Heavy Dark Matter in rapidly evolving massive stars

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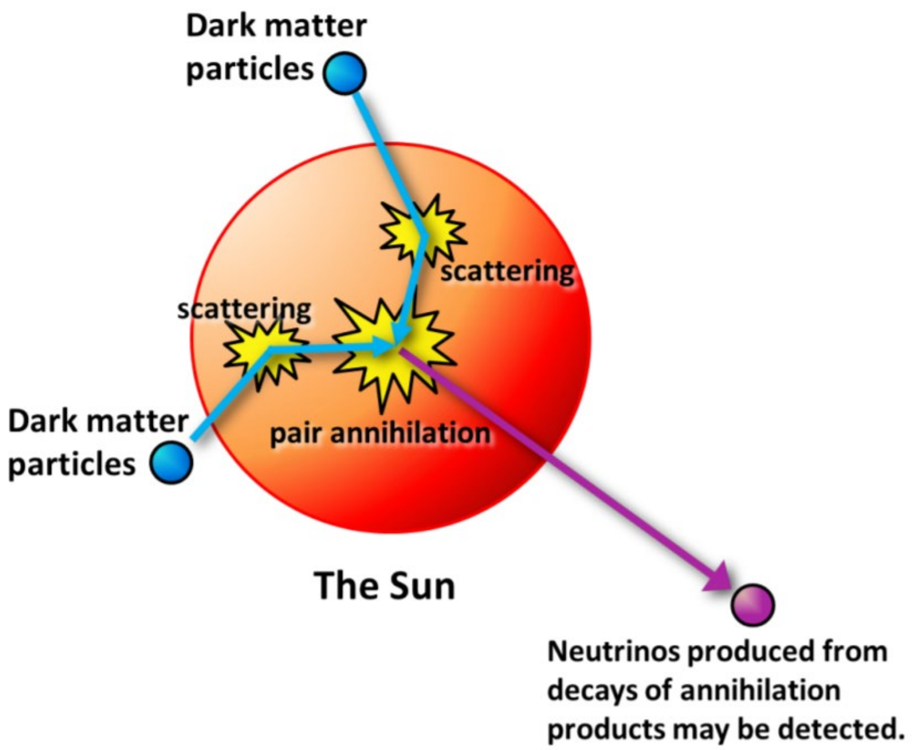
Outline

1. Motivations
2. Population III stars as DM laboratories
3. Dark Matter Capture Formalism [Based on 2404.16272, JCAP 07 (2024) 051]
4. Results [Based on 2512.22727, JCAP 03 (2026) 059]

DARK MATTER CAPTURE IN STARS



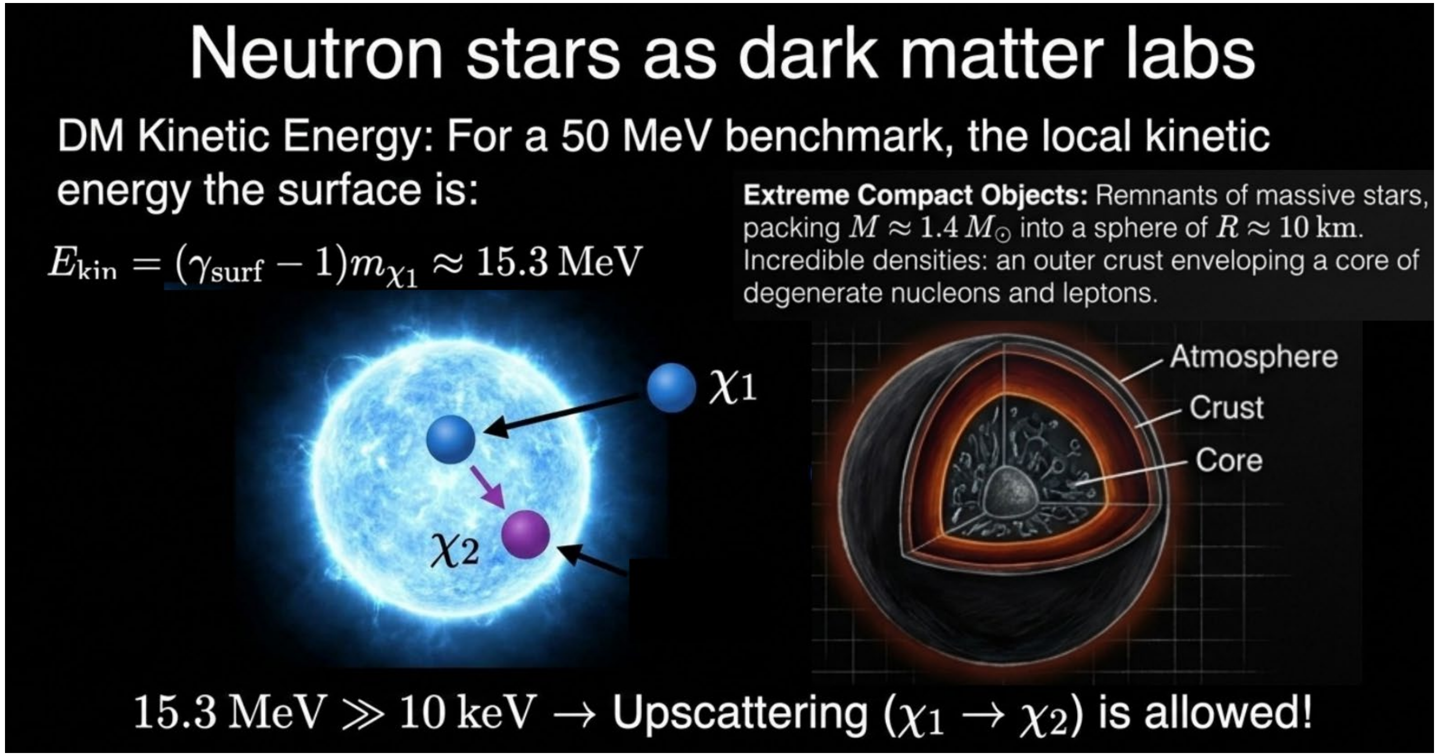
- In a typical collision, the Dark Matter loses enough energy to drop below the escape velocity and hence becomes gravitationally bound to the star
- Subsequent scatterings, lose energy, accumulates in the centre

- 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
- .....



See Monday plenary from Sebastian Trojanowski

Motivations

Why (consider Pop-III stars)?

What (could we observe/constrain)?

How (does Dark Matter interact with the stars)?

- **Probe of heavy Dark Matter**
- Large number of baryonic targets
- Multi-scattering regime naturally realized
- Complementarity to compact objects

- Sensitive to ultra-heavy masses ($\gtrsim 10^3$–10^{15} GeV)
- Regions not accessible to direct detection

Why Pop-III stars?

- Probe of heavy Dark Matter
- **Large number of baryonic targets**
- Multi-scattering regime naturally realized
- Complementarity to compact objects

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

Why Pop-III stars?

Probe of heavy Dark Matter

Large number of baryonic targets

Multi-scattering regime naturally realized

Complementarity to compact objects

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

Why Pop-III stars?

Why Pop-III stars?

- Probe of heavy Dark Matter
- Large number of baryonic targets
- Multi-scattering regime naturally realized
- Complementarity to compact objects

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

WHAT CAN WE OBSERVE?

Main signatures

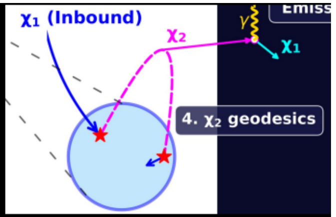
- Instability/collapse
- Modification internal structure
- Heat injection

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

Heating is applicable on a large mass range

Not just an exclusion tool!

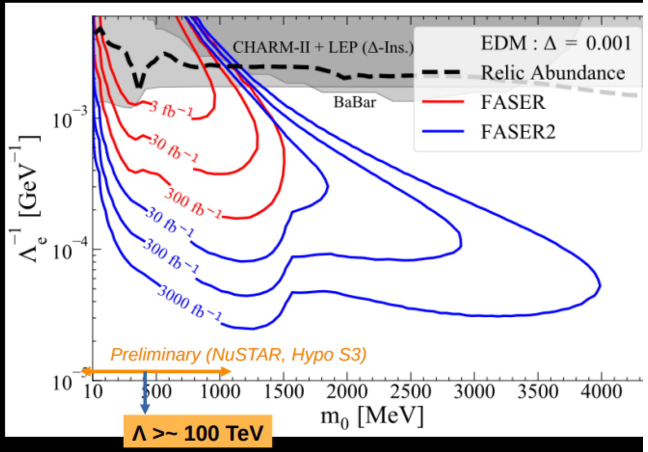
BSM sensitivity



$$\frac{d\sigma}{dE_R} \simeq \frac{4\alpha_{\rm EM}}{\Lambda^2 E_{\chi_1}^2}\left[\frac{E_{\chi_1}^2}{E_R} - \frac{m_{\chi_1}^2}{2m_p} - \Delta\frac{E_{\chi_1} m_{\chi_1}^2}{E_R m_p}\right] F_p^2(t)$$

Λ ~ 1 TeV (LHC probes): $\sigma_{\rm tot} \approx 9.40 \times 10^{-35}\ {\rm cm}^2$

Λ ~ 100 TeV (NS X rays): $\sigma_{\rm tot} \approx 9.40 \times 10^{-45}\ {\rm cm}^2$



2. Lifetime of χ_2 & re-scattering in NS
– limiting factor depending on the mass splitting

3. Sensitivity:
can be as large as Λ ~ 100 TeV for a few hundred MeV DM mass

4. Anomalous flare: if observed, strong hint of (inelastic) DM

DARK MATTER DISCOVERY TOOL
RATHER THAN EXCLUSION TOOL

See Monday plenary from Sebastian Trojanowski

WE WILL STUDY 2 DIFFERENT SETUPS

Annihilating Dark Matter

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

Non-Annihilating Dark Matter

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

How? List of challenges

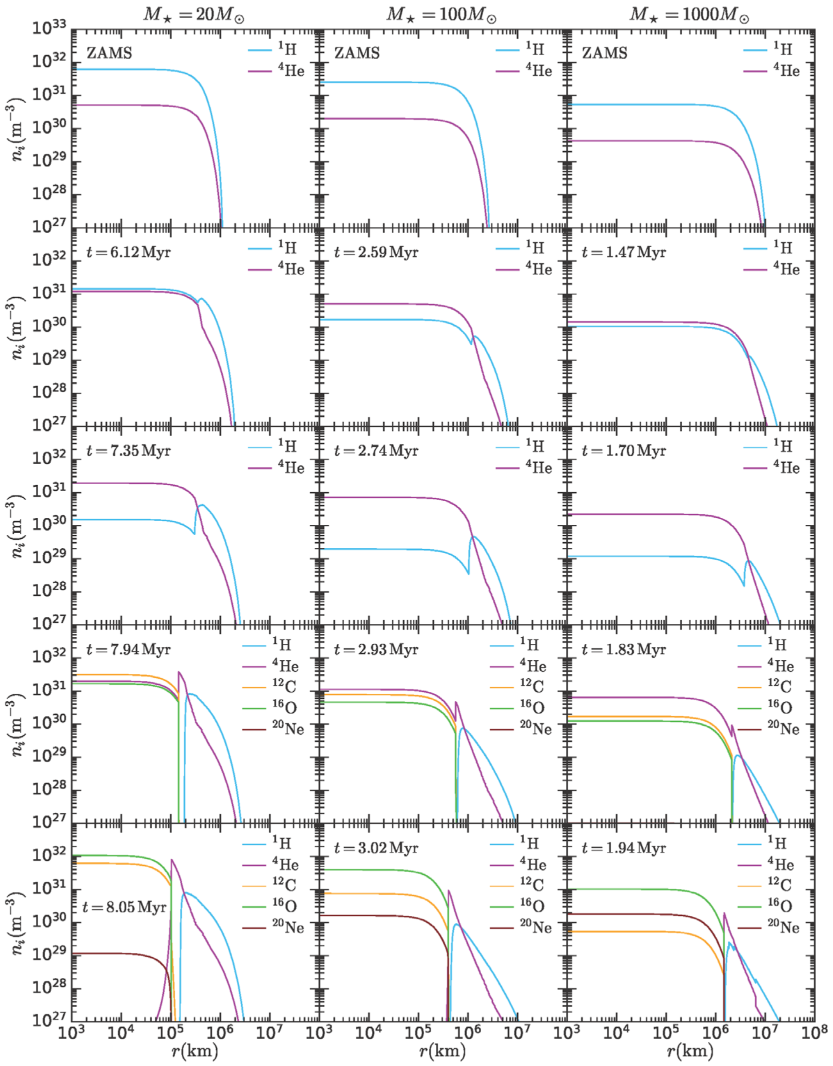
1. Stars evolve rapidly, so need to take into account time evolution into the evolution equation

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

2. Unknown DM speed distributions, especially close to galactice center

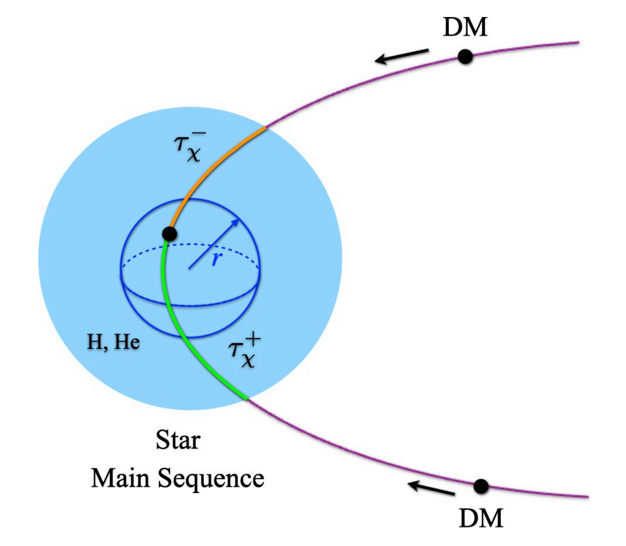
3. Multiple Types of targets are present and their abundance evolves with time

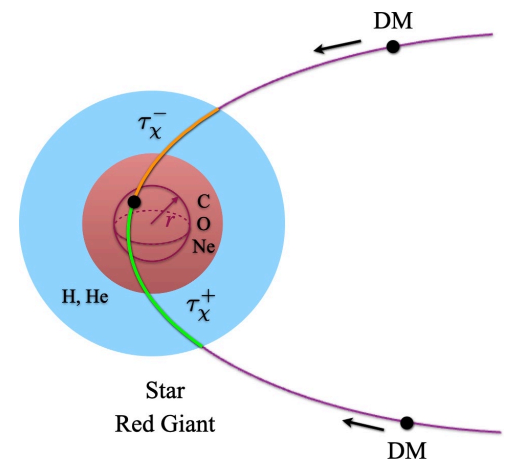
4. Heavy DM requires multiple scatterings (MS) for capture → need MS Capture formalism
   - MS semi analytical Formalism derived for White Dwarfs in 2404.16272
   - Allows to account for multiple targets without a MC simulation
   - Requires a star escape speed $v_e \gg u$ DM speed in the halo
   - This condition is verified in Pop-III stars



Pop-III stars as DM laboratories

- Time dependance 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 dependance of the total capture rate of the star as function of σ

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 ⚠
6. Differential cross section on target $d\sigma/dcos\theta$~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
   - $\sigma_{\chi p} \sim const \rightarrow \sigma_{\chi T} \propto e^{-E_R/E_0}$ ✓

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

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

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

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:

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

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

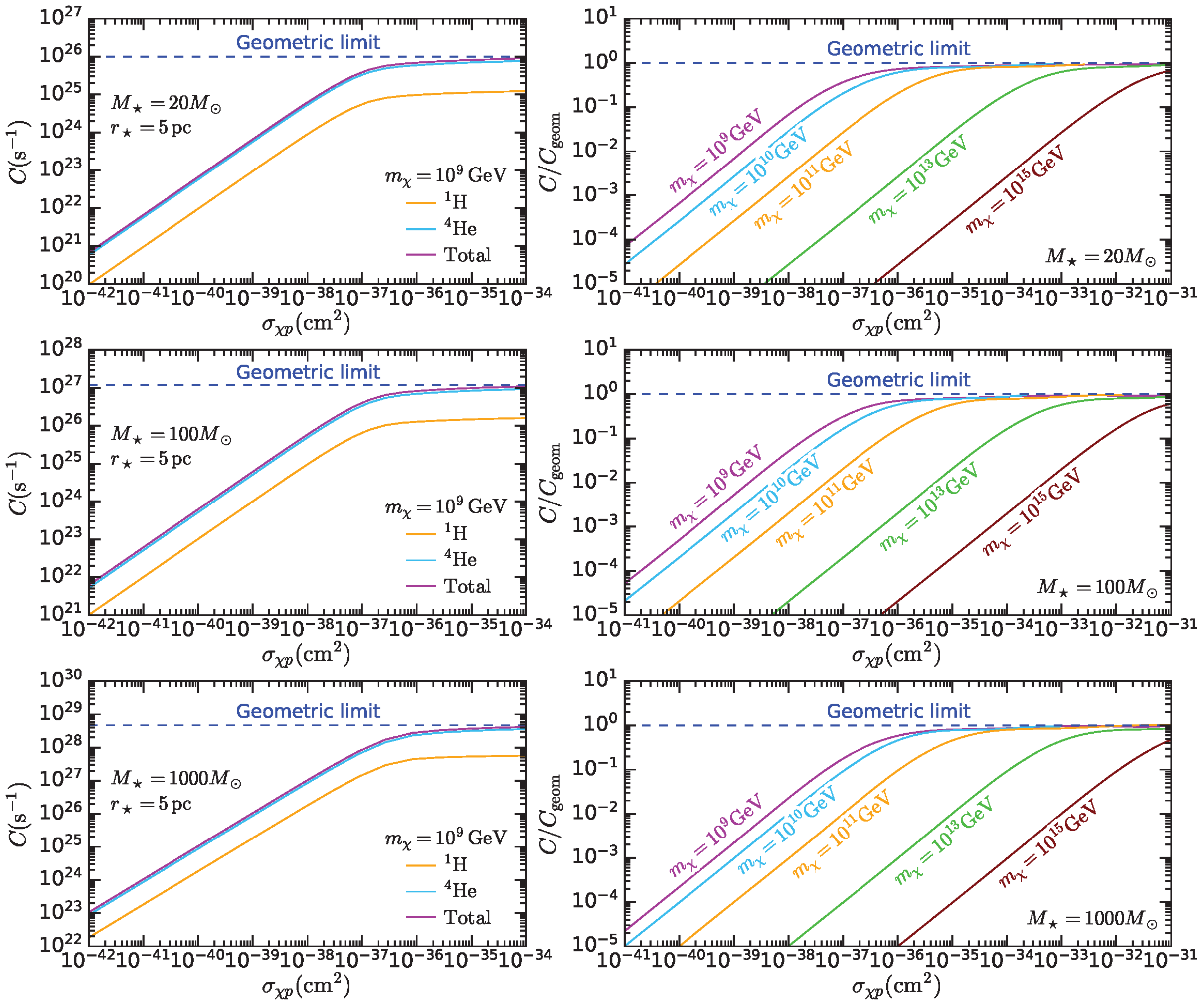
$$G_{2,ij}(\delta E) = \int_0^{\delta E/E_0^j} dz\, G\left(\tau_\chi^i, \frac{\delta E - zE_0^j}{E_0^i}\right)\left[-\frac{\partial}{\partial z}\mathcal{G}(\tau_\chi^j, z)\right]$$

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

- 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

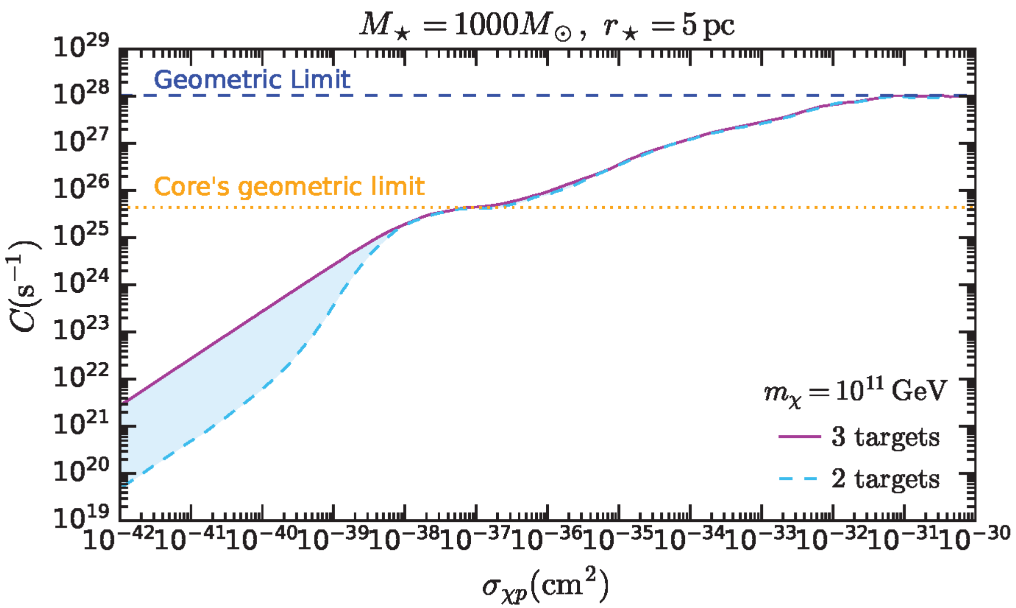
Results - ZAMS

- 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 $\sim 10^{9} GeV$ a single scattering is sufficient to capture
  - For DM masses of $\sim 10^{10} GeV$ or large, average number of scatterigns required starts to scale linearly with mass



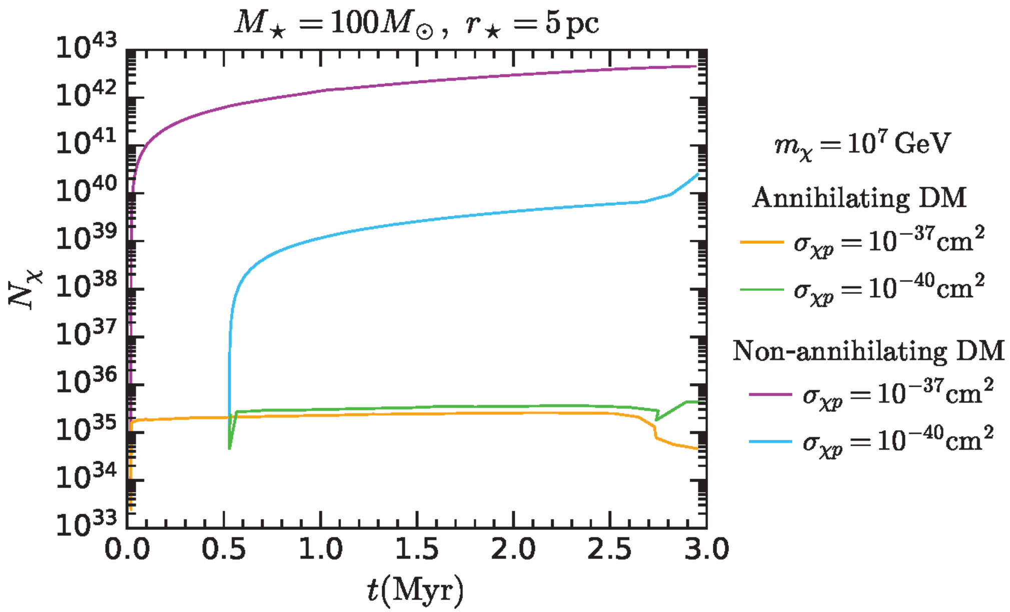
Results – Late phase

- Considers scattering with three targets: O, Ne, He (or H in atmosphere)
- Capture rate shows two saturation stages
  - First saturation (~10^{-37} 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 $m\chi \gtrsim 10^9$ GeV
  - Multiple scatterings become relevant



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 $\rho_\chi \sim 5 GeV/cm^3$
- 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

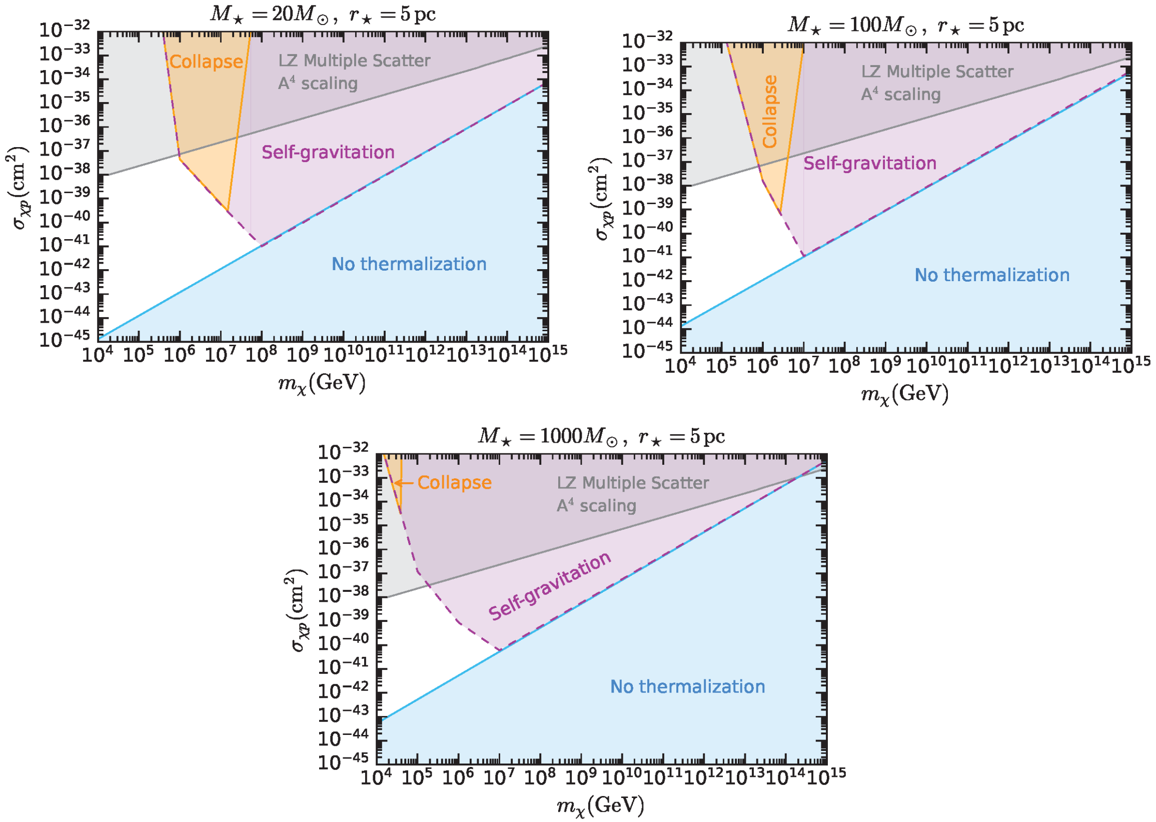


Non-annihilating DM: collapse

- Accumulation of large densities of DM can trigger collapse to BH
- Requires:
  - Self gravitating condition
  - Reaching critical density/DM number
  - 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
  - There is more matter to accrete, so more time is needed, but
  - They also have shorter life span
- We expect larger region of parameter space to allow collapse for lighter stars and intermediate values of DM mass

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 ($\rho_\chi \sim 5 GeV/cm^3$)

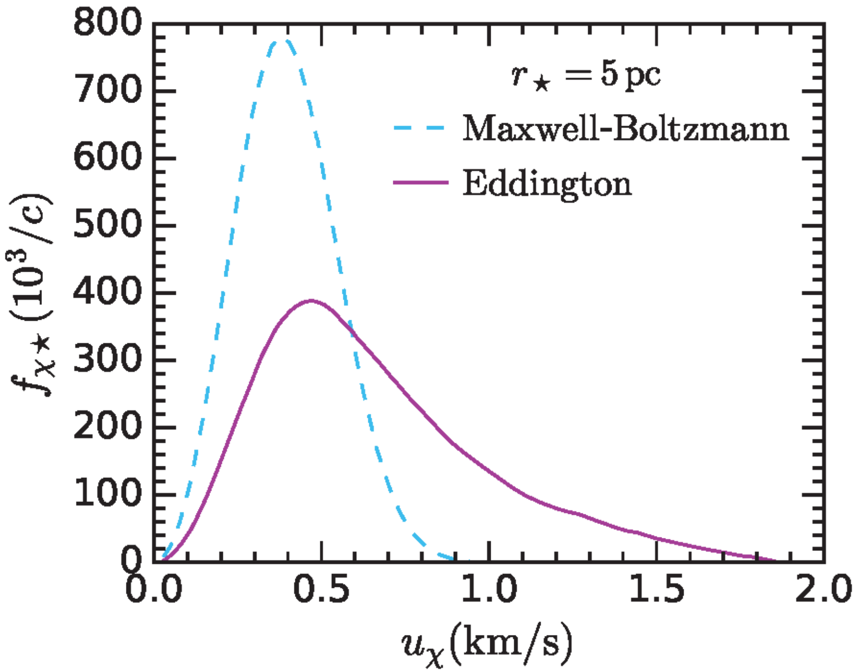


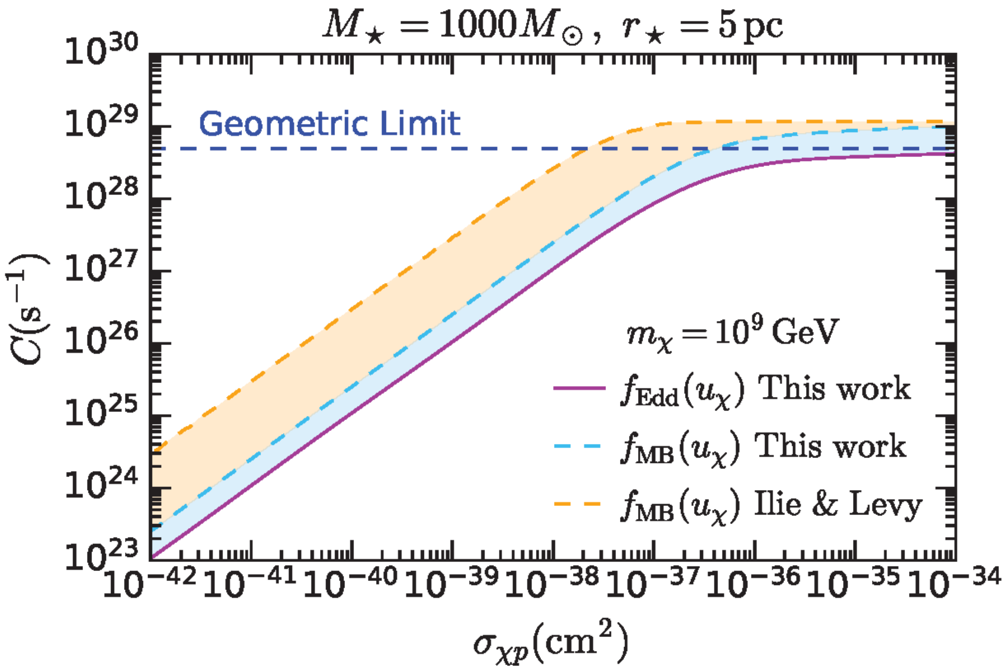
Conclusions

- 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

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

$$\frac{d\sigma_{T\chi}}{d\cos\theta_{\rm cm}} \propto e^{-\frac{E_R}{E_0}}, \tag{3.26}$$

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

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

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

Defining the dimensionless quantity

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

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

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

where the last expression corresponds to

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

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

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

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

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

CAPTURE BY MULTIPLE SCATTERING

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

$$C = \sum_N C_N. \tag{3.35}$$

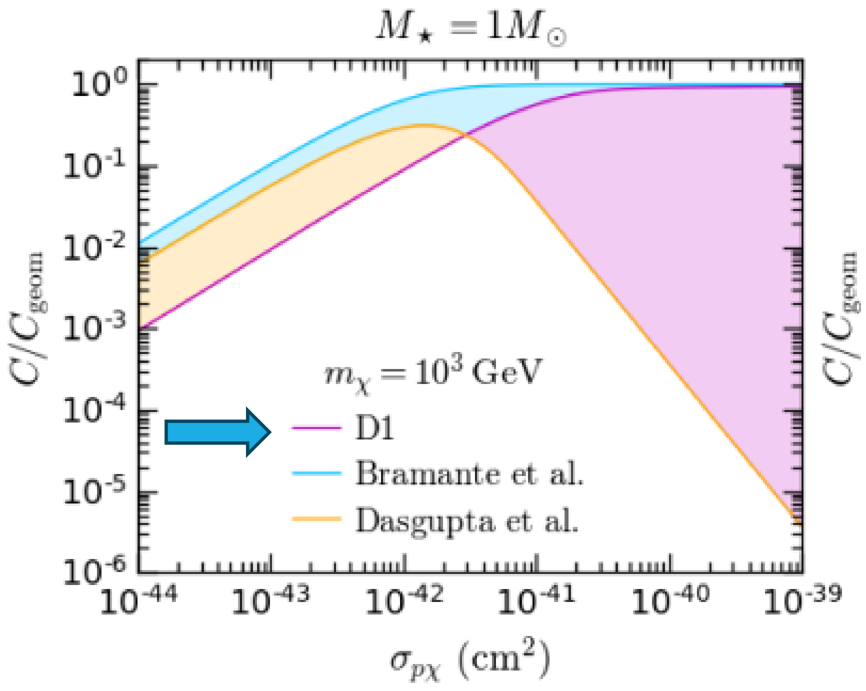
Next, instead of first evaluating the integrals in Eq. 3.34 and then summing over N, we sum the series first by introducing the response function, $G(\tau_\chi, \delta)$

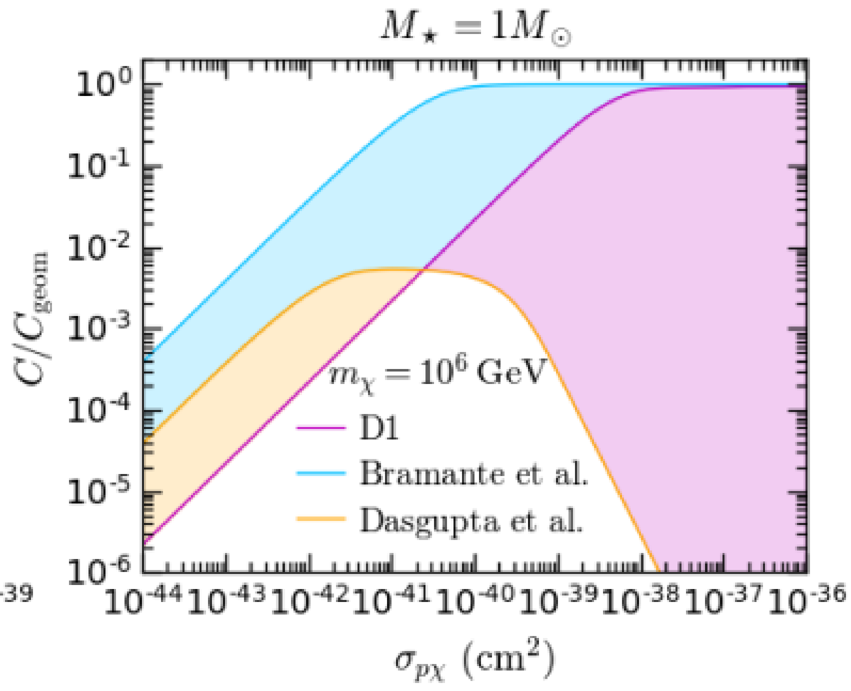
$$\begin{aligned} G(\tau_\chi, \delta) &\equiv \sum_{N=1}^{\infty} p_{N-1}(\tau_\chi)\mathcal{F}_N(\delta) = \sum_{N=1}^{\infty} \frac{e^{-\tau_\chi}\tau_\chi^{N-1}}{(N-1)!}\frac{e^{-\delta}\delta^{N-1}}{(N-1)!} \\ &= e^{-\tau_\chi-\delta} I_0\left(2\sqrt{\tau_\chi \delta}\right), \end{aligned} \tag{3.36}$$

- The resulting total Capture rate is

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

CAPTURE RATE





MULTIPLE TARGETS

- Can expand the formalism to include multiple types of targets

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

$$\delta_i = \frac{\delta E}{E_0^i}, \tag{3.43}$$

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 τ_χ^i is simply the integral of the differential element over the trajectory, i.e.

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

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

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

MULTIPLE TARGETS