Atomic Probes of Axionlike Particles and Dark Matter

Yevgeny Stadnik

Humboldt Fellow

Johannes Gutenberg University, Mainz, Germany

Collaborators (Theory):

Victor Flambaum (UNSW)

Collaborators (Experiment):

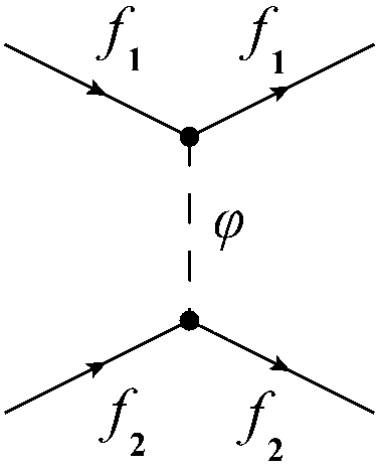
nEDM collaboration at PSI and Sussex

BASE collaboration at CERN and RIKEN

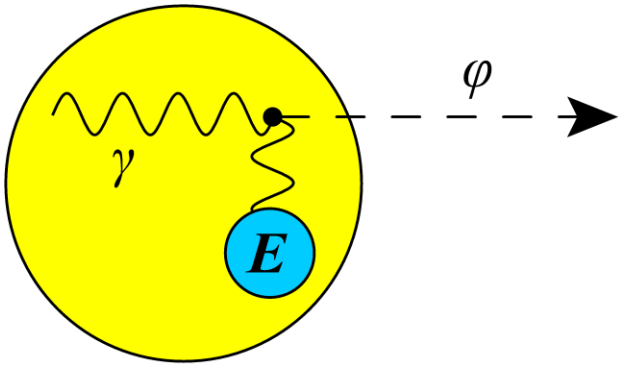
CASPEr collaboration at Mainz

14th Patras Workshop, DESY, June 2018

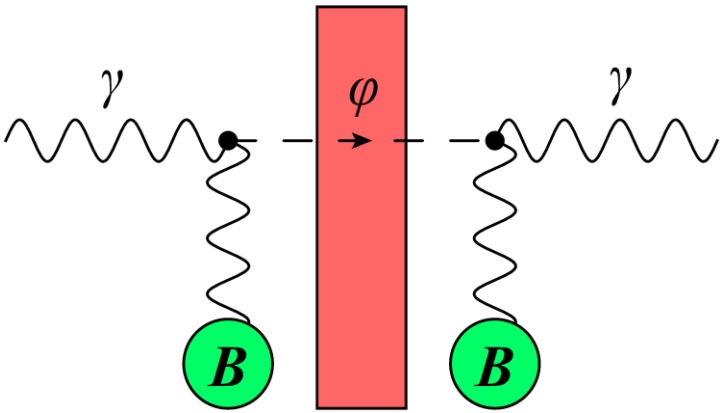
Manifestations of Dark Bosons



New forces



Stellar emission



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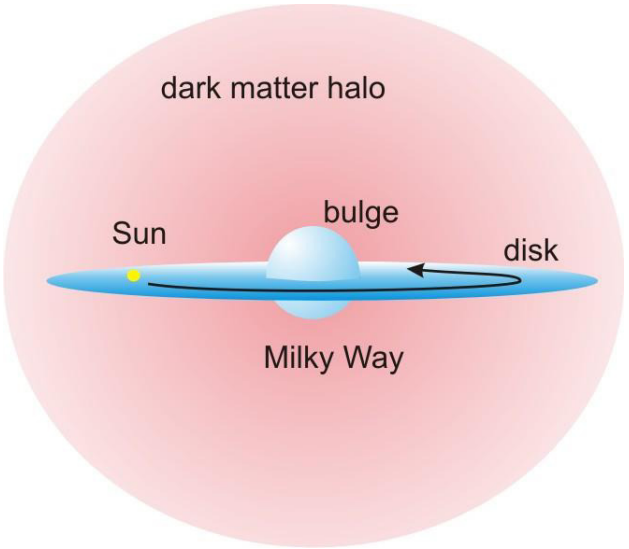

Dark matter

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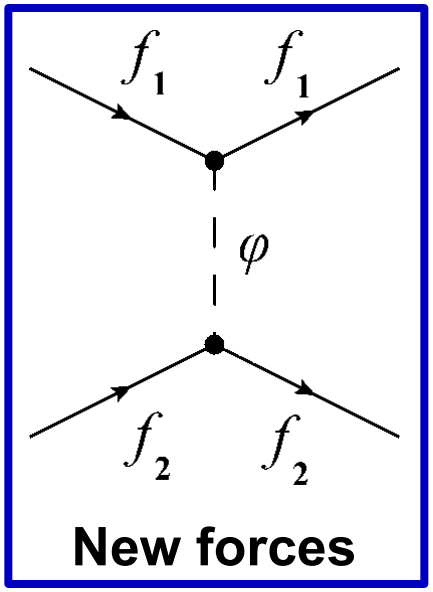

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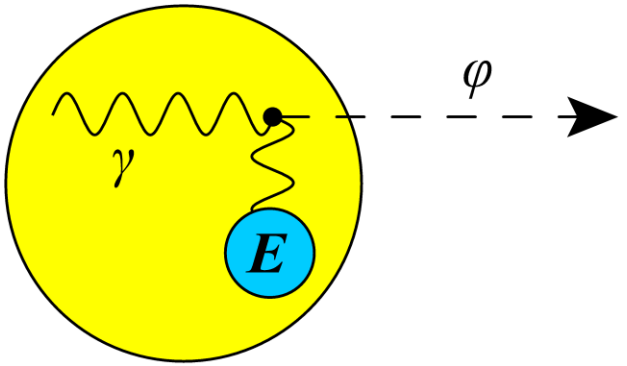

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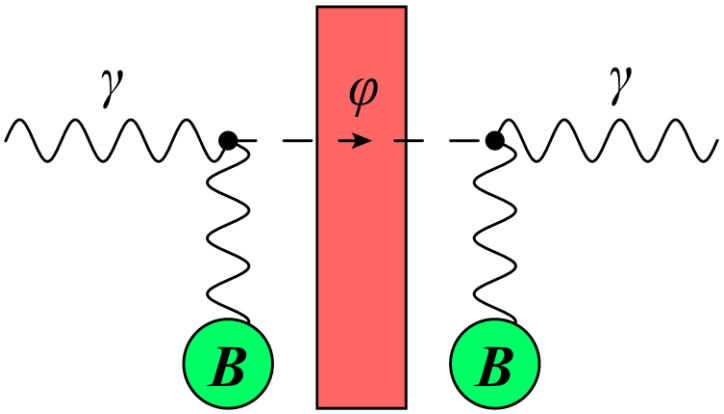

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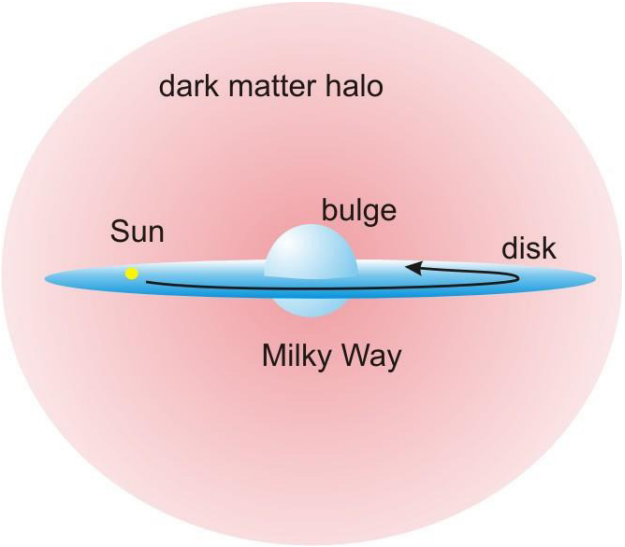

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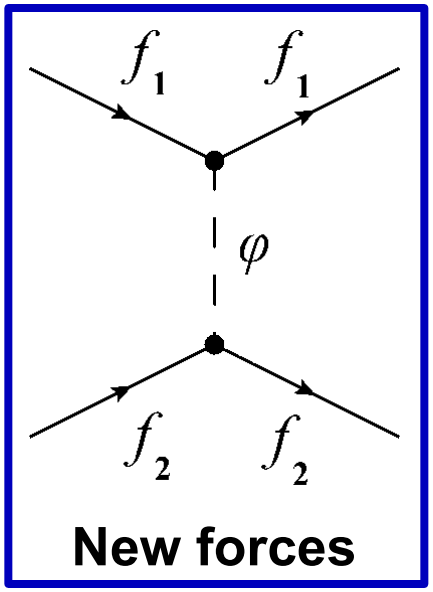

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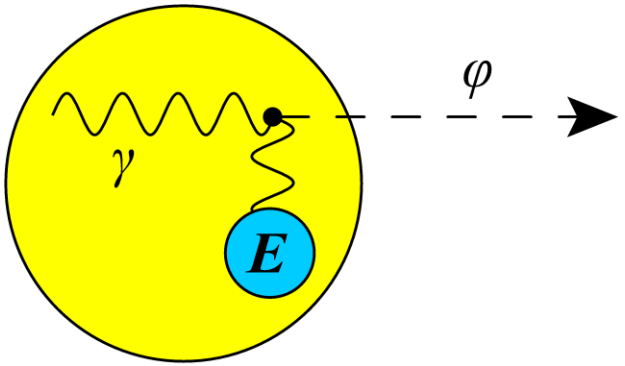

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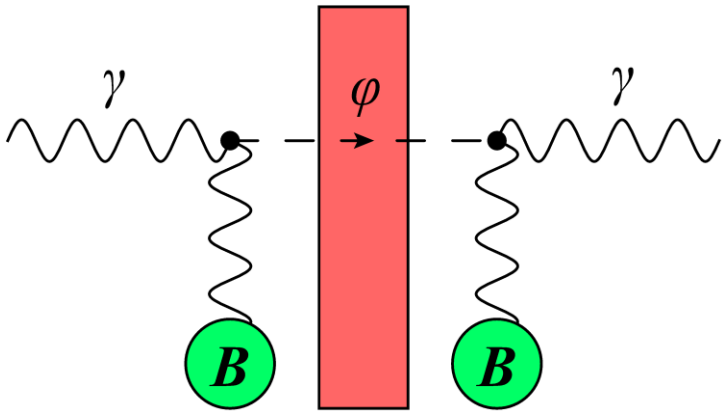

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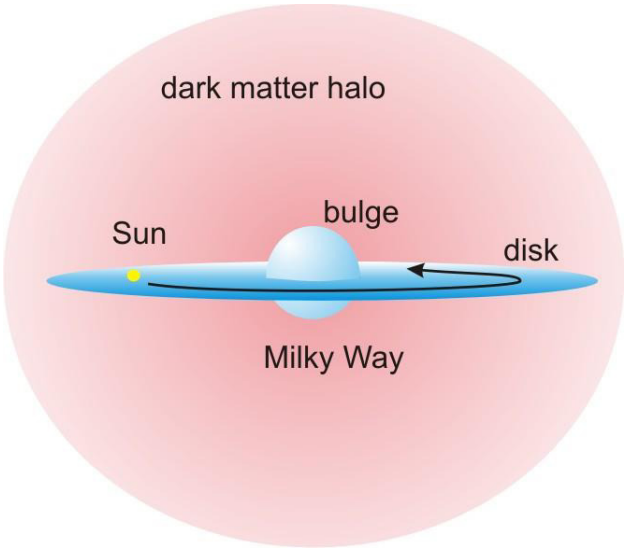
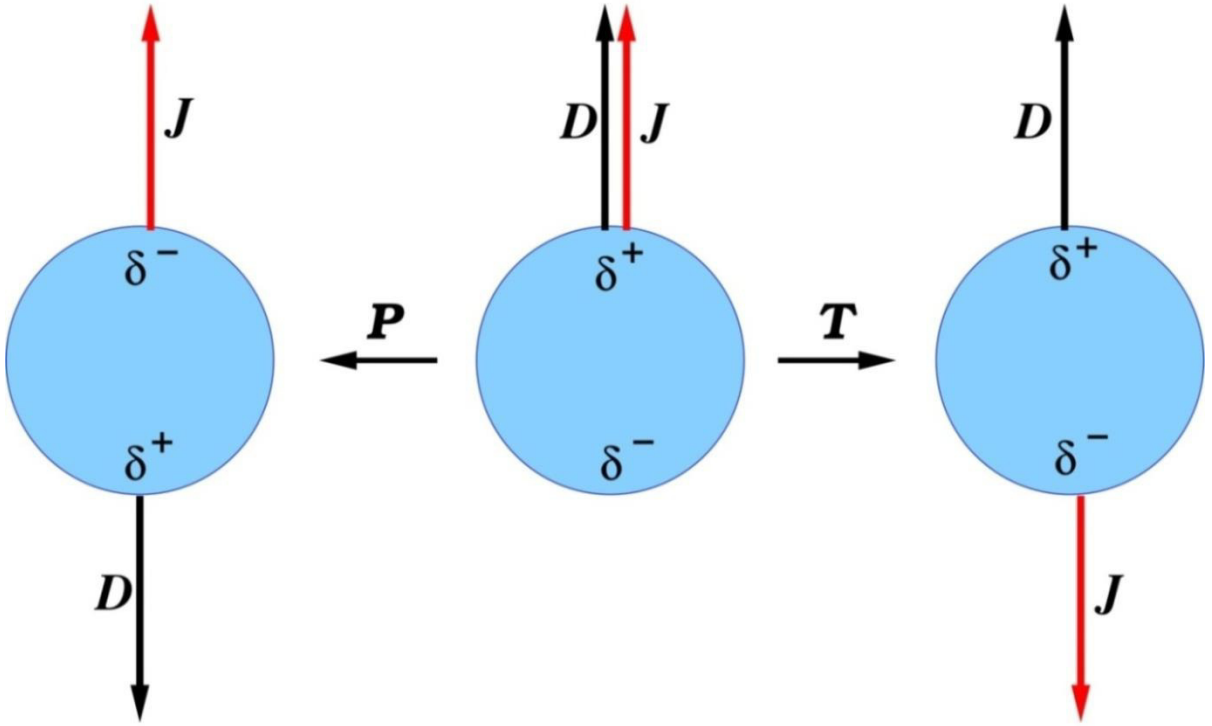


Dark matter

Basics of Atomic EDMs

Electric Dipole Moment (EDM) = parity (P) and time-reversal-invariance (T) violating electric moment



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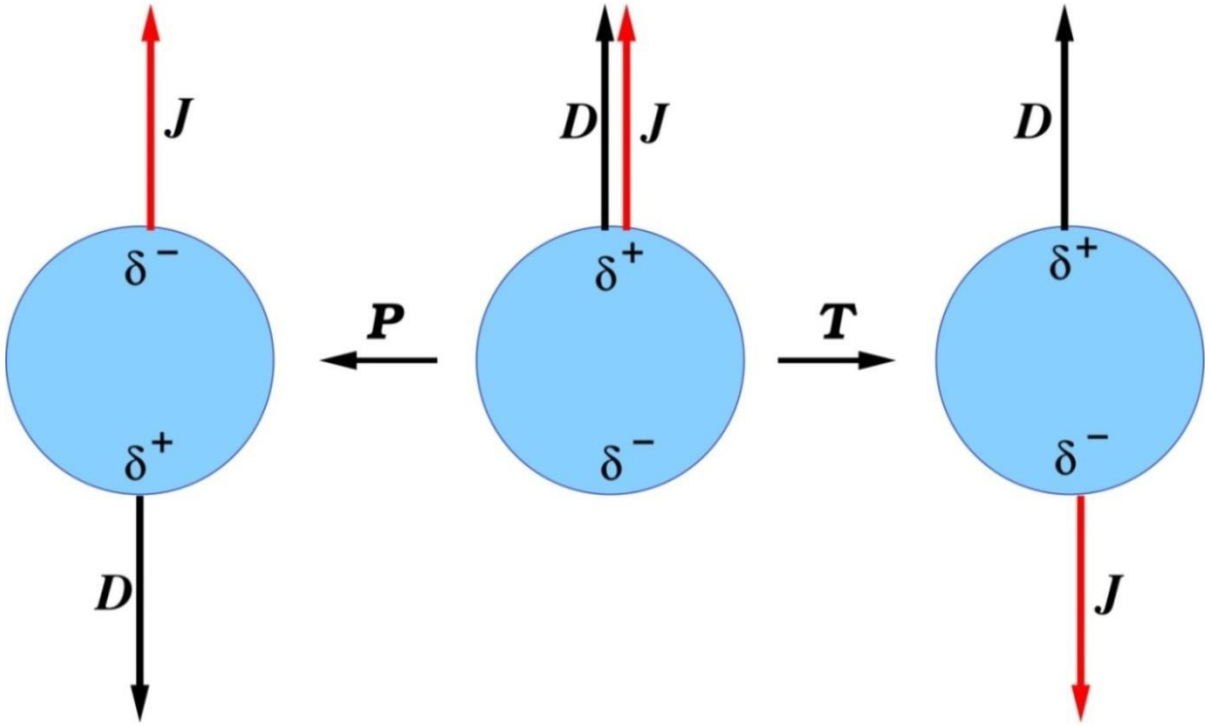

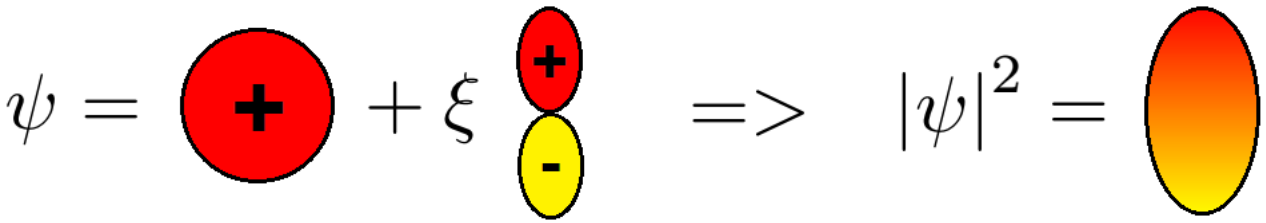

Non-Cosmological Sources of Dark Bosons

[Stadnik, Dzuba, Flambaum, *PRL* **120**, 013202 (2018)],
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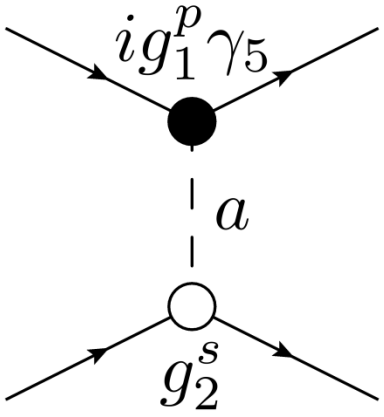

$$\mathcal{L}_{\rm int} = a\bar{f}\left(g_f^s + ig_f^p\gamma_5\right)f$$

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

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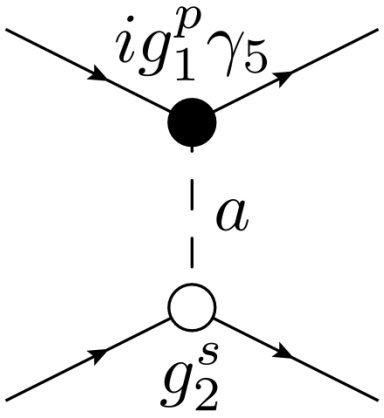

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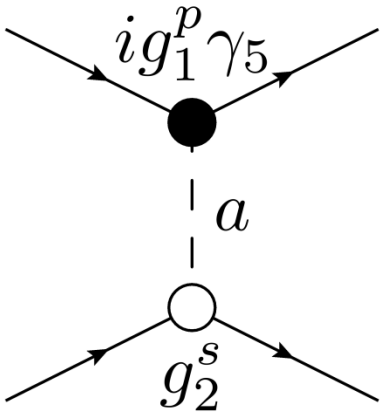

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P,*T*-violating forces => Atomic and Molecular EDMs

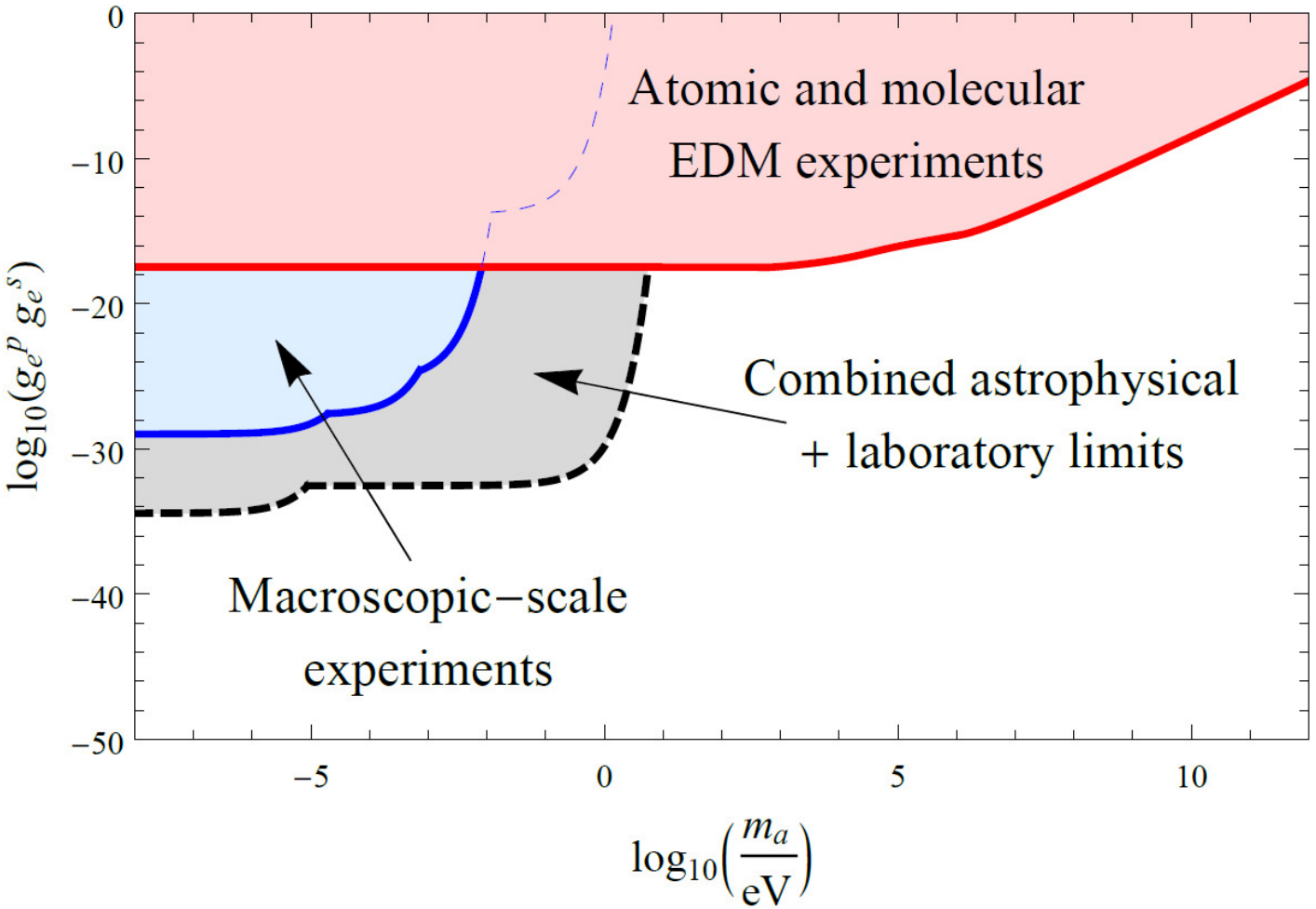
Atomic EDM experiments: Cs, Tl, Xe, **Hg**, Ra

Molecular EDM experiments: YbF, **HfF^+**, **ThO**

Constraints on Scalar-Pseudoscalar Electron-Electron Interaction

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

Many orders of magnitude improvement!



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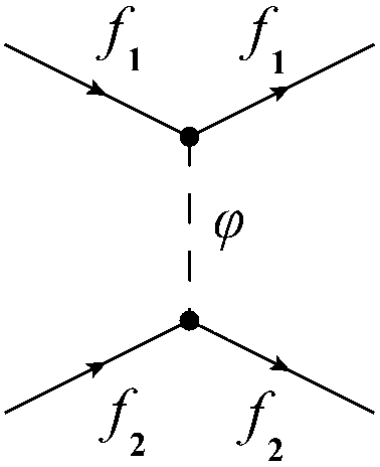

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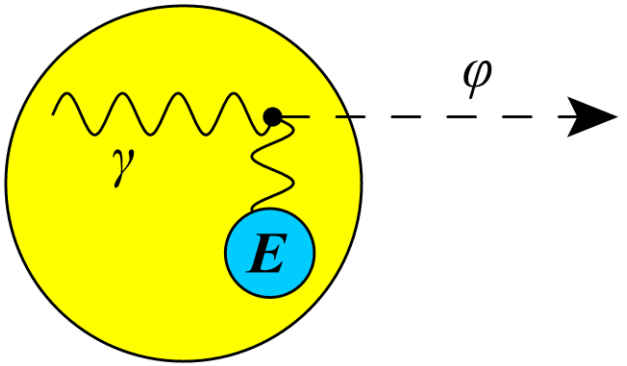

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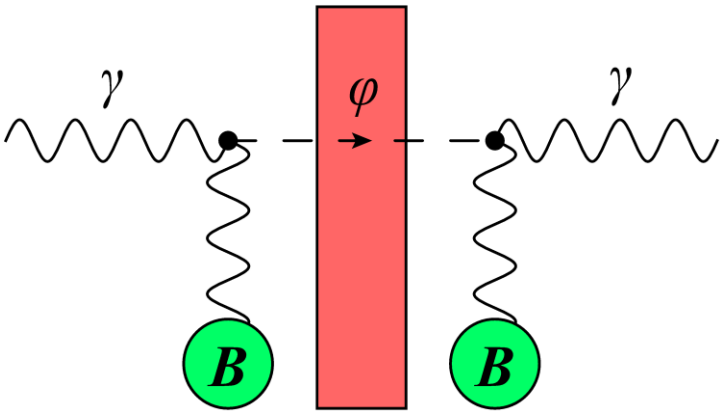

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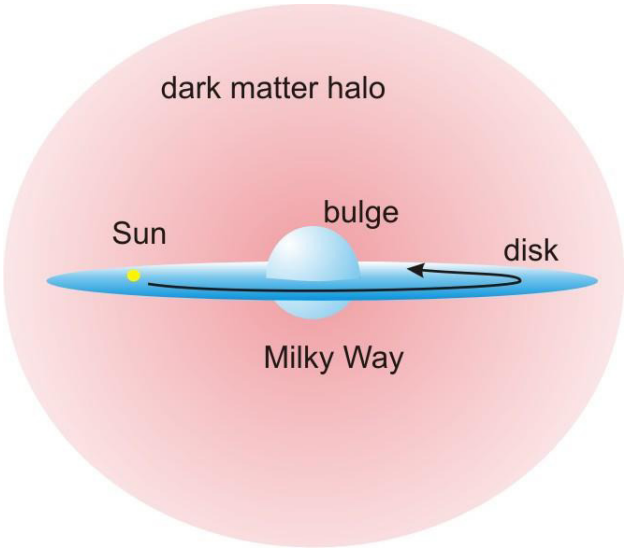
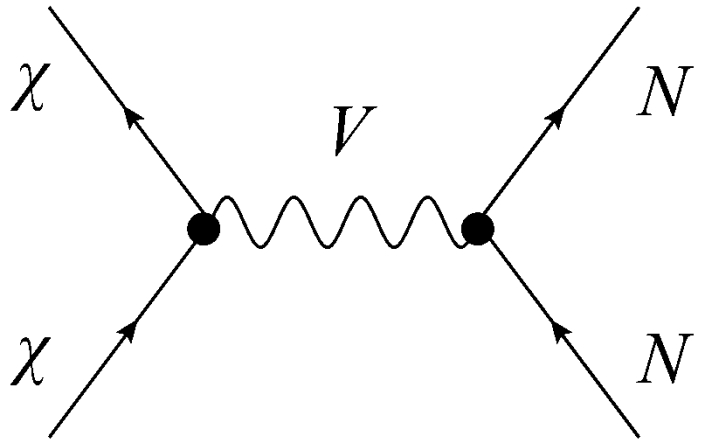


Dark matter

Motivation

Traditional “scattering-off-nuclei” searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



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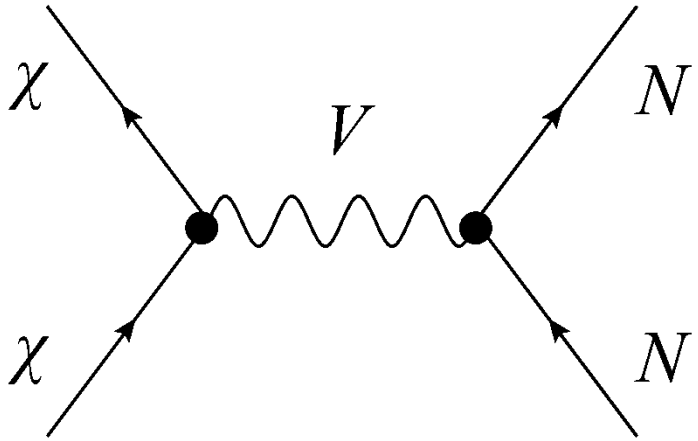

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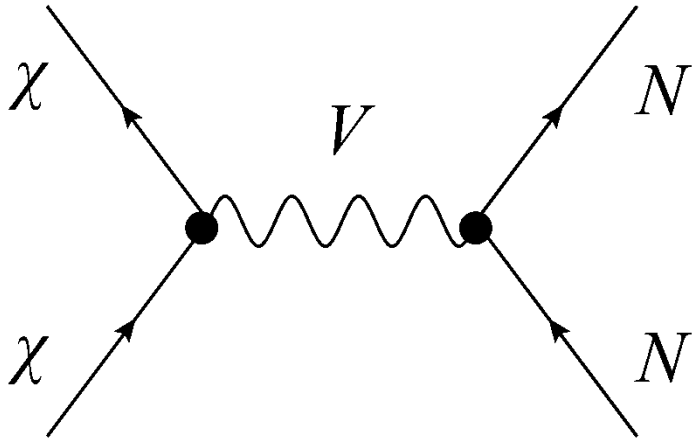

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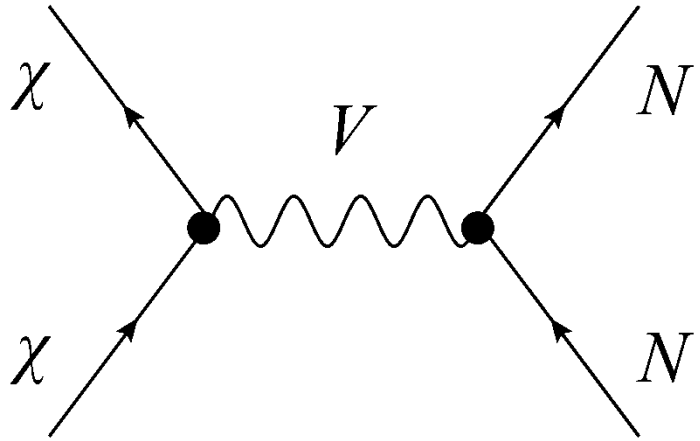

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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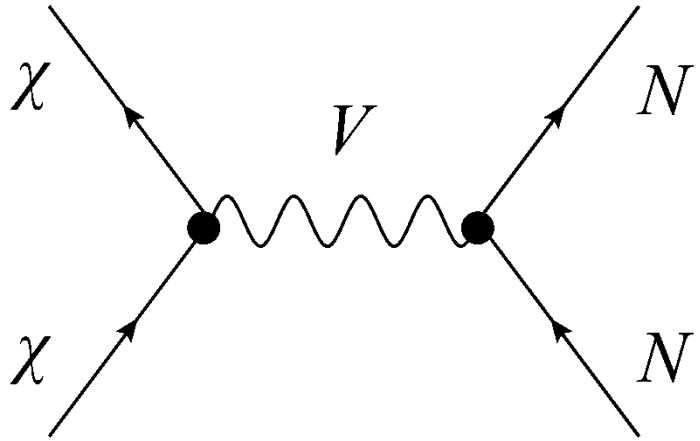

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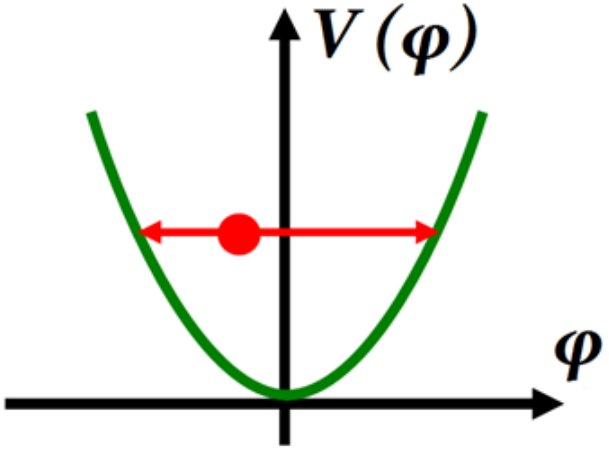
Question: *Can we instead look for effects of dark matter that are* ***first power*** *in the interaction constant?*

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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{DM,local} \approx 0.4$ GeV/cm^3)



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

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Classical field

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- $m_\varphi \sim 10^{-22}$ eV <=> $T \sim 1$ year

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- **First-power effects** => Improved sensitivity to certain DM interactions by up to **15 orders of magnitude** **(!)**

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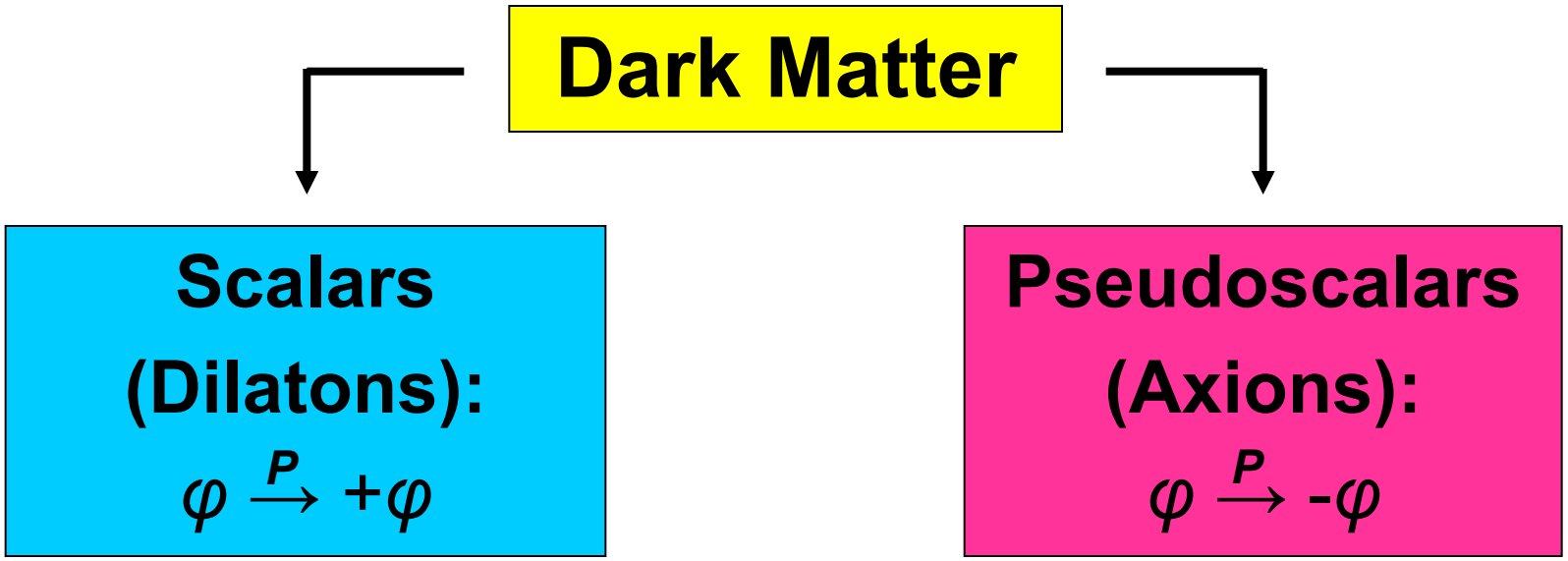


⟶ Time-varying fundamental constants

10^{15}-fold improvement

Victor Flambaum talk

⟶ Time-varying spin-dependent effects

1000-fold improvement

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

$\varphi \xrightarrow{P} -\varphi$

QCD axion resolves strong CP problem

$\longrightarrow$ Time-varying spin-dependent effects

1000-fold improvement

“Axion Wind” Spin-Precession Effect

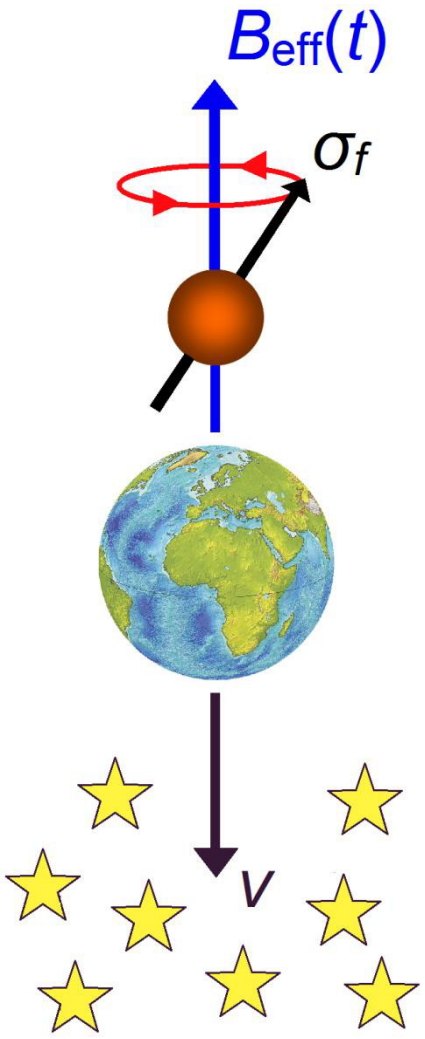
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a}\partial_i[a_0\cos(\varepsilon_a t - \boldsymbol{p}_a\cdot\boldsymbol{x})]\bar{f}\gamma^i\gamma^5 f$$

$$=> \quad H_{\rm eff}(t) \simeq \boldsymbol{\sigma}_f\cdot\boldsymbol{B}_{\rm eff}\sin(m_a t)$$

***Pseudo*-magnetic field**

$$\boldsymbol{B}_{\rm eff} \propto \boldsymbol{v}$$



Oscillating Electric Dipole Moments

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

Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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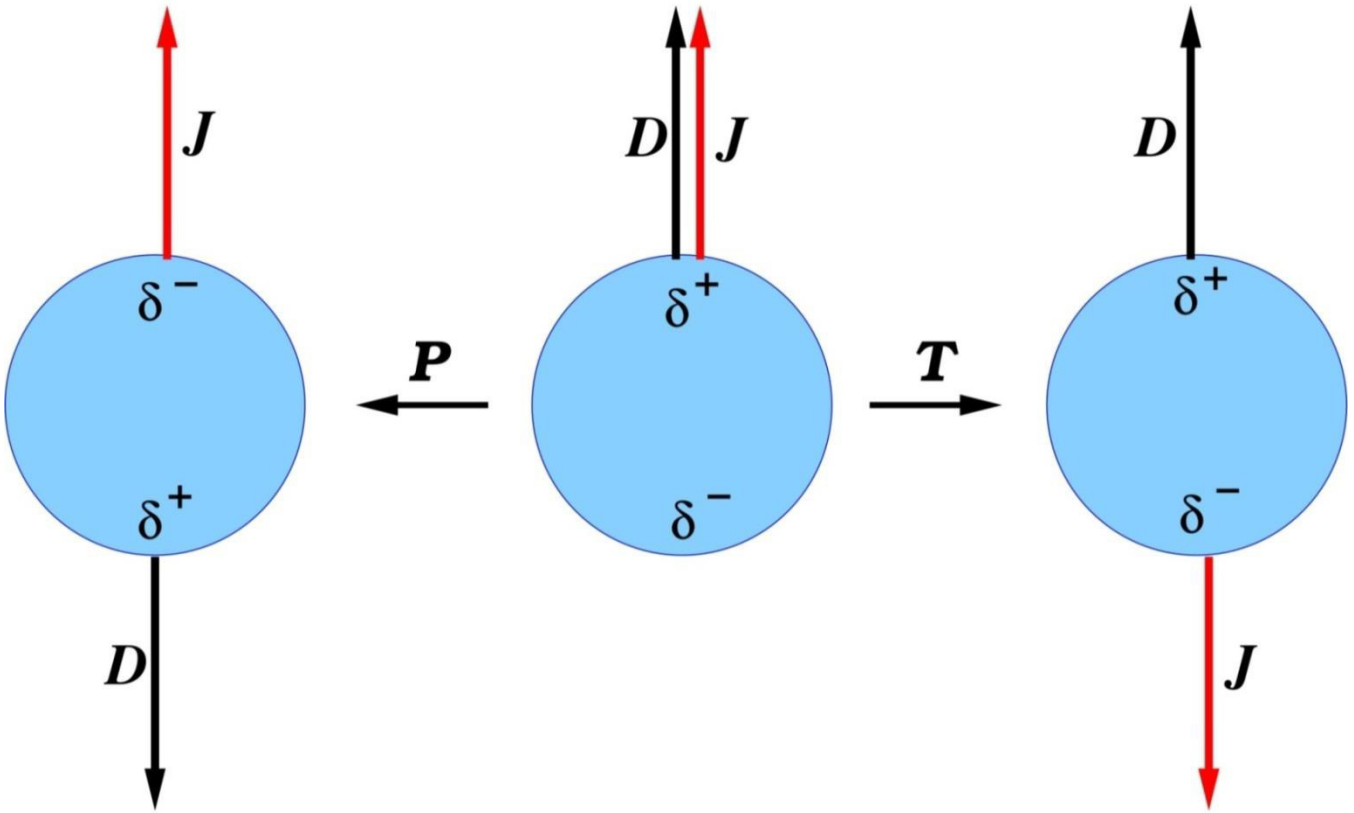

Searching for Spin-Dependent Effects

Proposals: [Flambaum, talk at *Patras Workshop*, 2013; Stadnik, Flambaum, *PRD* **89**, 043522 (2014); arXiv:1511.04098; Stadnik, PhD Thesis (2017)]

Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

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Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]

$$\frac{\nu_n}{\nu_{\rm Hg}} = \left| \frac{\gamma_n B}{\gamma_{\rm Hg} B} \right| + R(t)$$

***B*-field effect** | **Axion DM effect**

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Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]

$$\frac{\nu_n}{\nu_{\rm Hg}} = \left| \frac{\gamma_n \cancel{B}}{\gamma_{\rm Hg} \cancel{B}} \right| + R(t)$$

***B*-field effect**

Axion DM effect

Searching for Spin-Dependent Effects

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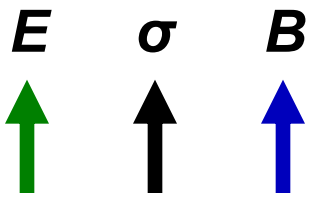
$$R_{\rm EDM}(t) \propto \cos(m_a t)$$



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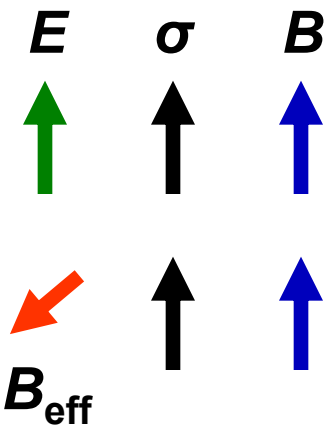
$$R_{\rm wind}(t) \propto \sum_{i=1,2,3} A_i \sin(\omega_i t)$$



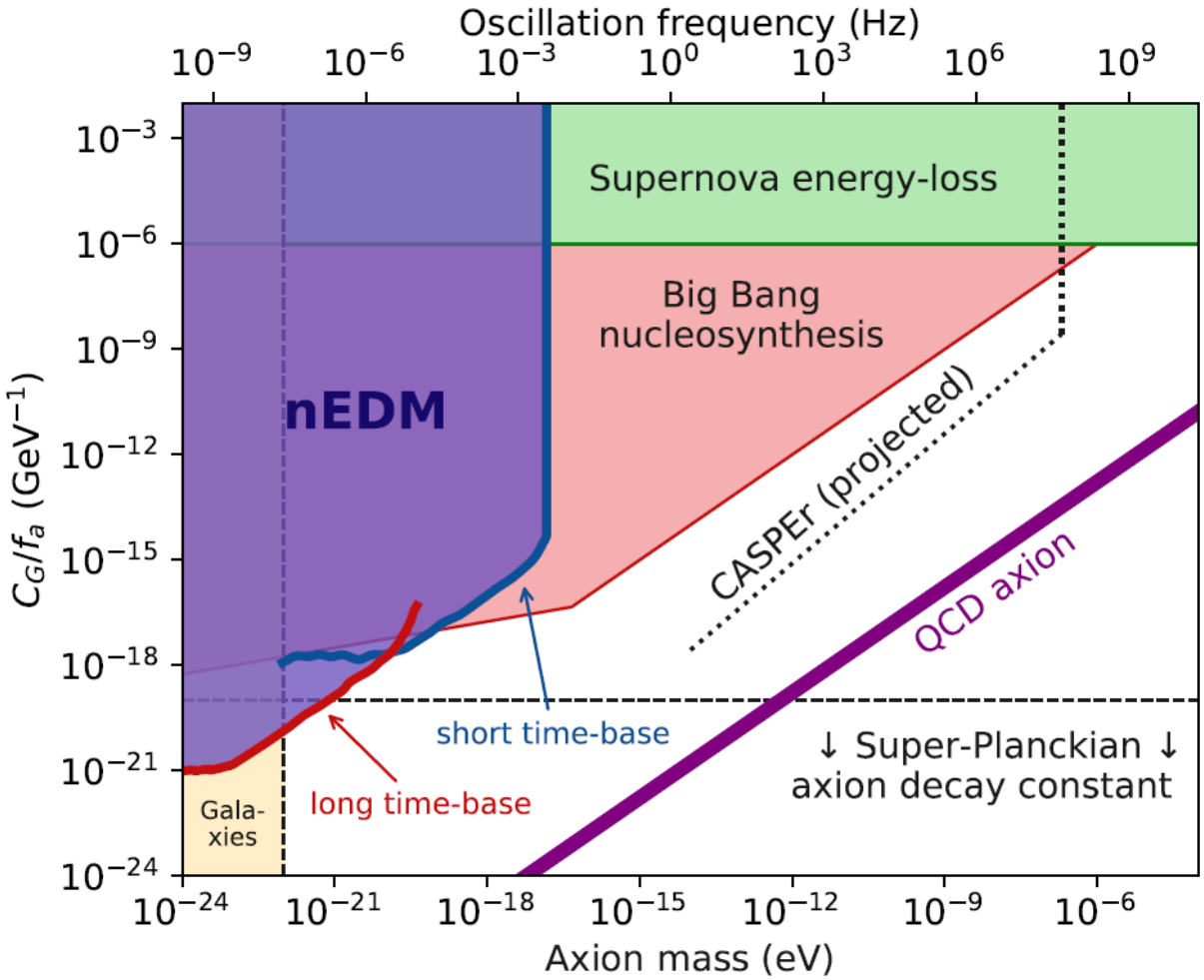
$$\omega_1 = m_a, \ \omega_2 = m_a + \Omega_{\rm sidereal}, \ \omega_3 = |m_a - \Omega_{\rm sidereal}|$$

Earth's rotation

Constraints on Interaction of Axion Dark Matter with Gluons

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

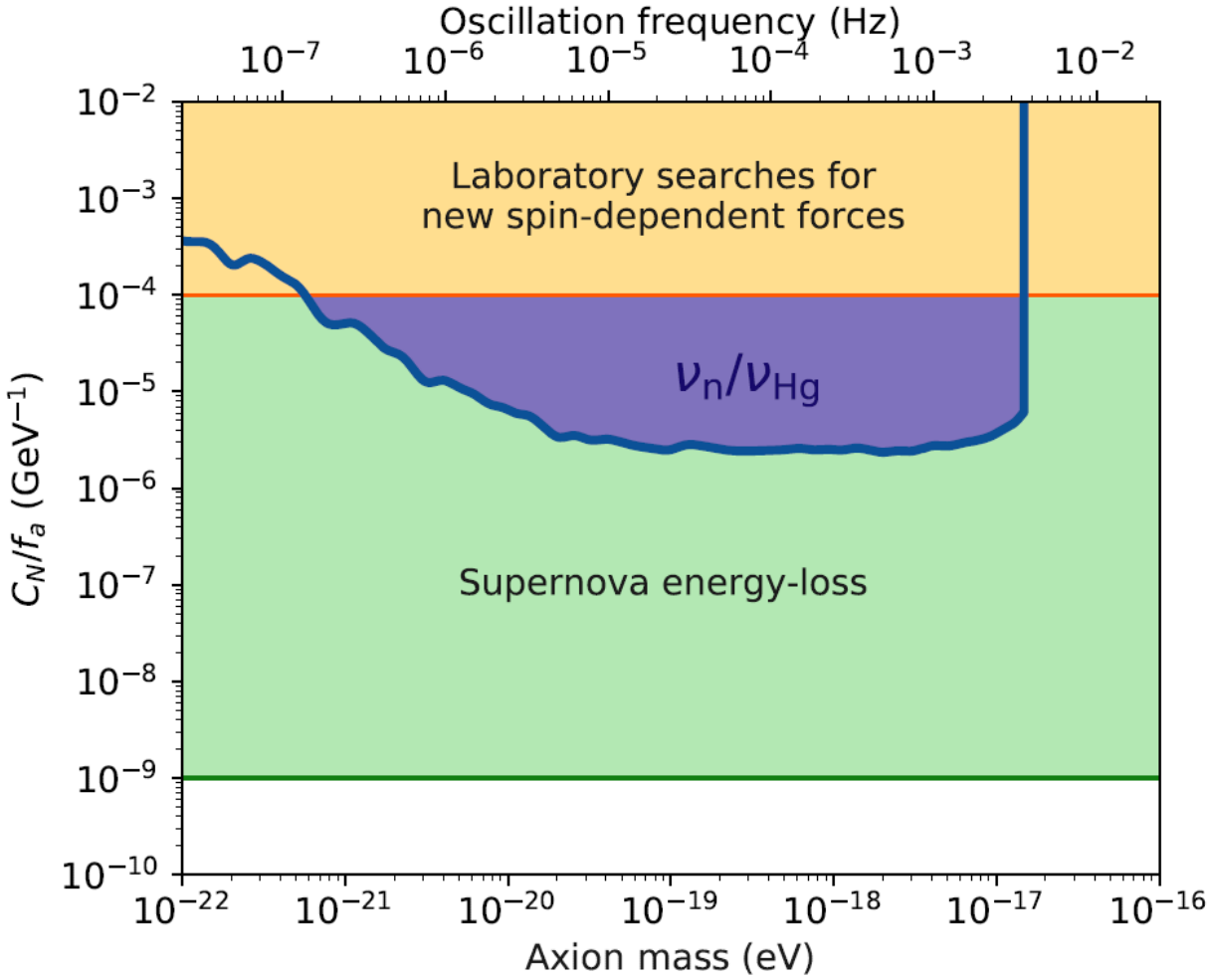
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

v_n/v_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

40-fold improvement (laboratory bounds)!



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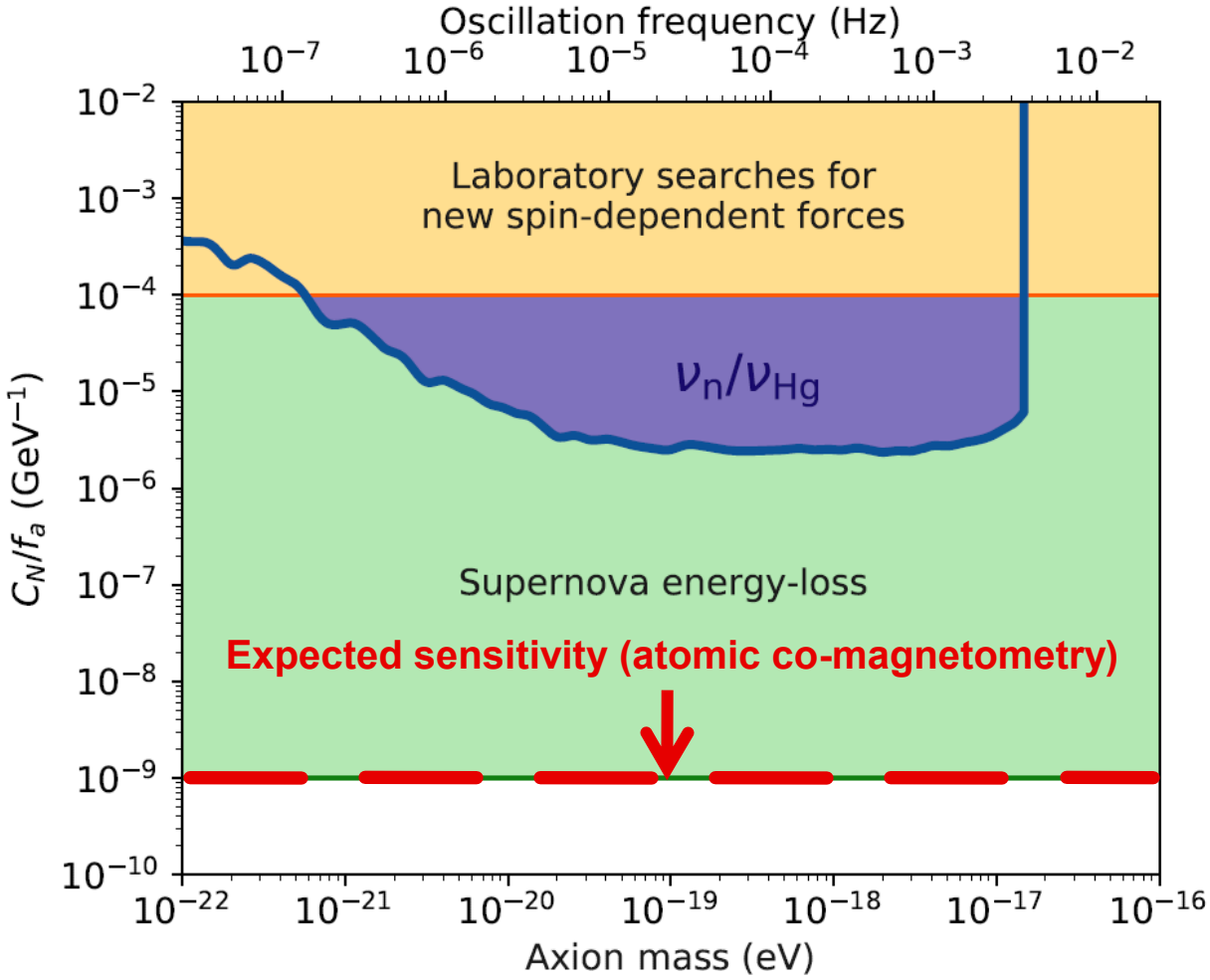
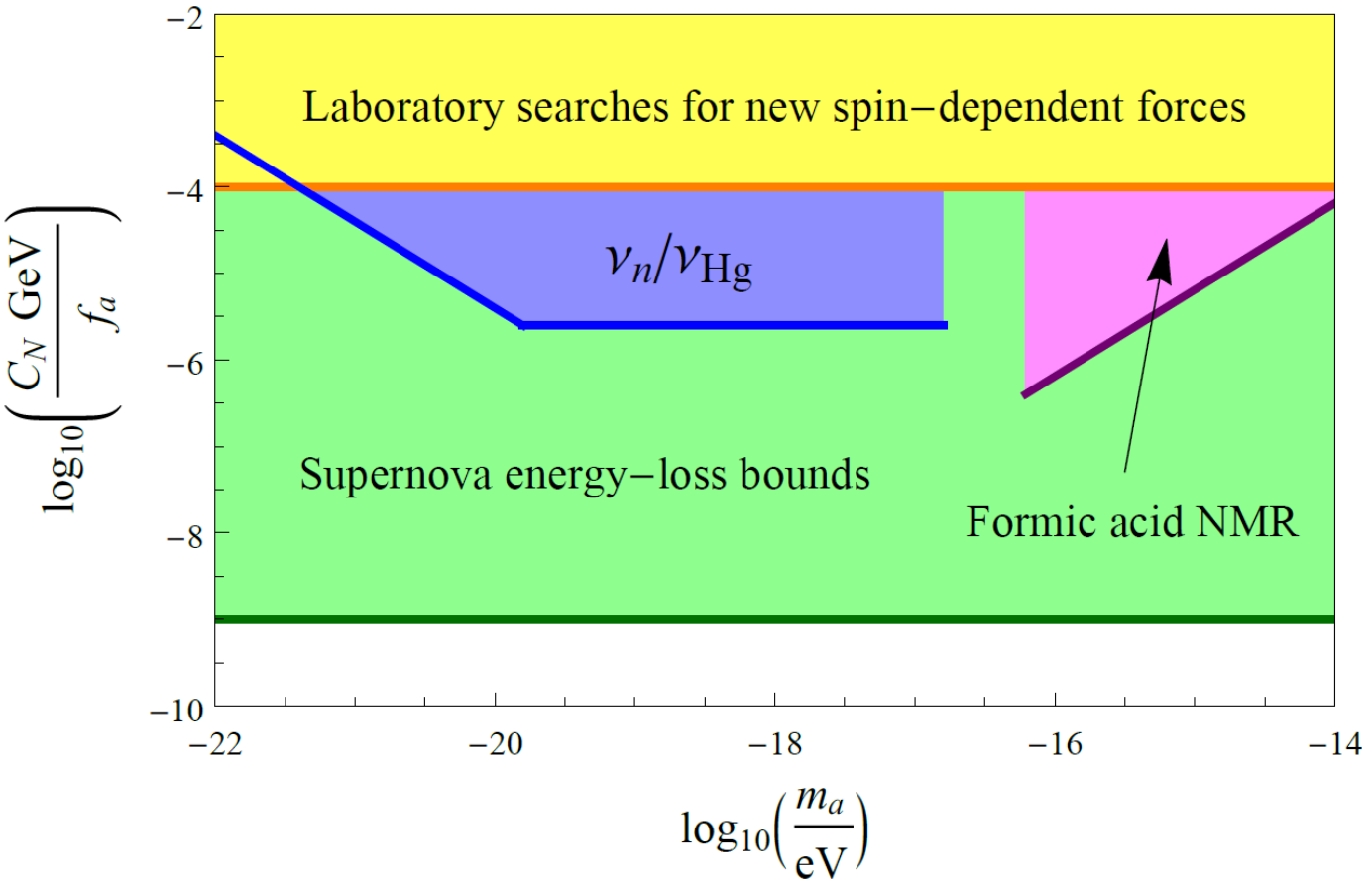


Constraints on Interaction of Axion Dark Matter with Nucleons

v_n/v_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

Formic acid NMR constraints: [CASPEr collaboration, Antoine Garcon talk]

2 orders of magnitude improvement (laboratory bounds)!



Summary

- New classes of dark matter effects that are **first power** in the underlying interaction constant
  => Up to **15 orders of magnitude improvement**

- **Improved limits** on dark bosons from atomic experiments (new forces, independent of ρ_{DM})

- **More details in full slides (also on ResearchGate)**