Low-Energy Atomic Probes of Dark Bosons and Neutrino-Mediated Forces

Yevgeny Stadnik

Humboldt Fellow

Johannes Gutenberg University, Mainz, Germany

Collaborators (Theory):

Victor Flambaum

Collaborators (Experiment):

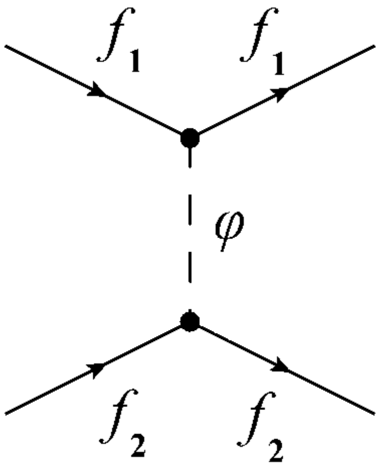
nEDM collaboration at PSI and Sussex

BASE collaboration at CERN and RIKEN

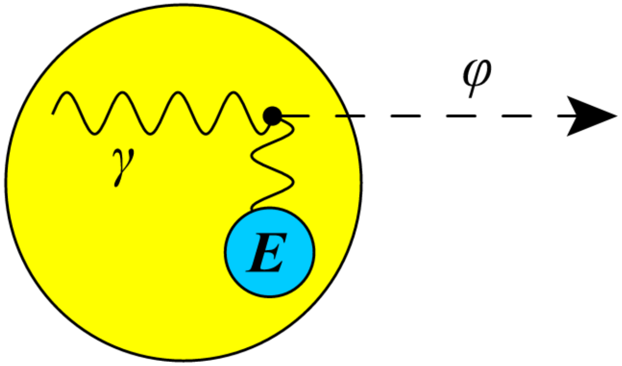
CASPEr collaboration at Mainz

MITP Scientific Program, Mainz, May 2018

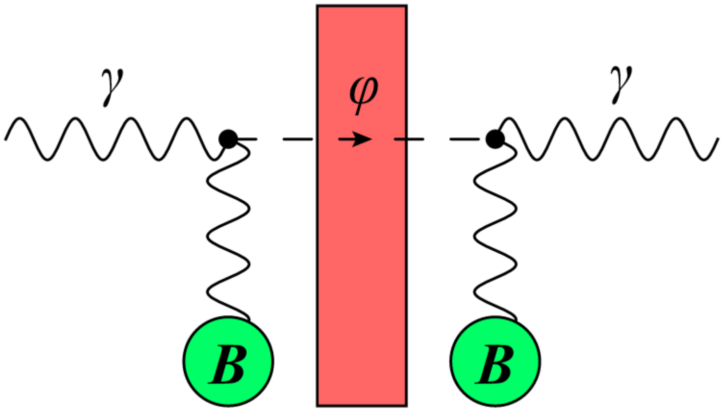
Manifestations of Dark Bosons



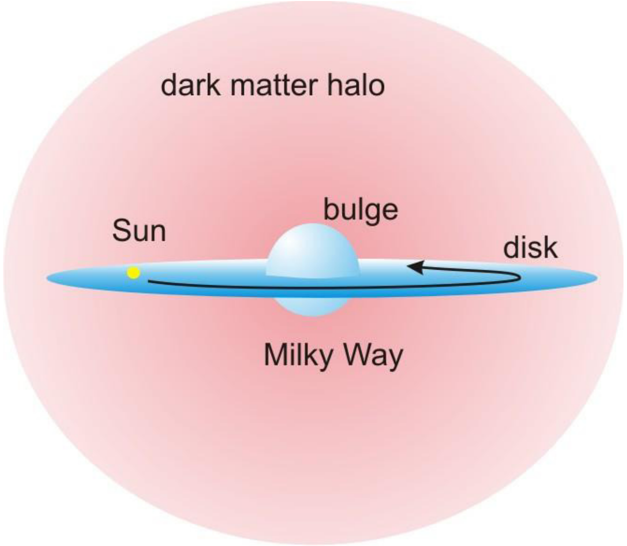
New forces



Stellar emission



Interconversion with ordinary particles



Dark matter

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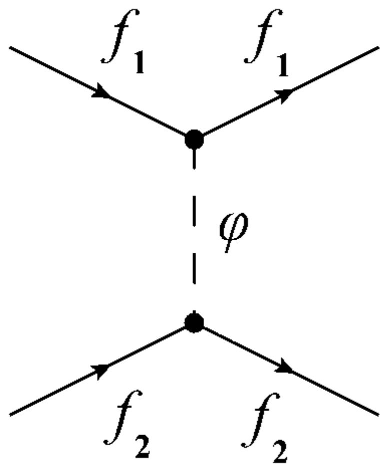

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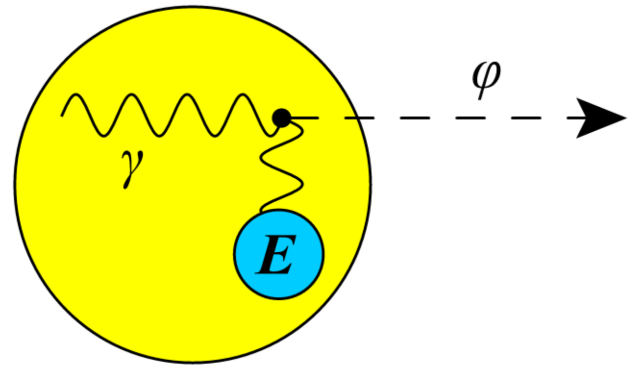

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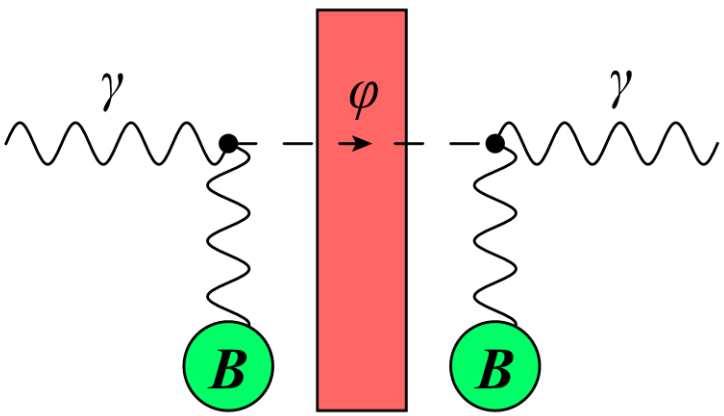

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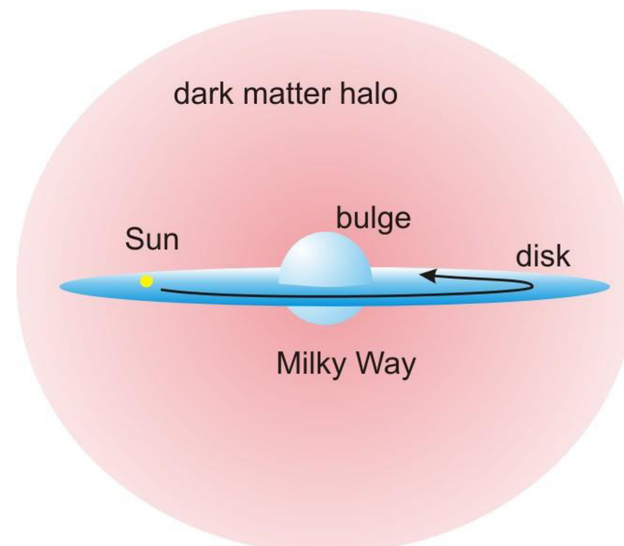

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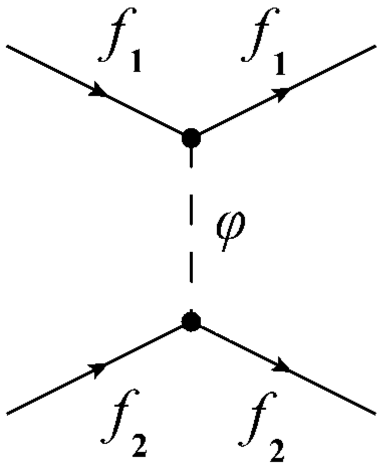

New forces

Atomic spectroscopy:

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Atomic PNC:

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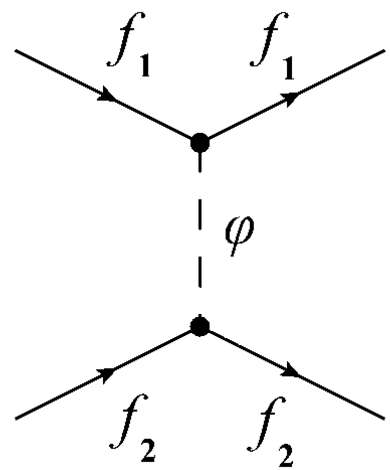

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Basics of Atomic PNC

Parity violation in weak neutral current interactions first discovered in bismuth optical rotation experiments in Novosibirsk

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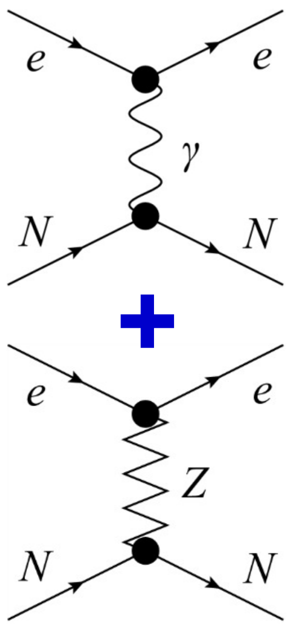

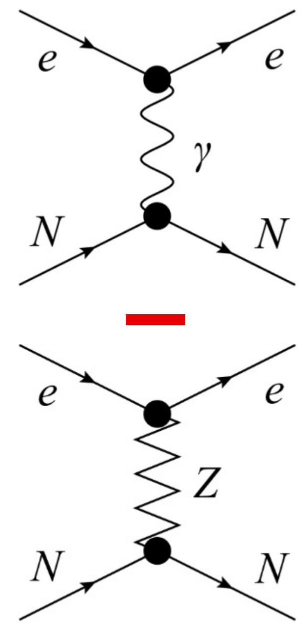

$$Q_W(^{133}\mathrm{Cs}) = -72.58(29)_{\mathrm{exp}}(32)_{\mathrm{theory}} \quad \text{c.f.} \quad Q_W(^{133}\mathrm{Cs})_{\mathrm{SM}} = -73.23(2)$$

Experiment: [Wood *et al.*, *Science* **275**, 1759 (1997)]

Theory: [Dzuba, Berengut, Flambaum, Roberts, *PRL* **109**, 203003 (2012)]

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- If $q_{\text{typical}} \sim 1/R_{\text{nucl}} >> m_e$, then $K_{\text{rel}} \approx 3$

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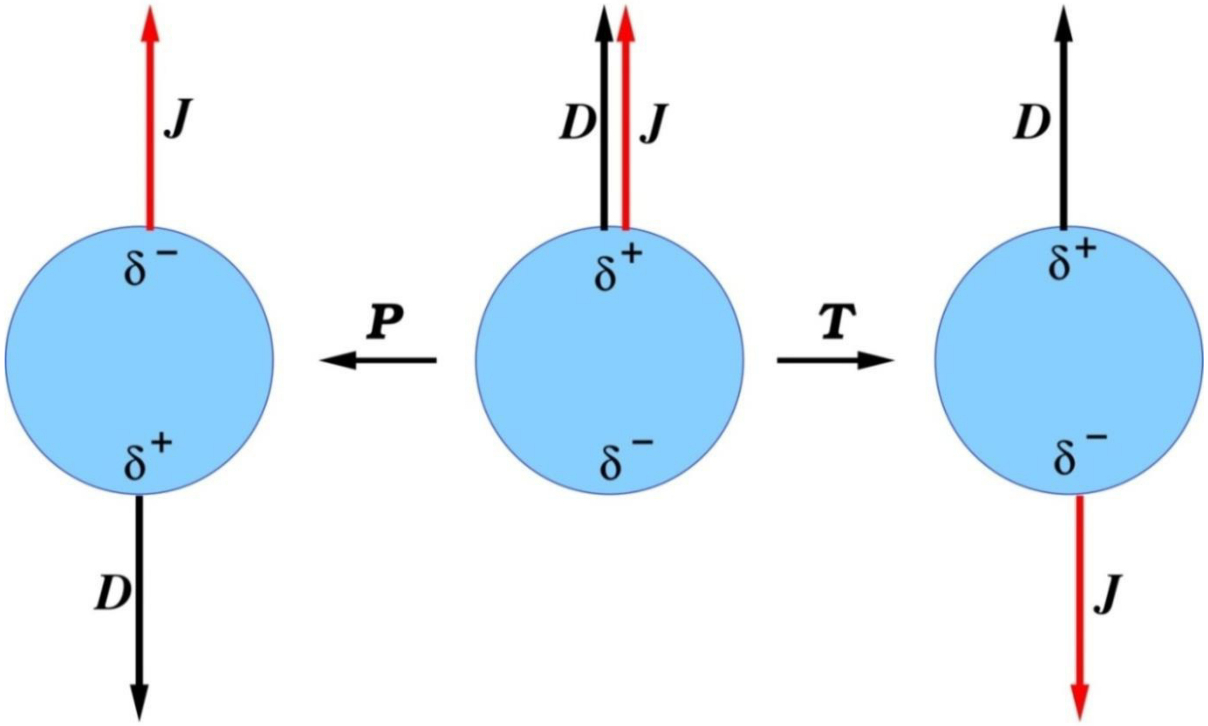
- If $q_{\mathrm{typical}} << m_e$ (like, e.g., in Z-boson exchange between valence electron and 1s electrons), then $K_{\mathrm{rel}} \approx 1$

Basics of Atomic EDMs

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



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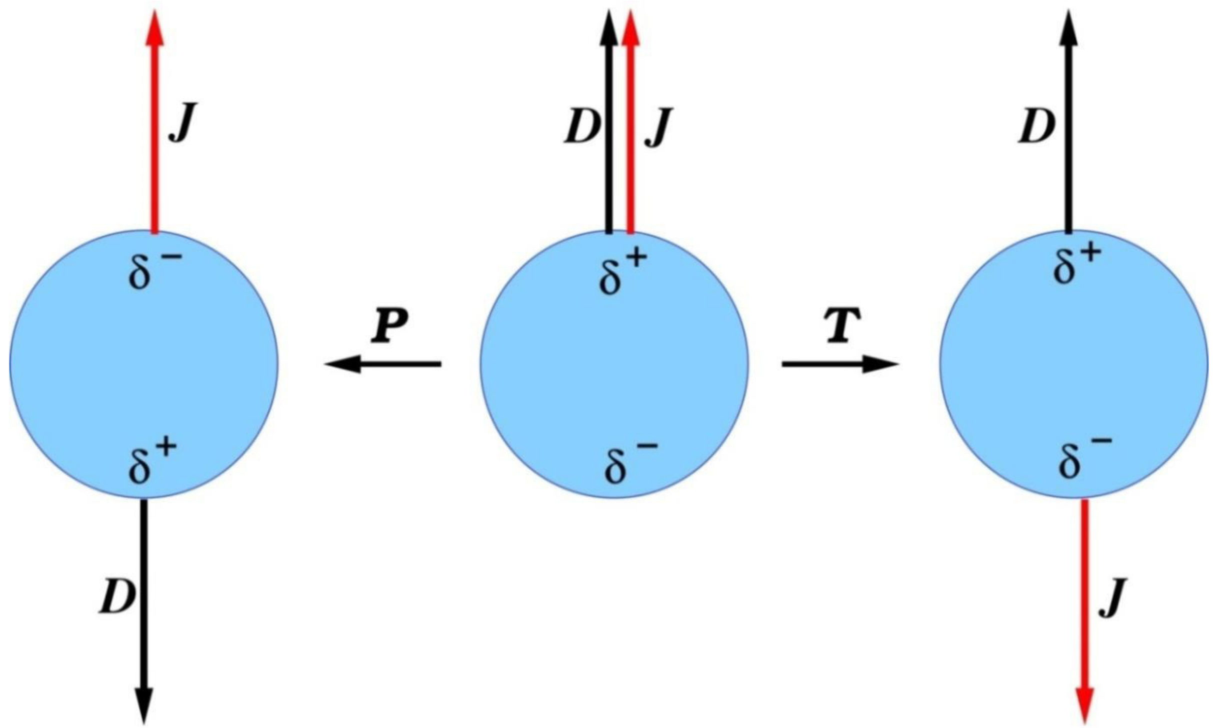
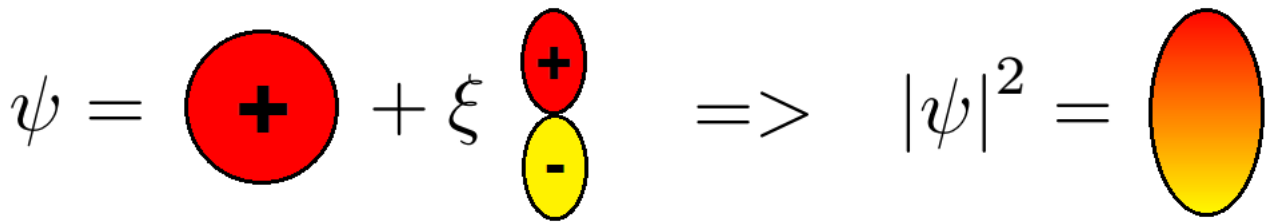
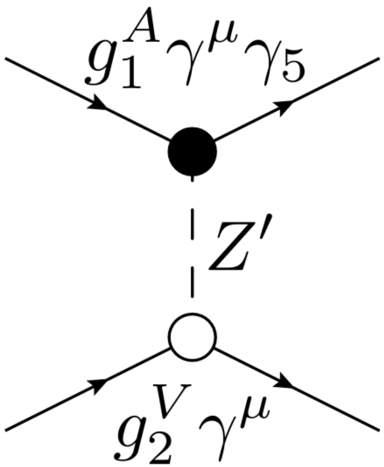




Non-Cosmological Sources of Dark Bosons

[Dzuba, Flambaum, Stadnik, *PRL* **119**, 223201 (2017)]



$$\mathcal{L}_{\mathrm{int}} = Z'_\mu \bar{f} \gamma^\mu \left(g_f^V + g_f^A \gamma_5 \right) f$$

$$V(r) \approx -\frac{g_1^A g_2^V}{8\pi m_1} \left\{ \boldsymbol{\sigma} \cdot \boldsymbol{p} \, , \, \frac{e^{-m_{Z'} r}}{r} \right\}$$

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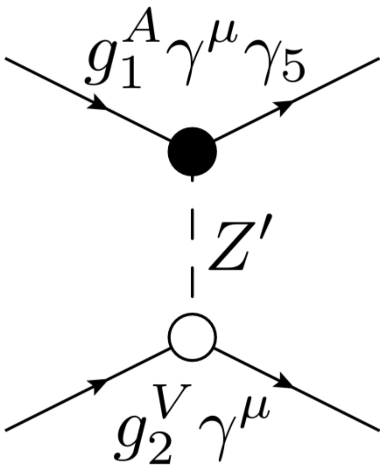

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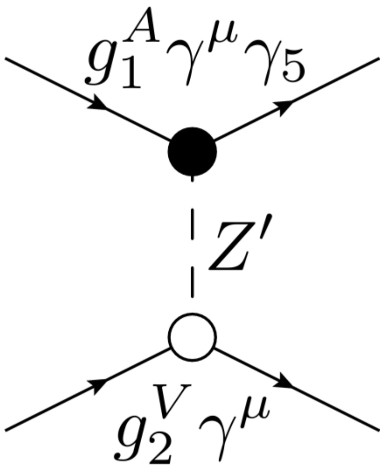

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Atomic PNC experiments: **Cs**, Yb, Tl

Constraints on Vector-Pseudovector Nucleon-Electron Interaction

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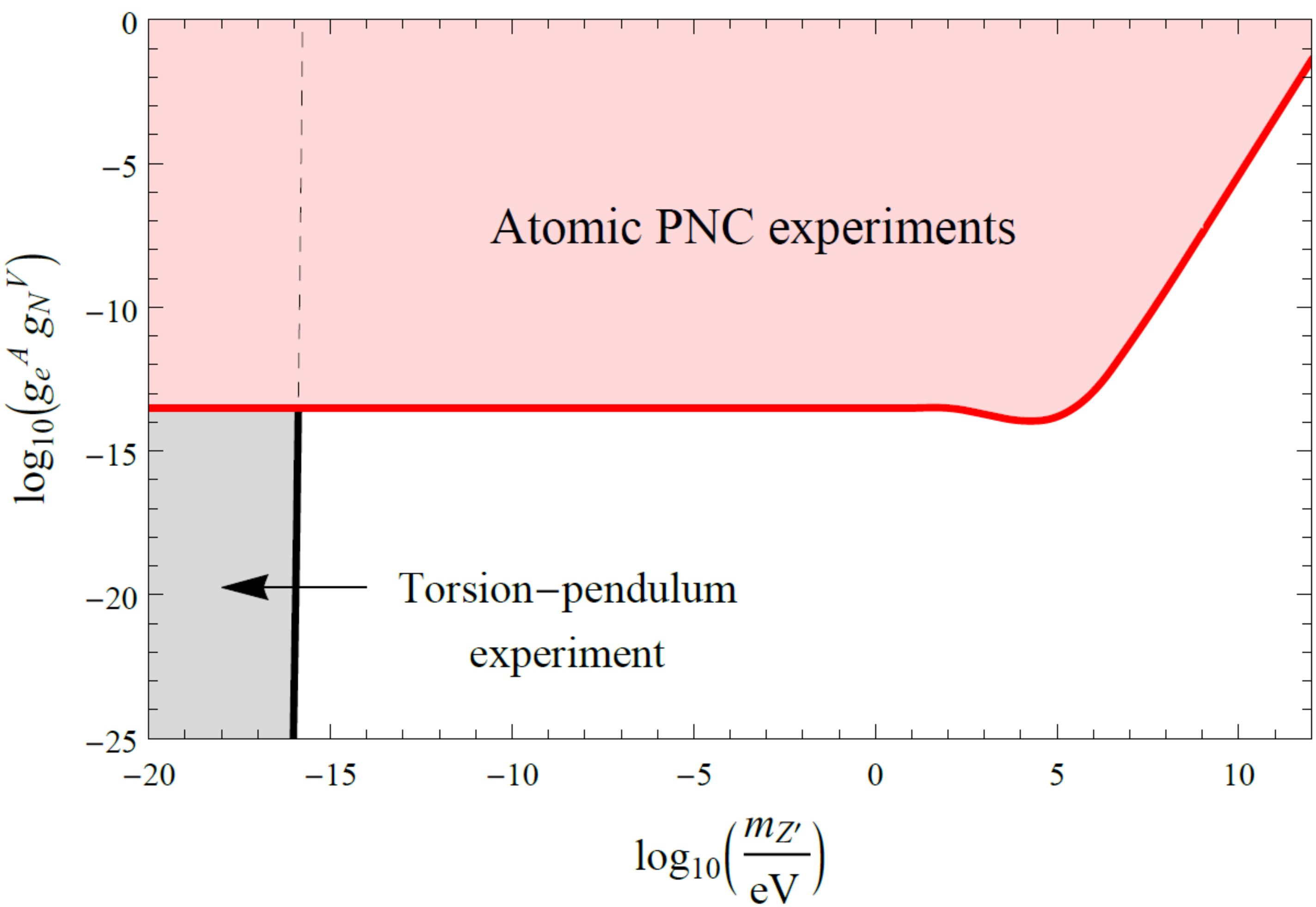
Many orders of magnitude improvement!



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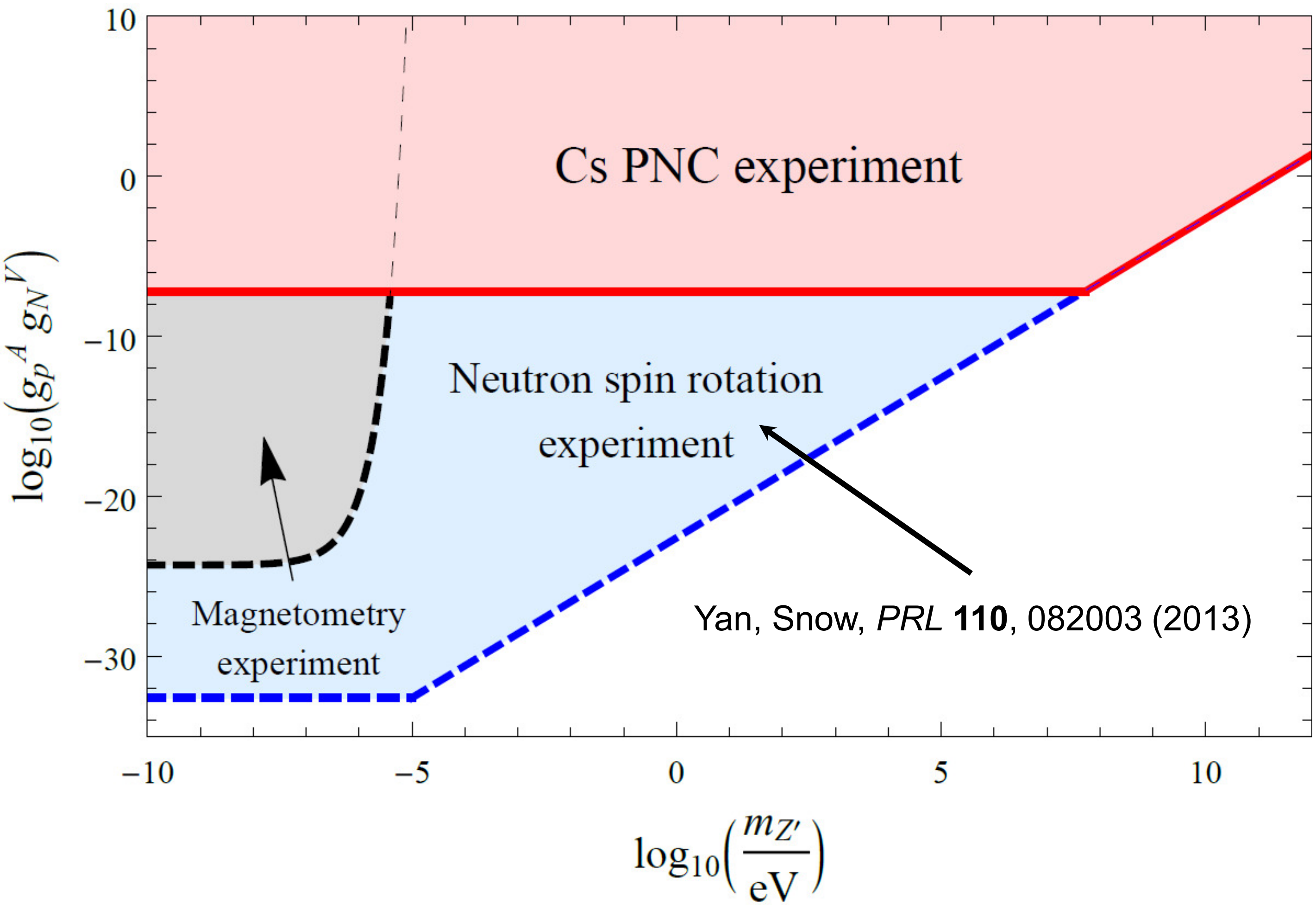

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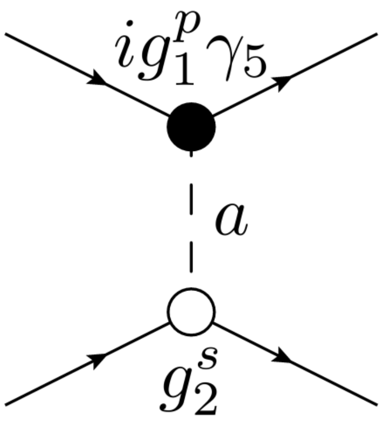

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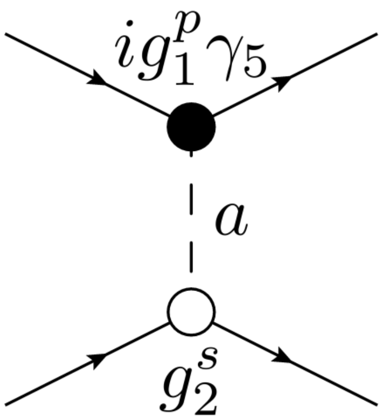

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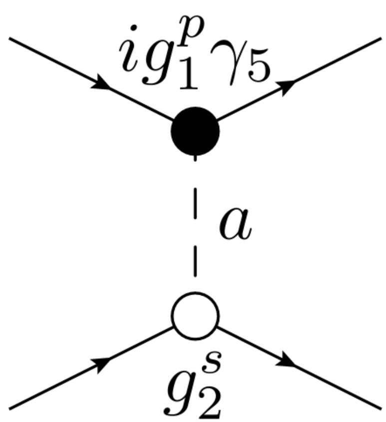

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P,*T*-violating forces => Atomic and Molecular EDMs

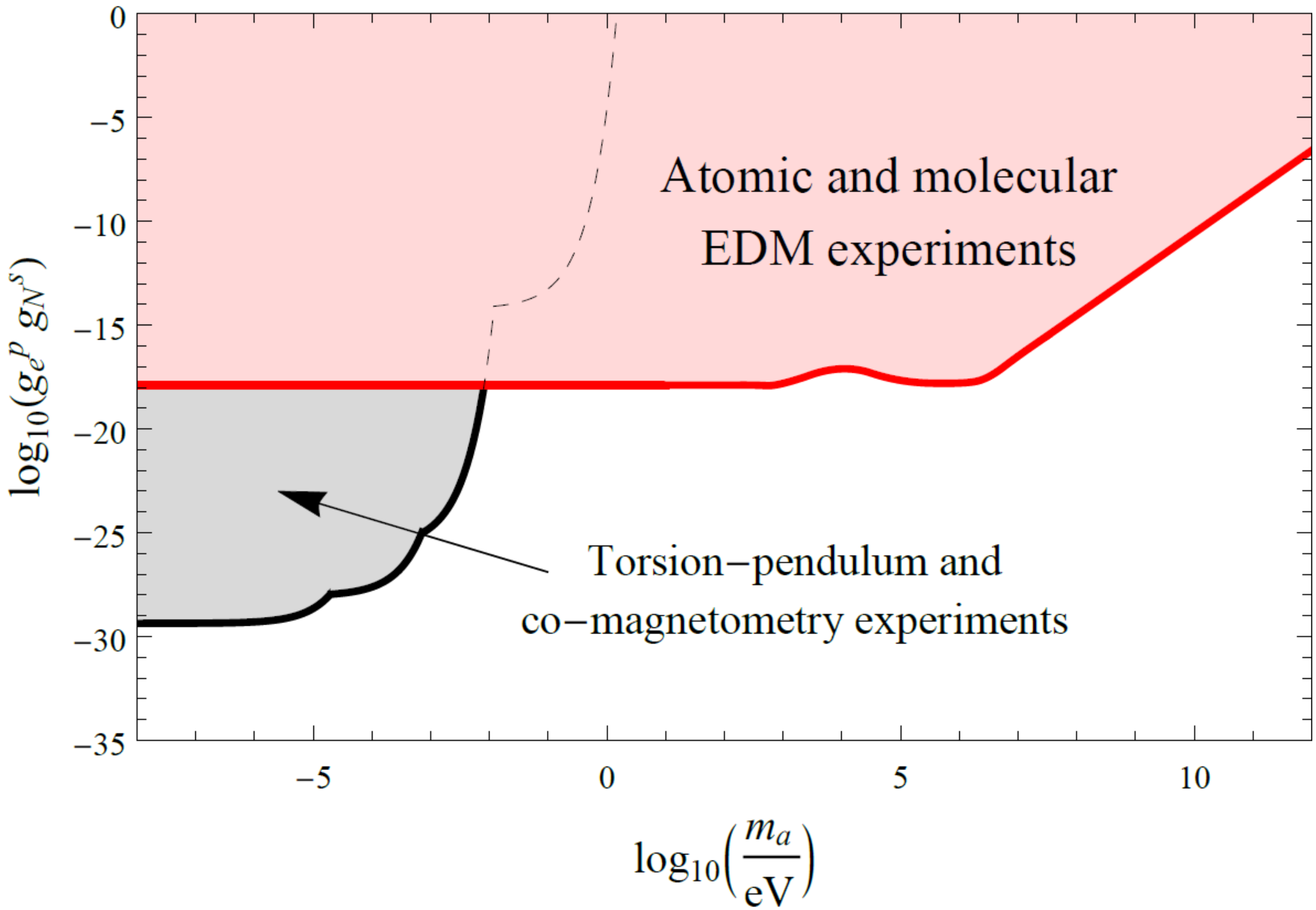
Atomic EDM experiments: Cs, Tl, Xe, **Hg**

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

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

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

Many orders of magnitude improvement!



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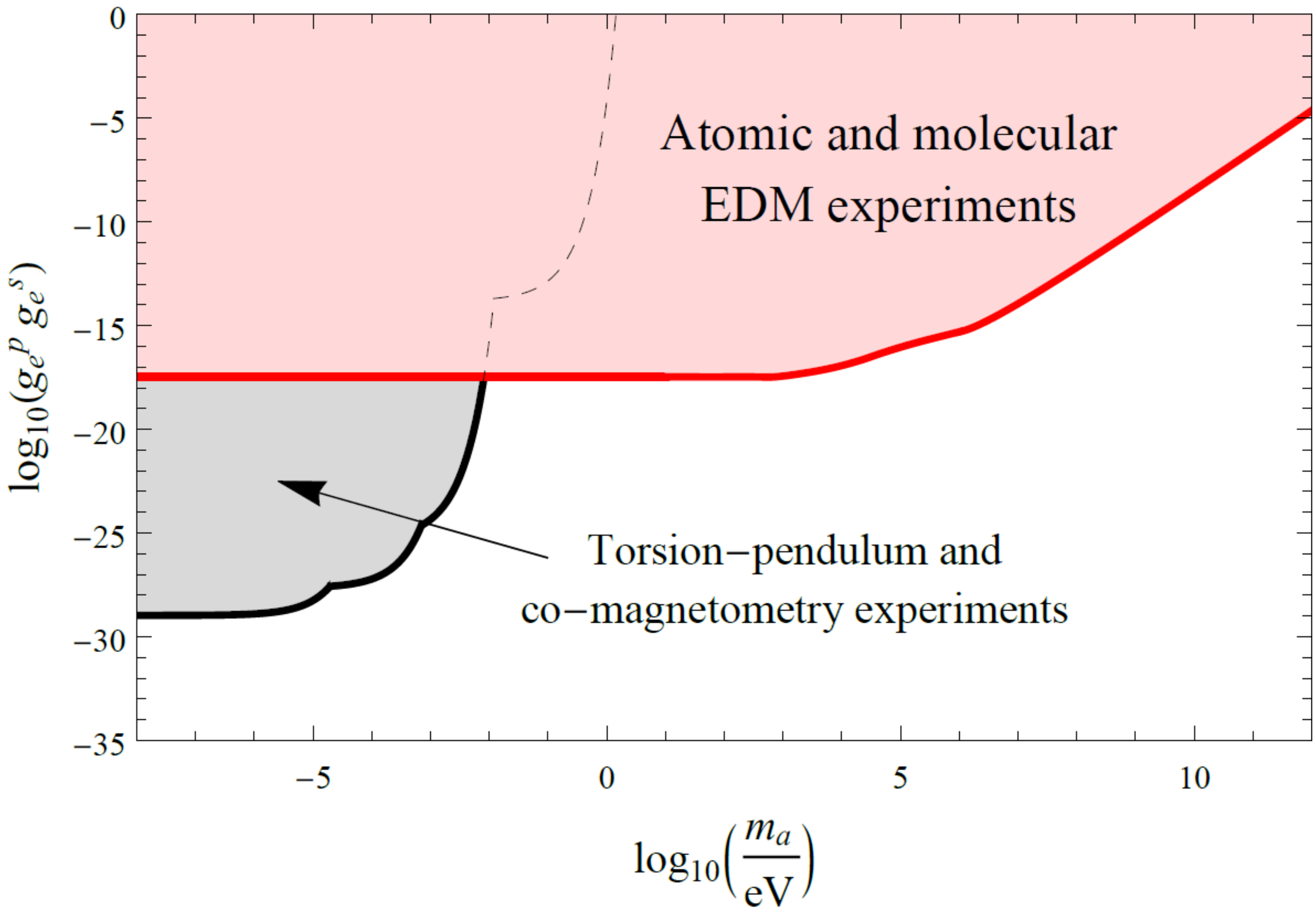

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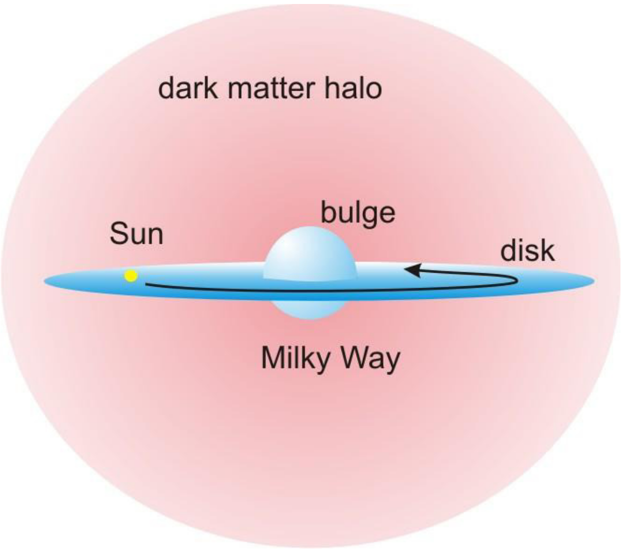

<u>Dark matter</u>

Spectroscopy, interferometry, cavities, BBN, CMB:

Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015); *PRA* **93**, 063630 (2016); *PRA* **94**, 022111 (2016)

Spin-precession effects, EDMs:

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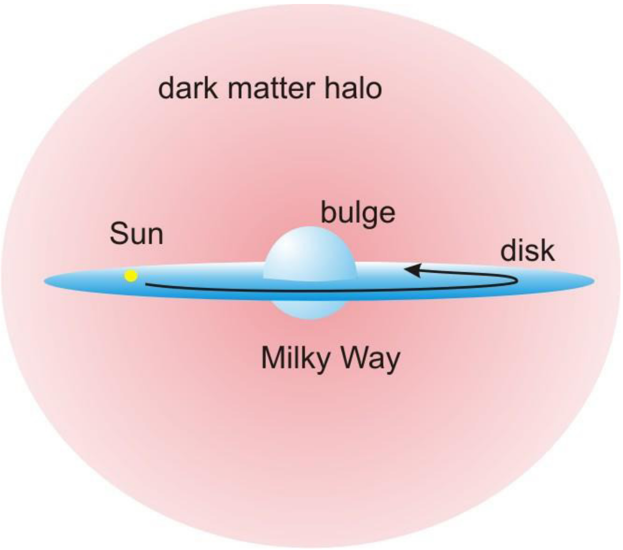

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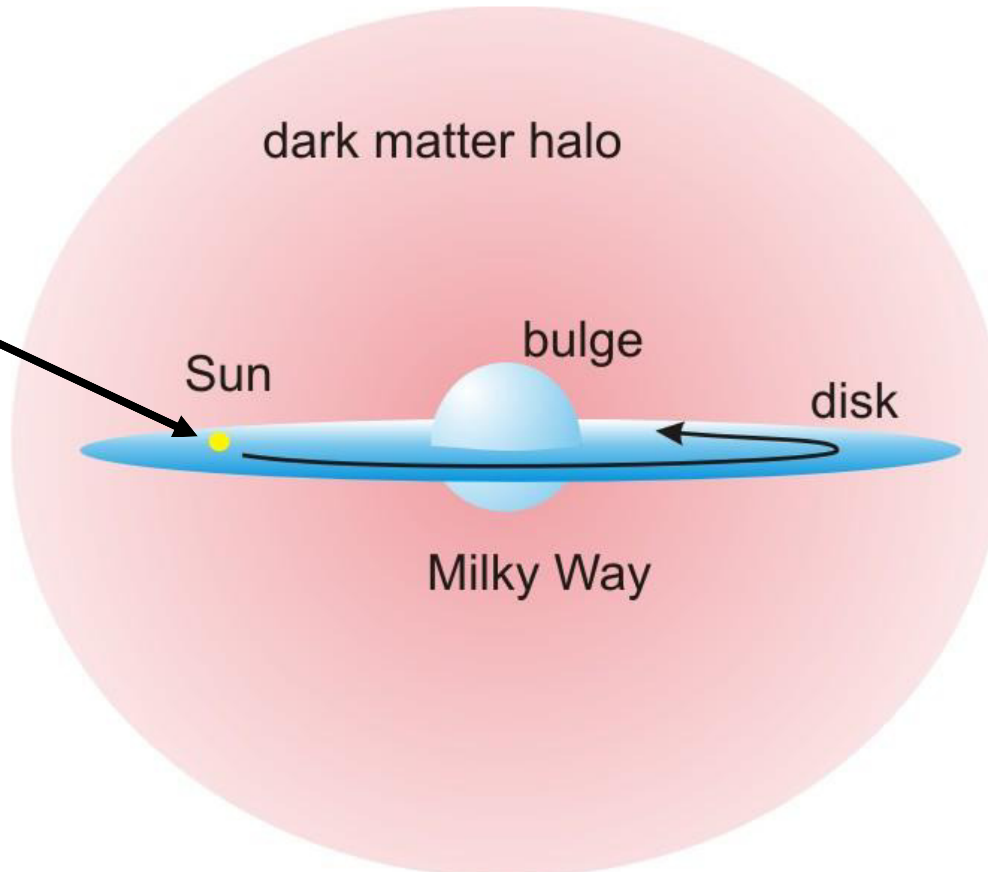
Motivation

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

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

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



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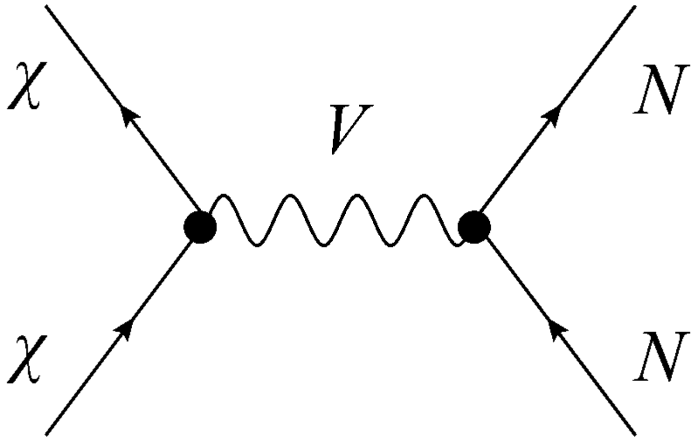
Traditional “scattering-off-nuclei” searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



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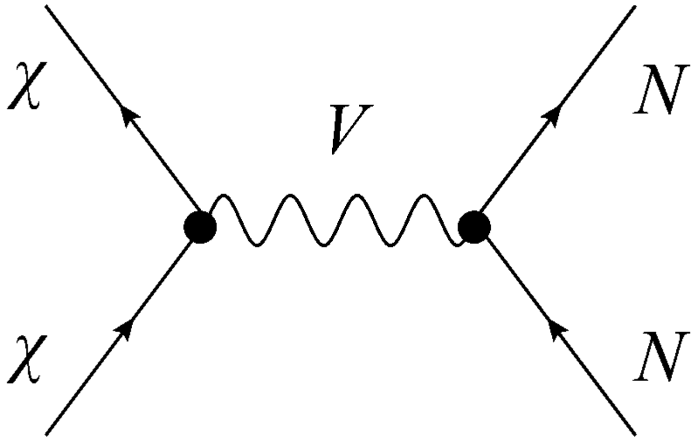

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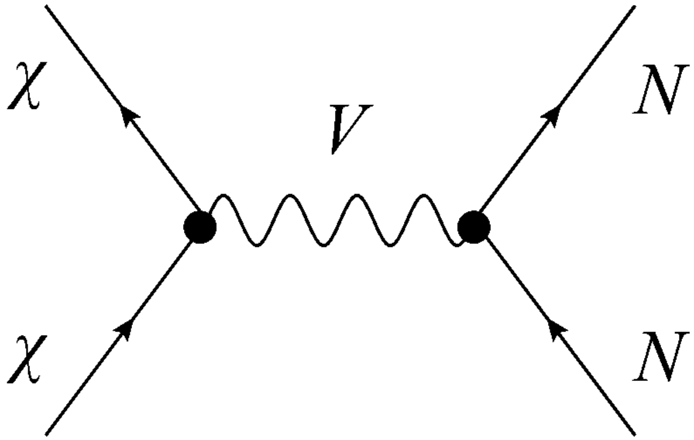

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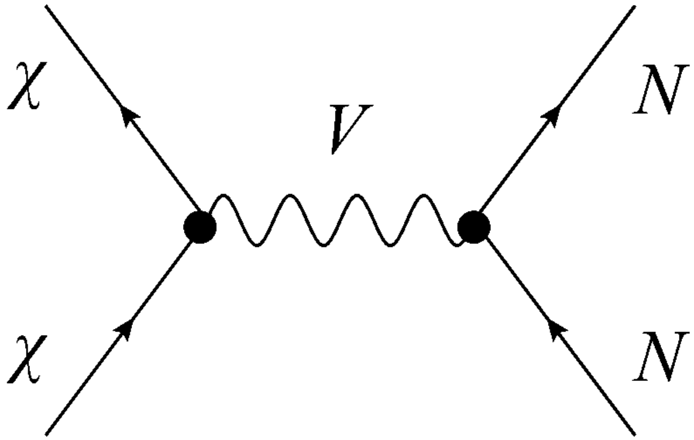

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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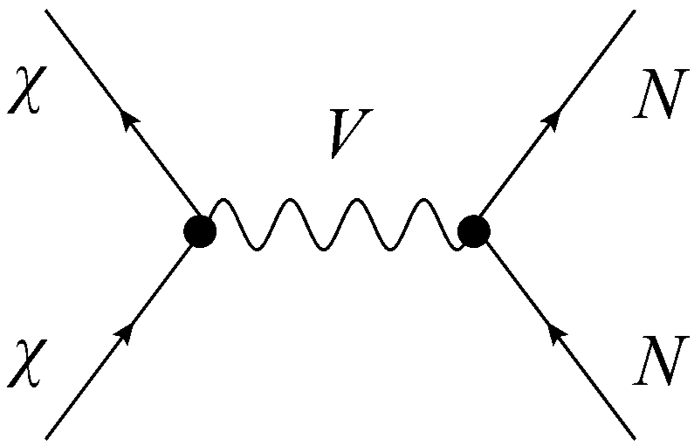

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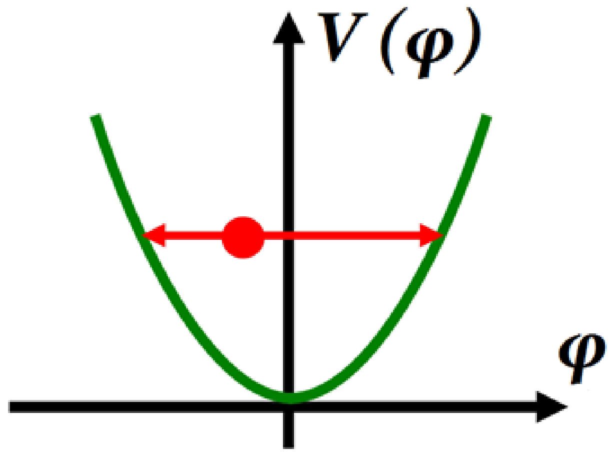
Question: *Can we instead look for effects of dark matter that are* ***first power*** *in the interaction constant?*

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



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

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- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \lesssim 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$

Low-mass Spin-0 Dark Matter

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$\lambda_{\mathrm{dB},\varphi} \leq L_{\text{dwarf galaxy}} \sim 1$ kpc

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons): $\varphi \xrightarrow{P} +\varphi$	**Pseudoscalars (Axions):** $\varphi \xrightarrow{P} -\varphi$
$\rightarrow$ **Time-varying fundamental constants**	$\rightarrow$ **Time-varying spin-dependent effects**
<u>10^{15}-fold improvement</u>	<u>1000-fold improvement</u>

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

QCD axion resolves strong CP problem

$\rightarrow$ Time-varying spin-dependent effects

1000-fold improvement

"Axion Wind" Spin-Precession Effect

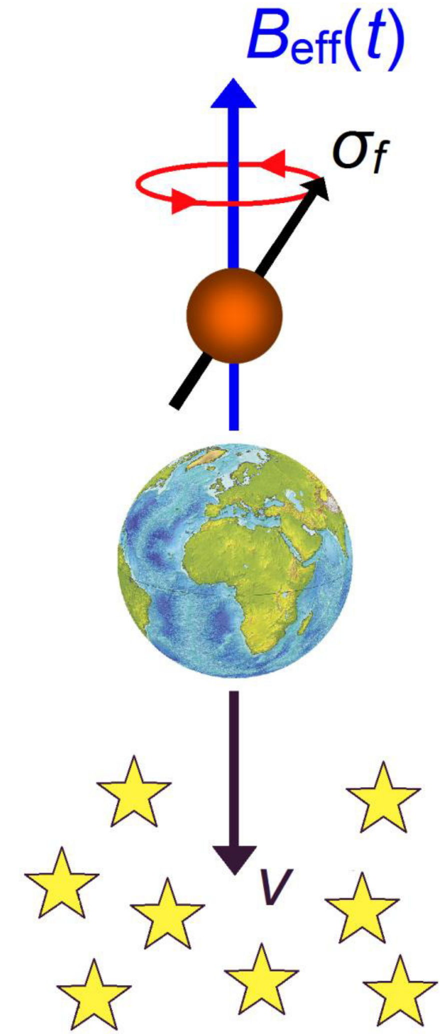
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field**

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

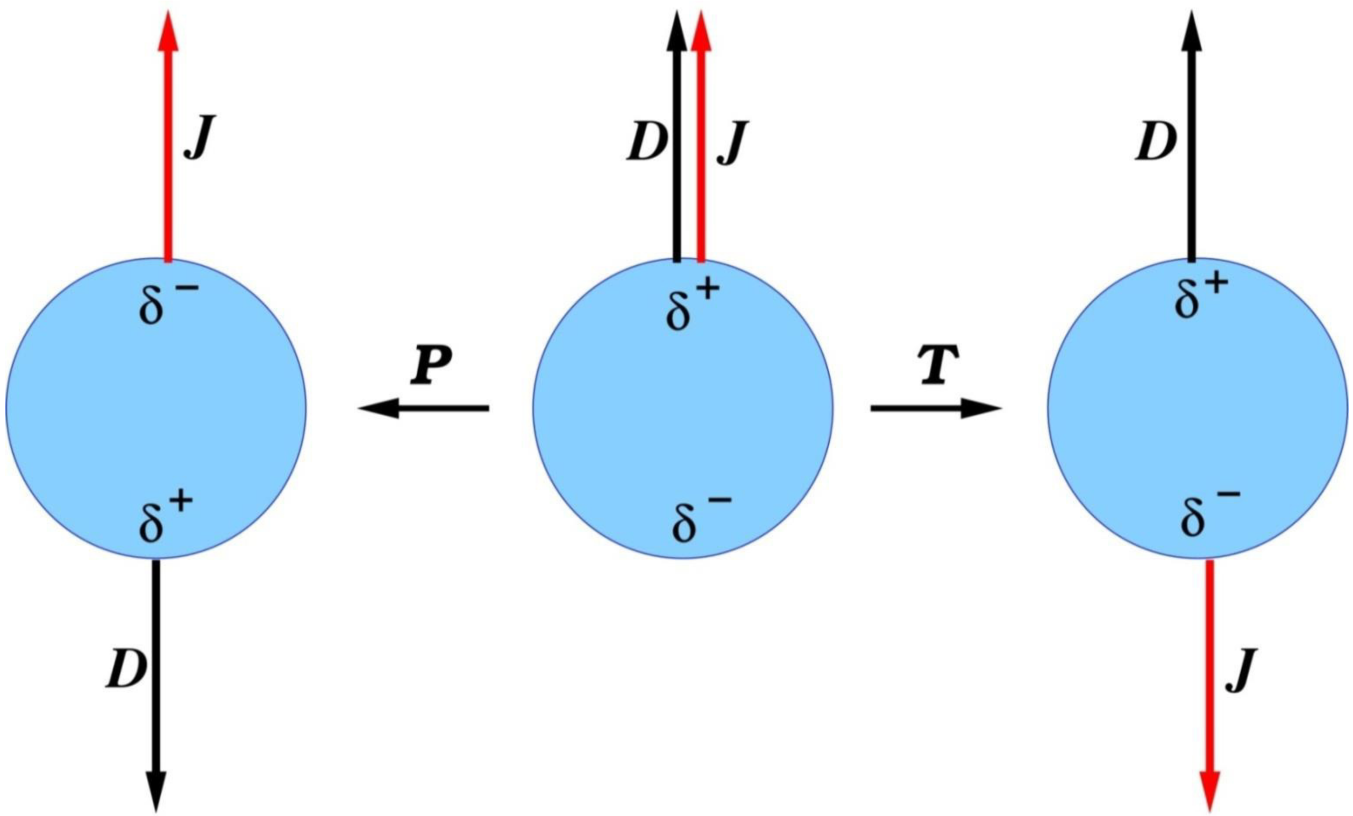


Oscillating Electric Dipole Moments

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

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

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



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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***B*-field effect**

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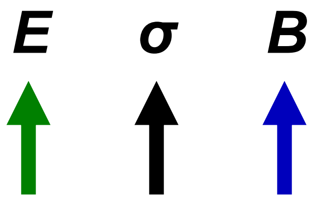

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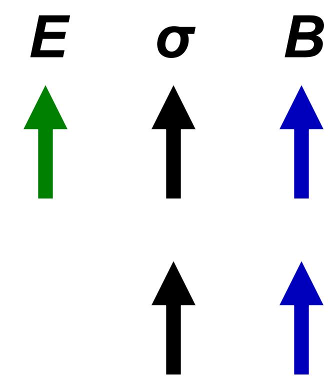

$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$

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

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

Earth's rotation

Searching for Spin-Dependent Effects

Proposals: [Budker, Graham, Ledbetter, Rajendran, A. O. Sushkov, *PRX* **4**, 021030 (2014); CASPEr collaboration, *Quantum Sci. Technol.* **3**, 014008 (2018)]

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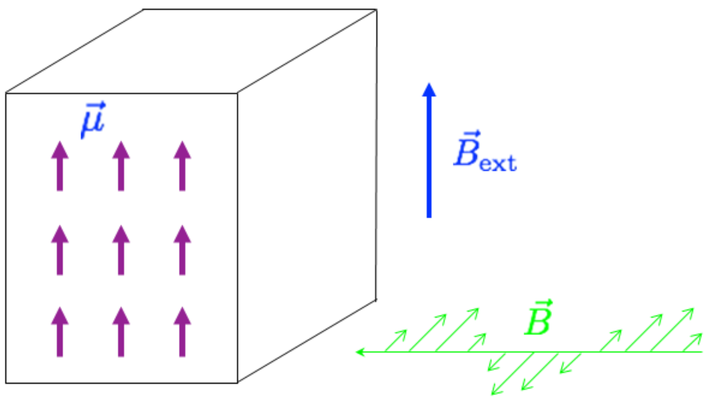

Resonance: $2\mu B_{\rm ext} = \omega$

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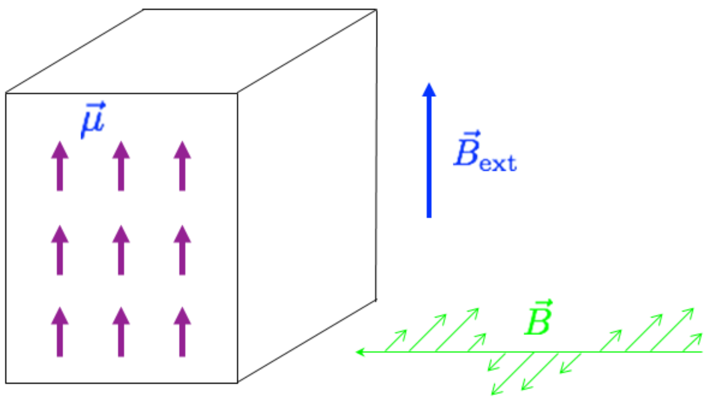

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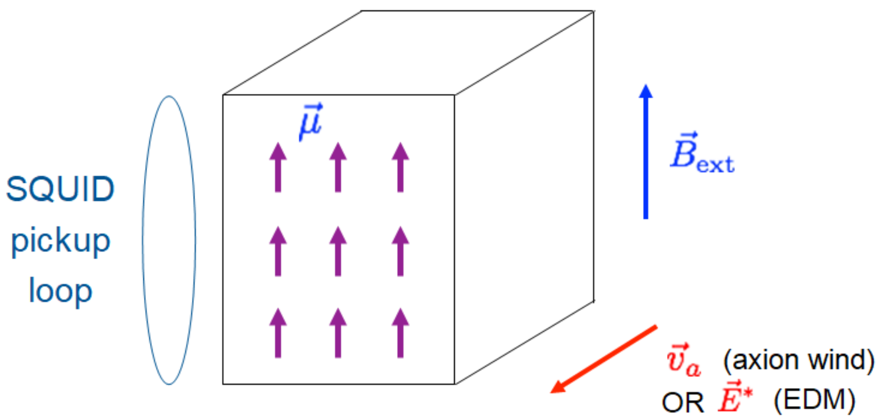
Dark-matter-driven NMR



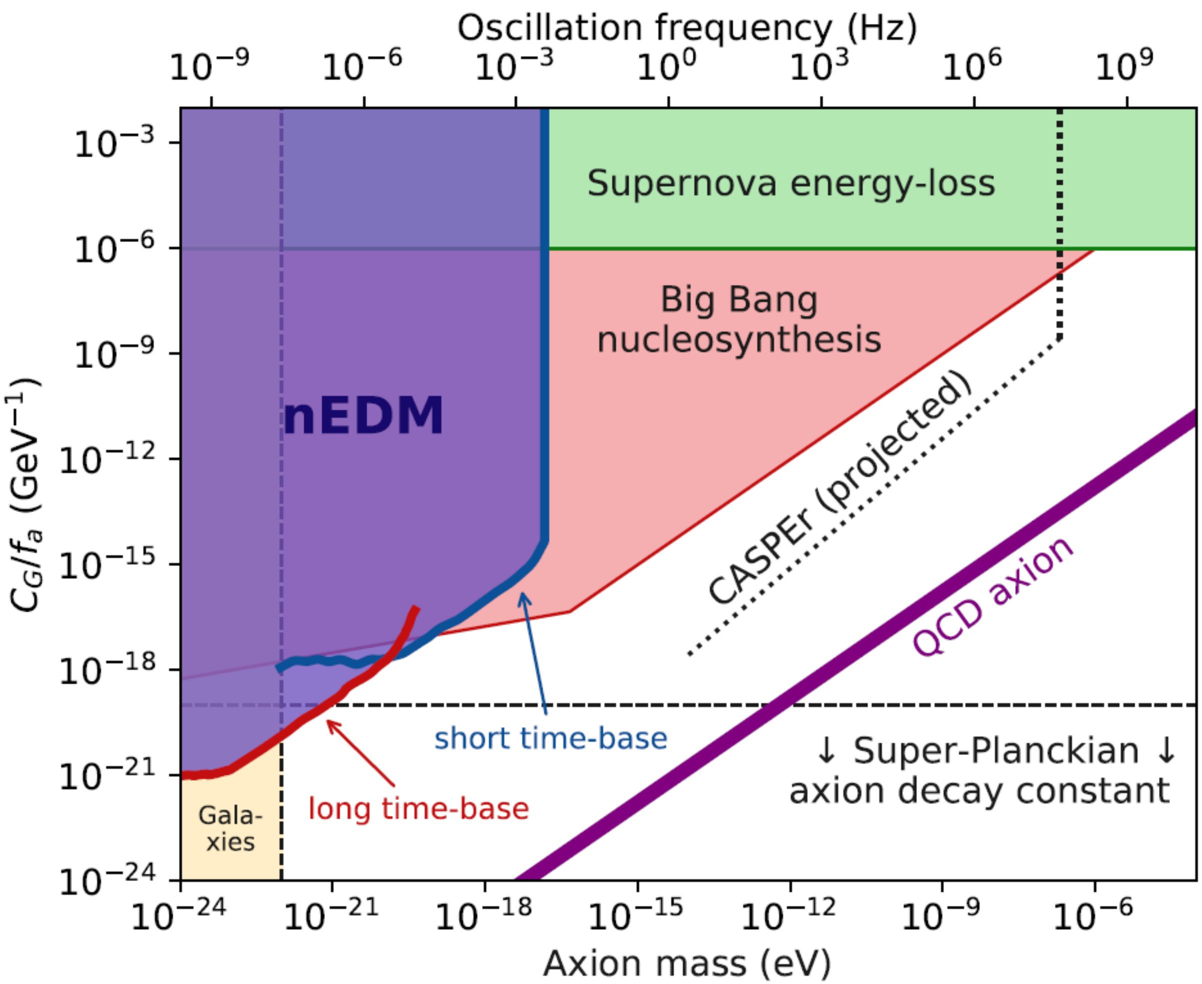
Resonance: $2\mu B_{\rm ext} \approx m_a$

Measure transverse magnetisation

Constraints on Interaction of Axion Dark Matter with Gluons

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

3 orders of magnitude improvement!



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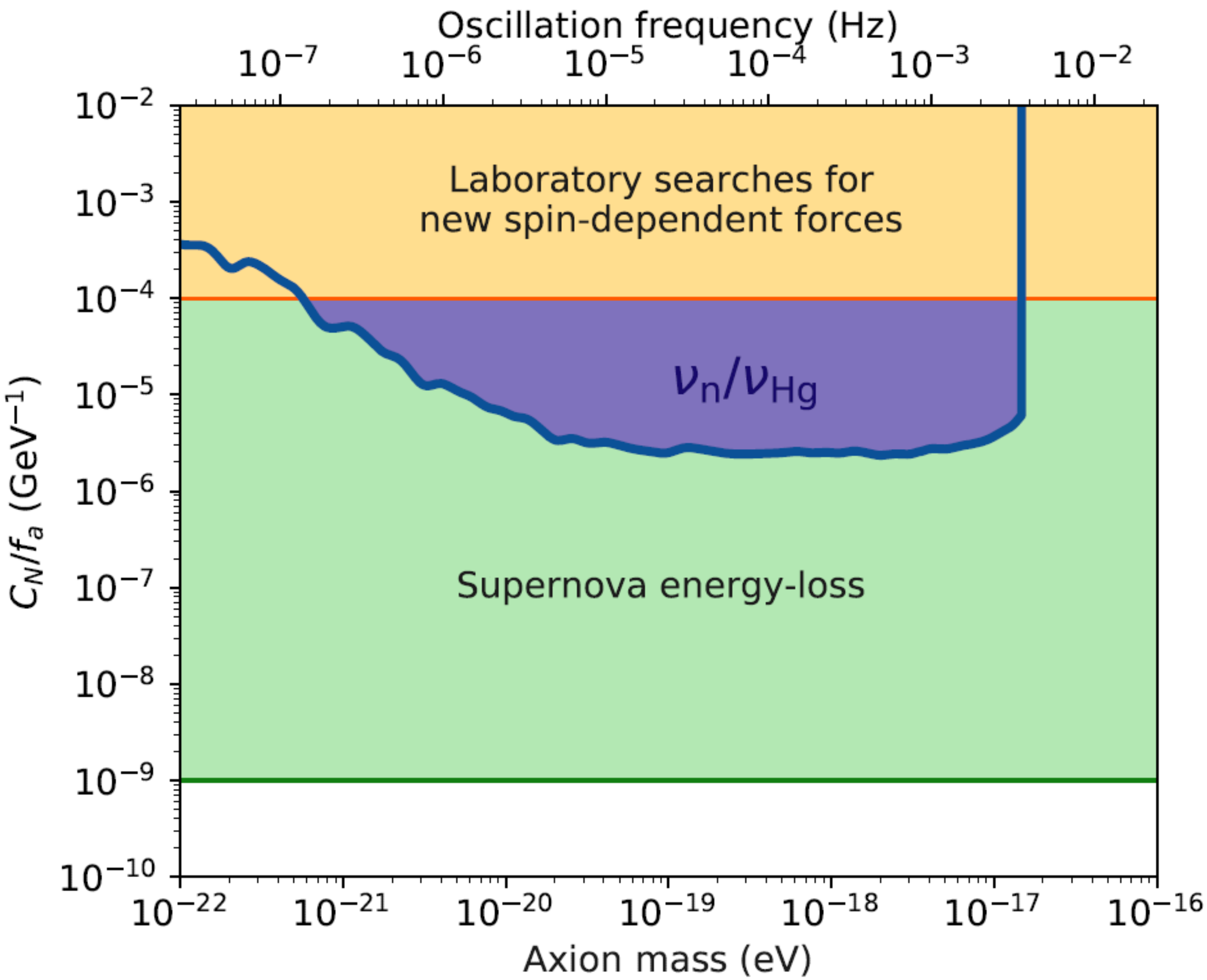
40-fold improvement (laboratory bounds)!



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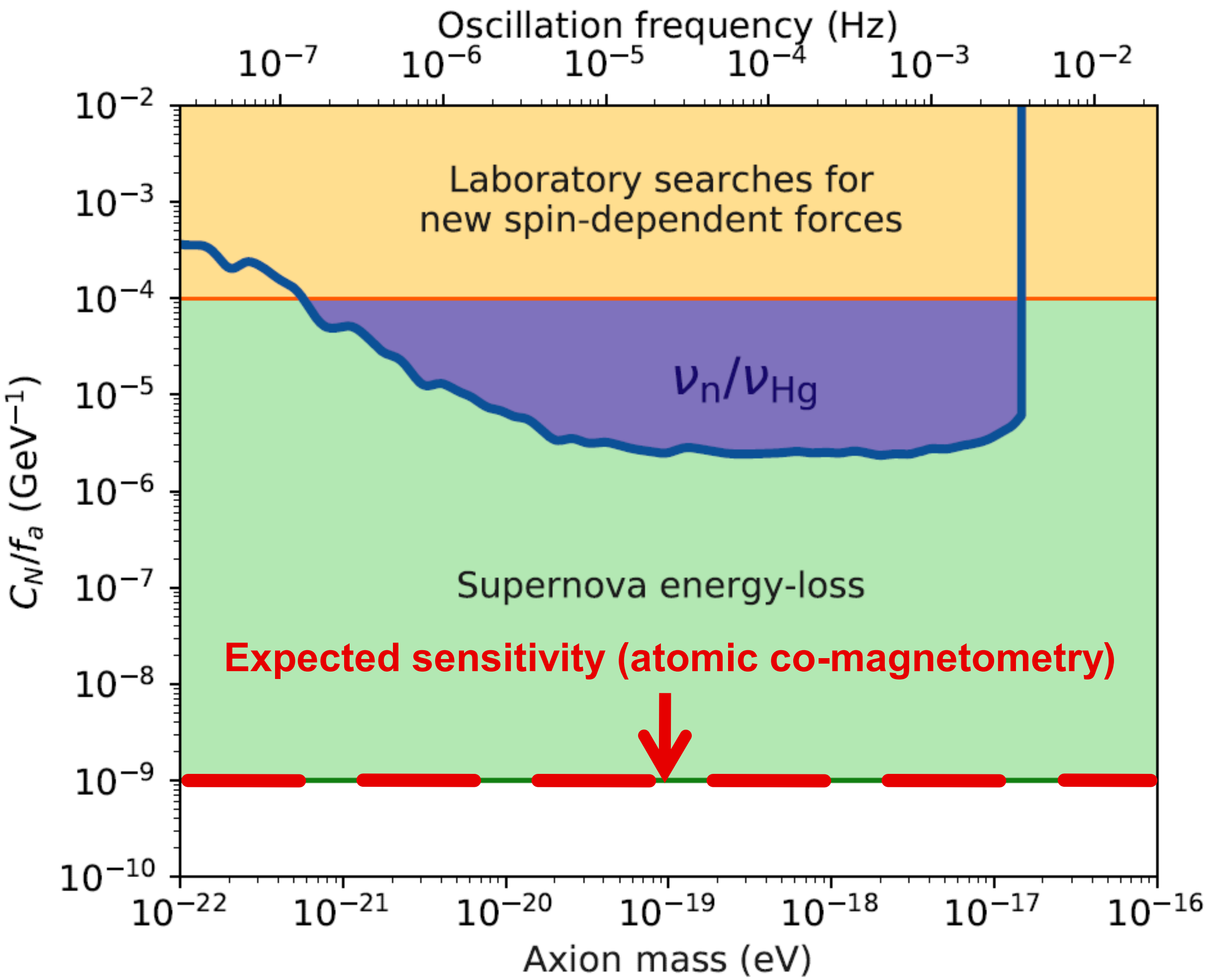

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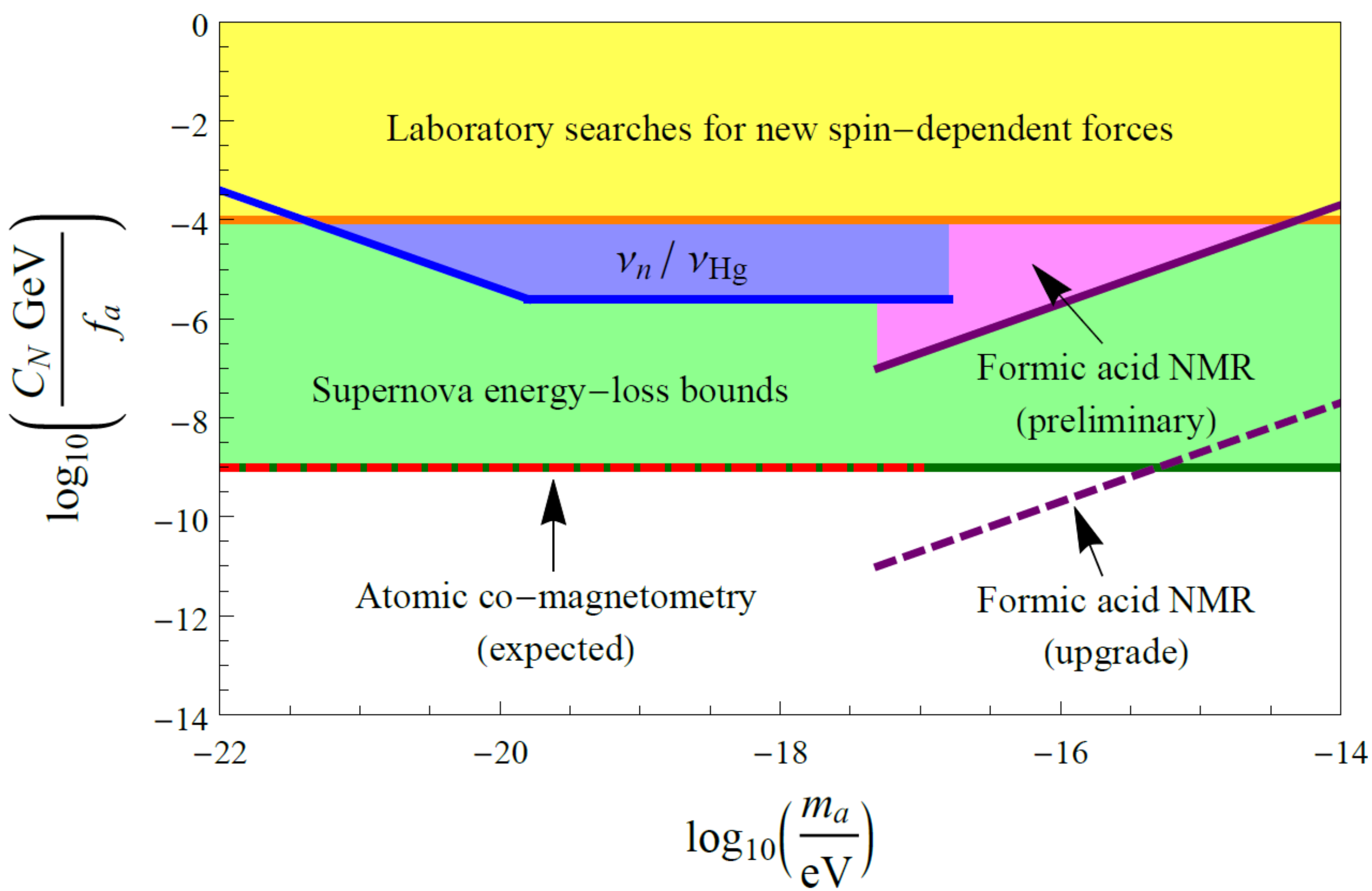
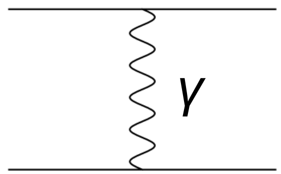
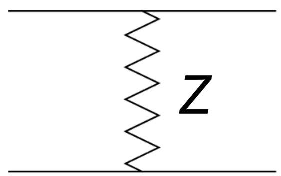


Electroweak Theory

$U(1)_{EM} \times SU(2)_{weak}$

γ ($m = 0$)

$\{Z, W^+, W^-\}$ ($m \approx 100$ GeV)

Interaction	Process	Range	$V(r)$
EM		∞	$1/r$
Weak		$1/m_Z \sim 10^{-18}$ m	$\delta(\boldsymbol{r})$

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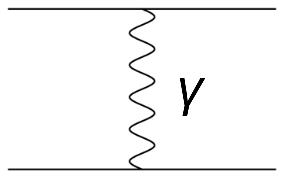
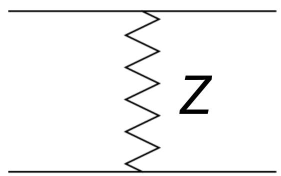
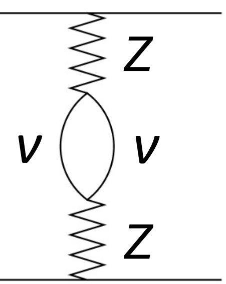
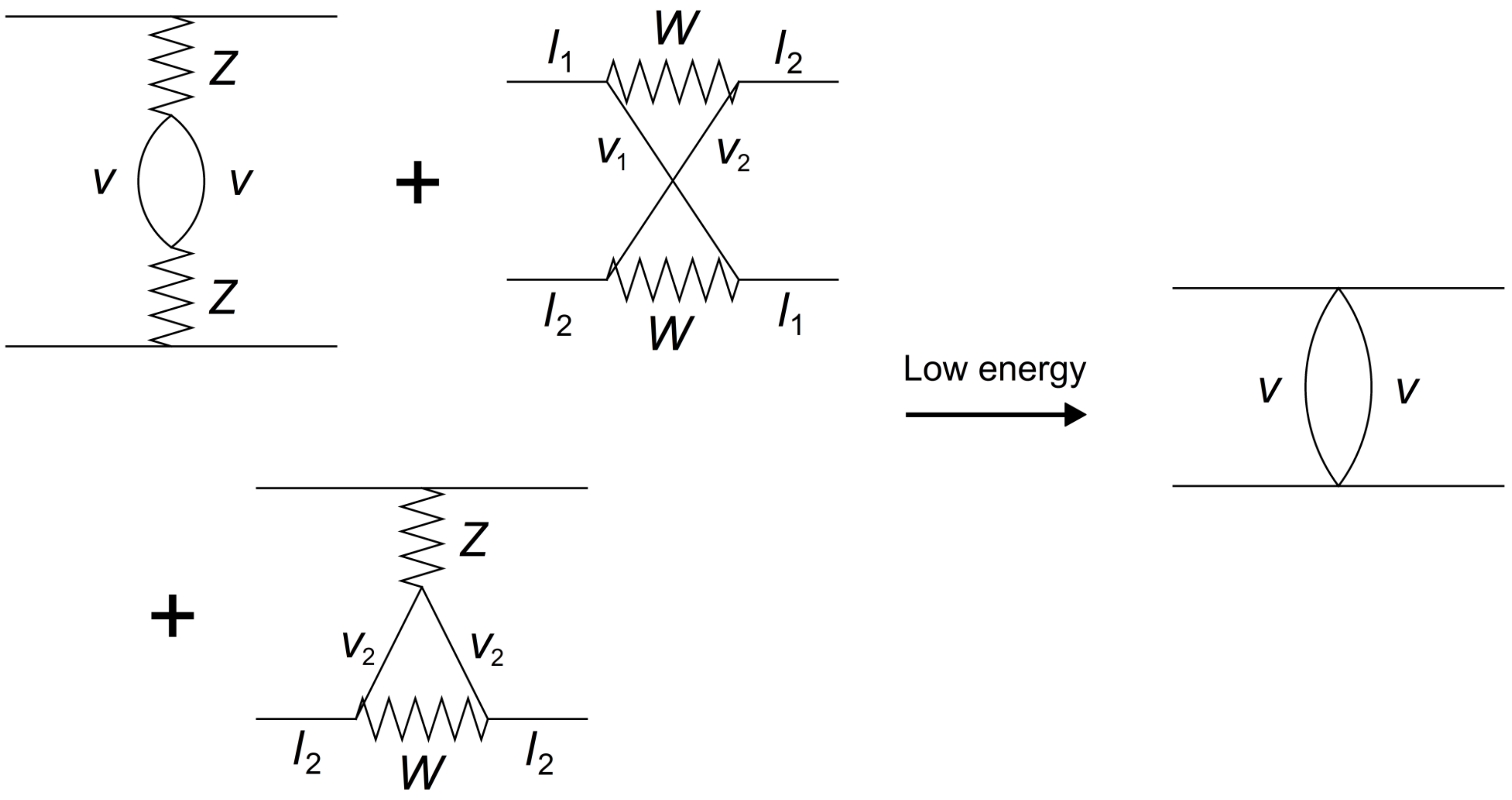
EM		∞	$1/r$
Weak		$1/m_Z \sim 10^{-18}$ m	$\delta(\boldsymbol{r})$
Weak		$1/(2m_\nu) \gtrsim 10^{-7}$ m	$1/r^5$

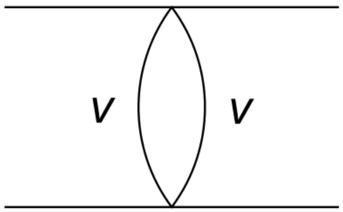
“Long-Range” Neutrino-Mediated Forces



$$V_\nu(r) \sim \frac{G_F^2}{r^5} \ + \ \text{spin-dependent terms}$$ [$1/m_{Z,W} << r << 1/(2m_\nu)$]

Probing “Long-Range” Neutrino-Mediated Forces

[Stadnik, arXiv:1711.03700]



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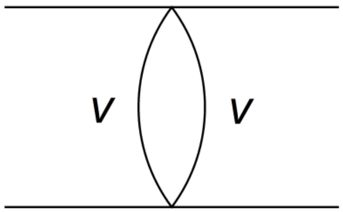

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Enormous enhancement of energy shift in *s*-wave atomic states (*l* = 0, no centrifugal barrier)!

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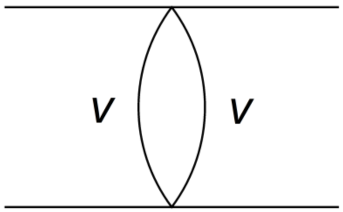

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$$\Delta E_{s\text{-wave}} \sim \boxed{\left(\frac{a_\mathrm{B}}{r_c}\right)^2} \frac{G_F^2}{a_\mathrm{B}^5}$$

r_c = "cutoff" radius

Finite-sized nucleus: $\boxed{(a_\mathrm{B}/r_c)^2 \approx (a_\mathrm{B}/R_\mathrm{nucl})^2 \sim 10^9}$

Point-like nucleus: $\boxed{(a_\mathrm{B}/r_c)^2 \approx (a_\mathrm{B}/\lambda_{Z,W})^2 \sim 10^{15}}$

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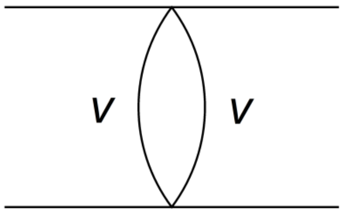
[Stadnik, arXiv:1711.03700]



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Spectroscopy measurements of and calculations in:

- Simple atoms (H, D)
- Exotic atoms (e^-e^+, $e^-\mu^+$)
- Simple nuclei (*np*)
- Heavy atoms (Ca^+)

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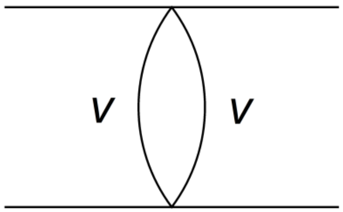
[Stadnik, arXiv:1711.03700]



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Muonium ground-state hyperfine interval:

ν_{exp} = 4463302776(51) Hz $\Delta\nu_{\text{neutrinos + other fermions}} \approx 2$ Hz

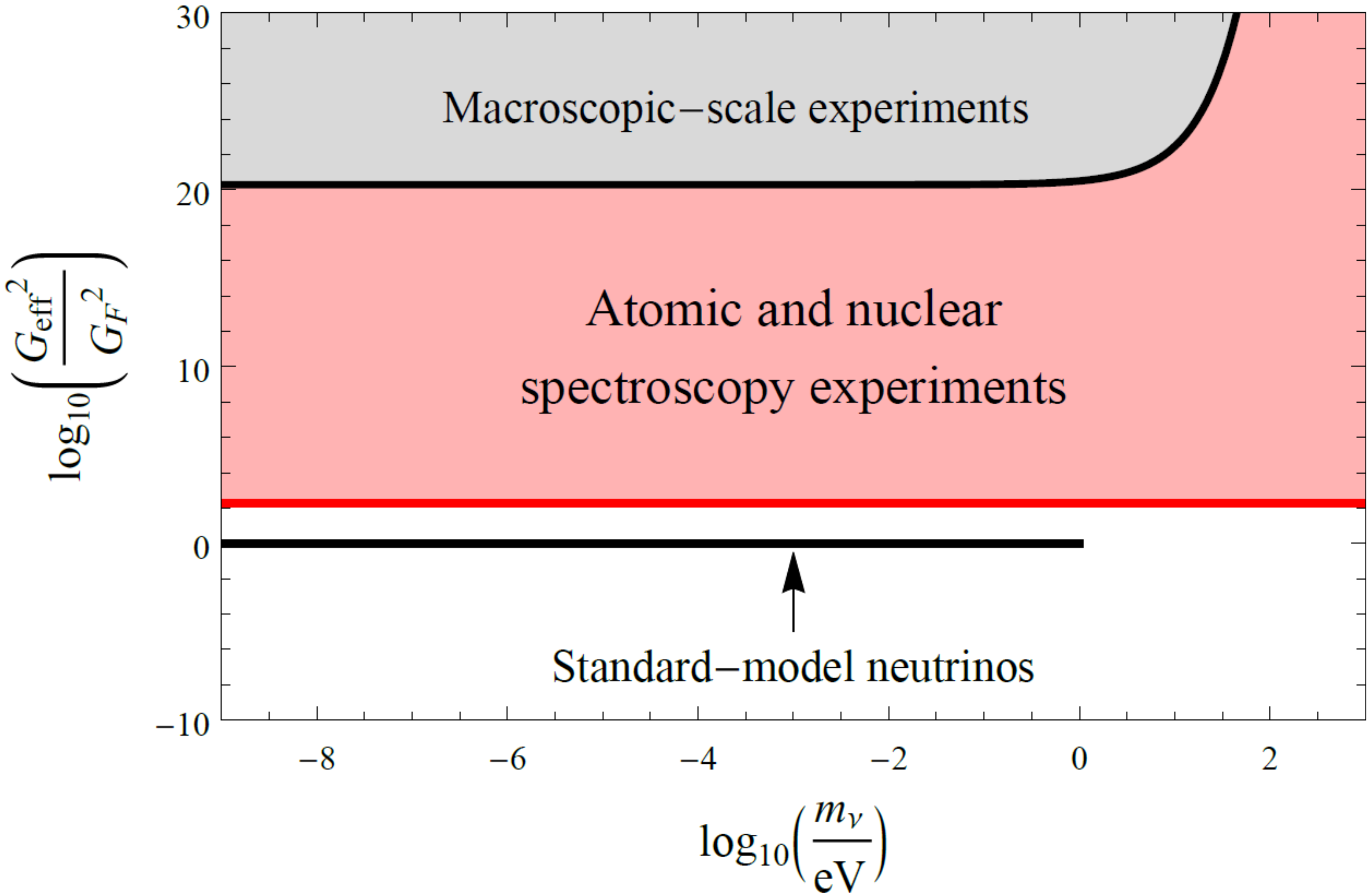
ν_{theor} = 4463302868(271)* Hz $\Delta\nu_{\text{neutrinos}} \approx 0.5$ Hz

* u[$\nu_{theor}(m_e/m_\mu)$] ≈ 260 Hz, u[ν_{theor}(4^{th}-order QED)] ≈ 85 Hz, u[ν_{theor}(others)] ≲ Hz

Constraints on "Long-Range" Neutrino-Mediated Forces

[Stadnik, arXiv:1711.03700]

18 orders of magnitude improvement!



Summary

- **Improved limits** on dark bosons from atomic experiments (independent of ρ_{DM})
- New classes of dark matter effects that are **first power** in the underlying interaction constant => Up to **15 orders of magnitude improvement**
- **18 orders of magnitude improvement** on "long-range" neutrino-mediated forces from atomic spectroscopy (Can we test the SM prediction?)
- **More details in full slides (also on ResearchGate)**