Probing dark matter interactions below the neutrino floor with Population III stars

CI, C. Levy, J. Pilawa, S. Zhang 2009.11478 and 2009.11474

PHENO21 **Cosmin Ilie** cilie@colgate.edu (Colgate University) May26

The team:

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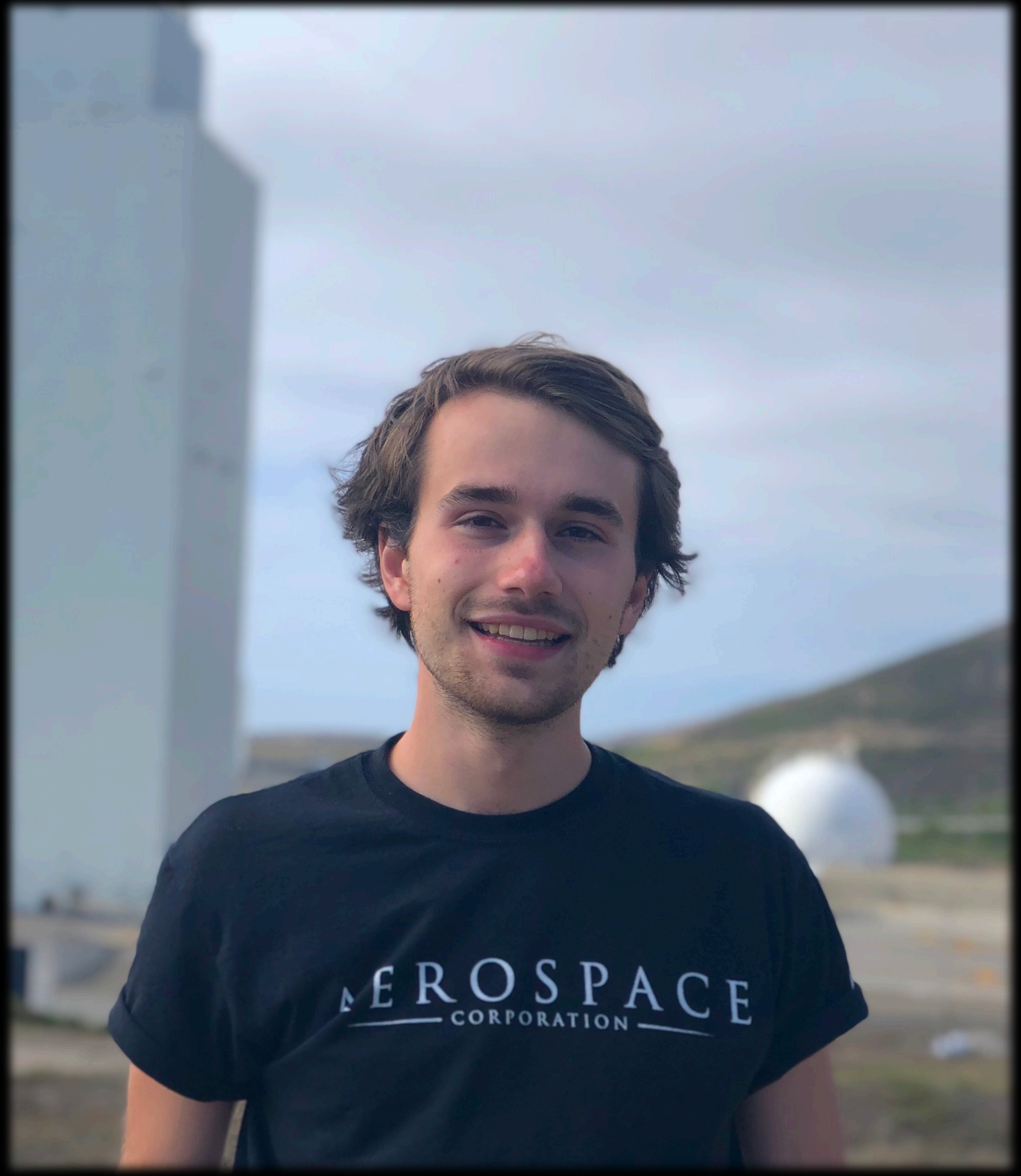


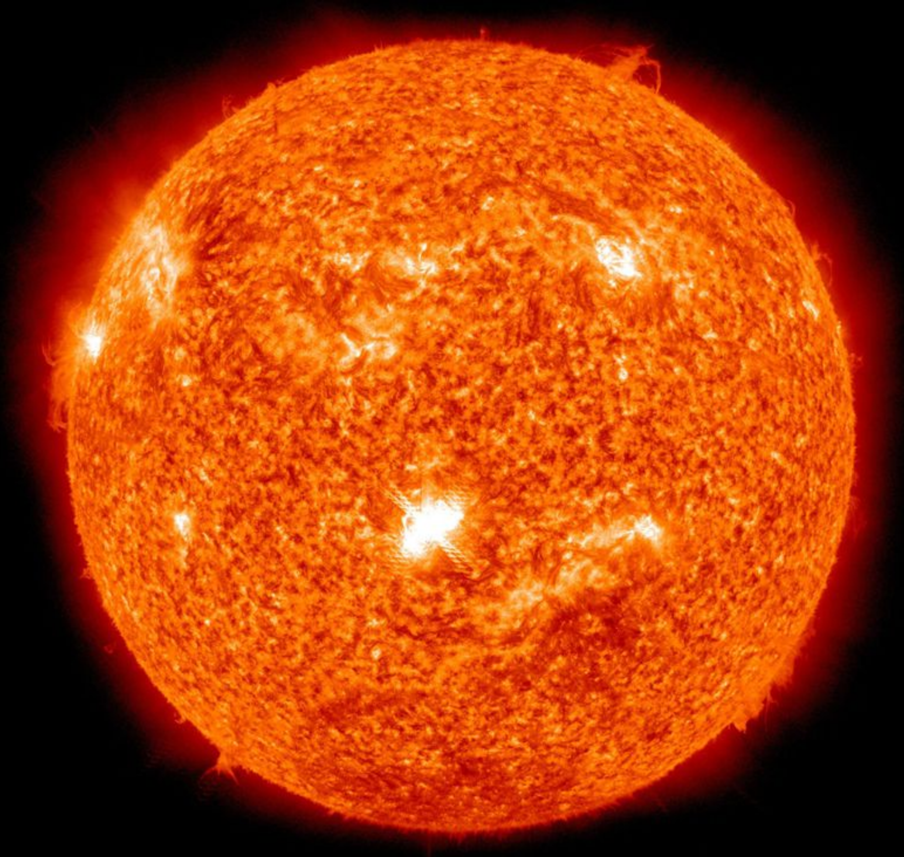
Jacob Pilawa (UC Berkeley)

Saiyang Zhang (UT Austin)

Astrophysical Objects as DM Probes

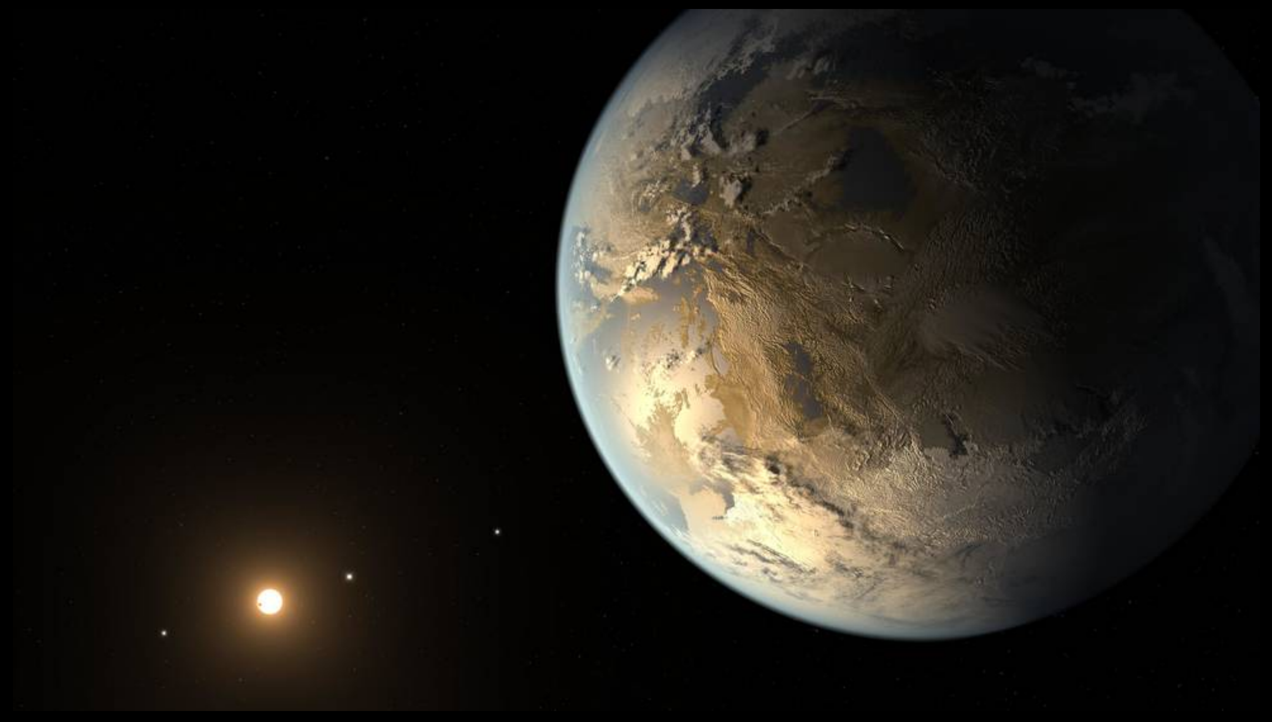
Earth

Moon



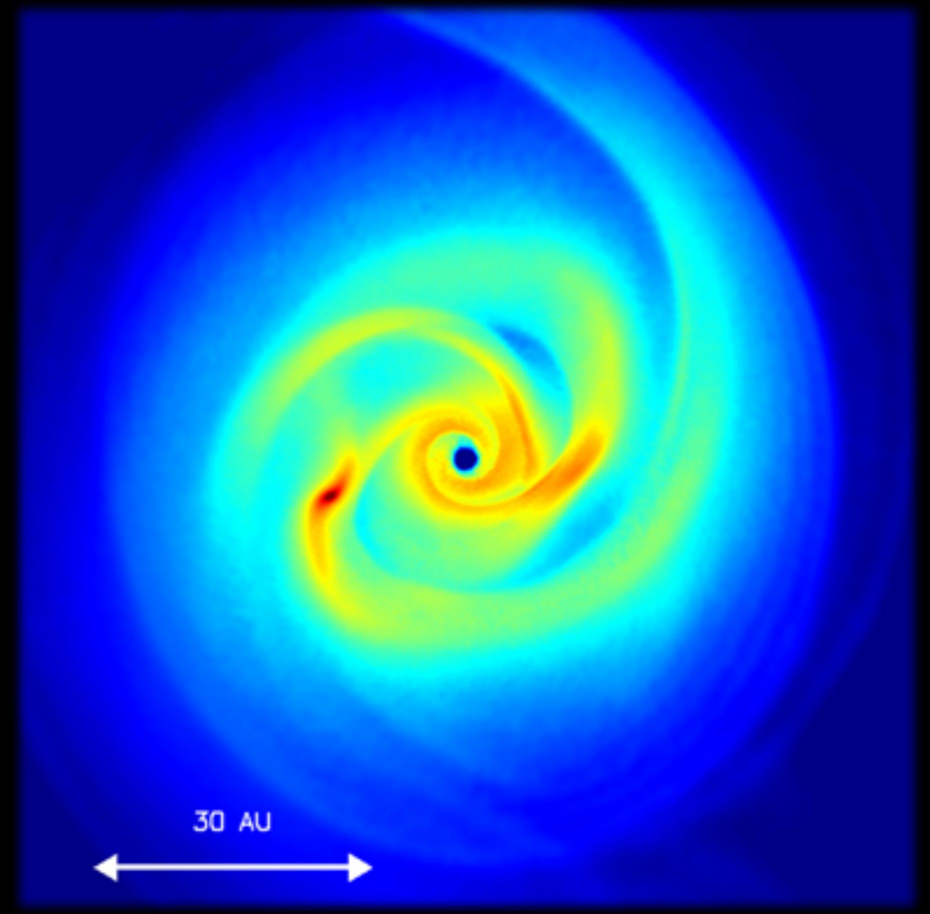
Sun

Neutron Stars



Exoplanets

White Dwarfs



The First Stars

The first Stars, bird's-eye view

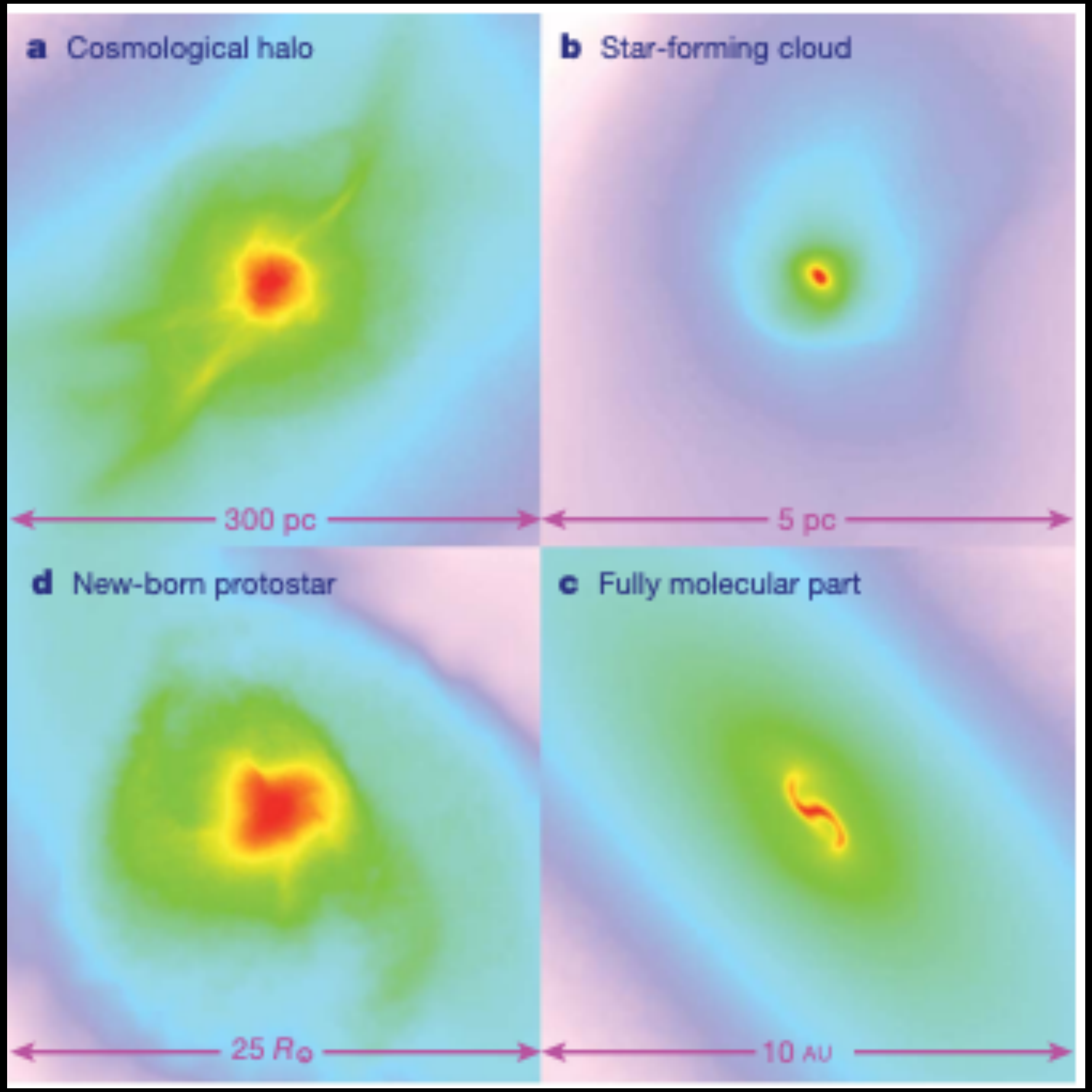
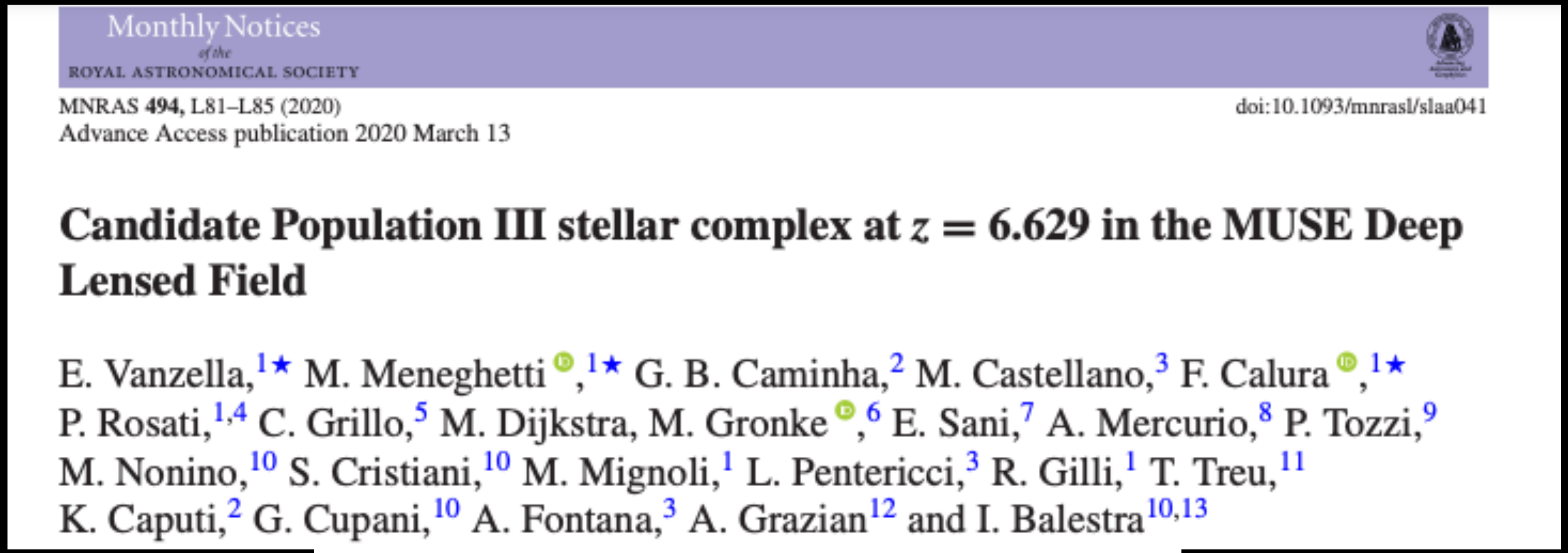


Figure From: Bromm et al. Nature 459 (2009)

- The form at high redshift (z~10-40) from pristine BBN H and He gas
- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions
- They can grow as massive as $1000 M_\odot$ (PopIII stars powered by H fusion)
- DM annihilations can lead to formation of Supermassive Dark Stars (SMDS) ($M_{SMDS} \sim 10^5\ M_\odot$) powered solely by DM)

Observational Status



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Candidate Population III stellar complex at $z = 6.629$ in the MUSE Deep Lensed Field

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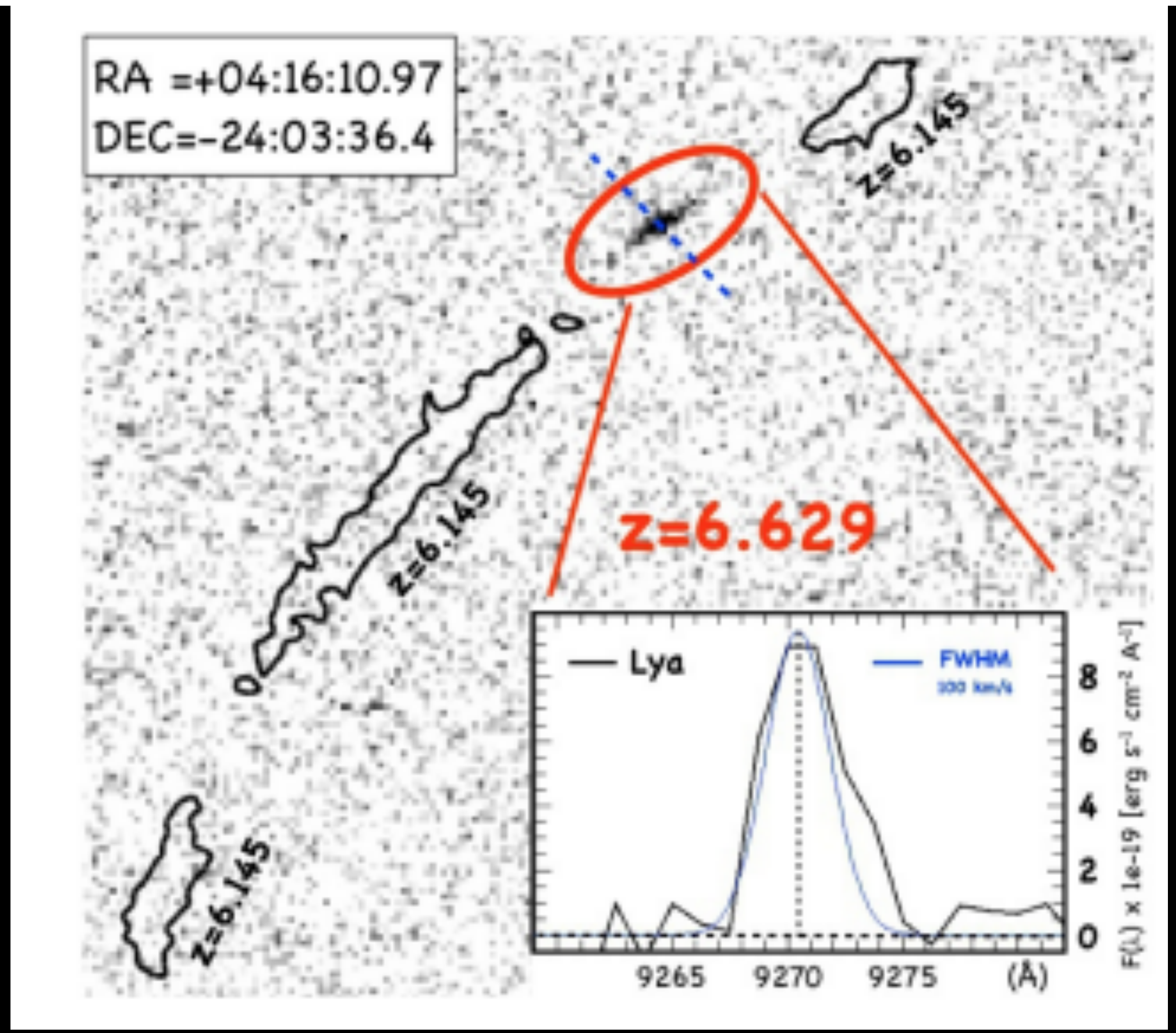
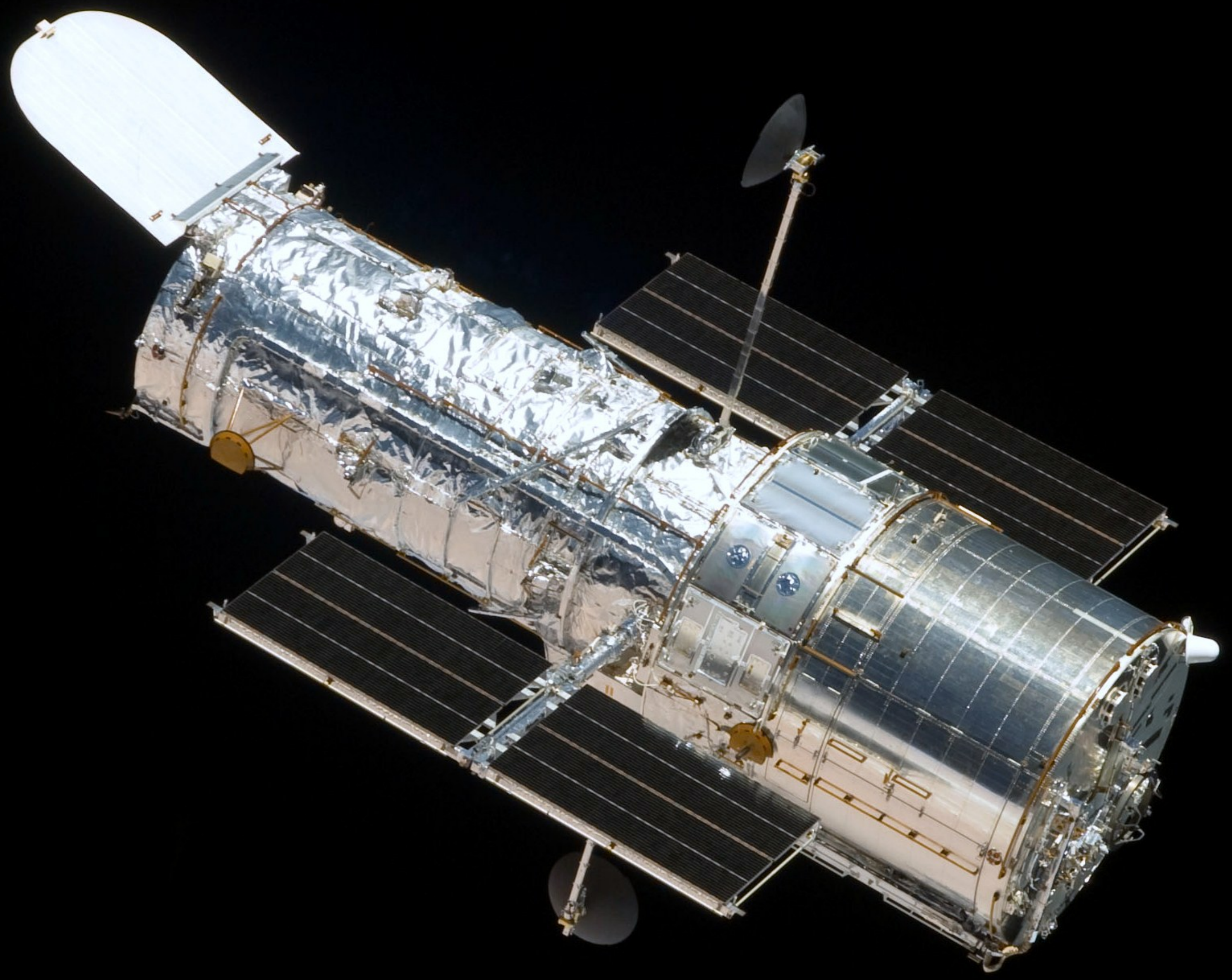
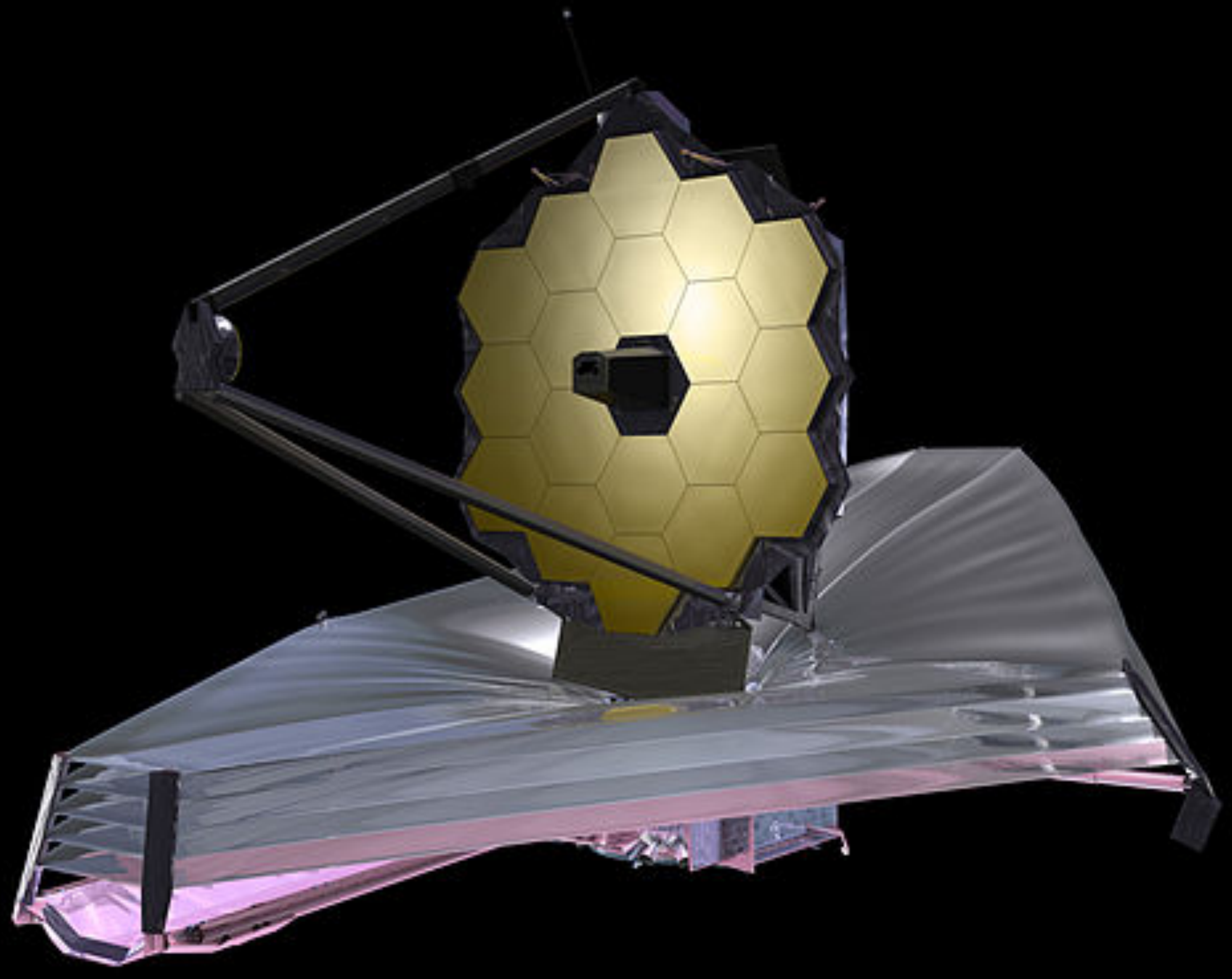


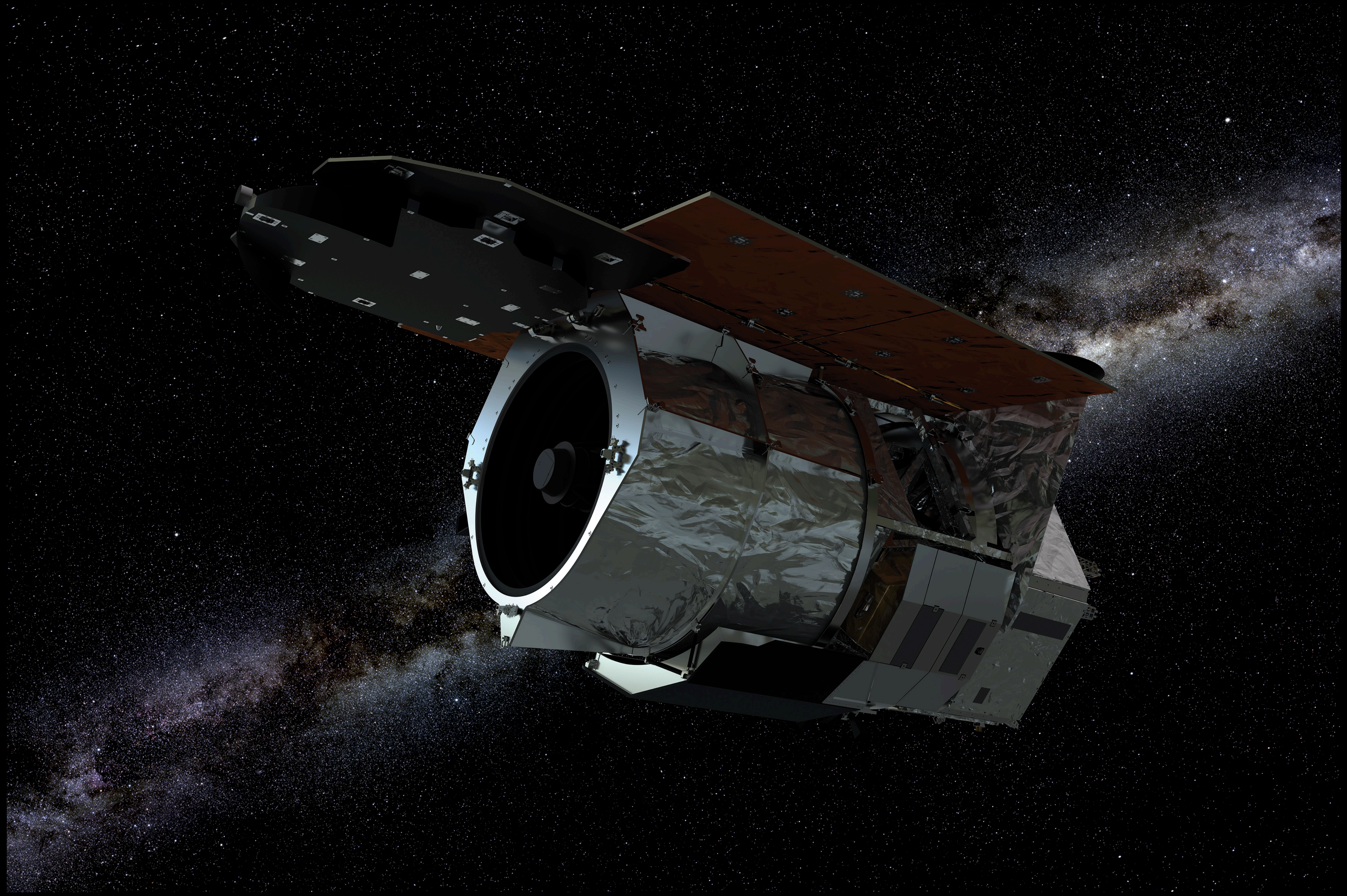
Fig. From Vanzella et al. MNRAS Lett. 294 (2020)



Observational Prospects

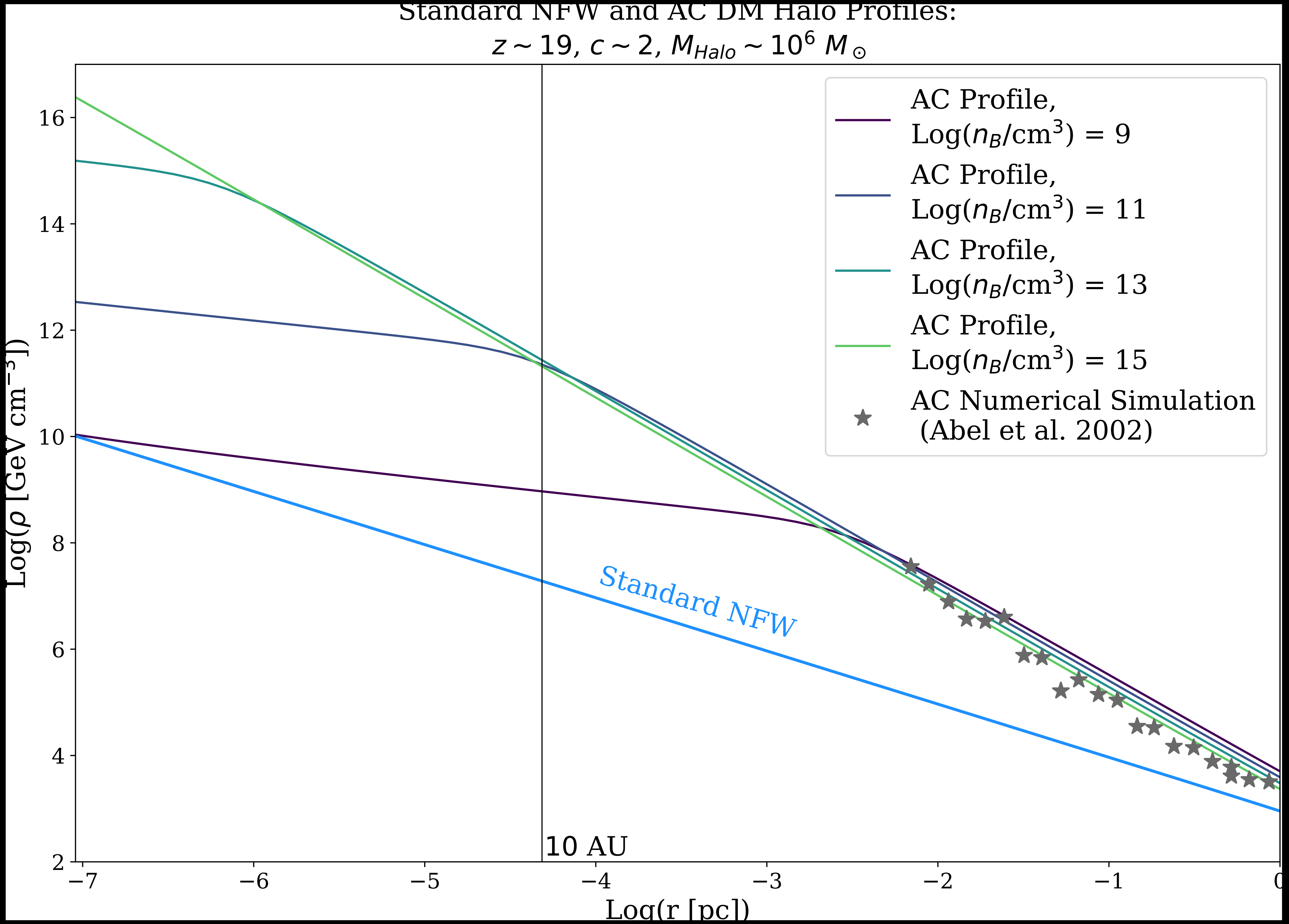


JWST

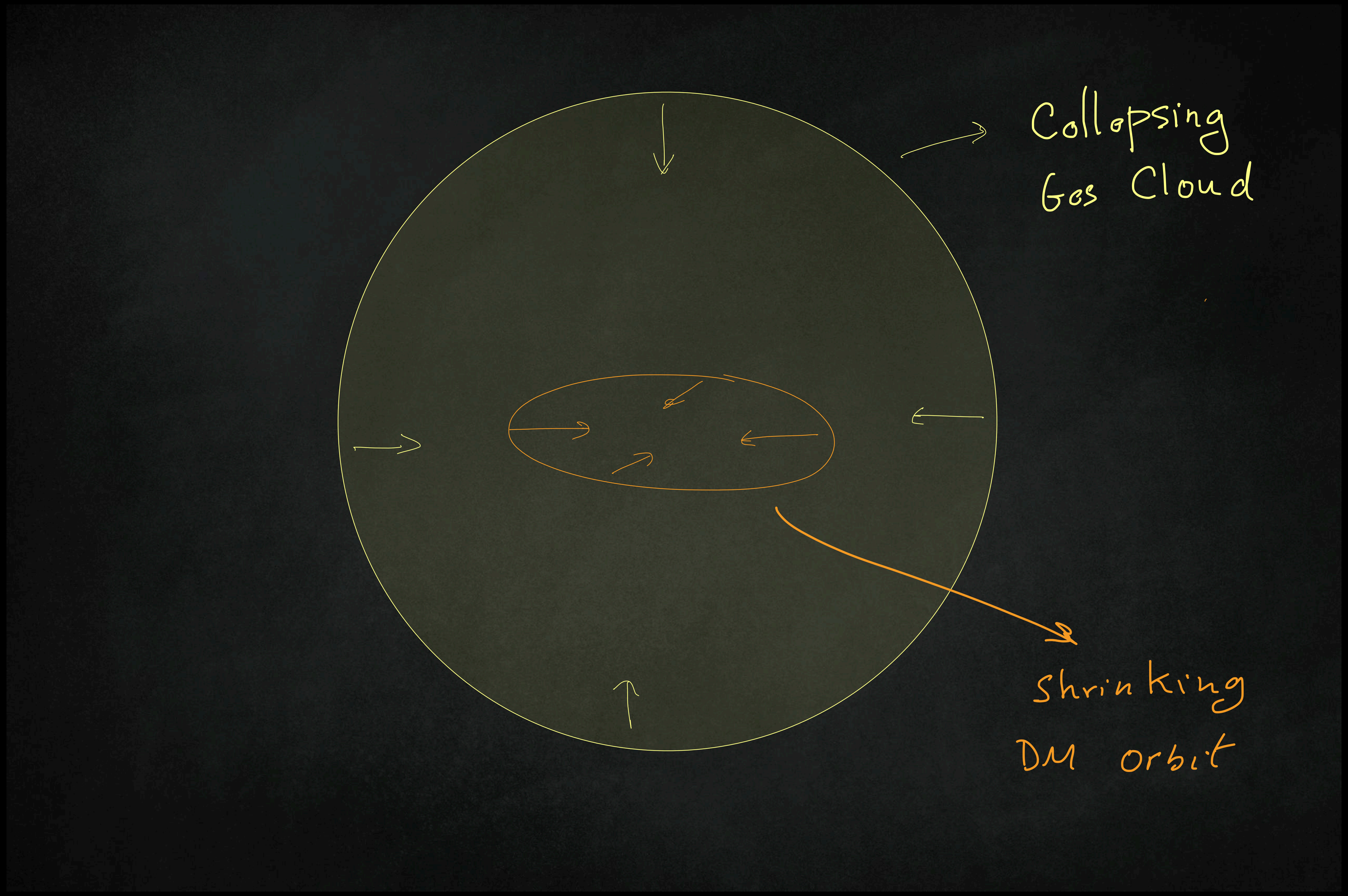


Roman (WFIRST)

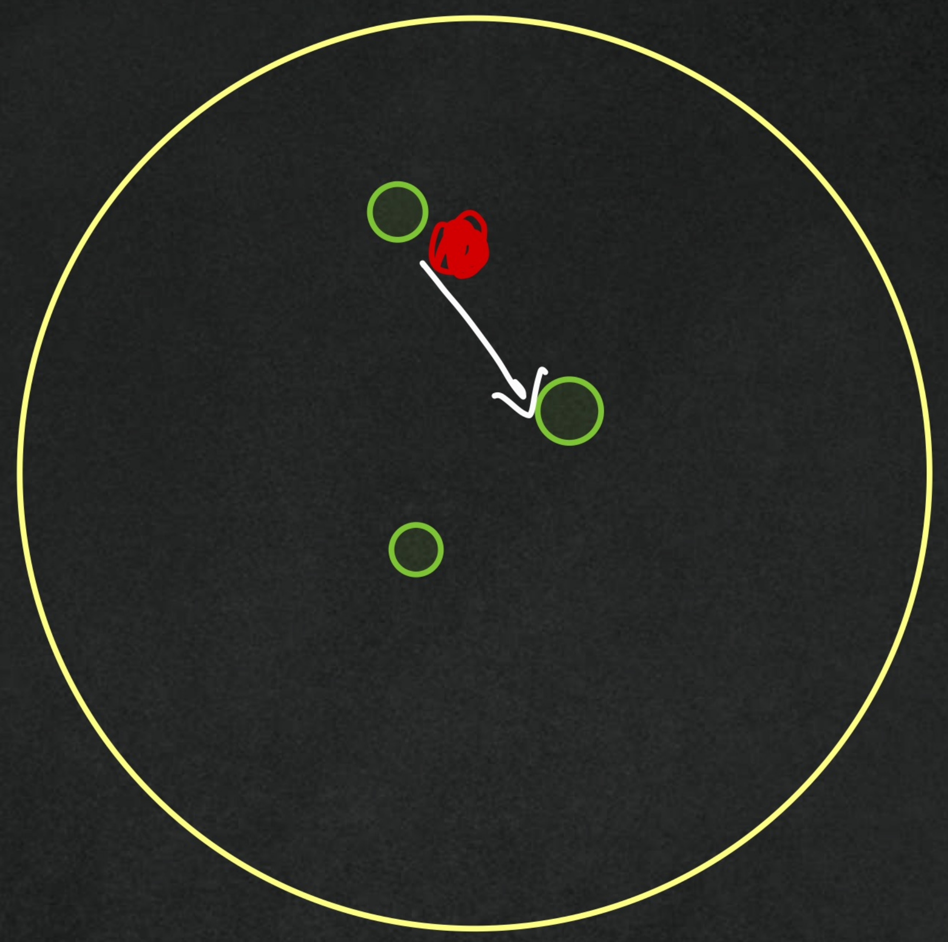
DM Densities (Adiabatic Compression)



Blumenthal AC formalism vs Abel et al Science (2002) Simulation

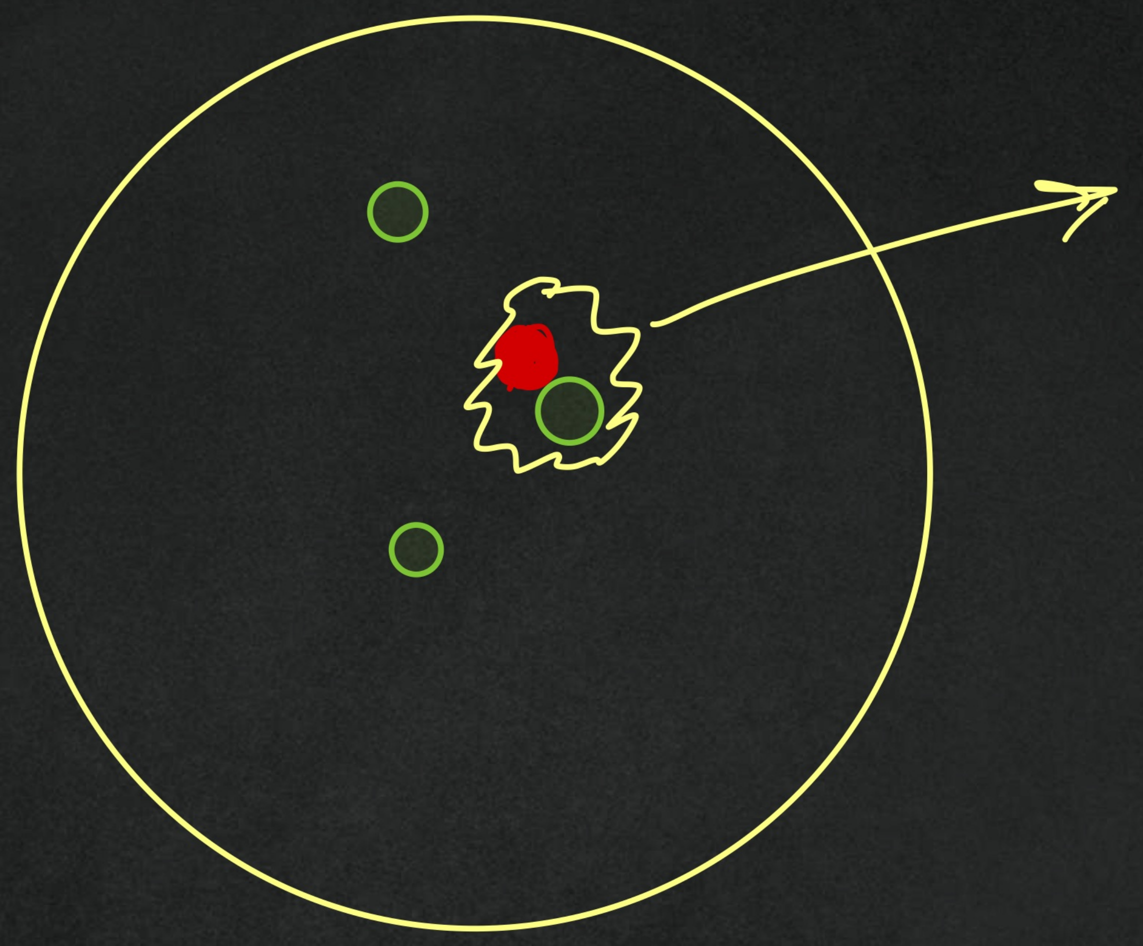


Dark Matter Capture



DM particle
gets deflected
towards
another nucleus

Dark Matter Capture

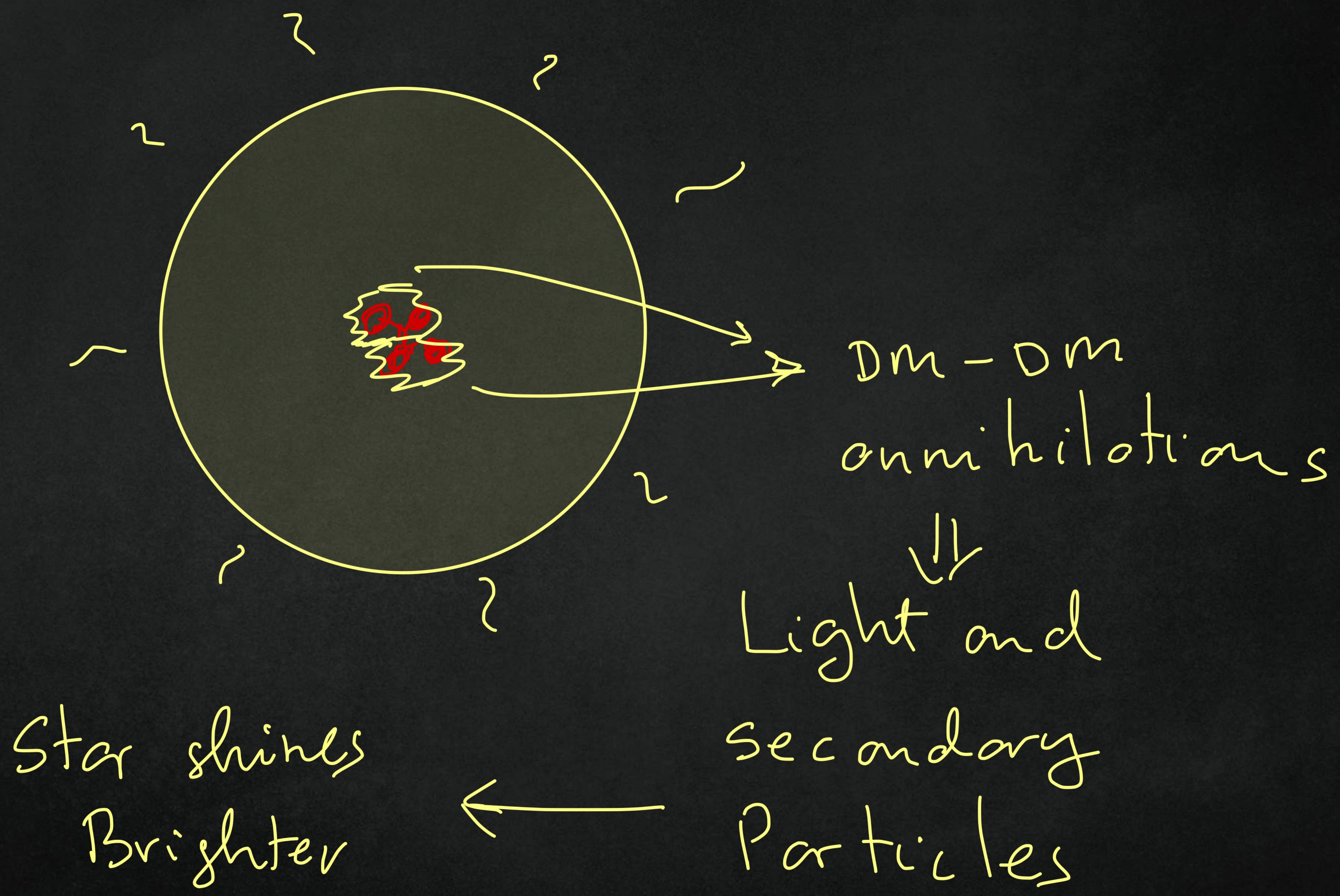


Another Collision

↓

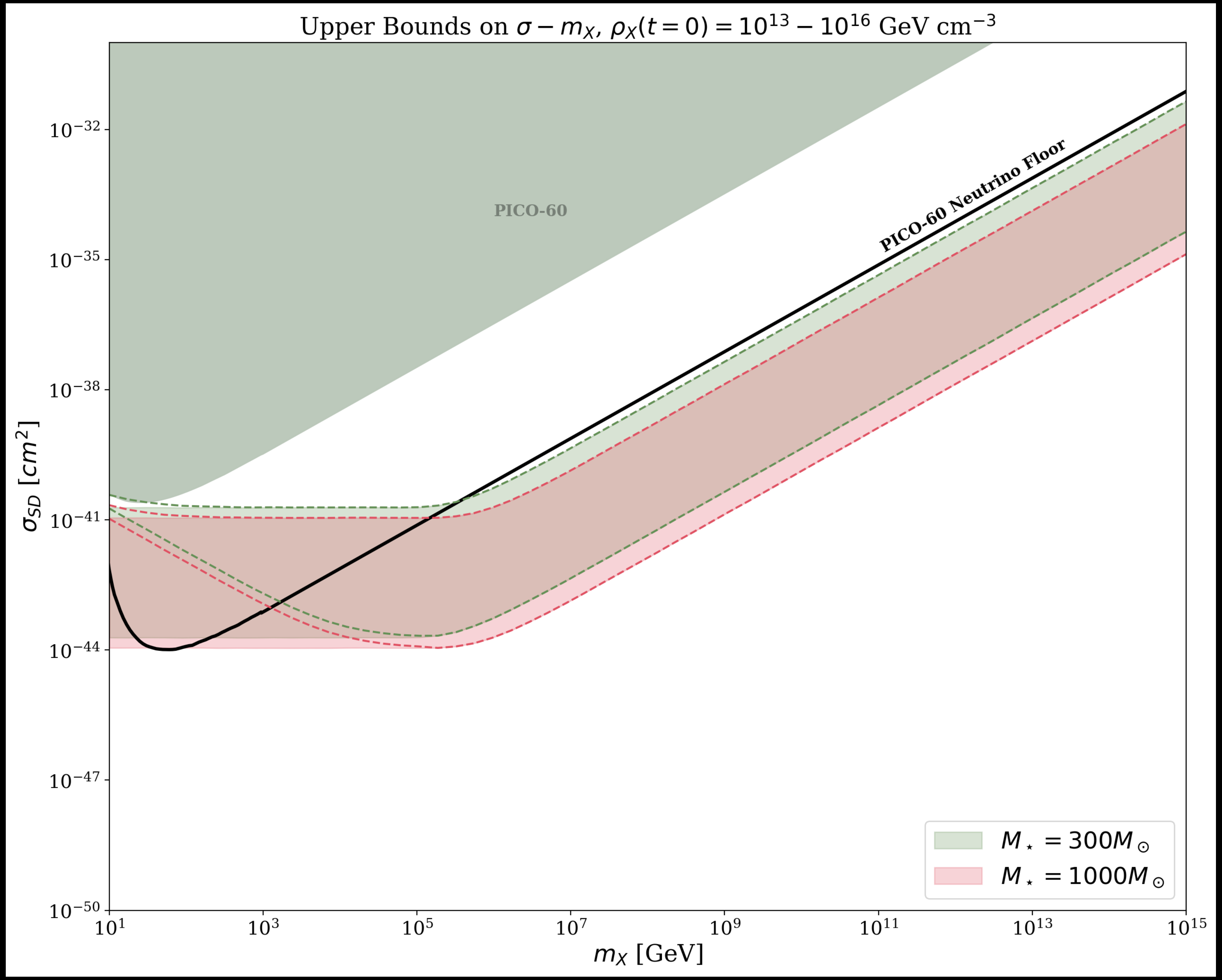
more Energy Lost by DM particle

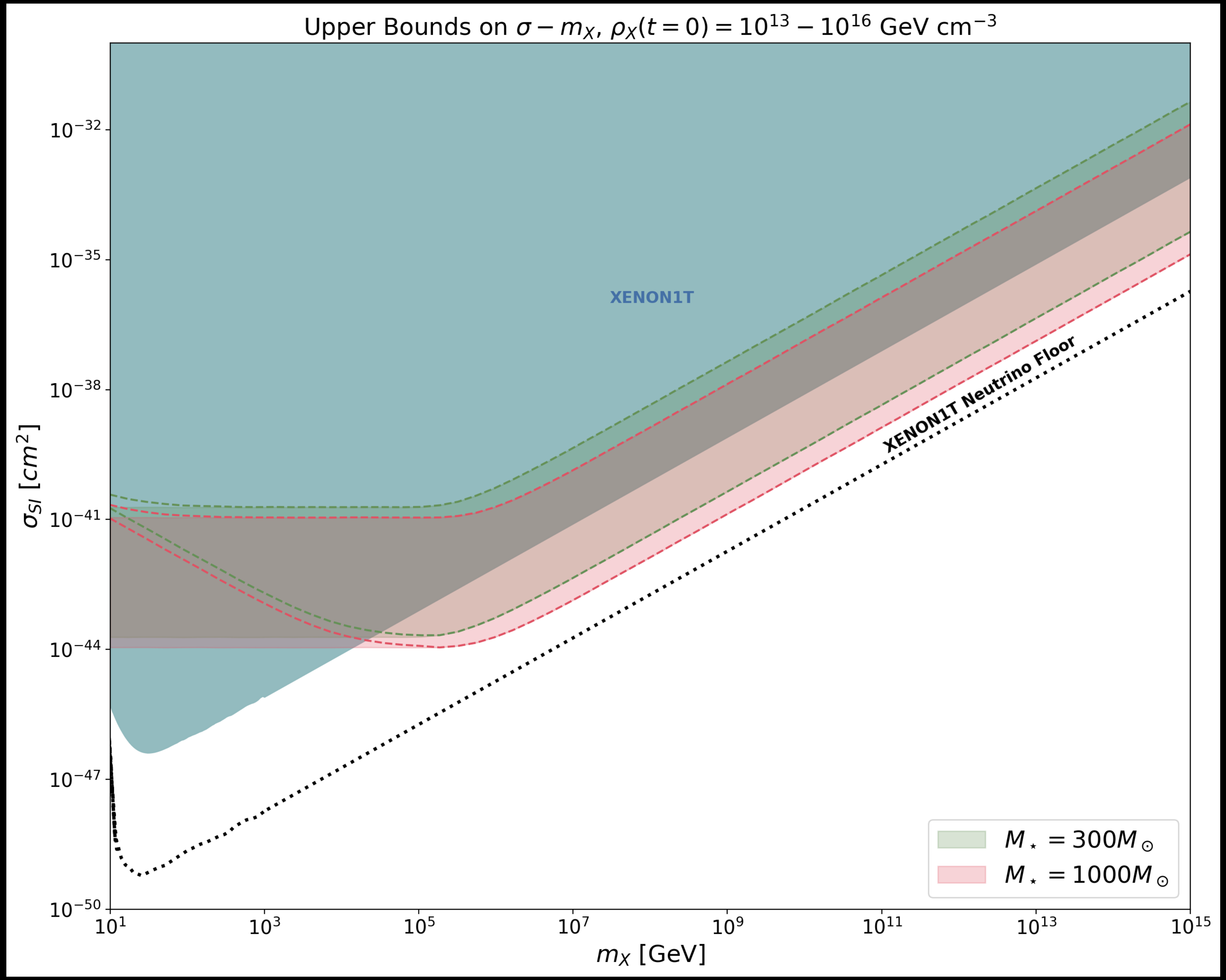
Annihilations of DM particles as a power source for the star



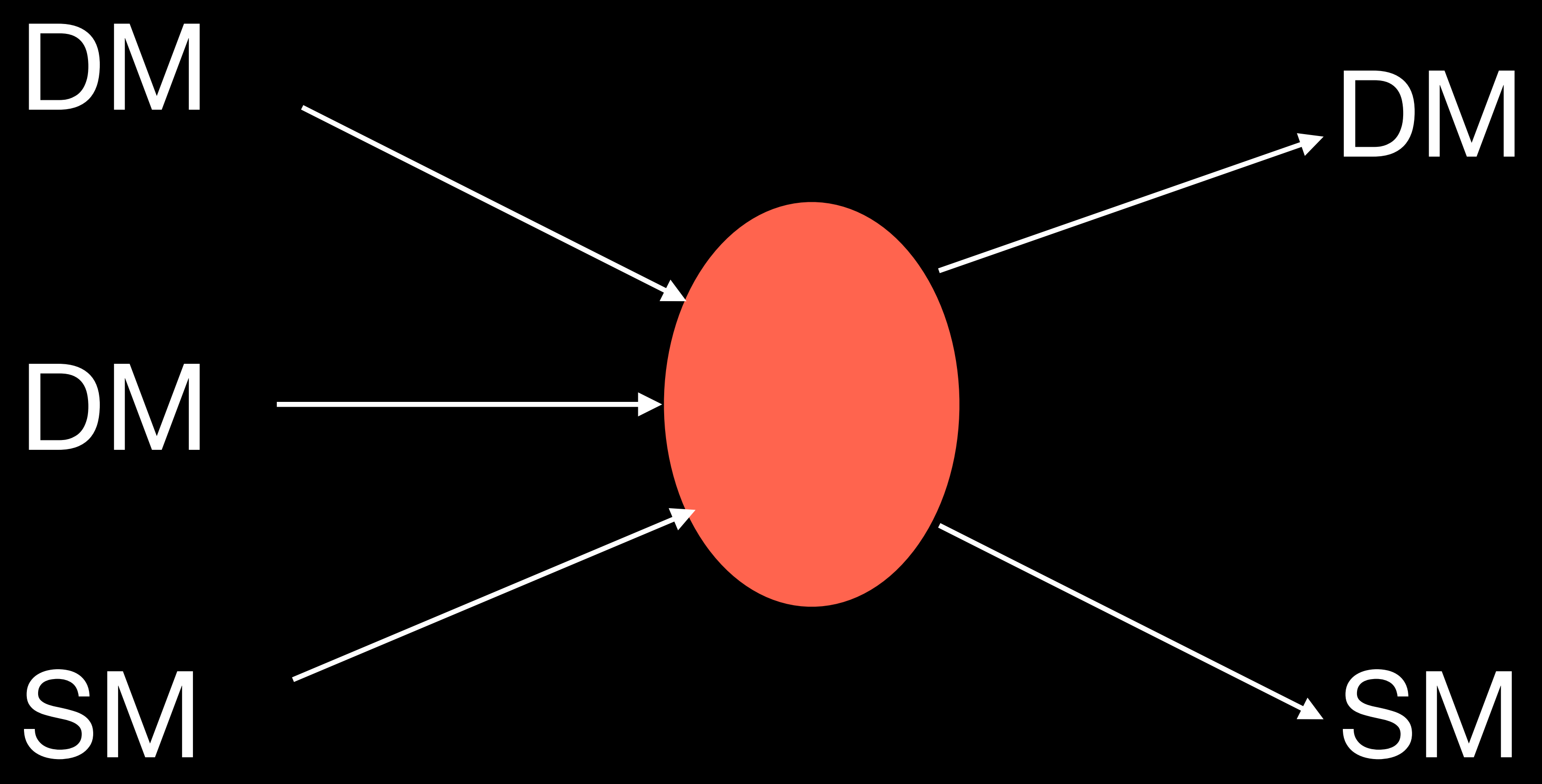
Bounds from imposing sub-Eddington Luminosity:

$$L_{DM}(M_\star, R_\star; DM\ params) \le L_{Edd}(M_\star) - L_{nuc}(M_\star)$$





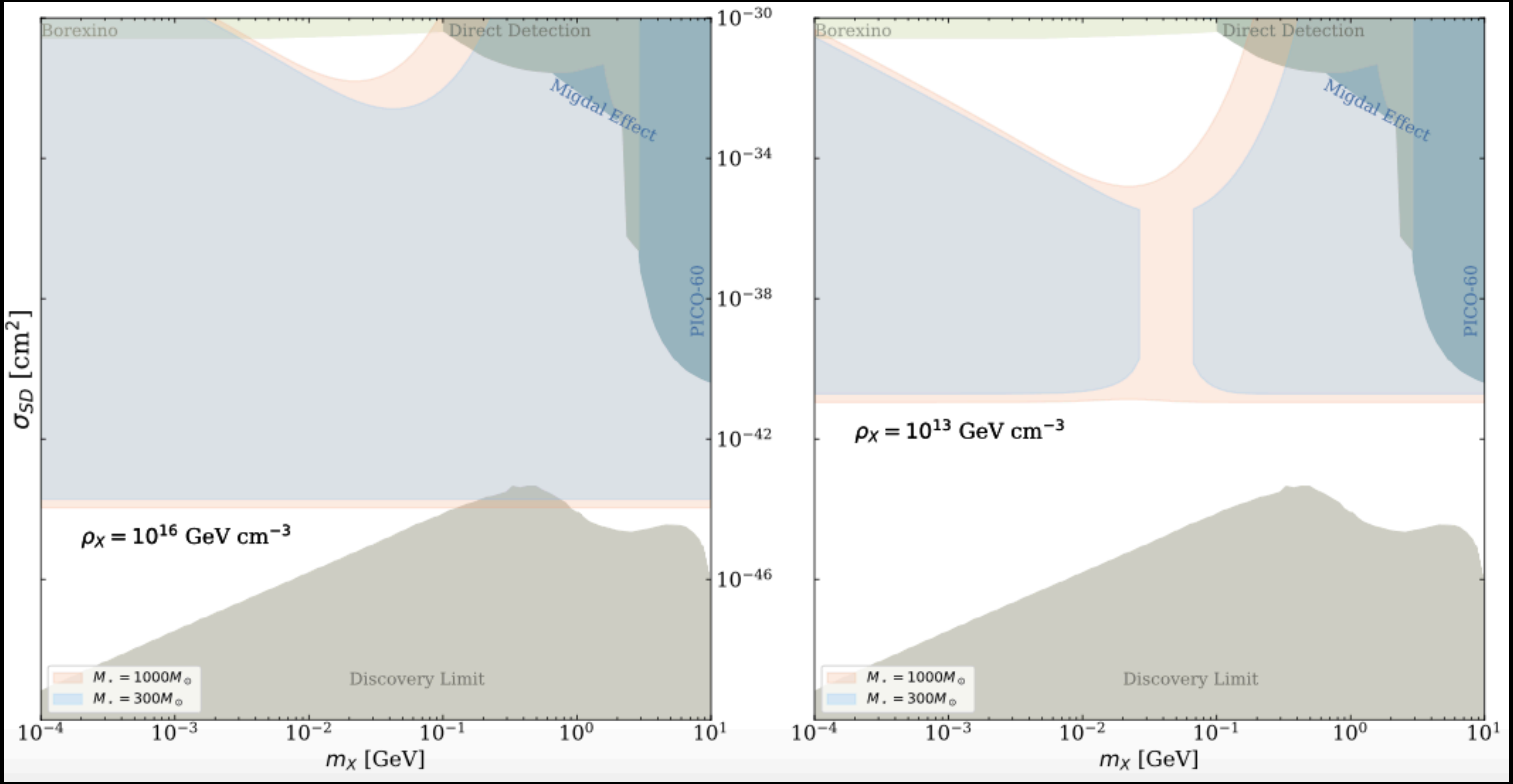
How about Sub GeV annihilating DM that can deposit energy inside a star?



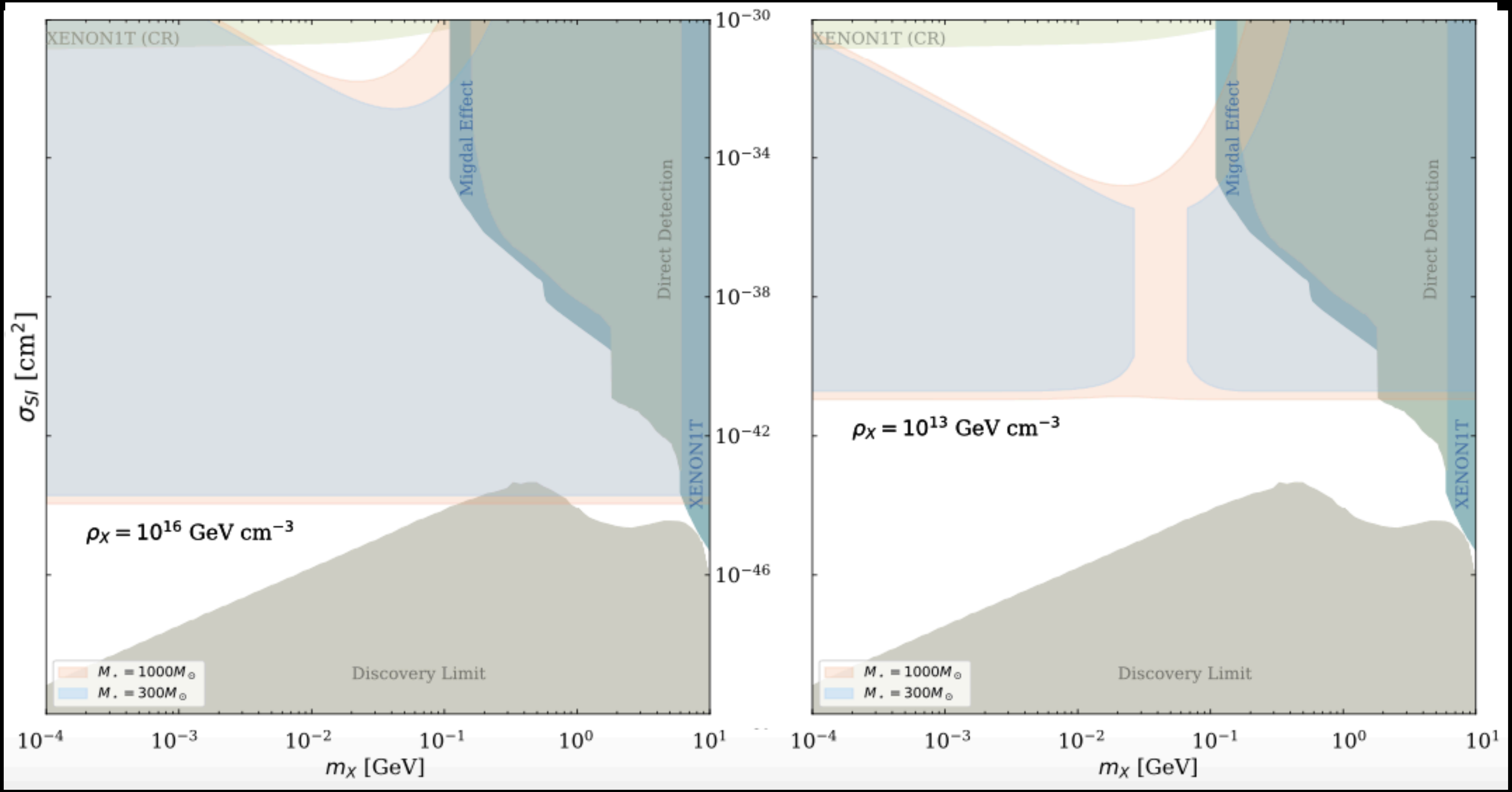
$$\langle \sigma_{CoSIMP} v^2 \rangle \sim 10^{12} \left(\frac{\mathrm{MeV}}{m_X} \right)^3 \left(\frac{0.12}{\Omega_X h^2} \right)^2 \mathrm{GeV}^{-5}$$

CoSIMP DM

SD Bounds on Co-SIMP sub GeV DM



SI Bounds on Co-SIMP sub GeV DM



PHENO21 DM bounds from POPIII stars **Cosmin Ilie** cilie@colgate.edu May26

Number of captured DM particles inside the star

$$\dot{N}_\chi = \underbrace{C_{TOT}}_{\text{Total Capture Rate}} - \underbrace{C_A \cdot}_{\text{Annihilation Rate } (\Gamma_A)} N_\chi^2 - \underbrace{E \cdot N_\chi}_{\text{Total Evaporation Rate}}$$

$$N_\chi(t) = \sqrt{\frac{C_{TOT}}{C_A}} \cdot \frac{\tanh\left(\frac{\kappa t}{\tau_{eq}}\right)}{\kappa + \frac{1}{2} E \cdot \tau_{eq} \tanh\left(\frac{\kappa t}{\tau_{eq}}\right)}$$

$$\boxed{\tau_{eq} \equiv \frac{1}{\sqrt{C_{TOT}\, C_A}}} \qquad \boxed{\kappa = \sqrt{1 + E^2 \tau_{eq}^2 / 4}}$$

DM Luminosity

$$L_{DM} = f \cdot \Gamma_A \cdot m_X$$

DM Luminosity

$$L_{DM} = f \cdot \Gamma_A \cdot m_X$$

Fraction of annihilation energy deposited inside the star, i.e. not lost to neutrinos. We assume f=1 but our results scale linearly with f

DM Luminosity

$$L_{DM} = f \cdot \Gamma_A \cdot m_X$$

$$\boxed{\Gamma_A = C_A N_X^2 \xrightarrow[t \gg \tau_{eq}/\kappa]{\text{Capture/Annihi/Evap Equil.}} \frac{C_{tot}}{(\kappa + 1/2E \cdot \tau_{eq})^2} \xrightarrow[E \cdot \tau_{eq} \ll 1]{\text{Evap negligeable}} C_{tot}}$$

Capture Rates when $v_{esc} \gg \bar{v}$

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sqrt{24\pi} G M_\star R_\star \frac{\rho_X}{m_X \bar{v}} \sum_{N=1}^{\infty} p_N(\tau) \left(1 - \left(1 + \frac{2 A_N^2 \bar{v}^2}{3 v_{esc}^2} \right) e^{-A_N^2} \right)$$

J. Bramante et al PRD 96 (2017); **CI,** J. Pilawa, S. Zhang PRD102 (2020)

Capture Rates when $v_{esc} \gg \bar{v}$

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sqrt{24\pi} G M_\star R_\star \frac{\rho_X}{m_X \bar{v}} \sum_{N=1}^{\infty} p_N(\tau) \left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3 v_{esc}^2} \right) e^{-A_N^2} \right)$$

Stellar Parameters

Capture Rates when $v_{esc} \gg \bar{v}$

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sqrt{24\pi} G M_\star R_\star \underbrace{\frac{\rho_X}{m_X \bar{v}}}_{\text{DM Parameters}} \sum_{N=1}^{\infty} p_N(\tau) \left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3 v_{esc}^2} \right) e^{-A_N^2} \right)$$

Capture Rates when $v_{esc} \gg \bar{v}$

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sqrt{24\pi} G M_\star R_\star \frac{\rho_X}{m_X \bar{v}} \sum_{N=1}^{\infty} p_N(\tau) \left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3 v_{esc}^2} \right) e^{-A_N^2} \right)$$

Probability a DM particle is captured after N collisions

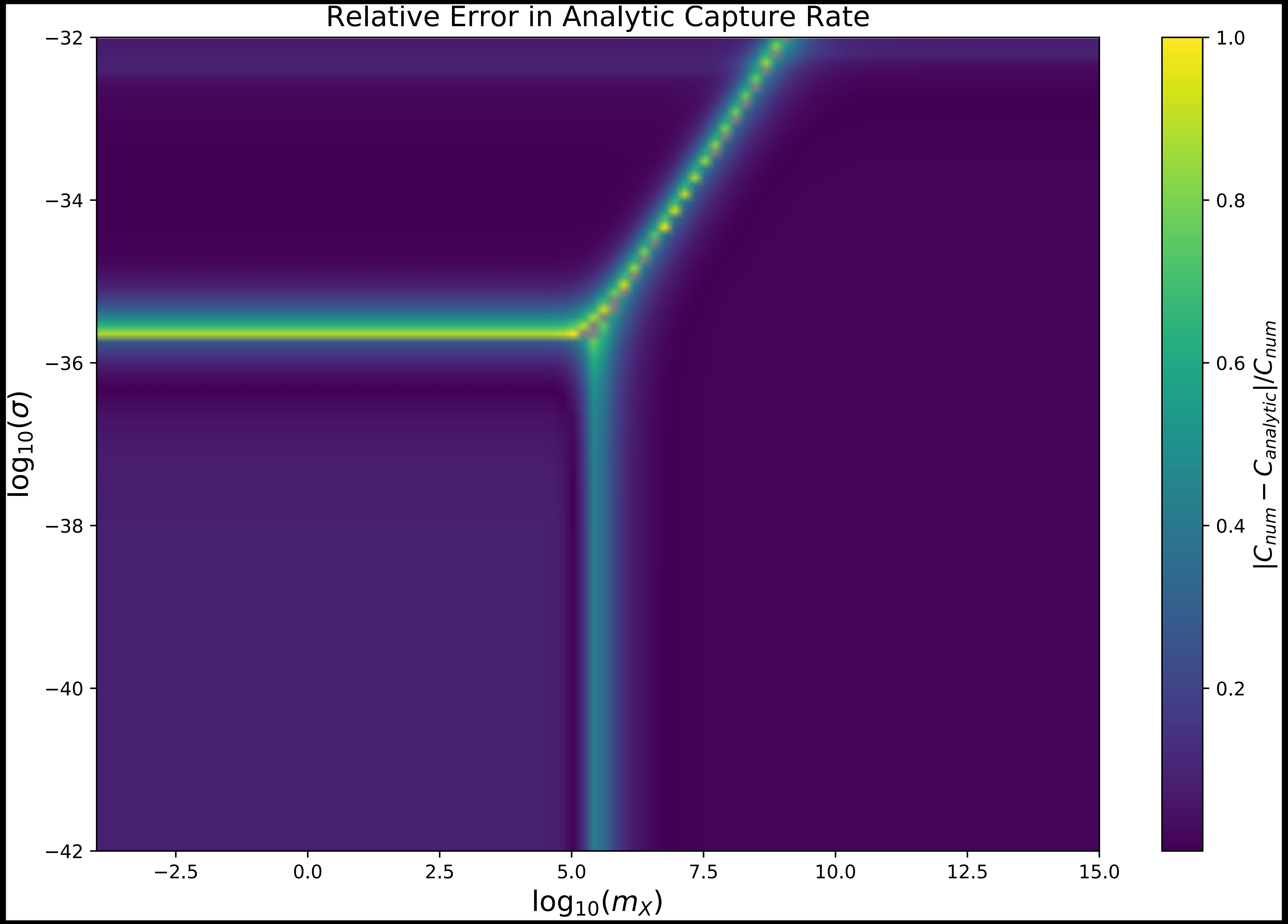
Capture Rates when $v_{esc} \gg \bar{v}$ and $m_X \gg m_p$

$$C_{tot} = \sum_{N=1}^{\infty} C_N = \sqrt{24\pi} G M_\star R_\star \frac{\rho_X}{m_X \bar{v}} \sum_{N=1}^{\infty} p_N(\tau) \left(1 - \left(1 + \frac{2A_N^2 \bar{v}^2}{3 v_{esc}^2} \right) e^{-A_N^2} \right)$$

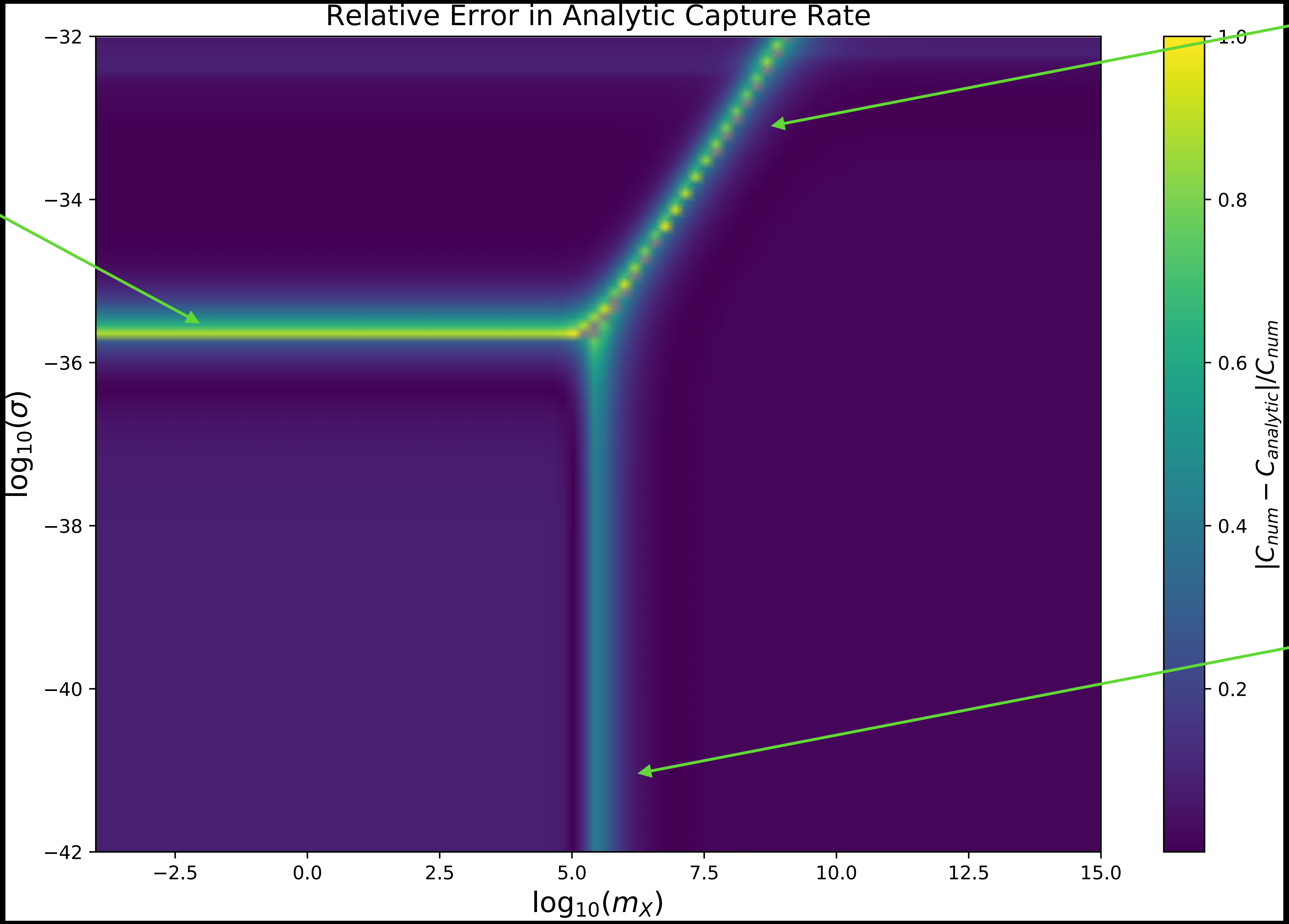
$$\downarrow$$

$$\boxed{A_N^2 = \frac{3 N m_p v_{esc}^2}{m_X \bar{v}^2}}$$

Analytic estimates of Capture Rates



Analytic estimates of Capture Rates

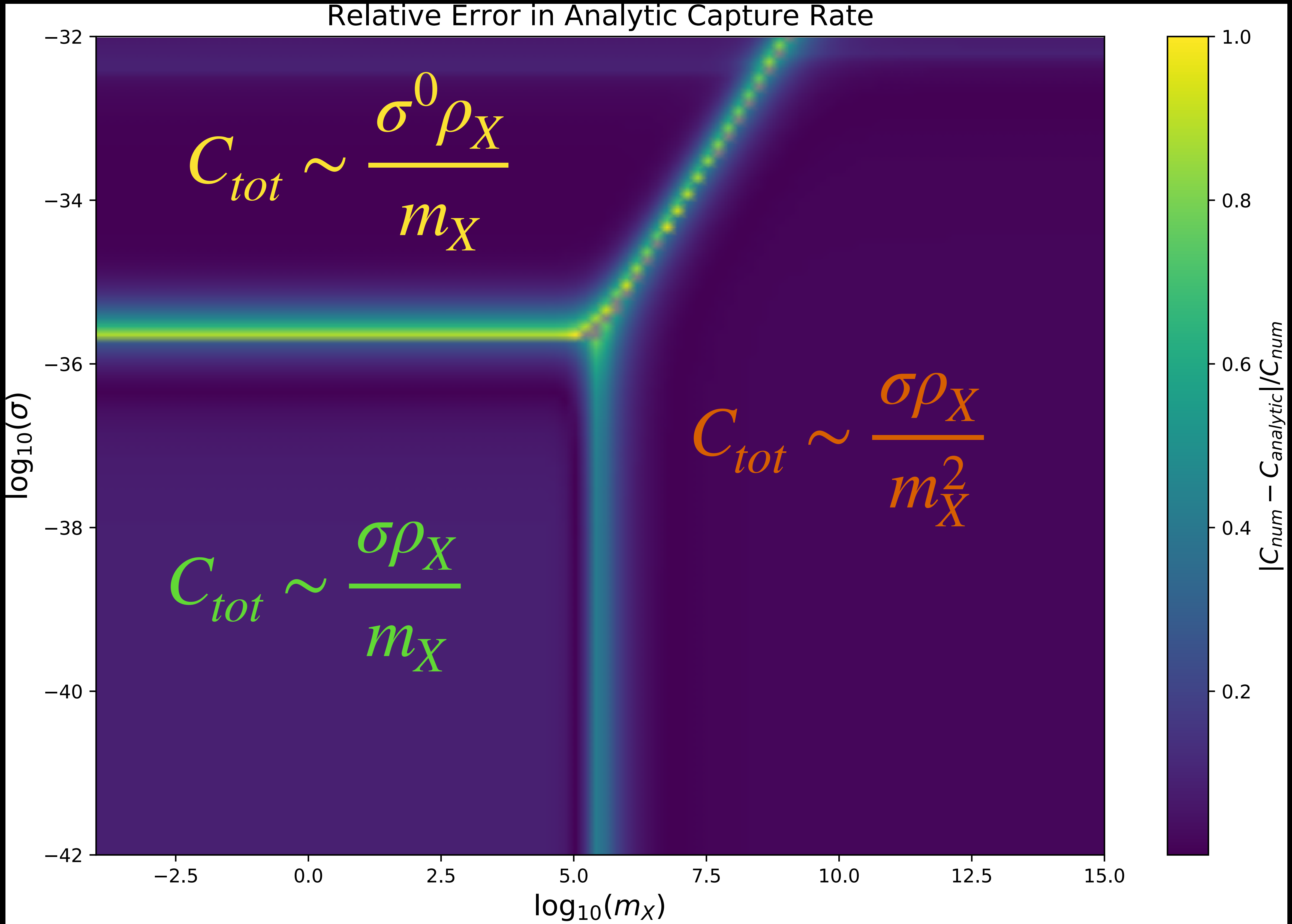


$\tau = 1$

$k \cdot \tau = 1$

$$k \equiv \frac{3 m_p v_{esc}^2}{m_X \bar{v}^2} = 1$$

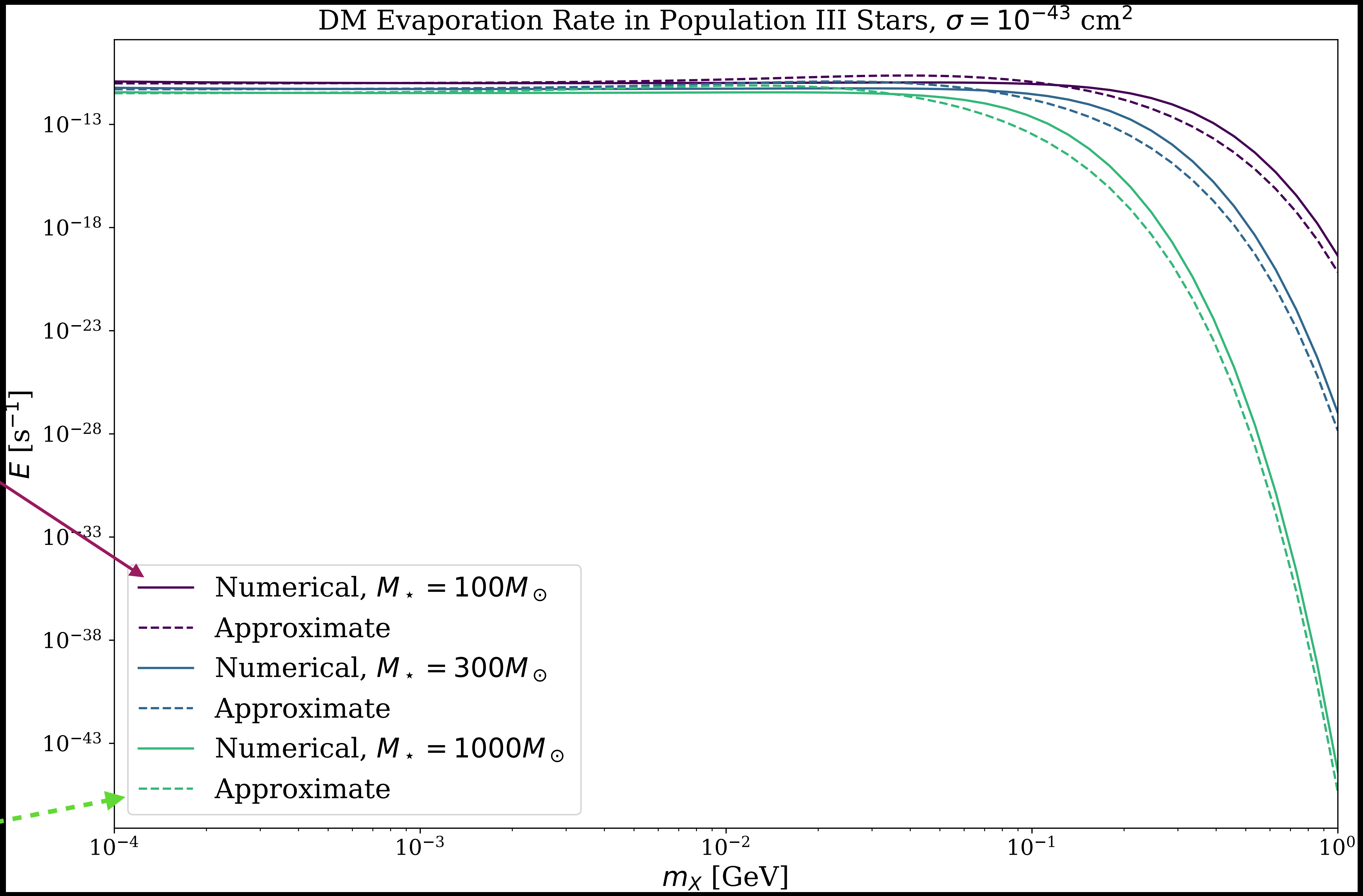
Analytic estimates of Capture Rates



Evaporation Rates for n=3 Polytropes

- We use the DM evaporation formalism of Gould ApJ 321(1987) and apply it to n=3 polytropes
- To calculate the captured DM temperature we use the Spergel & Press ApJ 294 (1985) formalism

$$E \approx \frac{3V_\star \cdot \bar{n}_p \cdot u_c \cdot \sigma}{2V_1\sqrt{\pi}} e^{-\frac{v_{esc}^2\mu}{u_c^2\Theta}(1+\xi_1/2)}$$



Summary

- PopIII stars can be very powerful DM probes
- If one assumes a DM density we can place bounds on DM-proton cross section
- If Direct detection experiments pin down the cross section we can use our method to constrain DM density at location of the first stars
- For sub GeV DM, even if evaporation is significant we can still place competitive bounds on σ with PopIII stars
- We find useful analytic approximations of the DM capture rates and evaporation rates (for n=3 Polytropes)