Searching for Dark Matter with Atoms, Molecules and Ultracold Neutrons

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EPJC **75**, 110 (2015); *PRA* **93**, 063630 (2016);
PRA **94**, 022111 (2016); arXiv:1607.04956.

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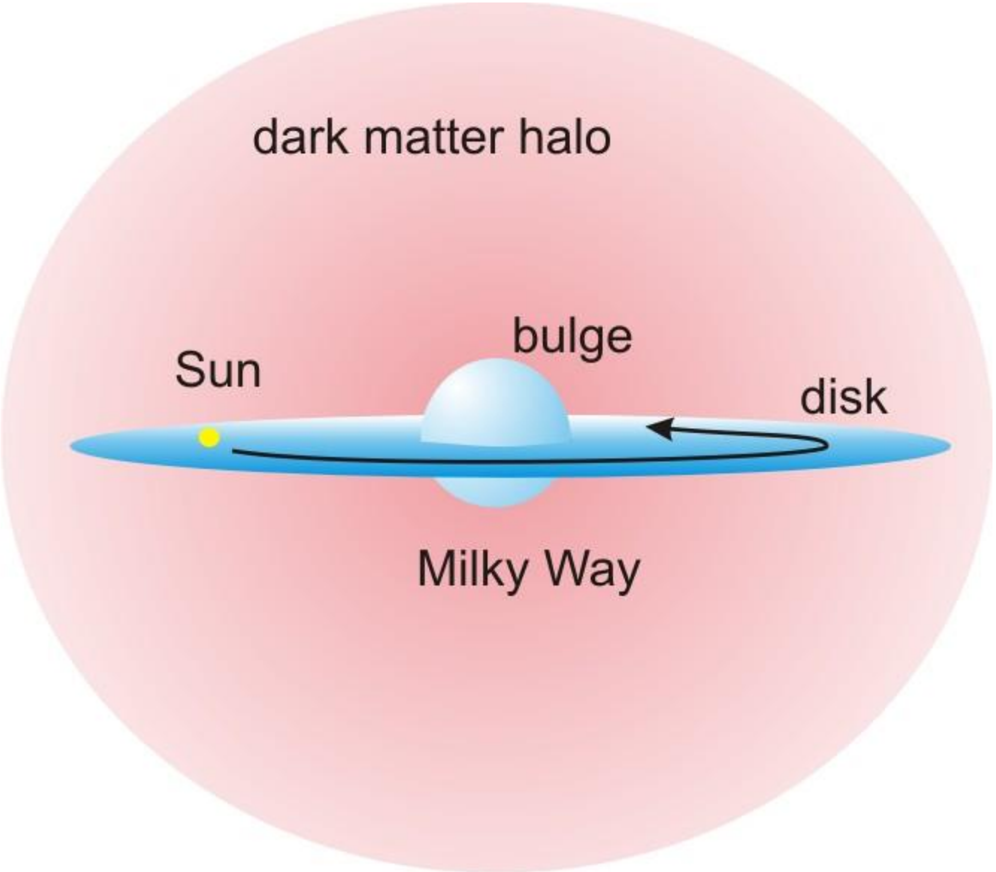
Motivation

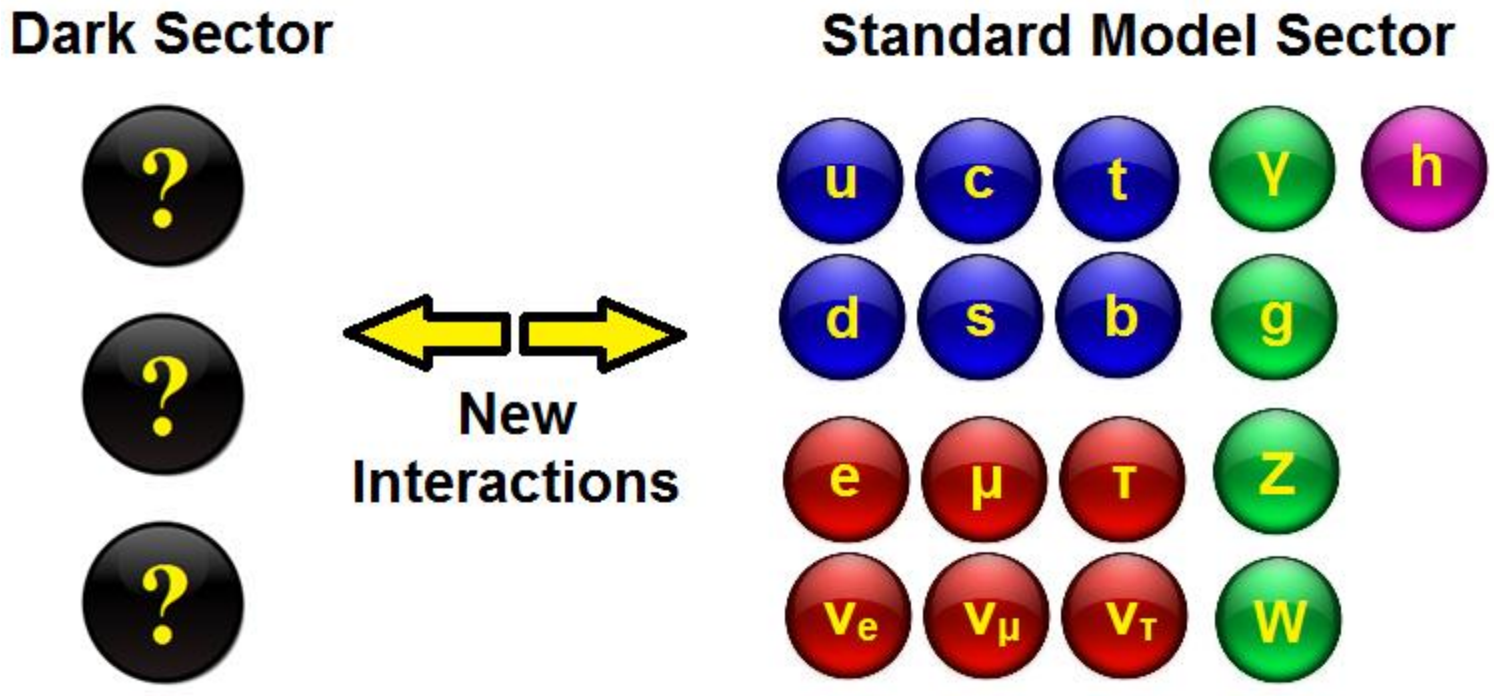
Overwhelming astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter).



Motivation

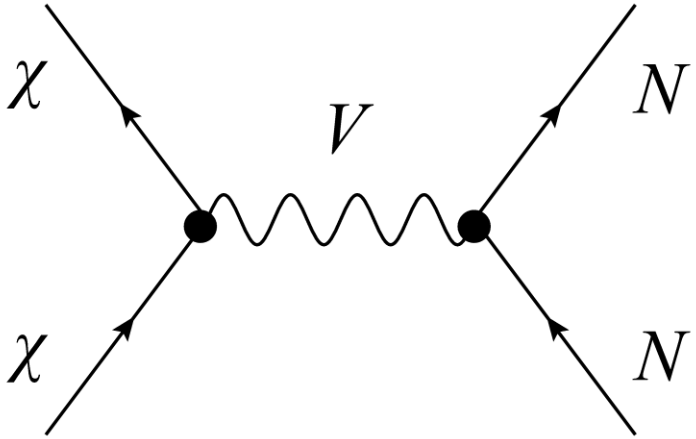
Overwhelming astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter).

– *"What is dark matter and how does it interact with ordinary matter **non-gravitationally**?"*



Motivation

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



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

$$=> \sigma_{\text{scat}} \propto (e')^4$$

Observable is **quartic** in the interaction constant *e'*, which is extremely small (*e'* << 1)!

Motivation

We propose to search for other well-motivated forms of dark matter: *low-mass spin-0 particles*, which form a *coherently* oscillating classical*† field ($\langle\rho_\varphi\rangle = m_\varphi^2\varphi_0^2/2$): $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, via effects that are **linear** in the interaction constant (Λ_X = new-physics energy scale).

$$\mathcal{L}_{\mathrm{eff}} = \frac{\phi}{\Lambda_X} X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \frac{1}{\Lambda_X}$$

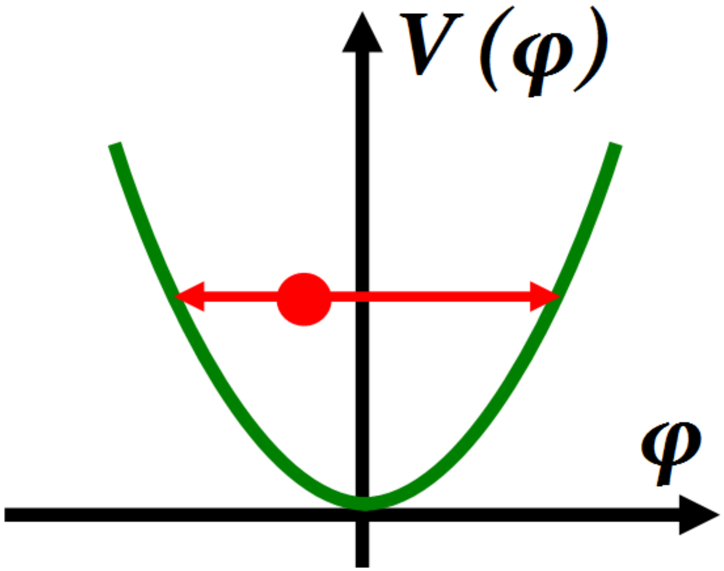
Consideration of *linear effects* has already allowed us to improve on existing constraints on some interactions of dark matter by up to **15 orders of magnitude**, as well as derive the **first constraints** on some other interactions of dark matter.

* Coherently oscillating field => *cold*, i.e., $E_\varphi \approx m_\varphi c^2$

† $n_\varphi(\lambda_{\mathrm{dB}}/2\pi)^3 \gg 1$

Low-mass Spin-0 Dark Matter

Non-thermal production of *coherently oscillating* classical field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, in the early Universe, e.g., via the misalignment mechanism. [10^{-22} eV ≤ m_φ ≤ 0.1 eV]



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

Sufficiently low-mass and feebly-interacting bosons are *practically stable* (m_φ ≤ 24 eV for the QCD axion), and survive to the present day to form galactic DM haloes (where they may be detected).

Low-mass Spin-0 Dark Matter

The mass range 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV is inaccessible to traditional "scattering-off-nuclei" and collider searches, but large regions are accessible to low-energy atomic experiments that search for **oscillating signals** produced by $\varphi(t) = \varphi_0 \cos(m_\varphi t)$ [10^{-8} Hz* $\leq f \leq 10^{13}$ Hz].

In particular, ultra-low-mass spin-0 DM with mass $m_\varphi \sim 10^{-22}$ eV has been proposed to resolve several long-standing "small-scale crises" of the cold DM model (cusp-core problem, missing satellite problem, etc.), due to its effects on structure formation†.

***** $f \sim 10^{-8}$ Hz corresponds to $T \sim 1$ year.

† On sub-wavelength length scales, the gravitational collapse of DM is prevented by quantum pressure.

Coherence of Galactic DM

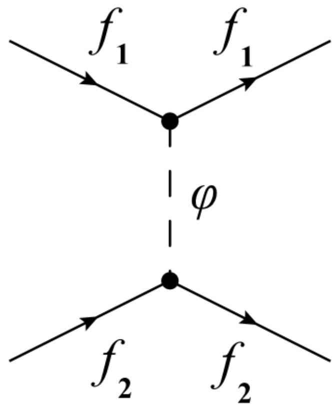
Gravitational interactions between DM and ordinary matter during galactic structure formation result in the virialisation of the DM particles ($v_{\mathrm{vir}} \sim 10^{-3}\, c$), which gives the galactic DM field the finite coherence time and finite coherence length:

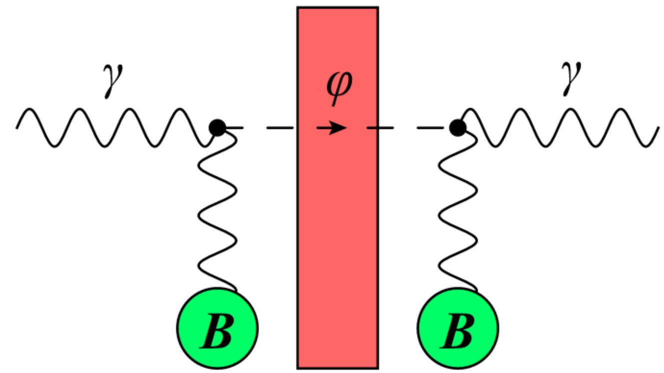
$$\tau_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi v_{\mathrm{vir}}^2} \sim 10^6 \left(\frac{2\pi}{m_\phi}\right) \;\; => \;\; \frac{\Delta f}{f} \sim 10^{-6}$$

$$l_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi v_{\mathrm{vir}}} \sim \frac{2\pi \cdot 10^3}{m_\phi} = 10^3 \lambda_{\mathrm{Compton}}$$

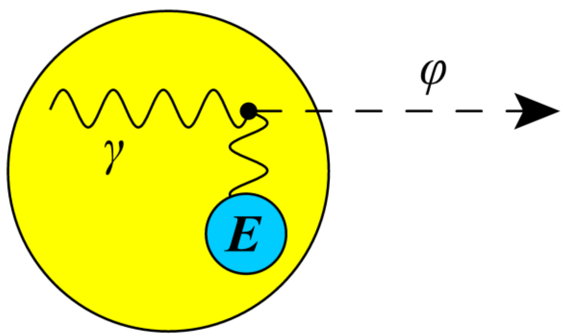
Non-Cosmological Sources of Exotic Bosons

- Mediators of fifth-forces and inter-conversion with SM particles





- Emission from stars, supernovae and white dwarves



- Non-cosmological phenomena assist in DM searches by ruling out large regions of physical parameter space

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions, ALPs): *Odd-parity*

→ Oscillating spin-dependent effects

- Atomic magnetometry
- Ultracold neutrons
- Solid-state magnetometry

Scalars: *Even-parity*

→ 'Slow' evolution and oscillating variation of fundamental constants

- Atomic clocks
- Highly-charged ions
- Molecules
- Nuclear clocks
- Laser interferometers

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars

(Axions, ALPs):

Odd-parity

→ Oscillating spin-dependent effects

- Atomic magnetometry
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- Solid-state magnetometry

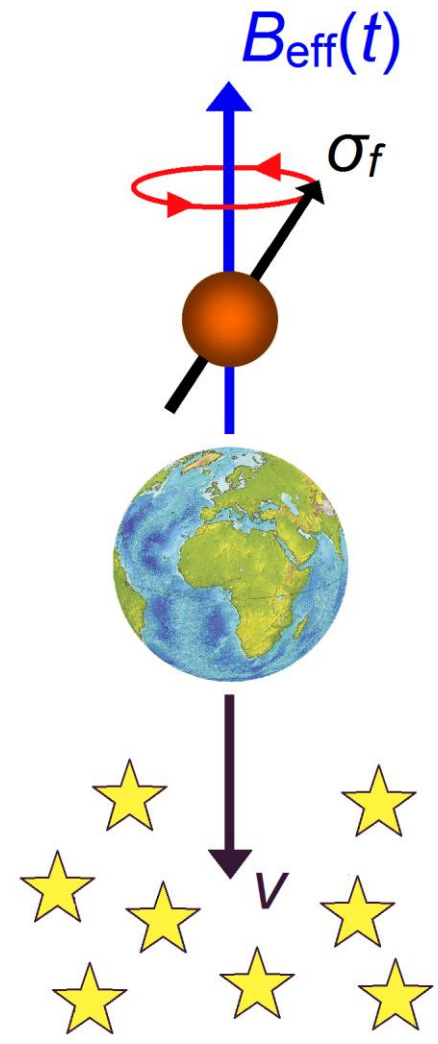
“Axion Wind” Spin-Precession Effect

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

Motion of Earth through galactic axion dark matter gives rise to the interaction of fermion spins with a time-dependent *pseudo*-magnetic field $B_{\text{eff}}(t)$, producing **spin-precession effects**.

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

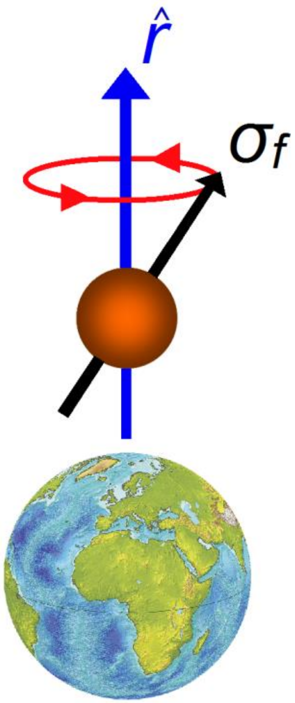
$$=> \quad H_{\text{eff}}(t) \simeq \underbrace{\frac{C_f a_0}{2f_a}\sin(m_a t)\; p_a}_{B_{\text{eff}}(t)} \cdot \sigma_f$$



Axion-Induced Oscillating Spin-Gravity Coupling

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

Distortion of axion field by gravitational field of Sun or Earth induces **oscillating spin-gravity couplings**.



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

$$=> \ H'_{\rm eff}(t) \propto \frac{C_f a_0}{f_a}\sin(m_a t)\ \sigma_f \cdot \hat{r}$$

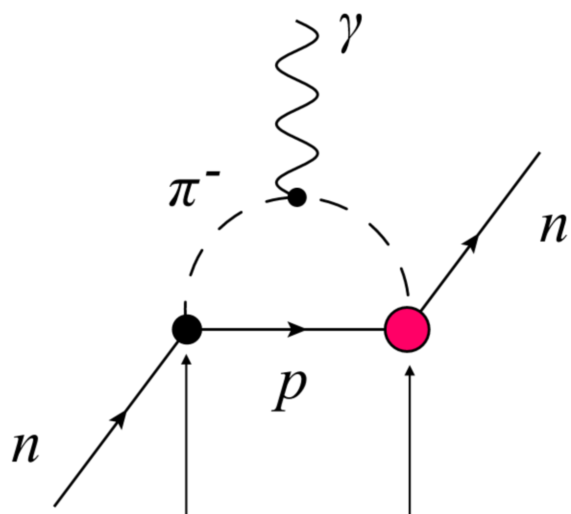
Spin-axion momentum and axion-induced oscillating spin-gravity couplings to nucleons may have isotopic dependence ($C_p \neq C_n$) – calculations of proton and neutron spin contents for nuclei of experimental interest have been performed, see, e.g., [Stadnik, Flambaum, *EPJC* **75**, 110 (2015)].

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)]

An oscillating axion field induces an **oscillating neutron electric dipole moment** via its coupling to gluons.*

$$\mathcal{L}_{agg} = \frac{a_0 \cos(m_{\rm a} t)}{f_{\rm a}} \frac{g^2}{32\pi^2} G\tilde{G} \qquad d_n(t) \approx 2.4 \times 10^{-16} \frac{a_0}{f_a} \cos(m_a t)\; e \cdot \mathrm{cm}$$



$$g_{\pi NN} = 13.5 \qquad \bar{g}^{(0)}_{\pi NN} \approx -0.027 a_0 \cos(m_a t)/f_a$$

***** d_n receives main contribution from the chirally enhanced process above, rather than from the process with the external photon line attached to the internal proton line.

Axion-Induced Oscillating Atomic and Molecular EDMs

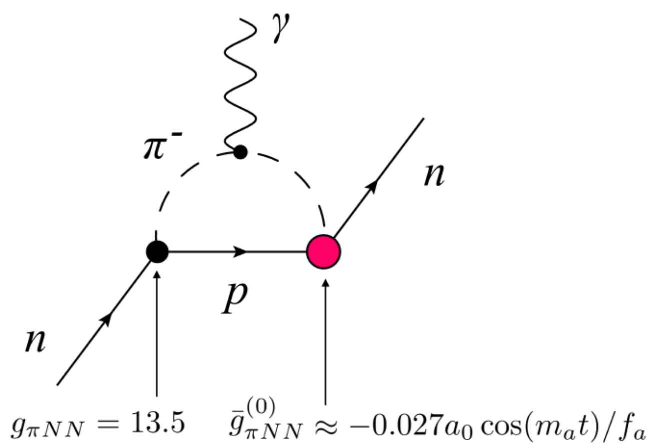
[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)],
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

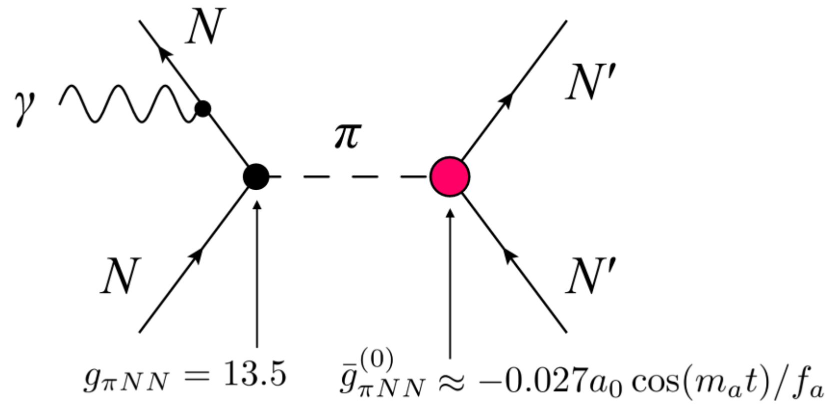
Oscillating atomic and molecular EDMs are induced through oscillating Schiff ($J \geq 0$) and oscillating magnetic quadrupole ($J \geq 1/2$, **no Schiff screening**) moments of nuclei, which arise from *intrinsic oscillating nucleon EDMs* and *oscillating P,T-violating intranuclear forces** (**larger by ~1–3 orders of magnitude**).

$$\mathcal{L}_{agg} = \frac{a_0 \cos(m_\mathrm{a} t)}{f_\mathrm{a}} \frac{g^2}{32\pi^2} G\tilde{G}$$

$$d\left({}^{199}\mathrm{Hg}\right)(t) \approx -1.8 \times 10^{-19} \frac{a_0}{f_a} \cos(m_a t)\ e \cdot \mathrm{cm}$$

$$d\left({}^{225}\mathrm{Ra}\right)(t) \approx 9.3 \times 10^{-17} \frac{a_0}{f_a} \cos(m_a t)\ e \cdot \mathrm{cm}$$





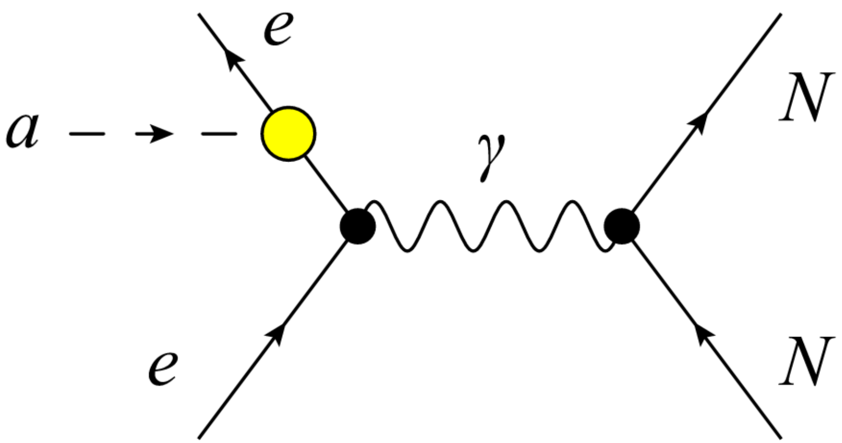
***** P,T-odd intranuclear forces arise at tree level, i.e., no loop suppression factor (c.f., $d_{n,p}$ which arise at 1-loop level), and typically produce sizeable enhancement factors of nuclear origin (especially large in deformed nuclei with close-level and collective enhancements).

Axion-Induced Oscillating EDMs of Paramagnetic Atoms and Molecules

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

In *paramagnetic* atoms and molecules, **oscillating EDMs** are also induced through *mixing of opposite-parity atomic/molecular states* via the interaction of the oscillating axion field with atomic/molecular electrons.

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



Axion-Induced Oscillating PNC Effects in Atoms and Molecules

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

Interaction of the oscillating axion field with atomic/molecular electrons mixes opposite-parity states, producing **oscillating PNC effects in atoms and molecules**.

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

Axion-induced oscillating atomic PNC effects are determined entirely by relativistic corrections (in the non-relativistic approximation, $K_{\mathrm{PNC}} = 0$)*.

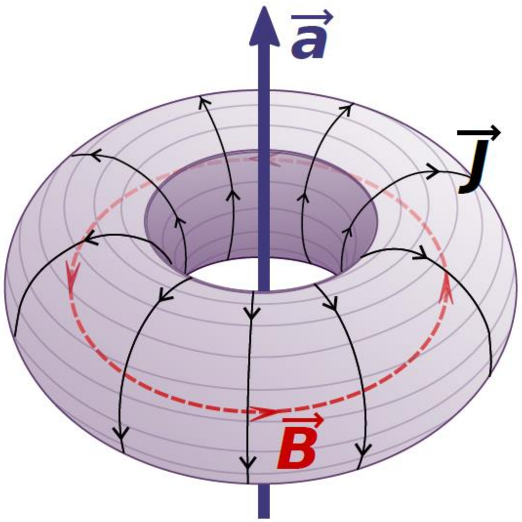
***** Compare with the Standard Model *static* atomic PNC effects in atoms, which are dominated by Z^0-boson exchange between atomic electrons and nucleons in the nucleus, where the effects arise already in the non-relativistic approximation, see, e.g., [Ginges, Flambaum, *Phys. Rept.* **397**, 63 (2004)] for an overview.

Axion-Induced Oscillating Nuclear Anapole Moments

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

Interaction of the oscillating axion field with nucleons in nuclei induces **oscillating nuclear anapole moments**.

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



$$\boldsymbol{a}(t) = -\frac{C_N a_0 m_a}{f_a}\frac{\pi e\mu}{m}\frac{K\boldsymbol{I}}{I(I+1)}\langle r^2\rangle\sin(m_a t)$$

Search for Axion Dark Matter with Ultracold Neutrons

Ongoing work with the nEDM collaboration (Ayres, Harris, Kirch, Rawlik *et al*.)

Experimental overview: Tuesday talk (10:15) by Michal Rawlik

- Ongoing search for "axion wind" spin-precession effect and axion-induced oscillating neutron EDM by the nEDM collaboration at PSI and Sussex, using a dual neutron/^{199}Hg co-magnetometer to measure the weighted combination of neutron and ^{199}Hg Larmor precession frequencies in an applied ***B***-field (and also in applied ***E***-field for oscillating d_n):

$$\Delta\omega(t) \equiv \omega_{L,n}(t) - \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\omega_{L,\mathrm{Hg}}(t)$$

- Exact frequency of oscillation is unknown: $\omega = m_a$ (10^{-22} eV $\leq m_a \leq 0.1$ eV => 10^{-8} Hz* $\leq f \leq 10^{13}$ Hz), with $\Delta f/f \sim 10^{-6}$.

***** $f \sim 10^{-8}$ Hz corresponds to $T \sim 1$ year.

Expected Sensitivity (Interaction of Axion Dark Matter with Nucleons)

Ongoing work with the nEDM collaboration (Ayres, Harris, Kirch, Rawlik *et al.*)

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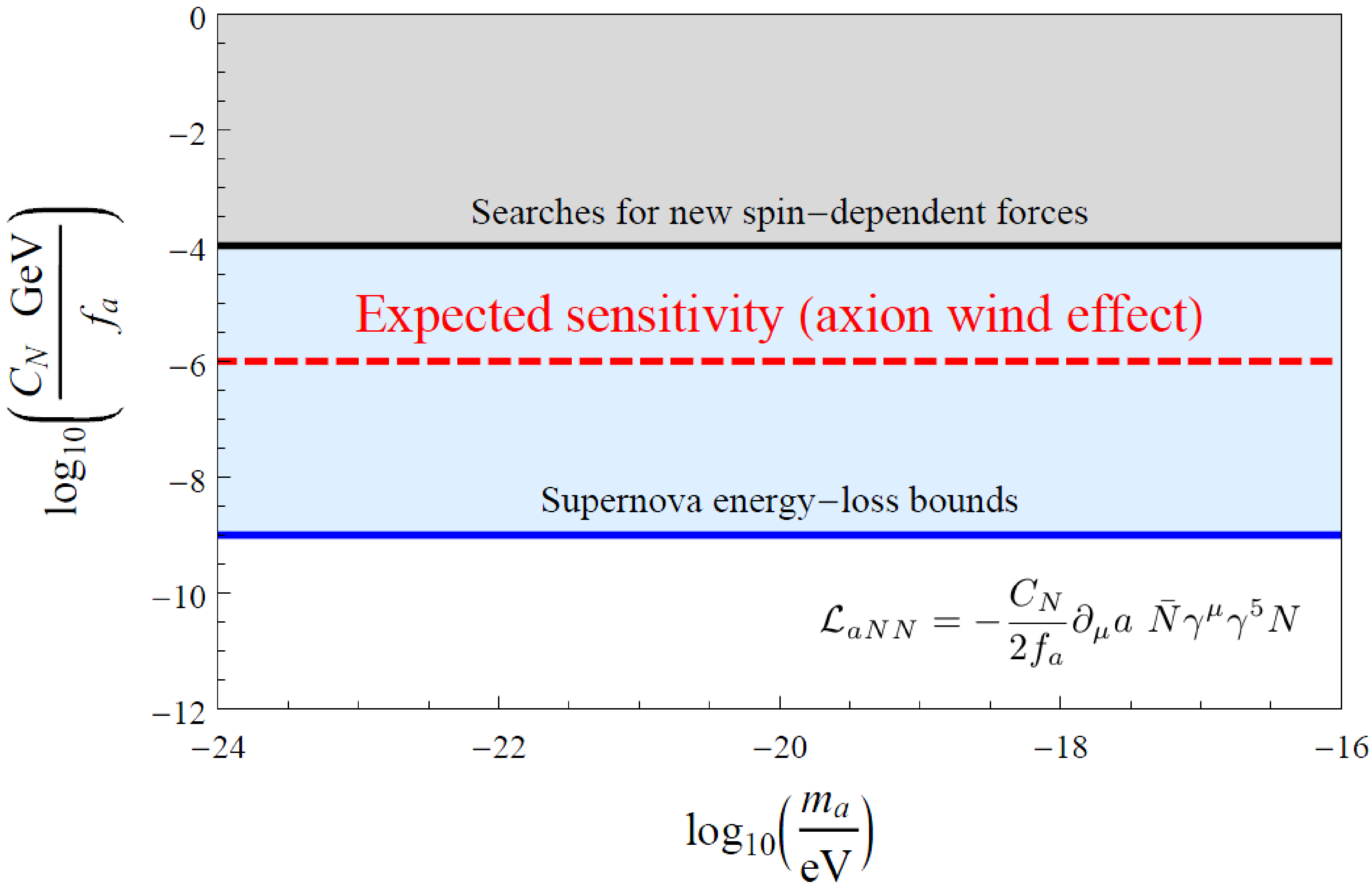

Expected Sensitivity (Interaction of Axion Dark Matter with Gluons)

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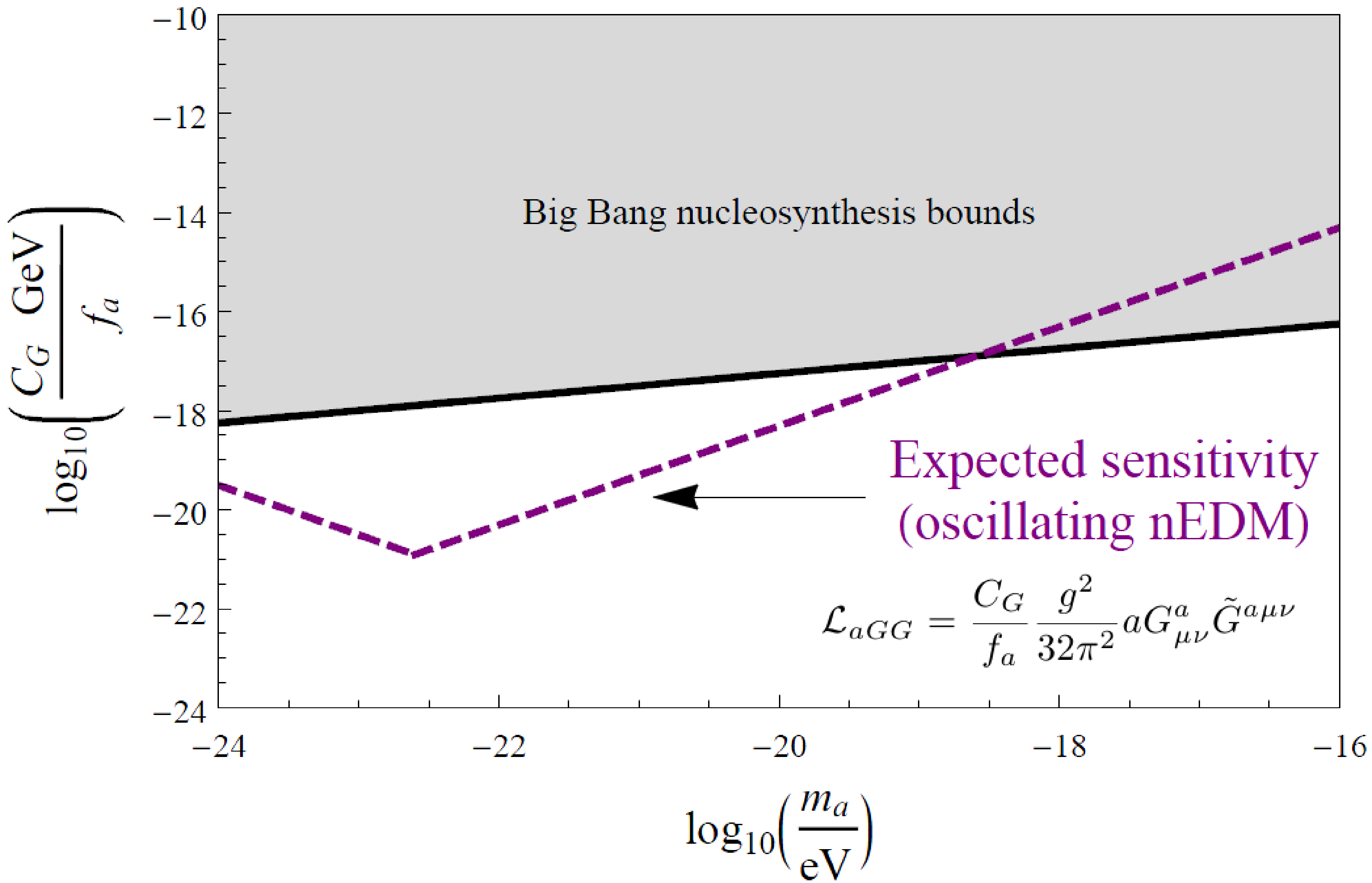

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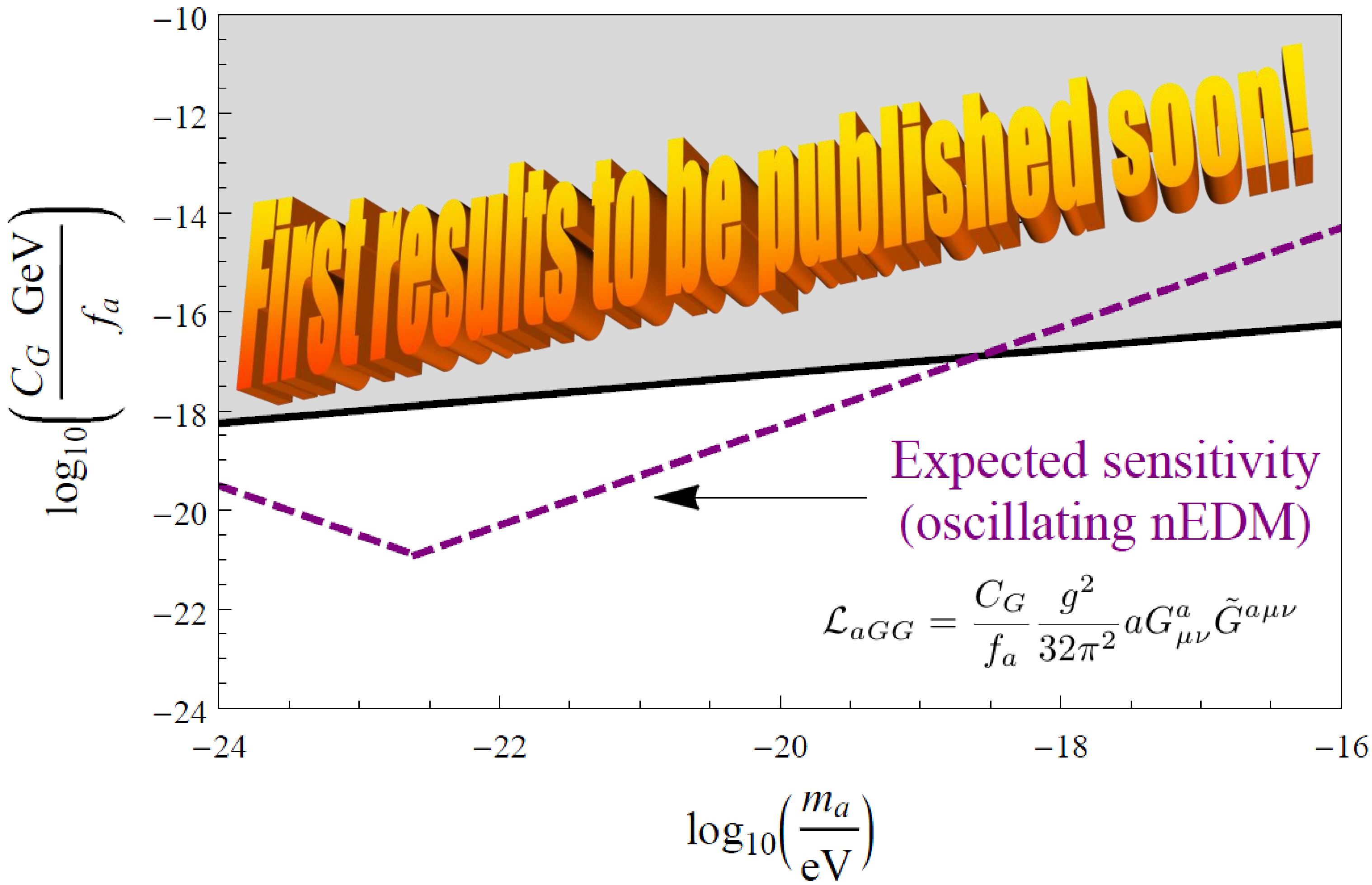

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars:

Even-parity

→ ‘Slow’ evolution and oscillating variation of fundamental constants

- Atomic clocks
- Highly-charged ions
- Molecules
- Nuclear clocks
- Laser interferometers

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

Consider an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, that interacts with SM fields (e.g., a fermion *f*) via *quadratic couplings* in φ.

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

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

$$\rho_\phi = \frac{m_\phi^2 \phi_0^2}{2} \quad => \quad \phi_0^2 \propto \rho_\phi$$

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'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* **115**, 201301 (2015)]

We can consider a wide range of quadratic-in-*φ* interactions with the SM sector:

Photon:

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

Fermions:

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

***W* and *Z* Bosons (mediators of weak interactions):**

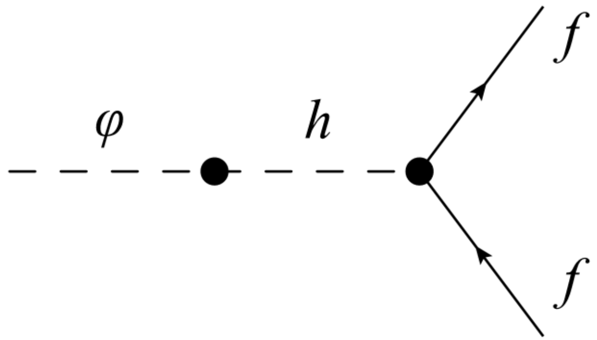
$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2}\frac{M_V^2}{2} V_\nu V^\nu \quad => M_V^2 \rightarrow M_V^2\left[1+\frac{\phi^2}{(\Lambda'_V)^2}\right]$$

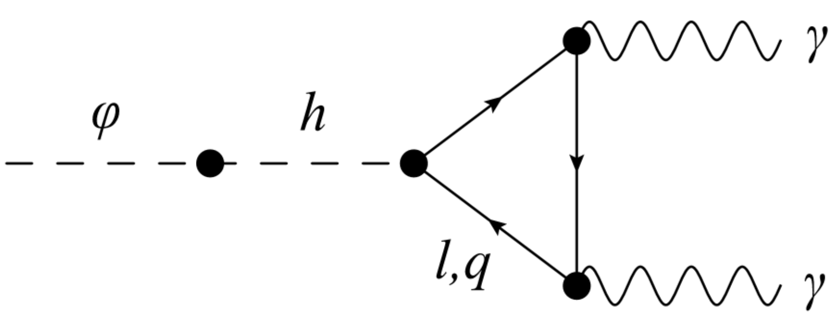
Dark Matter-Induced Oscillating Variation of the Fundamental Constants

Also possible to have linear-in-φ interactions with the SM sector, which may be generated, e.g., through the super-renormalisable interaction of φ with the Higgs boson*

[Piazza, Pospelov, *PRD* **82**, 043533 (2010)]:

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





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

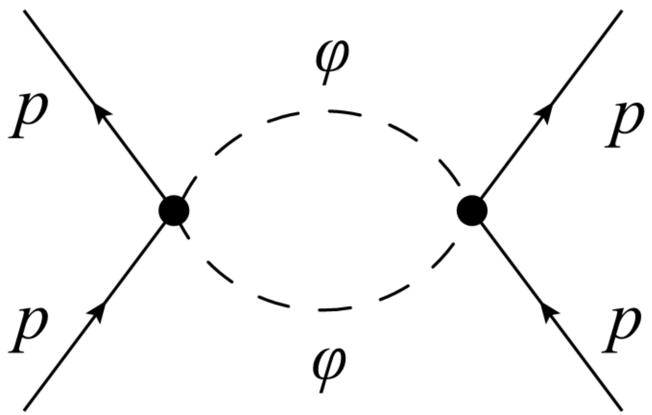
***** Produces logarithmically-divergent corrections to $(m_\varphi)^2$, i.e., technically natural for $A < m_\varphi$. Minimum of potential is stable (without adding extra φ^4 terms) for $(A/m_\varphi)^2 < 2\lambda$.

Generic Constraints on Quadratic Scalar Interactions

[Olive, Pospelov, *PRD* **77**, 043524 (2008)]

<u>Gravitational test constraints (fifth-force searches)</u>:

Exchange of a pair of virtual spin-0 bosons produces an attractive ~1/r^3 potential* between two SM particles.



$$\Lambda'_p > 2 \text{ TeV}$$

***** Similar to the 1-loop quantum correction to Newton's Law of Gravitation, see, e.g., [Kirilin, Khriplovich, *JETP* **95**, 981 (2002)] and [Bjerrum-Bohr, Donoghue, Holstein, *PRD* **67**, 084033 (2003)], and to theories with two large extra dimensions.

Generic Constraints on Quadratic Scalar Interactions

[Olive, Pospelov, *PRD* **77**, 043524 (2008)]

Astrophysical constraints (stellar energy loss bounds):
Pair annihilation of photons and bremsstrahlung-like emission processes can produce pairs of *φ*-quanta, increasing stellar energy loss rate.

$$\gamma + \gamma \to \phi + \phi \qquad \Lambda'_\gamma > 3 \text{ TeV}$$

$$N + N \to N + N + \phi + \phi \qquad \Lambda'_N > 15 \text{ TeV}$$

Astrophysical Constraints on ‘Slow’ Drifts in Fundamental Constants Induced by Scalar Dark Matter (BBN)

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

- Largest effects of scalar dark matter are in the early Universe (highest ρ_{DM} => highest φ_0^2).
- Earliest cosmological epoch that we can probe is Big Bang nucleosynthesis (from $t_{\mathrm{weak}} \approx$ 1s until $t_{\mathrm{BBN}} \approx$ 3 min).
- Primordial ^{4}He abundance is sensitive to relative abundance of neutrons to protons (almost all neutrons are bound in ^{4}He by the end of BBN).

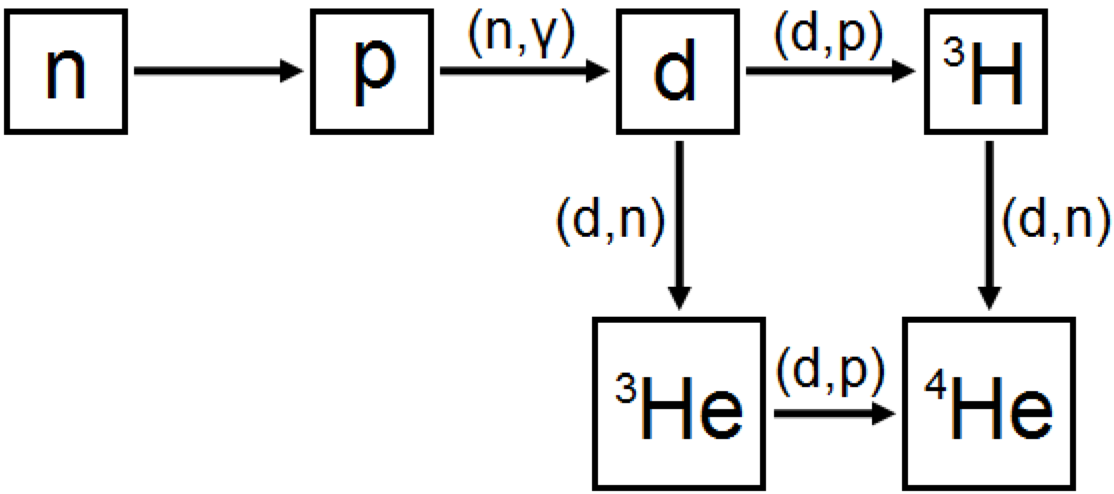
<u>Weak interactions:</u> freeze-out of weak interactions occurs at $t_{\mathrm{weak}} \approx$ 1s ($T_{\mathrm{weak}} \approx$ 0.75 MeV).

$$\begin{aligned} p + e^- &\rightleftharpoons n + \nu \\ n + e^+ &\rightleftharpoons p + \bar{\nu} \end{aligned} \qquad \left(\frac{n}{p}\right)_{\mathrm{weak}} = e^{-(m_n - m_p)/T_{\mathrm{weak}}}$$

Astrophysical Constraints on 'Slow' Drifts in Fundamental Constants Induced by Scalar Dark Matter (BBN)

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

BBN reactions: reaction channels that produce ^{4}He last until $t_{\mathrm{BBN}} \approx 3$ min ($T_{\mathrm{BBN}} \approx 60$ keV).



$$\frac{\Delta Y_p(^4\mathrm{He})}{Y_p(^4\mathrm{He})} \approx \frac{\Delta (n/p)_{\mathrm{weak}}}{(n/p)_{\mathrm{weak}}} - \Delta\left[\int_{t_{\mathrm{weak}}}^{t_{\mathrm{BBN}}} \Gamma_n(t)dt\right]$$ => Limits on Λ'_X

Astrophysical Constraints on 'Slow' Drifts in Fundamental Constants Induced by Scalar Dark Matter (CMB)

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

- Weaker astrophysical constraints come from CMB measurements (lower ρ_{DM}).
- Variations in α and m_e at the time of electron-proton recombination affect the ionisation fraction and Thomson scattering cross section, $\sigma_{\mathrm{Thomson}} = 8\pi\alpha^2/3m_e^2$, changing the mean-free-path length of photons at recombination and leaving distinct signatures in the CMB angular power spectrum.

$$\Lambda'_\gamma \gtrsim \frac{1\ \mathrm{eV}^2}{m_\phi}, \quad \Lambda'_e \gtrsim \frac{0.6\ \mathrm{eV}^2}{m_\phi}$$

Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015); Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- In the laboratory, we can search for **oscillating variations in the fundamental constants** induced by scalar DM, using **clock frequency comparison measurements**.

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

- Exact frequency of oscillation is unknown: $\omega = m_\varphi$ (linear) or $\omega = 2m_\varphi$ (quadratic) [10^{-22} eV ≤ m_φ ≤ 0.1 eV => 10^{-8} Hz* ≤ f ≤ 10^{14} Hz], with $\Delta f/f \sim 10^{-6}$.

***** $f \sim 10^{-8}$ Hz corresponds to $T \sim 1$ year.

Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

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

- Alternatively, we can compare *interferometer arm length* with *photon wavelength*. LIGO enhancement ~ 10^{14}.
- Accumulated phase in an arm, $\Phi = \omega L/c$, changes if the fundamental constants change ($L \sim N a_B$ and ω_{atomic} depend on the fundamental constants).

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

- Multiple reflections enhance observable effects due to variation of the fundamental constants by the effective mean number of passages N_{eff} (e.g., $N_{\text{eff}} \sim 10^5$ in a strontium clock – silicon cavity interferometer).

Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

Calculations performed by Flambaum group and co-workers (>100 systems!)

System	Λ'_γ	Λ'_e	Λ'_N	Λ'_q
Atomic (electronic)	+	-	-	-
Atomic (hyperfine)	+	+	+	+
Highly charged ionic	+	-	-	-
Molecular (rotational/hyperfine)	+	+	+	+
Molecular (fine-structure/vibrational)	+	+	+	+
Molecular (Ω-doubling/hyperfine)	+	+	+	+
Nuclear (e.g., ^{229}Th)	+	-	+	+
Laser interferometer	+	+	+	+

Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

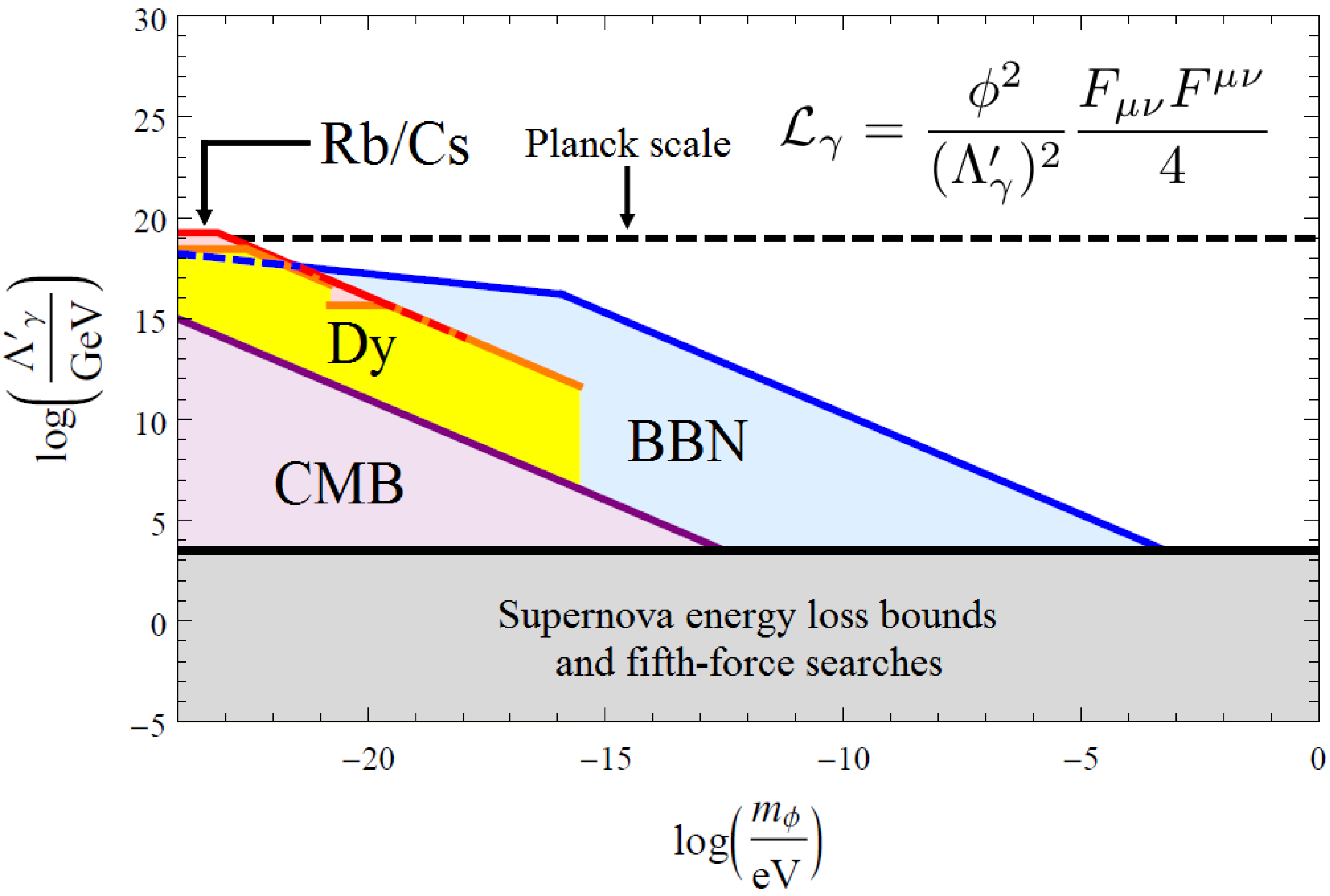
System	Laboratory	Constraints
^{162,164}Dy/^{133}Cs	UC Berkeley/Mainz	Van Tilburg, Leefer, Bougas, Budker, *PRL* **115**, 011802 (2015); Stadnik, Flambaum, *PRL* **115**, 201301 (2015) + *PRA* **94**, 022111 (2016)
^{87}Rb/^{133}Cs	LNE-SYRTE Paris	Hees, Guena, Abgrall, Bize, Wolf, *PRL* **117**, 061301 (2016); Stadnik, Flambaum, *PRA* **94**, 022111 (2016)

Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

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

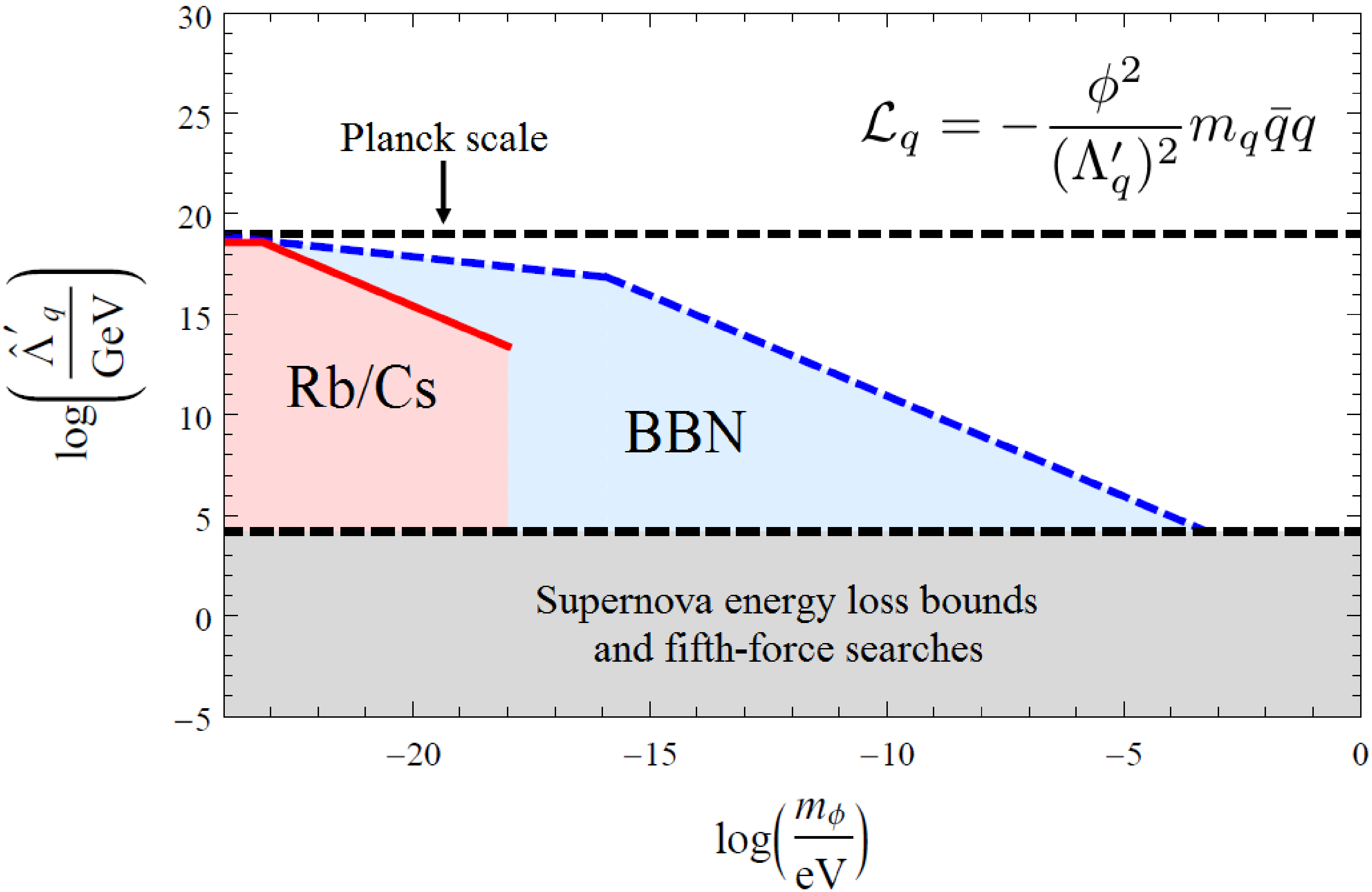
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

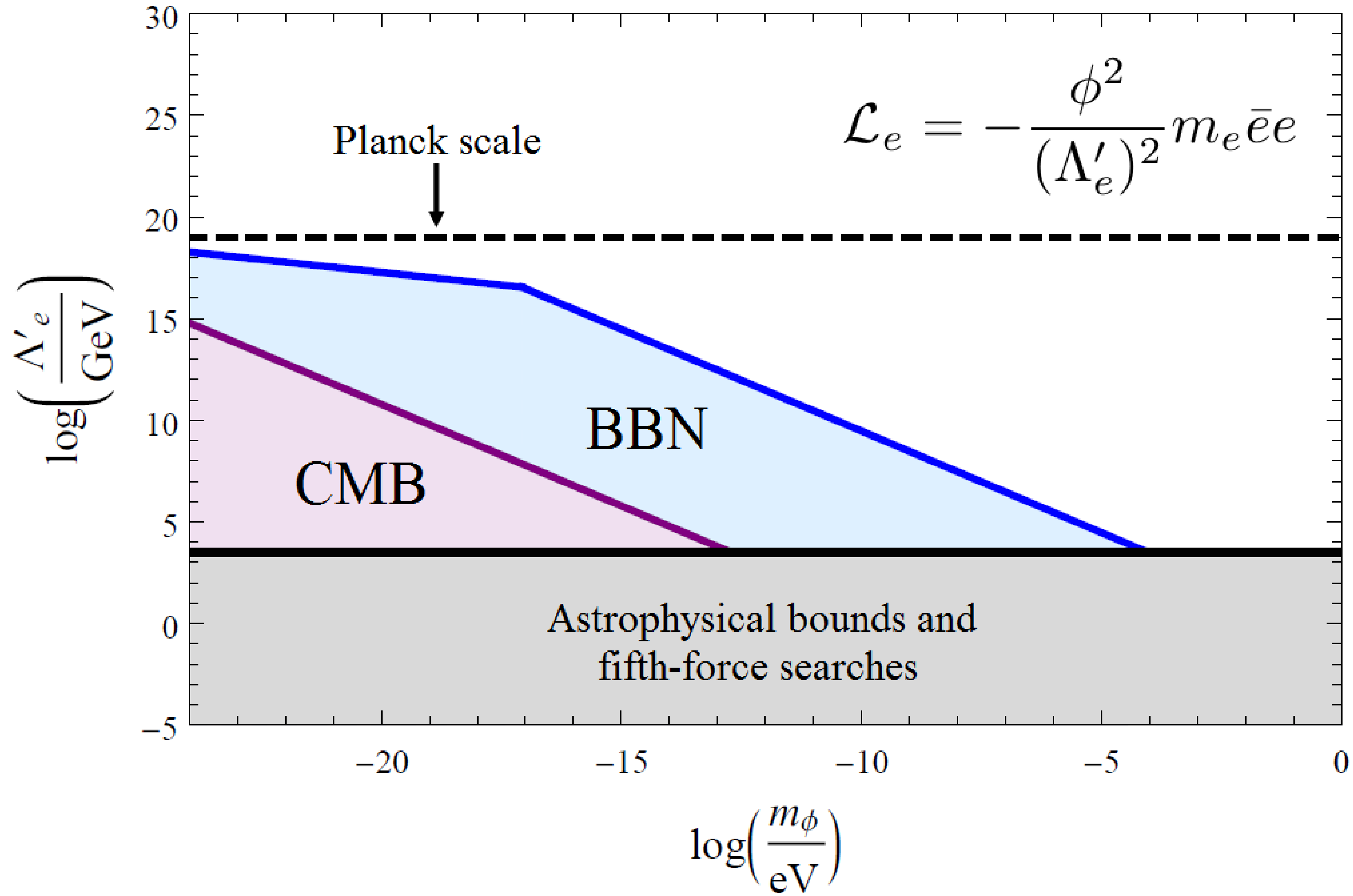
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015) + *PRA* **94**, 022111 (2016)]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

BBN and CMB constraints:

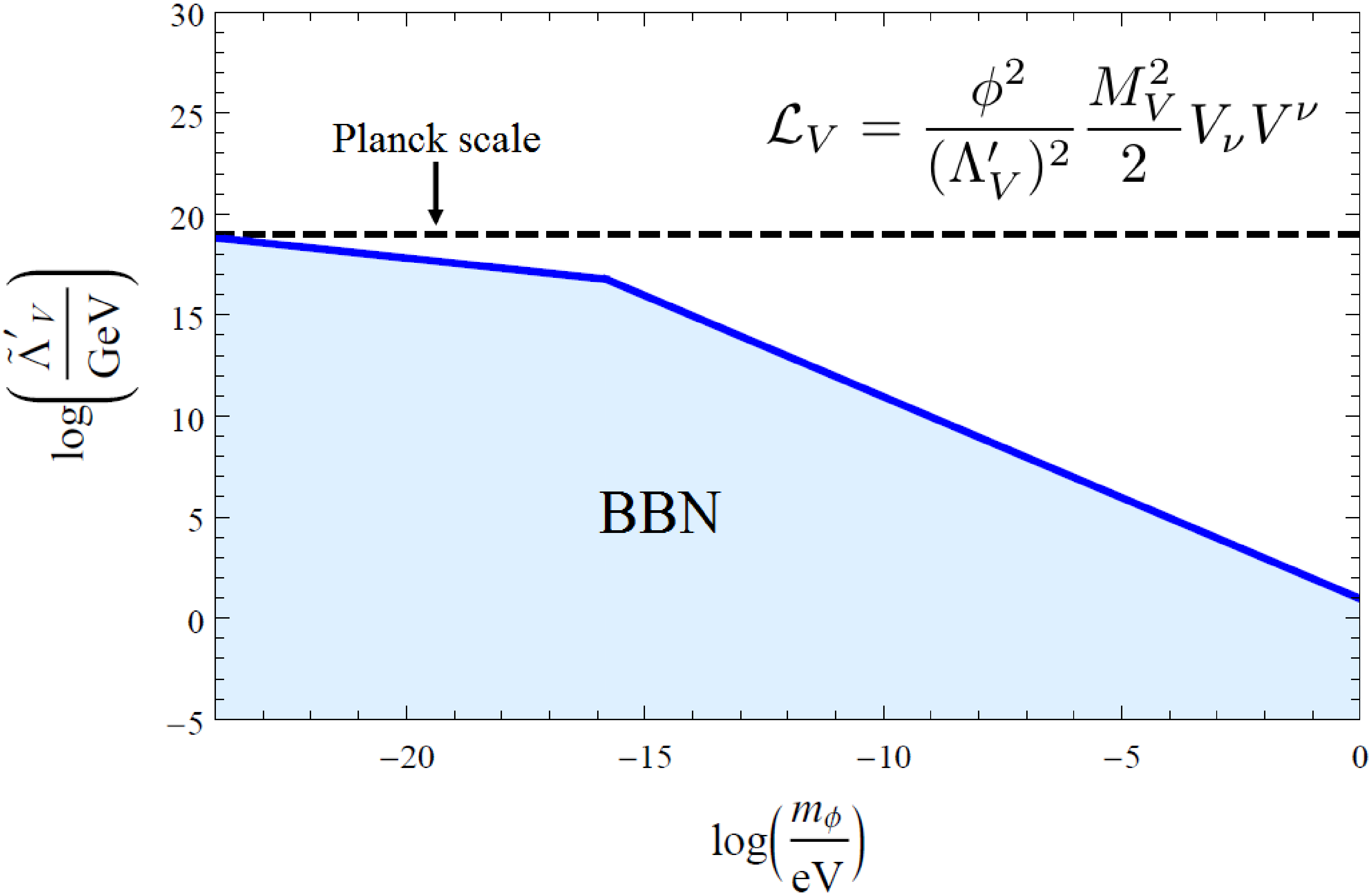
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

BBN constraints:

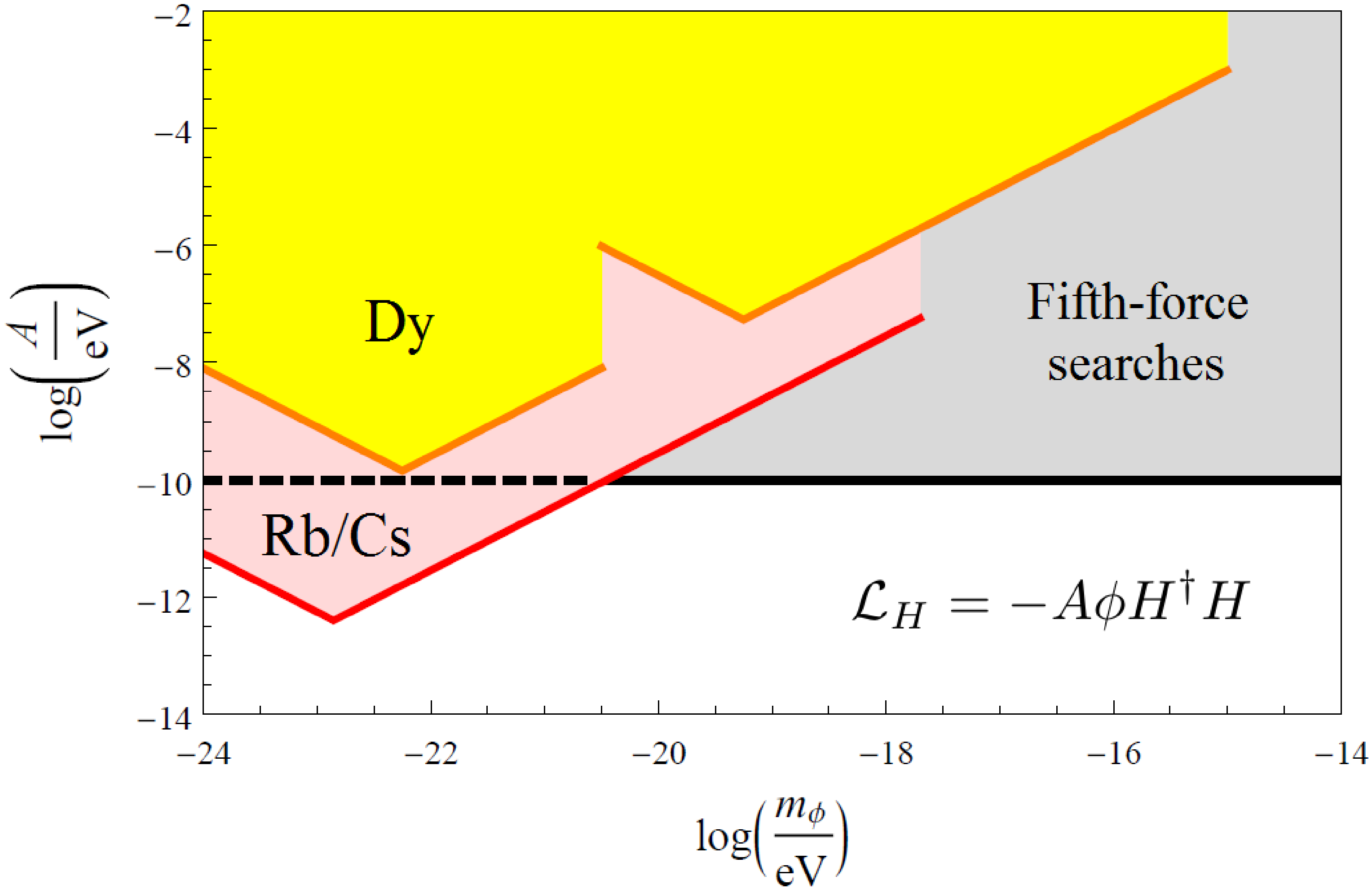
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

Dy and Rb/Cs constraints:

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

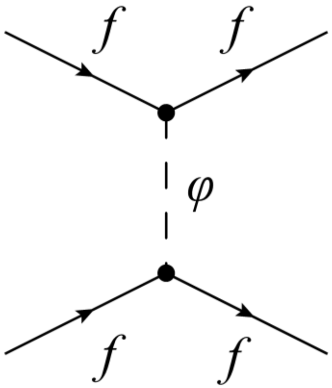


Yukawa-type Fifth-Forces

Yukawa-type interactions, e.g., between a spin-0 boson φ and a SM fermion *f*, produce an attractive Yukawa-type potential between two fermions:

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

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



Yukawa-type fifth-forces are traditionally sought for with measurements of *vector* quantities, usually the difference in acceleration of two test bodies in the presence of a massive body (Earth or Sun):

- Torsion pendulum experiments
- Lunar laser ranging
- Atom interferometry

Variation of Fundamental Constants Induced by a Massive Body

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]

Consider the Yukawa-type interactions again:

$$\mathcal{L}_{\mathrm{int}} = -\sum_f \frac{\phi}{\Lambda_f} m_f \bar{f} f + \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

The equations of motion for *φ* read:

$$\left(\partial_\mu \partial^\mu + m_\phi^2\right) \phi = \boxed{-\sum_f \frac{m_f \bar{f} f}{\Lambda_f} + \frac{F_{\mu\nu}F^{\mu\nu}}{4\Lambda_\gamma}}$$

SM fields source *φ*: $\phi(r) \propto \frac{e^{-m_\phi r}}{r}$

$$=> \frac{\delta m_f}{m_f} = \frac{\phi}{\Lambda_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \simeq \frac{\phi}{\Lambda_\gamma} \propto \frac{e^{-m_\phi r}}{r}$$

Variation of Fundamental Constants Induced by a Massive Body

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]

Varying the distance away from a massive body hence alters the fundamental constants, in the presence of Yukawa-type interactions:

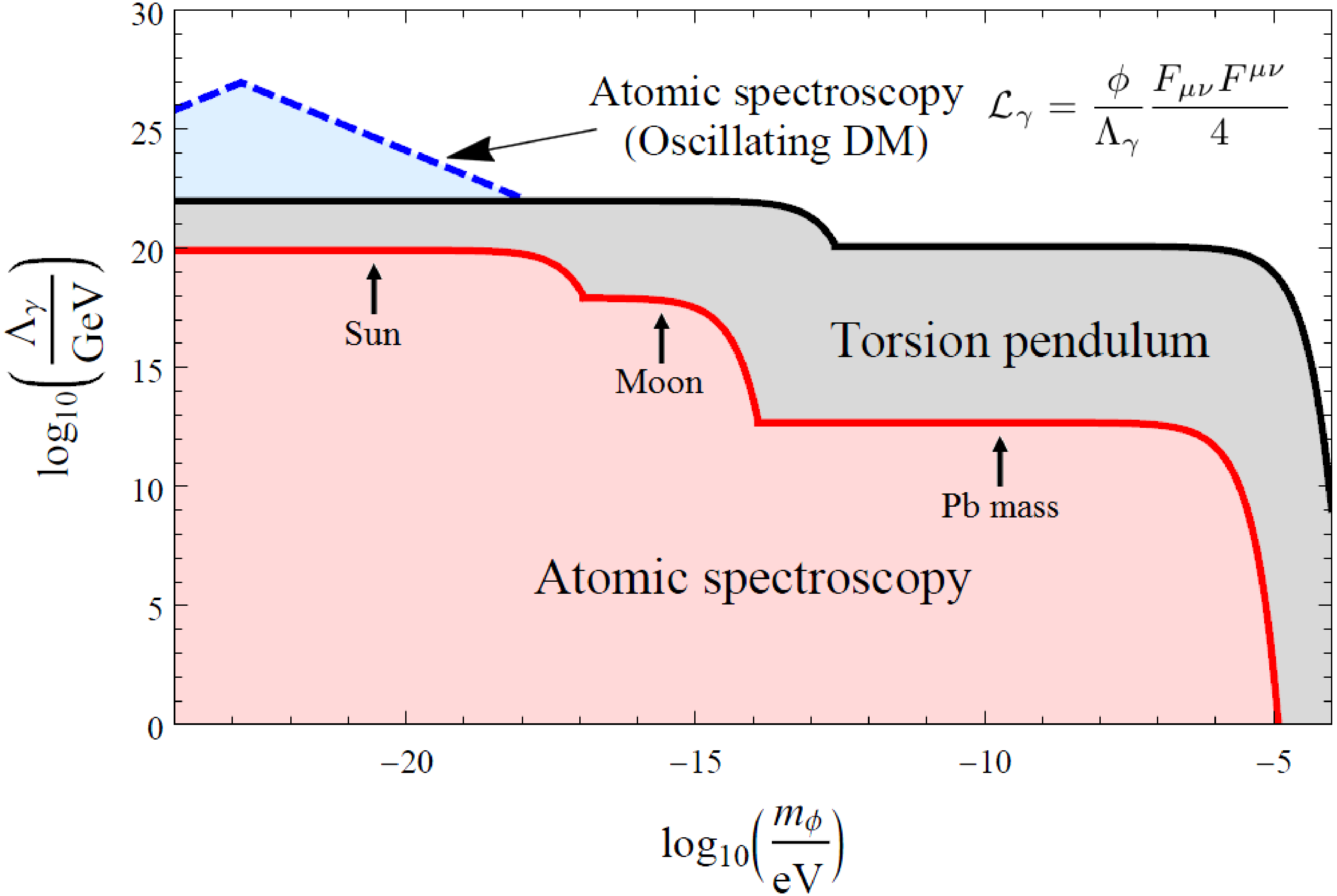
$$\frac{\delta m_f}{m_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \propto \frac{e^{-m_\phi r}}{r}$$

We can search for such alterations in the fundamental constants, using **clock frequency comparison measurements** (i.e., *scalar* quantities), **in the presence of a massive body at two different distances** away from the clock pair:

- Sun (e = 0.0167)
- Moon ($e \approx 0.05$, with seasonal variation and effect of finite Earth size)
- Massive objects in the laboratory (e.g., moveable 300kg Pb mass)

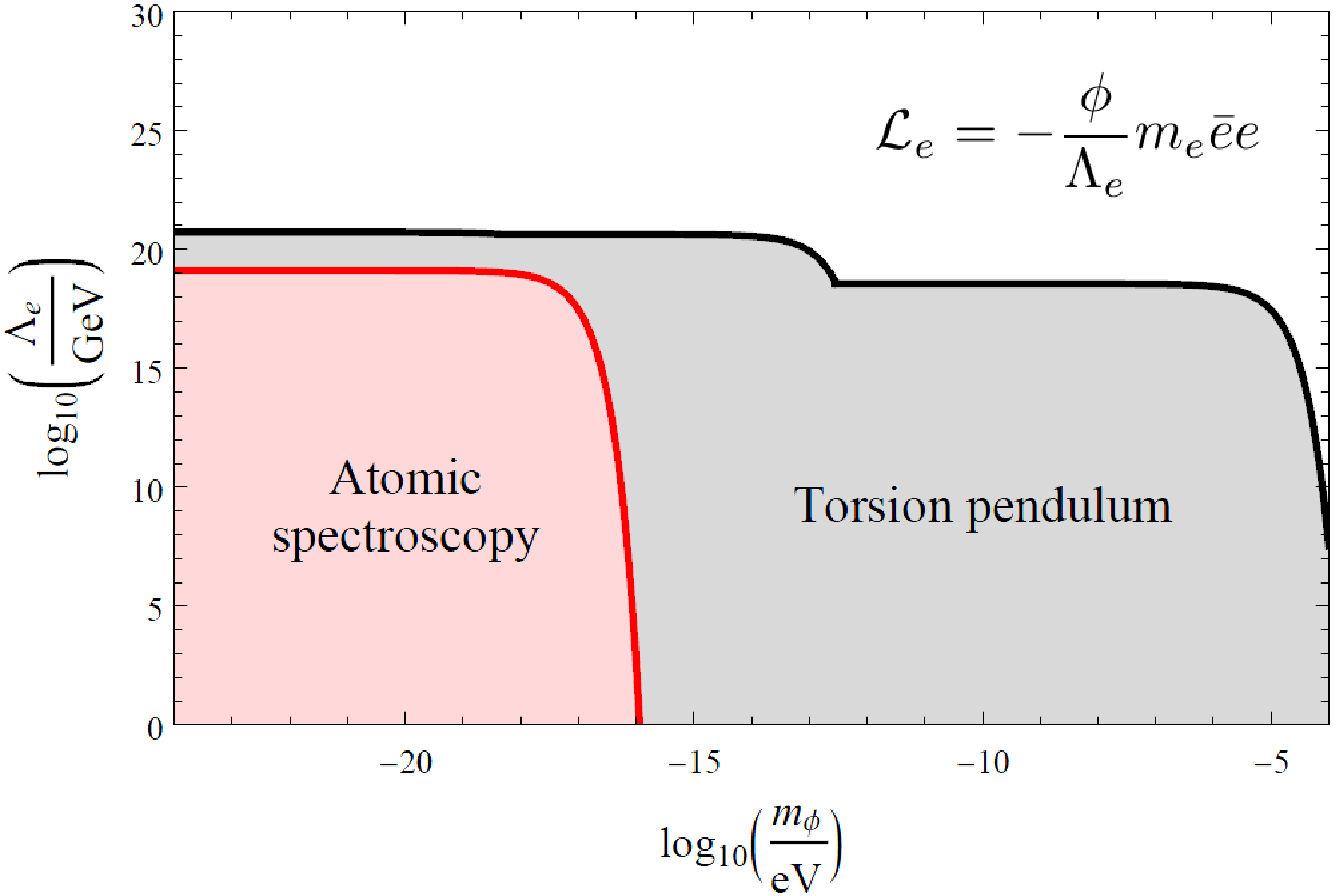
Constraints on Linear Yukawa Interaction of a Scalar Boson with the Photon

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]



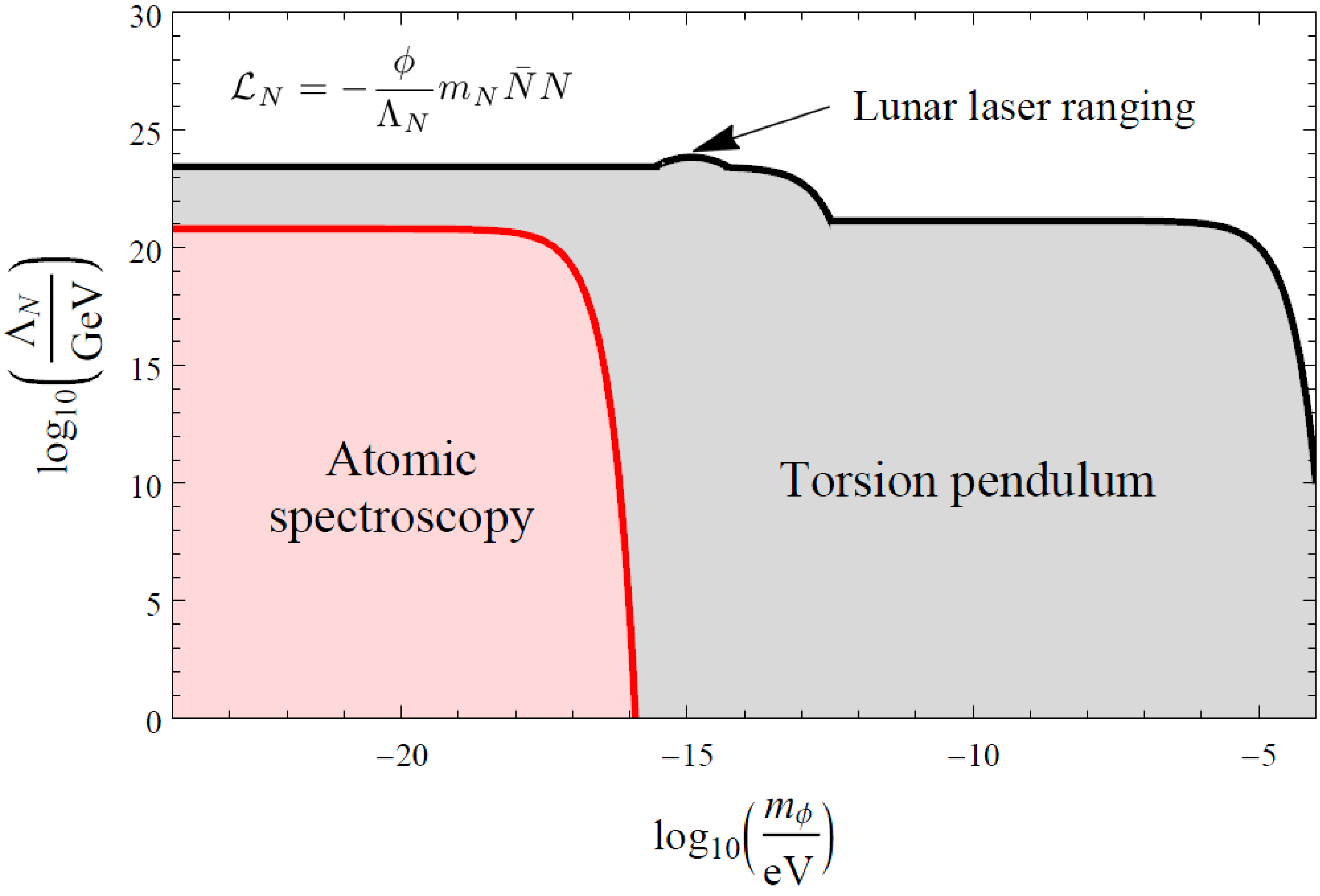
Constraints on Linear Yukawa Interaction of a Scalar Boson with the Electron

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]



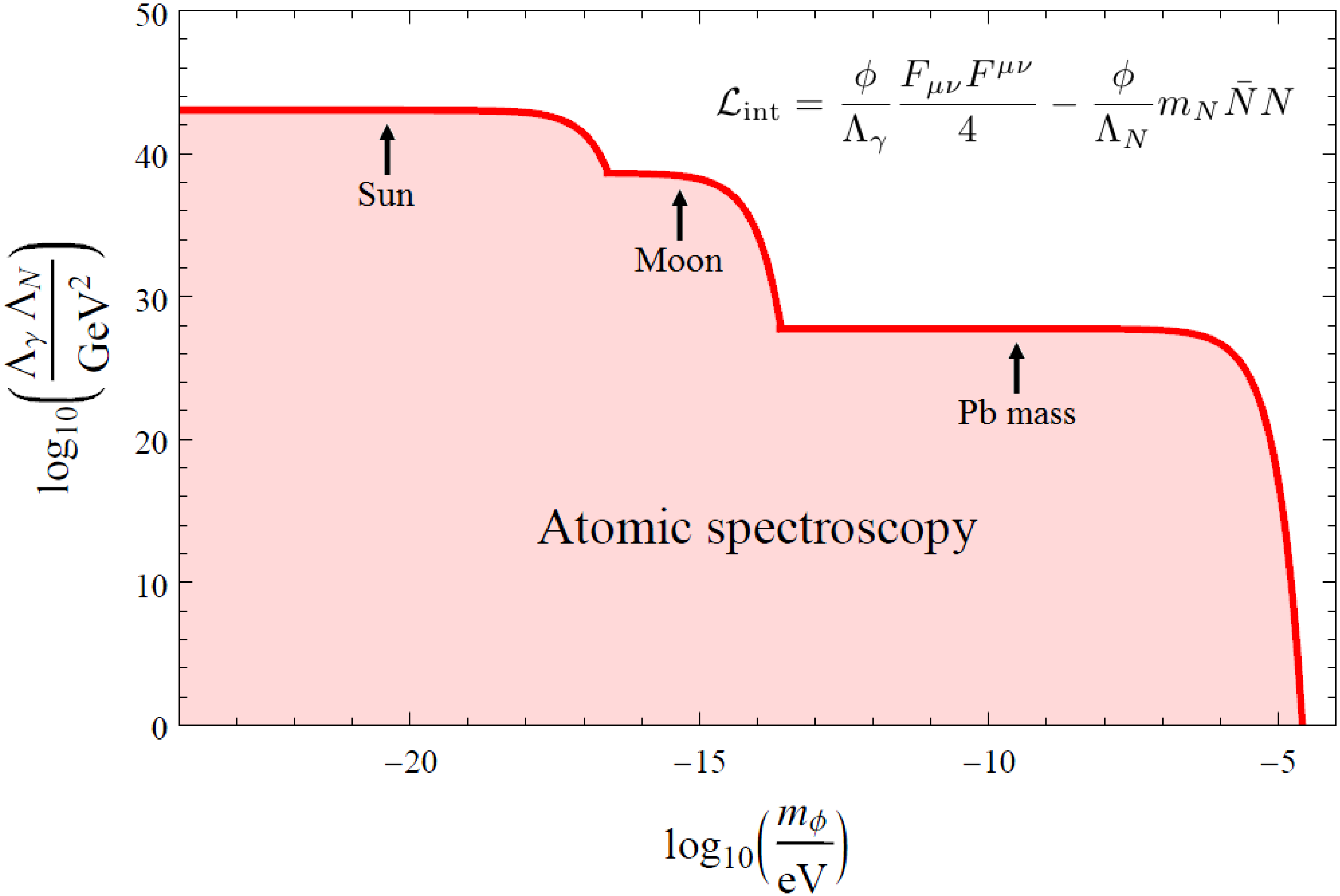
Constraints on Linear Yukawa Interaction of a Scalar Boson with the Nucleons

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]



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

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]



How to Probe Weaker Interactions?

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]

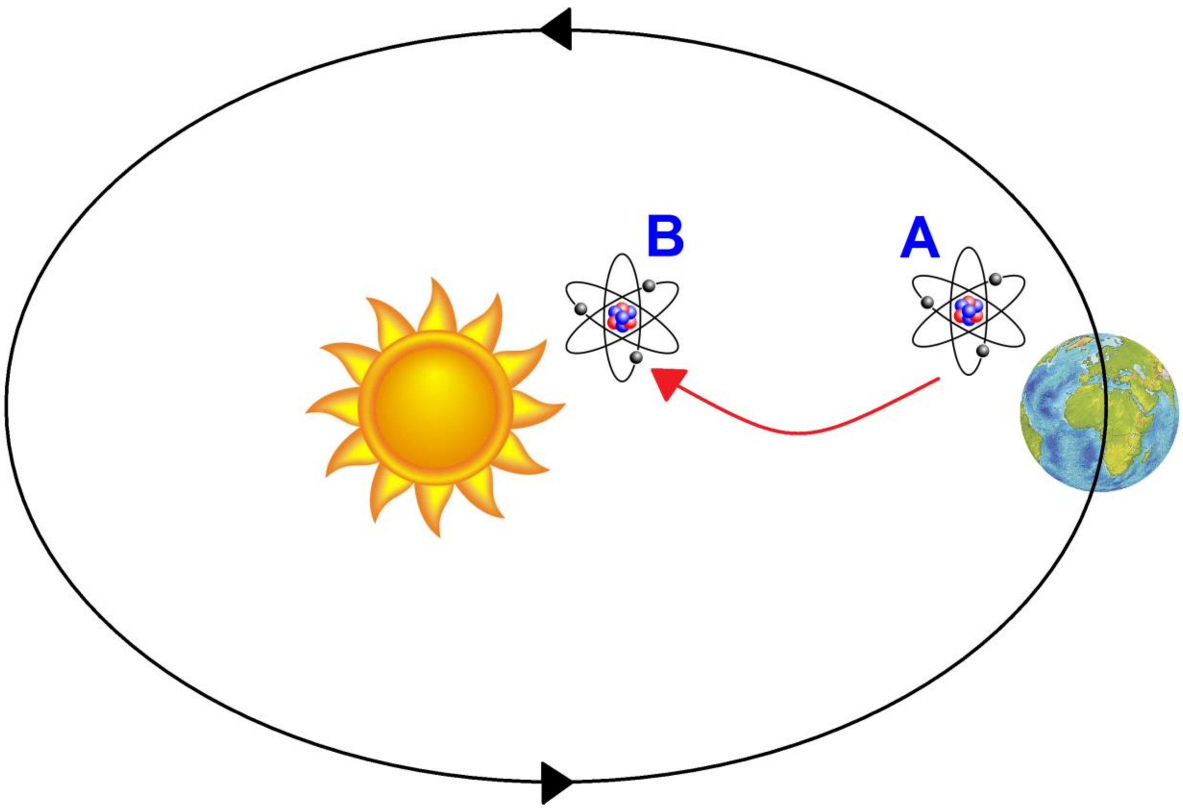
(1) Use different systems in the laboratory.

System	Λ'_γ	Λ'_e	Λ'_p	Λ'_q
Atomic (electronic)	+	-	-	-
Atomic (hyperfine)	+	+	+	+
Highly charged ionic	+	-	-	-
Molecular (rotational/hyperfine)	+	+	+	+
Molecular (fine-structure/vibrational)	+	+	+	+
Molecular (Ω-doubling/hyperfine)	+	+	+	+
Nuclear (e.g., ^{229}Th)	+	-	+	+
Laser interferometer	+	+	+	+

How to Probe Weaker Interactions?

[Leefer, Gerhardus, Budker, Flambaum, Stadnik, arXiv:1607.04956]

(2) Implement different experimental geometries (e.g., the size of the effect may be increased by up to **4 orders of magnitude** by measuring the difference in ω_1/ω_2 in the laboratory and on a space probe incident towards the Sun).



Conclusions

- New classes of dark matter effects that are **linear** in the underlying interaction constant (traditionally-sought effects of dark matter scale as second or fourth power)
- **15 orders of magnitude improvement** on quadratic interactions of scalar dark matter with the photon, electron, and light quarks (u,d)
- Improved limits on linear interaction of scalar dark matter with the Higgs boson
- **First limits** on linear and quadratic interactions of scalar dark matter with the W and Z bosons
- Enormous potential for low-energy experiments with atoms, molecules and ultracold neutrons to search for dark matter with unprecedented sensitivity
- **New results to be published soon!**

Acknowledgements

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Core-polarisation Corrections to *ab initio* Nuclear Shell Model Calculations

[Stadnik, Flambaum, *EPJC* **75**, 110 (2015)]

Minimal model correction scheme:

$$\left(\langle s_p^z \rangle - \langle s_p^z \rangle^0\right) = -\left(\langle s_n^z \rangle - \langle s_n^z \rangle^0\right) = \frac{\mu - \mu^0}{g_p - g_n}$$

Nucleus	Ref.	Ab initio model	$\langle s_n^z \rangle^0$	$\langle s_p^z \rangle^0$	$\langle s_n^z \rangle$	$\langle s_p^z \rangle$
^{125}Te	[69]	Bonn A	0.287	0.001	0.274	0.014
^{125}Te	[69]	Nijmegen II	0.323	−0.0003	0.297	0.026
^{127}I	[69]	Bonn A	0.075	0.309	0.071	0.313
^{127}I	[69]	Nijmegen II	0.064	0.354	0.100	0.318
^{127}I	[70]	Bonn-CD	0.030	0.418	0.108	0.340
^{129}Xe	[69]	Bonn A	0.359	0.028	0.337	0.050
^{129}Xe	[69]	Nijmegen II	0.300	0.0128	0.308	0.005
^{129}Xe	[70]	Bonn-CD	0.273	−0.0019	0.256	0.015
^{131}Xe	[69]	Bonn A	−0.227	−0.009	−0.196	−0.040
^{131}Xe	[69]	Nijmegen II	−0.217	−0.012	−0.187	−0.042
^{131}Xe	[68]	QTDA	−0.236	−0.041	−0.235	−0.042
^{131}Xe	[70]	Bonn-CD	−0.125	−0.00069	−0.122	−0.004
^{133}Cs	[70]	Bonn-CD	0.021	−0.318	−0.076	−0.221

Topological Defect Dark Matter

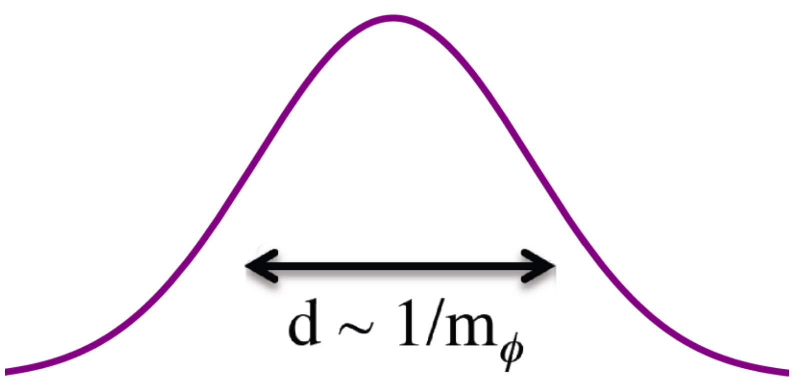
Take a simple scalar field and give it a *self-potential*, e.g., $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable **domain wall** will form in between, e.g., $\varphi(x) = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2} v$.

The characteristic "span" of this object is $d \sim 1/m_\varphi$, and it is carrying energy per area $\sim v^2/d \sim v^2 m_\varphi$. *Networks* of such *topological defects* can *give contributions to dark matter/dark energy* and *act as seeds for structure formation*.

0D object – a *Monopole*

1D object – a *String*

2D object – a *Domain wall*



Topological Defect Dark Matter

Topological defects may have *large amplitude*, *large transverse size* (possibly macroscopic) and *large distances* (possibly astronomical) between them.

=> *Signatures of topological defects are very different* from other forms of dark matter!

Topological defects produce **transient-in-time effects**.

Searching for Topological Defects

Detection of topological defects via transient-in-time effects requires searching for **correlated signals** using a terrestrial or space-based **network of detectors**.

Proposals include:

Magnetometers [Pospelov *et al.*, *PRL* **110**, 021803 (2013)]

Pulsar Timing [Stadnik, Flambaum, *PRL* **113**, 151301 (2014)]

Atomic Clocks [Derevianko, Pospelov, *Nature Physics* **10**, 933 (2014)]

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