Manifestations of Dark Matter and Variations of Fundamental Constants in Atoms and Astrophysical Phenomena

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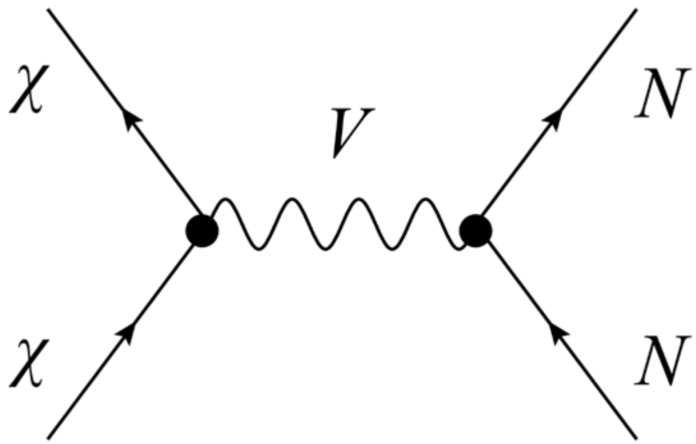
Conference, Location, Month 2015

Motivation

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



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

Observable is **quadratic** in α' (**quartic** in e') 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!

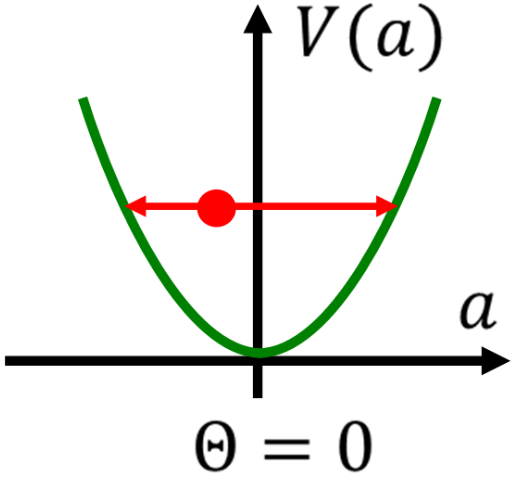
$$\mathcal{L}_{\mathrm{eff}} = \boxed{\left(\frac{\phi}{\Lambda_X}\right)^n} X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \boxed{\left(\frac{\phi}{\Lambda_X}\right)^n}$$

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).

Galactic Condensates of Light Bosons

The **QCD axion** is a good candidate for cold dark matter (along with light **pseudoscalar** (**ALP**) and **scalar** particles). Initial θ ~ 1, minimum θ=0. $\theta(t)=a(t)/f_a$.

An <u>*oscillating condensate*</u> (on a macroscopic scale) of bosons, $a(t) = a_0 \cos(m_a t)$, is believed to have been produced during the early Universe. For sufficiently light bosons ($m_a <$ ~1eV), a **galactic condensate of bosons** remains until the present day and may be detected.



Coherence of Galactic Condensate

Galactic condensate is virialised ($v_{\mathrm{Virial}} \sim 10^{-3}c$).

$$\frac{\Delta\omega_\phi}{\omega_\phi} \sim \frac{\frac{1}{2}m_\phi v^2}{m_\phi c^2} \sim 10^{-6}$$

$$\tau_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi v^2} \sim 10^6 \left(\frac{2\pi}{m_\phi}\right)$$

Zoo of axion effects-linear in interaction strength!

- Derivative-type coupling

$$\boxed{\mathcal{L}_{\mathrm{DT}} = -\frac{\partial_\mu a}{f_{\mathrm{a}}}\bar{\psi}\gamma^\mu\gamma^5\psi} \qquad \boxed{\psi = e, p, n}$$

- Produces oscillating effects :

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

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

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

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

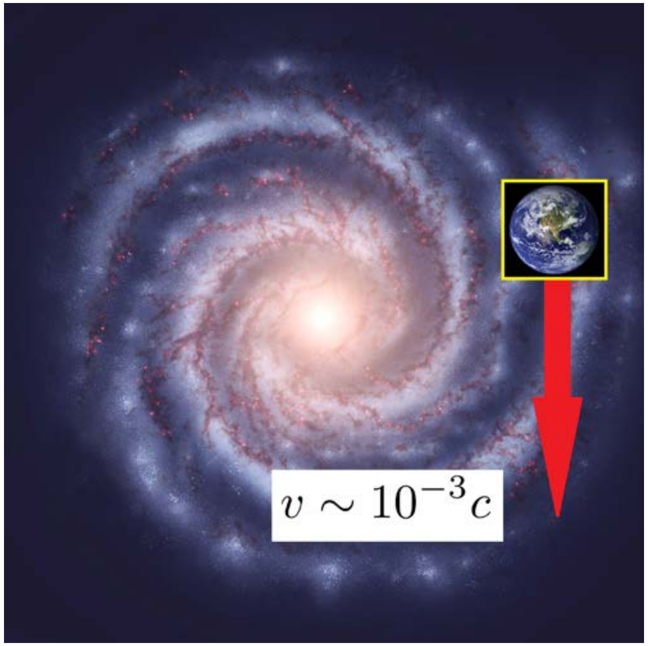
    [c.f. $H_{\mathrm{int}} \propto \boldsymbol{\sigma}\cdot\boldsymbol{B}_{\mathrm{eff}}(t)$ **]**

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

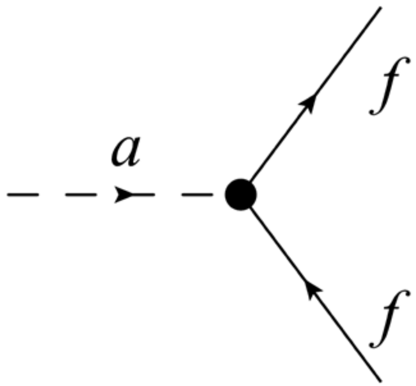
$$\boxed{H_{\mathrm{int}} \propto \boldsymbol{\sigma}\cdot\boldsymbol{g}\sin(m_a t)}$$

“Axion Wind” Effect (Axion and ALPs)

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).

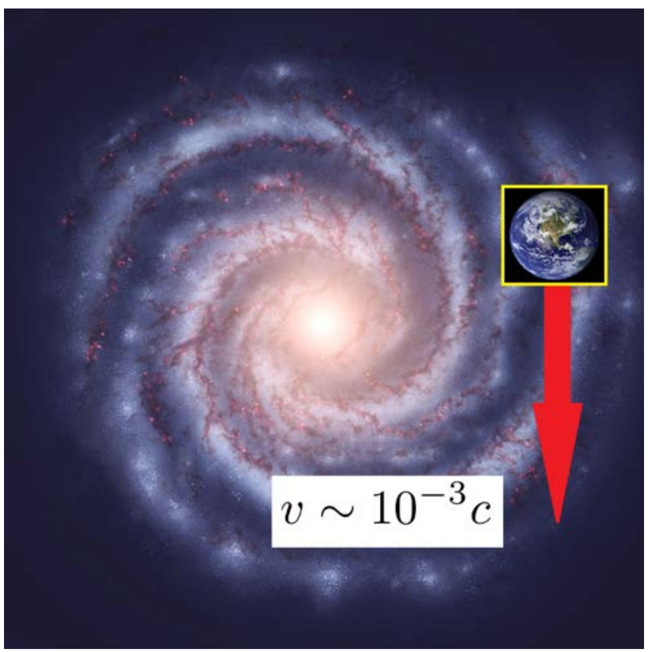


“Axion Wind” Effect (Axion and ALPs)



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

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



Axion-induced spin-precession effects are **linear** in a_0/f_a!

“Axion Wind” Effect (Axion and ALPs)

There are two distinct spin-precession frequencies:

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

$$\boxed{\omega_1 \approx \frac{m_a c^2}{\hbar}} \qquad \boxed{\omega_2 = \frac{2\pi}{T_{\text{sidereal}}}}$$

Spin-axion momentum couplings can be sought for with a variety of *spin-polarised* systems: **atomic co-magnetometers, torsion pendula** and **ultracold 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*.

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

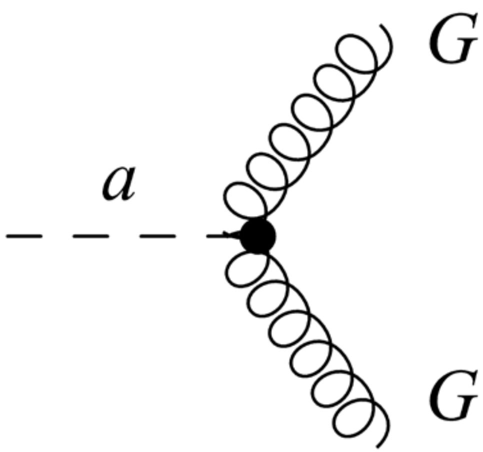
$$=> \quad H'_{\rm eff}(t) \propto \frac{C_f a_0}{f_a}\sin(m_a t)\ \sigma_f \cdot \hat{r}$$

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)

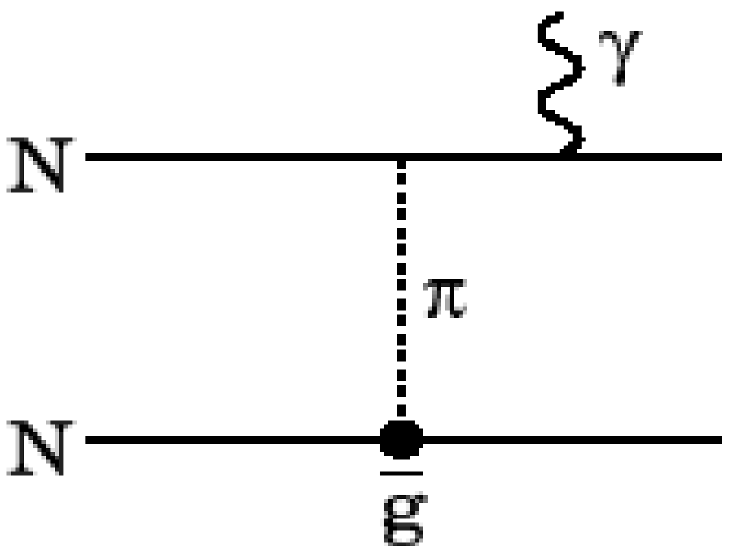
A galactic condensate consisting of the QCD axion induces oscillating *P*,*T*-odd electromagnetic moments in nuclei via two mechanisms:

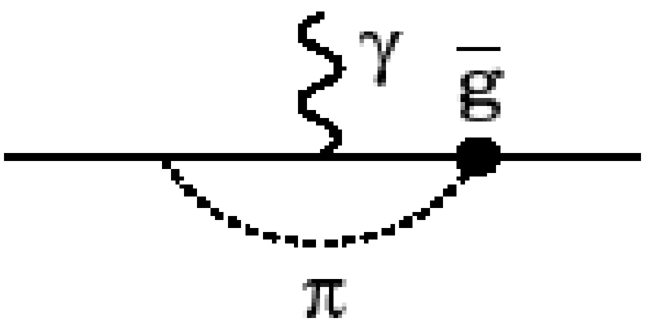
(1) *Oscillating nucleon EDMs* via axion coupling to gluon fields - dynamical $\theta(t)=a(t)/f_a$. [Graham, Rajendran, *PRD* **84**, 055013 (2011)]



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

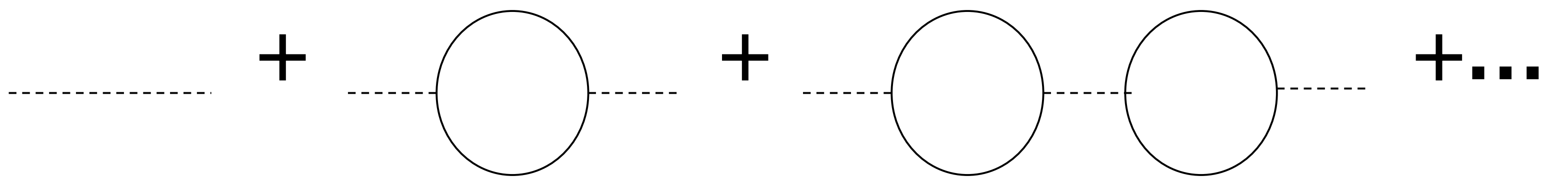
Nuclear EDM:
T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM
Sushkov, Flambaum, Khriplovich 1984

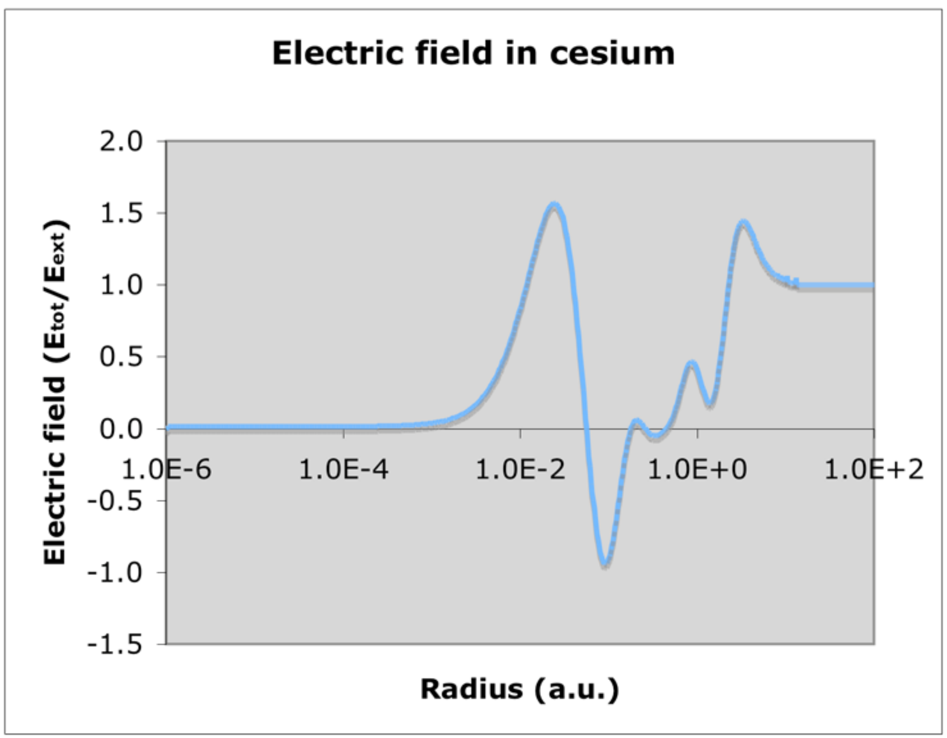




Screening of external electric field in atoms

Dzuba, Flambaum, Sushkov calculation





Diamagnetic atoms and molecules
Source-nuclear Schiff moment

SM appears when screening of external electric field by atomic electrons is taken into account.

Nuclear T,P-odd moments:

- EDM – non-observable due to total screening (Schiff theorem)

Nuclear electrostatic potential with screening (Sushkov, Flambaum, Khriplovich calculation following ideas of Schiff and Sandars):

$$\varphi(\mathbf{R}) = \int \frac{e\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r + \frac{1}{Z}(\mathbf{d} \bullet \nabla) \int \frac{\rho(\mathbf{r})}{|\mathbf{R}-\mathbf{r}|} d^3r$$

d is nuclear EDM, the term with **d** is the electron screening term

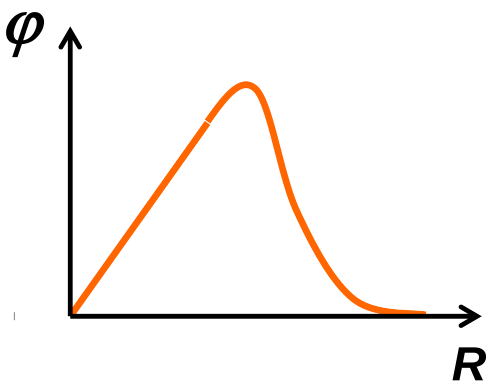
$\varphi(\mathbf{R})$ in multipole expansion is reduced to $\varphi(\mathbf{R}) = 4\pi \mathbf{S} \bullet \nabla \delta(\mathbf{R})$

where $\mathbf{S} = \frac{e}{10}\left[\langle r^2 \mathbf{r} \rangle - \frac{5}{3Z}\langle r^2 \rangle \langle \mathbf{r} \rangle\right]$ is Schiff moment.

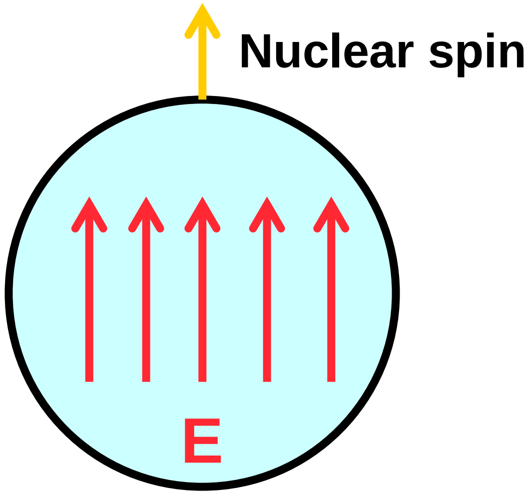
This expression is not suitable for relativistic calculations.

Flambaum,Ginges:
L=S(1 – c Z^2 α^2)

$$\phi(\mathbf{R}) = -\frac{3L \bullet \mathbf{R}}{B}\rho(R)$$ where $$B = \int \rho(R) R^4 dR$$



Electric field induced by T,P-odd nuclear forces which influence proton charge density

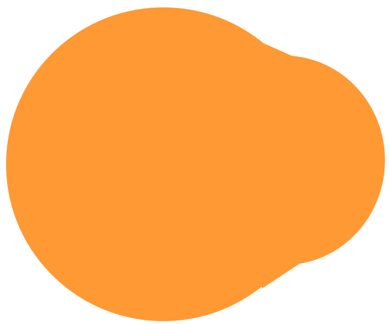


This potential has no singularities and may be used in relativistic calculations.
SM electric field polarizes atom and produces EDM.
Calculations of nuclear SM: Sushkov,Flambaum,Khriplovich ;Brown et al,Flambaum et al
Dmitriev et al,Auerbach et al,Engel et al, Liu et al,Sen'kov et al, Ban et al.
Atomic EDM: Sushkov,Flambaum,Khriplovich; Dzuba,Flambaum,Ginges,Kozlov.
Best limits from Hg EDM measurement in Seattle –
Crucial test of modern theories of CP violation (supersymmetry, etc.)

Nuclear enhancement

Auerbach, Flambaum, Spevak 1996

The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)

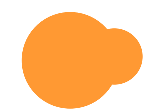


Intrinsic Schiff moment:

$$S_{\mathrm{intr}} \approx eZR_N^3 \frac{9\beta_2\beta_3}{20\pi\sqrt{35}}$$

$\beta_2 \approx 0.2$ **- quadrupole deformation**

$\beta_3 \approx 0.1$ **- octupole deformation**

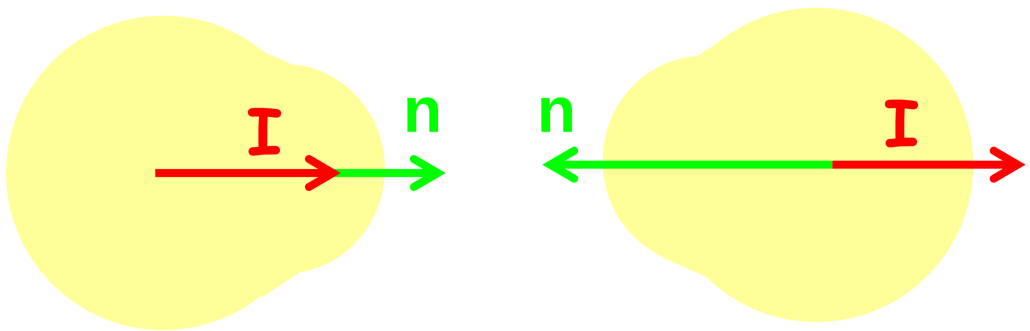


No T,P-odd forces are needed for the Schiff moment and EDM in intri
reference frame
However, in laboratory frame S=d=0 due to rotation

In the absence of T,P-odd forces: doublet (+) and (-)

$$\Psi = \frac{1}{\sqrt{2}}\left(\left|IMK\right\rangle + \left|IM-K\right\rangle\right)$$

and $\langle \mathbf{n} \rangle = 0$



T,P-odd mixing (β) with opposite parity state (-) of doublet:

$$\Psi = \frac{1}{\sqrt{2}}\left[(1+\beta)\left|IMK\right\rangle + (1-\beta)\left|IM-K\right\rangle\right]$$

and $\langle \mathbf{n} \rangle \propto \beta \mathbf{I}$

EDM and Schiff moment

$$\langle d \rangle, \langle \mathbf{S} \rangle \propto \langle \mathbf{n} \rangle \propto \beta \mathbf{I}$$

Simple estimate (Auerbach, Flambaum, Spevak):

$$S_{lab} \propto \frac{\langle + | H_{TP} | - \rangle}{E_+ - E_-} S_{body}$$

Two factors of enhancement:

1. **Large collective moment in the body frame**
2. **Small energy interval (E_+-E_-), 0.05 instead of 8 MeV**

$$S \approx 0.05 e \beta_2 \beta_3^2 Z A^{2/3} \eta r_0^3 \frac{\text{eV}}{E_+ - E_-} \approx 700 \times 10^{-8} \eta e \text{fm}^3 \approx 500 S(\text{Hg})$$

^{225}Ra,^{223}Rn, Fr,… -100-1000 times enhancemnt

Engel, Friar, Hayes (2000); Flambaum, Zelevinsky (2003): Static octupole deformation is not essential, nuclei with soft octupole vibrations also have the enhancement.

Nature 2013 Experiment : Octupole deformation in ^{224}Ra,^{220}Rn,
Measurements of 225 Ra EDM: Argonne PRL, 9 June 2015

Atomic EDM produced by nuclear magnetic quadrupole moment

Magnetic interaction is not screened!

MQM produced by nuclear T,P-odd forces (Khriplovich, Sushkov, Flambaum)

Collective enhancement in deformed nuclei (Flambaum). T,P-odd nuclear interaction produces spin hedgehog- correlation (s r)

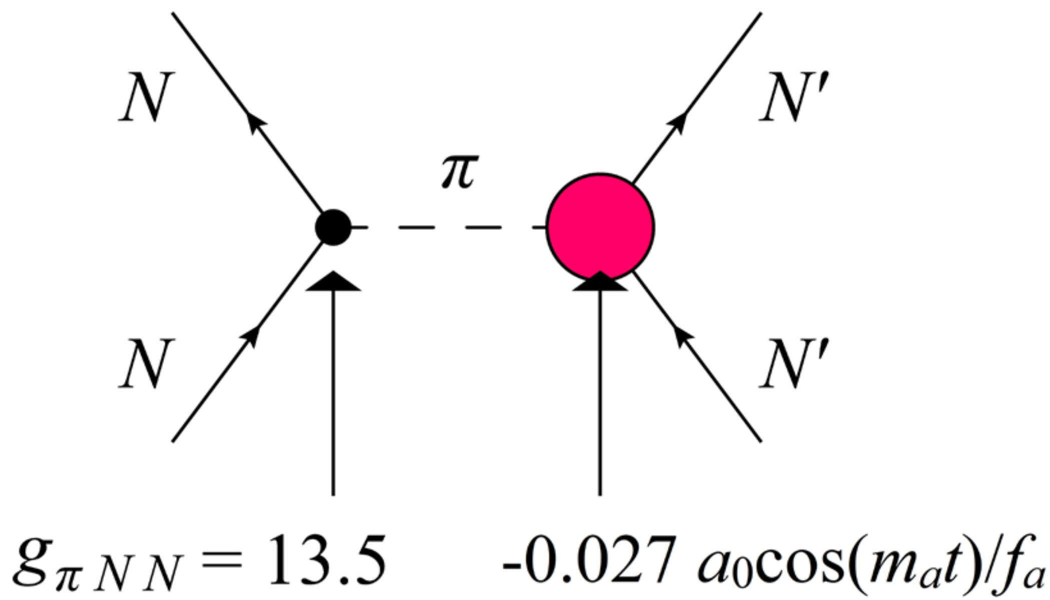
Spherical – magnetic monopole forbidden

Deformed- collective magnetic quadrupole

Paramagnetic molecules ThO,TaN,YbF,… (Flambaum, DeMille, Kozlov)

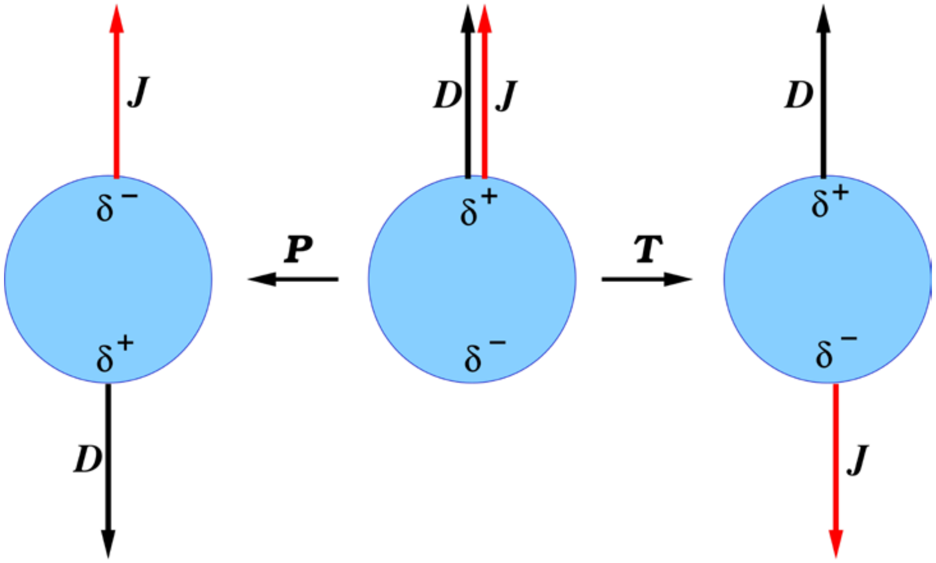
Oscillating *P*,*T*-odd Nuclear Electromagnetic Moments (QCD Axion)

(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 …

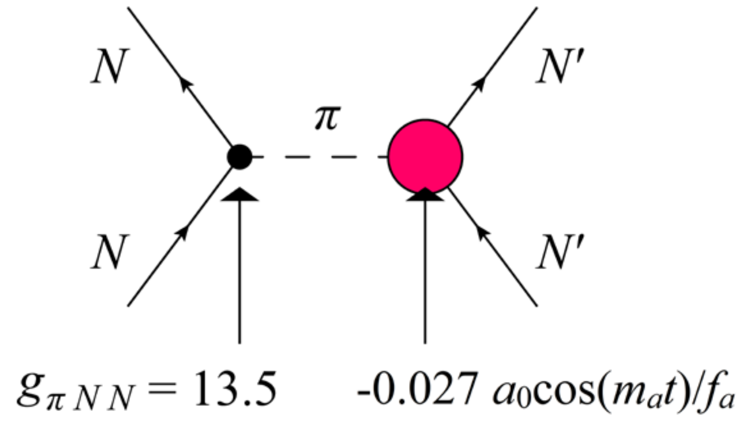
Oscillating EDMs of Paramagnetic Atoms and Molecules (Axion and ALPs)

[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*.

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



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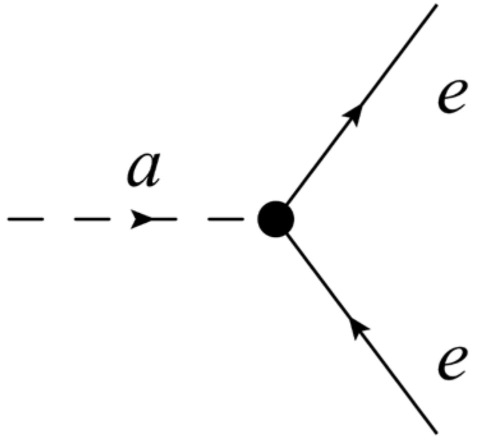
(2) *Derivative coupling of axion field to axial-vector currents of atomic/molecular electrons* (temporal component of interaction).

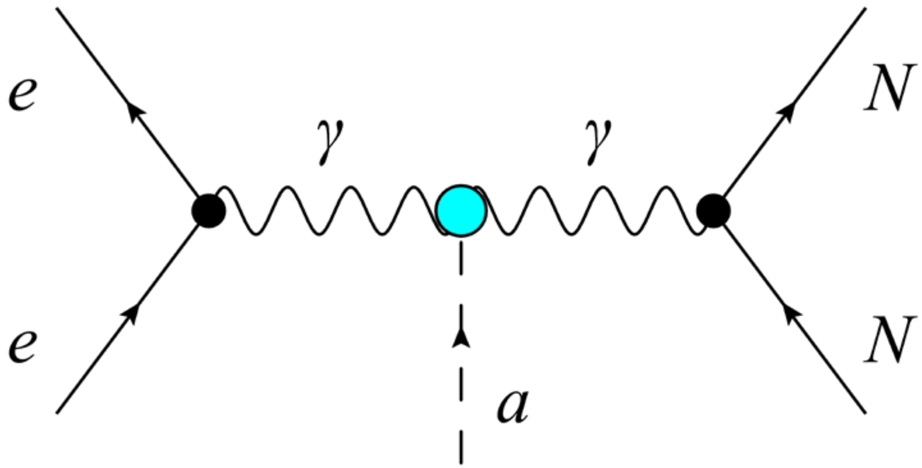


$$\mathcal{L}_{aee} = -\frac{C_e}{2f_a}\partial_0[a_0\cos(m_a t)]\bar{e}\gamma^0\gamma^5 e$$

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)]

(3) *Perturbation of electromagnetic electron-nucleon interaction by anomalous axion-photon interaction*.

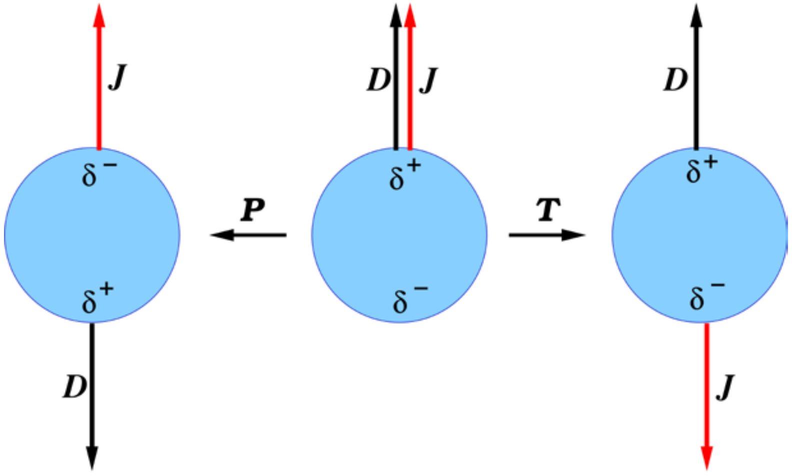


$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F \tilde{F}$$

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)]

Axion-induced oscillating atomic/molecular EDMs are **linear** in a_0/f_a!



Can search for these oscillating EDMs using **precision magnetometry** on paramagnetic atoms in the **solid-state**.

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?

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 …

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

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

We performed atomic, QCD and nuclear calculations.

Evidence for spatial variation of α

Quasar spectra

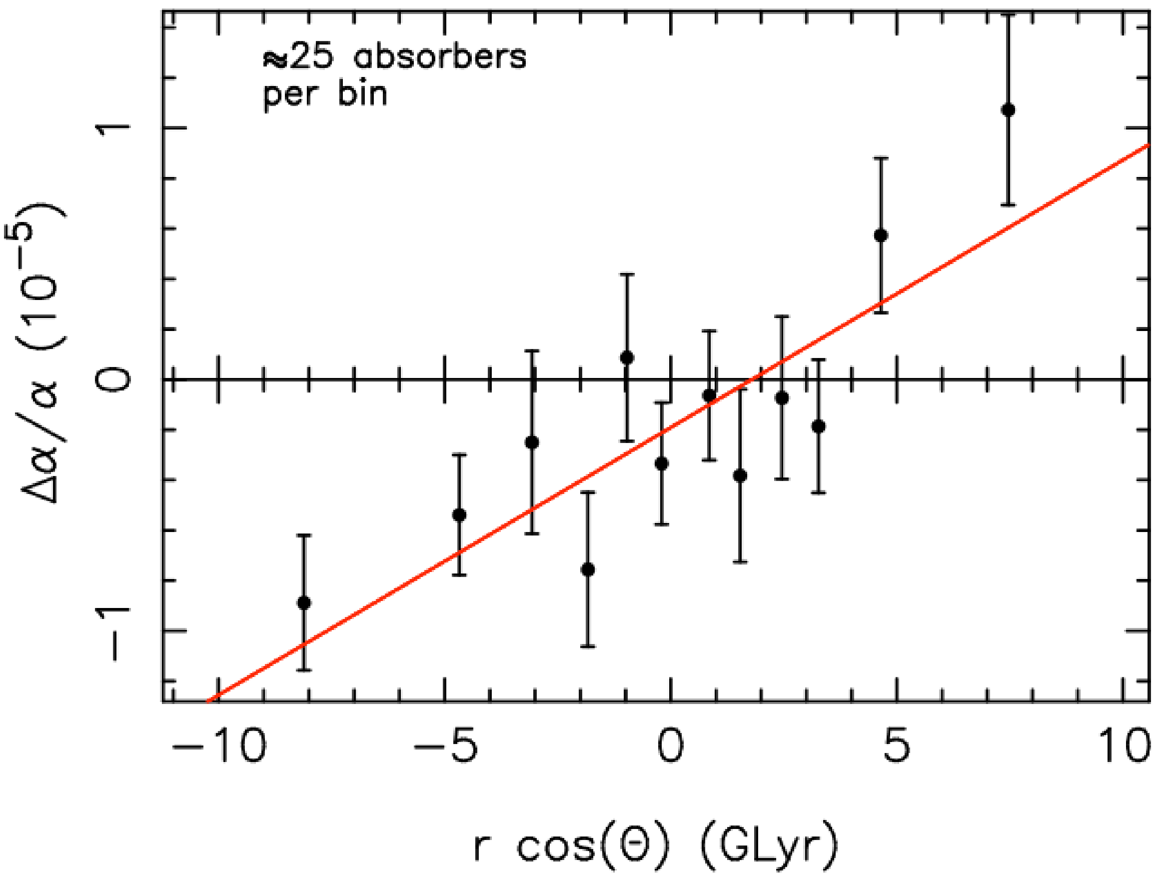
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, 2011

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

$x = r\cos(\phi)$, $r = ct$ – 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).

Results for variation of fundamental constants

Source	$Clock_1/Clock_2$	$d\alpha/dt/\alpha$ (10^{-16} yr^{-1})
Blatt *et al*, 2007	Sr(opt)/Cs(hfs)	-3.1(3.0)
Fortier *et al* 2007	Hg+(opt)/Cs(hfs)	-0.6(0.7)[a]
Rosenband *et al*08	Hg+(opt)/Al+(opt)	-0.16(0.23)
Peik *et al*, 2006	Yb+(opt)/Cs(hfs)	4(7)
Bize *et al*, 2005	Rb(hfs)/Cs(hfs)	1(10)[a]

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

Combined results: $d/dt \ln\alpha = -1.6(2.3) \times 10^{-17}$ **yr**$^{-1}$

$d/dt \ln(m_q/\Lambda_{QCD}) = 3(25) \times 10^{-15}$ **yr**$^{-1}$

m_e/M_p **or** m_e/Λ_{QCD} $-1.9(4.0)\times 10^{-16}$ **yr**$^{-1}$

Relative enhancement: transitions between close levels

Dy: $4f^{10}5d6s$ E=19797.96… cm^{-1} , q= 6000 cm^{-1}

$4f^{9}5d^{2}6s$ E=19797.96… cm^{-1} , q= -23000 cm^{-1}

Interval ω_0= 10^{-4} cm^{-1}

Our proposal and calculations : relative enhancement factor **K = 10^8** , i.e. $\Delta\omega/\omega_0 = 10^8\,\Delta\alpha/\alpha$

Measurements (Berkeley) $d\ln\alpha/dt$ =-7.5(6.9)x 10^{-17}yr^{-1}

Problem: states are not narrow!

Huge enhancement in nuclear clock Th229, highly charged ions and some molecules

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.

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

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

'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:

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

Fermions:

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

Massive Vector Bosons:

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

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*** $(m_n - m_p)/T_F$ ***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 $(n/p)_{\mathrm{weak}} = \exp[-(m_n - m_p)/T_F]$.

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

$$-0.59\frac{\Delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} + \frac{1}{3}\frac{\Delta M_{\mathrm{Planck}}}{M_{\mathrm{Planck}}} = 0.0033 \pm 0.0085$$

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) *Underdamped regime ($m_\varphi \gg H(t) \approx 1/2t$)*: 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 '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:

(2) *Overdamped regime ($m_\varphi << H(t) \approx 1/2t$)*: rate of DM oscillations << rate of Universe expansion, so condensate does *not* oscillate and evolution of DM field follows a dark energy-type volume-*independent* scaling:

$$\rho_{\mathrm{cond}} \approx \mathrm{constant}\ [1+z(t_m)]^3 \quad \text{with} \quad H(t_m) = m_\phi$$

$$=> \frac{1}{m_\phi^2}\left(\frac{m_\phi}{3\times 10^{-16}\ \mathrm{eV}}\right)^{3/2}\left[\frac{0.08}{(\Lambda'_\gamma)^2} + \frac{1.59}{m_d - m_u}\left(\frac{m_d}{(\Lambda'_d)^2} - \frac{m_u}{(\Lambda'_u)^2}\right) + \frac{3.32}{(\Lambda'_W)^2} - \frac{4.65}{(\Lambda'_Z)^2}\right] \simeq (0.5 \pm 1.3)\times 10^{-20}\ \mathrm{eV}^{-4}$$

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

Atomic Clocks

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

Atomic clocks may be used to search for ***oscillating effects*** produced by ***scalar condensate***:

Dy/Cs (UC Berkeley) => Λ'_γ

Yb^+/Cs (PTB Braunschweig) => Λ'_γ , Λ'_e , Λ'_p , Λ'_q

Sr/Yb/Hg (RIKEN Tokyo) => Λ'_γ , Λ'_e , Λ'_p , Λ'_q

Al^+/Hg^+ (NIST Boulder) => Λ'_γ

Sr/Cs (LNE-SYRTE Paris) => Λ'_γ , Λ'_e , Λ'_p , Λ'_q

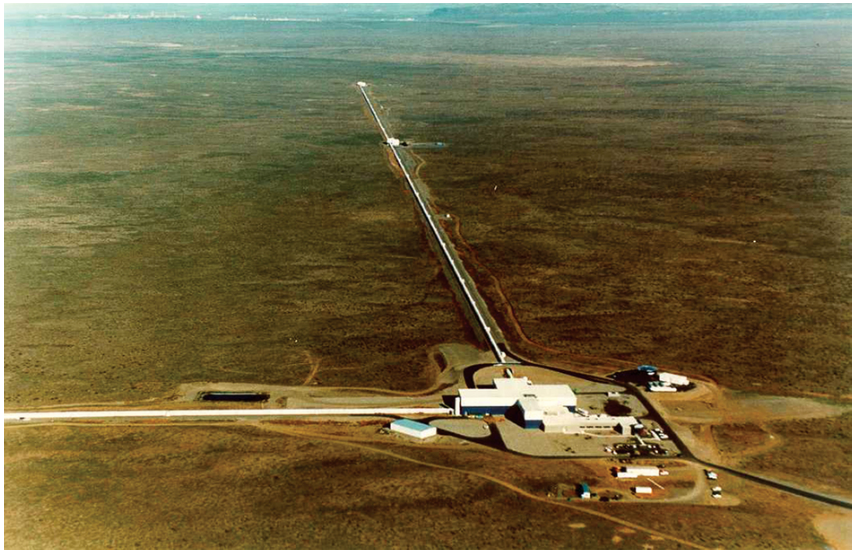
Yb^+/Yb^+ (NPL London, PTB) => Λ'_γ

Rb/Cs (LNE-SYRTE Paris) => Λ'_γ , Λ'_q

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 ($L = Na_{\mathrm{B}}$ and ω_{atomic} depend on the fundamental constants).

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

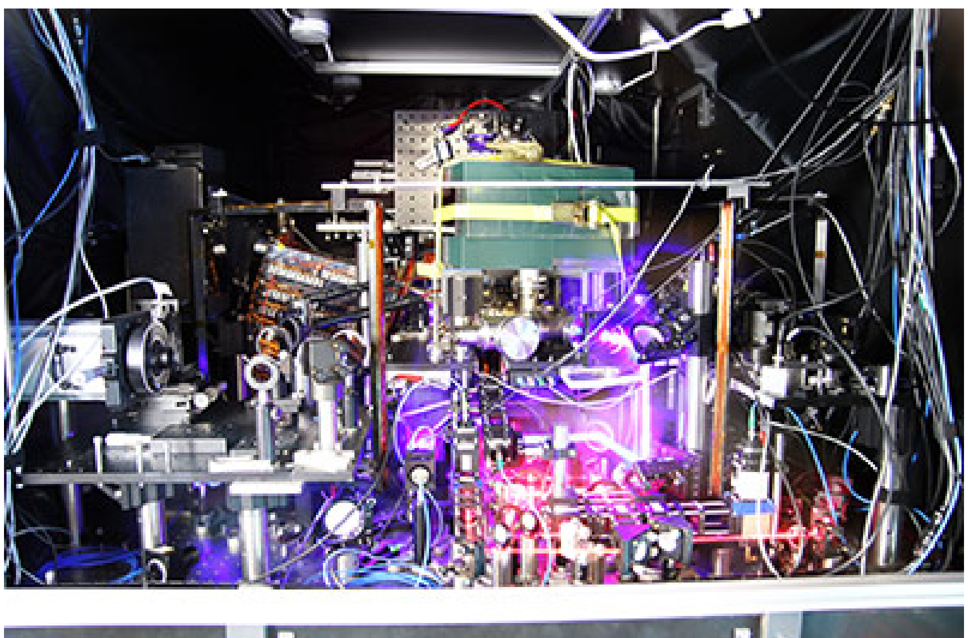
$$=> \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\,\delta\alpha/\alpha = 10^{11}\delta\alpha/\alpha$

Laser Interferometry (smaller-scale)

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

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 (smaller-scale)

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

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*.

Direct comparison of frequency (wavelength) with length.

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

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

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

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

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

If the laser cannot be locked to an atomic frequency (e.g. if changes occur too quickly), then the laser frequency is determined by the resonator length: $\omega \sim 1/L_{\mathrm{res}}$. In this case, the change in accumulated phase in an arm, $\Phi = \omega L_{\mathrm{arm}}/c \sim (N_1 a_{\mathrm{B}})/(N_2 a_{\mathrm{B}})$, is unchanged in the *non-relativistic limit*. Here the non-zero effects arise due to *relativistic corrections*.

$$\frac{\delta\Phi}{\Phi} \approx 2\alpha^2 \left[\frac{Z_{\mathrm{res}}^2}{\nu_{\mathrm{res}}(j_{\mathrm{res}}+1/2)} - \frac{Z_{\mathrm{arm}}^2}{\nu_{\mathrm{arm}}(j_{\mathrm{arm}}+1/2)} \right] \frac{\delta\alpha}{\alpha}$$

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).

Multiple-pendulum mirror shielding system in large-scale interferometer suppresses effects of variations in L, so $\Phi \sim \omega/c \sim m_e e^4/\hbar^3 c = (m_e c/\hbar)(e^2/\hbar c)^2$:

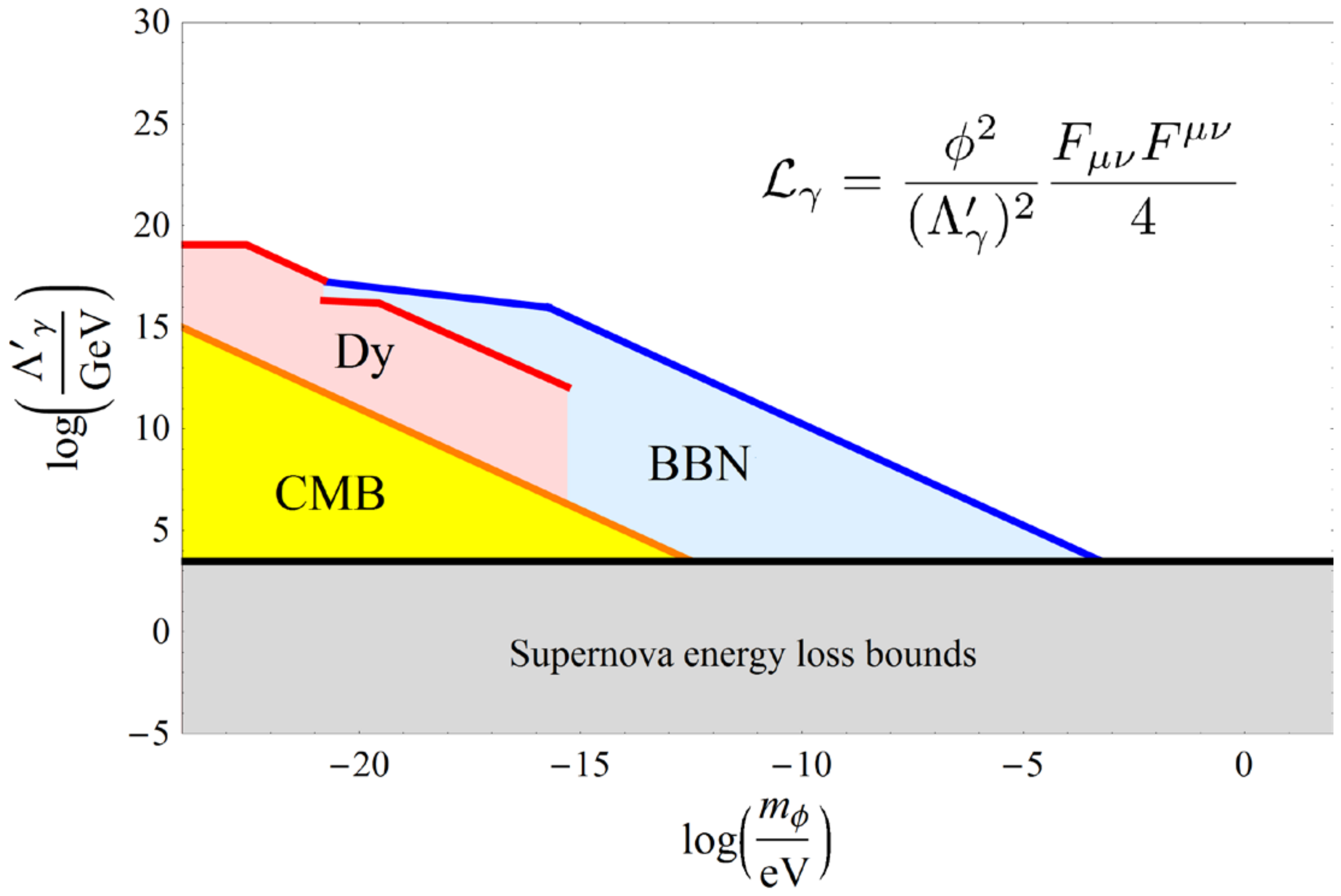
$$\frac{\delta\Phi}{\Phi} = \frac{\delta m_e}{m_e} + 2\frac{\delta\alpha}{\alpha}$$

Can search for **'slow drifts'**, **oscillating** and **transient-in-time variations** (see later) of constants.

Constraints on Scalar/Pseudoscalar Quadratic Interaction with the Photon

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

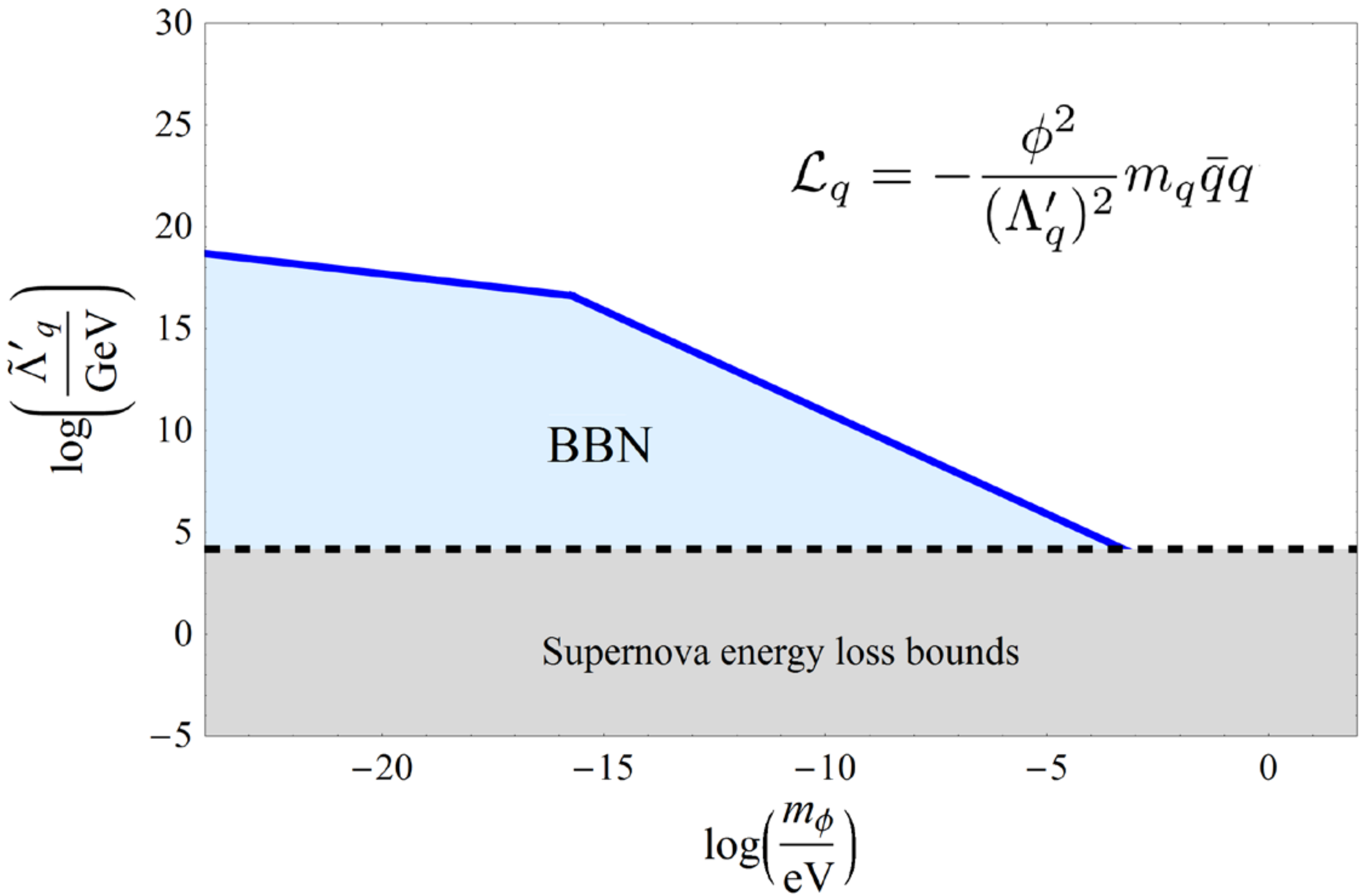
Supernova energy loss bounds: [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Constraints on Scalar/Pseudoscalar Quadratic Interactions with Quarks

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

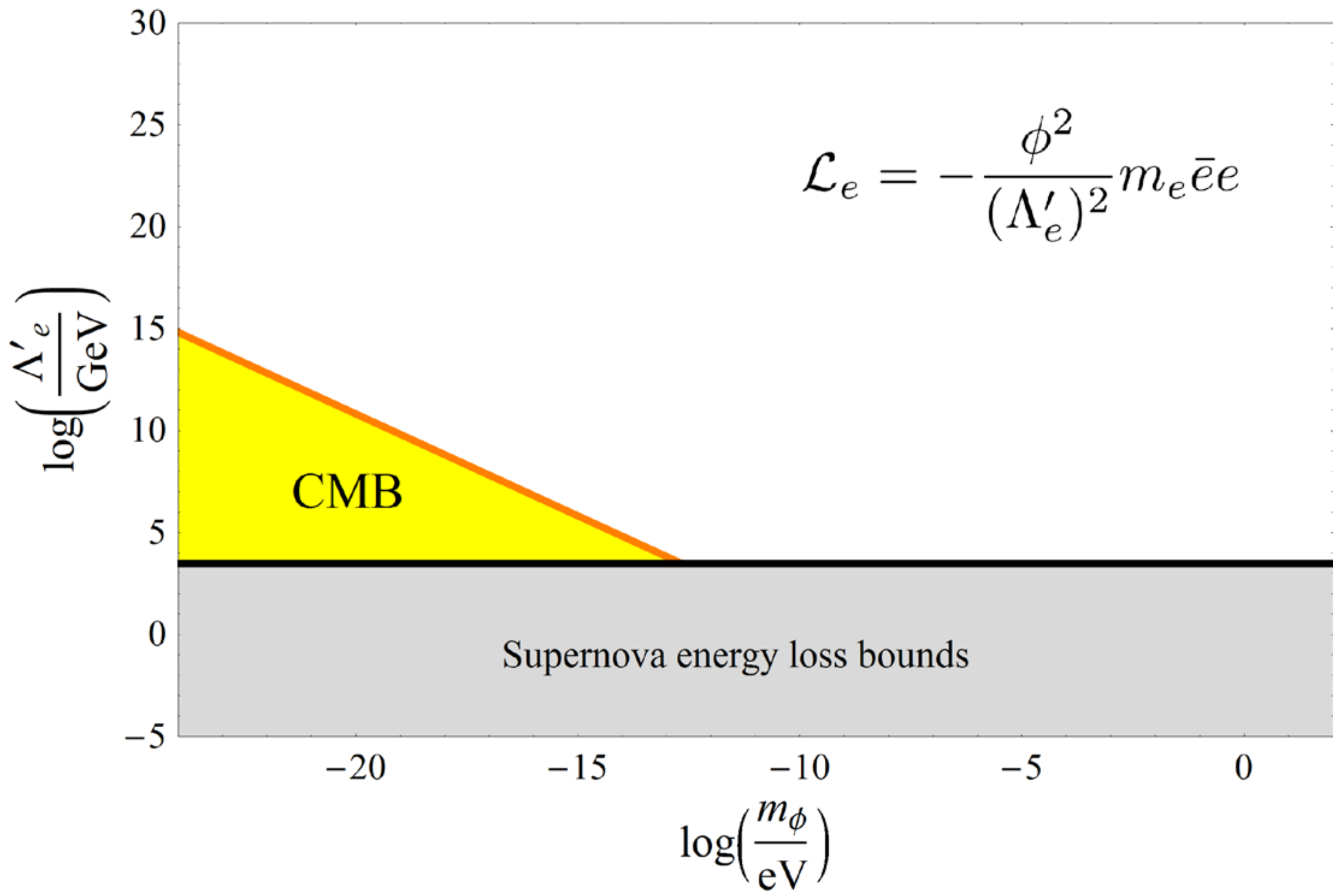
Supernova energy loss bounds (Proton): [Olive, Pospelov, *PRD* **77**, 043524 (2008)]



Constraints on Scalar/Pseudoscalar Quadratic Interaction with the Electron

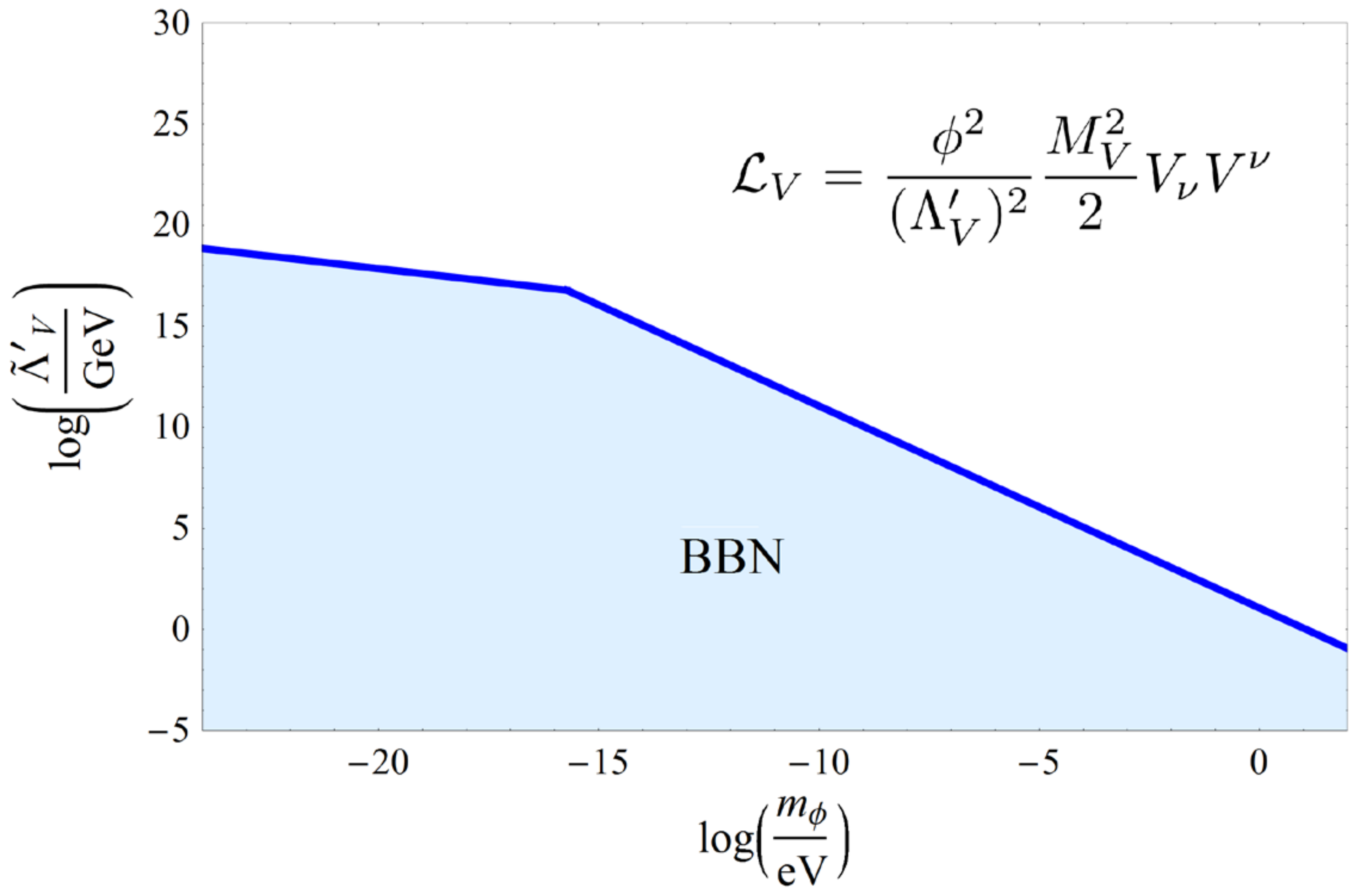
CMB: [Stadnik, Flambaum, arXiv:1503.08540]

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

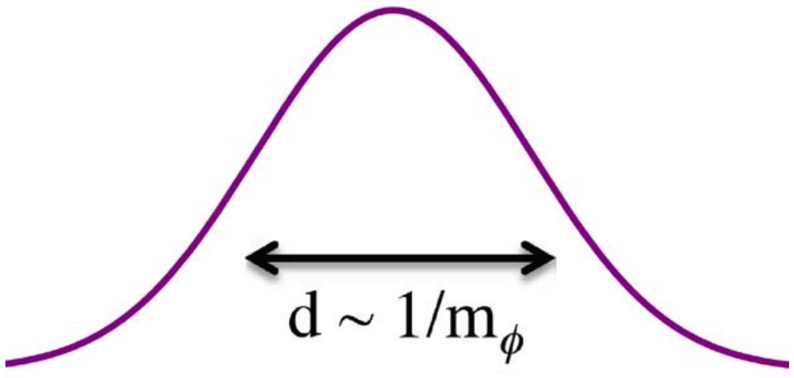
Take a simple scalar field and give it a *self-potential*, e.g. $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable *domain wall* will form in between, e.g. $\varphi = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2} v$.

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*



Topological Defect Dark Matter

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

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

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

Searching for Topological Defects

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

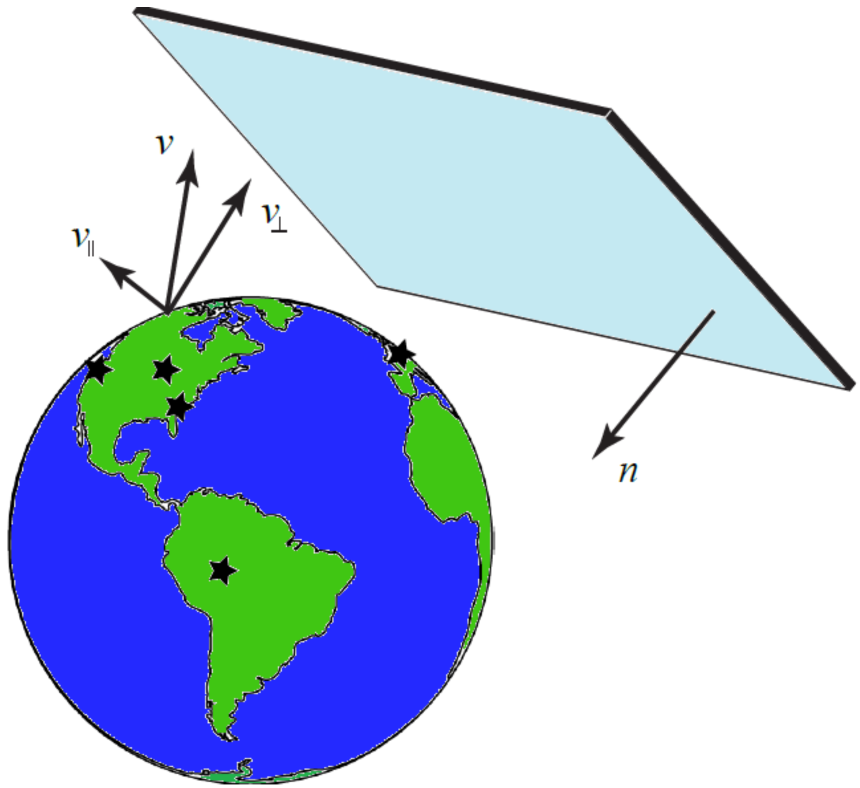
Recent proposals include:

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)]



Transient-in-Time Variations of the Fundamental Constants

[Derevianko, Pospelov, *Nature Physics* **10**, 933 (2014)],
[Stadnik, Flambaum, *PRL* **113**, 151301 (2014) + *PRL* **114**, 161301 (2015)]

Topological defects consisting of *scalar particles* (or also pseudoscalar particles for the quadratic portal) produce ***transient-in-time variations of the fundamental constants***.

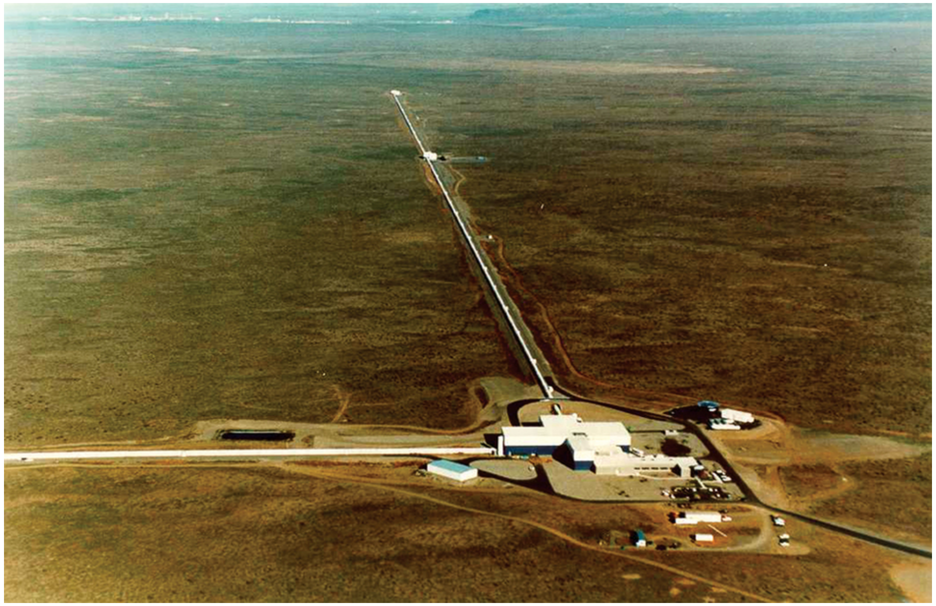
$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad => \alpha \to \frac{\alpha}{1-\phi^2/(\Lambda'_\gamma)^2} \simeq \alpha\left[1+\frac{\phi^2}{(\Lambda'_\gamma)^2}\right]$$

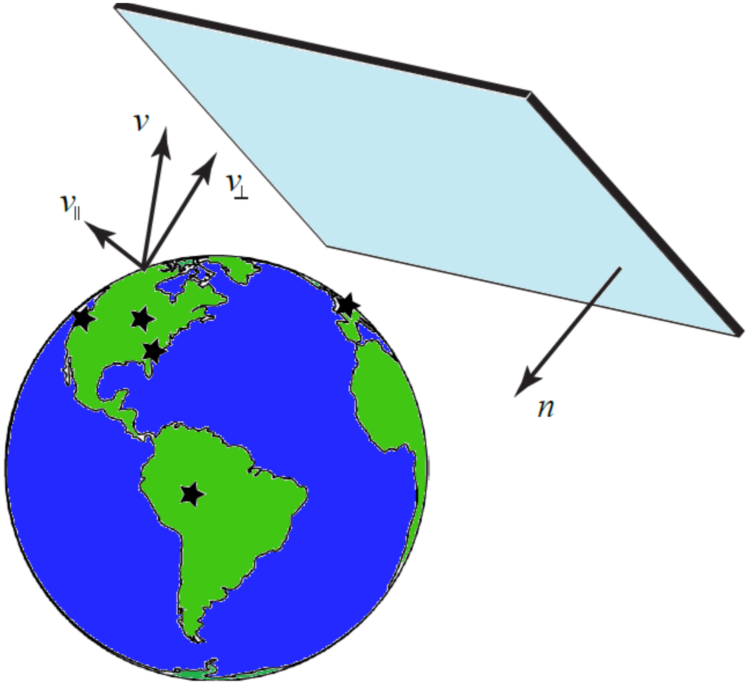
$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad => m_f \to m_f\left[1+\frac{\phi^2}{(\Lambda'_f)^2}\right]$$

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

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

A network of extremely sensitive *laser interferometers* can be used to search for *correlated effects* ($v_{\mathrm{TD}} \sim 10^{-3}c$) produced by *topological defects*.

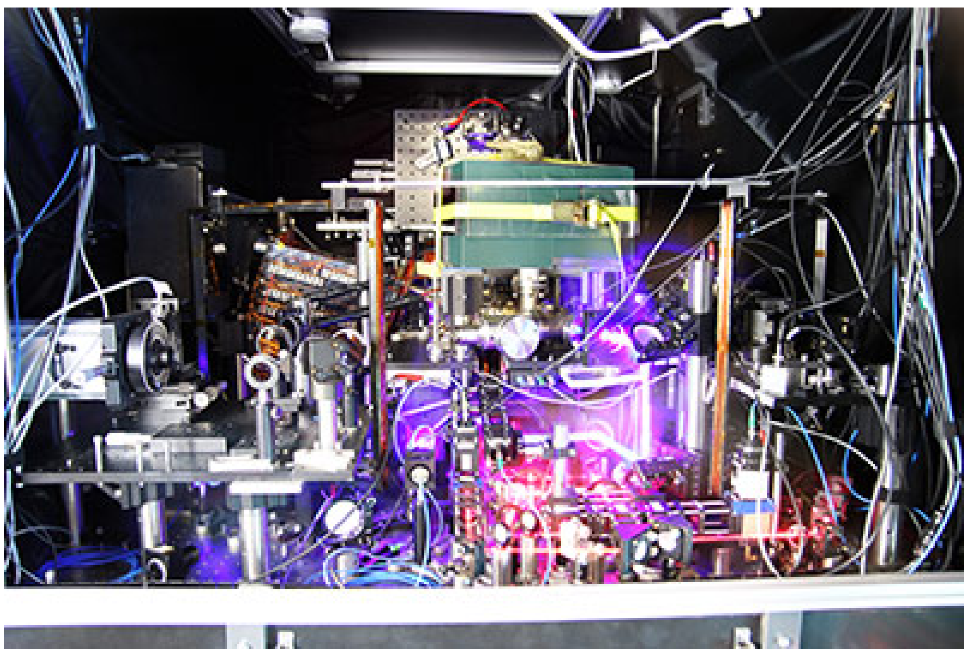




Laser Interferometers (smaller-scale)

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

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*.



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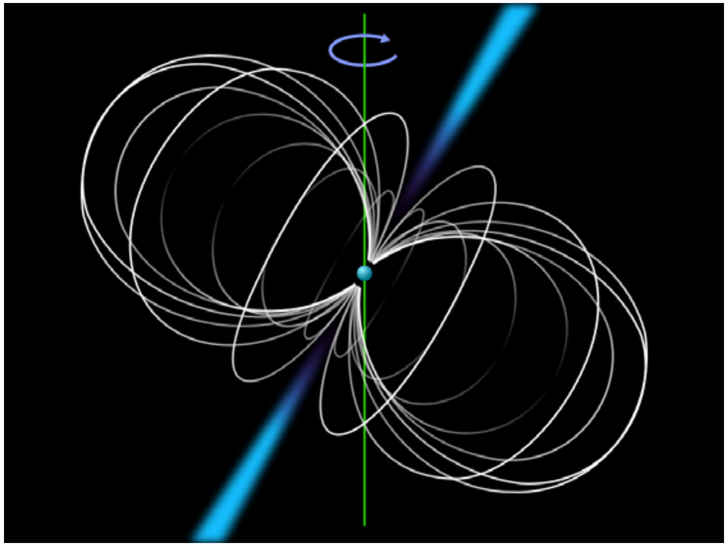
$$=> \quad \frac{\delta \Phi}{\Phi} \approx \frac{\delta \alpha}{\alpha}$$

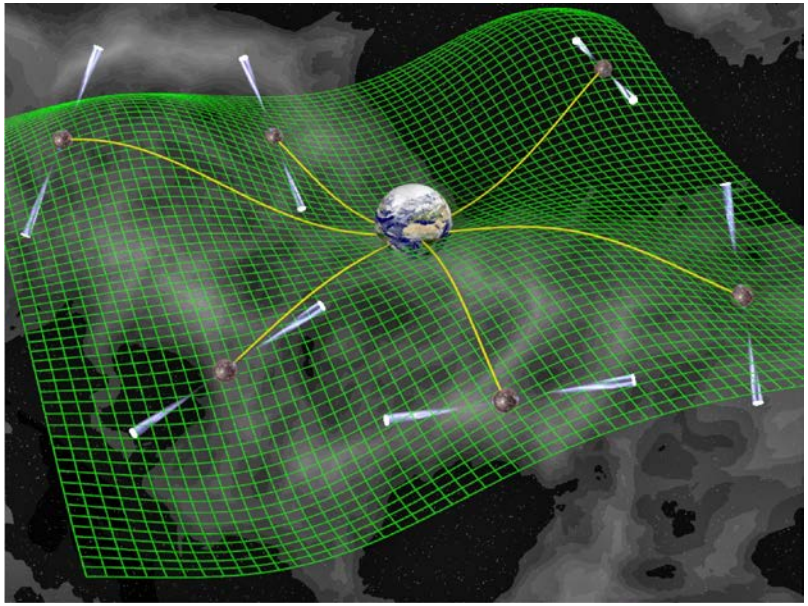
Pulsar Timing

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

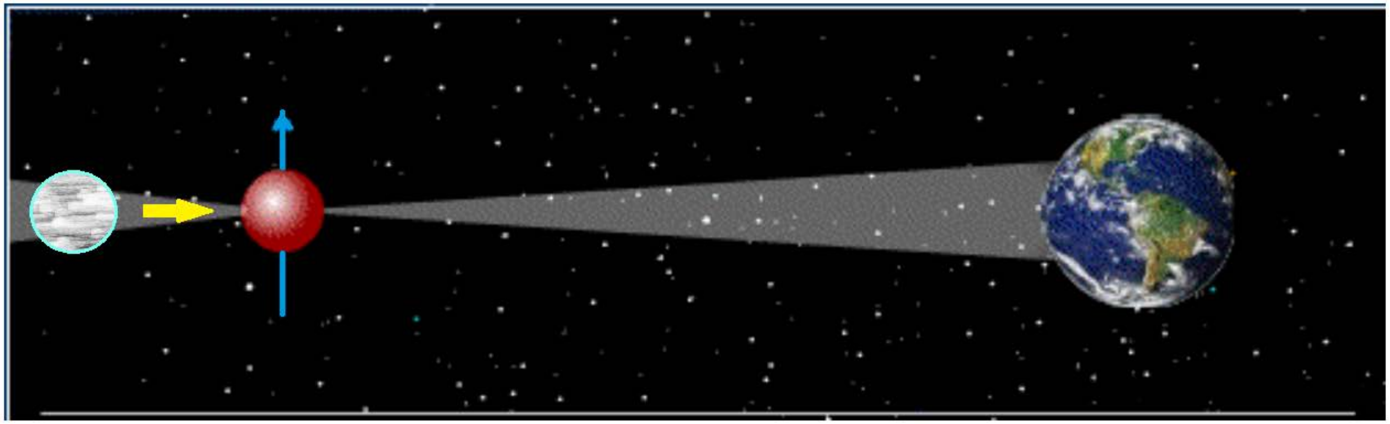




Pulsar Timing

[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***.



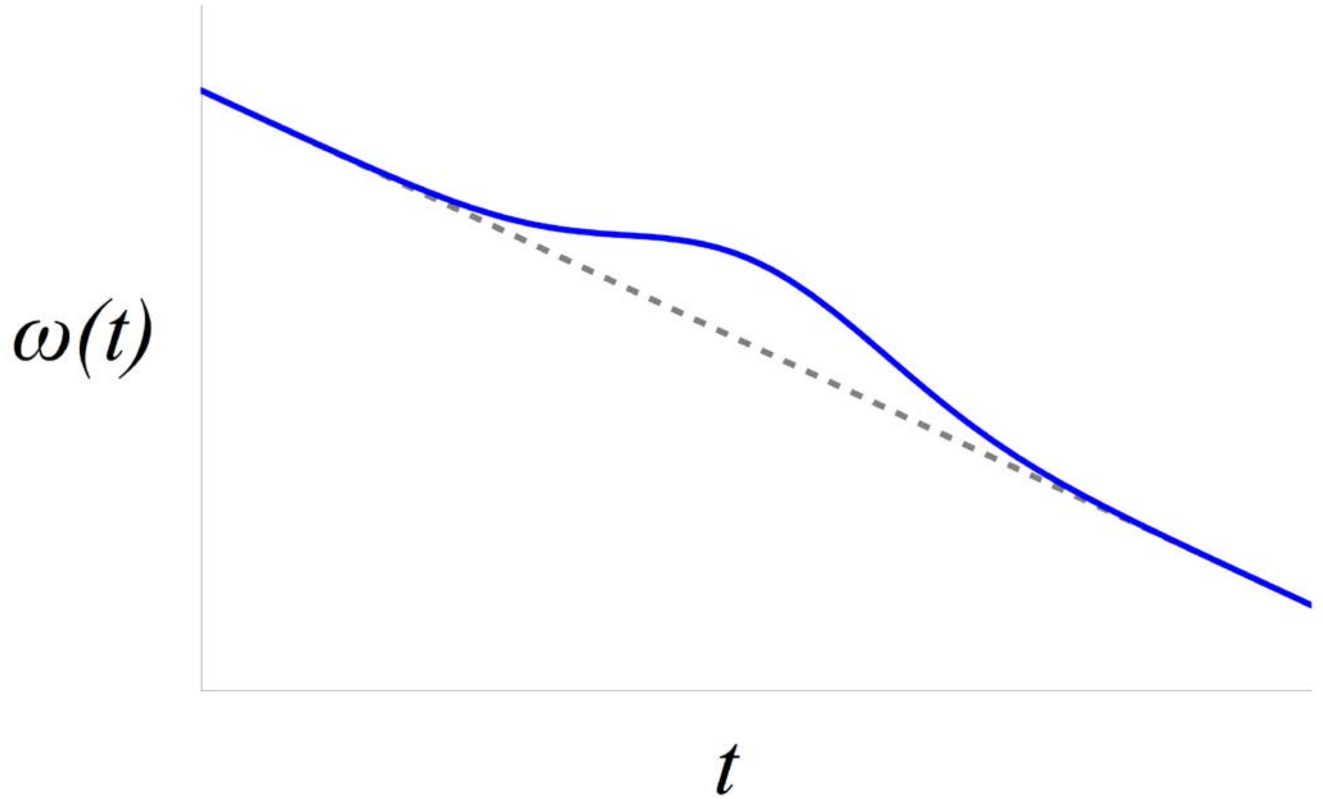
$$I \sim \frac{2MR^2}{5} \quad \text{and} \quad L = I\omega$$

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

Pulsar Timing

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

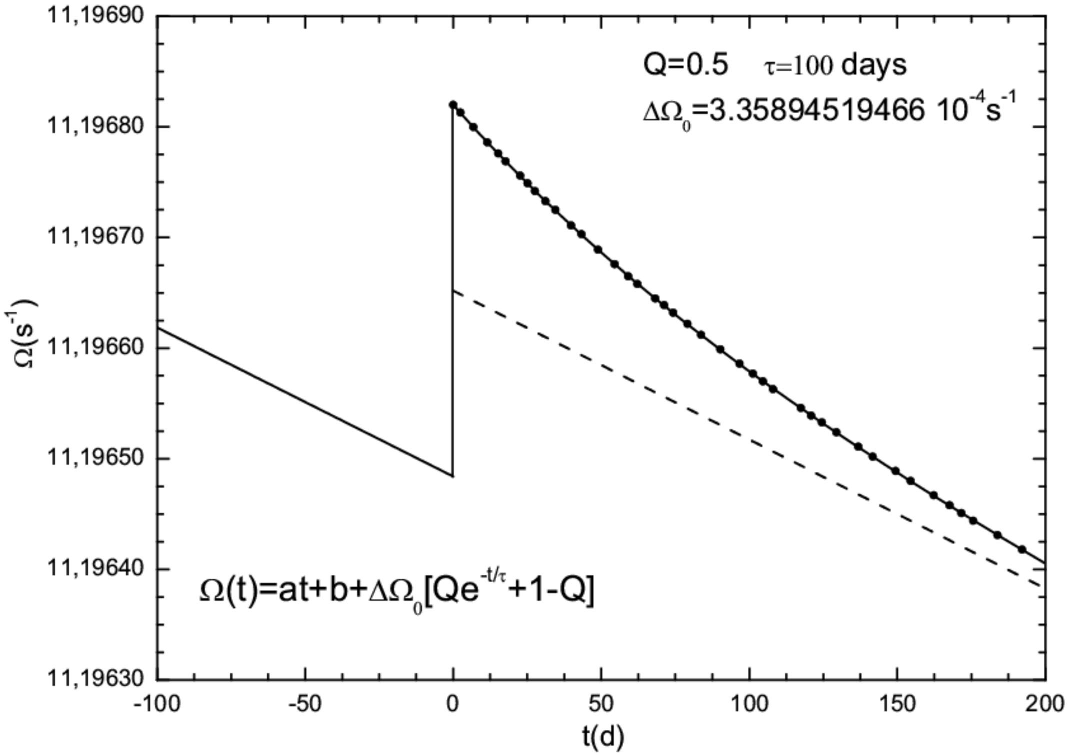
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile (**NOT** noise).



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).

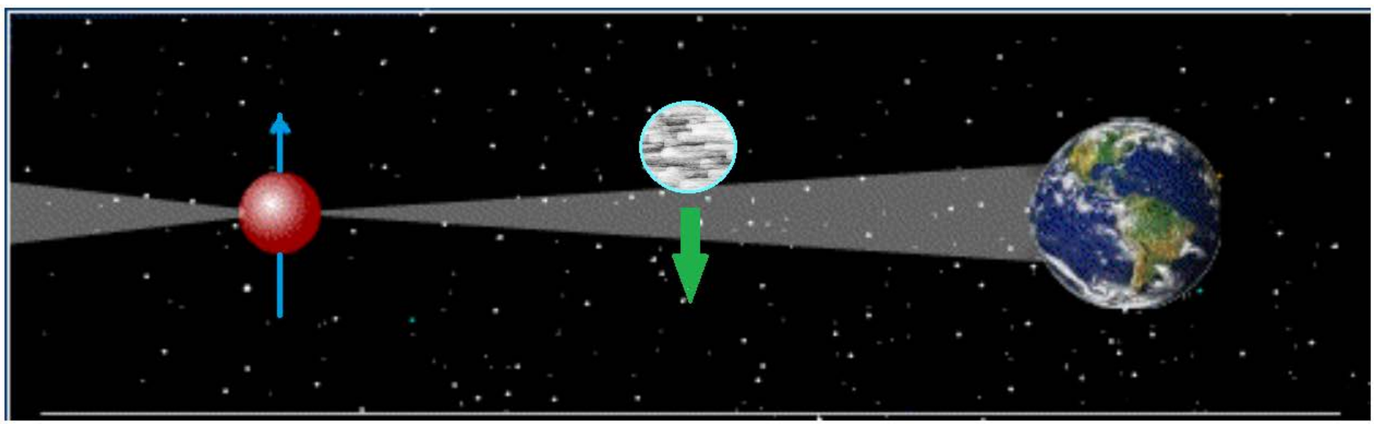


Non-Gravitational Lensing

[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.

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.

Acknowledgements

<u>We would like to thank the following people for helpful discussions:</u>

Francois Bondu, Julian Berengut, Dmitry Budker, Andrei Derevianko, Gleb Gribakin, Hartmut Grote, Sergey Klimenko, Guenakh Mitselmakher, Maxim Pospelov, Joan Sola, Ken Van Tilburg and Yvonne Wong

References (Axions)

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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.

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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.

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

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

If the laser cannot be locked to an atomic frequency (e.g. if changes occur too quickly), then the laser frequency is determined by the resonator length: $\omega \sim 1/L_{\mathrm{res}}$. In this case, the change in accumulated phase in an arm, $\Phi = \omega L_{\mathrm{arm}}/c \sim (N_1 a_B)/(N_2 a_B)$, is unchanged in the *non-relativistic limit*. Here the non-zero effects arise due to *relativistic corrections*.

$$\frac{\delta\Phi}{\Phi} \approx 2\alpha^2 \left[\frac{Z_{\mathrm{res}}^2}{\nu_{\mathrm{res}}(j_{\mathrm{res}}+1/2)} - \frac{Z_{\mathrm{arm}}^2}{\nu_{\mathrm{arm}}(j_{\mathrm{arm}}+1/2)} \right] \frac{\delta\alpha}{\alpha}$$

Coherence of Galactic Condensate

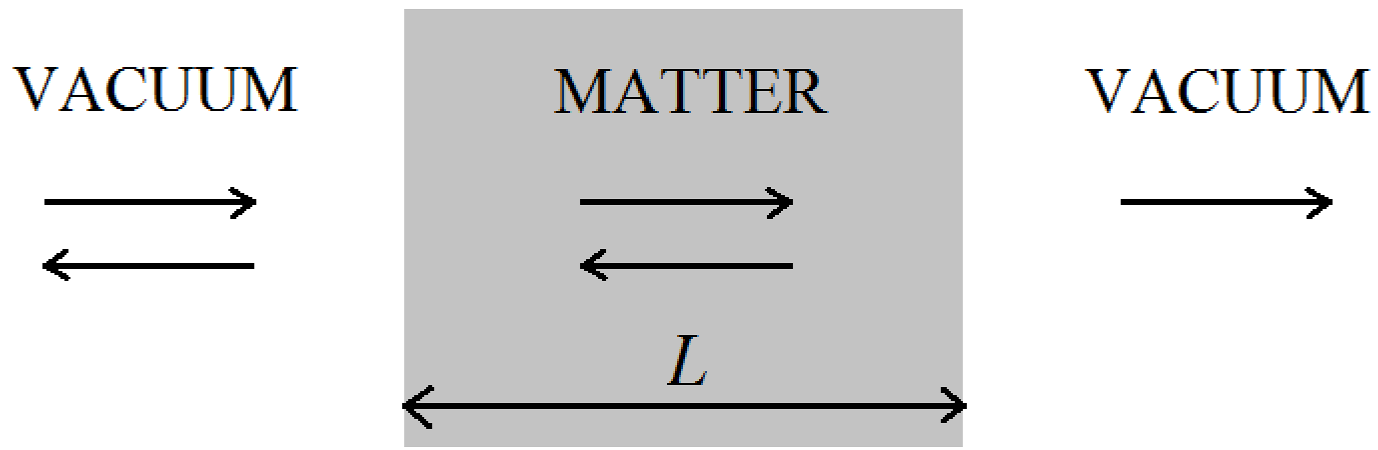
Galactic condensate is virialised ($v_{\mathrm{Virial}} \sim 10^{-3}c$).

$$\frac{\Delta\omega_\phi}{\omega_\phi} \sim \frac{\frac{1}{2}m_\phi v^2}{m_\phi c^2} \sim 10^{-6}$$

$$\tau_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi v^2} \sim 10^6 \left(\frac{2\pi}{m_\phi}\right)$$

1D Finite Attractive Barrier

$$\left[\partial_\mu \partial^\mu + m_\phi^2 - \frac{2\rho}{(\Lambda')^2}\right]\phi = 0\ , \quad \frac{\rho}{(\Lambda')^2} \equiv \frac{\rho_N}{(\Lambda'_N)^2} + \frac{\rho_e}{(\Lambda'_e)^2} + \frac{\rho_{\mathrm{Coulomb}}}{(\Lambda'_\gamma)^2}$$



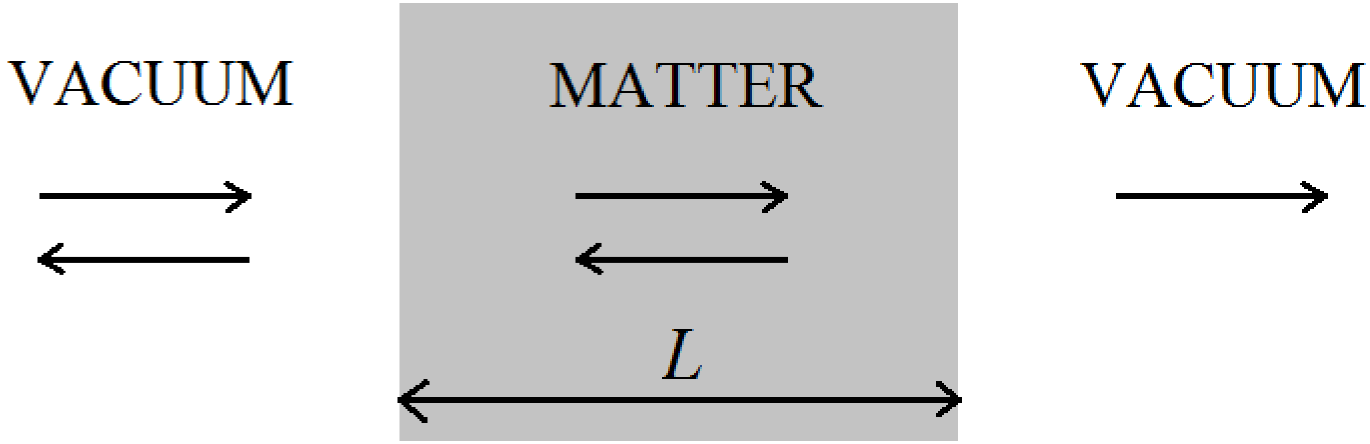
$$\phi = e^{i(kx-\varepsilon t)} + \mathcal{R}\ e^{-i(kx+\varepsilon t)}$$

$$\phi = \mathcal{A}\ e^{i(px-\varepsilon t)} + \mathcal{B}\ e^{-i(px+\varepsilon t)}$$

$$\phi = \mathcal{T}\ e^{i(kx-\varepsilon t)}$$

$$k = \sqrt{\varepsilon^2 - m_\phi^2} \qquad p = \sqrt{\varepsilon^2 - m_\phi^2 + 2\rho/(\Lambda')^2}$$

1D Finite Attractive Barrier



$$\phi = e^{i(kx-\varepsilon t)} + \mathcal{R}\, e^{-i(kx+\varepsilon t)}$$

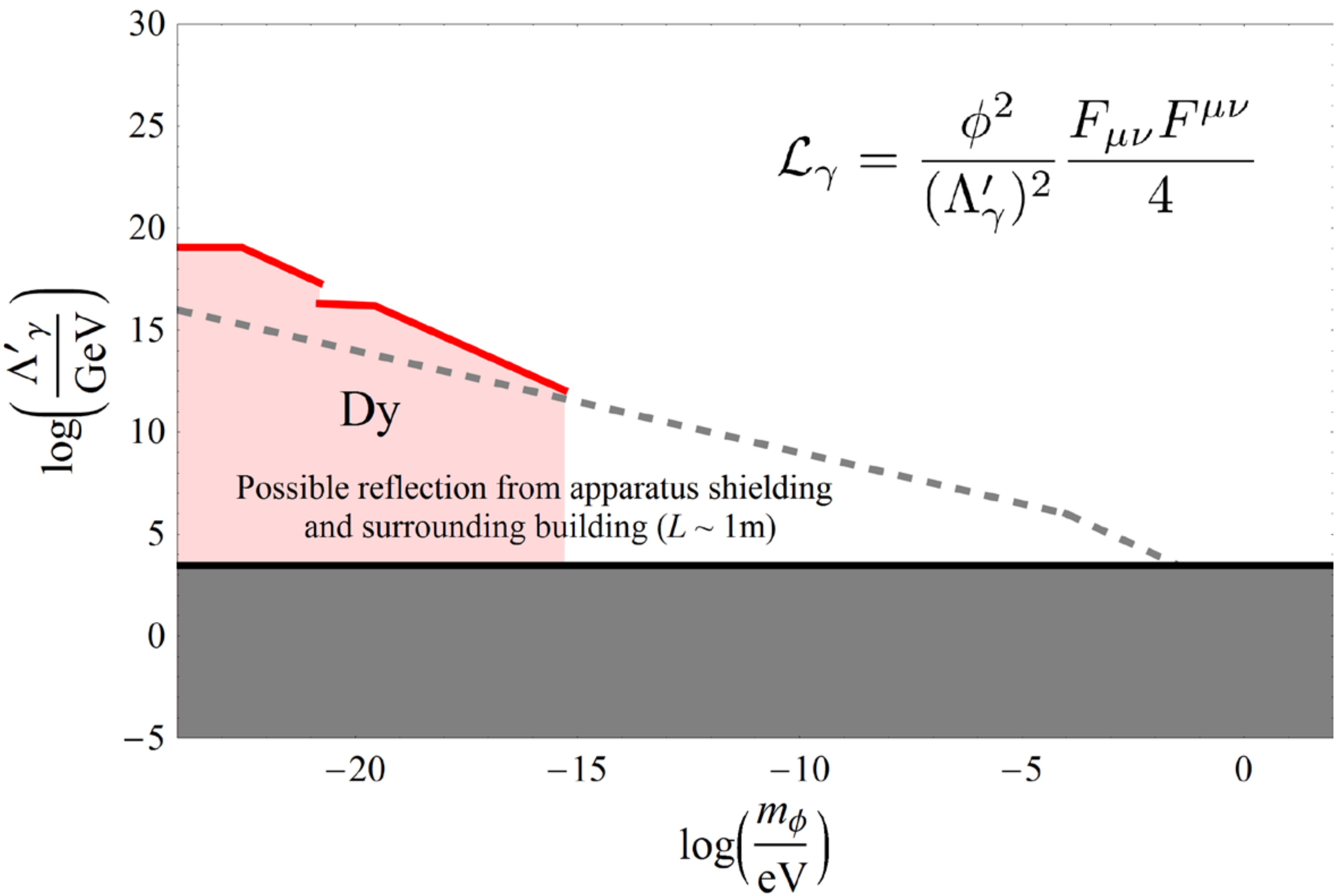
$$\phi = \mathcal{A}\, e^{i(px-\varepsilon t)} + \mathcal{B}\, e^{-i(px+\varepsilon t)}$$

$$\phi = \mathcal{T}\, e^{i(kx-\varepsilon t)}$$

$$\mathcal{R} = \frac{(k-p)(k+p)(e^{2iLp}-1)}{k^2(e^{2iLp}-1) - 2kp(e^{2iLp}+1) + p^2(e^{2iLp}-1)}$$

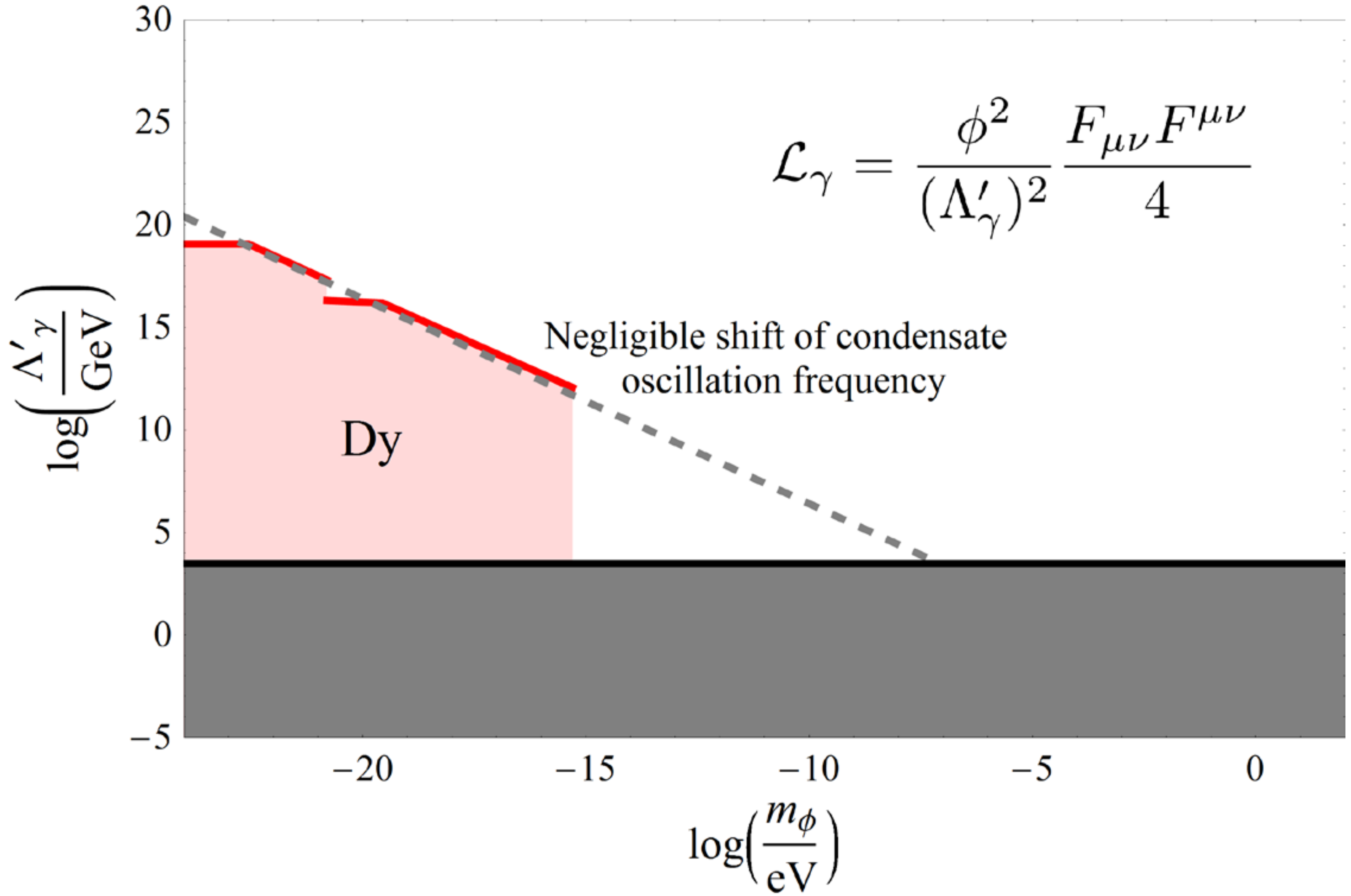
$$=> \ \mathcal{R} \simeq 0 \ \text{ if } k \simeq p, \ \text{ or } 2k \gg Lp^2 \ (\text{when } 2Lp \ll 1 \text{ and } k \ll p)$$

(Non-)reflection of Ultralight Scalar Particles from Experimental Environment



(Non-)shift of Condensate Oscillation Frequency in Terrestrial Experiments

$$\phi = \phi_0 \cos(\varepsilon t - \mathbf{p} \cdot \mathbf{r}) => |\delta\omega_\phi| \lesssim |\mathbf{p}||\mathbf{v}_{\text{Solar System}}|$$



Conventional 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)
- Rest of pulsar spun down electromagnetically
- Core tries to match slowdown rate of rest of pulsar by expelling vortices
- Strong vortex ‘pinning’ to neutron crust
- Magnus force on vortices builds up…

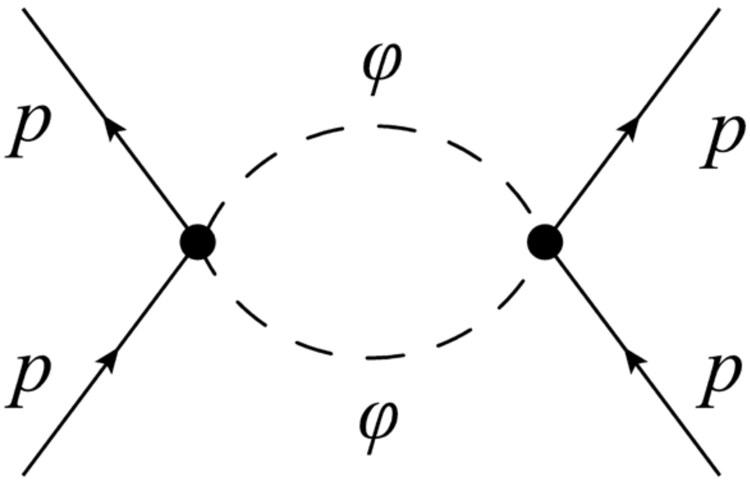
Conventional Glitch Theory

- Until critical threshold reached, when pinning cannot be sustained any longer
- Vortices expelled
- Transfer of angular momentum from core to rest of pulsar
- Pulsar left in long-lived, out-of-equilibrium state
- Quasi-exponential recovery
- Can vortices also be unpinned by defect passage through pulsar?
- Neutron equation-of-state in extremely dense environments not known precisely

Generic Constraints on Scalar and Pseudoscalar Quadratic Interactions

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

(1) *<u>Gravitational test constraints (fifth-force searches)</u>*: Exchange of a pair of virtual scalar/pseudoscalar particles produces an attractive ~$1/r^3$ potential between two SM particles.

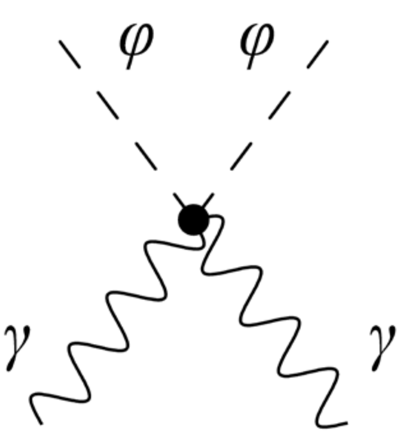


$$\Lambda'_p > 2\ \mathrm{TeV}$$

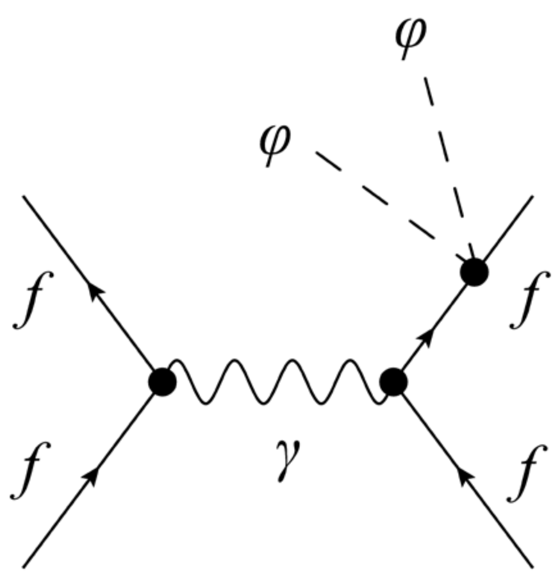
Generic Constraints on Scalar and Pseudoscalar Quadratic Interactions

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

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



$$\Lambda'_\gamma > 3 \text{ TeV}$$



$$\Lambda'_p > 15 \text{ TeV}$$

$$\Lambda'_e > 3 \text{ TeV}$$