MULTI-COMPONENT MULTISCATTER CAPTURE OF DARK MATTER

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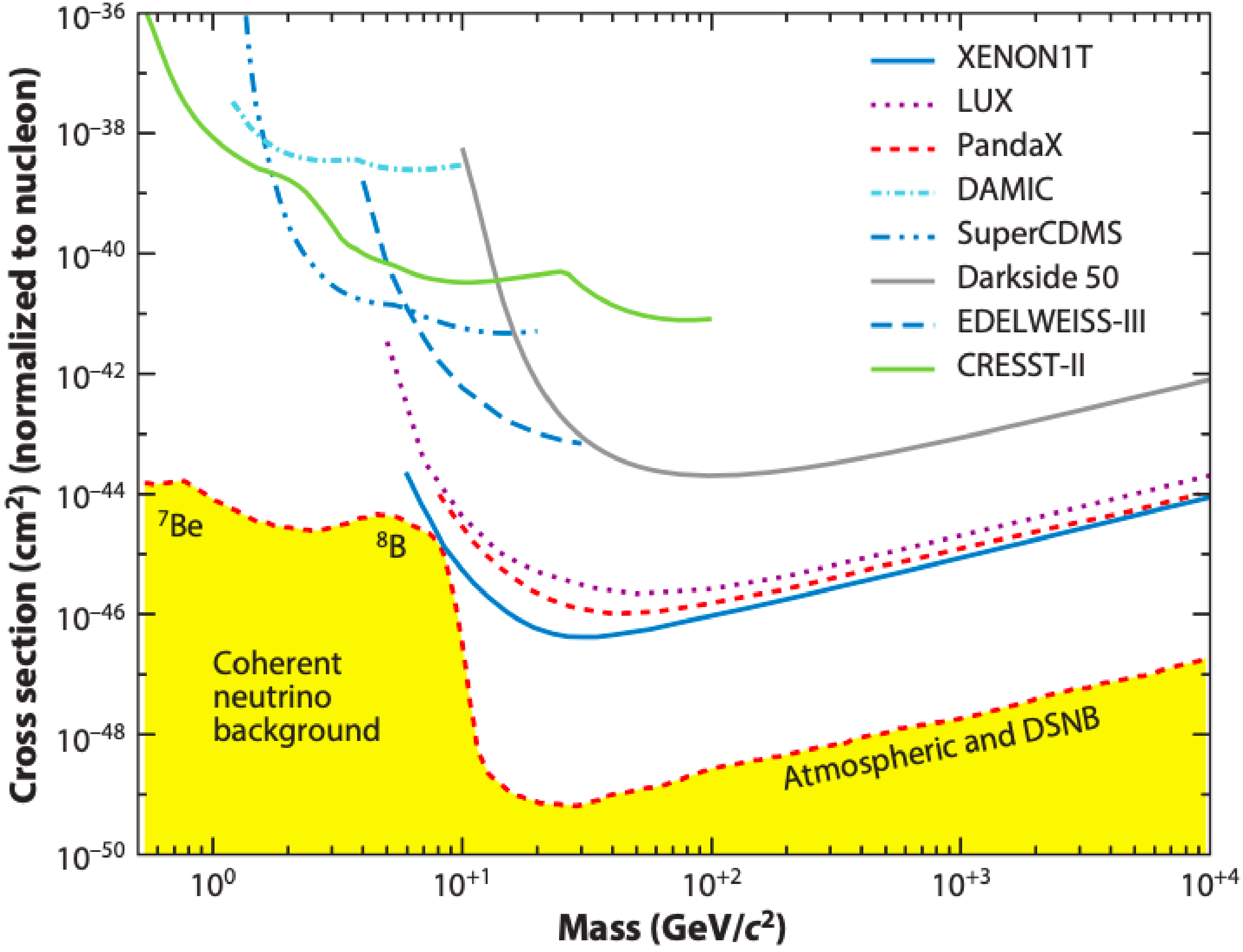
https://arxiv.org/abs/2105.09765

OUTLINE

- Introduction
- Dark Matter Capture
- DM Bounds with Pop. III Stars
- Conclusion

DETECTING DARK MATTER

- Direct detection
  - Approaching Neutrino Floor
- Indirect detection
- Particle creation
- Astrophysical bodies



Click Dutta, Bhaskar, and Louis E. Strigari. "Neutrino Physics with Dark Matter Detectors." Annual Review of Nuclear and Particle Science 69.1 (2019): 137–161.

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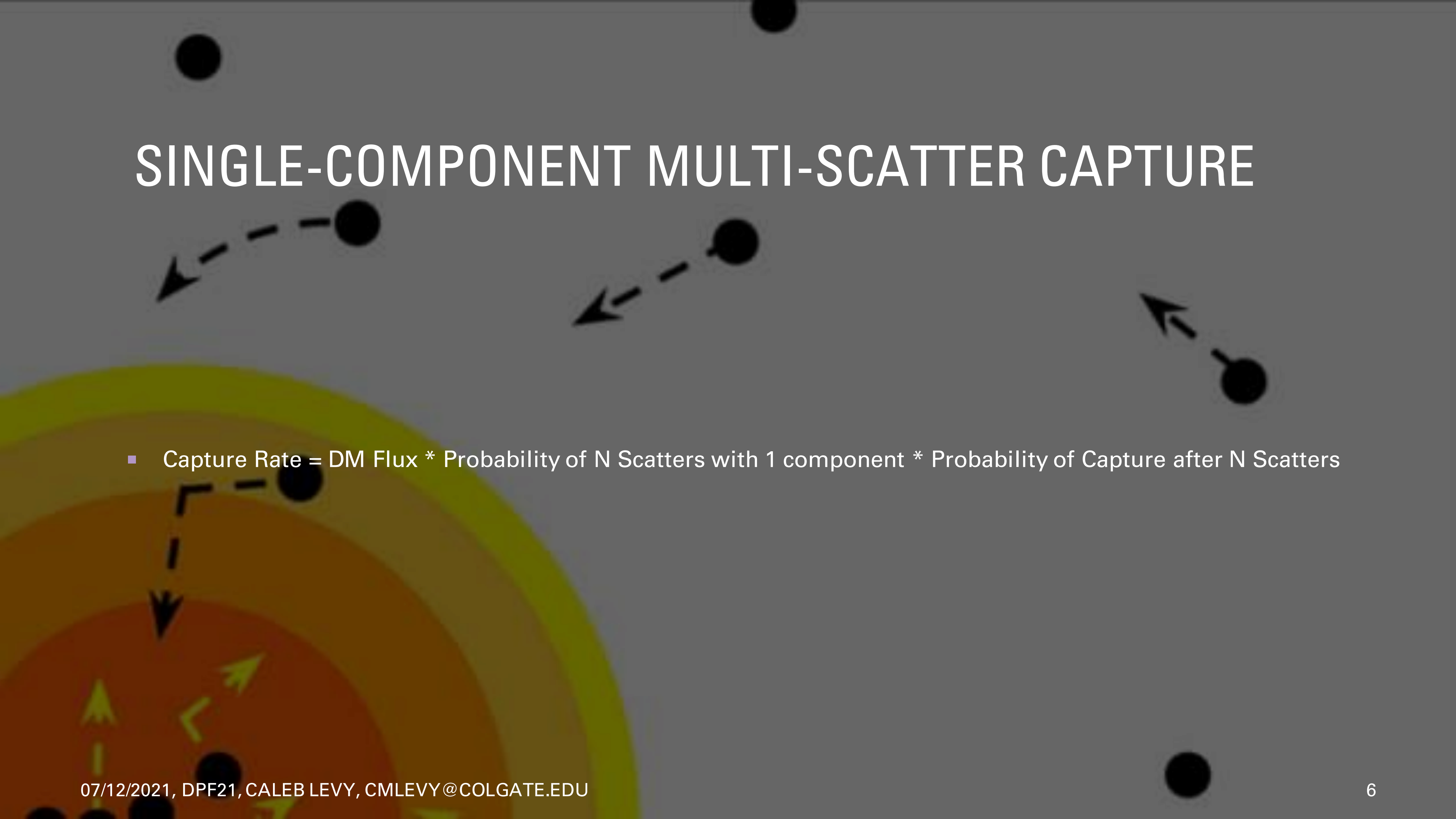
CAPTURE FORMALISM



SINGLE-COMPONENT MULTI-SCATTER CAPTURE

- Capture Rate = DM Flux * Probability of N Scatters with 1 component * Probability of Capture after N Scatters

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sum_{N=1}^{\infty} \underbrace{\pi R_\star^2}_{\text{capture area}} \times \underbrace{n_X \int_0^\infty \frac{f(u)du}{u}(u^2+v_{esc}^2)}_{\text{DM flux}} \times \underbrace{p_N(\tau)}_{\text{prob. for } N \text{ collisions}} \times \underbrace{g_N(u)}_{\text{prob. of capture}}$$

Optical Depth

$$\tau = 2R_\star \times \underbrace{\sigma}_{\text{DM-target cross section}} \times \overbrace{n_T}^{\text{Num. Density of Targets}}$$

SINGLE-COMPONENT MULTI-SCATTER CAPTURE

J. Bramante, A. Delgado, and A. Martin, Phys. Rev. D 96, 063002 (2017), arXiv:1703.04043 [hep-ph].

SINGLE TO 2-COMPONENT

Single-Component

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sum_{N=1}^{\infty} \underbrace{\pi R_\star^2}_{\text{capture area}} \times \underbrace{n_X \int_0^\infty \frac{f(u)du}{u}(u^2 + v_{esc}^2)}_{\text{DM flux}} \times \underbrace{p_N(\tau)}_{\text{prob. for } N \text{ collisions}} \times \underbrace{g_N(u)}_{\text{prob. of capture}}$$

N = i + j

Two-Component

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sum_{N=1}^{\infty} \sum_{i=0}^{N} \underbrace{\pi R^2}_{\text{Capture Area}} \times \underbrace{n_X \int_0^\infty \frac{f(u)du}{u}(u^2 + v_{esc}^2)}_{\text{DM Flux}} \times \underbrace{p_i(\tau_A) p_j(\tau_B)}_{\text{2-Comp Prob. of Collisions}} \times \underbrace{g_{ij}(u)}_{\text{2-Comp Prob. of Capture}}$$

$$C_{tot} = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} C_{ij}$$

$$C_{ij} = \pi R_\star^2 n_X \int_0^\infty \frac{f(u)du}{u}(u^2 + v_{esc}^2) p_i(\tau_A) p_j(\tau_B) g_{ij}(u)$$

ALTERNATE FORM

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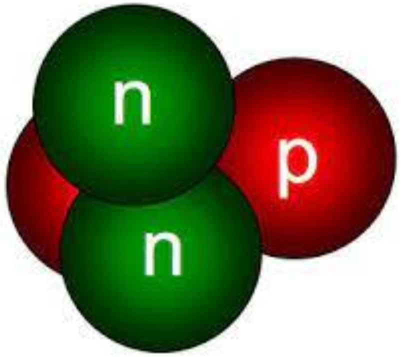
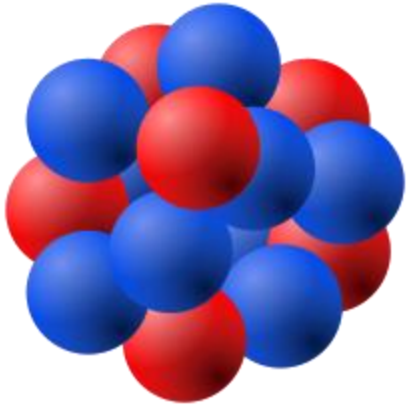
GENERALIZED MULTI-COMPONENT CAPTURE

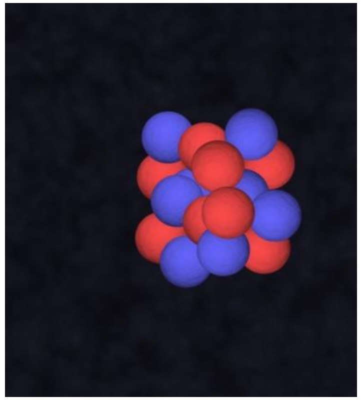


Component I, α scatters



Component II, β scatters

…



Component n, ω scatters

$$C(\alpha, \beta, \gamma, ..., \omega) = \pi R^2 p_\alpha(\tau_I) p_\beta(\tau_{II}) \times ... \times p_\omega(\tau_n) \int_{v_{esc}}^{\infty} dw \frac{f(u)}{u^2} w^3 g(w, \alpha, \beta, \gamma, ..., \omega).$$

$$C_{tot} = \sum_{\alpha=0}^{\infty} \sum_{\beta=0}^{\infty} ... \sum_{\omega=0}^{\infty} C(\alpha, \beta, ... , \omega)$$

POP III CAPTURE

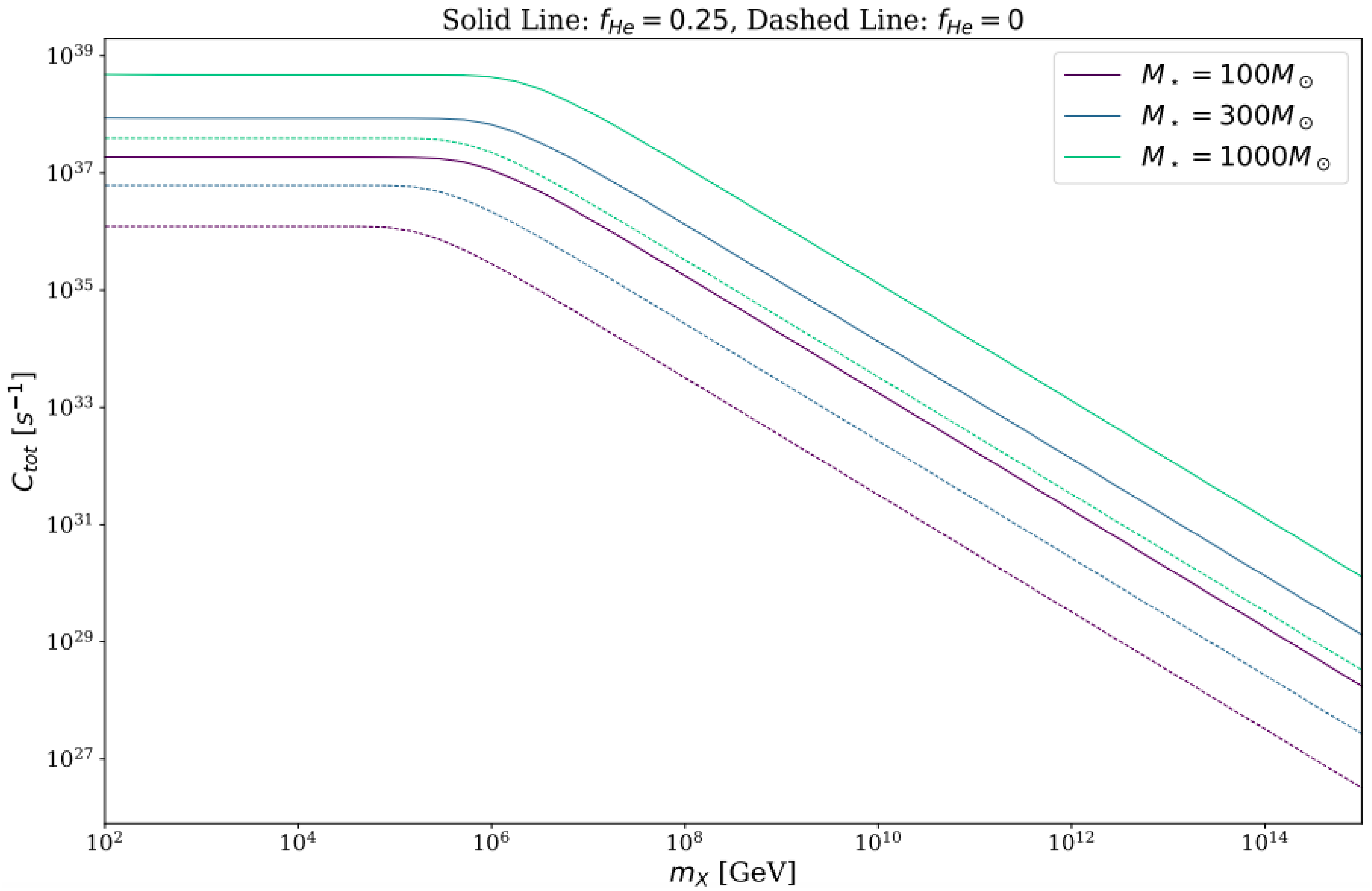
$$\sigma \equiv \sigma_H = \sigma_0^{SI-p},$$

$$\sigma_{He} = 4^4 \sigma_0^{SI-p} \langle F^2(E_R) \rangle,$$

$$\tau_H = 10^{-5} \left(\frac{\sigma_H}{1.26 \times 10^{-40}} \right) \left(\frac{M_\star}{M_\odot} \right) \left(\frac{R_\odot}{R_\star} \right)^2 \left(\frac{f_H}{0.75} \right),$$

$$\tau_{He} = 10^{-3} \left(\frac{\sigma_H}{1.26 \times 10^{-40}} \right) \left(\frac{M_\star}{M_\odot} \right) \left(\frac{R_\odot}{R_\star} \right)^2 \left(\frac{f_{He}}{0.25} \right) \left(\frac{\langle F^2(E_R) \rangle}{0.99} \right).$$

POP III STARS: TALE OF TWO TAUS



ENHANCED CAPTURE

- Cross section taken from XENON1T SI bounds
- Ambient DM density taken as 10^14 GeV/cm^-3

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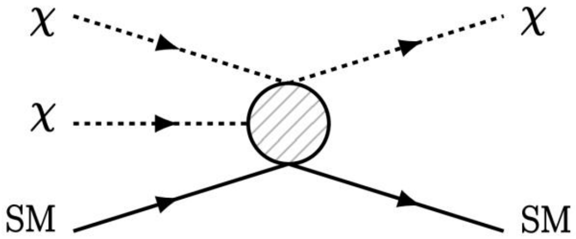
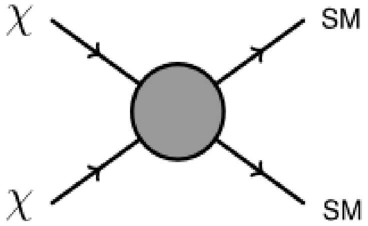
ANNIHILATION

- Provides an additional source of energy to the star
- Various Particle Models
  - CoSIMPs ~ sub-GeV
  - WIMPs ~ 10 GeV – 120 TeV
  - (S)HDM ~ > 120 TeV

CoSIMP Annihilation



WIMP Annihilation



EVAPORATION

RELEVANT IN SUB-GEV REGION – COSIMPS

$$E = \int n_\chi dV \int_0^\infty f(w) dw \quad \underbrace{\int_{v_{esc}}^\infty R^+(w \to v) dv}_{\text{Rate/particle/shell/velocity}}$$

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COMPETING EFFECTS: EQUILIBRATION

- Number of DM particles governed by differential equation
- Equilibrium occurs within lifetime of star for models considered
- Two distinct scenarios:
  - Capture-dominated (High Mass) --> DM luminosity depends on Capture
  - Evaporation-dominated (Low Mass) --> DM luminosity depends on Capture and Evaporation

$$\frac{dN_\chi}{dt} = \underbrace{C}_{\text{Capture}} - \overbrace{\Gamma_A}^{\text{Annihilation}} - \underbrace{E}_{\text{Evaporation}}$$

EQUILIBRIUM AND DARK MATTER LUMINOSITY

- Equilibrium means we can calculate DM luminosity in terms of **Capture** and **Evaporation**
- This leads to the possibility of constraining DM scattering cross-section

$$\Gamma_A = C - E$$

$$L_{DM} = \Gamma_A m_\chi = m_\chi[C(\sigma) - E(\sigma)]$$

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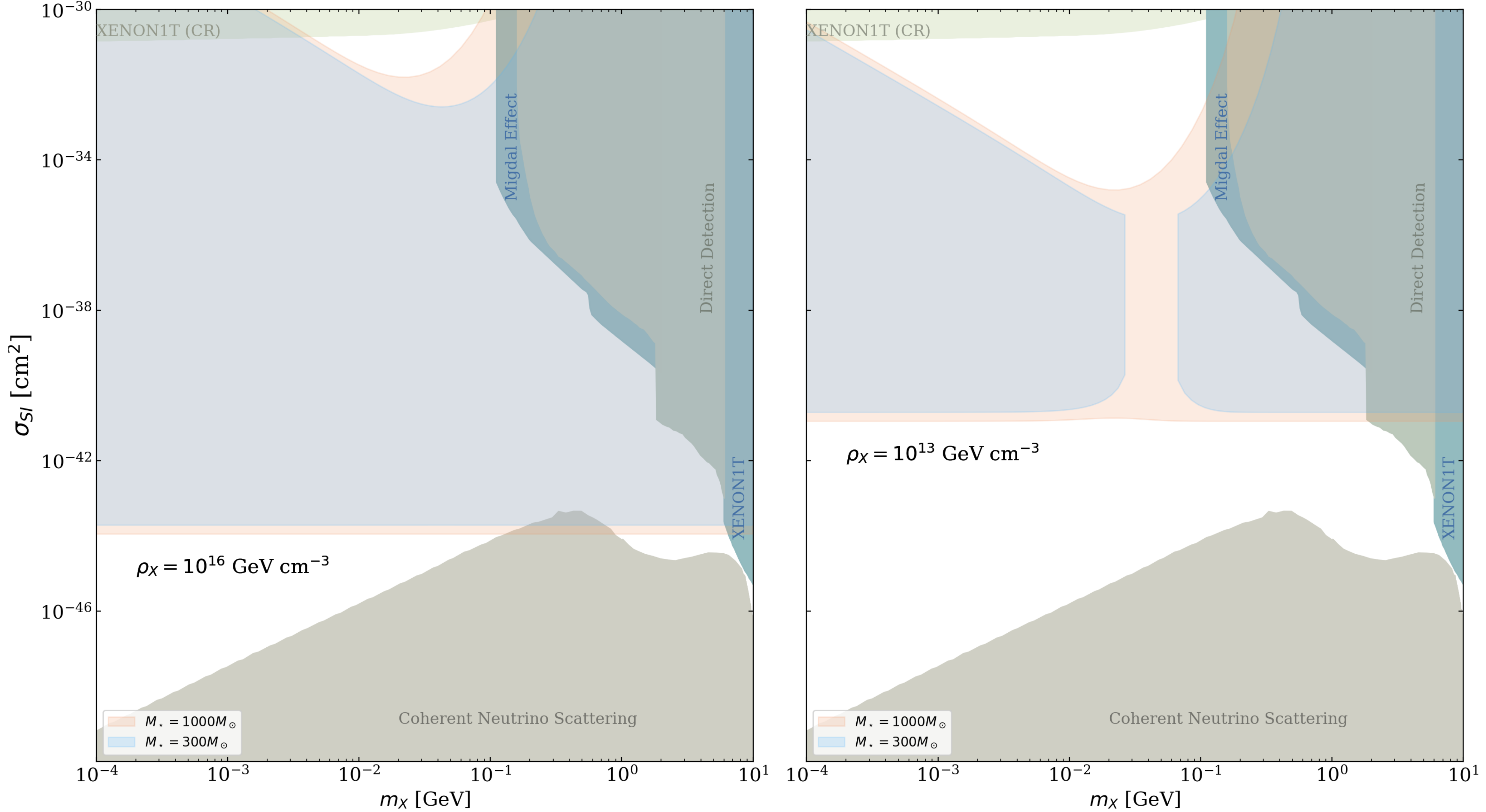
$$L_{Edd} = 3.5 \times 10^4 (M_\star / M_\odot) L_\odot$$

$$L_{nuc}(M_\star) + L_{cap}(M_\star; \text{DM params}) \leq L_{Edd}(M_\star)$$

EDDINGTON LUMINOSITY

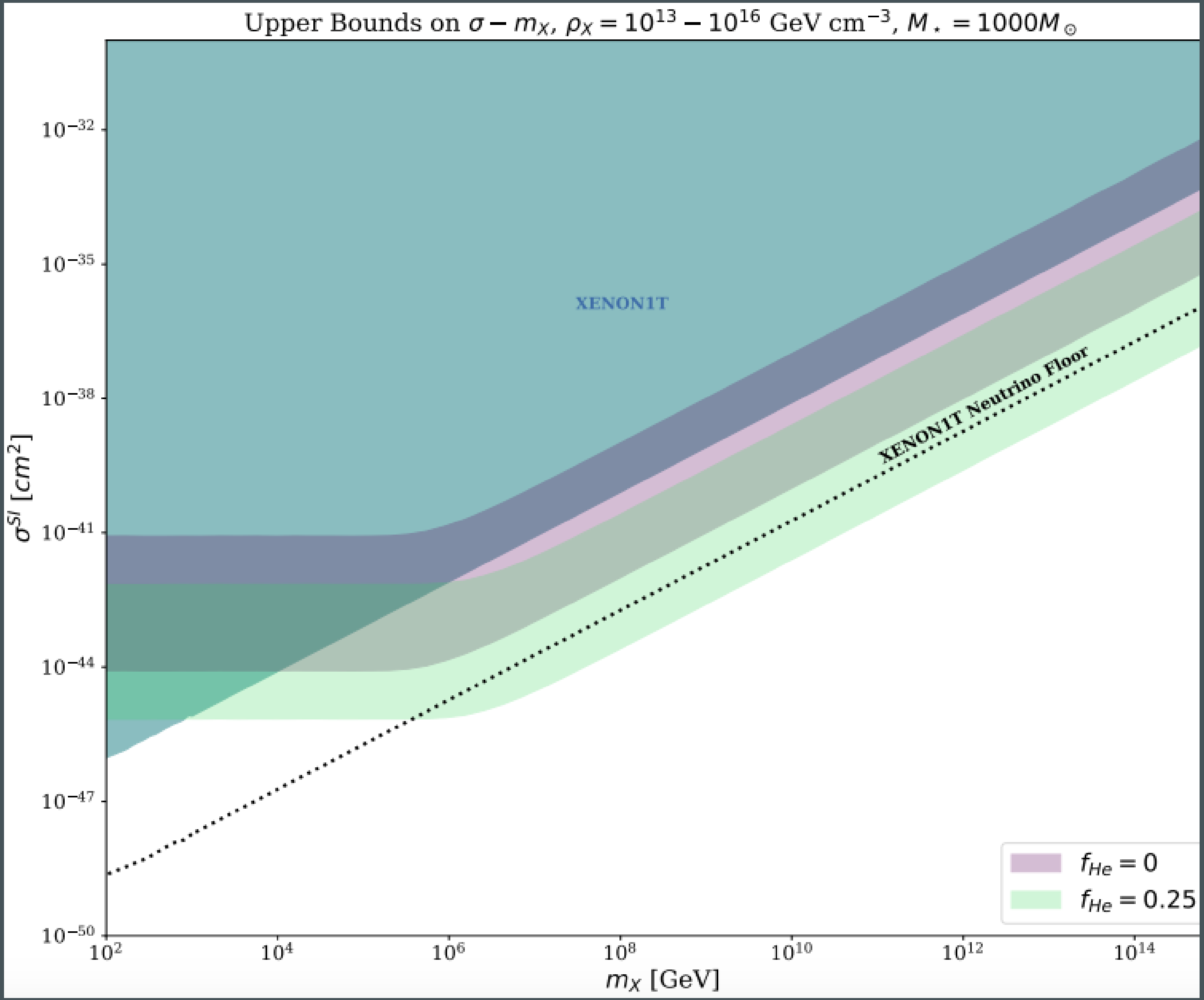
- This limit on luminosity provides a means to bound DM properties through the DM luminosity.

LOW-MASS BOUNDS


XENON1T (CR)
Migdal Effect
Direct Detection
XENON1T
Coherent Neutrino Scattering
$\rho_X = 10^{16}$ GeV cm^{-3}
$\rho_X = 10^{13}$ GeV cm^{-3}
$M_\star = 1000 M_\odot$
$M_\star = 300 M_\odot$
σ_{SI} [cm^2]
m_X [GeV]
10^{-30}
10^{-34}
10^{-38}
10^{-42}
10^{-46}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

HIGH-MASS BOUNDS

PROBING BELOW THE NEUTRINO FLOOR



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MAIN TAKEAWAYS

New formalism for multi-component DM capture

Enhanced DM capture and luminosity in Pop. III stars

Abiltiy to constrain DM cross section below the neutrino floor

FUTURE WORK

01

Apply formalism to other multi-component objects, such as white dwarves, exoplanets

02

Relax assumptions of even distributions of nuclei

03

Utilize stellar evolution code to directly implement multi-component capture

QUESTIONS?