Constraining Exotic Spin-Dependent Long-Range Interactions from Spin-Independent Experiments

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With William Michael Snow, Dennis E. Krause, Joshua C. Long

Phys. Rev. D 95, 096005 (2017) [arXiv:1611.01580] & work in progress

Motivation for New Long-Range Interactions

Standard Model extensions possess spontaneously broken continuous symmetries producing Weakly Interacting Sub-eV Particles (WISPs) such as axions, arions, familons, Majorons, etc.

B. Dobrescu and I. Mocioiu J. High Energy Phys. 11 (2006) 005.

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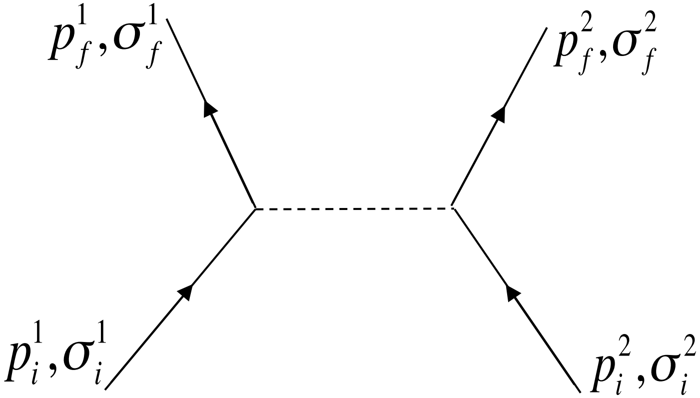

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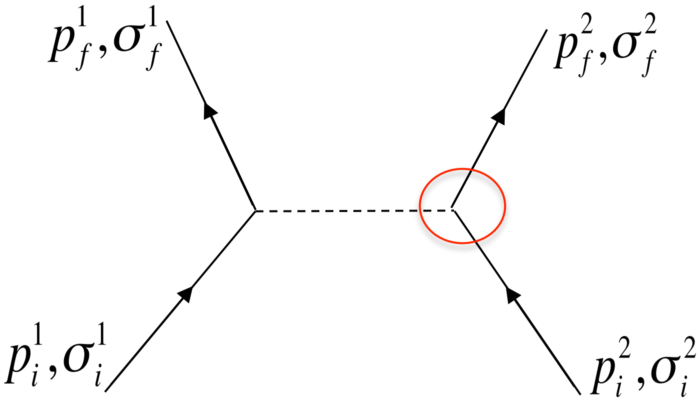

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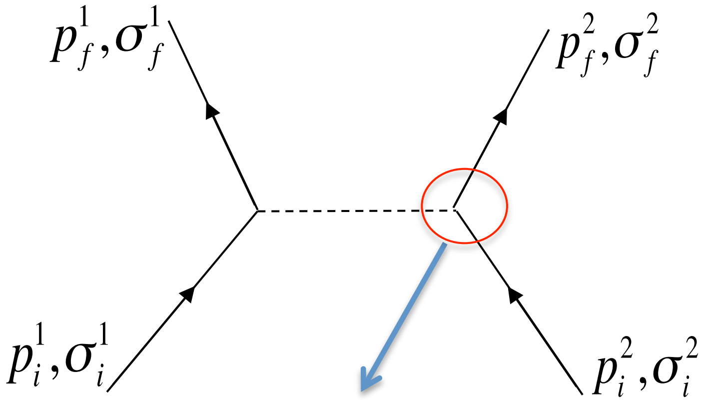

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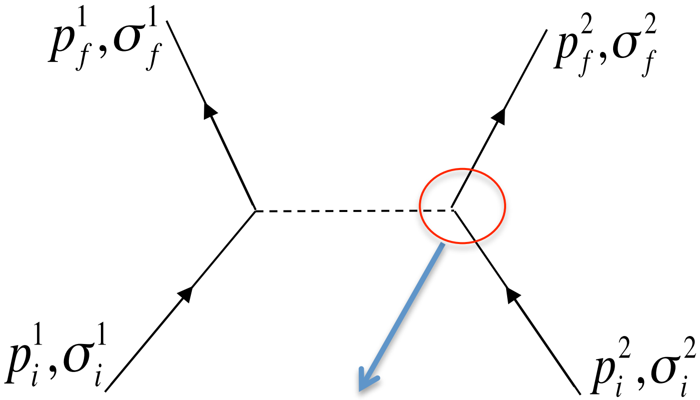

✓ Scalar

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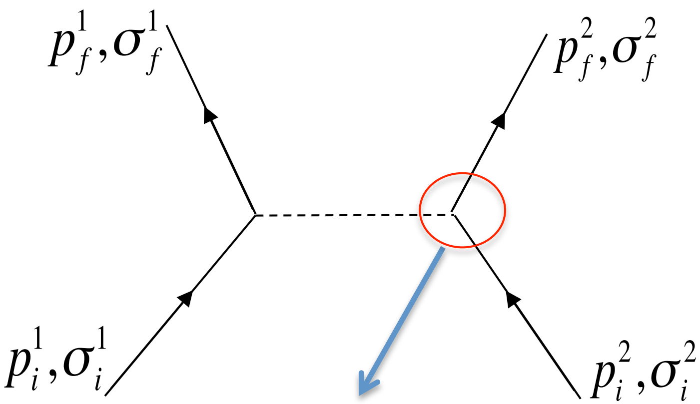

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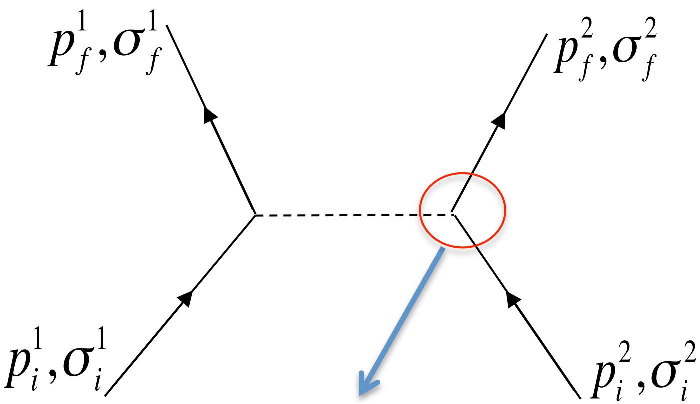

- ✓ Scalar
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- ✓ Vector

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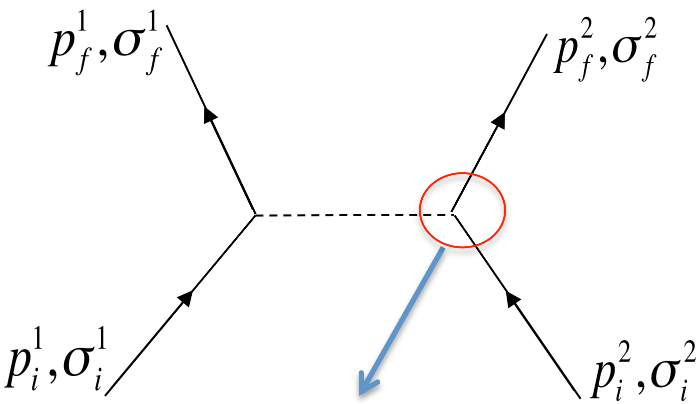

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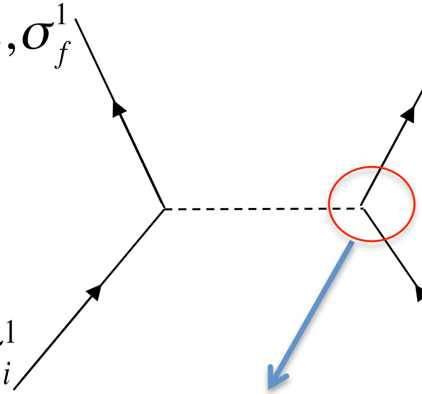

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The two-body interaction in coordinate space

$$V(r^2, P^2, \vec{r} \bullet \vec{P}) = \sum_{i=1}^{16} O_i \frac{e^{-\mu r}}{4\pi r}$$

$$O_i = f_1,\ f_2\ \vec{\sigma}_1 \bullet \vec{\sigma}_2,\ f_3\ \vec{\sigma}_1 \bullet \nabla\ \vec{\sigma}_2 \bullet \nabla,\ f_{4,5}\ (\vec{\sigma}_1 \pm \vec{\sigma}_2) \bullet P \times \nabla,$$
$$f_6\ \vec{\sigma}_1 \bullet P\ \vec{\sigma}_2 \bullet \nabla,\ f_7\ \vec{\sigma}_1 \bullet P\ \vec{\sigma}_2 \bullet P, \ldots\ldots,\ f_{16}\ \vec{\sigma}_1 \bullet (P \times \nabla)\ \vec{\sigma}_2 \bullet P$$

f : a dimensionless constant α g^2

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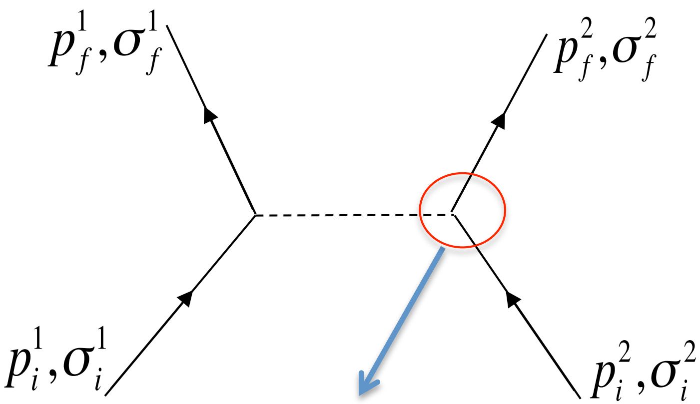

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Laboratory experiments provide very sensitive and model-independent probes of such particles [See Rev. of Mod. Phys. 90, 025008 (2018)].

B. Dobrescu and I. Mocioiu J. High Energy Phys. 11 (2006) 005.

Current Limits from Laboratory Experiments

- Very stringent limits on possible interactions arising from scalar and vector couplings from spin-independent experiments. In contrast, limits on pseudoscalar and axial couplings are many orders of magnitude weaker

- Limits on pseudoscalar couplings to nucleons are more suppressed than their electron analogs.

Type of coupling	μ≈[100 μeV, 10 meV]	
$g_S^2,\ g_V^2$	$10^{-40}-10^{-35}$	1
$\left(g_P^e\right)^2$	$10^{-16}-10^{-8}$	2
$\left(g_P^N\right)^2$	$10^{-4}-10^{-6}$	3
$\left(g_A^N\right)^2$	$10^{-15}-10^{-12}$	4
$\left(g_A^e\right)^2$	$10^{-32}-10^{-29}$	5
$g_S g_P^e$	$10^{-28}-10^{-21}$	6
$g_S g_P^N$	$10^{-25}-10^{-17}$	7
$g_V g_A^e$	$10^{-26}-10^{-23}$	8
$g_V g_A^N$	$10^{-29}-10^{-25}$	9

[1]R. S. Decca, et. al, PRL 116 (2016) 221102.

[2]W. A. Terrano, et. al, PRL 115 (2015) 20801.

[3]M. P. Ledbetter et. al, PRL 110, 040402 (2013), N. F. Ramsey, Physica A (Amsterdam) 96, 285 (1979).

[4]C. Haddock, et. al, PLB 783, (2018) 227.

[5,8]T. M. Leslie, et. al, Phys. Rev. D 89 (2014) 114022.

[6]B. R. Heckel, et. al, PRL 111 (2013) 15802.

[7]K. Tullney, et. al, PRL 111 (2013)100801, M. Bulatowicz, et. al, PRL 111(2013)102001(IU), A. K. Petukov, et. al, PRL 105 (2010) 170401.

[9]H. Yan, et. al, PRL 110 (2013) 082003.

Why are Limits on Pseudoscalar and Axial Couplings Poor?

1. Pseudoscalar and axial interactions are suppressed by factors of μ / m per vertex relative to scalar and vector interactions for nonrelativistic motion

$$g_S \bar{\psi}\psi\varphi(t,\vec{x}) \xrightarrow{\mathbf{P}} g_S \bar{\psi}\psi\varphi(t,-\vec{x})$$

$$g_V \bar{\psi}\gamma^\mu\psi A_\mu(t,\vec{x}) \longrightarrow g_V \bar{\psi}\gamma^\mu\psi A_\mu(t,-\vec{x})$$

$$g_P i\bar{\psi}\gamma_5\psi\varphi(t,\vec{x}) \xrightarrow{\mathbf{P}} -g_P i\bar{\psi}\gamma_5\psi\varphi(t,-\vec{x})$$

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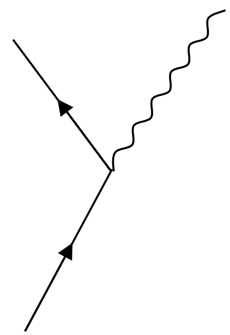

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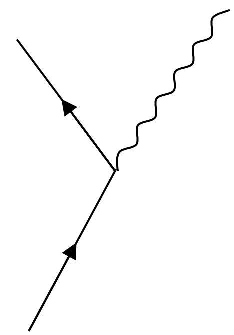

ex: for a nucleon and a 1 meV boson $\dfrac{\mu}{m} \approx 10^{-15}$

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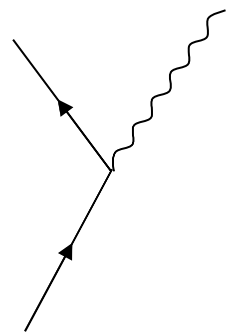

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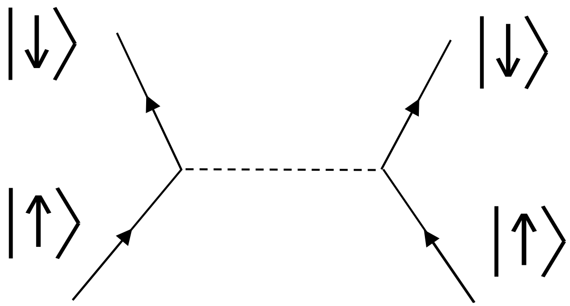
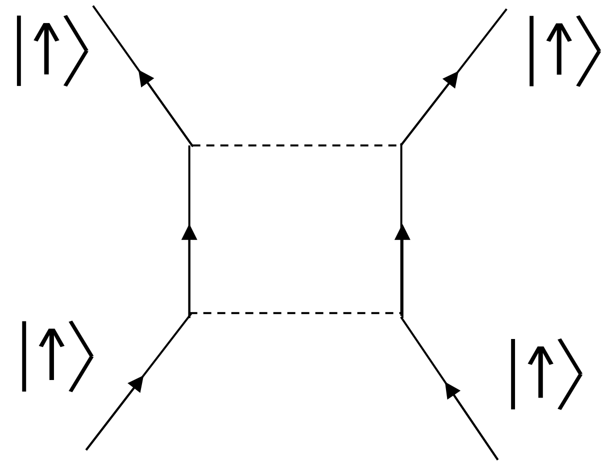
2. Necessarily spin-dependent at lowest order

Experimental difficulties associated with polarization:

- Only the valence fermions are accessible
- Large external magnetic fields.
- Polarization techniques vary widely in efficiency.
- Difficult to maintain polarization of members of the ensemble.
- Both internal and external magnetic fields produce large systematic effects in delicate experiments.
- ….

Two-Boson Exchange





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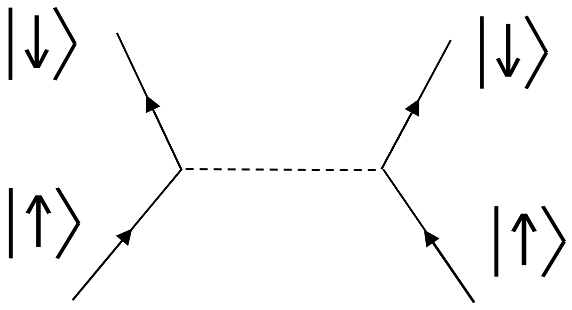
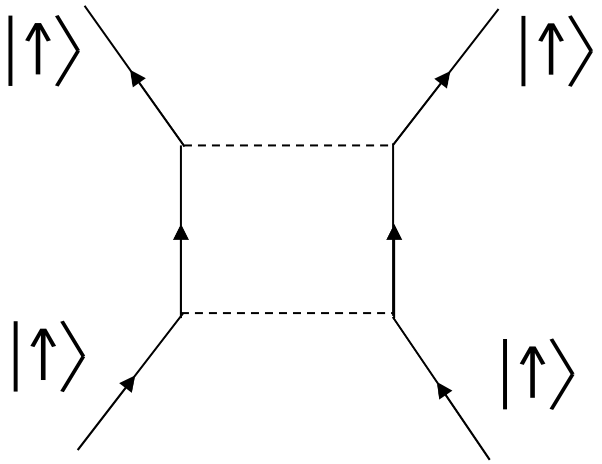




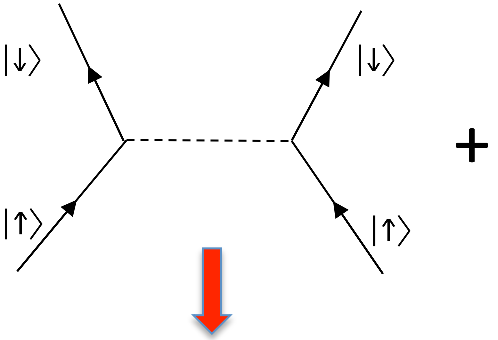
Aim of this work:

- derive all long-range *spin-independent* interactions from double boson exchange from spin-0 and spin-1 with *spin-dependent* couplings between a pair of NR Dirac fermions

- Use the derived expressions with the strong spin-independent limits to help improve constraints on interactions involving pseudoscalar and axial couplings.

$$L_P = -g_P\ \bar{\psi} i \gamma_5 \psi \varphi$$

Previous Work

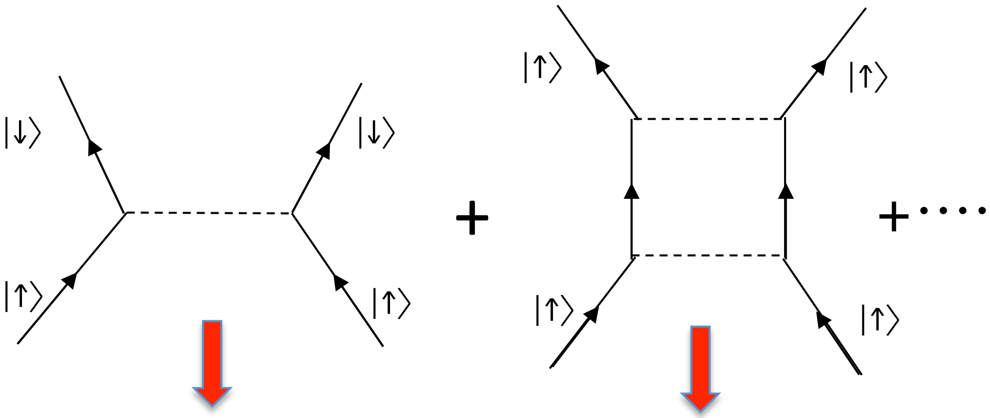


$$V_P = \left[\frac{g_P^2}{16\pi m^2} \vec{\sigma}_a \cdot \nabla \vec{\sigma}_b \cdot \nabla \frac{e^{-\mu r}}{r} \right.$$

$$L_P = -g_P \; \bar{\psi} i \gamma_5 \psi \varphi$$

Previous Work

$K_1(x)$: modified Bessel function of the second kind



$$V_P = \left[\frac{g_P^2}{16\pi m^2} \vec{\sigma}_a \cdot \nabla \vec{\sigma}_b \cdot \nabla \frac{e^{-\mu r}}{r} - \frac{g_P^4}{m^2} \mu \frac{K_1(2\mu r)}{4\pi^2 r^2} + \cdots \right.$$

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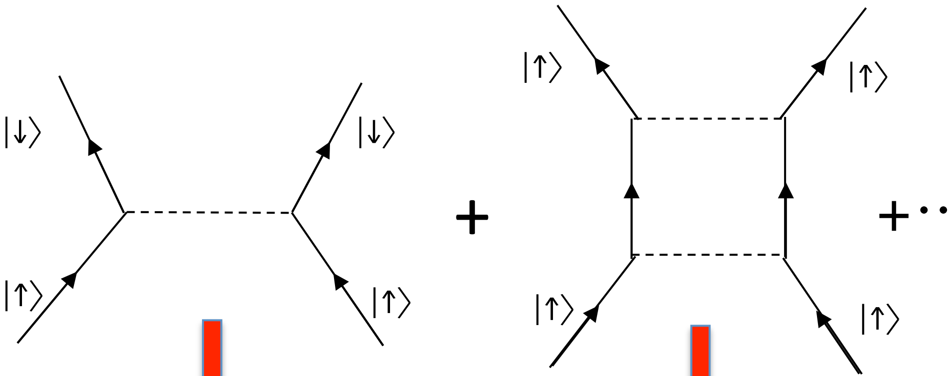

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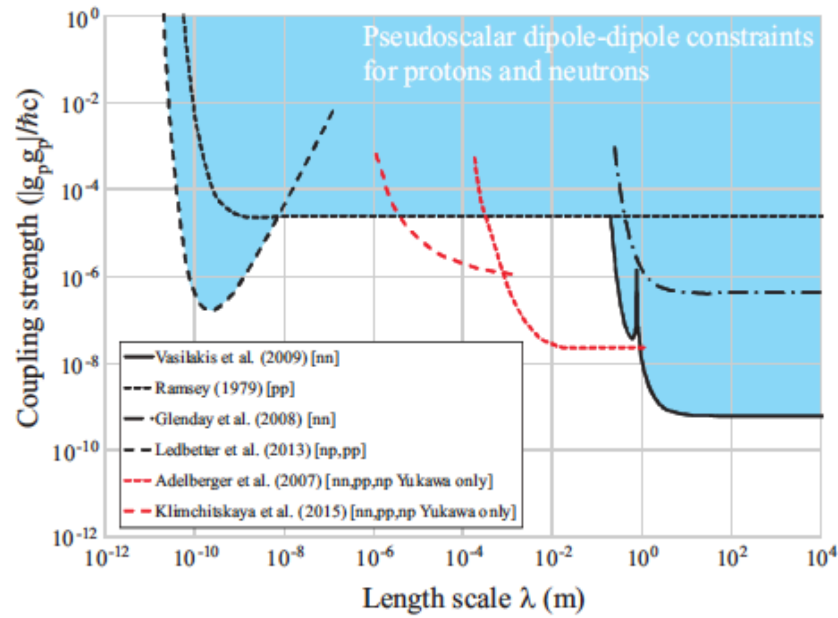

Blue → spin-dependent

Red → spin-independent

[E. Fischbach and D. E. Krause, (1999)]

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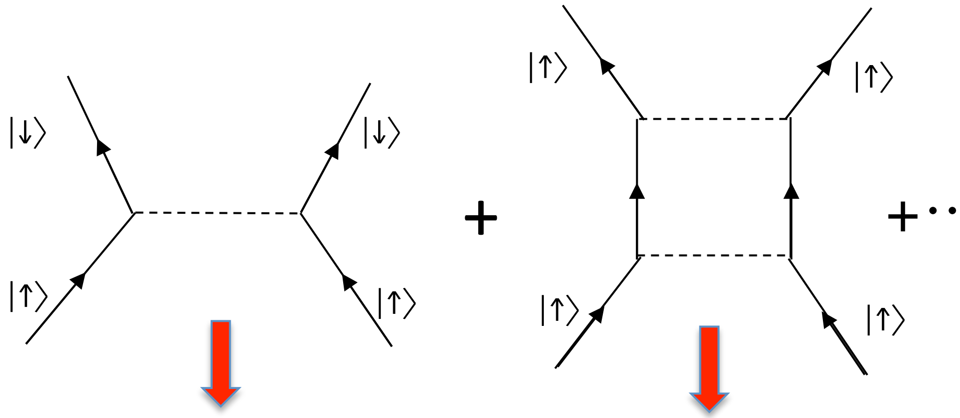

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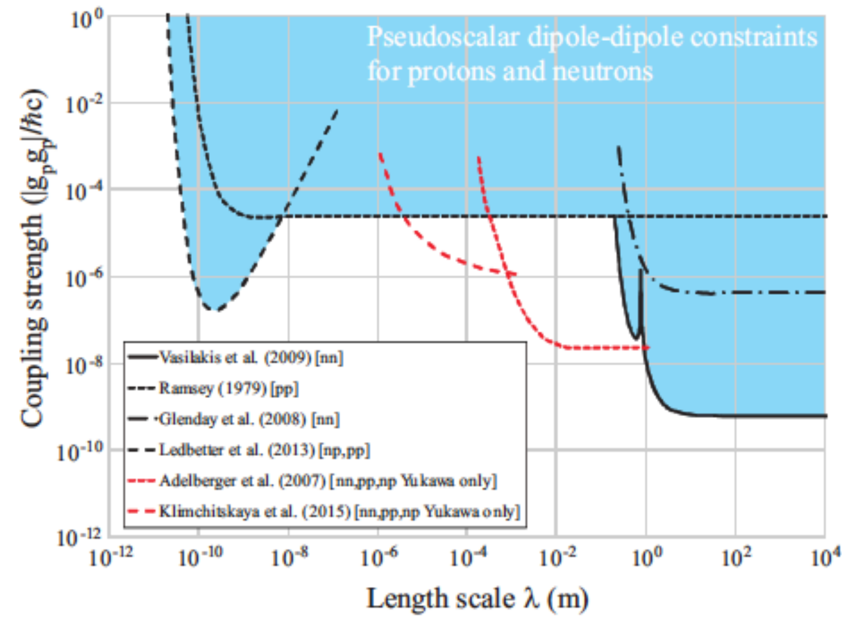

- No similar analysis done and no functional forms exist for interactions

$$\propto g_S^2 g_P^2, g_V^2 g_A^2,\ g_{PD}^4,\ g_S^2 g_{PD}^2, \text{ and } g_A^4$$

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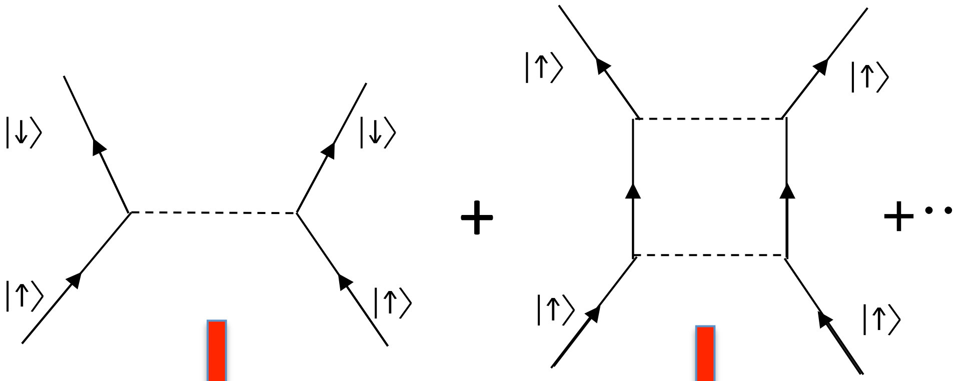

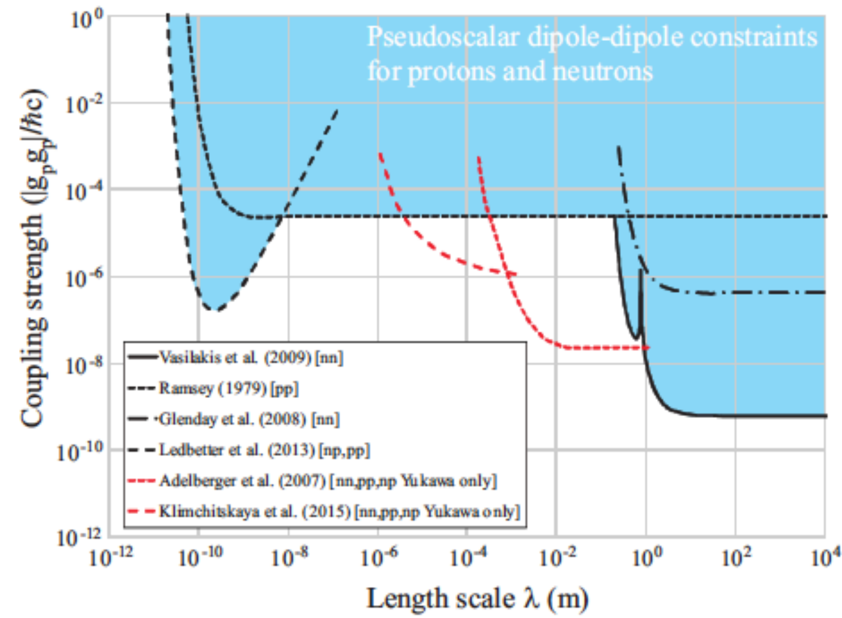

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$$\propto g_S^2 g_P^2, g_V^2 g_A^2,\; g_{PD}^4,\; g_S^2 g_{PD}^2, \text{ and } g_A^4$$

- Limits do not necessarily apply to the pseudoscalar derivative coupling

KSVZ axion

$$m \; \bar{\psi} e^{i\gamma_5 \varphi / f_a} \psi \approx -i \frac{m}{f_a} \; \bar{\psi} \gamma_5 \psi \varphi + \frac{m}{2 f_a^2} \; \bar{\psi} \psi \varphi^2 + \cdots$$

field redefinitions →

$$\frac{1}{2 f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \varphi$$

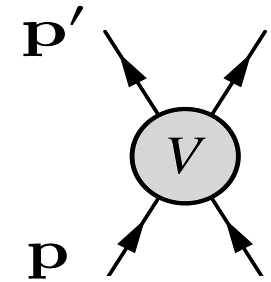
$$g_{PD} = \frac{m}{f_a}$$

Calculating an Interaction Energy

- Use non-relativistic Old-Fashioned Perturbation Theory (OFPT) to calculate a transition amplitude and relate to a potential via the Lippmann-Schwinger (LS) equation

$$\langle f|\,\mathcal{T}\,|i\rangle = \langle f|\,V\,|i\rangle + \sum_n \frac{\langle f|\,V\,|n\rangle\,\langle n|\,\mathcal{T}\,|i\rangle}{E_i - E_n + i\epsilon}.$$

The Green function of two fermions G_o



- No self-energy terms are considered since masses and couplings are taken from experiments.

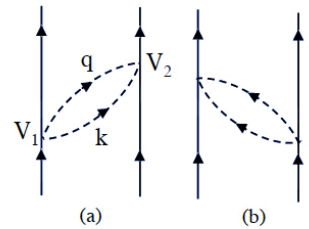
- Methods based on UT: Okubo (Prog. Theor. Phys. **12**, 603 1954), Epelbaum (Nucl. Phys. A **637**, 107 1998)

- Methods based on covariant PT: Dispersion Method (Feinberg and Sucher), EFT(Holstein), Chiral EFT (Kaiser, Machledit, etc.).

Results for the spin-independent long-range interaction from two boson exchange

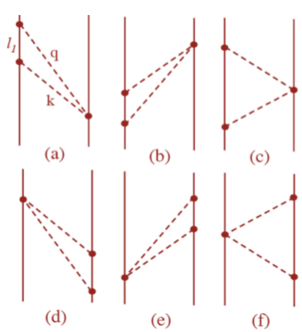
Range of applicability:
$r \geq \frac{1}{\mu} >> \frac{1}{m}$
with finite boson mass

$$V^{(0)} = T^{(0)}$$



$$V_{P-P} = -\frac{g_{P,1}^2 g_{P,2}^2}{4m_1 m_2} \frac{\mu K_1(2\mu r)}{8\pi^3 r^2}$$

Agrees with
S. D. Drell and K. Huang, Phys. Rev. 91, 1527 (1953).
F. Ferrer and J. A. Grifols, Phys. Rev. D 58, 096006 (1998).



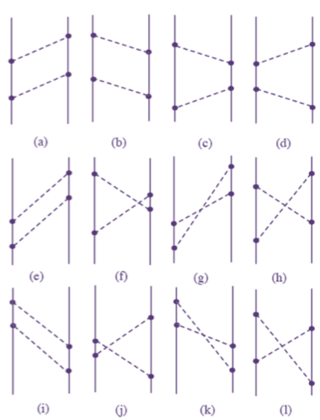
$$V_{S-P} = \left(\frac{g_{S,1}^2 g_{P,2}^2}{2m_2} + \frac{g_{S,2}^2 g_{P,1}^2}{2m_1}\right) \frac{e^{-2\mu r}}{16\pi^2 r^2}$$

$$V_{V-A}(r) \simeq \left[\frac{g_{V,1}^2 g_{A,2}^2}{2m_1} + \frac{g_{V,2}^2 g_{A,1}^2}{2m_2} + \left(\frac{g_{V,2}^2 g_{A,1}^2}{2m_1} + \frac{g_{V,1}^2 g_{A,2}^2}{2m_2}\right)\right] \frac{e^{-2\mu r}}{16\pi^2 r^2} + \ldots\ldots$$

S. Aldaihan, D. E. Krause, J. C. Long, and W. M. Snow, Phys. Rev. D 95, 096005 (2017).

$$V^{(1)} = T^{(1)} - [V^{(1)} G_o V^{(1)} + V^{(2)} G_o V^{(0)} + V^{(0)} G_o V^{(2)}]$$

$$x = \mu r$$



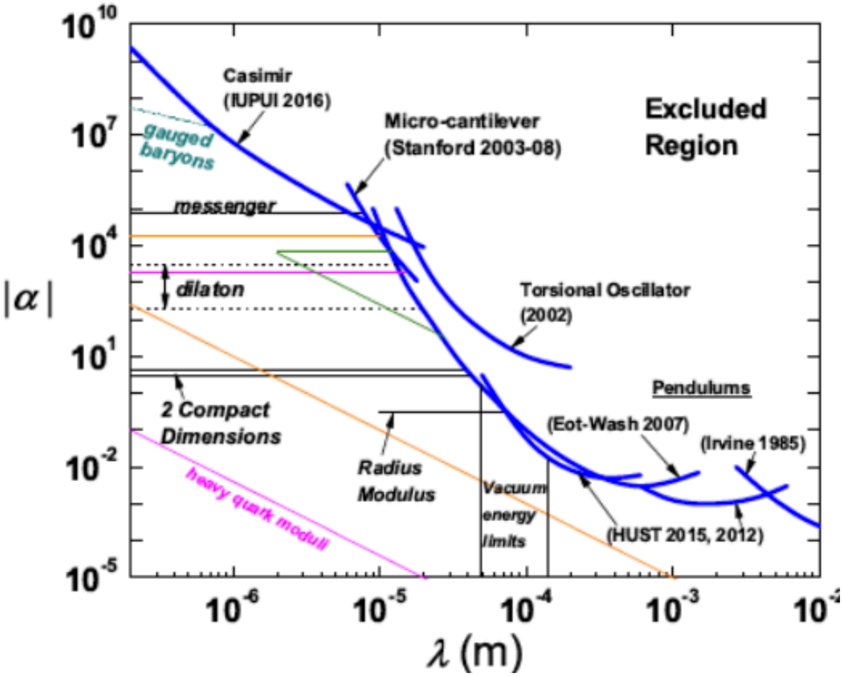
$$\overline{V}_{PD-PD} = -\frac{g_{PD}^4}{512 m^5} \frac{e^{-2x}}{2r^6} [5(6 + 12x + 10x^2 + 4x^3 + x^4) + 5x^2(x+1)^2 + 2x^5] + \ldots\ldots$$

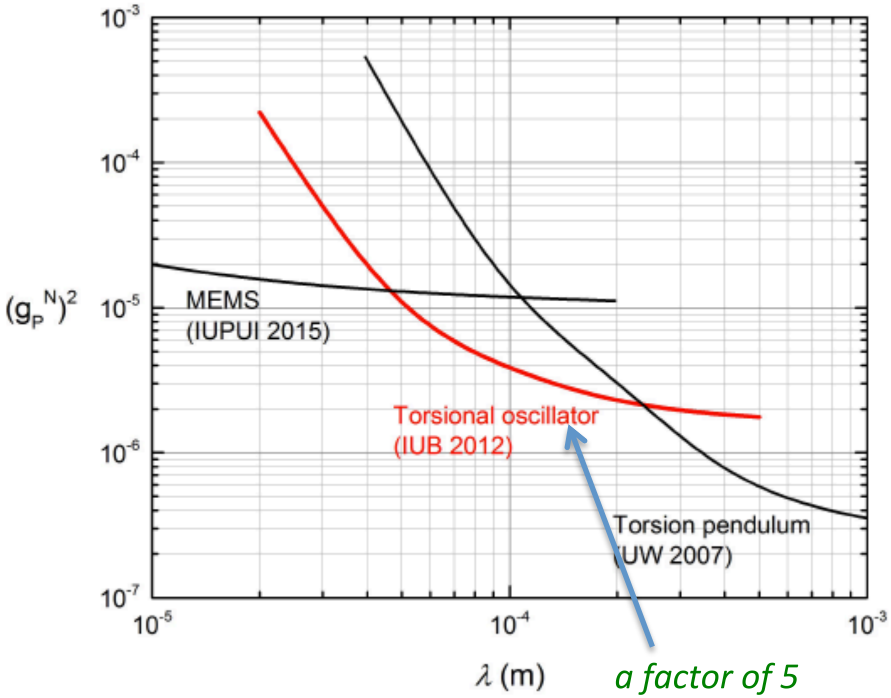
$$\overline{V}_{S-PD} = \frac{g_S^2\, g_{PD}^2}{128\pi^2 m^3} \frac{e^{-2x}}{r^4} (x+1)[2x^2 - 3x - 3] + \ldots\ldots$$

$$\overline{V}_{A-A} = \frac{3g_A^4}{64\pi^2 m} \frac{e^{-2x}}{r^2} (5 - 2x) + \ldots\ldots$$

Agrees (up to a minor discrepancy) with
N. Kaiser, R. Brockmann, and W. Weise, Nucl. Phys. A 625 758 (1997). M. Sugawara, S. Okuno, Phys. Rev. 117, 605 (1960). J. L. Friar, Phys. Rev. C 60 , 034002 (1999).

Constraints from Spin-Independent Experiments





$$V(r) = -\frac{Gm_1m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

$$\alpha = \frac{\hbar c}{4\pi G m_1 m_2}(g_S^X g_S^Y - g_V^X g_V^Y)$$

$$\approx 10^{-38}(g_S^X g_S^Y - g_V^X g_V^Y)$$

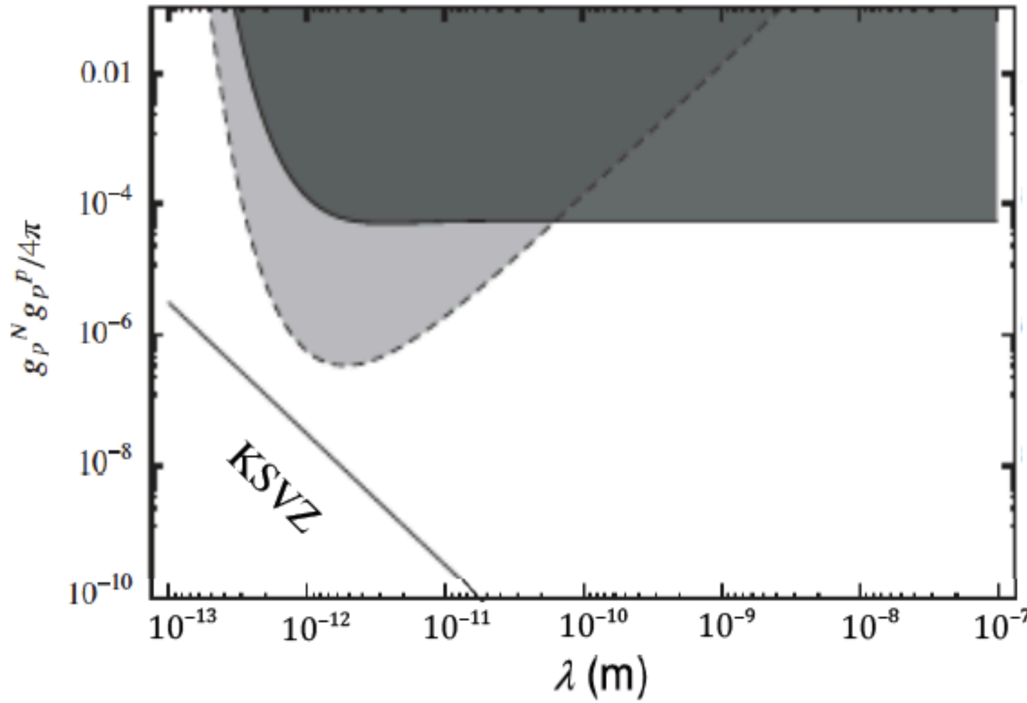
$$\lambda = 1/\mu$$

$$V_{P-P}(r) = -\frac{g_P^4}{4m^2r^2}\frac{K_1(2r/\lambda)}{8\pi^2\lambda}$$

an existence proof that sensitive experimental searches for spin-independent interactions can also yield interesting limits on spin-dependent interactions at certain distance scales.

S. Aldaihan, D. E. Krause, J. C. Long, and W. M. Snow, Phys. Rev. D 95, 096005 (2017).

Further Opportunities



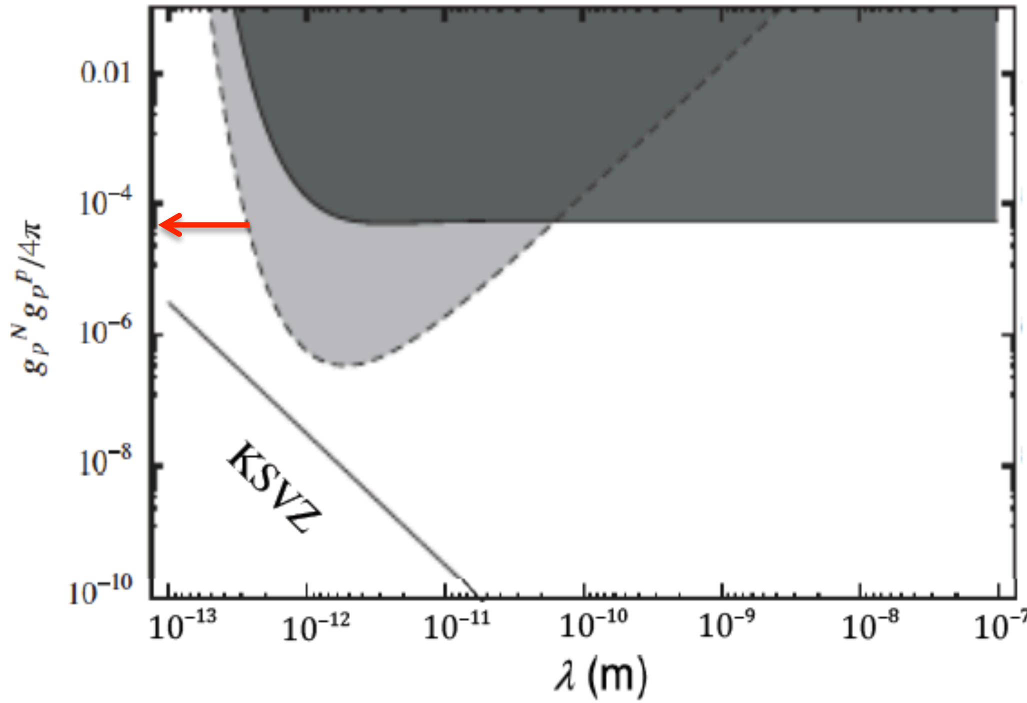
Constraints from spin-dependent experiments between protons and neutrons

$$V_P = \frac{g_P^2}{4\pi}\left(\frac{\mu}{2m}\right)^2\left[(\vec{\sigma}_1\cdot\vec{\sigma}_2)+S_{12}\left(\frac{1}{3}+\frac{1}{x}+\frac{1}{x^2}\right)\right]\frac{e^{-\mu r}}{r}$$

$$S_{12} = 3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})-\vec{\sigma}_1\cdot\vec{\sigma}_2$$

M. P. Ledbetter, M.V. Romalis. PRL 110, 040402 (2013).

Further Opportunities



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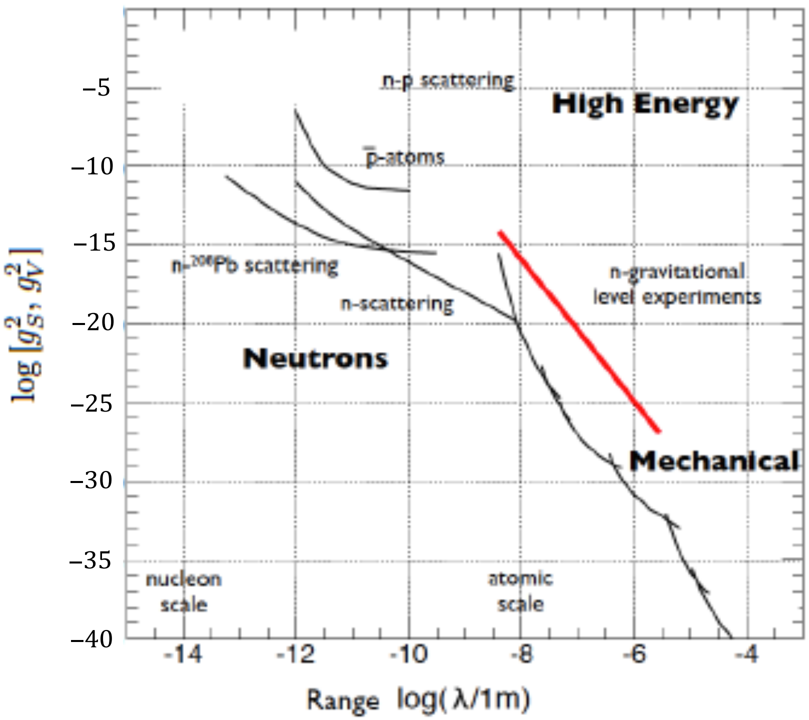
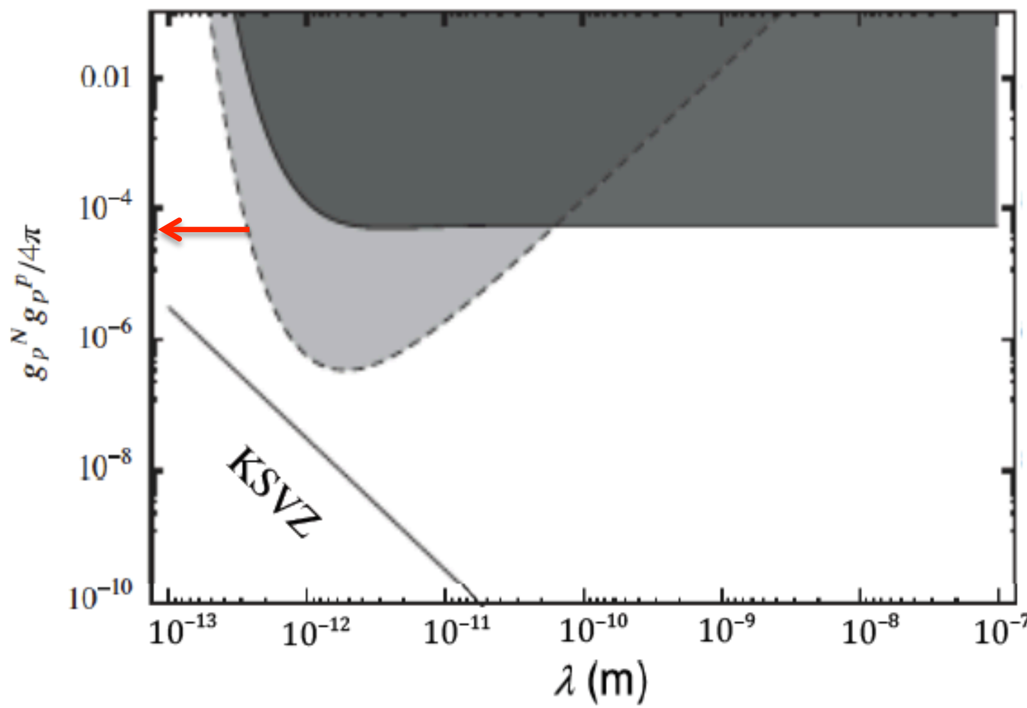
M. P. Ledbetter, M.V. Romalis. PRL 110, 040402 (2013).

Further Opportunities



Constraints on the scalar coupling from spin-independent experiments testing interactions between normal matter



Constraints from spin-dependent experiments between protons and neutrons

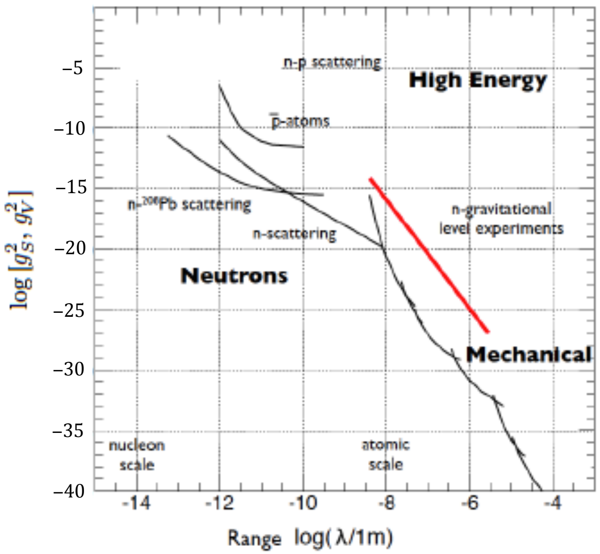
$$V_P = \frac{g_P^2}{4\pi}\left(\frac{\mu}{2m}\right)^2\left[(\vec{\sigma}_1\cdot\vec{\sigma}_2)+S_{12}\left(\frac{1}{3}+\frac{1}{x}+\frac{1}{x^2}\right)\right]\frac{e^{-\mu r}}{r}$$

$$S_{12}=3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})-\vec{\sigma}_1\cdot\vec{\sigma}_2$$

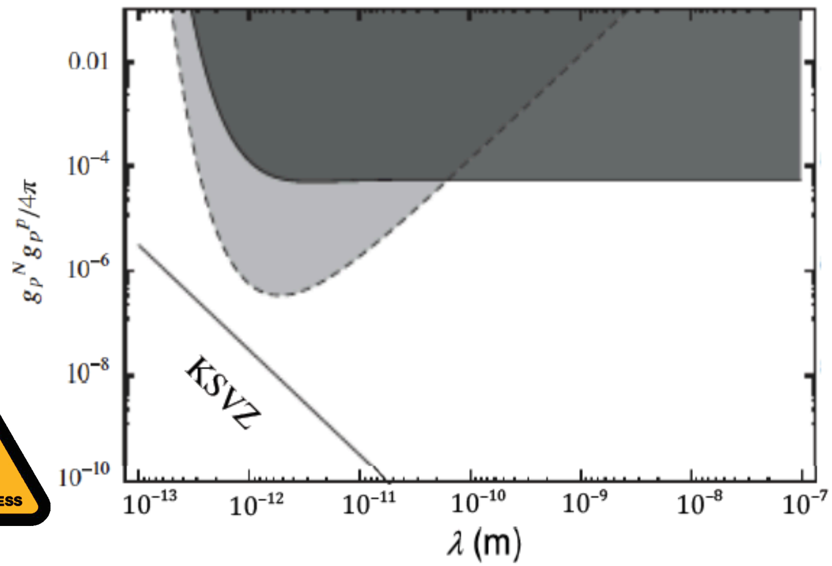
- $V_{PD\text{-}PD}$ α $1/r^6$ ➡ sensitive to short-length scales.
- No constrains on $(g^N_{PD})^2$ below 10^{-12} m, a theoretically interesting regime.

M. P. Ledbetter, M.V. Romalis. PRL 110, 040402 (2013).

Further Opportunities



Constraints on the scalar coupling from spin-independent experiments testing interactions between normal matter across a wide length scale



Constraints from spin-dependent experiments between protons and neutrons

- $V_{PD\text{-}PD} \propto 1/r^6$ ➡ sensitive to short-length scales.
- No constrains on $(g^N_{PD})^2$ below 10^{-12} m, a theoretically interesting regime.

$$V_P = \frac{g_P^2}{4\pi}\left(\frac{\mu}{2m}\right)^2\left[(\vec{\sigma}_1\cdot\vec{\sigma}_2)+S_{12}\left(\frac{1}{3}+\frac{1}{x}+\frac{1}{x^2}\right)\right]\frac{e^{-\mu r}}{r}$$

$$S_{12} = 3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})-\vec{\sigma}_1\cdot\vec{\sigma}_2$$

M. P. Ledbetter, M.V. Romalis. PRL 110, 040402 (2013).

Conclusion:

- ❖ Ultralight bosons, including axions, generate long-range interactions of various types that can be probed with precision laboratory experiments.

- ❖ Experiments testing spin-dependent interactions experience additional challenges that do not exist in spin-independent experiments.

- ❖ The functional forms derived from 2-boson exchange processes open up an opportunity to constrain, using spin-independent data, spin-dependent couplings over new length scales that are outside the sensitivity of current spin-dependent experiments.