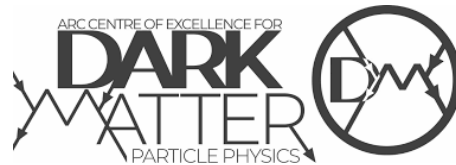


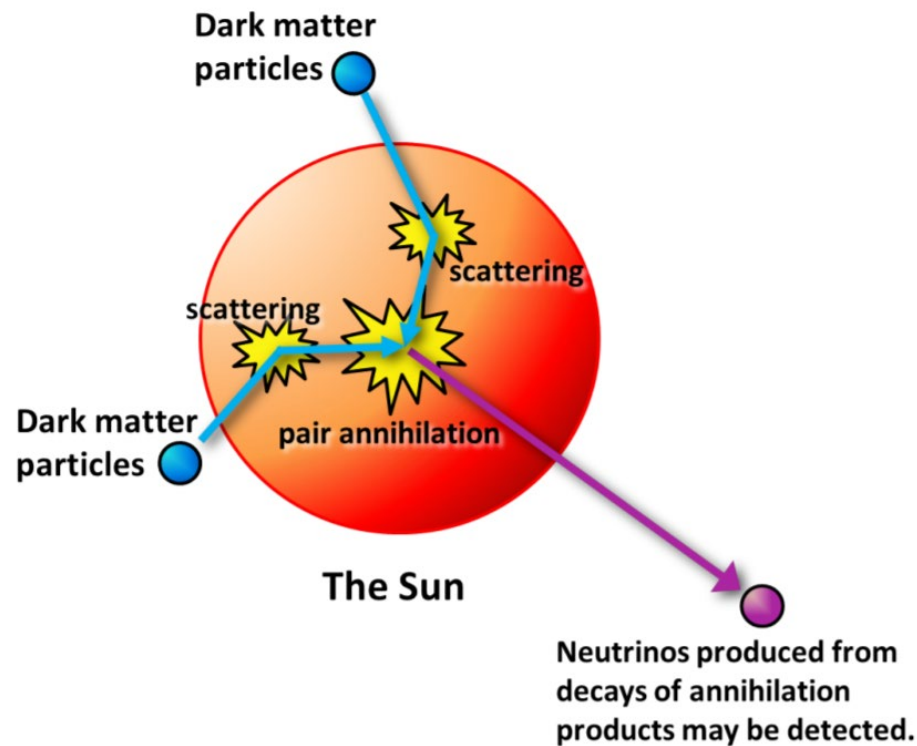
# Heavy Dark Matter in rapidly evolving massive stars

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# DARK MATTER CAPTURE IN STARS



- In a typical collision, the Dark Matter loses enough energy to drop below the escape velocity and hence becomes gravitationally bound to the star
- Subsequent scatterings, lose energy, accumulates in the centre
- Observable signal depends on Capture rate
  - Probes same parameter space as Direct Detection

# Dark Matter capture in stars

Other kind of stellar objects can be considered:

- Neutron Stars
- White Dwarfs
- Main Sequence Stars
- Exoplanets
- .....
- Pop III stars [this talk]

## Neutron stars as dark matter labs

DM Kinetic Energy: For a 50 MeV benchmark, the local kinetic energy the surface is:

$$E_{\text{kin}} = (\gamma_{\text{surf}} - 1)m_{\chi_1} \approx 15.3 \text{ MeV}$$

**Extreme Compact Objects:** Remnants of massive stars, packing  $M \approx 1.4 M_{\odot}$  into a sphere of  $R \approx 10 \text{ km}$ . Incredible densities: an outer crust enveloping a core of degenerate nucleons and leptons.



The diagram illustrates a neutron star as a bright blue sphere. Two dark matter particles, labeled  $\chi_1$  (blue) and  $\chi_2$  (purple), are shown approaching the star. Arrows indicate their trajectories towards the surface. To the right, a cross-section of the neutron star is shown, revealing its internal layers: the outermost 'Atmosphere', followed by the 'Crust', and the central 'Core'.

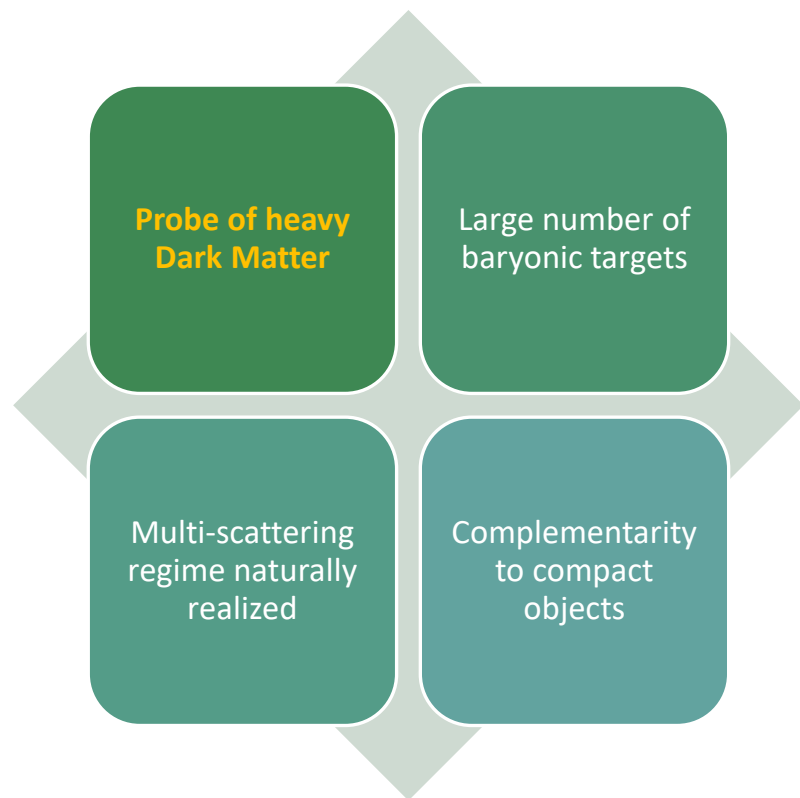
*Credit Sebastian Trojanowski*

# Motivations

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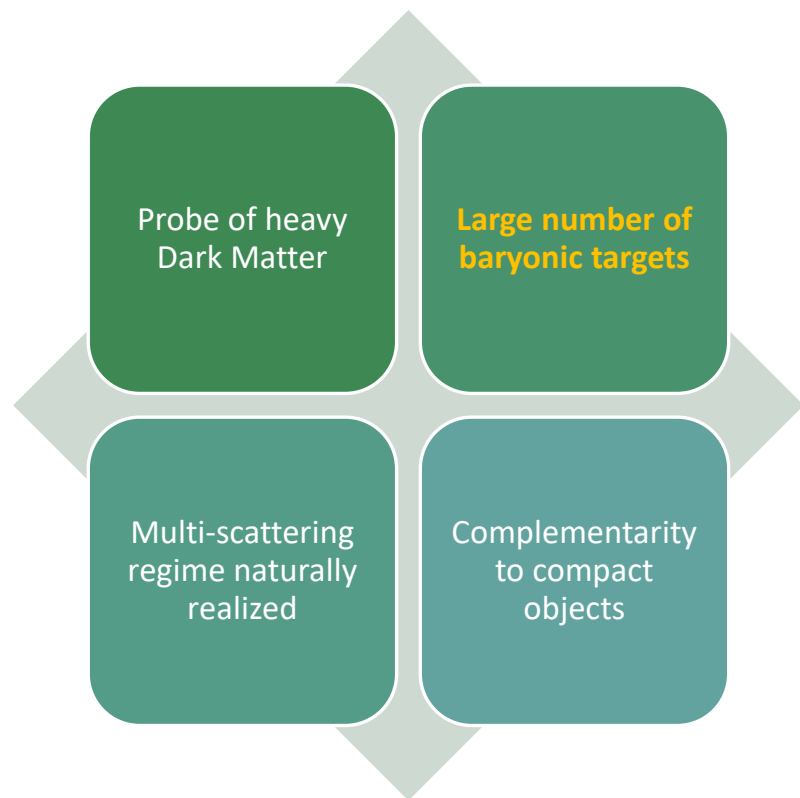
Why (consider Pop-III stars)?

What (could we observe/constrain)?



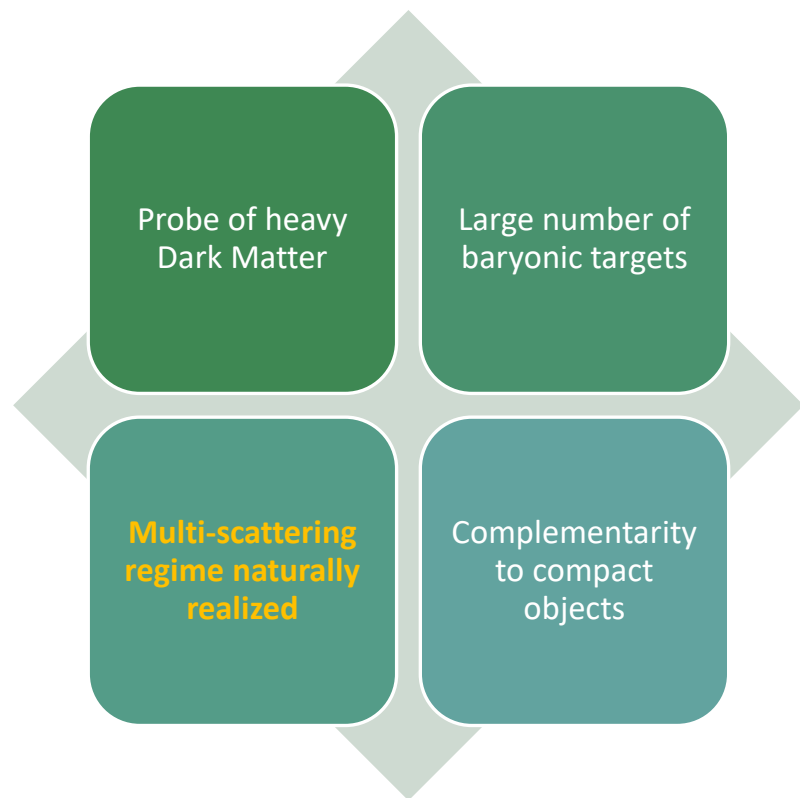
- Sensitive to ultra-heavy masses ( $\gtrsim 10^3\text{--}10^{15}$  GeV)
- Regions not accessible to Direct Detection

## Why Pop-III stars?



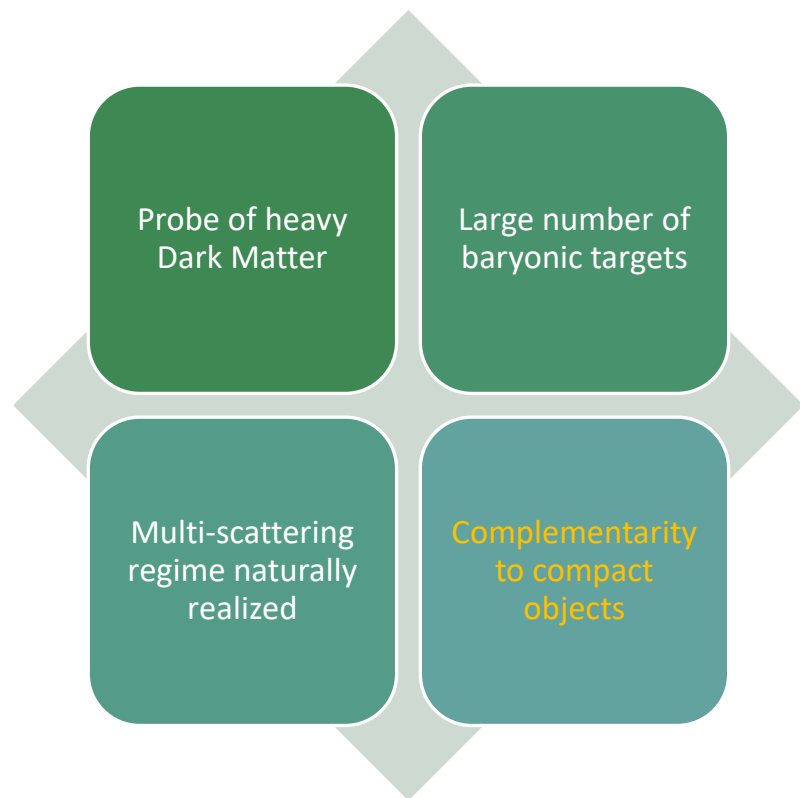
- Massive stars ( $\sim 10$ – $1000 M_{\odot}$ )
- Huge number of scattering targets  $\rightarrow$  efficient multi-scatter capture

## Why Pop-III stars?



- Essential for heavy DM ( $m_\chi \gtrsim \text{TeV-PeV}$ )
- Capture not limited to single-collision kinematics

## Why Pop-III stars?



- Lower density than NS, but:
  - Larger size → higher geometric capture
  - Different target mix (H/He vs neutrons)

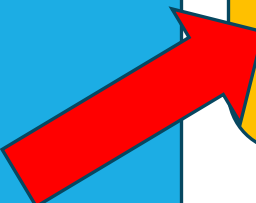
## Why Pop-III stars?

# WHAT CAN WE OBSERVE?

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## Main signatures

- Instability/collapse
- Modification internal structure
- Heat injection



Collapse usually requires very heavy DM to form a large over-density at the center



Heating is applicable on a large mass range

# WE STUDY 2 DIFFERENT SETUPS

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## Annihilating Dark Matter

- Capture/Annihilation equilibrium
- Can injected heat alter stellar evolution?

Answer: injected heat is well below the star luminosity for the considered DM density  $\rho_\chi \sim 5 \text{ GeV}/\text{cm}^3$

## Non-Annihilating Dark Matter

- Allows to accumulate a lot of Dark Matter
- Can trigger collapse to BH
- Observation of non-collapsed star  $\rightarrow$  constrain parameter space

# How? List of challenges

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1. Stars evolve rapidly, so need to take into account time evolution into the evolution equation

$$\frac{dN}{dt} = C(t) - E(t)N - A(t)N^2$$

2. Uncertainties on DM speed distributions
3. Multiple Types of targets (H, He,...) are present and their abundance evolves with time
4. Heavy DM requires multiple scatterings (MS) for capture → need MS Capture formalism
  - MS semi analytical Formalism derived for White Dwarfs in [2404.16272](#) (JCAP 07 (2024) 051)
  - Allows to account for multiple targets without a MC simulation
  - Requires a star escape speed  $v_e \gg u$  DM speed in the halo
  - This condition is verified in Pop-III stars

# Capture Rate with MS Formalism

DM Capture usually based on Gould seminal work for Capture in the Earth, based on:

1. DM trajectories are unaffected by collisions ✓
2. Constant escape velocity ✗
3. Constant iron (target) density ✗
4. DM follows linear trajectories outside and inside the Earth's core, thereby neglecting gravitational focusing/gravity effects ✗

Additional approximations usually made:

5. Simplified calculation of Star's optical depth !
6. Differential cross section on target  $d\sigma/d\cos\theta \sim \text{constant}$  !
7. Ad-Hoc treatment of Form factors !
8. Require to sum infinite series !

Our approach:

1. Assume only (i) DM trajectories are unaffected by collisions ✓
2. Optical depth inside star depends on interaction rate
  - Same interaction rate used for Capture for consistency ✓
  - Optical depth depends on the point in the star
  - Need to average over all trajectories
3. Consistent treatment of Form Factors
  - $\sigma_{\chi p} \sim \text{const} \rightarrow \sigma_{\chi T} \propto e^{-E_R/E_0}$  ✓

# Dark Matter MS Capture Formalism

The formalism is applicable if:

1. DM energy loss probability on a fixed kind of target does not depend on position
2. Star escape speed  $v_e \gg u$  DM speed in the halo

Result

➤ Capture rate for a single type of target can be computed as

$$C = \frac{\rho_\chi}{m_\chi} \int_0^{R_*} dr 4\pi r^2 n_T(r) v_{\text{esc}}^2(r) \sigma_{T\chi}(v_{\text{esc}}(r)) \int_0^\infty du_\chi \frac{f_{\text{MB}}(u_\chi)}{u_\chi} \tilde{G}\left(r, \frac{m_\chi u_\chi^2}{2E_0}\right),$$

Depends on the particular operator  
This result assumes\*  $\sigma_{\chi T} \propto e^{-E_R/E_0}$

$$G(\tau_\chi, \delta) \equiv \sum_{N=1}^{\infty} p_{N-1}(\tau_\chi) \mathcal{F}_N(\delta) = \sum_{N=1}^{\infty} \frac{e^{-\tau_\chi} \tau_\chi^{N-1}}{(N-1)!} \frac{e^{-\delta} \delta^{N-1}}{(N-1)!} \\ = e^{-\tau_\chi - \delta} I_0\left(2\sqrt{\tau_\chi \delta}\right),$$

Angular/trajectory average

$$\tilde{G}(r, \delta) = \int_0^1 dy \frac{y dy}{\sqrt{1-y^2}} \frac{G(\tau_\chi^-(r, y), \delta) + G(\tau_\chi^+(r, y), \delta)}{2}.$$

\*For H we needed to work out some approximated result for  $G$  as this does not hold for H

# Multiple kinds of targets

- Multiple kinds of targets can be implemented by convolution:

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

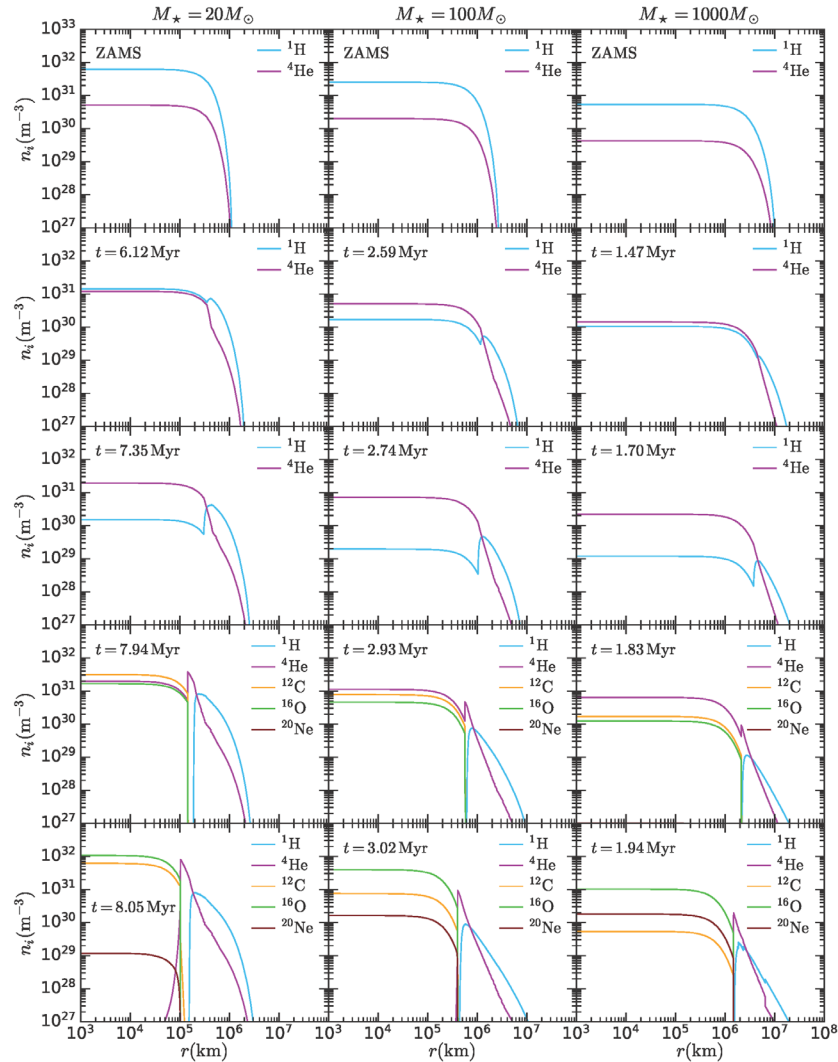
Capture by only scattering with i       $G_{12,ij} = G(\tau_\chi^i, \delta_i) e^{-\tau_\chi^j} + G_{2,ij},$       “Mixed” Capture i+j

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

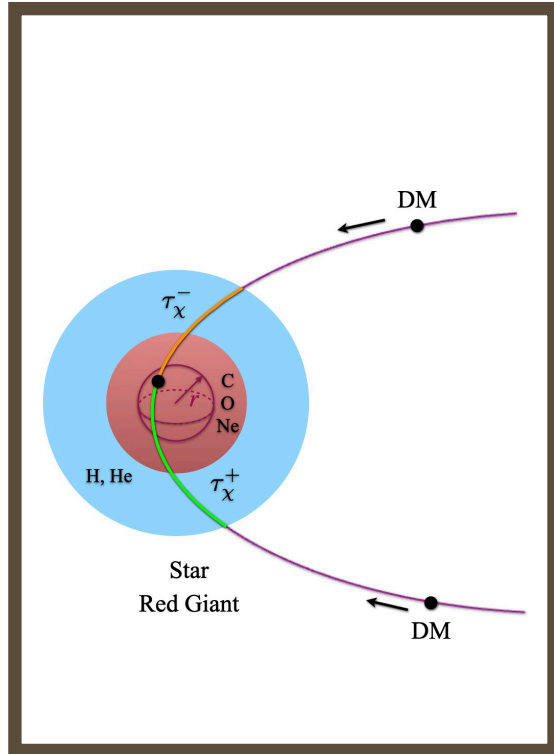
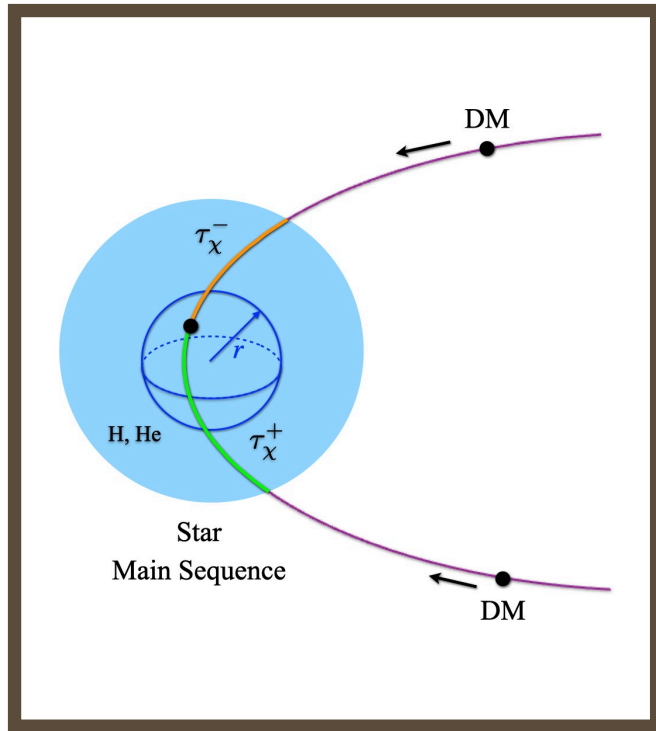
$$\mathcal{G}(\tau_\chi^i, \delta_i) = \int_0^{\tau_\chi^i} d\tau G(\tau, \delta_i)$$

- Convolutions can be nested multiple times for as many elements as necessary
  - This has large impact on computing time so no more than 4 elements are considered

# Pop-III stars as DM laboratories



- Time dependence of internal structure
- Number densities obtained from MESA simulation
  - Initially H dominated
  - Then He dominated
  - Late stages dominated by Heavier elements
- Interaction cross section for Spin-Independent interaction scales as  $A^4$ 
  - Heavier elements can dominate or have large contributions even if not the most abundant element

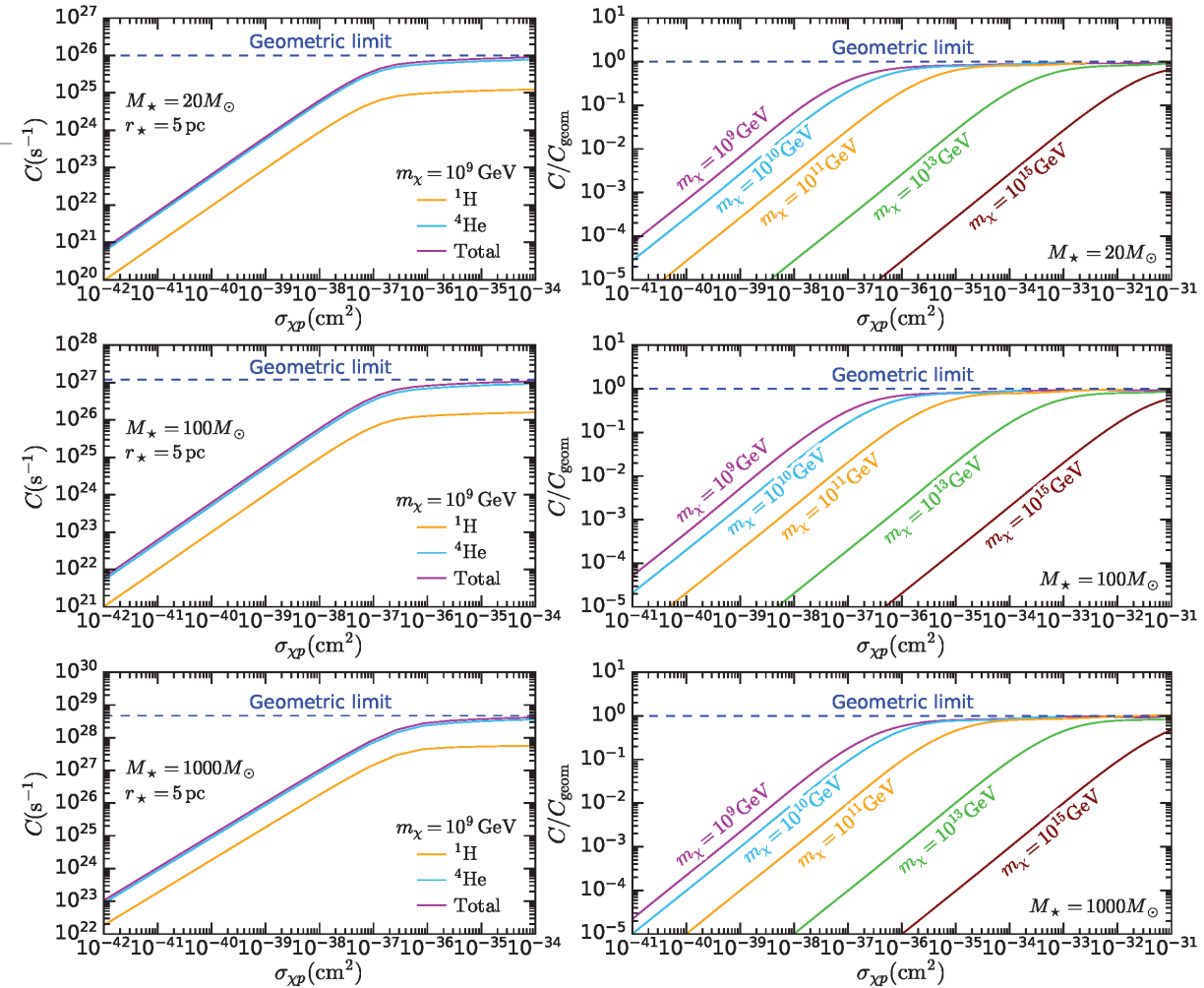


# DM Capture

- Early stages: DM interacting with Star made of H, He
- Late Stages: we can identify a core made of heavy elements and an outer region made of H, He
  - These regions will give a peculiar dependence of the total capture rate of the star as function of  $\sigma$

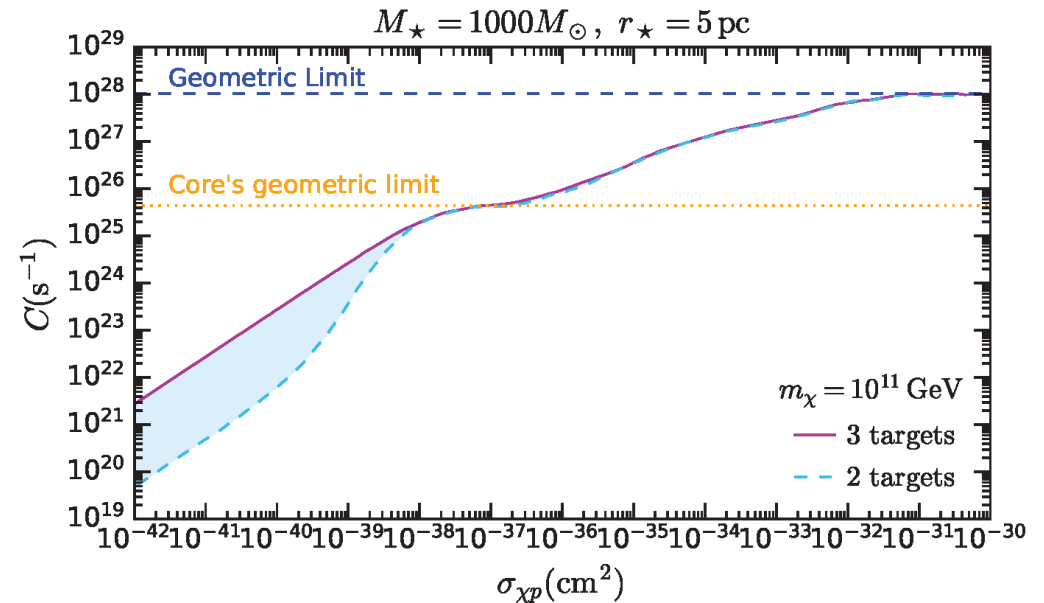
# Results - ZAMS

- ZAMS = Zero-Age Main Sequence
- Capture rates at ZAMS are He dominated
- Have “usual” features/functional dependence on parameters
- Multiple Scattering:
  - For DM masses below  $\sim 10^9 \text{ GeV}$  a single scattering is sufficient to capture
  - For DM masses of  $\sim 10^{10} \text{ GeV}$  or large, average number of scatterings required starts to scale linearly with mass



# Results – Late phase

- Considers scattering with three targets: O, Ne, He (or H in atmosphere)
- Capture rate shows two saturation stages
  - First saturation ( $\sim 10^{-37} \text{ cm}^2$ ):
    - Set by core geometric limit
    - Core acts as a distinct capture region
  - Higher cross sections:
    - All particles crossing the core are captured
    - Rate increases until stellar geometric limit
    - Eventually, particles entering the atmosphere are also captured
- Dashed line (two-target model):
  - Includes only O+Ne (core) and He+H (atmosphere)
  - Shows deficit at small cross sections
- Three-target effect (shaded region):
  - Important for  $m_\chi \gtrsim 10^9 \text{ GeV}$
  - Multiple scatterings become relevant



# Non-annihilating DM: collapse

➤ Accumulation of large densities of DM can trigger collapse to BH

➤ Requires:

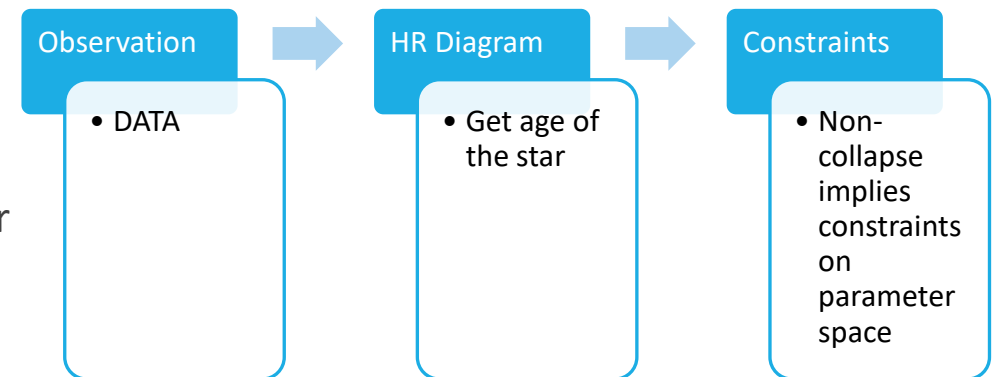
1. Self gravitating condition
2. Reaching critical density/DM number
3. BH needs to accrete the whole star within the star's lifetime

➤ Large DM mass means

- Larger density, so more likely to trigger collapse, but
- Means also smaller initial BH, and more time to accrete all matter

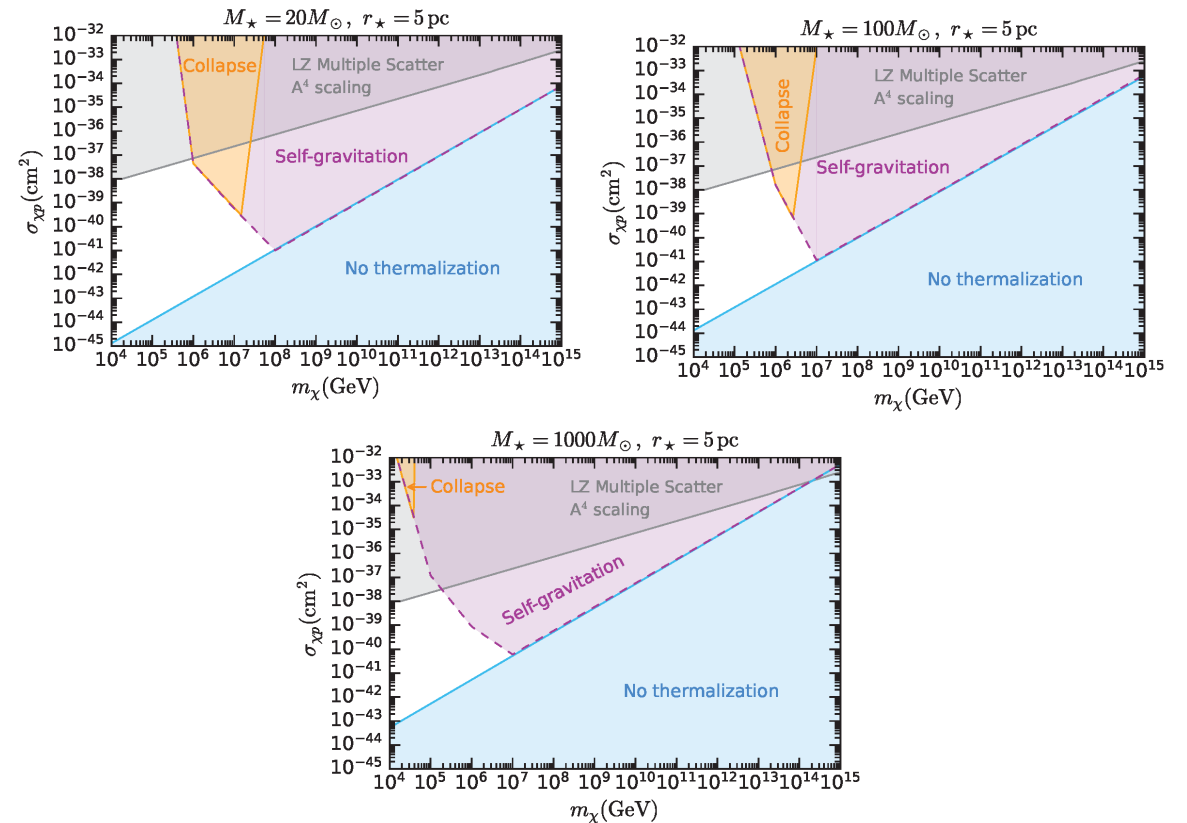
➤ More massive stars means

- Larger Capture rate, but
- There is more matter to accrete, so more time is needed, and
- They also have shorter life span



# Non-annihilating DM: collapse

- Parameter space regions:
  - Light blue: DM does not thermalize
  - Magenta: DM becomes self-gravitating
- Mass dependence:
  - Heavier stars → higher capture rates
  - Self-gravitating region grows with stellar mass
- BH formation & full stellar consumption (orange):
  - Collapse leads to BH that accretes entire star before end of lifetime
  - Present even in experimentally unexplored regions (gray)
- Outside orange region:
  - BH may still form
  - Accretion too slow → star survives until helium depletion
- Physical implications:
  - Larger stars → slower full accretion (orange shrinks)
  - Results hold at low DM density ( $\rho_\chi \sim 5 \text{ GeV}/\text{cm}^3$ )



2512.22727 (JCAP 03 (2026) 059)

# Conclusions

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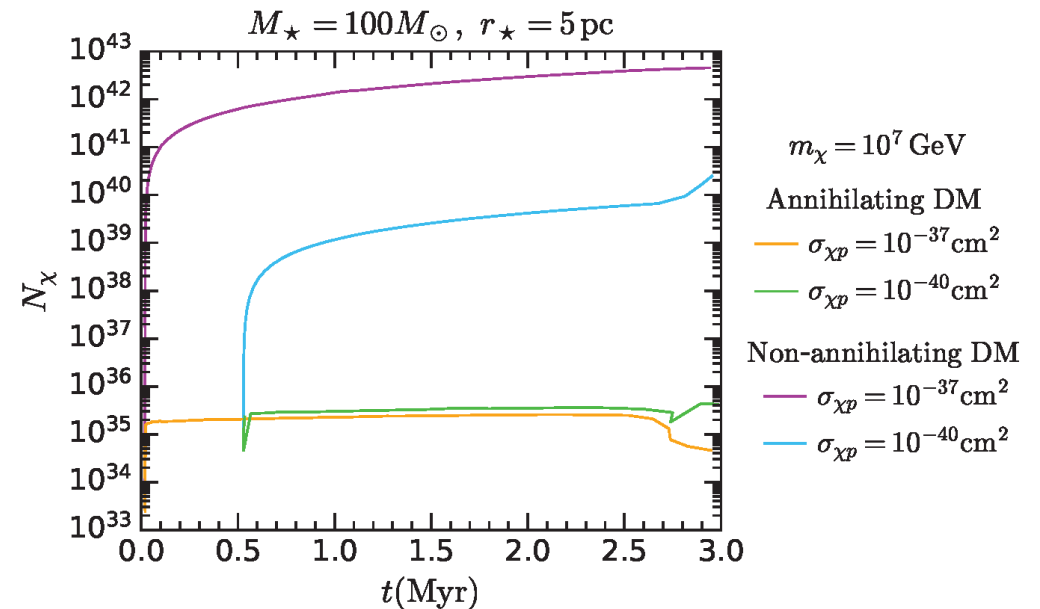
- We considered Dark Matter Capture in Population III stars
- We find that taking into account evolution of the star is important
  - Late stage of the star previously not accounted for in literature
- Late stage is sensitive to scattering over heavier elements
  - We used our Multiple scattering Capture formalism to compute Capture rates
  - We showed including 3 targets is essential to get the rates right at small cross section
  - The star interestingly shows 2 geometric limits, one for the core and one for the whole star
- We found regions of parameter space unconstrained by direct detection where DM could make the star collapse to a Black Hole
  - Absence of premature stellar collapse could constrain DM parameter space (e.g. with JWST Pop III observations)

# Backup

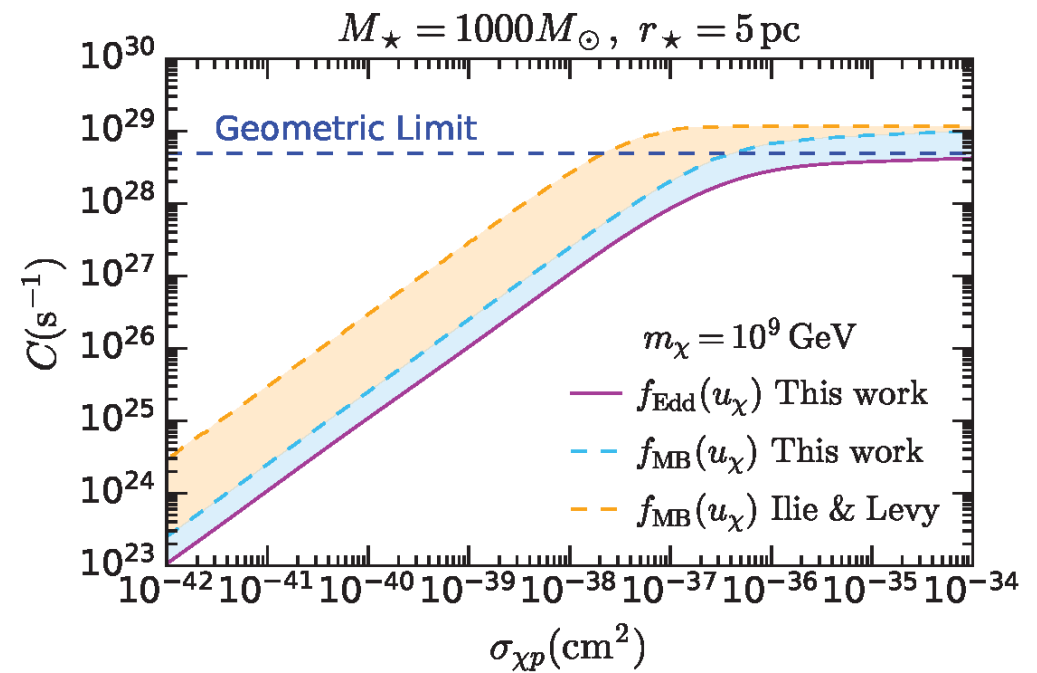
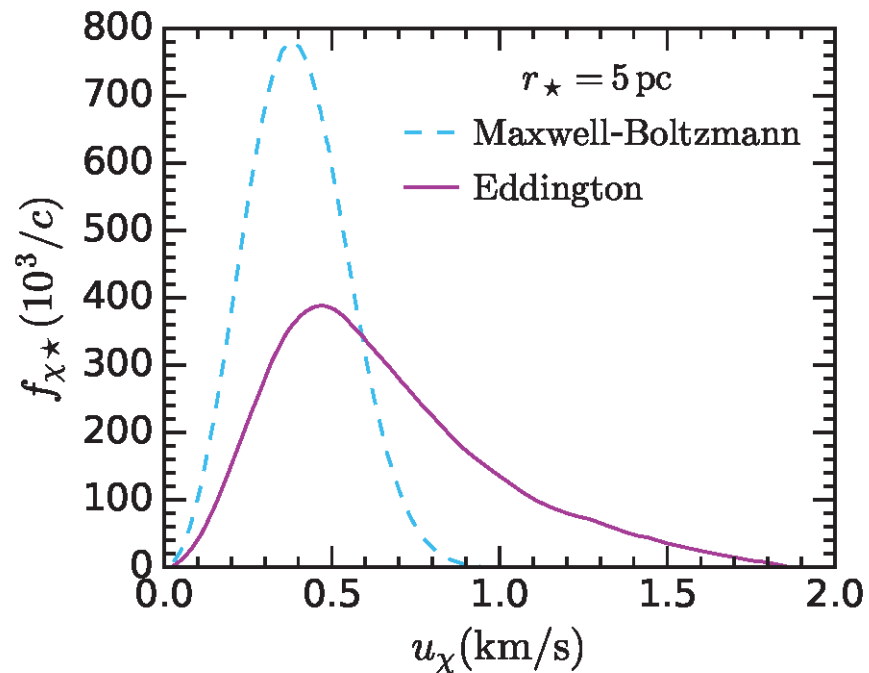
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# Constraints?

- We consider p-wave suppressed annihilation operator
- Annihilation rate is sufficient to limit growth of DM accumulation
- At equilibrium, Capture rate = Annihilation rate
- Heat injected =  $C(t)m_\chi$  is well below star's luminosity for  $\rho_\chi \sim 5 \text{ GeV}/\text{cm}^3$
- Star evolution still «slow» comparing to DM accumulation
  - Capture/Annihilation equilibrium timescale approximately  $t \sim \frac{1}{\sqrt{CA}}$  as in the time-independent case
  - Total annihilation rate  $\Gamma_{ann} \sim C/2$  soon after the ZAMS stage



# Dark Matter velocity distribution



# CAPTURE BY MULTIPLE SCATTERING

- This is the energy loss probability density distribution  $f(E_R) = \frac{1}{\sigma_{T\chi}} \frac{d\sigma_{T\chi}}{dE_R}(E_R)$ .
- Probability to lose at least a certain energy after one scattering  $\mathcal{F}_1(\delta E) = \int_{\delta E}^{\infty} dE_R f(E_R)$
- Similarly, after exactly  $N$  scatterings  $\mathcal{F}_N(\delta E) = \int_0^{\delta E} dE_R \mathcal{F}_{N-1}(\delta E - E_R) f(E_R)$
- It is easy to find these functions using Laplace transform  $\hat{\mathcal{F}}_N = \hat{\mathcal{F}}_{N-1} \hat{f}$

# CAPTURE BY MULTIPLE SCATTERING

For simplicity, we assume that the DM-target cross section is well approximated by

$$\frac{d\sigma_{T\chi}}{d\cos\theta_{\text{cm}}} \propto e^{-\frac{E_R}{E_0}}, \quad (3.26)$$

where  $E_R$  is the recoil energy and  $E_0$  depends on the specific nuclear target. That is, we assume exponential nuclear form factors similar to the Helm approximation. This leads to

$$f(E_R) = \frac{\Theta(E_R)}{E_0} e^{-\frac{E_R}{E_0}}, \quad (3.27)$$

$$\mathcal{F}_1(\delta E) = e^{-\frac{\delta E}{E_0}}. \quad (3.28)$$

Defining the dimensionless quantity

$$\delta = \frac{\delta E}{E_0} = \frac{m_\chi u_\chi^2}{2E_0}, \quad (3.29)$$

and taking the Laplace transform of the  $\mathcal{F}$  functions written in terms of  $\delta$ , we find

$$\tilde{\mathcal{F}}_1(s) = \frac{1}{1+s}, \quad \tilde{\mathcal{F}}_N(s) = \frac{1}{(1+s)^N}, \quad (3.30)$$

where the last expression corresponds to

$$\mathcal{F}_N(\delta) = \frac{e^{-\delta} \delta^{N-1}}{N-1!}. \quad (3.31)$$

# CAPTURE BY MULTIPLE SCATTERING

- Probability to have interacted already N times is given by Poisson distribution

$$p_N(\tau_\chi) = e^{-\tau_\chi} \frac{\tau_\chi^N}{N!}$$

- Therefore the single scattering Capture rate can be written as

$$C_1 = \frac{\rho_\chi}{m_\chi} \int_0^{R_\star} dr 4\pi r^2 n_T(r) \sigma_{T\chi}(v_{\text{esc}}(r)) v_{\text{esc}}^2(r) \int_0^1 \frac{y dy}{\sqrt{1-y^2}} \int_0^\infty du_\chi \frac{f_{\text{MB}}(u_\chi)}{u_\chi} p_0(\tau_\chi) \mathcal{F}_1(\delta)$$

- The Capture rate for exactly N scatterings can be obtained as

$$C_N = \frac{\rho_\chi}{m_\chi} \int_0^{R_\star} dr 4\pi r^2 n_T(r) \sigma_{T\chi}(v_{\text{esc}}(r)) v_{\text{esc}}^2(r) \int_0^1 \frac{y dy}{\sqrt{1-y^2}} \int_0^\infty du_\chi \frac{f_{\text{MB}}(u_\chi)}{u_\chi} p_{N-1}(\tau_\chi) \mathcal{F}_N(\delta)$$

# CAPTURE BY MULTIPLE SCATTERING

The total capture rate is given by the sum over all  $N$  collisions,

$$C = \sum_N C_N. \quad (3.35)$$

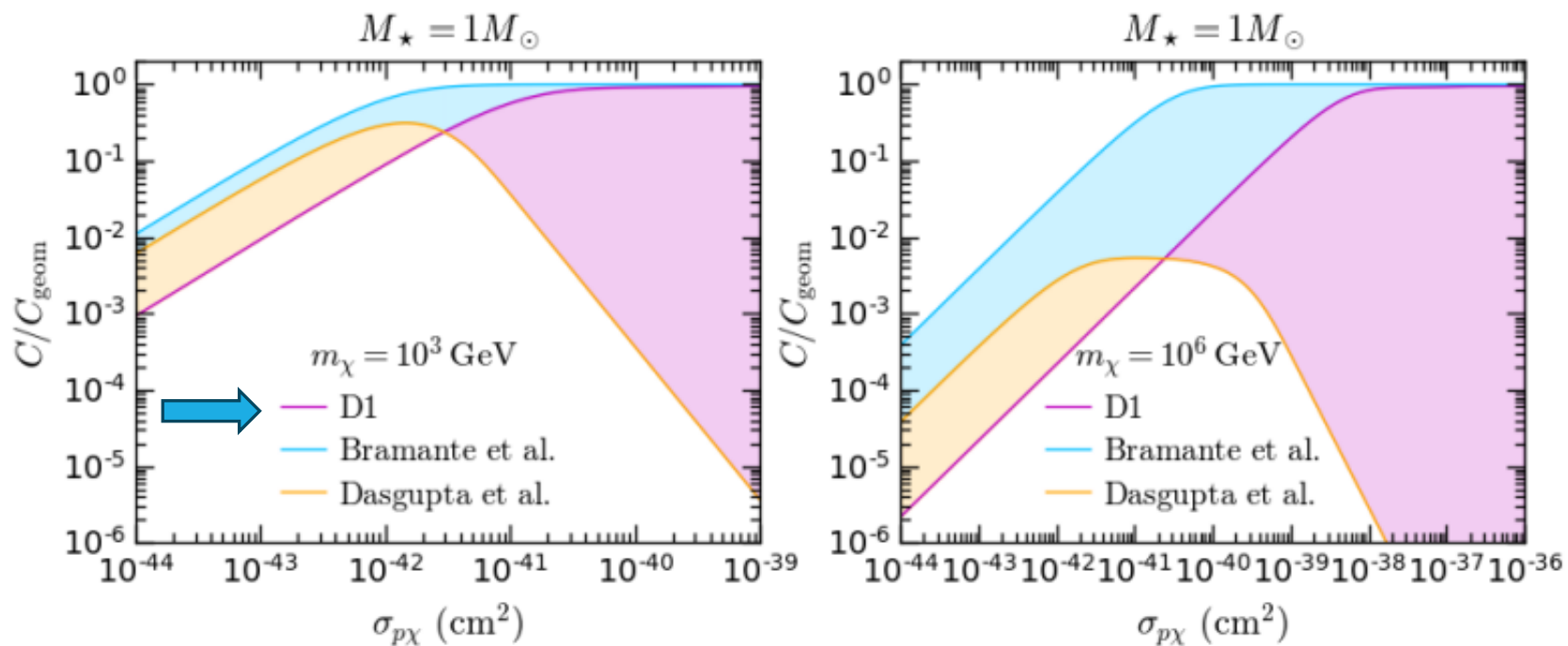
Next, instead of first evaluating the integrals in Eq. 3.34 and then summing over  $N$ , we sum the series first by introducing the response function,  $G(\tau_\chi, \delta)$

$$\begin{aligned} G(\tau_\chi, \delta) &\equiv \sum_{N=1}^{\infty} p_{N-1}(\tau_\chi) \mathcal{F}_N(\delta) = \sum_{N=1}^{\infty} \frac{e^{-\tau_\chi} \tau_\chi^{N-1}}{(N-1)!} \frac{e^{-\delta} \delta^{N-1}}{(N-1)!} \\ &= e^{-\tau_\chi - \delta} I_0(2\sqrt{\tau_\chi \delta}), \end{aligned} \quad (3.36)$$

- The resulting total Capture rate is

$$C = \frac{\rho_\chi}{m_\chi} \int_0^{R_\star} dr 4\pi r^2 n_T(r) v_{\text{esc}}^2(r) \sigma_{T\chi}(v_{\text{esc}}(r)) \int_0^\infty du_\chi \frac{f_{\text{MB}}(u_\chi)}{u_\chi} \tilde{G}\left(r, \frac{m_\chi u_\chi^2}{2E_0}\right)$$

# CAPTURE RATE



# MULTIPLE TARGETS

- Can expand the formalism to include multiple types of targets

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First, as in the previous section, we consider the probability for DM to interact with a target  $i$  and lose energy of at least  $\delta E$ , while travelling a length  $d\tau_\chi^i$ , starting from a layer in the WD with optical depth  $\tau_\chi^i$ . This is given by the differential element  $G(\tau_\chi^i, \delta_i)d\tau_\chi^i$ , where

$$\delta_i = \frac{\delta E}{E_0^i}, \quad (3.43)$$

and the energy scale  $E_0^i$  depends on the target  $i$  and is calculated using Eq. 3.40. Thus, the probability to interact and lose the same amount of energy when DM travels a path-length  $\tau_\chi^i$  is simply the integral of the differential element over the trajectory, i.e.

$$\mathcal{G}(\tau_\chi^i, \delta_i) = \int_0^{\tau_\chi^i} d\tau G(\tau, \delta_i). \quad (3.44)$$

Next, we introduce a second target species. In the presence of these two ionic targets, the cumulative probability of DM to lose an energy  $\delta E$  after travelling an optical depth  $\tau_\chi^i$  in the target  $i$  and  $\tau_\chi^j$  in the second target  $j$  is found to be

$$\mathcal{G}_{2,ij}(\delta E) = \int_0^{\delta E/E_0^j} dz \mathcal{G} \left( \tau_\chi^i, \frac{\delta E - zE_0^j}{E_0^i} \right) \left[ -\frac{\partial}{\partial z} \mathcal{G}(\tau_\chi^j, z) \right]. \quad (3.50)$$

# MULTIPLE TARGETS

