Renormalization-group Effects in Dark-Matter Direct Detection

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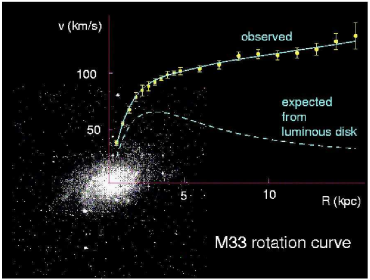
With Fady Bishara, Benjamin Grinstein, Jure Zupan – work in progress

With Aaron Gootjes-Dreesbach, Maximilian Reininghaus – work in progress

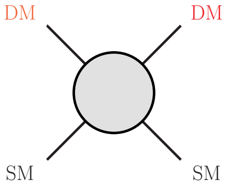
Dark Matter Facts

- DM exists
  - All evidence via its gravitation
- Particle nature?
- What we know about DM
  - DM is non-baryonic, cold, and neutral
  - Relic abundance $\Omega_{\rm DM} h^2 = 0.1198(26)$
    [PLANCK / PDG 2014]

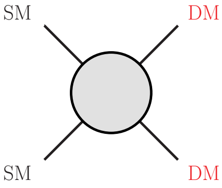


- Thermal history motivates interaction with SM

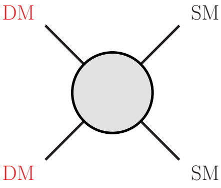
Three roads to discovery



Direct detection

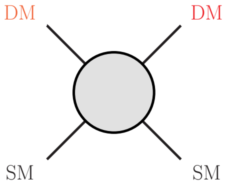


Collider searches

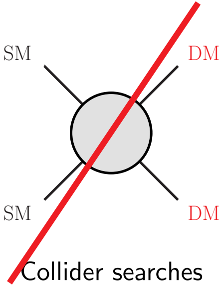


Indirect detection

Three roads to discovery



Direct detection



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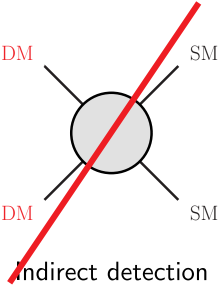


Indirect detection

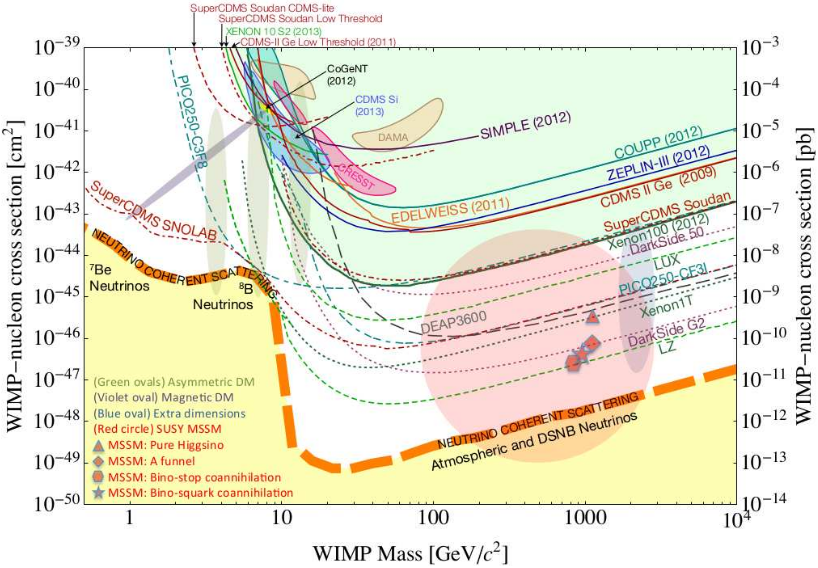
Direct Detection Basics

- Direct detection – scattering on nuclei
  - Complementary information, proves cosmological lifetime
  - Assume velocity distribution (Maxwell); $v \sim 10^{-3}$
  - Maximal momentum transfer is $q \lesssim 200\,\text{MeV}$

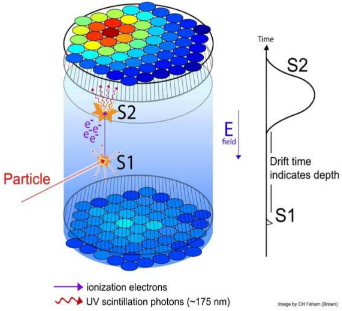
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_A m_\chi} \int_{v_{min}} dv\, v\, f_1(v) \frac{d\sigma}{dE_R}(v, E_R)\,.$$

[Lewin & Smith, Astropart.Phys.6 (1996)]

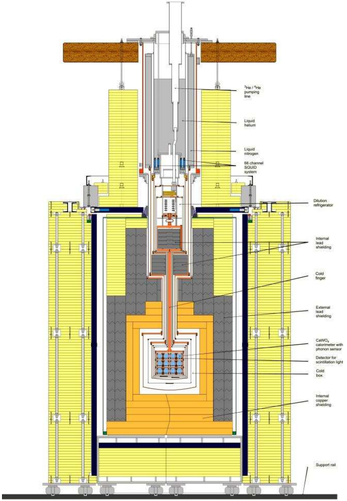
Direct Detection Limits



Direct Detection Experiments

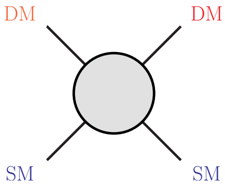


LUX



CRESST

Direct Detection



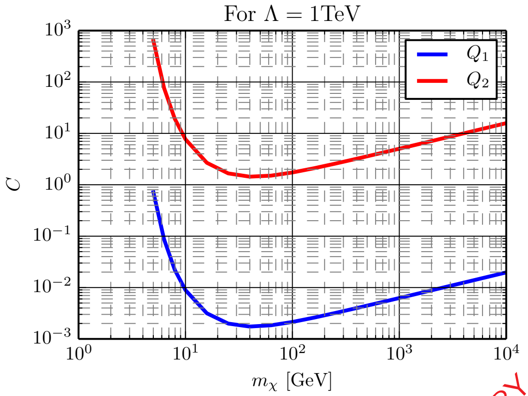
- What is the meaning of "SM"?
    - Write models at high energies – SM $\equiv Q_L, q_R, L_L, \ell_R, g, \ldots$
    - Scattering nonrelativistic, at very low energies – SM $\equiv p, n, (\pi,) \ldots$
- Use appropriate EFT (effective theory)
- UV operators have characteristic behaviour in the nonrelativistic limit

Nonrelativistic limit

- Traditionally, consider point-like nucleus (+ form factor)
  - "spin independent" vs. "spin dependent" scattering
  - momentum / velocity - suppressed interactions
- NR limit of SM currents
  - Axial vector: $\bar{p}\gamma^\mu\gamma_5 p \quad \rightsquigarrow \quad \Psi_p^\dagger\Big(\frac{\vec{q}\cdot\vec{S}_p}{m_N}, 2\vec{S}_p\Big)\Psi_p$
  - Vector: $\bar{p}\gamma^\mu p \quad \rightsquigarrow \quad \Psi_p^\dagger\Big(1,\ \frac{\vec{q}}{2m_N} - i\frac{\vec{q}\times\vec{S}_p}{m_N}\Big)\Psi_p$
- NR limit of DM currents
  - Axial vector: $\bar{\chi}\gamma^\mu\gamma_5\chi \quad \rightsquigarrow \quad \Psi_\chi^\dagger\Big(\vec{v}^\perp\cdot\vec{S}_\chi + \frac{\vec{q}\cdot\vec{S}_\chi}{2m_N},\ \vec{S}_\chi\Big)\Psi_\chi$
  - Vector: $\bar{\chi}\gamma^\mu\chi \quad \rightsquigarrow \quad \Psi_\chi^\dagger\Big(1,\quad \vec{v}^\perp + \frac{\vec{q}}{2m_N} + i\frac{\vec{q}\times\vec{S}_\chi}{m_\chi}\Big)\Psi_\chi$
- For extended nucleus, have six basic nuclear responses
  [Fitzpatrick et al., 1203.3542]

Velocity Suppression

- Recall DM velocity $v \sim 10^{-3}$
- Example:
  - $Q_1 = (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$
    not suppressed
  - $Q_2 = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$
    velocity suppressed



PRELIMINARY

[Data from LUX collaboration, 1310.8214]

Why complete EFT?

- A complete EFT framework for all scales is needed for the consistent interpretation of direct detection data.
  - Consistent power counting
  - Connect all scales from the UV to the atomic nuclei
  - Keep dependence on UV physics explicit

Relevant Scales

m_χ — heavy / e/w / (ultra-)light

E

Λ – heavy mediators

SM & DM effective Lagrangian

$v_{\mathbf{EW}}$ – electroweak symmetry breaking

five-flavor QCD + DM

m_b – b-quark threshold

four-flavor QCD + DM

m_c – c-quark threshold

three-flavor QCD + DM

$\Lambda_{\mathbf{QCD}}$ – chiral symmetry breaking

(Heavy Baryon) Chiral Effective Theory

m_π – pion threshold

pionless effective theory

$v, \vec{q}$ – DM-nucleus scattering kinematics

NR theory of nuclear response

Why mixing effects?

- Momentum-dependent interactions are leading in many UV models
- Electroweak loops can mix suppressed and unsuppressed operators [Freytsis & Ligeti, 1012.5317; see also Haisch et al. 1302.4454; Crivellin et al. 1402.1173, 1408.5046; D'Eramo et al. 1409.2893]
  - Calculate all relevant radiative corrections

The setup

- Assume DM is an electroweak multiplet χ, with $m_\chi \sim v_{\rm ew}$
  - Here, DM is a Dirac 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, ...]
- Potential mediators ϕ, integrated out at $\Lambda \sim m_\phi \gg m_\chi$
  - Dim.4 gauge interactions
  - Higher-dimensional effective operators

Effective Lagrangian above v_{EW}

- Construct operators in unbroken e/w phase

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{DM}} + \sum \frac{C_j^{(5)}}{\Lambda} Q_j^{(5)} + \sum \frac{C_j^{(6)}}{\Lambda^2} Q_j^{(6)} + \dots$$

- Expansion in inverse mediator mass Λ
- Generalizes "SM-EFT" [Buchmüller et al. 1986, Grzadkowski et al. 2010]

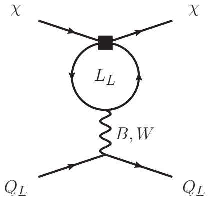
Mixing – General Structure

- RGE (Renormalization Group Equations):

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

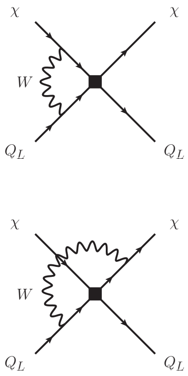
- Do we need to sum the logs?
  - $\alpha_1(\mu_{EW}) \approx 0.01$, $\alpha_2(\mu_{EW}) \approx 0.03$, $\alpha_\lambda(\mu_{EW}) \approx 0.04$, $\alpha_t(\mu_{EW}) \approx 0.08$
  - No – would need $\Lambda \sim 10^4$ TeV

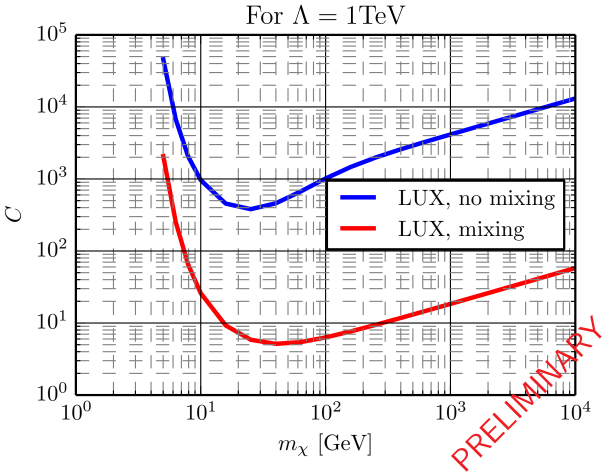
- Importance of RGE:
  - Mixing of suppressed and unsuppressed operators
  - Penguin insertions mix lepton and quark operators



Mixing Example – W Exchange

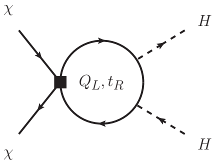
$$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i) \quad \Rightarrow \quad (\bar{\chi}\gamma_\mu\tilde{\tau}^a\chi)(\bar{Q}_L^i\gamma^\mu\tau^a Q_L^i),$$

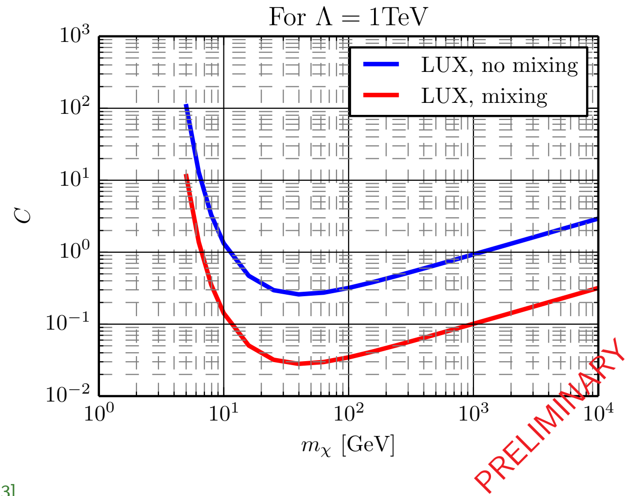




Mixing Example – top Yukawa

$$(\bar{\chi}\gamma_\mu\chi)(\bar{u}^i_R\gamma^\mu u^i_R) - (\bar{\chi}\gamma_\mu\chi)(\bar{Q}^i_L\gamma^\mu Q^i_L) \qquad \Rightarrow \qquad (\bar{\chi}\gamma^\mu\chi)(H^\dagger i \overleftrightarrow{D}_\mu H)$$





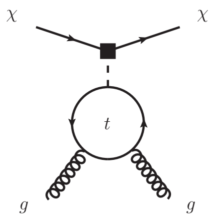
[See also Crivellin et al., 1402.1173]

Effective Lagrangian below v_{EW}

- E/w symmetry breaking introduces a new scale $v_{\rm EW}$
- Now have double expansion in $1/\Lambda$ and $1/v_{\rm EW}$

$$\mathcal{L}^{\rm eff} = \mathcal{L}^{(4)}|_{n_f} + \mathcal{L}^{\rm DM}|_{n_f} + \sum \hat{\mathcal{C}}_j^{(5)}|_{n_f} Q_j^{(5)} + \sum \hat{\mathcal{C}}_j^{(6)}|_{n_f} Q_j^{(6)} + \sum \hat{\mathcal{C}}_j^{(7)}|_{n_f} Q_j^{(7)} + \ldots$$

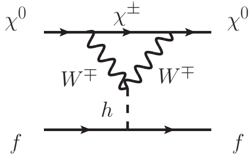
$$\hat{\mathcal{C}}_a^{(d)}|_{n_f} = \sum_n \frac{\mathcal{C}_a^{(d-n,n)}|_{n_f}}{\Lambda^{d-4-n} v_{\rm EW}^n} .$$



- E.g. integrating out Higgs and top results in $\mathcal{Q}_1^{(7)} \propto \mathcal{C}^{(5,2)} (\bar{\chi}\chi) G^{a,\mu\nu} G^a_{\mu\nu} / (\Lambda v_{\rm EW}^2)$

Matching

- E.g. "Higgs penguin" contribution for $Y = 0$
  - $m_\chi \sim v_{\text{ew}}$: DM is "HQET" field in EFT
  - Match onto $\mathcal{Q}^{(7)} = m_f(\bar{\chi}\chi)(\bar{f}f)$
  - $x = m_\chi / M_W$

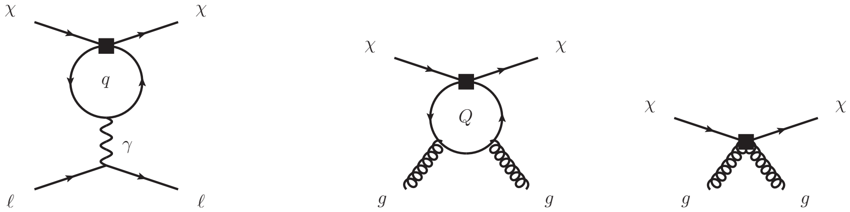


$$\mathcal{C}_{5,f}^{(4,3)} = \frac{J(J+1)}{2\pi^2 s_w^2 \lambda}\left[\frac{(2x^2-1)\left[5x + 2\sqrt{\frac{1+4x}{x^2}}\log\left(\frac{1}{2x} + \frac{1}{2}\sqrt{\frac{1+4x}{x^2}}\right)\right]}{4x^2-1} + \frac{2\log x}{x}\right],$$

- Similar matching conditions for higher-dimensional operators

Running and Matching at Flavor Thresholds

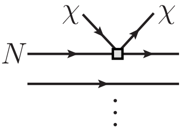
- QCD / QED running is well-known [E.g. Hill et al., 1409.8290]
- Penguin insertions will mix lepton and quark operators
- Matching at flavor thresholds



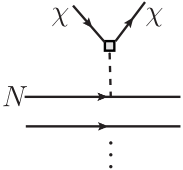
Transition to the nucleon picture

- Recall maximum momentum transfer in DM scattering is $q_{\text{max}} \approx 200\,\text{MeV}$
- Expansion in $q/(4\pi f_\pi)$ is good to $\mathcal{O}(20\%)$
- Can use Heavy Baryon Chiral Perturbation Theory (HBChPT)
  [Jenkins and Manohar, Phys.Lett. B255 (1991) 558]
  - Hadronic degrees of freedom are pions, nucleons,...
- Treat DM currents as $SU(3)_L \times SU(3)_R$ flavor-symmetric spurions
- Can write hadronization of quark currents explicitly, e.g.:
  - Pseudo-scalar meson current: $\bar{q} i \gamma_5 q \to -B_0 f_\pi m_u (\pi^0 + \eta/\sqrt{3}) + \ldots$
  - Nuclear vector current: $\bar{u}\gamma^\mu u \to \bar{p}\gamma^\mu p, \quad \bar{d}\gamma^\mu d \to \bar{n}\gamma^\mu n, \ldots$
- Describe hadronic physics in terms of few parameters $(f_\pi, g_A, \ldots)$

Chiral power counting – LO



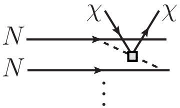
- Only leading diagram for $\bar{q}\gamma^\mu q$, $\bar{q}q$, $G_{\mu\nu}G^{\mu\nu}$, $\tilde{G}_{\mu\nu}G^{\mu\nu}$
- Leading diagram for $\bar{q}\gamma^\mu\gamma_5 q$



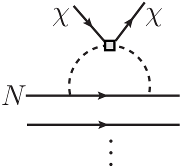
- Only leading diagram for $\bar{q}\gamma_5 q$
- Leading diagram for $\bar{q}\gamma^\mu\gamma_5 q$

Chiral power counting – beyond LO

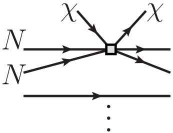
[cf. Cirigliano, Graesser, Ovanesyan 1205.2695]



- For $\bar{q}q$ scales as $\nu = \nu_{\text{LO}} + 1$



- For $\bar{q}q$ scales as $\nu = \nu_{\text{LO}} + 1$

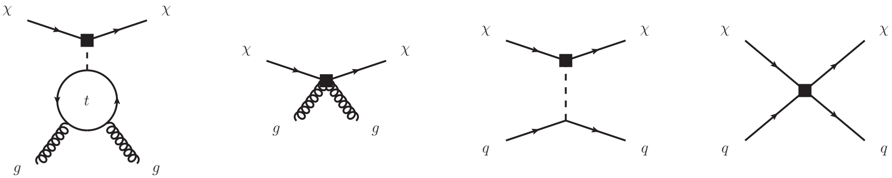


- Always scales as $\nu = \nu_{\text{LO}} + 2$

Nonrelativistic limit and nuclear matrix elements

- At $\mu \ll \Lambda_{\text{QCD}}$ transition to pionless EFT
  - Effectively introduce form factor $\propto 1/(m_\pi^2 - q^2)$
- Construct nonrelativistic, Galilean-invariant EFT for nuclear responses
  [Fitzpatrick et al. 1203.3542]
- Calculation of nuclear matrix elements for all nuclear response functions (available for F, Na, Ge, I, Xe)
  [Fitzpatrick et al. 1203.3542]
- Finally, convolution with velocity distribution and experimental efficiencies allows to calculate scattering rate for different experiments

Illustrative Example



$$\frac{C_{3,4}^{(5)}}{\Lambda} \xrightarrow{\mu\sim v_{\mathrm{EW}}} \frac{C_{3,4}^{(5)}}{\Lambda v_{\mathrm{EW}}^2} \xrightarrow{\mu\lesssim m_c} \frac{C_{3,4}^{(5)}}{\Lambda v_{\mathrm{EW}}^2} \times \left\{ \frac{2m_G}{27}\alpha_s \,,\; m_q \right\}$$

$$\sigma \propto \left(\frac{1}{\Lambda v_{\mathrm{EW}}^2} C_{3,4}^{(5)} \right)^2 \Bigg(\sum_{q_\ell = u,d,s} m_{q_\ell} + \sum_{q_h = c,b,t} \frac{2m_G}{27}\alpha_S \Bigg)^2 A^2$$

Summary and Outlook

- Complete EFT framework is important for consistent interpretation of direct detection data
- Our goal:
  - General setup that covers most models
  - Provide public code for automatic running from UV to nuclear scale
- Many future directions:
  - Several multiplets and Higgs interactions
  - Scalar and vector DM
  - Dimension-seven operators in the UV
  - Heavy DM