Dark Matter Searches in the Effective Field Theory Context

Arthur Plante

May 29, 2017

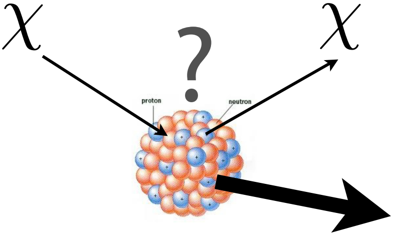
Outline

Introduction

Motivations

- SI & SD interactions are only a subset of all possible WIMP-nucleus interactions.

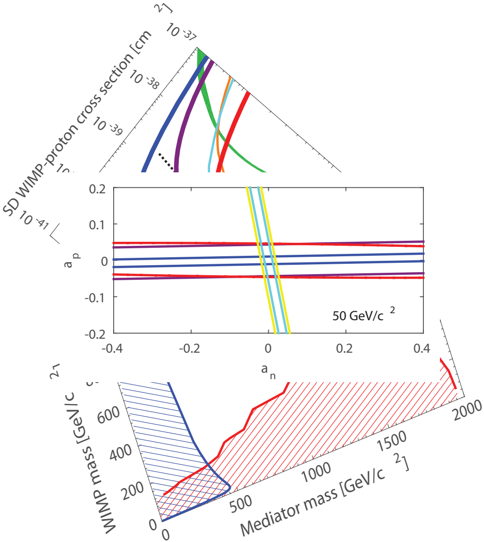
- Develop a model that describes all types of WIMP-nucleus interactions.



Introduction

Experimentalist goals

- Compare the results of the different experiments.
- Keep track of progress.
- Highlight the complementarity of the different experiments/nuclei.



Description of WIMP-nucleon interactions

Experimental output

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}} d^3v\, f(v)\, v\, \frac{d\sigma}{dE_R}$$

$N_T \equiv$ Nuclei per detector mass $\qquad f(\vec{v}) \equiv$ Halo velocity distribution

$$\frac{d\sigma}{dE_R} = \frac{m_T}{2\pi v^2} P_{tot}(v^2, q^2)$$

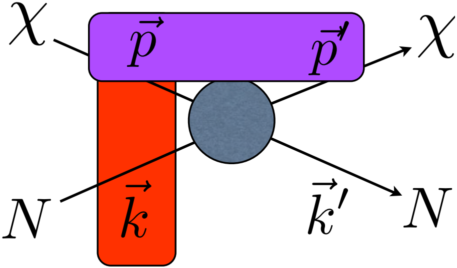
$$P_{tot} = \frac{1}{2j_\chi + 1} \frac{1}{2j_N + 1} \sum_{\text{spins}} |\mathcal{M}|^2_{\text{nucleus-HO/EFT}}$$

$$\mathcal{M}_{\text{nucleus-HO/EFT}} = \sum_{\tau=0,1} \langle j_\chi, M_\chi; j_N, M_N | \left[\sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau(i) \right] | j_\chi, M_\chi; j_N, M_N \rangle,$$

where c_i^τ and $\mathcal{O}_i$ are respectively the isospin couplings and EFT operators.

Basics of WIMP-nucleon EFT

Ingredients



- WIMP spin: $\vec{S}_\chi$
- Nucleon spin: $\vec{S}_N$
- Momentum conservation: $i\vec{q}$
- WIMPs velocity in the lab frame: $\vec{v}^\perp$

Basics of WIMP-nucleon EFT

Effective theory operators

$$\mathcal{O}_1 = 1_\chi 1_N$$ **(SI)**

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$ **(SD)**

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

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

Description of WIMP-nucleon EFT

Transition probability

$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2_{\text{nucleus-HO/EFT}} = \frac{4\pi}{2j_N+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}$$

$$\Bigg\{\Bigg[R_M^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_M^{\tau\tau'}(y) + R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_{\Sigma''}^{\tau\tau'}(y) +$$

$$R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})W_{\Sigma'}^{\tau\tau'}(y)\Bigg] + \frac{\vec{q}^{\,2}}{m_N^2}\Bigg[R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_{\Phi''}^{\tau\tau'}(y) +$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})W_{\tilde{\Phi}'}^{\tau\tau'}(y) \; + R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_{\Delta}^{\tau\tau'}(y)$$

$$R_{\Phi''M}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_{\Phi''M}^{\tau\tau'}(y) + R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2},\frac{\vec{q}^{\,2}}{m_N^2})\;W_{\Delta\Sigma'}^{\tau\tau'}(y)\Bigg]\Bigg\}$$

Nikhil Anand, A. Liam Fitzpatrick, and W. C. Haxton
https://doi.org/10.1103/PhysRevC.89.065501

Description of WIMP-nucleon EFT

WIMP and nuclear response

$$R_k^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}) \text{ and } W_k^{\tau\tau'}(y)$$

are respectively the WIMP and nuclear response function where $k = M, \Delta, \Sigma', \Sigma'', \tilde{\Phi}', \Phi''$ are the different possible interactions.

- Six interactions (k).
- Two interference terms.

$$R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{2}}{m_N^2}) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{2}}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{2}}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

Description of WIMP-nucleon EFT

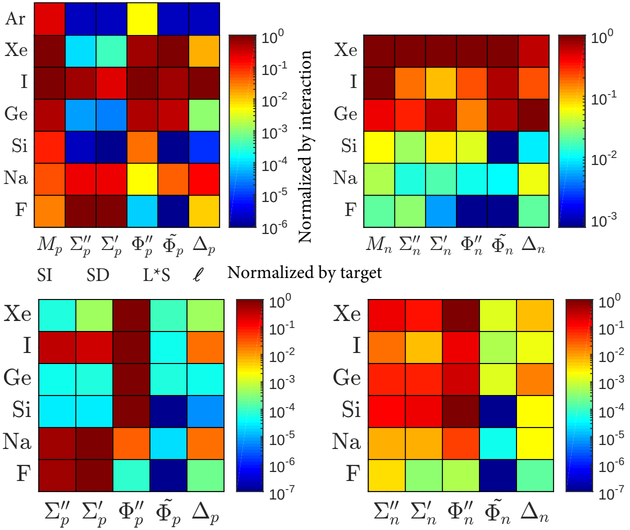
Nuclear operators

$$W_k^{\tau\tau'}(y) = \langle j_N || \; k_{J;\tau}(q) \; || j_N \rangle \langle j_N || \; k_{J;\tau'}(q) \; || j_N \rangle$$

- M: **SI** response
- Σ': $\vec{S}_N|_{\text{trans.}}$ with respect to $\vec{q}$ **(SD)**
- Σ'': $\vec{S}_N|_{\text{long.}}$ with respect to $\vec{q}$ **(SD)**
- Φ'': Spin-orbit interaction ($\vec{L} \cdot \vec{S}$)
- $\tilde{\Phi}'$: Also $\vec{L} \cdot \vec{S}$, but with CP-violation.
- Δ: Angular momentum of a nucleus (ℓ)

Physic outputs of EFT

Transition probability (P_{tot})



M_χ=100 GeV/c^2

Normalized with respect to most responsive target for a given interaction

$\Phi''(Ar) \sim \Phi''(Na)$

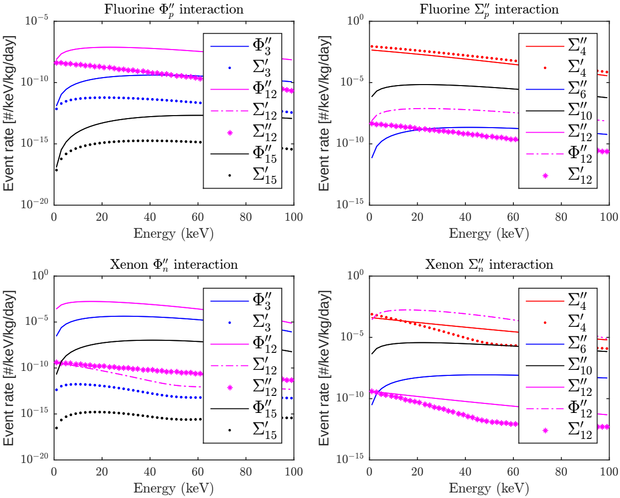
Ar: even neutrons, protons

Normalized with respect to most responsive interaction for a given target

Every target has $\Phi''_n \sim \Sigma''_n$

Backup slides

Recoil spectra composition



Recoil spectra composition of Φ'' and Σ''

M_χ=100 GeV/c^2

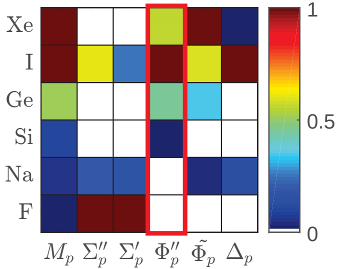
EFT operators couple to multiple interactions

$\mathcal{O}_{12}$ couples to $\Phi'', \Sigma'', \Sigma'$

$$R_{\Phi''}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) = \frac{\vec{q}^{\,2}}{4m_N^2} c_3^{\tau} c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^{\tau} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau}\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right)$$

Physic outputs of EFT

Spin orbit interaction Φ''



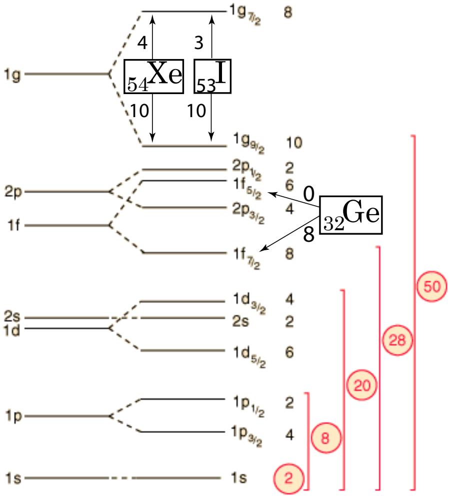
$\Phi'' \propto (\ell + 1)\, n_+ - \ell\, n_-$

$n_+ \equiv$ nucleons in $j = \ell + \frac{1}{2}$

$n_- \equiv$ nucleons in $j = \ell - \frac{1}{2}$

Xe=(4+1) × 10 - 4 × 4 =34

F = (2+1) × 1 - 2 × 0=3



Possible targets

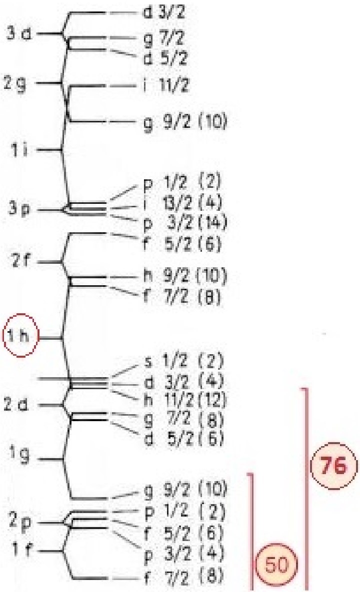
Decoupling Φ'' and Σ''

High Φ'': $n_+ =$ full, $n_- = 0$

Low Σ'': Even number of nucleons

ex: Full 1h$_{11/2}$ and
empty 1h$_{9/2}$ → 76-90 neutrons

- Remove ^{129}Xe (26.4%) and ^{131}Xe (21.2%) from Xe
- Remove ^{73}Ge (7.75%) from Ge



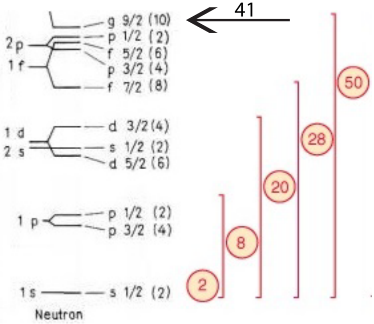
Possible targets

Decoupling Φ'' and Σ''

Low Φ'': neutrons, $n_+ \sim n_-$

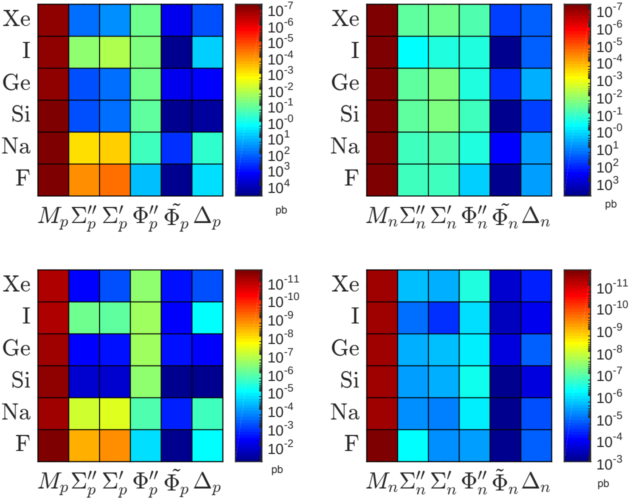
High Σ'': Odd number of neutrons

- ^{3}He
- Pure ^{73}Ge (41n) 7.75% +1n in g shell. It is the only Ge isotope with an odd number of neutrons, but still has good Φ''_p coupling.



Neutrino floor

Transition probability



M_χ=4 GeV/c^2

^{8}B neutrinos region

Cross section (pb) of each target for each operator, once that target has reached the neutrino floor

M_χ=100 GeV/c^2

Atmospheric neutrinos region

$$\sigma_{CNS} \sim \frac{(G_f E)^2}{4\pi} N^2$$

$$M_n \sim N^2$$

Summary

The pros and the cons

- Complete description of all WIMP-nuclei interactions.
- Highlights complementarity of targets
- List of targets that could be used to measure Σ'' and Φ'' separately
- Quantify the neutrino floor of the new interactions

- 28 free parameters.
- In case of no WIMP detection anything is possible

THANK YOU !

Weakly interacting massive particle-nucleus elastic scattering response, N. Anand, A. L. Fitzpatrick, and W. C. Haxton

The effective field theory of dark matter direct detection,A. L. Fitzpatrick, Wick Haxton, E. Katz, N. Lubbers, Y. Xu

Model Independent Direct Detection Analyses

Dark matter effective field theory scattering in direct detection experiments, SuperCDMS Collaboration

Complementarity of dark matter detectors in light of the neutrino background

Backup slides

Harmonic oscillator parameter

Nuclear response $\left(W_k^{\tau\tau'}(y)\right)$ depend on $y = (qb/2)^2$ where b is the harmonic oscillator parameter:

$$b \approx \sqrt{41.467/(45A^{-1/3} - 25A^{-2/3})}\ \text{fm}$$

Backup slides

Interference matrix

$$\begin{bmatrix} c_i^0 & c_i^1 & c_j^0 & c_j^1 \end{bmatrix} \begin{bmatrix} A_{ii}^{00} & A_{ii}^{01} & A_{ij}^{00} & A_{ij}^{01} \\ A_{ii}^{10} & A_{ii}^{11} & A_{ij}^{10} & A_{ij}^{11} \\ A_{ji}^{00} & A_{ji}^{01} & A_{jj}^{00} & A_{jj}^{01} \\ A_{ji}^{10} & A_{ji}^{11} & A_{jj}^{10} & A_{jj}^{11} \end{bmatrix} \begin{bmatrix} c_i^0 \\ c_i^1 \\ c_j^0 \\ c_j^1 \end{bmatrix}.$$

$A_{ij}^{\tau\tau'}$ is the transition probability for isospin operator τ and τ' and operators i and j.

Backup slides

Velocity operator

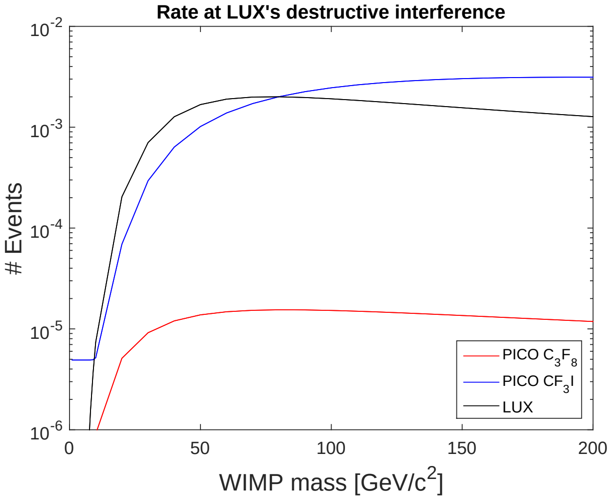
Need velocity related hermitian operator: $\vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu_N}$
$(\vec{v})^{\dagger} \to \vec{v}_{\chi,out} - \vec{v}_{N,out} = \vec{v} + \frac{\vec{q}}{\mu_N}$ and $\vec{q}$ is anti-hermitian.
Now $\vec{v}_T^{\perp}$: Comes from the separation of $\vec{v}^{\perp}$ in two terms:

- $\vec{v}_T^{\perp}$ acts on center-of-mass velocity of the atomic nucleus (Target)
- $\vec{v}_N^{\perp}$ acts on the relative distances of the nucleons inside the nucleus.

$\vec{v}^{\perp} = \vec{v}_T^{\perp} + \vec{v}_N^{\perp}$, where
$\vec{v}_T^{\perp} = \vec{v}_T + \frac{\vec{q}}{2\mu_N}$, $\vec{v}_T = \vec{v}_{\chi,in} - \vec{v}_{T,in} \equiv$ DM velocity in the lab frame
$\vec{v}_N^{\perp} = -\frac{1}{2}(\vec{v}_{N,in} + \vec{v}_{N,out})$

Backup slides

Isospin limits 0_5



At $\approx \theta = 75^\circ$ for 0_5 for $(c_5^0)^2 + (c_5^1)^2 = 1$

Backup slides

Details on nuclear operators

$$W_k^{\tau\tau'}(y) = \langle j_N ||\ k_{J;\tau}(q)\ || j_N \rangle \langle j_N ||\ k_{J;\tau'}(q)\ || j_N \rangle$$

$M_{JM}(q\vec{x}) \equiv j_J(qx) Y_{JM}(\Omega_x)$ and $\vec{M}_{JL}^{M} \equiv j_L(qx) \vec{Y}_{JLM}(\Omega_x)$

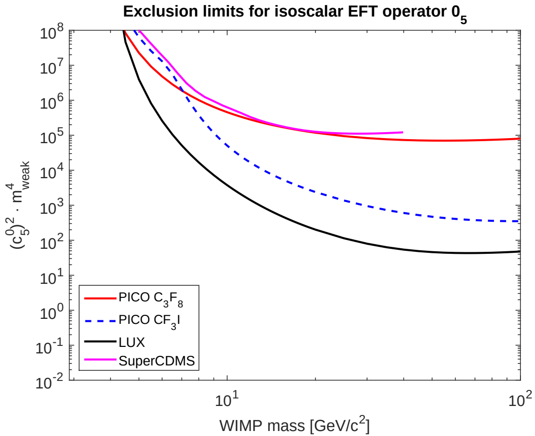
Ex: $M_{JM;\tau}(q) \equiv \sum_{i=1}^{A} M_{JM}(q\vec{x}_i)\ t^{\tau}(i)$

$\vec{x}_i$ is the nucleon coordinate within the nucleus

$$t^{\tau=0} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad t^{\tau=1} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Results

Limit plots



PICO CF$_3$I projection 100% efficiency & same exposure as PICO60 C$_3$F$_8$

$\mathcal{O}_5$ couples to M & Δ

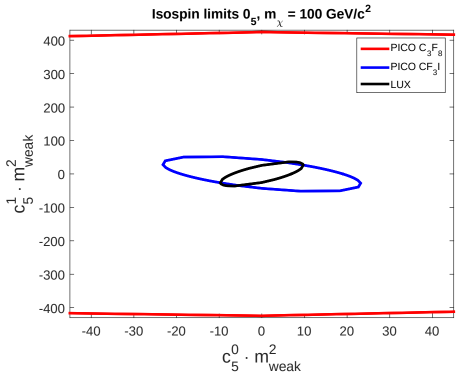
$$\mathcal{O}_5 \approx \frac{\vec{q}^2}{m_N^2}\left[\frac{\vec{q}^2}{m_N^2}(L_N)^2 + \vec{v}_T^{\perp 2} K_N^2\right]$$

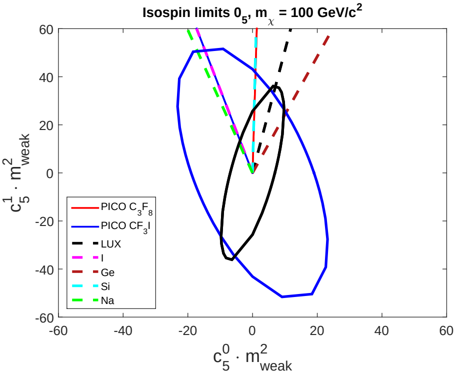
m_{weak} is the weak interaction mass scale $= (2G_F)^{(-1/2)} =$ 246.2 GeV

c=0.1 → 1/100th of weak interaction cross section.

Results

Isospin limits





- Find limit for $c_5^0 = c_5 \cdot cos(\theta)$ and $c_5^1 = c_5 \cdot sin(\theta)$
- The ellipse orientation is the same as the destructive interference for a given target/experiment.
- proton coupling: $c^0 = c^1$, neutron coupling: $c^0 = -c^1$

Description of WIMP-nucleon EFT

WIMP response

$$
\begin{aligned}
R_M^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^{\,2}}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right] \\
R_{\Phi''}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \frac{\vec{q}^{\,2}}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^{\tau'}\right) \\
R_{\Phi'' M}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^{\,2}}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'} \\
R_{\tilde{\Phi}'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^{\,2}}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right]
\end{aligned}
$$

Description of WIMP-nucleon EFT

WIMP response

$$\begin{aligned}
R_{\Sigma''}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) &= \frac{\vec{q}^2}{4m_N^2} c_{10}^{\tau} c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12} \Big[c_4^{\tau} c_4^{\tau'} + \\
&\quad \frac{\vec{q}^2}{m_N^2}\left(c_4^{\tau} c_6^{\tau'} + c_6^{\tau} c_4^{\tau'}\right) + \frac{\vec{q}^4}{m_N^4} c_6^{\tau} c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^{\tau} c_{12}^{\tau'} + \frac{\vec{q}^2}{m_N^2} \vec{v}_T^{\perp 2} c_{13}^{\tau} c_{13}^{\tau'} \Big] \\
R_{\Sigma'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) &= \frac{1}{8}\left[\frac{\vec{q}^2}{m_N^2} \vec{v}_T^{\perp 2} c_3^{\tau} c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^{\tau} c_7^{\tau'} \right] + \frac{j_\chi(j_\chi+1)}{12} \Big[c_4^{\tau} c_4^{\tau'} + \\
&\quad \frac{\vec{q}^2}{m_N^2} c_9^{\tau} c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^{\tau} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau}\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^2}{2m_N^2} \vec{v}_T^{\perp 2} c_{14}^{\tau} c_{14}^{\tau'} \Big] \\
R_{\Delta}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^2}{m_N^2} c_5^{\tau} c_5^{\tau'} + c_8^{\tau} c_8^{\tau'} \right] \\
R_{\Delta\Sigma'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) &= \frac{j_\chi(j_\chi+1)}{3}\left[c_5^{\tau} c_4^{\tau'} - c_8^{\tau} c_9^{\tau'} \right].
\end{aligned}$$

Description of WIMP-nucleon EFT

EFT interaction parametrization

- The strength of an EFT interaction is governed by the isospin couplings c_i^τs
- τ is the isospin
- $c_i^0 \equiv$ isoscalar
- $c_i^1 \equiv$ isovector
- Per definition: $c_i^0 = \frac{1}{2}(c_i^p + c_i^n)$ and $c_i^1 = \frac{1}{2}(c_i^p - c_i^n)$
- $c_i^p = c_i^0 + c_i^1$
- $c_i^n = c_i^0 - c_i^1$
- Pure proton coupling: $c_i^0 = c_i^1$
- Pure neutron coupling: $c_i^0 = -c_i^1$