

Solar Reflection of Light Dark Matter with Light Mediators

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Outline

I. Motivation

II. Solar reflection of light dark matter

III. Dark photon – mediated DM scatterings in a medium

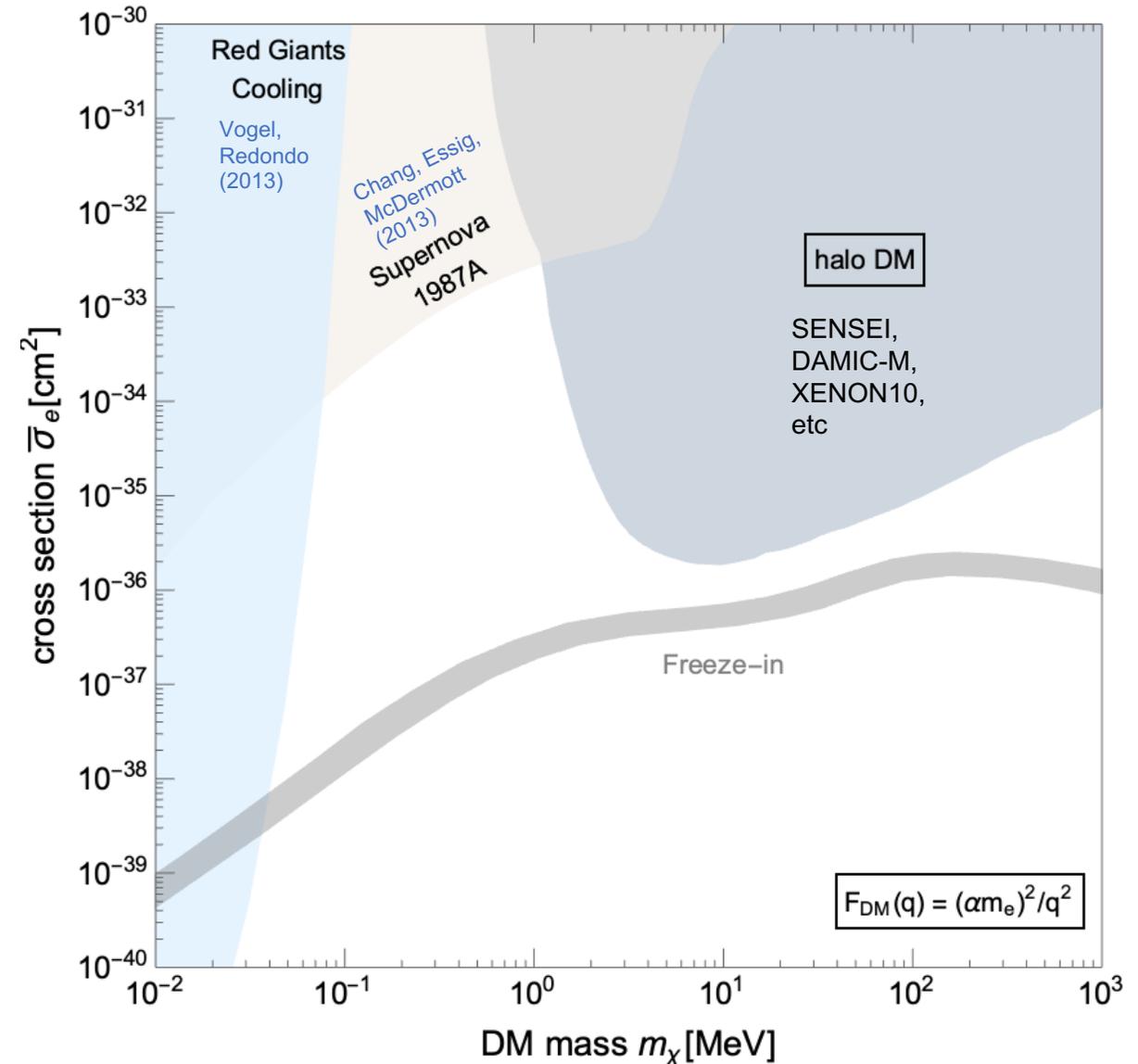
IV. Monte Carlo simulations via DaMaSCUS-SUN

V. Reflection flux, constraints, projections

VI. Conclusion

Direct Detection of Halo Dark Matter

- Searching for nuclear or electron recoils caused by **halo dark matter** particles
- Halo DM: can be as fast as ~ 840 km/s in Earth frame
- No existing direct detection bounds on sub-MeV DM



Solar Reflected Dark Matter (SRDM)

Emken, Kouvaris, Nielsen (2017)
An, Pospelov, Pradler, Ritz (2017)

- Halo DM particles get gravitationally attracted by the Sun, up-scatter in hot solar plasma, acquire energy, and escape
- Results in a highly energetic **solar reflected dark matter (SRDM)** flux
- Allows current direct-detection experiments to probe sub-MeV DM

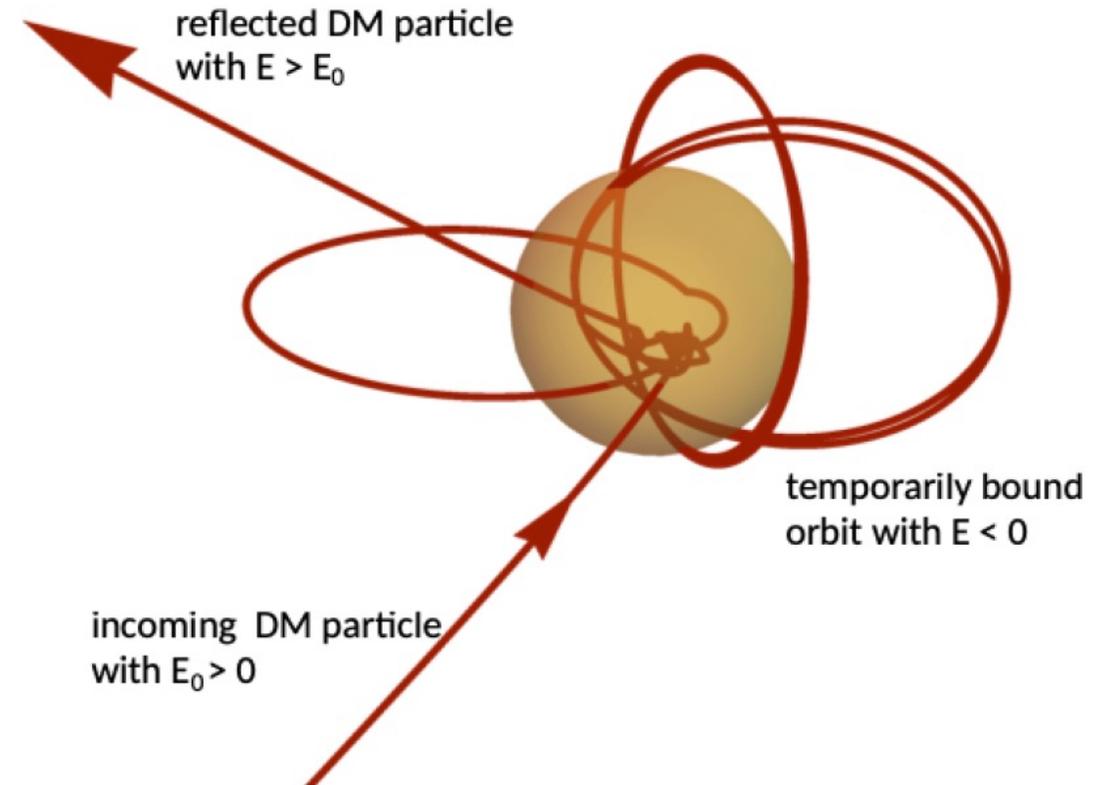


Figure credit: Emken

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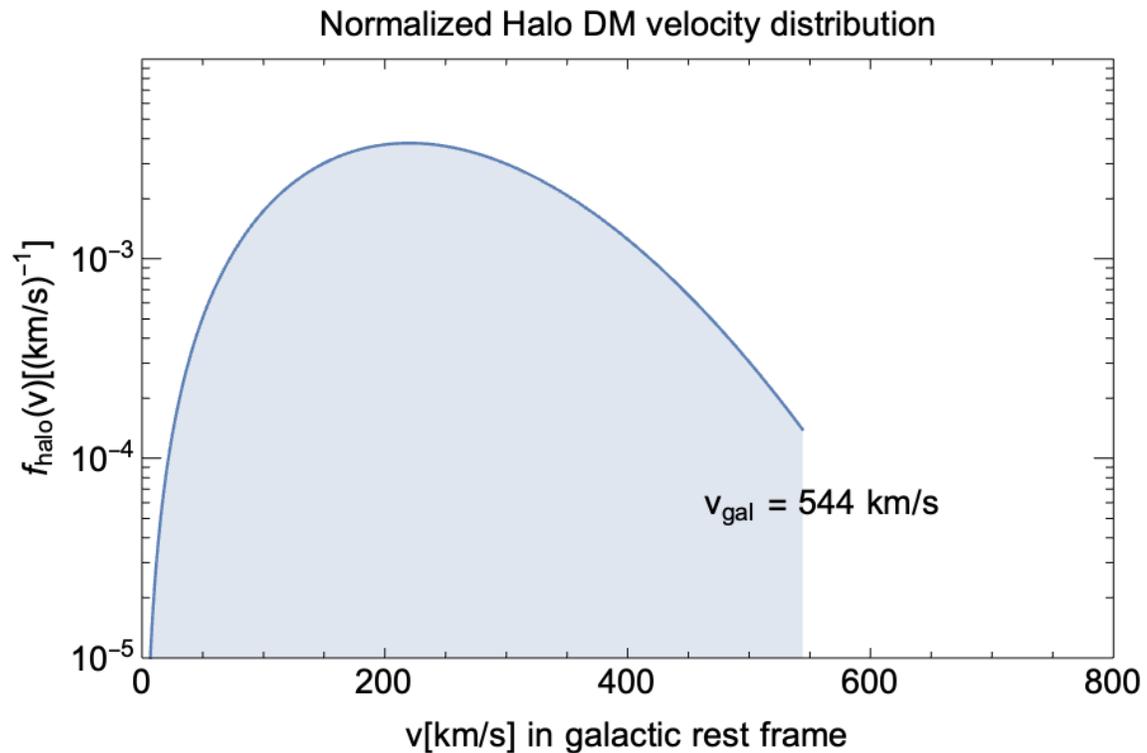
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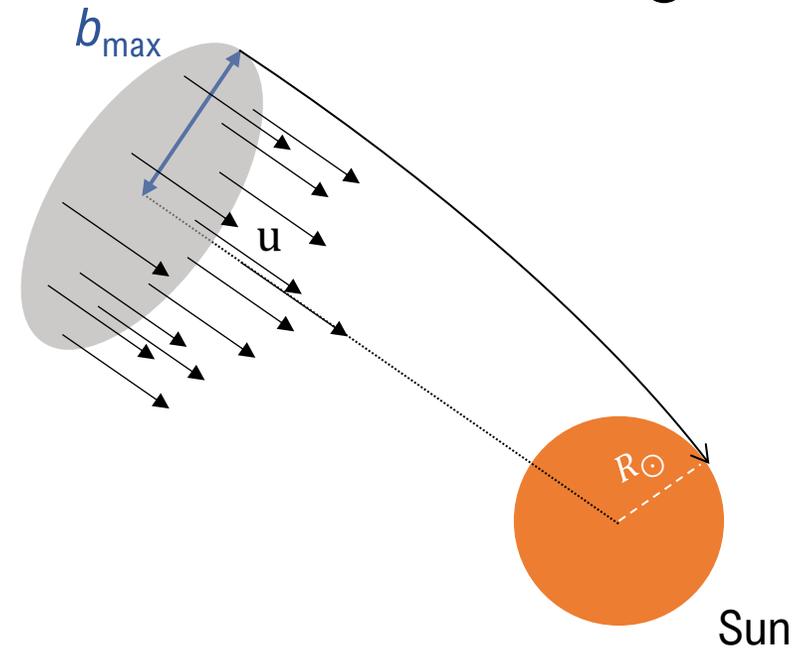
DM Falling Into Sun's Gravitational Well

- Halo DM, in galactic rest frame:



Switch to solar rest frame:

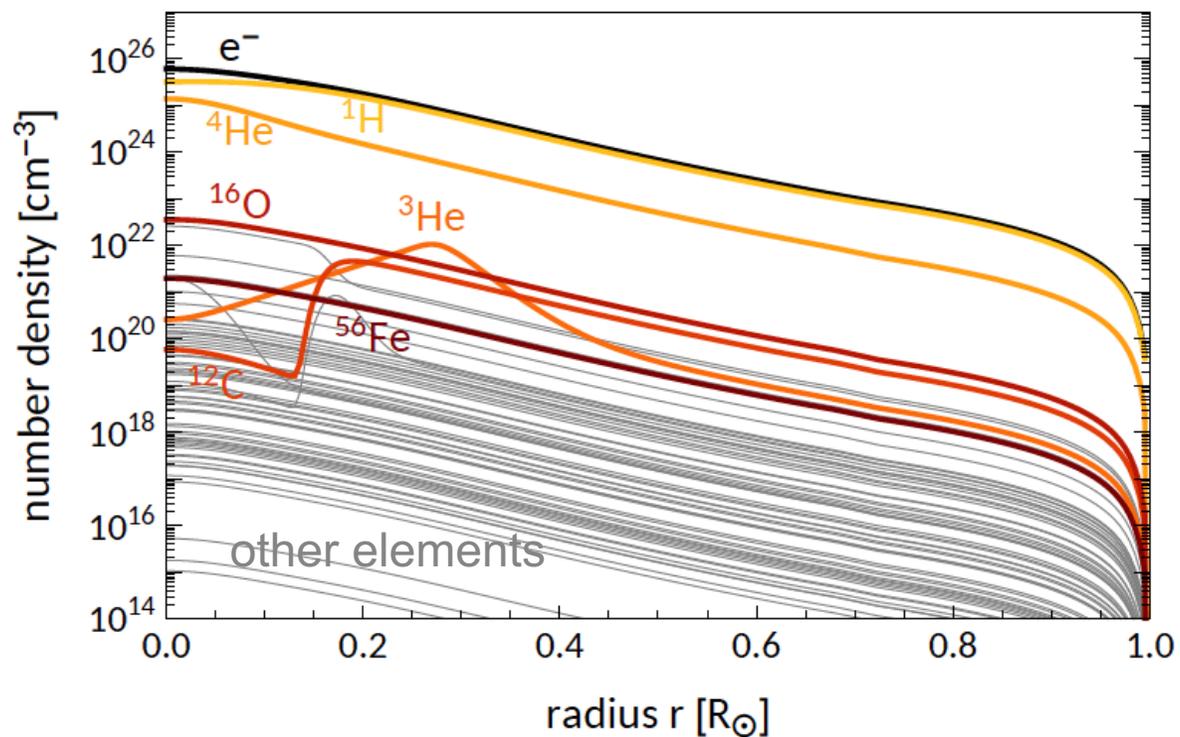
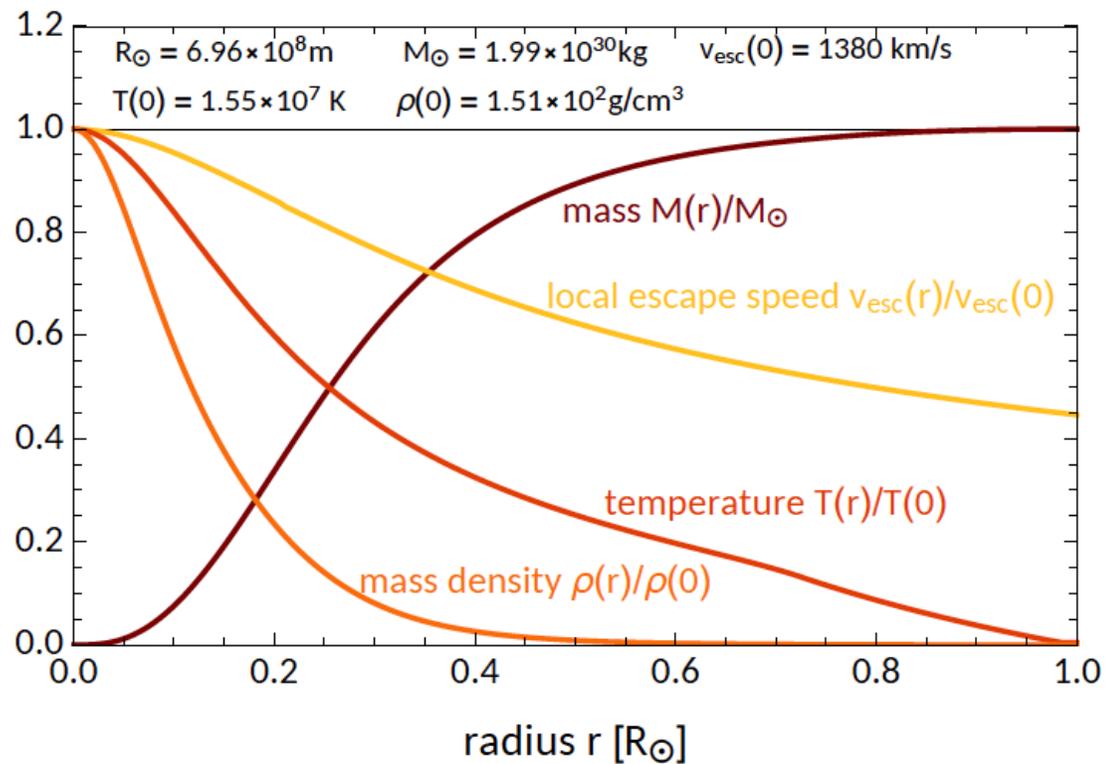
$$\mathbf{u} = \mathbf{v} - \mathbf{v}_{\odot}$$



$$b_{\text{max}} = \sqrt{1 + \frac{v_{\text{esc}}(R_{\odot})^2}{u^2}} R_{\odot}$$

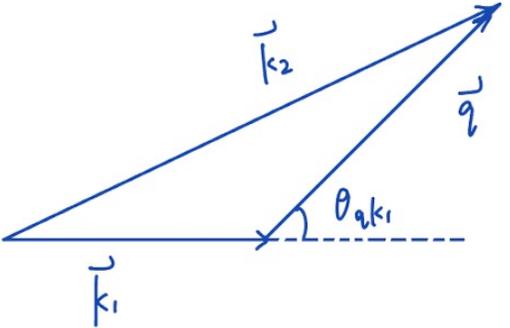
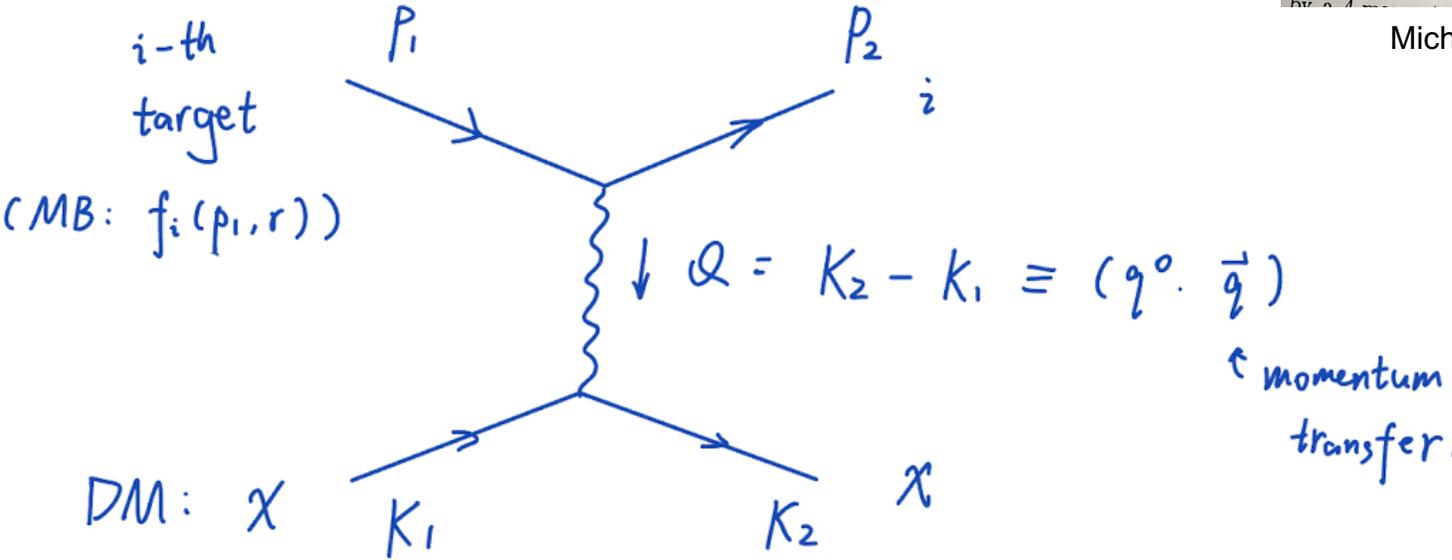
Standard Solar Model

Serenelli, Basu, Ferguson, Asplund (2009)



DM Scattering in Sun

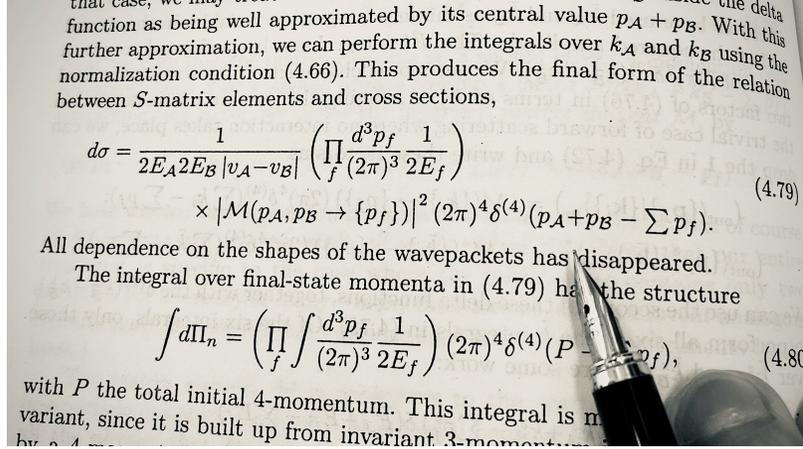
For scattering with i-th solar target:



$$\Omega_i = \frac{n_i}{32\pi m_i^2 m_\chi^2} \left(\frac{m_i}{2\pi T}\right)^{1/2} \int_0^\infty dq \int_{-1}^1 d\cos\theta_{qk_1} \times q \exp\left(-\frac{p_{1\min}^2}{2m_i T}\right) \langle |M_i(Q)|^2 \rangle$$

$$p_{1\min} = \left| \frac{q}{2} \left(\frac{m_i}{m_\chi} + 1\right) + \frac{m_i}{m_\chi} k_1 \cos\theta_{qk_1} \right|$$

Depends on model



Michael E. Peskin & Daniel V. Schroeder

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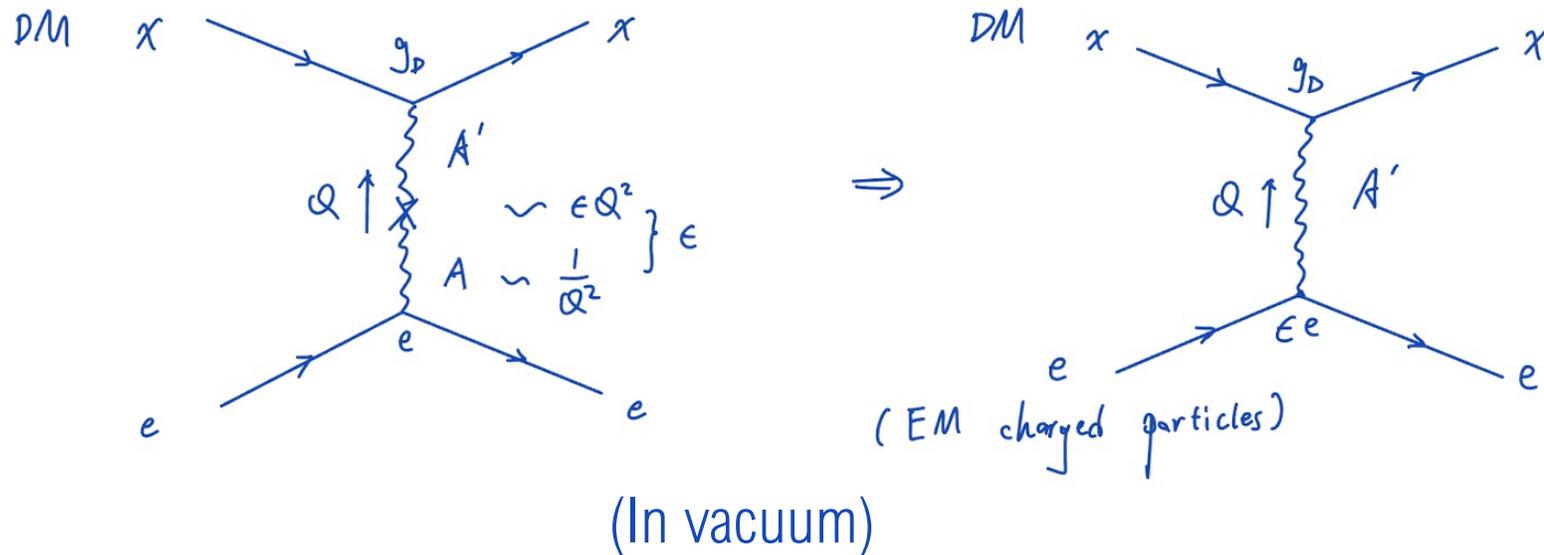
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Dark Photon Model

- Dark Photon A' : vector boson for $U(1)_D$, kinetically mixed with SM hypercharge. At low energies, mixing is between A' and A (ordinary photon).

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{SM photon kinetic term}} + \underbrace{-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}}_{\text{dark photon kinetic term}} + \underbrace{-\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}}_{\text{kinetic mixing}} + \underbrace{\frac{1}{2}m_{A'}^2 A'_\mu A'^\mu}_{\text{dark photon mass term}} + \underbrace{eA_\mu J_{\text{EM}}^\mu}_{\text{SM photon - current}} + \underbrace{g_D A'_\mu J_D^\mu}_{\text{dark photon - dark current}}$$



$$\langle |M_e(q)|^2 \rangle = \frac{16\epsilon^2 e^2 g_D^2 m_e^2 m_\chi^2}{(q^2 + m_{A'}^2)^2}$$

Scattering is q -dependent for light mediator.

In-Medium Effect

- Photon interacts with medium, acquires thermal mass, modifies propagator

$$i\Pi^{\mu\nu}(Q) = \text{Feynman diagram for photon self-interaction}$$

The diagram shows a loop of fermions. An incoming photon with momentum Q and index μ enters from the left. The loop consists of two fermion lines. The top line has momentum K and the bottom line has momentum $K - Q$. An outgoing photon with index ν exits to the right.

Feynman diagram for photon self-interaction

DeRocco, Galanis, Lasenby (2022)

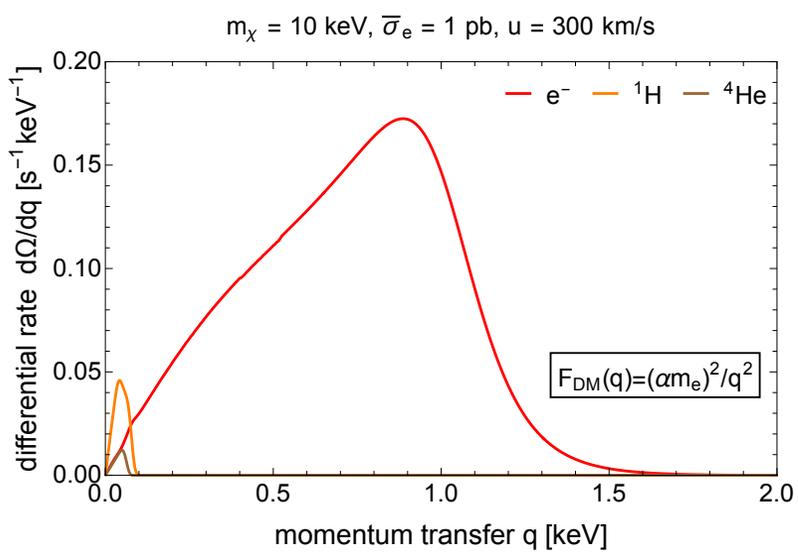
The diagram shows a dark photon χ (DM) interacting with an electron e . The dark photon has momentum Q and couples to the electron via a vertex g_D . The electron emits a photon A_L with momentum Q . The photon propagator is modified by the medium, represented by a dashed line with a wavy line inside, labeled A'_L . The effective coupling is given by the equation:

$$\frac{\epsilon Q^2}{Q^2 - \Pi_L(Q)} \equiv \epsilon_{\text{eff}} \approx \frac{\epsilon q^2}{q^2 + \Pi_L(Q)}$$

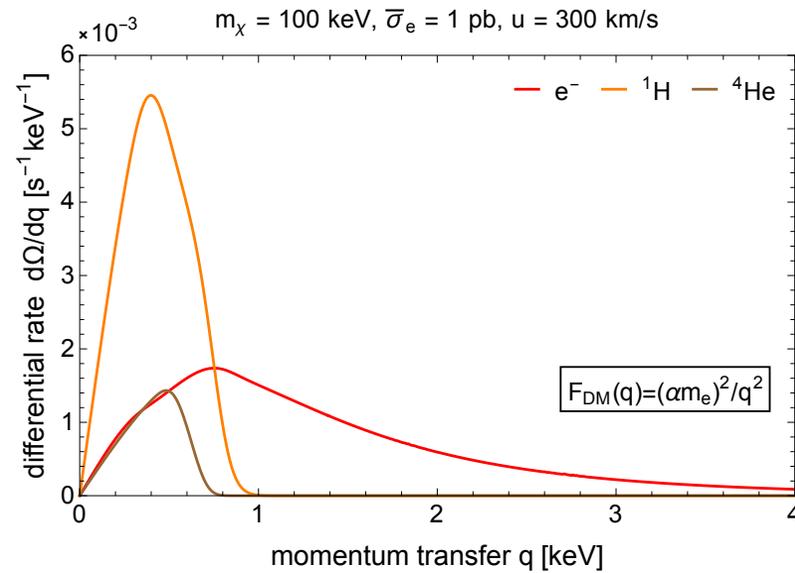
where $Q \equiv (q^0, \vec{q})$.

Dark photon's coupling to EM current: 'effective coupling' ϵ_{eff}

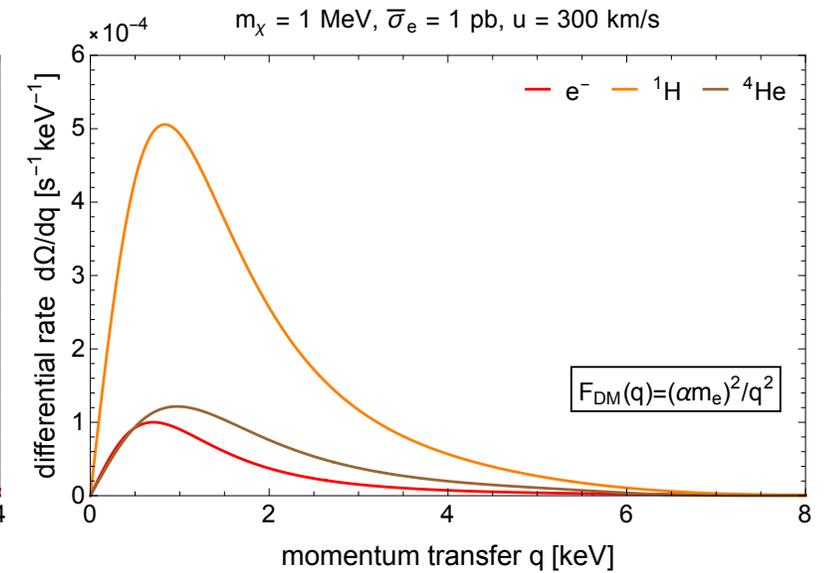
Scattering Cross Section



DM mass: 10 keV



100 keV



1 MeV

DaMaSCUS-SUN

- <https://github.com/temken/DaMaSCUS-SUN>
- <https://arxiv.org/abs/2102.12483> (heavy mediator)

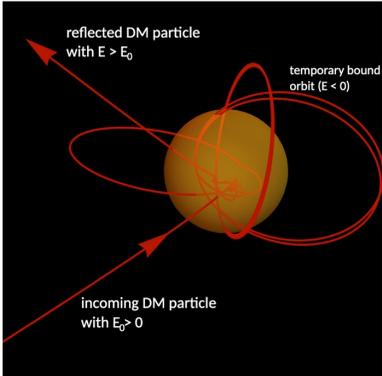
☰ README.md

Build & Tests passing codecov 81% License MIT

DaMaSCUS-SUN

ascl 2102.018 DOI 10.5281/zenodo.5957388 arXiv 2102.12483

Dark Matter Simulation Code for Underground Scatterings - Sun Edition



reflected DM particle with $E > E_0$

temporary bound orbit ($E < 0$)

incoming DM particle with $E_0 > 0$

DaMaSCUS-SUN is a Monte Carlo tool simulating the process of solar reflection of dark matter (DM) particles as described in detail in [this publication](#).



Timon Emken

temken · he/him

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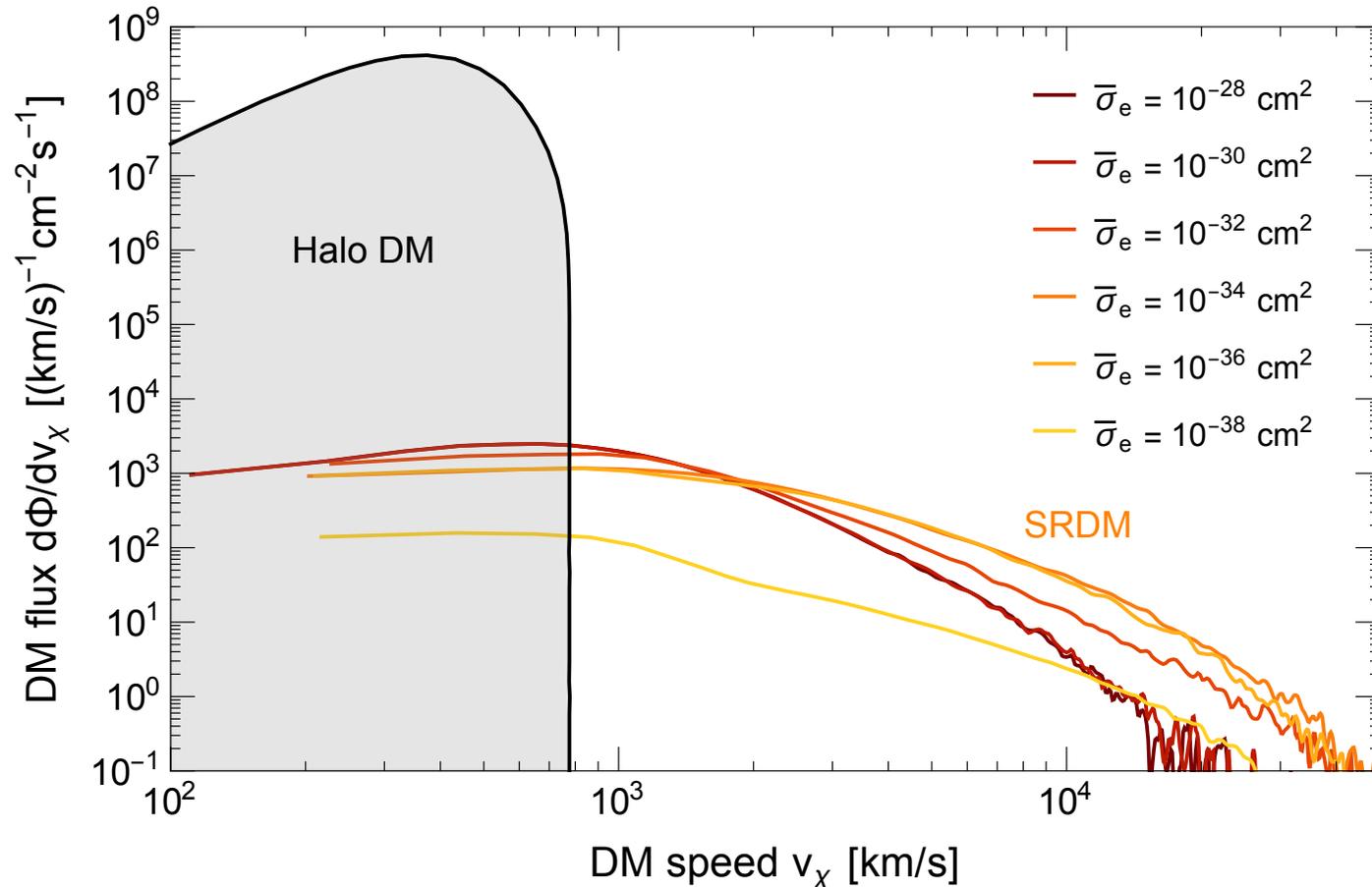
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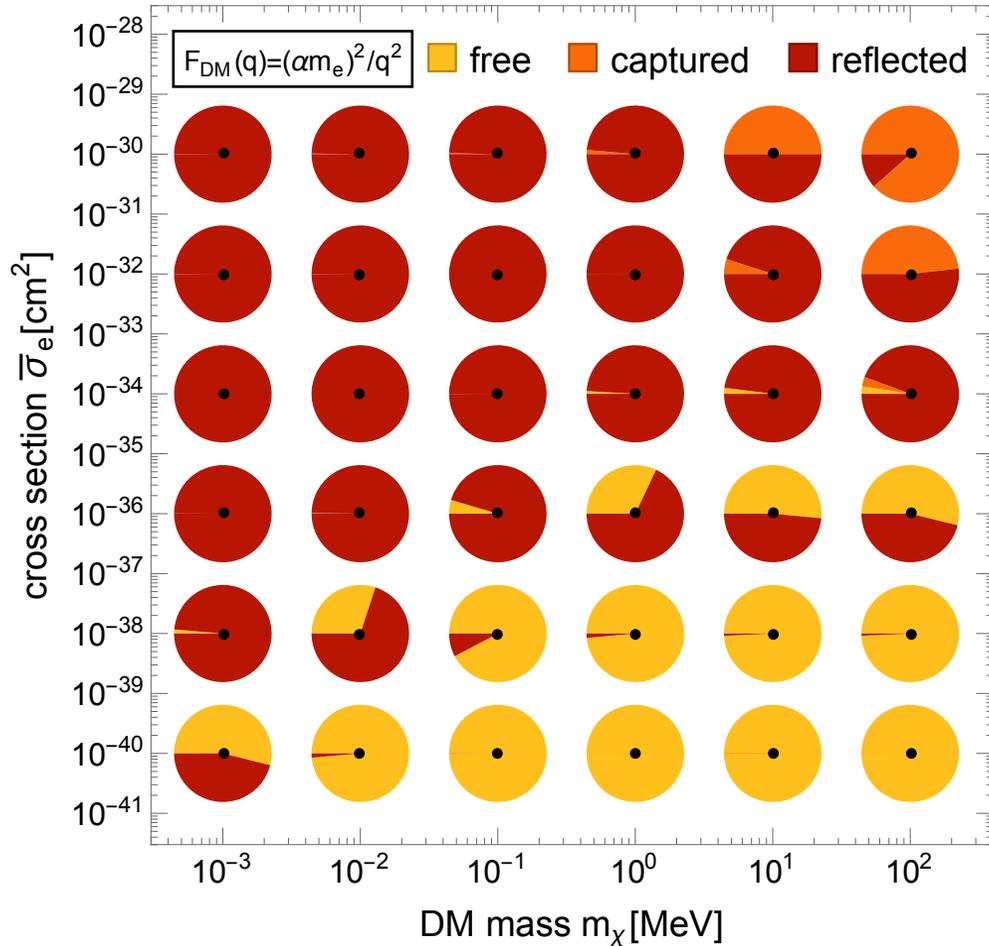
Reflected Flux

$$m_\chi = 100 \text{ keV}, F_{\text{DM}}(q) = (\alpha m_e)^2 / q^2$$



- Larger cross section σ : DM scatters at solar surface – cooler – fewer high-energy particles
- Lower σ : DM can access to hotter bulk – more high-energy particles
- Very low σ : transparent Sun. Flux is attenuated overall

Reflected, Captured, and Free Particles



- **Captured**: still in the Sun after 10^4 scatters or in a bound orbit for too long
- **Reflected**: gets scattered at least once and escapes
- **Free**: no scattering, and escapes

Direct Detection of SRDM

- Atomic ionization: XENON1T, ...
- Crystal excitation: SENSEI, DAMIC-M, Oscura(projected, 30kg Si), ...

❖ Silicon crystal form factor from QCDark

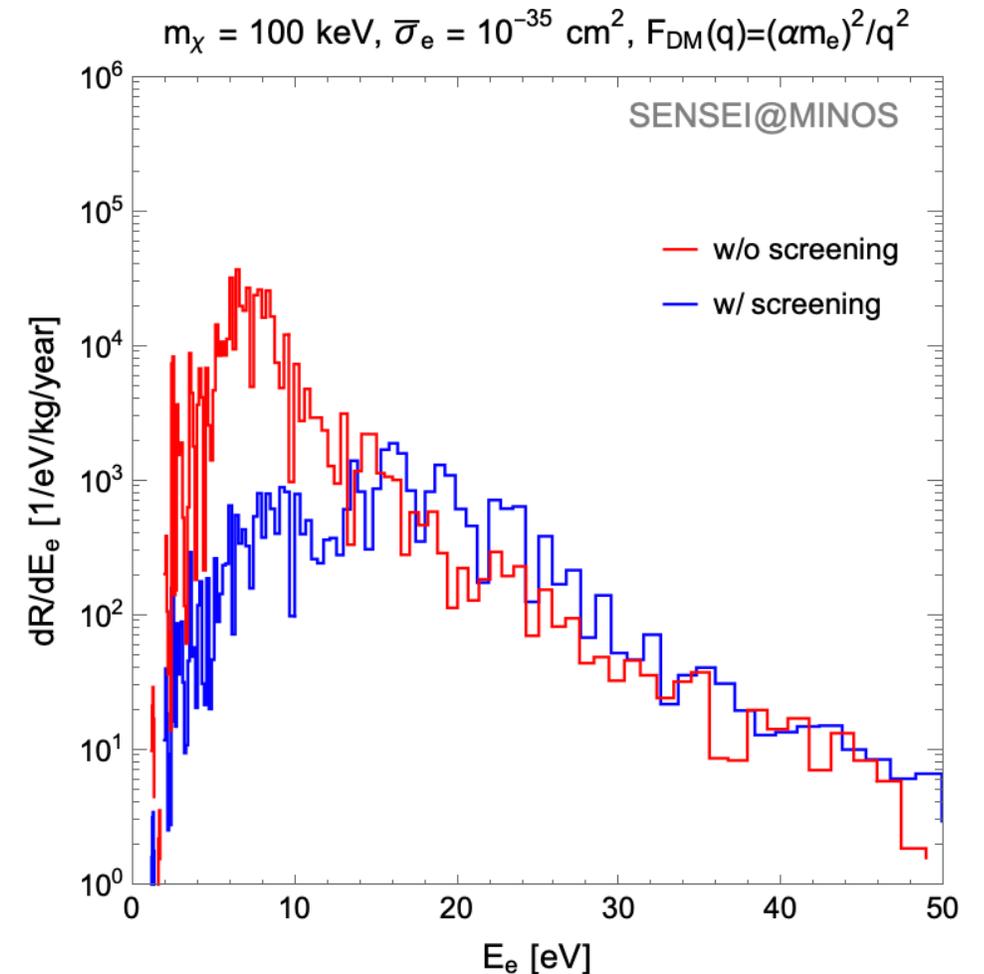
Singal, Essig, Dreyer, Fernandez-Serra (2023)

❖ Account for in-medium effects of the target

Knapen, Kozaczuk, Lin (2021)

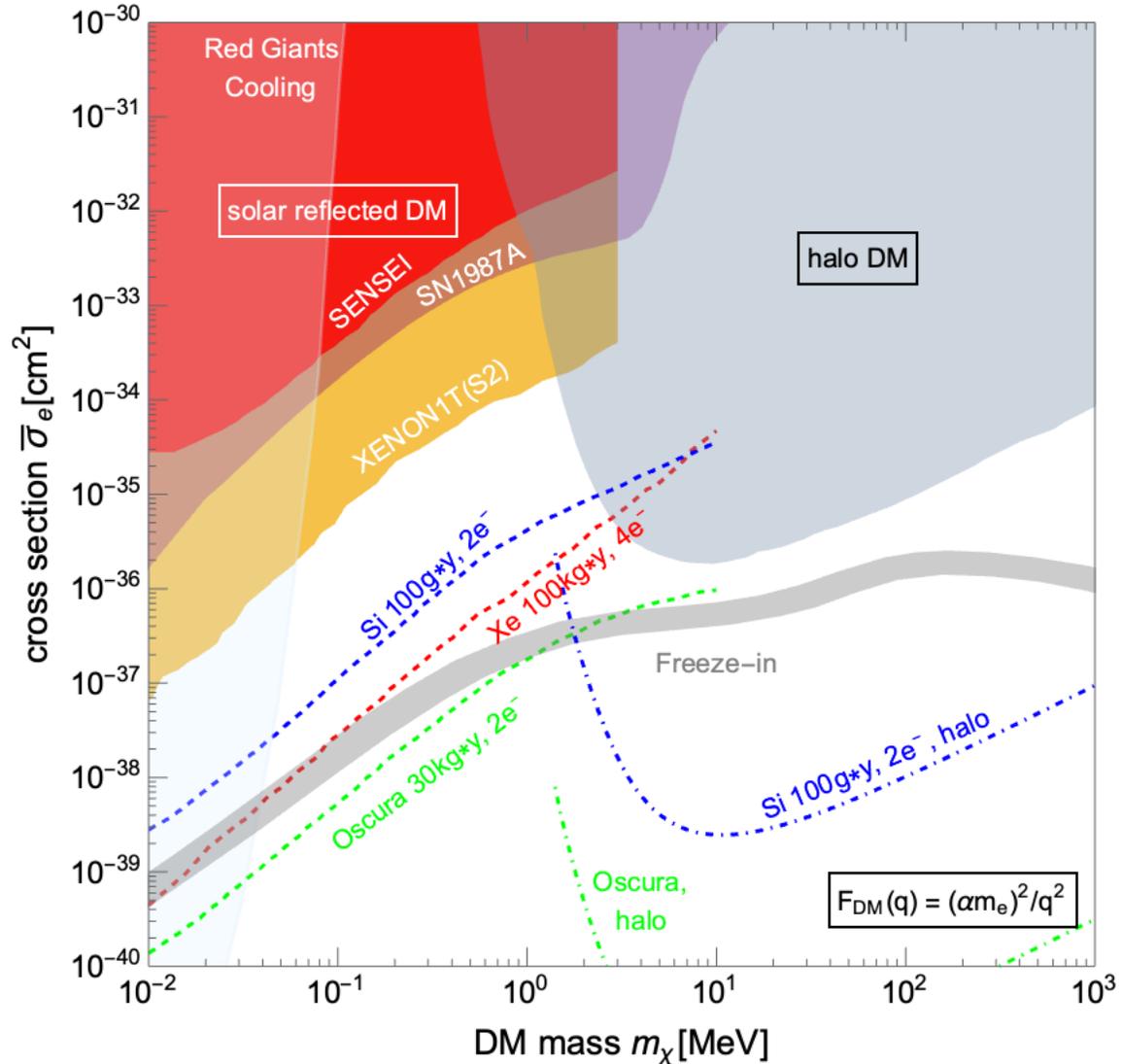
❖ Ionization modeling from Ramanathan & Kurinsky (2020)

Ramanathan, Kurinsky (2020)



Differential energy spectrum of SENSEI@MINOS for SRDM

Constraints and Projections



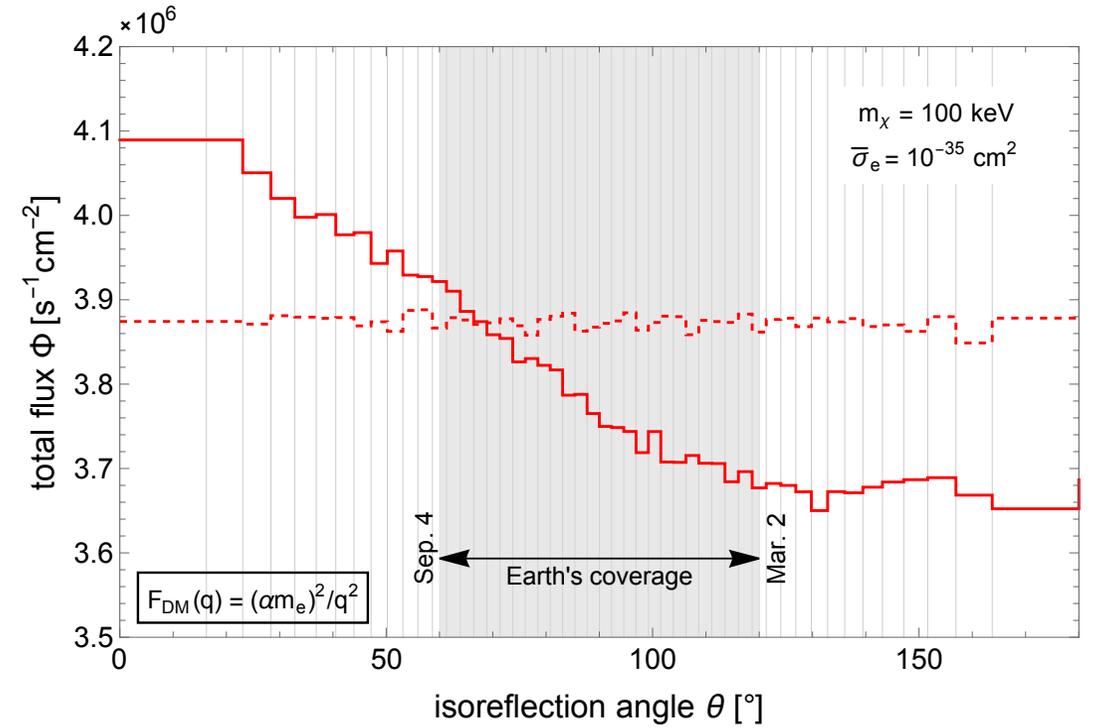
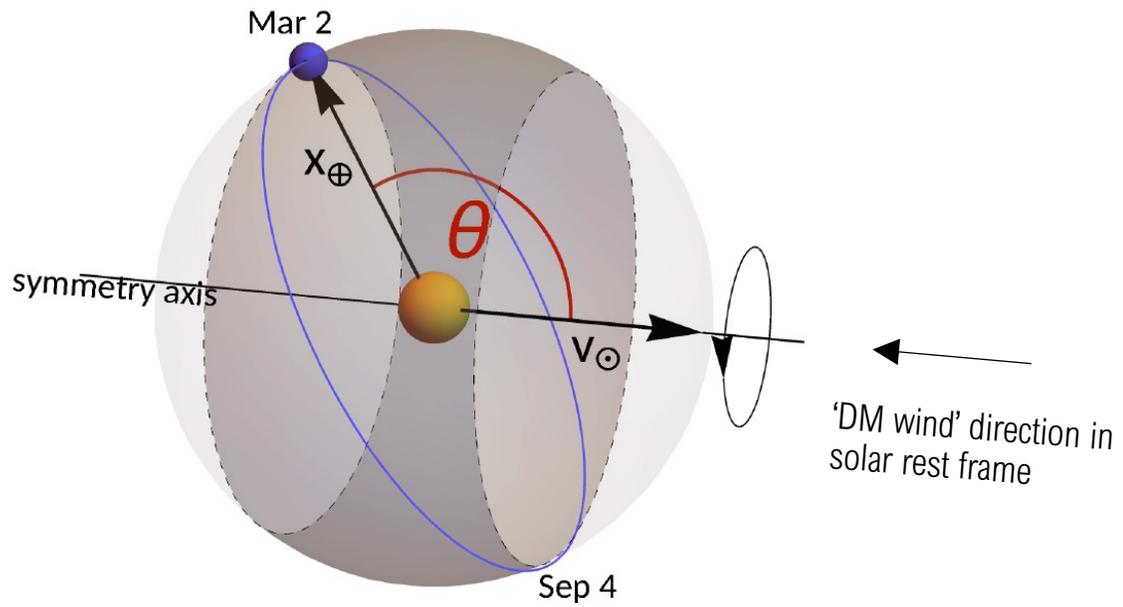
DM with ultralight dark photon

- Shaded areas are excluded.
- Projections are dashed lines.
 - no background, 3 events, 95%CL, Q_{th} labelled on plot

Conclusion

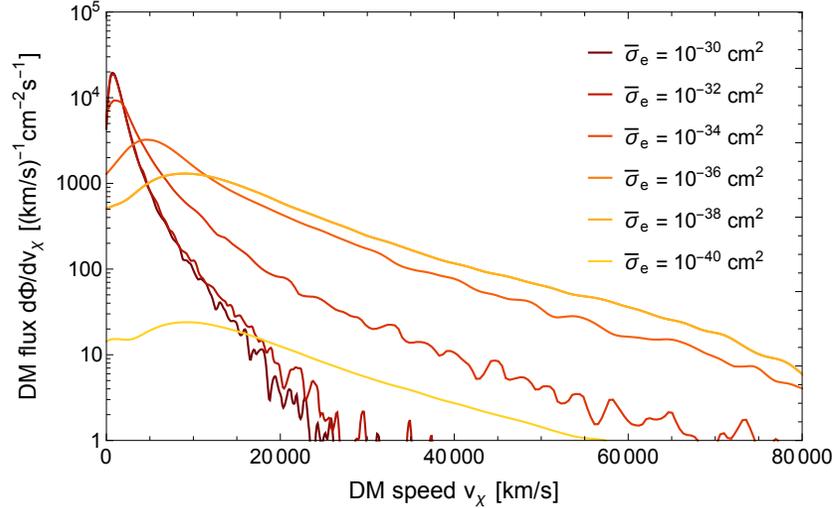
- Solar-reflected DM extends reach of current direct-detection experiments to sub-MeV DM
- Use updated and precise calculations and simulations for DM scattering in the solar medium, and for the SRDM scattering in the target
- Exclude large regions of parameter space for sub-MeV DM with ultralight dark photon mediator
- Future silicon and xenon experiments can probe entire freeze-in target, even below 1 MeV

Anisotropy

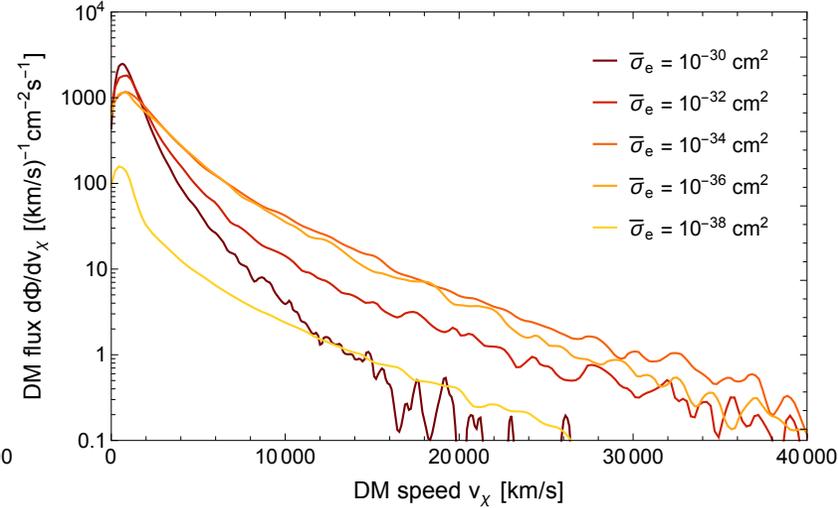


Supplementary materials: fluxes and spectra

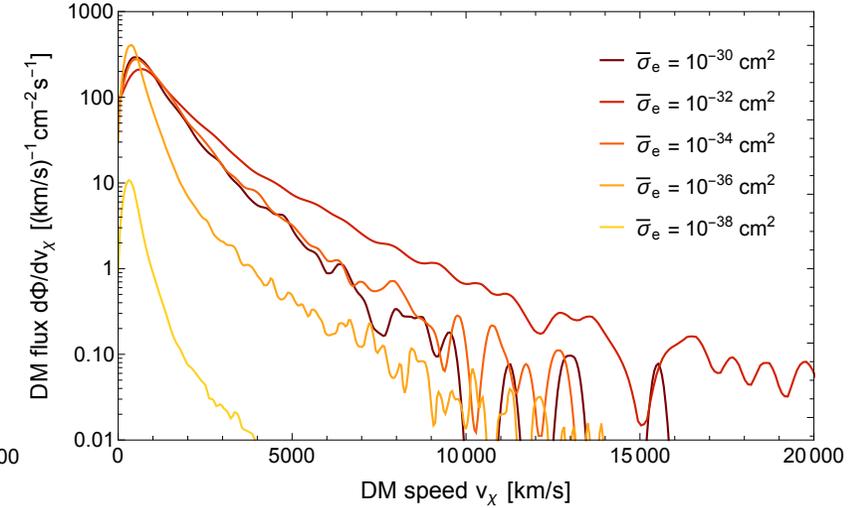
$m_\chi = 10 \text{ keV}, F_{\text{DM}}(q) = (\alpha m_e)^2 / q^2$



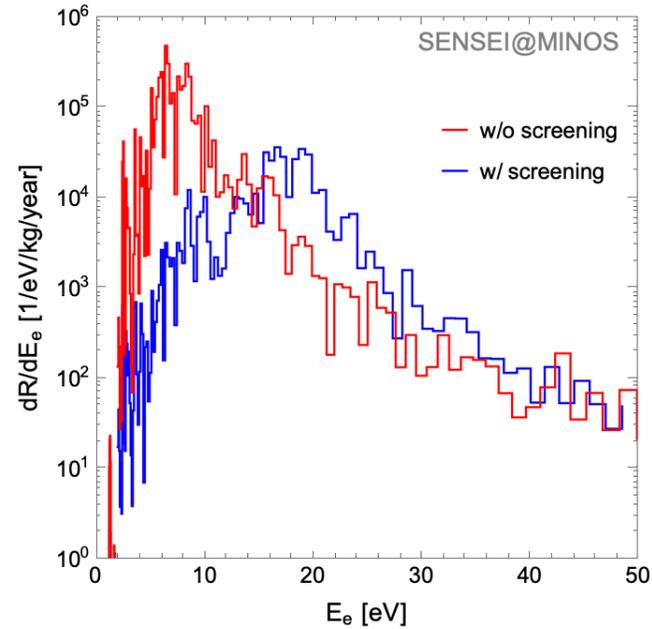
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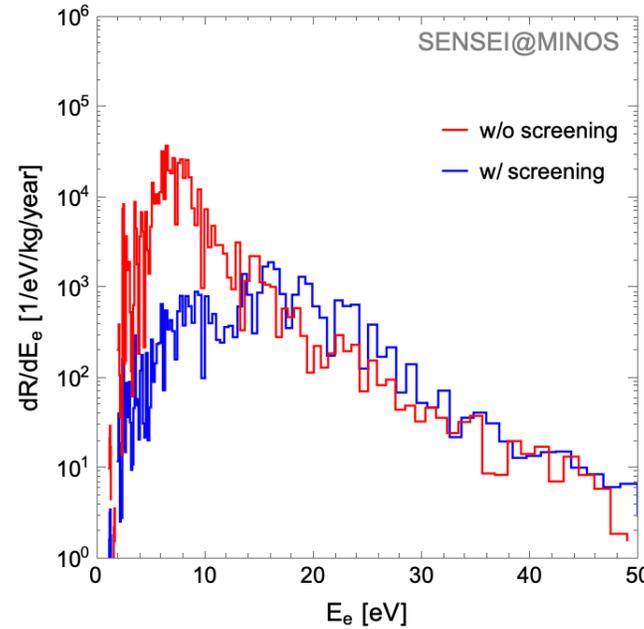
$m_\chi = 1 \text{ MeV}, F_{\text{DM}}(q) = (\alpha m_e)^2 / q^2$



$m_\chi = 10 \text{ keV}, \bar{\sigma}_e = 10^{-35} \text{ cm}^2, F_{\text{DM}}(q) = (\alpha m_e)^2 / q^2$



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