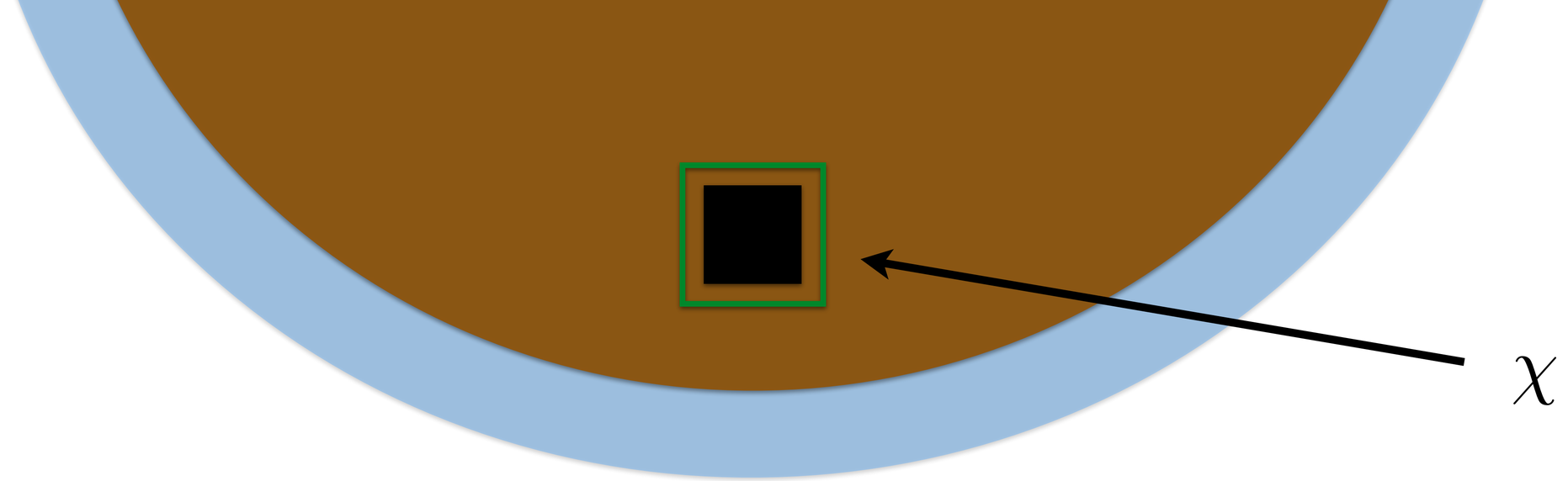


Earth-scattering of Dark Matter with VERNE

Bradley J Kavanagh [he/him]

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Instituto de Física de Cantabria (CSIC-UC)

GDR DUPhys Meeting

20 October 2026

Deep Underground Physics

Instituto de Física de Cantabria

Universidad de Cantabria

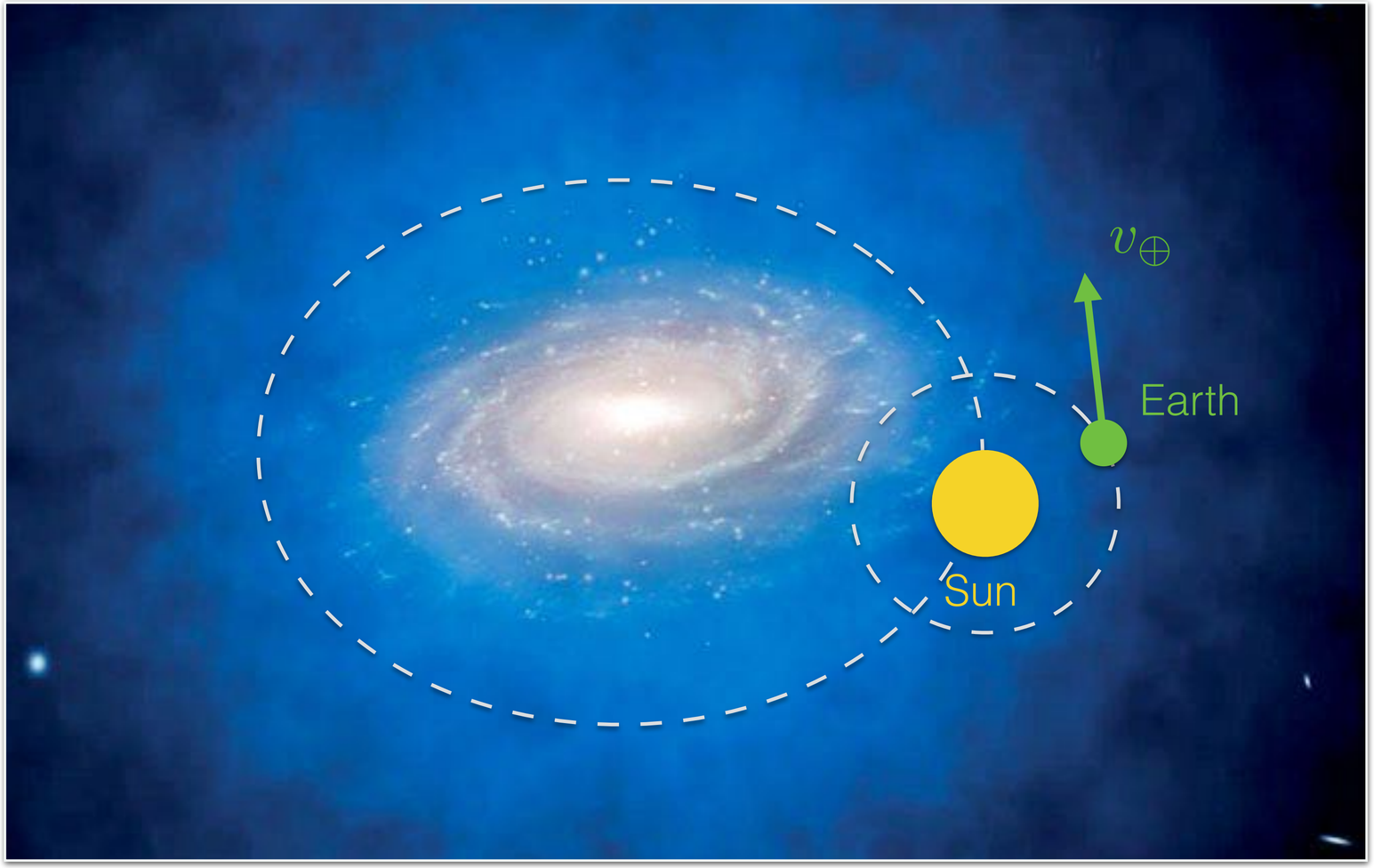
CSIC Consejo Superior de Investigaciones Científicas

Gobierno de España · Ministerio de Ciencia, Innovación y Universidades

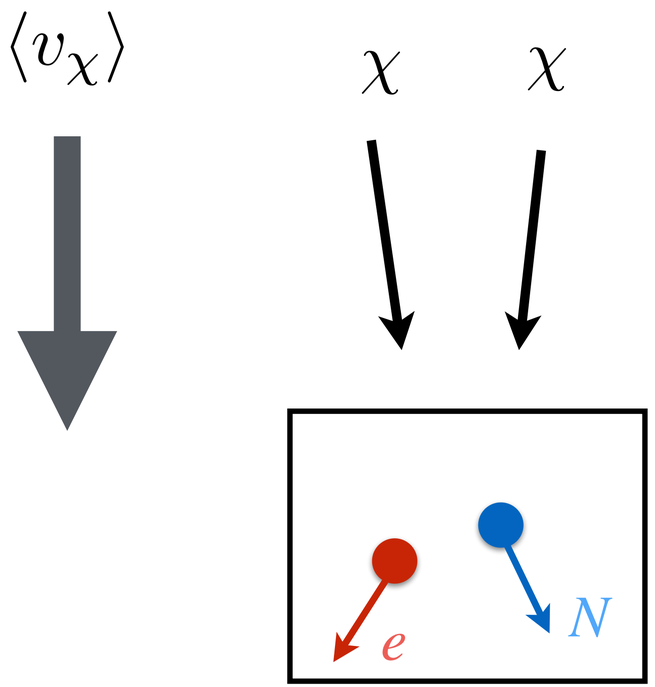
Unión Europea · Fondo Europeo de Desarrollo Regional

Agencia Estatal de Investigación

Direct Detection of Dark Matter



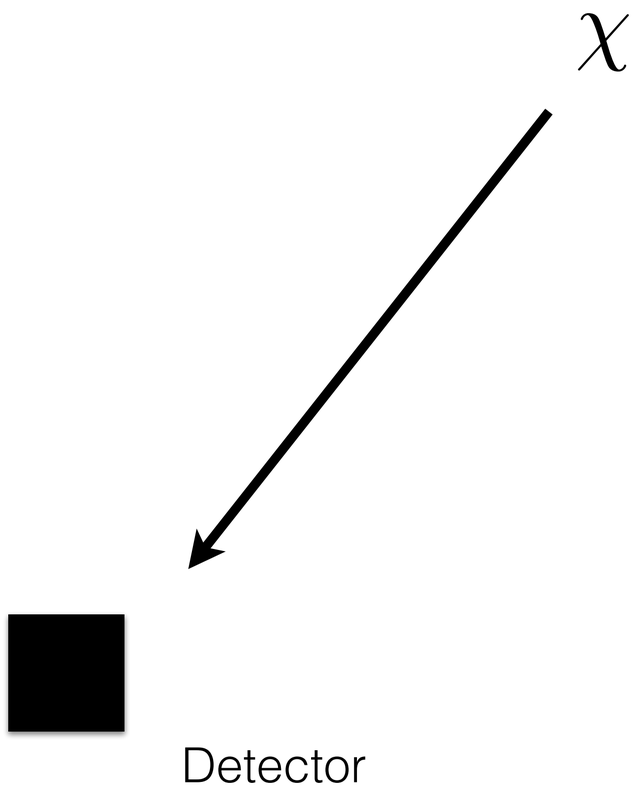
DM ‘Wind’



Dark Matter signal rate as a function of deposited energy E - convolve the DM flux, $\Phi_\chi = (\rho_\chi / m_\chi) v f(\mathbf{v})$,with the scattering cross section:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim \frac{\rho_\chi}{m_\chi} \int_{v_{\mathrm{min}}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E} \, \mathrm{d}^3\mathbf{v}$$

Earth scattering

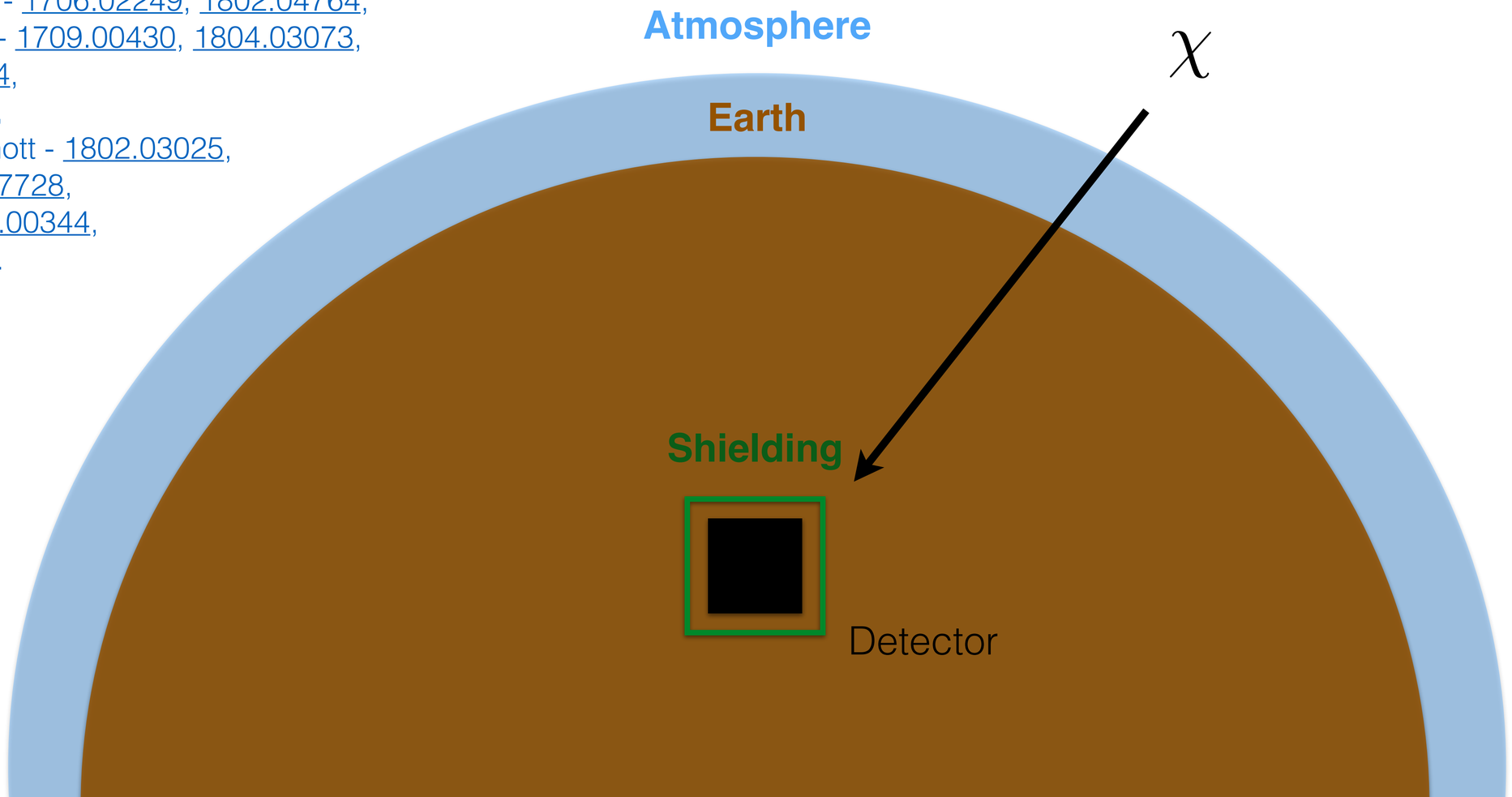


Earth scattering

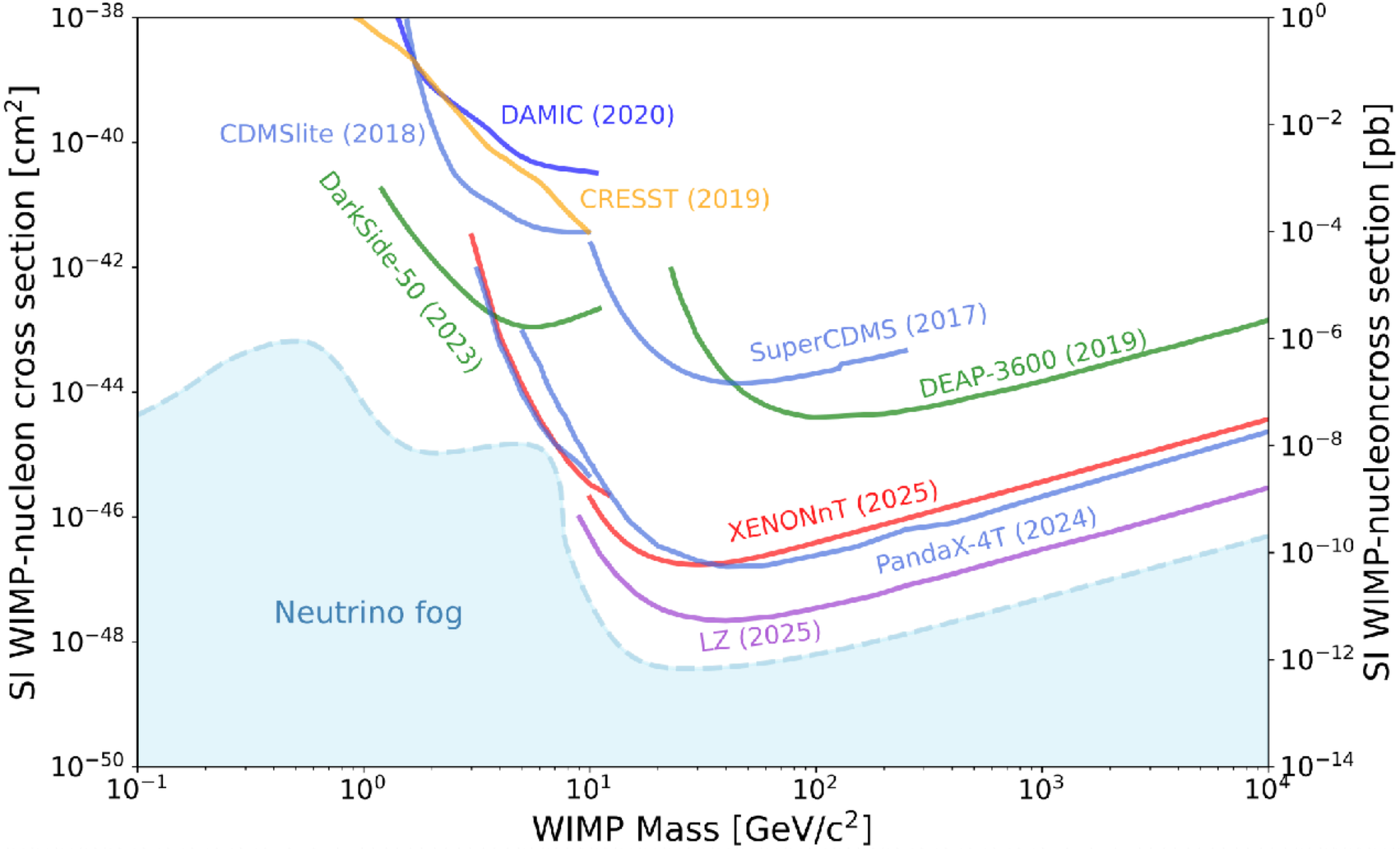
Collar & Avignone - PLB 275, 1992 and others

Kouvaris & Shoemaker - 1405.1729, 1509.08720,
DAMA - 1505.05336,
BJK, Catena, Kouvaris - 1611.05453,
Emken & Kouvaris - 1706.02249, 1802.04764,
Mahdawi & Farrar - 1709.00430, 1804.03073,
Davis - 1708.01484,
BJK - 1712.04901,
Hooper & McDermott - 1802.03025,
Cappiello - 2301.07728,
Bertou et al - 2507.00344,
and many others…

Scattering in the atmosphere, Earth and shielding can distort the DM flux!

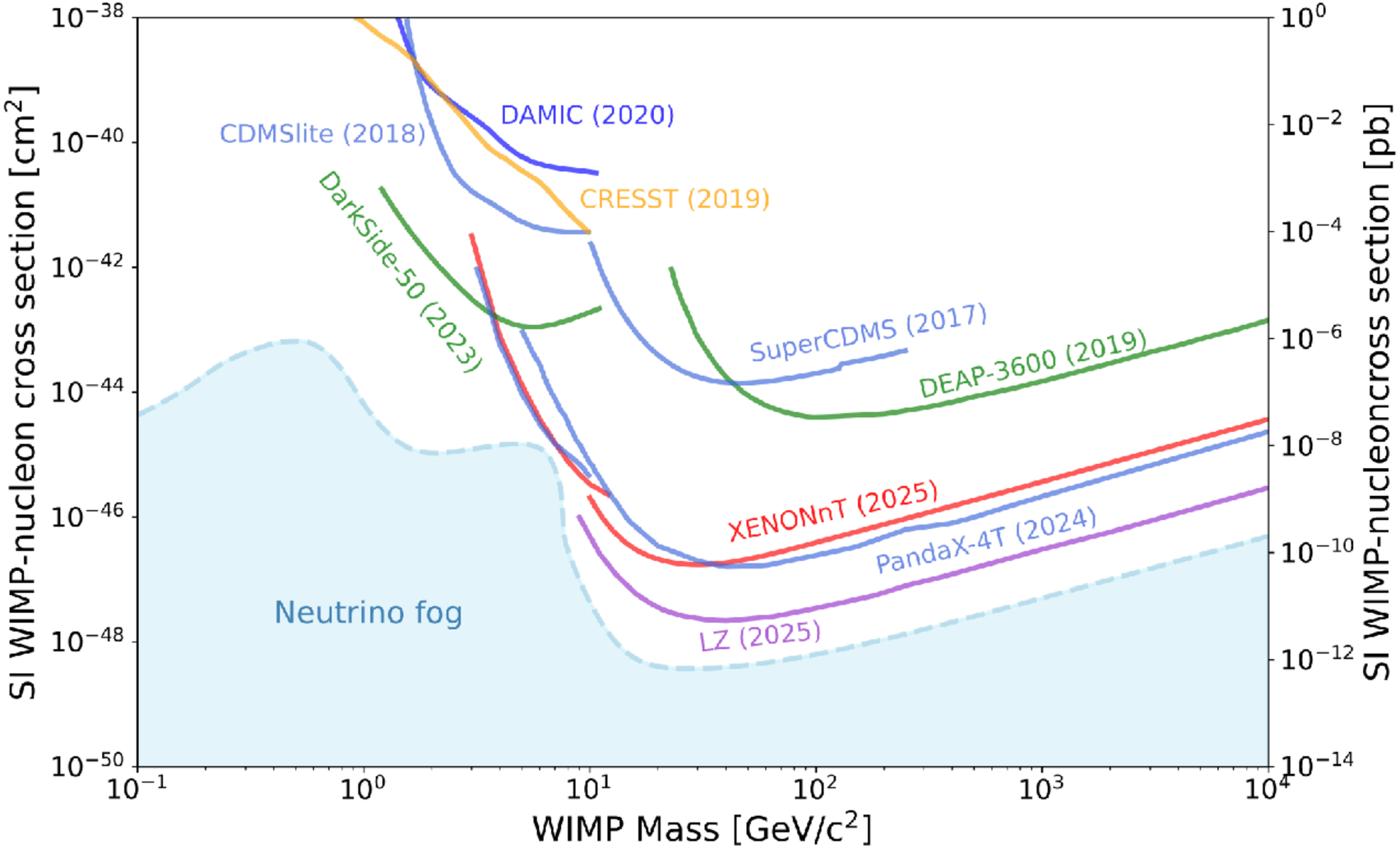


Why strongly-interacting DM?



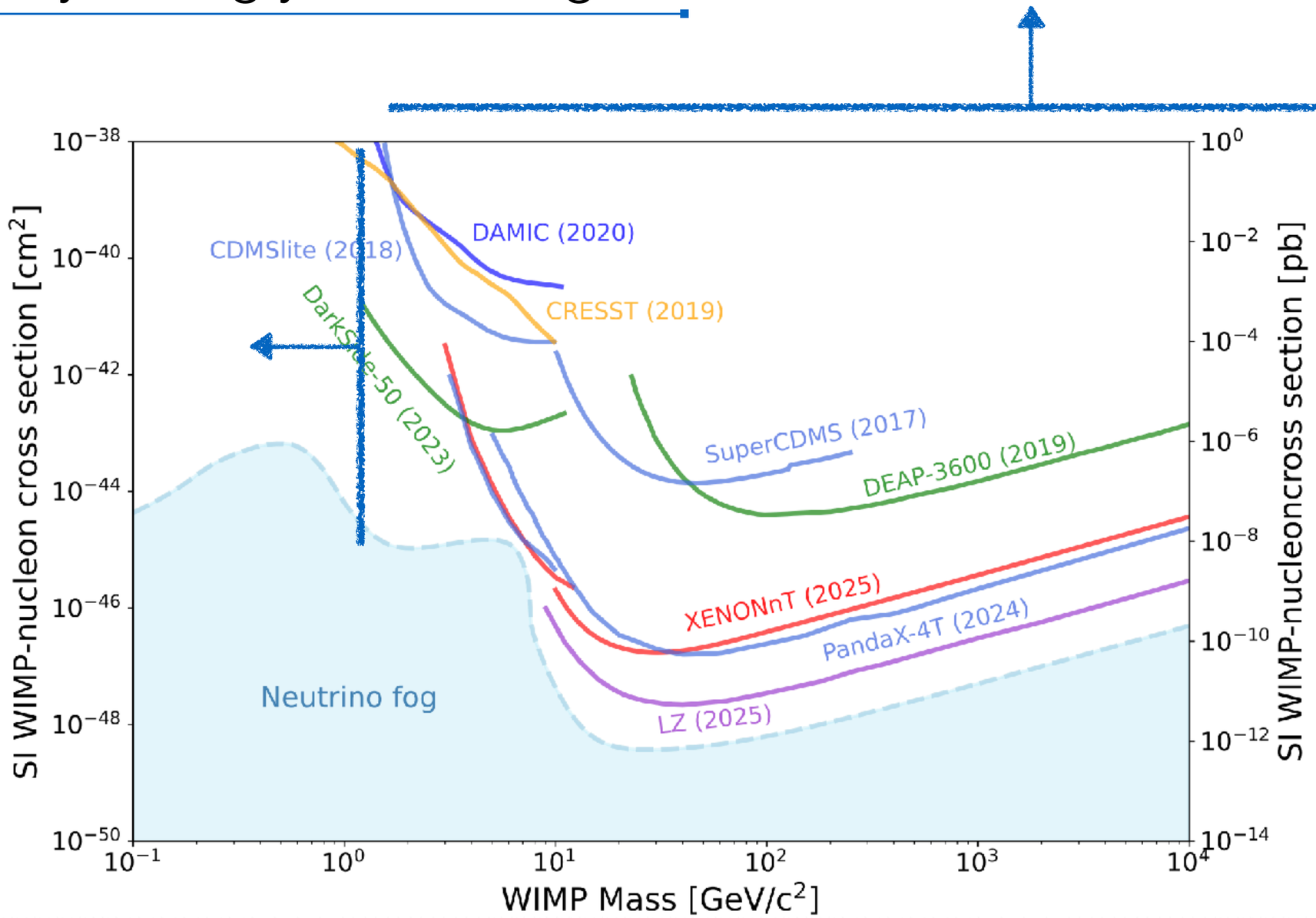
[Baudis, 2512.23039]

Why strongly-interacting DM?



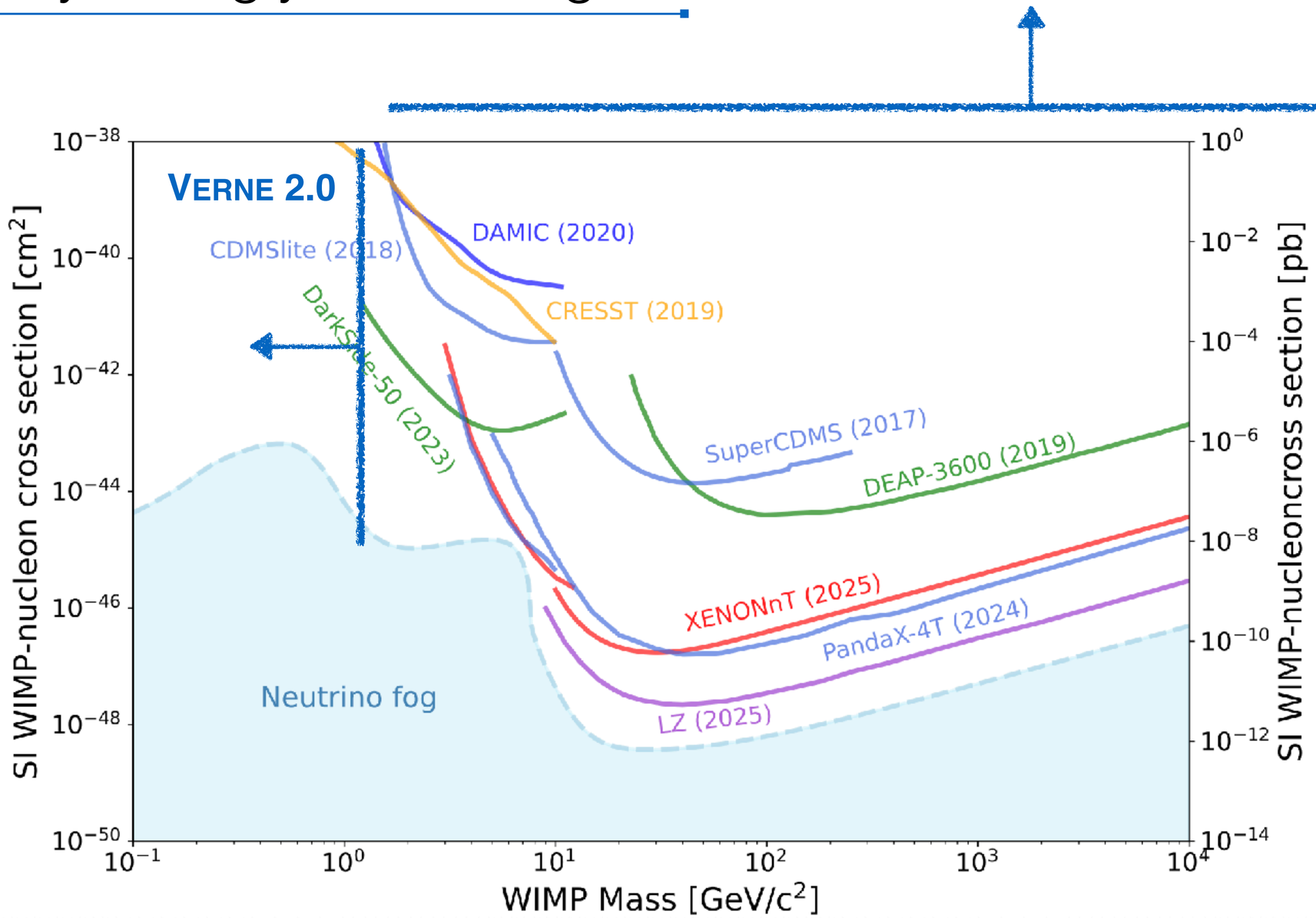
[Baudis, 2512.23039]

Why strongly-interacting DM?



[Baudis, 2512.23039]

Why strongly-interacting DM?



How can we take Earth-scattering into account?

What are its observational signatures?

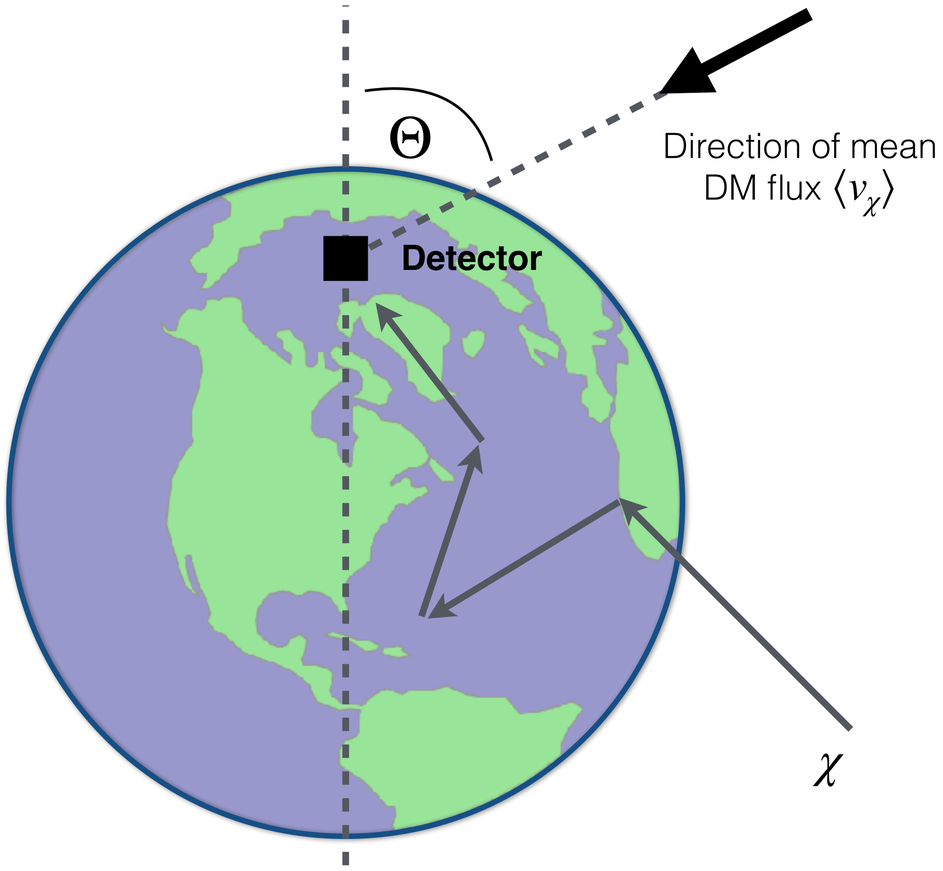
[Baudis, 2512.23039]

Monte Carlo Simulations

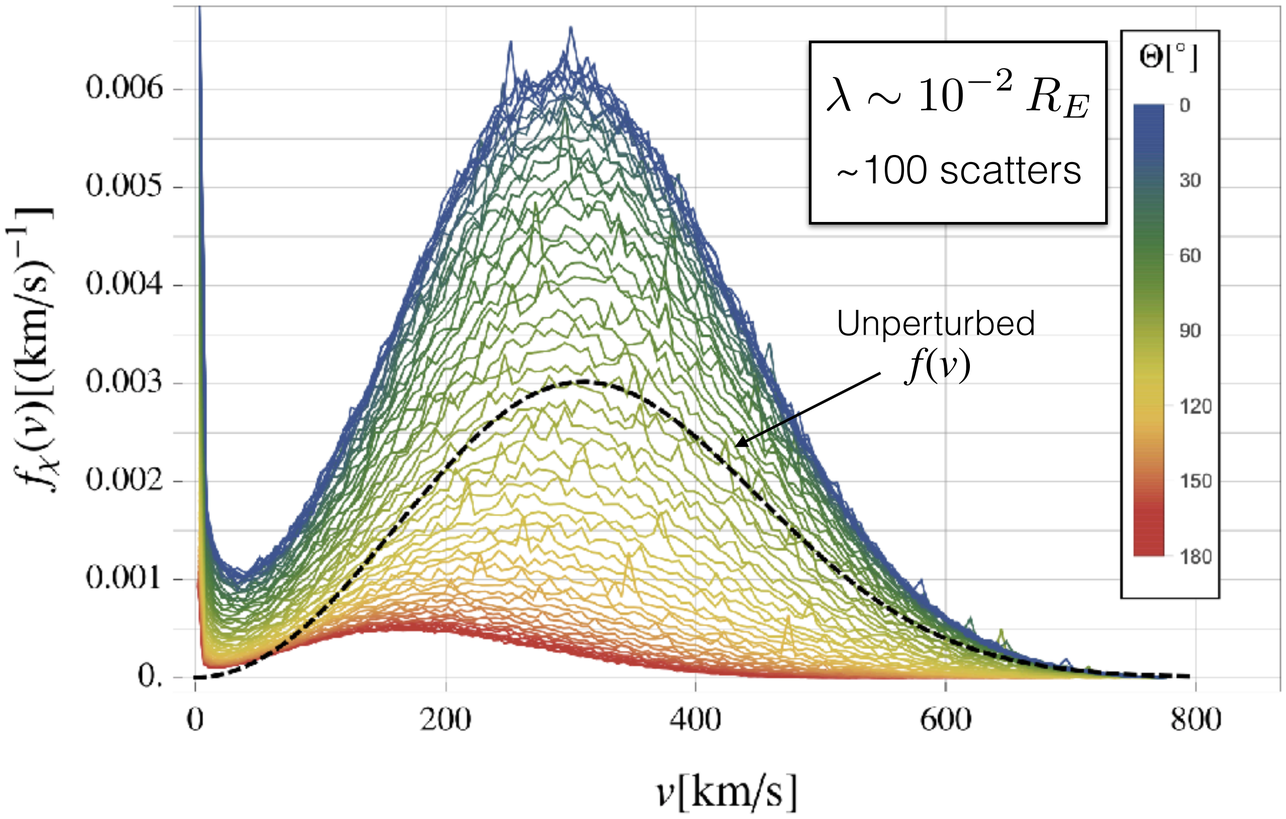
Monte Carlo simulations (especially DaMaSCUS) are the gold standard.

[Emken & Kouvaris - 1706.02249, 1802.04764]

DaMaSCUS: github.com/temken/DaMaSCUS
DaMaSCUS-CRUST: github.com/temken/damascus-crust



Effect depends on the *isodetection angle* Θ and mean free path $\lambda \sim (\sigma n)^{-1}$:

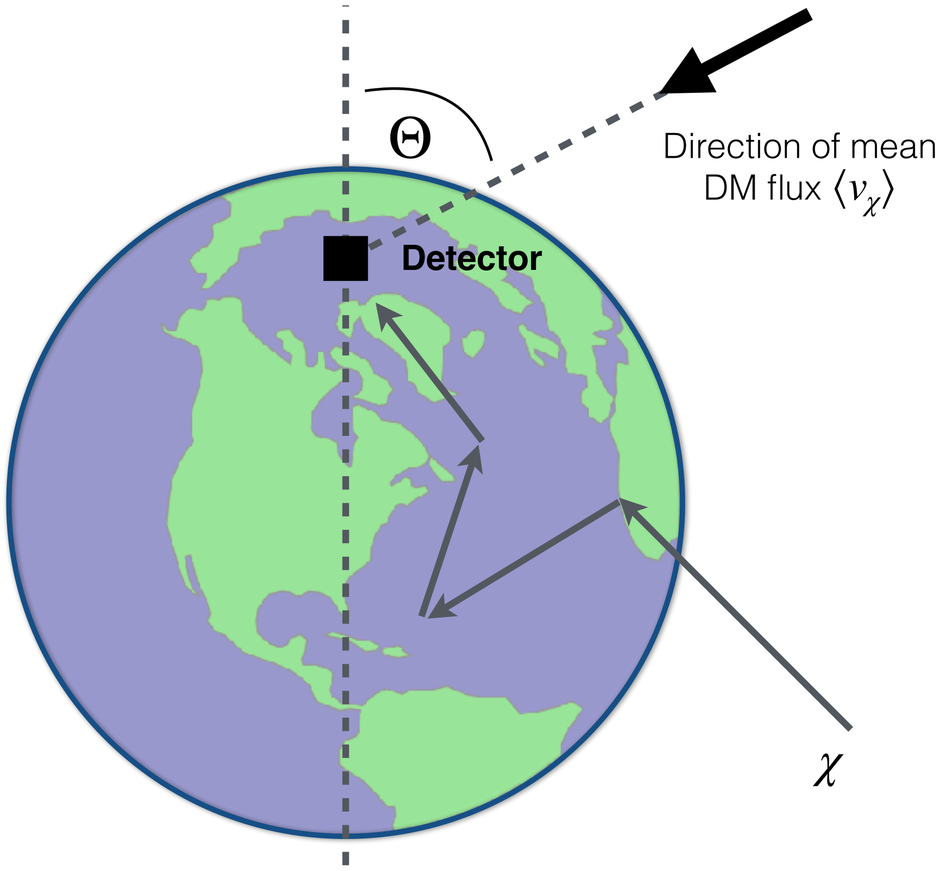


Monte Carlo Simulations

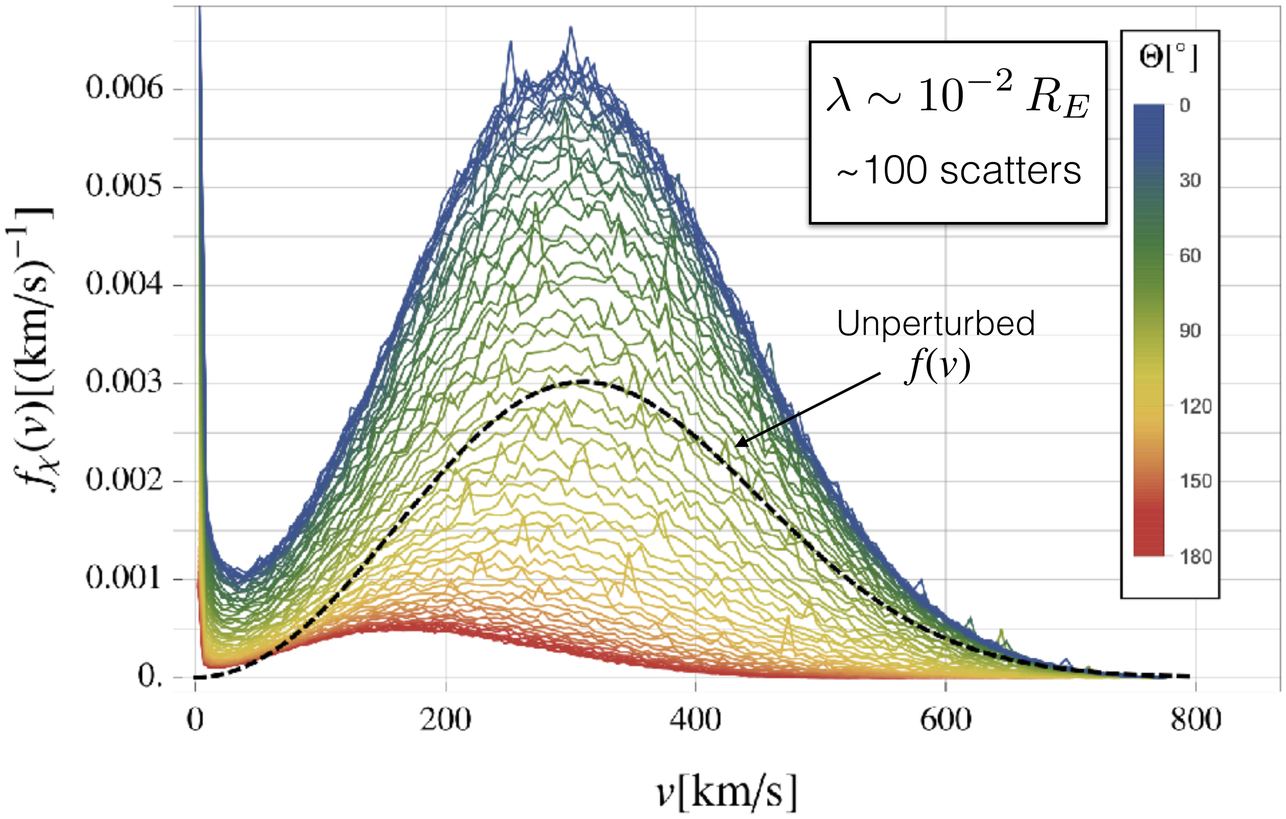
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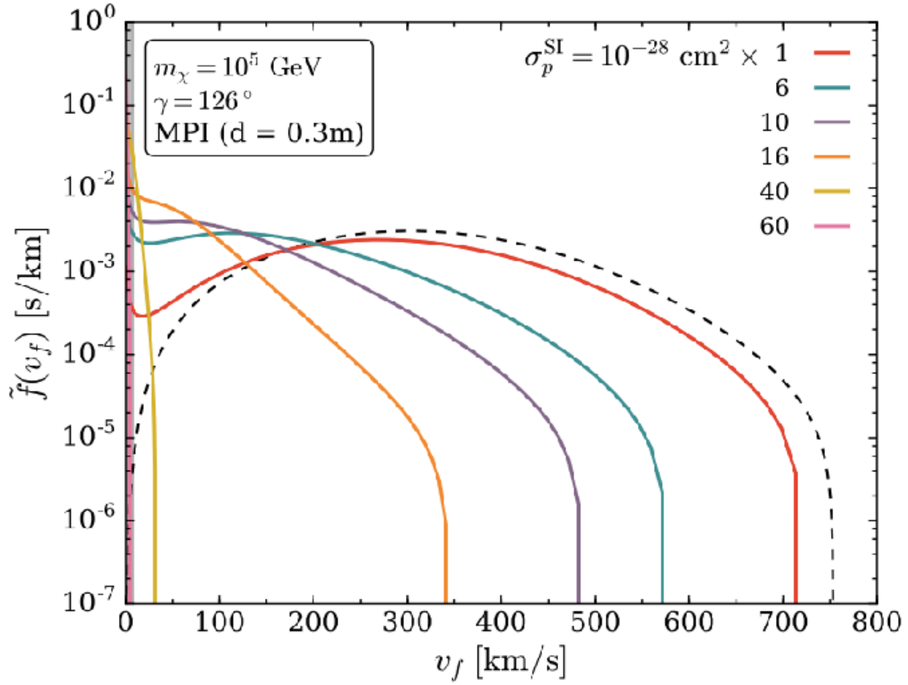
But MC simulations are slow!

VERNE 1.0: Heavy-ish DM

If DM is heavy enough ($\gtrsim$ GeV) with large enough cross-sections, we can assume that it travels in straight lines, losing energy as it scatters with nuclei:

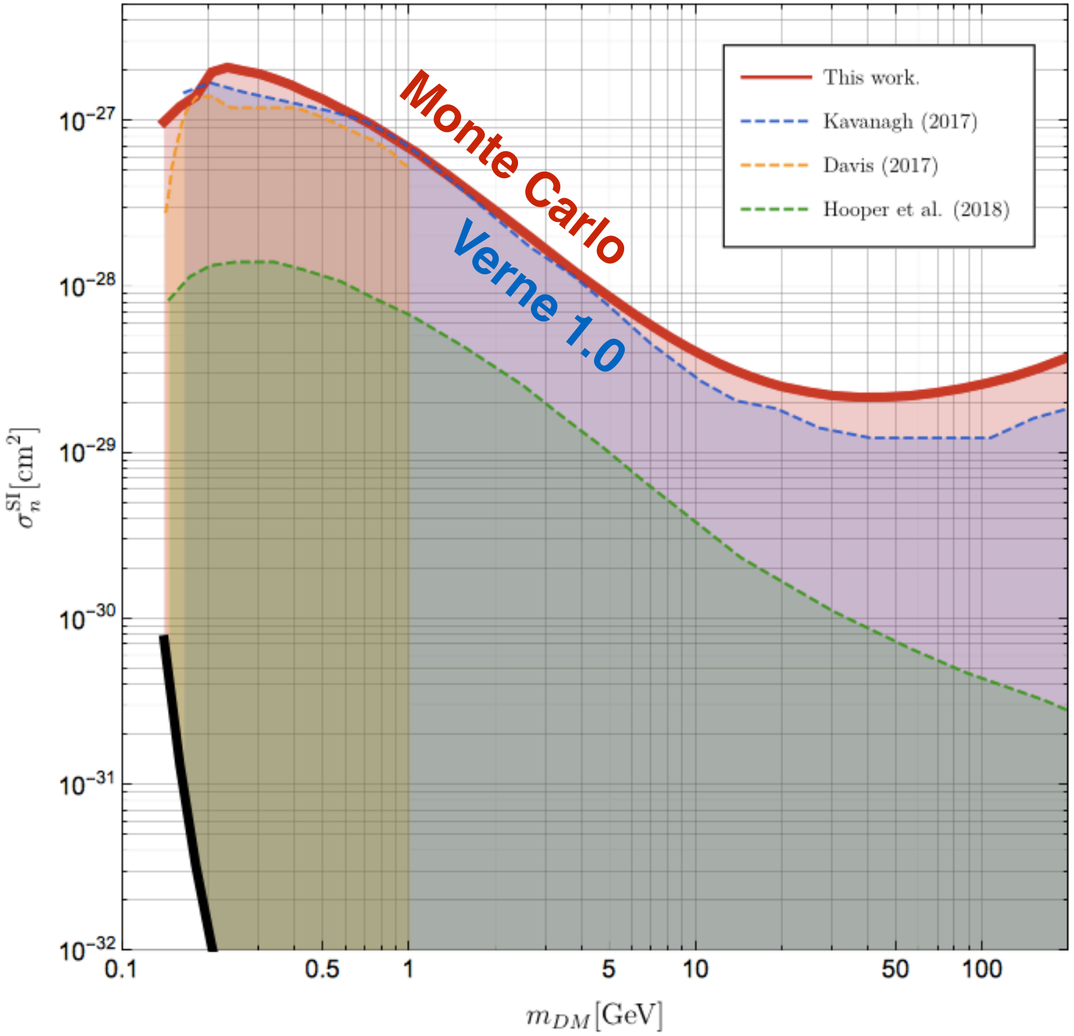
[e.g. Starkman et al. (1990), **BJK**, 1712.04901]

$$\frac{\mathrm{d}\langle E_\chi\rangle}{\mathrm{d}x} = -\sum_i n_i(\mathbf{r})\,\langle E_R\rangle_i\,\sigma_i(v)$$



[Implemented in VERNE 1.0 - https://github.com/bradkav/verne.
Used by EDELWEISS, XENON1T, SuperCDMS, TESSERACT and others]

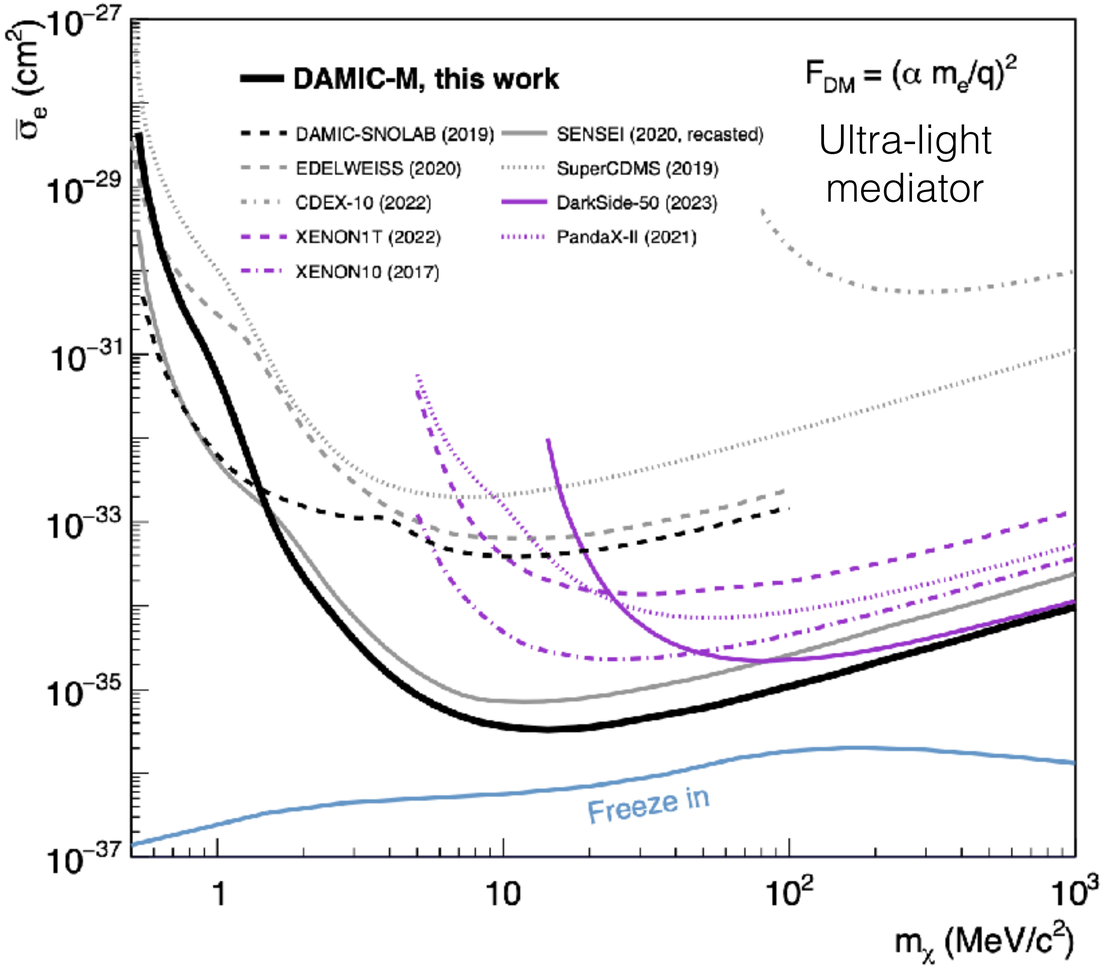
Excluded region from CRESST-surface (2017) using different methods

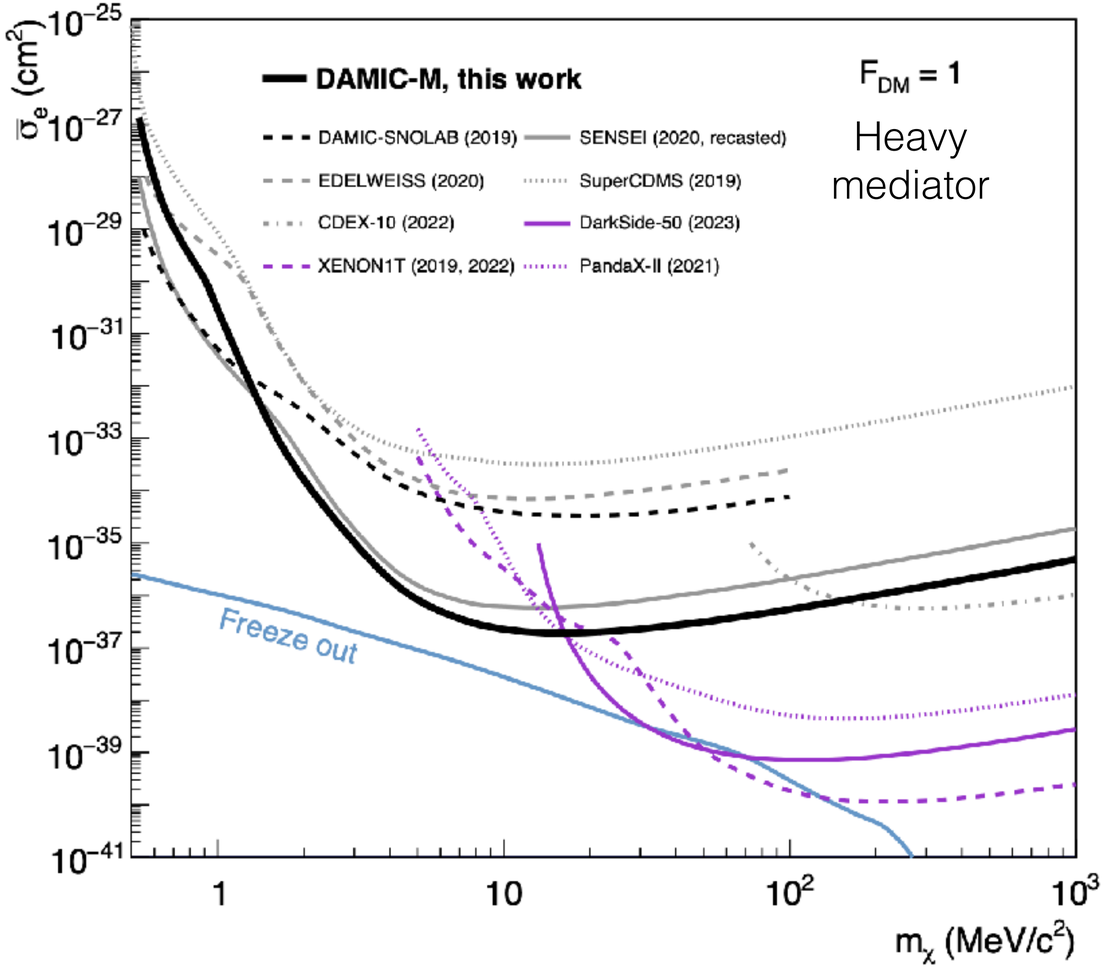


[Emken & Kouvaris - 1706.02249, 1802.04764]

DM-electron scattering

Want to extend to sub-GeV DM! Common benchmark is DM scattering mediated by a Dark Photon, which couples both to electrons and nuclei:





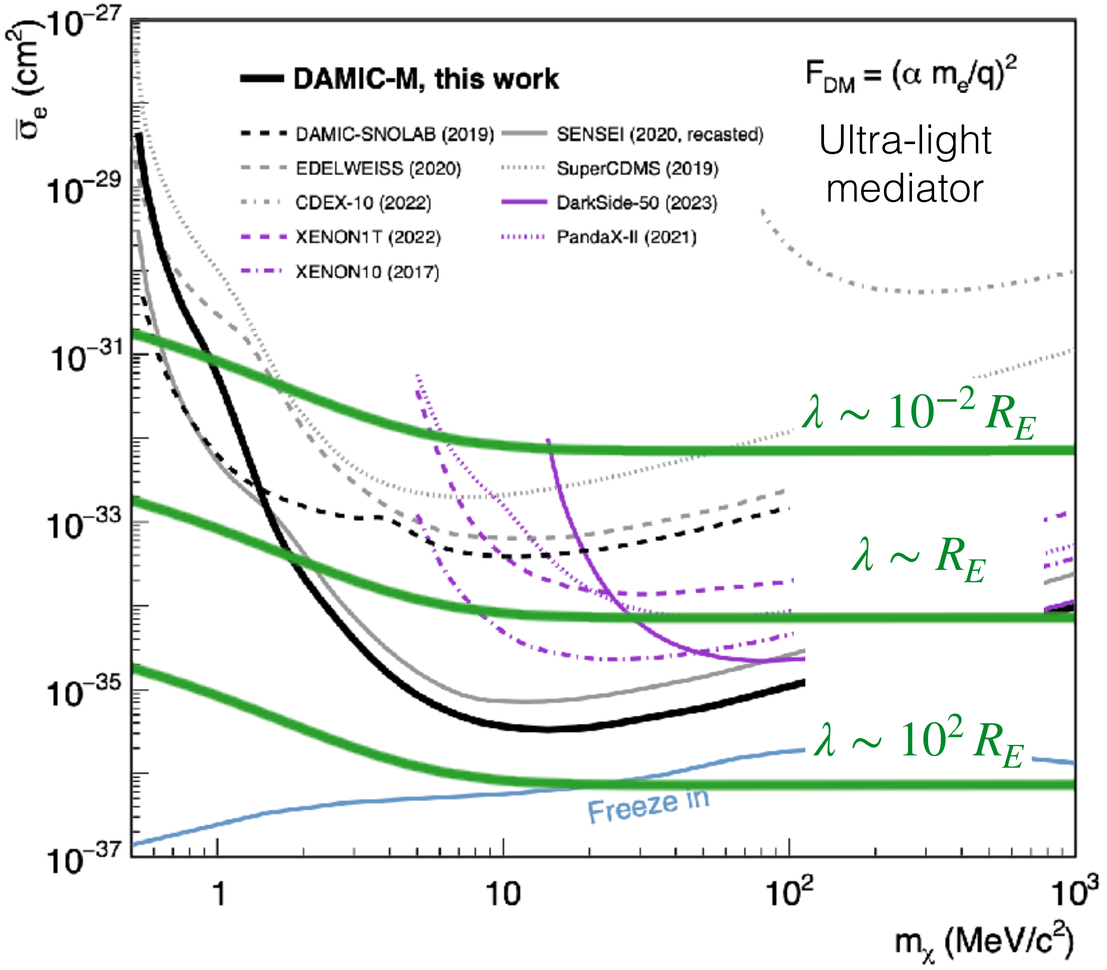
[DAMIC-M, 2302.02372]

DM-electron scattering

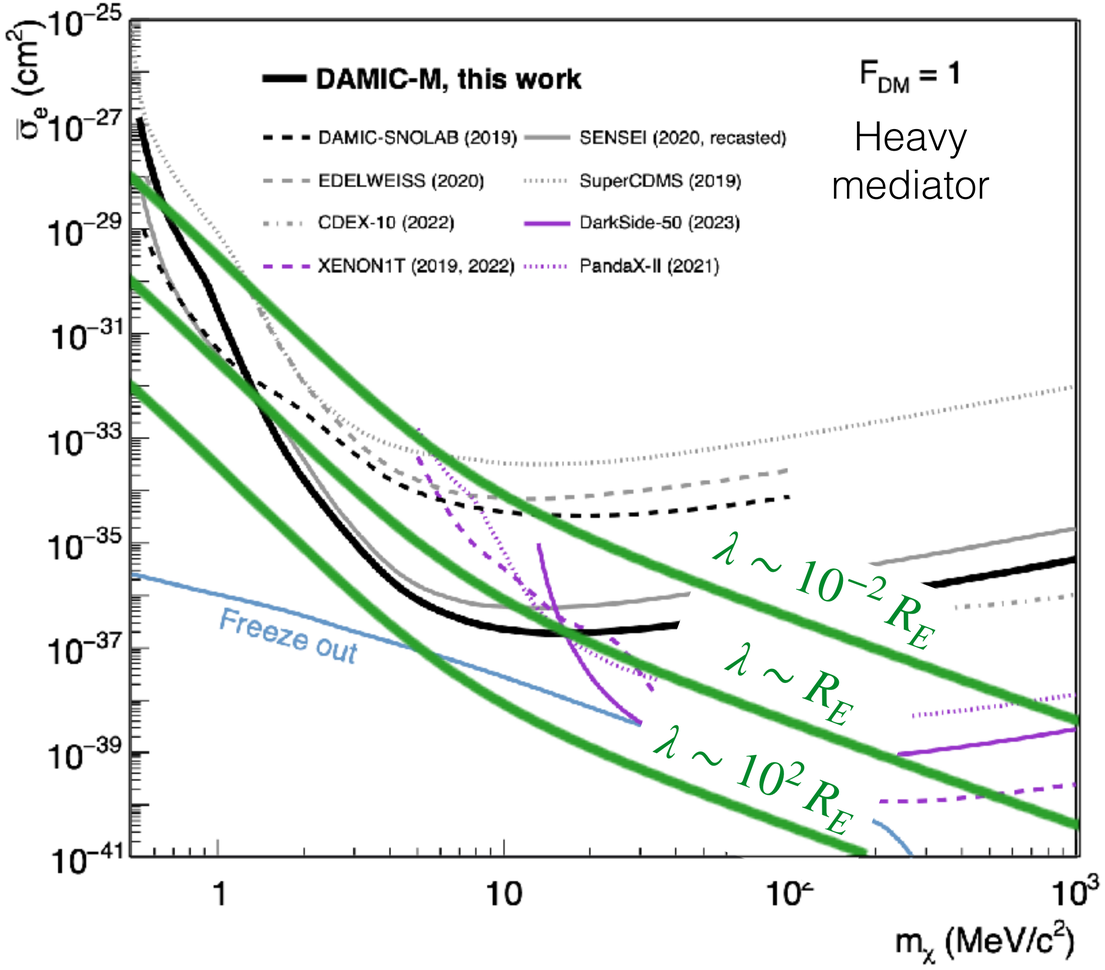
Note: even if the signal comes from DM-electron scattering, the Earth-scattering effect is dominated by DM-nucleus scattering

[Emken et al., 1905.06348]

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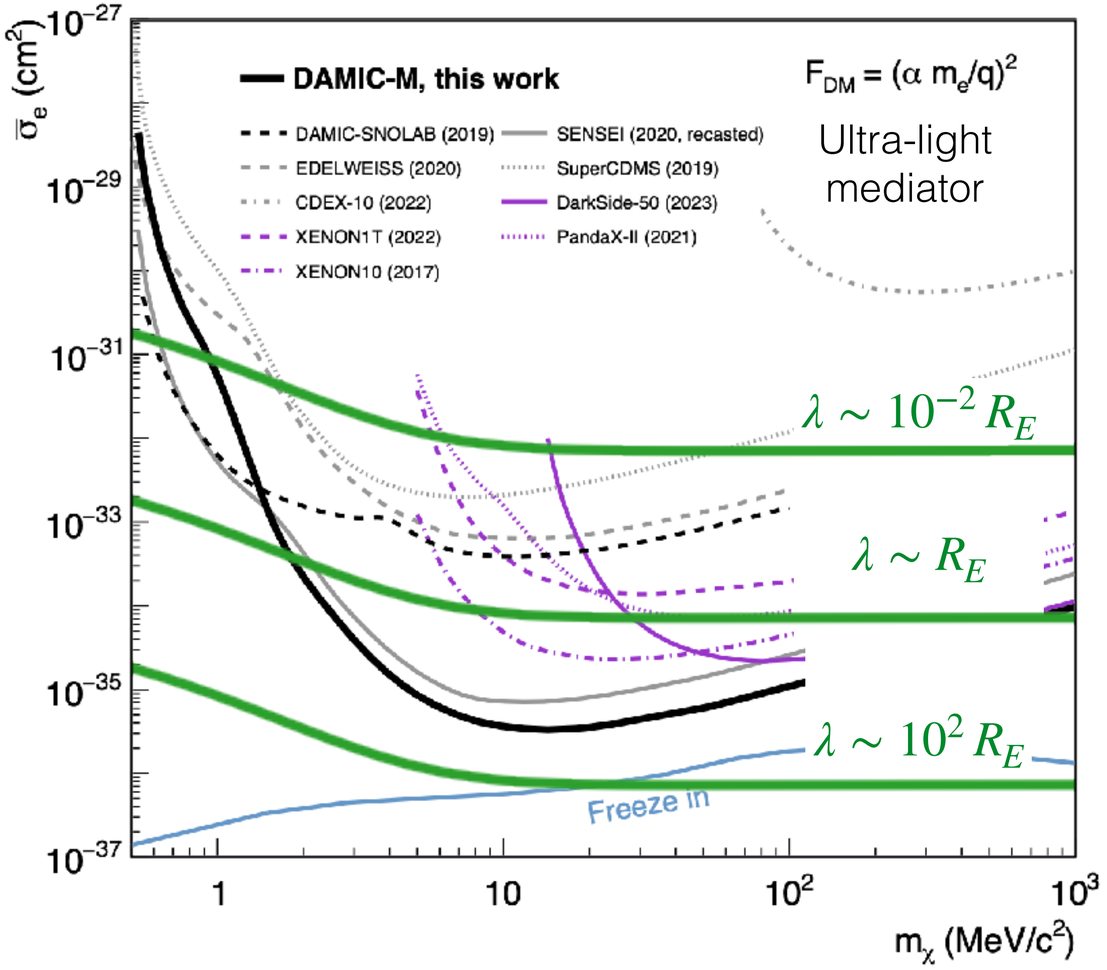


DM-electron scattering

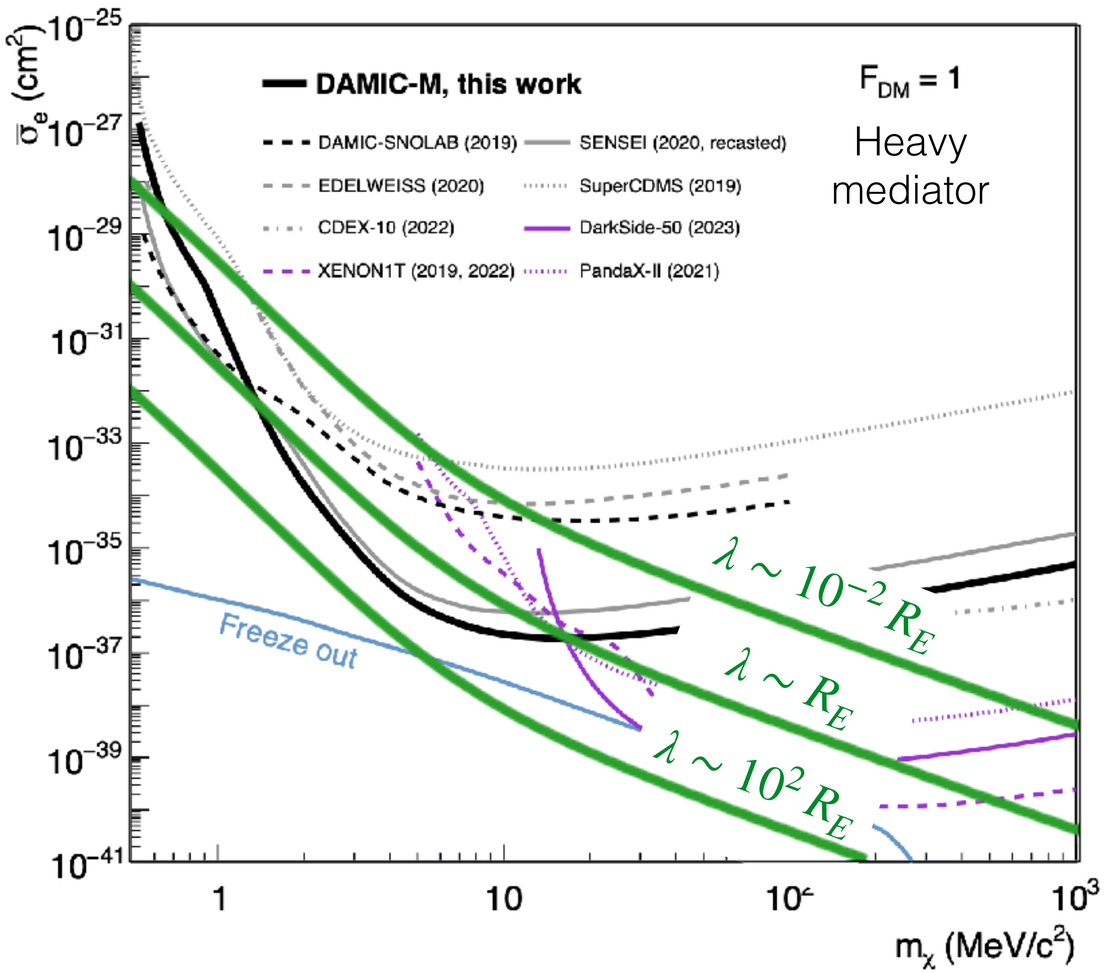
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[Emken et al., 1905.06348]

Want to extend to sub-GeV DM! Common benchmark is DM scattering mediated by a Dark Photon, which couples both to electrons and nuclei:



[DAMIC-M, 2302.02372]



But the original VERNE formalism fails for such light DM!

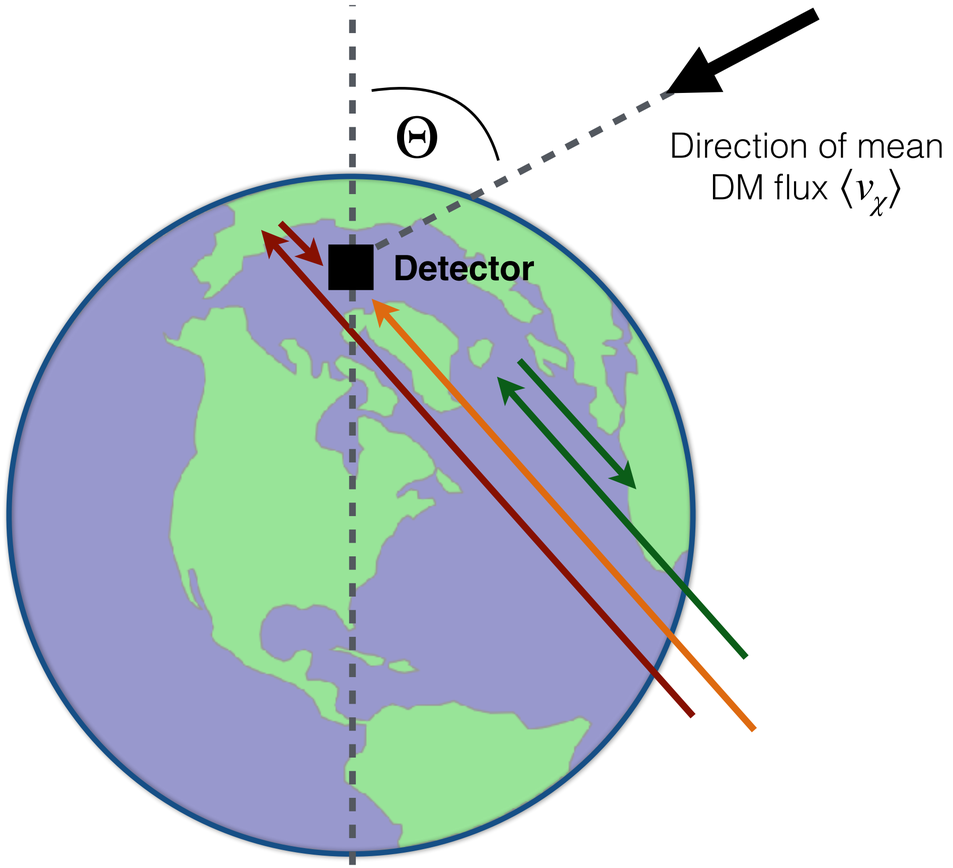
VERNE 2.0: Light DM

Note: even if the signal comes from DM-electron scattering, the Earth-scattering effect is dominated by DM-nucleus scattering

[Emken et al., 1905.06348]

At low mass, DM energy lost per scatter is
$\Delta E/E \sim m_\chi/m_N \ll 1$

For light DM, energy loss is negligible and *deflection* is the most important!



Semi-analytic approach:

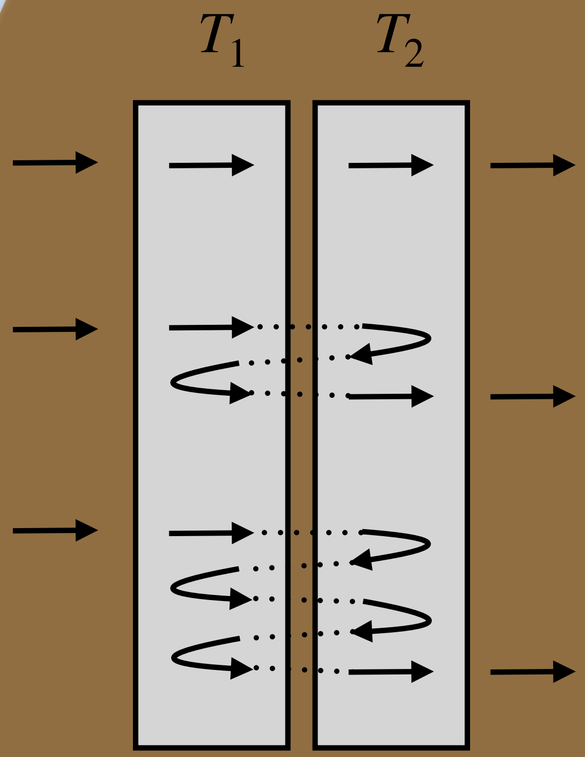
- Assume that DM travels in a straight line along its trajectory.
- If it scatters, it is reflected back along its initial trajectory (without losing energy) with probability $p_{\rm back}$
- For given incident angles (θ, ϕ) calculate flux due to DM particles **transmitted** to the detector $p_{\rm trans}$ and those **reflected** back after passing the detector $p_{\rm refl}$.
- Integrate over all possible incoming trajectories of DM:

[Lantero-Barreda, Centeno-Lorca, **BJK** & Castello-Mor, 2511.10589]

$$f(v,\Theta) = v^2 \int \left[p_{\rm trans}(v,\theta) + p_{\rm refl}(v,\theta)\right] f_i(v,\theta,\phi,\Theta) \mathrm{d}\cos\theta\, \mathrm{d}\phi$$

Transmission and Reflection

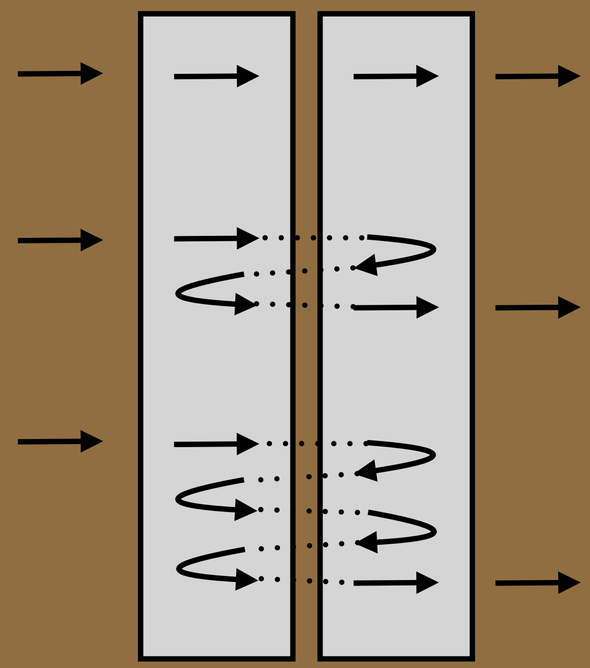
$$R_k = p_{\text{back}} \frac{\mathrm{d}\ell}{\lambda_k} \qquad T_k = 1 - R_k$$



Detector

Transmission and Reflection

$$R_k = p_{\text{back}} \frac{\mathrm{d}\ell}{\lambda_k} \qquad T_k = 1 - R_k$$



$$T^{(2)} =$$

$$T_1 T_2$$

$$+$$

$$T_1 R_1 R_2 T_2$$

$$+$$

$$T_1 (R_1 R_2)^2 T_2$$

$$\vdots$$

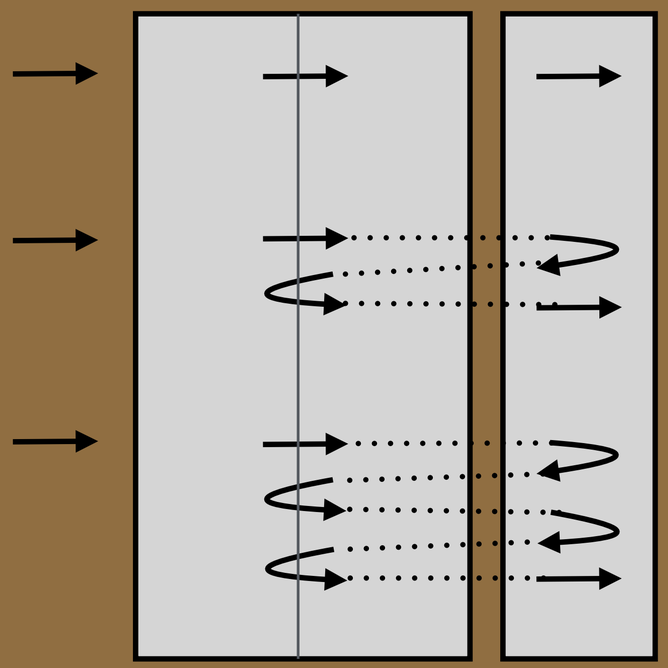
$$= \frac{T_1 T_2}{T_1 + T_2 - T_1 T_2}$$

Detector



Transmission and Reflection

$$R_k = p_{\text{back}} \frac{\mathrm{d}\ell}{\lambda_k} \qquad T_k = 1 - R_k$$



$$T^{(3)} =$$

$$T^{(2)}T_3$$

$$+$$

$$T^{(2)}R^{(2)}R_3T_3$$

$$+$$

$$T^{(2)}(R^{(2)}R_3)^2T_3$$

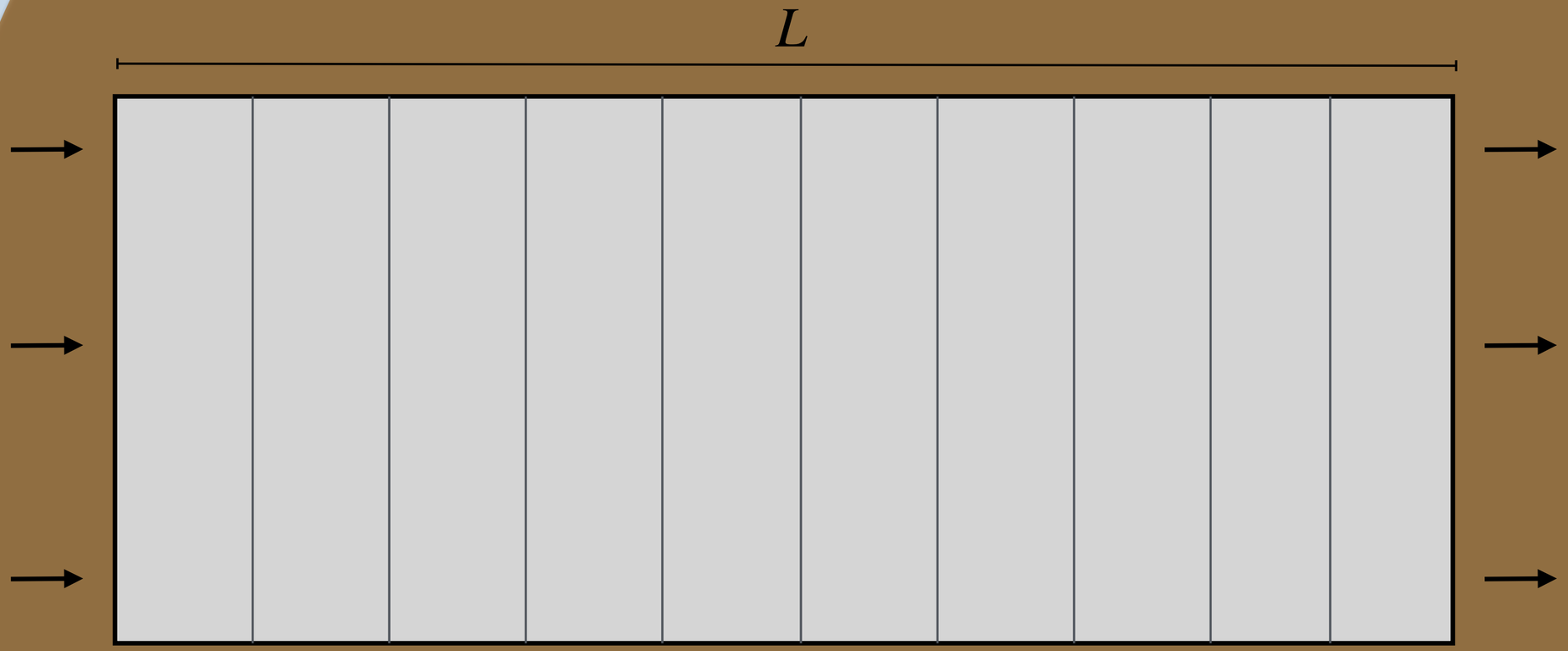
$$\vdots$$

$$= \frac{T_1T_2T_3}{T_1T_2 + T_2T_3 + T_1T_3 - 2T_1T_2T_3}$$

Detector

Transmission and Reflection

Divide the distance L into N layers, then take the limit $N \to \infty$



$$T_{\text{total}} \equiv p_{\text{trans}} = \frac{1}{\sum_k T_k^{-1} - (N-1)} \to \frac{1}{1+\tau(L)}$$

"Optical Depth"

$$\tau(L,v) = p_{\text{back}} \sum_i^{\text{species}} \int_0^L \frac{\mathrm{d}l}{\lambda_i(\mathbf{r},v)}$$

and analogously for the reflection probability

VERNE Code

Verne formalism for light DM now publicly available.

Code for calculating initial and final velocity distributions, and mapping between time and isodetection angle. Comes with several example scripts and notebooks

Includes tabulated density profiles for the Earth (O, Si, Mg, Fe, Ca, Na, S, Al) and atmosphere (O, N).

Includes several options for interactions:

- Standard Spin-independent (SI)
- Heavy dark photon mediator
- Ultra-light dark photon mediator

Actual transmission and reflection probabilities are simple, fast and accurate up to a large number of scatters!

Fast integration by tabulating the optical depth τ over all incoming directions.

README MIT license

[github.com/bradkav/verne]

Verne 2.1

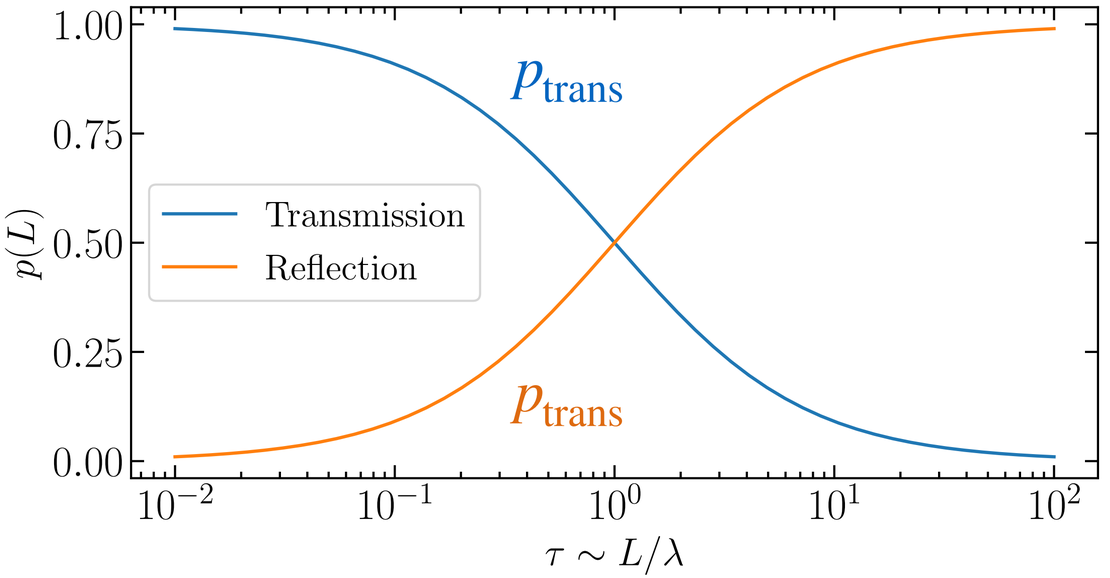
DOI 10.5281/zenodo.15359975 arXiv 1712.04901 licence MIT

Verne is a python code for calculating the Earth-stopping effect for Dark Matter (DM).

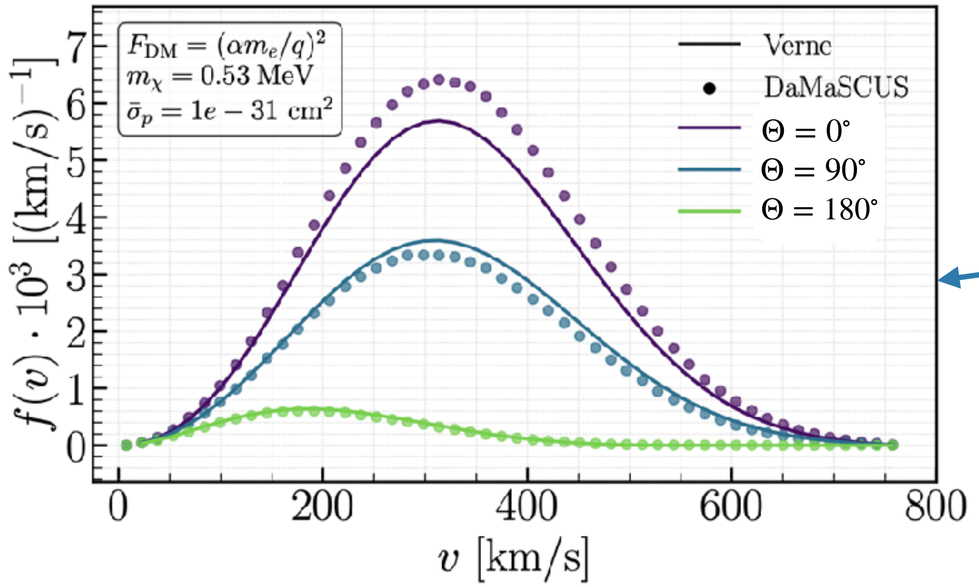
The code allows you to calculate the speed distribution (and DM signal rate) at detectors in the Earth's atmosphere, on the Earth's surface and at underground detector locations, such as MPI (the Max-Planck-Institute in Munich) and SUF (the Stanford Underground Facility). This can be done for a range of DM masses and cross sections (though the results will be most reliable for very heavy DM particles). This is because the code implements a 'continuous stopping' formalism, with DM particles travelling on straight-line trajectories. Further details about the physics behind the code can be found in arXiv:1712.04901.

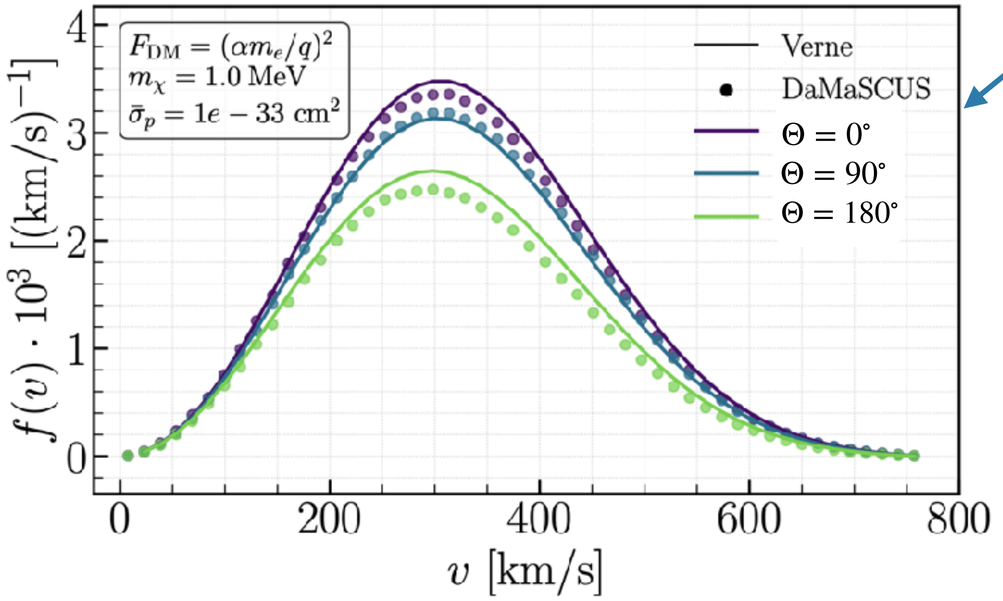
As of Version 2.0, there is now an additional module `verne_light`, which implements the Earth-scattering of very light DM, in which energy losses are negligible, and particles travel on straight-line trajectories with the possibility

Note: the Verne definition of the isodetection angle γ differs from that of DaMaSCUS: $\gamma = \pi - \Theta$

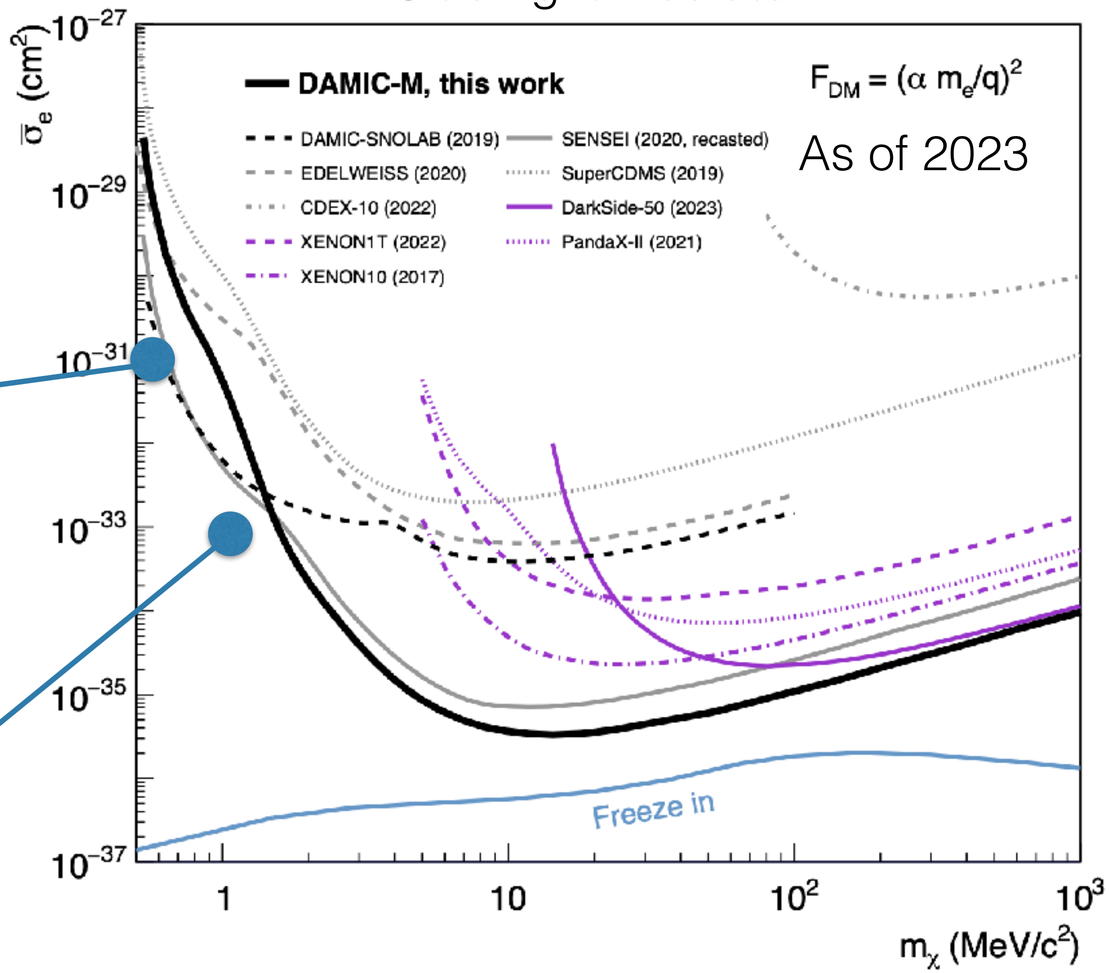


DaMaSCUS Comparison





Ultra-light mediator

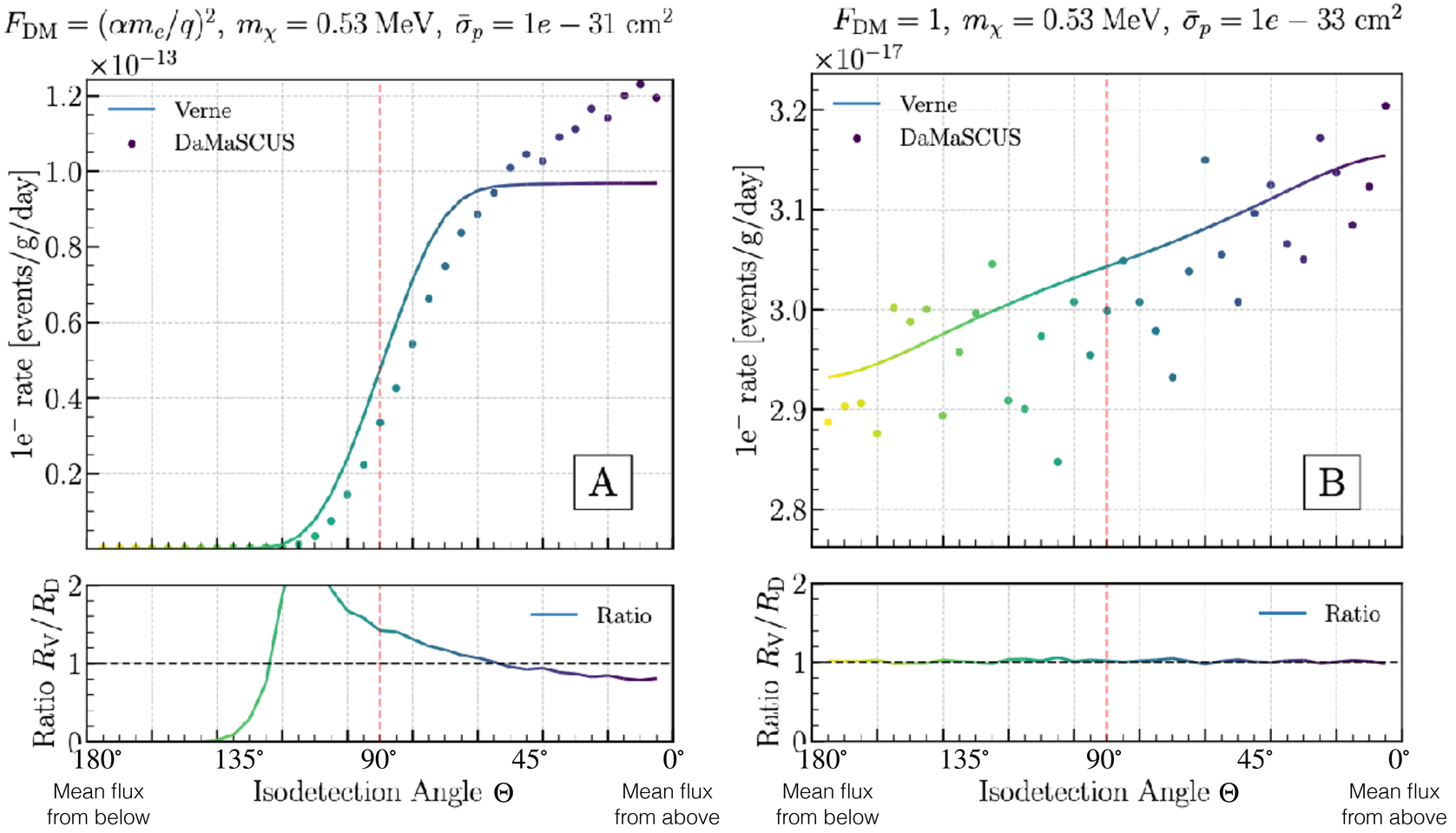


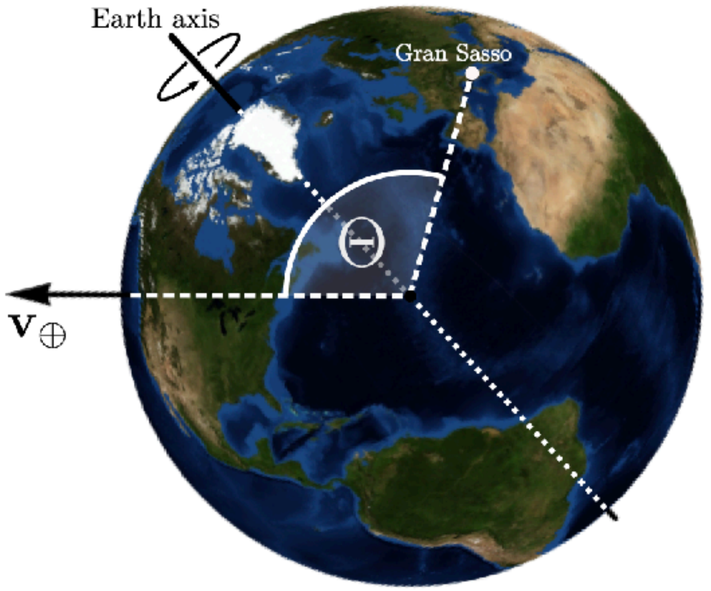
VERNE typically gives a 10-30% error on the rate, at a computational cost ~10^4 times smaller than DaMaSCUS (with less noise in the high-velocity tail)

[Lantero-Barreda, Centeno-Lorca, **BJK** & Castello-Mor, 2511.10589]

Daily Modulation Signals

Calculate single electron rate in Silicon as a function of isodetection angle:

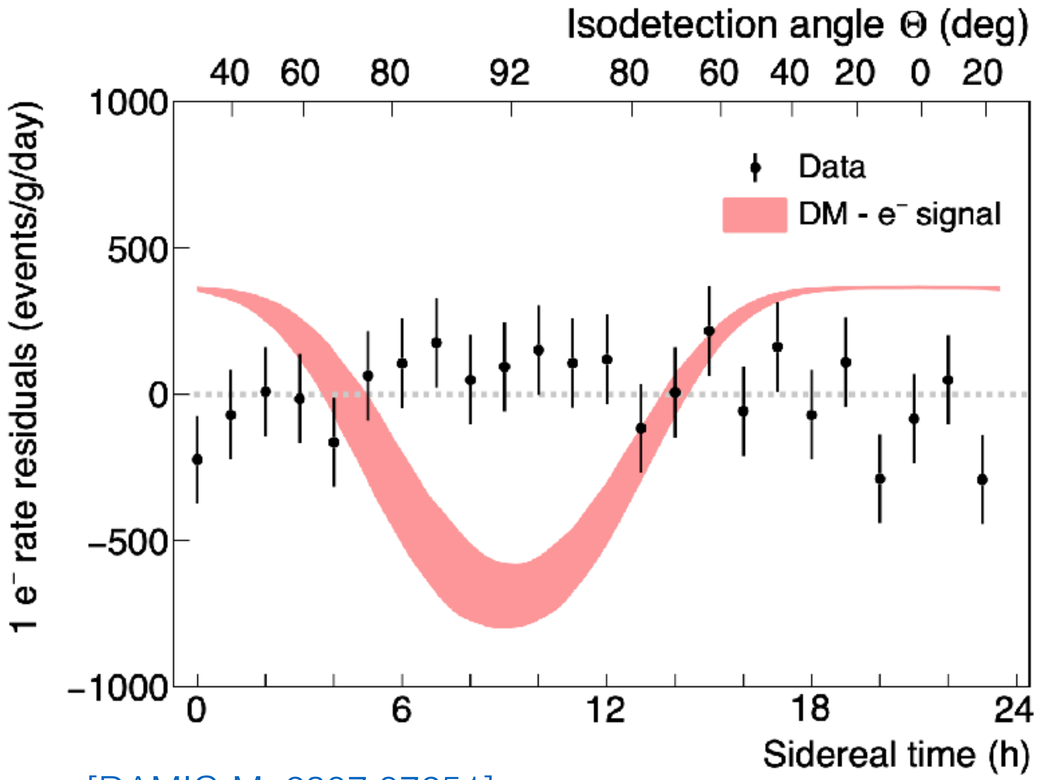




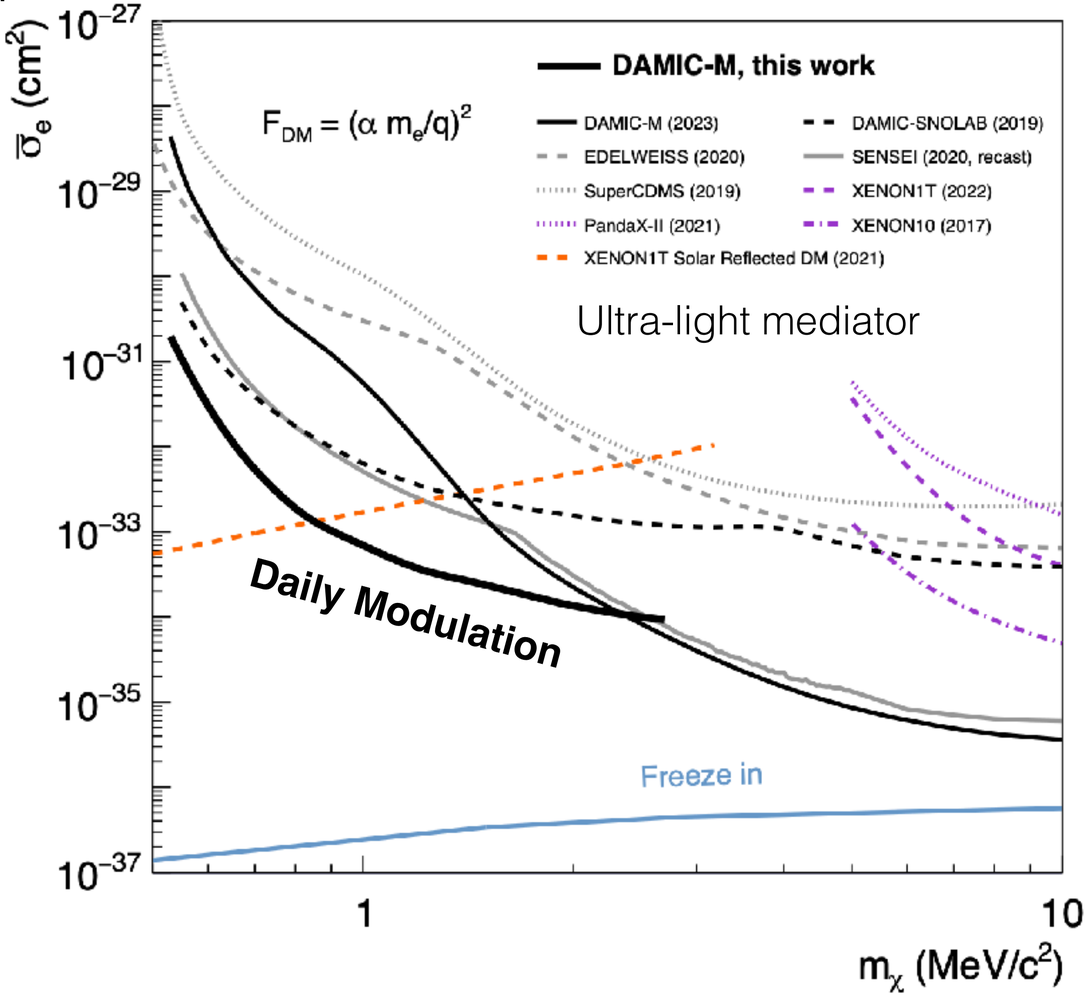
Gives rise to a characteristic daily modulation signal!

Constraints with DAMIC-M

Backgrounds and noise are not expected to exhibit this daily modulation signature. “Subtract off” the mean $1e^-$ rate and look only at the time-dependent signal:



[DAMIC-M, 2307.07251]

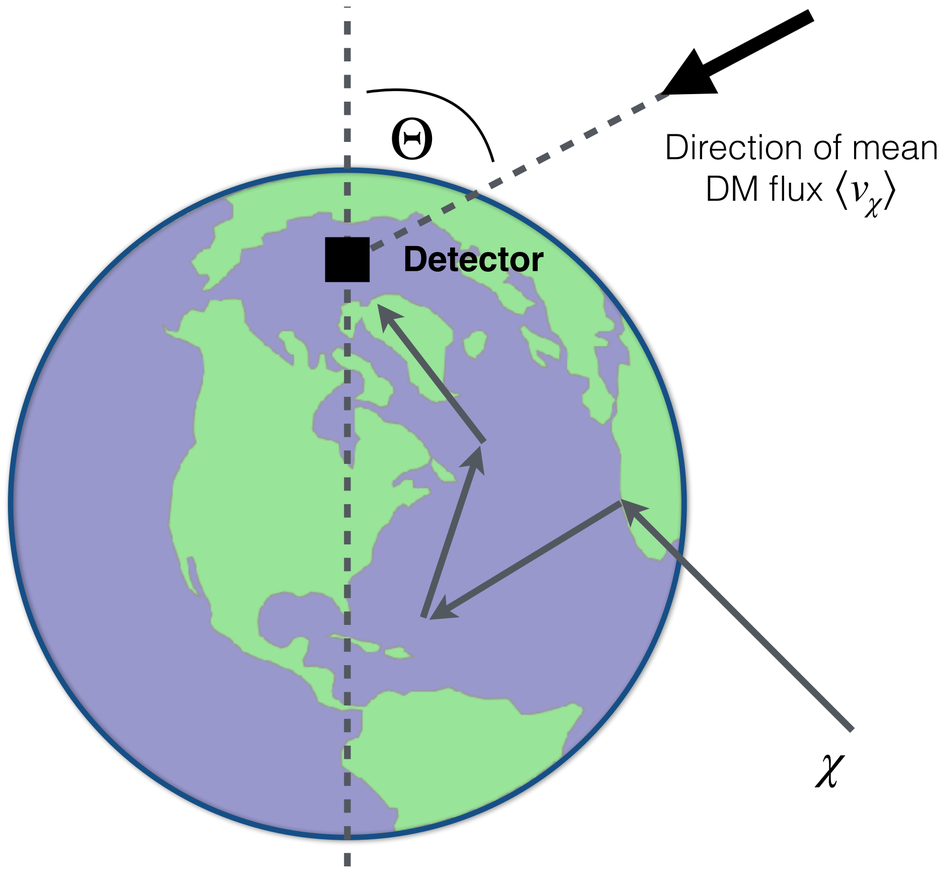


Fast calculations with VERNE meant that we could also study systematics in e.g. Earth’s orbital velocity!

[More recently updated daily modulation constraints in DAMIC-M, 2511.13962]

Conclusions

- **Earth-scattering effects** are inevitable as we probe new direct detection parameter space - and they give rise to interesting signals!
- Monte Carlo simulations like DAMASCUS are the gold standard, but slow!
- We want **fast simulations** to explore large parameter spaces and systematics. Potentially follow up signals/hints with dedicated MC simulations.
- **VERNE** provides these fast simulations in different mass regimes and for a range of DM interaction models
- I'm happy to take **suggestions**, or to help people use the code!

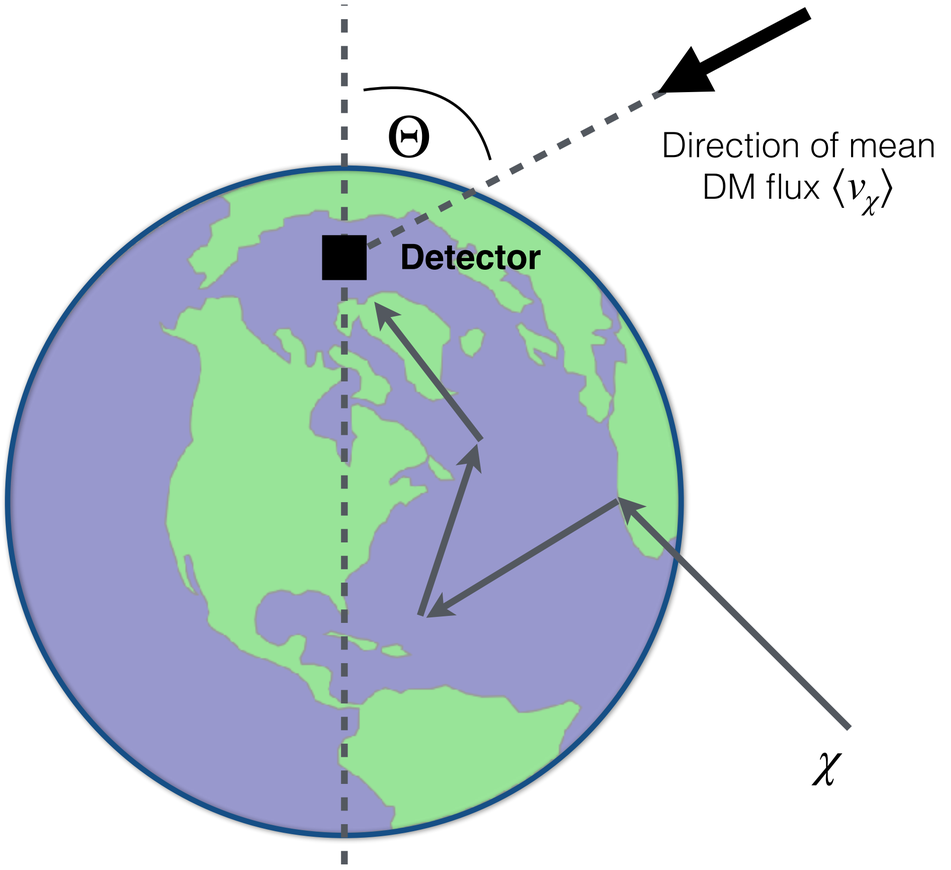


[**BJK**, 1712.04901; Lantero-Barreda, Centeno-Lorca, **BJK** & Castello-Mor, 2511.10589; github.com/bradkav/verne]

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Backup Slides

Back-scattering probability

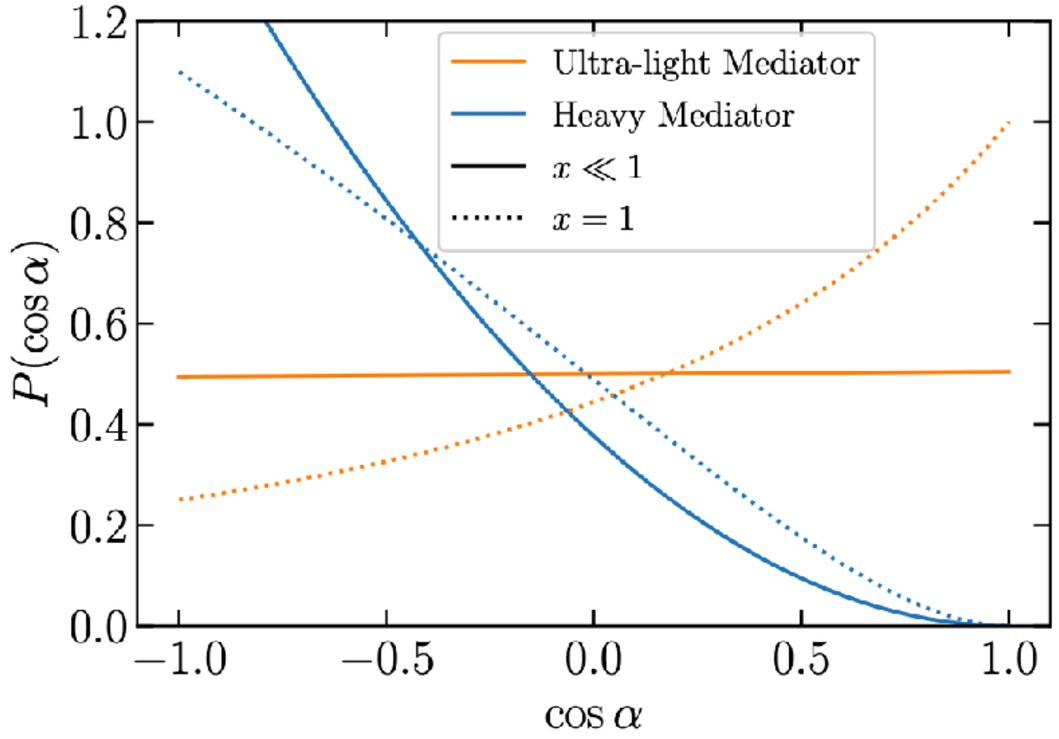


FIG. 3. **Distribution of the deflection angle α.** Note that $\cos\alpha = 1$ corresponds to forwards scattering while $\cos\alpha$ corresponds to backwards scattering.

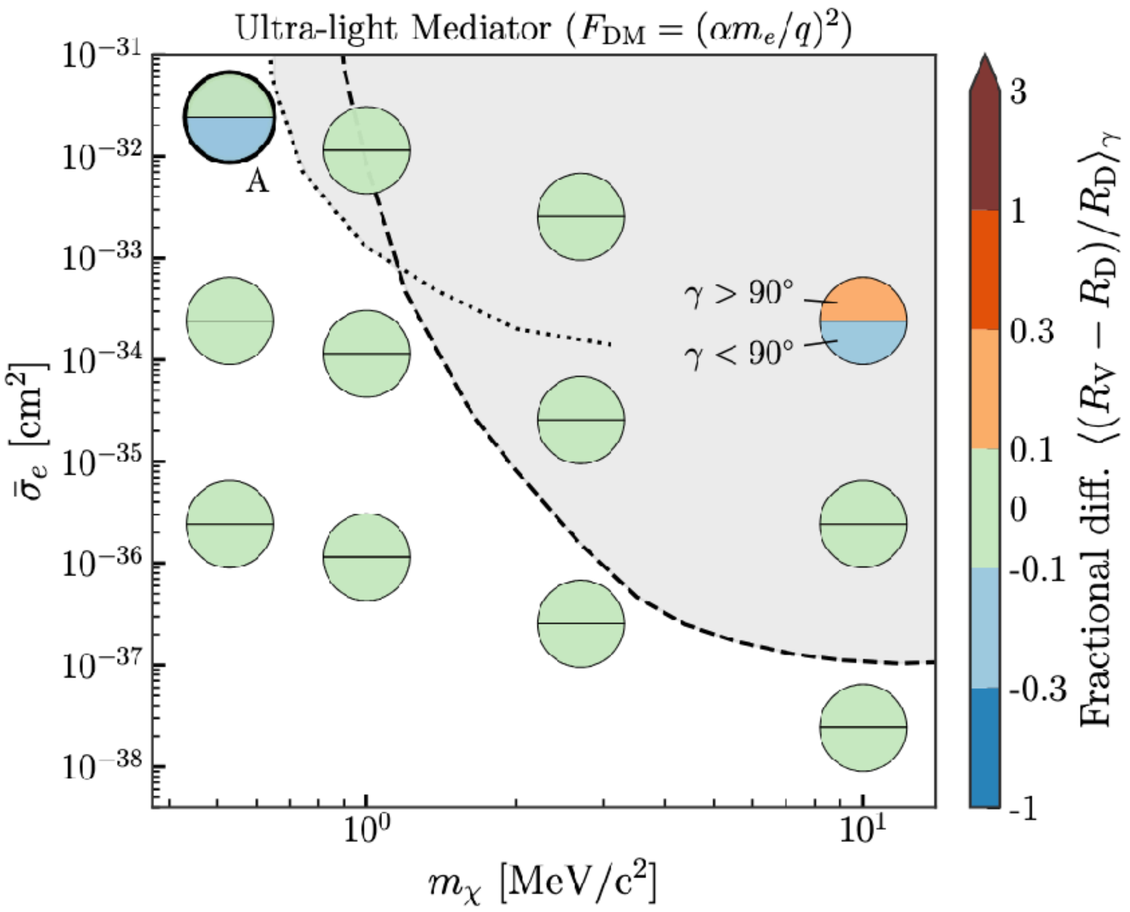
scattering dominates, but less justified for the ultra-light mediator, for which the deflection is nearly isotropic. In order to quantify the probability of backward scattering, we use the distributions in Eq. (8) to calculate:

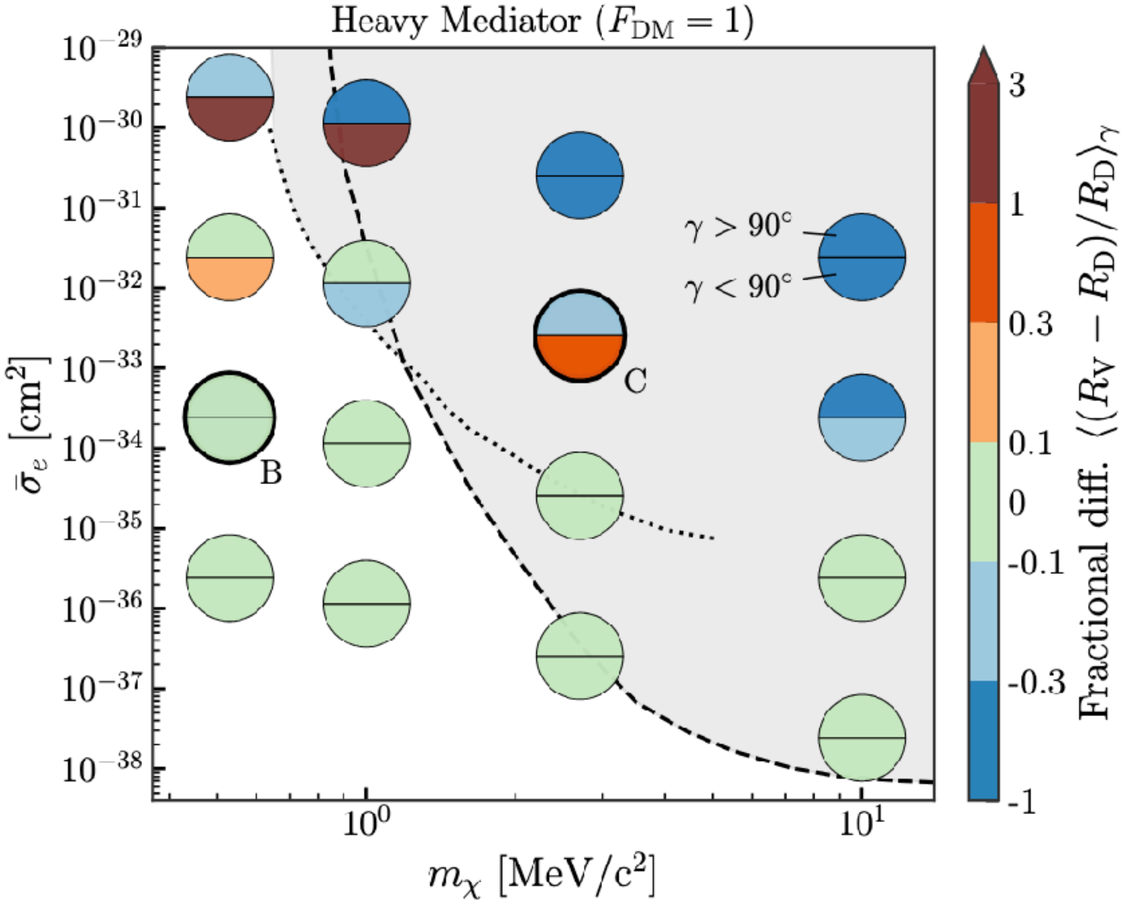
$$p_{\rm back} = \int_{-1}^{0} P(\cos\alpha)\, \mathrm{d}\cos\alpha\,. \tag{12}$$

This gives the fraction of scattering events in which the DM is deflected through more than 90°, into the backwards hemisphere. In the limit $x \to 0$, we obtain:

$$p_{\rm back} = \begin{cases} \frac{7}{8}\,, & \text{(HM)} \\ \frac{1}{2}\,. & \text{(ULM)} \end{cases} \tag{13}$$

Error on the rate



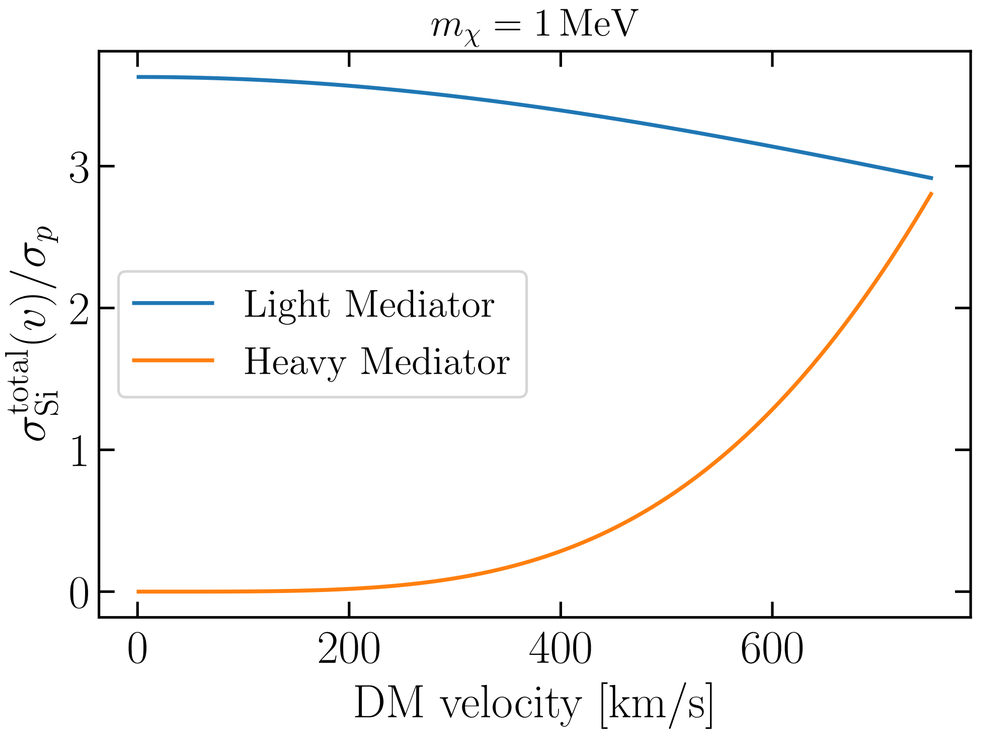


Total cross section

Heavy Mediator

$$\sigma_N^{\rm tot} = \bar{\sigma}_p \left(\frac{\mu_{\chi N}}{\mu_{\chi p}}\right)^2 Z^2 \times \begin{cases} \left(1 + \frac{1}{1+a^2 q_{\rm max}^2} - \frac{2}{a^2 q_{\rm max}^2} \log(1 + a^2 q_{\rm max}^2)\right) , & \text{for } F_{\rm DM}(q) = 1 , \\ \frac{a^4 q_{\rm ref}^4}{(1+a^2 q_{\rm max}^2)} , & \text{for } F_{\rm DM}(q) = \left(\frac{q_{\rm ref}}{q}\right)^2 \end{cases}$$

Light Mediator



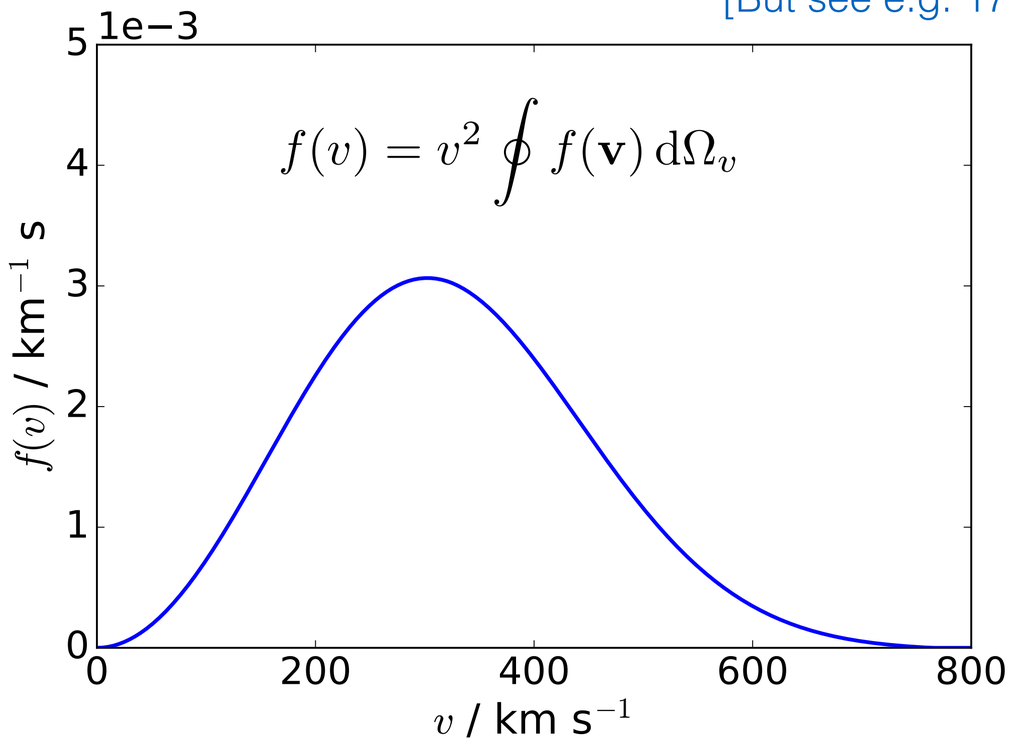
Standard Halo Model

Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution (*in the lab frame*):

$$f_{\rm Lab}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_{\rm e})^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v}-\mathbf{v}_{\rm e}| - v_{\rm esc})$$

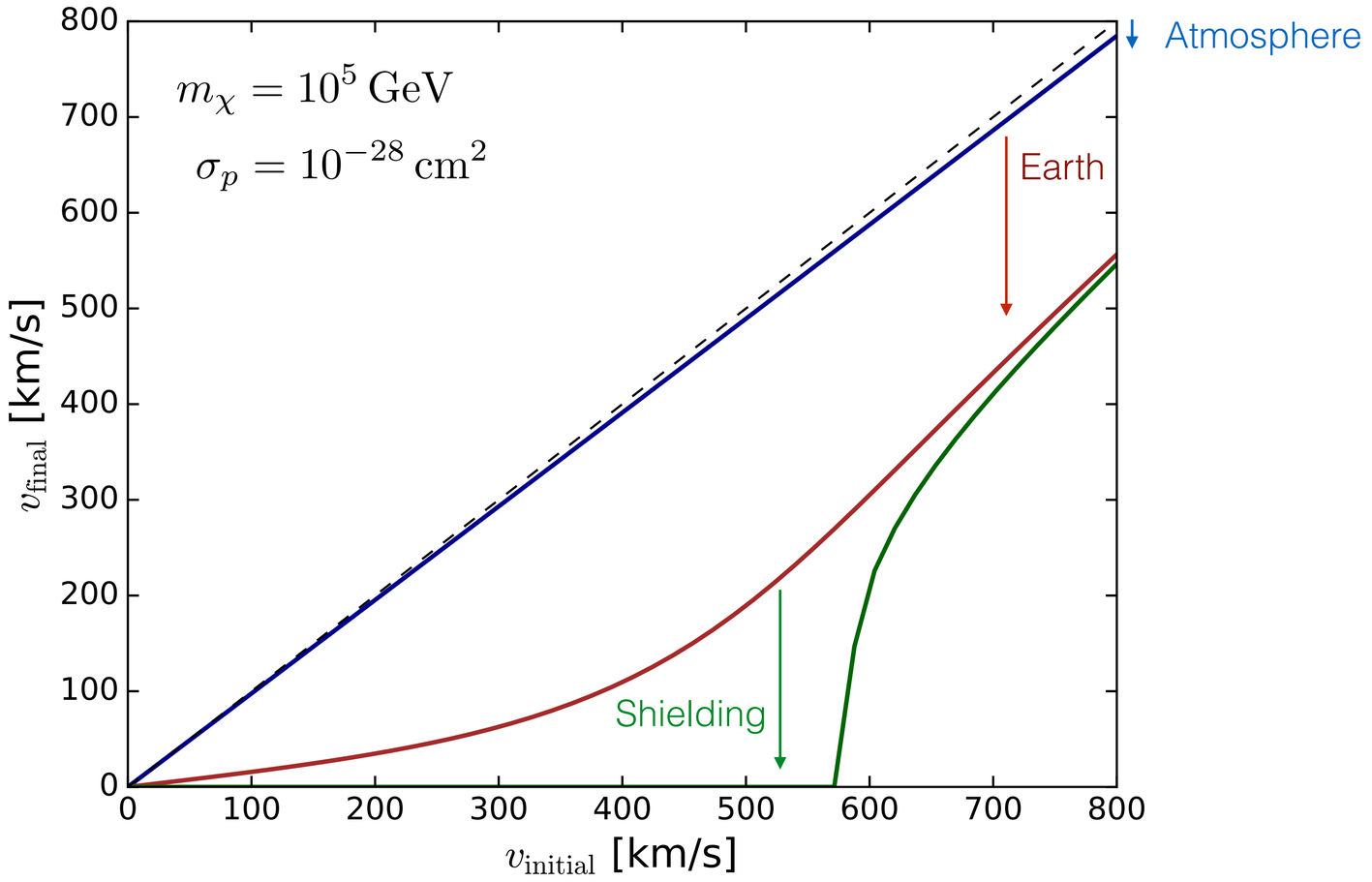
[But see e.g. 1705.05853]



Stopping Power

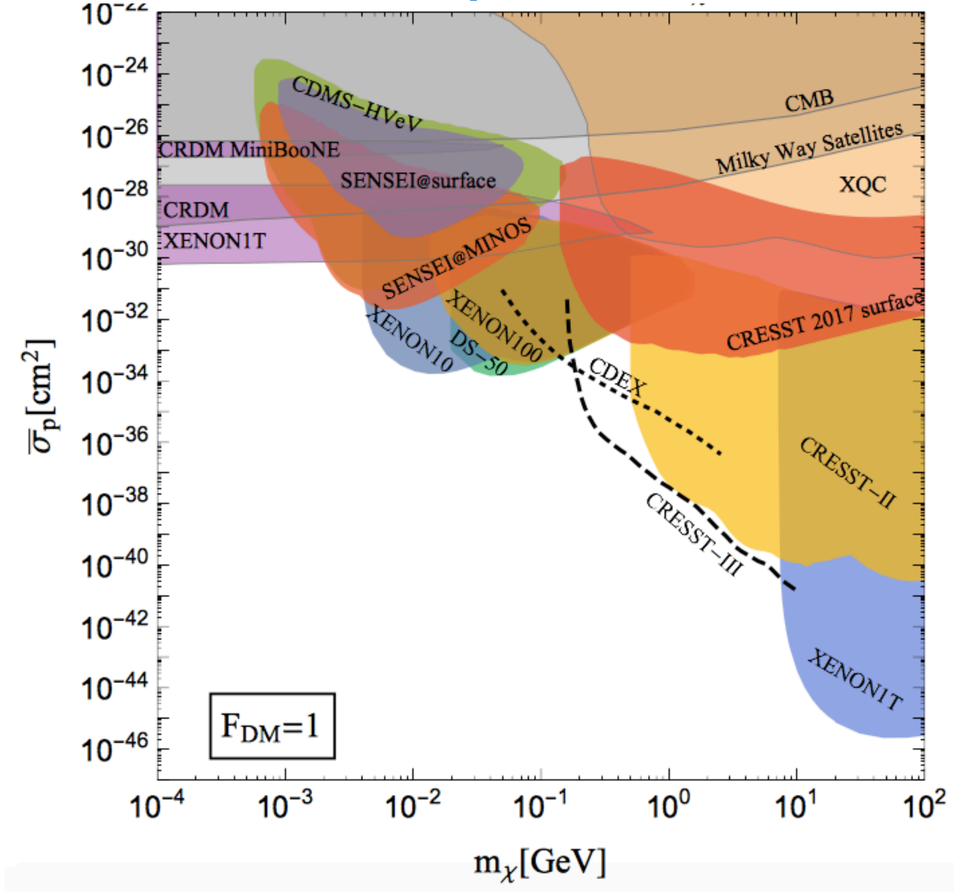
Consider a detector at a depth of 10.6m, with DM particles coming from directly overhead:

CDMS I at the Stanford Underground Facility
[astro-ph/0203500]

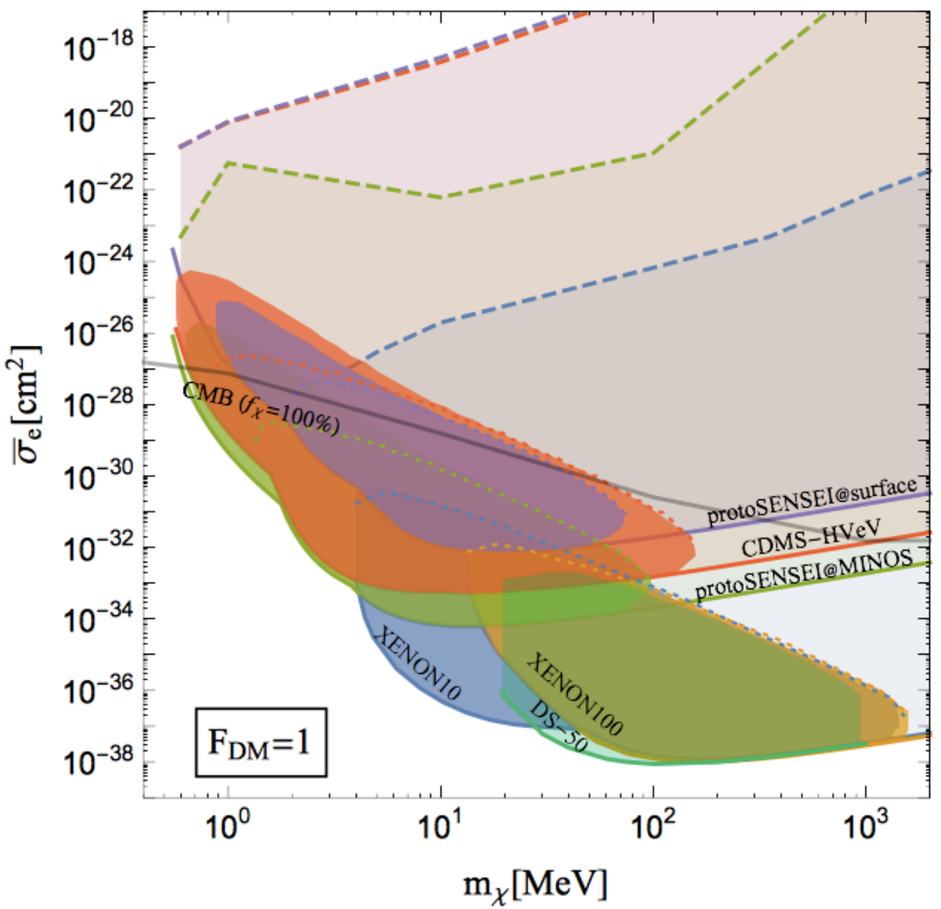


DM-Electron scattering + Monte Carlo

DM-proton



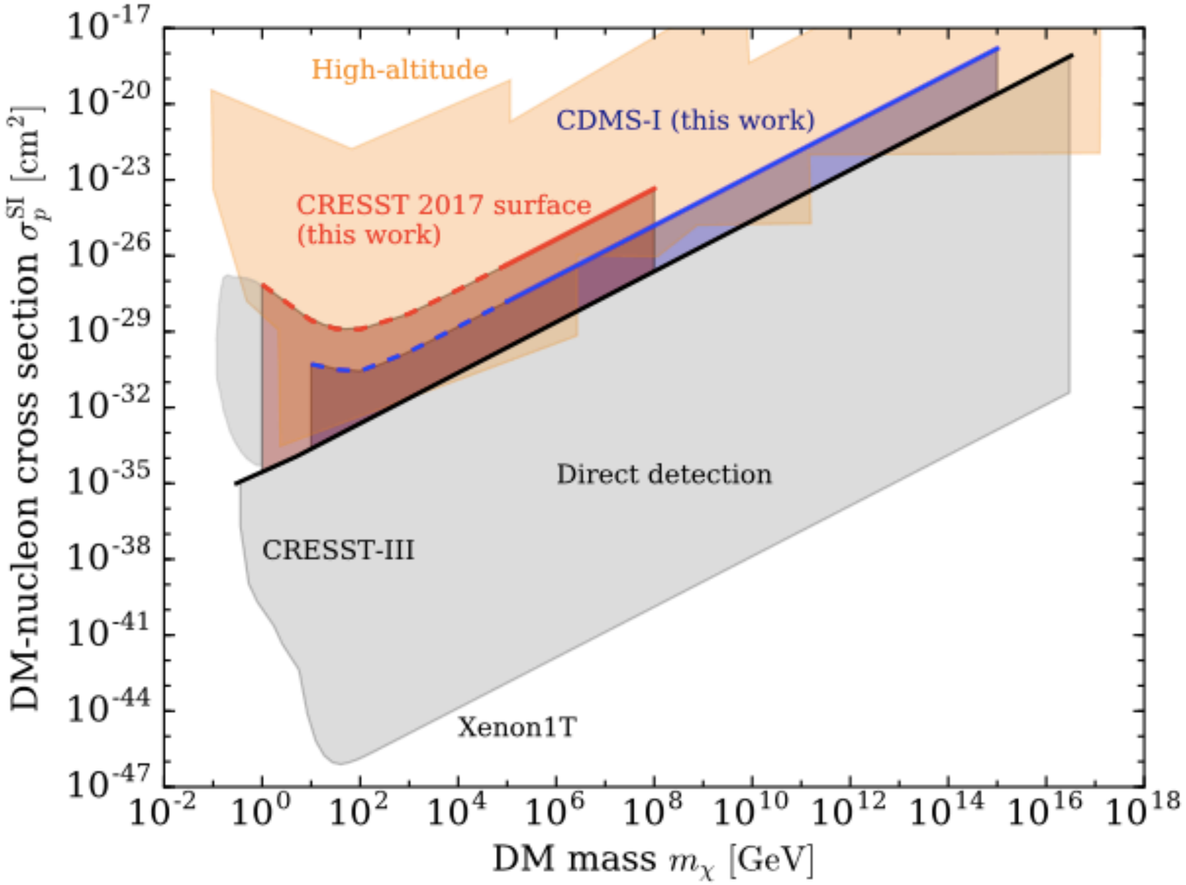
DM-electron



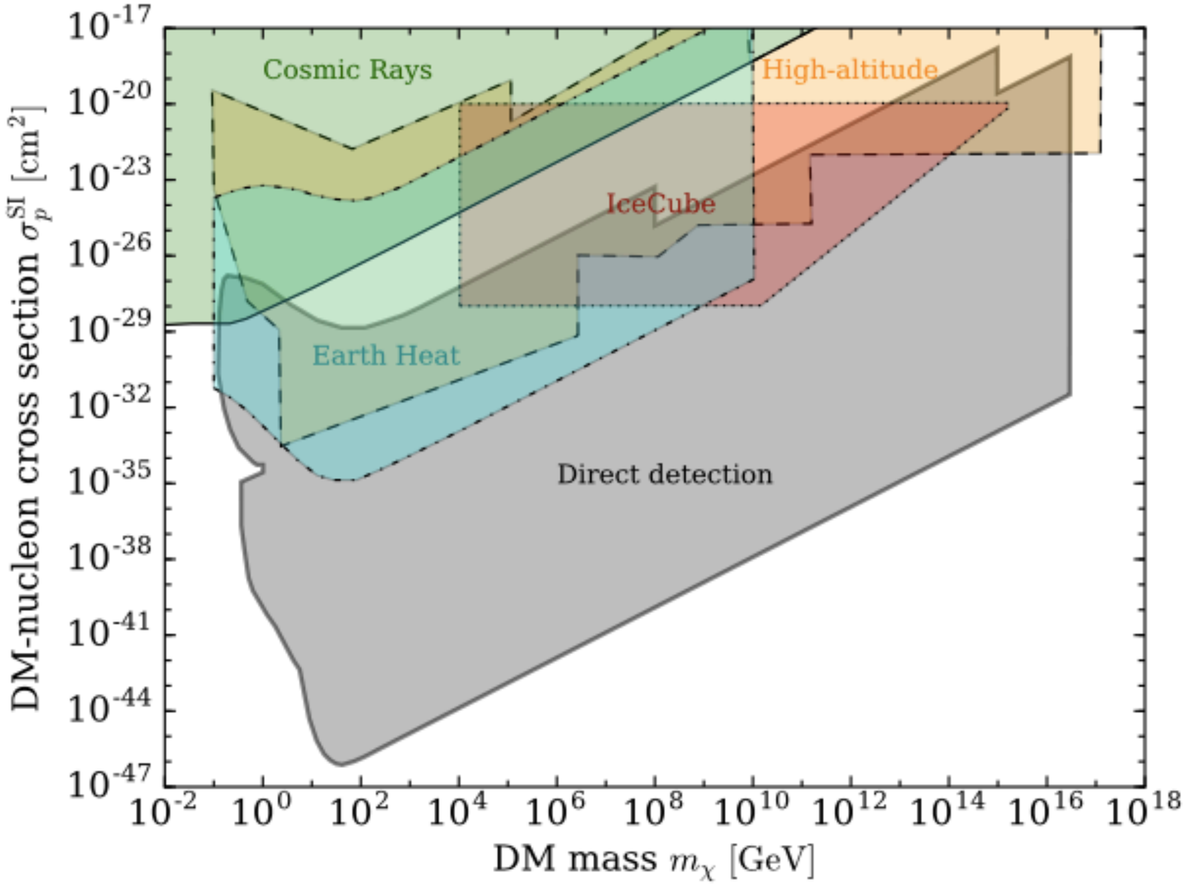
[Emken, Kouvaris & Shoemaker -1702.07750]

[Emken, Essig, Kouvaris & Sholapurkar - 1905.06348]

Direct Detection Landscape



[**BJK** - 1712.04901]



Albuquerque & Baudis [astro-ph/0301188]

Mack, Beacom & Bertone [0705.4298]

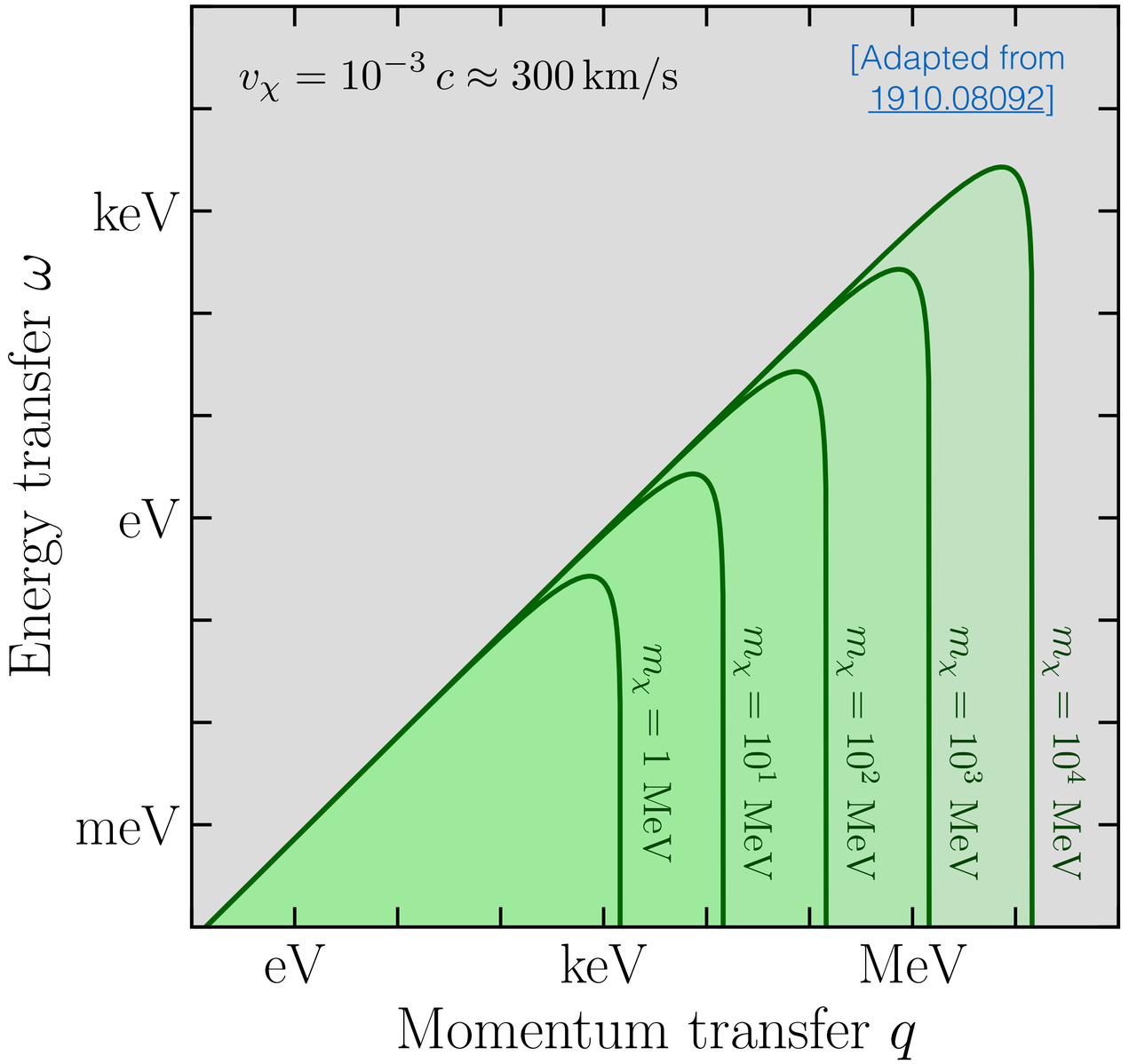
Scattering Kinematics

Allowed range of (ω, q) set by kinematics (green regions):

$$\omega \leq q v_\chi - q^2/2m_\chi$$

Consider:

- **Nuclear recoils** - can probe energies down to eV, but realistically can only measure recoil energies down to ~keV $\rightarrow m_\chi \gtrsim \mathrm{GeV}$
- **Electron ionisation** - possible for $\omega > \Delta \sim \mathrm{eV} \rightarrow m_\chi \gtrsim \mathrm{MeV}$
- **Phonon interactions** - possible for sufficiently small q, with $\omega_{\mathrm{ph}} \sim \mathcal{O}(10\mathrm{s})\,\mathrm{meV} \rightarrow m_\chi \sim \mathrm{keV} - 50\,\mathrm{MeV}$



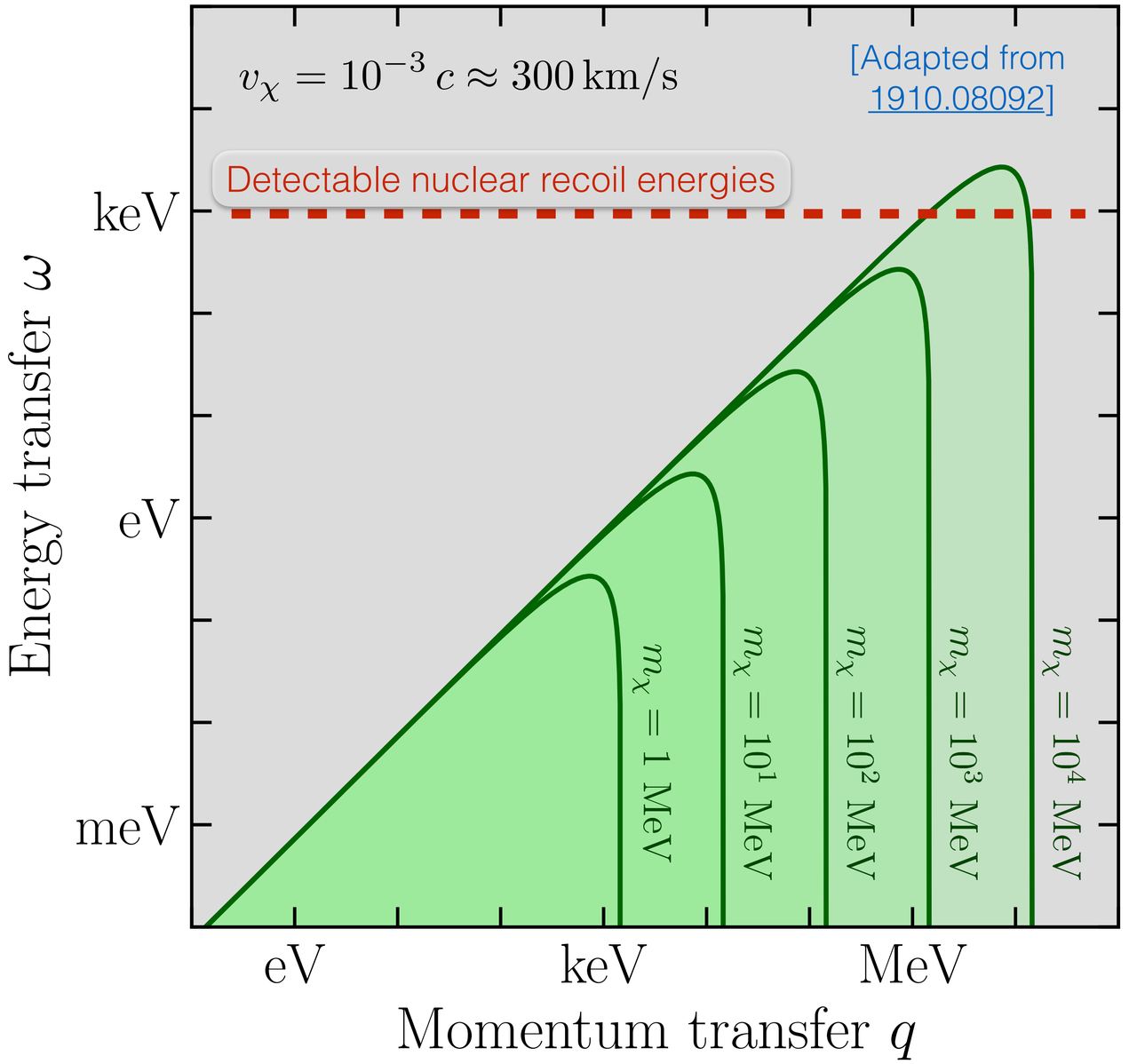
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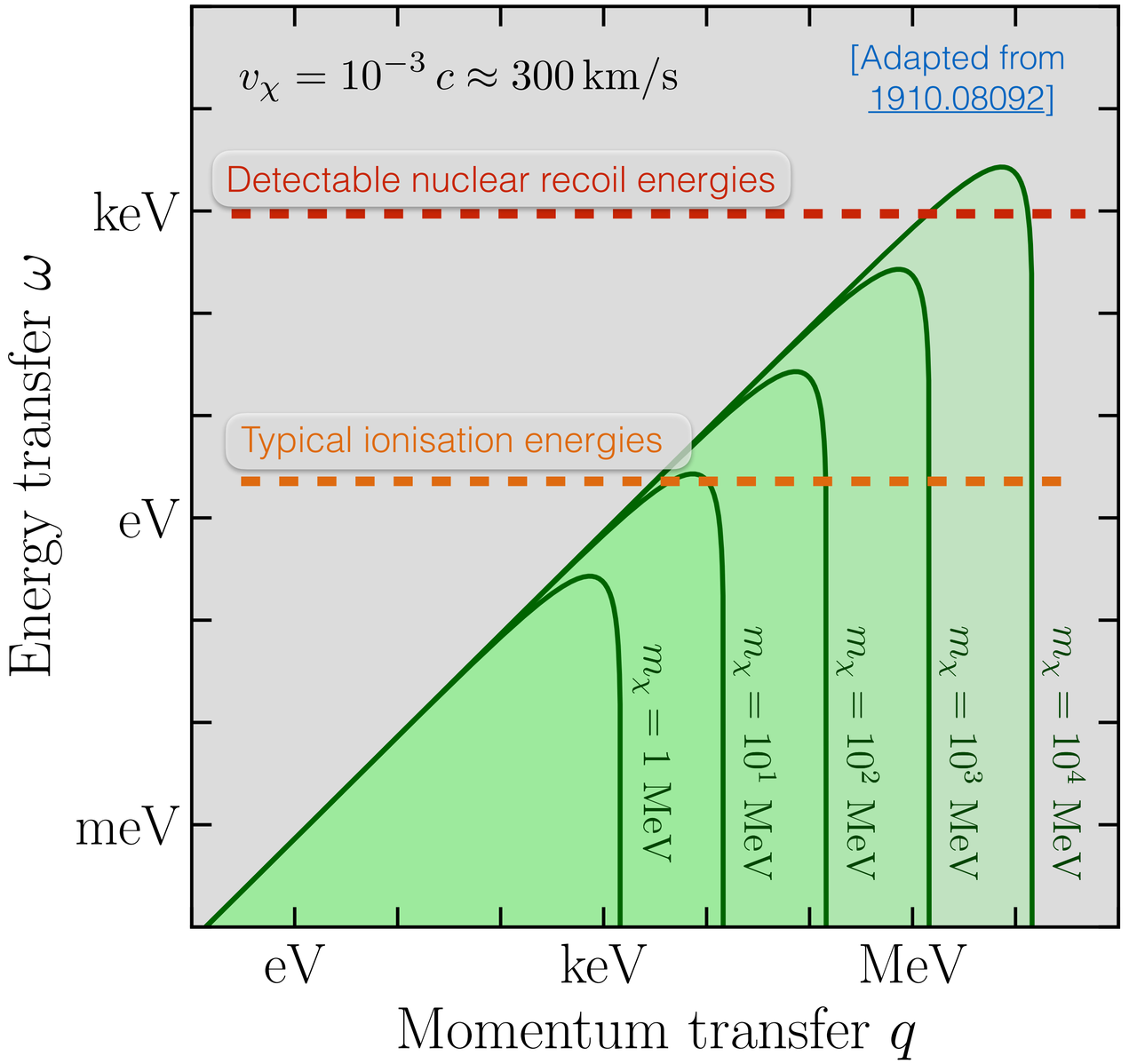
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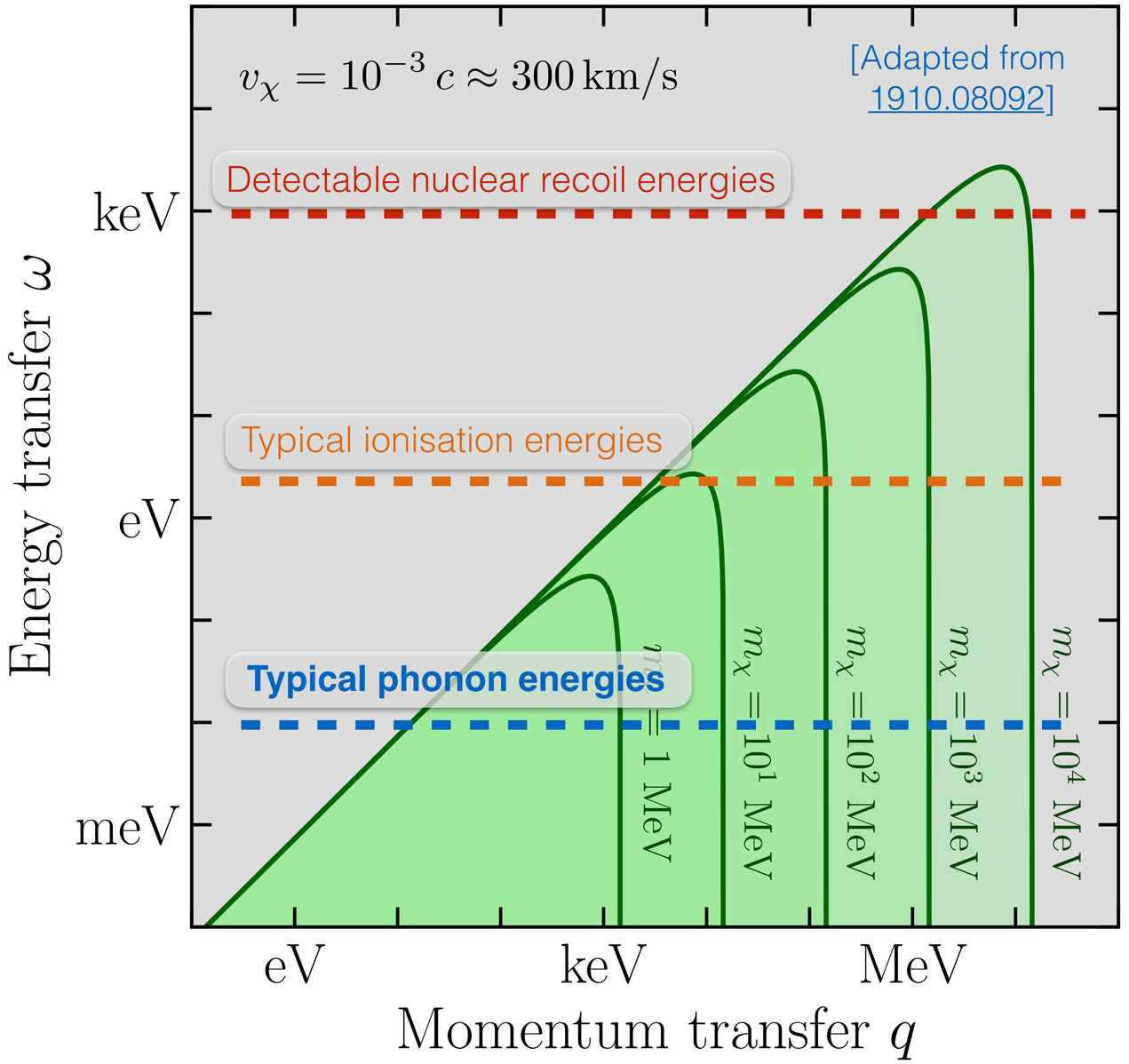
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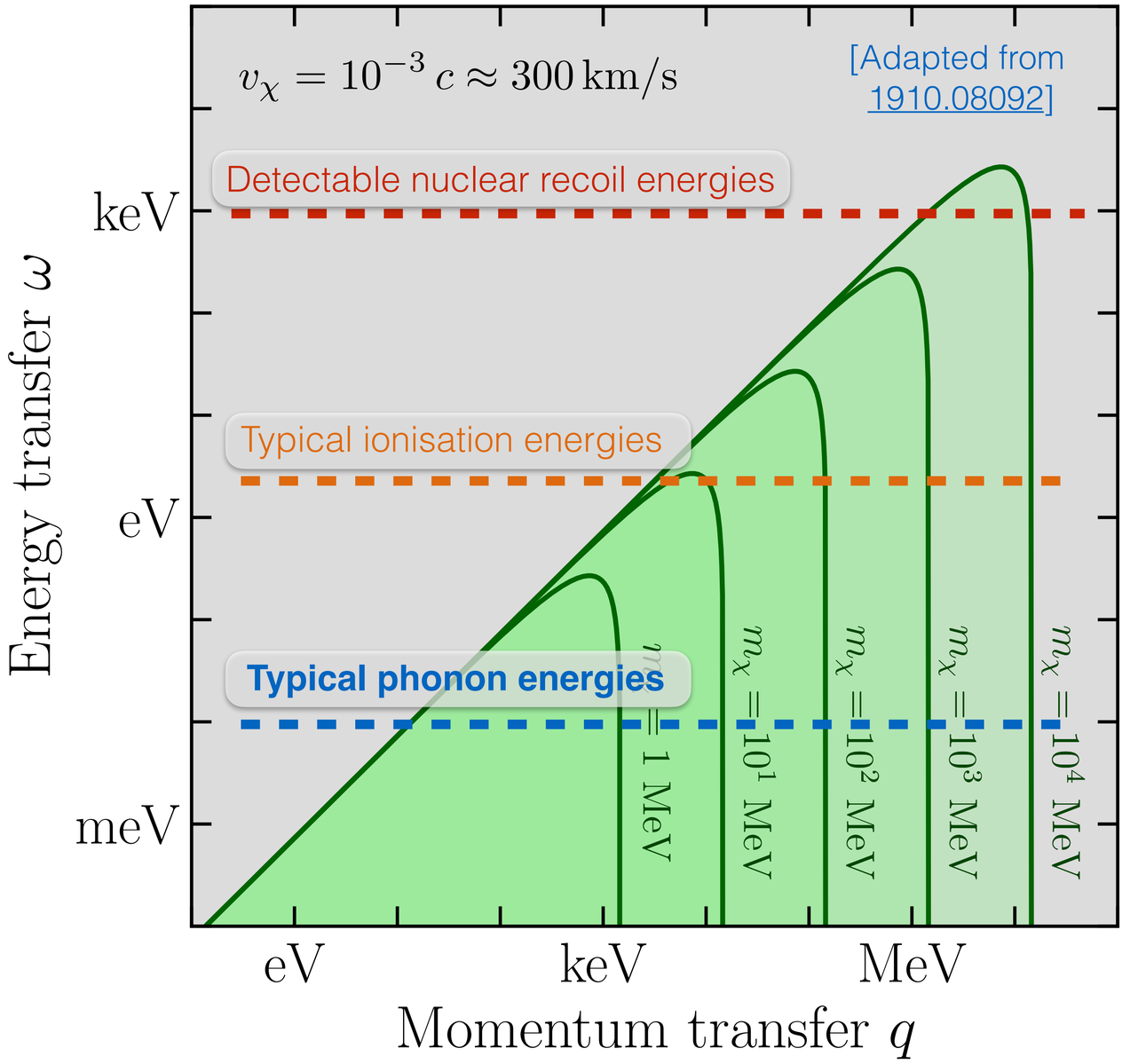
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DM mass ranges:

