Constraining Axion-Like Particles through Fifth-Force and EDM Limits

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“Theoretical issues and experimental opportunities in searches for time reversal invariance violation using neutrons”

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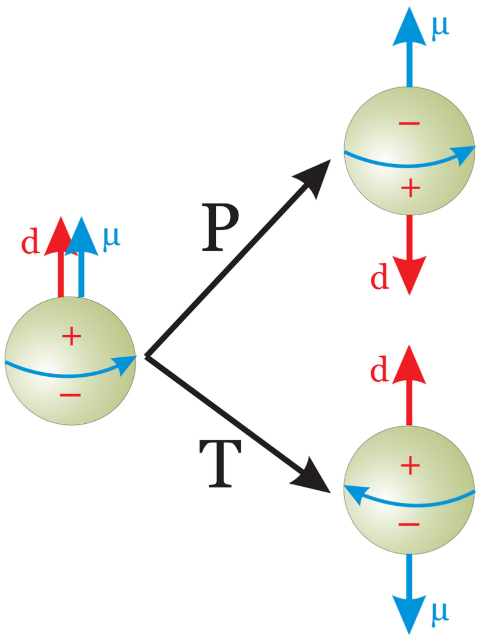
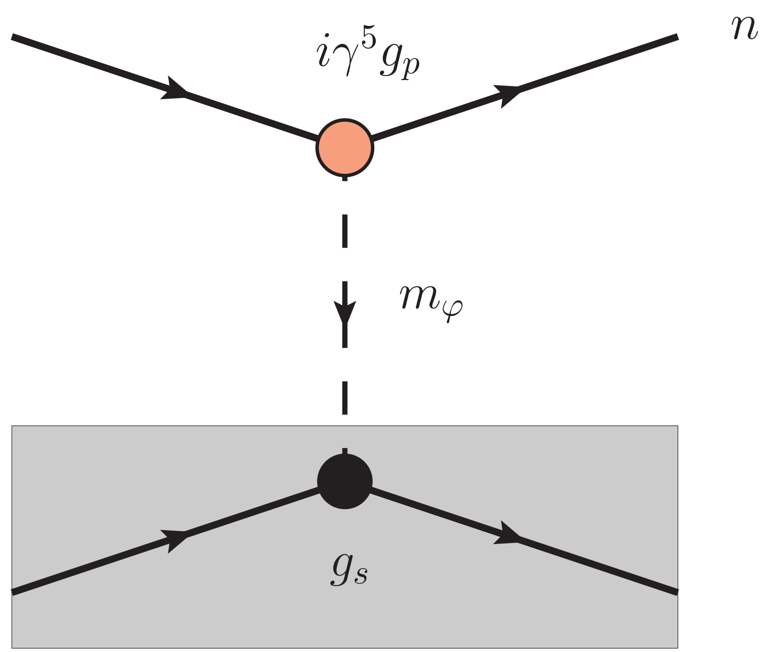
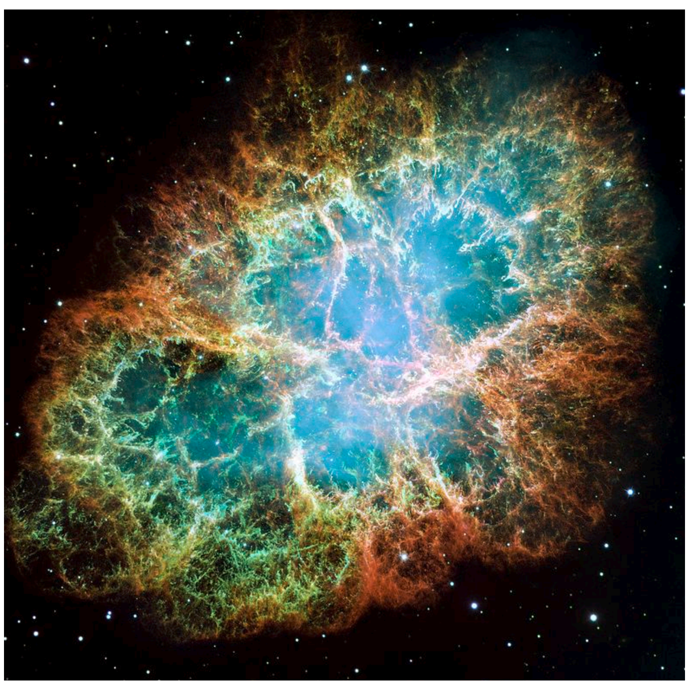
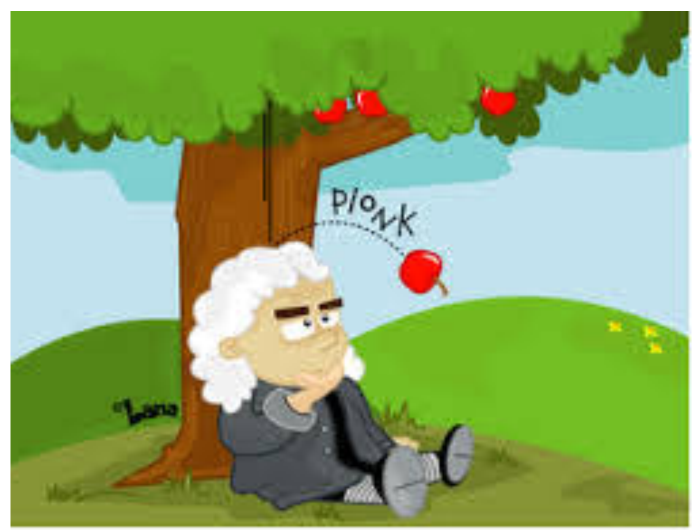
Constraining Axion-Like Particles





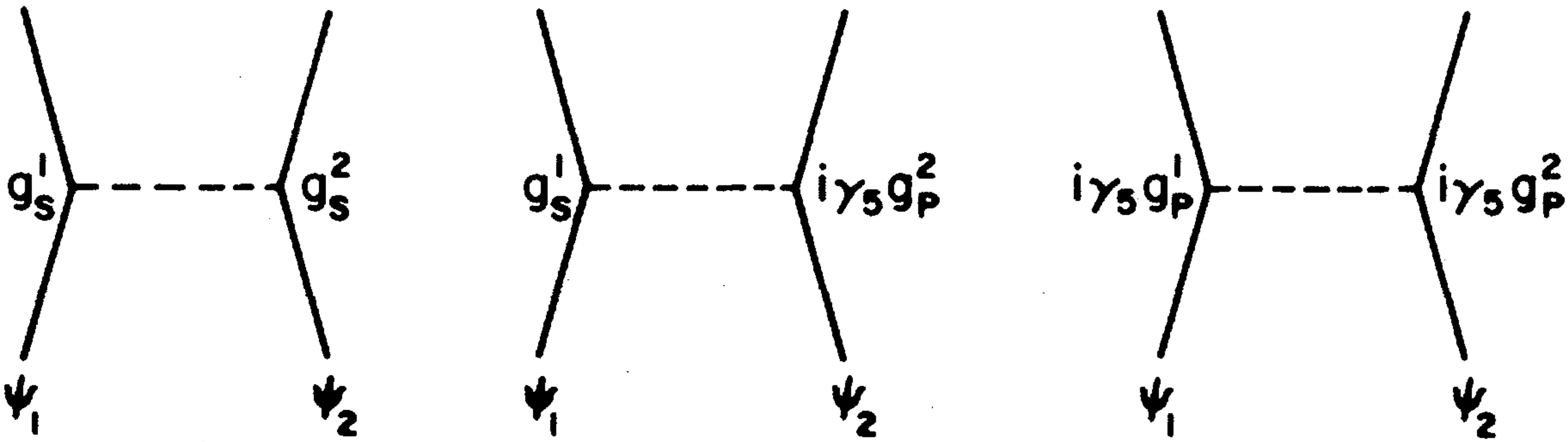




Macroscopic Spin-dependent Forces

Short Range Macroscopic Scalar Forces

(Moody, Wilczek)



Monopole-Monopole　　Monopole-Dipole　　Dipole-Dipole

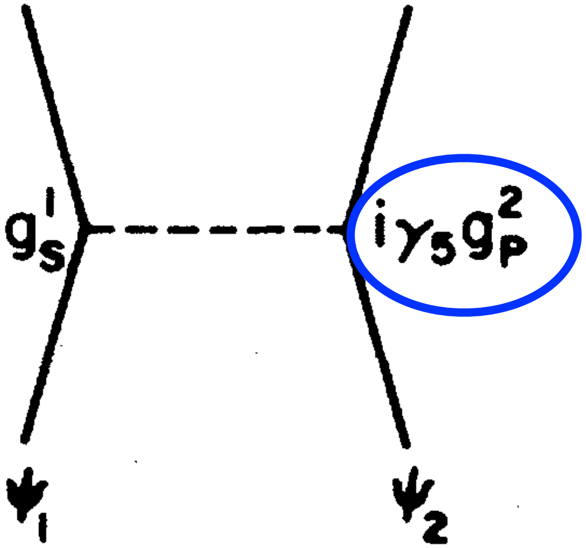
- New short range macroscopic forces beyond the SM?

$$m_\varphi \lesssim 10^{-2}\ \mathrm{eV} \longrightarrow \lambda \gtrsim 2\times 10^{-5}\ \mathrm{m}$$

$$m_\varphi \gtrsim 10^{-6}\ \mathrm{eV} \longrightarrow \lambda \lesssim 2\times 10^{-1}\ \mathrm{m}$$

Spin-Dependent Macroscopic Scalar Forces

(Moody, Wilczek)



Monopole-Dipole

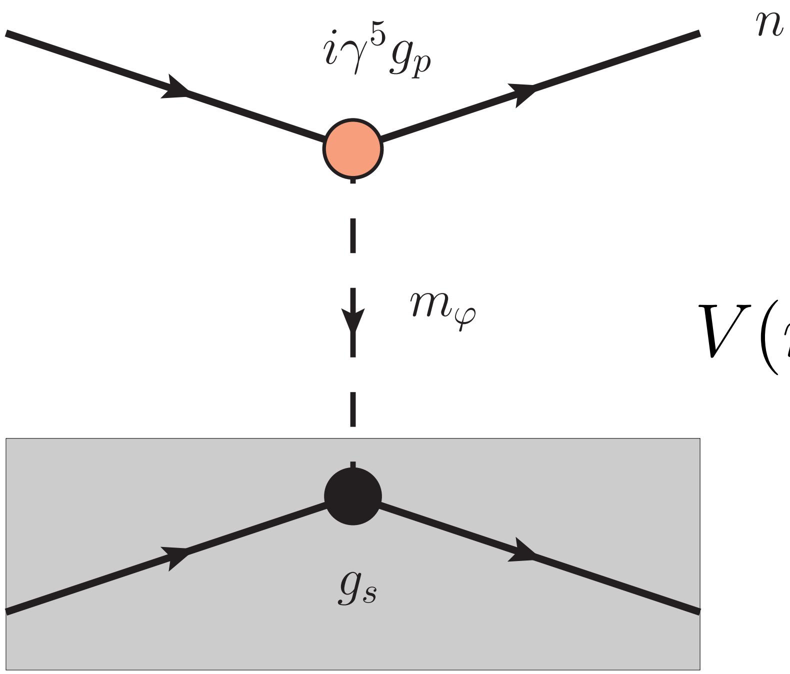
→ CP violating coupling

$$\mathcal{L}_{\varphi NN} = g_s\,\varphi \bar{N} N + g_p\,\varphi \bar{N} i\gamma_5 N$$

$$V(r) = g_s^1 g_p^2 \frac{\vec{\sigma}_2 \cdot \hat{r}}{8\pi M_2} \left[\frac{m_\varphi}{r} + \frac{1}{r^2}\right] e^{-m_\varphi r}$$

- CP violating coupling can induce non-zero EDMs.

Laboratory Tests



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- Shifts in quantum gravitational states of ultracold bouncing neutrons. (Abele et. al.)
- NMR frequency shifts when unpolarized mass is moved from and towards polarized gas. (Youdin et. al, Bulatowicz et. al., Petukhov et. al)
- Neutron diffraction (see talk by Ben Heacock)

Quantum Bouncing UltraCold Neutrons in a Gravitational Field

(Jenke, Stadler, Abele, Geltenbort)

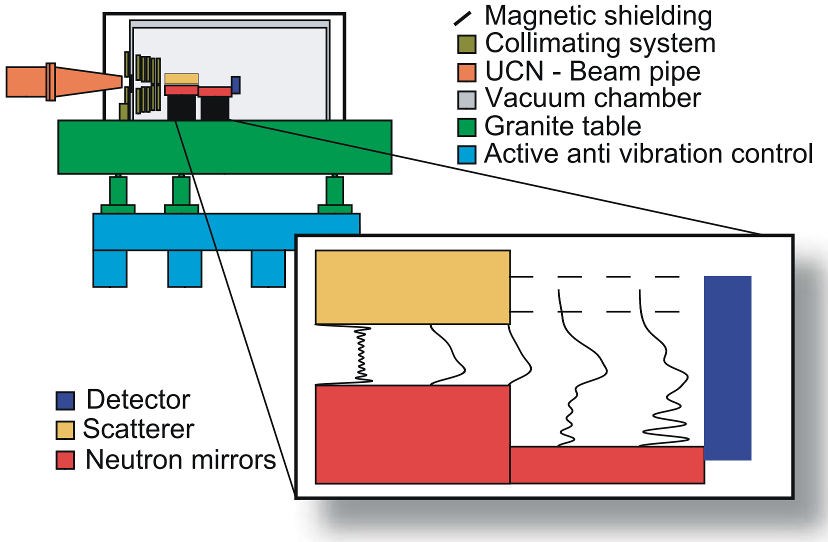


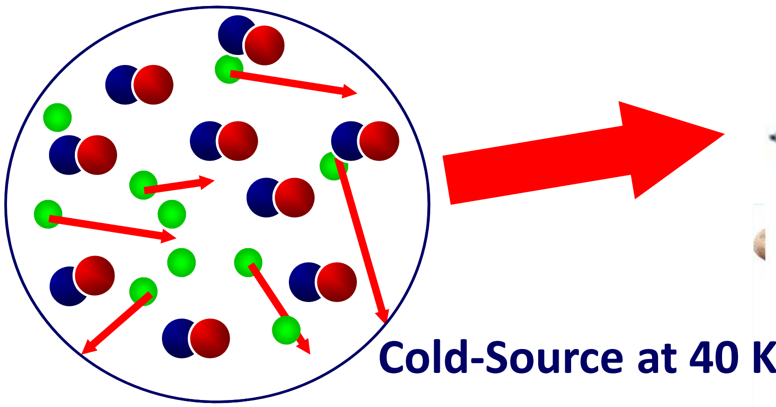
Fig. 1. Sketch of the setup used for the measurements at the ILL in 2008.

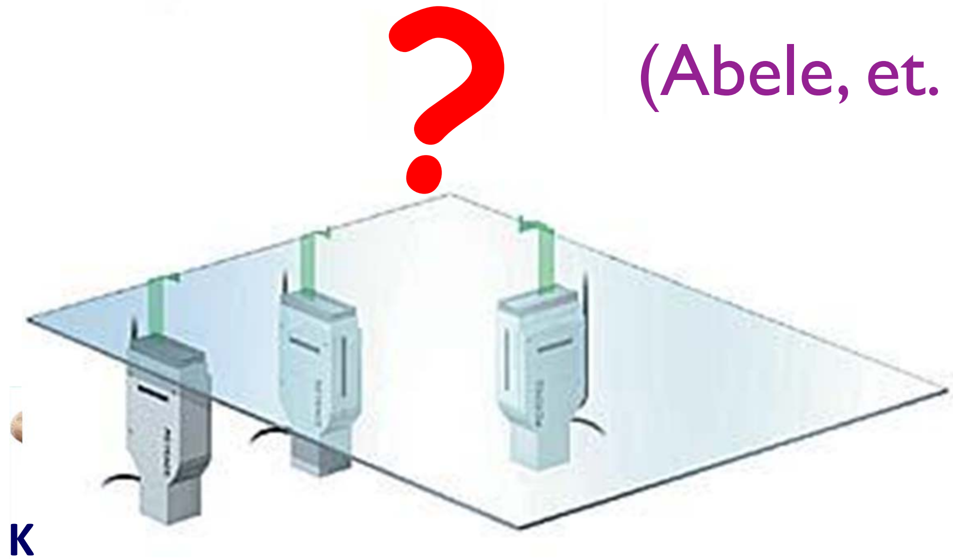
- Look for the effect of the monopole-dipole interaction on the flux of neutrons as a function of the height of the scatterer.

- Look for the effect of the monopole-dipole interaction on the neutron wave function in a gravitational field.

Quantum Bounce

(Abele, et. al.)





System Neutron & Earth

- Neutron bound in the gravity potential of the earth
- <r> = 6 μm
- Ground state energy of 1.4 peV
- 1 dim.
- Schrödinger Equ.
  - Airy Functions

Hydrogen Atom

- Electron bound in proton potential
- Bohr radius <r> = 1 A
- Ground state energy of 13 eV
- 3 dim.
- Schrödinger Equ.
  - Legrendre Polynomials

Neutron Q-bounce Experiment (Abele)

Schrödinger equation:

$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}+mgz\right)\varphi_n(z)=E_n\varphi_n(z)$$

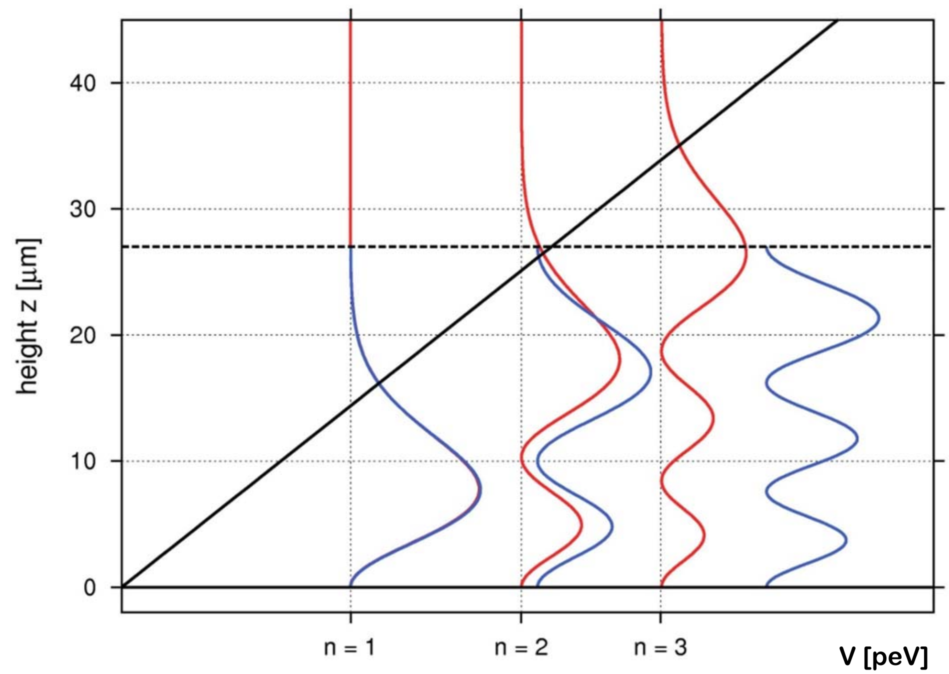
	E_n	E_n
1st state	1.41peV	1.41peV
2nd state	2.46peV	2.56peV
3rd state	3.32peV	3.97peV

boundary conditions:

$$\varphi_n(0)=0$$

with 2nd mirror at height l

$$\varphi_n(l)=0$$



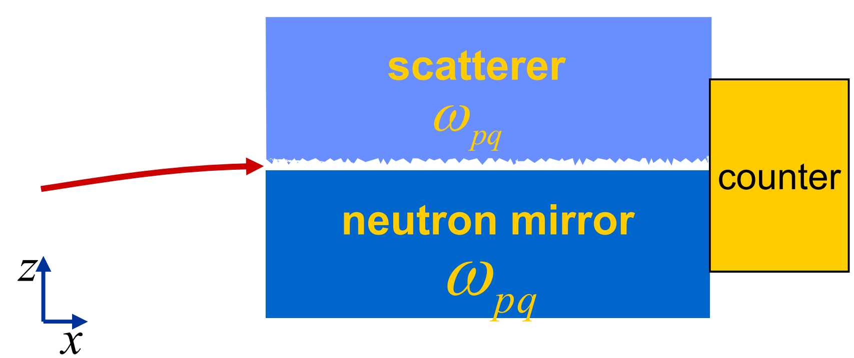
solutions: Airy-functions

scales:

energies: peV
length: μm

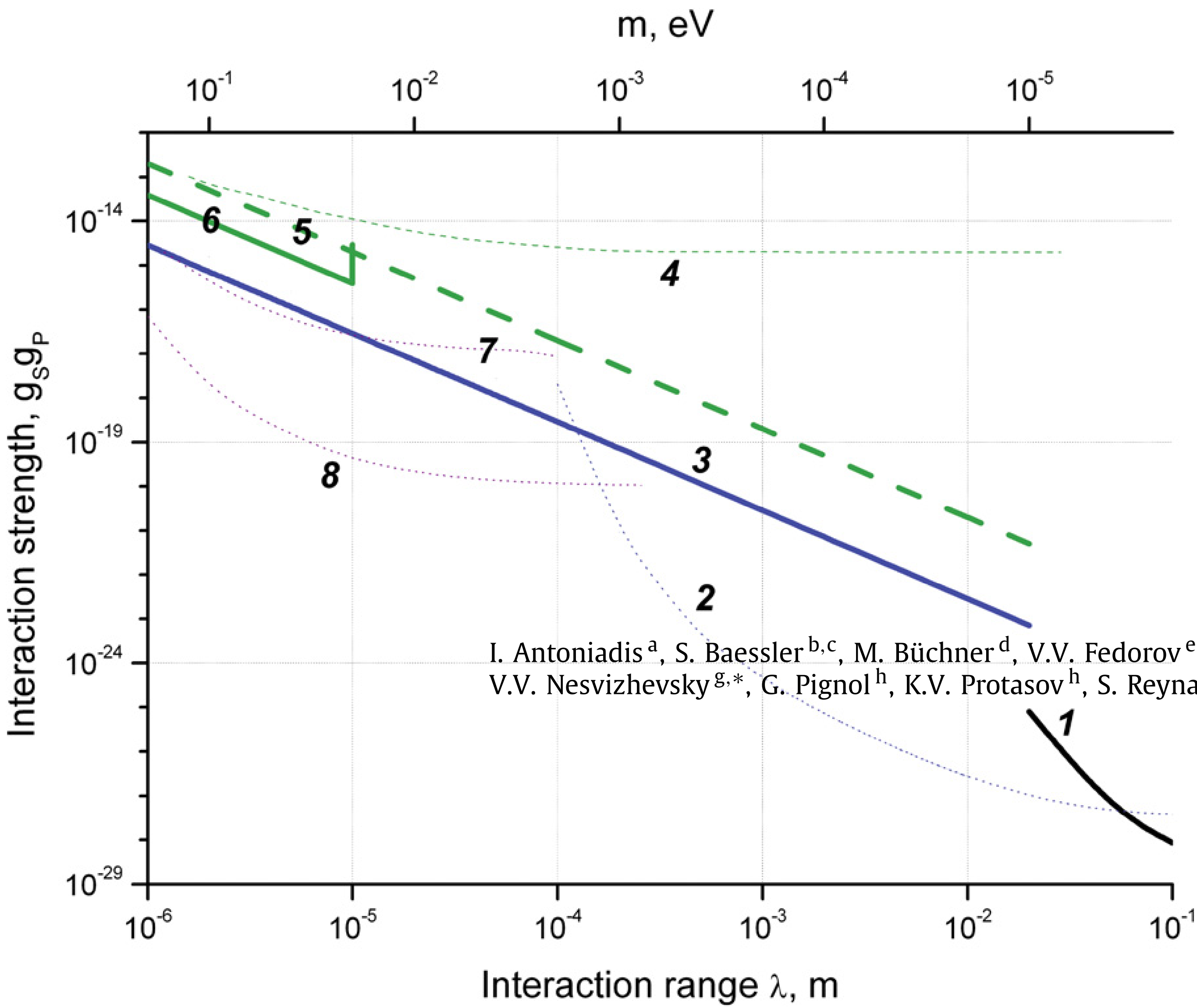
neutron mirror

Demonstration of Quantum States
in the Gravity Potential of the Earth
Nesvizhevsky, H.A. et al.
Nature 2002



Bounds on Spin-Dependent Fifth Forces

- Summary of bounds from various fifth-force experiments



I. Antoniadis [a], S. Baessler [b,c], M. Büchner [d], V.V. Fedorov [e], S. Hoedl [f], A. Lambrecht [i], V.V. Nesvizhevsky [g,*], G. Pignol [h], K.V. Protasov [h], S. Reynaud [i], Yu. Sobolev [j]

Laboratory and Astrophysical Constraints

Astrophysical Bounds and Gravitational Tests

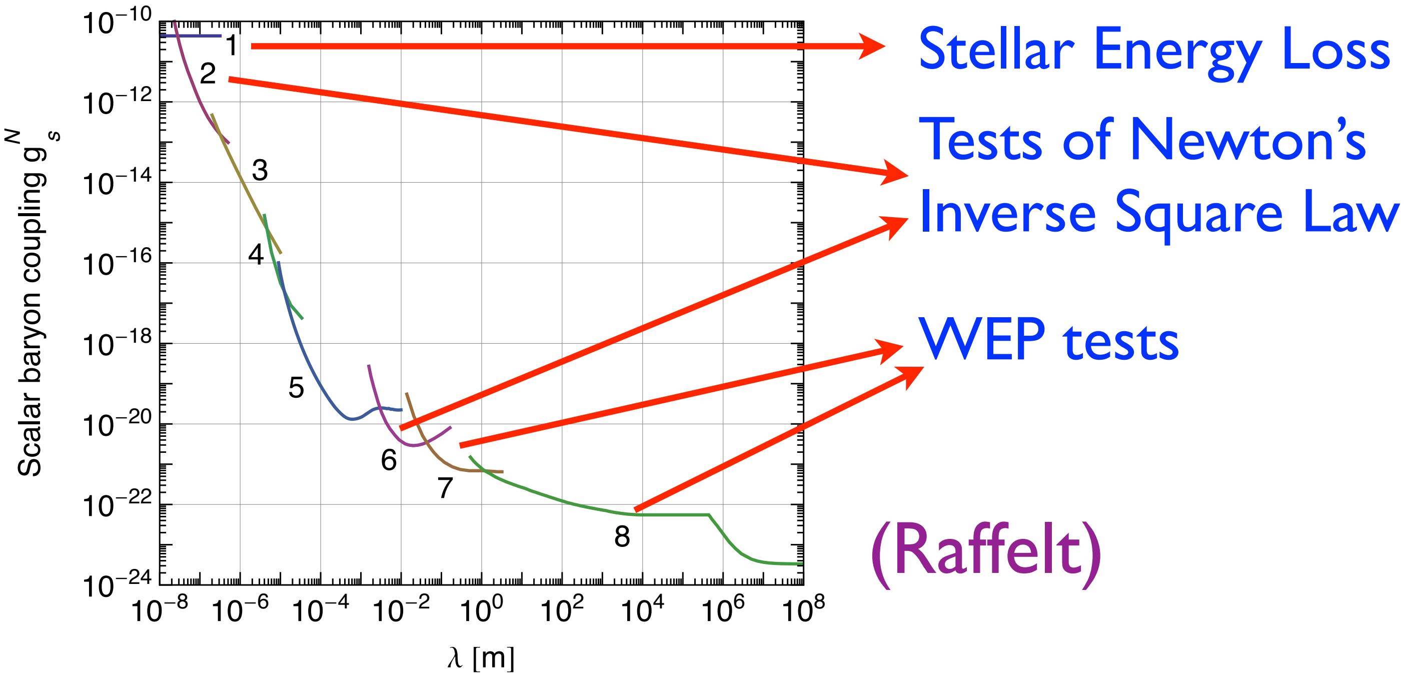
- Energy loss is stellar cooling constrains pseudoscalar coupling

$$N + N \to N + N + \phi$$

$$g_p^N \lesssim 3 \times 10^{-10} \, .$$

(Raffelt)

- Lab tests on Newton's inverse square law and WEP constrain the scalar coupling



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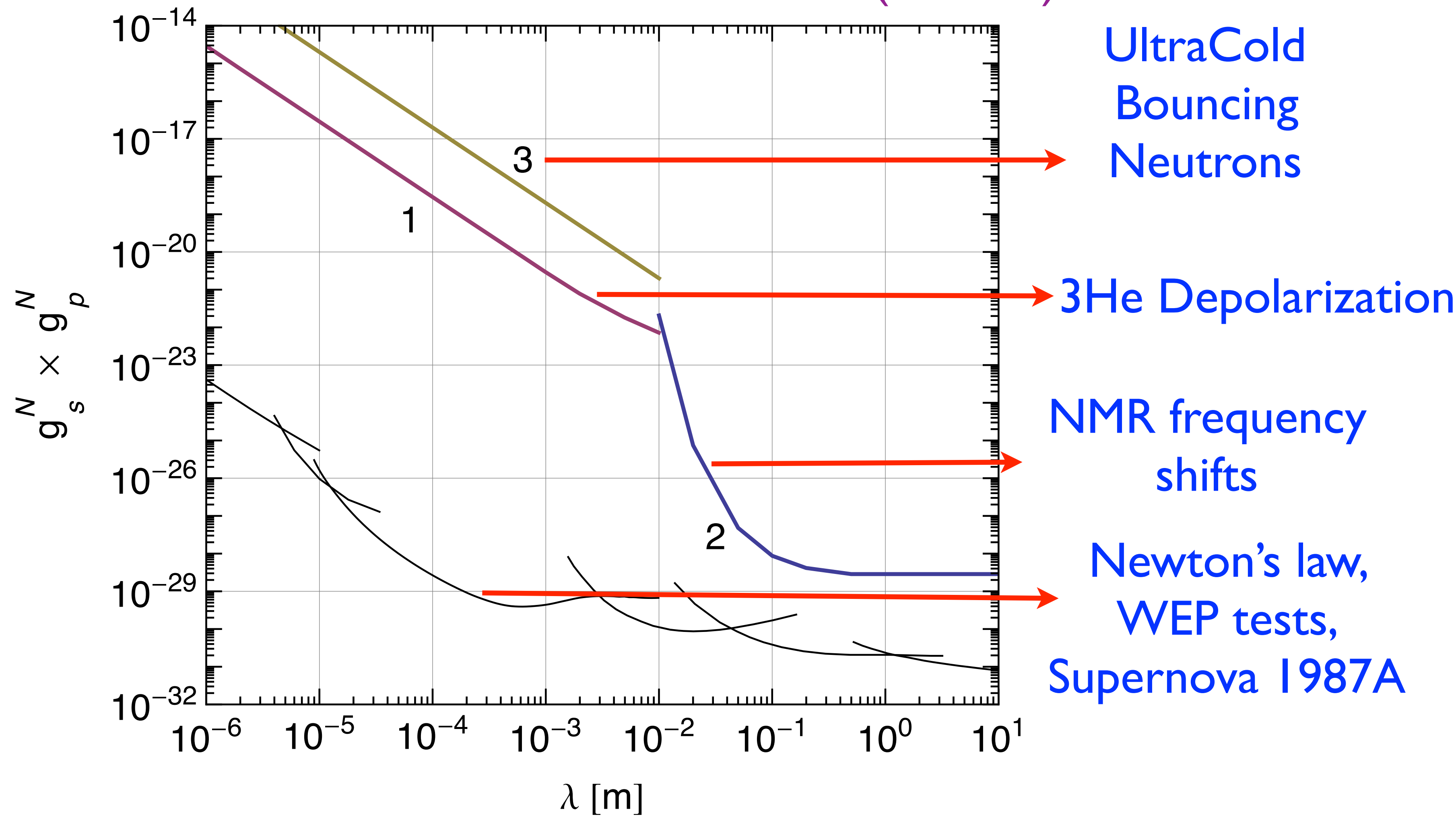
Laboratory and Astrophysical Bounds

(Raffelt)



- Note that combining separate tests of Newton's inverse square law/ WEP tests bonds on g_s^N and astrophysical constraints on g_p^N, currently gives stronger bounds than fifth-force experiments.

Electric Dipole Moments

EDMs

- Non-zero EDM arises from term of the form

$$\mathcal{L} \;=\; -d\frac{i}{2}\bar{\psi}\,\sigma^{\mu\nu}\gamma_5\,\psi\,F_{\mu\nu}$$

- In the non-relativistic limit, the EDM interaction with an external field is given by

$$H \;=\; -d\,\vec{E}\cdot\frac{\vec{S}}{S}$$

EDMs and CP Violation

- Interaction is T-odd:

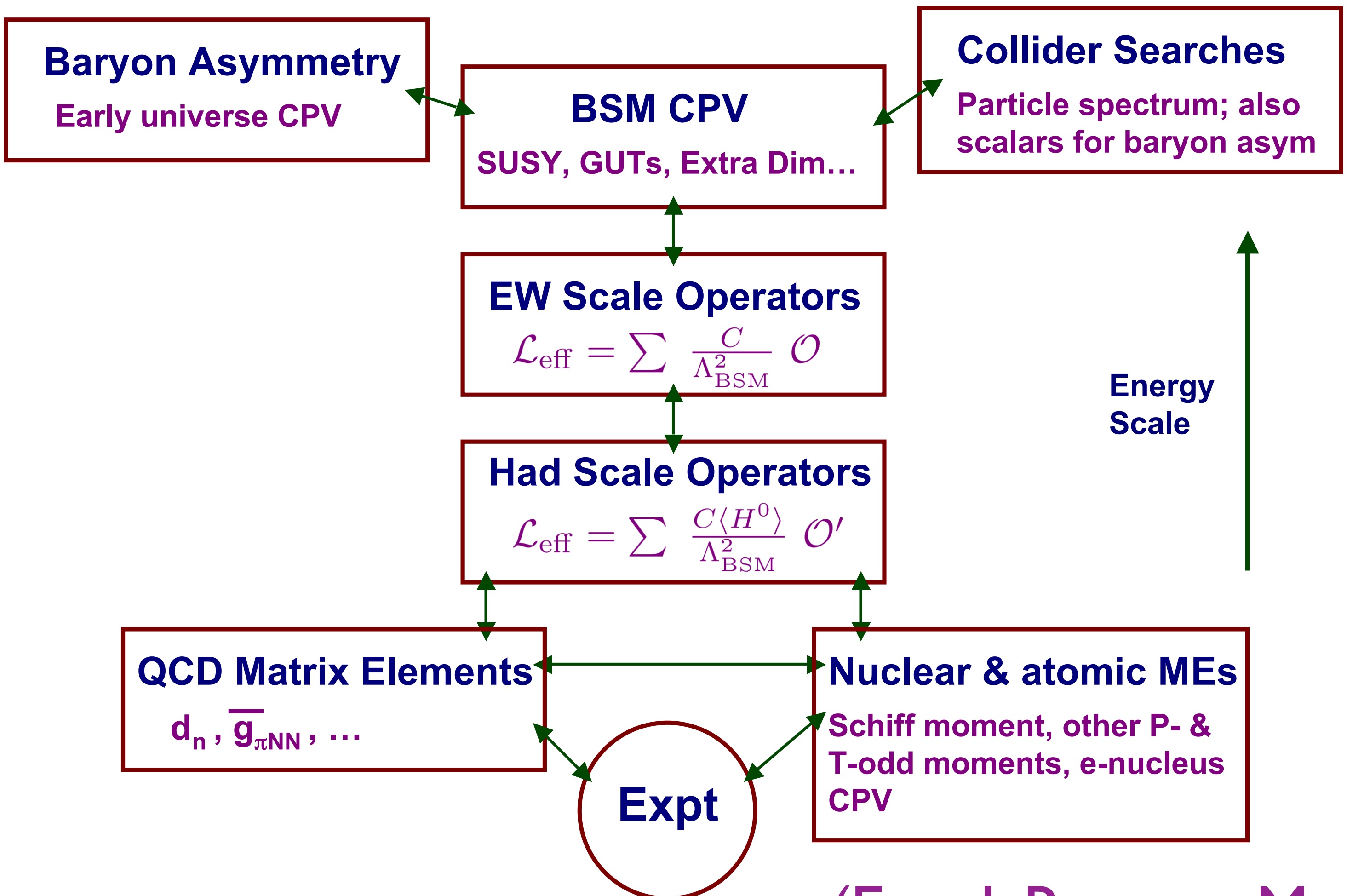
$$T(\vec{E}\cdot\vec{S}) = -\vec{E}\cdot\vec{S}$$

- By CPT theorem, a non-zero EDM implies CP violation.

- Any new sources of CP violation can contribute to EDMs.

- How can short range spin-dependent macroscopic forces contribute to EDMs?

The usual paradigm to connect BSM CP violation to EDMs



(Engel, Ramsey-Musolf, Van Kolck)

- Effective operators at hadronic scale. CP violation encoded in Wilson coefficients.

The usual paradigm to connect CP violation sources to EDMs

- For macroscopic short forces:

$$m_\varphi \ll \Lambda_{QCD}$$

- New physics corresponds to a new ultralight degree of freedom.

- Effective operator approach no longer applicable.

- EDM calculations need to incorporate the new light propagating degree of freedom in nuclear and atomic calculations.

EDM Sources in the SM

- Two sources of CP violation in the SM:

  - CKM phase

  - QCD θ-term

- CKM-generated EDM is too small for current experimental sensitivities

$$d_n \sim 10^{-31} \text{ e cm}$$

- Thus, a non-zero EDM would be interpreted in the SM as flavor diagonal strong CP violation

$$\mathcal{L}_{QCD}^{CPV} = \bar{\theta} \frac{\alpha_s}{16\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

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  - QCD θ-term

  → Effects not associated with a macroscopic force

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Connection of Strong CP with Axial U(1)

- U(1) axial rotations

$$\psi \to e^{-i\alpha\gamma_5}\psi, \qquad \bar{\psi} \to \bar{\psi}\, e^{-i\alpha\gamma_5}$$

$$\mathcal{D}\psi\mathcal{D}\bar{\psi} \to \mathcal{D}\psi\mathcal{D}\bar{\psi}\ \mathrm{Exp}\left[2i\alpha \int d^4x\ \frac{\alpha_s}{16\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\right]$$

- Axial U(1) symmetry is anomalous

$$j^5_\mu = \bar{\psi}\gamma_\mu\gamma_5\psi,$$

$$\partial^\mu j^5_\mu = 2im_q\bar{\psi}\gamma_5\psi + \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- For a massless quark, the net effect is a shift in the θ-parameter

$$\theta \to \theta + 2\alpha.$$

Connection with Axial U(1)

- In presence of a massless quark, strong CP violation can be rotated away.

- In the absence of a massless quark, strong CP violation can be rotated into the quark mass terms

$$\mathcal{L}_{QCD}^{CPV} = \bar{\theta}\frac{\alpha_s}{16\pi}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\downarrow$$

$$\mathcal{L}_{CPV} = i\bar{\theta}\frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}\left[\bar{u}\gamma_5 u + \bar{d}\gamma_5 d + \bar{s}\gamma_5 s\right]$$

- EDMs can then be generated through matrix elements of the CP violating quark mass terms.

Non-observation of flavor diagonal CP violation is the strong CP problem

Axions

An illustrative model: KSVZ Model

- SM + massless colored quark + complex scalar

$$\delta\mathcal{L} \;=\; \partial_\mu \Phi^\dagger \partial^\mu \Phi + \mu_\Phi^2 \Phi^\dagger \Phi - \lambda_\Phi (\Phi^\dagger \Phi)^2 + \bar{\psi} i \partial\!\!\!/ \psi + y\, \bar{\psi}_R \Phi \psi_L + h.c.$$

- U(1) Peccei-Quinn symmetry can be used to rotate away theta term

$$\psi \to e^{-i\alpha\gamma_5}\, \psi, \qquad \bar{\psi} \to \bar{\psi}\, e^{-i\alpha\gamma_5}, \qquad \Phi \to e^{-2i\alpha}\, \Phi$$

- Spontaneous symmetry breaking of Peccei-Quinn symmetry

$$\langle \Phi \rangle = f_a, \qquad \Phi(x) \;=\; \frac{f_a + \rho(x)}{\sqrt{2}}\, e^{i\mathrm{a}(x)/f_a}$$

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Axion

An illustrative model: KSVZ Model

- PQ symmetry breaking is typically constrained to be

$$10^9 \lesssim f_a \lesssim 10^{12} \text{ GeV} \qquad\qquad m_\psi \sim f_a$$

- Integrate out heavy degrees of freedom. Construct low energy EFT: SM + Axion. Note in full theory U(1) PQ causes the shifts:

$$\bar{\theta} \to \bar{\theta} + 2\alpha, \qquad \frac{\mathrm{a}(x)}{f_a} \to \frac{\mathrm{a}(x)}{f_a} - 2\alpha.$$

$$\boxed{\bar{\theta} + \frac{\mathrm{a}(x)}{f_a}}$$

→ Invariant combination

- Effective Axion Lagrangian:

$$\mathcal{L}_a = \frac{\alpha_s}{16\pi}\left(\bar{\theta} + \frac{\mathrm{a}}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - m_q \bar{q} q$$

Low Effective Lagrangian for Axion

- Axial U(1) transformation can move all CP violation into the quark mass terms:

$$\mathcal{L}_a = \frac{\alpha_s}{16\pi}\left(\bar{\theta} + \frac{\mathrm{a}}{f_a}\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - m_q \bar{q} q$$

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$\Big\downarrow$ Axial U(1) rotation

$$\mathcal{L}_a = -\cos\left(\bar{\theta} + \frac{\mathrm{a}}{f_a}\right) m_q \bar{q} q + m_q \sin\left(\bar{\theta} + \frac{\mathrm{a}}{f_a}\right) \bar{q} i \gamma^5 q$$

- Axion couplings to the quarks is now manifest.

Low Effective Lagrangian for Axion

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- Axion couplings to the quarks is now manifest.
- Quark condensate generates an axion potential:

$$\mathrm{a}(x) = \langle \mathrm{a} \rangle + a(x) \longrightarrow \theta_{\text{eff}} = \bar{\theta} + \frac{\langle \mathrm{a} \rangle}{f_a}$$

Axion Potential

- Axion potential is generated via the quark condensate

$$V\left(\theta_{\rm eff}+\frac{a}{f_a}\right) \;=\; -\chi(0)\cos\left(\theta_{\rm eff}+\frac{a}{f_a}\right) \quad , \qquad \chi(0) \;=\; -m_q\langle\bar{q}q\rangle$$

- The ground state potential can be expanded as

$$V(\theta_{\rm eff}) \;\simeq\; \frac{1}{2}\,\chi(0)\,\theta_{\rm eff}^2$$

- Minimum of the potential at:

$$\theta_{\rm eff} \;=\; 0$$

Dynamical relaxation of ground state Axion potential solves the strong CP problem

Higher dimension CP odd operators

- The presence of higher dimensional CP-odd operators can generate linear terms in the potential

$$V(\theta_{\rm eff}) \simeq \chi_{\rm CP}(0)\,\theta_{\rm eff} + \frac{\chi(0)}{2}\,\theta_{\rm eff}^2$$

- The coefficient of the linear term can arise from the correlator of the CP-odd higher dimension operator

$$\chi_{\rm CP}(0) = -i\,\lim_{k\to 0} \int d^4x\, e^{ik\cdot x} \langle 0|T(G\tilde{G}(x), \mathcal{O}_{\rm CP}(0))|0\rangle$$

- The minimum is shifted to a non-zero value

$$\theta_{\rm eff} = -\frac{\chi_{\rm CP}(0)}{\chi(0)}$$

→ Non-zero EDM

Axion Couplings

- Expanding the Axion Lagrangian gives

$$\mathcal{L}_a = \left(\frac{\theta_{\rm eff}}{f_a} a - 1\right) m_q\, \bar{q}q + \left(\theta_{\rm eff} + \frac{a}{f_a}\right) m_q\, \bar{q} i \gamma^5 q + \frac{m_q}{2 f_a^2}\, a^2\, \bar{q}q + \cdots$$

$$g^q_{a,s} = \frac{\theta_{\rm ind.} m_q}{f_a},$$

Scalar coupling

$$g^q_{a,p} = \frac{m_q}{f_a},$$

Pseudo-scalar coupling

$$m_a \simeq \frac{1}{f_a} |\chi(0)|^{1/2}$$

Axion mass

- Product of couplings proportional to theta parameter:

$$g^q_s g^q_p \propto \theta_{\rm eff} \frac{m_q^2}{f_a^2}$$

Axion Couplings

CP-odd quark mass generates EDM

- Expanding the Axion Lagrangian gives

$$\mathcal{L}_a = \left(\frac{\theta_{\rm eff}}{f_a} a - 1\right) m_q\, \bar{q}q + \left(\theta_{\rm eff} + \frac{a}{f_a}\right) m_q\, \bar{q} i\gamma^5 q + \frac{m_q}{2f_a^2}\, a^2\, \bar{q}q + \cdots$$

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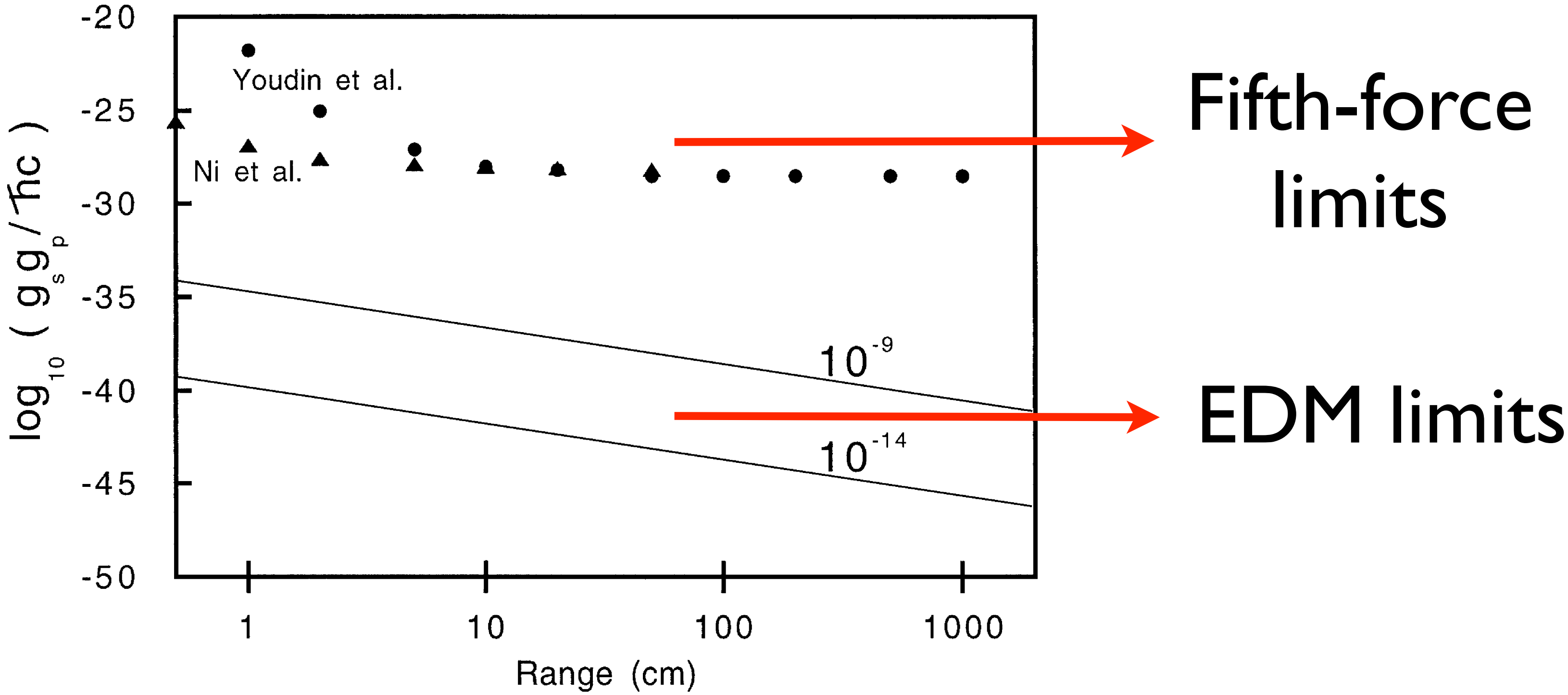
EDM Limits Dominate over Fifth Force Bounds



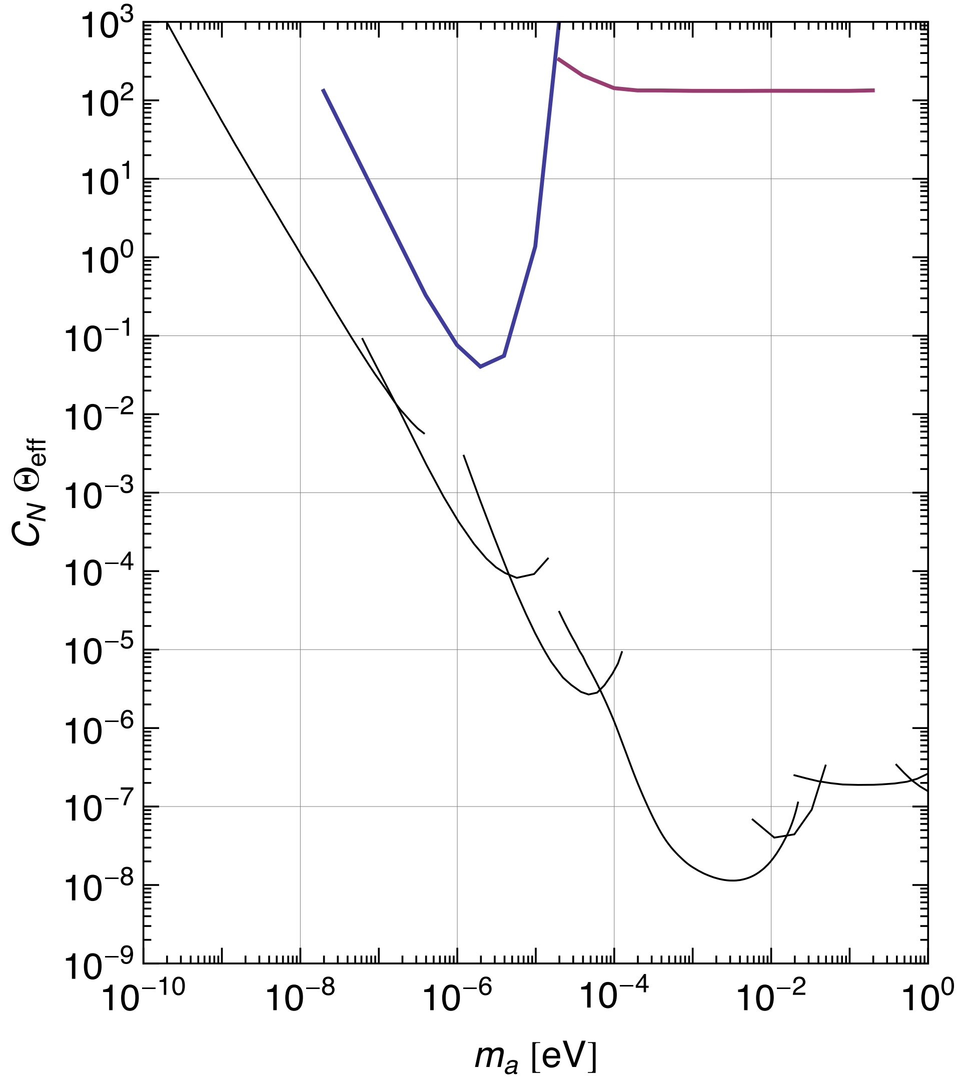
(Rosenberg, Bibber)

$$g_s g_p \simeq \frac{\bar{\theta}}{\lambda(\mathrm{mm})^2} 6 \times 10^{-27}$$

EDM limit

$$|\,\bar{\theta}\,| \lesssim 10^{-10}$$

Convert Laboratory and Astrophysical bounds as constraints on the Strong CP parameter



(Raffelt)

EDM limit

$$|\bar{\theta}| \lesssim 10^{-10}$$

- EDM Limits on Strong CP parameter still dominate.

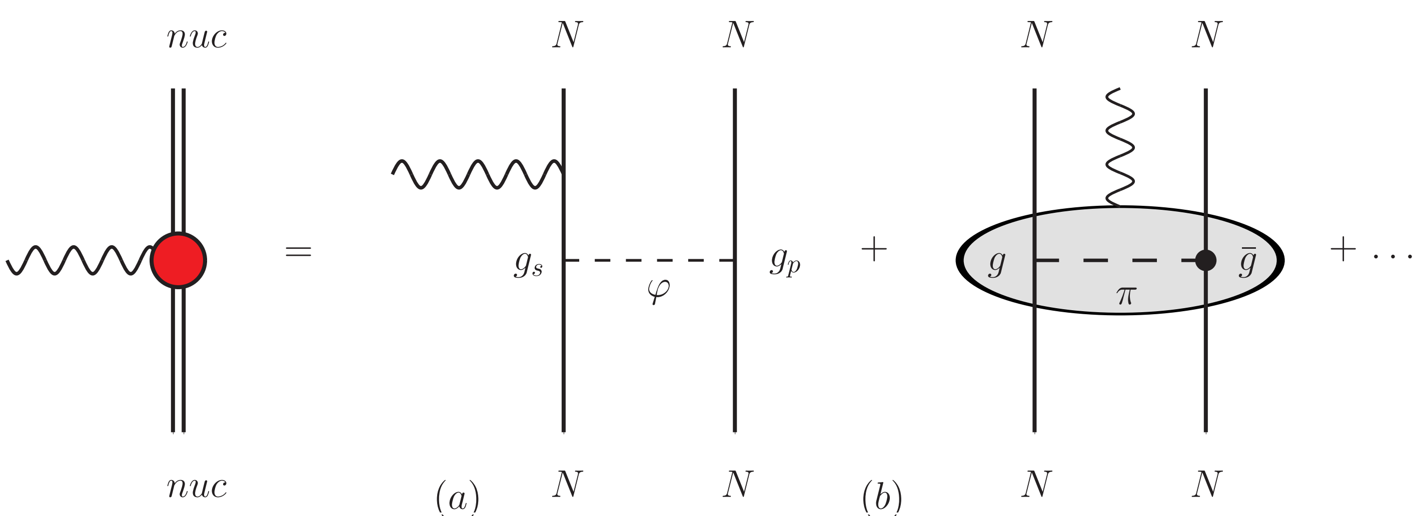
Generic Scalars (non-axions)

Arbitrary Couplings

- Nucleon level couplings:

$$\mathcal{L}_{\varphi NN} = g_s\, \varphi \bar{N} N + g_p\, \varphi \bar{N} i\gamma_5 N.$$

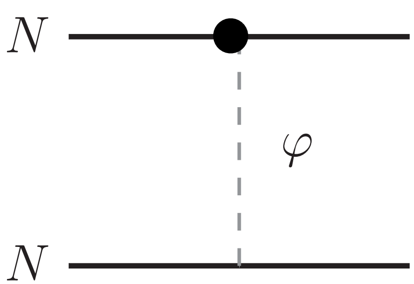
- EDMs induced by dynamical exchanges of light scalar. This is a different mechanism than the CP-odd quark mass terms in the case of axions.



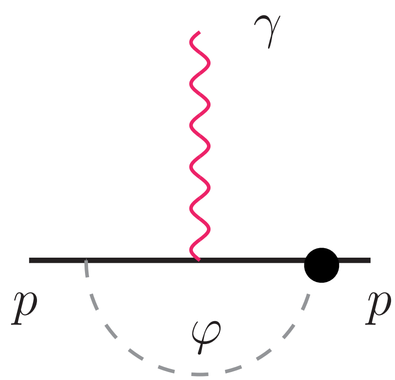
- Full EDM calculation must incorporate this propagating light scalar. Effective operator approach no longer applicable.

Estimate of Contribution to EDMs

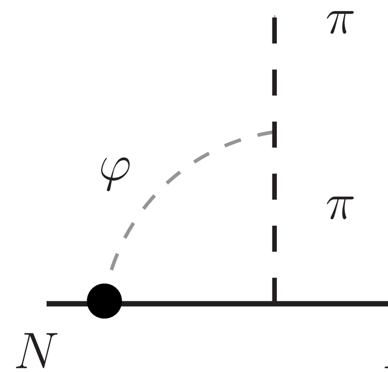
- Some example nucleon level diagrams that can contribute to the EDM:



Direct exchange



Proton EDM



Correction to pion nucleon coupling

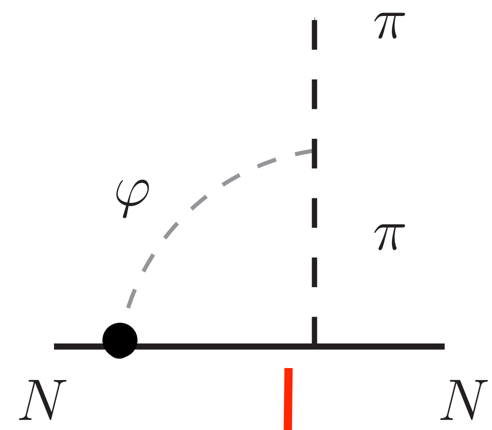
Estimate of Contribution to EDMs

(SM, Ramsey-Musolf, Pitschmann)

- An example nucleon level diagram that can contribute to the EDM:

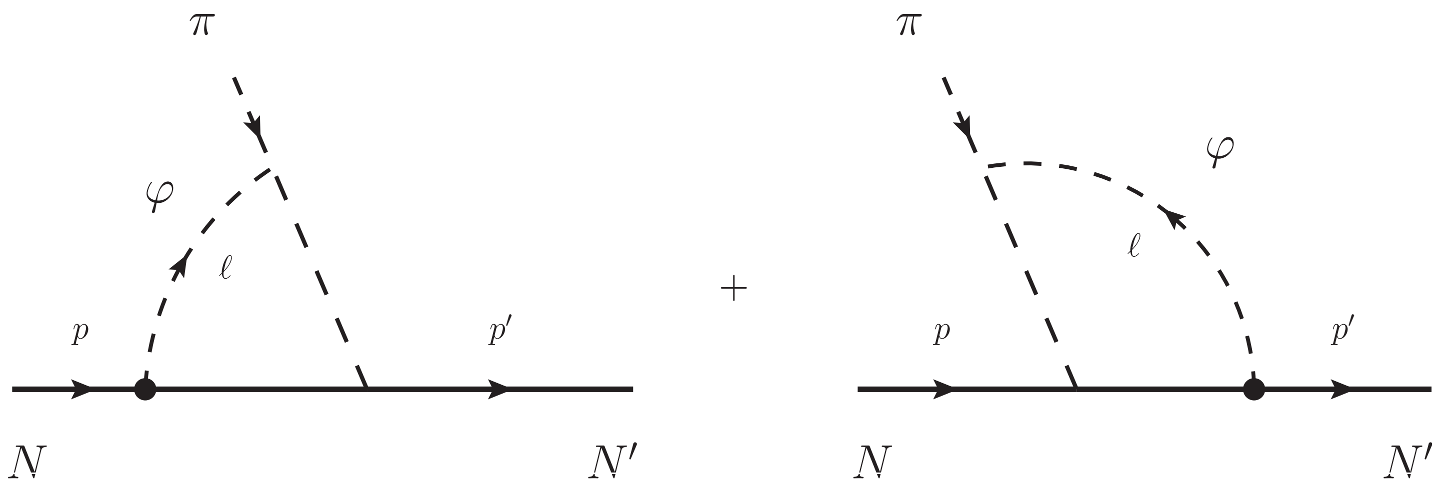
  - Treat as a shift to pion-nucleon coupling

  - Incorporate into existing results for the Schiff moment of the Mercury EDM



Correction to pion nucleon coupling

- Compute one loop diagrams using Heavy Baryon Chiral Perturbation theory (HBChPT)



$$\mathcal{L}_{\pi\bar{N}N} = \frac{2g_A}{f_\pi}\,\partial_\mu\pi^a\,\bar{N}_v\,\frac{\sigma^a}{2}S^\mu N_v,$$

$$\mathcal{L}_{\varphi\pi\pi} = g_s^\pi\,\varphi\,\pi^a\pi^a,$$

$$\mathcal{L}_{\varphi\bar{N}N} = -\frac{g_p}{m_N}\,\bar{N}_v\,(S^\mu\partial_\mu\varphi)\,N_v,$$

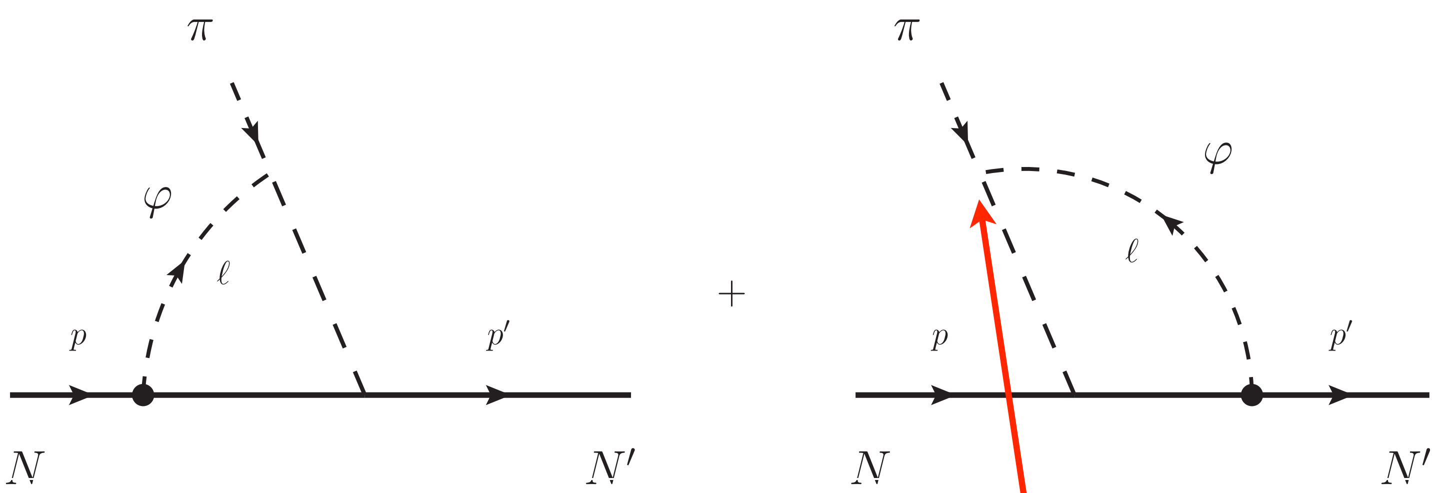
$$g_s^\pi = \frac{\langle\pi|\bar{u}u+\bar{d}d|\pi\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle}\,g_s$$

$$\frac{g_s^\pi}{g_s} \simeq \frac{m_\pi^2}{90\text{ MeV}} \simeq 218\text{ MeV}.$$

Vertices in HBChPT

Coupling to Pion

- Coupling to pion is related to scalar nucleon coupling:



$$\mathcal{L}_{\pi\bar{N}N} = \frac{2g_A}{f_\pi}\,\partial_\mu\pi^a\;\bar{N}_v\,\frac{\sigma^a}{2}S^\mu N_v,$$

$$\mathcal{L}_{\varphi\pi\pi} = g_s^\pi\;\varphi\;\pi^a\pi^a,$$

$$\mathcal{L}_{\varphi\bar{N}N} = -\frac{g_p}{m_N}\;\bar{N}_v\left(S^\mu\partial_\mu\varphi\right)N_v,$$

$$g_s^\pi = \frac{\langle\pi|\bar{u}u+\bar{d}d|\pi\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle}\,g_s$$

$$\frac{g_s^\pi}{g_s} \simeq \frac{m_\pi^2}{90\text{ MeV}} \simeq 218\text{ MeV}.$$

Vertices in HBChPT

Coupling to Pion

Shift in the Mercury EDM

- Shift in the Schiff moment will cause a shift in the EDM

$$\delta d_{Hg} = -2.8 \times 10^{-4} \, \frac{\delta S_{Hg}}{\text{fm}^2}$$ (Griffith;de Jesus, Engel)

- Shift in the Schiff moment arises from one-loop pion-nucleon couplings

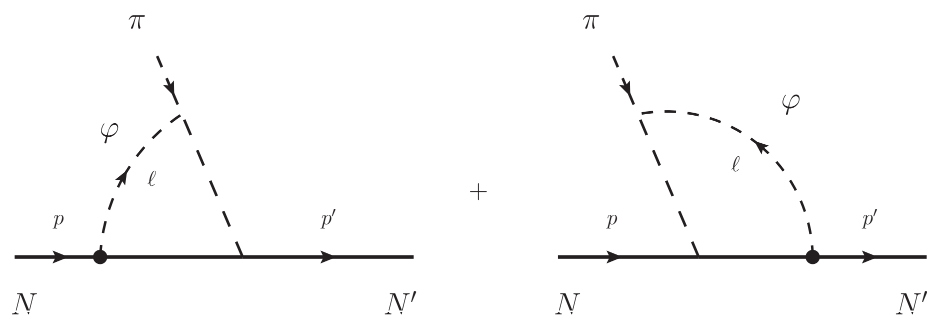
$$\delta S_{Hg} \;=\; g_{\pi NN} \left[\, 0.01 \, \delta \bar{g}^{(0)}_{\pi NN} + 0.07 \, \delta \bar{g}^{(1)}_{\pi NN} + 0.02 \, \delta \bar{g}^{(2)}_{\pi NN} \,\right] e \ \text{fm}^3$$

- Shift in CP-odd pion-nucleon couplings

$$\delta \bar{g}^{(0)}_{\pi NN} \simeq \frac{1}{16\pi} \frac{m_\pi^2 + m_\pi m_\varphi + m_\varphi^2}{m_\pi + m_\varphi} \frac{g_A m_\pi^2}{90 \text{ MeV} m_N f_\pi} g_s g_p$$

$$\delta \bar{g}^{(1)}_{\pi NN} = 0,$$

$$\delta \bar{g}^{(2)}_{\pi NN} = 0$$



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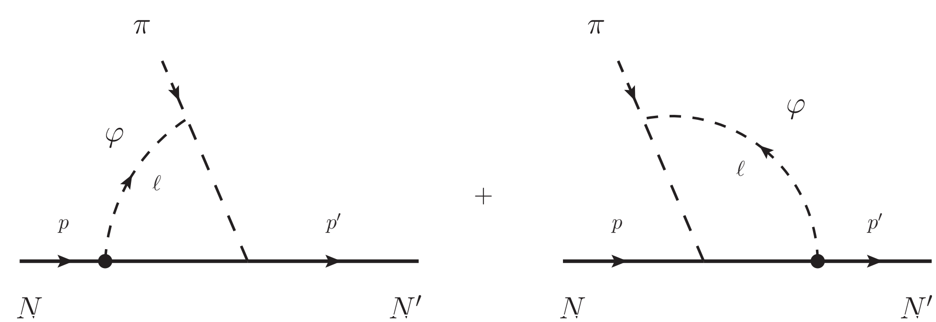
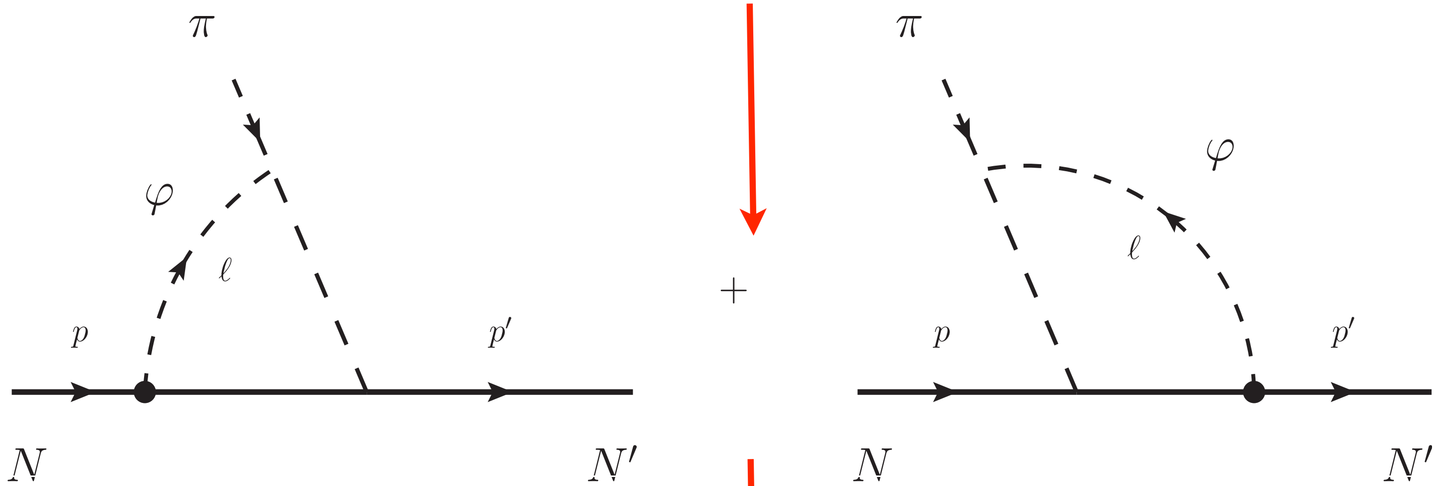


EDM Bound on Macroscopic Spin-Dependent Force

$$|d_{Hg}| \; < \; 3.1 \times 10^{-16} \text{ e fm}$$



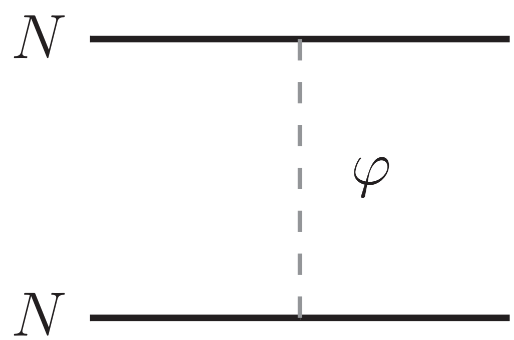
$$|g_s g_p| \lesssim 10^{-9}$$

Order of Magnitude Estimate on EDM Constraint

- Bound from the one-loop correction:

$$|g_s g_p| \lesssim 10^{-9}$$

- The tree level diagram can enhance the effect by two orders of magnitude.



- In the absence of a rigorous calculation, a first estimate is

$$g_s g_p \lesssim [10^{-11}, 10^{-9}].$$

Comparison with Fifth Force limits

- EDM limit:

$$g_s g_p \lesssim [10^{-11}, 10^{-9}].$$

- Summary of limits

Interaction range λ [m]	Fifth Force	EDM Generic Scalar	EDM Axion	Combined Laboratory & Astrophysics
$\sim 2 \times 10^{-5}$	$\sim 10^{-16}$	$\sim 10^{-9} - 10^{-11}$	$\sim 10^{-40} - 10^{-34}$	$\sim 10^{-27}$
$\sim 2 \times 10^{-1}$	$\sim 10^{-29}$	$\sim 10^{-9} - 10^{-11}$	$\sim 10^{-40} - 10^{-34}$	$\sim 10^{-30} - 10^{-34}$

↓ Generic ↓ Axion

- EDM limits appear to be the strongest for the axion while being the weakest for a generic (non-axion) scalar.

Conclusions

- Observations in fifth-force experiments, astrophysics, and EDM experiments can be combined to constrain the nature of axion-like particles.

- EDM limits dominate for Axion mediated forces.

- Laboratory fifth-force limits dominate EDM limits for non-axion generic scalars, for the range of force it probes. But EDM limits will still be relevant, if the range of the force is too small compared to the sensitivity of the fifth-force experiment.

- Astrophysical/gravity limits dominate for non-axion generic scalars.