RG Effects in Dark Matter Direct Detection

Fady Bishara

UNIVERSITY OF OXFORD

Dark Matter Interpretations for Direct Detection
9^{th} August, 2016

Based on: FB, J. Brod, B. Grinstein, and J. Zupan. [160Y.XXXXX]

Motivation

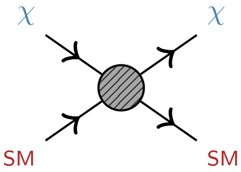
- There is overwhelming evidence for Dark Matter through its gravitational interactions
- What about its particle nature? There are several probes for discovery:
  - Direct detection
  - Indirect detection
  - Collider searches
- However, these experiments probe very different scales

Outline

- Dark matter search strategies & direct detection
- Relevant scales and tower of EFTs
- DM EFT above v_{EW}
- Heavy DM EFT
- Non-relativitic Lagrangian
- Heavy Baryon chiral Lagrangian and pion-less EFT
- Illustrative examples

Searches for Dark Matter

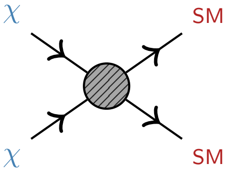
Direct Detection



$q^{(\text{max})}$

~ 200 [MeV]

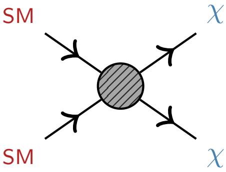
Indirect Detection



$m_\chi \sim v_{\text{EW}}$

~ 100 [GeV]

Collider Searches



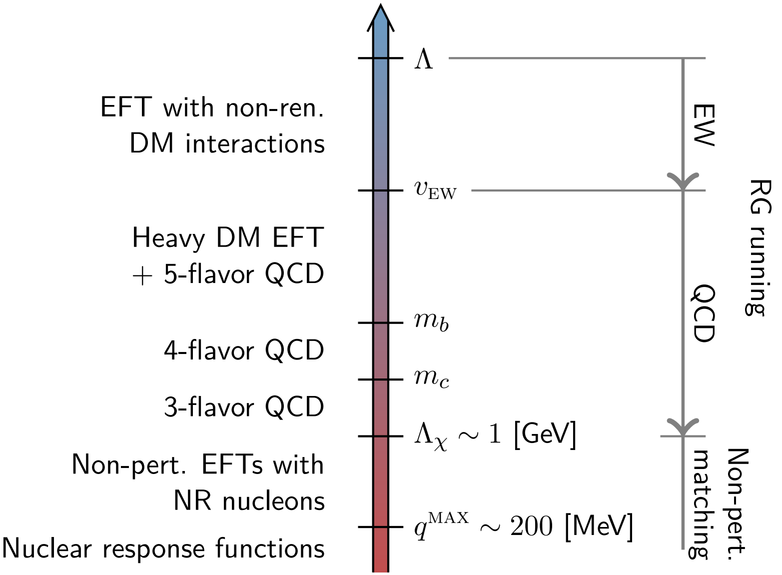
$\sqrt{\hat{s}}$

$\sim$ [TeV]

The setup

- Assume DM, χ, is an electroweak multiplet with $m_\chi \sim v_{\text{ew}}$ focusing on the case where χ is a fermion
- Several examples:
  - Neutralinos in the MSSM (bino, higgsino, wino)
  - Minimal Dark Matter [Cirelli et al. hep-ph/0512090, . . .]
  - "Technibaryons" [Nussinov, Phys.Lett. B165 (1985) 55, . . .]
- Mediators, ϕ, integrated out at $\Lambda \sim m_\phi \gg m_\chi$
  - Dim.4 gauge interactions
  - Higher-dimensional effective operators

Relevant scales and tower of EFTs



Renormalization group effects

- Mixing of operators through the renormalization group equations (RGEs)

$$\frac{d}{d\log\mu}\vec{\mathcal{C}}(\mu) = \gamma^T \vec{\mathcal{C}}(\mu)$$

- In particular, mixing of suppressed and un-suppressed operators [Freytsis & Ligeti, 1012.5317; Kopp et al. 0907.3159; Haisch & Kahlhoefer 1302.4454; Crivellin et al. 1402.1173, 1408.5046; D'Eramo et al. 1409.2893]

- Resummation of logarithms $\alpha\log(\mu/\Lambda)$: do we need to?
  - In general, no since

$\alpha_1(\mu_{EW}) \approx 0.01, \alpha_2(\mu_{EW}) \approx 0.03, \alpha_\lambda(\mu_{EW}) \approx 0.04, \alpha_t(\mu_{EW}) \approx 0.08$

  - Would need $\Lambda \gtrsim 10^4$ [TeV]
  - However, in some cases, can have $\gamma \sim \mathcal{O}(10) \rightarrow$ must resum logs to all orders in such cases

Effective Lagrangian above v_{EW}

- General Lagrangian given by [Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783; Bai, Fox, Harnik, 1005.3797; . . .]

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_\chi + \sum \frac{C^{(5)}}{\Lambda} Q^{(5)} + \sum \frac{C^{(6)}}{\Lambda^2} Q^{(6)} + \dots$$

- Generalization of SMEFT [Buchmüller et al. 1986, Grzadkowski et al. 2010]

- DM transforms under representation of electroweak gauge group s.t. $\mathscr{L}_\chi^{(4)} = \bar{\chi} i \not{D} \chi - m_\chi \bar{\chi}\chi$

$$D_\mu = \partial_\mu - i g_2 \tilde{\tau}_W^a W_\mu^a + i g_1 \frac{Y_\chi}{2} B_\mu$$

The operator basis

- Dimension 5 operators

$$(4):\quad \frac{1}{8\pi^2}\Big(\bar\chi\sigma^{\mu\nu}[1+i\gamma_5]\begin{Bmatrix}1\\ \tilde\tau^a\end{Bmatrix}\chi\Big)\begin{Bmatrix}g_1\,B_{\mu\nu}\\ g_2\,W^a_{\mu\nu}\end{Bmatrix}$$

$$(4):\quad \Big(\bar\chi[1+i\gamma_5]\begin{Bmatrix}1\\ \tilde\tau^a\end{Bmatrix}\chi\Big)\Big(H^\dagger\begin{Bmatrix}1\\ \tilde\tau^a\end{Bmatrix}H\Big)$$

- Dimension 6 operators

$$(8):\quad \Big(\bar\chi\gamma_\mu[1+\gamma_5]\begin{Bmatrix}1\\ \tilde\tau^a\end{Bmatrix}\chi\Big)(\bar F^i_L\gamma^\mu\begin{Bmatrix}1\\ \tau^a\end{Bmatrix}F^i_L)\,,\qquad F_L\in\{Q_L,L_L\}$$

$$(6):\quad (\bar\chi\gamma_\mu(1+\gamma_5)\chi)(\bar f_R\gamma^\mu f_R)\,,\qquad f_R\in\{u_R,d_R,\ell_R\}$$

$$(4):\quad \Big(\bar\chi\gamma^\mu[1+\gamma_5]\begin{Bmatrix}1\\ \tilde\tau^a\end{Bmatrix}\chi\Big)(H^\dagger\begin{Bmatrix}i\,\overleftrightarrow{D}_\mu\\ i\,\overleftrightarrow{D}^a_\mu\end{Bmatrix}H)\,,\qquad \begin{matrix}D^a_\mu\equiv\tau^a D_\mu\\ \overleftrightarrow{D}_\mu\equiv\overleftarrow{D}^\dagger_\mu-D_\mu\end{matrix}$$

Effective Lagrangian below v_{EW}

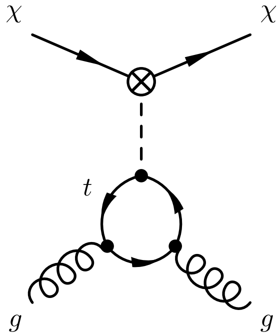
- Integrating out heavy states gives

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}}\Big|_{n_f} + \mathscr{L}_\chi + \sum_{d=5}^{6} \sum_j \hat{\mathcal{C}}_j^{(d)}\Big|_{n_f} \mathcal{Q}_j^{(d)} + \sum \hat{\mathcal{C}}_j^{(7)}\Big|_{n_f} \mathcal{Q}_j^{(7)} + \dots$$

- There are now two scales in the EFT – the Wilson coefficients are, then,

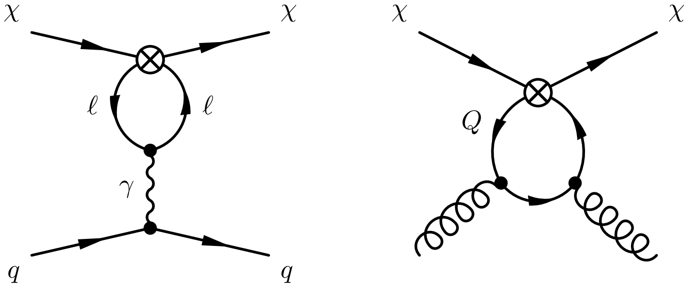
$$\hat{\mathcal{C}}_j^{(d)} = \sum_{\{n\}} \frac{\mathcal{C}_j^{(d-4,n)}}{\Lambda^{d-4-n} v_{\text{EW}}^n}$$

- Also, now generated dimension 7 operators that weren't in the UV operator basis



Running and matching at flavor thresholds

- QCD / QED running is well-known {e.g. Hill et al. [1409.8290]}
- Penguin insertions will mix lepton and quark operators
- Matching at flavor thresholds



Nonrelativistic limit

- DM currents

$$\bar{\chi}\gamma^{\mu}\chi \to 2m_{\chi}\Psi_{\chi}^{\dagger}\Big(1, \vec{v}^{\perp} + \frac{\vec{q}}{2m_N} + i\frac{\vec{q}\times\vec{S}_{\chi}}{m_{\chi}}\Big)\Psi_{\chi}$$

$$\bar{\chi}\gamma^{\mu}\gamma_5\chi \to 4m_{\chi}\Psi_{\chi}^{\dagger}\Big(\vec{v}^{\perp}\cdot\vec{S}_{\chi} + \frac{\vec{q}\cdot\vec{S}_{\chi}}{2m_N},\ \vec{S}_{\chi}\Big)\Psi_{\chi}$$

- Nucleon currents

$$\bar{p}\gamma^{\mu}p \to 2m_N\Psi_p^{\dagger}\Big(1, \frac{\vec{q}}{2m_N} - i\frac{\vec{q}\times\vec{S}_p}{m_N}\Big)\Psi_p$$

$$\bar{p}\gamma^{\mu}\gamma_5 p \to 4m_N\Psi_p^{\dagger}\Big(\frac{\vec{q}\cdot\vec{S}_p}{2m_N}, \vec{S}_p\Big)\Psi_p$$

Non-relativistic EFT

- Follow Anand, Fitzpatrick, & Haxton [1308.6288], [1203.3542]

$$\mathcal{L}_{\rm NR} = \sum_i 4 m_\chi m_N \left(c^n_{\mathrm{NR},i} \mathcal{O}^n_i + c^p_{\mathrm{NR},i} \mathcal{O}^p_i \right)$$

- Build NR operators out of the Galilean invariants

$$\left\{ \frac{i\vec{q}}{m_N}, \quad \vec{v}^\perp, \quad \vec{S}_\chi, \quad \vec{S}_N \right\}$$

- For spin 0, 1 mediators, get the following operators

$$\mathcal{O}^p_1 = \left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right), \qquad \mathcal{O}^p_2 = (v^\perp)^2 \left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

$$\mathcal{O}^p_3 = \frac{i}{m_N}\left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot (\vec{v}^\perp \times \vec{q}) \Psi_p\right) \qquad \mathcal{O}^p_4 = \left(\Psi^\dagger_\chi \vec{S}_\chi \Psi_\chi\right) \cdot \left(\Psi^\dagger_p \vec{S}_p \Psi_p\right)$$

$$\mathcal{O}^p_5 = \frac{i}{m_N}(\Psi^\dagger_\chi \vec{S}_\chi \cdot (\vec{v}^\perp \times \vec{q}) \Psi_\chi\big)\left(\Psi^\dagger_p \Psi_p\right) \qquad \mathcal{O}^p_6 = \frac{1}{m_N^2}\left(\Psi^\dagger_\chi \vec{S}_\chi \cdot \vec{q}\, \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{q}\, \Psi_p\right)$$

$$\mathcal{O}^p_7 = \left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{v}^\perp \Psi_p\right), \qquad \mathcal{O}^p_8 = \left(\Psi^\dagger_\chi \vec{S}_\chi \cdot \vec{v}^\perp \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

$$\mathcal{O}^p_9 = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \vec{S}_\chi \Psi_\chi\right) \cdot \left(\Psi^\dagger_p \vec{S}_p \times \vec{q}\, \Psi_p\right), \qquad \mathcal{O}^p_{10} = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{q}\, \Psi_p\right)$$

$$\mathcal{O}^p_{11} = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \vec{S}_\chi \cdot \vec{q} \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

Non-relativistic EFT

- Follow Anand, Fitzpatrick, & Haxton [1308.6288], [1203.3542]

$$\mathcal{L}_{\rm NR} = \sum_i 4 m_\chi m_N \left(c^n_{{\rm NR},i} \mathcal{O}^n_i + c^p_{{\rm NR},i} \mathcal{O}^p_i \right)$$

- Build NR operators out of the Galilean invariants

$$\left\{ \frac{i\vec{q}}{m_N}, \quad \vec{v}^\perp, \quad \vec{S}_\chi, \quad \vec{S}_N \right\}$$

$$\vec{v}^\perp = \vec{v} - \frac{\vec{q}}{2\mu_N}$$

$$\vec{v} \equiv \vec{v}_{\chi,\text{in}} - \vec{v}_{N,in}$$

$$\vec{v}^\perp \cdot \vec{q} = 0$$

- For spin 0, 1 mediators, get the following operators

$$\mathcal{O}^p_1 = \left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right), \qquad \ldots \Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

$$\mathcal{O}^p_3 = \frac{i}{m_N}\left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot (\vec{v}^\perp \times \ldots \qquad \ldots \Psi_\chi\right) \cdot \left(\Psi^\dagger_p \vec{S}_p \Psi_p\right)$$

$$\mathcal{O}^p_5 = \frac{i}{m_N}\left(\Psi^\dagger_\chi \vec{S}_\chi \cdot (\vec{v}^\perp \times \vec{q})\Psi_\chi\right)\left(\Psi \ldots \qquad \ldots {}^\dagger_\chi \vec{S}_\chi \cdot \vec{q}\,\Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{q}\,\Psi_p\right)$$

$$\mathcal{O}^p_7 = \left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{v}^\perp \Psi_p\right), \qquad \mathcal{O}^p_8 = \left(\Psi^\dagger_\chi \vec{S}_\chi \cdot \vec{v}^\perp \Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

$$\mathcal{O}^p_9 = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \vec{S}_\chi \Psi_\chi\right) \cdot \left(\Psi^\dagger_p \vec{S}_p \times \vec{q}\,\Psi_p\right), \qquad \mathcal{O}^p_{10} = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \Psi_\chi\right)\left(\Psi^\dagger_p \vec{S}_p \cdot \vec{q}\,\Psi_p\right)$$

$$\mathcal{O}^p_{11} = \frac{-i}{m_N}\left(\Psi^\dagger_\chi \vec{S}_\chi \cdot \vec{q}\Psi_\chi\right)\left(\Psi^\dagger_p \Psi_p\right)$$

Nuclear response

- The direct detection cross-section is proportional to

$$\sigma_{\rm DD} \propto \frac{4\pi}{2J_A+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\Big\{\Big[R_M^{\tau\tau'}W_M^{\tau\tau'}(y)+R_{\Sigma''}^{\tau\tau'}W_{\Sigma''}^{\tau\tau'}(y)+R_{\Sigma'}^{\tau\tau'}W_{\Sigma'}^{\tau\tau'}(y)\Big]$$

$$+\frac{\vec{q}^2}{m_N^2}\Big[R_{\Delta}^{\tau\tau'}W_{\Delta}^{\tau\tau'}(y)+R_{\Delta\Sigma'}^{\tau\tau'}W_{\Delta\Sigma'}^{\tau\tau'}(y)\Big]\Big\},$$

- Where, R_i contain the Wilson coefficients and W_i are the nuclear response functions.

- For example,

$$R_{\Sigma''}^{\tau\tau'} = (4m_\chi m_N)^2\frac{1}{16}\Big[c_{\rm NR,4}^{\tau}c_{\rm NR,4}^{\tau'}+\frac{\vec{q}^2}{m_N^2}(c_{\rm NR,4}^{\tau}c_{\rm NR,6}^{\tau'}+c_{\rm NR,6}^{\tau}c_{\rm NR,4}^{\tau'})$$

$$+\frac{\vec{q}^4}{m_N^4}c_{\rm NR,6}^{\tau}c_{\rm NR,6}^{\tau'}\Big]$$

Nuclear response functions

- In general, there are 6 nuclear responses [1308.6288]
- Only 3 are generated in our setup

Response	Property	Long wavelength behavior
W_M	spin-independent	counts nucleons (coherent scattering)
$W_{\Sigma',\Sigma''}$	spin-dependent	nucleon spin content of nucleus
W_Δ	nuclear ang. mom.	nucleon ang. mom. content of nucleus

- Rough scaling

$$W_M \sim \mathcal{O}(A^2), \qquad W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$$

Heavy baryon chiral perturbation theory (HBChPT)

- So far, assumed that DM scatters on a single nucleon
- Is this assumption justified?
- In other words, can we consistently ignore operators where the DM couples to 4 nucleons?
- To answer this question, we need a consistent power counting scheme [Jenkins & Manohar, Phys.Lett. B255 (1991) 558]

  $\Rightarrow$ Heavy baryon chiral perturbation theory (HBChPT)

- Nucleons are heavy w.r.t. to the scale in the problem

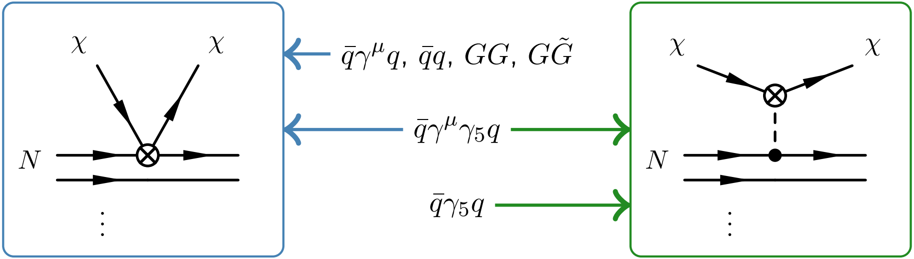
$$m_{p,n} \gg q \lesssim 200 \text{ [MeV]}$$

Leading order diagrams

$$\bar{q}\gamma^\mu q \to \tilde{J}^V_{q,\mu} \sim v^\mu_B \bar{N}N + \cdots \qquad GG \to \tilde{J}^G \sim \bar{N}N + \cdots$$

$$\bar{q}q \to \tilde{J}^S_q \sim m_q \bar{N}N + \cdots \qquad G\tilde{G} \to \tilde{J}^\theta \sim q_\mu S^\mu \bar{N}N + \cdots$$

$$\bar{q}\gamma^\mu\gamma_5 q \to \tilde{J}^A_{q,\mu} \sim S_\mu \bar{N}N + \cdots$$



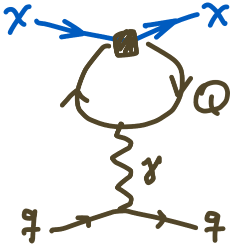
$$i\bar{q}\gamma_5 q \to J^P_q \sim m_q \pi + \cdots \qquad \bar{q}\gamma^\mu\gamma_5 q \to J^A_{q,\mu} \sim \partial_\mu \pi + \cdots$$

Illustrative Examples

Coupling to 3rd Generation – No Mixing

- Start with $Q_{6,3}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^3\gamma^\mu Q_L^3)$

- Need mixing into light-quark operators $\mathcal{Q}_{2,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$

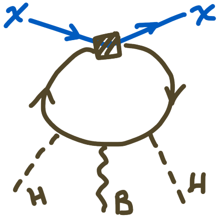


$$\frac{C_{6,3}^{(6)}}{\Lambda^2} \xrightarrow{\mu\sim v_{\rm EW}} \frac{\alpha}{4\pi}\frac{\mathcal{C}_{2q}^{(6)}}{\Lambda^2}$$

- $\mathcal{Q}_{2,q}^{(6)}$ has response $v^2\, W_M$, so the cross section scales as

$$\sigma \propto v^2 A^2 \left(\frac{\alpha}{4\pi}\frac{C_{6,3}^{(6)}}{\Lambda^2}\right)^2$$

Coupling to 3rd Generation – Mixing, Singlet DM



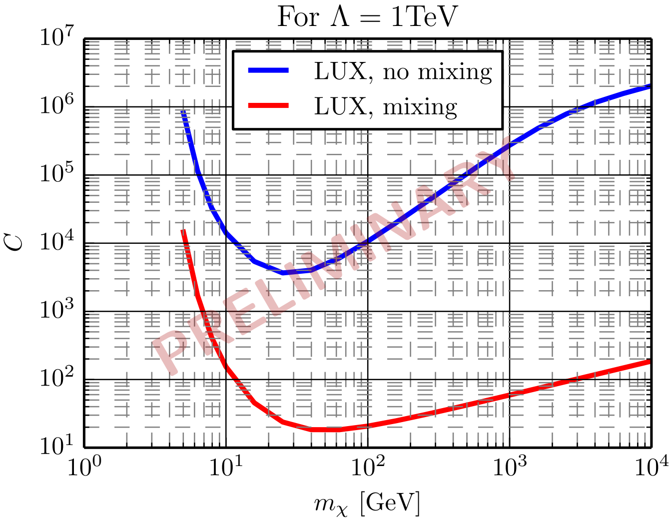
- Start with $Q_{6,3}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^3\gamma^\mu Q_L^3)$
- Mix into $Q_{18}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(H^\dagger i \overleftrightarrow{D}_\mu H)$
- Z exchange after EWSB, induces $\bar{q}\gamma^\mu\gamma_5 q$

$$\frac{C_{6,3}^{(6)}}{\Lambda^2} \xrightarrow{\mu\sim\Lambda} \frac{\alpha_t}{4\pi}\frac{C_{18}^{(6)}}{\Lambda^2} \xrightarrow{\mu\sim v_{\rm EW}} \frac{\alpha_t}{4\pi}\frac{\mathcal{C}_{4q}^{(6)}}{\Lambda^2}$$

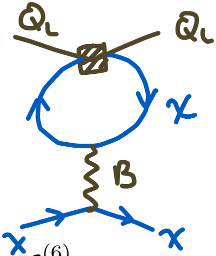
- $\mathcal{Q}_{4,q}^{(6)}$ has response $W_{\Sigma'}$, $W_{\Sigma''}$, so the cross section *really* scales as

$$\sigma \propto v^0 A^0 \left(\frac{\alpha_t}{4\pi}\frac{C_{6,3}^{(6)}}{\Lambda^2}\right)^2$$

Coupling to 3rd Generation – Mixing, Singlet DM



Coupling to 3rd Generation – Mixing, $Y_\chi \neq 0$



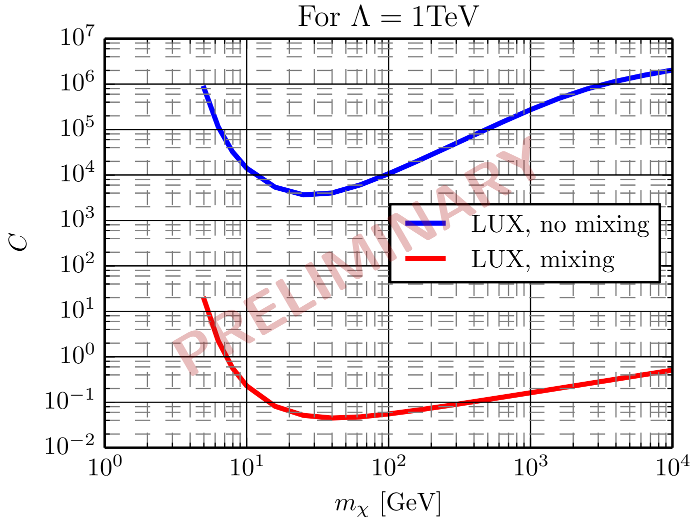
- Start with $Q^{(6)}_{6,3} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q^3_L\gamma^\mu Q^3_L)$
- Mix into $Q^{(6)}_{2,3} = (\bar\chi\gamma_\mu\chi)(\bar Q^3_L\gamma^\mu Q^3_L)$
- Need photon exchange to get to first generation

$$\frac{C^{(6)}_{6,3}}{\Lambda^2} \xrightarrow{\mu\sim\Lambda} \frac{\alpha_1}{4\pi}\frac{C^{(6)}_{2,3}}{\Lambda^2} \xrightarrow{\mu\sim v_{\rm EW}} \frac{\alpha_1}{4\pi}\frac{\alpha}{4\pi}\frac{\mathcal{C}^{(6)}_{1q}}{\Lambda^2}$$

- $\mathcal{Q}^{(6)}_{1,q}$ has response W_M, so the cross section scales as

$$\sigma \propto v^0 A^2 \left(\frac{\alpha_1}{4\pi}\frac{\alpha}{4\pi}\frac{C^{(6)}_{6,3}}{\Lambda^2}\right)^2$$

Coupling to 3rd Generation – Mixing, $Y_\chi \neq 0$



Summary and outlook

- Presented our effort to consistently treat all the relevant scales in DM direct detection in a large set of models
- Renormalization group effect are most important for suppressed operators; showed several examples
- Will provide public code (Mathematica) that implements our framework
- Many future directions: scalar DM, dim. 7 operators in the UV, more than one multiplet . . .

Backup

Dark Matter direct detection

- Goal is to calculate the scattering rate of DM on atomic nuclei

- The interaction rate per unit mass is given by [Lewin & Smith Astropart. Phys. 6 (1996)]

$$R = \frac{\Gamma}{m_A} = \frac{1}{m_A}\langle n_\chi \sigma\, v\rangle = \frac{\rho_\chi}{m_A\, m_\chi}\langle \sigma\, v\rangle$$

- However, we are interested in dR/dE_R (we must convolve with exp. eff. which is a function of E_R, e.g.)

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_A\, m_\chi}\left\langle \frac{d\sigma}{dE_R}\, v \right\rangle$$

- Finally, we have

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_A\, m_\chi}\int_{v_{\text{min}}} dv\;\, f(v)\frac{d\sigma}{dE_R}\, v$$

Dimension 5 operators

- CP even operators

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu}, \qquad Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu}$$

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H) \qquad Q_4^{(5)} = (\bar{\chi}\tilde{\tau}^a\chi)(H^\dagger\tau^a H)$$

- CP odd operators

$$Q_5^{(5)} = i\frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi)B_{\mu\nu}, \qquad Q_6^{(5)} = i\frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\gamma_5\chi)W^a_{\mu\nu}$$

$$Q_7^{(5)} = i(\bar{\chi}\gamma_5\chi)(H^\dagger H), \qquad Q_8^{(5)} = i(\bar{\chi}\tilde{\tau}^a\gamma_5\chi)(H^\dagger\tau^a H)$$

Dimension 6 operators

$$Q^{(6)}_{1,i} = (\bar{\chi}\gamma_\mu\tilde{\tau}^a\chi)(\bar{Q}^i_L\gamma^\mu\tau^a Q^i_L), \quad Q^{(6)}_{5,i} = (\bar{\chi}\gamma_\mu\gamma_5\tilde{\tau}^a\chi)(\bar{Q}^i_L\gamma^\mu\tau^a Q^i_L)$$

$$Q^{(6)}_{2,i} = (\bar{\chi}\gamma_\mu\chi)(\bar{Q}^i_L\gamma^\mu Q^i_L), \quad Q^{(6)}_{6,i} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}^i_L\gamma^\mu Q^i_L)$$

$$Q^{(6)}_{3,i} = (\bar{\chi}\gamma_\mu\chi)(\bar{u}^i_R\gamma^\mu u^i_R), \quad Q^{(6)}_{7,i} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}^i_R\gamma^\mu u^i_R)$$

$$Q^{(6)}_{4,i} = (\bar{\chi}\gamma_\mu\chi)(\bar{d}^i_R\gamma^\mu d^i_R), \quad Q^{(6)}_{8,i} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}^i_R\gamma^\mu d^i_R)$$

$$Q^{(6)}_{9,i} = (\bar{\chi}\gamma_\mu\tilde{\tau}^a\chi)(\bar{L}^i_L\gamma^\mu\tau^a L^i_L), \quad Q^{(6)}_{12,i} = (\bar{\chi}\gamma_\mu\gamma_5\tilde{\tau}^a\chi)(\bar{L}^i_L\gamma^\mu\tau^a L^i_L)$$

$$Q^{(6)}_{10,i} = (\bar{\chi}\gamma_\mu\chi)(\bar{L}^i_L\gamma^\mu L^i_L), \quad Q^{(6)}_{13,i} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{L}^i_L\gamma^\mu L^i_L),$$

$$Q^{(6)}_{11,i} = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}^i_R\gamma^\mu \ell^i_R), \quad Q^{(6)}_{14,i} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}^i_R\gamma^\mu \ell^i_R)$$

$$Q^{(6)}_{15} = (\bar{\chi}\gamma^\mu\tilde{\tau}^a\chi)(H^\dagger i \overleftrightarrow{D}^a{}_\mu H), \quad Q^{(6)}_{17} = (\bar{\chi}\gamma^\mu\gamma_5\tilde{\tau}^a\chi)(H^\dagger i \overleftrightarrow{D}^a{}_\mu H)$$

$$Q^{(6)}_{16} = (\bar{\chi}\gamma^\mu\chi)(H^\dagger i \overleftrightarrow{D}_\mu H), \quad Q^{(6)}_{18} = (\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i \overleftrightarrow{D}_\mu H)$$

Power counting

- Interested in A-nucleon irreducible amplitudes with one insertion of DM current, $M_{A,\chi}$, which scale as [Weinberg, NPB363, 3 (1991); Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan, 1205.2695]

$$M_{A,\chi} \sim q^{\nu}$$

where

$$\nu = 4 - A - 2C + 2L + \sum_i V_i \left(d_i + n_i/2 - 2 \right) + \epsilon_\chi$$

effective chiral dim. (ϵ_χ)

no. of connected diag's (C)

no. of loops (L)

chiral dim. $\sim$ no. of deriv's (d_i)

no. of nuc. legs (n_i)

- Gives scaling for LO and NLO potentials
  more nucleons legs in vertex $\rightarrow$ more suppressed