New Probes for Low-Mass Bosonic Dark Matter and Neutrino-Mediated Forces

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Collaborators (Experiment):
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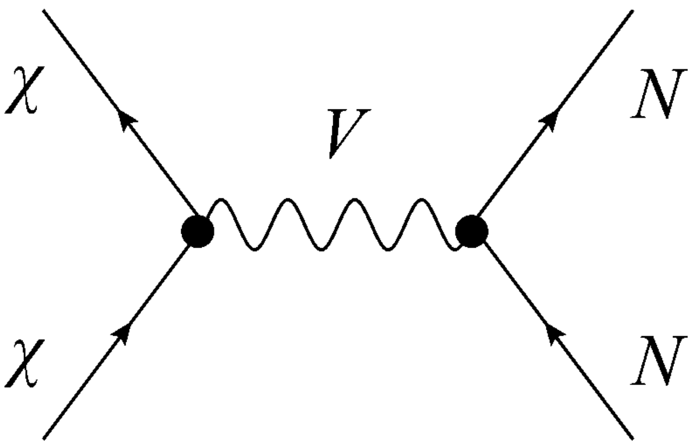
Alexander von Humboldt Stiftung/Foundation

JG|U

53rd Rencontres de Moriond EW, La Thuile, March 2018

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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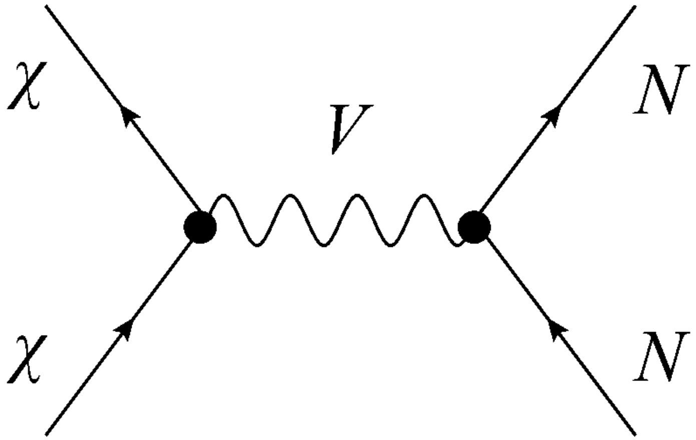

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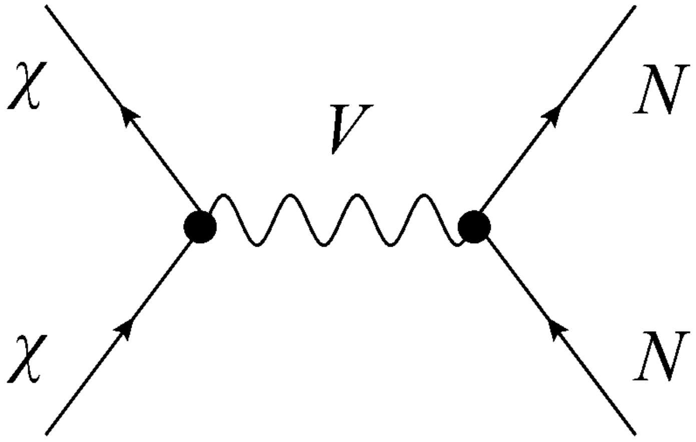

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$$=> \frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 \propto (e')^4$$

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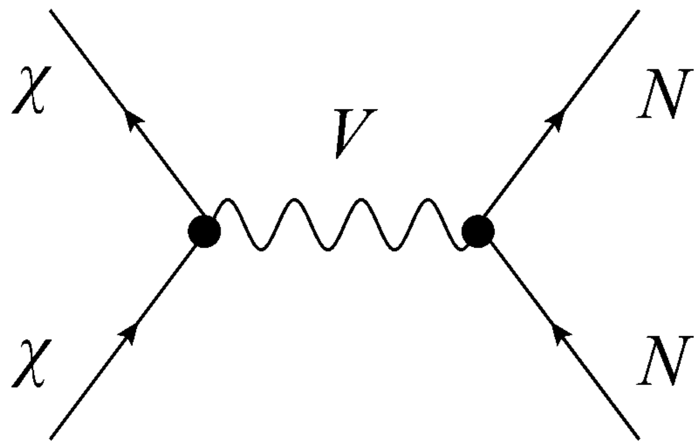

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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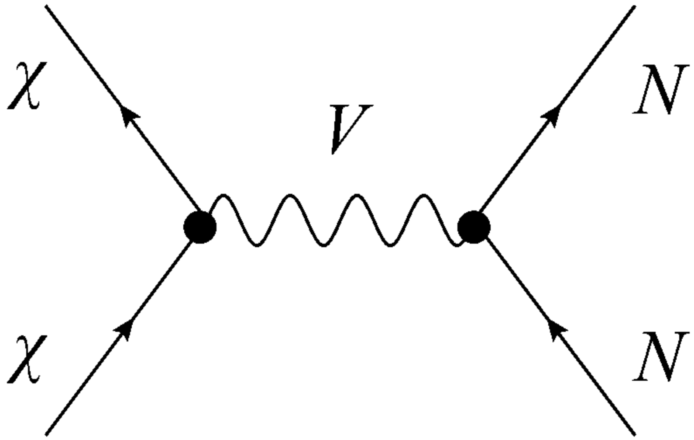


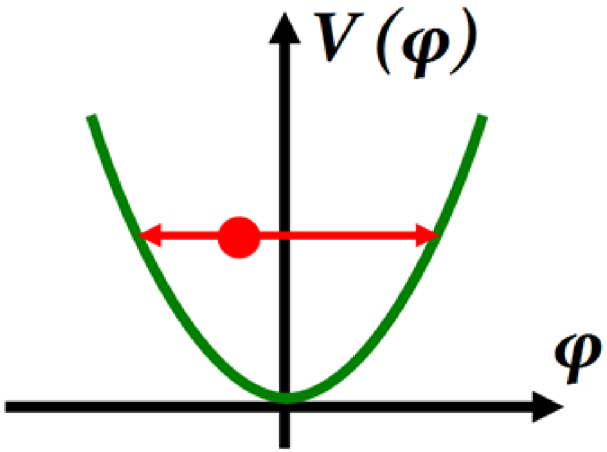
$$\mathcal{M} \propto (e')^2$$

$$\Rightarrow \frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 \propto (e')^4$$

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

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

Classical field

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- $m_\varphi \sim 10^{-22}$ 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):

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

$\rightarrow$ Time-varying fundamental constants

$\rightarrow$ Time-varying spin-dependent effects

10^{15}-fold improvement

1000-fold improvement

See 2017 Moriond Gravitation talk

“Axion Wind” Spin-Precession Effect

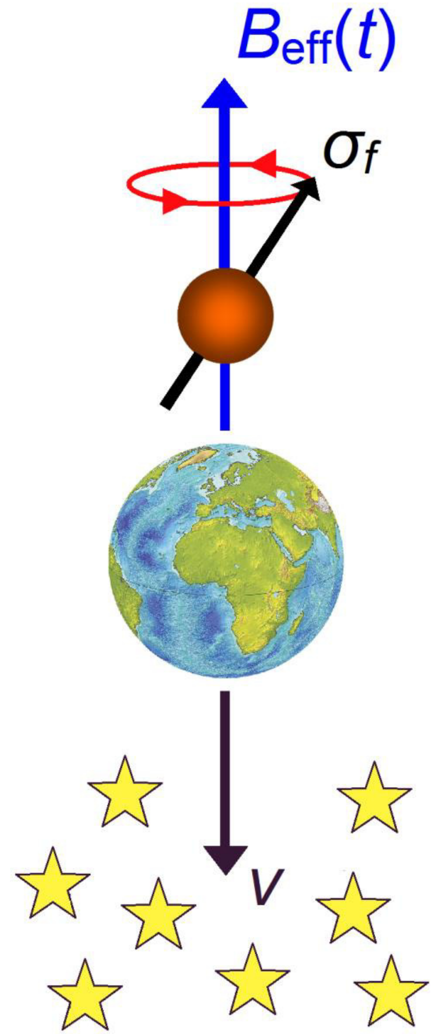
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field**

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

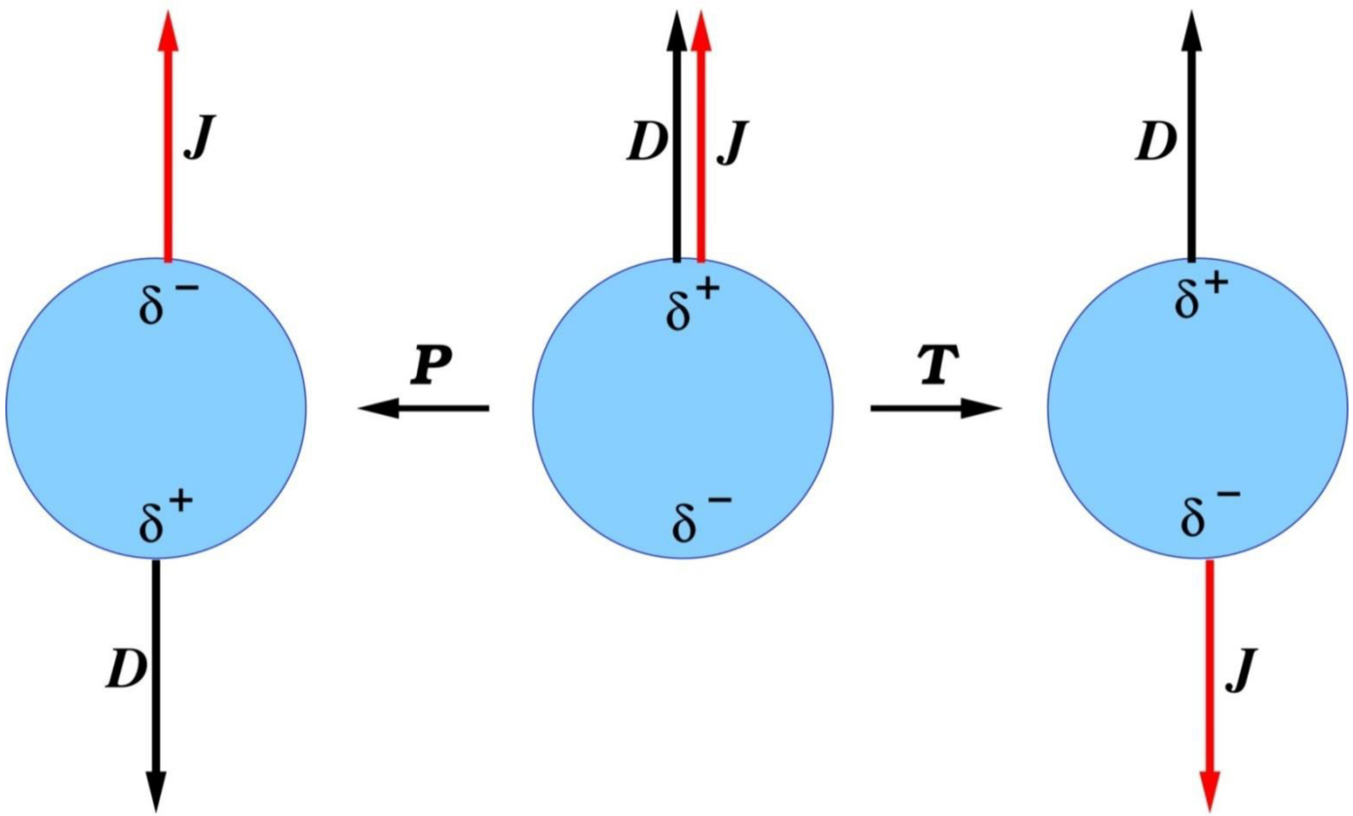


Oscillating Electric Dipole Moments

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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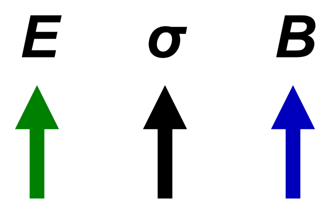

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E ***σ*** ***B***

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

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

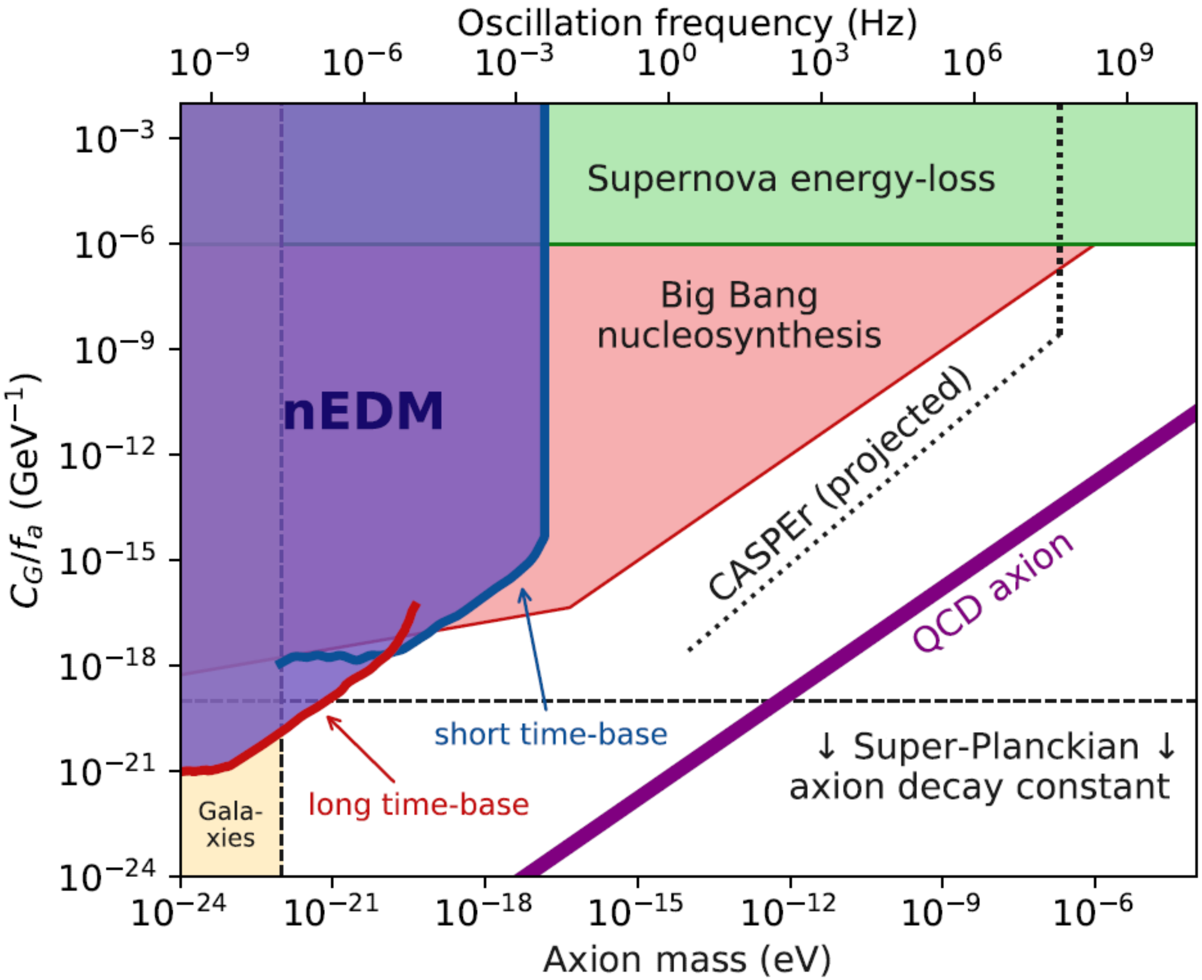
$$\omega_1 = m_a, \ \omega_2 = m_a + \Omega_{\mathrm{sidereal}}, \ \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

Earth's rotation

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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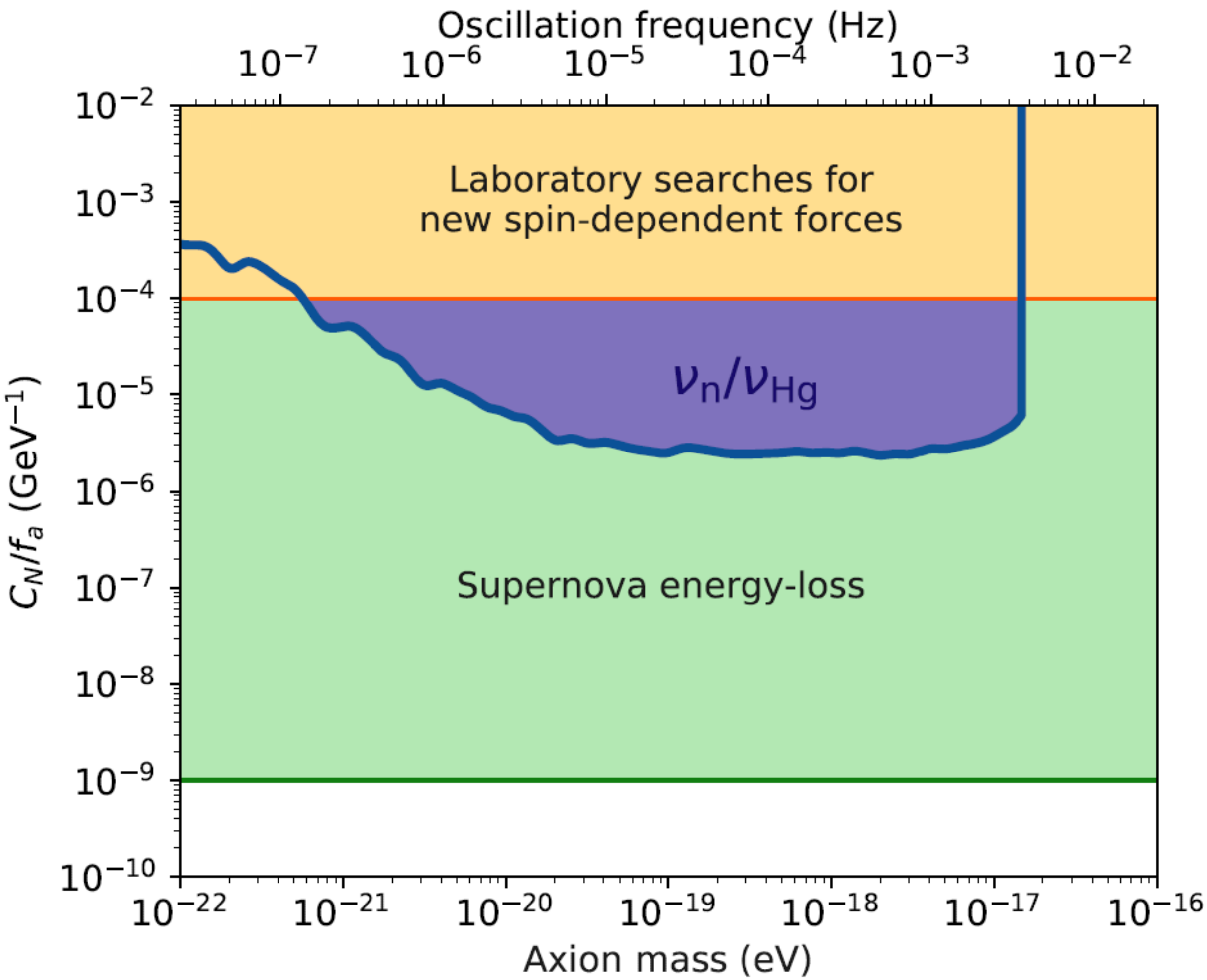
40-fold improvement (laboratory bounds)!



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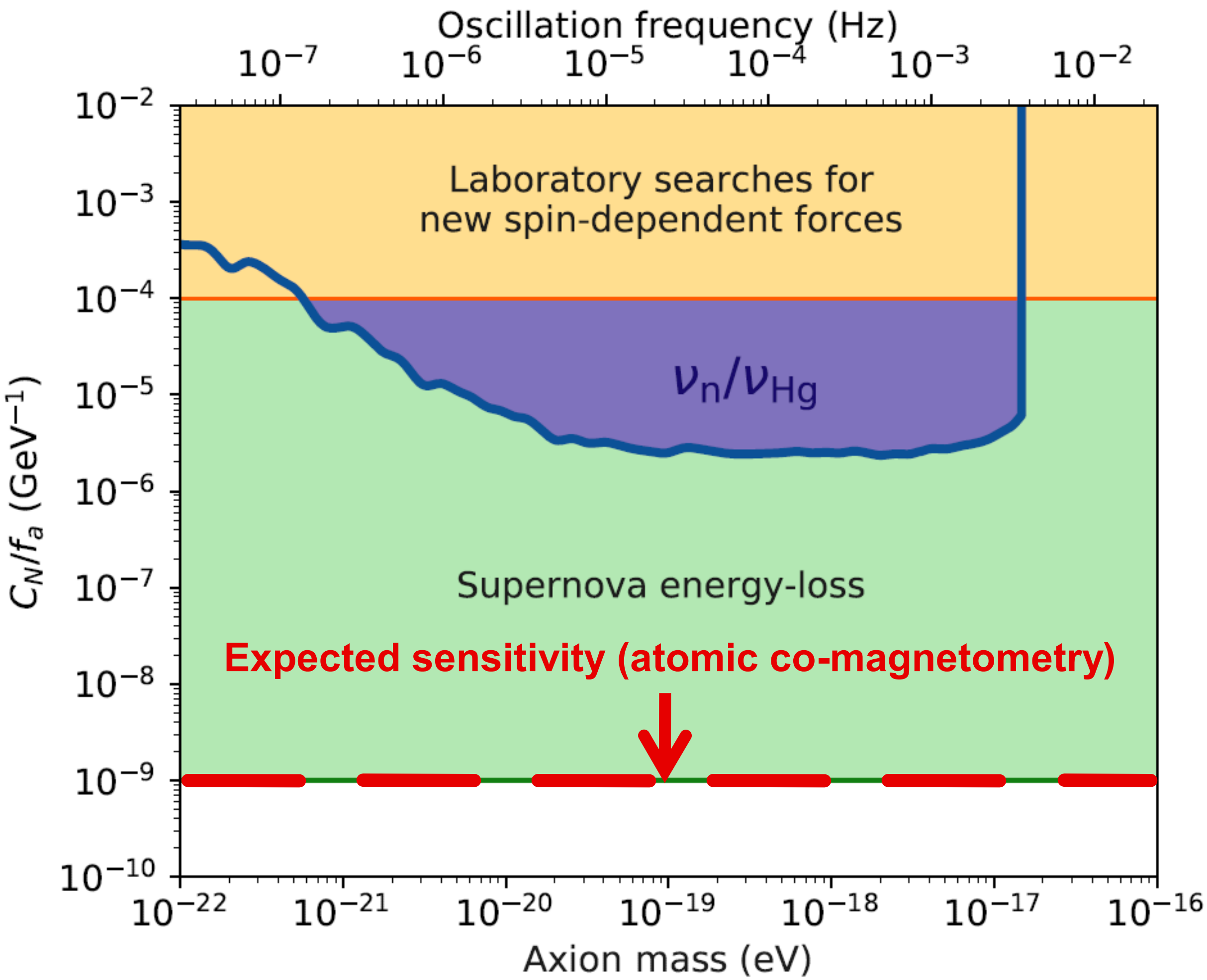
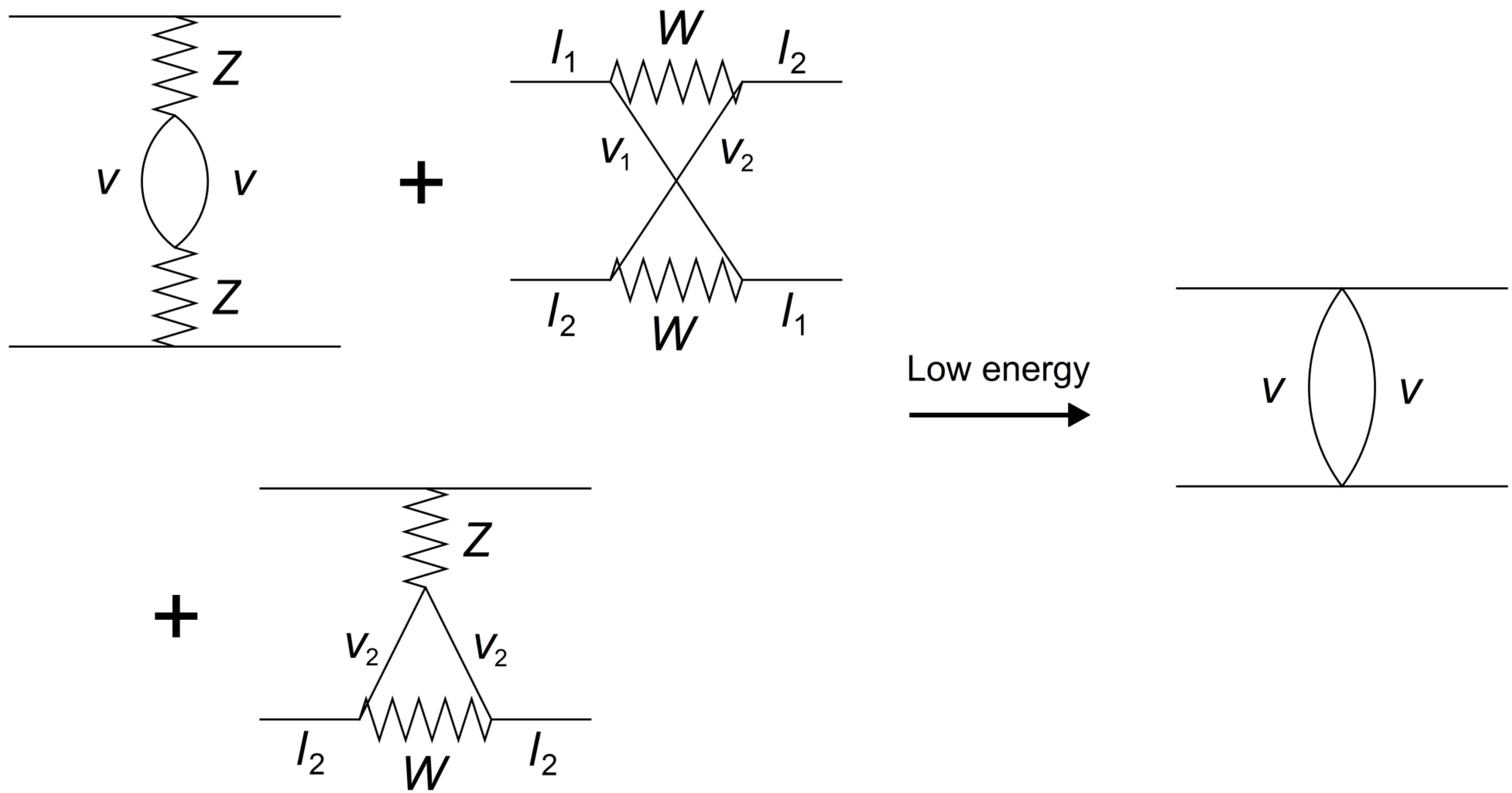


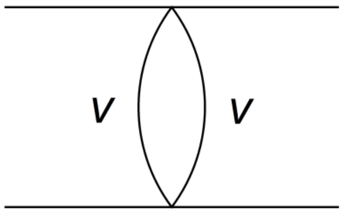
“Long-Range” Neutrino-Mediated Forces



$$V_\nu(r) \sim \frac{G_F^2}{r^5} \; + \; \text{spin-dependent terms}$$

Probing "Long-Range" Neutrino-Mediated Forces

[Stadnik, arXiv:1711.03700]



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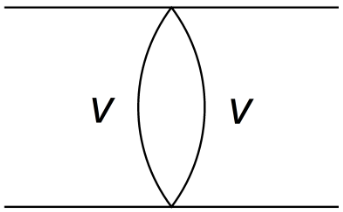

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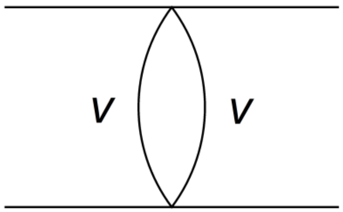

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$$\Delta E_{s\text{-wave}} \sim \boxed{\left(\frac{a_\mathrm{B}}{r_c}\right)^2} \frac{G_F^2}{a_\mathrm{B}^5}$$

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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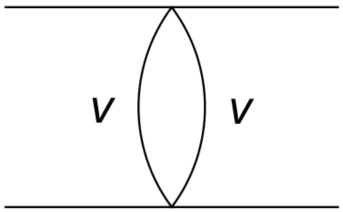
[Stadnik, arXiv:1711.03700]



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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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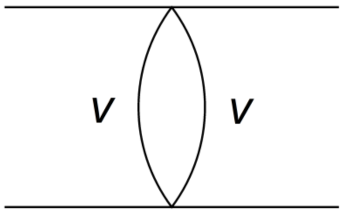

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<u>Muonium ground-state hyperfine interval</u>:

$$\nu_{\mathrm{exp}} = 4463302776(51)\ \mathrm{Hz}$$

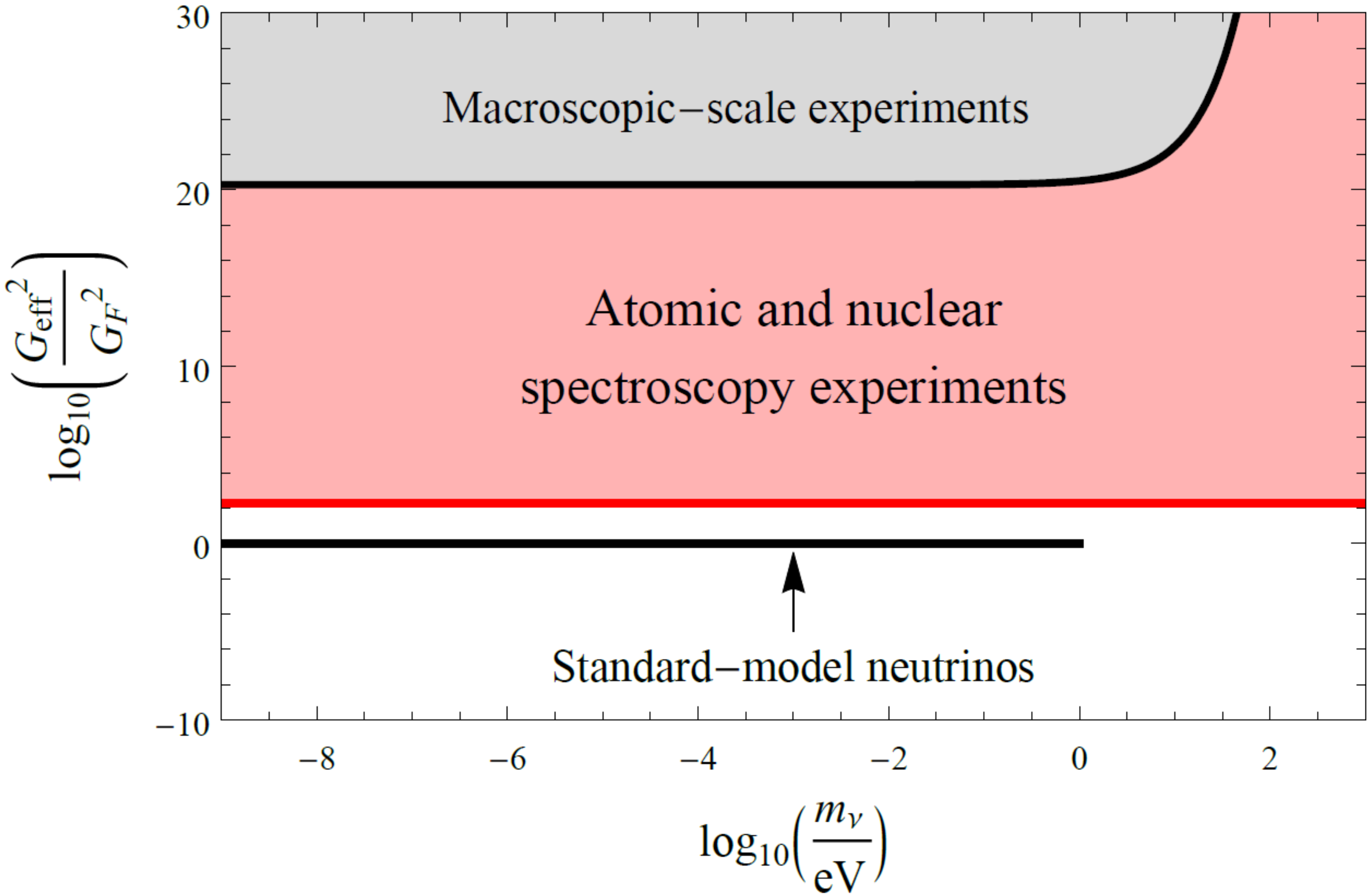
$$\nu_{\mathrm{theor}} = 4463302868(271)\ \mathrm{Hz}$$

$$\Delta\nu_{\mathrm{neutrinos}} \approx 2\ \mathrm{Hz}$$

Constraints on "Long-Range" Neutrino-Mediated Forces

[Stadnik, arXiv:1711.03700]

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 (close to testing the SM prediction!)
- **More details in full slides (also on ResearchGate)**

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

$\rightarrow$ **Time-varying spin-dependent effects**

1000-fold improvement

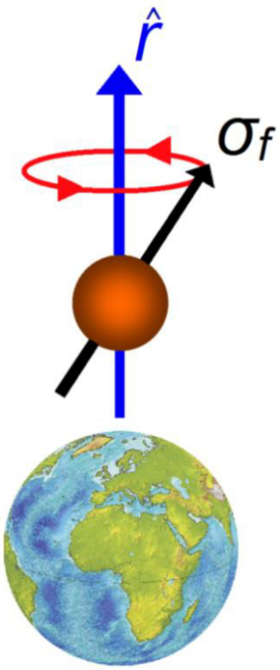
Axion-Induced Oscillating Spin-Gravity Coupling

[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

Distortion of DM field by massive body

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

$$=> \quad H_{\text{eff}}(t) \propto \boldsymbol{\sigma}_f \cdot \hat{\boldsymbol{r}}\sin(m_a t)$$

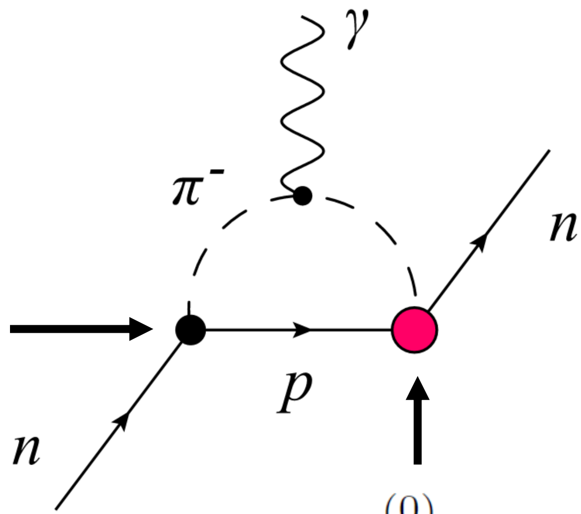


Axion-Induced Oscillating Neutron EDM

[Crewther, Di Vecchia, Veneziano, Witten, *PLB* **88**, 123 (1979)], [Pospelov, Ritz, *PRL* **83**, 2526 (1999)], [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

$$\mathcal{L}_{aGG} = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad => \quad d_n(t) \propto \cos(m_a t)$$

$g_{\pi NN} = 13.5$

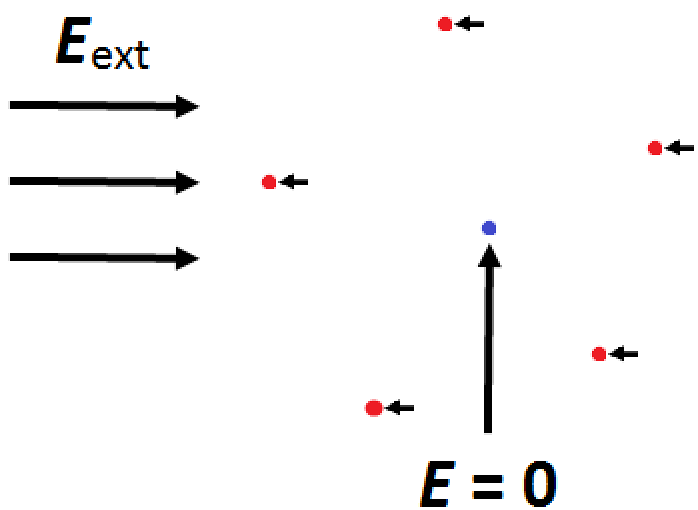


$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$

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."

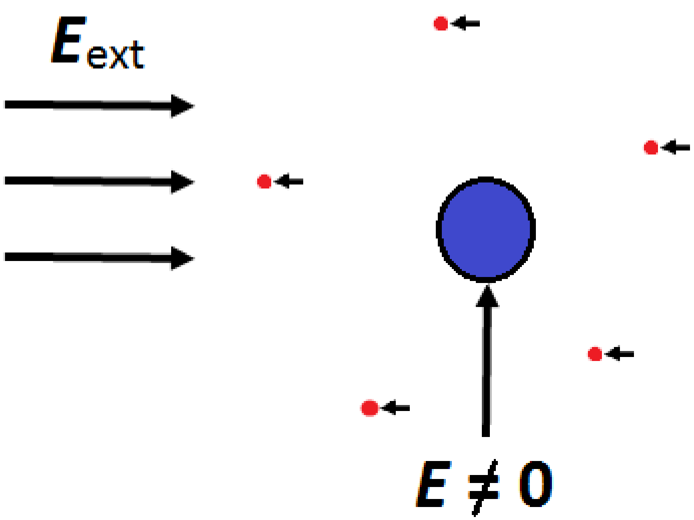


Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

Lifting of Schiff's Theorem

[Sandars, *PRL* **19**, 1396 (1967)],
[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

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



Axion-Induced Oscillating Atomic and Molecular EDMs

[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)],
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

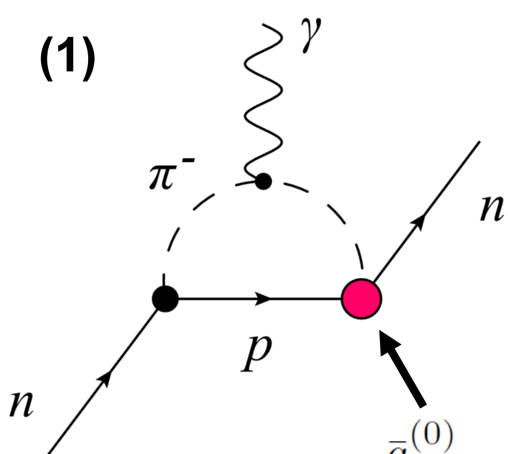
Induced through *hadronic mechanisms*:

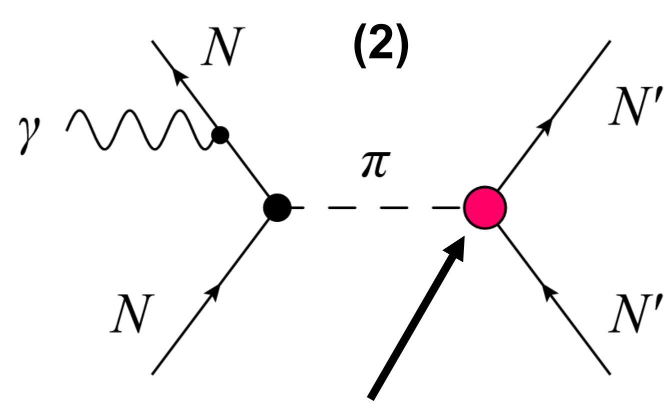
- Oscillating nuclear Schiff moments ($I \geq 1/2$ => $J \geq 0$)
- Oscillating nuclear magnetic quadrupole moments ($I \geq 1$ => $J \geq 1/2$; *magnetic* => no Schiff screening)

Underlying mechanisms:

(1) Intrinsic oscillating nucleon EDMs (1-loop level)

(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~$4\pi^2 \approx 40$**; up to **extra 1000-fold enhancement** in deformed nuclei)





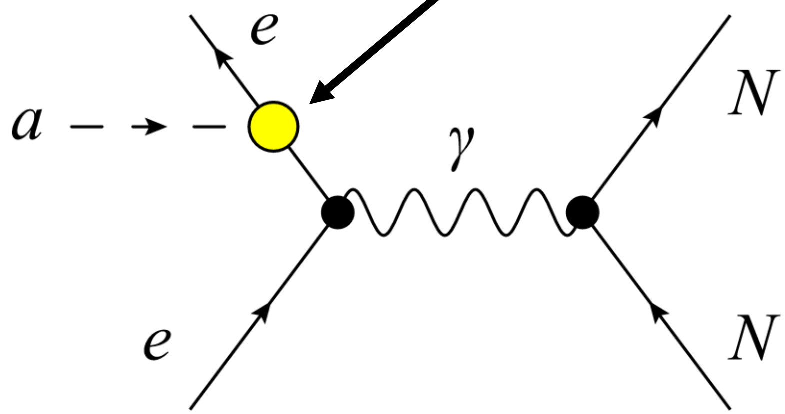
$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

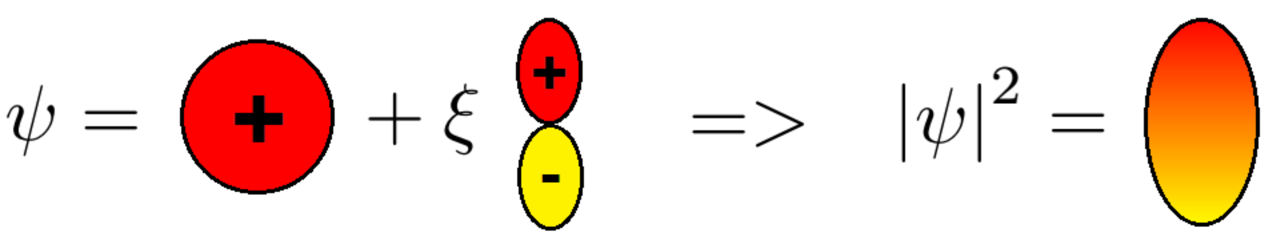
Axion-Induced Oscillating Atomic and Molecular EDMs

[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)], [Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, *PRL* **113**, 081601 (2014); *PRD* **90**, 096005 (2014)]

Also induced through *non-hadronic mechanisms* for $J \geq 1/2$ atoms, via mixing of opposite-parity atomic states.

$$\mathcal{L}_{aee} = -\frac{C_e}{2f_a}\partial_0[a_0\cos(m_a t)]\bar{e}\gamma^0\gamma^5 e$$





Low-mass Spin-0 Dark Matter

Dark Matter

Scalars
(Dilatons):
$\varphi \xrightarrow{P} +\varphi$

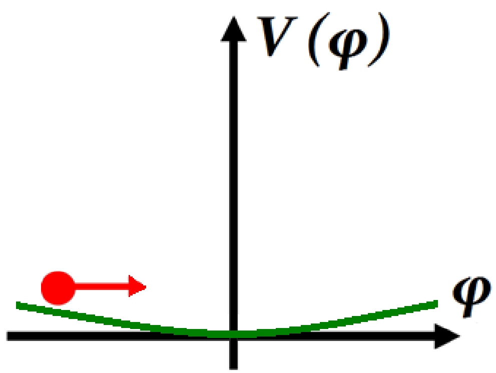
$\longrightarrow$ **Time-varying fundamental constants**

10^{15}-fold improvement

Cosmological Evolution of the Fundamental 'Constants'

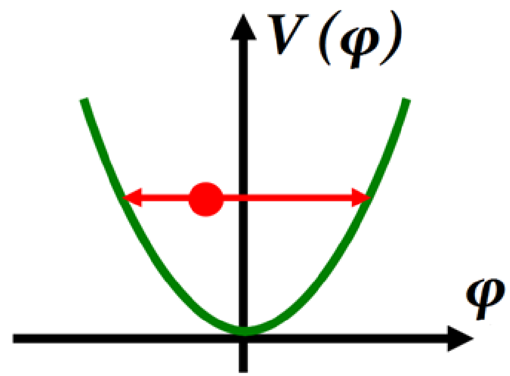
- Dirac's large numbers hypothesis: $G \propto 1/t$
- Fundamental constants not predicted from theory, but determined from measurements (local – not universal)
- Possible models for cosmological evolution of fundamental constants?

Dark energy ($m_\varphi \approx 0$)



Slow rolling ($t \sim t_{\text{Universe}}$)

Dark matter?



$\varphi(t) = \varphi_0 \cos(m_\varphi t)$

$\langle\varphi\rangle = 0$

$\boldsymbol{\langle\varphi^2\rangle = \varphi_0^2/2 \propto \rho_\varphi}$

Rapid oscillations ($t \ll t_{\text{Universe}}$)

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)]

Consider *quadratic couplings* of an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad \text{c.f.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad => \quad m_f \rightarrow m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

'Slow' drifts [Astrophysics (high ρ_{DM}): BBN, CMB]

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)]

Fermions:

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad => m_f \rightarrow m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2}\right]$$

Photon:

$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \quad => \alpha \rightarrow \frac{\alpha}{1 - \phi^2/(\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \frac{\phi^2}{(\Lambda'_\gamma)^2}\right]$$

***W* and *Z* Bosons:**

$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu \quad => M_V^2 \rightarrow M_V^2 \left[1 + \frac{\phi^2}{(\Lambda'_V)^2}\right]$$

BBN Constraints on 'Slow' Drifts in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- Largest effects of DM in early Universe (highest ρ_{DM})
- Big Bang nucleosynthesis ($t_{\mathrm{weak}} \approx 1\mathrm{s} - t_{\mathrm{BBN}} \approx 3$ min)
- Primordial ^{4}He abundance sensitive to n/p ratio

  (almost all neutrons bound in ^{4}He after BBN)

$$\frac{\Delta Y_p(^4\mathrm{He})}{Y_p(^4\mathrm{He})} \approx \frac{\Delta (n/p)_{\mathrm{weak}}}{(n/p)_{\mathrm{weak}}} - \Delta \left[\int_{t_{\mathrm{weak}}}^{t_{\mathrm{BBN}}} \Gamma_n(t) dt \right]$$

$$p + e^- \rightleftharpoons n + \nu_e$$

$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik, Flambaum, *PRL* **114**, 161301 (2015)]

$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_X \left(K_{X,1} - K_{X,2}\right)\cos\left(\omega t\right)$$

$\omega = m_\varphi$ (linear coupling) or $\omega = 2m_\varphi$ (quadratic coupling)

- Precision of optical clocks approaching $\sim 10^{-18}$ fractional level
- Sensitivity coefficients K_X calculated extensively by Flambaum group and co-workers (1998 – present)

Dy/Cs: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

Rb/Cs: [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999);
Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum, *PRA* **70**, 014102 (2004); Dzuba, Flambaum, *PRA* **77**, 012515 (2008)]

- Atomic optical transitions:

$$\omega_{\mathrm{opt}} \propto \underbrace{\left(\frac{m_e e^4}{\hbar^3}\right)}_{\text{Non-relativistic atomic unit of frequency}} \underbrace{F_{\mathrm{rel}}^{\mathrm{opt}}(Z\alpha)}_{\text{Relativistic factor}}$$

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999); Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum, *PRA* **70**, 014102 (2004); Dzuba, Flambaum, *PRA* **77**, 012515 (2008)]

- Atomic optical transitions:

$$\omega_{\text{opt}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) F_{\text{rel}}^{\text{opt}}(Z\alpha)$$

$$\frac{\omega_{\text{opt},1}}{\omega_{\text{opt},2}} \propto \frac{\cancel{\left(m_e e^4/\hbar^3\right)}\, F_{\text{rel},1}^{\text{opt}}(Z\alpha)}{\cancel{\left(m_e e^4/\hbar^3\right)}\, F_{\text{rel},2}^{\text{opt}}(Z\alpha)}$$

Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); *PRA* **59**, 230 (1999); Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum, *PRA* **70**, 014102 (2004); Dzuba, Flambaum, *PRA* **77**, 012515 (2008)]

- Atomic optical transitions:

$$\omega_{\mathrm{opt}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) F_{\mathrm{rel}}^{\mathrm{opt}}(Z\alpha)$$

$K_\alpha(\mathrm{Sr}) = 0.06$, $K_\alpha(\mathrm{Yb}) = 0.3$, $K_\alpha(\mathrm{Hg}) = 0.8$

Increasing *Z*

- Atomic hyperfine transitions:

$$\omega_{\mathrm{hf}} \propto \left(\frac{m_e e^4}{\hbar^3}\right) \left[\alpha^2 F_{\mathrm{rel}}^{\mathrm{hf}}(Z\alpha)\right] \boxed{\left(\frac{m_e}{m_N}\right)} \mu \longleftarrow K_{m_q} \neq 0$$

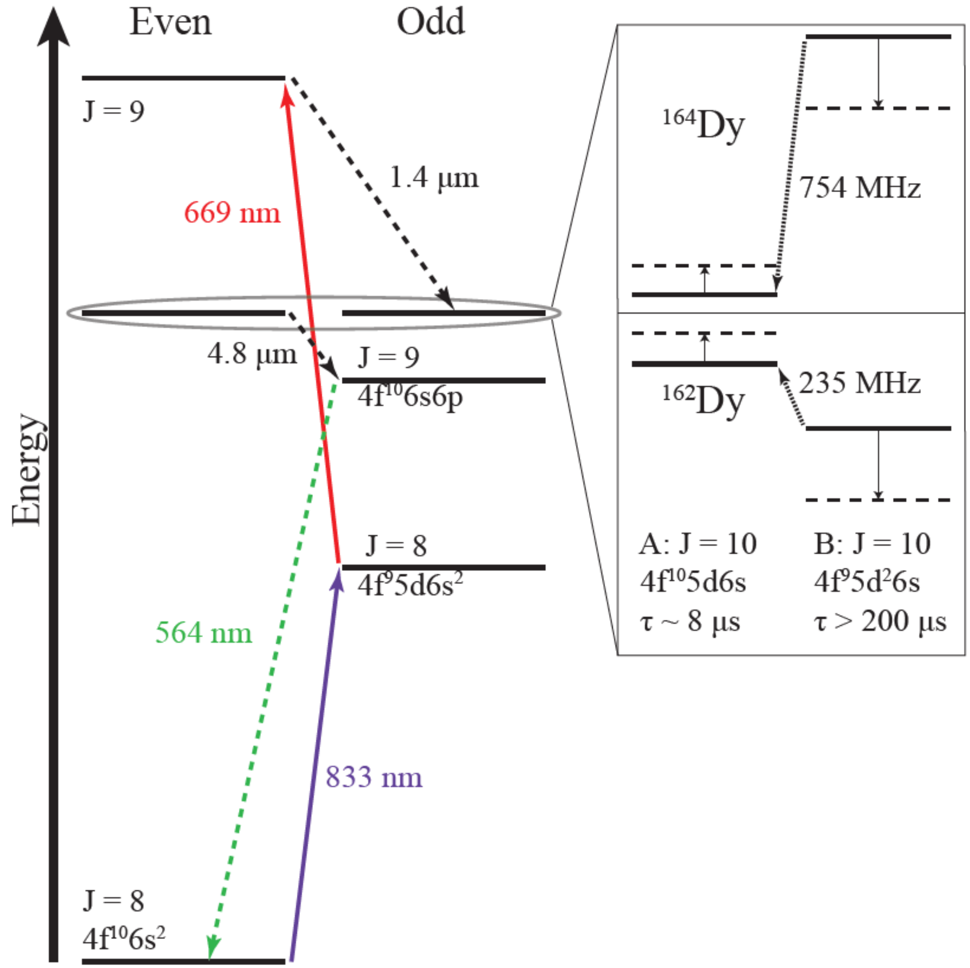
$K_\alpha(^1\mathrm{H}) = 2.0$, $K_\alpha(^{87}\mathrm{Rb}) = 2.3$, $K_\alpha(^{133}\mathrm{Cs}) = 2.8$ $\quad K_{m_e/m_N} = 1$

Increasing *Z*

Enhanced Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba, Flambaum, Webb, *PRL* **82**, 888 (1999); Flambaum, *PRL* **97**, 092502 (2006); *PRA* **73**, 034101 (2006); Berengut, Dzuba, Flambaum, *PRL* **105**, 120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels:
  - Atoms (e.g., $|K_\alpha(\text{Dy})| \sim 10^6 - 10^7$)
  - Molecules
  - Highly-charged ions
  - Nuclei



Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Gravitational-wave detector (LIGO/Virgo), *L* ~ 4 km

Small-scale cavity, *L* ~ 0.2 m

Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

- Compare $L \sim Na_{\mathrm{B}}$ with λ

$$\Phi = \frac{\omega L}{c} \propto \left(\frac{e^2}{a_{\mathrm{B}}\hbar}\right)\left(\frac{Na_{\mathrm{B}}}{c}\right) = N\alpha \quad => \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

- Multiple reflections of light beam enhance effect ($N_{\mathrm{eff}} \sim 10^5$ in small-scale interferometers with highly reflective mirrors)

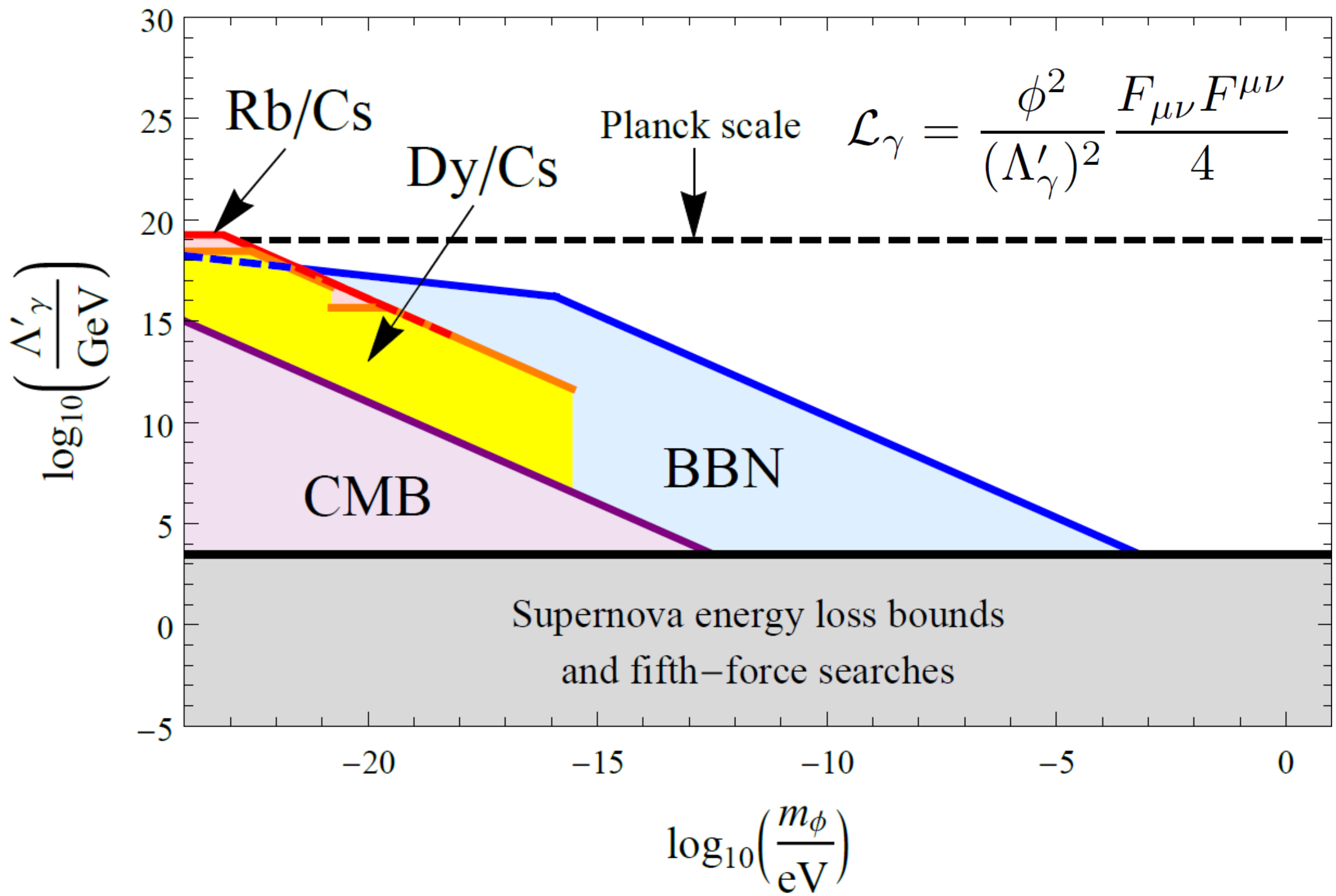
Sr/Cavity (Domain wall DM): [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]

Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy/Cs and Rb/Cs constraints:

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]

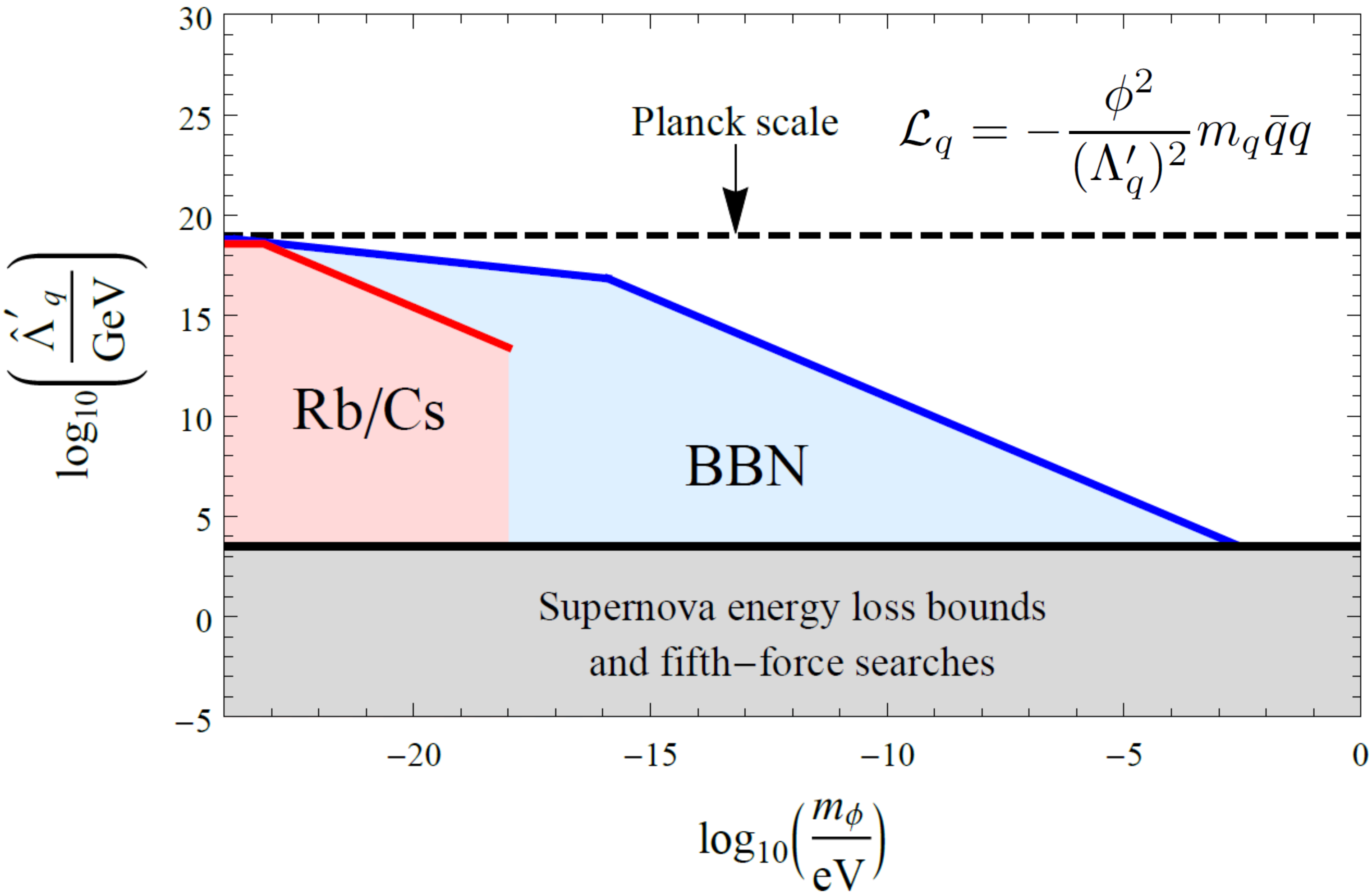
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

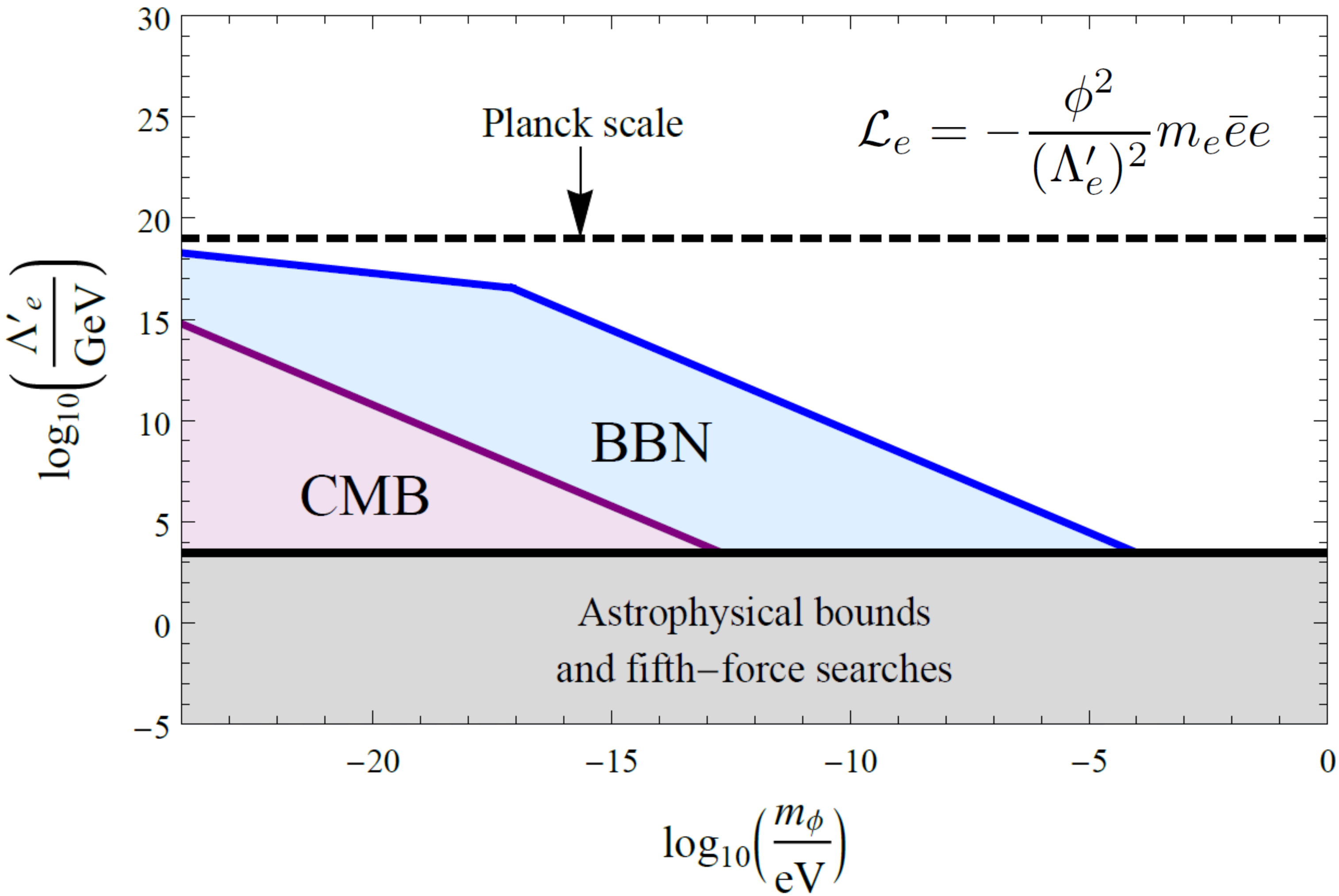
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

BBN and CMB constraints:

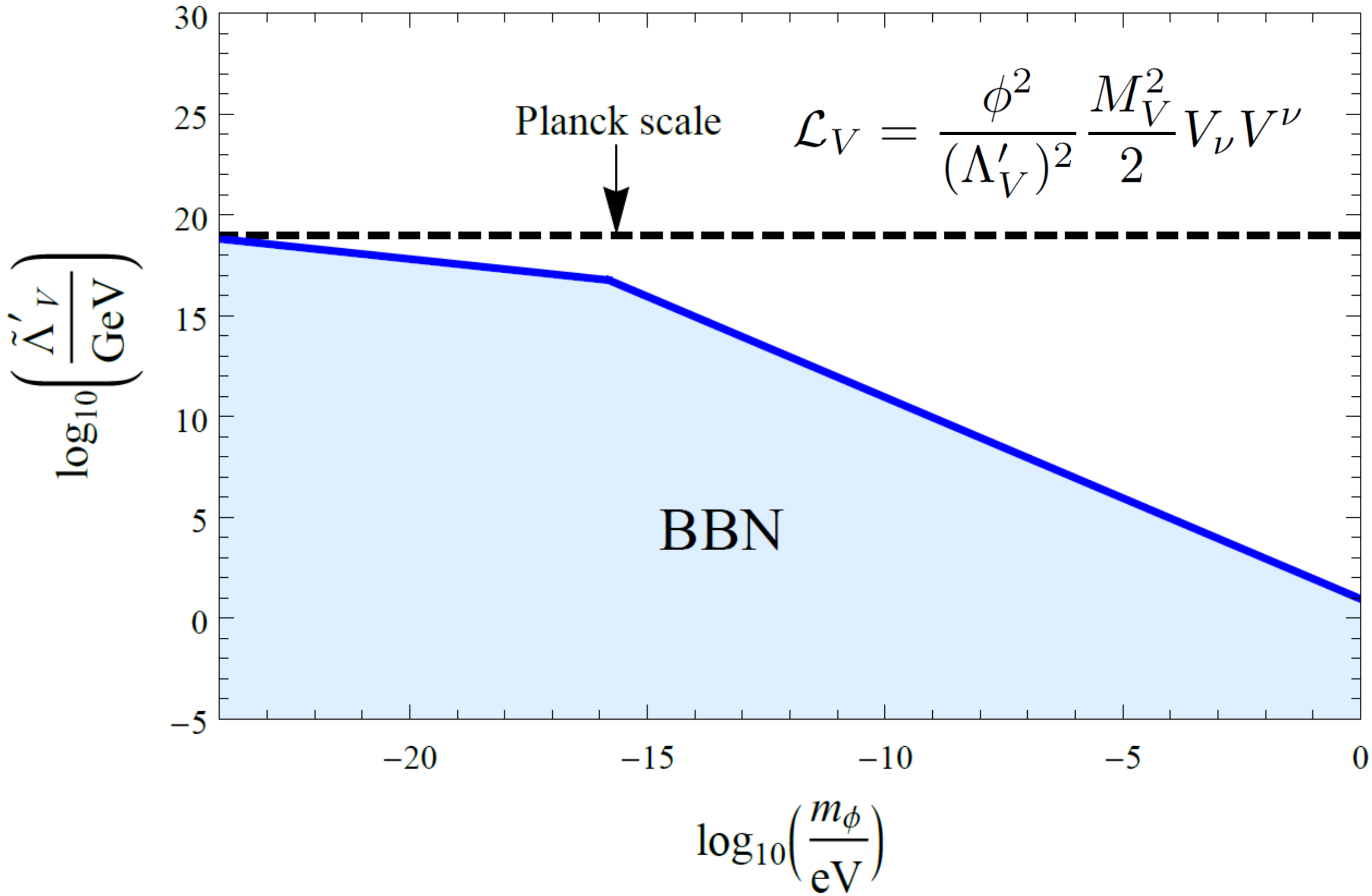
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



Constraints on Quadratic Interactions of Scalar Dark Matter with *W* and *Z* Bosons

BBN constraints:

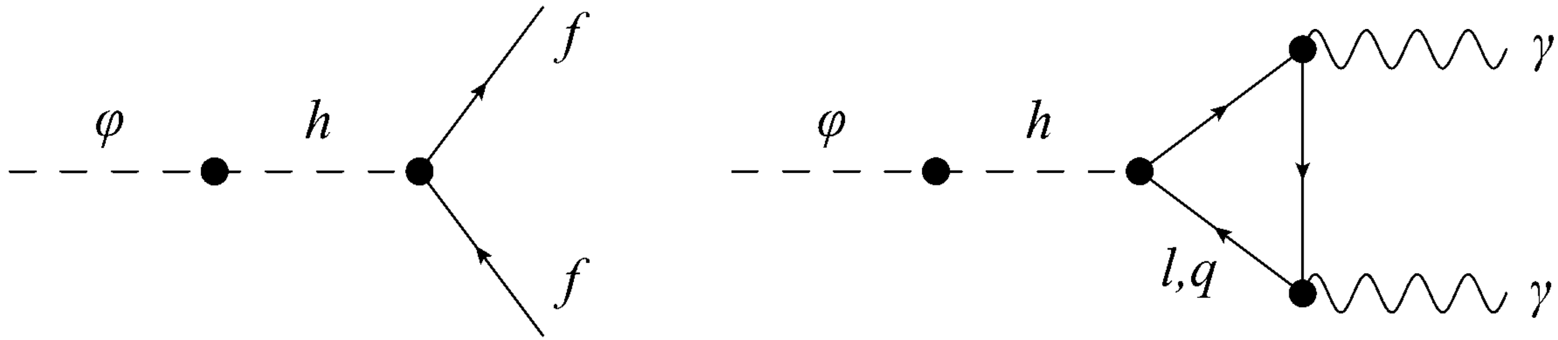
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



Dark Matter-Induced Oscillating Variation of the Fundamental Constants

Linear couplings with the SM sector may be generated through the interaction of φ with the Higgs boson*
[Piazza, Pospelov, *PRD* **82**, 043533 (2010)]:

$$\mathcal{L}_H = -A\phi H^\dagger H$$



$$m_f \to m_f \left[1 - \frac{A g_{hff} \langle h \rangle \phi}{m_f m_h^2}\right] \qquad \alpha \to \alpha \left[1 + \frac{4 A g_{h\gamma\gamma} \phi}{m_h^2}\right]$$

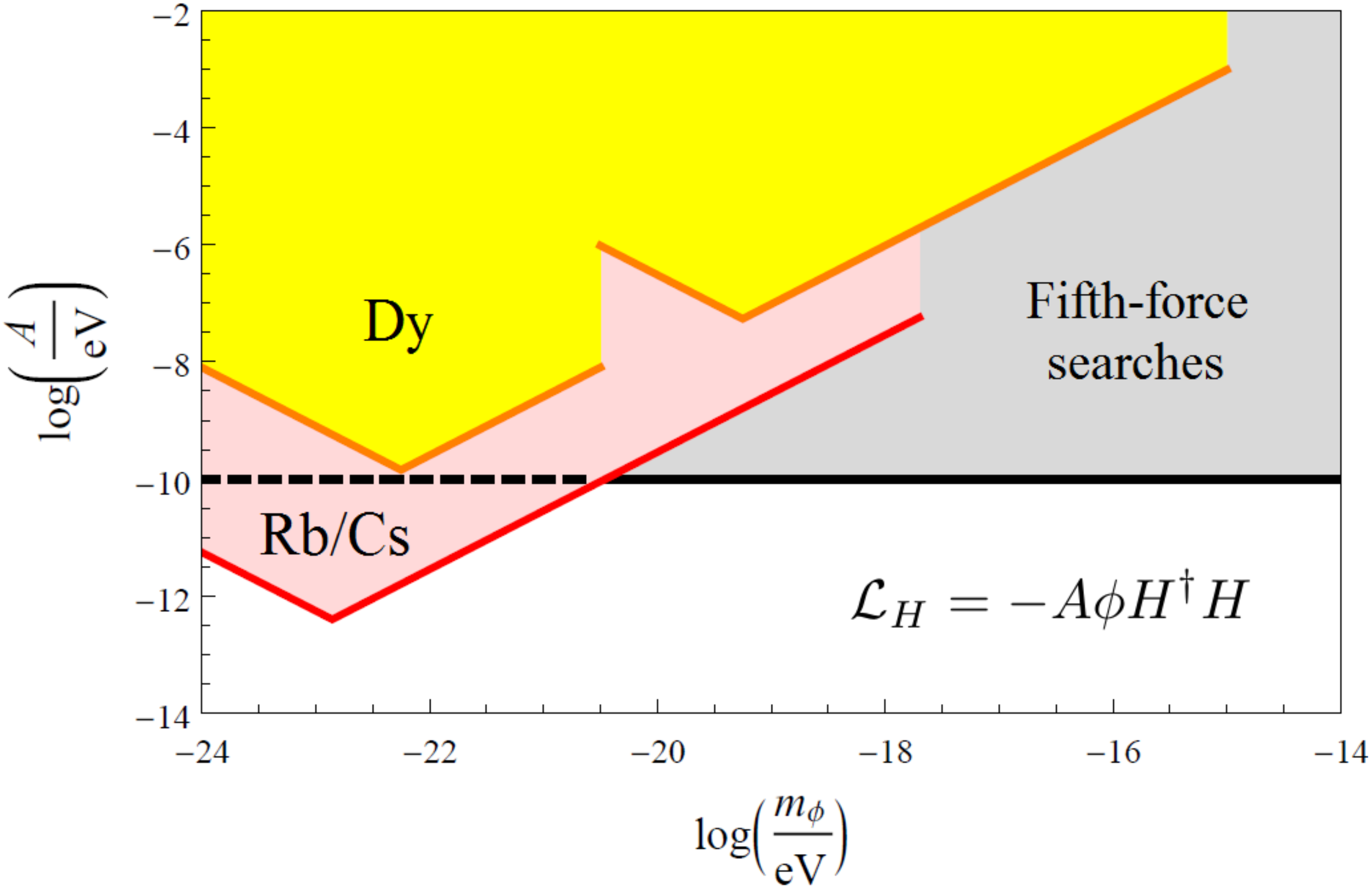
* This technically natural interaction also appears in some types of relaxion models.

Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

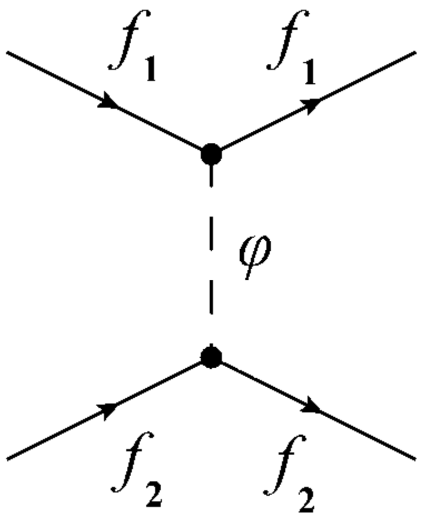
Rb/Cs constraints:

[Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

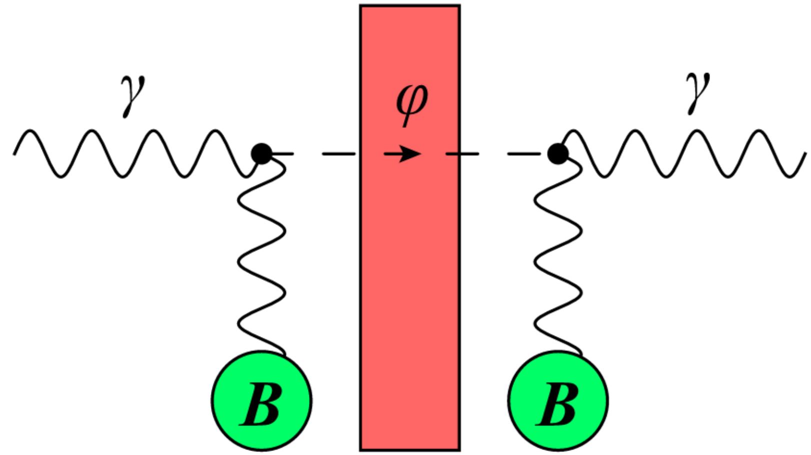
2 – 3 orders of magnitude improvement!



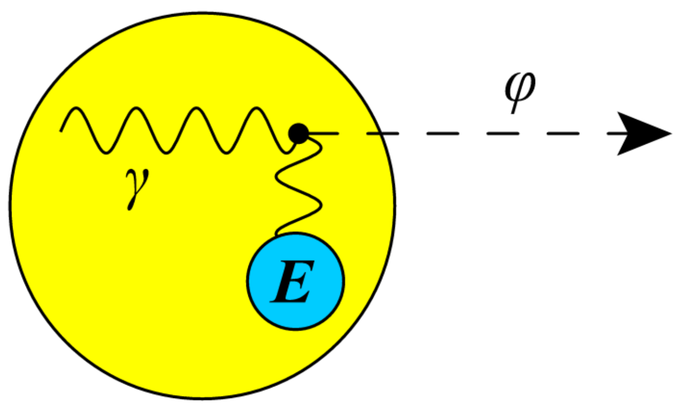
Non-Cosmological Sources of Exotic Bosons



New forces



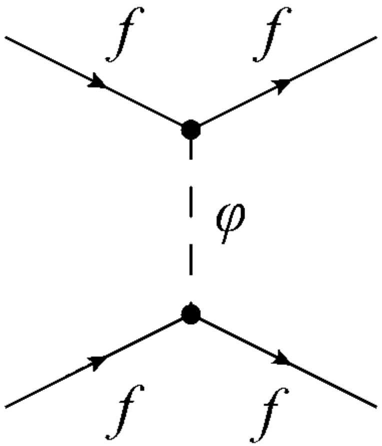
Interconversion with ordinary particles



Stellar emission

Non-Cosmological Sources of Exotic Bosons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



$$\mathcal{L}_{\mathrm{int}} = -\frac{\phi}{\Lambda_f} m_f \bar{f} f$$

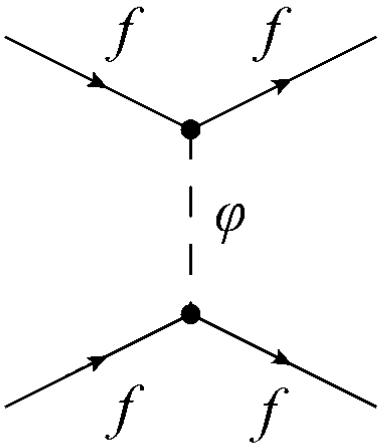
$$V(r) = -\left(\frac{m_f}{\Lambda_f}\right)^2 \frac{e^{-m_\phi r}}{4\pi r}$$

$$\frac{\delta m_f}{m_f} = \frac{\phi}{\Lambda_f} \propto \frac{e^{-m_\phi r}}{r}$$

=> Perturbation of atomic transition frequencies as distance changes

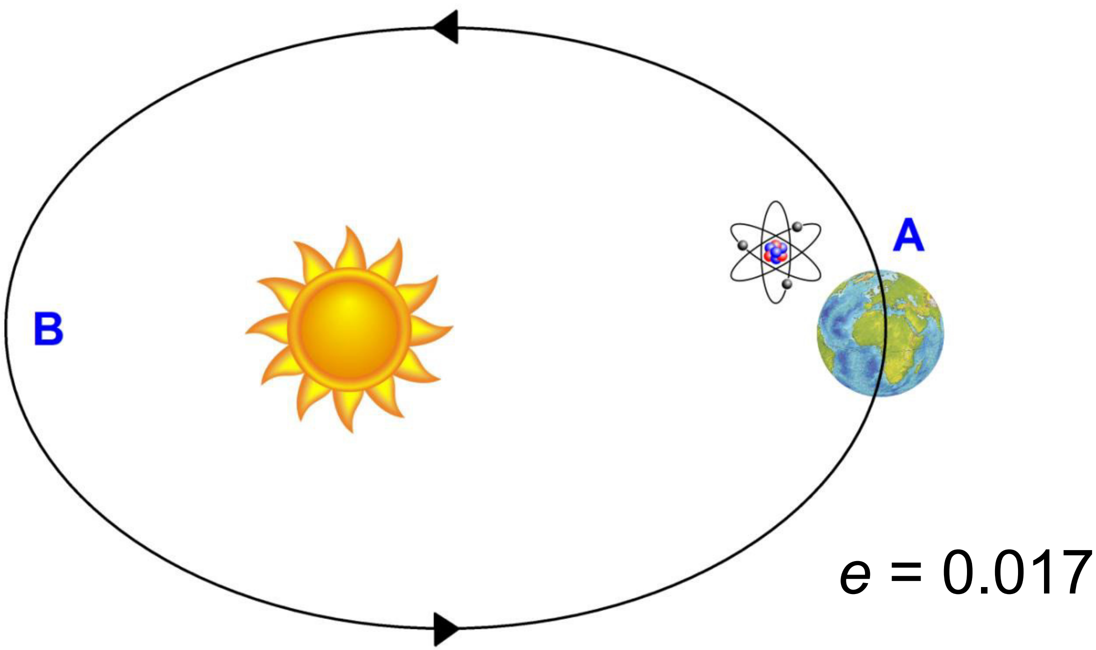
Non-Cosmological Sources of Exotic Bosons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



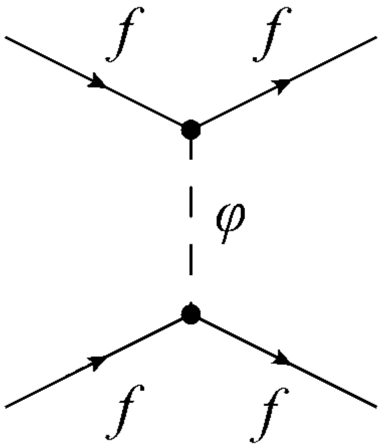
$$\mathcal{L}_{\text{int}} = -\frac{\phi}{\Lambda_f} m_f \bar{f} f$$

$$V(r) = -\left(\frac{m_f}{\Lambda_f}\right)^2 \frac{e^{-m_\phi r}}{4\pi r}$$



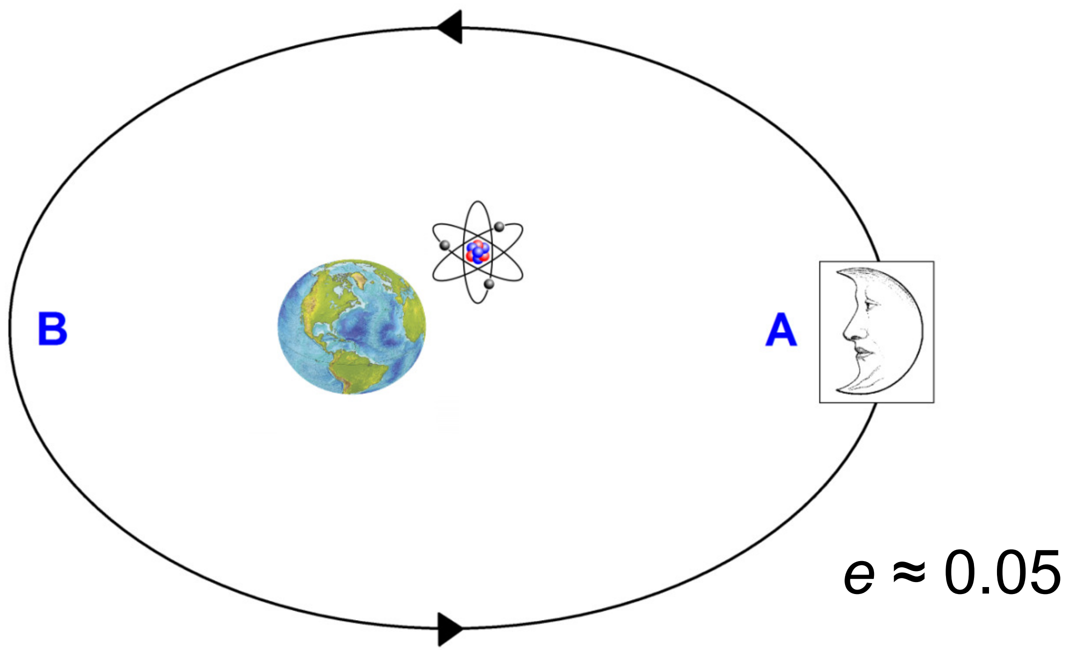
Non-Cosmological Sources of Exotic Bosons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



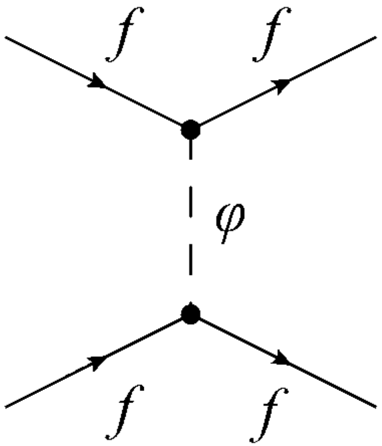
$$\mathcal{L}_{\text{int}} = -\frac{\phi}{\Lambda_f} m_f \bar{f} f$$

$$V(r) = -\left(\frac{m_f}{\Lambda_f}\right)^2 \frac{e^{-m_\phi r}}{4\pi r}$$



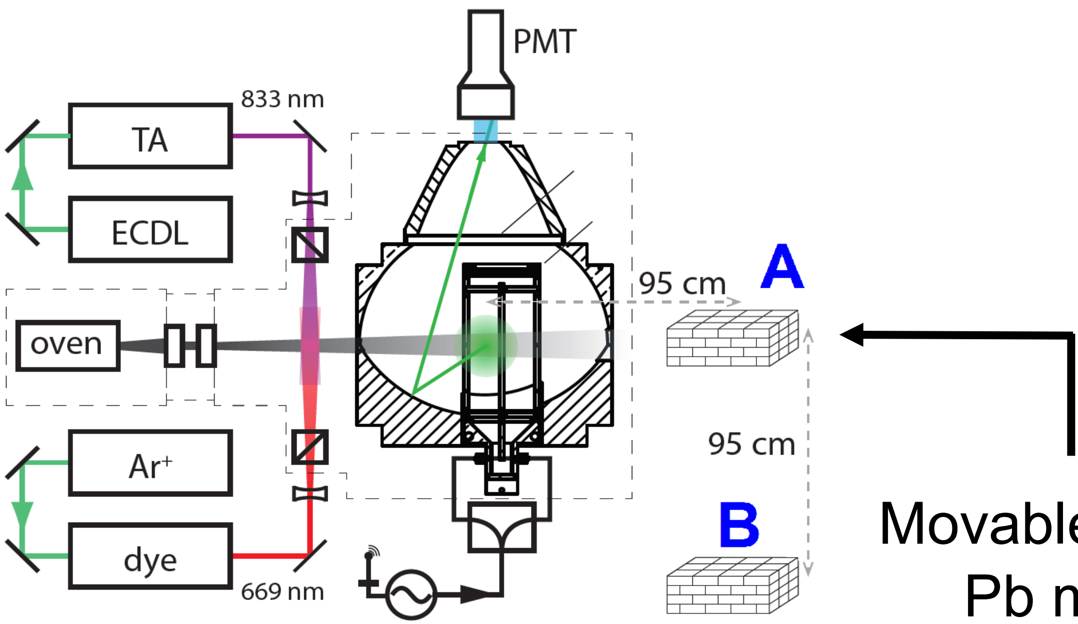
Non-Cosmological Sources of Exotic Bosons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



$$\mathcal{L}_{\text{int}} = -\frac{\phi}{\Lambda_f} m_f \bar{f} f$$

$$V(r) = -\left(\frac{m_f}{\Lambda_f}\right)^2 \frac{e^{-m_\phi r}}{4\pi r}$$

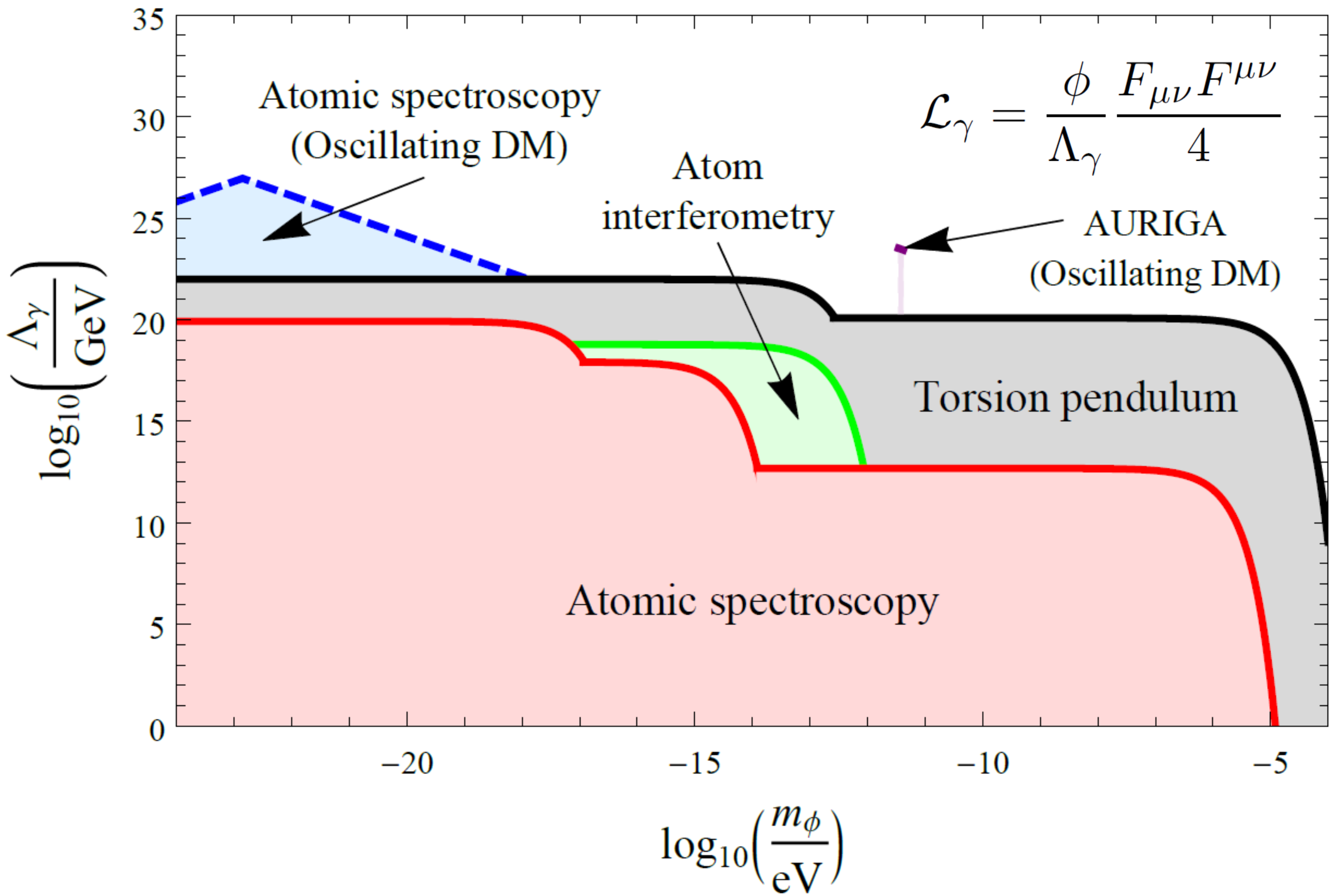


Movable 300kg Pb mass

Constraints on Linear Yukawa Interaction of a Scalar Boson with the Photon

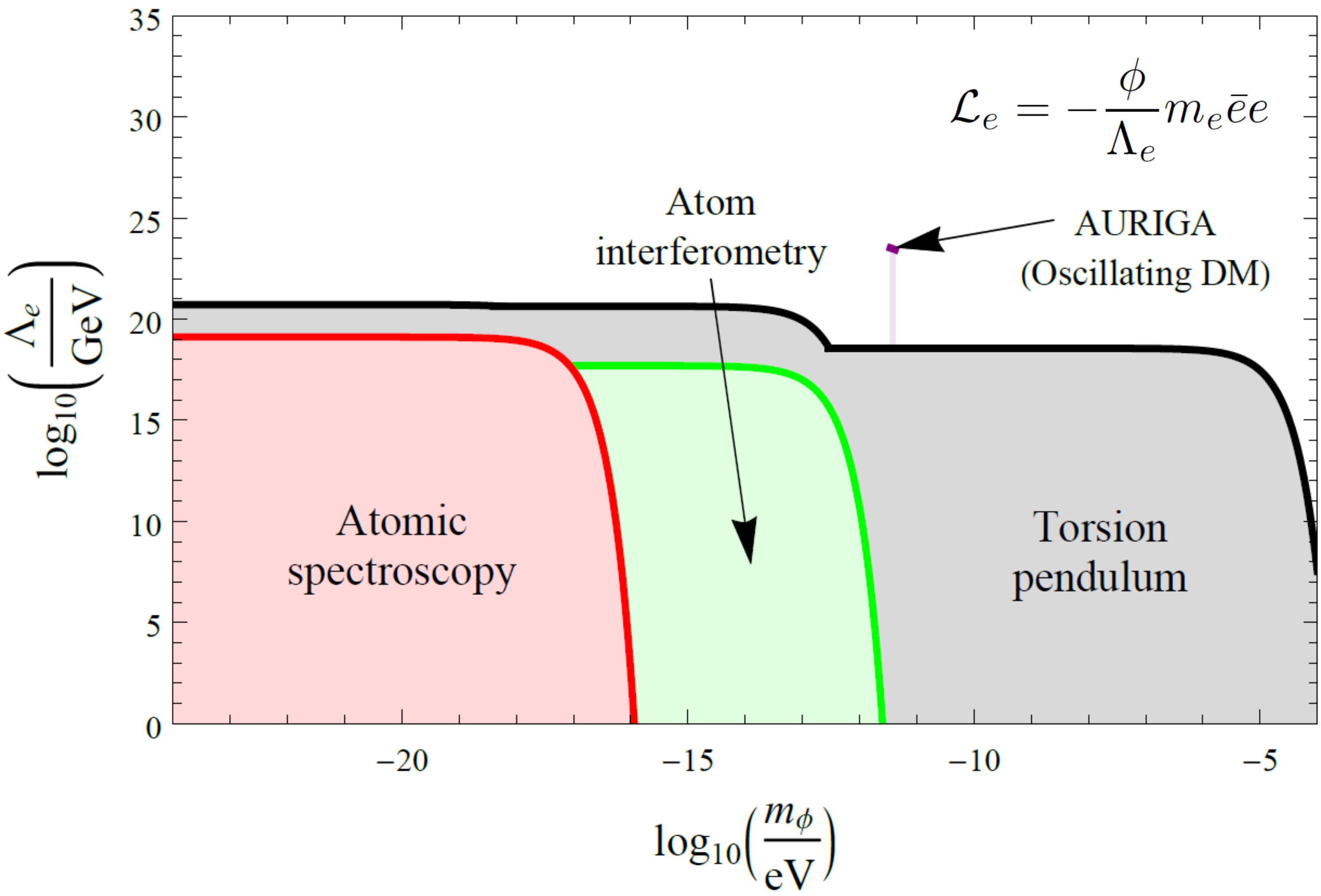
Spectroscopy constraints: [Leefer *et al.*, *PRL* **117**, 271601 (2016)]

DM constraints: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Hees *et al.*, *PRL* **117**, 061301 (2016)]



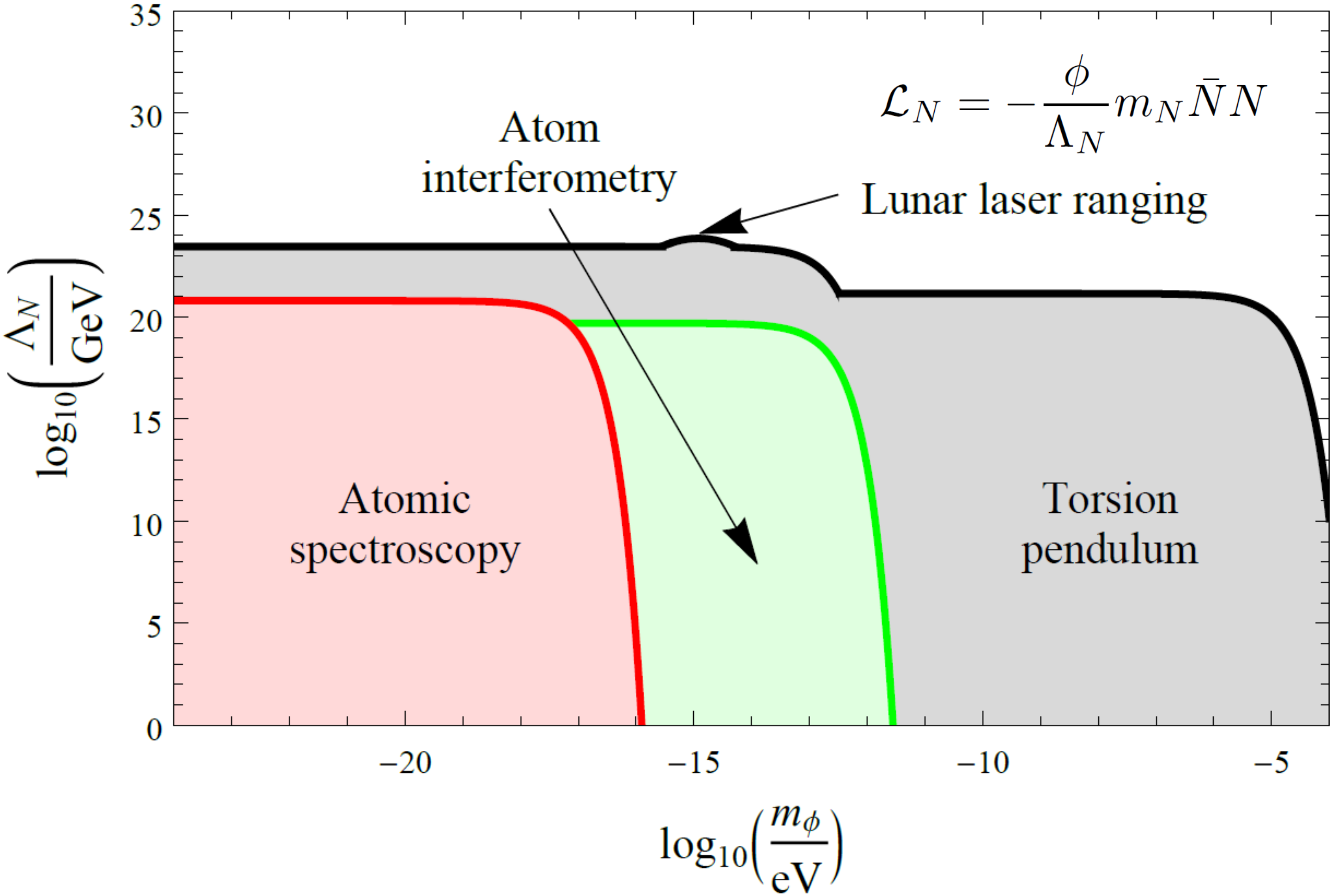
Constraints on Linear Yukawa Interaction of a Scalar Boson with the Electron

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



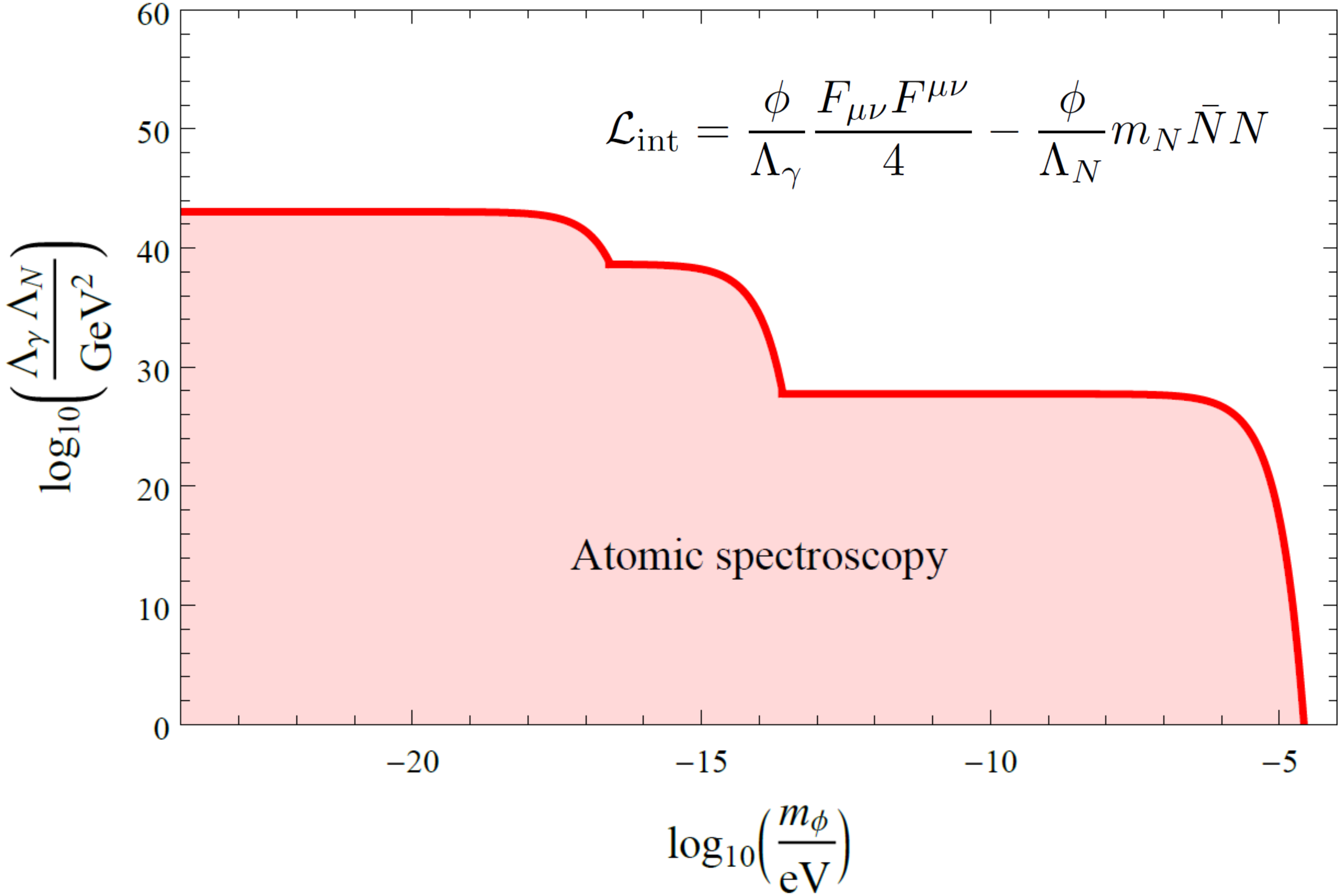
Constraints on Linear Yukawa Interaction of a Scalar Boson with the Nucleons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



Constraints on a Combination of Linear Yukawa Interactions of a Scalar Boson

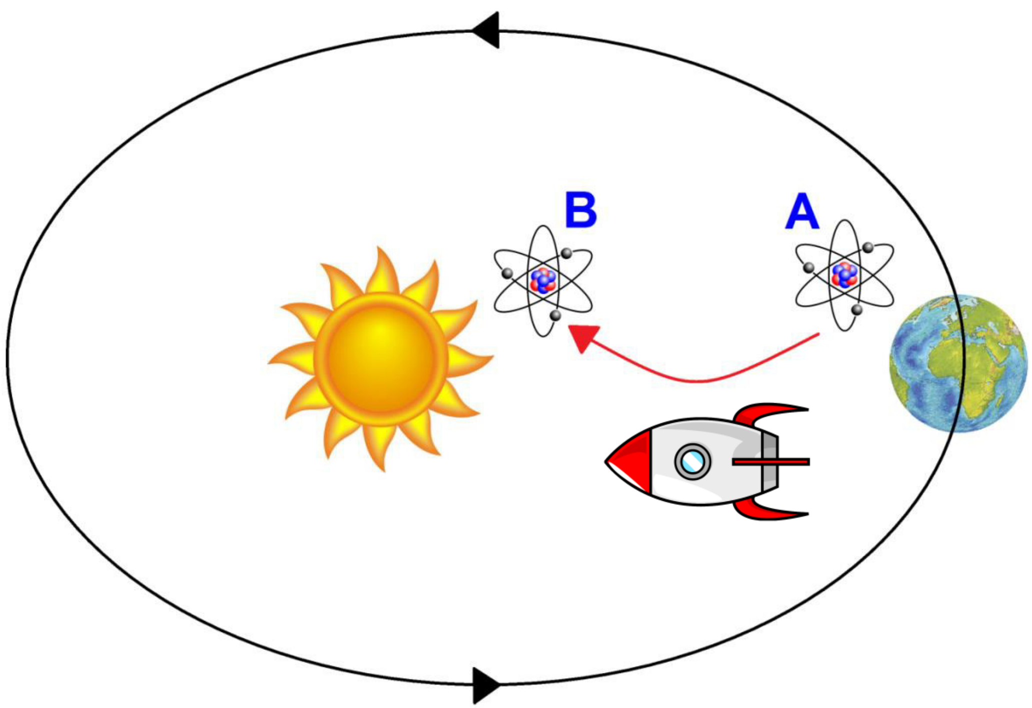
[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]



How to Probe Weaker Interactions?

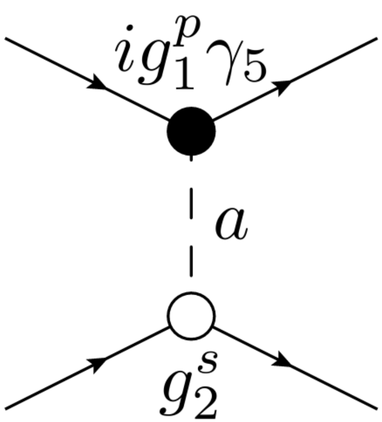
[Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)]

1. Use different systems in the laboratory
2. Implement different experimental geometries (e.g., effect increased by up to **4 orders of magnitude** if clock pair brought close to Sun)



Non-Cosmological Sources of Exotic Bosons

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



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

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

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

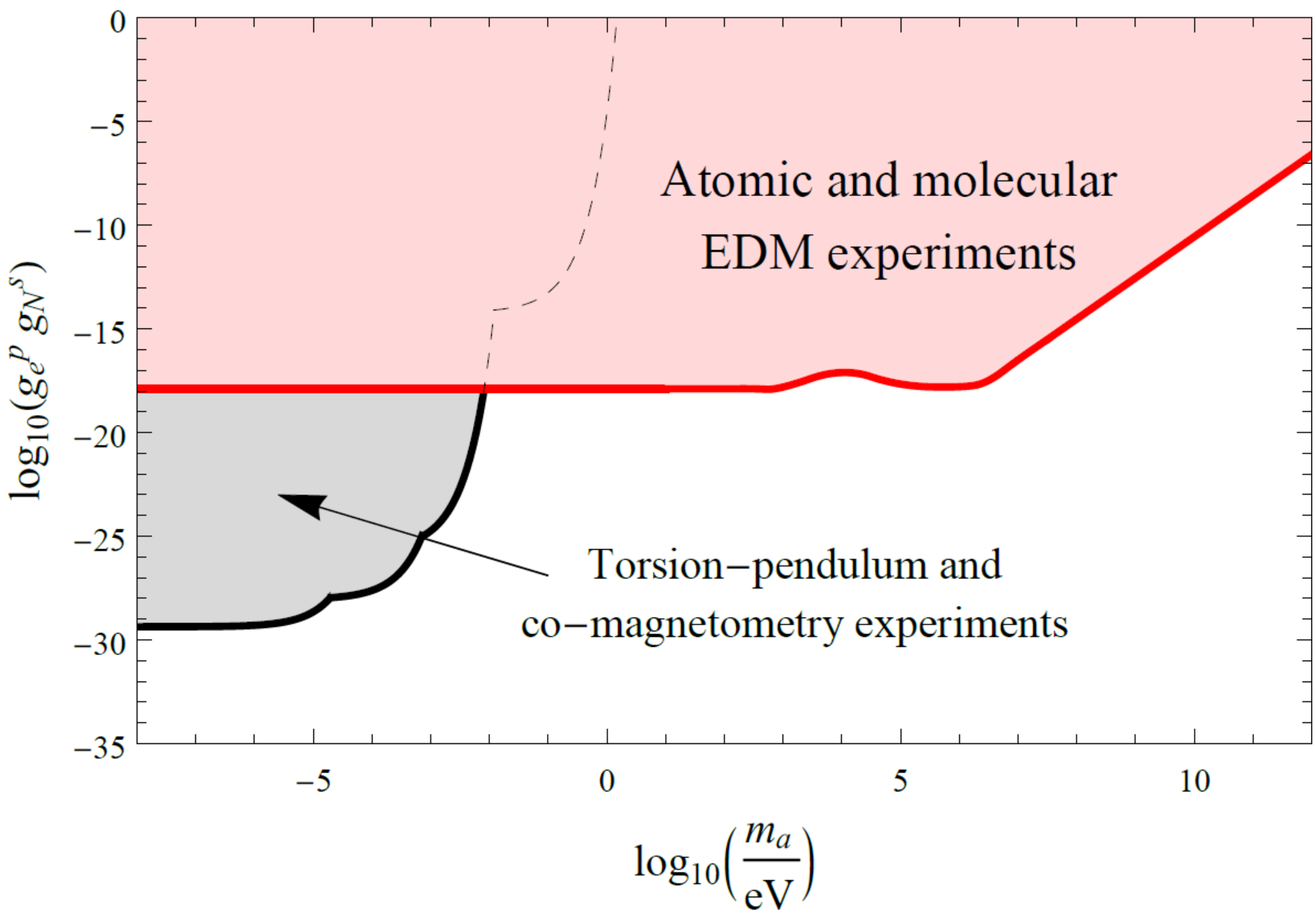
Atomic EDM experiments: Cs, Tl, Xe, **Hg**

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

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

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

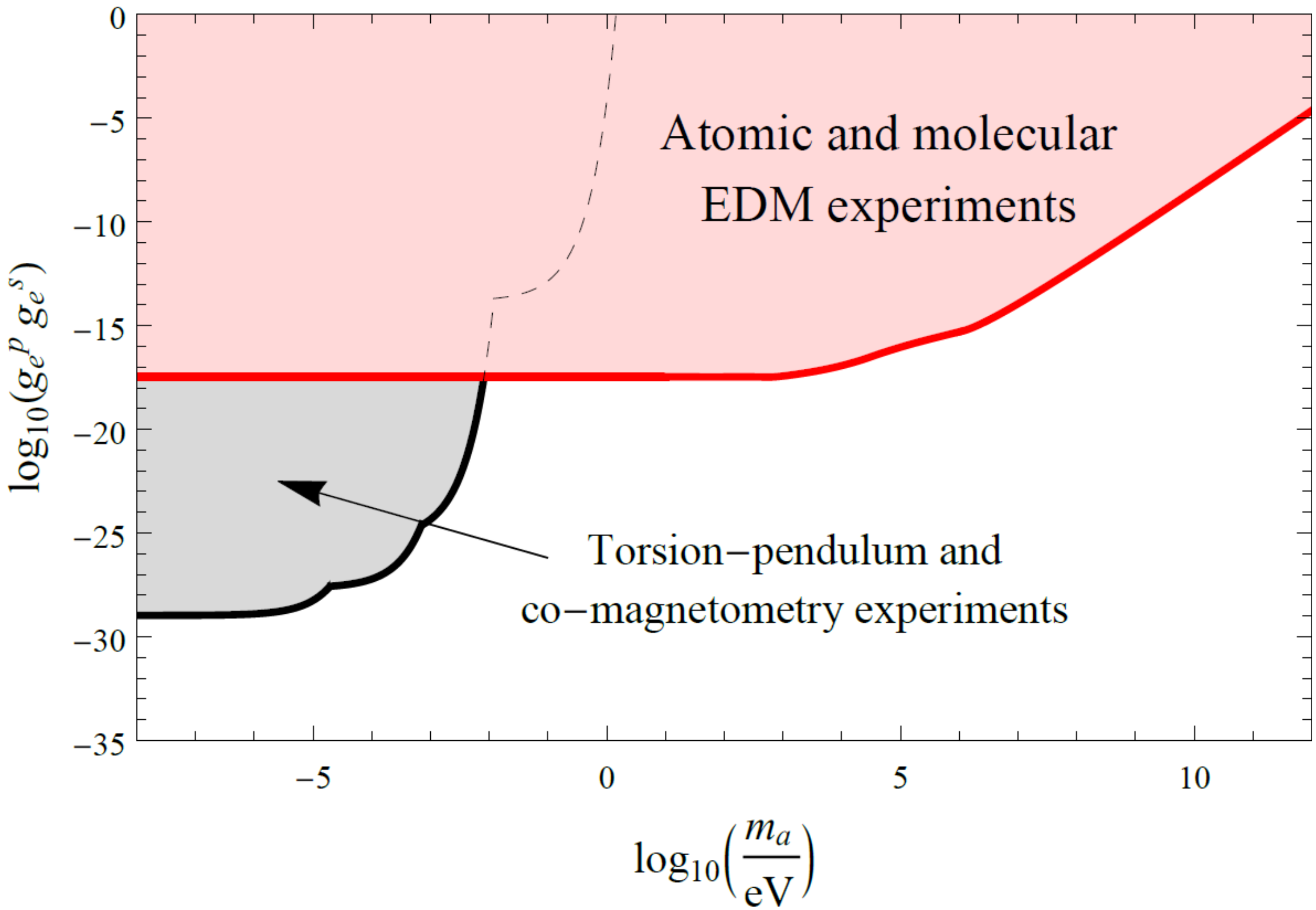
Many orders of magnitude improvement!



Constraints on Scalar-Pseudoscalar Electron-Electron Interaction

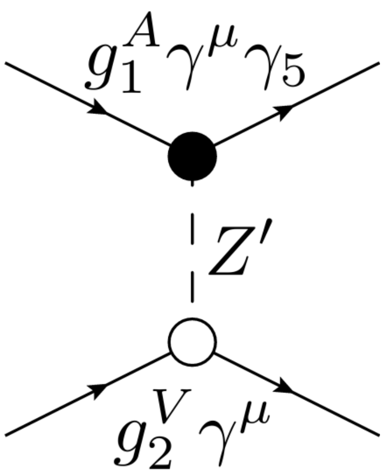
EDM constraints: [Stadnik, Dzuba, Flambaum, *PRL* **120**, 013202 (2018)]

Many orders of magnitude improvement!



Non-Cosmological Sources of Exotic Bosons

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



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

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

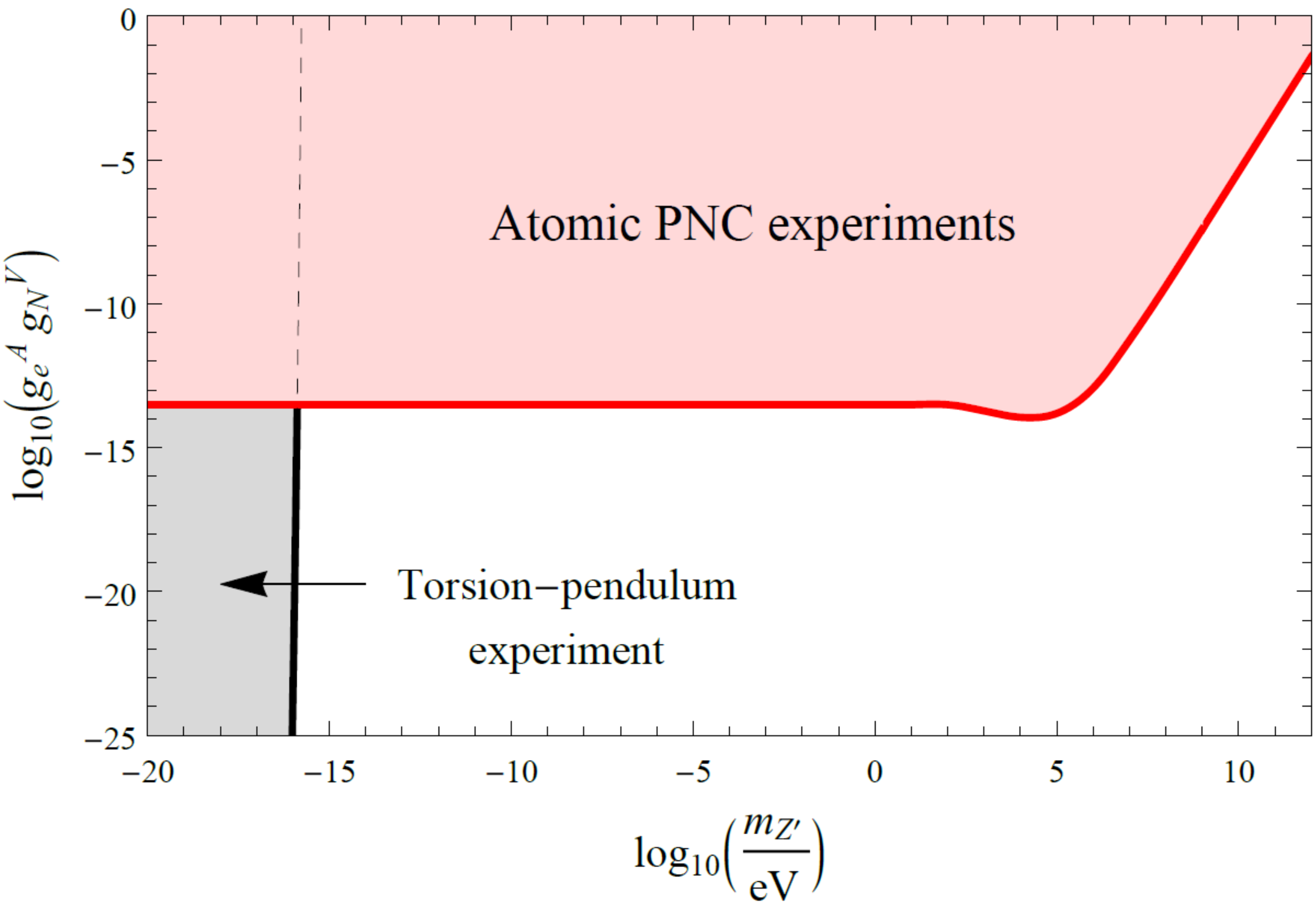
P-violating forces => Atomic parity-nonconserving effects and nuclear anapole moments

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

Constraints on Vector-Pseudovector Nucleon-Electron Interaction

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

Many orders of magnitude improvement!



Constraints on Vector-Pseudovector Nucleon-Proton Interaction

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

Many orders of magnitude improvement!