EDMs as Probes of Macroscopic Spin-Dependent Forces

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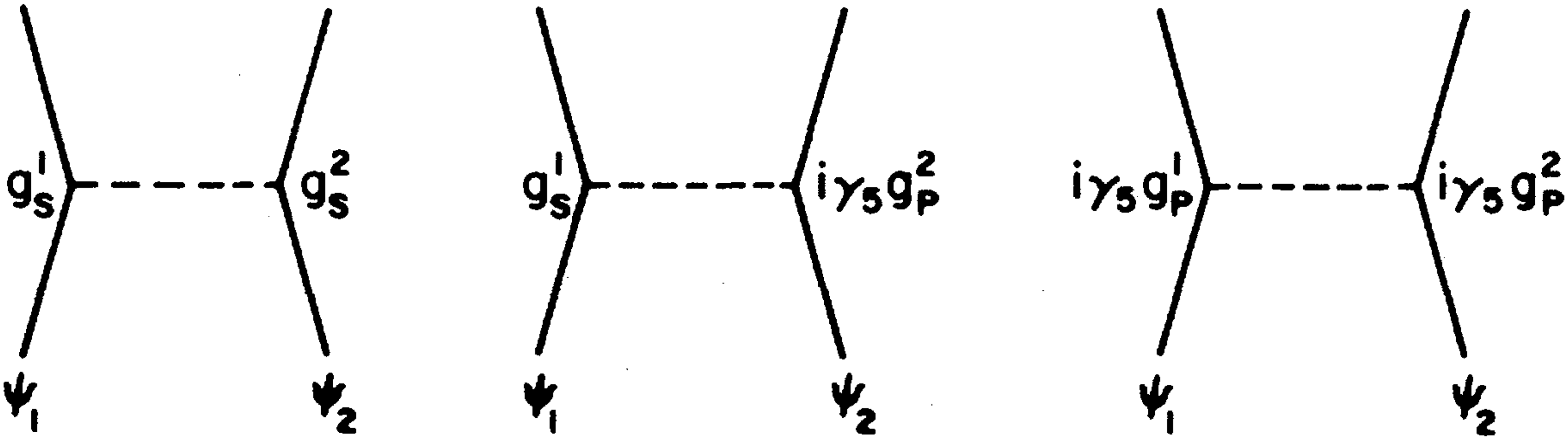
Outline

- Short range spin-dependent forces.
- EDMs in the SM.
- Axions: EDMs and short range forces
- Generic scalars: EDMs and short range forces
- Conclusion

Short Range Macroscopic Scalar Forces

(Moody, Wilczek)



Monopole-Monopole   Monopole-Dipole   Dipole-Dipole

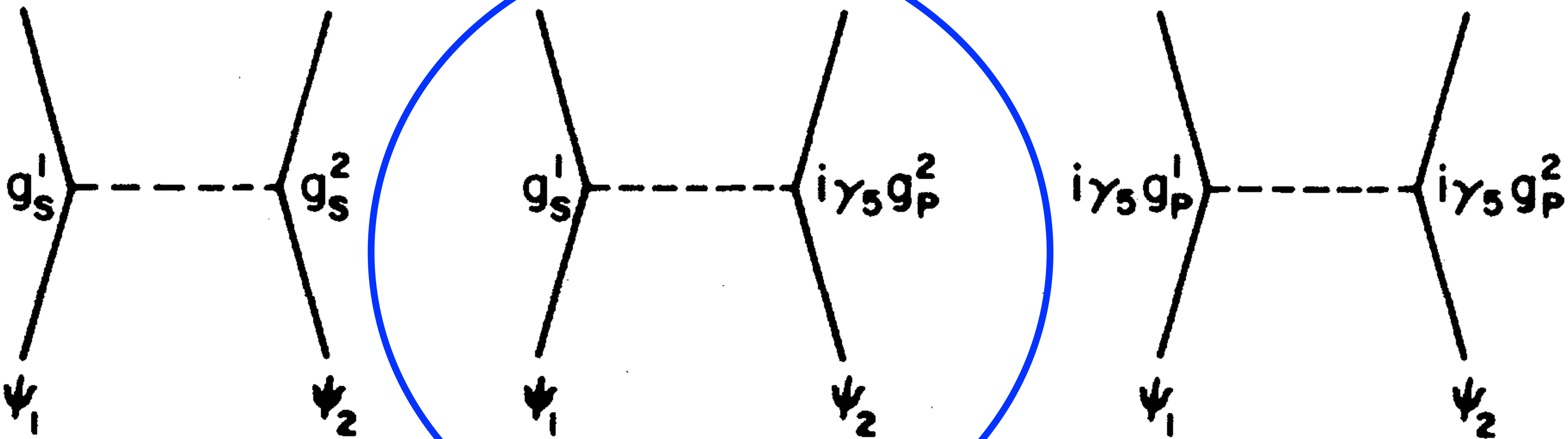
- New short range macroscopic forces beyond the SM?

$$m_\varphi \lesssim 10^{-2}\ \mathrm{eV} \longrightarrow \lambda \gtrsim 2\times 10^{-5}\ \mathrm{m}$$
$$m_\varphi \gtrsim 10^{-6}\ \mathrm{eV} \longrightarrow \lambda \lesssim 2\times 10^{-1}\ \mathrm{m}$$

- How can we search for such forces?
- Can they be correlated with CP violation and EDM constraints?

Short Range Macroscopic Scalar Forces

(Moody, Wilczek)



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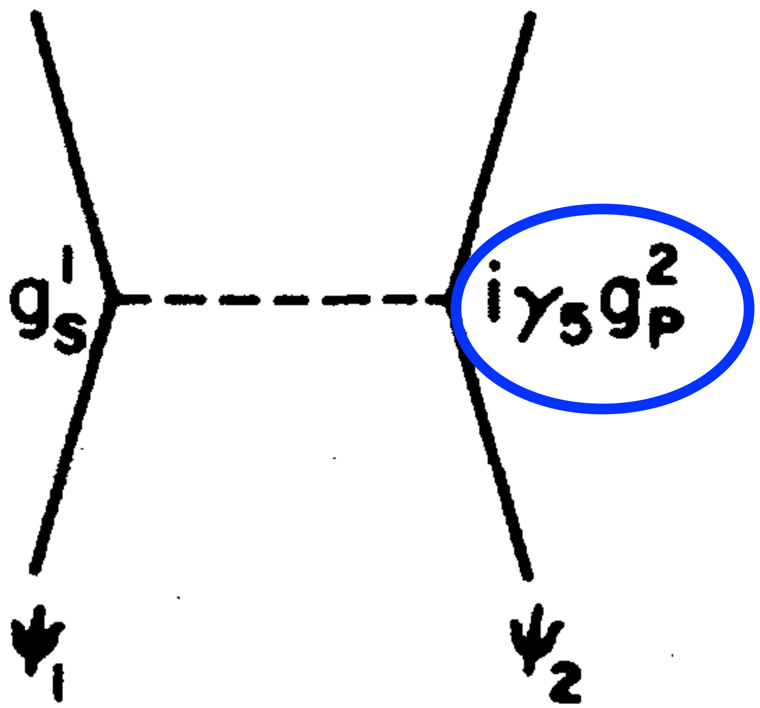
Spin-Dependent Macroscopic Scalar Forces

(Moody, Wilczek)



Monopole-Dipole

→ CP violating coupling

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

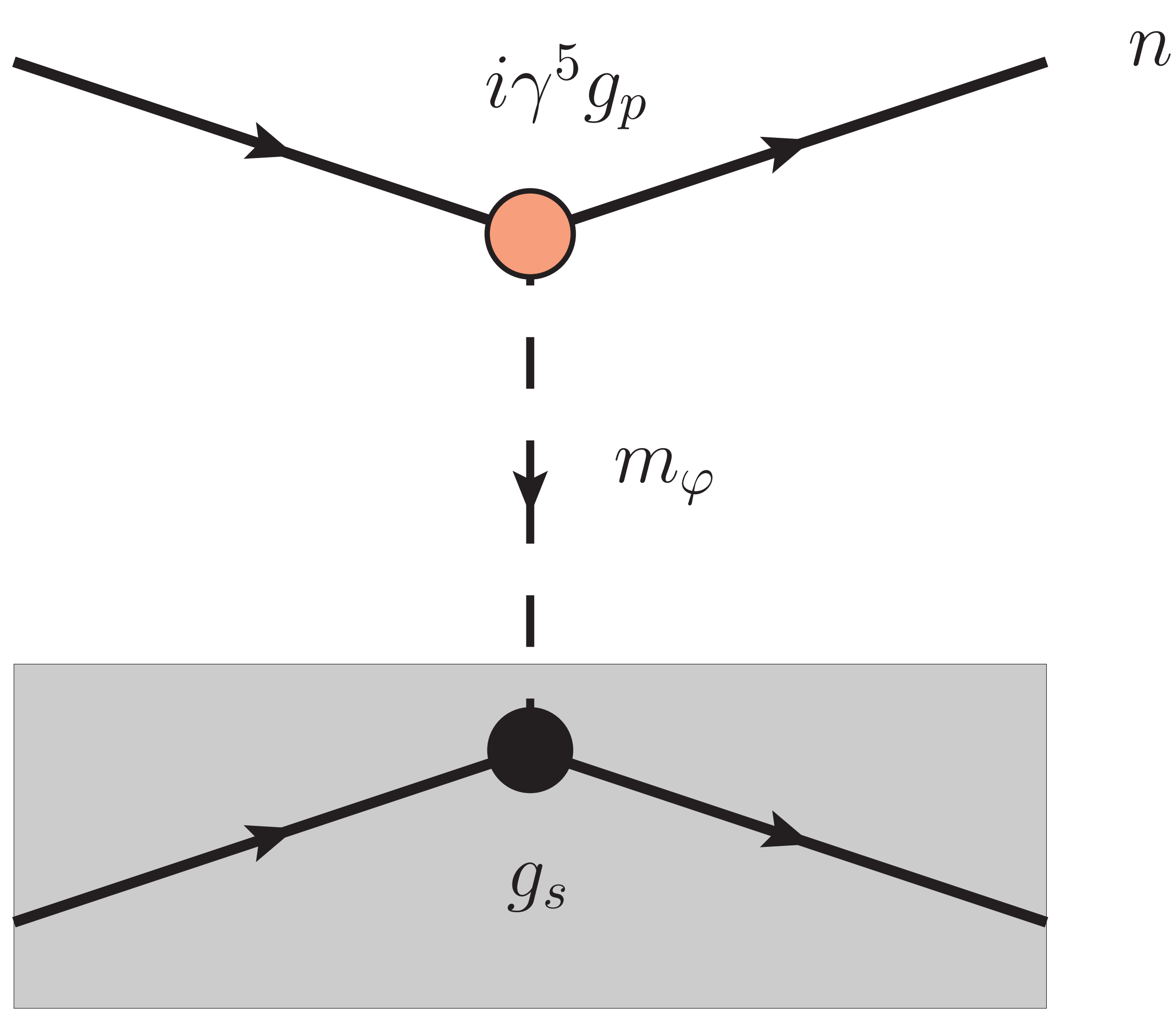
$$V(r) = g_s^1 g_p^2 \frac{\vec{\sigma}_2 \cdot \hat{r}}{8\pi M_2} \left[\frac{m_\varphi}{r} + \frac{1}{r^2}\right] e^{-m_\varphi r}$$

- CP violating coupling can induce non-zero EDMs.

- Fifth-force and EDM experiments can then be complementary probes of such phenomena.

Fifth-Force Experiments

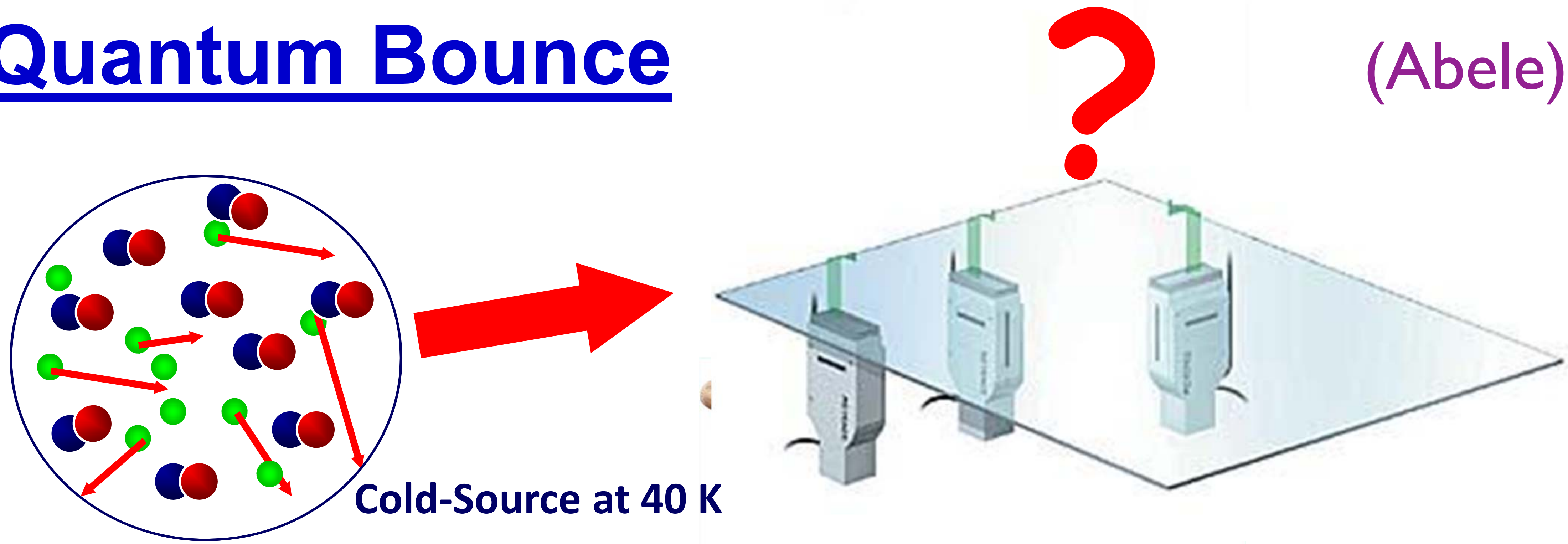
Neutron Q-bounce Experiment



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

Quantum Bounce

(Abele)



- **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:

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

boundary conditions:

$$\varphi_n(0)=0$$

with 2nd mirror at height l

$$\varphi_n(l)=0$$

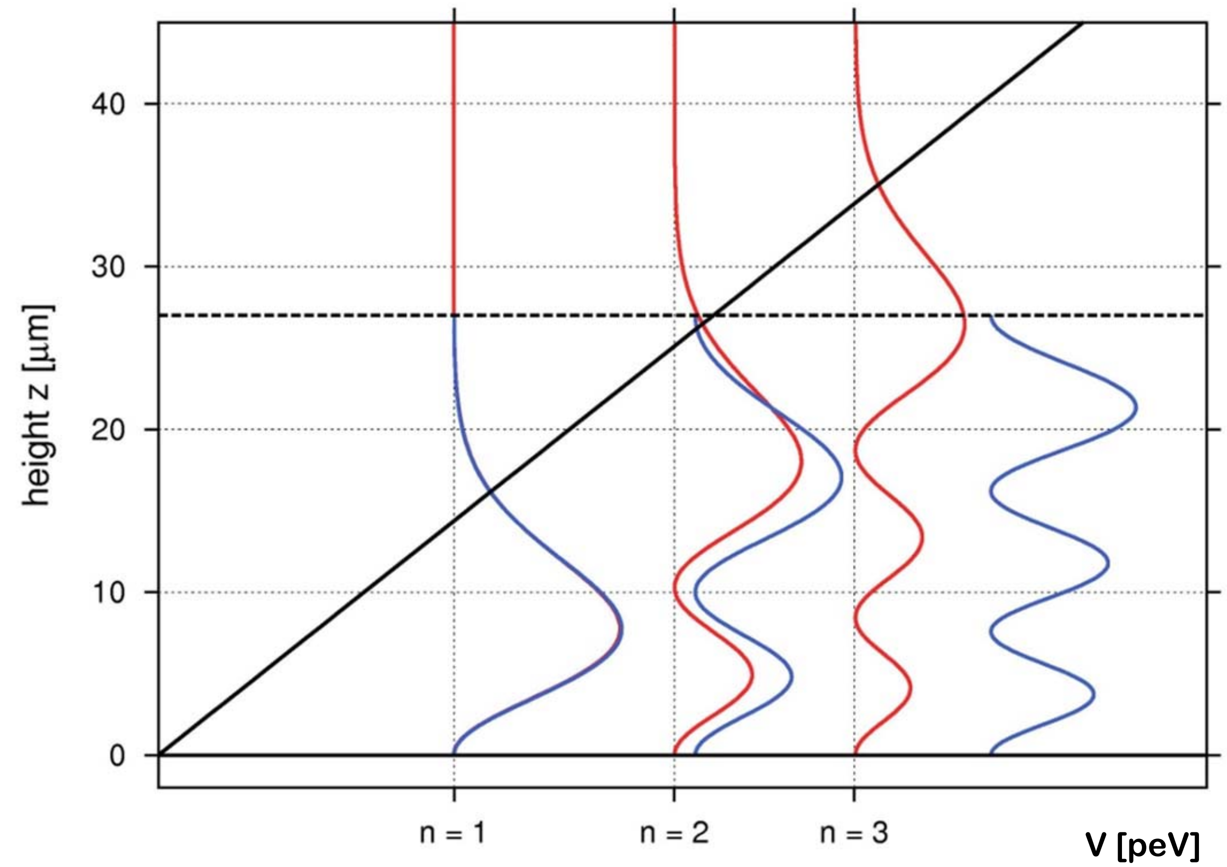
solutions: Airy-functions

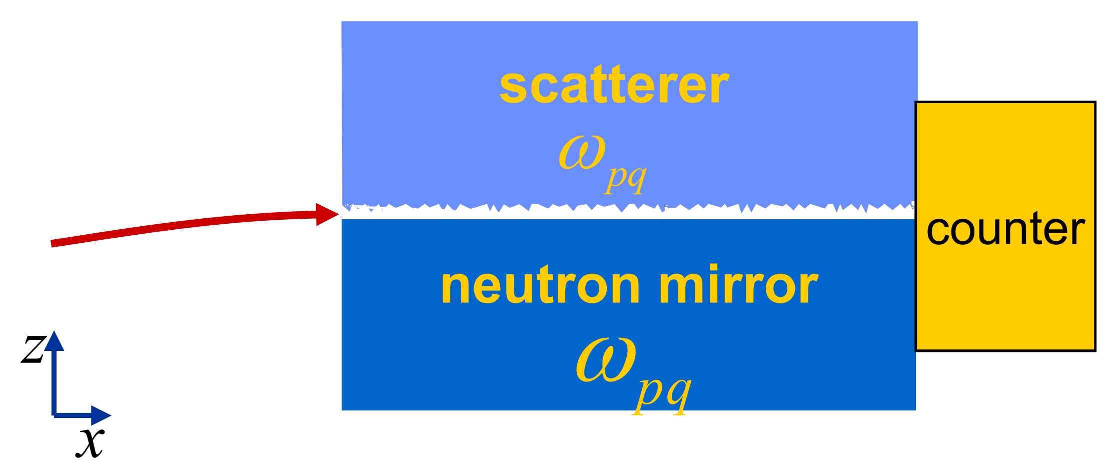
scales:

energies: peV
length: μm

neutron mirror

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



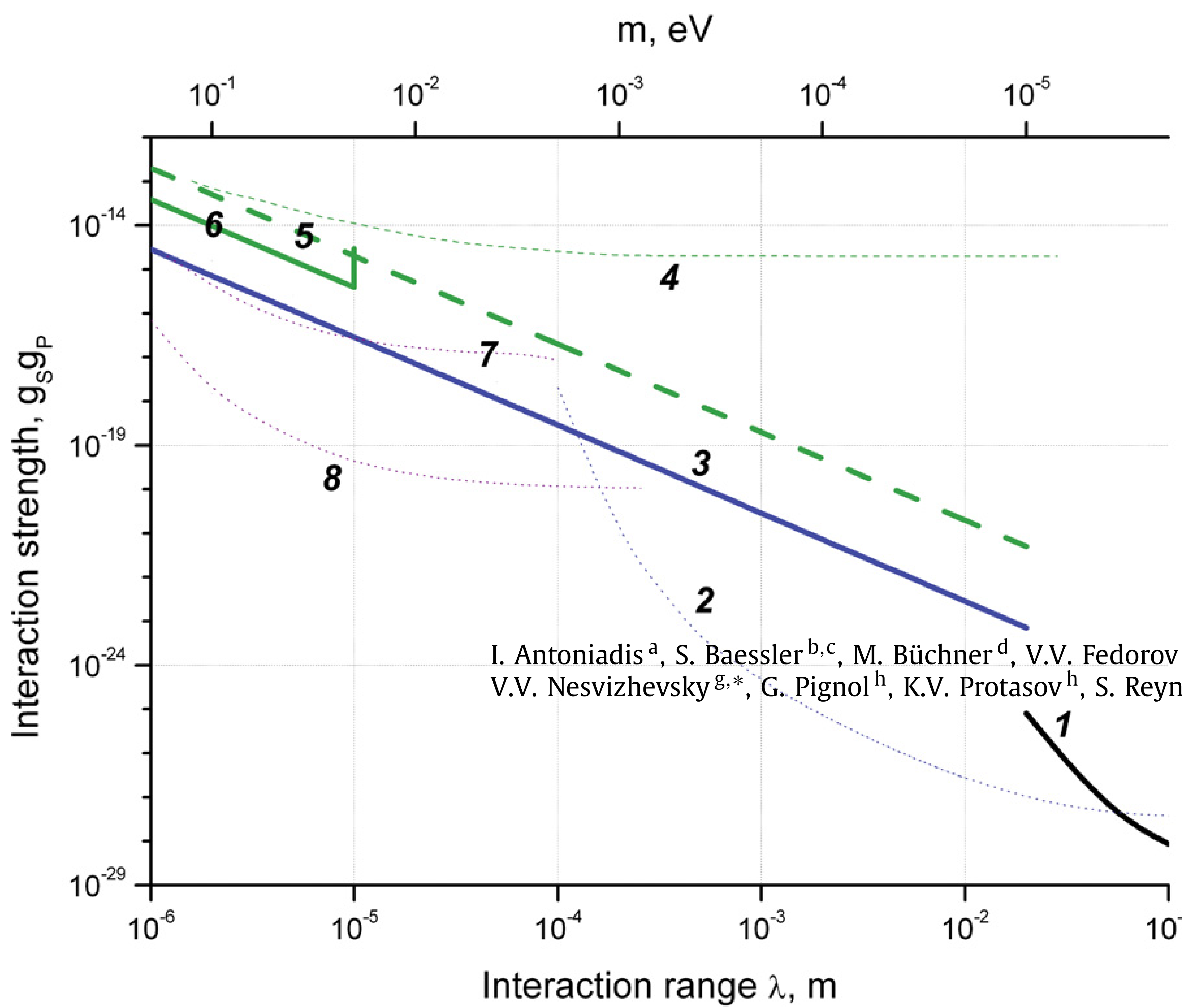


Demonstration of Quantum States in the Gravity Potential of the Earth

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]

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:

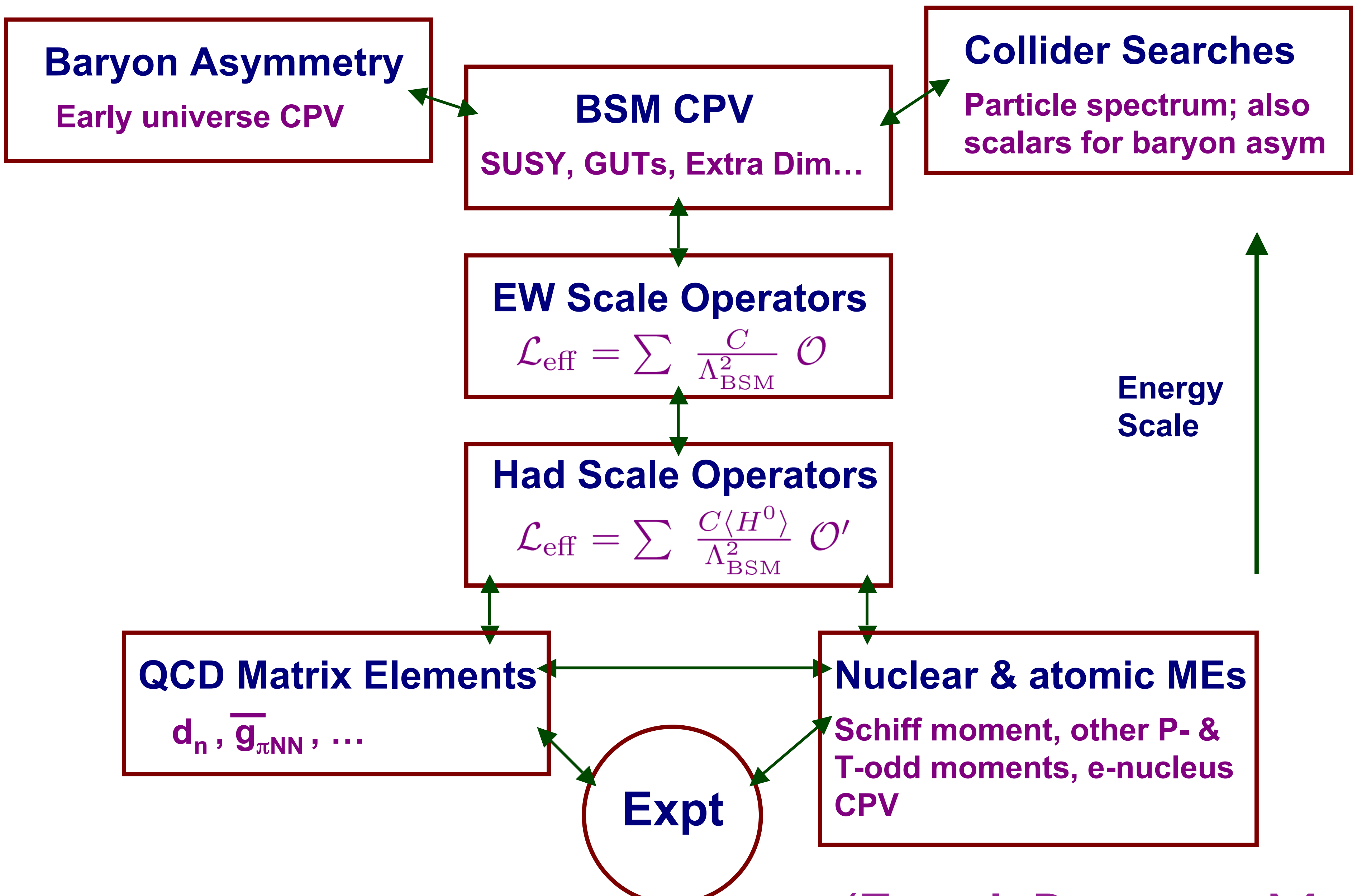
$$T(\vec{E} \cdot \vec{S}) = -\vec{E} \cdot \vec{S}$$

- 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

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

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  → Effects not associated with a macroscopic force

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Connection 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

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

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

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Axion

An illustrative model: KSVZ Model

- PQ symmetry breaking is typically constrained to be

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

- 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:

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

Axial U(1) Rotation

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

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

$$\downarrow$$

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

- Axion couplings to the quarks is now manifest.

Axion Vacuum Expectation Value

- Axion can acquire a non-zero vev:

$$\mathrm{a}(x) \;=\; \langle \mathrm{a} \rangle + a(x) \quad \longrightarrow \quad \theta_{\mathrm{ind.}} \;=\; \bar{\theta} + \frac{\langle \mathrm{a} \rangle}{f_a}\,;$$

- The Axion Lagrangian now takes the form:

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

Axion Potential

- Axion potential is generated via the quark condensate

$$V\left(\theta_{\rm ind.} + \frac{a}{f_a}\right) \;=\; m_q \left\langle \bar{q} q \right\rangle \cos\left(\theta_{\rm ind.} + \frac{a}{f_a}\right)$$

- The ground state potential can be expanded as

$$V(\theta_{\rm ind.}) \simeq \frac{1}{2}\chi(0)\,\theta^2_{\rm ind.}, \qquad \chi(0) = -m_q \langle \bar{q} q \rangle$$

- Minimum of the potential at:

$$\theta_{\rm ind.} = 0$$

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

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

- The coefficient of the linear term is given by 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

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

→ Non-zero EDM

Axion Couplings

- Expanding the Axion Lagrangian gives

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

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

Scalar coupling

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

Pseudo-scalar coupling

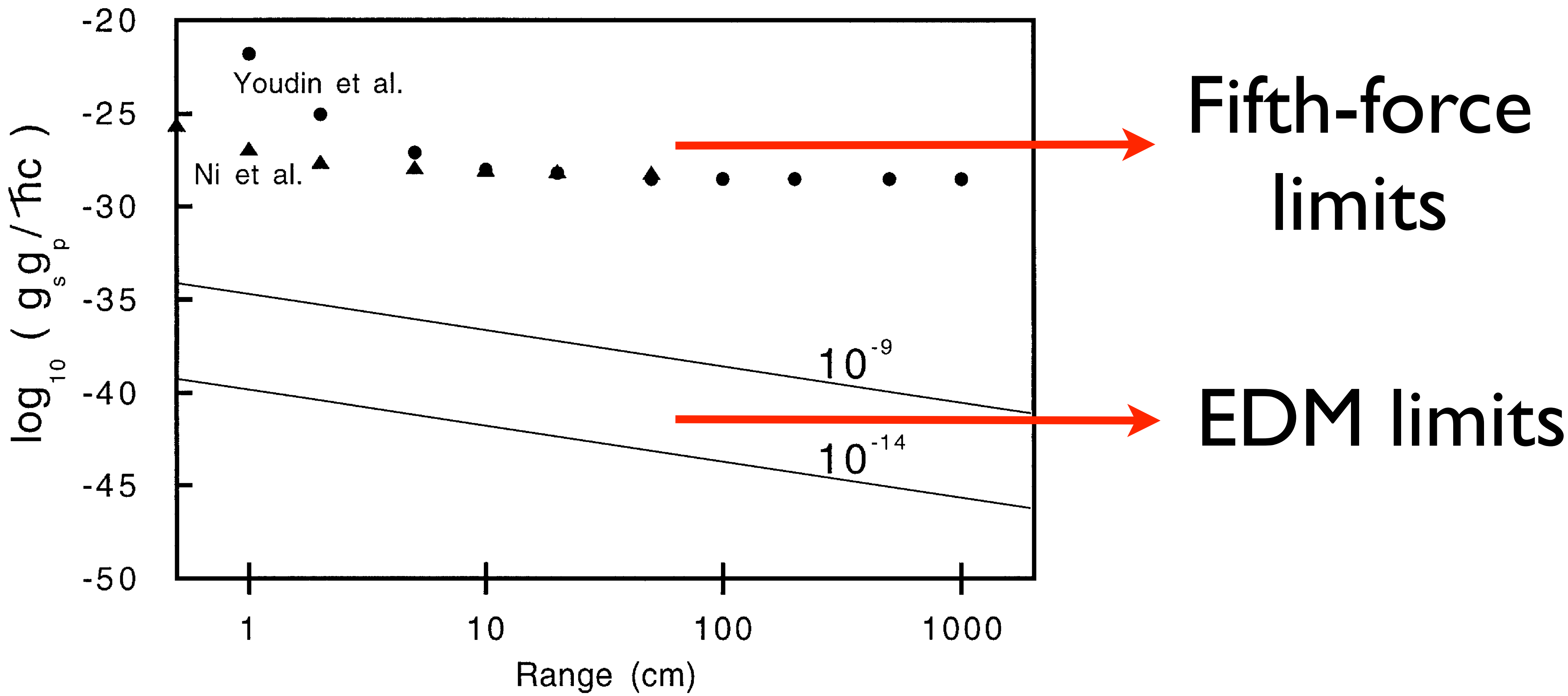
$$m_a \simeq \frac{1}{f_a} |\chi(0)|^{1/2}$$

Axion mass

- Product of couplings proportional to theta parameter:

$$g^1_s g^2_p \propto \theta_{\text{ind.}} \frac{m_q^2}{f_a^2}$$

EDM Limits Dominate over Fifth Force Bounds



(Rosenberg, Bibber)

$$g_{\rm s} g_{\rm p} \simeq \frac{\bar{\theta}}{\lambda({\rm mm})^2} 6 \times 10^{-27}$$

EDM limit

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

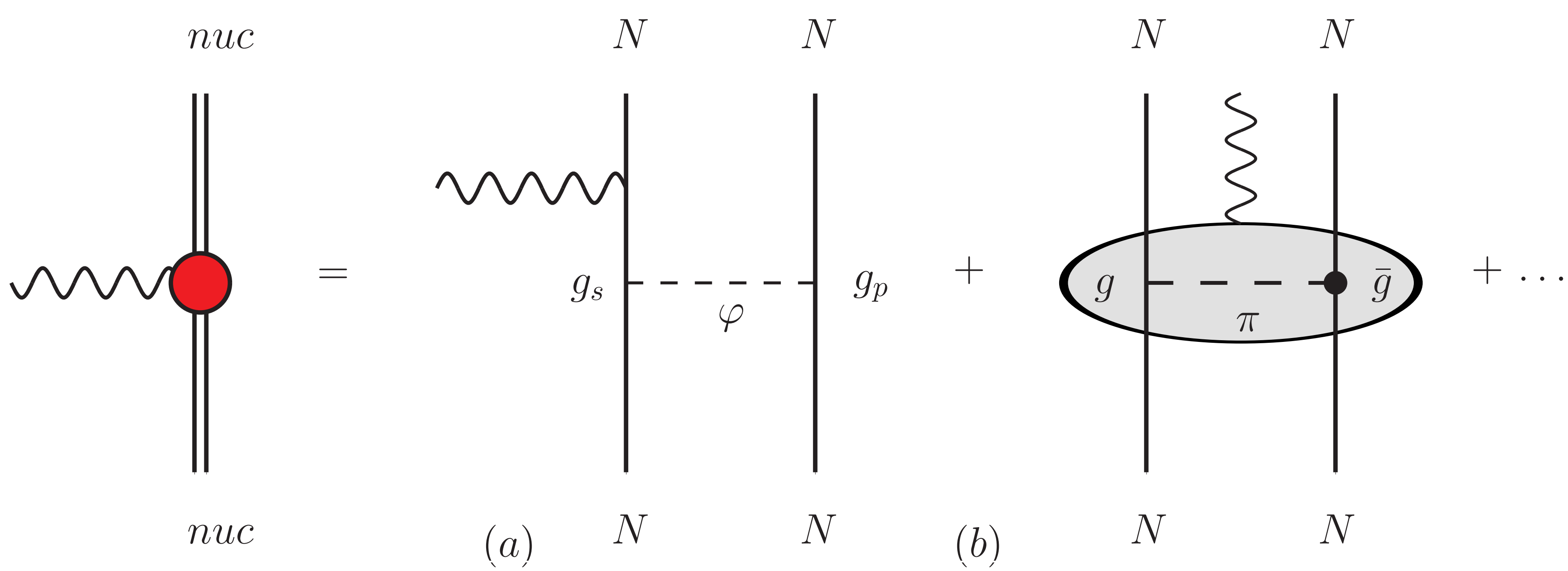
Generic Scalars

Arbitrary Couplings

- Nucleon level couplings:

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

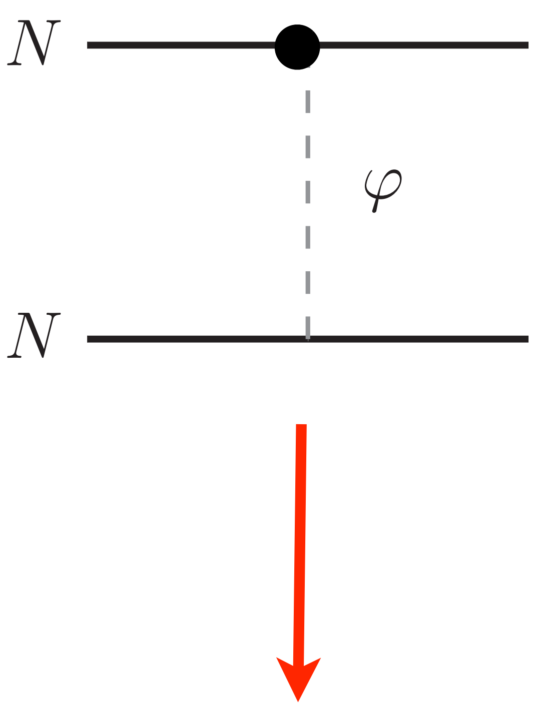
- EDMs induced by dynamical exchanges of light scalar



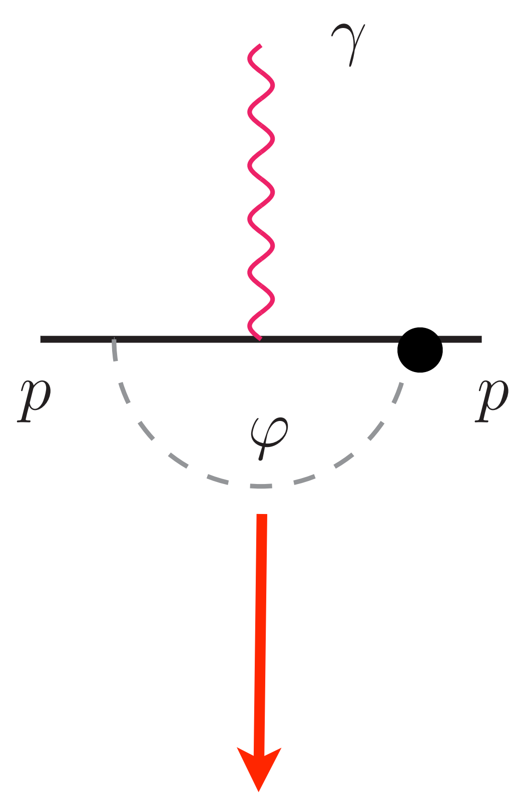
- Full EDM calculation must incorporate this propagating light scalar. Effective operator approach no longer applicable.

Estimate of Contribution to EDMs

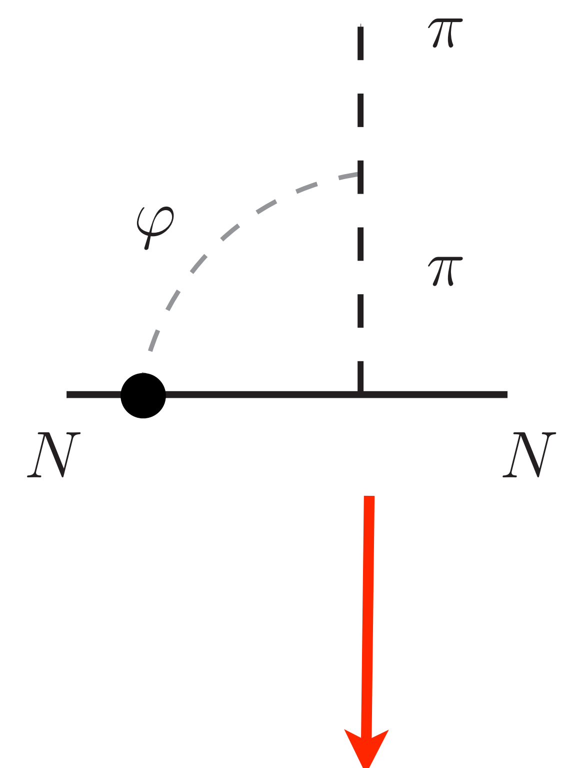
- A full EDM calculation with a new light scalar is beyond the scope of this work.
- Some example nucleon level diagrams that can contribute to the EDM:



Direct exchange



Proton EDM

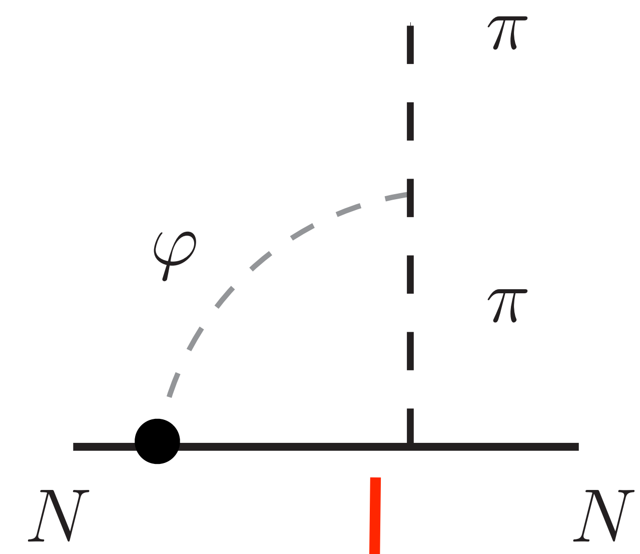


Correction to pion nucleon coupling

Estimate of Contribution to EDMs

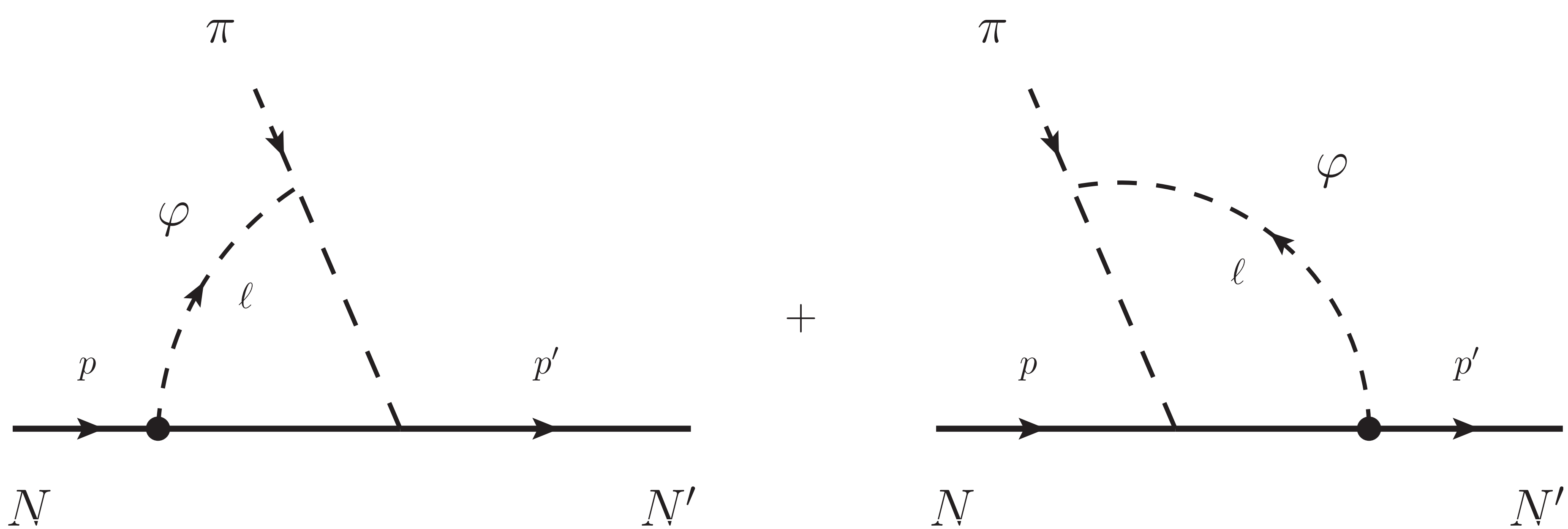
- A full EDM calculation with a new light scalar is beyond the scope of this work.
- Some example nucleon level diagrams that can contribute to the EDM:

  - 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)



$$\mathcal{L}_{\pi\bar{N}N} = \frac{2g_A}{f_\pi}\,\partial_\mu \pi^a\;\bar{N}_v\,\frac{\sigma^a}{2} S^\mu N_v,$$
$$\mathcal{L}_{\varphi\pi\pi} = g_s^\pi\;\varphi\;\pi^a\pi^a,$$
$$\mathcal{L}_{\varphi\bar{N}N} = -\frac{g_p}{m_N}\;\bar{N}_v\,(S^\mu\partial_\mu\varphi)\,N_v,$$

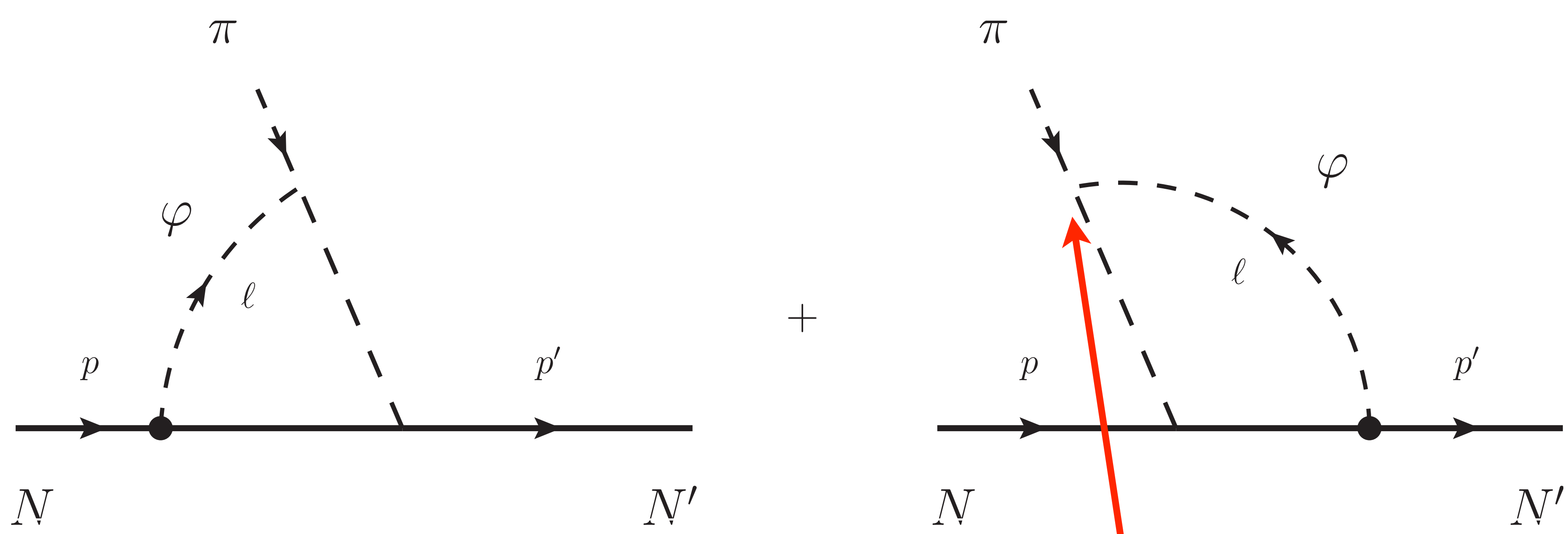
$$g_s^\pi = \frac{\langle\pi|\bar{u}u+\bar{d}d|\pi\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle}\,g_s$$

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

Vertices in HBChPT

Coupling to Pion

- Coupling to pion is related to scalar nucleon coupling:



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

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

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

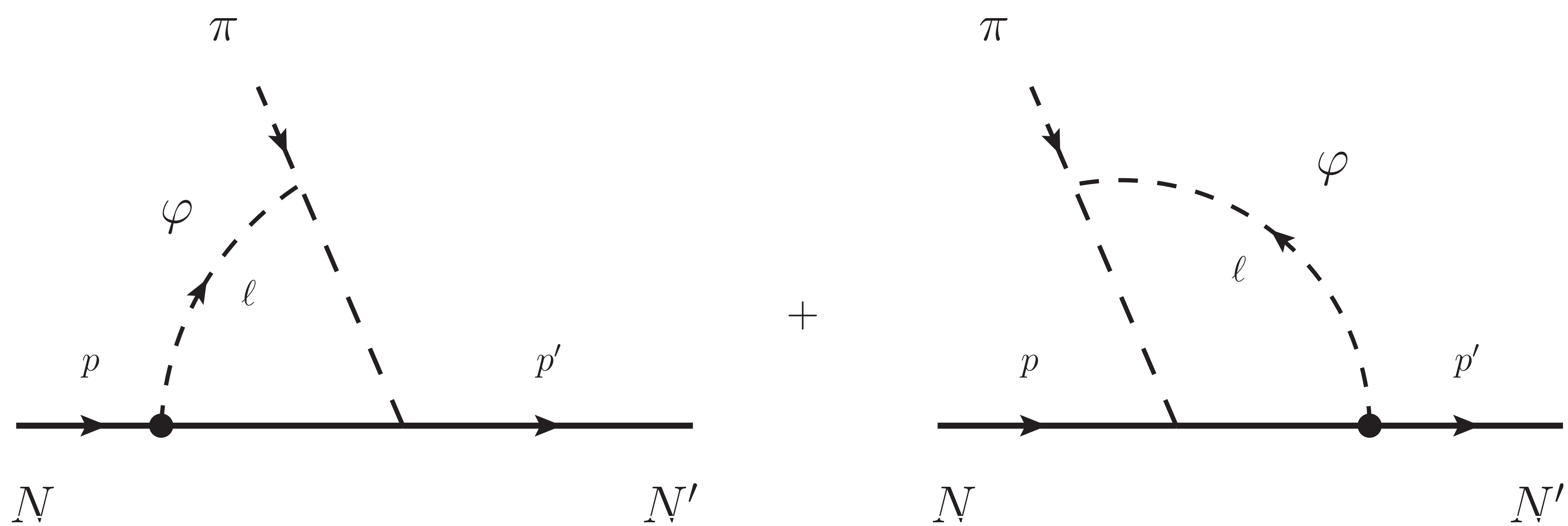
$$g_s^\pi = \frac{\langle \pi|\bar{u}u + \bar{d}d|\pi\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}\, g_s$$

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

Vertices in HBChPT

Coupling to Pion

- Result of computation



$$\mathcal{M}^a = \frac{i}{16\pi}\frac{m_\pi^2 + m_\pi m_\varphi + m_\varphi^2}{m_\pi + m_\varphi}\frac{g_s^\pi g_p g_A}{m_N f_\pi}\,\bar{N}_v(p')\sigma^a N_v(p)$$

- Write as new contribution to CP-odd pion-nucleon coupling

$$\mathcal{L}_{\pi\bar{N}N}^{CPV} = \frac{1}{16\pi}\frac{m_\pi^2 + m_\pi m_\varphi + m_\varphi^2}{m_\pi + m_\varphi}\frac{g_s^\pi g_p g_A}{m_N f_\pi}\,\pi^a \bar{N}\,\sigma^a N$$

Mercury EDM

- The mercury EDM in terms of the Schiff moment

$$d_{Hg} = -2.8 \times 10^{-4} \, \frac{S_{Hg}}{\mathrm{fm}^2}$$

(Griffith;de Jesus, Engel)

- Schiff moment in terms of pion-nucleon couplings

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

- Definition of pion-nucleon couplings

$$\mathcal{L}_{\pi NN} \ = \ \bar{g}^{(0)}_{\pi NN} \bar{N} \tau^a N \pi^a + \bar{g}^{(1)}_{\pi NN} \bar{N} N \pi^0 + \bar{g}^{(2)}_{\pi NN} (\bar{N} \tau^a N \pi^a - 3 \bar{N} \tau^3 N \pi^0)$$

Shift in the Mercury EDM

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

$$\delta d_{Hg} = -2.8 \times 10^{-4} \frac{\delta S_{Hg}}{\text{fm}^2}$$

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

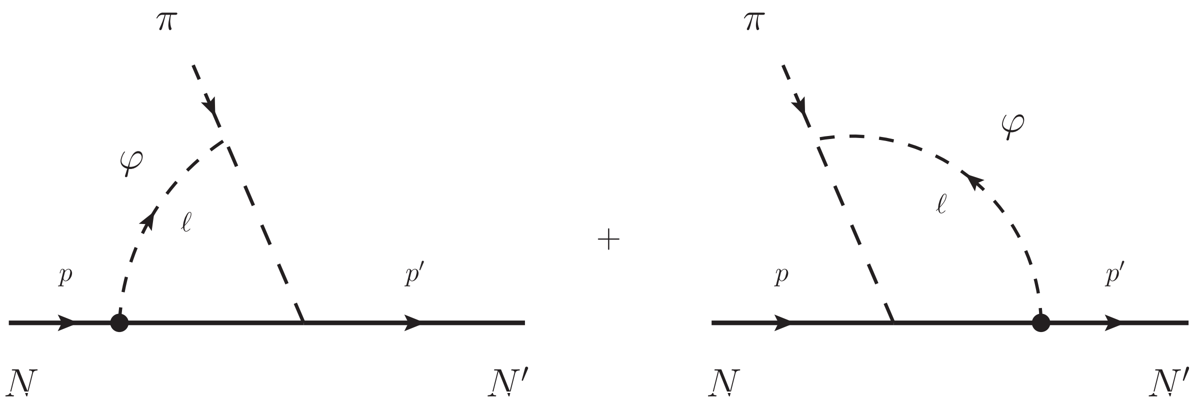
$$\delta S_{Hg} \;=\; g_{\pi NN} \left[\, 0.01\, \delta\bar{g}^{(0)}_{\pi NN} + 0.07\, \delta\bar{g}^{(1)}_{\pi NN} + 0.02\, \delta\bar{g}^{(2)}_{\pi NN} \,\right] e\ \text{fm}^3$$

- 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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- Shift in CP-odd pion-nucleon couplings

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

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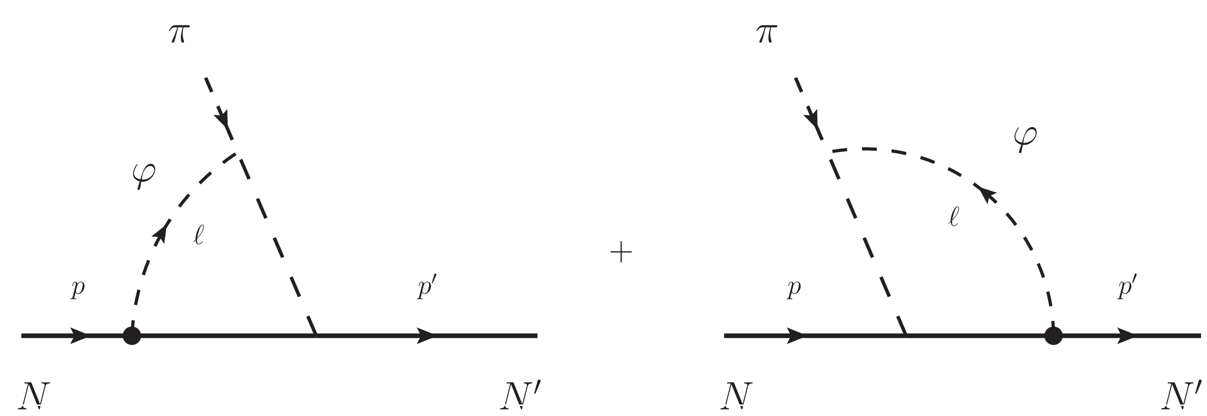
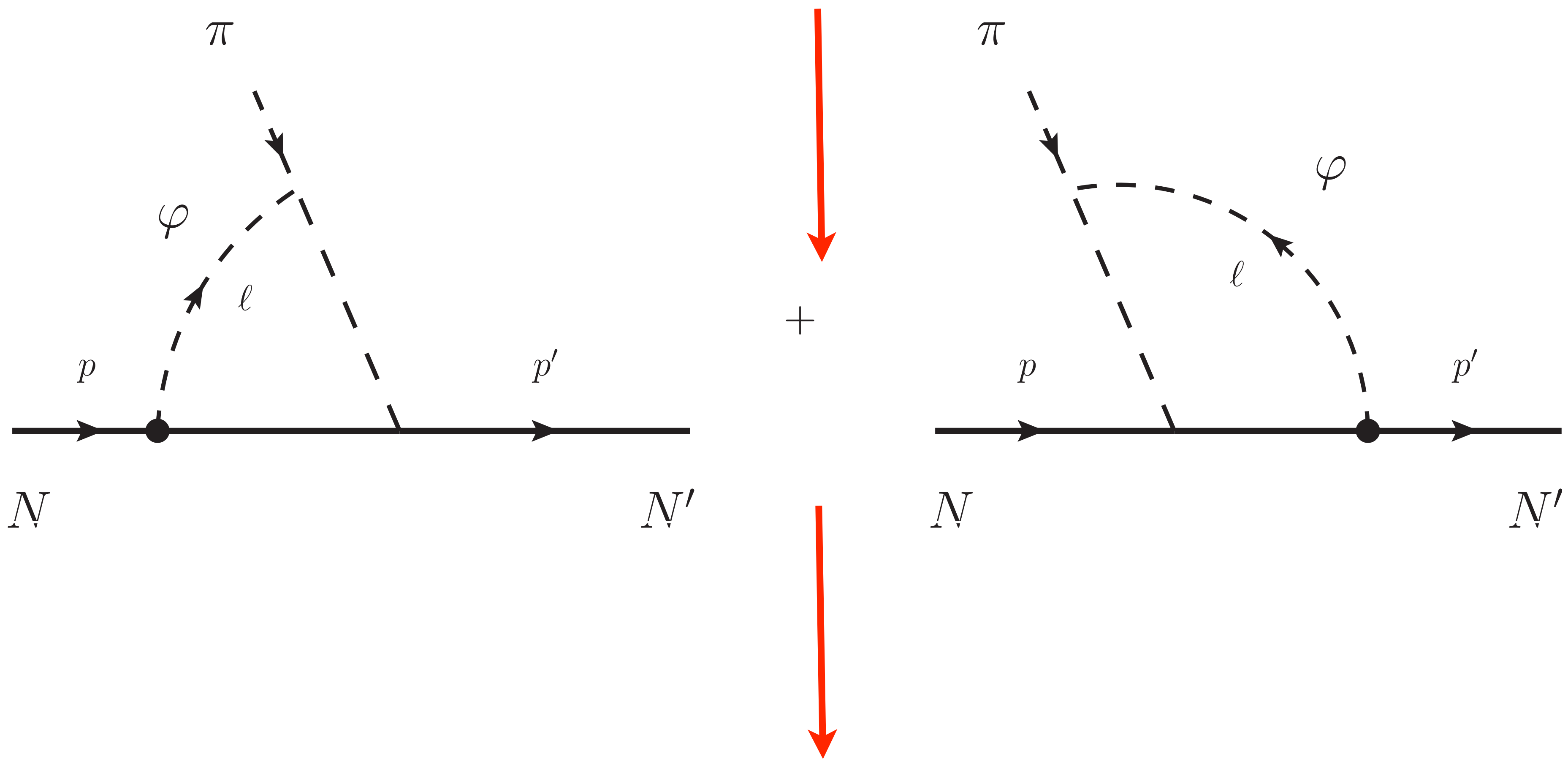


EDM Bound on Macroscopic Spin-Dependent Force

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



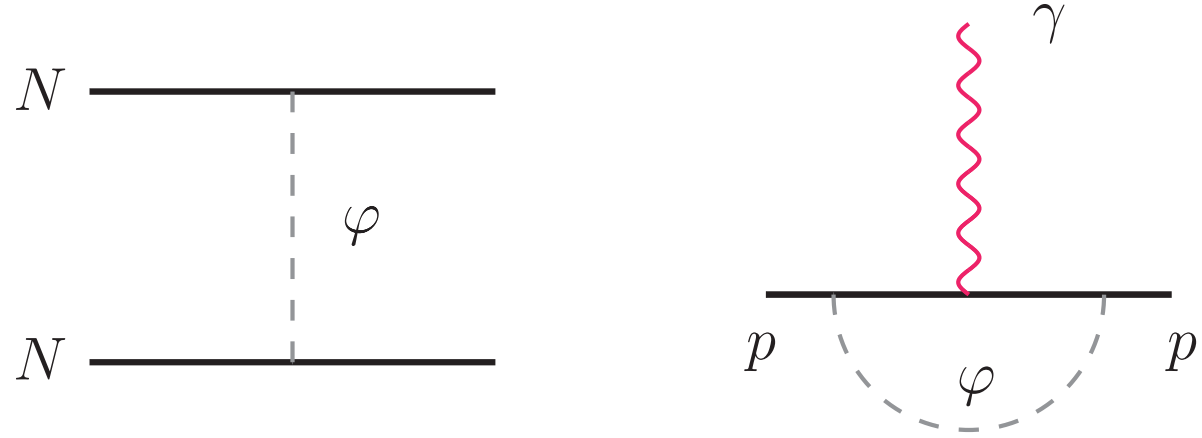
$$|g_s g_p| \lesssim 10^{-9}$$

Corrections

- Bound from the one-loop correction to the CP-odd pion-nucleon coupling

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

- This result will be modified by order one nuclear effects and additional diagrams. The tree level diagram can enhance the effect by two orders of magnitude.



- A rigorous calculation with all effects included is expected to yield

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

Comparison with Fifth Force limits

- EDM limit:

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

- Fifth force limits:

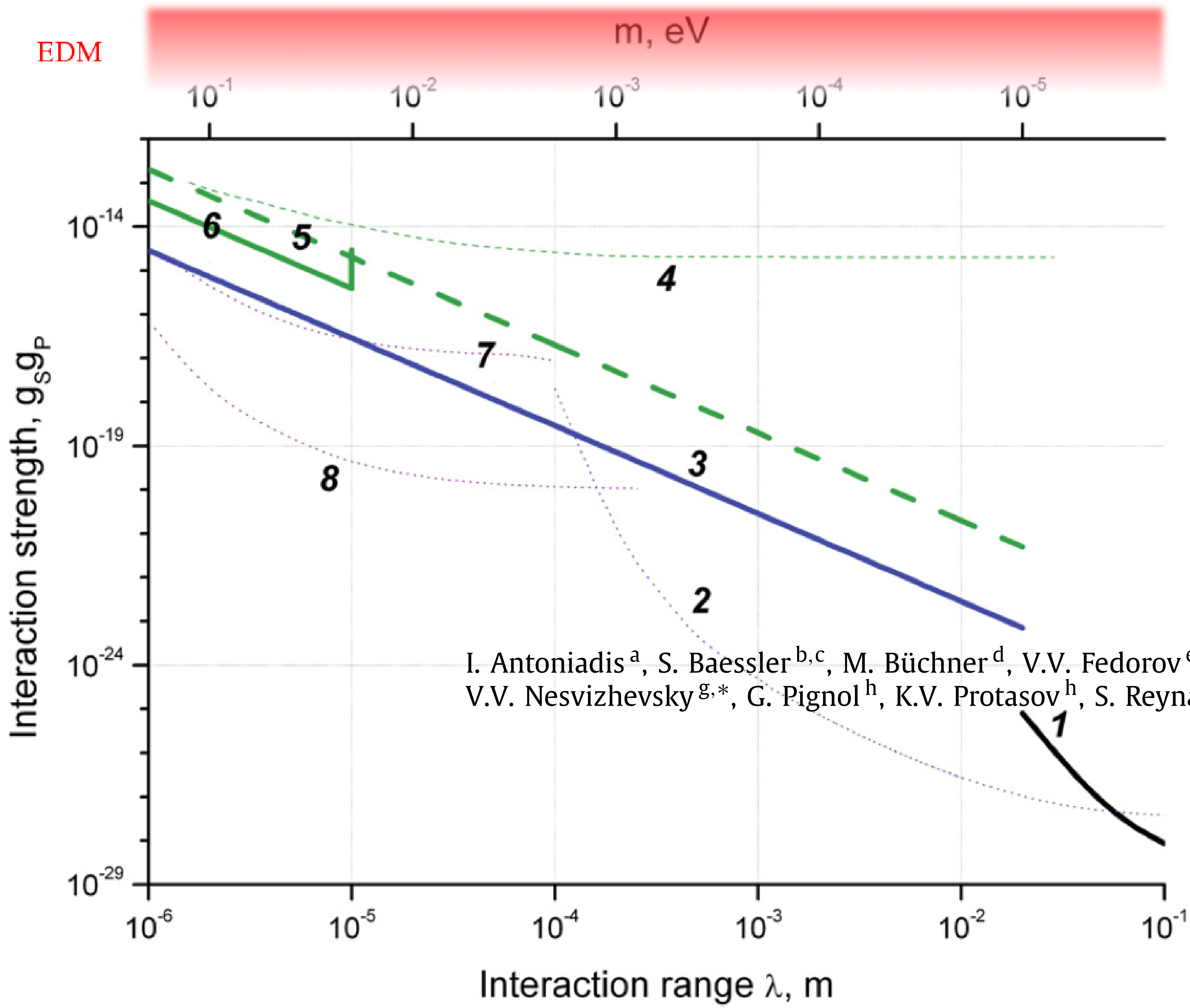
Interaction range λ [m]	m_φ [eV]	$\lvert g_s g_p \rvert$
$\sim 2 \times 10^{-5}$	$\sim 10^{-2}$	$< 10^{-16}$
$\sim 2 \times 10^{-1}$	$\sim 10^{-6}$	$< 10^{-29}$

- EDM limit on axion forces:

$$g_s g_p \big|_{\text{axion}} \propto \theta_{\text{ind.}} \frac{m_q^2}{f_a^2} < 10^{-40} - 10^{-34}$$

Comparison with Fifth Force limits

EDM



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Conclusions

- A signal for short range spin-dependent forces implies CP violation beyond the SM.
- Observations in fifth Force experiments can be correlated with EDM constraints.
- EDM limits always dominate constraints on Axion mediated short range forces.
- For generic scalars EDM and fifth force limits can compete or one can dominate depending on the region of parameter space.