Complementary Constraints on LDM
from Heavy Quarkonium Decays

Patrick Stengel

University of Hawaii

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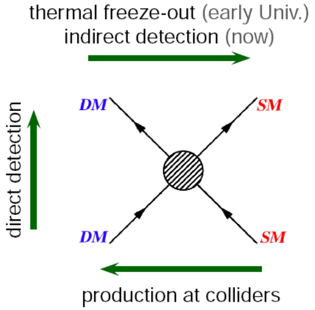
[arXiv:1404.6599]

with Nicolas Fernandez, Jason Kumar and Ilsoo Seong

Model Independent Constraints on Light Dark Matter

bilinear	C	P	J	state
$\bar{\psi}\psi$	+	+	0	$S=1,\ L=1$
$i\bar{\psi}\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^0\psi$	-	+	0	none
$\bar{\psi}\gamma^i\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\gamma^0\gamma^5\psi$	+	-	0	$S=0,\ L=0$
$\bar{\psi}\gamma^i\gamma^5\psi$	+	+	1	$S=1,\ L=1$
$\bar{\psi}\sigma^{0i}\psi$	-	-	1	$S=1,\ L=0,2$
$\bar{\psi}\sigma^{ij}\psi$	-	+	1	$S=0,\ L=1$
$\phi^\dagger\phi$	+	+	0	$S=0,\ L=0$
$iIm(\phi^\dagger\partial^0\phi)$	-	+	0	none
$iIm(\phi^\dagger\partial^i\phi)$	-	-	1	$S=0,\ L=1$
$B^\dagger_\mu B^\mu$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$iIm(B^\dagger_\nu\partial^0 B^\nu)$	-	+	0	none
$iIm(B^\dagger_\nu\partial^i B^\nu)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$i(B^\dagger_i B_j - B^\dagger_j B_i)$	-	+	1	$S=1,\ L=0,2$
$i(B^\dagger_i B_0 - B^\dagger_0 B_i)$	-	-	1	$S=0,\ L=1;\ S=2,\ L=1,3$
$\epsilon^{0ijk}B_i\partial_j B_k$	+	-	0	$S=1,\ L=1$
$-\epsilon^{0ijk}B_0\partial_j B_k$	+	+	1	$S=2,\ L=2$
$B^\nu\partial_\nu B_0$	+	+	0	$S=0,\ L=0;\ S=2,\ L=2$
$B^\nu\partial_\nu B_i$	+	-	1	$S=1,\ L=1$



Invisible $\Upsilon(1S)$ and J/Ψ Decays

- Can constrain SM-DM interactions for $2m_X < M$
- $J^{PC} = 1^{--}$: $\bar{q}\gamma^i q$ or $\bar{q}\sigma^{0i}q$

Use $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ to Detect $\Upsilon(1S)$ Peak

$$M_{rec}^2 = s + M_{\pi\pi}^2 - 2\sqrt{s}E_{\pi\pi}^*$$

- M_{rec} recoil mass distribution
- $M_{\pi\pi}$ invariant mass of dipion
- $E_{\pi\pi}^*$ dipion energy $\Upsilon(3S)$ frame
- $\sqrt{s} \sim 10\,\mathrm{GeV}$ $\Upsilon(3S)$ resonance

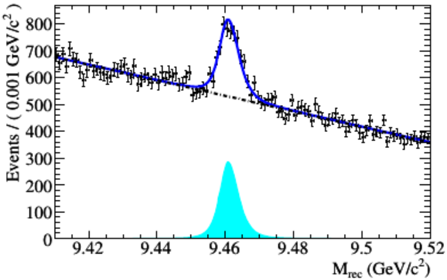


Figure: Maximum likelihood fit for M_{rec} at BaBar [arXiv:0908.2840]. The total fit (solid line) is composed of nonpeaking background (dashed line) and peaking component (solid filled). Invisible width calculated by subtracting background peak contribution.

$$\mathcal{B}(\Upsilon(1S) \to invisible) < 3.0 \times 10^{-4}$$
$$\mathcal{B}(J/\Psi \to invisible) < 7.2 \times 10^{-4}$$

$$\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = 9.85 \times 10^{-6}$$
$$\mathcal{B}(J/\Psi \to \nu\bar{\nu}) = 2.70 \times 10^{-8}$$

Limits on Gamma Ray Flux

$$\mu(\Phi_{PP}, J) = (A_{eff} T_{obs}) \times \frac{\langle \sigma_A v \rangle}{8\pi m_X^2} \int_{E_{thr}}^{m_X} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times \int_{\Delta\Omega} \int_l \rho_X^2 \, dl \, d\Omega$$

Expected number of signal events factorizes nicely into particle physics and DM astrophysics, with annihilation cross section $\langle \sigma_A v \rangle$ and associated photon spectrum dN_γ / dE_γ along l over solid angle $\Delta\Omega$ [arXiv:1108.2914].

Dwarf Spheroidal Galaxies

- Large DM content inferred by observation of baryons
- Lack of SM astrophysical production mechanisms
- Correlate with DM annihilation signals at Galactic center

Navarro-Frenk-White DM Density Profile

$$\rho_X(r) = \frac{\rho_{X0} r_s^3}{r(r_s + r)^2}$$

Particle Physics Constraint from Stacked Analysis of Dwarf Spheroidal Galaxies

$$\Phi_{PP} < 5.0^{+4.3}_{-4.5} \times 10^{-30} \, \mathrm{cm}^3 \, \mathrm{s}^{-1} \, \mathrm{GeV}^{-2}$$

Relevant Effective Contact Operators

Name	Interaction Structure	Annihilation	Scattering
F5	$(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	Yes	SI
F6	$(1/\Lambda^2)\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	No	No
F9	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$	Yes	SD
F10	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$	Yes	No
S3	$(1/\Lambda^2)\imath Im(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	No	SI
V3	$(1/\Lambda^2)\imath Im(B_\nu^\dagger\partial_\mu B^\nu)\bar{q}\gamma^\mu q$	No	SI
V5	$(1/\Lambda)(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu} q$	No	SD
V7	$(1/\Lambda^2)B_\nu^{(\dagger)}\partial^\nu B_\mu\bar{q}\gamma^\mu q$	No	No
V9	$(1/\Lambda^2)\epsilon^{\mu\nu\rho\sigma} B_\nu^{(\dagger)}\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No	No

Table: EFT operators which can mediate the decay of a $J^{PC} = 1^{--}$ quarkonium bound state. We also indicate if the operator can permit an s-wave dark matter initial state to annihilate to $q\bar{q}$; if so, then a bound can also be set by indirect observations of photons originating from dwarf spheroidals. Lastly, we indicate if the operator can mediate velocity-independent scattering [arXiv:1305.1611].

Relevant Bilinears for Our Matrix Elements

Bilinear	C	P	J	State
$\bar{\psi}\gamma^i\psi$	$-$	$-$	1	$S=1, L=0,2$
$\bar{\psi}\gamma^i\gamma^5\psi$	$+$	$+$	1	$S=1, L=1$
$\bar{\psi}\sigma^{0i}\psi$	$-$	$-$	1	$S=1, L=0,2$
$\imath Im(\phi^\dagger\partial^i\phi)$	$-$	$-$	1	$S=0, L=1$
$\imath Im(B^\dagger_\nu\partial^i B^\nu)$	$-$	$-$	1	$S=0, L=1; S=2, L=1,3$
$\imath(B^\dagger_i B_0 - B^\dagger_0 B_i)$	$-$	$-$	1	$S=0, L=1; S=2, L=1,3$
$-\epsilon^{0ijk}B_0\partial_j B_k$	$+$	$+$	1	$S=2, L=2$
$B_\nu\partial^\nu B_i$	$+$	$-$	1	$S=1, L=1$

Table: In general, allow for violation of C and/or P, but must conserve total J. Fermionic bilinears with $J^{PC}=1^{--}$ are for bound state quarkonium or dark matter. F5 and F9 should have two terms in their respective matrix elements for $L=0$ and $L=2$. Interaction structures with scalar or vector DM have matrix elements that are necessarily velocity supressed. Bounds on V5 will be enhanced since it is dimension 5. Conjugate decay matrix elements for DM annihilation.

Branching Fractions to Scalar and Fermionic Dark Matter

$$\mathcal{B}_{F5}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{16\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{1/2}\left(1+\frac{2m_X^2}{M^2}\right)$$

$$\mathcal{B}_{F6}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{16\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

$$\mathcal{B}_{F9}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{8\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{1/2}\left(1+\frac{8m_X^2}{M^2}\right)$$

$$\mathcal{B}_{F10}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{8\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

$$\mathcal{B}_{S3}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{256\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}$$

We have written the decay rates in terms of $\mathcal{B}(e^+e^-)$ instead of $\psi(0)$. Note $q = b$ for $\Upsilon(1S)$ or $q = c$ for J/ψ. F6, F10 and S3 are p-wave suppressed because the DM bilinears can't annihilate an $L = 0$ state.

Branching Fractions to Vector Dark Matter

$$\mathcal{B}_{V3}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{128\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\left(1+\frac{M^4}{8m_X^4}\left(1-\frac{2m_X^2}{M^2}\right)^2\right)$$

$$\mathcal{B}_{V5}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^2}{16\pi^2\alpha^2 Q^2 \Lambda^2}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\frac{M^2}{m_X^2}\left(1+\frac{M^2}{4m_X^2}\right)$$

$$\mathcal{B}_{V7}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{64\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{3/2}\frac{M^2}{m_X^2}$$

$$\mathcal{B}_{V9}(\bar{X}X) = \frac{\mathcal{B}(e^+e^-)M^4}{256\pi^2\alpha^2 Q^2 \Lambda^4}\left(1-\frac{4m_X^2}{M^2}\right)^{5/2}\frac{M^2}{m_X^2}$$

Terms in which scale as m_X^{-2} (m_X^{-4}) have one (two) longitudinally polarized vector boson in a final state with total spin $S = 1$ ($S = 0, 2$). Note the constraints from unitarity are trivial in the non-relativistic limit, because the elastic scattering cross section is at threshold [eg arXiv:1403.6610].

Annihilation Cross Sections

$$\langle \sigma_A^{F10} v \rangle = \frac{6}{\pi \Lambda^4} \left(1 - \frac{m_q^2}{m_X^2}\right)^{3/2} m_X^2$$

$$\langle \sigma_A^{F9} v \rangle = \frac{6}{\pi \Lambda^4} \left(1 - \frac{m_q^2}{m_X^2}\right)^{1/2} (m_X^2 + 2m_q^2)$$

$$\langle \sigma_A^{F5} v \rangle = \frac{3}{2\pi \Lambda^4} \left(1 - \frac{m_q^2}{m_X^2}\right)^{1/2} (2m_X^2 + m_q^2)$$

Recall

$$\Phi_{PP} = \frac{\langle \sigma_A v \rangle}{8\pi m_X^2} \int_{E_{thr}}^{m_X} \frac{dN_\gamma}{dE_\gamma} dE_\gamma$$

$$\Phi_{PP} \lesssim 5 \ \mathrm{cm}^3 \, \mathrm{s}^{-1} \, \mathrm{GeV}^{-2}$$

These are the only operators with *s*-wave meson states and DM initial states. As the meson decay and DM annihilation matrix elements are conjugate, F10 is still p-wave suppressed. Note that for the operators we are considering, only fermionic dark matter can annihilate from an *s*-wave initial state. Assuming universal quark coupling, $u\bar{u}$ and $d\bar{d}$ channel yield the strongest bounds from DM annihilation due to the analysis threshold.

$\Upsilon(1S)$ Mediator Scale

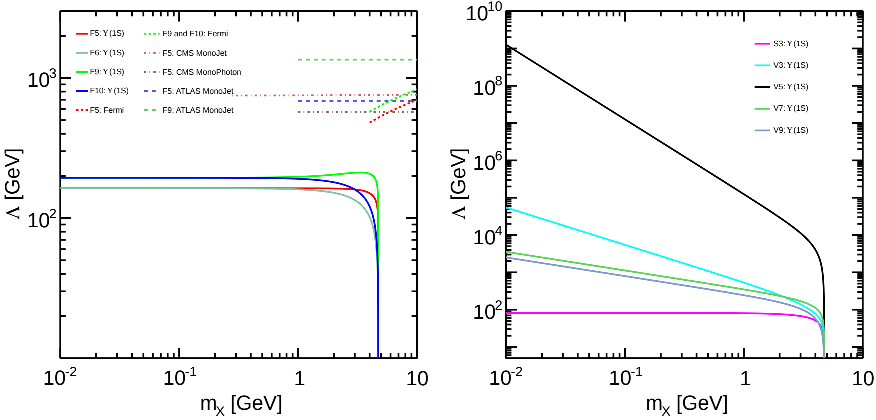


Figure: Bounds on the mediator scale, Λ, for fermionic and scalar DM (left panel) and vector DM (right panel) of mass m_X arising from constraints on $\Upsilon(1S) \to$ *nothing* decays, from constraints on DM annihilation to light quarks in dwarf spheroidal galaxies, and from monojet/photon searches at LHC.

Scattering Cross Sections

We are looking for velocity independent scattering off of protons

$$\sigma^p_{SI} \sim \mu_p^2 \left| \sum_q \frac{B^p_q}{m_X m_q} \mathcal{M}_{Xq \to Xq} \right|^2 , \; \sigma^p_{SD} \sim \mu_p^2 \left| \sum_q \frac{\delta^p_q}{m_X m_q} \mathcal{M}_{Xq \to Xq} \right|^2$$

$$\sigma^{F5}_{SI} = \frac{\mu_p^2}{\pi \Lambda^4} \left(B^p_u + B^p_d \right)^2$$

$$\sigma^{S3}_{SI} = \sigma^{V3}_{SI} = \frac{\mu_p^2}{4\pi \Lambda^4} \left(B^p_u + B^p_d \right)^2$$

$$\sigma^{F9}_{SD} = \frac{12\mu_p^2}{\pi \Lambda^4} \left(\delta^p_u + \delta^p_d \right)^2$$

$$\sigma^{V5}_{SD} = \frac{2\mu_p^2}{\pi \Lambda^2 m_X^2} \left(\delta^p_u + \delta^p_d \right)^2$$

Form Factors and Comments

- $B^p_u = B^n_d = 2, \; B^n_u = B^p_d = 1$
- $\delta^p_u = 0.54^{+0.09}_{-0.22}, \; \delta^p_d = -0.23^{+0.09}_{-0.16}$
- Need universal coupling to u, d
- Enhancement from longitudinal polarization of vector LDM
- Enhancement from dimension 5

$\Upsilon(1S)$ Complementary Bounds on Dark Matter Scattering

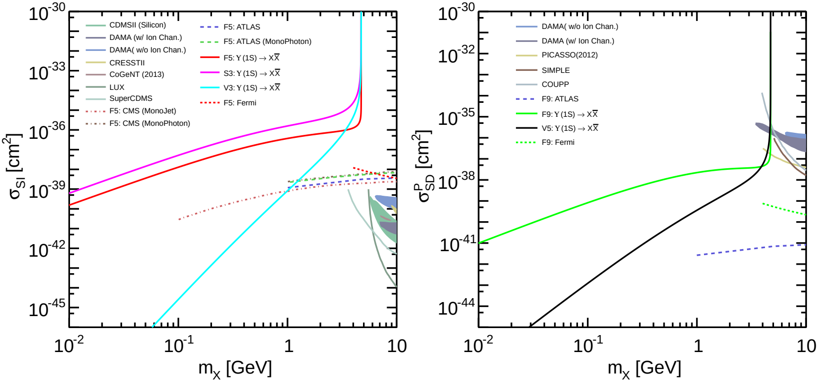
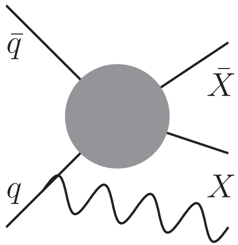


Figure: DM-p SI (left panel) and SD (right panel) scattering for DM coupling universally to quarks through the indicated effective contact operator. The labeled exclusion contours indicate 90 % CL from limits on invisible decays of $\Upsilon(1S)$, 95 % CL from Fermi constraints, and 90 % CL from monojet searches. Signal regions are also shown, as are the 90 % CL exclusion contours from direct detection.

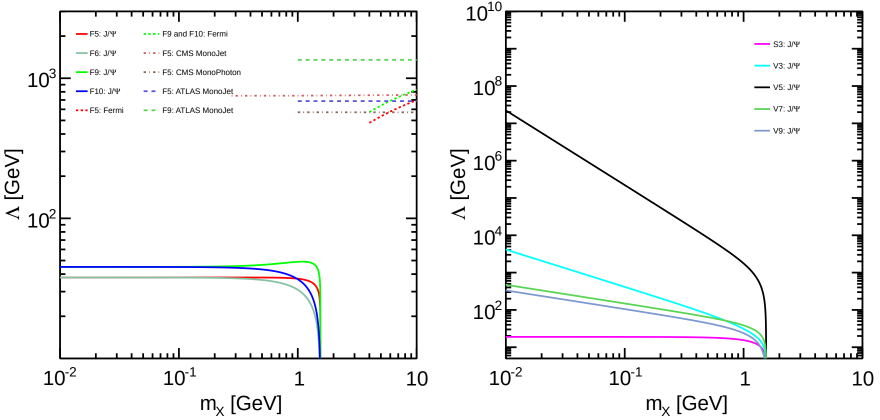
Summary and Outlook

- LDM bounds from Fermi for $m_X \gtrsim 1\,\mathrm{GeV}$ compliment $\Upsilon(1S)$ decay bounds at lower m_X
- Bounds from LHC stronger, constrained by unitarity
- $\Upsilon(1S)$ EFT valid for mediator mass $\sim 10\,\mathrm{GeV} - 1\,\mathrm{TeV}$
- LDM mass better resolved by $\sqrt{s} \sim 10\,\mathrm{GeV}$ beam energy
- Complements LHC searches by distinguishing operators which vanish in nonrelativistic limit
- J/Ψ bounds are weaker, allow larger range of mediator masses



- UV completions with psuedoscalar Higgs or dark photon with $m_{A'} \gtrsim 10\,\mathrm{GeV}$
- $\mathcal{B}(\Upsilon(1S) \to X\bar{X}\gamma) \lesssim 10^{-5}$
- Different set of interaction structures (eg 0909.4919)

J/Ψ Mediator Scale



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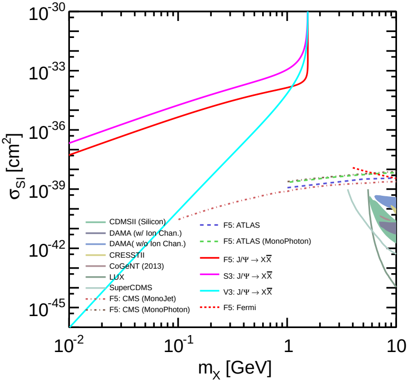
J/Ψ Complementary Bounds on Dark Matter Scattering



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Constraints on $q\bar{q}$ Annihilation Channels

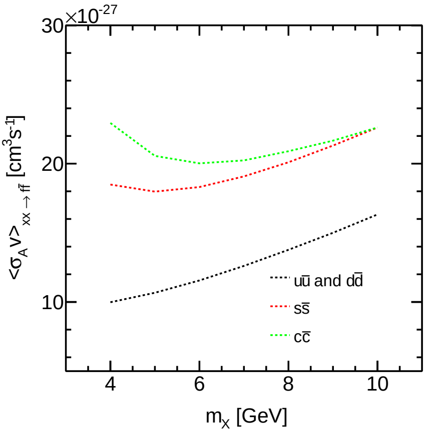

Figure: Bounds on the annihilation cross section, $\langle \sigma_A v \rangle$, for DM of mass m_X annihilating to quarks in dwarf spheroids.

Remarks

- For $m_X \gtrsim 5\,\mathrm{GeV}$, bounds strengthen with smaller m_X due to larger number density
- For $m_X \lesssim 5\,\mathrm{GeV}$, bounds weaken due to $E_{thr} \sim 1\,\mathrm{GeV}$ and threshold for $c\bar{c}$, $s\bar{s}$
- Need $E_\gamma > E_{thr}$ to contribute
- For $m_X \lesssim 4\,\mathrm{GeV}$, quark energy near hadronization scale
- $u\bar{u}$ and $d\bar{d}$ annihilation channels are visually identical
- CMB constrains s-wave annihilation at recombination