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Dark-Matter-Induced Weak Equivalence Principle Violation

Sean M. Carroll, Sonny Mantry, Michael J. Ramsey-Musolf and Christopher W. Stubbs

A long-range fifth force coupled to dark matter can induce a coupling to ordinary matter if the dark matter interacts with Standard Model fields. We consider constraints on such a scenario from both astrophysical observations and laboratory experiments. We also examine the case where the dark matter is a weakly interacting massive particle, and derive relations between the coupling to dark matter and the coupling to ordinary matter for different models. Currently, this scenario is most tightly constrained by galactic dynamics, but improvements in Eötvös experiments can probe unconstrained regions of parameter space.

A light scalar field \( \phi \) coupled to dark matter (DM) could mediate a long-range force of strength comparable to gravity. A number of models along these lines have been proposed, motivated both by attempts to account for features in the distribution of DM and to explore interactions with quintessence. Interesting limits on such a force have been derived from observations of DM dynamics in the tidal stream of the Sagittarius dwarf galaxy. The detection of a new mass hierarchy, between the light scalar and the weak scale \( m_W \approx 100 \text{ GeV} \), could mediate a long-range force of strength comparable to gravity.

If the scalar couples to Standard Model (SM) fields, it will give rise to a composition-dependent force acting on ordinary matter. Eötvös experiments looking for violations of the Weak Equivalence Principle (WEP) place constraints on couplings of a light scalar \( \phi \) to ordinary matter. We assume the existence of a mechanism that keeps its mass small. The static potential \( V = \frac{GM_o M_s}{r} \left( 1 + \frac{1}{4 \pi G \mu} \frac{q_o q_s}{m_o m_s} \right) \) is then

\[
V = \frac{GM_o M_s}{r} \left( 1 + \frac{1}{4 \pi G \mu} \frac{q_o q_s}{m_o m_s} \right), \tag{1}
\]

where \( q/\mu \) is the charge per unit mass and \( G = M_p^{-2} \) for a fermion \( \psi_i \) with mass \( m_i \) and Yukawa coupling \( \mathcal{L} = g_i \phi \bar{\psi}_i \psi_{i} \), we have \( q/\mu = g_i/m_i \).

The parameter \( \eta = \frac{2}{|a_1 + a_2|} \), where \( a_1 \) and \( a_2 \) are the accelerations of two bodies with different compositions.

We will assume that the dominant couplings of \( \phi \) to ordinary matter are to protons (\( p \)), neutrons (\( n \)), and electrons (\( e \)), neglecting, for example, couplings to atomic binding energy. Then for a neutral object made of ordinary matter we can define

\[
\frac{g_p + g_e}{m_p + m_e} \equiv \frac{g_e}{m_p}, \quad \frac{g_n}{m_n} \equiv (1 + \epsilon) \frac{g_e}{m_p}. \tag{3}
\]
For a source made of DM and test bodies of ordinary matter, we obtain
\[ \eta_{DM} \approx \frac{M_p^2}{4\pi} \left| \epsilon(f_1 - f_2) \right| \left( \frac{g_*}{m_p} \right)^2, \]  
where “DM” denotes accelerations sourced by dark matter. The best current limits on anomalous accelerations in the direction of the galactic center give \( \eta_{DM} < 10^{-5} \) \[16\], corresponding to \( g_\chi/m_p m_\chi < 5 \times 10^{-38} \text{GeV}^{-2} \). This is plotted as a downward-sloping diagonal line in Fig. 1.

Separate limits on \( g_\chi/m_\chi \) are obtained from astrophysical tests, such as the dynamics of galactic tidal streams \[13\] \[14\]. In this case, the constraint limits the strength of the force due to \( \phi \) relative to that due to gravity, rather than a composition-dependent acceleration. The relevant parameter is
\[ \beta = \frac{M_p}{\sqrt{4\pi}} \frac{g_\chi}{m_\chi}. \]

For reasonable models of the Sagittarius tidal stream, we obtain \( \beta < 0.2 \) \[13\] \[14\], corresponding to \( g_\chi/m_\chi < 10^{-19} \text{ GeV}^{-1} \), plotted as a horizontal line in Fig. 1.

From Fig. 1, it is clear that current bounds on constraints on anomalous accelerations toward the galactic center do not cover any region of parameter space that is not already excluded by constraints on the couplings to ordinary matter and DM alone. Assuming that limits on \( \beta \) do not appreciably improve, \( \eta_{DM} \) will only probe unconstrained parameter space once it is more sensitive to \( g_\chi/m_p \) for \( g_\chi/m_\chi \sim 10^{-19} \text{ GeV}^{-1} \) (the value along the the \( \beta \) constraint line) than \( \eta_{OM} \). Although any improvement in sensitivity to \( |a_1 - a_2| \) will lead to the same improvements in \( \eta_{DM} \) and \( \eta_{OM} \), they depend linearly and quadratically on \( g_\chi/m_p \), respectively. Since the \( \eta_{DM} \) constraint currently is weaker by a factor of \( 10^4 \) than the \( \eta_{OM} \) bound along the \( \beta \) constraint line, one must improve sensitivity to \( |a_1 - a_2| \) by at least \( 10^6 \). This corresponds to \( \eta_{OM} \sim 10^{-21}, \eta_{DM} \sim 10^{-13}, g_\chi/m_p \sim 10^{-27} \text{ GeV}^{-1} \). The proposed STEP experiment aims at \( \eta_{OM} < 10^{-17} \) \[29\], not enough to achieve this goal. If an anomalous acceleration toward the galactic center were detected with \( \eta_{DM} > 10^{-13} \) but with no corresponding detection of \( \eta_{OM} \), it could not be accommodated by the type of theory considered here.

Model Examples: WIMP Dark Matter. The most popular DM models involve WIMPs – stable neutral particles \( \chi \) living in some representation of the electroweak gauge and Poincaré groups. Their interactions with electroweak gauge bosons provide an annihilation cross-section that leads to cosmologically interesting relic abundances. A classification of the various possible representations containing a viable DM candidate can be found in \[28\]. Here, we select a few cases to illustrate the range of scenarios for WIMP-induced fifth-force couplings to ordinary matter.

Figs. 2 and 3 show the lowest-order processes that generate the gauge-invariant interaction
\[ c_i \bar{\psi}_i L H \psi_i R / \Lambda + \text{h.c.} \]
involving $\phi$, the Higgs doublet $H$ and the left-handed doublet and right-handed singlet components of a SM fermion $\psi_i$. Here, $\Lambda$ is a mass scale associated with the particles in the loops and $c_i$ is proportional to the fermion Yukawa coupling $y_i$. After electroweak symmetry breaking, in which the neutral component of $H$ obtains a vacuum expectation value $v = 246$ GeV, this interaction yields the coupling $g_i \phi \bar{\psi}_i \psi_i$ with $g_i \sim m_i / \Lambda$.

Since right-handed fermions do not couple to the SU(2)$_L$ gauge bosons $W^\alpha$, Fig. 2 only contributes if the WIMP $\chi$ has nonvanishing hypercharge. In that case, the hypercharge gauge boson $B$, can couple $\chi$ to both $\psi_{iL}$ and $\psi_{iR}$. The “Compton scattering” process of Fig. 3 in contrast, contributes for all WIMPs, with those having $Y = 0$ receiving contributions only from internal SU(2)$_L$ gauge bosons. The two-loop subgraph of Fig. 3 generates the structure $P' + P''$ involving the incoming and outgoing fermion momenta. The $P''$ cancels the $1/P'$ of the intermediate $\psi_L$, leading to the momentum-independent interaction $m_i \phi B - \bar{B} \psi_L$. Formally, the two-loop subgraph of Fig. 3 — along with diagrams involving external gauge boson insertions (not shown) — yields the operator $\bar{\psi}_i \phi \psi_i$ that is equivalent to $m_i \phi B - \bar{B} \psi_L$ by virtue of the equation of motion for $\psi_L$.

The simplest realization of this scenario occurs when $\chi$ is a scalar SU(2)$_L$ doublet, having an elementary $g_\chi \phi \chi^\dagger \chi$ interaction with the long-range force mediator. A mass $m_\chi \sim 0.5$ TeV is needed to obtain the observed DM relic density. A fermionic realization requires the presence of two doublets with $Y = \pm 1$ to cancel anomalies and $m_\chi$ of order 1 TeV. For either case, the graph in Fig. 2 is finite and a simple estimate yields

$$g_i \sim \left( \frac{\alpha_{em}}{4\pi} \right)^2 \frac{m_i}{m_\chi} g_\chi.$$  (8)

The contribution from Fig. 3 is naively an order of magnitude larger since it involves four powers of the SU(2)$_L$ gauge coupling that is roughly twice as large as the U(1)$_Y$ coupling entering Fig. 2

$$g_i \sim \left( \frac{\alpha_{em}}{4\pi} \right)^2 \frac{m_i}{m_\chi} g_\chi.$$  (9)

In terms of the nucleon coupling $g_\star$ defined in (8), the estimate (8) becomes

$$g_\star \sim 10^{-7} \frac{g_\chi}{m_\chi}.$$  (10)

This provides a lower limit (upper dotted line in Fig. 1) on the coupling strength induced by WIMP dark matter, and would be relevant if $\chi$ were a singlet of SU(2)$_L$ with non-zero hypercharge. If $\chi$ is a doublet or triplet of SU(2)$_L$, equation (9) applies, and the resulting coupling is an order of magnitude larger, $g_\star \sim 10^{-8} g_\chi / m_\chi$.

Realistic implementations of the WIMP idea often introduce more than just a single DM field (and its charged partners). In supersymmetry, for example, the $\chi$ is the lightest supersymmetric particle (LSP) and is a linear superposition of the superpartners of the electroweak gauge bosons (winos and binos) and Higgs bosons (higgsinos). In addition, one has scalar squarks and sleptons $\tilde{\psi}$ that interact with their partners and the LSP via an interaction $\lambda \bar{\tilde{\psi}} \tilde{\chi}^H + h.c.$ If $\phi$ is the scalar component of a singlet superfield $\phi$, a superpotential term of the form $\tilde{S}H_u \cdot H_d$ will generate a coupling of $\phi$ to the higgsino components of the LSP. As a result, we expect a one-loop coupling of $\phi$ to SM fermions, as shown in Fig. 4 which gives

$$g_i \sim \frac{1}{16\pi^2} \frac{m_i \mu^2}{M_{susy}^2} g_\chi,$$  (11)

where $\mu$ is the $\mu$-parameter of supersymmetry and $M_{susy}$ is the mass of the heaviest superpartner in the loop. We assume for simplicity that $m_\chi \approx M_{susy} \approx \mu \approx v$. The most favorable case is when the DM $\chi$ is primarily a bino, in which case $\lambda = g_1$, the $U(1)_Y$ gauge coupling. This implies

$$g_\star \sim 10^{-4} \frac{g_\chi}{m_\chi},$$  (12)

leading to the lower dotted line in Fig. 1. In this case, where the existence of the squarks enables a one-loop contribution, the coupling to ordinary matter is enhanced by a factor of order $10^4$. This is the most optimistic scenario.
We have found that a weakly-interacting dark matter particle $\chi$ coupled to a light scalar $\phi$ with strength $g_\chi$ naturally induces an effective coupling to ordinary matter with strength $g_\chi/m_\chi \sim (10^{-7} - 10^{-4})g_\chi/m_\chi$. The low end of this range corresponds to minimal WIMP models with only higher-loop contributions to the interaction of $\phi$ with SM fields, through SU(2)$_L$ gauge bosons, while the high end corresponds to bino-like DM with one-loop contributions. Comparing with Fig. [1], we see that the best current limits on these models come from purely astrophysical bounds on new long-range forces in the dark sector; if improvements in these techniques discovered such a force, it would predict a new force between ordinary matter if the DM were WIMPs. Meanwhile, improvements in the sensitivity of Eötvös-type experiments could provide interesting new constraints on a WIMP-mediated coupling. Any improvement of the limits on $g_\chi/m_\chi$ would begin cutting into the predictions of the models examined here (at the order-of-magnitude precision we considered). Currently, constraints on a fifth force in the direction of the galactic center do not independently constrain any of the parameter space; measurements of anomalous accelerations would have to improve by a factor of about $10^8$ before they would begin to do so.

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