Cored Dark Halo in the Cosmic Neutrino Background

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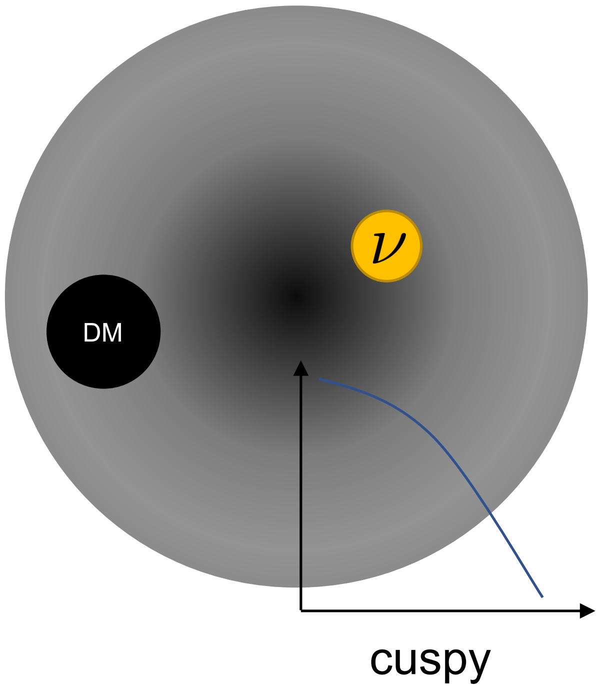
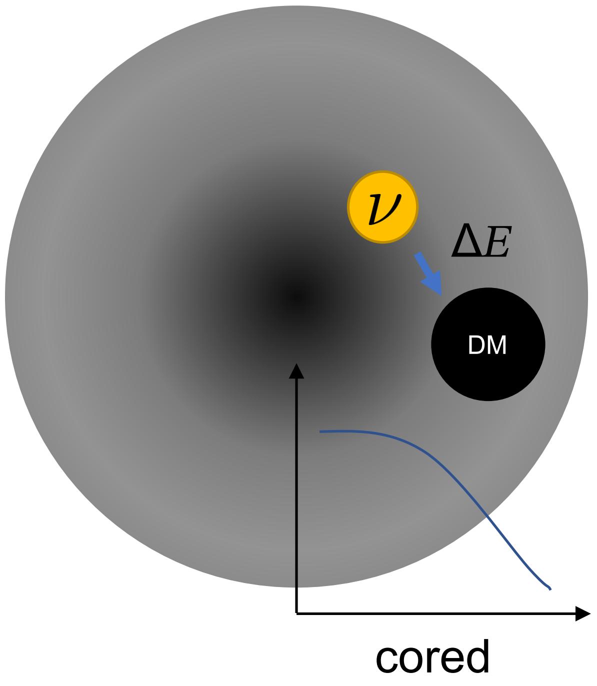
Movitation: Neutrino-DM interaction

Without DM-neutrino interaction



With DM-neutrino interaction



Cosmic Neutrino Background: CνB

- Decoupled from matter when age of universe is around 1 sec
  $n_\nu = n_{\nu,0} + \bar{n}_{\nu,0} = \mathbf{112}\ (1+z)^3\ \mathbf{cm}^{-3}$
- Having Low Energy
  - $T_\nu = \frac{1}{2} m_\nu \langle v \rangle^2 \simeq 1.4 \times 10^{-9}\ \mathrm{keV}\ (1+z)^2 \left(\frac{0.1\ \mathrm{eV}}{m_\nu}\right)$
  - $\langle v \rangle \simeq 1.6 \times 10^3\ (1+z)\ \left(\frac{0.1\ \mathrm{eV}}{m_\nu}\right)\ \mathrm{km/s}$
- Notoriously difficult to detect

Initial Condition & Assumptions

1. DM-neutrino scattering does not affect the formation/virialization stage of halos.
2. Considering the importance of the heating towards early epochs, the initial virialized density profile of halos may not be the NFW profile.

Heating

- Heating time scale

$$t_{heat}^{-1} = \frac{1}{w^2}\frac{\delta q}{\delta t} = \frac{n_\nu \sigma_{\chi\nu}\langle v_\nu \rangle}{w^2}\frac{\Delta E}{m_\chi}$$

$$\simeq \frac{9\times 10^{-6}(1+z)^6}{\mathrm{Gyr}}\left(\frac{10\mathrm{km/s}}{w}\right)^2\left(\frac{0.1\mathrm{keV}}{m_\chi}\right)^2\left(\frac{\sigma_{\chi\nu}}{10^{-31}\mathrm{cm}^2}\right)\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)$$

- Energy transfer form CνB to DM

$$\Delta E = \frac{2m_\nu m_\chi}{(m_\nu + m_\chi)^2}(T_\nu - T_\chi)$$

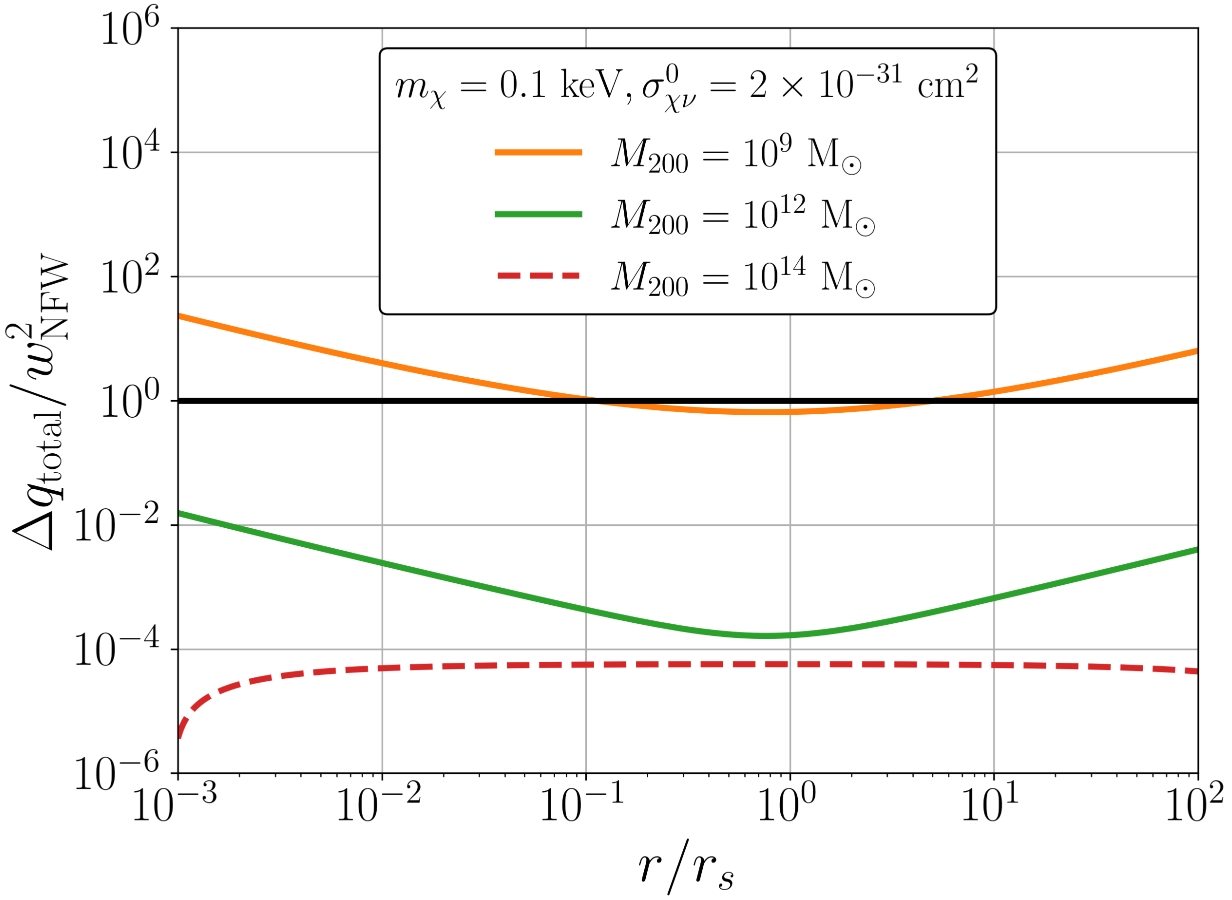
$$\simeq 2.8\times 10^{-12}\ \mathrm{keV}\ (1+z)^2\left(\frac{0.1\ \mathrm{keV}}{m_\chi}\right)\left(1-\frac{T_\chi}{T_\nu}\right)$$

- Total heat transfer per DM mass during evolution

$\Delta q_{total} \equiv \int_{t_*}^{t_{age}} \frac{\delta q}{\delta t} dt$

Heating

- Heating is efficient when $\Delta q_{total}/w_{NFW}^2 > 1$
- When the mass of DM halo is smaller, heating is more efficient than larger mass of DM halo.
- When mass of DM halo is big as galaxy cluster, DM even transfer energy to neutrino.



Gravothermal Fluid Model

- Neglect LHS of Euler equation and V_r in the limit of quasi static equilibrium and Lagrangian formalism

$$t_{\text{heat}} \gg t_G = 1/\sqrt{4\pi G\rho} \simeq 0.1\ \text{Gyr}\ (0.01\ \text{M}_\odot \cdot \text{pc}^{-3}/\rho)^{-1/2}$$

- Rate of specific heat injection

$$\text{continuity equation}: \frac{\partial\rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho V_r) = 0,$$

$$\text{Poisson's equation}: \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\Phi}{\partial r}\right) = 4\pi G\rho,$$

$$\text{Euler equation}: \frac{\partial V_r}{\partial t} + V_r\frac{\partial V_r}{\partial r} = -\frac{\partial\Phi}{\partial r} - \frac{1}{\rho}\frac{\partial(\rho w^2)}{\partial r},$$

$$\text{entropy}: \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V_r) + \frac{3}{w}\left[\frac{\partial w}{\partial t} + V_r\frac{\partial w}{\partial r}\right] = \frac{1}{w^2}\frac{\delta q}{\delta t},$$

Gravothermal Fluid Model

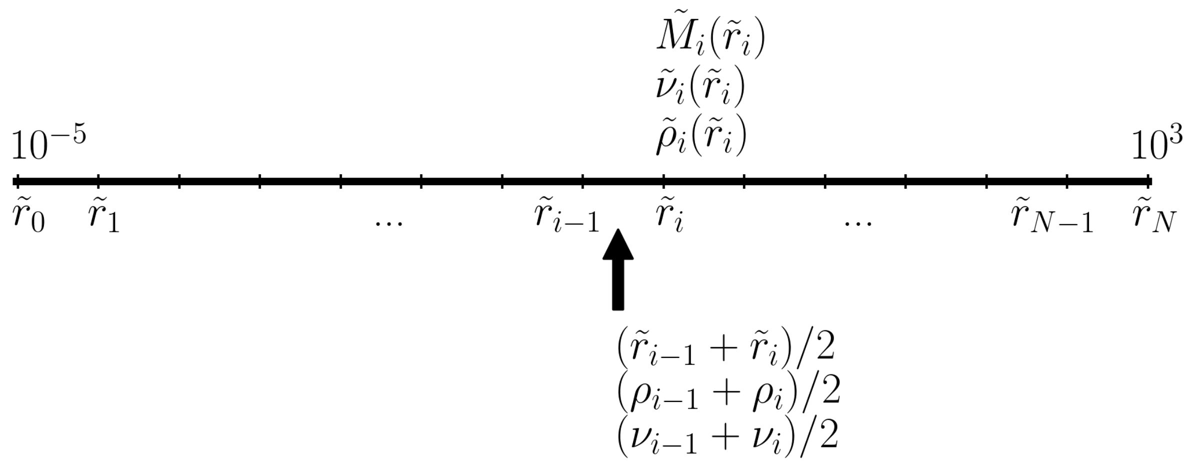
$$\text{mass conservation}: \frac{\partial M}{\partial r} = 4\pi r^2 \rho \,,$$

$$\text{hydrostatic equilibrium}: \frac{\partial \left(\rho w^2\right)}{\partial r} + \frac{G M \rho}{r^2} = 0 \,,$$

$$\text{entropy}: \left(\frac{\partial}{\partial t}\right)_M \ln \frac{w^3}{\rho} = \frac{1}{w^2} \frac{\delta q}{\delta t} \,,$$

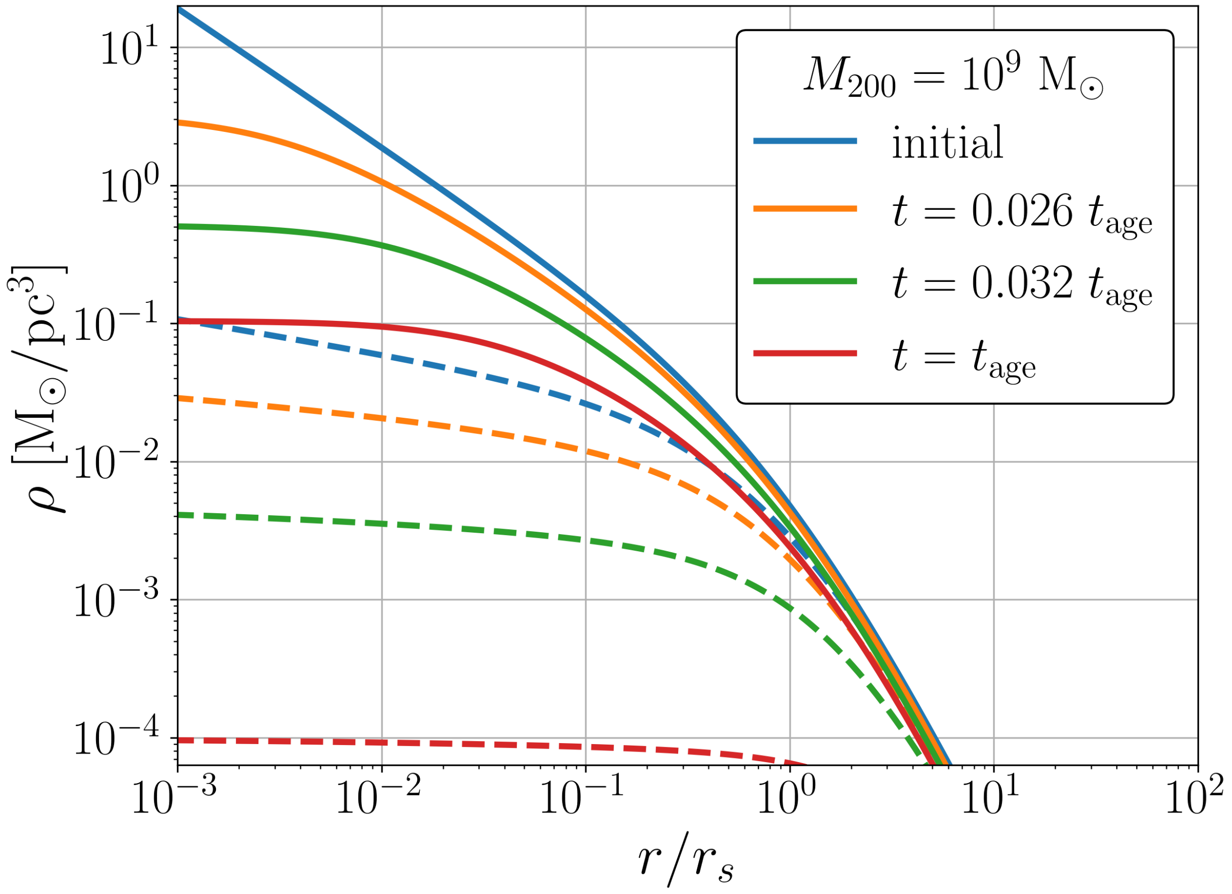
Numerical Method: Gravothermal Fluid

- Heating Step
  $$3\delta w_i^2 = n_\nu \sigma_{\chi\nu} \langle v_\nu \rangle \frac{\Delta E}{m_\chi} \delta t$$
- Return to Hydrostatic equilibrium
  $$\frac{\partial M}{\partial r} = 4\pi r^2 \rho,$$
  $$\frac{\partial(\rho w^2)}{\partial r} + \frac{GM\rho}{r^2} = 0$$



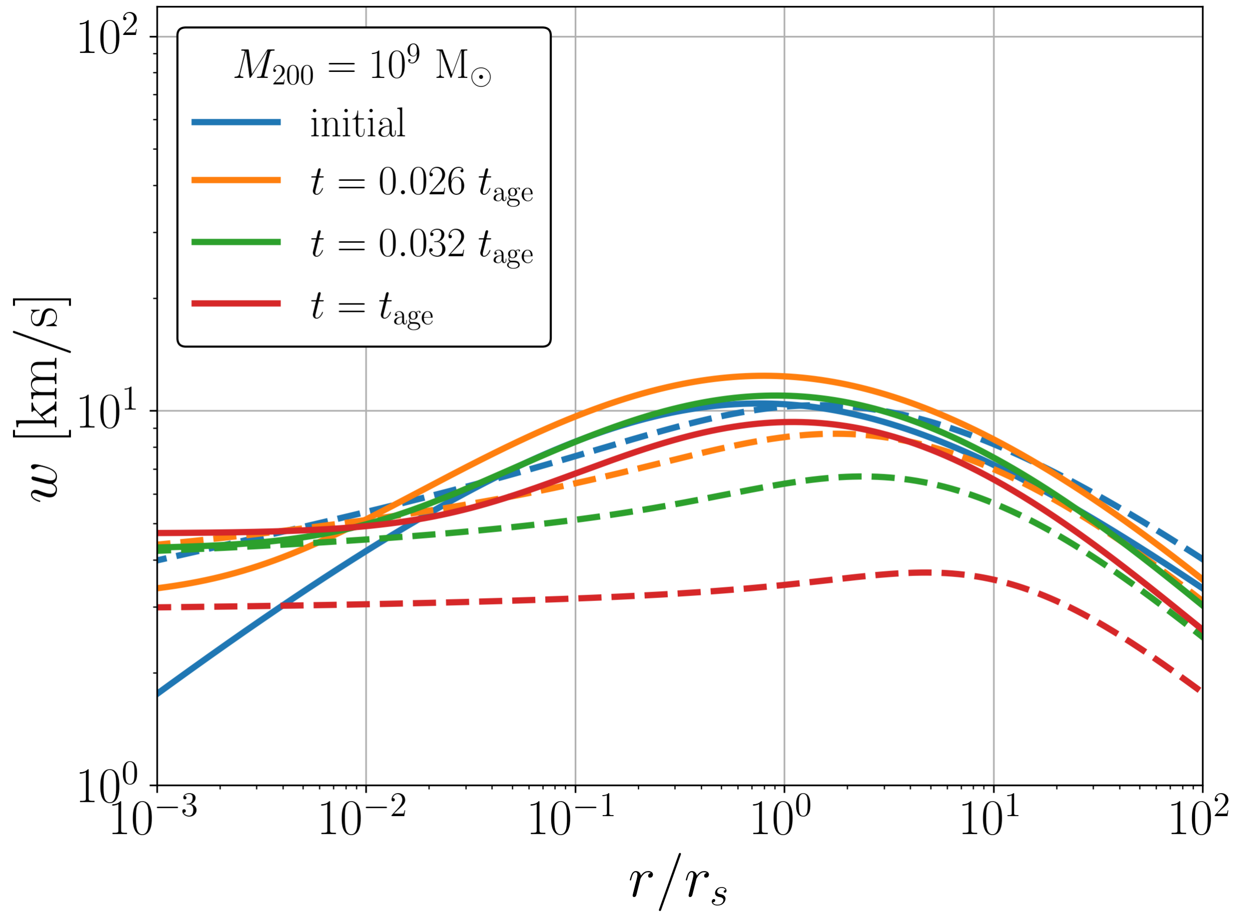
Evolution of DM Halo

- Evolution of mass density of DM halo when $\sigma_{\chi\nu} = 2 \times 10^{-31}\ \mathrm{cm}^2$, $m_\chi = 0.1\ \mathrm{keV}$, and $m_\nu = 0.1\ \mathrm{eV}$.
- Solid line is evolution of NFW profiles
- The central density of DM halo decreases



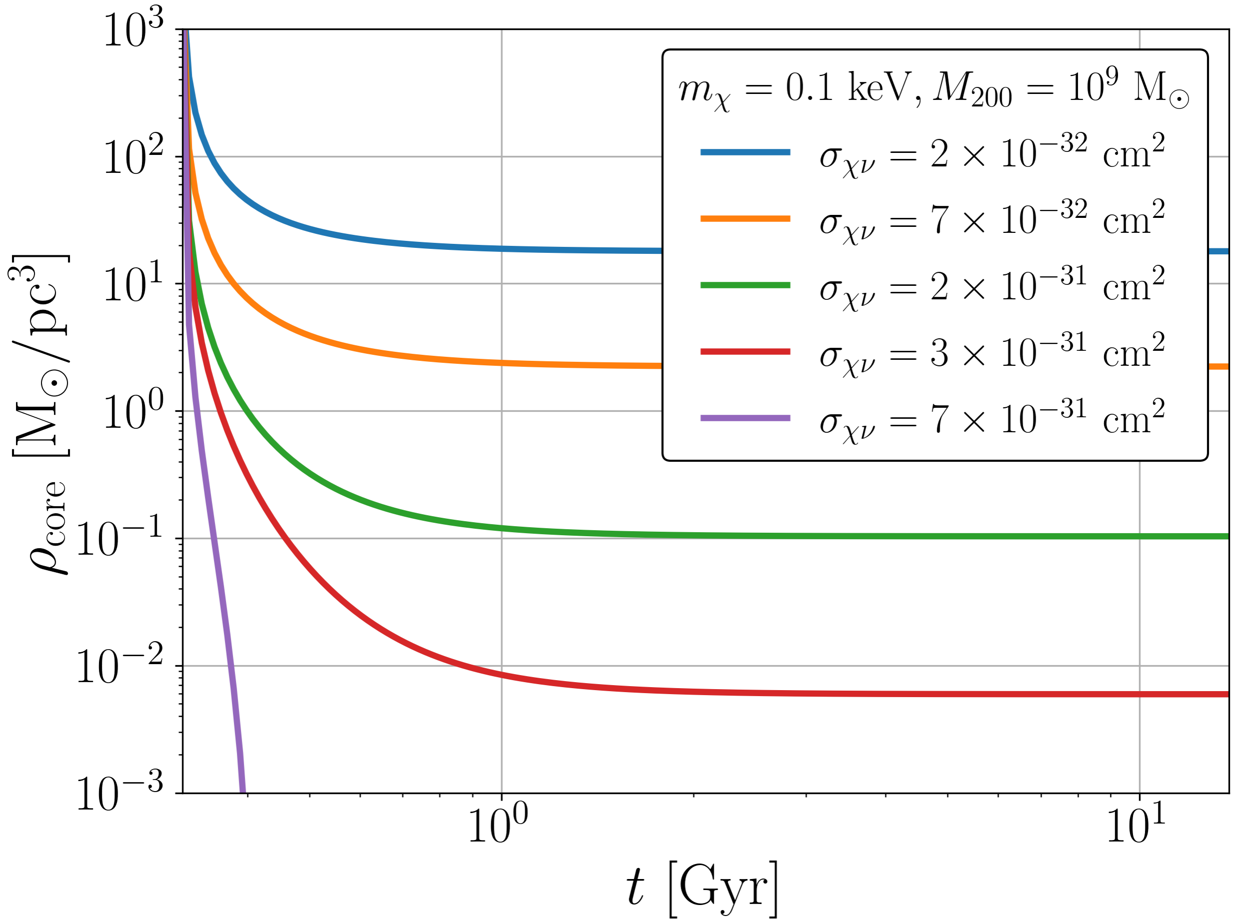
Evolution of DM Halo

- Time evolution of velocity dispersion w
- The velocity dispersion in the center grows to satisfy hydrostatic equilibrium



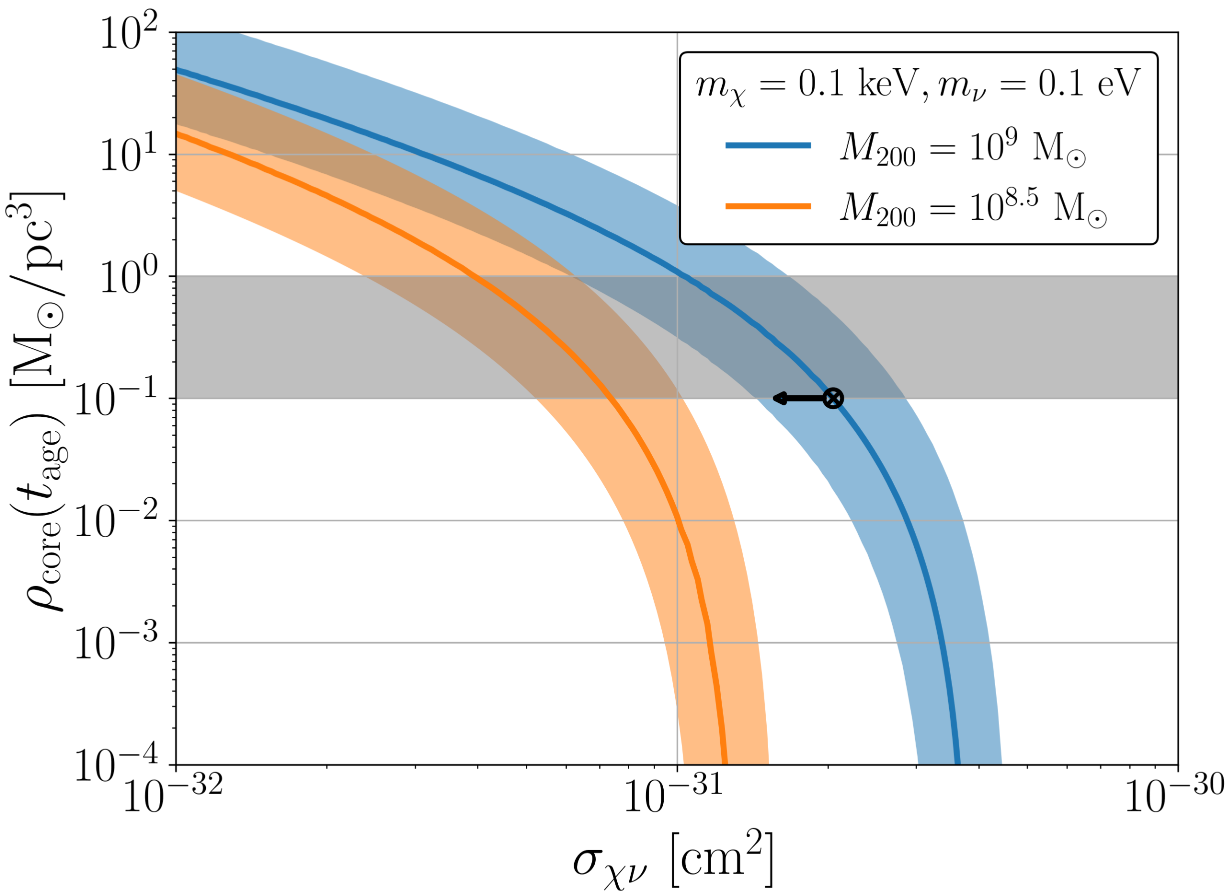
Constraints on DM-Neutrino cross section

- Time evolution of core density
- Core formation is efficient in the early time of the evolution



Constraints on DM-Neutrino cross section

- Cored density when $t = t_{age}$
- $\rho^{obs}_{\rm core}(t_{\rm age}) \gtrsim 0.1$ gives upper bound on DM-neutrino scattering
  $\sigma_{\chi\nu} \lesssim 2 \times 10^{-31} \mathrm{cm}^2$



Summary

- The impact of the heating is stronger towards smaller-size halos, and we have used the observations on central densities of MW satellites to constrain the DM-neutrino scattering cross section in the non-relativistic regime $\boldsymbol{\sigma_{\chi\nu} \lesssim 10^{-31}\ \mathrm{cm}^2}$ for $\boldsymbol{m_\chi = 0.1\,\mathrm{keV}, m_\nu = 0.1\,\mathrm{eV}}$.
- If the mass of an MW satellite is smaller, the heating would have a more significant impact since the typical kinetic energy of DM particles is smaller.