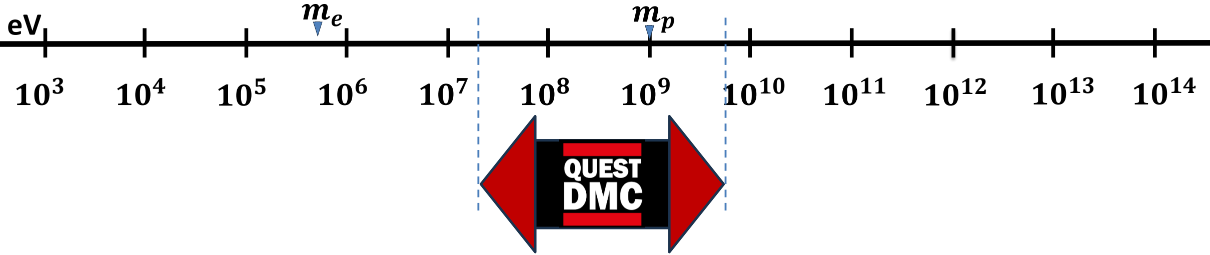

Recent theoretical highlights and future prospects in dark matter research

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October 2025, Liverpool

From EFT to NREFT

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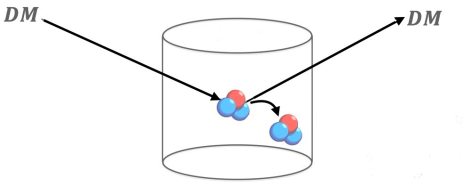


$$\mathcal{L}^{\rm rel}_{\chi N} = c_w\,(\bar{\chi}\Gamma\chi)(\bar{N}\Gamma' N)$$

$$\Gamma \in \{1,\, i\gamma_5,\, \gamma^\mu,\, \gamma^\mu\gamma^5,\, \sigma^{\mu\nu}\}.$$

low energy & NR reduction

$$\Longrightarrow$$

$$\hat{H} = \sum_{\tau=0,1}\sum_{i=1}^{15} c_i^\tau\, \mathcal{O}_i\, t^\tau$$

$$t^0 = \sigma_0,\ t^1 = \sigma_3.$$

NREFT operators

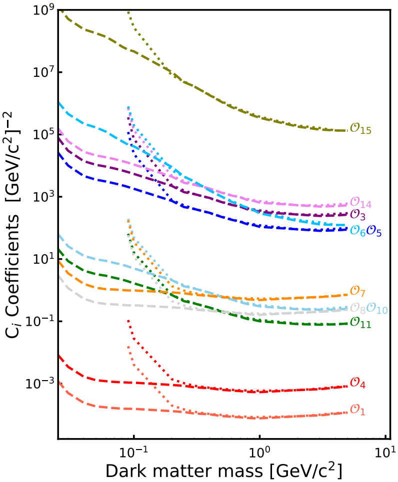
1. $\mathcal{O}_1 = 1_\chi\, 1_N$
2. $\mathcal{O}_2 = \mathbf{v}_\perp^2$
3. $\mathcal{O}_3 = i\,\mathbf{S}_N\cdot(\frac{\mathbf{q}}{m_N}\times\mathbf{v}_\perp)$
4. $\mathcal{O}_4 = \mathbf{S}_\chi\cdot\mathbf{S}_N$
5. $\mathcal{O}_5 = i\,\mathbf{S}_\chi\cdot(\frac{\mathbf{q}}{m_N}\times\mathbf{v}_\perp)$
6. $\mathcal{O}_6 = (\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N})(\mathbf{S}_N\cdot\frac{\mathbf{q}}{m_N})$
7. $\mathcal{O}_7 = \mathbf{S}_N\cdot\mathbf{v}_\perp$
8. $\mathcal{O}_8 = \mathbf{S}_\chi\cdot\mathbf{v}_\perp$
9. $\mathcal{O}_9 = i\,\mathbf{S}_\chi\cdot(\mathbf{S}_N\times\frac{\mathbf{q}}{m_N})$
10. $\mathcal{O}_{10} = i\,\mathbf{S}_N\cdot\frac{\mathbf{q}}{m_N}$
11. $\mathcal{O}_{11} = i\,\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N}$
12. $\mathcal{O}_{12} = \mathbf{S}_\chi\cdot(\mathbf{S}_N\times\mathbf{v}_\perp)$
13. $\mathcal{O}_{13} = i\,(\mathbf{S}_\chi\cdot\mathbf{v}_\perp)(\mathbf{S}_N\cdot\frac{\mathbf{q}}{m_N})$
14. $\mathcal{O}_{14} = i\,(\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N})(\mathbf{S}_N\cdot\mathbf{v}_\perp)$
15. $\mathcal{O}_{15} = -(\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N})[(\mathbf{S}_N\times\mathbf{v}_\perp)\cdot\frac{\mathbf{q}}{m_N}]$

Wilson Coefficients

$$P_{\text{tot}} = \frac{1}{2j_\chi + 1}\frac{1}{2j_N + 1} \times \sum_{\text{spins}} \left|\mathcal{M}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \{c_i^\tau c_j^{\tau'}\}\right)\right|^2$$

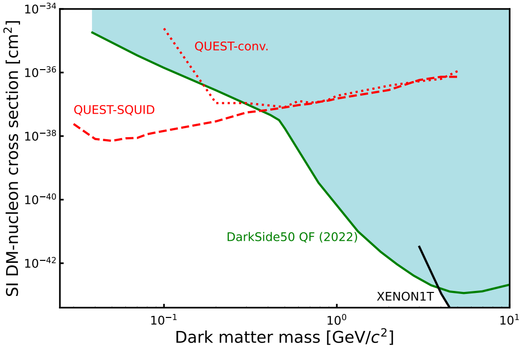
◇ Differential rate per recoil energy:

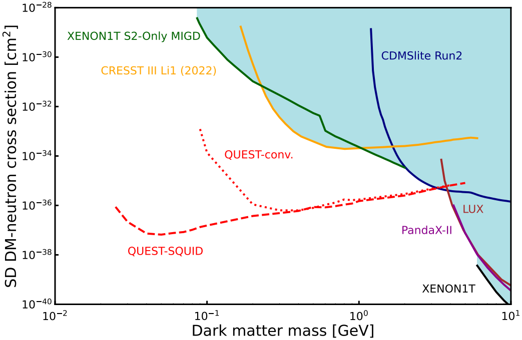
$$\frac{\mathrm{d}R}{\mathrm{d}E_{\text{NR}}} = \frac{\rho_\chi}{m_\chi m_{\text{N}}} \int_{v_{\min}}^{\infty} \frac{1}{v} P_{\text{tot}}(v^2, q^2) f(\mathbf{v})\, \mathrm{d}^3\mathbf{v}.$$



SI and SD Projection Sensitivities

$$\mathcal{O}_1 \rightarrow \sigma^{\mathrm{SI}}_{\chi n} = \frac{c_1^2\, \mu^2_{\chi n}}{\pi} \quad \text{and} \quad \mathcal{O}_4 \rightarrow \sigma^{\mathrm{SD}}_{\chi n} = \frac{c_4^2\, \mu^2_{\chi n}\, j_\chi (j_\chi + 1)}{4\pi}$$





◇ World-leading sensitivity to SD and SI interactions.

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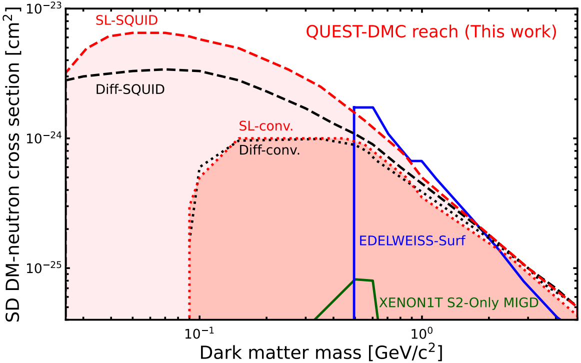
Sensitivity Ceiling

An upper limit in the cross-section sensitivity region is present due to DM scattering in the Earth and atmosphere and would never reach the detector.

We evaluate the cross-section sensitivity ceiling via two primary trajectories:

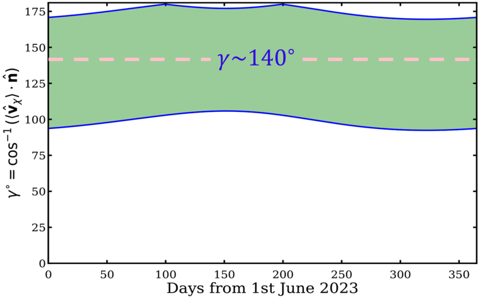
- ◇ Straight-line (SL) path approximation
- ◇ Diffusion framework (Diff)

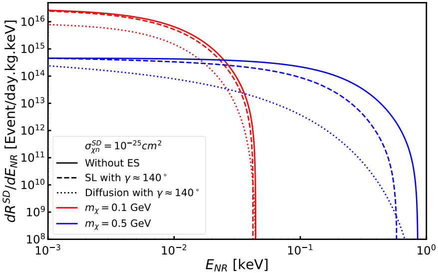


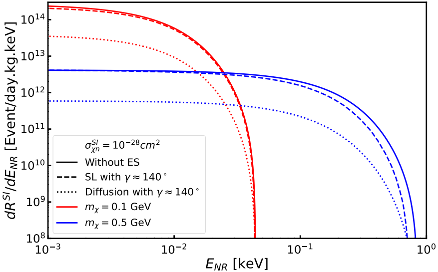
The Event Rates

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{NR}}} = \frac{\rho_\chi}{m_\chi m_{\mathrm{N}}} \int_{v_{\min}}^{\infty} \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{NR}}} v\, f(\mathbf{v},\gamma)\mathrm{d}^3\mathbf{v},$$

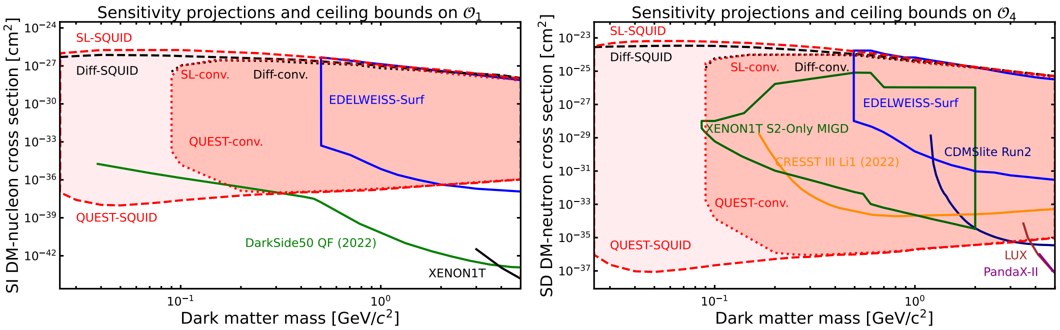
where $v_{\min} = (m_{\mathrm{N}} E_{\mathrm{NR}}/2\mu_{\chi\mathrm{N}}^2)^{1/2}$







SI and SD Projection Sensitivities



◇ The *small* and *large* cross-sections for $\mathcal{O}_1$ and $\mathcal{O}_4$ interactions.

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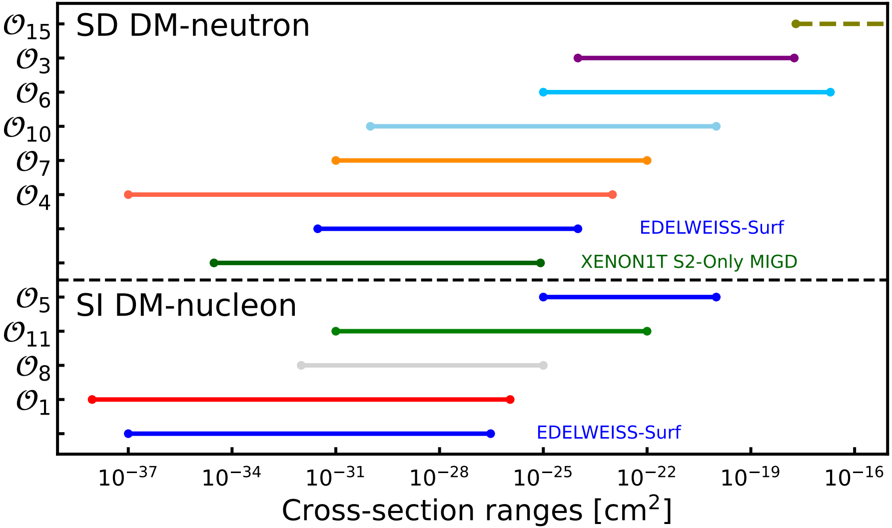
Non Relativistic EFT Operators of DM



Relativistic EFT Reduction

Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times\mathcal{O}_i$
$(\bar\chi\chi)(\bar N N)$ Scalar–Scalar	$\mathcal{O}_1$ [and $4\frac{m_\chi m_N}{M^2}\mathcal{O}_1$]
$(\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)\frac{K_\mu}{M}(\bar N N)$ Tensor–Scalar	$\frac{1}{M^2}(\frac{m_N}{m_\chi}\vec{q}^2\mathcal{O}_1 - 4m_N^2\mathcal{O}_5)$
$(\bar\chi\gamma^\mu\gamma^5\chi)\frac{K_\mu}{M}(\bar N N)$ Axialvector–Scalar	$4\frac{m_N}{M}\mathcal{O}_8$
$i(\bar\chi\gamma^5\chi)(\bar N N)$ Pseudoscalar–Scalar	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$ [and $-4\frac{m_N^2}{M^2}\mathcal{O}_{11}$]

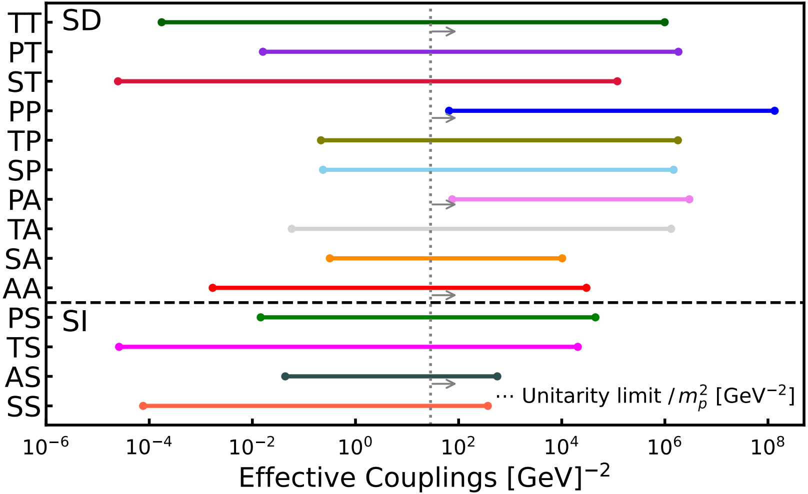
Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times\mathcal{O}_i$
$(\bar\chi\gamma^\mu\gamma^5\chi)(\bar N\gamma_\mu\gamma^5 N)$ Axialvector–Axialvector	$-4\mathcal{O}_4$
$\frac{P^\mu}{M}(\bar\chi\chi)(\bar N\gamma_\mu\gamma^5 N)$ Scalar–Axialvector	$-4\frac{m_\chi}{M}\mathcal{O}_7$
$(\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)(\bar N\gamma_\mu\gamma^5 N)$ Tensor–Axialvector	$-4\frac{m_N}{M}\mathcal{O}_9$
$i\frac{P^\mu}{M}(\bar\chi\gamma^5\chi)(\bar N\gamma_\mu\gamma^5 N)$ Pseudoscalar–Axialvector	$4\frac{m_N}{M}\mathcal{O}_{14}$

Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times\mathcal{O}_i$
$i(\bar\chi\chi)(\bar N\gamma^5 N)$ Scalar–Pseudoscalar	$\mathcal{O}_{10}$ [and $4\frac{m_\chi m_N}{M^2}\mathcal{O}_{10}$]
$(\bar\chi\gamma^5\chi)(\bar N\gamma^5 N)$ Pseudoscalar–Pseudoscalar	$-\frac{m_N}{m_\chi}\mathcal{O}_6$ [and $-4\frac{m_N^2}{M^2}\mathcal{O}_6$]
$i(\bar\chi\gamma^\mu\gamma^5\chi)\frac{K_\mu}{M}(\bar N\gamma^5 N)$ Axialvector–Pseudoscalar	$4\frac{m_N}{M}\mathcal{O}_{13}$
$i(\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)\frac{K_\mu}{M}(\bar N\gamma^5 N)$ Tensor–Pseudoscalar	$\frac{4\vec{q}^2}{M^2}(\frac{m_N}{4m_\chi}\mathcal{O}_{10}+\mathcal{O}_{12})+\frac{4m_N^2}{M^2}\mathcal{O}_{15}$

Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times\mathcal{O}_i$
$\frac{P^\mu}{M}(\bar\chi\chi)(\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Scalar–Tensor	$\frac{m_\chi m_N}{M^2}(-\frac{\vec{q}^2}{m_N^2}\mathcal{O}_1+4\mathcal{O}_3)$
$i\frac{P^\mu}{M}(\bar\chi\gamma^5\chi)(\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Pseudoscalar–Tensor	$\frac{1}{M^2}(\vec{q}^2\mathcal{O}_{11}+4m_N^2\mathcal{O}_{15})$
$(\bar\chi\gamma^\mu\gamma^5\chi)(\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Axialvector–Tensor	$4\frac{m_N}{M}\mathcal{O}_9$
$(\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)(\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Tensor–Tensor	$\frac{4}{M^2}(\vec{q}^2\mathcal{O}_4 - m_N^2\mathcal{O}_6)$

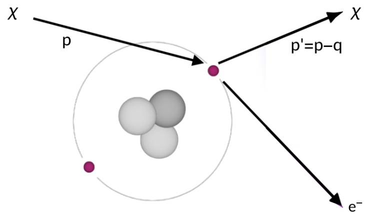
Non-relativistic Reduction of Relativistic Operators

Relativistic EFT Reduction



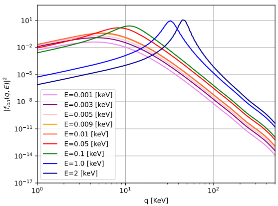
DM–Electron Scattering in 3He

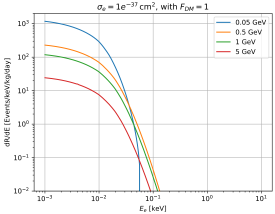
$$\frac{\partial^2 R}{\partial E_e\,\partial q} = \frac{1}{m_A}\frac{\rho_\chi}{m_\chi}\frac{1}{E_e}\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\,q \times \left|f_{\text{ion}}^{i\to f}(q,E_e)\right|^2 \left|F_\chi(q)\right|^2 \eta\big(v_{\text{min}}^i(q)\big)$$

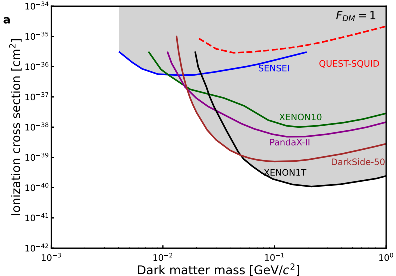


The DM form factor F_χ can be:

- short-range: $m_{med} \gg (\alpha m_e) \rightarrow F_\chi = 1$
- long-range: $m_{med} \ll (\alpha m_e) \rightarrow F_\chi = \frac{(\alpha m_e)^2}{|\mathbf{q}|^2}$





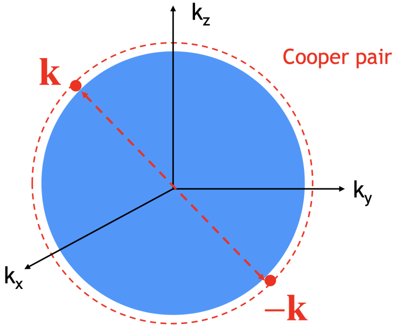


DM Scattering off Cooper Pairs

Interactions with Cooper pairs directly look for the excitation of quasi-particles.

In superfluid ^{3}He:

- ^{3}He atoms form pairs of quasiparticles with opposite momentum.
- These Cooper pairs are typically in a p-wave state ($l = 1, S = 1$).
- The signal:



$$\frac{d^2 R}{d\omega\, dq} = \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}}{2\,\mu_{\chi N}^2} \left|F_{\mathrm{DM}}(q)\right|^2 q\, \eta\big(v_{\min}(\omega, q)\big)\; S(q,\omega)$$

Master formula (density coupling):

$$\frac{d^2R}{d\omega\, dq} = \frac{\rho_\chi}{m_\chi}\,\frac{\bar\sigma}{2\,\mu_{\chi N}^2}\,\left|F_{\rm DM}(q)\right|^2 q\,\eta\big(v_{\rm min}(\omega,q)\big)\;S(q,\omega)$$

$S(q,\omega)$ decomposition at $T \simeq 0$:

$$S(q,\omega) = \underbrace{Z(q)\,\delta(\omega - c_s q)}_{\text{collective mode}} + \underbrace{S_{\rm pb}(q,\omega)}_{\text{pair-breaking continuum}}$$

$$S_{\rm pb}(q,\omega) = \int \frac{d^3k}{(2\pi)^3}\,\Big(u_{k+q}v_k - v_{k+q}u_k\Big)^2\,\delta\big(\omega - E_{k+q} - E_k\big)\,\Theta(\omega - 2\Delta).$$

Using the superfluid ground state: $\alpha_{\mathbf{k}\sigma}\,|{\rm BCS}\rangle = 0 \quad \forall\,\mathbf{k},\sigma$

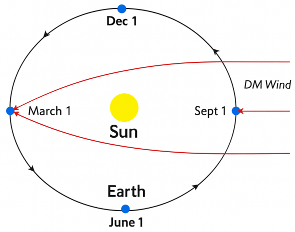
Bogoliubov transform: $\alpha_{\mathbf{k}\uparrow} = u_k\,c_{\mathbf{k}\uparrow} - v_k\,c^\dagger_{-\mathbf{k}\downarrow}, \qquad \alpha_{-\mathbf{k}\downarrow} = u_k\,c_{-\mathbf{k}\downarrow} + v_k\,c^\dagger_{\mathbf{k}\uparrow}$

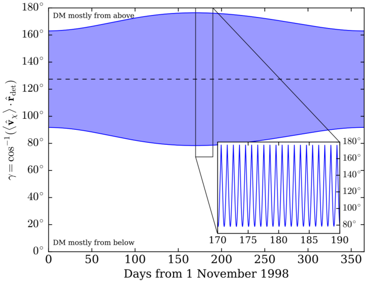
$$u_k^2 = \tfrac{1}{2}\left(1 + \tfrac{\xi_k}{E_k}\right), \quad v_k^2 = \tfrac{1}{2}\left(1 - \tfrac{\xi_k}{E_k}\right), \quad u_k v_k = \frac{\Delta}{2E_k}, \quad E_k = \sqrt{\xi_k^2 + \Delta^2}$$

[work in progress with Adam]

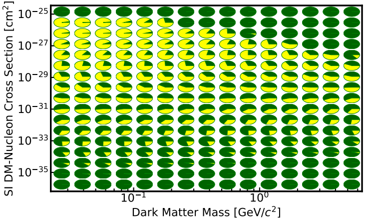
What left to do: Time-dependecy and attenuation

- DM flux at the detector over a year





- Attenuation for low cross-section

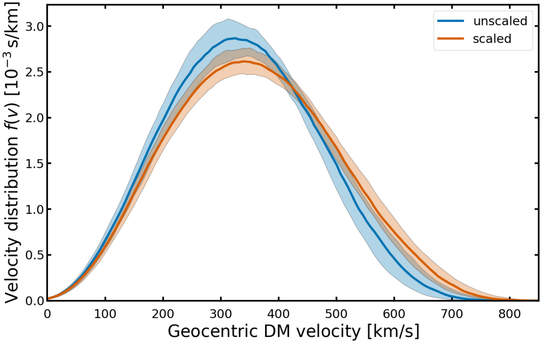


- Methods and problems:
  - Straight-line path: Not accurate for light-DM
  - Monto-carlo: Super-slow
  - Diffusion: Fails at low cross-section, as we considered Earth to be fully opaque to DM.

Future plan: Velocity distribution modification

- Standard Halo Model (SHM) $\rightarrow$ distribution based on the Sun's position in an idealised Milky Way, smooth and isotropic.
- It does not account for variations in galaxy formation history, mergers, substructure, or deviations from isotropy.

- Using cosmological simulations of different Milky Way–like galaxies, one can capture this diversity.
- The resulting velocity distributions differ from the SHM by up to about 60% in predicted event rates.



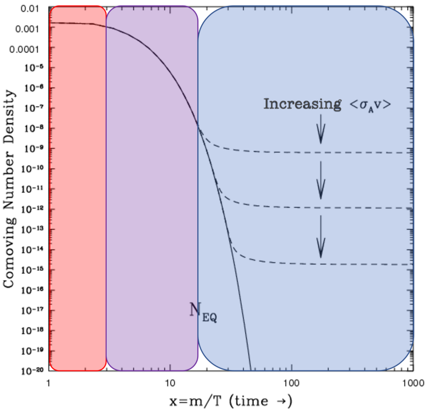
Theoretical benchmarks

Production Mechanism

- Freeze-out
- Freeze-in
- Asymmetric
- Freeze-out& decay
- ...

Freeze-out

- DM density in thermal equilibrium
- Red: production⇔ annihilation
- Purple: production < annihilation
- Blue: annihilation < expansion of the universe.



Production Mechanism

- Freeze-out
- Freeze-in
- Asymmetric
- Freeze-out& decay
- $\dots$

Freeze-out

The relic density provided by the Planck collaboration:

$$\Omega_{\rm DM}^{\rm obs} h^2 = 0.1199 \pm 0.0027$$

DM annihilation should be fitted in the following:

$$\Omega_{\rm DM}^{\rm obs} h^2 \simeq \frac{2 \times 2.4 \times 10^{-10}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle_{\rm ann}} \simeq \frac{2 \times 6 \times 10^{-11}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle_{*}}$$

$$\mathcal{O}_S \ = \ \frac{1}{\Lambda^2} \left[\bar{\chi}\chi\right] \left[\bar{f} f\right]$$

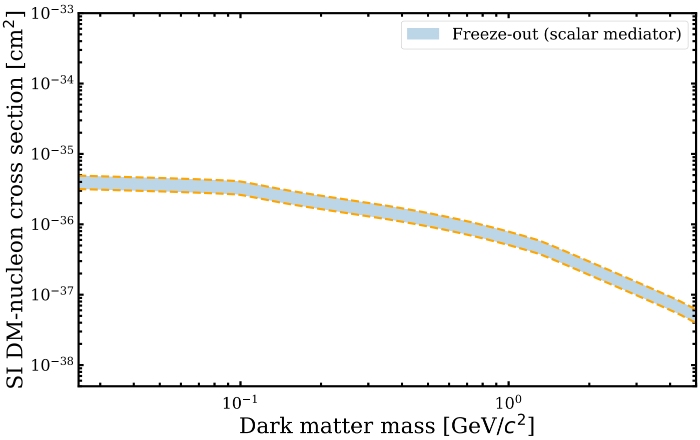
$$(\sigma v)_*^S \ \simeq \ \frac{N_c}{2\pi\,\Lambda^4}\, m_{DM}^2 \left(1 - \frac{m_f^2}{m_{\rm DM}^2}\right)^{3/2} v^2$$

Theoretical benchmarks

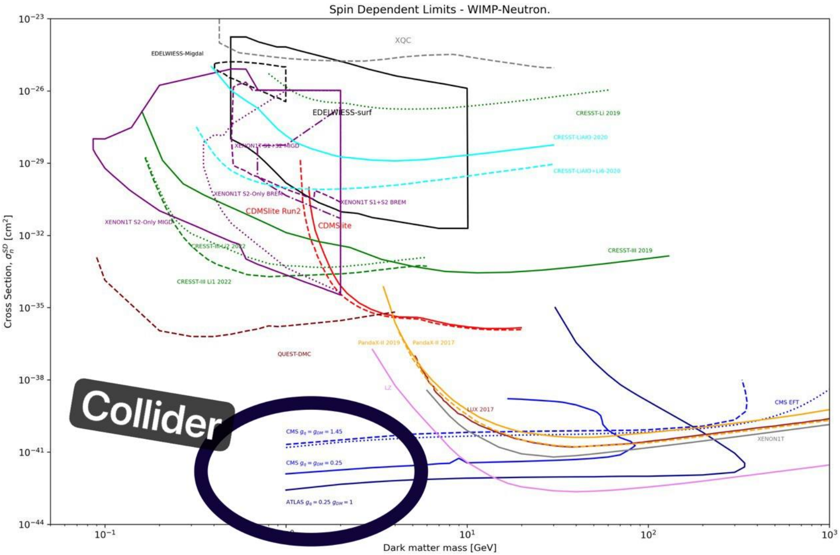
Production Mechanism

- Freeze-out
- Freeze-in
- Asymmetric
- Freeze-out& decay
- ...

Freeze-out

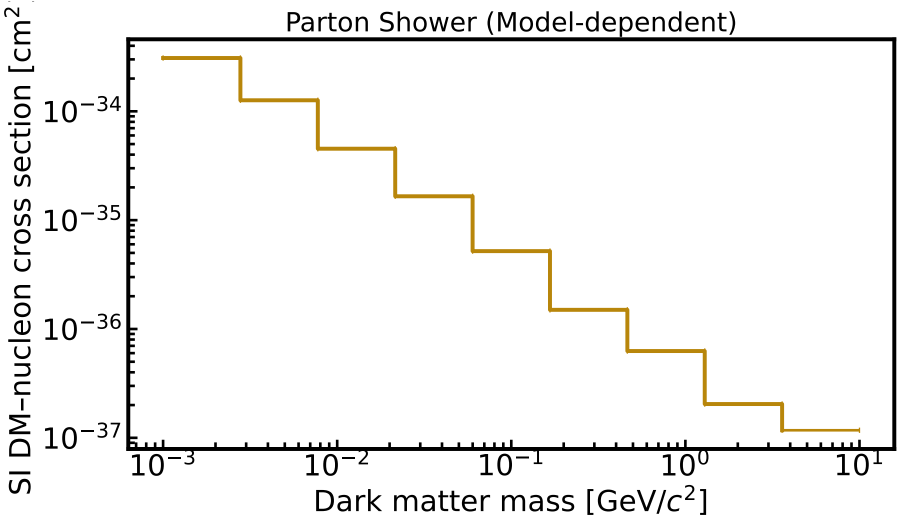


Benchmark from production at collider:



Benchmark from production at collider:

DM production through parton shower:



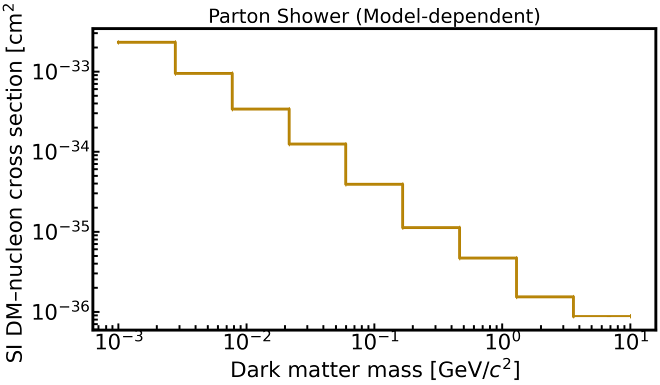
Analysis Approach & UFO Status

These analyses can be done:

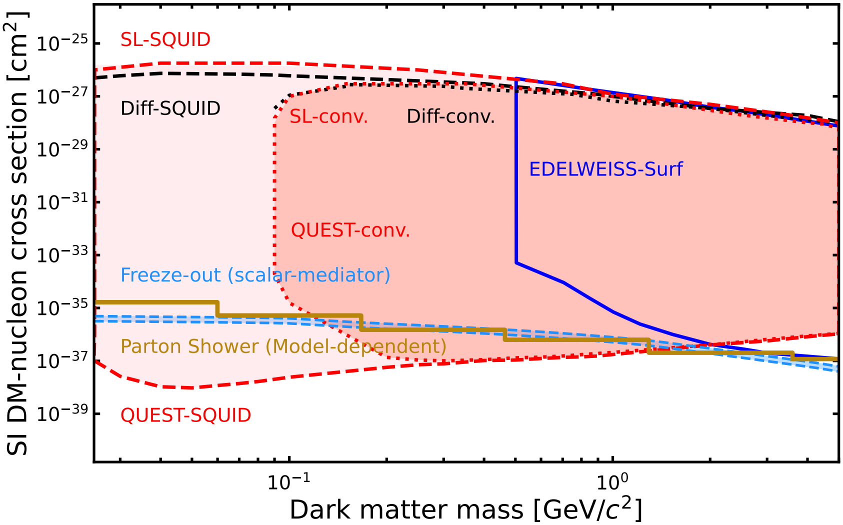
- **Model-dependent**
- **Model-independent**

In any event, we need a **[UFO]** (Universal FeynRules Output).

Built a model-dependent UFO for:
2HDM + Complex Singlet



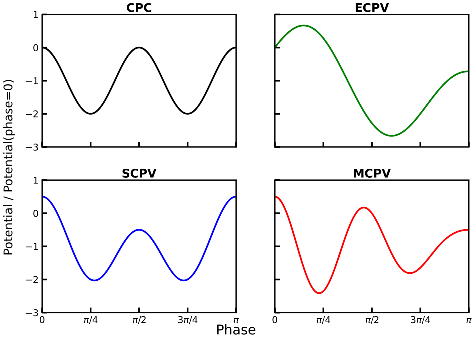
Dark matter searches strategies



Why it matters: CPV is tiny and insufficient in the SM.

Consider CPV operators in a dark sector:

$$\mathcal{L}_{\rm CPV} \supset \frac{1}{\Lambda^2}(\bar{\chi}\, i\gamma_5\chi)(\bar{q}q) \;\; , \;\; \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}\, i\gamma_5 q), \cdots .$$



CPV sources:

- **Explicit** CPV: complex couplings/phases in the Lagrangian.
- **Spontaneous** CPV: vacuum phases.
- **Mixed**: both explicit and spontaneous.

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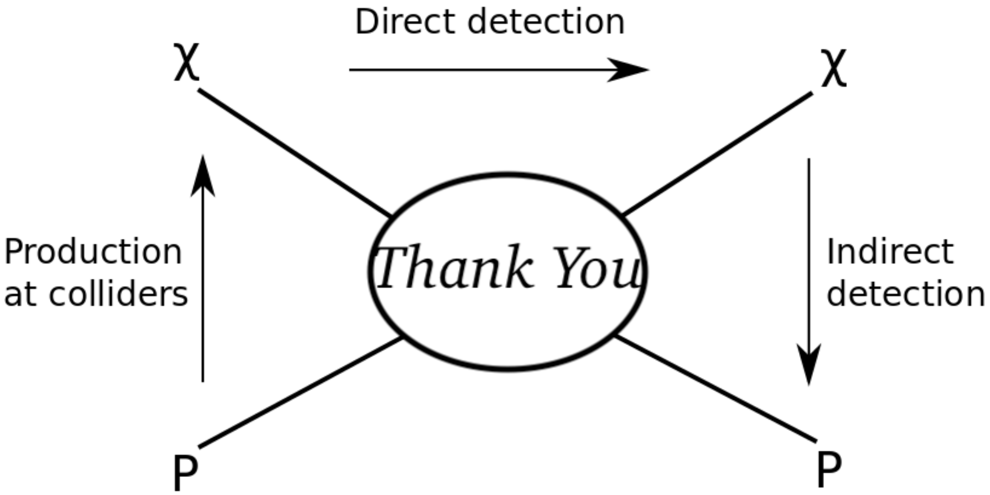
What left to do: Interaction

- Include long-range interactions:

$$c_i = \left(c_i^s + c_i^\ell \frac{(\alpha m_e)^2}{|\mathbf{q}|^2} \right)$$

- Limit setting on Dark Photon and Axions as DM.
- We considered from high-energy DM nucleon interactions down to NREFT. The complete approach is from DM quarks/gluons down to low-energy.
- Please add directions that you would like to explore further ...


Direct detection
χ
χ
Production
at colliders
Thank You
Indirect
detection
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