A hypothetical effect
of
Maxwell-Proca electromagnetic stresses
on
galaxy rotation curves

D.D. Ryutov, D.Budker, and V.V. Flambaum

Interference-assisted resonance detection of axion

Tran Tan, Flambaum, Samsonov, Stadnik, Budker, arxiv:1803.09388

Axions are produced from photons in magnetic field B_1, photons and axions travel to detection area where they are captured by an atom. Interference between the axion and photon capture amplitudes is the first order effect in the axion-electron interaction constant g_{ae}.

M0 transition $J^P=0^+ - 0^-$ is forbidden for photons, allowed for axions. Weak magnetic field B_2 mixes state 0^- with 1^-, opens the transition for photons and allows the interference.

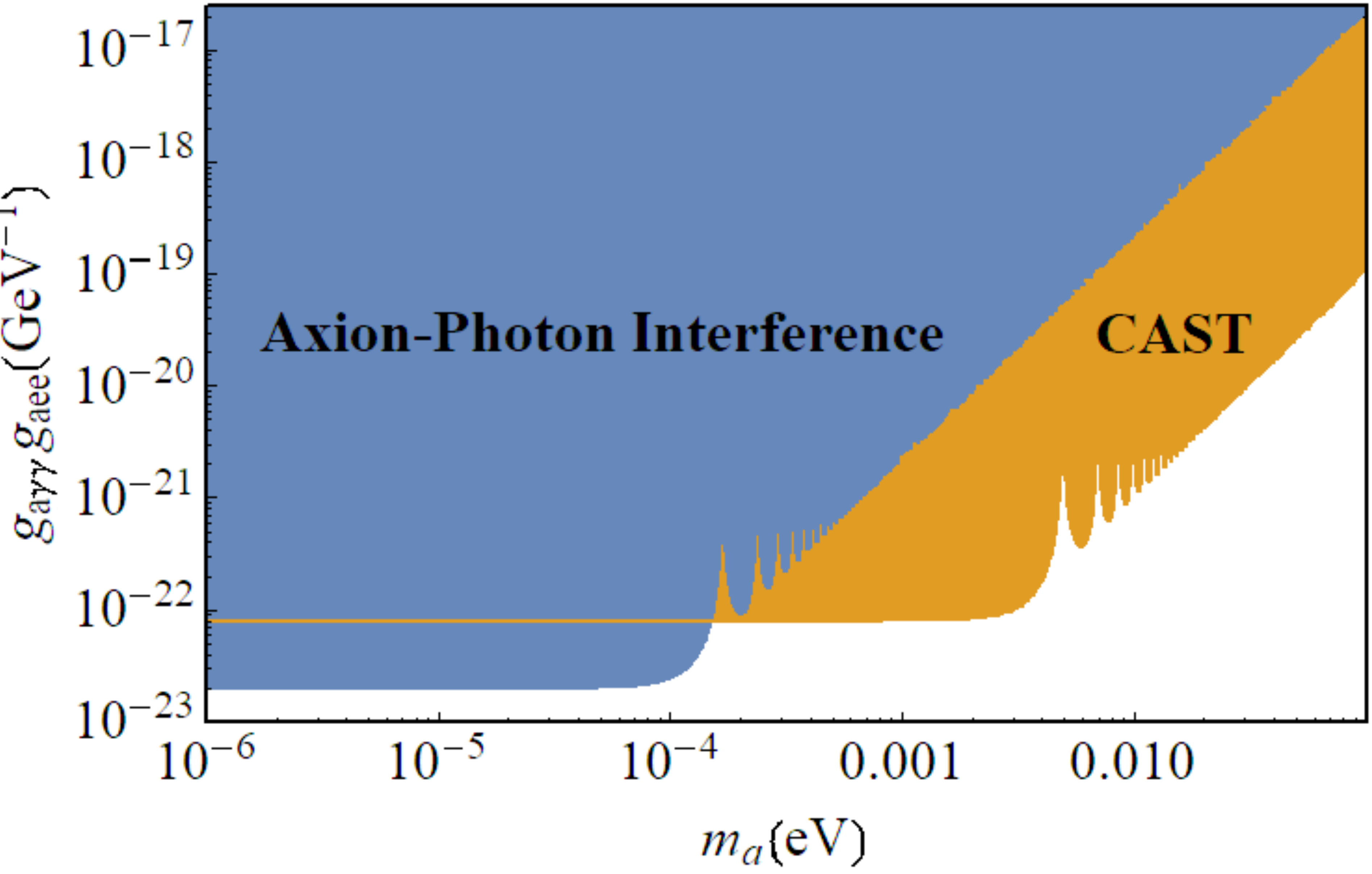
To separate the interference term

change sign of B_1 in the axion production area or change sign of B_2 in the axion capture area. The interference term changes sign.

The interference in M1 transitions may be even better than in M0. Both photon and axion amplitudes are allowed, however the axion amplitude in M1 is ~1/alpha=137 times larger than in M0. Shining through a semi-transpared wall to suppress the photon beam and increase the ratio axion/photon capture amplitudes.

The interference method may be competitive for axion mass

$m_a < 10^{-4}$ eV


Axion-Photon Interference
CAST
$g_{a\gamma\gamma} g_{aee} (\mathrm{GeV}^{-1})$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-6}
10^{-5}
10^{-4}
0.001
0.010
$m_a(\mathrm{eV})$

M0: Ca, Sr, Ba, Hg, Yb, Ne, Ar, Kr, Xe

M1: Tl, Pb, Bi,⋯

Heterodyne detection: wall completely absorbs photons from the first laser (which created axions), use interference with a second laser of a slightly different frequency. Beats in the interference term. Separation of the first harmonic in the beat frequency kills the photon signal, i.e. only the interference term survives.

Coherent axion-photon transformation in the forward scattering on atoms

Flambaum, Samsonov, Budker, arxiv: 1805.01793

Forward scattering is always coherent, production or capture of axions is proportional to L^2 , L is the length, similar to the production or detection of axions in magnetic field. We calculated effective magnetic and electric fields for the photon-axion transformation in M0 and M1 atomic transitions, $L_{eff}=g_{ae}a(EB_{eff}+BE_{eff})$

Effect of photon mass on Galaxy rotational curve instead of dark matter

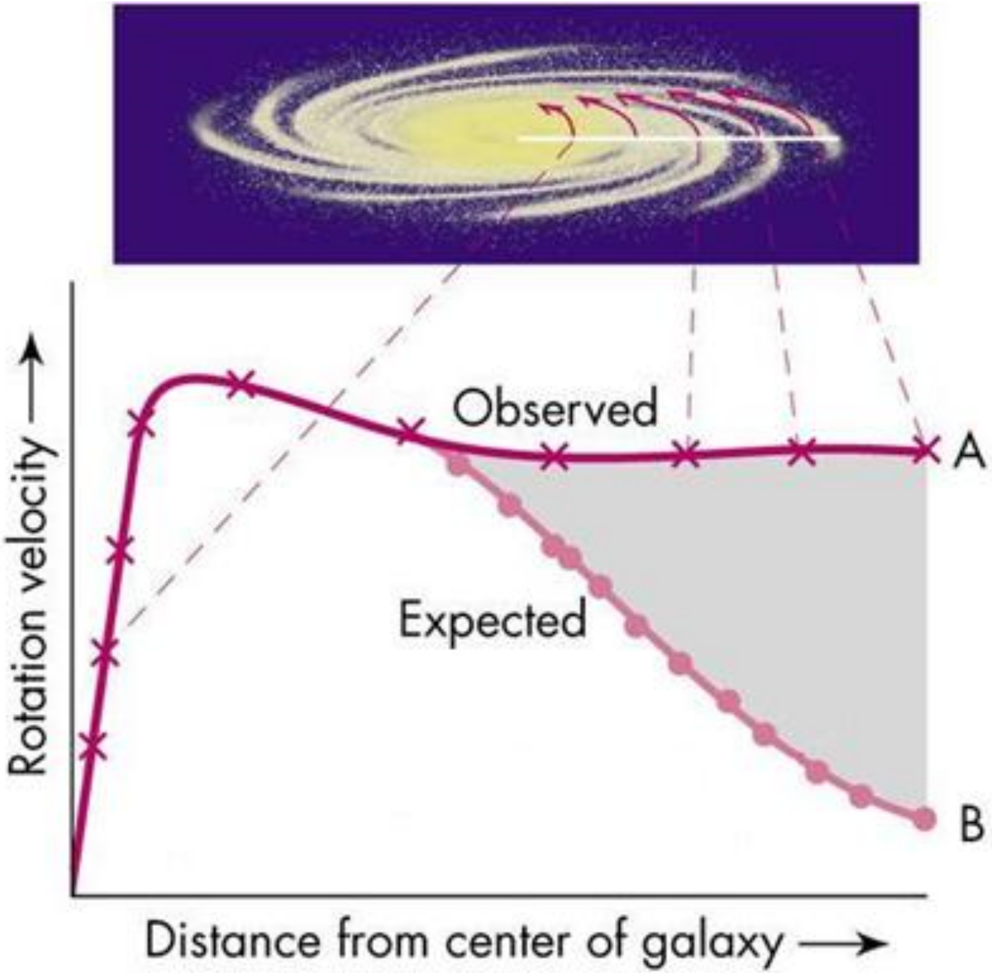
- *Negative pressure inside Galactic plasma* $p= -\varepsilon/3$ (similar to dark energy). Magnetic force imitates gravity!

A hypothetical effect of Maxwell-Proca electromagnetic stresses on galaxy rotation curve

D.Ryutov, D. Budker, V.Flambaum, arxiv:1708.09514

Motivation

Studies of galactic rotation curves (Zwicky 1930s; Rubin *et al.* 1970s)



Effect of Photon Mass on Galaxies?

Key points:

- **Sufficiently strong forces to explain galactic rotation curves without dark matter**
- **The effect of mass is through Magnetic HydroDynamics (MHD)**

Maxwell-Proca Equations

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t};$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A};$$

$$\nabla \times \boldsymbol{B} + \frac{\boldsymbol{A}}{\lambda\!\!\!^{-}{}^2} = \frac{4\pi}{c}\boldsymbol{j} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t};$$

$$\nabla \cdot \boldsymbol{E} + \frac{\varphi}{\lambda\!\!\!^{-}{}^2} = 4\pi\rho;$$

Quasistatic case $\nabla \cdot A = 0$

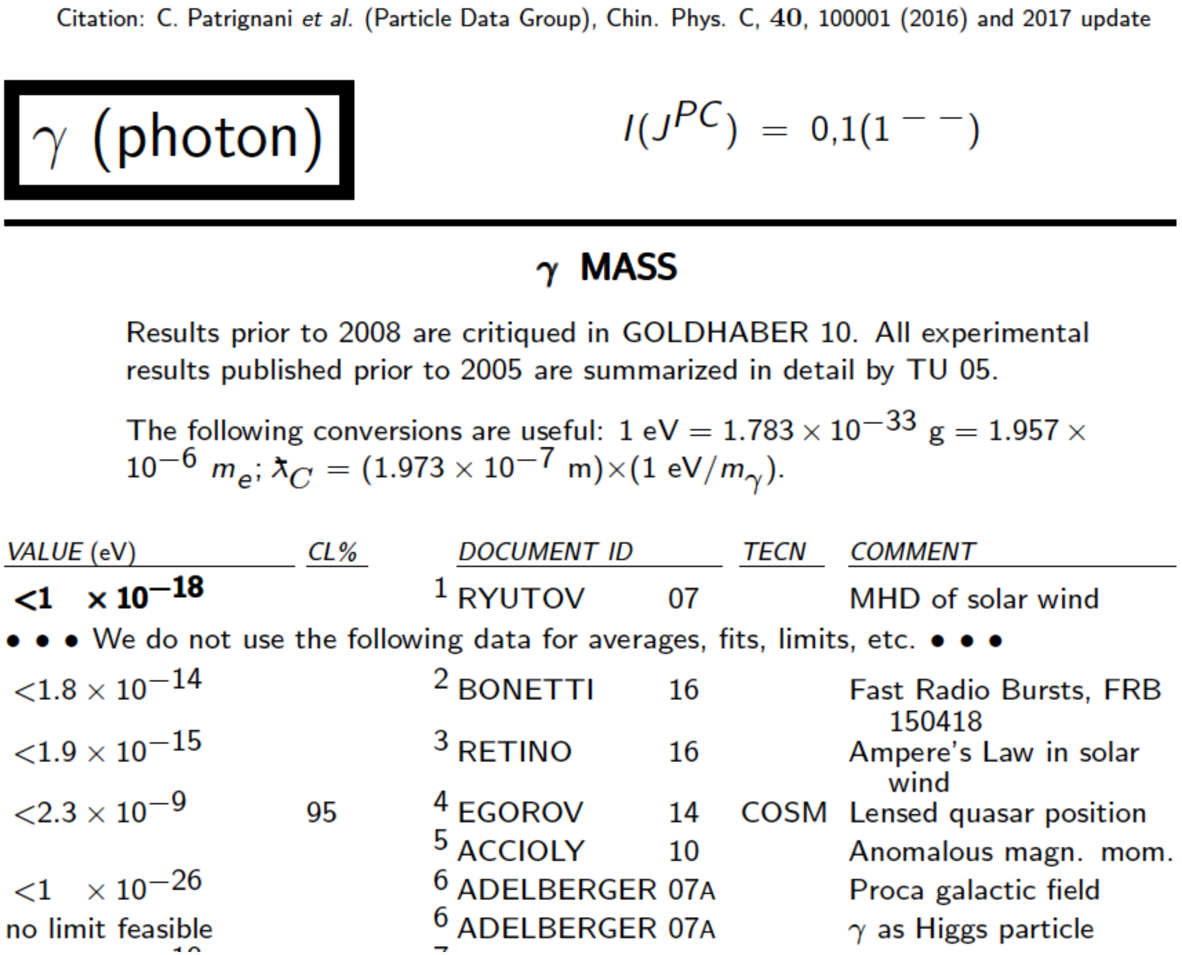
No gauge invariance! Vector-potential is defined by the Maxwell-Proca equations

Effect of photon mass on Galaxy rotational curve instead of dark matter

D.Ryutov, D. Budker, V.Flambaum, arxiv:1708.09514

- **Slowly varying random magnetic field B permeates Galactic plasma, $B \sim A/L$, A is the vector potential, L is the correlation length.**
- **Maxwell-Proca equation for photon with mass m:**
  $\mathrm{curl}\, B + m^2 A = j$, $B = \mathrm{curl}\, A$
- **Lorentz force**
  $j \times B = -(B \times \mathrm{curl}\, B) + m^2 (A \times \mathrm{curl}\, A)$, note opposite sign for mass term
- **Maxwell stress tensor:**
  energy density $T_{00} = \varepsilon = (B^2 + m^2 A^2)/2 = B^2(1 + m^2 L^2)/2$
- **Space components averaged over directions:**
  pressure $T_{ii} = p = (B^2 - m^2 A^2)/6 = B^2(1 - m^2 L^2)/6$
- **If $m=0$ then $p = \varepsilon/3$, usual relation for massless particles**
- **$m^2 L^2 \gg 1$ *Negative pressure inside plasma* $p = -\varepsilon/3$ (similar to dark energy). Imitates gravity!**

Limit on photon mass



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

γ (photon)

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: $1\ \text{eV} = 1.783\times10^{-33}\ \text{g} = 1.957\times10^{-6}\ m_e$; $\bar{\lambda}_C = (1.973\times10^{-7}\ \text{m})\times(1\ \text{eV}/m_\gamma)$.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1\times10^{-18}$		[1] RYUTOV 07		MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.8\times10^{-14}$		[2] BONETTI 16		Fast Radio Bursts, FRB 150418
$<1.9\times10^{-15}$		[3] RETINO 16		Ampere's Law in solar wind
$<2.3\times10^{-9}$	95	[4] EGOROV 14	COSM	Lensed quasar position
		[5] ACCIOLY 10		Anomalous magn. mom.
$<1\times10^{-26}$		[6] ADELBERGER 07A		Proca galactic field
no limit feasible		[6] ADELBERGER 07A		γ as Higgs particle

Effect of photon mass on Galaxy rotational curve instead of dark matter

D.Ryutov, D. Budker, V.Flambaum, arxiv:1708.09514

- Slowly varying random magnetic field **B permeates Galactic plasma, B=A/L, A is the vector potential, L is the correlation length.**
- Maxwell equation for photon with mass m: **curl B+m^2A=j, B=curl A**
- Lorentz force **jxB= -(B x curl B)+m^2(A x curl A)**, opposite sign for mass term
- Maxwell stress tensor: **energy density T_{00} =ε=(B^2+m^2A^2)/2= B^2(1+m^2L^2)/2**
- Space components averaged over directions: **pressure T_{ii}=p= (B^2−m^2A^2)/6=. B^2(1−m^2L^2)/6. If m=0 then p= ε/3, usual relation for massless particles**
- m^2L^2=600 to reproduce Galaxy rotation curve.
- *Negative pressure inside plasma* p= -ε/3 **(similar to dark energy). Gradient of pressure produces attraction towards Centre of the Galaxy and Galaxy plane,** imitates gravity.
- Small photon mass m instead of dark matter? **Data L=10 pc and m^2L^2=600 give photon mass m=10^{-23} eV, 5 orders of magnitude smaller than the limit on m**
- Magnetic field is everywhere in the Universe − cosmological effects
- **Tully-Fisher relation − velocity is determined by barionic matter**

Effect of photon mass on Galaxy rotational curve instead of dark matter

- *Negative pressure inside plasma* $p= -\varepsilon/3$ (similar to dark energy). Gradient of pressure produces attraction towards Centre of the Galaxy and Galaxy plane, imitates gravity.
- Small photon mass m instead of dark matter?
  Data for Galactic magnetic field give correlation length L=1- 10 pc.
  We need $m^2L^2=600$ to reproduce Galaxy rotation curve.
  This gives photon mass $m=10^{-24}$ eV, 6 orders of magnitude smaller than the current limit on the photon mass $m < 10^{-18}$ eV
- Magnetic field is everywhere in the Universe – cosmological effects
- Tully-Fisher relation – rotation velocity V in different galaxies is function of total barionic mass M (sum of gas and stars), $M= \text{const}\ V^x$, x=3.5- 4. Different from Kepler law, there is an extra contribution to the attractive force.
  Mass of dark matter is a function of barionic mass M?
  Non-gravitational contribution to the attraction (the effect of photon mass)?

Effects of Dark Matter in atomic phenomena: Variation of the Fundamental Constants and Violation of Fundamental Symmetries

Y. Stadnik, V. Flambaum, et al.

Physical Review Letters 120, 0132024 (2018)

Physical Review Letters **119**, 223201 (2017)

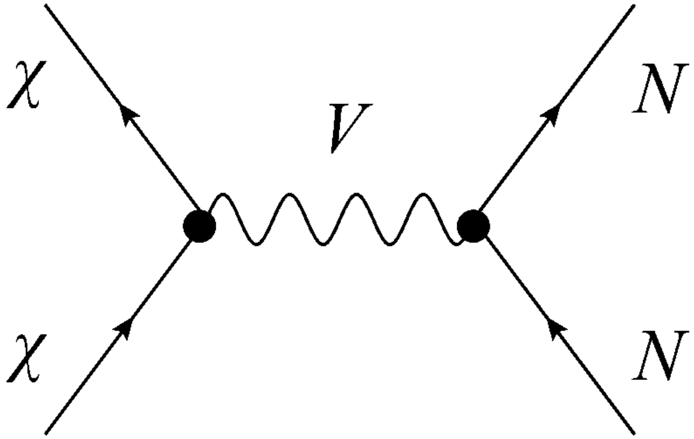
Physical Review Letters **118**, 142501 (2017)

Physical Review Letters **116**, 023201 (2016)
Physical Review Letters **117**, 271601(2016)

Physical Review Letters **115**, 201301 (2015)
Physical Review Letters **114**, 161301 (2015)
Physical Review Letters **113**, 151301 (2014)
Physical Review Letters **113**, 081601 (2014)
Physical Review D **89**, 043522 (2014)
Physical Review D **90**, 096005 (2014)

Motivation

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



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

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

Problem: Observable is **quartic** in the interaction constant e’, which is extremely small (e1 << ’)! We consider **linear** effects. Enormous advantage!

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 $<\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ GeV/cm^3)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 >> 1$
- Coherent + classical DM field = **"Cosmic maser"**
- 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)
- 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 **linear** in the interaction constant κ:

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

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

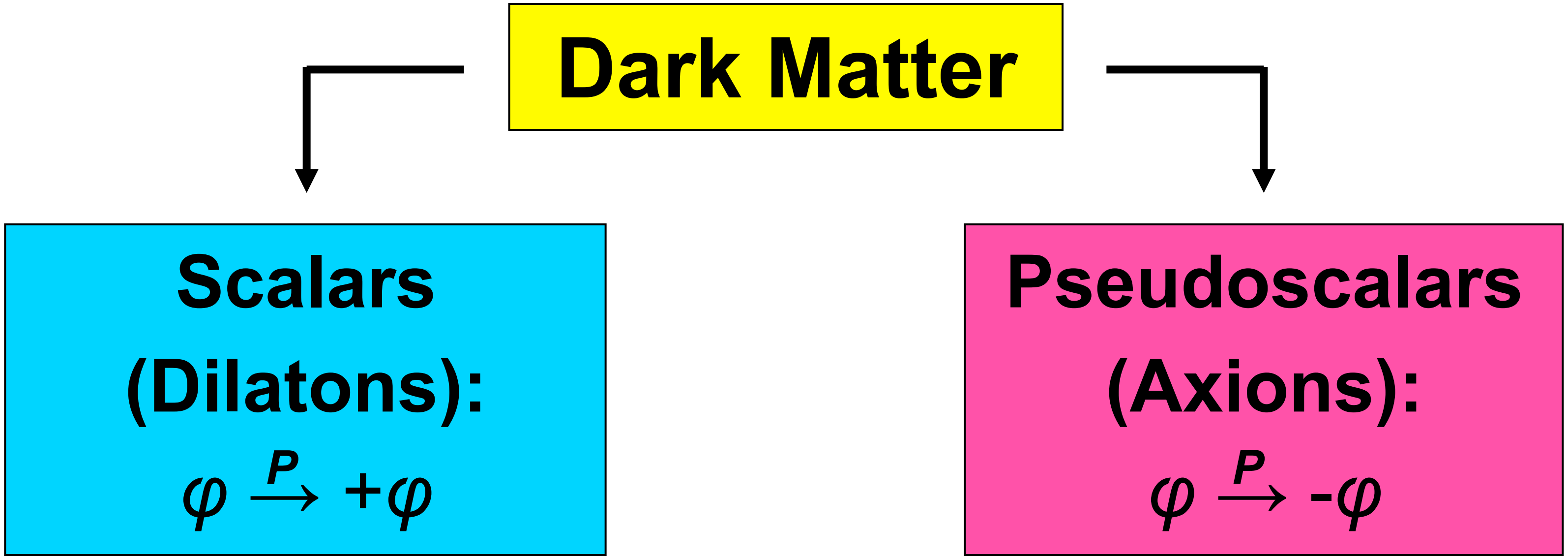
Coherence of Galactic DM

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 a finite coherence time and finite coherence length. Scalar “maser”.

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

$$l_{\mathrm{coh}} \sim \frac{1}{m_\phi v_{\mathrm{vir}}} \sim \frac{10^3}{m_\phi} = \frac{10^3}{2\pi} \lambda_{\mathrm{Compton}}$$

Low-mass Spin-0 Dark Matter



Dark Matter

Scalars (Dilatons):

$\varphi \xrightarrow{P} +\varphi$

Pseudoscalars (Axions):

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

→ Time-varying fundamental constants

10^{15} improvement

→ Time-varying spin-dependent effects

10^{3} improvement

Evidence for spatial variation of the fine structure constant

$$\alpha = e^2/2\varepsilon_0 hc = 1/137.036$$

Quasar spectra

Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

$$\alpha(x) = \alpha(0) + \alpha'(0)\, x + \ldots$$

$x = r\cos(\phi)$, $r = ct$ – distance (t - light travel time, c - speed of light)

Reconciles all measurements of the variation

Results for variation of fundamental constants: Clocks comparison

Source	$\mathrm{Clock}_1/\mathrm{Clock}_2$	$d\alpha/dt/\alpha(10^{-16}\,\mathrm{yr}^{-1})$
Godun *et al*, 2014	Yb+opt/Yb+/Cs(hfs)	-0.07(0.21)
Leefer *et al* 2013	Dy/Cs(hfs)	-0.6(0.7)
Rosenband *et al*08	Hg+(opt)/Al+(opt)	-0.16(0.23)
Huntemann *et al*14	Yb+opt/Yb+/Cs(hfs)	-0.2(0.2)
Guena *et al*, 2012	Rb(hfs)/Cs(hfs)	3(2)[a]

[a] **assuming $m_{q,e}/\Lambda_{QCD} = Const$**

Combined results: $d/dt \ln\alpha = -1.5(1.0) \times 10^{-17}\,\mathrm{yr}^{-1}$

$d/dt \ln(m_q/\Lambda_{QCD}) = 7(4) \times 10^{-15}\,\mathrm{yr}^{-1}$

m_e/M_p **or** m_e/Λ_{QCD} $-0.1(1.0)\times 10^{-16}$ **yr**

-1

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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.

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

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

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

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, and V.F. *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)]

Fermions:

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

Photon:

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

W and *Z* Bosons:

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

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Fermions:

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

Photon:

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

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

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

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

[Stadnik, and V.F., *PRL* **115**, 201301 (2015)]

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

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

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

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

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

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

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

[Stadnik and V.F., *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, $\sigma_{Thomson} = 8\pi\alpha^2/3m_e^2$, changing the mean-free-path length of photons at recombination and leaving distinct signatures in the CMB angular power spectrum.

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

We performed calculations to link change of atomic transition frequencies to change of fundamental constants:

optical transitions: <u>atomic calculations</u>
for quasar absorption spectra and for
atomic clocks transitions in Al II, Ca I, Sr I,
Sr II, In II, Ba II, Dy I, Yb I, Yb II, Yb III, Hg I,
Hg II, Tl II, Ra II, Th III, highly charged ions,

$$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$$

Nuclear clock ^{229}Th ,

Microwave transitions: hyperfine frequency is sensitive to α , nuclear magnetic moments and nuclear radii.

We performed atomic, QCD and nuclear calculations.

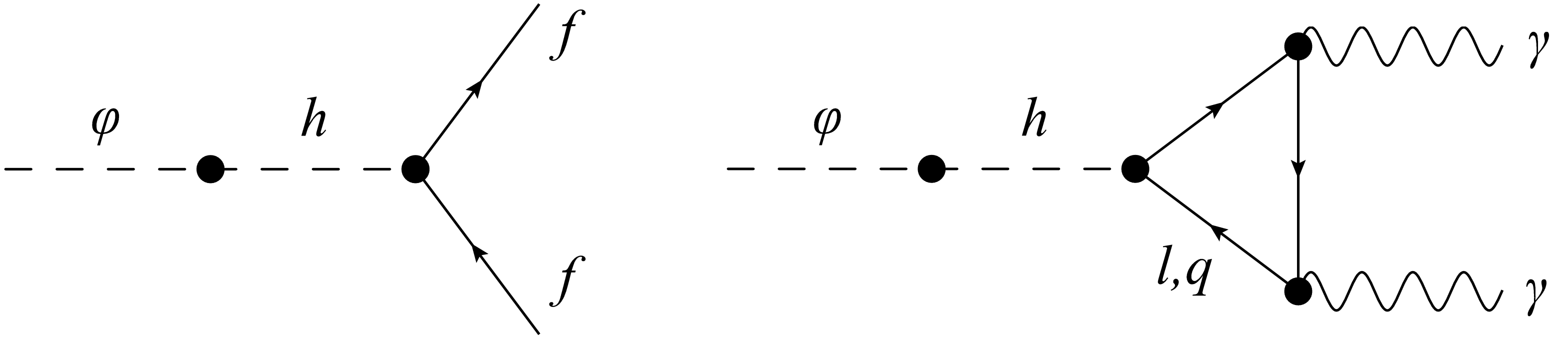
Molecular calculations

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)]:

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



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

* 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 $(A/m_\varphi)^2 < 2\lambda$.

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:

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

Non-relativistic atomic unit of frequency

Relativistic factor

Effects of Varying Fundamental Constants on Atomic Transitions

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Dzuba, Flambaum, Marchenko, *PRA* **68**, 022506 (2003); Angstmann, Dzuba, Flambaum,
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- Atomic optical transitions:

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

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

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,
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Thomas,Young, Phys.Rev.D69,115006 (2004).Flambaum,Tedesco,Phys.RevC73,055501(2006).]

- Atomic optical transitions:

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

$K_\alpha(\text{Sr}) = 0.06$, $K_\alpha(\text{Yb}) = 0.3$, $K_\alpha(\text{Hg}) = 0.8$, $K_\alpha(\text{Hg+}) = -3$

Increasing *Z*

- Atomic hyperfine transitions:

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

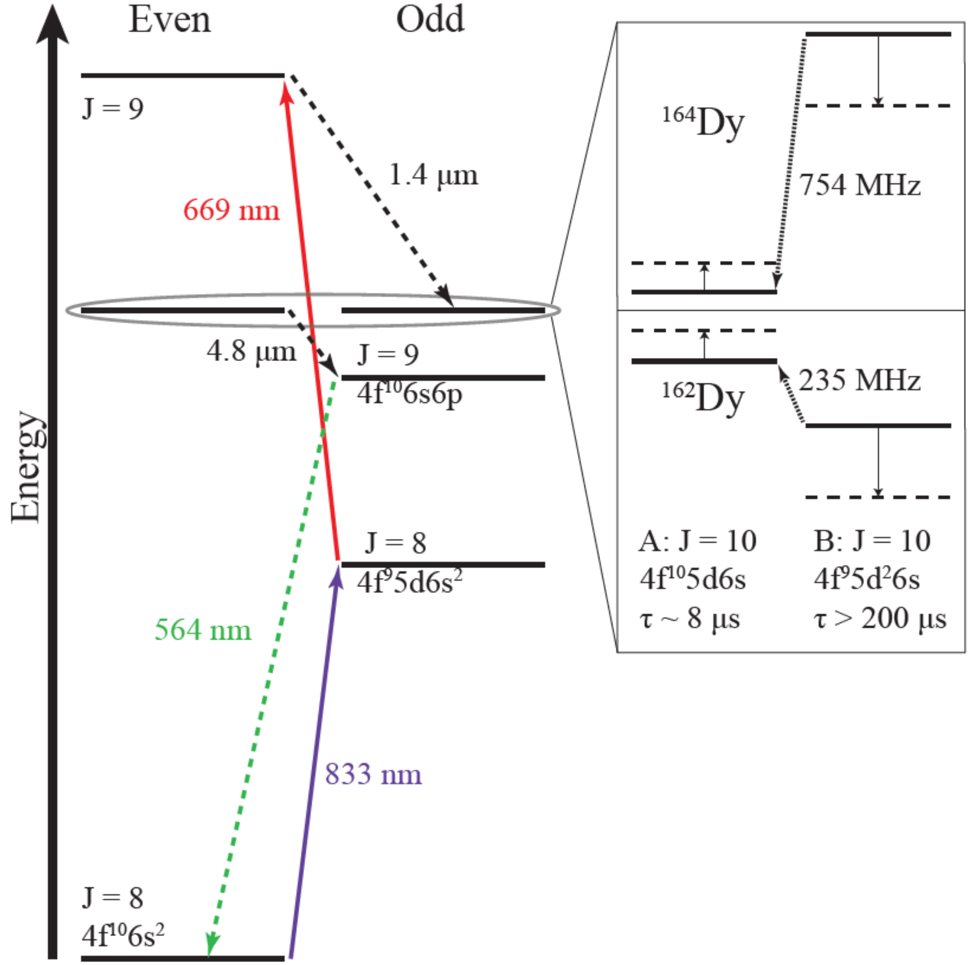
$K_\alpha({}^1\text{H}) = 2.0$, $K_\alpha({}^{87}\text{Rb}) = 2.3$, $K_\alpha({}^{133}\text{Cs}) = 2.8$ $K_{m_e/m_N} = 1$

Increasing *Z*

Enhanced Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba,Flambaum,Webb,*PRL* **82**,888(1999); Flambaum PRL 97,092502(2006); PRA73,034101(2006); Berengut,Dzuba,Flambaum PRL105,120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels:
  - Atoms (e.g., $|K_\alpha(\text{Dy})| \sim 10^6 - 10^8$
  - Molecules
  - Highly-charged ions
  - Nuclei ^{229}Th



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

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

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Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

$\alpha(x) = \alpha(0) + \alpha'(0)\, x + \ldots$

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Guena *et al*, 2012	Rb(hfs)/Cs(hfs)	3(2)[a]

[a] **assuming** $m_{q,e}/\Lambda_{QCD} = Const$

Combined results: $\frac{d}{dt}\ln\alpha = -1.5(1.0) \times 10^{-17}\ \text{yr}^{-1}$

$\frac{d}{dt}\ln(m_q/\Lambda_{QCD}) = 7(4) \times 10^{-15}\ \text{yr}^{-1}$

m_e/M_p **or** m_e/Λ_{QCD} $\;-0.1(1.0)\times 10^{-16}\ \text{yr}$

-1

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

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik and V.F., *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 portal) or $\omega = 2m_\varphi$ (quadratic portal)

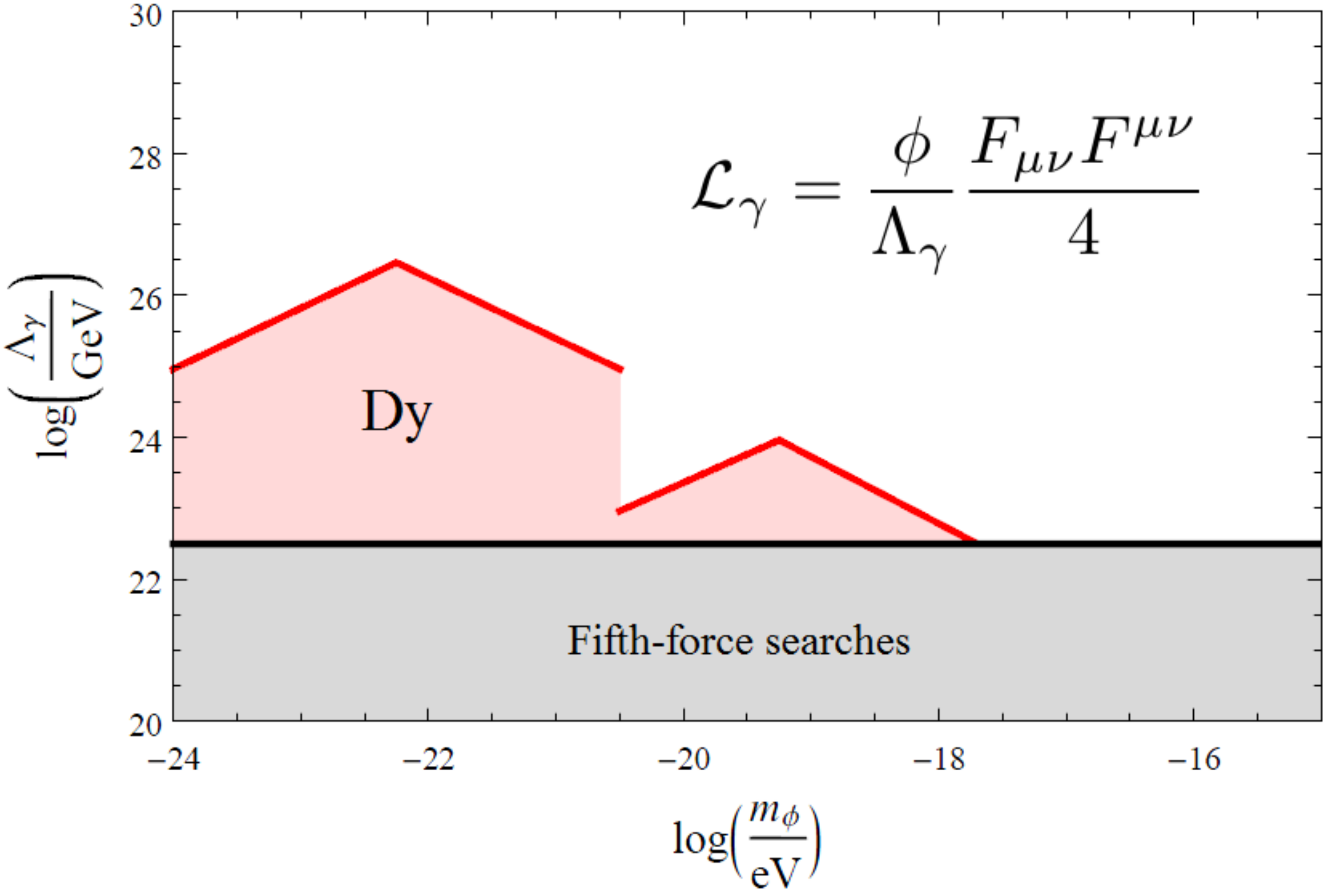
- Precision of optical clocks approaching ~10^{-18} fractional level
- Sensitivity coefficients K_X calculated extensively by our group (1998 – present)

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

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

Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

[Van Tilburg, Leefer, Bougas, Budker, *PRL* **115**, 011802 (2015)]

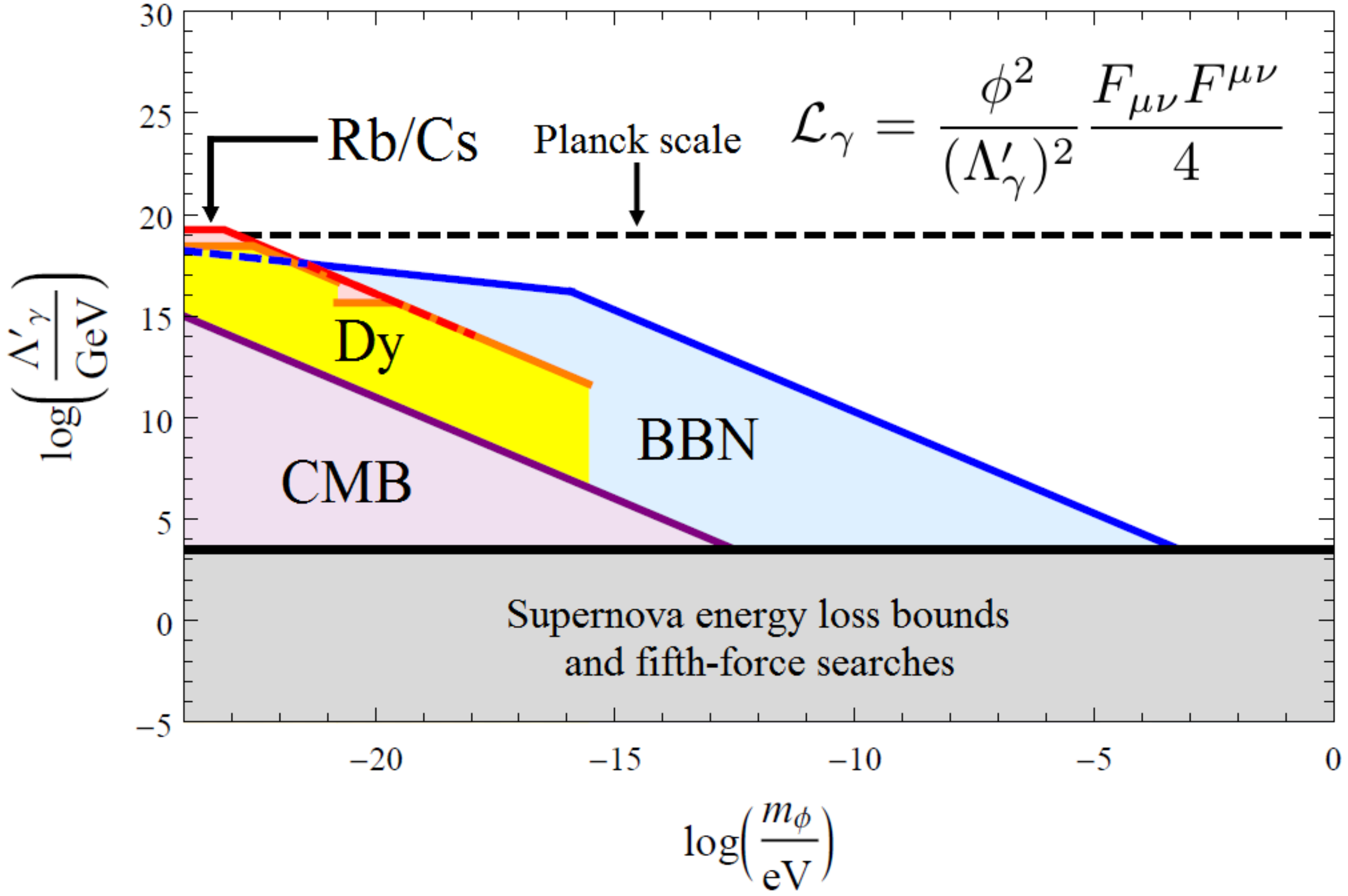


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]

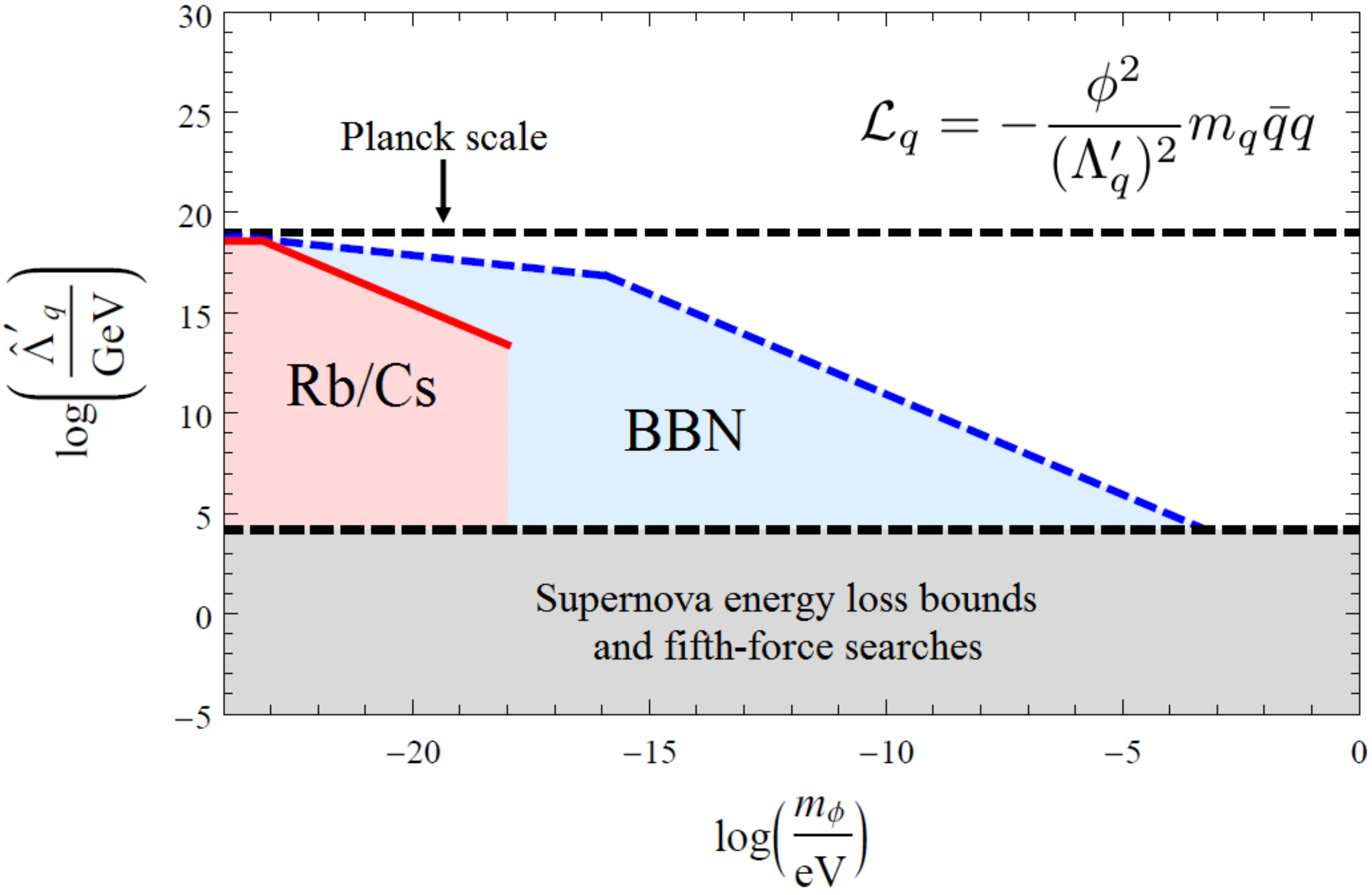
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

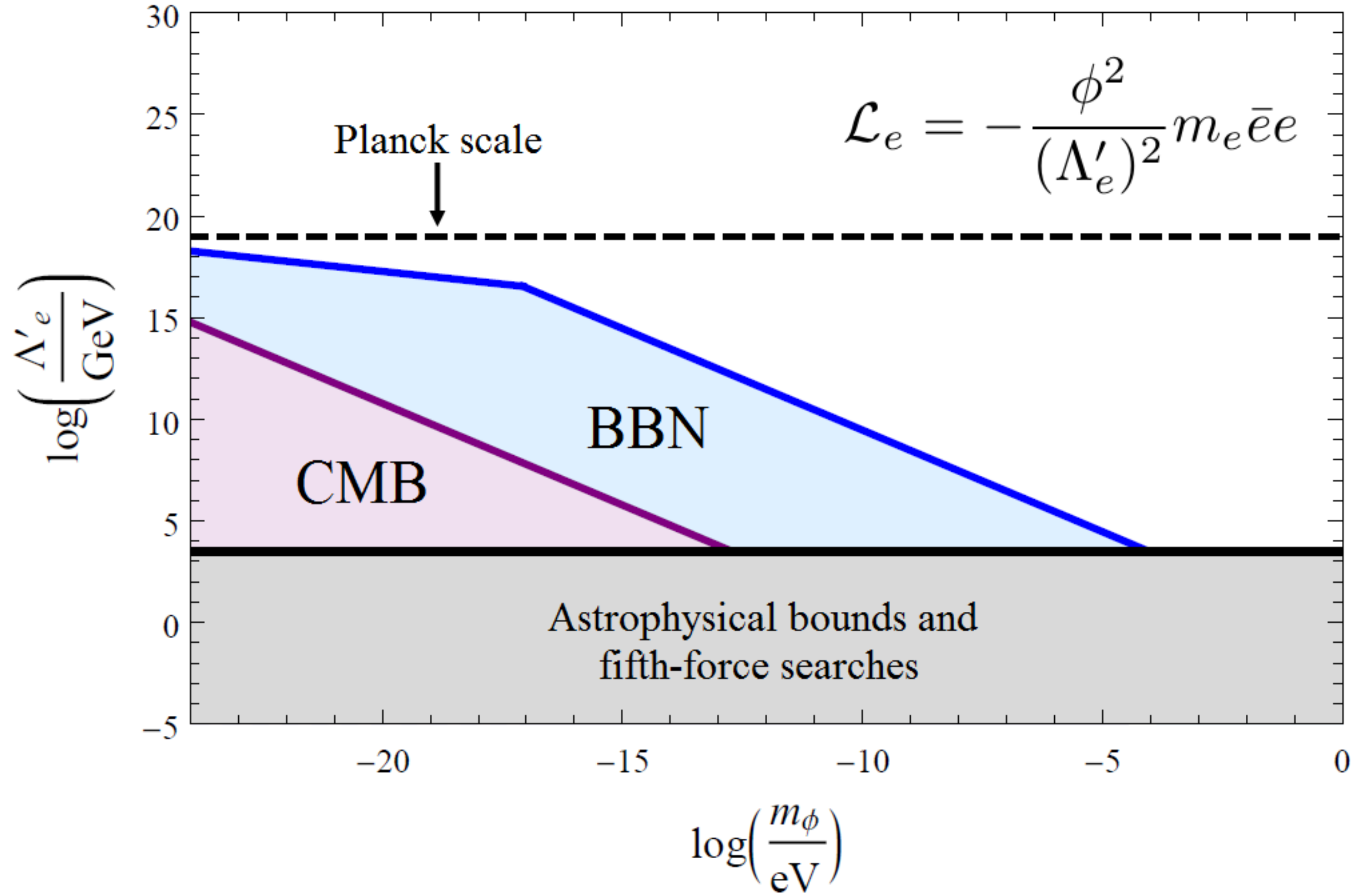
[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

BBN and CMB constraints:

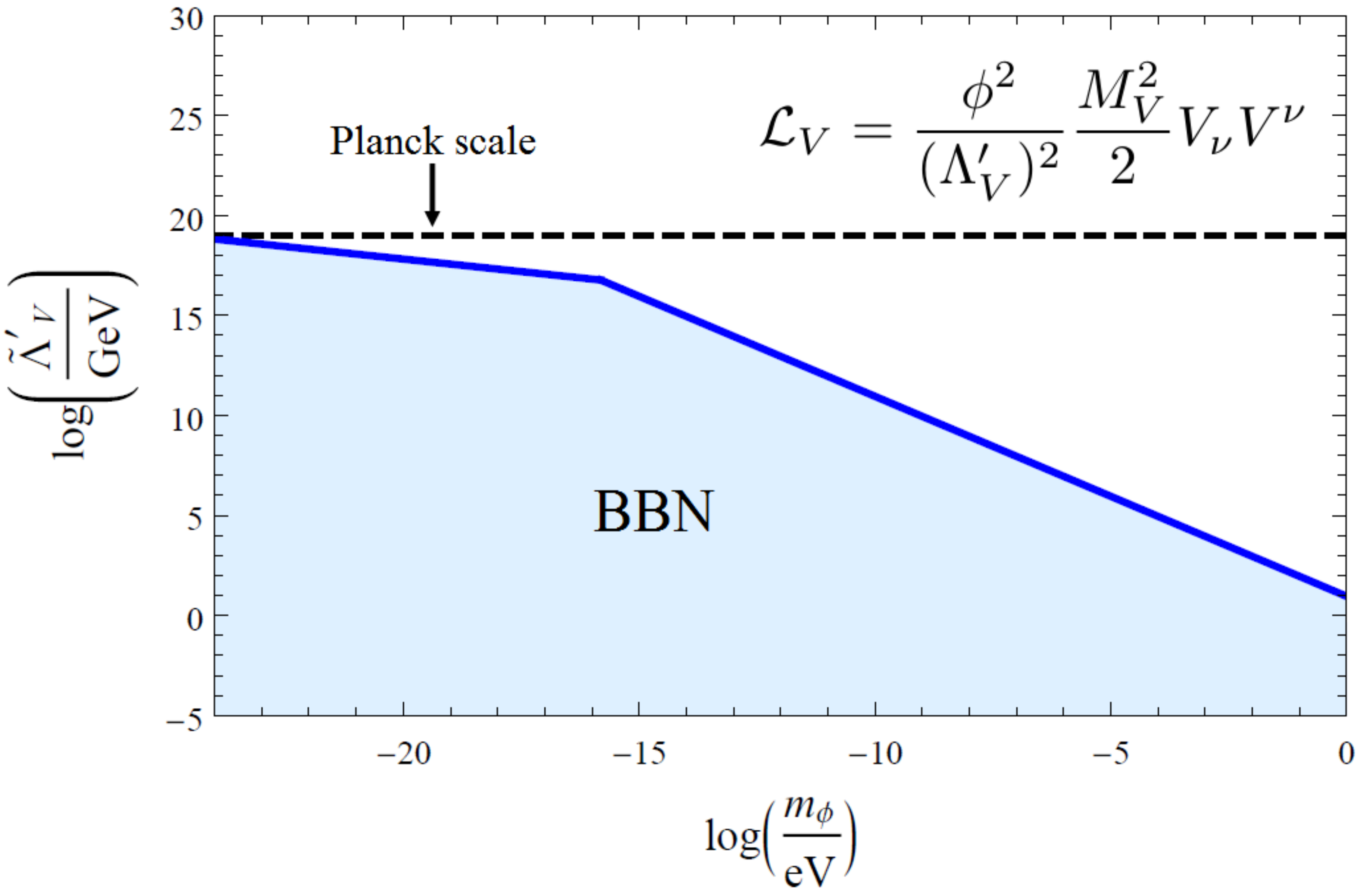
[Stadnik and V.F., *PRL* **115**, 201301 (2015)]



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

BBN constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015)]

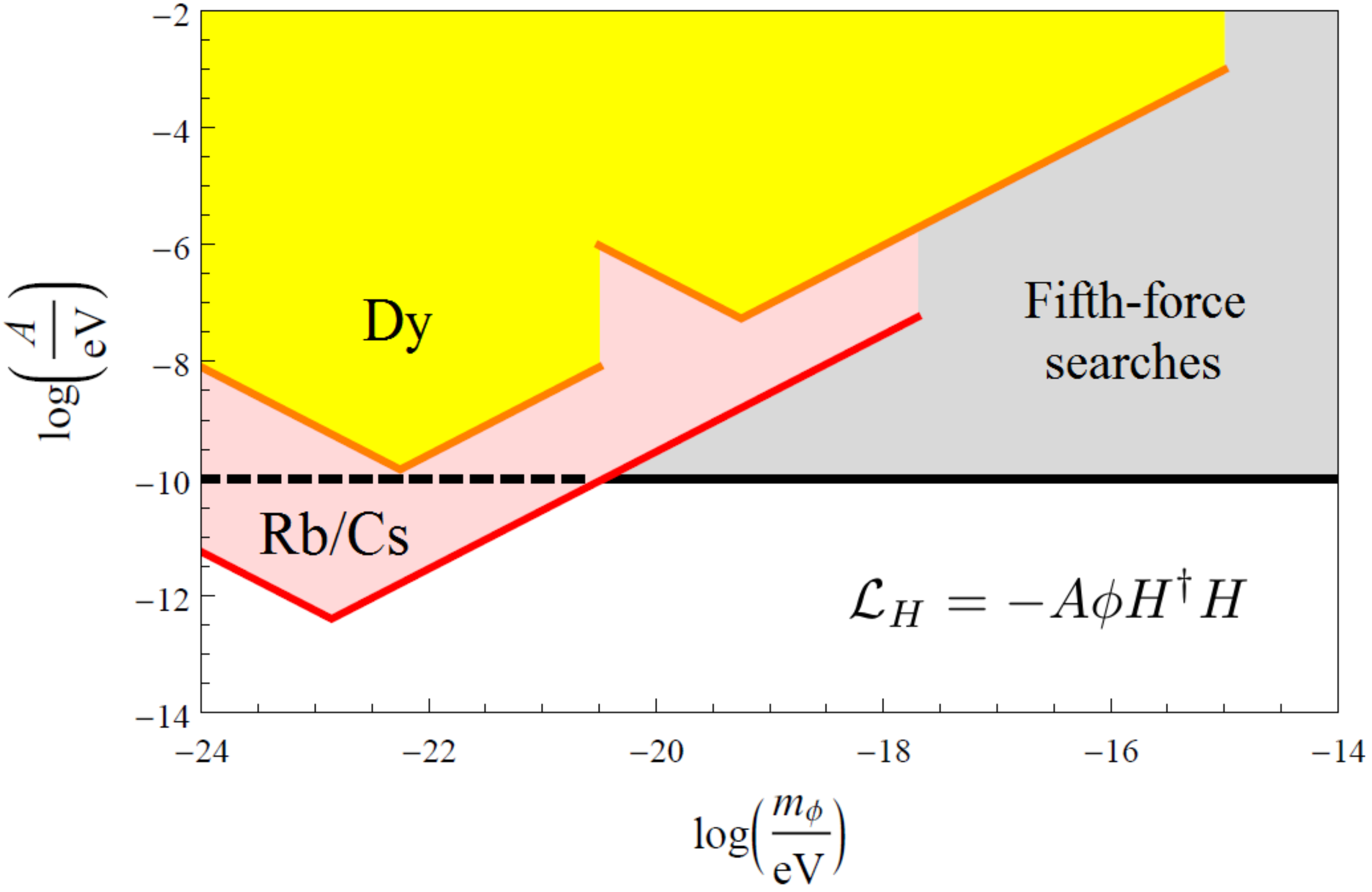


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

[Stadnik and V.F., *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!



Topological Defect Dark Matter

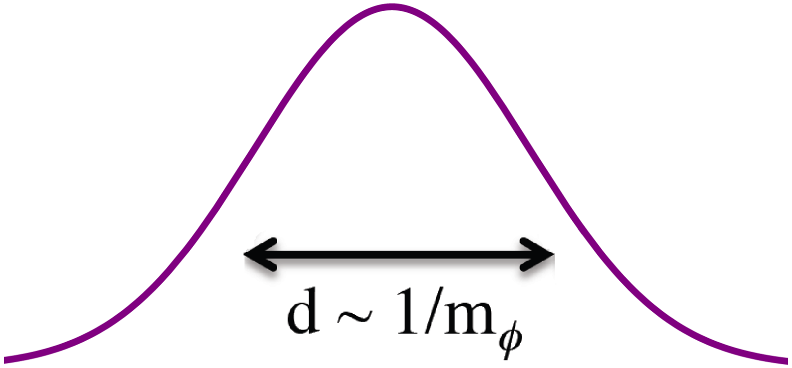
Take a simple scalar field and give it a *self-potential*, e.g. $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable *domain wall* will form in between, e.g. $\varphi = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2} v$.

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*



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**.

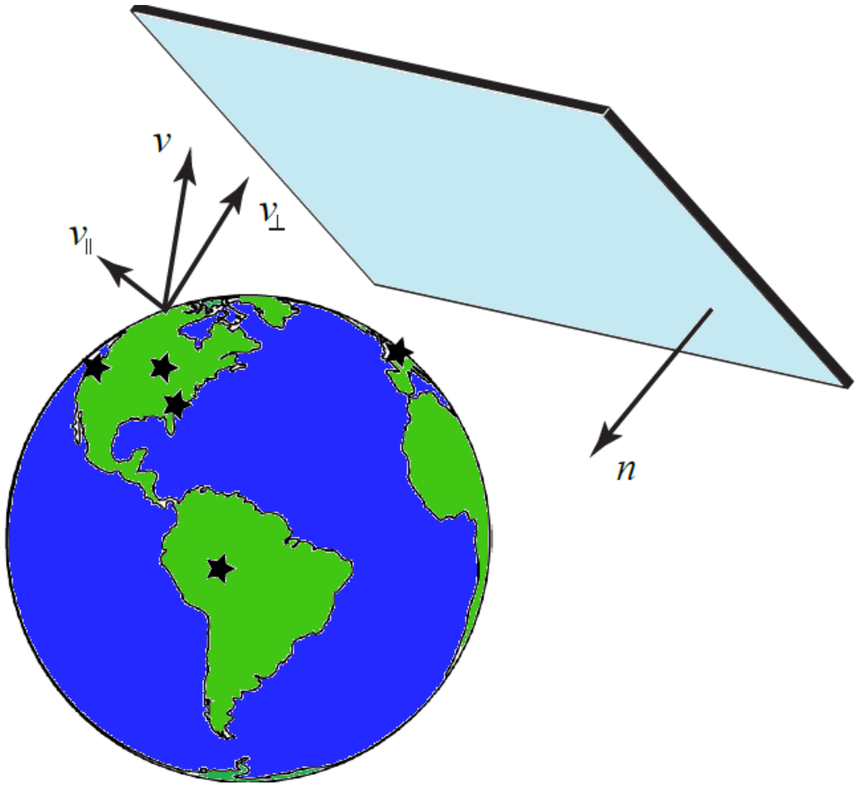
Recent proposals include:

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

Pulsar Timing [Stadnik and V.F, *PRL* **113**, 151301 (2014)]

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

Laser Interferometers [Stadnik and V.F., *PRL* **114**, 161301 (2015); arXiv:1511.00447]

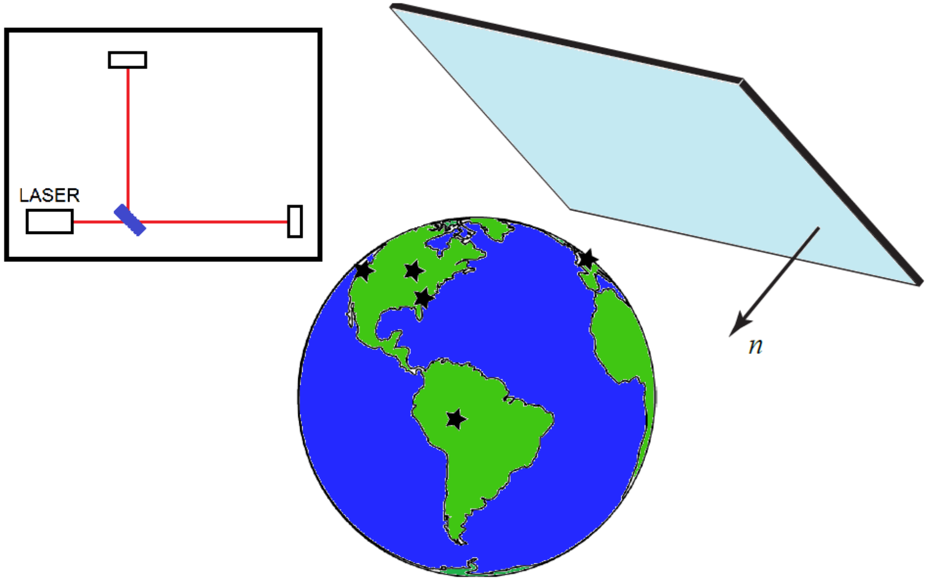


Global Network of Laser/Maser Interferometers (LIGO, Virgo, GEO600, TAMA300)

Stadnik and V.F., Phys. Rev.Lett. 2015 + Ongoing collaboration with LIGO and VIRGO

$$\mathcal{L}^{f}_{\mathrm{int}} = - \sum_{f=e,p,n} m_f \left(\frac{\phi c}{\Lambda'_f} \right)^2 \bar{f} f \qquad \mathcal{L}^{\gamma}_{\mathrm{int}} = \left(\frac{\phi}{\Lambda'_\gamma} \right)^2 \frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

***Topological defects*, which consist of *scalar particles*, *temporarily alter the masses of the electron, proton, neutron and photon*, as well as the *fine-structure constant α*. This may produce a *difference in the phases of light* propagating in the two arms (*Φ = kL*). One can search for defects through *correlated signals* in a *global network of interferometers* ($v_{TD} \sim 10^{-3}\, c$).**



Laser Interferometry (smaller-scale)

[Stadnik and V.F., *PRL* **114**, 161301 (2015); PRA **93**, 063630 (2016)]

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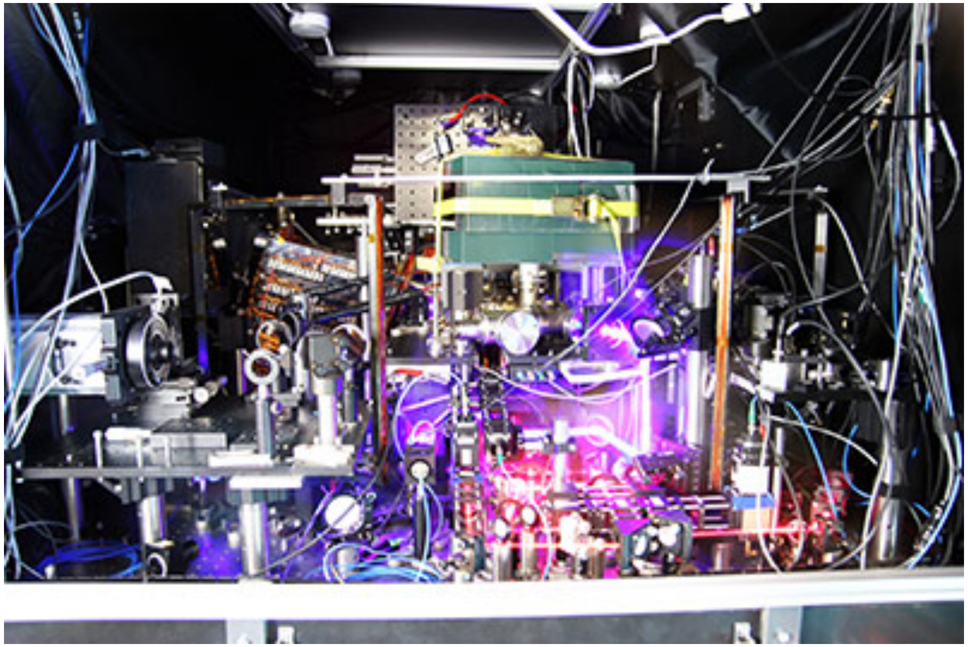
In collaboration with Jun Ye, we propose to use an extremely stable and sensitive optical interferometer consisting of a *strontium lattice clock* and *silicon single-crystal cavity*.



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

[Stadnik and V.F., *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

- Compare $L \sim Na_B$ with λ

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

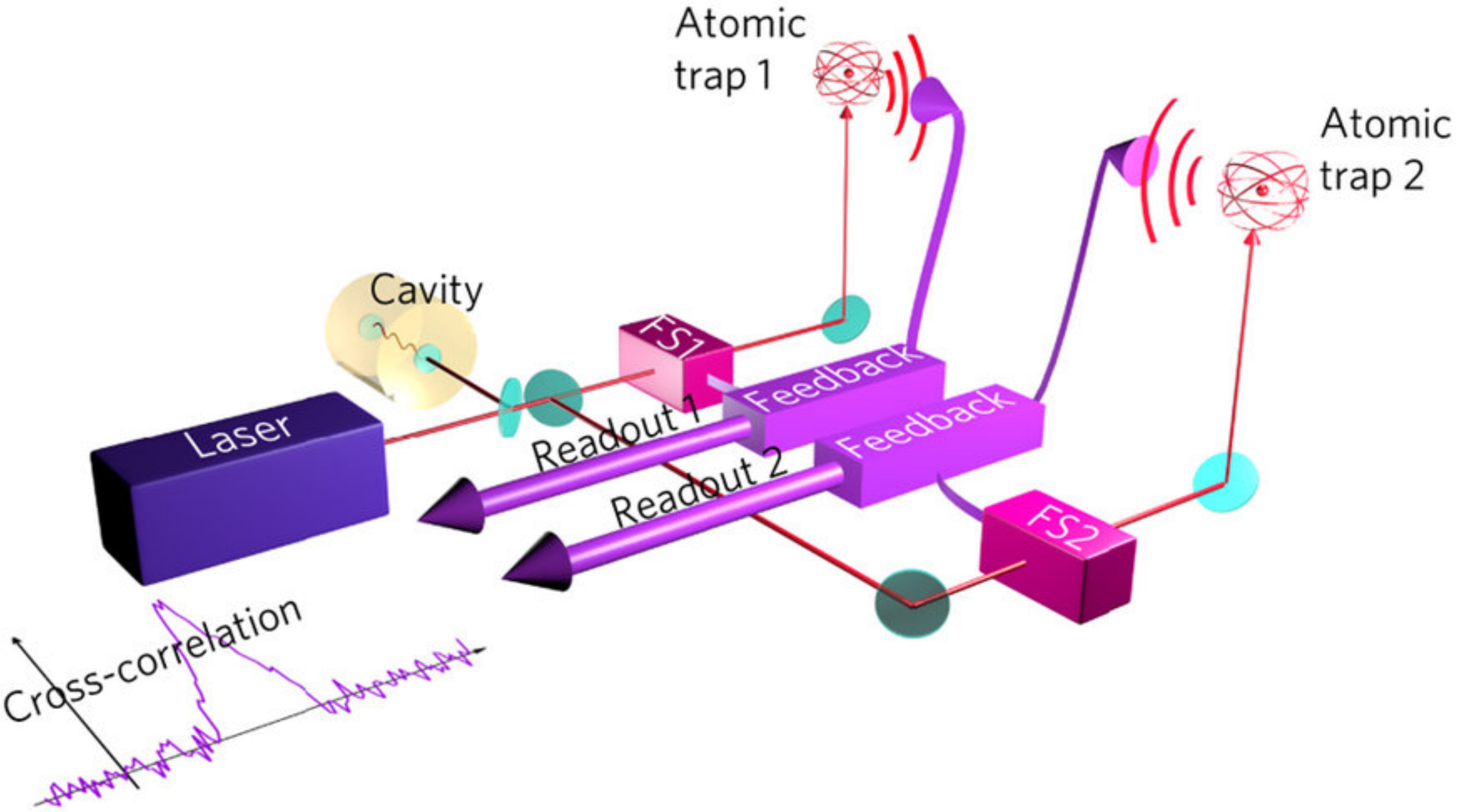
Multiple reflections of light beam enhance effect ($N_{eff} \sim 10^5$ in small-scale interferometers with highly reflective mirrors).

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\, \delta\alpha/\alpha = 10^7\, \delta\alpha/\alpha$ single passage, $10^{12}\, \delta\alpha/\alpha$ for maximal number of reflections

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

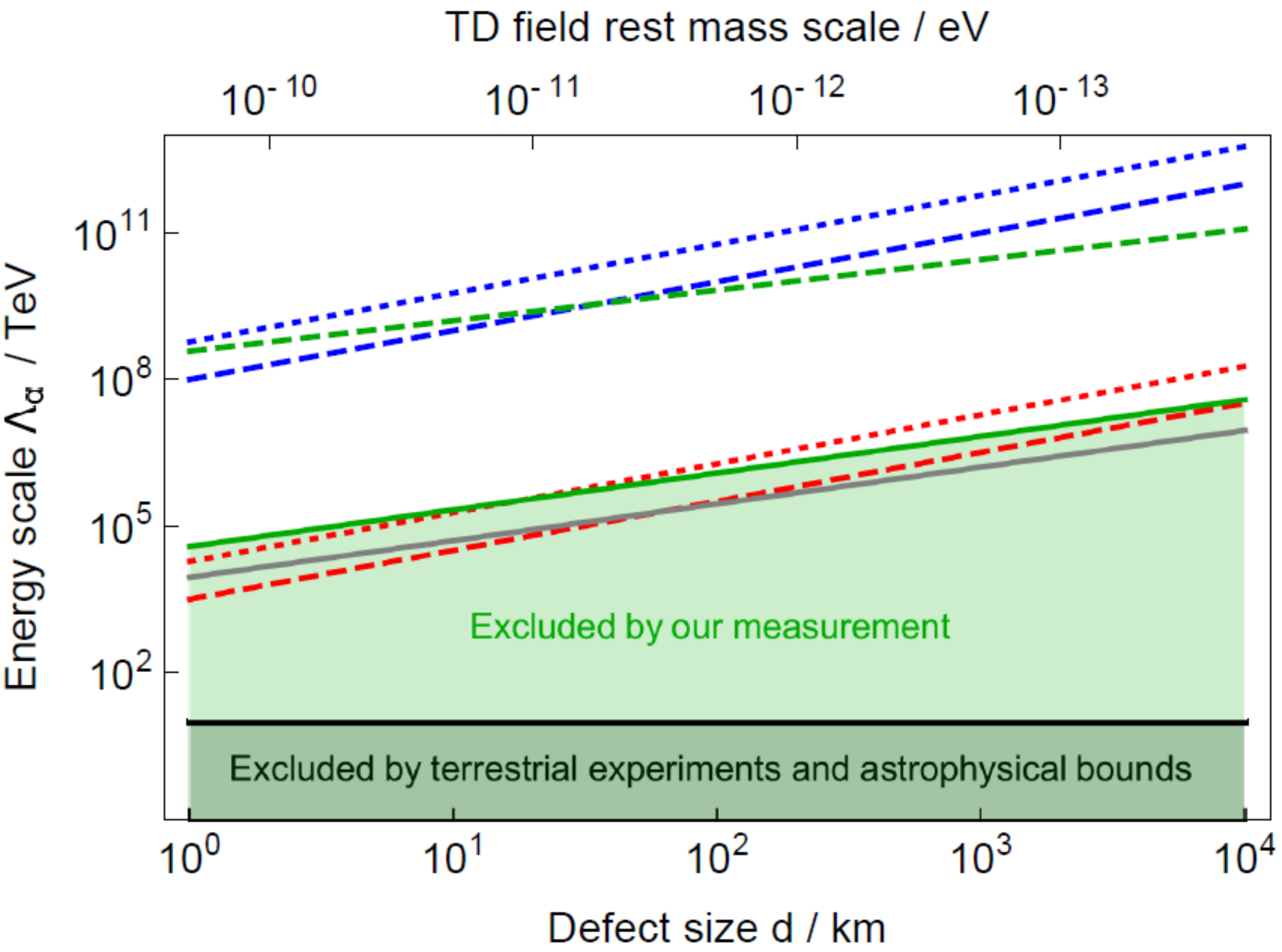
Recent Search for Topological Defects with Strontium Clock – Silicon Cavity System

[Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]



Recent Search for Topological Defects with Strontium Clock – Silicon Cavity System

[Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]

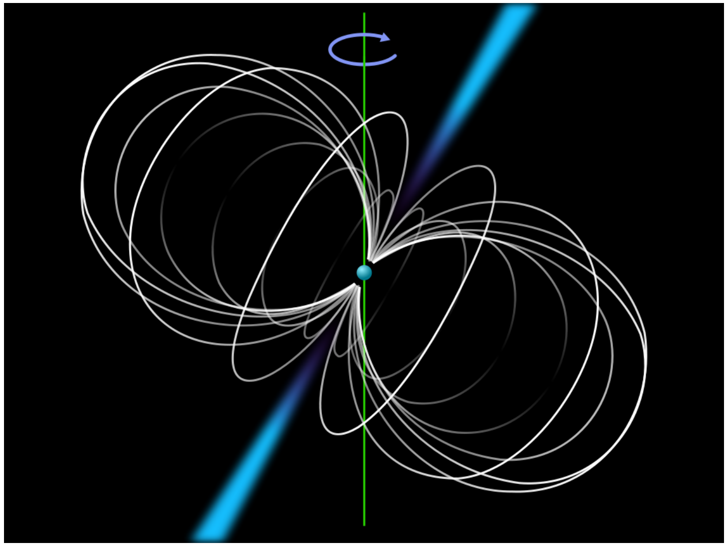


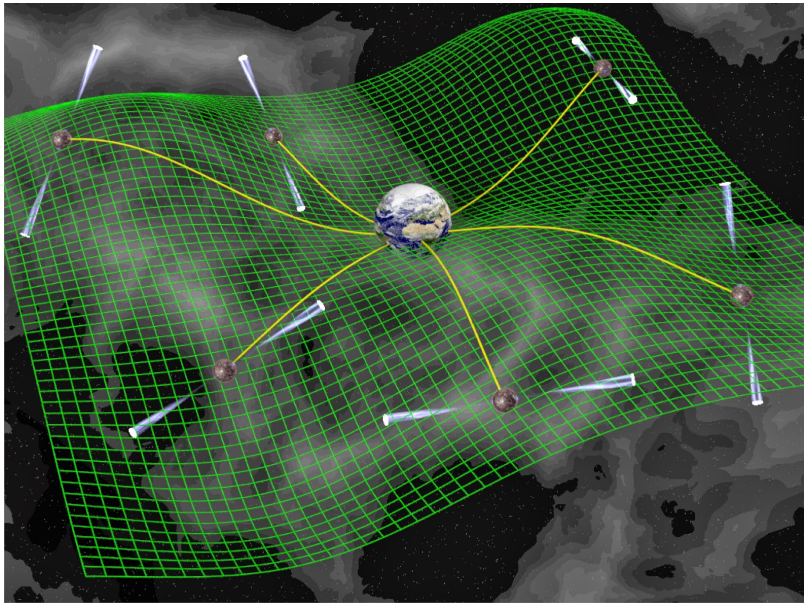
Pulsar Timing

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

Pulsars are highly-magnetised, rapidly rotating neutron stars (T_{rot} ~ 1 ms – 10 s), with very high long-term period stability (~10^{-15}).

A *network of pulsars* can be used to search for *correlated effects* ($v_{TD} \sim 10^{-3}c$) produced by dark matter *topological defects*.

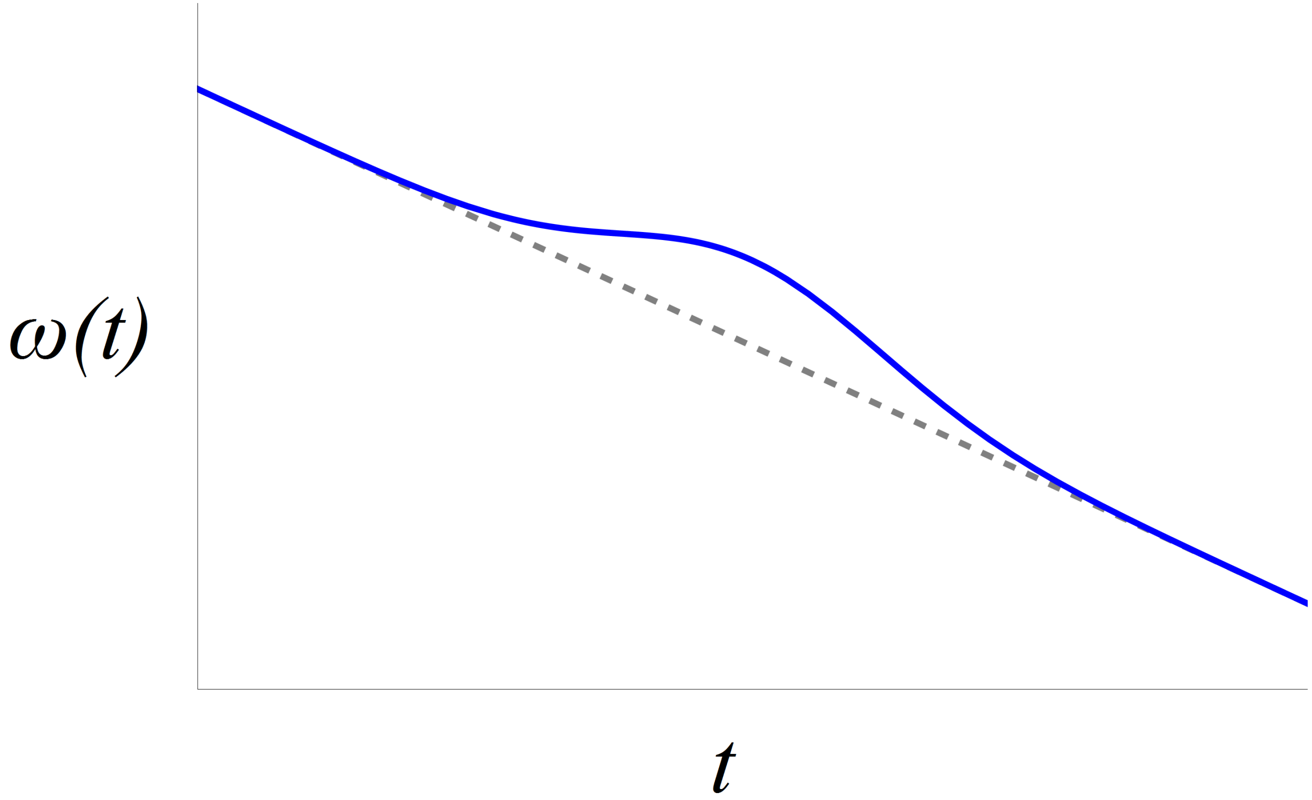




Pulsar Timing

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

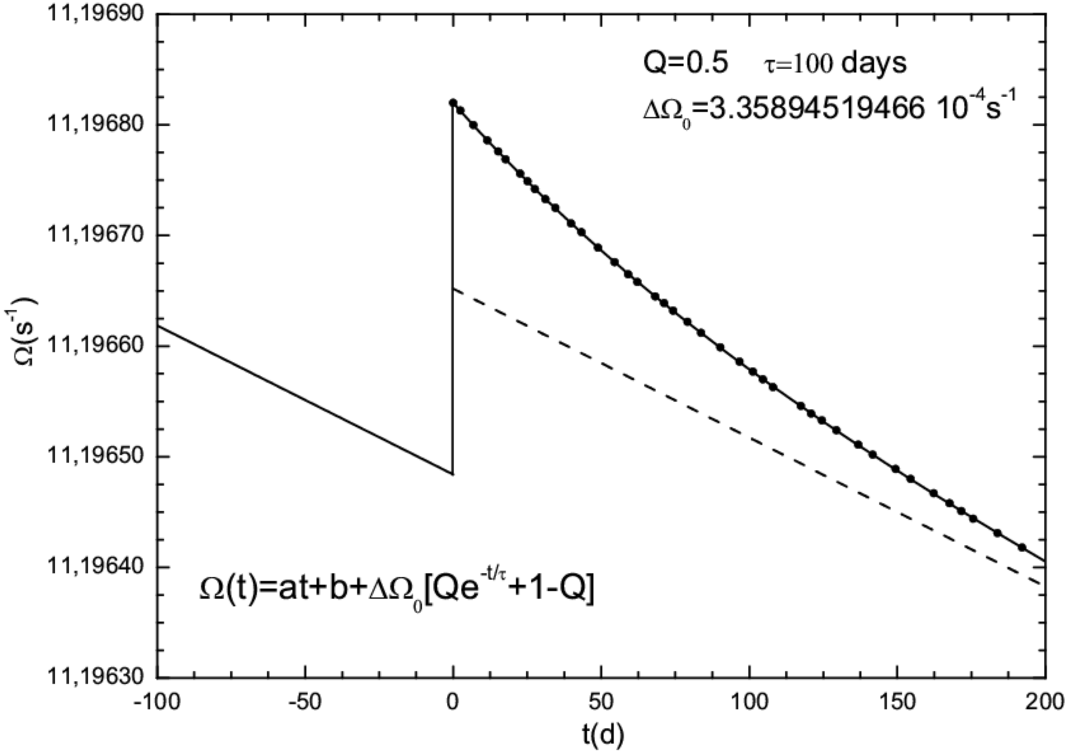
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile



Pulsar Timing

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

Non-adiabatic passage of a topological defect through a pulsar may trigger a *pulsar 'glitch' event* (which have already been observed, but their underlying cause is still disputed).



Glitch Theory

- Model pulsar as 2-component system: neutron superfluid core, surrounded by neutron crust
- 2 components can rotate independently of one another
- Rotation of neutron superfluid core quantified by area density of quantised vortices (which carry angular momentum)
- Strong vortex ‘pinning’ to neutron crust
- Can vortices be unpinned by topological defect?
- Vortices avalanche = pulsar glitch

Variation of Fundamental Constants Induced by a Massive Body

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* **117**, 271601 (2016)]

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

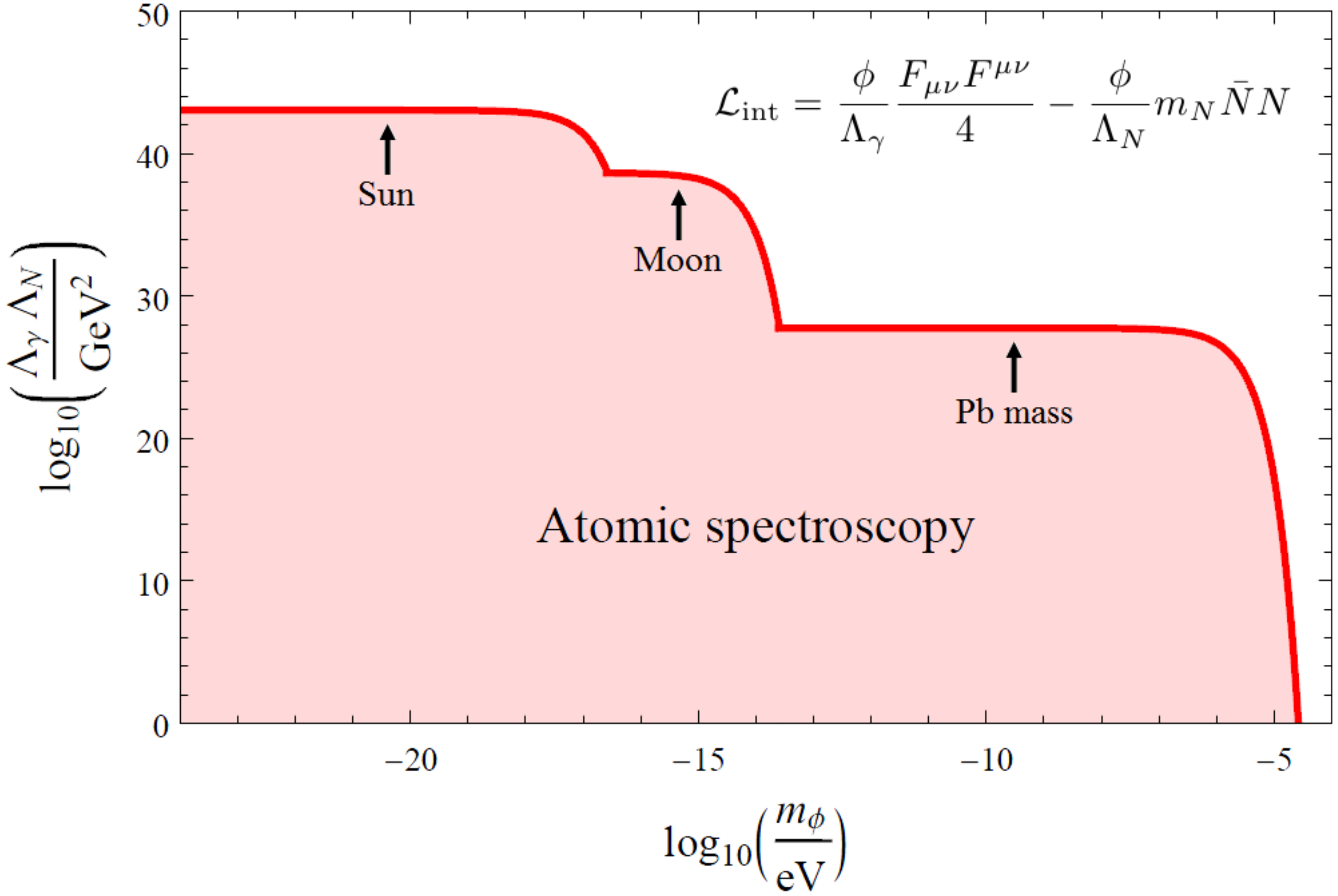
$$\frac{\delta m_f}{m_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \propto \frac{e^{-m_\phi r}}{r}$$

We can search for such alterations in the fundamental constants, using **clock frequency comparison measurements** (ω_1/ω_2 => *scalar* quantities), **in the presence of a massive body at two different distances** away from the clock pair:

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

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

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* **117**, 271601 (2016)]



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

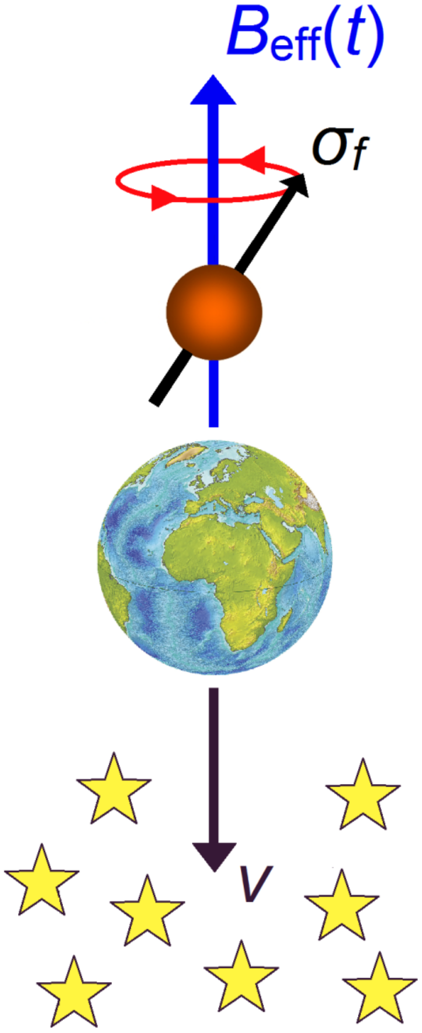
[V.F., talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik and V.F., *PRD* **89**, 043522 (2014)] [CASPEr PRX 2014]

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

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

***Pseudo*-magnetic field**

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



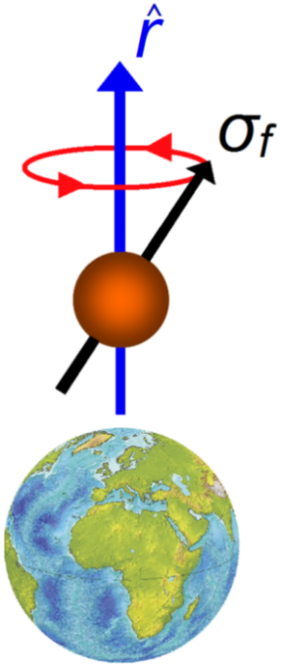
Axion-Induced Oscillating Spin-Gravity Coupling

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

Distortion of DM field by massive body

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

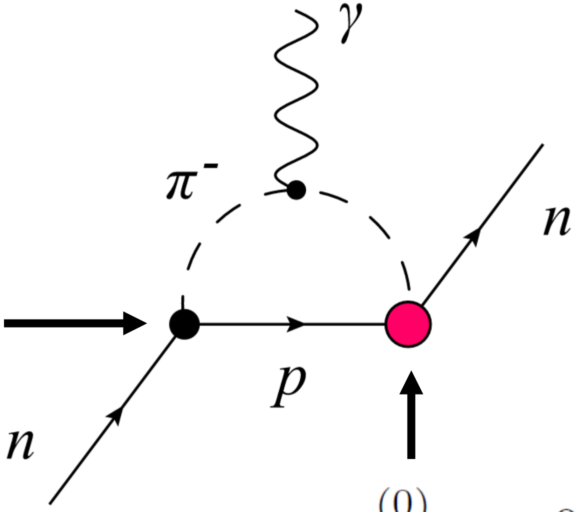
$$=> \quad H_{\text{eff}}(t) \propto \boldsymbol{\sigma}_f \cdot \hat{\boldsymbol{r}} \sin(m_a t)$$



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)]

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



$g_{\pi NN} = 13.5$

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

Atomic EDMs

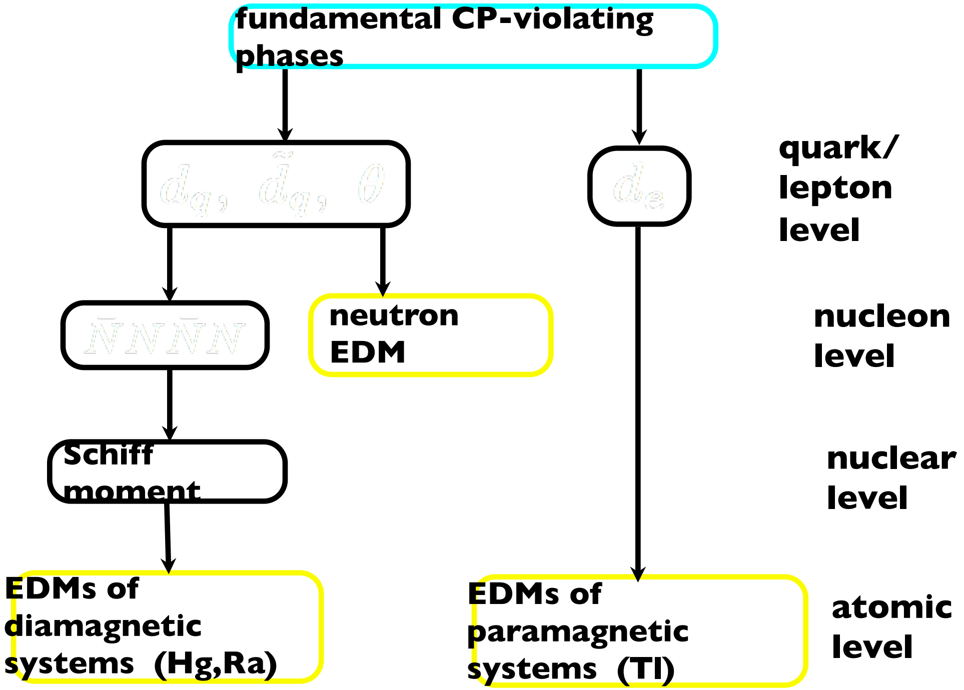
Best limits

$|d(^{199}\text{Hg})| < 10^{-29}$ e cm
(95% c.l., Seattle, 2016)

$|d(^{205}\text{Tl})| < 9.6 \times 10^{-25}$ e cm
(90% c.l., Berkeley, 2002)
YbF, London , ThO Harvard, HfF+ Boulder

$|d(\text{n})| < 2.9 \times 10^{-26}$ e cm
(90% c.l., Grenoble, 2006)

Leading mechanisms for EDM generation



fundamental CP-violating phases

$d_q,\ \tilde{d}_q,\ \theta$

d_e

quark/ lepton level

$\bar{N}N\bar{N}N$

neutron EDM

nucleon level

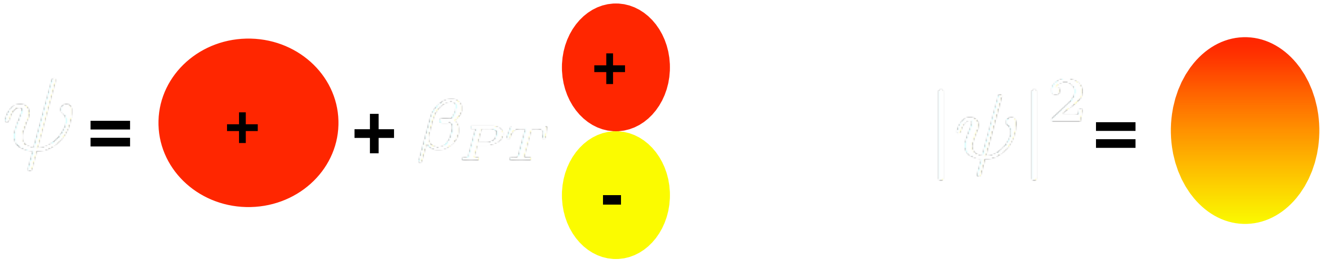
Schiff moment

nuclear level

EDMs of diamagnetic systems (Hg,Ra)

EDMs of paramagnetic systems (Tl)

atomic level



Axion-Induced Oscillating Atomic and Molecular EDMs

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

Induced through *hadronic mechanisms*:

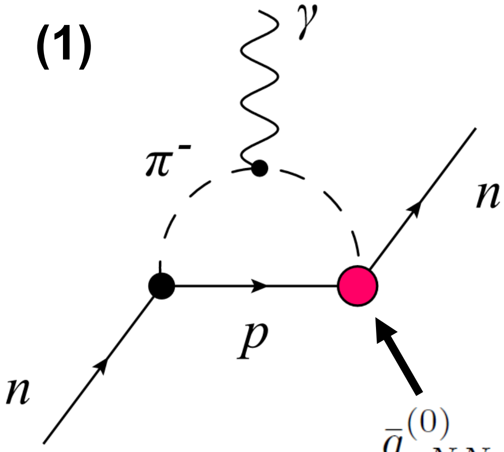
- Oscillating nuclear Schiff moments (*I* ≥ 1/2 => *J* ≥ 0)
- Oscillating nuclear magnetic quadrupole moments (*I* ≥ 1 => *J* ≥ 1/2; *magnetic* => no Schiff screening)

Underlying mechanisms:

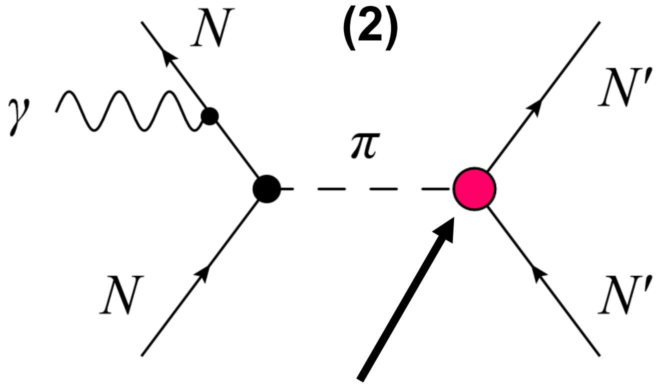
(1) Intrinsic oscillating nucleon EDMs (1-loop level)

(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~$4\pi^2$ ≈ 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

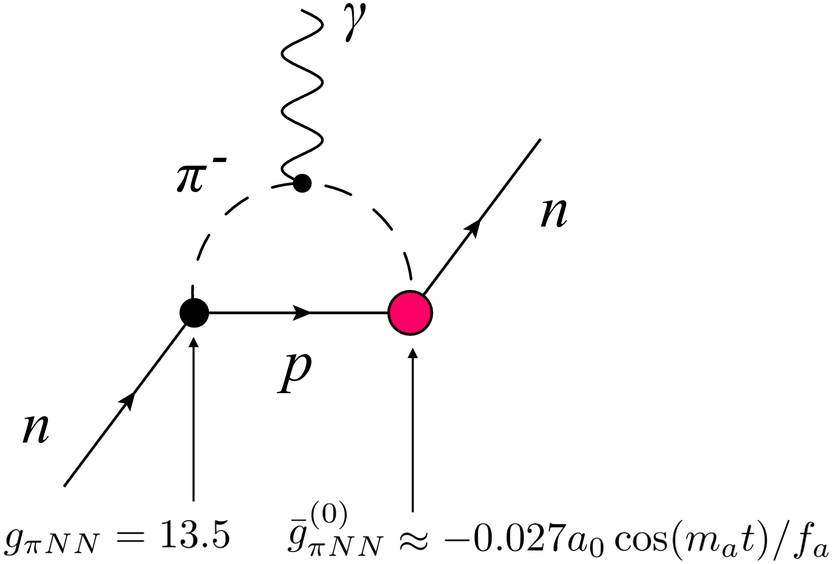
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)] CASPEr collaboration 2014

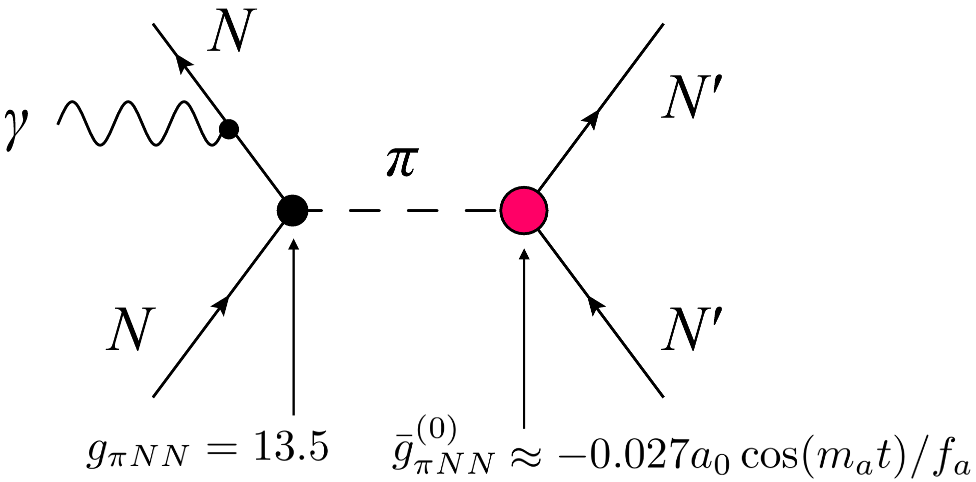
Oscillating atomic and molecular EDMs are induced through oscillating Schiff ($J \geq 0$) and oscillating magnetic quadrupole ($J \geq 1/2$, **no Schiff screening**) moments of nuclei, which arise from *intrinsic oscillating nucleon EDMs* and *oscillating P,T-violating intranuclear forces* (**larger by factor of 10 – 1000**).

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

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

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



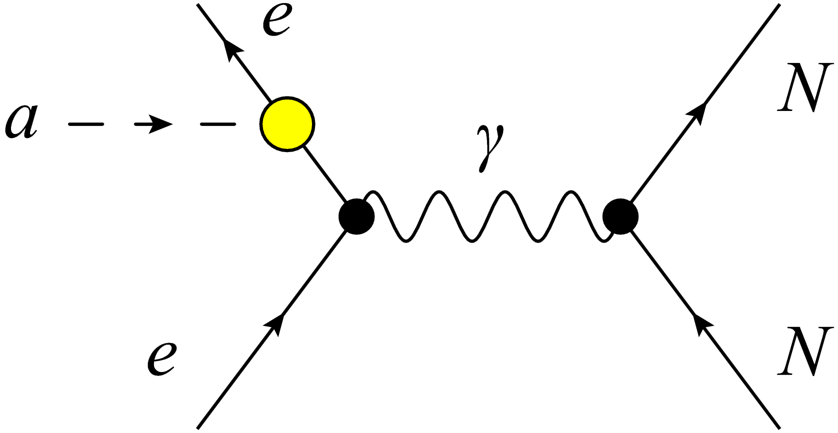


Axion-Induced Oscillating EDMs of Paramagnetic Atoms and Molecules

[Stadnik, V.F., *PRD* **89**, 043522 (2014)], [Roberts, Stadnik, Dzuba, V.F., 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 states* via the interaction of the oscillating axion field with atomic/molecular electrons.

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



Search for Axion Dark Matter with Ultracold Neutrons and Hg atoms

Ongoing work with the nEDM collaboration at PSI and Sussex (Rawlik *et al.*)

- 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 Larmor precession frequencies:

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

- 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 $\Delta f/f \sim 10^{-6}$.
- Need to search over a broad range of frequencies.

Searching for Spin-Dependent Effects

Oscillating neutron and Hg EDM and spins (axion wind)

n/Hg: [nEDM collaboration (Ayres, Harris, Kirch, Rawlik *et al.*), Flambaum, Stadnik]

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

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

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

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

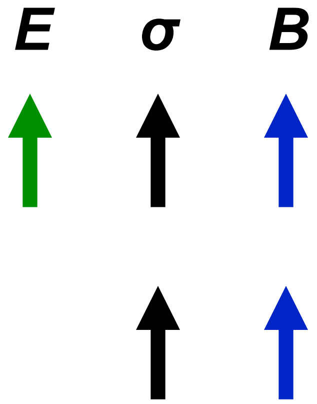
Earth’s rotation

Searching for Spin-Dependent Effects

Need spin-polarised sources!

n/Hg: [nEDM collaboration, Phys. Rev. X 7, 041034, 2017]

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



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

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

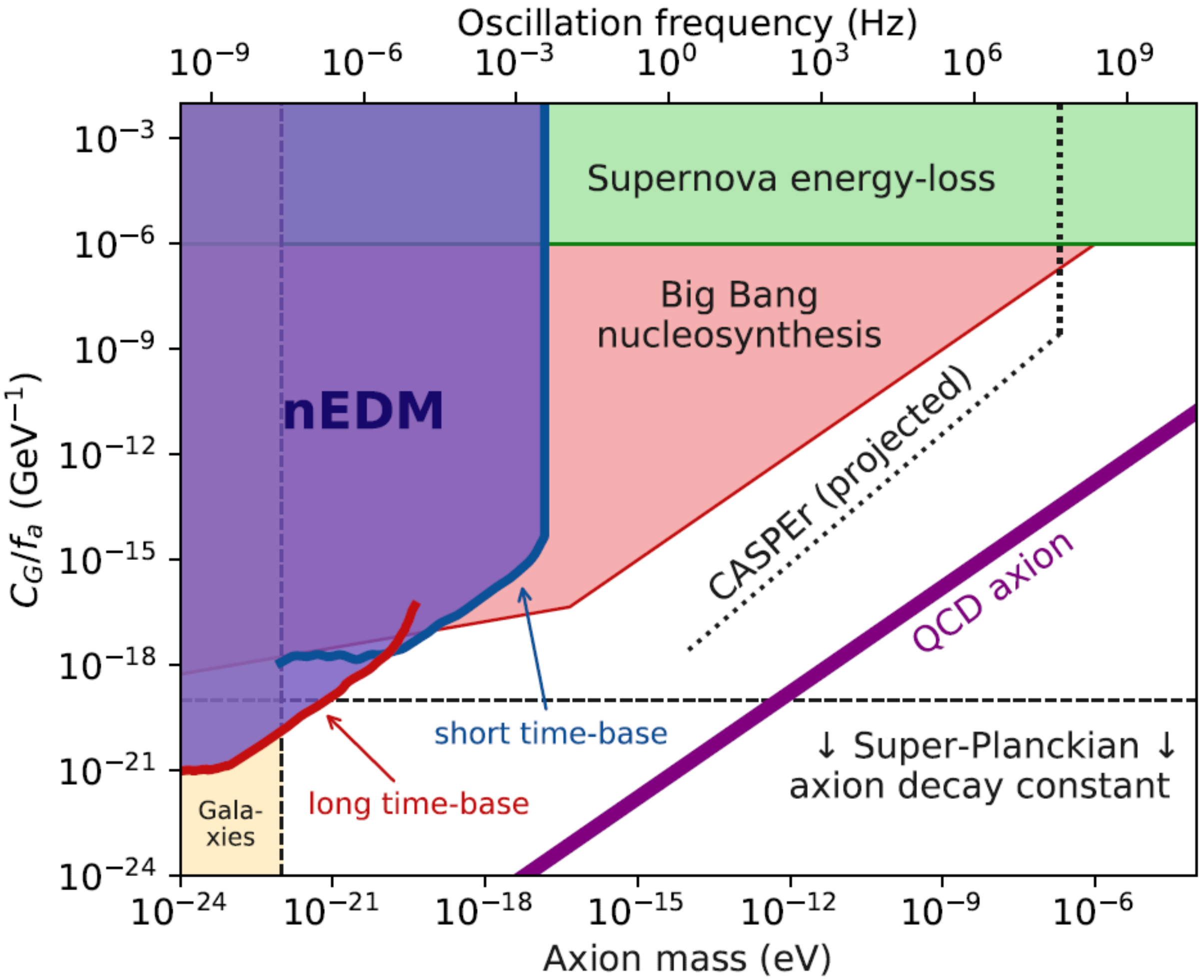
$$\omega_1 = m_a, \;\; \omega_2 = m_a + \Omega_{\mathrm{sidereal}}, \;\; \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

Earth's rotation

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, Phys. Rev. X 7, 041034, 2017]

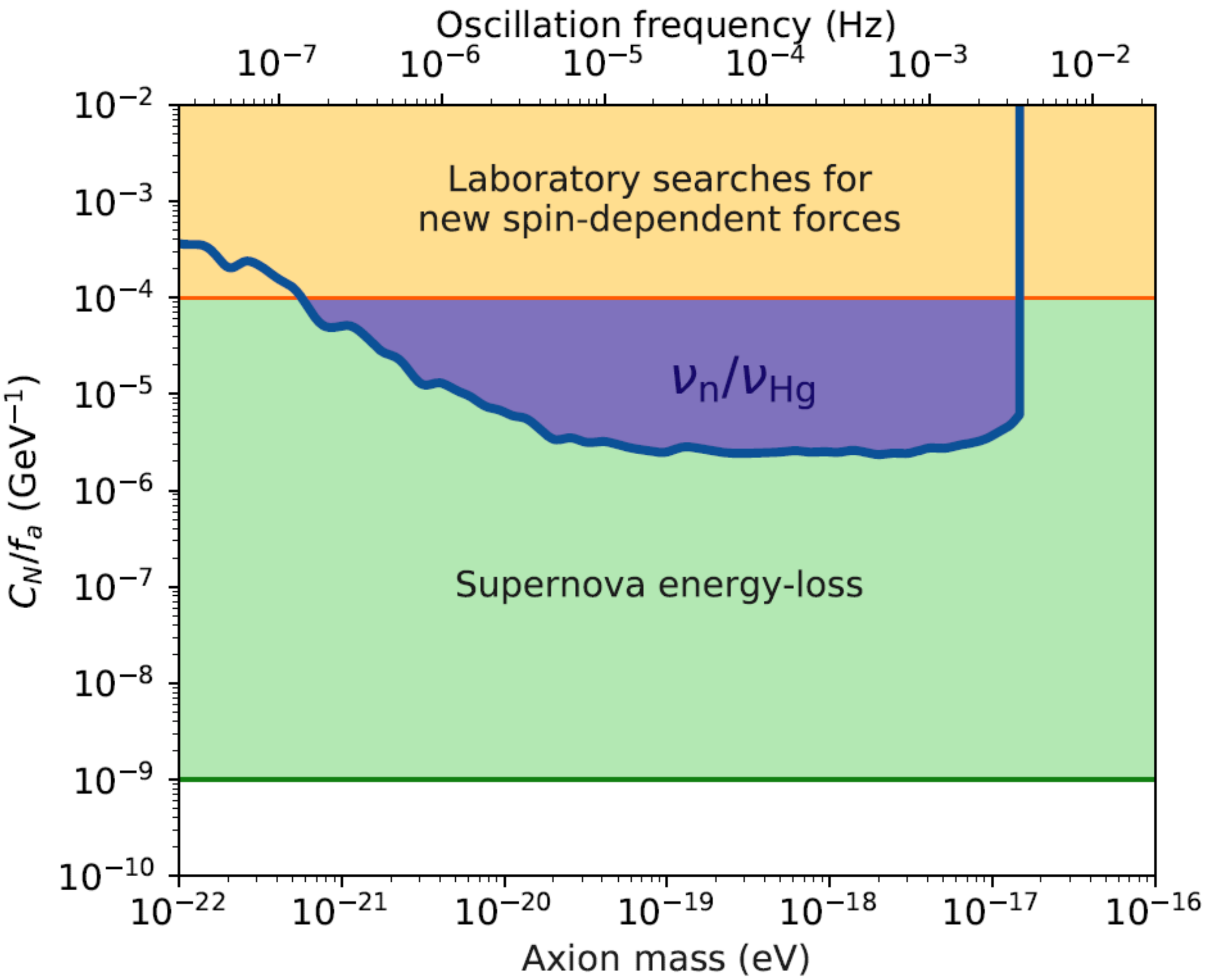
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

v_n/v_{Hg} constraints: [nEDM collaboration, Phys. Rev. X 7, 041034, 2017]

40-fold improvement!



Axion-Induced Oscillating Parity Non-Conservation in Atoms and Molecules

[Stadnik and V.F. *PRD* **89**, 043522 (2014)], [Roberts, Stadnik, Dzuba, V.F., 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, $K_{\mathrm{PNC}} = 0$)*.

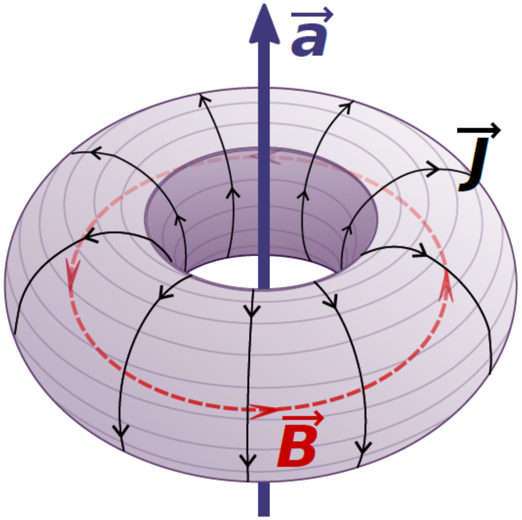
* Compare with the Standard Model *static* atomic PNC effects in atoms, which are dominated by Z^0-boson exchange between atomic electrons and nucleons in the nucleus, where the effects arise already in the non-relativistic approximation.

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)]

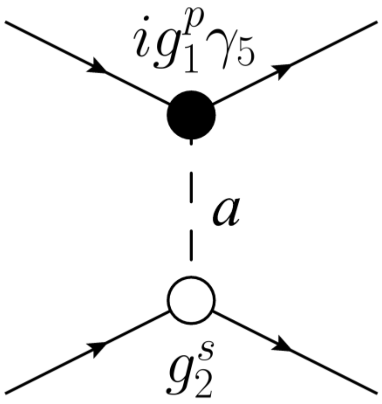
Interaction of the oscillating axion field with nucleons in nuclei induces **oscillating nuclear anapole moments**.

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



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

Non-Cosmological Sources of Exotic Bosons: axion



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

$$V_{12}(r) \approx \frac{g_1^p g_2^s}{8\pi m_1}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}}\left(\frac{m_a}{r}+\frac{1}{r^2}\right)e^{-m_a r}$$

- Macroscopic fifth-forces [Moody, Wilczek, *PRD* **30**, 130 (1984)]

- *P*,*T*-violating forces => Atomic and Molecular EDMs
[Stadnik, Dzuba, and V.F, Phys. Rev. Lett.120, 0132024(2018)]

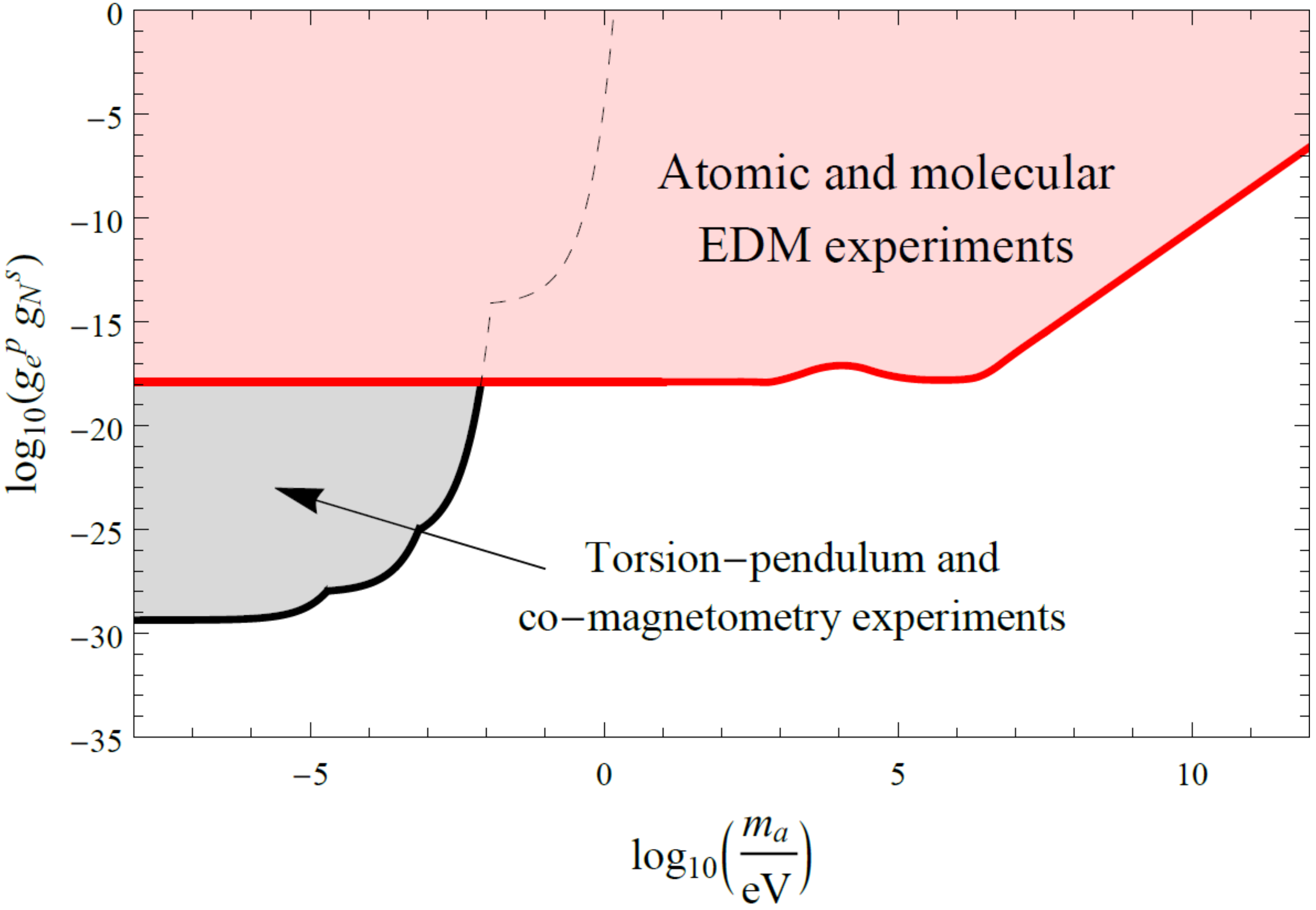
Atomic EDM experiments: Cs, Tl, Xe, Hg

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

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

EDM constraints: [Stadnik, Dzuba and V.F., Phys. Rev. Lett.120, 0132024(2018)]

Many orders of magnitude improvement!



Non-Cosmological Sources of Exotic Bosons

- Probing low-mass vector bosons with parity nonconservation and nuclear anapole moment measurements in atoms and molecules.
- Dzuba, V. F. , Stadnik, Phys. Rev. Lett. 119, 223201 (2017).
- Best limits on extra Z' boson. **Many orders of magnitude improvement!**

Atomic experiments: Cs, Yb, Dy, Tl, Pb, Bi,

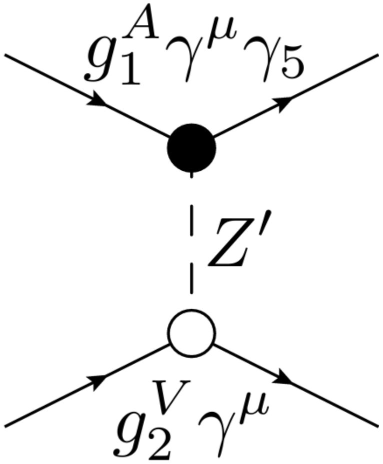
Fr, Ra+

Molecular experiments: BaF, ...

Chiral molecules

Non-Cosmological Sources of Exotic Bosons

Z' boson [Dzuba, V.F., Stadnik, *PRL* **119**, 223201 (2017)]



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

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

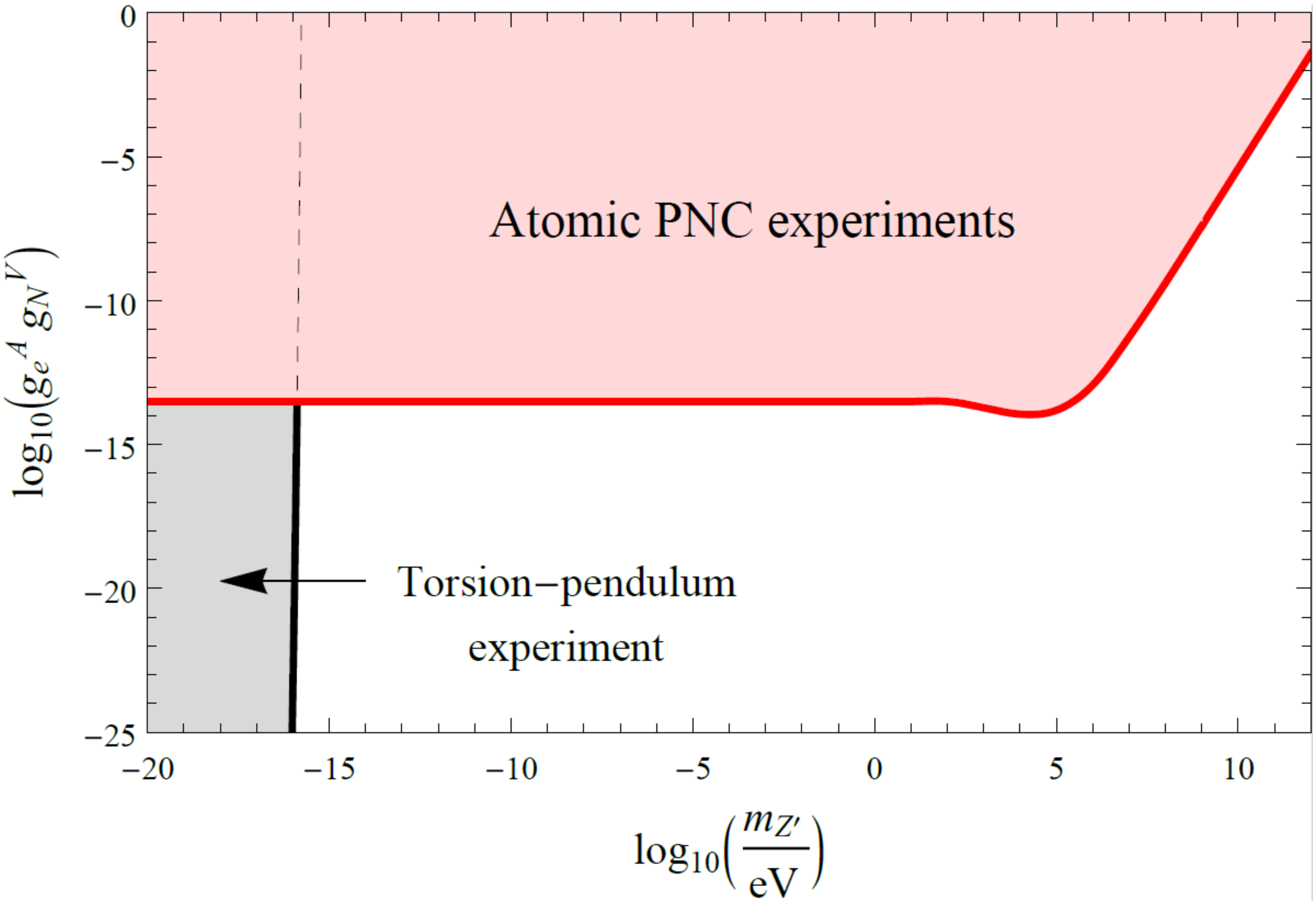
P-violating forces => Atomic parity-nonconserving effects and nuclear anapole moments

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

Constraints on Vector-Pseudovector Nucleon-Electron Interaction

PNC constraints: [Dzuba, V.F. , Stadnik, *PRL* **119**, 223201 (2017)]

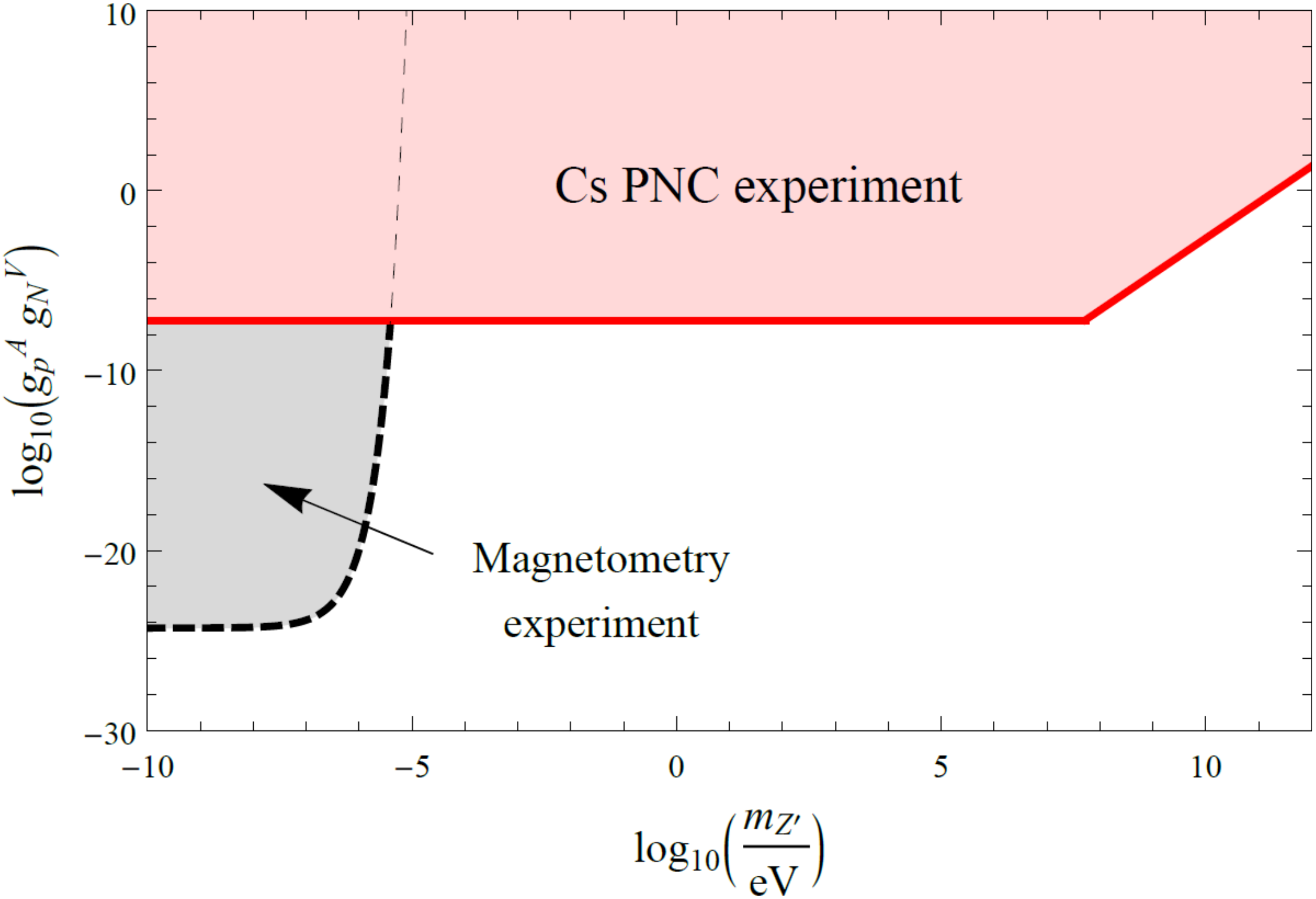
Many orders of magnitude improvement!



Constraints on Vector-Pseudovector Nucleon-Proton Interaction

PNC constraints: [Dzuba, V.F., Stadnik, *PRL* **119**, 223201 (2017)]

Many orders of magnitude improvement!



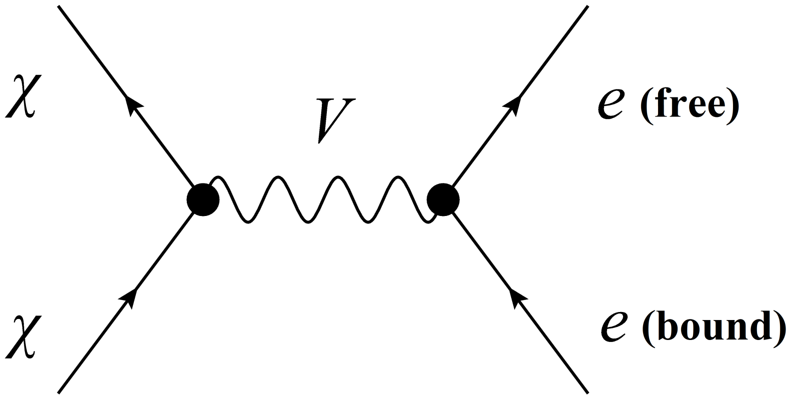
Relativistic effects increase ionisation by dark matter scattering on electrons by up to 3 orders of magnitude!

[Roberts, V.F., Gribakin, PRL **116**, 023201 (2016)]

- Important for numerous existing and future dark matter detectors.
- Detailed relativistic many-body calculations in [Roberts, Dzuba, Flambaum, Pospelov, Stadnik, Phys. Rev. D 2016]
- DAMA collaboration claims detection of dark matter, others – no detection. Possible explanation: scattering of dark matter on electrons (instead of scattering on nuclei).
- Our calculations show tension between DAMA and XENON results.

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!

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 $r \to 0$, $\gamma^2 = 1 - (Z\alpha)^2$]*:

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

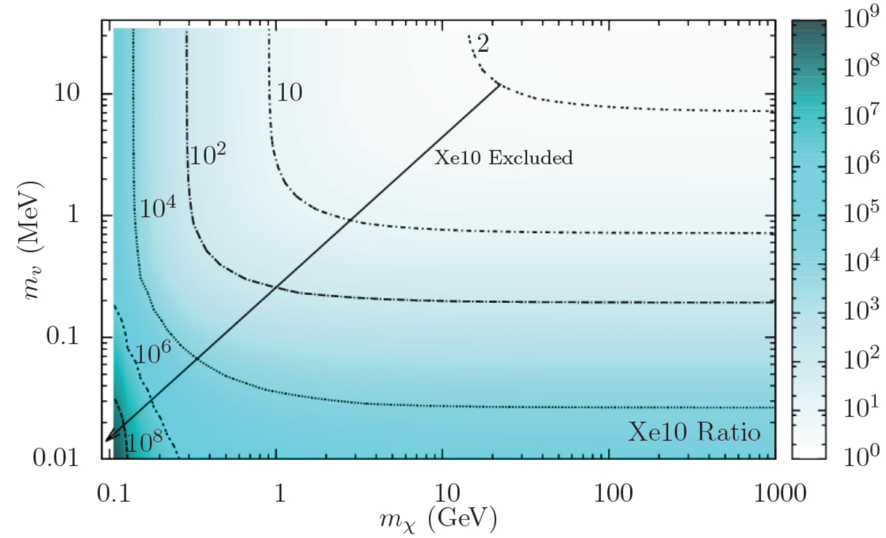
- Relativistic contribution to $\sigma_{\chi e}$ dominates by several orders of magnitude for large q!

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

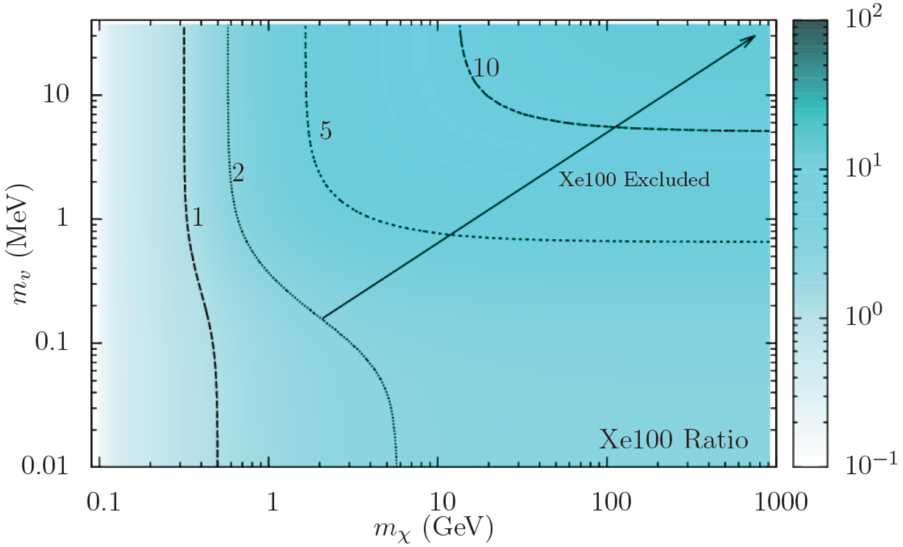
Can the DAMA result be explained by the ionising scattering of WIMPs on electrons?

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

XENON10 (expected/observed ratio)



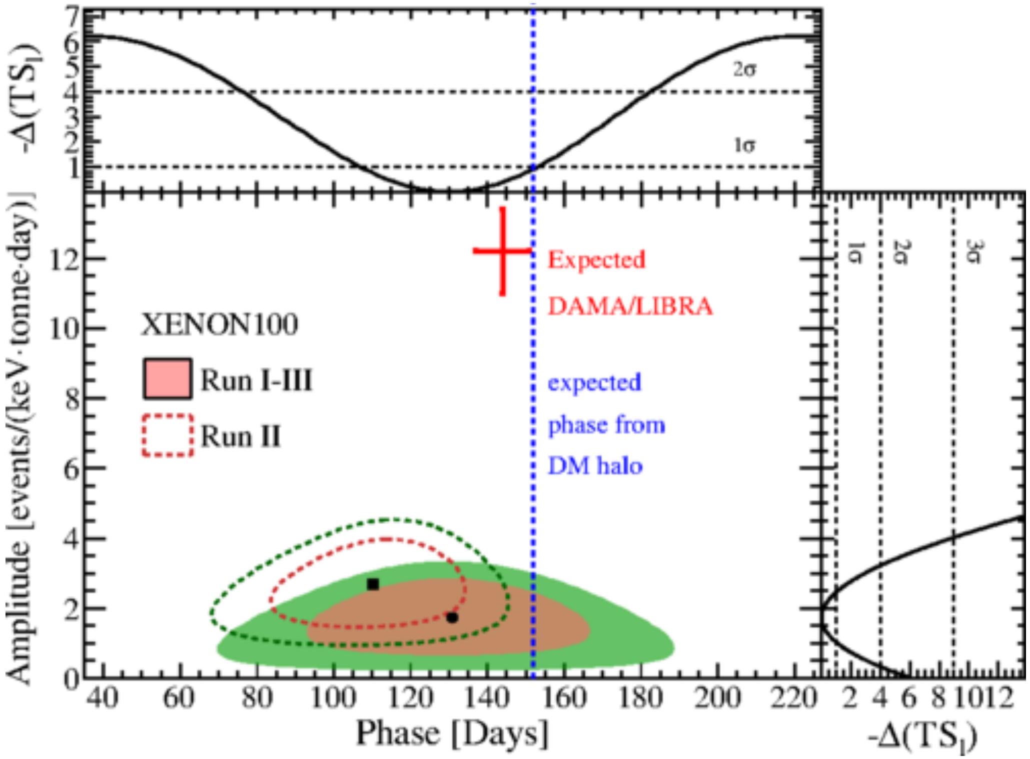
XENON100 (expected/observed ratio)



- 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.

Recent constraints from XENON Collaboration using our atomic calculations

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



Conclusions

- **Small photon mass may imitate gravitational pull assigned to dark matter**
- 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 with the Higgs boson.
- **First limits** on linear and quadratic interactions of scalar dark matter with vector bosons (W^+,W^-,Z^0)
- Oscillating effects of variation of fundamental constants and violation of the fundamental symmetries: P, T, EDM, Lorentz, Einstein equivalence principle

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
- Relativistic (electron) effects enhance cross-section for ionising scattering of atomic electrons by WIMPs with $m_\chi > 1$ GeV by **several orders of magnitude**, compared with non-relativistic contribution

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References (Scalar Dark Matter)

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Y. V. Stadnik and V. V. Flambaum. *Axion-induced effects in atoms, molecules and nuclei: Parity nonconservation, anapole moments, electric dipole moments, and spin-gravity and spin-axion momentum couplings*. Physical Review D **89**, 043522 (2014). arXiv:1312.6667.

B. M. Roberts, Y. V. Stadnik, V. A. Dzuba, V. V. Flambaum, N. Leefer and D. Budker. *Limiting P-odd interactions of Cosmic Fields with Electrons, Protons and Neutrons*. Physical Review Letters **113**, 081601 (2014). arXiv:1404.2723.

B. M. Roberts, Y. V. Stadnik, V. A. Dzuba, V. V. Flambaum, N. Leefer and D. Budker. *Parity-violating interactions of cosmic fields with atoms, molecules and nuclei: Concepts and calculations for laboratory searches and extracting limits*. Physical Review D **90**, 096005 (2014). arXiv:1409.2564.

Y. V. Stadnik and V. V. Flambaum. *Nuclear spin-dependent interactions: searches for WIMP, axion and topological defect dark matter, and tests of fundamental symmetries*. European Physical Journal C **75**, 110 (2015). arXiv:1408.2184.

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**.