New effects of dark matter which are linear in the interaction strength: Variation of the fundamental constants

V. Flambaum, Y. Stadnik, B. Roberts, V. Dzuba, D. Budker, N. Leefer

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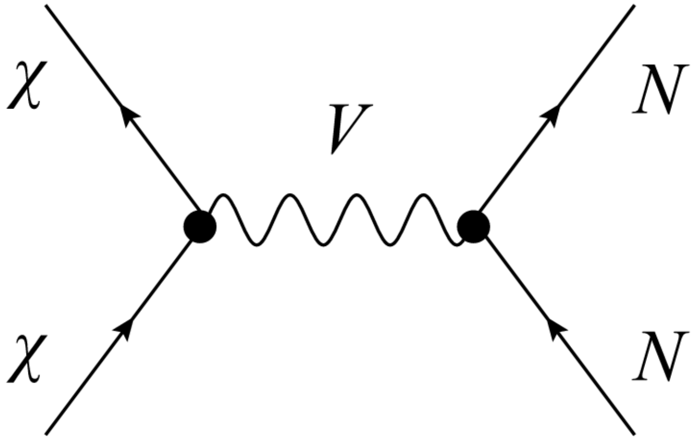
University of New South Wales, Sydney, Australia

Motivation

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



$$\mathcal{M}_{\rm scat} \propto (e')^2$$
$$=> \sigma_{\rm scat} \propto (e')^4$$

Observable is **quartic** in the interaction constant *e'*, which is extremely small!

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 ($\langle\rho_\varphi\rangle \approx m_\varphi^2\varphi_0^2/2$): $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, via effects that are <u>**linear**</u> 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 <u>**15 orders of magnitude**</u>, as well as derive the <u>**first constraints**</u> on some other interactions of dark matter.

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

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

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 and molecular 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 astrophysical puzzles (cusp-core, missing satellite and too-big-to-fail problems, etc.)

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,

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

Molecular calculations

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

We performed atomic, QCD and nuclear calculations.

Nuclear clock ^{229}Th

Evidence for spatial variation of the fine structure constant

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

Quasar spectra

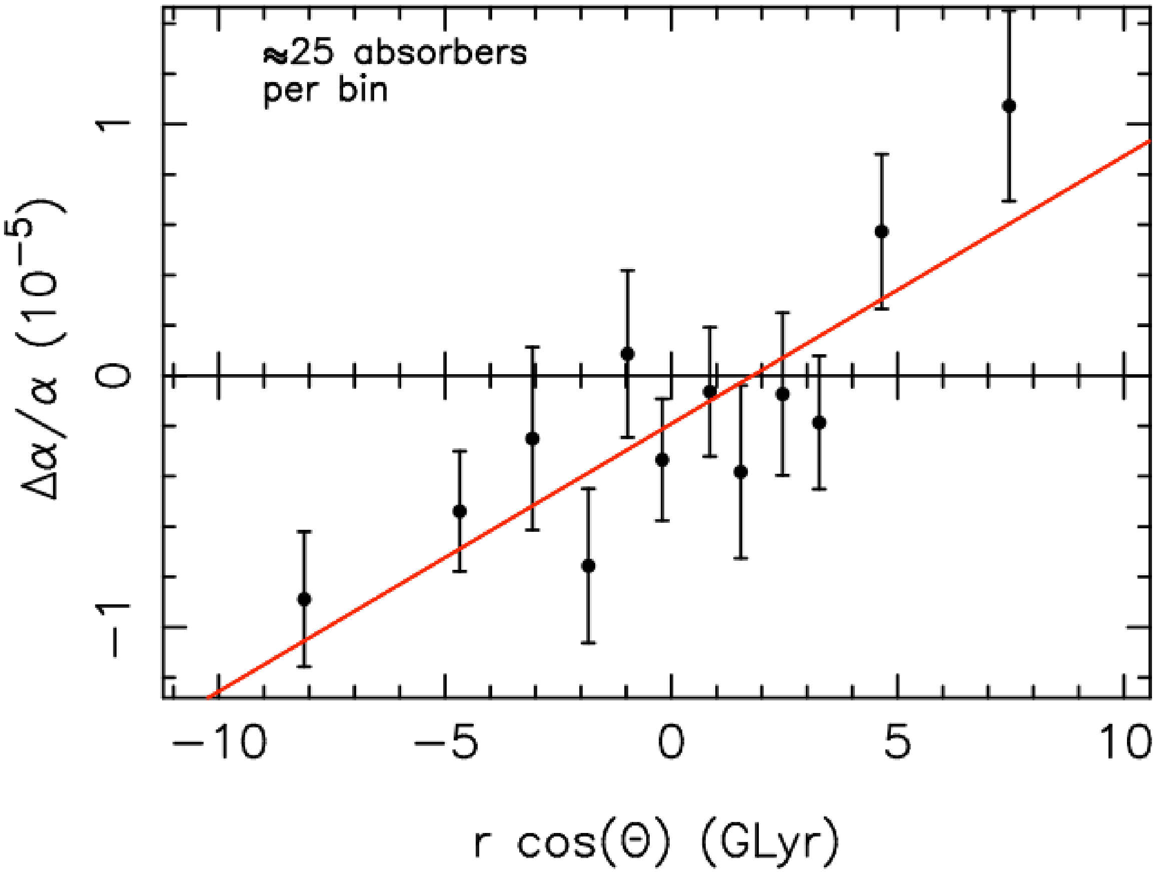
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

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

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

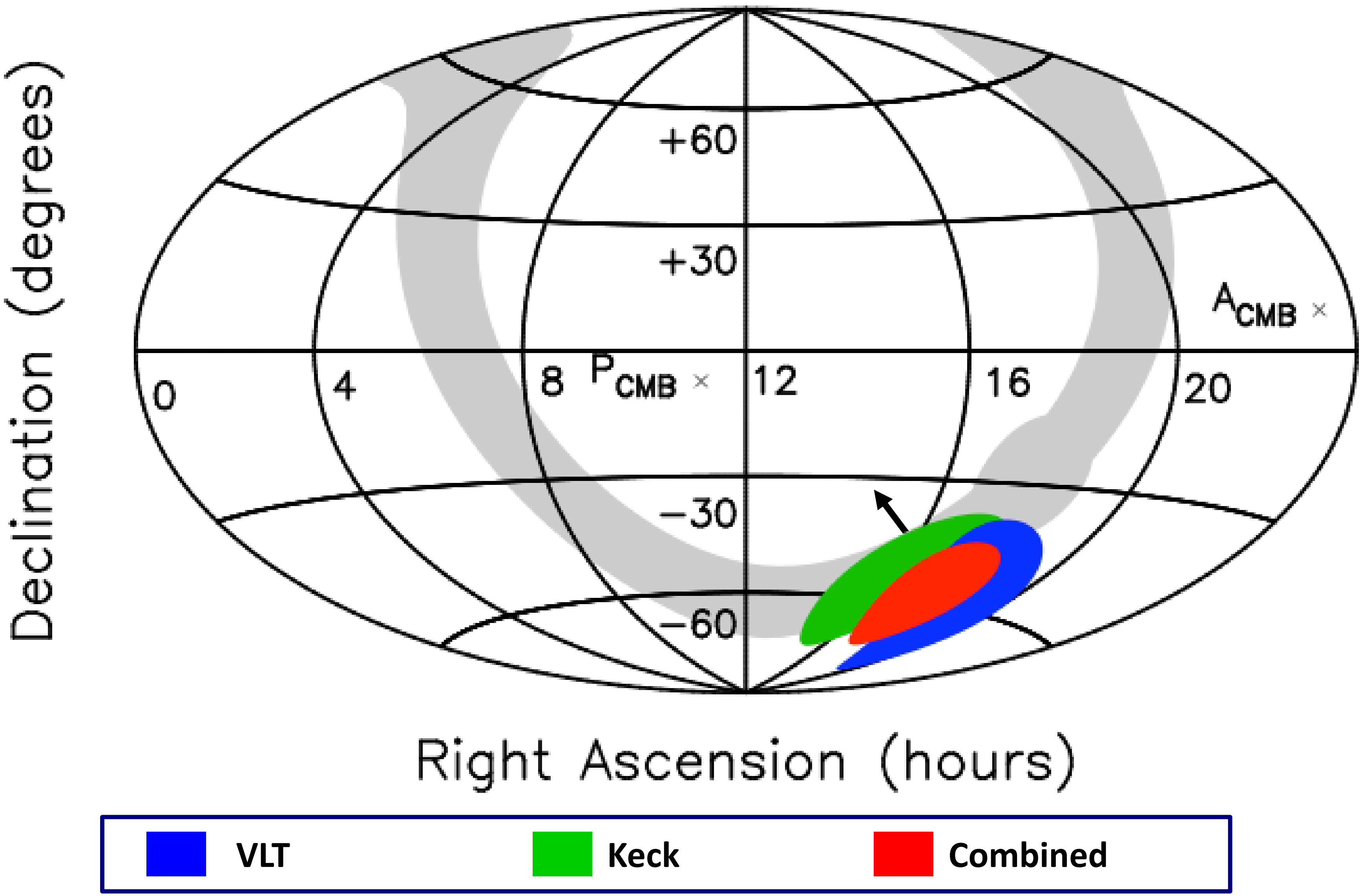
Reconciles all measurements of the variation

Distance dependence

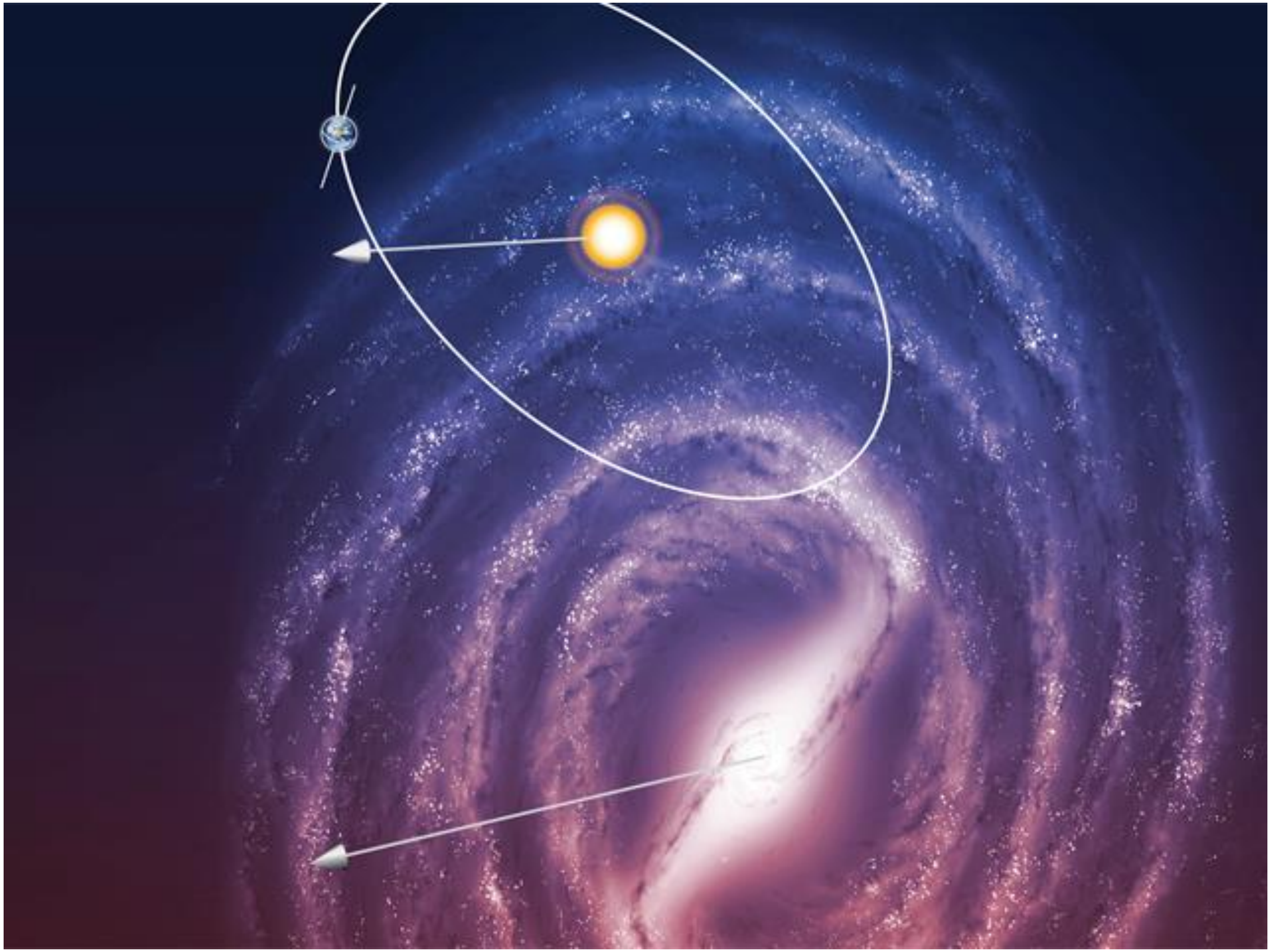


Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} GLyr^{-1} and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically 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%



Gradient α points down



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

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

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

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

[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.

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

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

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

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

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

Photon:

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

Fermions:

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

Bosons W,Z (mediators of weak interactions):

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

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_{weak} = 1s until t_{BBN} = 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).

Weak interactions: freeze-out of weak interactions occurs at t_{weak} = 1s (T_{weak} = 0.75 MeV).

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

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

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

Laser Interferometry (LIGO, Virgo, GEO600, TAMA300, smaller-scale)

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

Laser interferometers can be used to search for *oscillating effects* produced by *scalar field*.

Accumulated phase in an arm, $\Phi = \omega L/c$, changes if fundamental constants change ($L = Na_B$ and ω_{atomic} depend on the fundamental constants).

$$\Phi = \frac{\omega_{\mathrm{electronic}} L}{c} \approx \left(\frac{e^2}{a_{\mathrm{B}}\hbar}\right)\left(\frac{N a_{\mathrm{B}}}{c}\right) = N\alpha$$

$$=> \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\, \delta\alpha/\alpha = 10^{11}\, \delta\alpha/\alpha$ single passage, up to $10^{14}\, \delta\alpha/\alpha$ for maximal number of reflections

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

[Arvanitaki, Huang,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 $\leq m_\varphi \leq 0.1$ eV => 10^{-8} Hz $\leq f \leq 10^{14}$ Hz], with $\Delta f/f \sim 10^{-6}$.
- Need to search over a broad range of frequencies.

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

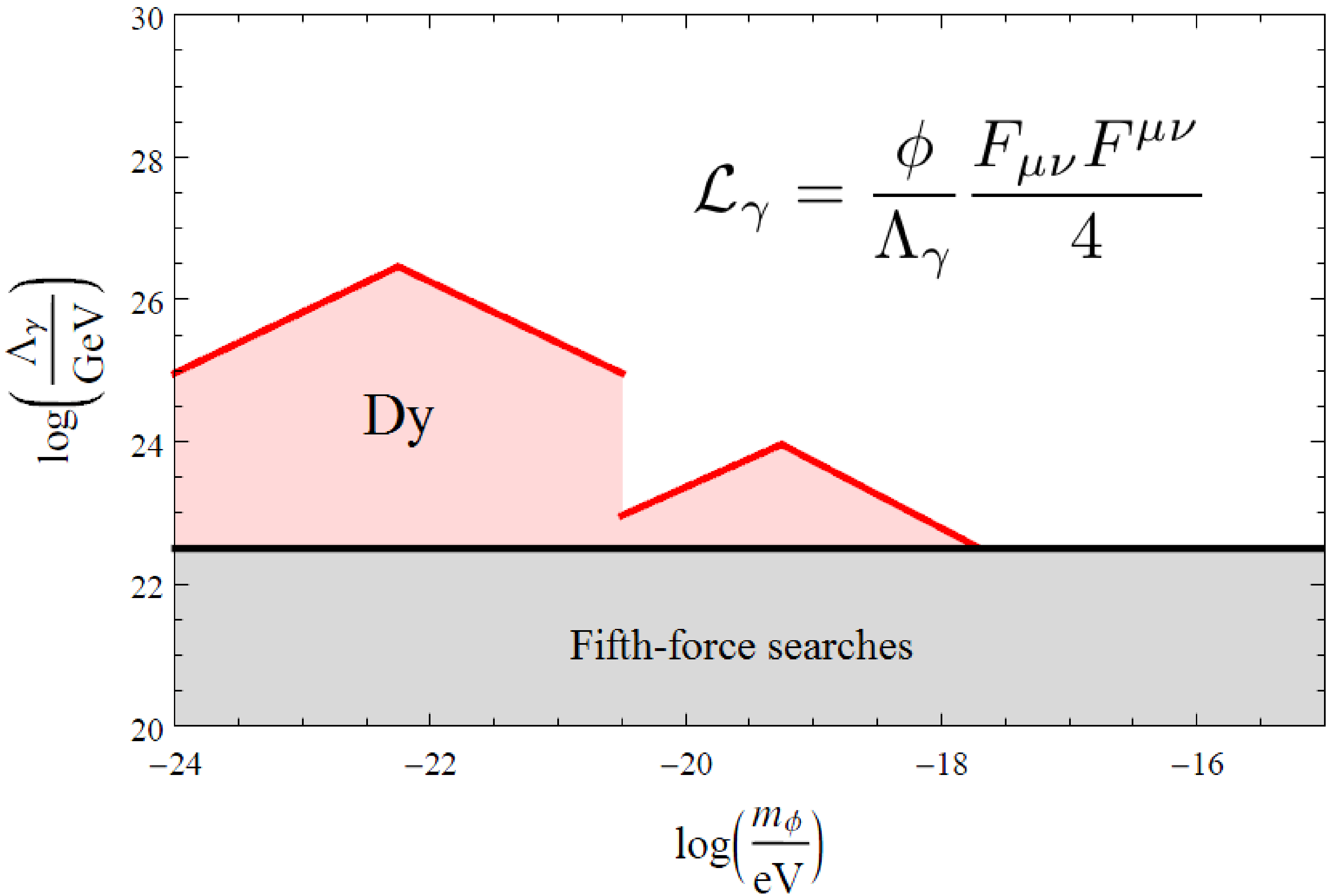
System	Λ'_γ	Λ'_e	Λ'_p	Λ'_q
Atomic (Dy, optical clock)	+	-	-	-
Atomic (hyperfine)	+	+	+	+
Highly charged ionic	+	-	-	-
Molecular (hyperfine/rotational)	+	+	+	+
Molecular (fine-structure/vibrational)	+	+	+	+
Molecular (Ω-doubling/hyperfine)	+	+	+	+
Nuclear (e.g. ^{229}Th)	+	-	+	+
Laser interferometer,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

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

System	Laboratory	Constraints
$^{162,164}Dy/^{133}Cs$	UC Berkeley	Van Tilburg, Leefer, Bougas, Budker, *PRL* **115**, 011802 (2015); Stadnik, Flambaum, *PRL* **115**, 201301 (2015) + arXiv:1605.04028
$^{87}Rb/^{133}Cs$	LNE-SYRTE Paris	Hees, Guena, Abgrall, Bize, Wolf, arXiv:1604.08514; Stadnik, Flambaum, arXiv:1605.04028

Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

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

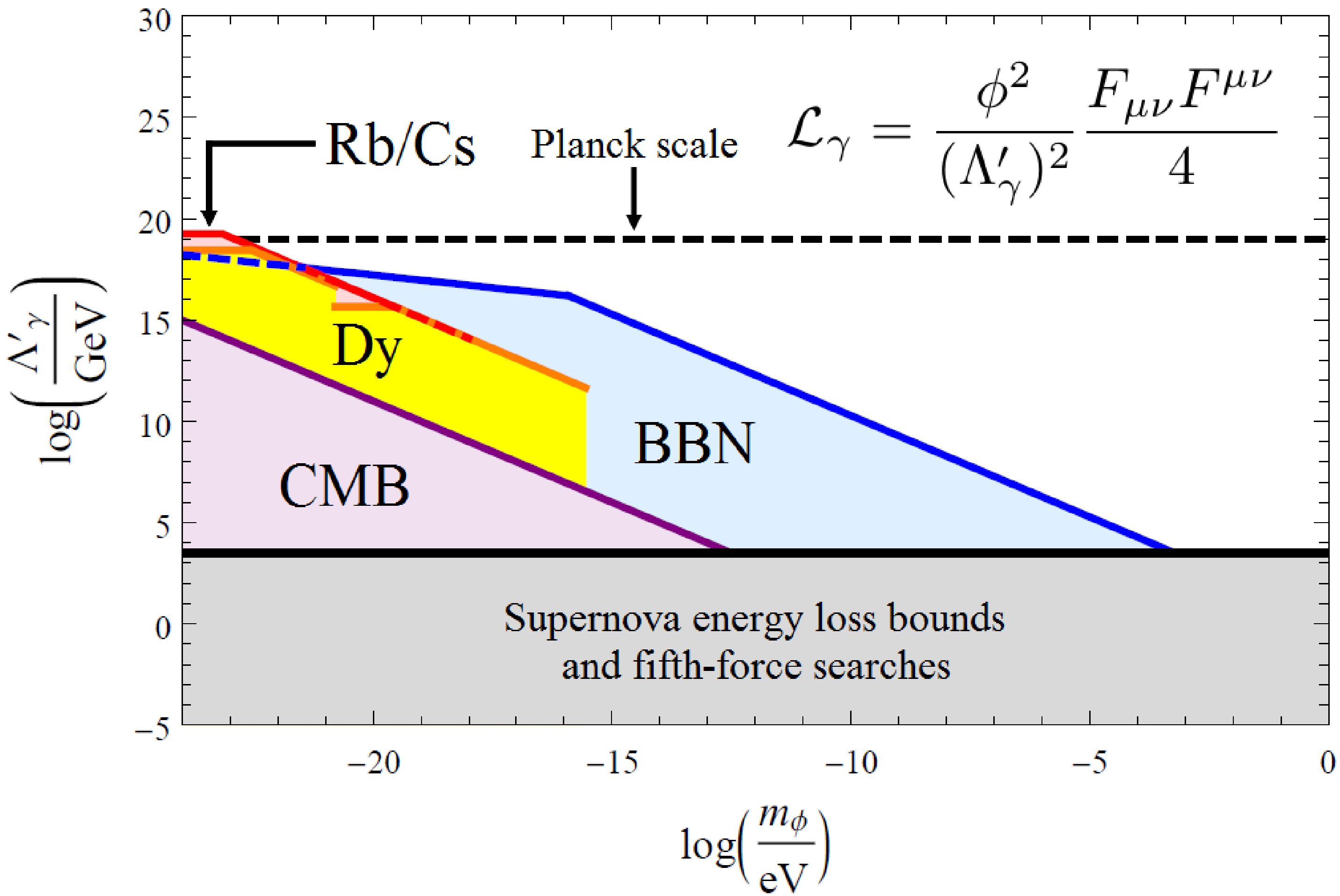


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

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

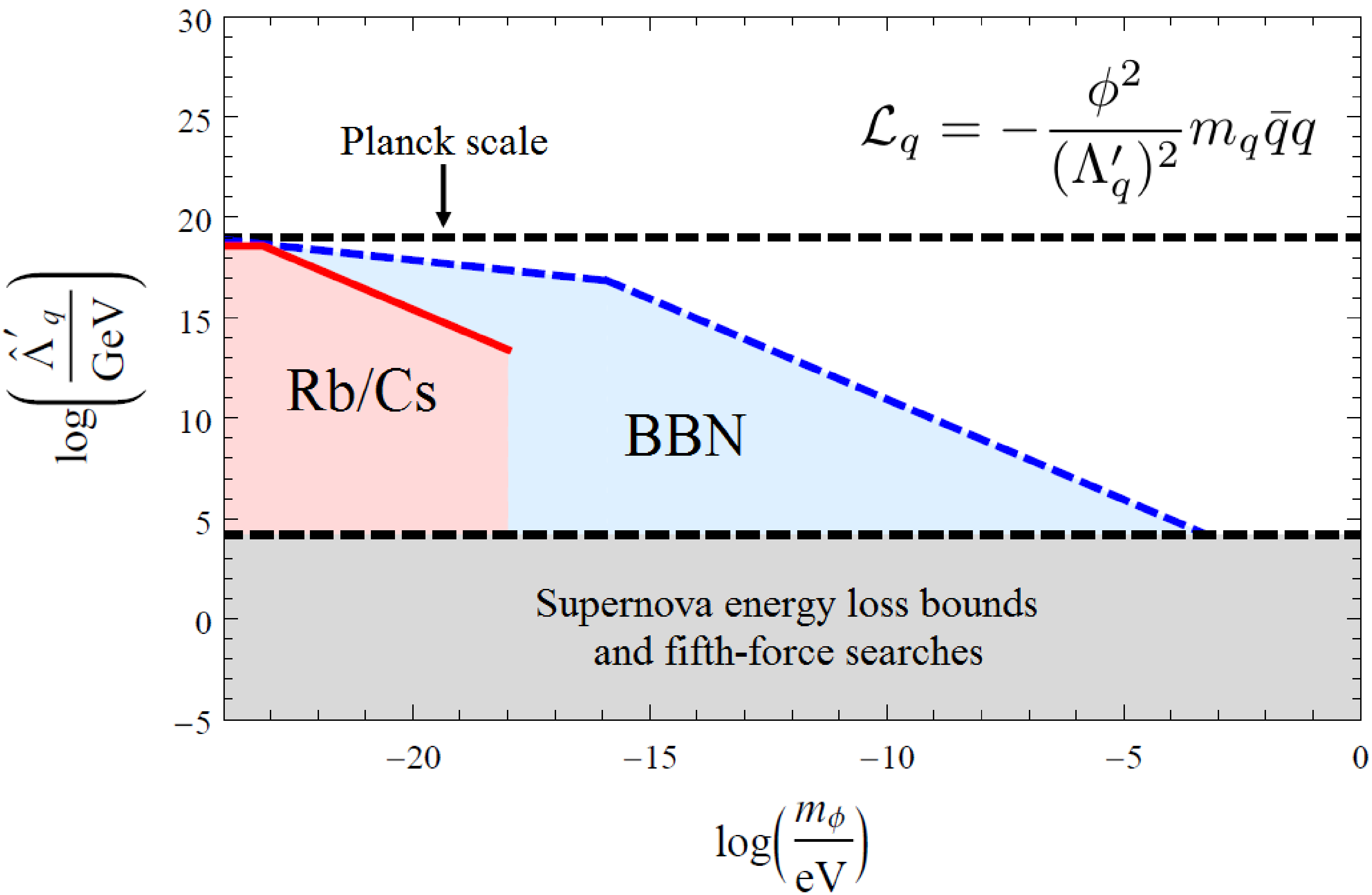
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:

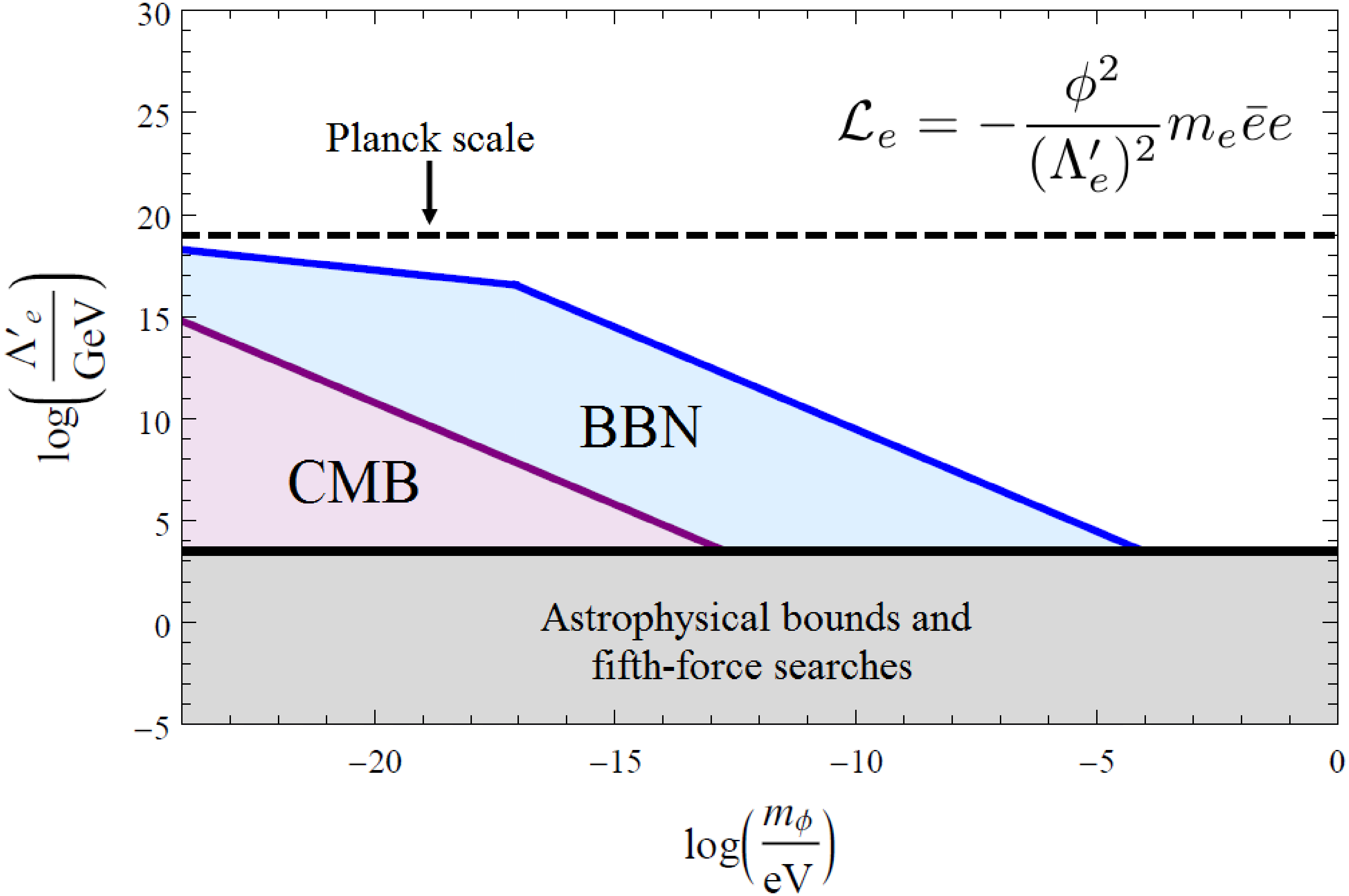
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

BBN and CMB constraints:

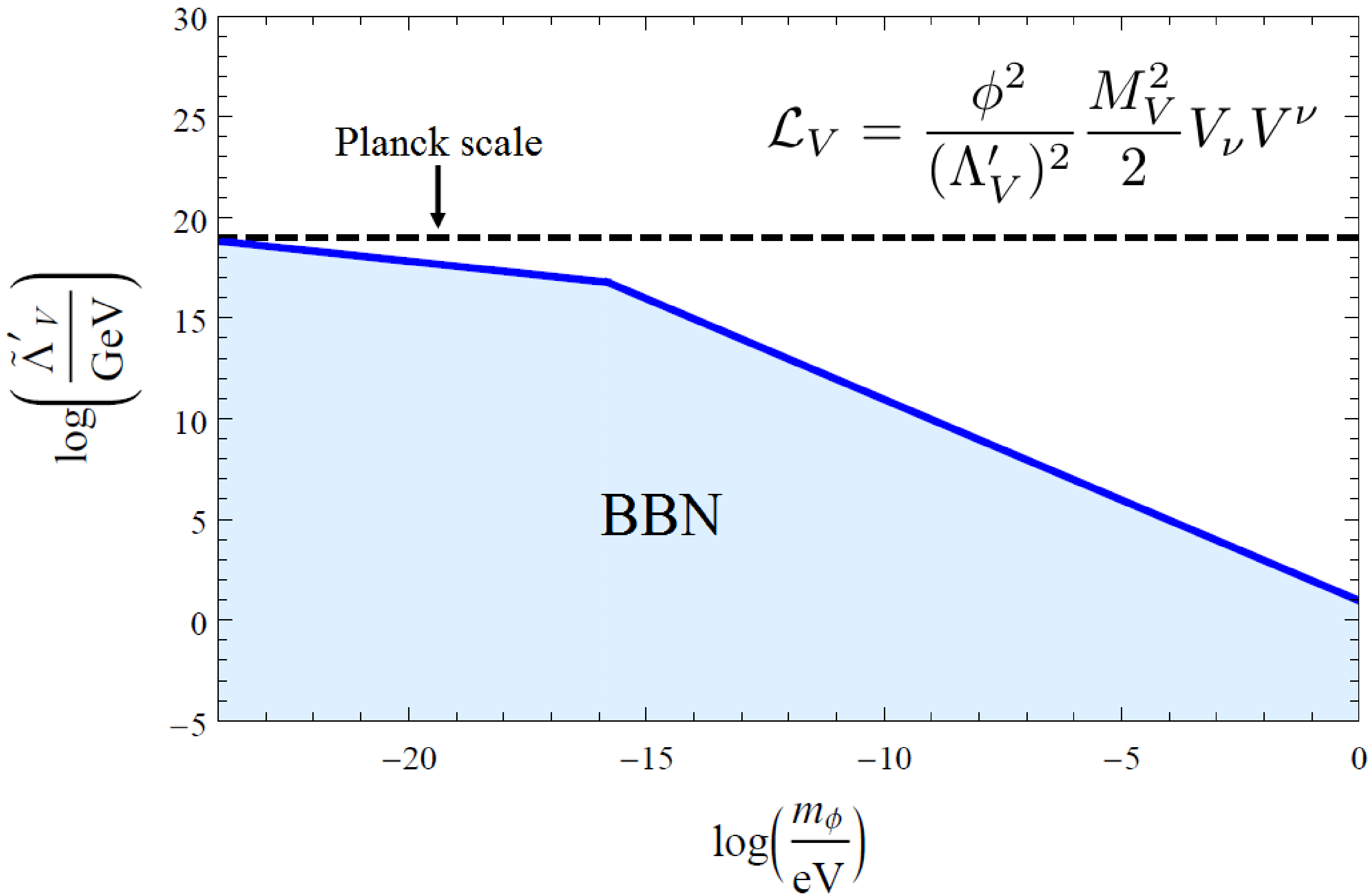
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

BBN constraints:

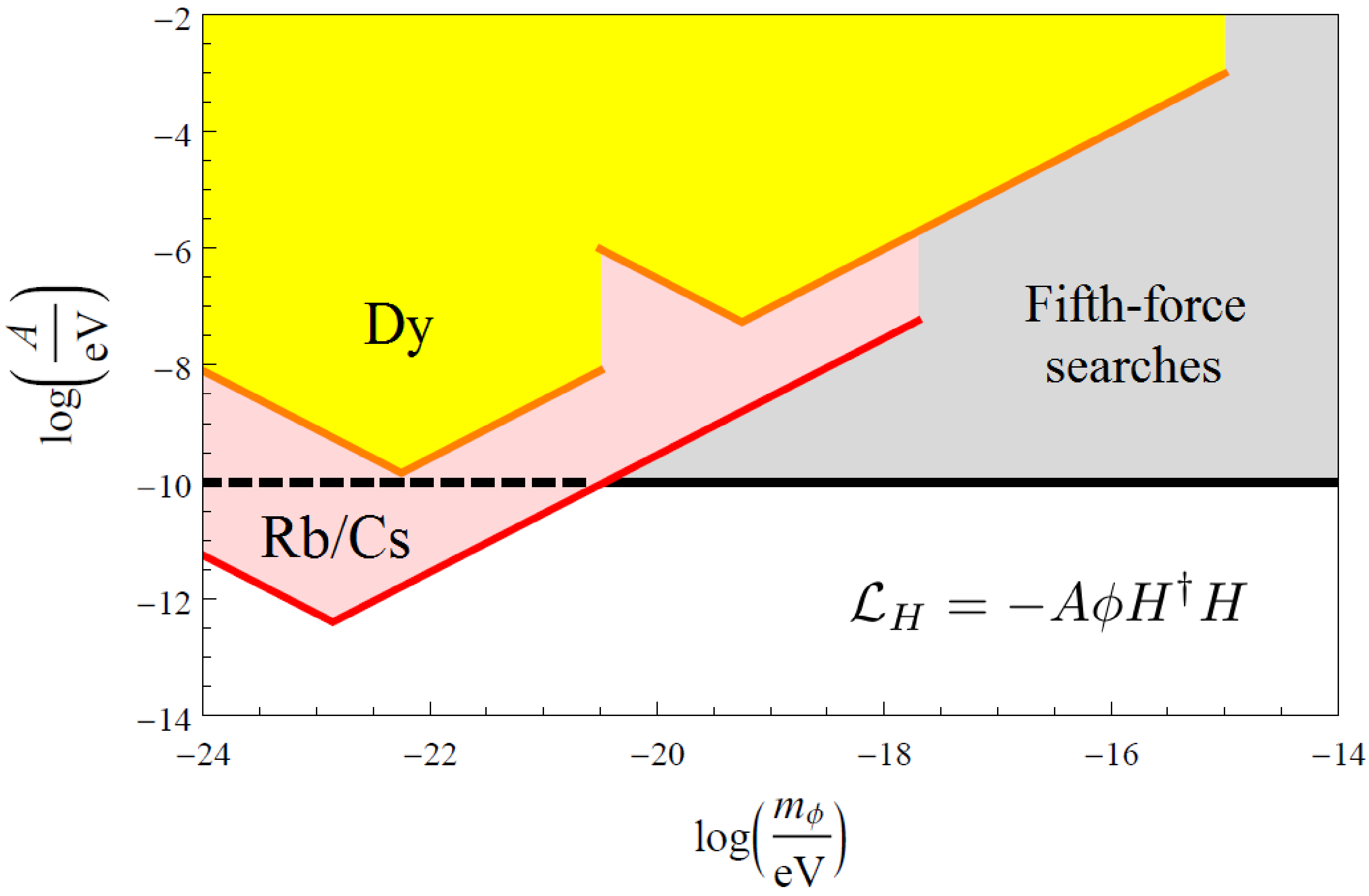
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

Dy and Rb/Cs constraints:

[Stadnik, Flambaum, Phys. Rev. D 2016]



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**.

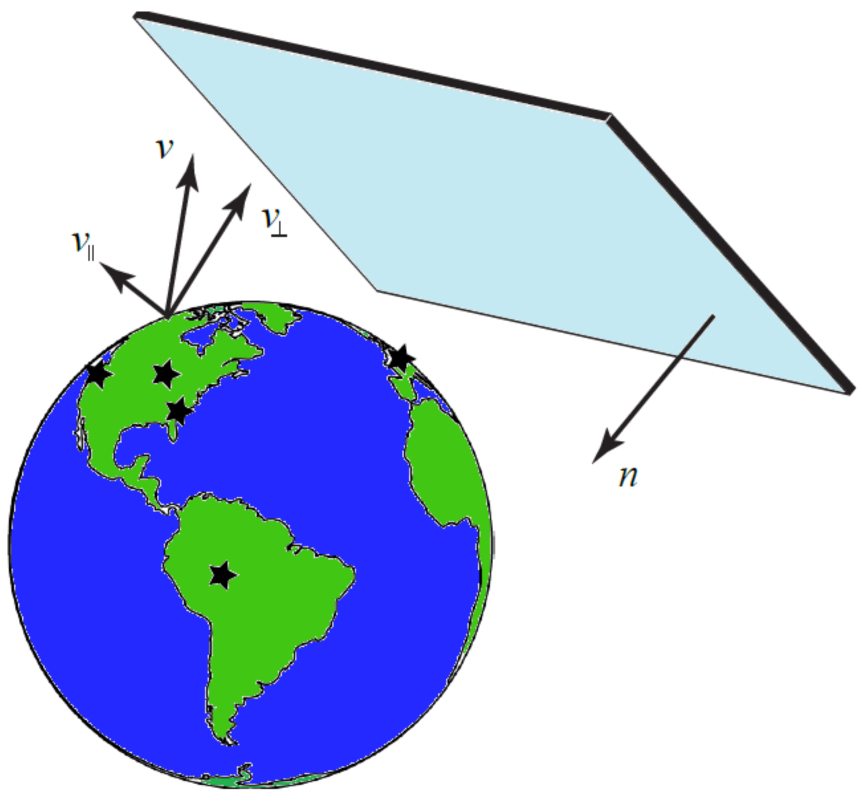
Recent proposals include:

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

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

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

Laser Interferometers [Stadnik, Flambaum, *PRL* **114**, 161301 (2015); arXiv:1511.00447]

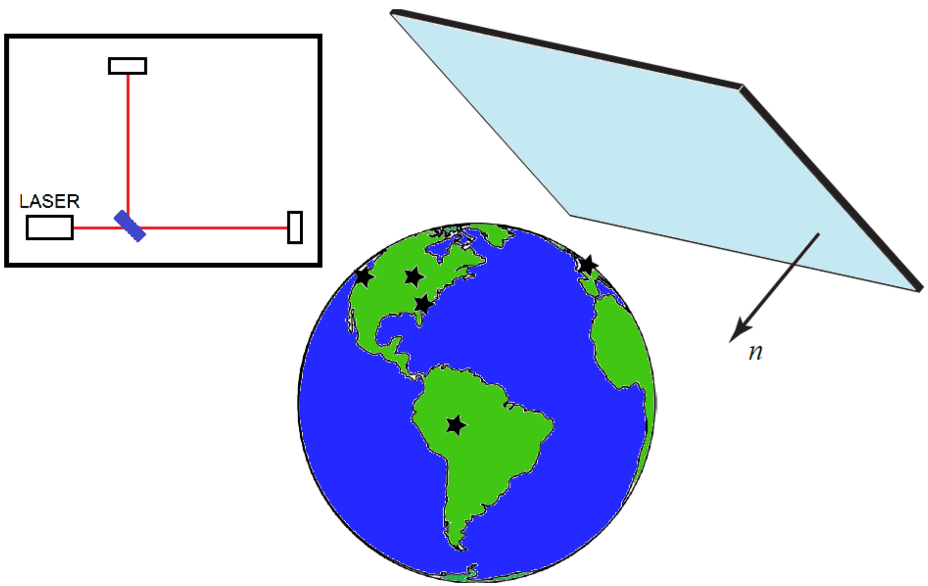


Global Network of Laser/Maser Interferometers (LIGO, Virgo, GEO600, TAMA300)

Stadnik, Flambaum, Phys. Rev.Lett. 2015 + Ongoing collaboration with LIGO and VIRGO (Klimenko, Mitselmakher)

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

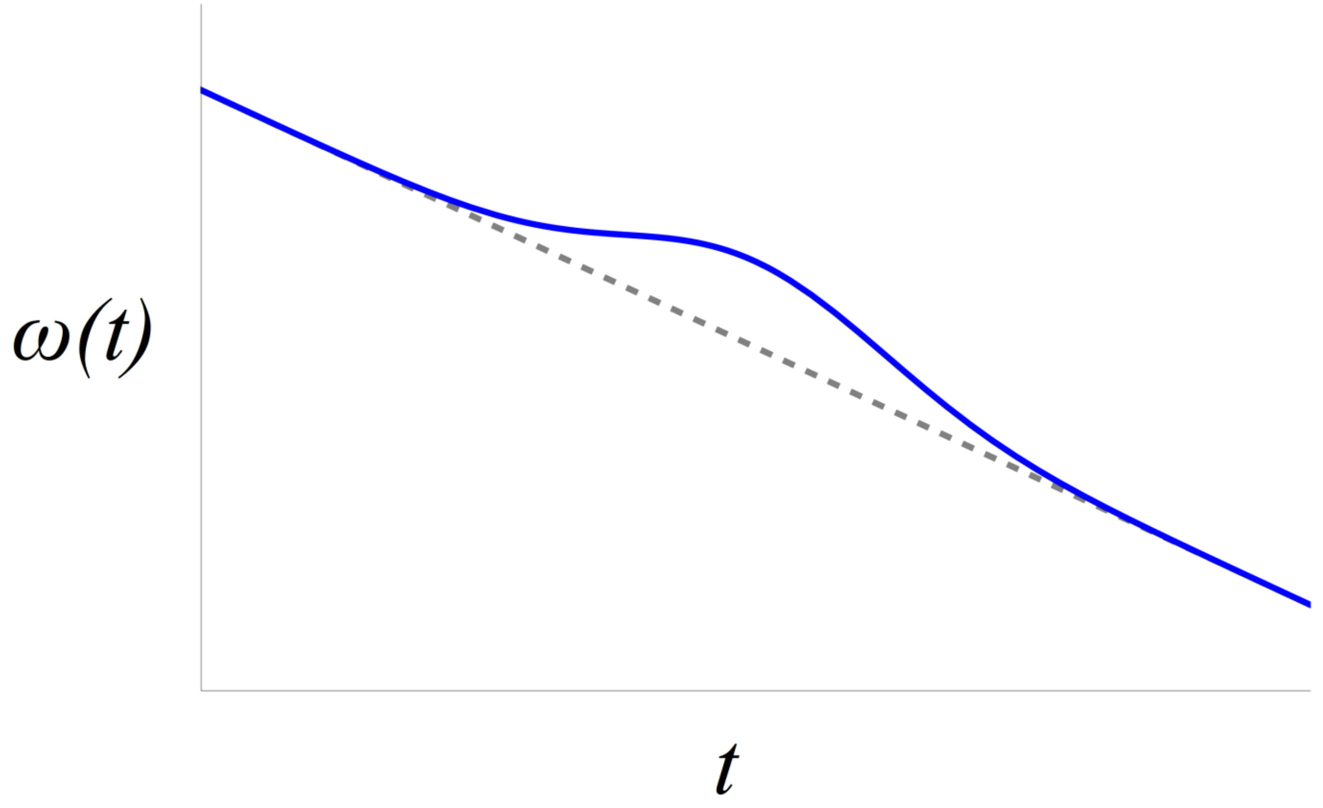
Topological defects, **which consist of *scalar particles*, *temporarily alter the masses of the electron, proton, neutron and photon*, as well as the *fine-structure constant α*. This may produce a *difference in the phases of light* propagating in the two arms (*Φ* = *kL*). One can search for defects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



Pulsar Timing

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

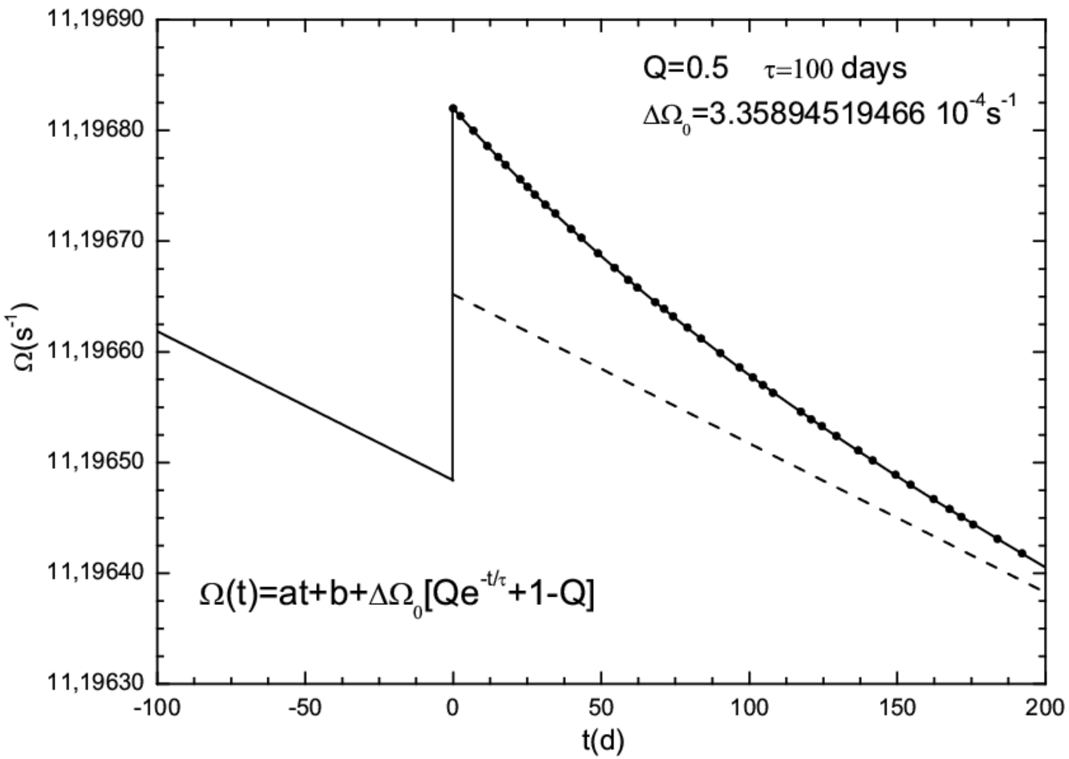
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile



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

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 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
- Enormous potential for low-energy atomic experiments to search for dark matter with unprecedented sensitivity

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.

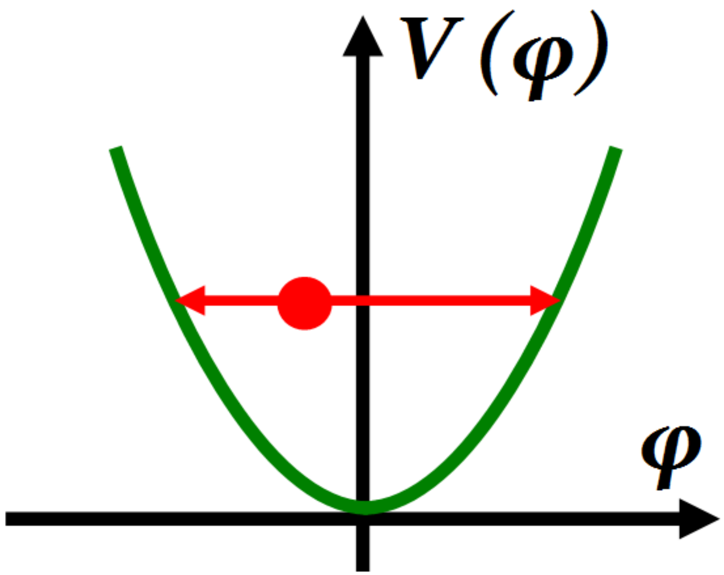
300 absorption systems, 30 atomic lines

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.

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.

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 $\leq m_\varphi \leq$ 0.1 eV]



$V(\varphi) = m_\varphi^2 \varphi^2 / 2$

Sufficiently low-mass bosons are practically *stable* ($m_\varphi \leq$ 24 eV for the QCD axion), and survive to the present day to form galactic DM haloes (where they may be detected).

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:

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

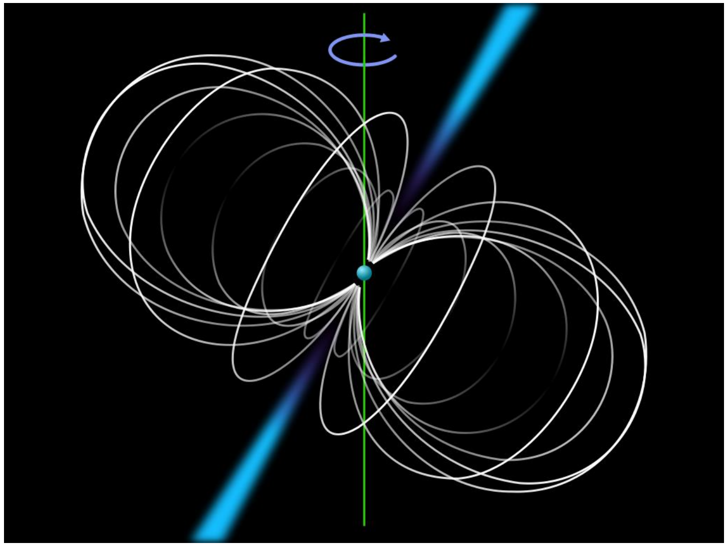
$$l_{\mathrm{coh}} \sim \frac{1}{m_\phi v_{\mathrm{vir}}} \sim \frac{10^3}{m_\phi} = \frac{10^3}{2\pi} \lambda_{\mathrm{Compton}}$$

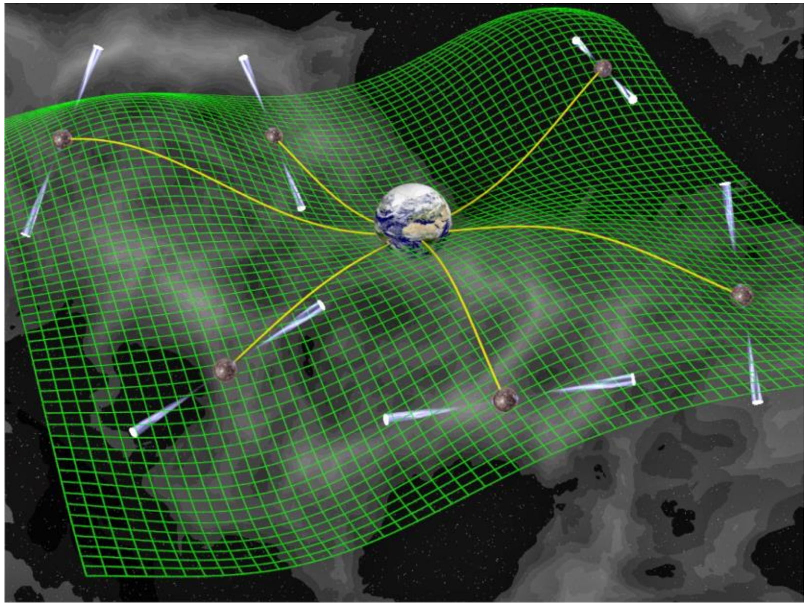
Pulsar Timing

[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* ($v_{\text{TD}} \sim 10^{-3}c$) produced by dark matter *topological defects*.

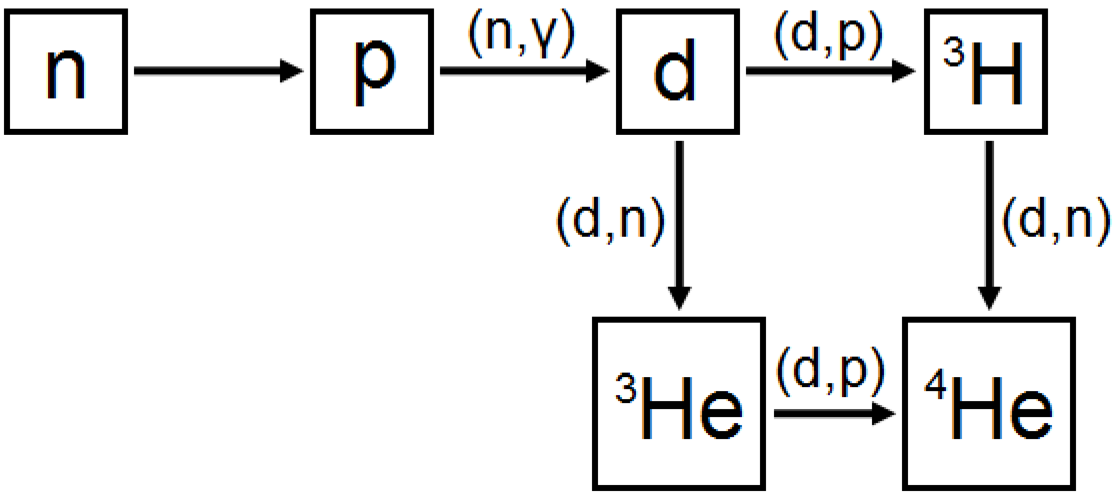




Astrophysical Constraints on ‘Slow’ Drifts in Fundamental Constants Induced by Scalar Dark Matter (BBN)

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

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

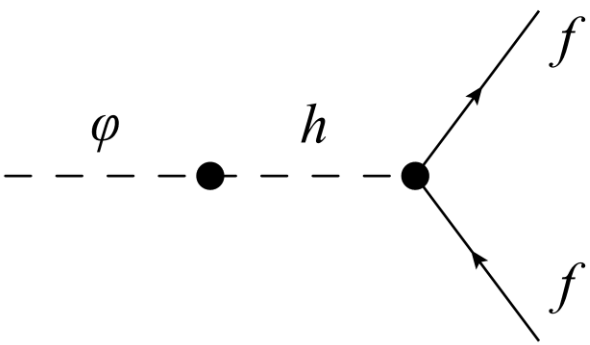


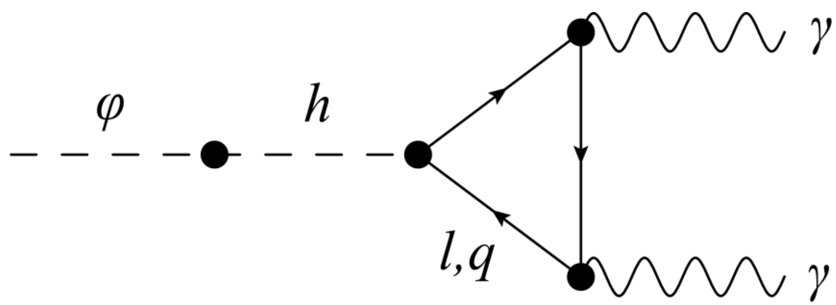
$$\frac{\Delta Y_p(^4\mathrm{He})}{Y_p(^4\mathrm{He})} \approx \frac{\Delta(n/p)_{\mathrm{weak}}}{(n/p)_{\mathrm{weak}}} - \Delta\left[\int_{t_{\mathrm{weak}}}^{t_{\mathrm{BBN}}} \Gamma_n(t)dt\right]$$ => Limits on Λ'_X

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

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

$\longrightarrow$ Oscillating spin-dependent effects, EDM, *P*,*T*, Lorentz and Einstein symmetry violation

- Atomic magnetometry
- Ultracold neutrons
- Solid-state magnetometry

Topological Defect Dark Matter

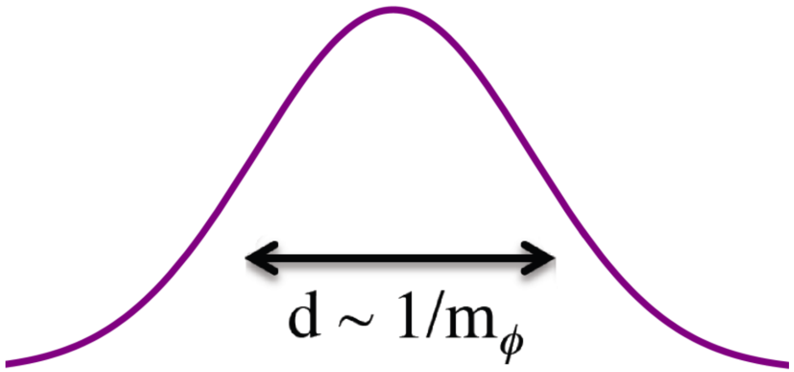
Take a simple scalar field and give it a *self-potential*, e.g. $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable *domain wall* will form in between, e.g. $\varphi = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2} v$.

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*



Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

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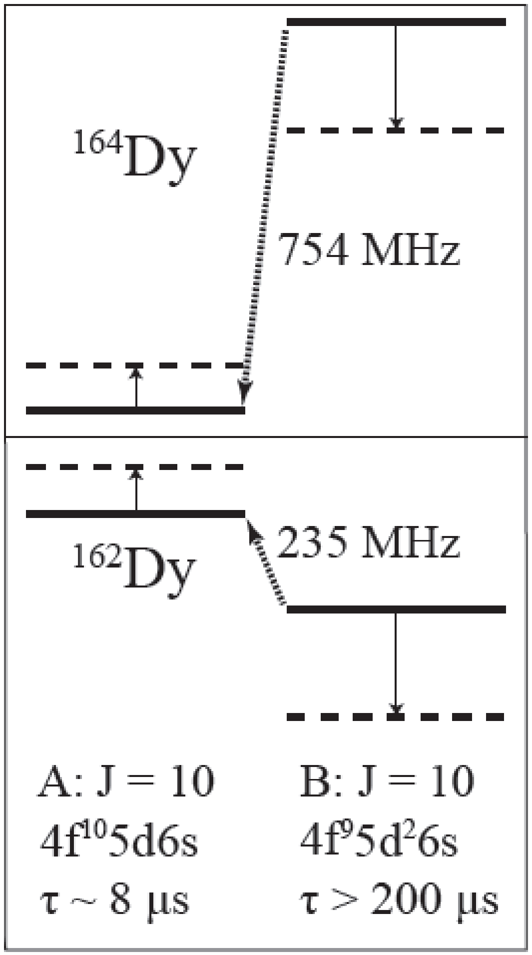
Using the recent atomic dysprosium spectroscopy data of [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], we have derived constraints on the quadratic coupling of scalar dark matter to the photon.



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

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

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); arXiv:1511.00447]

- We can compare a *photon wavelength* with an *interferometer arm length*.
- 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).

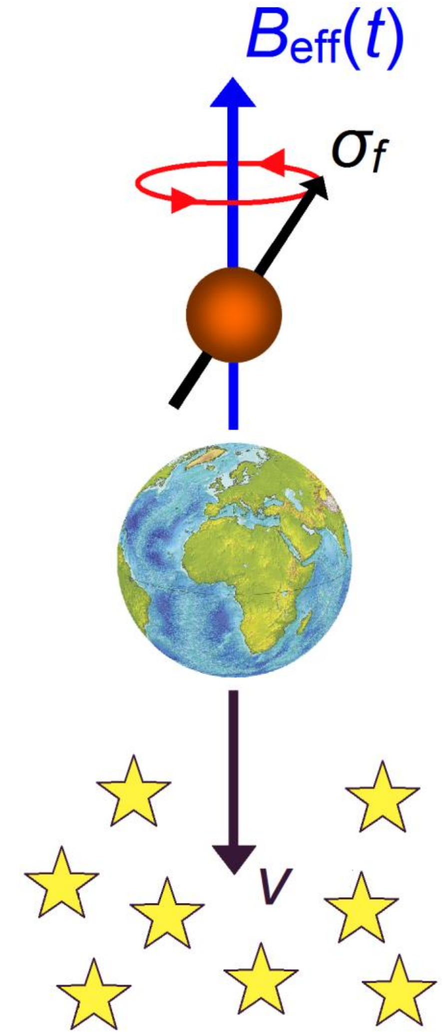
"Axion Wind" Spin-Precession Effect

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

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

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

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

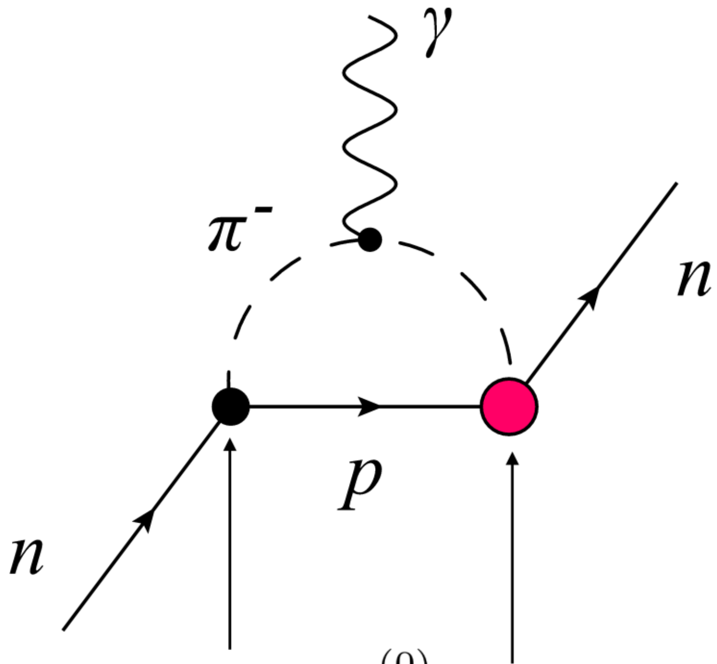


Axion-Induced Oscillating Neutron EDM

[Graham, Rajendran, *PRD* **84**, 055013 (2011)]

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

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



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

Axion-Induced Oscillating Atomic and Molecular EDMs

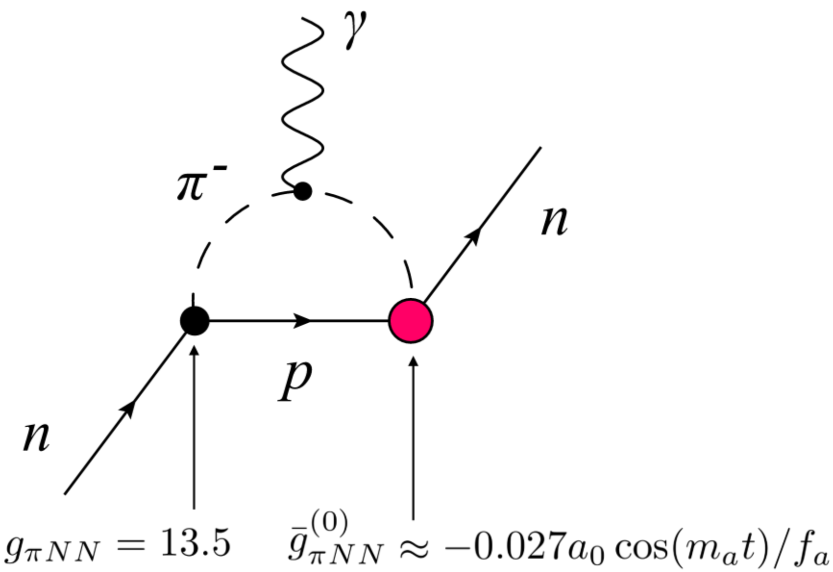
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)] CASPEr

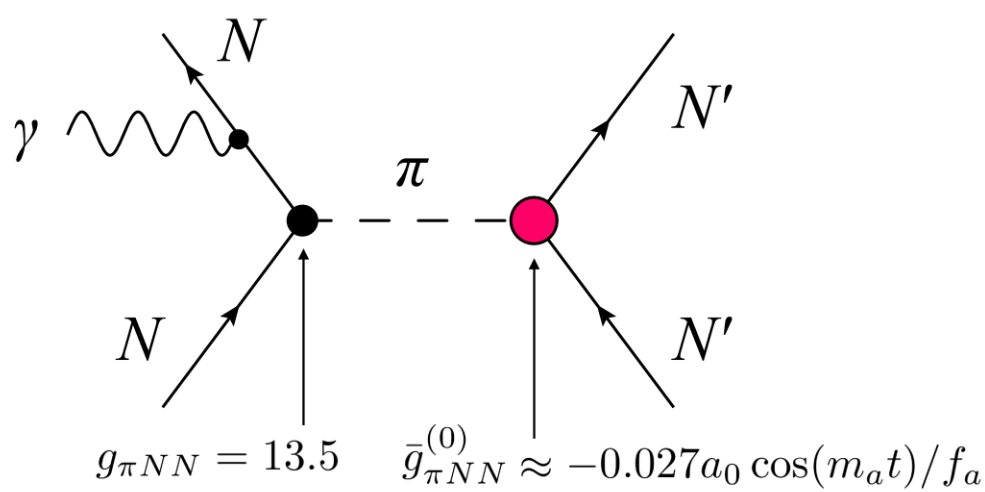
Oscillating atomic and molecular EDMs are induced through oscillating Schiff ($J \geq 0$) and oscillating magnetic quadrupole ($J \geq 1/2$, **no Schiff screening**) moments of nuclei, which arise from *intrinsic oscillating nucleon EDMs* and *oscillating P,T-violating intranuclear forces* (**larger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

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

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

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



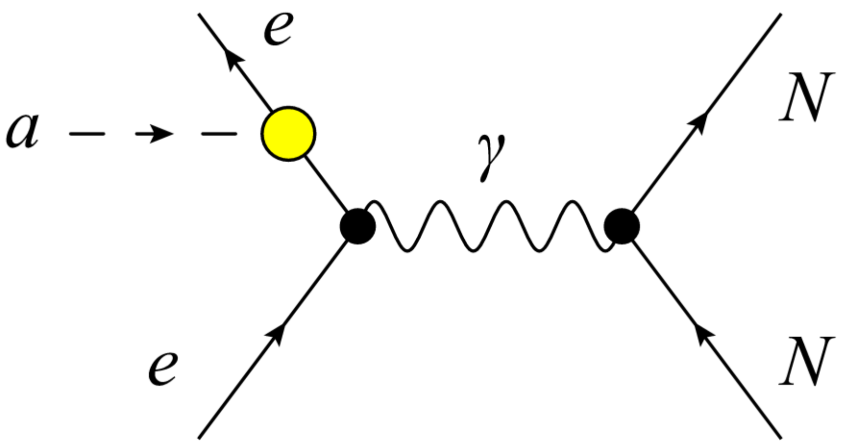


Axion-Induced Oscillating EDMs of Paramagnetic Atoms and Molecules

[Stadnik, 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 states* via the interaction of the oscillating axion field with atomic/molecular electrons.

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



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

[Roberts, Flambaum, 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.

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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**.