

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: power-law velocity dep.



Evolution of the density profile
(n = 1)

- Initial profile NFW

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

- Self-interaction

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

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

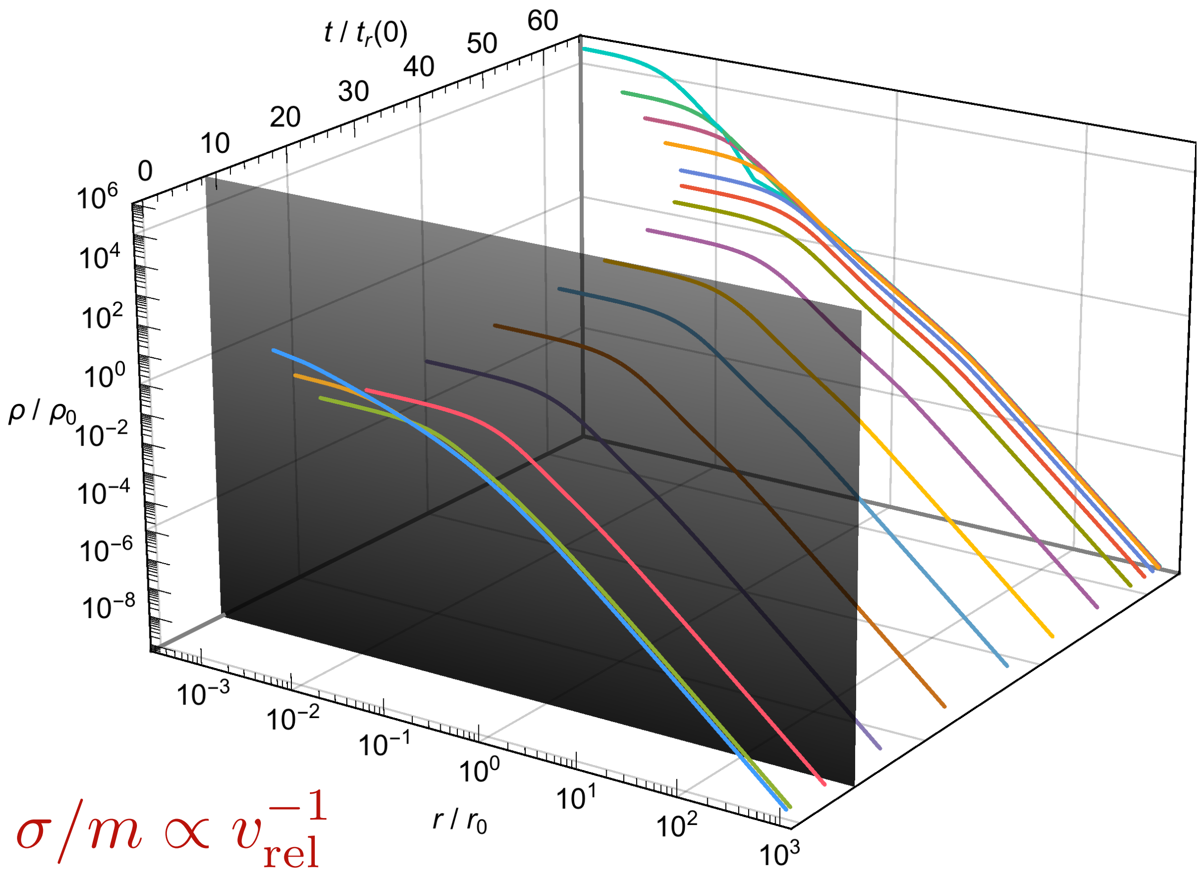
- Unit time

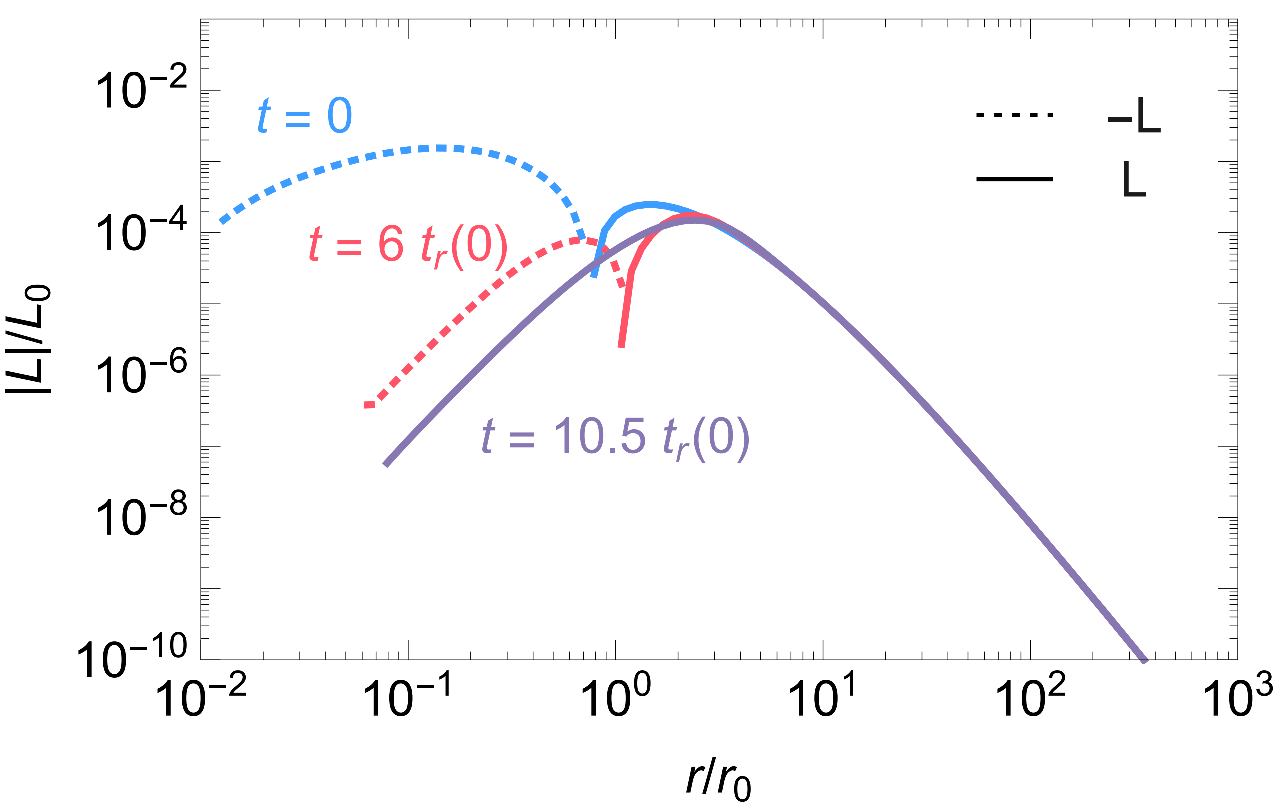
$$t_r(0) \equiv \frac{1}{a_n \rho_0 (\sigma/m)_p (\nu_0/\nu_{\substack{t=0\\ r=r_0}})^n \nu_0}$$

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

not relaxation time

1. Core develops

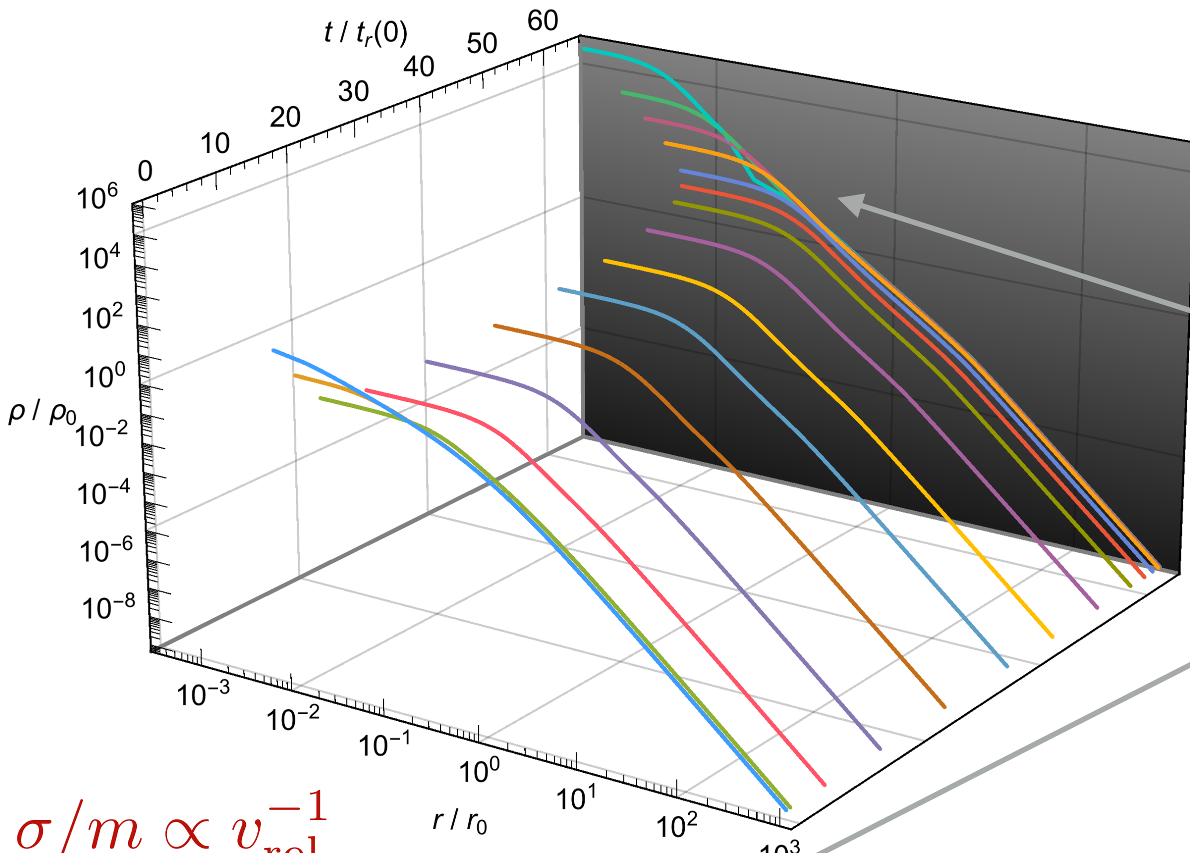




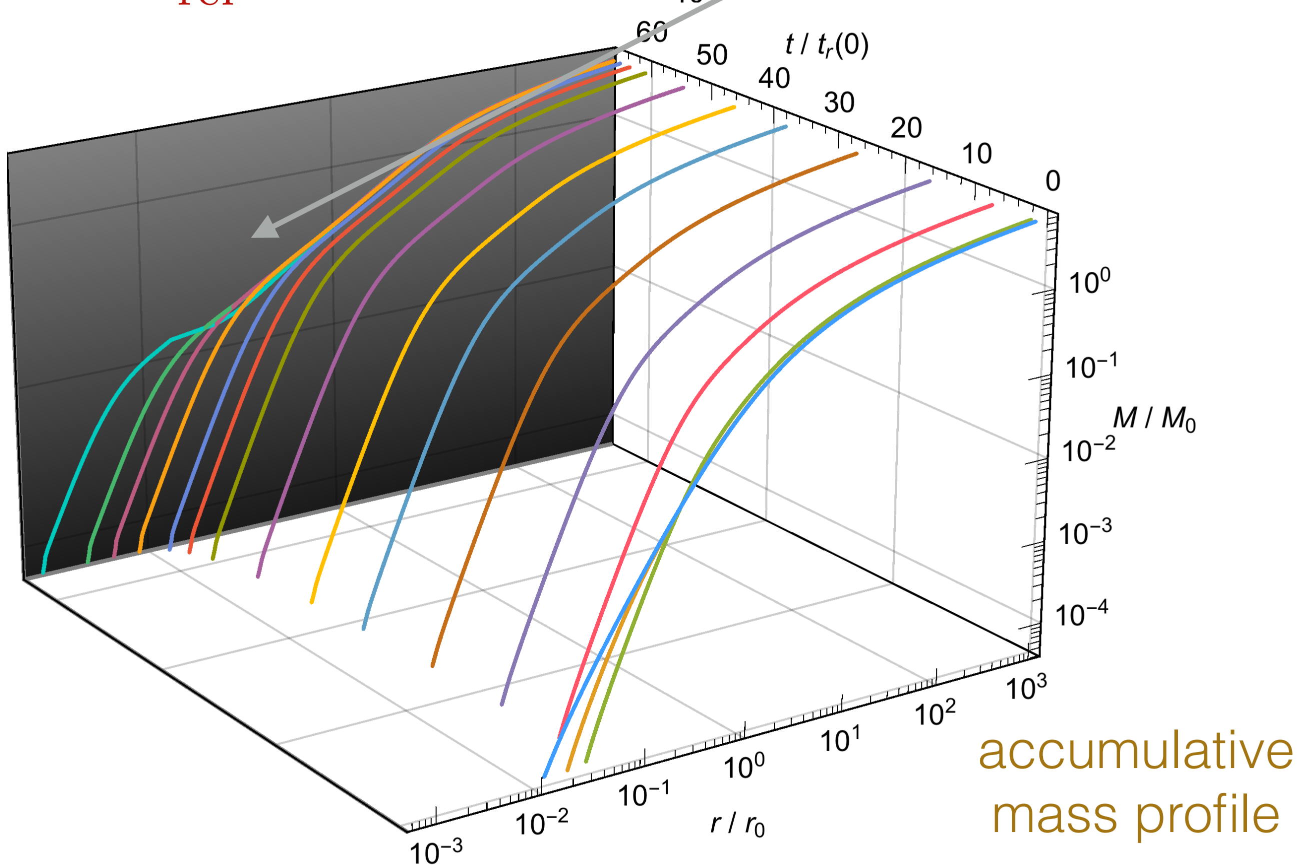
- Central density drops; cuspy quickly resolve to core
- Luminosity switches from negative to positive and finally becomes everywhere positive

luminosity:
heat flow per unit time per unit area,
outward: positive, inward: negative

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

Time scales

- Time for collapse to start

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

	$n=-2$	$n=-1$	$n=0$	$n=1$	$n=2$	$n=4$
$t_{\rm coll.\ start}/t_r(0)$	6.0×10^2	1.4×10^2	65	9.5	2.8	1.1

vdSIDM (n = −2, −1) · viSIDM (n = 0) · vdSIDM (n = 1, 2, 4)

- Time for collapse to end

	$n=-2$	$n=-1$	$n=0$	$n=1$	$n=2$	$n=4$
$t_{\rm coll.\ end}/t_r(0)$	4.0×10^3	9.4×10^2	4.4×10^2	65	19	8.0

vdSIDM (n = −2, −1) · viSIDM (n = 0) · vdSIDM (n = 1, 2, 4)

- n>0, evolution speeds up; n<0, evolution slows down

Avoiding core collapse

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

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

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

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

SMBH formation

- We find several dozen SMBHs with mass ~10^9 M⊙ at z ≳ 6. Can be explained if it is entirely formed from the secondary core of a SIDM halo

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

Mortlock et al 2011, Venemans et al 2012

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

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

$$\sigma/m \simeq 0.66\, {\rm cm^2/g} \left(\frac{\rho_0}{10^{-24}\,{\rm g/cm^3}}\right)^{-1} \left(\frac{v_{rel}}{200\,{\rm km/s}}\right)^{-1} \left(\frac{f}{0.1}\right)^{-1}$$

Summary

- DM self-interactions cause gravothermal evolution of DM halo: can provide interesting observational consequences.
- vdSIDM has different time scales to viSIDM.
- Results need further calibration. N-body simulation studies on time scales are encouraged.
- Future look: implications on DM models. e.g., double-disk dark matter.

Backup

Conducting gas/fluid model

- The evolution is determined by

$$m\nu^2 = k_B T$$

1. Hydrostatic equilibrium

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

2. Thermodynamic relation

$$dw = Tds + VdP \quad \Rightarrow \quad \frac{\partial F}{\partial r} = -\rho \nu^2 \left(\frac{\partial}{\partial t}\right)_M \ln \frac{\nu^3}{\rho}$$

for conduction, heat flux is given by

$$F = -\kappa \frac{\partial T}{\partial r}$$

Conductivity

- All the interactions are characterized in the scalar conductivity κ
- Two interactions: self-interaction & gravitational interaction
- Optical thick (fluid) region: self-interaction dominant

$$\kappa_{\rm thick} = \frac{3}{2}\frac{k_B}{m} b\rho\nu\lambda$$

mean free path $\lambda \equiv \frac{m}{\rho\sigma}$

Hachisu et al, 1978

Conductivity

- Optical thin (gas) region: gravitational interaction dominant

  - Replace λ by H*(t_d/t_r)

scale height of the orbit $H \equiv \sqrt{\nu^2/4\pi G\rho}$

$$\kappa_{\rm thin} = \frac{3}{2}\frac{k_B}{m}b\rho\nu H\frac{t_d}{t_r} = \frac{3}{2}\frac{k_B}{m}b\rho\frac{H^2}{t_r}$$

dynamical time $t_d = H/\nu$

relaxation time $t_r = m/\rho\langle\sigma v_{rel}\rangle$

Lynden-Bell & Eggleton, 1980

- Bridge the two regions: $\kappa = (\kappa_{\rm thick}^{-1} + \kappa_{\rm thin}^{-1})^{-1}$

Balberg et al, 2000

More on conductivity

- *b* coefficient can be calculated from transport theory; to agree with the N-body simulation, it needs calibration

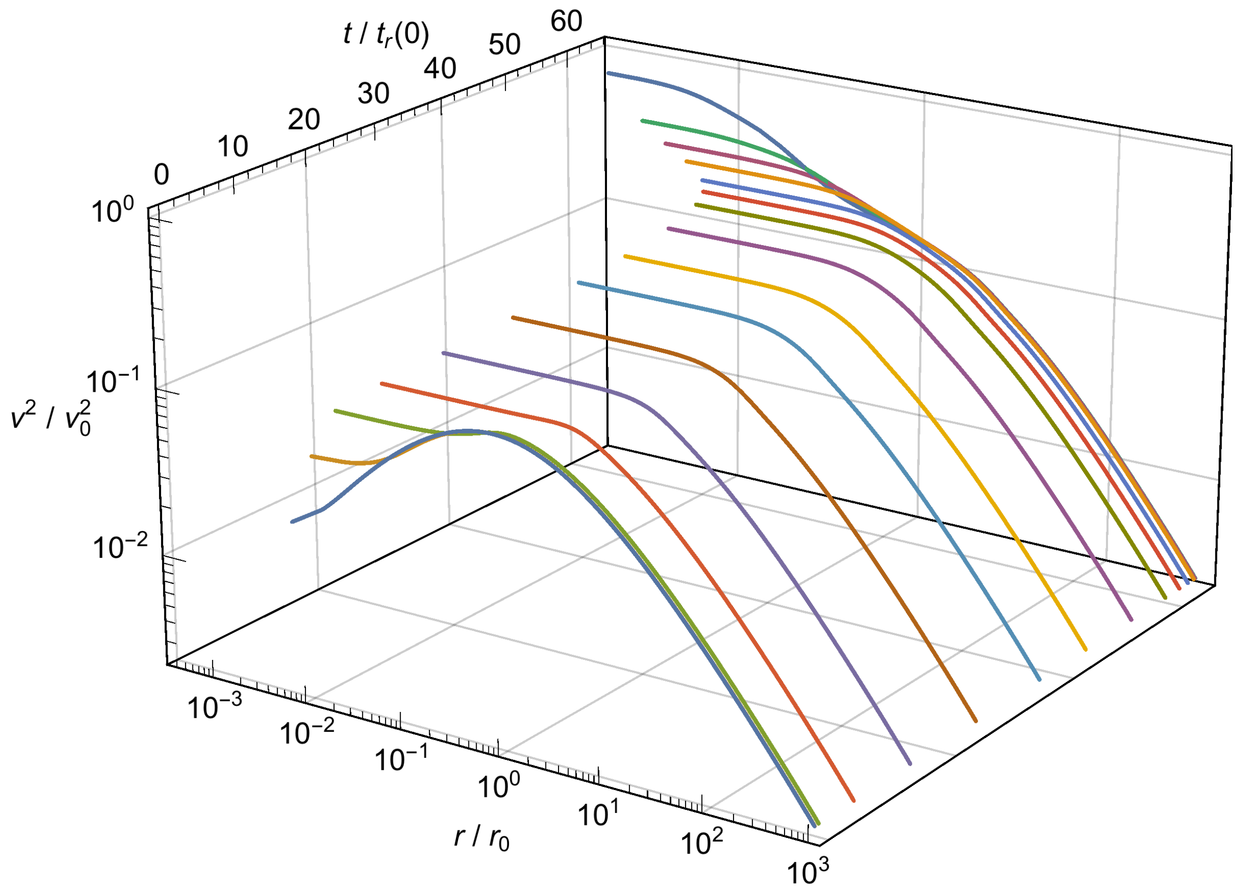
Koda & Shapiro, 2011

$$\kappa_{\rm thin} = \frac{3}{2}\frac{k_B}{m} b\rho \frac{H^2}{t_r} \to \frac{3}{2}\frac{k_B}{m} c\rho \frac{H^2}{t_r}$$

- 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: e.g. Zavala et al, 2012, Vogelsberger et al 2012, 2014, Buckley et al 2014, Robertson et al 2015

Time scales



Evolution of the velocity profile (n = 1)

- $\kappa_{\rm thin} \propto \sigma/m, \quad \kappa_{\rm thick} \propto (\sigma/m)^{-1}$
  Optical thin region, σ/m↑⇒ conductivity↑;
  Optical thick region, σ/m↓⇒ conductivity↑;
- take n > 0 for $\sigma/m = (\sigma/m)_p\,(v_p/v_{\rm rel})^n$
  low velocity at early time⇒ σ/m↑ ⇒ conductivity↑ ⇒ faster evolution
  high velocity at late time ⇒ σ/m↓ ⇒ conductivity↑⇒ faster evolution