Direct Detection of General Heavy WIMPs

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Why WIMPs? (WIMP Miracle)

- DM as a particle once was thermally in equilibrium with other particles in the early Universe $\bar{\chi}\chi \Leftrightarrow \bar{\psi}\psi$ (Review by Jungman, Kaminonkowski, Griest, 1996)

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

$$\Omega_\chi h^2 \sim 0.12$$ (Planck, 2018)

- Annihilation cross section for a weakly interacting particle with coupling $\alpha \sim 0.01$

$$\langle \sigma v \rangle \sim \alpha^2 (100\,\mathrm{GeV})^{-2} \sim 10^{-25}\mathrm{cm}^3\mathrm{s}^{-1}$$

Direct Detection Experiments

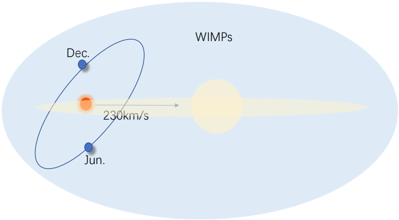


Figure: WIMPs travel to the earth.

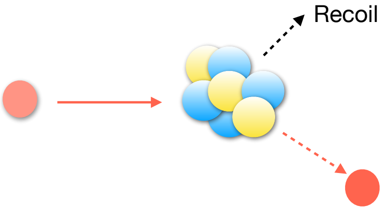


Figure: WIMP scatters on the lab target.

Heavy WIMPs

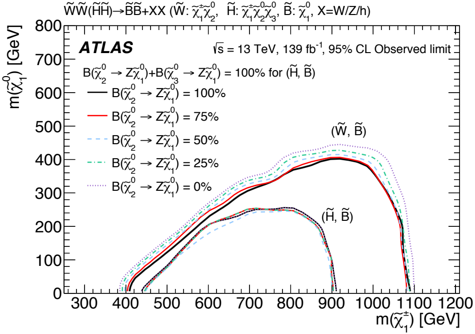


Figure: Collider searches for neutralinos (ATLAS, 2022)

- Thermal WIMPs annihilation tells us $M_{\tilde{H}} \sim 1.1$ TeV and $M_{\tilde{W}} \sim 3$ TeV.
  (Cirelli, Fornengo and Strumia, 2006)

Heavy WIMP EFT

A WIMP is a massive representation of $SU(2)_W \times U(1)_Y$.

Lorentz:

$\mathrm{spin}-0$
$\mathrm{spin}-1/2$
$\mathrm{spin}-1$
$\mathrm{spin}-3/2$

Gauge:

(J, Y)

Heavy WIMP EFT

Consider a self-conjugate electroweak multiplet with mass $M \gg m_W$. The effective theory in the one-heavy-particle sector takes the form
(QC et al, 2022, in preparation)

$$\mathcal{L}^{\text{spin}-0}_{\text{HWET}} = \phi_v^\dagger \left[iv\cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} + \dots \right] \phi_v \,,$$

$$\begin{aligned}\mathcal{L}^{\text{spin}-1/2}_{\text{HWET}} = \bar{\chi}_v \Big[& iv\cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} \\ & + \frac{1+c_{\chi F1}}{4M} \sigma_\perp^{\alpha\beta} \left[D_\alpha^\perp , D_\beta^\perp\right] + \frac{c_{\chi F2}}{2M} \epsilon^{\alpha\beta\mu\nu} \sigma^\perp_{\alpha\beta} \left[D_\mu^\perp , D_\nu^\perp\right] + \dots \Big] \chi_v \,,\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{\text{spin}-1}_{\text{HWET}} = V_v^{\mu\dagger} \Big[& \left(iv\cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} \right) (-g_{\mu\nu}) + \frac{1}{2M} \left[D_\mu^\perp , D_\nu^\perp\right] \\ & + \epsilon_{\mu\alpha\beta\nu} \frac{c_{VF}}{2M} \left[D_\alpha^\perp , D_\beta^\perp\right] + \dots \Big] V_v^\nu \,,\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{\text{spin}-3/2}_{\text{HWET}} = \bar{\xi}_v^\mu \Big[& \left(iv\cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} \right) g_{\mu\nu} - \frac{1}{2M} \left[D_\mu^\perp , D_\nu^\perp\right] - \epsilon_{\mu\alpha\beta\nu} \frac{c_{\xi F1}}{2M} \left[D_\alpha^\perp , D_\beta^\perp\right] \\ & + \frac{1+c_{\xi F2}}{4M} \sigma_\perp^{\alpha\beta} \left[D_\alpha^\perp , D_\beta^\perp\right] g_{\mu\nu} + \frac{c_{\xi F3}}{2M} \epsilon^{\alpha\beta\rho\sigma} \sigma^\perp_{\alpha\beta} \left[D_\rho^\perp , D_\sigma^\perp\right] g_{\mu\nu} \\ & + c_{\xi K} \epsilon_{\alpha\beta\mu\nu} \sigma_\perp^{\alpha\beta} \left(iv\cdot D - \delta M - \frac{D_\perp^2}{2M} - \frac{f(H)}{M} \right) + \dots \Big] \xi_v^\nu \,,\end{aligned}$$

- Kinetic terms: Universal
- Interaction terms: UV and representation-dependent

Low Energy Effective Theory: Building Blocks

Integrating out the weak scale particles $W^{\pm}$, Z^0, $h(\mathrm{NGBs})$ and t-quark yields a 5-flavor(u,d,s,c,b) effective theory constructed from heavy particle, quark and gluon bilinears: $\bar{h}_v \Gamma_{\mathrm{DM}} h_v \bar{q} \Gamma_q q$ and $\bar{h}_v \Gamma_{\mathrm{DM}} h_v G \Gamma_g G$,

Dimension	Quark operators	Gluon operators
3	$V_q^\mu = \bar{q}\gamma^\mu q$	-
	$A_q^\mu = \bar{q}\gamma^\mu\gamma^5 q$	-
4	$O_q^{(0)} = m_q \bar{q} q$	$O_g^{(0)} = G^{A\,\mu\nu} G^A_{\mu\nu}$
	$O_{5q}^{(0)} = m_q \bar{q} i\gamma^5 q$	$O_{5g}^{(0)} = G^{A\,\mu\nu} \tilde{G}^A_{\mu\nu}$
	$O_q^{(2)\mu\nu} = \frac{1}{2}\bar{q}\left(\gamma^{\{\mu} iD_-^{\nu\}} - \frac{g^{\mu\nu}}{d} i\not{D}_-\right) q$	$O_g^{(2)\mu\nu} = -G^{A\mu\lambda} G^{A\nu}{}_{\lambda} + \frac{1}{d} g^{\mu\nu} (G^A_{\alpha\beta})^2$
	$O_{5q}^{(2)\mu\nu} = \frac{1}{2}\bar{q}\gamma^{\{\mu} iD_-^{\nu\}}\gamma^5 q$	
	$T_q^{\mu\nu} = i m_q \bar{q}\sigma^{\mu\nu}\gamma^5 q$	

Table 1: QCD bilinear operators.

$$\Gamma_{\mathrm{DM}} = \left\{1,\ v^\mu + \frac{i\partial^\mu_{\perp -}}{2M},\ \sigma_\perp^{\mu\nu}\right\}\left\{1,\ i\partial^\rho_{\perp +}\right\}$$

Low Energy Effective Theory

The spin-independent interaction of spin-0(1) and spin-1/2(3/2) heavy WIMP with quarks and gluons is

$$\mathcal{L} = \bar{h}_0^{(\mu),\text{low}} h_{0\,(\mu)}^{\text{low}} \Bigg\{ \sum_{q=u,d,s,c,b} \left[c_q^{(0)} O_q^{(0)} + c_q^{(2)} v_\alpha v_\beta O_q^{(2)\alpha\beta} \right] + c_g^{(0)} O_g^{(0)} + c_g^{(2)} v_\alpha v_\beta O_g^{(2)\alpha\beta} \Bigg\}.$$

Matching

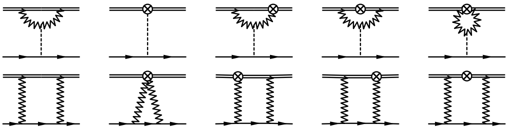


Figure: Diagrams contributing to quark operators matching. Double line denotes heavy WIMP, dashed line denotes Higgs boson, solid line denotes quark, zigzag line denotes W/Z bosons, encircled cross denotes insertion of a $1/M$ effective theory vertex.

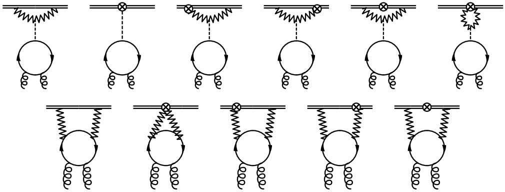


Figure: Diagrams contributing to gluon operators matching. Curly line denotes gluon.

Renormalization Group Evolution

We first need to run the 5-flavor effective theory from weak scale μ_t to bottom quark mass scale μ_b.

$$\frac{d}{d\log\mu}O_i = -\gamma_{ij}O_j, \quad \frac{d}{d\log\mu}c_i = \gamma_{ji}c_j$$

with solution

$$c_i(\mu_l) = R_{ij}(\mu_l,\mu_h)c_j(\mu_h)$$

Operator	Anomalous dimension
$O_q^{(0)}, O_g^{(0)}$	$\gamma_{qq}^{(0)} = 0, \quad \gamma_{qg}^{(0)} = 0$
	$\gamma_{gq}^{(0)} = -2\frac{\partial\gamma_m}{\partial\log g}, \quad \gamma_{gg}^{(0)} = \frac{\partial(\beta/g)}{\partial\log g}$
$O_q^{(2)}, O_g^{(2)}$	$\gamma_{qq}^{(2)} = \frac{\alpha_s}{4\pi}\frac{64}{9}, \quad \gamma_{qg}^{(2)} = -\frac{\alpha_s}{4\pi}\frac{4}{3}$
	$\gamma_{gq}^{(2)} = -\frac{\alpha_s}{4\pi}\frac{64}{9}, \quad \gamma_{gg}^{(2)} = \frac{\alpha_s}{4\pi}\frac{4n_f}{3}$

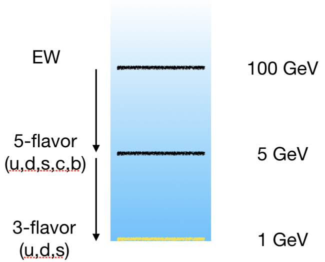
Table: Anomalous dimensions for quark and gluon operators, γ_m: anomalous dimension of quark mass, $\beta = dg/d\log\mu$: QCD beta function.

Heavy Quark Threshold Matching

- The coefficients in the $(n_f + 1)$- and n_f-flavor theories are related by physical matrix elements

$$c'_i \langle O'_i \rangle = c_i \langle O_i \rangle + \mathcal{O}(1/m_Q)$$

where primed: $(n_f + 1)$-flavor, unprimed: n_f-flavor and m_Q is the heavy quark.



- Applying QCD sum rule

$$\langle T^{\mu}_{\mu} \rangle = \sum_q (1 - \gamma_m) \langle O_q^{(0)} \rangle + \frac{\tilde{\beta}}{2} \langle O_g^{(0)} \rangle$$
$$\langle T^{\mu\nu} \rangle = \sum_q \langle O_q^{(2)\mu\nu} \rangle + \langle O_g^{(2)\mu\nu} \rangle$$

to solve the above threshold matching condition, we obtain the n_f-flavor theory coefficients

$$c_i(\mu_Q) = M_{ij}(\mu_Q) c'_j(\mu_Q)$$

Cross Section

Threshold matching and RG evolution from the 5-flavor(u,d,s,c,b) theory to the 3-flavor(u,d,s) theory

$$c_j(\mu_0) = R_{jk}(\mu_0, \mu_c) M_{kl}(\mu_c) R_{lm}(\mu_c, \mu_b) M_{mn}(\mu_b) R_{ni}(\mu_b, \mu_t) c_i(\mu_t)$$

Take matrix elements from Lattice QCD and obtain cross section

$$\sigma_N = \frac{m_r^2}{\pi} |\mathcal{M}_N^{(0)} + \mathcal{M}_N^{(2)}|^2, \quad \mathcal{M}_N^{(S)} = \sum_{i=q,g} c_i^{(S)}(\mu_0) \langle N | \mathcal{O}_i^{(S)}(\mu_0) | N \rangle$$

$$\begin{aligned} \mathcal{M}_p &= \mathcal{M}_p^{(0)} + \mathcal{M}_p^{(2)} \\ &= 0.019 J(J+1) - 0.072 Y^2 \\ &+ \frac{m_W}{M} \left[32.36 c_H - 0.057 J(J+1) + 0.0077 Y^2 \right] \end{aligned}$$

Experimental Constraints

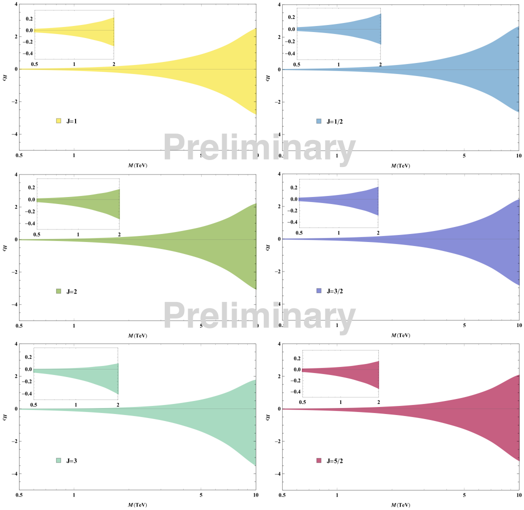


Figure: Current constraints of parameter c_H for spin-0 and spin-1/2 particles.
(QC et al, 2022, in preparation)

Experimental Constraints

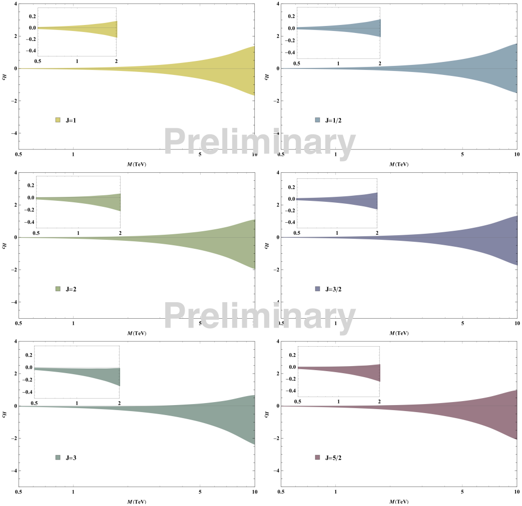


Figure: Current constraints of parameter c_H for spin-1 and spin-3/2 particles.
(QC et al, 2022, in preparation)

Illustrative UV Completion

Consider minimal UV completion with adding a massive electroweak multiplet for various-spin particles in SM.

$$\mathcal{L}_{\rm UV}^{\rm spin-0} = \frac{1}{2}\left(D_\mu \phi\right)^\dagger D^\mu \phi - \frac{1}{2} M^2 \phi^\dagger \phi$$

$$\mathcal{L}_{\rm UV}^{\rm spin-1} = -\frac{1}{2}\left(D_\mu V_\nu - D_\nu V_\mu\right)^\dagger \left(D^\mu V^\nu - D^\nu V^\mu\right) + M^2 V_\mu^\dagger V^\mu$$

$$\mathcal{L}_{\rm UV}^{\rm spin-1/2} = \bar{\psi}(i\not{D} - M)\psi + \frac{1}{2}\bar{\chi}'(i\not{D} - M')\chi' - \frac{1}{2}\bar{\lambda}F(H)\lambda$$

$$\mathcal{L}_{\rm UV}^{\rm spin-3/2} = \bar{\Psi}^\mu \left[\left(i\not{D} - M\right) g_{\mu\nu} - \frac{1}{3}\left(i\gamma_\mu D_\nu + i\gamma_\nu D_\mu\right) + \frac{1}{3}\gamma_\mu \left(i\not{D} + M\right)\gamma_\nu\right]\Psi^\nu$$

where $\lambda = \left(\chi', \quad \chi_1, \quad \chi_2\right)^T$, $\chi_1 = (\psi + \psi^c)/\sqrt{2}$ and $\chi_2 = i(\psi - \psi^c)/\sqrt{2}$.

Match the above UV theories onto the HWETs at the electroweak scale and obtain concrete values of c_H.

Cross Sections

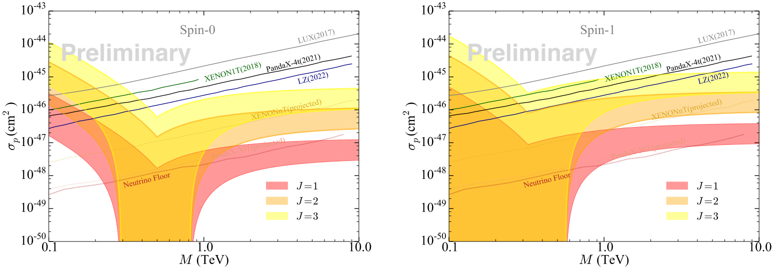


Figure: Scattering cross section for different bosonic WIMP multiplets on proton. (QC et al, 2022, in preparation)

Cross Sections

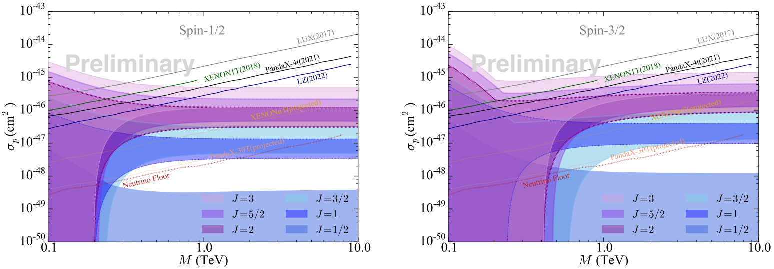


Figure: Scattering cross section for different fermionic WIMP multiplets on proton. (QC et al, 2022, in preparation)

Higgsino-like result (QC and R.J. Hill, PLB 2020, arXiv:1912.07795)

Summary

- Higher spin WIMPs have higher cross sections
- Higher isospin WIMPs have higher cross sections
- All TeV WIMPs with isospin lower than $5/2$ survive current experimental limits, and pure Higgsino-like WIMP cross section is well below the neutrino floor.

Thank you!

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