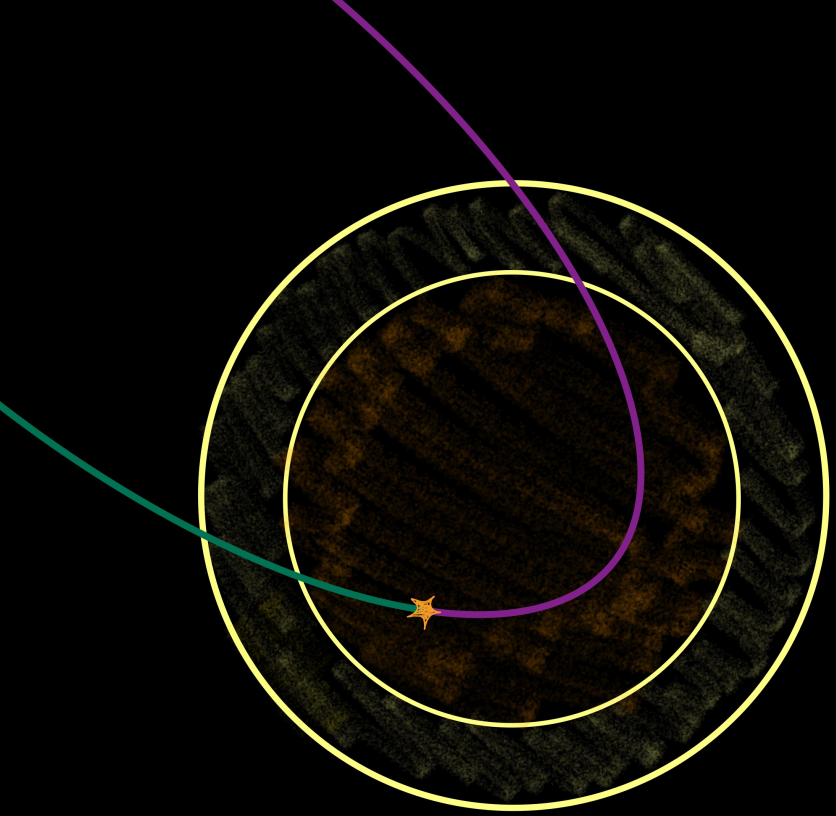


Heavy dark matter in rapidly evolving massive stars

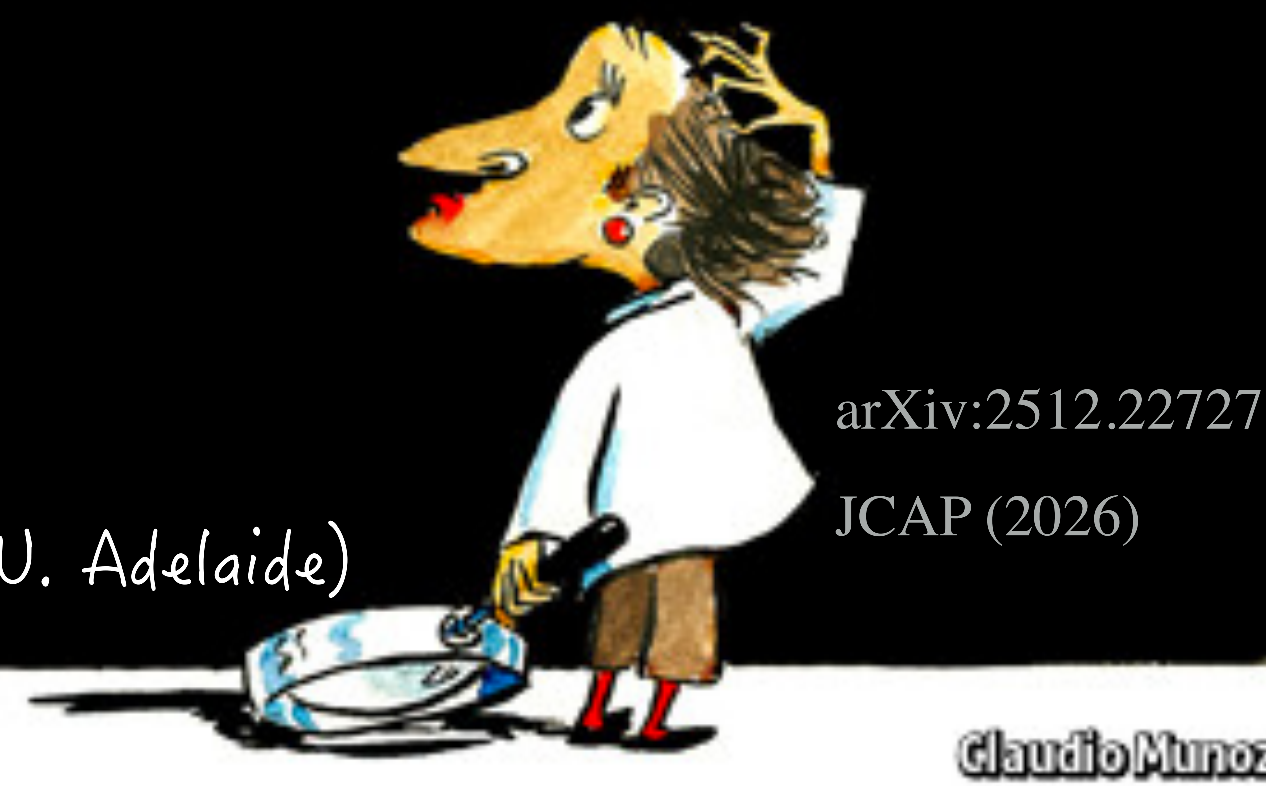
Φαινό 2026

The 2026 Phenomenology Symposium

Walter Tangarife

Loyola University Chicago

with Sandra Robles (Fermilab), Giorgio Busoni (U. Adelaide)



arXiv:2512.22727

JCAP (2026)

LOYOLA UNIVERSITY CHICAGO

Supported by NSF grant No. PHY-2310224

Can first-generation stars tell us anything about dark matter?

The capture of dark matter by stars and other compact objects

has been extensively studied before.

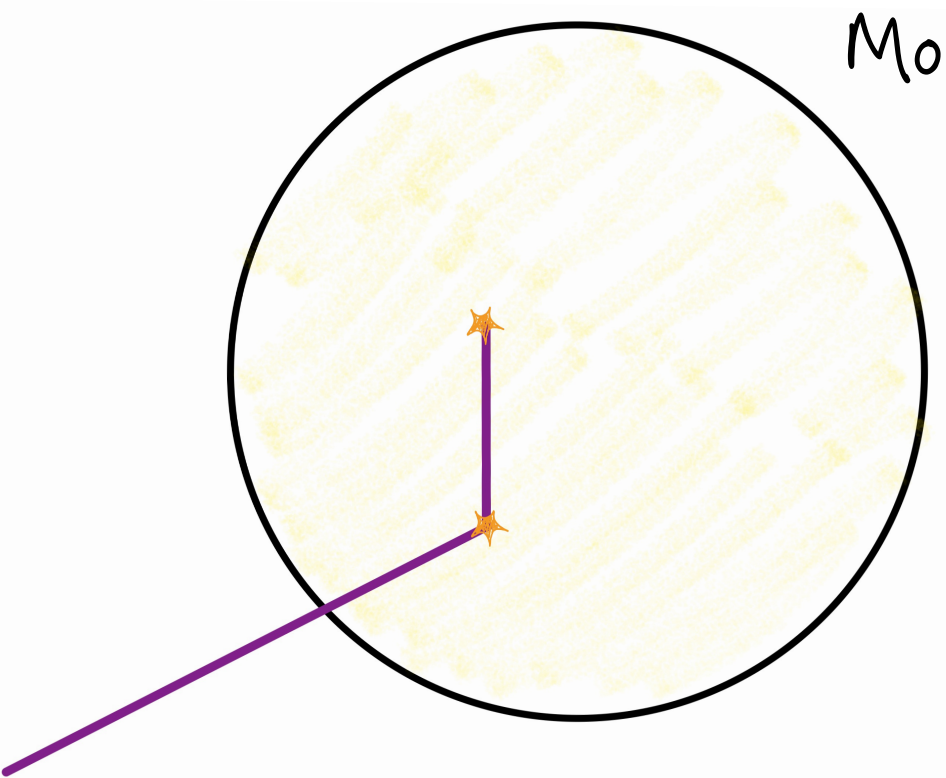
Single collisions

Press & Spergel (1985)
Gould (1987)

Multiple collisions

Bramante et al. (2017);
Dasgupta et al. (2019)
Ilie et al. (2019), 2x(2020), (2021)
Leane & Smirnov (2023)
…

DM scatters, loses energy, becomes gravitationally bound to the star



Most works are based on Gould's assumptions (1987)

- DM follows a linear path
- Escape velocity is constant, $v_{\rm esc} = v_{\rm esc}(R_*)$
- Constant star density

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- DM follows a linear path
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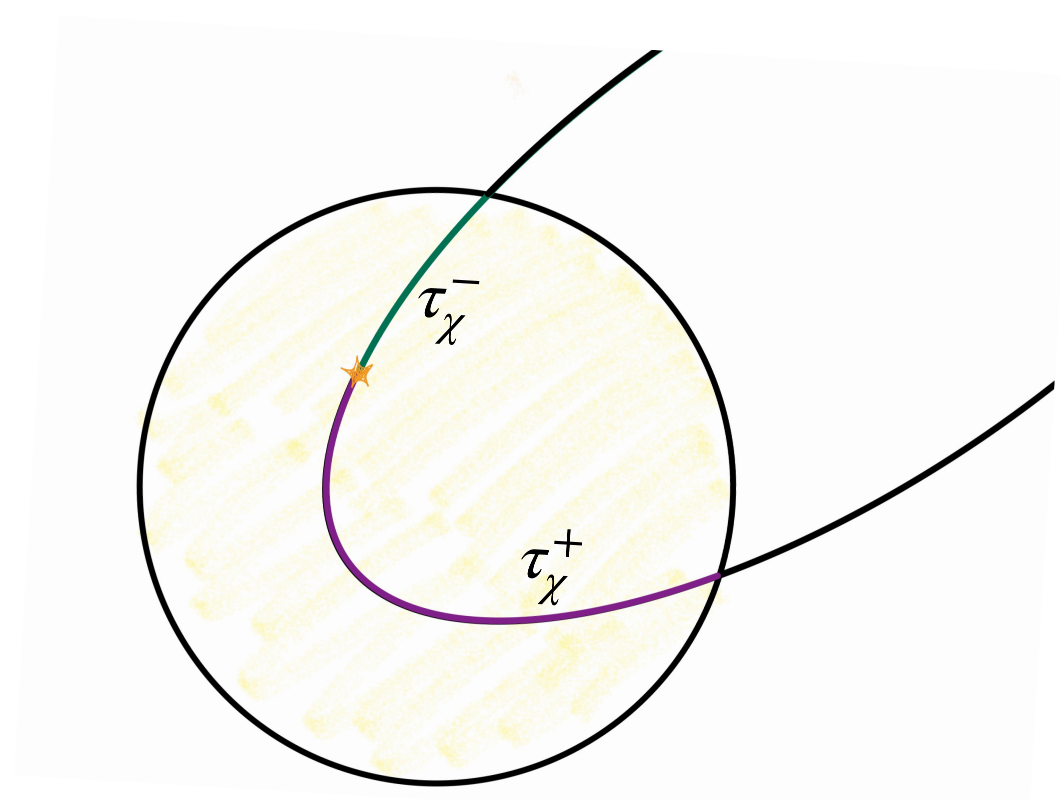
- Constant star density

More recently, a multi-scattering formalism was presented in which these assumptions are lifted

Bell, Busoni, Robles et al. (2020, 2024)

- A response function provides the scattering probability and includes the star opacity
- Considers angular momentum conservation and gravitational focusing
- Density and escape velocity are functions the radial position



Walter Tangarife

Population-III stars

Formed from metal-free primordial gas (in DM reach environments): These stars must have initiated the creation of all heavier chemical elements

For a review, see Broom et al. (2002), Klessen & Glover (1987)

$10^5 M_\odot - 10^6 M_\odot$ halos

Formation peaks around $z \sim 15 - 20$

They continue to evolve, producing metals in their cores

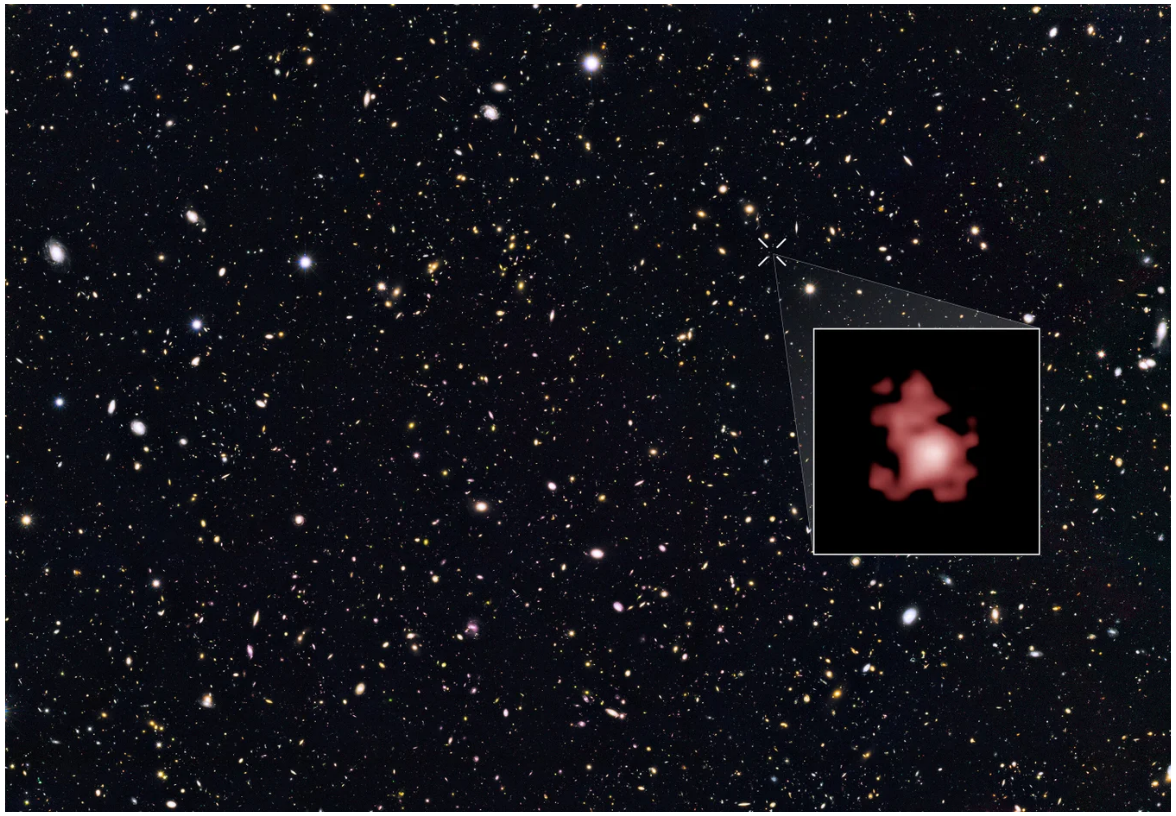


Image credit: NASA

Pop-III stars play a role in connecting metal-free and high-metallicity stars

They may be instrumental in probing DM physics

Ilie et al. (2020), (2021)

A Pop-III star evolution from MESA

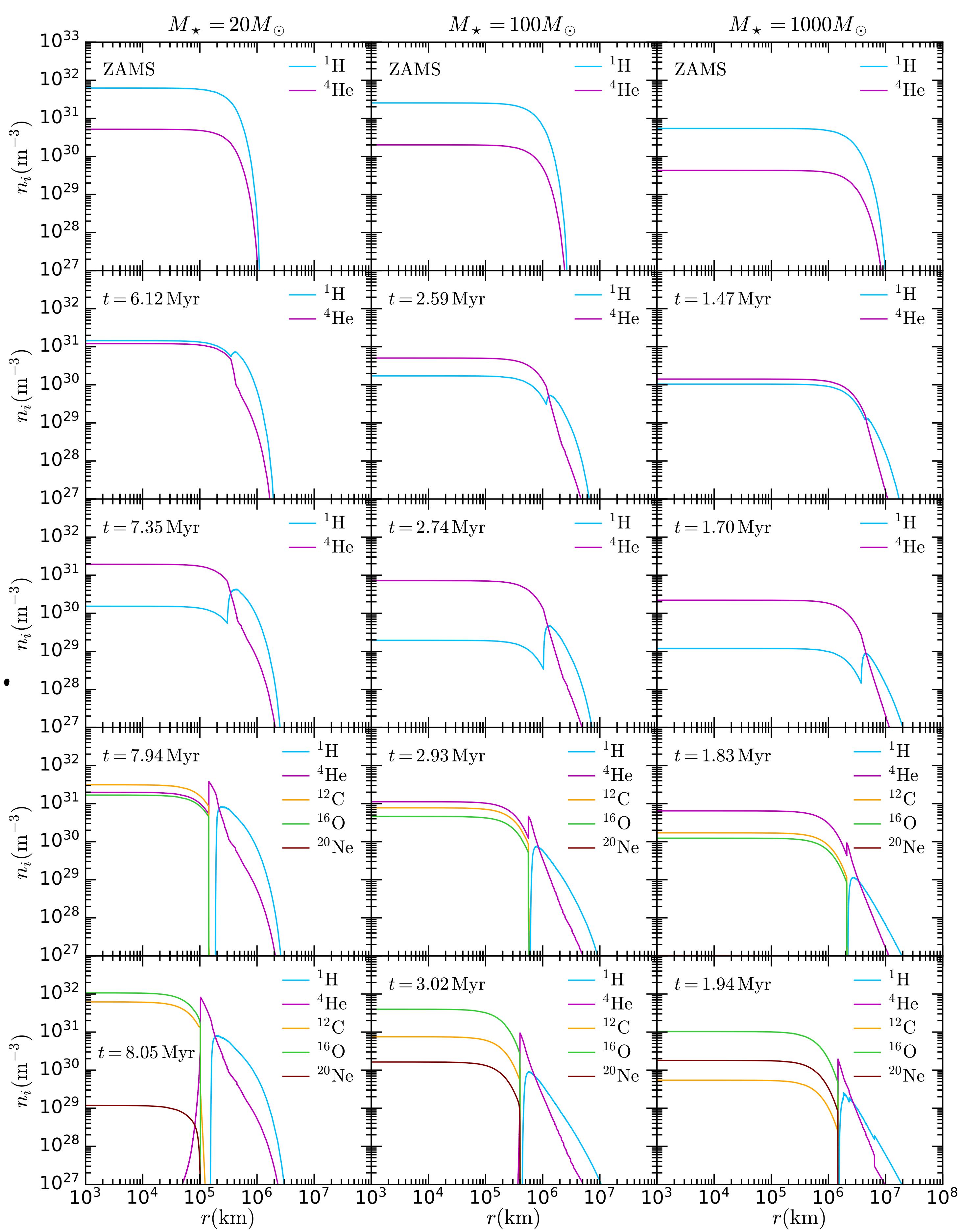
MESA: Modules for Experiments in Stellar Astrophysics

Paxton et al. (2011)

We simulated non-rotating single stars, with masses 20, 100 and 1000 M⊙, and no metallicity, Z = 0.

We evolved these stars from ZAMS, at redshift z ~ 10, up to the moment when helium is depleted from the star's core

Busoni ,Robles, Tangarife (2025)



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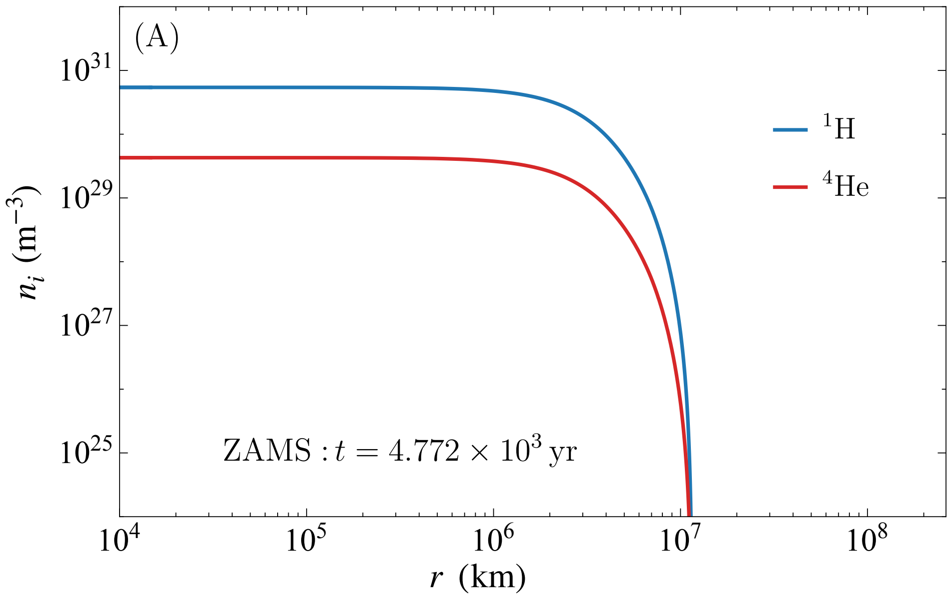
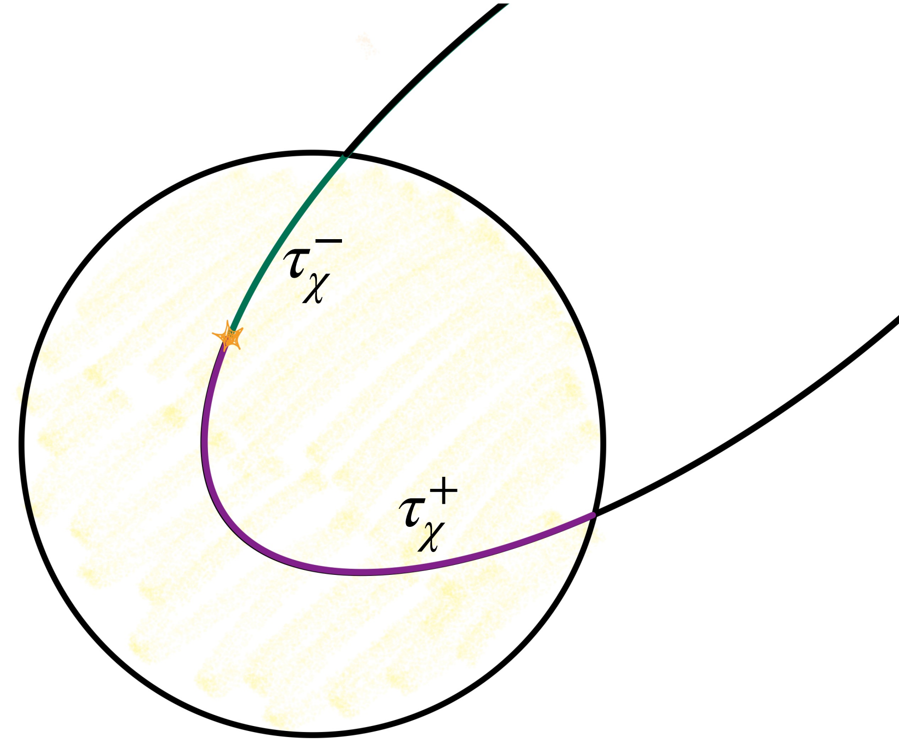
Multiple scattering with multiple targets





$$\mathscr{L}_{\rm eff} \supset \frac{c_S}{\Lambda^2}\bar{\chi}\chi\bar{N}N$$

For each target element:

~probability to capture one DM particle

~ flux of DM

$$C_i = \frac{\rho_\chi}{m_\chi}\int_0^{R_*} dr \int_0^\infty du\, n_i(r)\,\sigma_{i\chi}(r)\,G_i\left(r, \frac{m_\chi u^2}{2E_0^i}\right) 4\pi r^2 v_{\rm esc}^2(r)\frac{f(u)}{u}$$

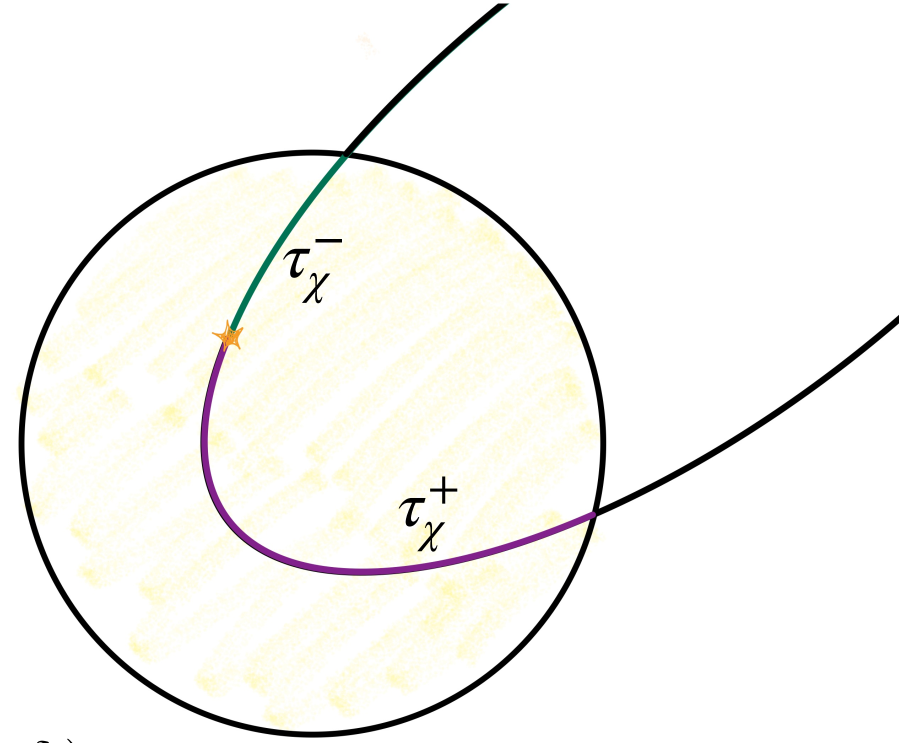
Capture rate

The response function incorporates the probability of losing kinetic energy through multiple collisions

Total capture: $C = C_i + C_j$

Bell, Busoni, Robles et al. (2024)

Multiple scattering with multiple targets



Cumulative probability of DM to lose energy in the presence of two targets:

$$G_{2,ij}(\delta E) = \int_0^{\delta E/E_0^j} dz\, G\left(\tau_\chi^i, \frac{\delta E - zE_0^j}{E_0^i}\right)\left[-\frac{\partial}{\partial z}\mathcal{G}(\tau_\chi^j, z)\right]$$

$$\mathcal{G}(\tau_\chi^i, \delta_i) = \int_0^{\tau_\chi^i} d\tau\, G(\tau, \delta_i)$$

Capture after scatterings with one or two targets:

$$G_{12,ij} = G(\tau_\chi^i, \delta_i)e^{-\tau_\chi^j} + G_{2,ij}$$

Then the capture rate where species i dominates:

$$C_i = \frac{\rho_\chi}{m_\chi}\int_0^{R_\star} dr 4\pi r^2 v_{\rm esc}^2(r)\int_0^\infty du_\chi \frac{f_{\rm MB}(u_\chi)}{u_\chi}\sum_i n_i(r)\sigma_{i\chi}(r)\tilde{G}_{12,ij}\left(r, \frac{m_\chi u_\chi^2}{2E_0^i}\right)$$

$$C_{tot} = C_i + C_j$$

Bell, Busoni, Robles et al. (2024)

Walter Tangarife

The DM velocity distribution

The DM phase-space distribution function has a non-trivial effect on the total capture rate

Most studies assume that the DM speed follows a Maxwell-Boltzmann (MB) distribution function

$$f_{\rm MB}(u_\chi) = \frac{u_\chi}{v_d\, v_\star}\sqrt{\frac{3}{2\pi}}\left[{\rm Exp}\left(-\frac{3}{2v_d^2}\left(u_\chi - v_\star\right)^2\right) - {\rm Exp}\left(-\frac{3}{2v_d^2}\left(u_\chi + v_\star\right)^2\right)\right]$$

good assumption for our solar system!

MB assumes a an isothermal sphere: an equilibrium distribution of a collisionless gas

At short radii, MB leads to an overestimation of the low-velocity population

Lopes, Lacroix, Lopes (2021)

The DM velocity distribution

We used the Eddington inversion method

$$F(\mathcal{E}) = \frac{1}{\sqrt{8}\,\pi^2}\left[\frac{1}{\sqrt{\mathcal{E}}}\left(\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}\right)_{\Psi=0} + \int_0^{\mathcal{E}} \frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2}\frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\right]$$

$$f_{\chi\star}(r,u_\chi) = 2\pi\, u_\chi^2 \int_0^{\pi} \mathrm{d}\theta\, \sin\theta\, \frac{F(\mathcal{E})}{\rho(r)}$$

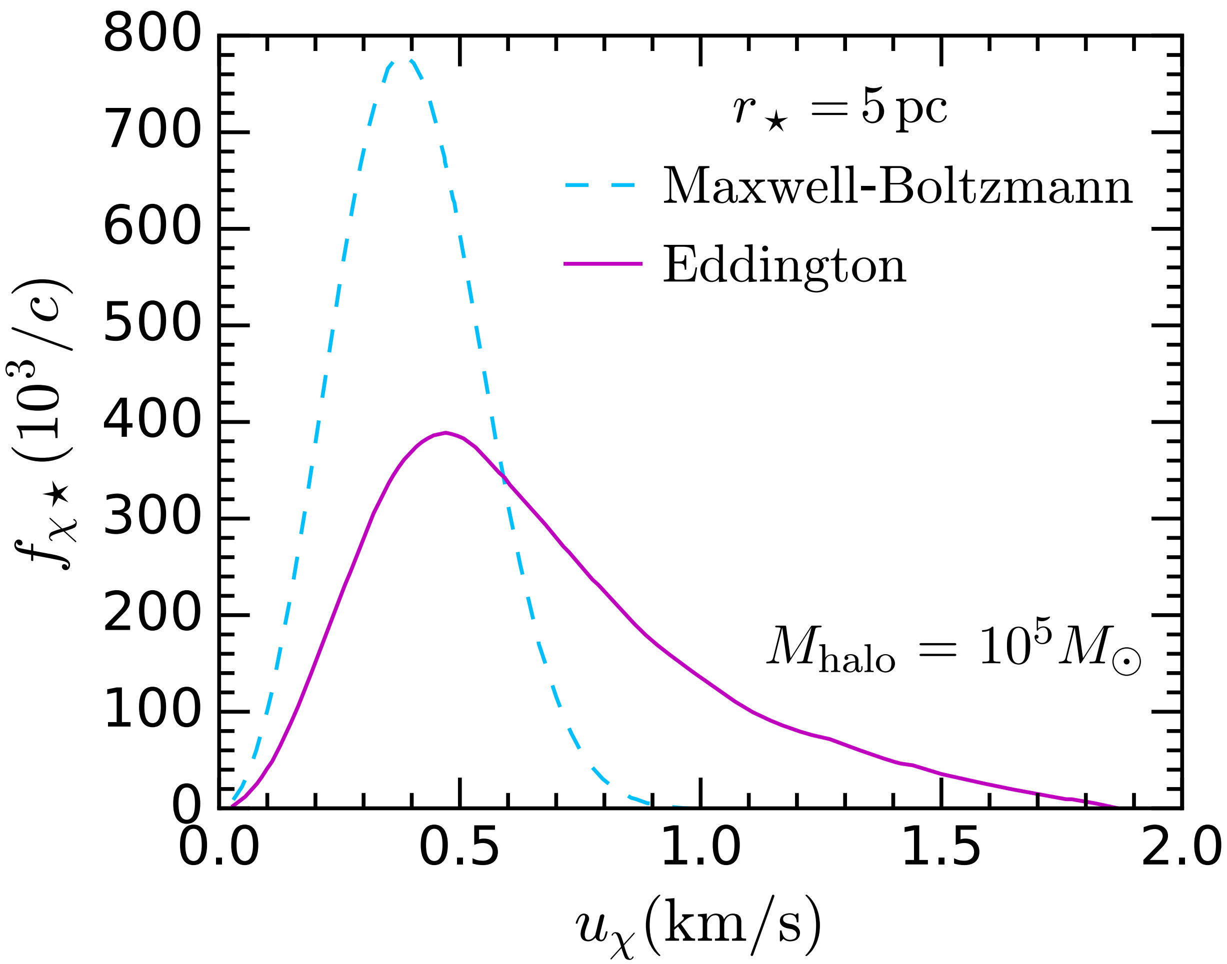
$$\mathcal{E} = \Psi(r) - \tfrac{1}{2}(u_\chi^2 + v_\star^2 + 2u_\chi v_\star\, \cos\theta)$$

Eddington (1916)

It includes how the DM speed distribution varies with the position in the galaxy

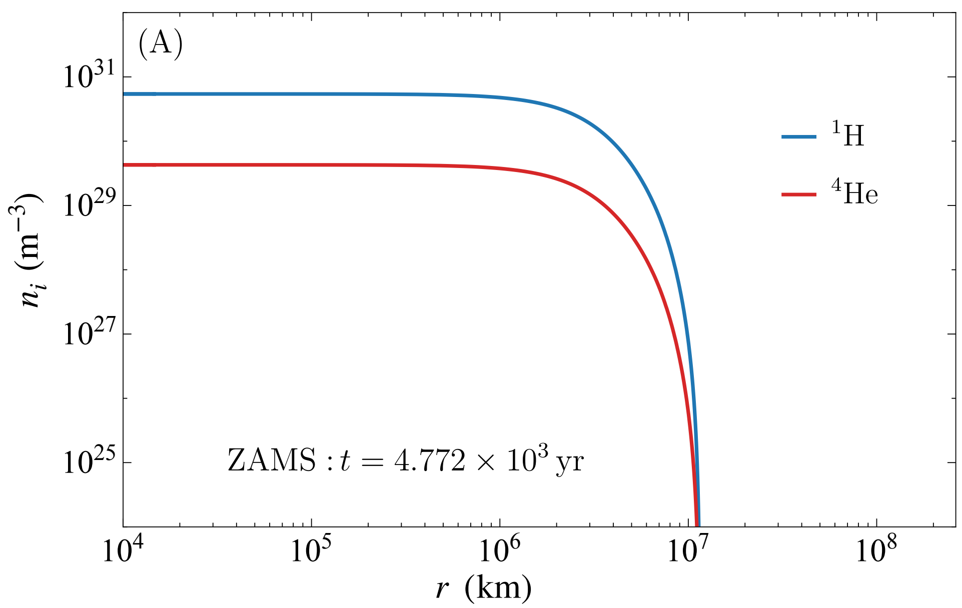
It integrates over all orbit families that are consistent with the gravitational potential, without artificially preferring one type

$\rho_\chi \approx 5.3\,\mathrm{GeV/cm^3}$

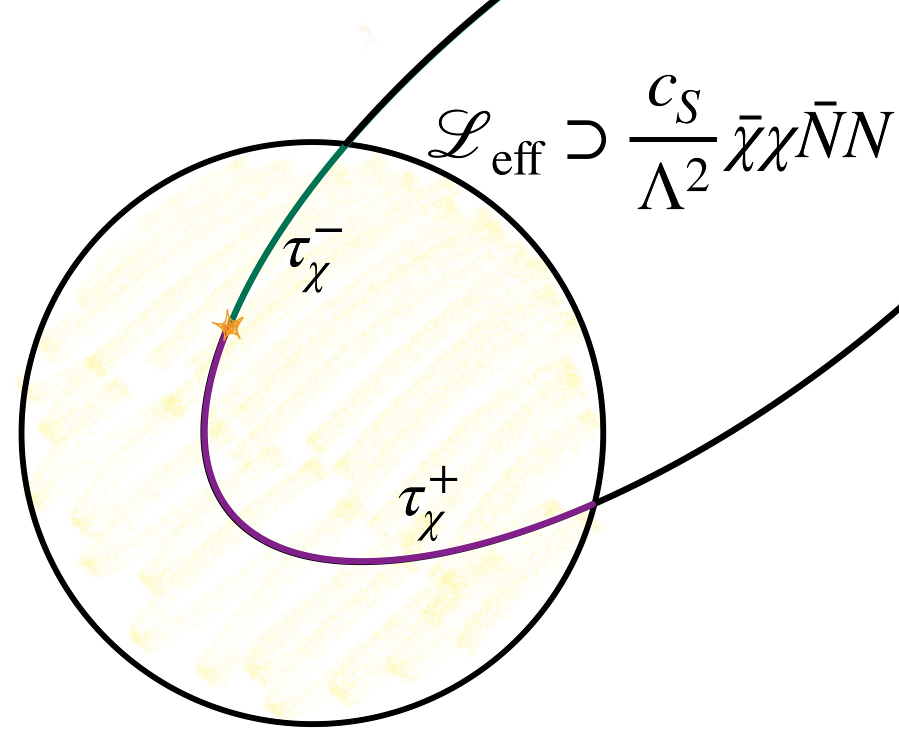


Busoni, Robles, Tangarife (2025)

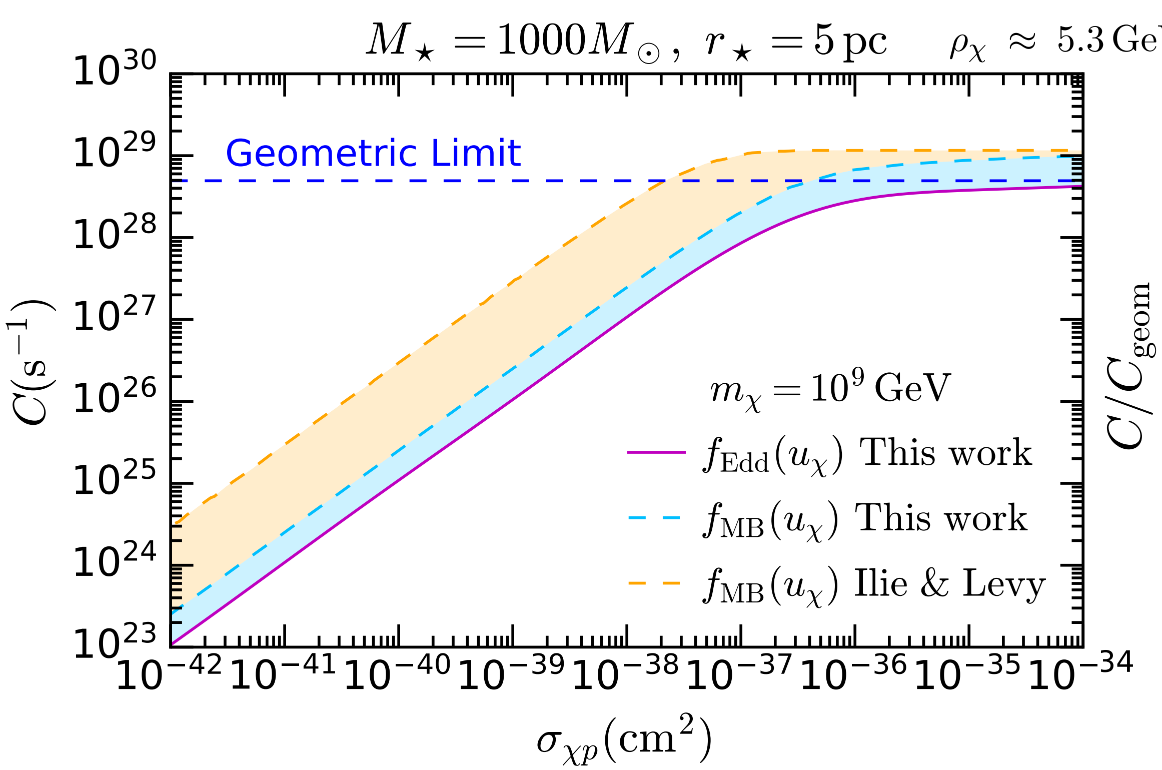
Capture by the early star

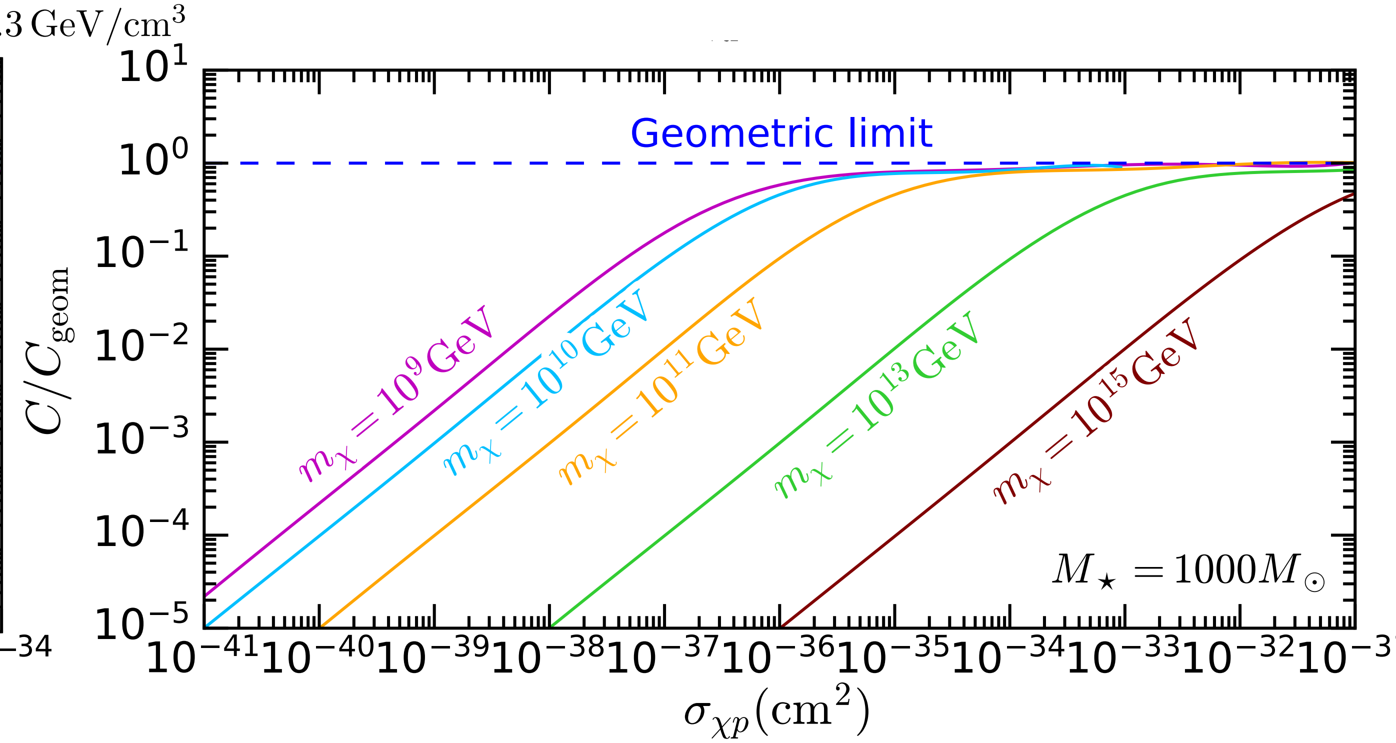


$$\mathscr{L}_{\rm eff} \supset \frac{c_S}{\Lambda^2} \bar{\chi}\chi\bar{N}N$$



$$C_{\rm geom} = \frac{\pi R_\star^2\, \rho_\chi(r_\star)}{m_\chi} \int_0^{v_{\rm esc}^{\rm halo}(r_\star)} {\rm d}u_\chi \frac{v_{\rm esc}^2(R_\star) + u_\chi^2}{u_\chi} f_{\chi\star}(u_\chi)$$





single-scattering regime

$m_\chi \leq 10^9\,{\rm GeV} \rightarrow C \sim m_\chi^{-1}$

multiple-scattering regime

$m_\chi > 10^9\,{\rm GeV} \rightarrow C \sim m_\chi^{-2}$

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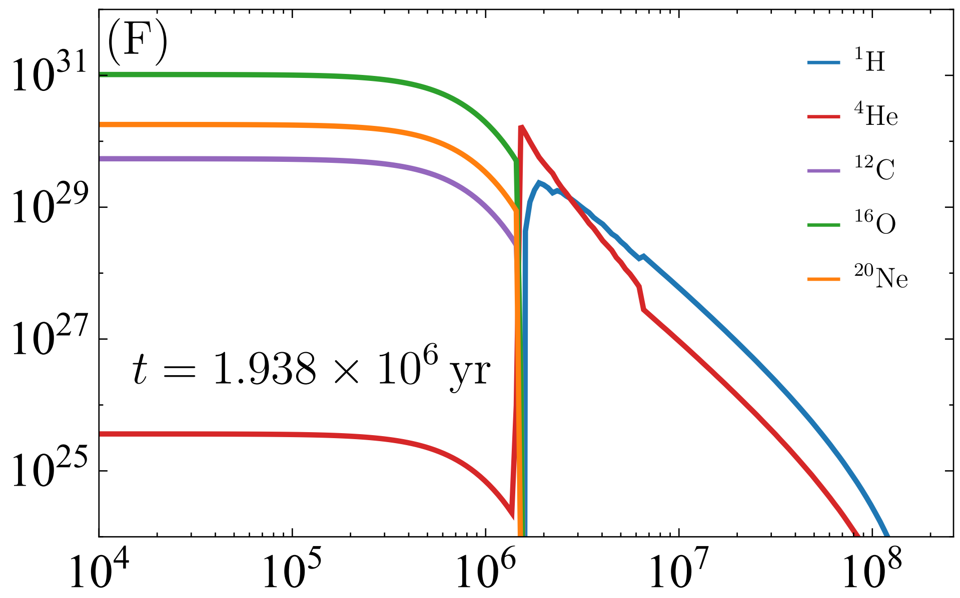
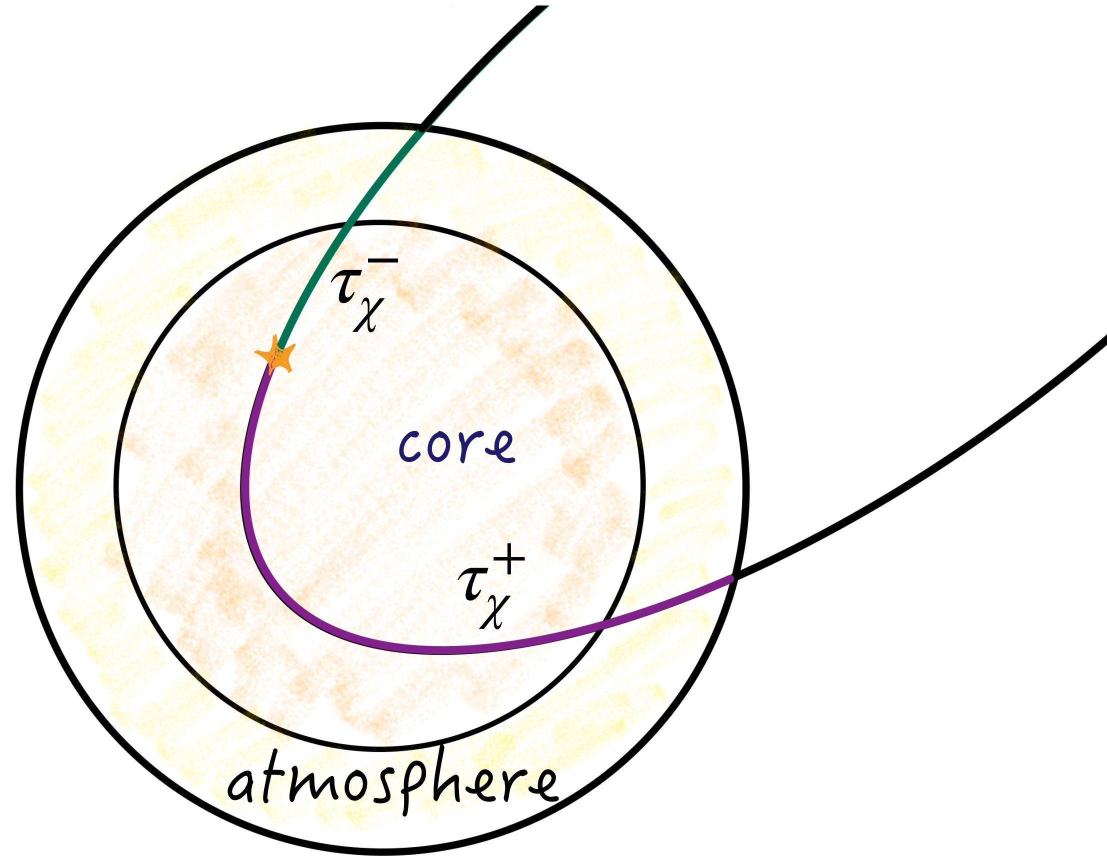
Capture by the late star



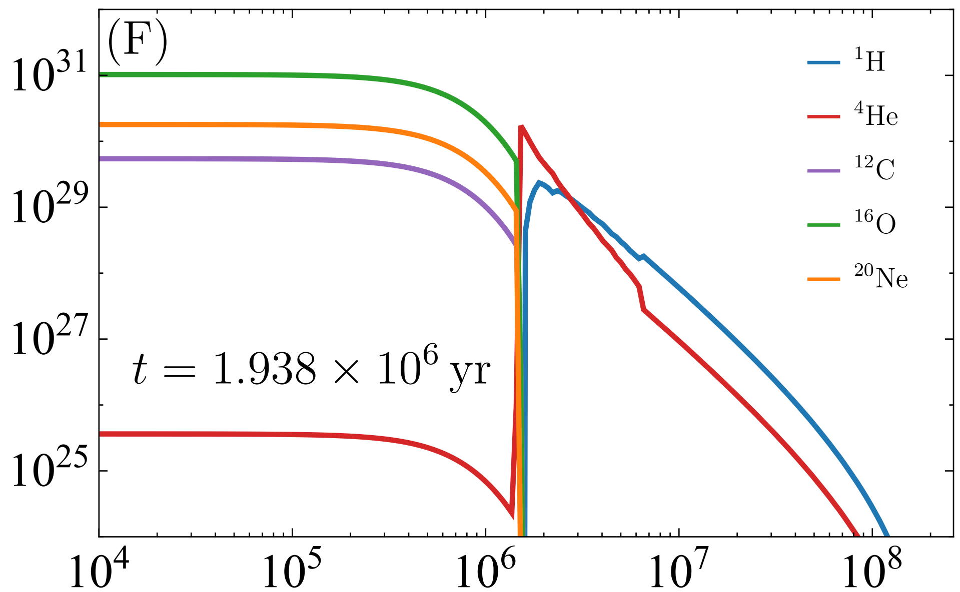


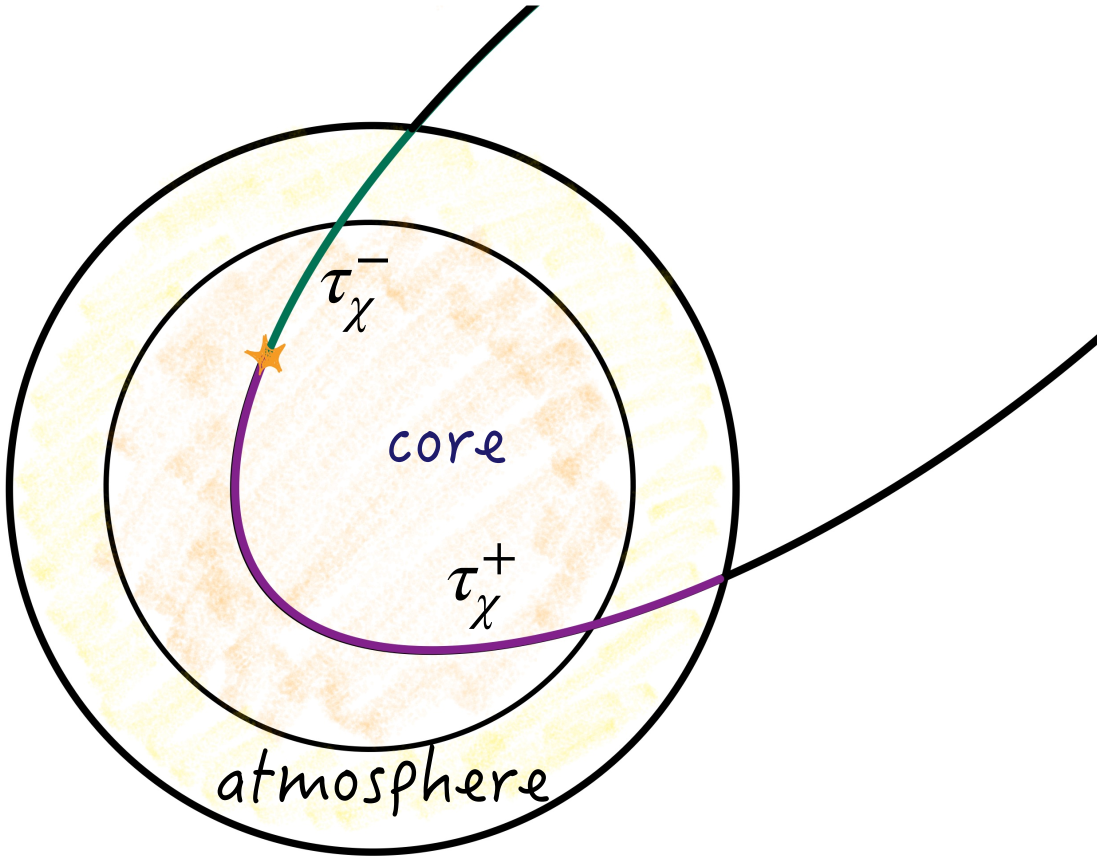
$G_i =$ Prob. capture after interactions only with target i + Prob. capture after interactions with target i and j + Prob. capture after interactions with target i and k + Prob. capture after interactions with target i, then j, k

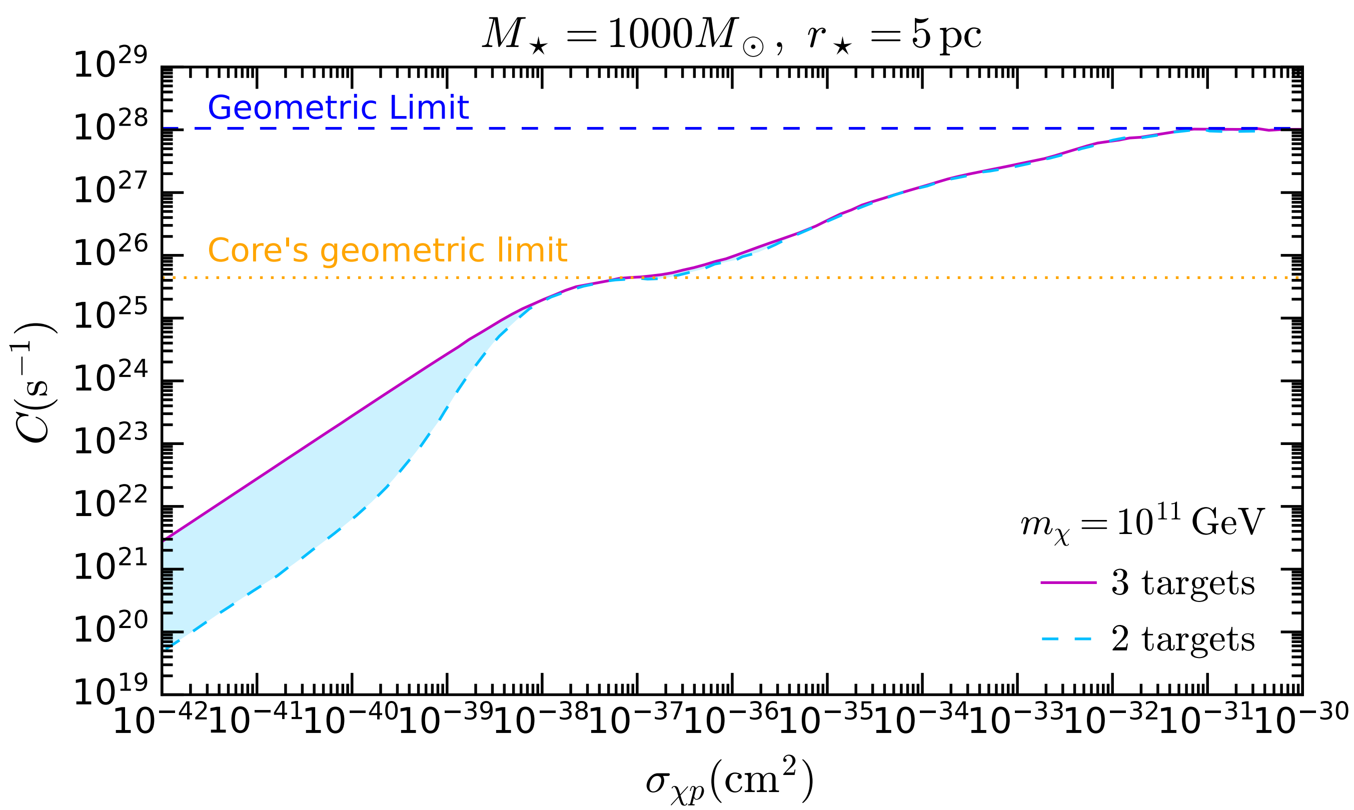
Hong & Vincent (2024) also considered this core-atmosphere structure in red giants

Busoni, Robles, Tangarife (2025)

Capture by the late star







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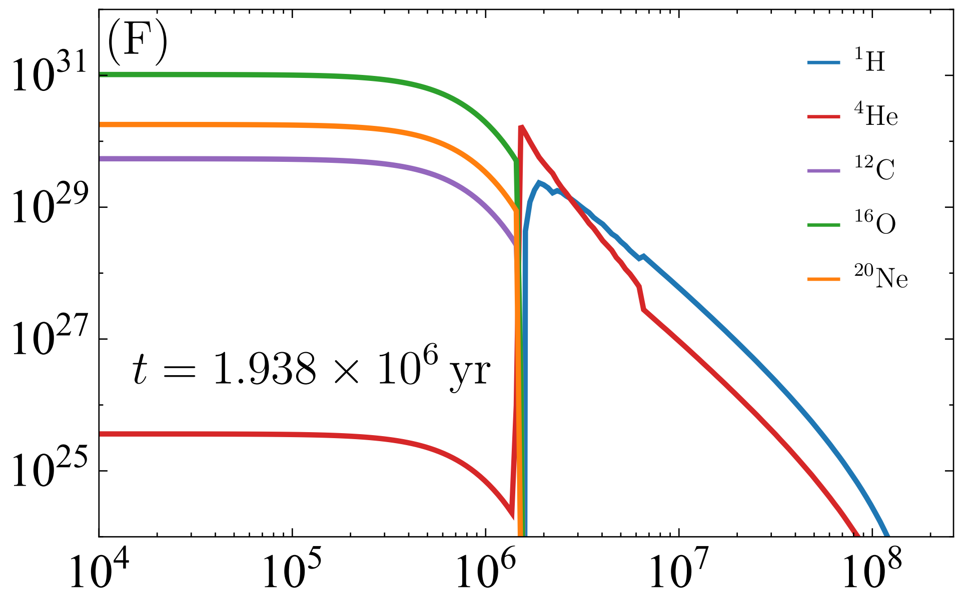
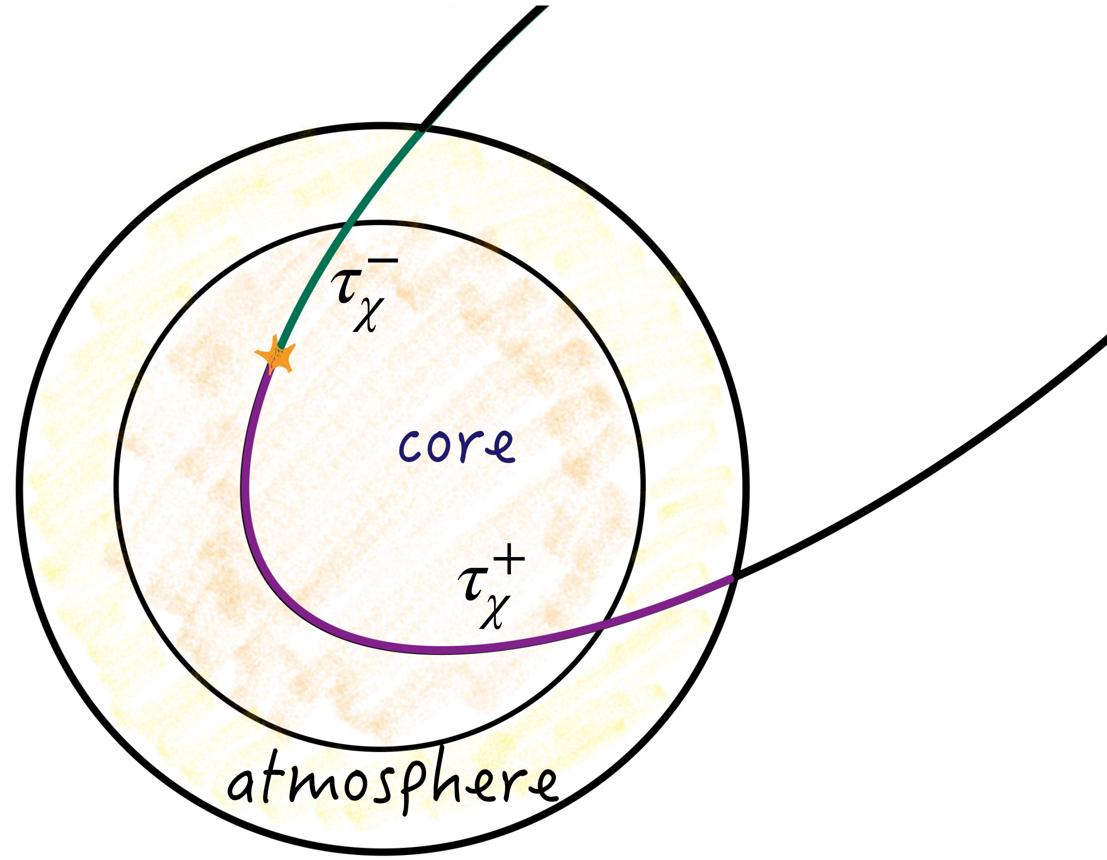
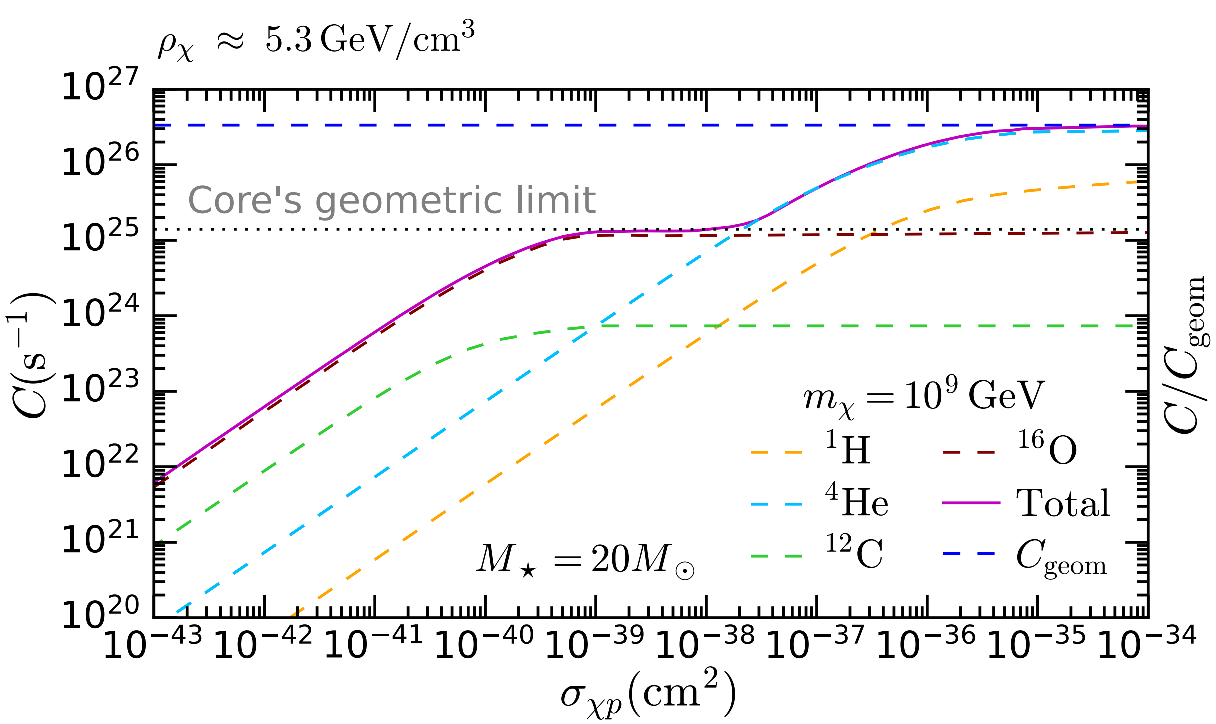
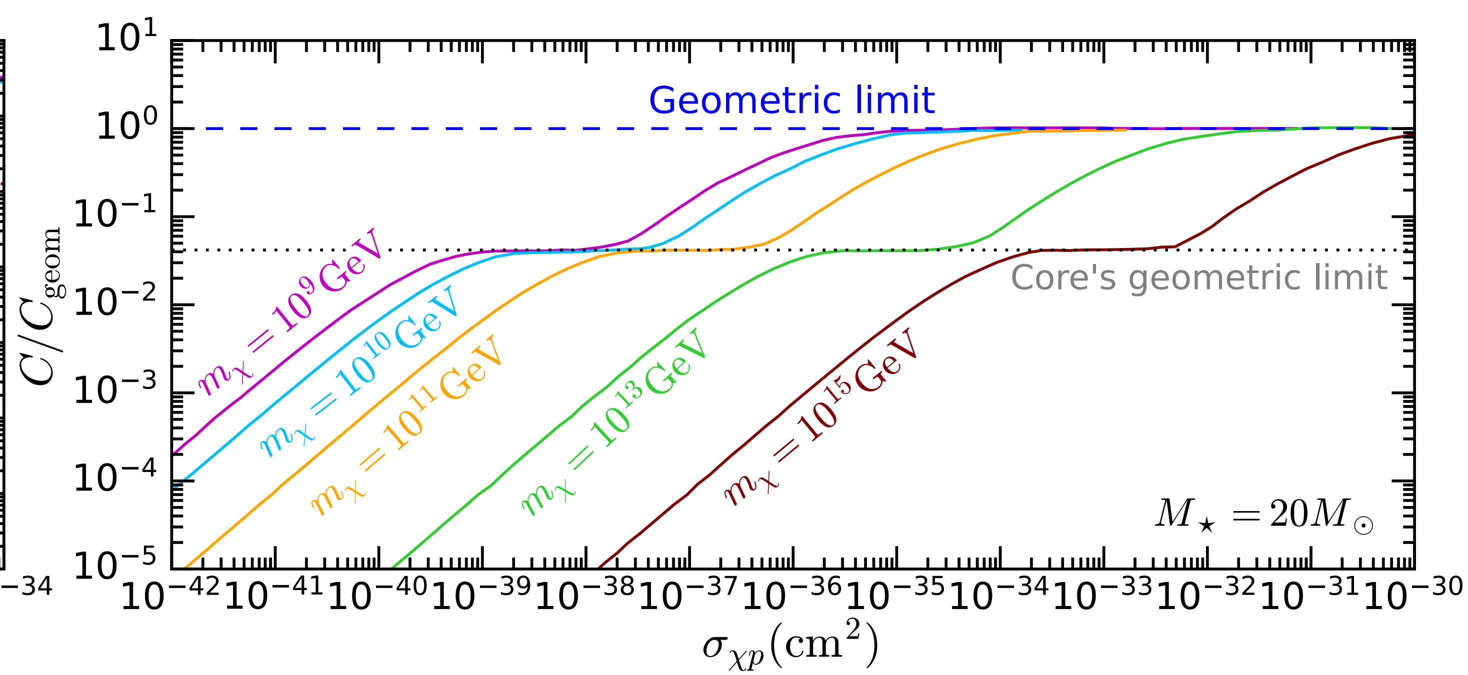




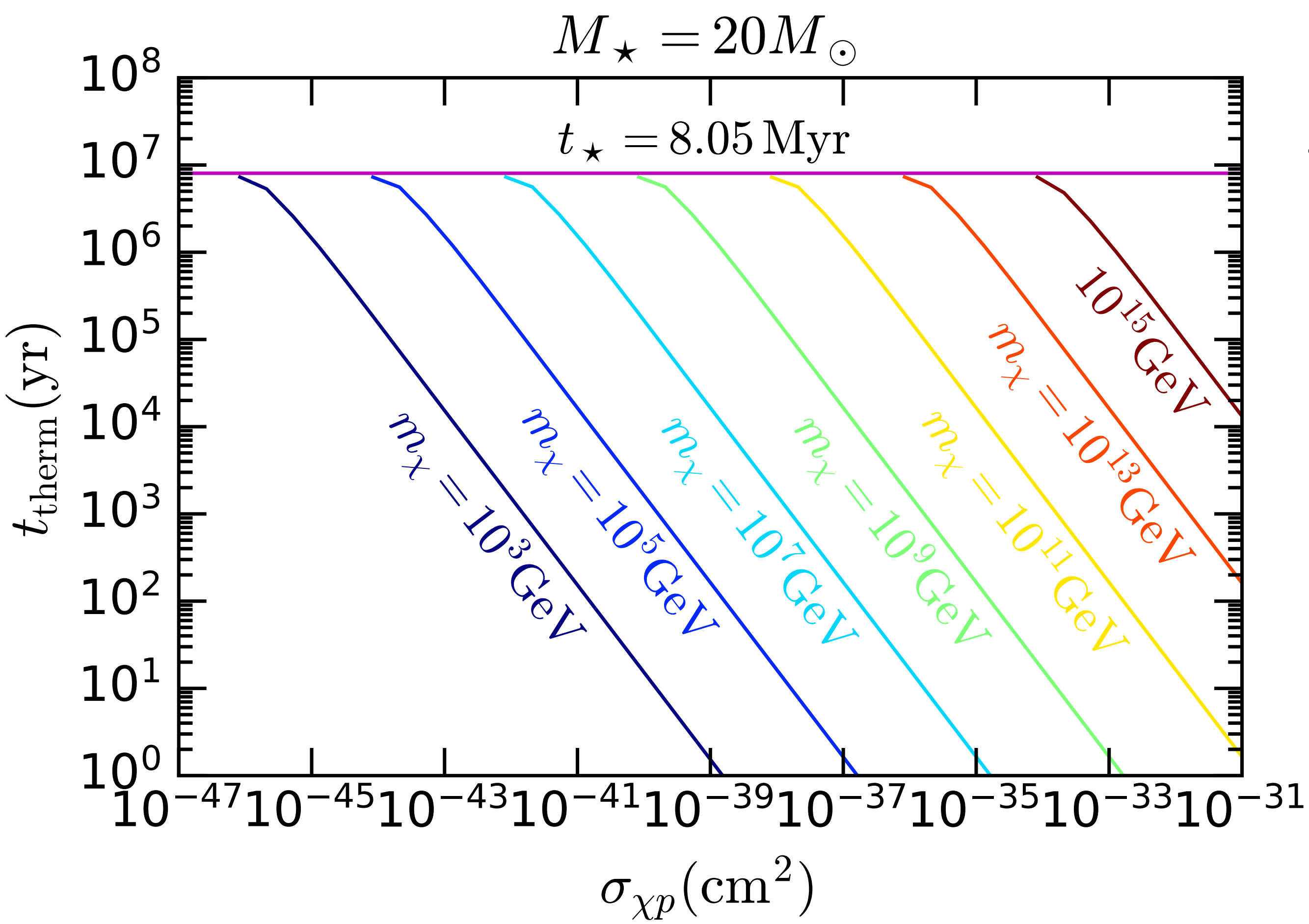




Busoni, Robles, Tangarife (2025)

DM thermalization and annihilation

As captured DM particles interact with ordinary matter in the star, they thermalize in the innermost region of the stellar core



The thermalized DM occupies a sphere of radius

$$r_\chi(t) = \sqrt{\frac{3T_c(t)}{2\pi G m_\chi \rho_c(t)}}$$

Number of particles in the isothermal sphere

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C(t) - A(t) N_\chi^2$$

$$A \equiv \frac{\langle \sigma_{\chi\chi} v_\chi \rangle}{N_\chi^2(t)} \int \mathrm{d}^3 r\, n_\chi^2(r,t)$$

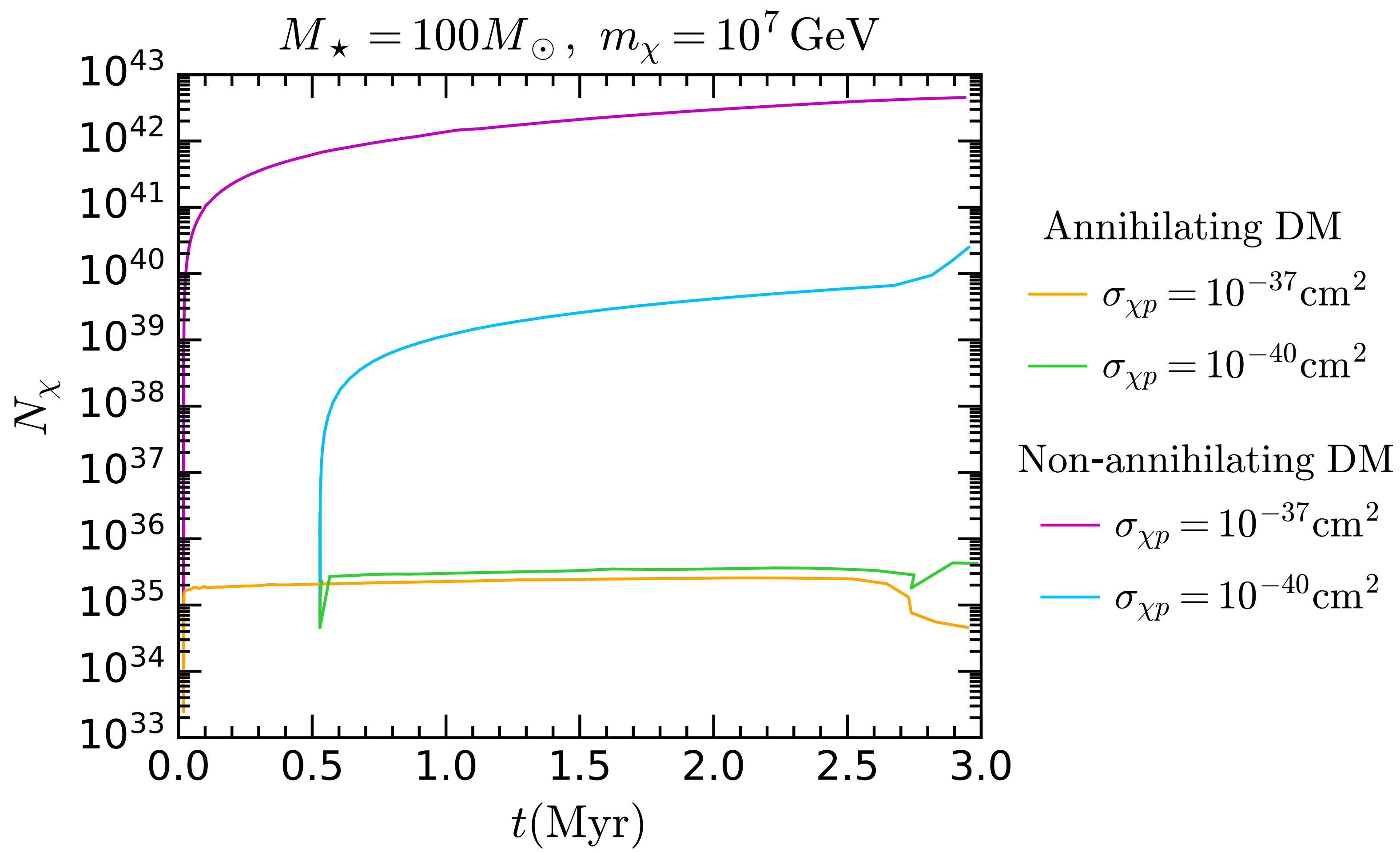
Walter Tangarife

DM thermalization and annihilation

Number of particles in the isothermal sphere

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C(t) - A(t)N_\chi^2 \qquad A \equiv \frac{\langle \sigma_{\chi\chi} v_\chi \rangle}{N_\chi^2(t)} \int \mathrm{d}^3 r\, n_\chi^2(r,t)$$

The annihilation of DM prevents the accumulated DM population from growing to a point that significantly affects the stellar structure



Busoni, Robles, Tangarife (2025)

DM self-gravitation and collapse

Non-annihilating DM:

The DM population becomes self-gravitating when the total mass in a region exceeds the mass of baryonic matter contained in the same region

$$N_\chi(t) \geq \frac{4\sqrt{2}\pi^{3/2} r_\chi^3(t)\rho_c(t)}{3\sqrt{3}m_\chi}$$

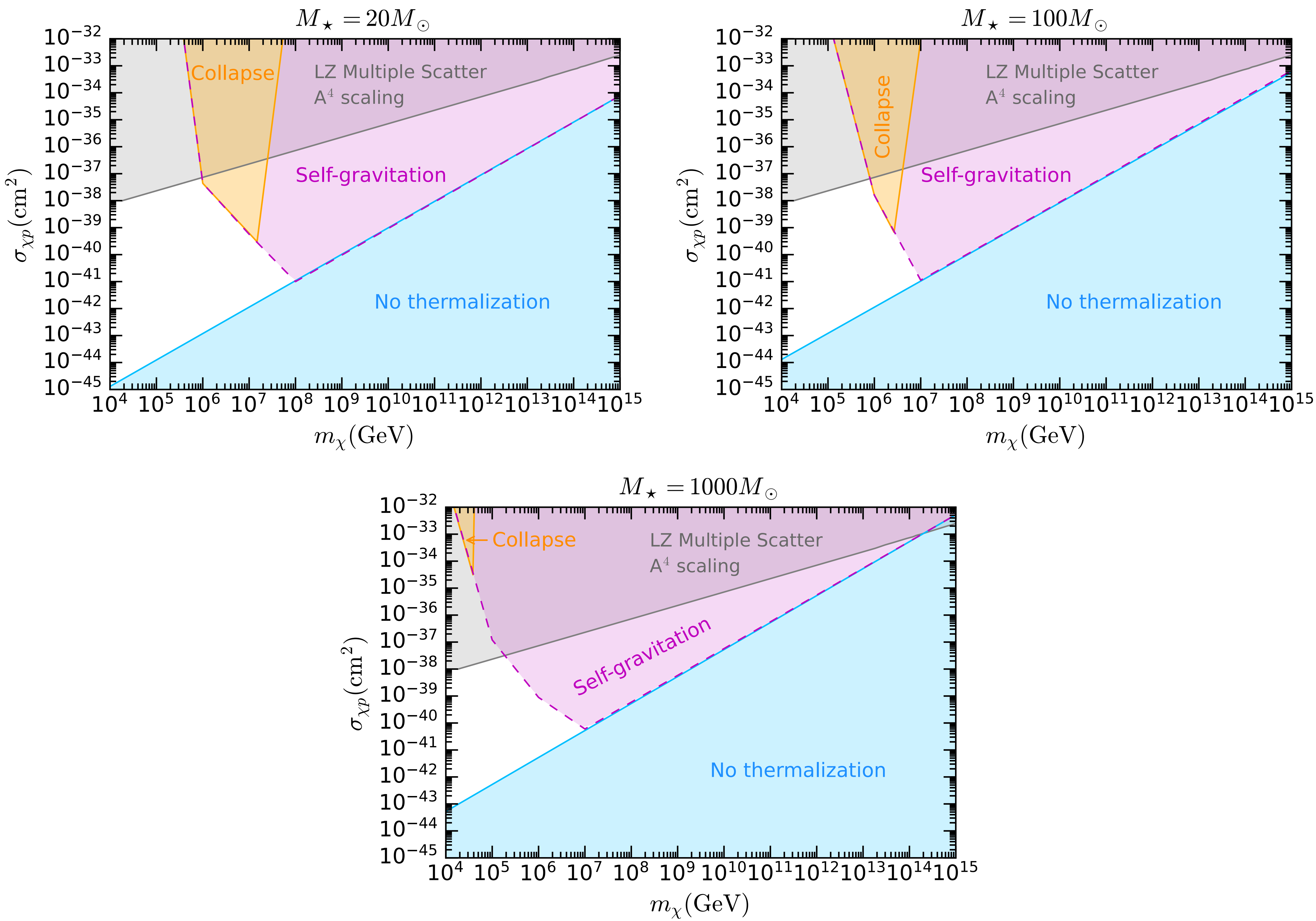
The isothermal sphere may become unstable against gravitational collapse when gravitational energy exceeds kinetic energy

$$N_\chi(t) > (2)^{3/4}\pi\sqrt{3}\left(\frac{M_{\rm Pl}}{m_\chi}\right)^3 = N_{\rm Ch}$$

~Chandrasekhar limit

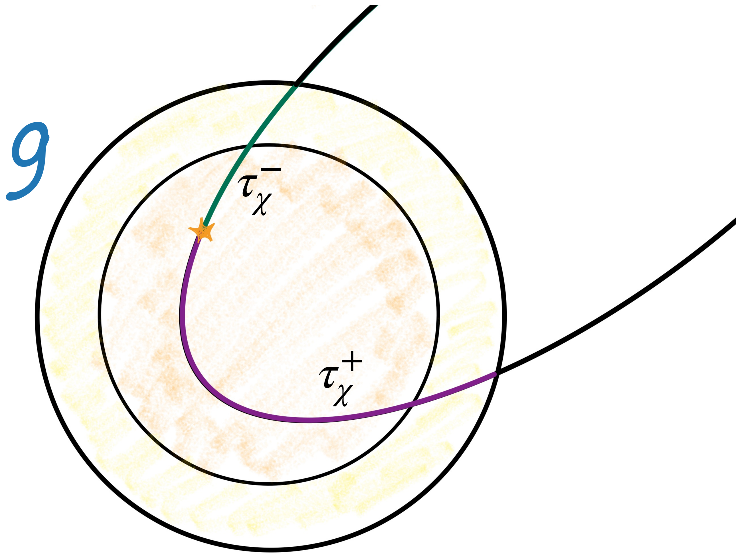
So, we can ask: What region of the parameter space would lead to self-gravitation, collapse, and subsequent accretion of the star into the resultant black hole?

DM self-gravitation and collapse



Busoni, Robles, Tangarife (2025)

Can first-generation stars tell us anything about dark matter?



Maybe!

DM capture effects in the first stars, and in general in massive stars, are highly sensitive to stellar evolution, internal composition, and the surrounding halo environment. Accurate modeling of these effects is essential for deriving robust constraints on heavy DM from primordial stellar populations and for assessing the potential astrophysical impact of DM in the first generation of stars.