Opportunities for Radioactive Molecules in Tests of Fundamental Symmetries and Searches for New Physics

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Kavli IPMU, University of Tokyo, Japan

New Opportunities for Fundamental Research with Radioactive Molecules, MIT, July 2021

Conventional Wisdom in the Classification of Atomic/Molecular EDM Experiments

Diamagnetic systems (contain *no* unpaired electrons) are mainly sensitive to **hadronic** sources of CP violation – e.g., **Hg**, **Xe**, **n**

Paramagnetic systems (contain *one or more* unpaired electrons) are mainly sensitive to **leptonic** sources of CP violation – e.g., **ThO**, **HfF^+**, **YbF**, **Tl, Cs**

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For **semi-leptonic** sources of CP violation, the story is more complicated – the “classification” generally depends on whether the interactions involve mainly electron spin or nuclear spin

Leptonic CP Violation in Paramagnetic Molecules

Over the past decade, molecular experiments have improved the sensitivity to electron EDM d_e by more than 100-fold:

^{232}ThO bound: $|d_e| < 10^{-29}\ e\ \mathrm{cm}$

[Andreev *et al*. (ACME collaboration), *Nature* **562**, 355 (2018)]

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What about sensitivity of paramagnetic systems to hadronic CP violation?

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Hadronic CP Violation in Diamagnetic Atoms

Illustrative example: $$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

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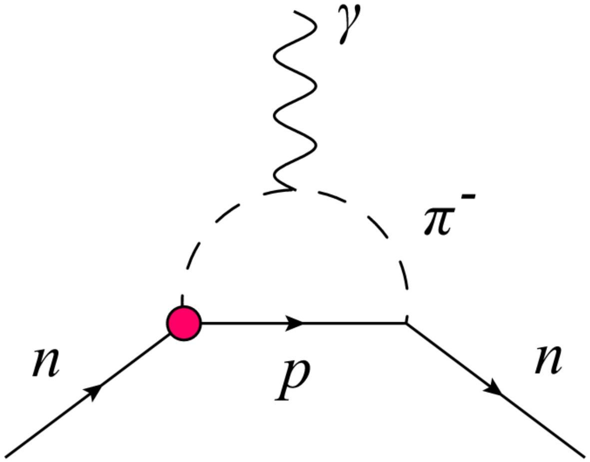

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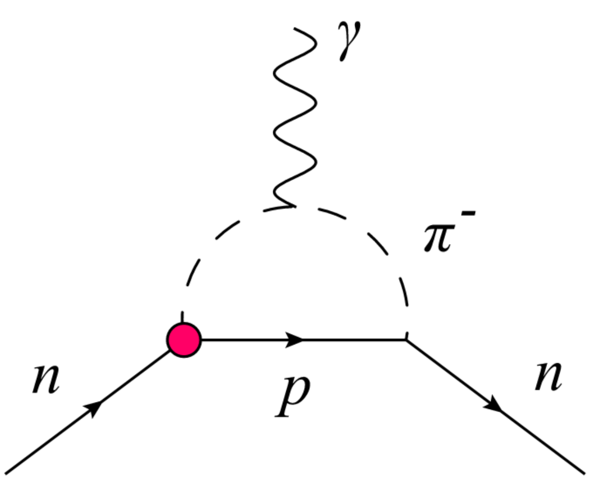
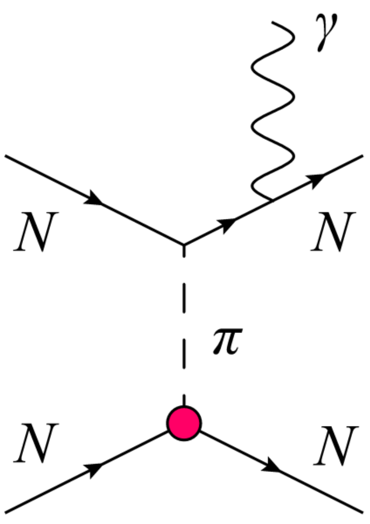


CP-violating intranuclear forces



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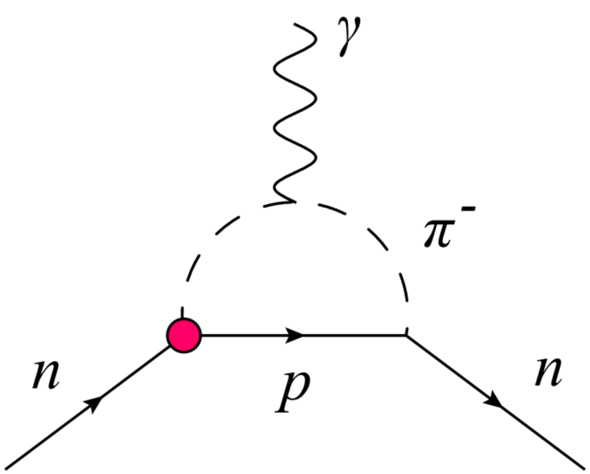

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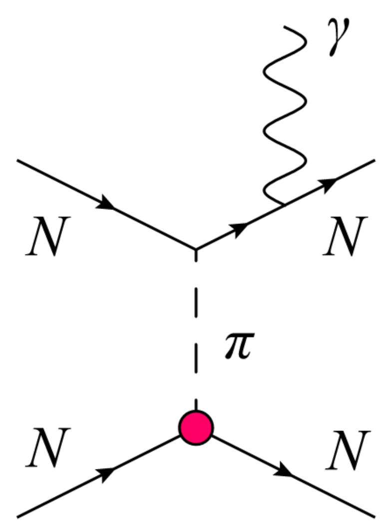
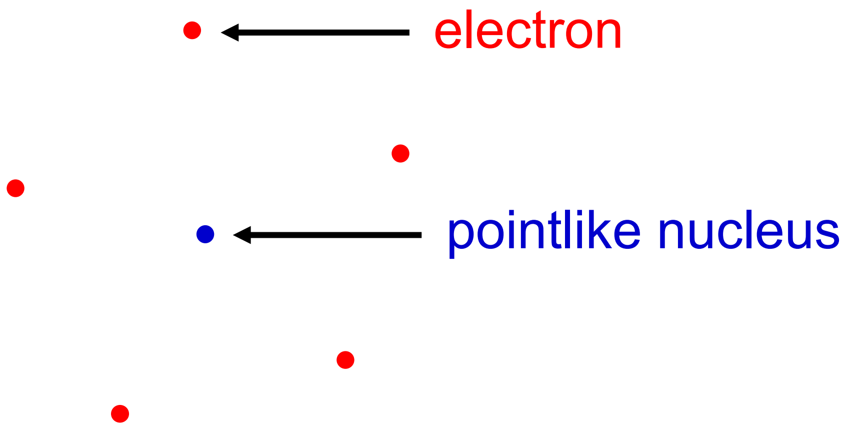


In nuclei, **tree-level** CP-violating intranuclear forces dominate over **loop-induced** nucleon EDMs [loop factor = $1/(8\pi^2)$].

Schiff's Theorem

[Schiff, *Phys. Rev.* **132**, 2194 (1963)]

Schiff's Theorem: "In a neutral atom made up of point-like non-relativistic charged particles (interacting only electrostatically), the constituent EDMs are screened from an external electric field."



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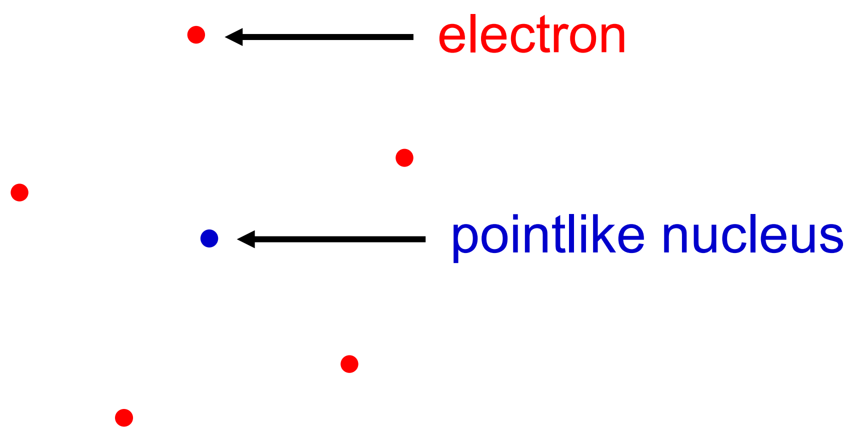

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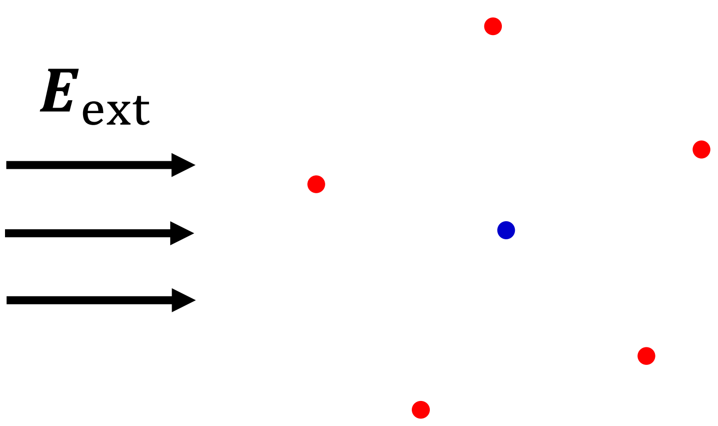

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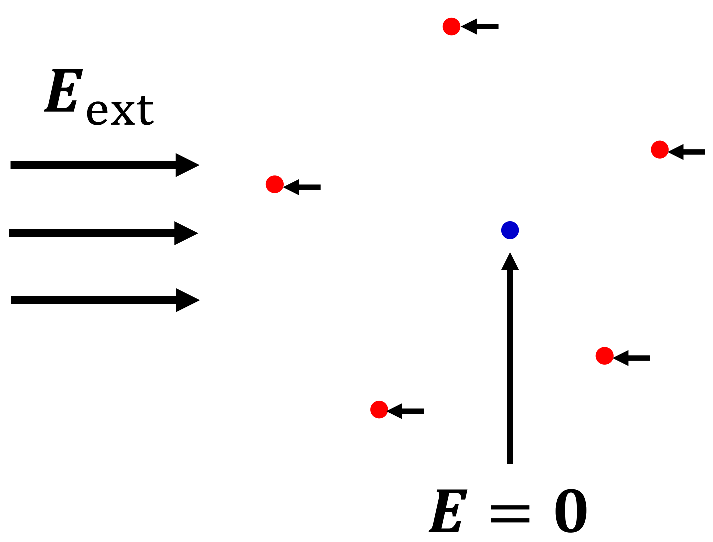

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Lifting of Schiff's Theorem

[Sandars, *PRL* **19**, 1396 (1967)],

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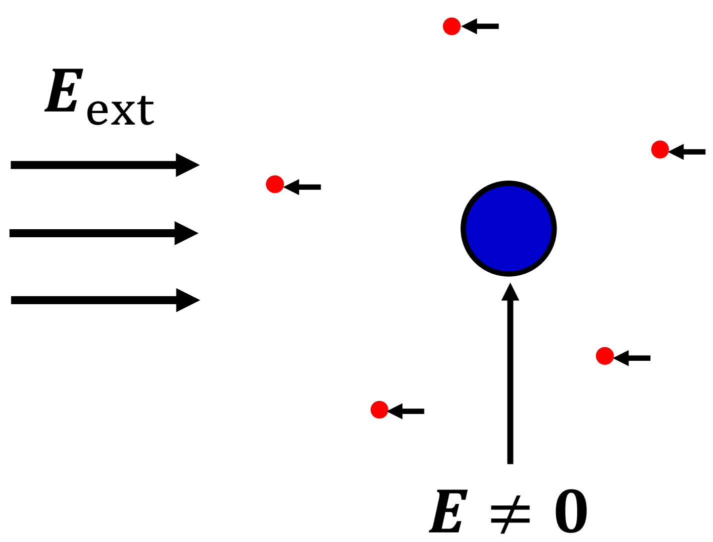
In real (heavy) atoms: Incomplete screening of external electric field due to finite nuclear size, parametrised by **nuclear Schiff moment**.



Hadronic CP Violation in Paramagnetic Molecules

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

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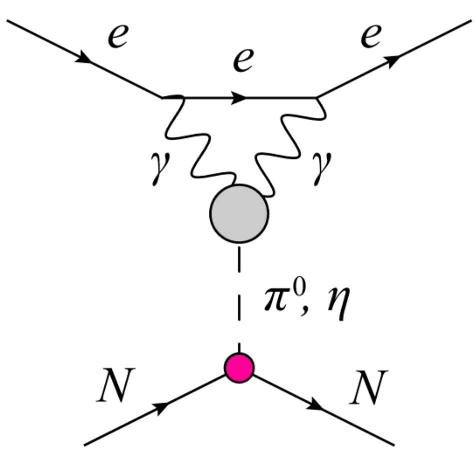

CP-odd nucleon polarisabilities $(\propto \boldsymbol{E} \cdot \boldsymbol{B})$

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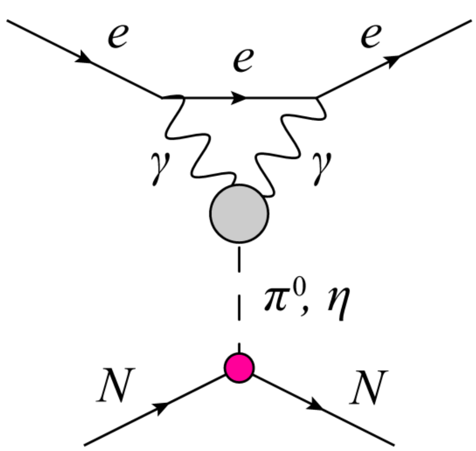

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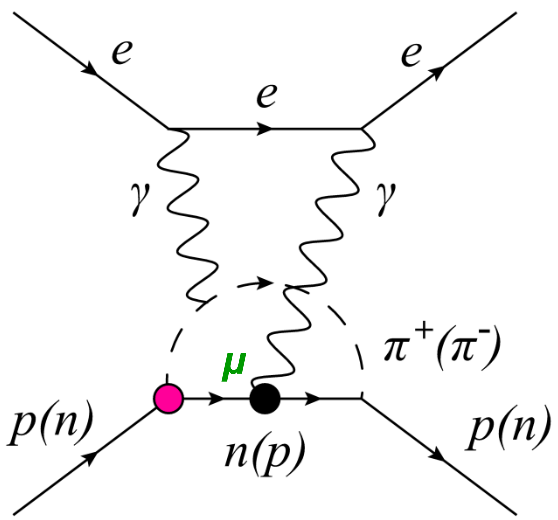

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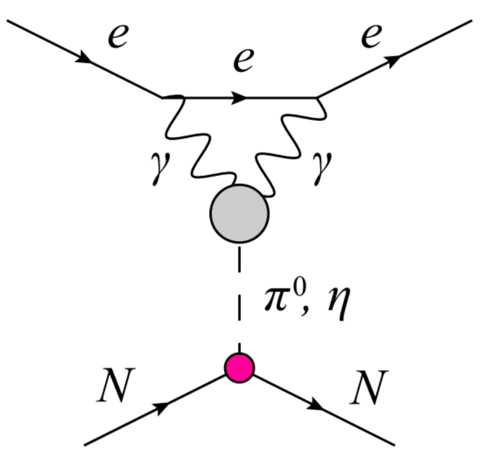

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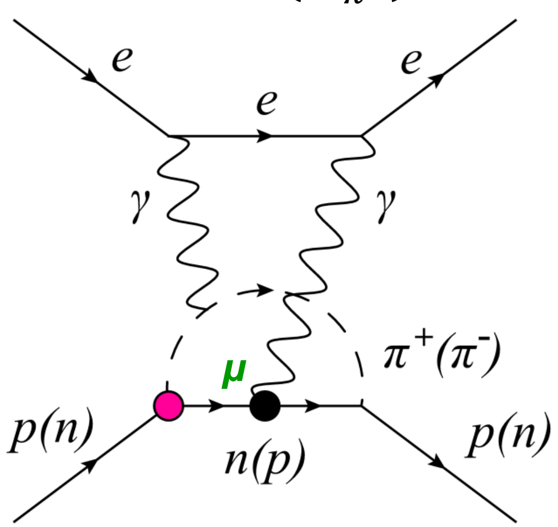

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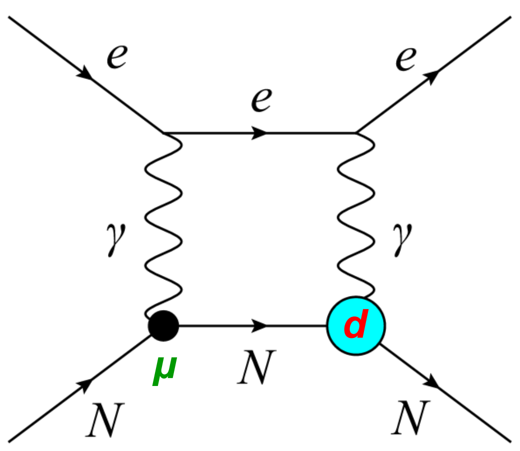
($\boldsymbol{\mu}-\boldsymbol{d}$): $\mathcal{O}[\ln(A)/p_{\mathrm{F}}]$

[Fermi-gas model]



Internal nuclear excitations

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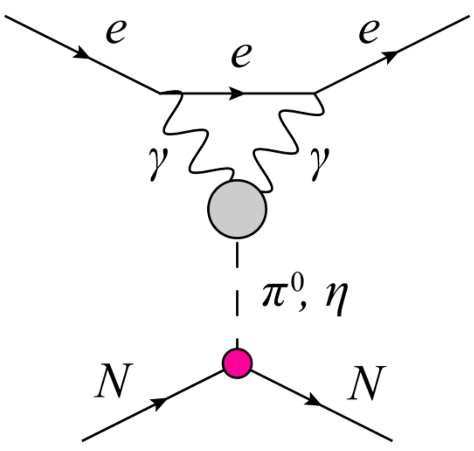

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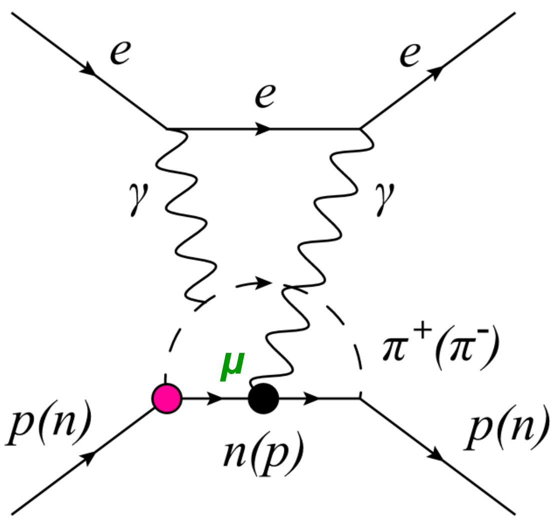

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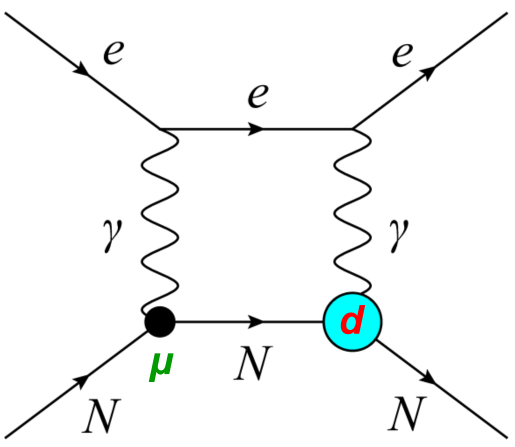

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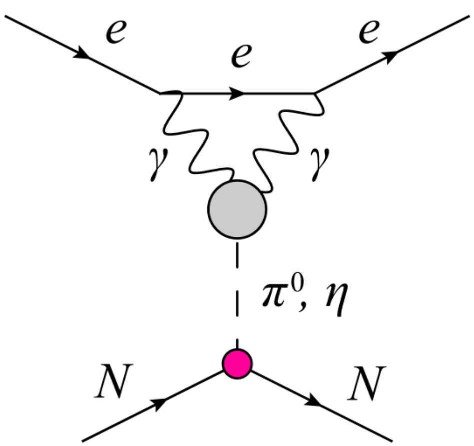

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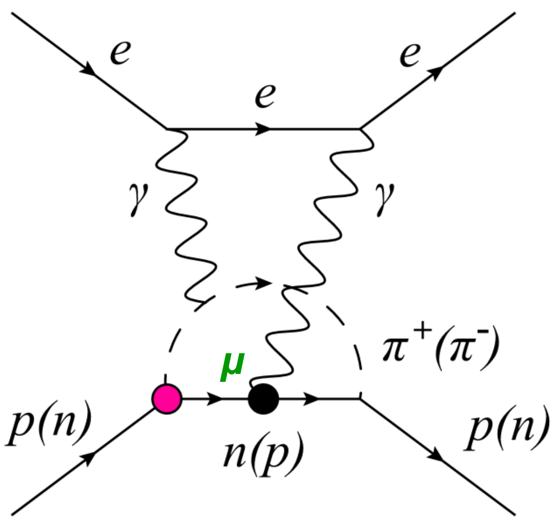

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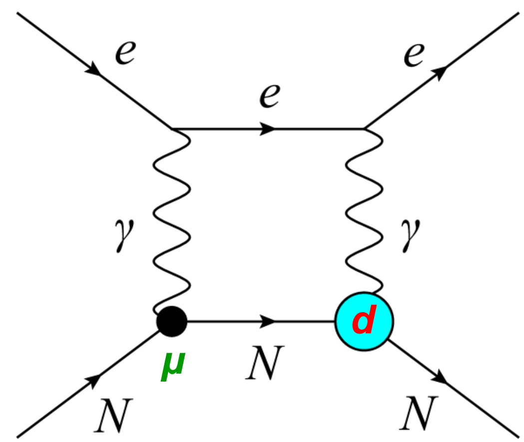

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- One of photons interacts *magnetically* with nucleus => **no Schiff screening**
  - $\boldsymbol{\mathcal{O}(A)}$**-enhanced** CP-odd nuclear *scalar* polarisability
  - Operative even in *spinless* nuclei (e.g., ^{232}ThO, ^{180}HfF$^+$)

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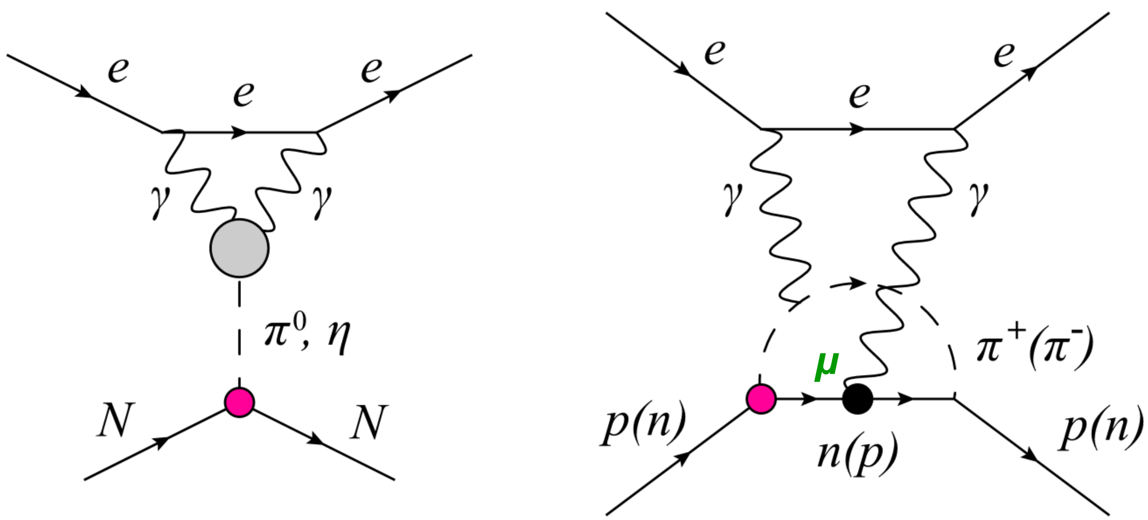

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Internal nuclear excitations

Isoscalar CP-Odd π-N Coupling

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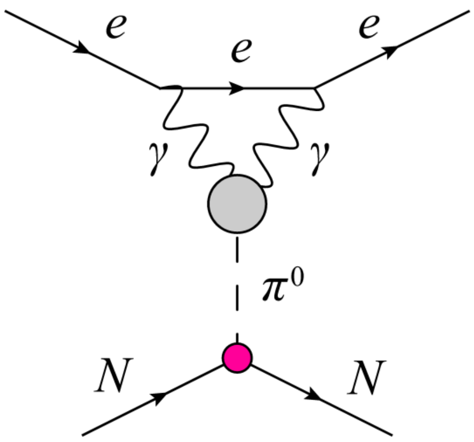

π^0 exchange

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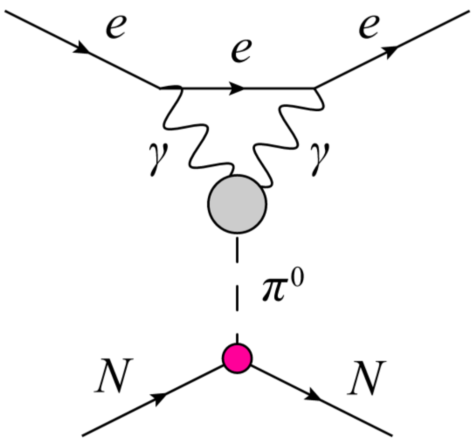

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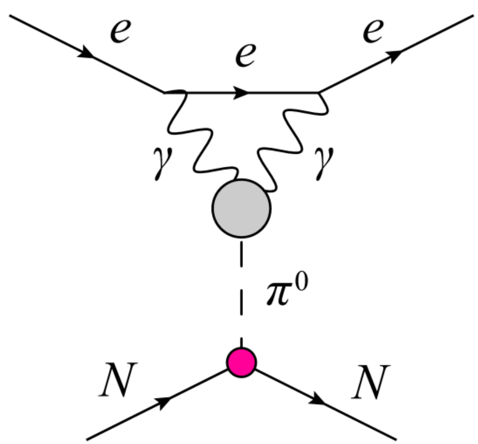

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=> Clean bounds, since less sensitivity to details of nuclear structure

(cf. strong sensitivity of ^{199}Hg Schiff moment to assumptions about underlying nuclear structure – different models give different signs for sensitivity coefficient)

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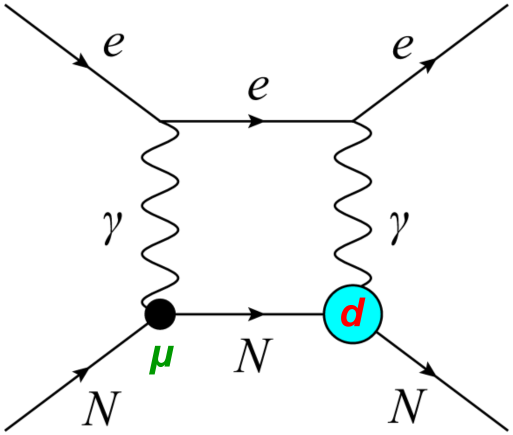

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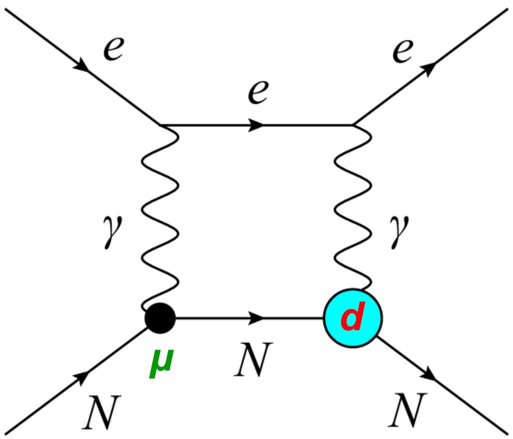

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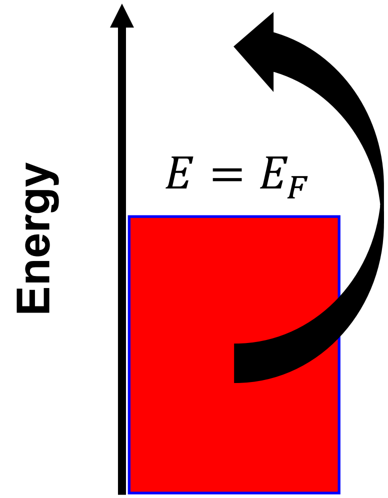

Continuum

Excitations to continuum above Fermi surface: $\sim \ln(A)/p_{\mathrm{F}}$ [Fermi-gas model]

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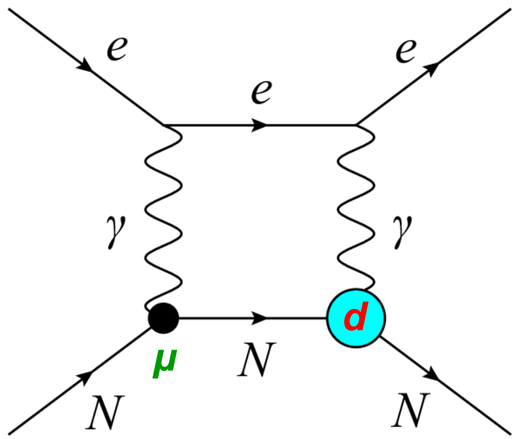

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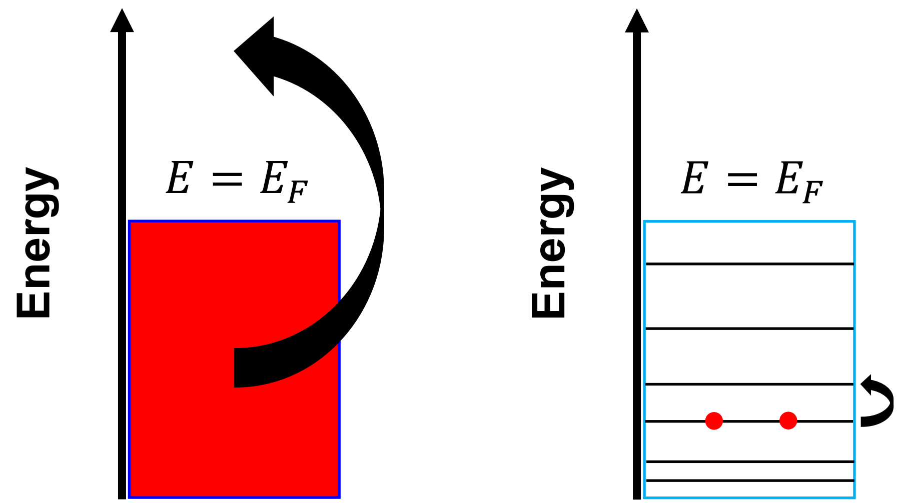

Continuum **Discrete**

Excitations to continuum above Fermi surface: $\sim \ln(A)/p_{\mathrm{F}}$ [Fermi-gas model]

Discrete transitions between L-S doublets: $\sim[\mathcal{O}(10)/A] \times (1/\Delta E_{\mathrm{nucl}})$

[Giant resonance model – Flambaum, Samsonov, Tran Tan, *JHEP* **10** (2020) 077]

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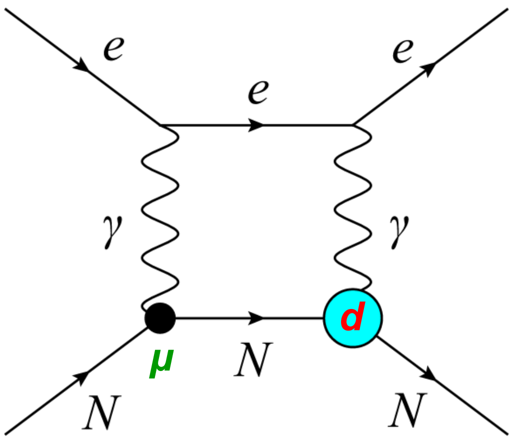

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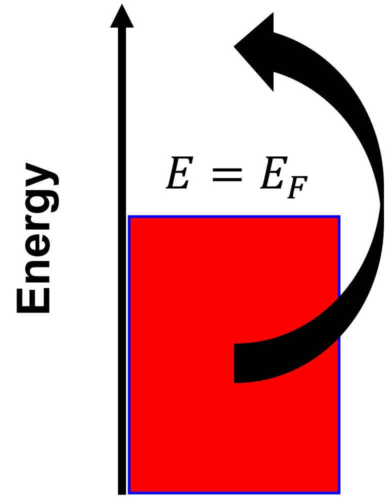

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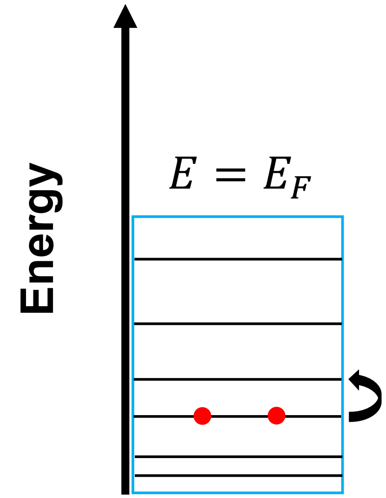

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For $A \sim 200$ and $\Delta E_\mathrm{nucl} \sim \mathrm{several\ MeV}$, the two contributions are comparable in size (and of the same sign)

QCD Vacuum Angle $\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$

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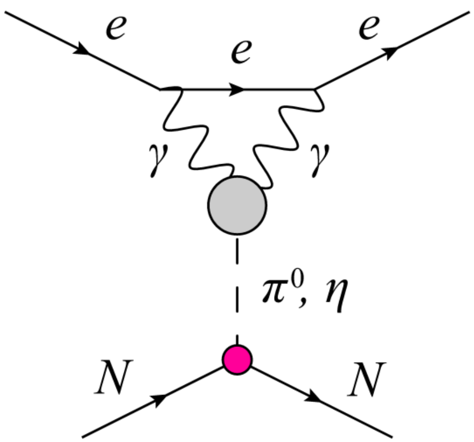
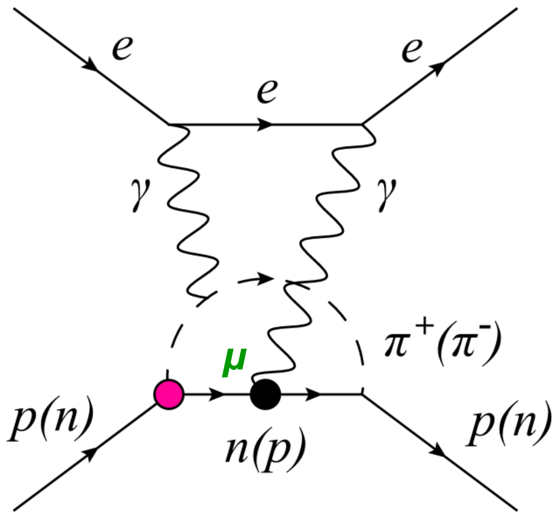
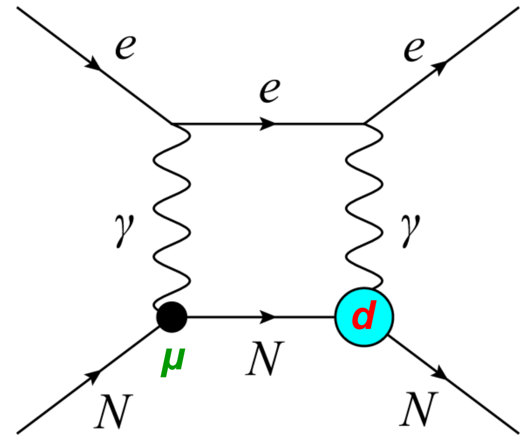


NLO: $\mathcal{O}(m_\pi^{-1})$



$(\boldsymbol{\mu} - \boldsymbol{d})$: $\mathcal{O}[\ln(A)/p_{\mathrm{F}}]$

[Fermi-gas model]



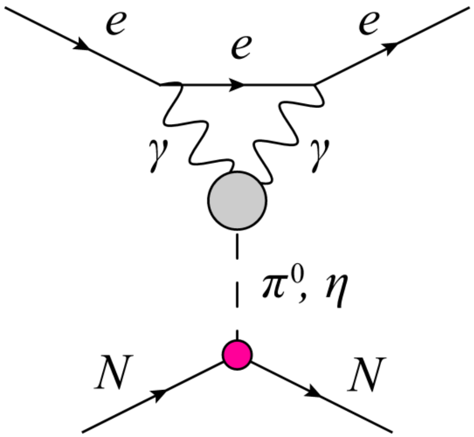
π^0, η contributions: ***opposite*** sign (near-cancellation in heavy nuclei)

p, n contributions: ***same*** sign

QCD Vacuum Angle $\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

LO: $\mathcal{O}(m_\pi^{-2})$



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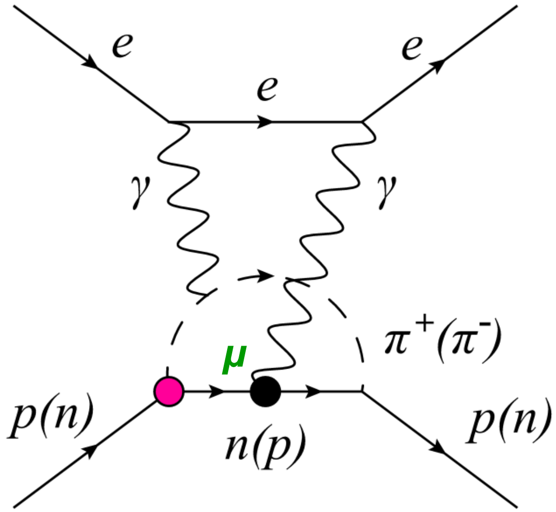

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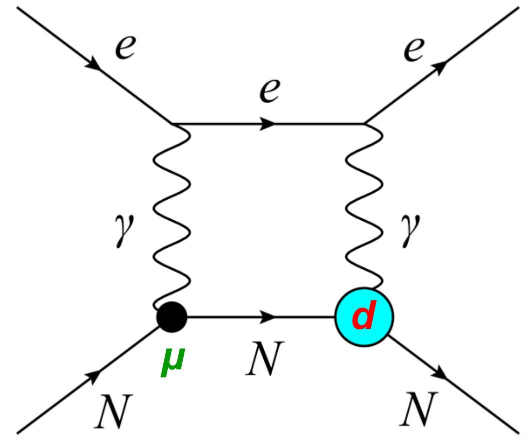

π^0, η contributions:
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p, n contributions: ***same*** sign

For $Z \sim 80$ & $A \sim 200$: $C_\mathrm{SP}(\theta) \approx \left[0.1_\mathrm{LO} + 1.0_\mathrm{NLO} + 1.7_{(\mu - d)}\right] \times 10^{-2}\theta \approx 0.03\theta$

$$\mathcal{L}_\mathrm{contact} = -\frac{G_F C_\mathrm{SP} \bar{N} N \bar{e} i \gamma_5 e}{\sqrt{2}}$$

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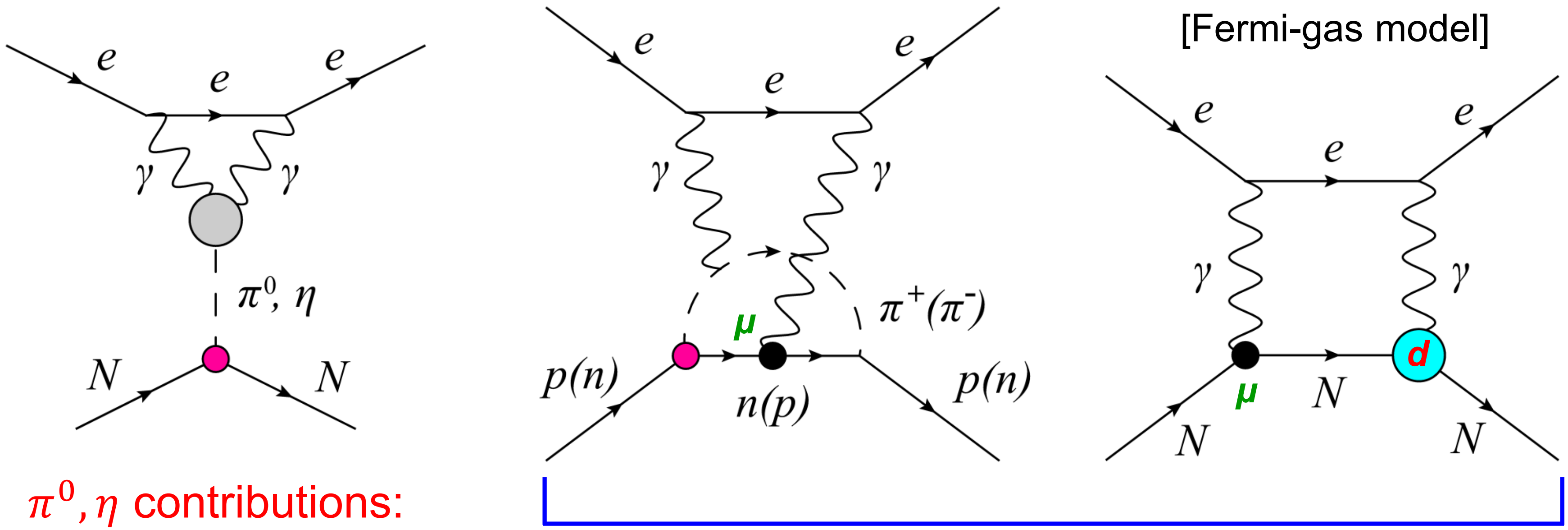
LO: $\mathcal{O}(m_\pi^{-2})$ | **NLO:** $\mathcal{O}(m_\pi^{-1})$ | **($\boldsymbol{\mu - d}$):** $\mathcal{O}[\ln(A)/p_\mathrm{F}]$ [Fermi-gas model]



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Future work: η' contribution and other N^{2}LO contributions, nuclear in-medium effects (NLO process), nuclear structure effects [$(\mu - d)$ process]

Bounds on Hadronic CP Violation Parameters

ThO bounds: [Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

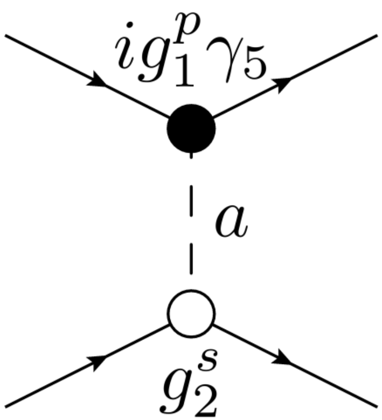
System	$\left\|\bar{g}_{\pi NN}^{(1)}\right\|$	$\left\|\tilde{d}_u - \tilde{d}_d\right\|$ (cm)	$\left\|d_p\right\|$ (e cm)	$\|\theta\|$
ThO	$\mathbf{4 \times 10^{-10}}$	$\mathbf{2 \times 10^{-24}}$	$\mathbf{2 \times 10^{-23}}$	$\mathbf{3 \times 10^{-8}}$
n	1.1×10^{-10}	5×10^{-25}	—	2.0×10^{-10}
Hg	1×10^{-12}	5×10^{-27}	2.0×10^{-25}	1.5×10^{-10}
Xe	6.7×10^{-8}	3×10^{-22}	3.2×10^{-22}	3.2×10^{-6}

* These limits can formally be null within nuclear uncertainties

Current bounds from molecules are $\sim 10 - 100$ times weaker than from Hg & n, but are $\sim 10 - 100$ times stronger than bounds from Xe

P,T-Violating Forces Mediated by Dark Bosons

[Stadnik, Dzuba, Flambaum, *PRL* **120**, 013202 (2018)],
[Dzuba, Flambaum, Samsonov, Stadnik, *PRD* **98**, 035048 (2018)]



$$\mathcal{L}_{\text{int}} = a\bar{f}\left(g_f^s + ig_f^p\gamma_5\right)f$$

$$V(r) \approx \frac{g_1^p g_2^s}{8\pi m_1}\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}}\left(\frac{m_a}{r} + \frac{1}{r^2}\right)e^{-m_a r}$$

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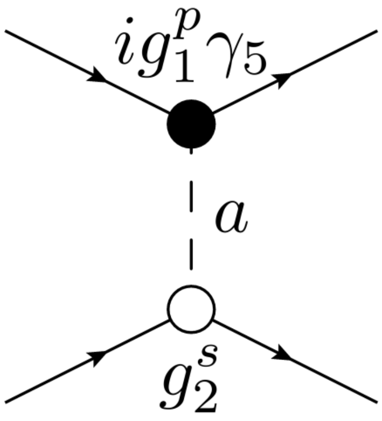

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P,T-violating forces => Atomic and Molecular EDMs

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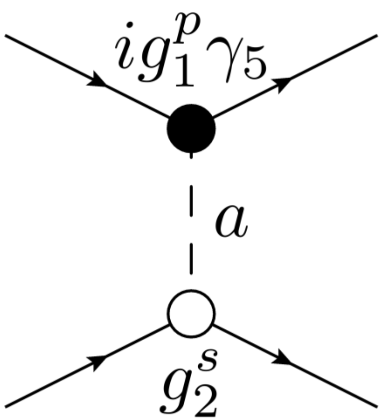

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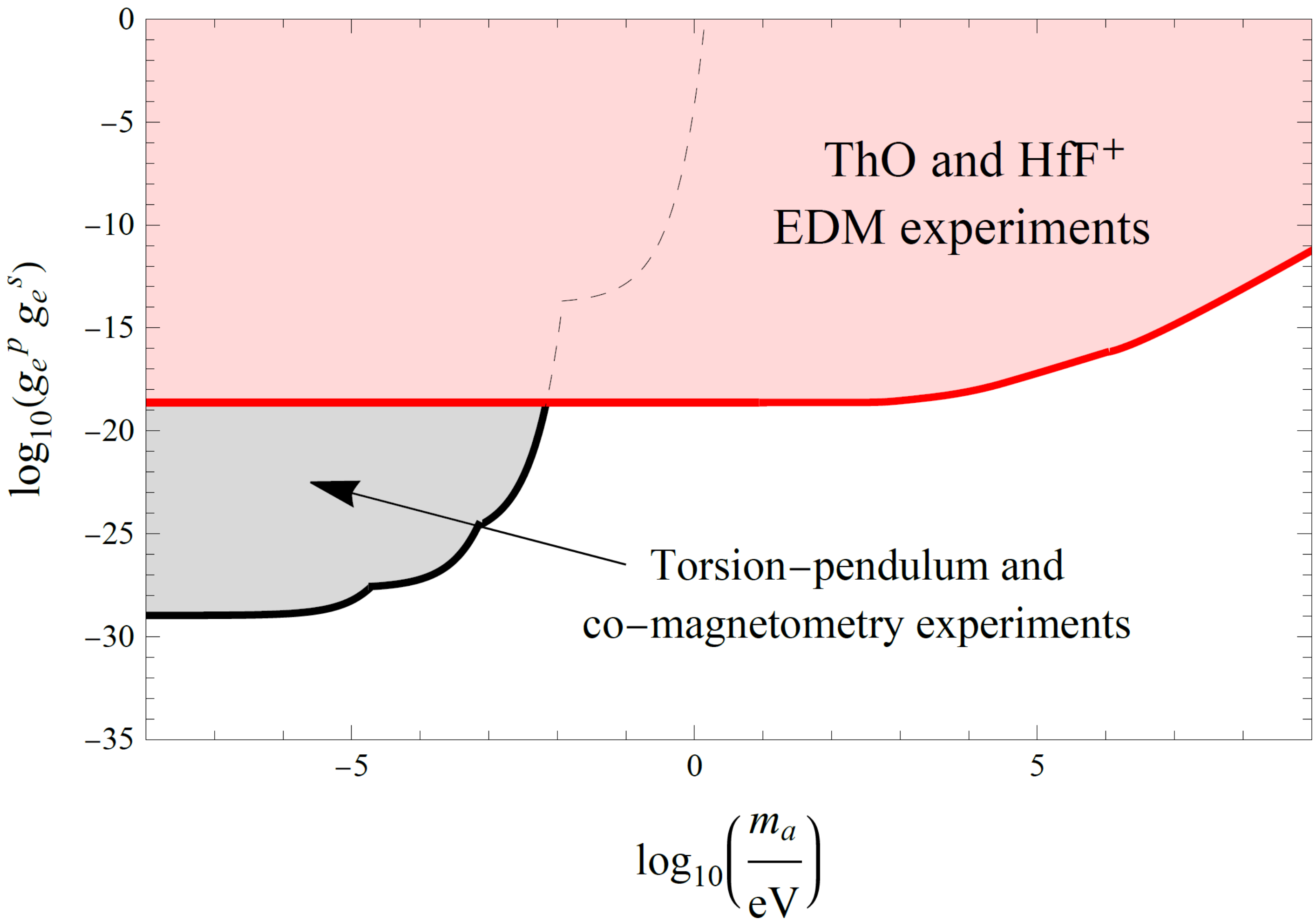
P,T-violating forces => Atomic and Molecular EDMs

If exchanged boson is sufficiently low-mass, then P,T-violating forces are long-range on the scale of atom/molecule, and the non-vanishing contribution arises from the Thomas-Fermi length scale $r \sim a_{\mathrm{B}}/Z^{1/3}$

Constraints on Scalar-Pseudoscalar Electron-Electron Interaction

EDM constraints: [Stadnik, Dzuba, Flambaum, *PRL* **120**, 013202 (2018); arXiv:1708.00486]

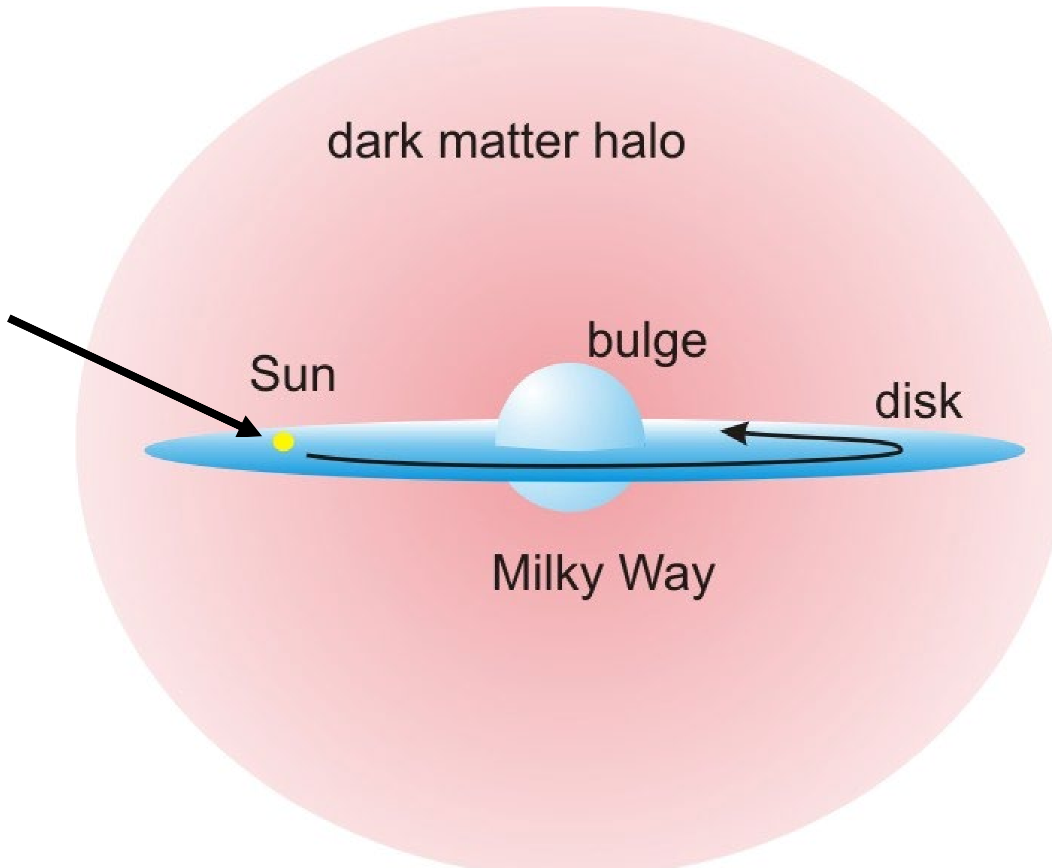


Dark Matter

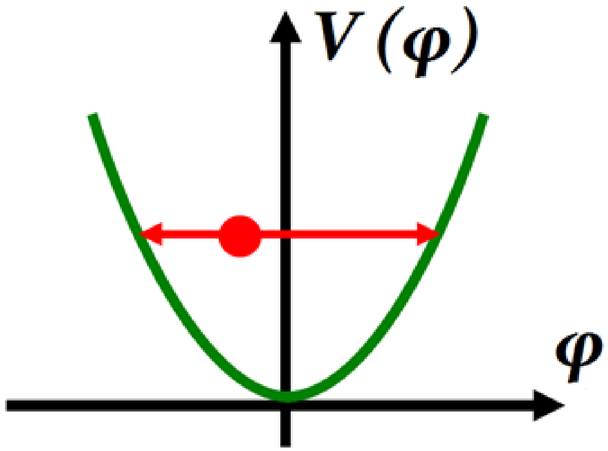
Strong astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter)

$$\rho_{\mathrm{DM}} \approx 0.4\ \mathrm{GeV/cm^3}$$

$$v_{\mathrm{DM}} \sim 300\ \mathrm{km/s}$$



Oscillating Electric Dipole Moments



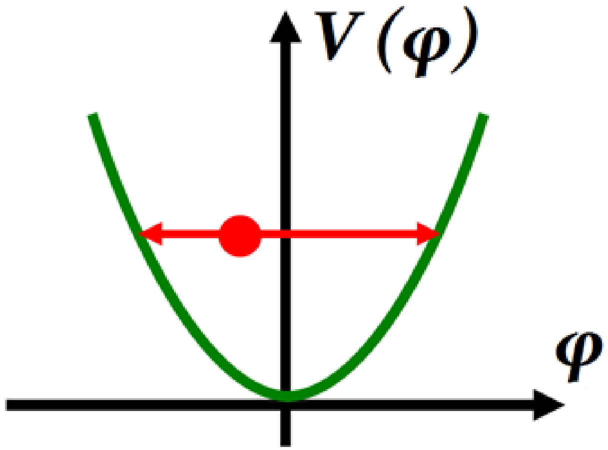
$$\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right),$$

$$\langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2 / 2$$

Oscillating Electric Dipole Moments

Nucleons: [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]; [Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]



$$\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right),$$

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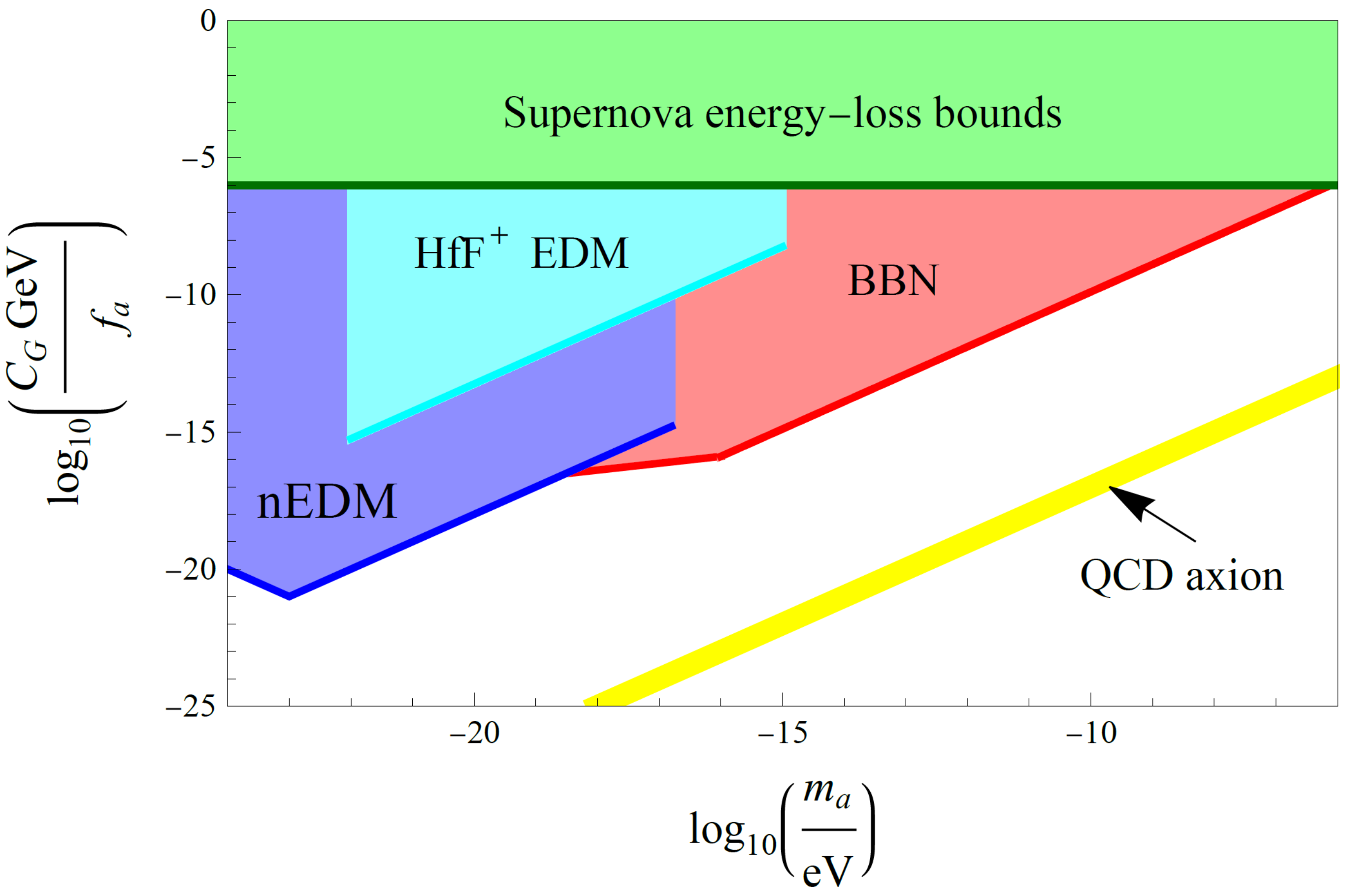
$$\mathcal{L} = \frac{C_G g_s^2}{32\pi^2 f_a} \varphi_0 \cos\left(m_\varphi t\right) G\tilde{G} \quad \Rightarrow \quad \boldsymbol{d}(t) \propto \boldsymbol{J} \cos\left(m_\varphi t\right), \quad H_{\mathrm{EDM}}(t) = \boldsymbol{d}(t) \cdot \boldsymbol{E}$$

$$\text{cf.} \quad \mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \quad \Rightarrow \quad \theta \leftrightarrow C_G \varphi_0 \cos\left(m_\varphi t\right) / f_a$$

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

HfF^+ EDM constraints: [Roussy *et al*., *PRL* **126**, 171301 (2021)]



Summary

- Plethora of opportunities for radioactive molecules in tests of fundamental symmetries and searches for new physics:
  - Paramagnetic molecules sensitive to hadronic sources of CP violation via two-photon-exchange processes (*regardless* of nucleus spin; i.e., operative for *spinless* nuclei, such as in ^{232}ThO, $^{180}HfF^{+}$)
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  - Low-mass bosonic dark matter can induce oscillating-in-time EDMs

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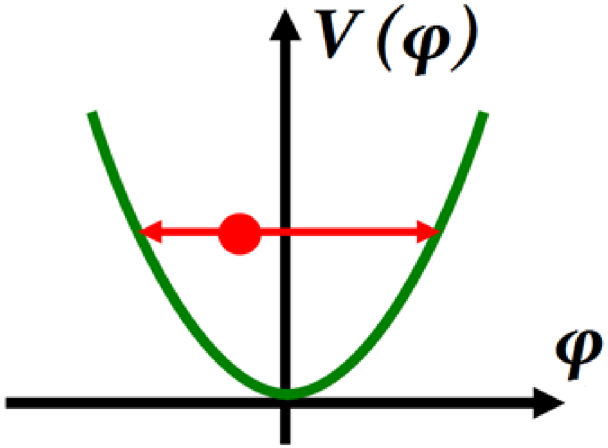
  - Low-mass bosonic dark matter can induce oscillating-in-time EDMs
- Further work:
  - *For two-photon-exchange processes*: nuclear structure effects, nuclear in-medium effects, η' and other N^{2}LO contributions
  - *For nucleon-spin-dependent phenomena*: improved knowledge of proton and neutron spin contributions in heavy nuclei
  - Improved calculations of Schiff moments of heavy nuclei

Back-Up Slides

Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2/2$ $(\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3})$



$$V(\varphi) = \frac{m_\varphi^2 \varphi^2}{2}$$

$$\ddot{\varphi} + m_\varphi^2 \varphi \approx 0$$

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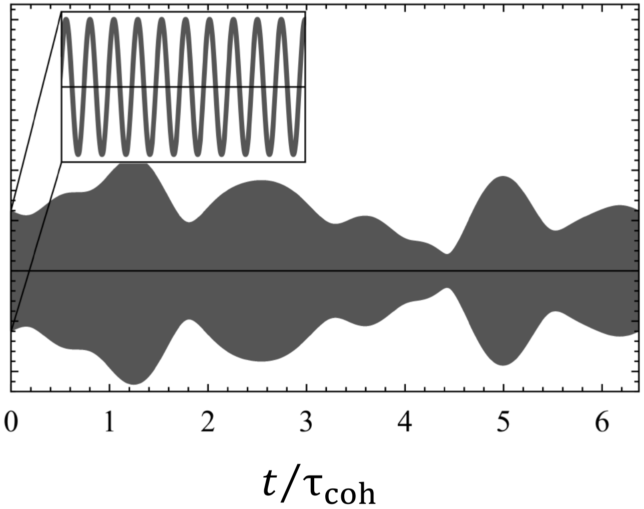
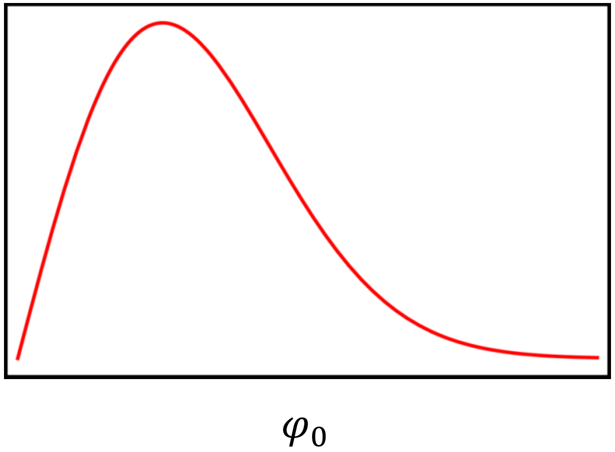
Evolution of φ_0 with time



Probability distribution function of φ_0 (e.g., Rayleigh distribution)



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$T_{\mathrm{osc}} \sim 1\ \mathrm{month}$

IR frequencies

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

[Related figure-of-merit: $\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\mathrm{dwarf\ galaxy}} \sim 100\ \mathrm{pc} \ \Rightarrow \ m_\varphi \gtrsim 10^{-21}\ \mathrm{eV}$]

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↑

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]