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

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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)

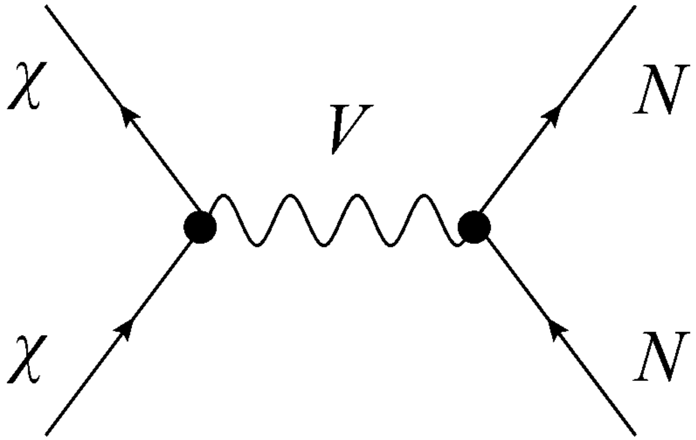
Physical Review Letters **113**, 081601 (2014)

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 ($e' \ll 1$)! 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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)
- 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 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

Dark Matter

Scalars or quadratic axions

→ **'Slow' evolution and oscillating variation of fundamental constants**

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

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

→ **Oscillating spin-dependent effects, EDM, *P*,*T*, Lorentz and Einstein symmetry violation**

- Atomic magnetometry
- Ultracold neutrons
- Solid-state magnetometry

Variation of fundamental constants (fine structure constant α, α_s , masses) due to Dark matter

" Fine tuning" of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

Variation of coupling constants in space provide natural explanation of the "fine tuning": we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

Source of the variation: Dark matter?

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

Evidence for spatial variation of the fine structure constant

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

Quasar spectra

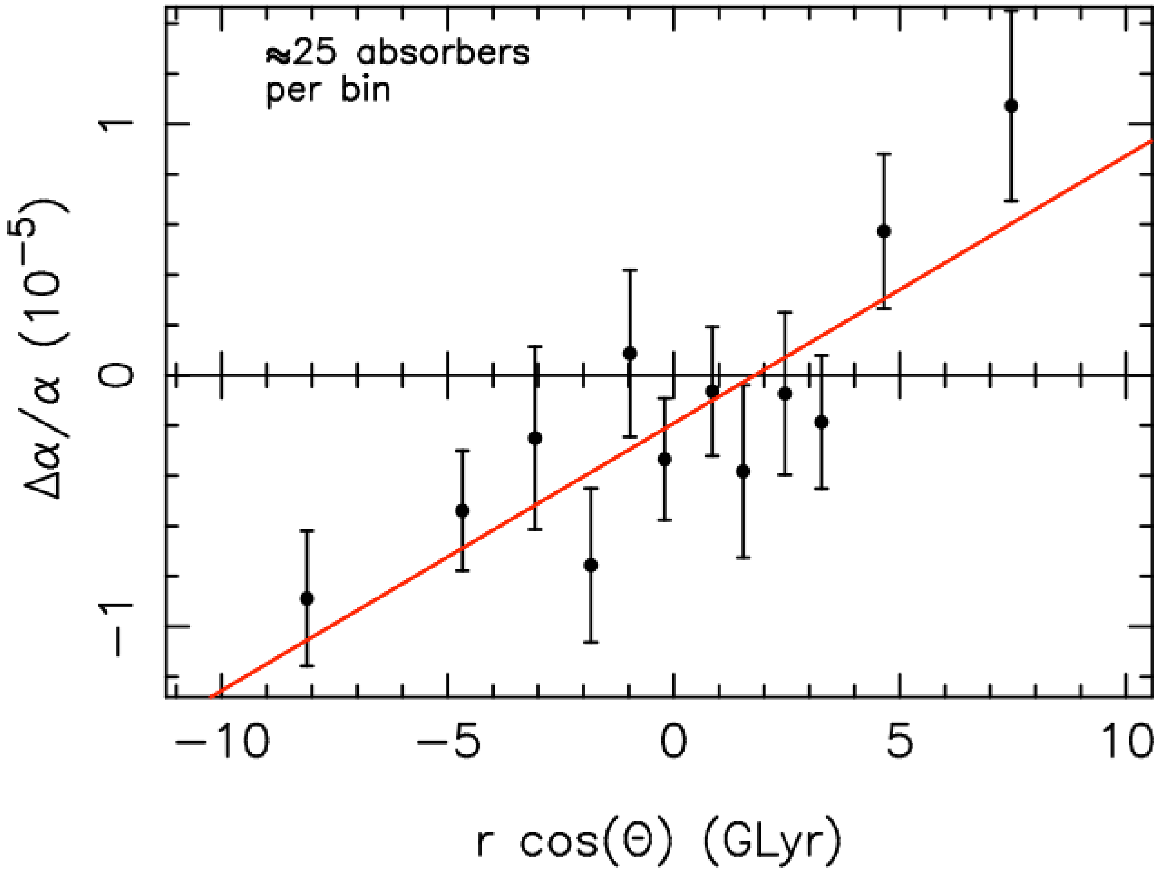
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

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

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

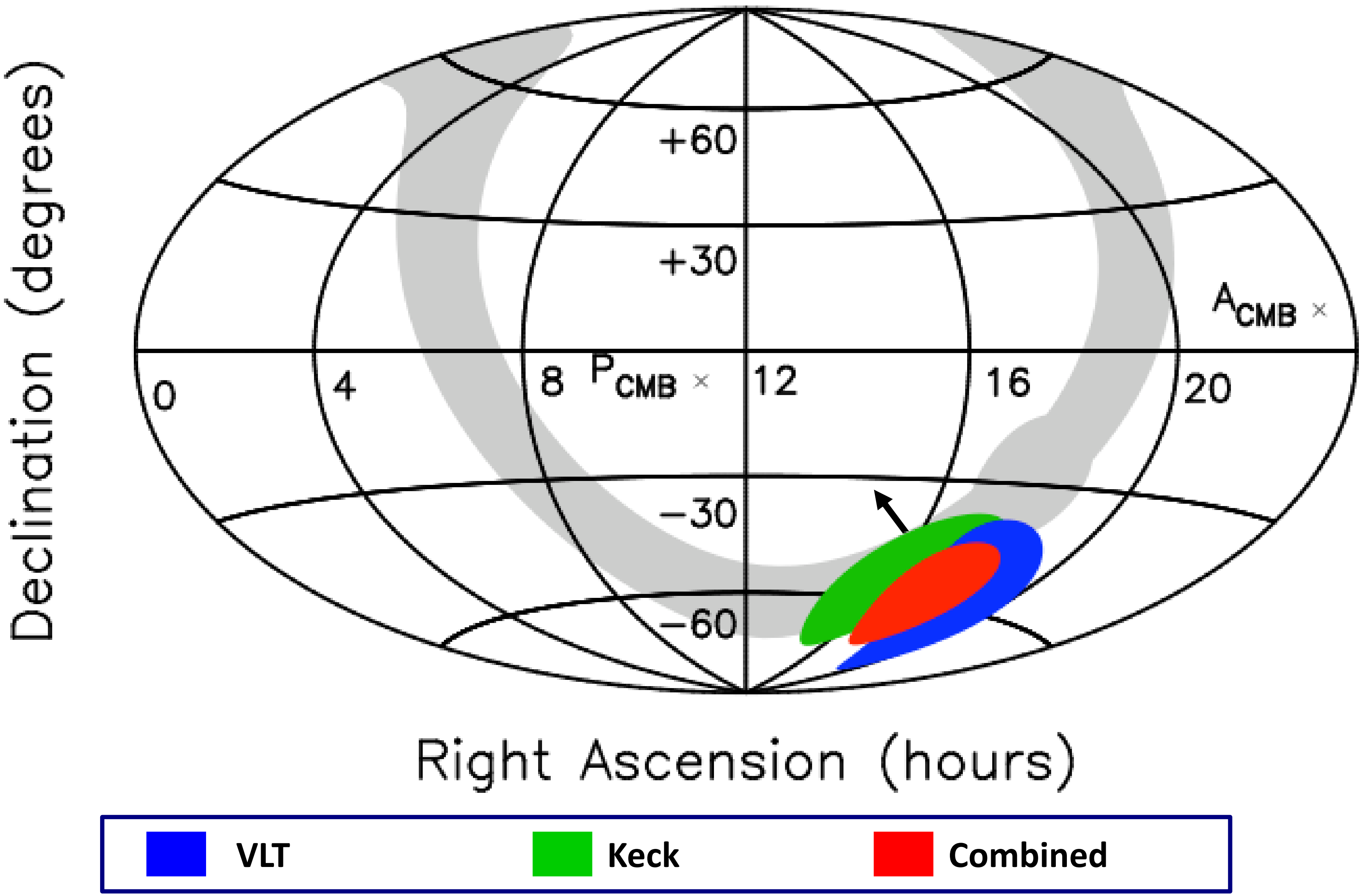
Reconciles all measurements of the variation

Distance dependence



Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} GLyr^{-1} and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.1σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

Keck & VLT dipoles independently agree, p=4%



Hints that this result might be real

Two internal consistencies:

1 Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2 High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

300 absorption systems, 30 atomic lines

Plank satellite Cosmic Microwave Background data 2013:
Universe is not symmetric!
CMB fluctuations are different in different directions. Dipoles in CMB fluctuations, Dark Energy (supernova), Matter flow agree with alpha dipole.

Berengut et al. Limits on dependence of alpha on gravity from white dwarf spectra Fe^{4+},Ni^{4+} 4.2(1.6) 10^{-5}. Accurate laboratory spectra needed.

Consequences for atomic clocks

- Sun moves 369 km/s relative to CMB
  $\cos(\phi)=0.1$
  This gives average laboratory variation
  $\Delta\alpha/\alpha = 1.5\ 10^{-18}\ \cos(\phi)$ per year

- Earth moves 30 km/s relative to Sun-
  $1.6\ 10^{-20}\ \cos(\omega t)$ annual modulation
  [Berengut and V.F. (2012)]

Results for variation of fundamental constants: Clocks comparison

Source	$Clock_1/Clock_2$	$d\alpha/dt/\alpha$ (10^{-16} 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 19	Yb+opt/Yb+/Cs(hfs)	-0.2(0.2) 0.02
Guena *et al*, 2012	Rb(hfs)/Cs(hfs)	3(2)[a]

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

d/dt **ln(**m_q/Λ_{QCD}**) = 7(4) x**10^{-15} **yr**$^{-1}$

m_e/M_p **or** m_e/Λ_{QCD} **-0.1(1.0)x**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.

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

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

'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:

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

Photon:

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

W and *Z* Bosons:

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

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

[Stadnik, 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.

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

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)

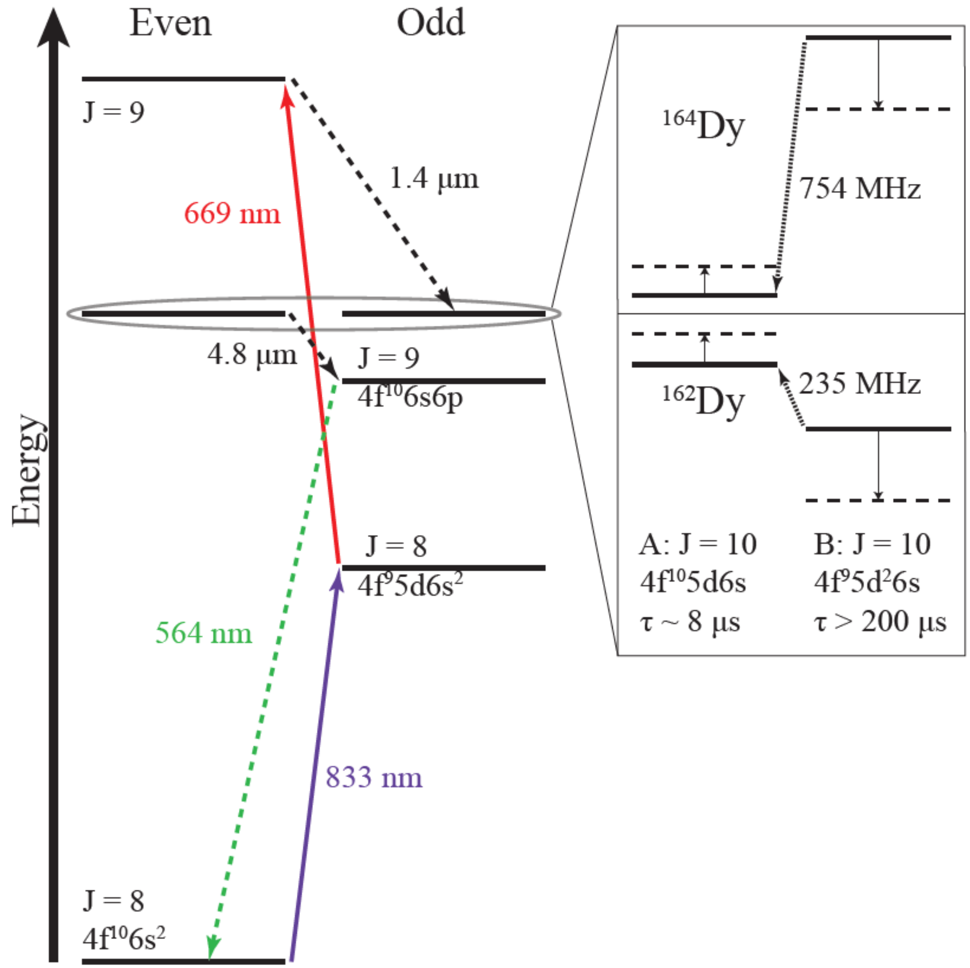
Dy/Cs: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik and V.F., *PRL* **115**, 201301 (2015)]

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

Enhanced Effects of Varying Fundamental Constants on Atomic Transitions

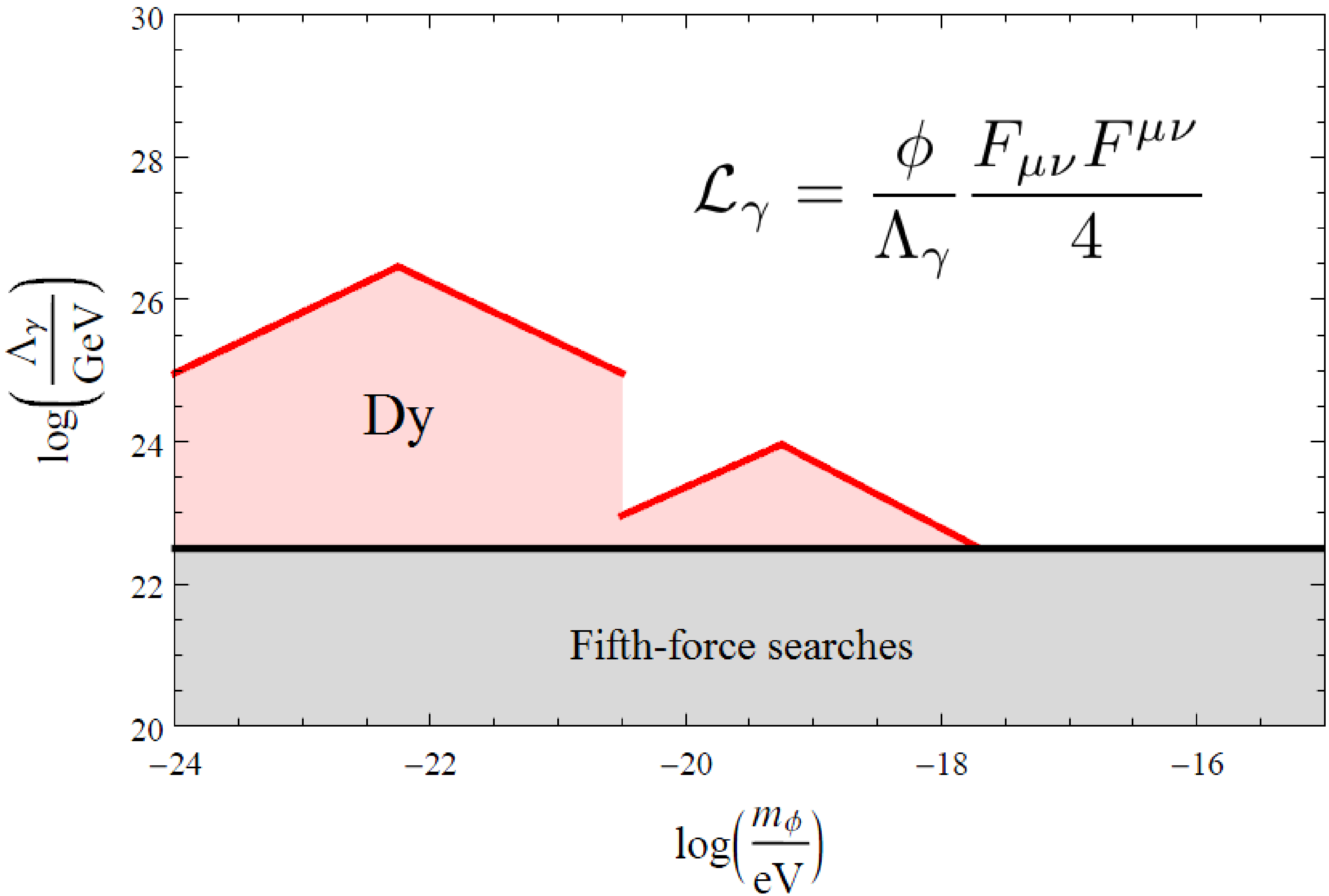
[Dzuba,Flambaum,Webb,*PRL* **82**,888(1999); Flambaum PRL 97,092502(2006); PRA73,034101(2006); Berengut,Dzuba,Flambaum PRL105,120801 (2010)]

- 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 Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

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

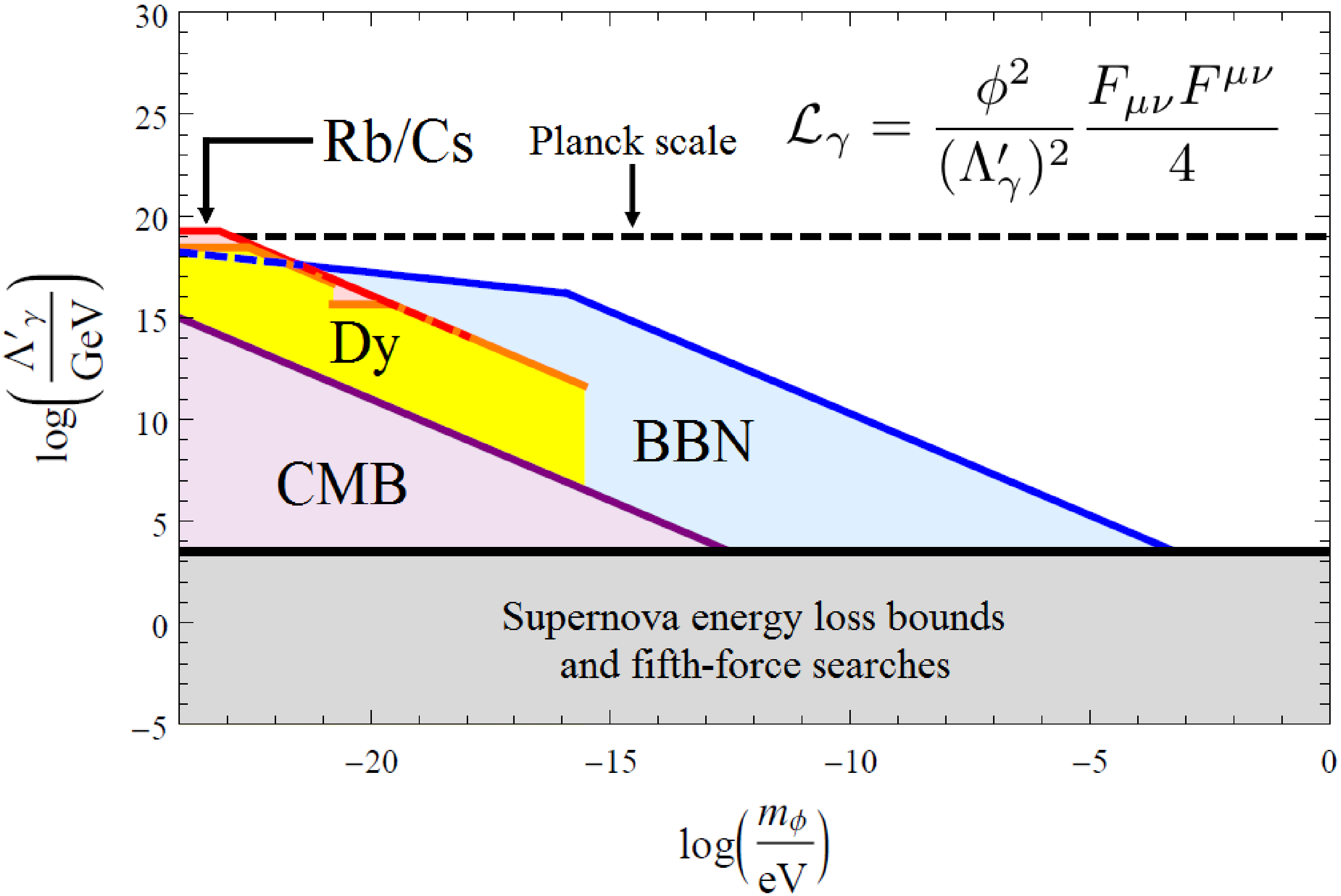


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

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

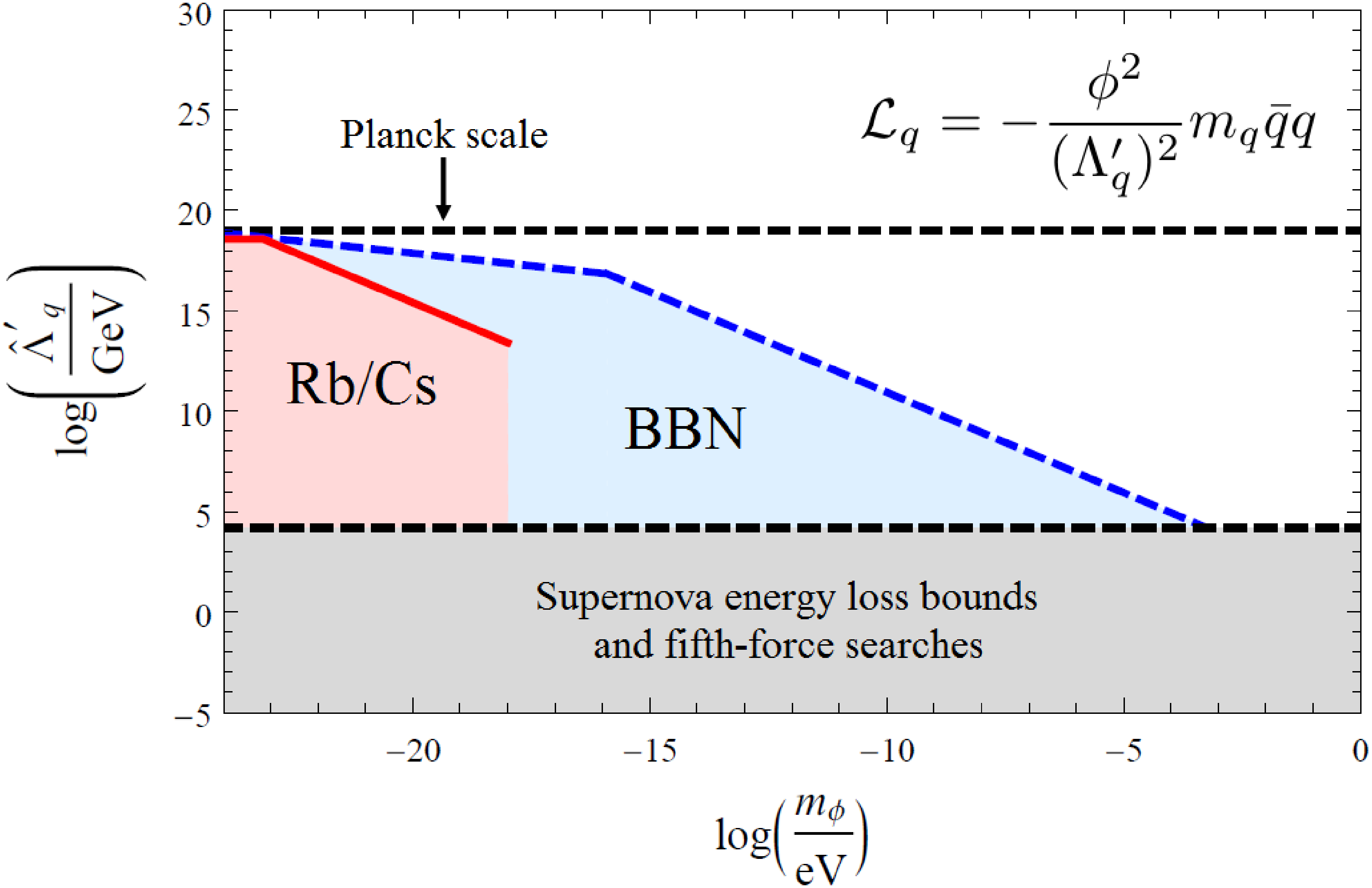
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

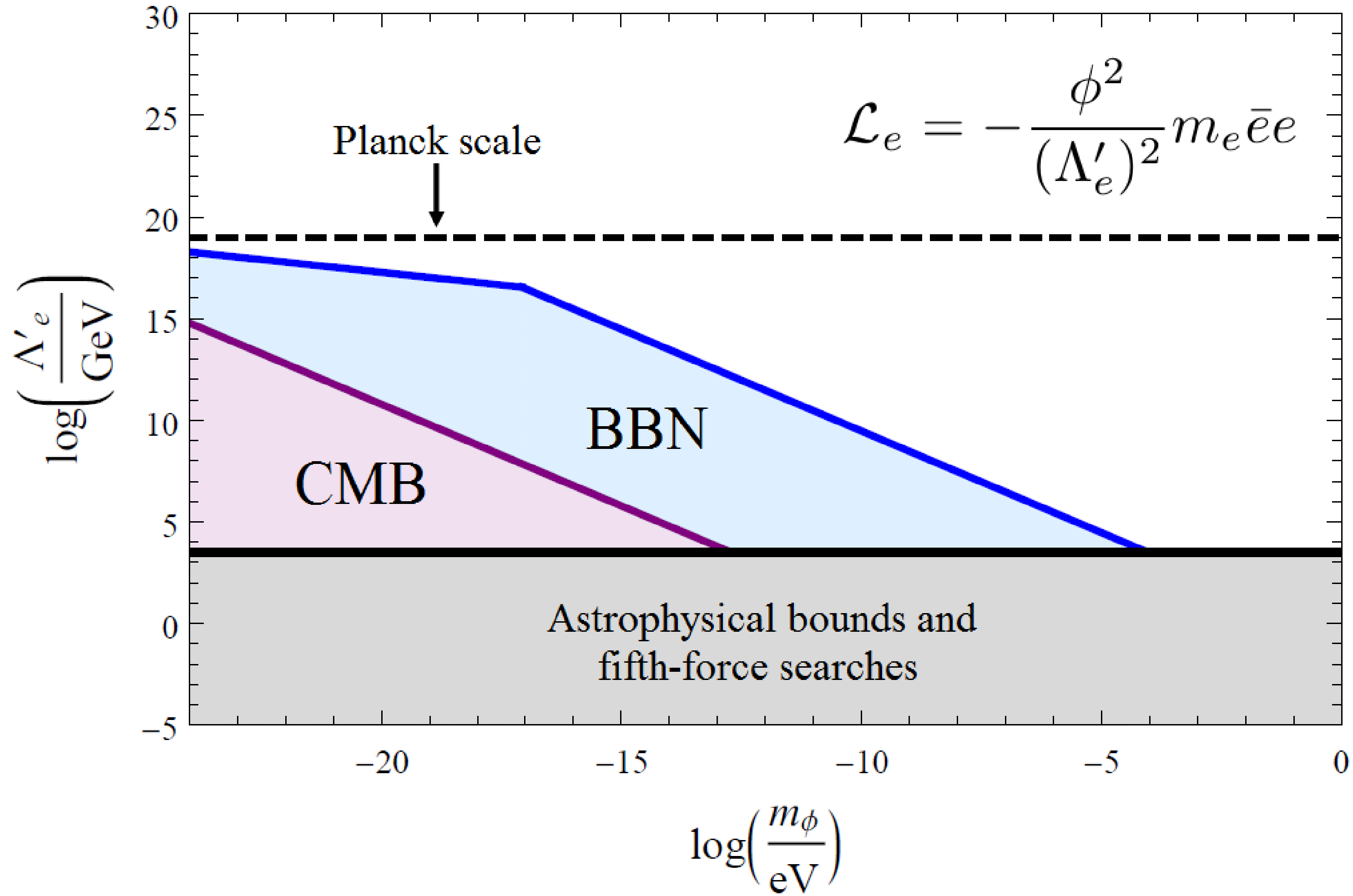
[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

BBN and CMB constraints:

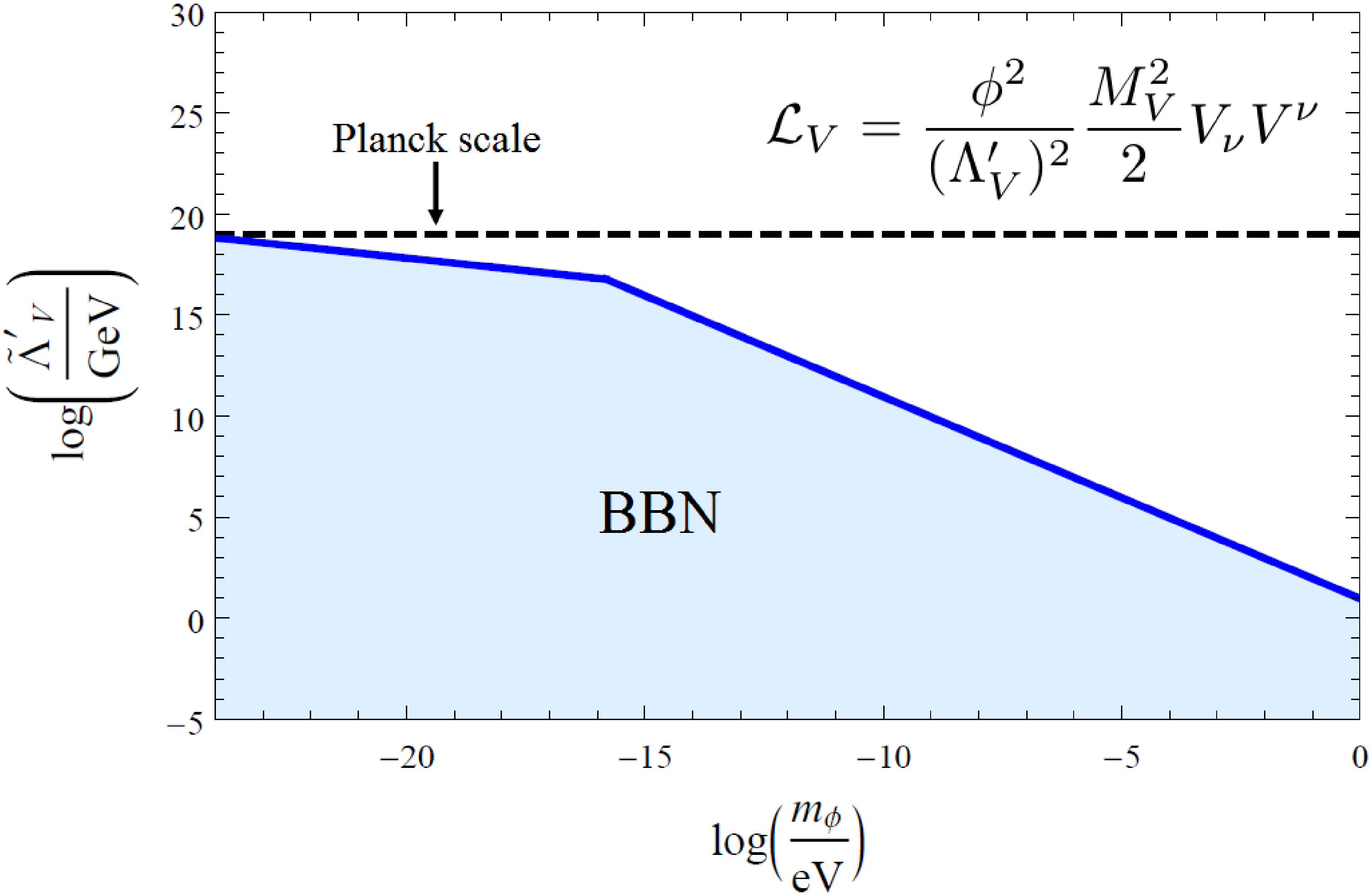
[Stadnik and V.F., *PRL* **115**, 201301 (2015)]



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

BBN constraints:

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

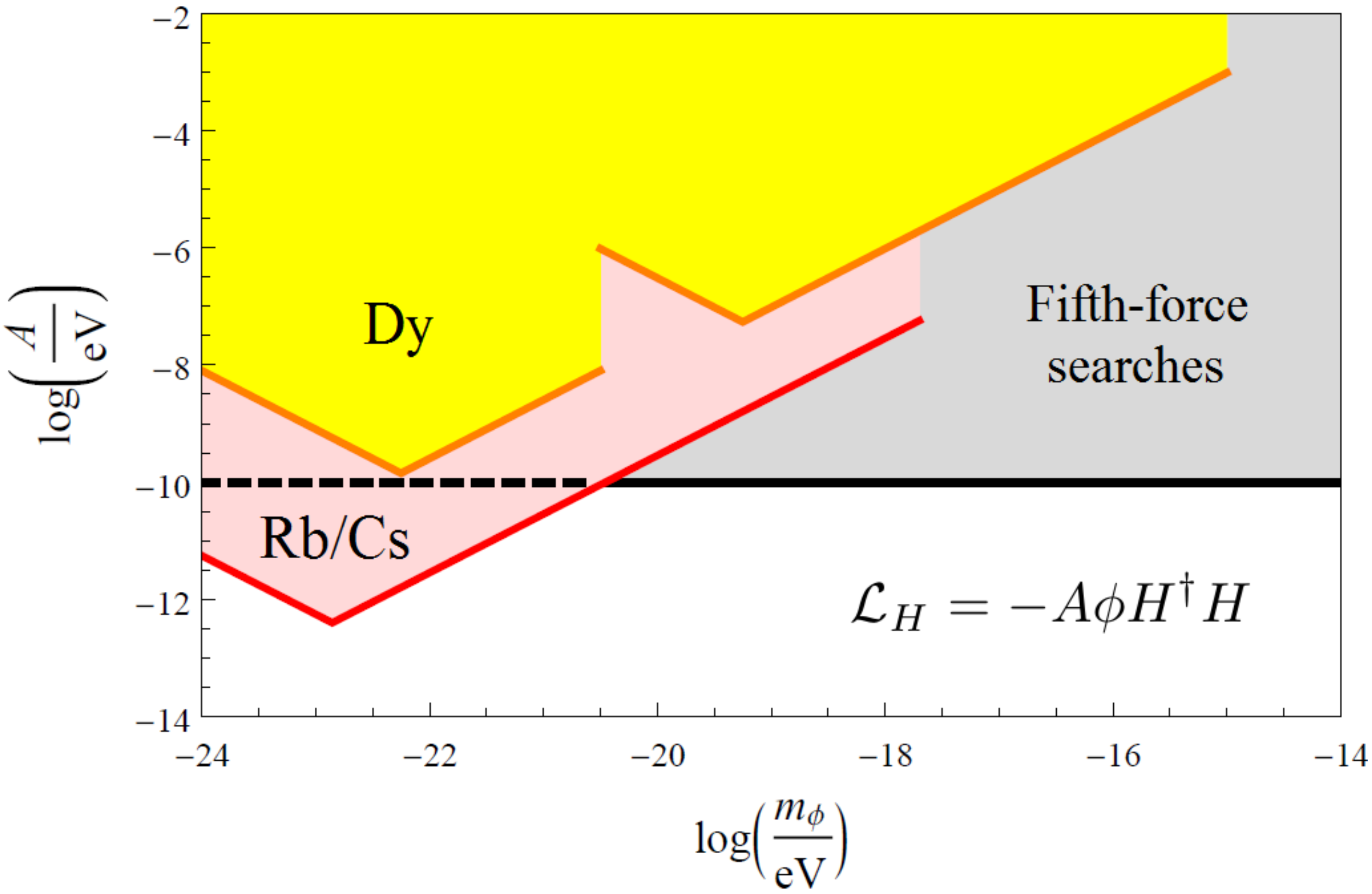


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

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

2 – 3 orders of magnitude improvement!



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

- Compare $L \sim N a_B$ with λ

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

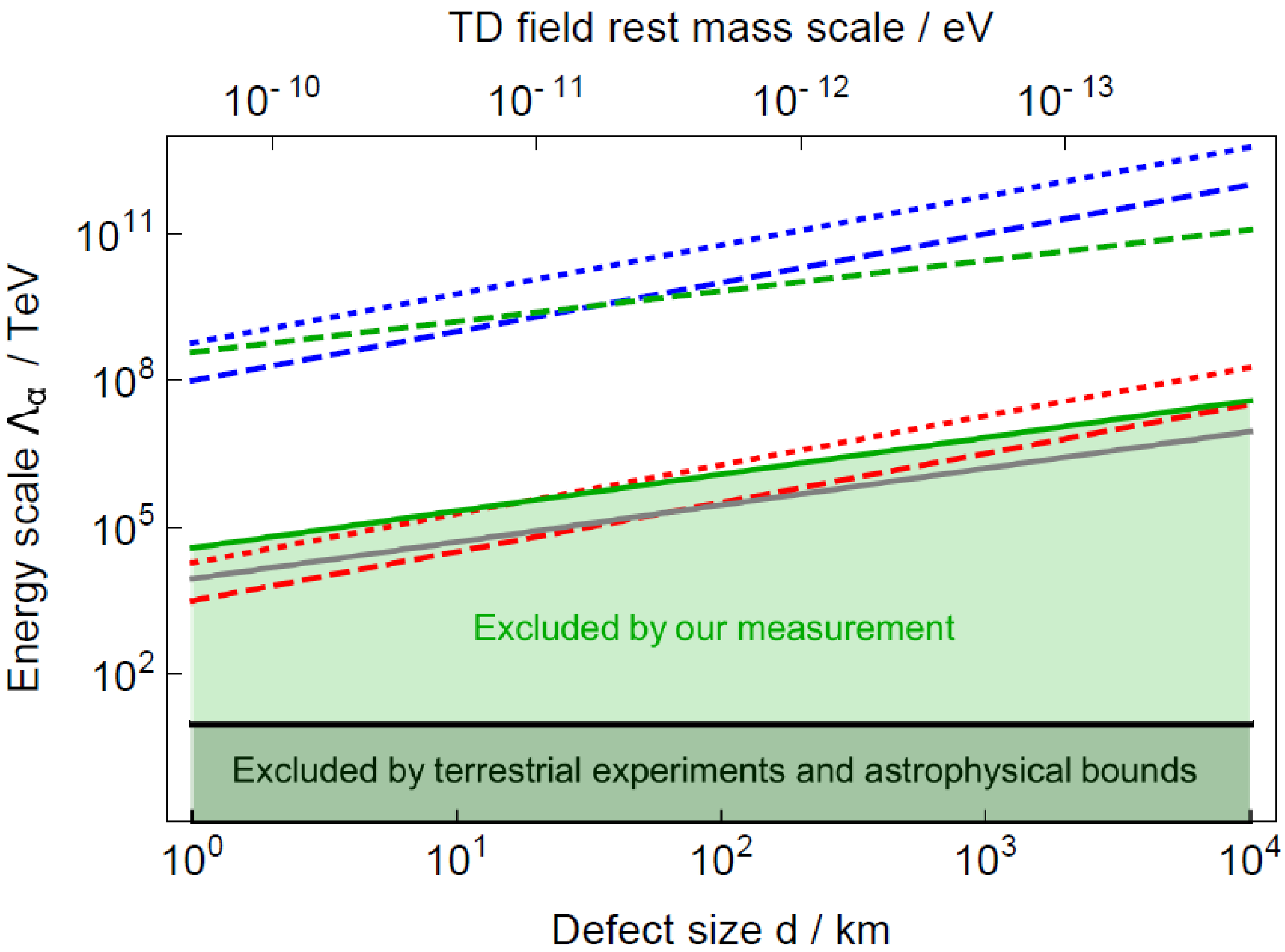
Multiple reflections of light beam enhance effect ($N_{eff} \sim 10^5$ in small-scale interferometers with highly reflective mirrors).

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\, \delta\alpha/\alpha = 10^7\, \delta\alpha/\alpha$ 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)]

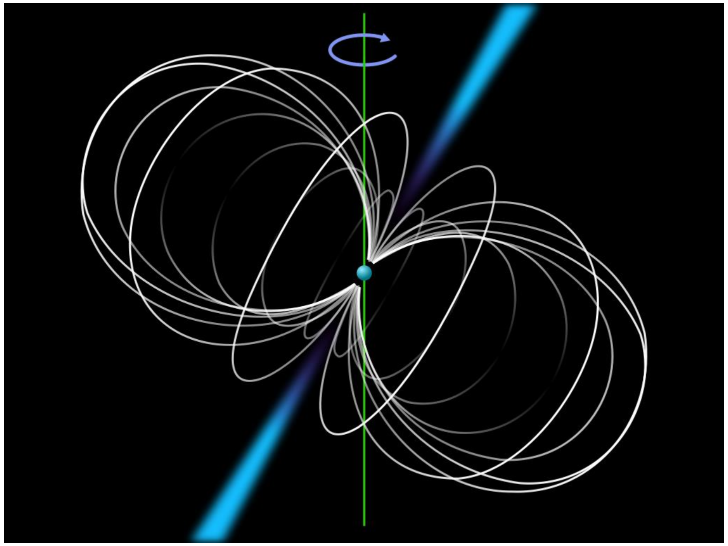


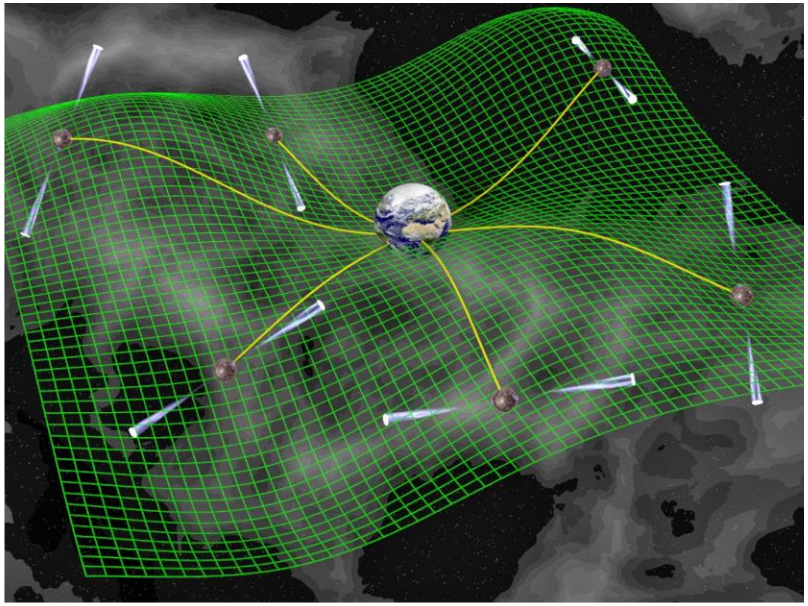
Pulsar Timing

[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*.

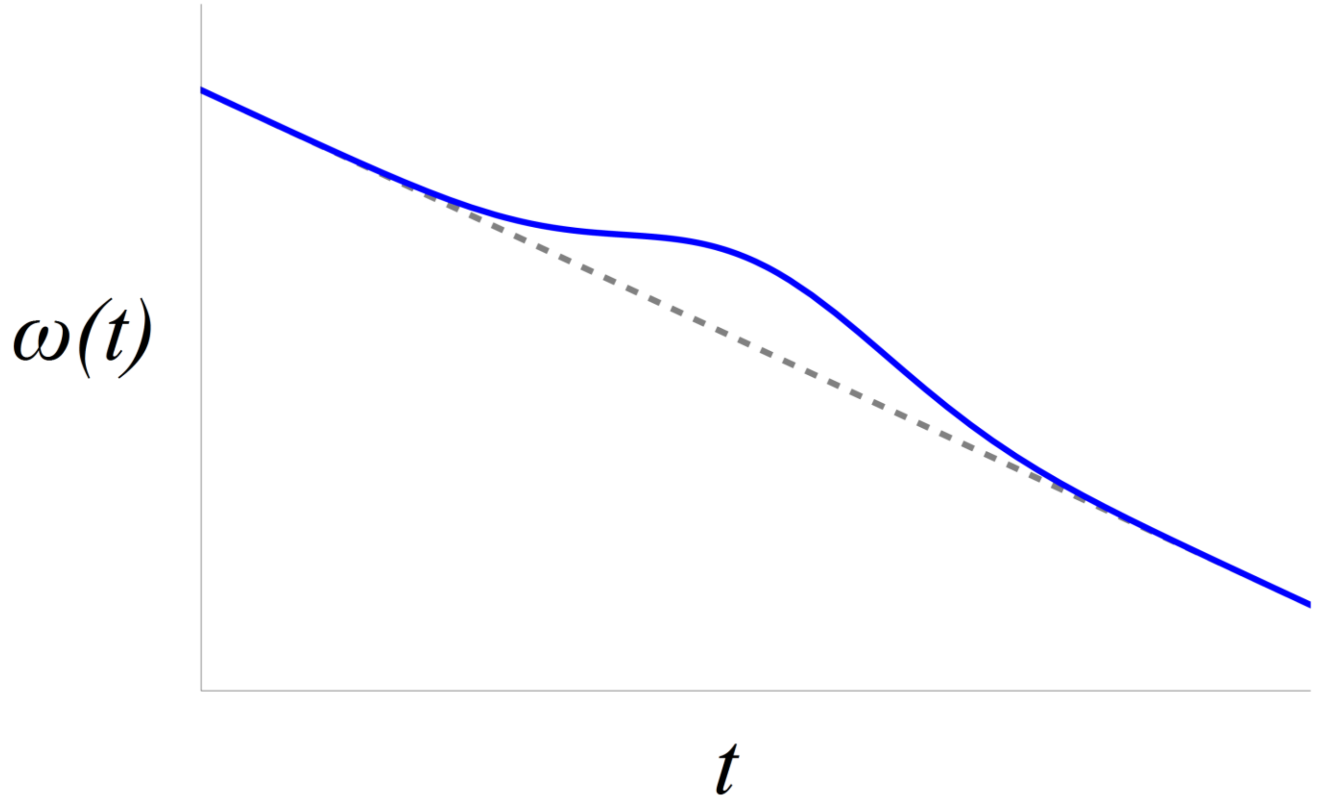




Pulsar Timing

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

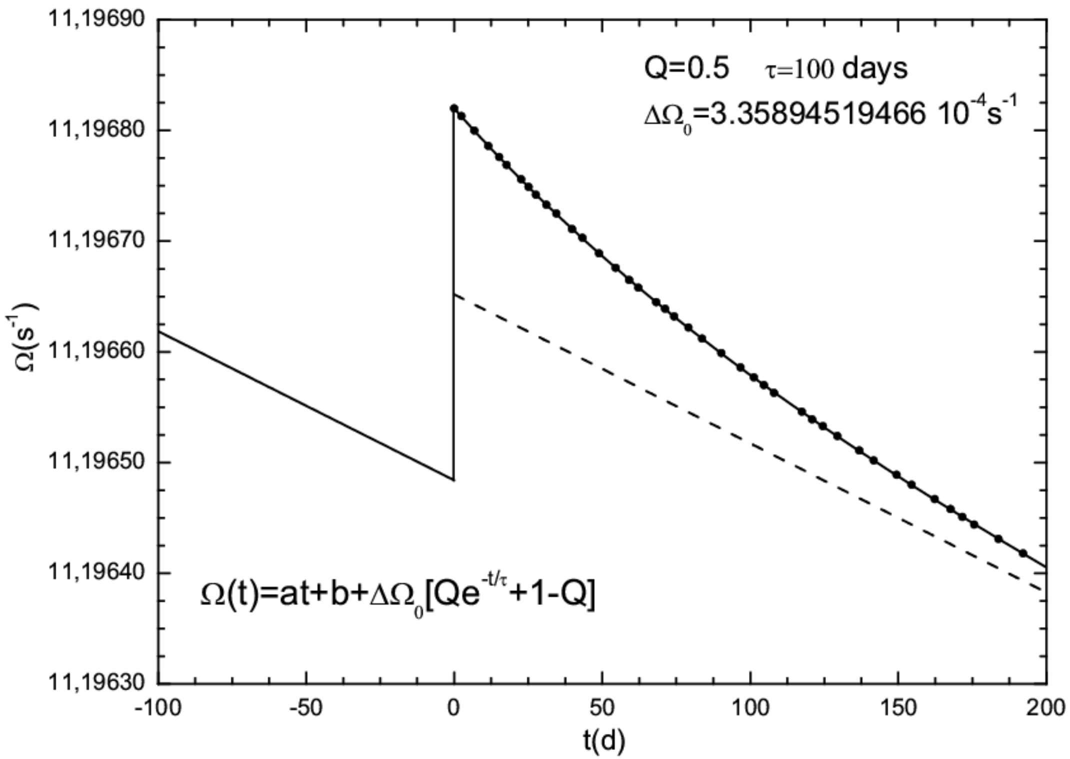
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile



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:

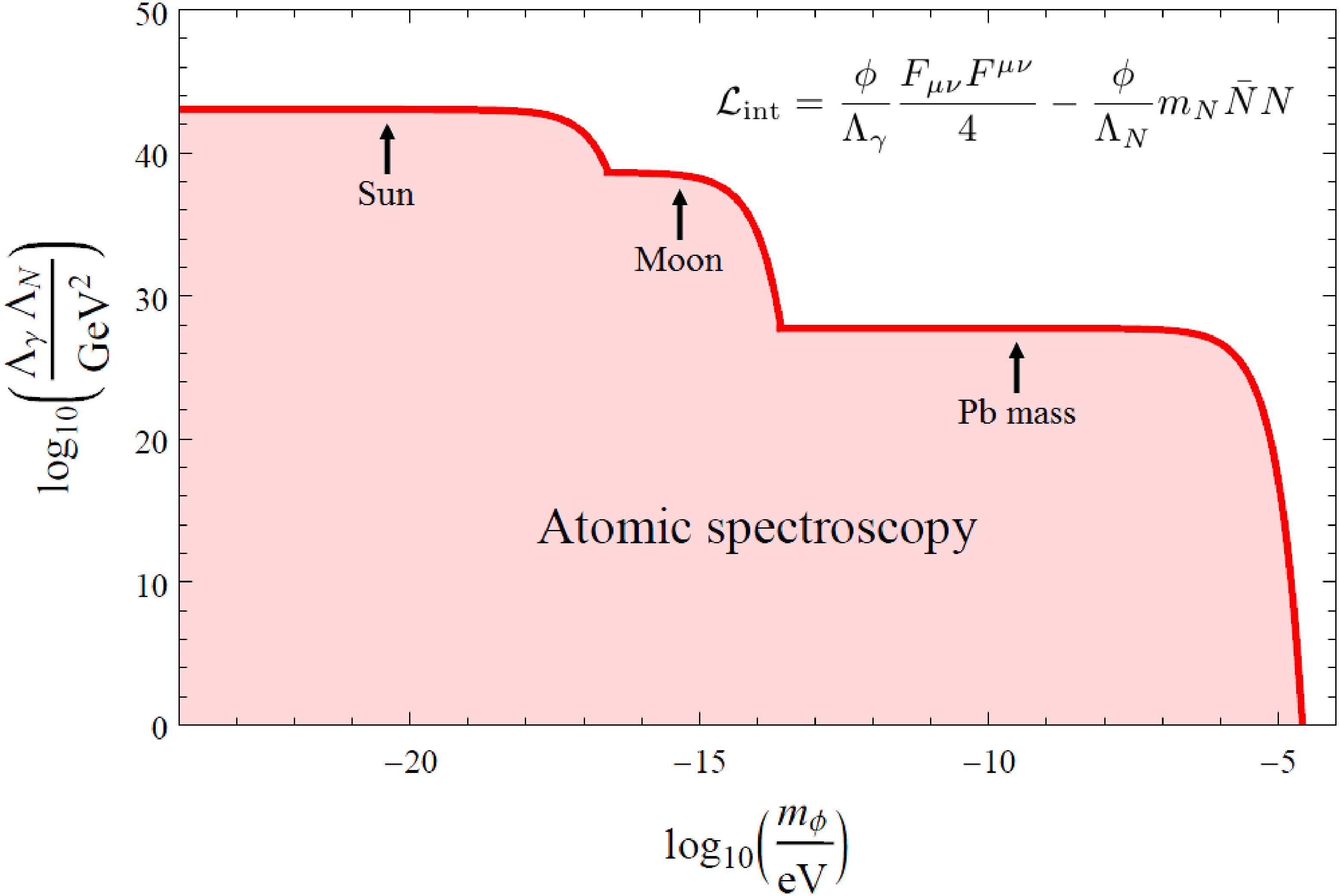
$$\frac{\delta m_f}{m_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \propto \frac{e^{-m_\phi r}}{r}$$

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

Constraints on 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, ALPs): *Odd-parity*

Axions explain the absence of *CP* violation in the strong interaction and are a leading dark matter candidate

⟶ Oscillating spin-dependent effects, EDM, *P*,*T*, Lorentz and Einstein symmetry violation

- Atomic and solid sate magnetometry
- Ultracold neutrons
- Electric dipole moments

"Axion Wind" Spin-Precession Effect

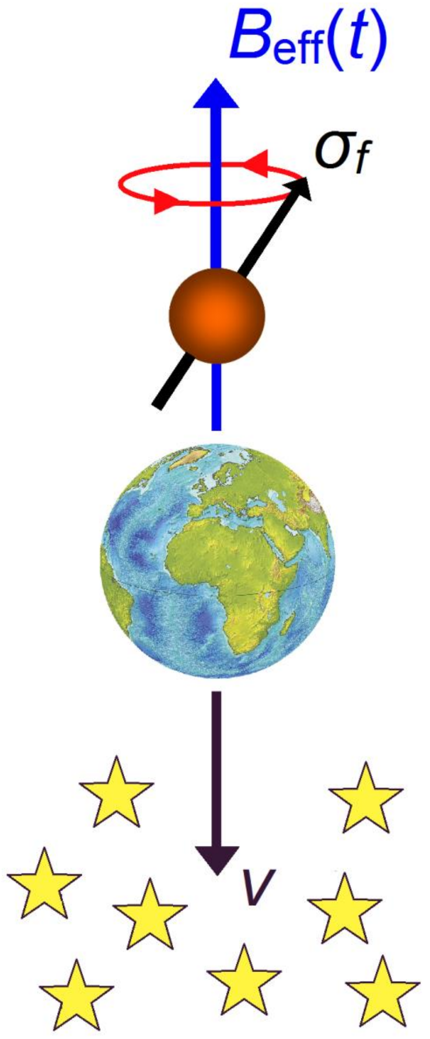
[V.F., talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik and V.F., *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field**

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

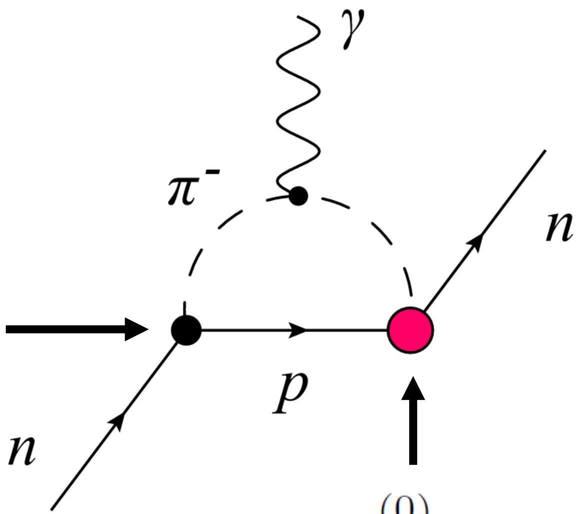


Axion-Induced Oscillating Neutron EDM

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

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

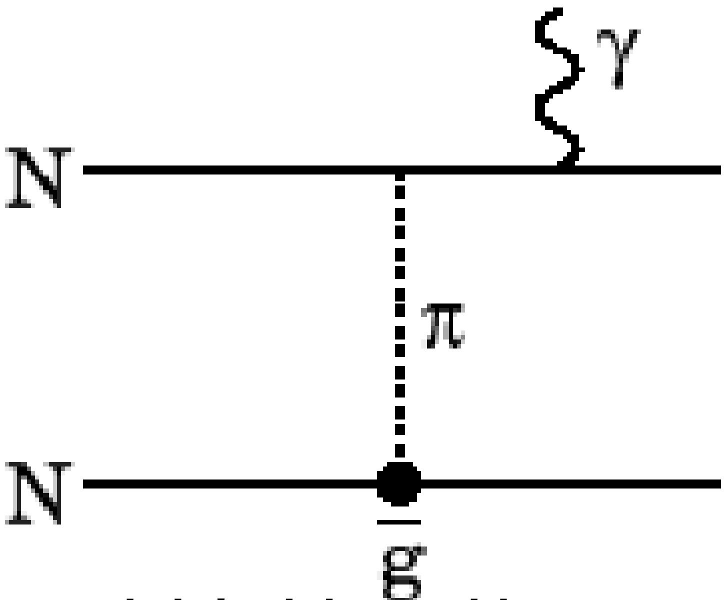
$$g_{\pi NN} = 13.5$$

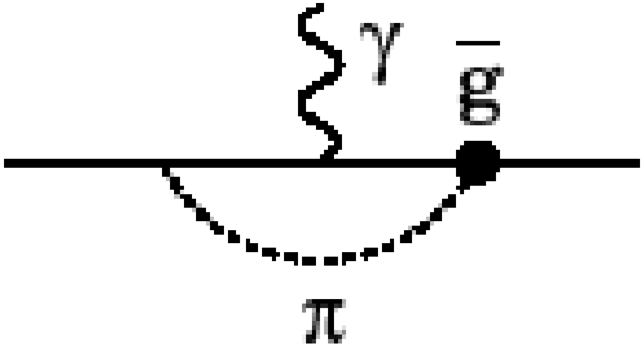


$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

Nuclear EDM: *P*,*T*-odd *NN* interaction gives 40 times larger contribution than intrinsic nucleon EDM

[Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]





Flambaum, Khriplovich, Sushkov 1984, 1986 calculations of nuclear EDM, Schiff moments, magnetic quadrupoles, atomic and molecular EDMs. Collective effects in deformed nuclei: further enhancement 10-1000 times, magnetic quadrupole(Flambaum), Schiff moment (Auerbach, Flambaum, Spevak)

Nuclear EDM-screening: d_N E_N

- Schiff theorem: $E_N=0$, neutral systems
- Extension for ions and molecules:

Ion acceleration $a= Z_i\, eE/M$

Nucleus acceleration $a=Z\, eE_N/M$, $E_N=E\, Z_i/Z$

SCREENING AND ENHANCEMENT OF OSCILLATING NUCLEAR ELECTRIC DIPOLE MOMENT INDUCED BY AXIONIC DARK MATTER

V. F. and H. B. Tran Tan,
arxiv:1904.07609

Oscillating nuclear EDM

$$d_N = d_0 \cos\omega t$$

- If $\omega \sim$ energy of the first rotational level or Ω-doublet $\bar{\omega}$

$$\vec{d}_{mol} \approx -\frac{2\mu\bar{\omega}\bar{X}\vec{d}}{3}\frac{\omega^2}{\bar{\omega}^2-\omega^2}\left(\frac{\vec{d}_1}{Z_1}-\frac{\vec{d}_2}{Z_2}\right) \approx -\frac{2\mu\bar{\omega}\bar{X}\vec{d}}{3}\frac{\omega^2}{\bar{\omega}^2-\omega^2}\frac{\vec{d}_1}{Z_1}$$

assuming $Z_1 \ll Z_2$. Light nucleus dominate (recall static case $Z_i\ /Z$).

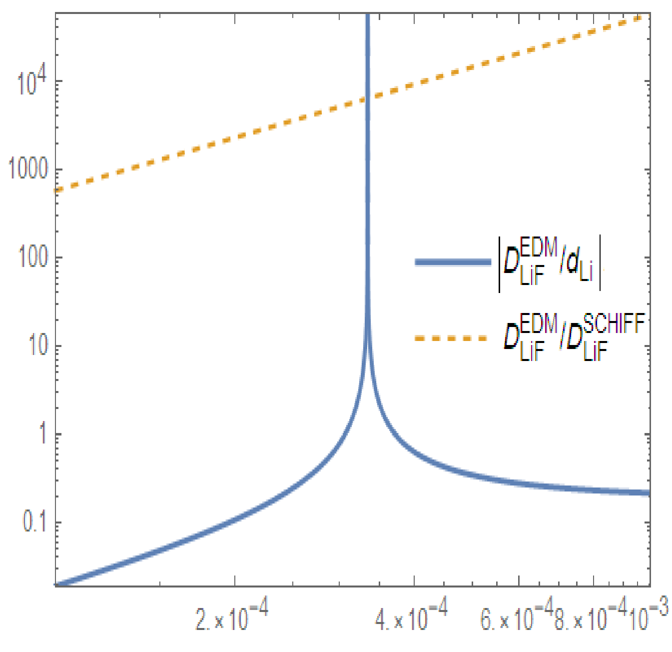
- In resonance $\omega = \bar{\omega}$: $\vec{d}_{mol} \approx -\frac{2\vec{d}}{3Z_1\bar{X}}\frac{\bar{\omega}}{\Gamma}\vec{d}_1$ where

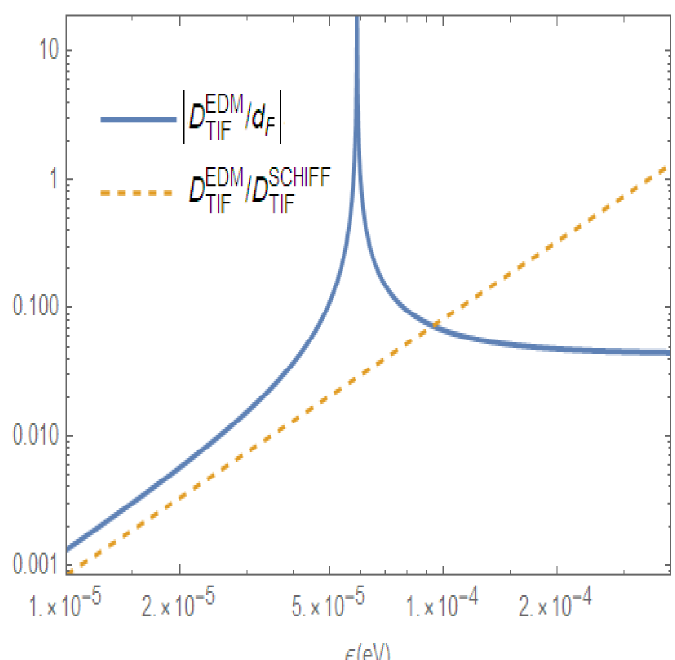
$$\frac{\Gamma}{\bar{\omega}} \approx \frac{\langle v^2 \rangle}{c^2} \sim 10^{-6}$$

- Big resonance enhancement factor.
- The mechanisms of enhancement in molecules : d_{mol}/d_N has large coefficient $\frac{\mu}{m_e} \sim 10^4$, μ is the reduced nuclear mass. Nuclei moves slowly and do not provide efficient screening of oscillating nuclear EDM. Small rotational energy denominator gives additional enhancement factor $\frac{\mu}{m_e} \sim 10^4$. Resonance gives an additional enhancement.

Ratio of oscillating molecular and nuclear EDM – LiF and TlF

- **Solid line**: ratio of induced molecular EDM and nuclear EDM (V. F. and H. B. Tran Tan - arXiv:1904.07609).
- **Dashed line**: ratio between induced molecular EDM produce by nuclear EDM and by oscillating nuclear Schiff moment (O. Sushkov, V. F. and I. Khriplovich – *JETP* 60, 873, 1984; Y. Stadnik and V.F. – PRD 89, 043522





Why are molecules good?

- Nuclei are much heavier than electrons → react much more slowly to an oscillating perturbation → screening is weaken. This is the root of the enhancement factor $M_{nuc}/m_e \geq 10^4$.
- Further possible enhancement from small energy denominator and large polarizability.
- Possibility of resonances since expected dark matter mass is in the resonance region (first rotational level or Ω-doublet).
- Possibility of resonance energy interval tuning by magnetic and electric fields.

Axion-Induced Oscillating Atomic and Molecular EDMs

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

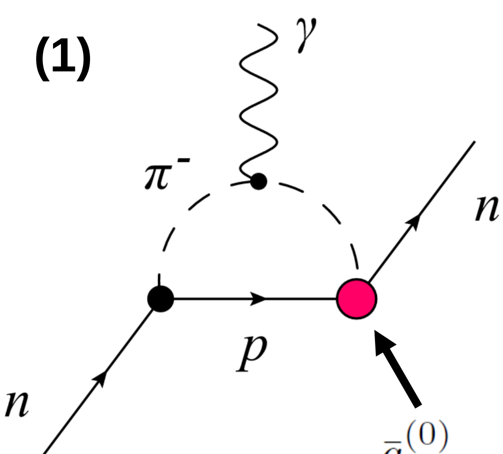
Induced through *hadronic mechanisms*:

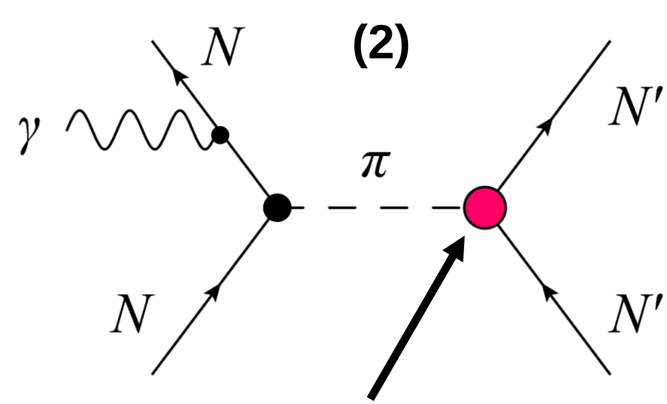
- Oscillating nuclear EDM and Schiff moments (*I* ≥ 1/2 => *J* ≥ 0)
- Oscillating nuclear magnetic quadrupole moments (*I* ≥ 1 => *J* ≥ 1/2; *magnetic* => no Schiff screening)

Underlying mechanisms:

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

(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~4π² ≈ 40**; up to **extra 1000-fold enhancement** in deformed nuclei)



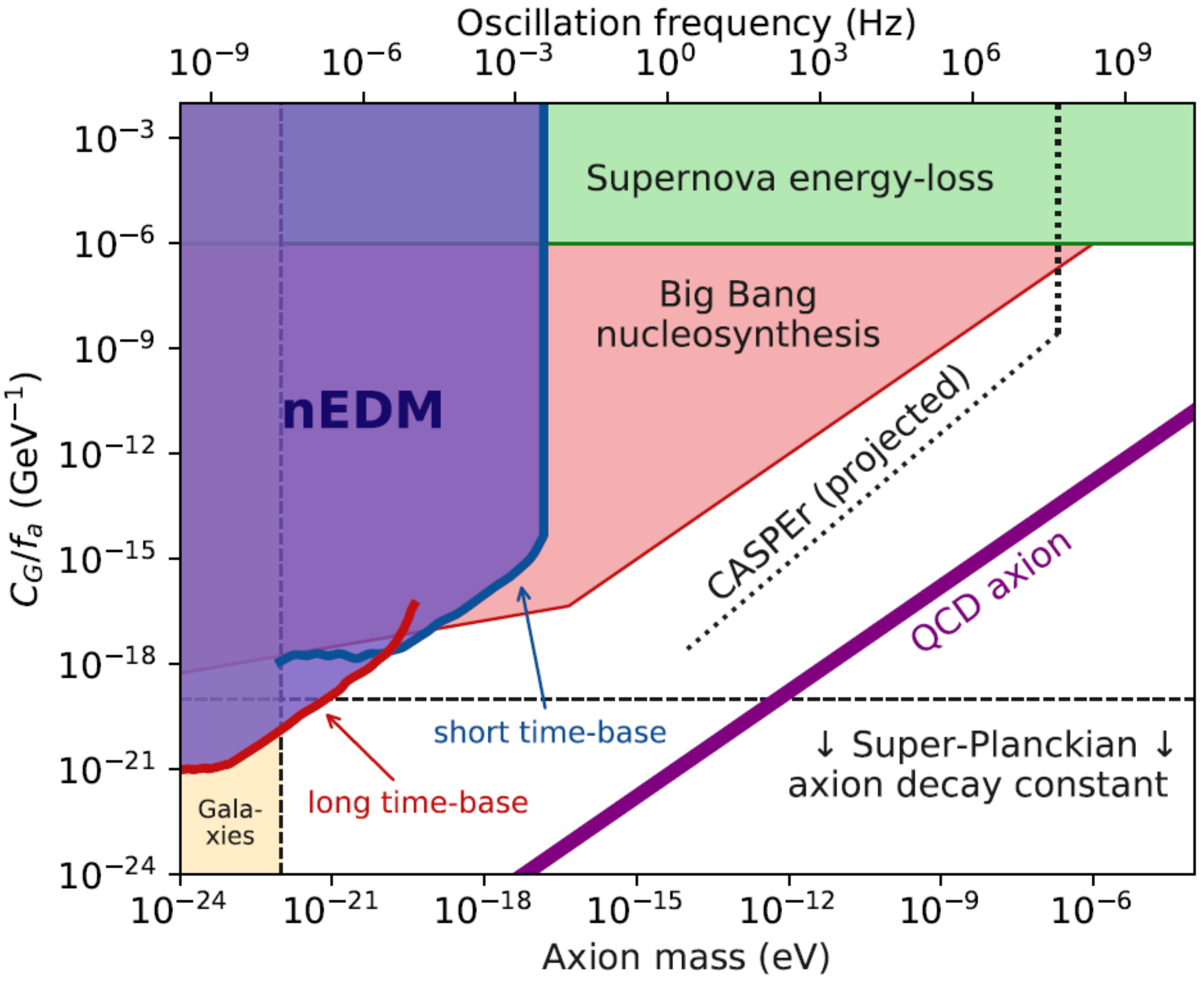


$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\; C_G a_0 \cos(m_a t)/f_a$$

Constraints on Interaction of Axion Dark Matter with Gluons

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

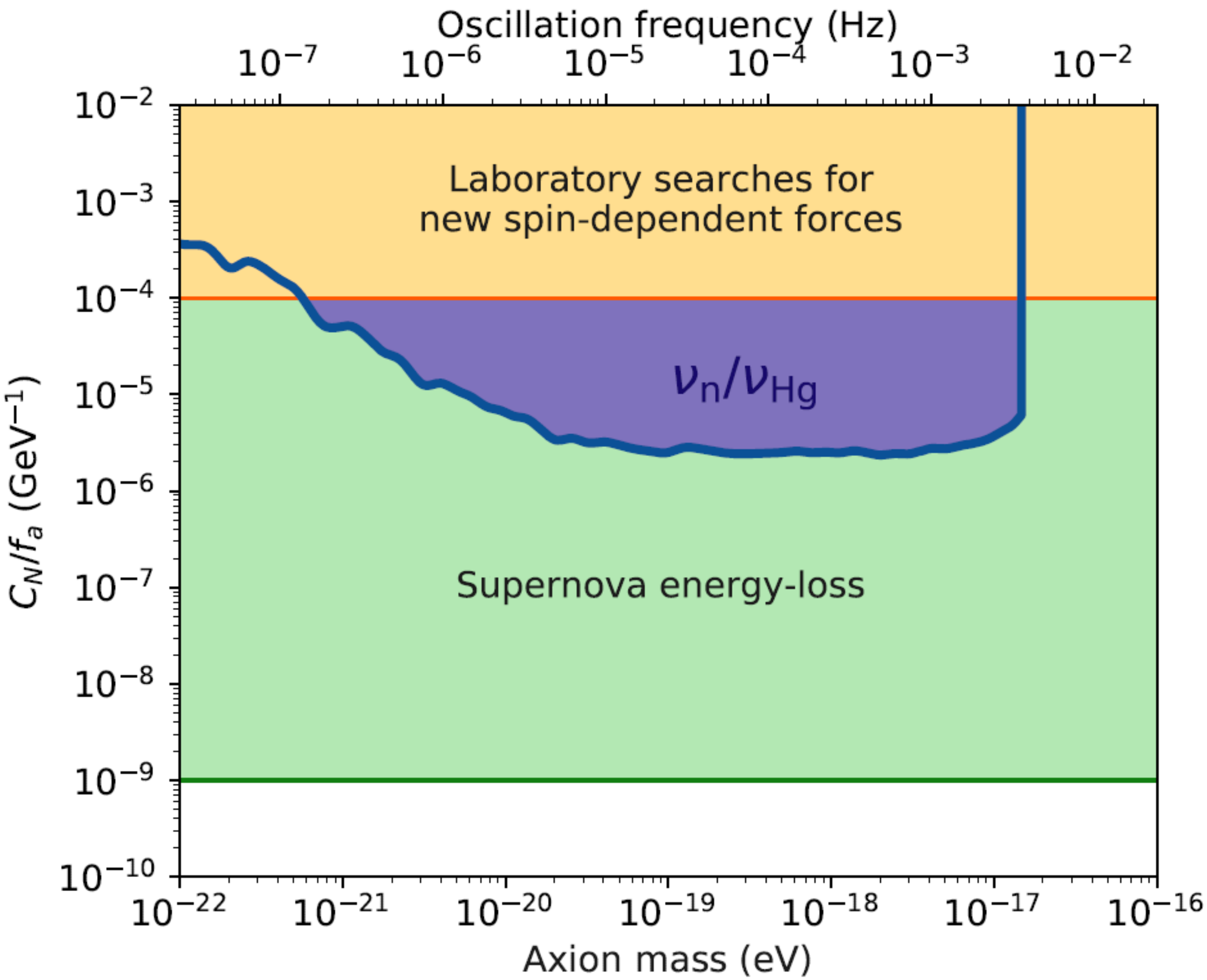
EDM n, Hg. 3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

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

40-fold improvement!



OSCILLATING NUCLEAR ELECTRIC DIPOLE, MAGNETIC QUADRUPOLE AND SCHIFF MOMENTS, INDUCED BY AXIONIC DARK MATTER, PRODUCE MOLECULEAR TRANSITIONS

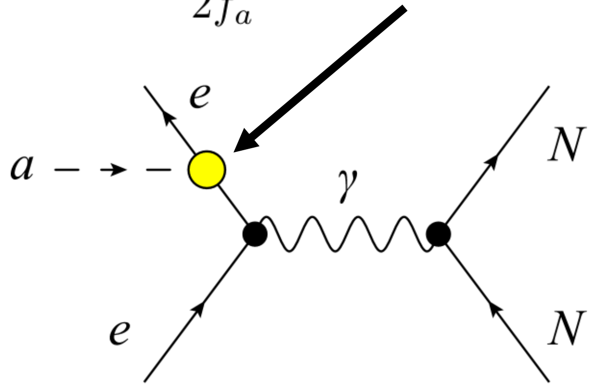
V. F. , Budker, Wickenbrock, arxiv: 1909.04970

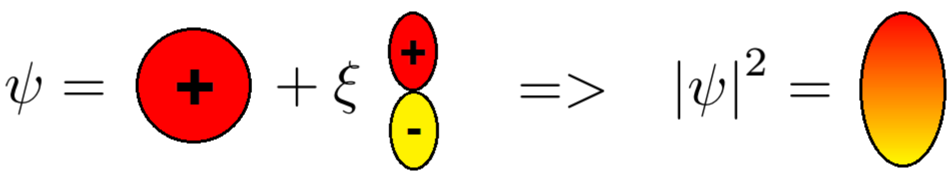
Axion-Induced Oscillating Atomic and Molecular EDMs in paramagnetic systems

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

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

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





Interference-assisted resonance detection of axion and dark photon

Tran Tan, V.F. , Samsonov, Stadnik, Budker, 2018

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}.

Coherent axion-photon transformation in the forward scattering on atoms

V.F., Samsonov, Tran Tan, Budker, PRD 2018

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.

$$L_{eff}=g_{ae}a(EB_{eff}+BE_{eff})$$

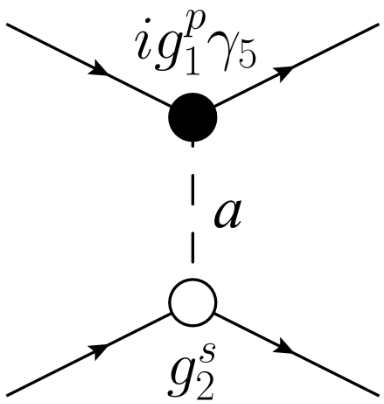
Witten; Zhitnitsky et al: Axion quark nuggets (AQN) and antinuggets.
Spherical axion domain wall produces pressure keeping inside quarks or antiquarks in color superconducting state.
Solution for dark matter and bariogenesis. Equal number of quarks and antiquarks but antiquarks survived inside antinuggets only.

Primordial Lithium Puzzle and the Axion Quark Nugget Dark Matter Model. V.F. and R. Zhitnitsky, Phys. Rev. D 99, 023517 (2019), arXiv:1811.01965

Capture rate ~ exp(-Z^{AQN} Z e^2/RT), AQN captures Li (Z=3) and Be (Z=4), this explains factor of 3 suppression of the primordial Li abundance

Axion Quark Nuggets and how a Global Network can discover them, Budker, V.F. , Liang, Zhitnitsky, arXiv: 1909.
AQN passes through Earth and generates axion wave which produces correlated effects in a network of devices (GNOME model)

Non-Cosmological Sources of Exotic Bosons



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

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

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

- *P*,*T*-violating forces => Atomic and Molecular EDMs
  [Stadnik, Dzuba, and V.F, arXiv:1708.00486]

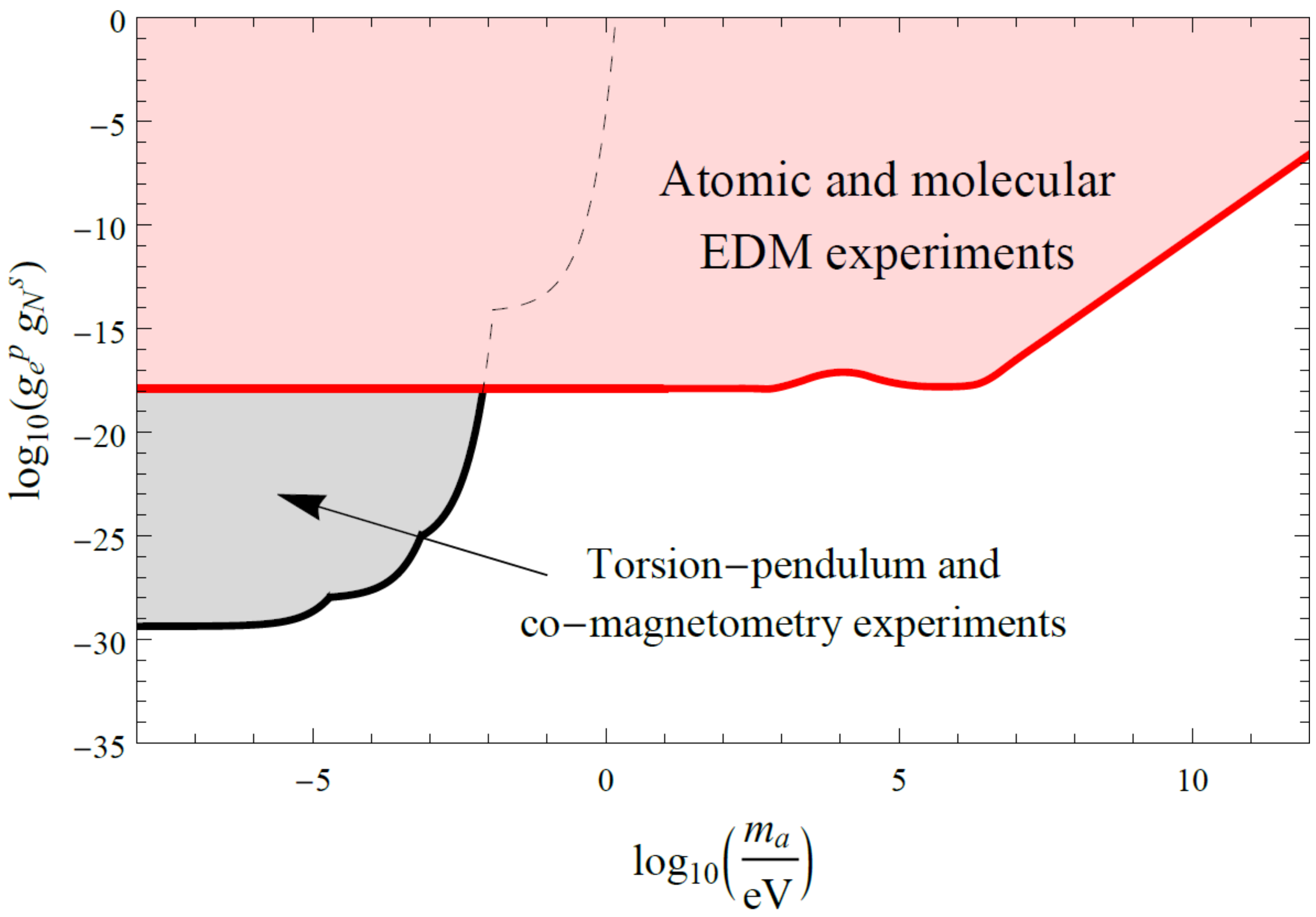
Atomic EDM experiments: Cs, Tl, Xe, Hg

Molecular EDM experiments: YbF, HfF^+, ThO

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

EDM constraints: [Stadnik, Dzuba and V.F., arXiv:1708.00486]

Many orders of magnitude improvement!



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)
- **Up to 15 orders of magnitude improvement** on interactions of scalar dark matter with the photon, electron, quarks, Higgs, W^+,W^-,Z^0
- Oscillating effects of variation of fundamental constants and violation of the fundamental symmetries: P, T, EDM, Lorentz, Einstein equivalence principle
- **Axion Quark Nugget passes through Earth and generates axion wave which produces correlated effects in a network of devices (GNOME model)**
- Enormous potential for low-energy atomic experiments to search for dark matter with unprecedented sensitivity