State of the Universe Seminar
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Based on
[arXiv:2102.12483]

Solar reflection of light dark matter

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Solar reflection of sub-GeV DM

I. Direct detection of (sub-GeV) dark matter

II. Dark matter in the Sun

III. Monte Carlo simulation of solar reflection

IV. Results

V. Summary & Outlook

I.

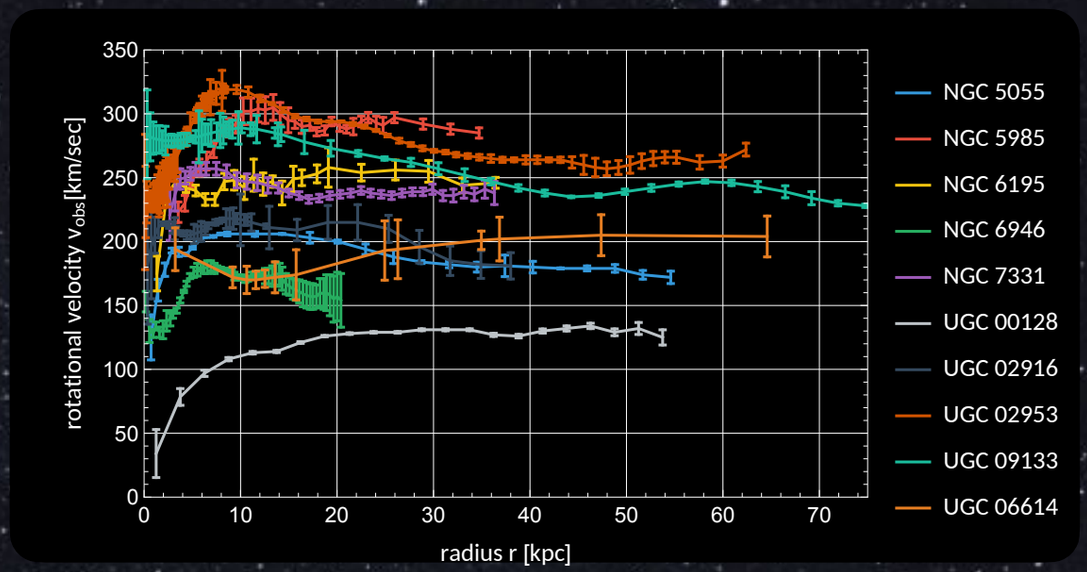
Direct Detection of (sub-GeV) Dark Matter

How do we know about dark matter?

(a) Fritz Zwicky and the Coma cluster

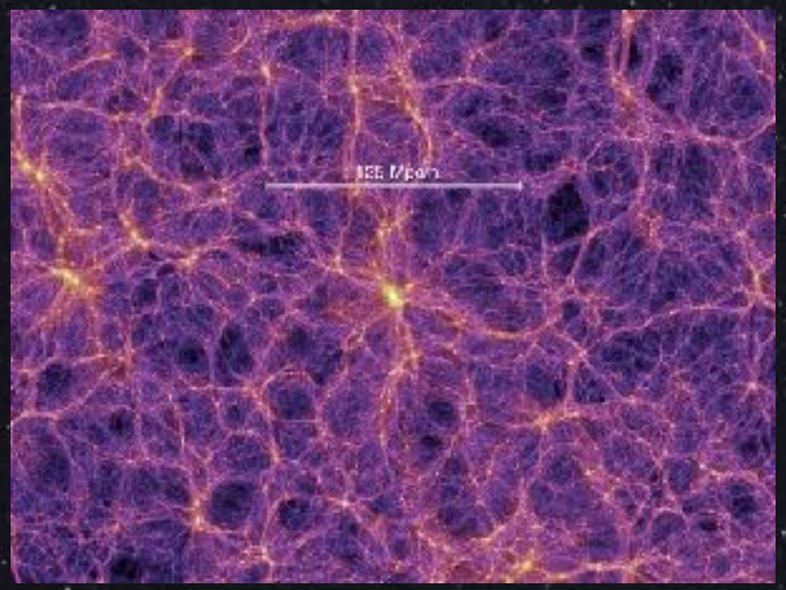
Photo: F. Clark (1971)
F. Zwicky, Helv. Phys. Acta 6 (1933), 249

(b) Galactic rotation curves



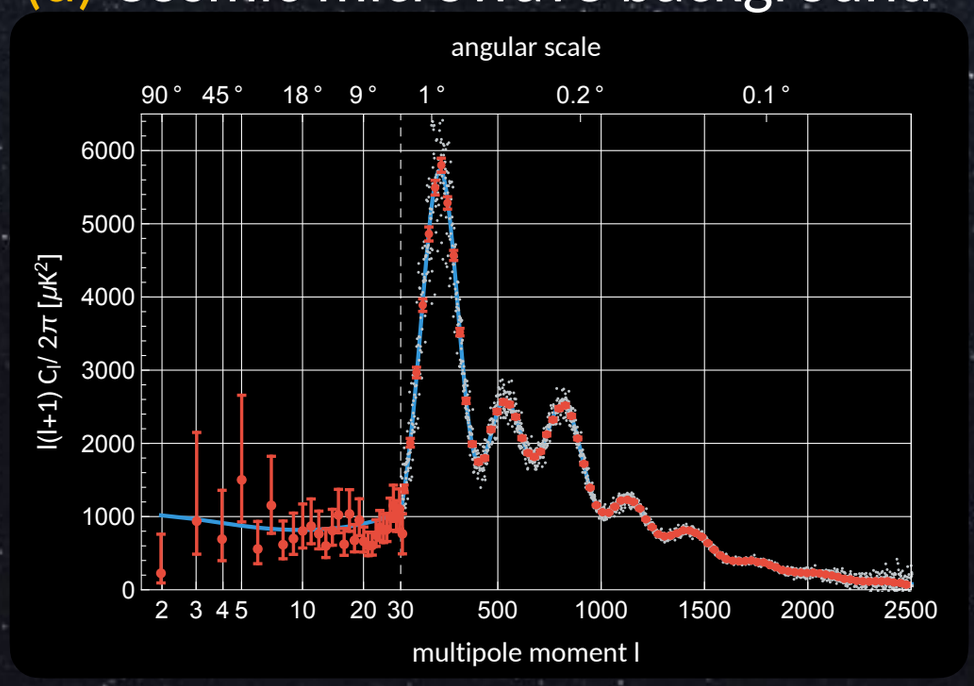
F. Lelli et al., Astron. J. 152 (2016), 157

(c) Cosmological structure formation



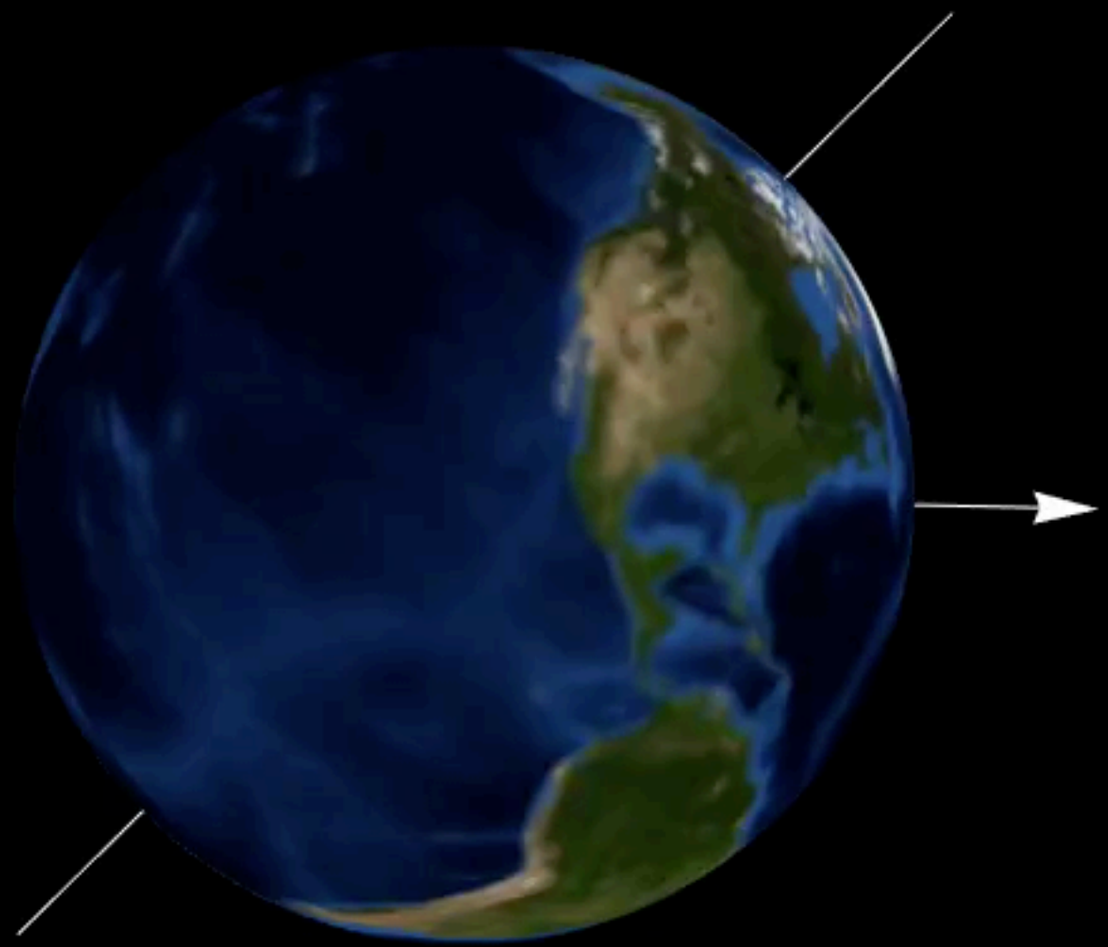
Springel et al., Nature 435 (2005), 629-636

(d) Cosmic microwave background



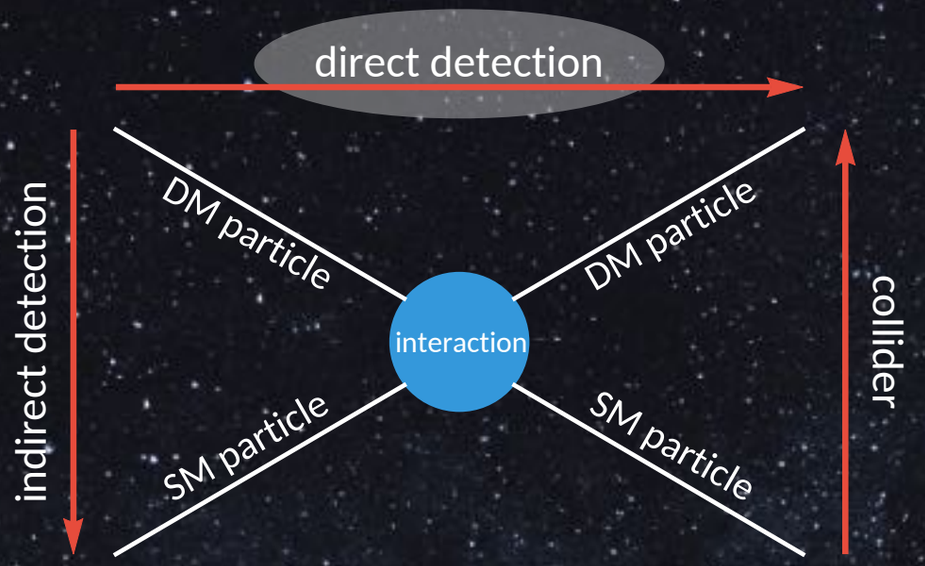
Planck Collaboration, Planck Legacy Archive, (2018)

The dark matter “wind”

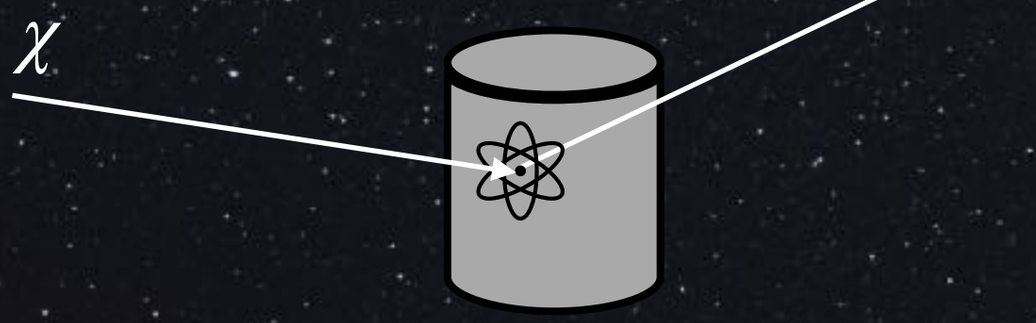


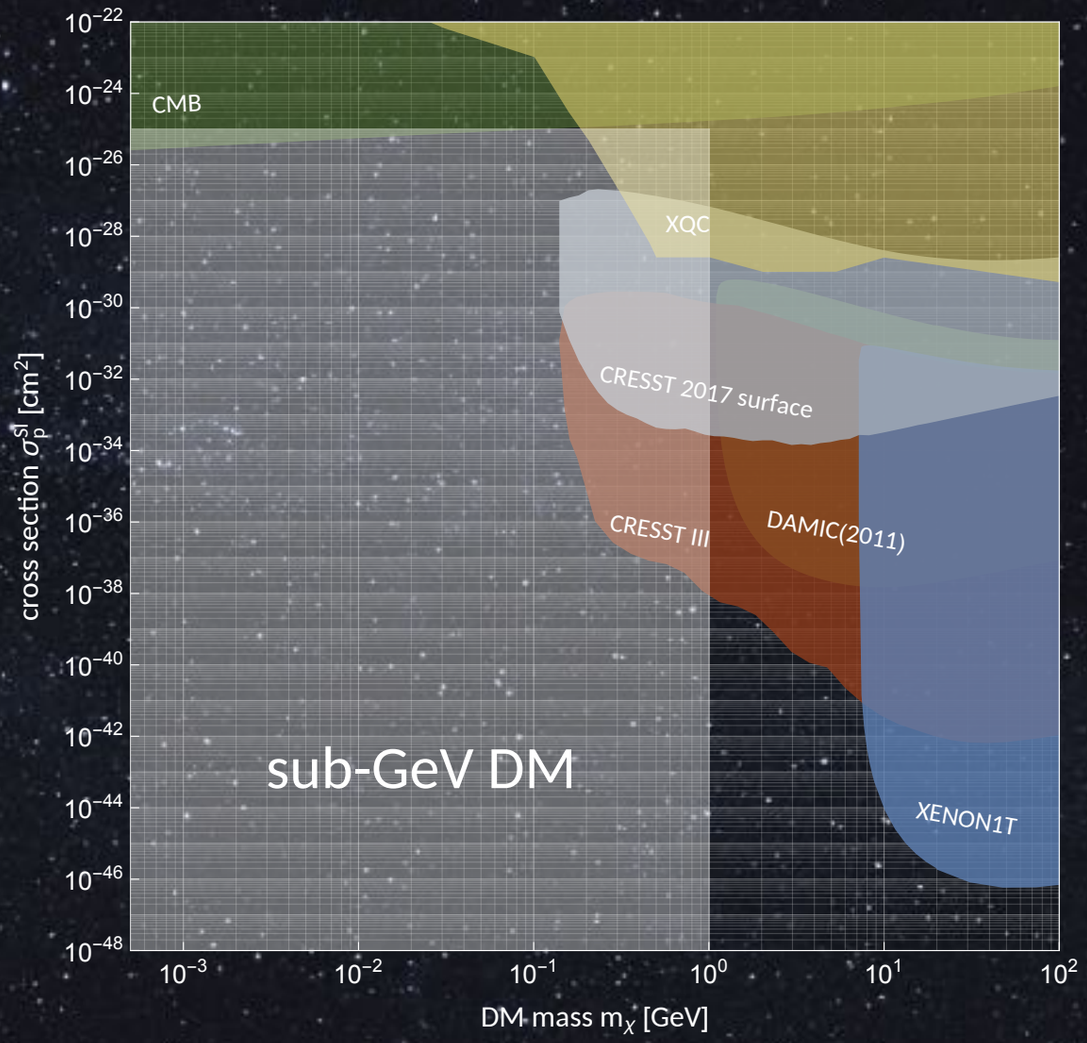
Emken 2016

Direct detection of dark matter



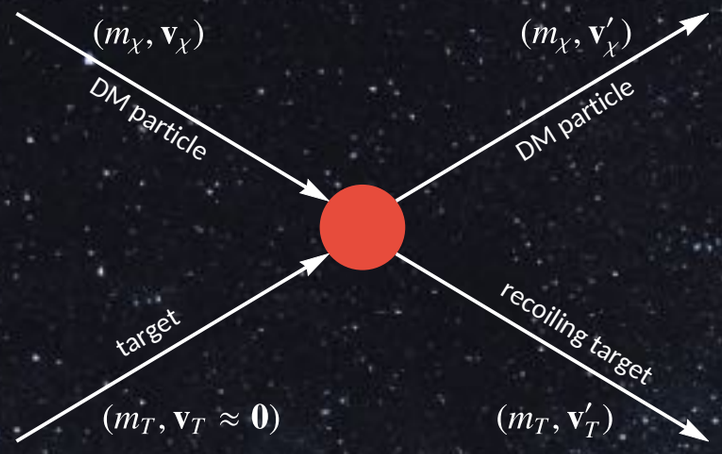
Basic idea: Measure the energy deposit of a DM-matter collision inside a detector.





- Conventional direct DM searches lose sensitivity to DM masses below ~ 1 GeV.
- Why? And what can be done to probe lighter masses?

Detecting DM via nuclear recoils



Nuclear recoils as observable for GeV-scale DM searches.

M.W. Goodman and E. Witten, Phys.Rev. D31 (1985) 3059
I. Wasserman, Phys. Rev. D33 (1986) 2071
A.K. Drukier et al., Phys. Rev. D33 (1986) 3495

Event spectrum:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \frac{\rho_\chi}{m_\chi} \iiint \mathrm{d}^3\mathbf{v}\, v f_\chi(\mathbf{v}) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R} \Theta(v - v_{\min}(E_R)) \,.$$

Detector size
Astrophysics
Particle physics
Kinematics

DM velocity distribution:

$$f_{\mathrm{halo}}(\mathbf{v}) = \frac{1}{N_{\mathrm{esc}} \pi^{3/2} v_0^3} \exp\left(-\frac{\mathbf{v}^2}{v_0^2}\right) \Theta(v_{\mathrm{gal}} - |\mathbf{v}|)$$

sharp speed cutoff

The low mass frontier of DM searches

- Typical nuclear recoil:

$$E_R^{\mathrm{typ}} \sim \frac{2m_\chi^2 v_\chi^2}{mT} \approx 2\ \mathrm{keV} \times \left(\frac{m_\chi}{10\mathrm{GeV}}\right)^2 \left(\frac{v_\chi}{10^{-3}}\right)^2 \left(\frac{m_T}{m_{\mathrm{Xe}}}\right)^{-1}$$

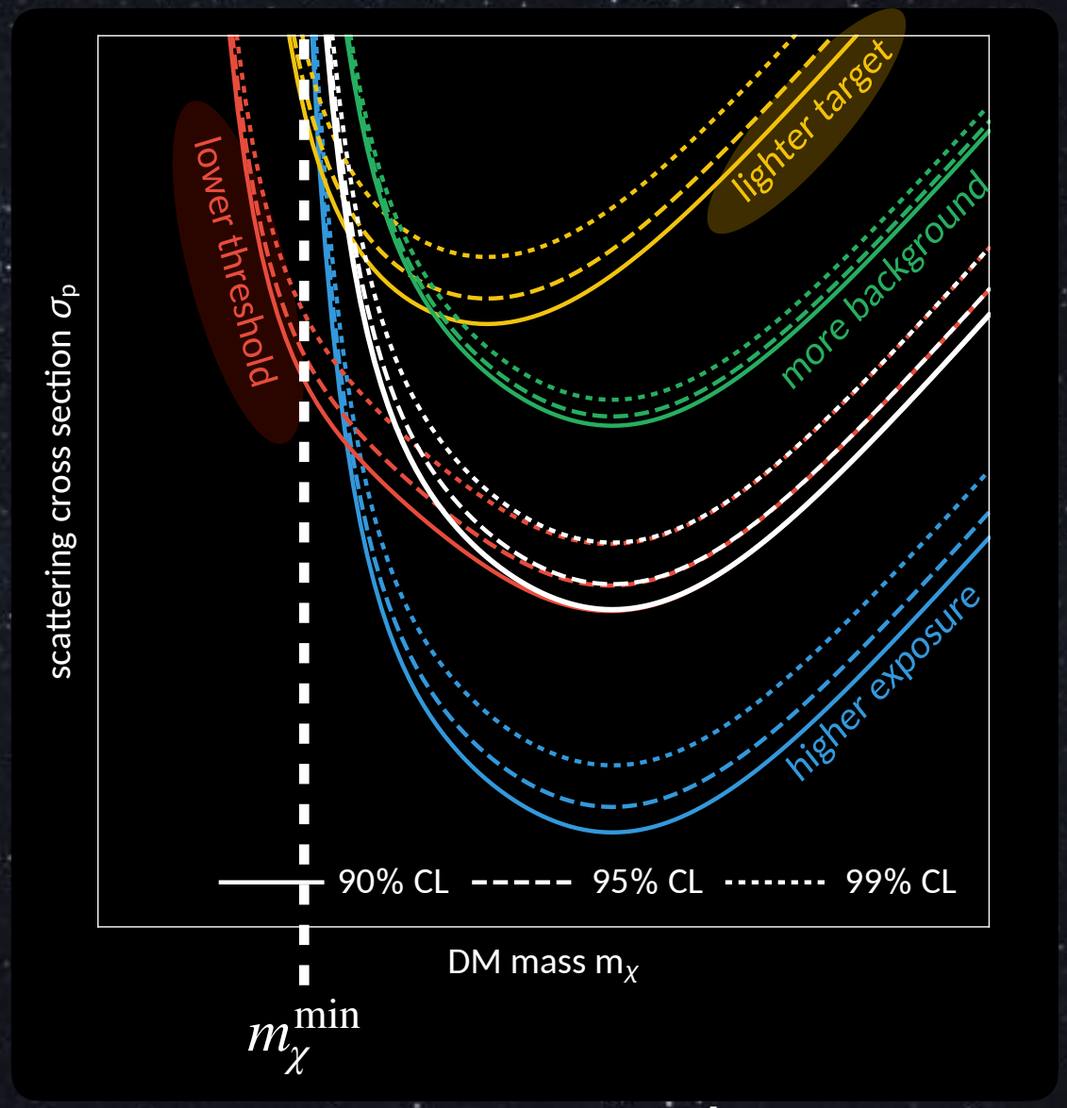
- Kinematic lower bound on the testable mass for a given recoil threshold.

$$m_\chi^{\mathrm{min}} = \frac{m_T}{\sqrt{\frac{2m_T}{E_{\mathrm{thr}}}} v_{\mathrm{max}} - 1}$$

- Example: Threshold of XENON1T

$$E_{\mathrm{thr}} \approx 5\ \mathrm{keV} \Rightarrow m_\chi^{\mathrm{min}} \approx 7\ \mathrm{GeV}$$

Aprile et al., PRL 119 (2017)181301



Larger exposures do not probe lower masses.

Direct Detection of Dark Matter via electron recoils

J. Kopp et al., Phys. Rev. D80 (2009) 083502
R. Essig et al., Phys. Rev. D85 (2012) 076007

Instead of nuclear recoils, search for DM-electron interactions.

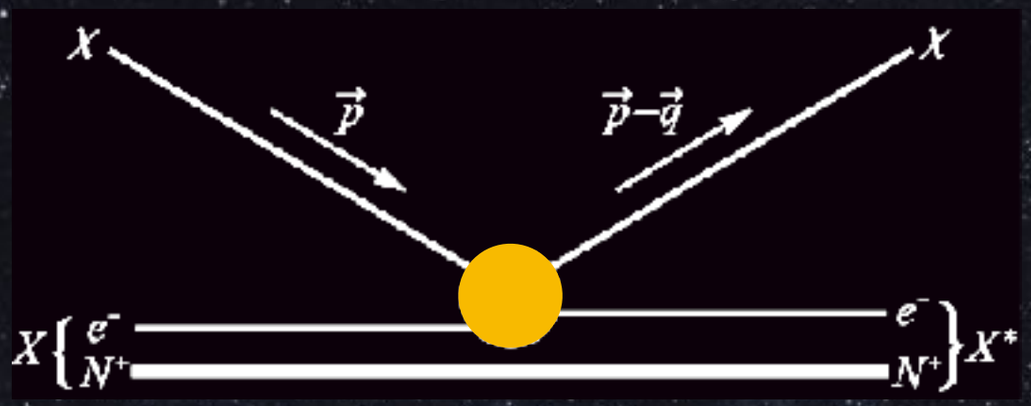


Figure from Essig et al., [arXiv:1509.01598]

- Different kinematics:

$$E_e^{\max} = \frac{1}{2}\mu_{\chi N} v^2 \lesssim E_\chi \sim \text{eV}\left(\frac{m_\chi}{\text{MeV}}\right)$$

Compare to $E_{\text{NR}}^{\max} = \gamma E_\chi$

$$\gamma \approx 4\frac{m_\chi}{m_N} \ll 1 \quad \text{for } m_\chi \ll m_N$$

- No kinematic penalty: $E_e \leq E_\chi$.
- Lowest DM mass to excite/ionize an electron in…
  - …an isolated atom:

$$E_B \approx 10\,\text{eV}$$
$$\Rightarrow\ m_\chi^{\min} \approx 5\,\text{MeV}$$

  - …a semiconductor:

$$E_{\text{gap}} \approx 1\,\text{eV}$$
$$\Rightarrow\ m_\chi^{\min} \approx 500\,\text{keV}$$

Lee et al., PRD 92 (2015) 083517
Essig et al., JHEP 1605 (2016) 046

DM induced electron transitions & ionizations

- Complication: Target electrons are bound states, energy eigenstates, but not momentum eigenstates.

$$\frac{\mathrm{d}R_{\mathrm{ion}}}{\mathrm{d}E_e} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\sum_{nl}\frac{\langle \mathrm{d}\sigma^{nl}_{\mathrm{ion}} v\rangle}{\mathrm{d}E_e}$$

Ionization form factor

$$\frac{\mathrm{d}\langle\sigma^{nl}_{\mathrm{ion}} v\rangle}{\mathrm{d}E_e} = \frac{\sigma_e}{8\mu^2_{\chi e}E_e}\int \mathrm{d}q\, q\, \left|F_{\mathrm{DM}}(q)\right|^2 \left|f^{nl}_{\mathrm{ion}}(k',q)\right|^2 \eta\left(v_{\mathrm{min}}(\Delta E_e, q)\right)$$

- Depending on the target, this requires condensed matter theory.
- The ionization form factor only applies to a certain class of DM models.

Catena, R., TE, Spaldin N., Tarantino, W., PRR 2 (2020) 033195
Catena, R., TE, Matas, M, Spaldin, N., Urdshals, E., PRR 3 (2021) 033149

Recent results on DM electron scattering experiments

- Semiconductor target experiments

1. SENSEI
   Barak et al, PRL 125 (2020) 17, 171802
   Abramoff et al., PRL 122 (2019) 161801
   Crisler et al., PRL 121 (2018) 061803
2. SuperCDMS
   Agnese et al., PRL 121 (2018) 051301
3. DAMIC at SNOLAB
   Aguilar-Arevalo et al., [arXiv:1907.12628]

- Liquid noble gas targets

1. XENON10, XENON100, XENON1T
   Essig et al., PRL 109 (2012), 021301
   Essig et al., PRD 96 (2017), 043017
   Aprile et al.,PRL 123 (2019), 251801
2. DarkSide-50 (liquid argon)
   Agnes et al., PRL 121 (2018) 111303

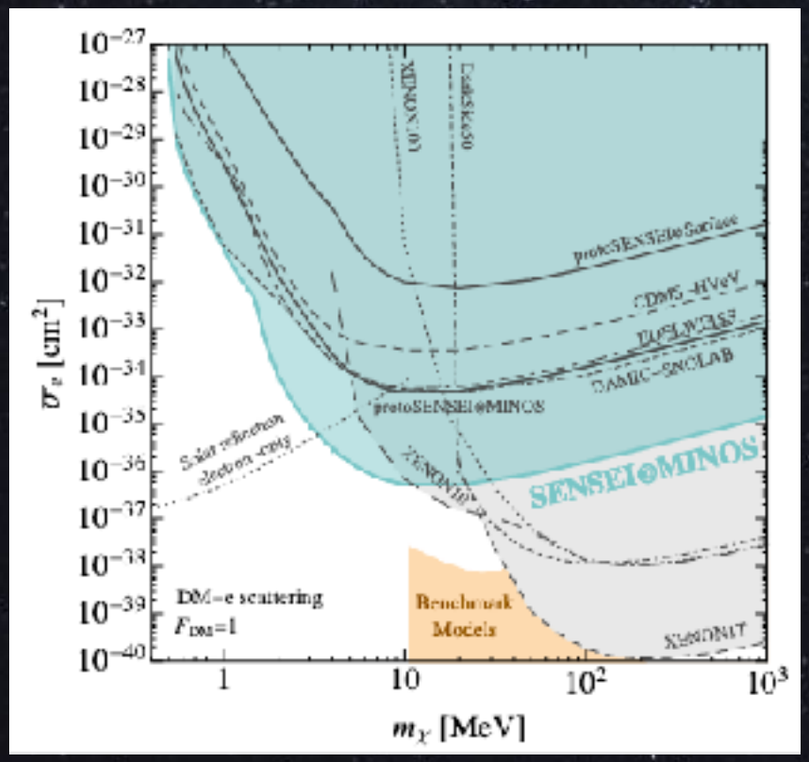


Figure from [2004.11378].

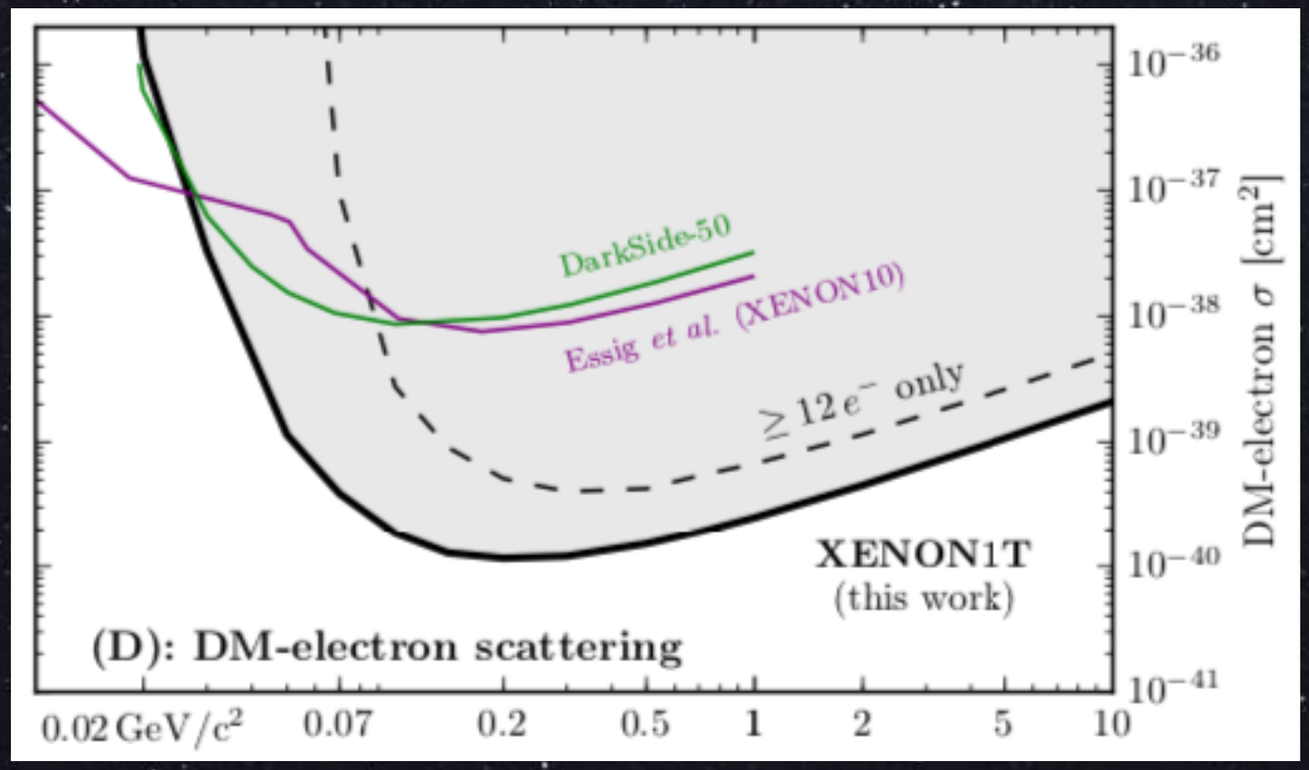


Figure from [1907.11485].

An incomplete list of search strategies for sub-GeV DM

- Bremsstrahlung emission from the recoiling nucleus.

Kouvaris & Pradler, PRL 118 (2017) 031803
McCabe, PRD 96 (2017) 043010

- Migdal effect

Ibe et al., JHEP 1803 (2018) 194
Dolan et al., PRL 121 (2018) 101801

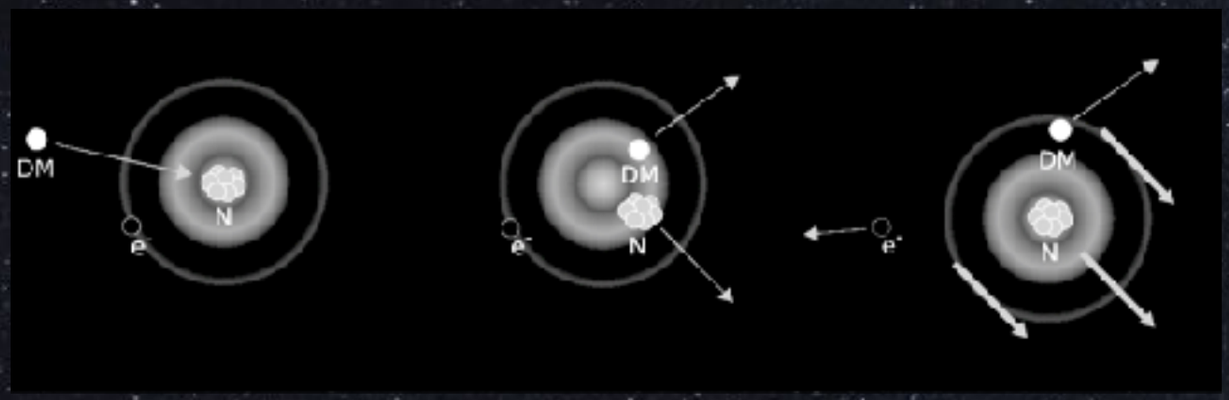


Figure from [1711.09906].

- Dirac materials (e.g. graphene) for directional detection.

Hochberg et al., Phys. Lett. B772 (2017) 239
Coskuner et al., PRD, [arXiv:1909.09170]
Geilhufe et al., PRD, [arXiv:1910.02091]

- Excitations of molecules in gases.

Essig et al., PRR, [arXiv:1907.07682]

- Up-scattering of DM by cosmic rays.

Bringmann & Pospelov, PRL 122 (2019) 171801
Ema et al., PRL 122 (2019) 181802
Alvey et al., PRL, [arXiv:1905.05776]
Cappiello & Beacom, PRD, [arXiv:1906.11283]

II.

Dark matter in the Sun

Solar Reflection of DM (SRDM)

H. An, M. Pospelov, J. Pradler, A. Ritz, PRL 120 (2018), 141801
TE, C. Kouvaris, N. G. Nielsen, PRD, 97 (2018), 063007

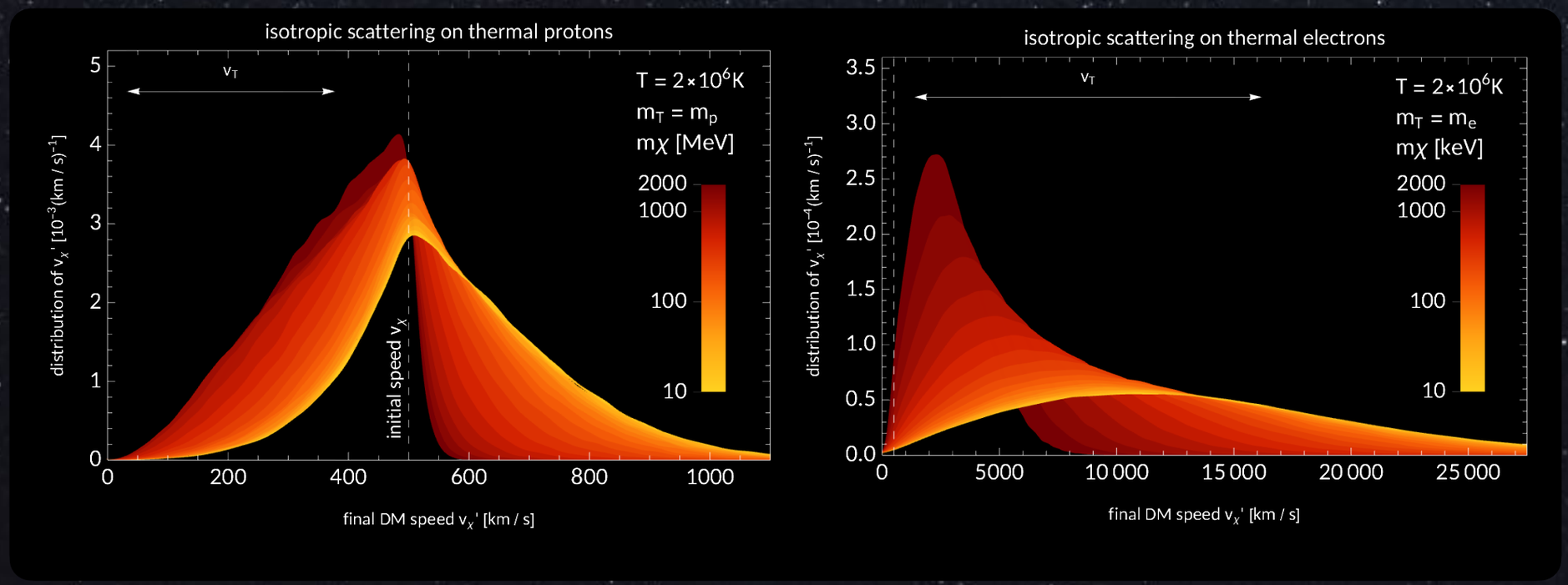
- Pro memoriam:

$$m_\chi \gtrsim \frac{m_T}{\sqrt{\frac{2m_T}{E_{\rm thr}} v_{\rm max}} - 1} \qquad m_\chi \gtrsim \frac{2E_{\rm gap}}{v_{\rm max}^2}$$

- What if some process could increase the maximum DM speed somehow?

$$v_{\rm max} > v_{\rm esc}^{\rm (gal)} + v_\oplus$$

- Elastic scatterings on thermal targets inside the Sun could do just that.



$t = 0.\,\mathrm{hr}$

$N_s = 0$

$v_\chi = 368\,\frac{\mathrm{km}}{\mathrm{s}}$

$E_\chi / E_0 = 1.$

$m_\chi = 100\,\mathrm{MeV}$

$\sigma_p = 0.2\,\mathrm{pb}$

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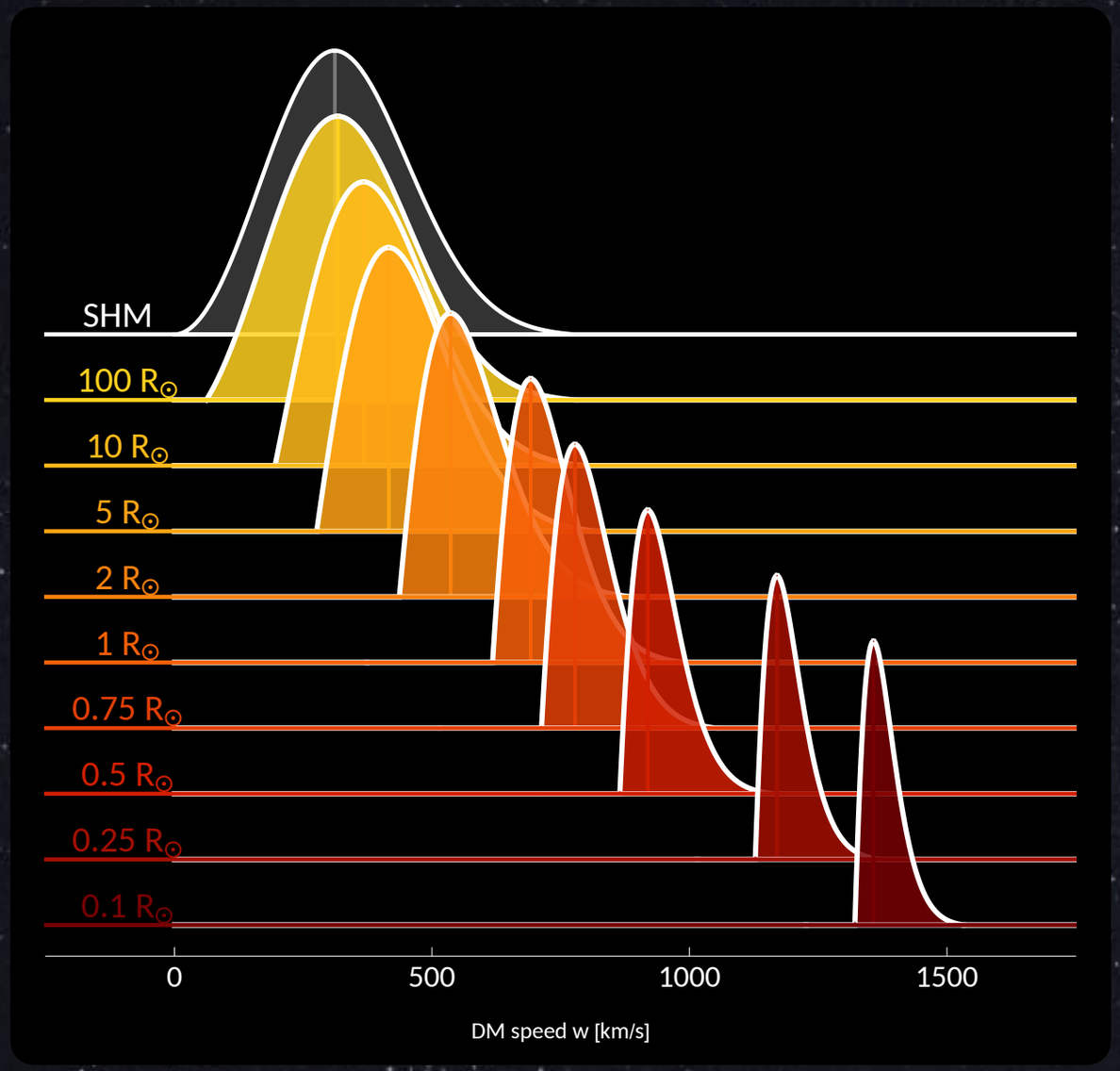
DM particles passing through the Sun

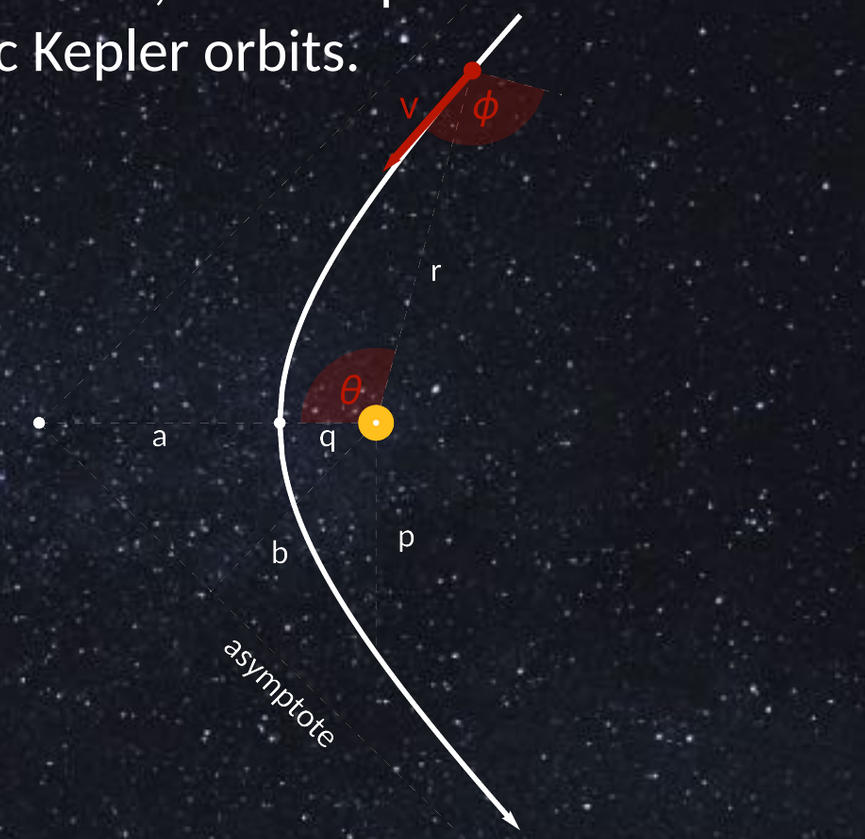
- Gravitational acceleration



$$w(u,r) = \sqrt{u^2 + v_{\rm esc}(r)^2}$$

$$v_{\rm esc}(r) = \sqrt{\frac{2G_N M_\odot}{r}}$$

- Outside the Sun, the DM particles follow hyperbolic Kepler orbits.



- The rate of DM particles entering the Sun is given by

$$\Gamma(m_\chi) = n_\chi \pi R_\odot^2 \int {\rm d}u\, f_{\rm halo}(u) \left(u + \frac{v_{\rm esc}(R_\odot)^2}{u} \right)$$

$$\approx 1.1 \cdot 10^{33} \left(\frac{m_\chi}{\rm MeV} \right)^{-1} {\rm s}^{-1}$$

DM interaction models with heavy mediators

- We focused on the 4 standard scenarios in this study.

1. Spin-Independent nuclear interactions (SI)

$$\frac{\mathrm{d}\sigma_N^{\mathrm{SI}}}{\mathrm{d}E_R} = \frac{m_N\,\sigma_p^{\mathrm{SI}}}{2\mu_{\chi p}^2 v_\chi^2}\left[Z + \frac{f_n}{f_p}(A-Z)\right]^2 \left|F_N(q)\right|^2$$

2. Spin-Dependent nuclear interactions (SD)

$$\frac{\mathrm{d}\sigma_N^{\mathrm{SD}}}{\mathrm{d}E_R} = \frac{2m_N\sigma_p^{\mathrm{SD}}}{3\mu_{\chi p}^2 v_\chi^2}\frac{J+1}{J}\left[\langle S_p\rangle + \frac{f_n}{f_p}\langle S_n\rangle\right]^2 \left|F_N^{\mathrm{SD}}(q)\right|^2$$

3. Electron interactions only.

$$\frac{\mathrm{d}\sigma_e}{\mathrm{d}q^2} = \frac{\bar{\sigma}_e}{4\mu_{\chi e}^2 v_\chi^2} F_{\mathrm{DM}}(q)^2$$

4. Dark photon model

A small dark sector with an addition U(1) gauge group (broken) and kinetic mixing term.

$$\mathscr{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m_{A'}^2 A'_\mu A'^\mu + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

$$\frac{\bar{\sigma}_p}{\bar{\sigma}_e} = \left(\frac{\mu_{\chi p}}{\mu_{\chi e}}\right)^2$$

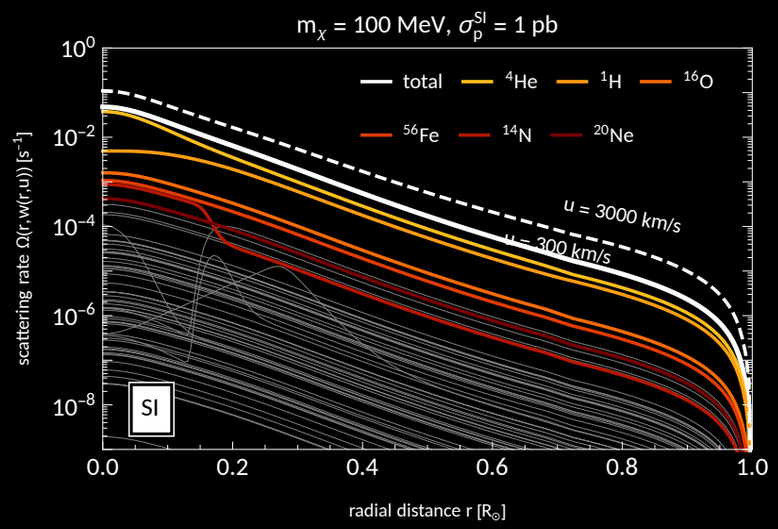
➡ Hierarchy of cross sections

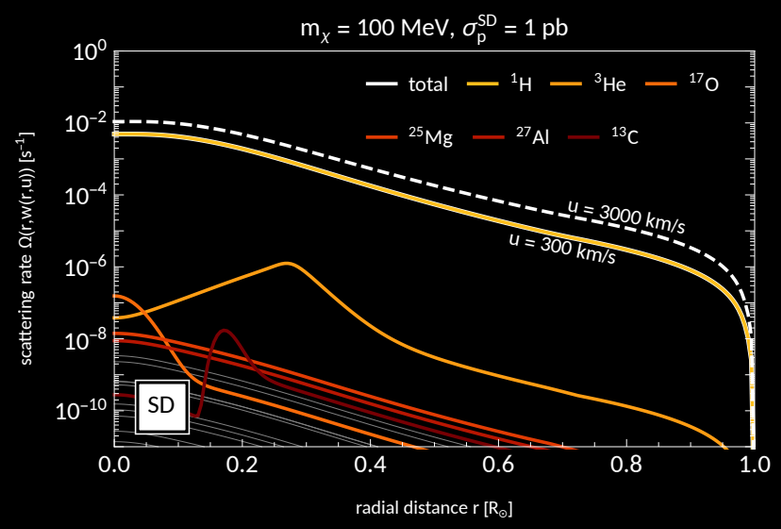
Underground DM scattering rates

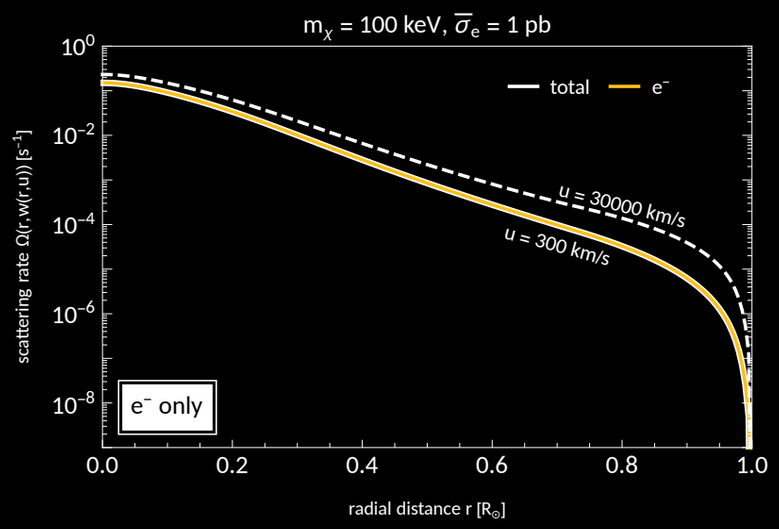
$$\Omega(r, \mathbf{v}_\chi) = \sum_i n_i(r) \langle \sigma_i | \mathbf{v}_\chi - \mathbf{v}_{T,i} | \rangle$$

Number density
Total cross section
Relative speed

$\langle \cdot \rangle$: Thermal average

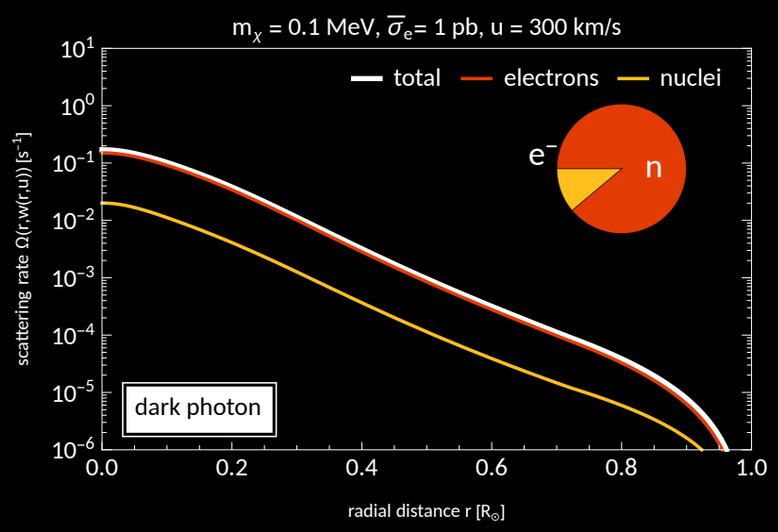


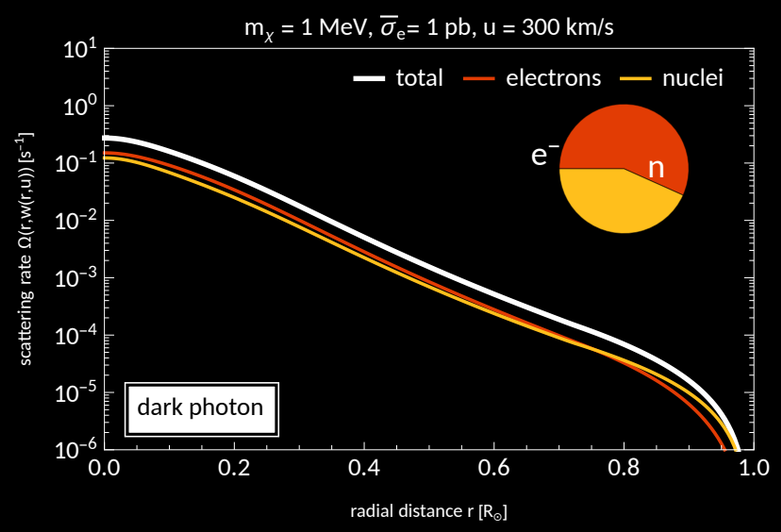


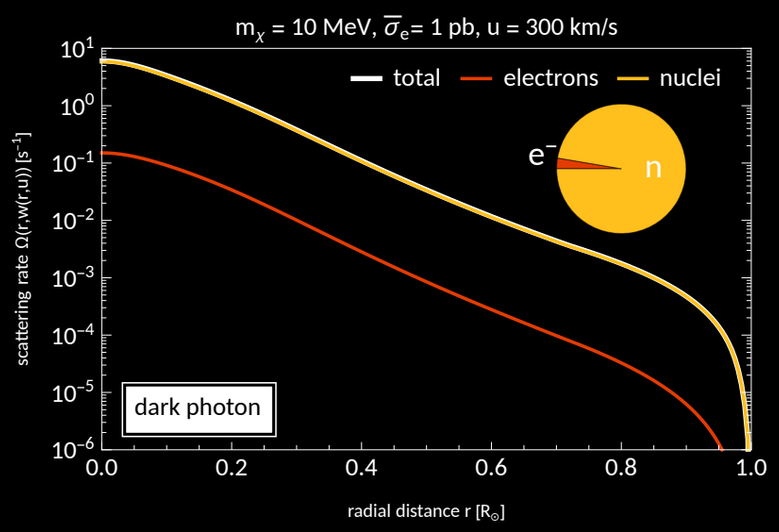


- Dark photon model:

$$\frac{\Omega_e}{\Omega_p} \propto \frac{\bar{\sigma}_e}{\bar{\sigma}_p} \frac{\langle | \vec{v}_\chi - \vec{v}_e | \rangle}{\langle | \vec{v}_\chi - \vec{v}_p | \rangle} = \left(\frac{\mu_{\chi p}}{\mu_{\chi e}} \right)^2 \times \mathcal{O}(10)$$







First estimate of the SRDM flux

- We can make a first estimate of the total solar reflection rate.

$$\mathscr{R}_\odot(m_\chi) = p_{\rm refl} \times \Gamma(m_\chi)$$

- Here we assume an average probability for a DM particle to get reflected, $p_{\rm refl}$.
- The total flux is therefore

$$\Phi_\odot(m_\chi) = \frac{\mathscr{R}_\odot}{4\pi\ell^2} \approx 3.8 \cdot 10^5 \; p_{\rm refl} \left(\frac{m_\chi}{\rm MeV}\right)^{-1} \; {\rm s}^{-1}{\rm cm}^{-2}$$

- Compare this to the halo DM flux

$$\Phi_{\rm halo}(m_\chi) \approx 1.3 \cdot 10^{10} \left(\frac{m_\chi}{\rm MeV}\right)^{-1} \; {\rm s}^{-1}{\rm cm}^{-2}$$

Direct detection of SRDM

- The nuclear recoil spectrum caused by a generic DM flux is given by

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \int_{v_\chi > v_{\min}} \mathrm{d}v_\chi \frac{\mathrm{d}\Phi_\chi}{\mathrm{d}v_\chi} \frac{\mathrm{d}\sigma_{\chi N}}{\mathrm{d}E_R}$$

- For halo DM, we usually directly insert

$$\frac{\mathrm{d}\Phi_{\mathrm{halo}}}{\mathrm{d}v_\chi} = \frac{\rho_\chi}{m_\chi} v_\chi f_\chi(v_\chi)$$

- The SRDM flux can simply be added,

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \int \mathrm{d}v_\chi \left(\frac{\mathrm{d}\Phi_{\mathrm{halo}}}{\mathrm{d}v_\chi} + \frac{\mathrm{d}\Phi_\odot}{\mathrm{d}v_\chi} \right) \frac{\mathrm{d}\sigma_{\chi N}}{\mathrm{d}E_R}$$

Halo DM

SRDM

- But one of the two fluxes will always dominate the other one.

Distinguishing SRDM from background or halo DM

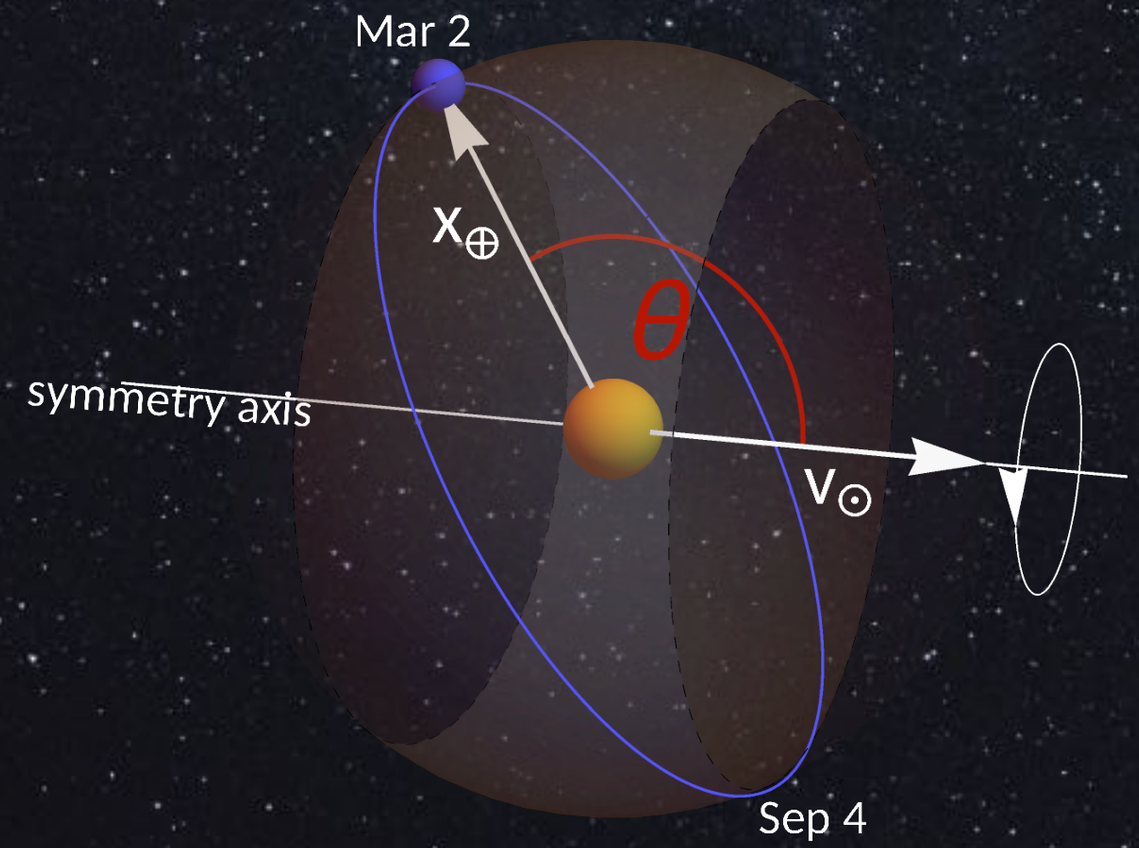
Signatures of a SRDM signal:

1. Directionality: If the detector is sensitive to the DM particle's incoming direction in the Sky, the Sun could be identified as the signal's origin.
2. Annual modulation: There are two source of annual modulation:
   - Orbital modulation: The flux scales as ℓ^{-2}. Due to the Earth's orbital eccentricity this causes a small annual modulation.
   - Anisotropy modulation: If the Sun ejects the SRDM flux anisotropically, this could be a 2nd source of annual modulations.
3. Diurnal modulations: Underground scatterings inside the Earth would typically cause a day-night modulation.

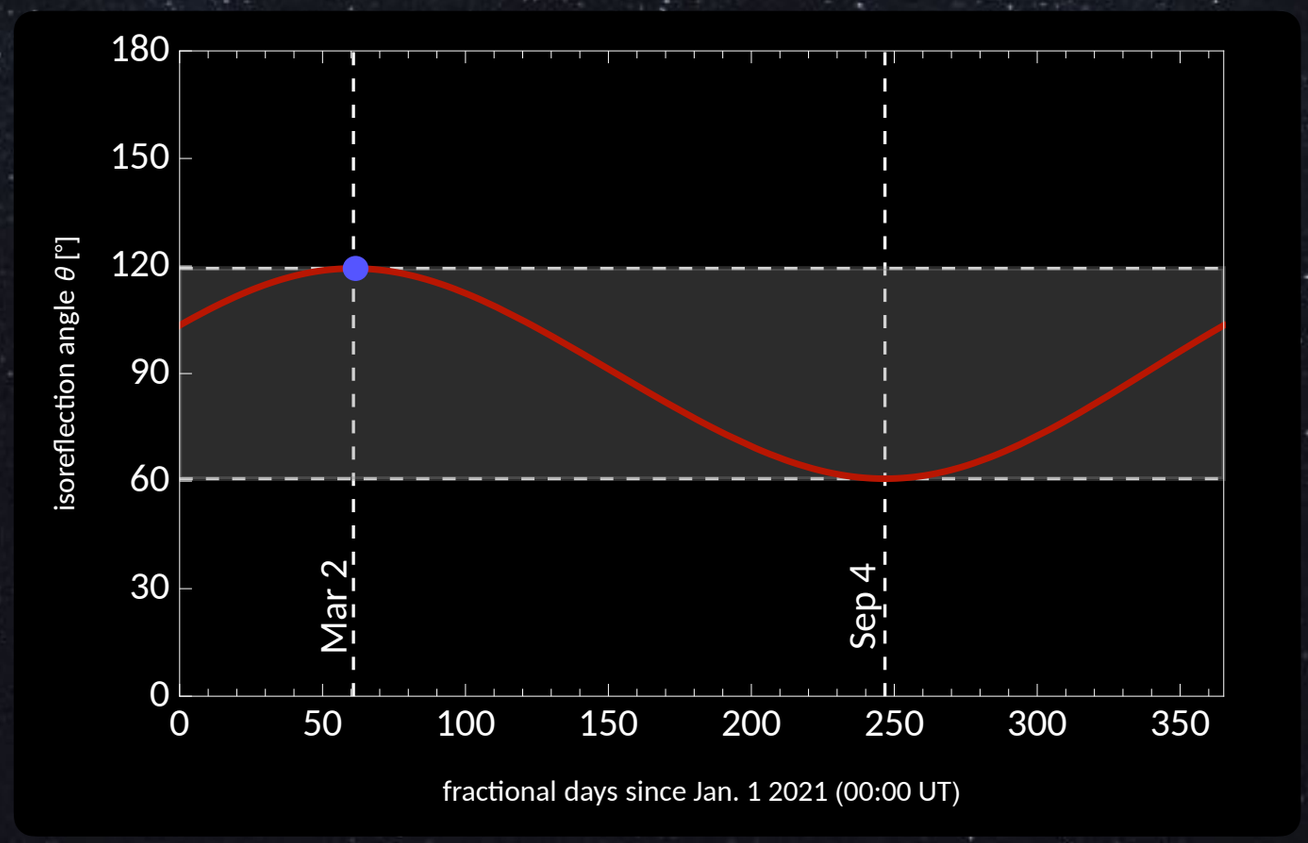
The isoreflection angle

- The boost into the Sun's rest frame gives rise to the DM wind.
- The system is symmetric under rotations around the Sun's velocity.
- We define the polar angle of this symmetry axis as the isoreflection angle:

$$\theta = \sphericalangle(\mathbf{x}_\oplus, \mathbf{v}_\odot)$$



- Time evolution of the Earth's isoreflection angle



III.

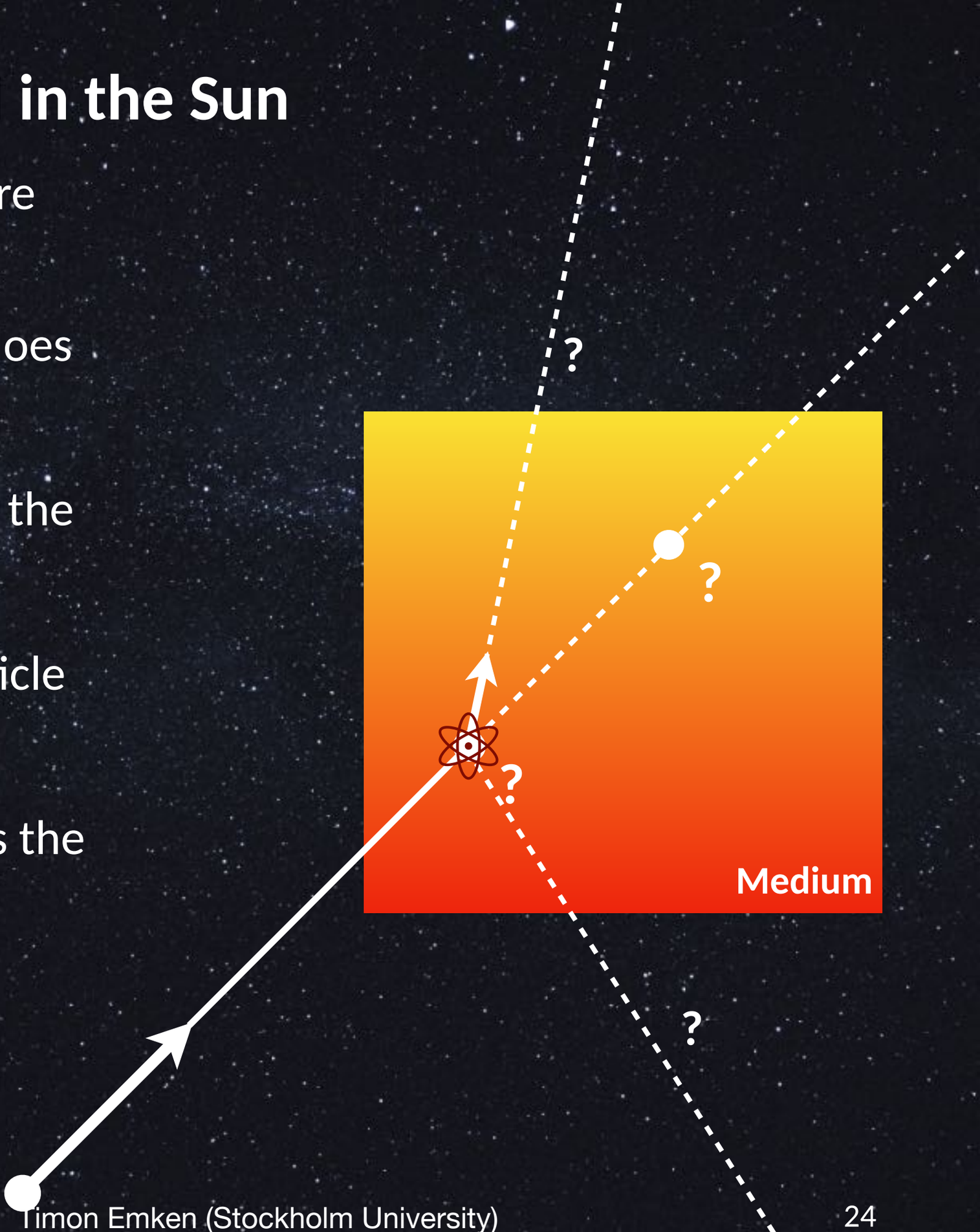
Monte Carlo simulation of solar reflection

MC Simulations of DM in the Sun

The main random processes are

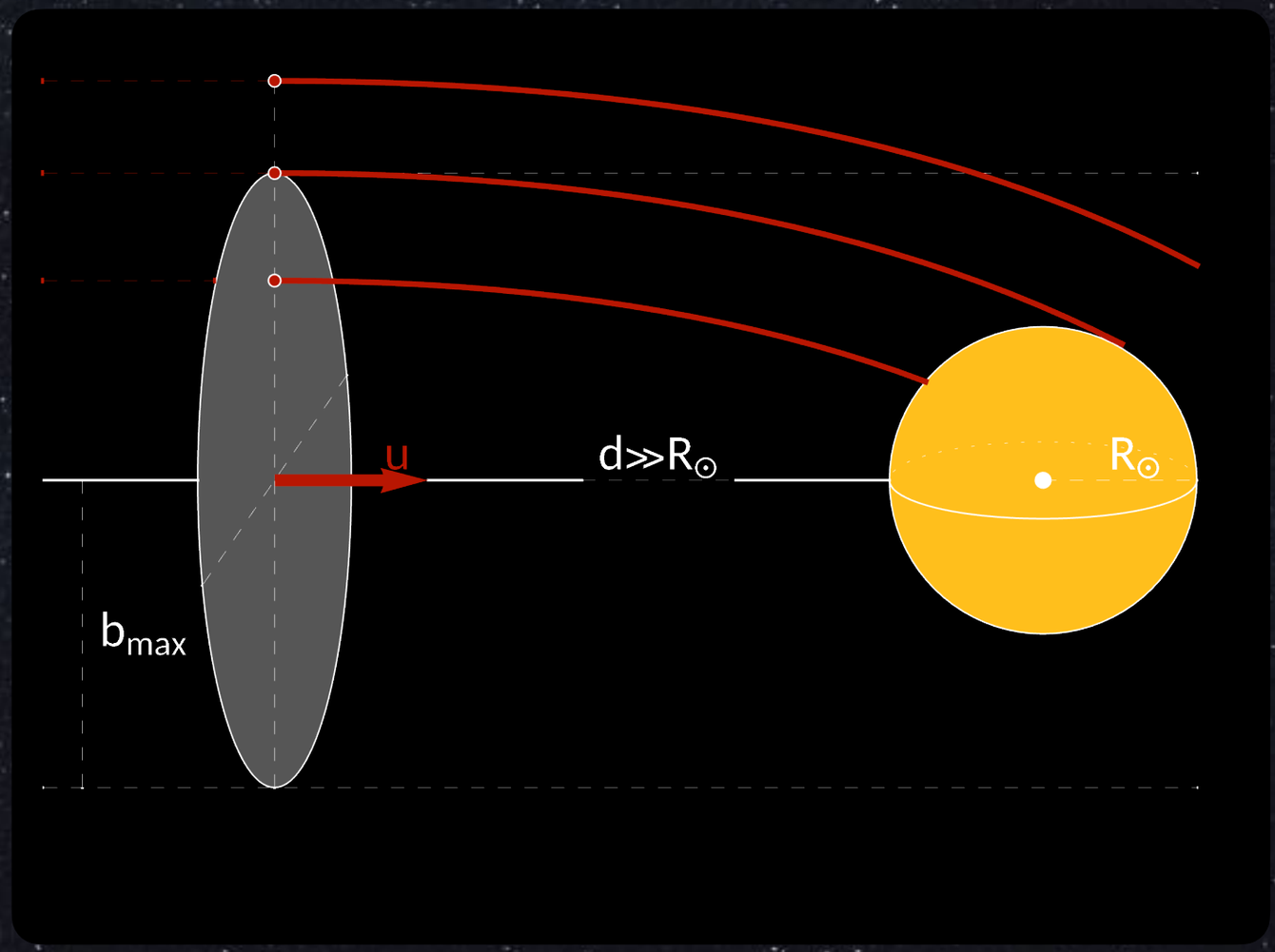
1. **Initial Conditions**: Where does the particle start?
2. **Free distance**: Where does the particle scatter?
3. **Target**: What does the particle scatter on? How fast is it?
4. **Scattering angle**: How does the particle scatter?

Repeat steps 2-4.



Initial conditions

1. Sample a velocity u far away from the Sun from the halo.
2. Sample the initial position with a maximum impact parameter.
3. Propagate the particle analytically on its hyperbolic Kepler orbit to a location close to the Sun.



Free propagation

- The probability for a DM particle to propagate underground without scattering:

$$P(\Delta t) = 1 - \exp\left(- \int_0^{\Delta t} \frac{\mathrm{d}t}{\tau(r(t), v(t))} \right)$$

- Here, we used the mean free time

$$\tau(r, v) = \Omega(r, v)^{-1}$$

- This enables us to find the location of the next scattering.
- We solve the equations of motion iteratively using the Runge-Kutta-Fehlberg method. The particle scatters as soon as

$$\sum_i \frac{\Delta t_i}{\tau(r_i, v_i)} > - \ln(\xi)$$

Scatterings inside the Sun

- Once we know that the DM particle scatters at a radial distance r, we can identify the target species. The probability to scatter on target i is

$$P_i = \frac{\Omega_i(r, v_\chi)}{\Omega(r, v_\chi)}$$

- The target's velocity can be sampled from the following distribution,

$$f(\mathbf{v}_T) = \frac{|\mathbf{v}_\chi - \mathbf{v}_T|}{\langle |\mathbf{v}_\chi - \mathbf{v}_T| \rangle} f_i(\mathbf{v}_T, T)$$

Maxwell-Boltzmann distribution

- Since we assume contact interactions with heavy mediators, the scattering is isotropic.

- Finally, the new DM velocity is given by

$$\mathbf{v}'_\chi = \frac{m_T |\mathbf{v}_\chi - \mathbf{v}_T|}{m_T + m_\chi} \hat{\mathbf{n}} + \frac{m_\chi \mathbf{v}_\chi + m_T \mathbf{v}_T}{m_T + m_\chi}$$

$t = 0.\ \mathrm{hr}$

$N_s = 0$

$v_\chi = 456\,\frac{\mathrm{km}}{\mathrm{s}}$

$E_\chi / E_0 = 1.$

$m_\chi = 100\,\mathrm{MeV}$

$\sigma_p = 0.2\,\mathrm{pb}$

Emken 2019

From MC simulation to the SRDM flux

- The total reflection rate and flux is found given by the amount of reflections among the simulated particles.

$$\mathscr{R}_\odot^{\mathrm{MC}} = \frac{N_{\mathrm{refl}}}{N_{\mathrm{sim}}}\Gamma(m_\chi) \qquad \Phi_\odot^{\mathrm{MC}} = \frac{\mathscr{R}_\odot^{\mathrm{MC}}}{4\pi\ell^2} \qquad \ell = 1\,\mathrm{AU}$$

- The reflection spectrum is based on the speed data recorded at 1 AU distance. Instead of histograms, we prefer a smooth distribution and use Kernel density estimation (KDE).

$$\frac{\mathrm{d}\mathscr{R}_\odot}{\mathrm{d}v_\chi} = \mathscr{R}_\odot^{\mathrm{MC}} f_\odot^{\mathrm{KDE}}(v_\chi) \qquad \frac{\mathrm{d}\Phi_\odot^{\mathrm{MC}}}{\mathrm{d}v_\chi} = \frac{1}{4\pi\ell^2}\frac{\mathrm{d}\mathscr{R}_\odot}{\mathrm{d}v_\chi}$$

- To study anisotropies of the SRDM flux, we define equal-area isoreflection rings and perform the analysis for each ring.

The Simulation Code

"The code is what you did, the paper is what you think you did."

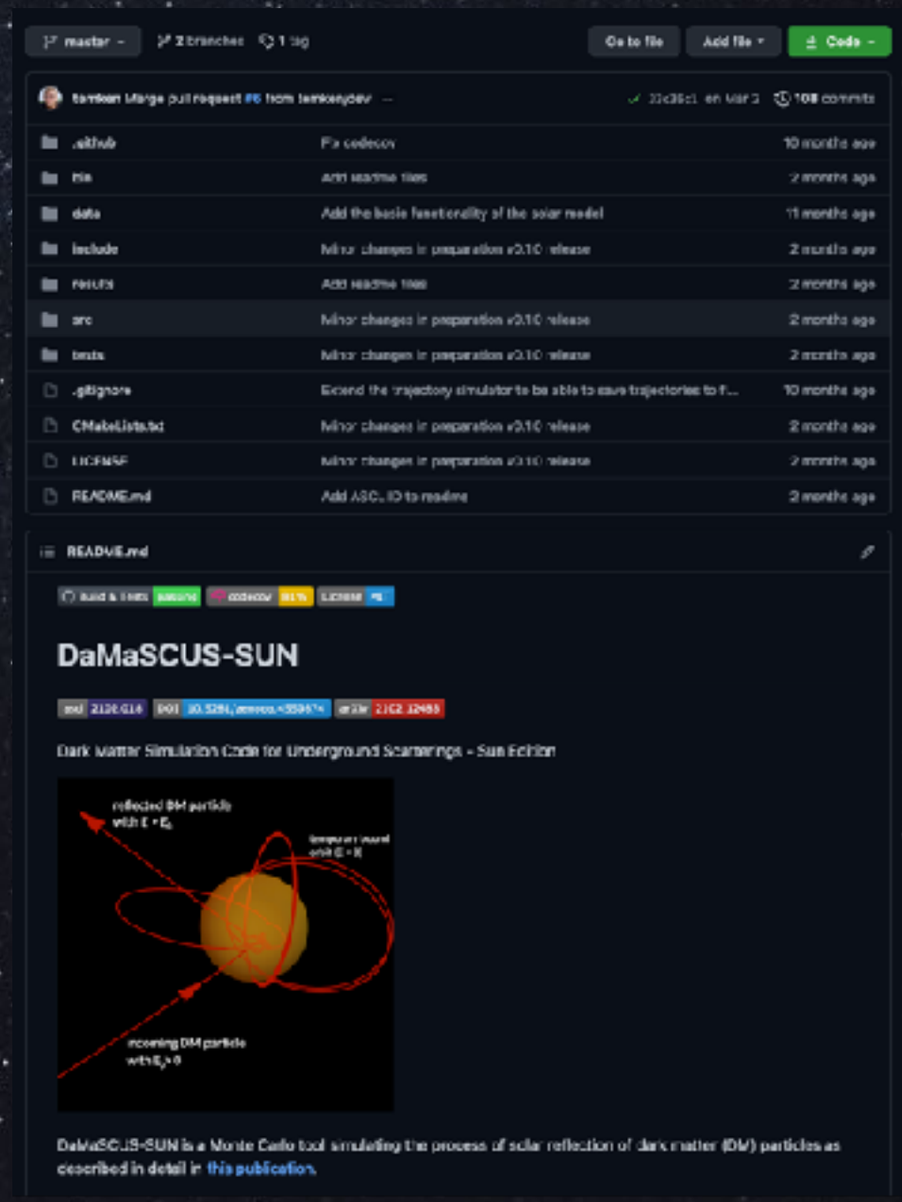
-Patrick Koppenburg on Twitter

- The *Dark Matter Simulation Code for Underground Scatterings - Sun Edition* (DaMaSCUS-SUN) is publicly available on *github*.

https://github.com/temken/DaMaSCUS-SUN

- Written in C++, built with CMake, set up with unit and build testing, code coverage,...

- Fully parallelized (MPI), ready to run on HPC clusters.

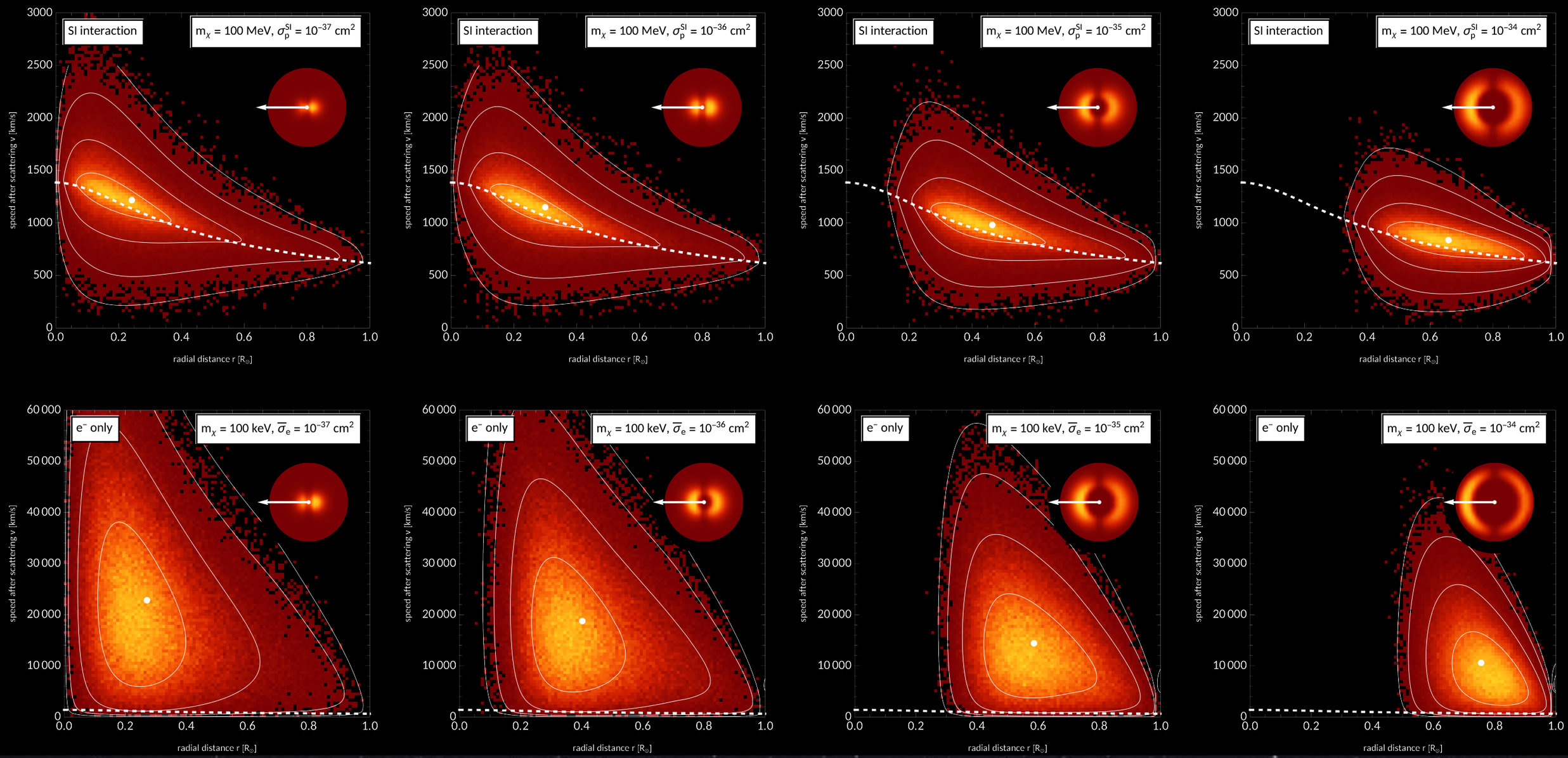


IV.
Results

The first scattering inside the Sun

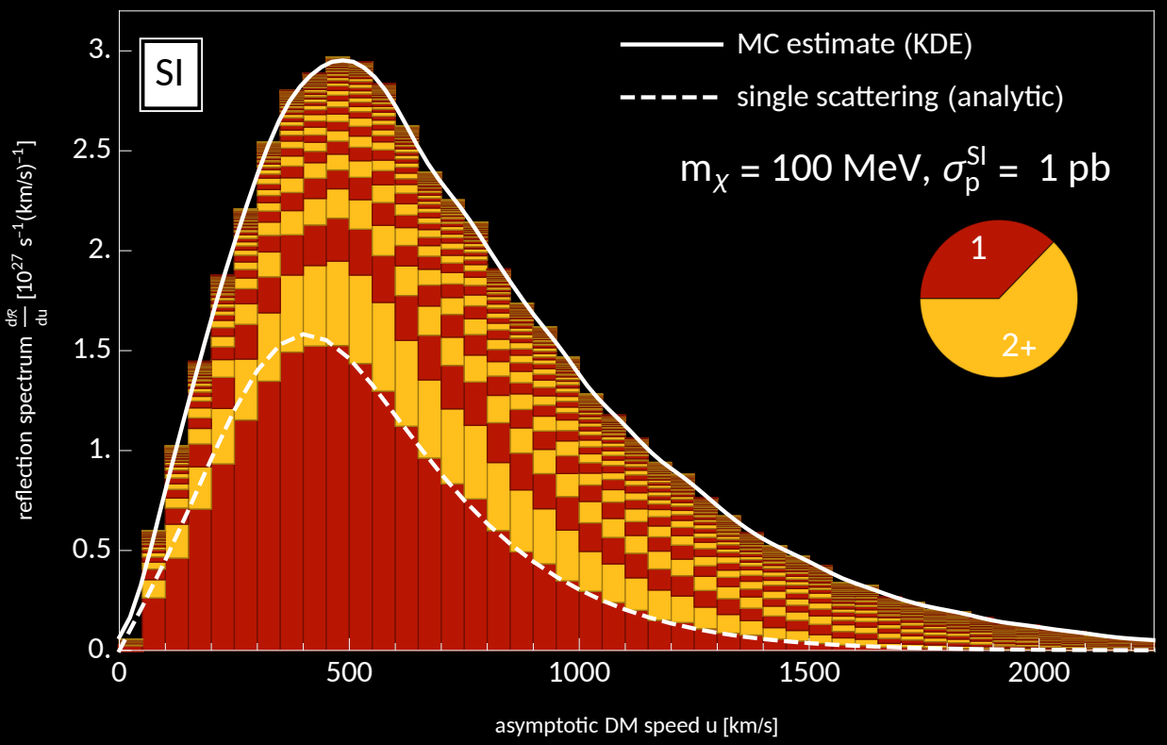
- The first scattering allows comparison with our analytic description of DM scatterings inside the Sun.

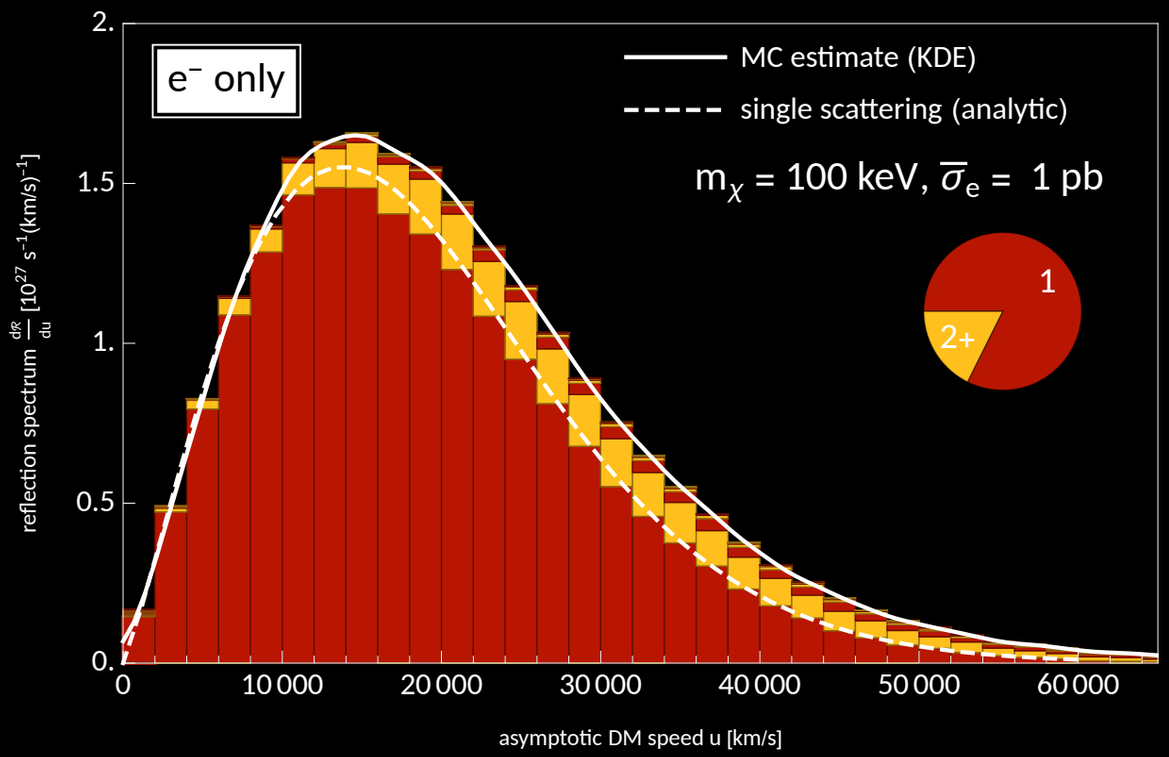
TE, C. Kouvaris, N. G. Nielsen, PRD, 97 (2018), 063007



The impact of multiple scatterings

- Using MC simulations allows to quantize the contribution of multiple scatterings to the SRDM flux.

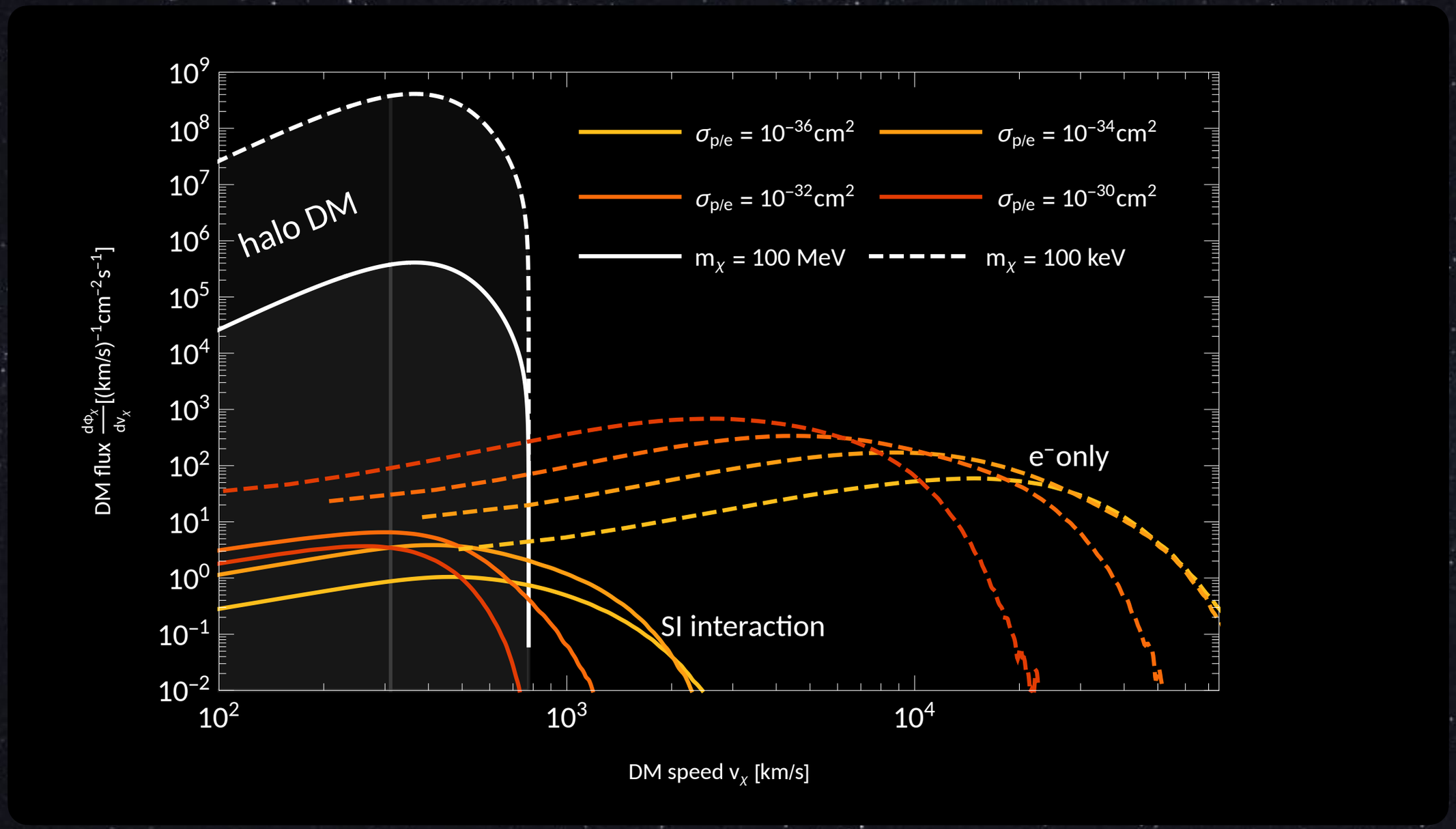




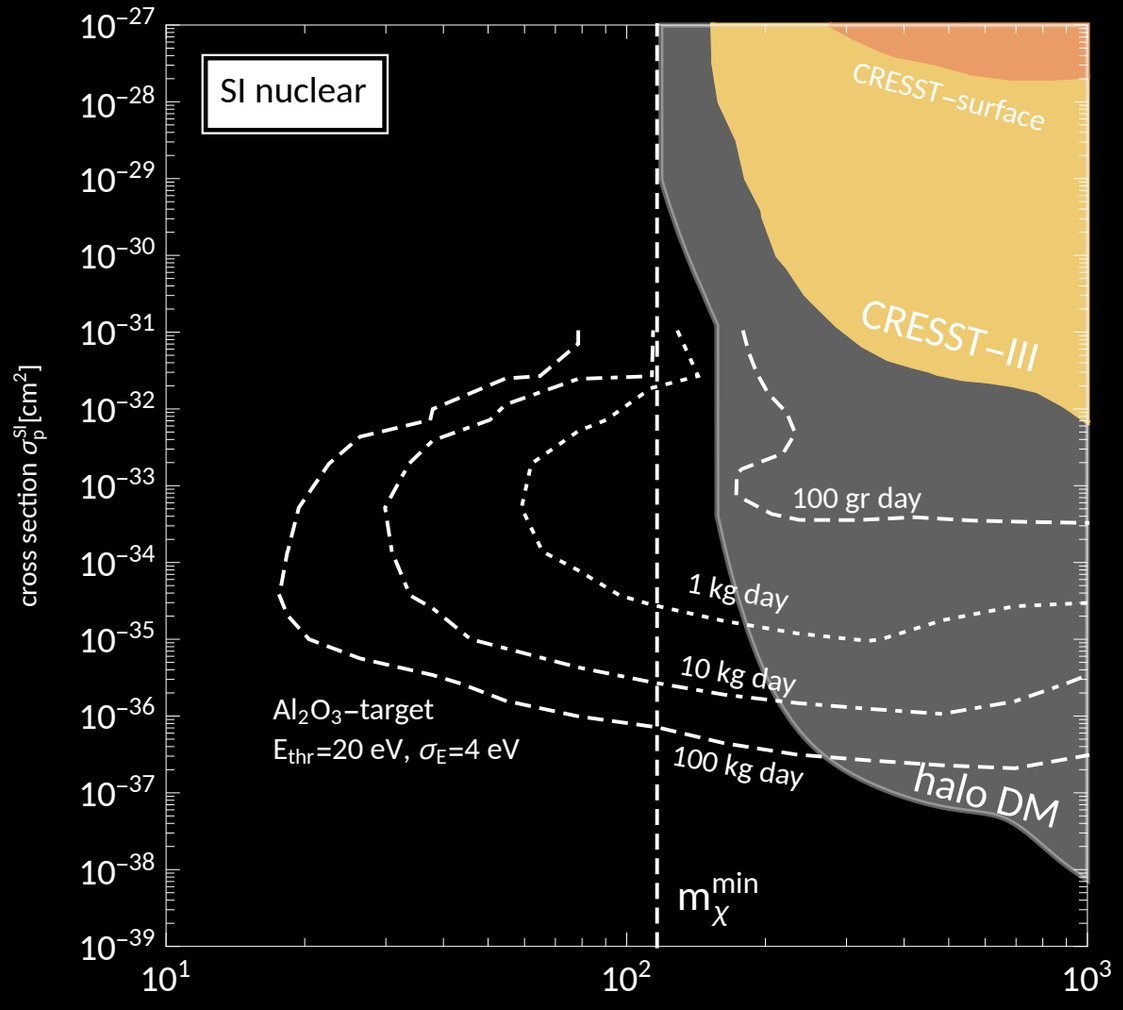
➡ Great consistency between analytic formalism and MC description!

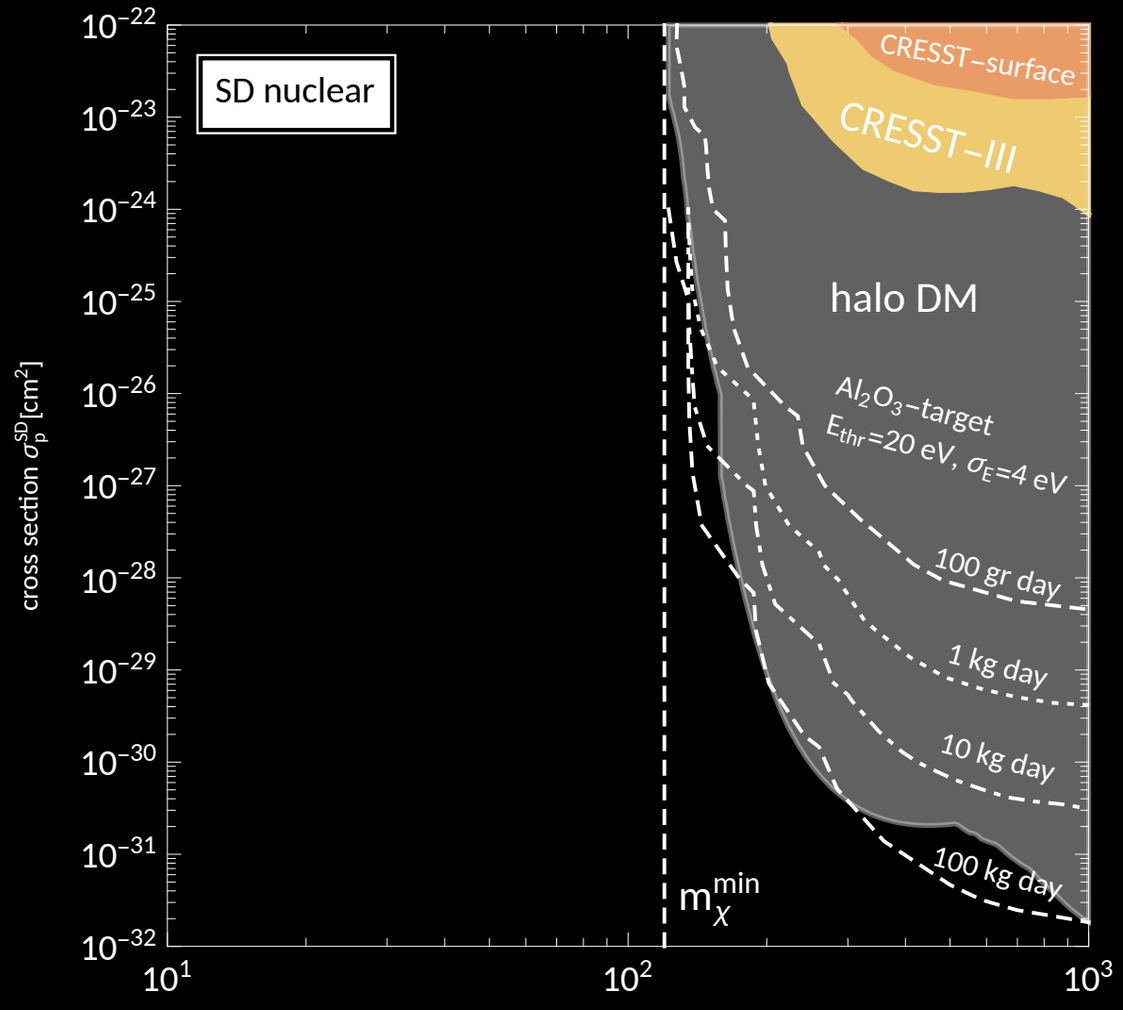
The solar reflection DM flux

- Compare the SRDM flux to the halo DM flux.



Exclusion limits for DM-nucleus interactions

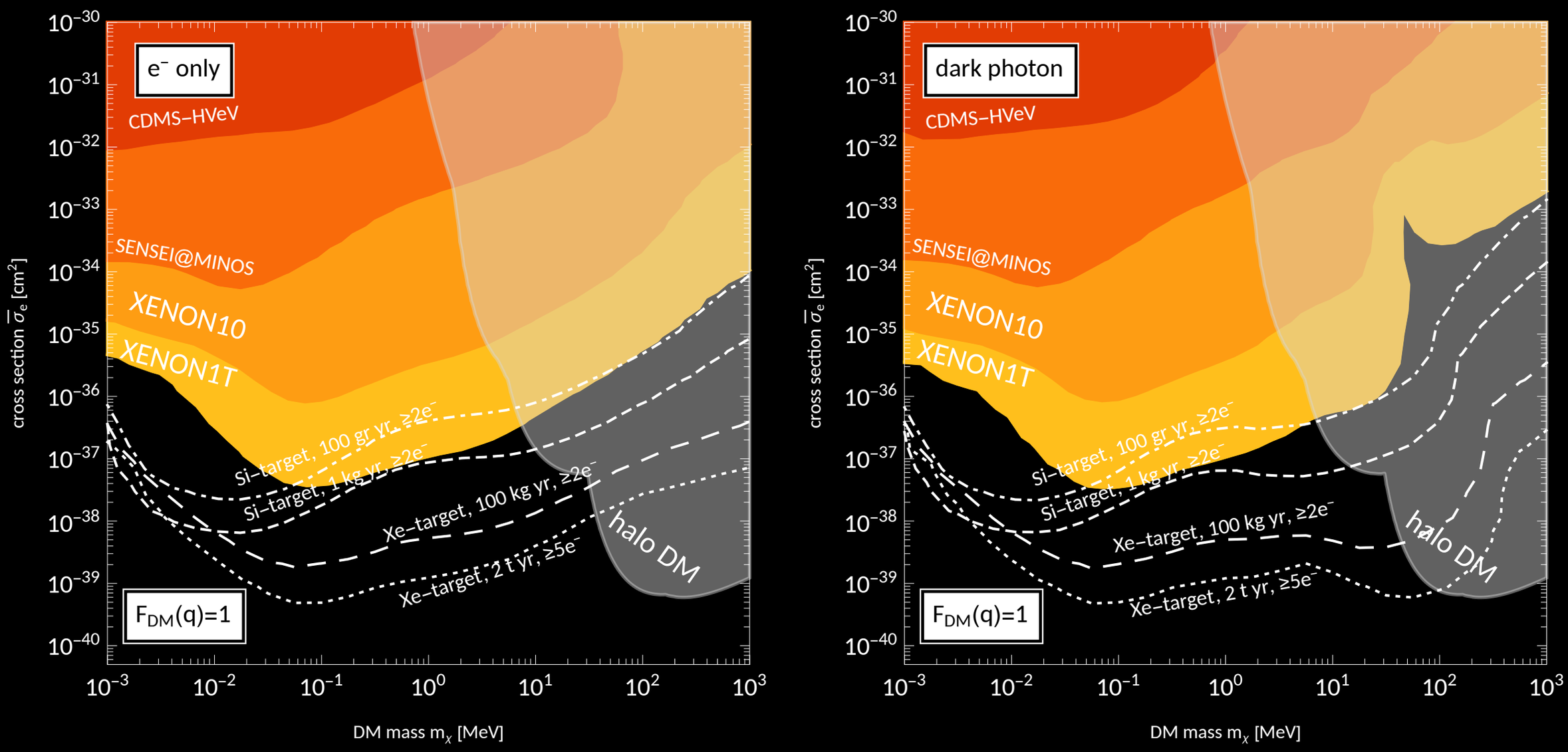




➡ Higher exposures probe lower masses!

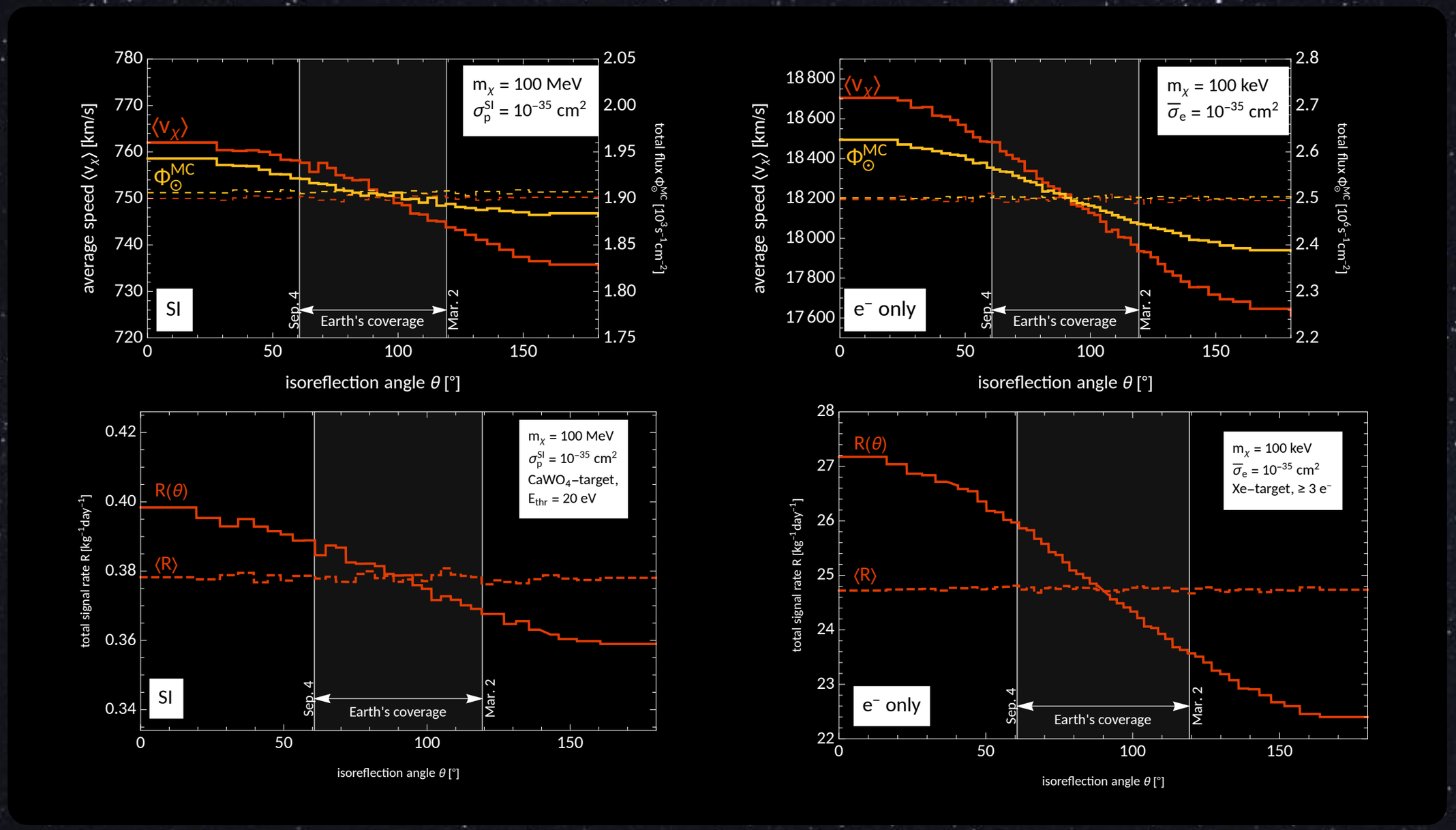
- For SI interactions, next generation experiments can extend their sensitivity to lower masses through SRDM.

Exclusion limits for DM-electron interactions



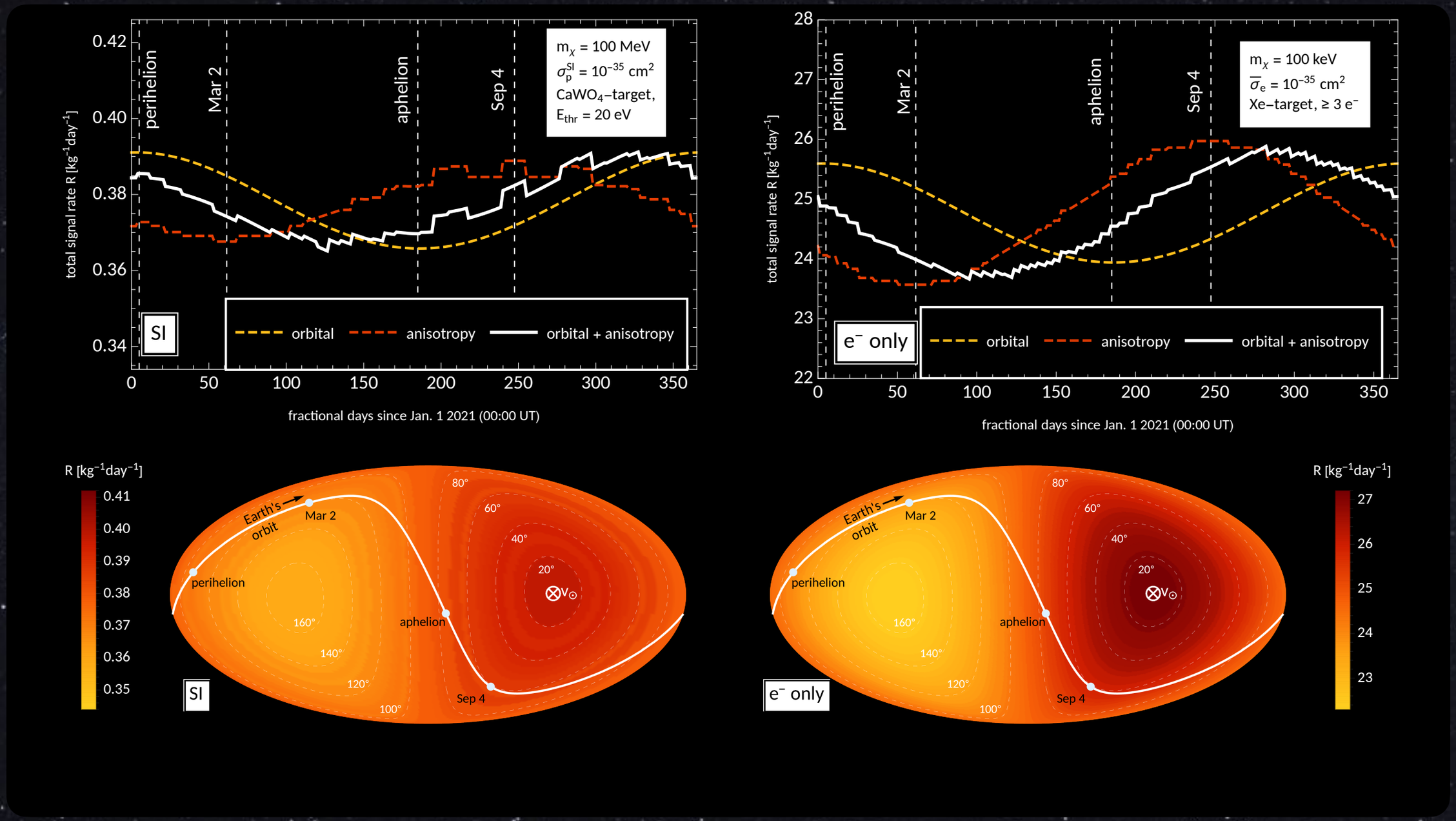
➡ Solar reflection extends the experiments' mass sensitivity by multiple orders of magnitude.

Anisotropies of the SRDM flux



➡ The Sun does not eject SRDM particles isotropically into the solar system.

Annual signal modulations



➡ The orbital and anisotropy modulations feature comparable amplitudes.

V. Summary & Outlook

- Scatterings on hot solar targets can accelerate light DM particles.
- The energetic flux of reflected DM particles can extend the sensitivity of direct detection experiments to lower masses especially for DM-electron interactions.
- We performed MC simulations to describe the SRDM flux for 4 different DM scenarios and derived exclusion limits based on existing and planned experiments.
- An SRDM signal would feature a rich modulation signature. We investigated the annual modulation.

- So far we only considered heavy mediators. What about light mediators?

  An, H., et al., [arXiv:2108.10332]
- Migdal scatterings + SRDM could potentially extend sensitivity to low mass DM searches via nuclear recoils.

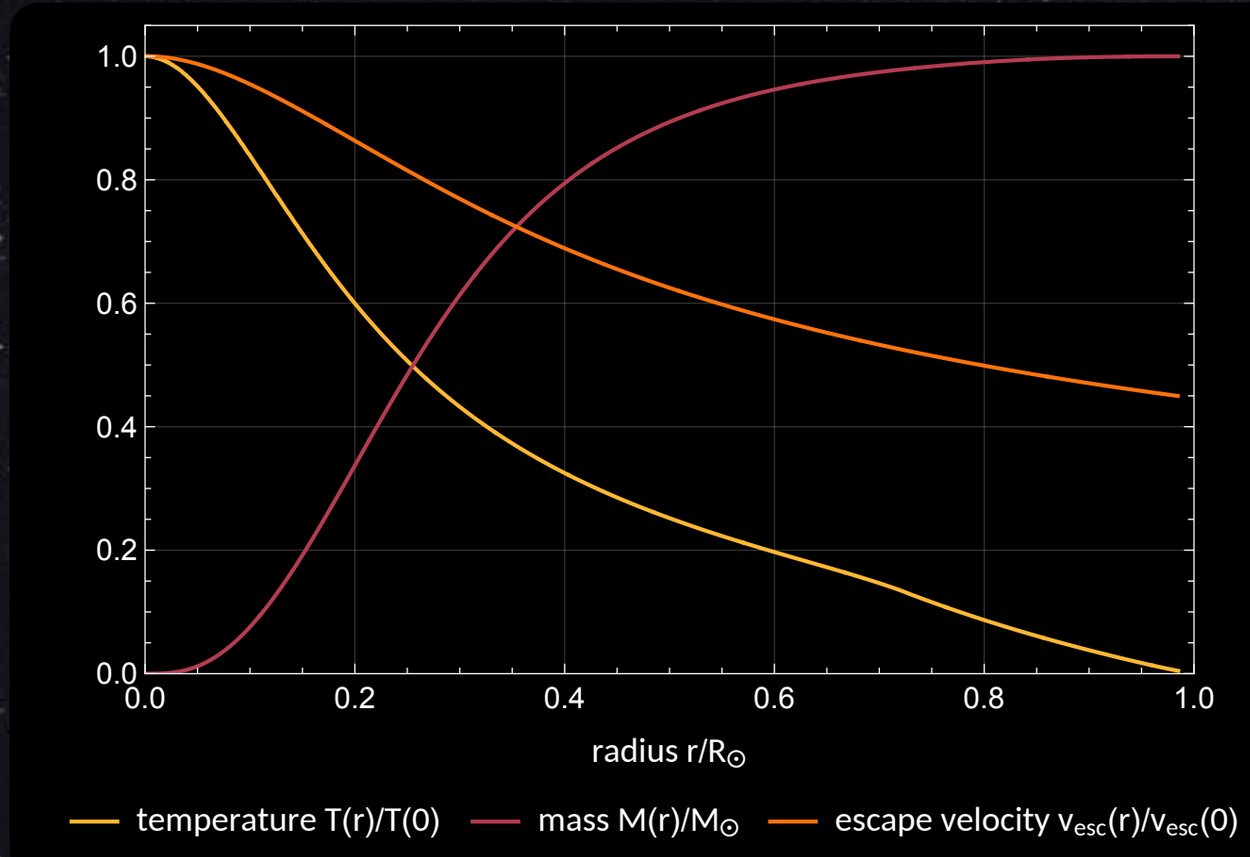
Thank you!

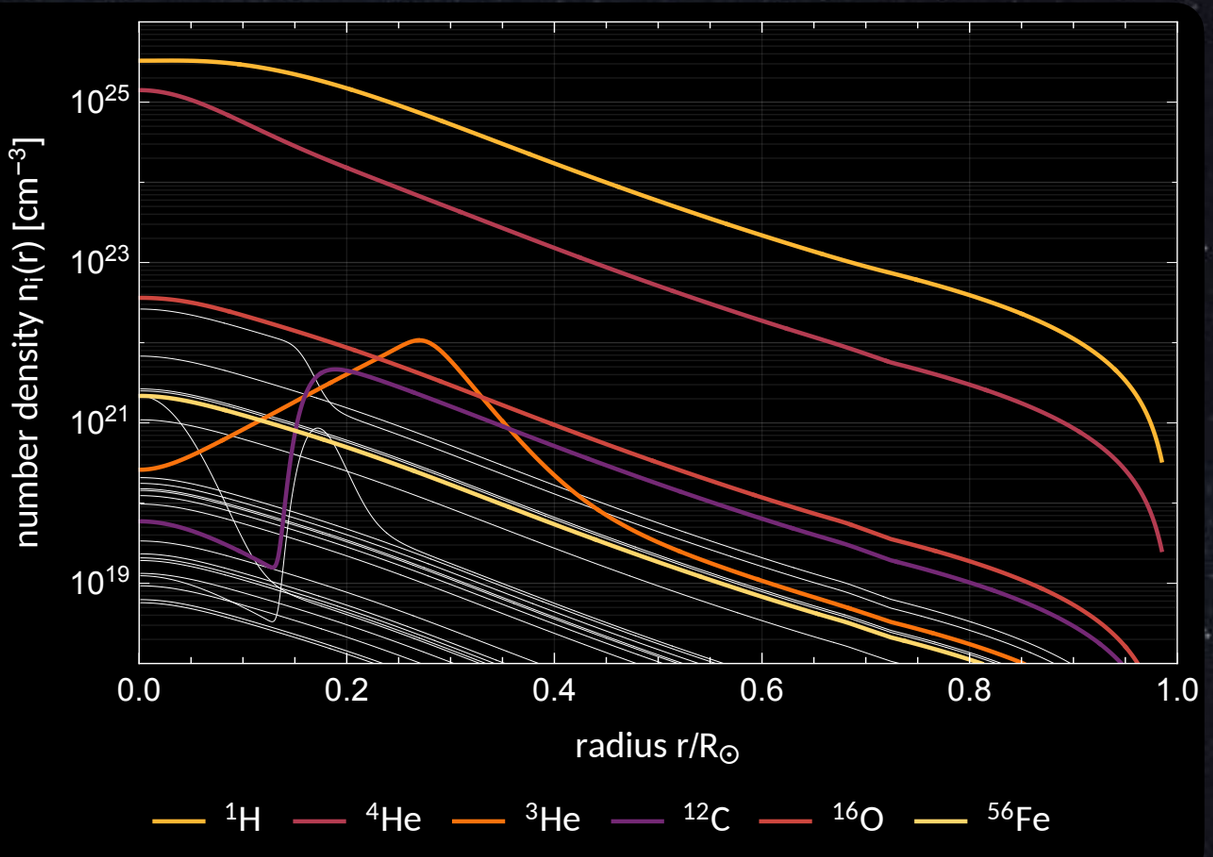
VI.
Backup Slides

The solar model

Standard Solar Model AGSS09

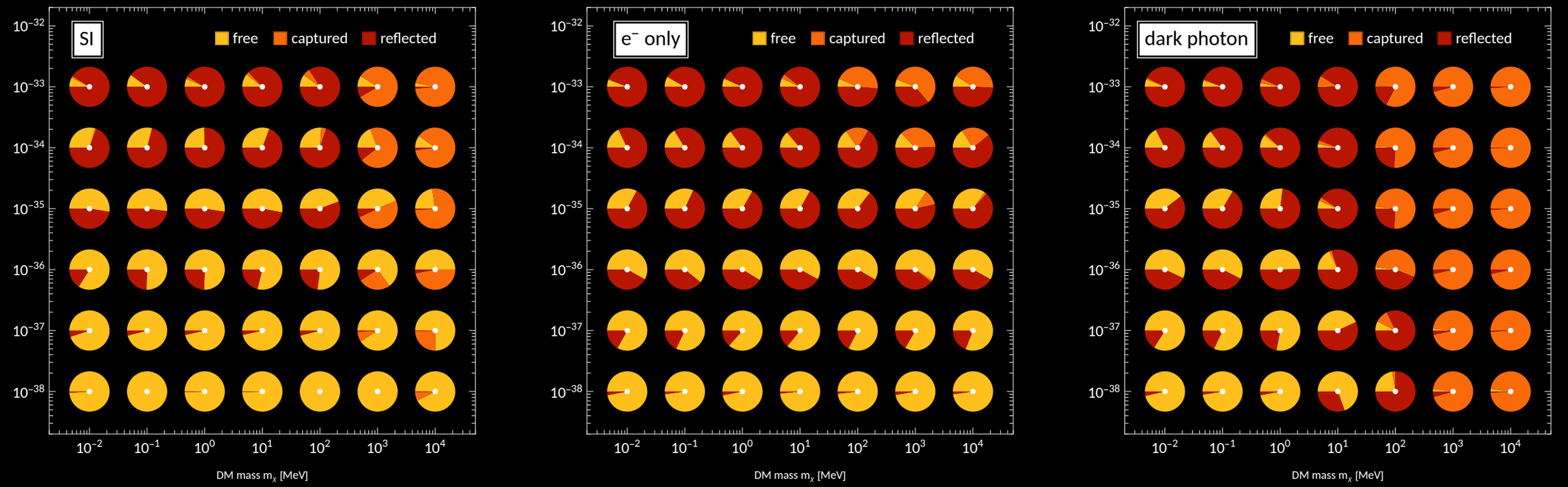
A. Serenelli et al., Astrophys. J. 705 (2009), L123-L127





- Mass Function M(r)
- Temperature T(r)
- Nuclear composition
- Number densities

DM Gravitational capture rate



Runge-Kutta-Fehlberg (RK45)

E. Fehlberg, NASA technical report, NASA, 1969

Adaptive method for the numerical solution of 1st order ODEs.

$$\dot{y} = f(t, y)\,, \quad y(t_0) = y_0\,,$$

Requires the same number of function evaluation of RK6, but is rather a combination of RK4,

$$y_{k+1} = y_k + \frac{25}{216}k_1 + \frac{1408}{2565}k_3 + \frac{2197}{4101}k_4 - \frac{1}{5}k_5\,,$$

and RK5,

$$\tilde{y}_{k+1} = y_k + \frac{16}{135}k_1 + \frac{6656}{12825}k_3 + \frac{28561}{56430}k_4 - \frac{9}{50}k_5 + \frac{2}{55}k_6\,.$$

The comparison of both yields an estimate of the error, and allows to choose the step size adaptively.

$$\Delta t_{k+1} = 0.84 \left(\frac{\epsilon}{\left| y_{k+1} - \tilde{y}_{k+1} \right|} \right)^{1/4} \Delta t_k$$