Cooling of self-interacting dark matter halos

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In collaboration w/ R. Essig, S. McDermott, H.-B. Yu
arXiv:1809.01144
w/ W.-X. Feng, R. Huo, H.-B. Yu, work in progress

CTPU-IBS, 04/26/2019

Outline

- Motivation
- Gravothermal collapse from DM self-interactions
- Constraining DM self-interactions by avoiding gravothermal collapse
- Giving birth to the first super massive black holes

Gravitational probes

- Dark matter (DM) can be part of the dark sector.
- Dark sectors may completely decouple from our visible sector.
- Gravitational probes provide a unique opportunity in such nightmare scenario ⇒

  Looking into DM distribution in cosmology and astronomy

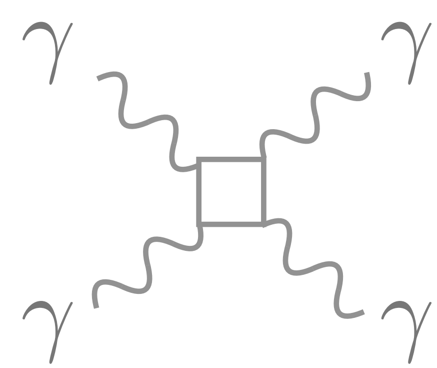
Self-interacting DM

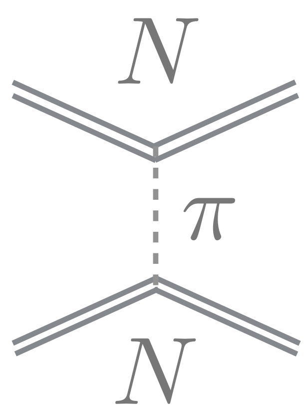
1. Self-interactions are common for normal matter

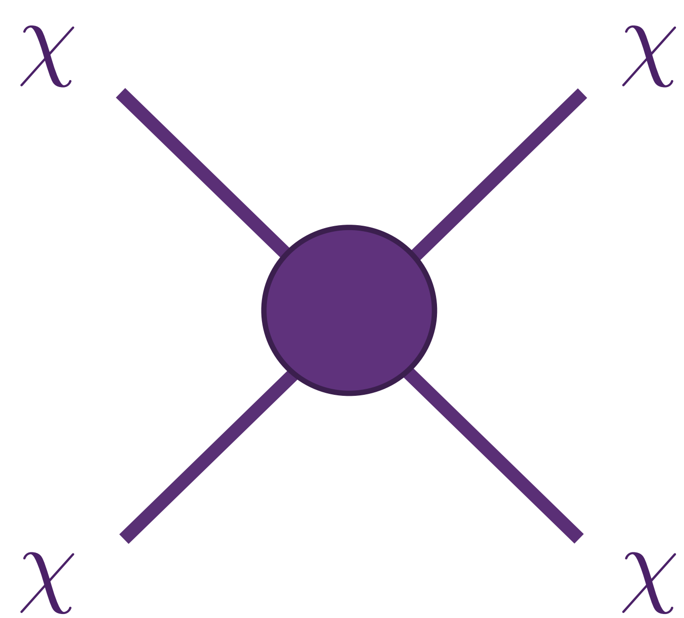
   Why not dark matter?

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)



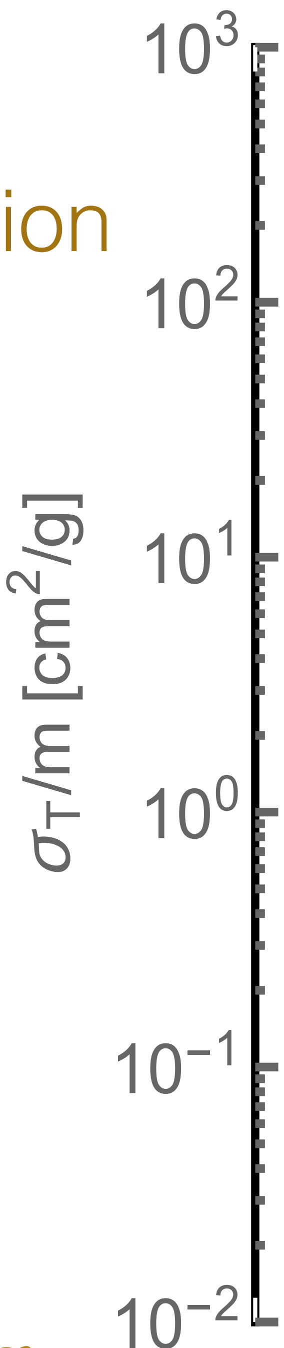




Spergel & Steinhardt '00
see review by Tulin & Yu '16

Dark matter self-interaction

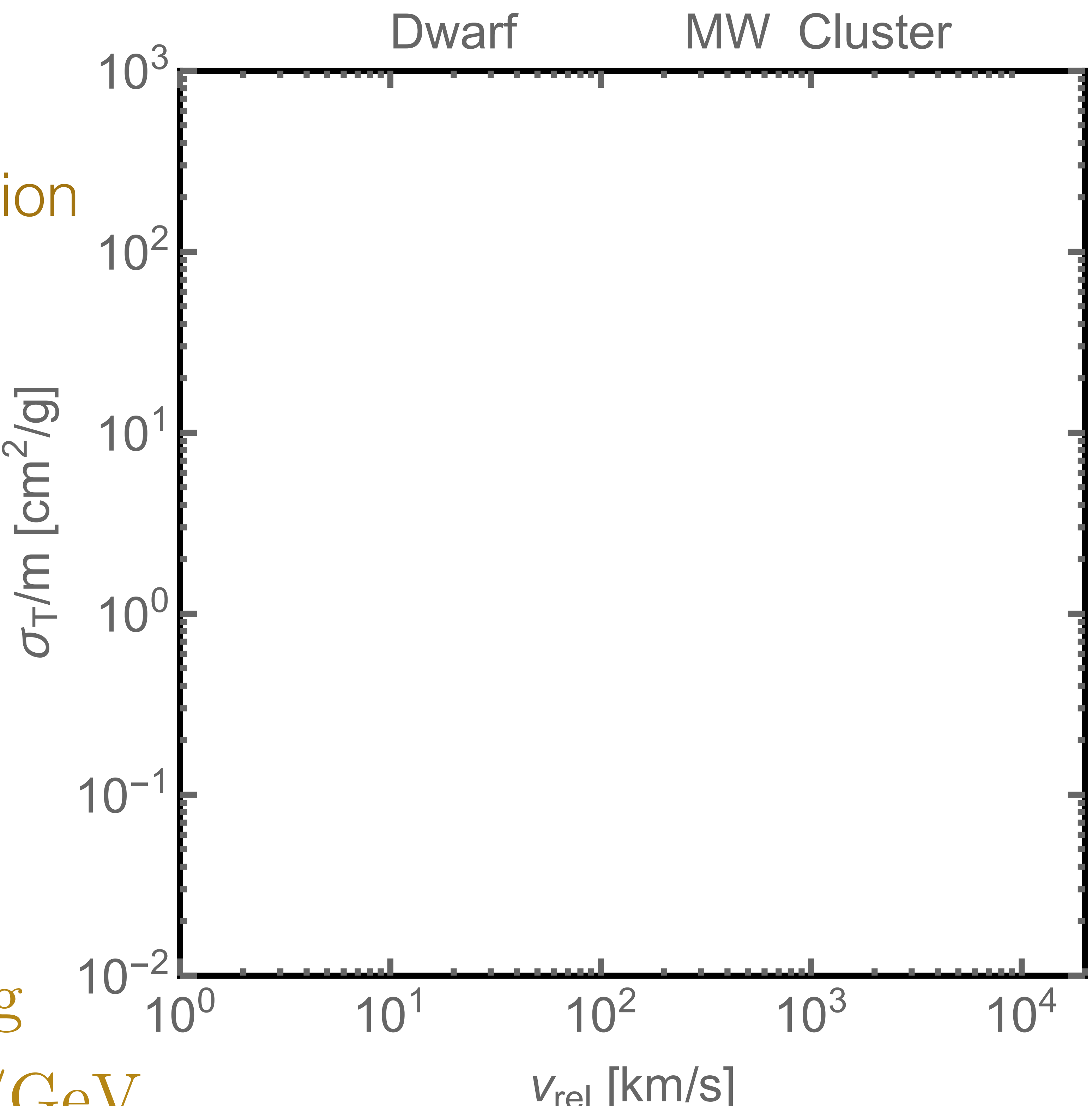
Self-interaction strength



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

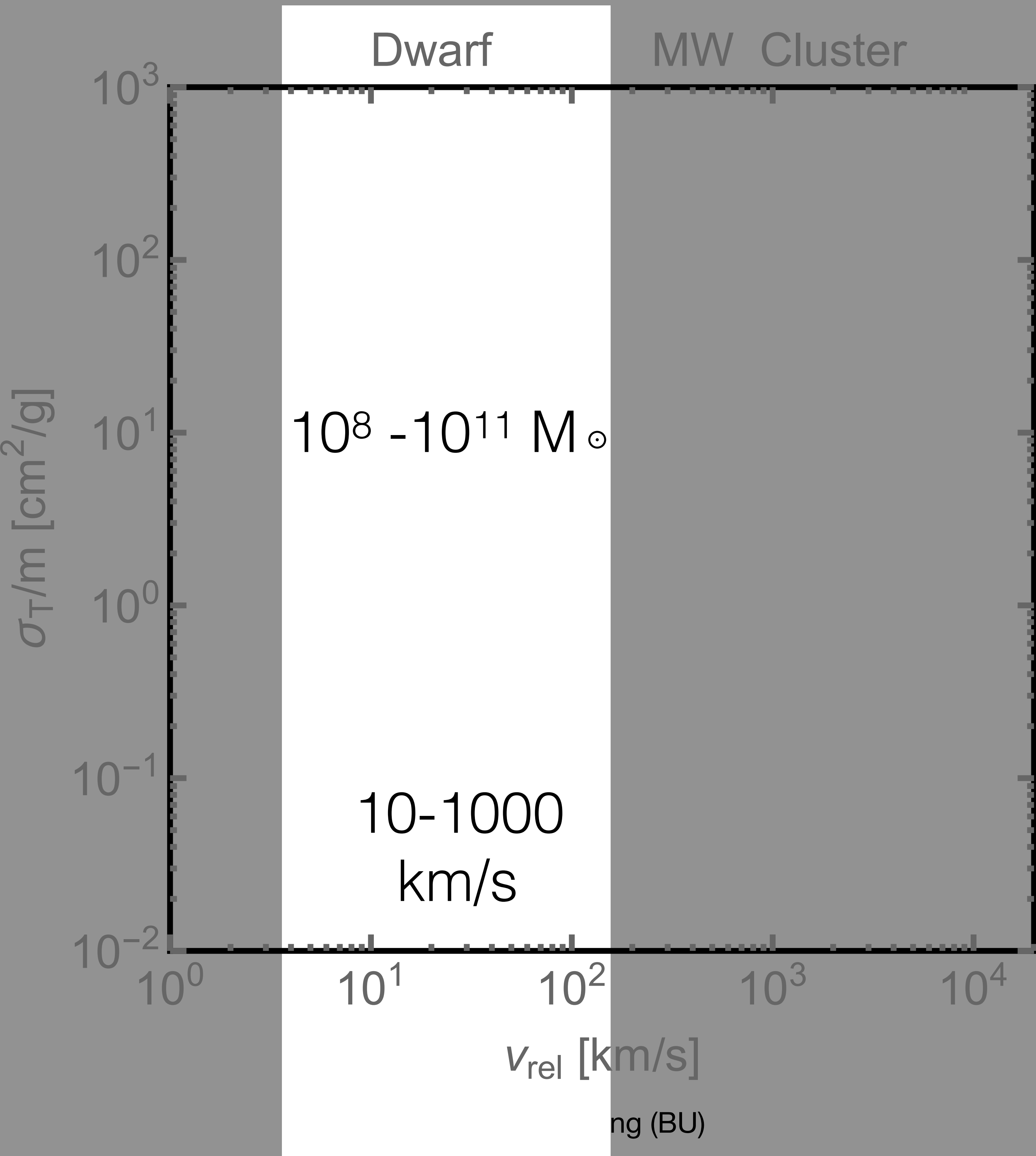
Astrophysical probes

Self-interaction strength

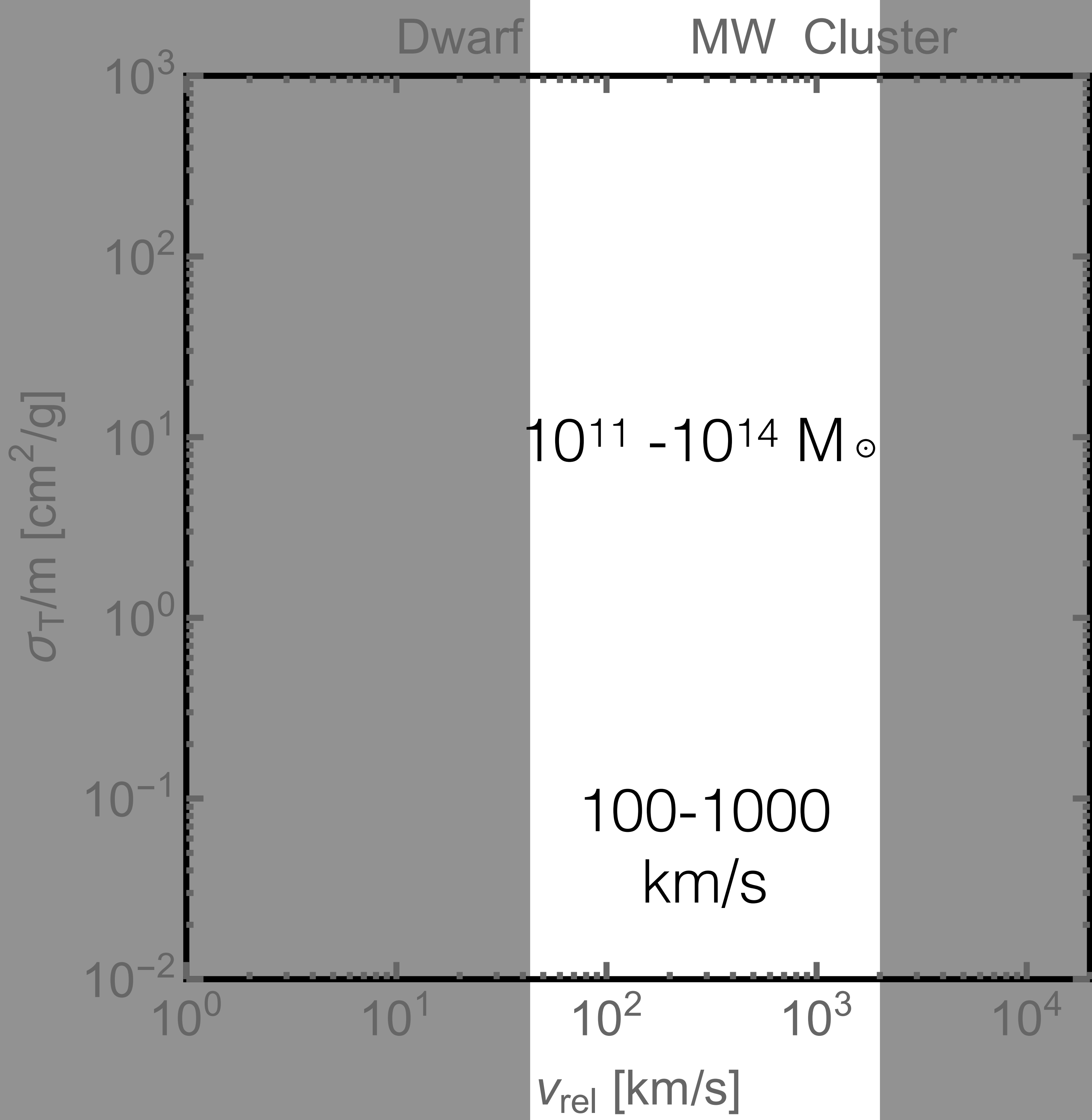


$$1\,\mathrm{cm}^2/\mathrm{g}$$
$$\approx 2\,\mathrm{barn}/\mathrm{GeV}$$

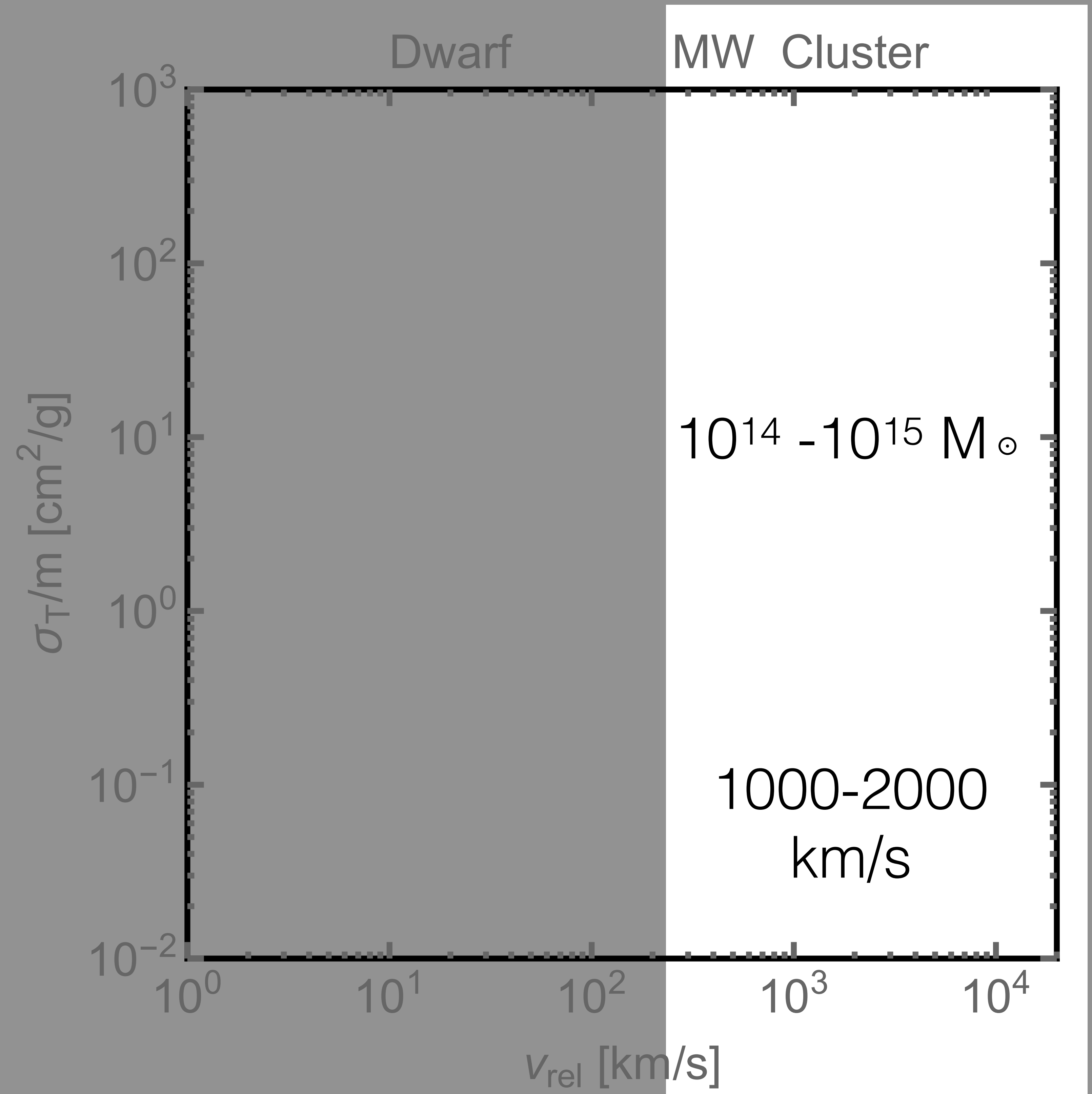
Astrophysical probes



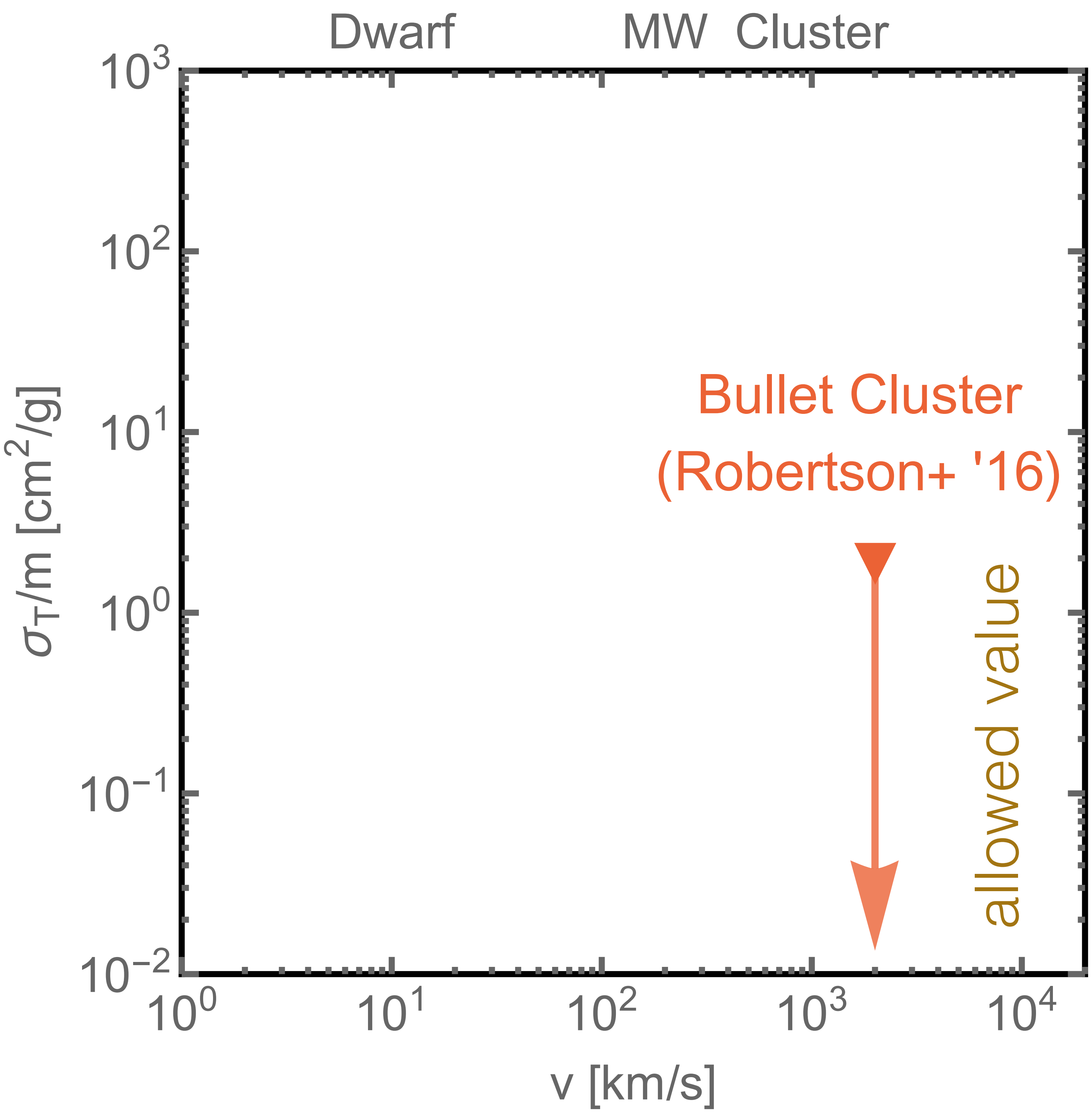
Astrophysical probes



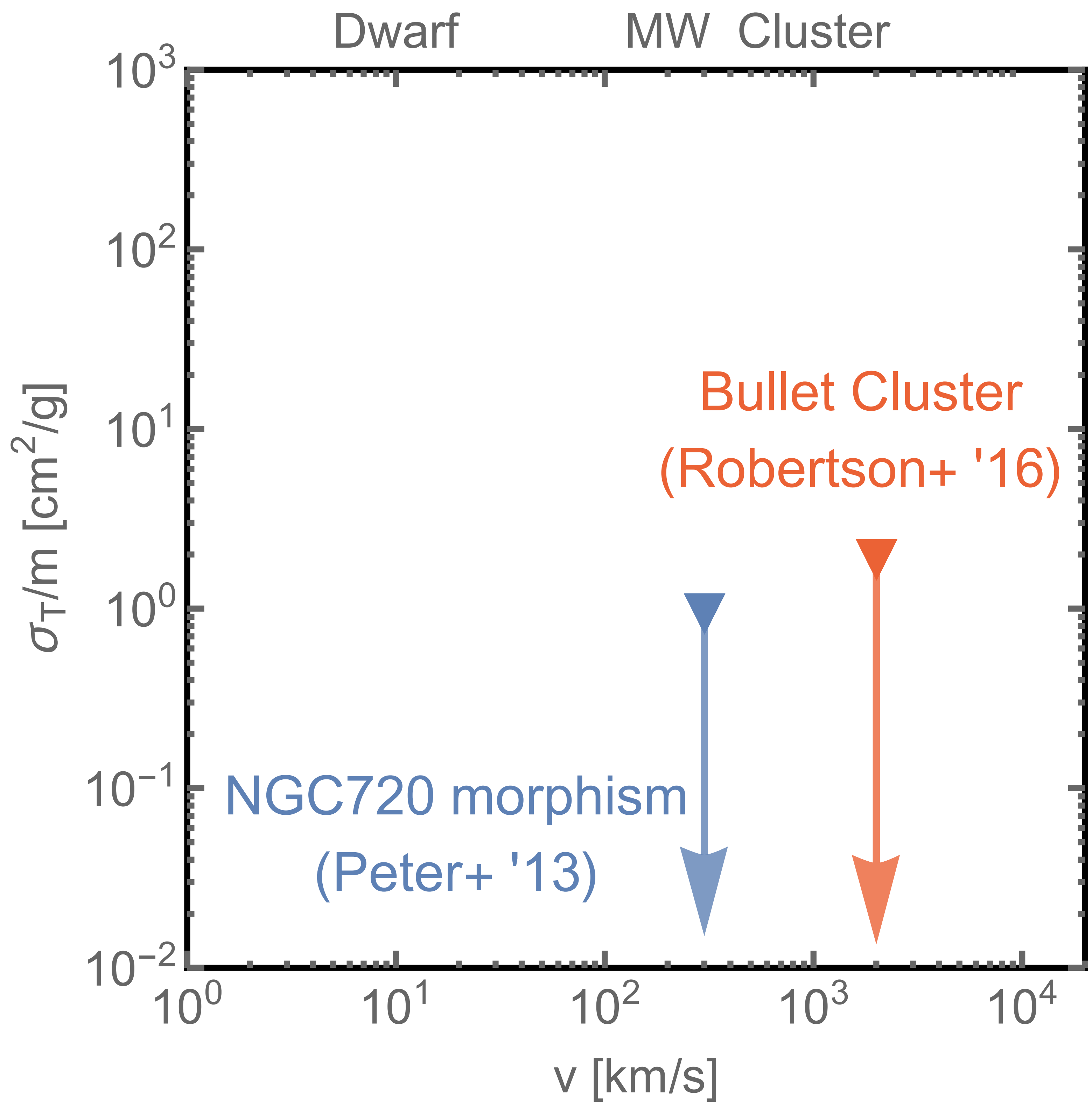
Astrophysical probes



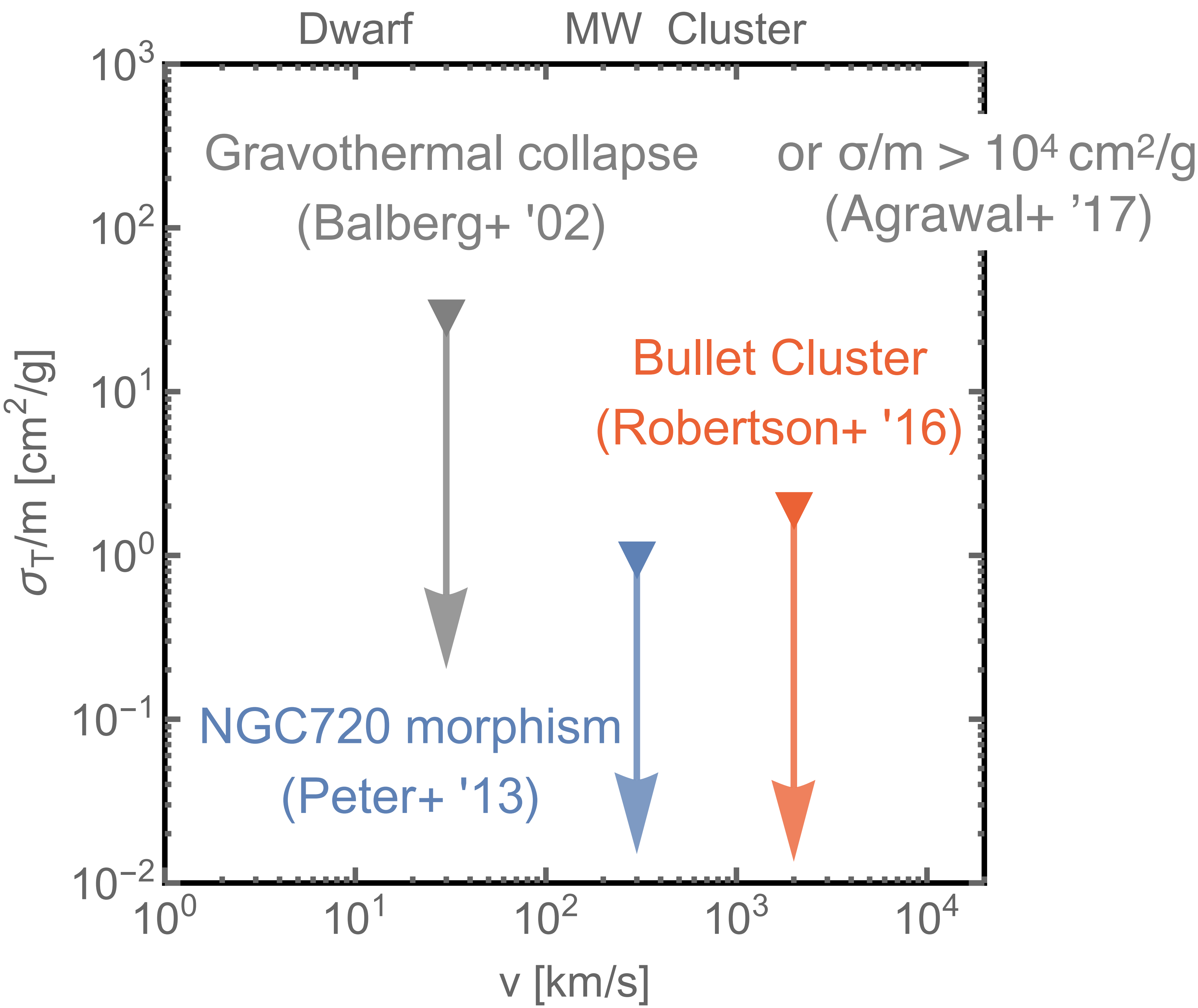
Cluster crossing



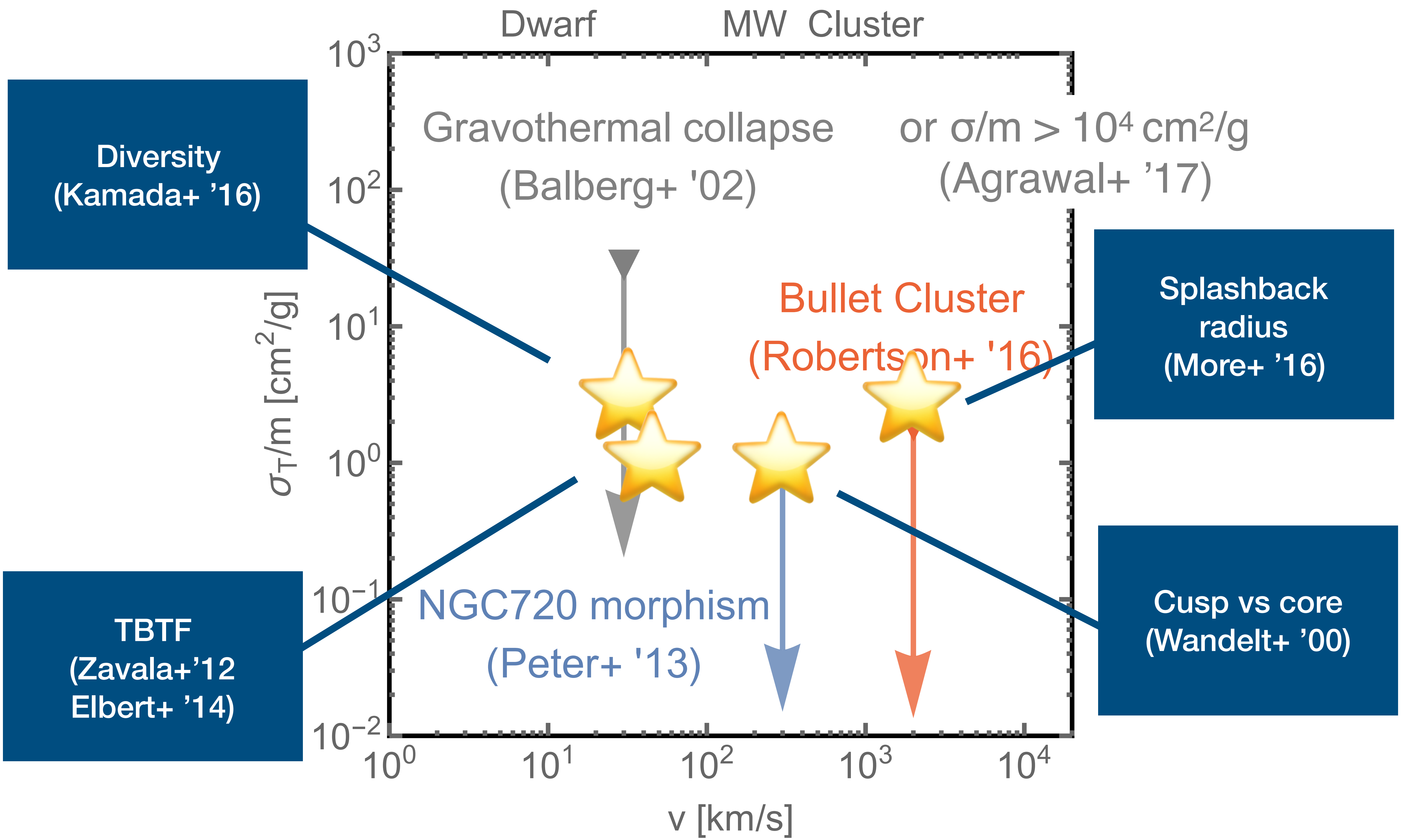
Galaxy morphism



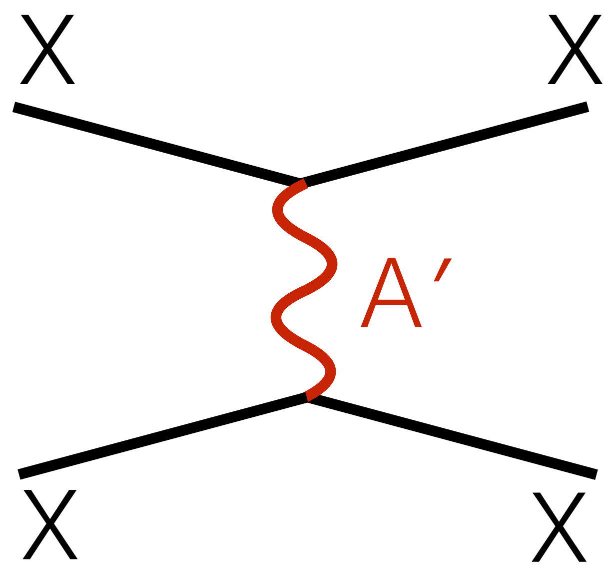
Gravothermal collapse

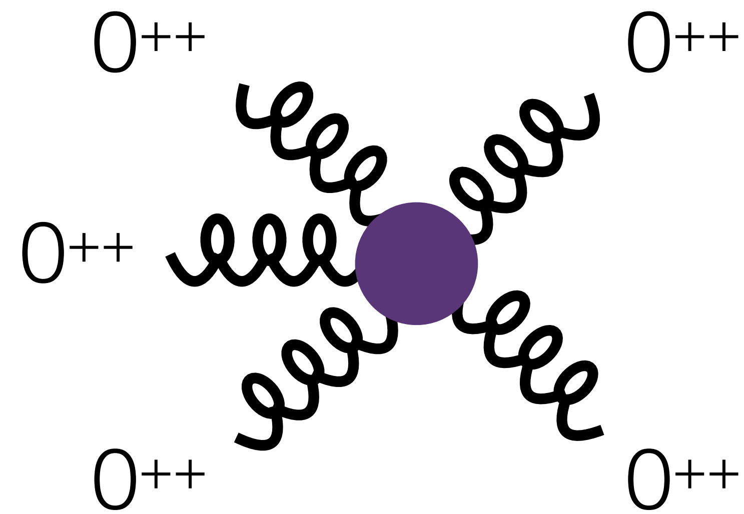


Gravothermal collapse

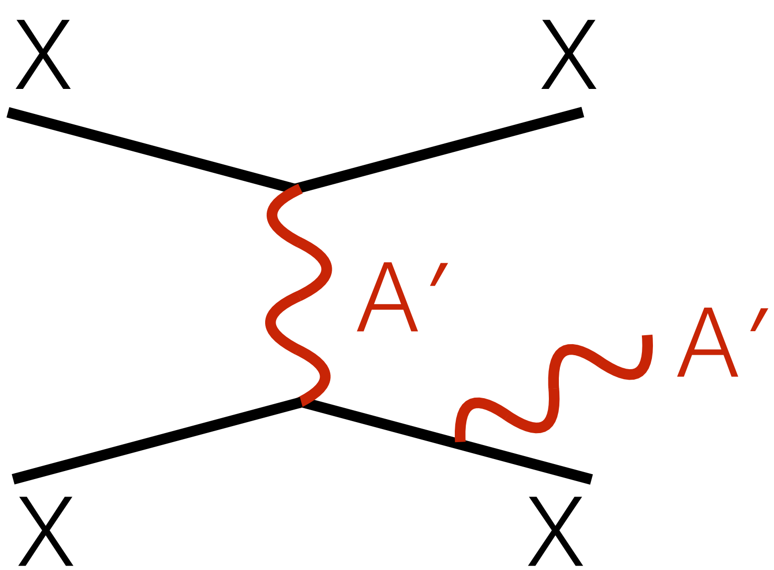


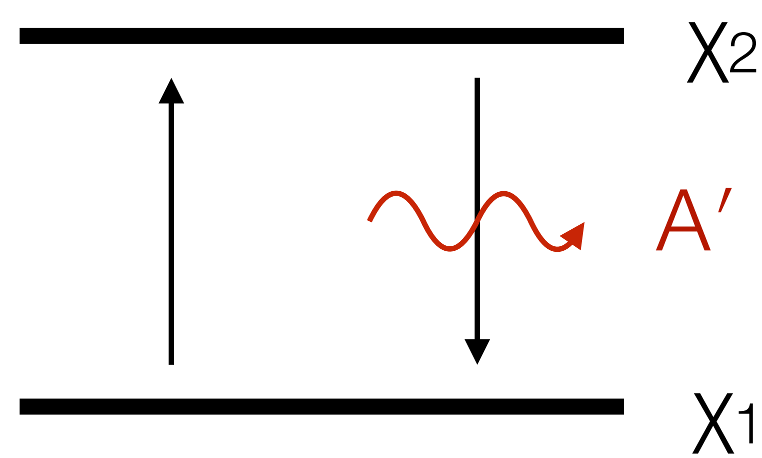
Dark sector is richer

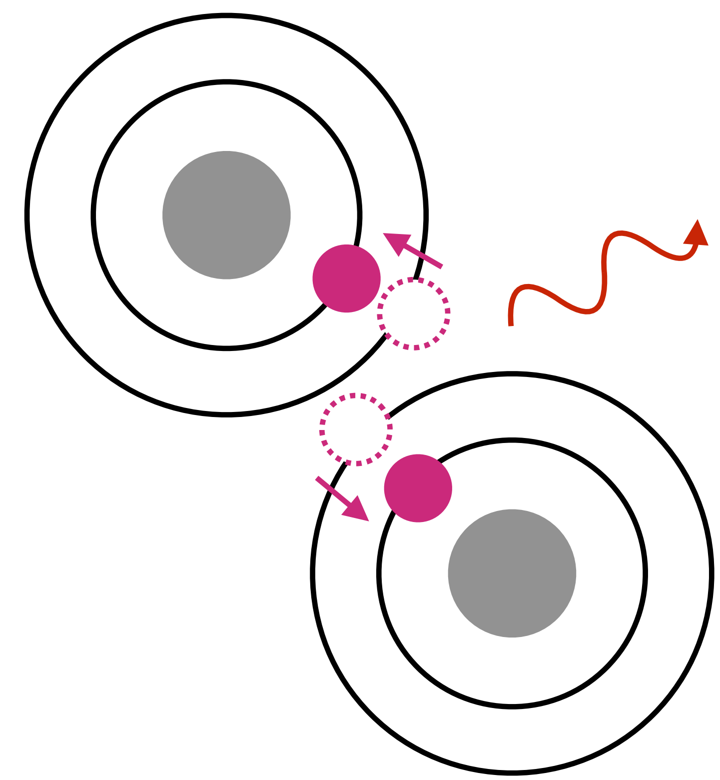




e.g. Ackerman et al ’09, Loeb & Weiner ’10, Boddy et al’16……
Fan et al ’13, Agrawal ’16, ’17……



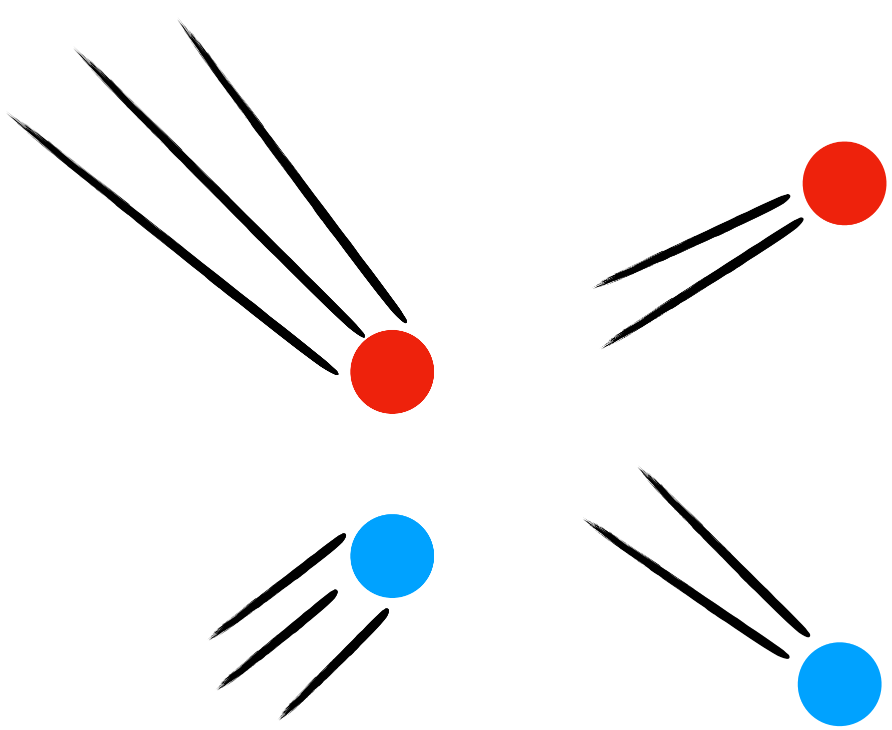




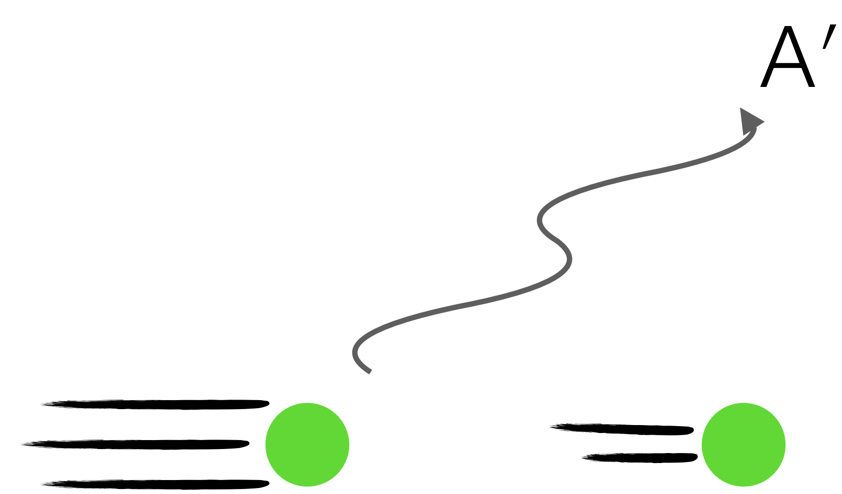
Gravothermal collapse

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

Elastic DM
self-scattering



Dissipative DM
self-scattering



Virial theorem

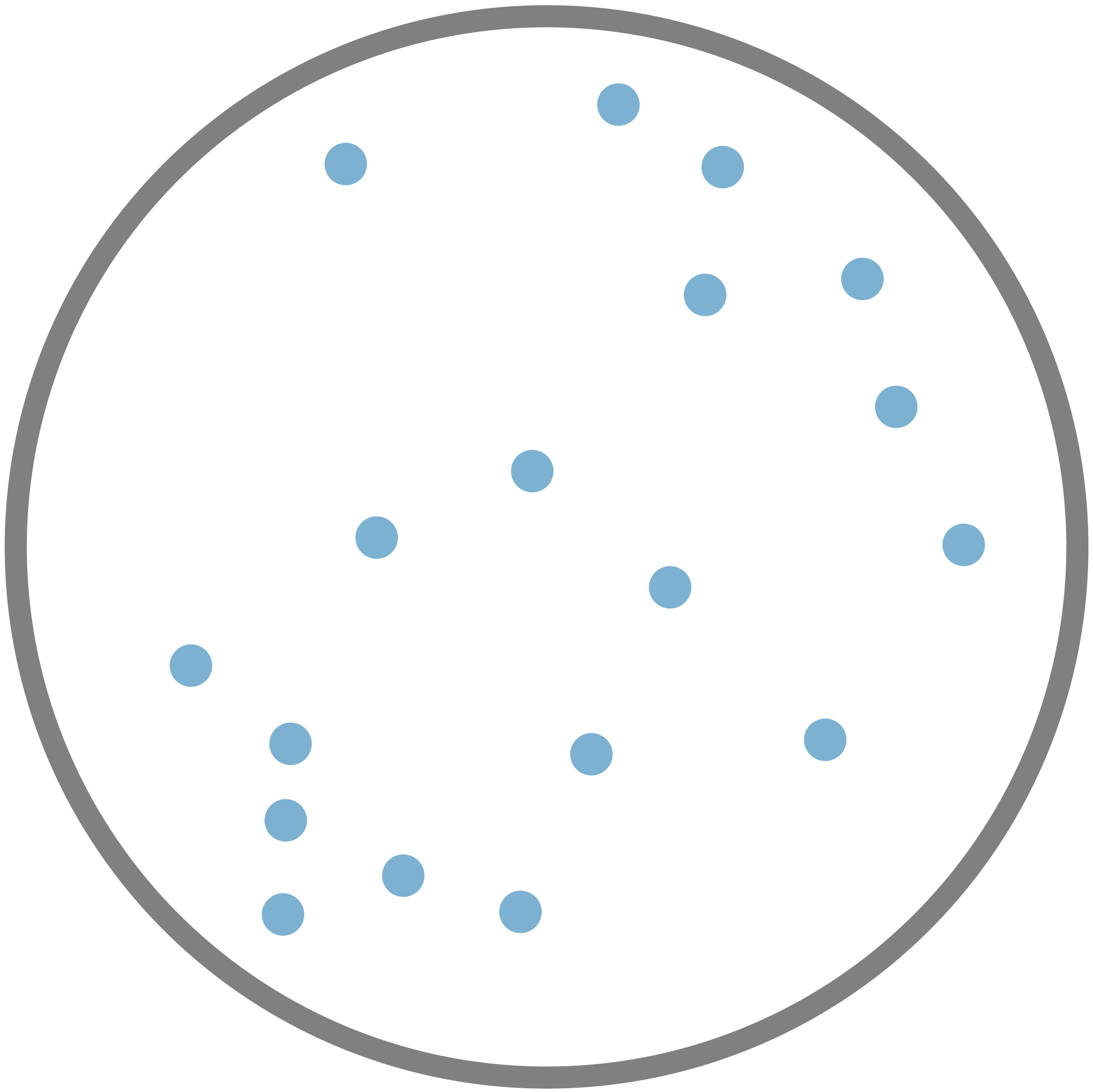
$$2K.E. + P.E. = 0$$

$$\Rightarrow \qquad E_{\text{tot}} = -K.E.$$

$$\Rightarrow \qquad \frac{E_{\text{tot}}}{T} < 0$$

Negative heat capacity!

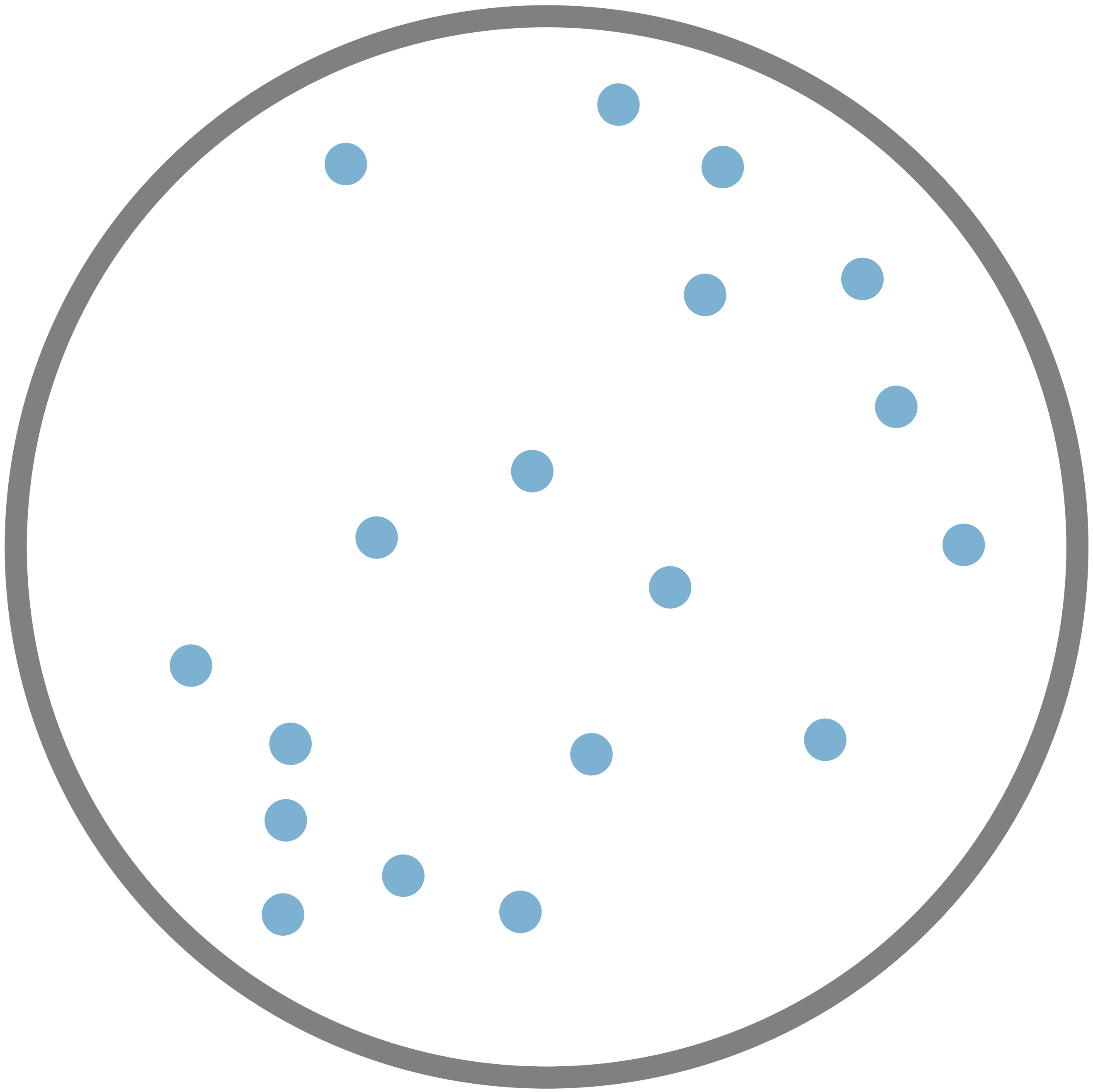
Gravothermal collapse



Core region of a halo

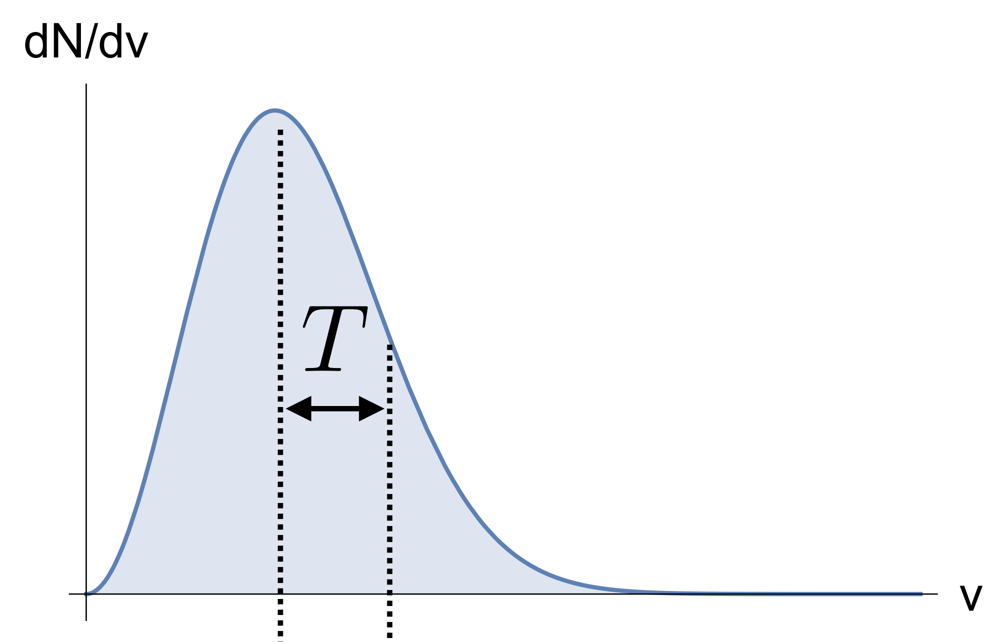
Take a halo w/
an iso-thermal
profile

Gravothermal collapse

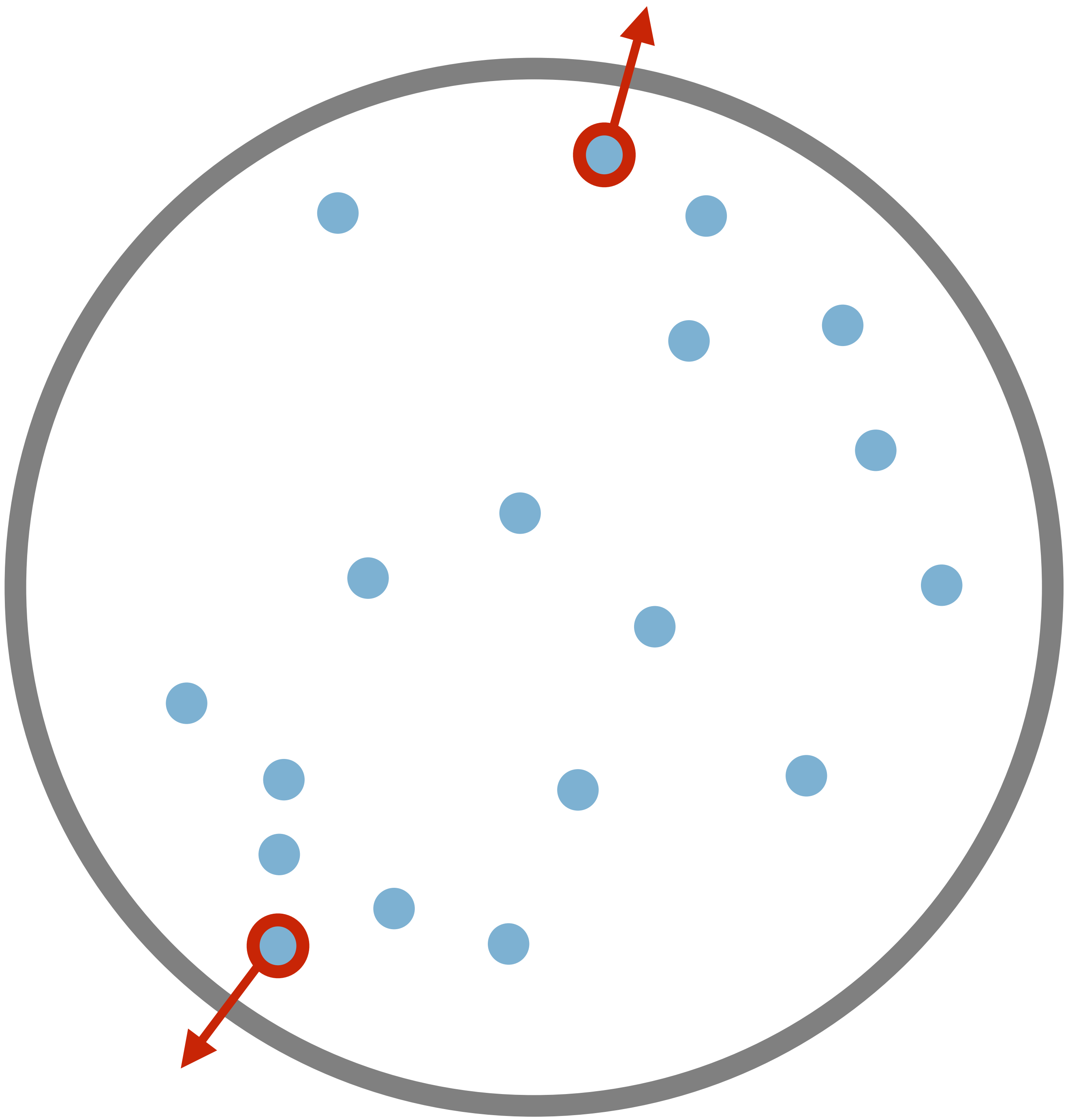


Core region of a halo

Velocity-distribution
of DM particles

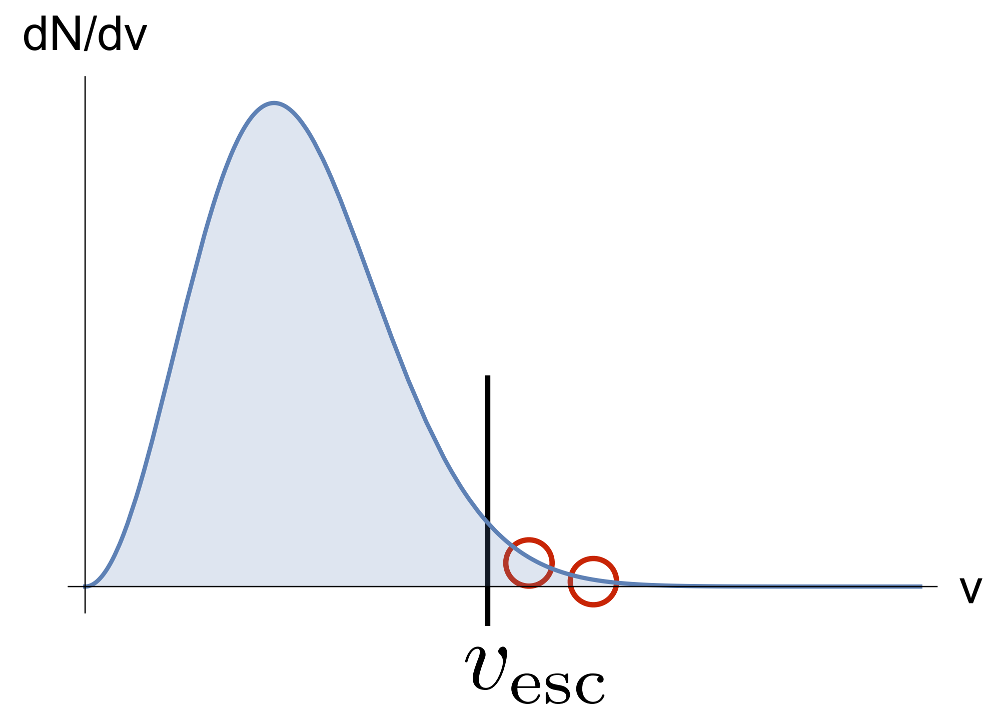


Gravothermal collapse



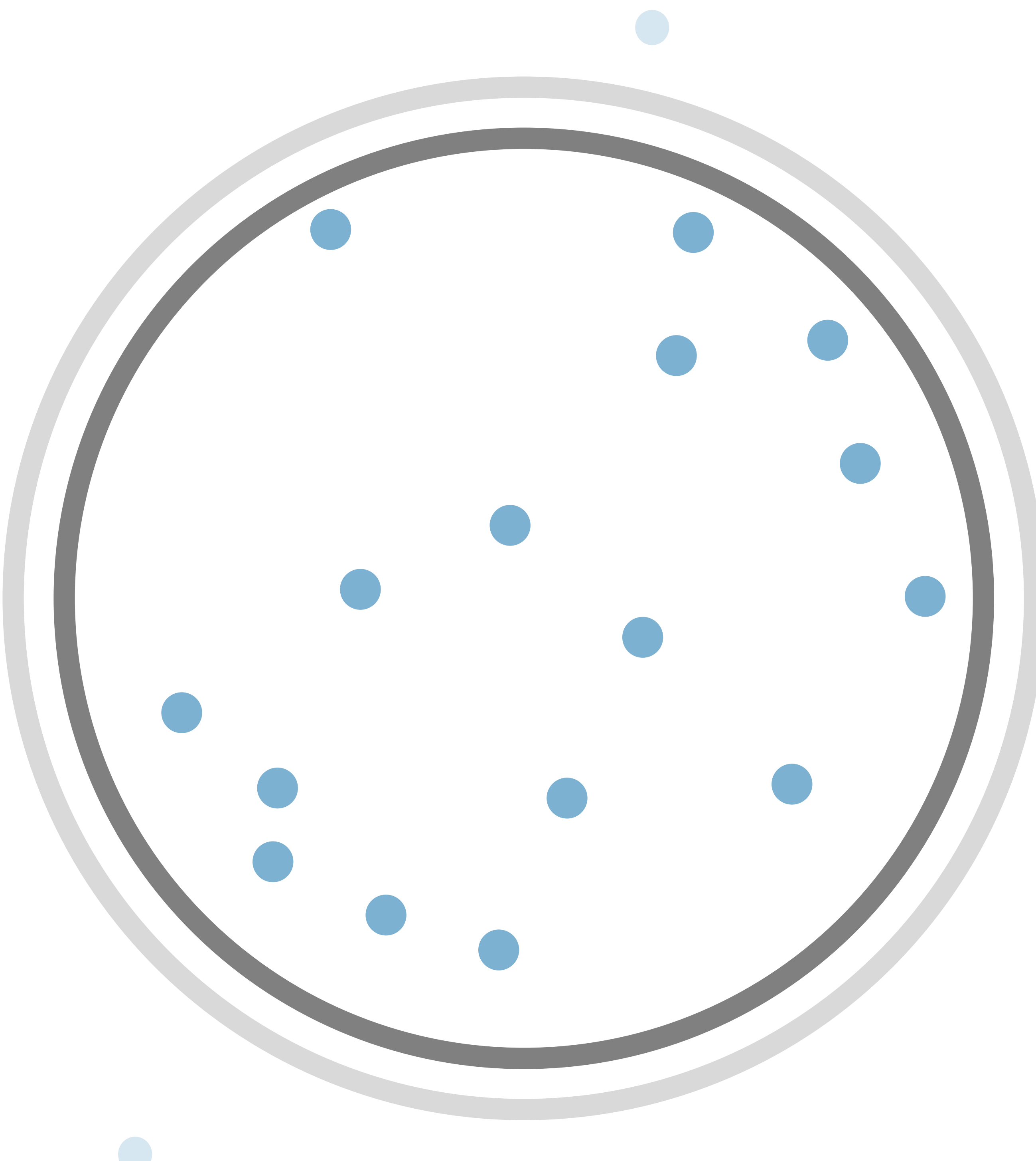
Core region of a halo

Velocity-distribution of DM particles



Particles in the “tail” can evaporate

Gravothermal collapse



Core region of a halo

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

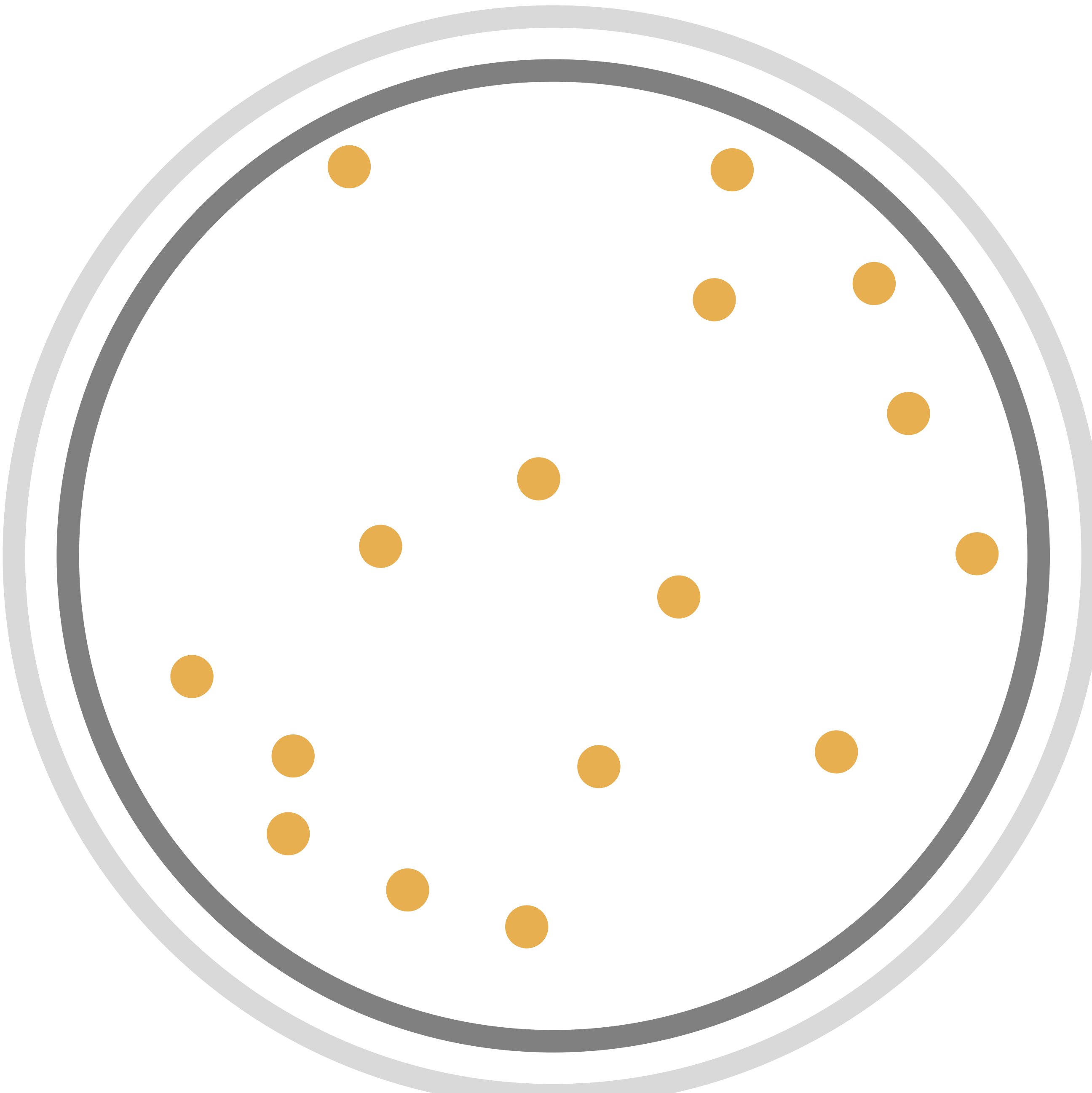
But overall

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

Out of virial

Gravity is no longer supported by random motion

Gravothermal collapse



Core region of a halo

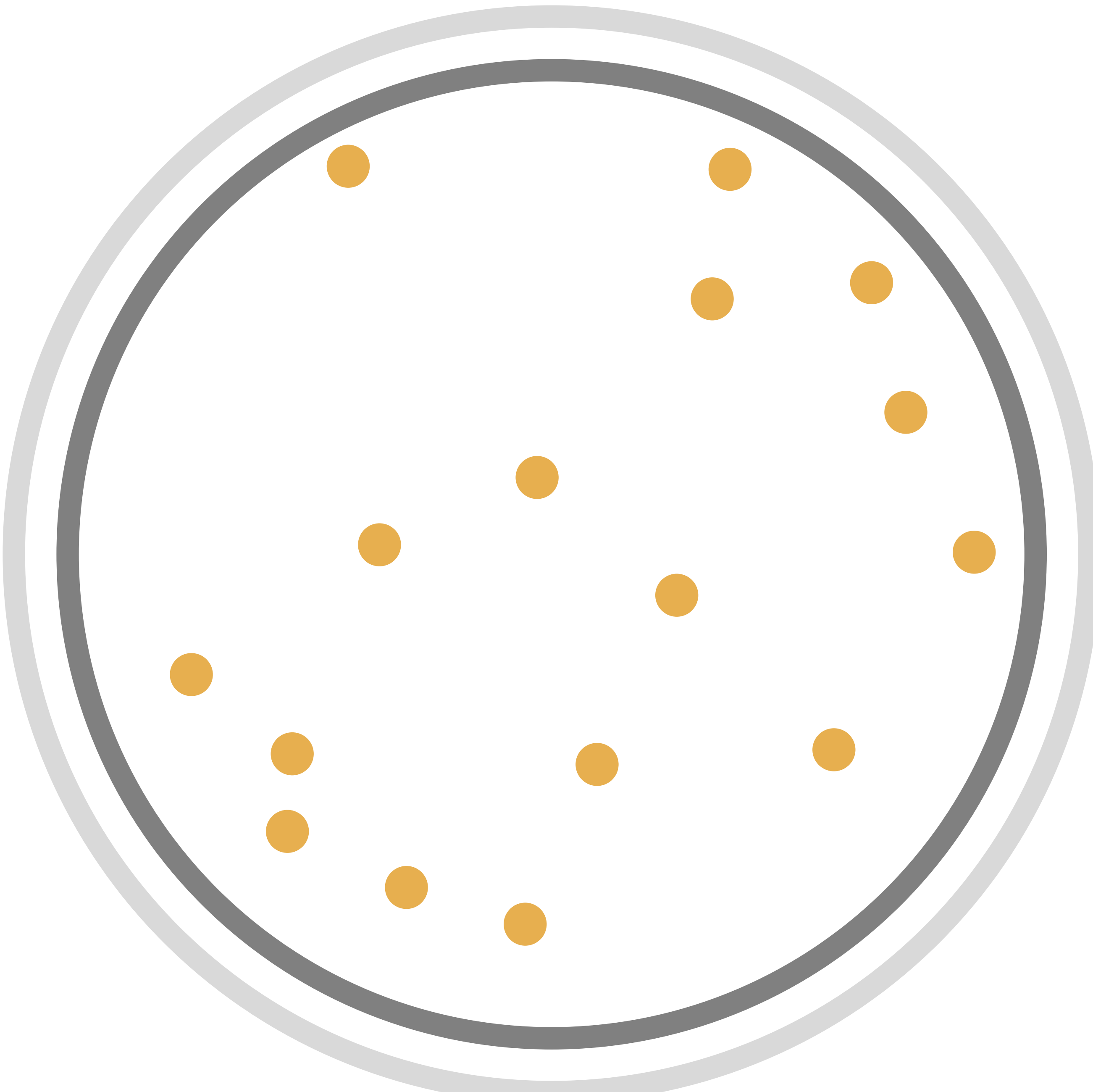
Back to virial through relaxation:

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

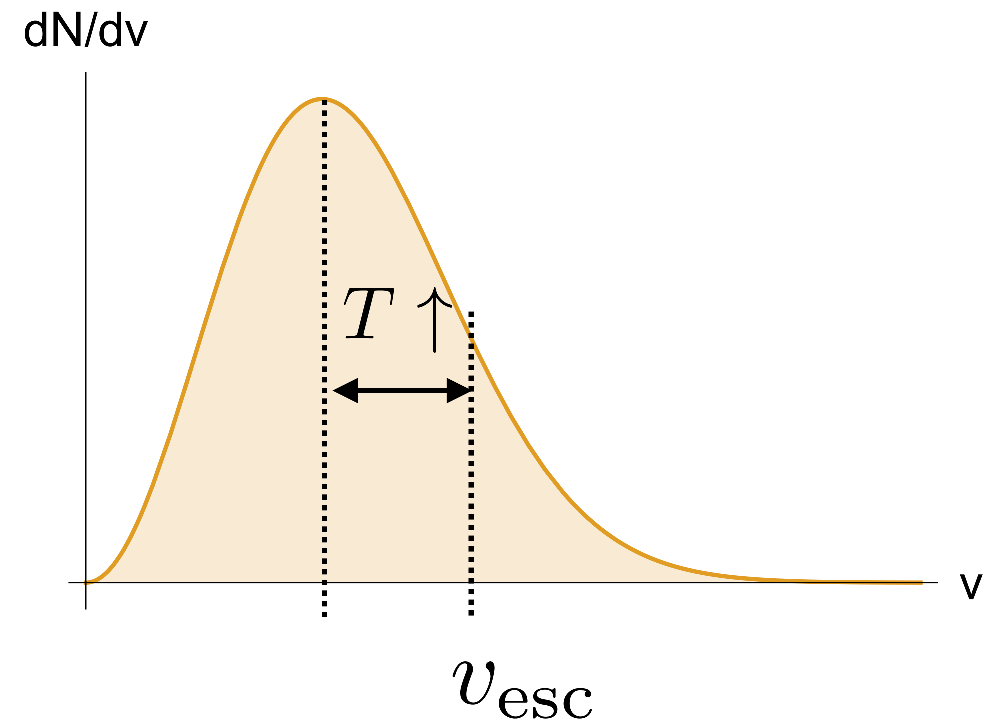
$$2K.E. + P.E. = 0$$

Gravothermal collapse

However

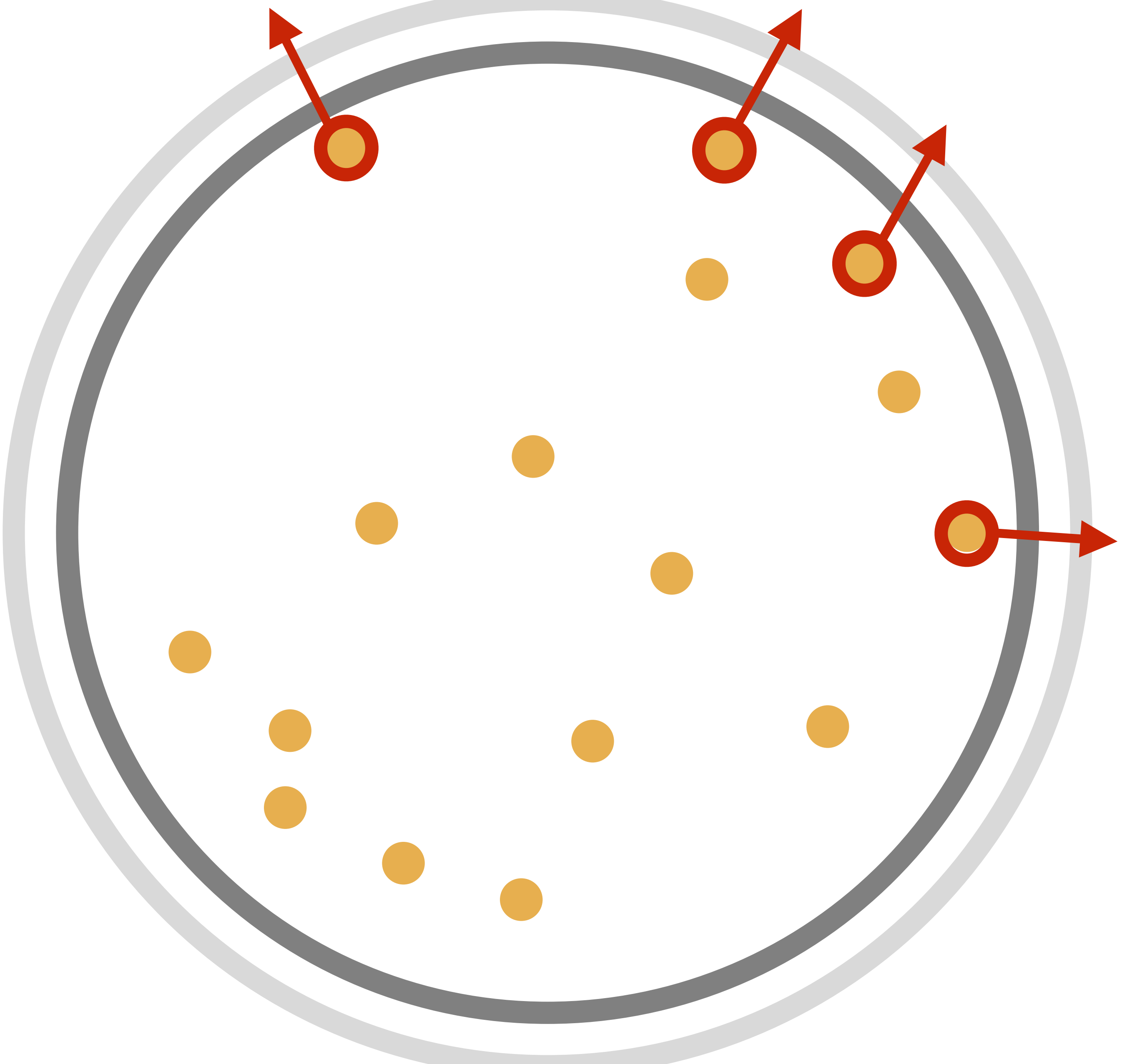


Core region of a halo



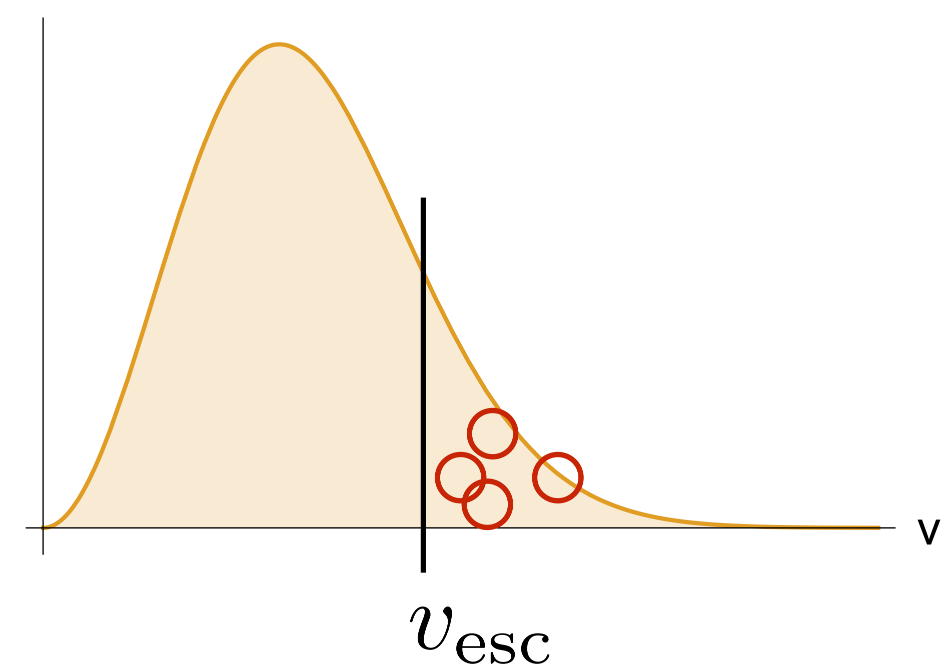
A fatter velocity distribution

Gravothermal collapse



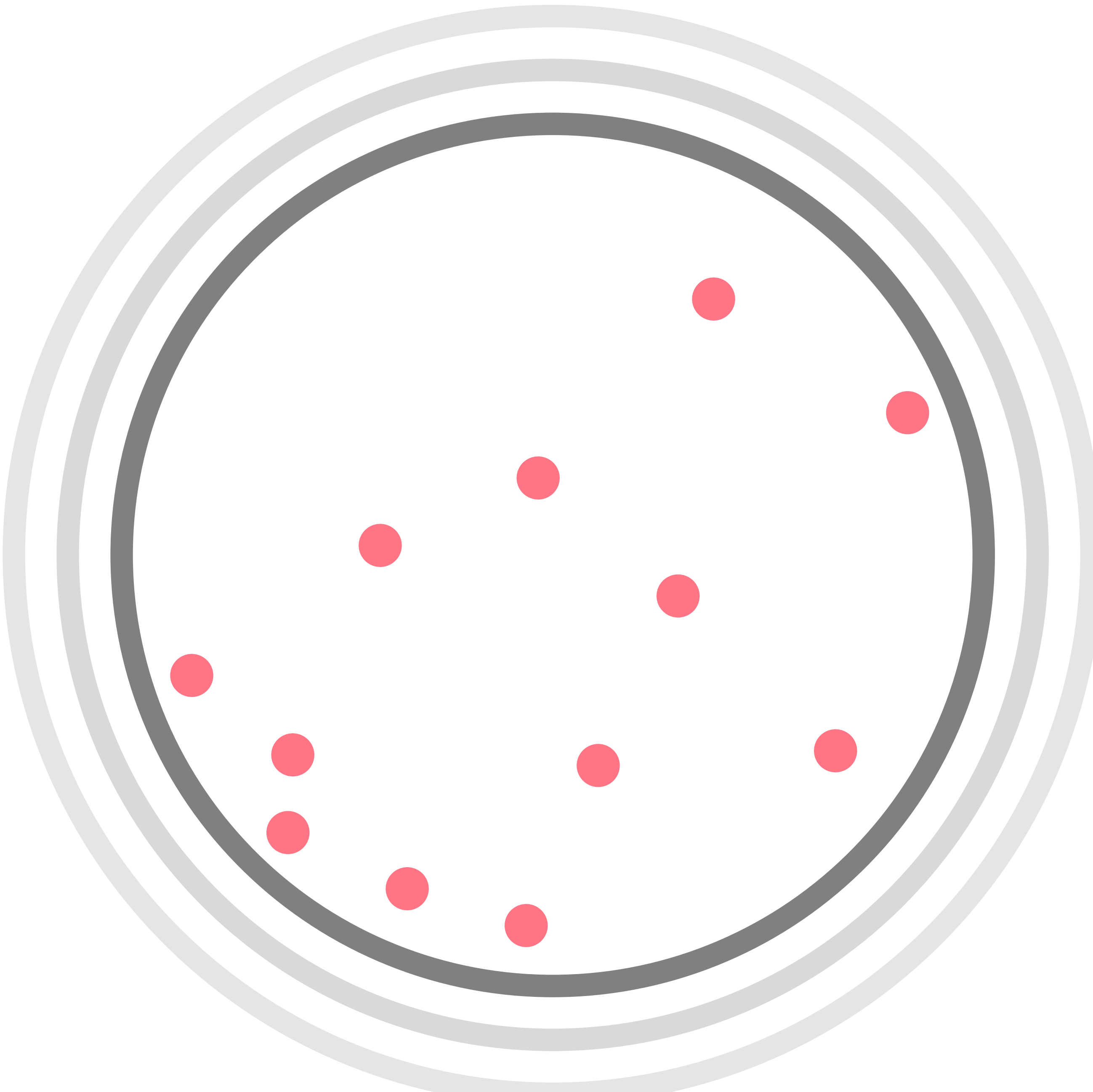
Core region of a halo

However

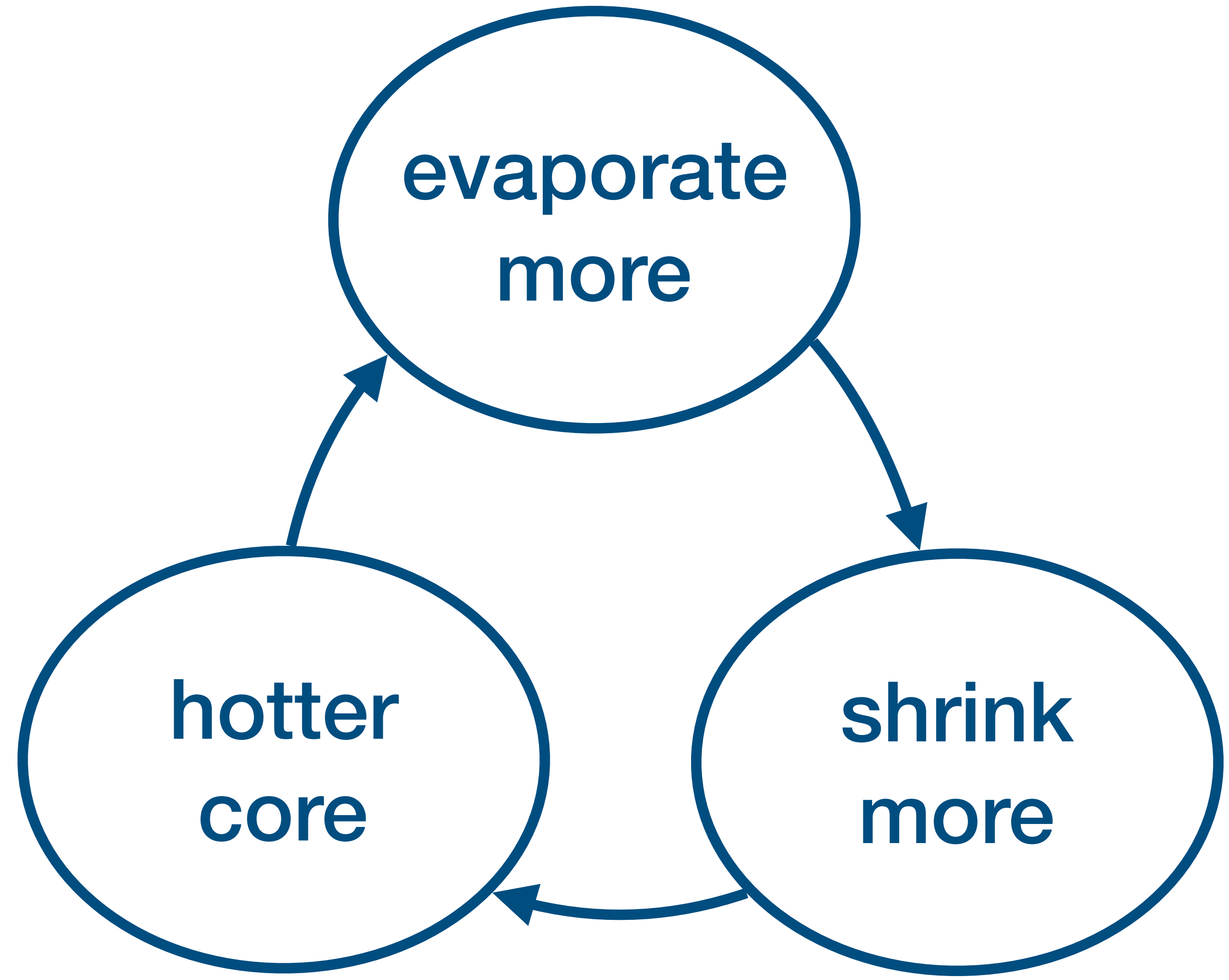


More particles are likely to evaporate

Gravothermal collapse



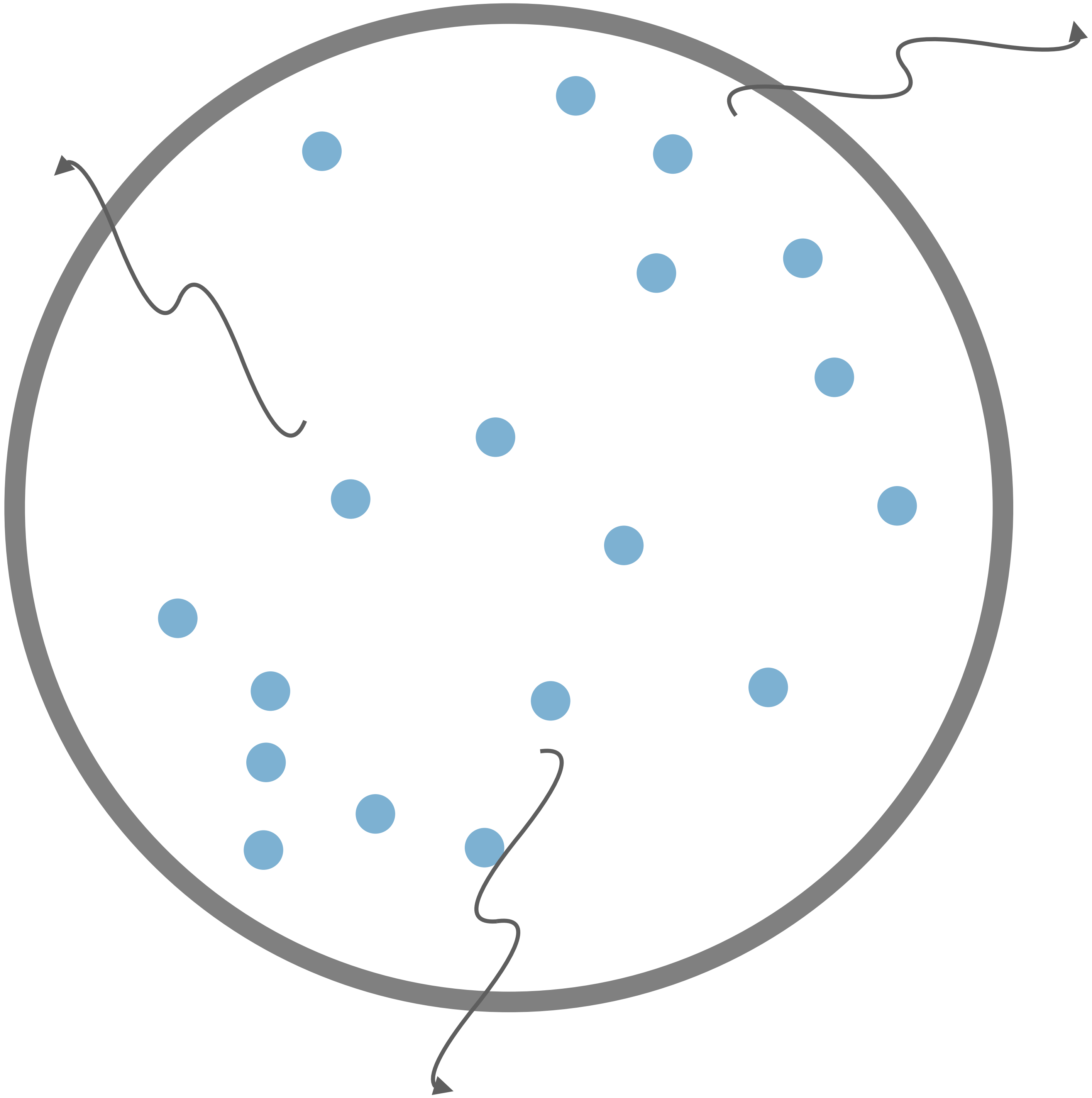
Core region of a halo



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

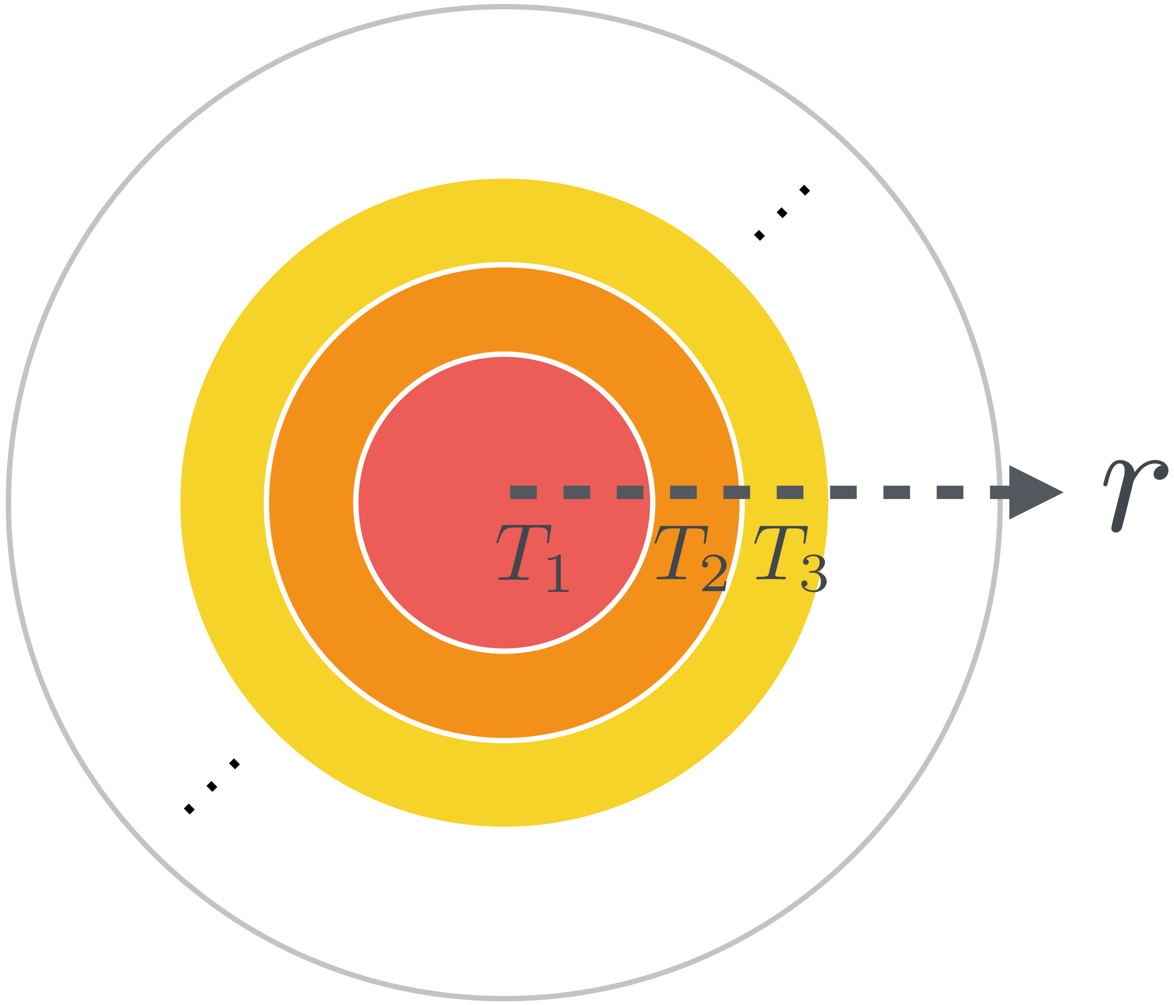
N-body simulation	Semi-analytical method
first principle	approximate
symmetries are not manifested	symmetries are imposed
hard to resolve deep profiles	easy to resolve deep profiles
computational costly, especially for high resolution	can be done on a laptop, easy for parameter scan

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).

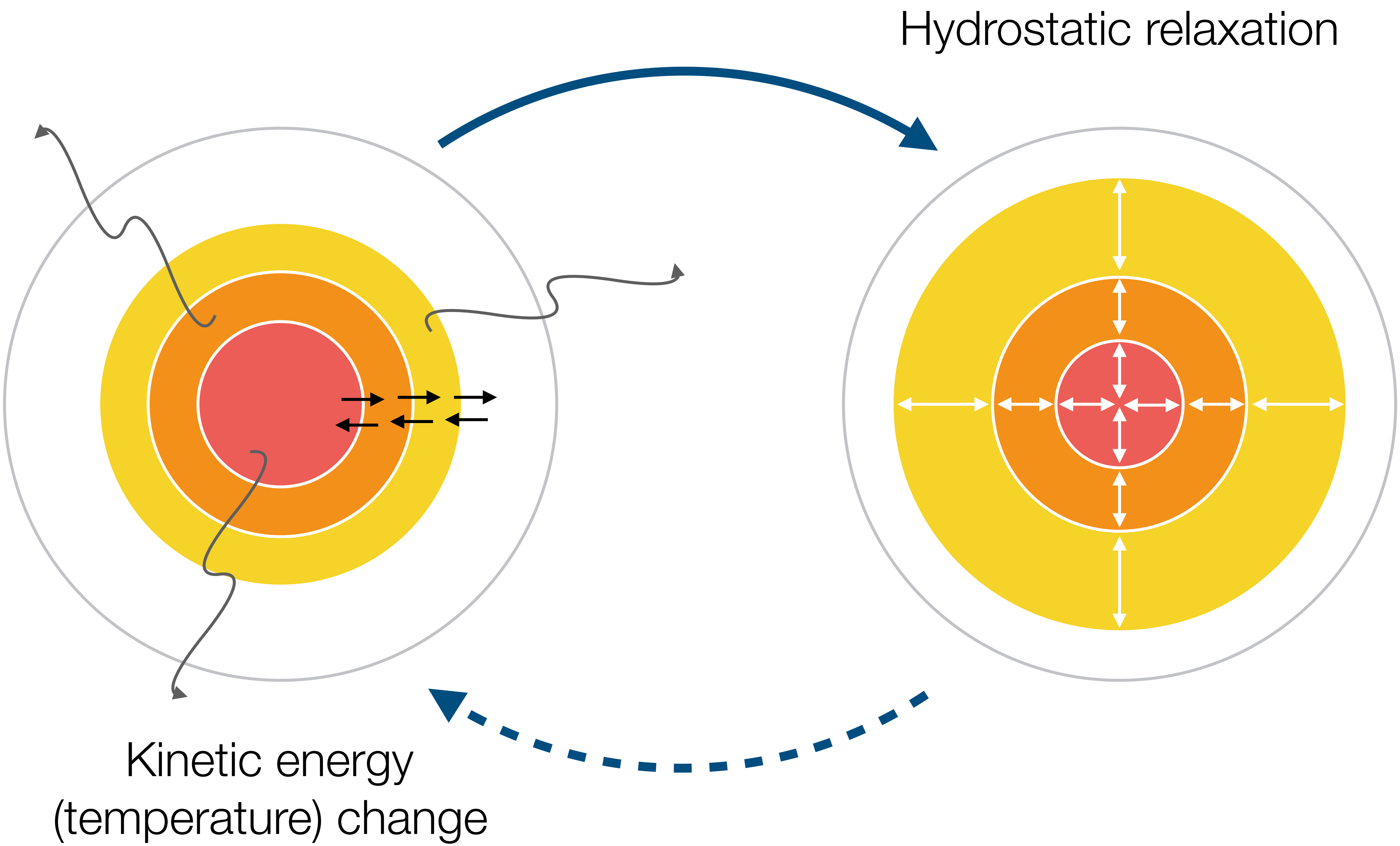
Hachisu et al ’78, Lynden-Bell & Eggleton, ’80; Inagaki & Lynden-Bell ’83; Heggie ’84; Goodman ’84; Balberg & Shapiro, ’02; Balberg et al ’02; Ahn & Shapiro, ’08; Koda & Shapiro, '11; Pollack et al, '15

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. Continuity equation: mass conservation

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

M: enclosed mass

Transportation equations

2. Euler's equation: momentum conservation

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

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

Transportation equations

3. Thermodynamic relation: 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)

Lagrangian derivative

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

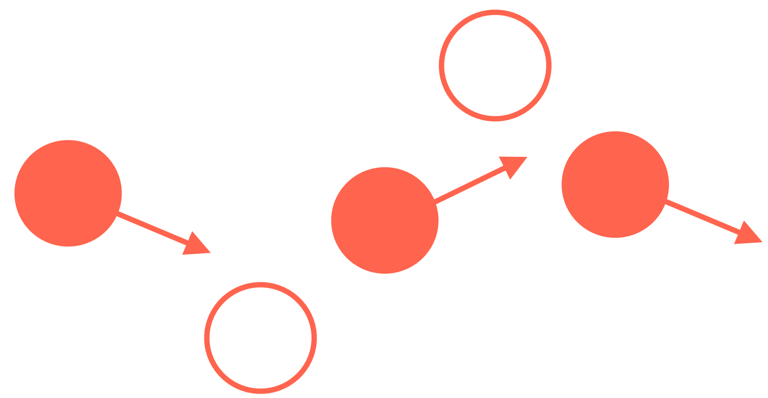
More on conductivity

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

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

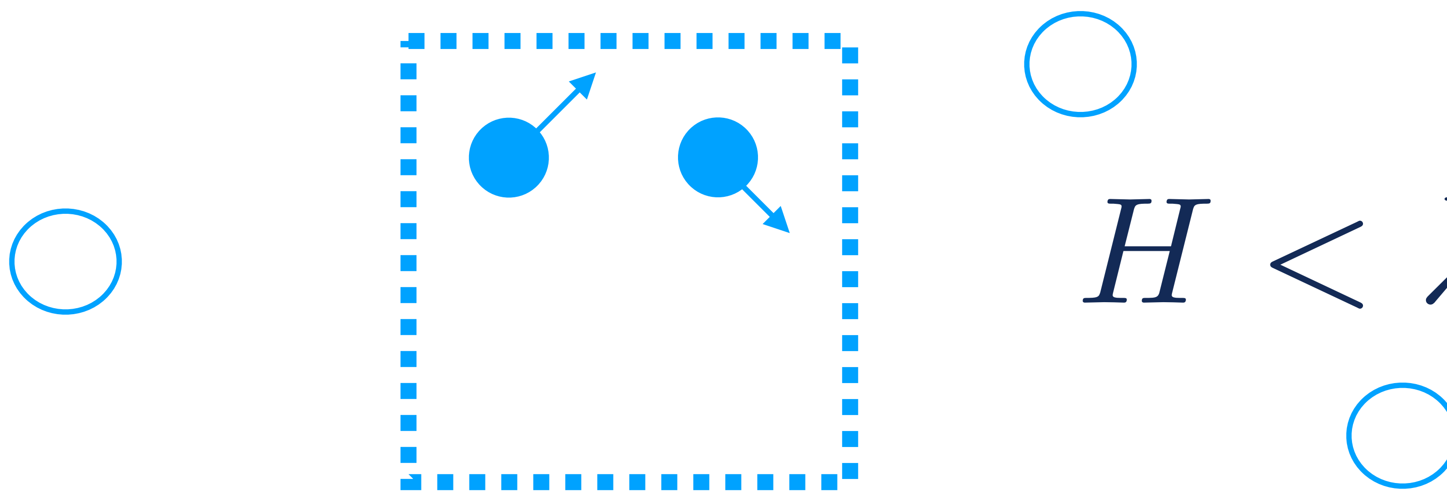
conductivity

More on conductivity



- Collisions w/ other particles
- Characterized by mean free path: $\lambda = 1/(n\sigma)$
- $\kappa_{\rm smfp} \approx n\nu\lambda = \frac{\nu}{\sigma}$

Another length can be relevant



$$H < \lambda$$

- Collisions are restricted by a "box"

Lynden-Bell & Eggleton, '80

- Characterized by the orbit height (Jean's length)

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

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

β: fixed by calibrating to N-body simulations

Combine the two

long-mean-free-path region, H is more important

$$\kappa = \begin{cases} \kappa_{\mathrm{lmfp}}, & H < \lambda \\ \kappa_{\mathrm{smfp}}, & \lambda < H \end{cases}$$

short-mean-free-path region, λ is more important

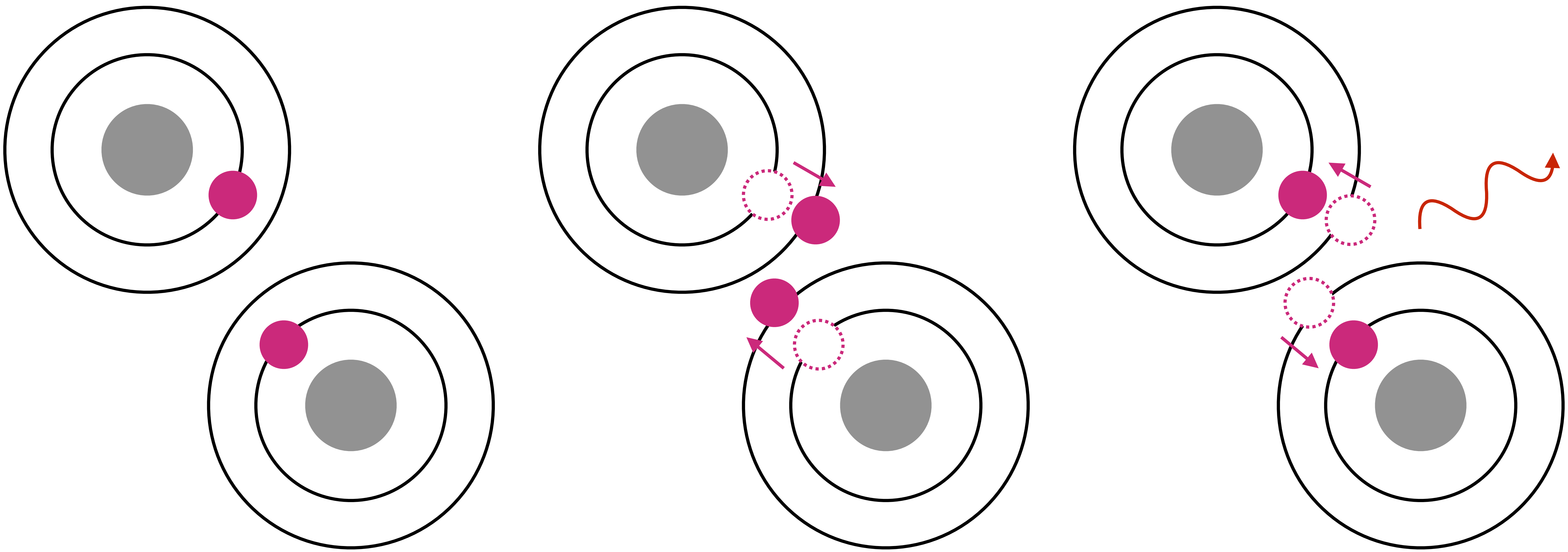
$$\Downarrow$$

$$\kappa = \frac{1}{\kappa_{\mathrm{lmfp}}^{-1} + \kappa_{\mathrm{smfp}}^{-1}}$$

Balberg & Shapiro, '02

More on the bulk cooling rate

- We consider the collisional cooling



More on the cooling rate

- We consider the collisional cooling

energy loss
in unit vol.
& unit time

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

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

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

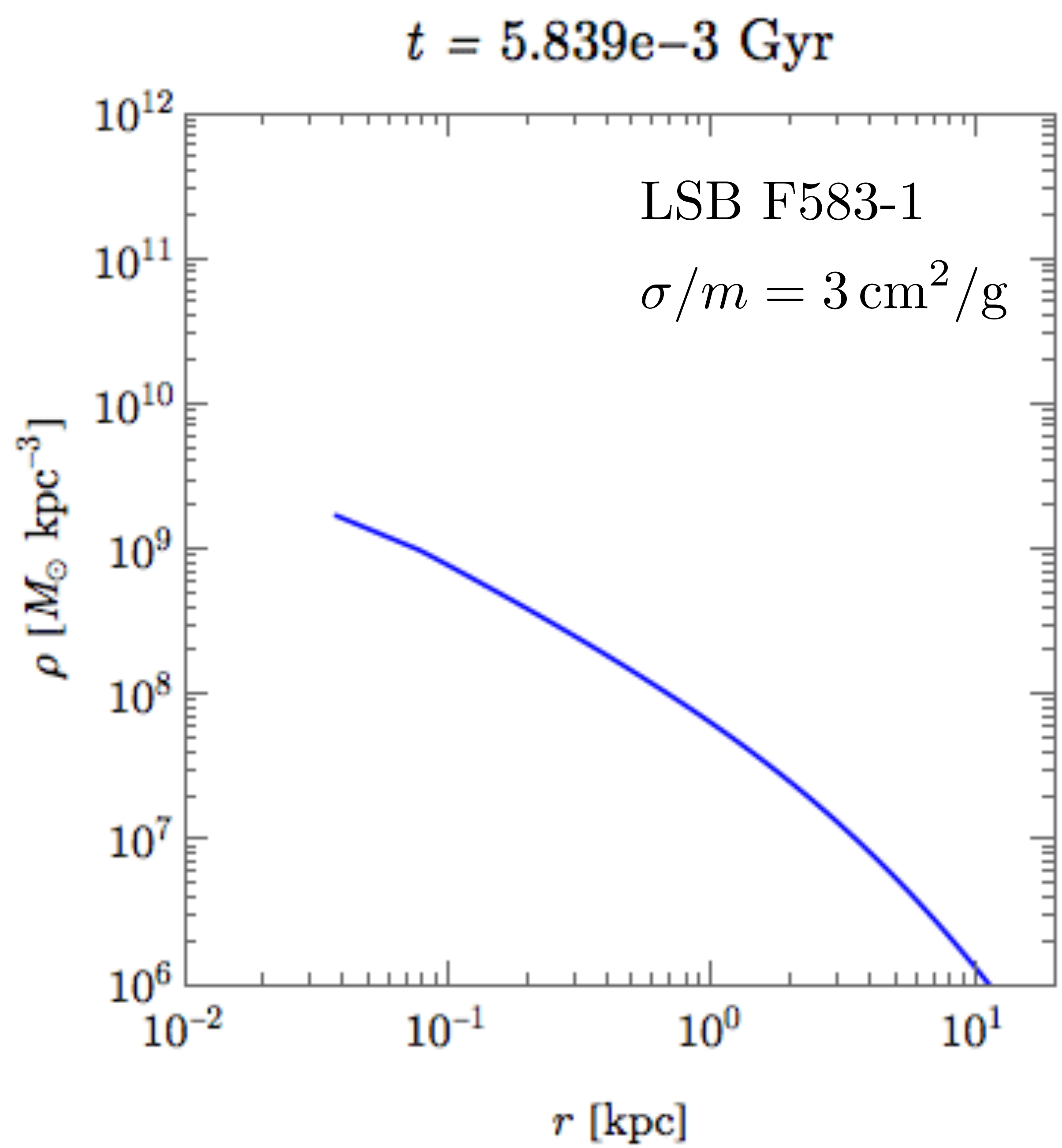
Other details on setups

- 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

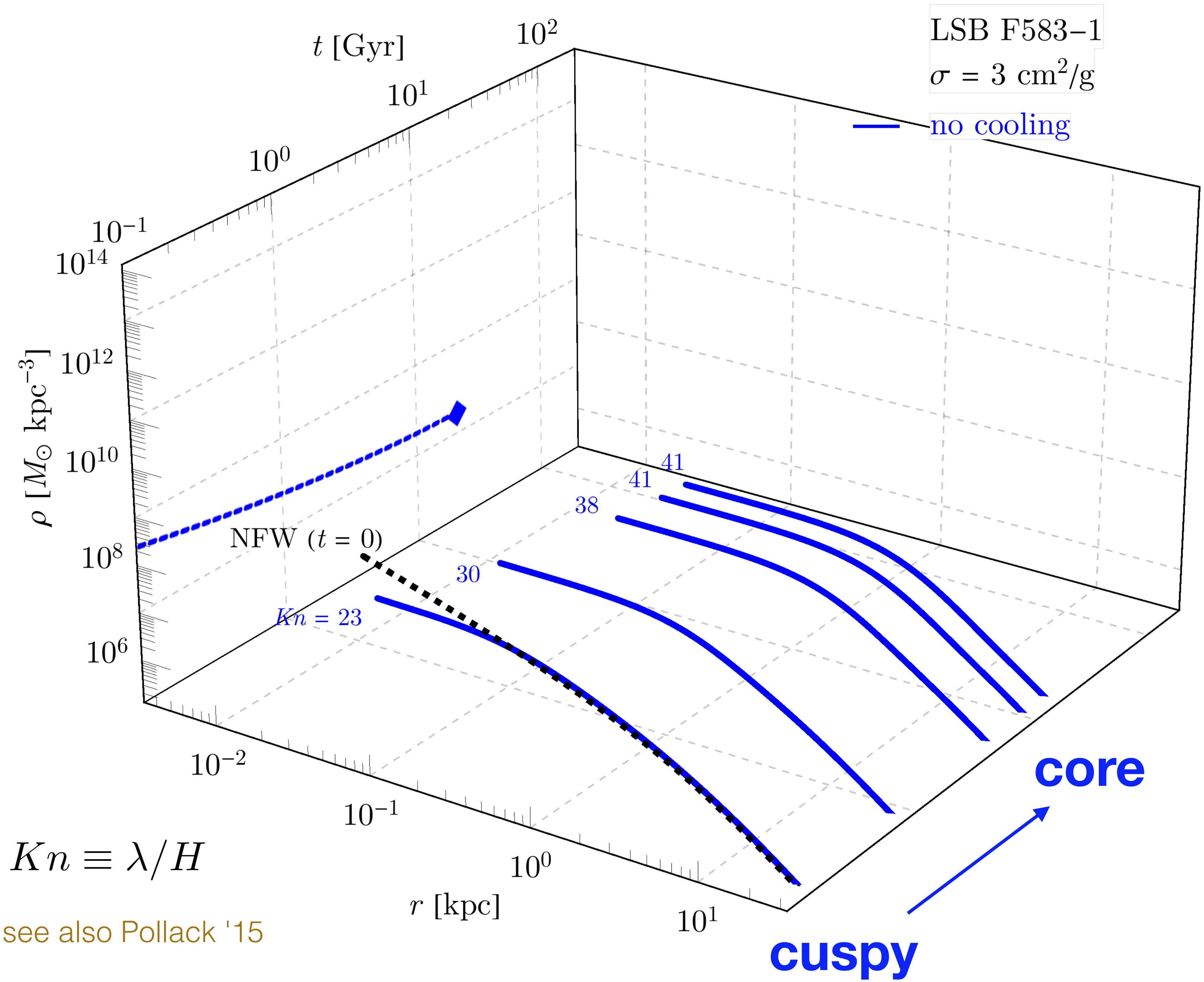
Evolution of the density profile



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

pure elastic

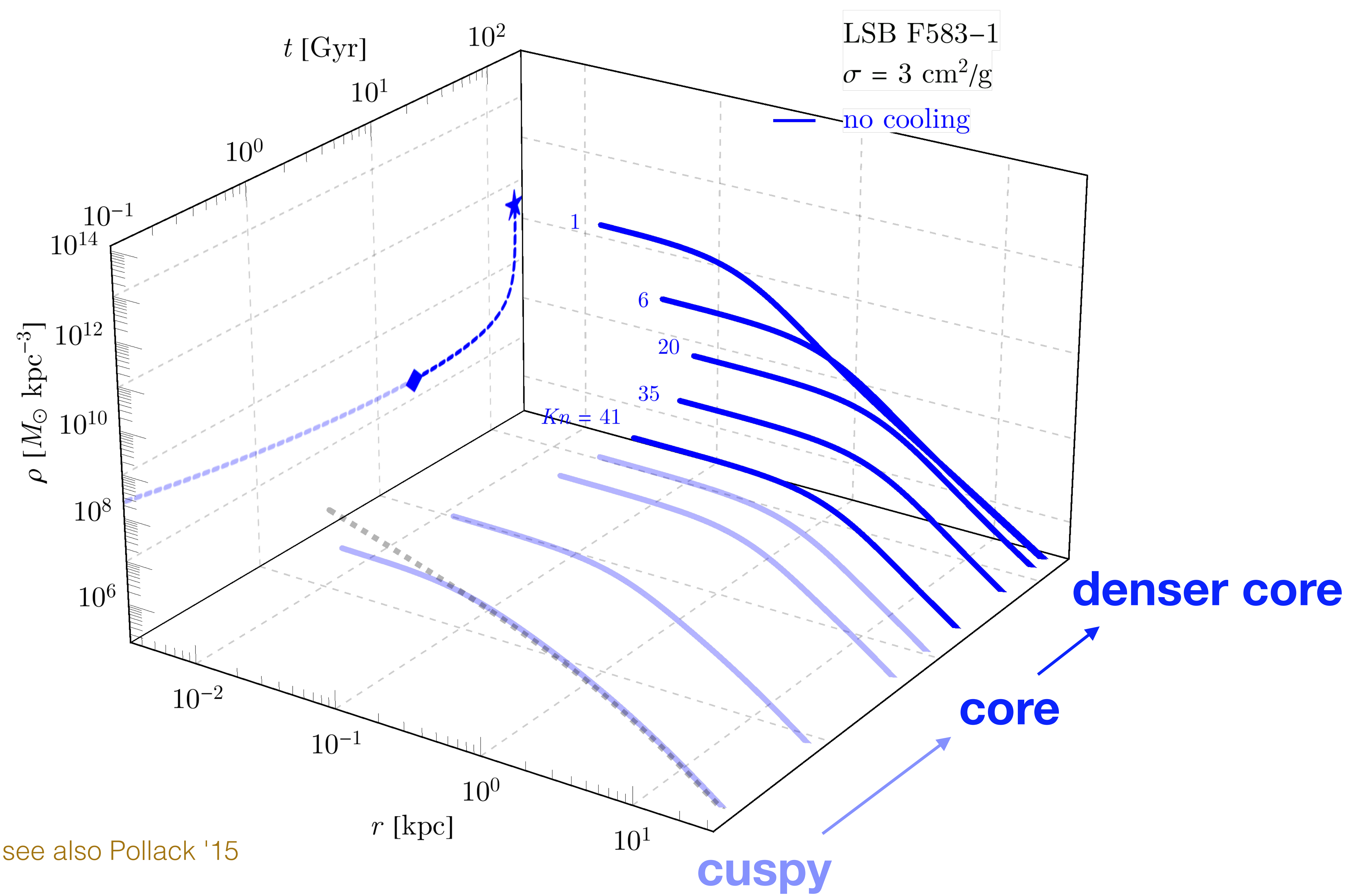
Stage 1: develops a core



$$Kn \equiv \lambda / H$$

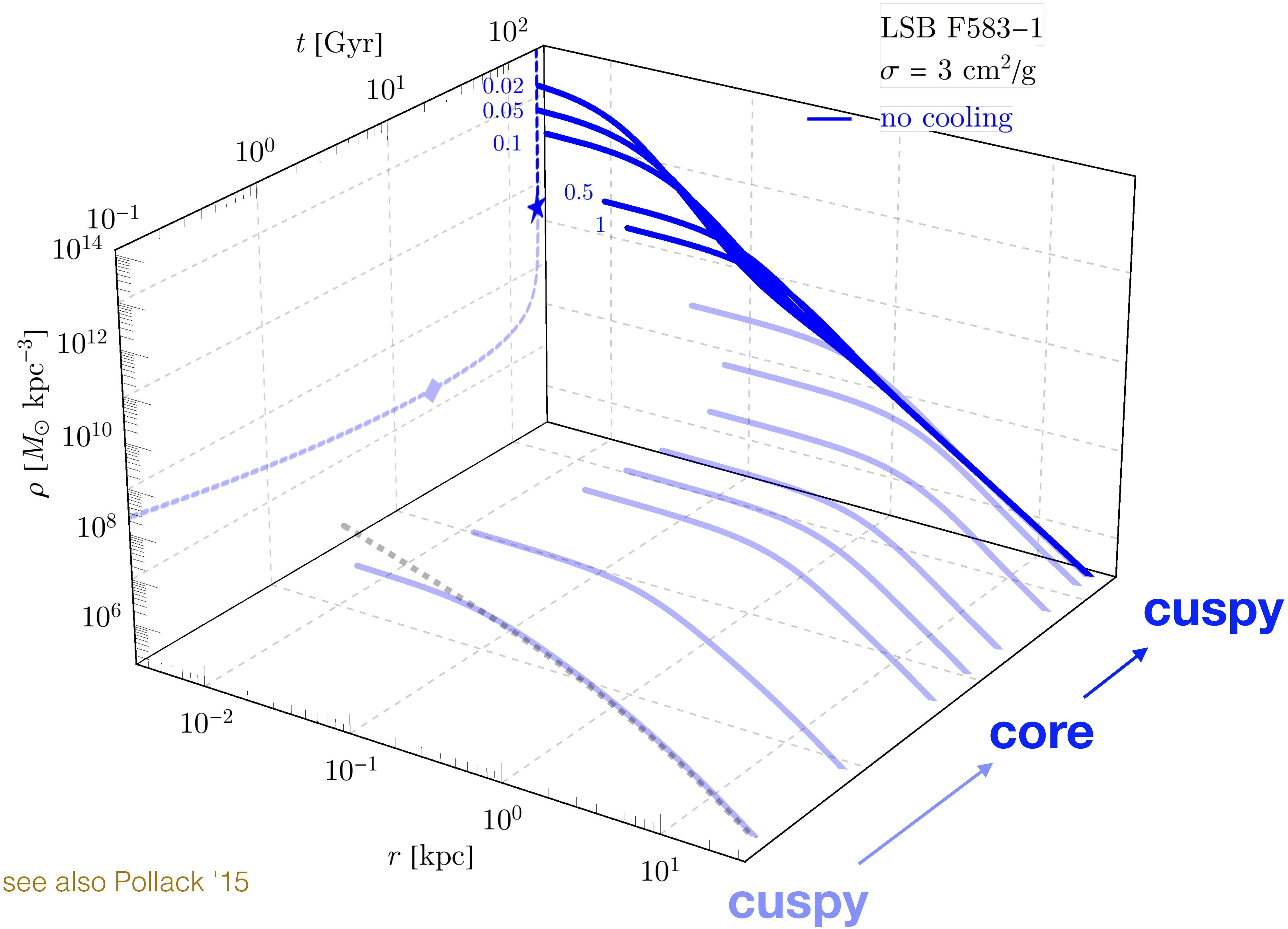
see also Pollack '15

Stage 2: runaway collapse



see also Pollack '15

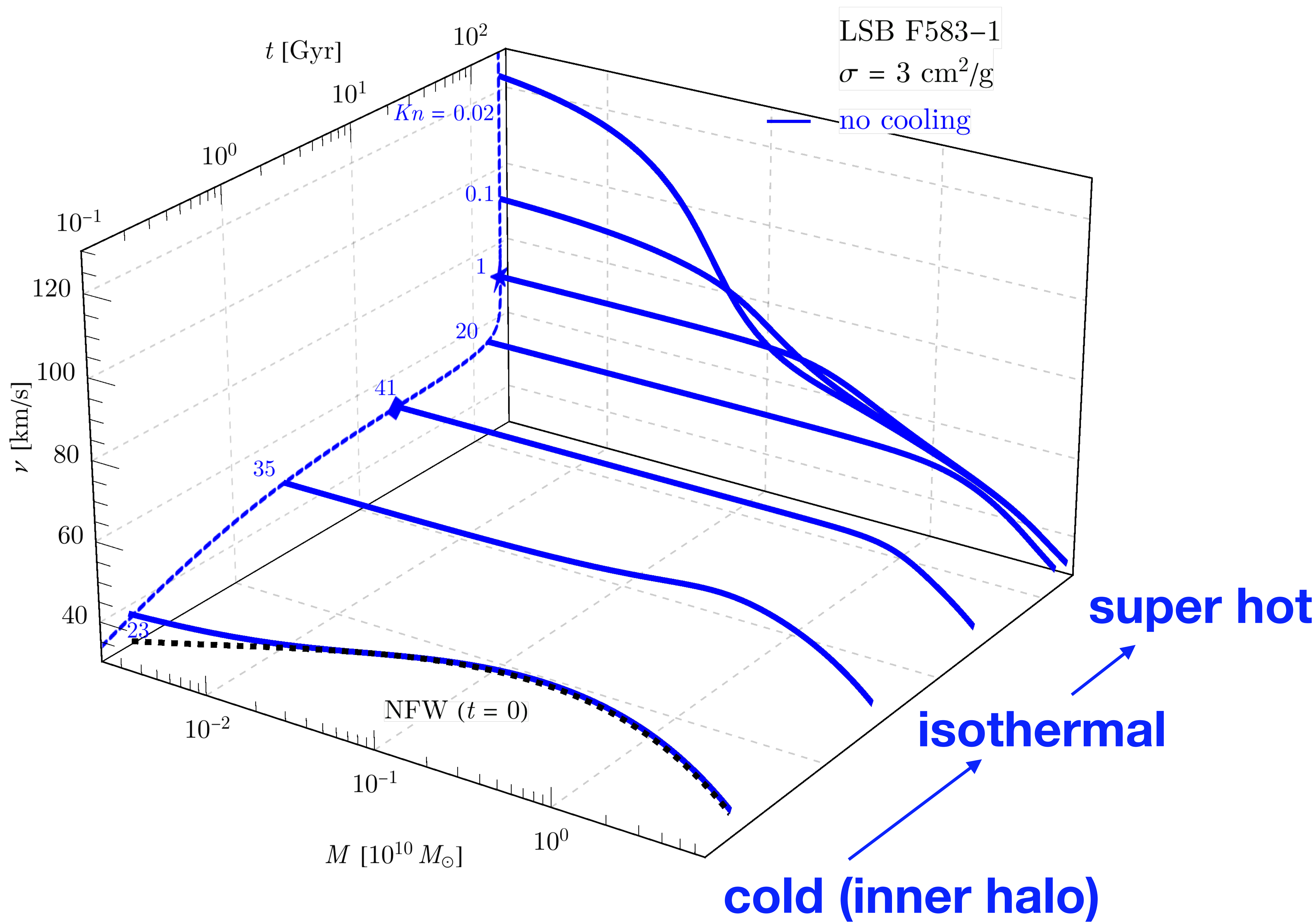
Stage 3: develop a 2nd core



see also Pollack '15

Yi-Ming Zhong (BU)

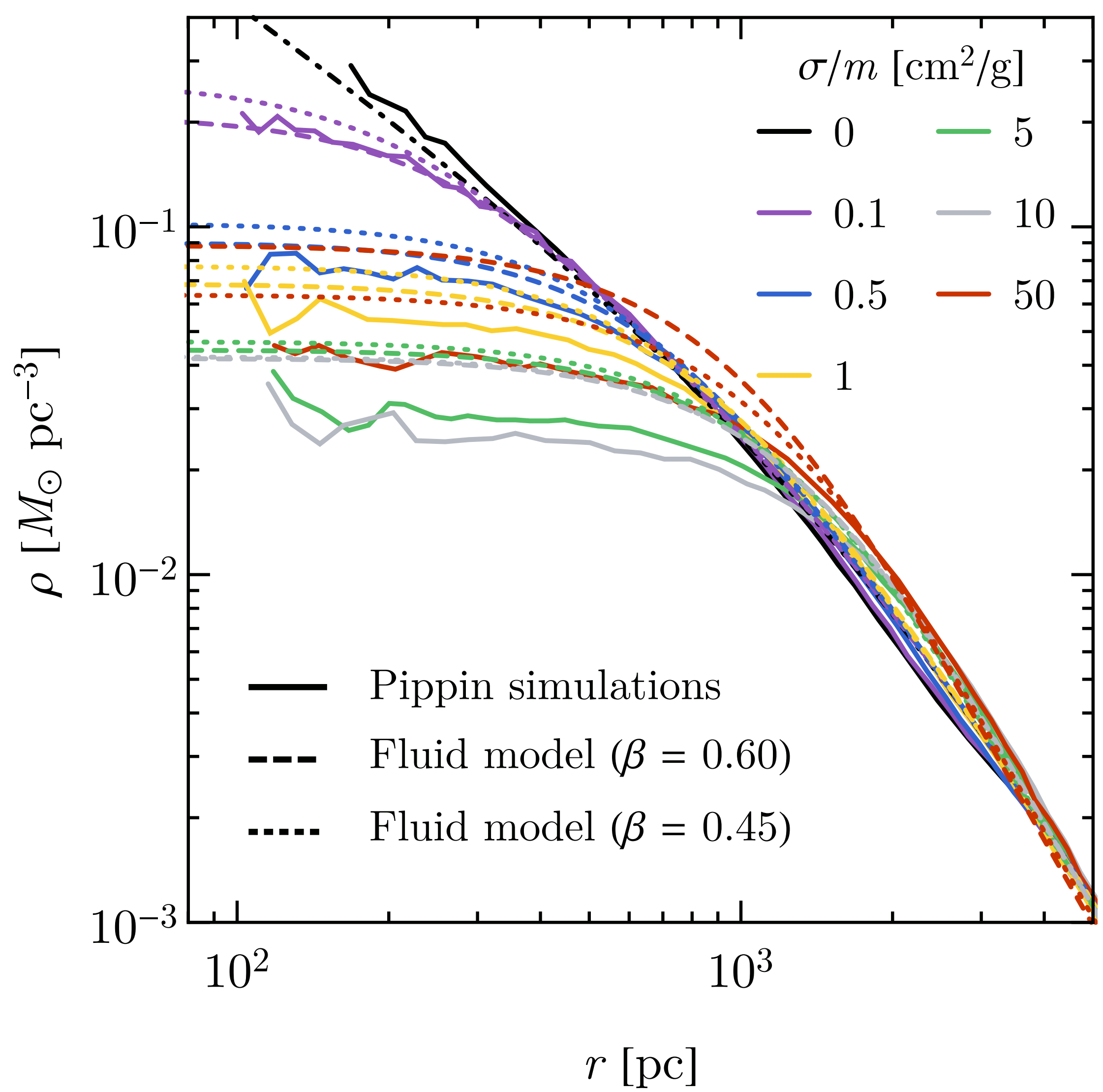
1D velocity-dispersion profile



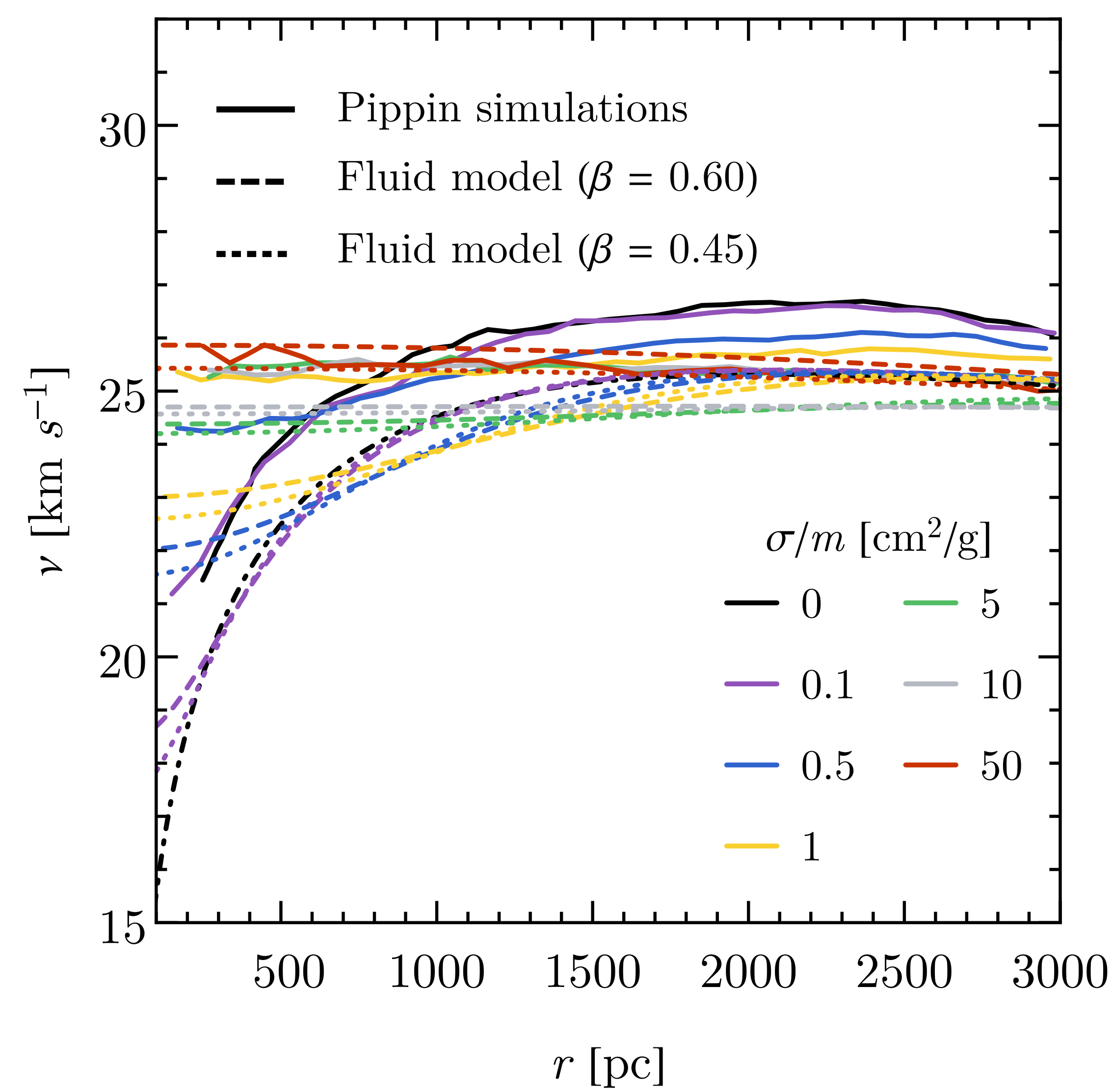
Calibrating β from N-body simulations

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

Density

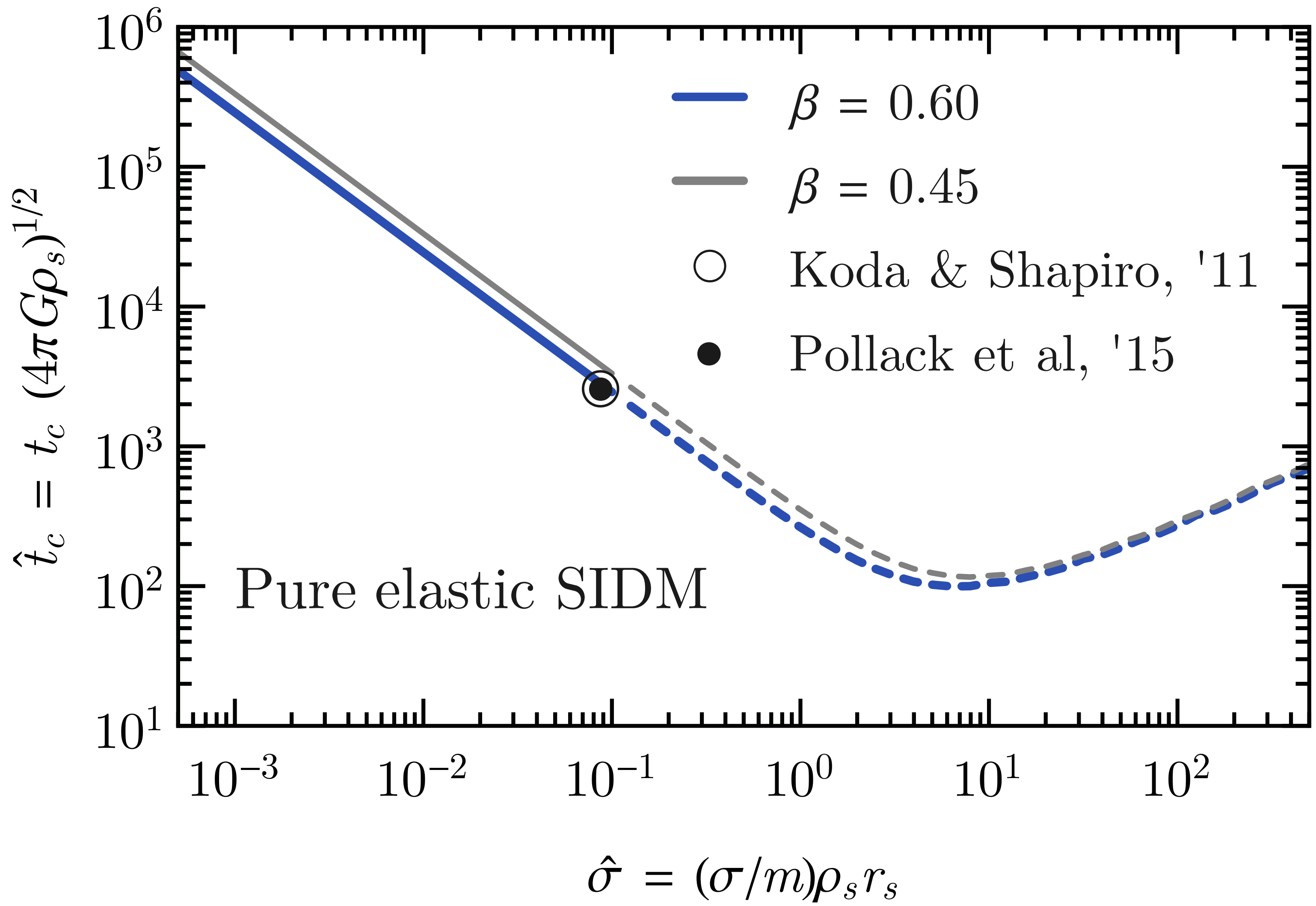


1D velocity dispersion



Pure elastic

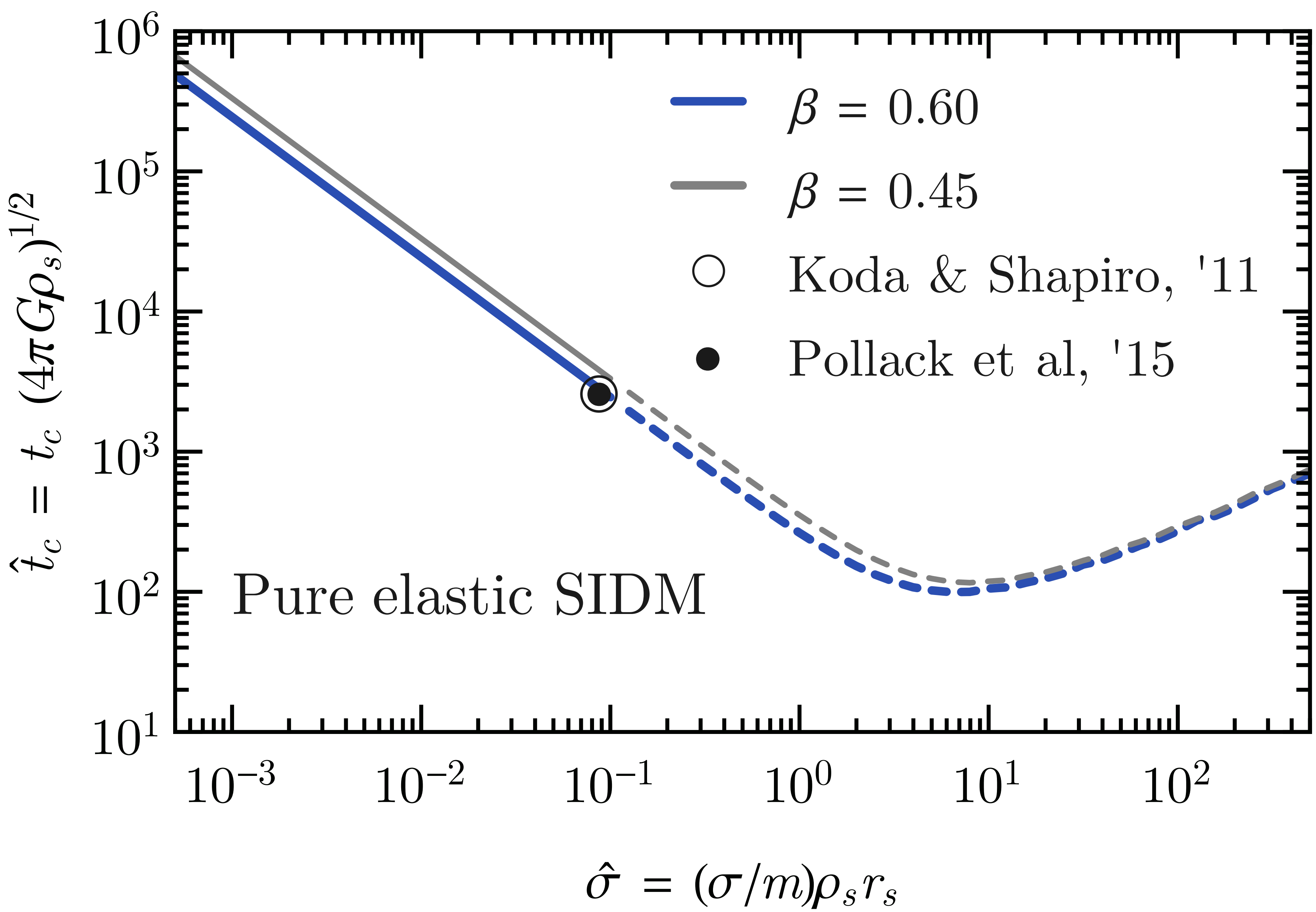
The collapse time t_c



for $(\sigma/m)\rho_s r_s \ll 1$

$$t_c \approx \frac{100\,\mathrm{Gyr}}{\beta}\,\frac{3\,\mathrm{cm^2\,g^{-1}}}{\sigma/m}\,\frac{10\,\mathrm{kpc}}{r_s}\left(\frac{10^7\,M_\odot\,\mathrm{kpc}^{-3}}{\rho_s}\right)^{3/2}$$

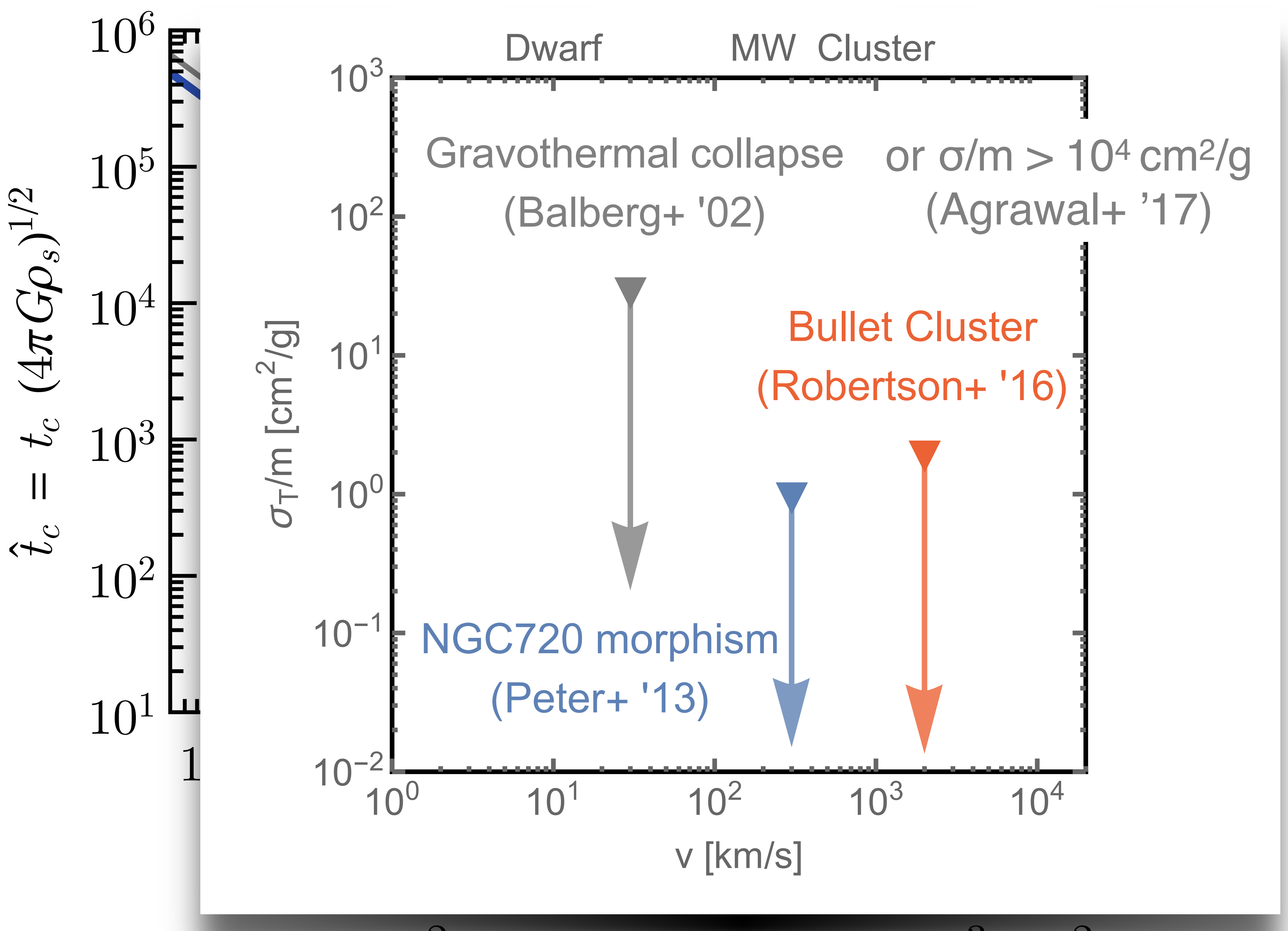
The collapse time t_c



$$57\,\mathrm{cm}^2/\mathrm{g} \lesssim \sigma/m \lesssim 5.5\times 10^3\,\mathrm{cm}^2/\mathrm{g} \qquad (\ \beta = 0.60\ )$$

are disfavors by LSB F583-1

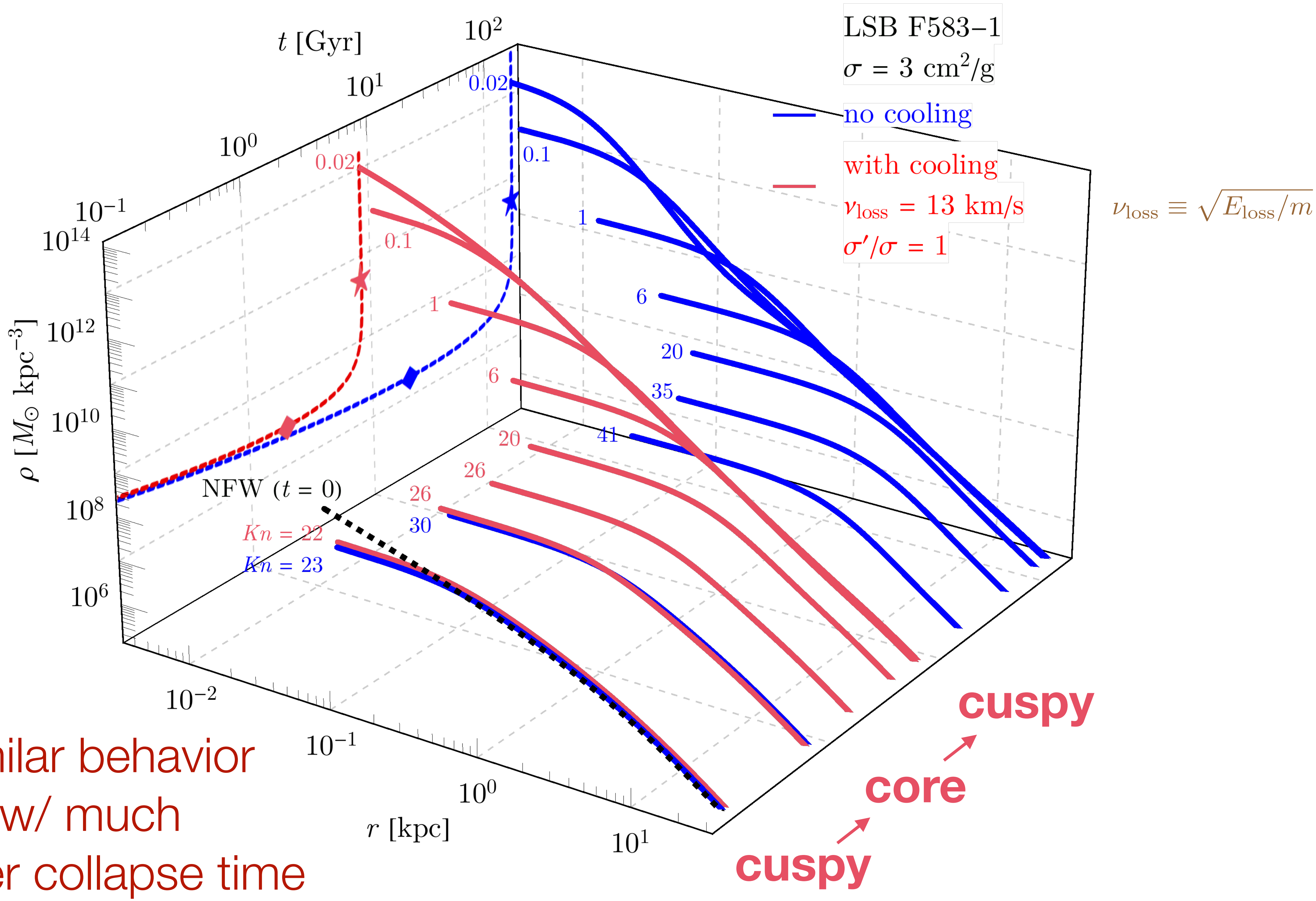
The collapse time t_c



$$57\,\mathrm{cm^2/g} \lesssim \sigma/m \lesssim 5.5\times 10^3\,\mathrm{cm^2/g} \qquad (\ \beta = 0.60\ )$$

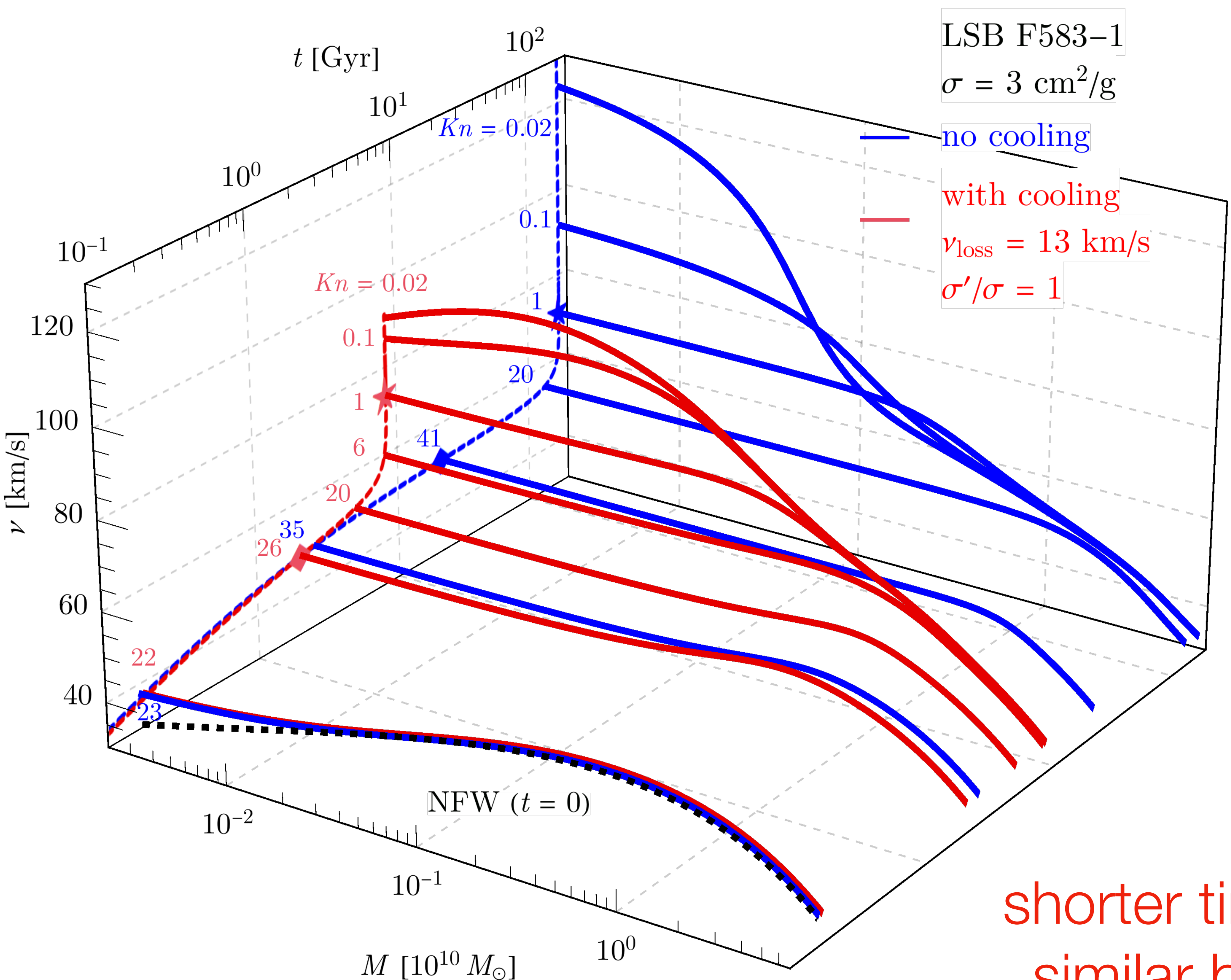
are disfavors by LSB F583-1

Add a mild cooling



Similar behavior w/ much shorter collapse time

Add a mild cooling



shorter time scale
similar behavior

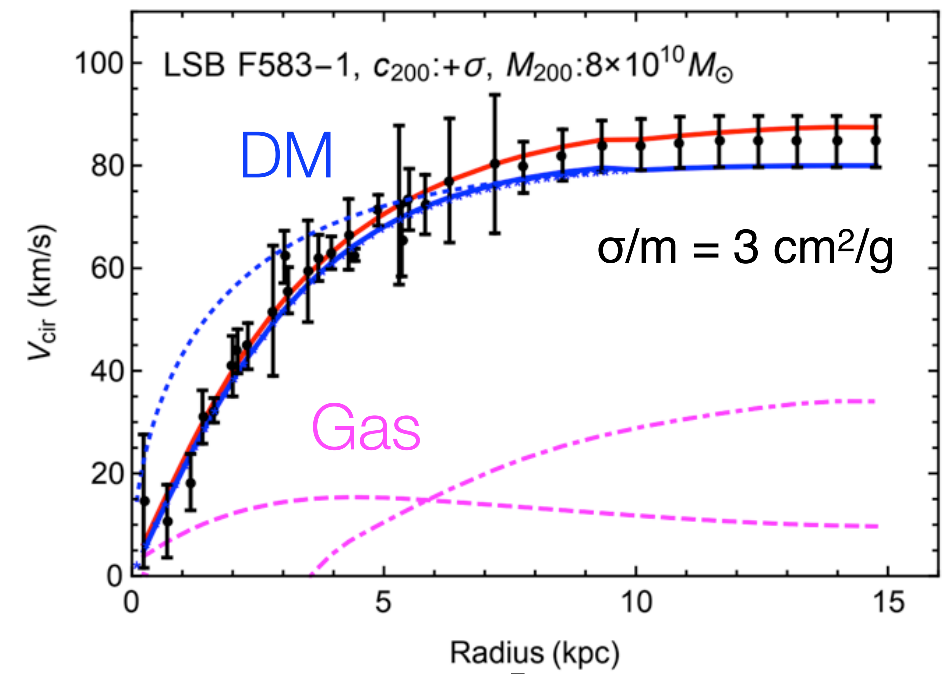
Constraints

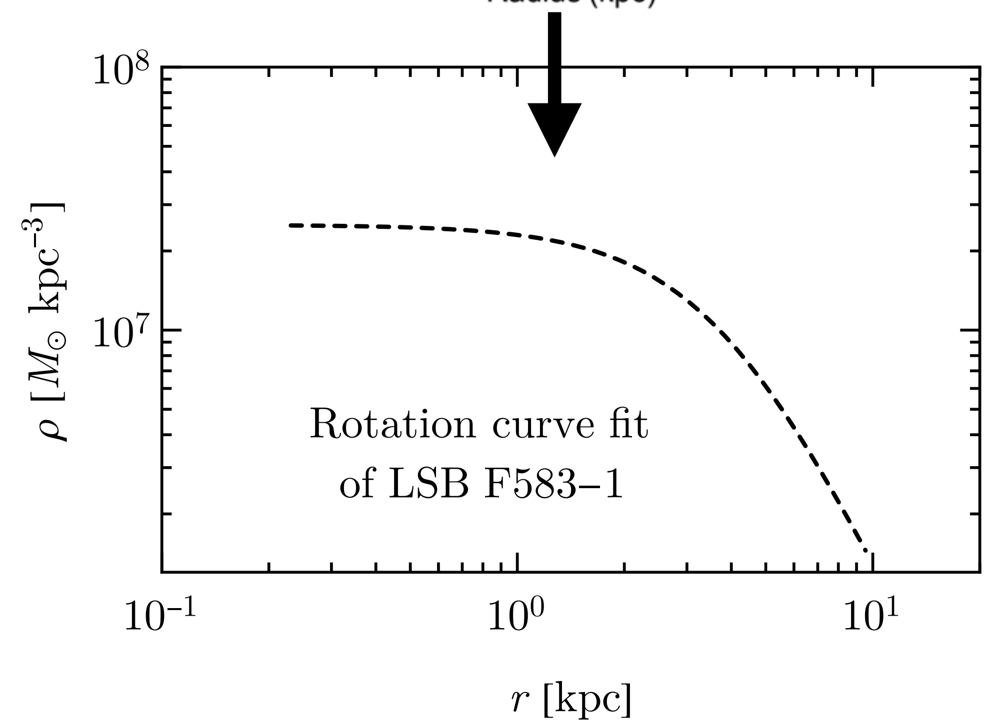
Dwarf/LSB observations

Near-field,
w/ low-baryonic content

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

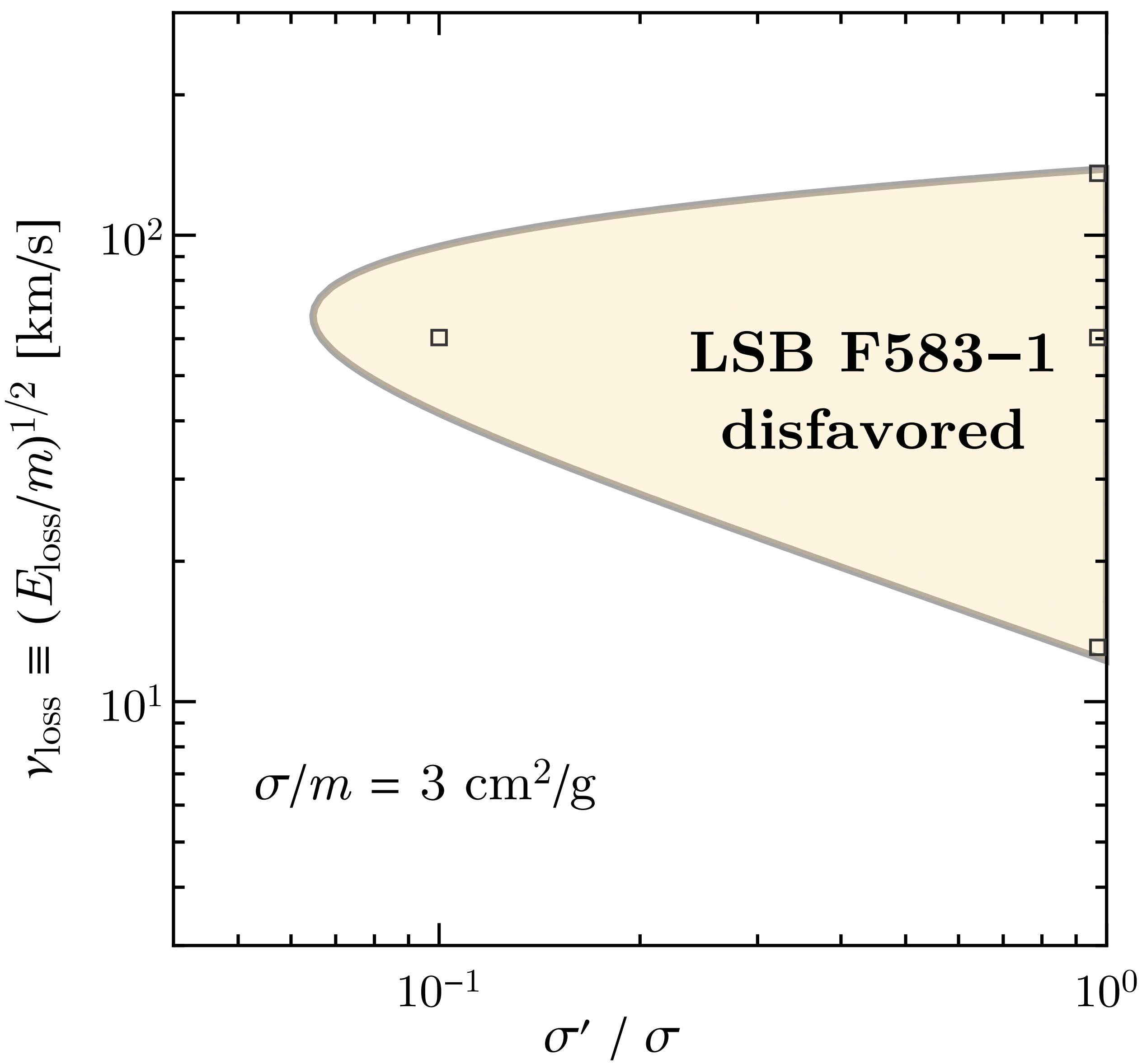


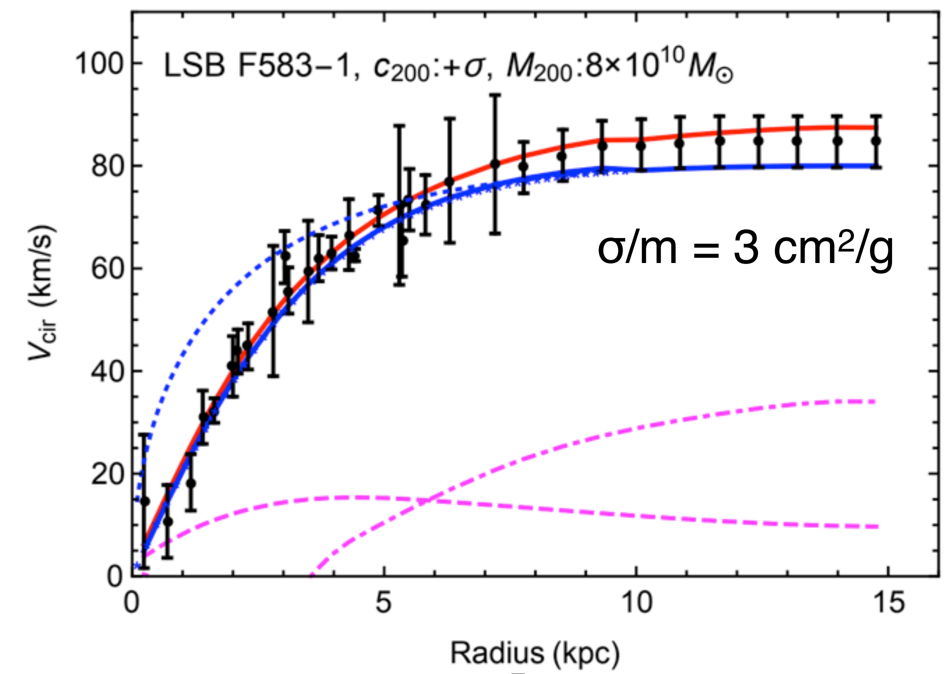


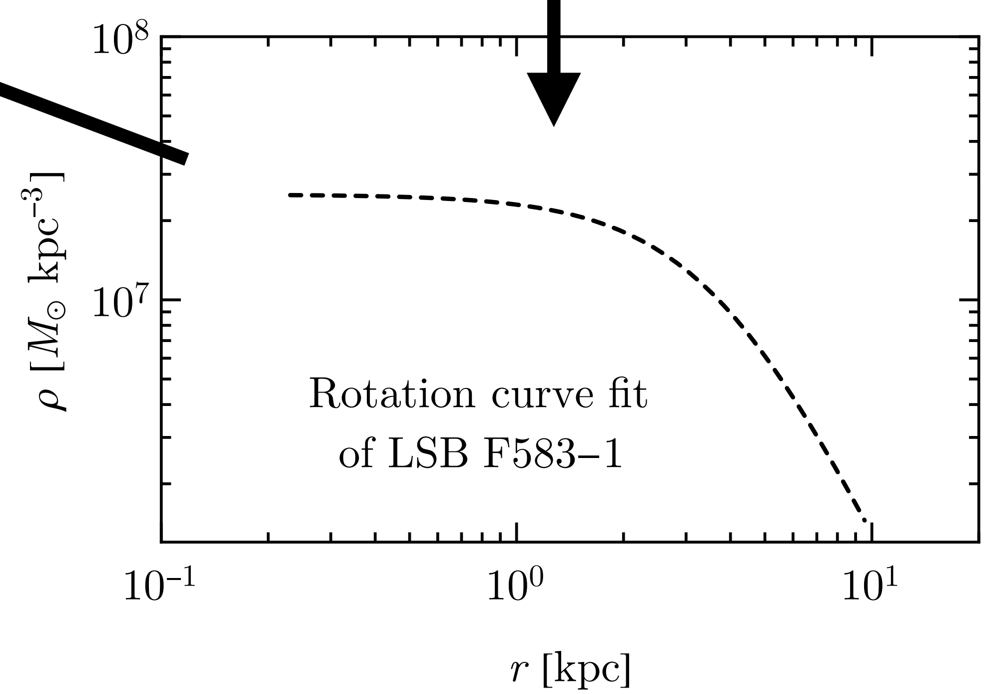
core-like profile

Dwarf/LSB observations

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



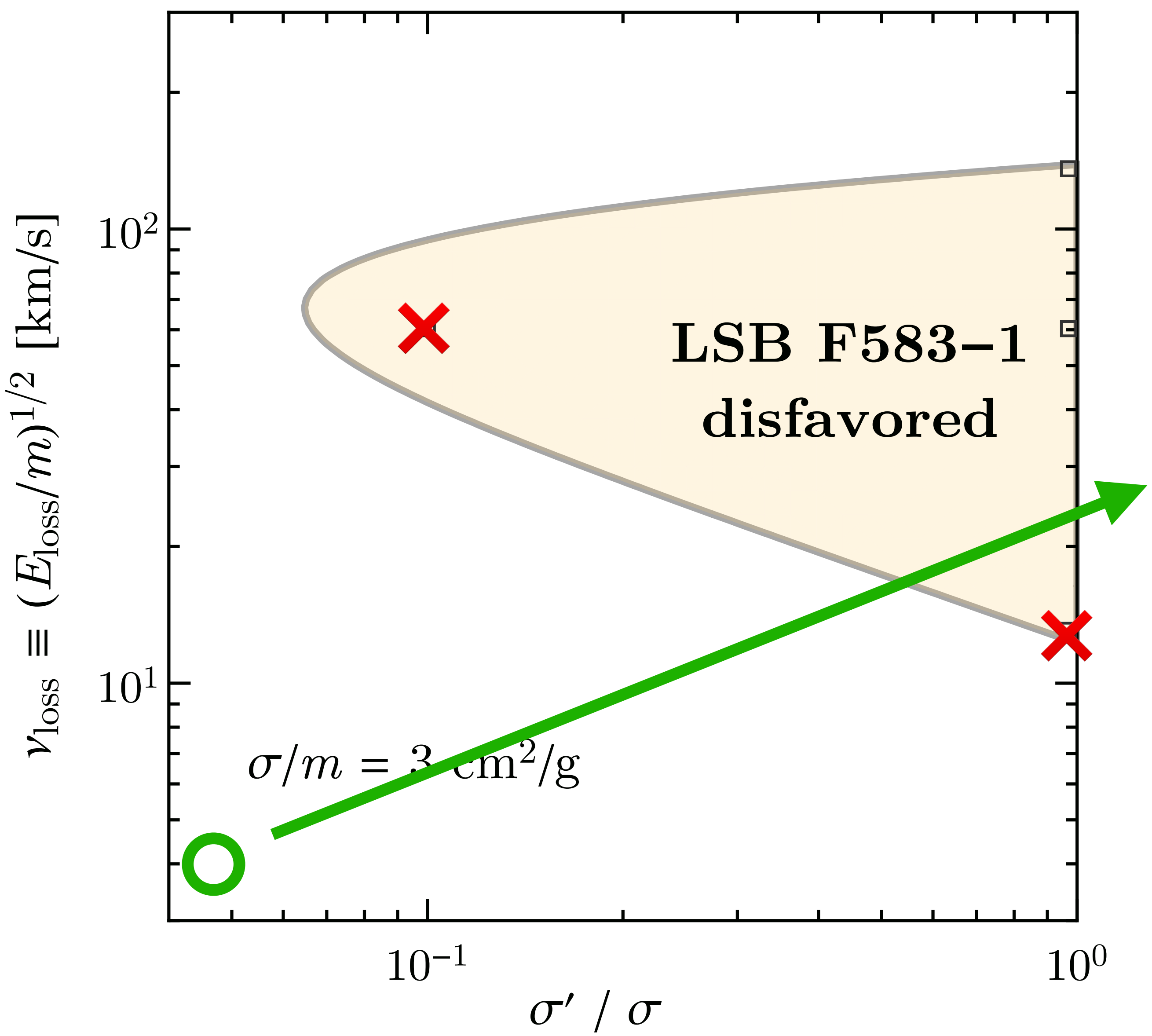


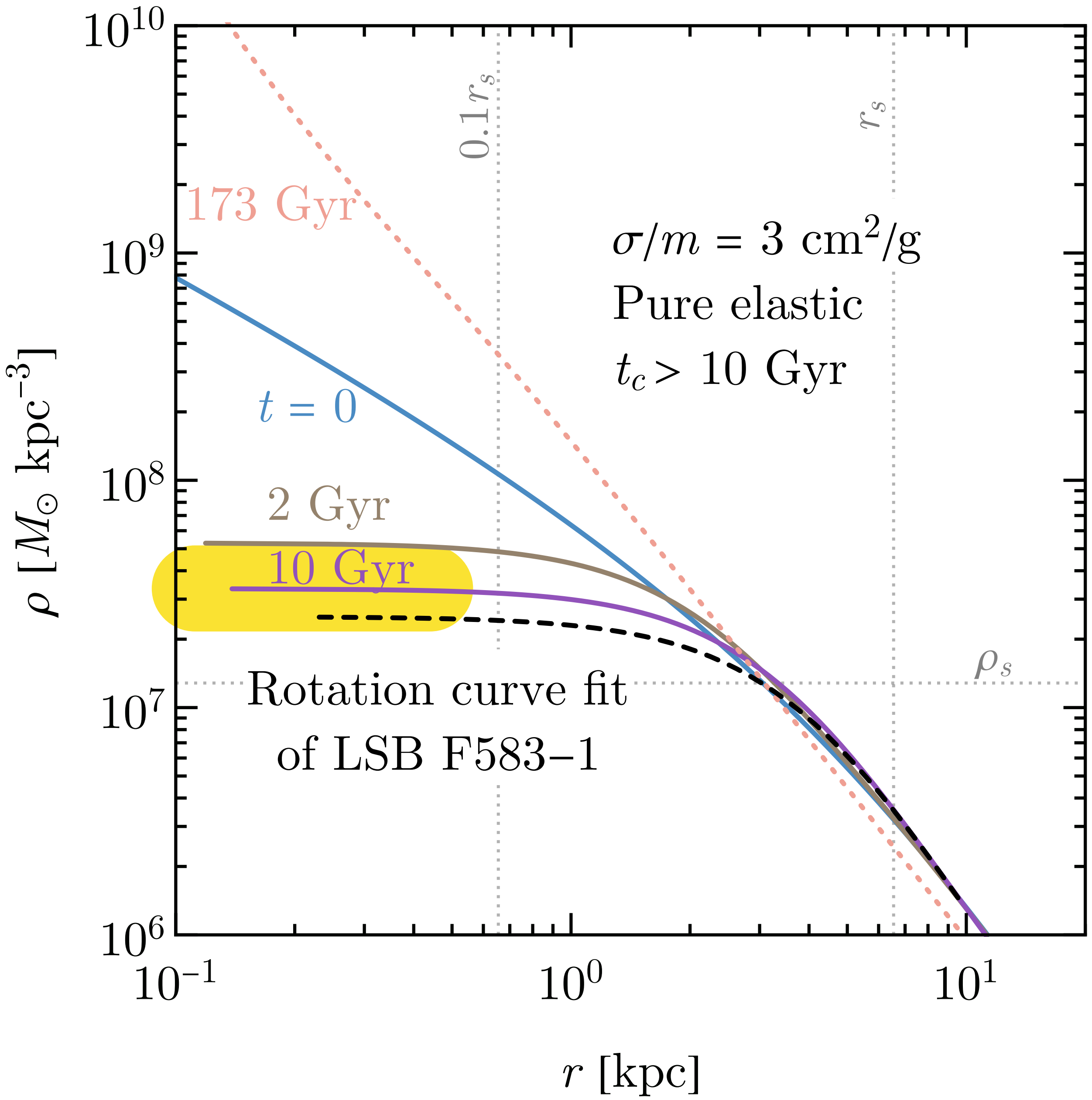


core-like profile

Favored parameter space

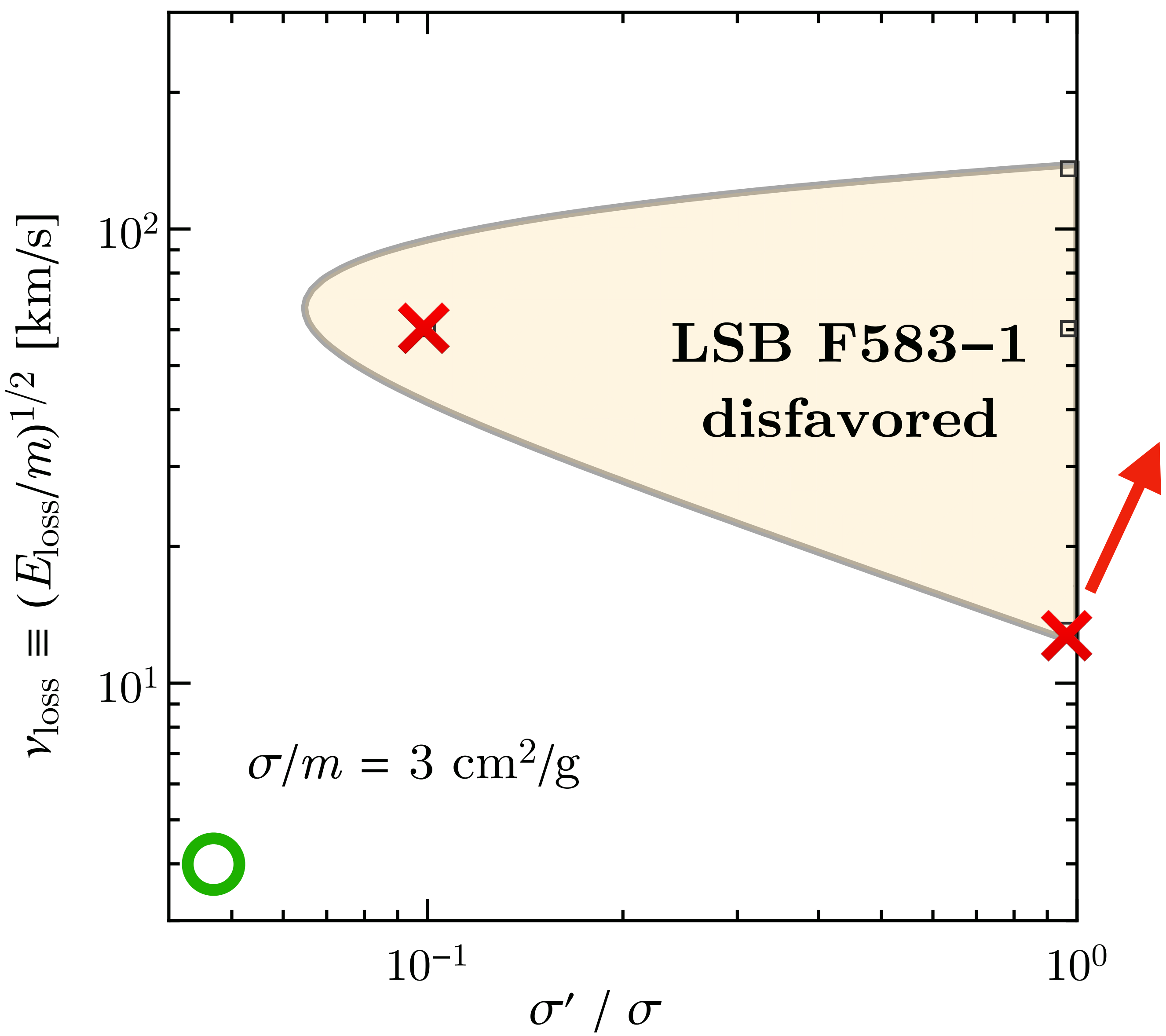
semi-analytical simulation



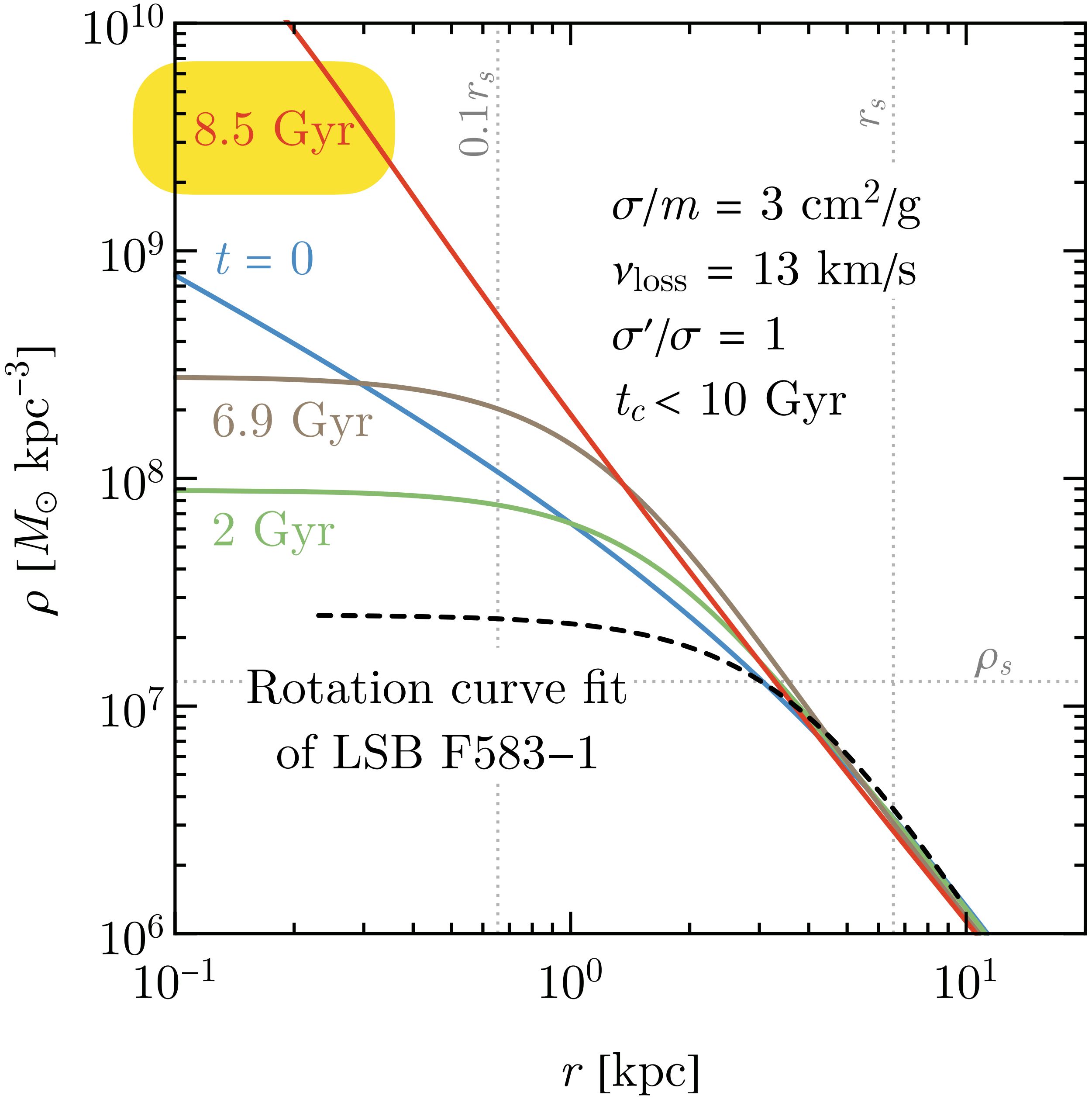


core-like profile

Disfavored parameter space



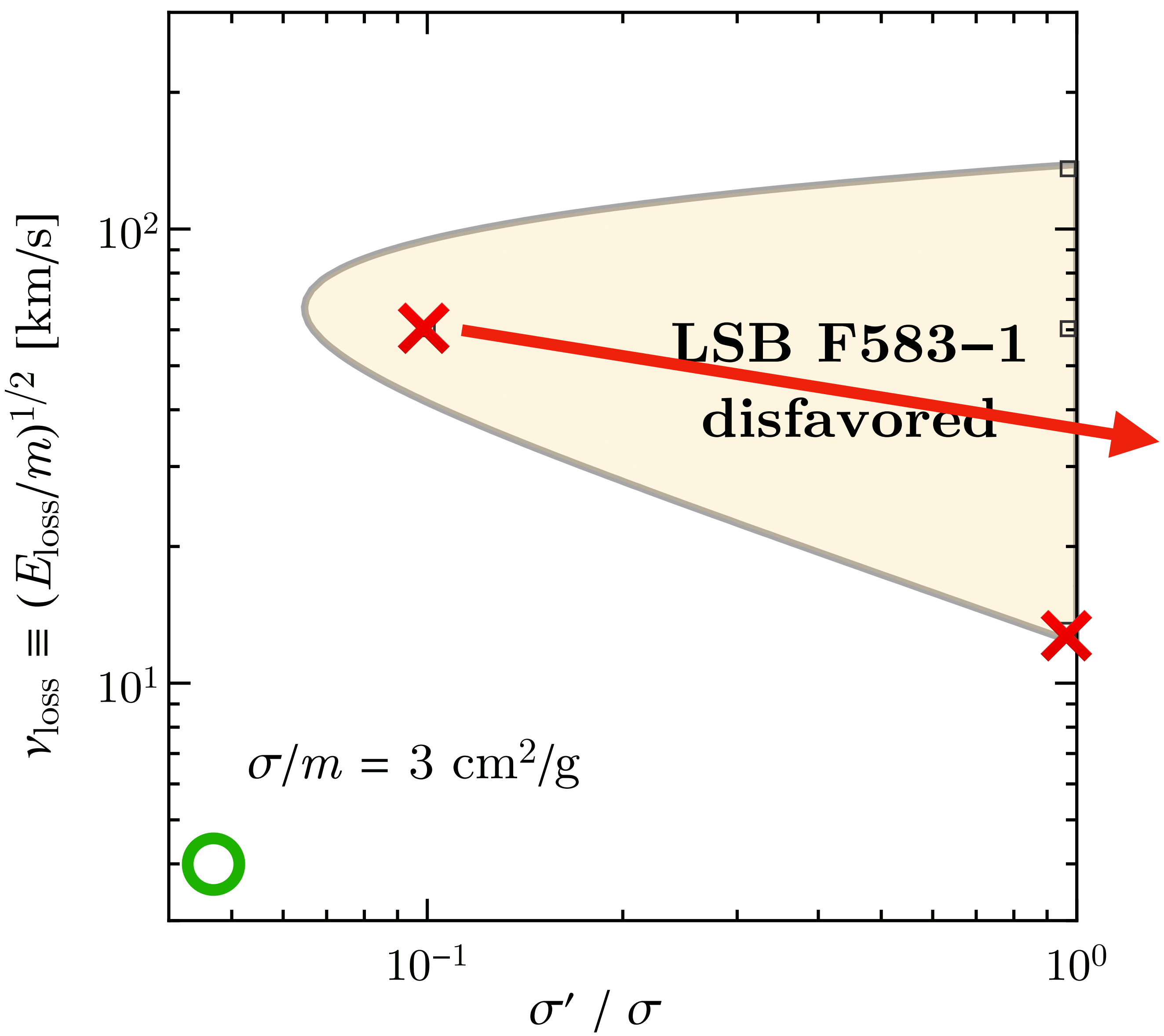
semi-analytical simulation

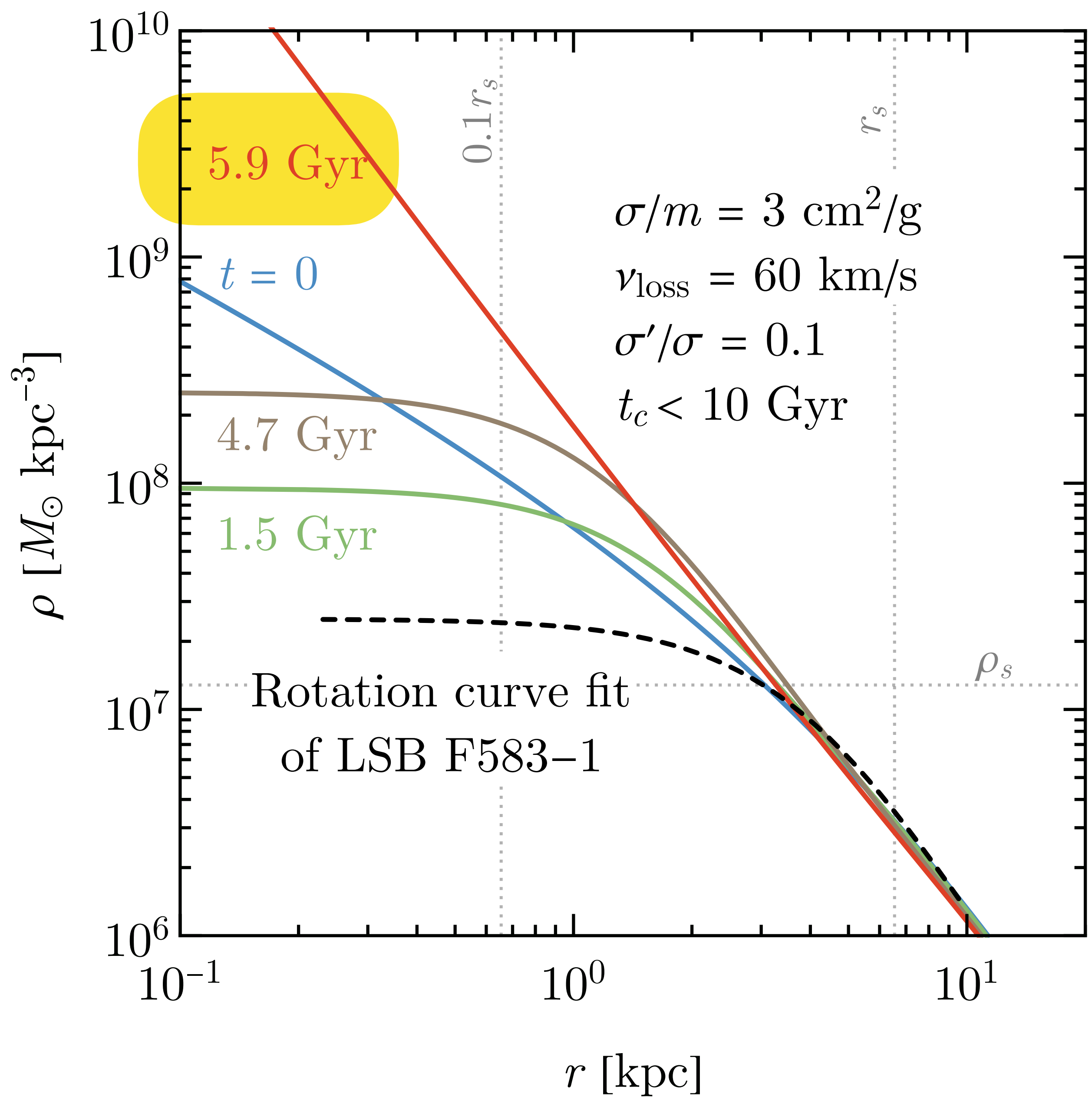


collapsed core

Disfavored parameter space

semi-analytical simulation

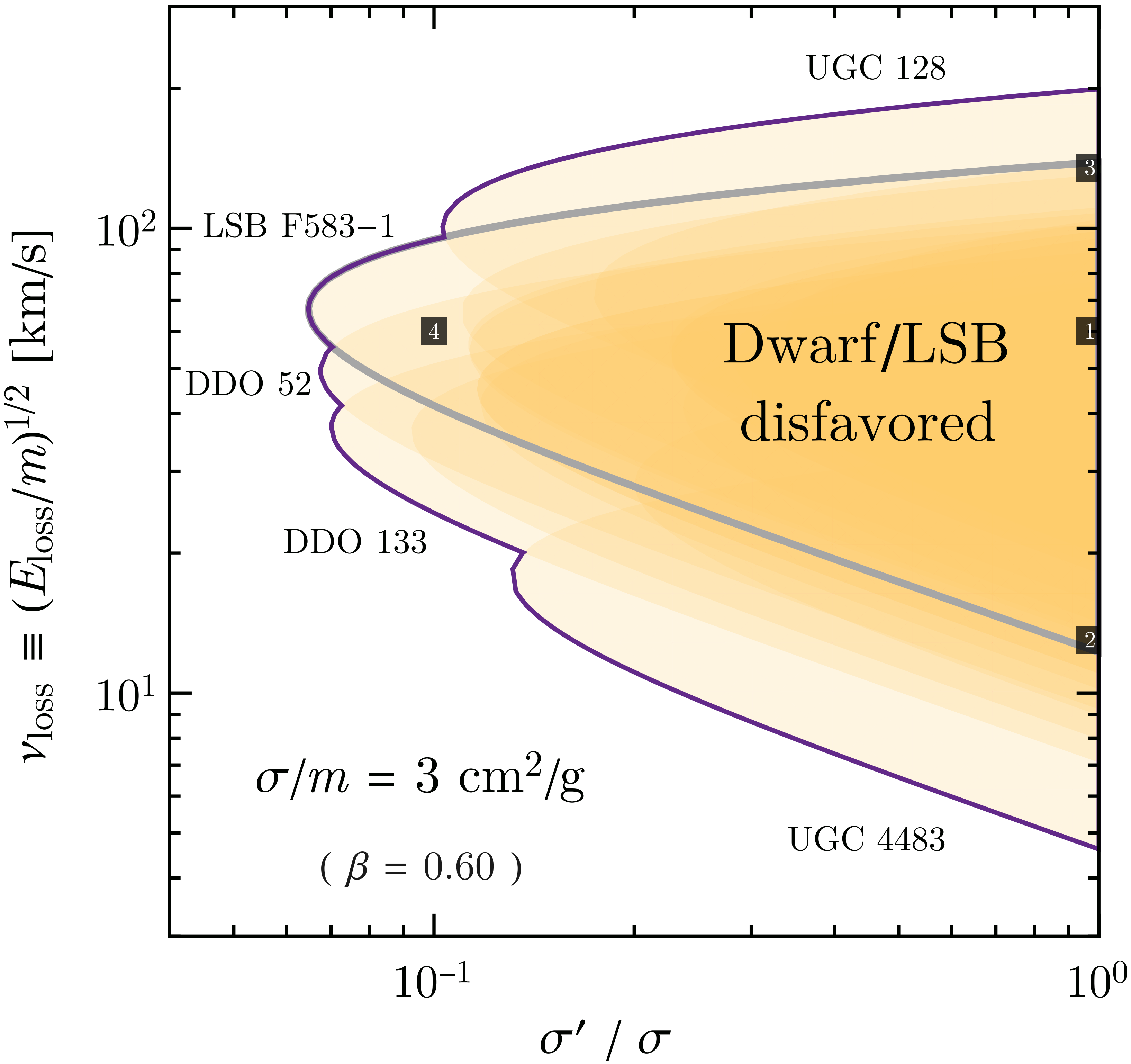




collapsed core

Dwarf/LSB disfavored

Kamada et al, '16



Near-field,
w/ low-baryonic content

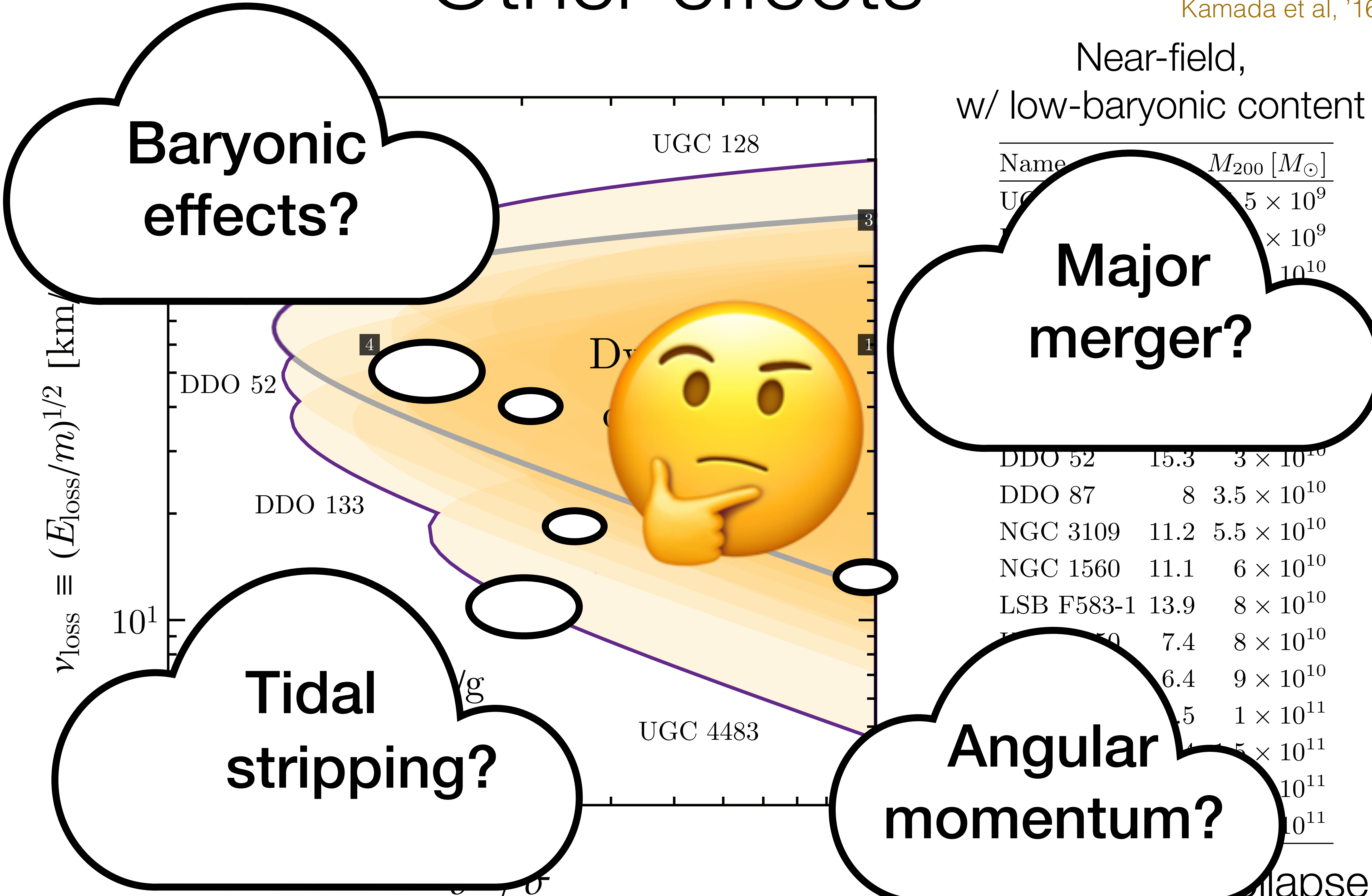
Name	c_{200}	$M_{200}\ [M_\odot]$
UGC 4483	16.1	1.5×10^9
DDO 126	10.4	9×10^9
DDO 133	16.8	1.2×10^{10}
DDO 154	14.7	1.3×10^{10}
NGC 2366	12.2	2.3×10^{10}
UGCA 442	11.9	3×10^{10}
UGC 1281	11.9	3×10^{10}
DDO 52	15.3	3×10^{10}
DDO 87	8	3.5×10^{10}
NGC 3109	11.2	5.5×10^{10}
NGC 1560	11.1	6×10^{10}
LSB F583-1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

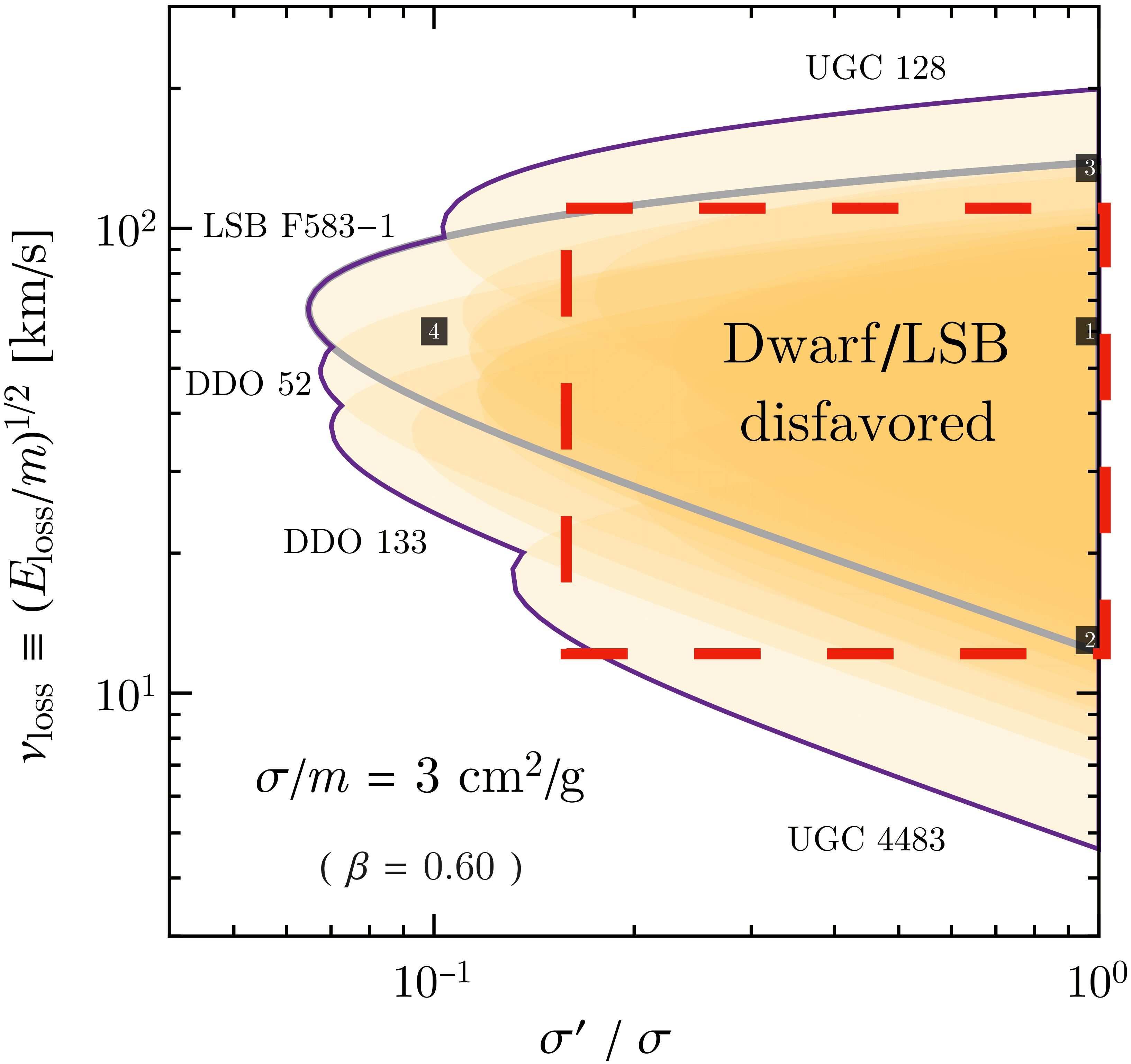
Near-field,
w/ low-baryonic content



Other effects

Baryonic effects?	Select halos w/ low-baryonic content
Angular momentum?	Rotational energy is small (~1%) compared to KE
Tidal stripping?	Accelerating gravothermal collapse
Major merger?	Rare since dark energy dominance

Dwarf/LSB disfavored



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

$$\Downarrow$$

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

Give birth to the first Super Massive Black Holes (SMBHs)

The first SMBHs puzzle

- We see several BH's with mass $\geq 10^8\ M_\odot$ at a very high red-shifts ($z > 6$). e.g.

Name	Mass	Redshift	Ref
J1120+0641	$2.0 \times 10^9\ M_\odot$	7.09	Mortlock+ '11
J0100+2802	$1.2 \times 10^{10}\ M_\odot$	6.33	Wu+ '15
J1342+0928	$7.8 \times 10^8\ M_\odot$	7.54	Bañados+ '17
J0038–1527	$1.3 \times 10^9\ M_\odot$	7.02	Wang+'18

The first SMBHs puzzle

- We see several BH's with mass $\geq 10^8\ M_\odot$ at a very high red-shifts ($z > 6$). e.g.

Name	Mass		
J1120+0641	2.0×10^9 M…		Mortlock+ '11
J0100+2802		…33	Wu+ '15
J134…		7.54	Bañados+ '17
J00…	…$\times 10^9\ M_\odot$	7.02	Wang+'18

So massive & so ancient

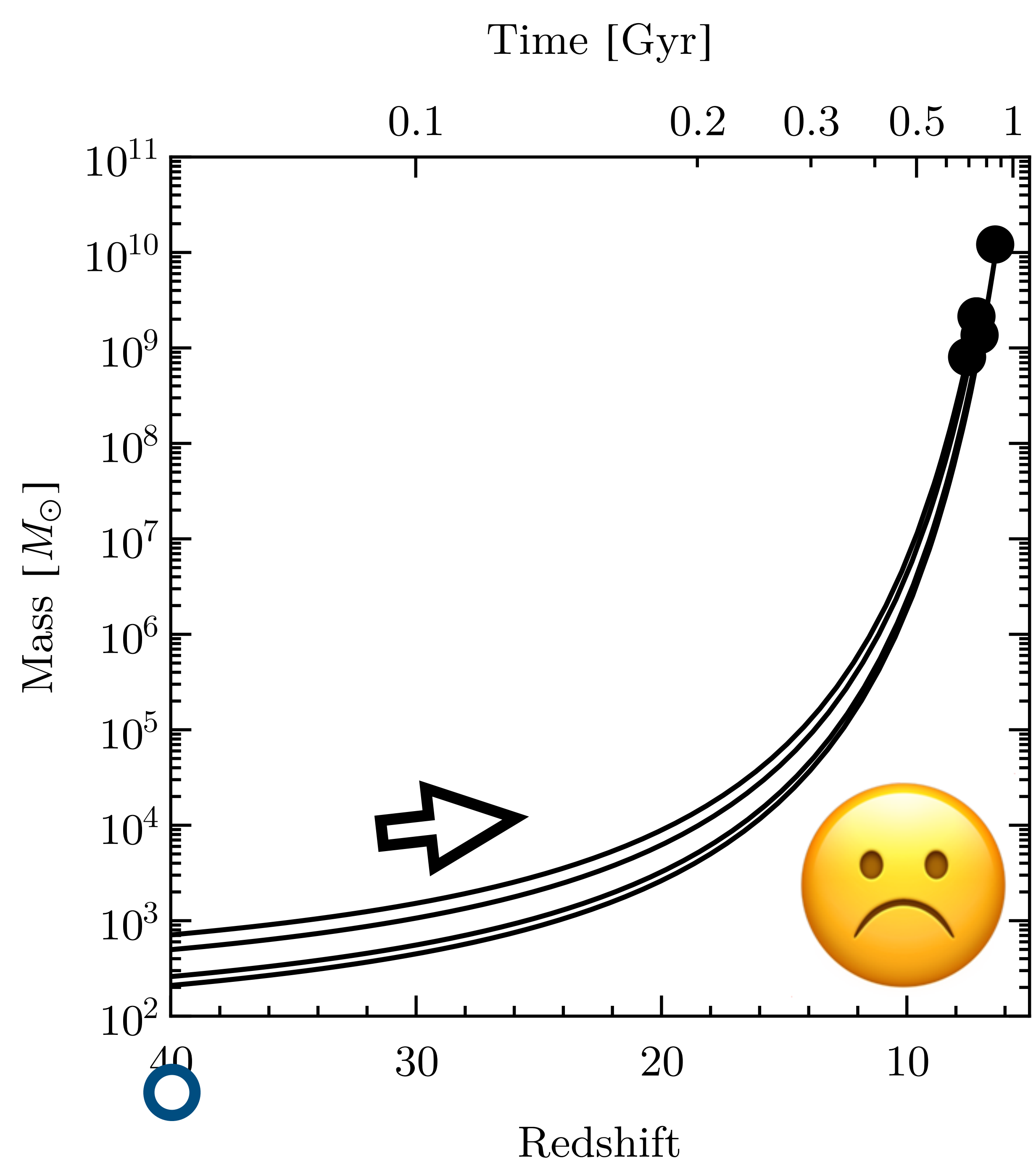
How do they form??

The first SMBH puzzle

- Classical solution:
  - PopIII star collapses (10-100 $M_\odot$) ⇒ seed BH ⇒

    Eddington accretion ⇒ massive BH
  - Need to fine tune the baryonic physics

see review by Volonteri '10



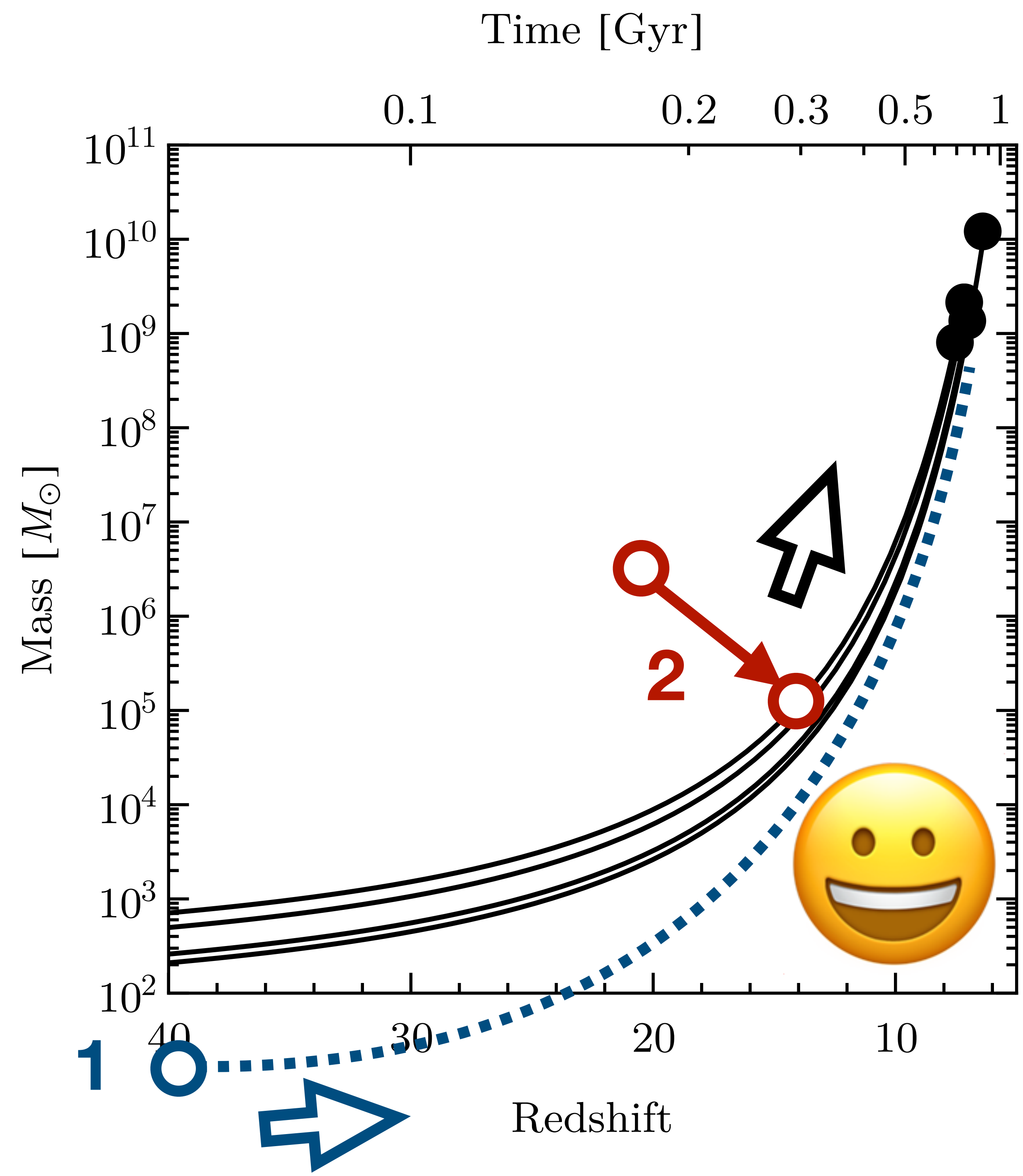
The SMBH puzzle

- More likely solutions:

  1. Faster accretion,
     e.g. BH merger…

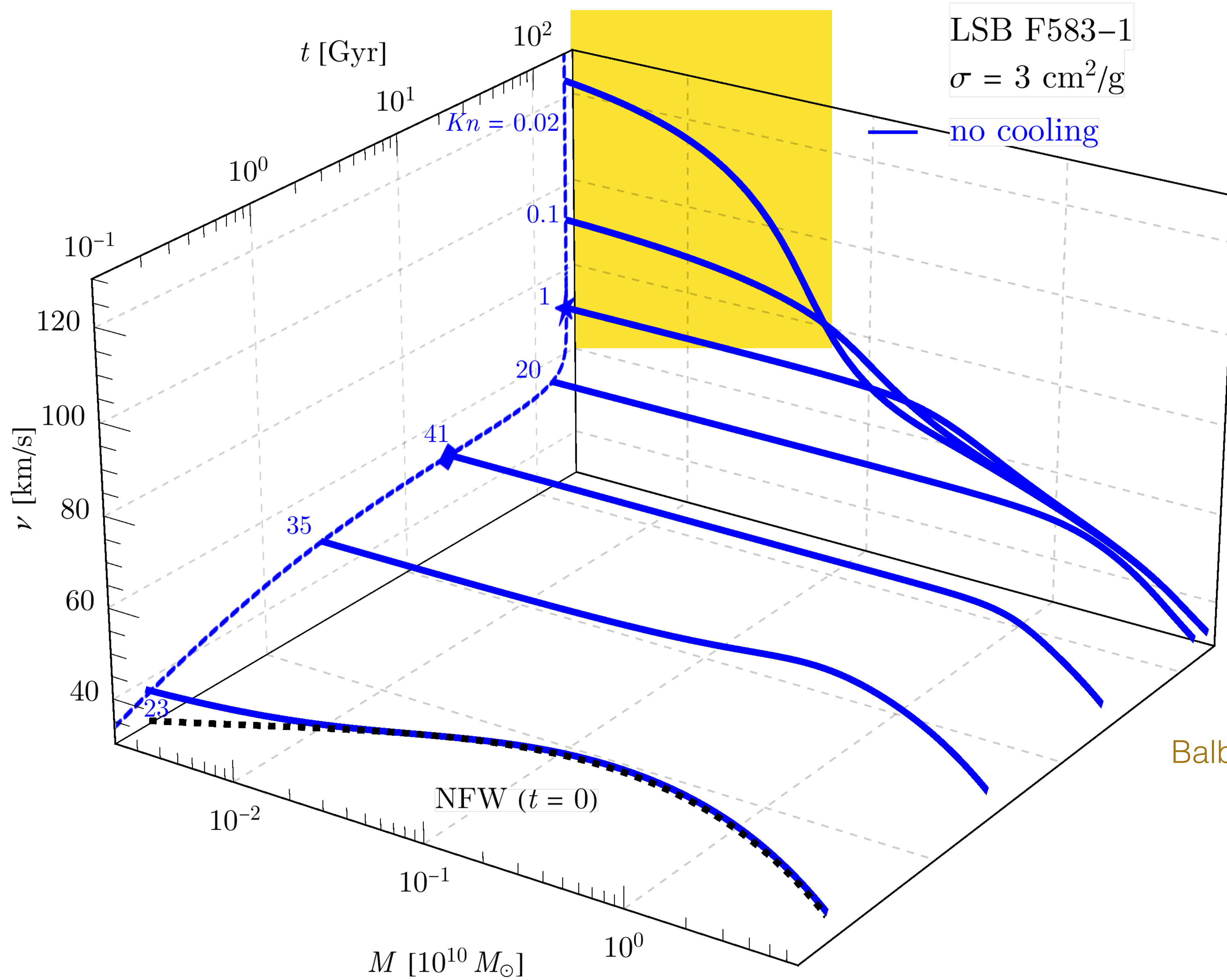
  2. Bigger seed BH:
     e.g. direct collapse of pre-galactic gas discs…

Lodato & Natarajan '06



DM halo ⇒ Black hole

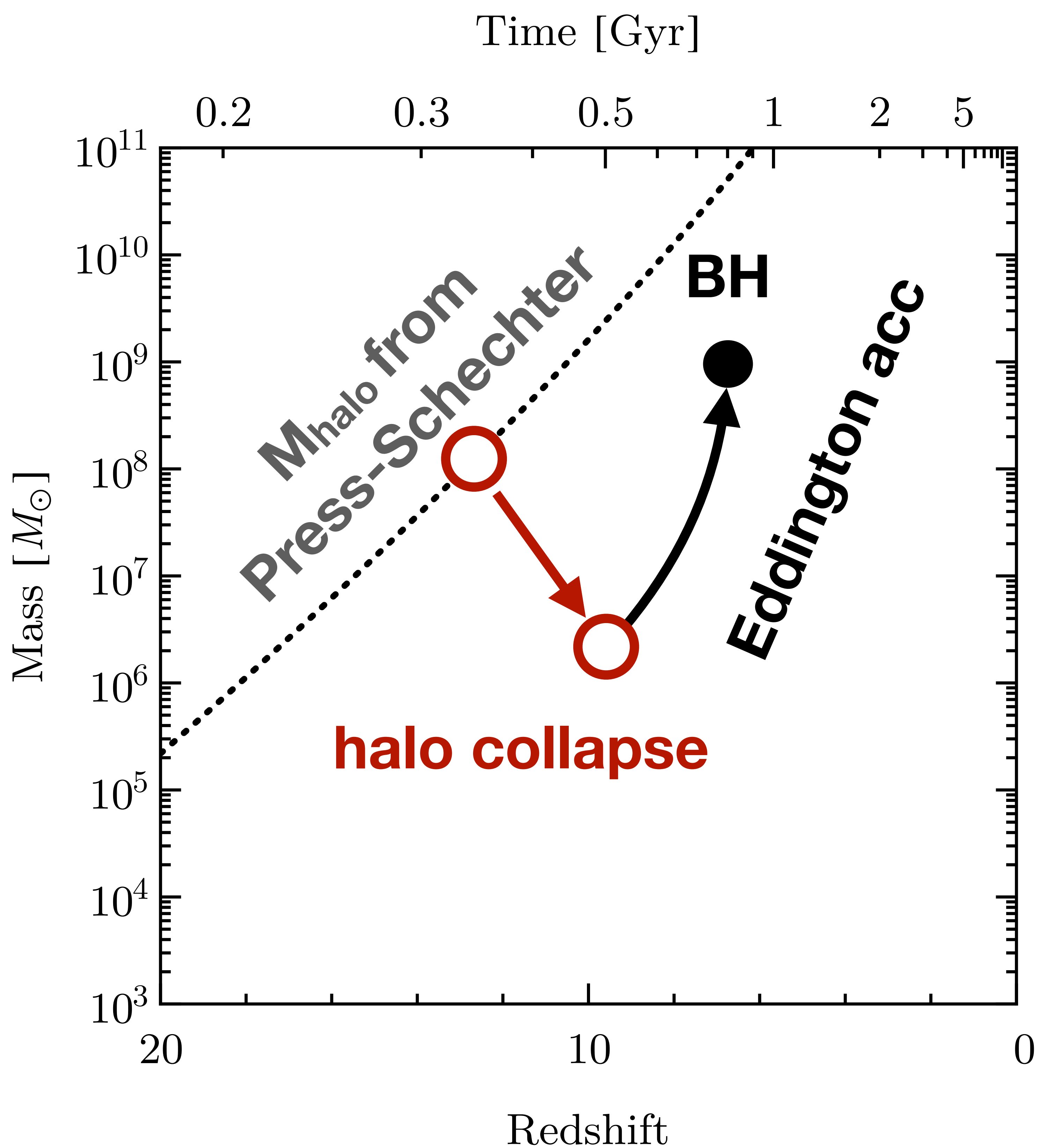
Relativistic instability ⇒ Big Seed BH



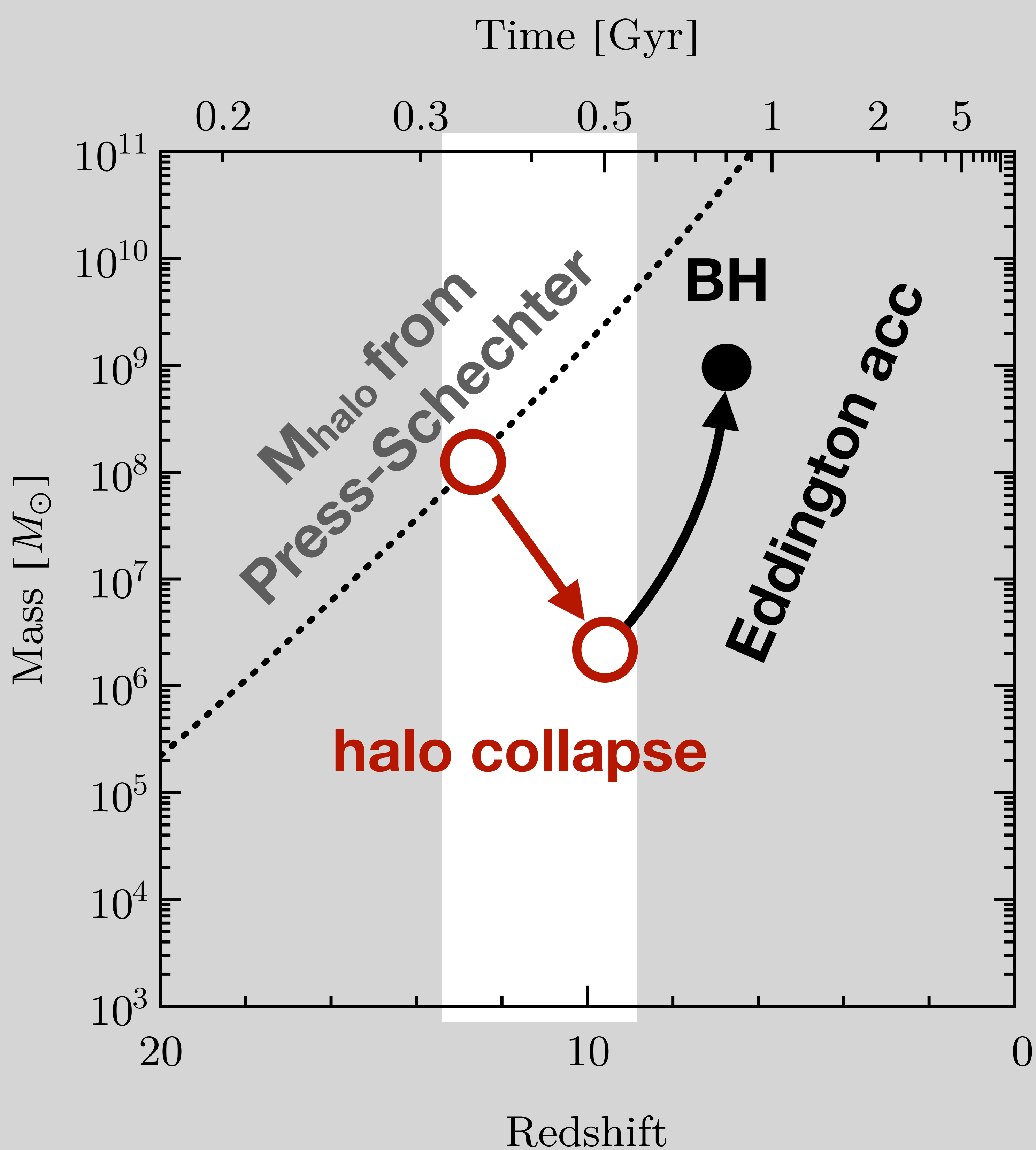
Balberg & Shapiro '02,
Pollack + '15

Yi-Ming Zhong (BU)

DM halo ⇒ Black hole



DM halo ⇒ Black hole



Reduce the collapse time

- Pure elastic SIDM Pollack+ '15, update Choquette+ '18
  ⇒ $\sigma/m > O(10\text{-}100\ \mathrm{cm}^2/\mathrm{g})$ && ultra-concentrated halo ⇒ very unlikely
- **Dissipative SIDM**
- Large tidal disruption Nishikawa+'19, Sameie+ '19
- Central baryon content

Summary

- Galaxy observations can be a powerful tool to probe DM self-interactions.
- DM self-interactions (elastic and dissipative) will change the evolution of the halos. The inner halo experiences cuspy→core→cuspy.
- More *N*-body simulations are encouraged
  c.f. Choquette+ 2018, Ran, Yu, & YZ to appear.