THE LIFE AND DEATH OF DARK MATTER HALOS

Project 4: Analysing the interaction patterns of Dark Matter with Darren Singh, Hannah Vormann, Megan Gran, and Tobias Raum

With Professor Sean Tulin and Junior Mentor Reuben Blaff

MOTIVATION

- Cold Dark Matter (CDM) Model ⊄ small-scale data
  - Gravity-based interactions
- Two big questions:
  - How do different particle physics structures affect the structure of dark matter halos?
  - How does this structure compare to observational data?

D. H. Weinberg et al, *Proc. Nat. Acad. Sci.* 112, 12249 (2015)

OUTLINE

1. Overview + Introduction: Meg
2. Fractional Model: Darren
3. Dissipative Model: Hannah
4. Annihilating Model: Tobias

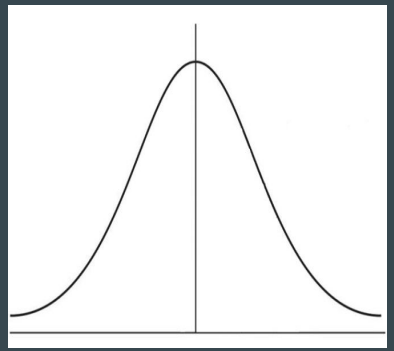
WHAT IS SPH? WHY IS IT IMPORTANT?

Smoothed - particles smeared by smoothing kernel.

Particle - using fluids treated as a collection of particles.

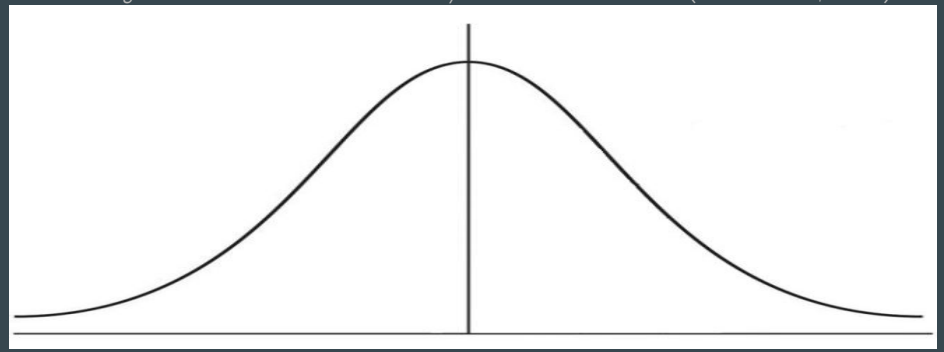
Hydrodynamics - solving Euler's equations for hydrodynamics.

Image from: Calculate the Probability Under a Normal Curve (P. Kazarinoff, 2021)



Small h

h = smoothing length

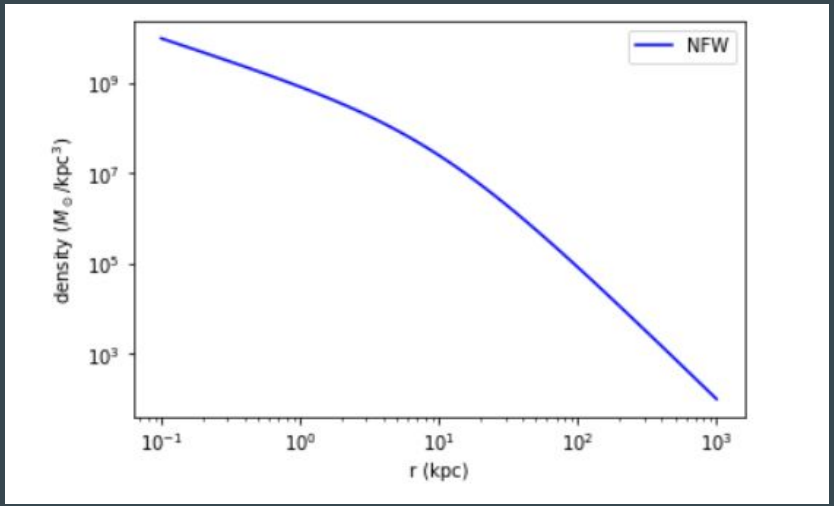


Large h

Smoothing Kernel - how particles are localized in position

J. J. Monaghan, Ann. *Rev. Astron. Astrophys.* 30, 543 (1992).

QUESTION FOR THE AUDIENCE



Q: If mass is constant, how does the smoothing length (h_i) increase?

$$h_i = \eta \left(\frac{m_i}{\rho_i} \right)^{1/3}$$

S. Tulin and R. Blaff, *Life and Death of Dark Matter Halos*, 14 (2021).

THE SPHERICAL PACKAGE

- Created by professor Sean Tulin and Reuben Blaff
- Properties of each shell, i:
  - mass, m_i
  - radius, r_i
  - radial velocity, v_i
  - internal energy, e_i
  - smoothing length, h_i
- Base of all models included in today's presentations
- Assumes spherical symmetry

Image From: Application of net radiation transfer method for optimization and calculation of reduction heat transfer, using spherical radiation shields (M. Torabi, 2010)

FRACTIONAL MODEL

Darren Singh

WHAT IS THE FRACTIONAL MODEL?

- Fractional Model → Subhalos of more than one DM species
  - Tested CDM and SIDM mix

CDM

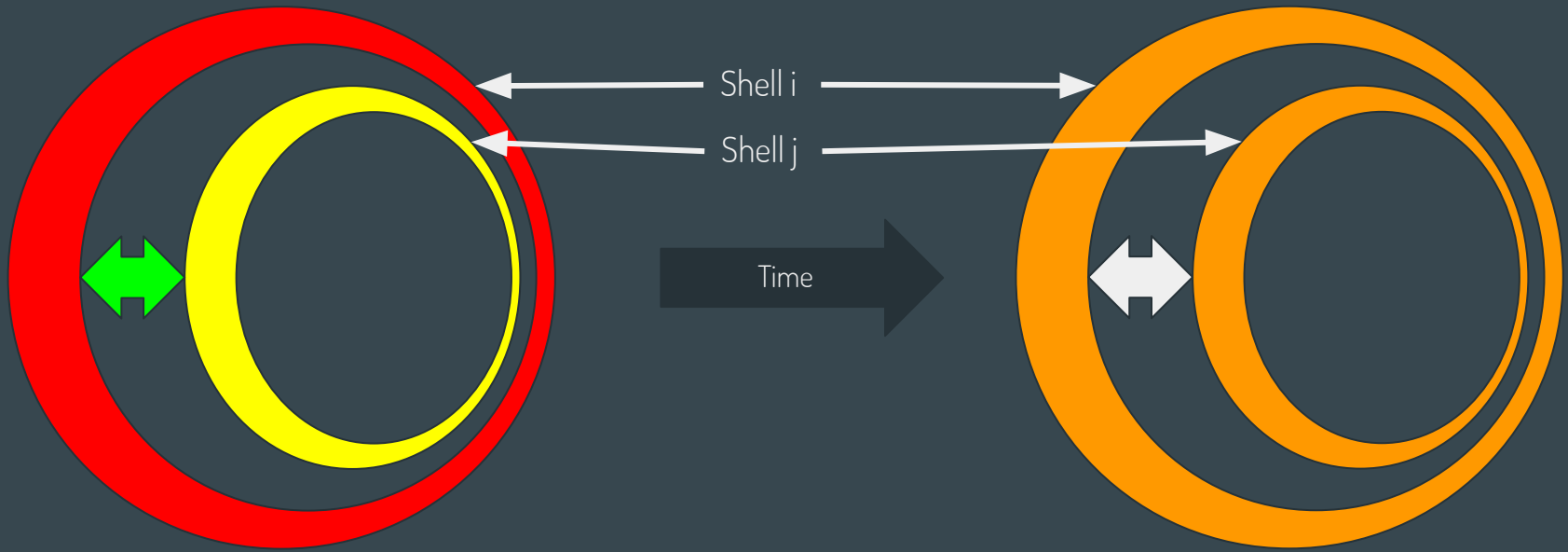
- Cold Dark Matter
- Does not self-interact
- NFW, Cuspy Profile

SIDM

- Self-Interacting Dark Matter
- Elastic Scattering
- Cored Profile
- χ = Dark Matter Particle
- $\chi\chi \rightarrow \chi\chi$

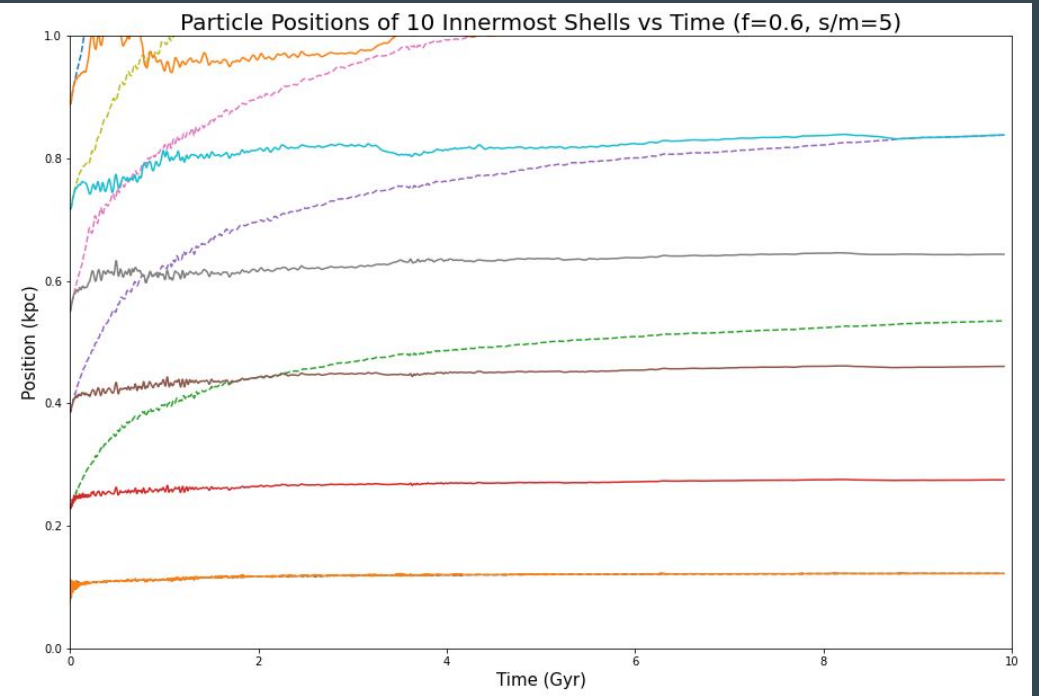
HOW IS IT IMPLEMENTED?

- Ensemble object creates mixed subhalo
- Heat conduction term allows for heat transfer with SIDM scattering
- = Heat Transfer, = Equilibrium



QUESTION FOR AUDIENCE

- Why is it that the positions of the innermost SIDM shells increase as time goes on, but the positions of the innermost CDM shells do not change much as time goes on?



NOTES

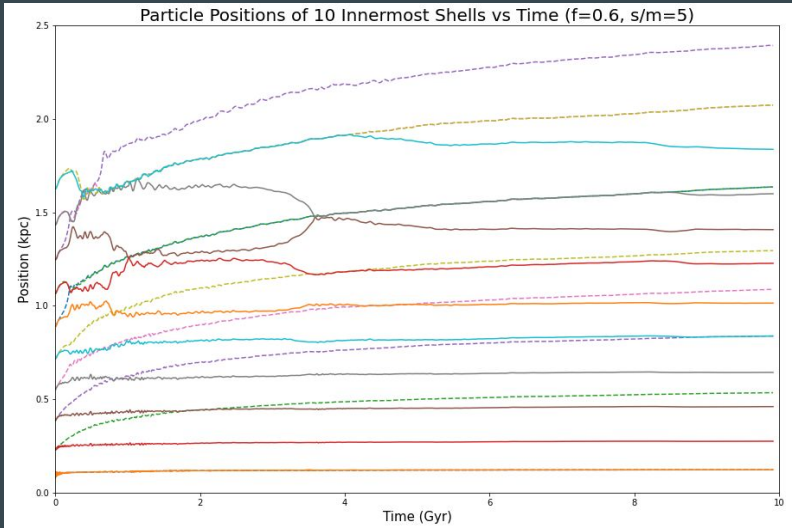
- Solid = CDM
- Dashed = SIDM

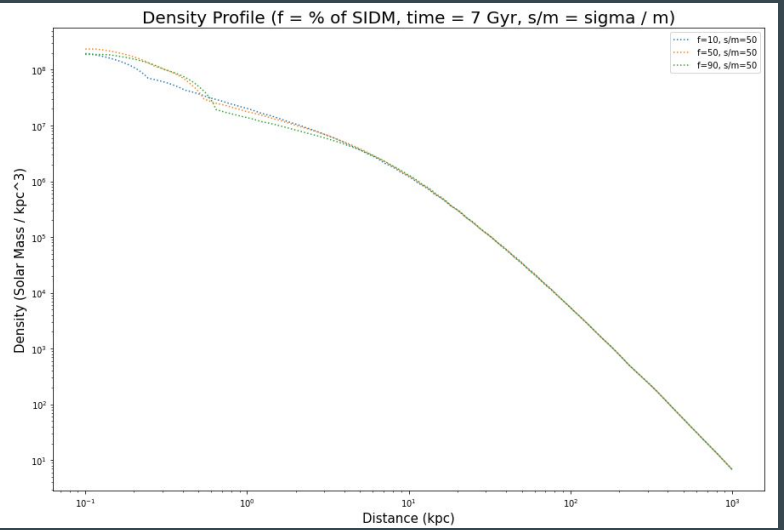
HINTS

- SIDM = Collisions
- Collisions = Energy (Heat) Transfer
- More Energy = More Velocity

SOMETHING TO KEEP IN MIND

- Resolution Issue





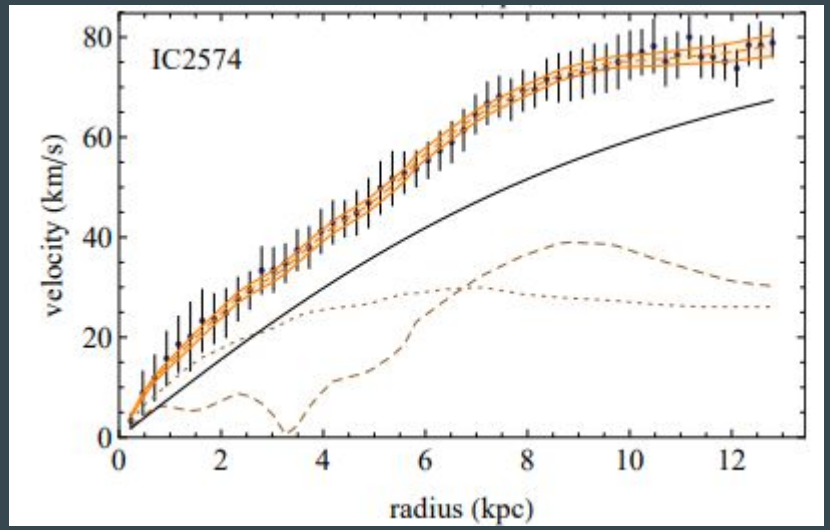
WHAT IS A ROTATION CURVE?

- A plot of circular velocity vs radial distance
- Total Rotation Curve: Includes Dark and Baryonic Matter
- DM Rotation Curve: Only Dark Matter

- Circular Velocity: $V_c = \sqrt{\frac{G * M_{encl}(r)}{r}}$

DWARF GALAXY IC2574

- Highly cored galaxy
  - 90% of mass is Dark Matter



Credits: Kaplinghat et al (2015)

ROTATION CURVE OF IC2574

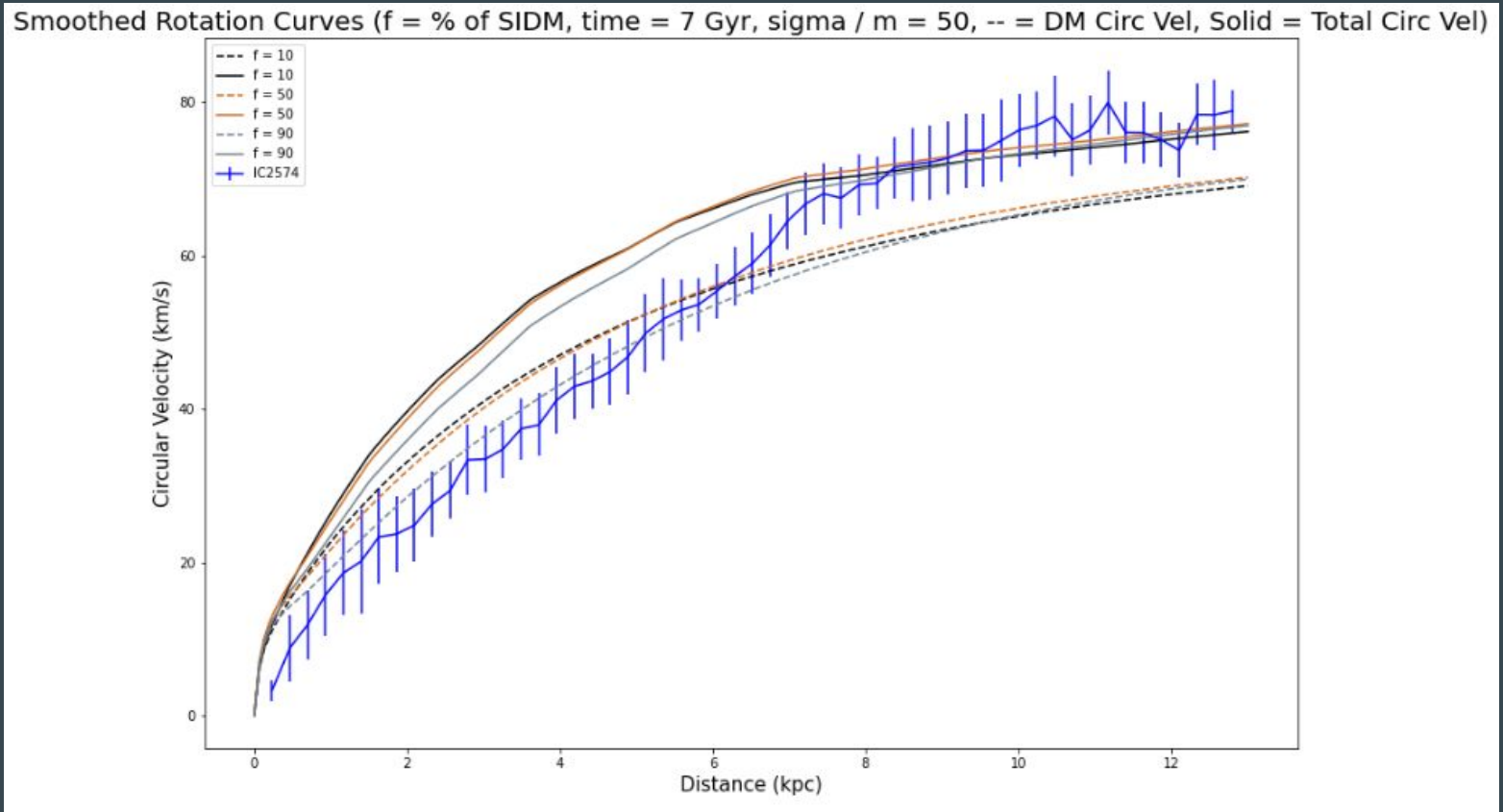
- Solid = SIDM Halo
- Dashed = Gas Disk
- Dotted = Stellar Disk
- Orange = SIDM Fit to Total Rotation Curve of IC2574

SIMULATION RESULTS

- Simulated several fractional dark matter halos similar to IC2574
  - Fraction of SIDM (f) = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
  - Cross Section per unit mass (sigma / m) = 5, 10, 20, 50 cm^2/g
  - Time = 7 Gyr

- IC2574 data obtained from The HI Nearby Galaxy Survey (THINGS)

RESULTS AND COMPARISON



WHAT'S NEXT

- Fine tune parameters
- Longer simulations can be done (10+ Gyr)
- Different combinations of input parameters can be tested (cross section per unit mass, number of shells, etc.)
- Fractional models with species other than just SIDM and CDM can be explored
    - Stay tuned for more on other species

DISSIPATION

What is it?

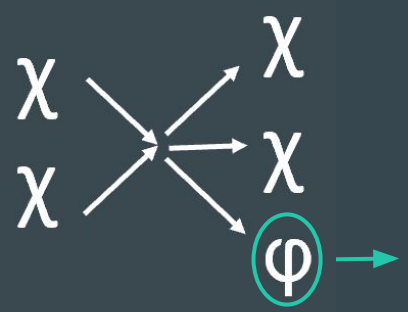
Why?

How does it influence the time evolution of DM halos?

Hannah Vormann

DISSIPATION

- inelastic scattering:
- χ: DM particle
- φ: "dark" boson, e.g. "dark photon"



energy loss!

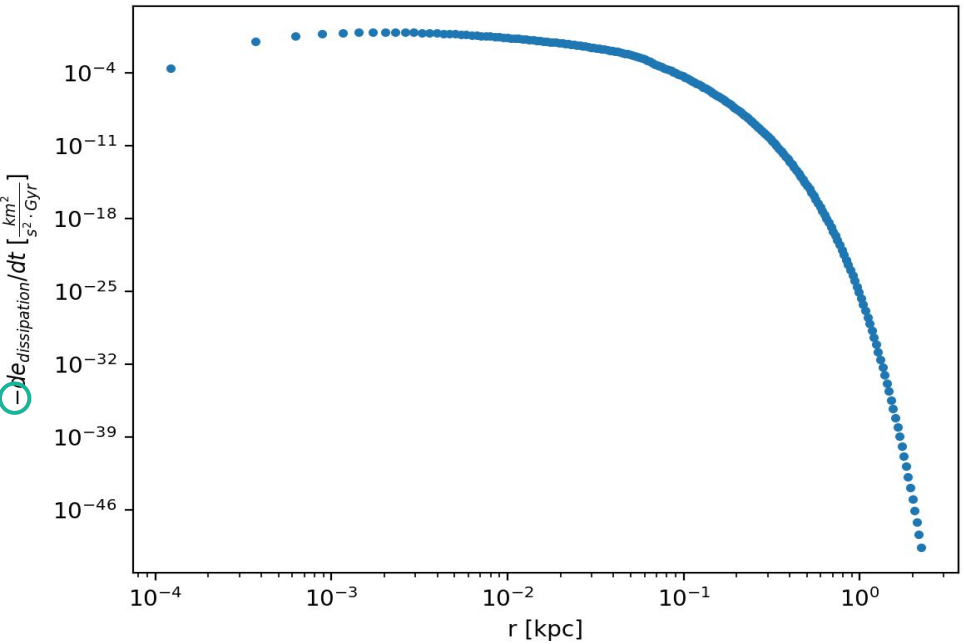
$$v_{loss} \equiv \sqrt{\frac{E_{loss}}{m}}$$

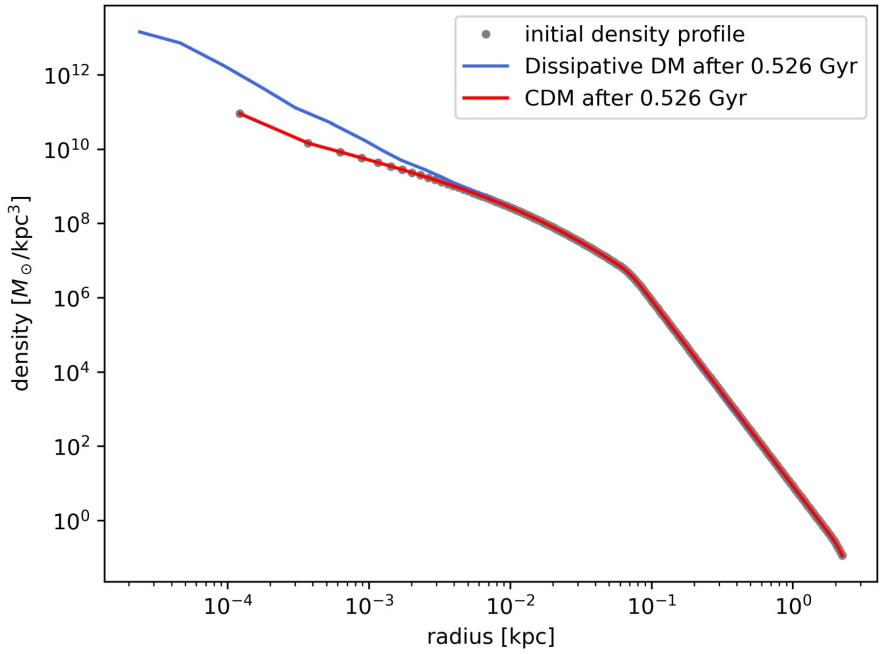
MOTIVATION

- “dark” Standard Model + possibility for SI
  -> intuition: also dissipation
- completely dark subhalos
  - no constraints on density profiles yet
  - “tune” predictions with dissipation: opposite effect of SI
- formation of supermassive black holes

EFFECTS OF DISSIPATION ON DM HALOS

- σ/m = 5 cm^2/g, v_{loss} = 1 km/s





COMPUTATIONAL SETUP (I)

- cooling rate:

$$C = \left\langle \frac{n\, E_{loss}}{t_r} \right\rangle = \rho^2 \frac{\sigma}{m} \frac{4\, v\, v_{loss}^2}{\sqrt{\pi}} \left(1 + \frac{v_{loss}^2}{v^2}\right) e^{-\frac{v_{loss}^2}{v^2}}$$

  - σ: cross section
  - v: velocity dispersion

Essig *et al. Phys. Rev. Lett.* **123**, 121102 (2019)

COMPUTATIONAL SETUP (2)

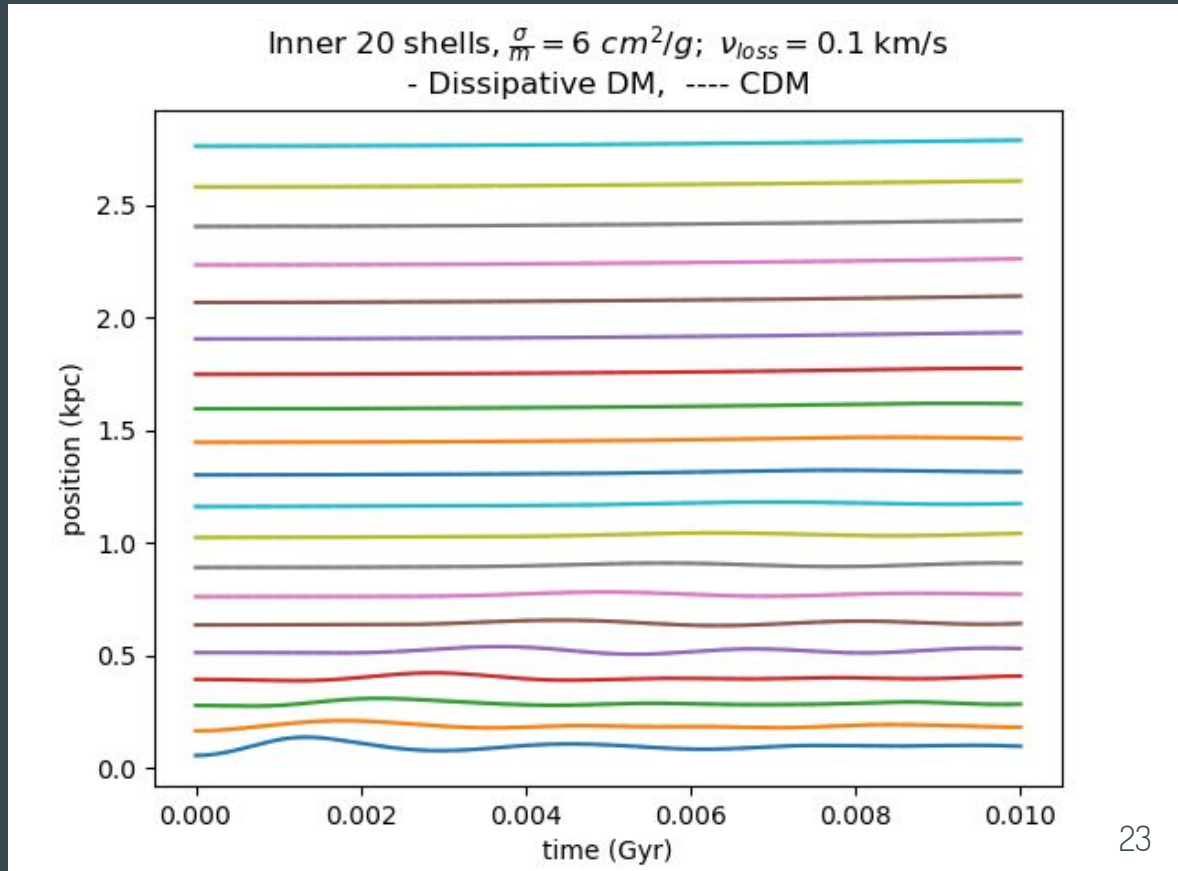
- $\langle\ \rangle$: thermal average over Boltzmann distribution of v_{rel}
  - with restriction $v_{rel} \geq 2\ v_{loss}$

$\longrightarrow$ add energy loss in SPH equations: $\frac{de}{dt} = -\frac{C}{\rho}$

FREE PARAMETERS

- σ/m
- v_{loss}

Question: Why is there no significant effect for relatively small and high v_{loss}?



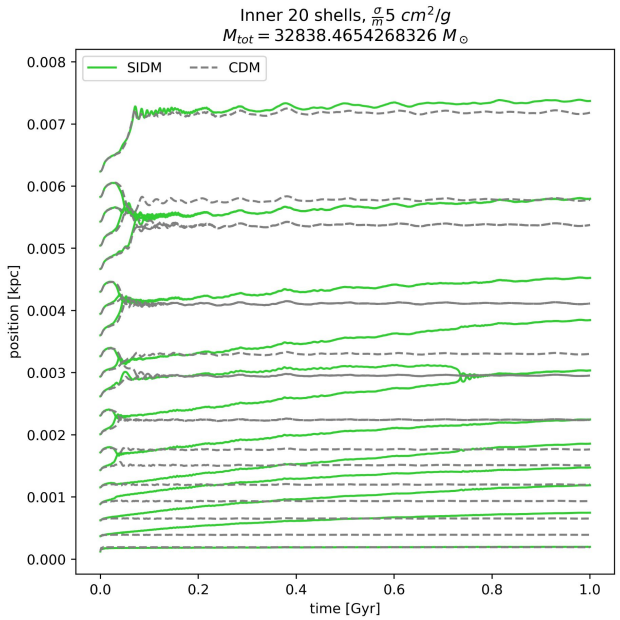
DISSIPATION AND SELFINTERACTIONS (I)

- time evolution of small subhalos for 1 Gyr
- candidates for completely dark subhalos
- start with (truncated) NFW profile
- 200 shells
- CDM vs SIDM vs dissipation vs SI + dissipation

DISSIPATION AND SELFINTERACTIONS (2)

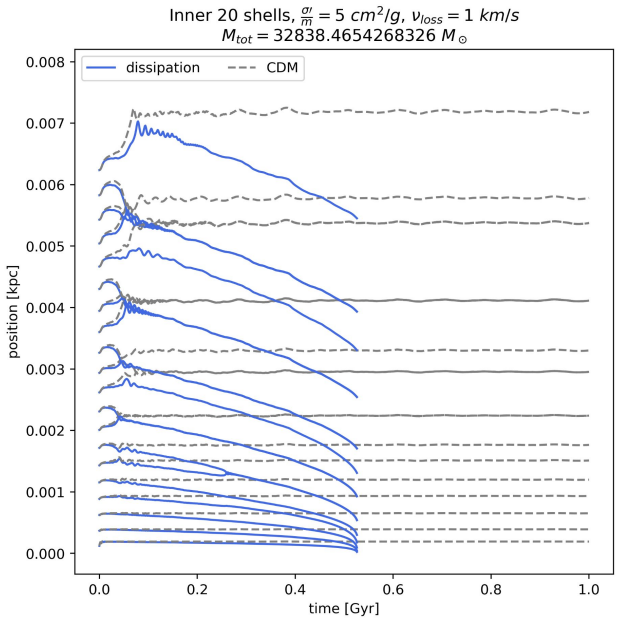
- position of inner 20 shells:

SIDM



move outwards

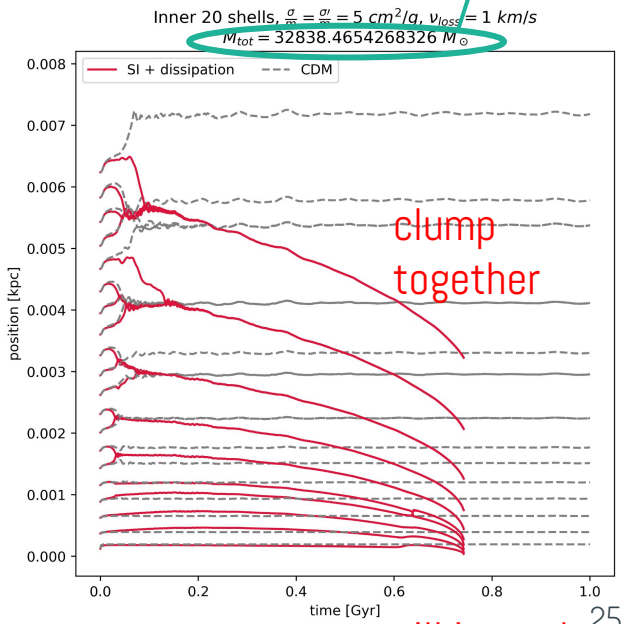
dissipation



move inwards

very small halo!

SI + dissipation

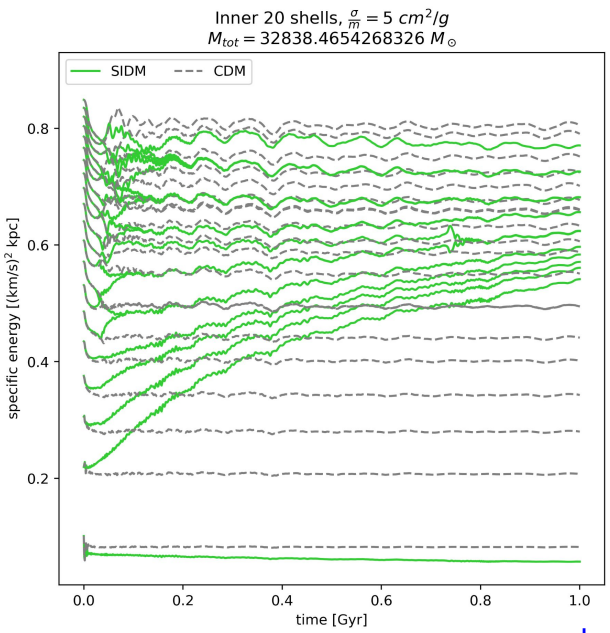


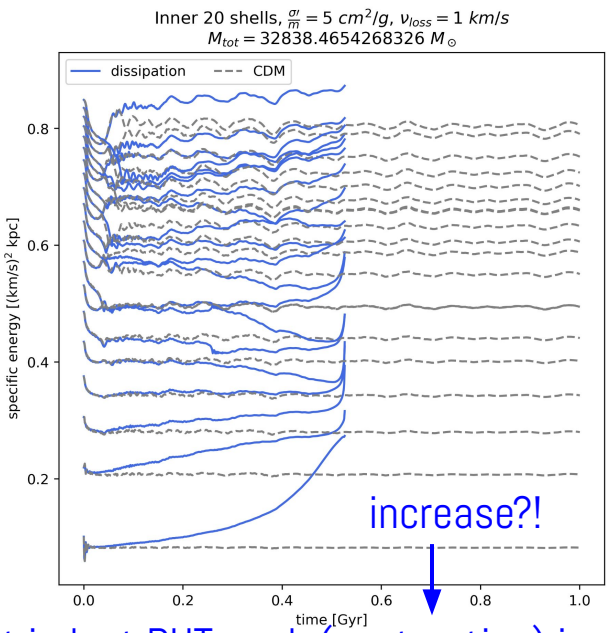
still inwards

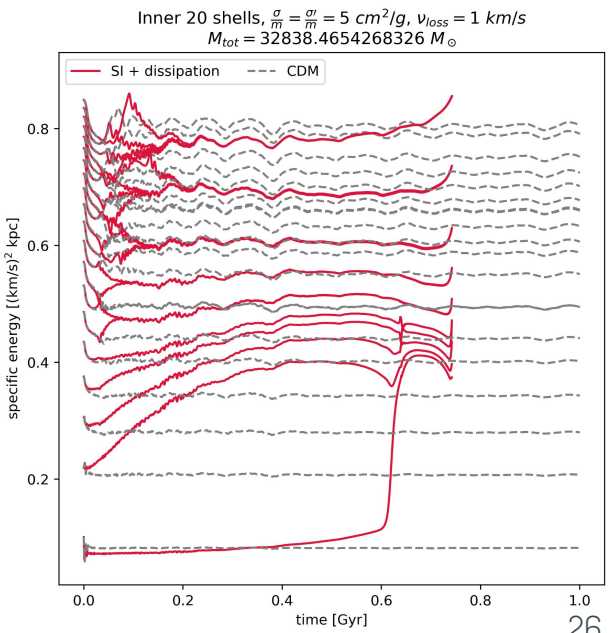
DISSIPATION AND SELFINTERACTIONS (3)

- internal energy of inner 20 shells

SIDM dissipation SI + dissipation

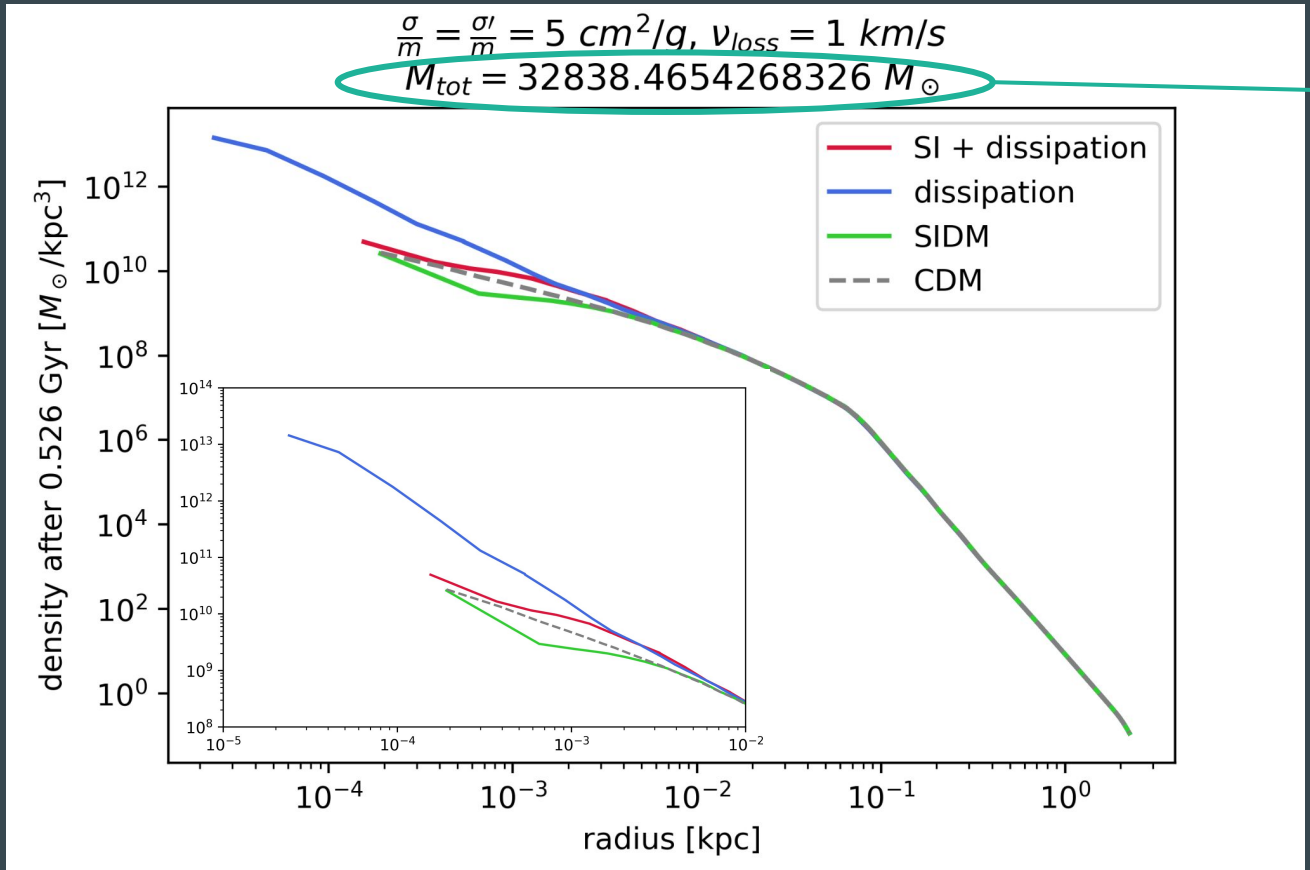






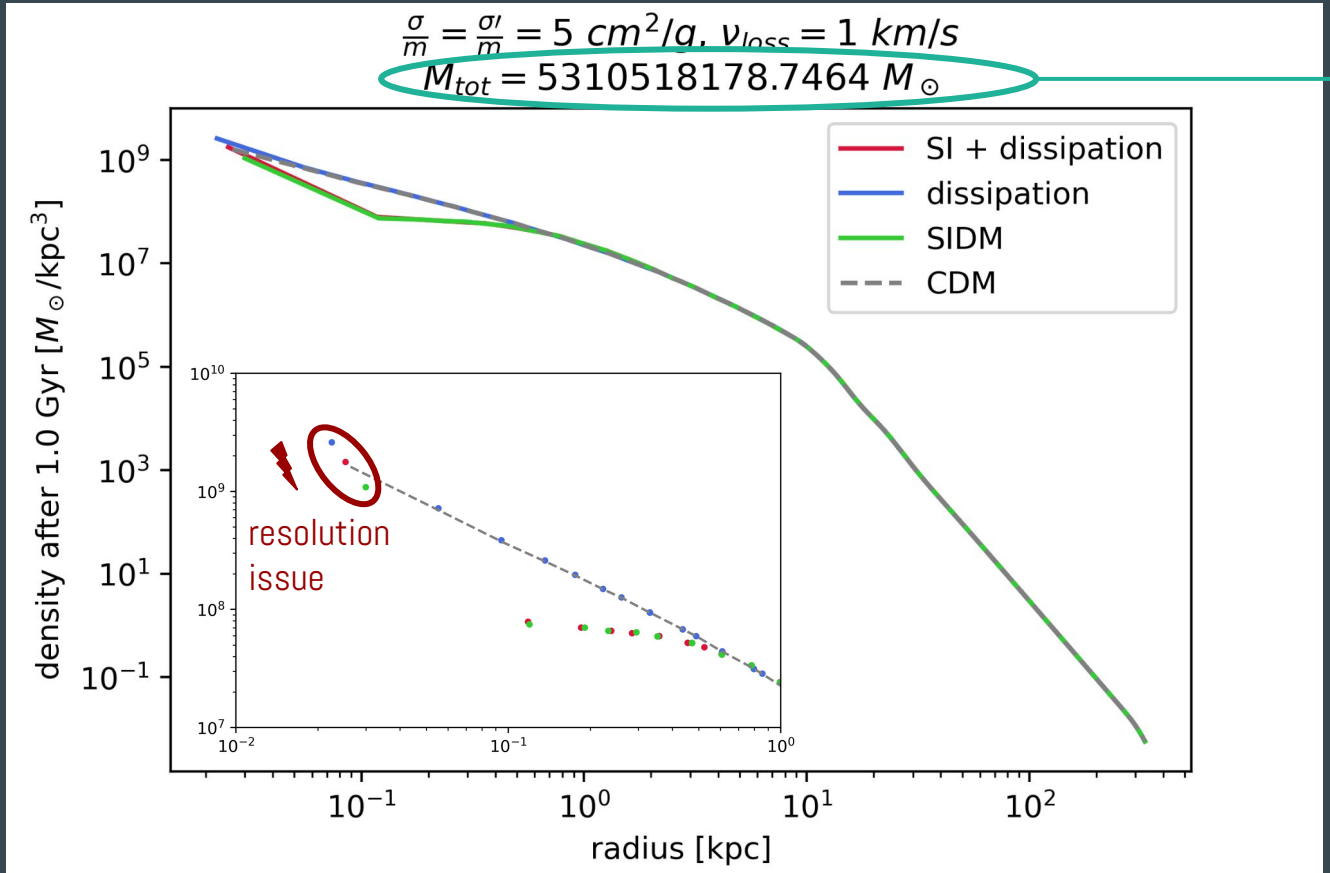
heat is lost BUT work (contraction) is done

DISSIPATION AND SELFINTERACTIONS (4)



very small halo

DISSIPATION AND SELFINTERACTIONS (5)



bigger halo

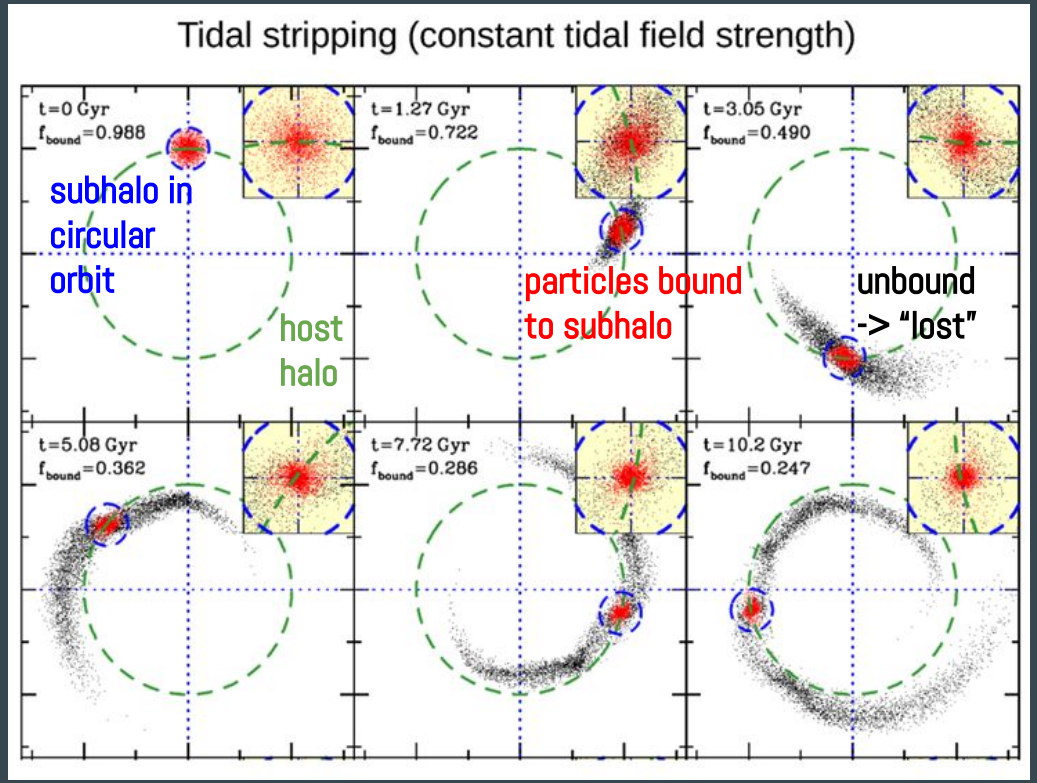
➔ impact relative to SI depends on size

CONCLUSION & OUTLOOK

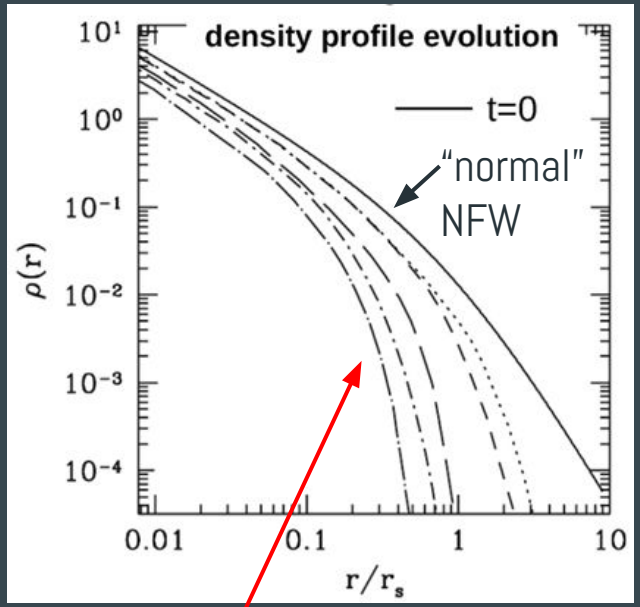
- dissipation ⟶ inner region: T↑, ρ↑
- negative h: gravothermal collapse
  - too early...
- future: longer runs
  - constraints on free parameters by Essig *et al.*

(EXTRA SLIDES DISSIPATION)

TIDAL STRIPPING OF SUBHALOS IN A BIGGER HOST HALO

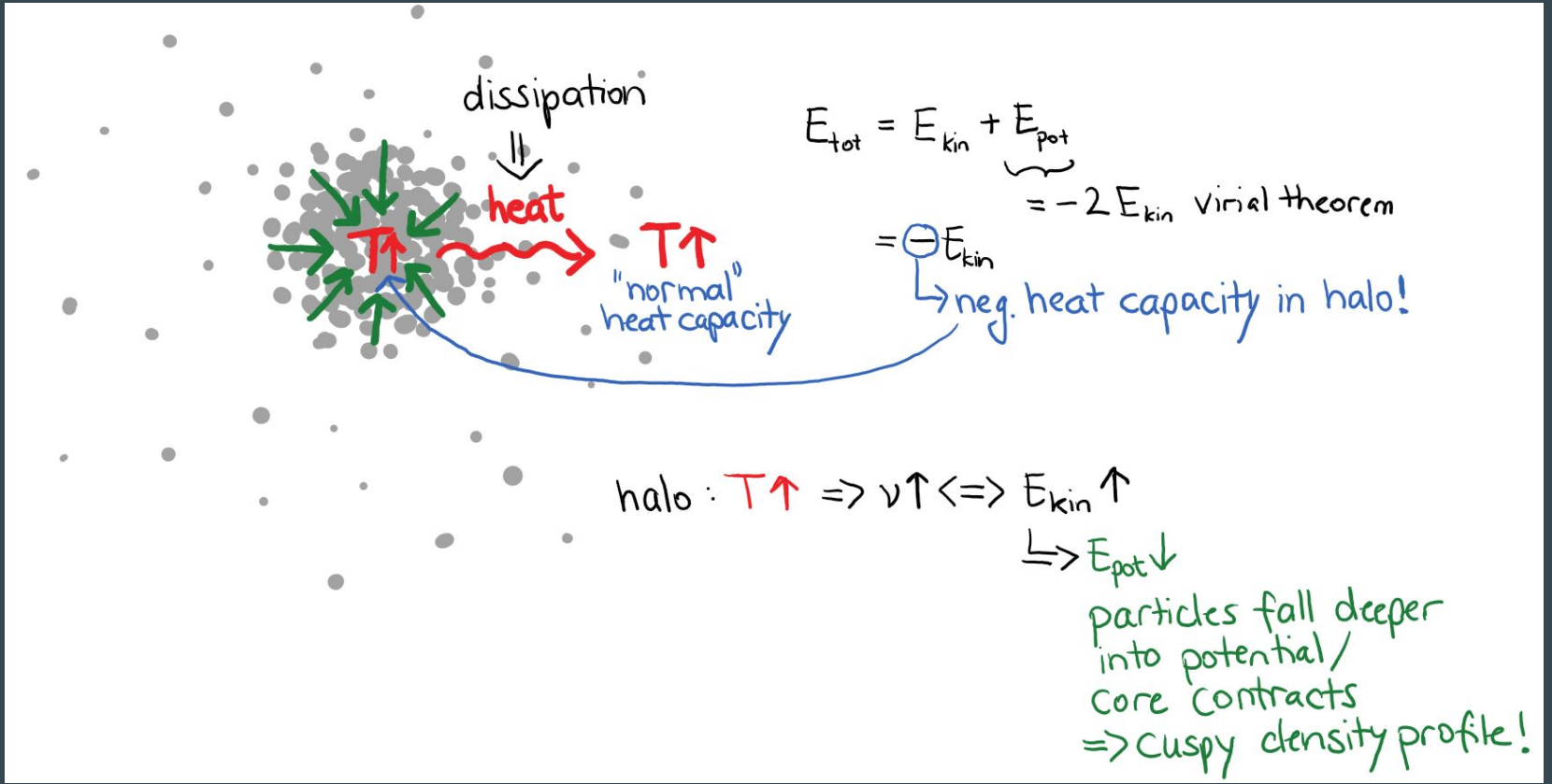


adapted from: Zavala, Frenk *Galaxies* 7(4), 81, (2019)



~ truncated NFW profile
-> use as initial profile for our simulations of dark subhalos!

GRAVOTHERMAL EVOLUTION



D. Lynden-Bell and R. Wood, *Mon. Not. R. Astron. Soc.* **138**, 495 (1968)

ANNIHILATION

WHAT IS ANNIHILATING DARK MATTER?

- 2 DM particles collide/interact and annihilate
- χ: DM particle, f: fermion
- φ: dark boson (i.e. dark photon)
- Different models:
  - DM/anti-DM annihilation: $\chi + \bar{\chi} \rightarrow 2\,\varphi$ [1]
  - Collision of DM WIMPs: $\chi + \chi \rightarrow f + \bar{f}$, $W^+ + W^-$, etc. [2]

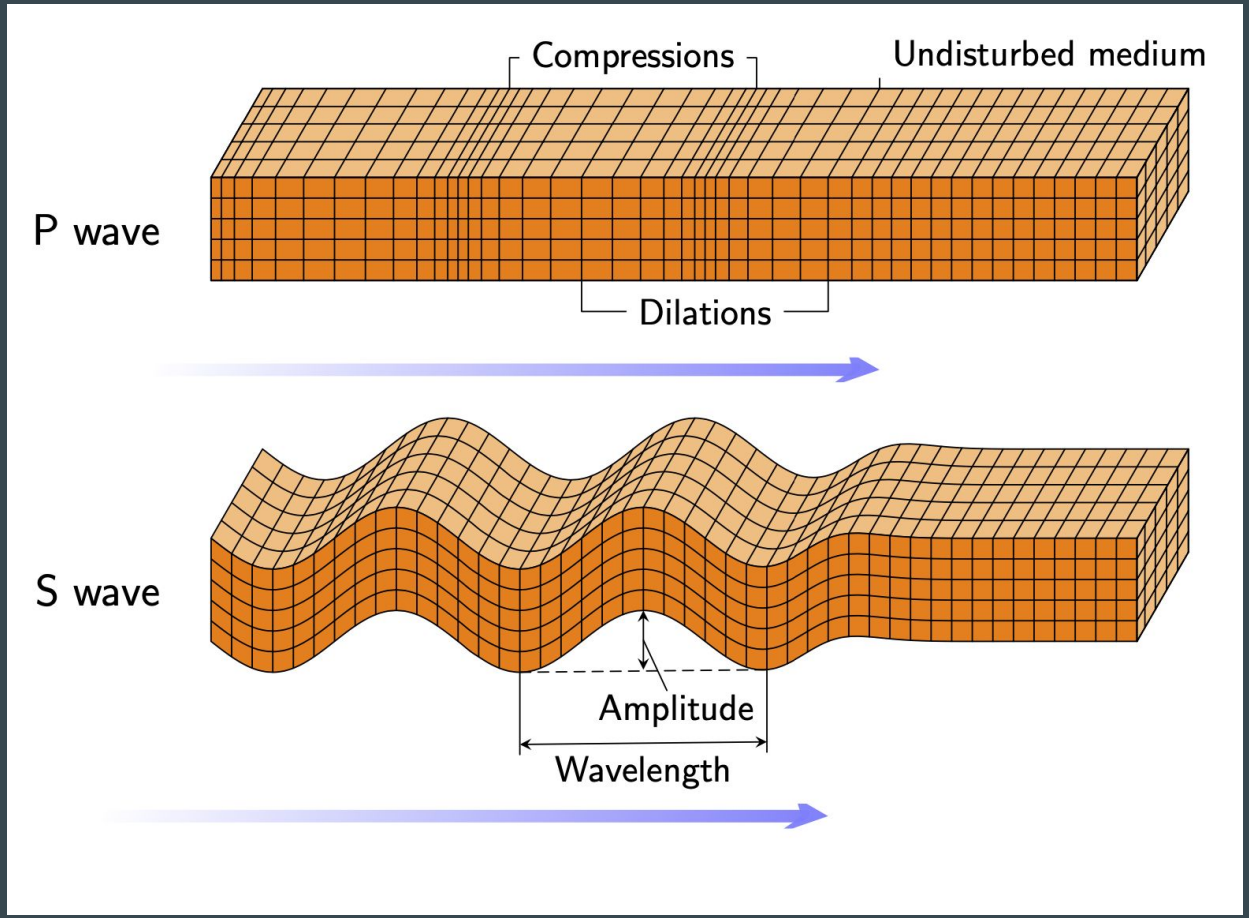
[1]: Salati (2014), arXiv:1403.4495
[2]: Dutra et. al. (2018), arXiv:1801.05447

HOW TO IMPLEMENT ANNIHILATION

- Annihilation rate per particle: $\Gamma = n \cdot \langle \sigma | v | \rangle = (\rho/m) \cdot \langle \sigma | v | \rangle$ [3]
  - n: number density, ρ: mass density
  - m: DM particle mass, M: shell mass
- $\langle \sigma$ |v|$\rangle$ has velocity dependence of:
  - S wave: v^0
  - P wave: v^2
  - General: $v^x \Rightarrow \langle \sigma | v | \rangle = \sigma' \cdot v^x$
- Mass loss within shell:

$$dM/dt = -M \cdot \Gamma = -M \cdot \rho \cdot (\sigma'/m) \cdot v^x$$

[3]: Kaplinghat et. al. (2000), arXiv:astro-ph/005210



https://i.stack.imgur.com/JpTgB.png

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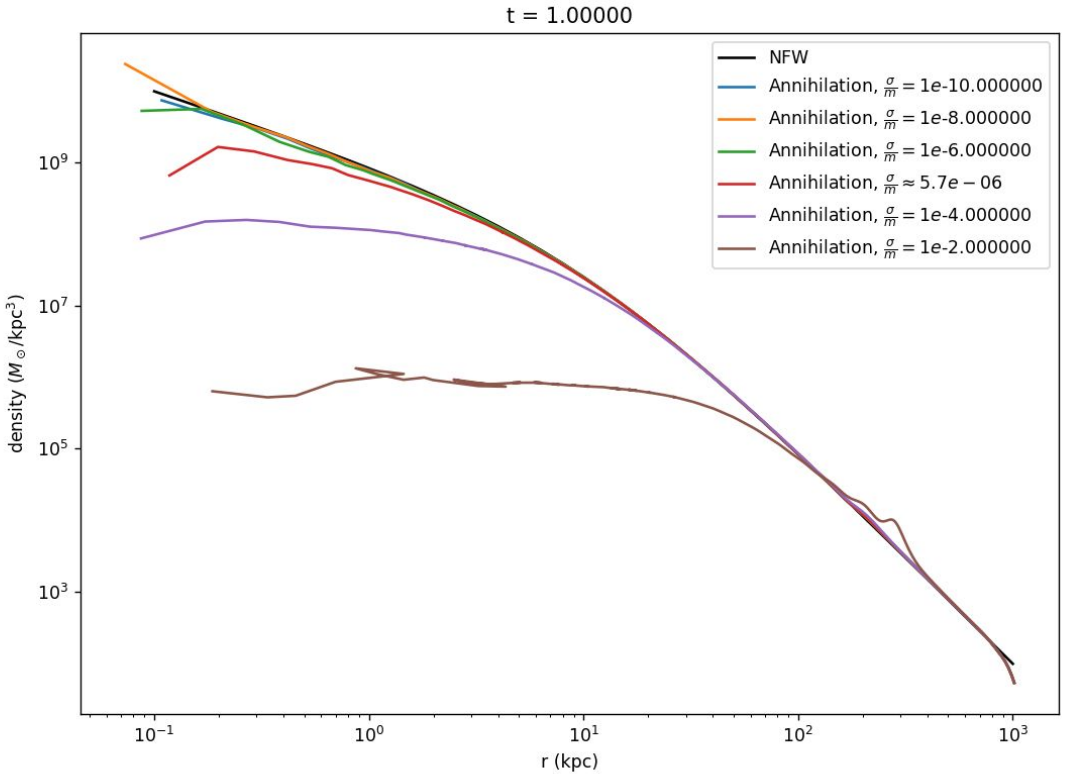
HOW TO IMPLEMENT ANNIHILATION: PROBLEMS

- [3]: promising results with S wave (v^0) and $\langle\sigma|v|\rangle/_m = 10^{-29}\,\mathrm{cm}^2/_{\mathrm{GeV}}$
- $\langle\sigma\,|v|\rangle$ given in units of σ (missing velocity units)
  - Solution: multiply with c
  - For consistency: v → v/c
- With that: units correct!
- But: Time evolution crashed (mass or position negative)
  - Solution: smaller time steps
  - Manually set to zero when negative
  - Different methods for time evolution

RESULTS: FIRST GYR



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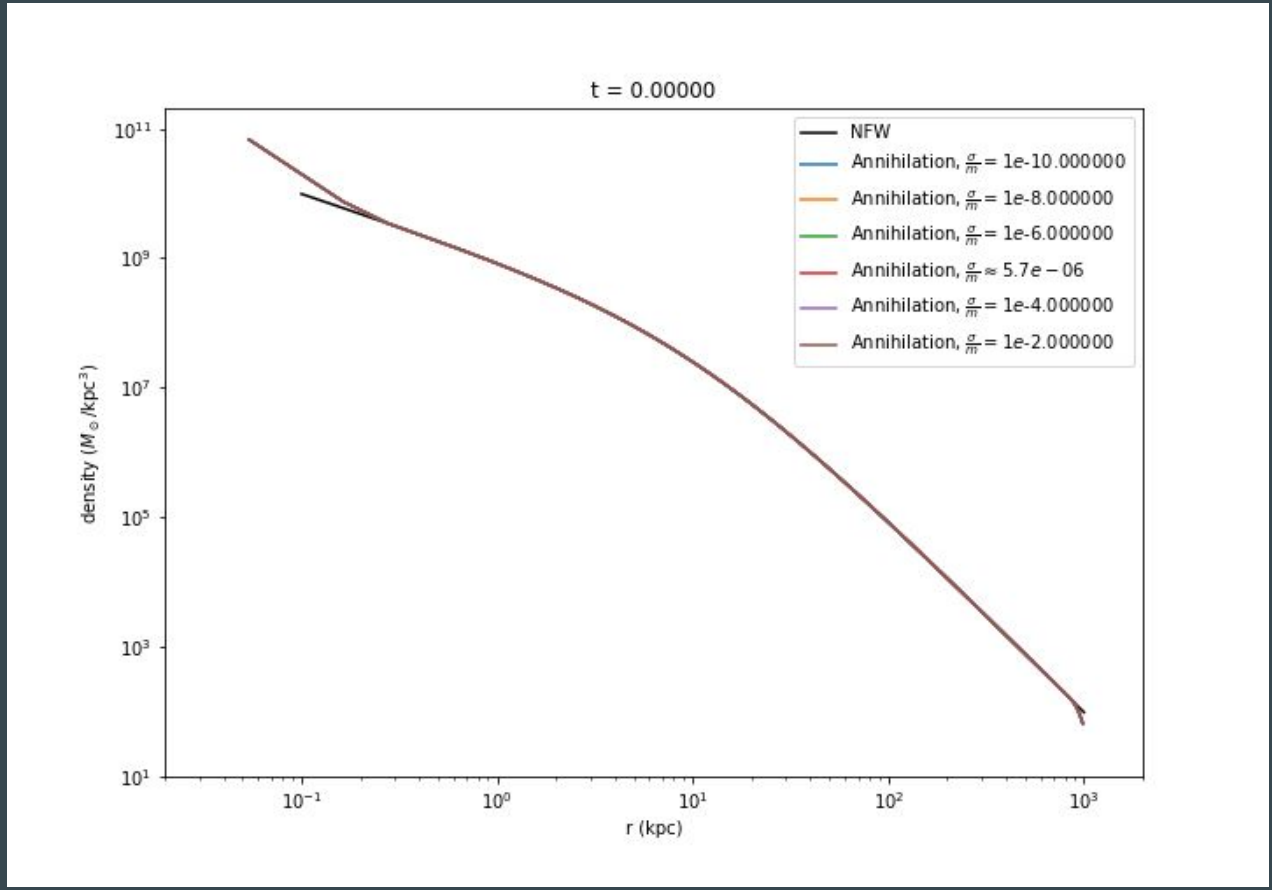

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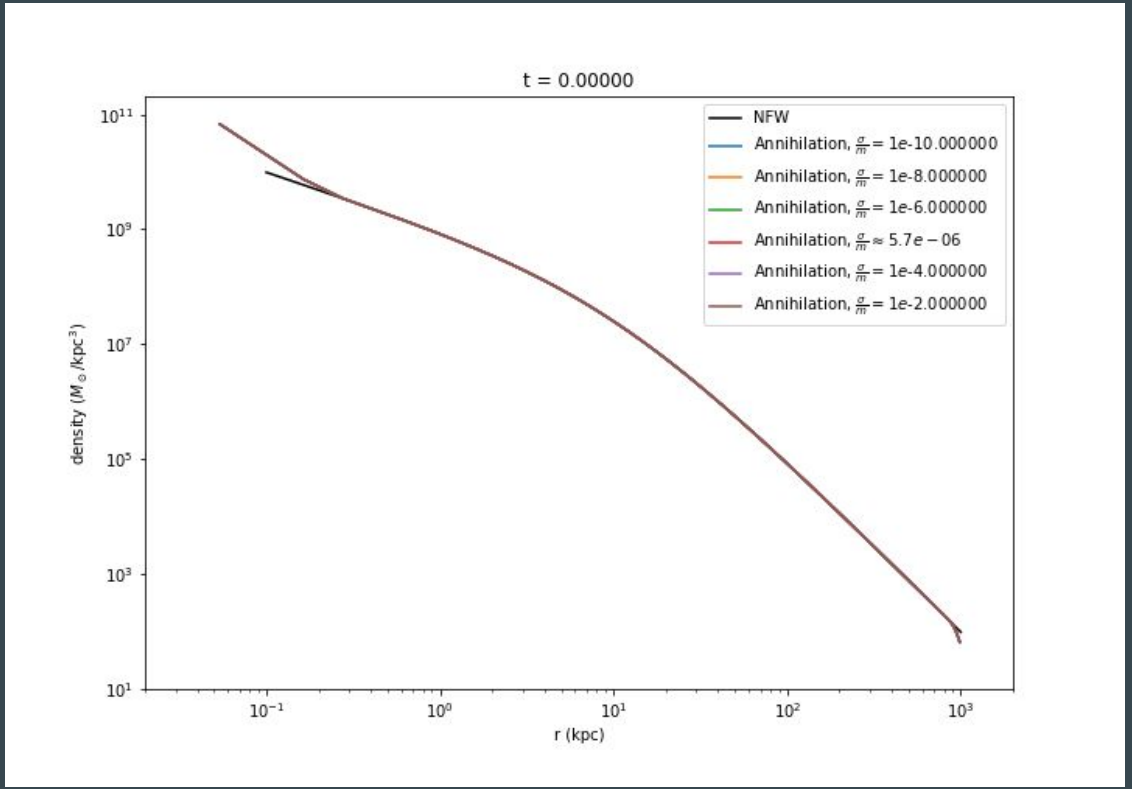
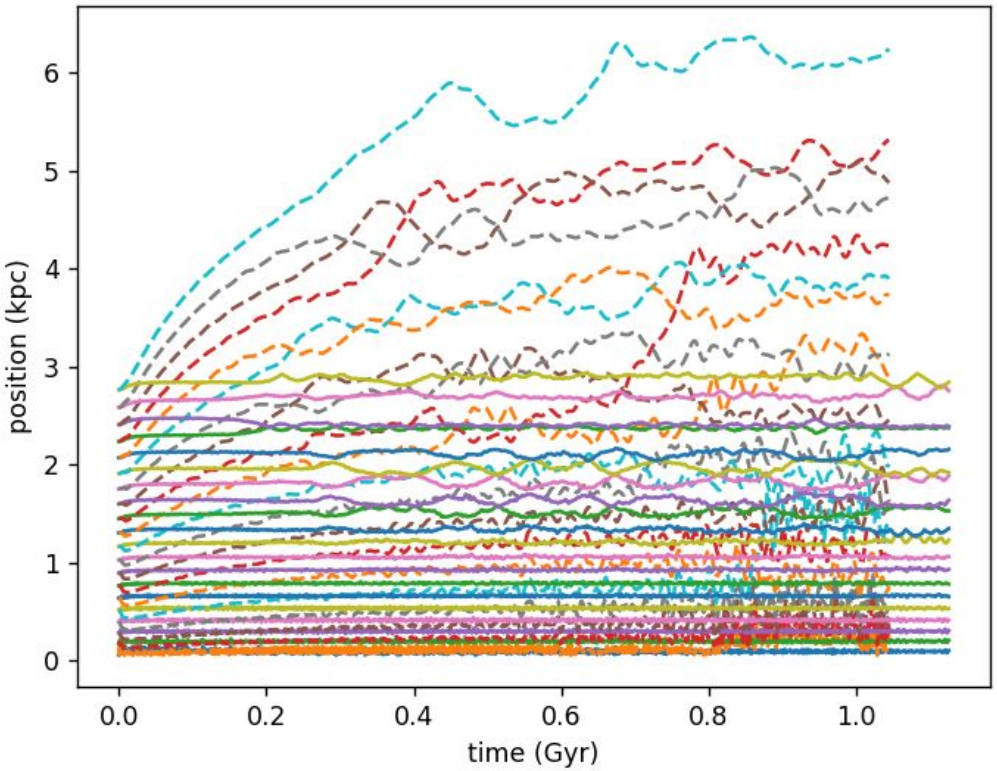
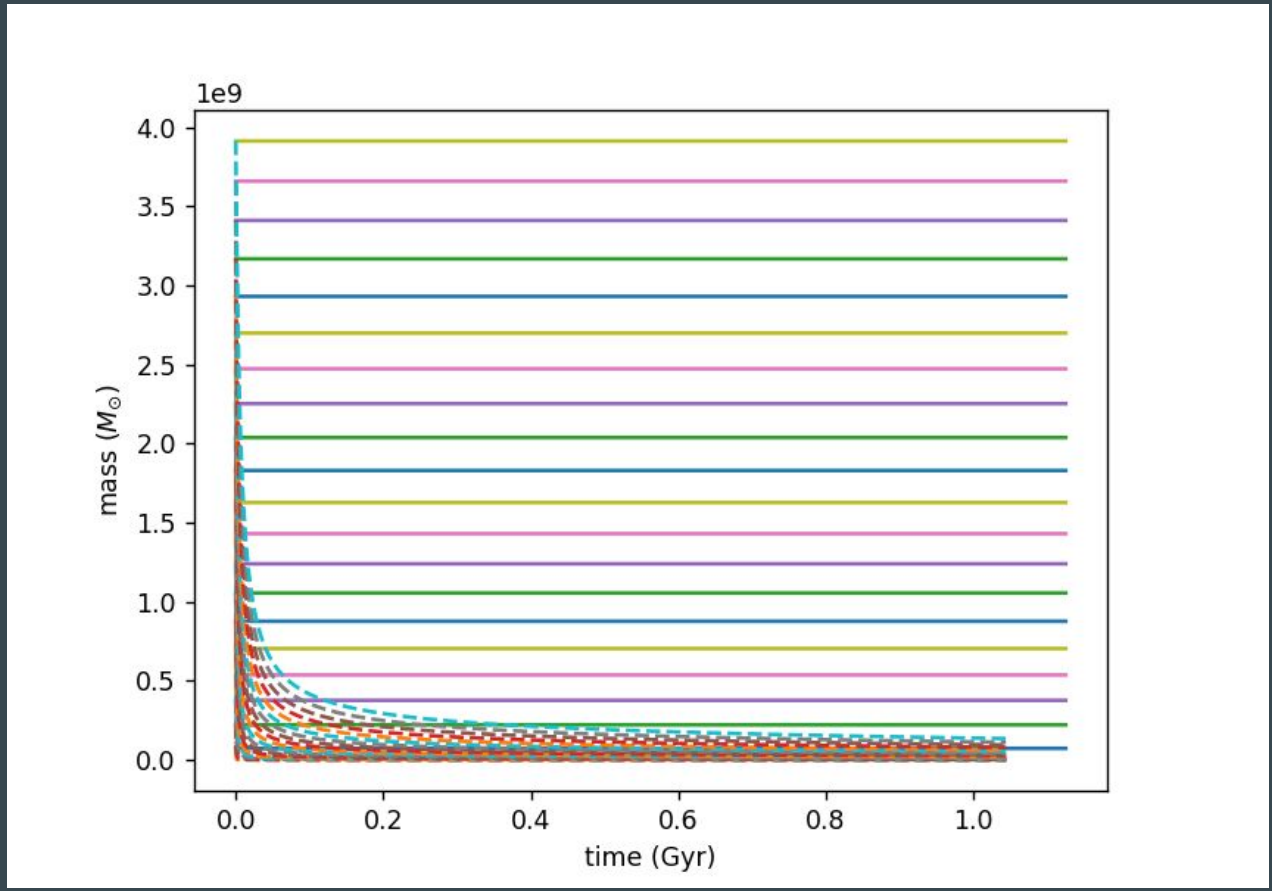


Question: Why does the density behave “erratic” at small radii?

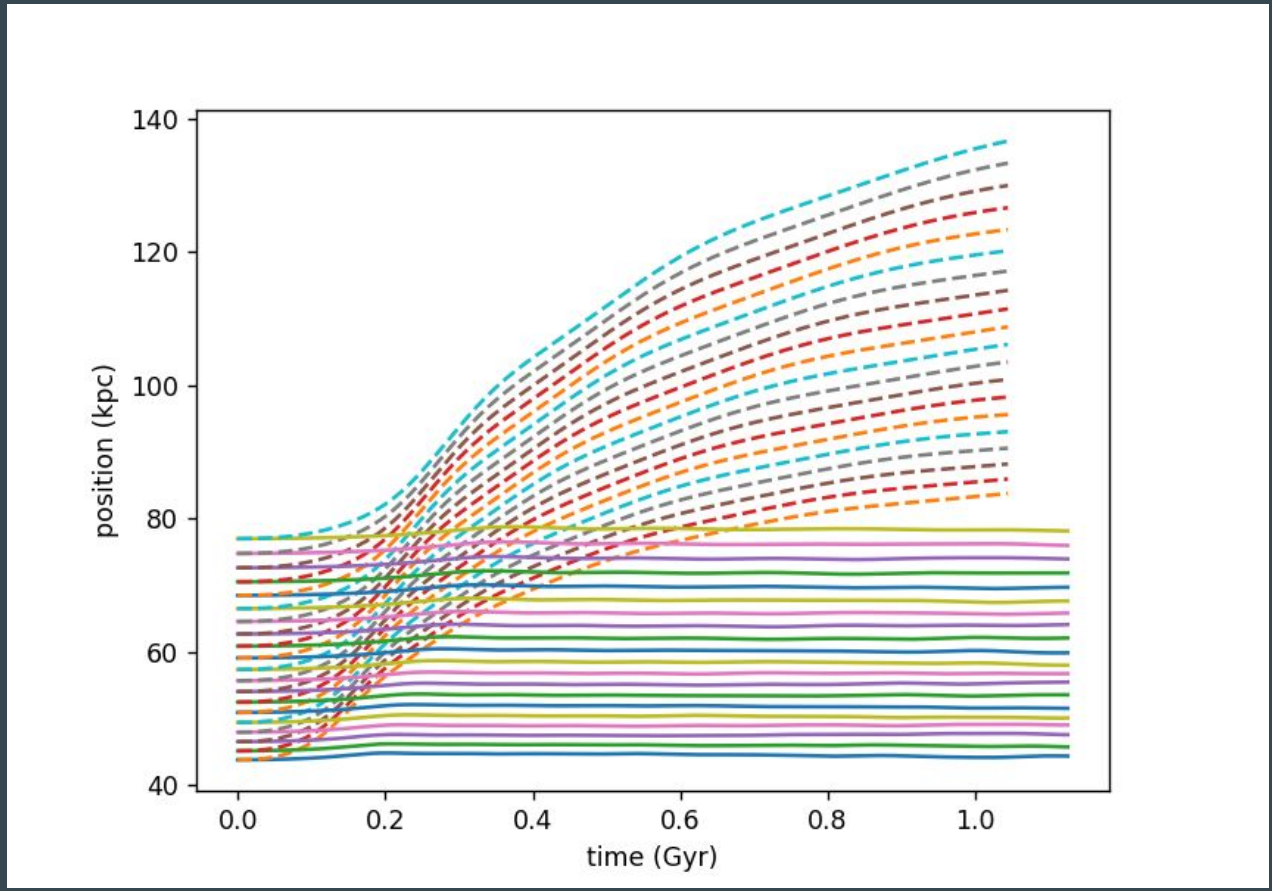
RESULTS: FIRST GYR (INNER 20 SHELLS)



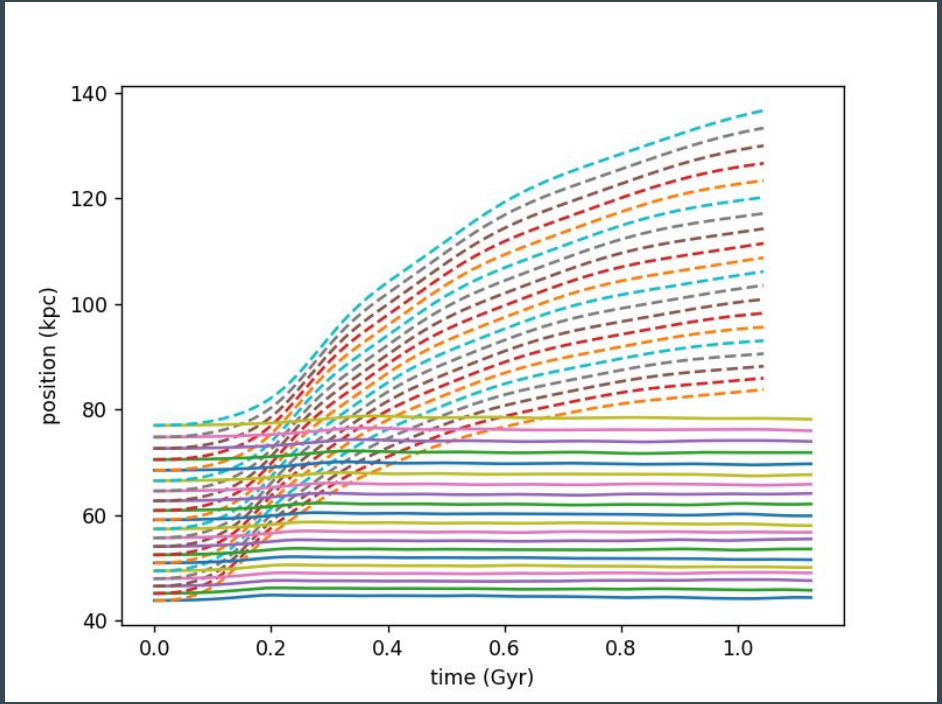
RESULTS: FIRST GYR (INNER 20 SHELLS)



RESULTS: FIRST GYR (MIDDLE 20 SHELLS)

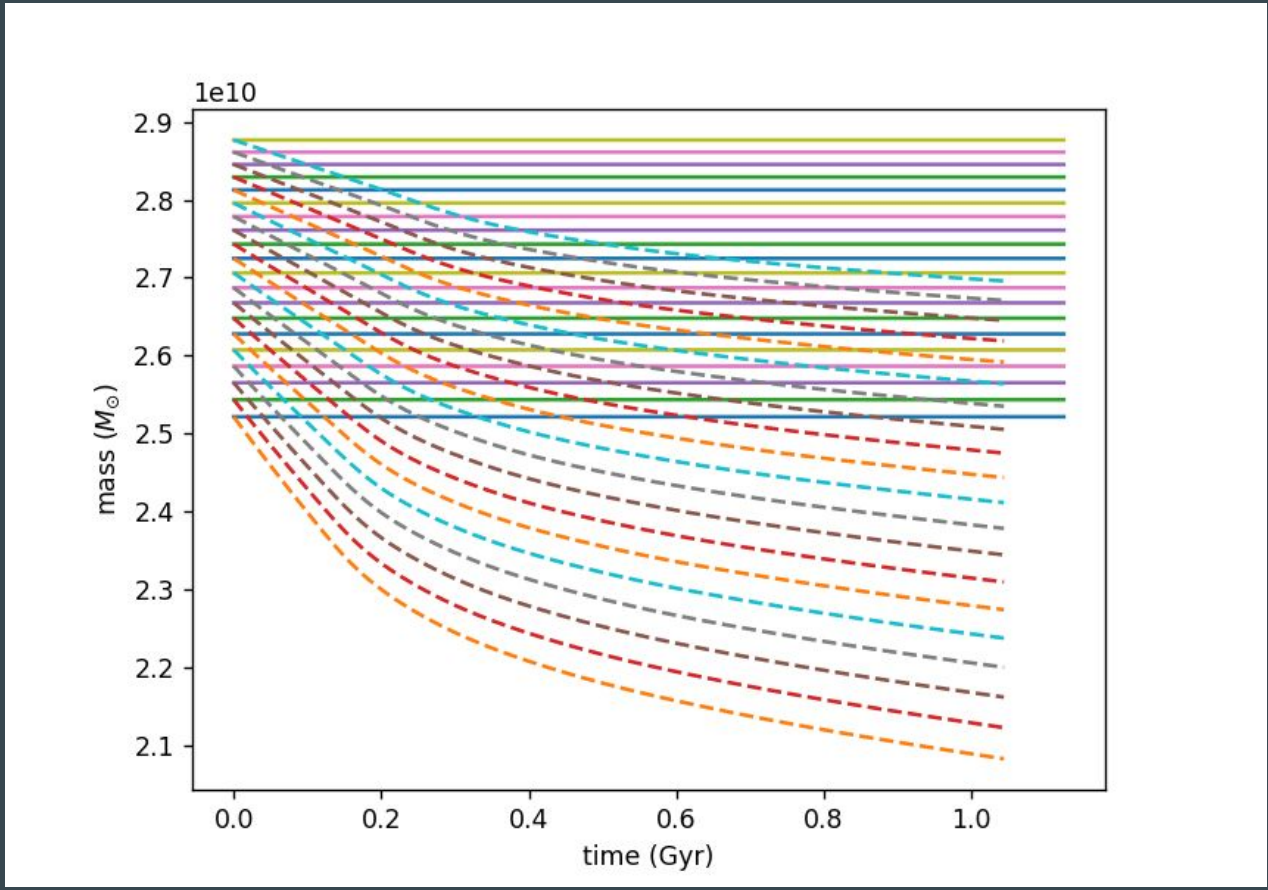


RESULTS: FIRST GYR (MIDDLE 20 SHELLS)

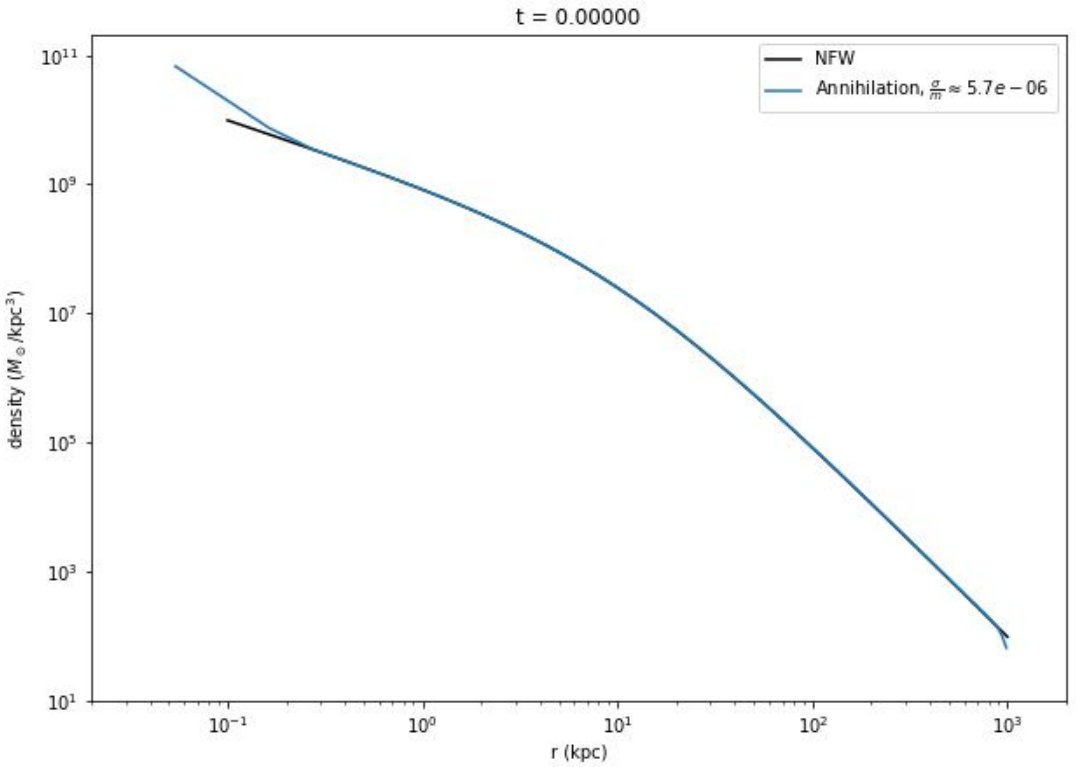


Question: Why do the shells move outwards?

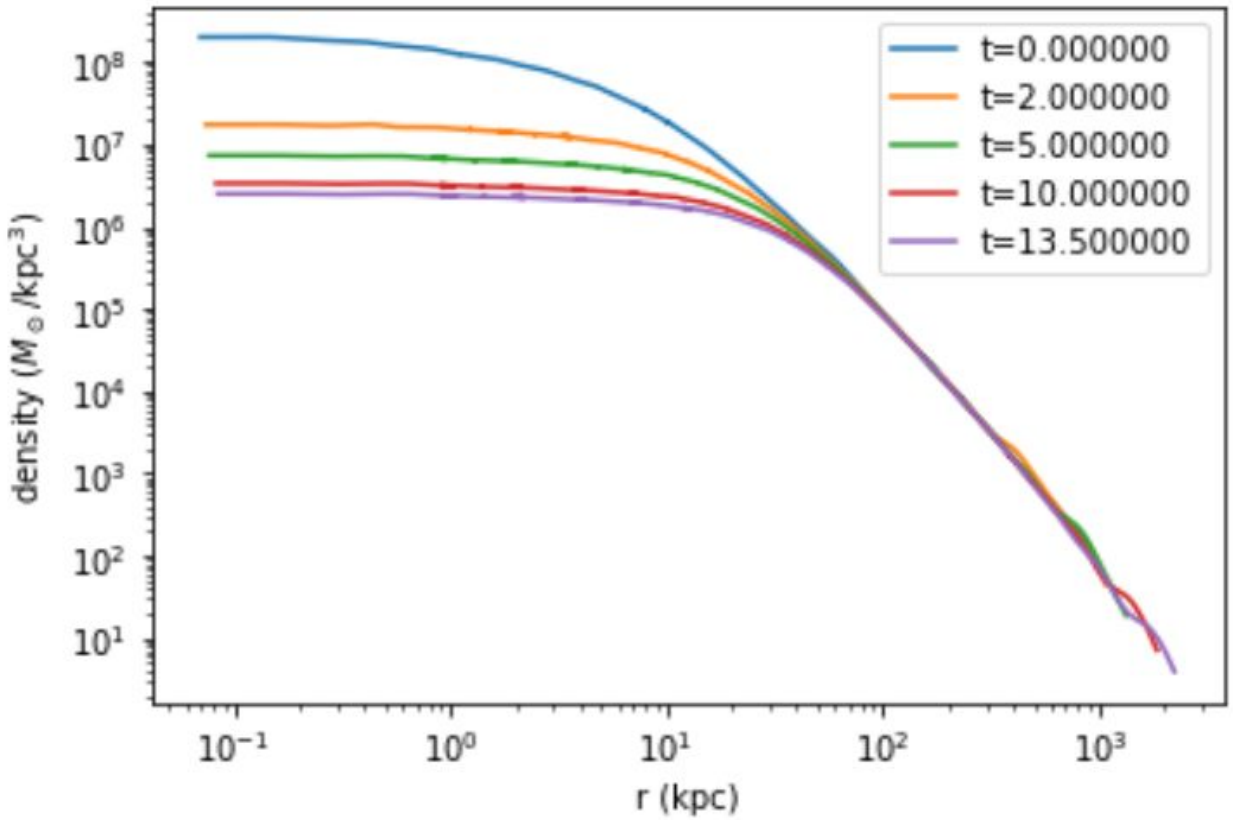
RESULTS: FIRST GYR (MIDDLE 20 SHELLS)



RESULTS VS PREDICTION



RESULTS: DENSITY PROFILE (AGE OF THE MILKY WAY)



RESULTS: PROBLEMS & OPEN QUESTIONS

- Annihilated mass “ignored”
  - No equilibrium state
  - Search for way to include annihilated mass in model
- Study of P wave annihilation

THANK YOU