Constraining Dark Matter Self-Interactions from Weak Lensing

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w/ S. Adhikari, A. Banerjee, B. Jain & T.-H. Shin [arXiv: 2401.05788]

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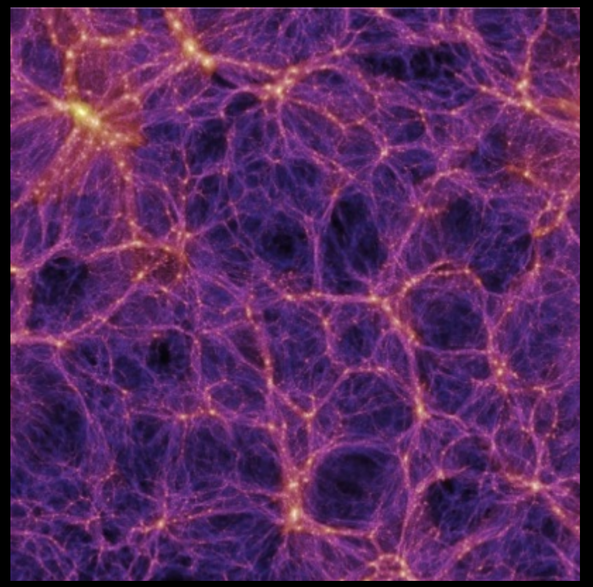
Outline

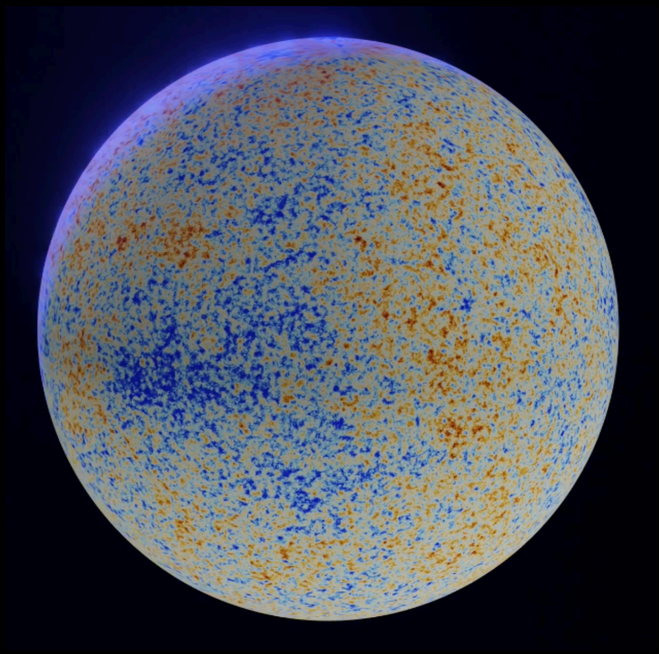
- Introduction
  - Dark matter self-interactions
  - Effects on halos
- Using ACT x DES weak lensing measurement to constrain SIDM
- Summary

Evidence for dark matter

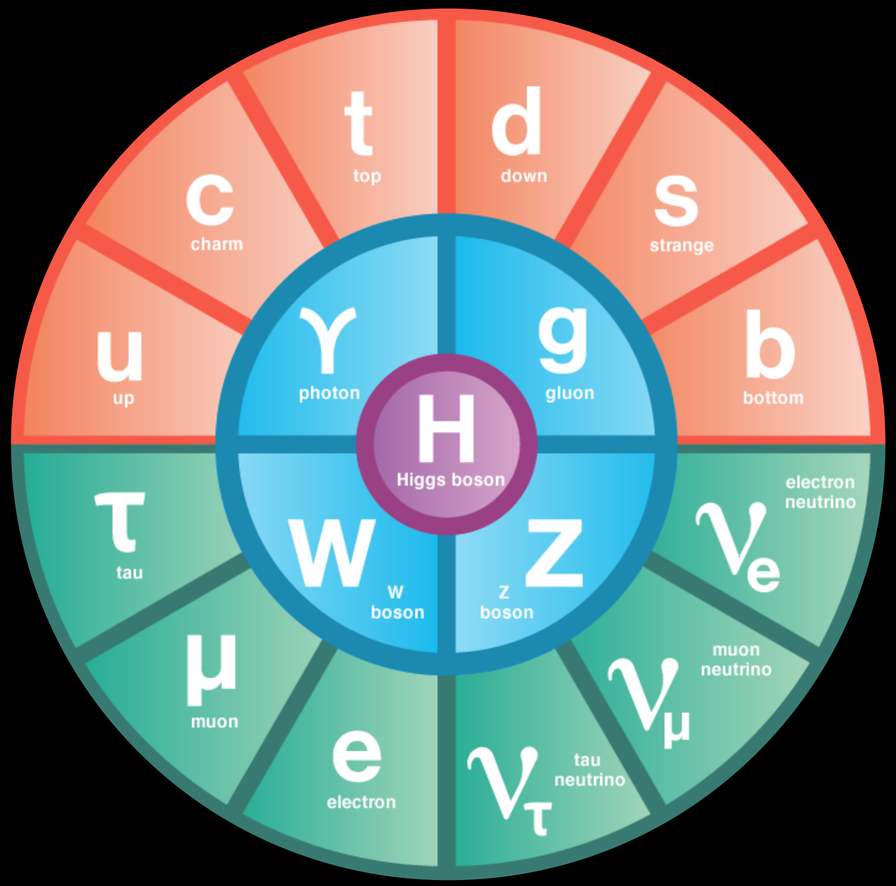
Bullet Cluster



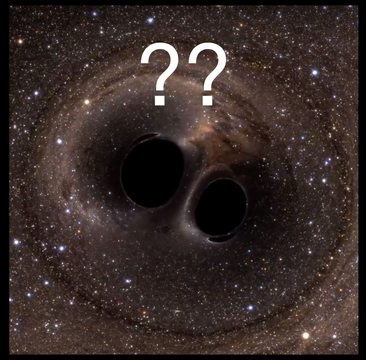
Large-Scale Structure

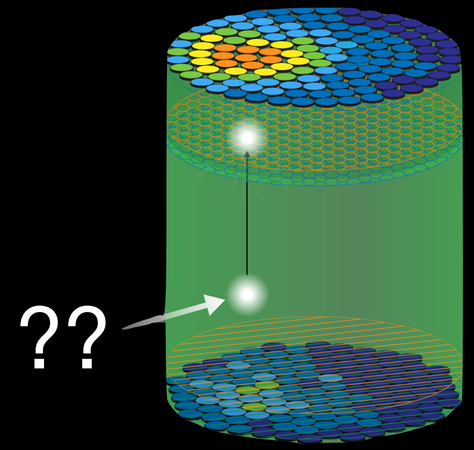


Cosmic Microwave Background



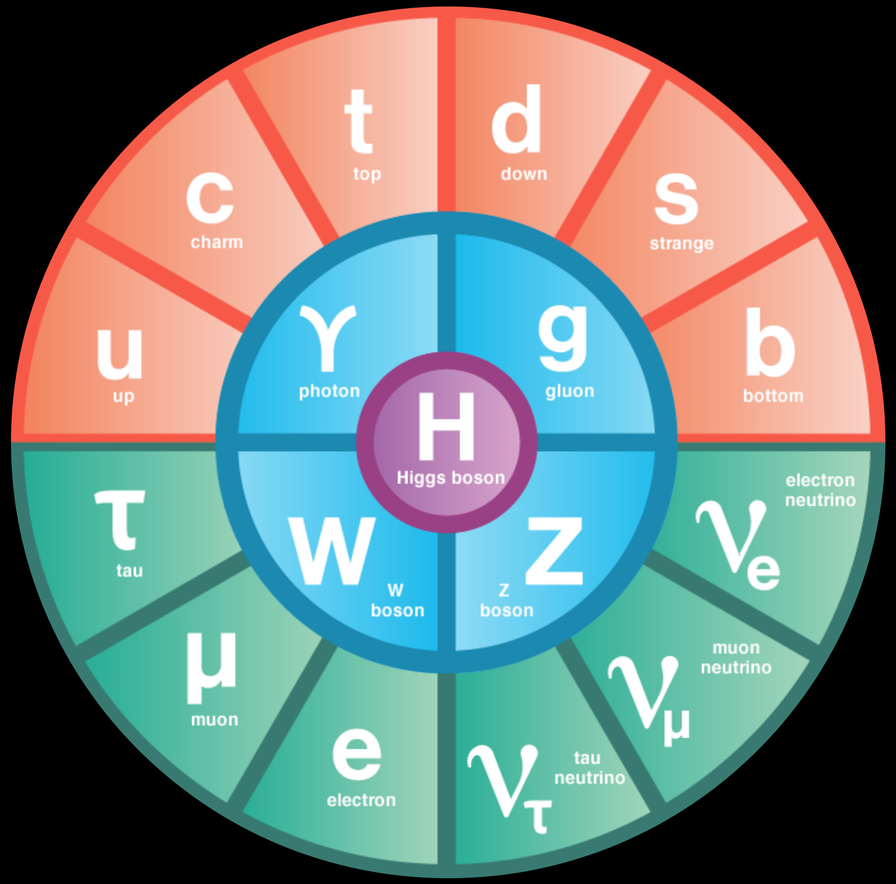
Ordinary matter



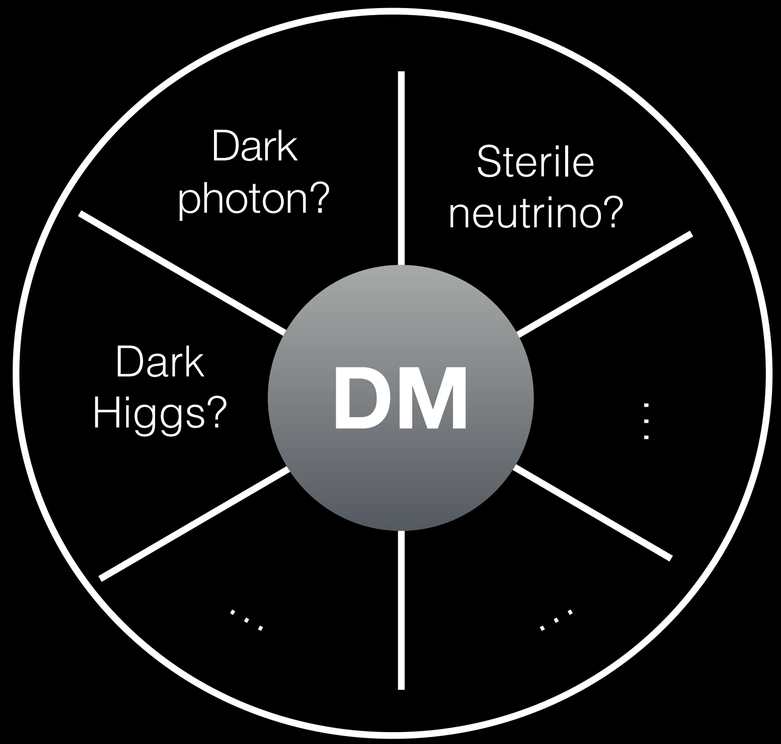


What is dark matter?

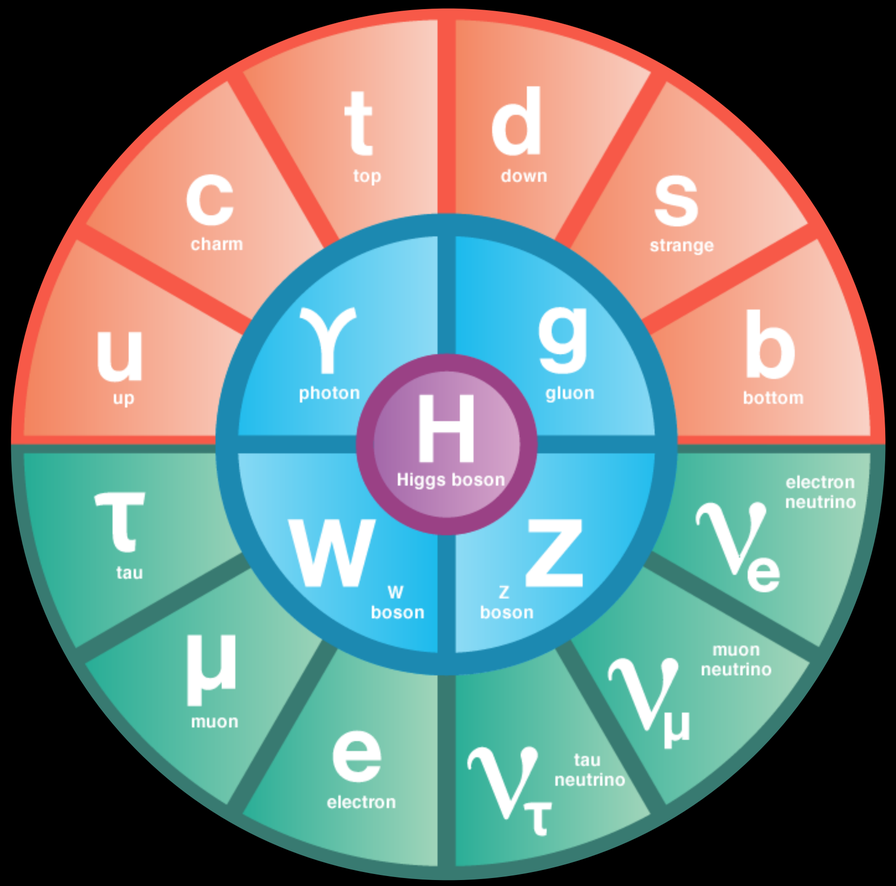
Maybe dark matter is not alone…



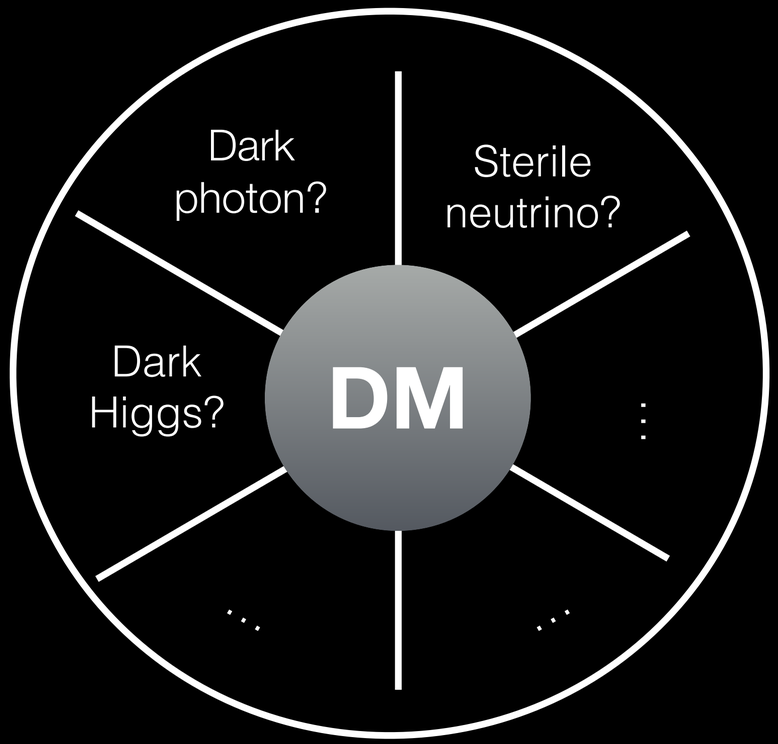
Ordinary matter



Dark sector



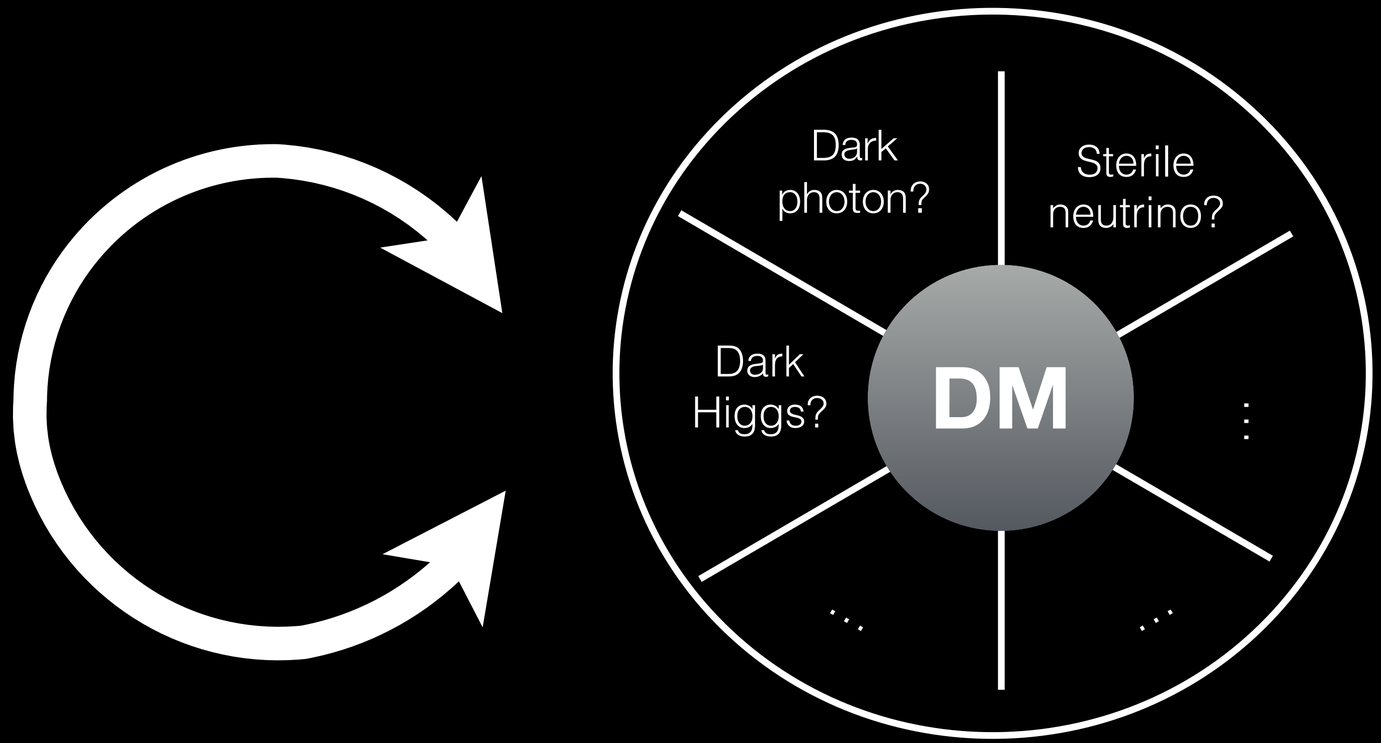
Portal?



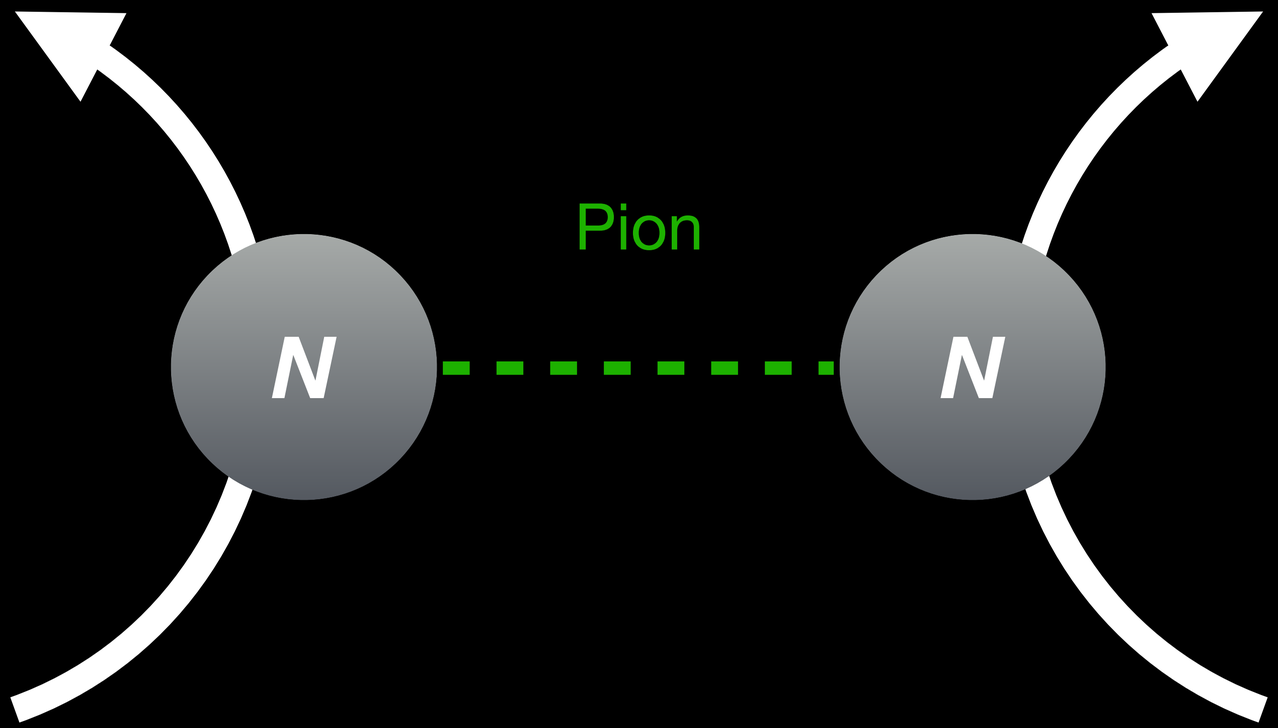
Ordinary matter

Dark sector

Self-interactions?



Dark sector

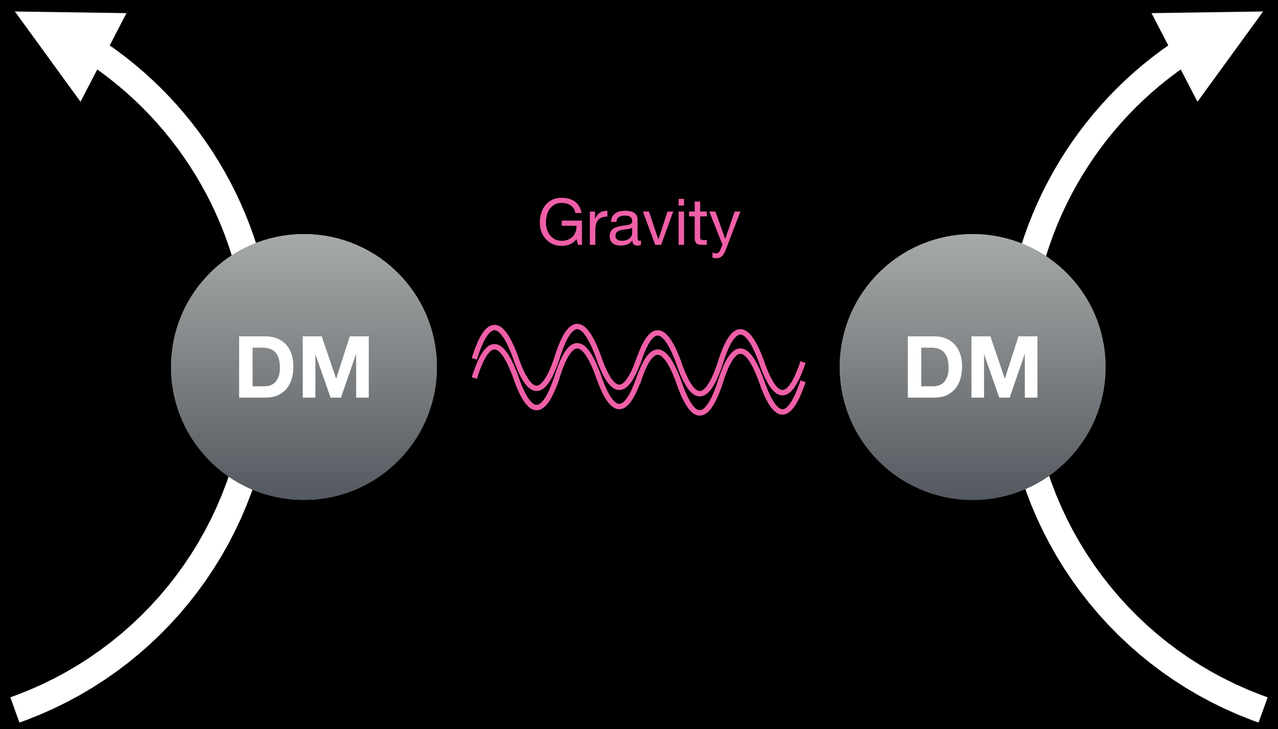


Nucleon-nucleon self-interaction

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

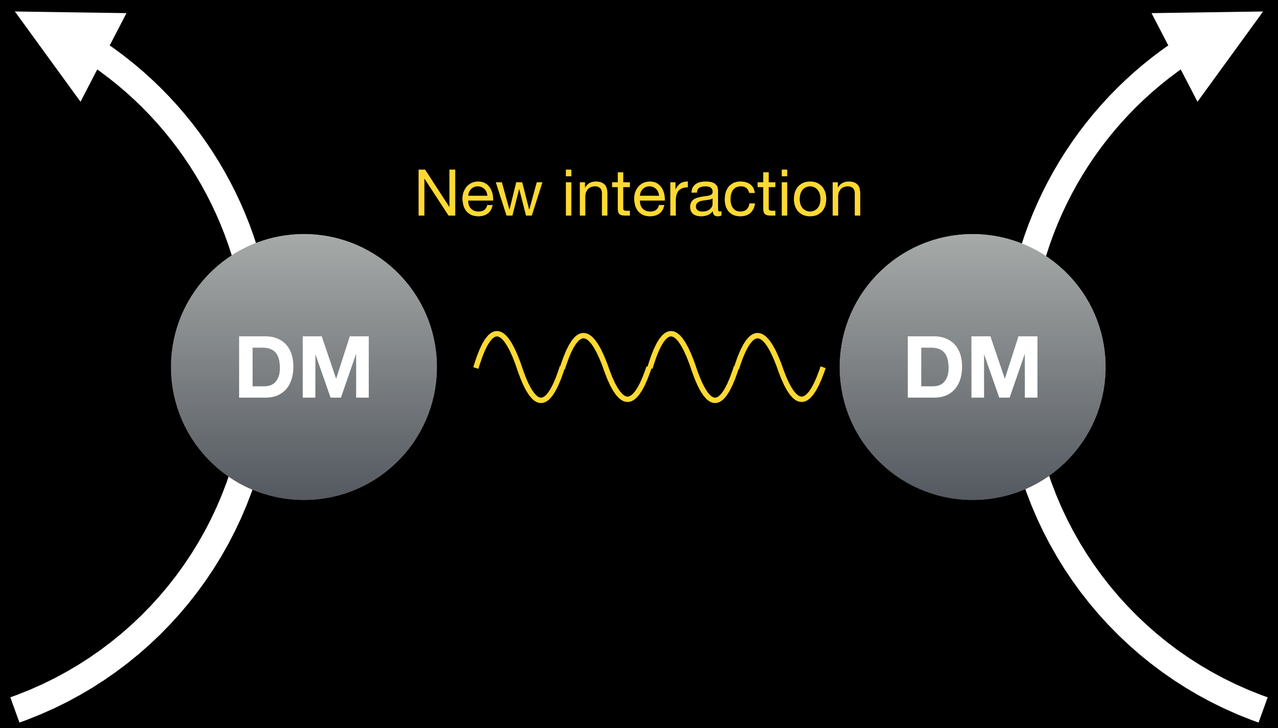
Nuclear Data Sheets '11

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



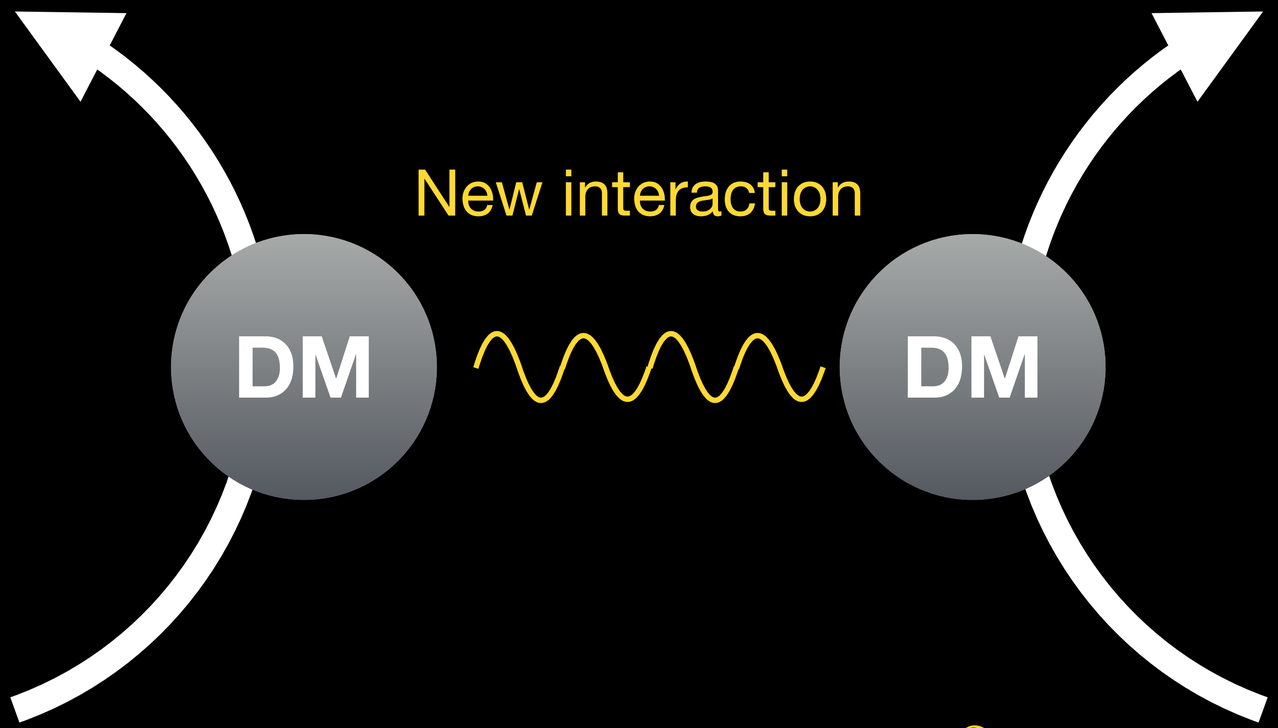
Cold Collisionless Dark Matter (CDM)

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

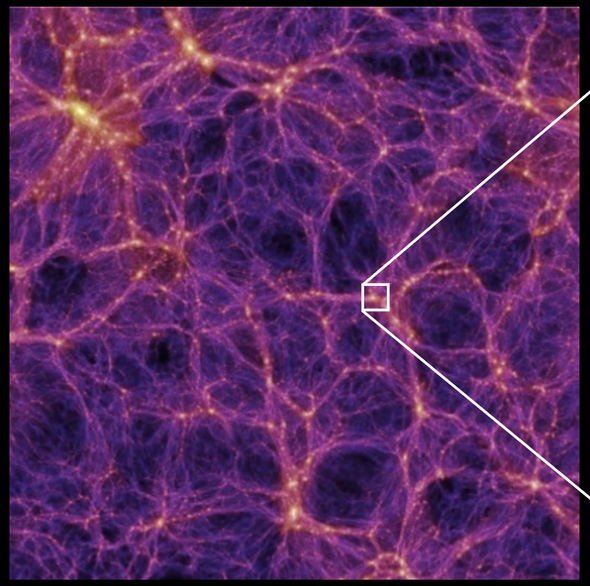


$$\sigma_{\rm T}/m_{\rm DM} \sim 1\,{\rm cm}^2/{\rm g}$$

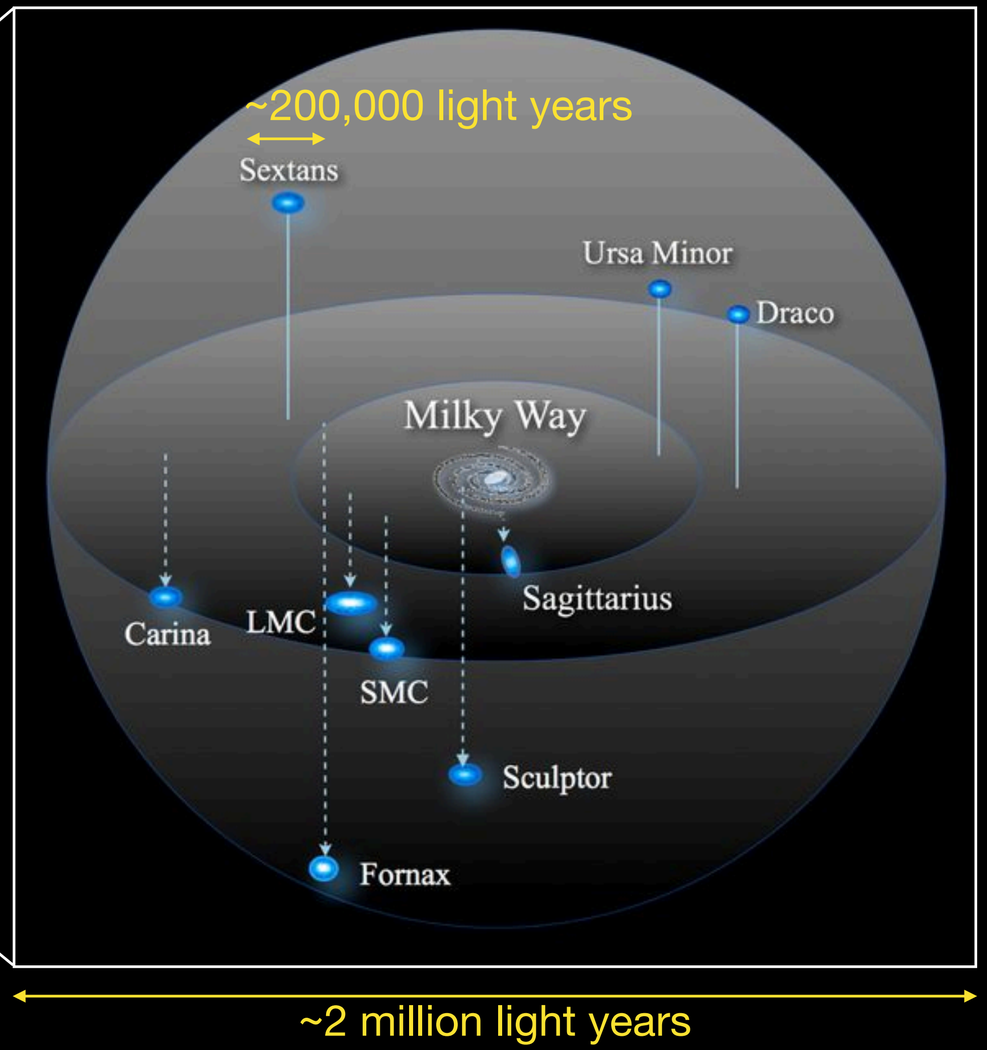
$$t_{\rm rlx} = \frac{1}{\rho(\sigma/m)v} \sim 10\,{\rm Gyr}\left(\frac{0.4\,{\rm GeV/cm}^3}{\rho}\right)\left(\frac{1\,{\rm cm}^2/{\rm g}}{\sigma/m}\right)\left(\frac{200\,{\rm km/s}}{v}\right)$$

Spergel & Steinhardt ‘00

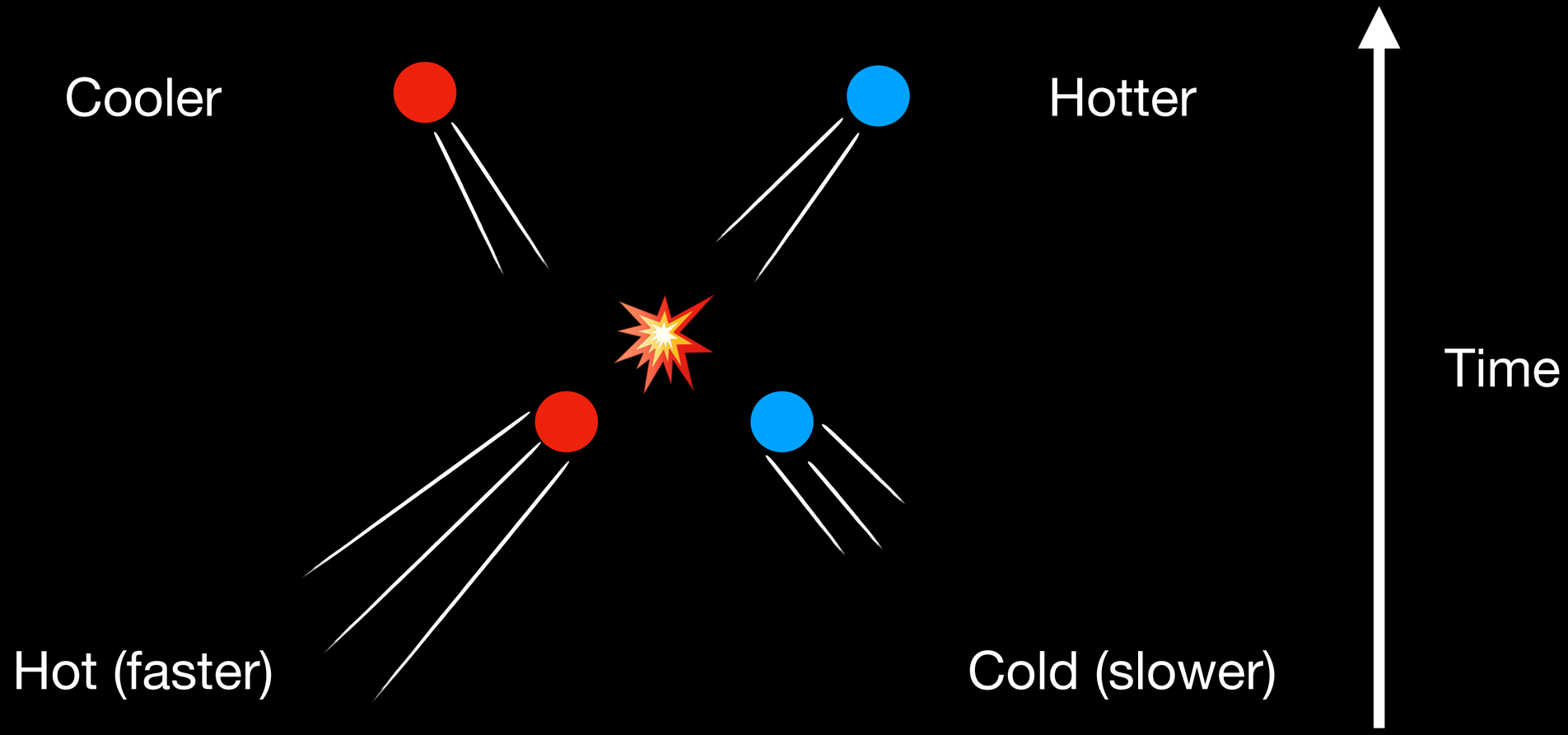
Where to look at?



Dark matter halos



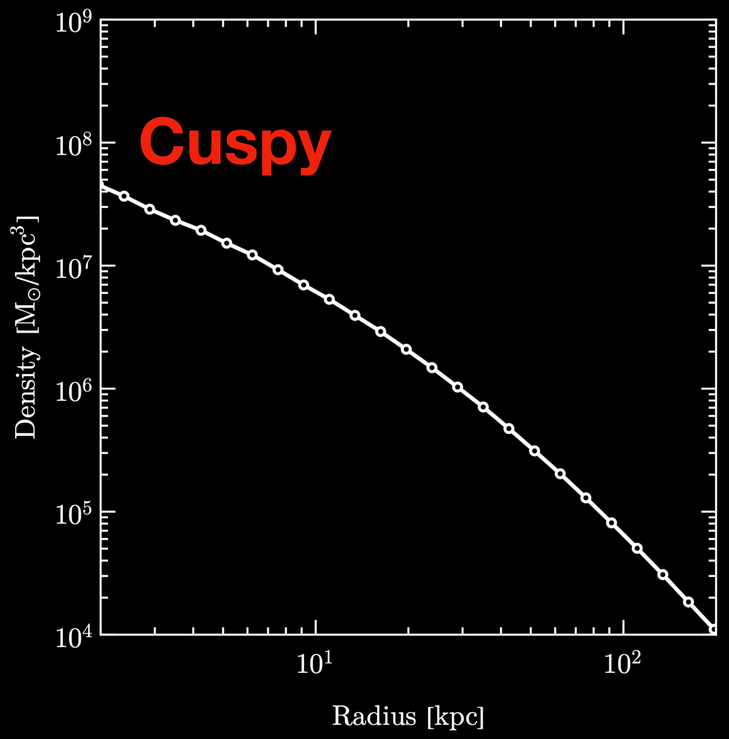
Effects of self-interaction

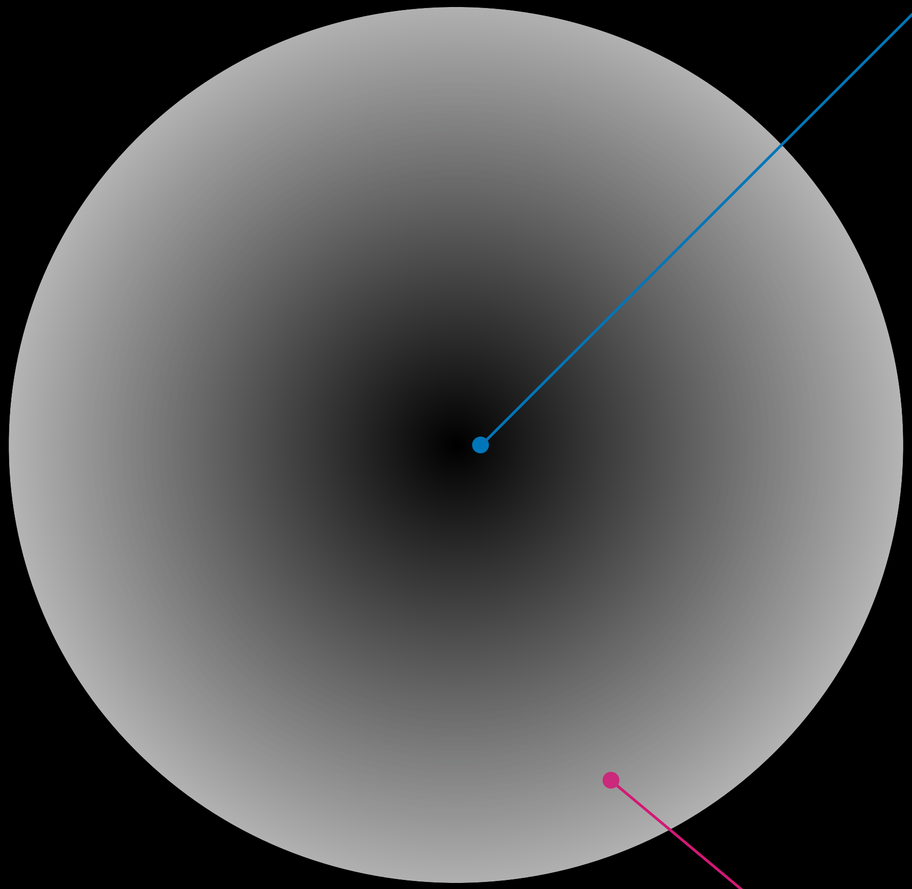


Equipartition

0. Halo formation

Density profile
(density at given radii)

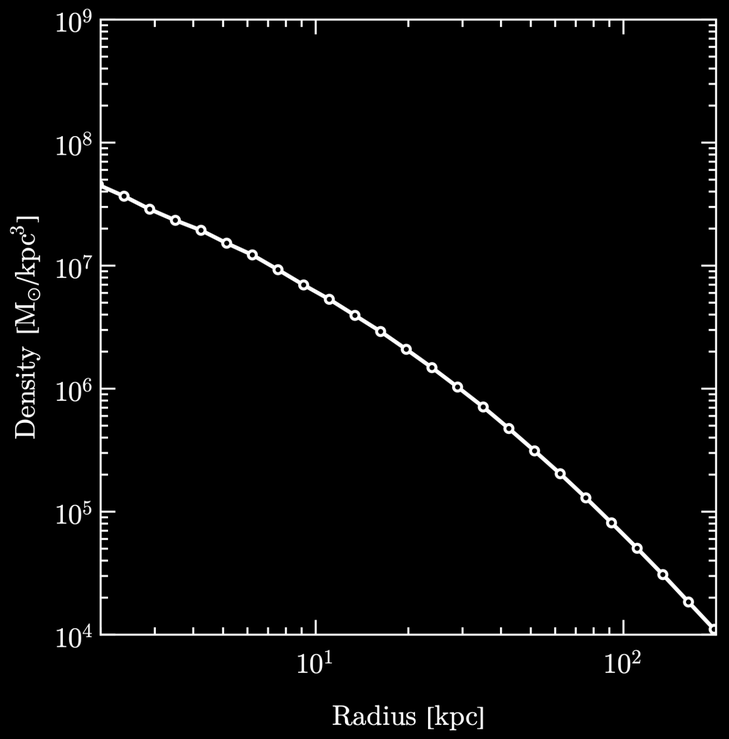


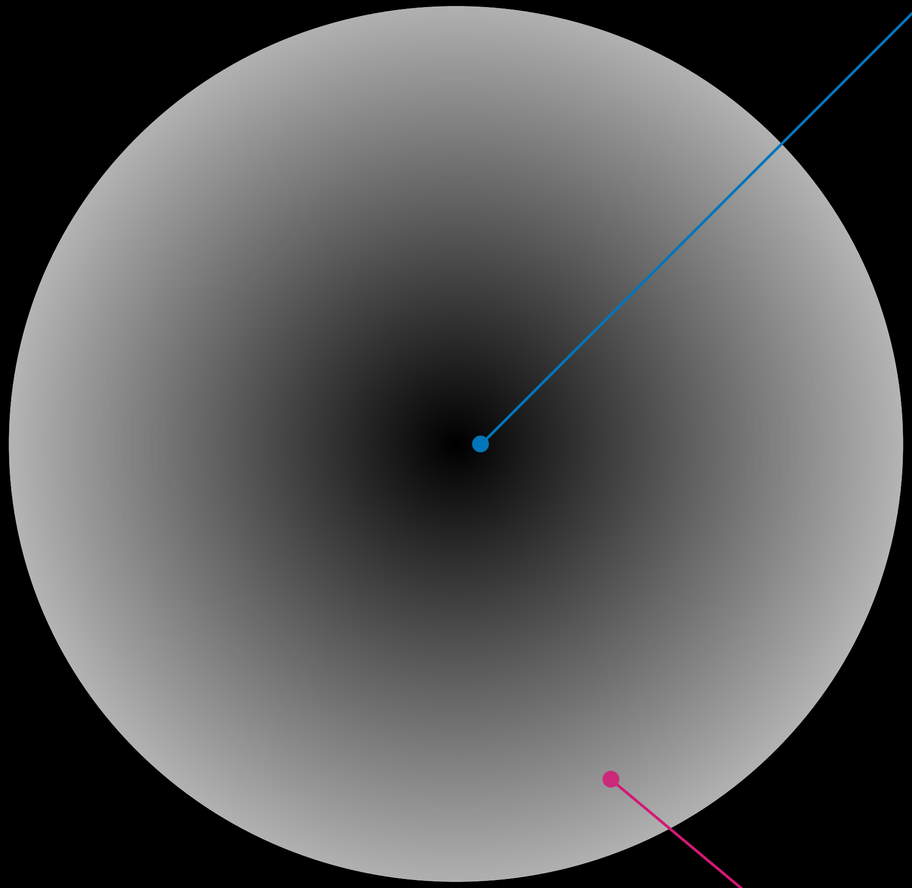


Navarro-Frenk-White (NFW) profile $\rho = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2}$

0. Halo formation

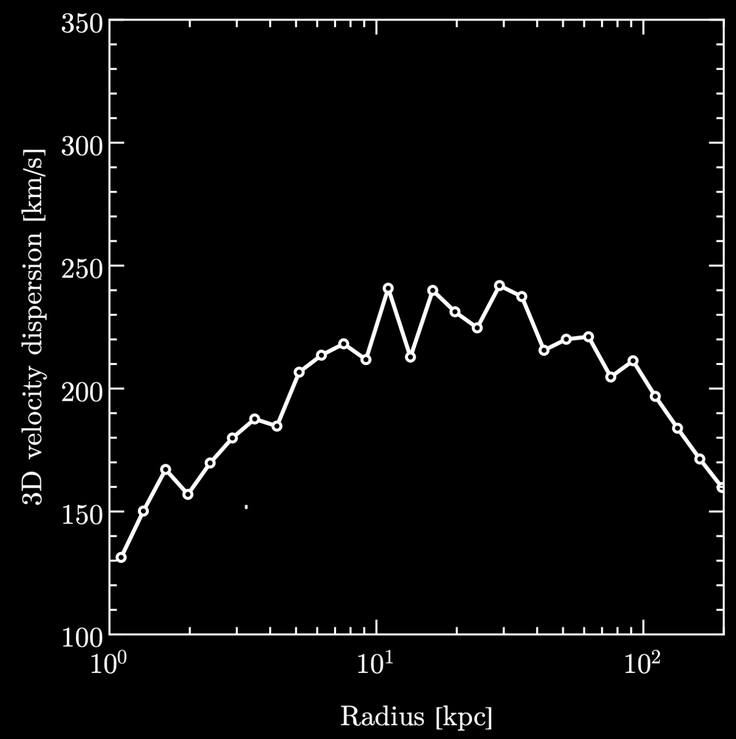
Density profile
(density at given radii)





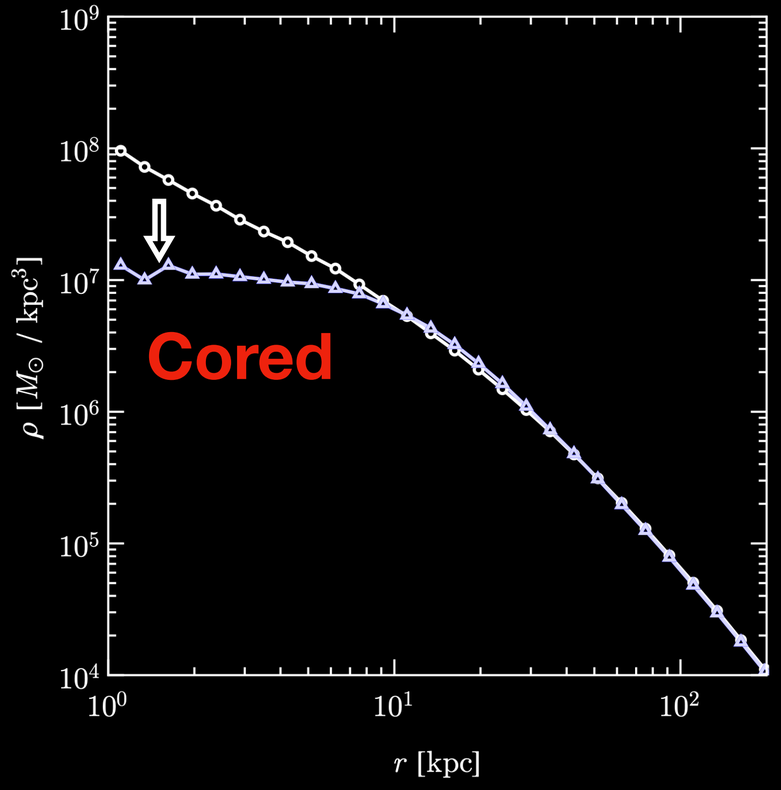
Dense, Cold

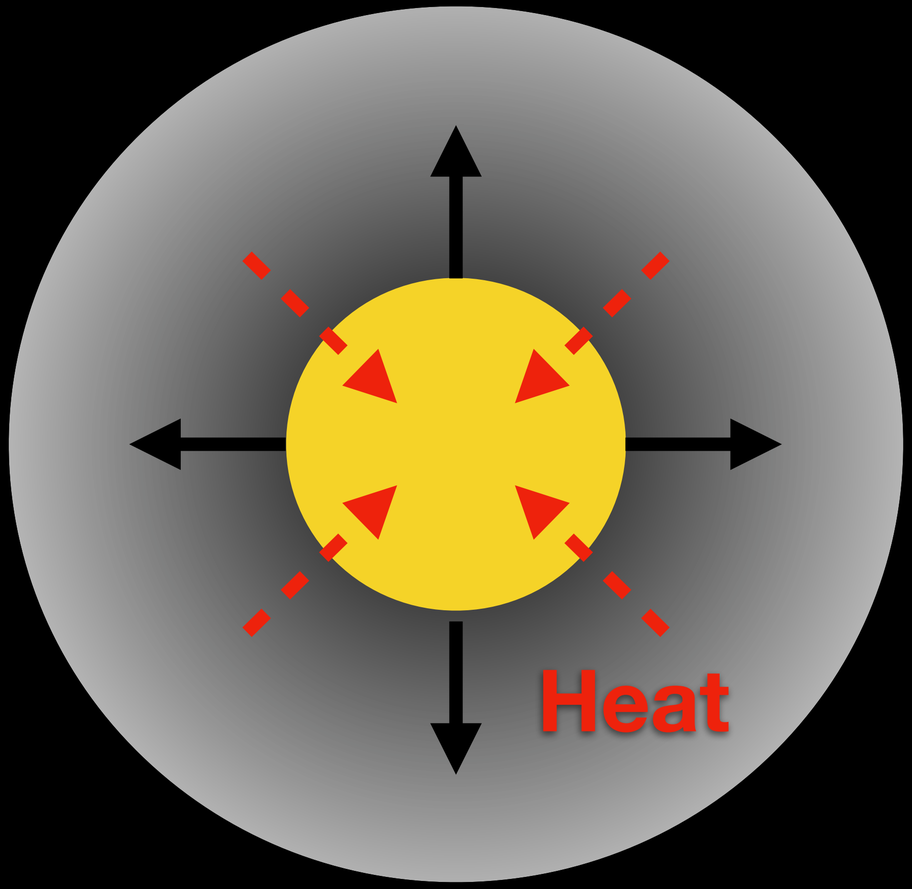
Velocity dispersion profile

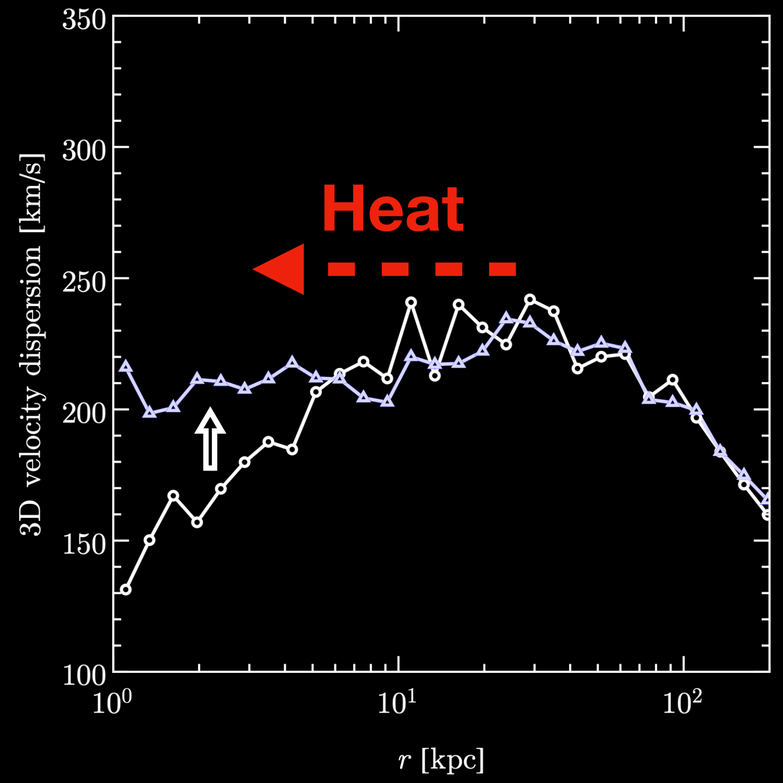


Sparse, Hot

1. Core expansion

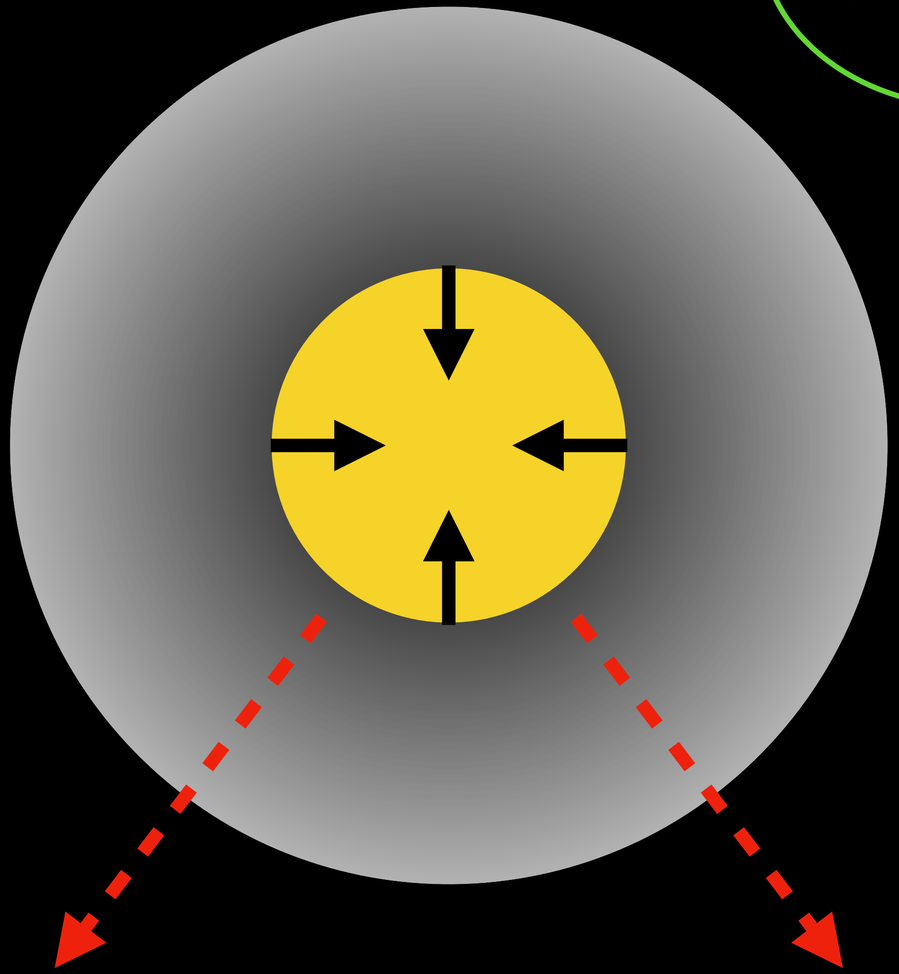




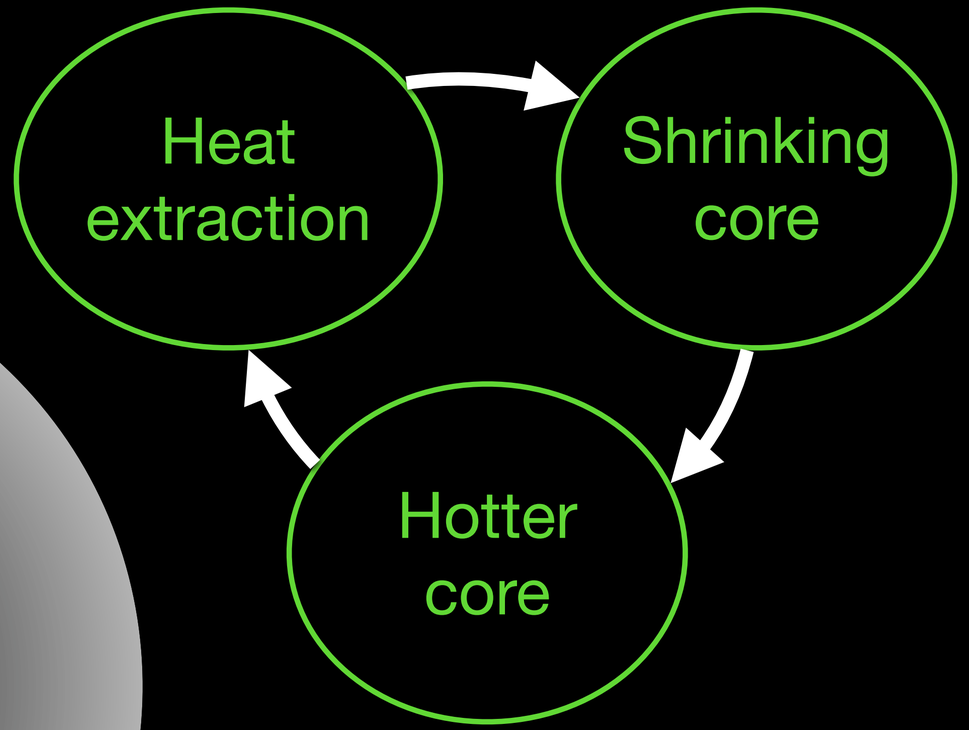


Huo, Yu & **YZ** ‘20

2. Core collapse



Heat



2. Core collapse

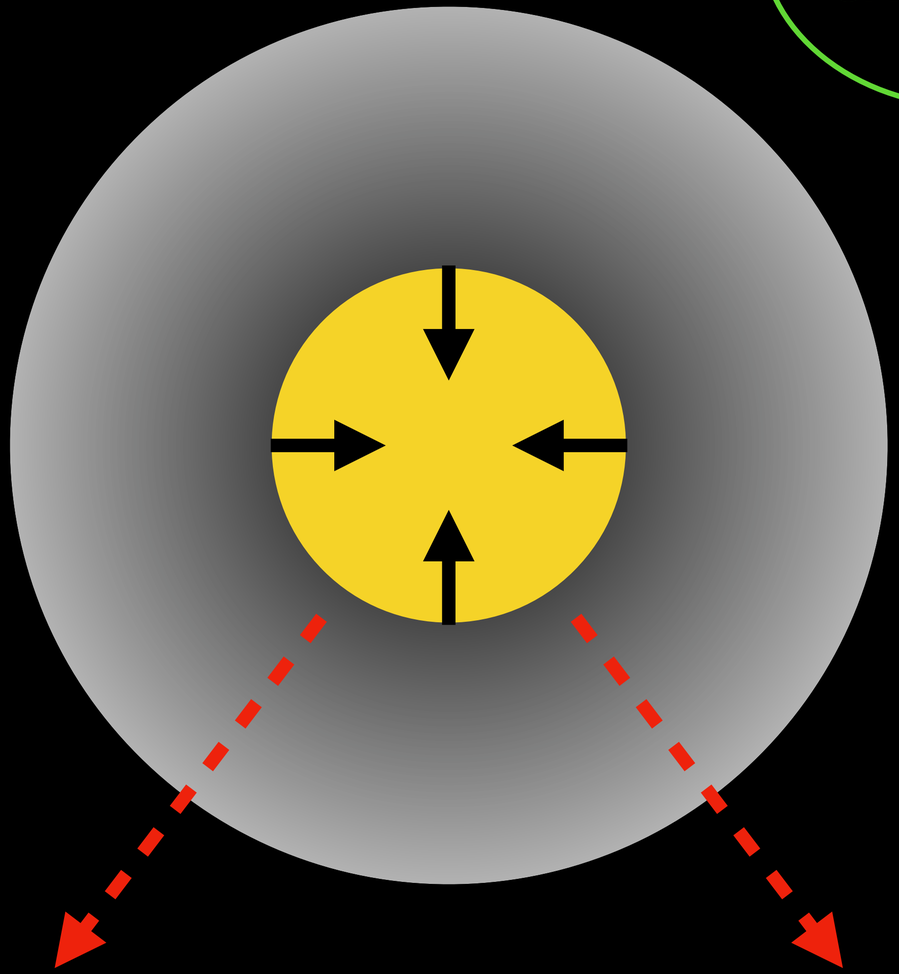
$$2E_{\rm kin} + E_{\rm pot} = 0$$

$$\Downarrow$$

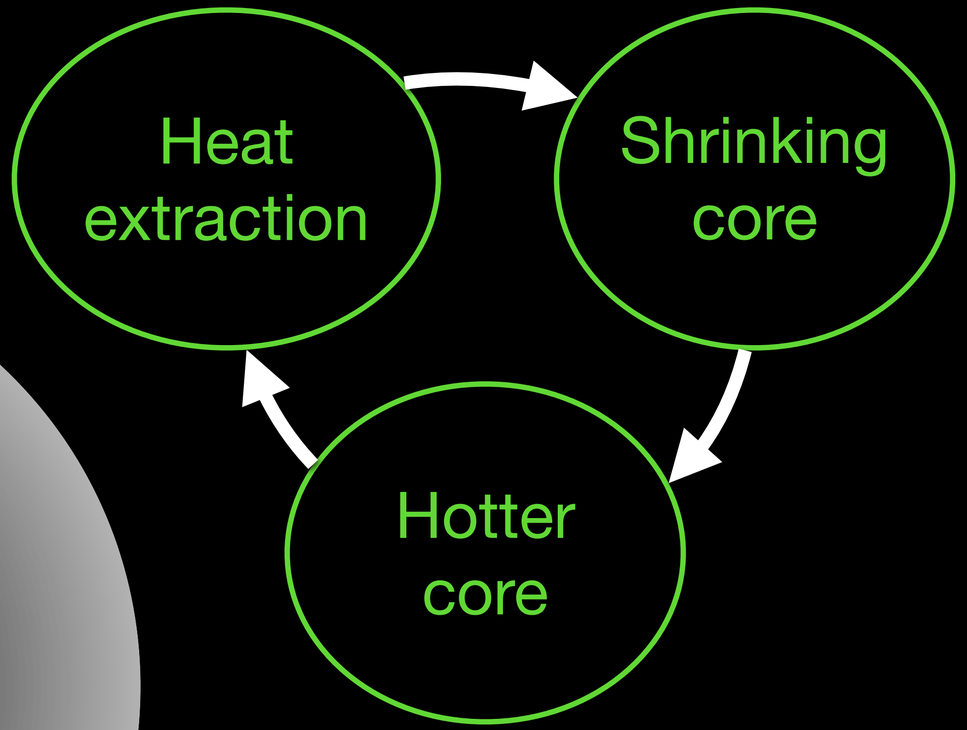
$$E_{\rm total} = -E_{\rm kin}$$

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

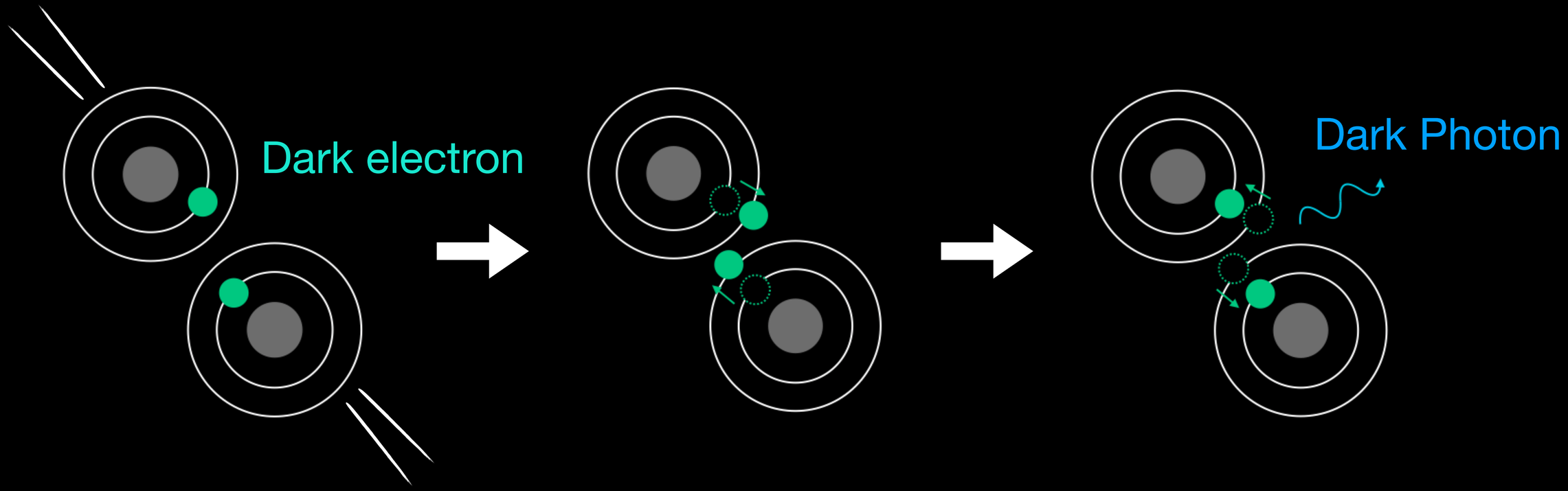
$$C \equiv \frac{E_{\rm total}}{T} < 0$$



Heat

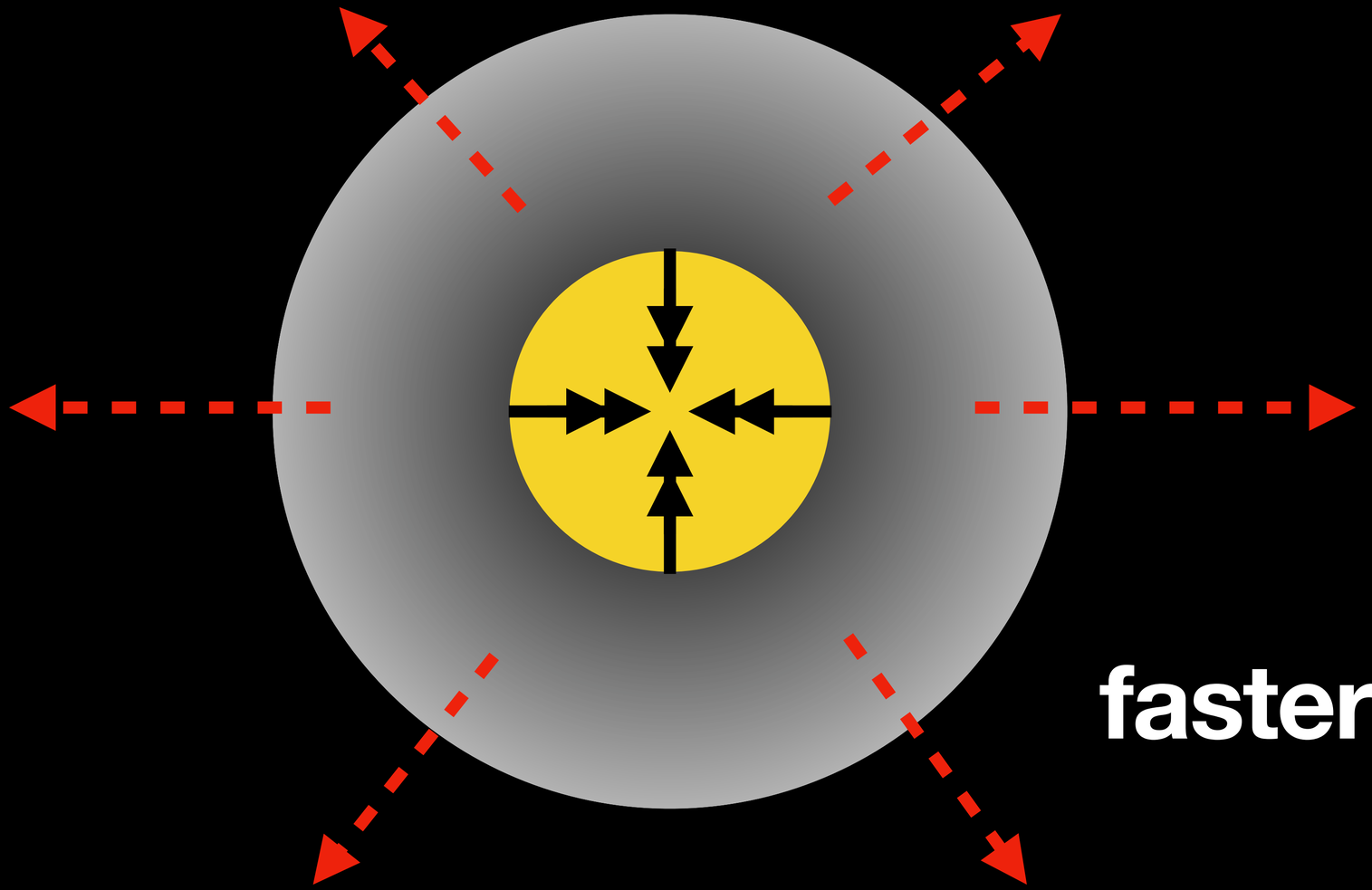


Dissipative SIDM



Atomic Dark Matter

More heat out



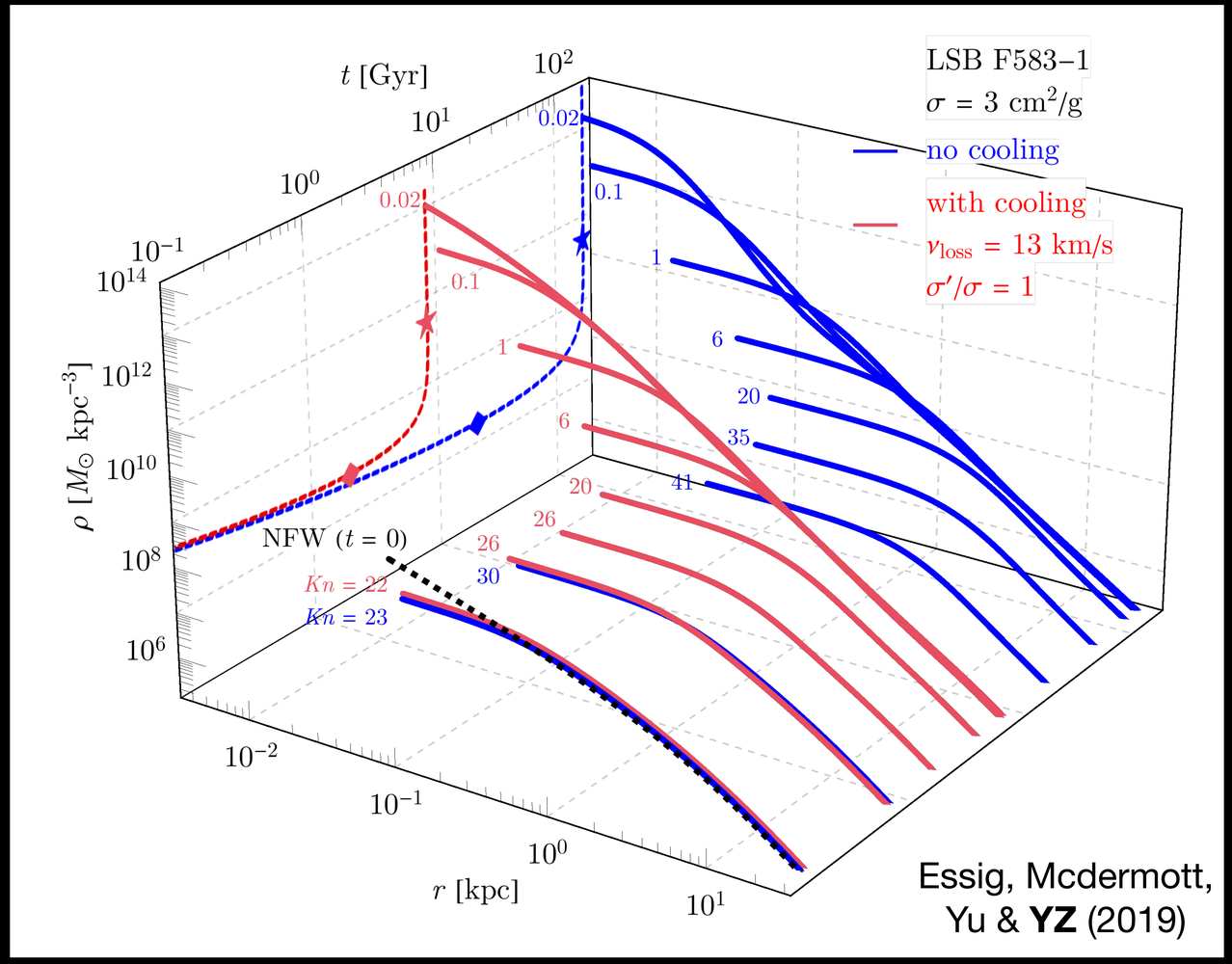
faster collapse

Density profile evolution

Evolution stages:

0. Halo formation
1. Core expansion
2. Core collapse

Dissipative SIDM Elastic SIDM



Density profile evolution

Cut at t = 10 Gyrs:

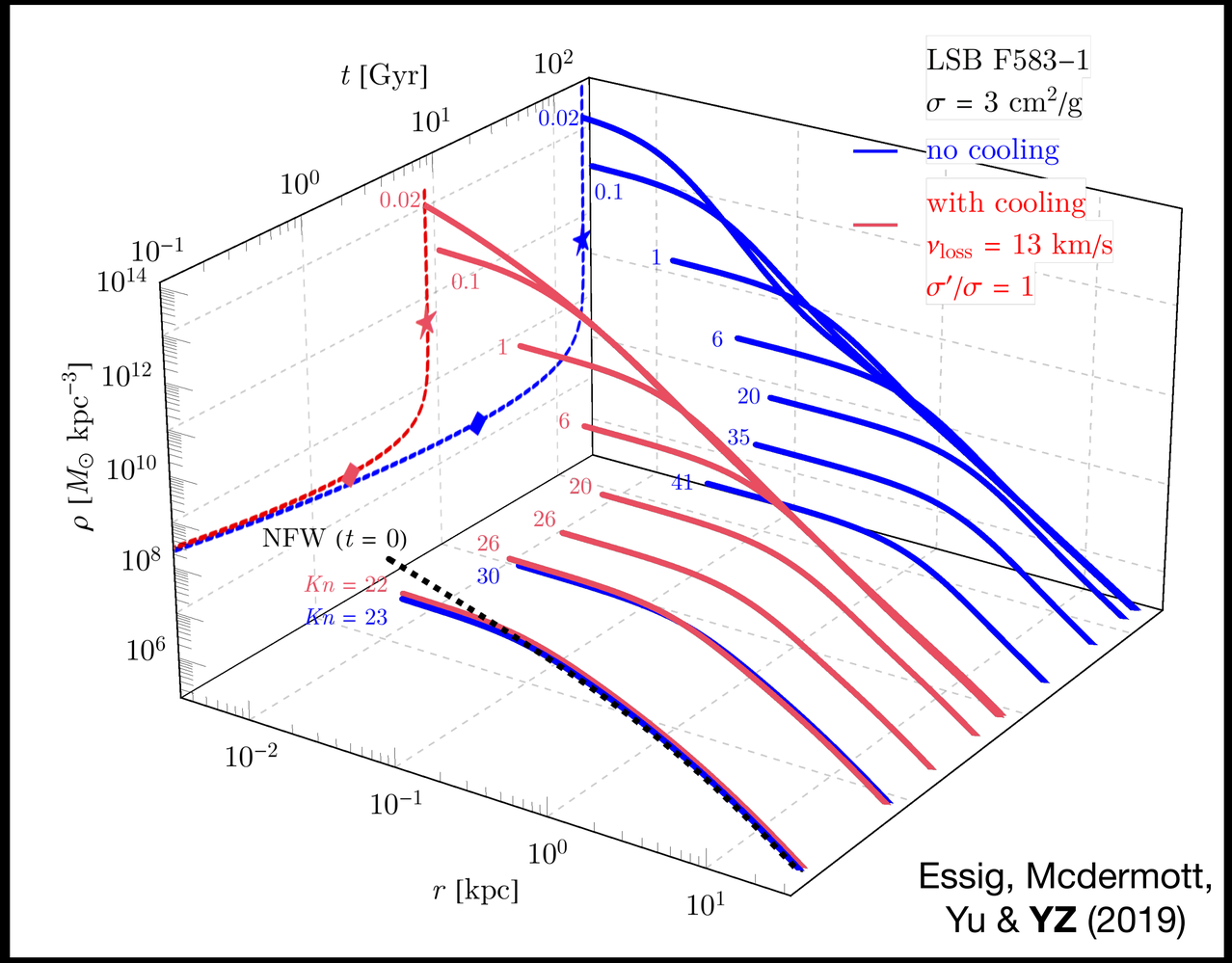
Elastic SIDM:

- Cored profile

Dissipative SIDM:

- Quasi-isothermal profile (cuspier than NFW)

Dissipative SIDM Elastic SIDM



Density profile evolution

Evolution time is set by:

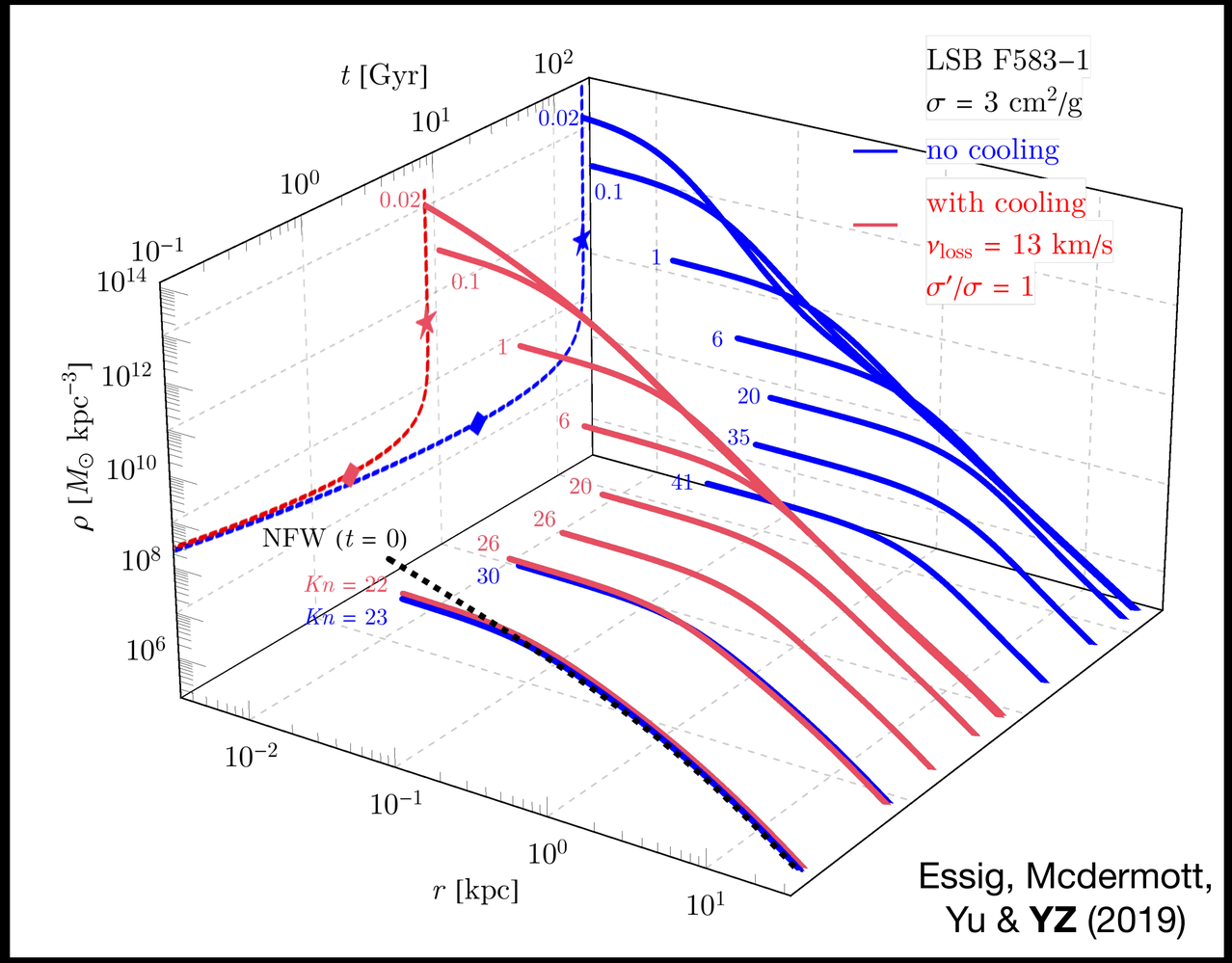
Elastic SIDM

- Cross section strength

Dissipative SIDM

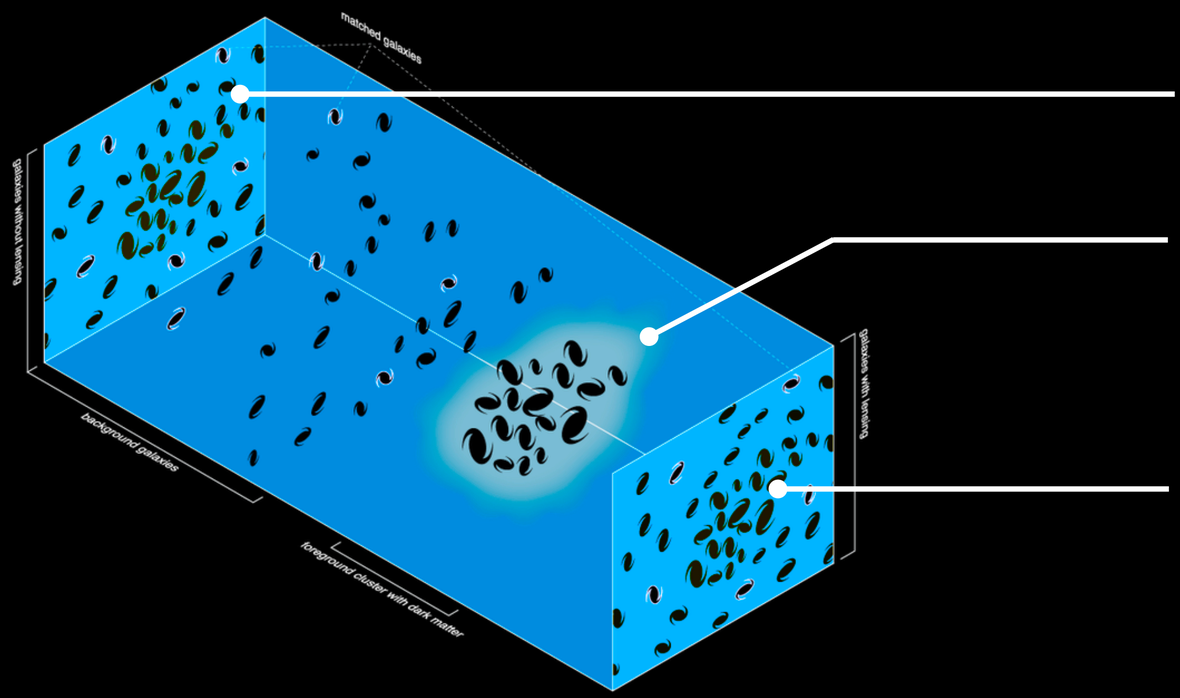
- Cross section strengths
- Energy loss per collision

Dissipative SIDM Elastic SIDM



Constraining SIDM from ACT x DES weak lensing measurement

Weak lensing

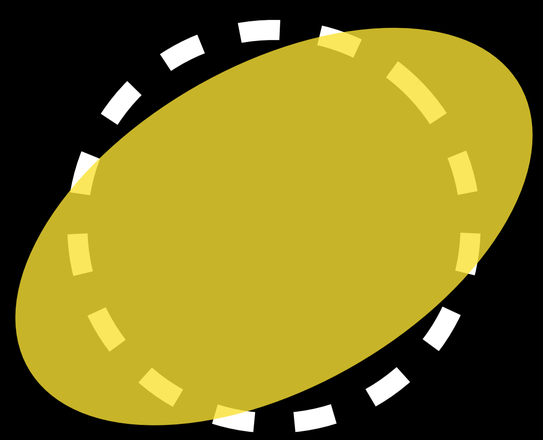


Credit: Sachs

Source (galaxies)

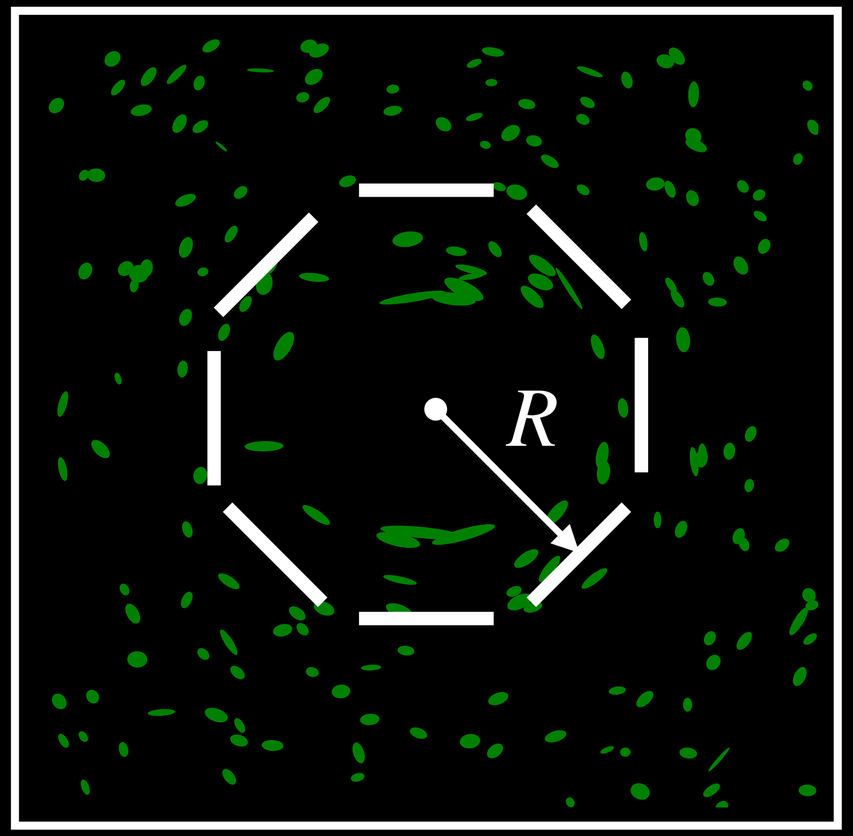
Lens (cluster)

Image (galaxies)



Shear

Tangential Shear & halo's density



The tangential shear, γ_t, is sensitive to the excess of the projected lens mass

$$-\gamma_t(R) \propto \Sigma(R) - \langle \Sigma(< R) \rangle$$

$$\frac{1}{\pi R^2} \int_{R' < R} \mathrm{d}^2 R' \, \Sigma(R')$$

See Dodelson '22

Data

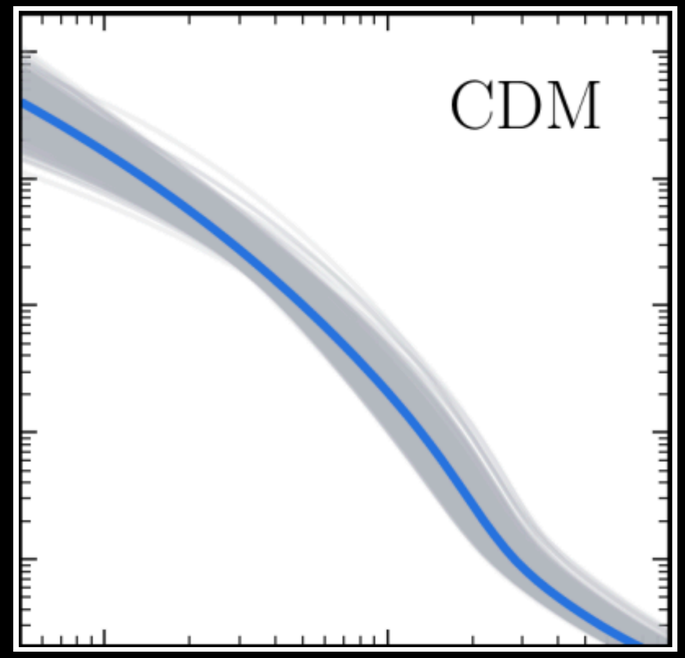
- Used the weak lensing measurement from Shin et al. (2021).
- Lens: clusters sampled from Atacama Cosmology Telescope (ACT) DR5.
- Source/Image: galaxies from the Dark Energy Survey (DES) Y3 near the sampled clusters.


ACT credit: J. Ward


DES credit: E. Krause

Selection of the lens

- Stacked ~1000 galaxy clusters
- Redshift: 0.15—0.7
- Mass: ~$10^{14}\,\mathrm{M}_{\odot}/h$
- Radius range: 0.2—20 Mpc/h



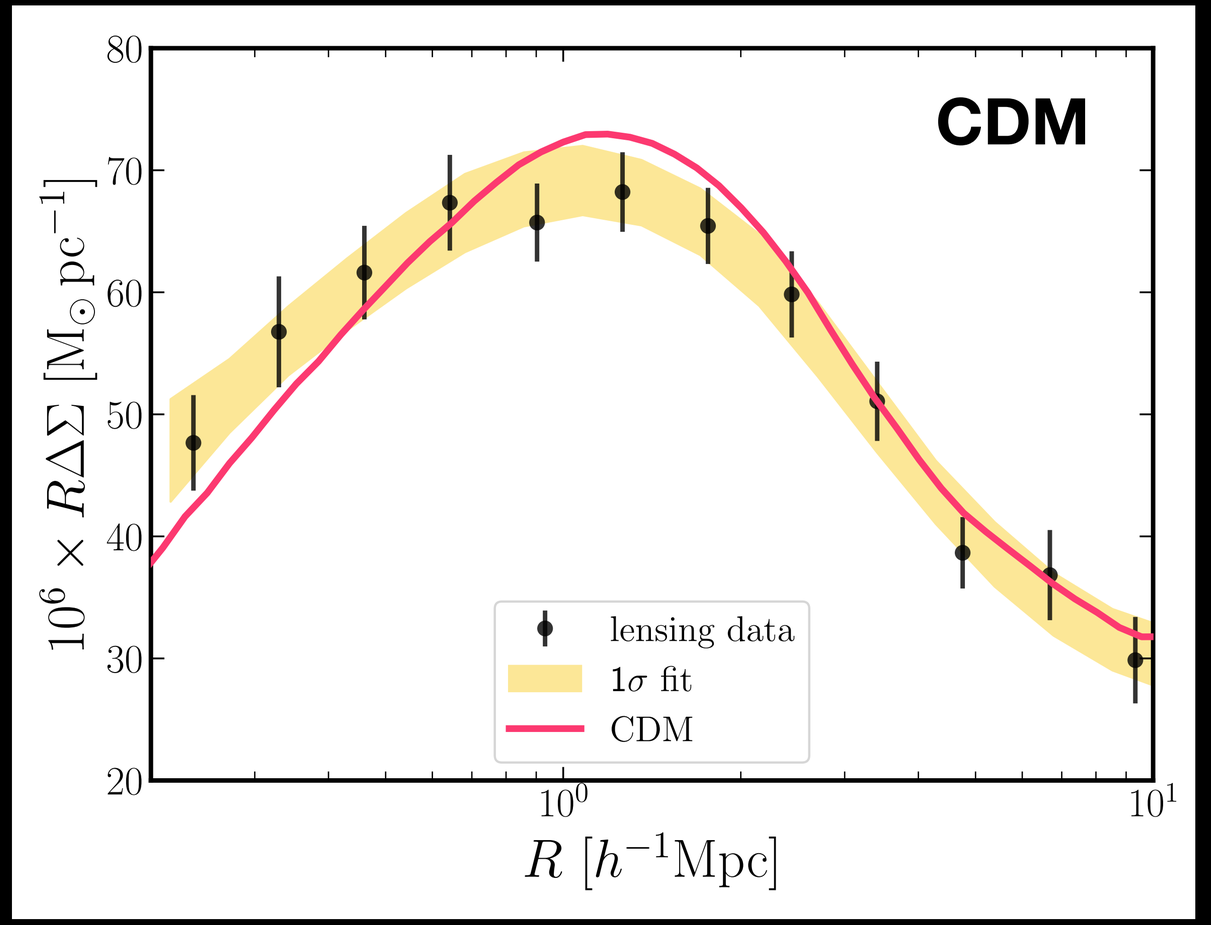
Modeling of the lens

- Modeled the lens for CDM, elastic SIDM (eSIDM), and dissipative SIDM (dSIDM).
- Simulated 1000+ halos for each benchmark.

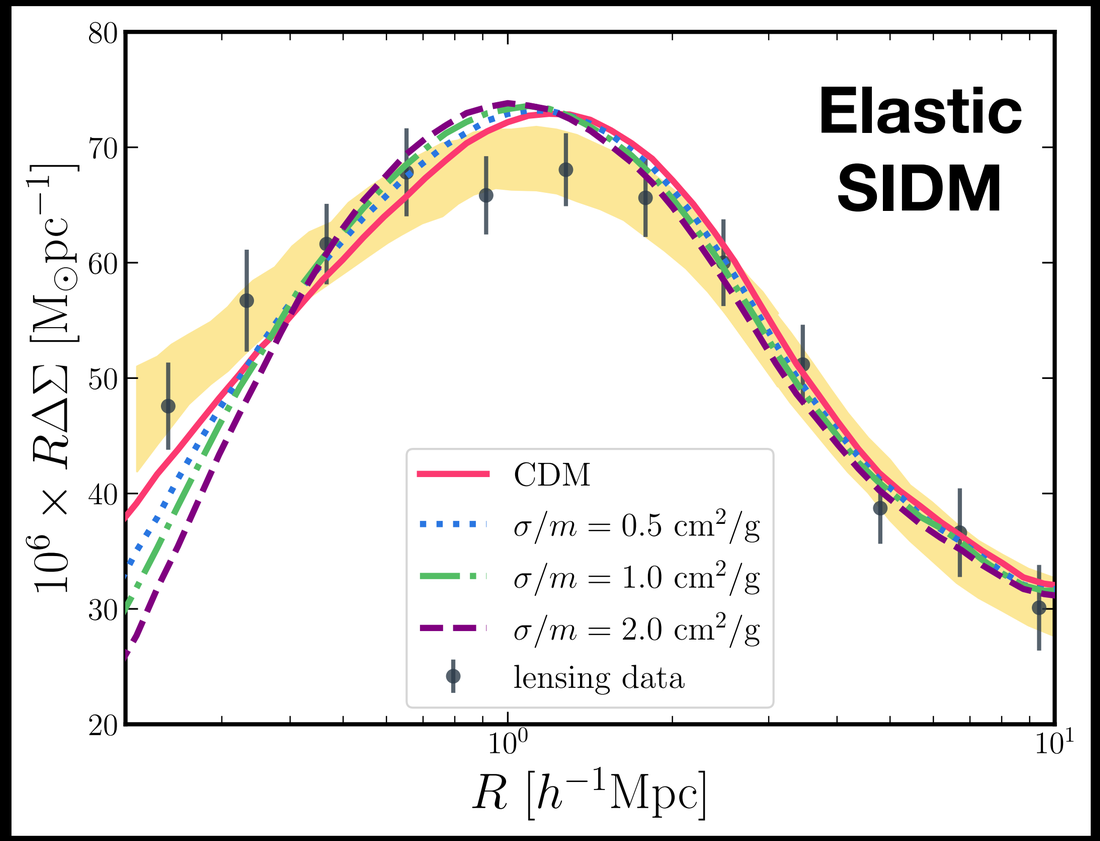
Name	σ/m [cm^2/g]	σ'/m [cm^2/g]	$v_{\rm loss}$ [km/s]
CDM	–	–	–
eSIDM	0.2	–	–
	0.5	–	–
	1.0	–	–
	2.0	–	–
dSIDM-300	1.0	1.0	300
dSIDM-600	1.0	1.0	600
dSIDM-2000	1.0	1.0	2000

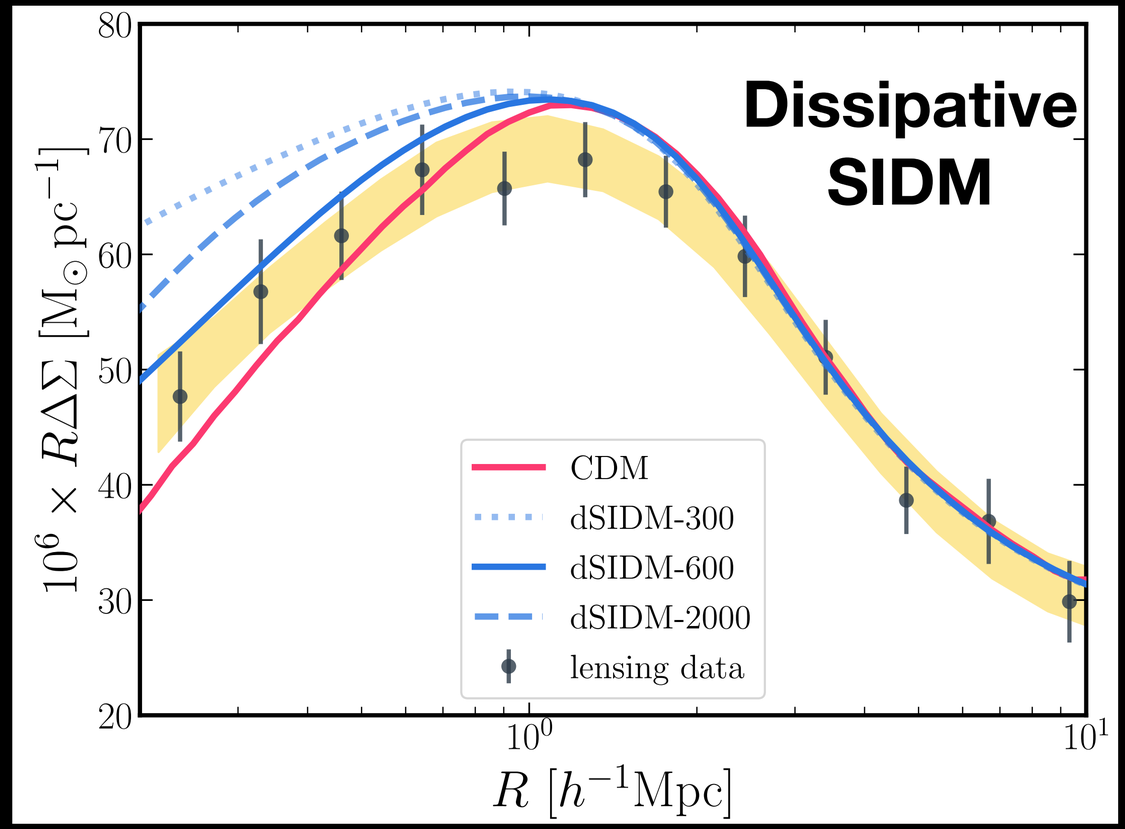
Excess of stacked surface density

CDM under predicts $\Delta\Sigma$ at small radii.



Excess of stacked surface density





Better fit by dSIDM-600

Constraints on SIDM

Elastic SIDM

$$\sigma/m < 1\,\mathrm{cm}^2/\mathrm{g}$$

(95% CL)

Dissipative SIDM

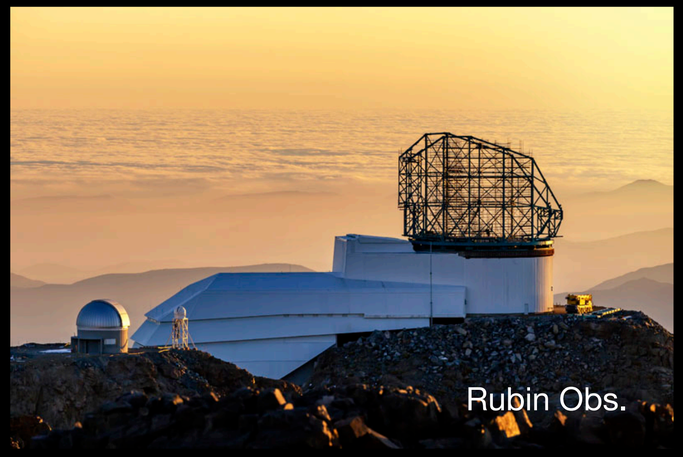
Assume $\sigma/m = \sigma'/m = 1\,\mathrm{cm}^2/\mathrm{g}$

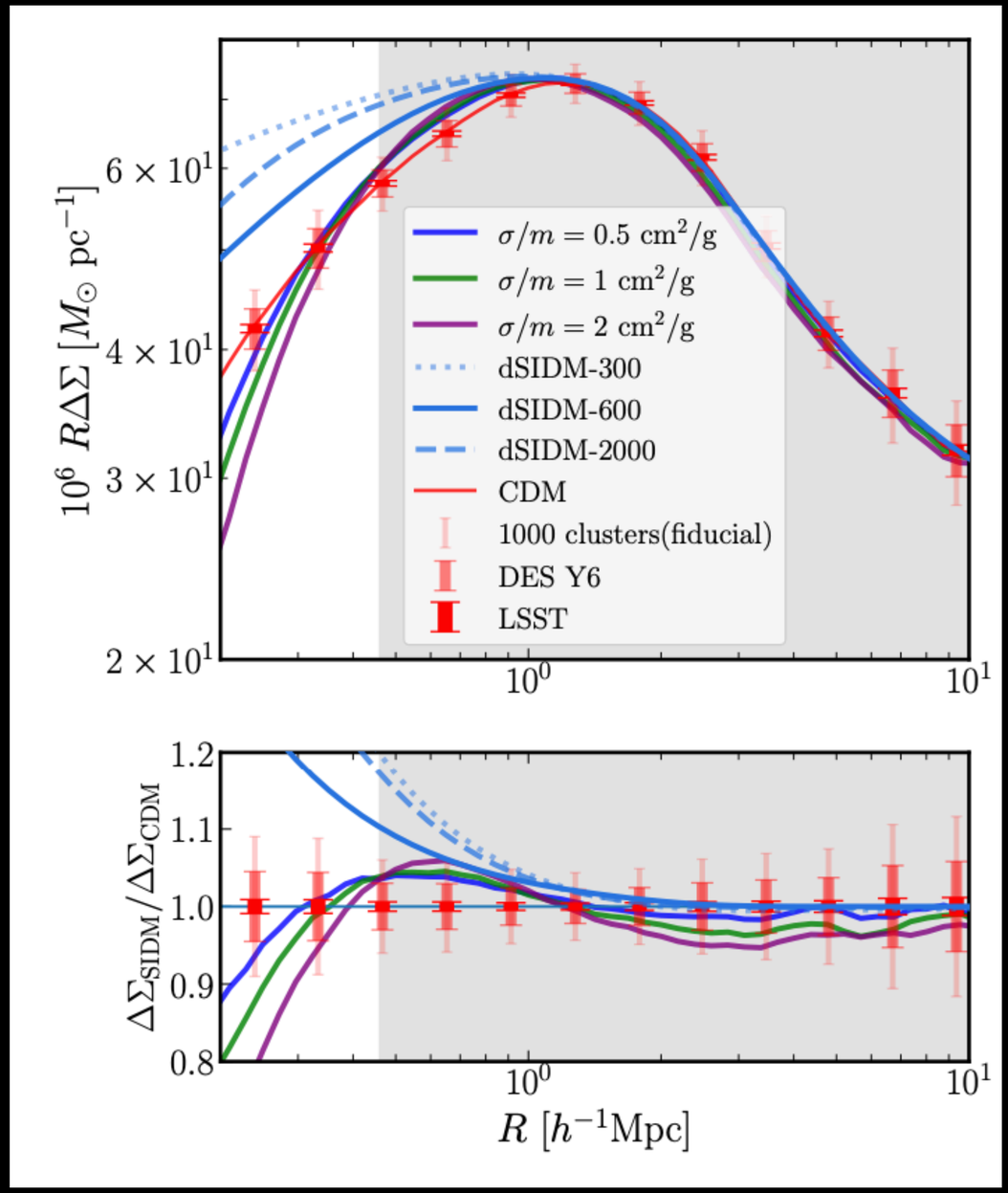
$$\nu_{\mathrm{loss}} \equiv \sqrt{\frac{E_{\mathrm{loss}}}{m}} \subset [1.6\times10^2, 2.4\times10^2]\,\mathrm{km/s} \cup [3.2\times10^2, 1.6\times10^3]\,\mathrm{km/s} \cup [2\times10^3, 2.8\times10^3]\,\mathrm{km/s}$$

(95% CL)

Outlook

- Future surveys, like Rubin Observatory, will increase the cluster sample size by ~10^5.
- Can significantly reduce the statistical & systematical errors.





Summary

- Halos are interesting probes of dark matter properties.
- Gravothermal evolution increases the diversity of SIDM halos.
- Weak lensing measurements from current and future galaxy surveys can effectively probe various types of dark matter self-interactions.