Probing Dark Matter Self-interactions in the Sky

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arXiv:2306.08028, 2401.05788, 2506.17641

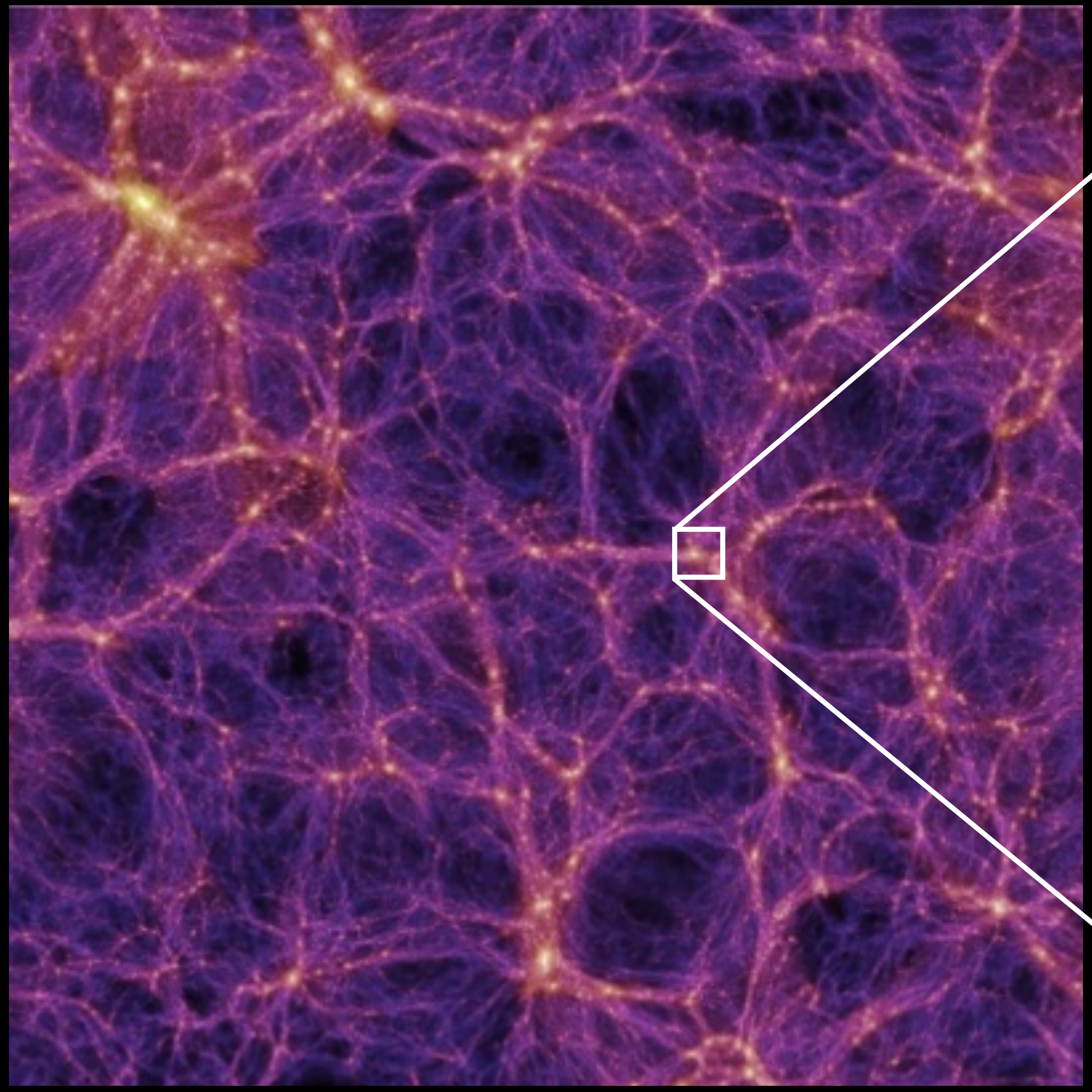
The XIX International Conference on Topics in Astroparticle and Underground Physics, 26 August 2025

Outline

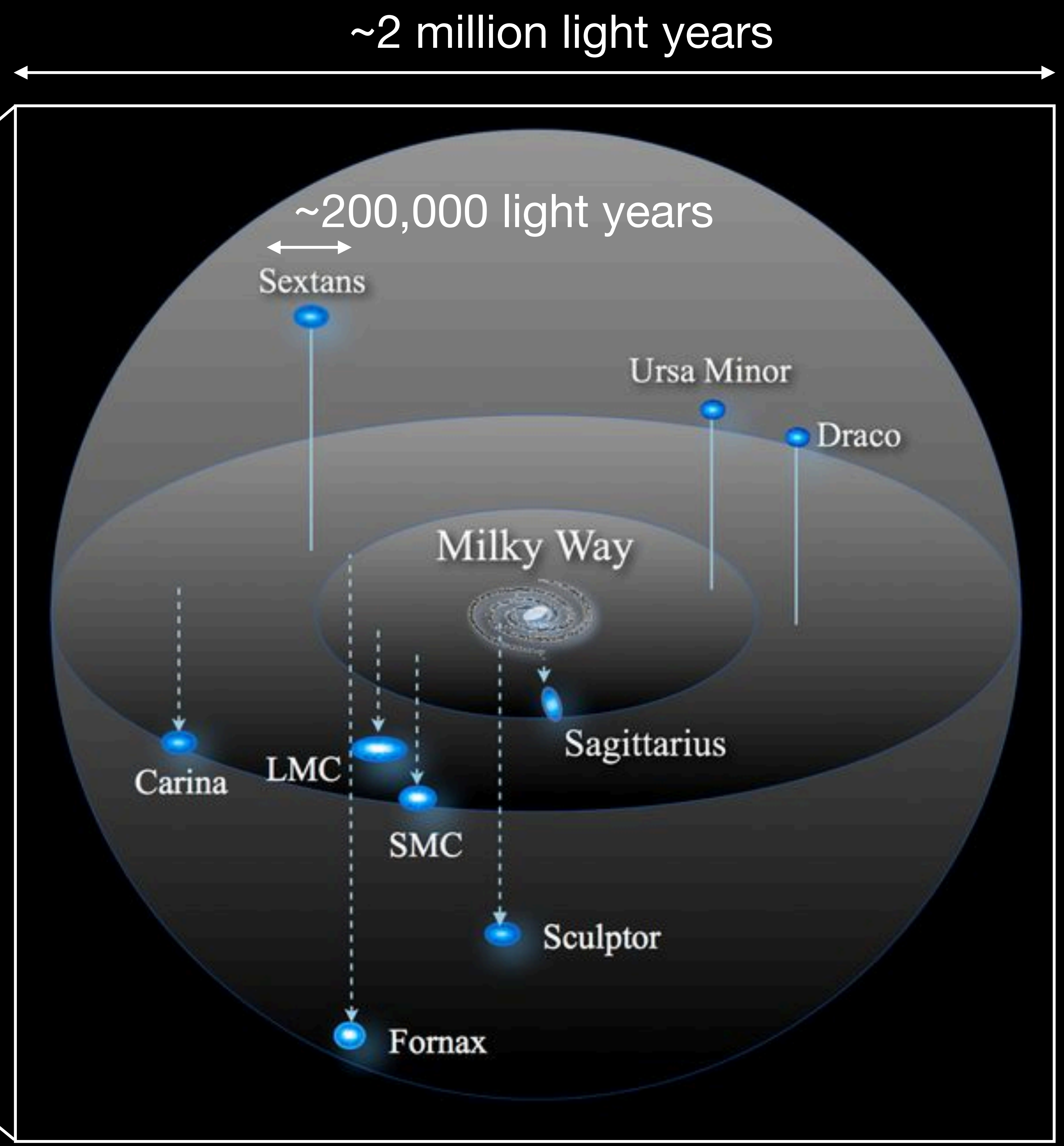
- Review
  - Cold & collisionless dark matter and its challenges
  - Self-interacting dark matter
  - The core-collapse of dark matter halo
- Seeding high-z supermassive black holes [with Feng & Yu, arXiv: 2506.17641]
- Summary

The CDM paradigm

Cold and Collsionless Dark Matter



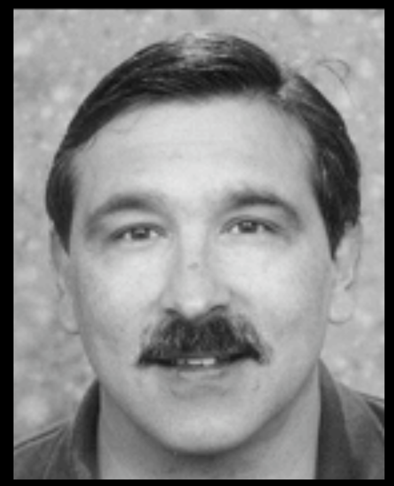
Cosmic Web



Dark matter halos

The Navarro–Frenk–White profile


J. Navarro

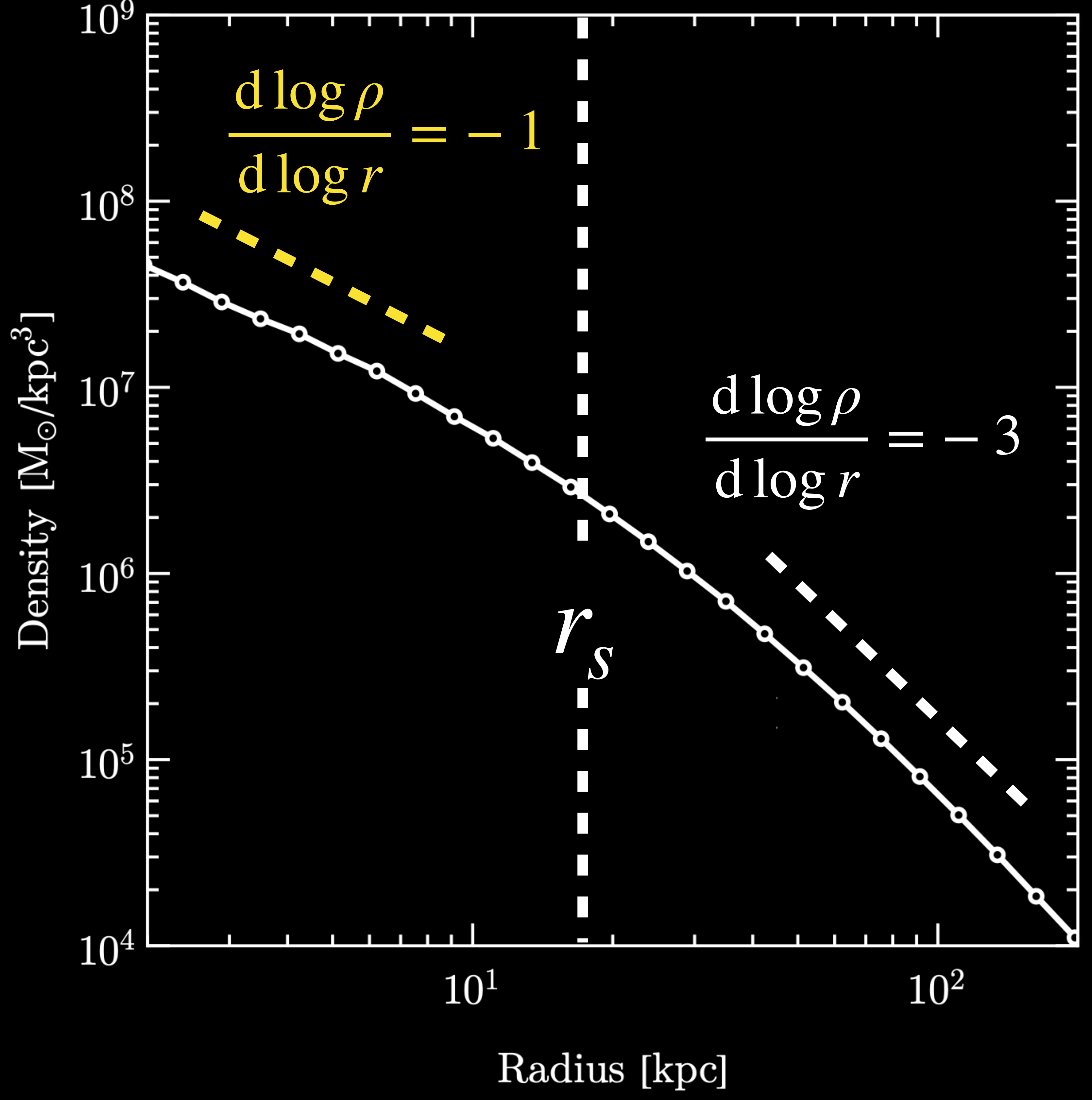

C. Frenk


S. White

- From CDM simulations, all halos obey a universal density profile

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

- Valid for halos with mass $10^{-6} - 10^{14}\,\mathrm{M}_\odot$.

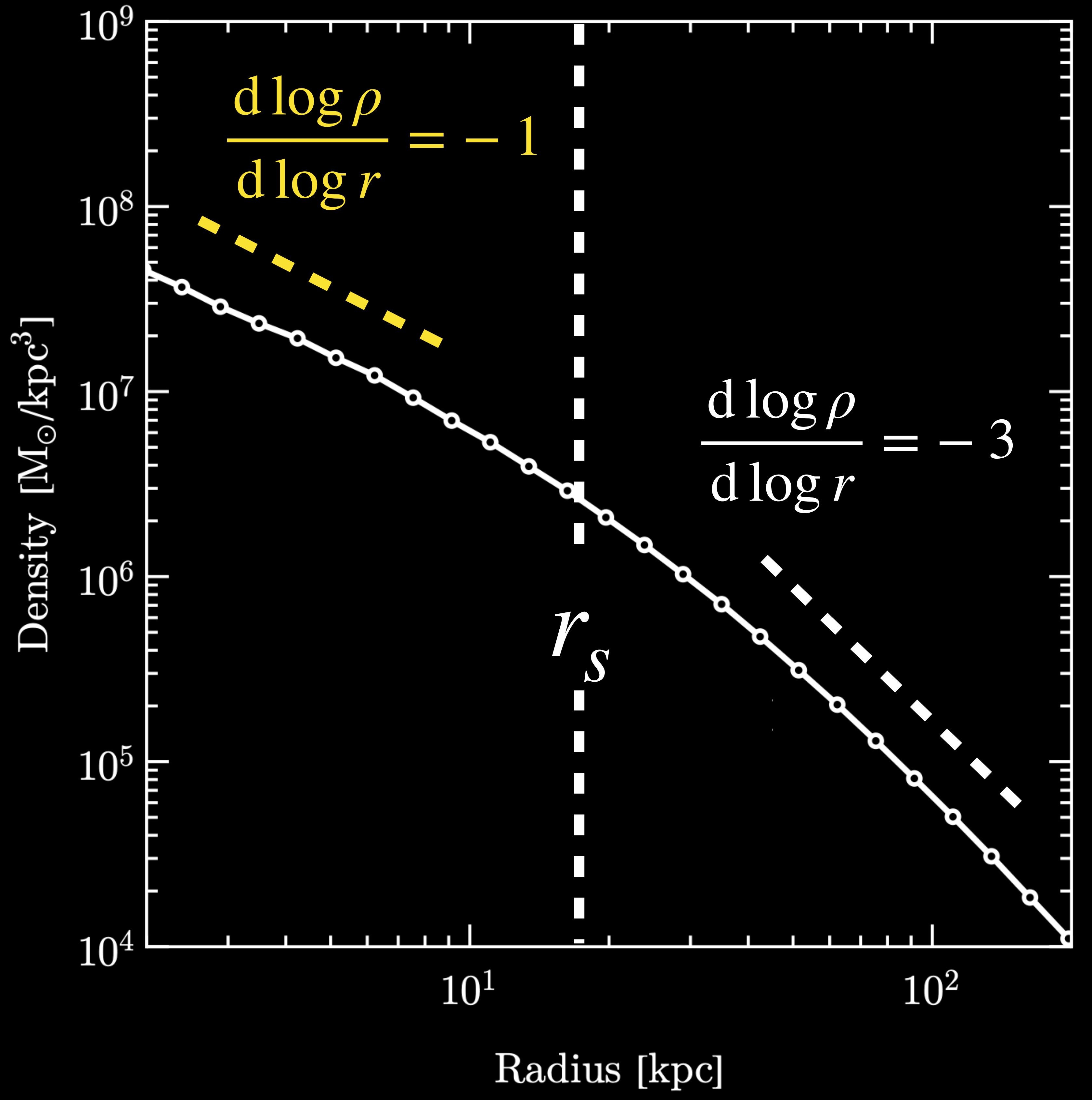


Wang+ ’19

The Navarro–Frenk–White profile

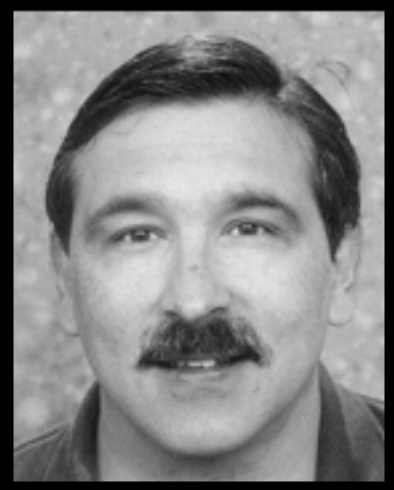
J. Navarro C. Frenk S. White

- The NFW profile is based on numerical simulations.
- Is this consistent with observations?
  - Core-cusp problem — Oh+ ‘15
  - Diversity problem — See Tulin & Yu ‘18



The Navarro–Frenk–White profile

J. Navarro

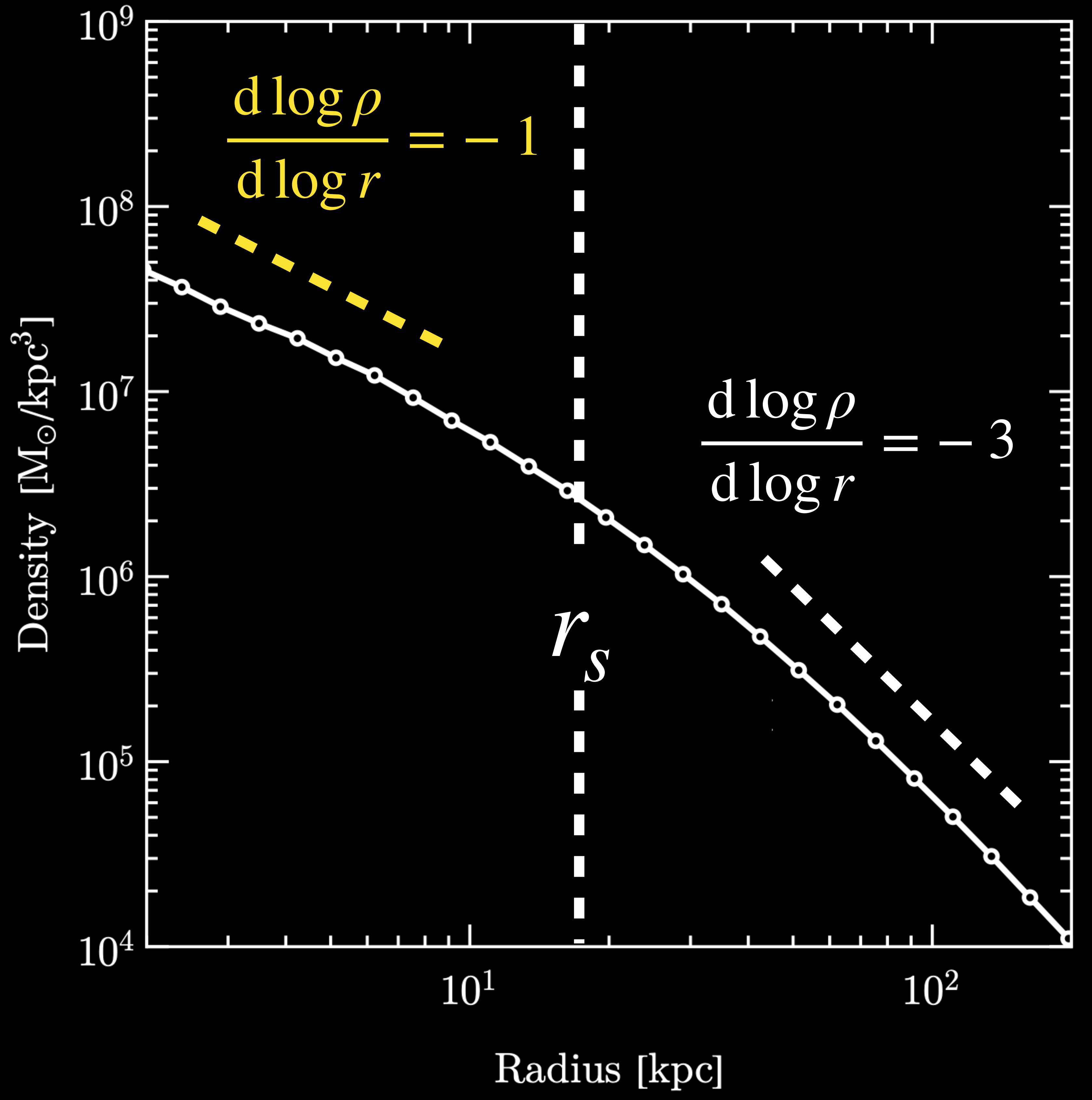


C. Frenk

S. White

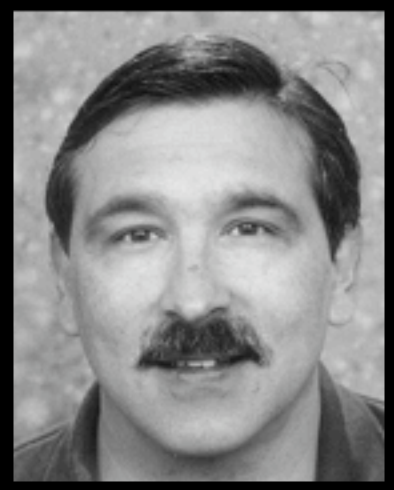
Baryons

- The NFW profile is based on numerical simulations.
- Is this consistent with observations?
  - Core-cusp problem   Oh+ ‘15
  - Diversity problem   See Tulin & Yu ‘18



The Navarro–Frenk–White profile

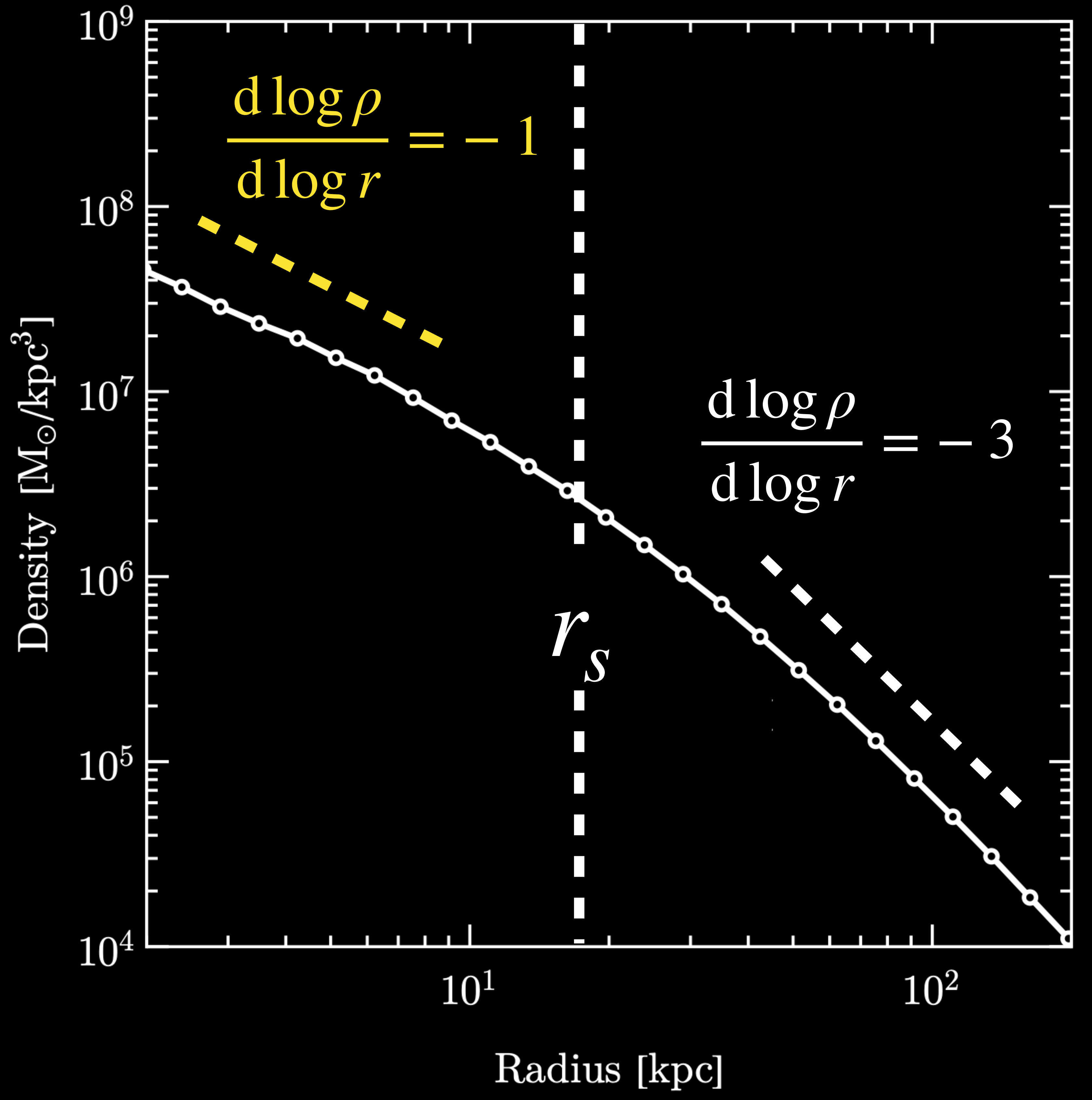
J. Navarro



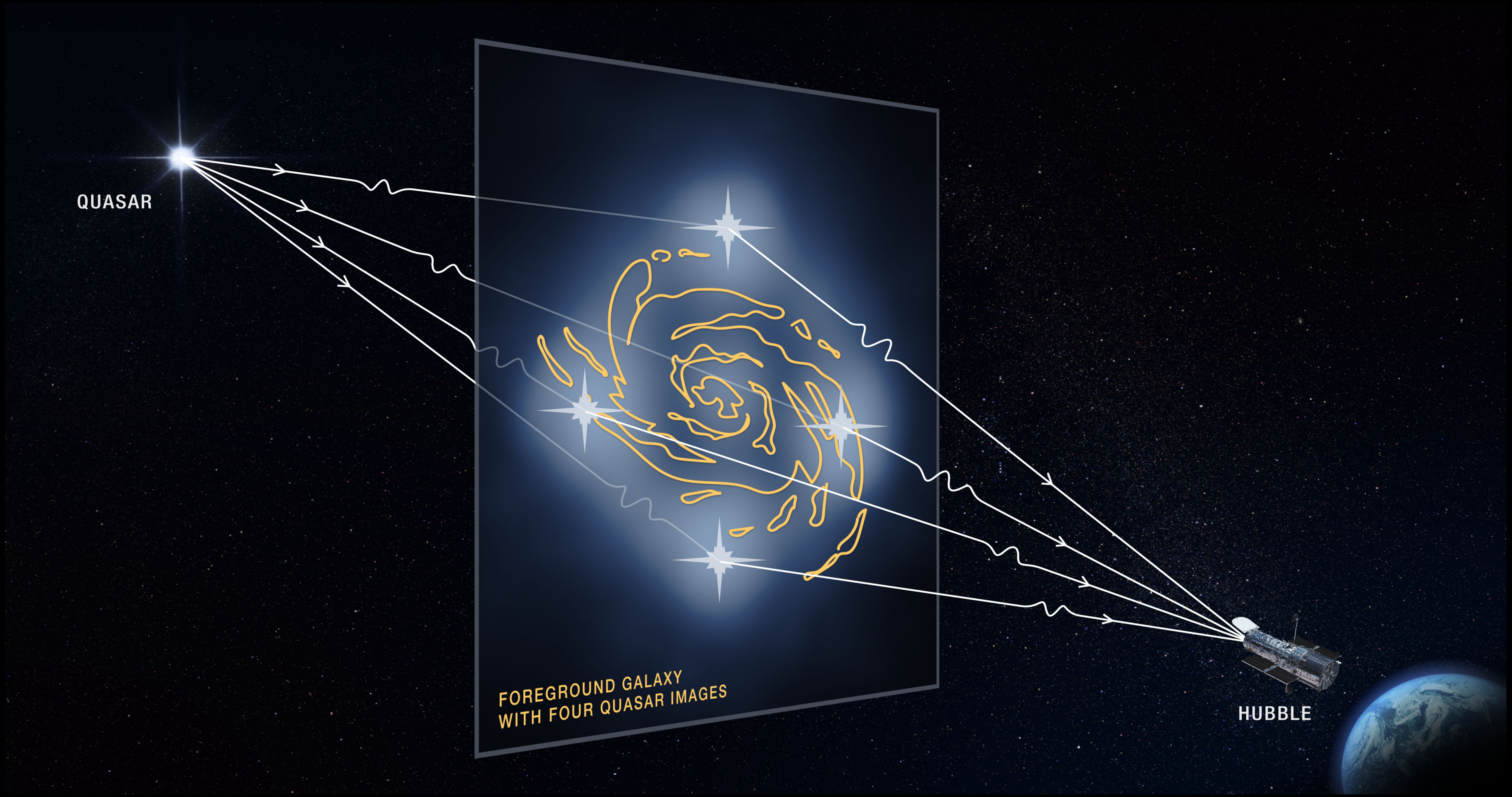
C. Frenk

S. White

- The NFW profile is based on numerical simulations.
- Is this consistent with observations?
  - Core-cusp problem — Oh+ ‘15
  - Diversity problem — See Tulin & Yu ‘18
  - ***Ultra-dense structure problem***



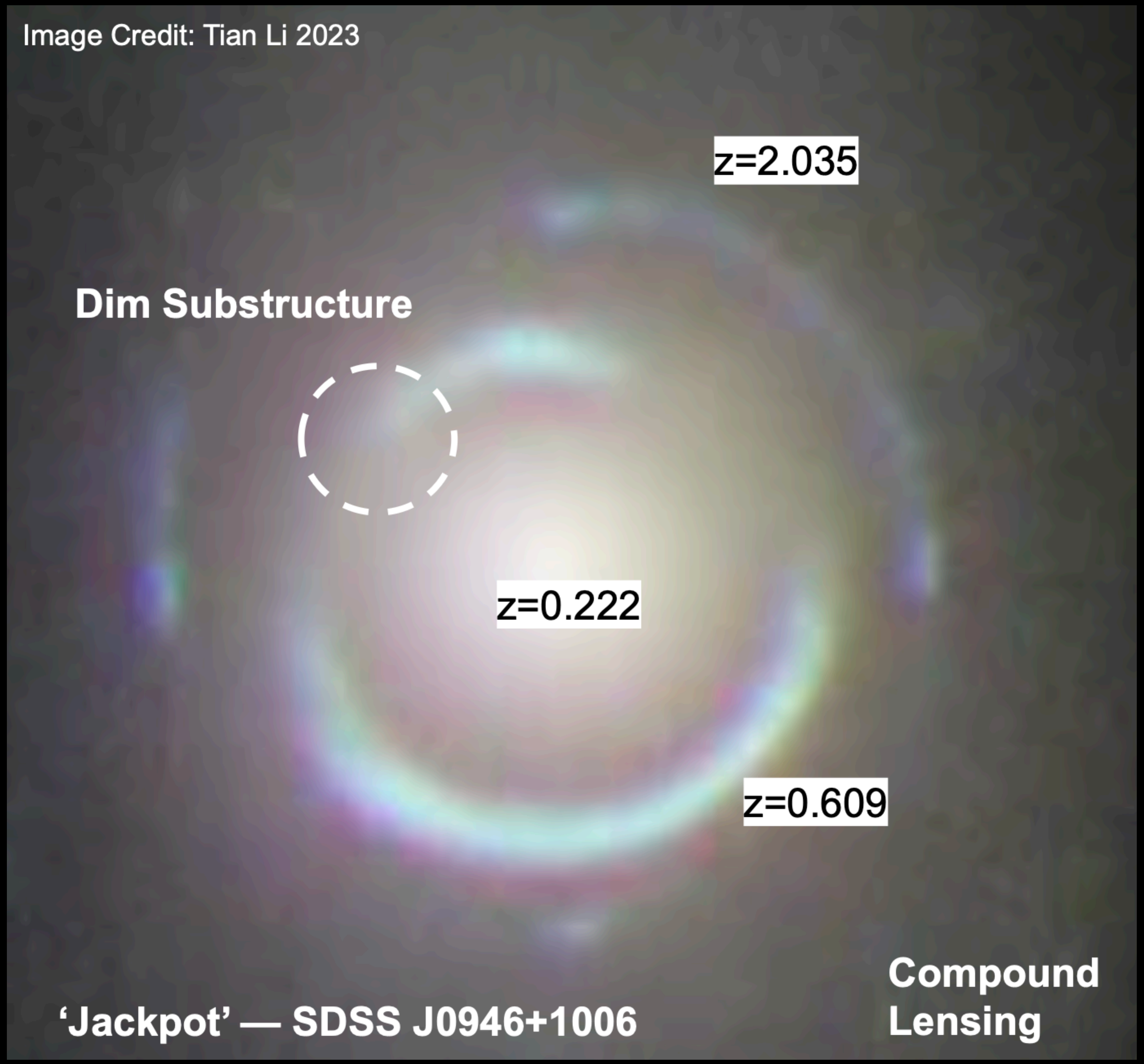
Gravitational lensing



Credit: NASA

Some challenges to CDM (Jackpot)

- SDSS J0946+1006, a.k.a. "Jackpot", contains a dim substructure.
- It could be a $\sim 10^9\,\mathrm{M}_\odot$ halo with an inner slope of $\gamma \equiv \mathrm{d}\log\rho/\mathrm{d}\log r \simeq -2.3$.

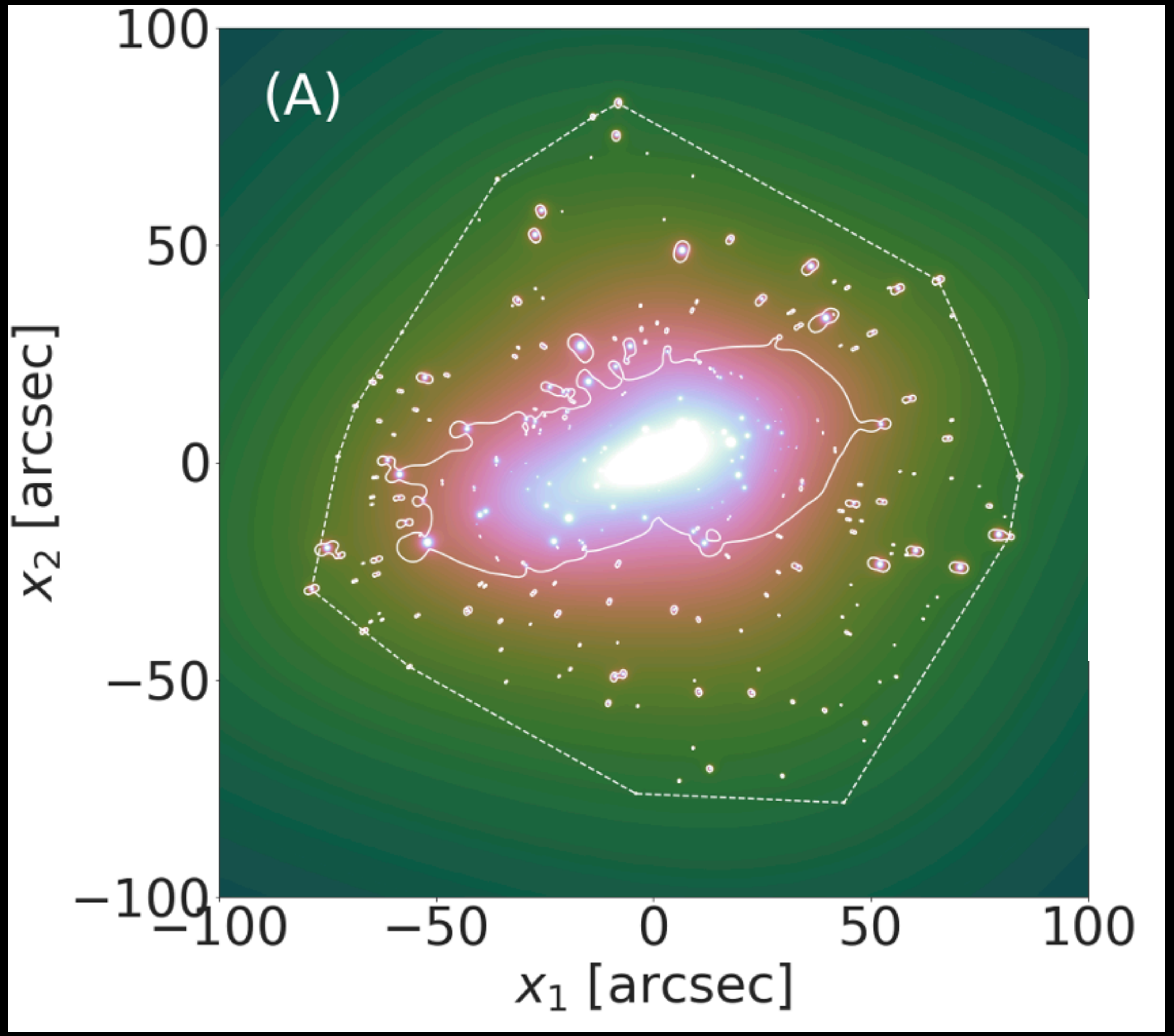


Vegetti+ ' 10, Minor+ '21, Nightingale+ '22, Despali+ '24, Enzi+ '25…
[translated from γ_{2D} by $\gamma = \gamma_{2D} - 1$]

Some challenges to CDM (GGSL)

- Meneghetti+ ’20 studied galaxy-galaxy strong lensing (GGSL).
- Those $10^{10} - 10^{12}\,\mathrm{M}_{\odot}$ halos favor $\gamma \leq -2.5$.

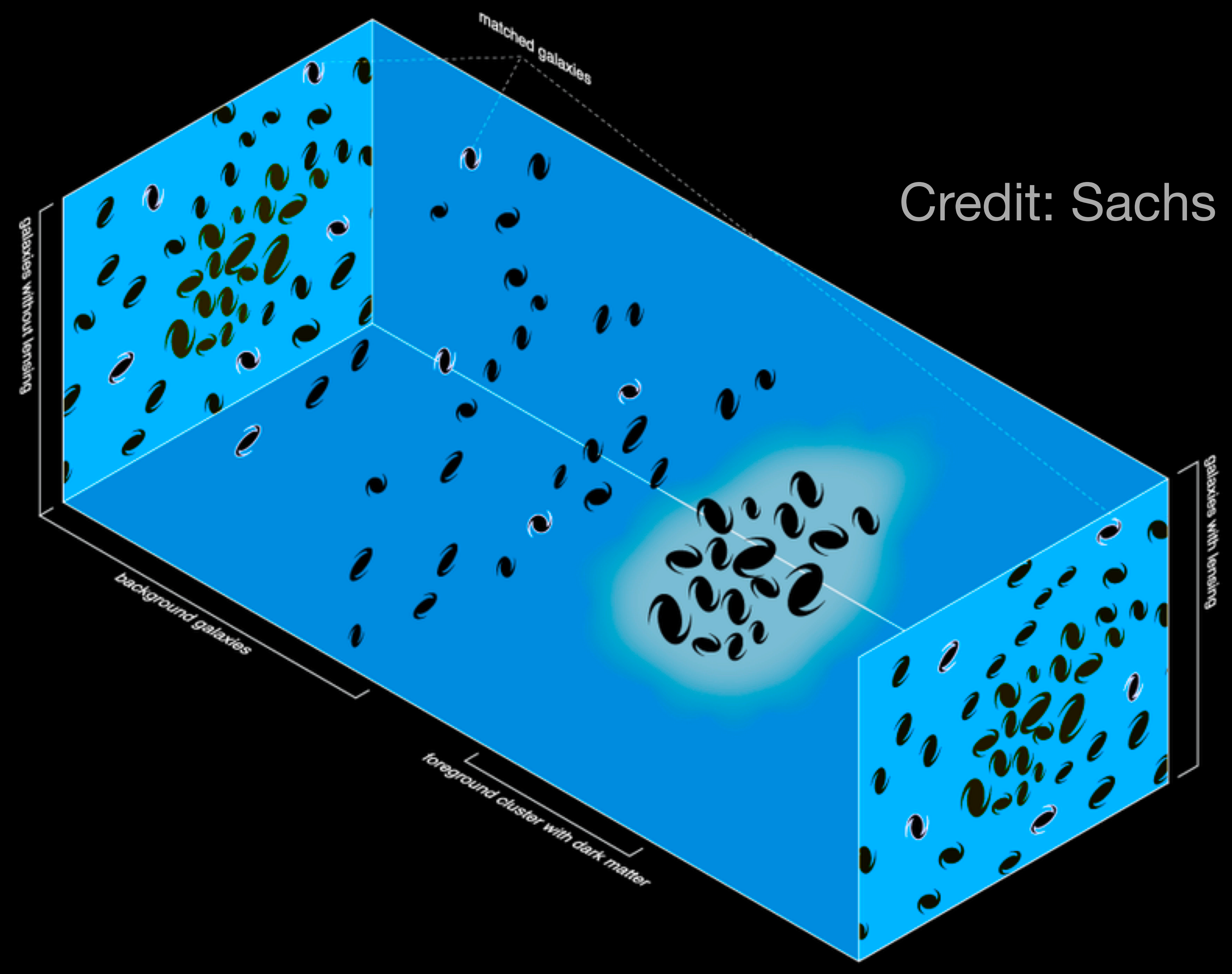
Dutra, Natarajan & Gilman ’24, also see Yang’s talk



MACSJ1206 , Meneghetti+ ’20

Some challenges to CDM (ACT×DES)

- Adhikari+ ’24 (+YZ) studied weak lensing of 908 ACTxDES lens.
- Those $\sim 10^{14}\,\mathrm{M}_{\odot}$ halos (slightly) prefer $\gamma = -1.5 \sim -2.$

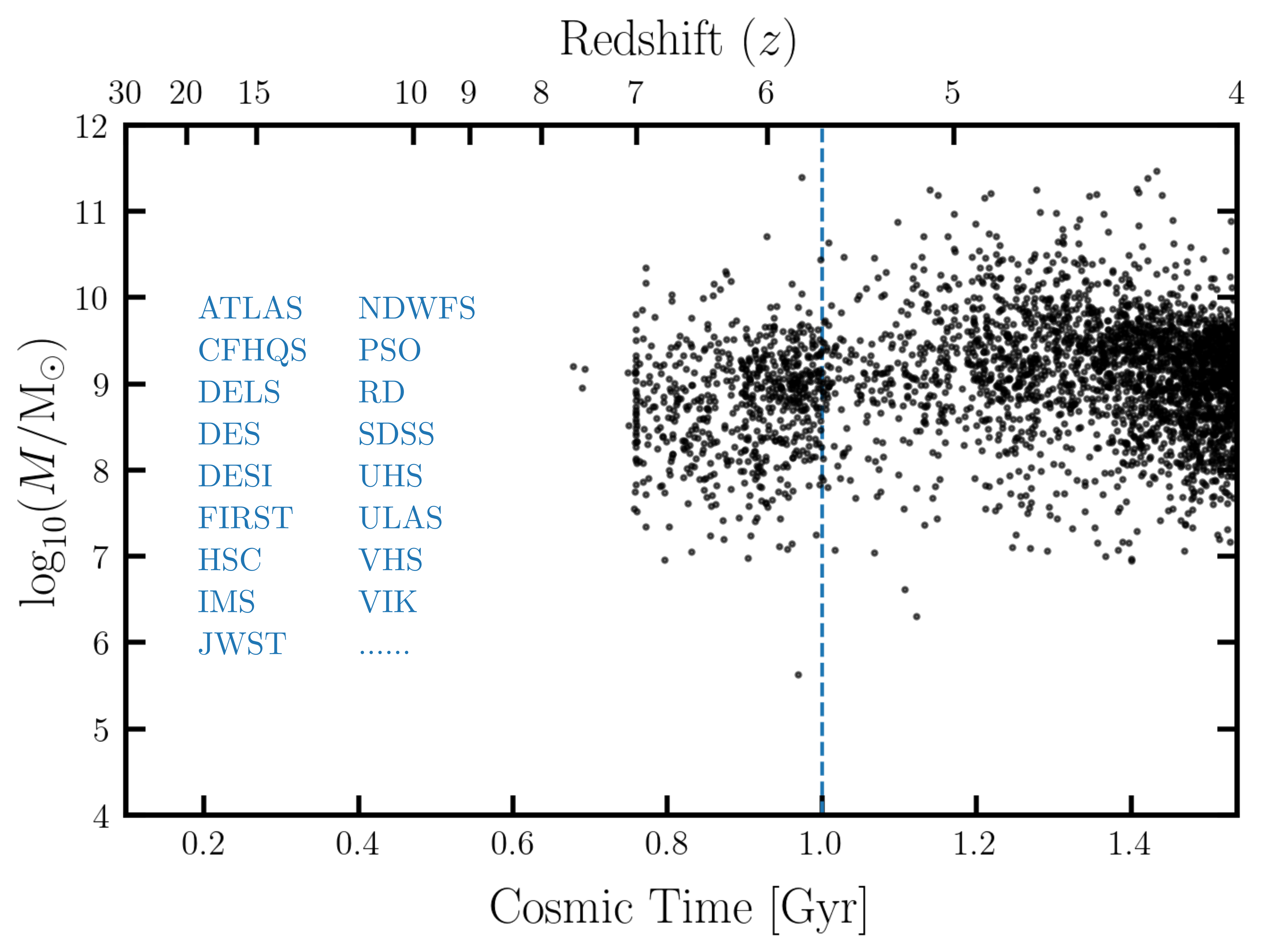


Credit: Sachs

Weak lensing

High-z supermassive black holes (SMBHs)

- Various telescopes found 700+ SMBHs within the first billion years of the Universe.



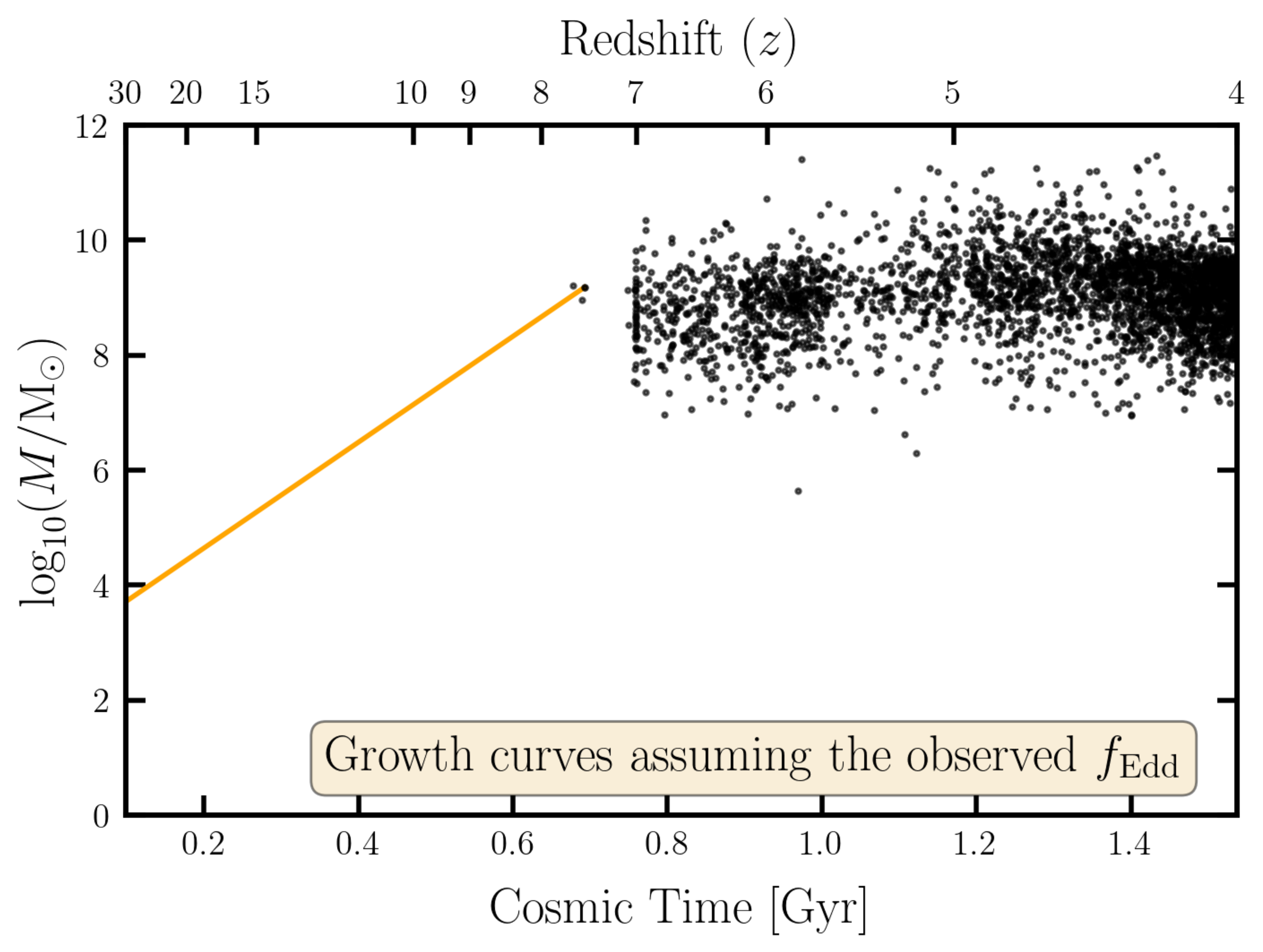
Complied catalog is available at https://github.com/Kscey/HZBC
[Kacey Chan + YZ]

High-z supermassive black holes (SMBHs)

- Stellar black hole + Eddington accretion limit.

$$\dot{M}_{\rm Edd} = \frac{M_{\rm BH}}{50\,{\rm Myr}/f_{\rm Edd}}$$

$$f_{\rm Edd} \equiv L_{\rm bol}/L_{\rm Edd}$$



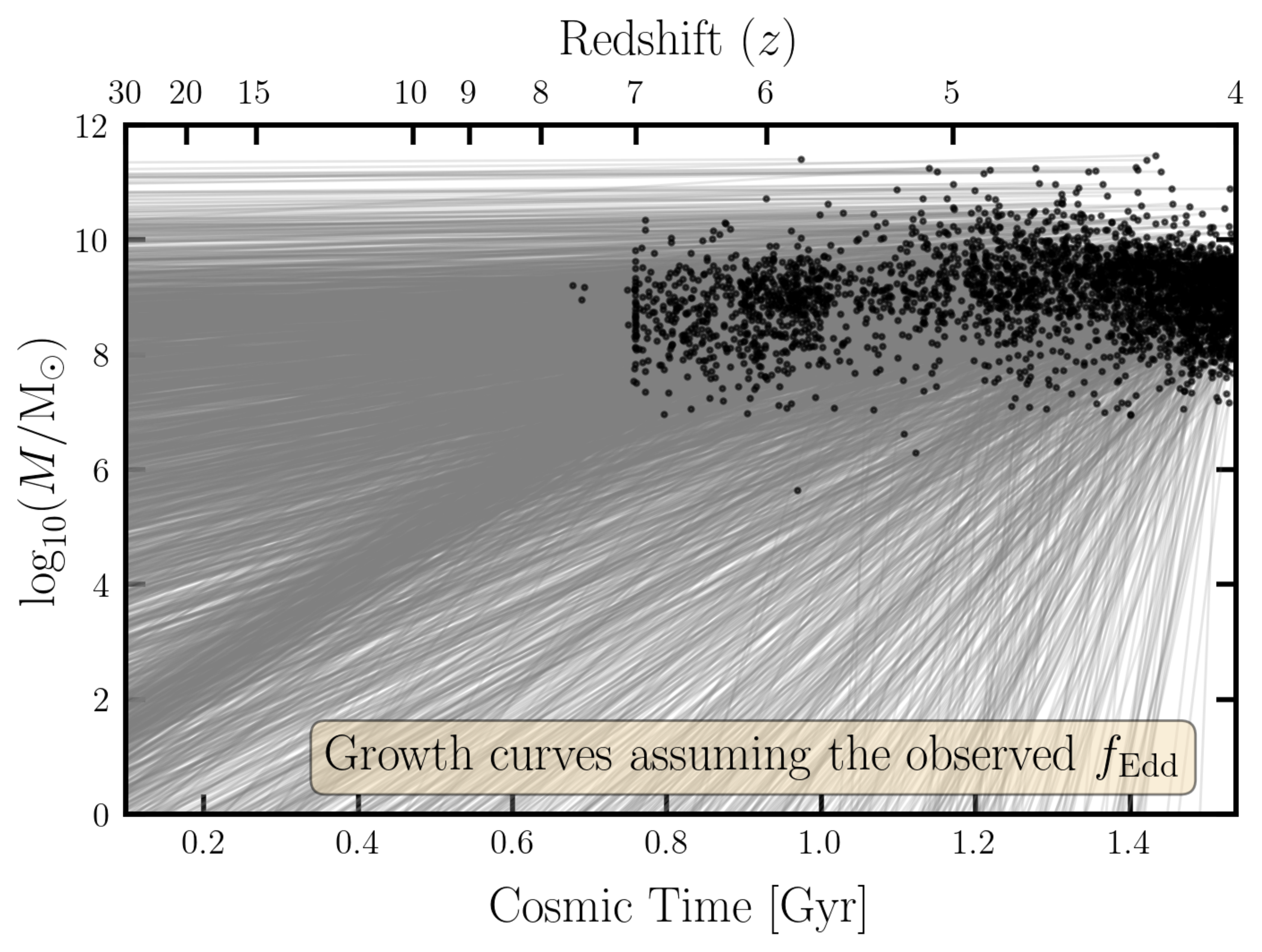
Complied catalog is available at https://github.com/Kscey/HZBC
[Kacey Chan + YZ]

High-z supermassive black holes (SMBHs)

- Many of them are very dim.

$\Downarrow$

Vanilla stellar BH + Eddington accretion cannot explain their formation.



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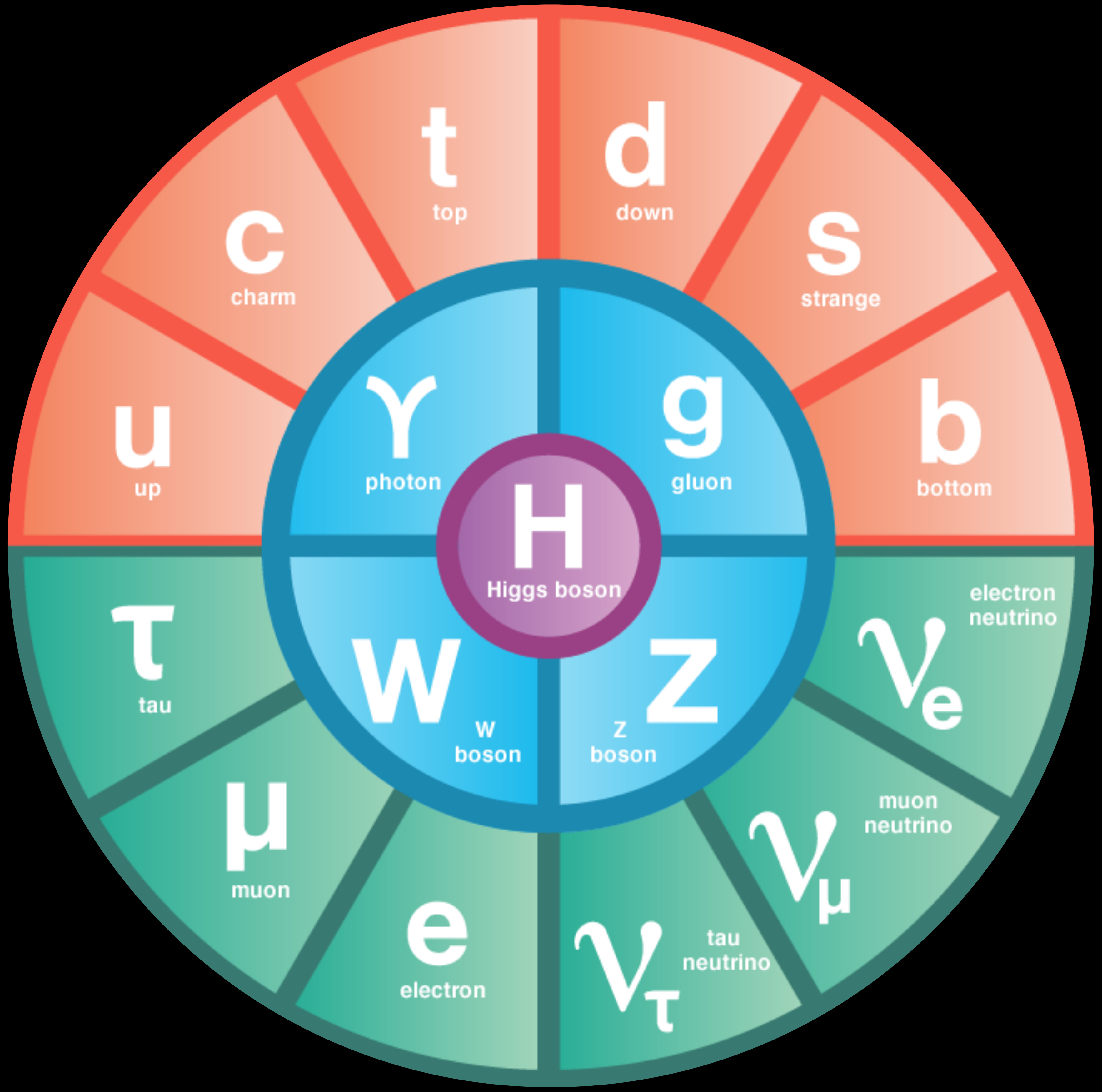
[Kacey Chan + YZ]

Do ***ultra-dense structures*** hint dark matter beyond CDM?

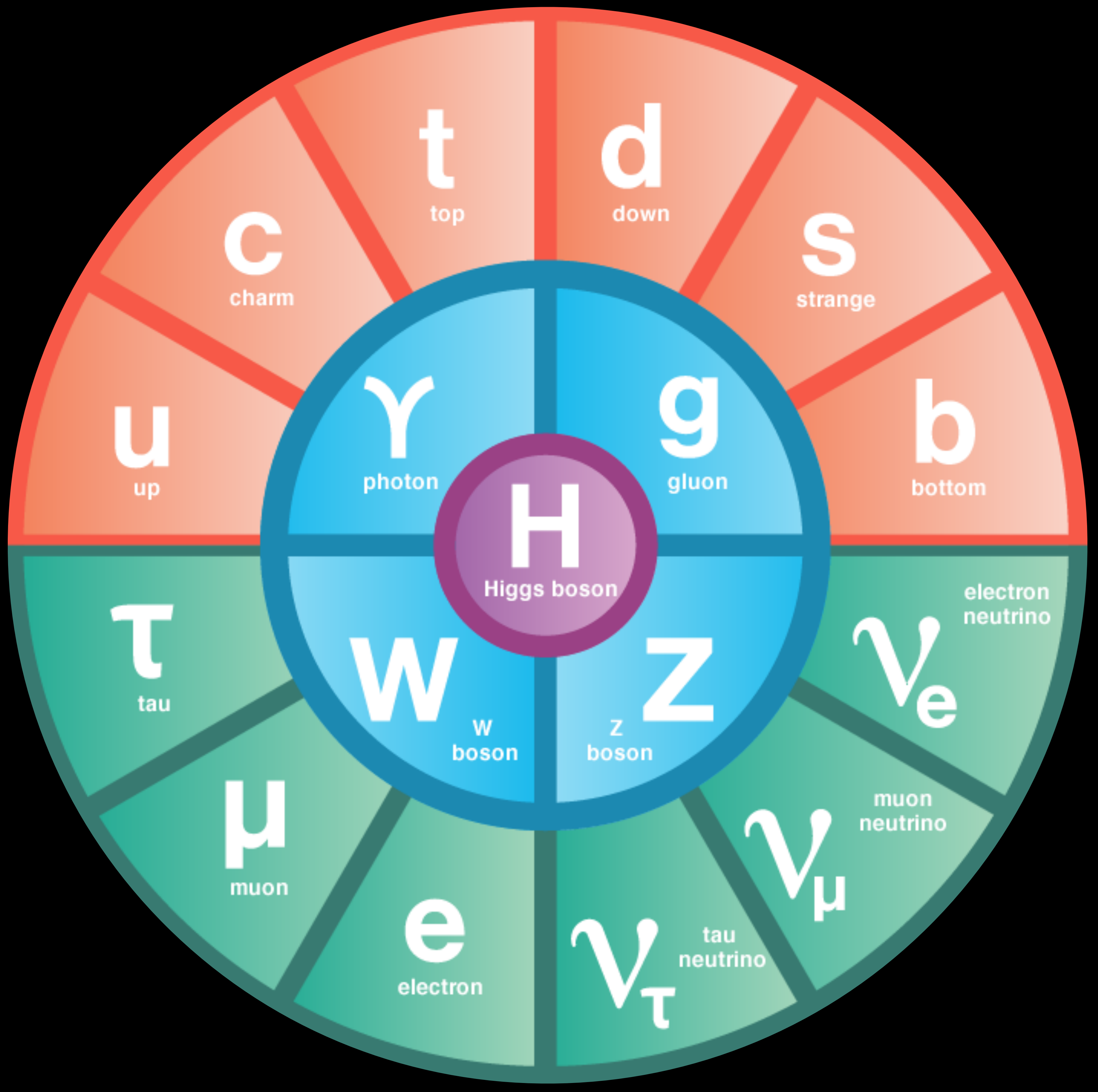
Self-interacting dark matter

Is dark matter alone?

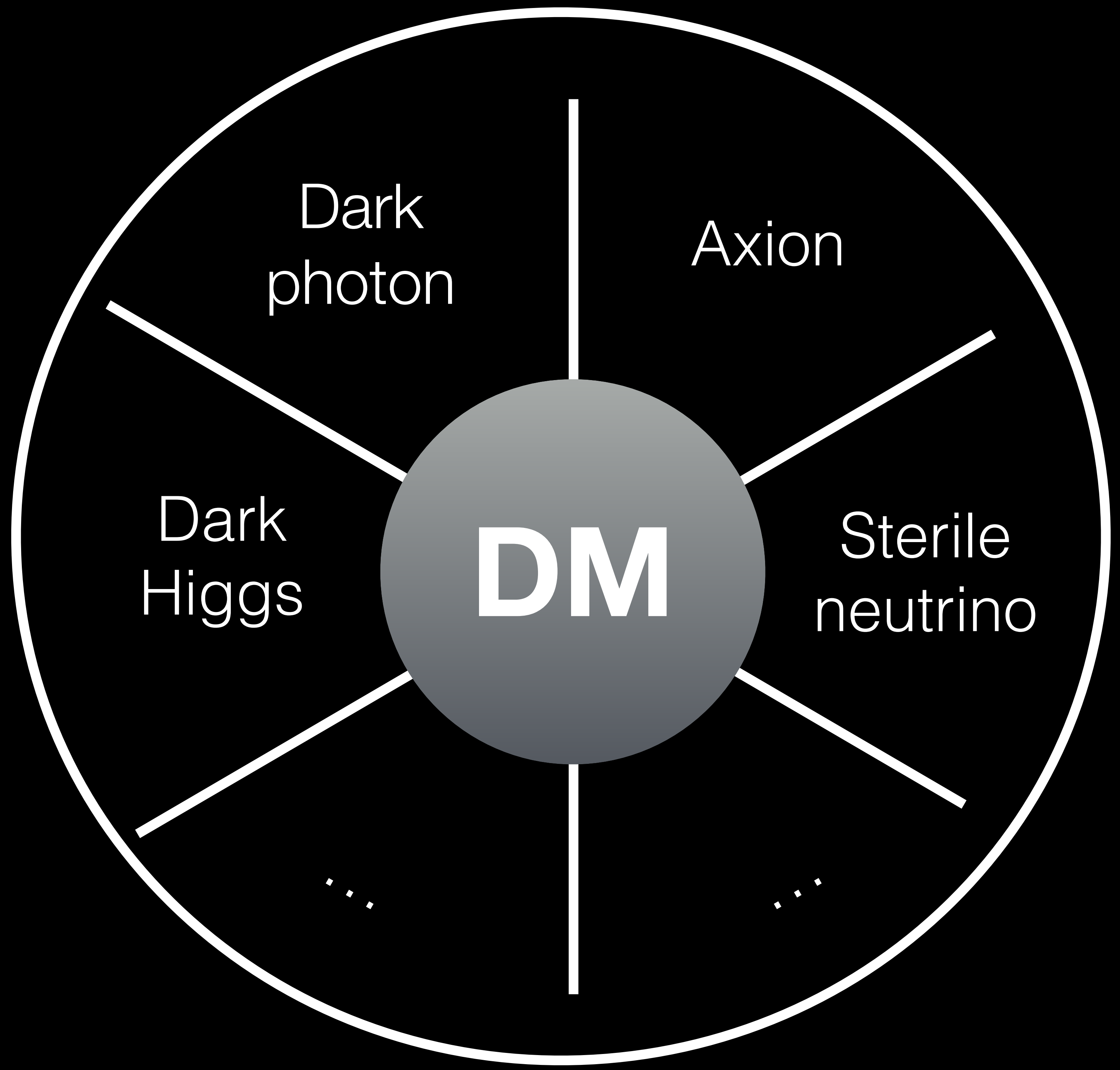


Ordinary matter

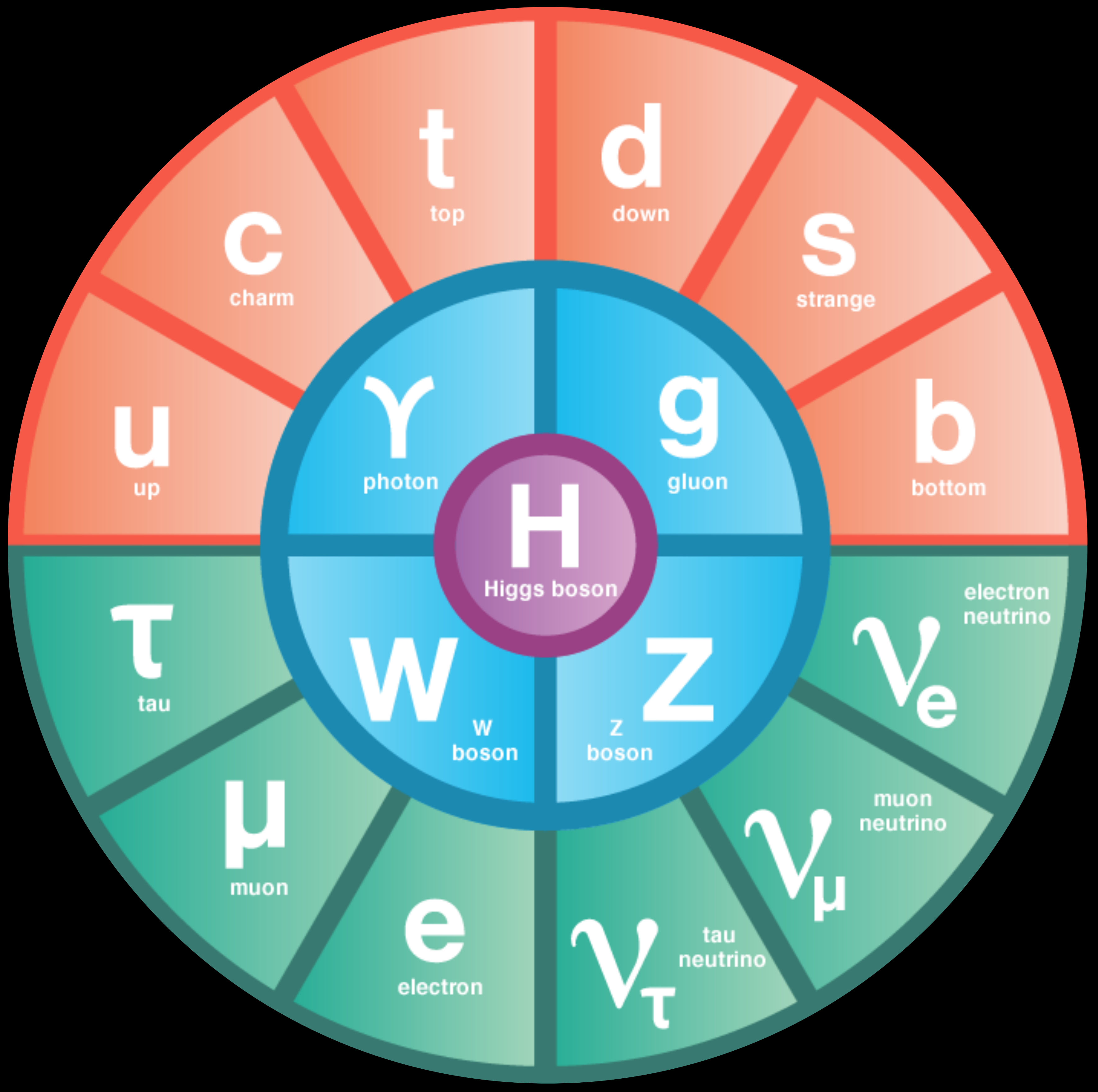
Is dark matter alone?



Ordinary matter



Dark sectors



Ordinary matter

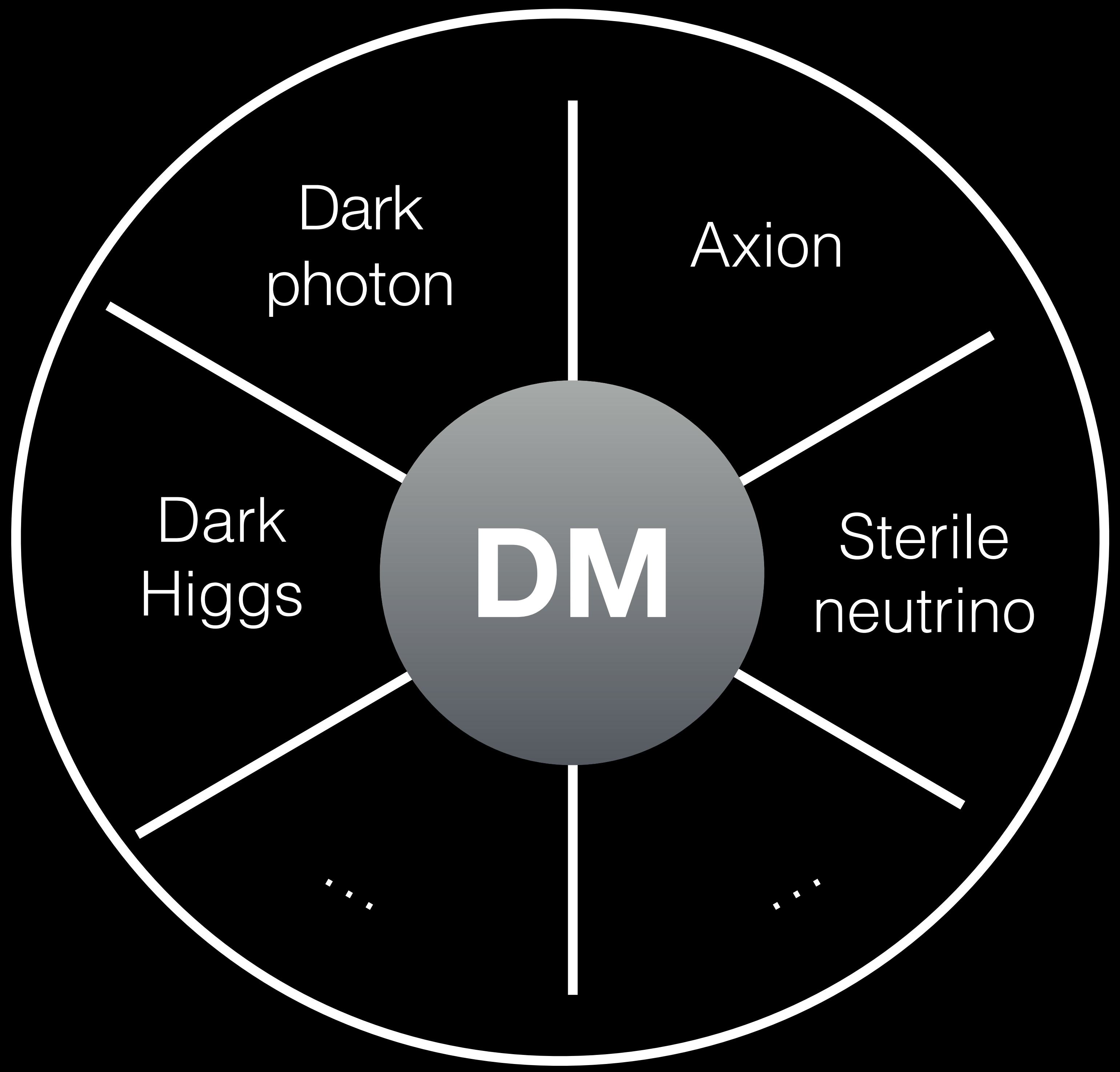
Portal?

$$\epsilon F_{\mu\nu} F'^{\mu\nu}$$

$$y_N L H N$$

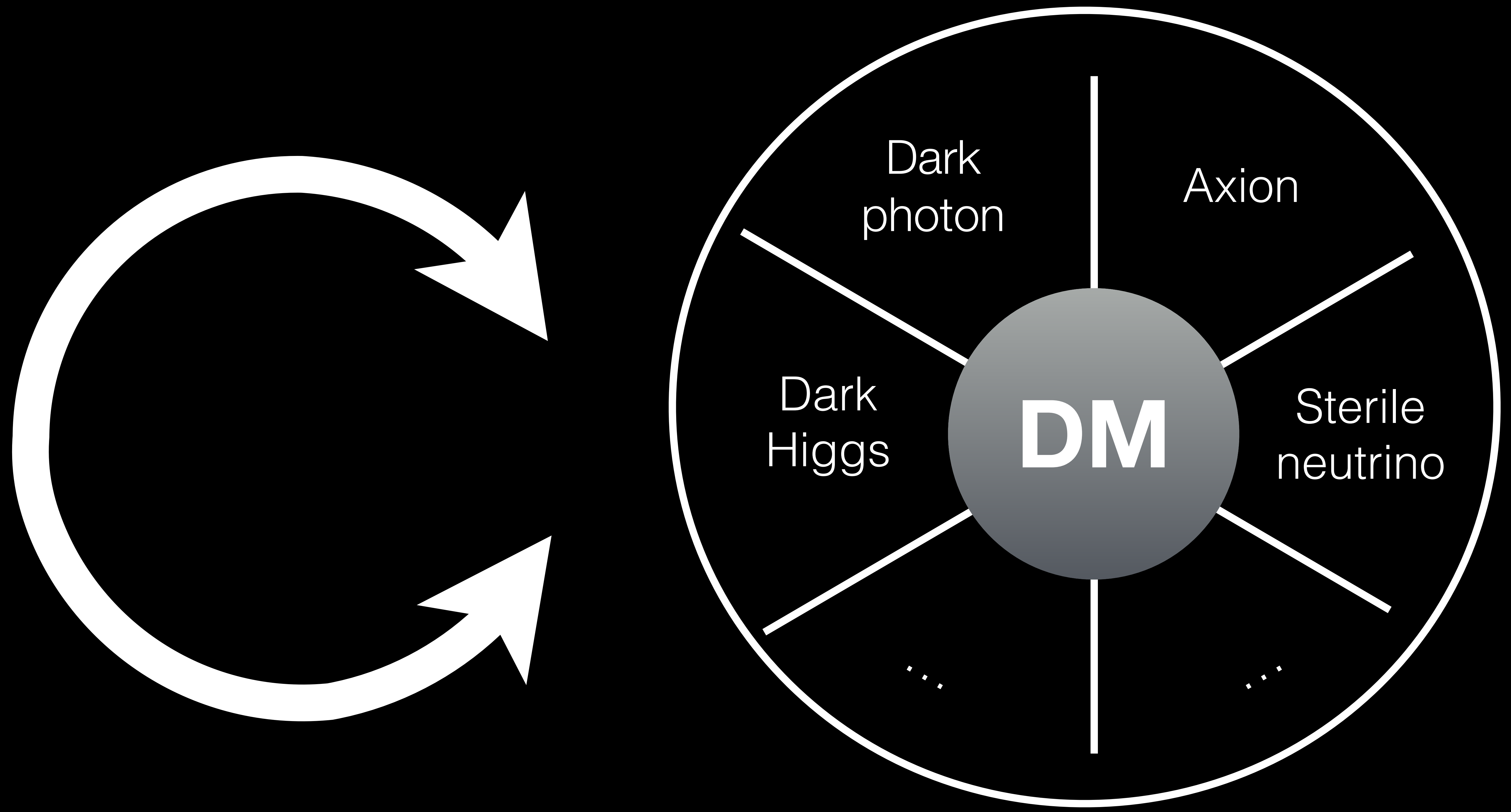
$$\frac{\partial_\mu a}{\Lambda} \bar{\psi}\gamma^\mu\gamma^5\psi$$

......

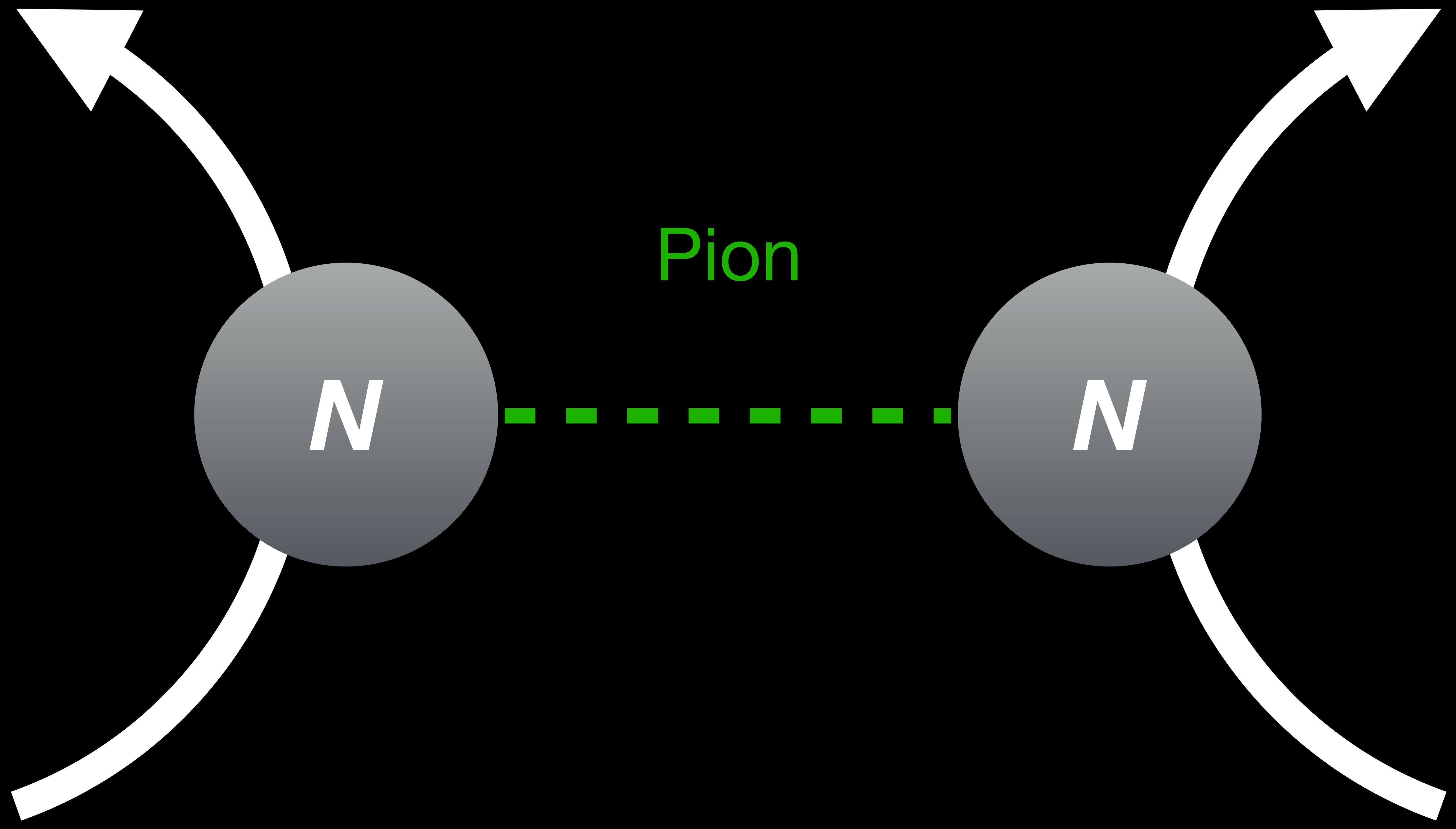


Dark sectors

Self-interactions?



Dark sectors

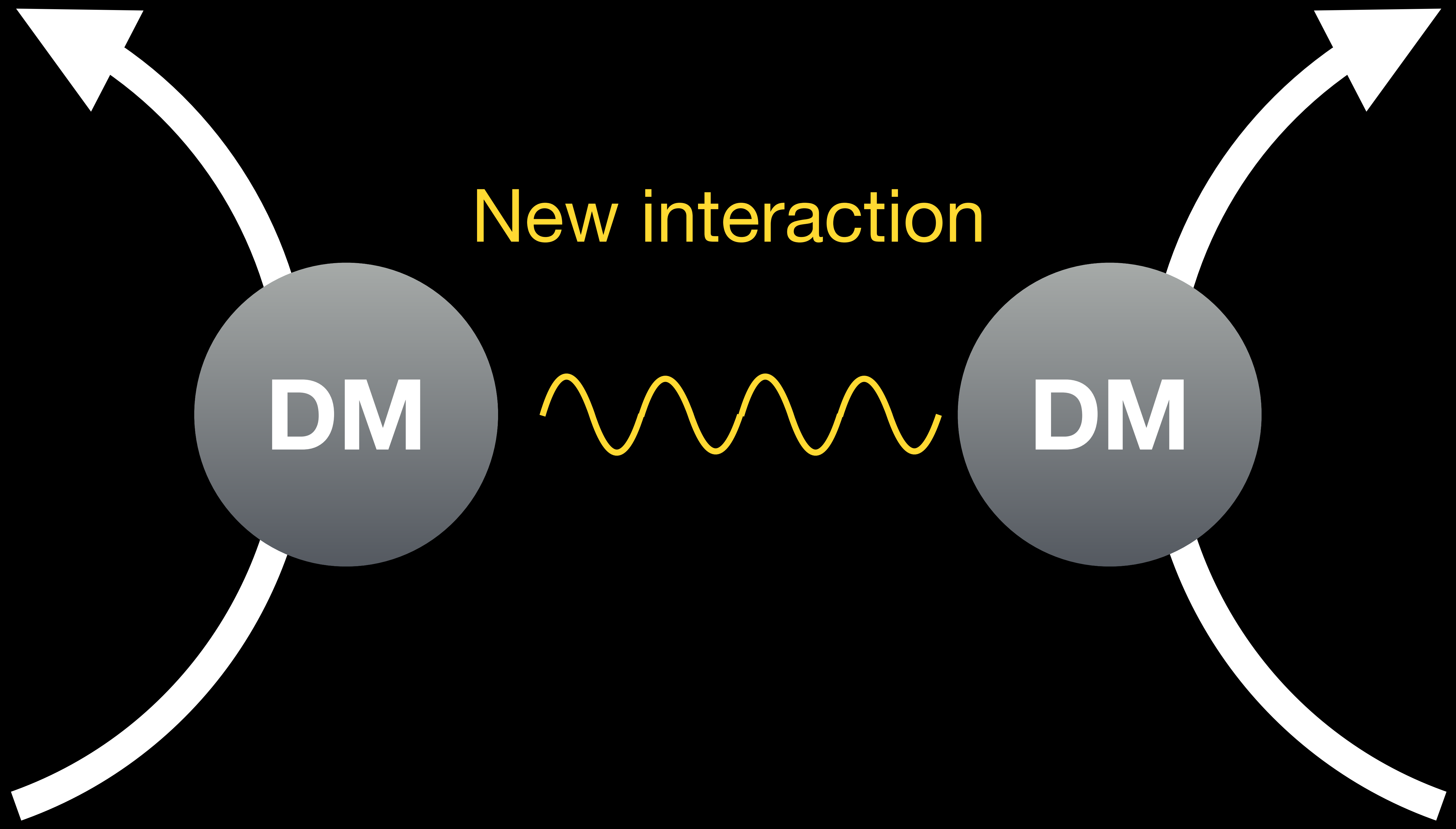


Nucleon-nucleon self-interaction

Cross section strength: $\sigma_{\mathrm{T}}/m_{\mathrm{N}} \sim 10\,\mathrm{cm}^2/\mathrm{g}$

Nuclear Data Sheets ’11

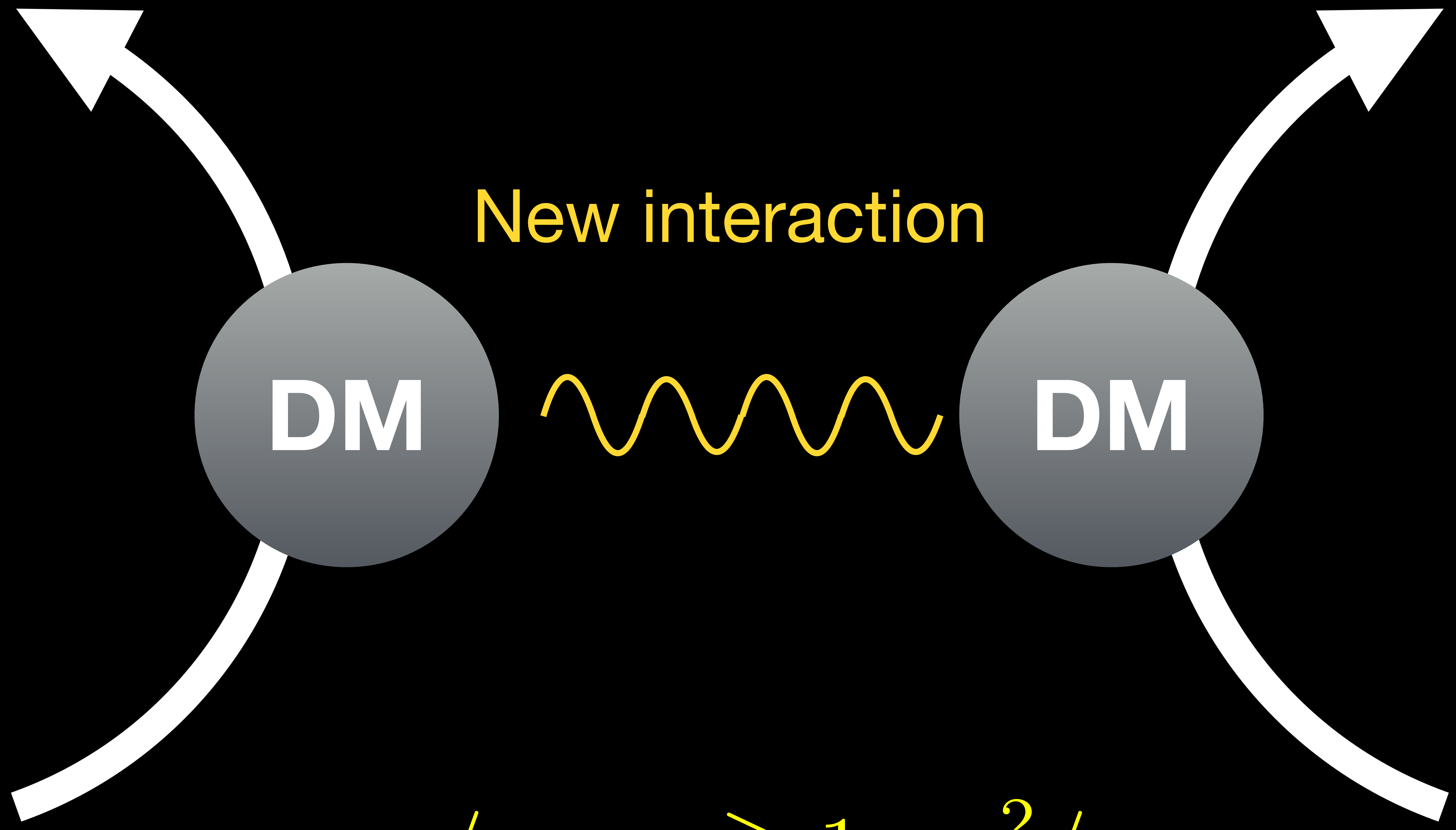
$1\,\mathrm{cm}^2/\mathrm{g}$
$\approx 2\,\mathrm{barn}/\mathrm{GeV}$



Self-Interacting Dark Matter (SIDM)

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

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



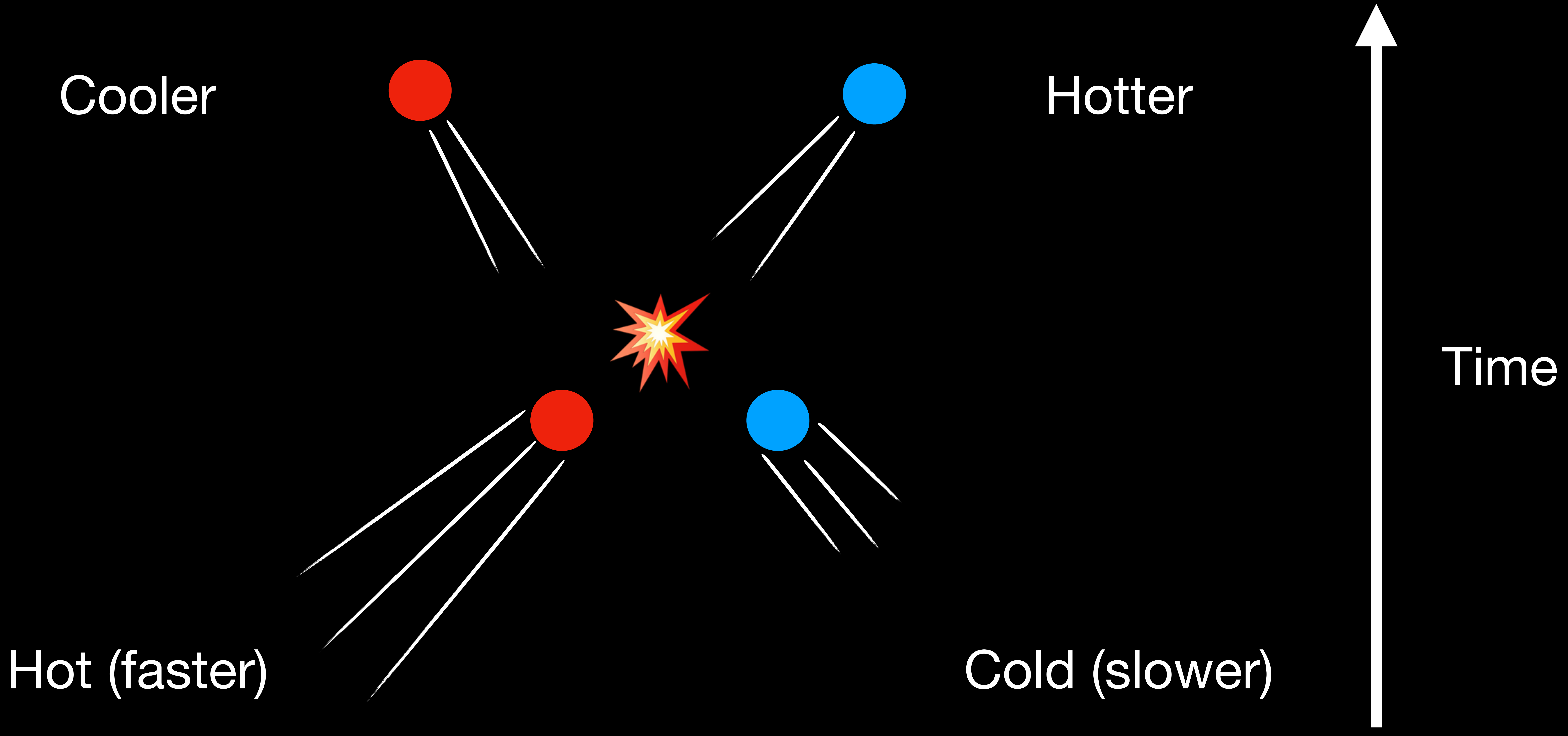
$$\sigma_{\mathrm{T}}/m_{\mathrm{DM}} \gtrsim 1\,\mathrm{cm}^2/\mathrm{g}$$

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

Spergel & Steinhardt ‘00

The core-collapse of dark matter halo

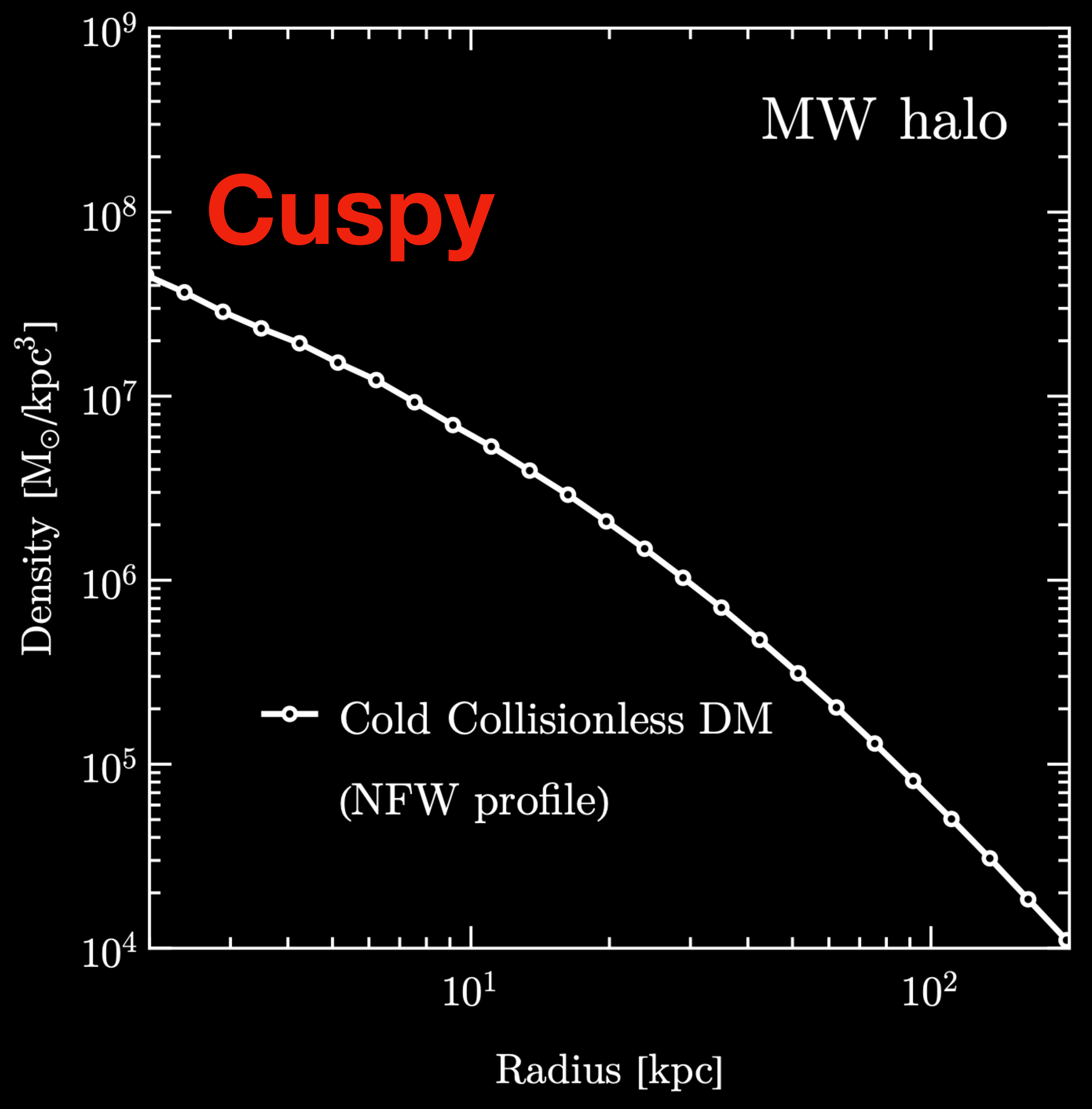
Effects of self-interaction

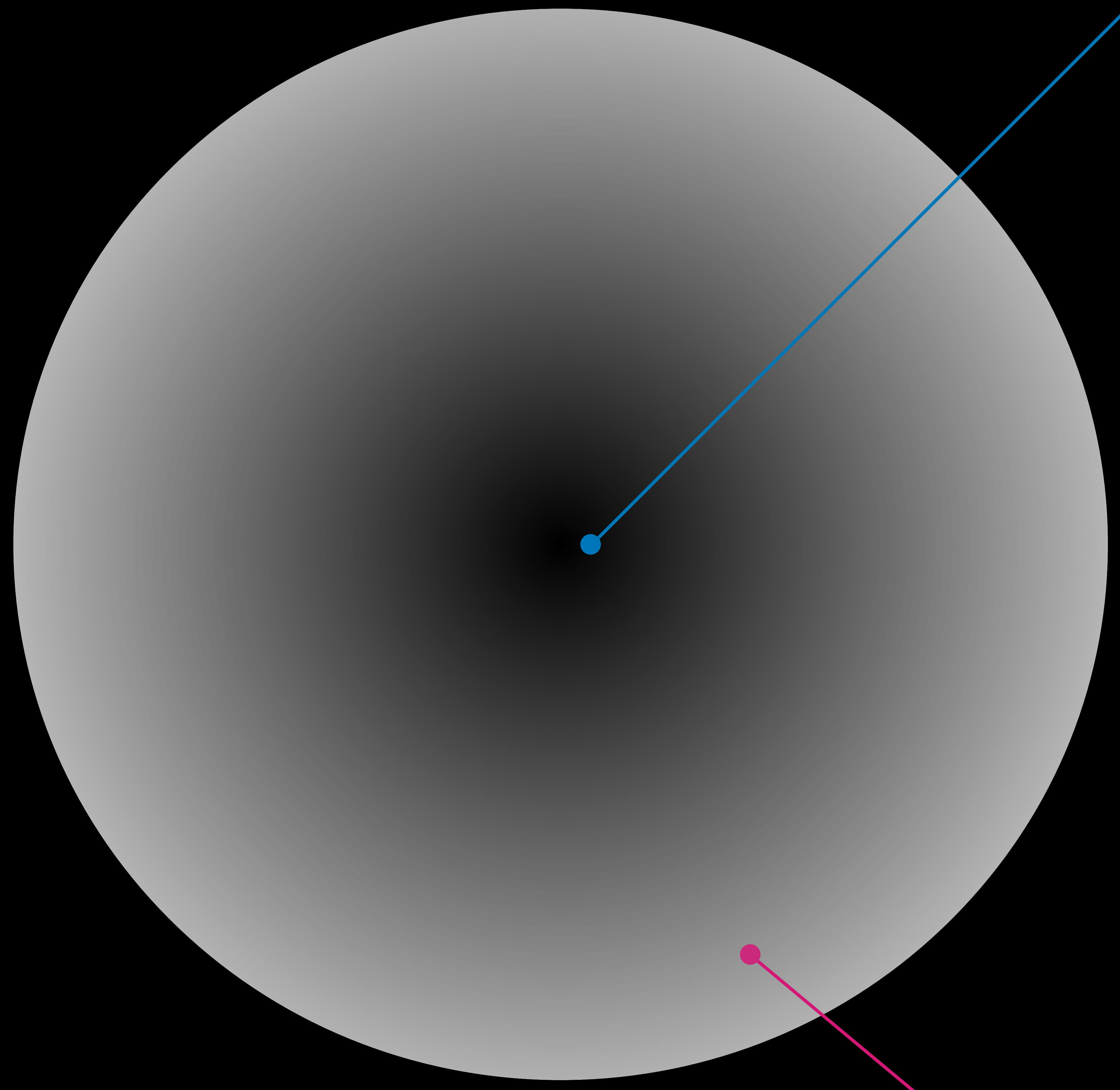


Equipartition

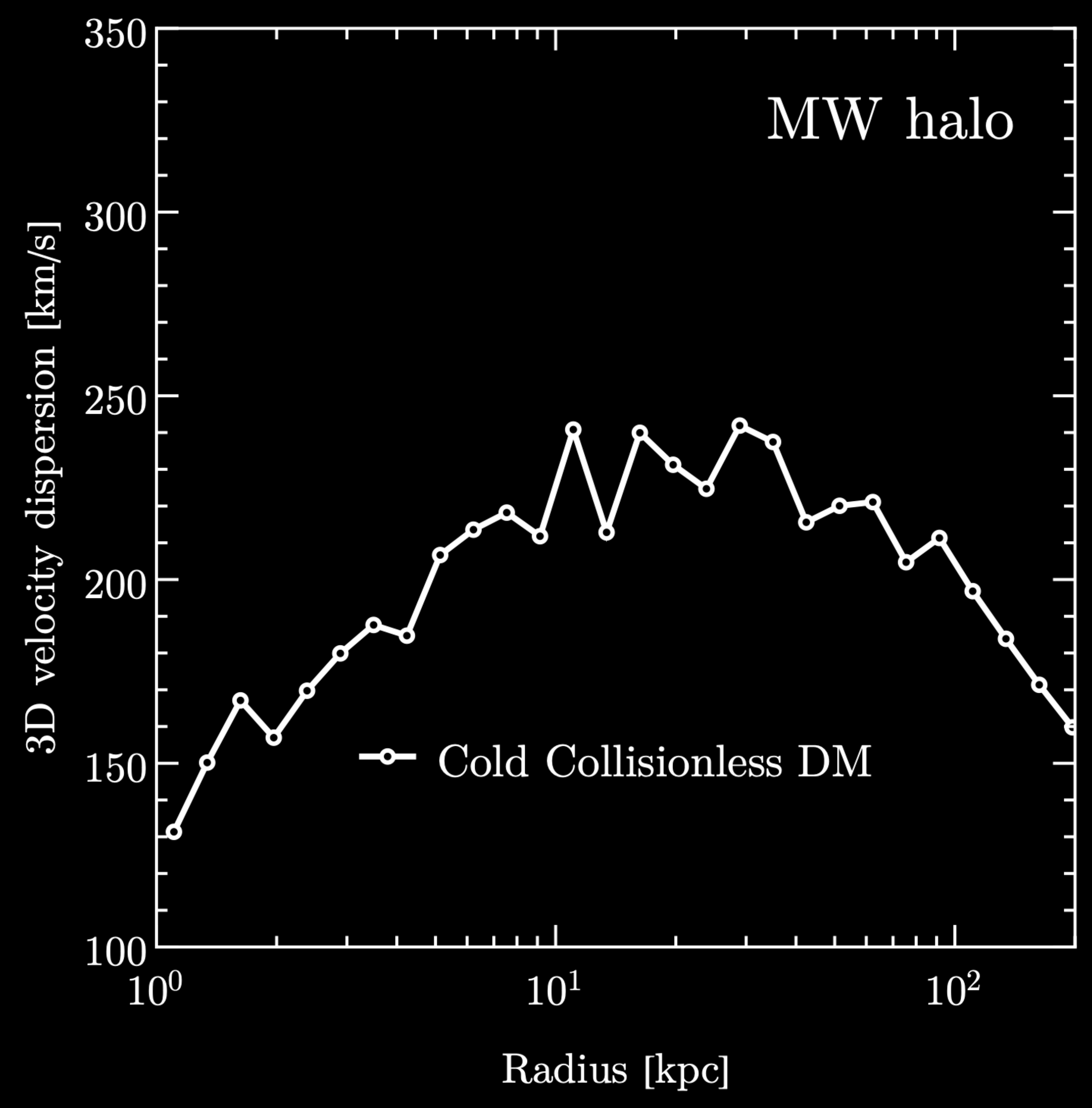
Halo formation

Density profile
(density at given radii)



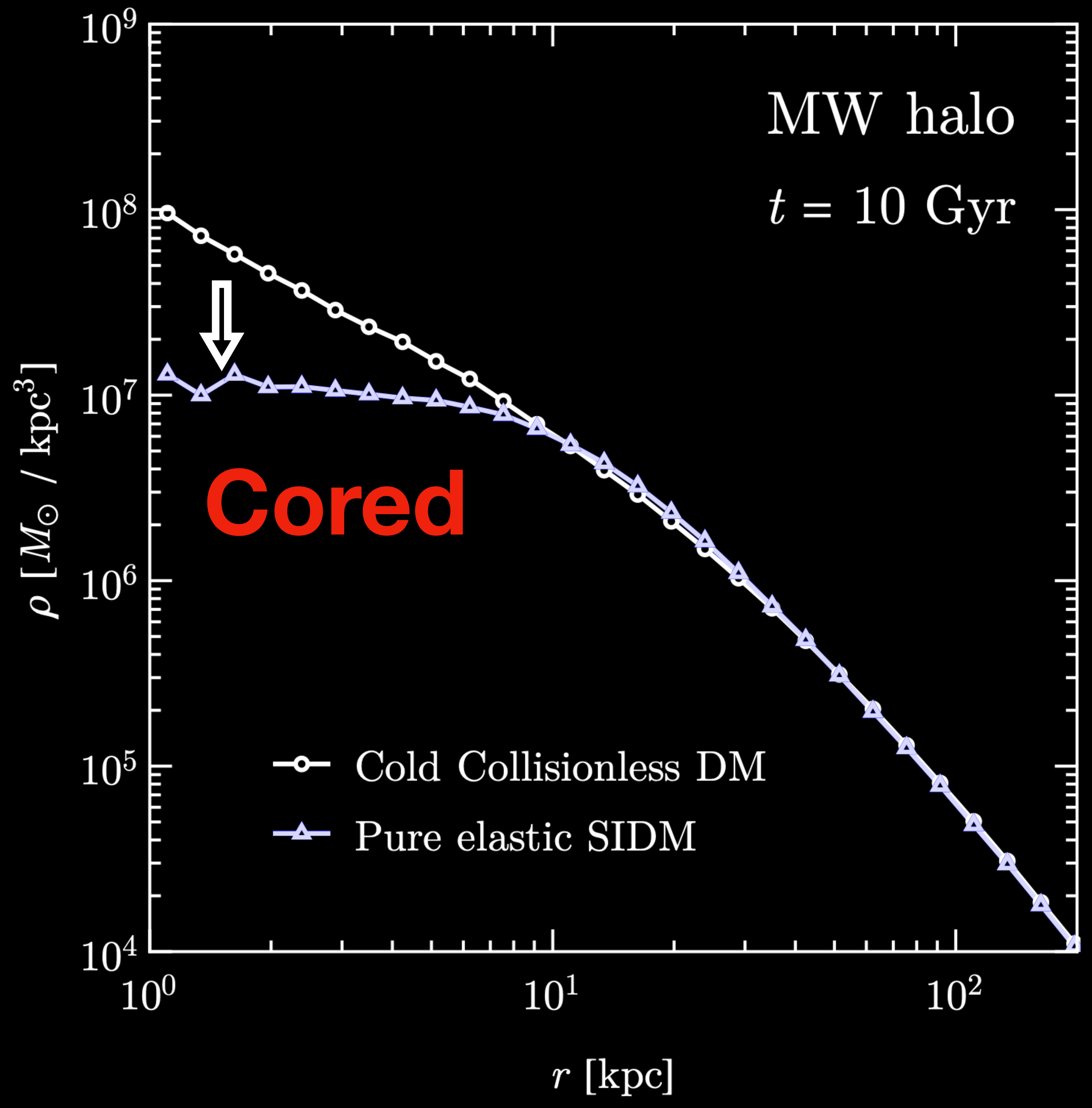


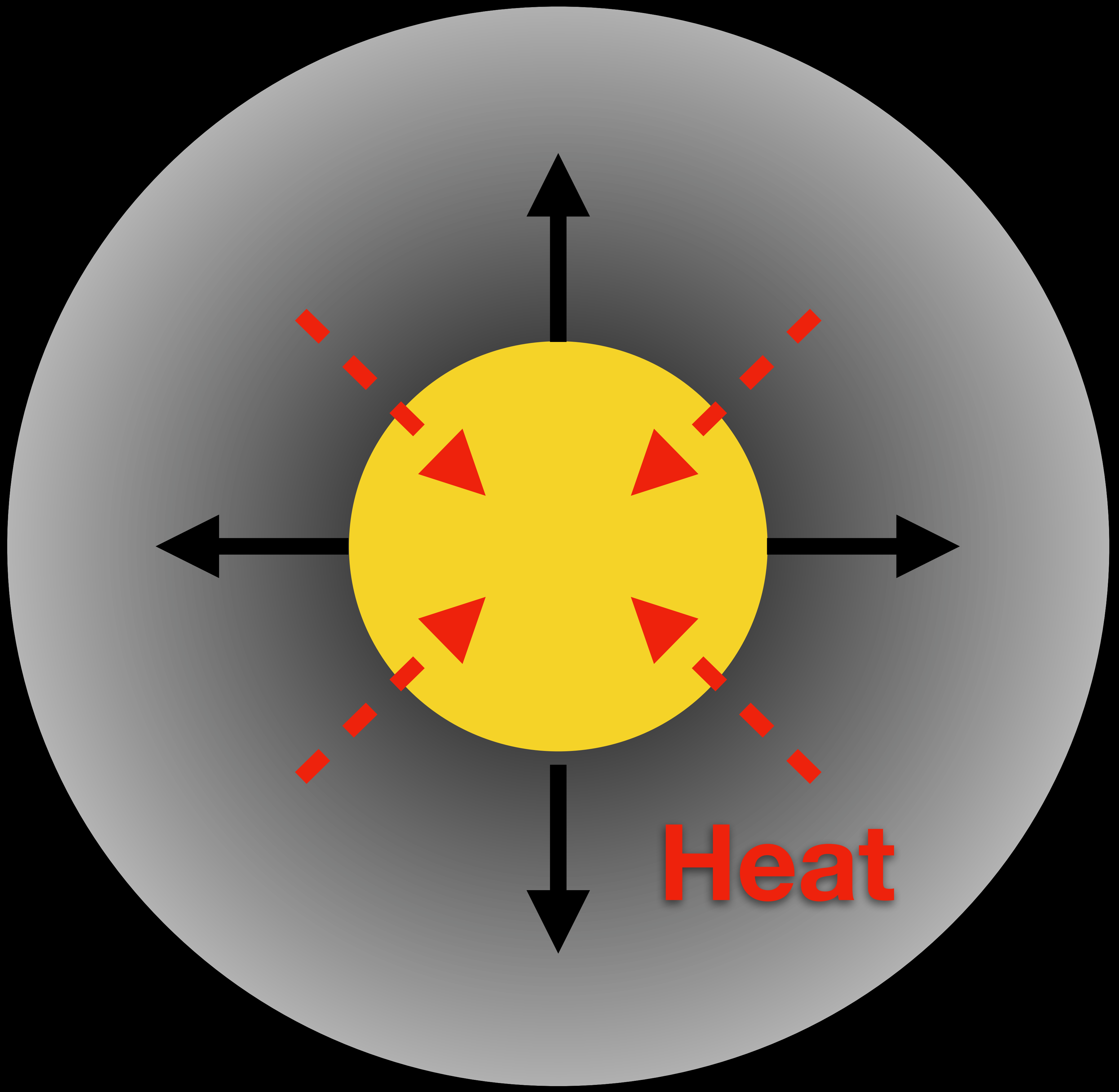
Velocity dispersion profile

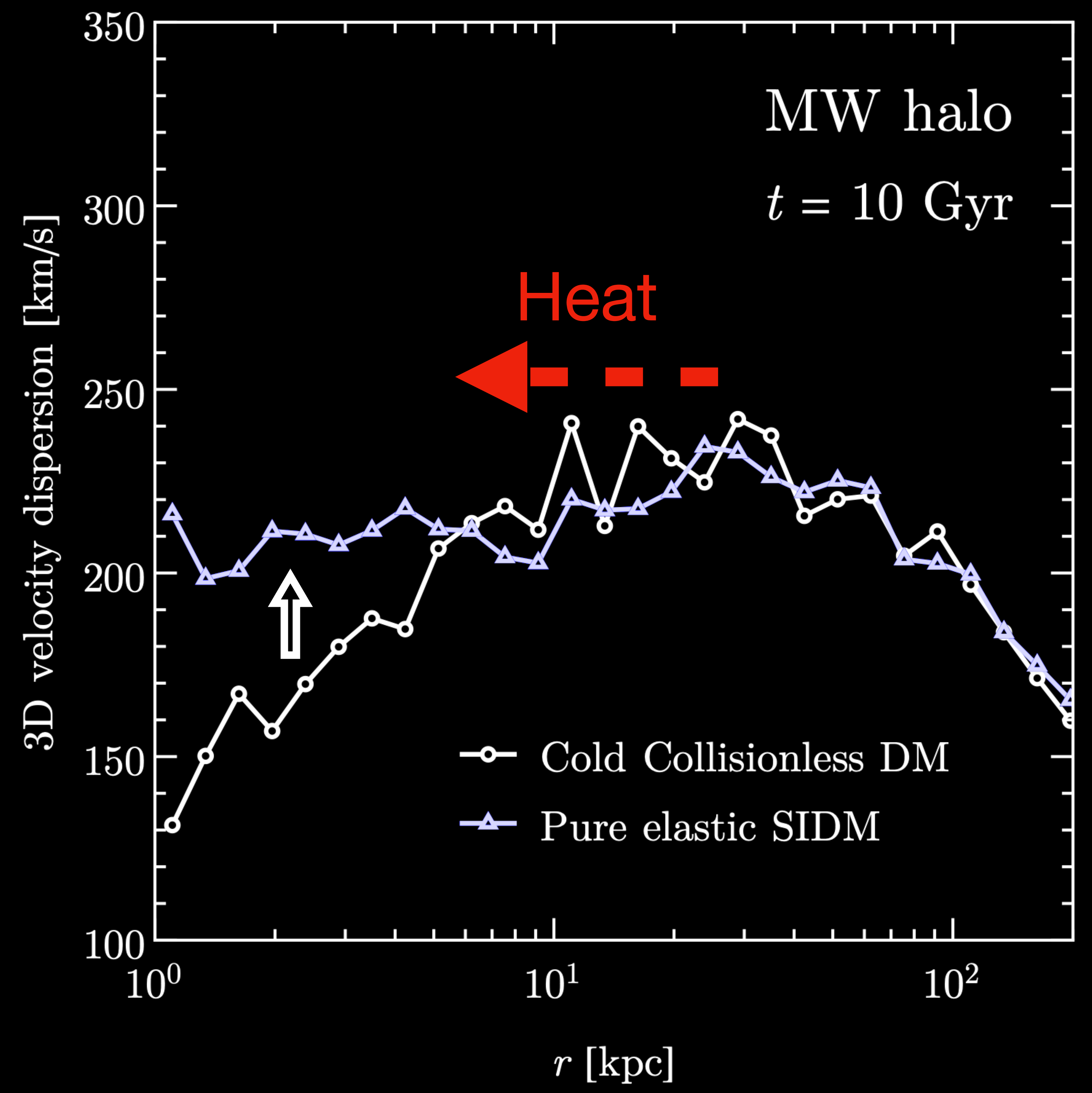


Navarro-Frenk-White (NFW) profile $$\rho = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$$

Core expansion

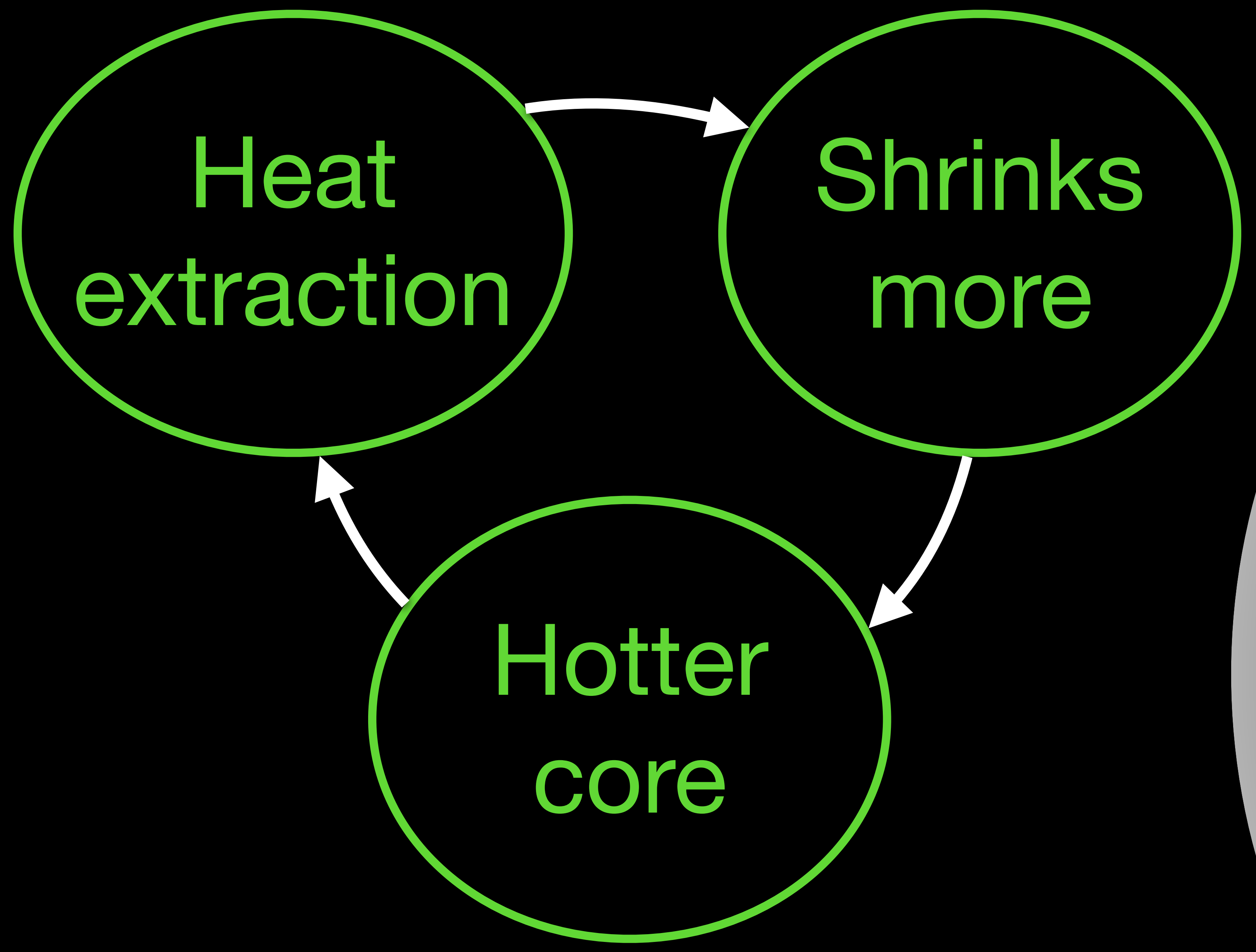




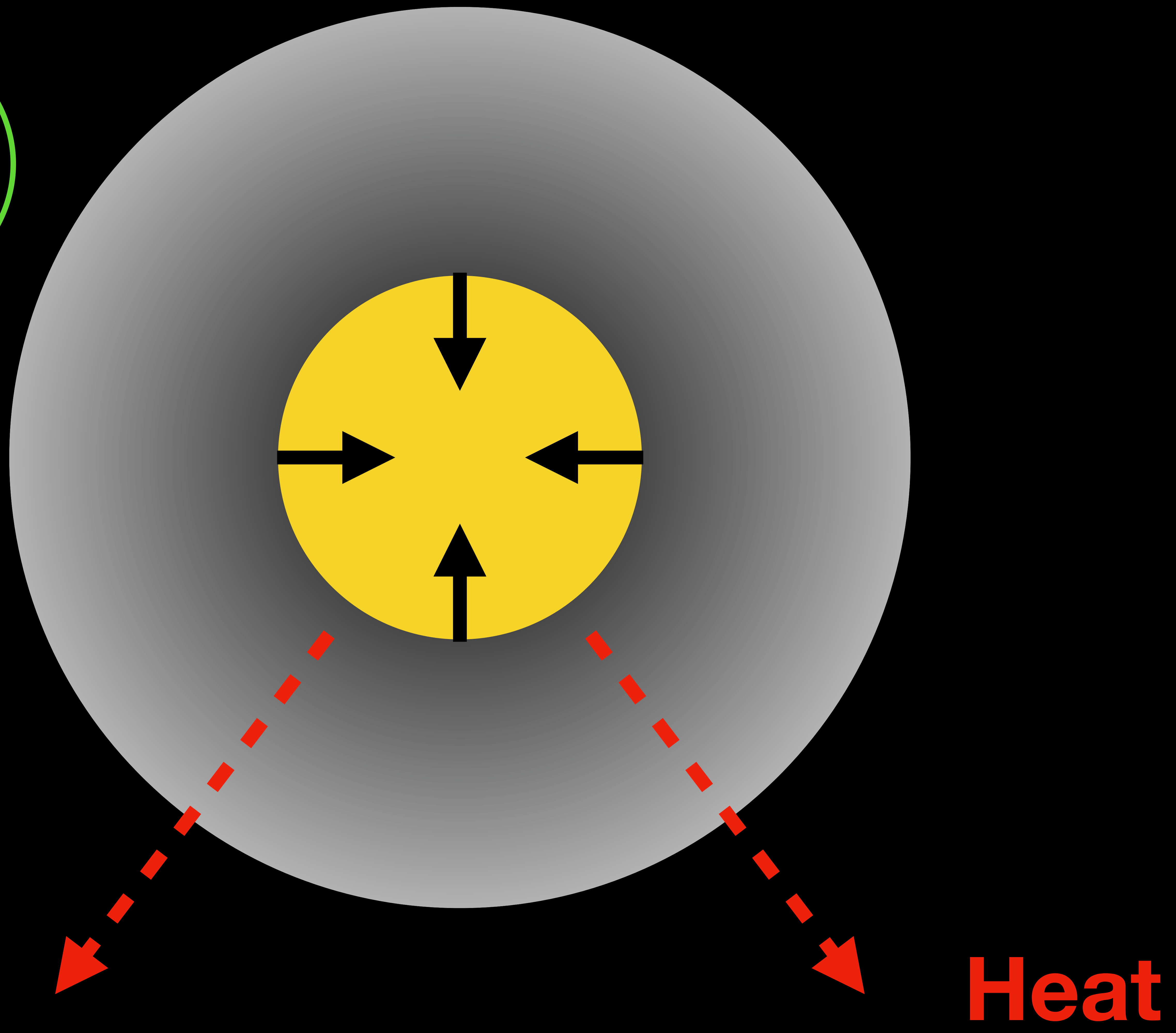


Huo, Yu & YZ '20

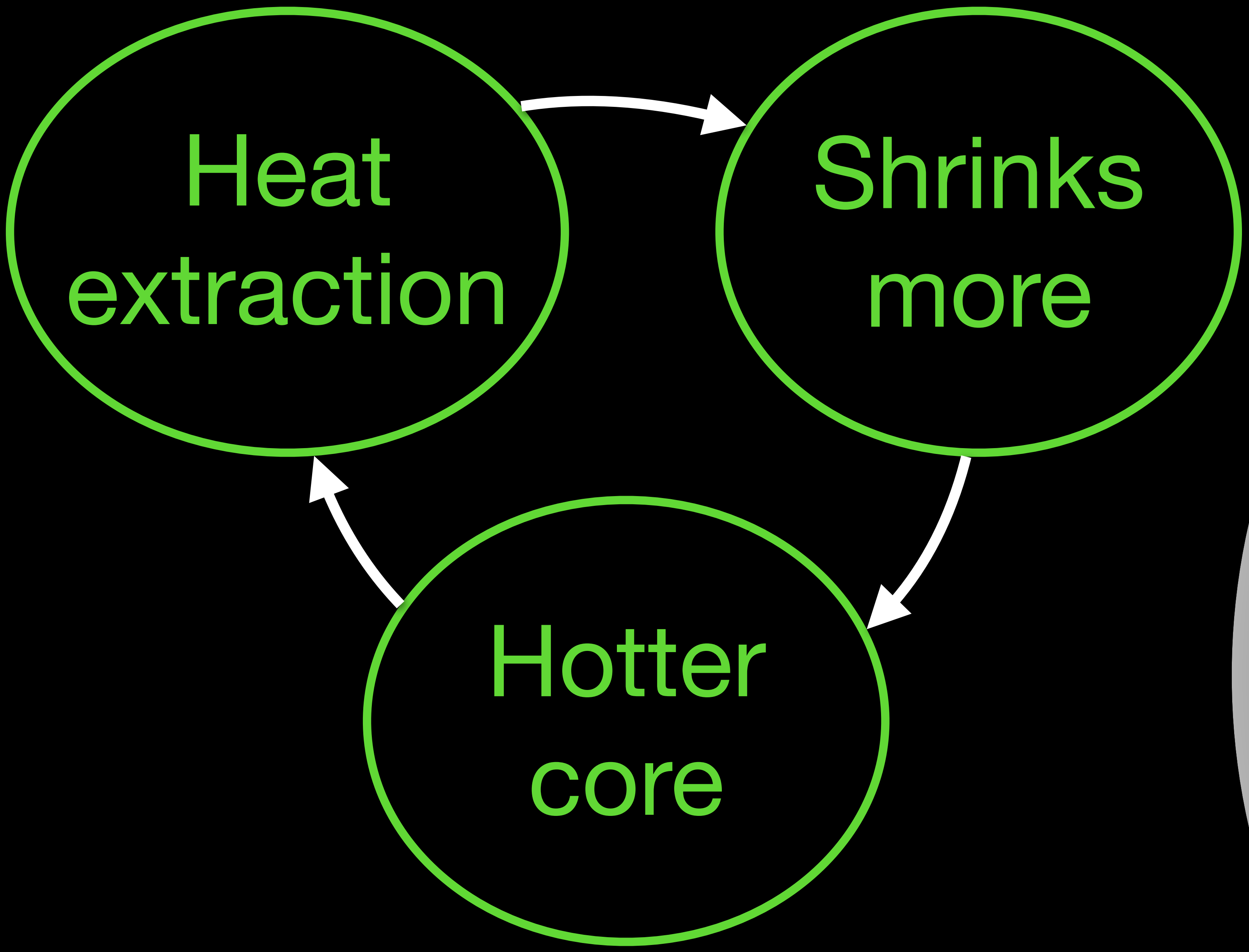
Core collapse



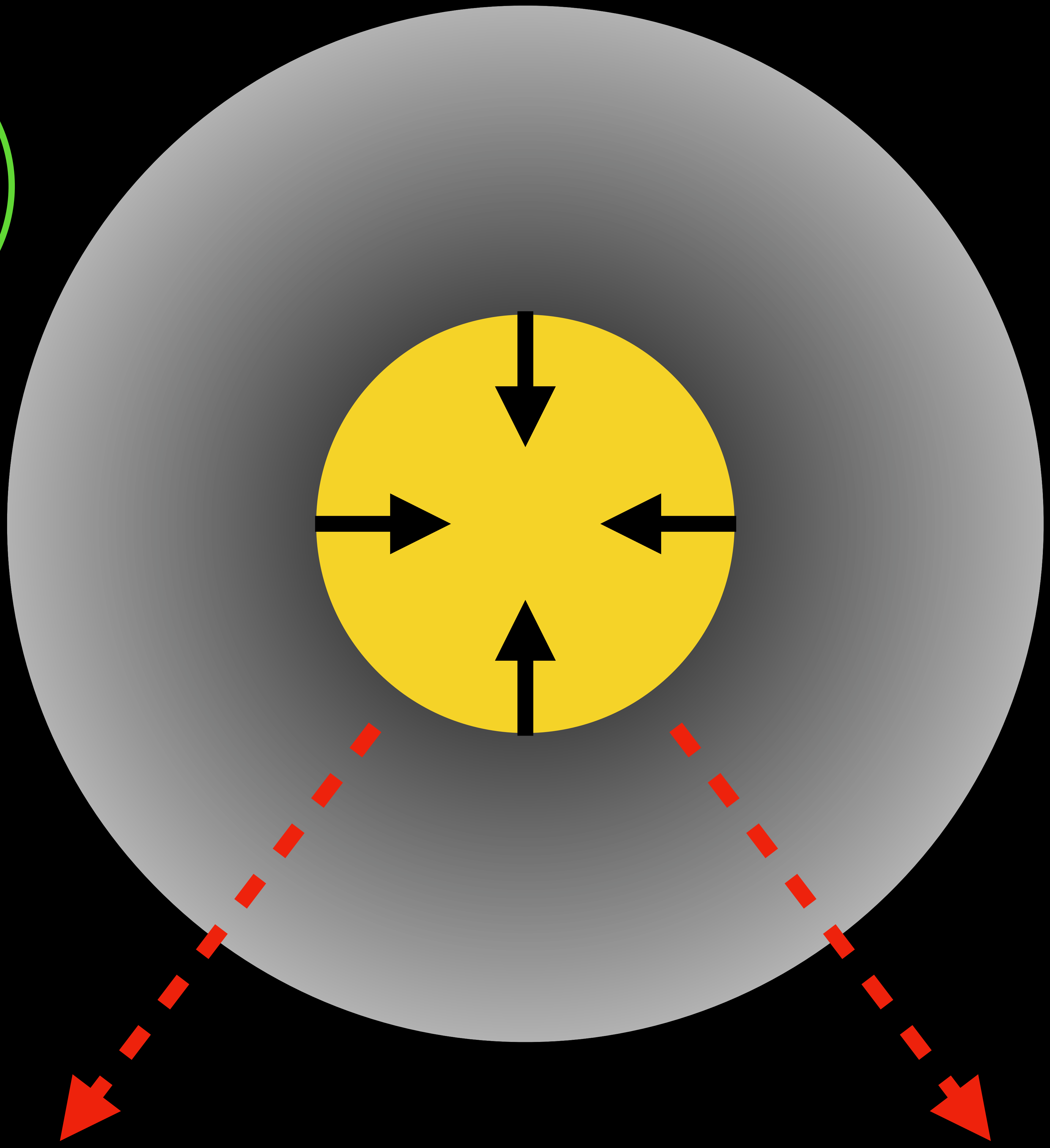
Spergel & Steinhardt '00



Core collapse



Spergel & Steinhardt '00



Heat

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

$$\Downarrow$$

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

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

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

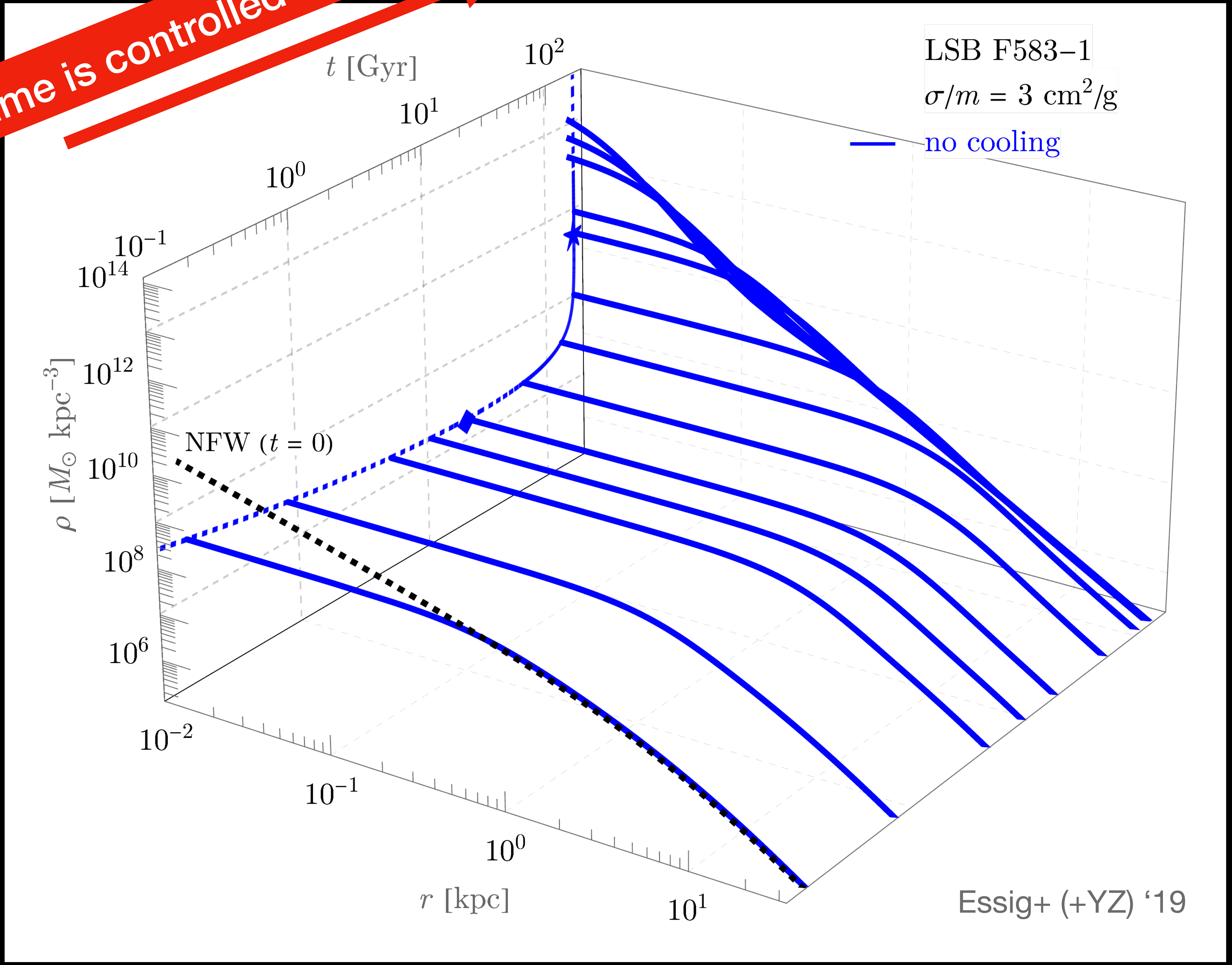
Overall evolution

Evolution stages:

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

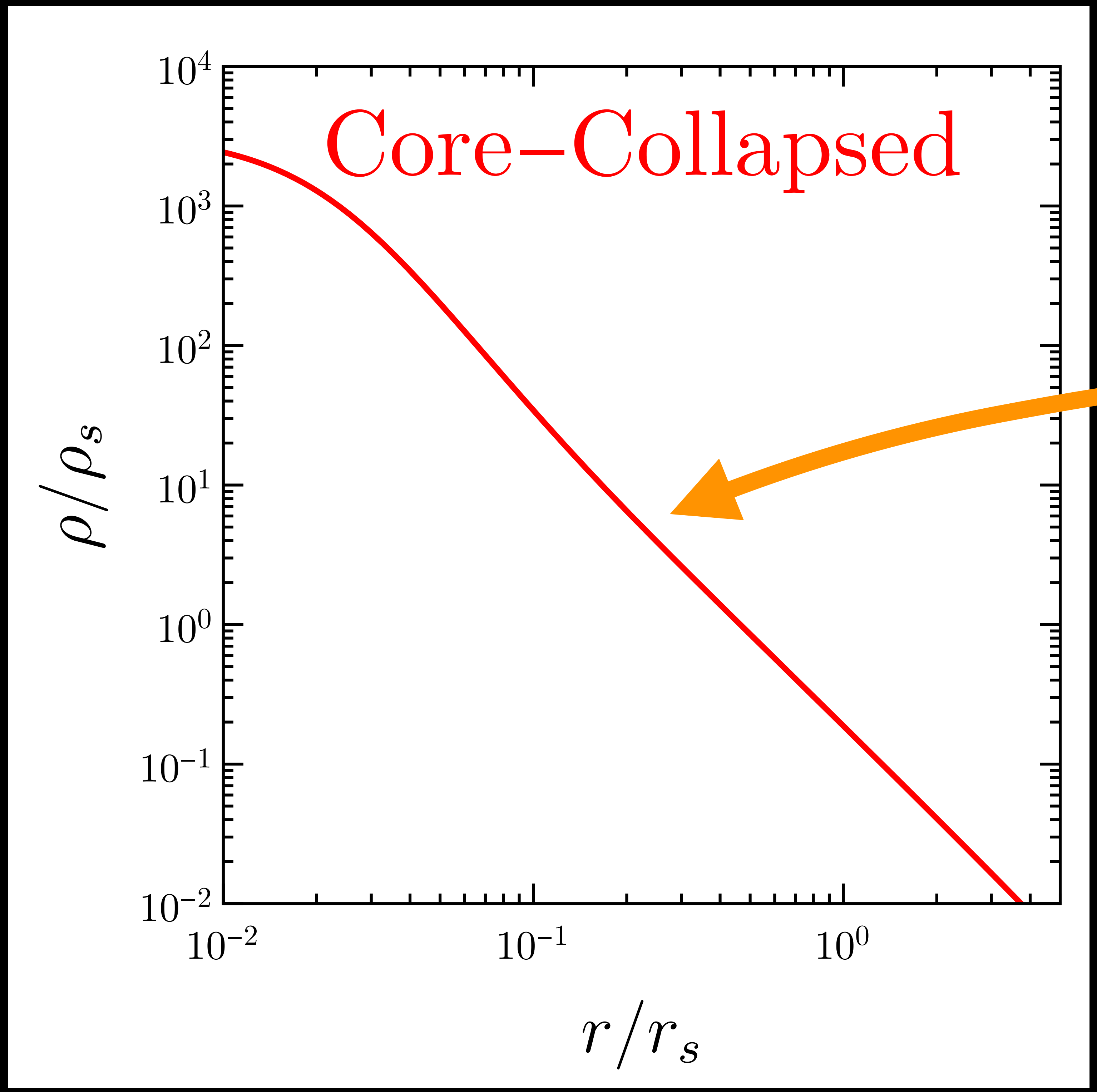
Evolution time is controlled by σ/m

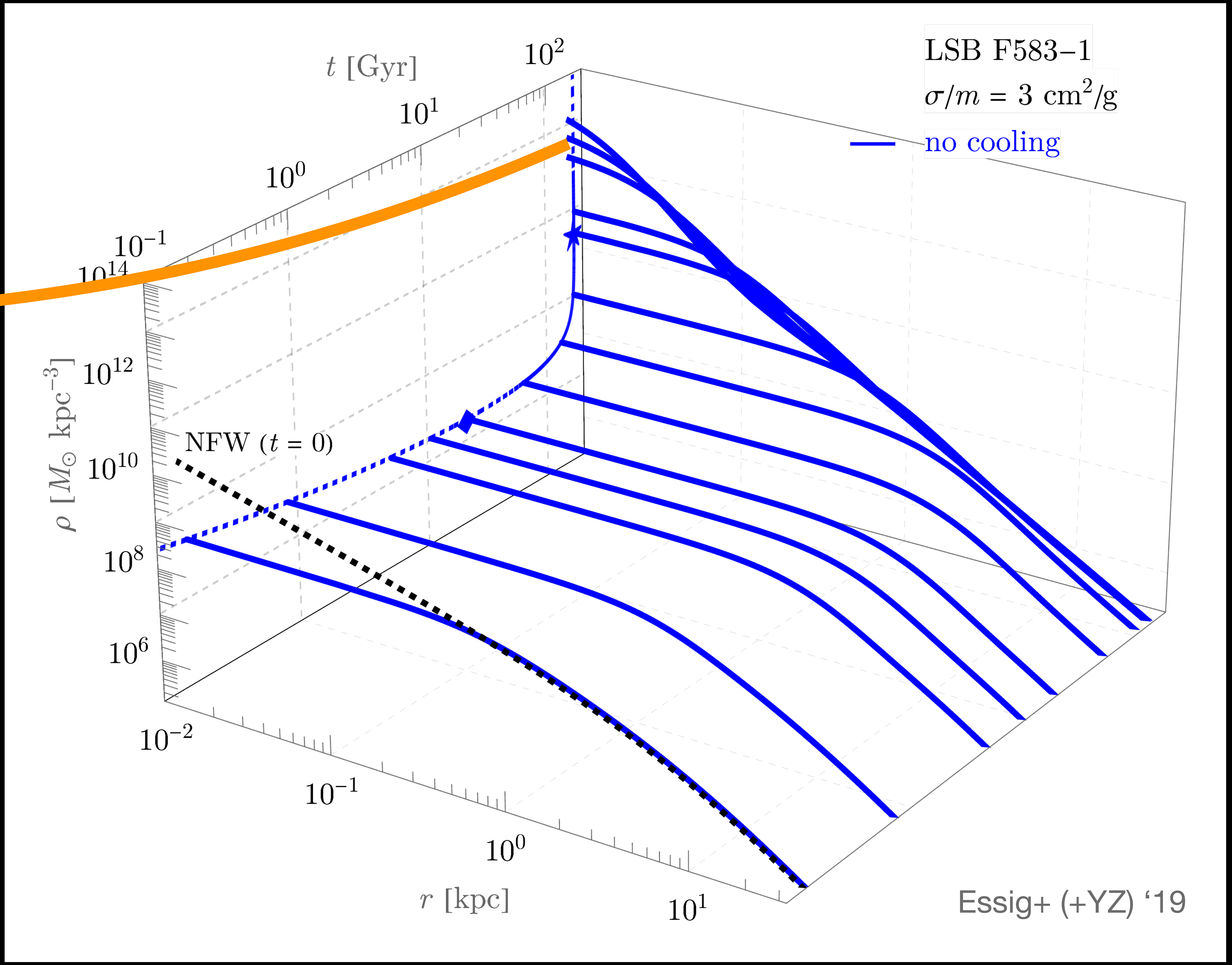
Density evolution



The core-collapsed profile is ultra-dense

Density evolution

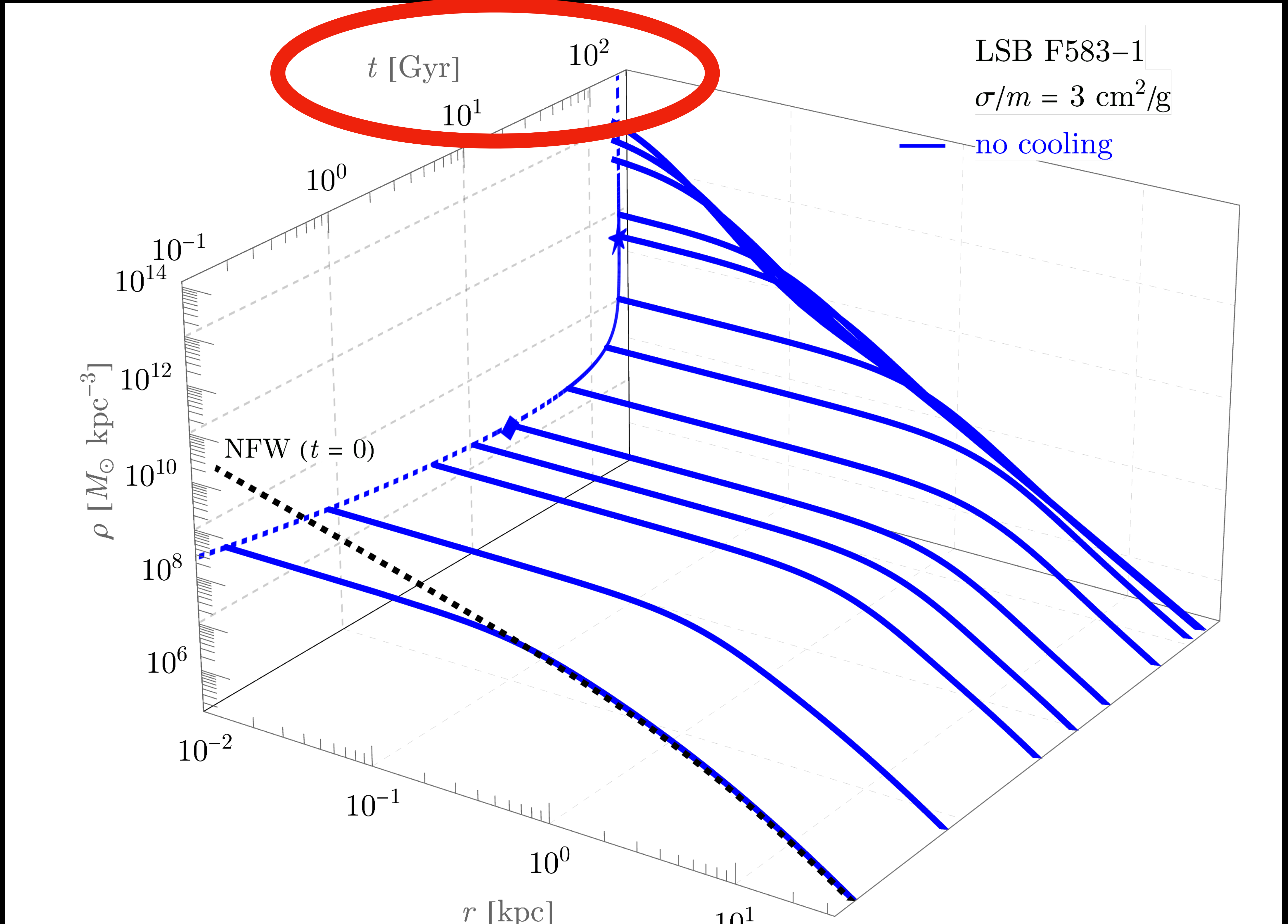




log-slope steeper than -2, extending to $r \sim r_s$

However, the core-collapse time is too long…

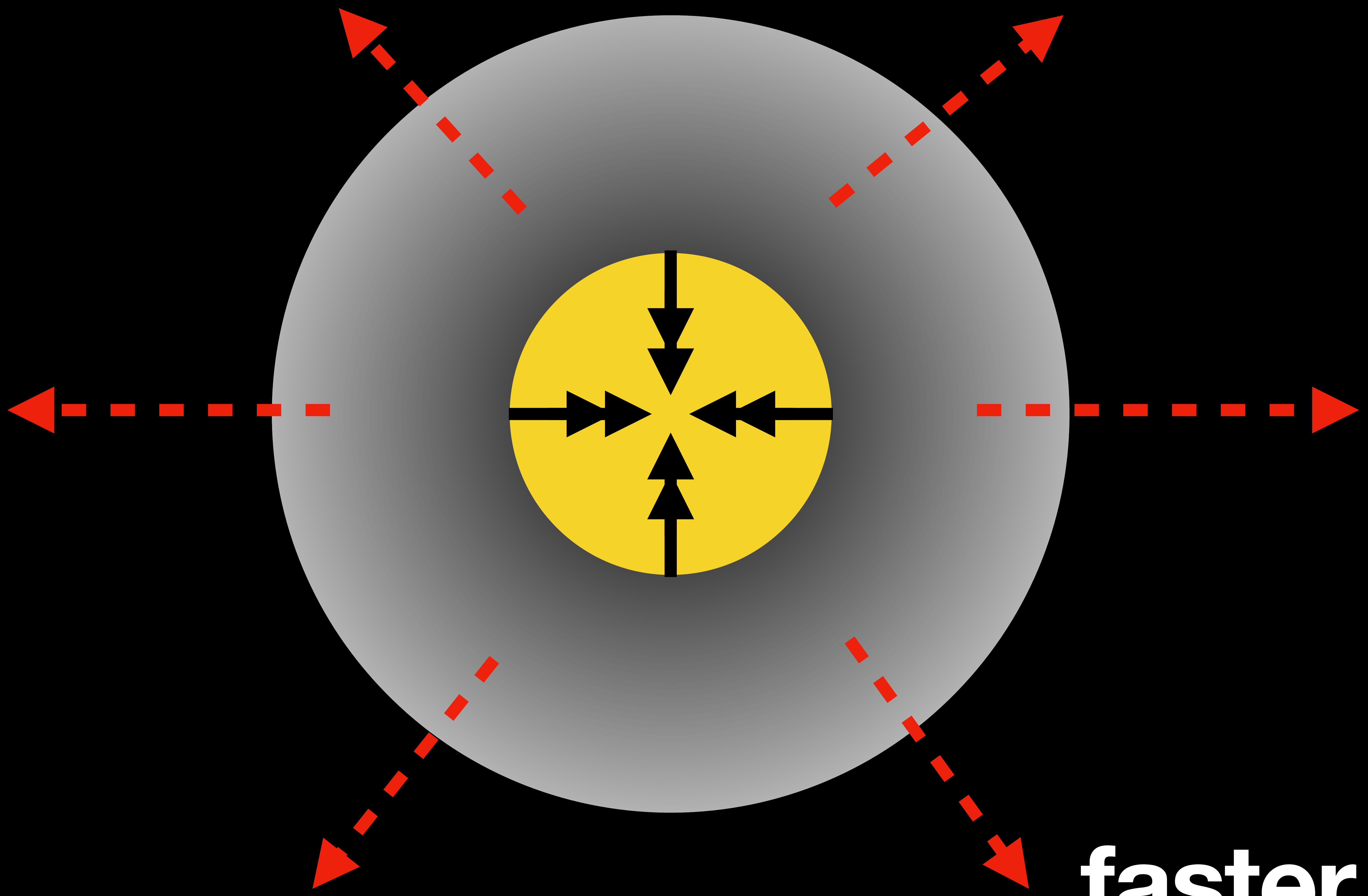
For $\mathcal{O}(1)$ cm²/g,*
collapse time ~ 100 Gyr



Essig+ (+YZ) '19

* given various constraints on SIDM

If more heat goes out



faster collapse

How to transfer more heat out?

Changing the interaction.

- Larger cross section ~100 cm²/g ⇒ Velocity-dependent SIDM

  Rutherford-like, resonant….

- Dissipative self-interaction

Essig+ (+YZ) ’19, Huo, Yu & YZ ’20…

Changing the halo.

- Larger concentration

  Pollack ’15, Essig+ (+YZ) ’19…

- Central baryon component

  Yang, Yu & YZ ’23, Yang+ ’23…

- Tidal stripping

  Nishikawa+ ’19…

- Mass segregation

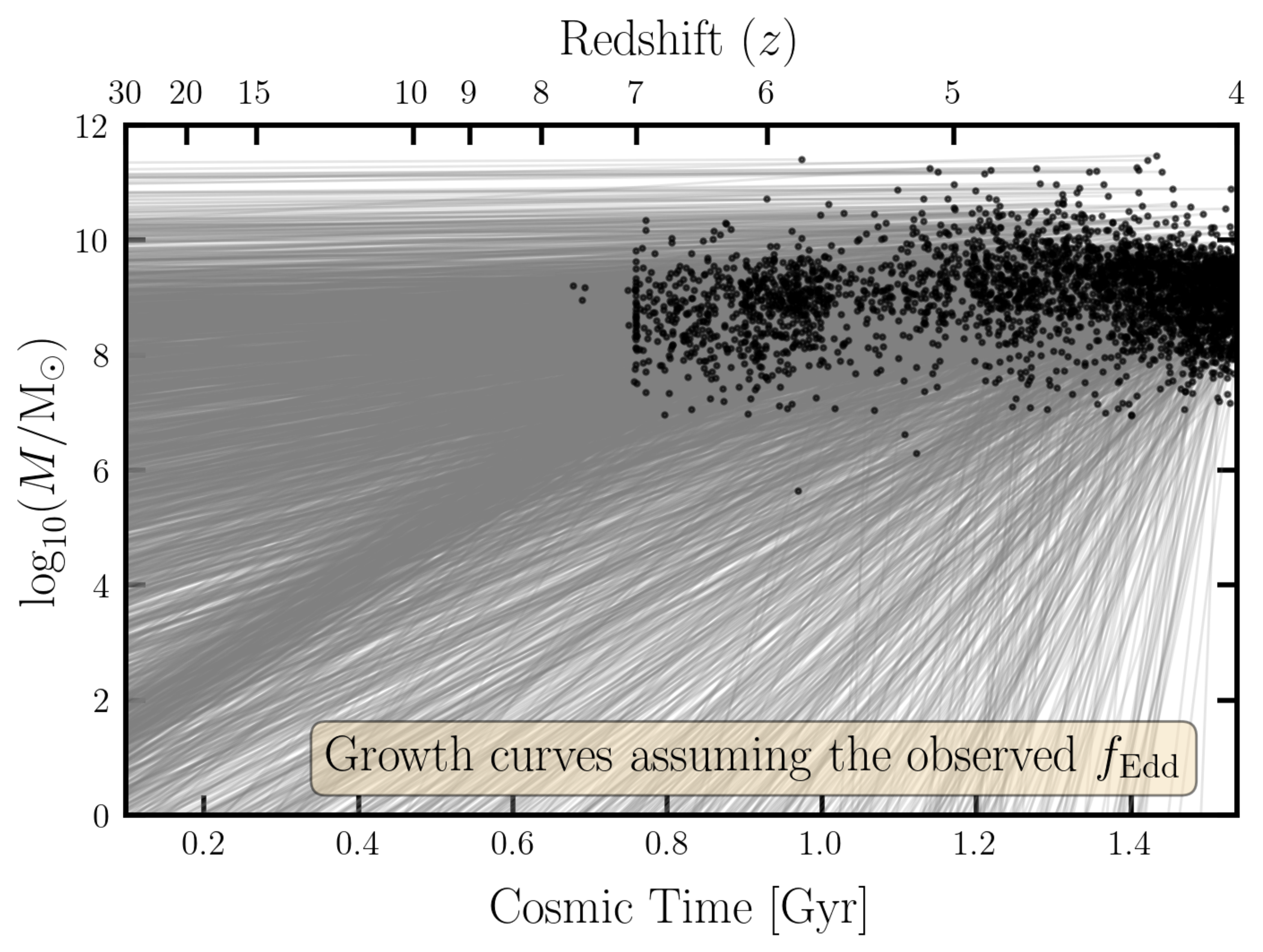
  Yang+ ’25, Patil+ ‘25

Seeding high-z supermassive black holes

Beyond stellar BH + Eddington accretion

- We need either:
  1. Heavier seed black holes.
  2. Super-Eddington accretion.

See review by Inayoshi ’19, ‘25



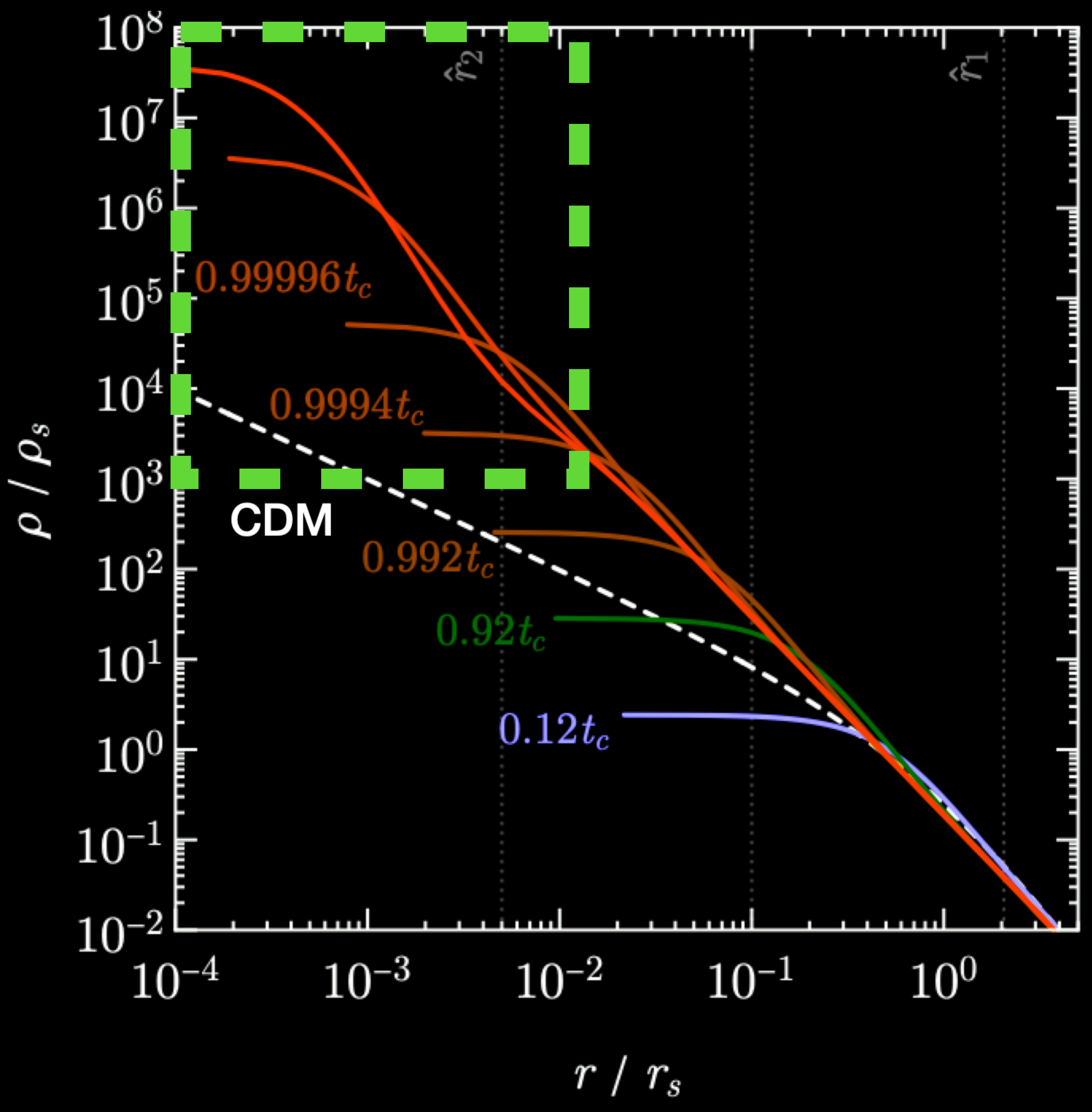
Heavier seed solution

Pollack, Spergel & Steinhardt ’15, Essig+ (+YZ) ’19, Feng, Yu & YZ ’21, Zhang+ ’25, Nadler+ ’25, Jiang+ ’25

- Previous works proposed that SMBHs are formed from the **ultra-dense cores** of collapsed SIDM halos.
- However, there are doubts on the fraction $M_{\rm BH}/M_{\rm core}$.
- More detailed simulations are needed.

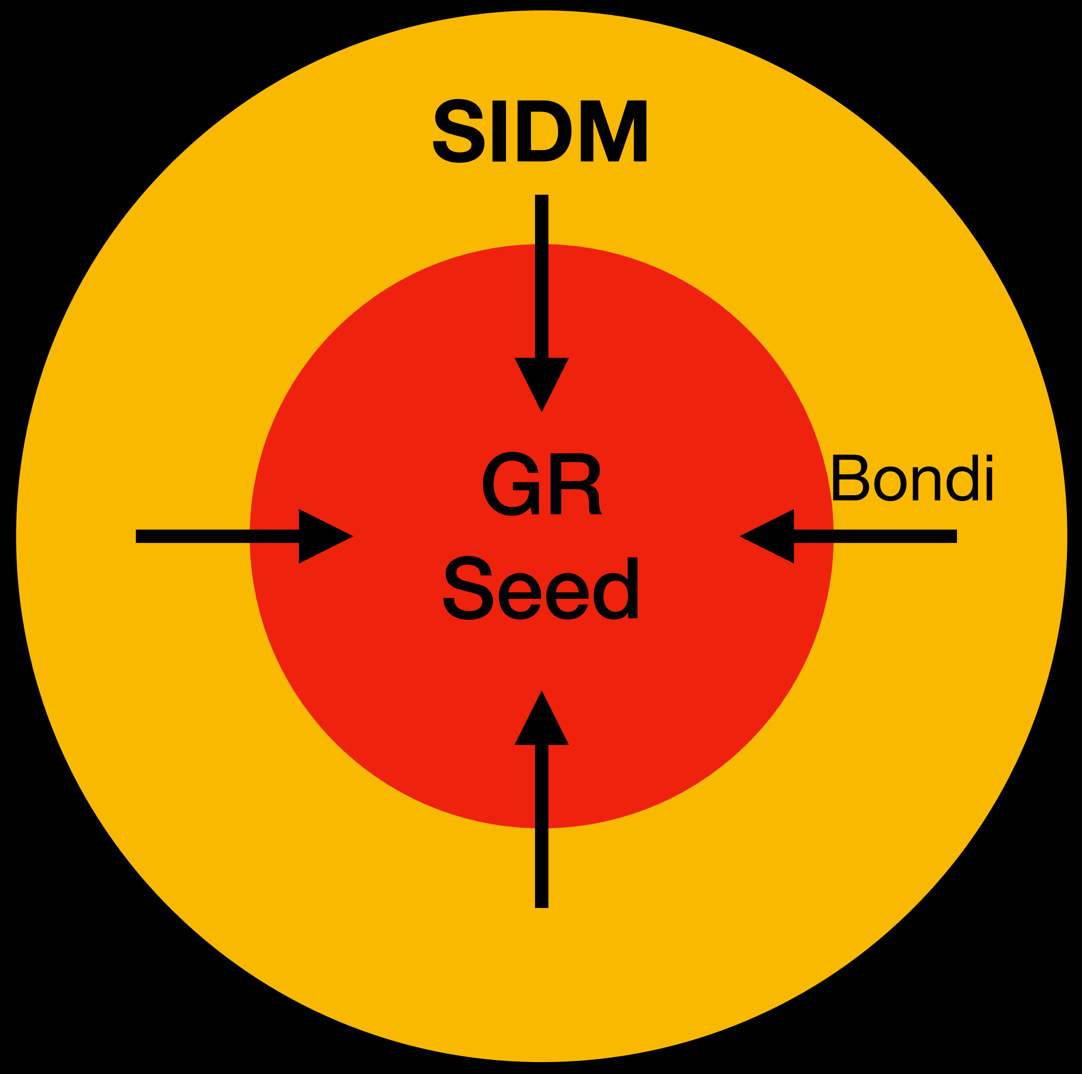
Balberg & Shapiro ‘00
Ralegankar+ ’24,
Gad-Naser+ ‘24

$M_{\rm core}/M_{\rm halo} = 10^{-3} - 10^{-2}$



Super-Eddington accretion solution

- In this work, we focus on solution 2:
  - Bondi accretion of SIDM, $\dot{M}_{\mathrm{Bon}} \propto M_{\mathrm{BH}}^2$.
  - In contrast, $\dot{M}_{\mathrm{Edd}} \propto M_{\mathrm{BH}}$.
- Bondi accretion of SIDM offers a natural mechanism for super-Eddington accretion.



Challenges

- How do we obtain a reservoir of SIDM to fuel the Bondi accretion?
- Bondi accretion is slower than Eddington accretion when $M_{\rm BH}$ is small. How do we obtain the initial kick?

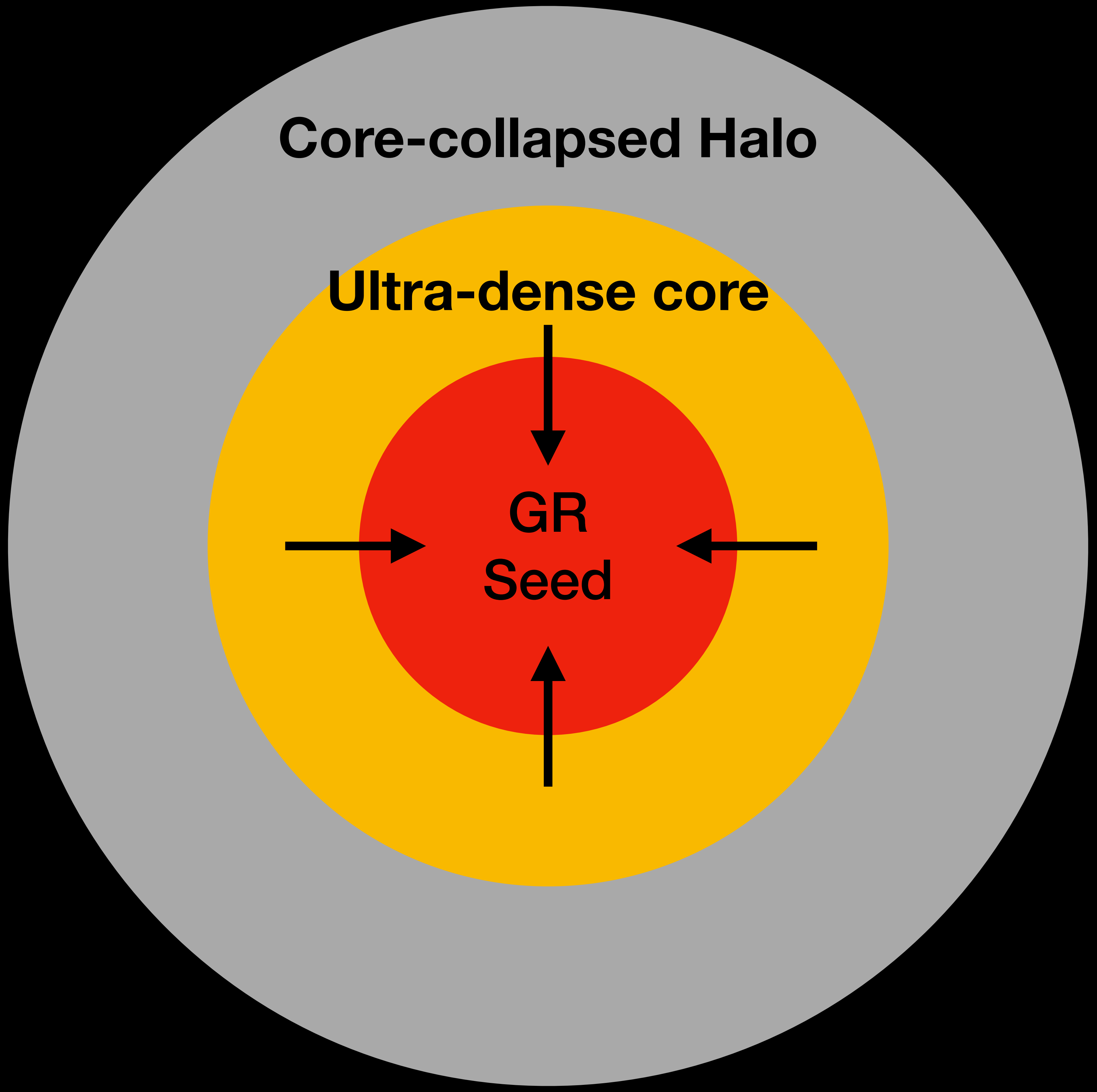
Solving Challenge 1

- Seed the BH at collapsed SIDM cores.

  - $M_{\rm core}/M_{\rm halo} = 10^{-3} - 10^{-2}$

    $\Downarrow$

    The core supplies sufficient SIDM for the BH to grow.

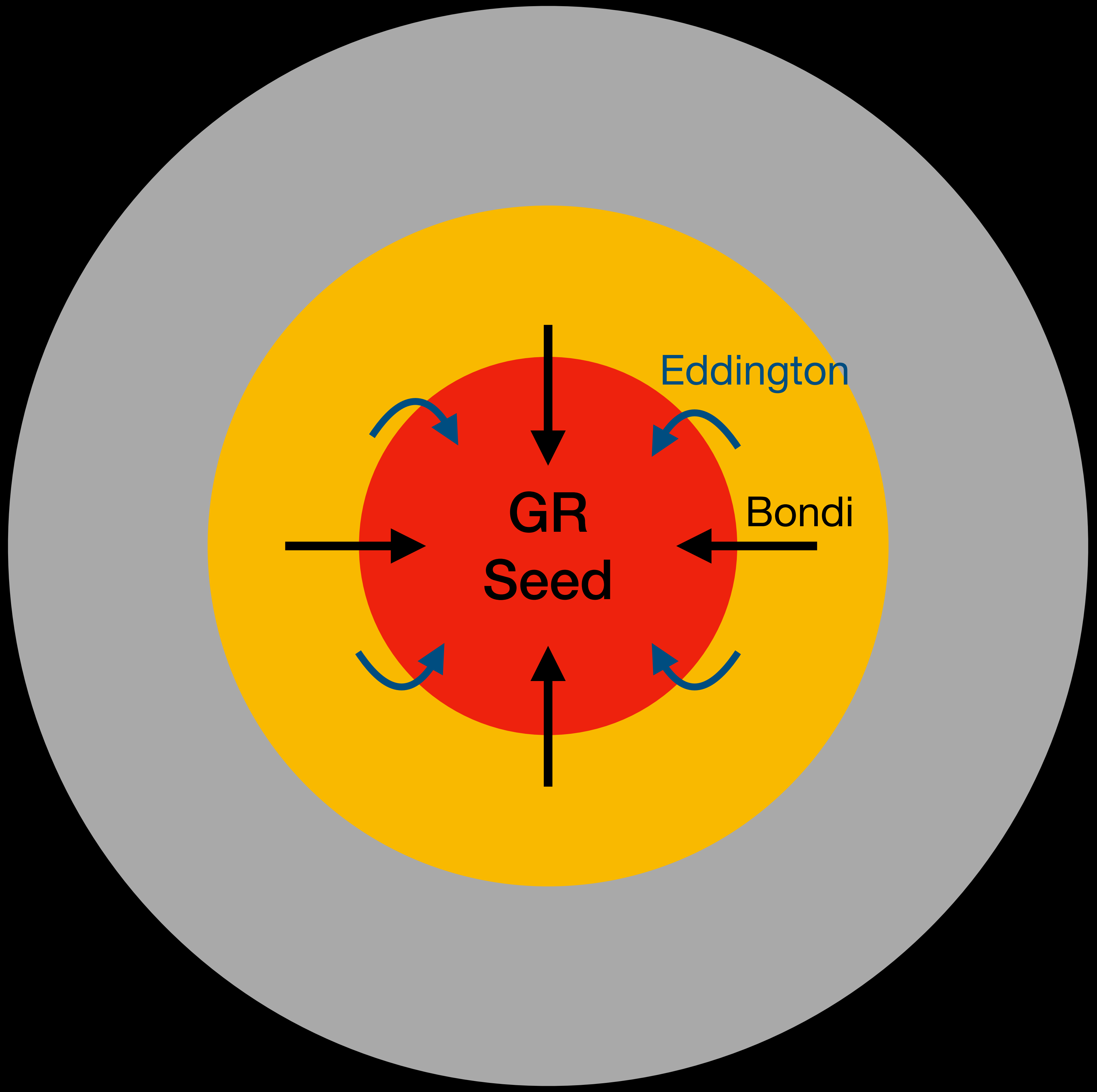


Solving Challenge 2

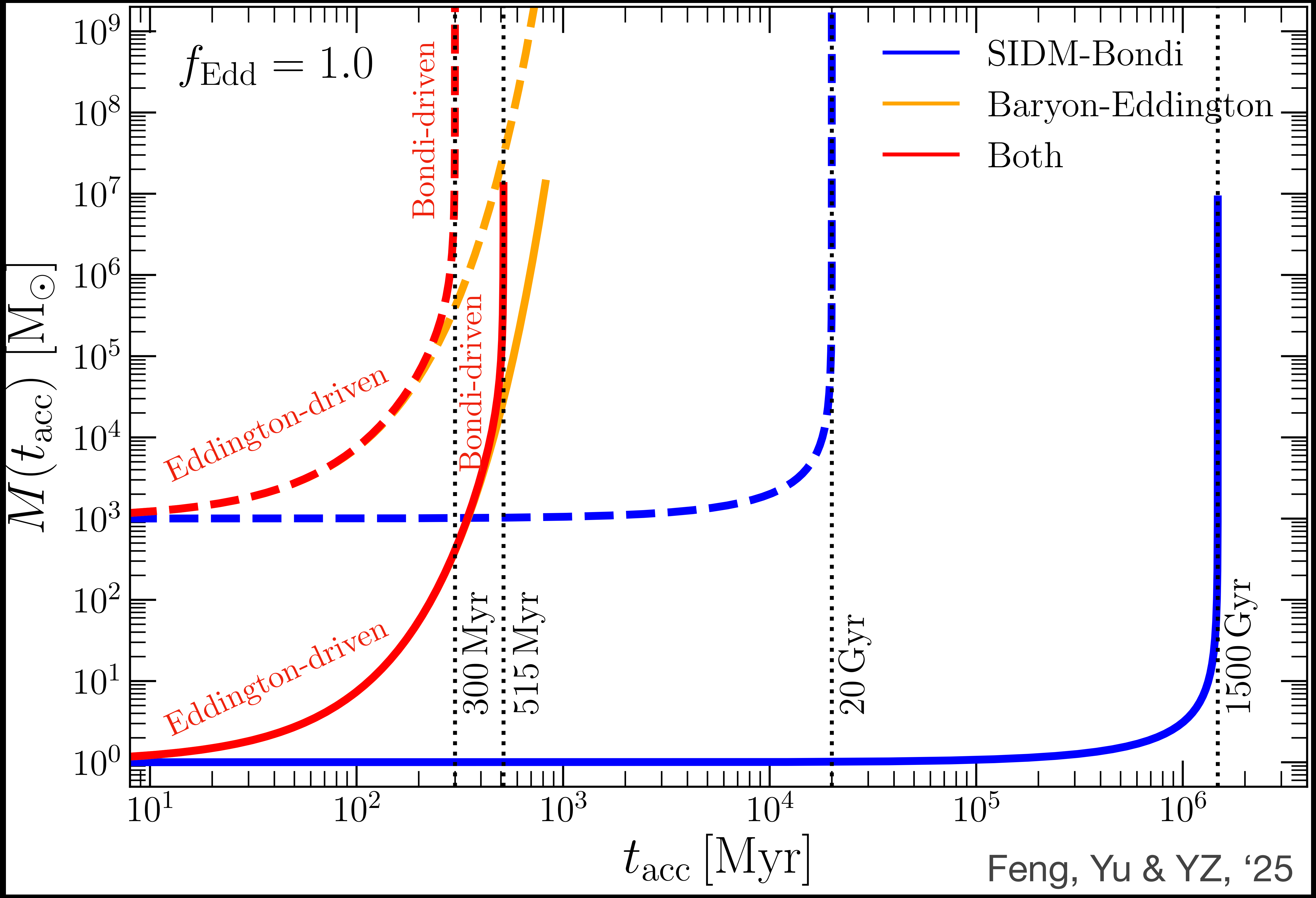
- Eddington-aided growth
  - The seed BH experiences both Bondi accretion of SIDM + Eddington accretion of normal matter.

    $\Downarrow$

    Early growth is Eddington-driven; later growth is Bondi-driven.



The new growth curve



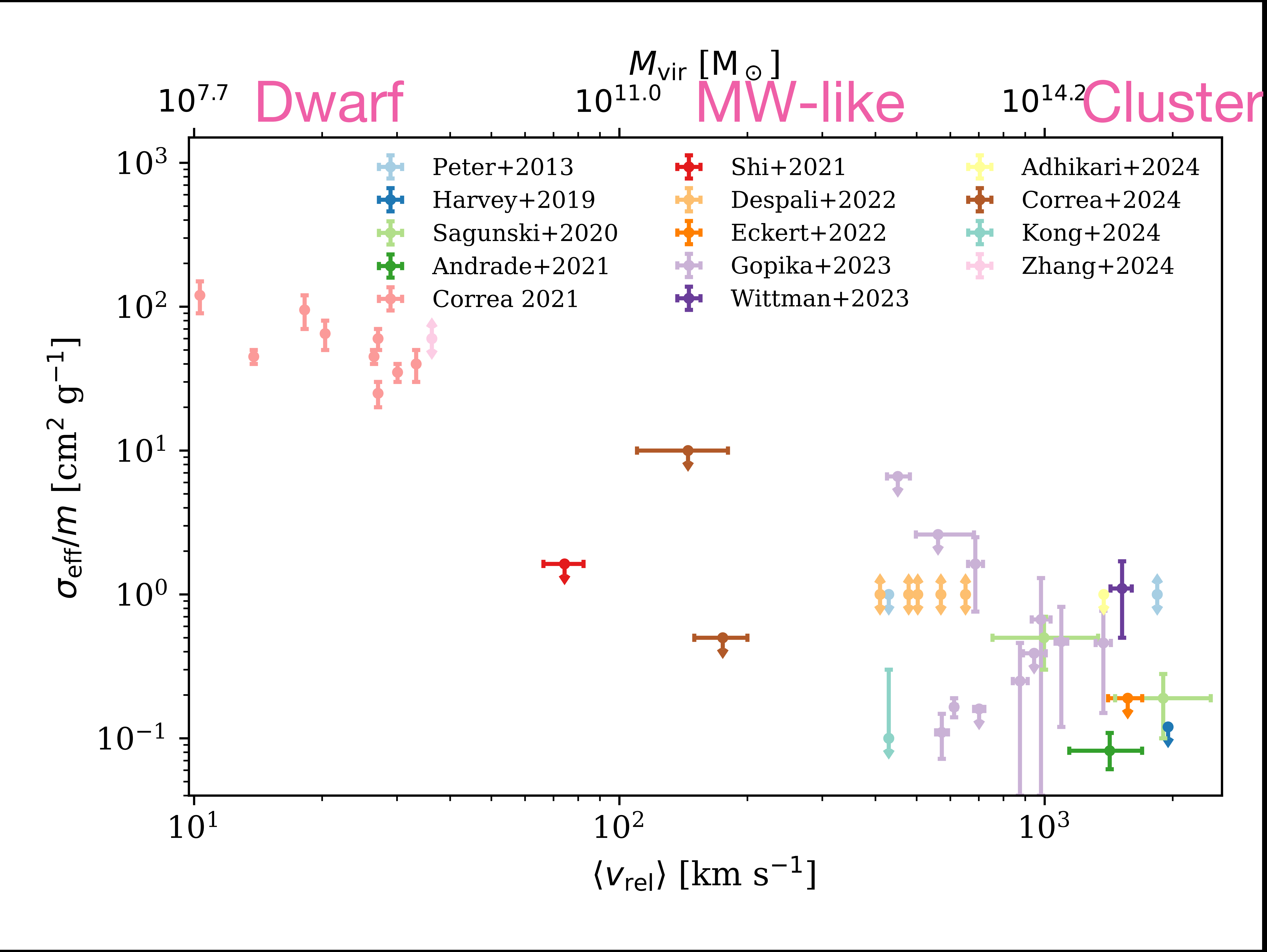
Summary

- The ultra-dense structures pose a new challenge to the CDM paradigm.
- SIDM provides a natural explanation to the ultra-dense structures through core-collapsed halos.
- SIDM may also explain the high-redshift SMBHs through Eddington-aided SIDM Bondi accretion.

Backup

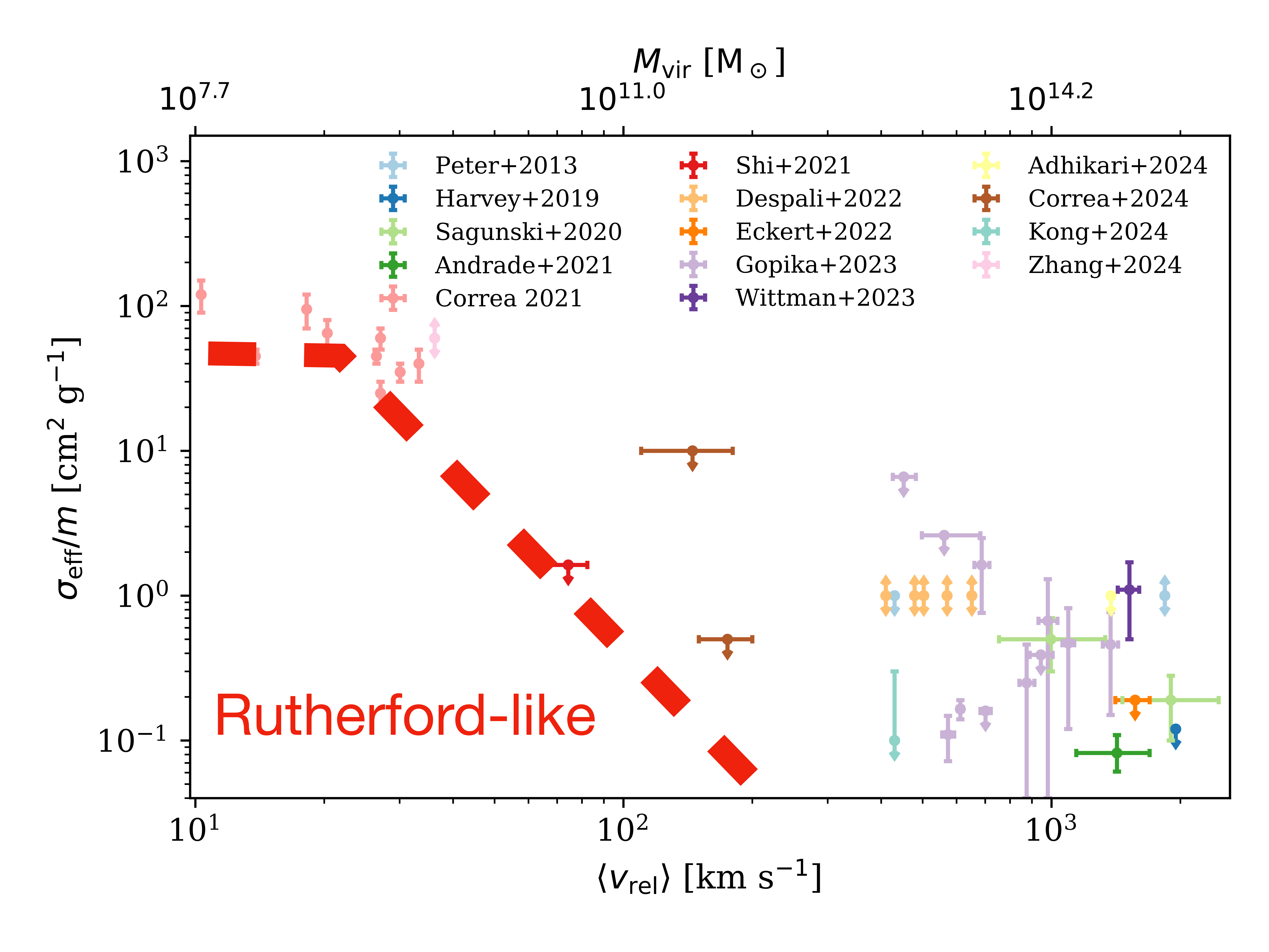
Constraints on dark matter self-interaction

Lensing,
Stellar kinematics,
Halo morphology
……



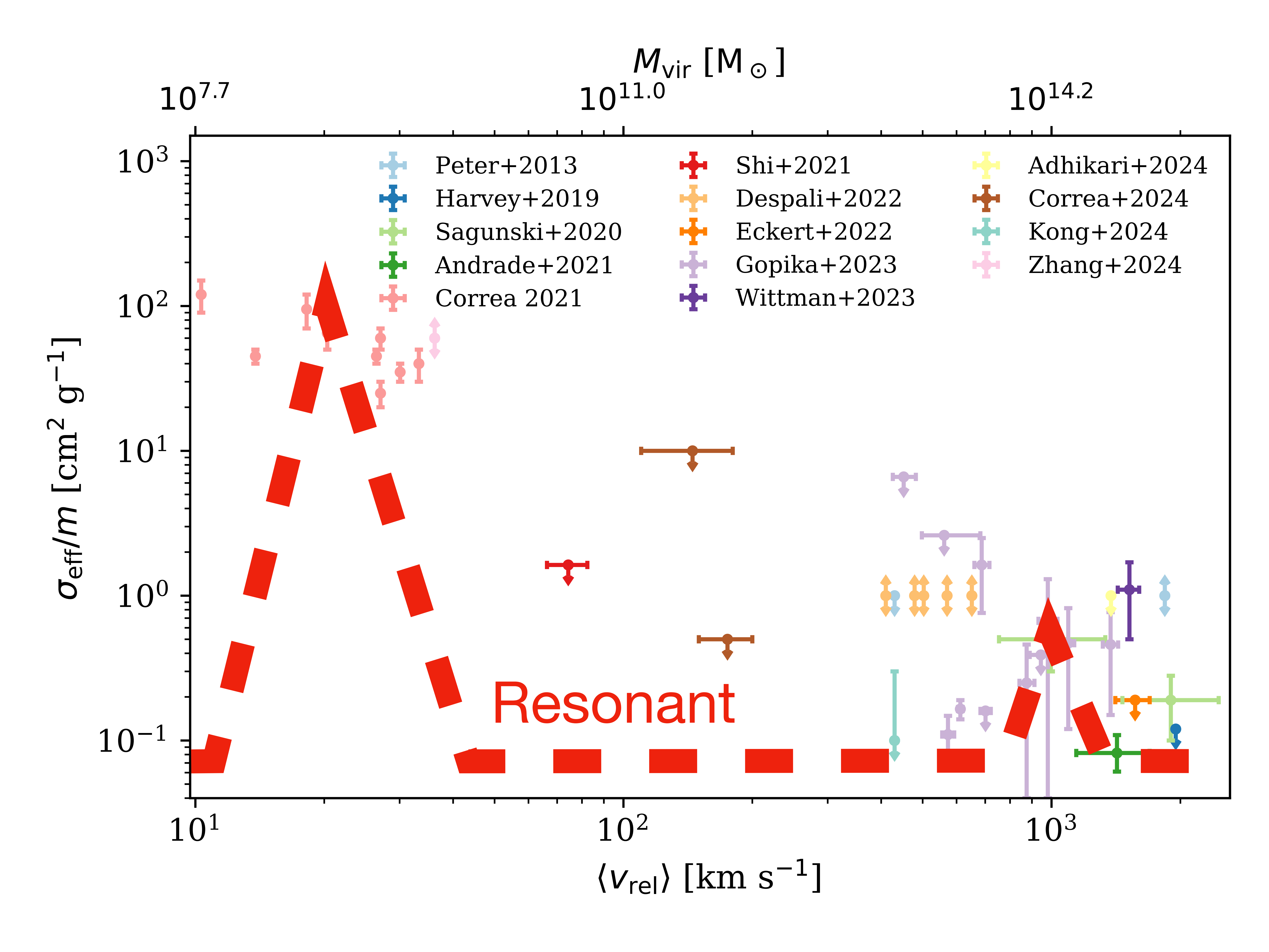
Credit: Moritz S. Fischer

Elastic SIDM model



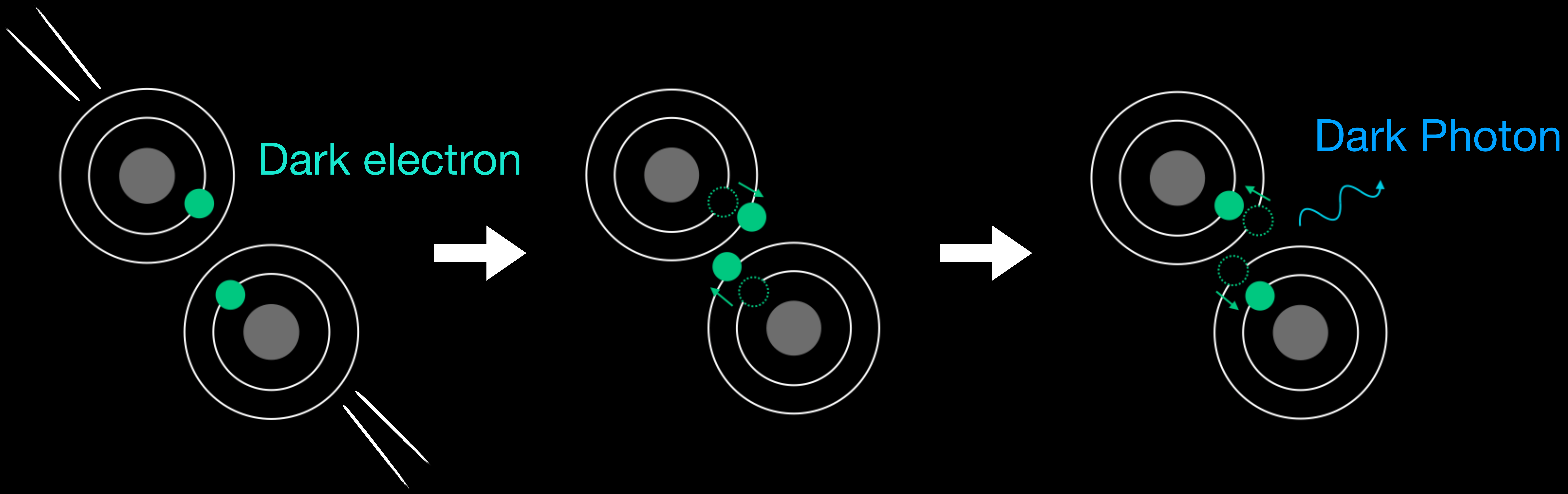
Credit: Moritz S. Fischer

Elastic SIDM model



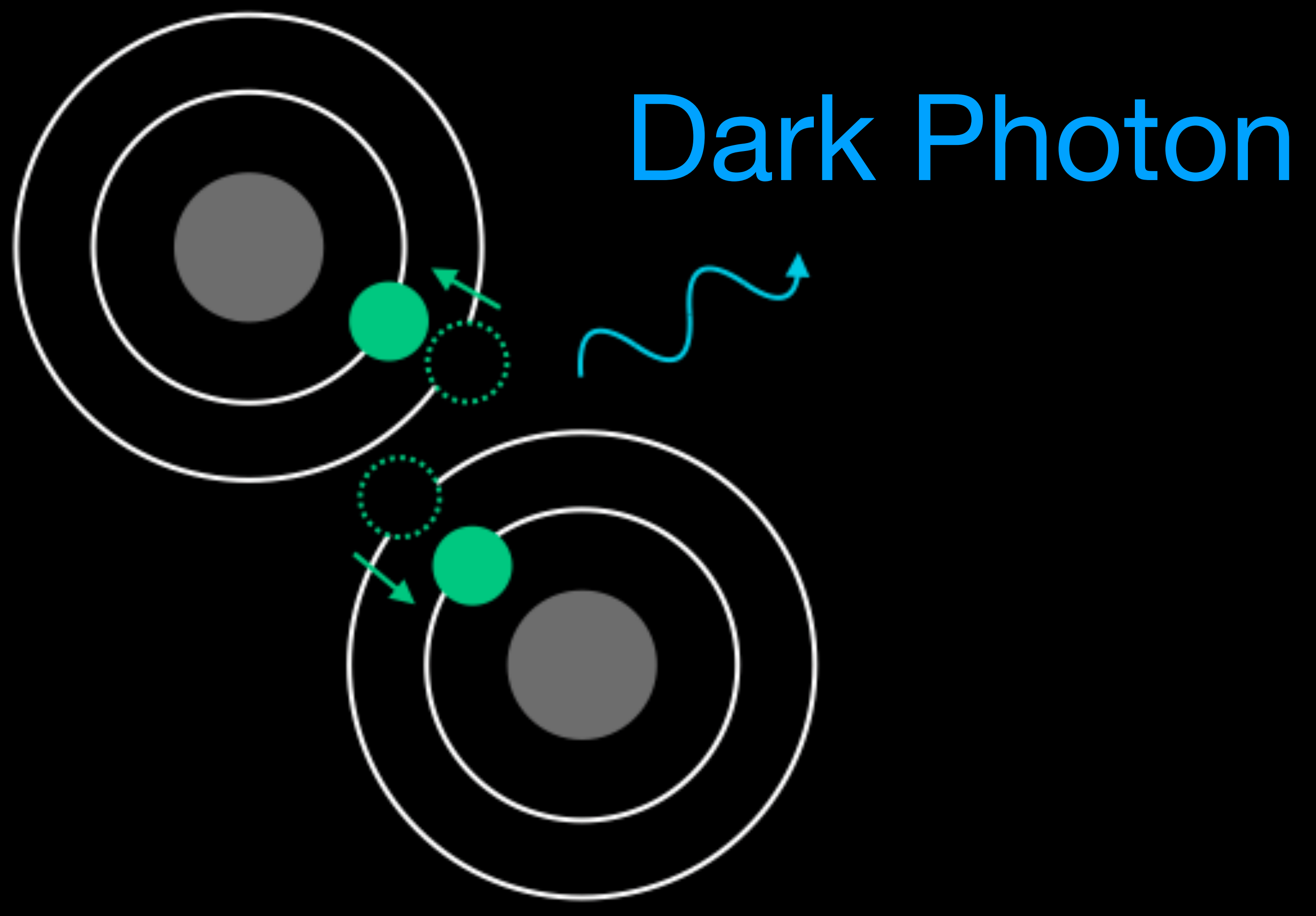
Credit: Moritz S. Fischer

Dissipative SIDM



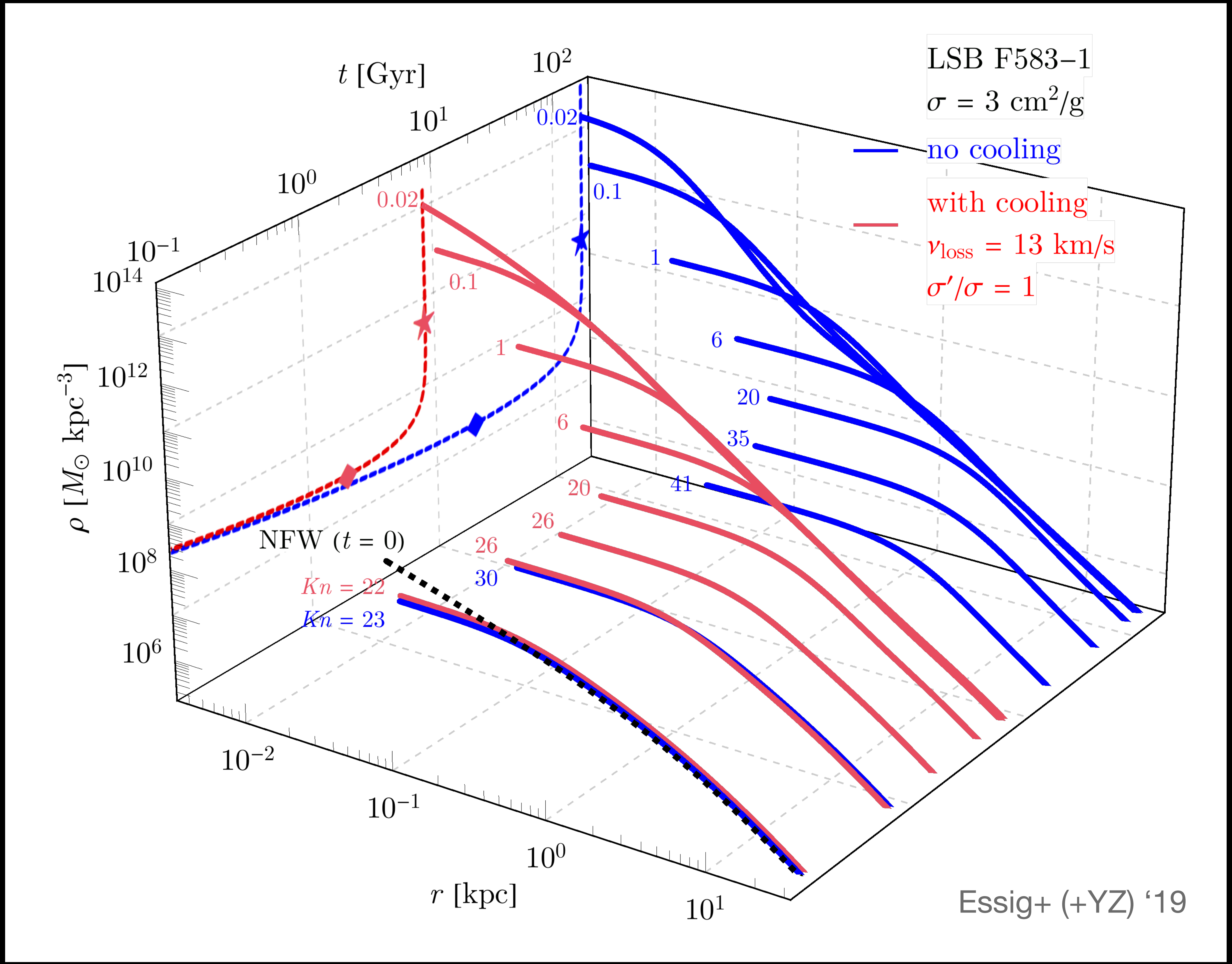
e.g., Atomic Dark Matter

Atomic dark matter

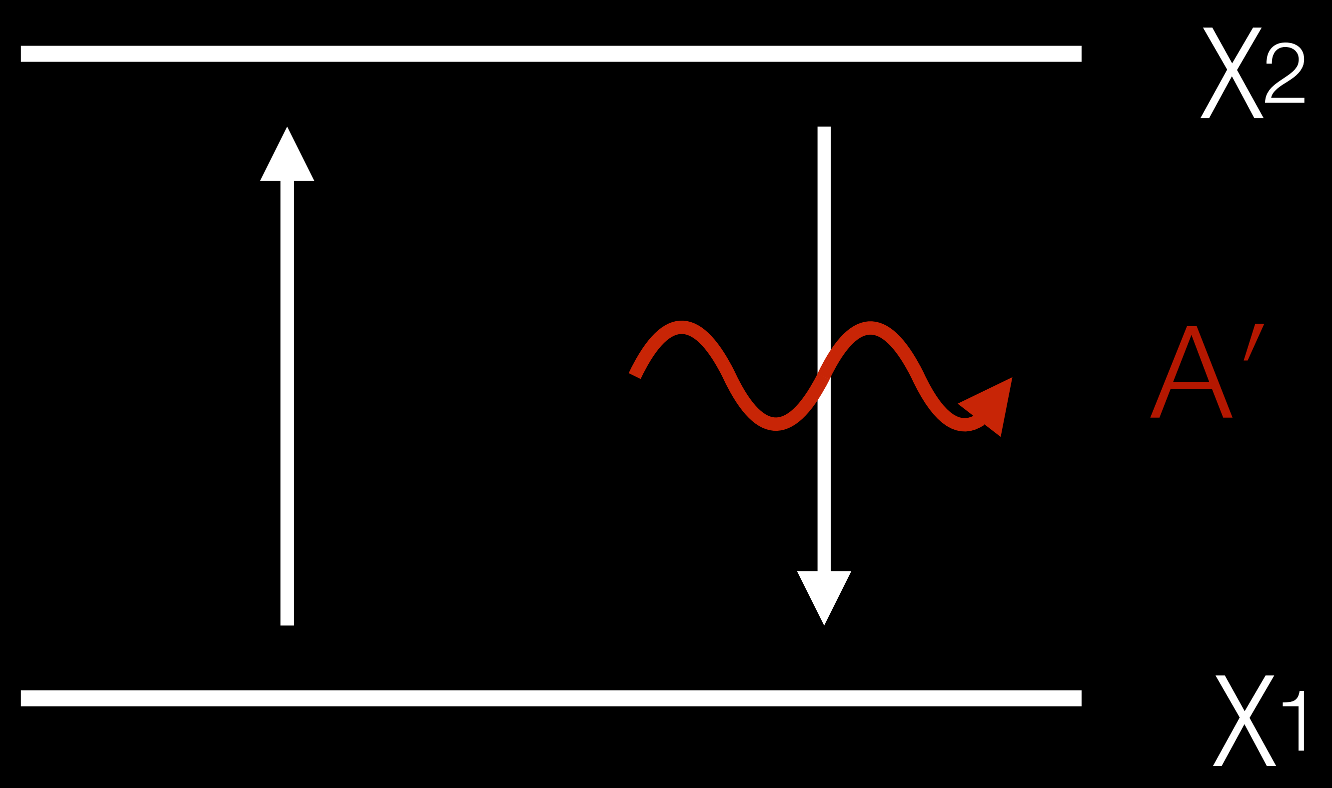


Accelerated up to ~100-1000

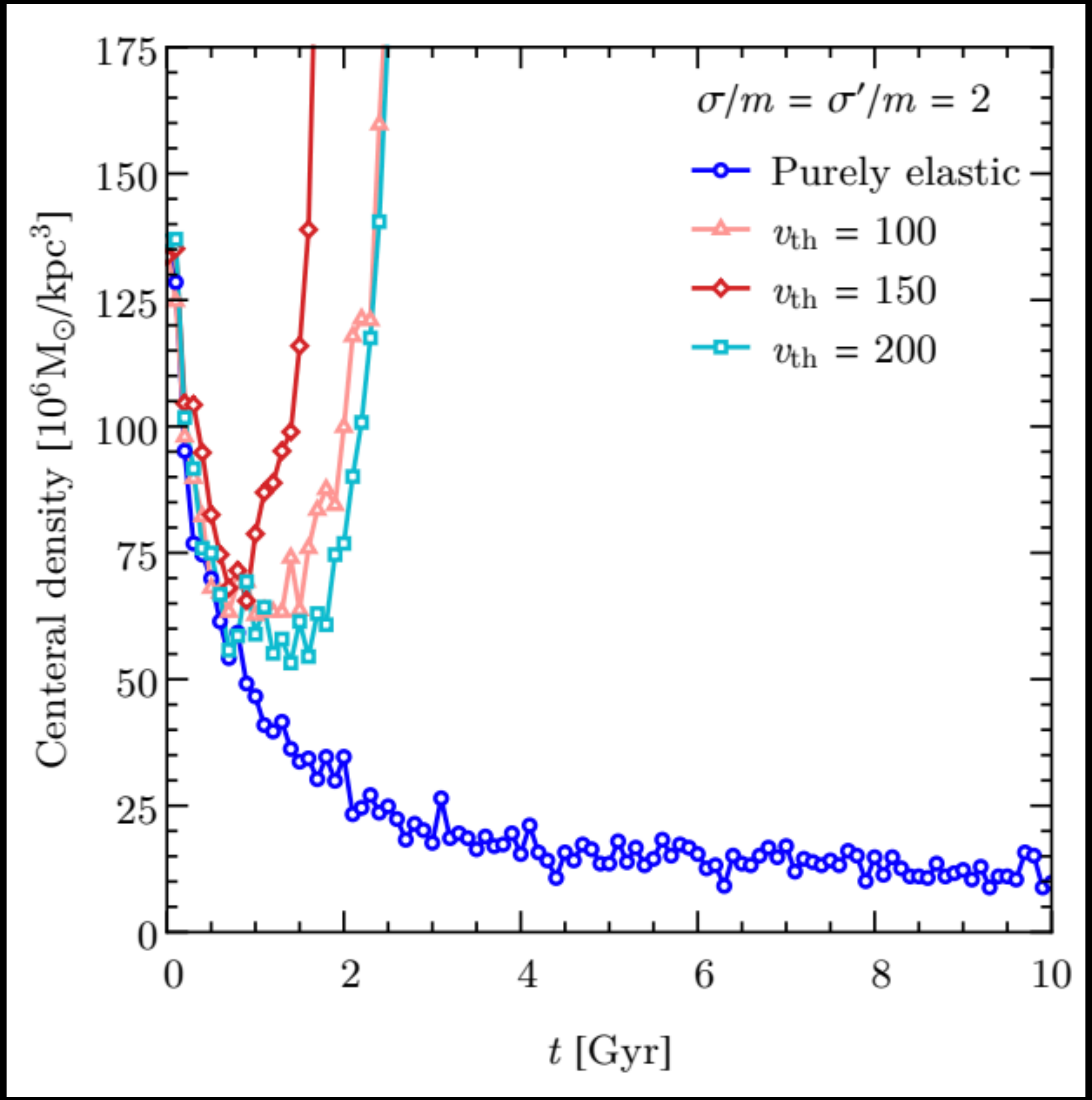
Dissipative SIDM Elastic SIDM



Inelastic dark matter



Accelerated up to ~100-1000



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