New Effects of Dark Matter which are Linear in the Interaction Strength

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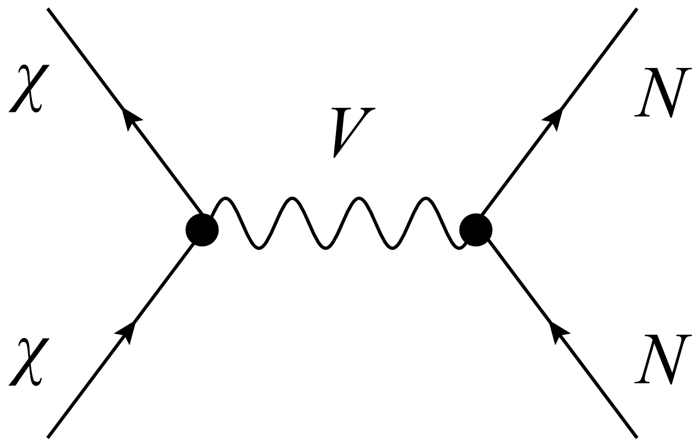
Patras: Axion & WIMP conference, Zaragoza, June 2015

Motivation

Consider a typical "scattering-off-nuclei" search for **WIMP** dark matter (χ) (e.g. CoGeNT, CRESST, DAMA/LIBRA, LUX, Super-CDMS, XENON100, …)



$$\mathcal{L}_{\rm eff} = \frac{\alpha'}{M_V^2}(\bar{\chi}\gamma^\mu\chi)(\bar{N}\gamma_\mu N) \implies \sigma_{\rm scat} \propto \left(\frac{\alpha'}{M_V^2}\right)^2$$

Observable is **quartic** in e' **(** $\alpha' = (e')^2$) which is <u>*extremely small*</u>*!*

Motivation

We instead propose to search for **light bosonic** dark matter (**galactic condensates** and **topological defects**) through observables that are **linear** in underlying interaction parameters using **new high-precision** detection methods!

$$\mathcal{L}_{\mathrm{eff}} = \boxed{\left(\frac{\phi}{\Lambda_X}\right)^n} X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \boxed{\left(\frac{\phi}{\Lambda_X}\right)^n}$$

Detection methods include the use of **terrestrial measurements** (atomic clocks, magnetometers, torsion pendula, ultracold neutrons, laser interferometers) and **astrophysical observations** (pulsar timing, cosmic radiation lensing).

Zoo of axion effects-linear in interaction strength!

- Derivative-type coupling

$$\mathcal{L}_{\rm DT} = -\frac{\partial_\mu a}{f_{\rm a}} \bar{\psi}\gamma^\mu\gamma^5\psi$$

$$\psi = e, p, n$$

- Produces oscillating effects :

$$H_{\rm int}^{\mu=0} \propto \boldsymbol{\sigma}\cdot\boldsymbol{p}\sin(m_a t)$$

  - **PNC effects**
  - **EDMs**
  - **Anapole moments**

$$H_{\rm int}^{\mu=i} \propto \boldsymbol{\sigma}\cdot\boldsymbol{p}_a\sin(m_a t)$$

  - **Axion 'wind'**
  - **Energy shifts**

$$H_{\rm int} \propto \boldsymbol{\sigma}\cdot\boldsymbol{B}_{\rm eff}(t)$$

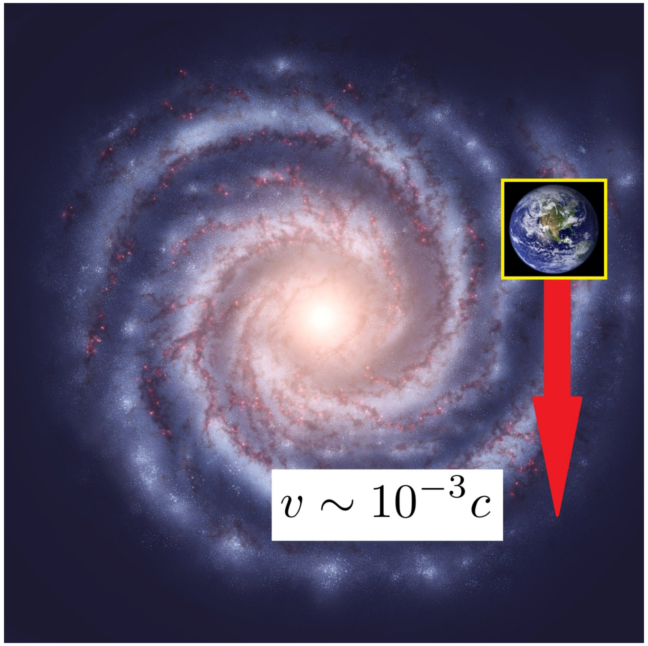
- **Axion field modified by Earth's gravitational field:**

$$H_{\rm int} \propto \boldsymbol{\sigma}\cdot\boldsymbol{g}\sin(m_a t)$$

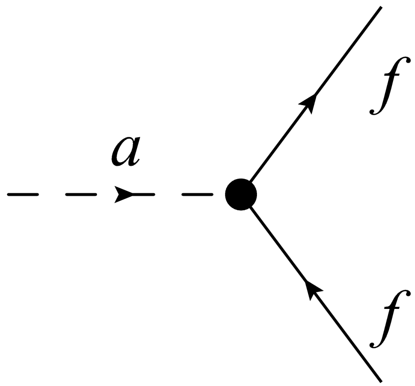
“Axion Wind” Effect (Axion and ALPs)

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

As Earth moves through galactic condensate of axions/ALPs ($v \sim 10^{-3}c$), **spin-precession effects** arise from *derivative coupling of axion field to axial-vector currents of electrons or nucleons* (spatial components of interaction).

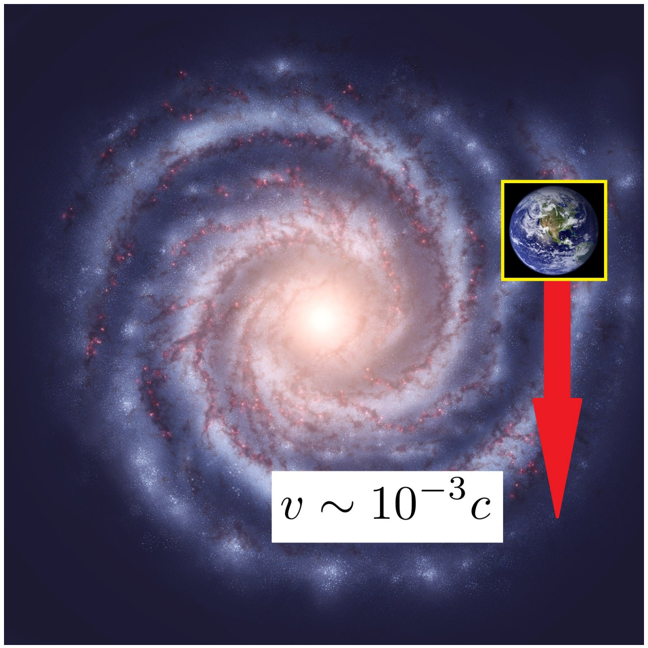


"Axion Wind" Effect (Axion and ALPs)



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

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



Axion-induced spin-precession effects are **linear** in a_0/f_a! **Spin-axion momentum couplings can be sought for with a variety of *spin-polarised* systems: atomic magnetometers, torsion pendula and cold neutrons.**

“Axion Wind” Effect (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

Distortion of axion/ALP field by gravitational fields of Sun and Earth induces *oscillating spin-gravity couplings*.

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

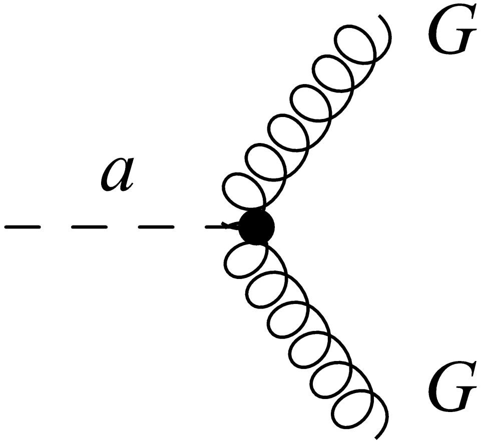
$$=> \ H'_{\rm eff}(t) \propto \frac{C_f a_0}{f_a}\sin(m_a t)\ \sigma_f \cdot \hat{r}$$

Spin-axion momentum and axion-mediated spin-gravity couplings to nucleons may have isotopic dependence ($C_p \neq C_n$) – calculations of required proton and neutron spin contents (^{3}He, ^{21}Ne, $^{39/41}$K, $^{85/87}$Rb, ^{129}Xe, ^{133}Cs, $^{199/201}$Hg, …) have been performed in [Stadnik, Flambaum, *EPJC* **75**, 110 (2015)]

Oscillating *P*,*T*-odd Nuclear Electromagnetic Moments (QCD Axion)

A galactic condensate consisting of the QCD axion induces oscillating *P*,*T*-odd electromagnetic moments in nuclei via two mechanisms:

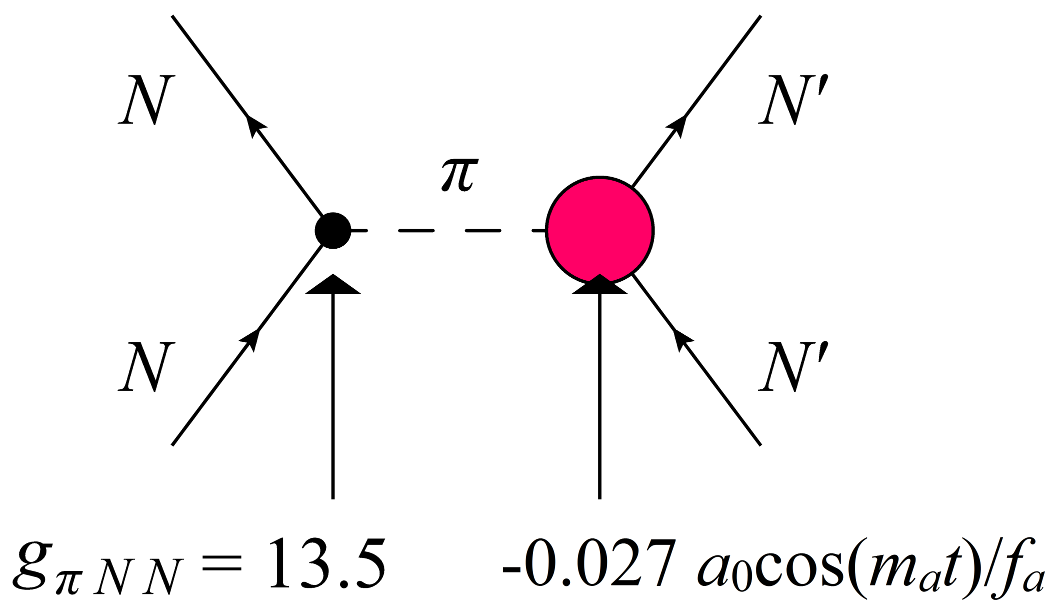
(1) *Oscillating nucleon EDMs* via axion coupling to gluon fields - dynamical $\theta(t)=a(t)/f_a$. [Graham, Rajendran, *PRD* **84**, 055013 (2011)]



$$\mathcal{L}_{agg} = \frac{a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G\tilde{G}$$

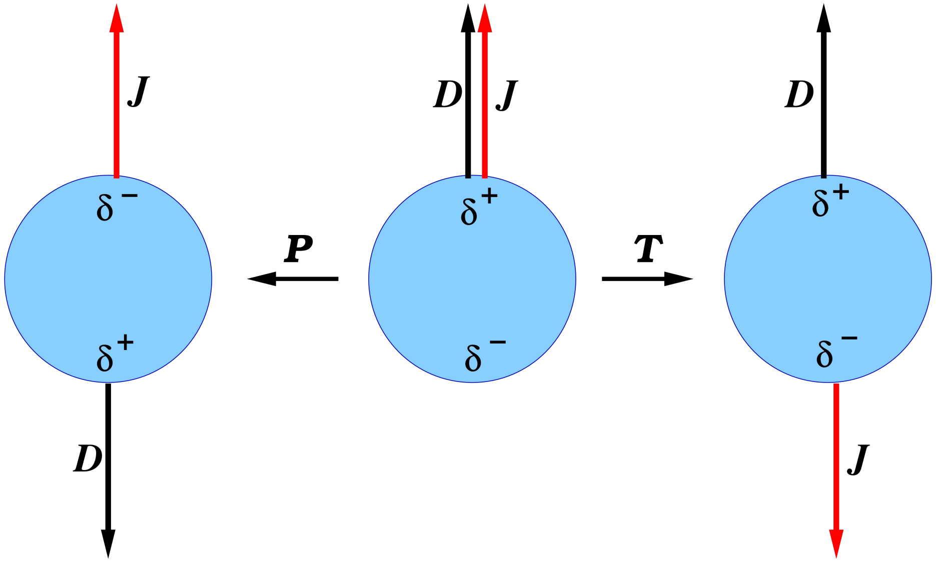
Oscillating *P*,*T*-odd Nuclear Electromagnetic Moments (QCD Axion)

(2) ***P,T*-violating nucleon-nucleon interaction via pion exchange** (axion-gluon interaction provides oscillating source of *P* and *T* violation at one of the vertices) –
Dominant mechanism in most nuclei!
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]



Oscillating *P*,*T*-odd Nuclear Electromagnetic Moments (QCD Axion)

Axion-induced oscillating *P*,*T*-odd nuclear electromagnetic moments are **linear** in a_0/f_a!



Can search for oscillating nuclear Schiff moments using **precision magnetometry** on diamagnetic atoms in the **solid-state** (CASPEr) [Budker, Graham, Ledbetter, Rajendran, A. Sushkov, *PRX* **4**, 021030 (2014)], or …

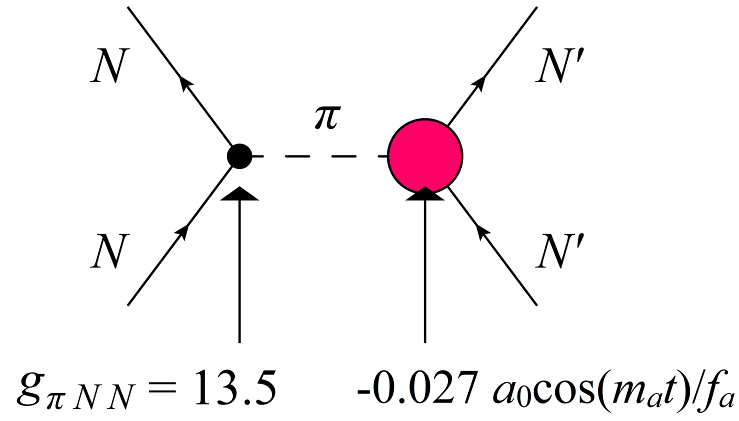
Oscillating EDMs of Paramagnetic Atoms and Molecules (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)], [Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, *PRL* **113**, 081601 (2014) + *PRD* **90**, 096005 (2014)], [Roberts, Stadnik, Flambaum, (In preparation)]

A galactic condensate consisting of axions or ALPs induces oscillating EDMs in atoms and molecules via three types of interactions:

(1) *Oscillating P,T-odd nuclear EM moments* (nuclear Schiff moments and magnetic quadrupole moments), produced by *coupling of the axion to gluon fields*.

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



Oscillating EDMs of Paramagnetic Atoms and Molecules (Axion and ALPs)

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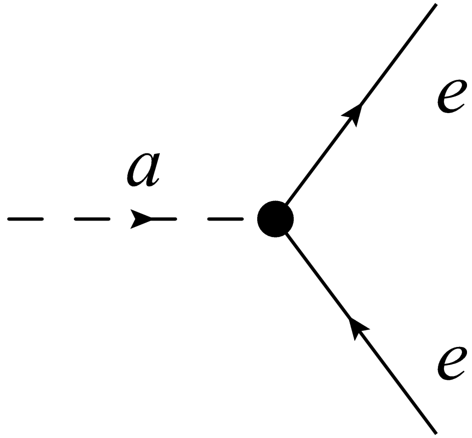
(2) *Derivative coupling of axion field to axial-vector currents of atomic/molecular electrons* (temporal component of interaction).



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

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.

There are theories which suggest variation of the fundamental constants in expanding Universe.

Source: Dark energy or Dark Matter?

Cosmological Evolution of the Fundamental Constants of Nature

Most contemporary dark energy-type theories, which predict a cosmological evolution of the fundamental constants (e.g. Brans-Dicke, string dilaton, chameleon and Bekenstein models), assume that the underlying field is *(nearly) massless* …

– *Are there models, in which a* ***more natural 'massive' field*** *can produce a cosmological evolution of the fundamental constants?*

Yes!!!

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

Consider a *condensate* consisting of a *scalar or pseudoscalar particle*, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, that interacts with SM particles via *quadratic* couplings in φ.

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

$$=> \frac{\delta\alpha}{\alpha} \quad = \boxed{\frac{\phi_0^2}{2(\Lambda'_\gamma)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_\gamma)^2} \cos(2m_\phi t)}$$

'Slow drifts' — Oscillating variations

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

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

Photon:

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

Fermions:

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

Massive Vector Bosons:

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

Constraints on 'Slow Drifts' in Fundamental Constants Induced by Scalar/Pseudoscalar Condensate (CMB)

[Stadnik, Flambaum, arXiv:1503.08540]

The dynamics of electron-proton recombination is governed by α and m_e. CMB measurements constrain possible variations in α and m_e.

$$\left|\frac{\Delta\alpha}{\alpha}\right| \lesssim 10^{-2} \;\; => \;\; \Lambda'_\gamma \gtrsim \frac{2\mathrm{eV}^2}{m_\phi}$$

$$\left|\frac{\Delta m_e}{m_e}\right| \lesssim 3 \times 10^{-2} \;\; => \;\; \Lambda'_e \gtrsim \frac{1\mathrm{eV}^2}{m_\phi}$$

Constraints on 'Slow Drifts' in Fundamental Constants Induced by Scalar/Pseudoscalar Condensate (BBN)

[Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

Most stringent constraints on 'slow drifts' in fundamental constants induced by a scalar or pseudoscalar condensate come from *measurements of* $(m_n\text{-}m_p)/T_F$ *at the time of weak interaction freeze-out* (ρ_{cond} is largest), *prior to Big Bang nucleosynthesis*.

Scalar/pseudoscalar condensate can alter primordial light elemental abundances (especially ^{4}He) through changes in $(n/p)_{\mathrm{weak}} = \exp[-(m_n\text{-}m_p)/T_F]$.

$$0.08\frac{\Delta\alpha}{\alpha}+1.59\frac{\Delta(m_d-m_u)}{(m_d-m_u)}+3.32\frac{\Delta M_W}{M_W}-4.65\frac{\Delta M_Z}{M_Z}$$

$$-0.59\frac{\Delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}}+\frac{1}{3}\frac{\Delta M_{\mathrm{Planck}}}{M_{\mathrm{Planck}}}=0.0033\pm0.0085$$

Constraints on 'Slow Drifts' in Fundamental Constants Induced by Scalar/Pseudoscalar Condensate (BBN)

[Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

There are two limiting mass regions to consider:

(1) <u>*Underdamped regime* ($m_\varphi \gg H(t) \approx 1/2t$)</u>: rate of DM oscillations >> rate of Universe expansion, so condensate oscillates and evolution of non-relativistic DM field follows the usual volume-dependent scaling for cold matter:

$$\rho_{\mathrm{cond}} \propto [1 + z(t)]^3$$

$$\Rightarrow \frac{1}{m_\phi^2}\left[\frac{0.08}{(\Lambda'_\gamma)^2} + \frac{1.59}{m_d - m_u}\left(\frac{m_d}{(\Lambda'_d)^2} - \frac{m_u}{(\Lambda'_u)^2}\right) + \frac{3.32}{(\Lambda'_W)^2} - \frac{4.65}{(\Lambda'_Z)^2}\right] \simeq (1.0 \pm 2.5) \times 10^{-20}\ \mathrm{eV}^{-4}$$

Constraints on Oscillating Variations in Fundamental Constants Induced by Scalar/Pseudoscalar Condensate

[Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

Constraints on oscillating variations in the fundamental constants can come from a number of high-precision terrestrial experiments:

- **Atomic Clocks and Atomic Spectroscopy** (Sr, Yb^+, Al^+, Hg+, Cs, Rb, Dy, …)
- **Laser Interferometers** (LIGO, Virgo, GEO600, TAMA300, and smaller-scale experiments)

We have derived constraints on the quadratic coupling of φ to the photon, using recent atomic dysprosium spectroscopy data from [van Tilburg, Leefer, Bougas, Budker, arXiv:1503.06886] where limits on dilaton interaction were obtained

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

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

Extremely sensitive *laser interferometers* can be used to search for *oscillating effects* produced by *scalar condensate*.

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 condensate*.

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).

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

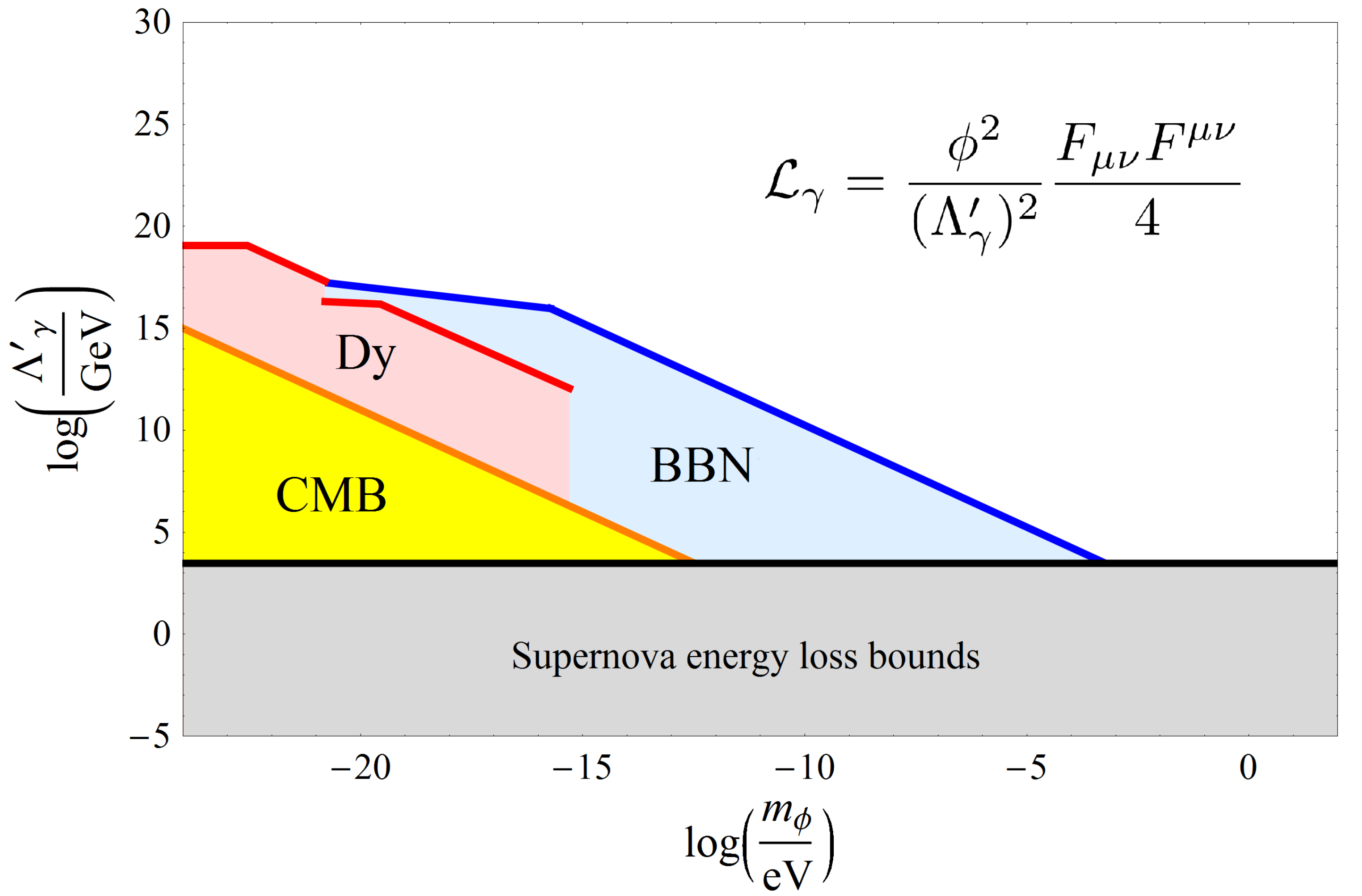
$$=> \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

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

Constraints on Scalar/Pseudoscalar Quadratic Interaction with the Photon

BBN, CMB and Dy: [Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

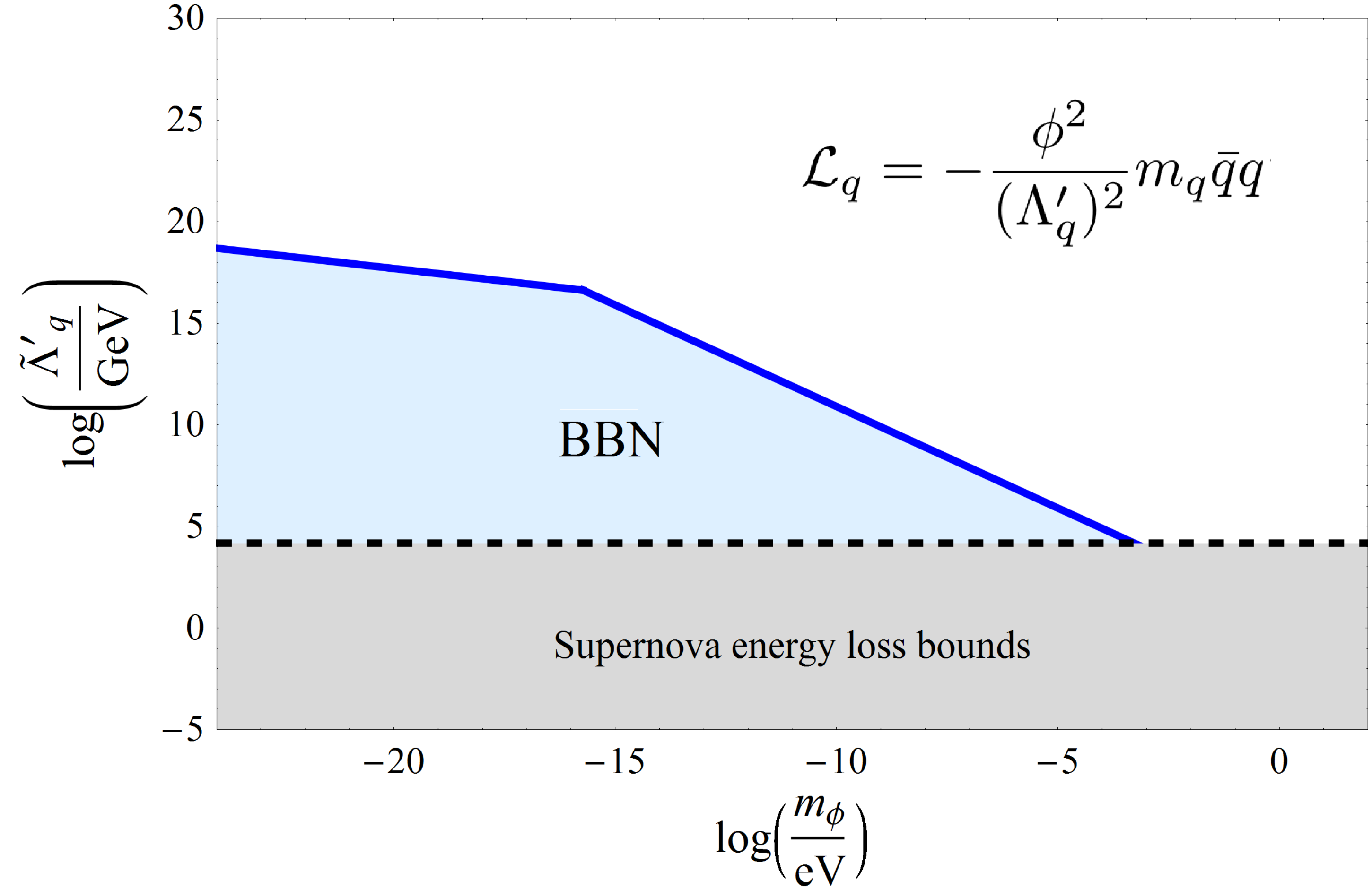
Supernova energy loss bounds: [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Constraints on Scalar/Pseudoscalar Quadratic Interactions with Quarks

BBN (Quarks): [Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]

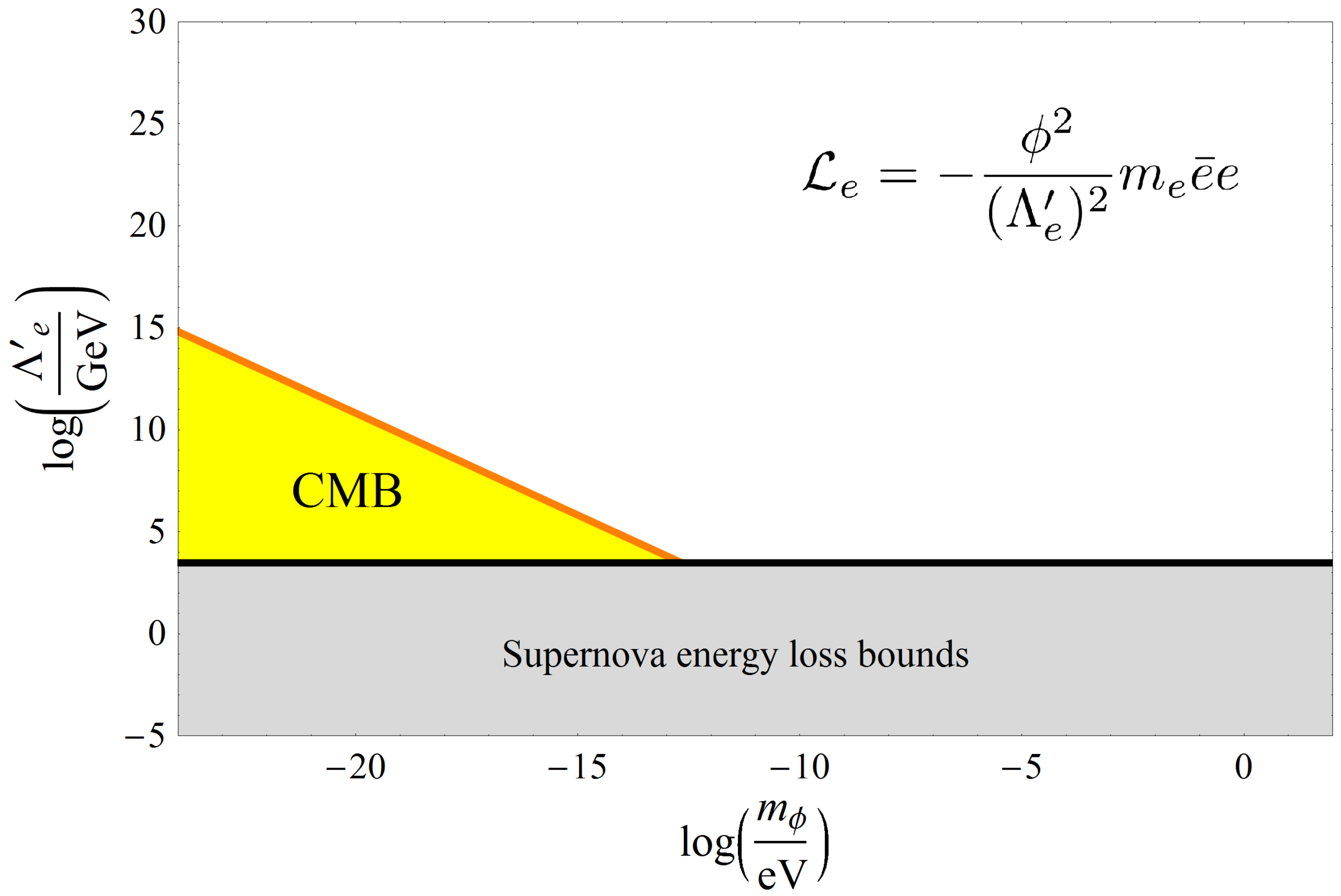
Supernova energy loss bounds (Proton): [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Constraints on Scalar/Pseudoscalar Quadratic Interaction with the Electron

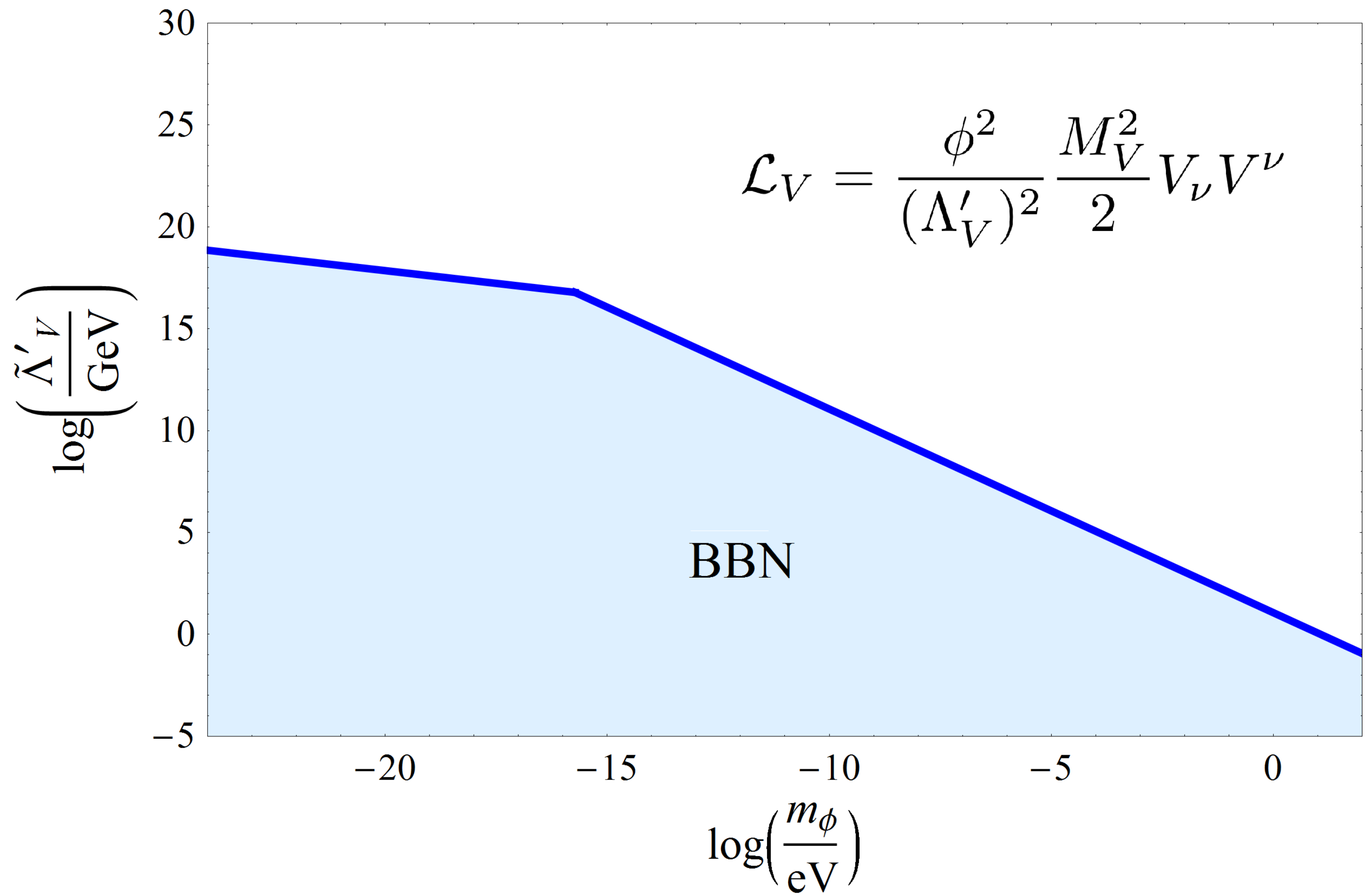
CMB: [Stadnik, Flambaum, arXiv:1503.08540]

Supernova energy loss bounds: [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Constraints on Scalar/Pseudoscalar Quadratic Interactions with Z and W Bosons

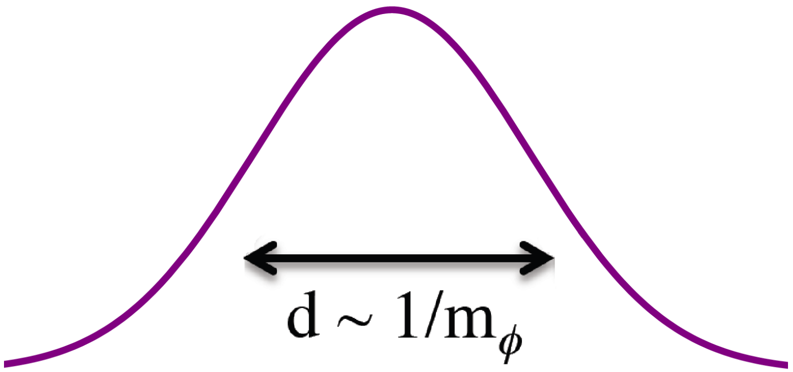
BBN: [Stadnik, Flambaum, arXiv:1503.08540 + arXiv:1504.01798]



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**.

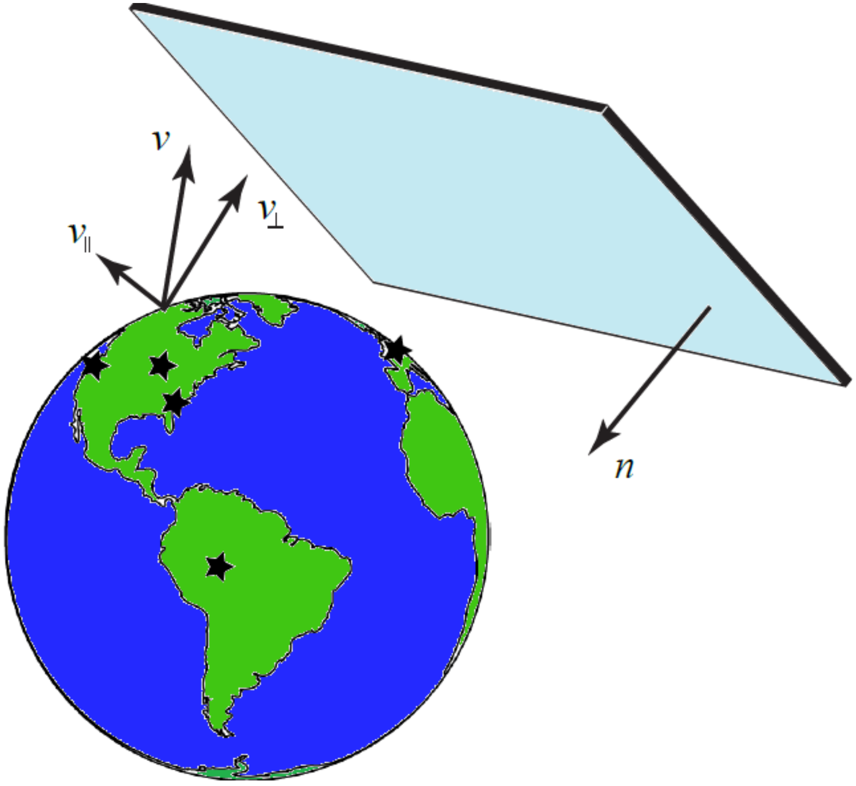
Recent proposals include:

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

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)]

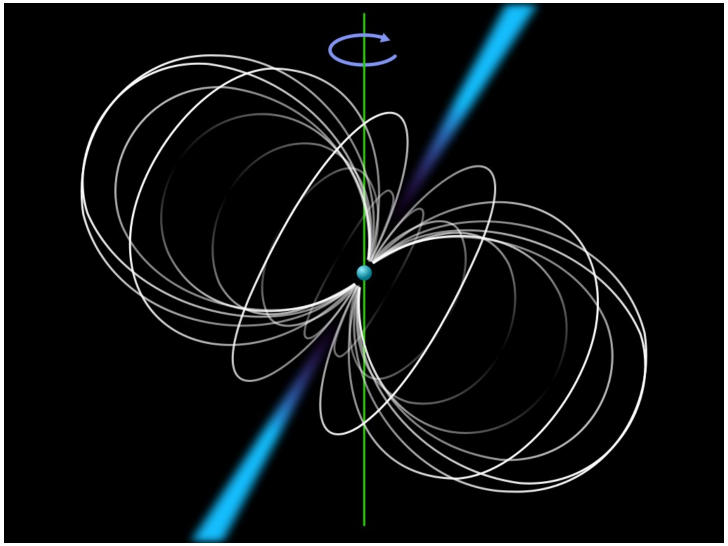


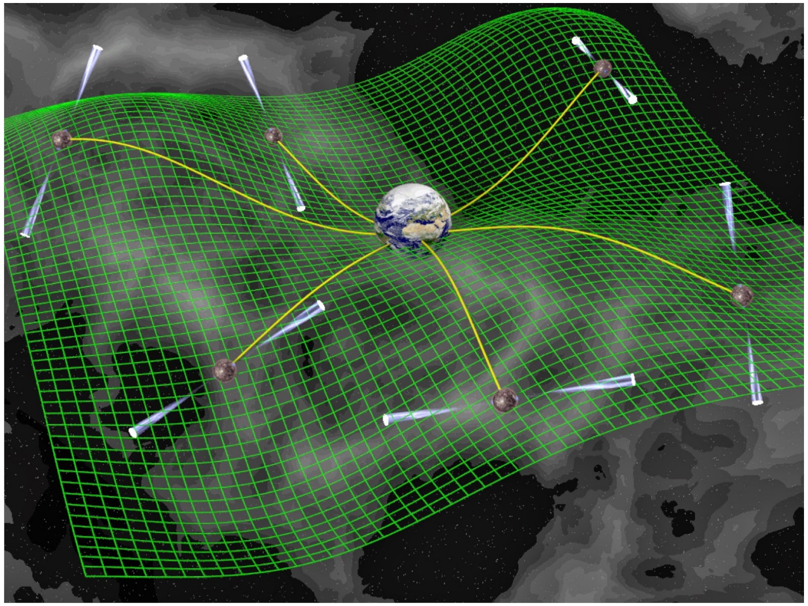
Pulsar Timing

[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 *topological defects*.

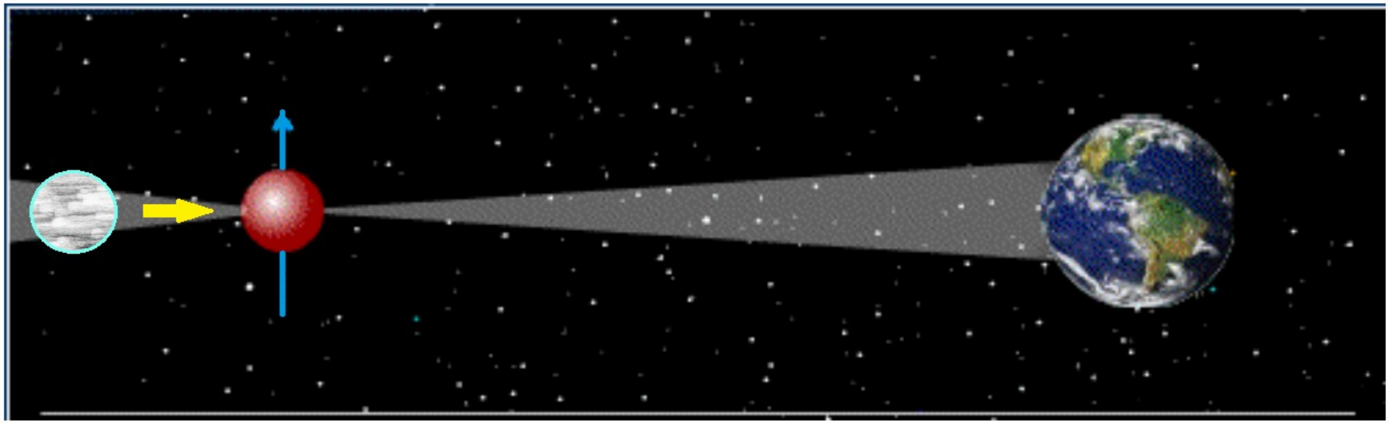




Pulsar Timing

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

Interactions with *topological defects* can *temporarily alter* the neutron mass inside a pulsar, changing pulsar mass (and possibly radius) and *hence temporarily alter the pulsar's frequency of rotation*.



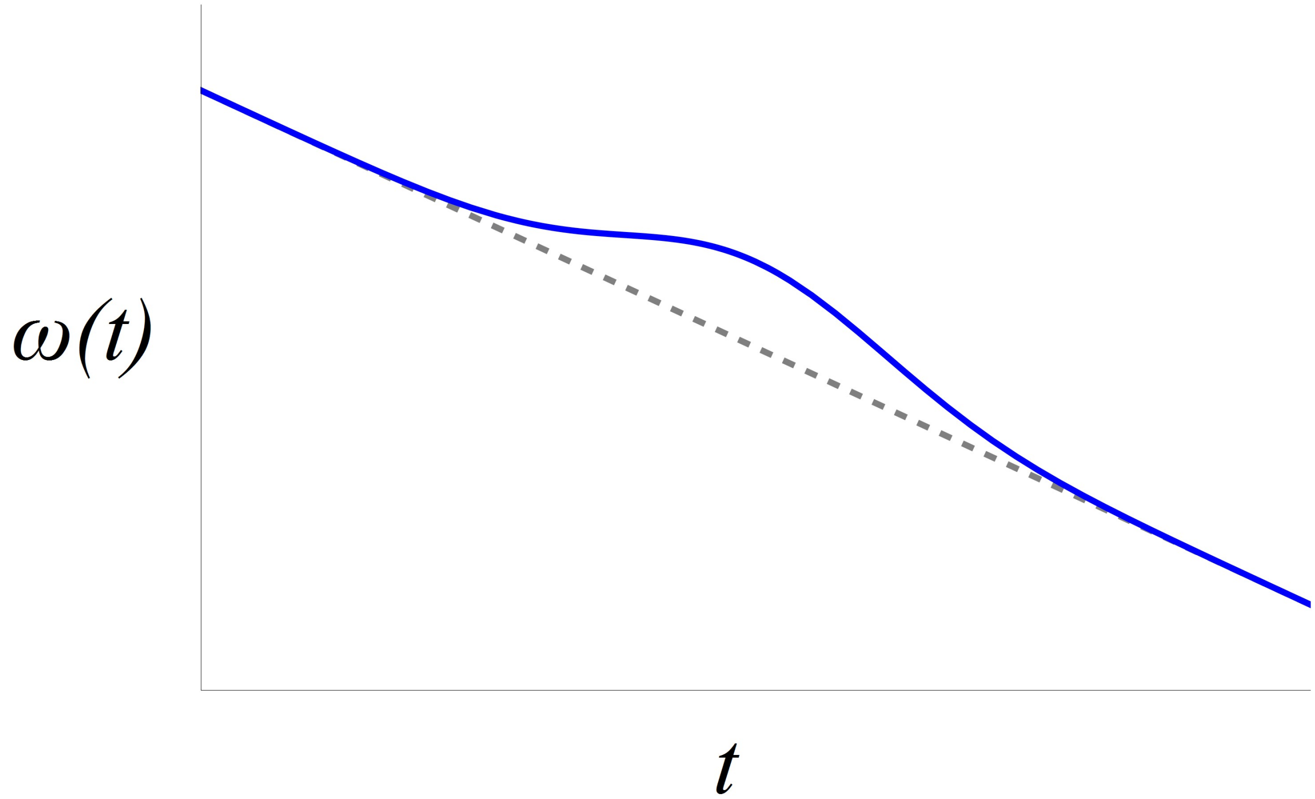
$$I \sim \frac{2MR^2}{5} \quad \text{and} \quad L = I\omega$$

$$=> \quad \frac{\delta\omega(t)}{\omega} \sim -\frac{\delta M(t)}{M} \simeq -\frac{\delta m_n(t)}{m_n}$$

Pulsar Timing

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

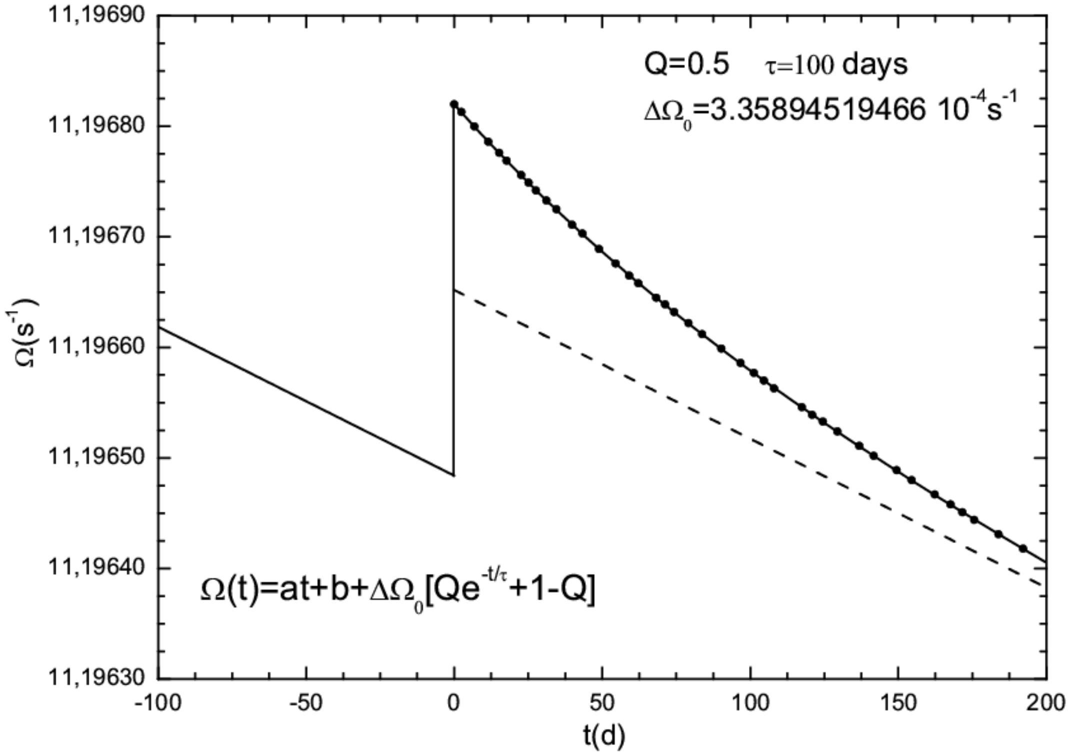
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile (**NOT** noise).



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

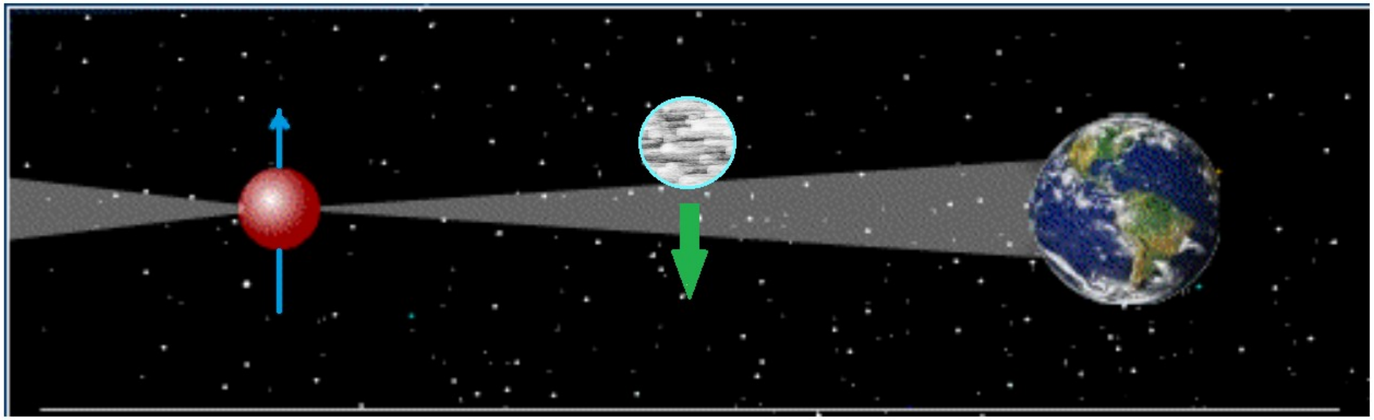
- Model pulsar as 2-component system: neutron superfluid core, surrounded by neutron crust
- 2 components can rotate independently of one another
- Rotation of neutron superfluid core quantified by area density of quantised vortices (which carry angular momentum)
- Strong vortex ‘pinning’ to neutron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

Non-Gravitational Lensing

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

The photon mass may be *non-zero inside a topological defect*, making a defect act as a *cosmic dielectric material* with a distinctive *frequency-dependent index of refraction*:

$$n(\omega) \approx 1 + \frac{m_\gamma^2}{2\omega^2}$$



Can search for *time delay/advancement effects* with pulsars, or *dispersive lensing* (*Rainbow effect*) from luminous astrophysical sources of electromagnetic radiation.

Acknowledgements

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References (Axions)

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.

References (Scalars)

Y. V. Stadnik and V. V. Flambaum. *Can dark matter induce cosmological evolution of the fundamental constants of Nature*? arXiv:1503.08540.

Y. V. Stadnik and V. V. Flambaum. *Constraining scalar dark matter with Big Bang nucleosynthesis and atomic spectroscopy*. arXiv:1504.01798.

Y. V. Stadnik and V. V. Flambaum. *Searching for Dark Matter and Variation of Fundamental Constants with Laser and Maser Interferometry*. Physical Review Letters **114**, 161301 (2015). arXiv:1412.7801.

Y. V. Stadnik and V. V. Flambaum. *Searching for Topological Defect Dark Matter via Nongravitational Signatures*. Physical Review Letters **113**, 151301 (2014). arXiv:1405.5337.

Conclusions

We propose to search for **light bosonic** dark matter (**galactic condensates** and **topological defects**) through observables that are **linear** in underlying interaction parameters using **new high-precision** detection methods!

Detection methods include the use of **terrestrial measurements** (atomic clocks, magnetometers, torsion pendula, ultracold neutrons, laser interferometers) and **astrophysical observations** (pulsar timing, cosmic radiation lensing).

We propose a **new model for the cosmological evolution of the fundamental constants**, in which a scalar/pseudoscalar condensate that interacts with SM particles via quadratic couplings in φ produces both 'slow drifts' and oscillating variations of the fundamental constants.