Self-interacting dark matter, collapsed halos, and high-redshift supermassive black holes

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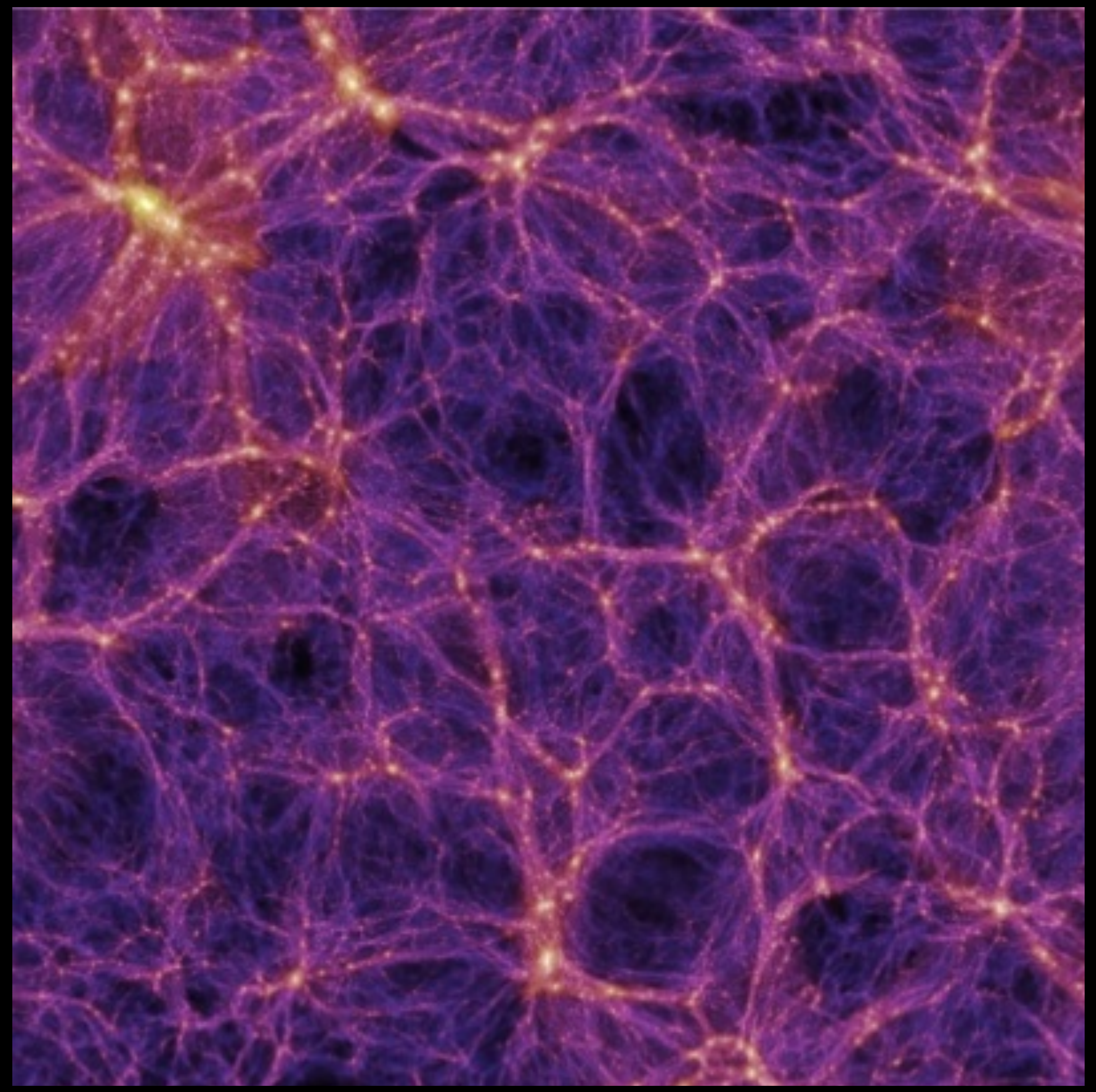
chan Island
大铲岛
RESIDENTIAL
DISTRICT
粤海
SHEKOU
RESIDENTIAL
DISTRICT
蛇口
Dapen
Peninsu
大鹏半
CUHK
CityU
HKUST
Kau Sai Chau
滘西洲
Tsing Yi
Village
Airport
Hong Kong
香港
Chek Lap Kok
赤鱲角
HKU
Lantau Island
大嶼山
Hong Kong
Island
香港島
Cheung Sha
Lamma Island
南丫島

Outline

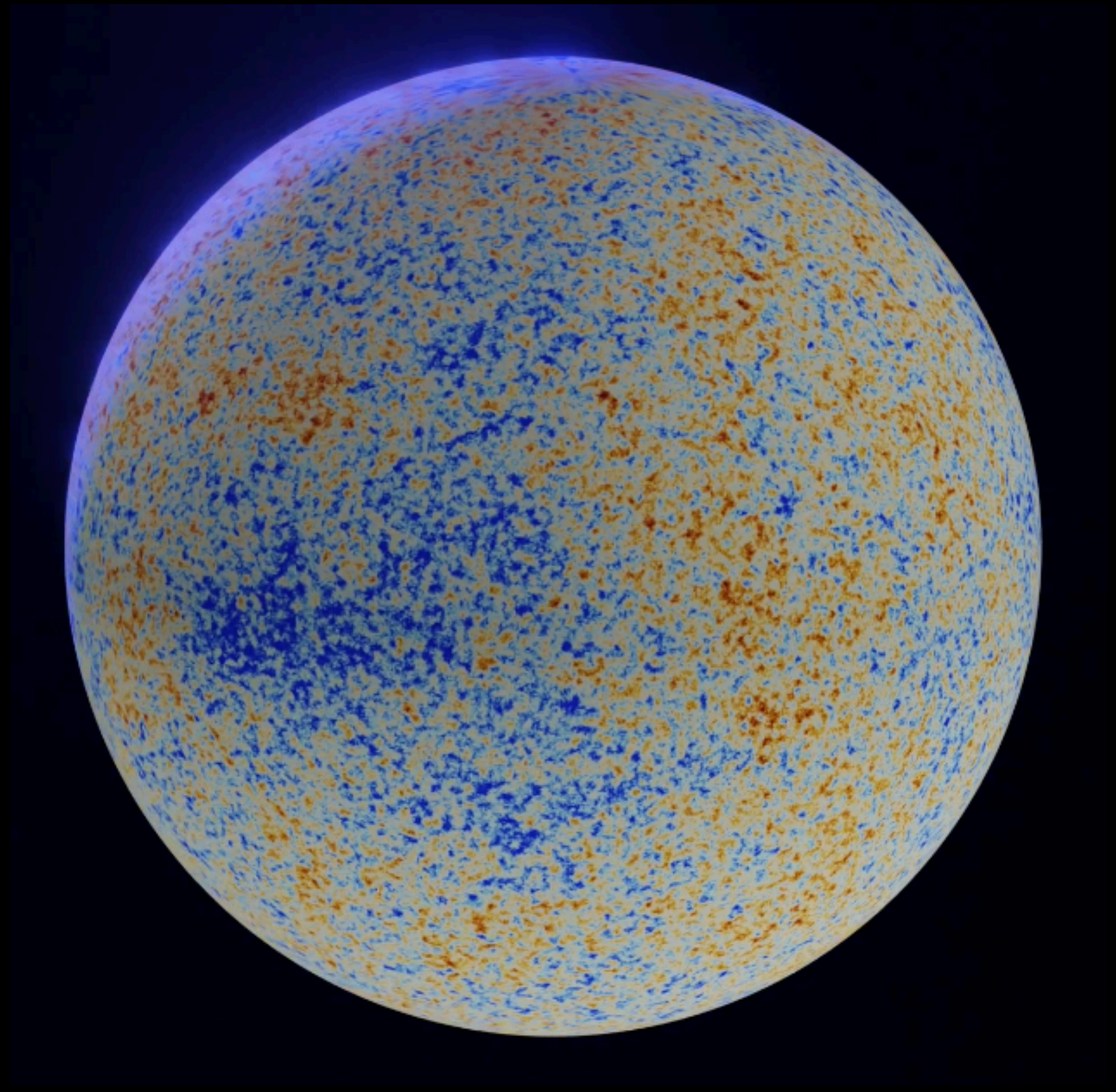
- Introduction
- Gravothermal collapse of self-interacting dark matter (SIDM) halos
- Collapsed halos give birth to high-z supermassive black holes
- Summary

Evidence for dark matter

Bullet Cluster

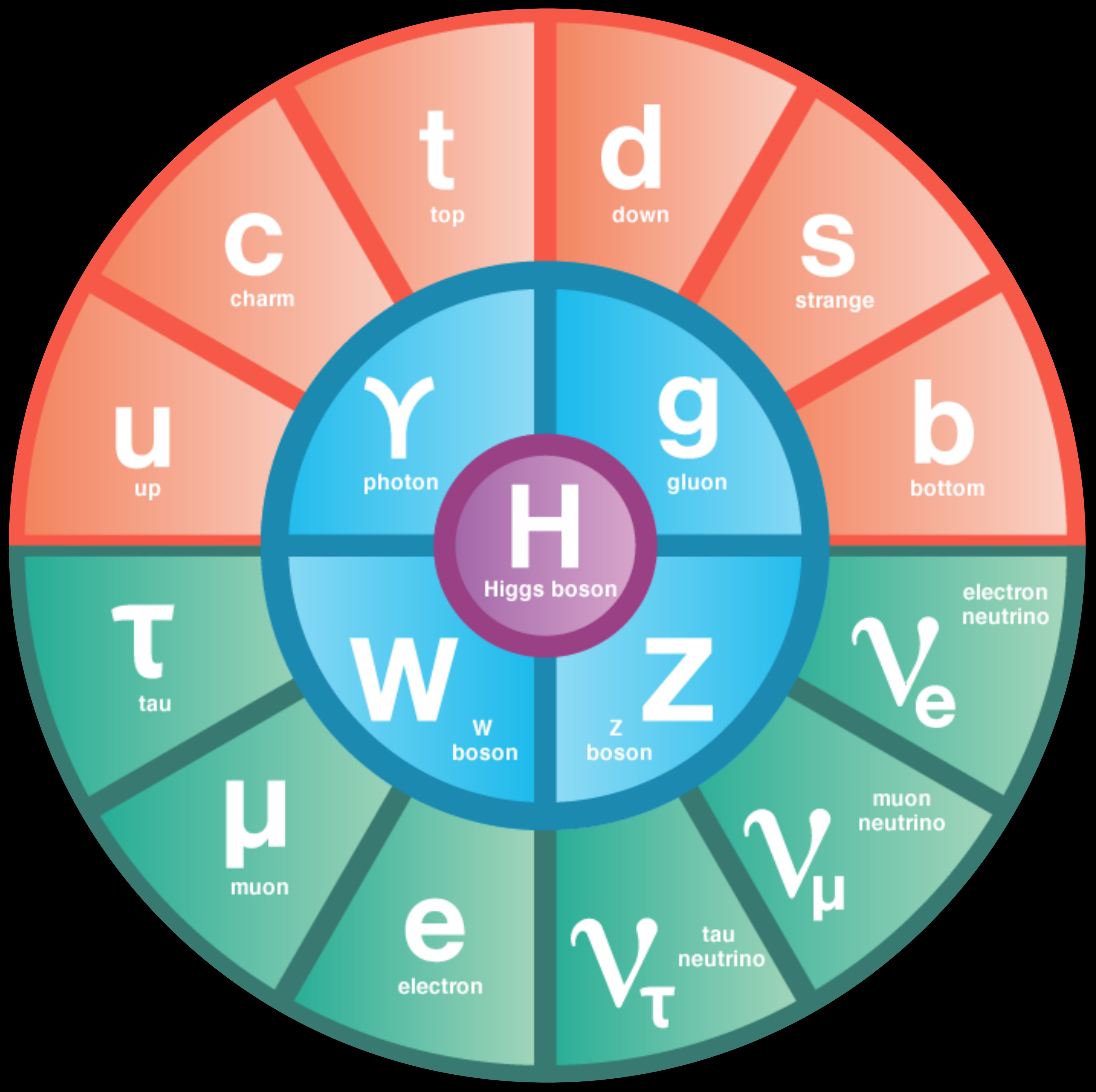


Large-Scale Structure

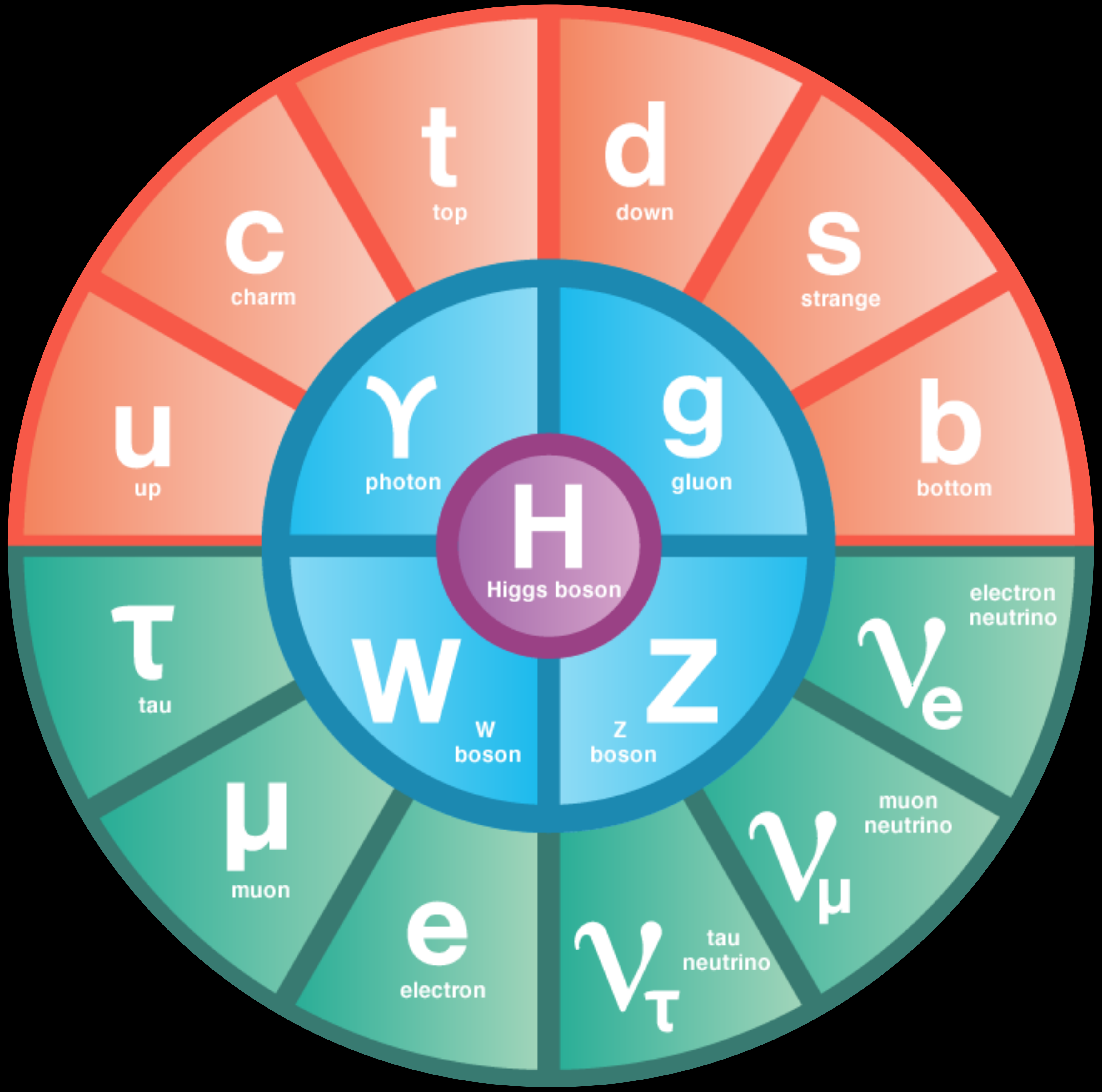


Cosmic Microwave Background

Ordinary matter



The Standard Model of Particle Physics



Ordinary matter

What is dark matter?

Dark matter candidate

Astro bound

Ultralight dark matter (e.g. axion, dark photon)

Weakly interacting massive particles (WIMP)

Ultraheavy dark matter (e.g. black holes)

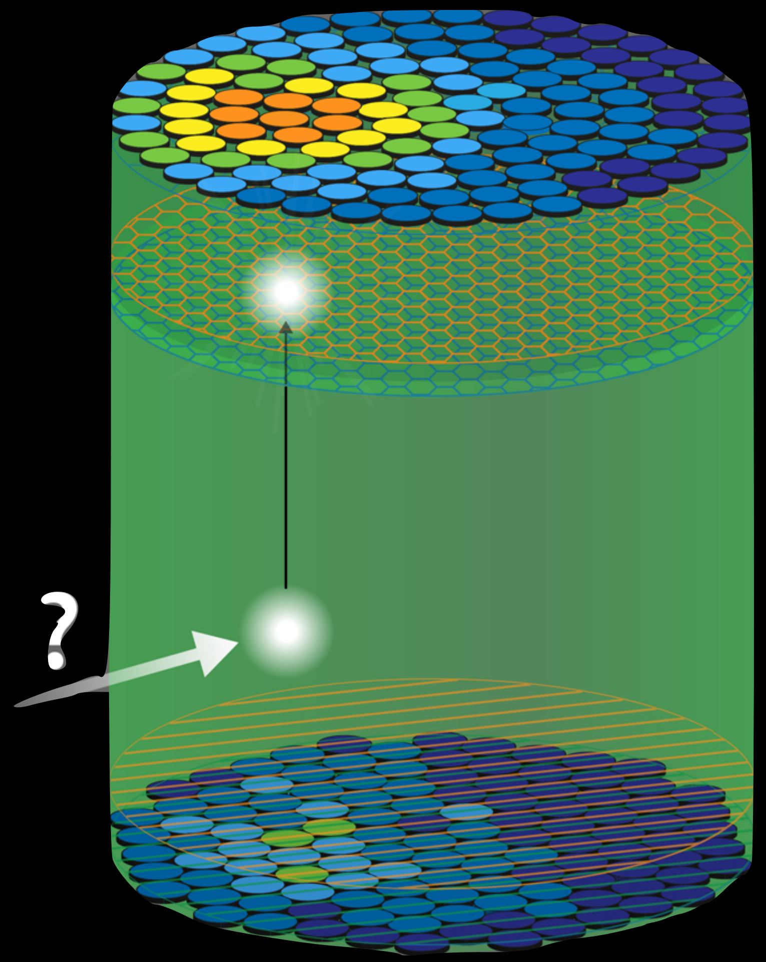
Astro bound

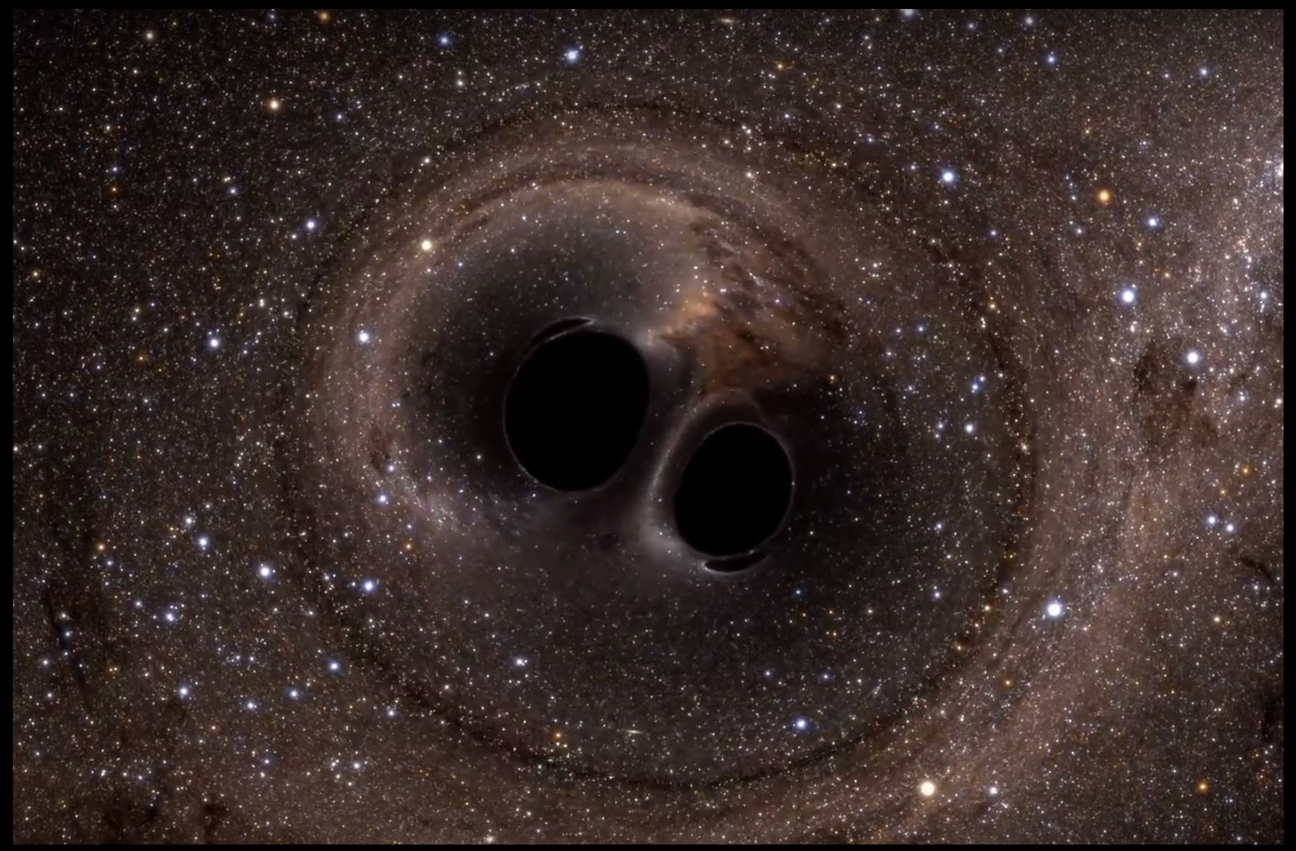
mass

10^{-22} eV — 1 eV

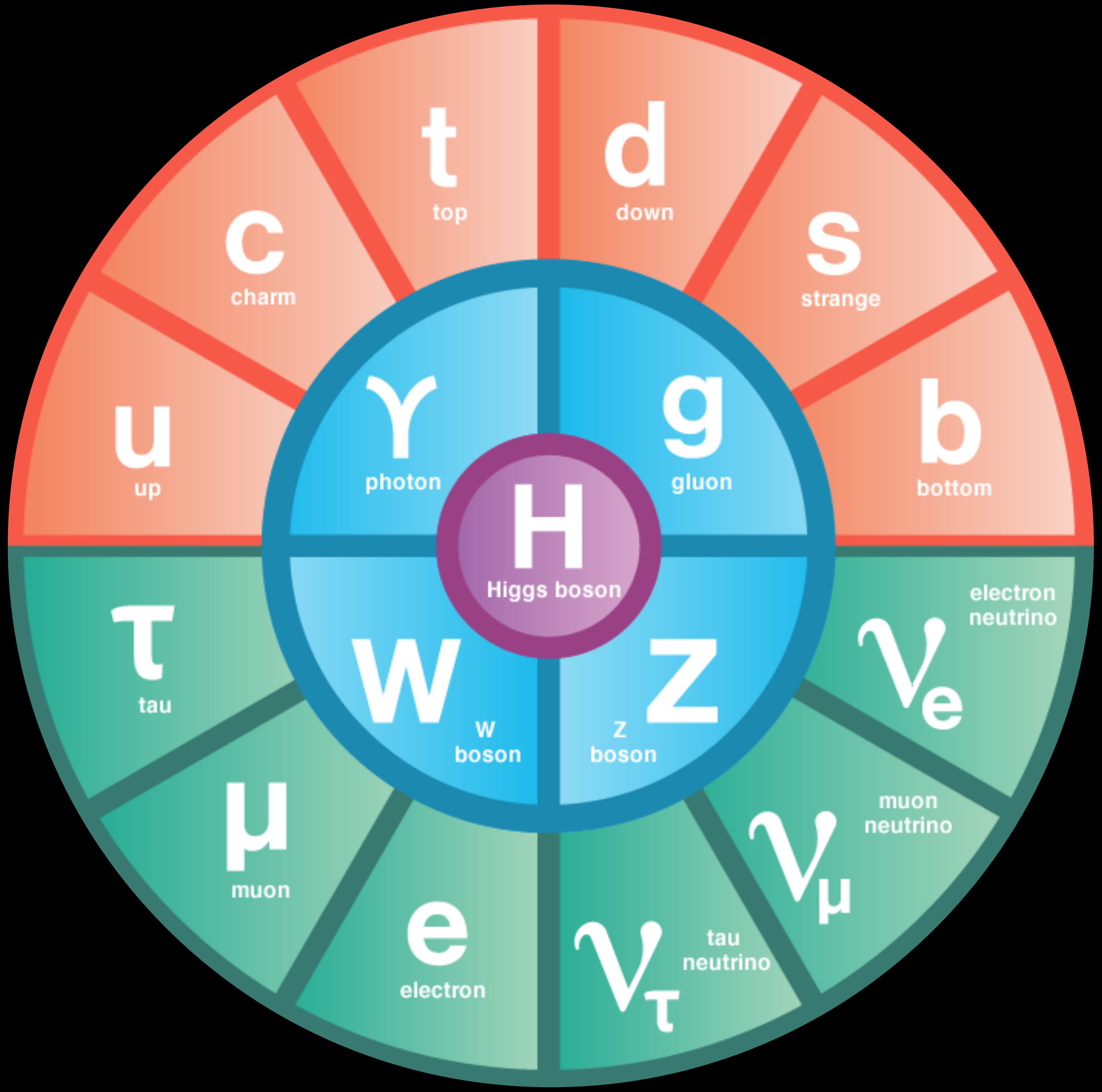
10^{9} eV — 10^{13} eV

10^{50} eV — 10^{53} eV

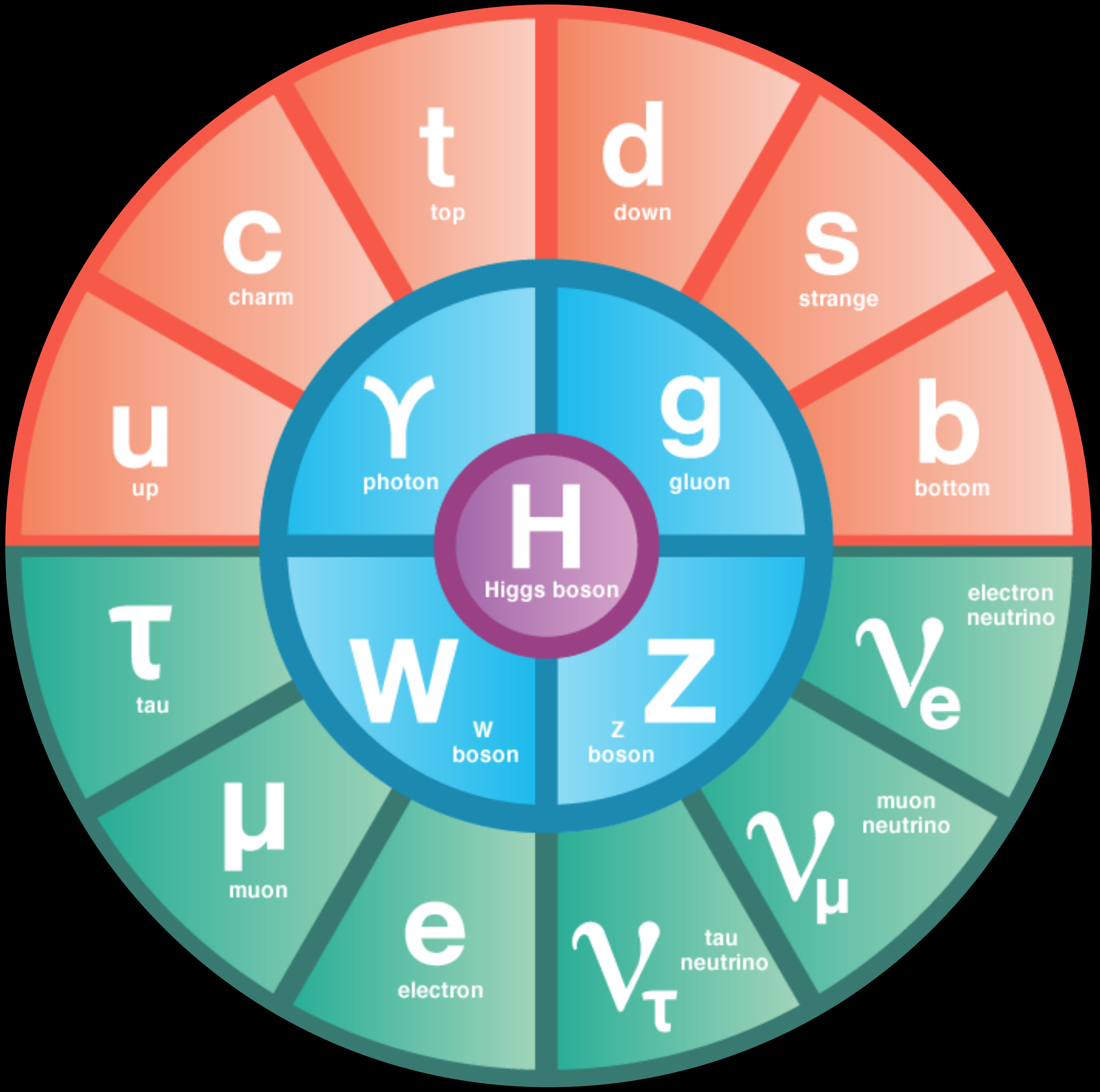




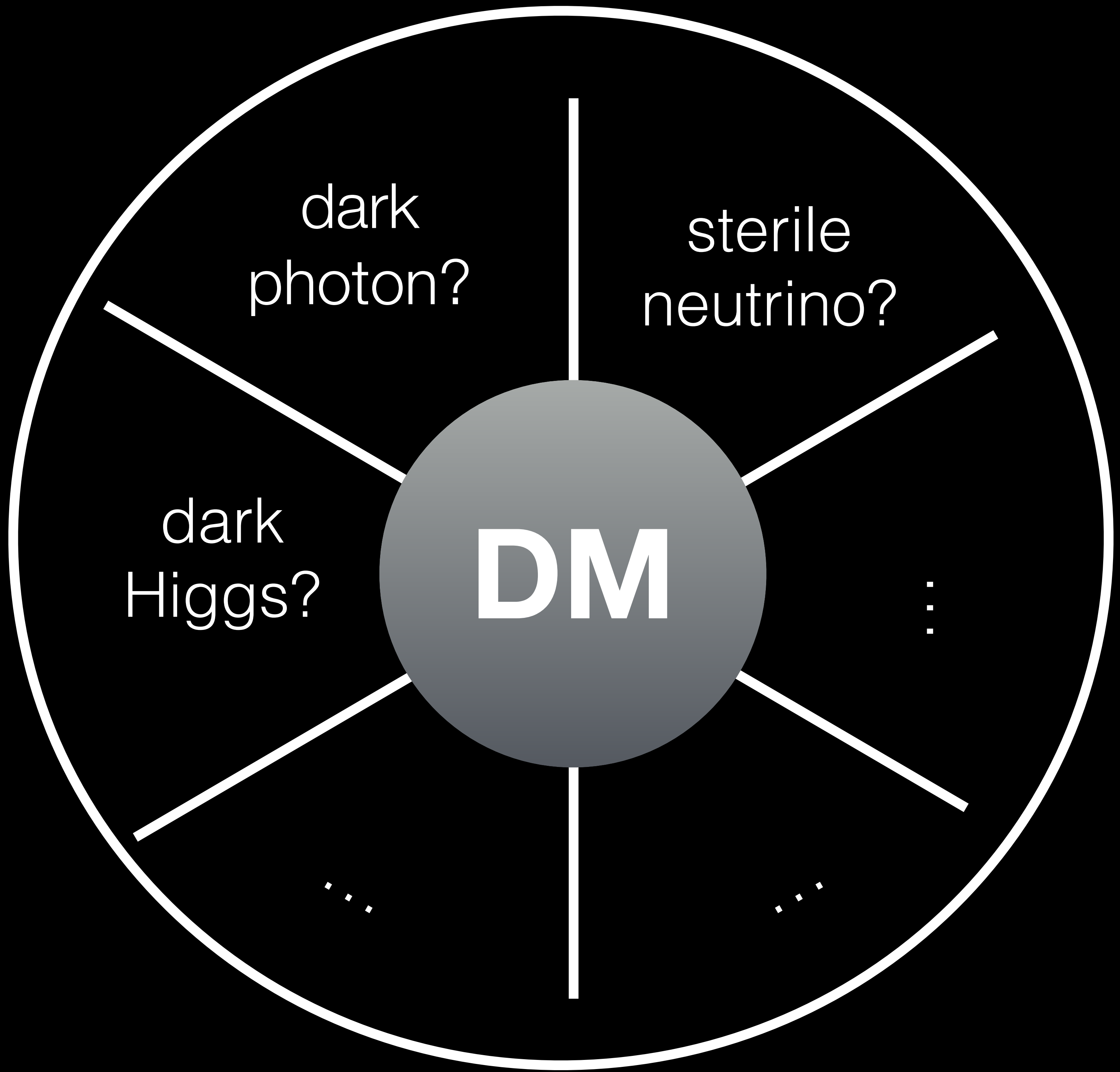
Is dark matter alone?



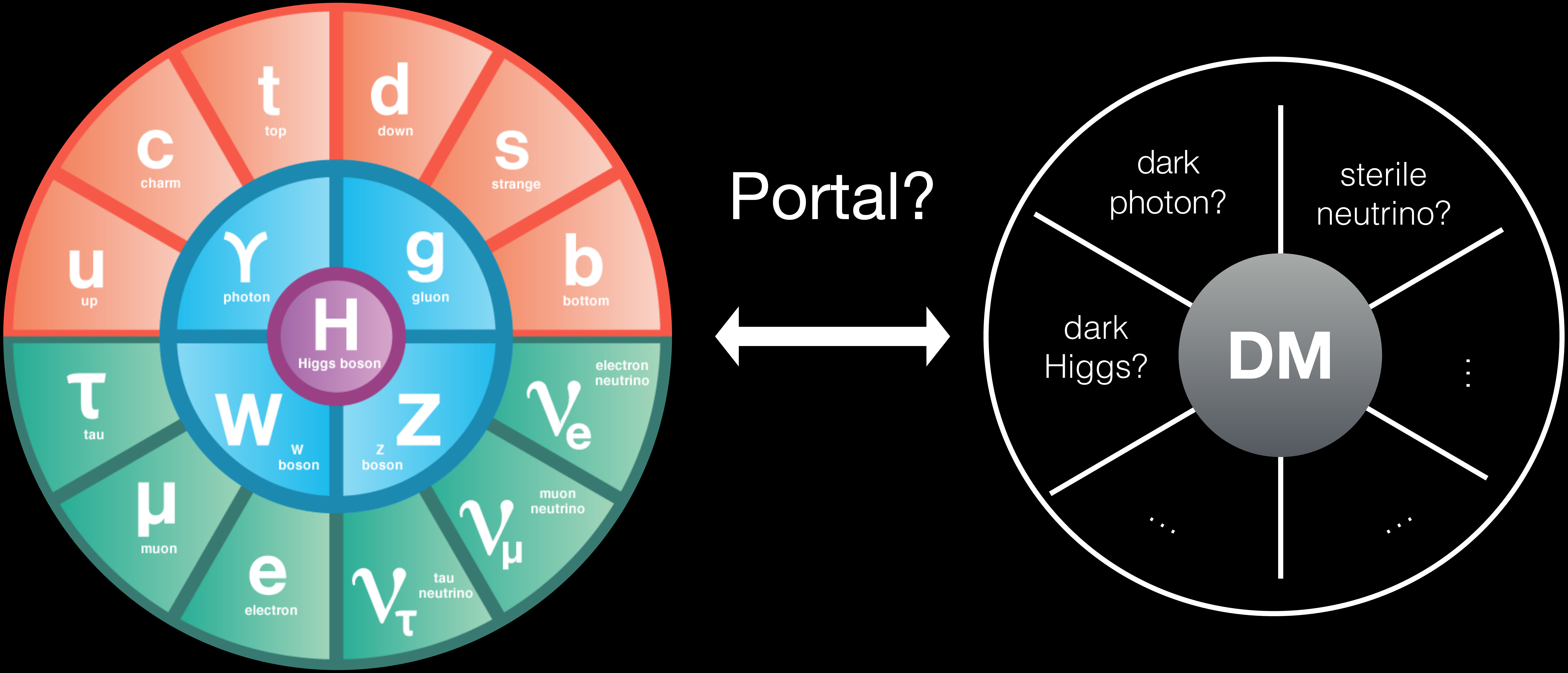
Ordinary matter



Ordinary matter



Dark sector

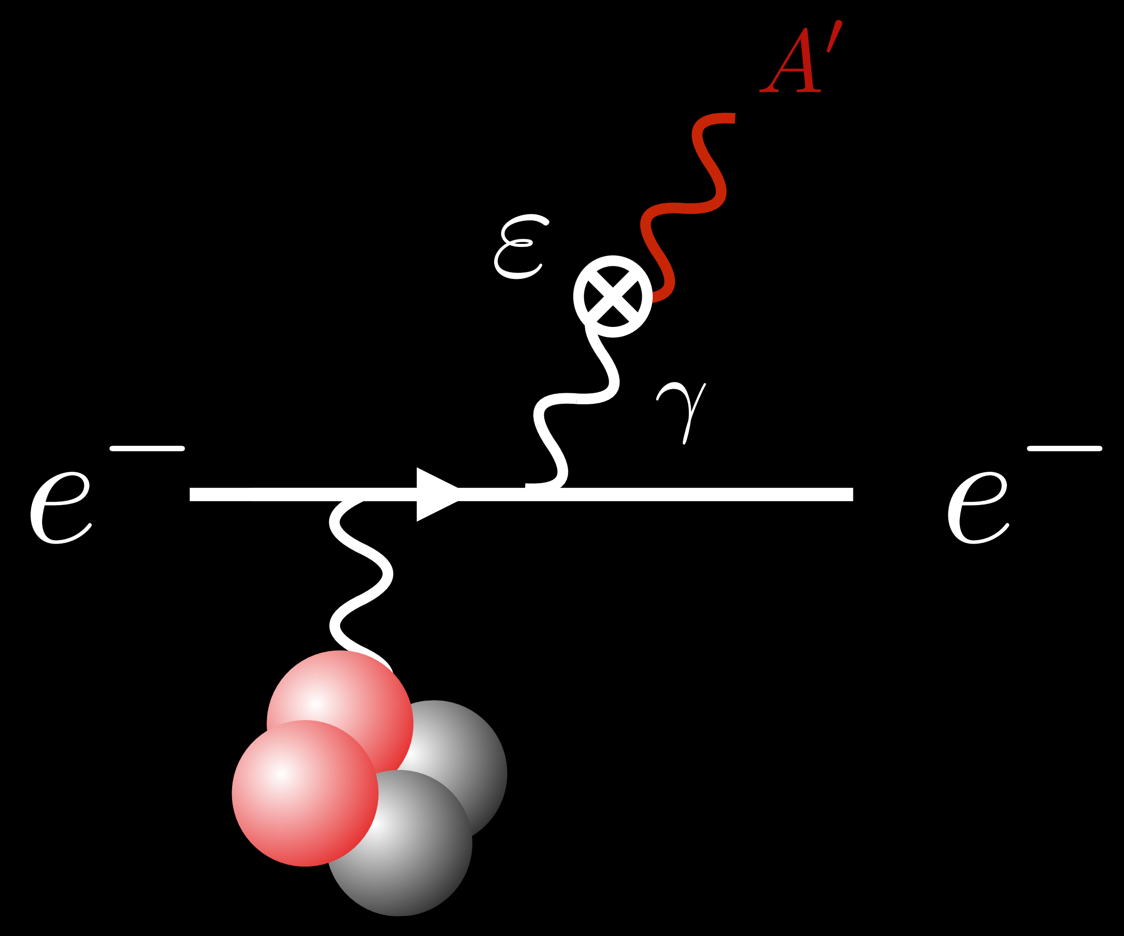


Ordinary matter

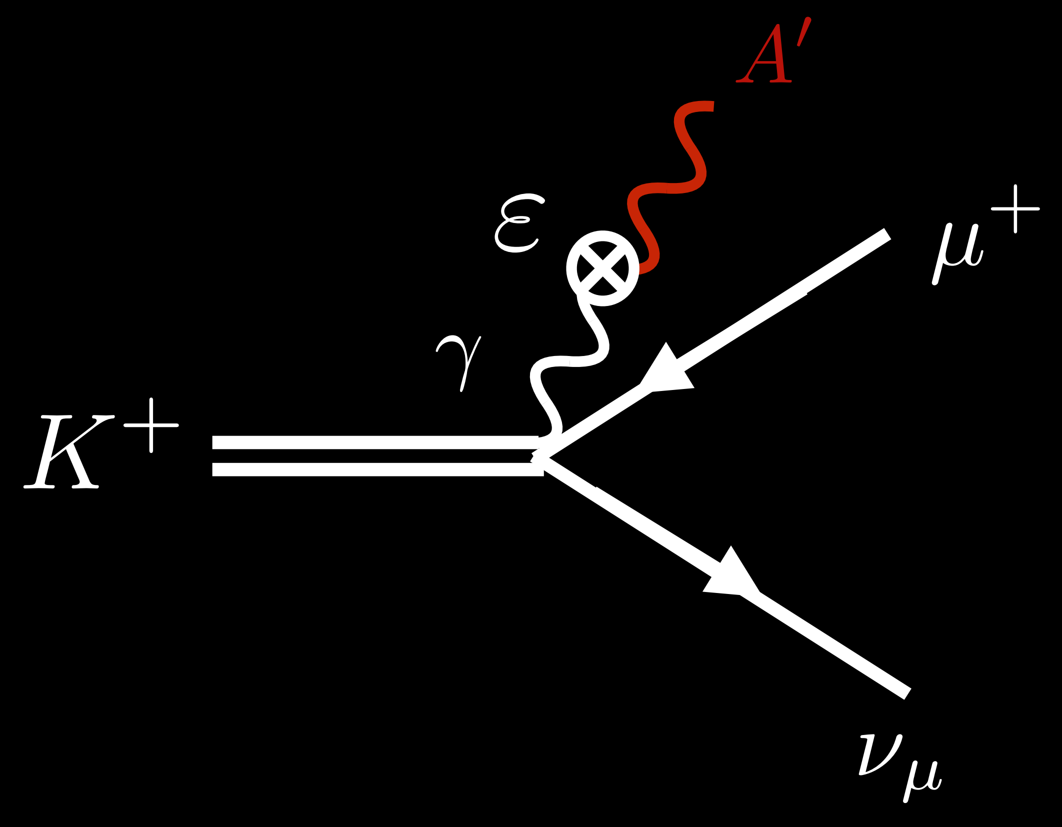
Dark sector

Dark sector searches

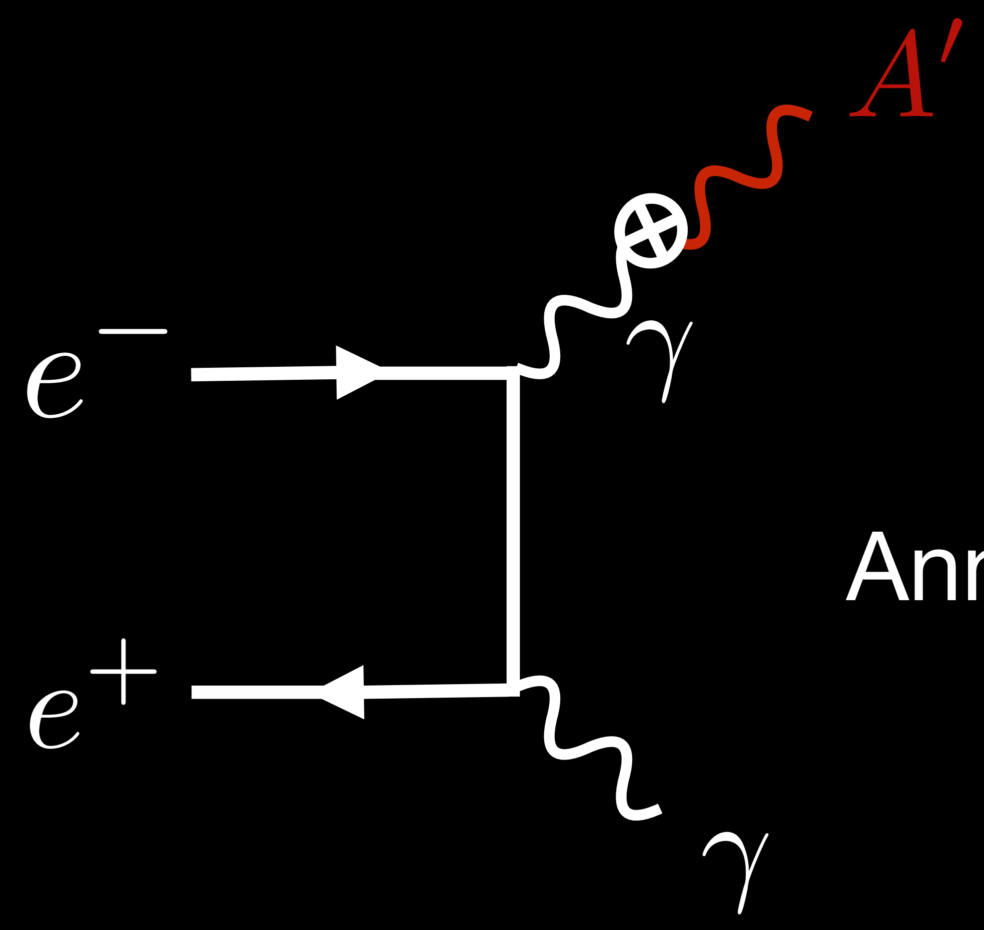
If dark photon couples to the Standard Model charged particles



Bremsstrahlung



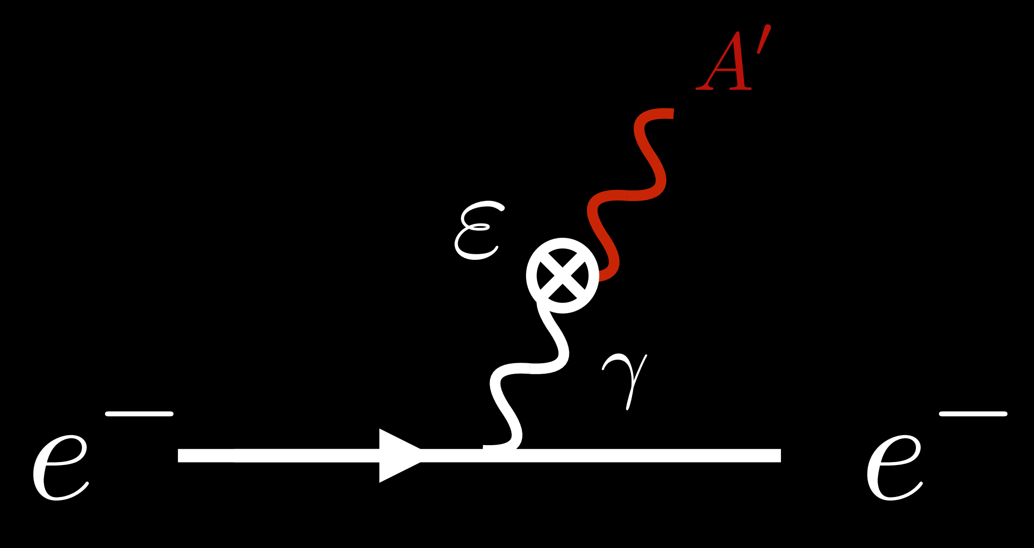
Decay



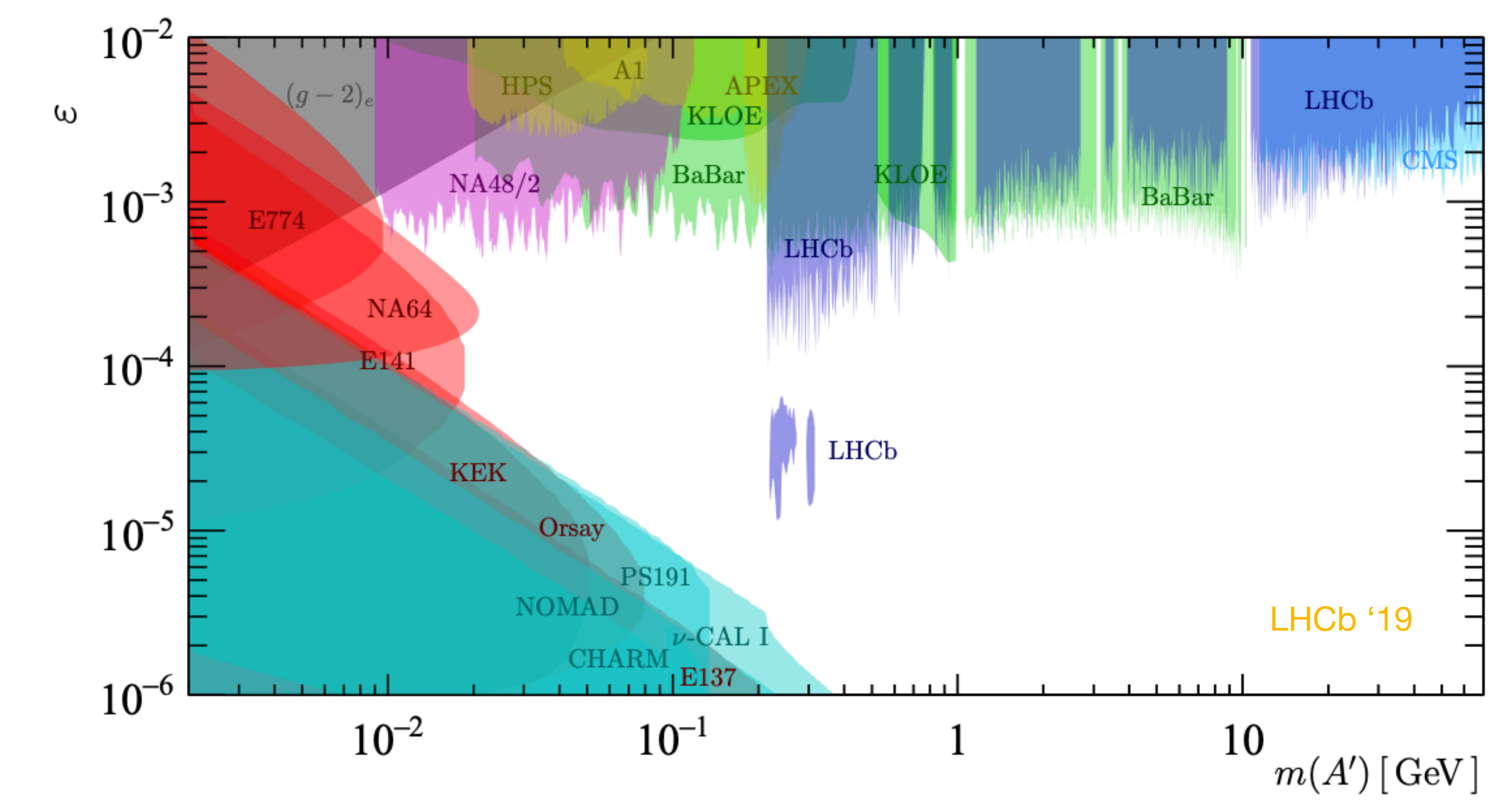
Annihilation

Dark sector searches

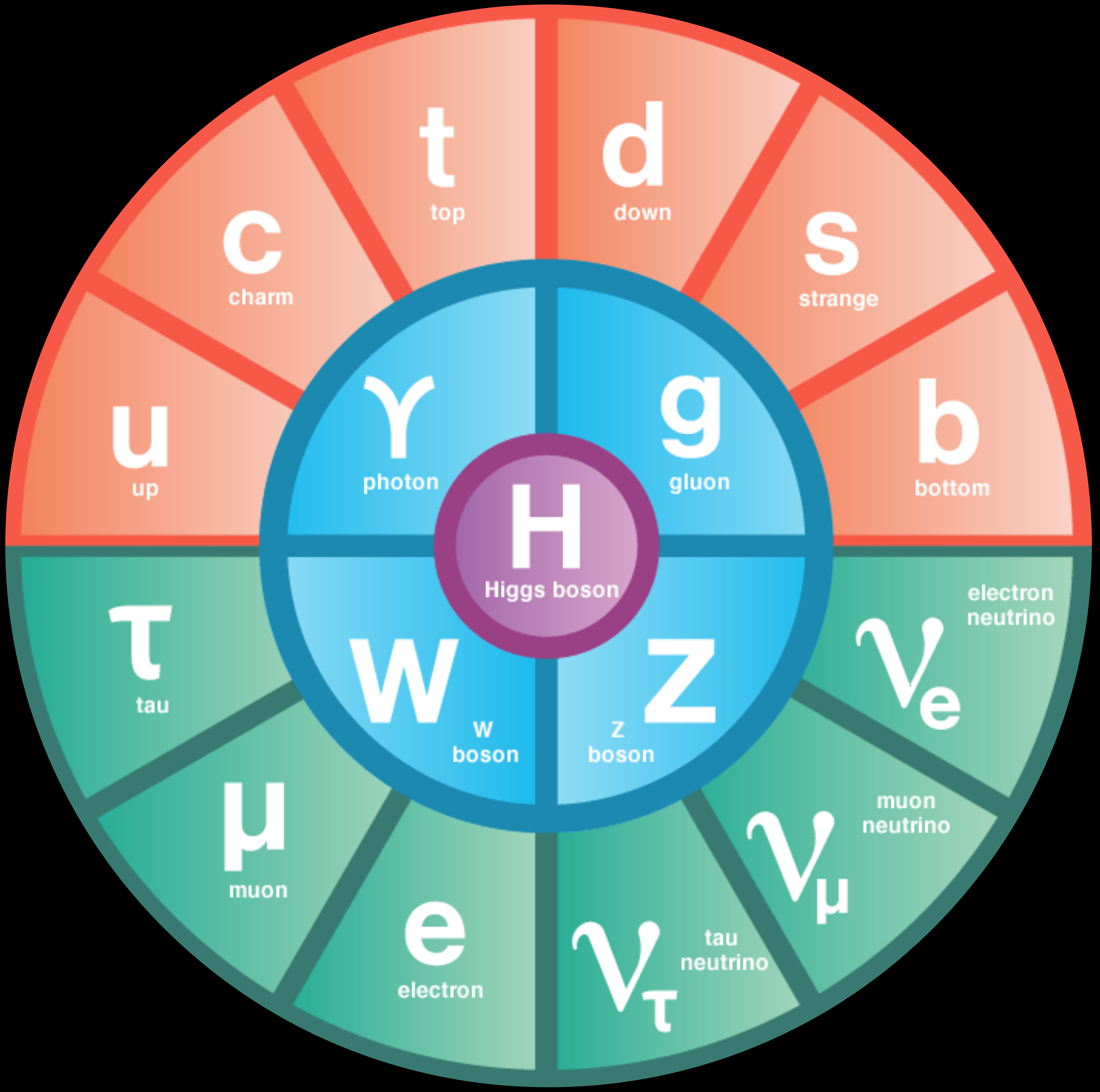
Coupling to the Standard Model charged particles



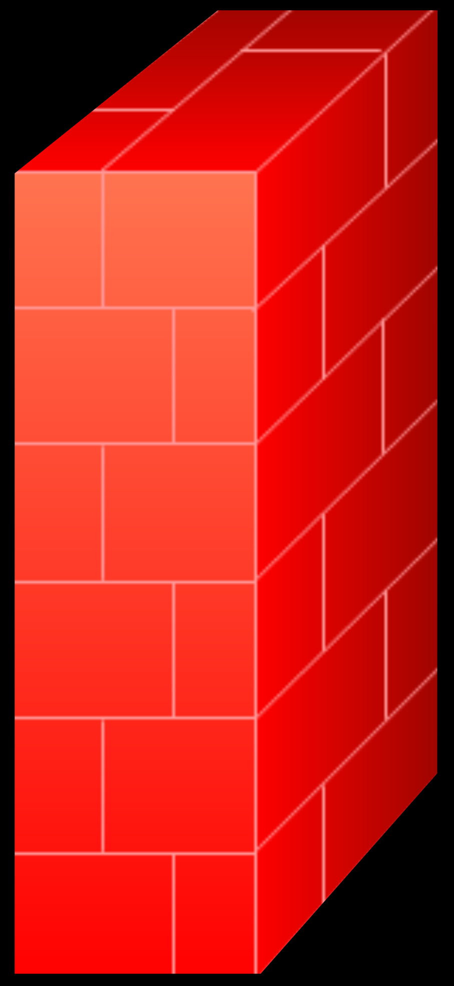
Except ATOMKI'16, JAM '23

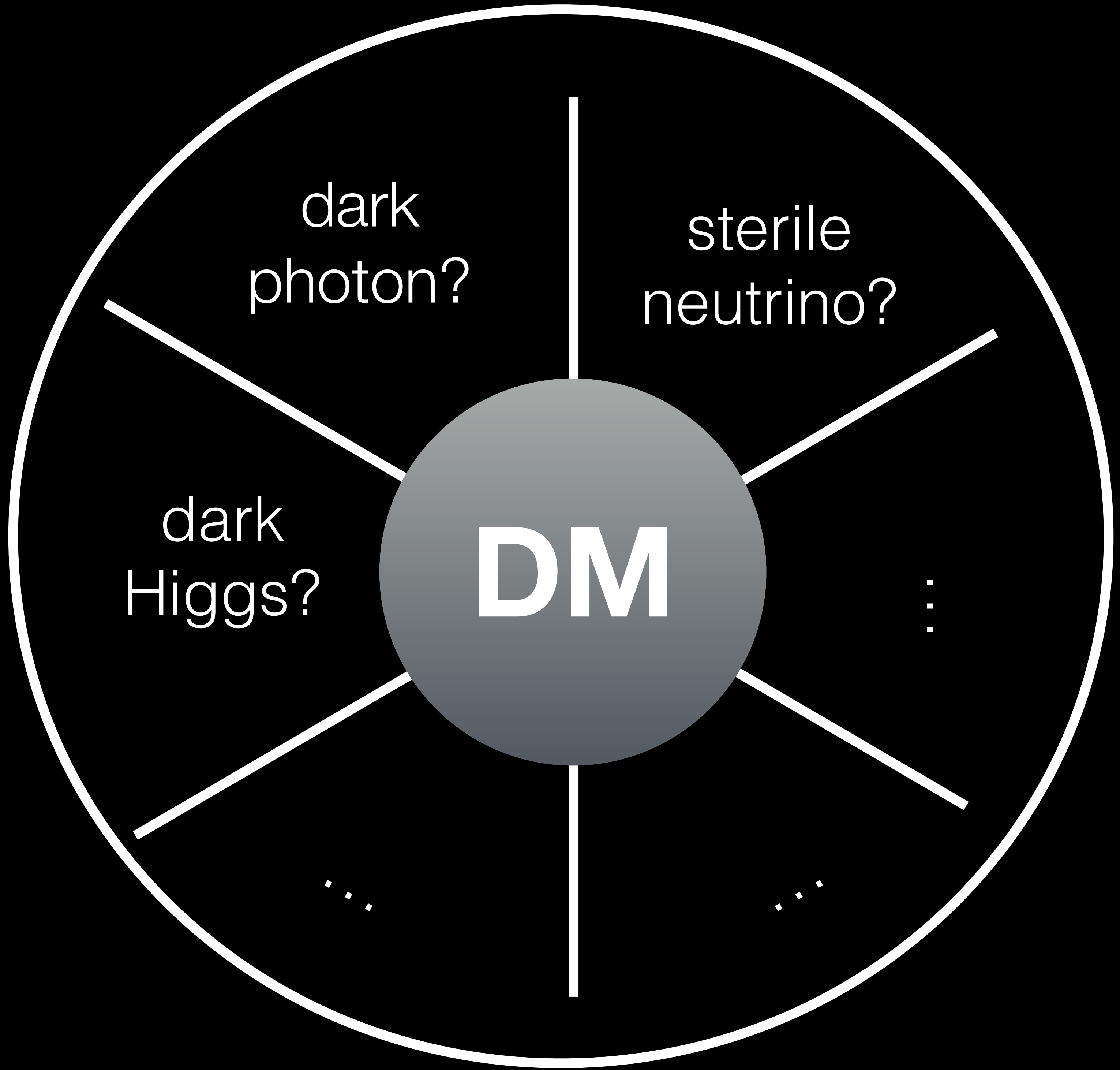


Dark photon mass

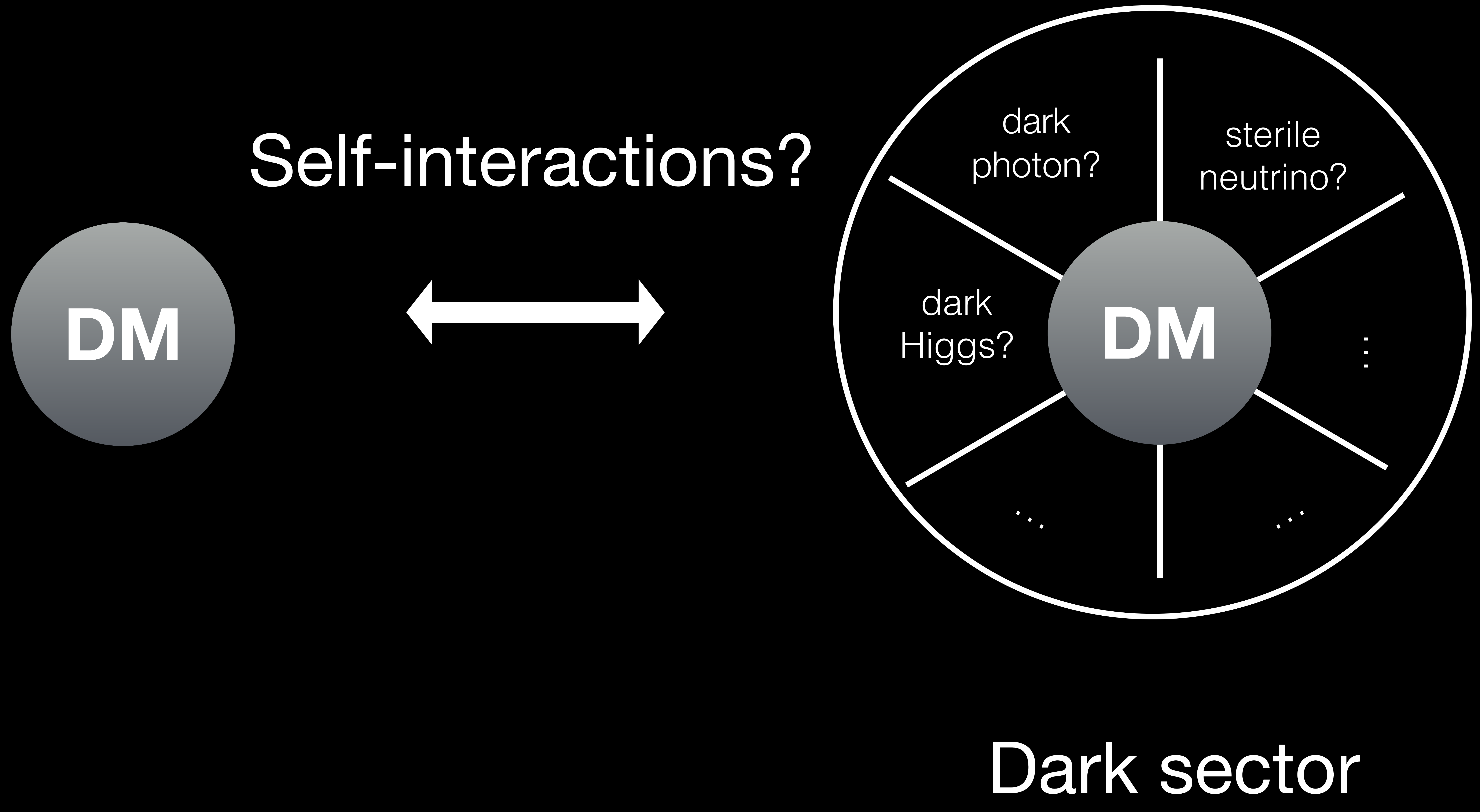


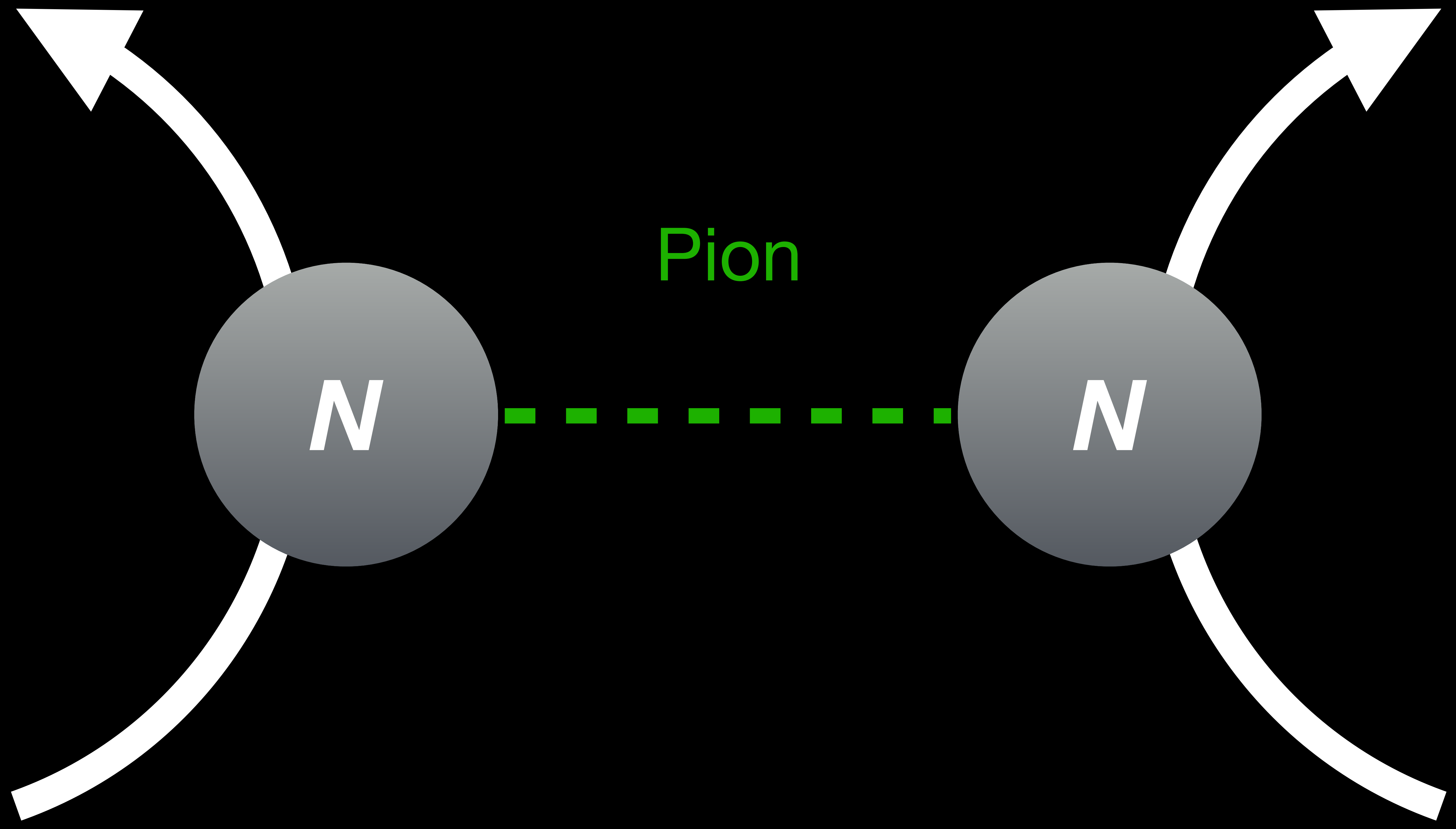
Ordinary matter





Dark sector


DM
Self-interactions?
dark
photon?
sterile
neutrino?
dark
Higgs?
DM
Dark sector

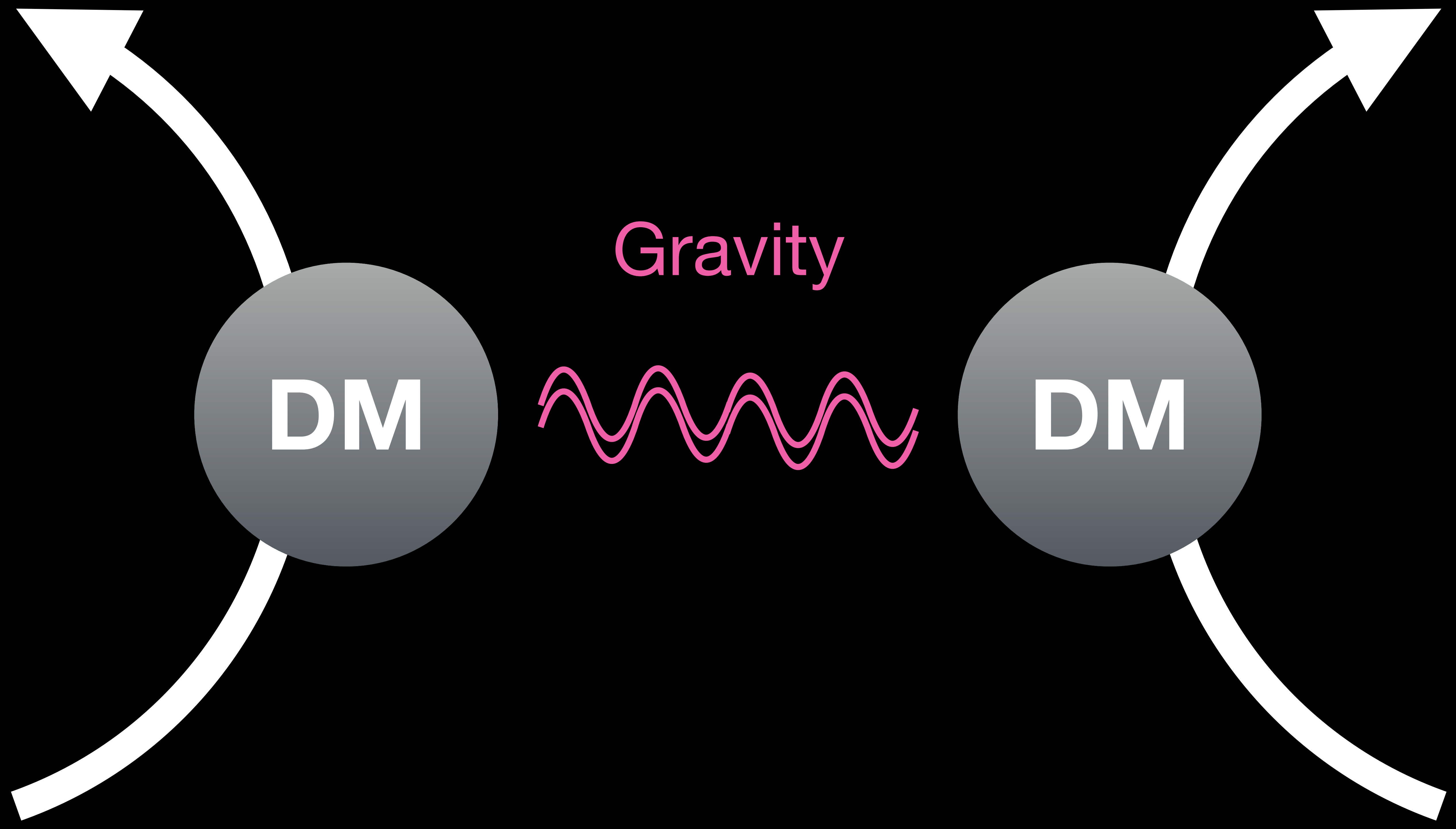


Nucleon-nucleon self-interaction

Cross section strength: $\sigma_T/m_N \sim 10\,\mathrm{cm}^2/\mathrm{g}$

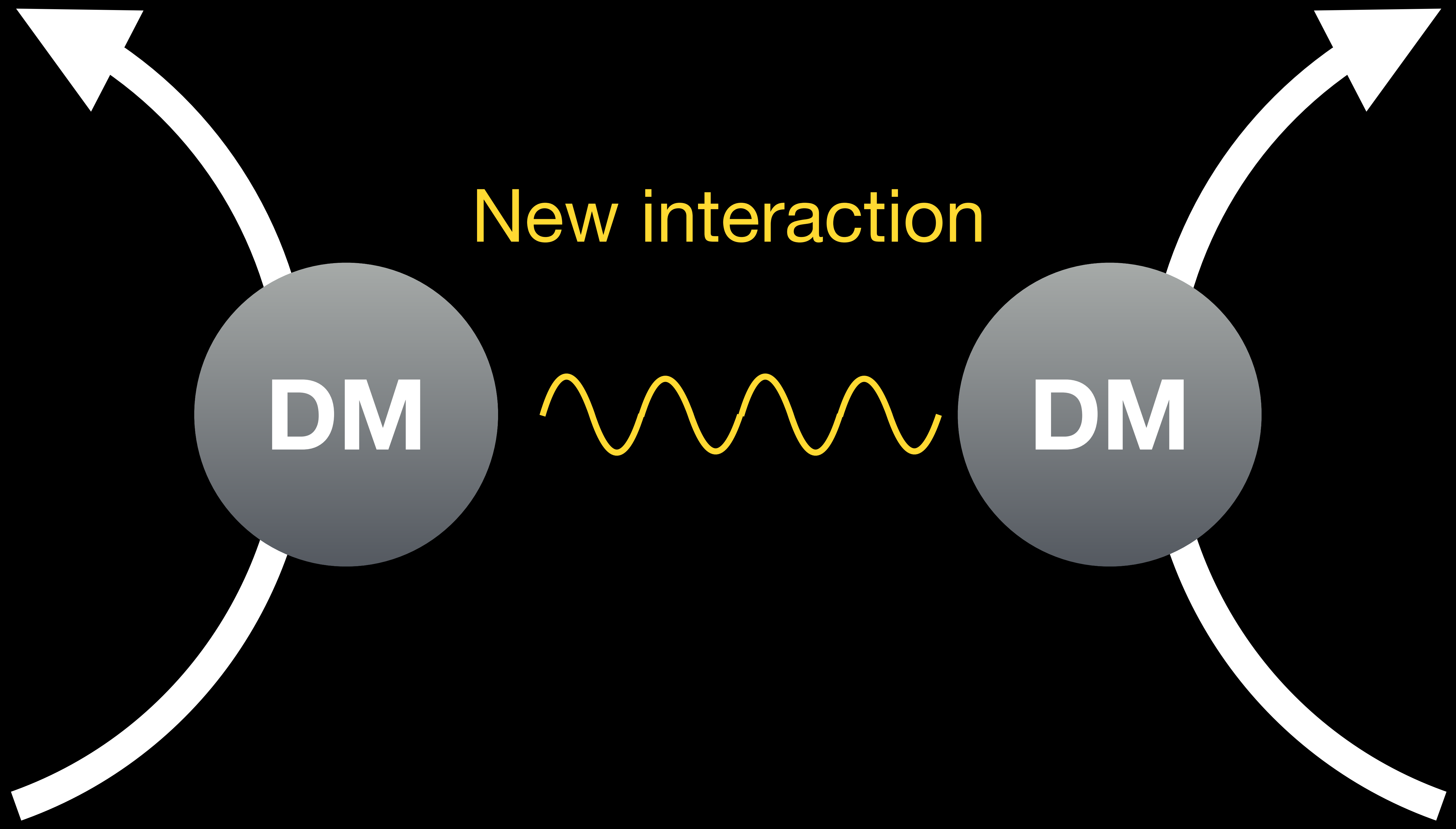
Nuclear Data Sheets ’11

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



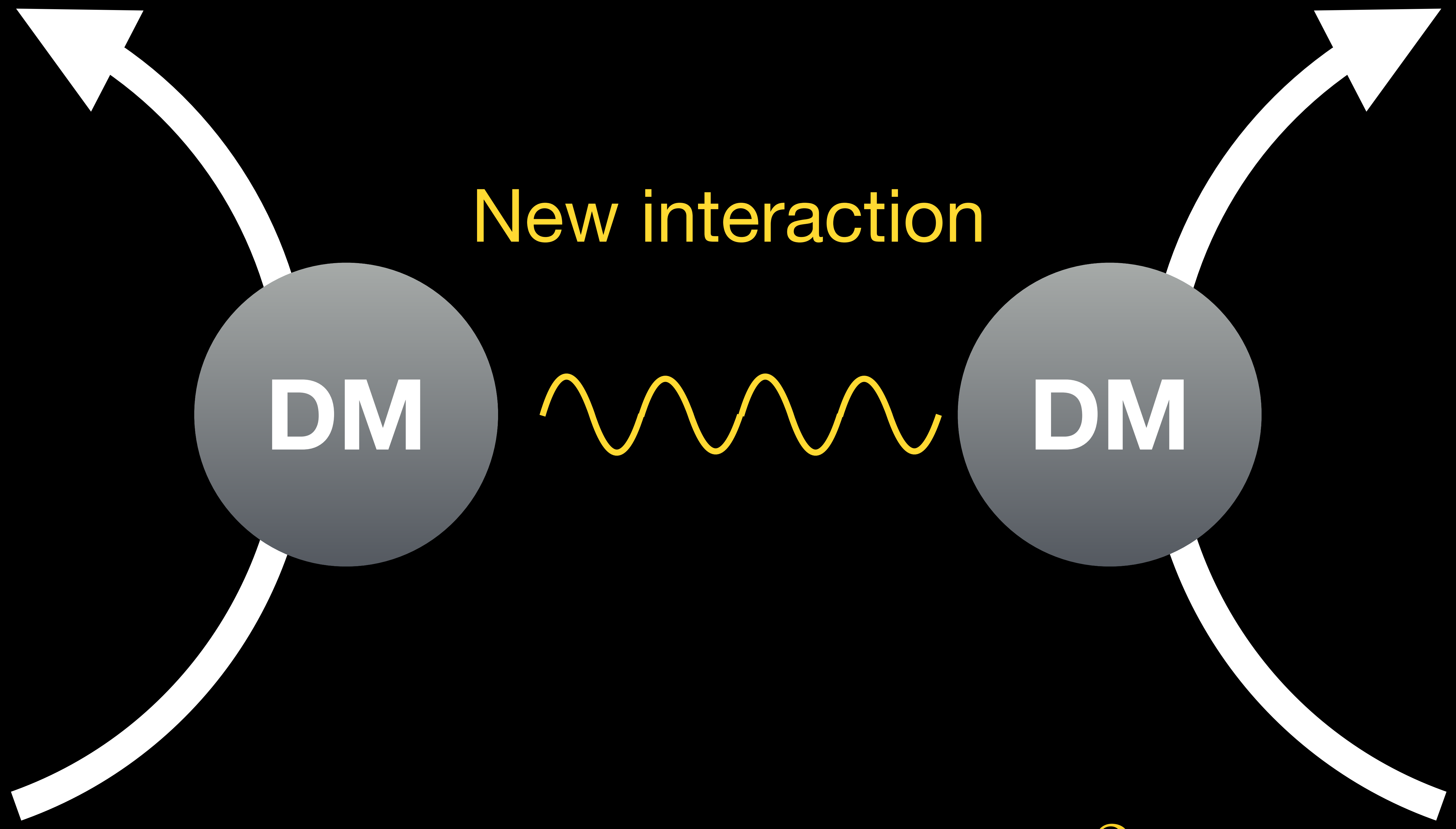
Cold Collisionless Dark Matter (CDM)

Cross section strength: $\sigma_{\rm T}/m_{\rm DM} \sim 10^{-70}\,{\rm cm}^2/{\rm g}$ (DM mass~ GeV)



Self-Interacting Dark Matter (SIDM)

Cross section strength: $\sigma_{\mathrm{T}}/m_{\mathrm{DM}} \sim 1\,\mathrm{cm}^2/\mathrm{g}$

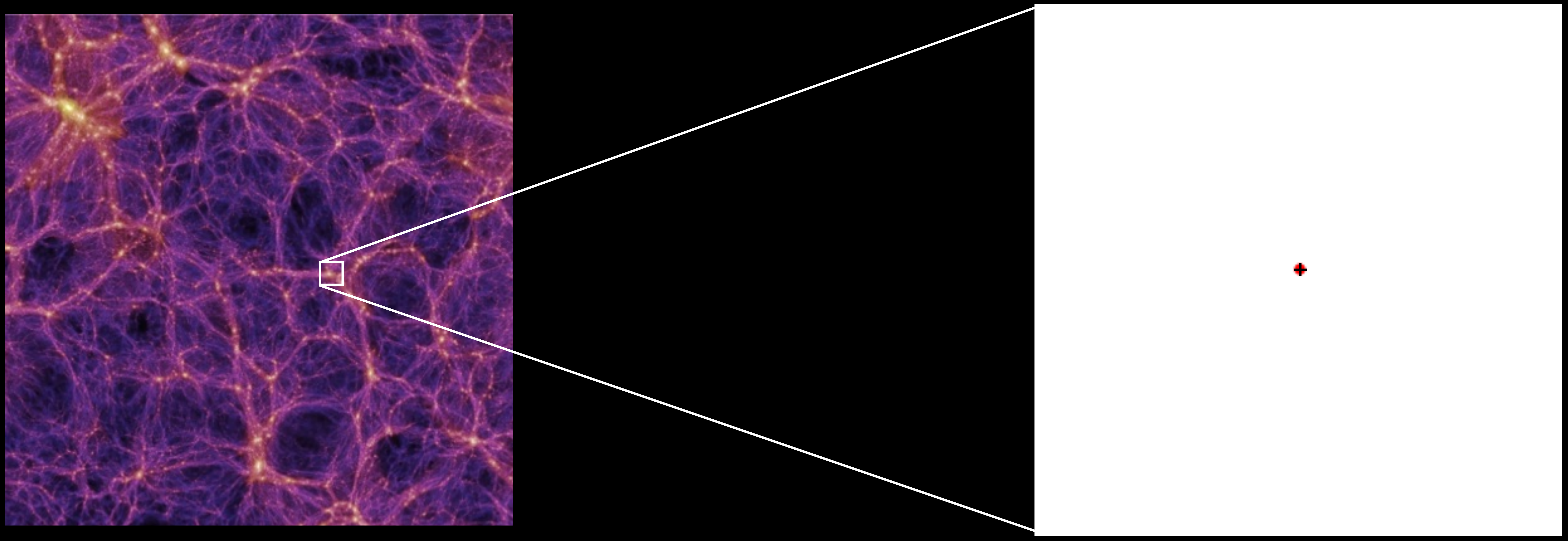


$$\sigma_{\mathrm{T}}/m_{\mathrm{DM}} \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

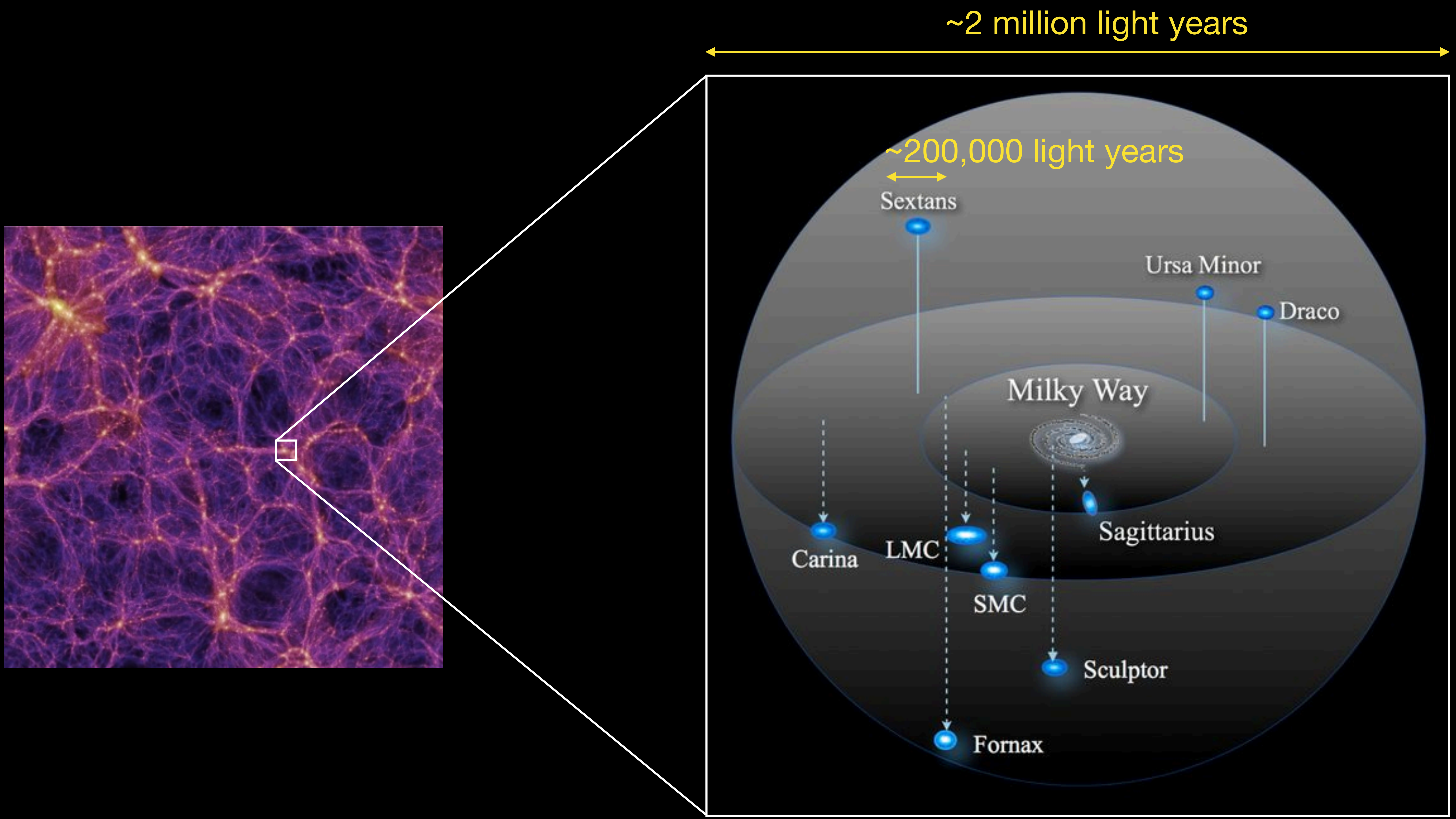
$$t_{\mathrm{rlx}} = \frac{1}{\rho(\sigma/m)v} \sim 10\,\mathrm{Gyr}\left(\frac{0.4\,\mathrm{GeV/cm^3}}{\rho}\right)\left(\frac{1\,\mathrm{cm^2/g}}{\sigma/m}\right)\left(\frac{200\,\mathrm{km/s}}{v}\right)$$

Spergel & Steinhardt ‘00

Where to look at?

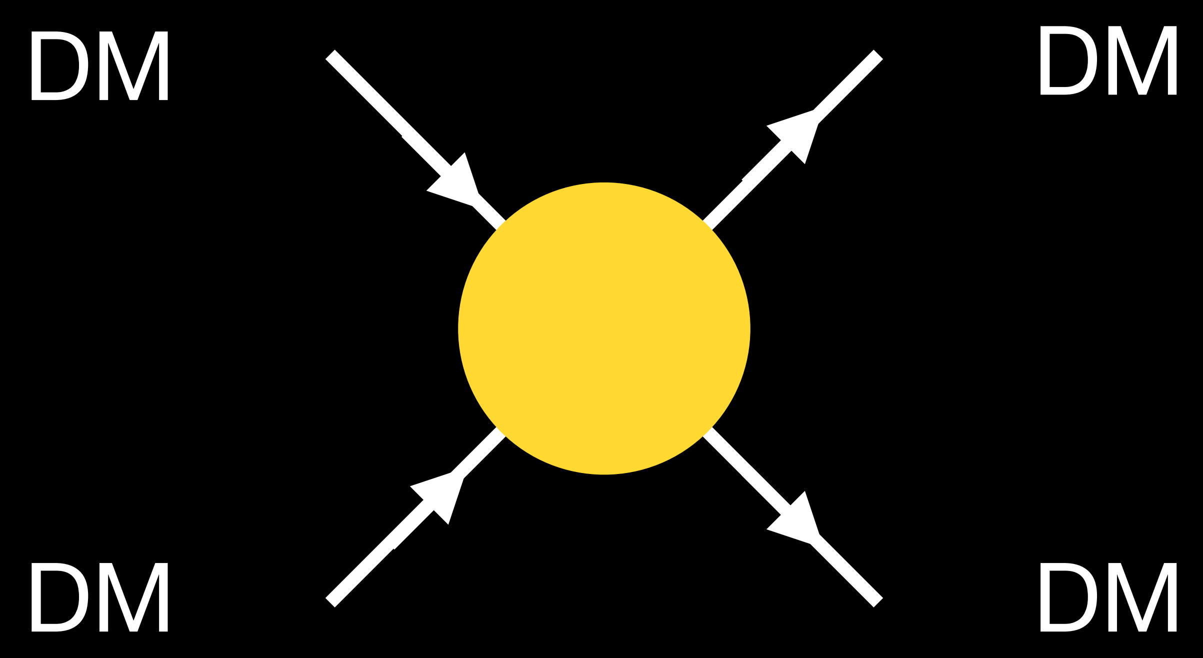


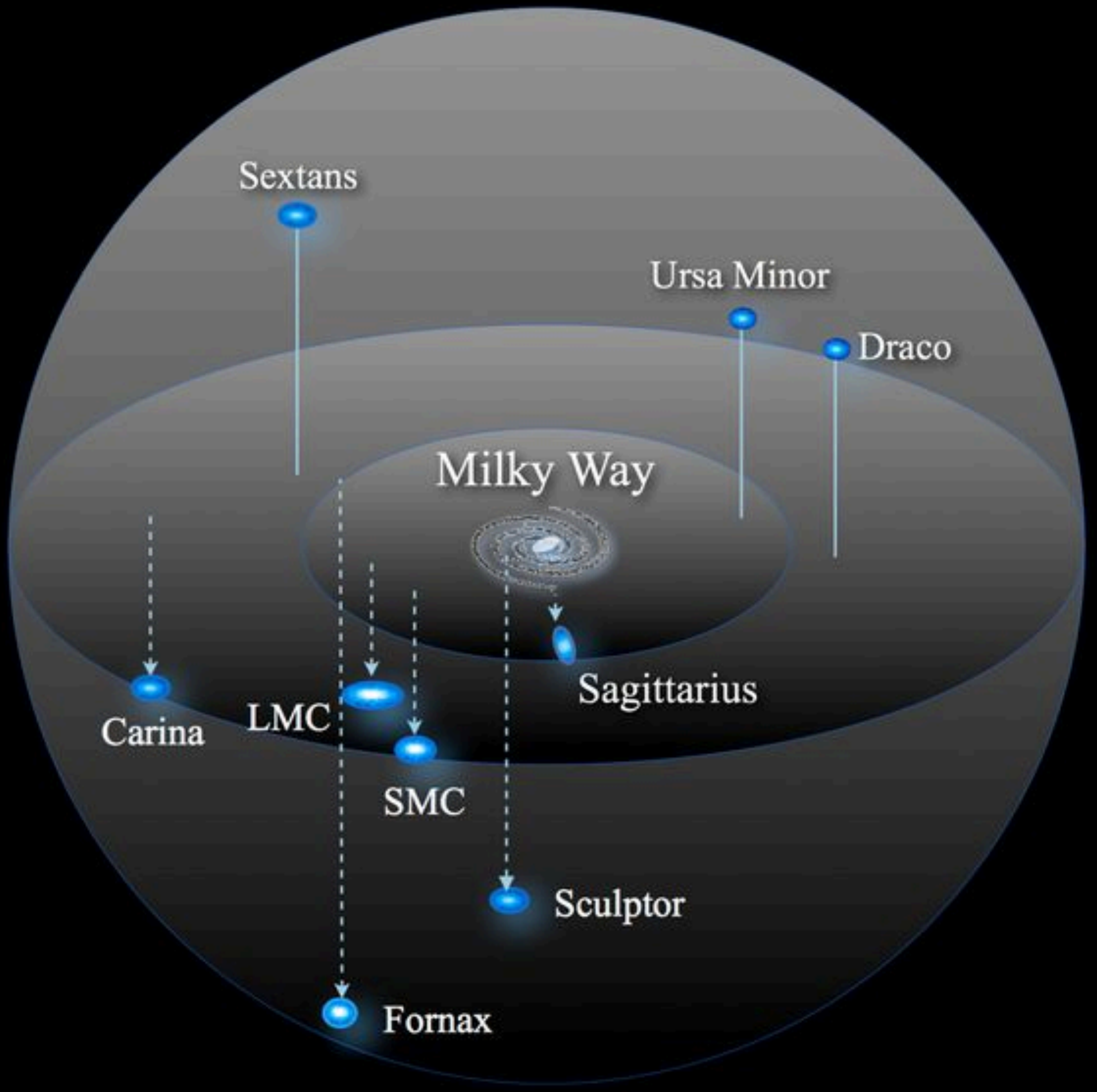
Where to look at?



Dark matter halos

Dark matter halos can probe self-interactions



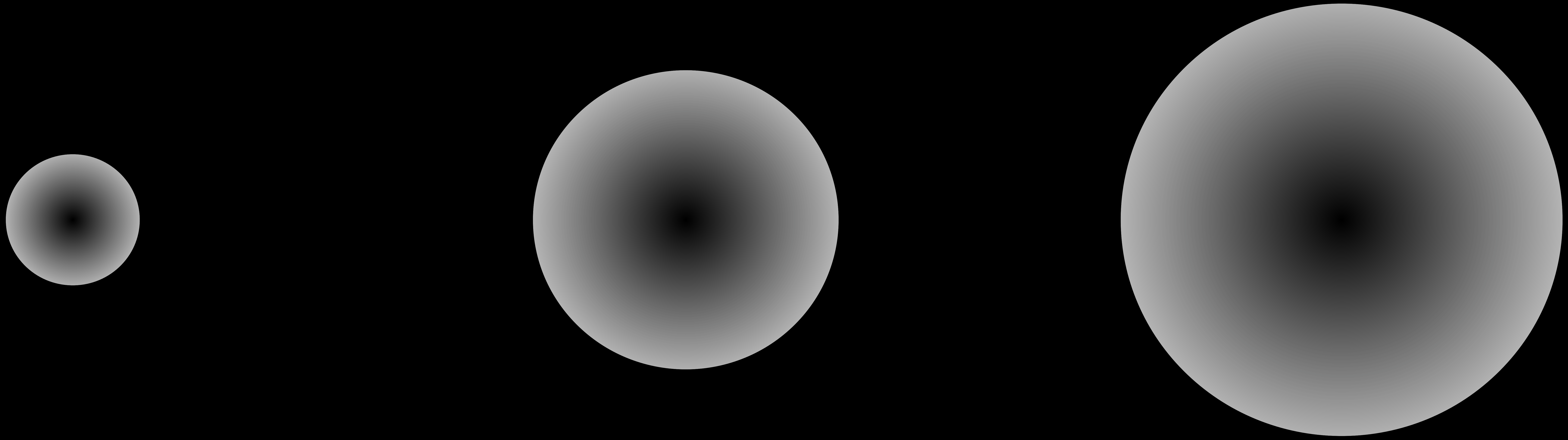


Dark matter self-interactions

Dark matter halo properties

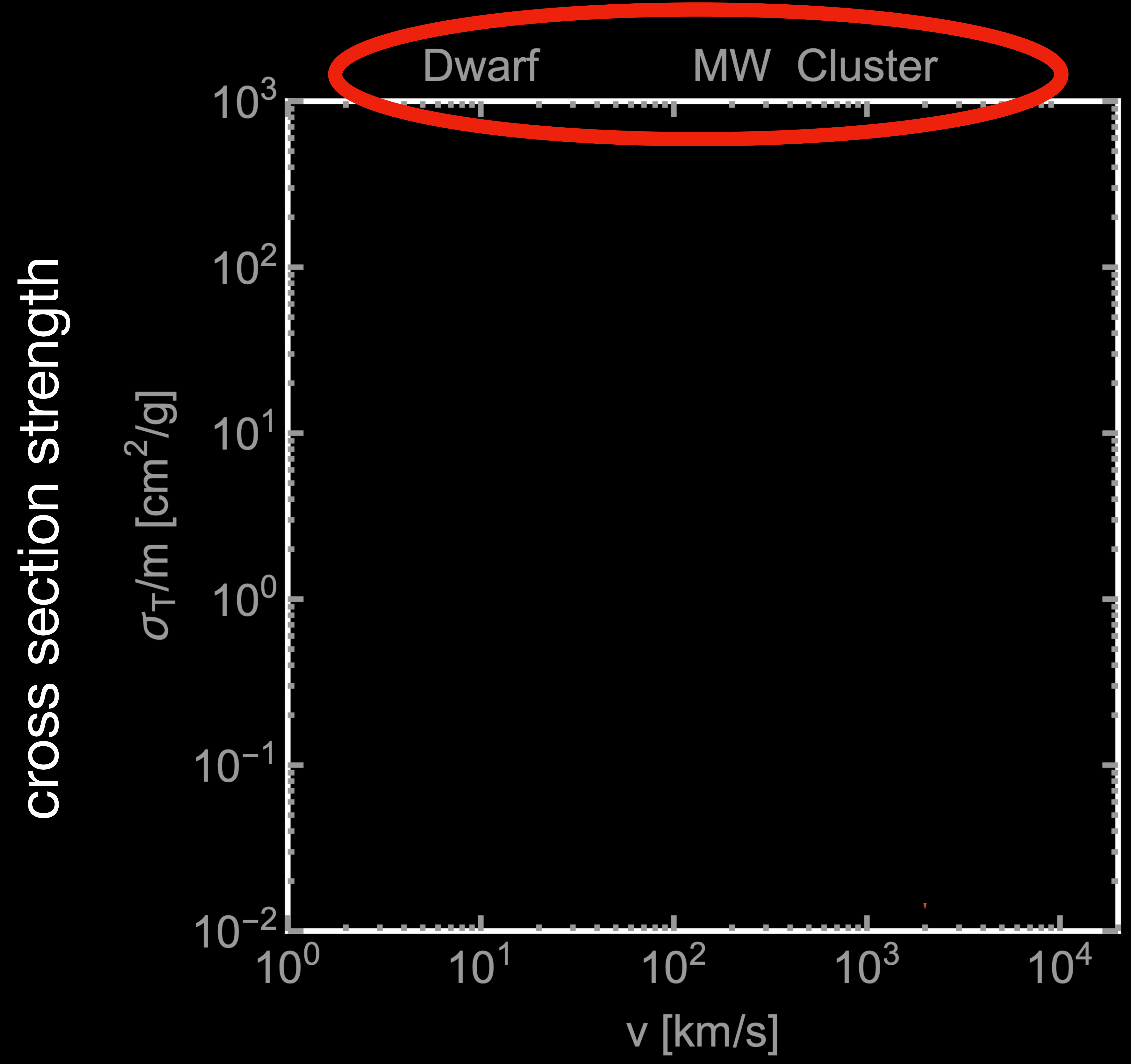
Dark matter halo classes

Dwarf halos | Milky Way-sized halos | Galaxy cluster halos



$10^{8} \sim 10^{11}\ M_{\odot}$ | $10^{11} \sim 10^{14}\ M_{\odot}$ | $10^{14} \sim 10^{15}\ M_{\odot}$

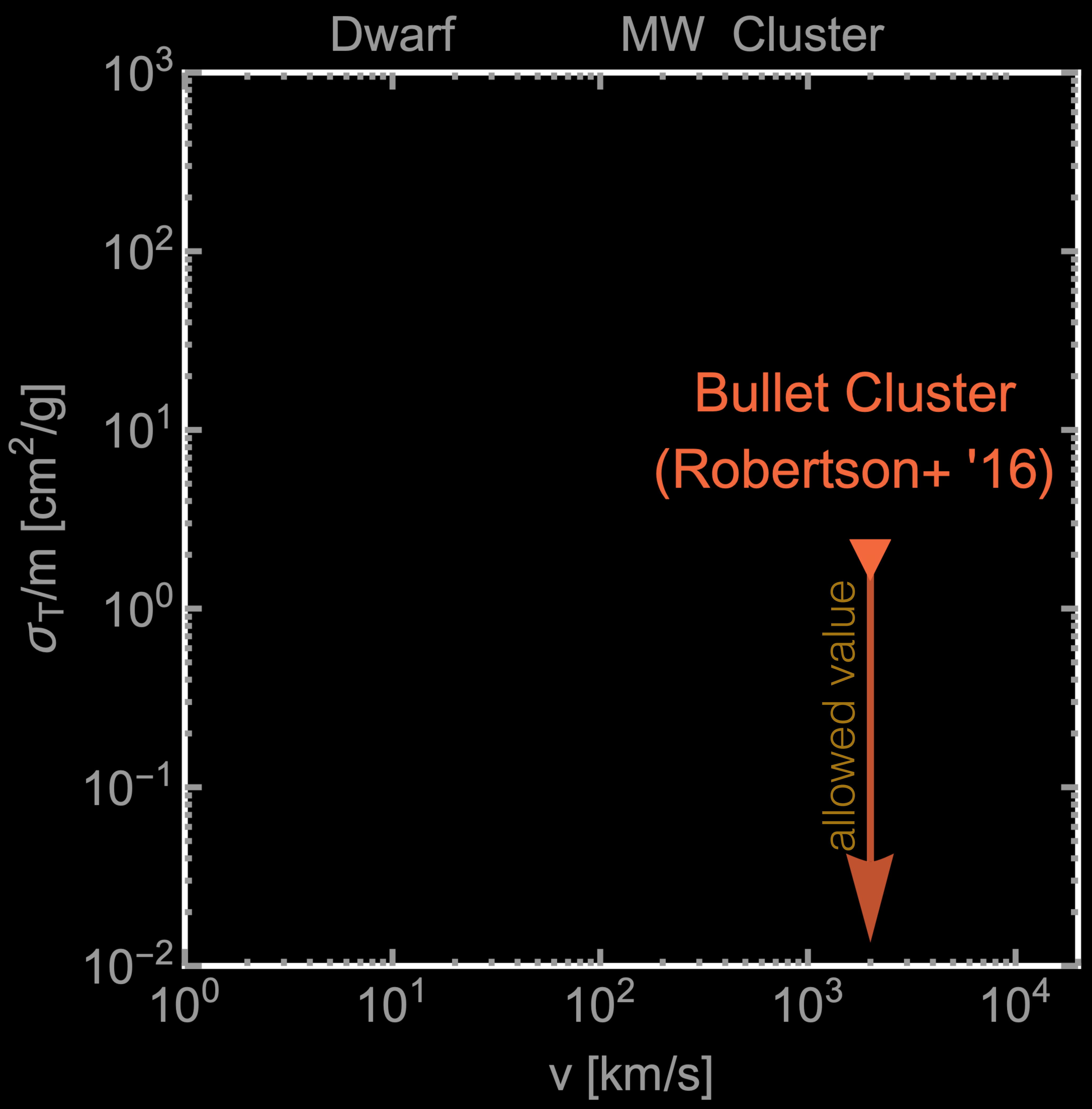
Constraints on dark matter self-interaction



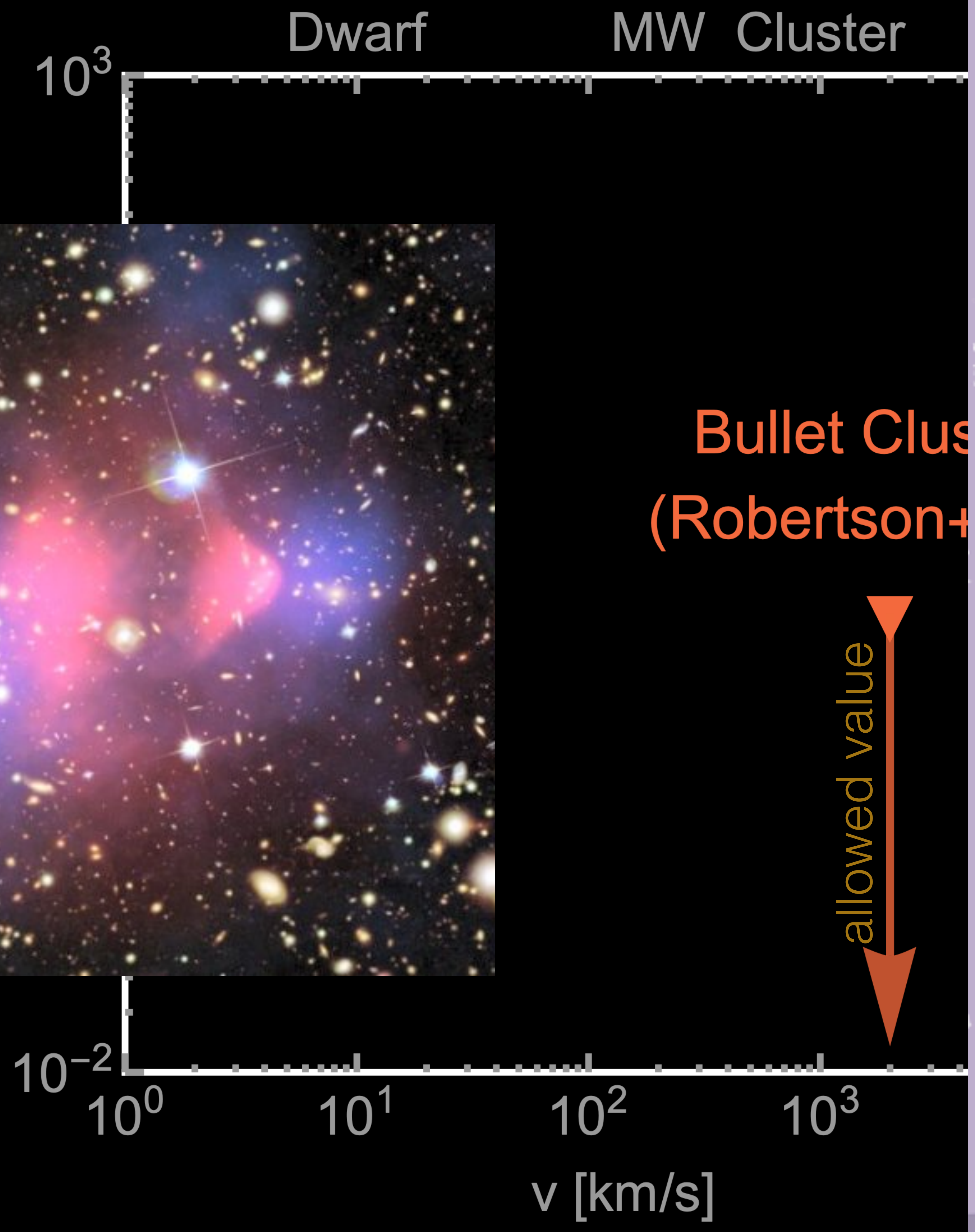
$$1\,\mathrm{cm}^2/\mathrm{g}$$
$$\approx 2\,\mathrm{barn}/\mathrm{GeV}$$

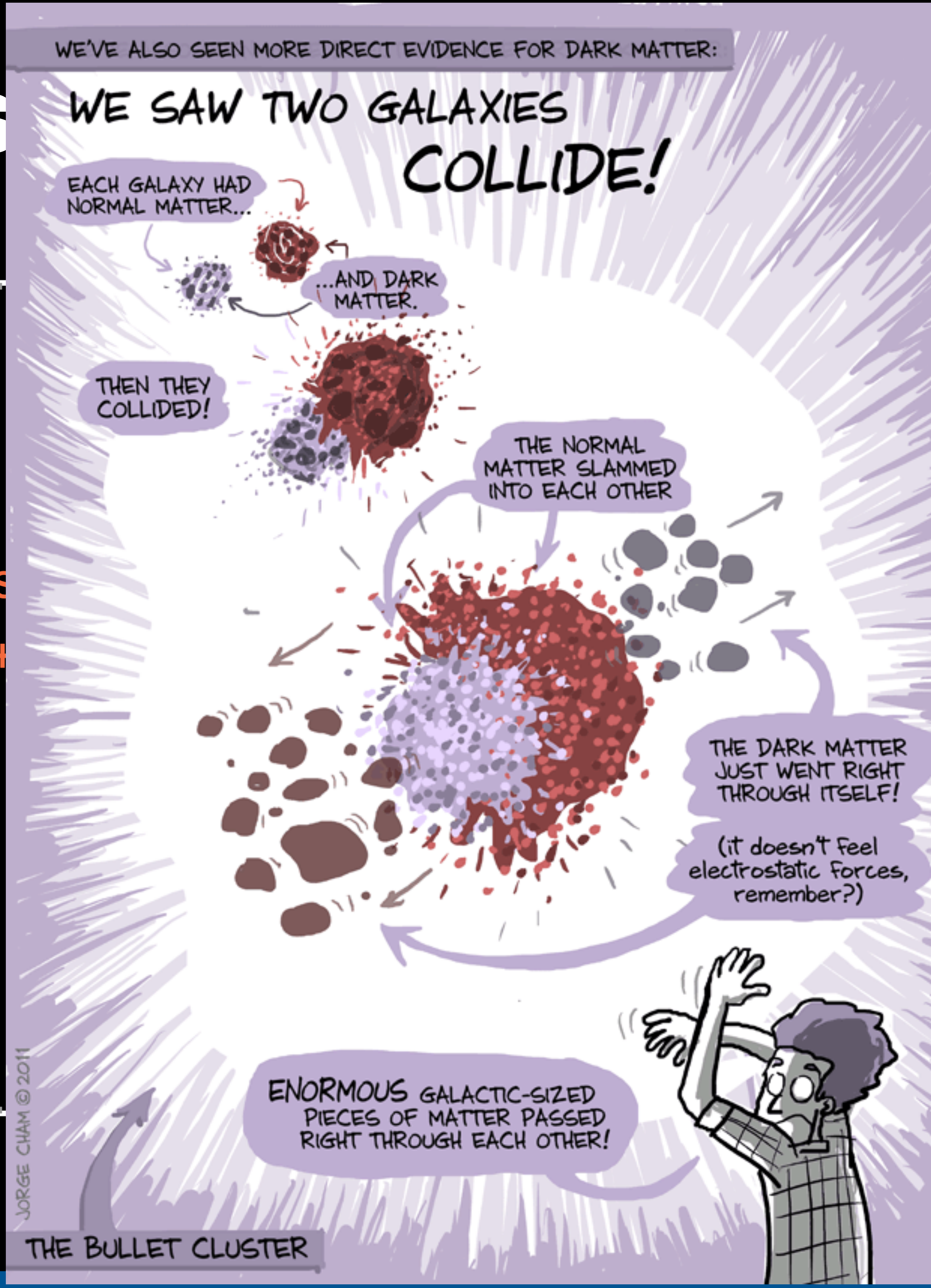
Constraints on dark matter self-interaction

cross section strength

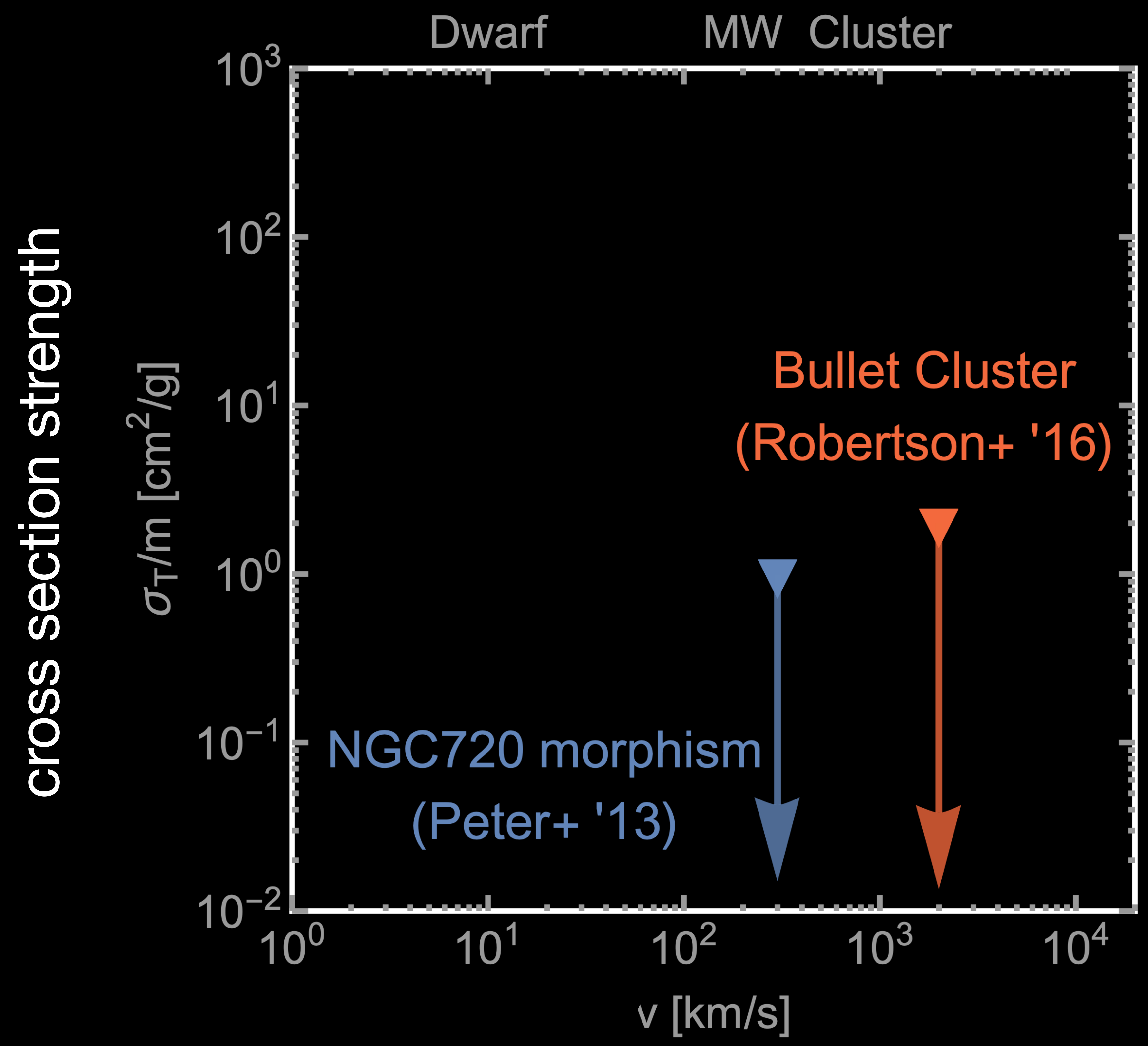


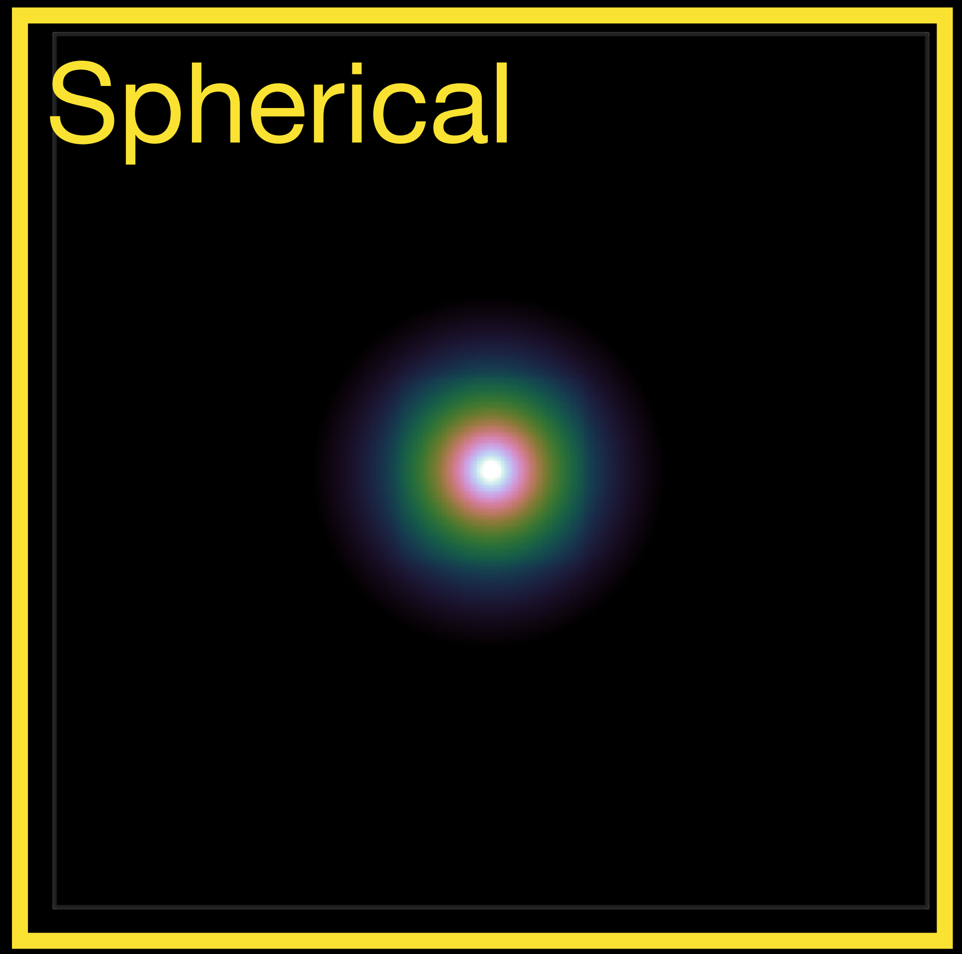
Constraints on dark matter s

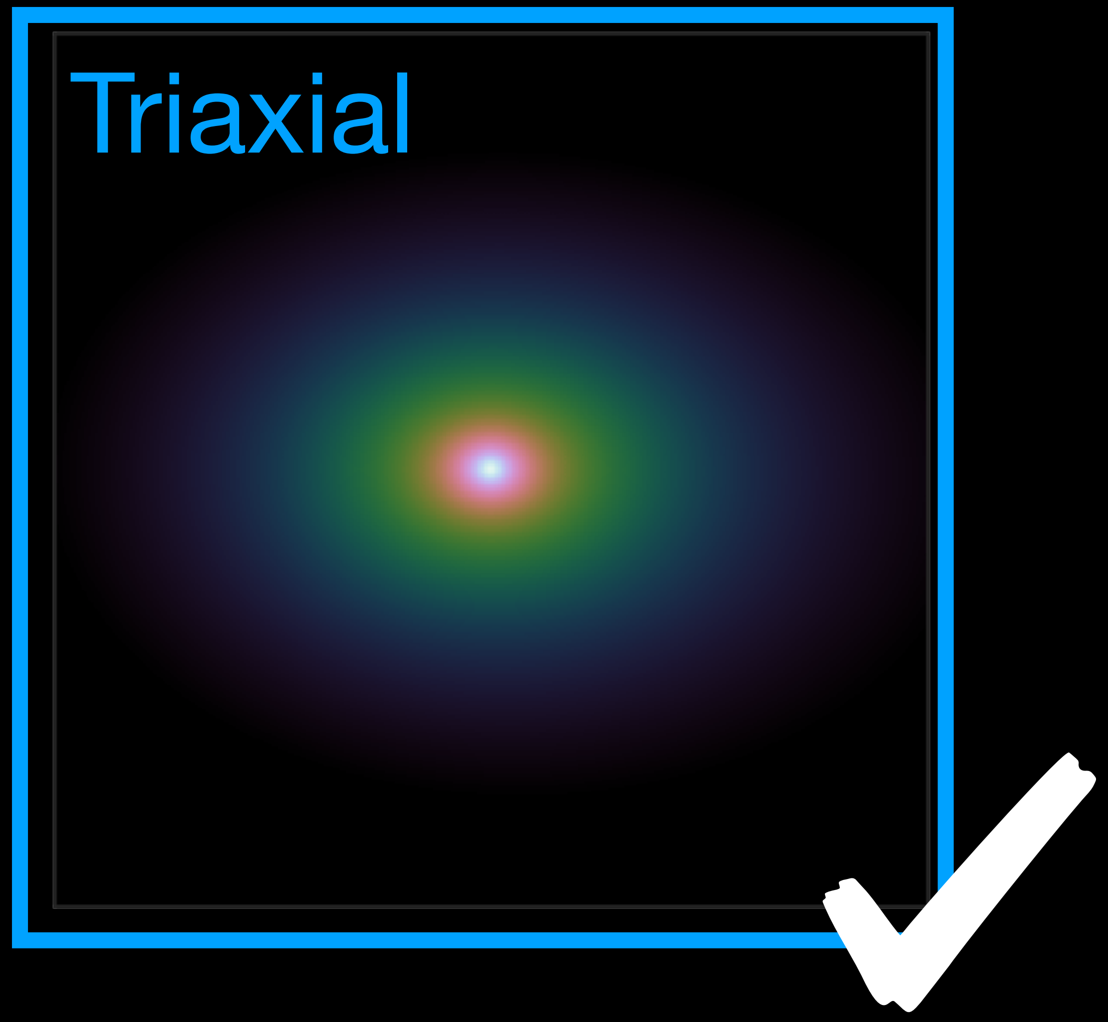




Constraints on dark matter self-interaction

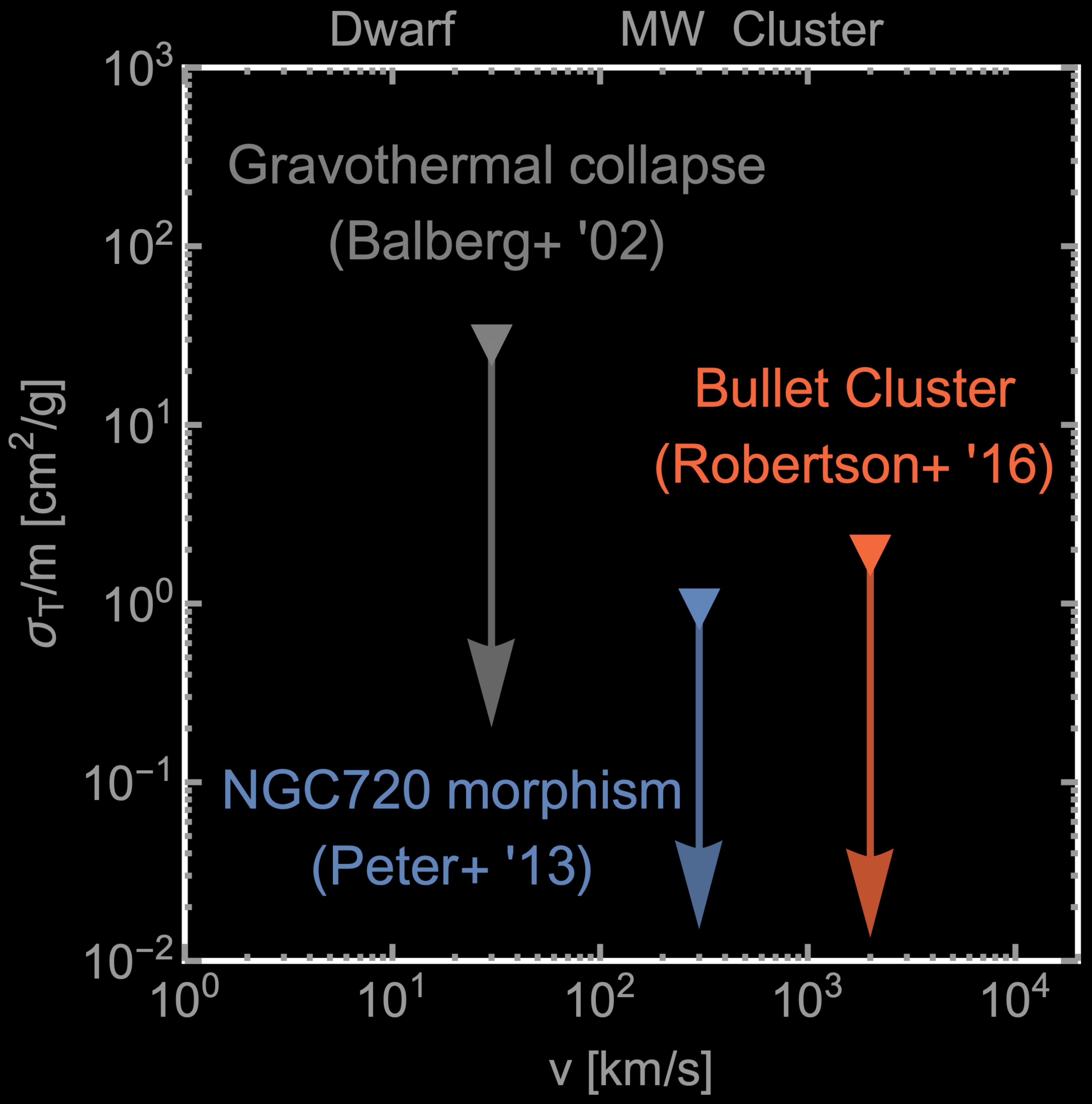






Constraints on dark matter self-interaction

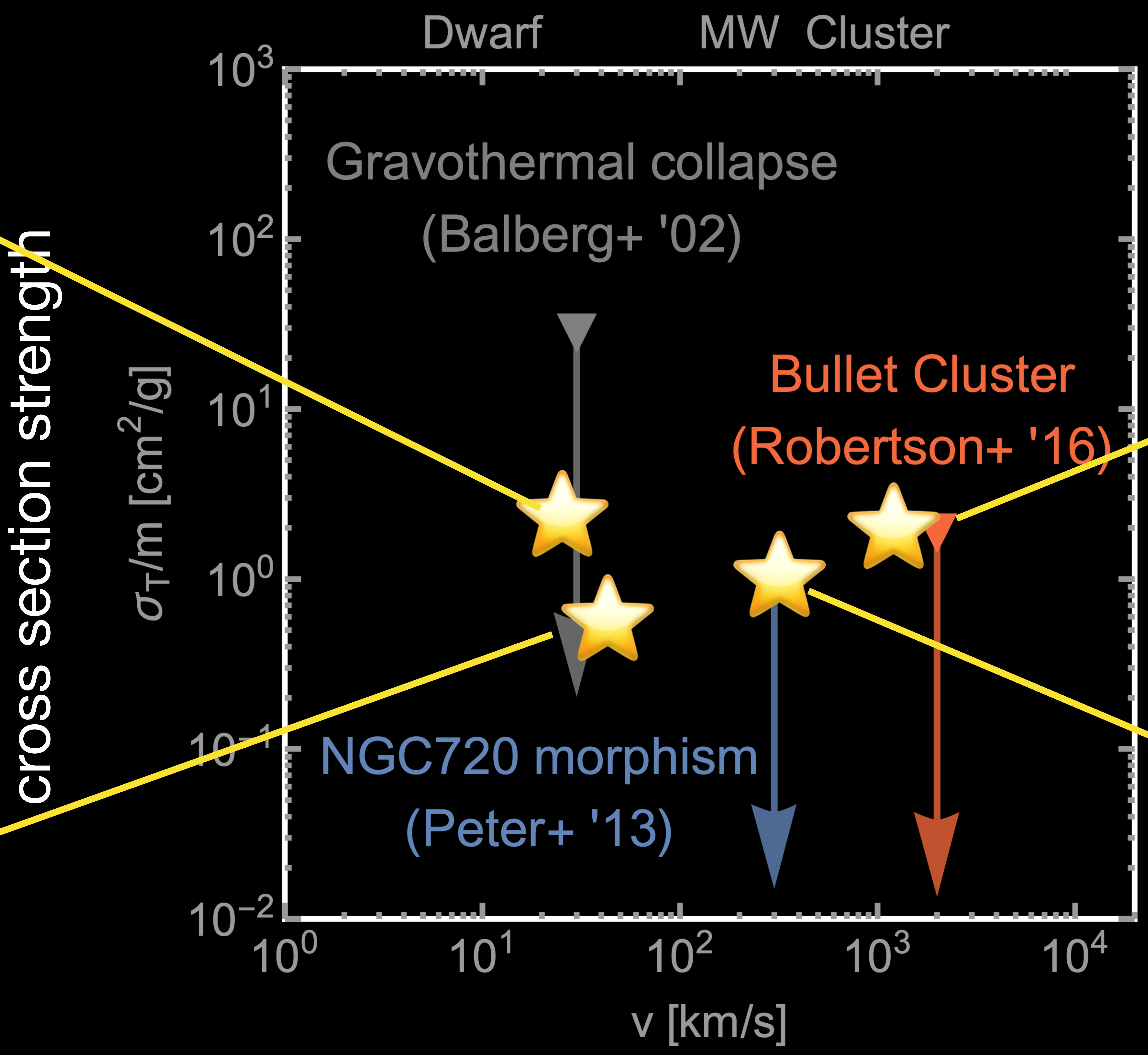
cross section strength



Solving "small-scale problems" of CDM

Diversity
(Kamada+ '16)

Too big to fail
(Zavala+'12
Elbert+ '14)



Splashback
radius deficit
(More+ '16)

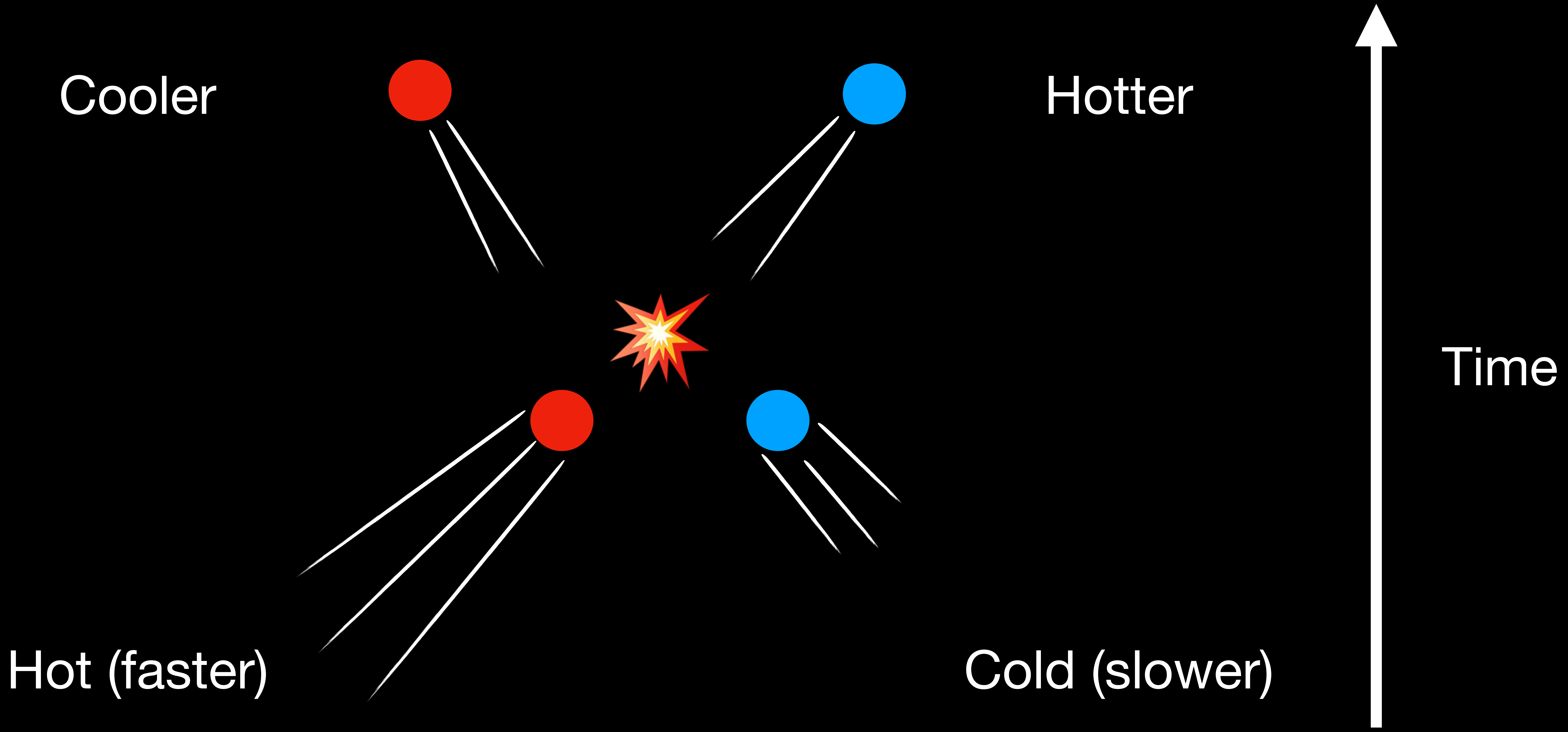
Cusp vs core
(Wandelt+ '00)

Solving small-scale problems of CDM

Probing dark sectors

Gravothermal collapse of self-interacting dark matter halos

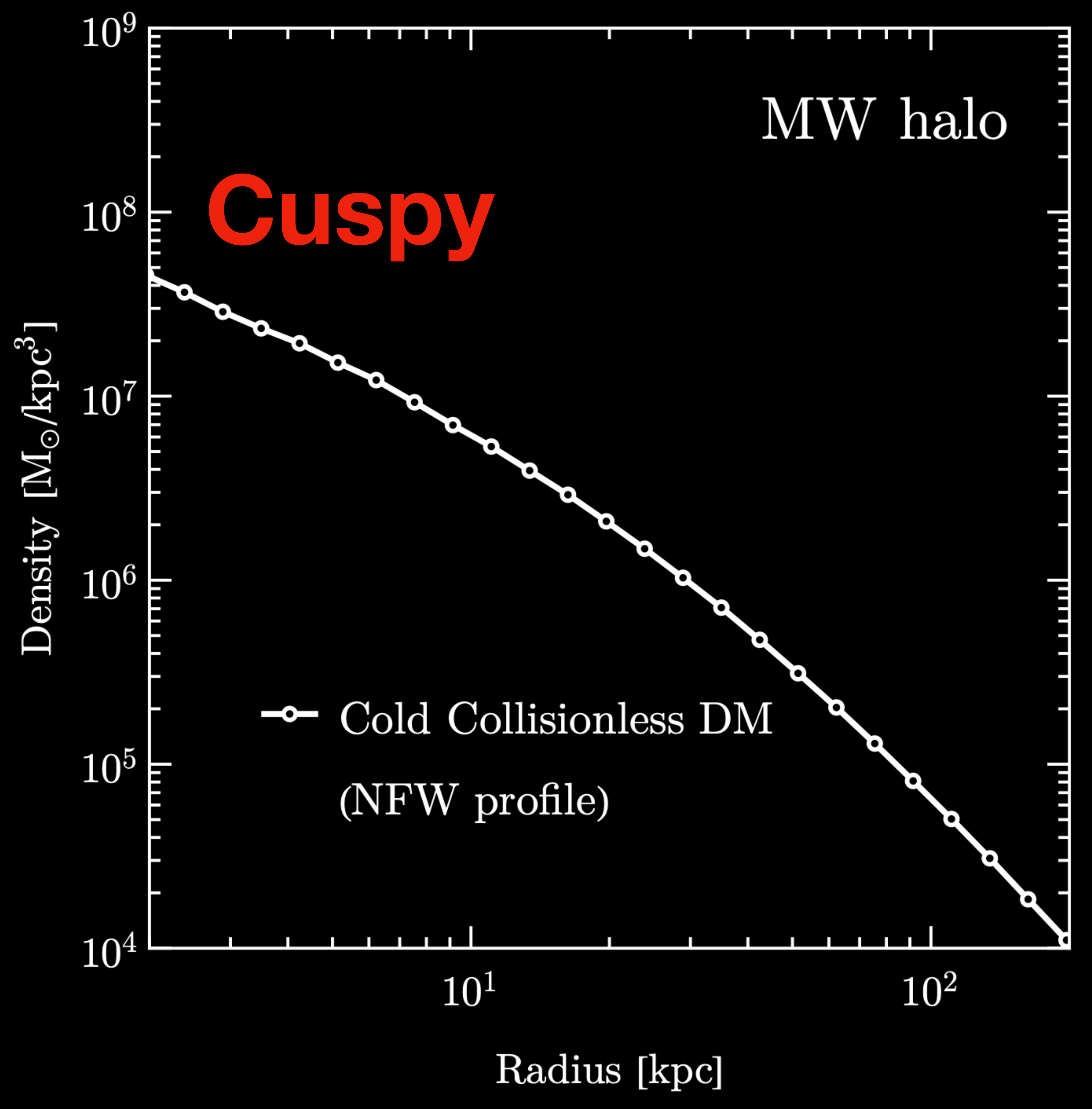
Effects of self-interaction



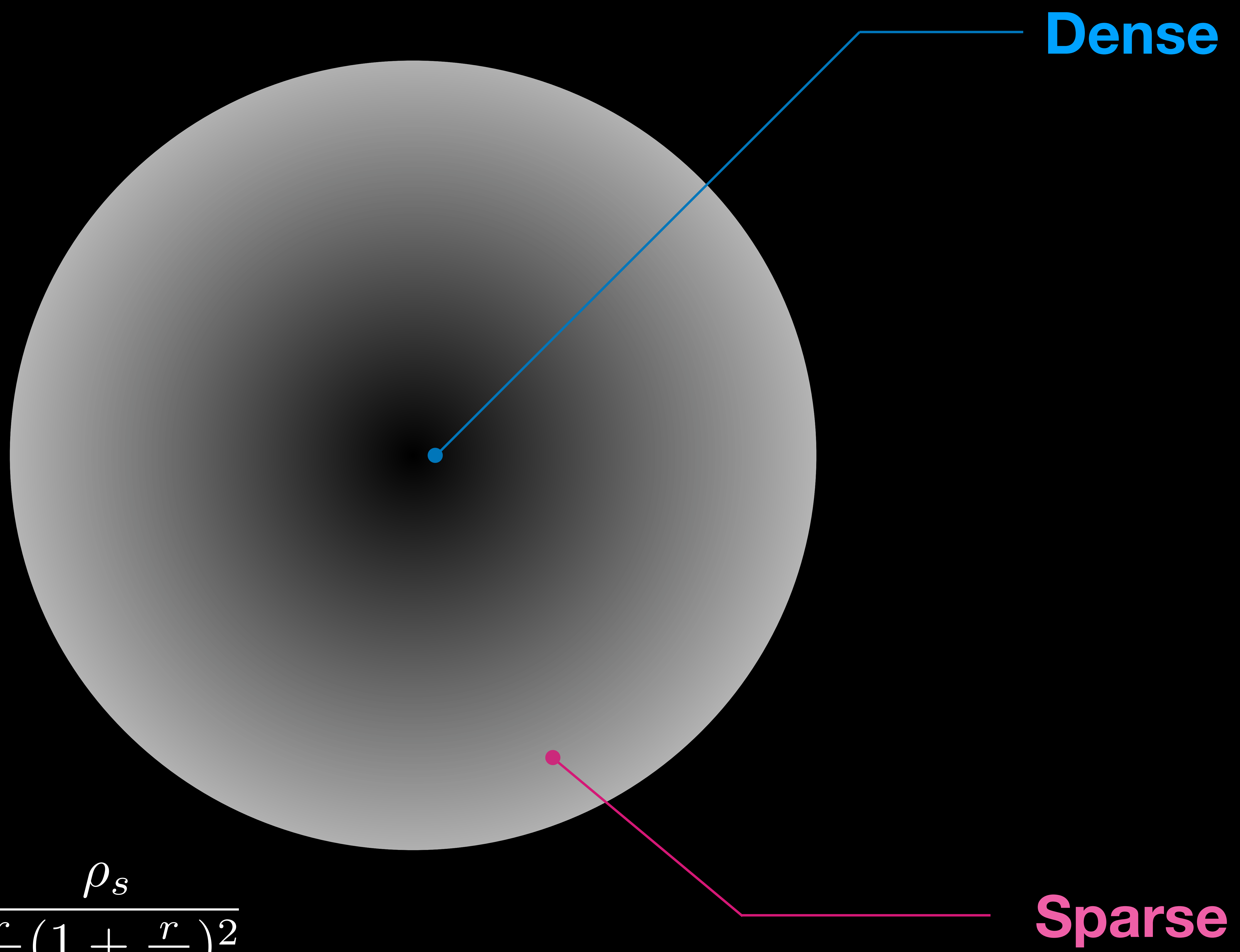
Equipartition

I. Halo formation

Density profile
(density at given radii)

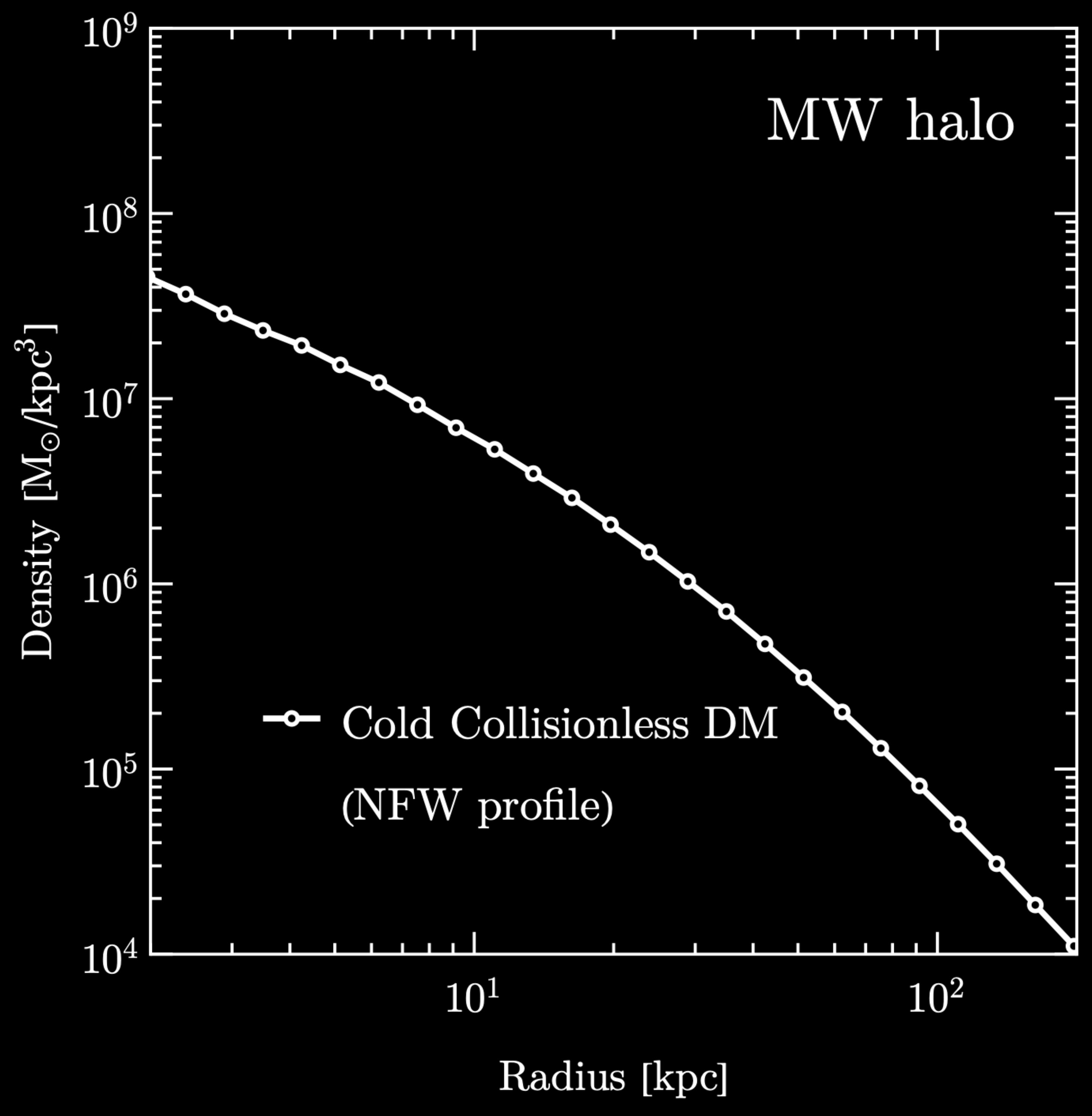


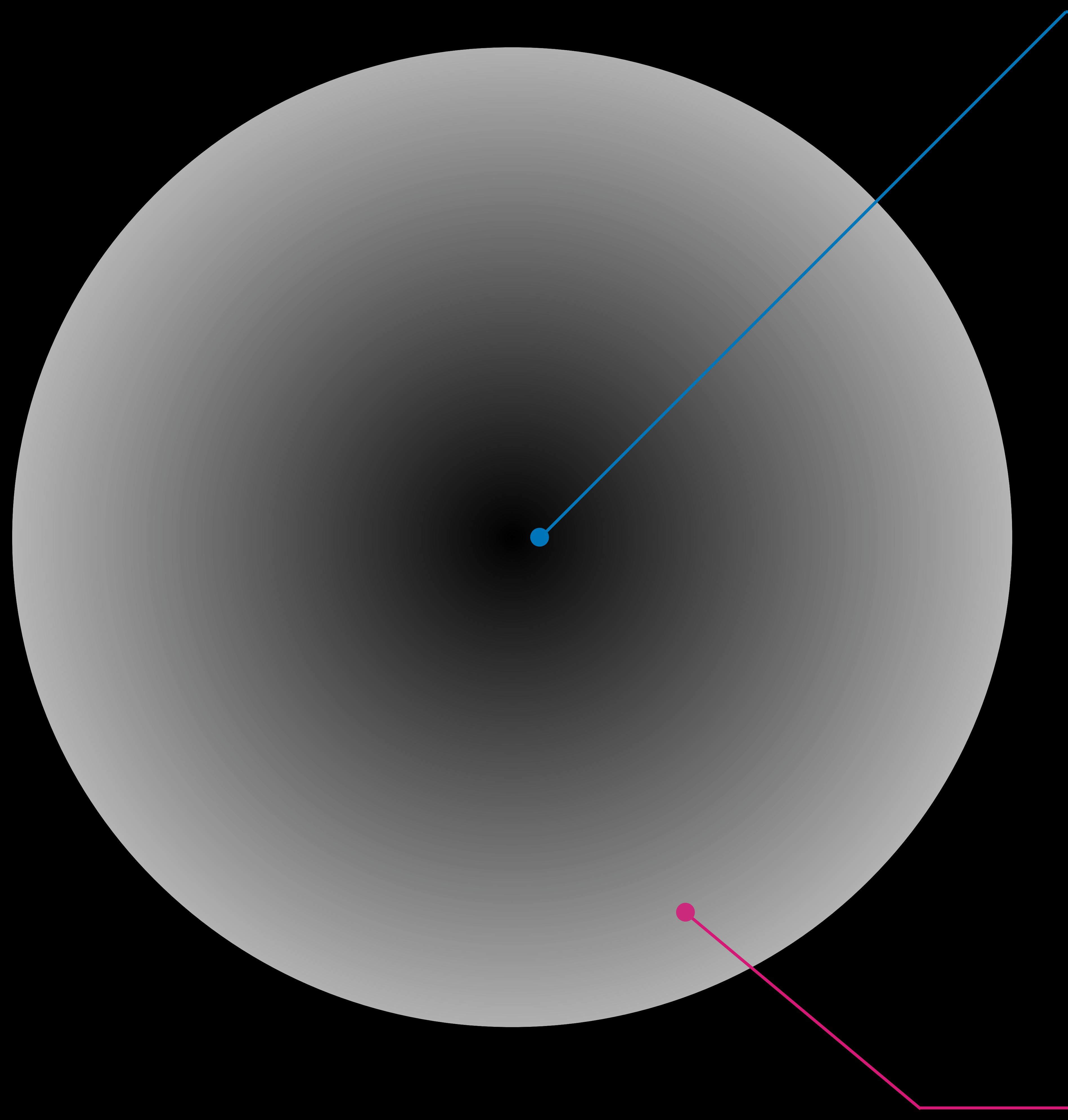
Navarro-Frenk-White (NFW) profile $\rho = \dfrac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$



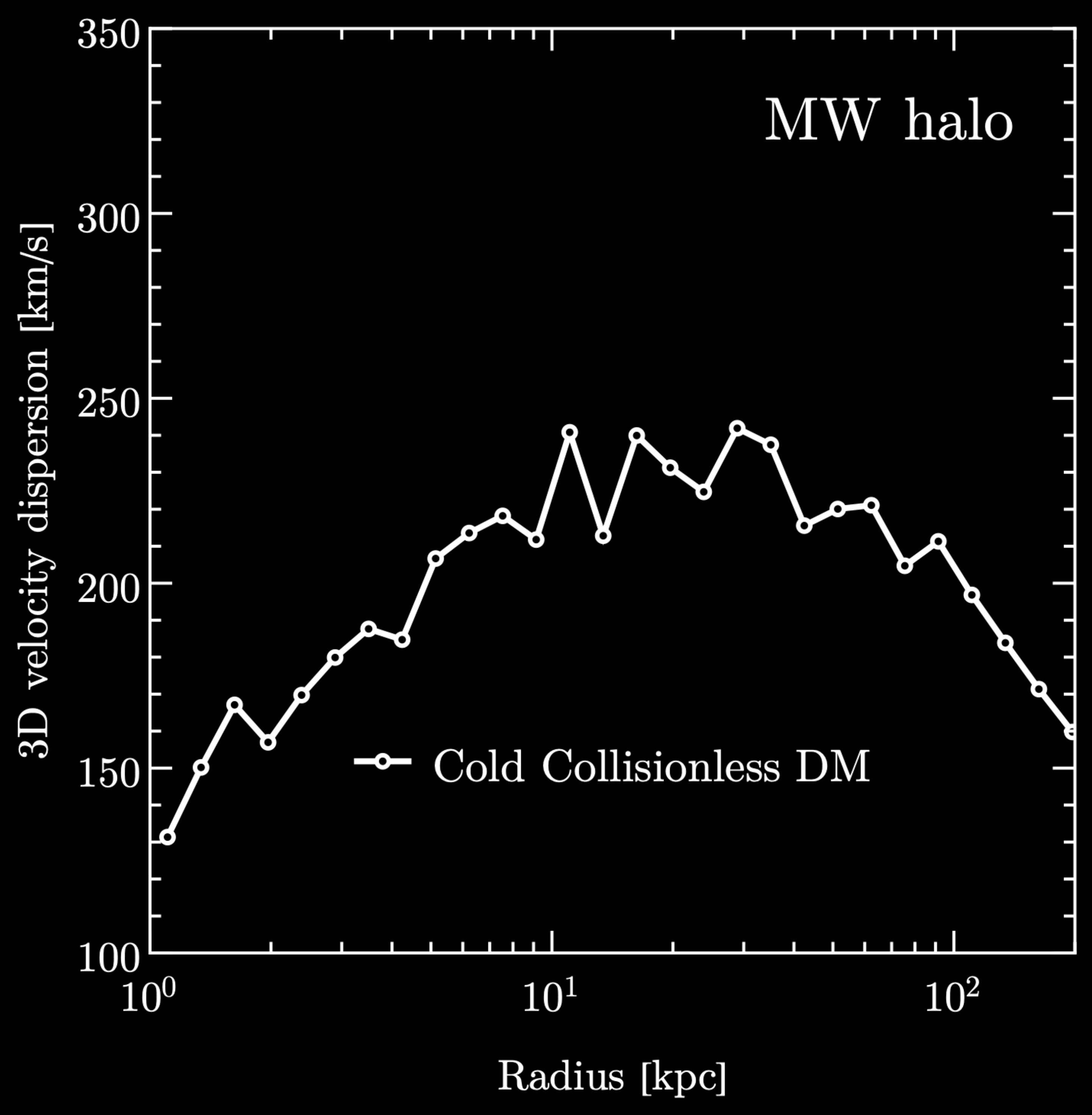
I. Halo formation

Density profile
(density at given radii)

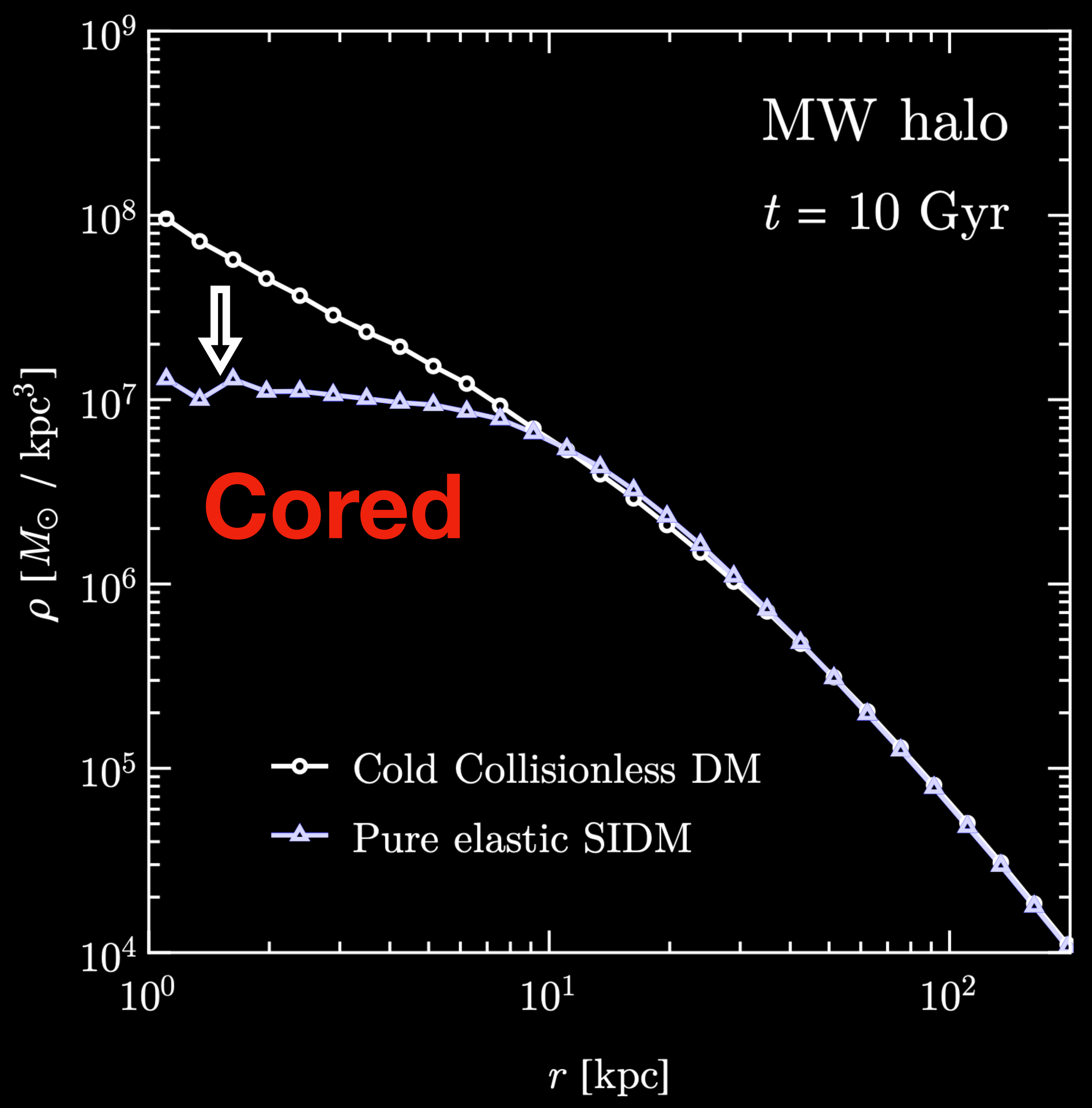


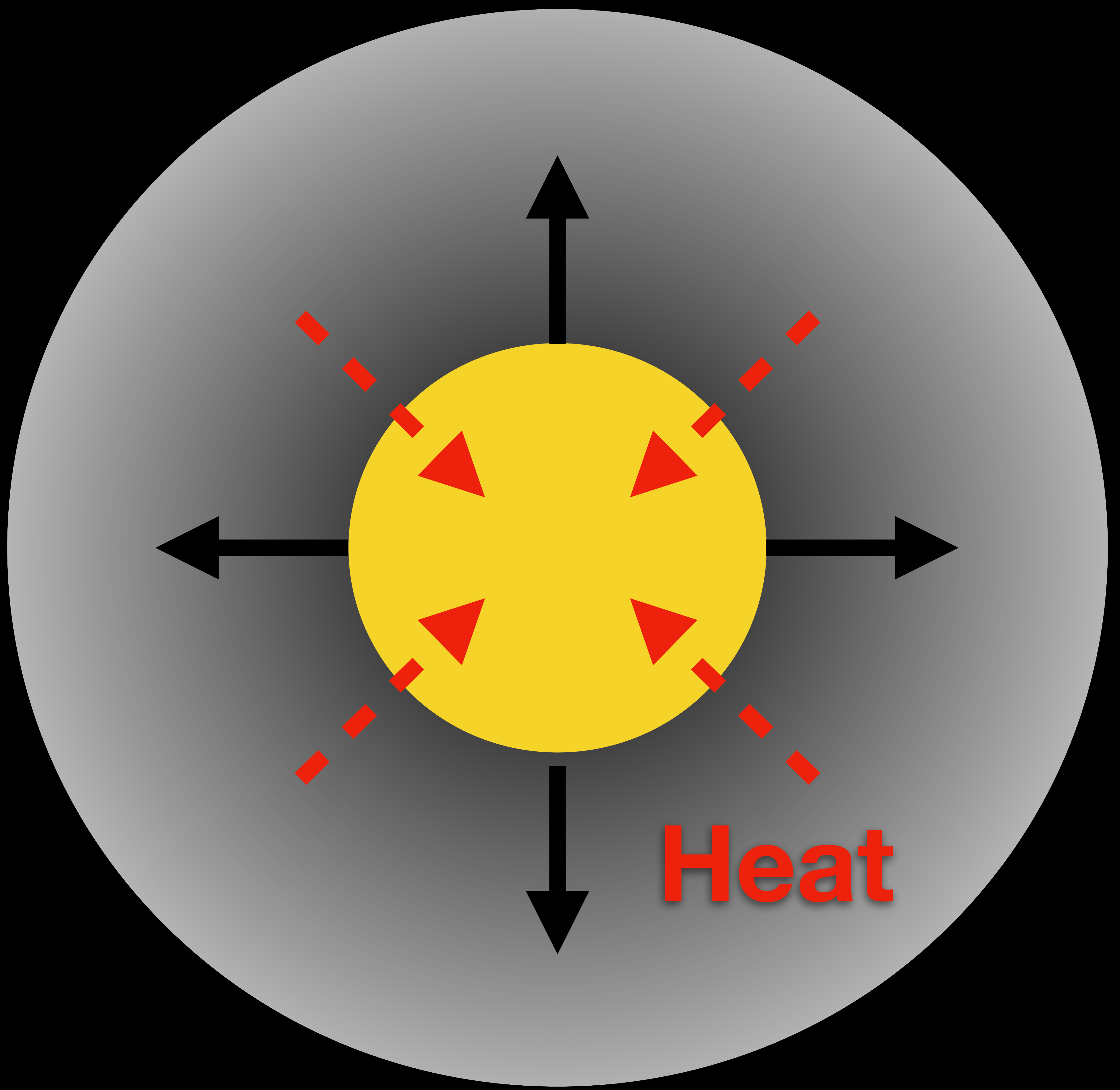


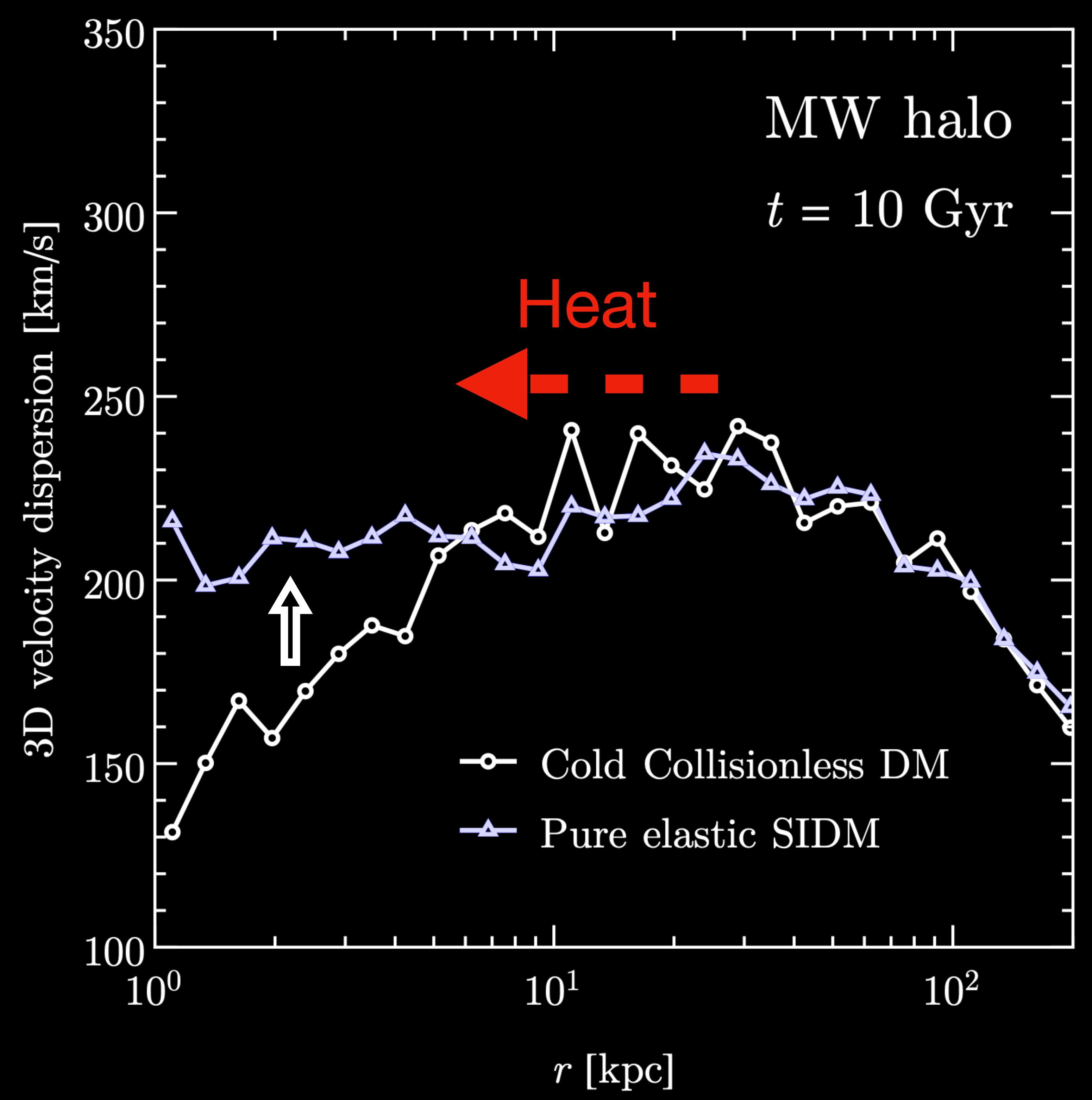
Vel. dispersion profile



II. Core expansion

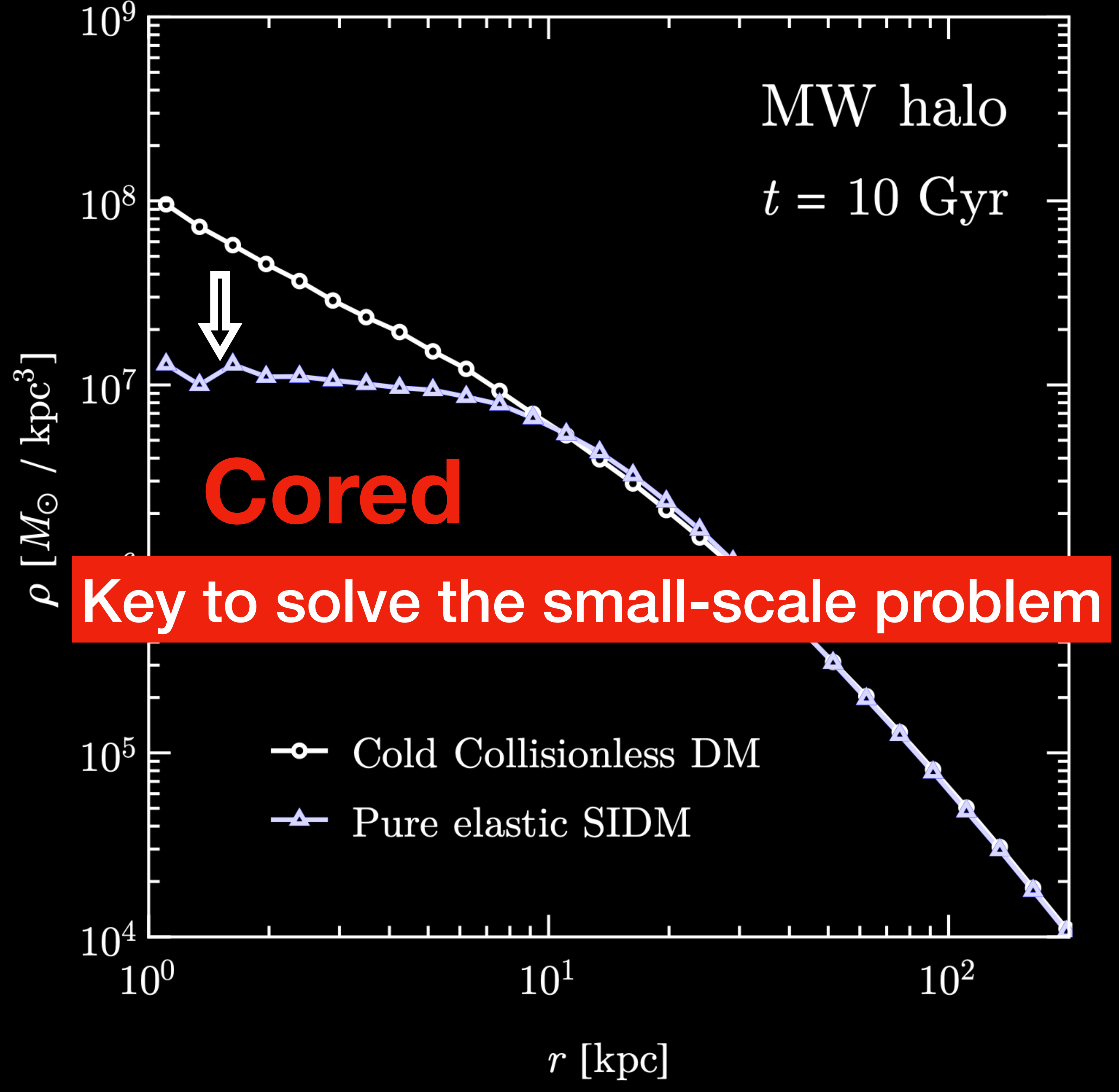


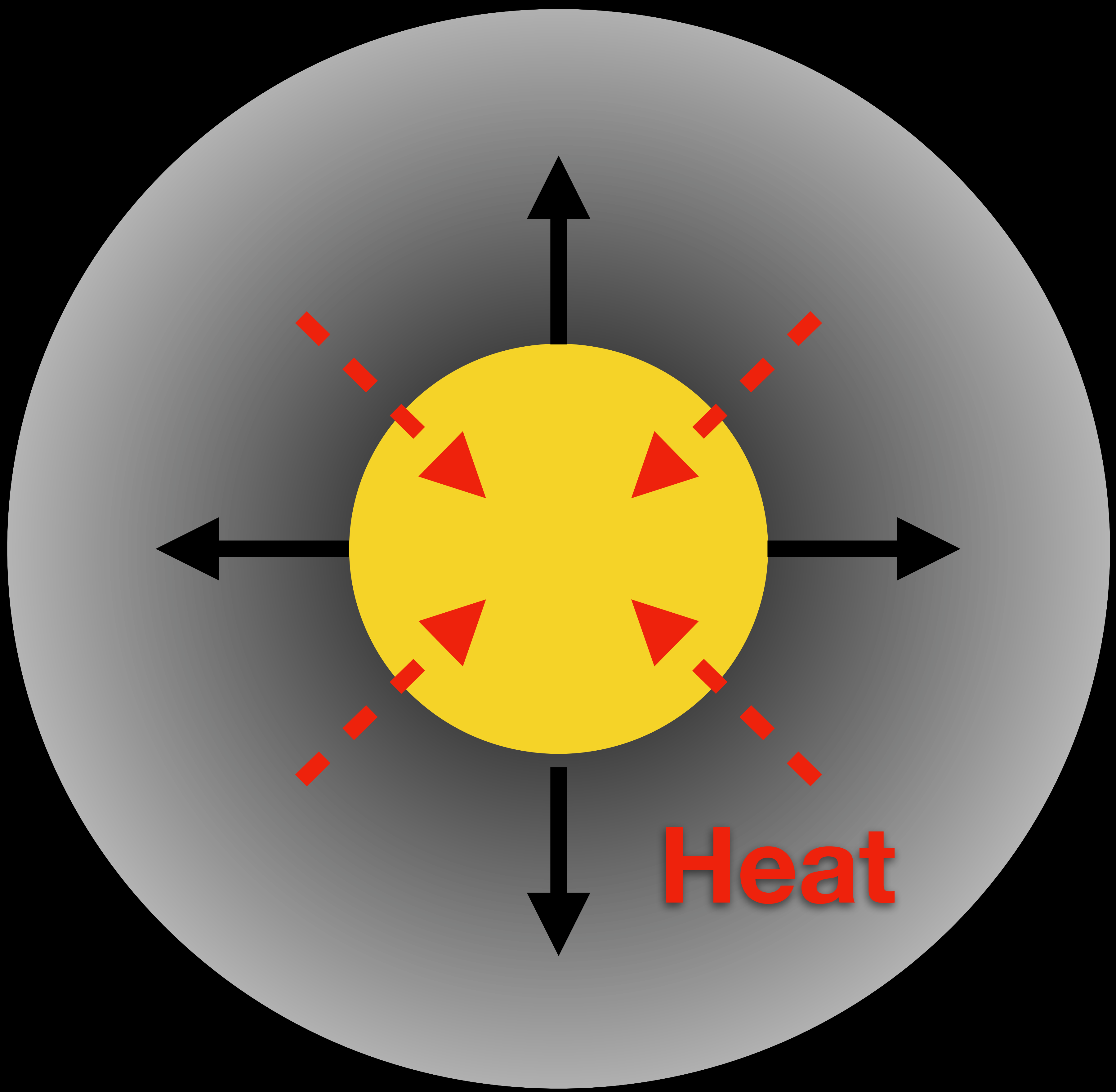


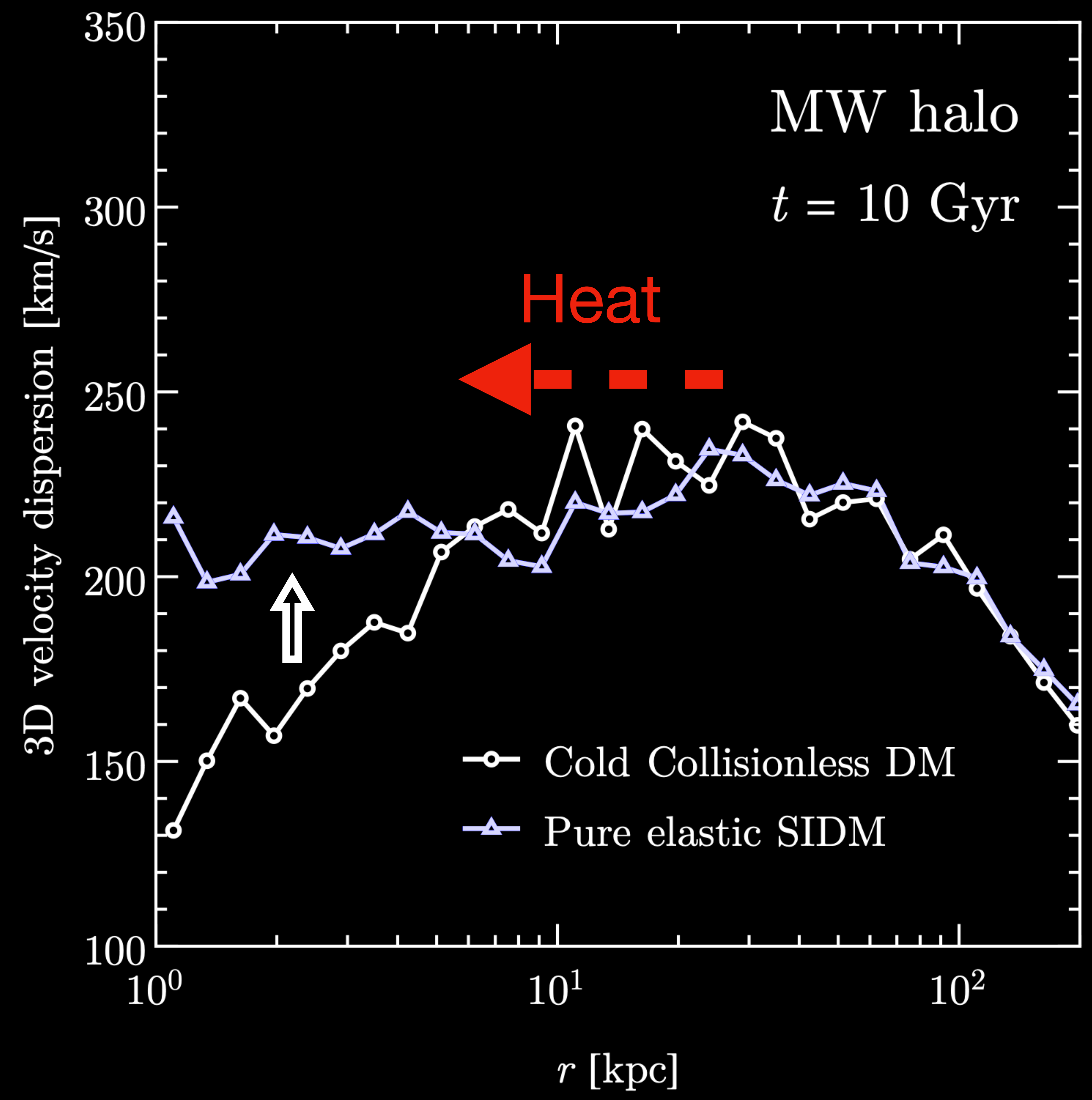


Huo, Yu & **YZ** '20

II. Core expansion

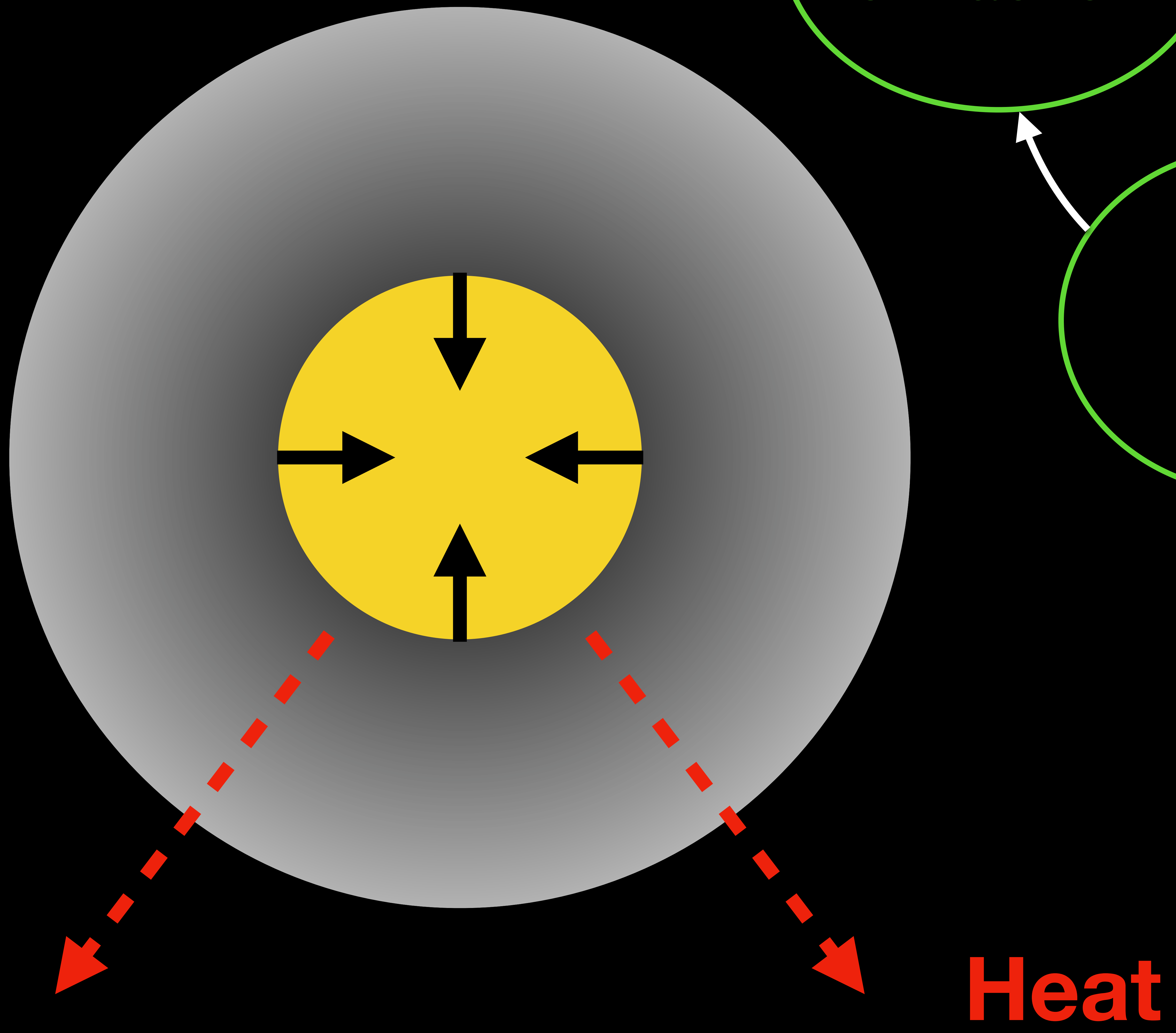


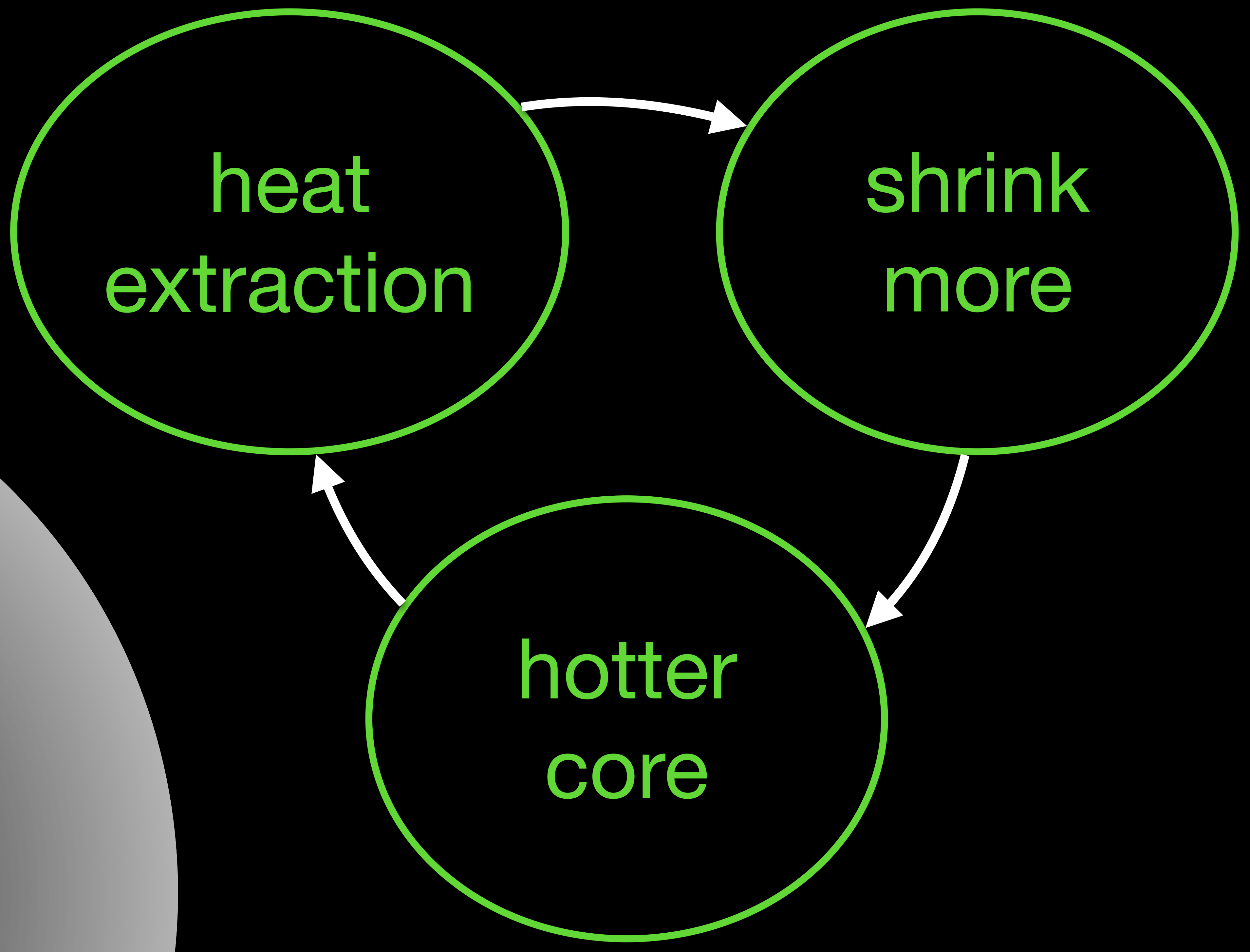




Huo, Yu & **YZ** ‘20

III. Core collapse





Spergel & Steinhardt ‘00

III. Core collapse

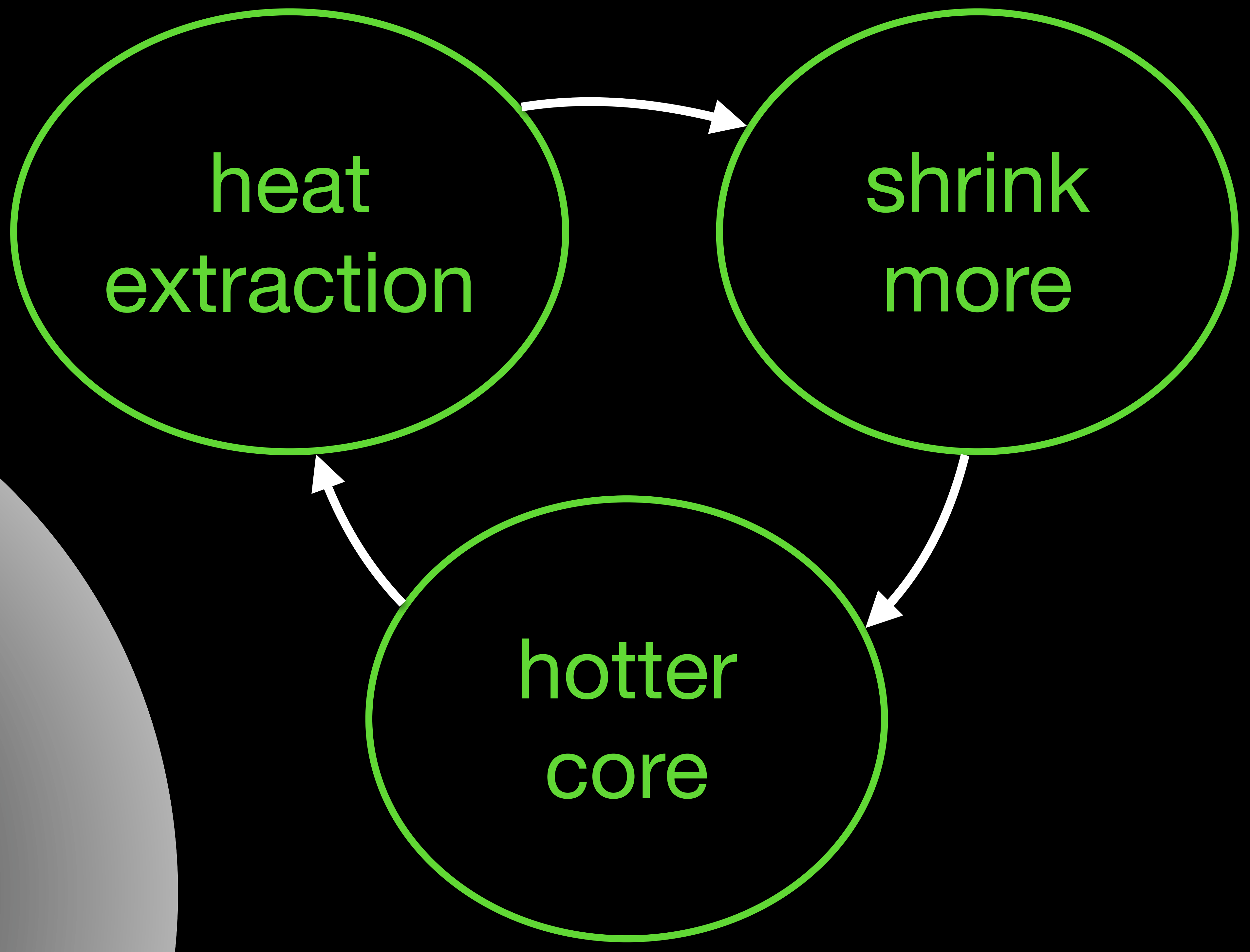
$$2E_{\rm kin} + E_{\rm pot} = 0$$

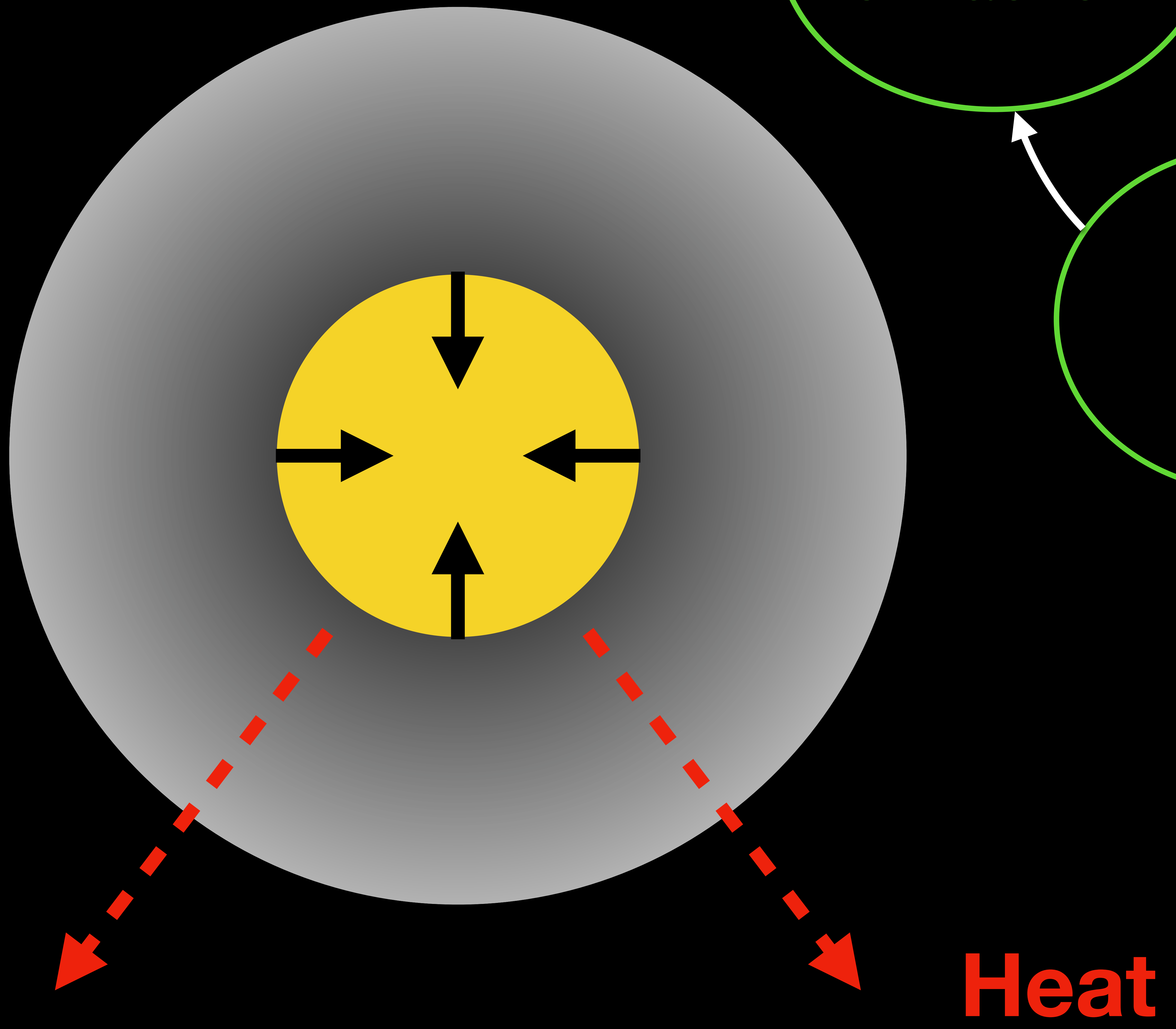
$$\Downarrow$$

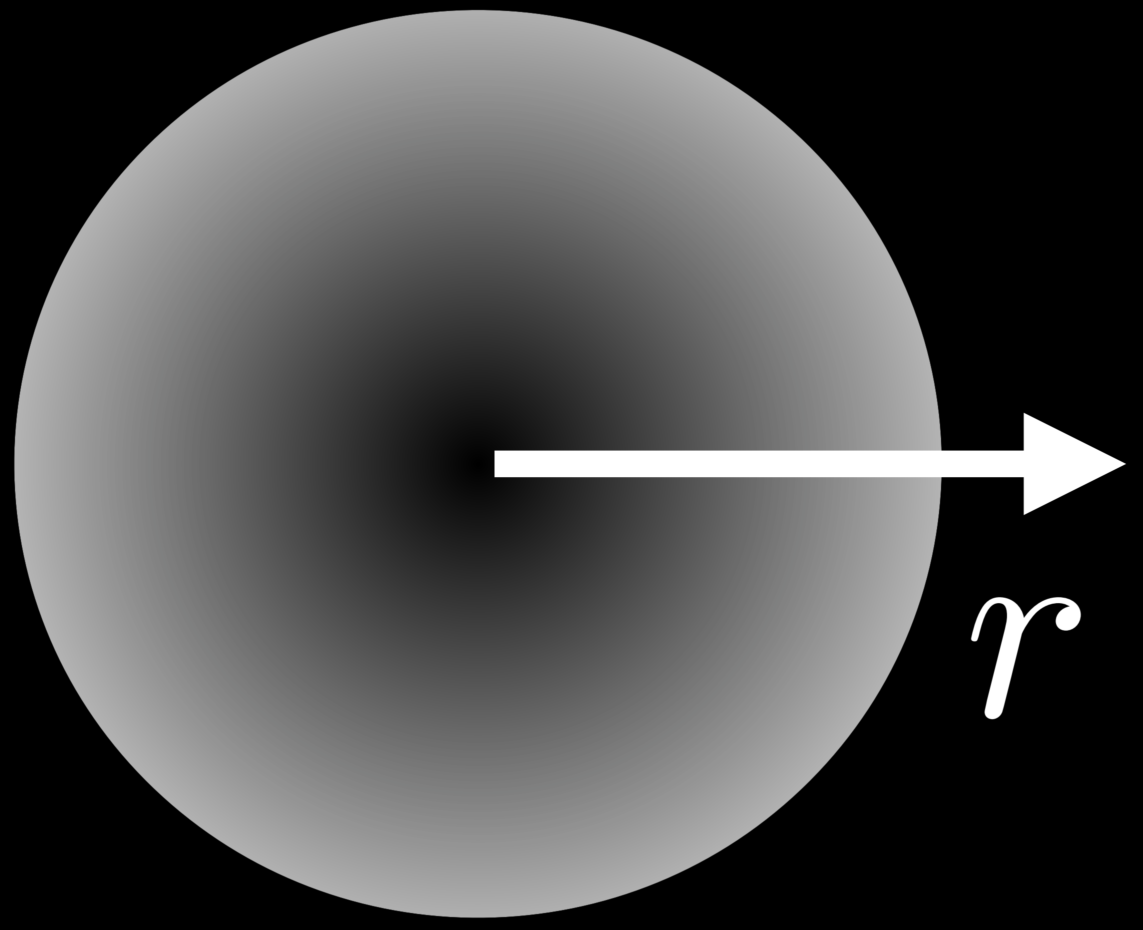
$$E_{\rm total} = -E_{\rm kin}$$

$$\Downarrow \quad E_{\rm kin} \propto T$$

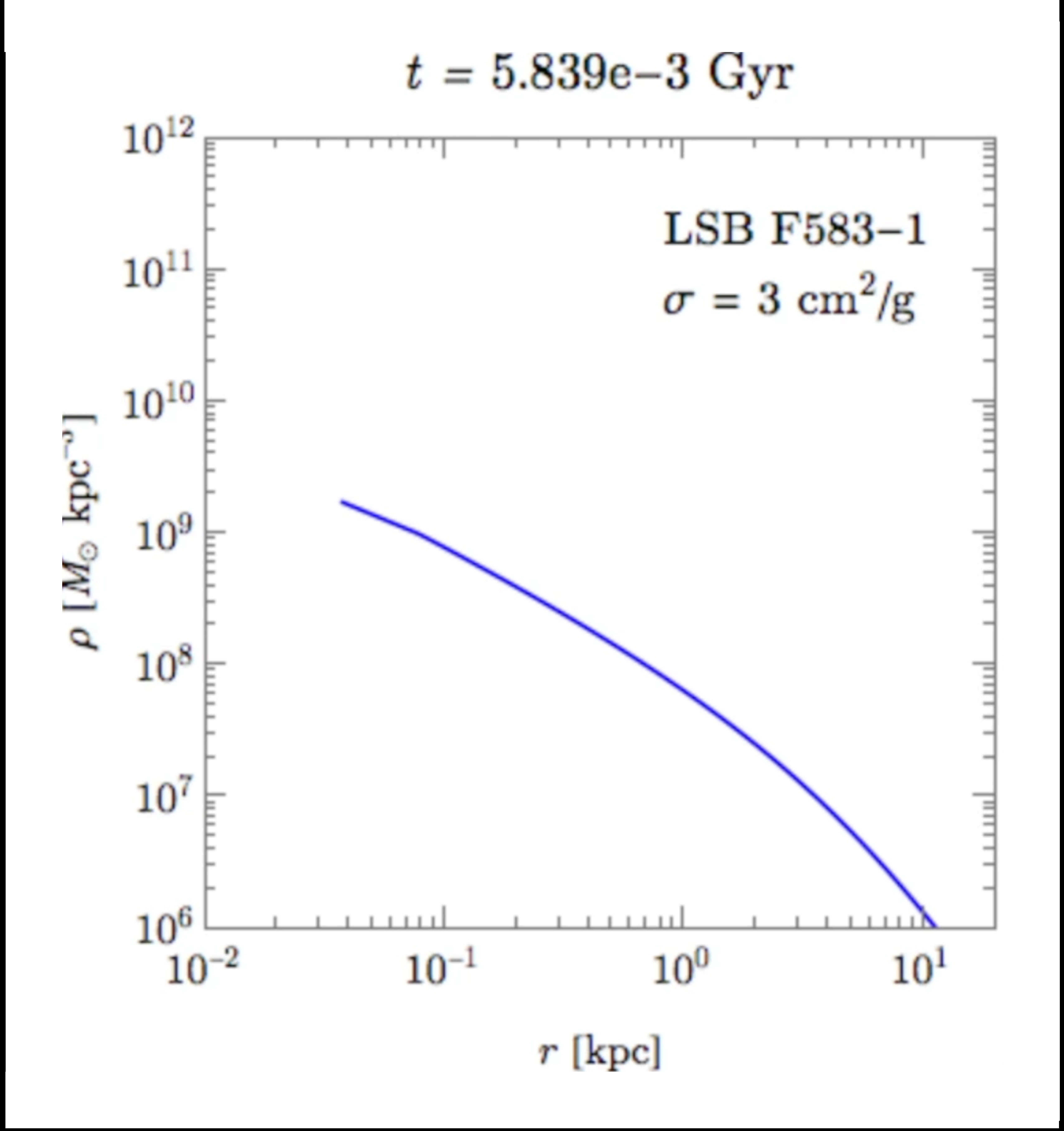
$$C \equiv \frac{E_{\rm total}}{T} < 0$$







Dark matter halo

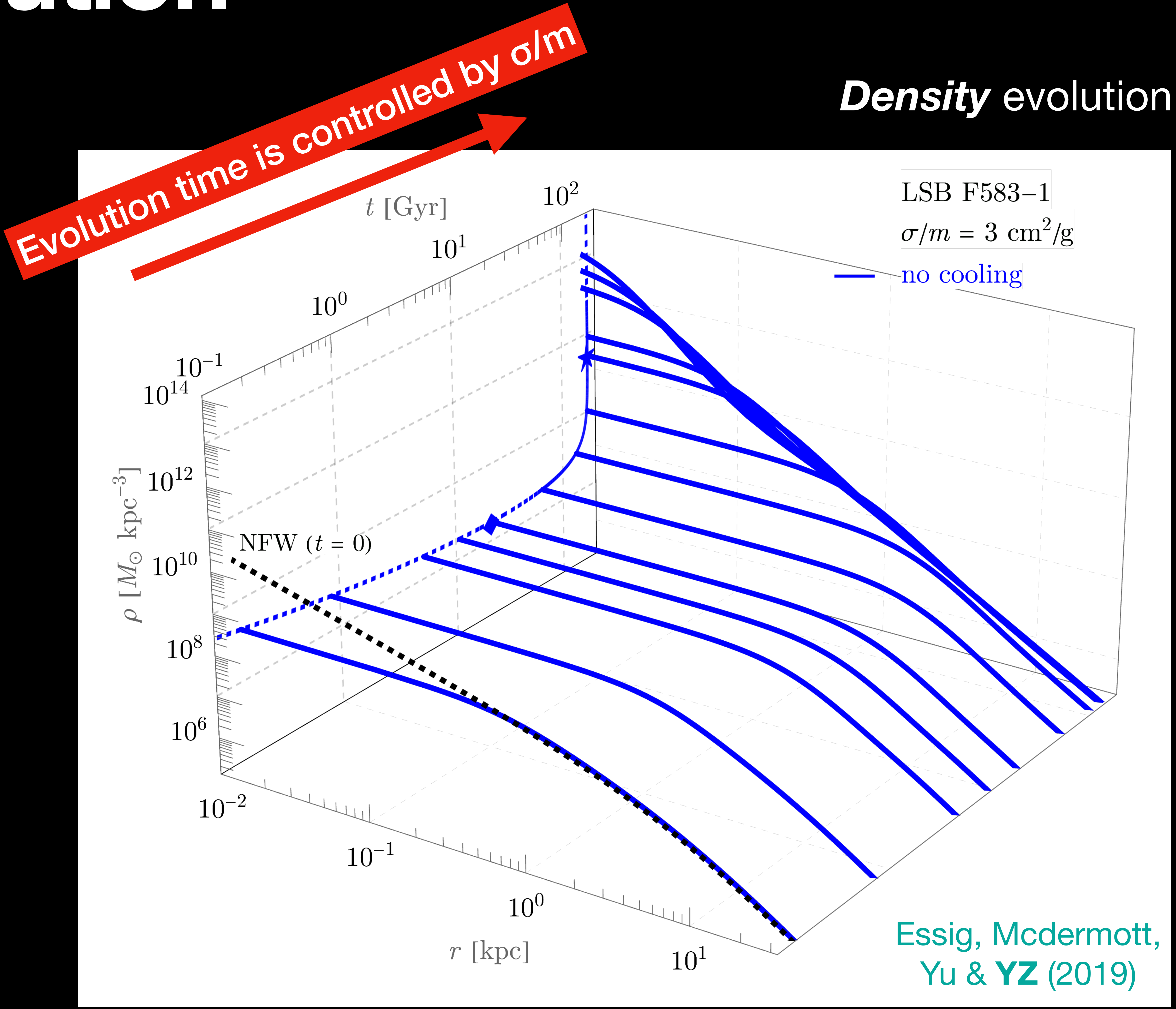


Gravothermal evolution

Evolution stages:

0. Halo formation
1. Core expansion
2. Quasi-stable
3. Core collapse

Density evolution



Essig, Mcdermott, Yu & **YZ** (2019)

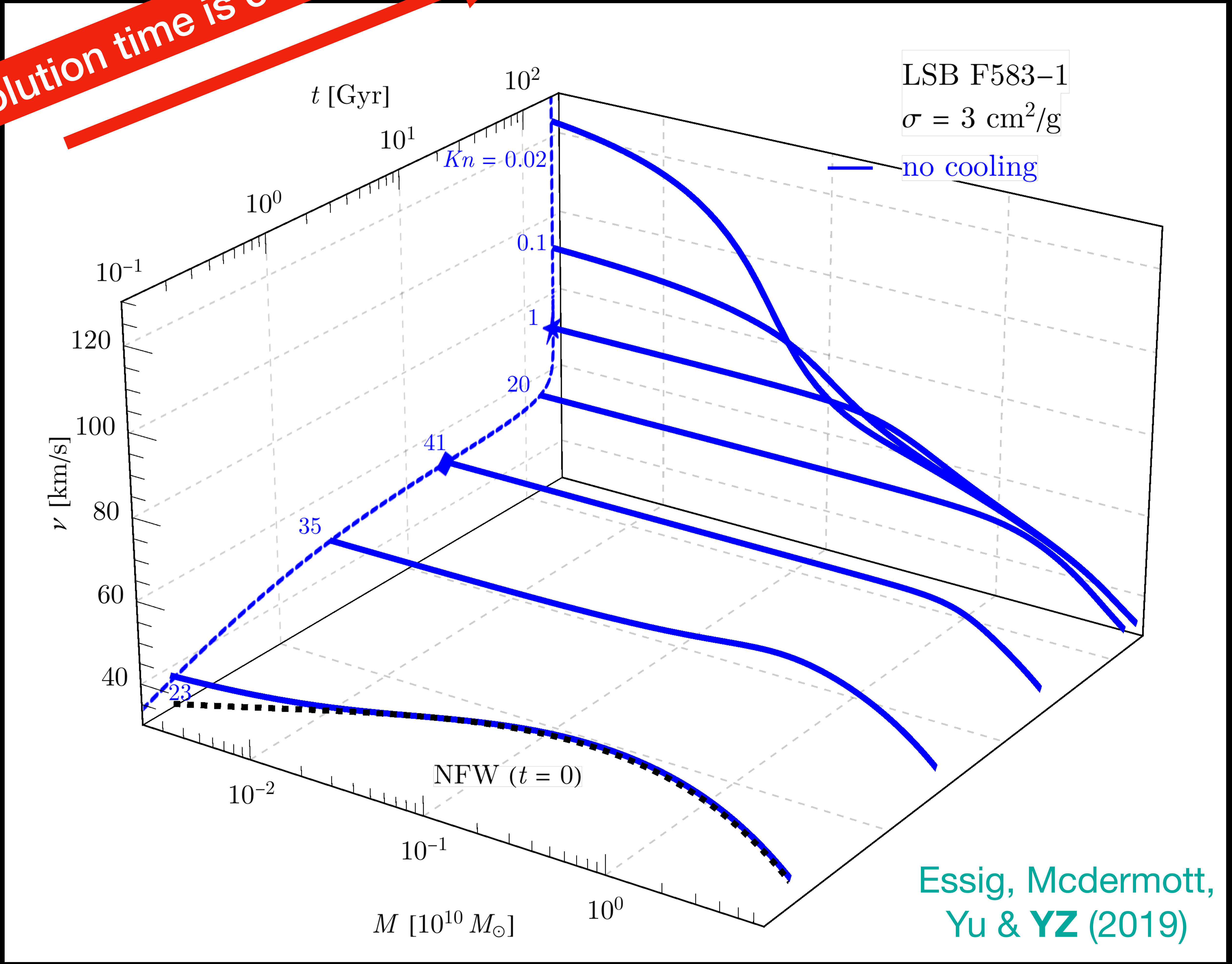
Gravothermal evolution

Evolution time is controlled by σ/m

Velocity dispersion evolution

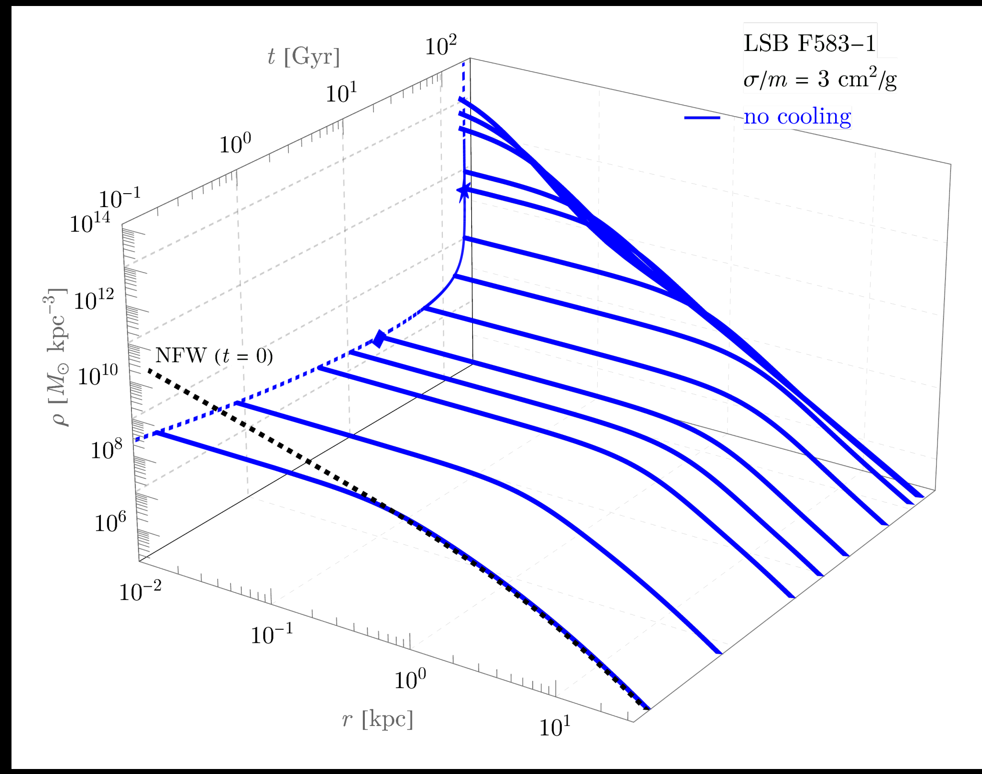
Evolution stages:

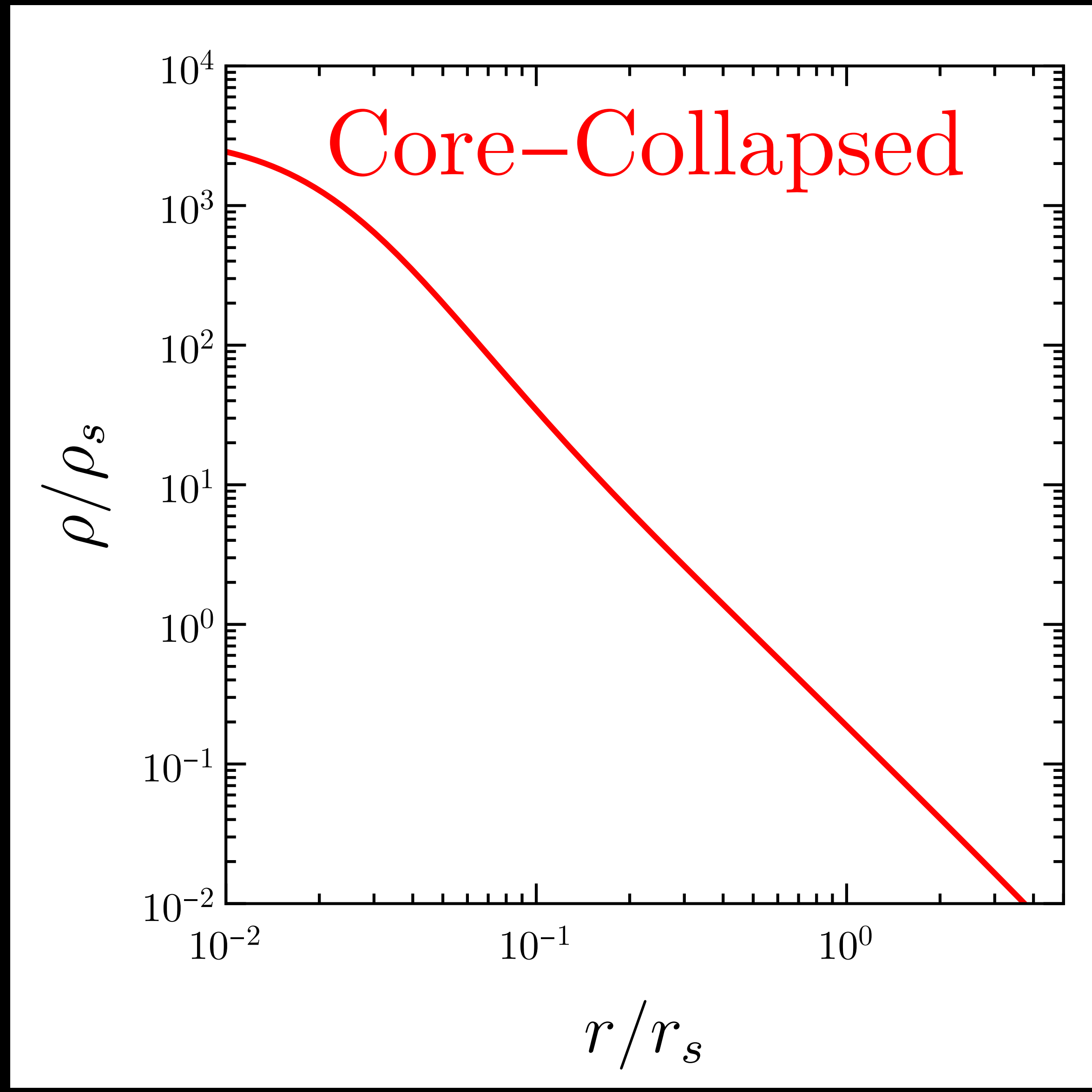
0. Halo formation
1. Core expansion
2. Quasi-stable
3. Core collapse

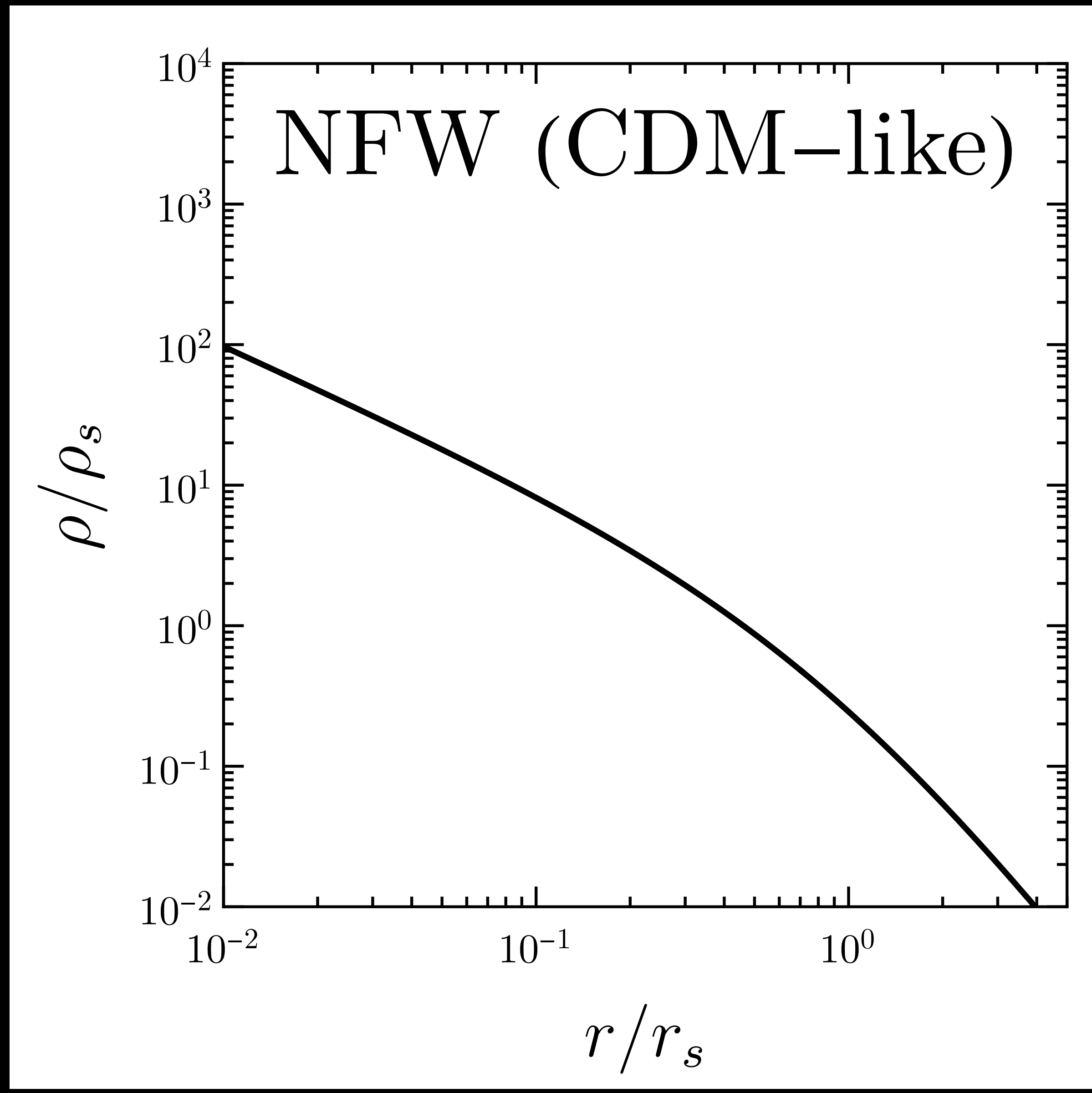


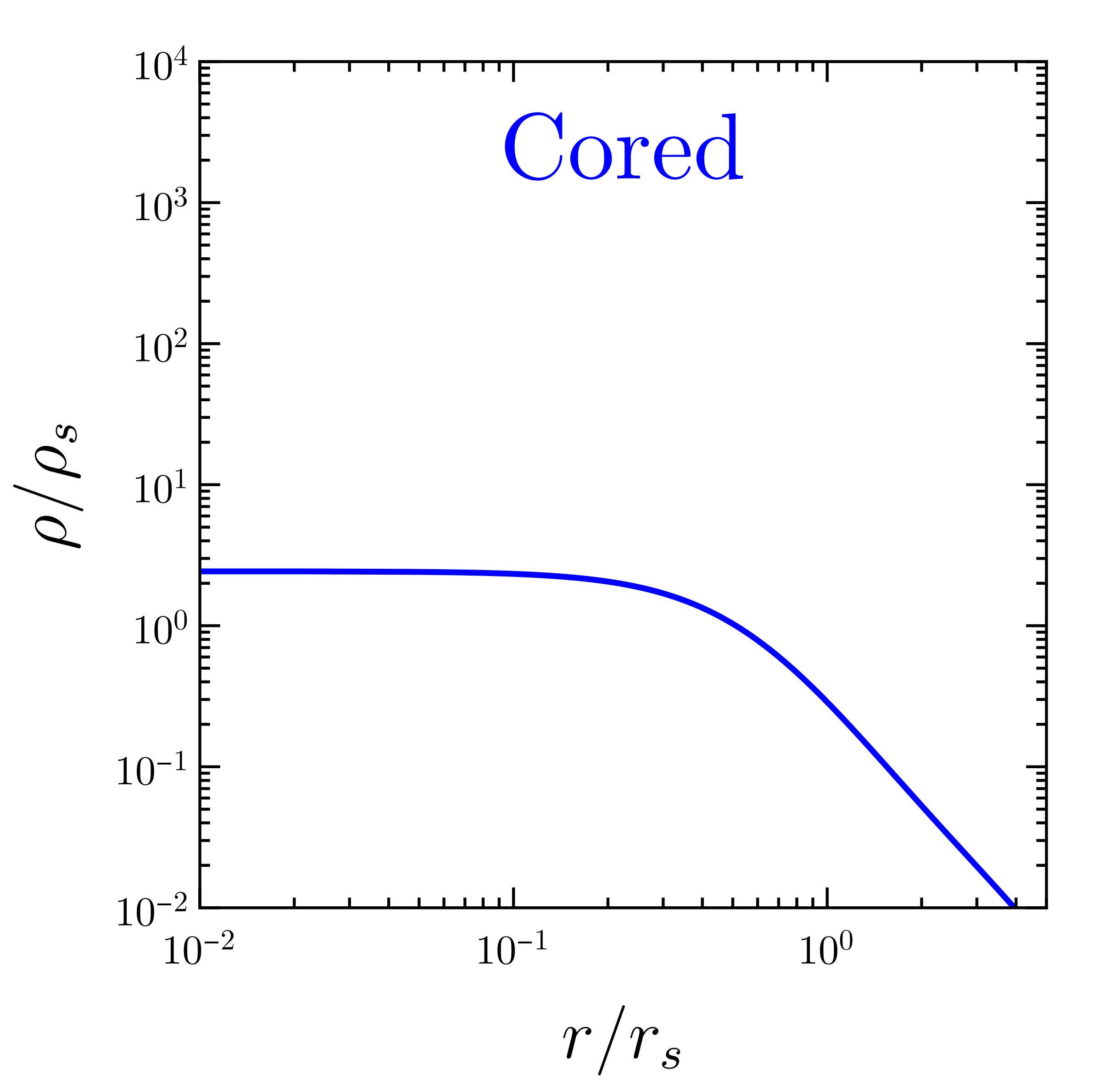
Essig, Mcdermott, Yu & **YZ** (2019)

Self-interactions increase halo's ***diversity***

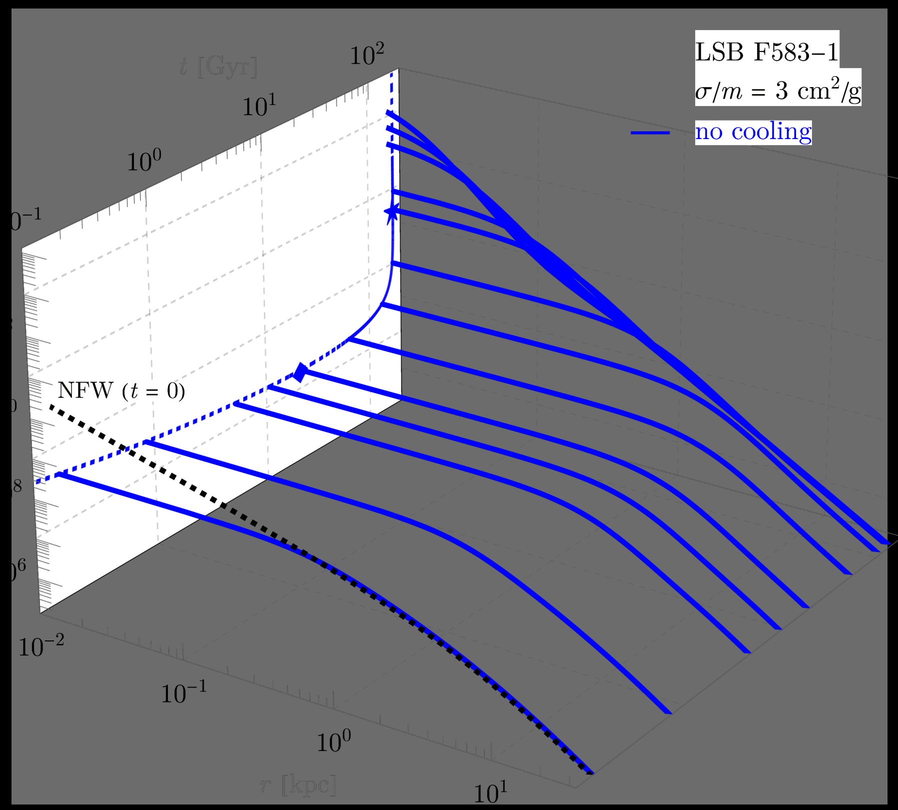


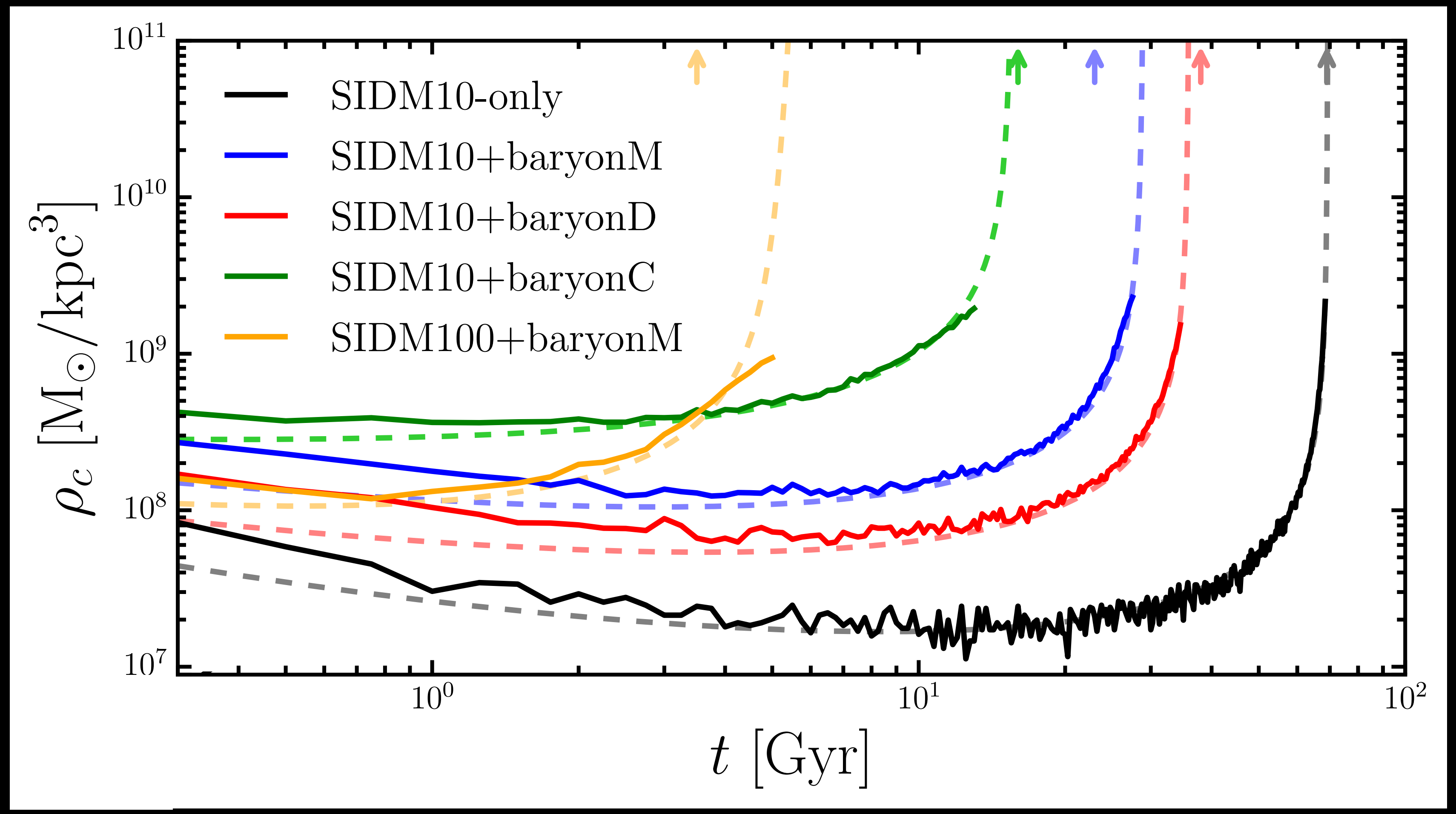






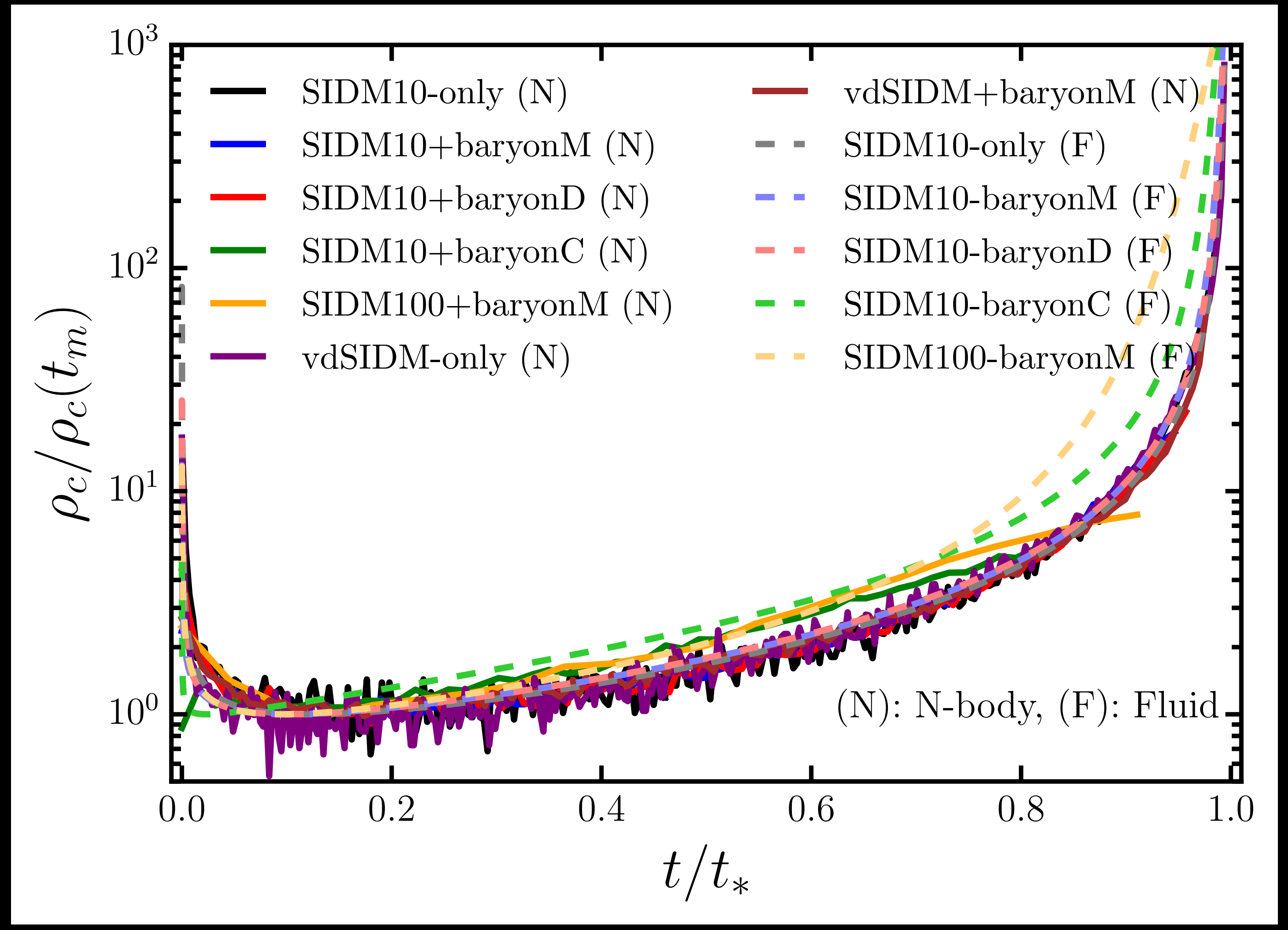
Self-interactions enforce halo's ***universality***





Different halo configurations

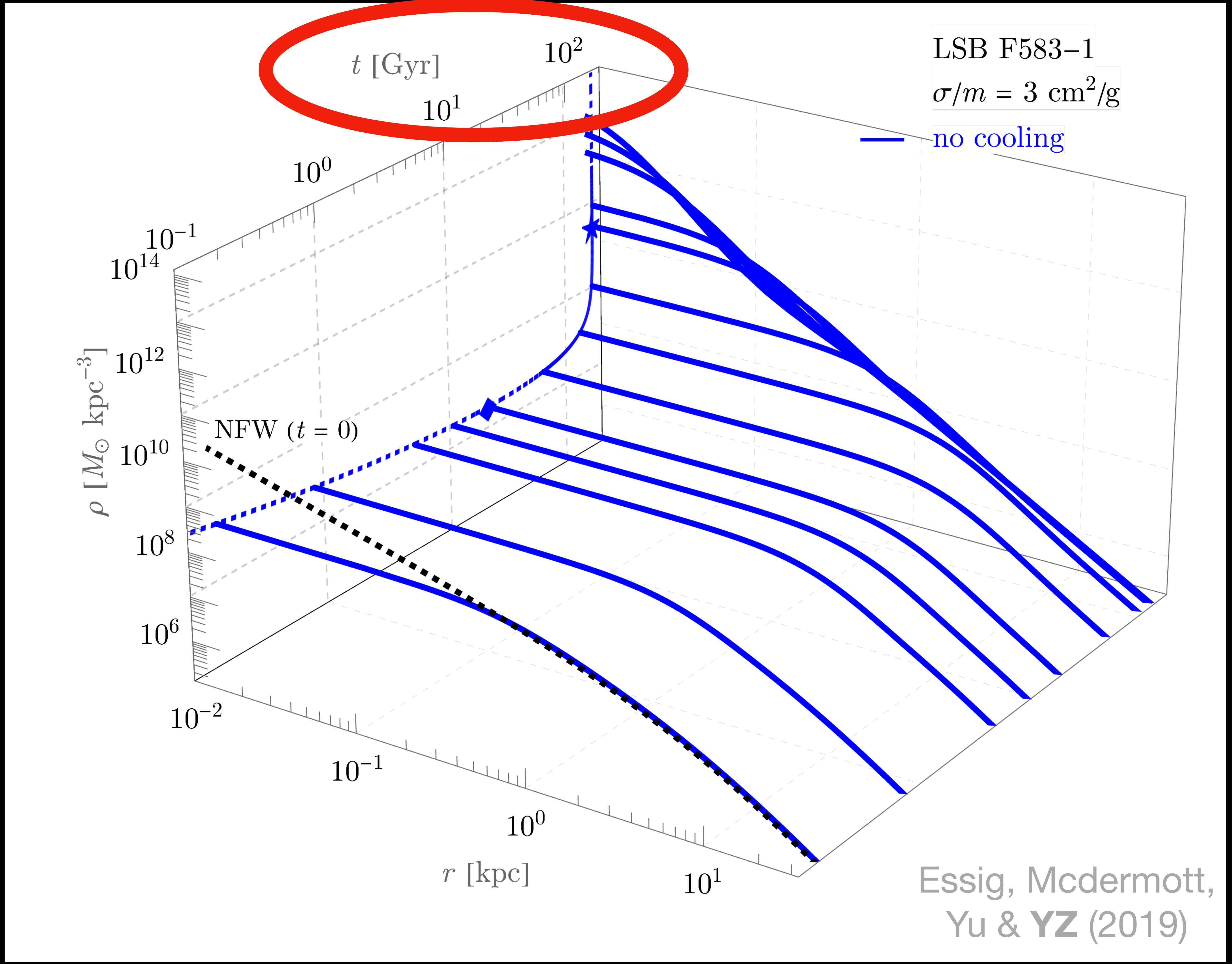
Rescaling



YZ, Yang & Yu '23

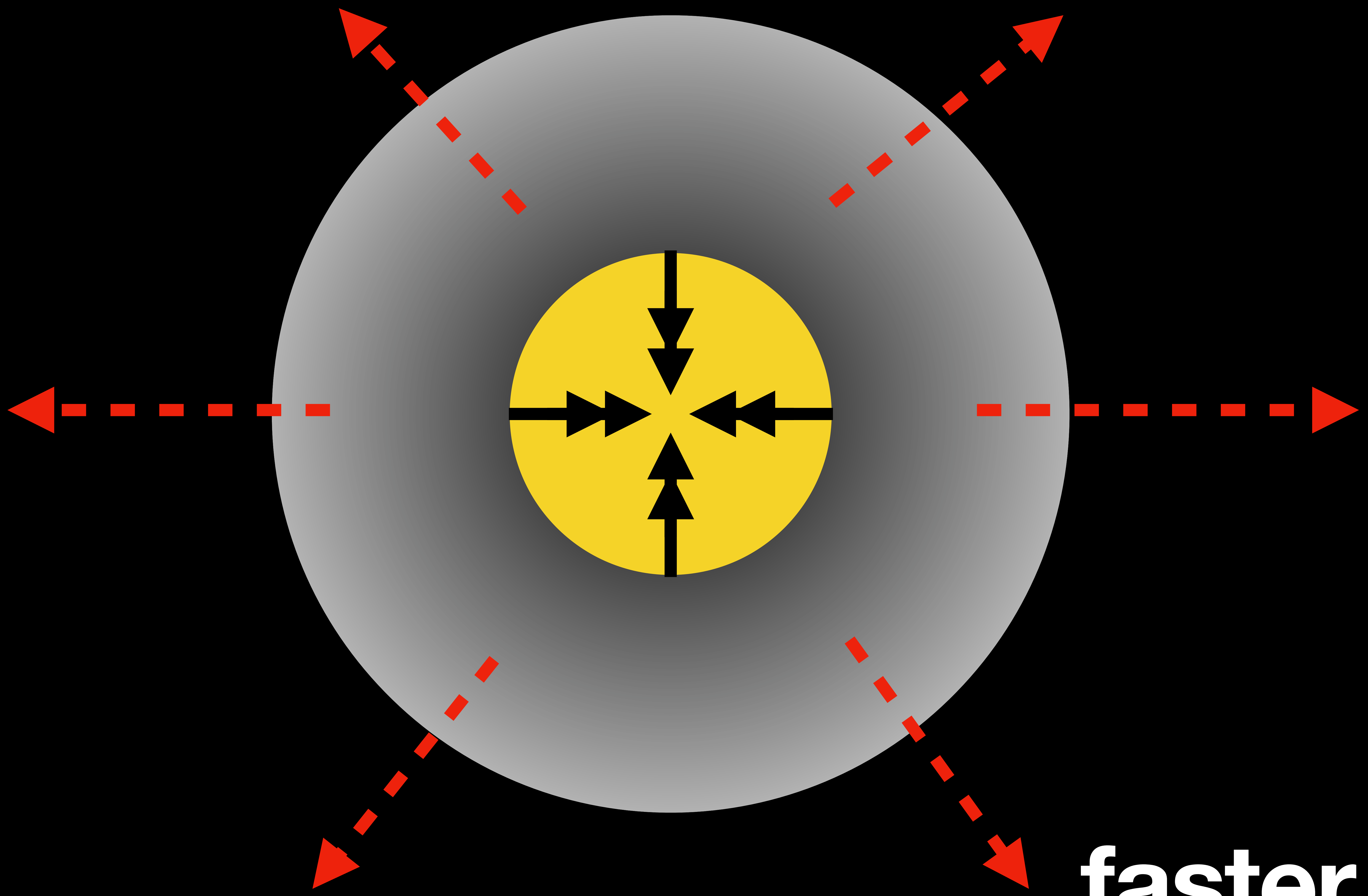
But it takes too long…

Why should we care?



Essig, Mcdermott, Yu & **YZ** (2019)

If more heat goes out

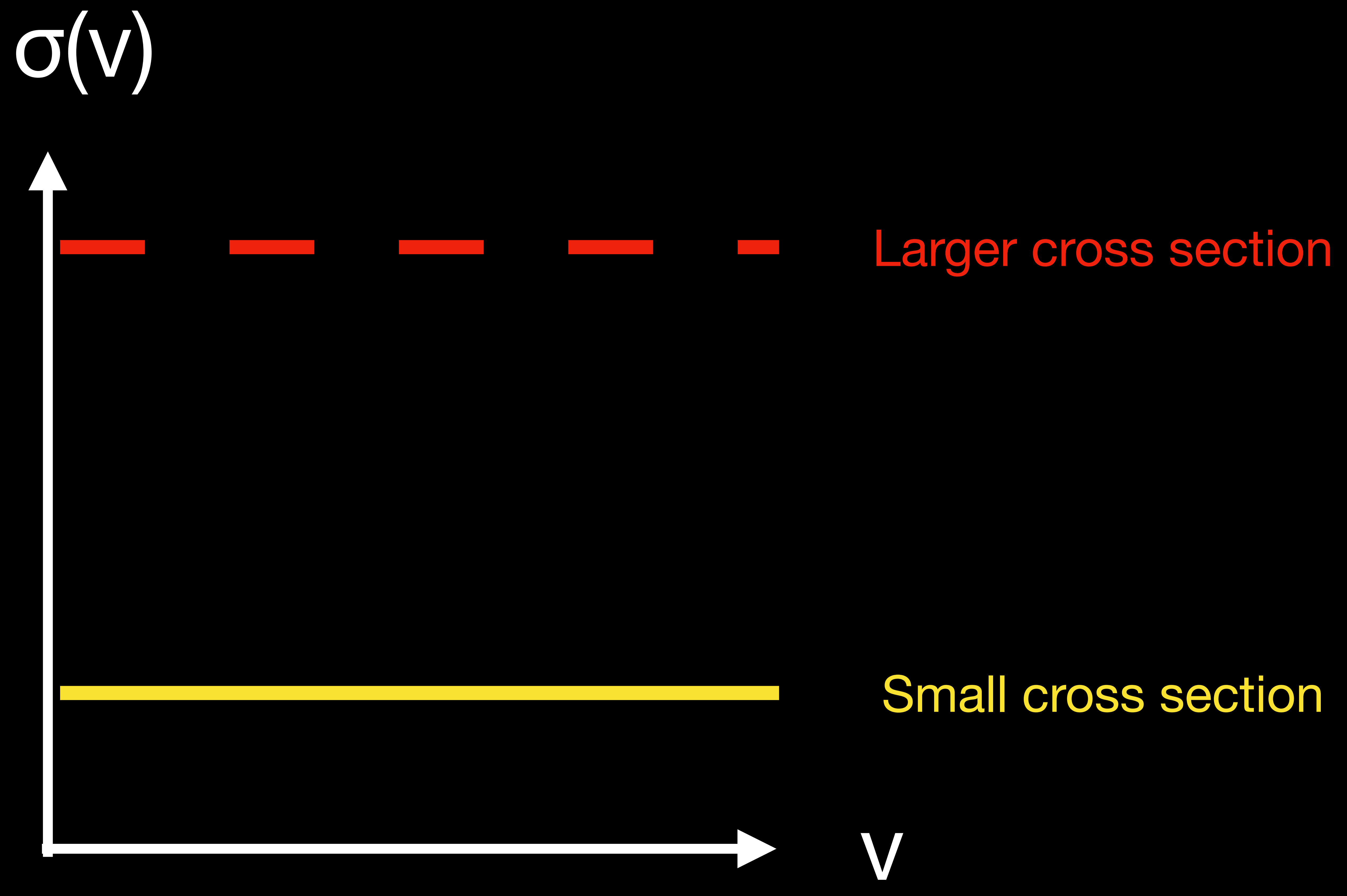


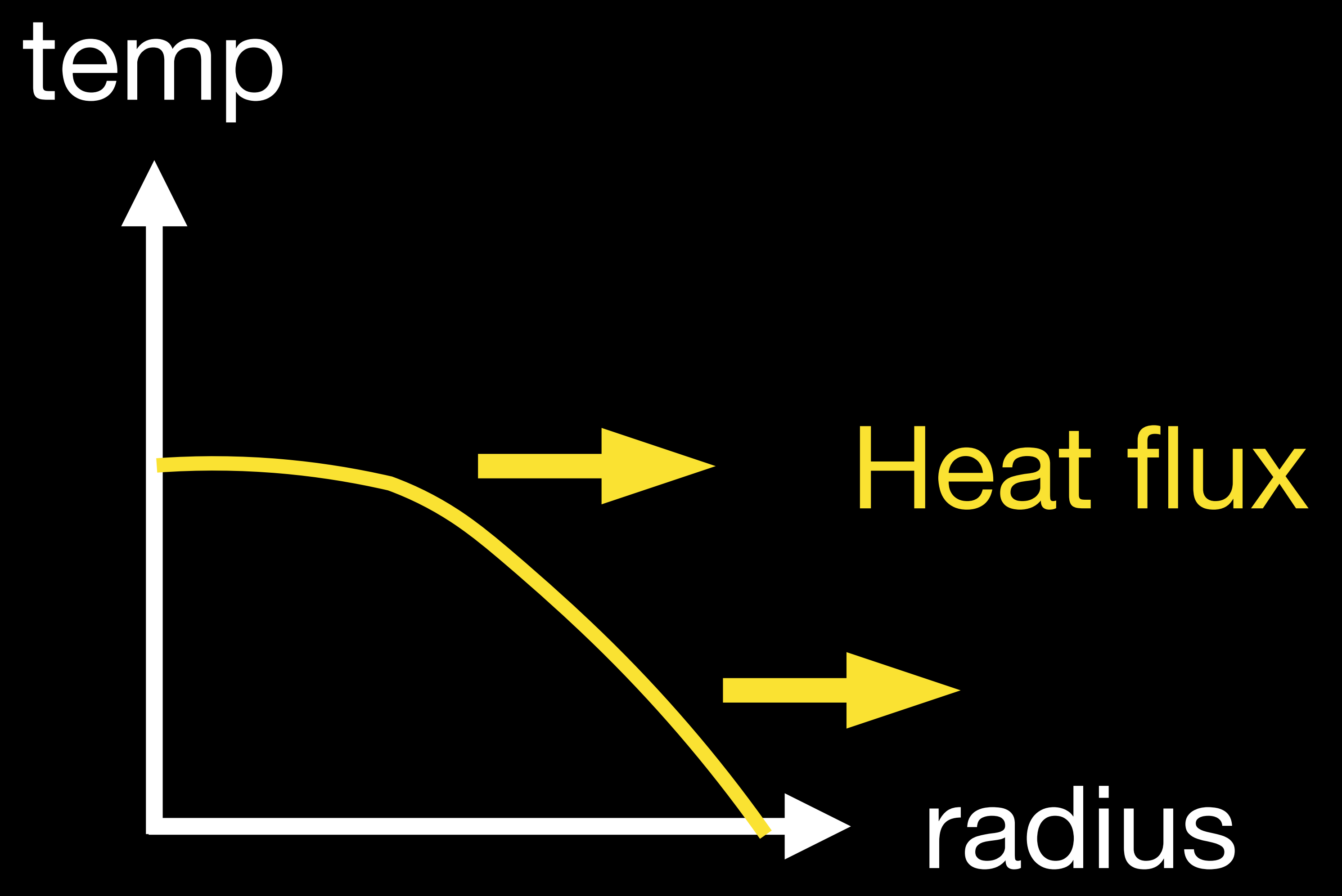
faster collapse

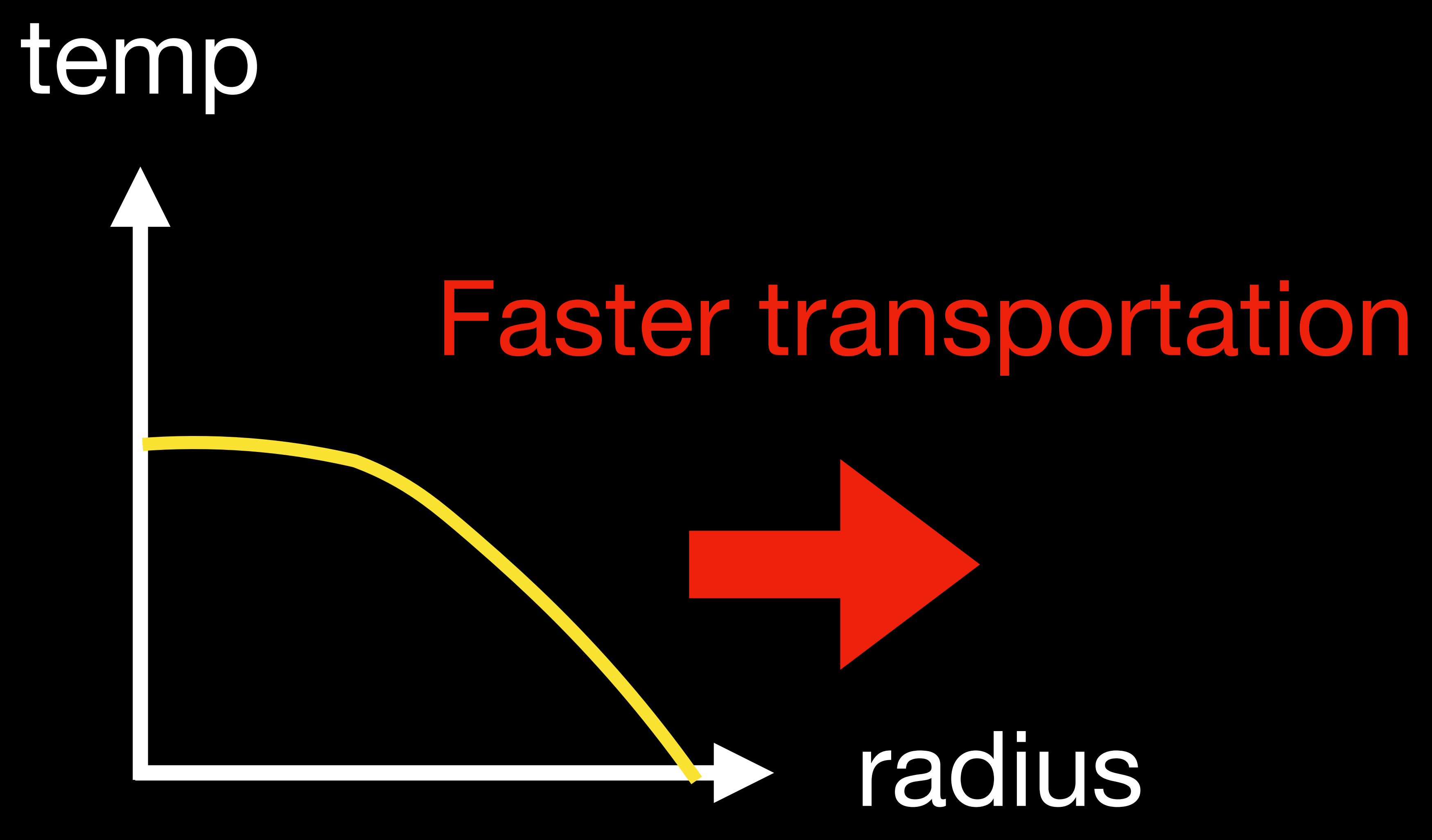
How to transfer more heat out?

- Velocity-dependent (vd) self-interaction
- Dissipative self-interaction — Essig, Mcdermott, Yu & **YZ** (2019); Huo, Yu & **YZ** (2020)
- Central baryon component — Yang, Yu & **YZ** (2023); Yang+ (**YZ** included, 2023)
- Tidal stripping — Nishikawa+ (2019)
- …….

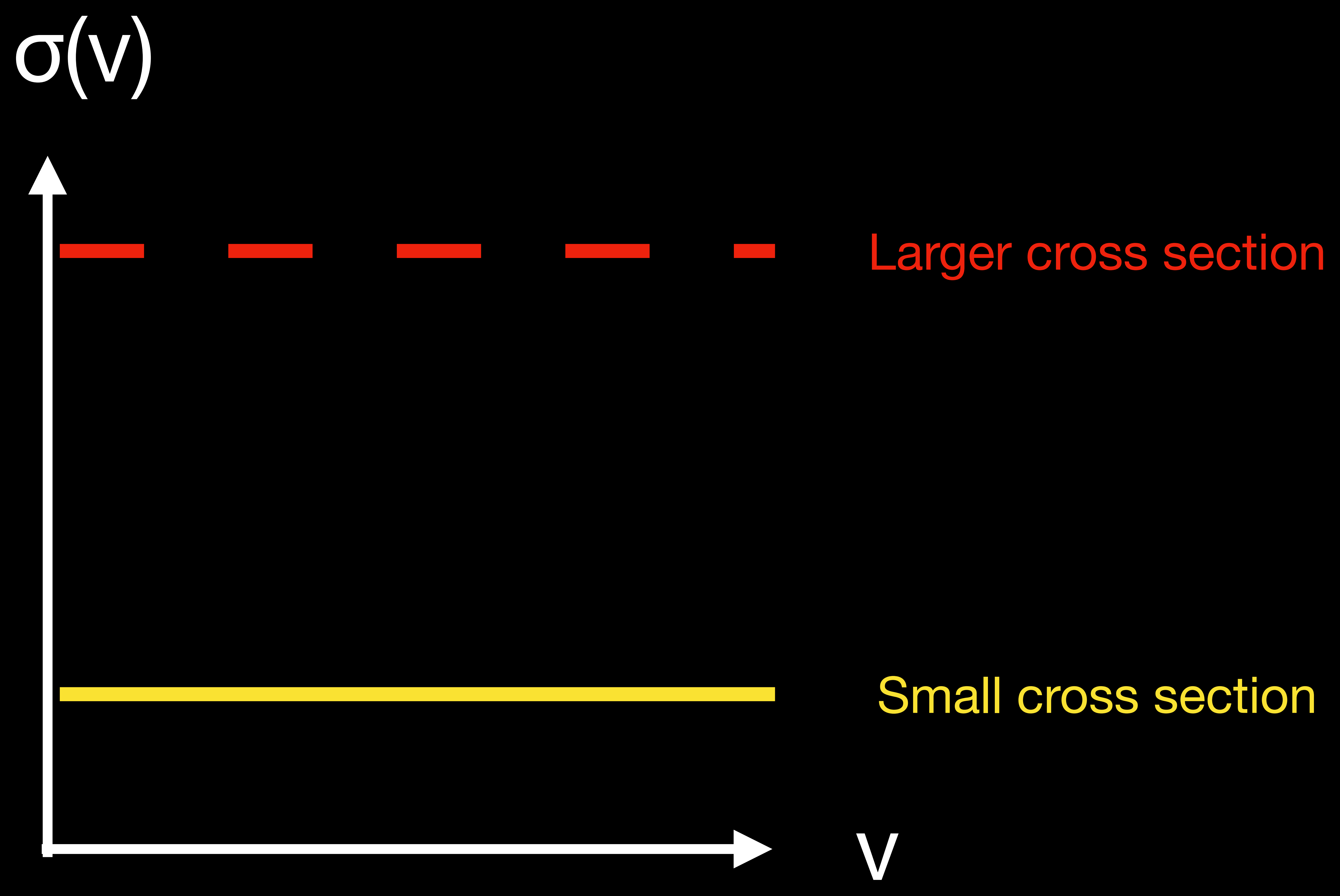
1. Larger self-interaction





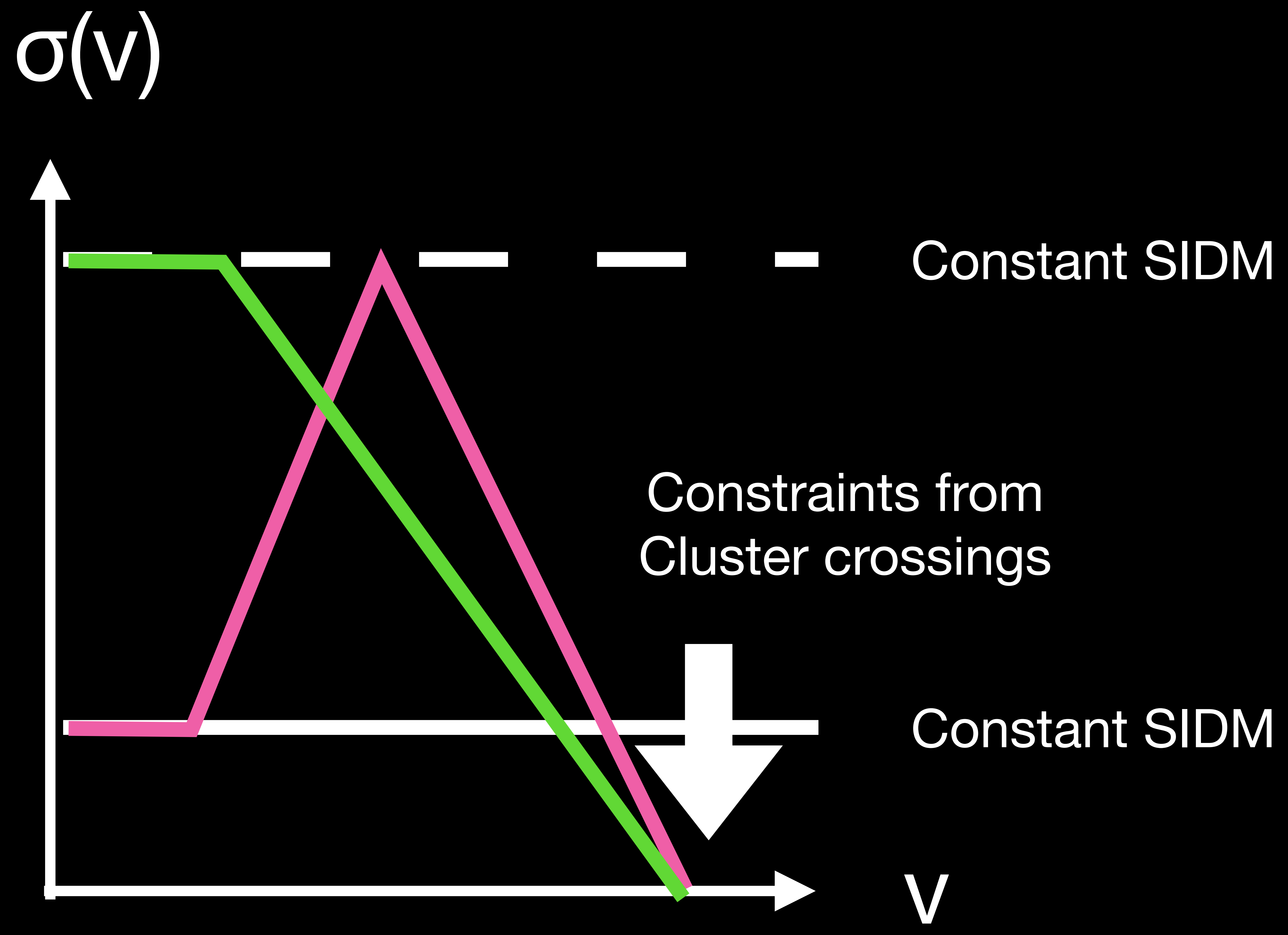


1. Larger self-interaction



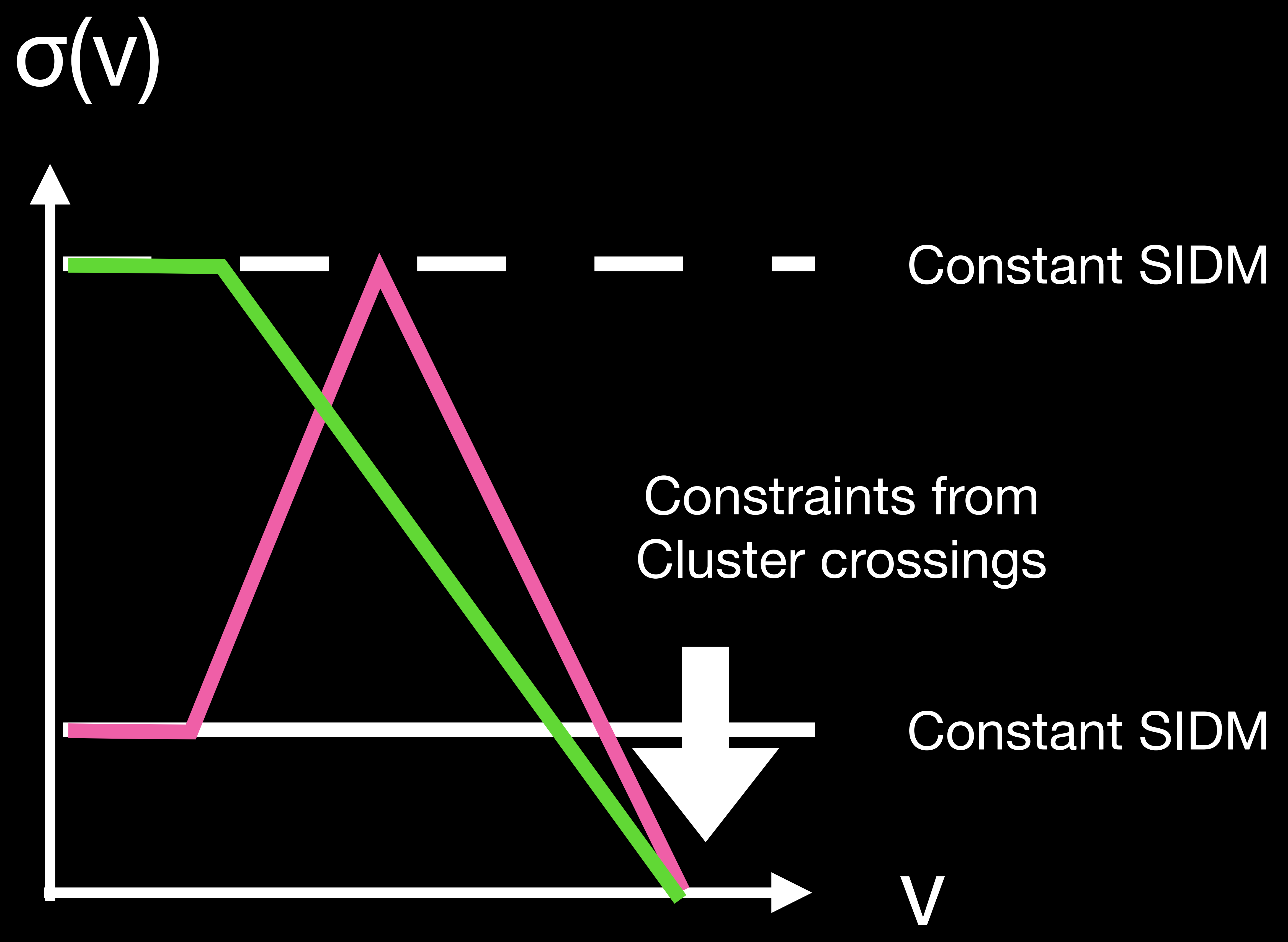
Bullet cluster crossing

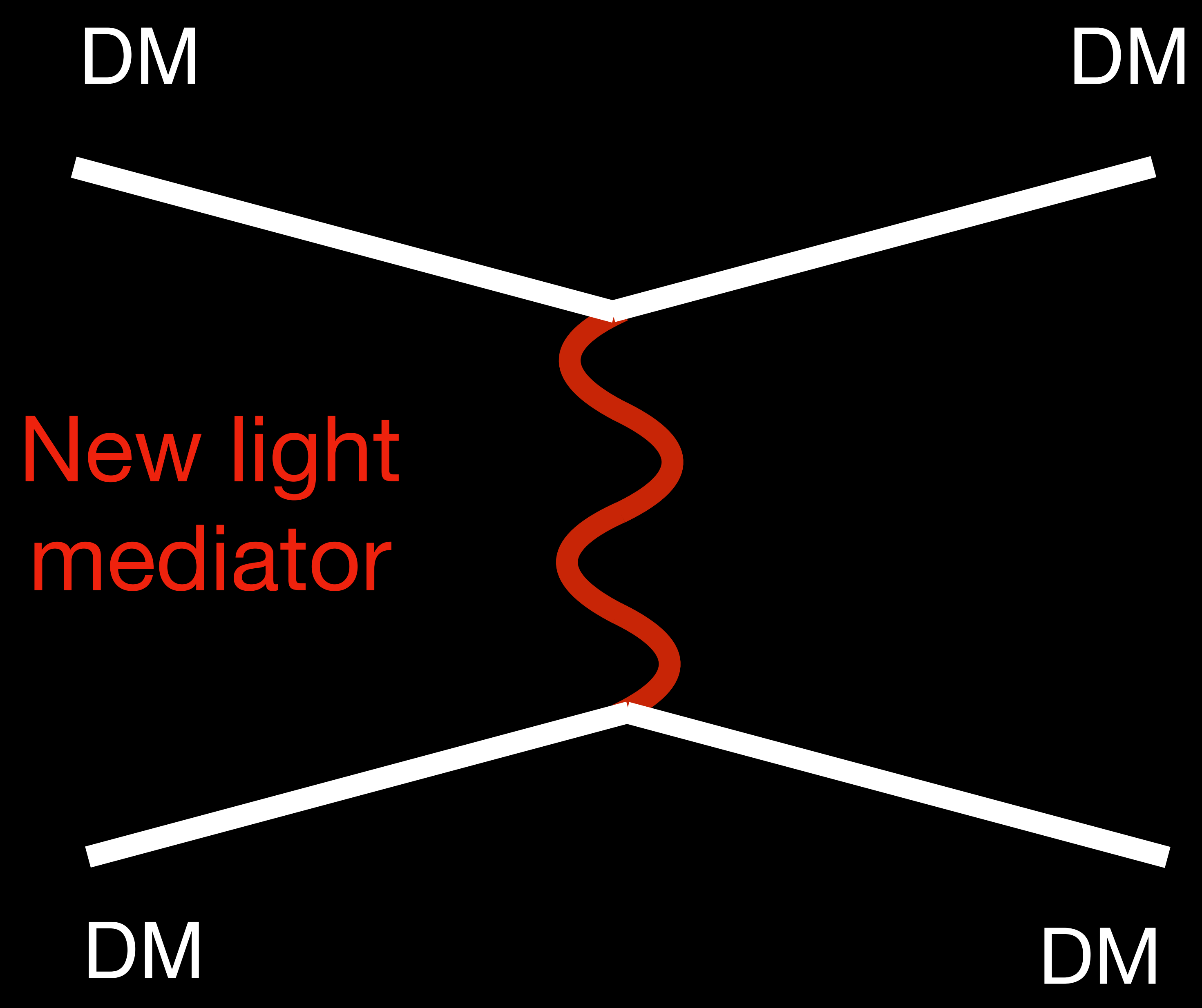
1. Velocity-dependent SIDM



Bullet cluster crossing

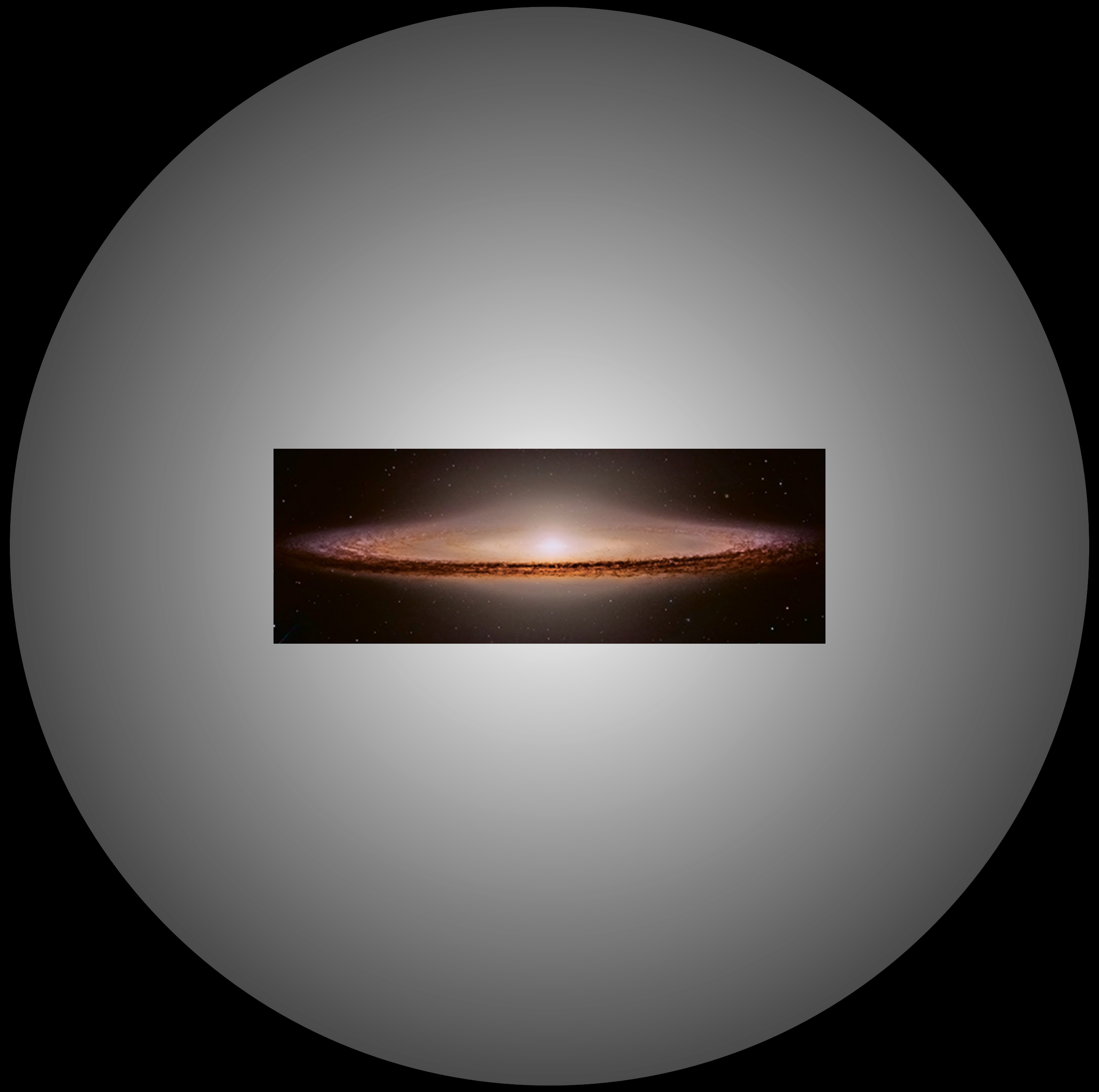
1. Velocity-dependent SIDM



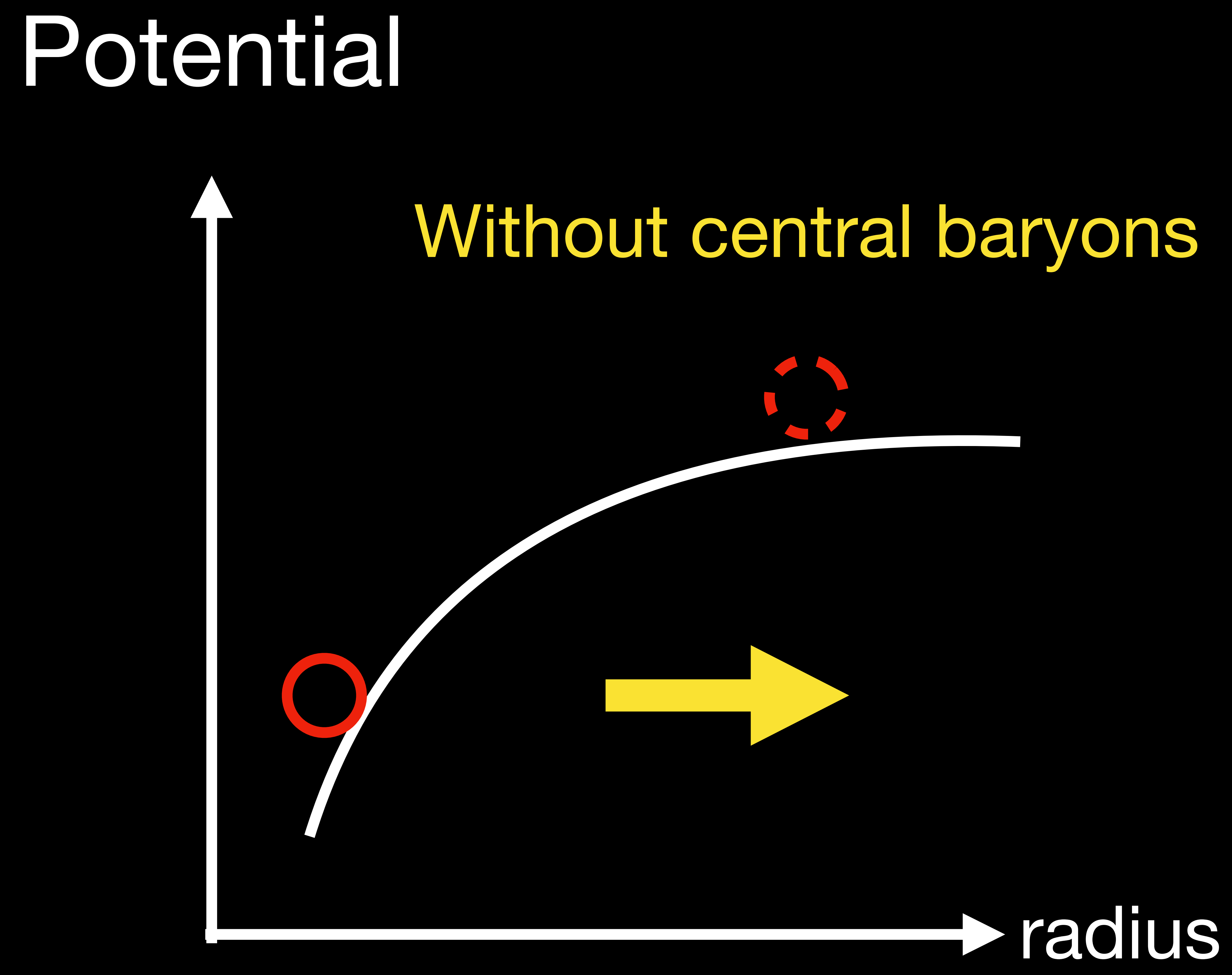


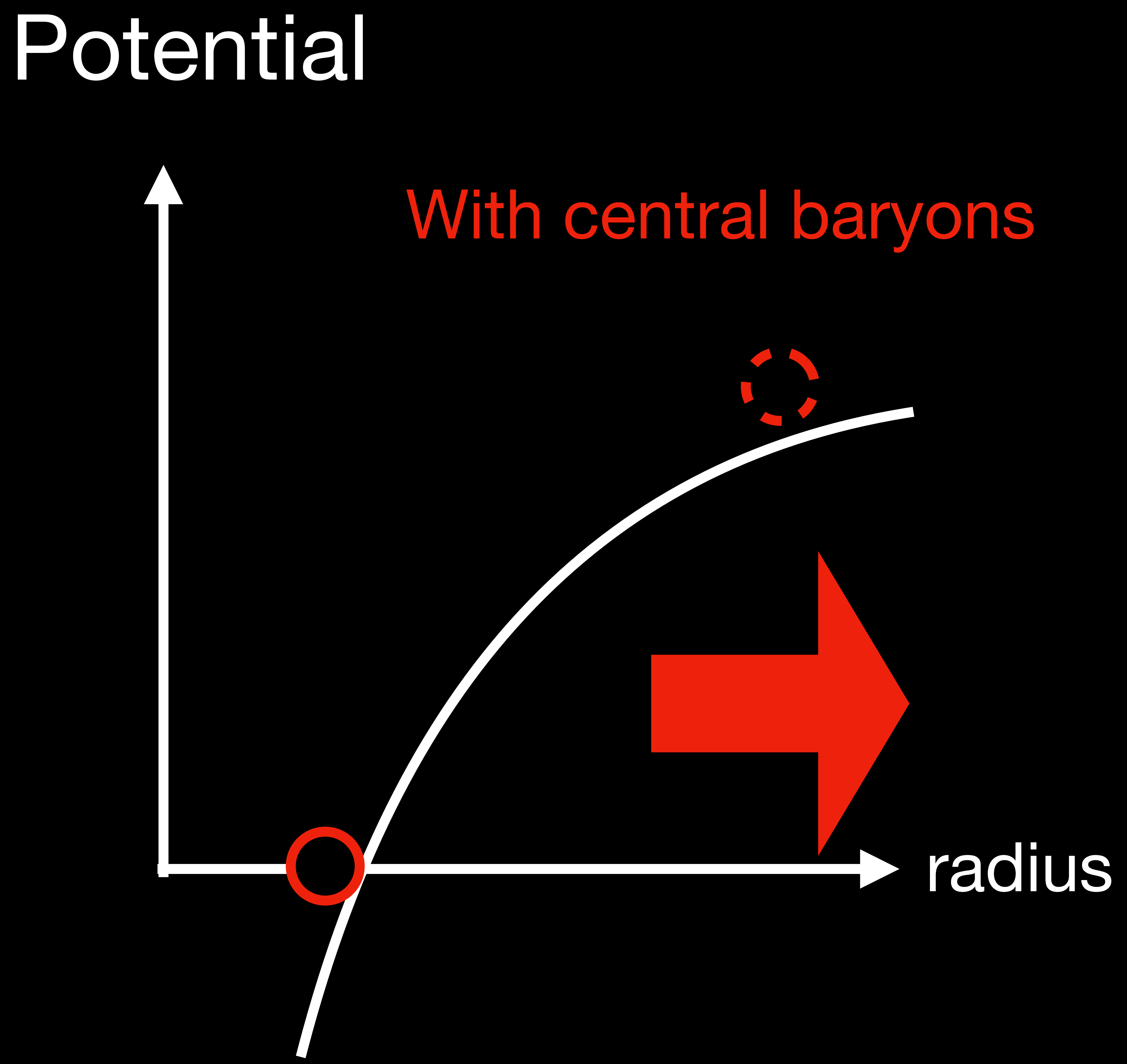
Central baryonic component (CBC)

Objects made of ordinary particles
(gas, stars, disk, bulge…)

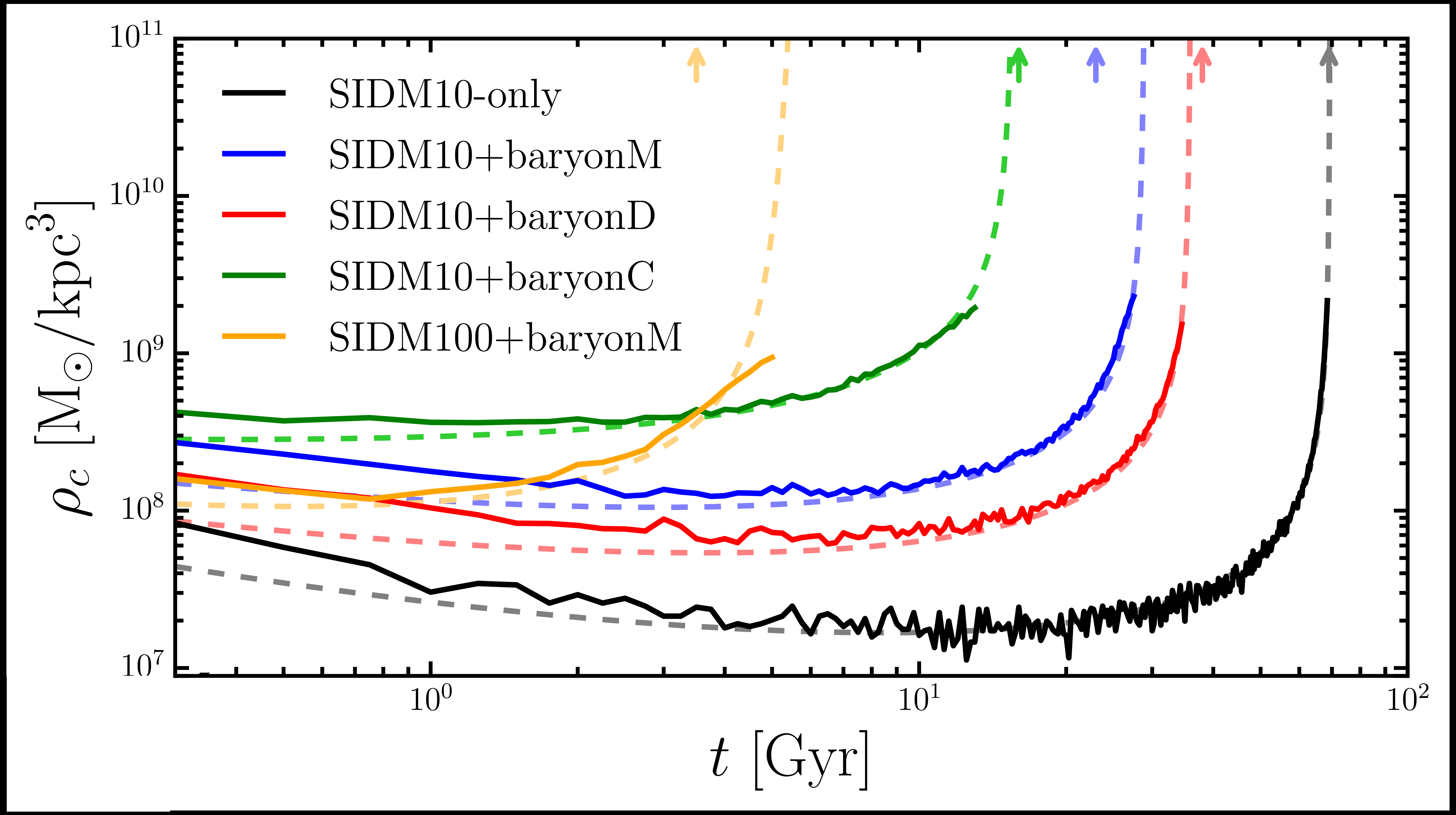


Central baryonic component (CBC)





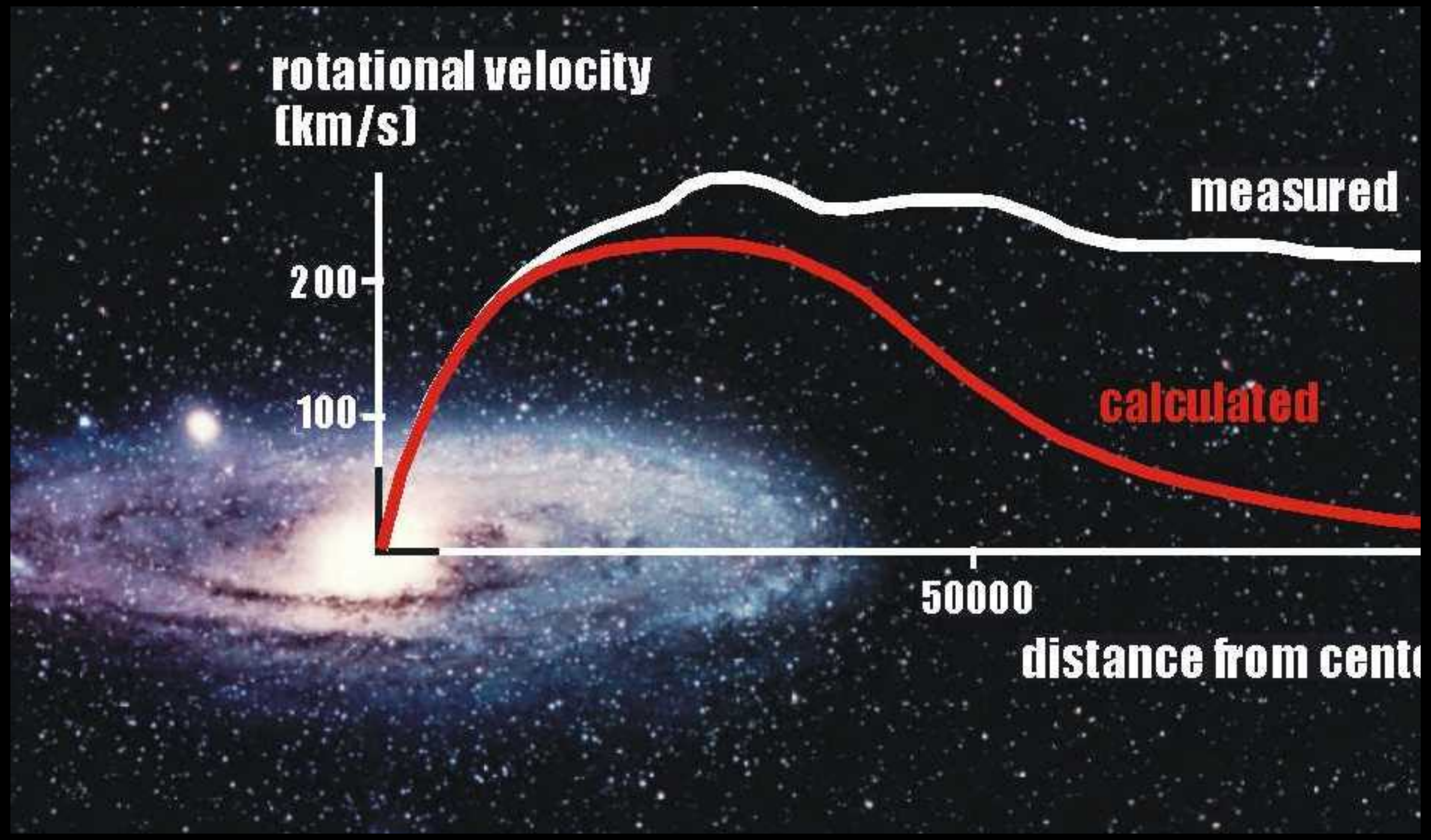
Central baryonic component (CBC)



Collapse much faster

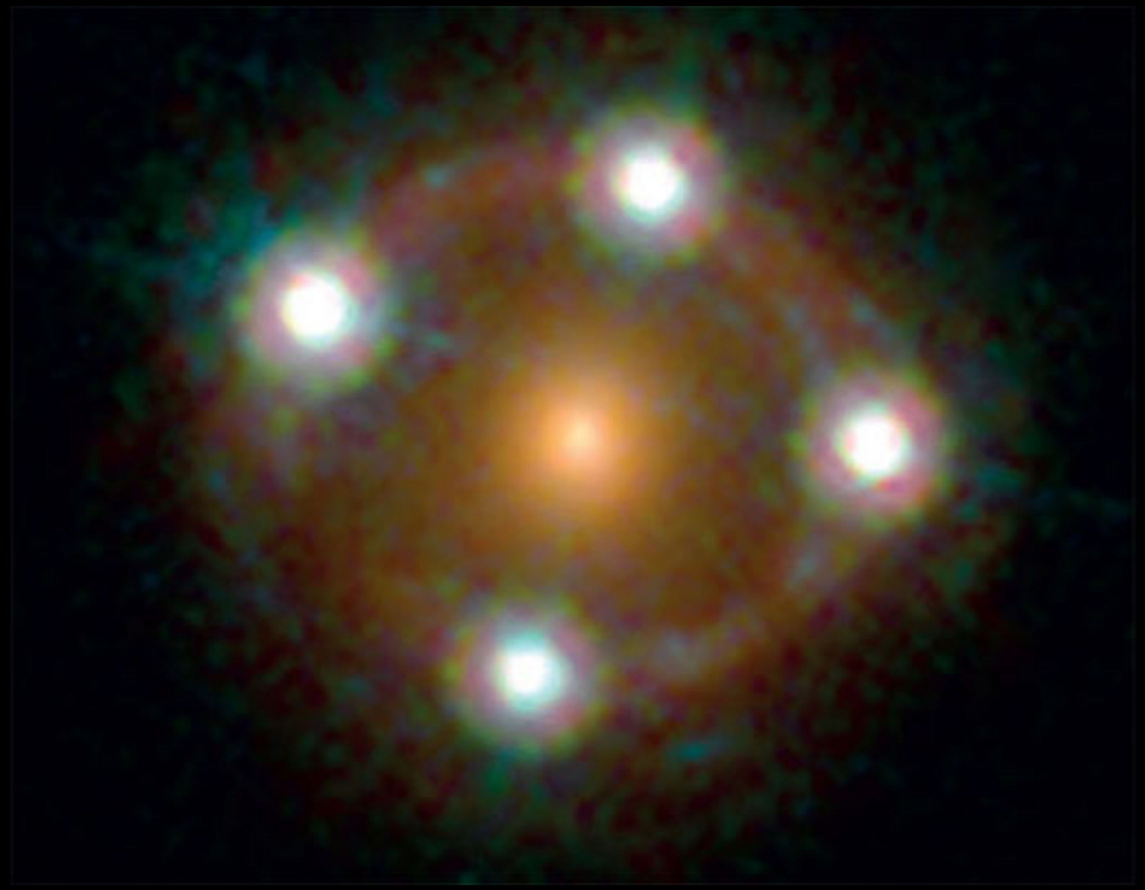
(Up to a factor of 10–100)

How to probe self-interacting dark matter?



Rotation curves

Essig, Mcdermott, Yu & **YZ** (2018),
Yang+ (**YZ** included, 2023)



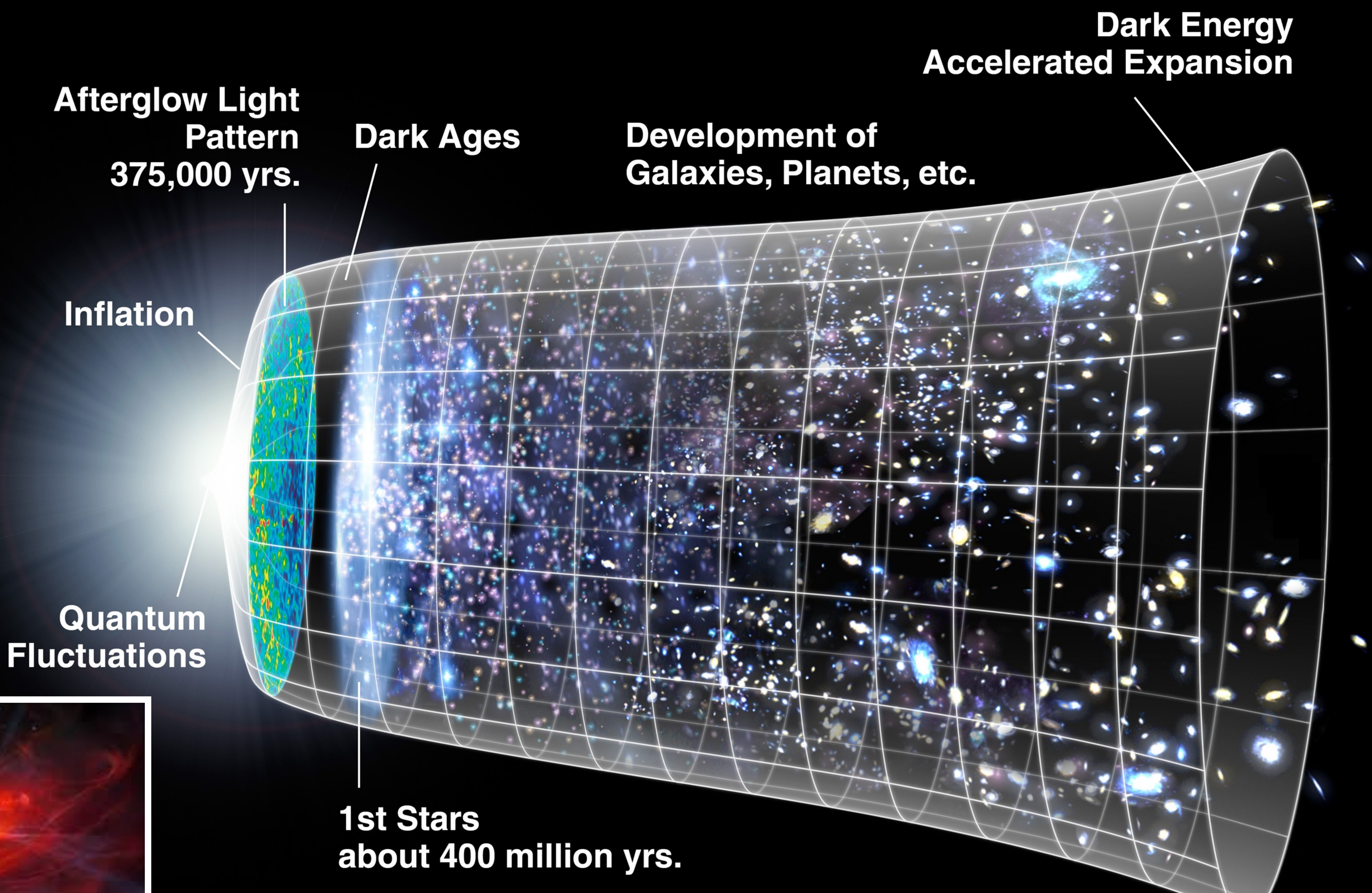
Strong lensing

Gilman+ (2021),
Gilman, **YZ** & Bovy (2022)

Weak lensing

Adhikari, Banerjee, Jain, Hyeon-Shin
& **YZ** (2024)

Give birth to high-z
supermassive black holes

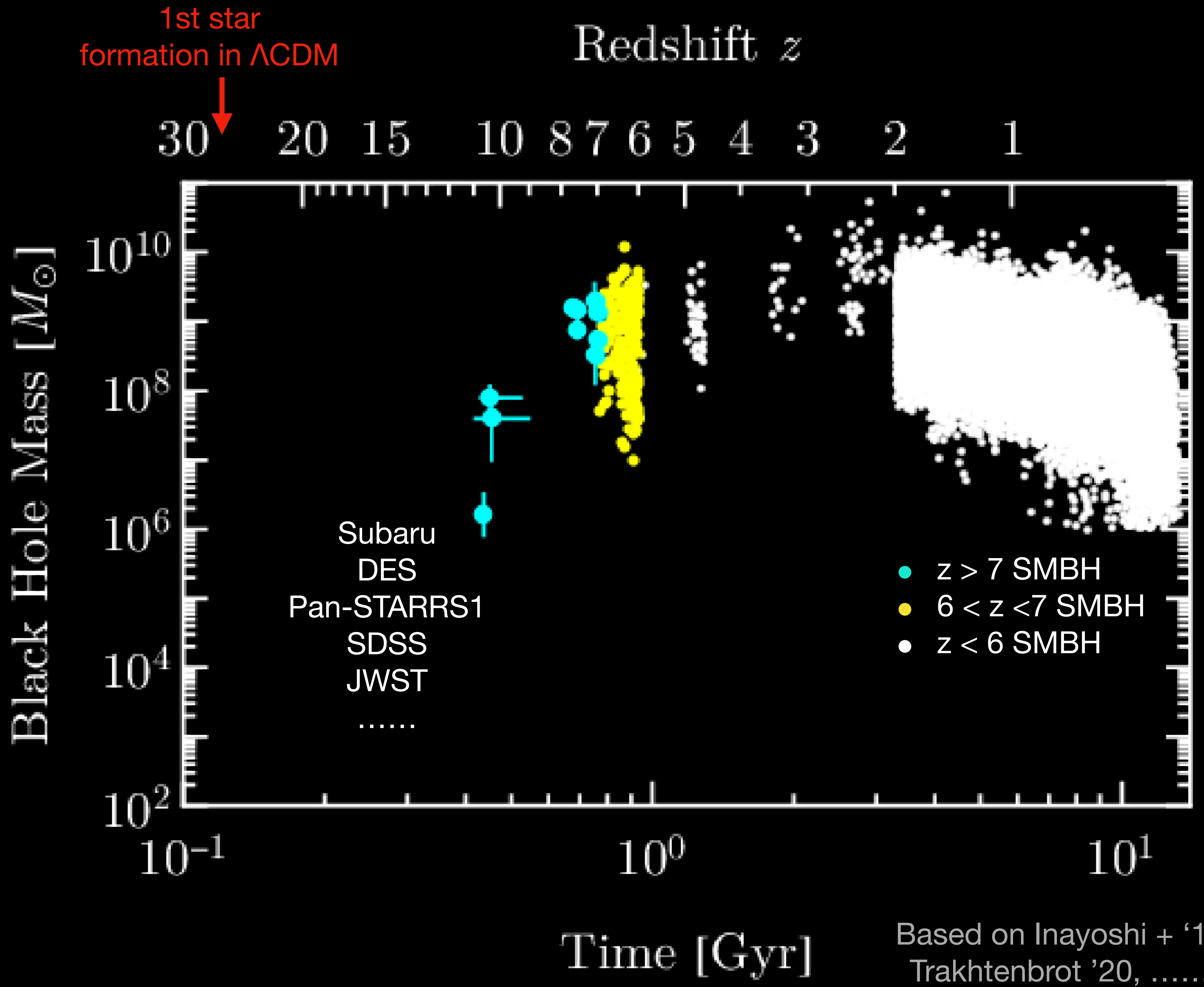


High-z supermassive black holes (SMBHs)

The high-z supermassive black holes

> 200 SMBHs with mass ≥ $10^6 M_\odot$ at z > 6
(7% of the age of Universe)

11 SMBHs with mass ≥ $10^8 M_\odot$ at z > 7
(5% of the age of Universe)



Based on Inayoshi + '19
Trakhtenbrot '20, ……

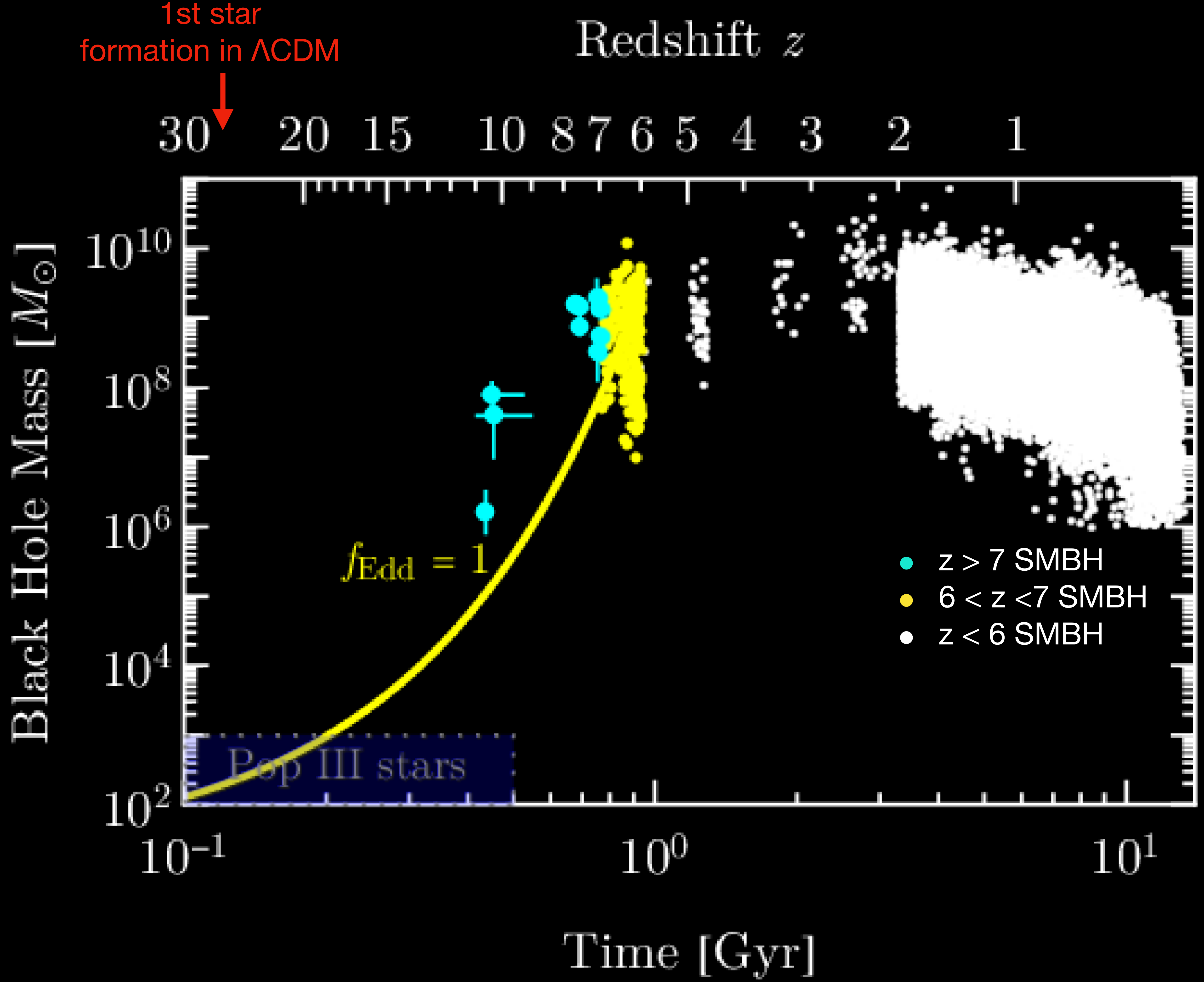
Eddington limit

Eddington limit:
max accretion rate of BH

elapse time

$$M_{\rm BH} = M_{\rm seed}\exp(\Delta t/\tau)$$

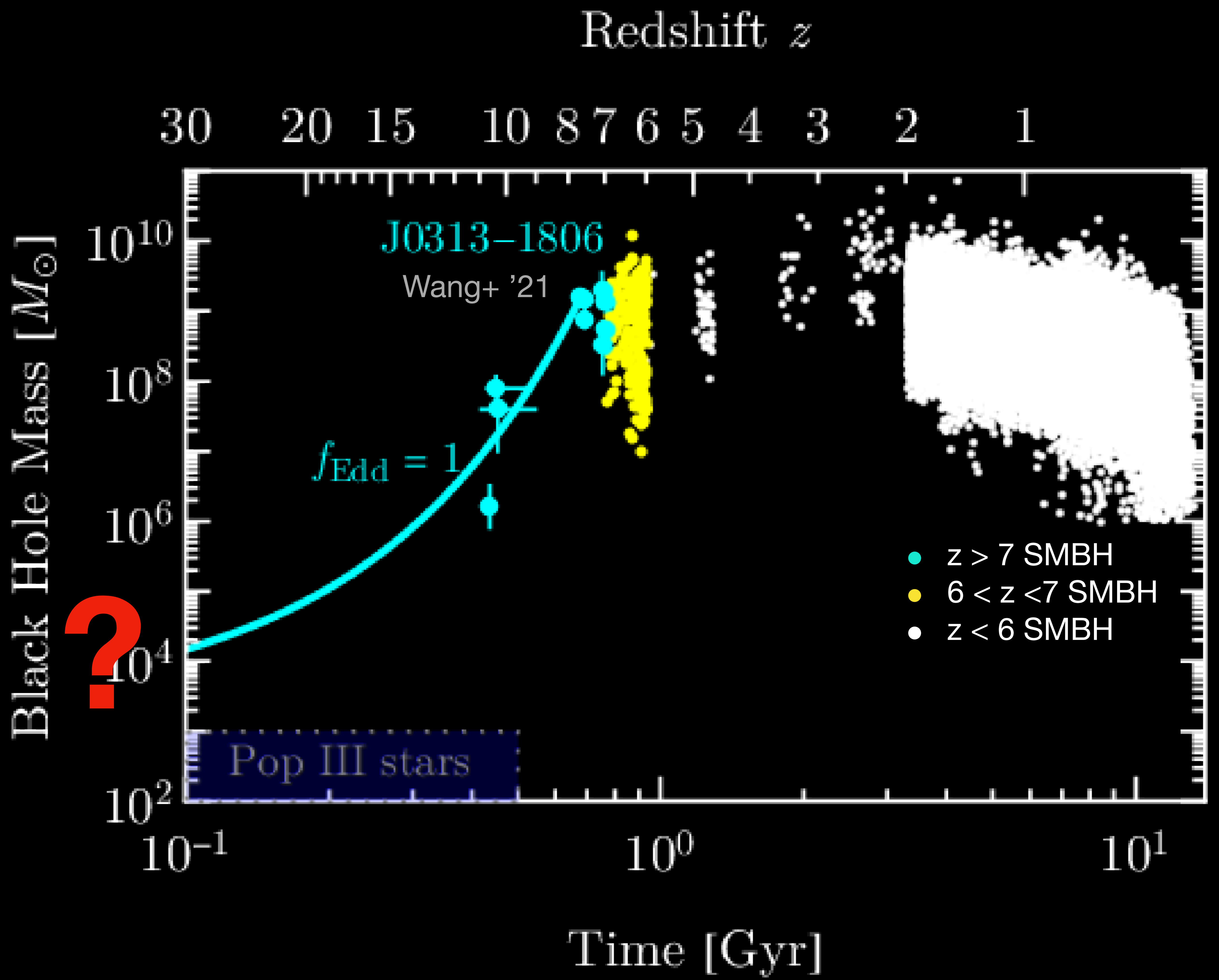
e-folding time $\tau = 0.5 \text{ Gyr } f_{\rm Edd}$



The growth puzzle

- For z > 7 SMBHs, collapsed Pop III stars are not heavy enough.

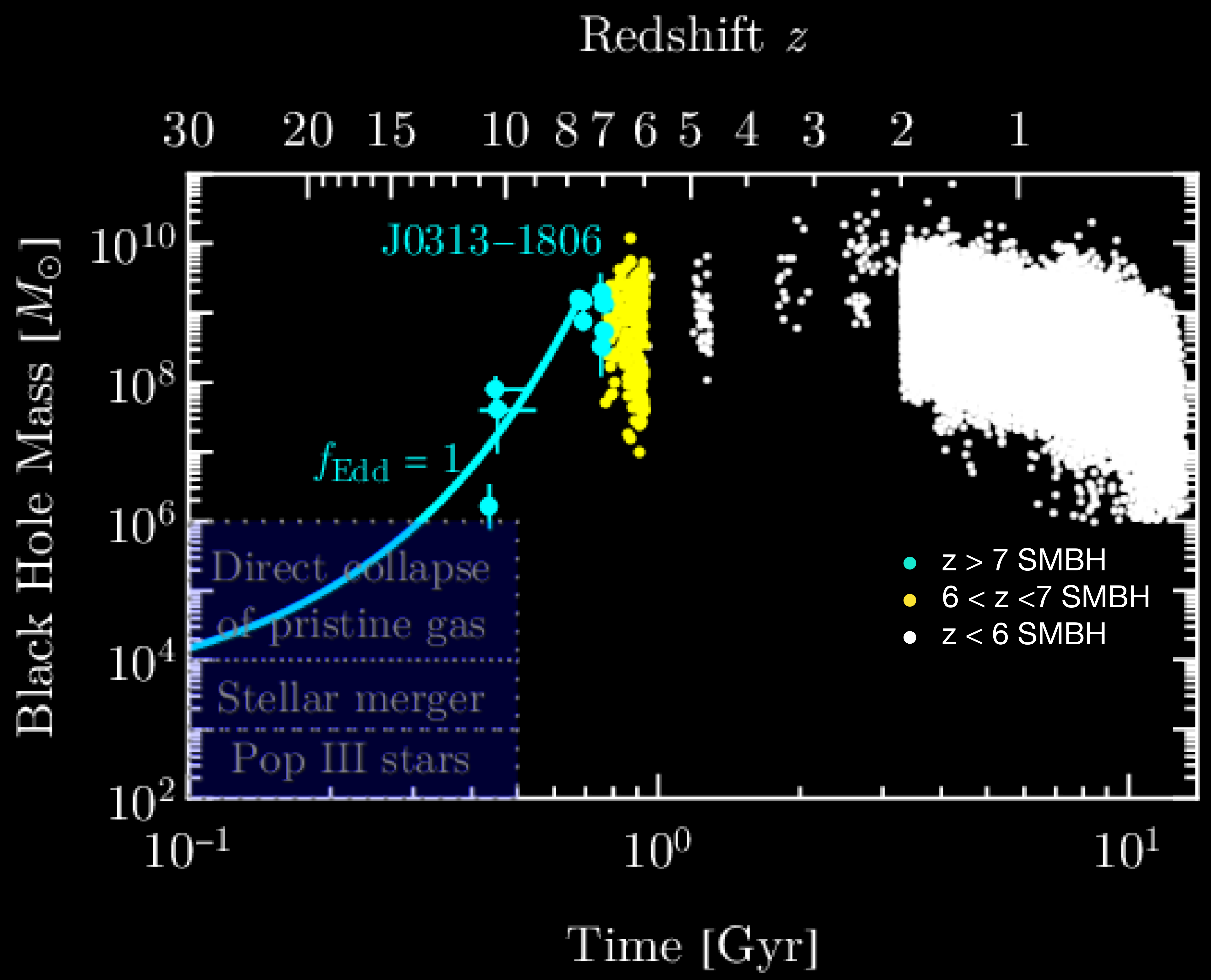
e.g. Wang+ ‘21



The growth puzzle

- For z > 7 SMBHs, collapsed Pop III stars are not heavy enough.
- One way to solve the puzzle is to form more massive seed BHs
  - Direct collapse of pristine gas …

Omukai ’01, Bromm & Loeb ’03, Begelman+ ’06, Hosokawa+, ’13 Regan+ ’17, Ardaneh+ ’18, Wise+ ’19…



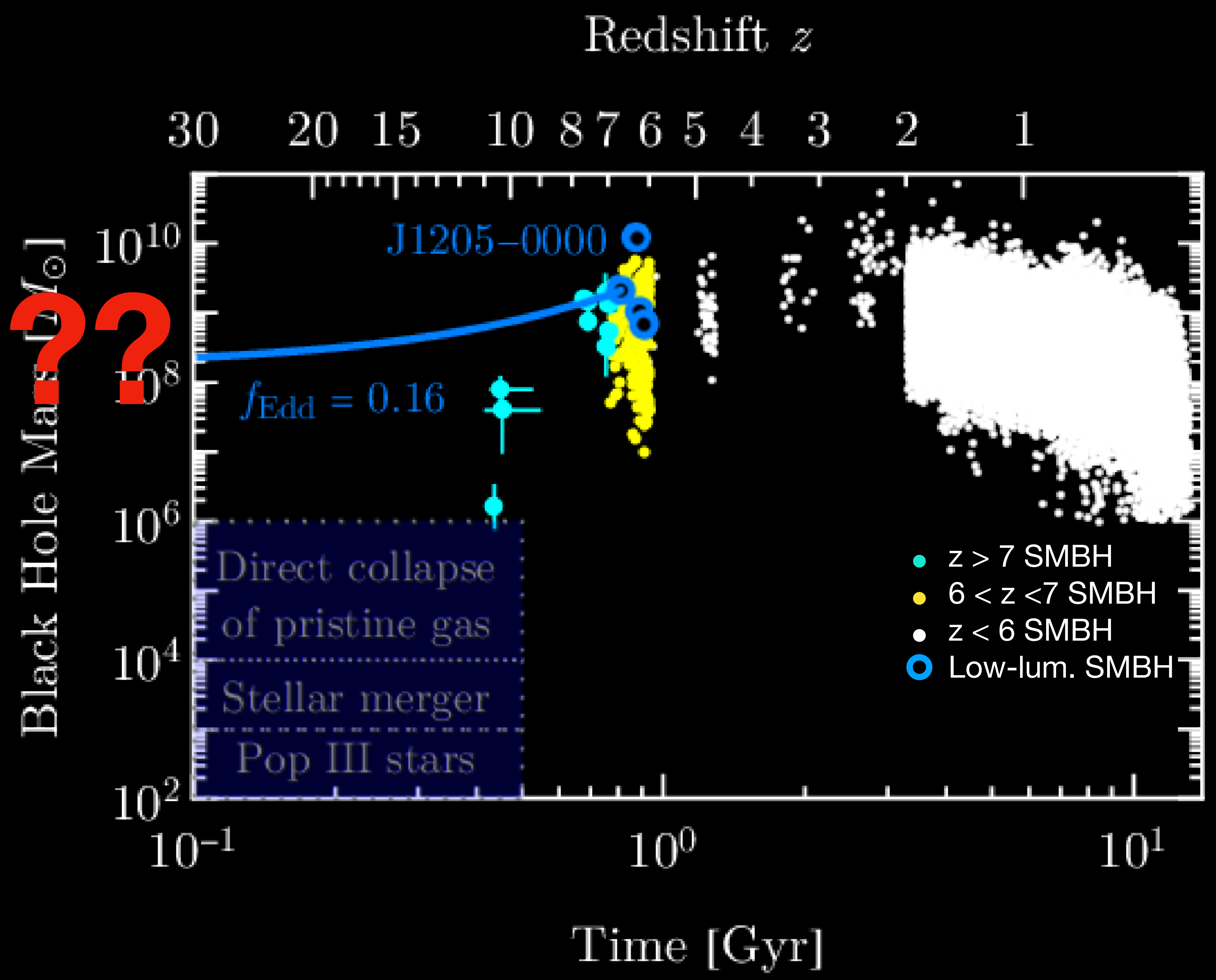
A worse puzzle

- For z > 7 SMBHs, collapsed Pop III stars are not heavy enough.

  e.g. Wang+ '21

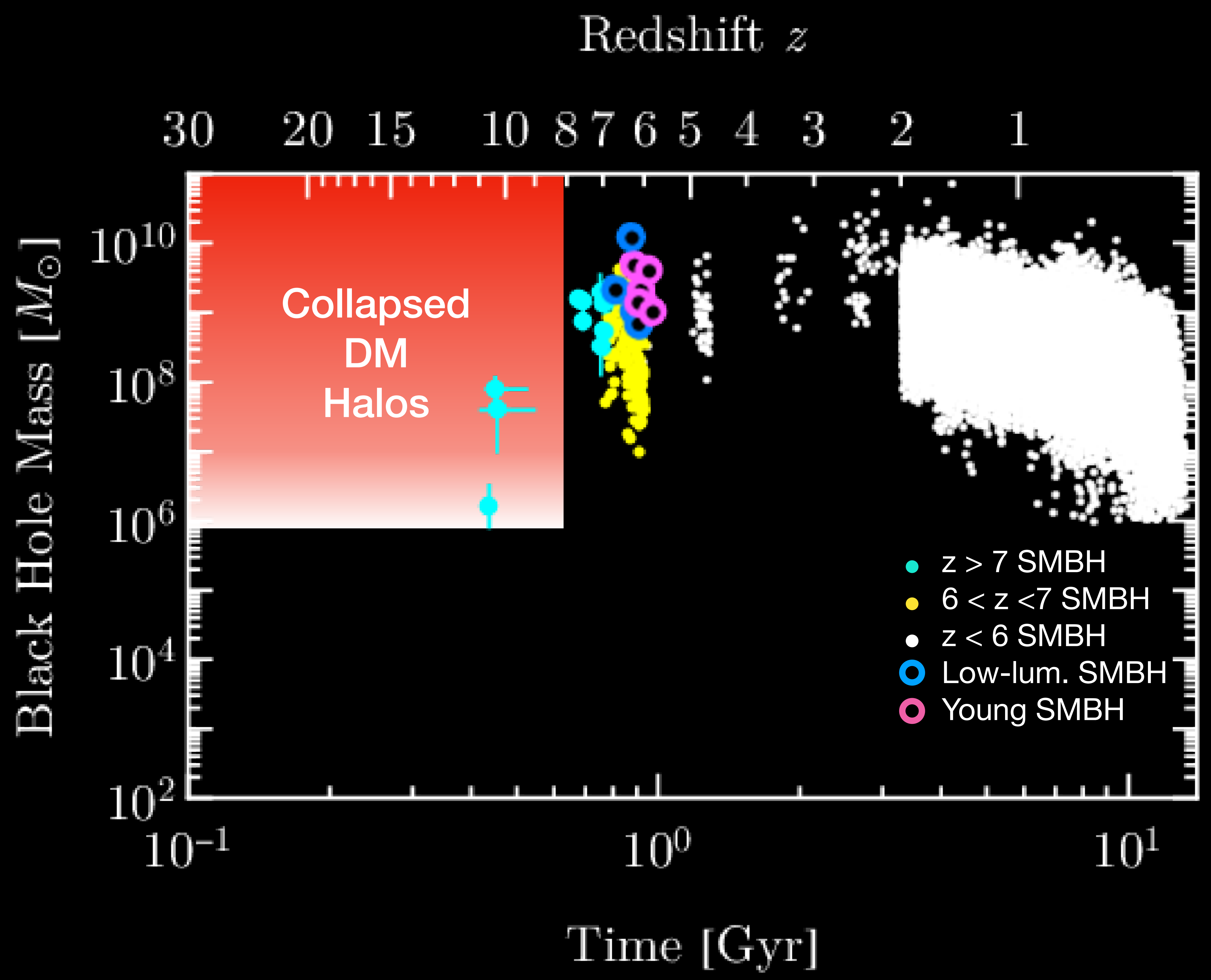
- There is also a population of low accretion SMBHs. $f_{\rm Edd} \ll 1$

  Mazzucchelli+ '17, Shen+ '19, Onoue+ '19 [**SHELLQs**]…

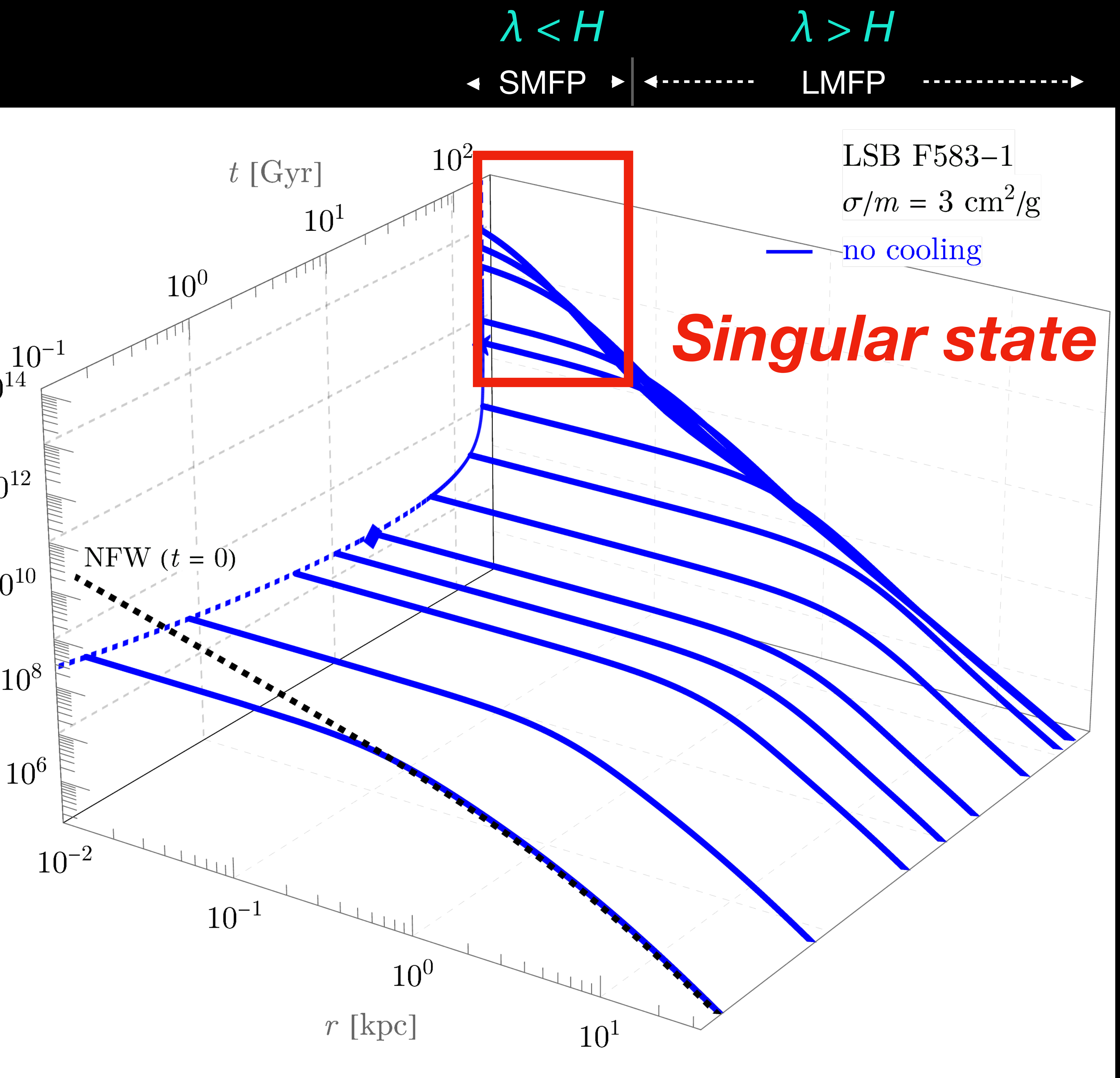


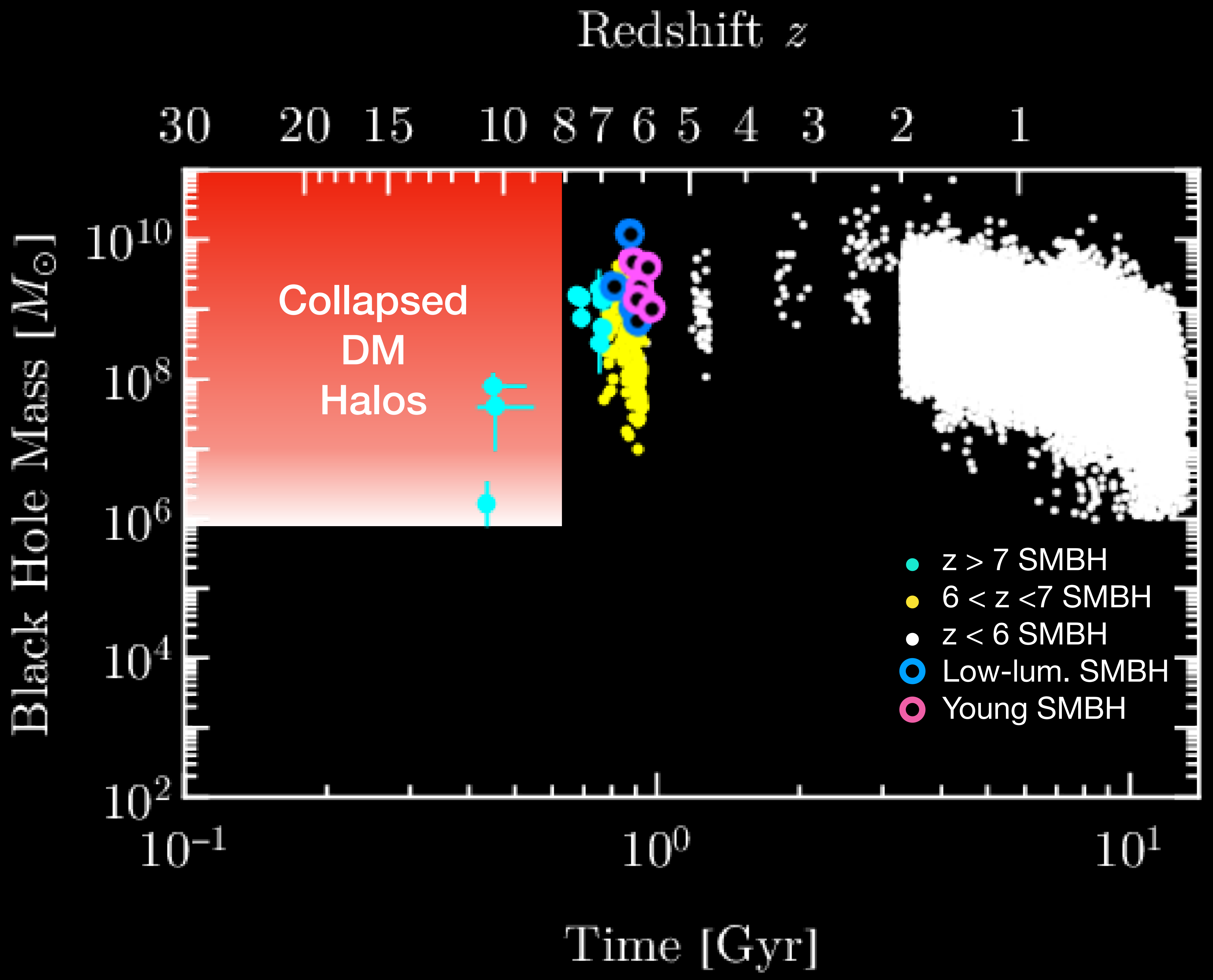
Seeding SMBHs from collapsed DM halos

Feng, Yu & YZ ’21



Our idea

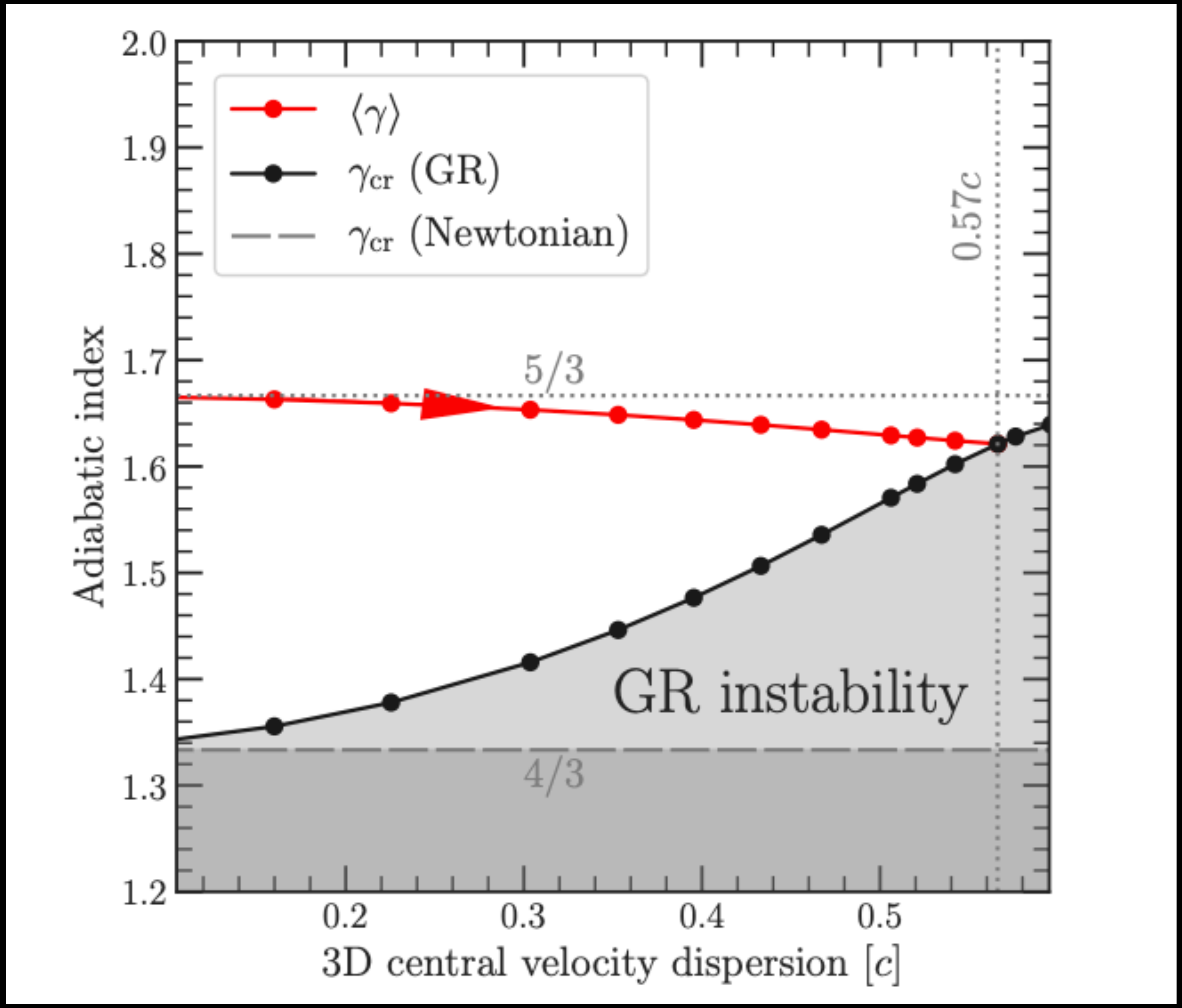

λ < H
λ > H
SMFP
LMFP
t [Gyr]
r [kpc]
LSB F583−1
σ/m = 3 cm²/g
no cooling
NFW (t = 0)
Singular state


Redshift z
30 20 15 10 8 7 6 5 4 3 2 1
Black Hole Mass [M⊙]
Time [Gyr]
Collapsed
DM
Halos
z > 7 SMBH
6 < z <7 SMBH
z < 6 SMBH
Low-lum. SMBH
Young SMBH

Our idea

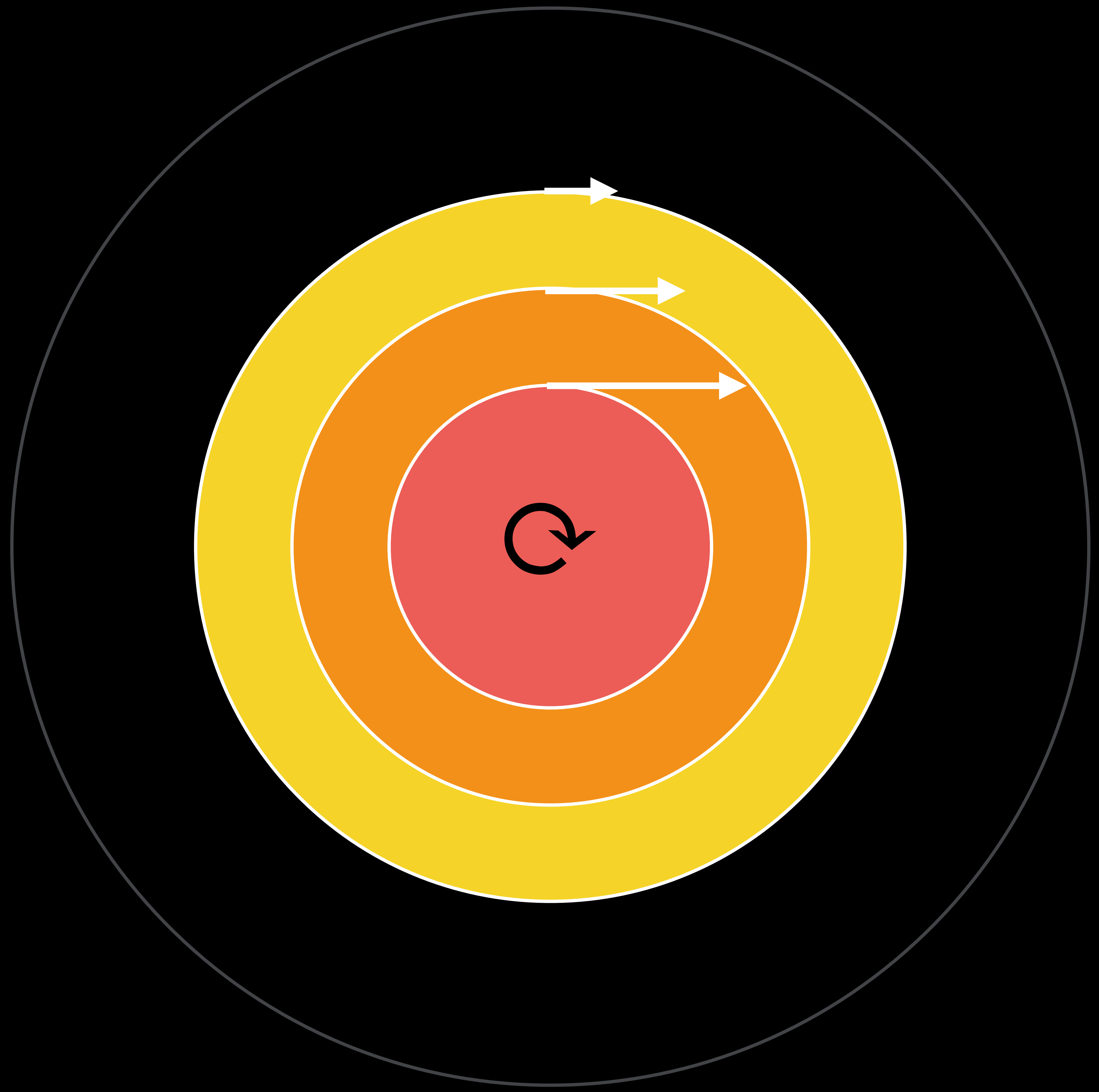
The singular state:

- Can trigger GR instability (Feng, Yu & YZ ’21, ’22)
- Leads to large seed BH mass (~ 10^{-3} halo mass)



How to dissipate angular momentum?

Collisional viscosity



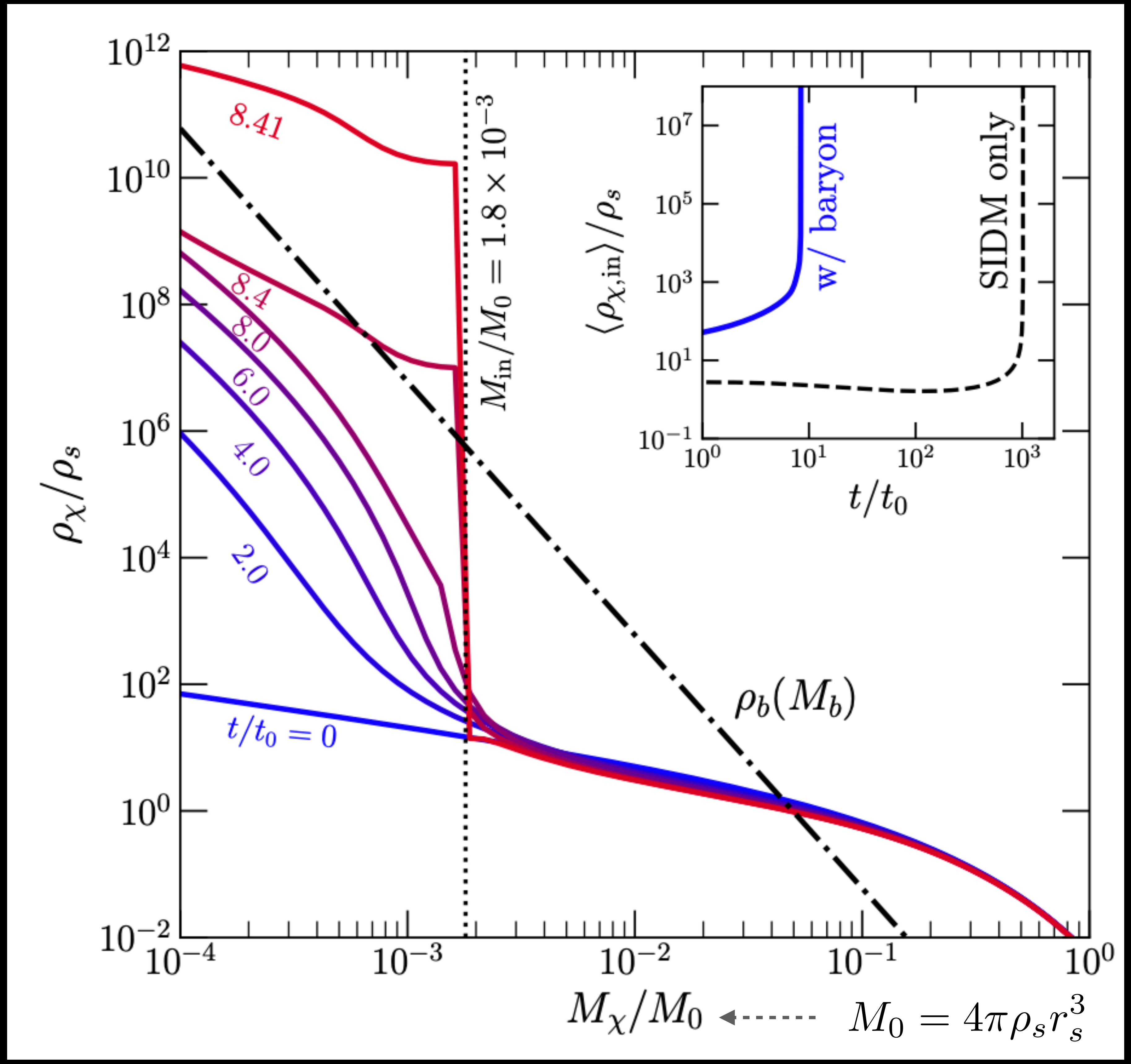
Angular momentum for the central region can be dissipated efficiently by self-interactions.

Feng, Yu & **YZ**, ‘21

Singular state

$\lambda < H$ SMFP

$\lambda > H$ LMFP



$r_s\rho_s\sigma/m = 0.2$

Feng, Yu & **YZ**, '21

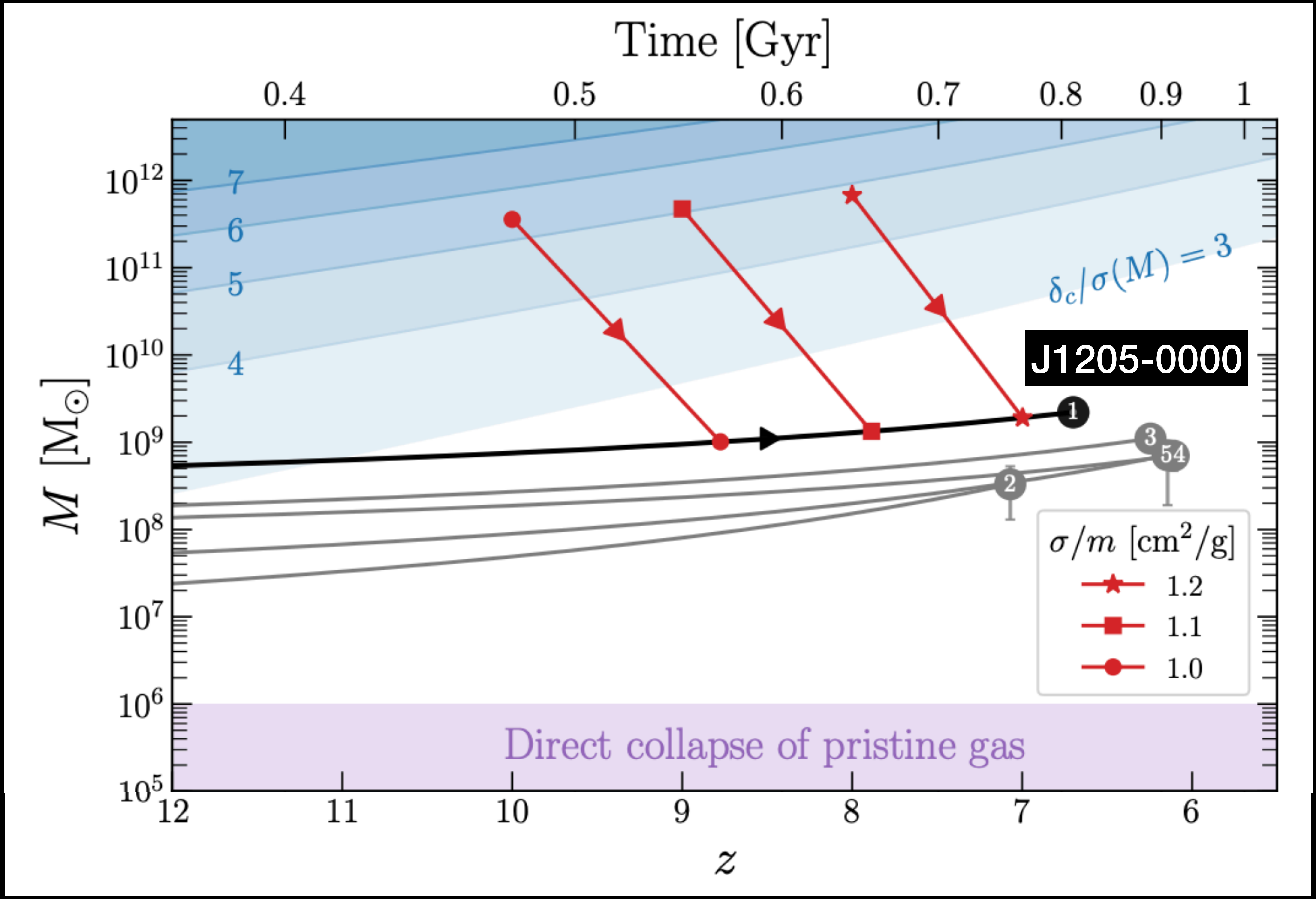
- Need to collapse fast ⇒ adding central baryonic components.

To form low-luminosity high-z SMBHs

- Need galactic-sized DM halos at high redshift (rare in the early Universe).
- Need compact central baryons.
- Need cross section strength $\sigma/m \sim O(1\ \mathrm{cm}^2/\mathrm{g})$.

solve the small-scale problems of the CDM paradigm

To form low-luminosity high-z SMBHs



$$\frac{dn(M,z)}{dM} \propto \exp\left[-\frac{\delta_c^2(z)}{2\sigma^2(M)}\right]$$

Feng, Yu & **YZ**, '21

Summary

- The nature of dark matter remains unknown. Dark matter halos are important way to probe dark matter/dark sectors.
- The collapsed SIDM halos could be common.
- Many interesting observational signatures (rotation curves, strong lensing, weak lensing…), including solving the puzzle of high-z supermassive black holes.