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Solar Dark Matter below the Evaporation Limit

A Monte Carlo Study

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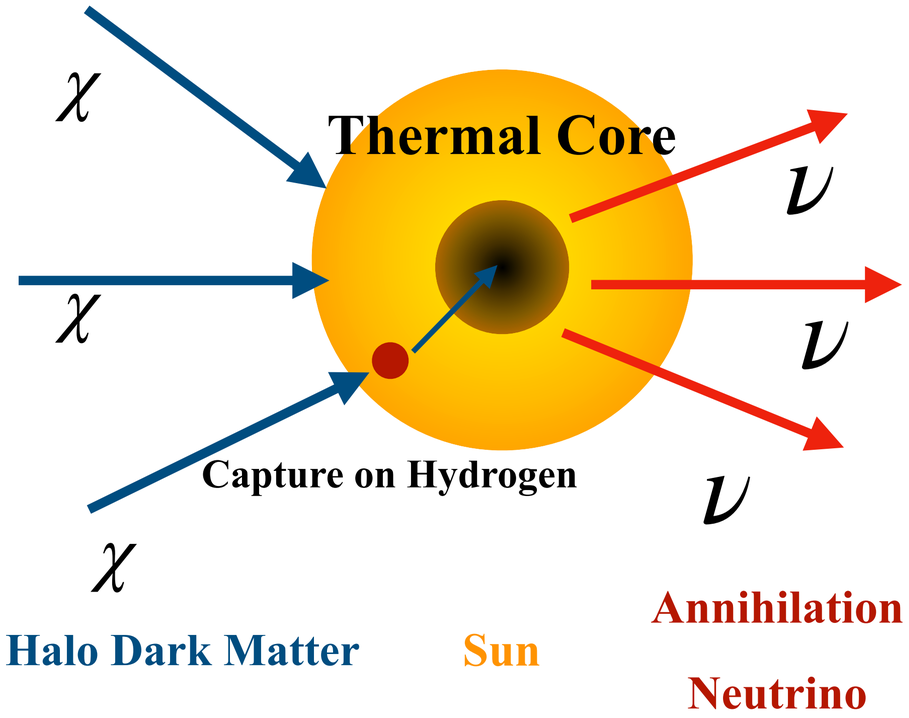
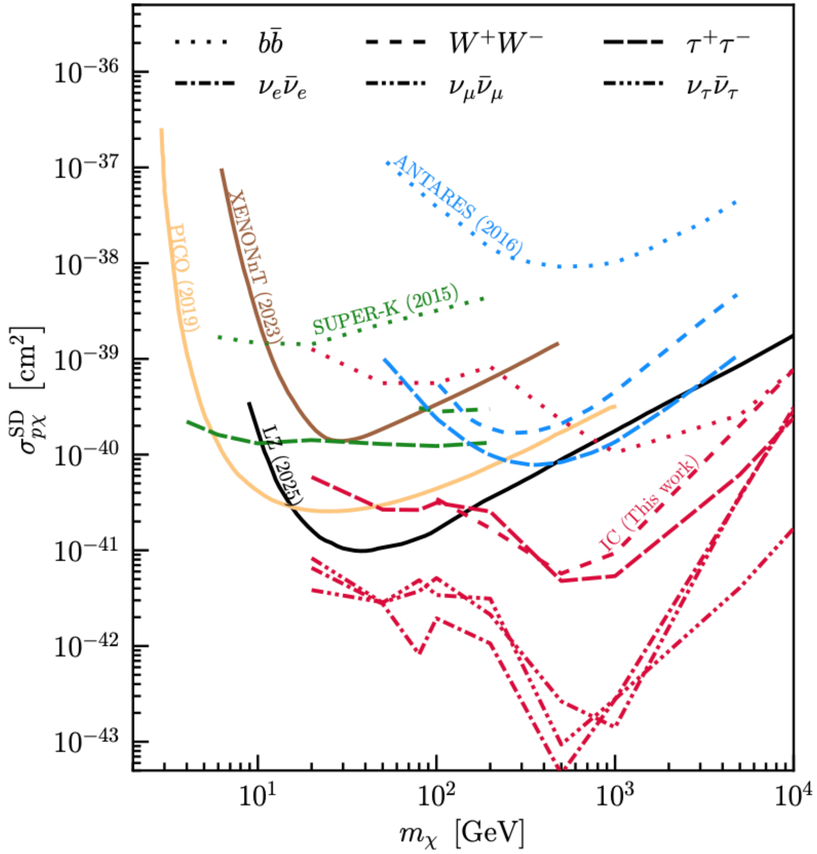
September 2, 2026

The Conventional Solar-WIMP Search



- Solar capture probes DM–matter scattering
- Annihilation products, especially neutrinos, provide the indirect observable
- Current searches already give leading SD constraints — but mainly above the evaporation regime



Abbasi et al. [IceCube], arXiv:2507.08457 (2025)

Under capture–annihilation equilibrium, a neutrino-flux limit can convert to a limit on $\sigma^{SD}_{\chi p}$

Refs: Gould, ApJ 321, 560 (1987); Griest & Seckel, NPB 283, 681 (1987); Abbasi et al. [IceCube], arXiv:2507.08457 (2025); Choi et al. [Super-K], PRL 114, 141301 (2015)

The Standard Theory of the Solar DM

$$\dot{N}_\chi(t) = C_\odot - A_\odot N_\chi^2 - E_\odot N_\chi(t)$$

- **Conventional WIMP regime:**

$$N_\chi^{\rm eq} \simeq \sqrt{\frac{C_\odot}{A_\odot}}, \Gamma_A = \frac{1}{2} A_\odot N_\chi^2 = \frac{1}{2} C_\odot$$

- **Evaporation-dominated regime**:

$$N_\chi^{\rm eq} \simeq \frac{C_\odot}{E_\odot}, \Gamma_A \simeq \frac{A_\odot C_\odot^2}{2E_\odot^2}$$

Density Profile: $n_\chi(r) = N_\chi g_\chi(r), \int g_\chi(r) {\rm d}V = 1$

Annihilation Coe.: $A_\odot = \langle \sigma v \rangle \int g_\chi^2(r) {\rm d}V$

$$K \equiv \frac{\text{Mean Free Path}}{\text{DM scale height}}$$

$K \gg 1$: Long Mean Free Path

Isothermal: $T_\chi = \text{Const.}$

$K \ll 1$: Short Mean Free Path

Local Thermal Equilibrium: $T_\chi(r) = T_\odot(r)$

Evaporation brings the post-capture distribution back into the signal prediction.

Refs: Griest & Seckel (1987); Gould (1987)

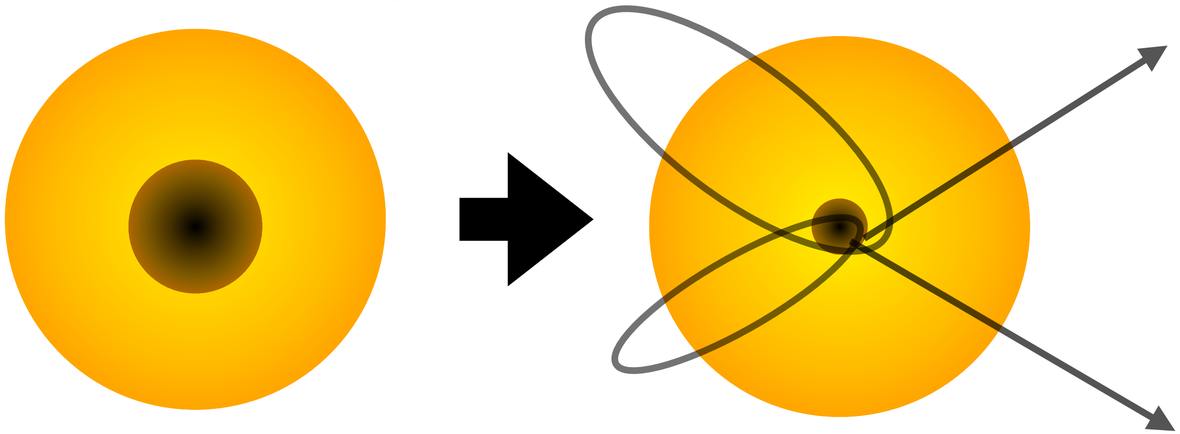
Below the Evaporation Limit, the Timescale Hierarchy Can Break Down

WIMP DM

$\tau_{\rm th} \ll \tau_{\rm evap}$

Low-Mass DM

$\tau_{\rm th} \sim \tau_{\rm evap}$



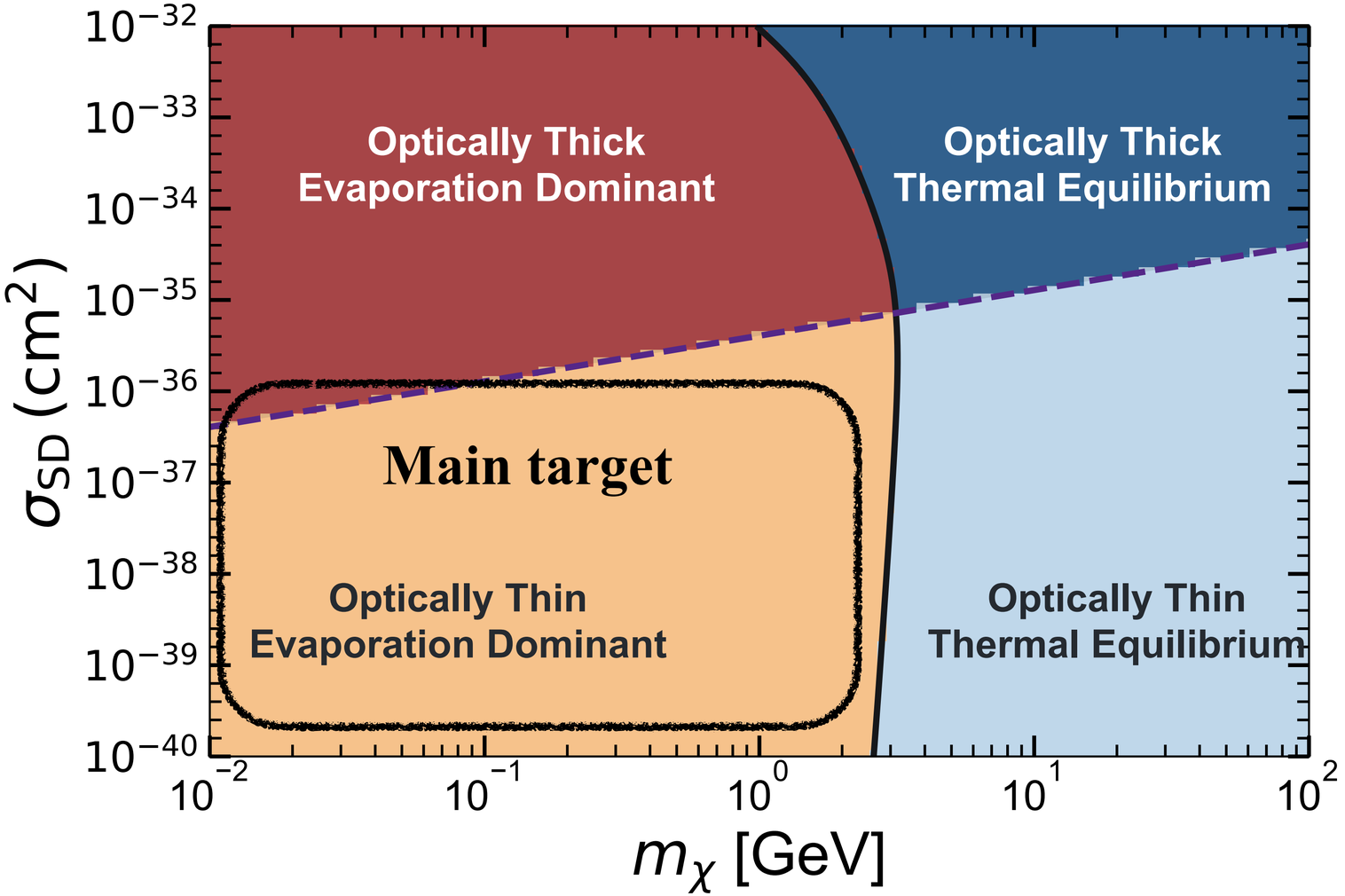
Escape can occur before the particle joins the quasi-static distribution.

- Evaporation Rate: $E_\odot^{MC} \stackrel{?}{=} E_\odot^{\rm std}$
- Spatial profile: $g_\chi^{\rm MC}(r) \stackrel{?}{=} g_\chi^{\rm std}(r)$
- Final signal: $\Gamma_A^{\rm MC} \stackrel{?}{=} \Gamma_A^{\rm std}$

If weakly bound orbits build up outside the Sun, how much annihilation survives there?

Refs: Busoni et al. (2017); Liang et al., JCAP 09 (2016) 018; Widmark, JCAP 05, 046 (2017)

Our Benchmarks Probe the Optically Thin, Evaporation-dominated Regime



Solid Line: Evaporation boundary

Dashed Line: Optical-depth boundary

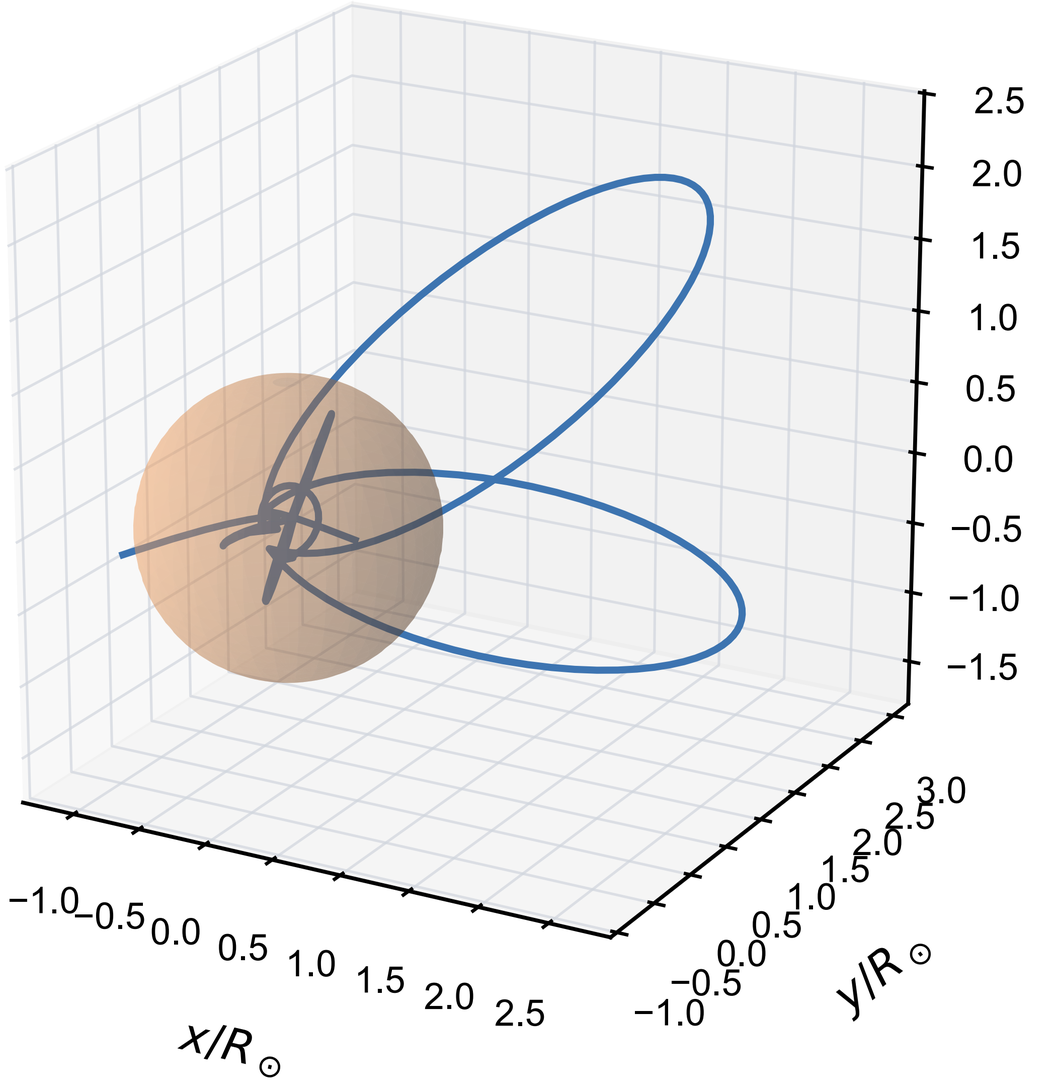
Interaction:

SD, elastic, contact scattering

Benchmark: $\sigma_{\chi p}^{SD} = 10^{-36}\mathrm{cm}^2$

Refs: Gould (1987); Busoni et al. (2017); Asplund et al. (2009).

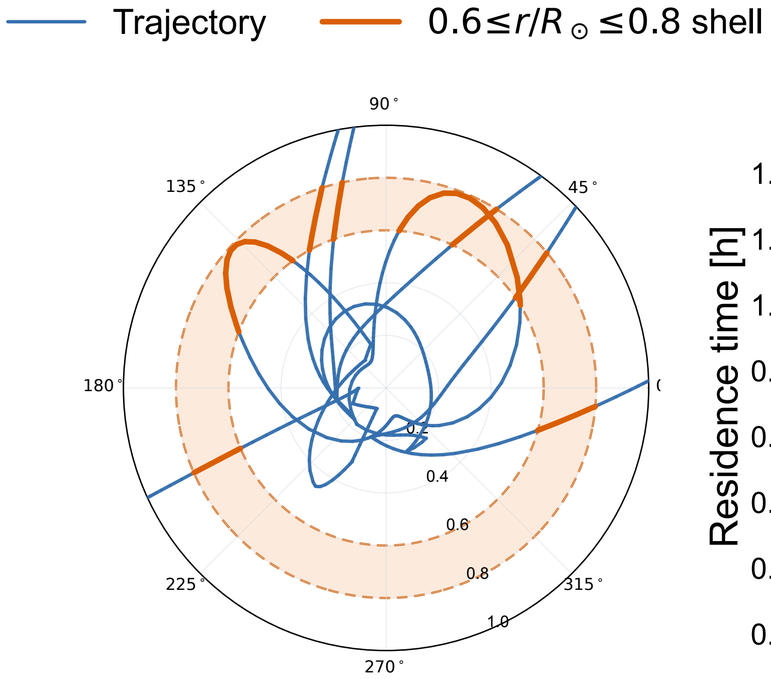
Follow the Full Post-Capture Orbital History

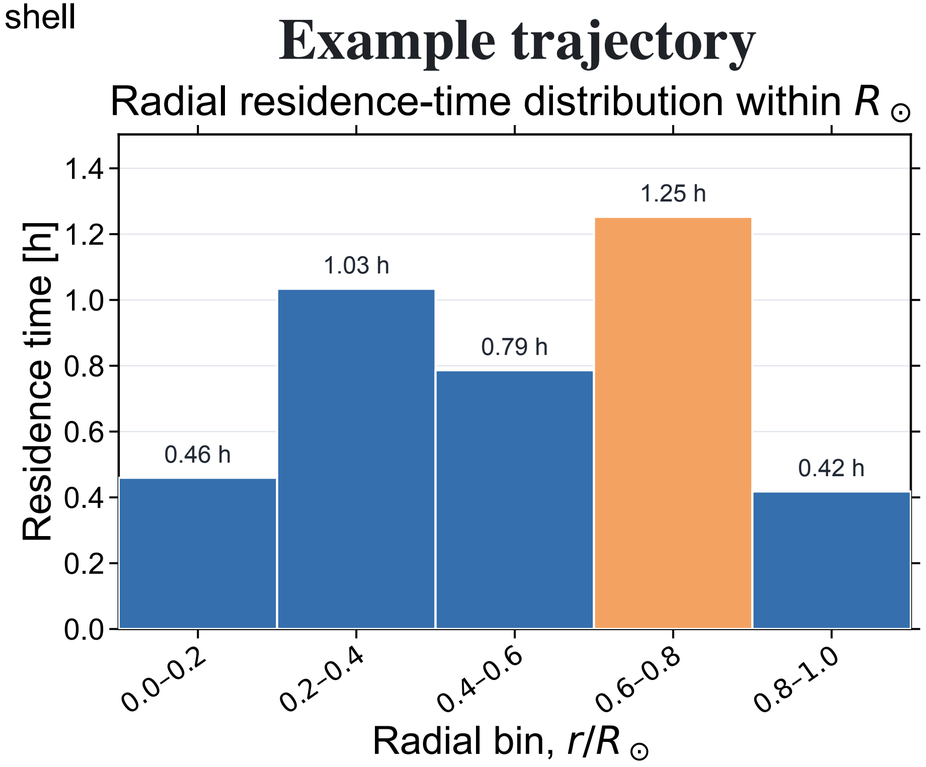


- Base framework: **DaMaSCUS-SUN**
- Each captured particle is propagated through solar crossings and scatterings until escape.
- Follow each captured particle trajectory, we record: $\mathcal{T}_i = \{r_i(t), v_i(t), E_i(t), L_i(t)\}$
- Annihilation is **ignored** during orbit propagation and evaluated in post-processing.

Refs: Emken (2022); DaMaSCUS-SUN, ASCL:2102.018; reconstruction: this work.

From Orbital Histories to Density Profile





Δt_{ij} = total time spent in radial shell j

Average over captured particles:

$$\langle \Delta t_j \rangle = \frac{1}{N_{\rm cap}} \sum_i \Delta t_{ij}$$

Occupancy =

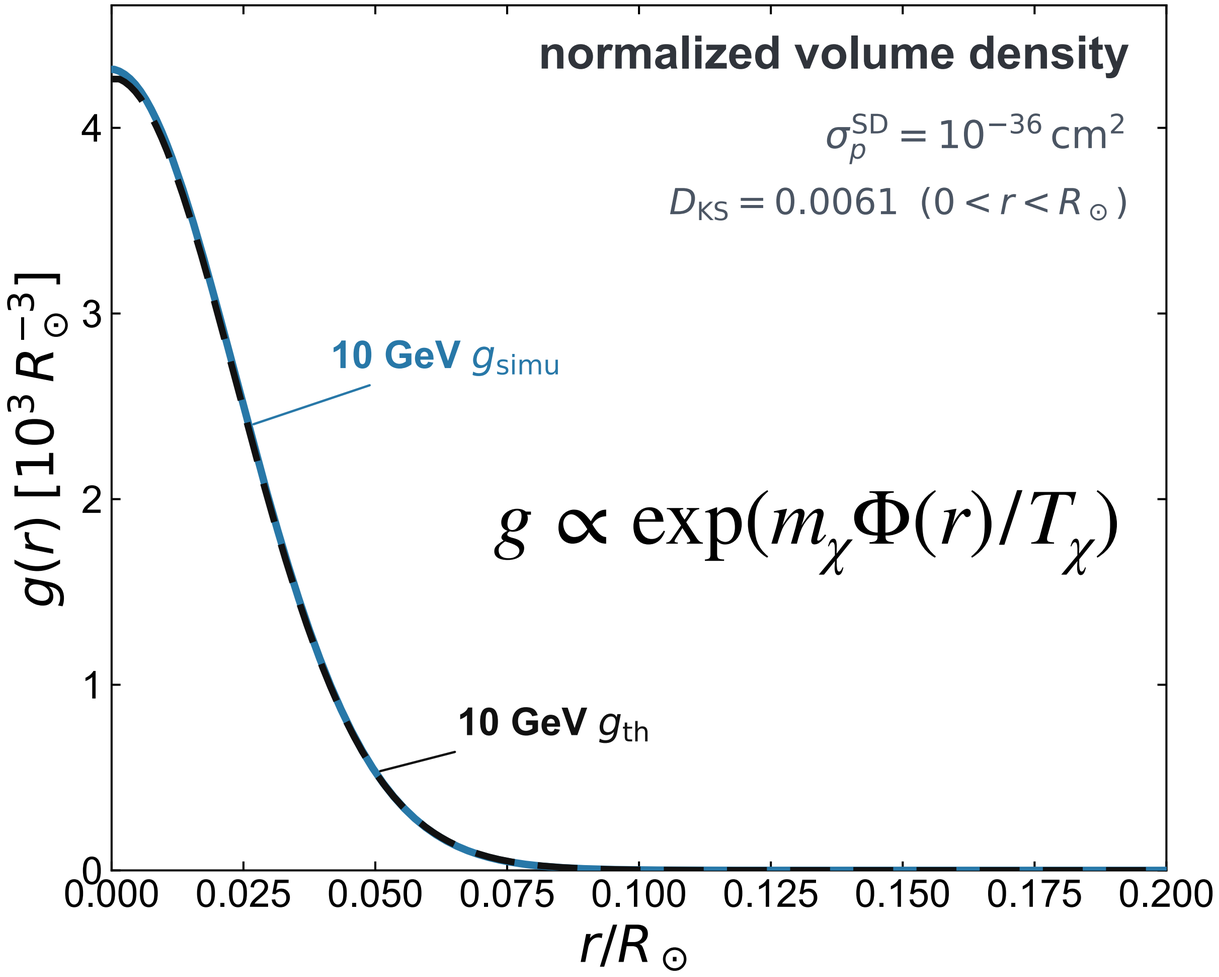
injection rate × residence time

$$n_\chi(r_j) = \frac{C_\odot}{\Delta V_j} \langle \Delta t_j \rangle$$

$$N_\chi = C_\odot \cdot \langle T_{\rm esc} \rangle$$

Refs: Emken (2022); residence-time reconstruction: this work.

The Reconstruction reproduce the Thermal Limit



$$F(<r) = \frac{\int_0^r 4\pi r^2 g(r) dr}{\int_0^{R_\odot} 4\pi r^2 g(r) dr}$$

$$D_{\mathrm{KS}} = \max_{r<R_\odot} \left| F_{\mathrm{MC}}(<r) - F_{\mathrm{std}}(<r) \right|$$

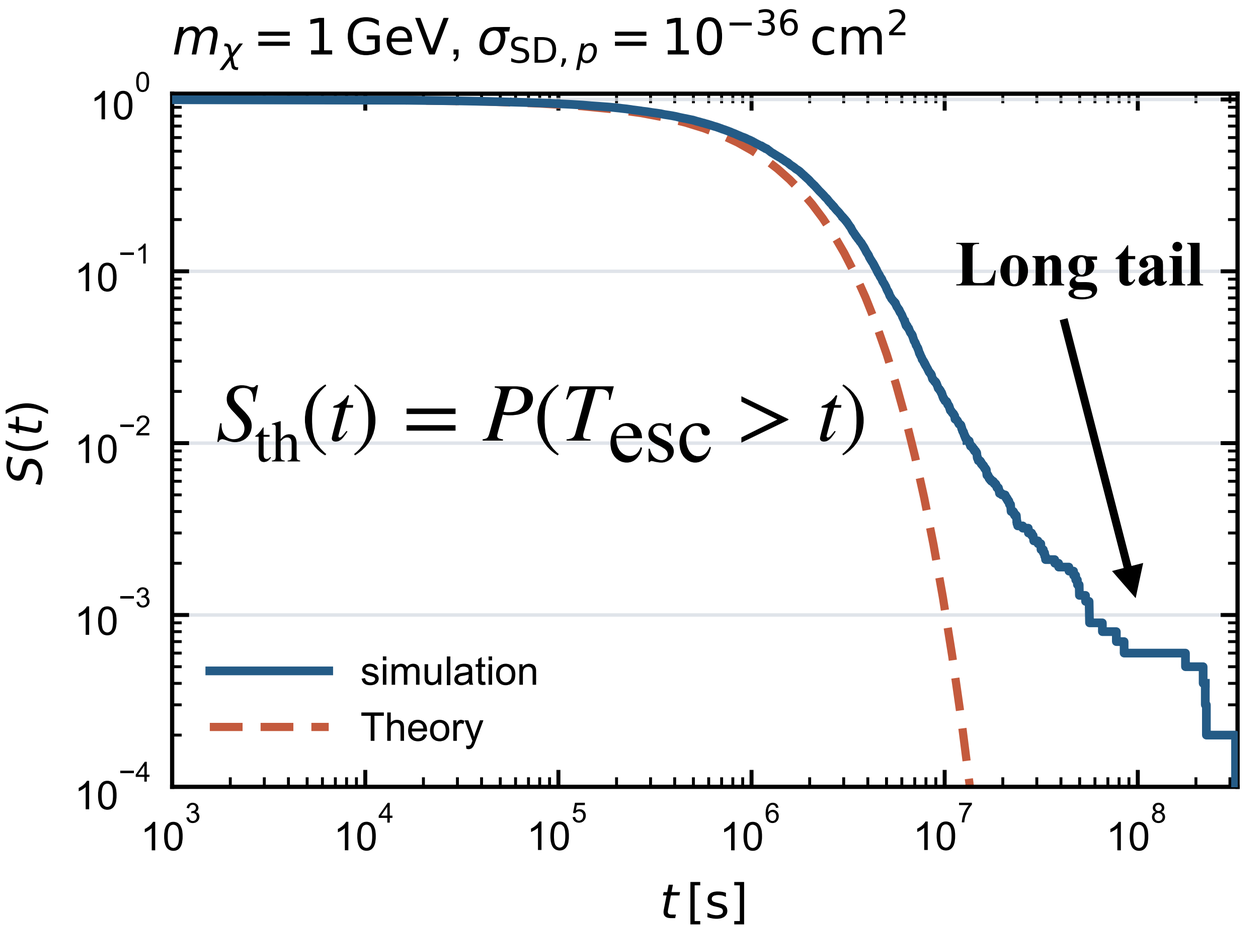
$$D_{KS} = 0.0061$$

$D_{KS} = 0$: identical distribution

This validates the simulation in the regime where thermalization is expected.

Refs: Gould & Raffelt (1990); Busoni et al. (2017); Widmark (2017); **Simulation**: This Work

A Long-lived Tail Enhances the Steady-state Occupancy



Constant evaporation rate:

$$\frac{dN_\chi}{dt} = -E_\odot^{\mathrm{std}} N_\chi \Rightarrow S_{\mathrm{th}}(t) = \frac{N_\chi(t)}{N_\chi(0)} = e^{-E_\odot^{\mathrm{std}} t}$$

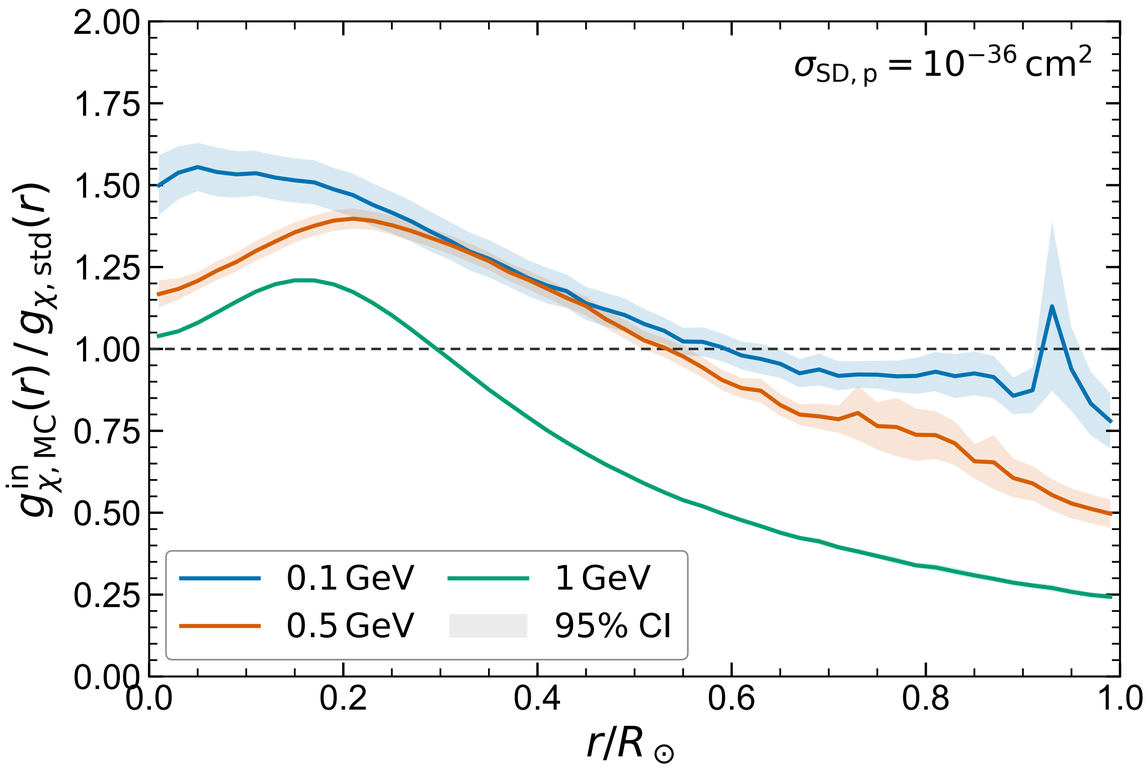
$$\frac{1}{E_\odot^{\mathrm{std}}} = 1.47 \times 10^6 \mathrm{s} \quad \text{vs.} \quad \langle T_{\mathrm{esc}} \rangle_{\mathrm{MC}} = 2.22 \times 10^6 \mathrm{s}$$

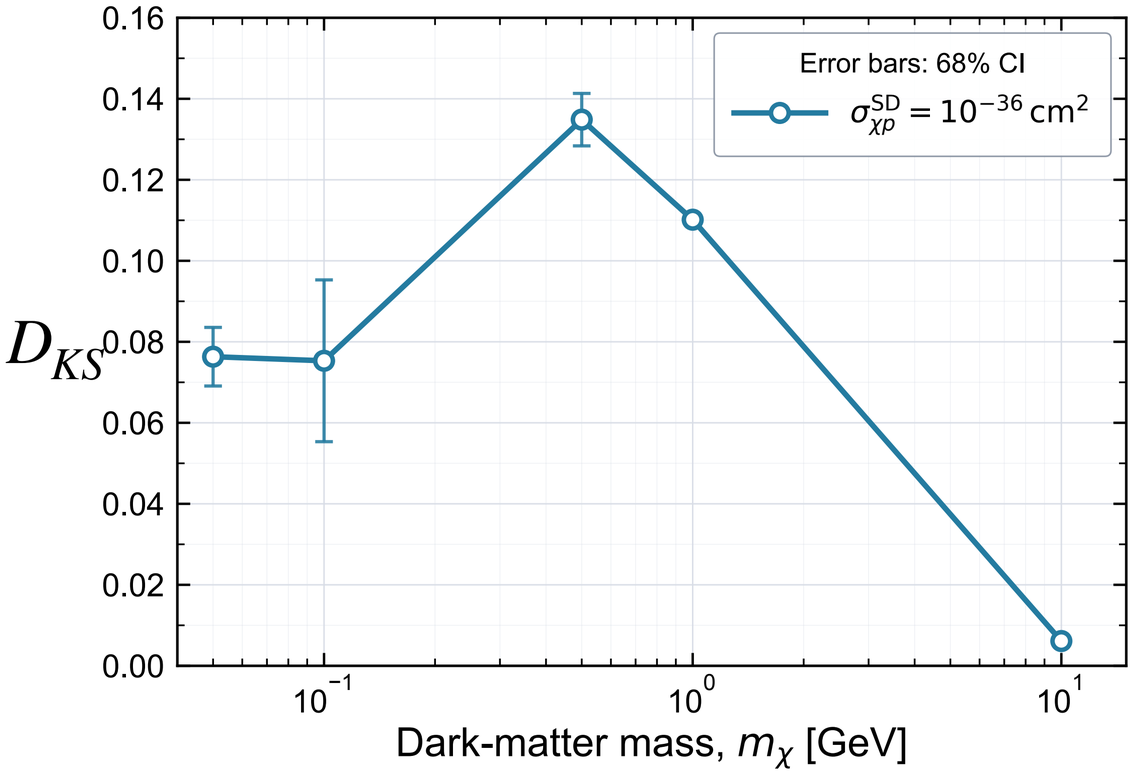
$$\langle T_{\mathrm{esc}} \rangle \uparrow \Rightarrow N_\chi = C_\odot \cdot \langle T_{\mathrm{esc}} \rangle \uparrow$$

Refs: Gould (1987); Busoni et al. (2017); simulation: this work

The Inner Spatial Profile Departs from the Thermal Closure

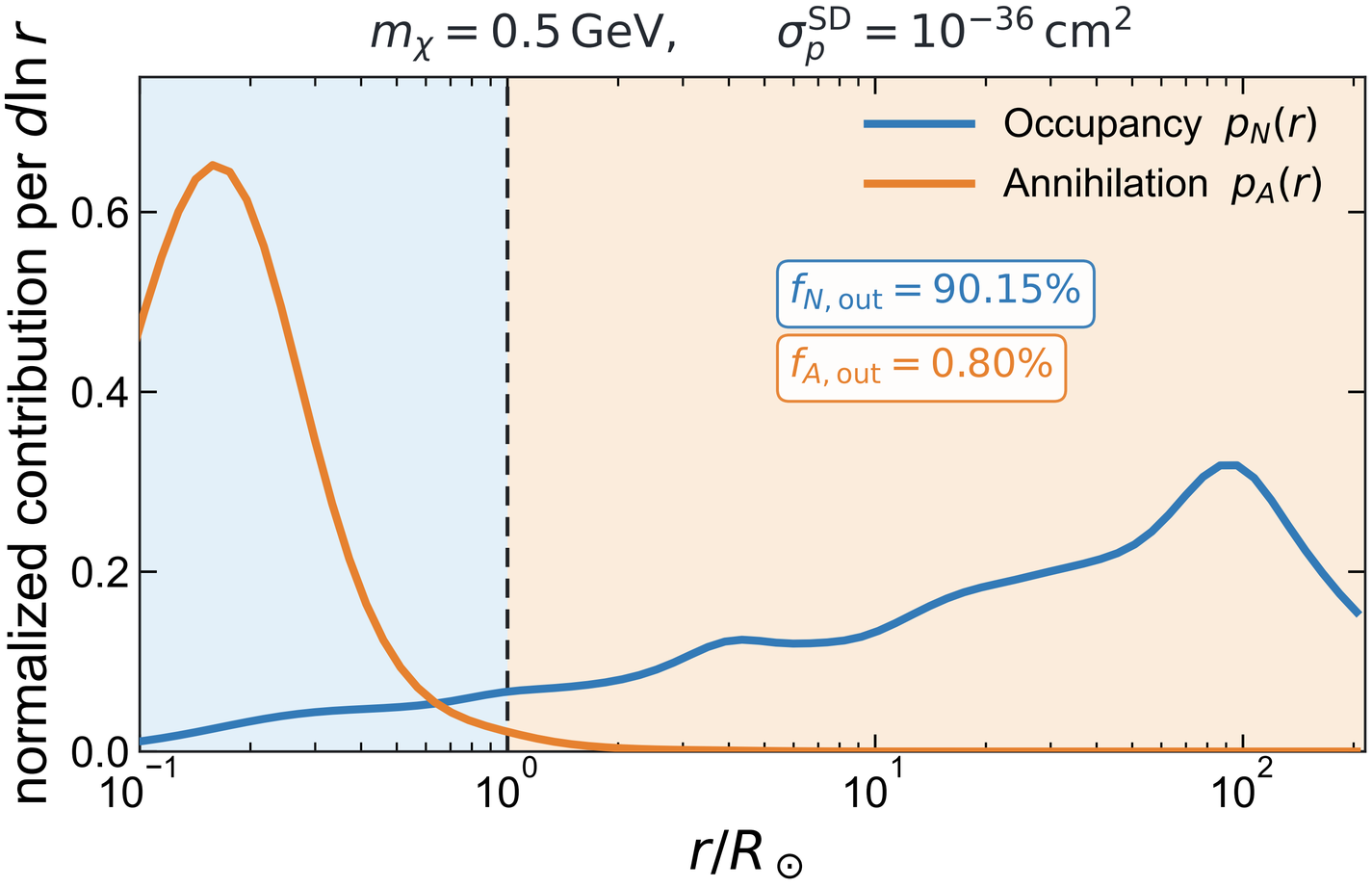
Conditional normalization inside $R_\odot$





Inside the Sun: Radial-shape deviations reach $\mathcal{O}(10\%)$ in the evaporation regime.

A Large Exterior Population Does Not Imply Large Exterior Annihilation



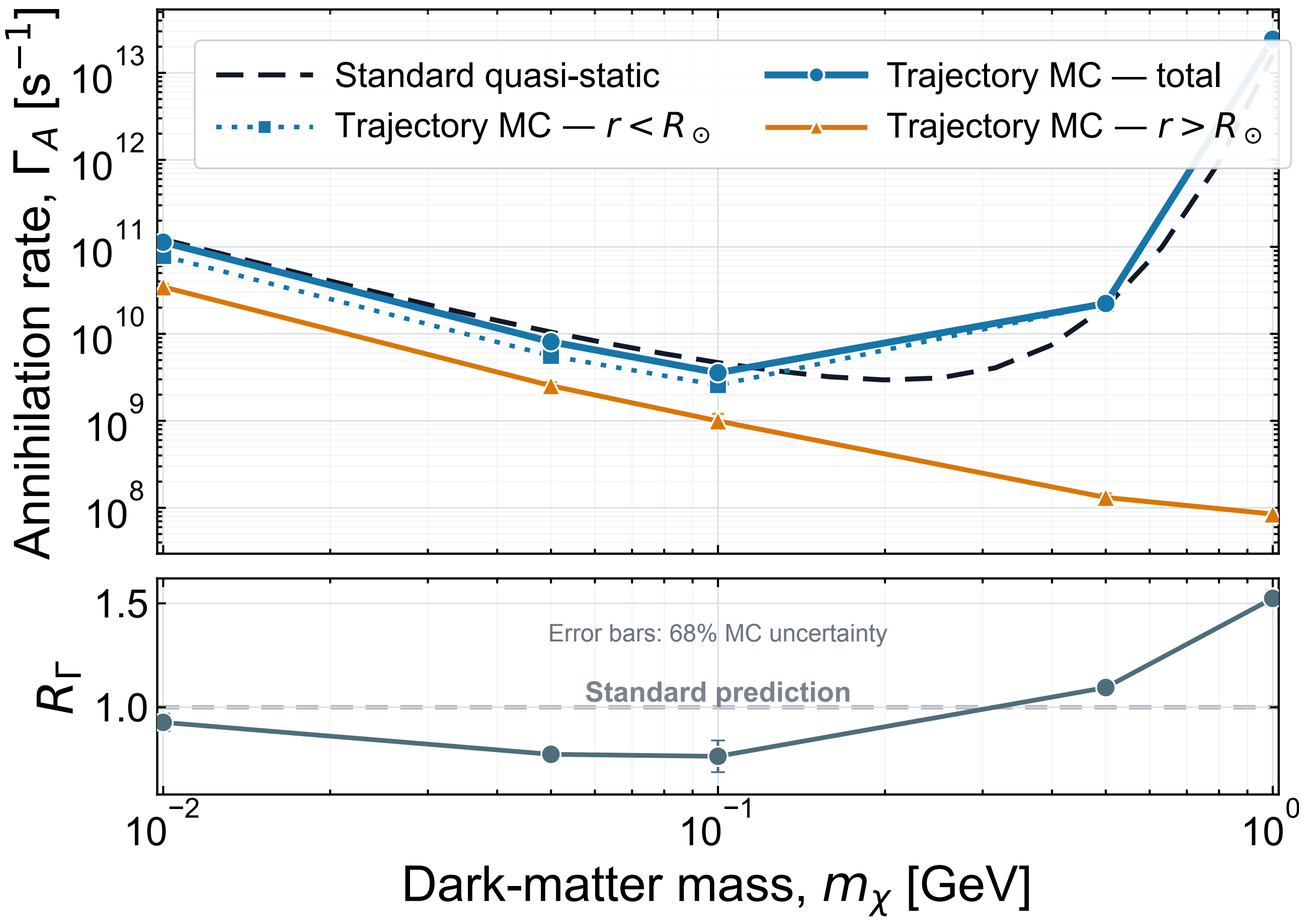
$$p_N(r) \equiv \frac{1}{N_\chi}\frac{dN_\chi}{d\ln r} = \frac{4\pi r^3 n_\chi(r)}{N_\chi}$$

$$p_A(r) \equiv \frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\ln r} = \frac{4\pi r^3 n_\chi^2(r)}{\int 4\pi r^2 n_\chi^2(r)\,dr}$$

- Long orbital periods shift the occupancy to large radii.
- A large exterior population is therefore not equivalent to a large exterior signal.

Lifetime Enhancement and Profile Dilution Compete in the Annihilation Rate

$\sigma_{\chi p}^{\mathrm{SD}} = 10^{-36}\,\mathrm{cm}^2 \qquad \langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$



$$R_\Gamma \equiv \frac{\Gamma_A^{\mathrm{MC}}}{\Gamma_A^{\mathrm{std}}} = \left(\frac{N_\chi^{\mathrm{MC}}}{N_\chi^{\mathrm{std}}}\right)^2 \frac{\int [g_\chi^{\mathrm{MC}}(r)]^2 dV}{\int [g_\chi^{\mathrm{std}}(r)]^2 dV}$$

$m_\chi = 0.5\ \mathrm{GeV} : \mathrm{R}_\Gamma = 6.54 \times 0.17 = 1.10$

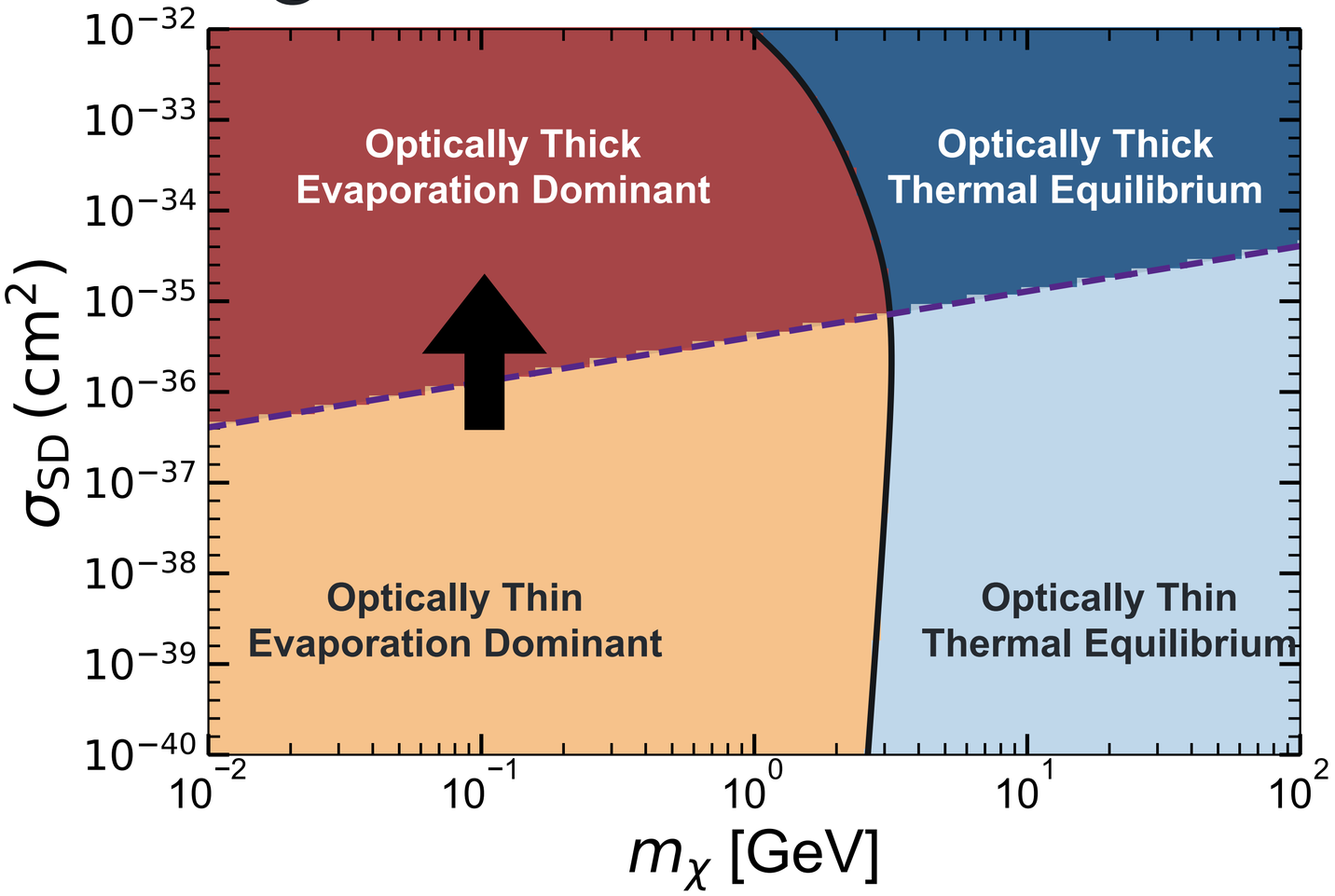
- **Long residence time:** enhances population.
- **Spatial dilution:** suppresses overlap.
- The two effects can nearly cancel.

$m_\chi = 0.1\ \mathrm{GeV}$:

$\Gamma_{A,\mathrm{out}}^{\mathrm{eASTROGAM}} \approx 5.3 \times 10^{17}\ \mathrm{s}^{-1}$

Refs: Griest & Seckel (1987); De Angelis et al. [e-ASTROGAM], JHEAp 19, 1 (2018);simulation and decomposition: this work

Toward Stronger Signals in the Optically Thick Regime



At our current benchmark:

- Exterior annihilation remains small.
- The total annihilation correction is $\mathcal{O}(1)$
- Therefore this point is not yet experimentally competitive.

Toward larger cross sections:

- Capture becomes more efficient.
- A larger bound population can enhance the annihilation rate.
- The optically thick regime is therefore the natural next target.

Refs:; Rebecca K. Leane and Juri Smirnov JCAP10(2023)057

Conclusion & Discussion

What we have established:

- **Full trajectories produce:**
  long-lived population;
  modified spatial profile.
- **Signal corrections come from competing effects**
  Population enhancement and spatial dilution can partially cancel but .

Next: scan toward the optically thick regime for stronger annihilation signals.

From Full Trajectories to Constraints

$(m_\chi, \sigma_{\chi p}^{\mathrm{SD}})$

↓

Simulation

↓

$N_\chi,\ g_\chi(r),\ \Gamma_A,\ \Gamma_{A,\mathrm{out}}$

↓

Experimental sensitivity

↓

$\sigma_{\chi p}^{\mathrm{limit}}(m_\chi)$

Thanks! Questions?

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Physics Setup & Assumptions

1. **Scattering**: $\chi + p \rightarrow \chi + p$

- Spin-dependent
- Elastic, contact
- Velocity-independent
- Benchmark: $\sigma_{\chi p}^{SD} = 10^{-38}, 10^{-36}$ cm^2

2. **Environment:**

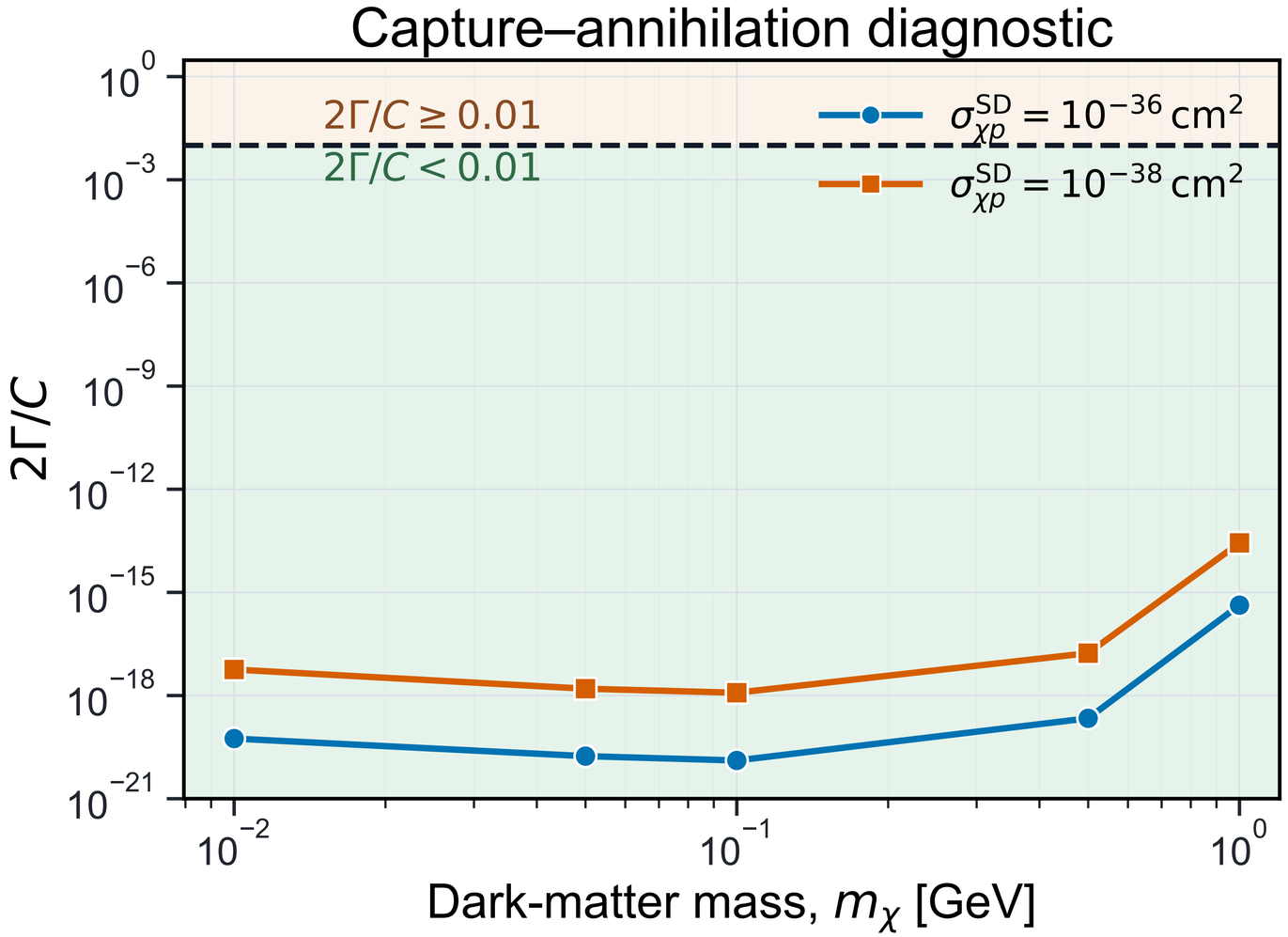
- **Solar Model:** AGSS09
- Standard Halo Model
- $\rho_\chi = 0.4$ GeV/cm^3, $v_0 = 220$ km/s, $v_{\rm esc} = 544$ km/s

3. What is not simulated**: No annihilation during trajectory evolution**

$$n_\chi(r) \rightarrow \Gamma_A = \frac{1}{2}\langle\sigma v\rangle \int n_\chi^2 dV \,.\langle\sigma v\rangle = 3 \times 10^{-26} \text{cm}^3/\text{s}$$

Refs: Emken, PRD 105, 063020 (2022); Asplund et al., ARA&A 47, 481 (2009).

Validation: Non-Annihilation Assumption



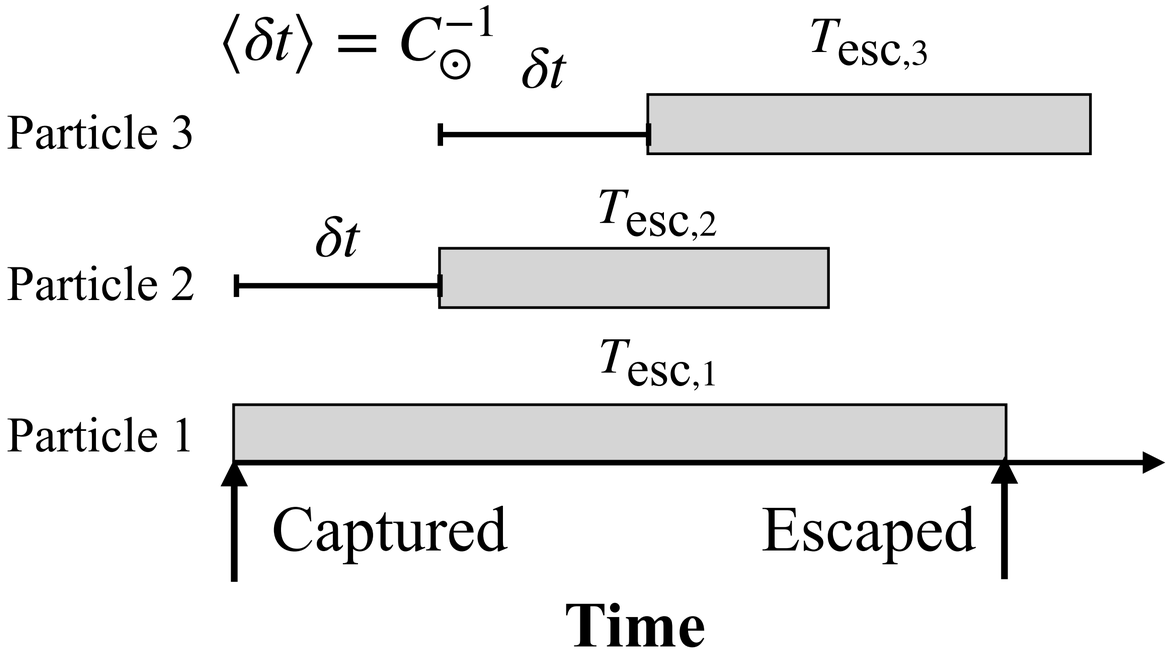
- Annihilation removes only a negligible fraction of the captured population before evaporation, validating the post-processing treatment.

$$\epsilon = \frac{2\Gamma}{C_\odot}$$

From Evaporation Rate to Particle Lifetime

$$\dot{N}_\chi(t) = C_\odot - A_\odot N_\chi^2 - E_\odot N_\chi(t)$$

If annihilation is negligible and steady state is reached, $N_\chi \simeq \frac{C_\odot}{E_\odot}$, $\tau_{\rm evap}^{\rm th} \equiv E_\odot^{-1}$



Steady-state occupancy =

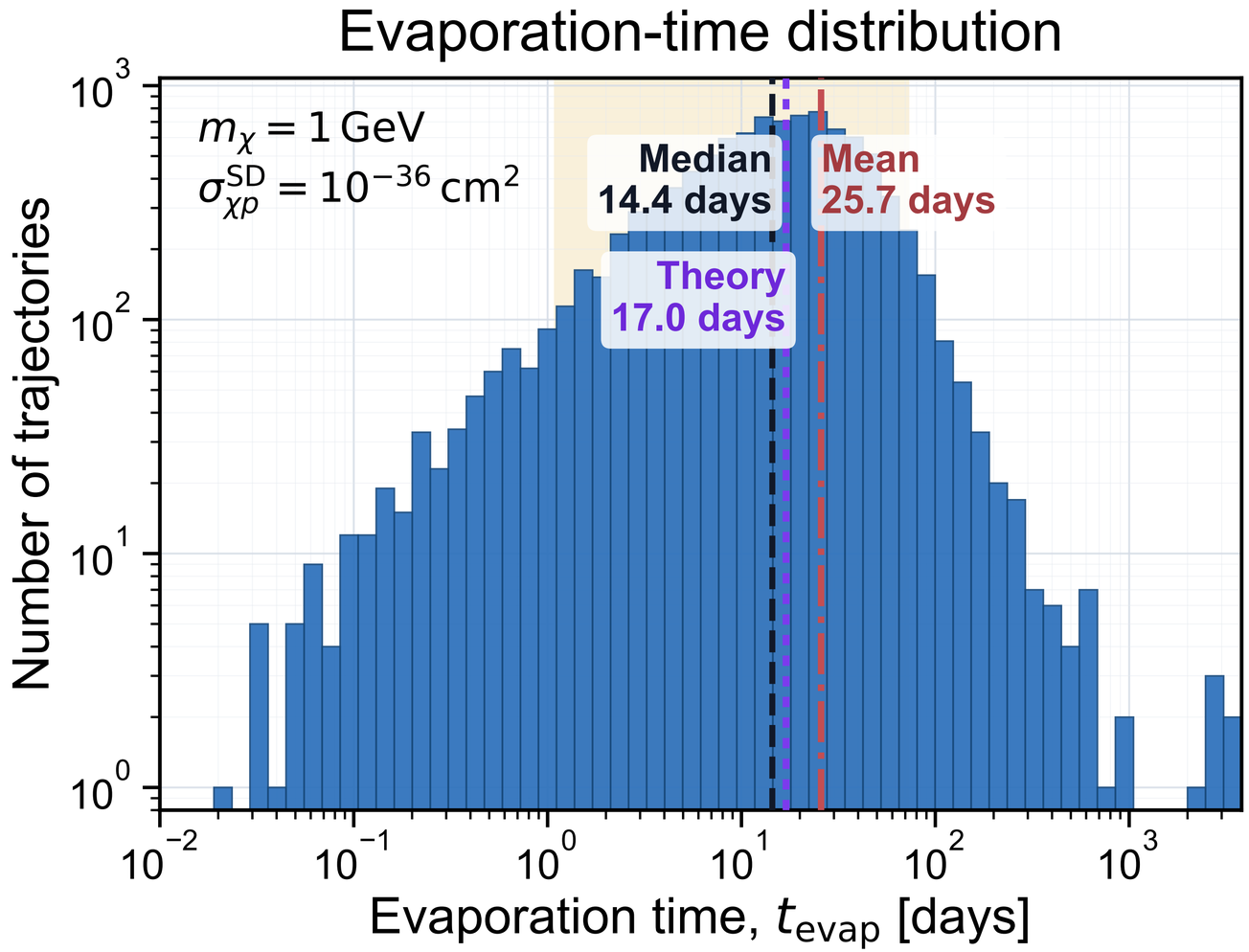
capture rate × mean residence time

Global $N_\chi = C_\odot \cdot \langle T_{\rm esc} \rangle_{\rm cap}$

Local $n_\chi(r_j) = \frac{\Delta N_j}{\Delta V_j} = \frac{C_\odot}{\Delta V_j} \langle \Delta t_j \rangle_{\rm cap}$

The mean controls occupancy

Result I:Evaporation Is a Distribution of Lifetimes



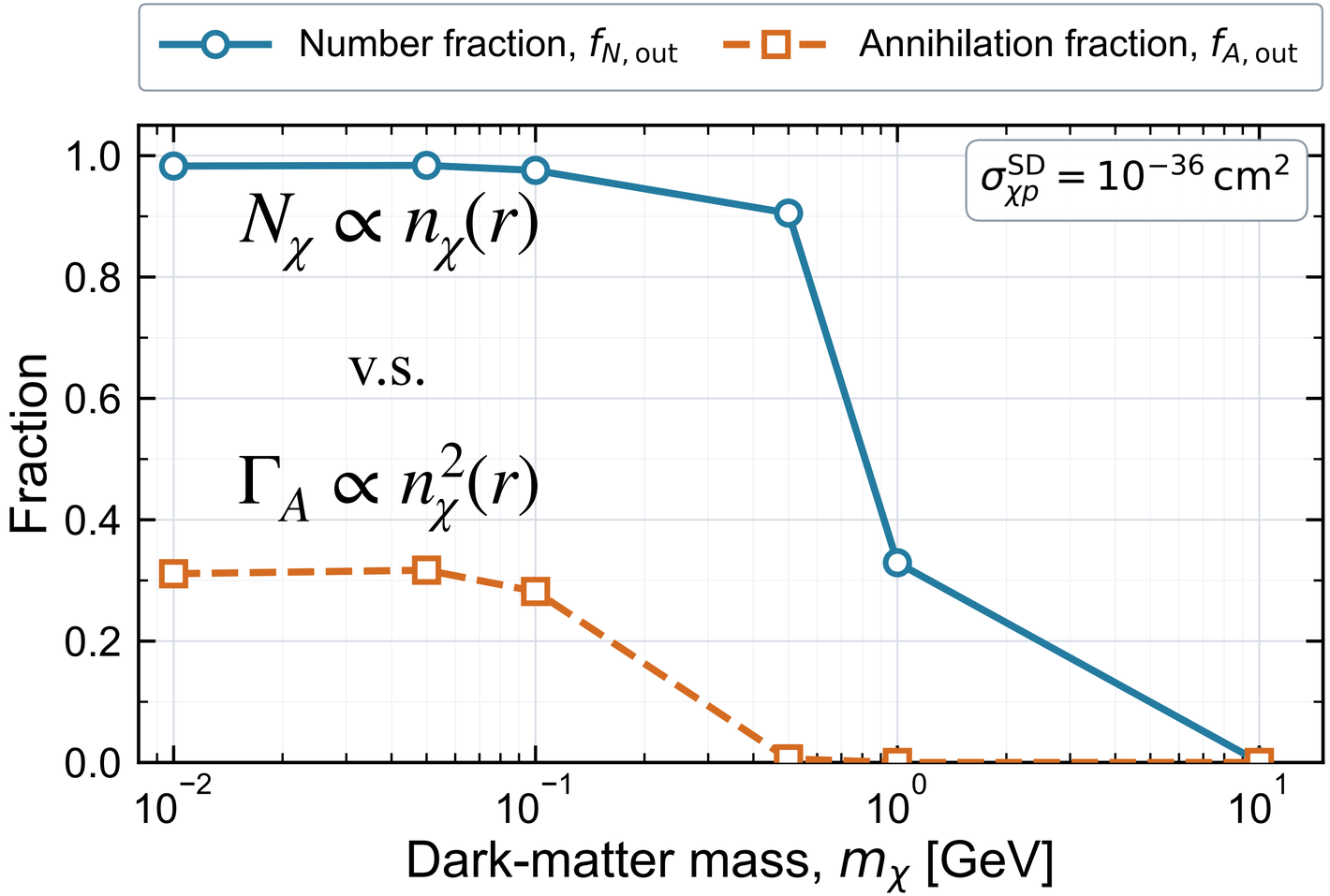
$\tau^{th} = 17\ d,\ T_{med} = 14.4\ d,\ \langle T \rangle = 25.7\ d$

- **The full lifetime distribution is broad and develops a long-lived tail.**

Rare long-lived trajectories can disproportionately affect the population estimate — motivating a spatially resolved residence-time reconstruction.

Refs: Busoni et al., JCAP 10, 037 (2017).

A Large Exterior Population Does Not Imply Large Exterior Annihilation



$$f_{A,\mathrm{out}} = \frac{\int_{r>R_\odot} n_\chi^2 dV}{\int n_\chi^2 dV}$$

The exterior component is strongly suppressed relative to the particle population, but it is not identically zero.

Refs: Griest & Seckel, Nucl. Phys. B 283, 681 (1987). **Simulation**: this work.