New Atomic Probes for Dark Matter and Neutrino-Mediated Forces

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Collaborators (Theory):

Victor Flambaum

Collaborators (Experiment):

nEDM collaboration at PSI and Sussex

BASE collaboration at CERN and RIKEN

CASPEr collaboration at Mainz

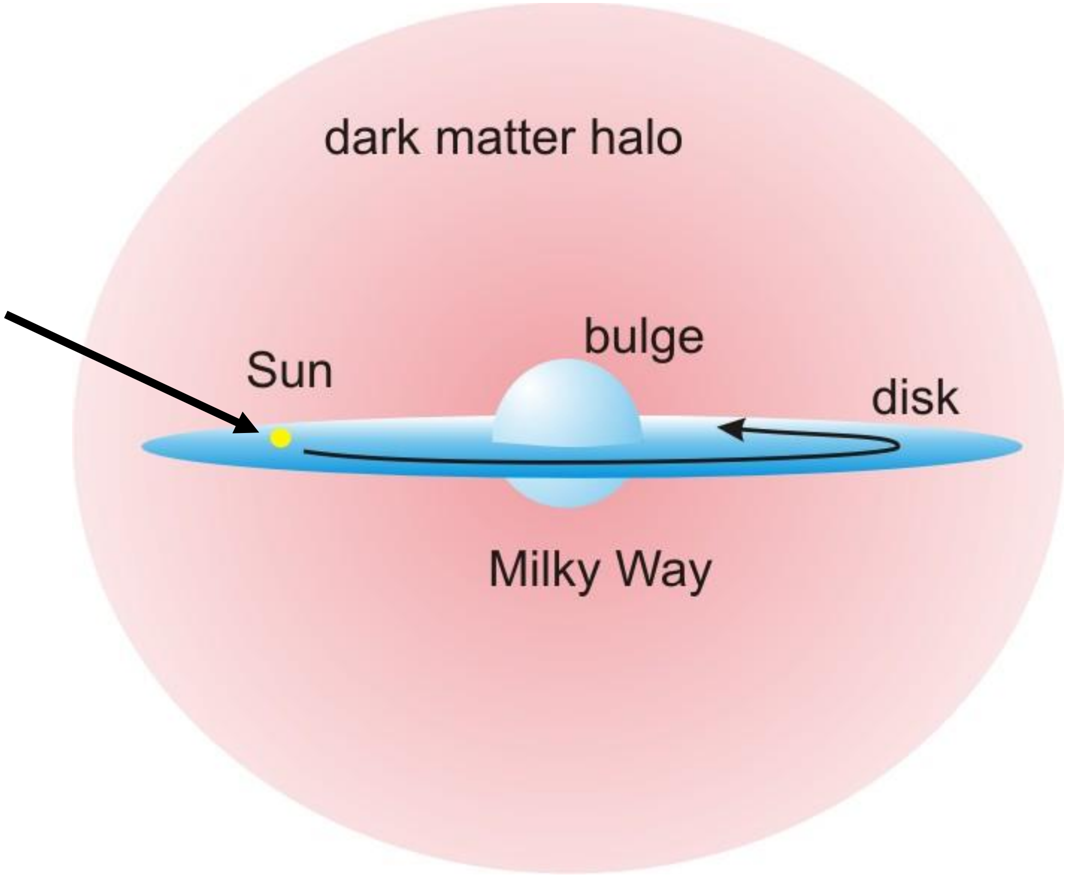
PSAS, Vienna, May 2018

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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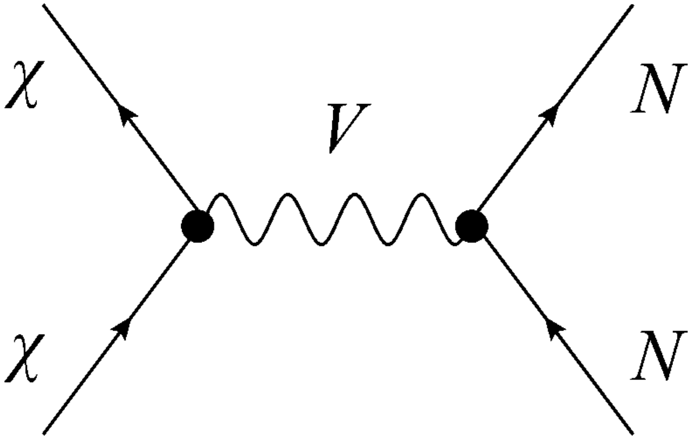

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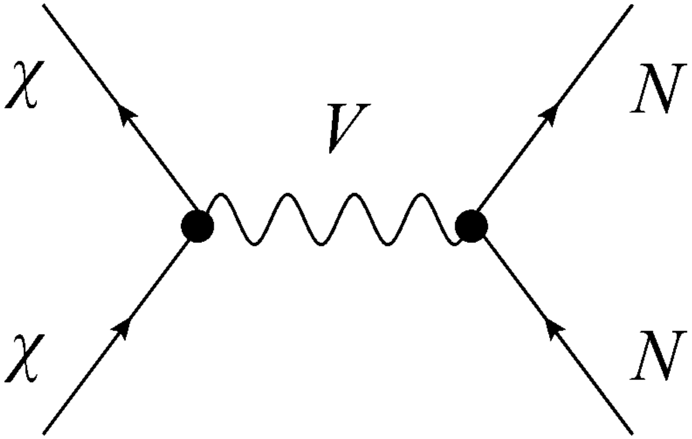

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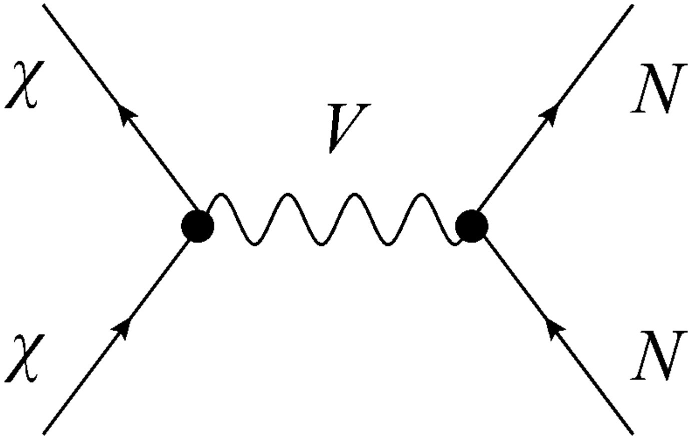

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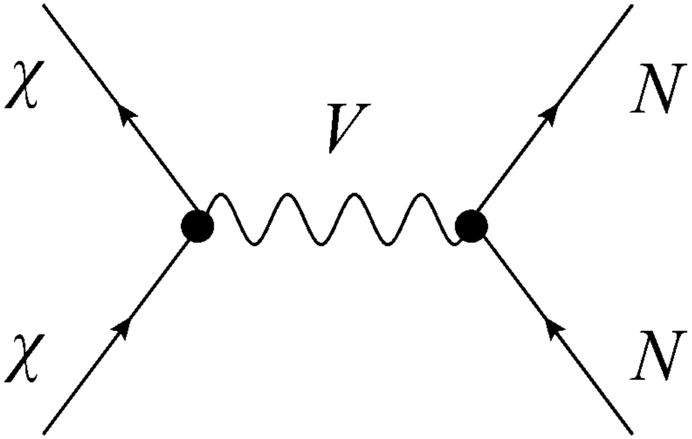

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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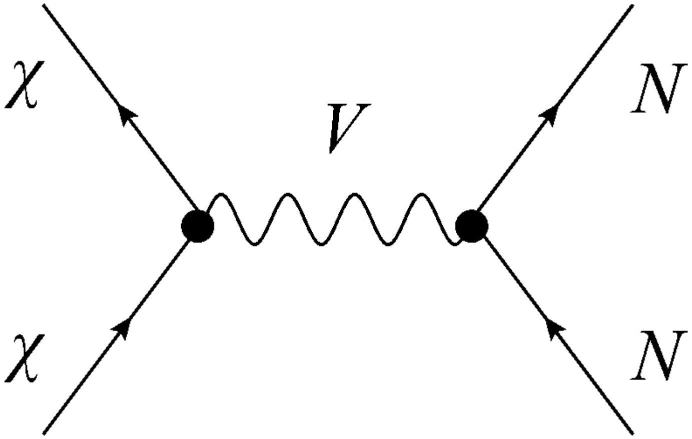

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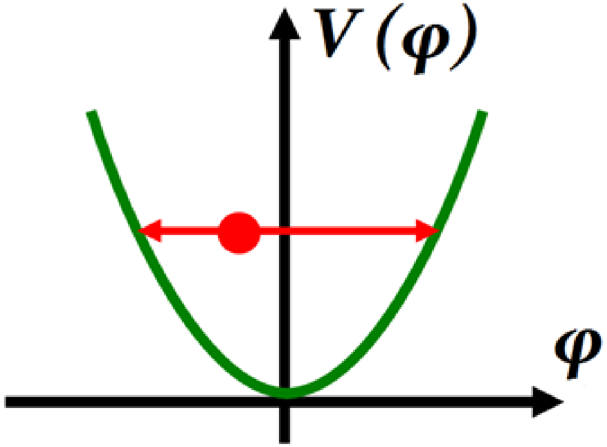
Question: *Can we instead look for effects of dark matter that are* ***first power*** *in the interaction constant?*

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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- 10^{-22} eV $\lesssim m_\varphi \lesssim 0.1$ eV <=> 10^{-8} Hz $\lesssim f \lesssim 10^{13}$ Hz

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

Classical field

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Classical field

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

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- BUT can look for *coherent effects of a low-mass DM field* in low-energy atomic and astrophysical phenomena that are **first power** in the interaction constant κ:

$$\mathcal{L}_{\mathrm{eff}} = \kappa \phi^n X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \kappa$$

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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):

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

→ Time-varying fundamental constants

→ Time-varying spin-dependent effects

10^{15}-fold improvement

1000-fold improvement

Low-Mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

QCD axion resolves strong CP problem

→ Time-varying spin-dependent effects

1000-fold improvement

“Axion Wind” Spin-Precession Effect

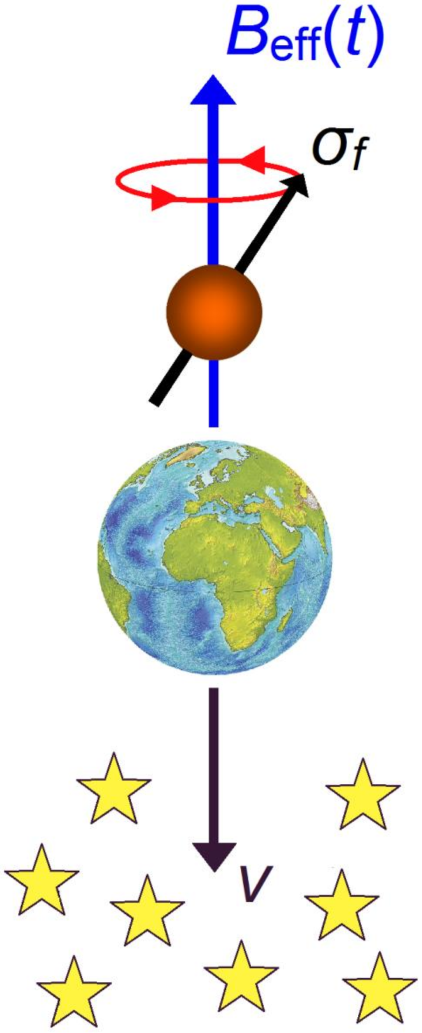
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field**

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

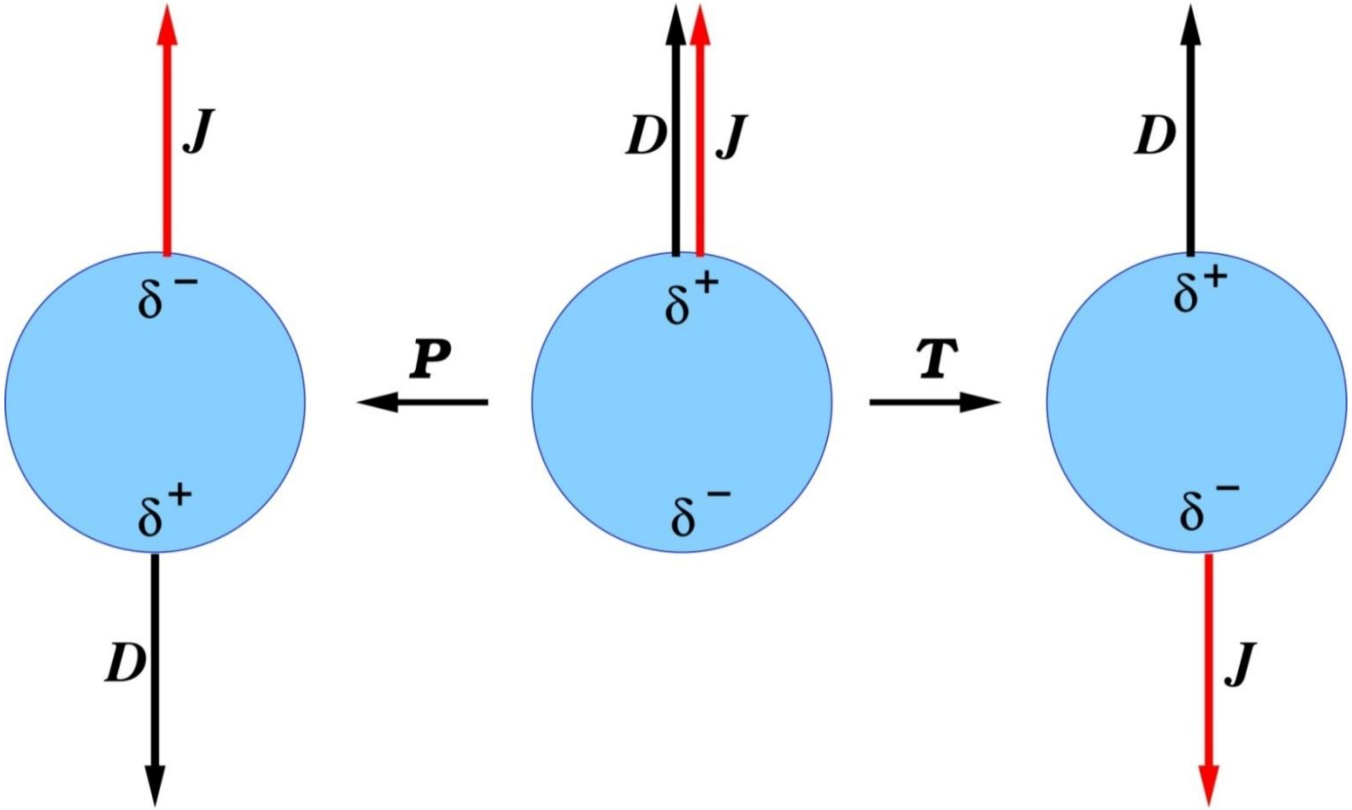


Oscillating Electric Dipole Moments

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

***B*-field effect**

Axion DM effect

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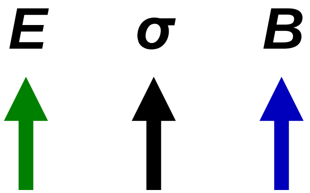

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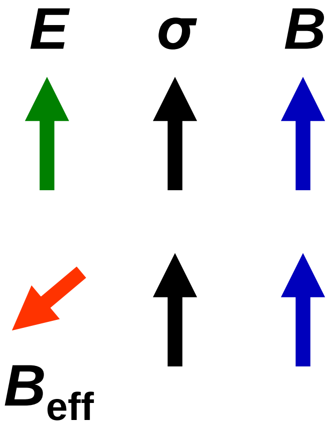
$$R_{\mathrm{wind}}(t) \propto \sum_{i=1,2,3} A_i \sin(\omega_i t)$$

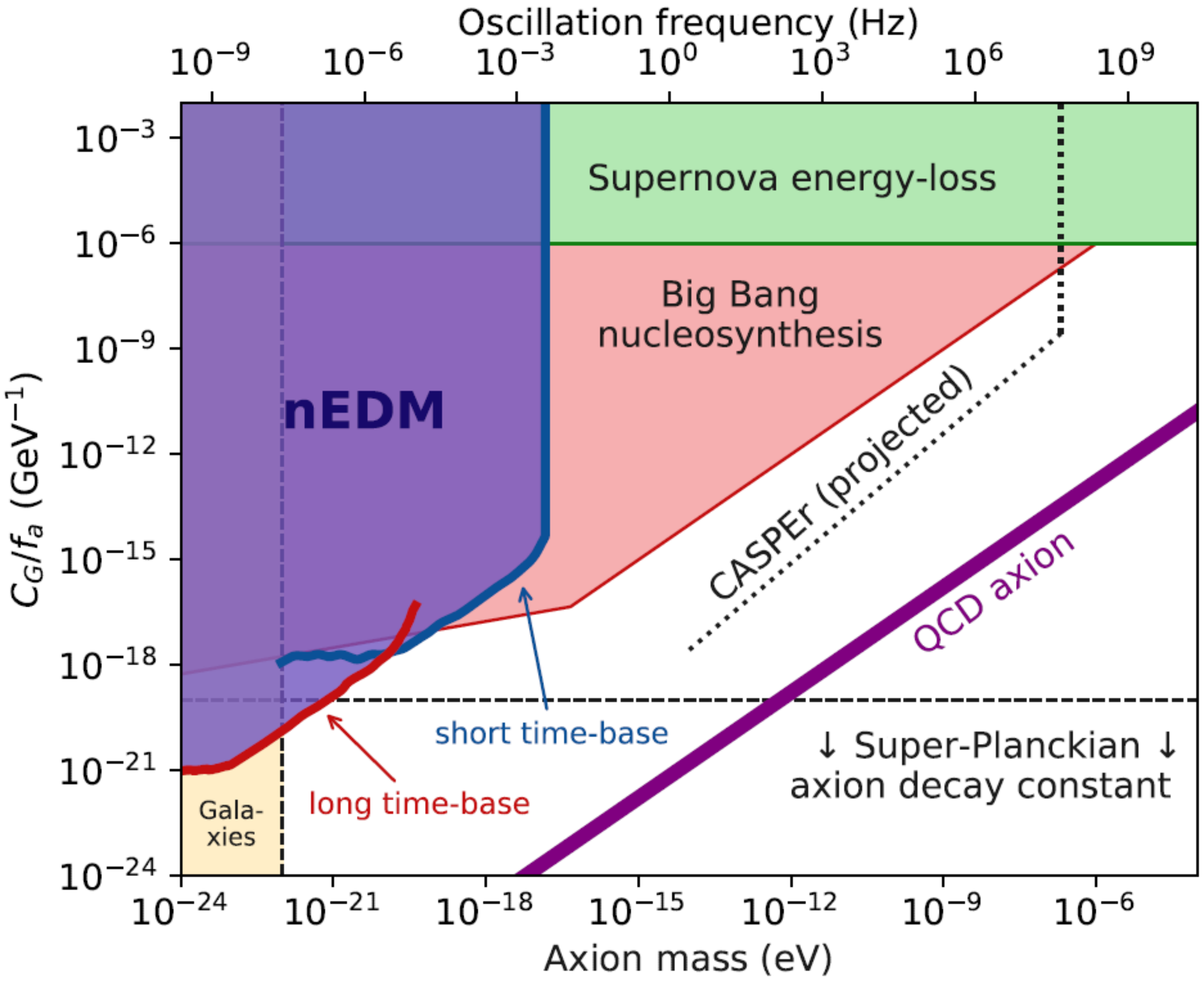


$$\omega_1 = m_a,\ \omega_2 = m_a + \Omega_{\mathrm{sidereal}},\ \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

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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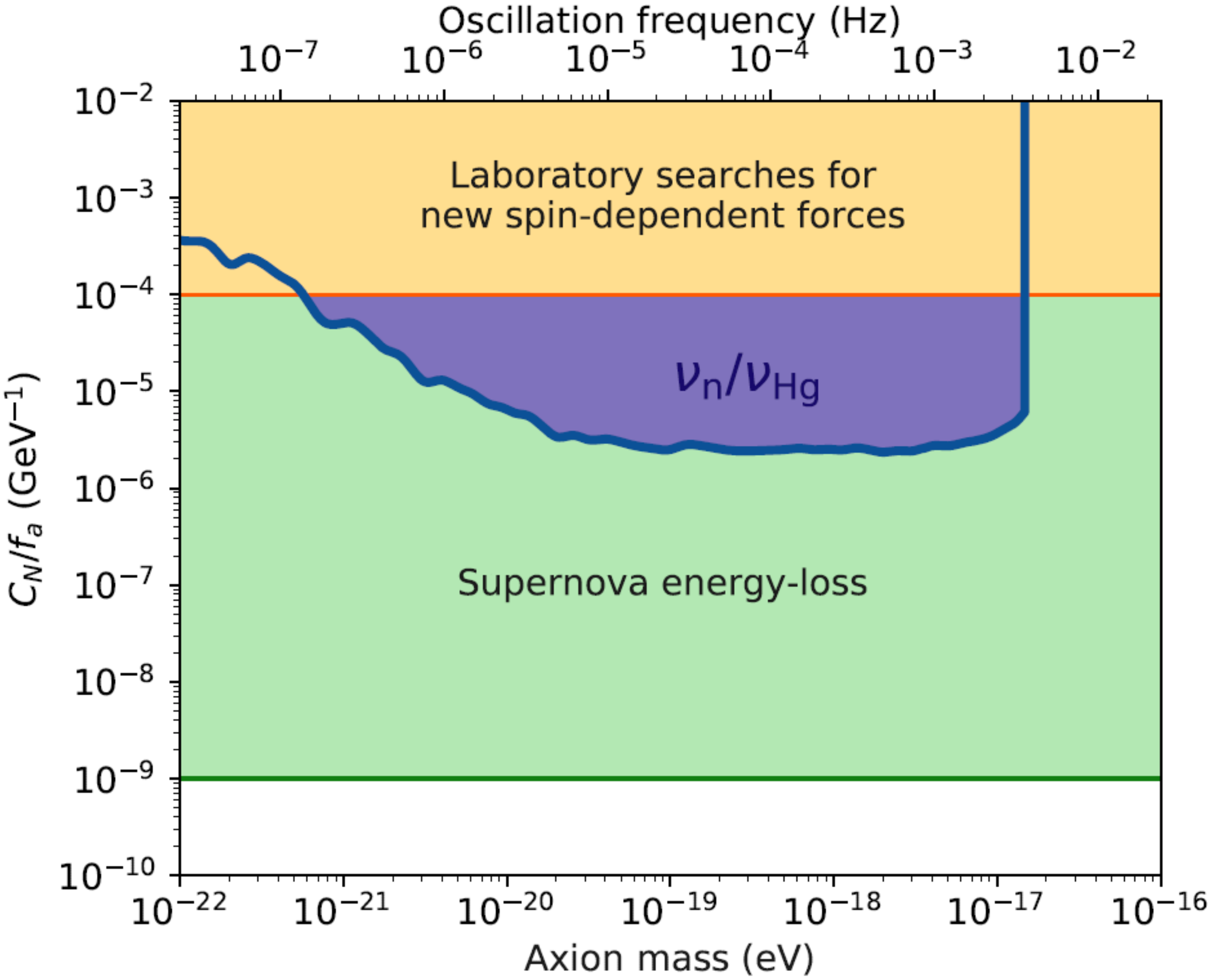
40-fold improvement (laboratory bounds)!



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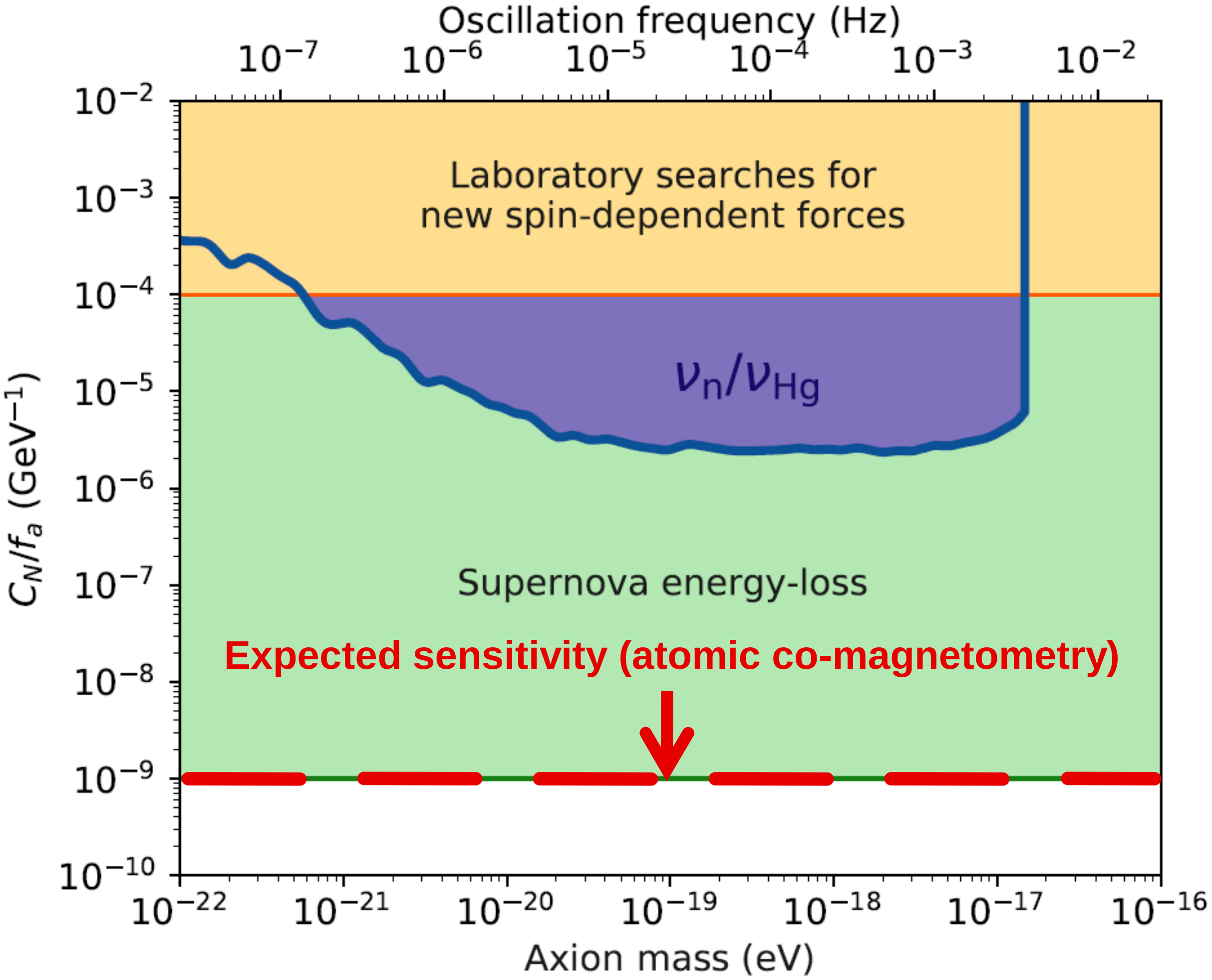
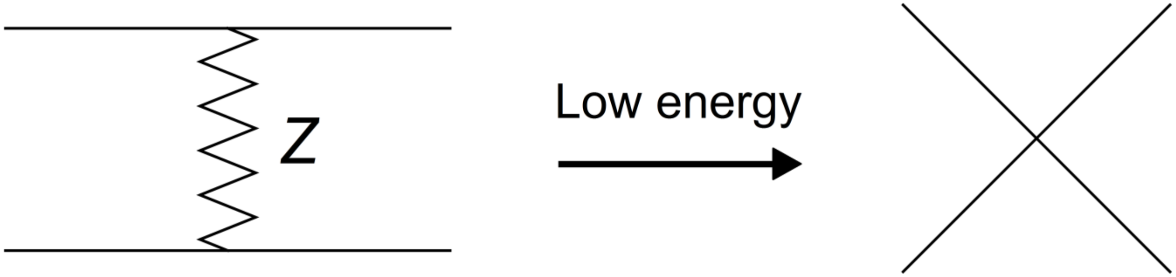


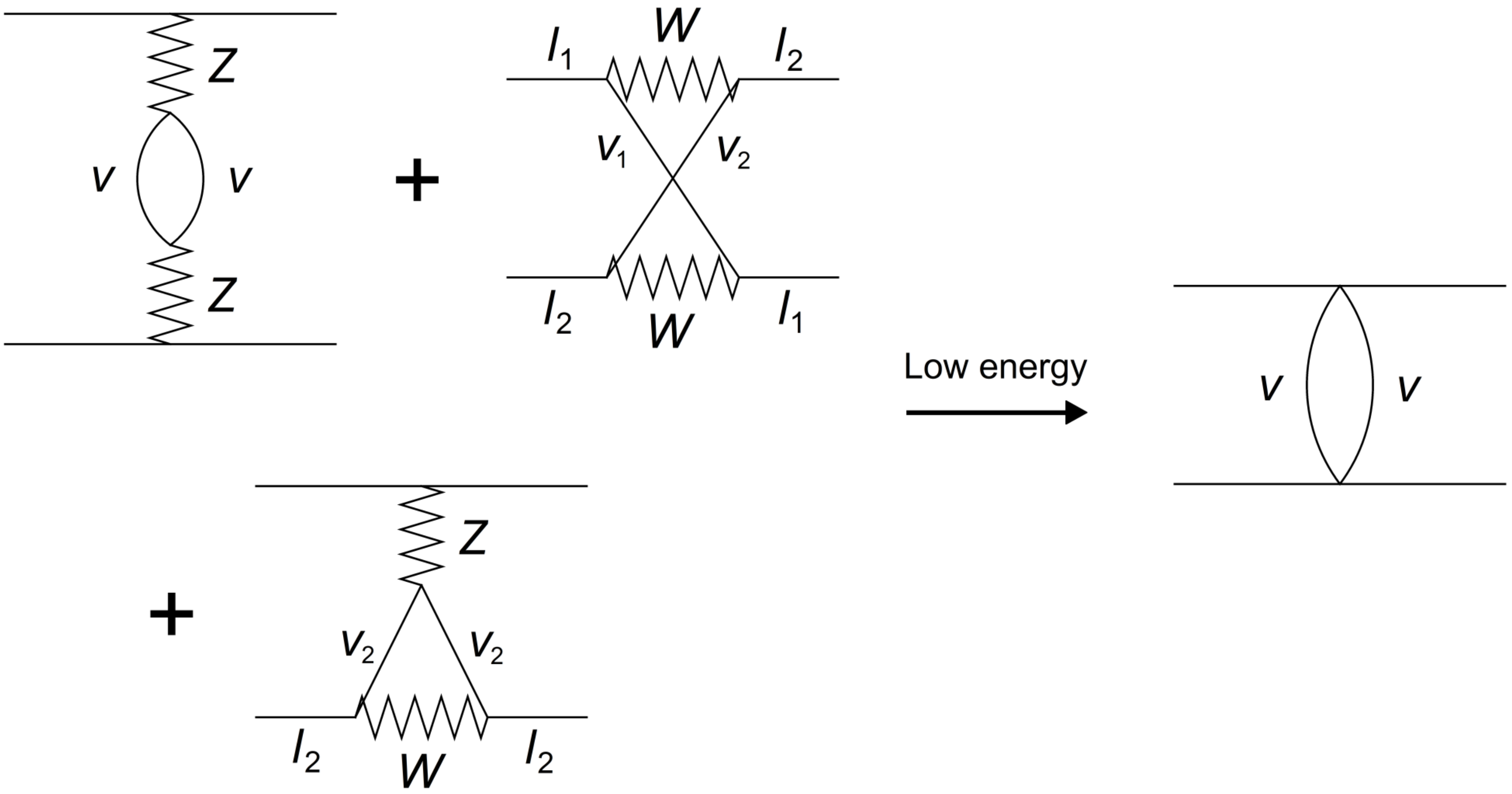
Expected sensitivity (atomic co-magnetometry)

Classical (Tree-Level) Weak Force



$$\boxed{V(r) \sim G_F\,\delta(\boldsymbol{r})\ +\ \text{spin-dependent terms}\qquad [r >> 1/m_Z]}$$

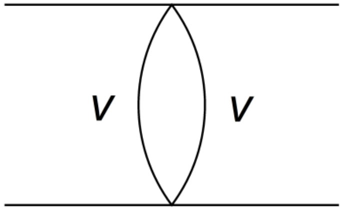
"Long-Range" Neutrino-Mediated Forces



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

Probing "Long-Range" Neutrino-Mediated Forces

[Stadnik, arXiv:1711.03700, *PRL* (In press)]



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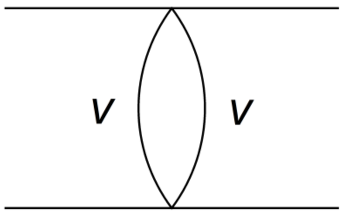

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Enormous enhancement of energy shift in *s*-wave atomic states (*l* = 0, no centrifugal barrier)!

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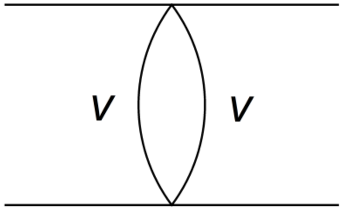

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$$\Delta E_{s\text{-wave}} \sim \boxed{\left(\frac{a_\mathrm{B}}{r_c}\right)^2} \frac{G_F^2}{a_\mathrm{B}^5}$$

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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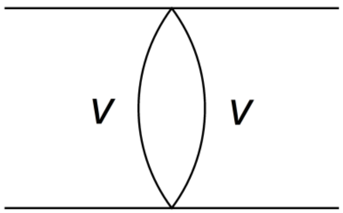

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Spectroscopy measurements of and calculations in:

- Simple atoms (H, D)
- Exotic atoms (e^-e^+, $e^-\mu^+$)
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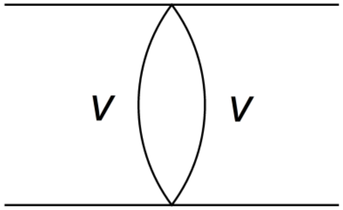

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Muonium ground-state hyperfine interval:

ν_{exp} = 4463302776(51) Hz $\qquad$ $\Delta\nu_{\text{neutrinos}} \approx 0.5$ Hz

ν_{theor} = 4463302868(271)* Hz $\qquad$ $\Delta\nu_{\text{neutrinos + other fermions}} \approx 2$ Hz

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

Constraints on "Long-Range" Neutrino-Mediated Forces

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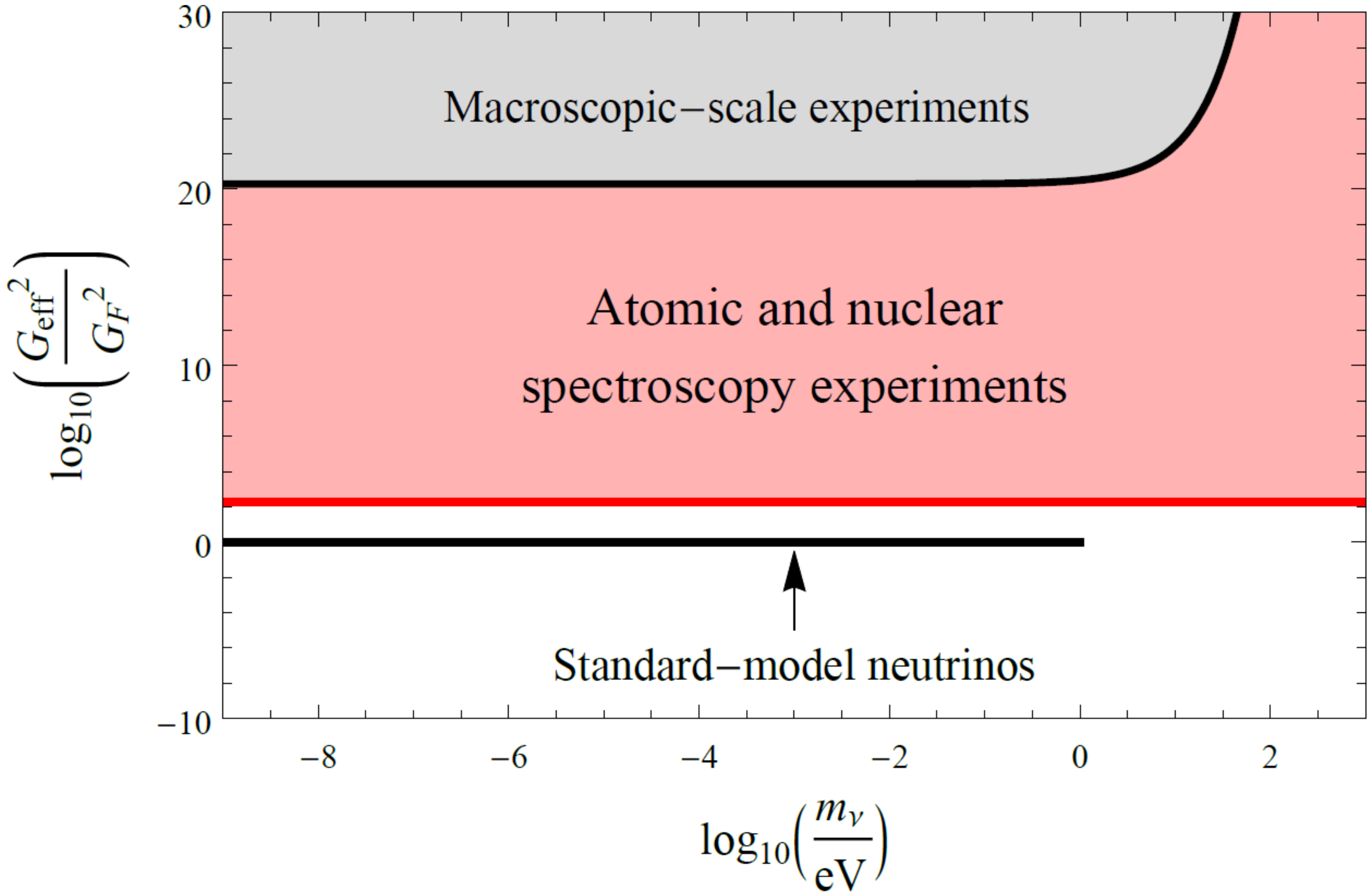
18 orders of magnitude improvement!



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 (independent of ρ_{DM})
- **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)**