

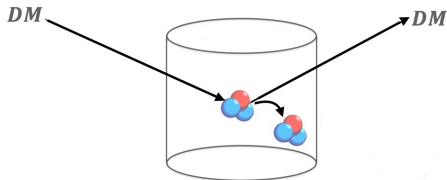
Recent theoretical highlights and future prospects in dark matter research

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

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

low energy & NR reduction



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

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

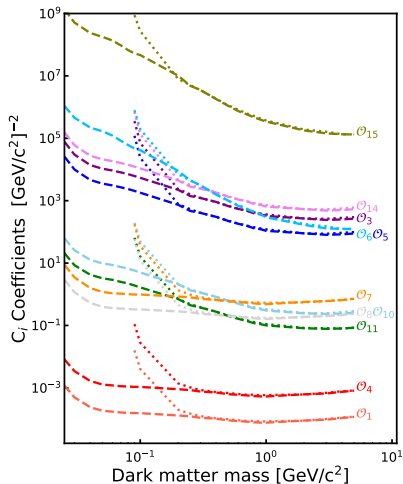
NREFT operators

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. $\mathcal{O}_{15} = -(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}) [(\mathbf{S}_N \times \mathbf{v}_\perp) \cdot \frac{\mathbf{q}}{m_N}]$

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

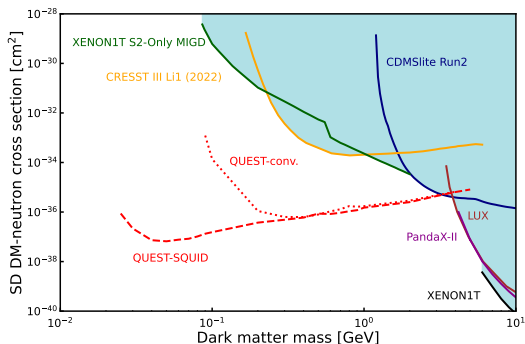
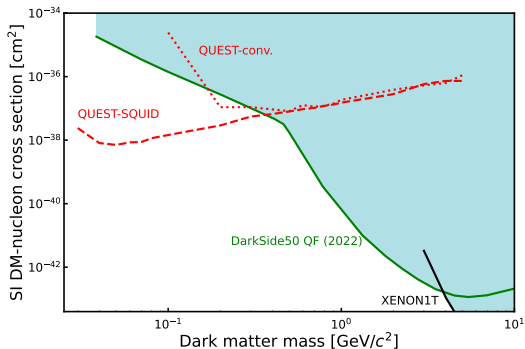
◇ Differential rate per recoil energy:

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



$$\mathcal{O}_1 \rightarrow \sigma_{\chi n}^{\text{SI}} = \frac{c_1^2 \mu_{\chi n}^2}{\pi} \quad \text{and}$$

$$\mathcal{O}_4 \rightarrow \sigma_{\chi n}^{\text{SD}} = \frac{c_4^2 \mu_{\chi n}^2 j_\chi (j_\chi + 1)}{4\pi}$$

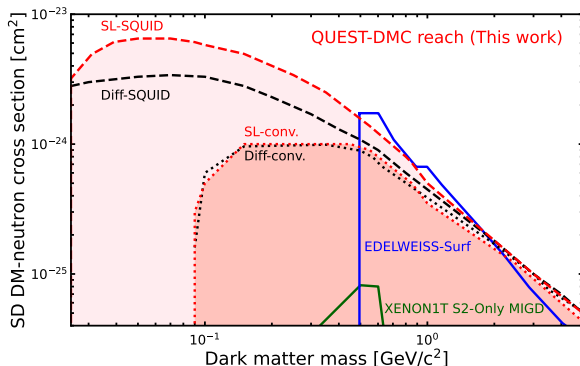


◇ World-leading sensitivity to SD and SI interactions.

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)

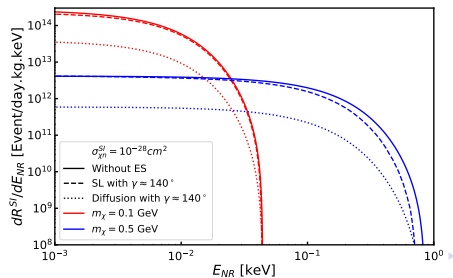
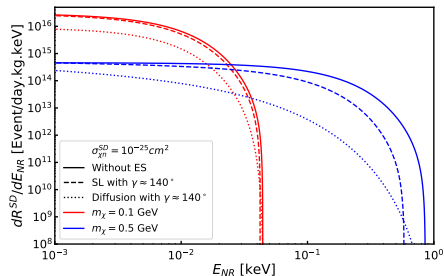
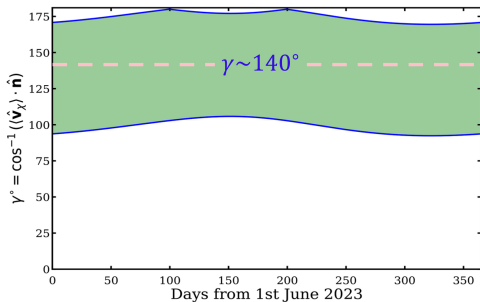


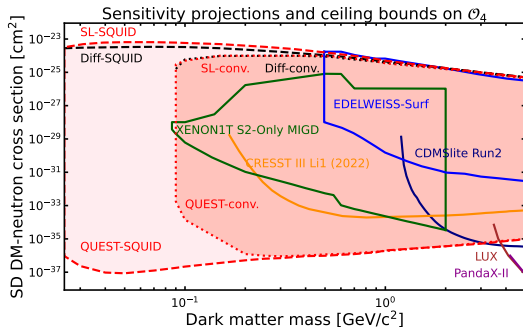
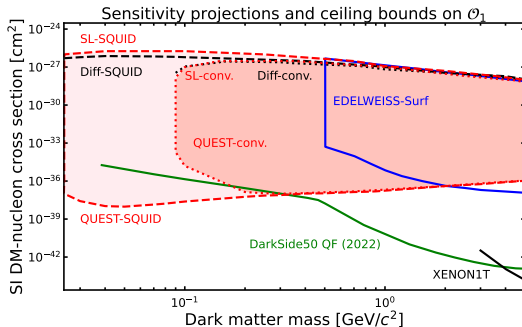
The Event Rates



$$\frac{dR}{dE_{NR}} = \frac{\rho_\chi}{m_\chi m_N} \int_{v_{\min}}^{\infty} \frac{d\sigma}{dE_{NR}} v f(\mathbf{v}, \gamma) d^3\mathbf{v},$$

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

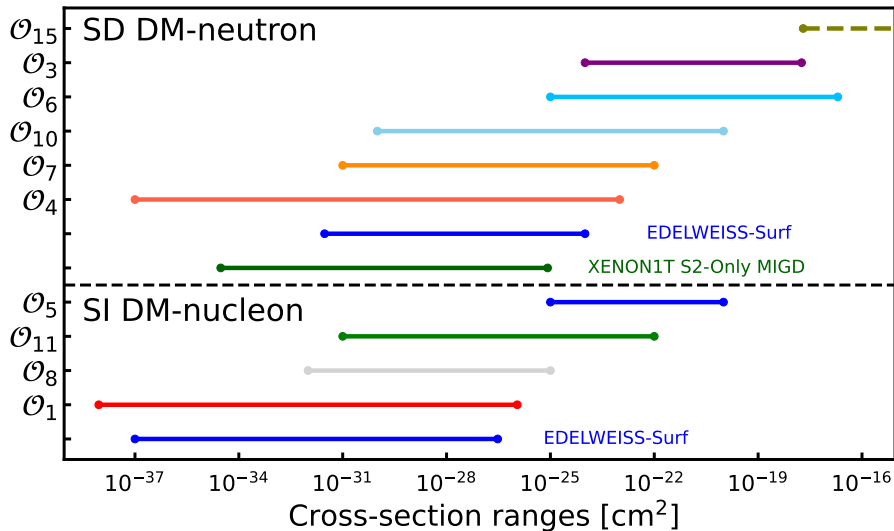




◇ The *small* and *large* cross-sections for $\mathcal{O}_1$ and $\mathcal{O}_4$ interactions.

JCAP 04 (2025) 017

Non Relativistic EFT Operators of DM

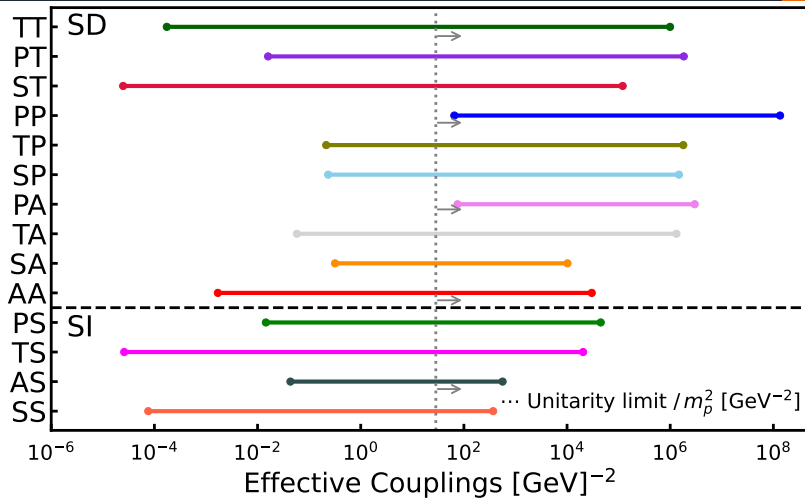


Relativistic EFT Reduction



Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times \mathcal{O}_i$	Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times \mathcal{O}_i$
$(\bar{\chi}\chi)(\bar{N}N)$ Scalar–Scalar	$\mathcal{O}_1$ [and $4\frac{m_\chi m_N}{M^2}\mathcal{O}_1$]	$(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{N}\gamma_\mu\gamma^5N)$ Axialvector–Axialvector	$-4\mathcal{O}_4$
$(\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)\frac{K_\mu}{M}(\bar{N}N)$ Tensor–Scalar	$\frac{1}{M^2}(\frac{m_N}{m_\chi}\bar{q}^2\mathcal{O}_1 - 4m_N^2\mathcal{O}_5)$	$\frac{P^\mu}{M}(\bar{\chi}\chi)(\bar{N}\gamma_\mu\gamma^5N)$ Scalar–Axialvector	$-4\frac{m_\chi}{M}\mathcal{O}_7$
$(\bar{\chi}\gamma^\mu\gamma^5\chi)\frac{K_\mu}{M}(\bar{N}N)$ Axialvector–Scalar	$4\frac{m_N}{M}\mathcal{O}_8$	$(\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)(\bar{N}\gamma_\mu\gamma^5N)$ Tensor–Axialvector	$-4\frac{m_N}{M}\mathcal{O}_9$
$i(\bar{\chi}\gamma^5\chi)(\bar{N}N)$ Pseudoscalar–Scalar	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$ [and $-4\frac{m_N^2}{M^2}\mathcal{O}_{11}$]	$i\frac{P^\mu}{M}(\bar{\chi}\gamma^5\chi)(\bar{N}\gamma_\mu\gamma^5N)$ Pseudoscalar–Axialvector	$4\frac{m_N}{M}\mathcal{O}_{14}$
Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times \mathcal{O}_i$	Relativistic Operator (Spinor Bilinear Labelling)	Factor $\times \mathcal{O}_i$
$i(\bar{\chi}\chi)(\bar{N}\gamma^5N)$ Scalar–Pseudoscalar	$\mathcal{O}_{10}$ [and $4\frac{m_\chi m_N}{M^2}\mathcal{O}_{10}$]	$\frac{P^\mu}{M}(\bar{\chi}\chi)(\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Scalar–Tensor	$\frac{m_\chi m_N}{M^2}(-\frac{\bar{q}^2}{m_N^2}\mathcal{O}_1 + 4\mathcal{O}_3)$
$(\bar{\chi}\gamma^5\chi)(\bar{N}\gamma^5N)$ Pseudoscalar–Pseudoscalar	$-\frac{m_N}{m_\chi}\mathcal{O}_6$ [and $-4\frac{m_N^2}{M^2}\mathcal{O}_6$]	$i\frac{P^\mu}{M}(\bar{\chi}\gamma^5\chi)(\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Pseudoscalar–Tensor	$\frac{1}{M^2}(\bar{q}^2\mathcal{O}_{11} + 4m_N^2\mathcal{O}_{15})$
$i(\bar{\chi}\gamma^\mu\gamma^5\chi)\frac{K_\mu}{M}(\bar{N}\gamma^5N)$ Axialvector–Pseudoscalar	$4\frac{m_N}{M}\mathcal{O}_{13}$	$(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Axialvector–Tensor	$4\frac{m_N}{M}\mathcal{O}_9$
$i(\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)\frac{K_\mu}{M}(\bar{N}\gamma^5N)$ Tensor–Pseudoscalar	$\frac{4\bar{q}^2}{M^2}(\frac{m_N}{4m_\chi}\mathcal{O}_{10} + \mathcal{O}_{12}) + \frac{4m_N^2}{M^2}\mathcal{O}_{15}$	$(\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{M}\chi)(\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{M}N)$ Tensor–Tensor	$\frac{4}{M^2}(\bar{q}^2\mathcal{O}_4 - m_N^2\mathcal{O}_6)$

**Non-relativistic Reduction of
Relativistic Operators**



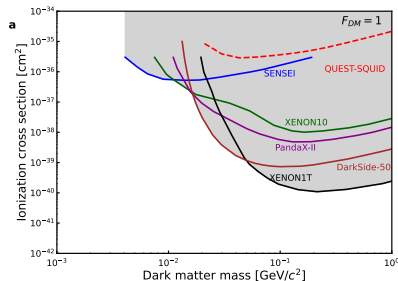
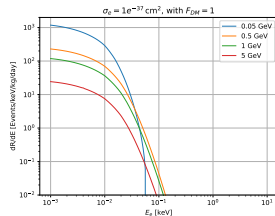
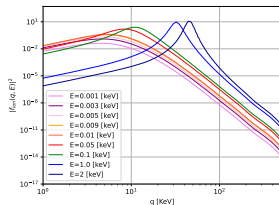
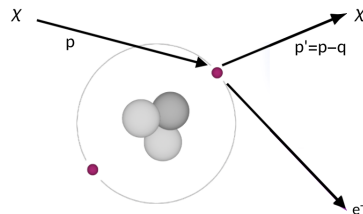
DM–Electron Scattering in ^3He



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

The DM form factor F_χ can be:

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

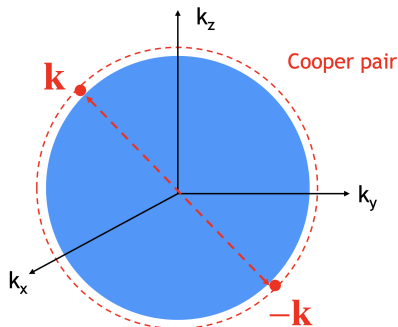


Interactions with Cooper pairs directly look for the excitation of quasi-particles.

In superfluid ^3He :

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

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





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

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

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

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

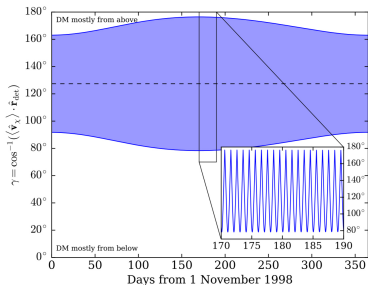
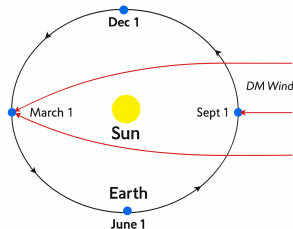
Using the superfluid ground state: $\alpha_{\mathbf{k}\sigma} |\text{BCS}\rangle = 0 \quad \forall \mathbf{k}, \sigma$

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

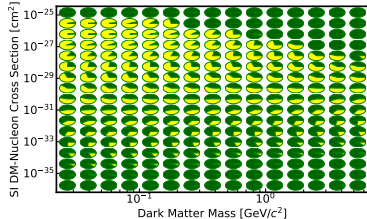
$$u_k^2 = \frac{1}{2} \left(1 + \frac{\xi_k}{E_k} \right), \quad v_k^2 = \frac{1}{2} \left(1 - \frac{\xi_k}{E_k} \right), \quad u_k v_k = \frac{\Delta}{2E_k}, \quad E_k = \sqrt{\xi_k^2 + \Delta^2}$$

What left to do: Time-dependency and attenuation

DM flux at the detector over a year



Attenuation for low cross-section



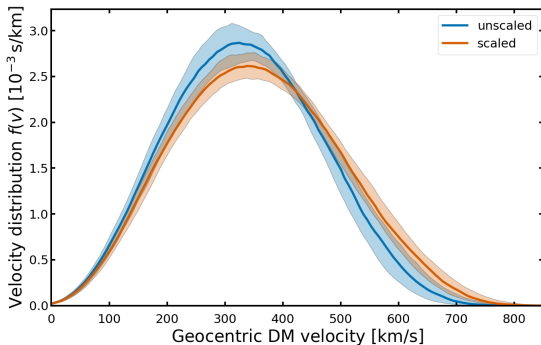
Methods and problems:

- ▶ 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) → 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.

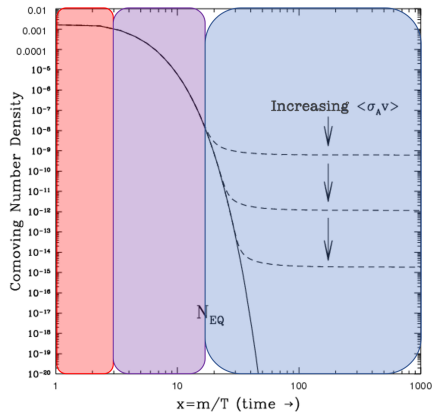


Production Mechanism

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

Freeze-out

- ▶ DM density in thermal equilibrium
- ▶ Red: production $\Leftrightarrow$ annihilation
- ▶ Purple: production $<$ annihilation
- ▶ Blue: annihilation $<$ expansion of the universe.





Production Mechanism

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

Freeze-out

The relic density provided by the Planck collaboration:

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

DM annihilation should be fitted in the following:

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

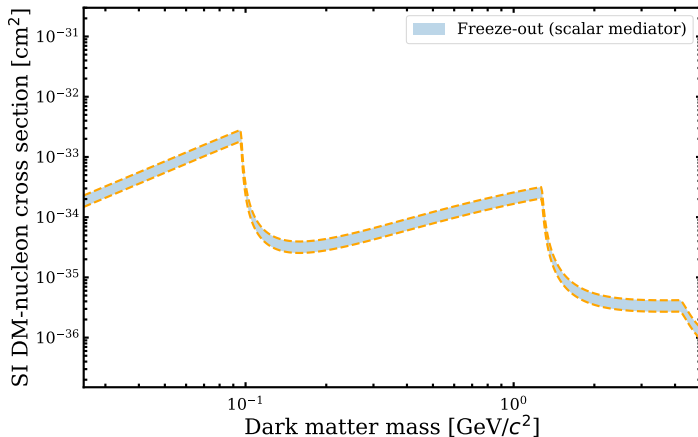
$$\mathcal{O}_S = \frac{1}{\Lambda^2} [\bar{\chi} \chi] [\bar{f} f]$$

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

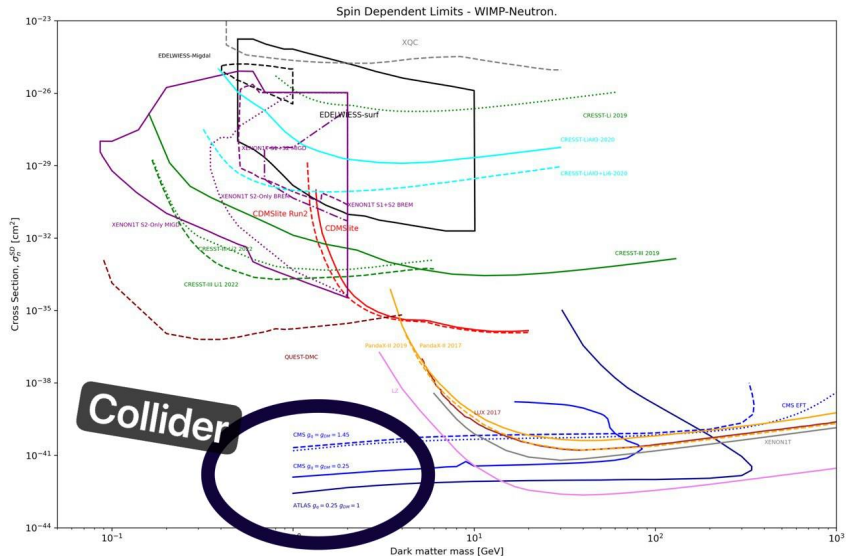
Production Mechanism

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Freeze-out



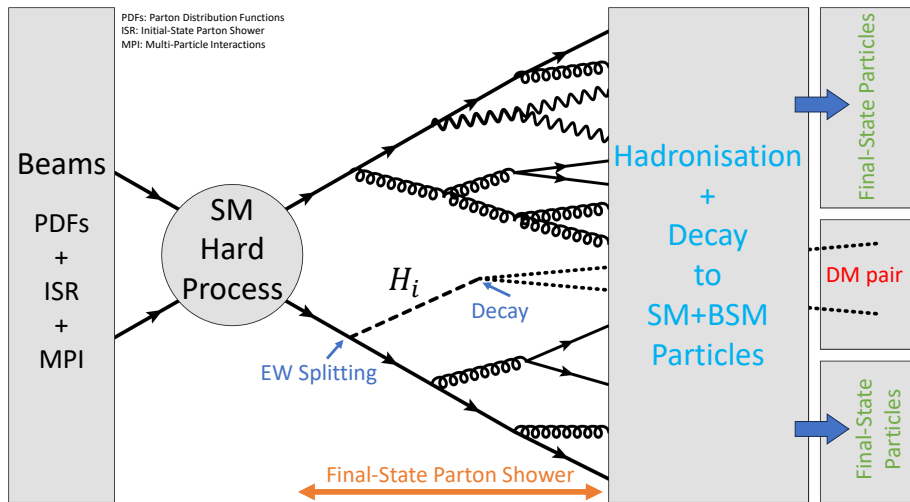
Benchmark from production at collider:



Benchmark from production at collider:



DM production through parton shower:



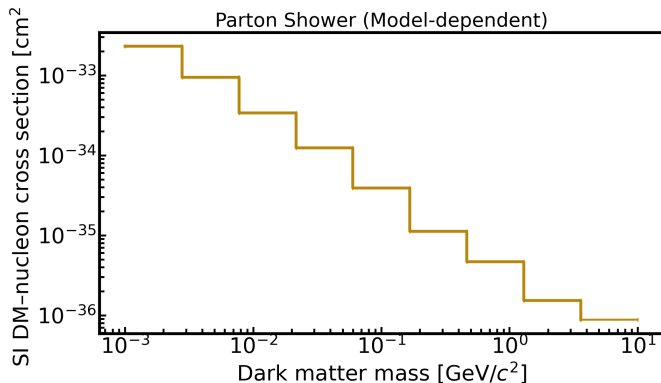
These analyses can be done:

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

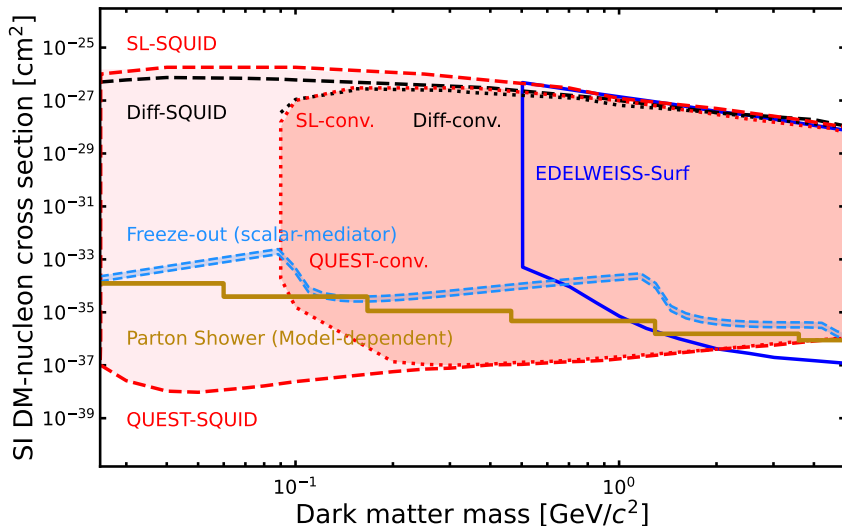
In any event, we need a **[UFO]**
(Universal FeynRules Output).

Built a model-dependent UFO
for:

2HDM + Complex Singlet



Dark matter searches strategies



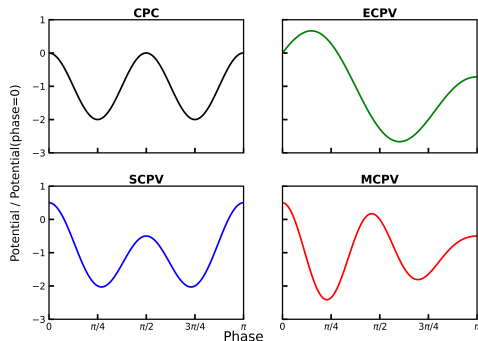
Why it matters: CPV is tiny and insufficient in the SM.

Consider CPV operators in a dark sector:

$$\mathcal{L}_{\text{CPV}} \supset \frac{1}{\Lambda^2} (\bar{\chi} i\gamma_5 \chi)(\bar{q}q) , \frac{1}{\Lambda^2} (\bar{\chi}\chi)(\bar{q} i\gamma_5 q), \dots$$

CPV sources:

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



JHEP 05 (2024) 233



- ▶ 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 ...

