Cooling of self-interacting dark matter halos & the birth of the first supermassive black holes

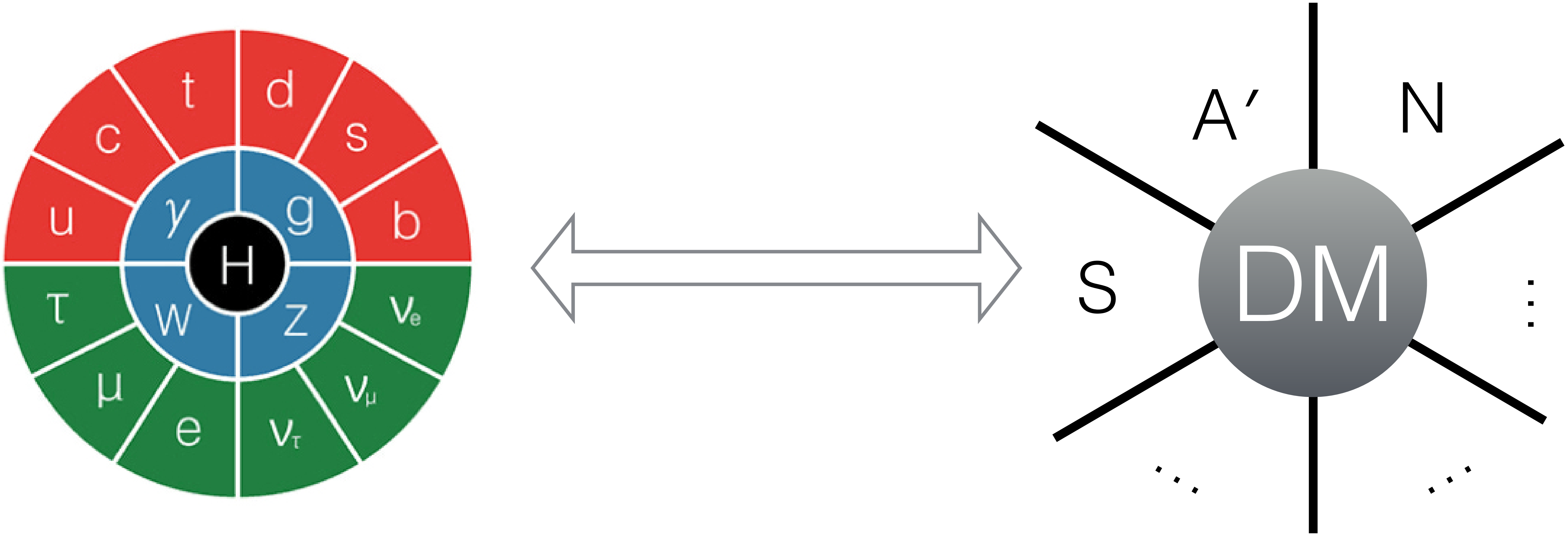
Yi-Ming Zhong

Boston University

In collaboration w/ R. Essig, S. McDermott, H.-B. Yu
Work in progress

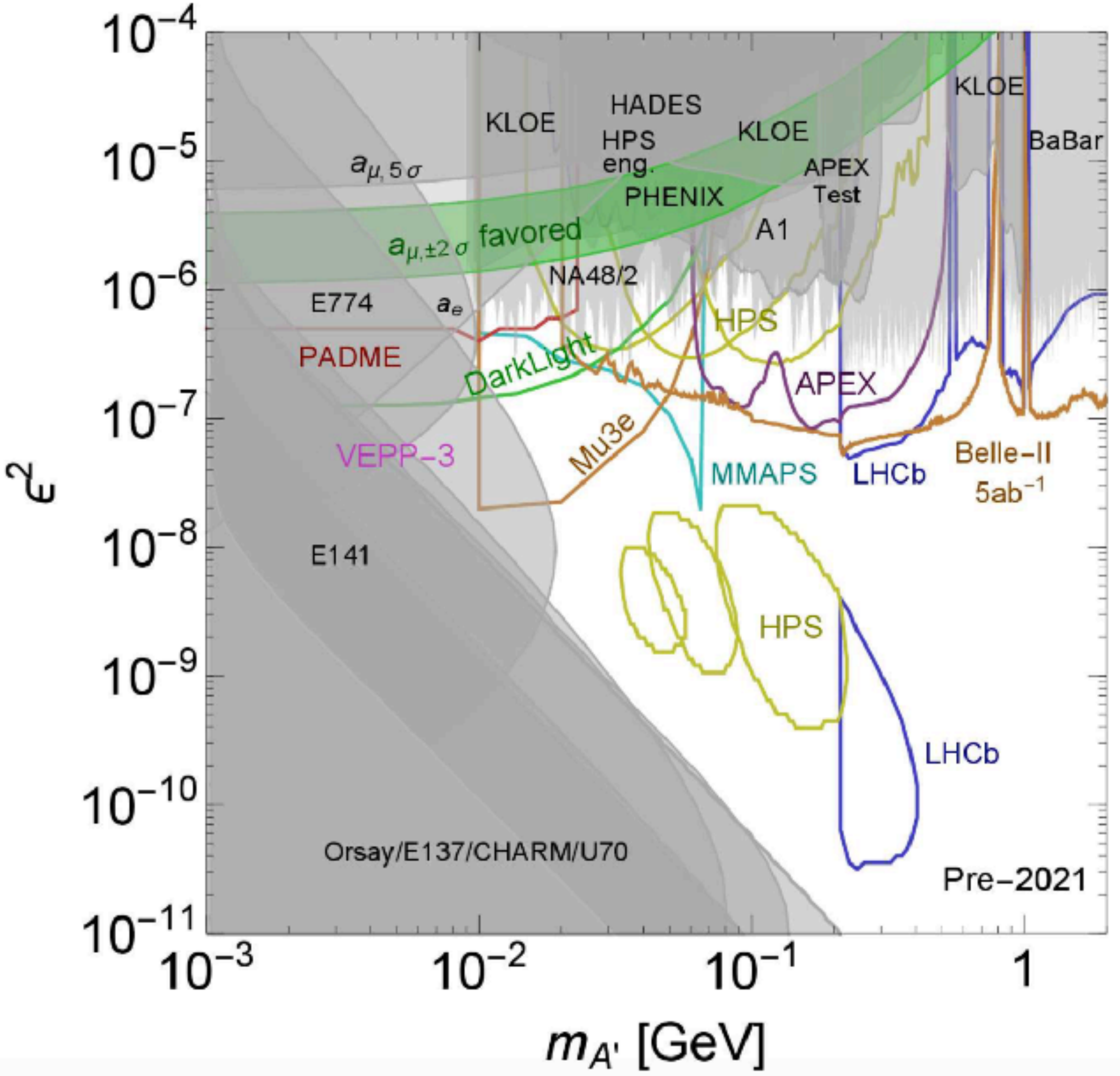
The Small-Scale Structure of Cold(?) Dark Matter, KITP, 05/16/2018

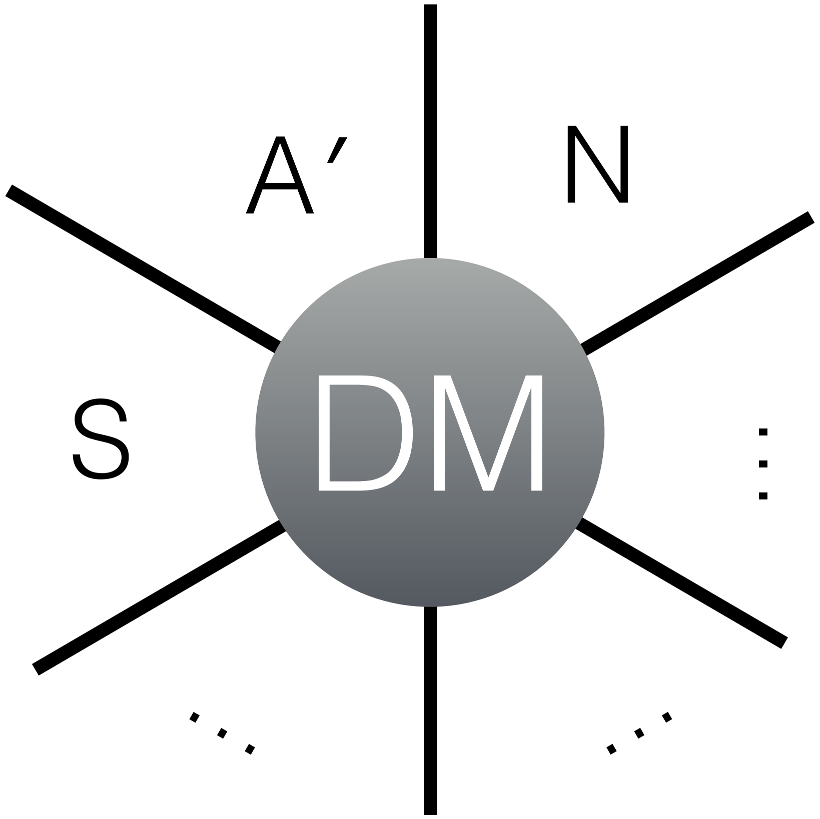
The dark sector paradigm



from Particle Fever

The dark sector paradigm

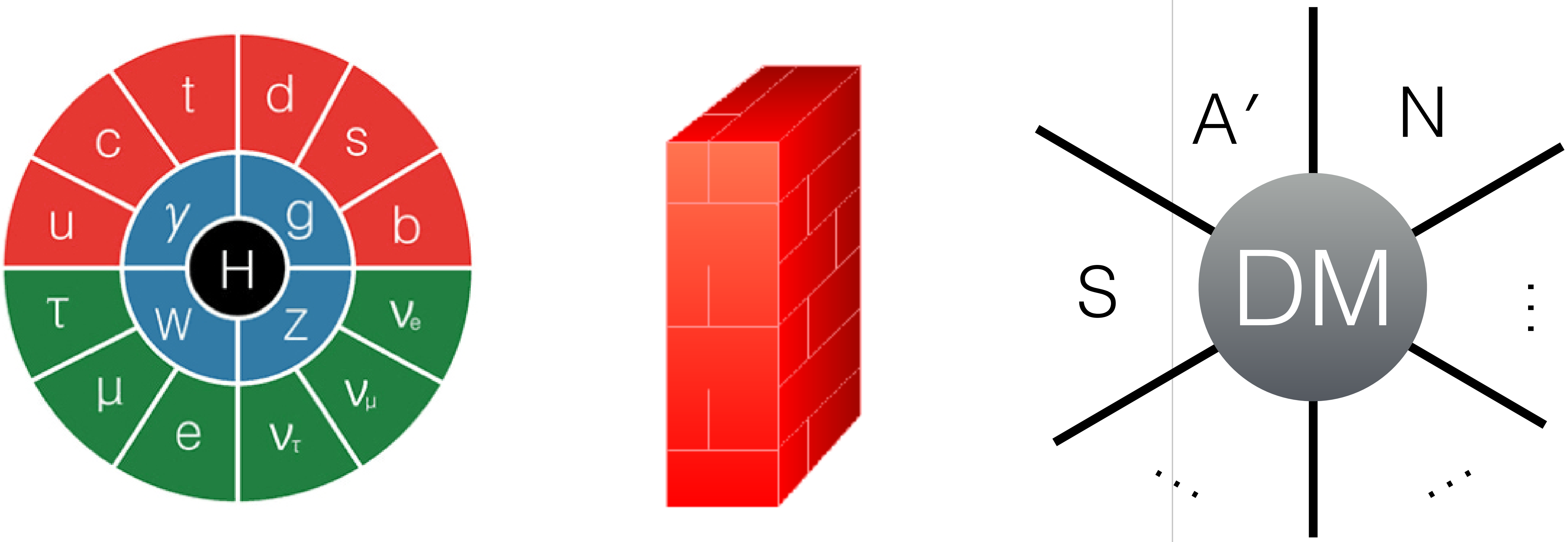




A′ search (2017)

from US Cosmic Visions

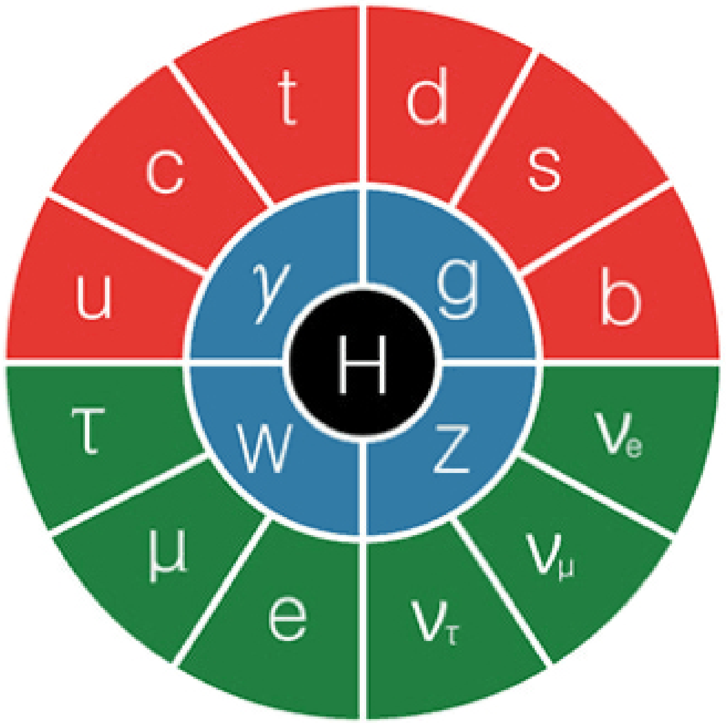
The dark sector paradigm



from Particle Fever

What if dark sectors completely decouple from the visible sector?

The dark sector paradigm



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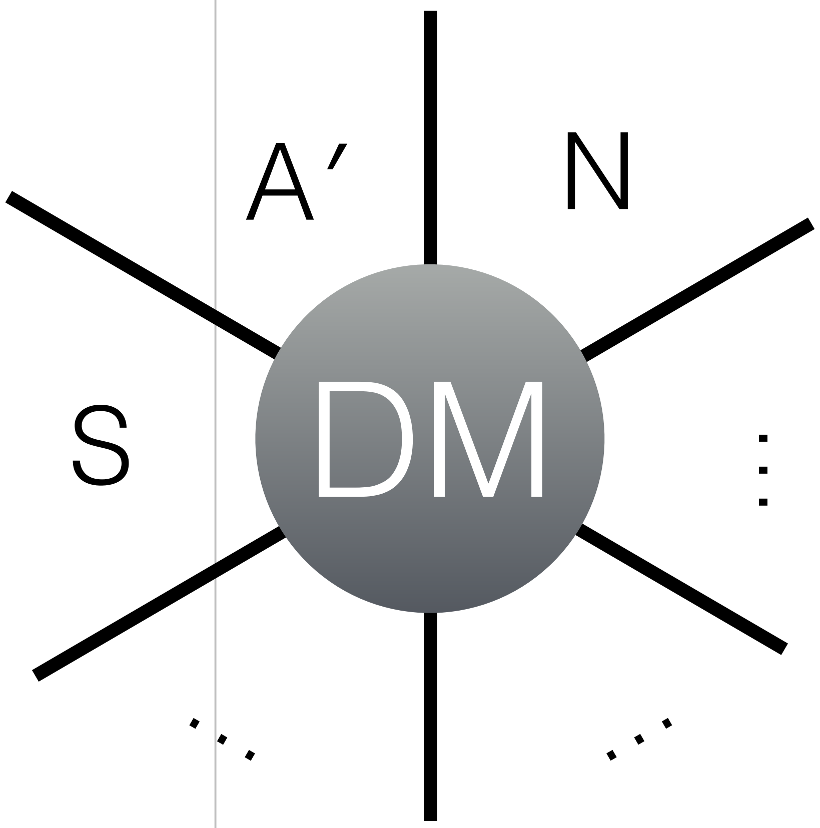
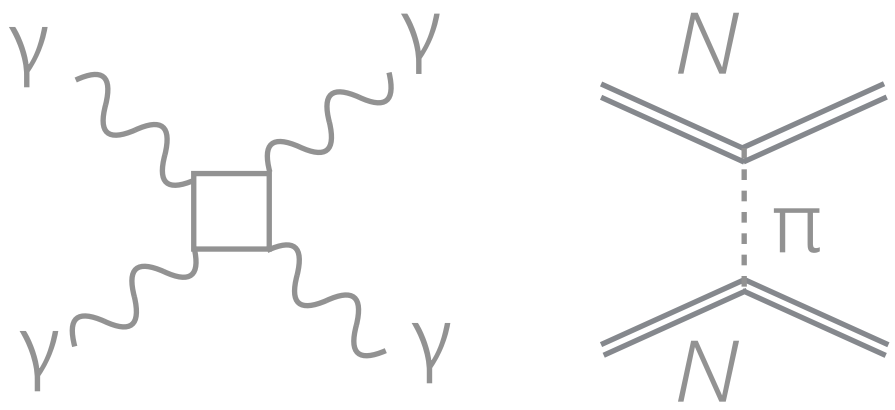


Use gravitational probes

Example: self-interacting DM

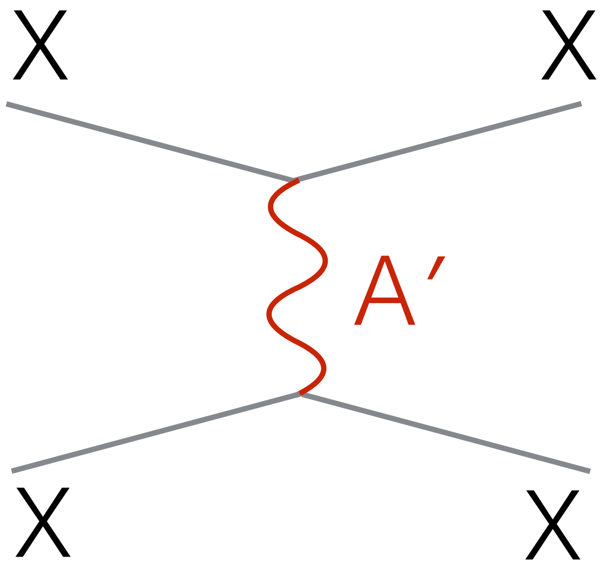


1. Self-interactions are common for normal matter

   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)

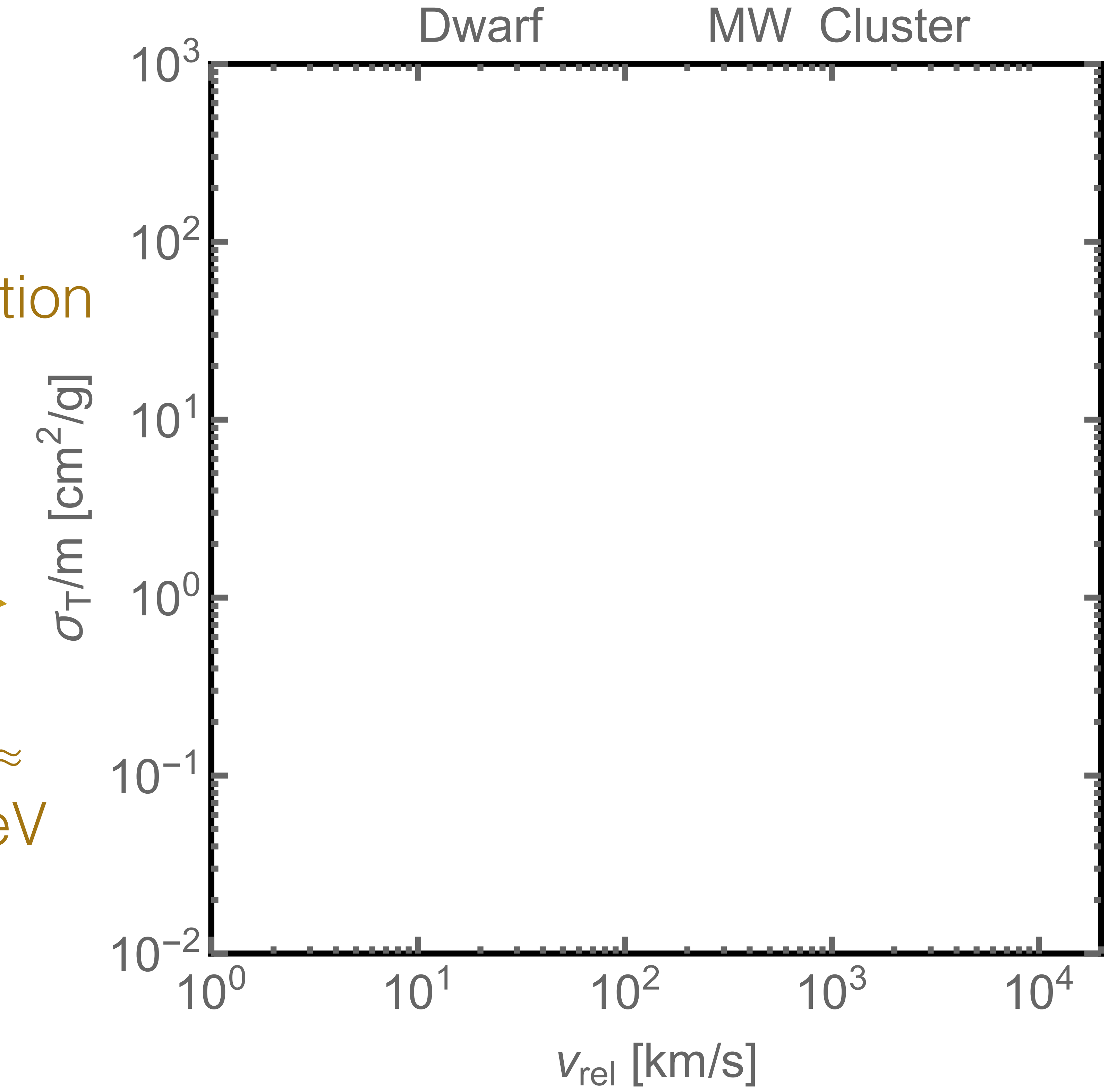


Spergel & Steinhardt '00
see review by Tulin & Yu ‘16

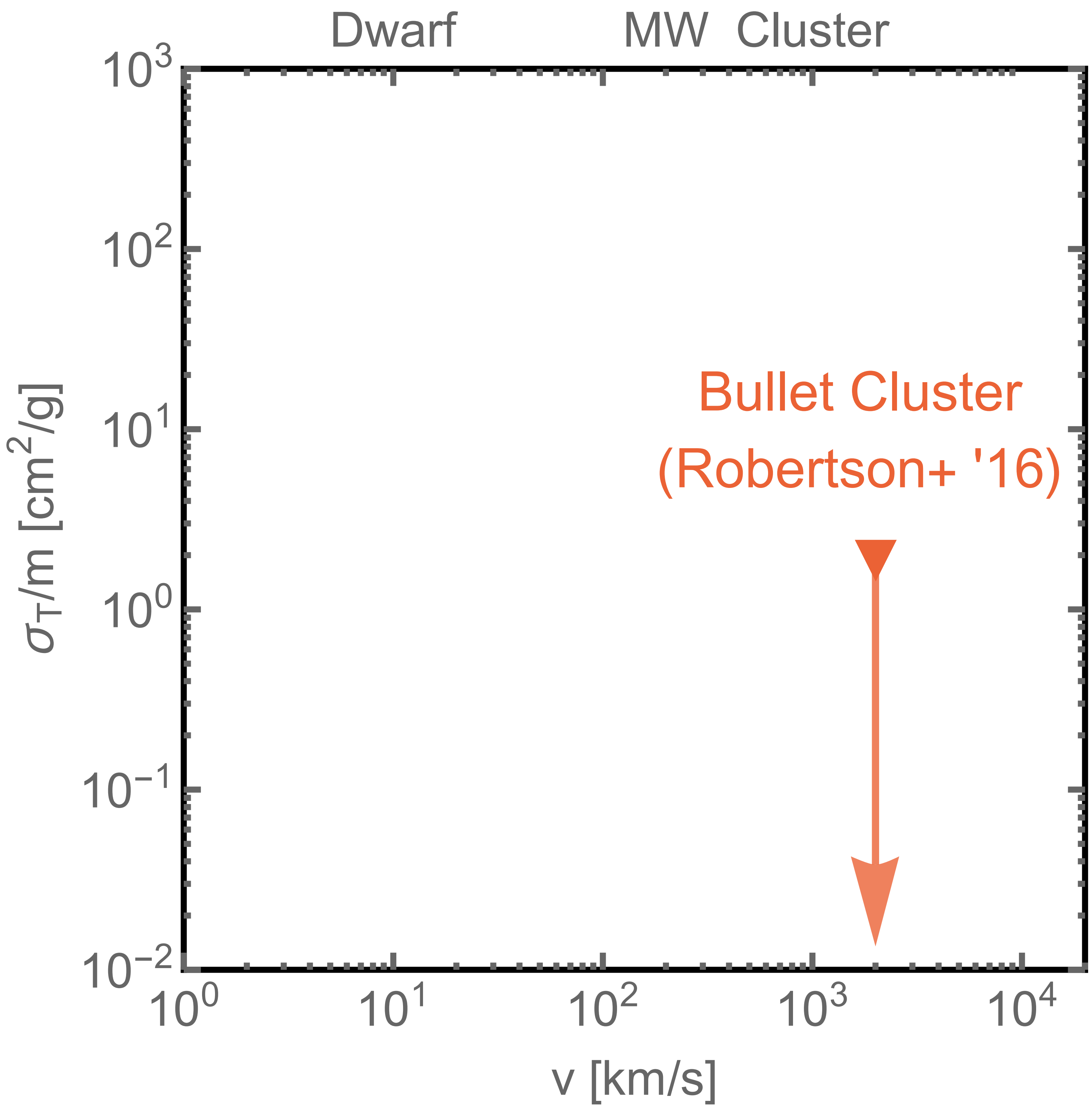
Probing SIDM in astrophysics

Self-interaction strength

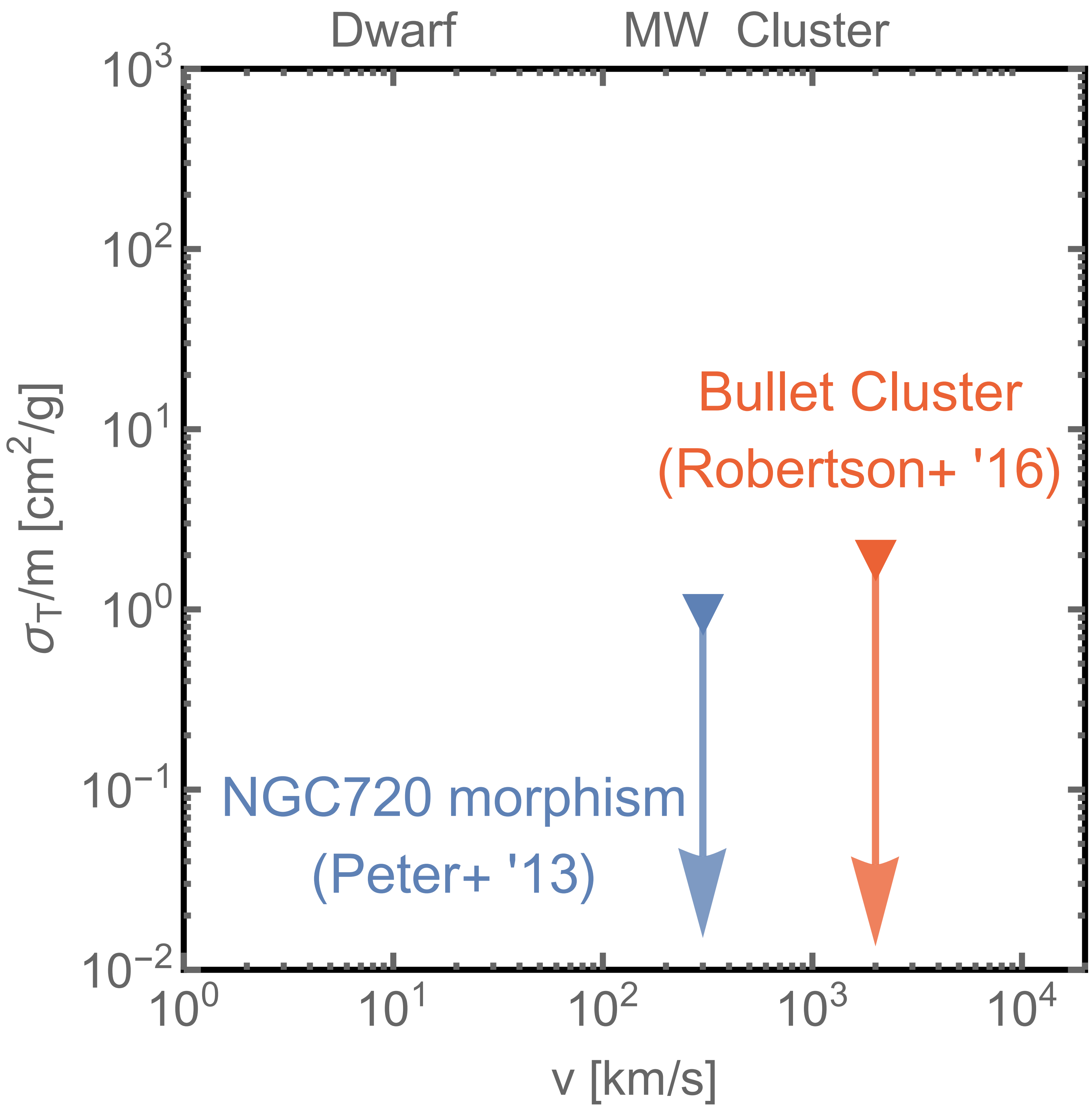
$1\ \mathrm{cm^2/g} \approx$
$2\ \mathrm{barn/GeV}$



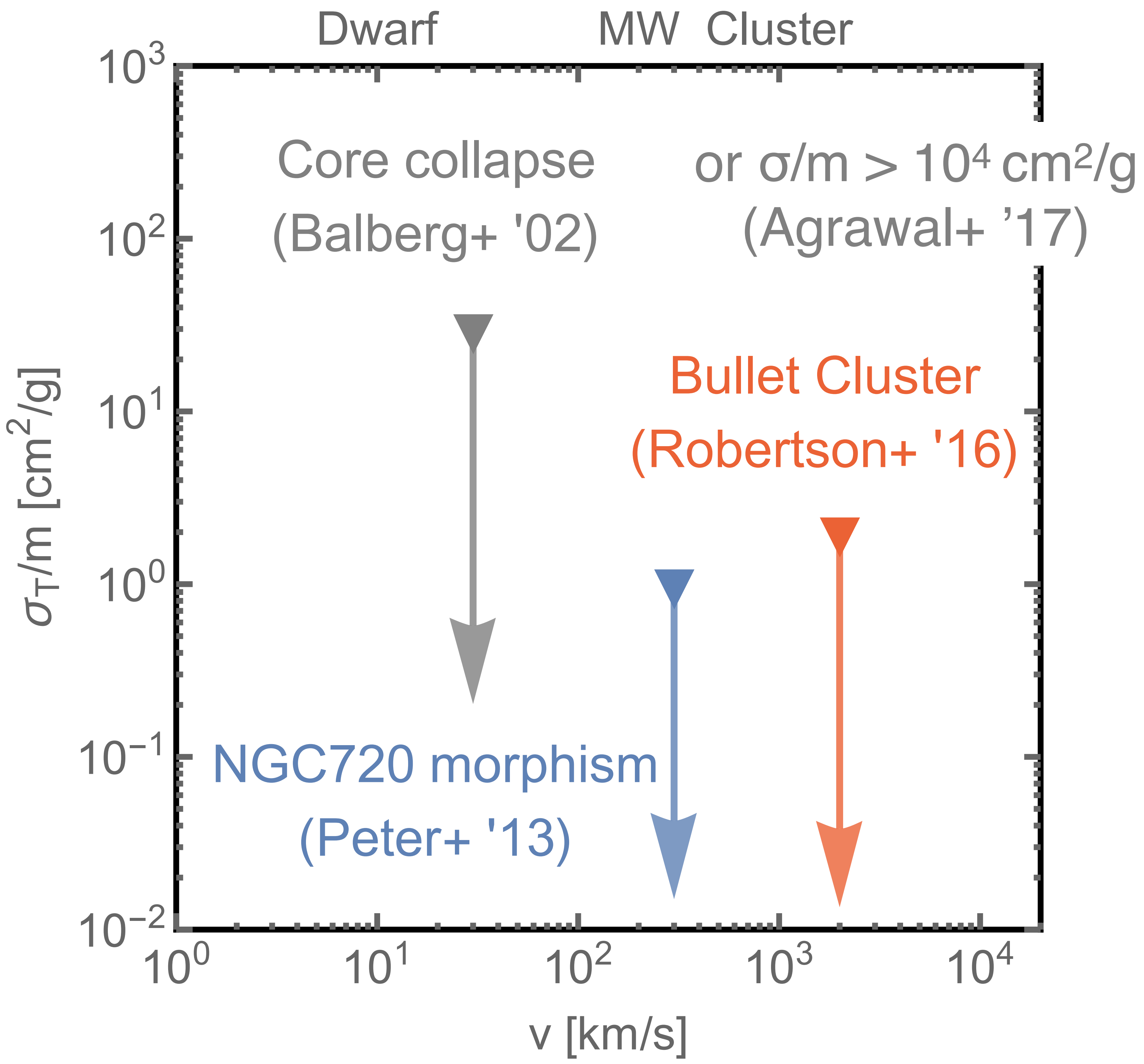
Cluster crossing



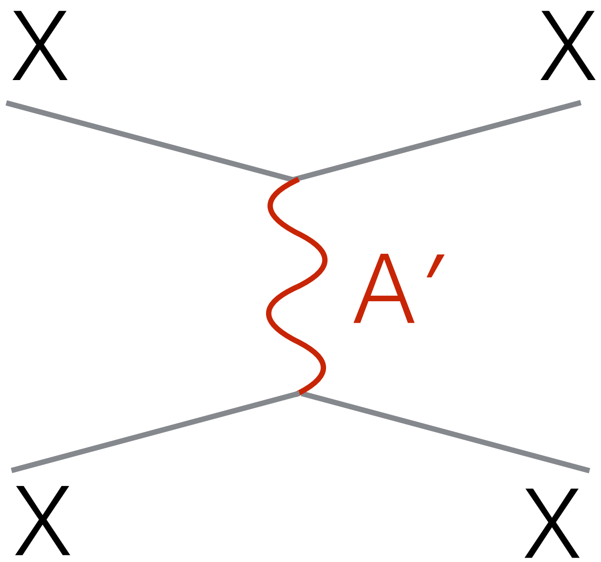
Galaxy morphism

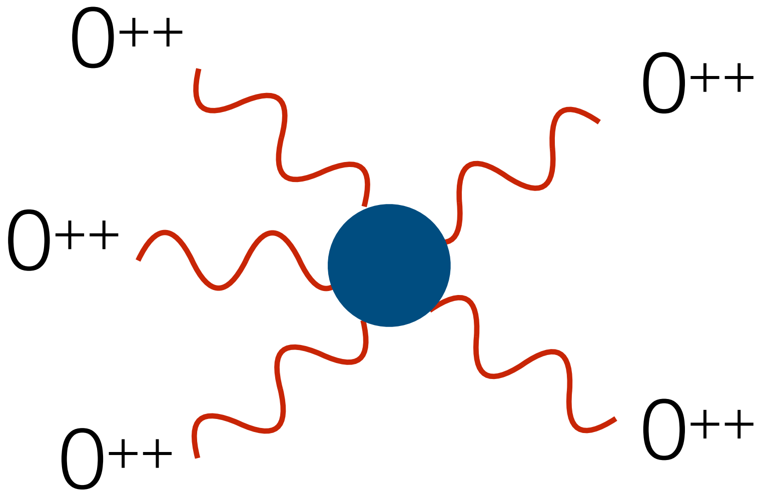


Gravothermal collapse

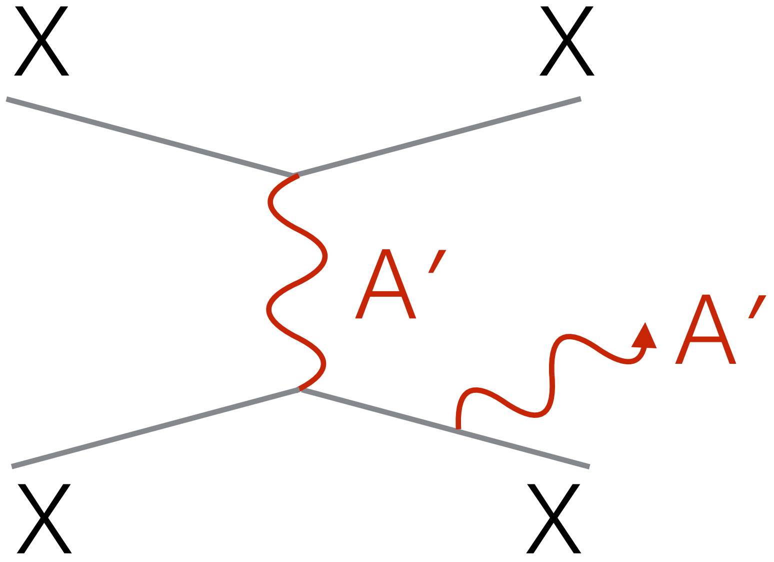


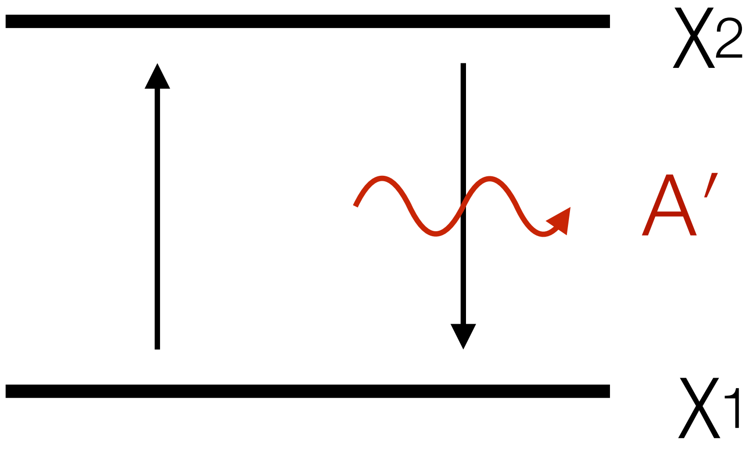
Dark sector is richer

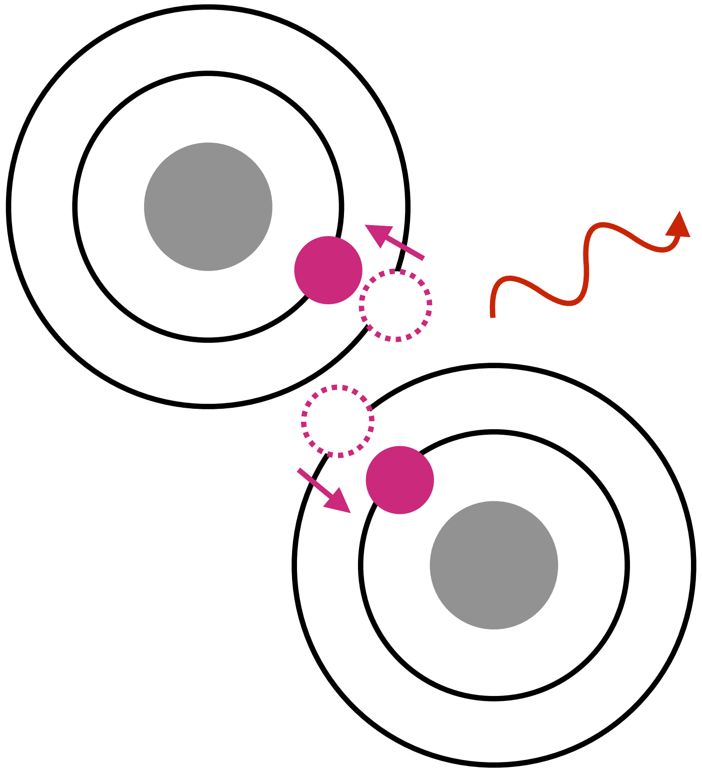




e.g. Ackerman et al ’09, Feng et al ’09 ’10,
Loeb & Weiner ’10, Tulin et al '10 '12 ’13
Boddy et al’16……







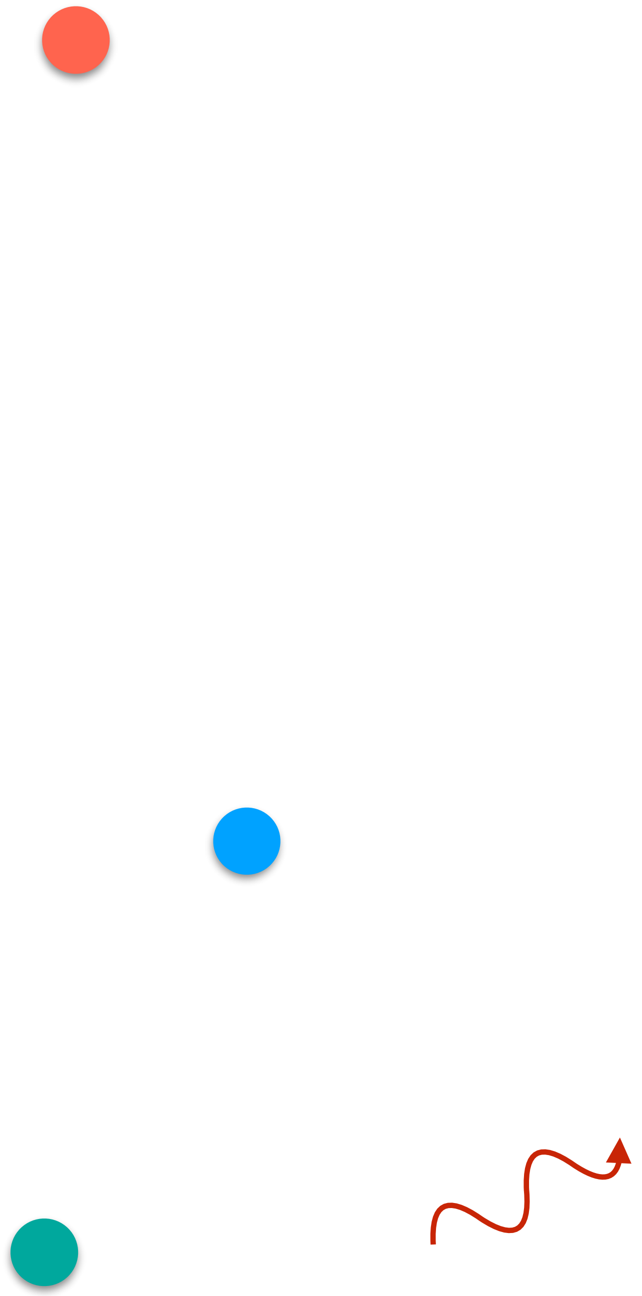
Outline

- Gravothermal evolution
- Simulation
- Results and constraints on SIDM cooling

✻ Give birth to the first super massive black holes (SMBH)

- Summary

Why do SIDM halos collapse?



- Because the SIDM halo gets cooled

- Elastic scattering
  ⇒ redistribute kinetic energy

  ⇒ heat flow

  ⇒ gravothermal instability

- Dissipative scattering
  ⇒ lose energy through dark radiation

a.k.a gravothermal catastrophe, core collapse

Gravothermal collapse

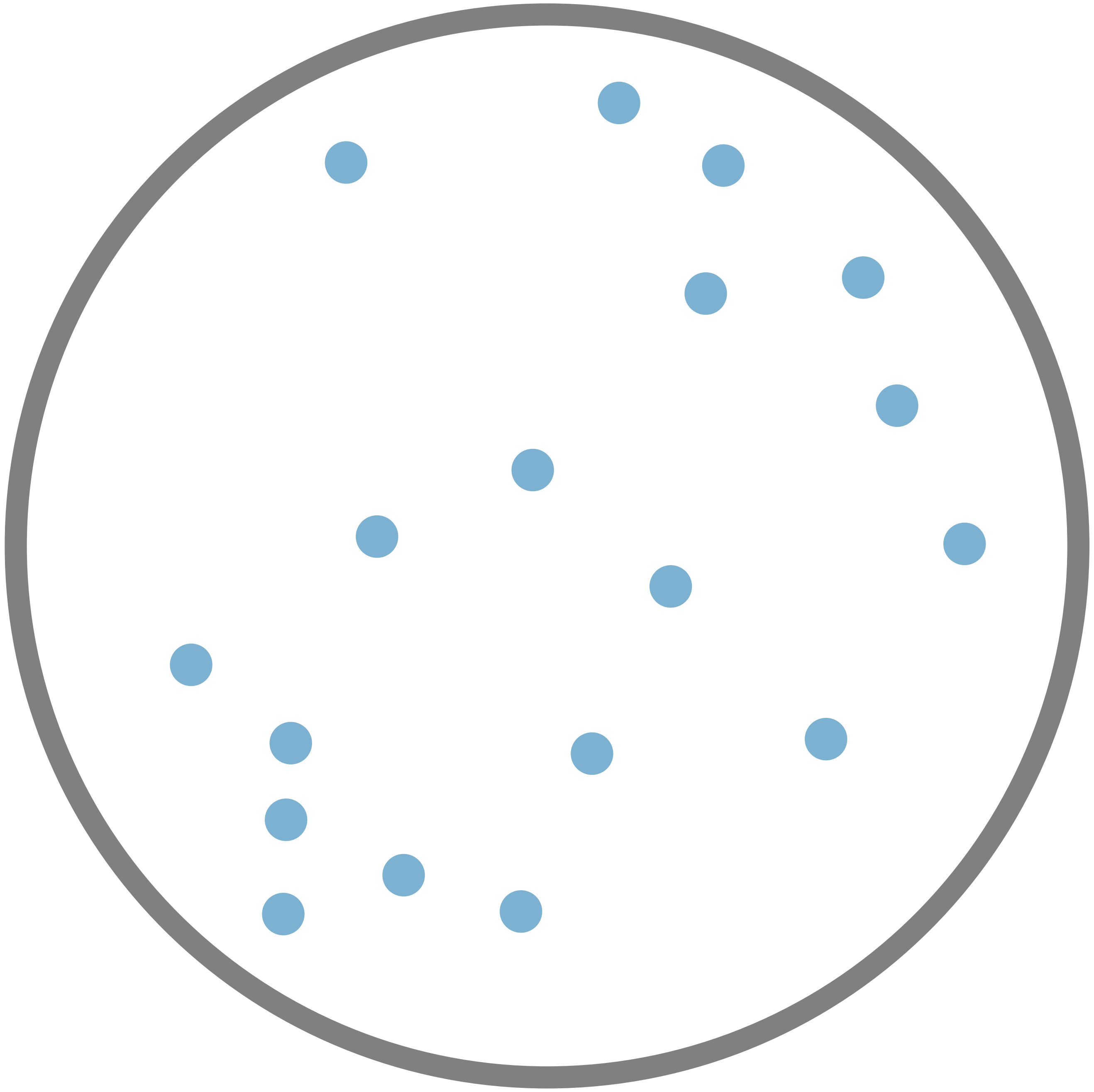
$$\boxed{\begin{array}{c}\textbf{Virial theorem:}\\ \mathbf{2\ K.E. + P.\ E. = 0}\end{array}}$$

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

$$\Rightarrow K.E.\,/\,E_{tot} < 0$$

Negative heat capacity

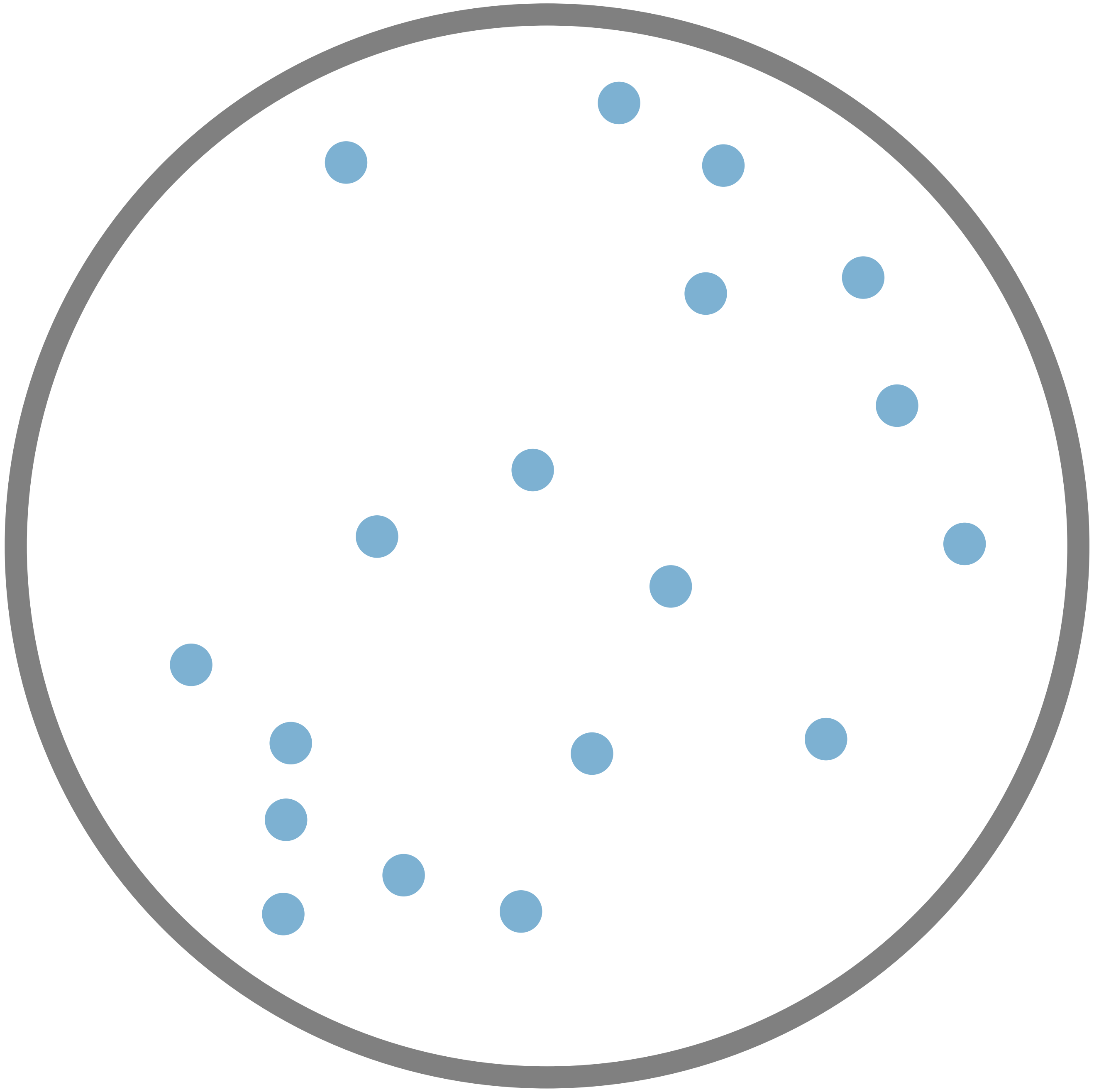
Gravothermal collapse



Core region of a halo

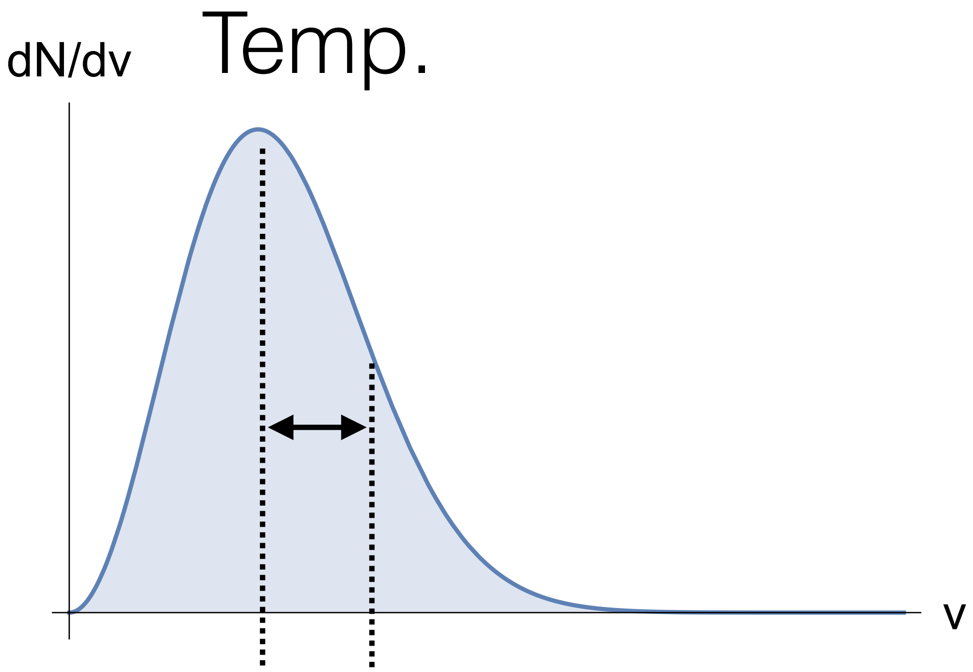
Take a halo w/
an iso-thermal
profile

Gravothermal collapse

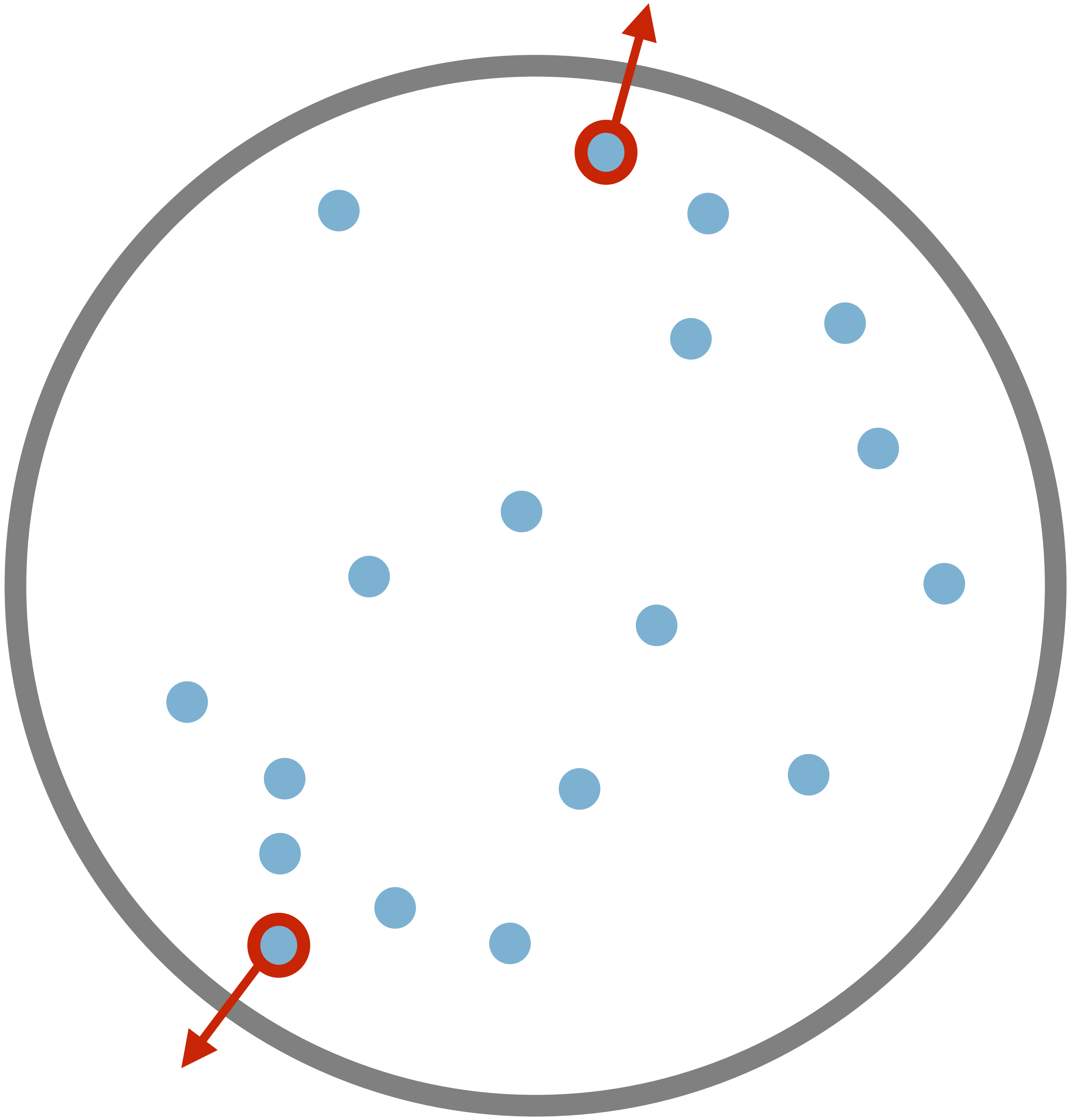


Core region of a halo

Velocity-distribution of DM particles



Gravothermal collapse



Core region of a halo

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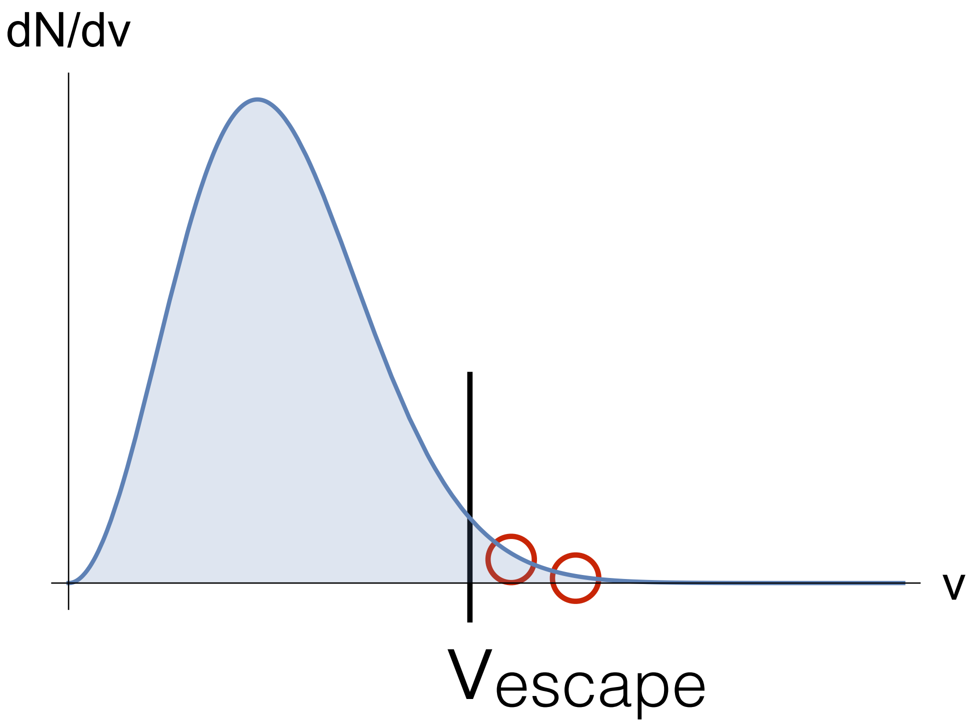
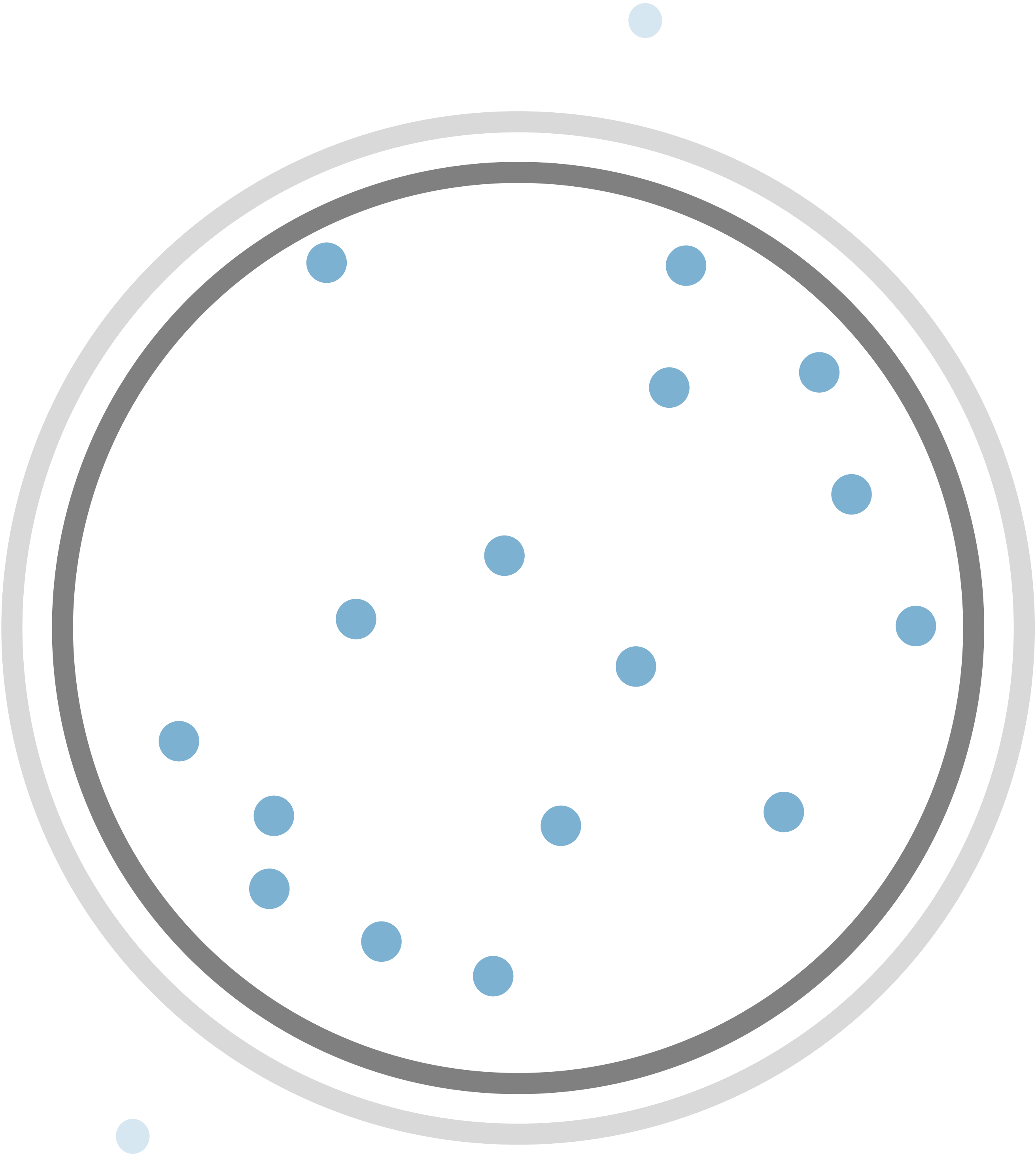


Particles in the “tail” can evaporate

Gravothermal collapse



Core region of a halo

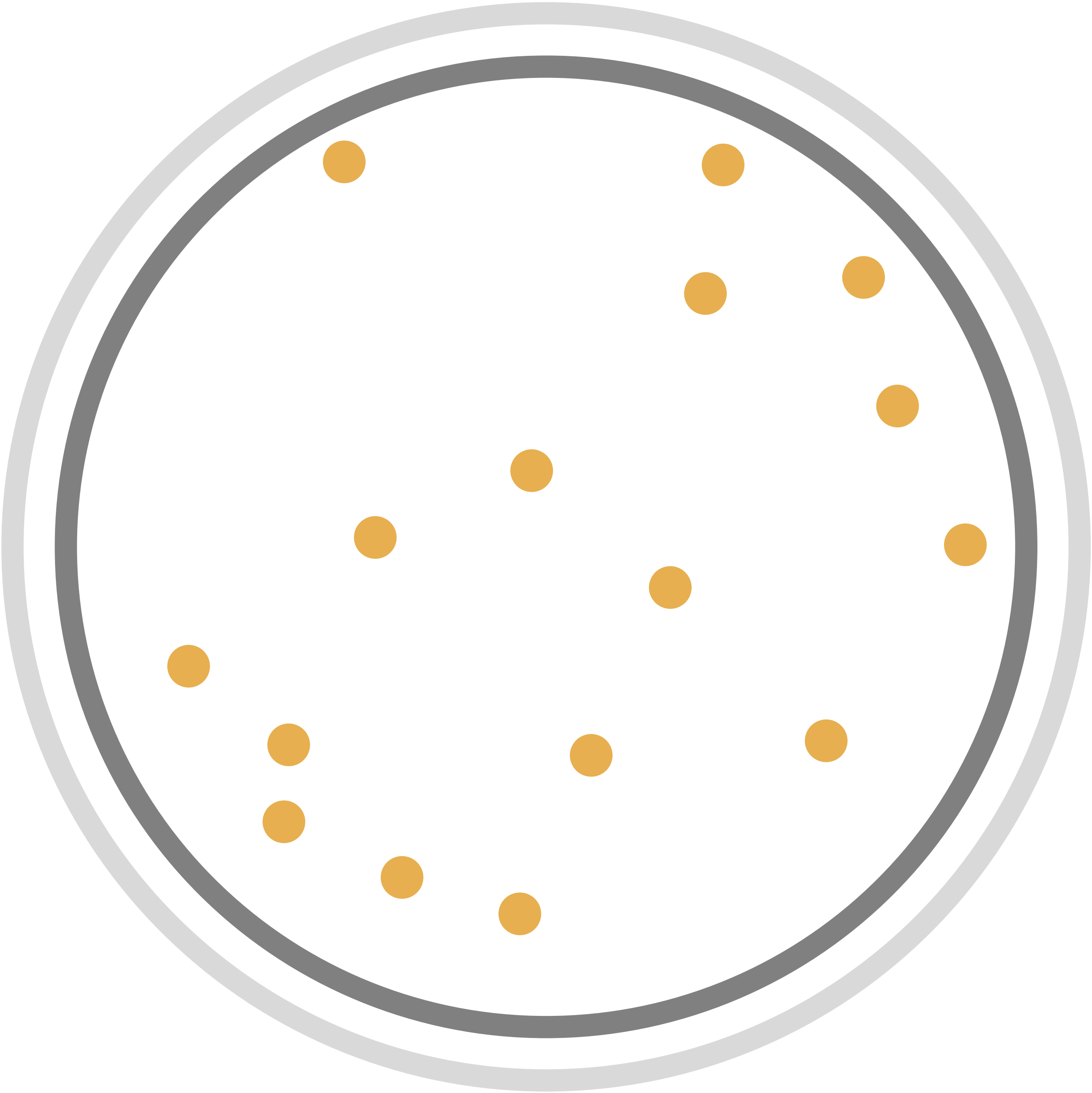
K.E.↓ P.E.↑

But overall
2 K.E. + P.E. < 0

Out of virial

Gravity is no longer supported by random motion

Gravothermal collapse

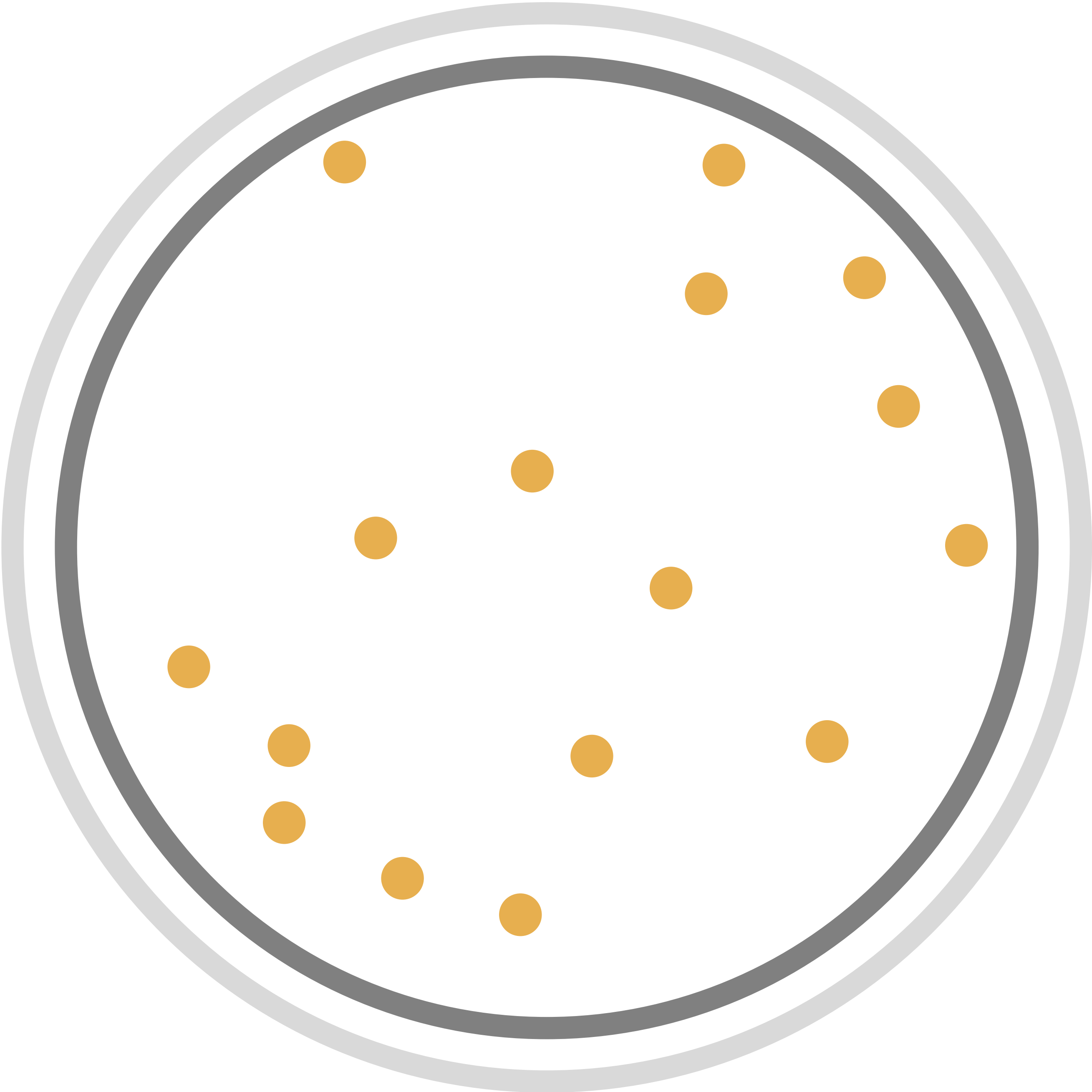


Core region of a halo

Back to virial:

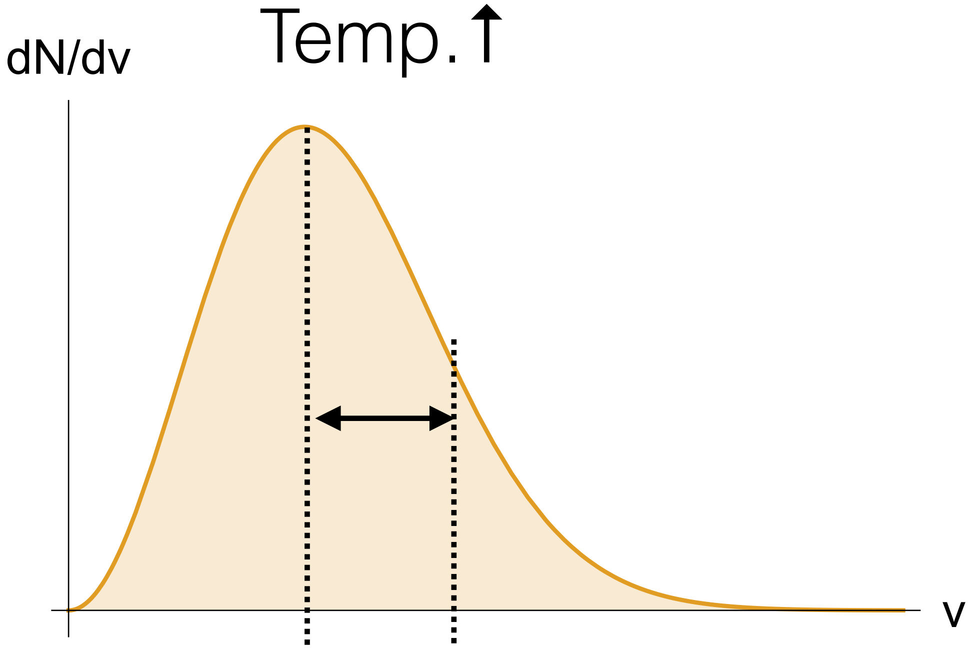
Averaged velocity increases (temp. ↑)

Gravothermal collapse



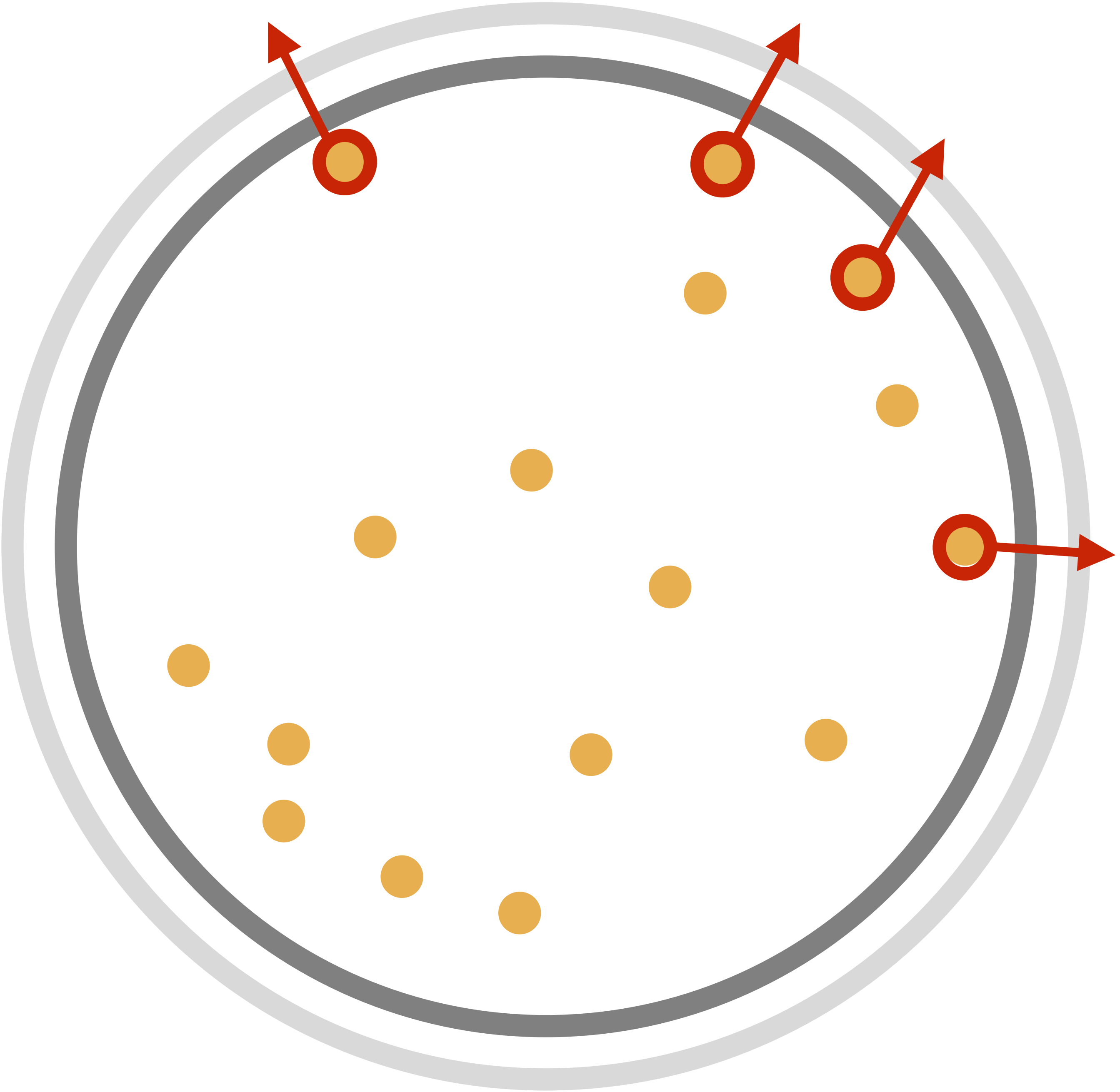
Core region of a halo

But…



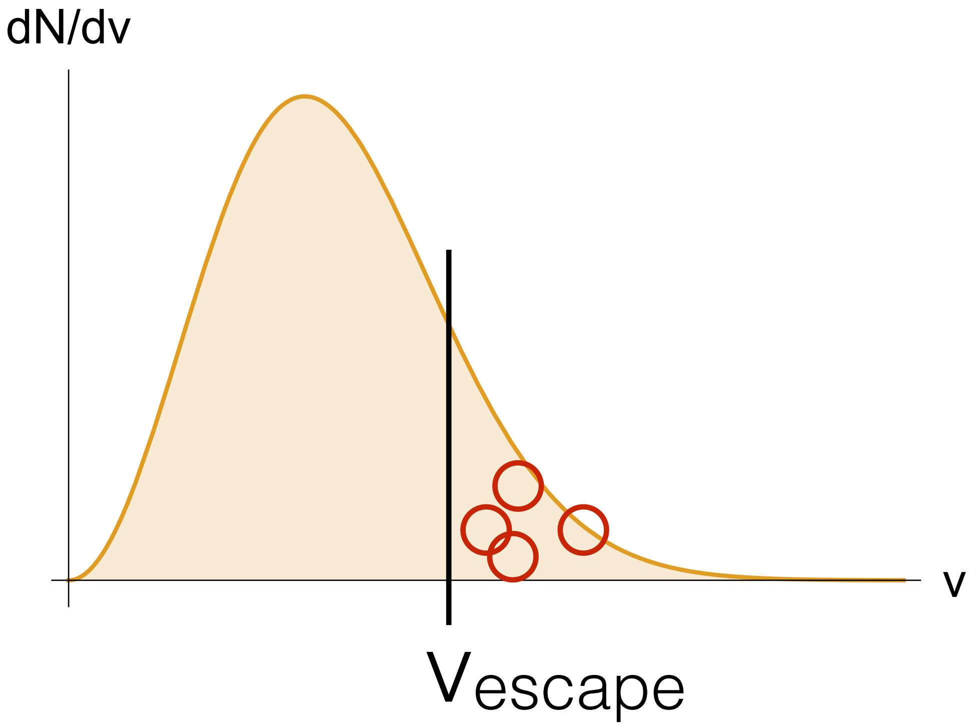
A fatter velocity distribution

Gravothermal collapse



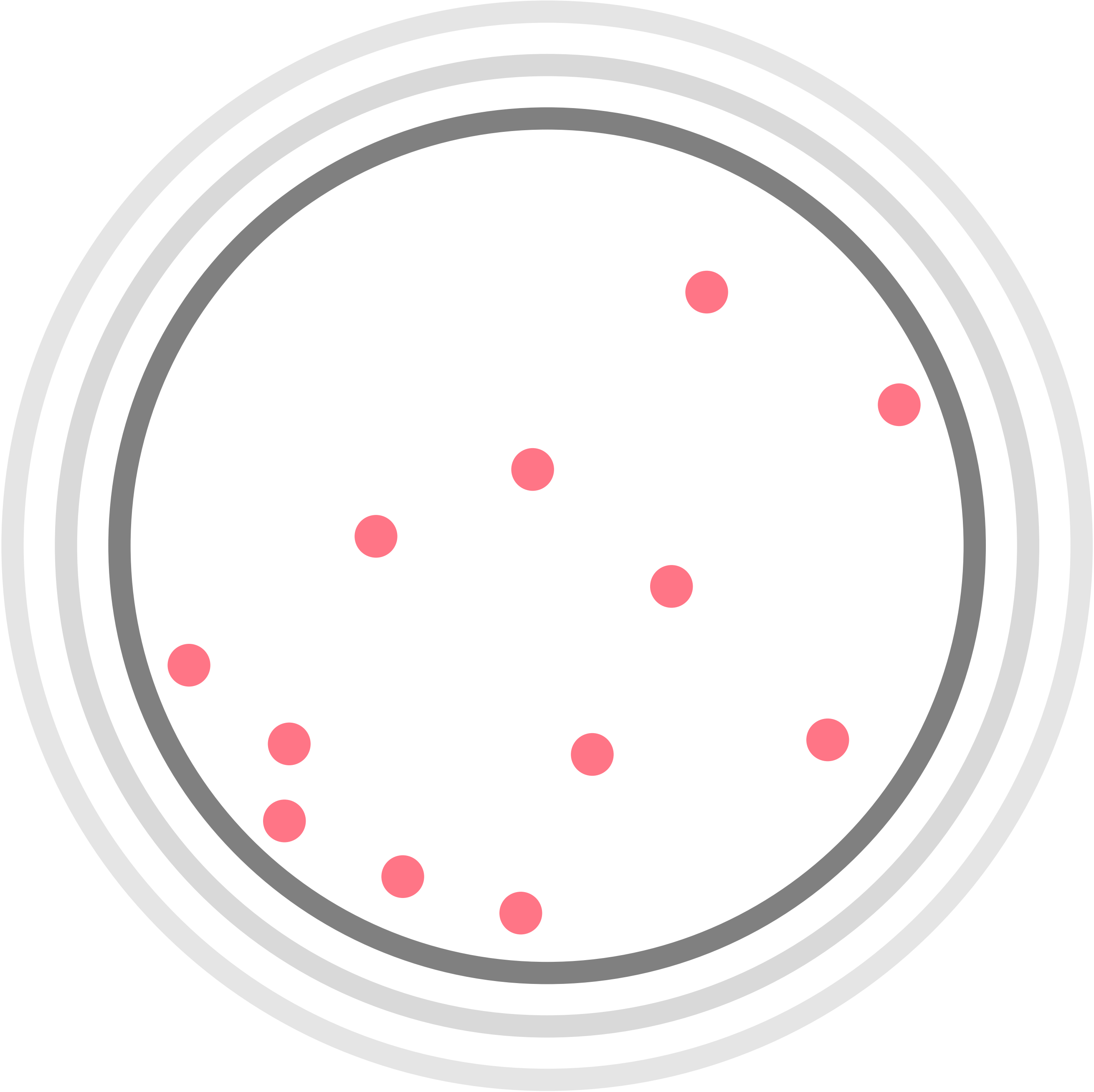
Core region of a halo

But…



More particles in the “tail”

Gravothermal collapse

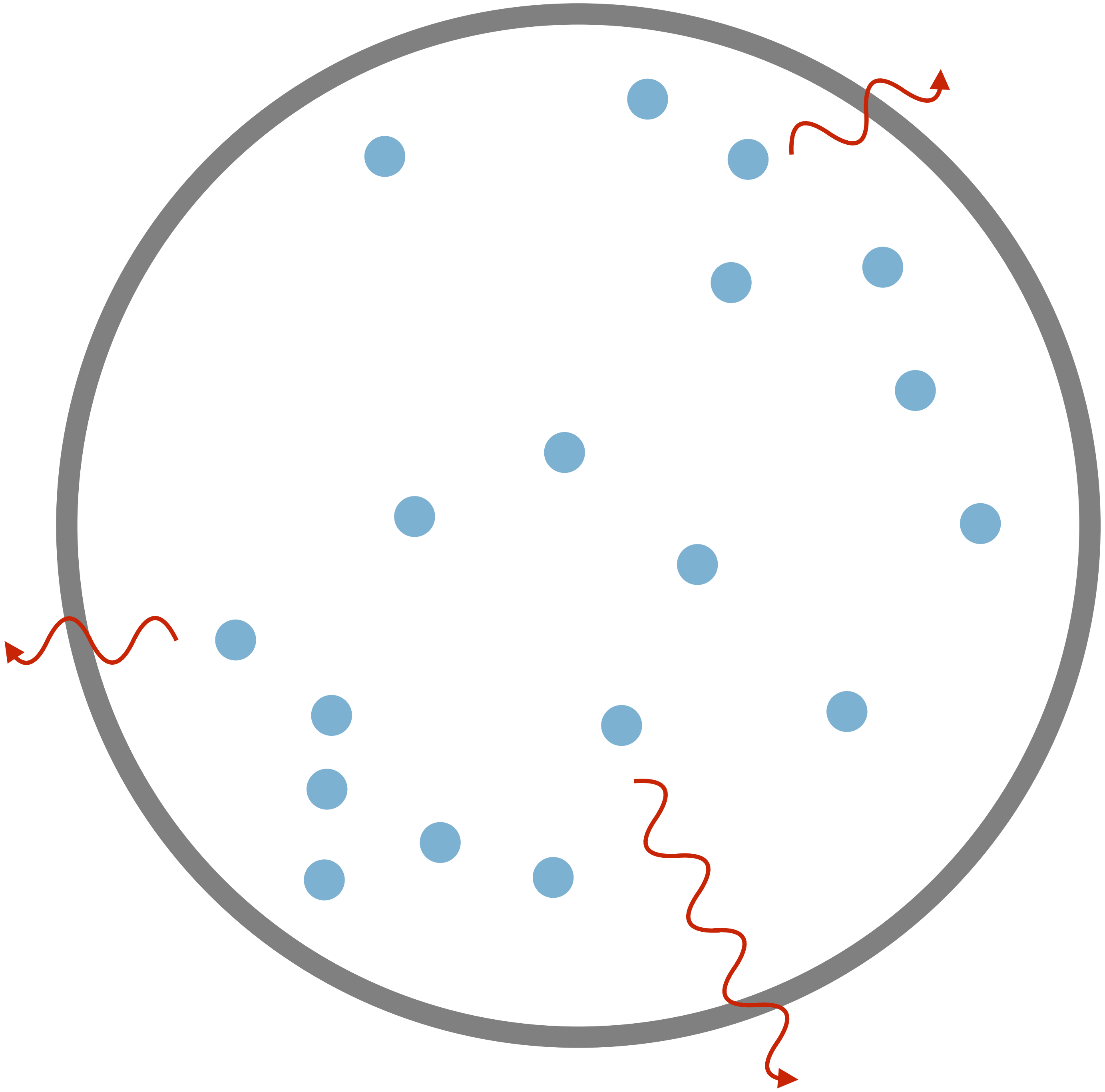


Core region of a halo

More evaporation
Further shirk
Core gets hotter
Even more evaporation
……

Runaway collapse!

Bulk cooling



- Dissipative scattering causes extra kinetic energy loss (e.g. carried away by dark radiations)
- Assume the halo is optical thin to the dark radiation (no re-absorption)
- Happens everywhere

Simulation

Method

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

Fluid model

- Used to study **isolated, non/low-spin, single-component, no/low-baryonic content** & **spherical** halo

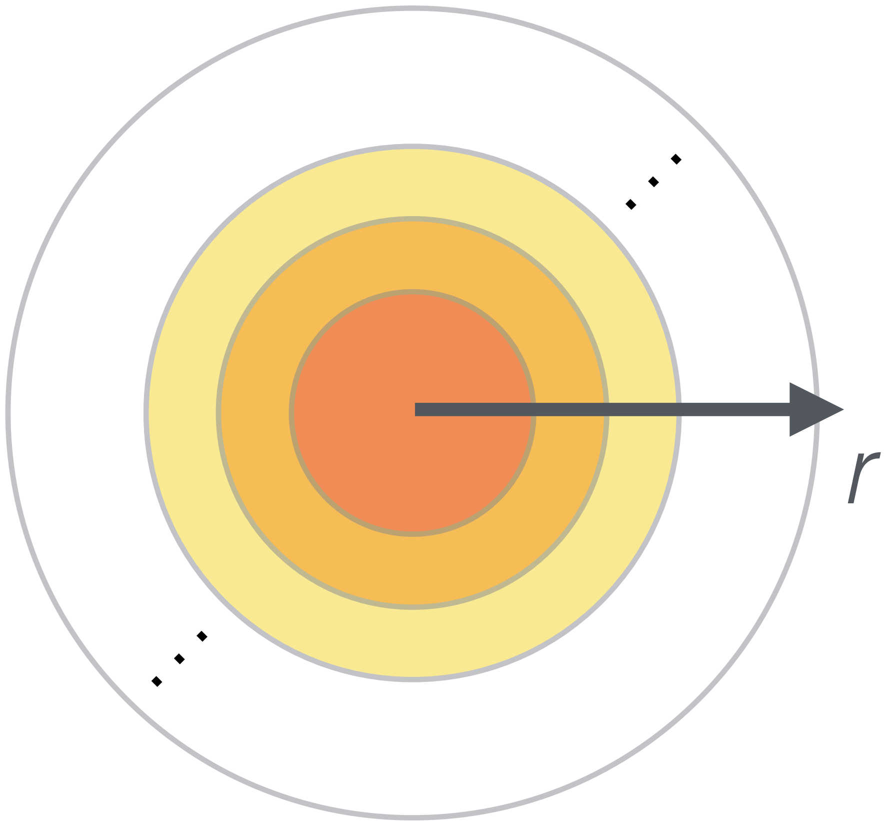
- First adopted in studies of gravothermal evolution of the globular clusters

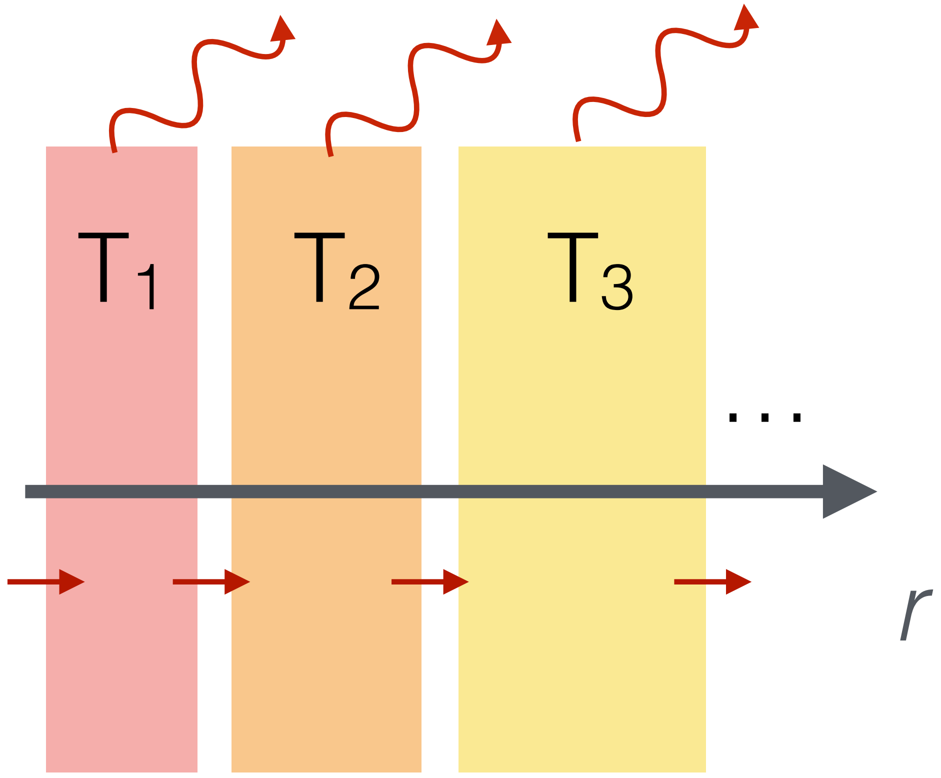
Hachisu et al ’78, Lynden-Bell & Eggleton, ’80;
Inagaki & Lynden-Bell ’83; Heggie ’84; Goodman ’84;

- Later adopted in studies of the gravothermal evolution of the SIDM halos

Balberg & Shapiro, ’02; Balberg et al '02;
Ahn & Shapiro, ’08; Koda & Shapiro, '11;
Pollack et al, '15

Fluid model





- Assume each shell is in its thermal equilibrium. Different shells have different temperatures.

- Evolution: temperature change → hydrostatic relaxation → temperature change → hydrostatic relaxation → …

Sets of equations

1. Mass conservation

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

2. Momentum conservation

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

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

Sets of 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

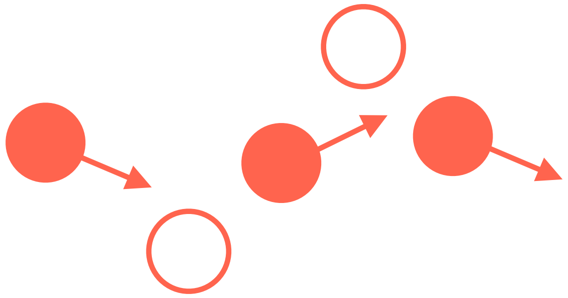
bulk cooling rate
energy loss
in unit vol.
& unit time

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

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

conductivity

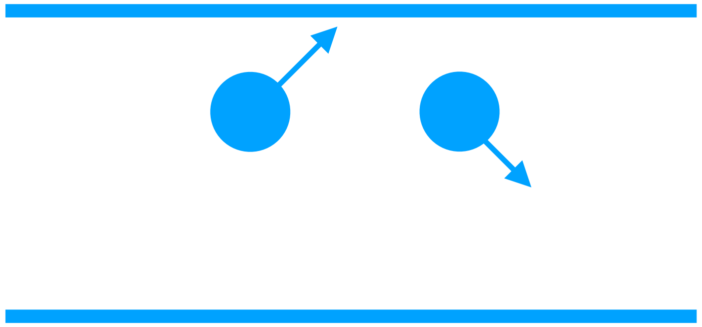
More on κ



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

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

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



Lynden-Bell & Eggleton, '80

- Collisions w/ the "wall"
- Characterized by the orbit height of the halo

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

- $\kappa_{\rm lmfp} \sim (n\nu H)\dfrac{H/\nu}{t_r} \sim \dfrac{n\nu^3\sigma}{Gm}$

More on κ

- $Kn \equiv \lambda / H$
  - $Kn > 1 \Rightarrow$ **gravitational** conduction dominates **(long-mean-free-path region)**
  - $Kn < 1 \Rightarrow$ **self-interaction** conduction dominates **(short-mean-free-path region)**
- Combine the two $\kappa = (\kappa_{\mathrm{lmfp}}^{-1} + \kappa_{\mathrm{smfp}}^{-1})^{-1}$

More on C

- We consider collisional cooling

energy loss per collision

t_{in}: relaxation time for inelastic scattering

energy loss
in unit vol.
& unit time

$$C = \left\langle \frac{n E_{\text{loss}}}{t_r'} \right\rangle$$

$T \geq E_{\text{loss}}$

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

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

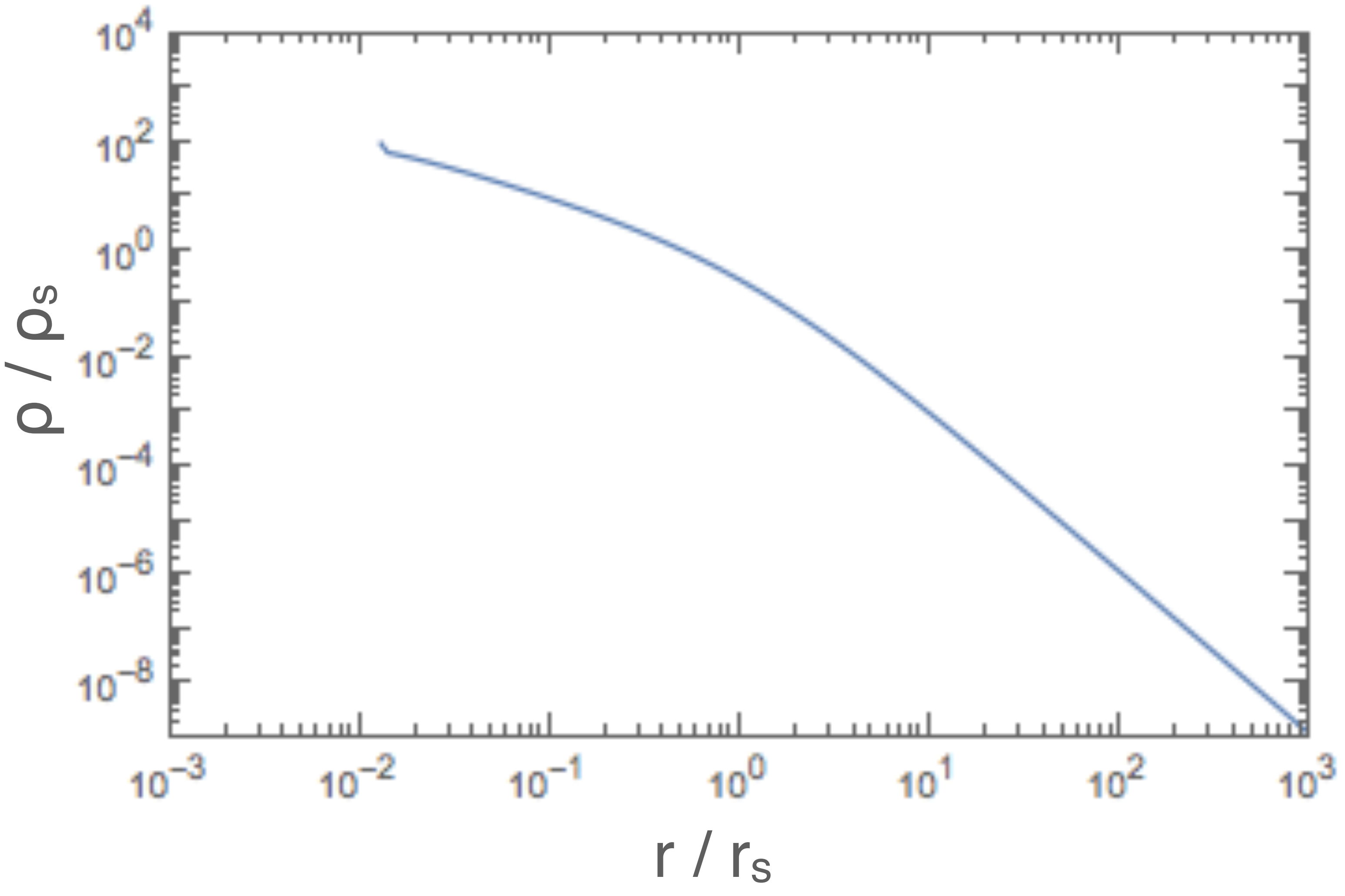
a “soft” cutoff

Other setup

- 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 = const., L = 0 @ r = r_{max}
- Small self-interaction strength ⇒ evolution starts from the optical thin region
- Mild cooling ⇒ cooling time >> free-fall time
  ⇒ not isothermal/free-fall collapse

Result

Evolution of Density Profile


Conduction only

Virialized halo

Expansion

Max core expansion

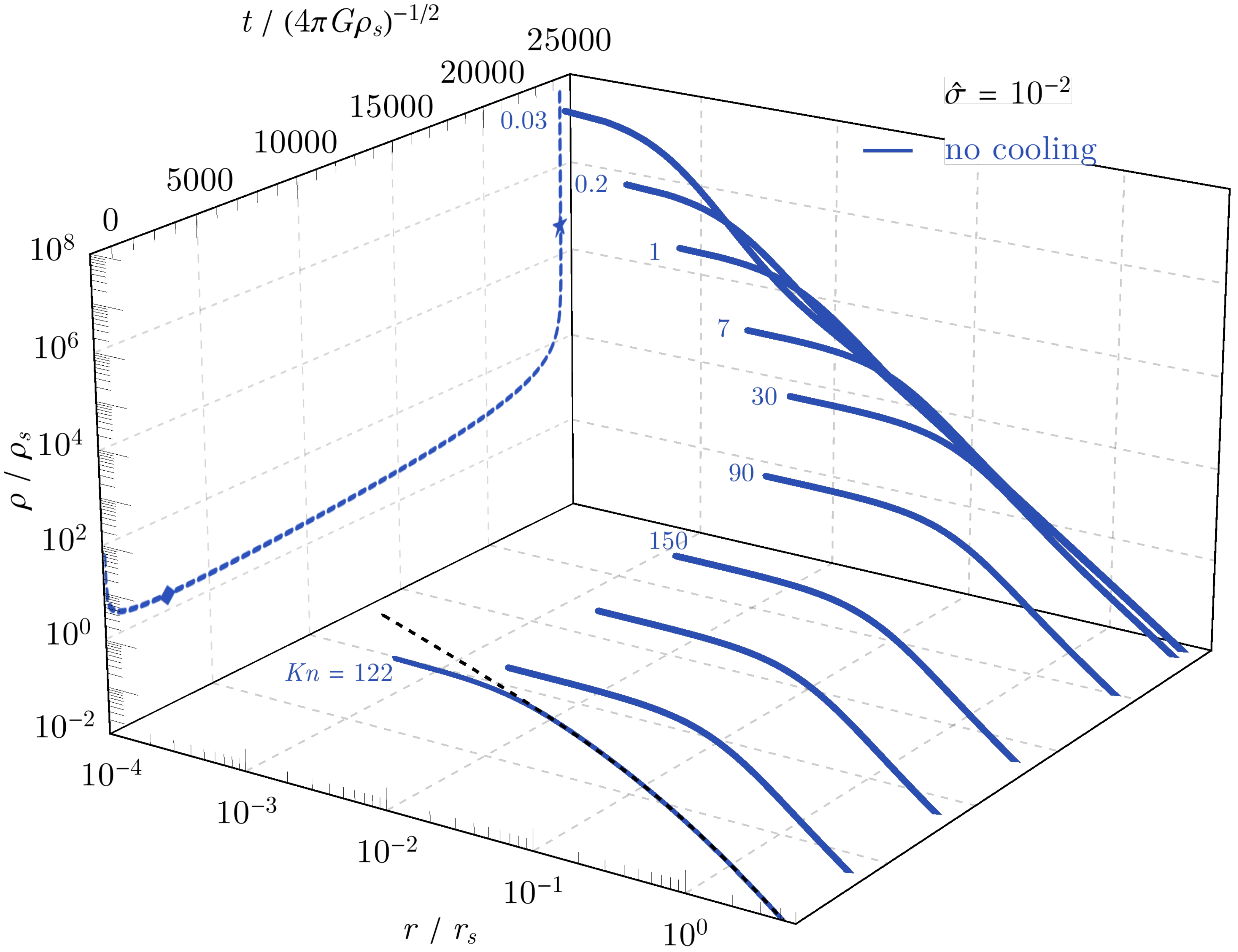
Runaway collapse

Develop a “2nd core”

Cont. collapse

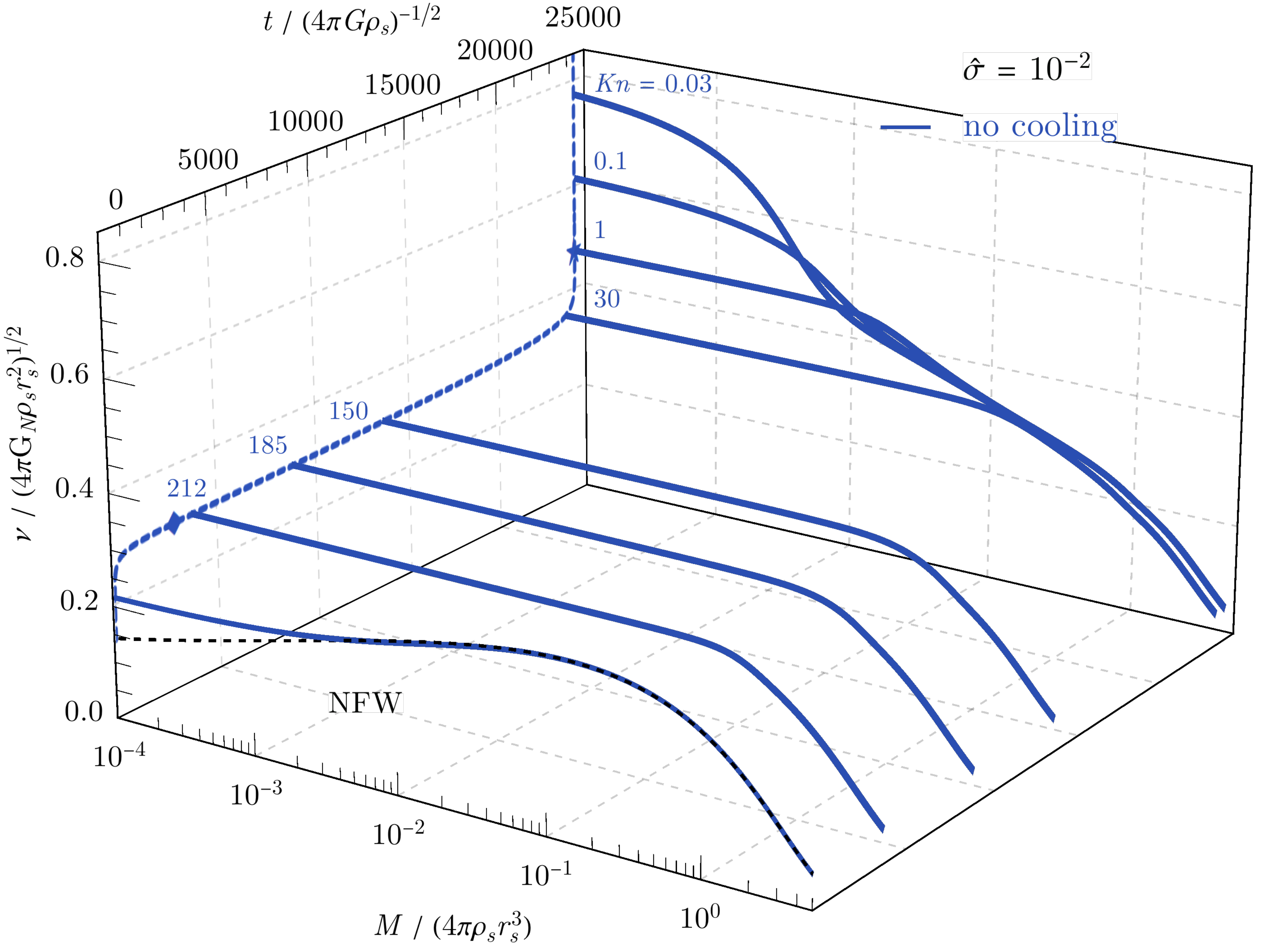
a singular state

Evolution of density profile



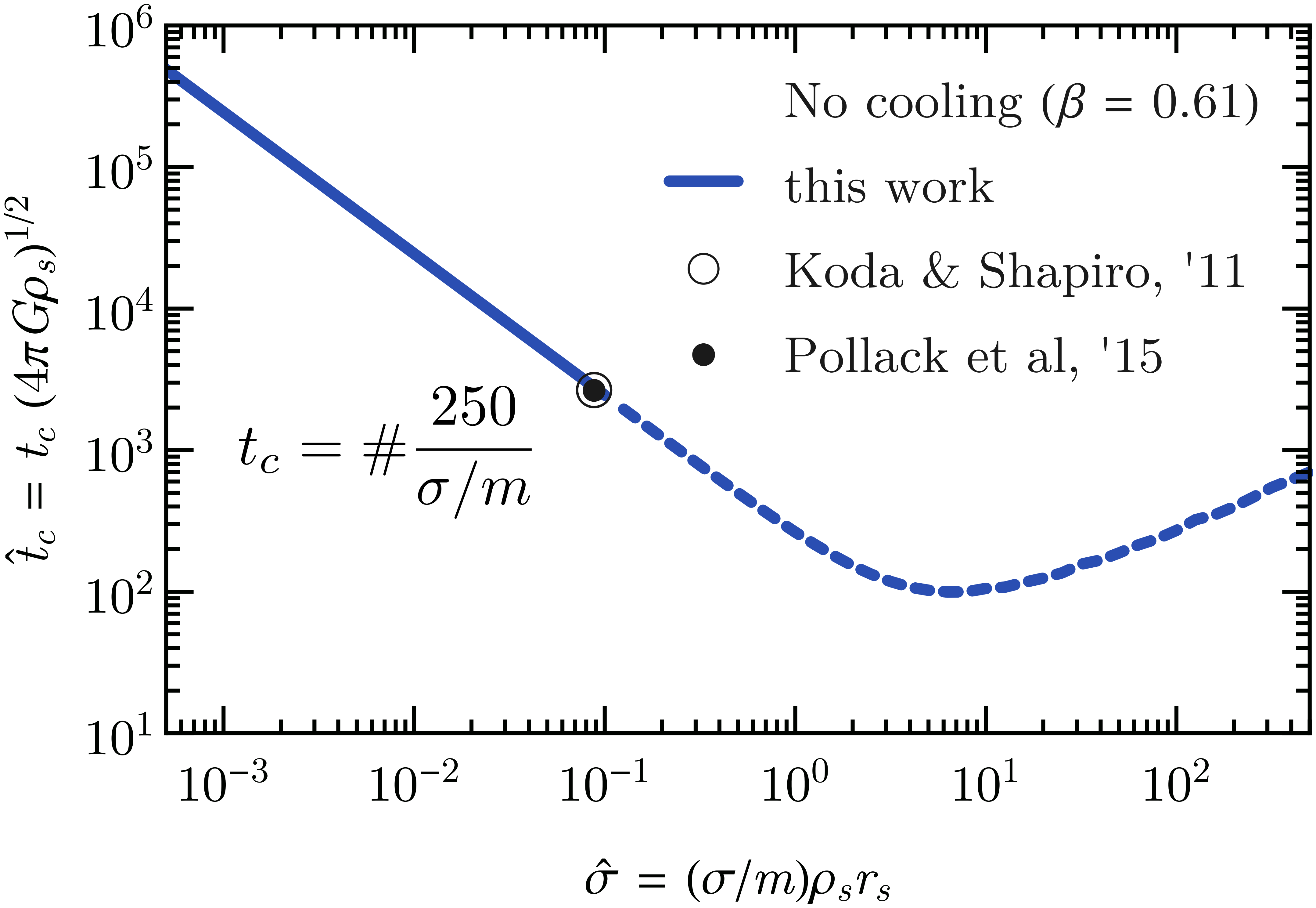
$\hat\sigma \equiv (\sigma/m)\rho_s r_s$

Evolution of velocity dispersion profile



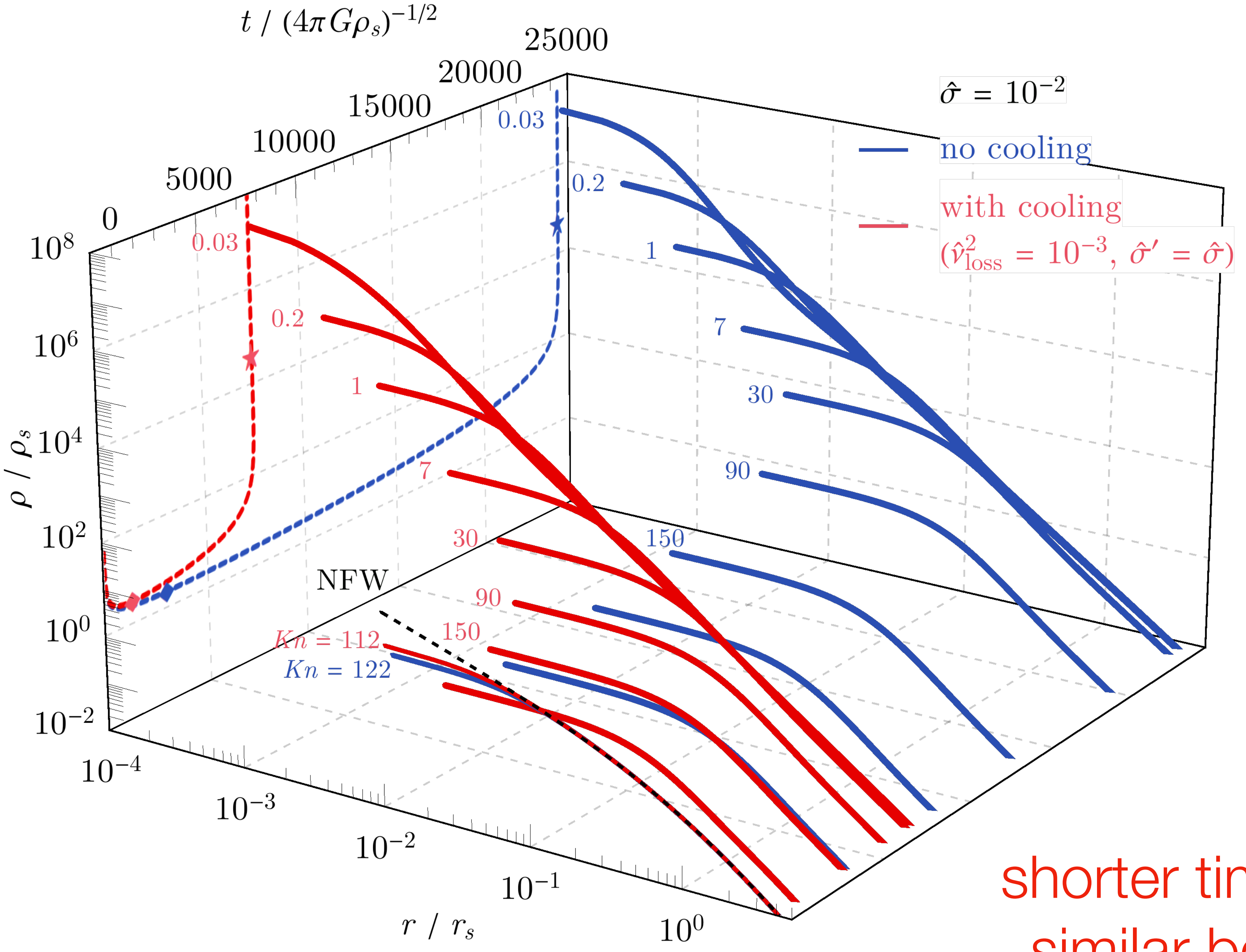
$\hat{\sigma} \equiv (\sigma/m)\rho_s r_s$

The collapse time



$$t_c = \#\frac{250}{\sigma/m}$$

Add a mild cooling



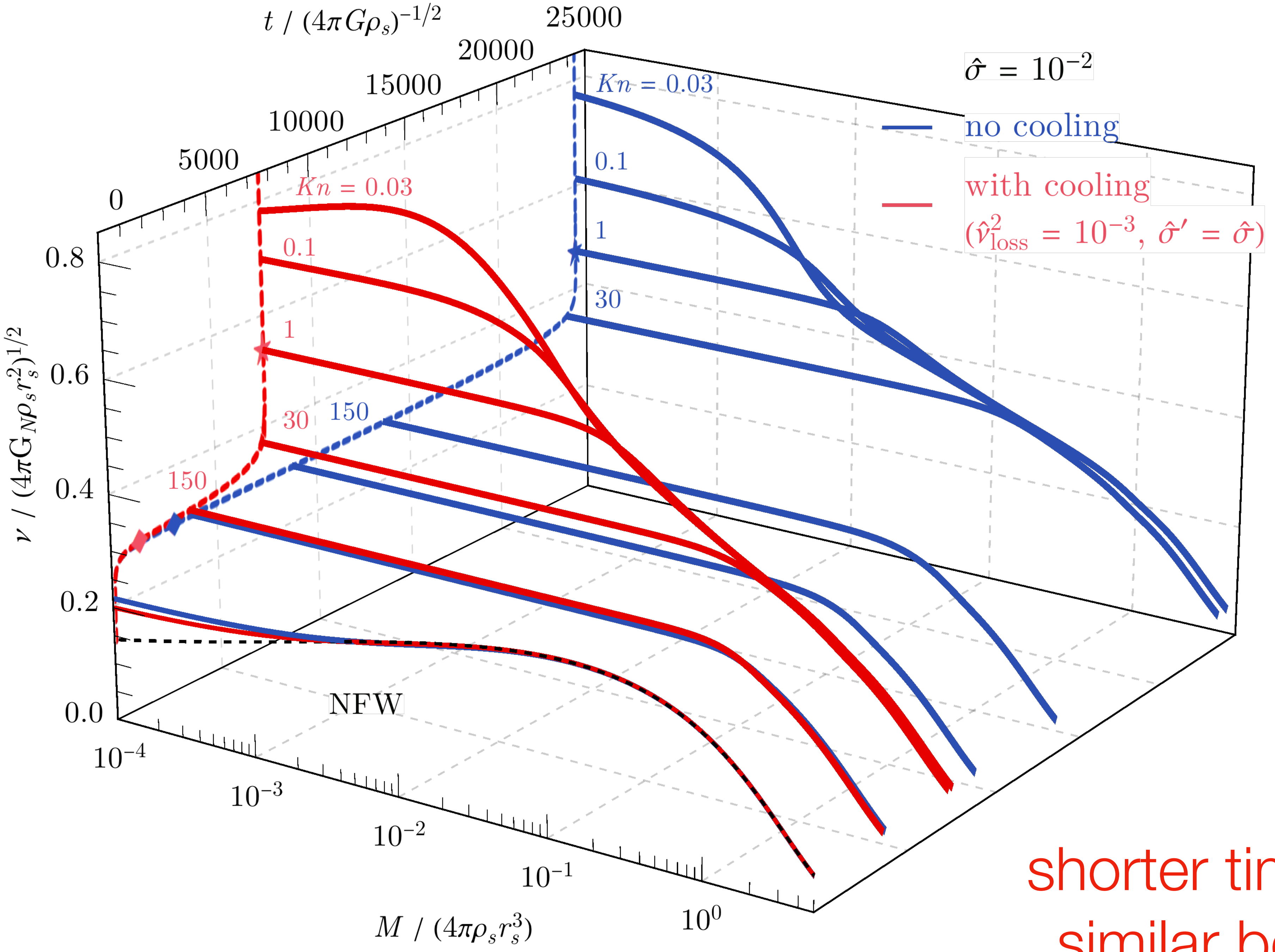
$$\hat{\sigma} \equiv (\sigma/m)\rho_s r_s$$

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

$$\hat{\nu}_{\rm loss} \equiv \frac{\nu_{\rm loss}}{\sqrt{4\pi G\rho_s r_s^2}}$$

shorter time scale
similar behavior

Add a mild cooling



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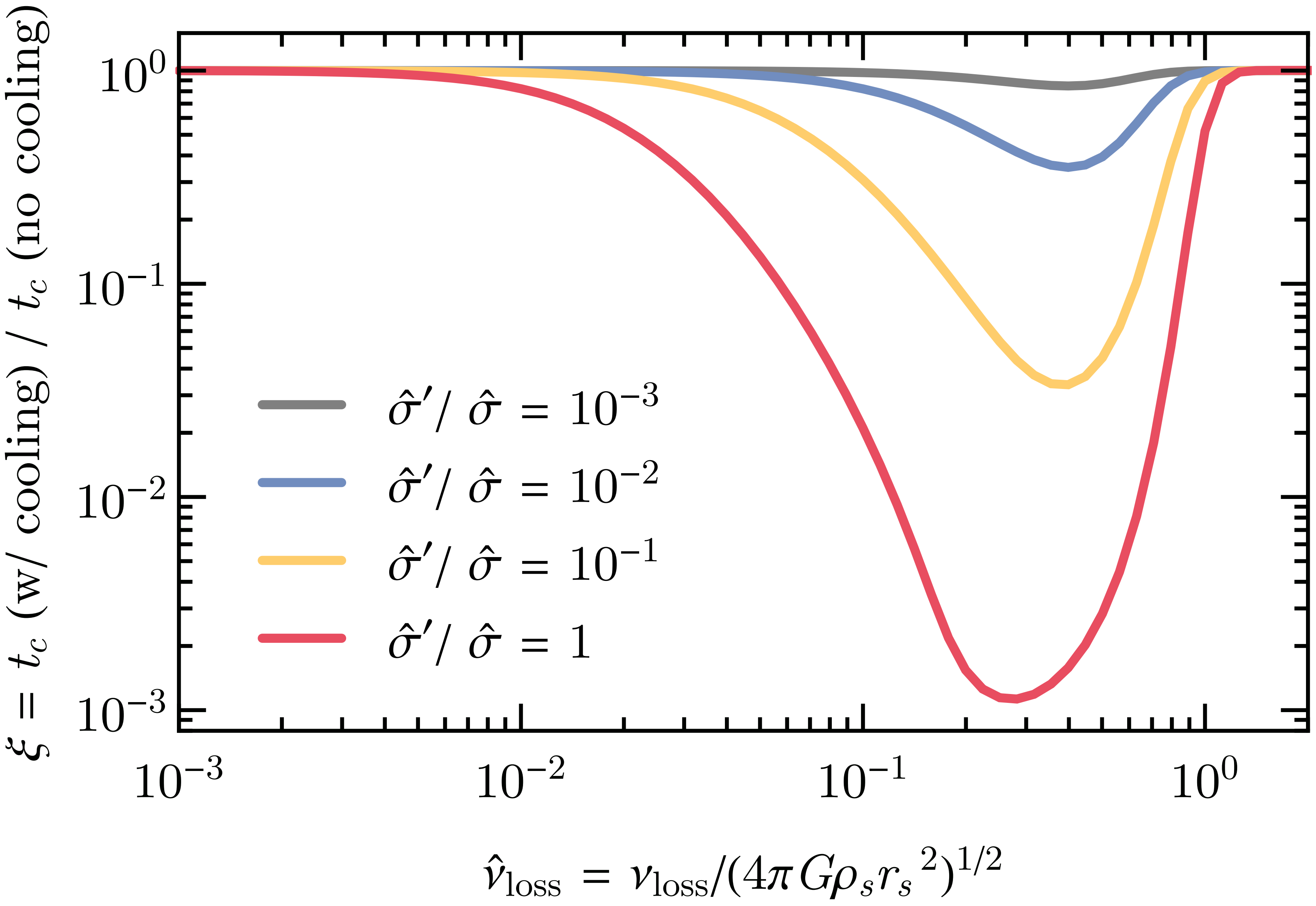
shorter time scale
similar behavior

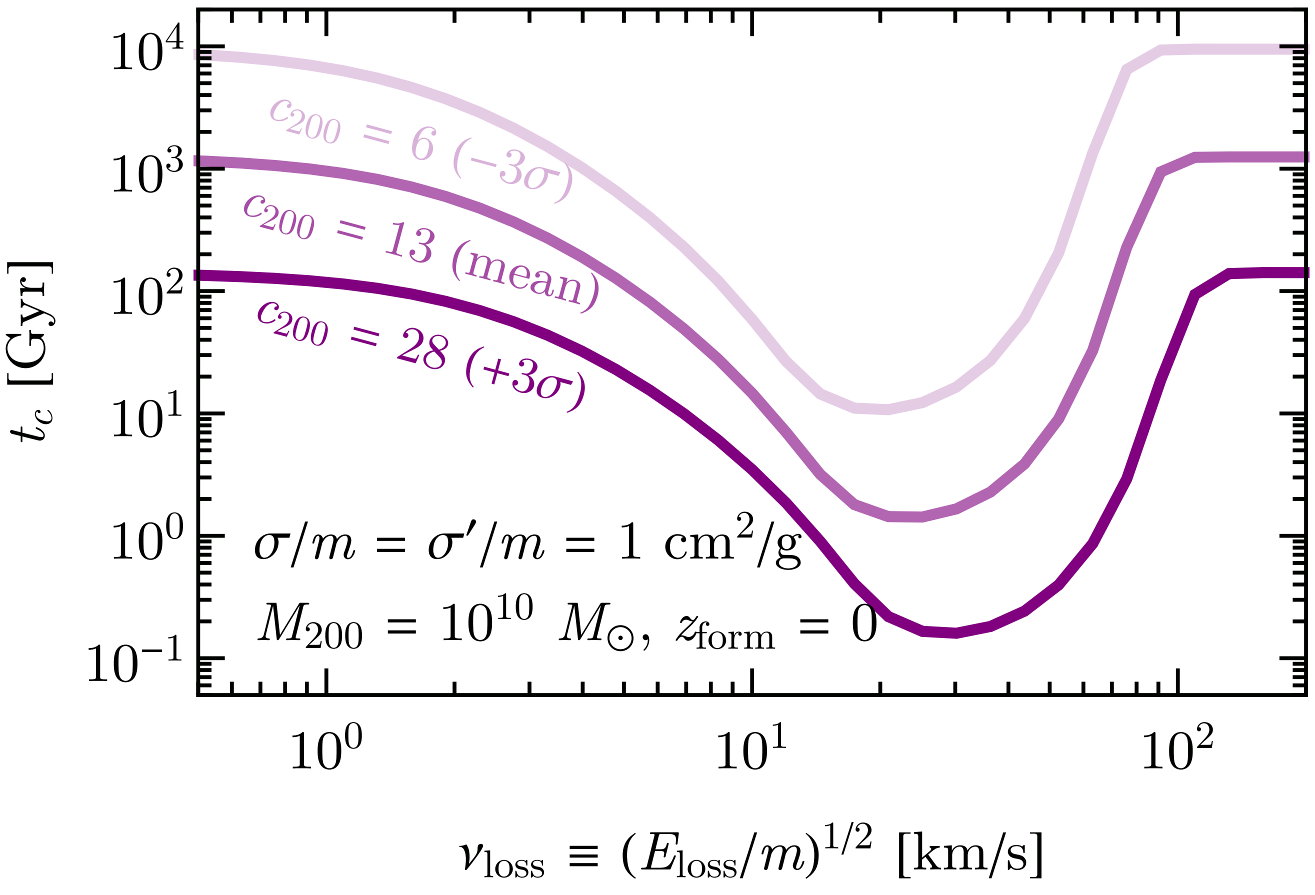
The reduction in the collapse time

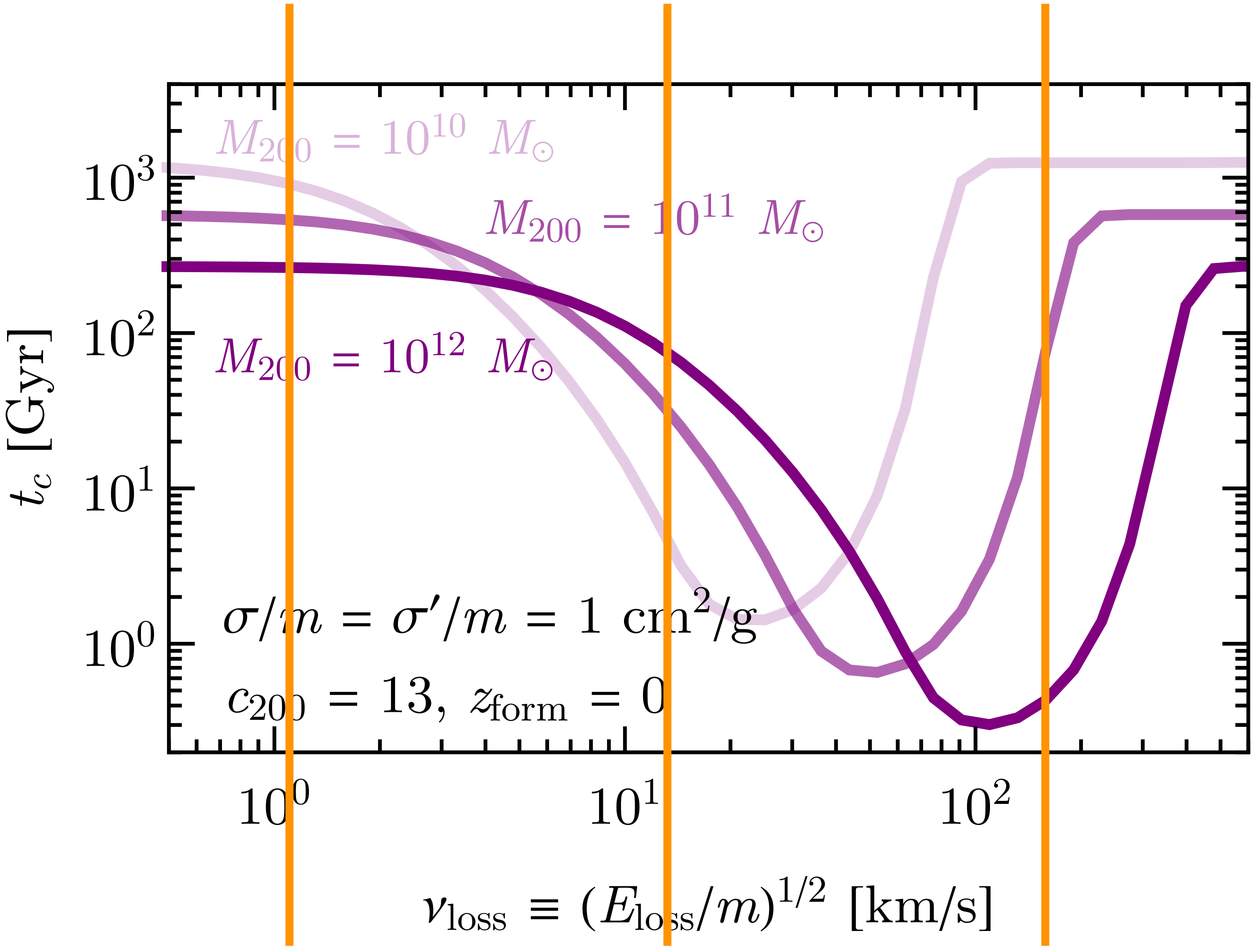
Scan over $(\hat{\sigma}, \hat{\sigma}', \hat{\nu}_{\rm loss})$ and compute the time reduction



Back to dimensional quantities

$$\rho_s = \frac{200\rho_c c_{200}^3}{3K_{c_{200}}}, \qquad r_s = \left(\frac{3M_{200}}{800\pi c_{200}^3 \rho_c}\right)^{1/3}$$

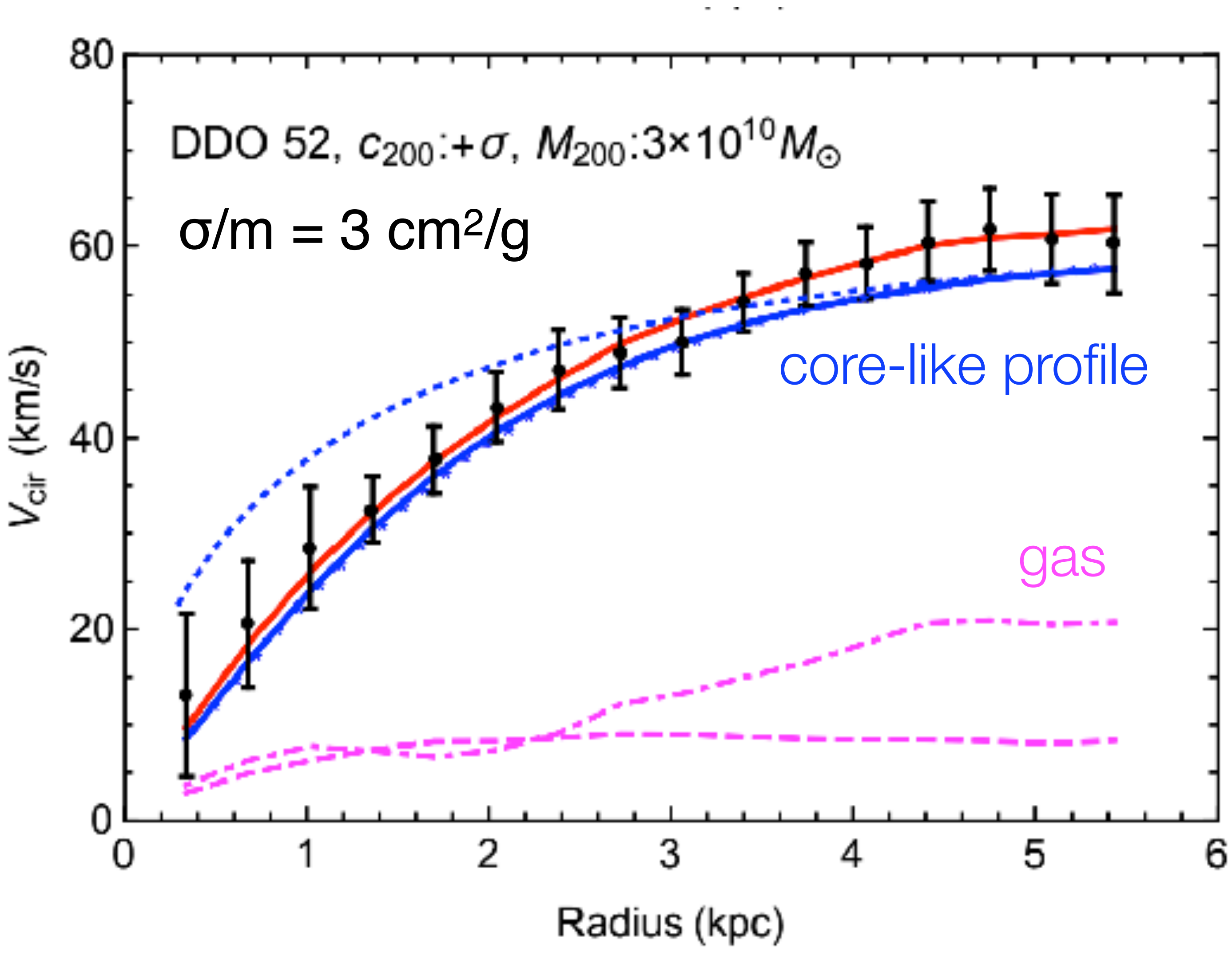




Halos with higher concentrations collapse faster

More complicated dependence on halo mass

Dwarf/LSB disfavored



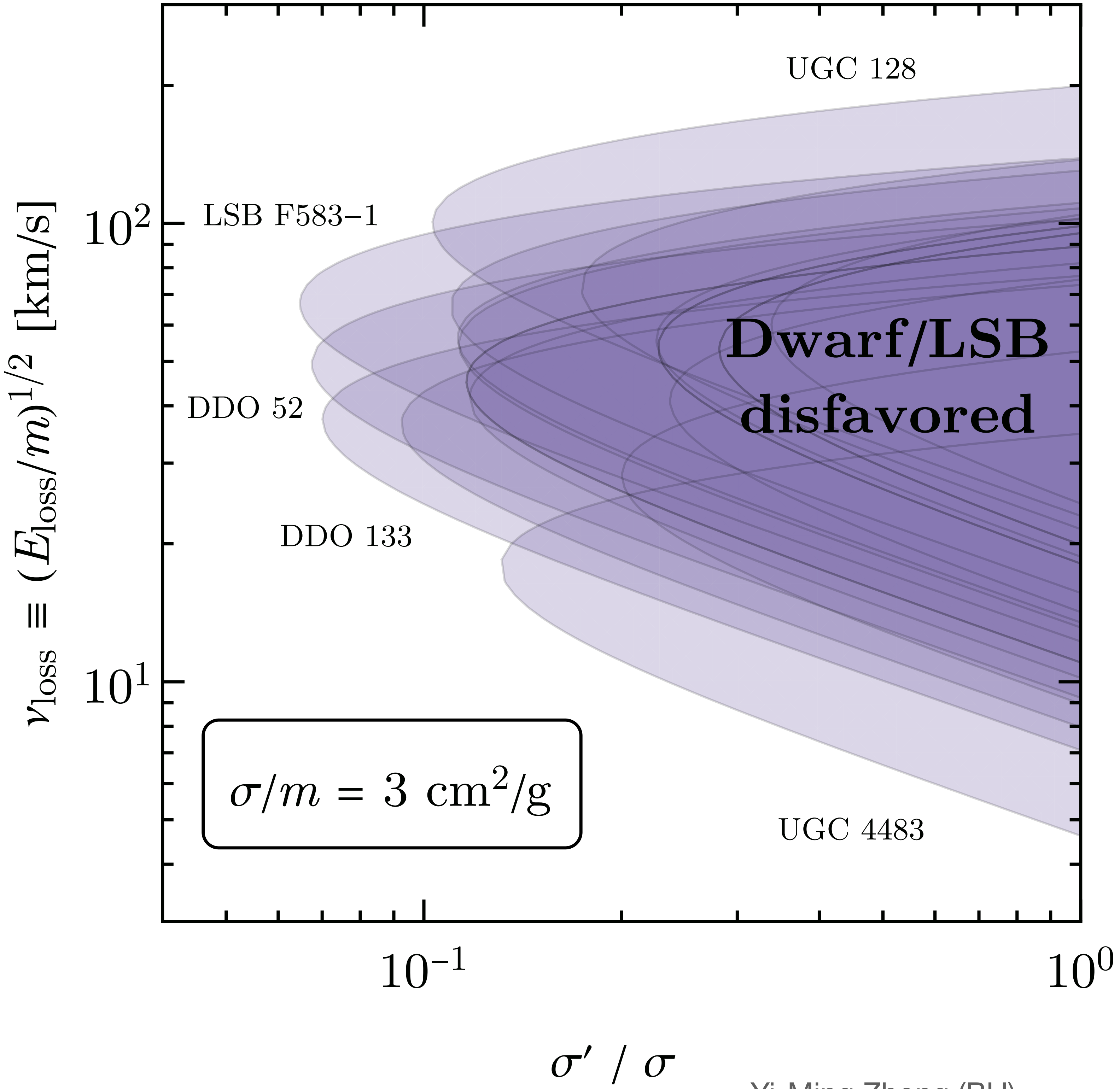
Kamada et al, '16, data from Oh eta al '15

Dwarfs/LSB 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

Dwarf/LSB disfavored



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Not see core collapse

Discussions

- Environment effects:
  - Major merger ⇒ re-virialize the merger halo ⇒ reset the clock of the evolution
  - Continuous infall/minor merger ⇒ heat the halo if significant
- Baryonic effects
- Spin

Give birth to the first 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.:
  - J1342+0928: $M = 7.8 \times 10^8\ M_\odot$, $z = 7.54$ — Bañados et al, '17
  - J1120+0641: $M = 2.0 \times 10^9\ M_\odot$, $z = 7.09$ — Mortlock et al, '11
  - J0100+2802: $M = 1.2 \times 10^{10}\ M_\odot$, $z = 6.33$ — Wu et al, '15
- **So massive & so ancient. How do they form??**

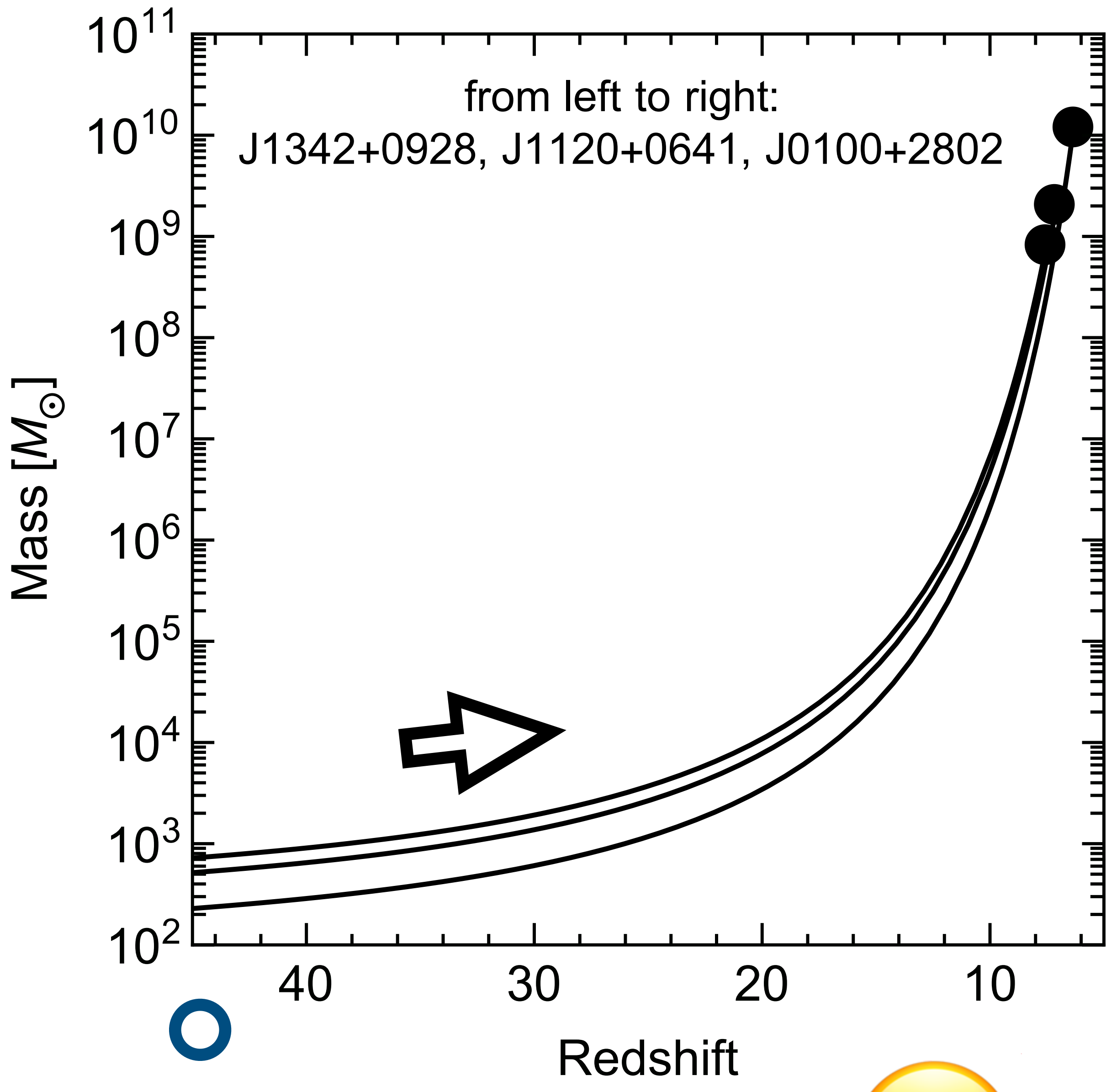
The first SMBH puzzle

see review by Volonteri ‘10

- Classical solution:
  - PopIII star collapses (10-100 M⊙) ⇒ seed BH ⇒

    Eddington accretion ⇒ massive BH

  - Need to fine tune the baryonic physics



🙁

The SMBH puzzle

- More likely solutions:

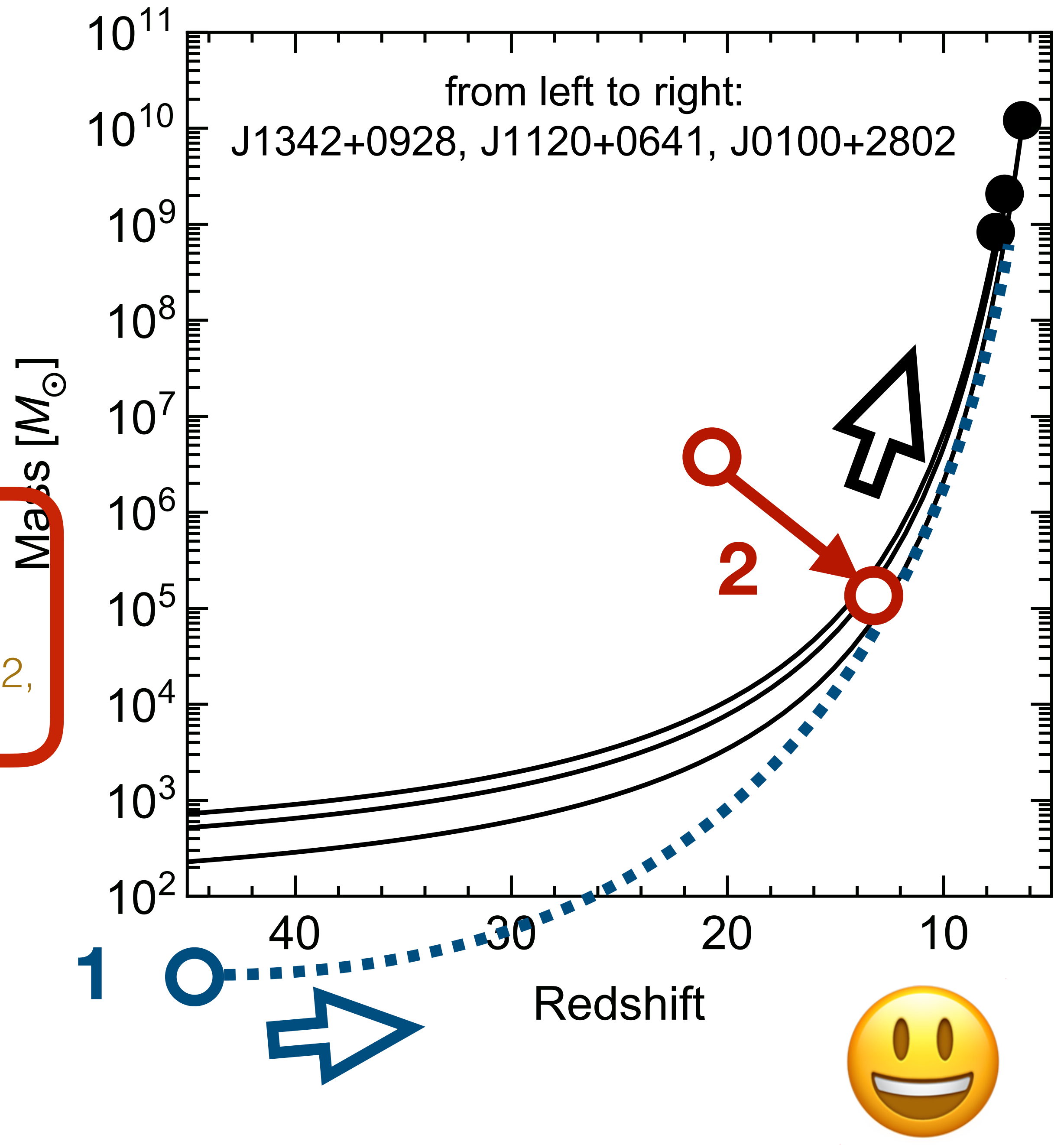
1. Faster accretion:
   BH merger…

2. Larger seed BH:

   gravothermal collapse
   of SIDM halos, Balberg & Shapiro ’02, Pollack et al '15

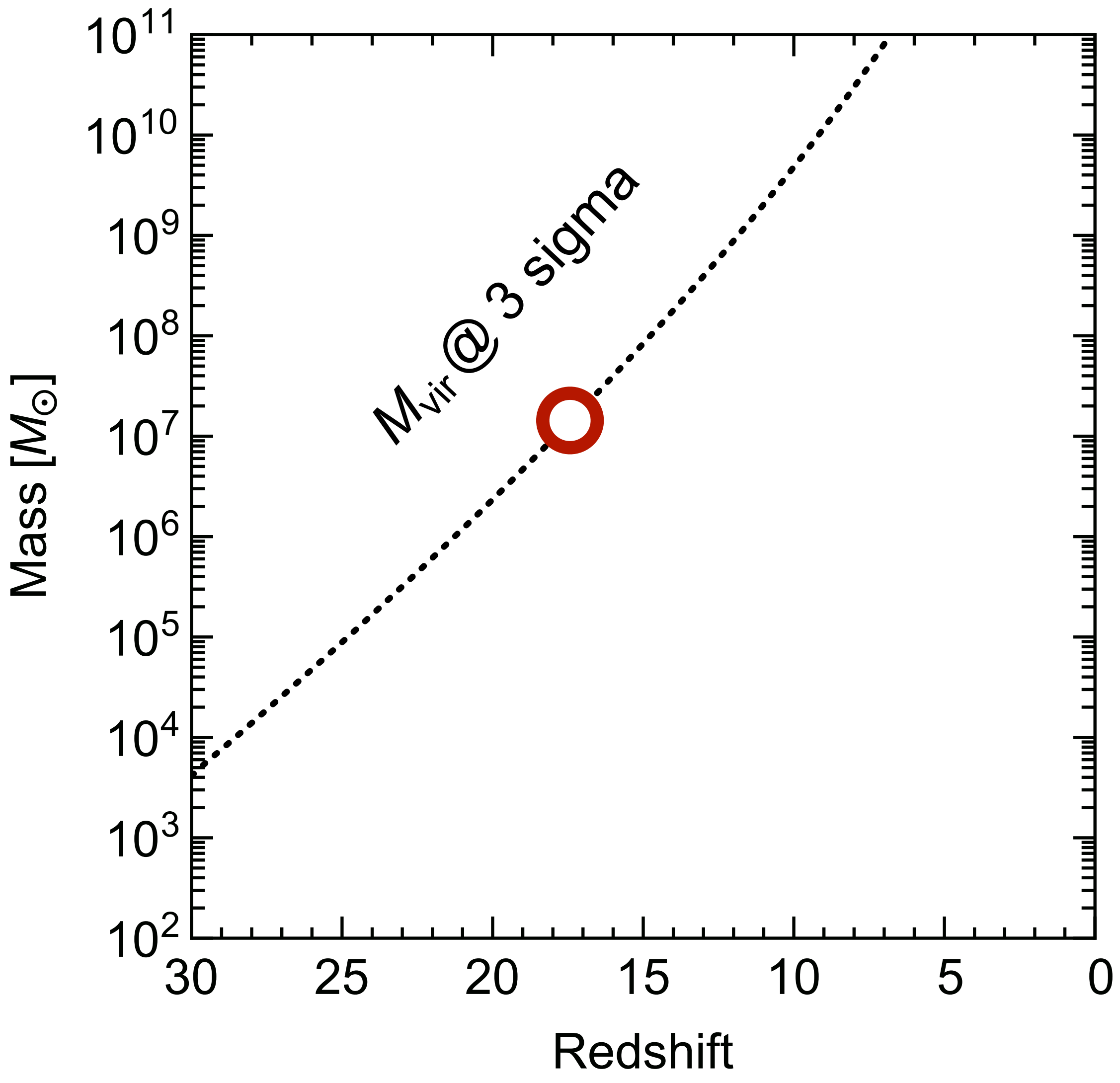
   direct collapse of pre-galactic gas discs…

   Lodato & Natarajan ‘06



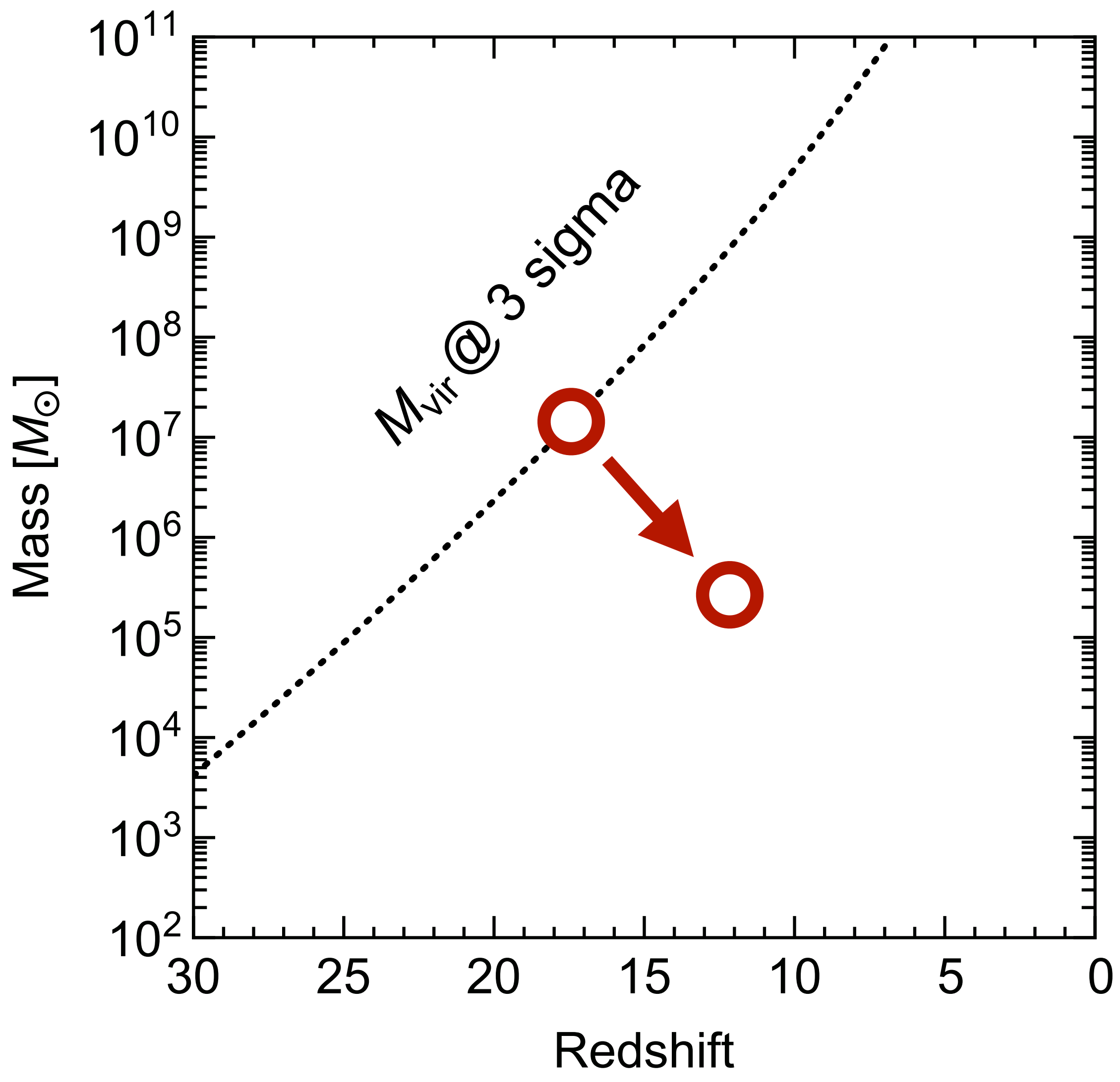
Brief history of SMBH

1. Take an initial halo from cosmological density perturbation (e.g. 3σ fluctuation from Press-Schechter)



Brief history of SMBH

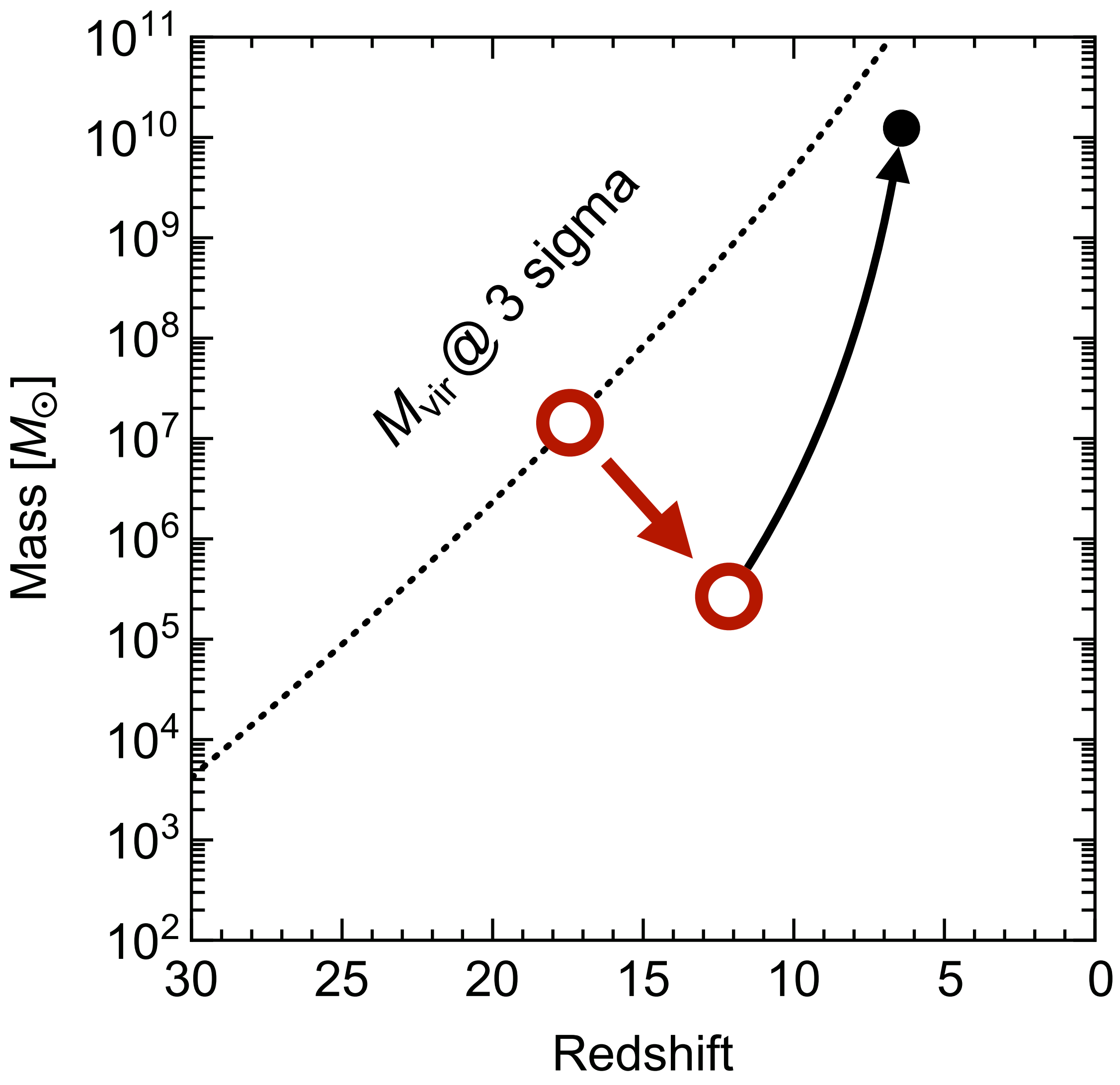
2. Collapse according to gravothermal evolution



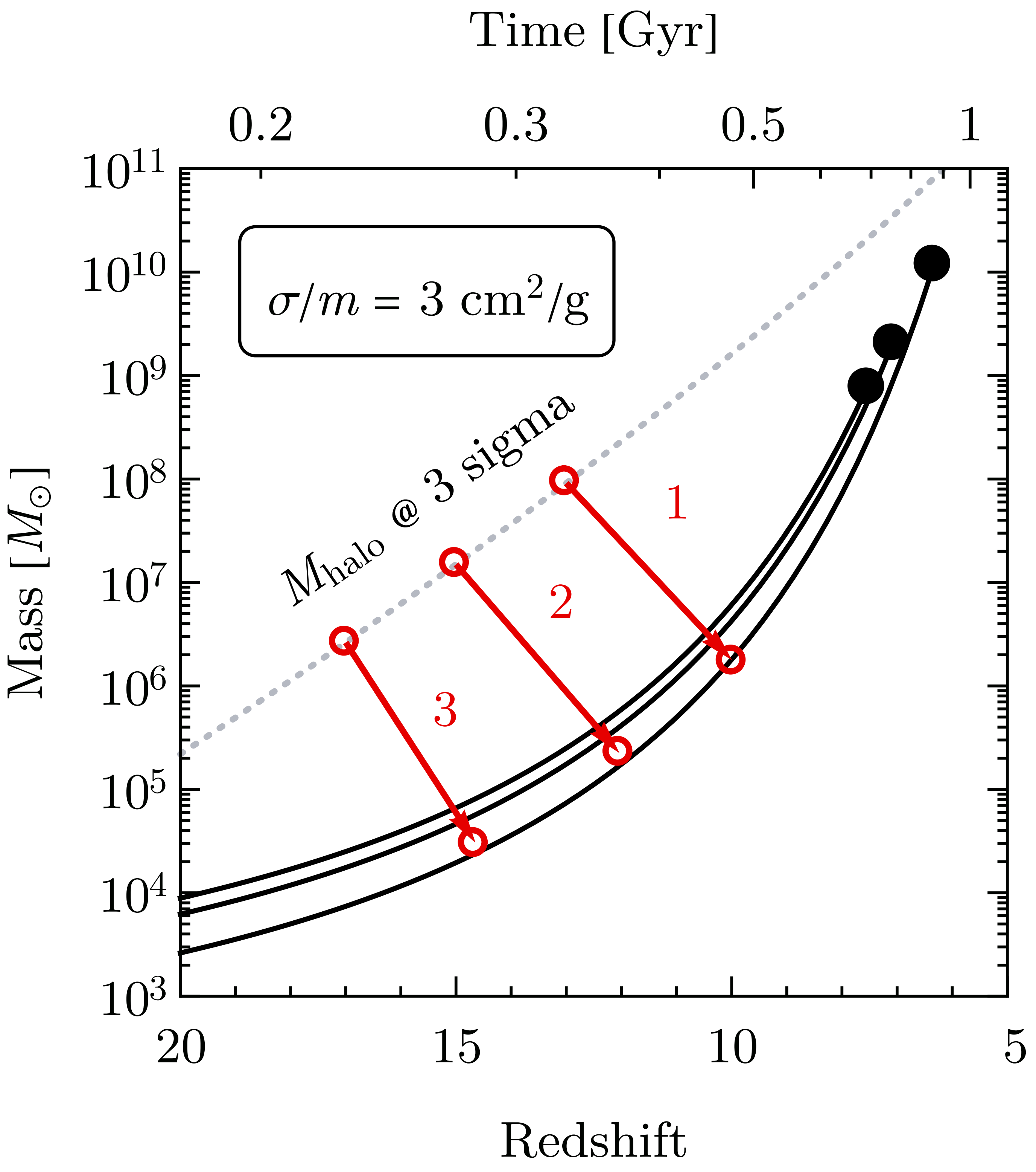
Brief history of SMBH

3. Eddington accretion

(t_{Edd} = 450 Myr, ϵ = 0.1)

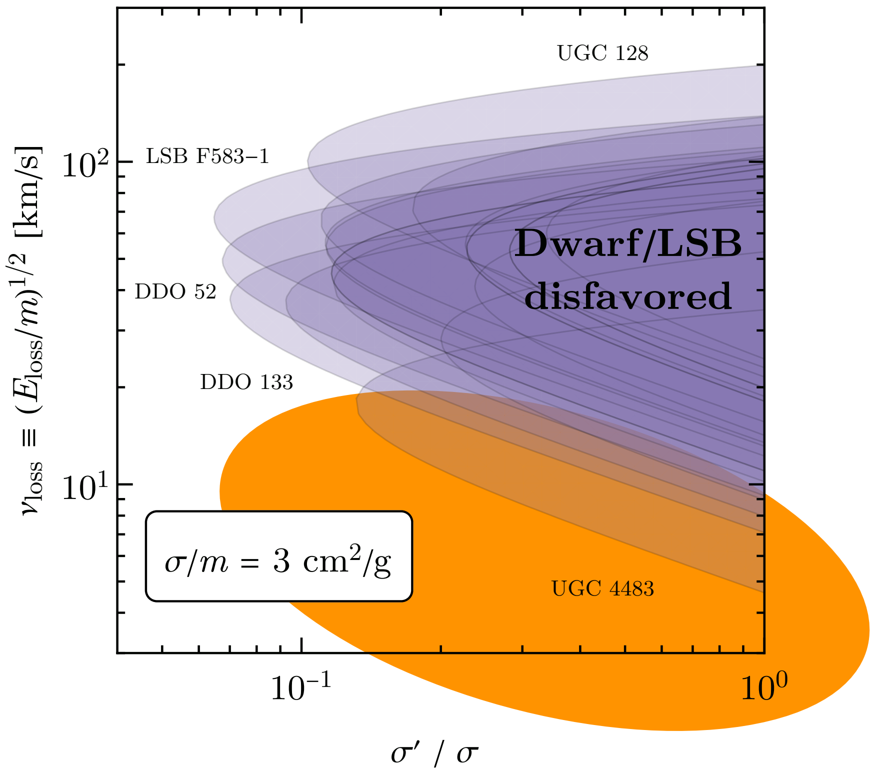


Preliminary result



	σ'/σ	$\nu_{\rm loss}$ [km/s]	M_{200} [$M_\odot$]	c_{200}
1	0.1	20	9.1×10^7	7
2	0.2	10	1.5×10^7	6
3	0.7	3	2.6×10^6	5

prefer high *c*



Discussions

The lucky few??

- Environment effects:
  - Major merger ⇒ re-virialize the merger halo ⇒ reset the clock of the evolution
  - Continuous infall/minor merger ⇒ heat the halo if significant
- Baryonic effects
- Spin

Observation

- Look into the position of SMBH (at the halo center) and the inner density profile of the host halos (cuspy w/ log-slope ~-2)
  [different from “SIDM accretion”]

- James Webb Space Telescope has the capacity to discover more SMBH’s
  ⇒ sharpen the SMBH puzzle

- Discover SMBHs in ultra-diffuse dwarfs
  ⇒ strong support for SMBH from collapsed DM halo

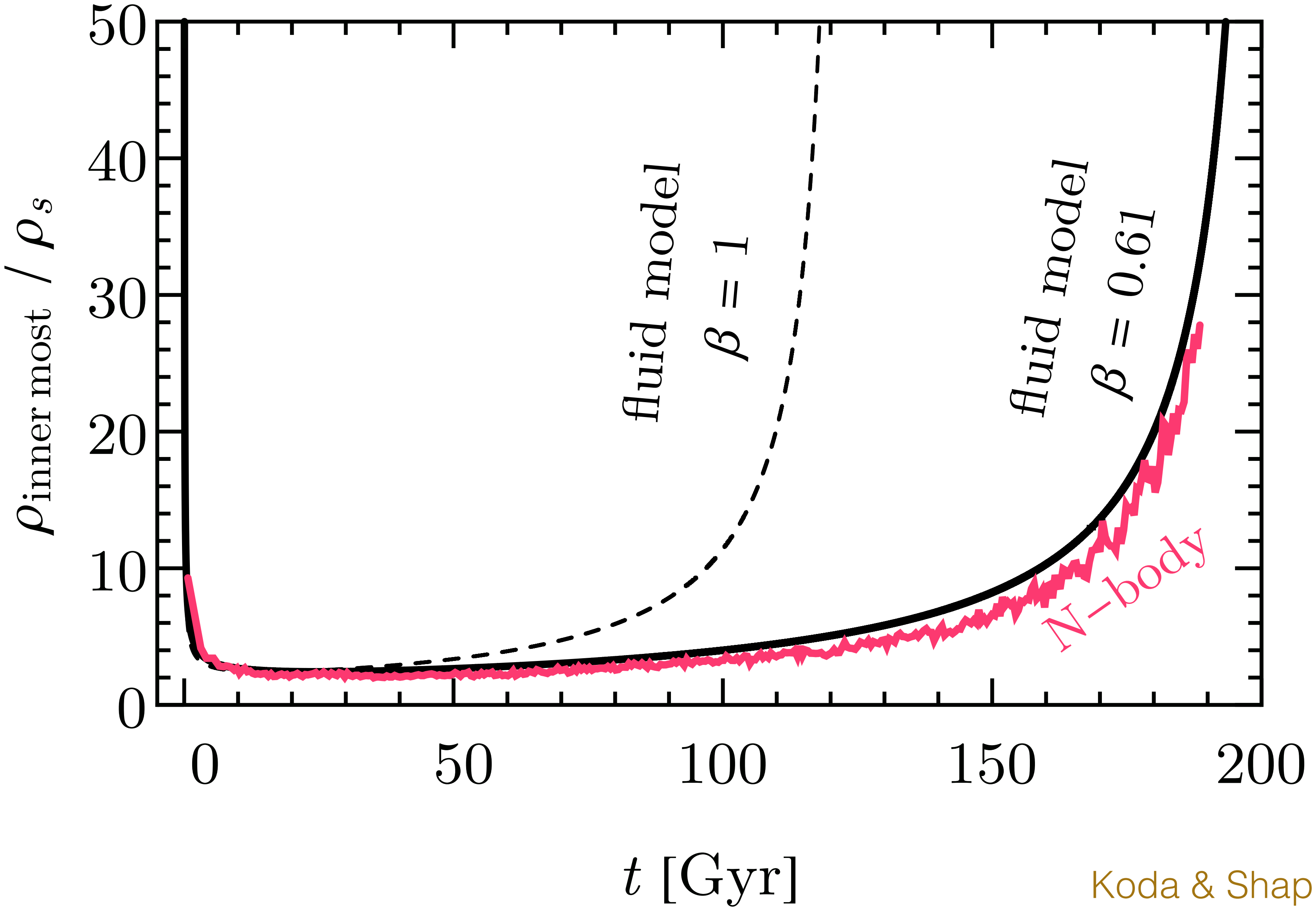
Summary

- DM self-interactions (elastic/dissipative) may change halos’ evolution. They can be probed by astronomical observations.

- The collapsed halo provide new ways to form the SMBH’s. (SMBH’s are likely surrounded by cuspy inner profiles.)

Backup

Calibration



Koda & Shapiro, '11