Cooling of self-interacting dark matter halos

Yi-Ming Zhong

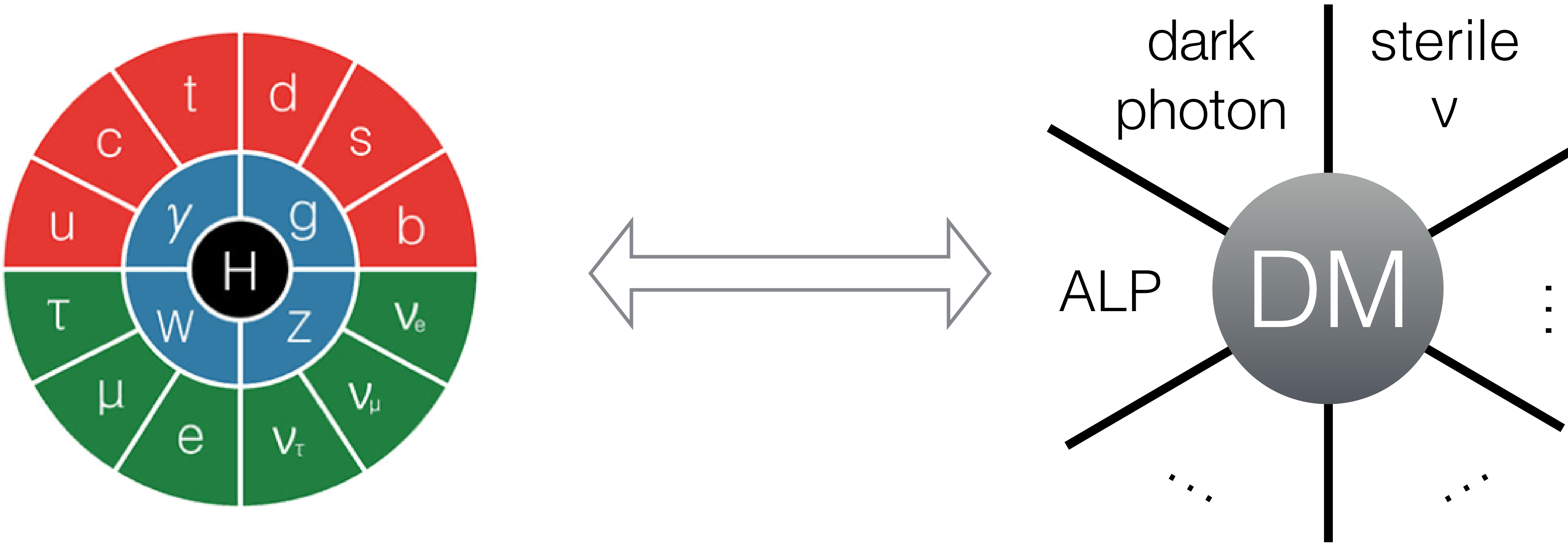
Boston University

In collaboration w/ R. Essig, S. McDermott, H.-B. Yu
arXiv:1809.01144

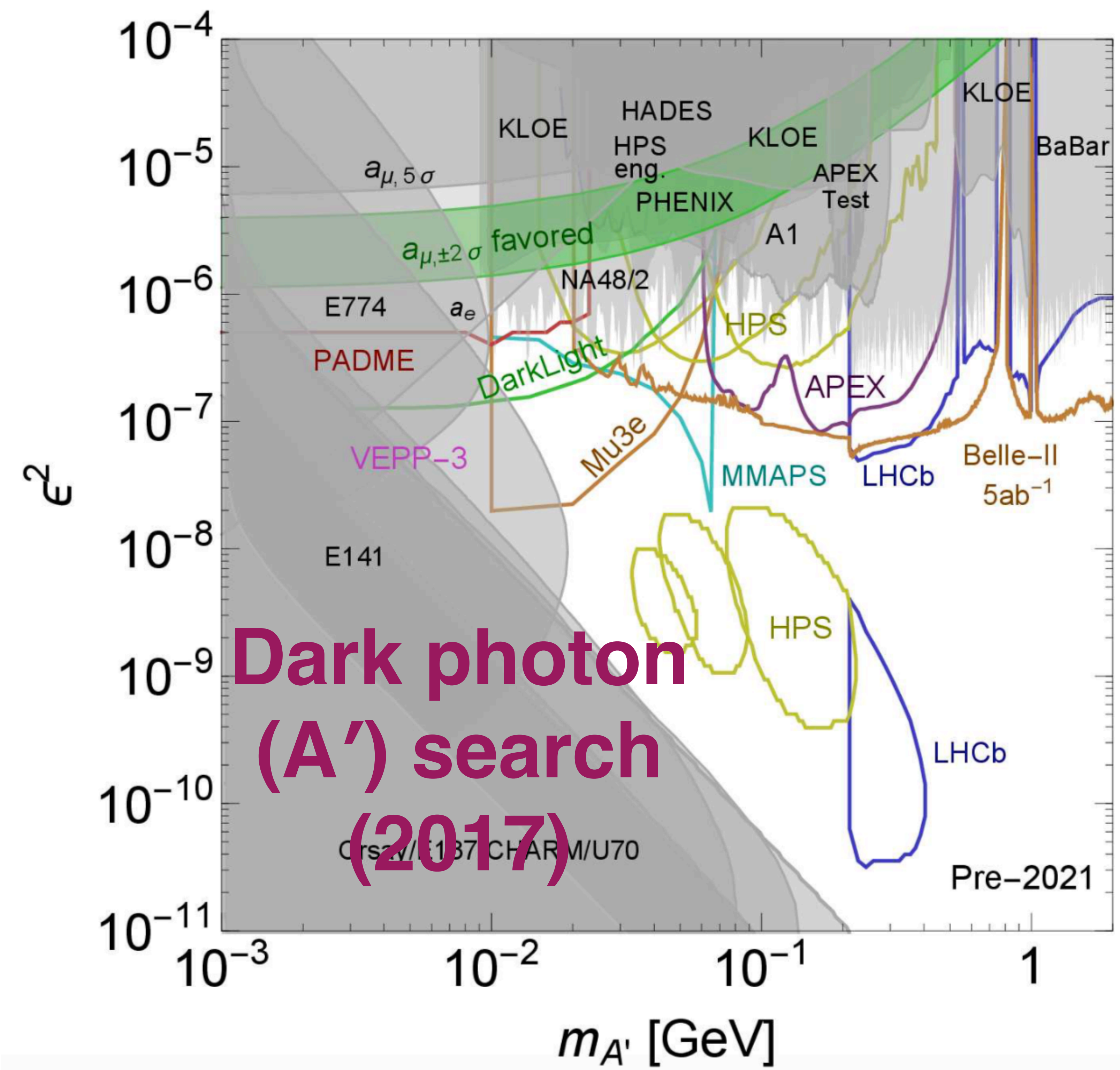
LBL, 10/10/2018

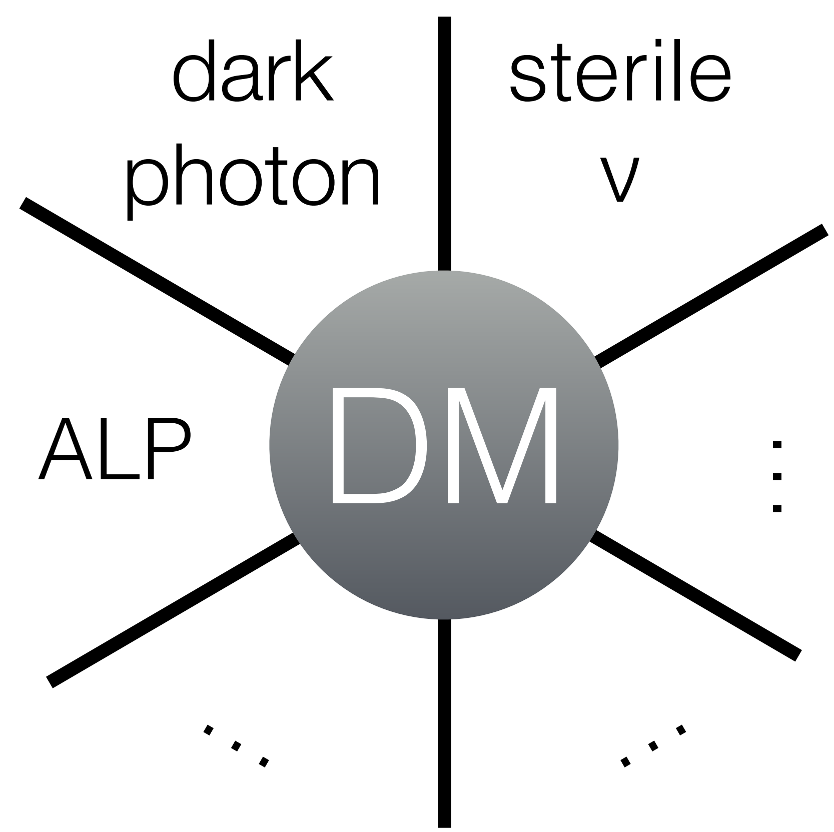
The dark sector paradigm

from Particle Fever



The dark sector paradigm

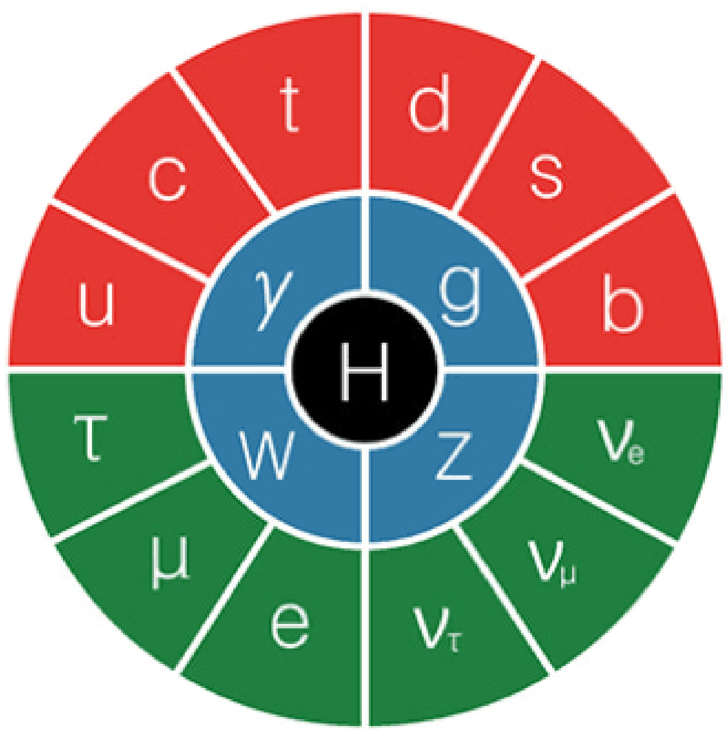


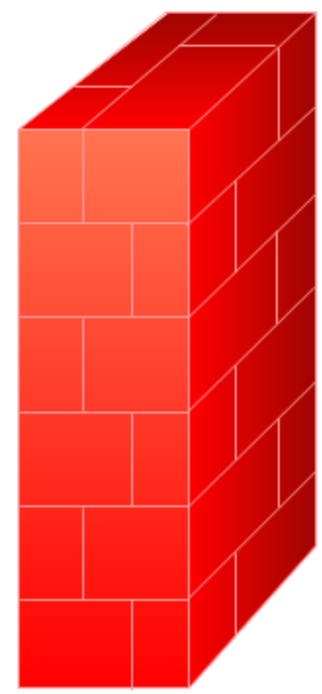


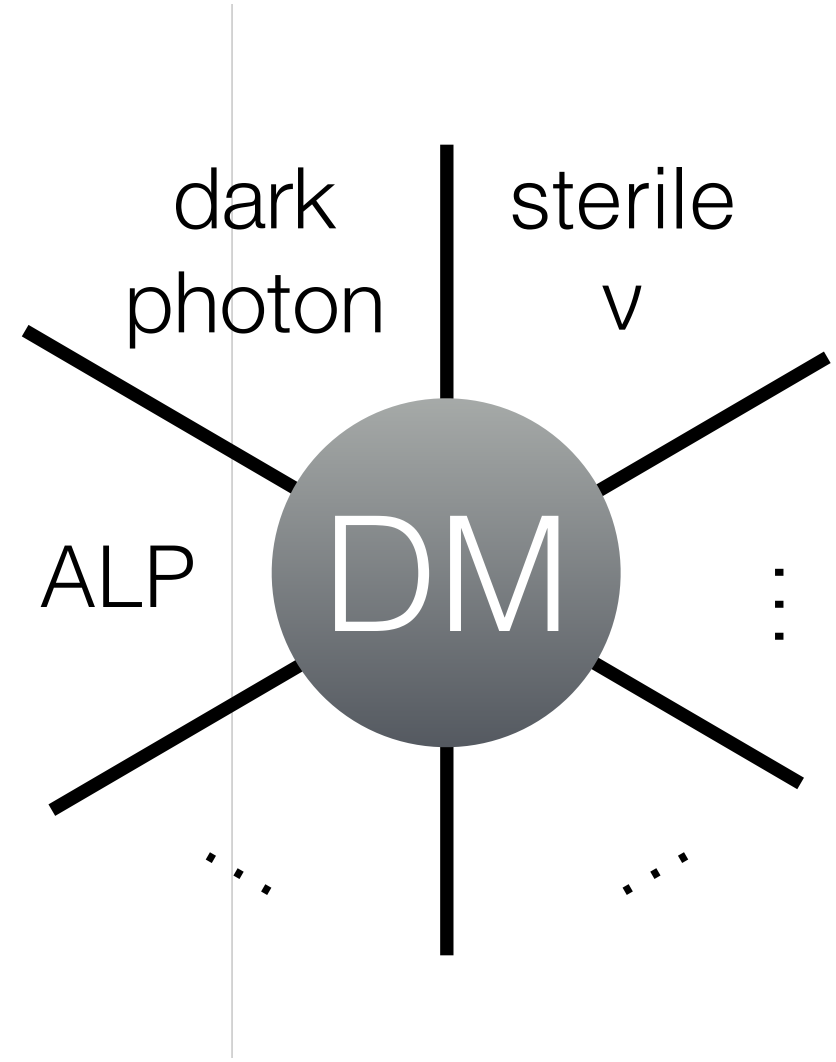
from US Cosmic Visions

The dark sector paradigm

from Particle Fever



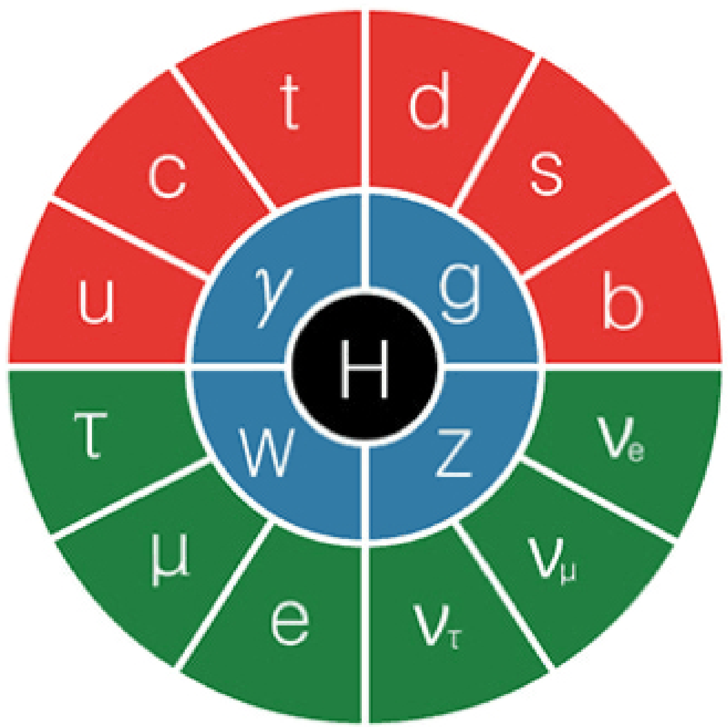


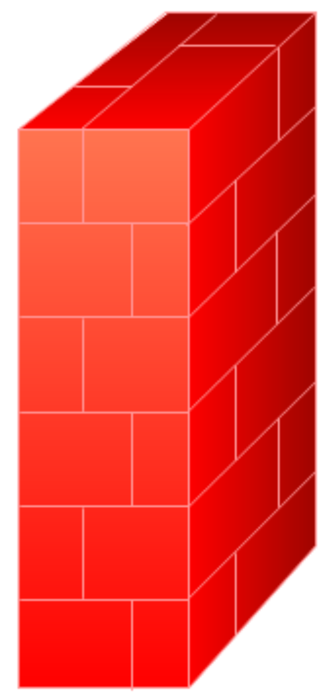


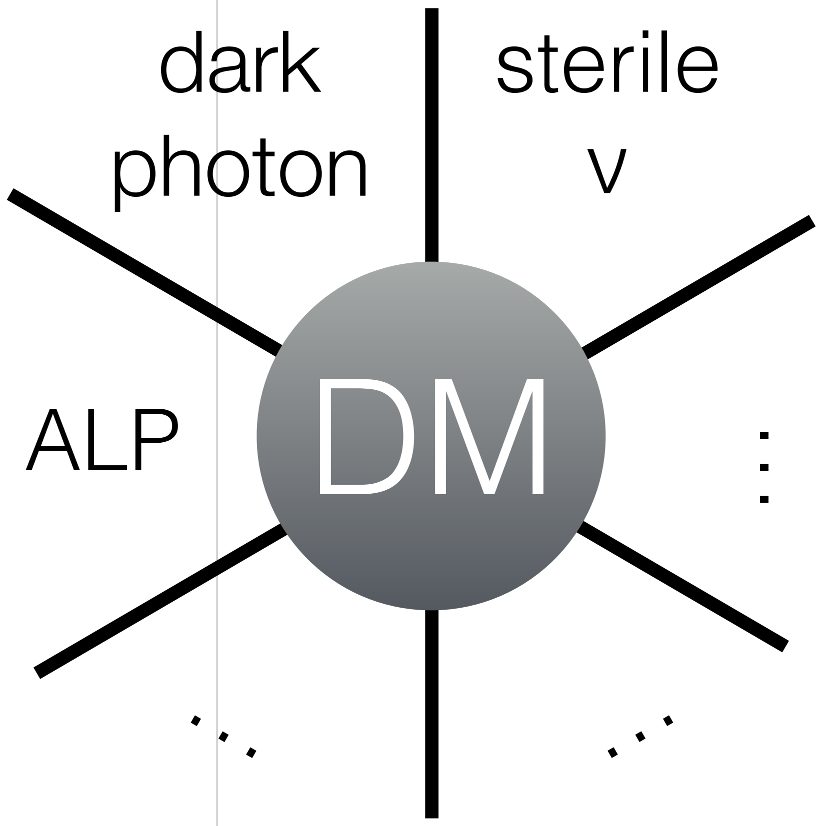
What if dark sectors completely decouple from the visible sector?

The dark sector paradigm

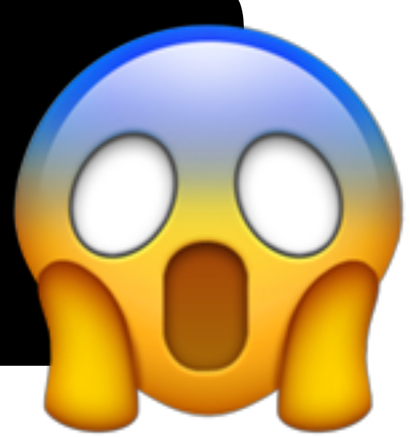
from Particle Fever





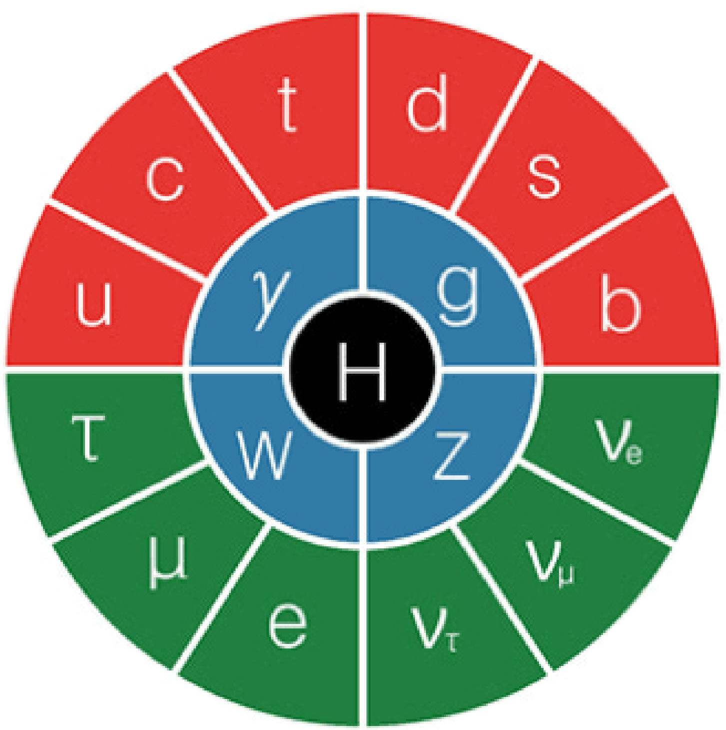


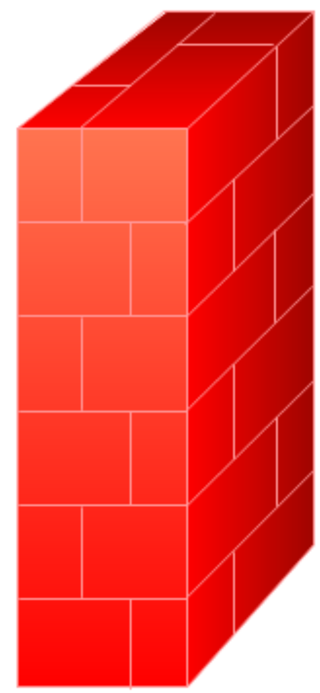
What if dark sectors completely decouple from the visible sector?

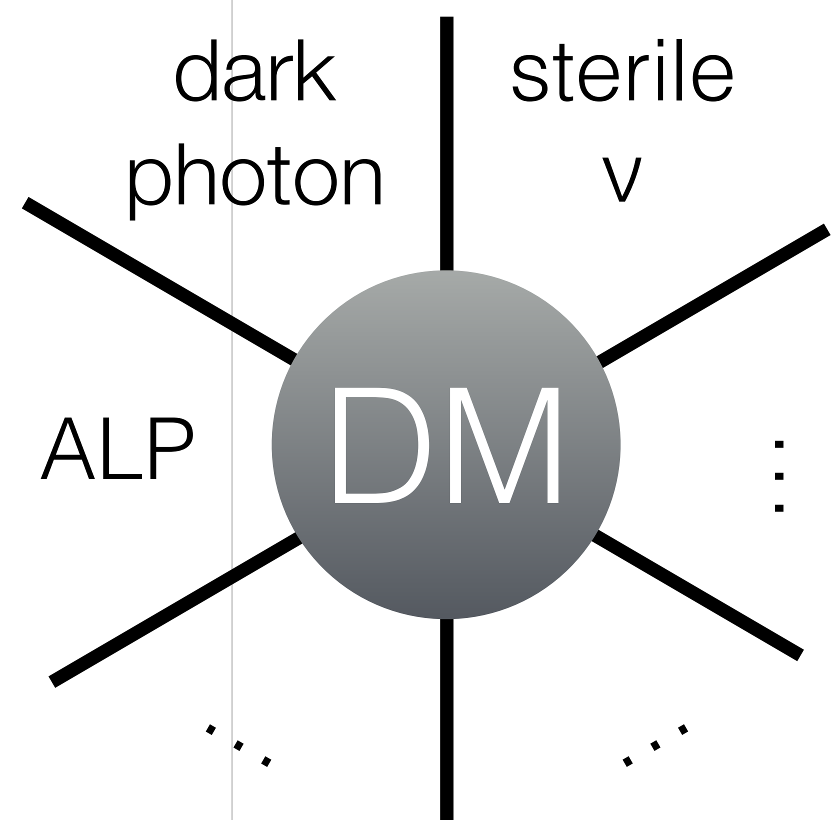


The dark sector paradigm

from Particle Fever



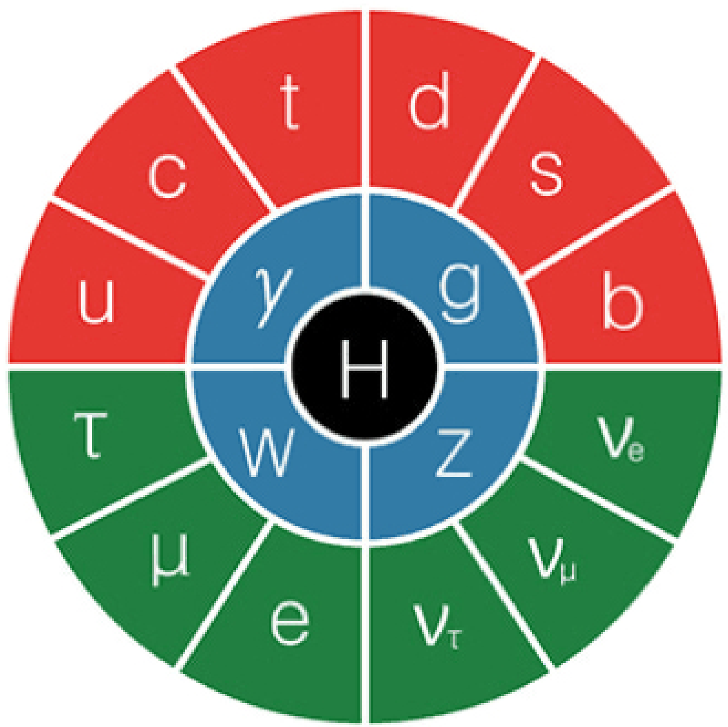


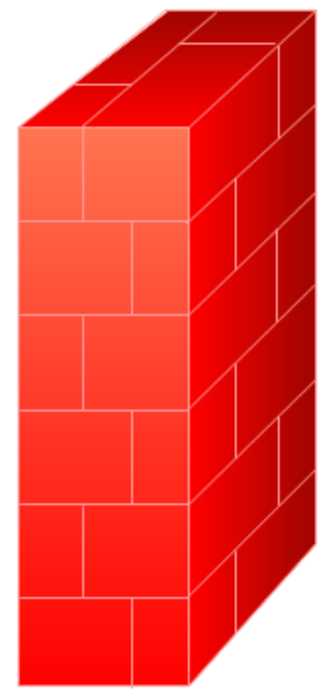


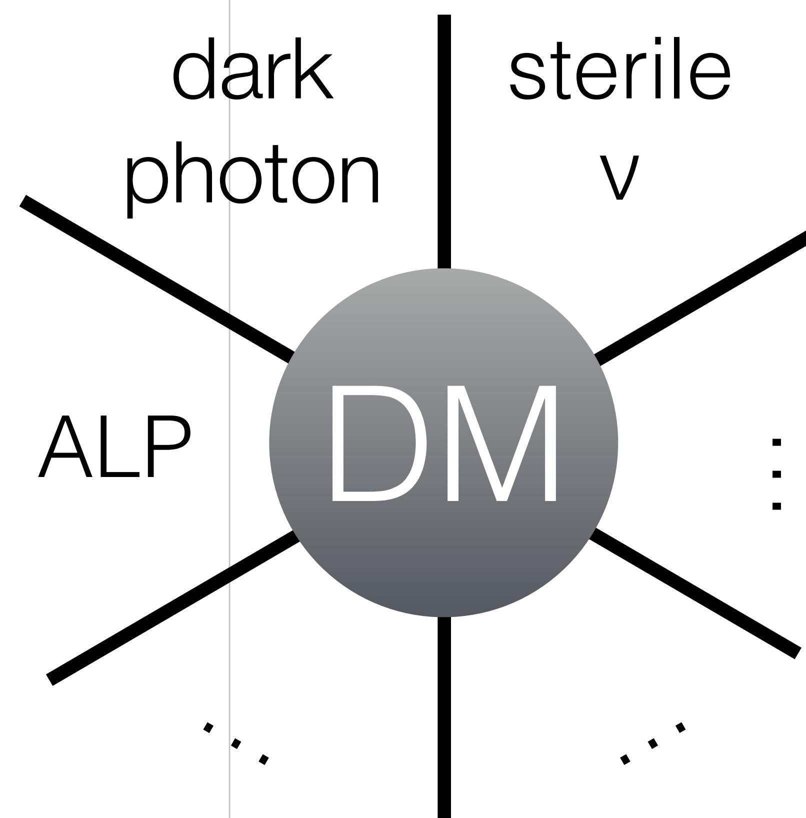
Gravitational probes

The dark sector paradigm

from Particle Fever







DM distributions in cosmology & astronomy

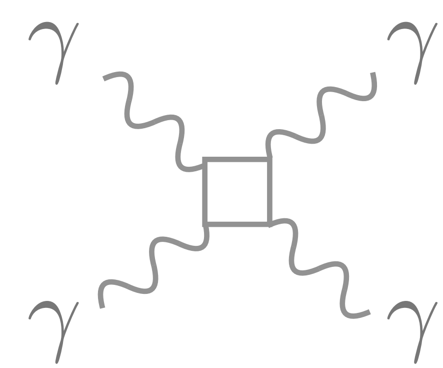
Self-interacting DM

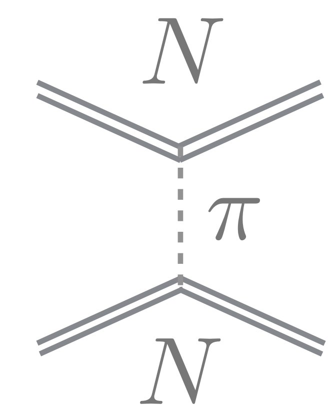
1. Self-interactions are common for normal matter

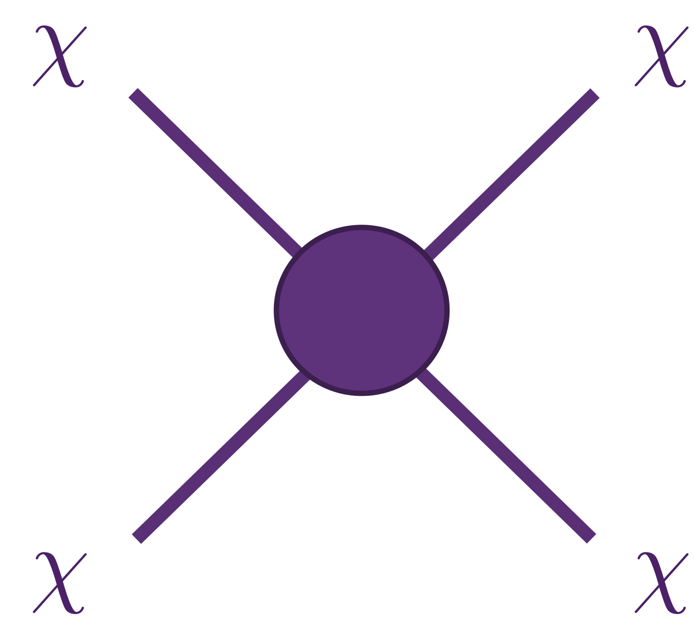
   Why not dark matter?

2. Significant self-interaction in DM dense regions (e.g. center of a halo)

3. Negligible self-interaction in DM sparse regions (e.g. large scale)



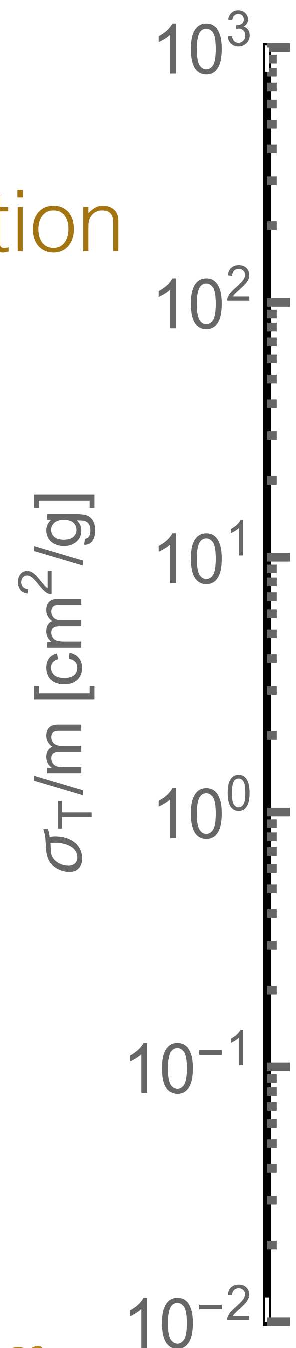




Spergel & Steinhardt '00
see review by Tulin & Yu '16

Dark matter self-interaction

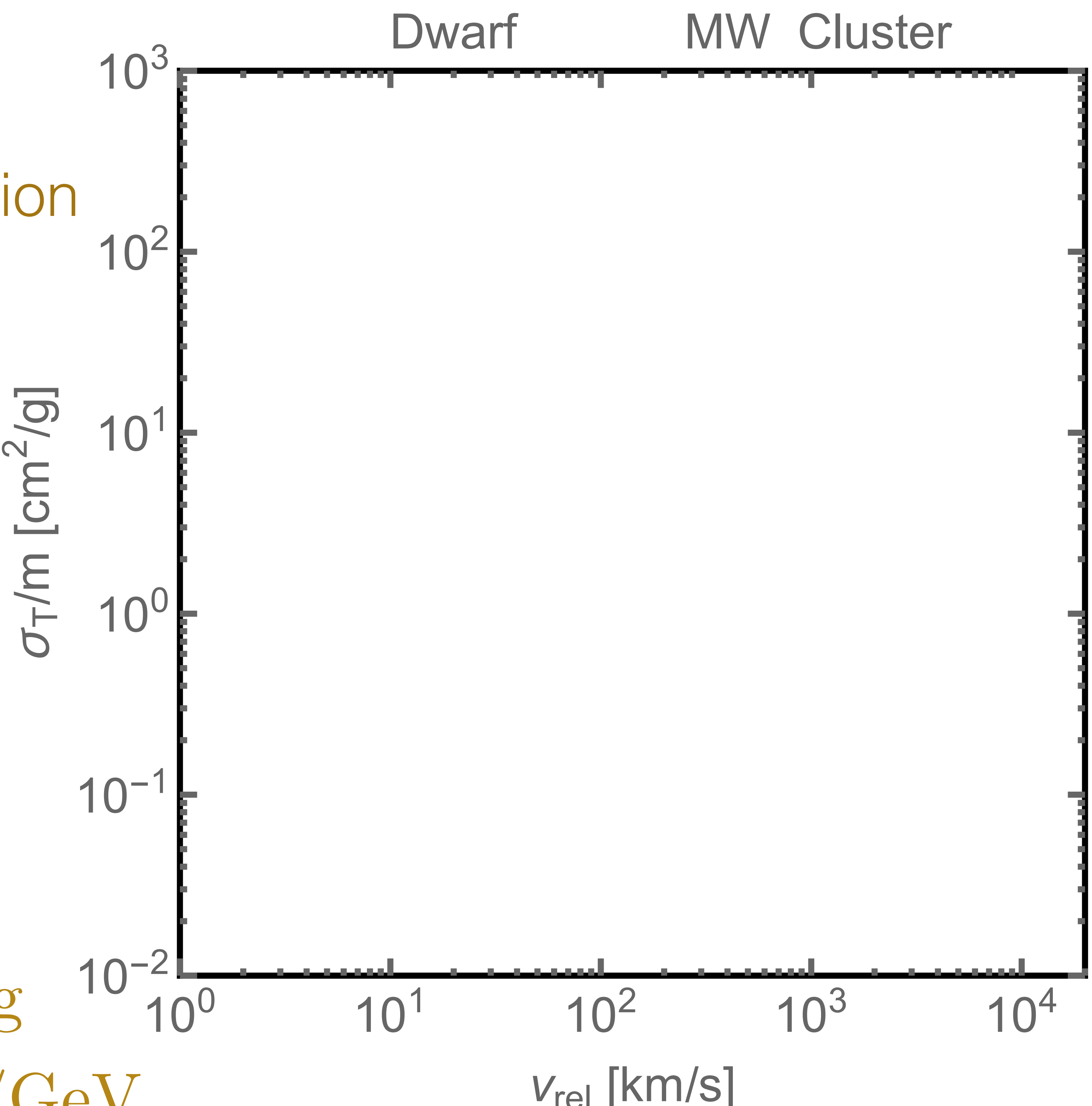
Self-interaction strength



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

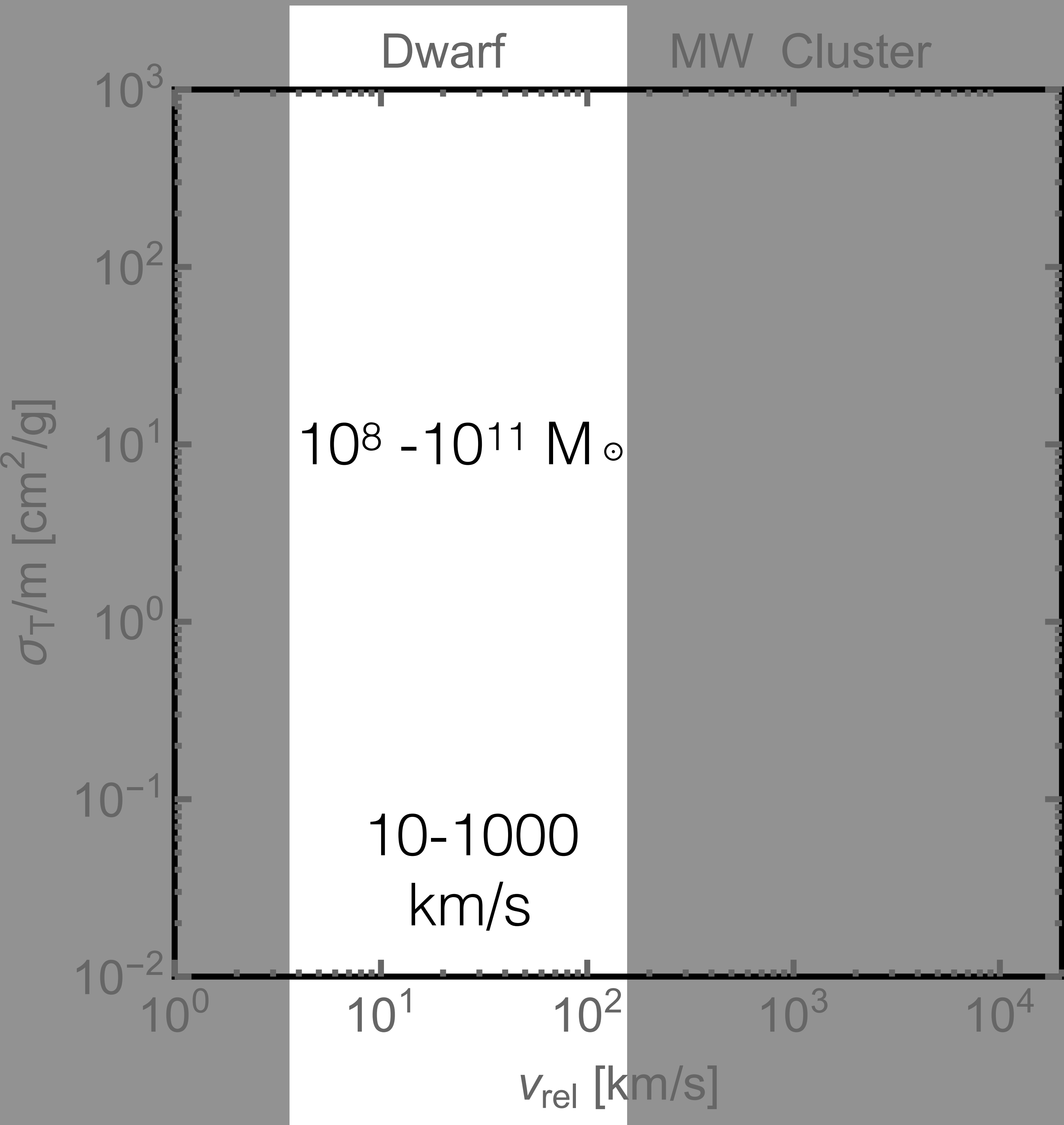
Probing SIDM in astrophysics

Self-interaction strength



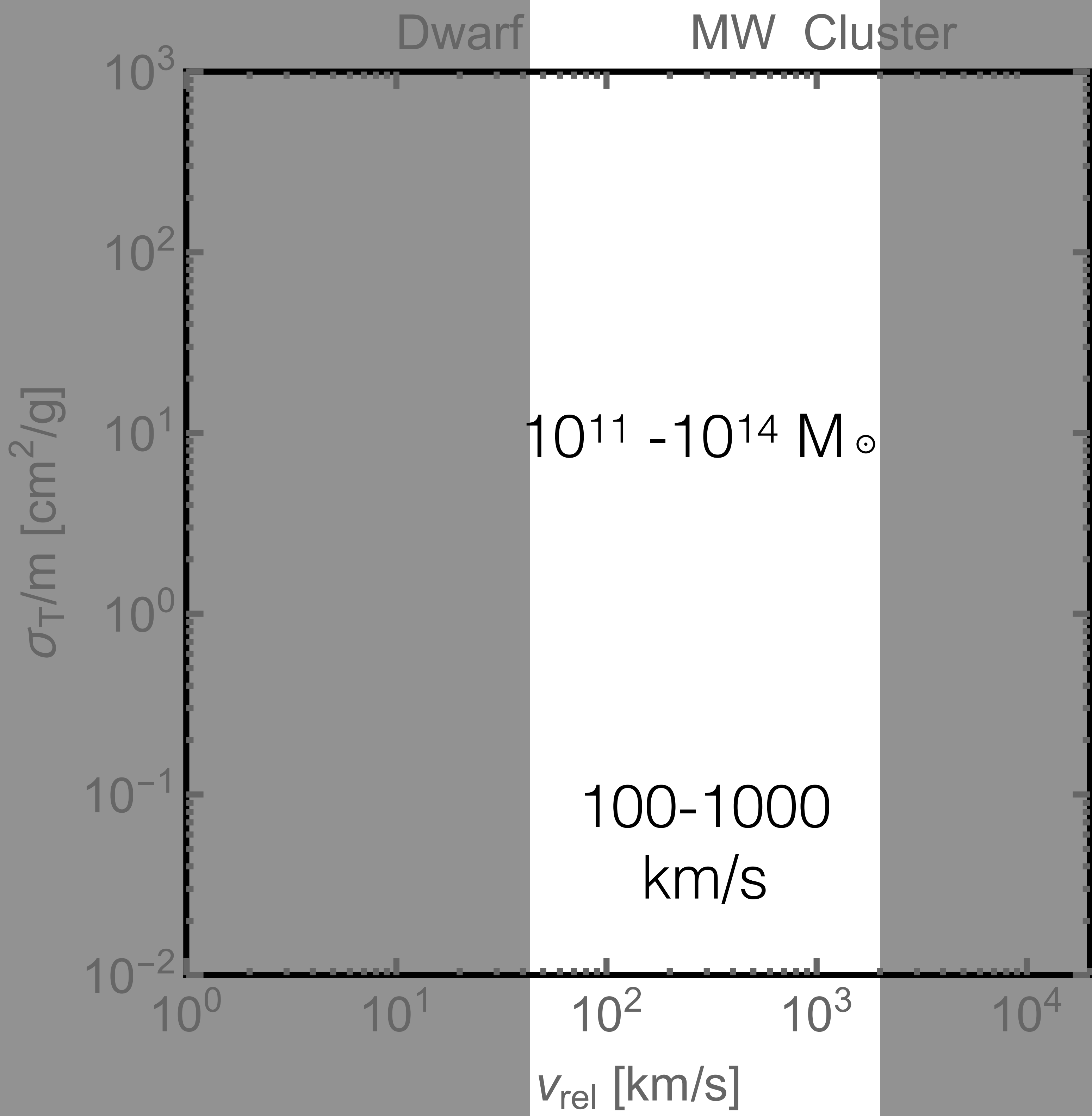
$$1\,\mathrm{cm}^2/\mathrm{g}$$
$$\approx 2\,\mathrm{barn}/\mathrm{GeV}$$

Dark matter self-interaction

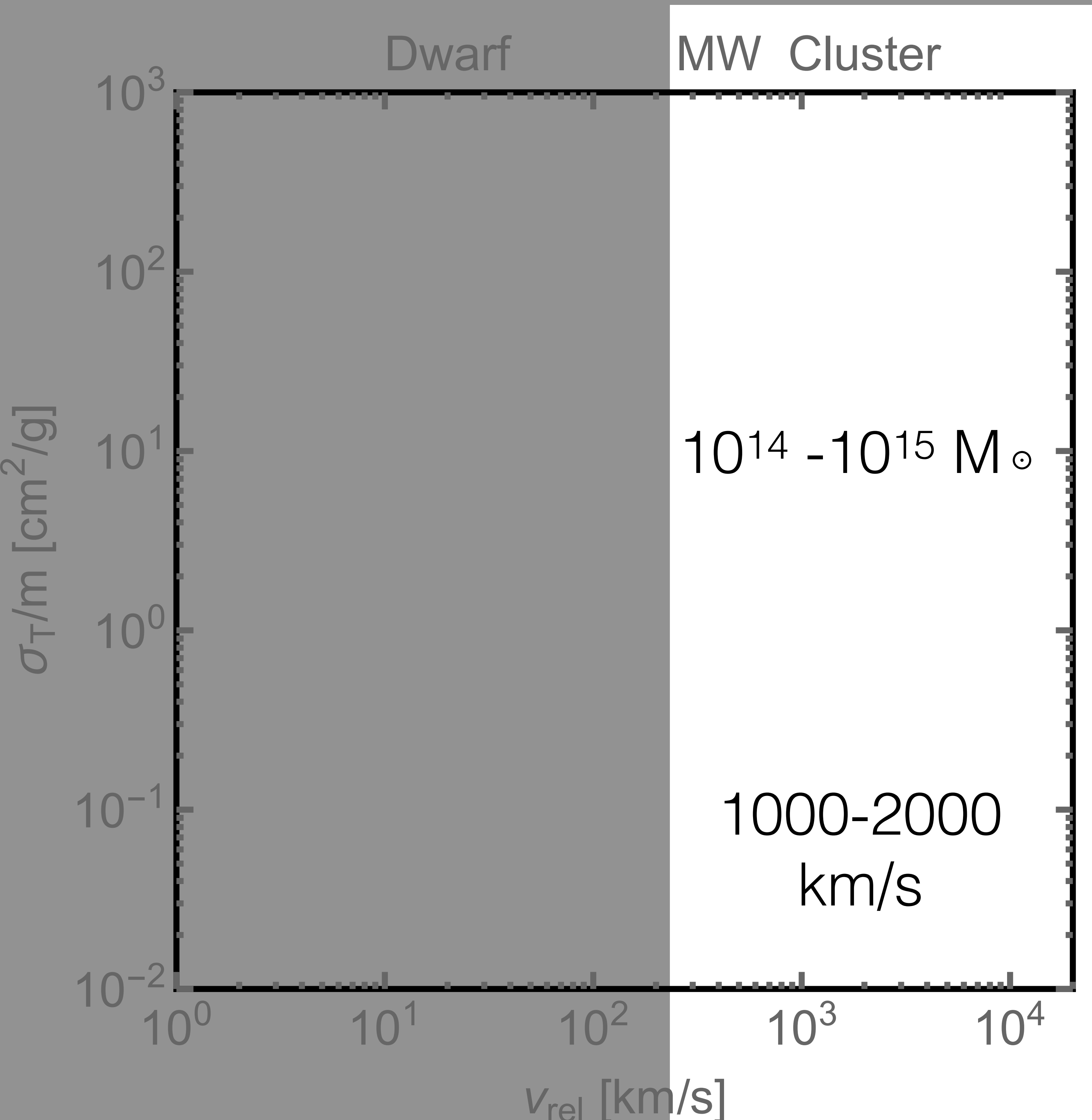


ng (BU)

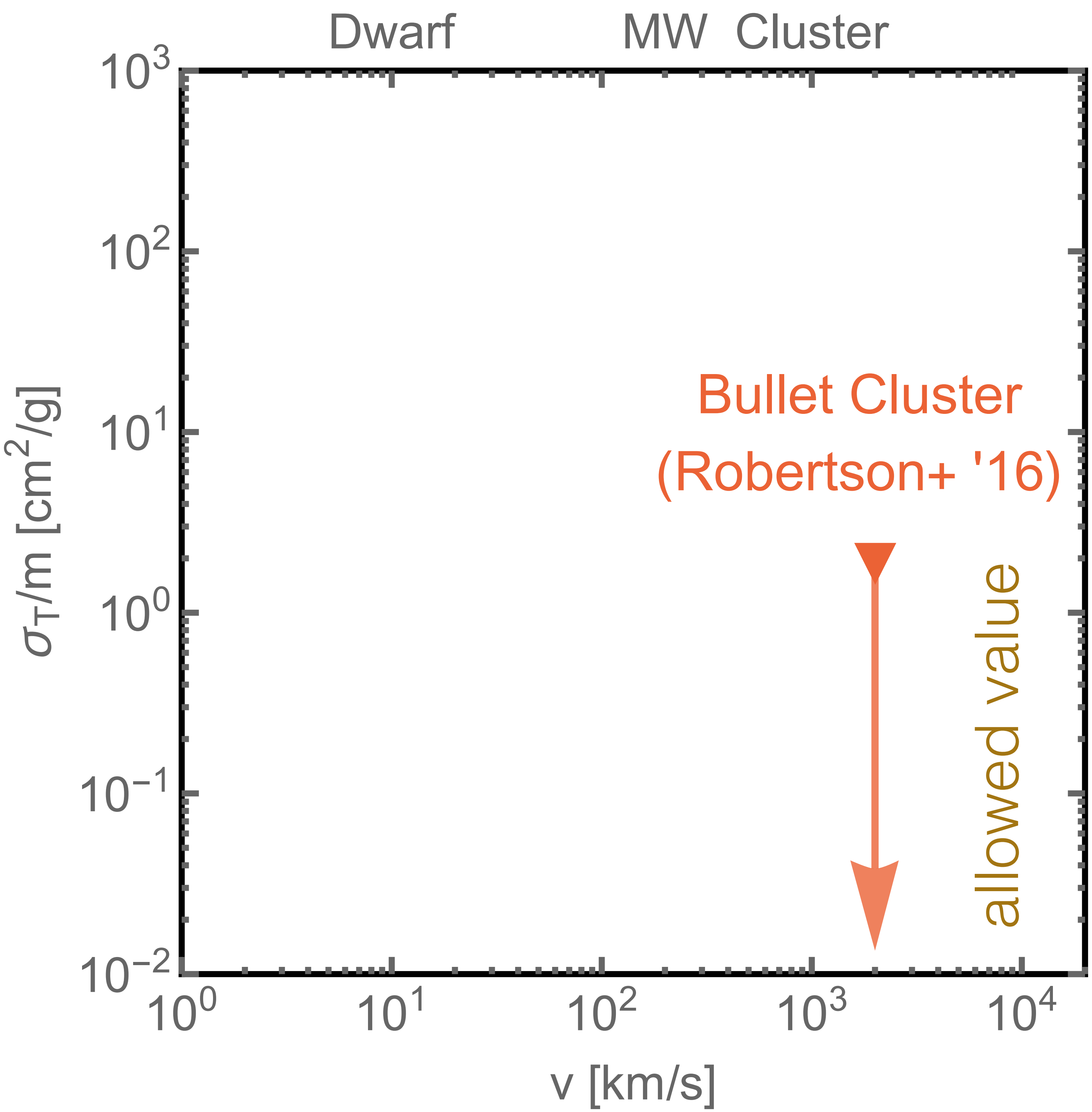
Dark matter self-interaction



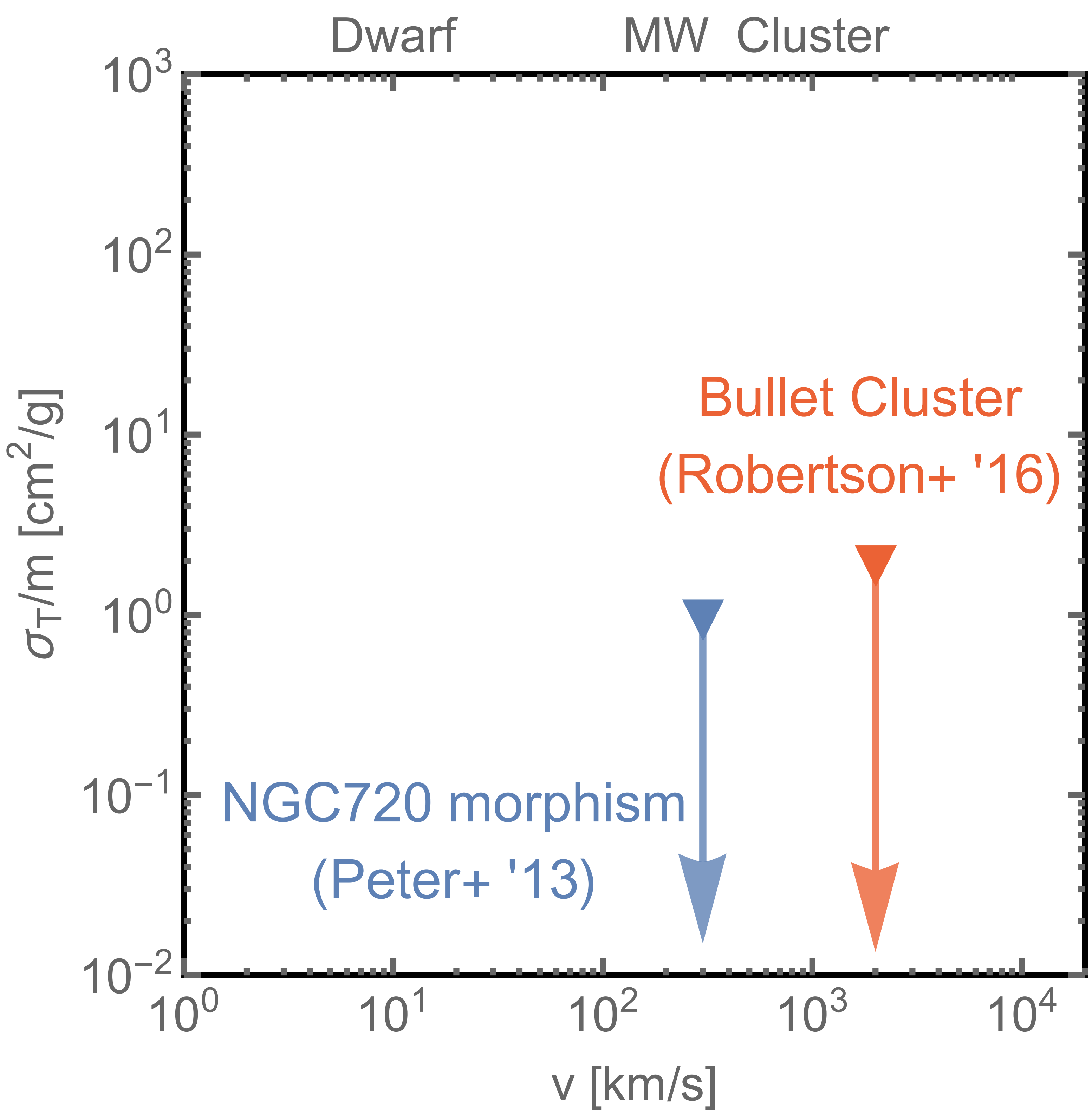
Dark matter self-interaction



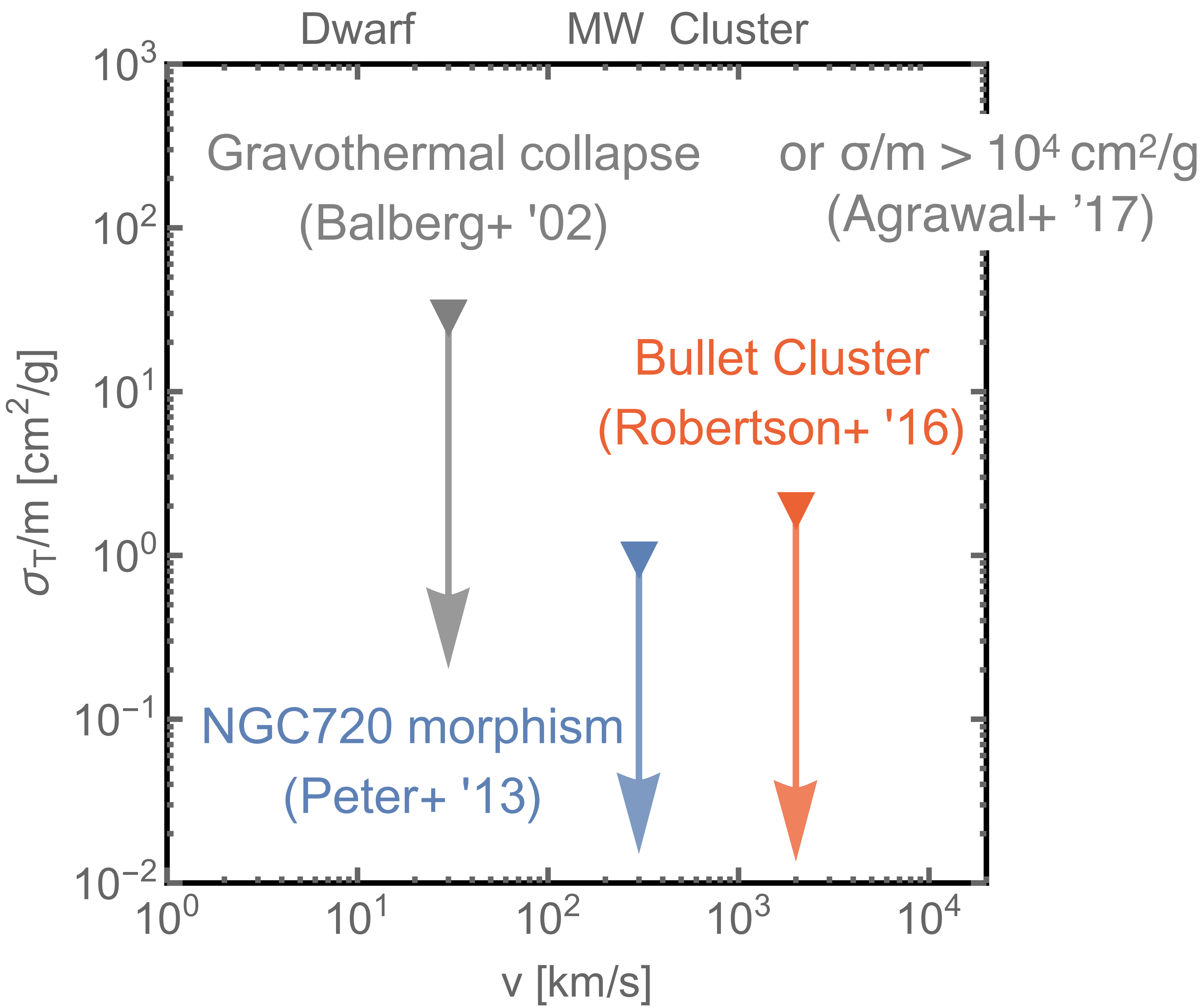
Cluster crossing



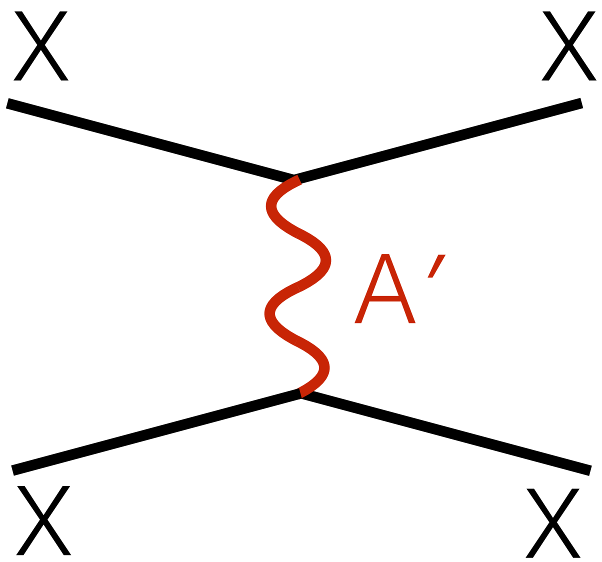
Galaxy morphism

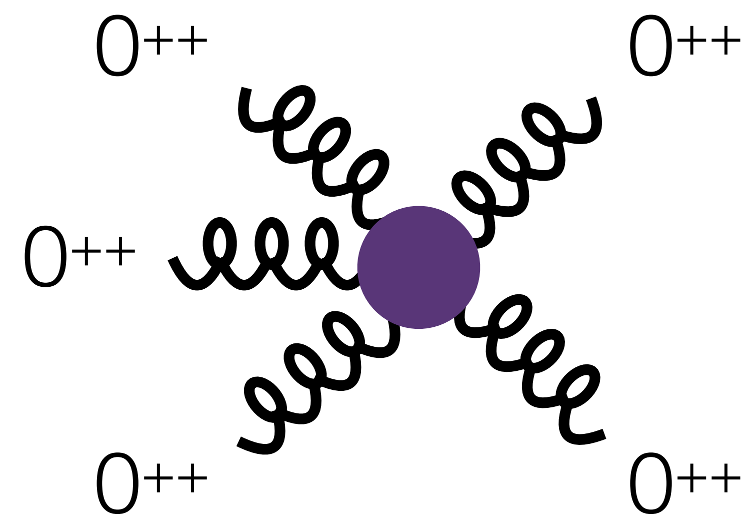


Gravothermal collapse

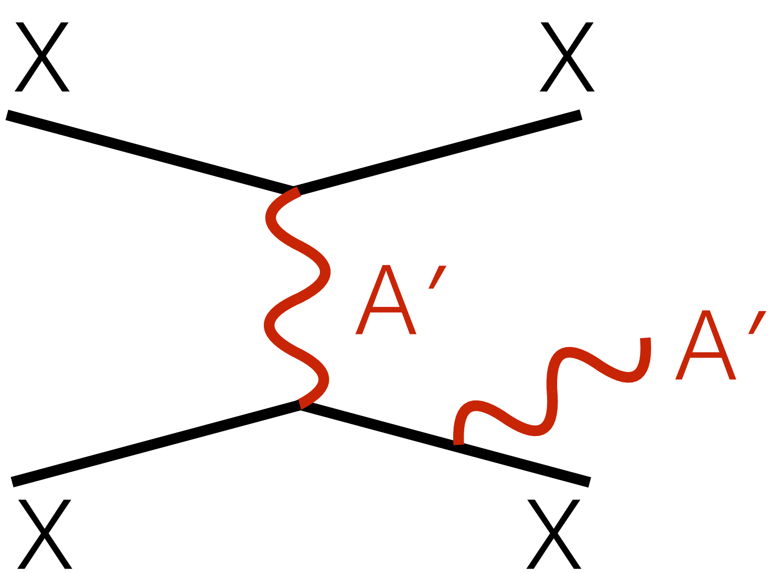


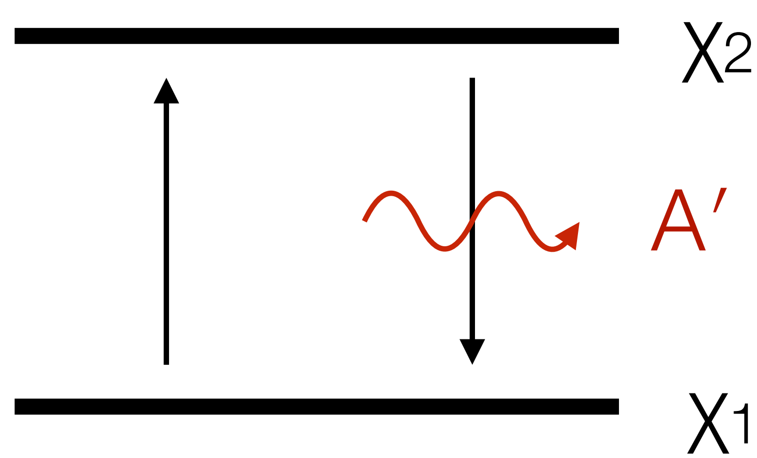
Dark sector is richer

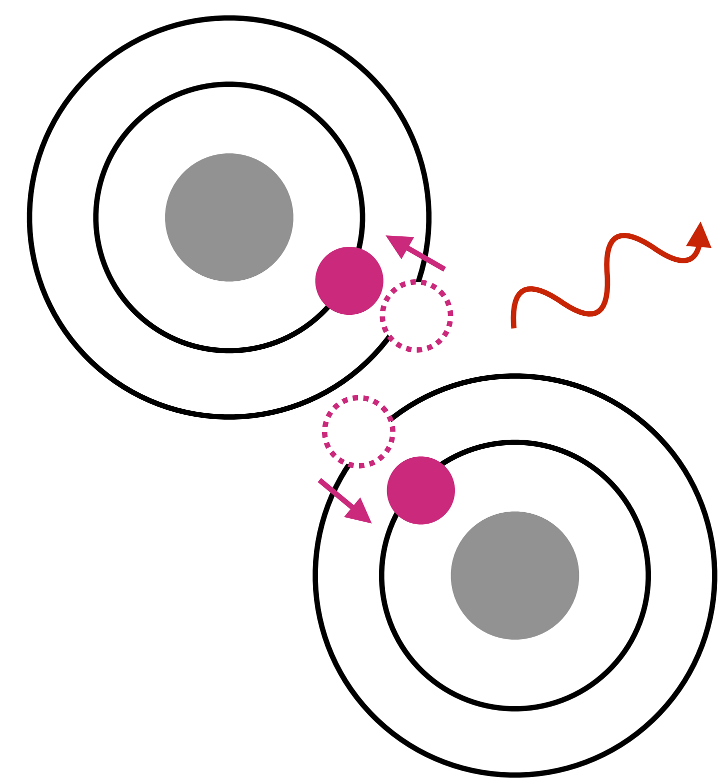




e.g. Ackerman et al '09, Loeb & Weiner '10, Boddy et al'16……
Fan et al '13, Agrawal '16, '17……







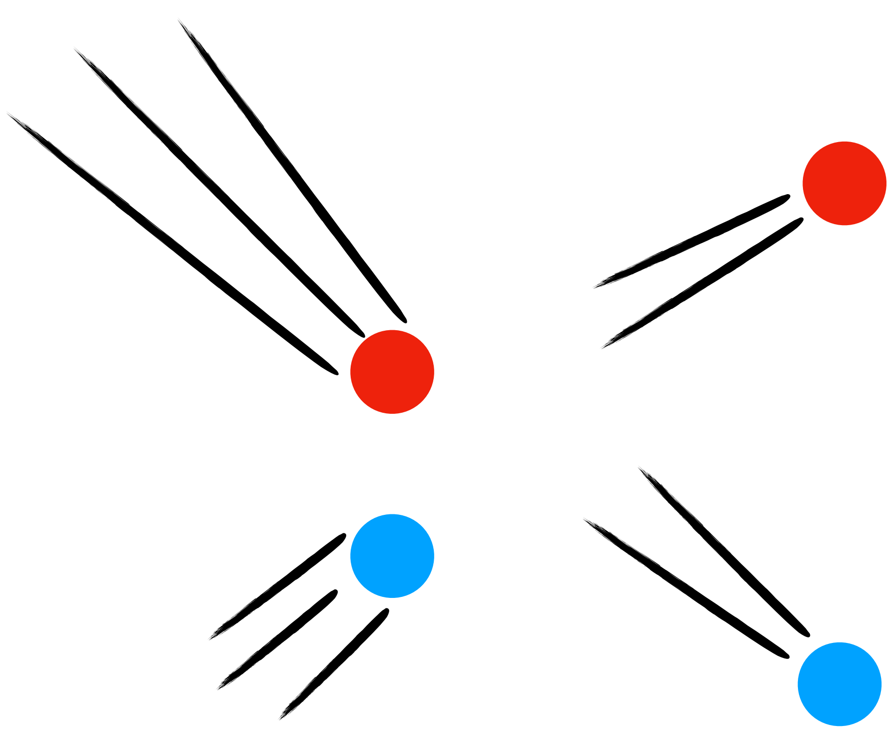
Outline

- Gravothermal collapse from DM self-interactions
- Method: fluid model
- Constraining DM self-interactions by avoiding gravothermal collapse
- Summary

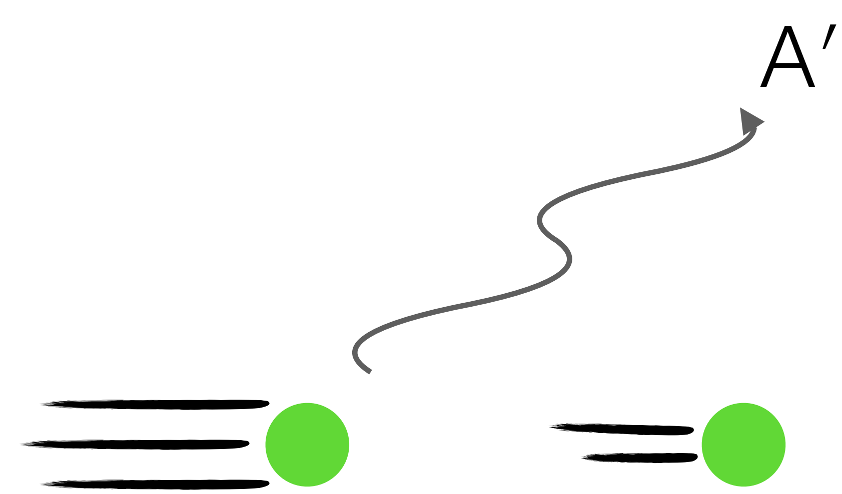
Gravothermal collapse

-Why do halos collapse?
-Because halos get cooled.

Elastic DM
self-scattering



Dissipative DM
self-scattering



Virial theorem

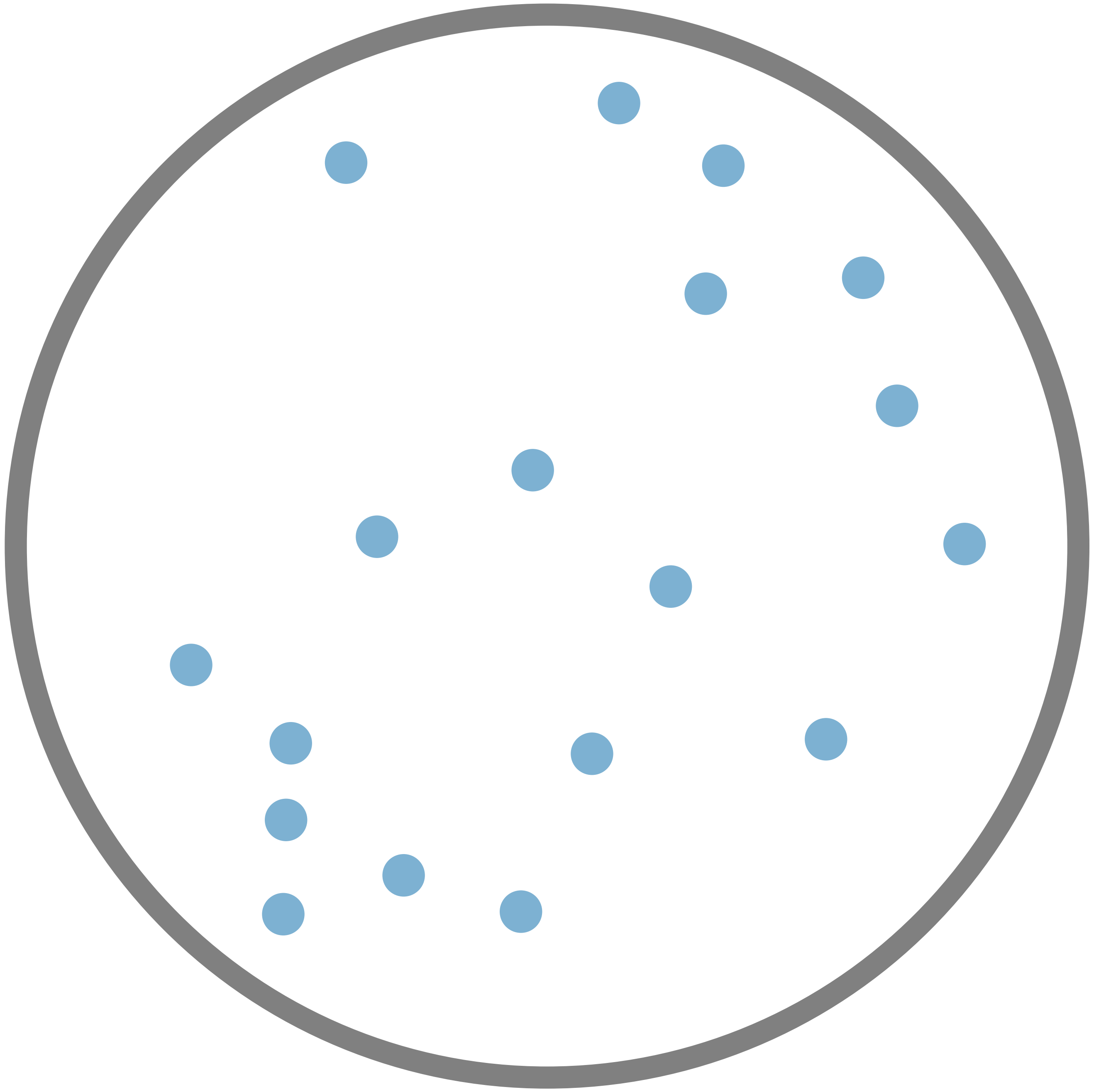
$$2K.E. + P.E. = 0$$

$$\Rightarrow \quad E_{\rm tot} = -K.E.$$

$$\Rightarrow \quad \frac{E_{\rm tot}}{T} < 0$$

Negative heat capacity!

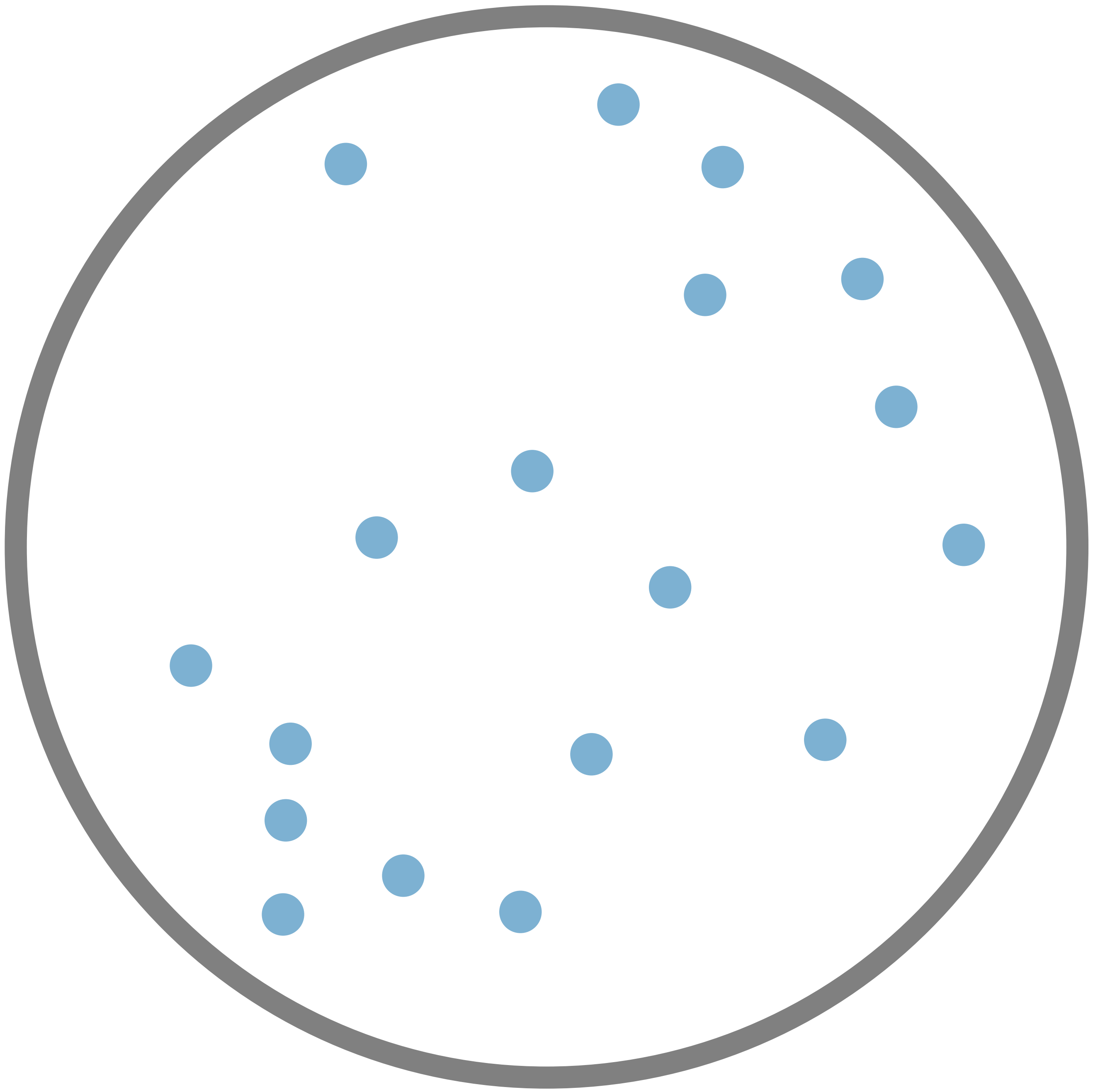
Gravothermal collapse



Core region of a halo

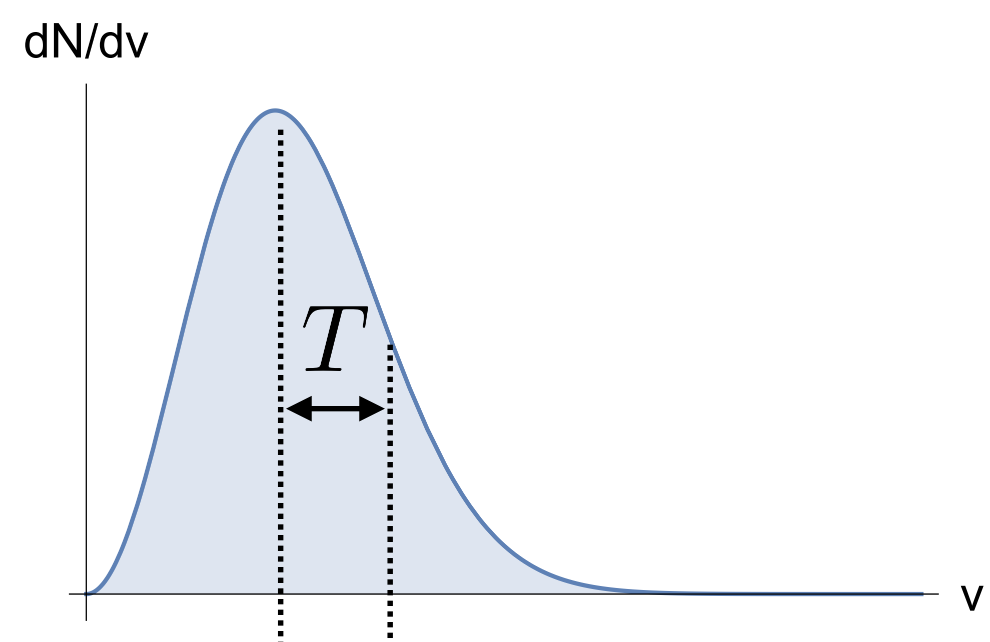
Take a halo w/
an iso-thermal
profile

Gravothermal collapse

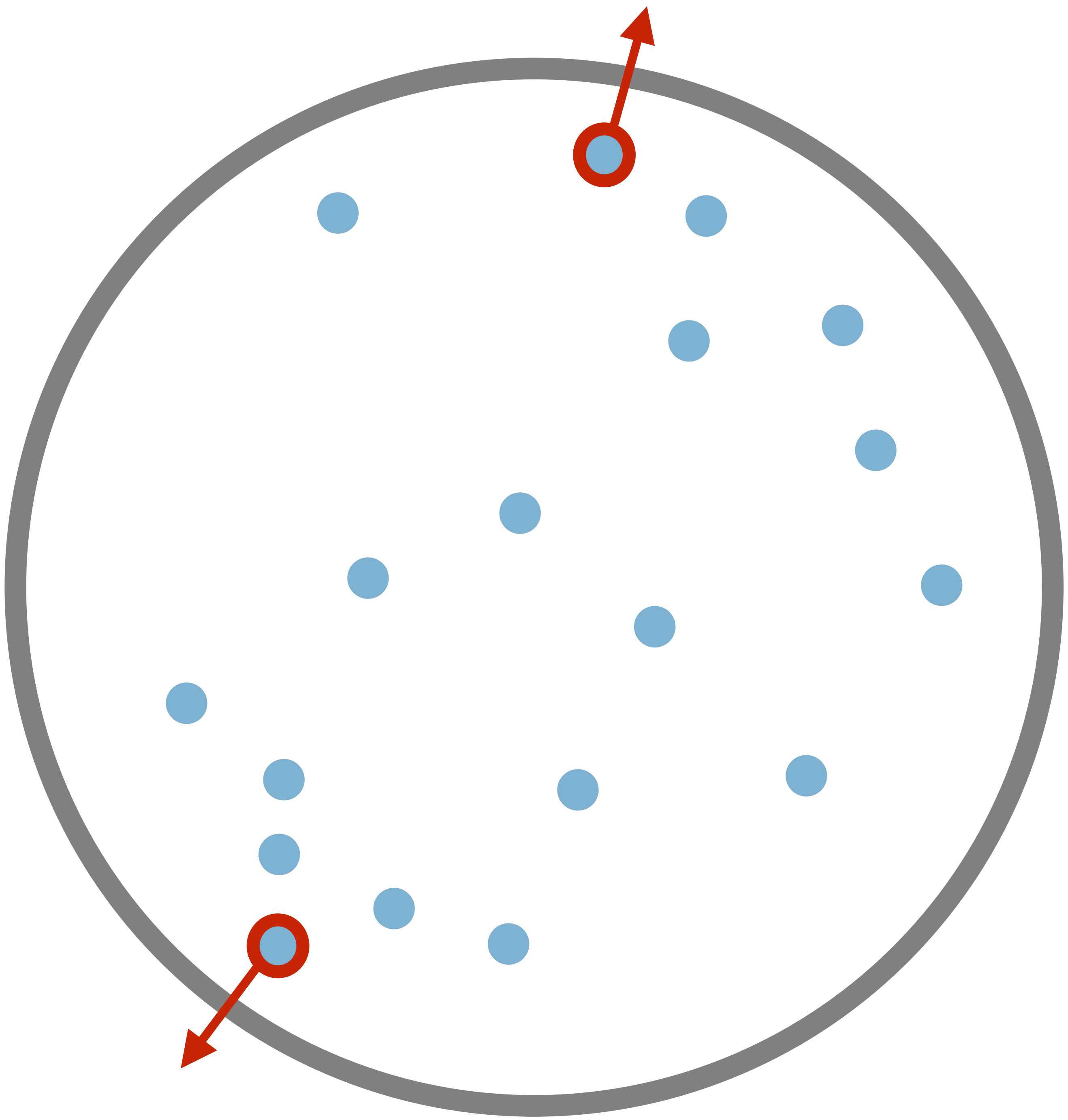


Core region of a halo

Velocity-distribution of DM particles

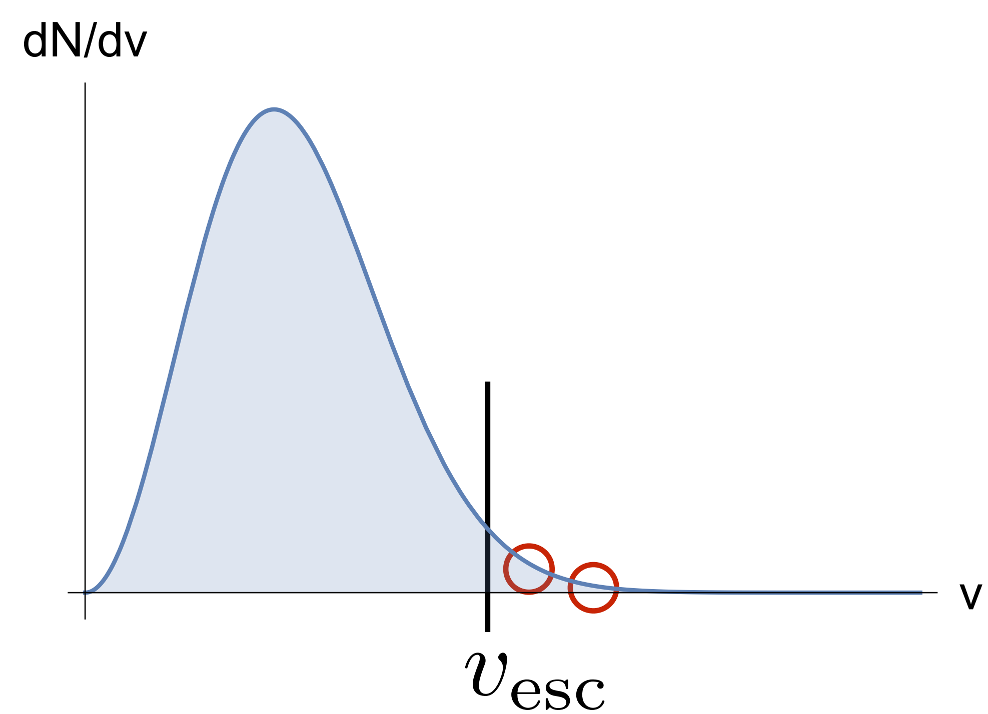


Gravothermal collapse



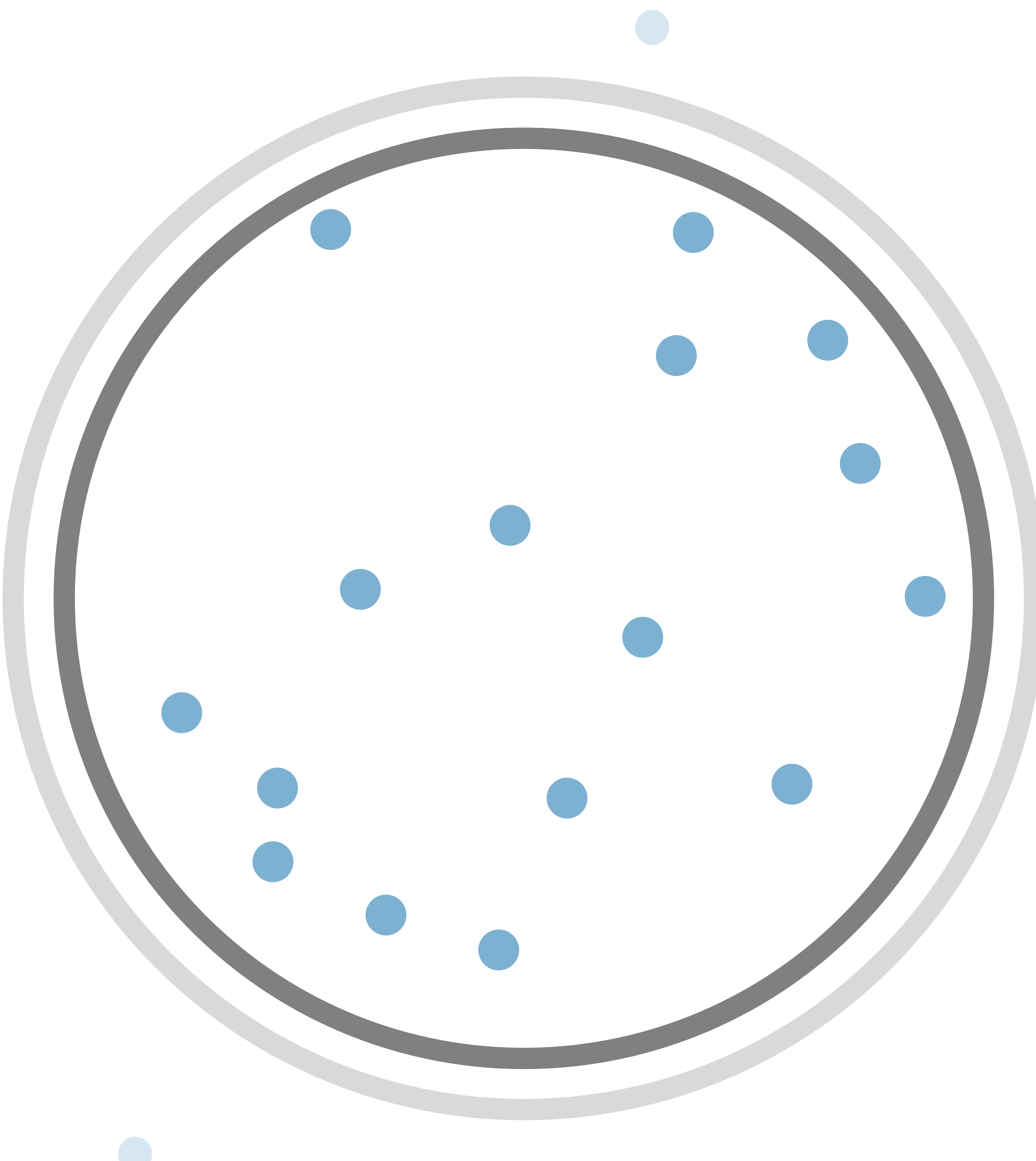
Core region of a halo

Velocity-distribution of DM particles



Particles in the “tail” can evaporate

Gravothermal collapse



Core region of a halo

$$K.E. \downarrow, \;\; P.E. \uparrow$$

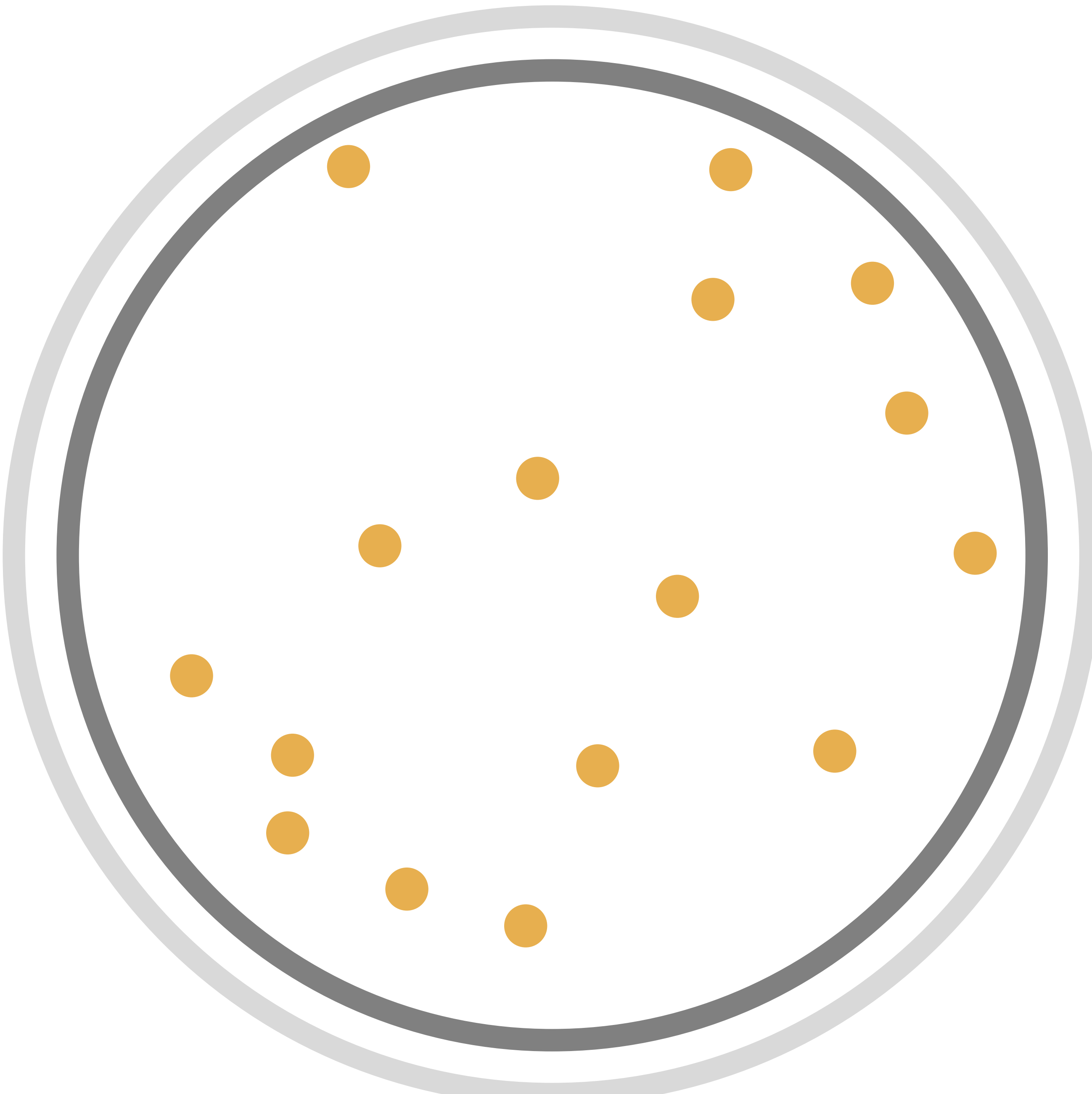
But overall

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

Out of virial

Gravity is no longer supported by random motion

Gravothermal collapse



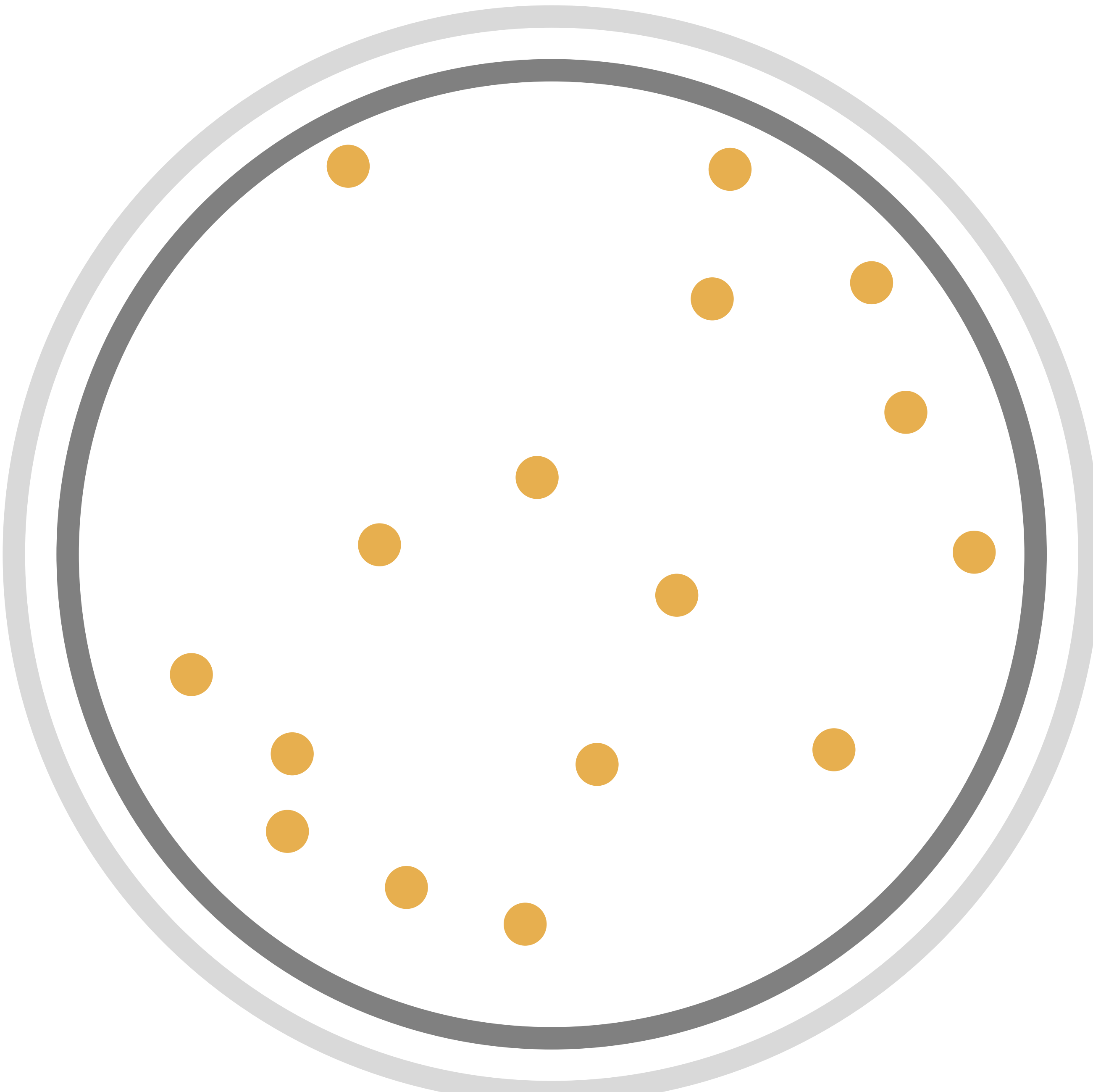
Core region of a halo

Back to virial through relaxation:

Averaged velocity increases ($T \uparrow$) such that

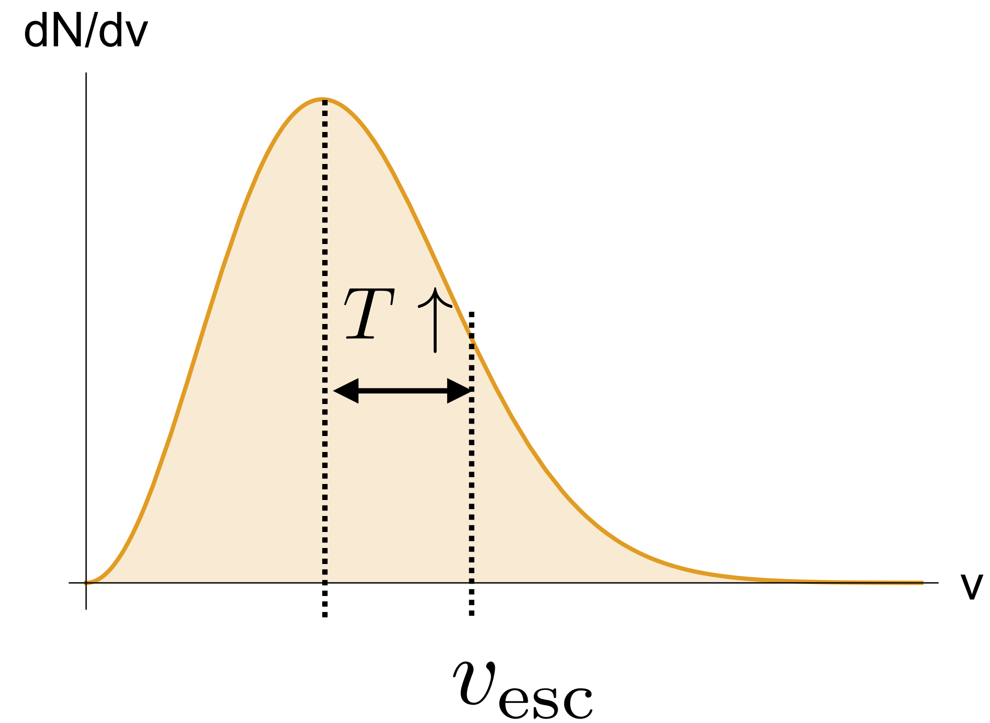
$$2K.E. + P.E. = 0$$

Gravothermal collapse



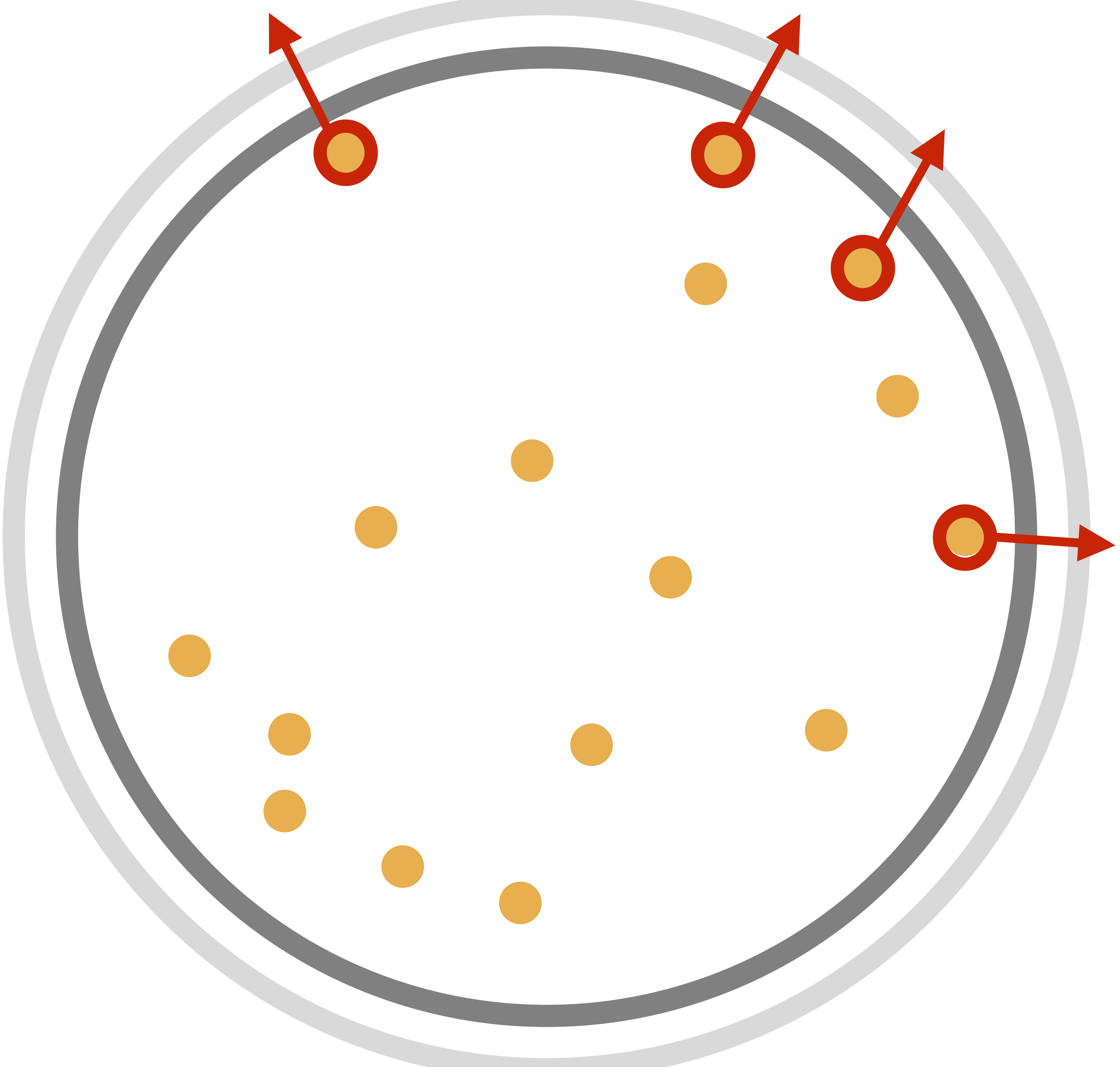
Core region of a halo

However



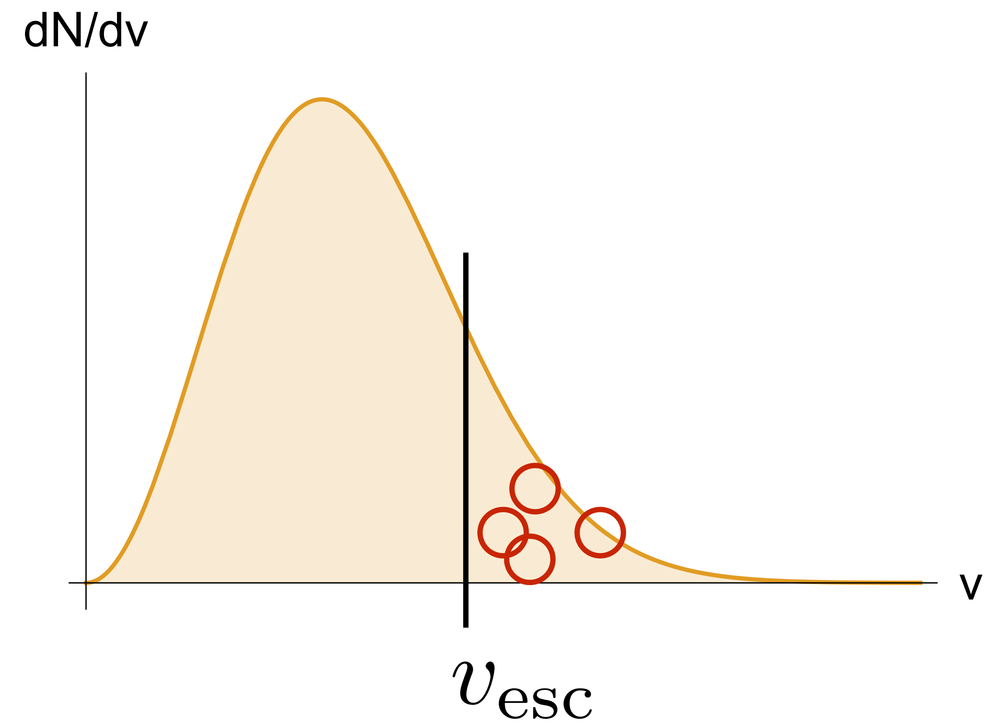
A fatter velocity distribution

Gravothermal collapse



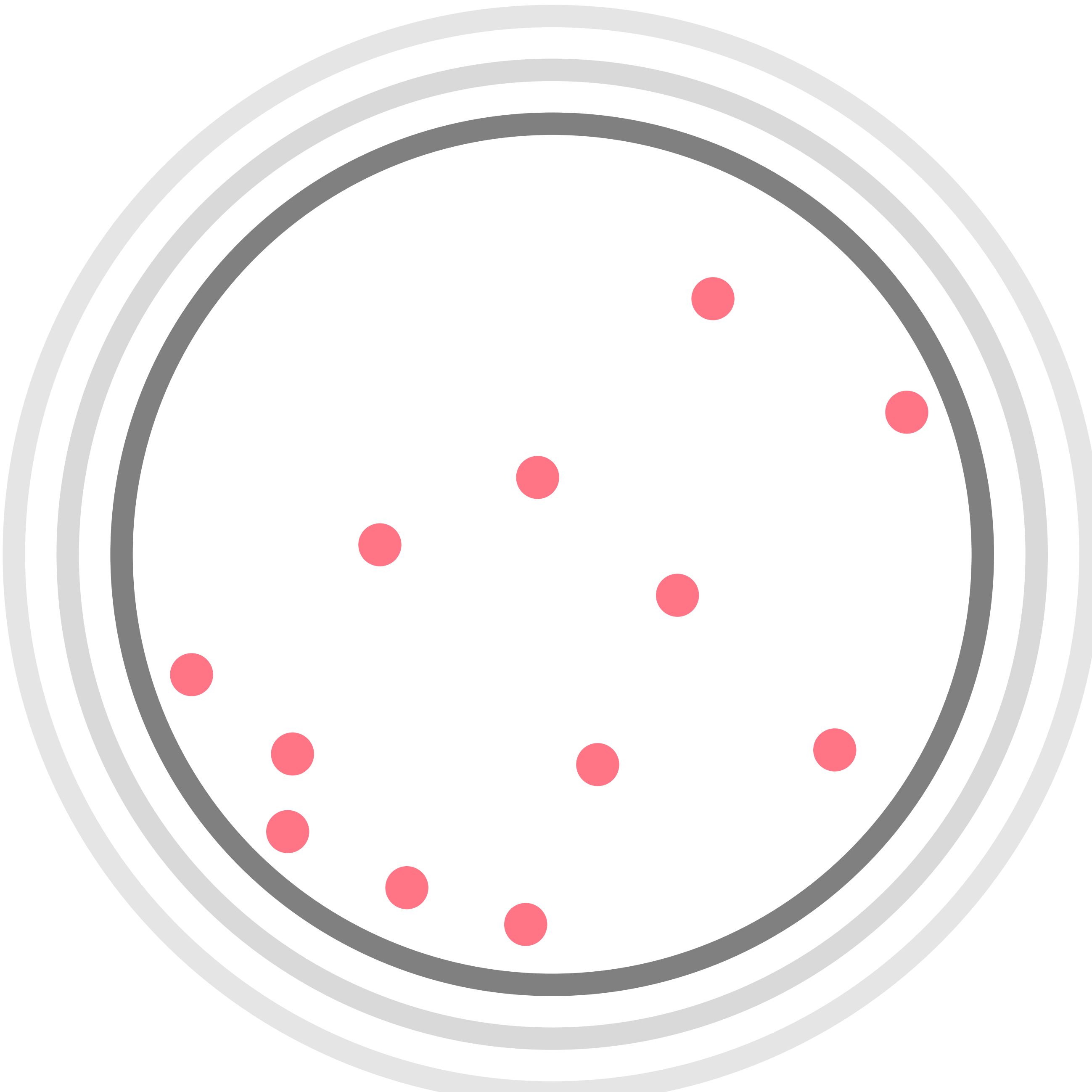
Core region of a halo

However

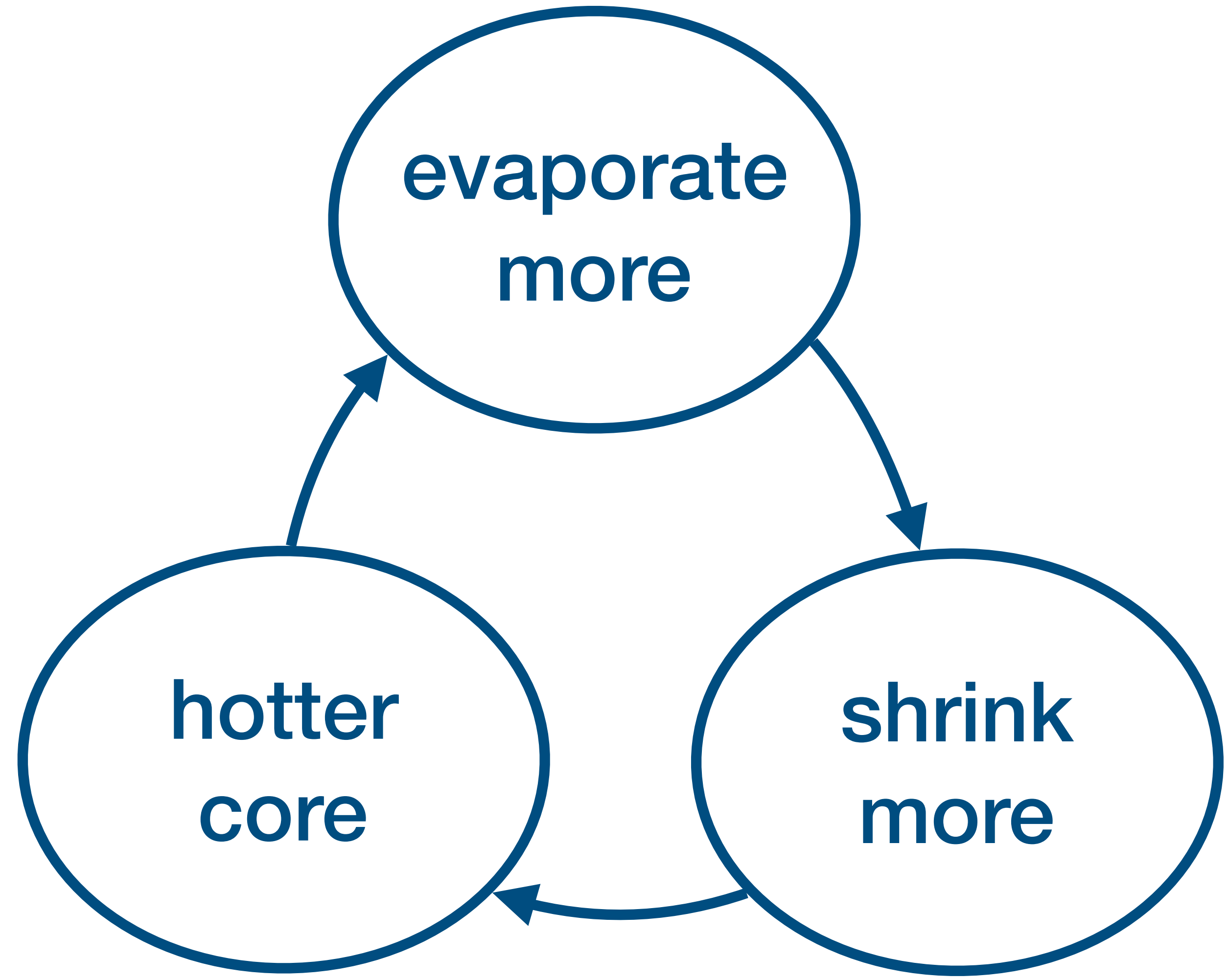


More particles are likely to evaporate

Gravothermal collapse



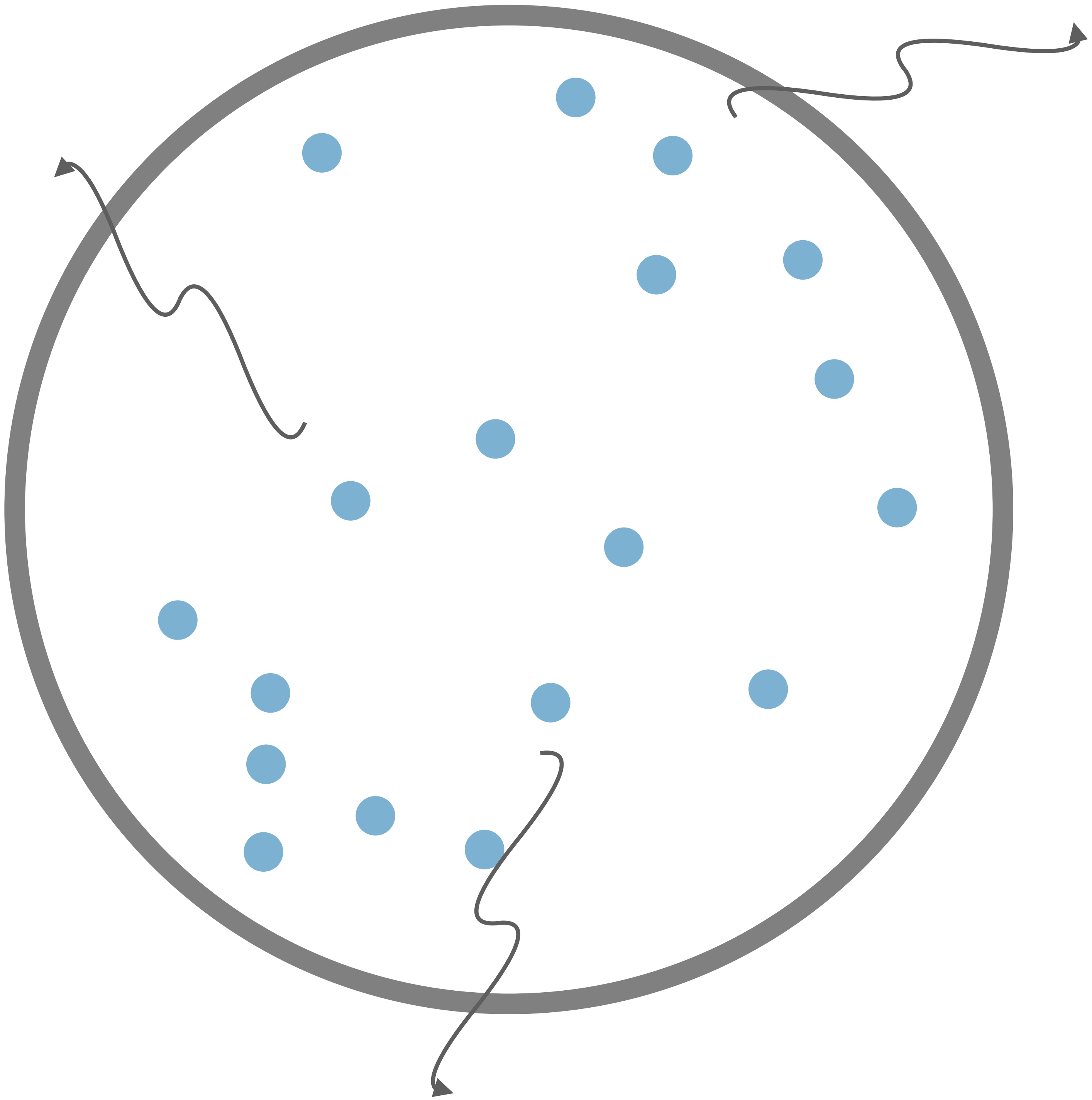
Core region of a halo



Runaway collapse!

a.k.a self-similar collapse

Bulk cooling



- Dissipative scattering causes extra energy loss, e.g. carried away by dark radiations
- Assume no re-absorption of the dark radiations
- Happens everywhere

Method

Method

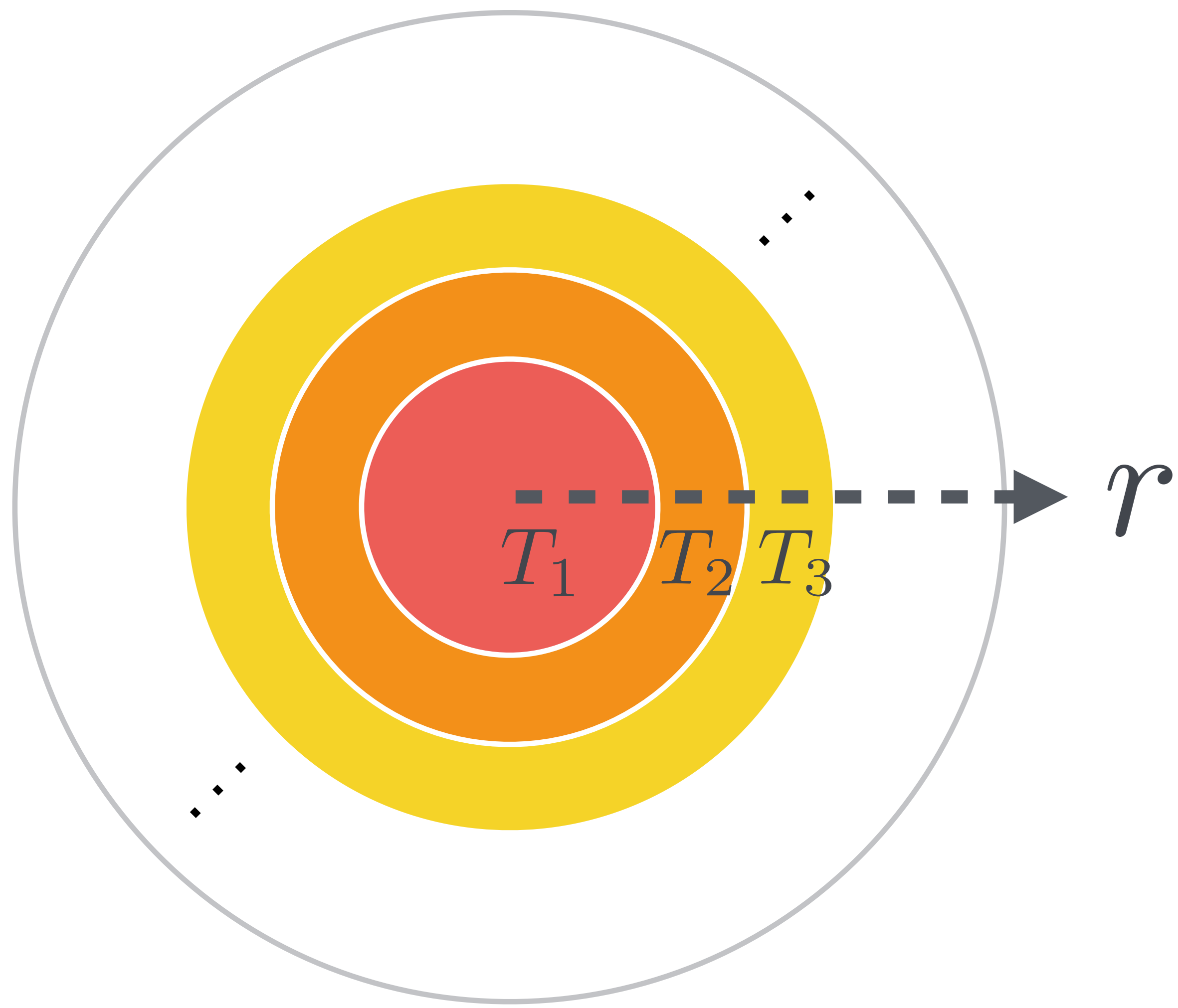
N-body simulation	Semi-analytical method
first principle	approximate
hard to resolve deep profiles	easy to resolve deep profiles
difficult to interpret results	more intuitive physical picture
computational costly, especially for high resolution	can be done on a laptop, easy for parameter scan

Fluid model

- A semi-analytical method to study **isolated, non/low-spin, single-component, no/low-baryonic content** & **spherical** halos
- Use to study globular clusters in 1980s & self-interacting dark matter (SIDM) halos in 2000s
- Good agreements with *N*-body simulations (pure elastic).

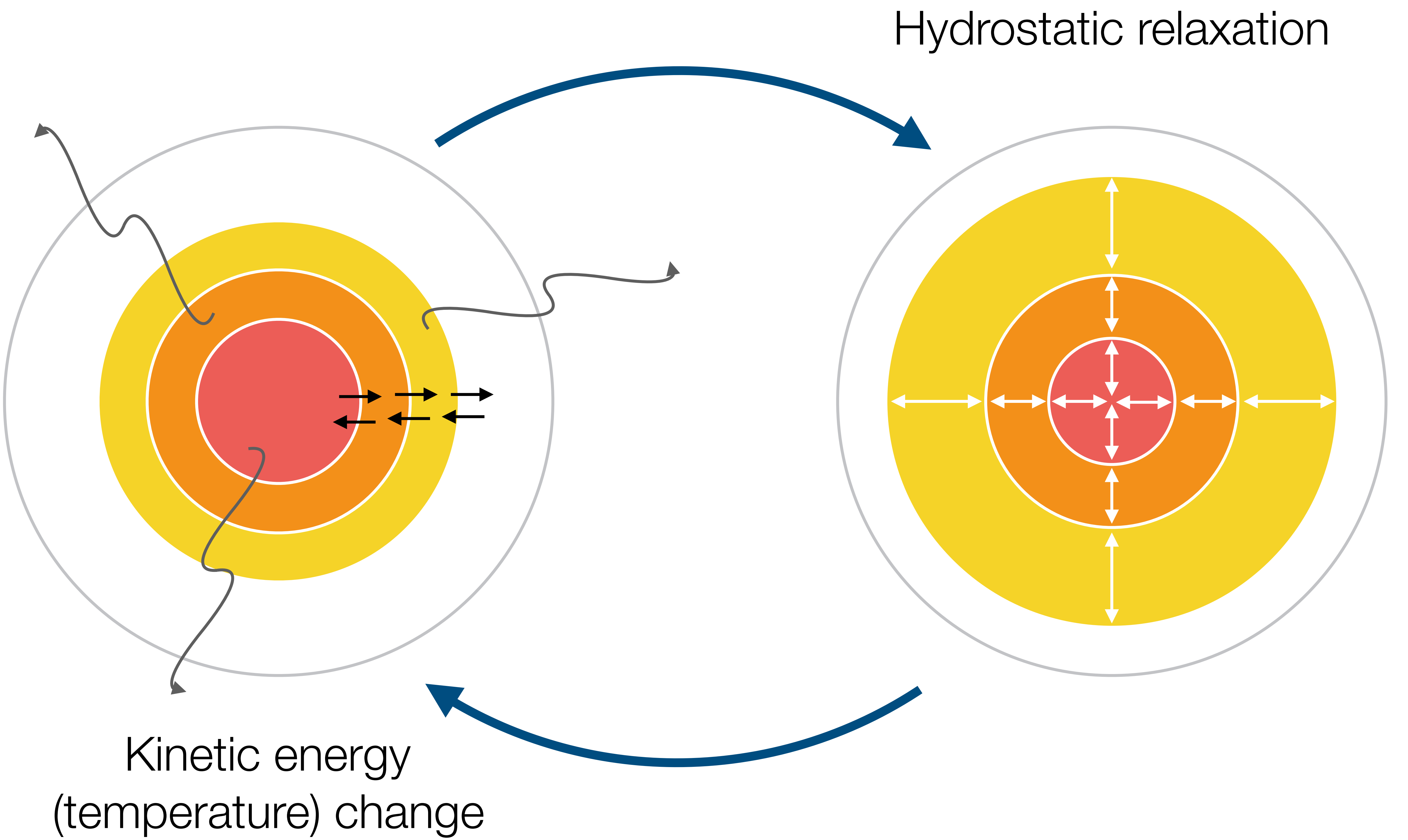
Hachisu et al ’78, Lynden-Bell & Eggleton, ’80; Inagaki & Lynden-Bell ’83; Heggie ’84; Goodman ’84; Balberg & Shapiro, ’02; Balberg et al ’02; Ahn & Shapiro, ’08; Koda & Shapiro, '11; Pollack et al, '15

Fluid model



Assume all the shells are in the hydrostatic equilibrium & local thermal equilibrium

Fluid model


Hydrostatic relaxation
Kinetic energy
(temperature) change

Transportation equations

1. Mass conservation

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

M: enclosed mass

Transportation equations

2. Momentum conservation

$$\frac{\partial}{\partial r}p = -\frac{GM\rho}{r^2}$$

p: pressure (= ρv^2)
v: 1-dim velocity dispersion

Transportation equations

3. Energy conservation

entropy

surface luminosity

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

γ: adiabatic index (=5/3)

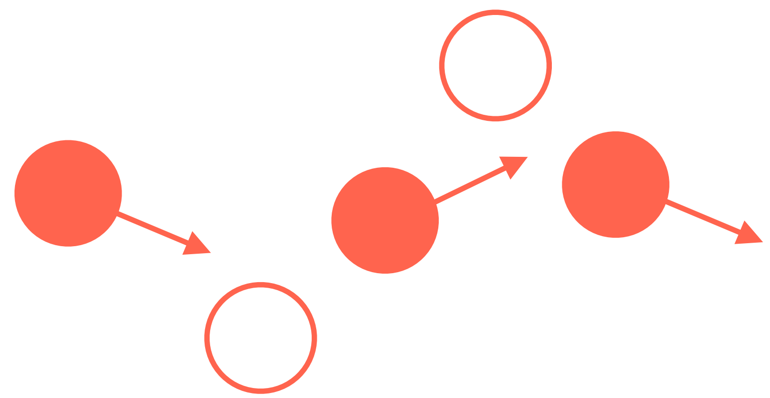
bulk cooling rate
energy loss
in unit vol.
& unit time

- Self-interactions are encoded in the conductivity & bulk cooling rate

$$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r}$$

conductivity

More on conductivity

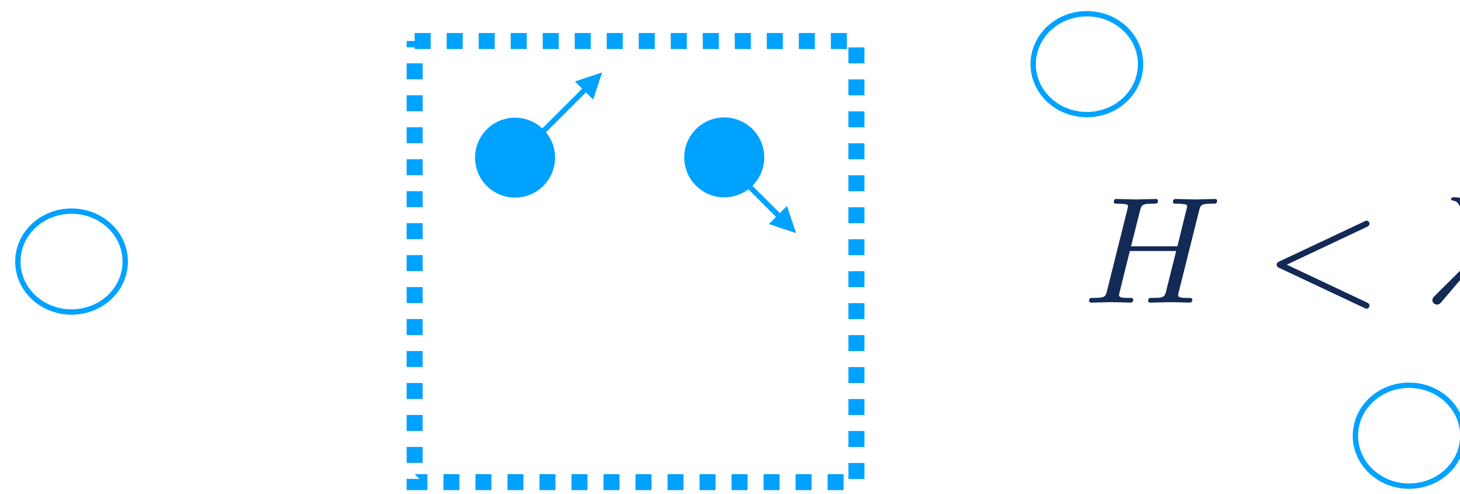


- Collisions w/ other particles
- Characterized by mean free path of the self-scattering:

$$\lambda = 1/(n\sigma)$$

- $\kappa_{\rm smfp} \approx n\nu\lambda = \dfrac{\nu}{\sigma}$

Another length can be relevant



$$H < \lambda$$

- Collisions are restricted by a "box"
- Characterized by the orbit height (Jean's length) of the halo

$$H = \sqrt{\nu^2 / 4\pi G \rho}$$

Lynden-Bell & Eggleton, '80

- $\kappa_{\mathrm{lmfp}} \simeq \beta (n \nu H) \frac{t_{\mathrm{dy}}}{t_r} \simeq \beta \frac{n \nu^3 \sigma}{G m}$

β: fixed by calibrating to N-body simulations

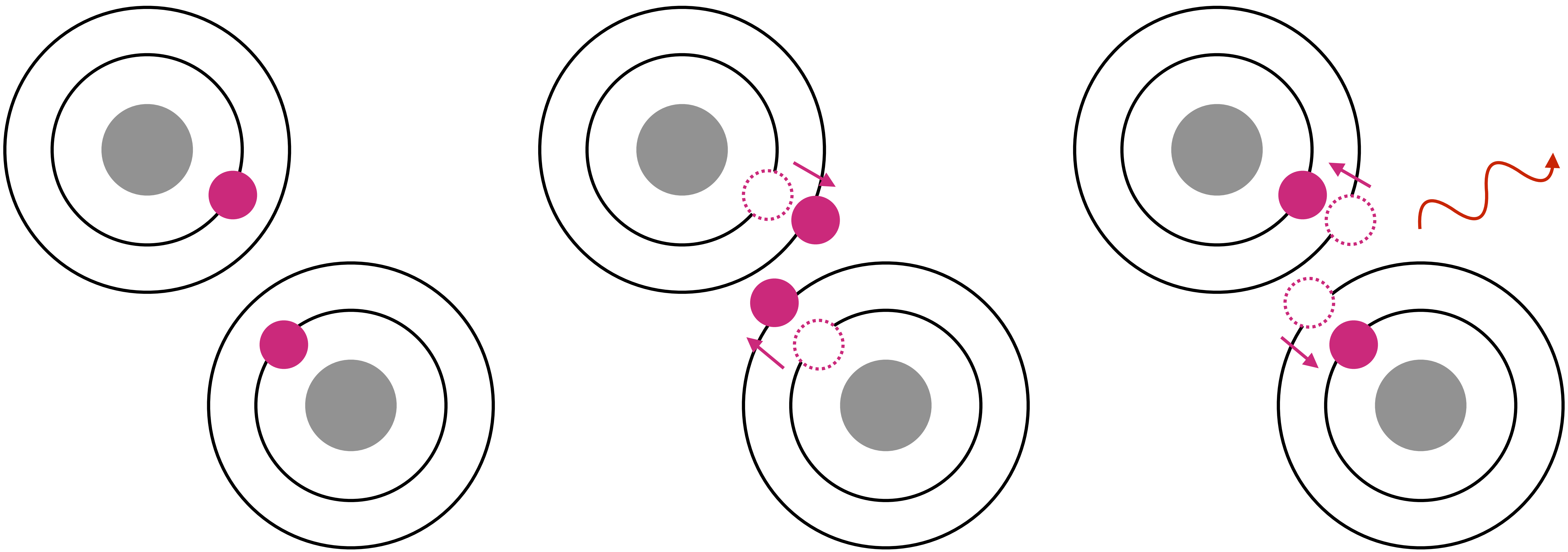
More on conductivity

- Knudsen number $Kn \equiv \lambda / H$
  - $Kn > 1 \Rightarrow$ ***H* is more important $\Rightarrow$ long-mean-free-path (lmfp) region**
  - $Kn < 1 \Rightarrow$ **λ is more important ⇒ short-mean-free-path (smfp) region**
- Combine the two $\kappa = (\kappa_{\rm lmfp}^{-1} + \kappa_{\rm smfp}^{-1})^{-1}$

Balberg & Shapiro, '02

More on the cooling rate

- We consider the collisional cooling



More on the cooling rate

- We consider the collisional cooling

energy loss
in unit vol.
& unit time

$$C = \left\langle \frac{n E_{\text{loss}}}{t'_r} \right\rangle_{T \geq E_{\text{loss}}}$$

$$\nu_{\text{loss}} \equiv \sqrt{E_{\text{loss}}/m}$$

$$= \frac{4}{\sqrt{\pi}} \frac{\sigma'}{m} \rho^2 \nu \nu_{\text{loss}}^2 \left(1 + \frac{\nu_{\text{loss}}^2}{\nu^2}\right) e^{-\frac{\nu_{\text{loss}}^2}{\nu^2}}$$

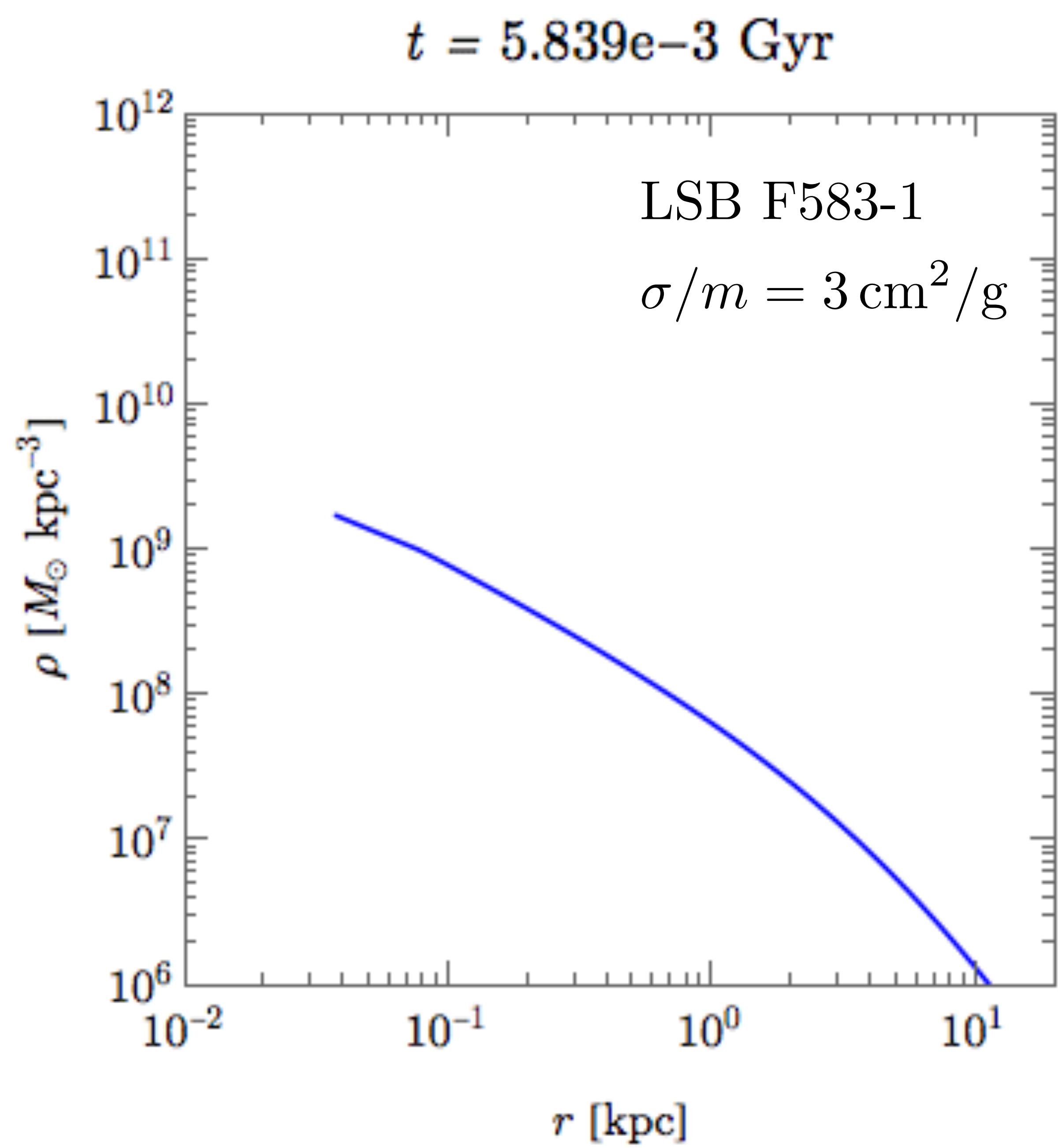
Other details on setups

- Initial density profile: NFW $$\rho = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$
- Boundary condition: M = 0, L = 0 @ r = 0
  M = finite, L = 0 @ r =r_{max}
- Small self-interaction strength ⇒ evolution starts when the self-interaction is insignificant ⇒ cuspy initial density profile
- Mild cooling ⇒ cooling time >> free-fall time

  ⇒ not isothermal/free-fall collapse

Result

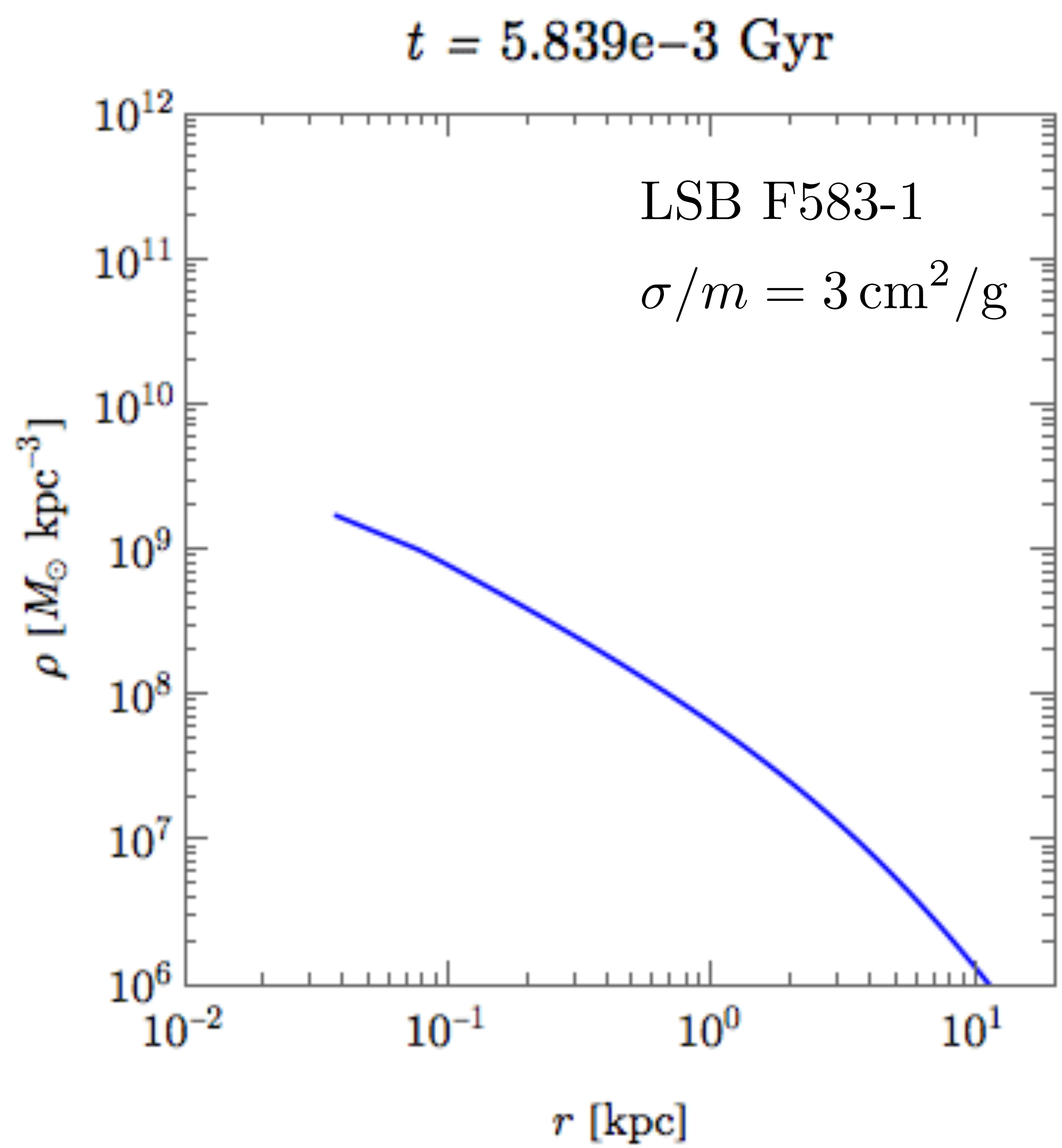
Evolution of the density profile



LSB F583-1
Mass: $8\times10^{10}\ M_\odot$

pure elastic

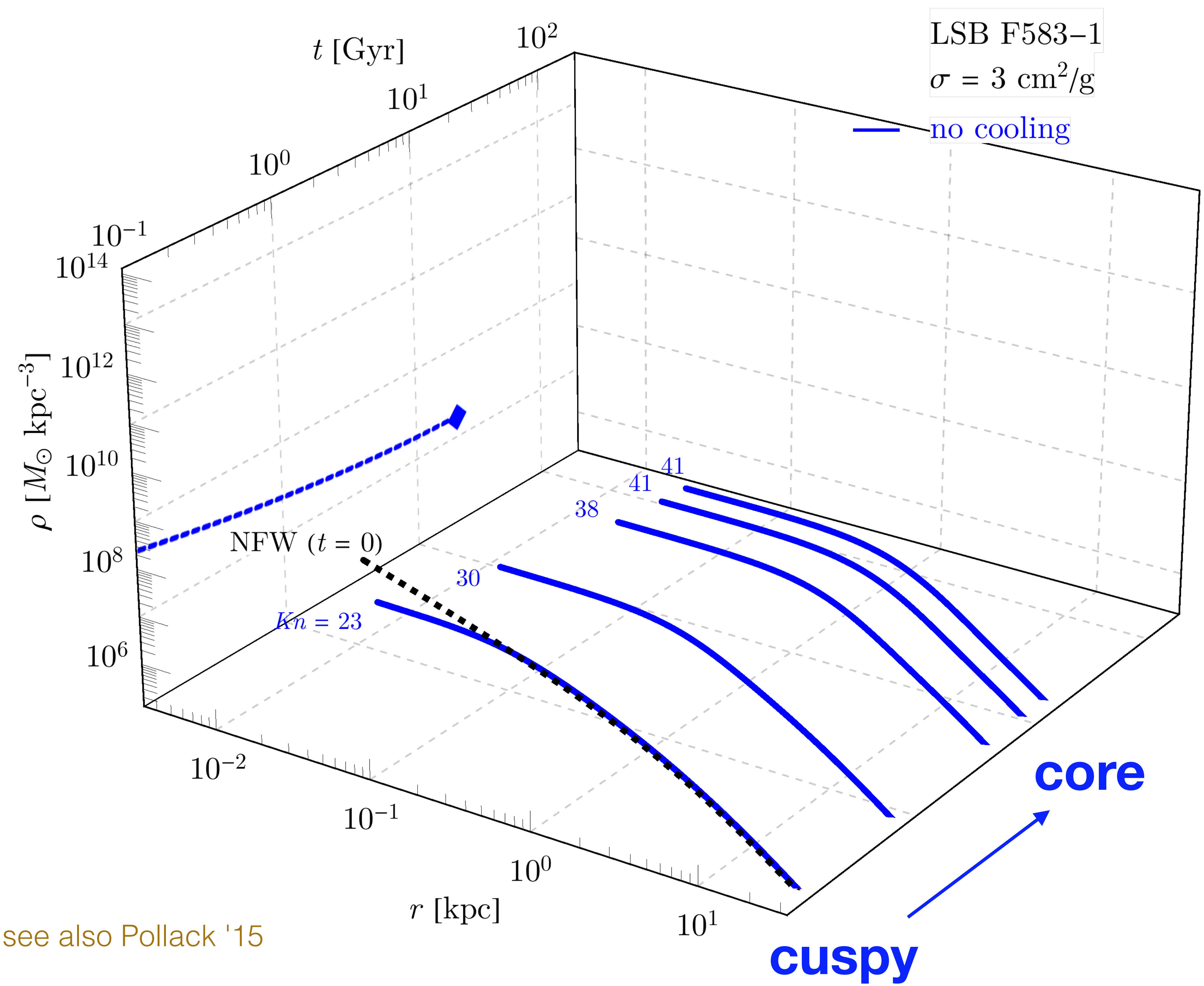
Evolution of the density profile



LSB F583-1
Mass: $8\times10^{10}\ M_\odot$

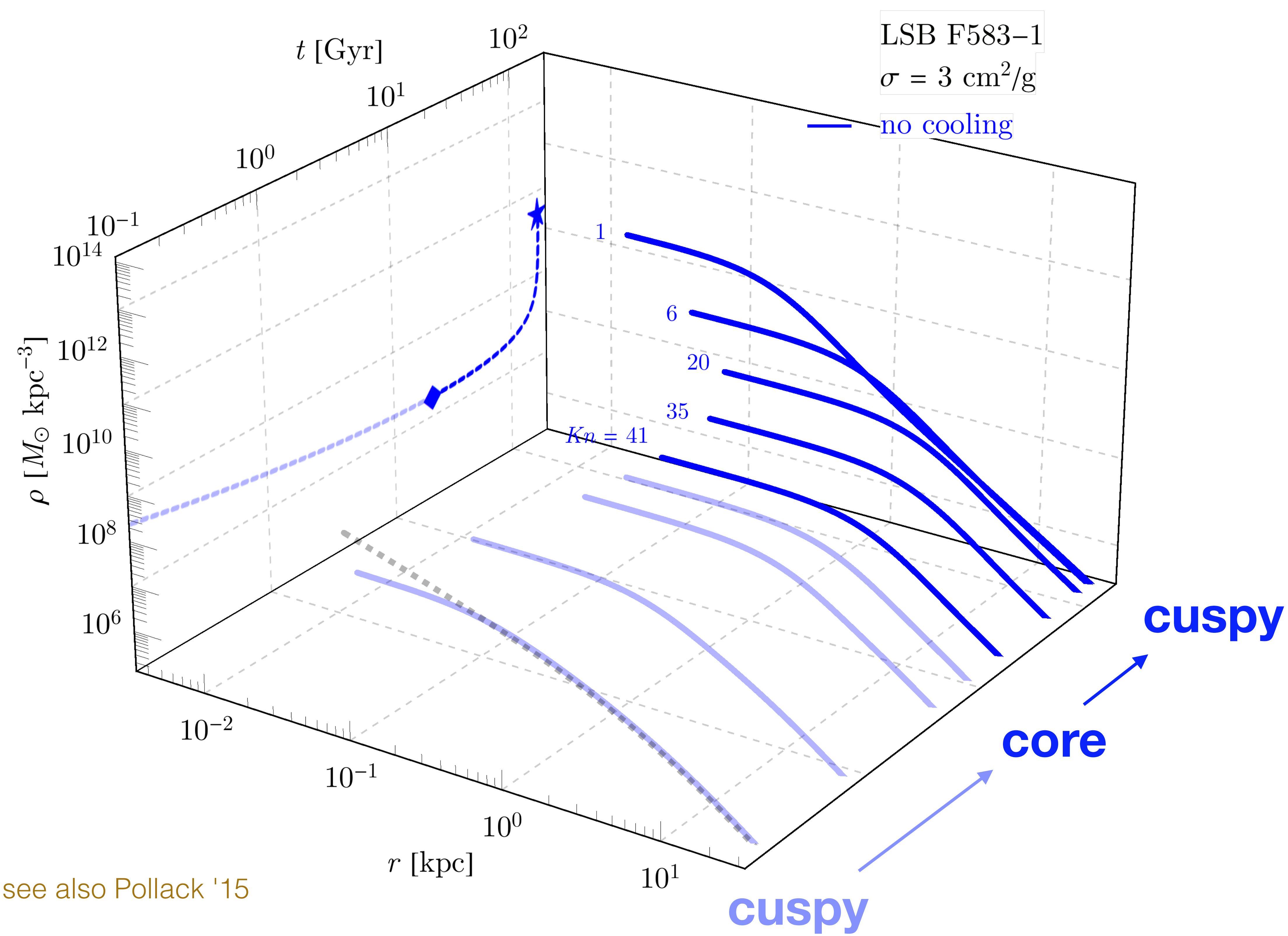
pure elastic

Stage 1: develops a core



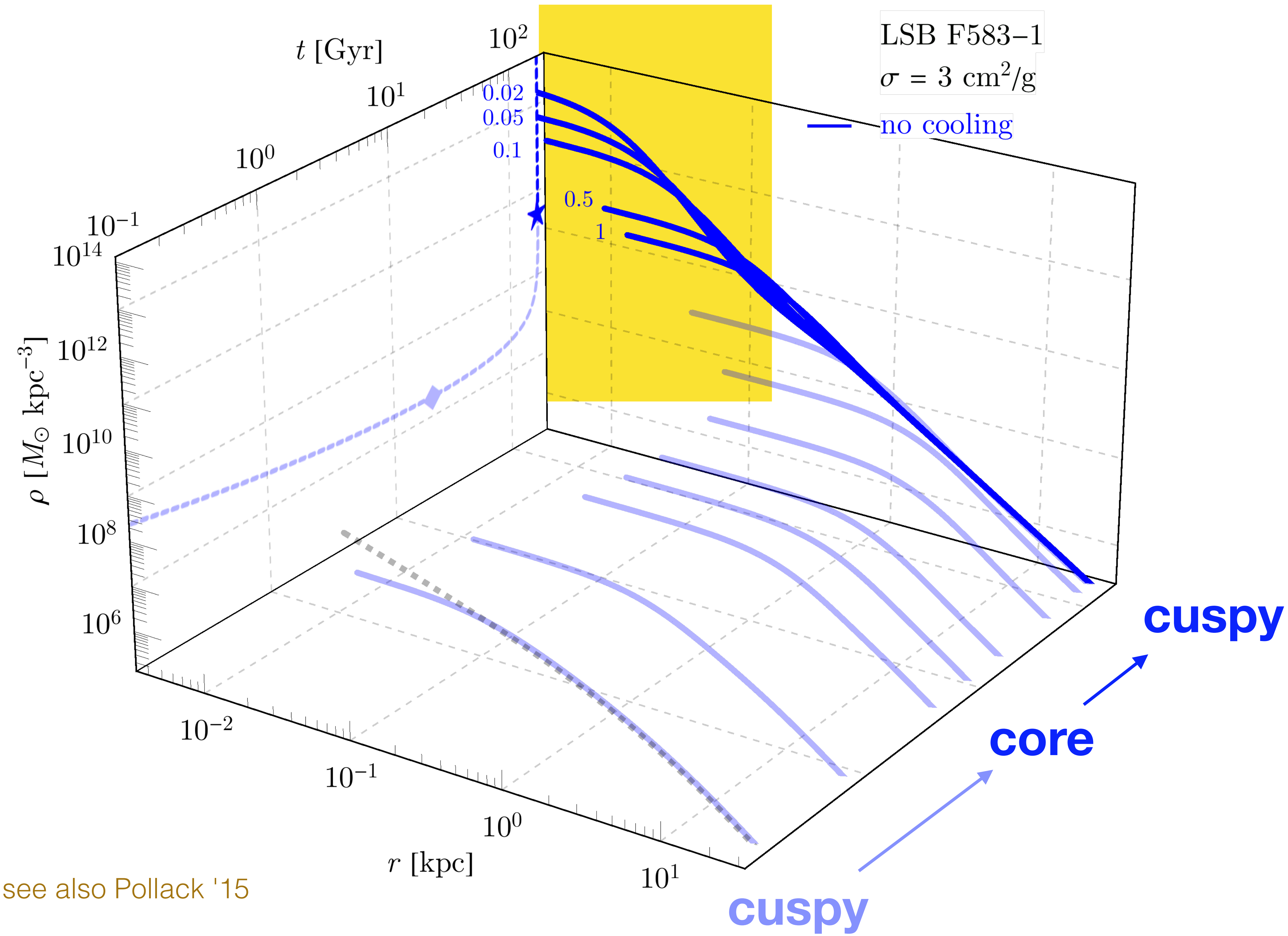
see also Pollack '15

Stage 2: runaway collapse



see also Pollack '15

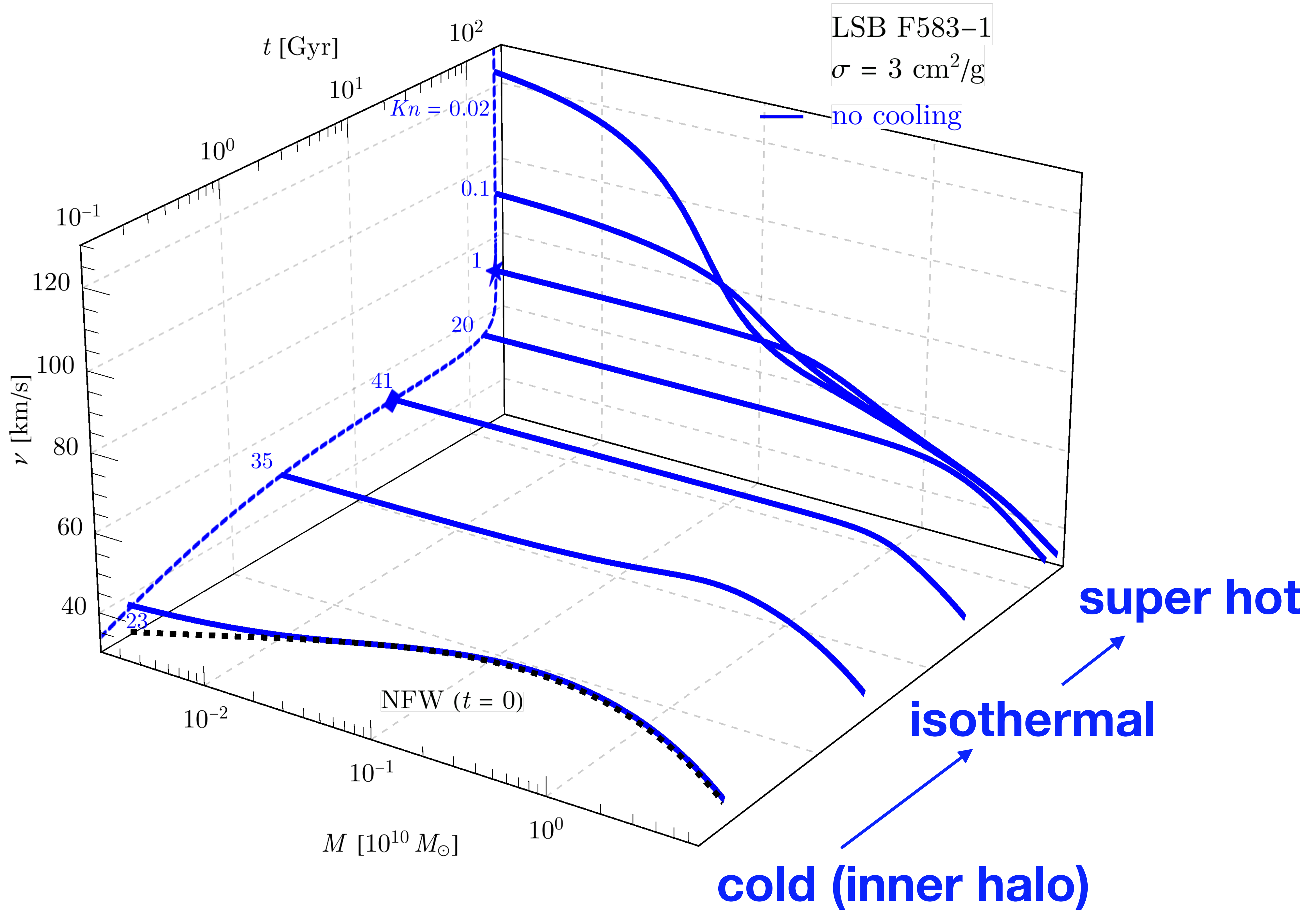
Stage 3: develop a 2nd core



see also Pollack '15

Yi-Ming Zhong (BU)

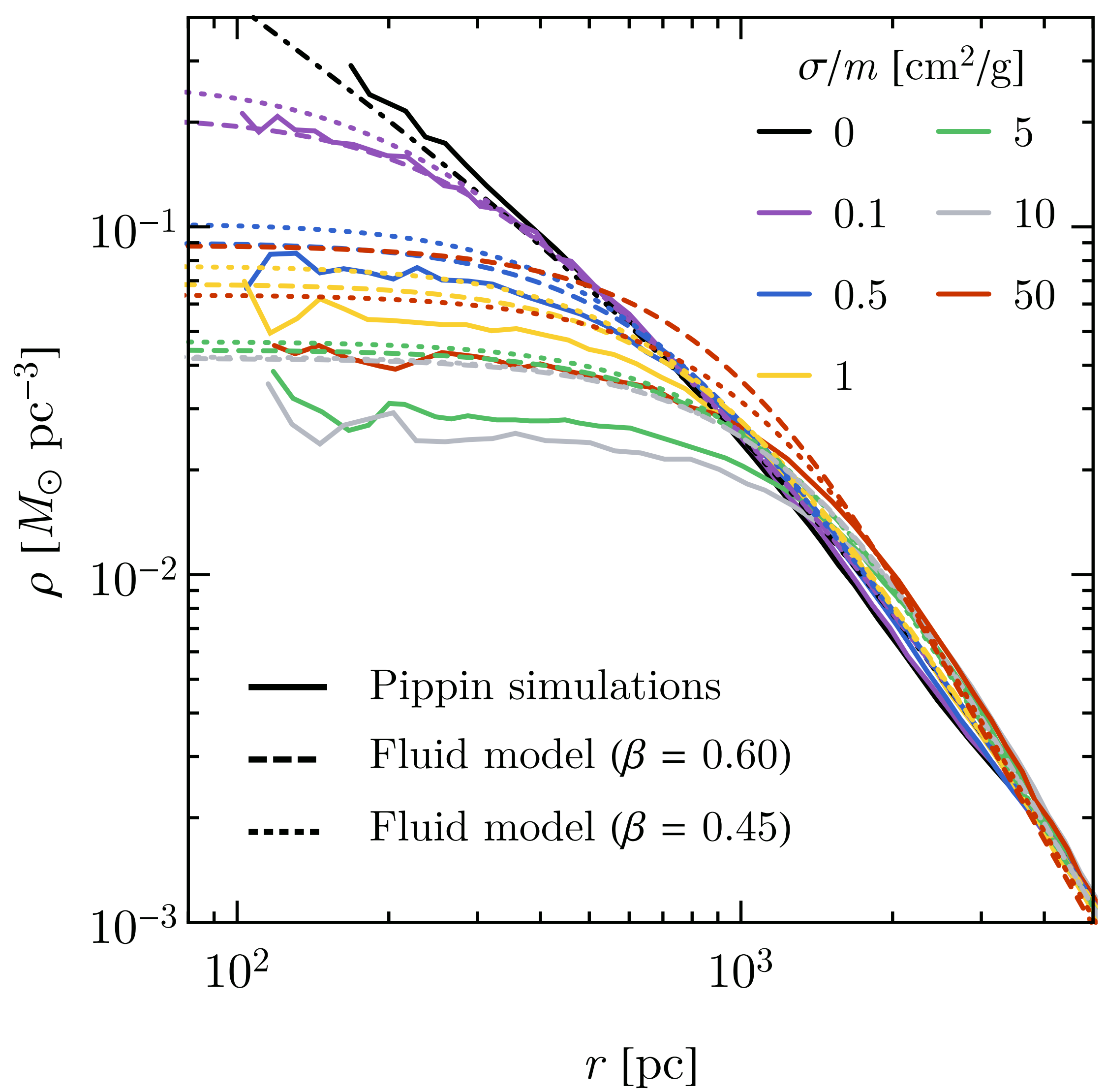
1D velocity-dispersion profile



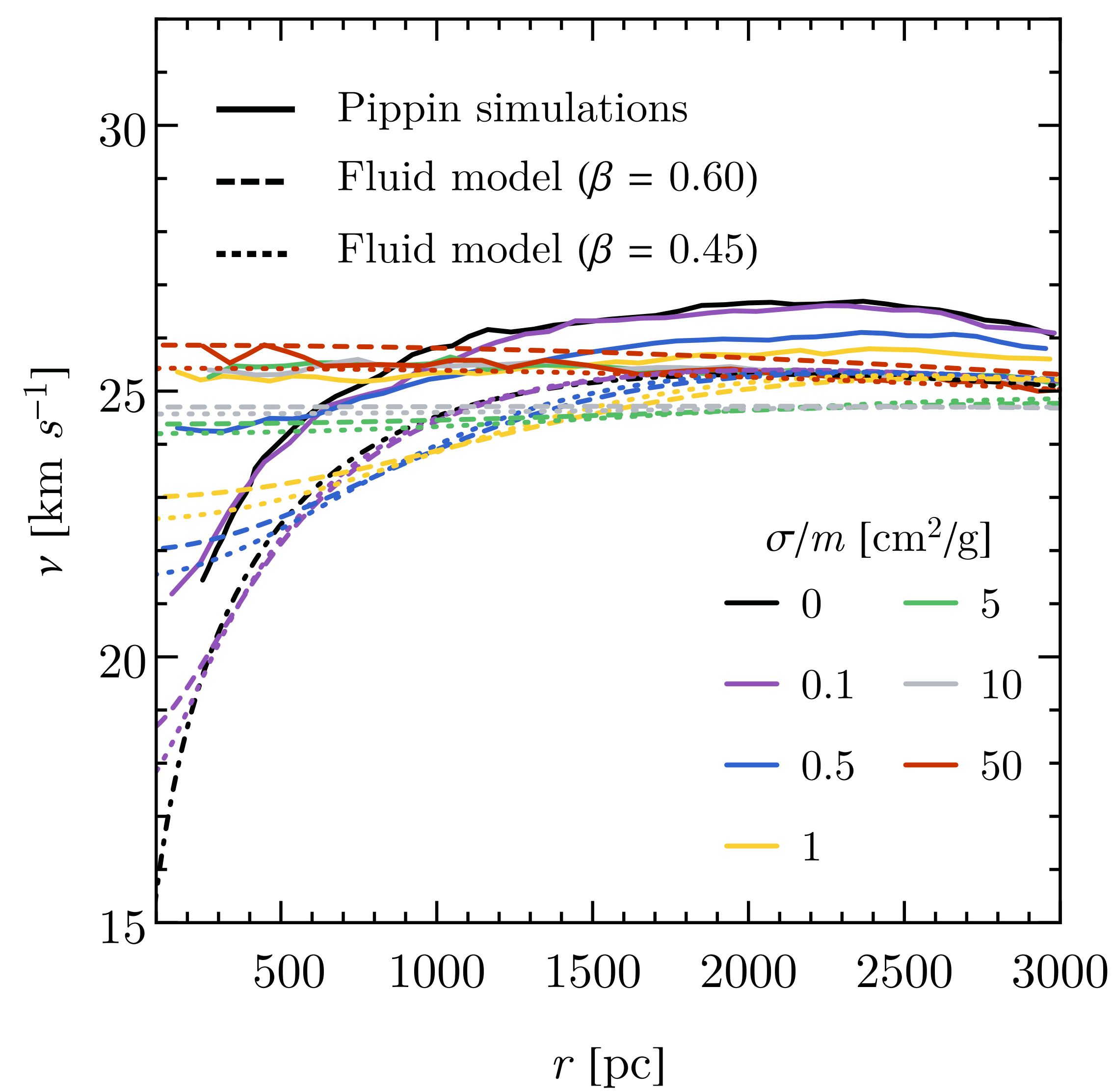
Calibrating β from N-body simulations

w/ cosmological N-body simulations Elbert et al, '15

Density

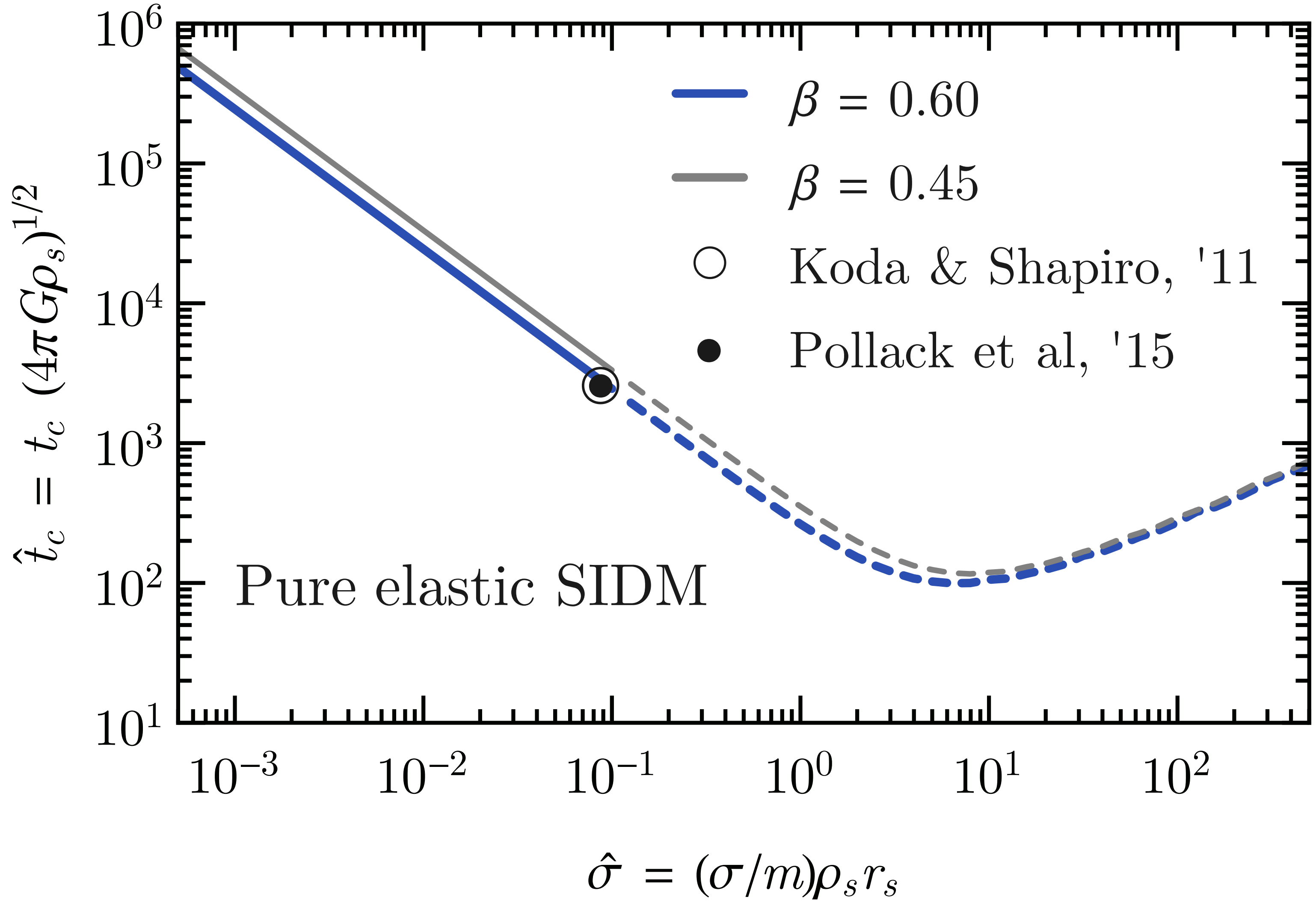


1D velocity dispersion



Pure elastic

The collapse time t_c

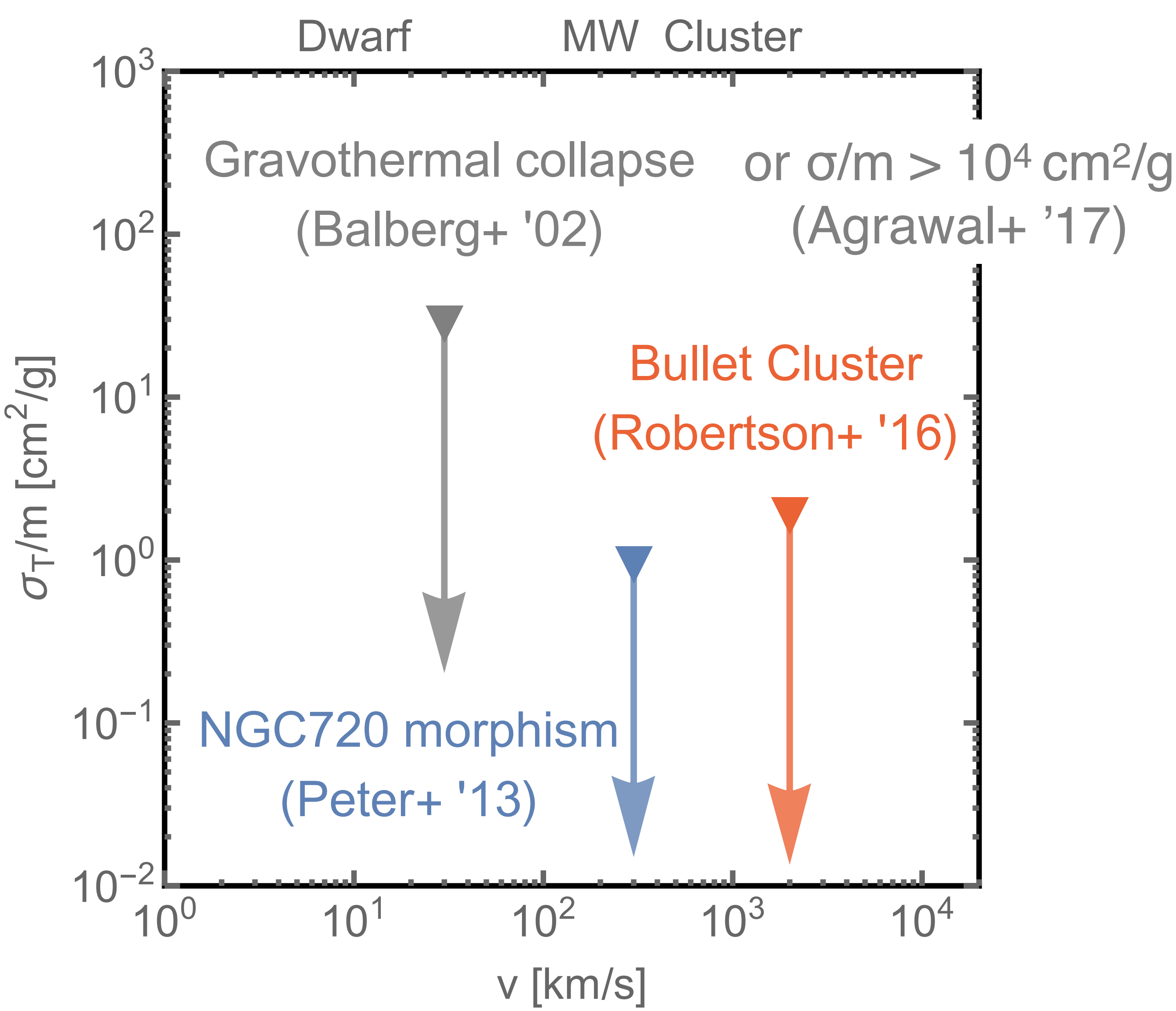


LSB F583-1 disfavors

$$57\,\mathrm{cm^2/g} \lesssim \sigma/m \lesssim 5.5\times 10^3\,\mathrm{cm^2/g}$$

($\beta = 0.60$)

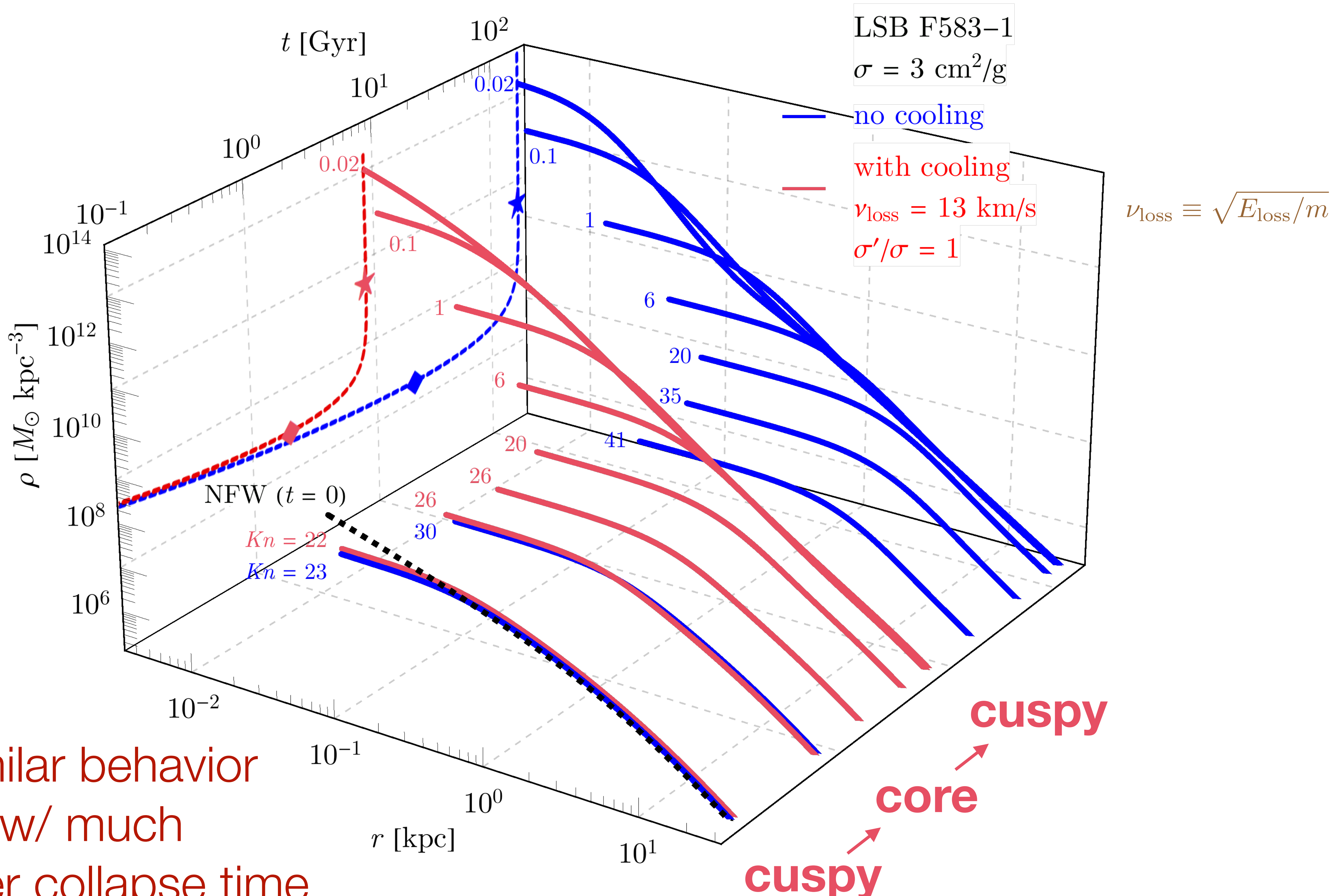
The collapse time t_c



LSB F583-1 disfavors

$$57\,\mathrm{cm}^2/\mathrm{g} \lesssim \sigma/m \lesssim 5.5\times10^3\,\mathrm{cm}^2/\mathrm{g} \qquad (\ \beta = 0.60\ )$$

Add a mild cooling



Similar behavior w/ much shorter collapse time

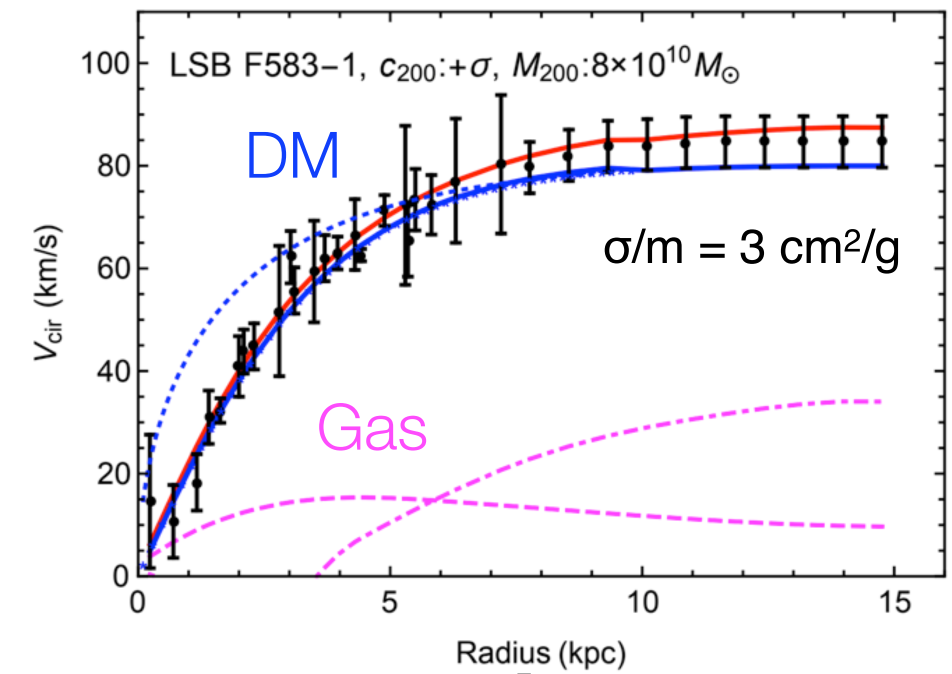
Constraints

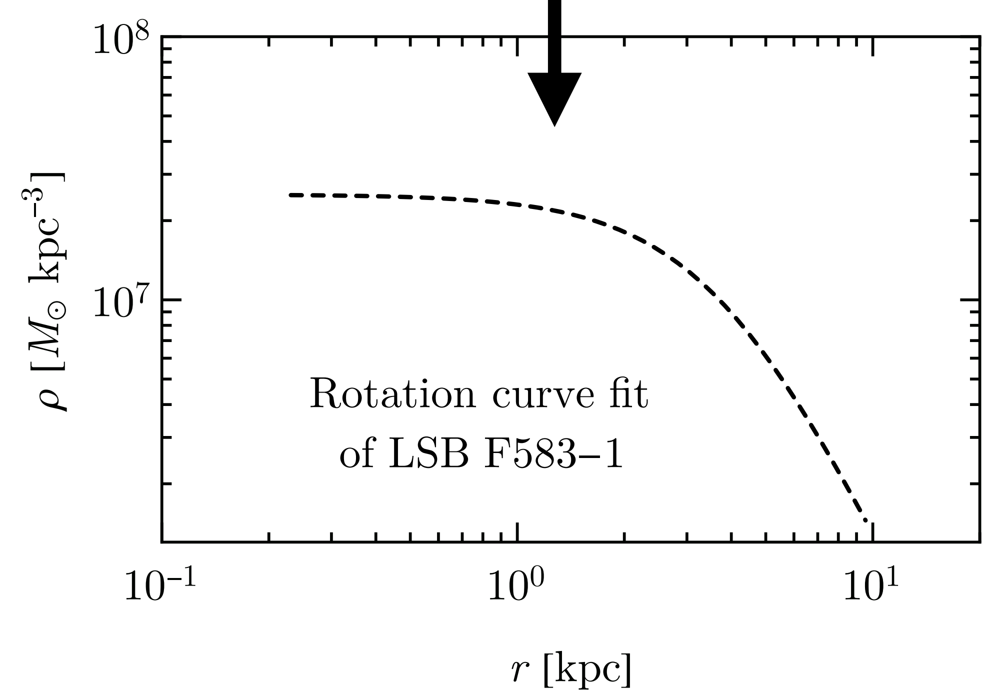
Dwarf/LSB observations

Near-field,
w/ low-baryonic content

Name	c_{200}	$M_{200}\ [M_\odot]$
UGC 4483	6.4	1.5×10^9
DDO 126	16.1	9×10^9
DDO 133	10.4	1.2×10^{10}
DDO 154	16.8	1.3×10^{10}
NGC 2366	14.7	2.3×10^{10}
UGCA 442	11.2	3×10^{10}
UGC 1281	12.2	3×10^{10}
DDO 52	8	3×10^{10}
DDO 87	15.3	3.5×10^{10}
NGC 3109	11.9	5.5×10^{10}
NGC 1560	11.9	6×10^{10}
UGC 3371	7.4	8×10^{10}
LSB F583-1	11.1	8×10^{10}
UGC 5750	13.9	8×10^{10}
IC 2574	7.4	9×10^{10}
UGC 3371	6.4	9×10^{10}
UGC 5750	7.3	9×10^{10}
UGC 11707	5.4	10^{11}
IC 2574	10.5	1.5×10^{11}
UGC 5005	7.7	1.8×10^{11}
UGC 128	9.2	3.8×10^{11}

Kamada et al, ’16, data mostly from Oh eta al ‘15

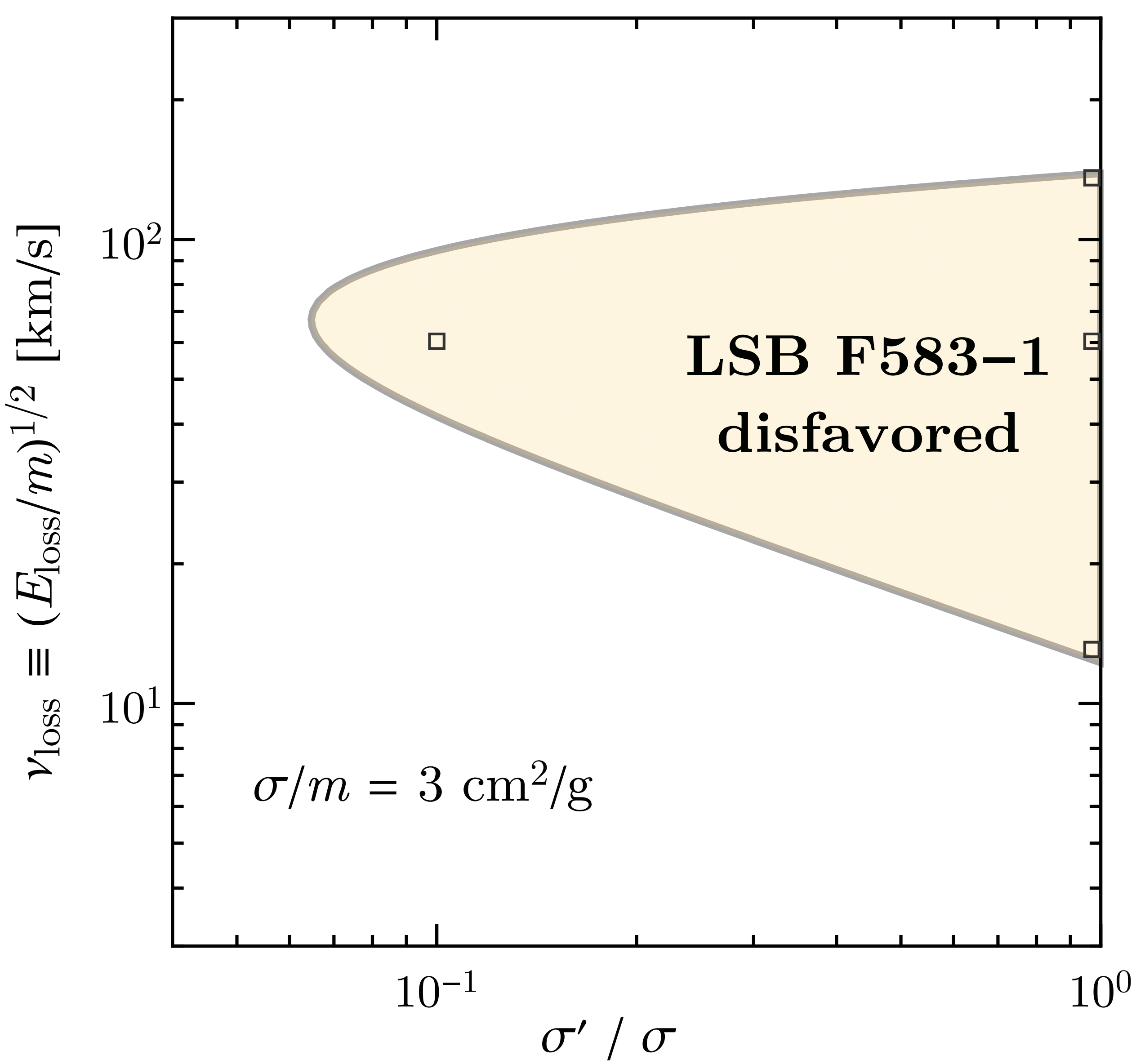


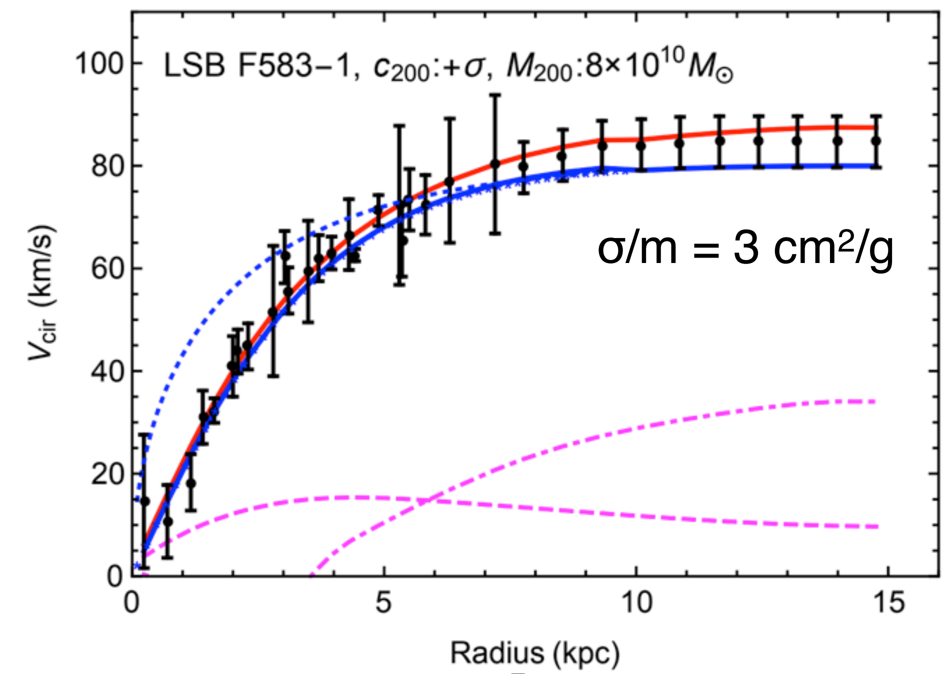


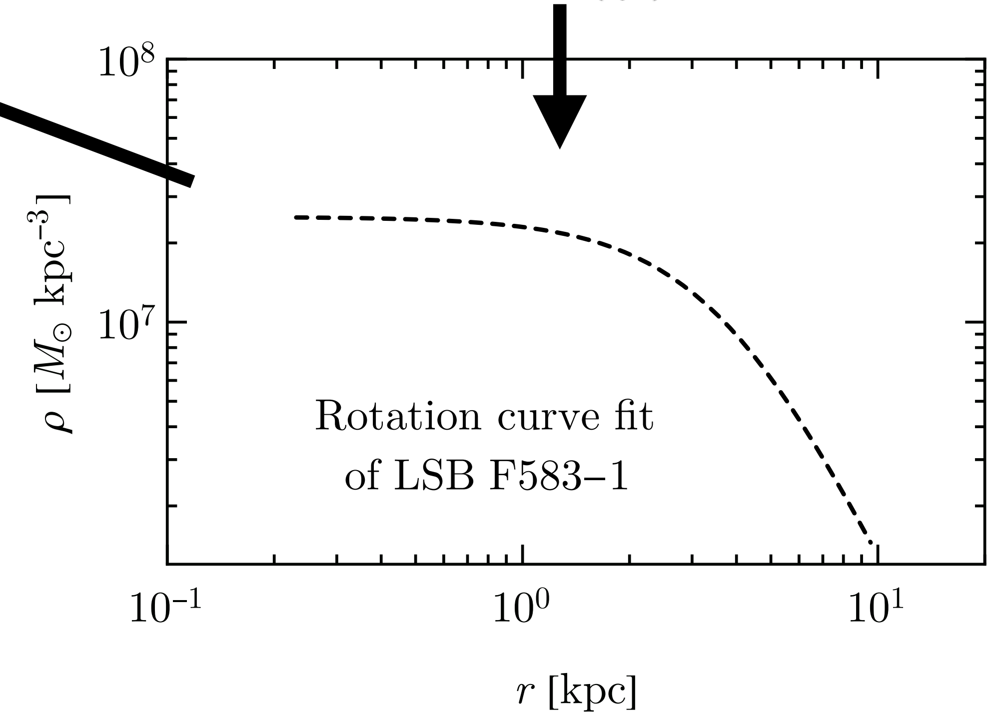
core-like profile

Dwarf/LSB observations

Kamada et al, '16, data mostly from Oh eta al '15

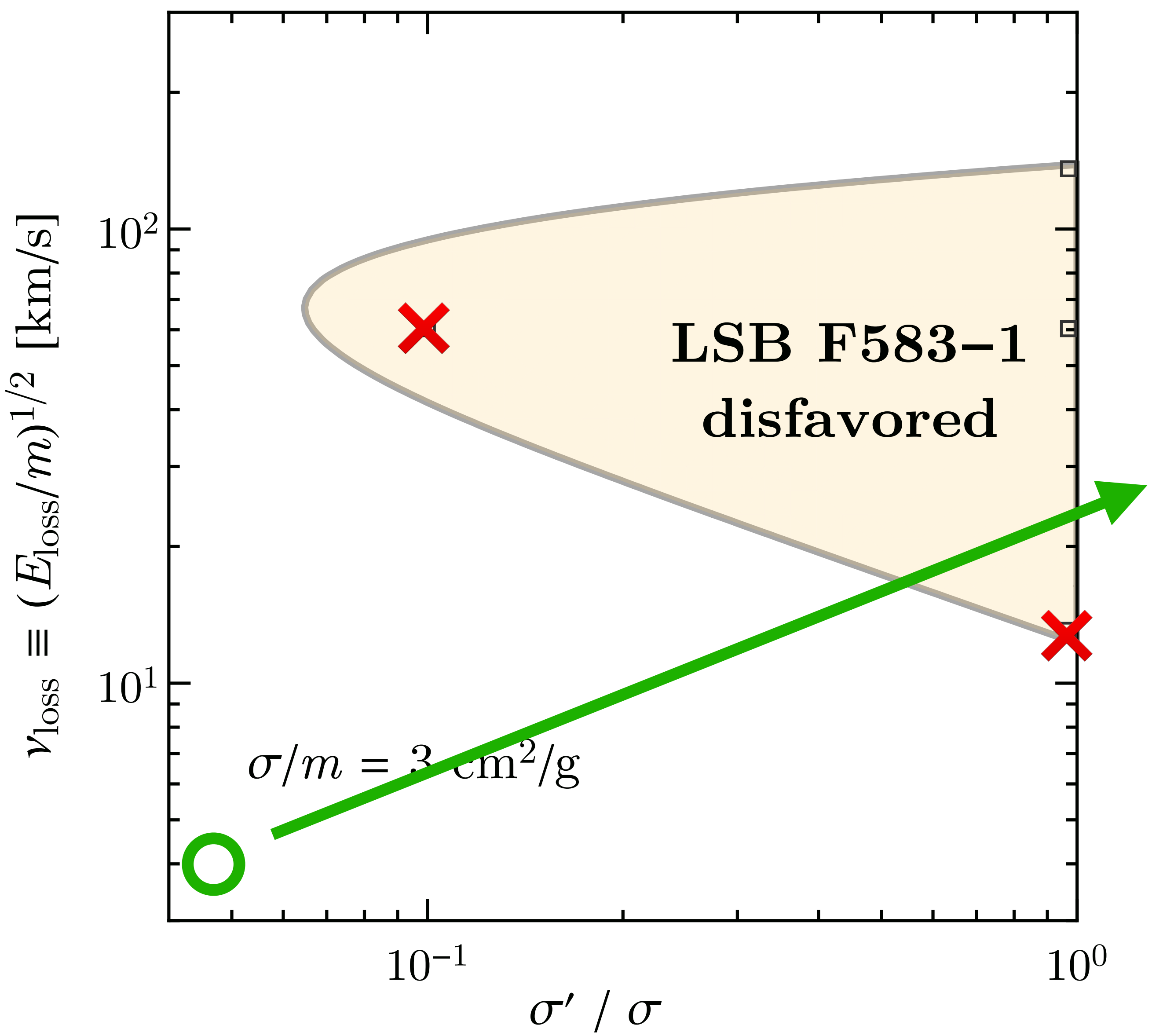




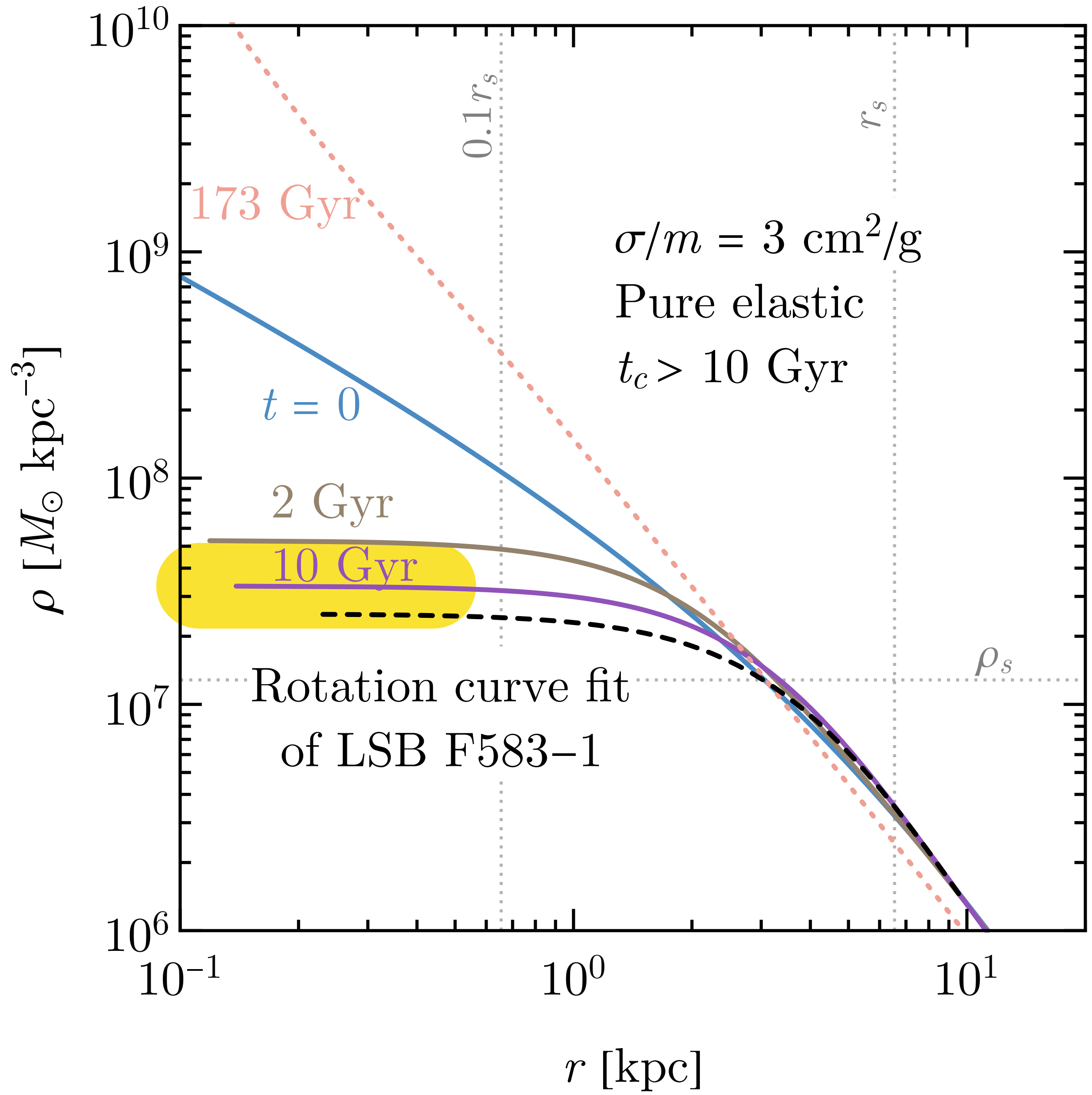


core-like profile

Favored parameter space

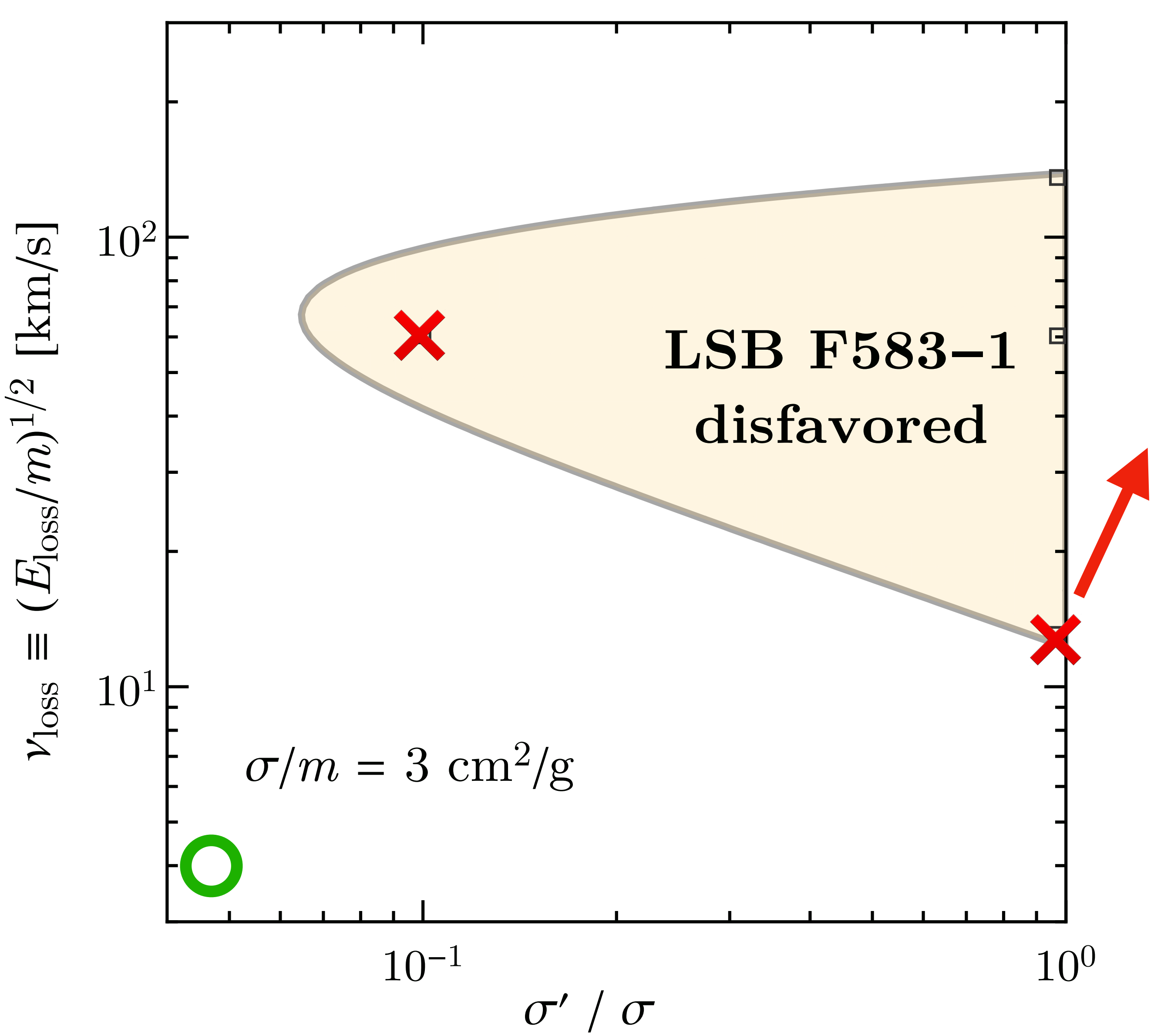


semi-analytical simulation

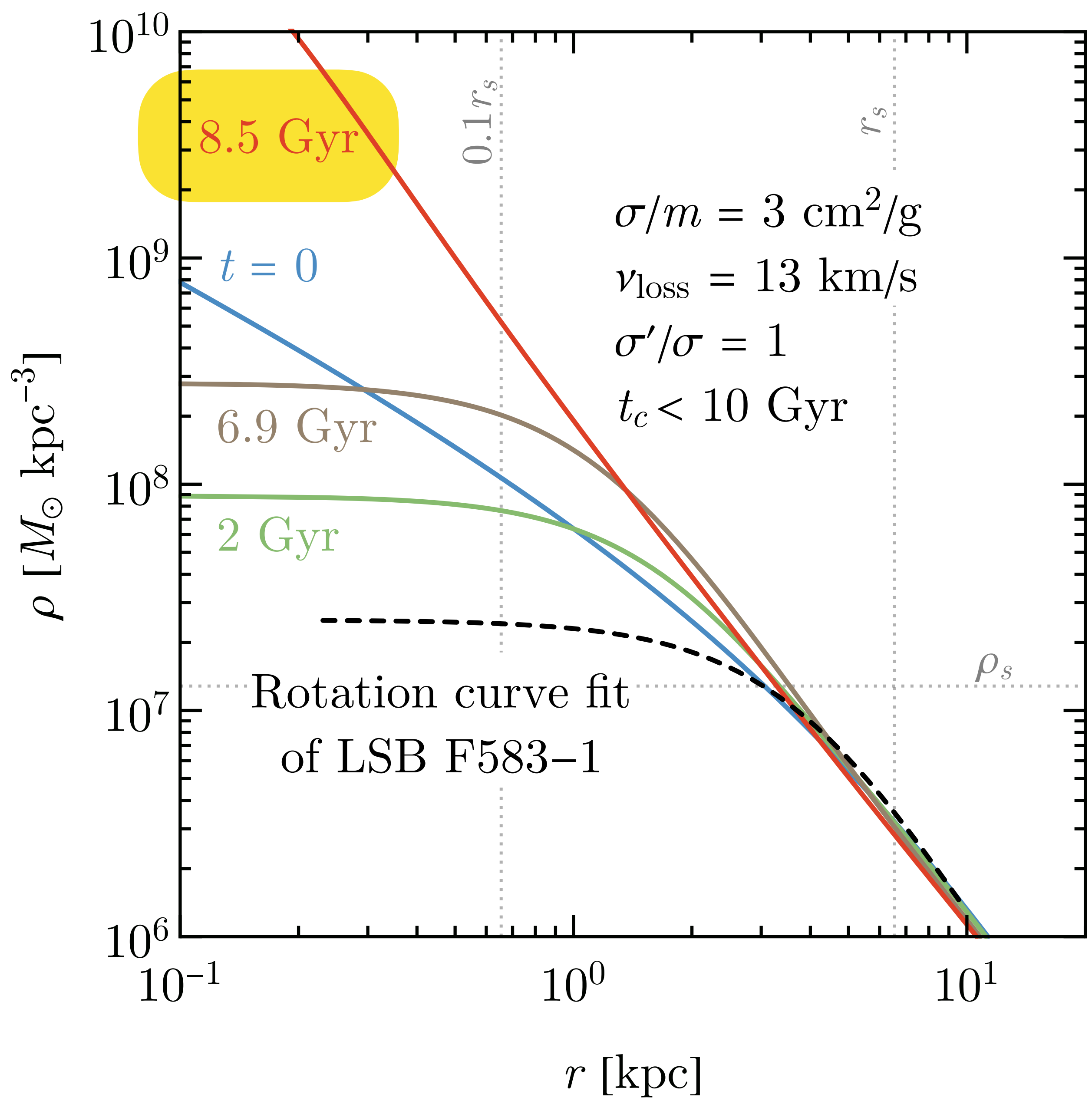


core-like profile

Disfavored parameter space



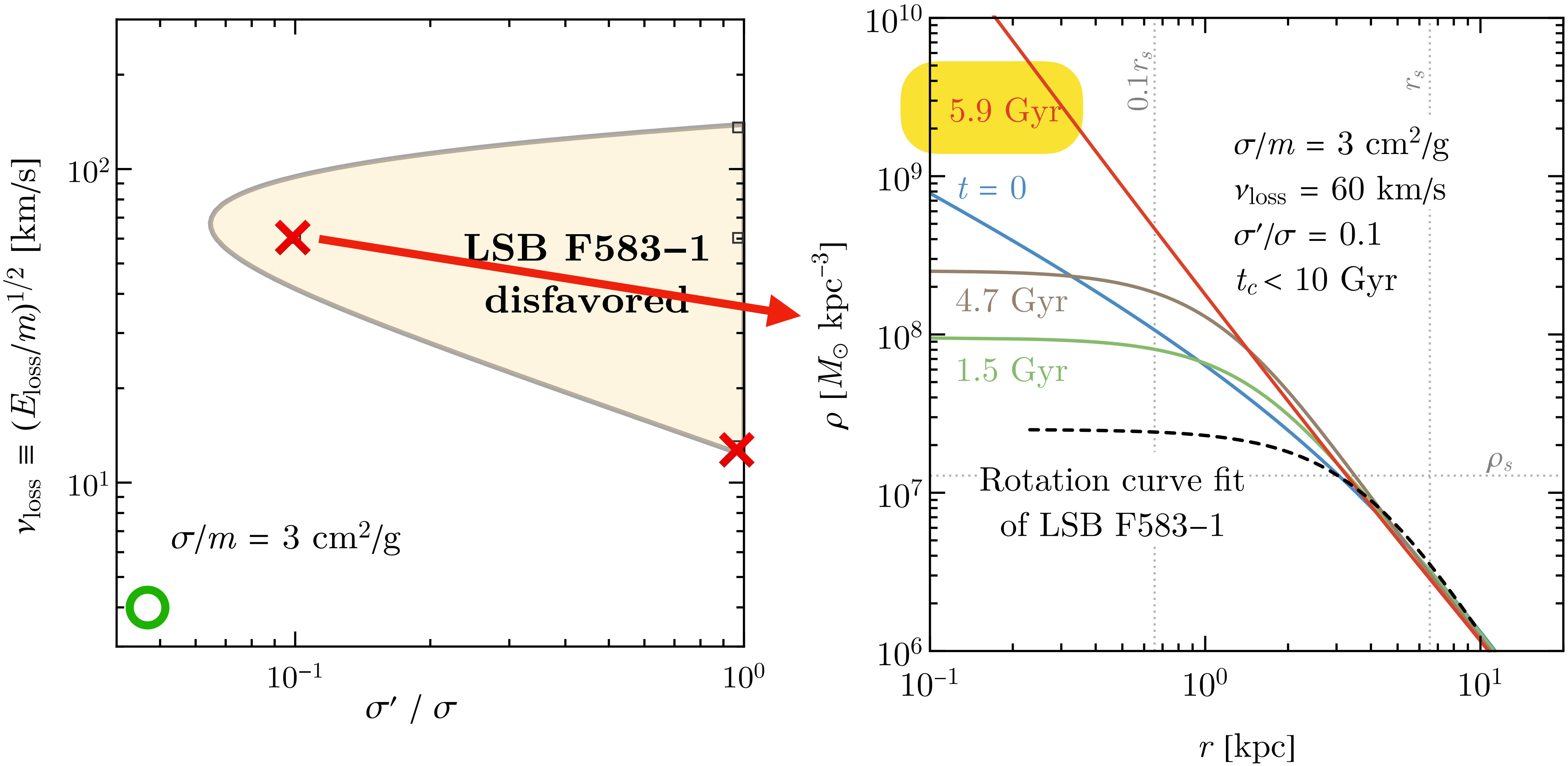
semi-analytical simulation



collapsed core

Disfavored parameter space

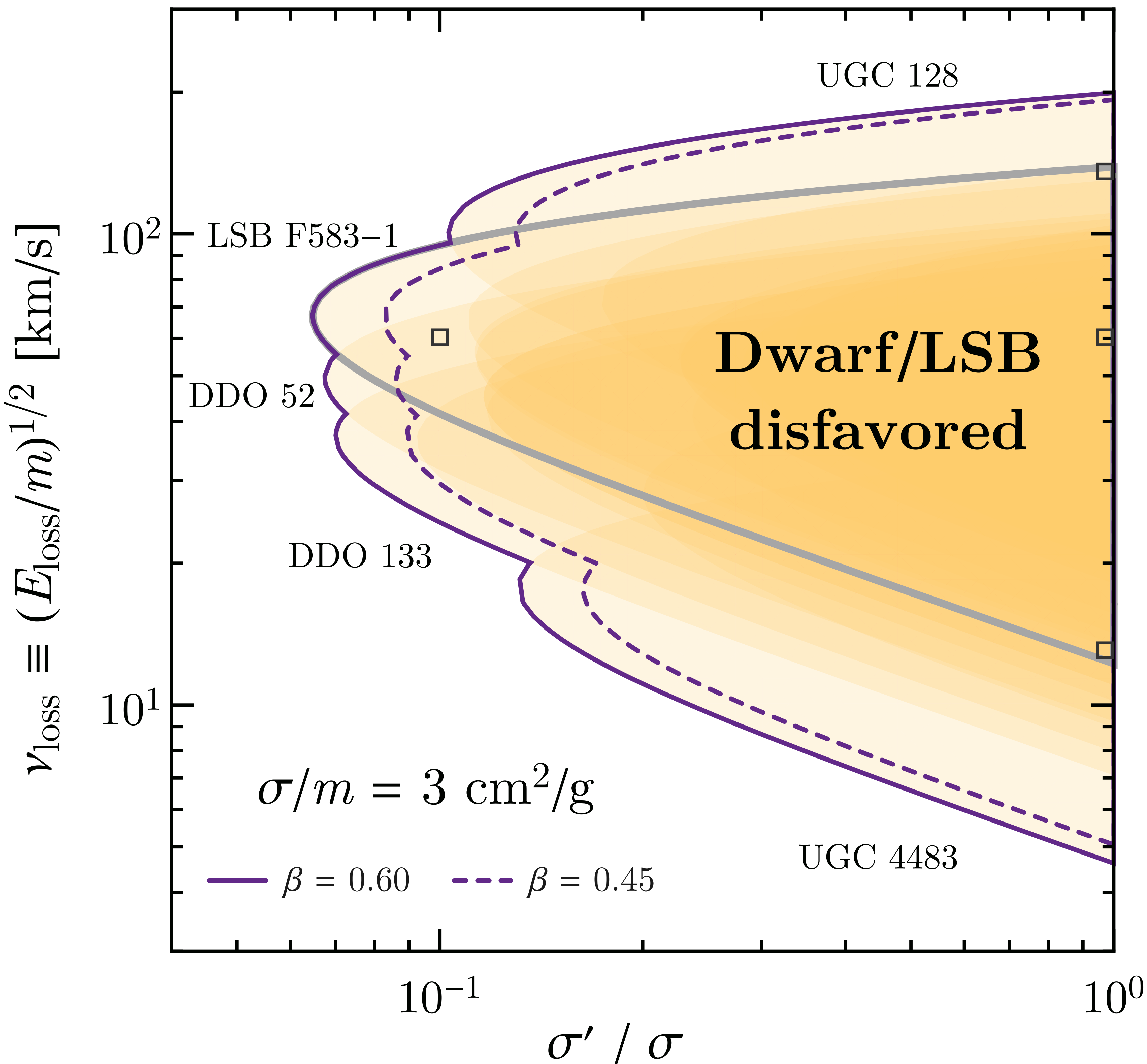
semi-analytical simulation



collapsed core

Dwarf/LSB disfavored

Kamada et al, '16



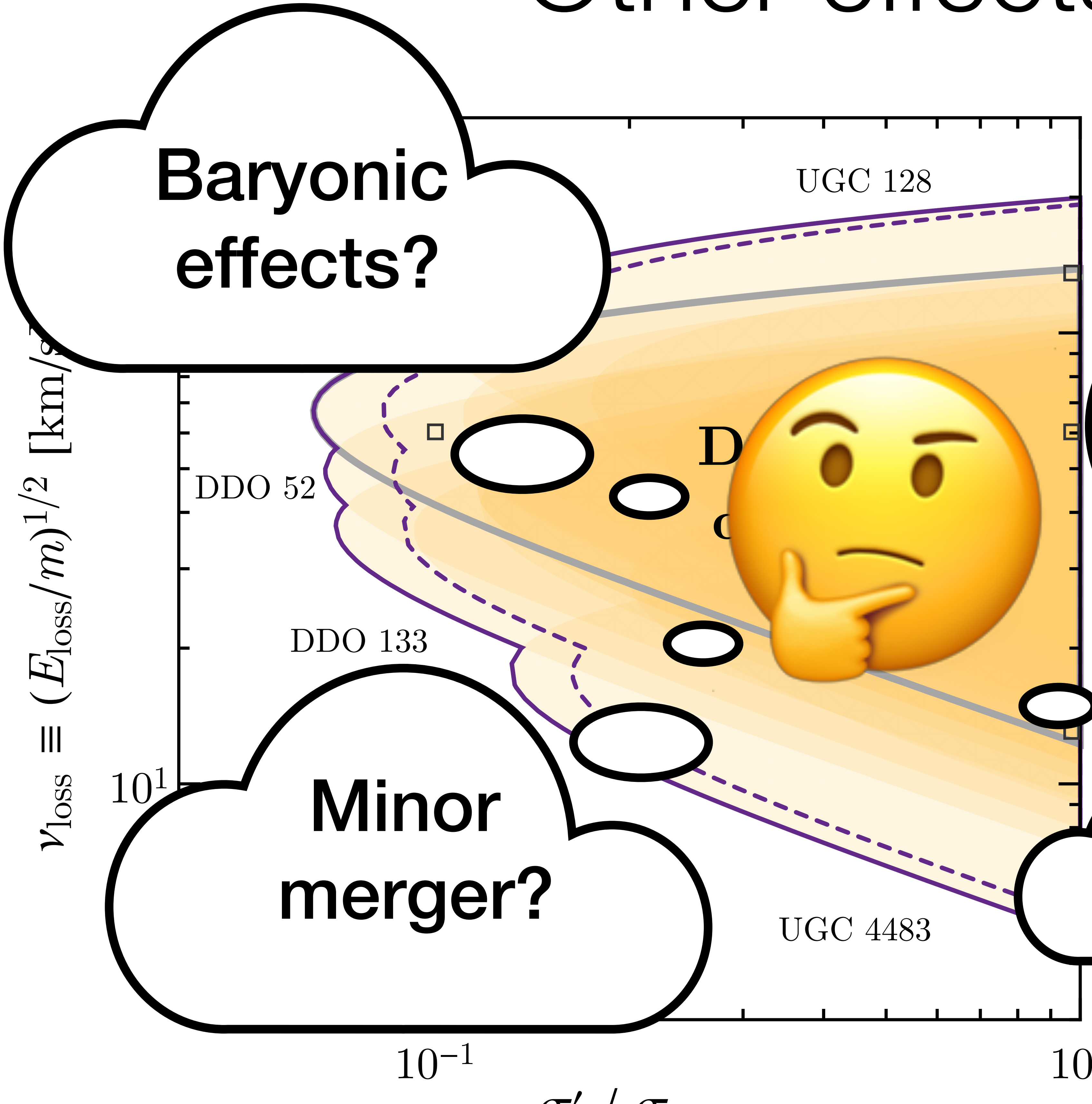
Near-field,
w/ low-baryonic content

Name	c_{200}	$M_{200}\ [M_\odot]$
UGC 4483	6.4	1.5×10^{9}
DDO 126	16.1	9×10^{9}
DDO 133	10.4	1.2×10^{10}
DDO 154	16.8	1.3×10^{10}
NGC 2366	14.7	2.3×10^{10}
UGCA 442	11.2	3×10^{10}
UGC 1281	12.2	3×10^{10}
DDO 52	8	3×10^{10}
DDO 87	15.3	3.5×10^{10}
NGC 3109	11.9	5.5×10^{10}
NGC 1560	11.9	6×10^{10}
UGC 3371	7.4	8×10^{10}
LSB F583-1	11.1	8×10^{10}
UGC 5750	13.9	8×10^{10}
IC 2574	7.4	9×10^{10}
UGC 3371	6.4	9×10^{10}
UGC 5750	7.3	9×10^{10}
UGC 11707	5.4	10^{11}
IC 2574	10.5	1.5×10^{11}
UGC 5005	7.7	1.8×10^{11}
UGC 128	9.2	3.8×10^{11}

Not see core collapse

Other effects

Kamada et al, '16

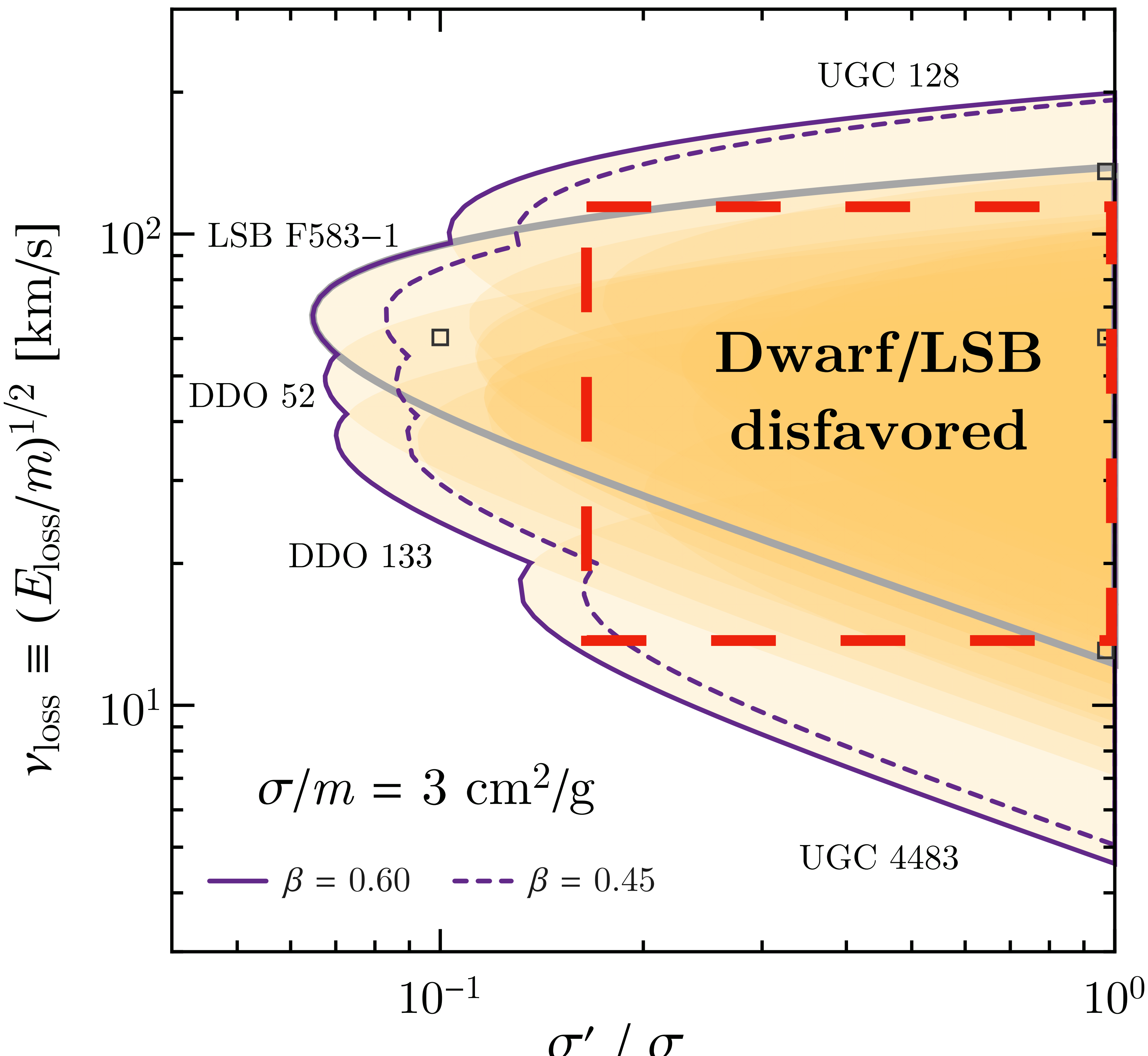


Near-field,
w/ low-baryonic content

Name		M_{200} [$M_\odot$]
[illegible]	[illegible]	[illegible]5×10^9
[illegible]	[illegible]	[illegible]$\times 10^9$
[illegible]	[illegible]	[illegible]10^{10}
[illegible]	[illegible]	[illegible]
NGC 3109	11.9	5.5×10^{10}
NGC 1560	11.9	6×10^{10}
UGC 3371	7.4	8×10^{10}
LSB F583-1	11.1	8×10^{10}
[illegible]	13.9	8×10^{10}
[illegible]	7.4	9×10^{10}
[illegible]	[illegible]	9×10^{10}
[illegible]	[illegible]	9×10^{10}
[illegible]	[illegible]	10^{11}
[illegible]	10.5	1.5×10^{11}
UGC 5005	7.7	1.8×10^{11}
UGC 128	9.2	3.8×10^{11}

Not see core collapse

Dwarf/LSB disfavored



$$10\,\mathrm{km/s} \lesssim \nu_{\mathrm{loss}} \lesssim 100\,\mathrm{km/s}$$

$$\Downarrow$$

$$E_{\mathrm{split}} = (0.5 - 50)\,\mathrm{eV}(m/\mathrm{GeV})$$

Summary

- DM self-interactions (elastic and dissipative) may change the evolution of the halos. The inner halo experiences cuspy→core→cuspy.

- Galaxy observations can be used to probe DM self-interactions.

- Further *N*-body simulations are encouraged.