New Laboratory and Astrophysical Probes for Low-Mass Dark Matter and Dark Bosons

Yevgeny Stadnik

Johannes Gutenberg University, Mainz, Germany

Collaborators (Theory):
Victor Flambaum, Vladimir Dzuba, Benjamin Roberts

Collaborators (Experiment):
nEDM collaboration at PSI and Sussex

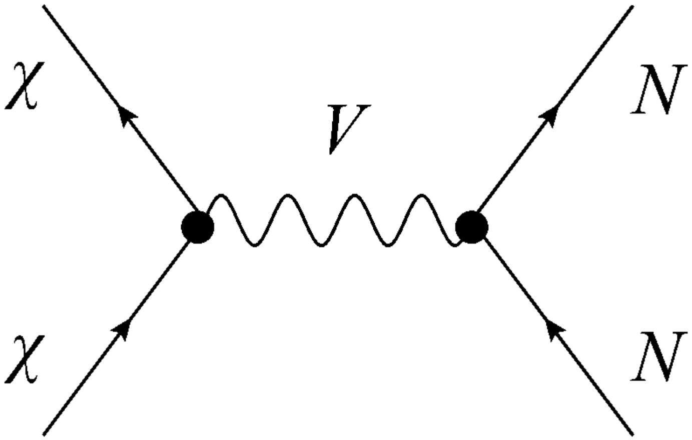
Alexander von Humboldt Stiftung/Foundation

JG|U

UCLA Dark Matter 2018, Los Angeles, February 2018

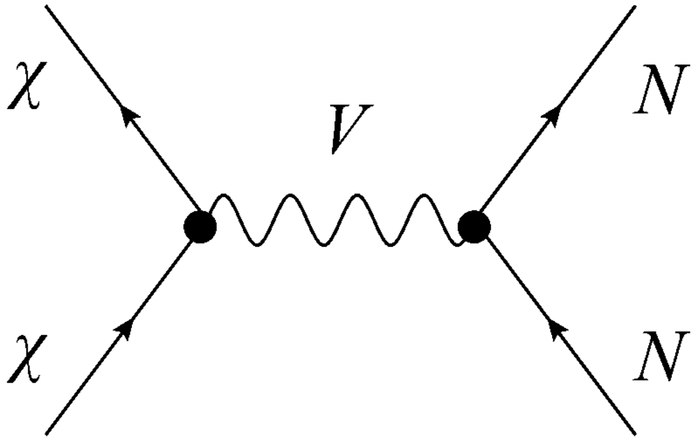
Motivation

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



Motivation

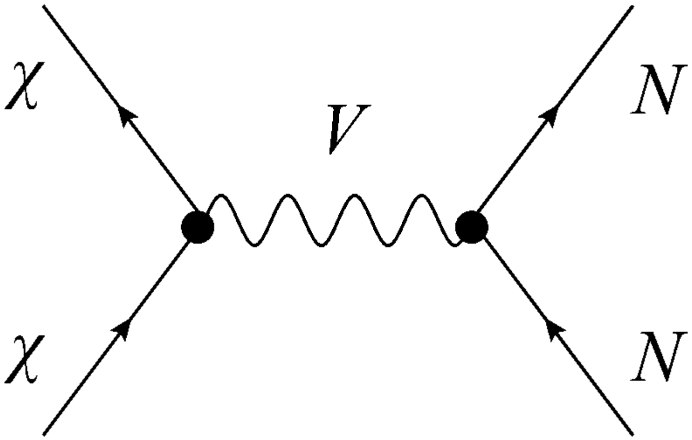
Traditional “scattering-off-nuclei” searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



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

Motivation

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

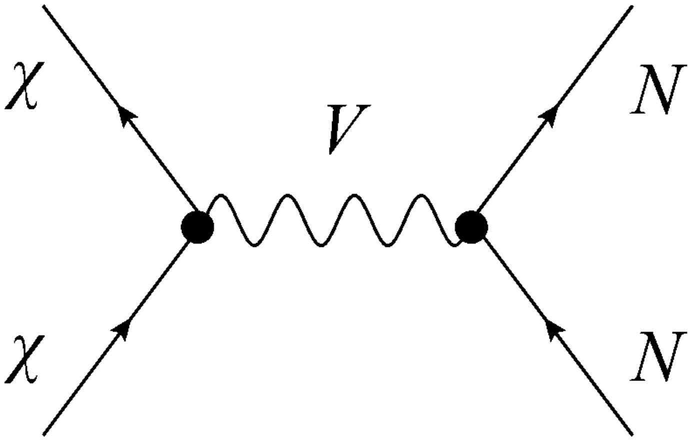


$$\mathcal{M} \propto (e')^2$$

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

Motivation

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



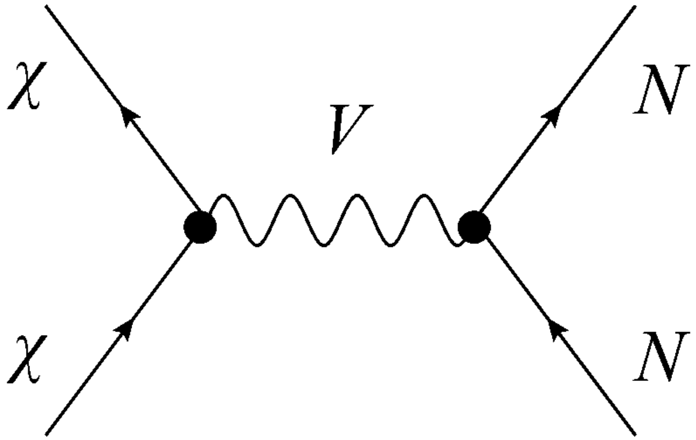
$$\mathcal{M} \propto (e')^2$$

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

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

Motivation

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



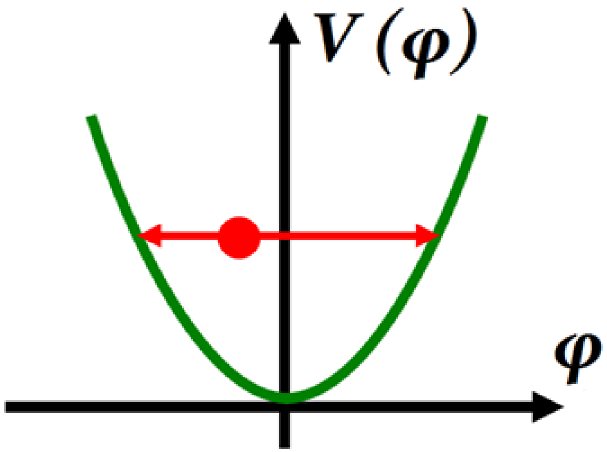
$$\mathcal{M} \propto (e')^2$$

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

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



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

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)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)

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

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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = **"Cosmic laser"**

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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = **"Cosmic laser"**
- 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

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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = **"Cosmic laser"**
- 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

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

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)

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)
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV inaccessible to traditional "scattering-off-nuclei" searches, since $|\boldsymbol{p}_\varphi| \sim 10^{-3} m_\varphi$ is extremely small => recoil effects suppressed

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)
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV inaccessible to traditional "scattering-off-nuclei" searches, since $|\boldsymbol{p}_\varphi| \sim 10^{-3} m_\varphi$ is extremely small => recoil effects suppressed
- BUT can look for novel effects of low-mass DM in low-energy atomic and astrophysical phenomena that are **first power** in the interaction constant κ:

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

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)
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV inaccessible to traditional "scattering-off-nuclei" searches, since $|\boldsymbol{p}_\varphi| \sim 10^{-3} m_\varphi$ is extremely small => recoil effects suppressed
- BUT can look for novel effects of low-mass DM in low-energy atomic and astrophysical phenomena that are **first power** in the interaction constant κ:

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

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

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

"Axion Wind" Spin-Precession Effect

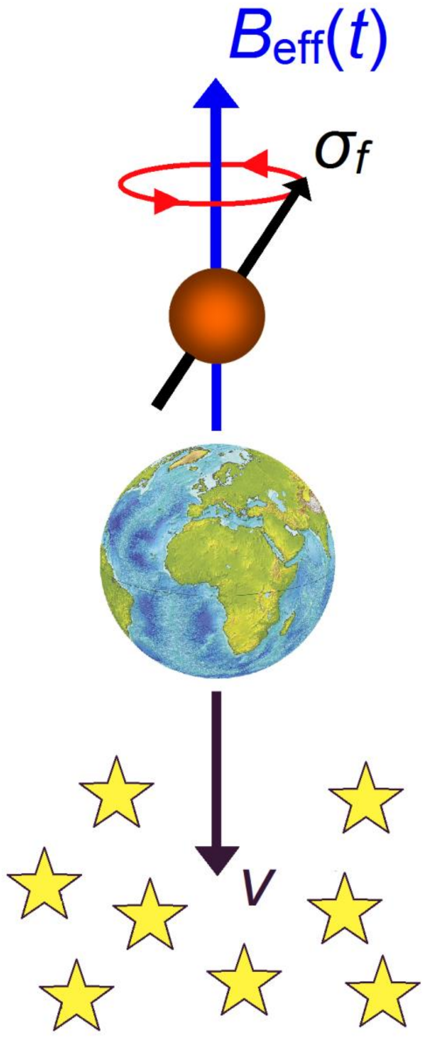
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field**

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

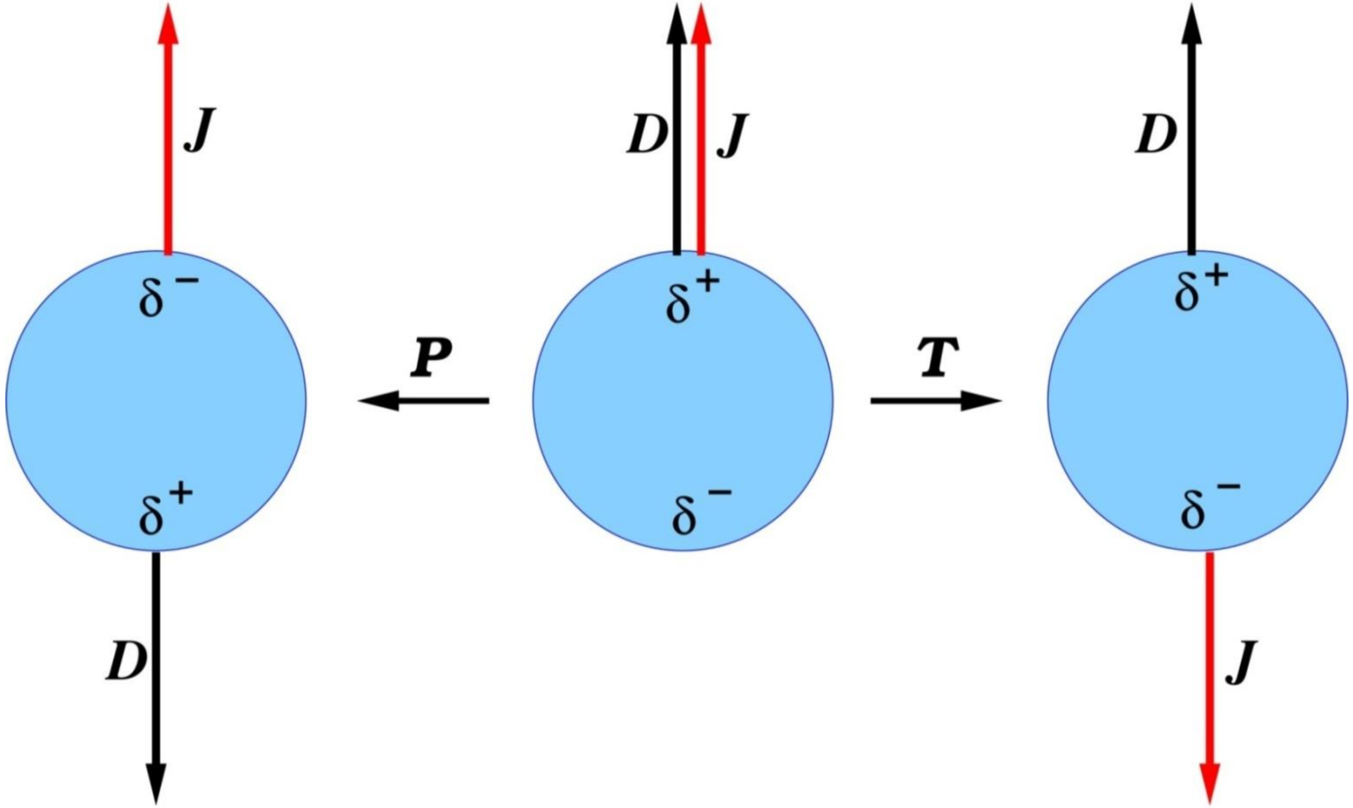


Oscillating Electric Dipole Moments

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

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

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

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

***B*-field effect**

Axion DM effect

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

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

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

***B*-field effect**

Axion DM effect

Searching for Spin-Dependent Effects

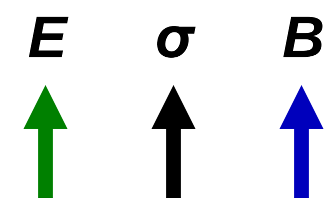
Proposals: [Flambaum, talk at *Patras Workshop*, 2013; Stadnik, Flambaum, *PRD* **89**, 043522 (2014); arXiv:1511.04098; Stadnik, PhD Thesis (2017)]

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

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

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

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



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)]

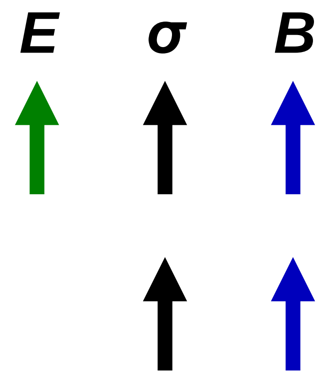
Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

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

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

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

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



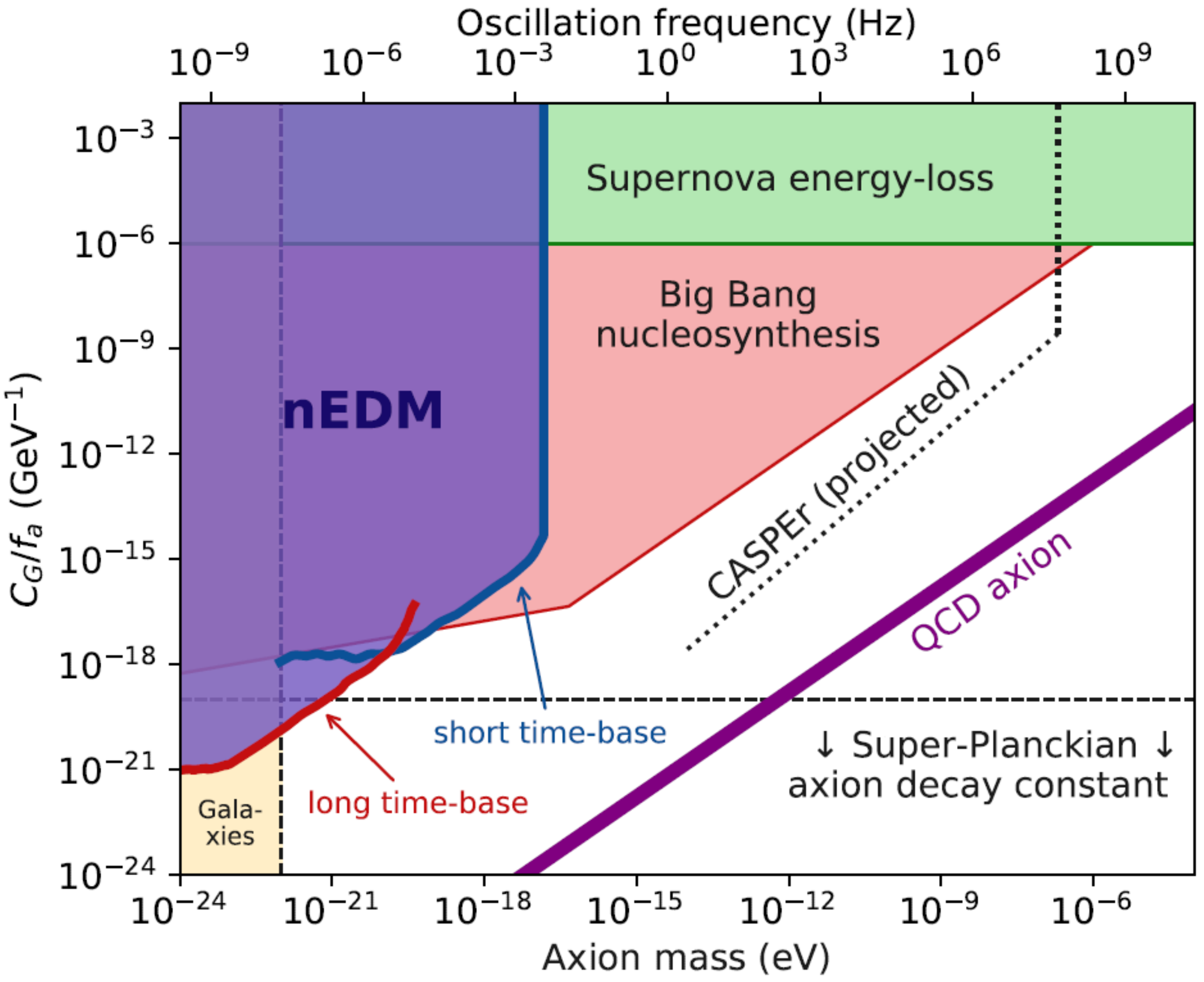
$$\omega_1 = m_a, \ \omega_2 = m_a + \Omega_{\mathrm{sidereal}}, \ \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

Earth's rotation

Constraints on Interaction of Axion Dark Matter with Gluons

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

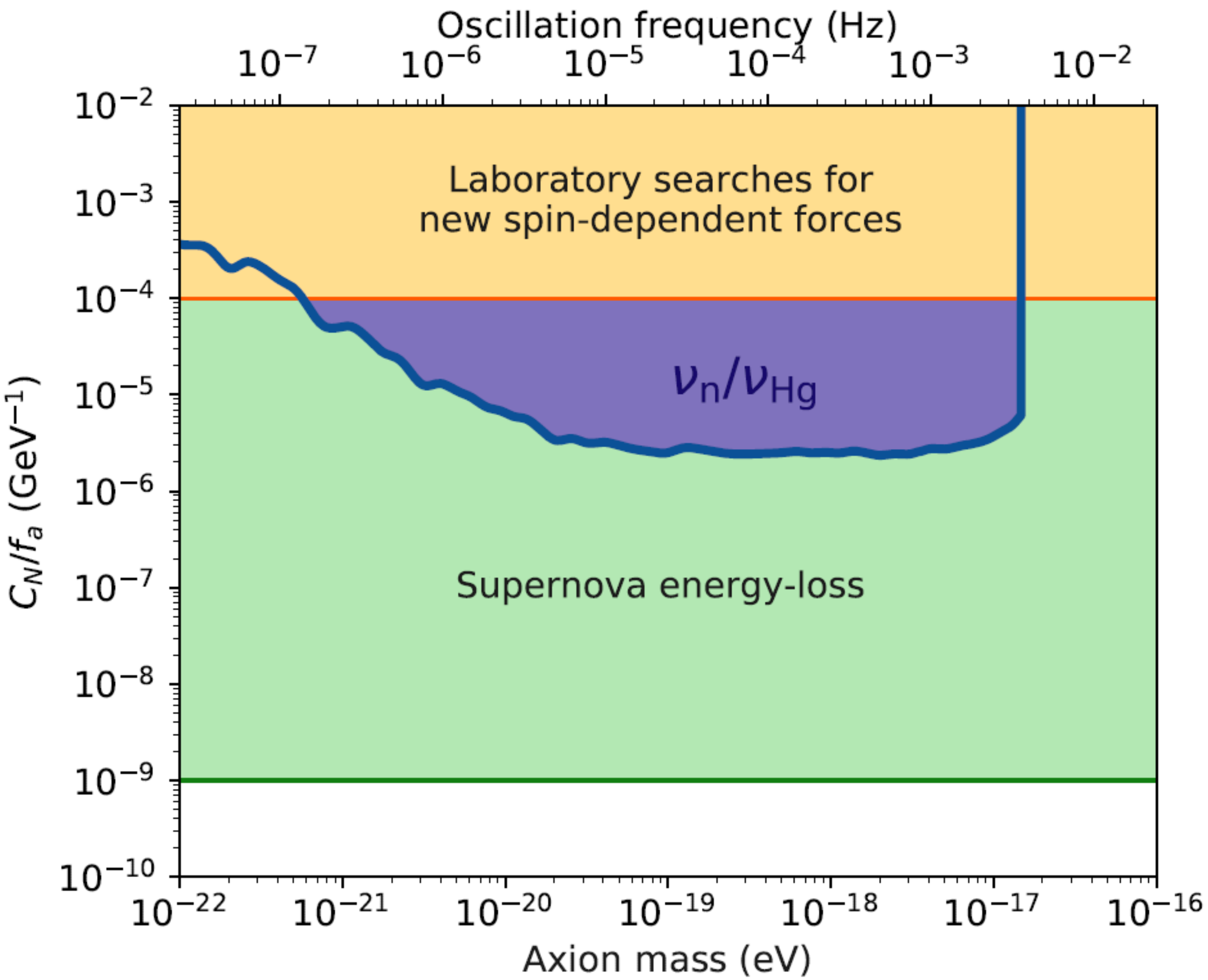
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

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

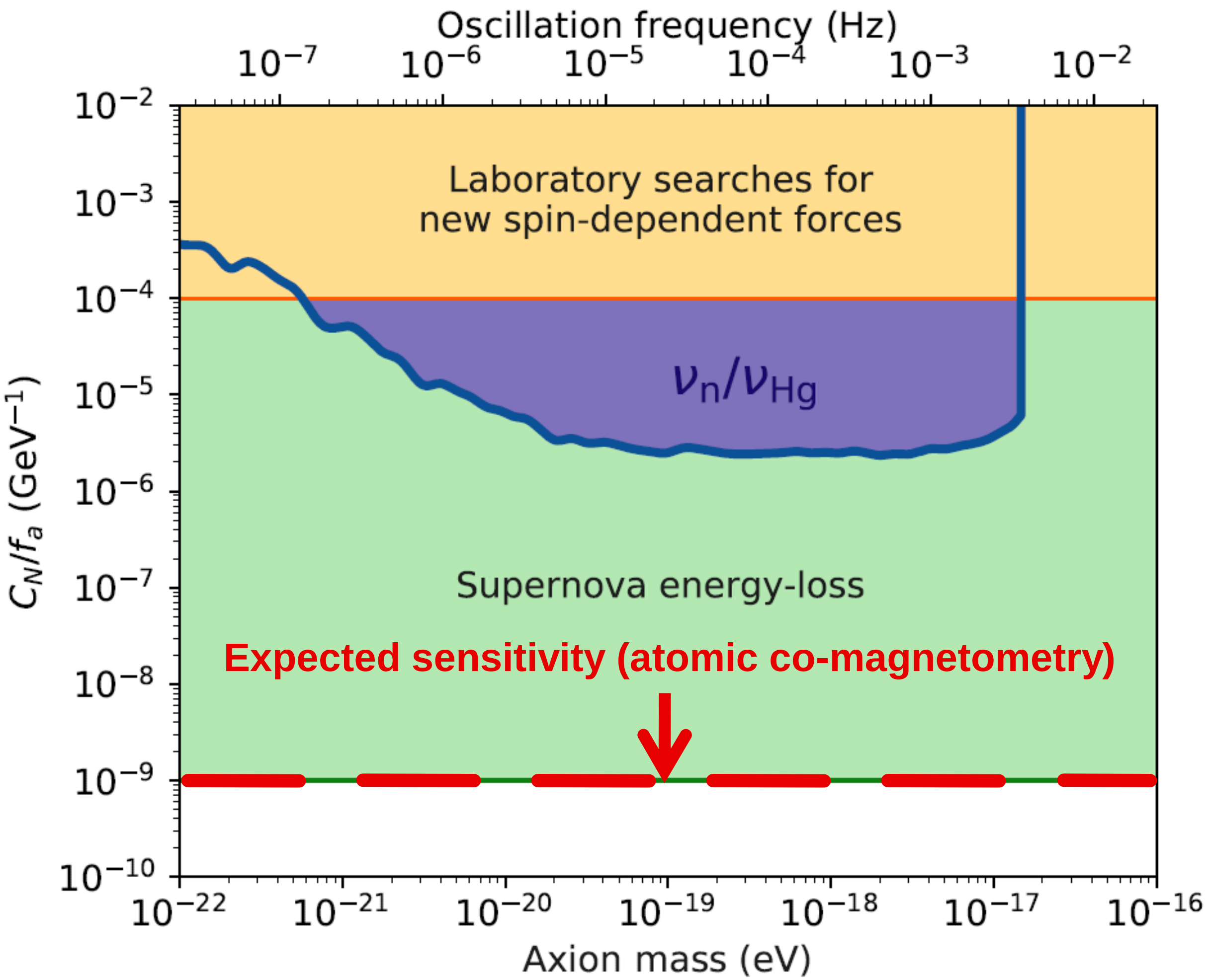
40-fold improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

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

40-fold improvement!

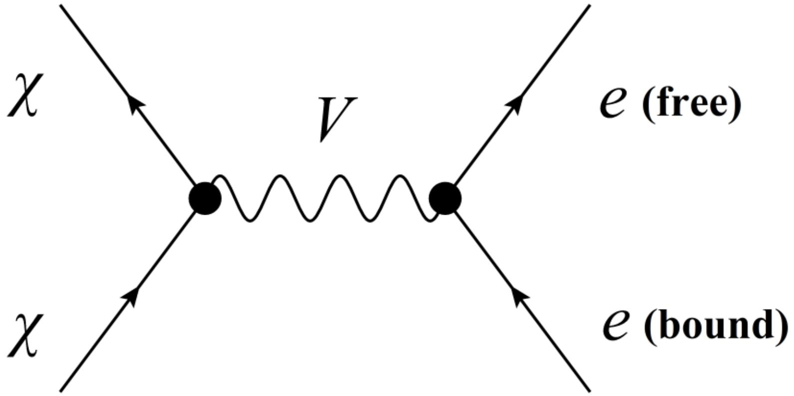


Summary

- 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})
- Relativistic atomic effects increase WIMP-electron ionising scattering rate by up to **a factor of 1000** (see also recent XENON100 analysis)
- **More details in full slides (also on ResearchGate)**

WIMP-Electron Ionising Scattering

- Search for annual modulation in $\sigma_{\chi e}$ (velocity dependent)



- Previous analyses treated atomic electrons *non-relativistically*
- Non-relativistic treatment of atomic electrons **inadequate** for m_χ > 1 GeV!
- Need relativistic atomic calculations for m_χ > 1 GeV!

Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

- Consider $m_\chi \sim 10$ GeV, $\langle v_\chi \rangle \sim 10^{-3}$
- $\langle q \rangle \sim \langle p_\chi \rangle \sim 10$ MeV >> m_e

  => Relativistic process on atomic scale!
- Large $q \sim 1000$ a.u. corresponds to small $r \sim 1/q \ll a_B/Z$
- Largest contribution to $\sigma_{\chi e}$ comes from innermost atomic orbitals – for $\langle \Delta E \rangle \sim \langle T_\chi \rangle \sim 5$ keV:
  - Na (1*s*)
  - Ge (2*s*)
  - I (3*s*/2*s*)
  - Xe (3*s*/2*s*)
  - Tl (3*s*)

Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

- Non-relativistic and relativistic contributions to $\sigma_{\chi e}$ are very different for large q, for scalar, pseudoscalar, vector and pseudovector interaction portals:

Non-relativistic [s-wave, $\psi \propto r^{0}(1 - Zr/a_B)$ as $r \to 0$)]*****:

$$d\sigma_{\chi e} \propto 1/q^{8}$$

Relativistic [$s_{1/2}$, $p_{1/2}$-wave, $\psi \propto r^{\gamma-1}$ as $r \to 0$, $\gamma^2 = 1 - (Z\alpha)^2$]*****:

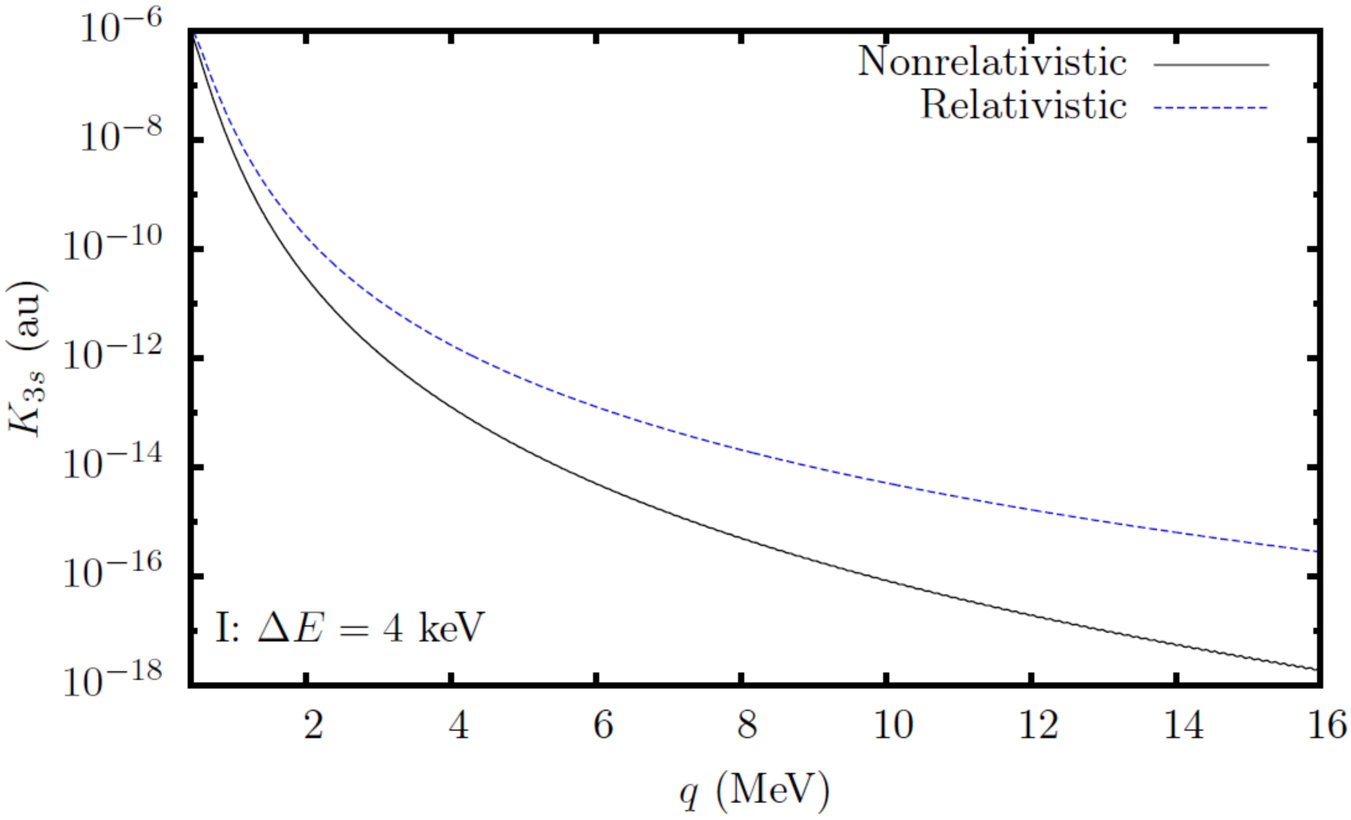
$$d\sigma_{\chi e} \propto 1/q^{6-2(Z\alpha)^2} \qquad (d\sigma_{\chi e} \propto 1/q^{5.7} \text{ for Xe and I})$$

- Relativistic contribution to $\sigma_{\chi e}$ dominates by several orders of magnitude for large q!

***** We present the leading atomic-structure contribution to the cross-sections here

Why are electron relativistic effects so important?

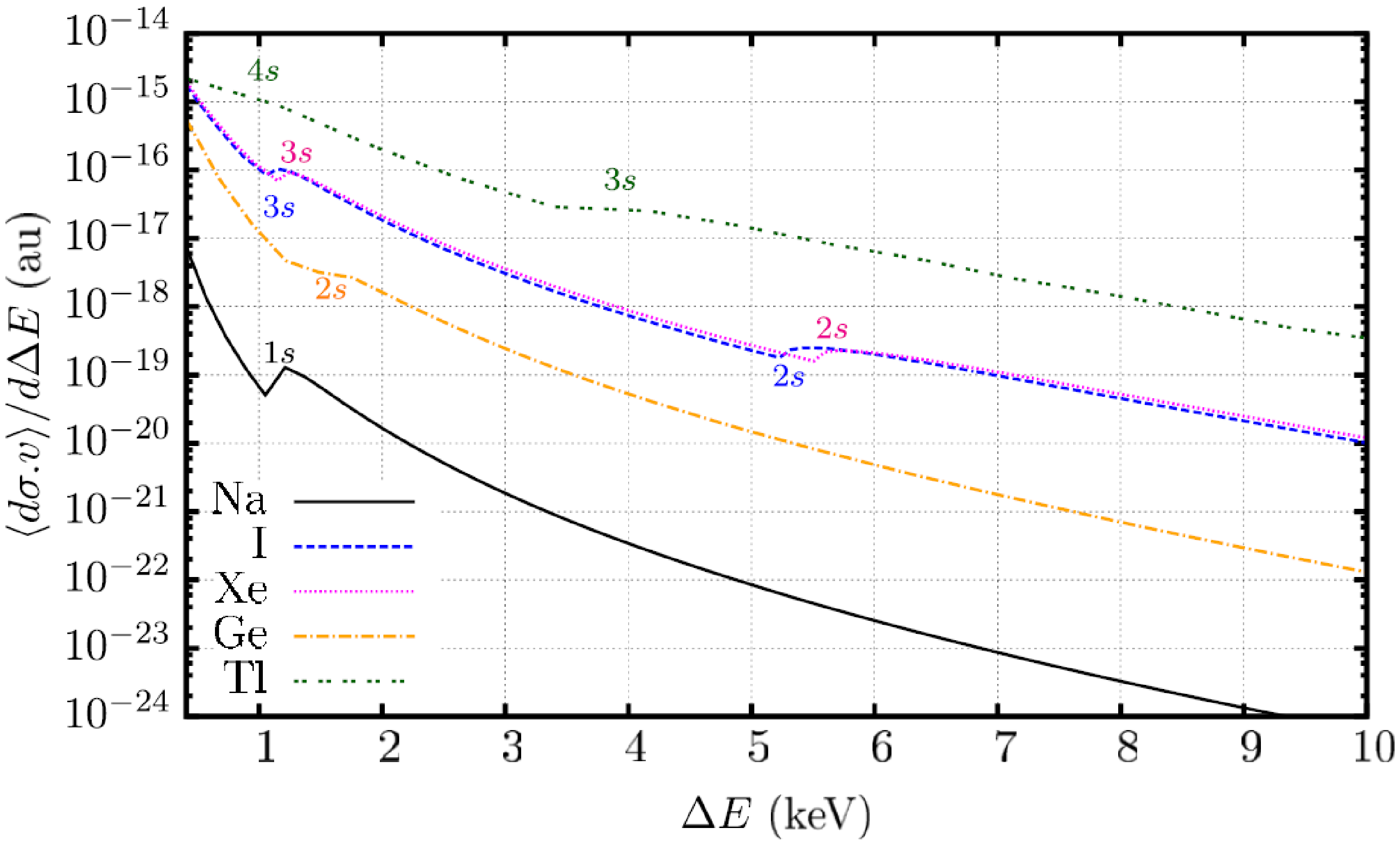
[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]



Calculated atomic-structure functions for ionisation of I from 3*s* atomic orbital as a function of *q*; ΔE = 4 keV, vector interaction portal

Accurate relativistic atomic calculations

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

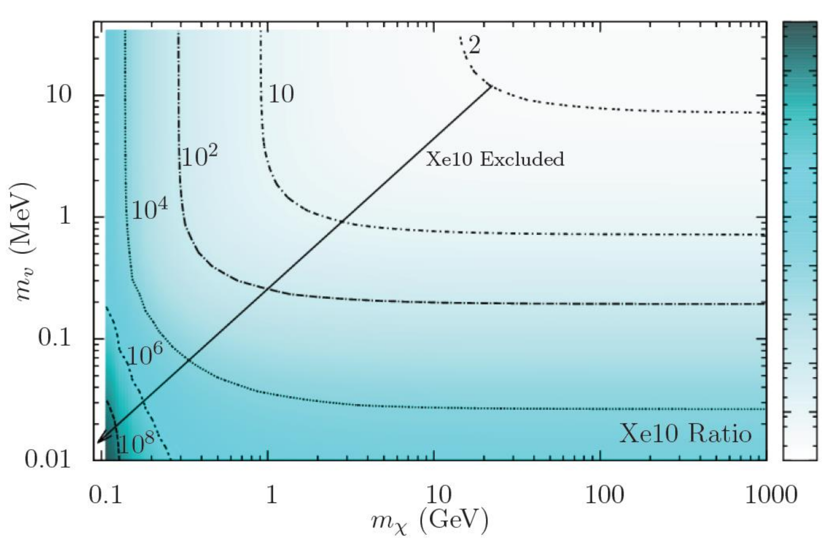


Calculated differential $\sigma_{\chi e}$ as a function of total energy deposition (ΔE); m_χ = 10 GeV, m_V = 10 MeV, α_χ = 1, vector interaction portal

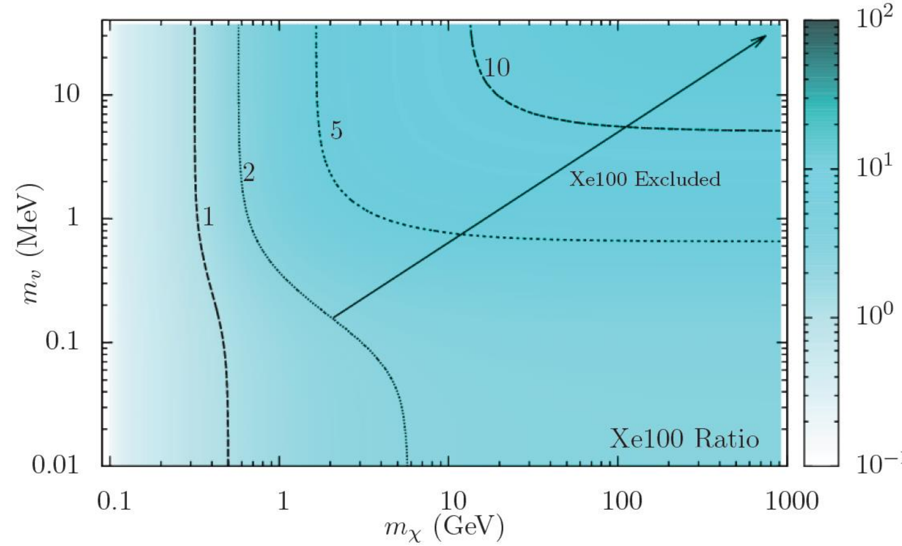
Can the DAMA result be explained by the ionising scattering of WIMPs on electrons?

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

XENON10 (expected/observed ratio)



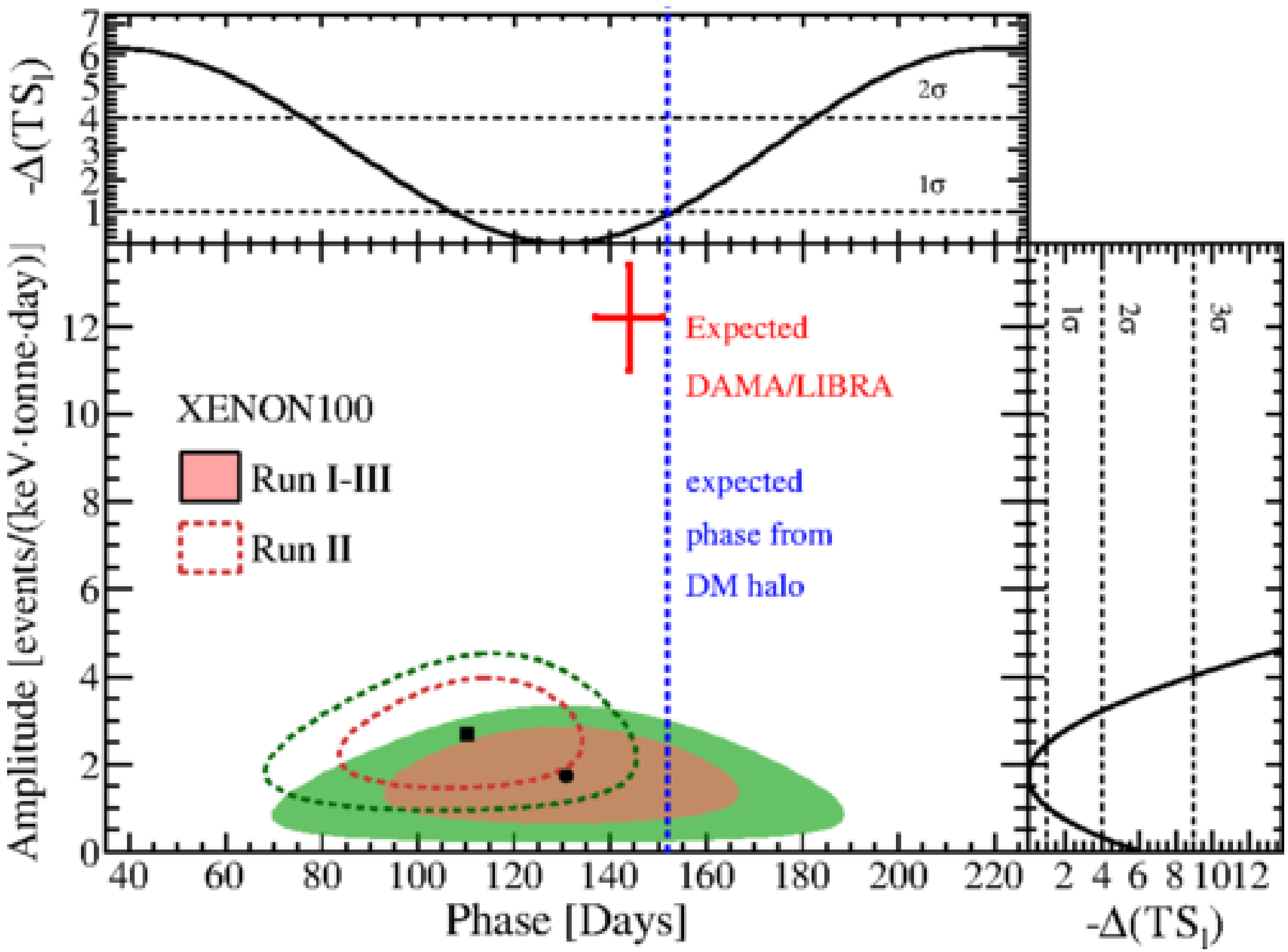
XENON100 (expected/observed ratio)



- Using results of XENON10 and XENON100, we find no region of parameter space in m_χ and m_V that is consistent with interpretation of DAMA result in terms of "ionising scattering on electrons" scenario.

Can the DAMA result be explained by the ionising scattering of WIMPs on electrons?

[XENON collaboration, *PRL* **118**, 101101 (2017)]



Low-mass Spin-0 Dark Matter

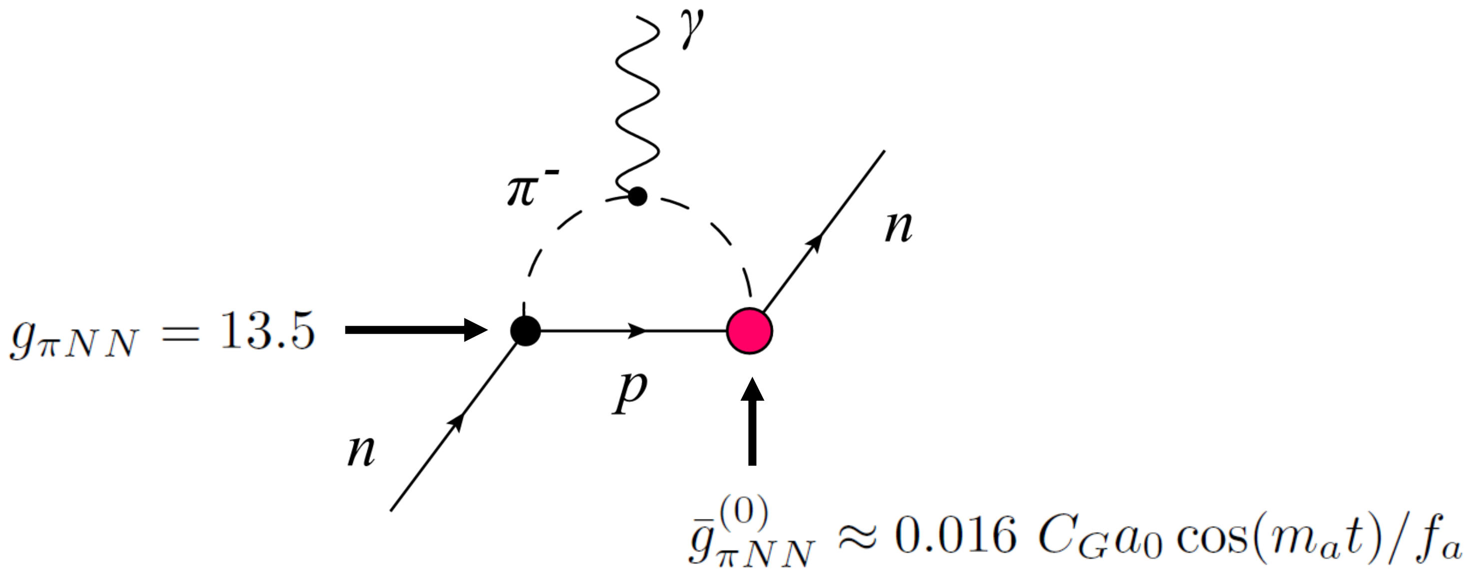
Dark Matter

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

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)]

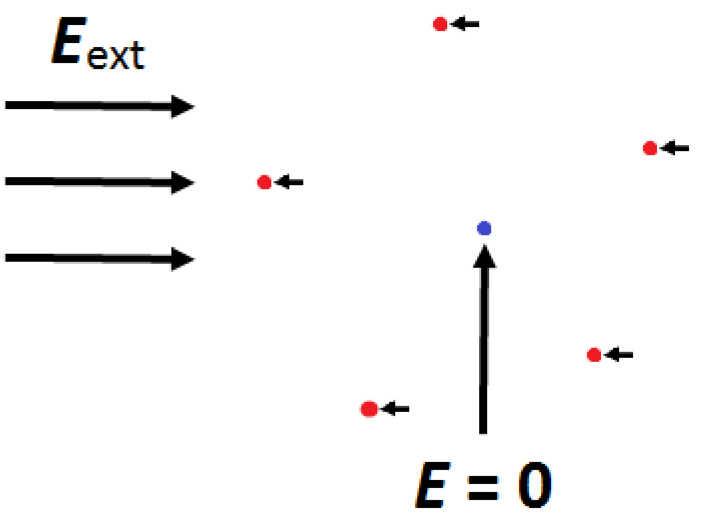
$$\mathcal{L}_{aGG} = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad => \quad d_n(t) \propto \cos(m_a t)$$



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."

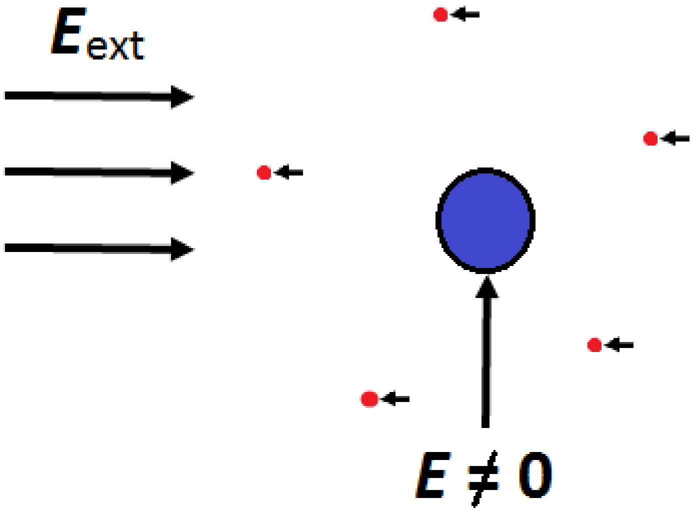


Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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*:

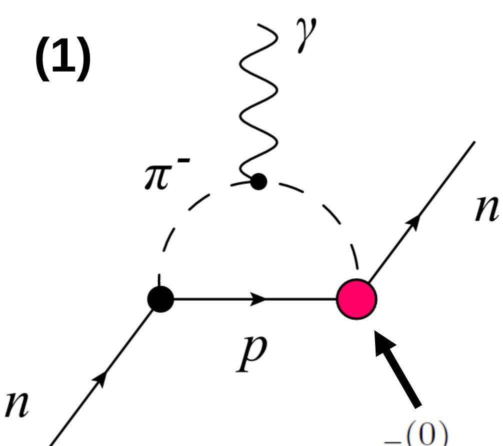
- Oscillating nuclear Schiff moments ($I \geq 1/2 \Rightarrow J \geq 0$)
- Oscillating nuclear magnetic quadrupole moments ($I \geq 1 \Rightarrow J \geq 1/2$; *magnetic* => no Schiff screening)

Underlying mechanisms:

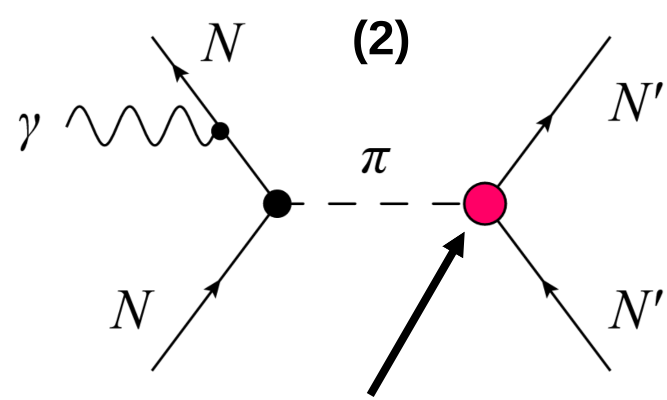
(1) Intrinsic oscillating nucleon EDMs (1-loop level)

(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)

(1)



(2)



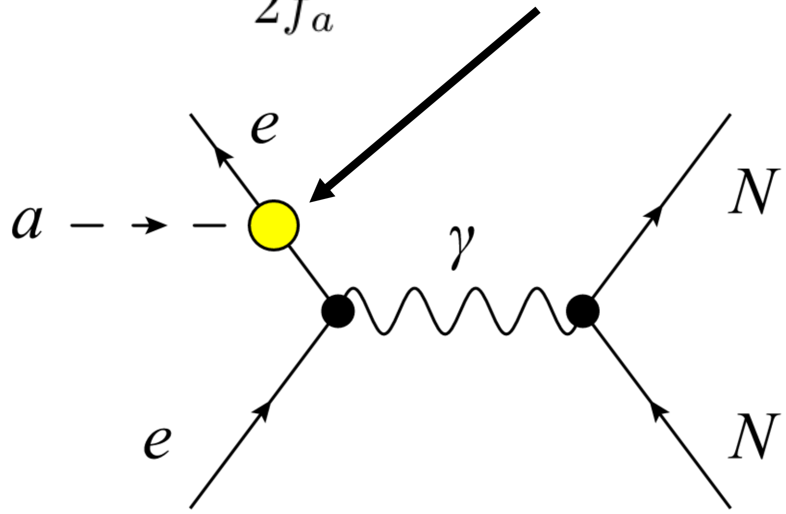
$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

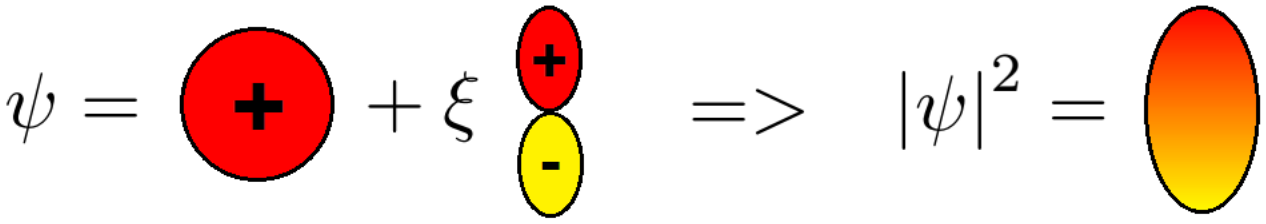
Axion-Induced Oscillating Atomic and Molecular EDMs

[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.

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

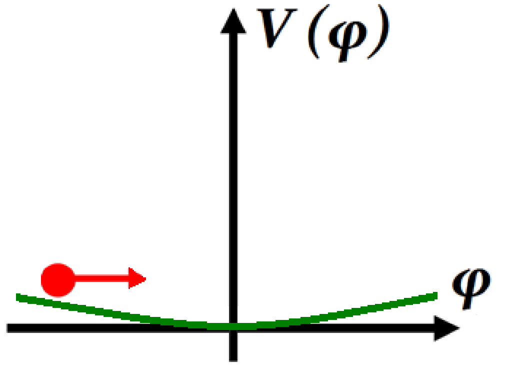




Cosmological Evolution of the Fundamental ‘Constants’

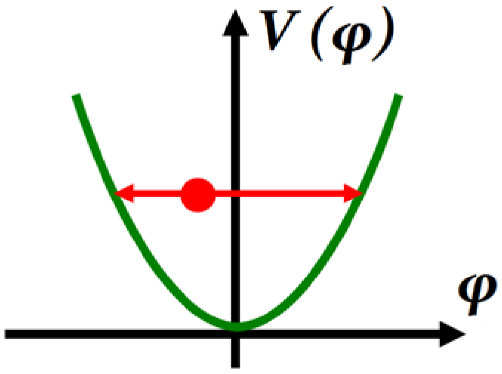
- Dirac’s large numbers hypothesis: $G \propto 1/t$
- Fundamental constants not predicted from theory, but determined from measurements (local – not universal)
- Possible models for cosmological evolution of fundamental constants?

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



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

Dark matter?



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

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

$\langle\varphi\rangle = 0$

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

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.

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

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

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

Oscillating variations [Laboratory (high precision)]

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)

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

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

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

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

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 ~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:

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

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

Increasing *Z*

- Atomic hyperfine transitions:

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

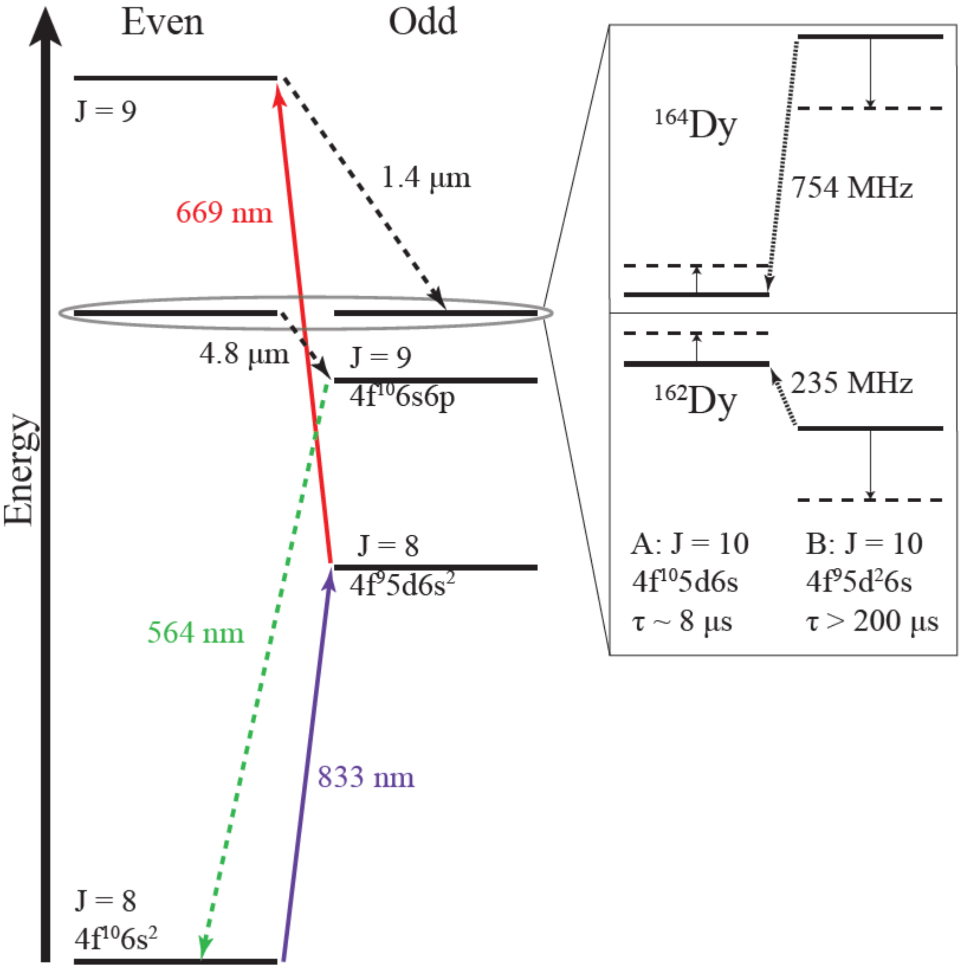
$K_\alpha(^1\mathrm{H}) = 2.0$, $K_\alpha(^{87}\mathrm{Rb}) = 2.3$, $K_\alpha(^{133}\mathrm{Cs}) = 2.8$ $\quad K_{m_e/m_N} = 1$

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., $|K_\alpha(\mathrm{Dy})| \sim 10^6 - 10^7$)
  - 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 $L \sim N a_B$ with λ

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

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

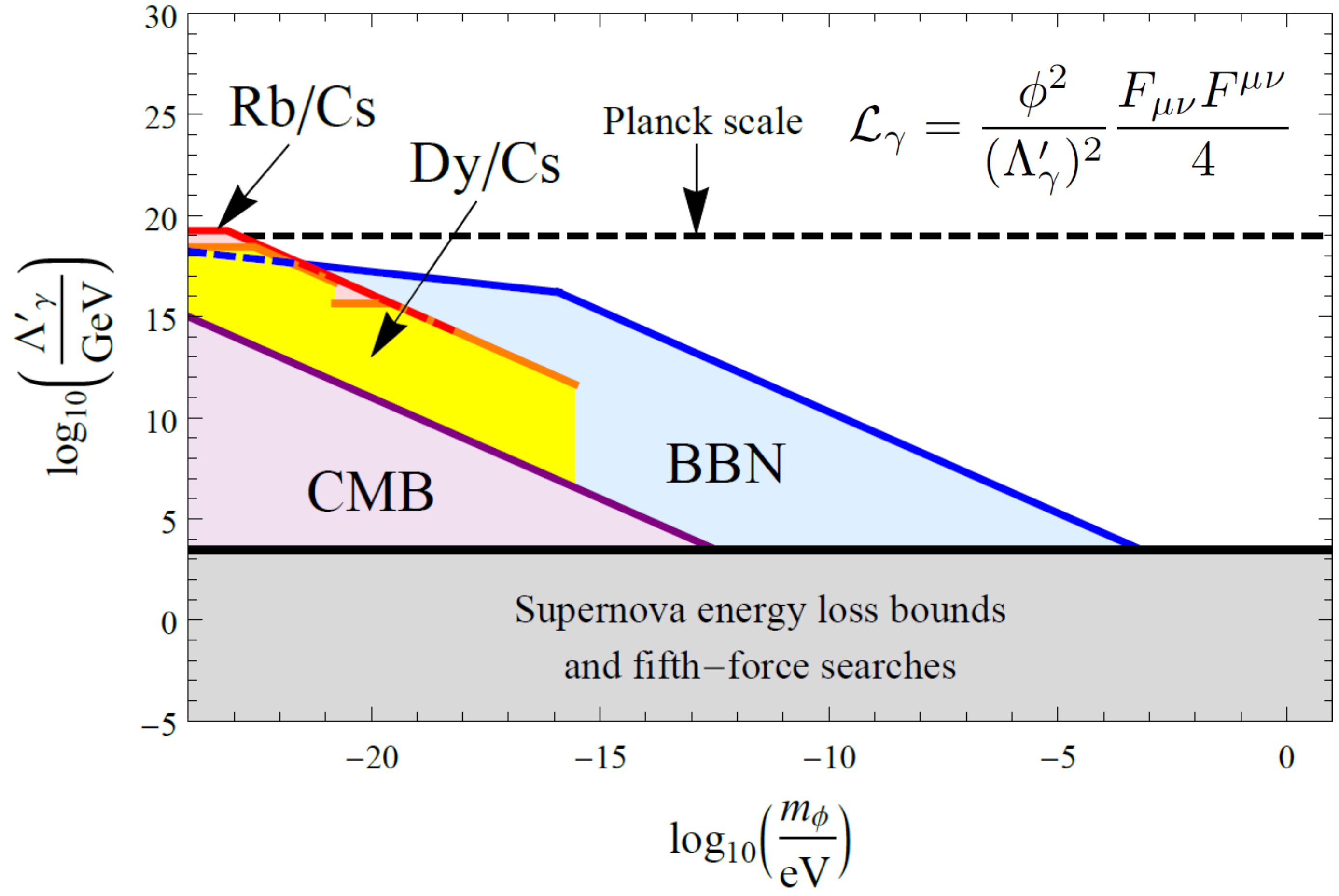
Sr/Cavity (Domain wall DM): [Wcislo *et al*., *Nature Astronomy* **1**, 0009 (2016)]

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!

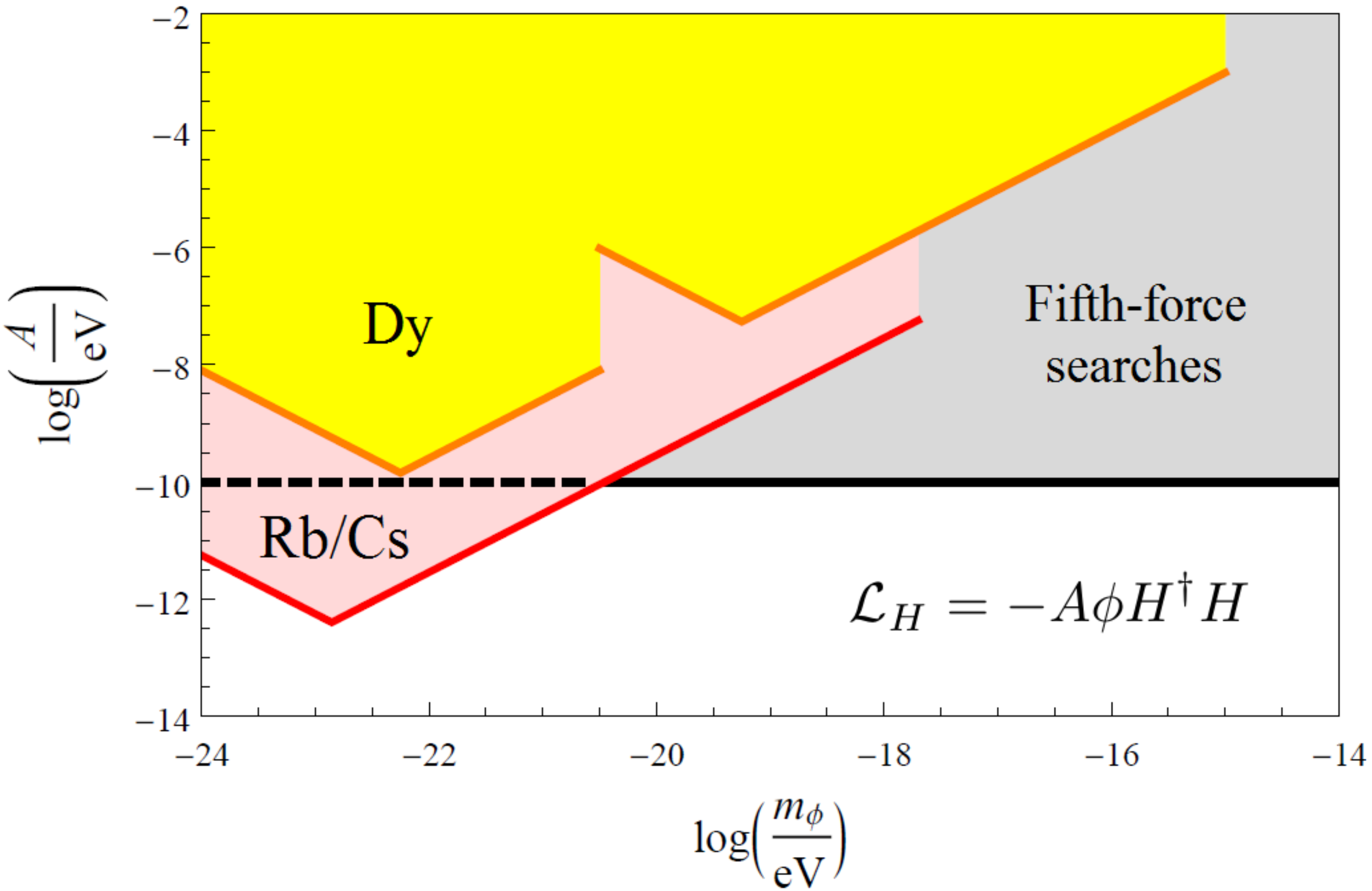


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

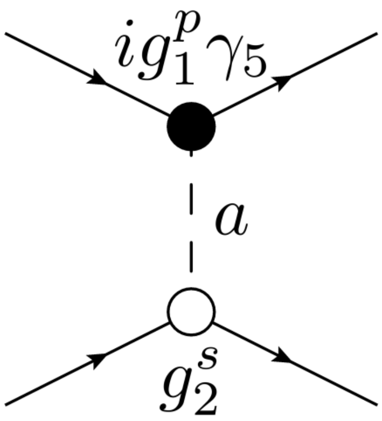
[Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!



Non-Cosmological Sources of Exotic Bosons

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



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

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

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

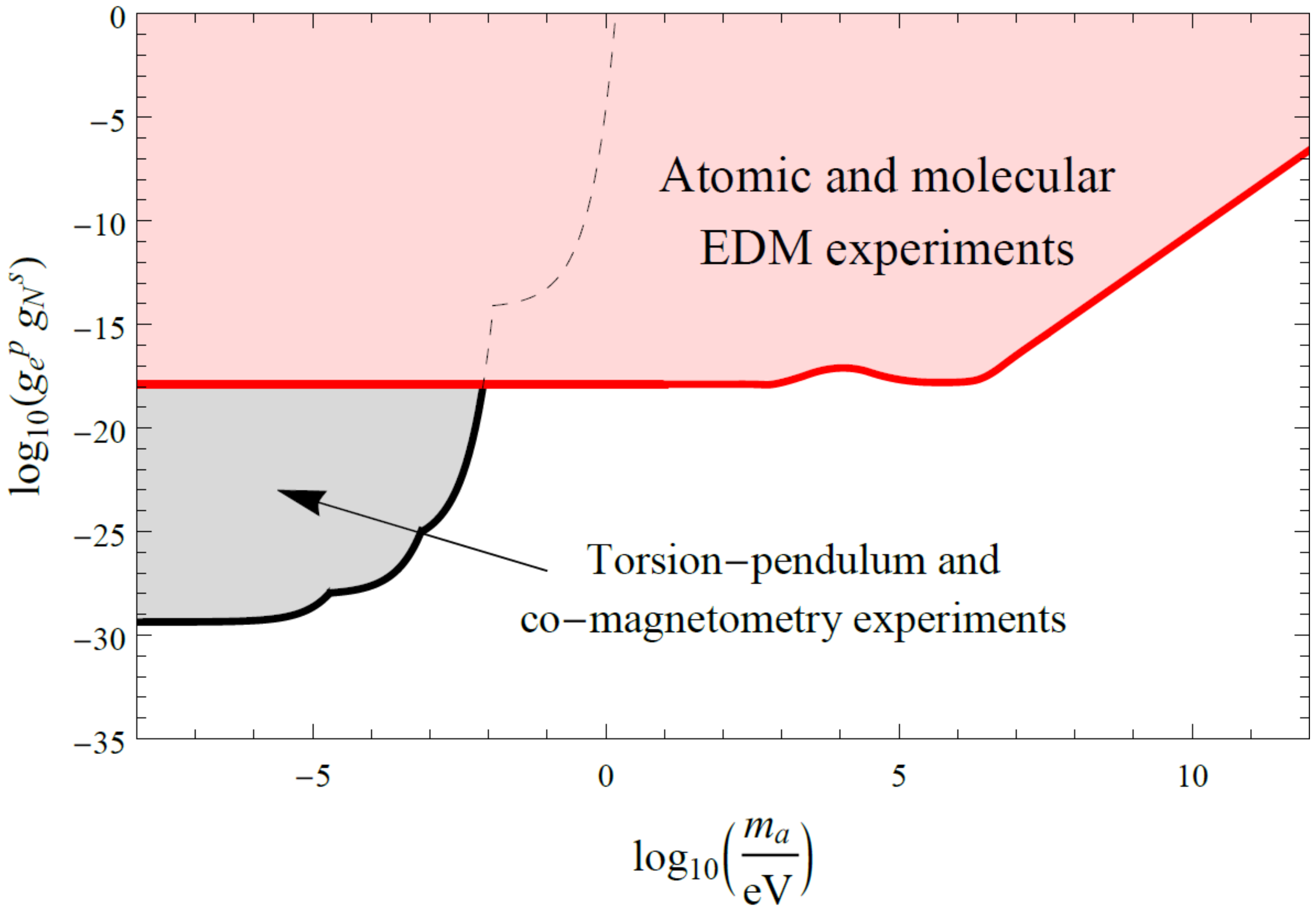
Atomic EDM experiments: Cs, Tl, Xe, **Hg**

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

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

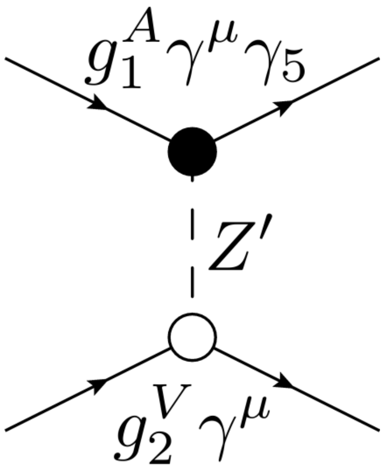
EDM constraints: [Stadnik, Dzuba, Flambaum, *PRL* **120**, 013202 (2018)]

Many orders of magnitude improvement!



Non-Cosmological Sources of Exotic Bosons

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



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

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

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!