Dark Matter, EDM and bariogenesis

V. Flambaum, Y. Stadnik, B. Roberts, V. Dzuba

University of New South Wales, Sydney, Australia

Physical Review Letters **116**, 023201 (2016)
Physical Review Letters **115**, 201301 (2015)
Physical Review Letters **114**, 161301 (2015)
Physical Review Letters **113**, 151301 (2014)
Physical Review Letters **113**, 081601 (2014)
Physical Review D **89**, 043522 (2014)
Physical Review D **90**, 096005 (2014)
European Physical Journal C **75**, 110 (2015)
arXiv:1511.00447, 1604.04559, 1605.04028
Nature Physics 12, 465 (2016)

Manifestations of Dark Matter and Variation of the Fundamental Constants in Atomic and Astrophysical Phenomena

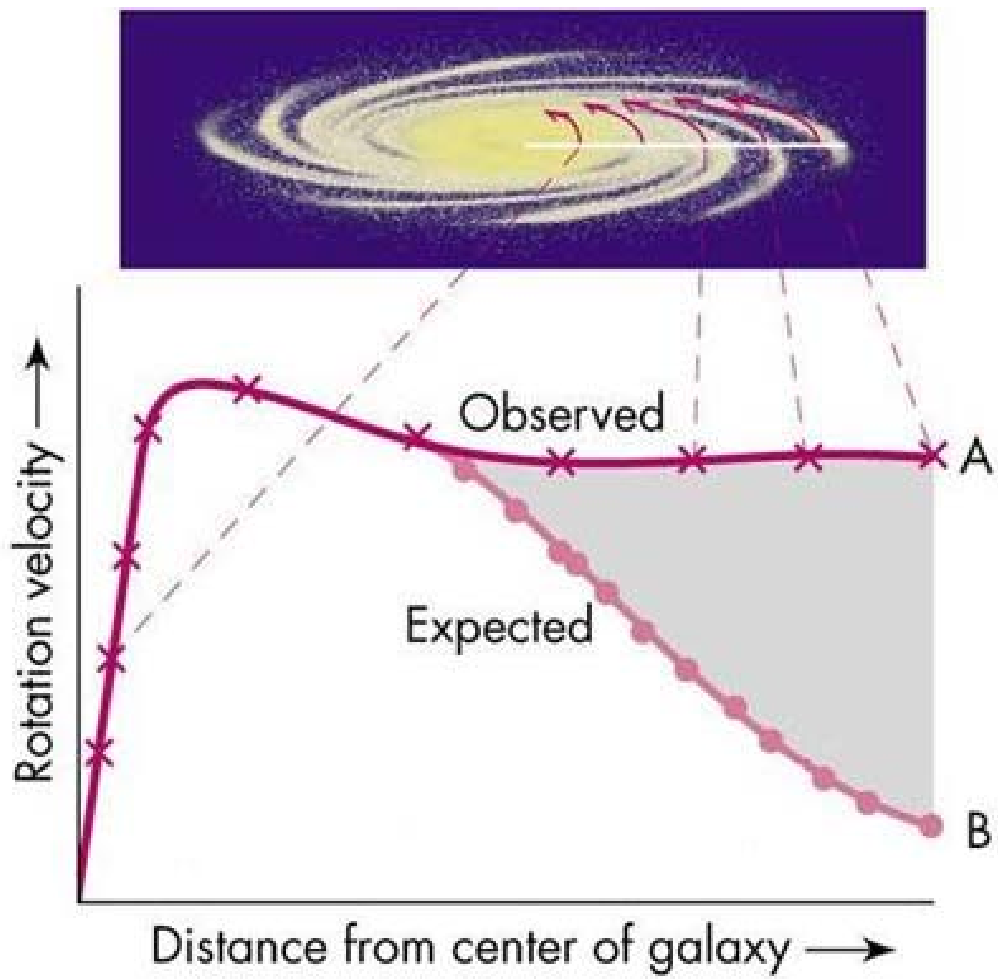
V. Flambaum, Y. Stadnik, B. Roberts, V. Dzuba, D. Budker, N. Leefer

Physical Review Letters **116**, 023201 (2016)
Physical Review Letters **115**, 201301 (2015)
Physical Review Letters **114**, 161301 (2015)
Physical Review Letters **113**, 151301 (2014)
Physical Review Letters **113**, 081601 (2014)
Physical Review D **89**, 043522 (2014)
Physical Review D **90**, 096005 (2014)
European Physical Journal C **75**, 110 (2015)
arXiv:1511.00447, 1604.04559, 1605.04028
Nature Physics 12, 465 (2016)

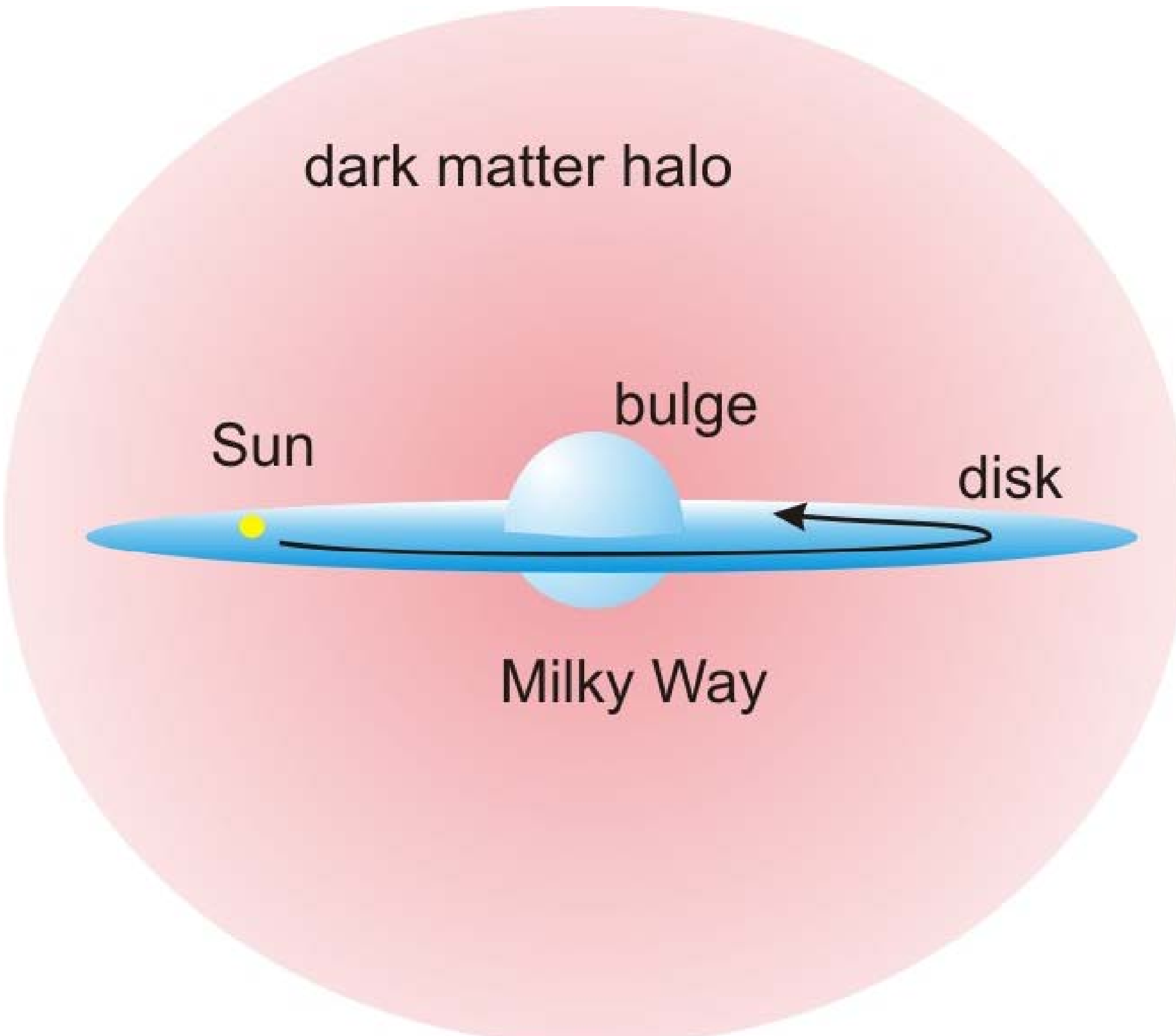
University of New South Wales, Sydney, Australia

Motivation

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



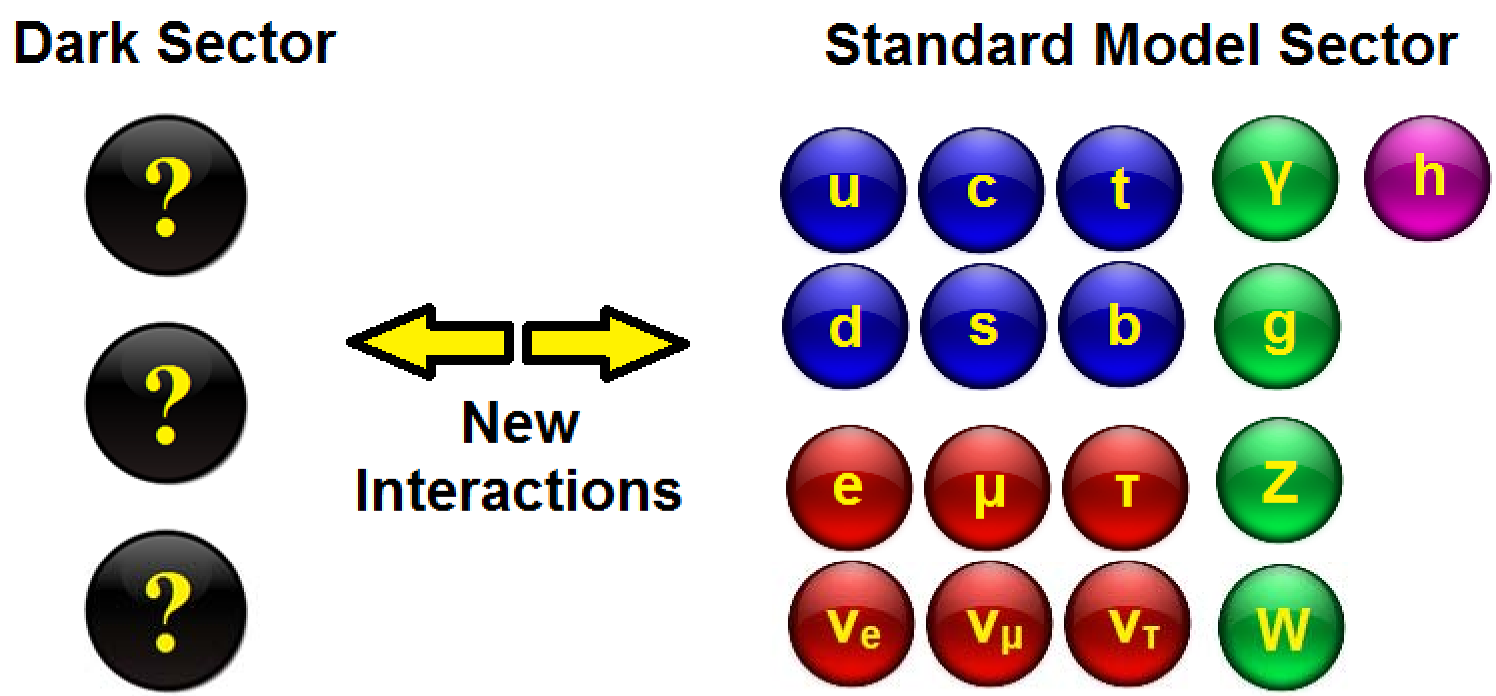
Motivation



Motivation

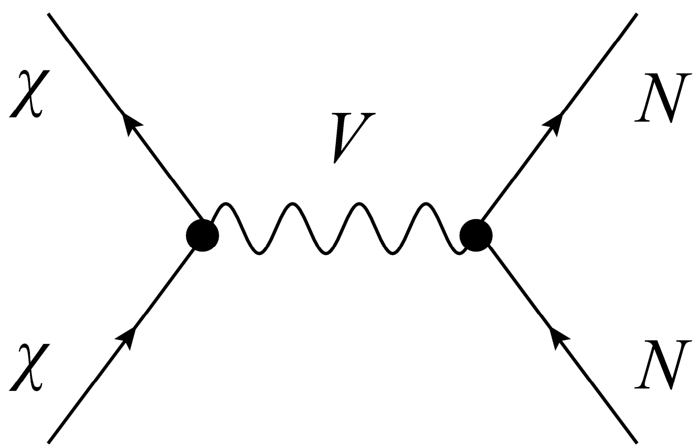
Overwhelming astrophysical evidence for existence of dark matter (~5 times more dark matter than ordinary matter).

– *"What is dark matter and how does it interact with ordinary matter* ***non-gravitationally****?"*



Motivation

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



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

Observable is **<u>quartic</u>** 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:
$\varphi(t) = \varphi_0 \cos(m_\varphi t)$, via effects that are **linear** in the interaction constant (Λ_X = new-physics energy scale).

$$\mathcal{L}_{\mathrm{eff}} = \frac{\phi}{\Lambda_X} X_{\mathrm{SM}} X_{\mathrm{SM}} \quad => \quad \mathcal{O} \propto \frac{1}{\Lambda_X}$$

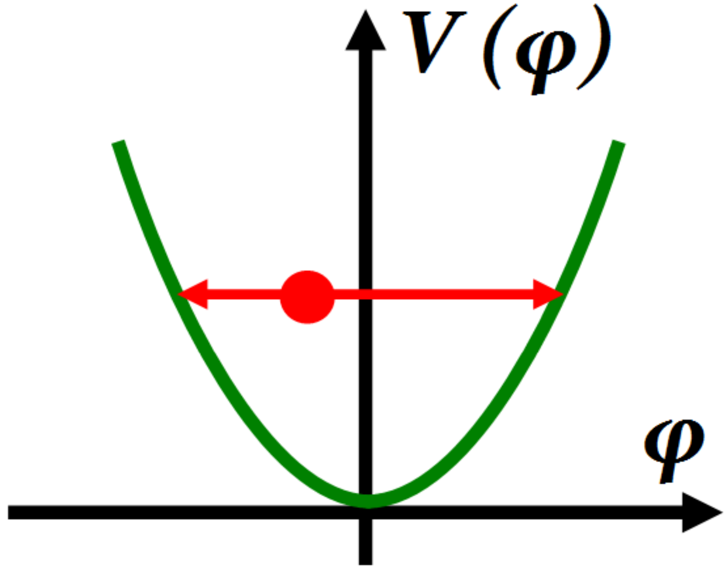
Consideration of *linear effects* has already allowed us to improve on existing constraints on some interactions of dark matter by up to **15 orders of magnitude**, as well as derive the **first constraints** on some other interactions of dark matter.

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

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

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 ≤ m_φ ≤ 0.1 eV]



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

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

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.)

Coherence of Galactic DM

Gravitational interactions between DM and ordinary matter during galactic structure formation result in the virialisation of the DM particles ($v_{vir} \sim 10^{-3}\, c$), which gives the galactic DM field a finite coherence time and finite coherence length:

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

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars:
Even-parity

→ **'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

Low-mass Spin-0 Dark Matter

Dark Matter

↓

Scalars:

Even-parity

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

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

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?

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, Th III …

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

Molecular calculations

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

We performed atomic, QCD and nuclear calculations.

Evidence for spatial variation of the fine structure constant

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

Quasar spectra

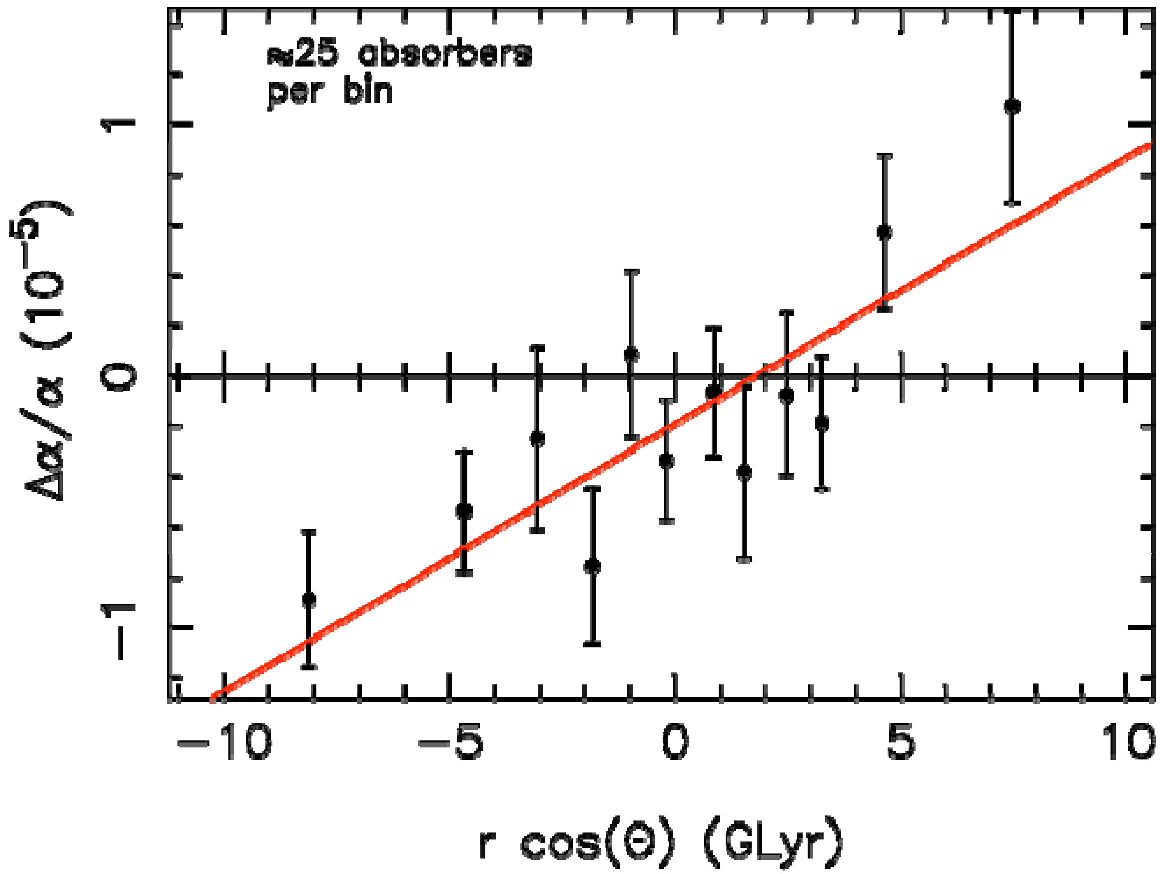
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

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

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

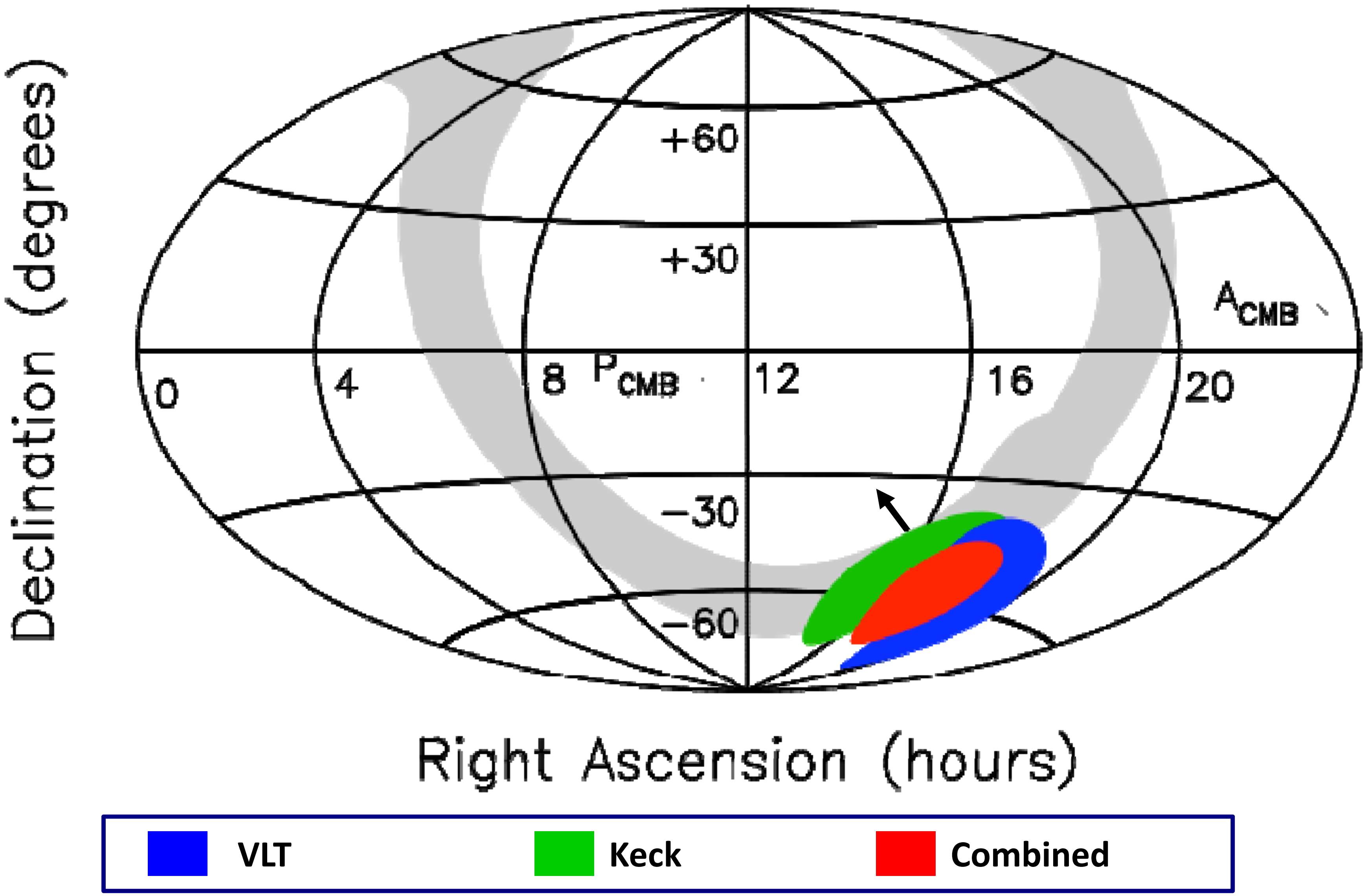
Reconciles all measurements of the variation

Distance dependence



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

Keck & VLT dipoles independently agree, p=4%



Hints that this result might be real

Two internal consistencies:

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

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

300 absorption systems, 30 atomic lines

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

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.

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

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

m_e/M_p **or** m_e/Λ_{QCD} $-0.1(1.0) \times 10^{-16}\ yr^{-1}$

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars:
Even-parity

→ **'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, *P*,*T*, Lorentz and Einstein symmetry violation**

- Atomic magnetometry
- Ultracold neutrons
- Solid-state magnetometry

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars:

Even-parity

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

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

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.

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

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

'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:

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

Fermions:

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

Bosons W,Z (mediators of weak interactions):

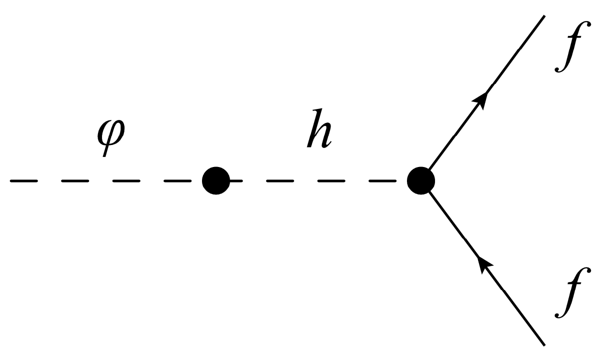
$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2}\frac{M_V^2}{2} V_\nu V^\nu \;\; => M_V^2 \rightarrow M_V^2\left[1+\frac{\phi^2}{(\Lambda'_V)^2}\right]$$

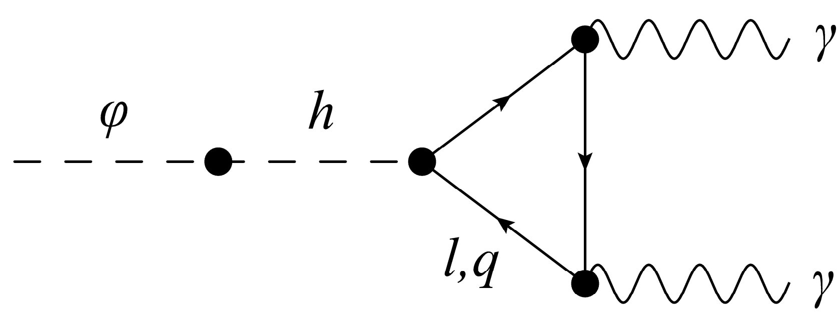
Dark Matter-Induced Oscillating Variation of the Fundamental Constants

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

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).

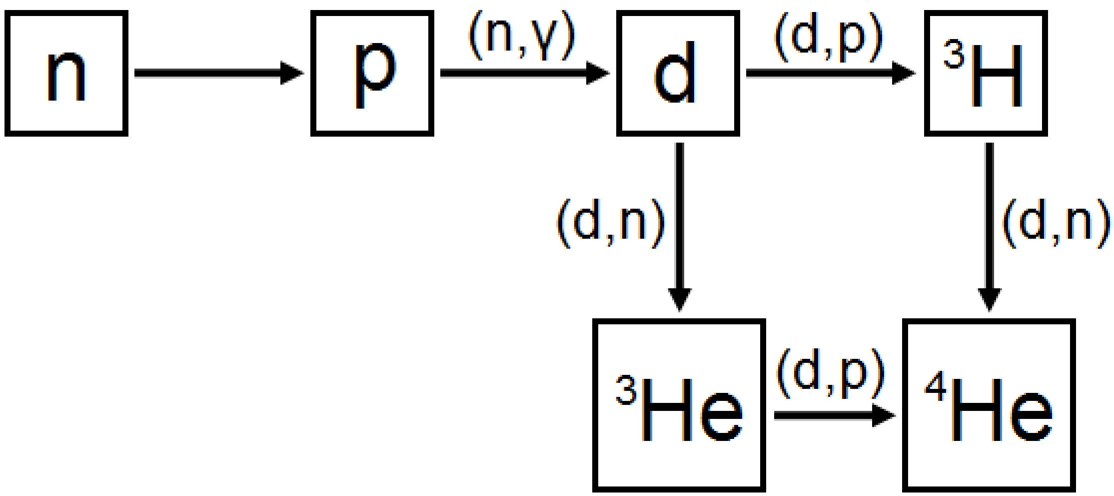
$$p + e^- \rightleftharpoons n + \nu$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

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

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

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.

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

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 ≤ m_φ ≤ 0.1 eV => 10^{-8} Hz ≤ f ≤ 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

[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.

$$\delta\left(\frac{\omega_1}{\omega_2}\right) \propto \cos(2m_\phi t)$$

- Exact frequency of oscillation is unknown: $\omega = 2m_\varphi$ (10^{-22} eV $\leq m_\varphi \leq 0.1$ eV => 10^{-7} Hz $\leq f \leq 10^{14}$ Hz), with $\Delta f/f \sim 10^{-6}$.
- Need to search over a broad range of frequencies.

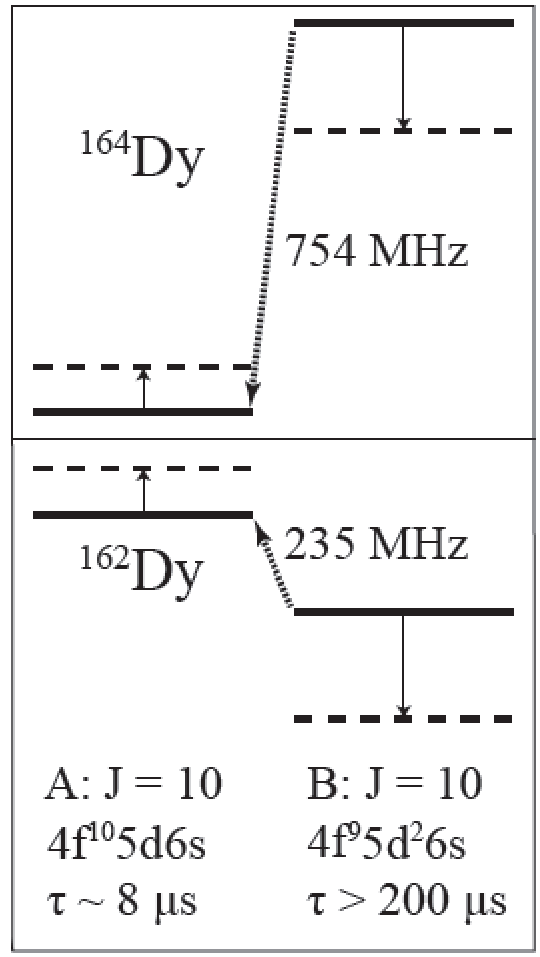
Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

System	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

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)]



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 field*.

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).

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

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

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

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).

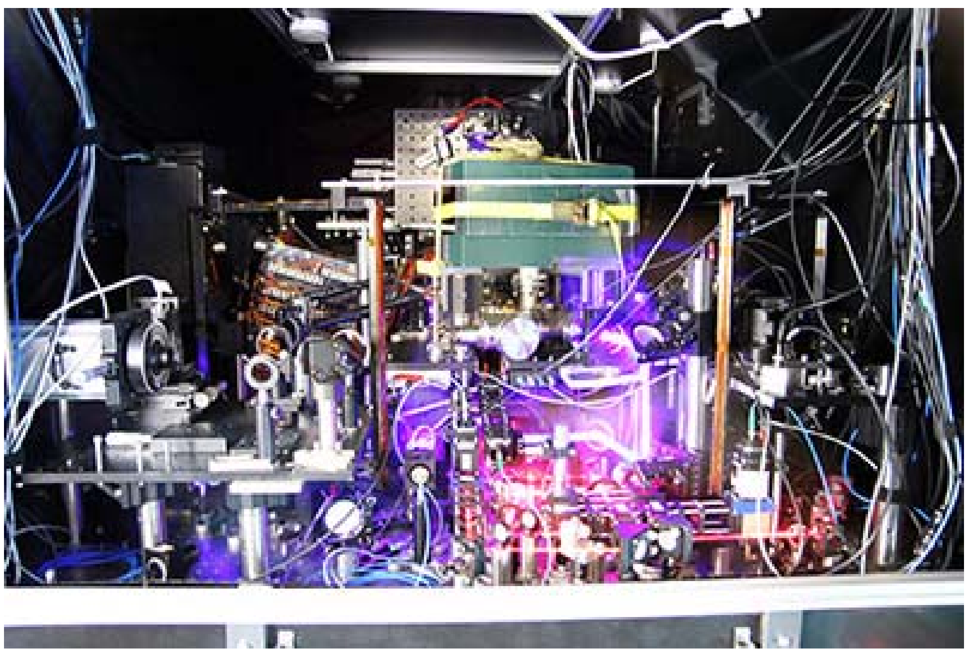
$$\Phi = \frac{\omega L}{c} \propto \left(\frac{e^2}{a_{\mathrm{B}}\hbar}\right)\left(\frac{N a_{\mathrm{B}}}{c}\right) = N\alpha \quad => \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

- 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).

Laser Interferometry (smaller-scale)

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

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*. Bar detectors.

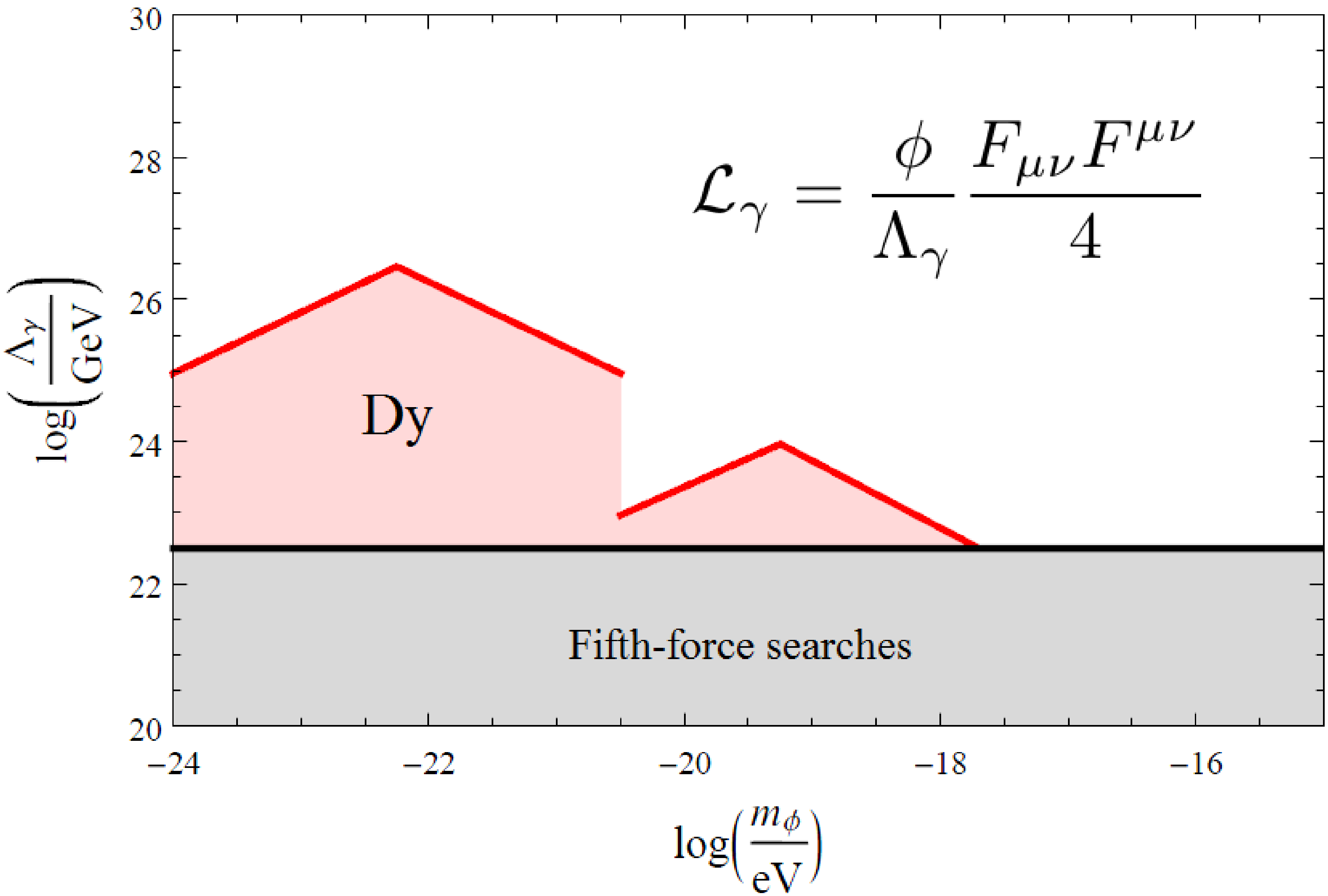


Laboratory Searches for Oscillating Variations in Fundamental Constants Induced by Scalar Dark Matter

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 Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

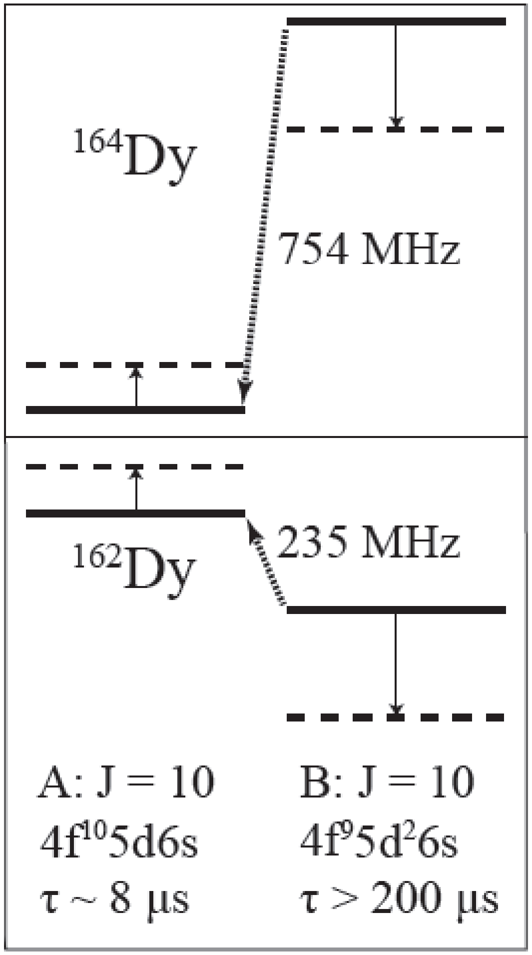
[Van Tilburg, Leefer, Bougas, Budker, *PRL* **115**, 011802 (2015)]



Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

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

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.

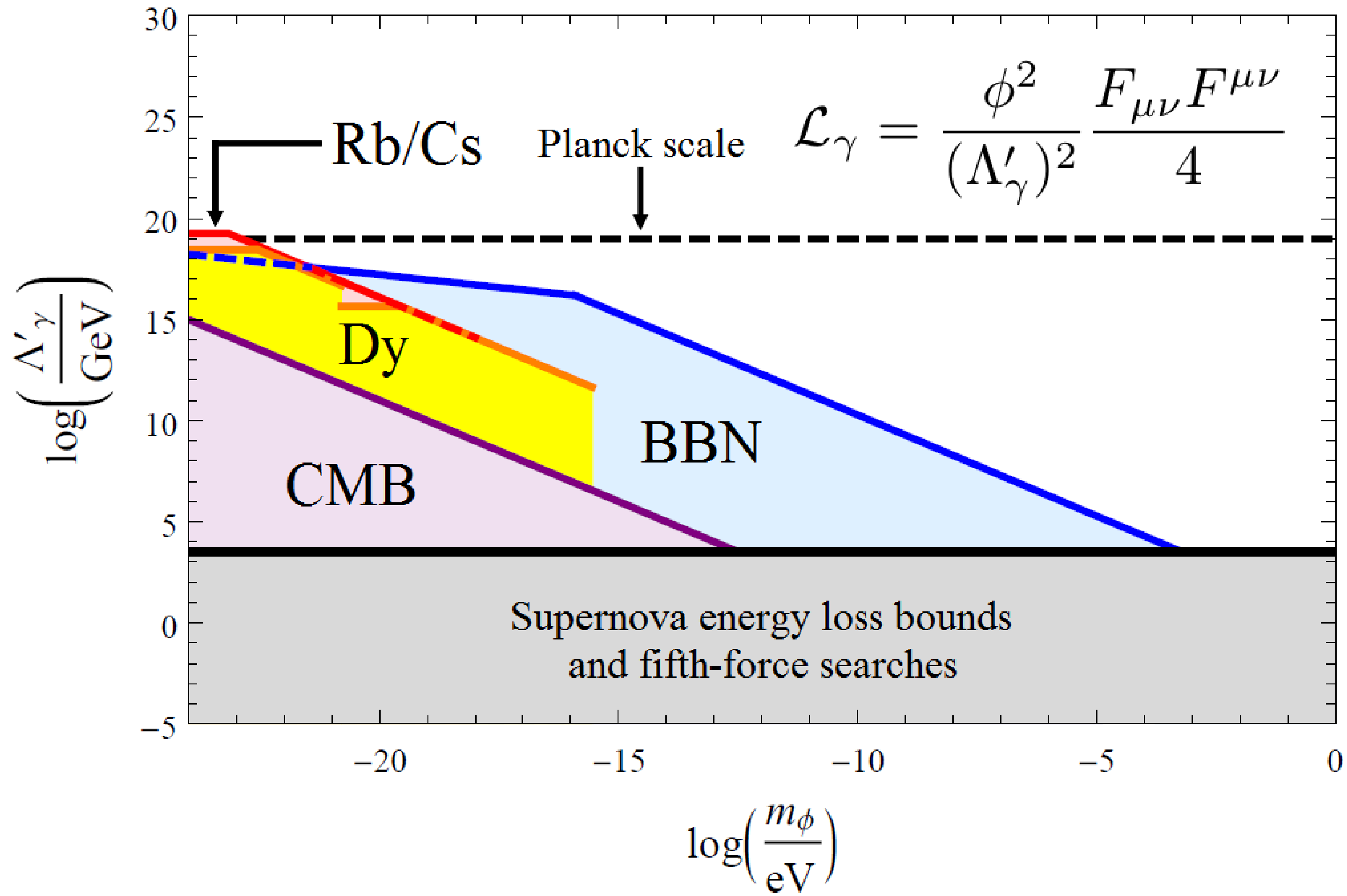


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

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

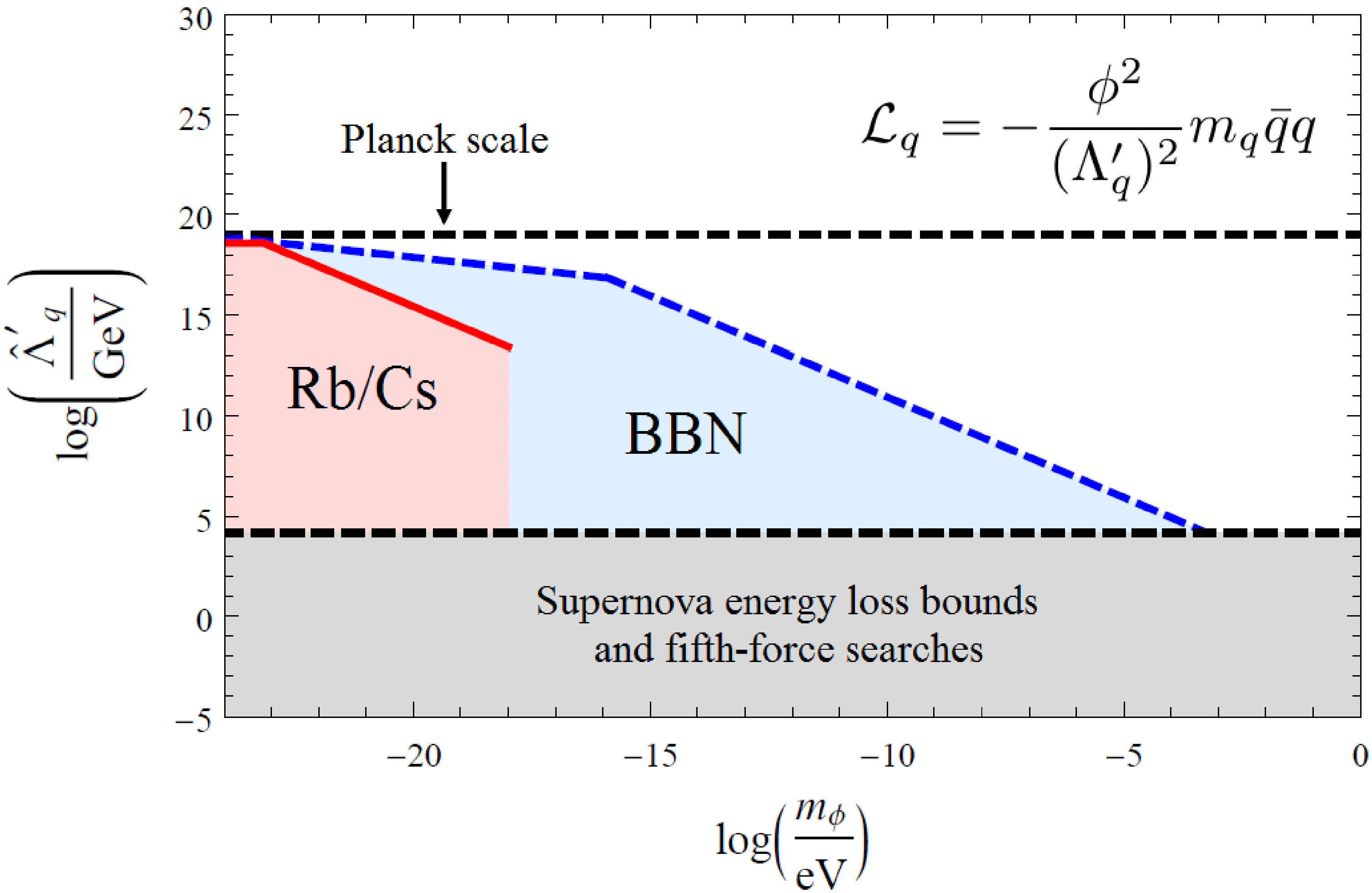
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

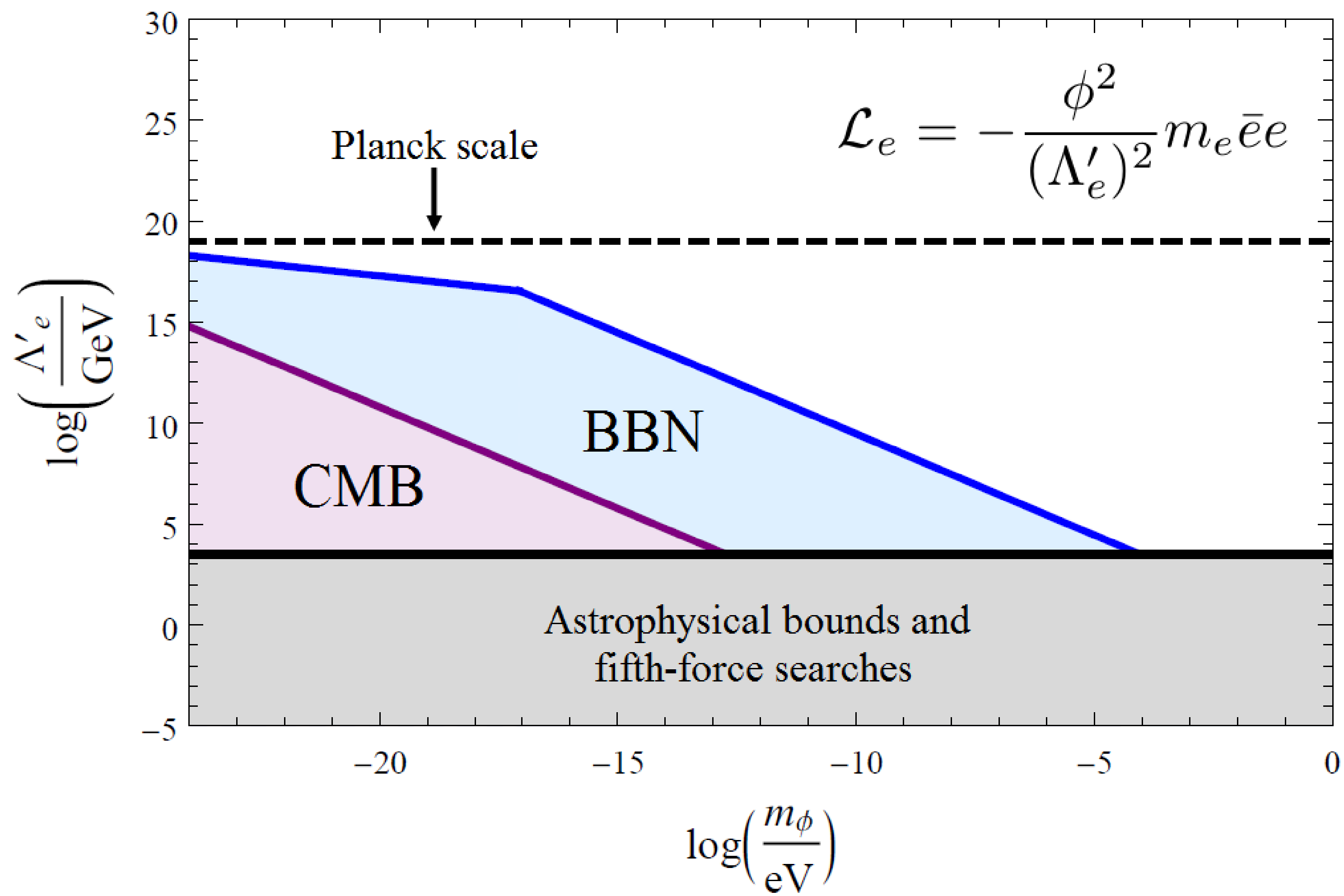
BBN and Rb/Cs constraints:

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



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

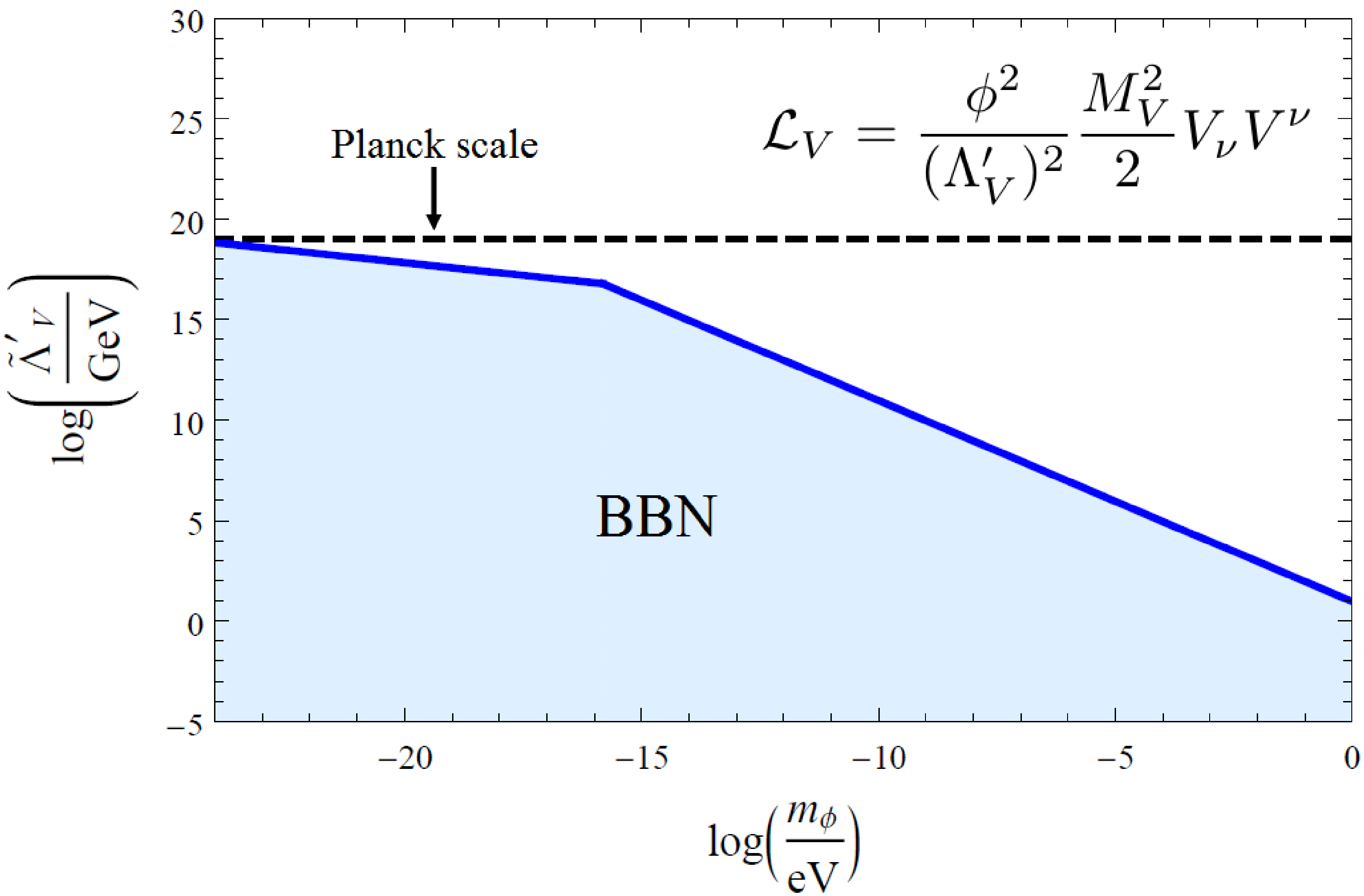
BBN and CMB constraints:
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

BBN constraints:

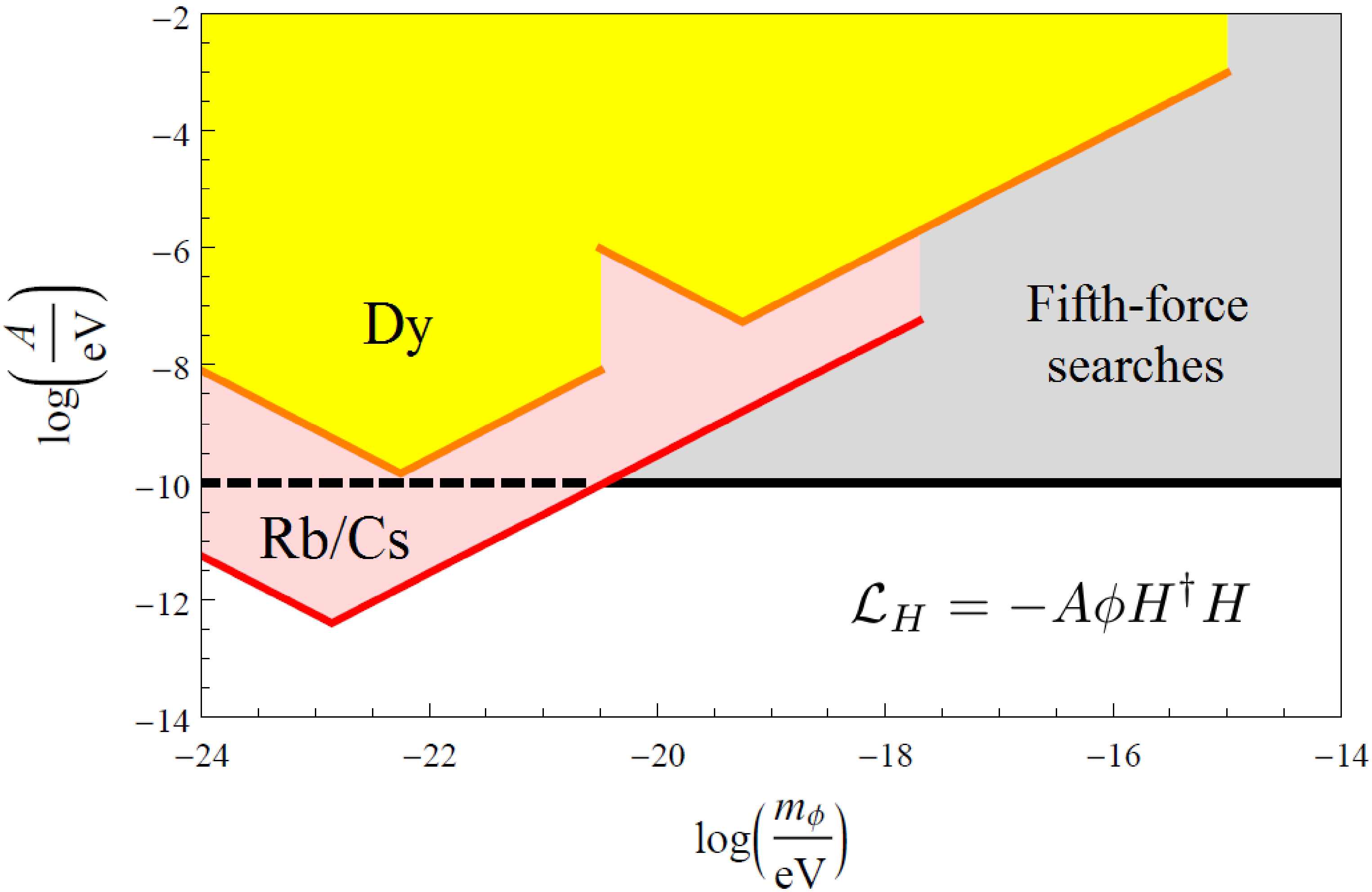
[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]



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

Dy and Rb/Cs constraints:

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



Topological Defect Dark Matter

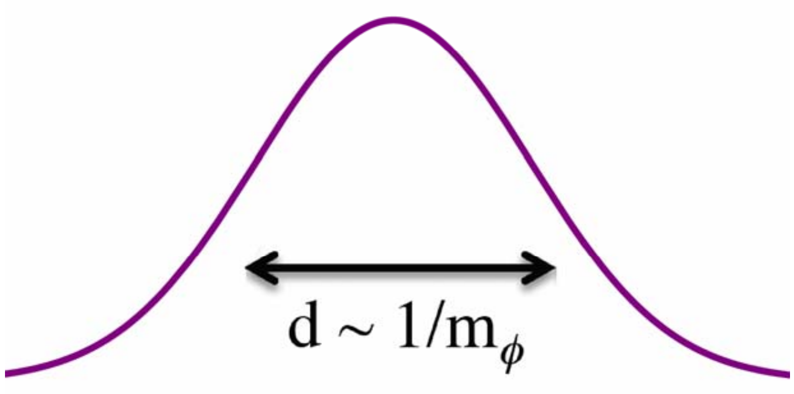
Take a simple scalar field and give it a *self-potential*, e.g. $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable *domain wall* will form in between, e.g. $\varphi = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2} v$.

The characteristic "span" of this object is $d \sim 1/m_\varphi$, and it is carrying energy per area $\sim v^2/d \sim v^2 m_\varphi$. *Networks* of such *topological defects* can *give contributions to dark matter/dark energy* and *act as seeds for structure formation*.

0D object – a *Monopole*

1D object – a *String*

2D object – a *Domain wall*



Searching for Topological Defects

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

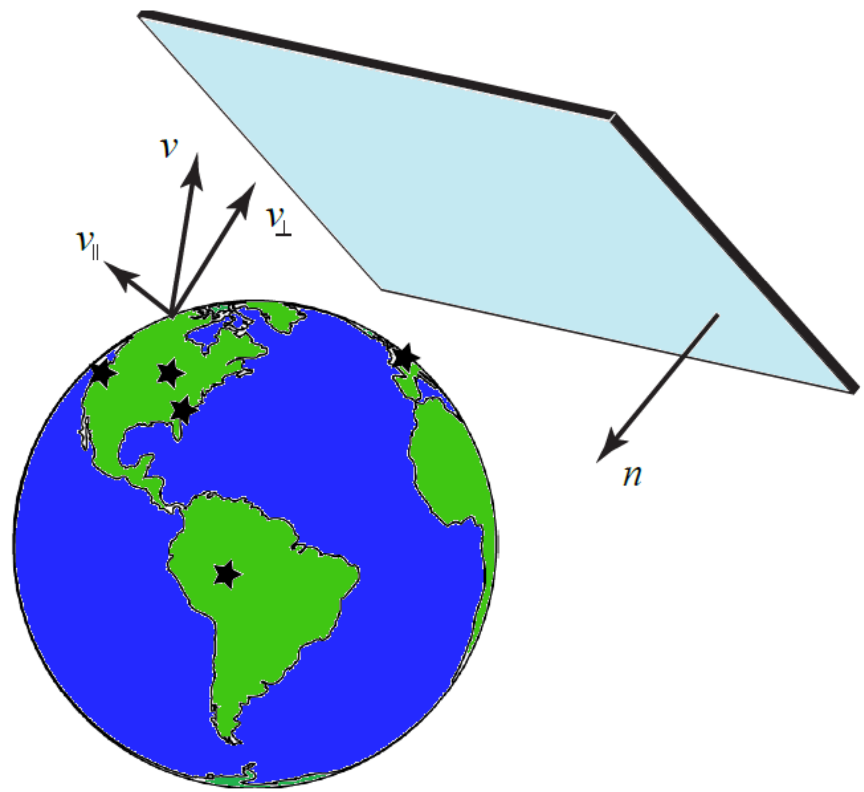
Recent proposals include:

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

Pulsar Timing [Stadnik, 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]

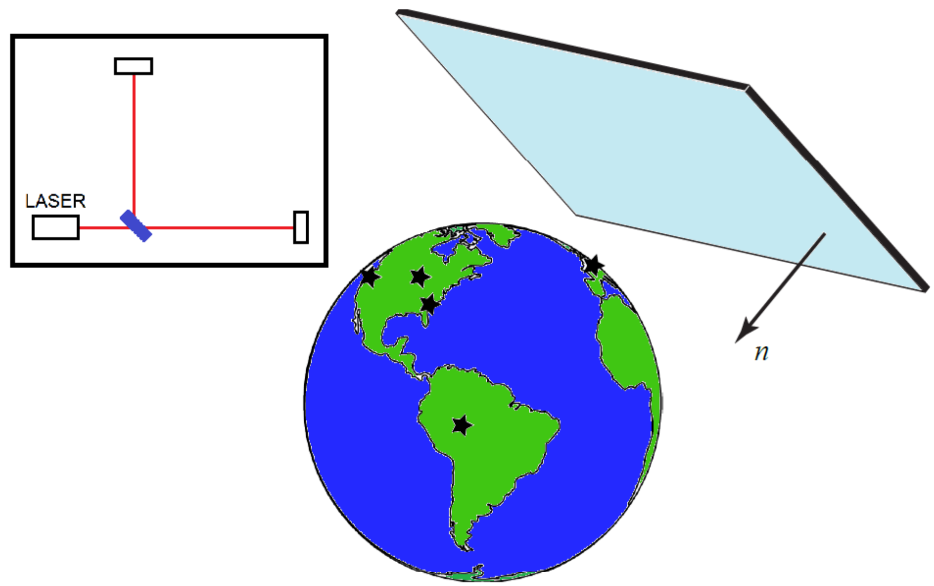


Global Network of Laser/Maser Interferometers (LIGO, Virgo, GEO600, TAMA300)

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

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

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

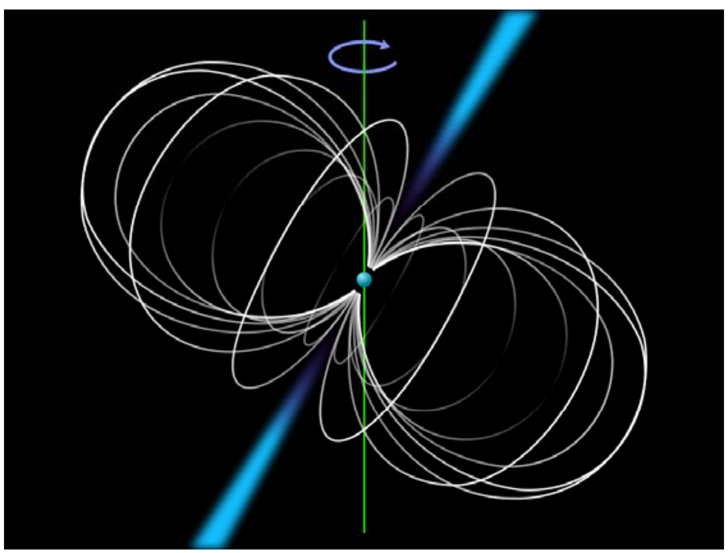


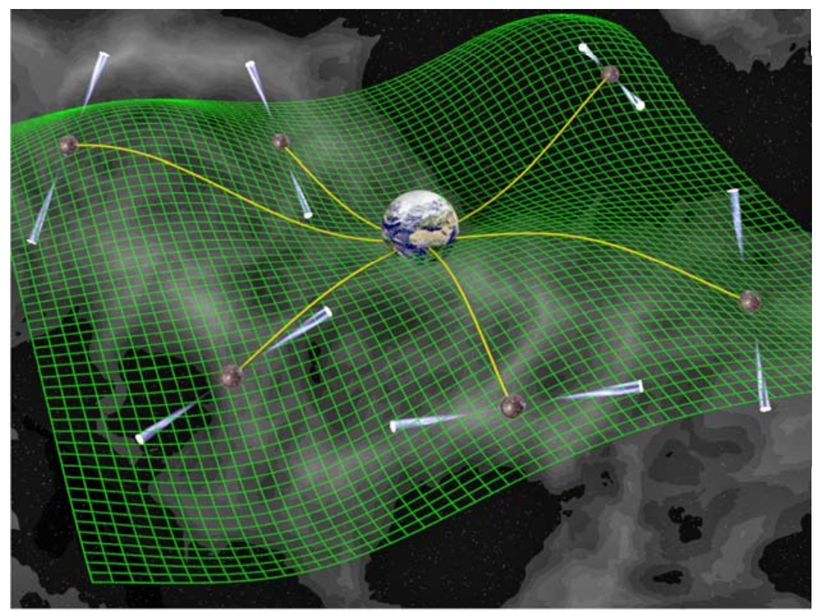
Pulsar Timing

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

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

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

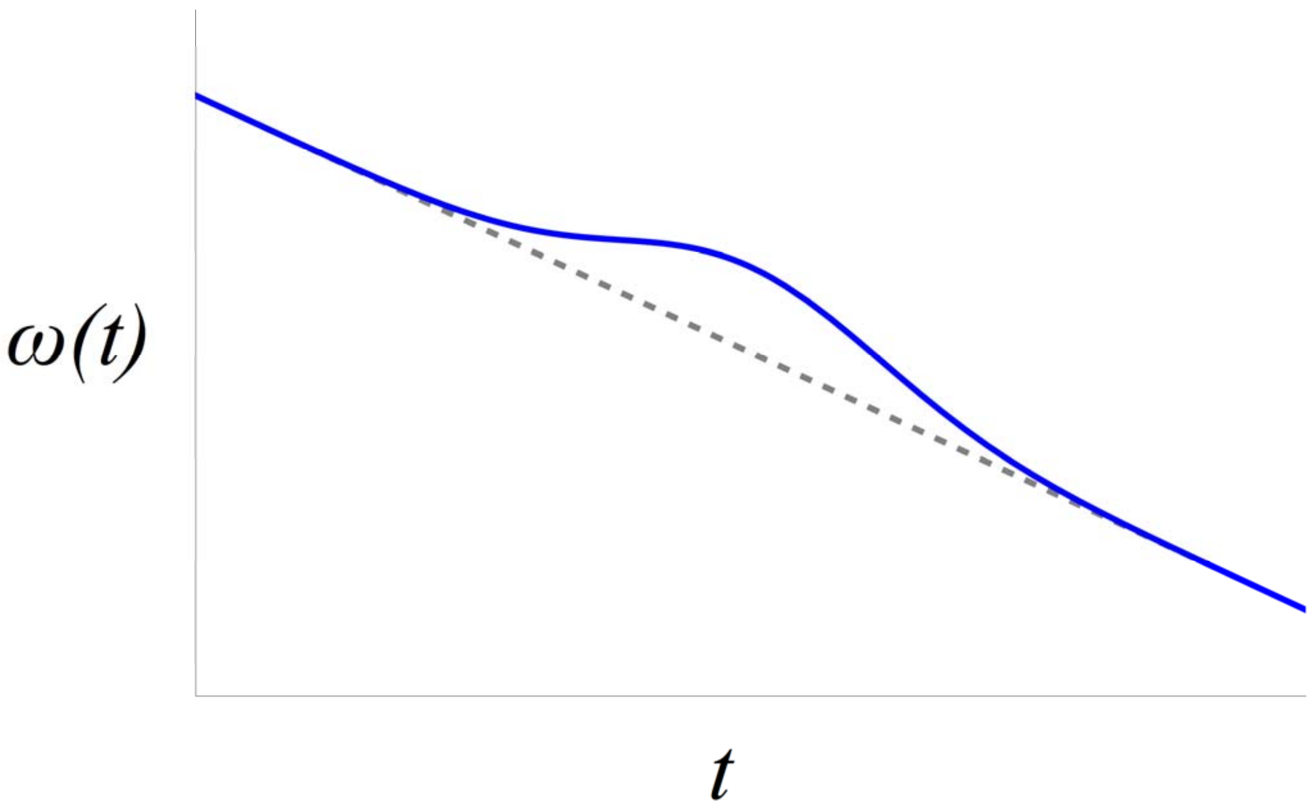




Pulsar Timing

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

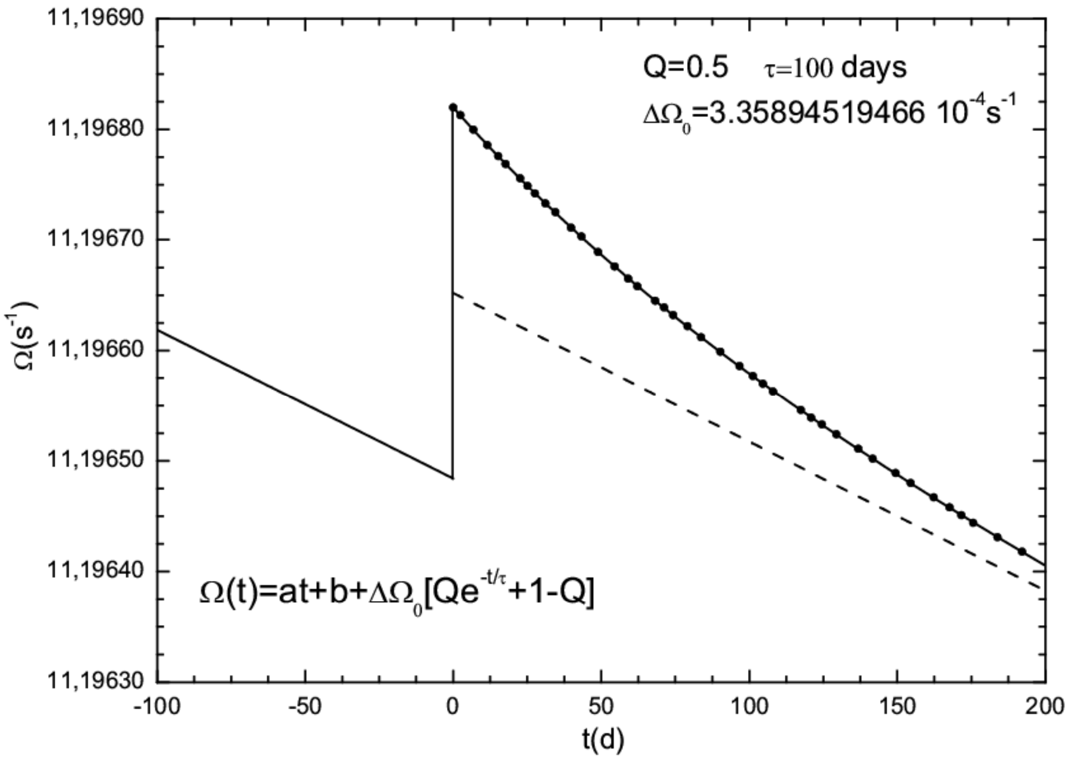
Adiabatic passage of a topological defect though a pulsar produces a *Gaussian-shaped modulation* in the pulsar rotational frequency profile



Pulsar Timing

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

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



Glitch Theory

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

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions, ALPs):
Odd-parity

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

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

- Atomic magnetometry
- Ultracold neutrons
- Solid-state magnetometry

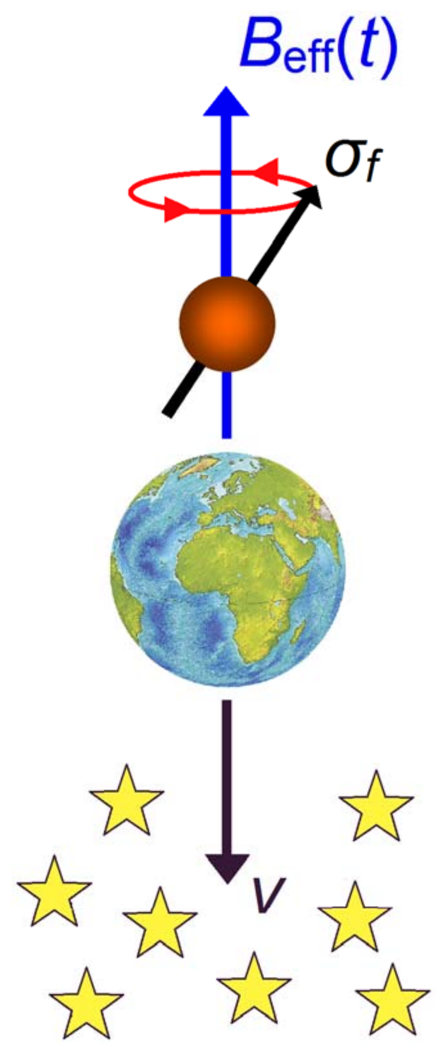
"Axion Wind" Spin-Precession Effect

[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**.

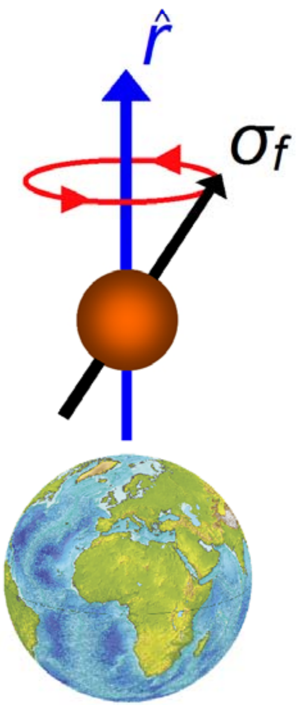
$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a}\partial_i[a_0\cos(\varepsilon_a t - p_a \cdot r)]\bar{f}\gamma^i\gamma^5 f$$

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



Axion-Induced Oscillating Spin-Gravity Coupling

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



Distortion of axion field by gravitational field of Sun or Earth induces **oscillating spin-gravity couplings**.

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

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

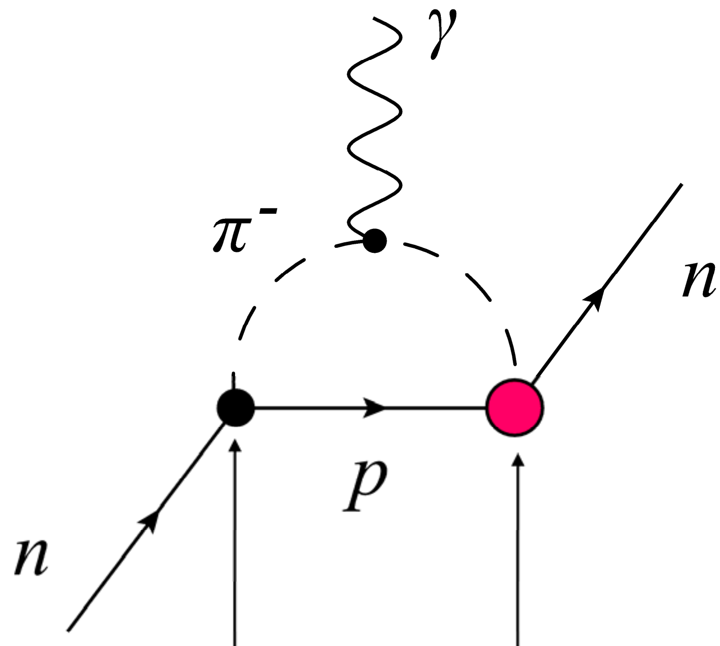
Spin-axion momentum and axion-induced oscillating spin-gravity couplings to nucleons may have isotopic dependence ($C_p \neq C_n$) – calculations of proton and neutron spin contents for nuclei of experimental interest have been performed, see, e.g., [Stadnik, Flambaum, *EPJC* **75**, 110 (2015)].

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.

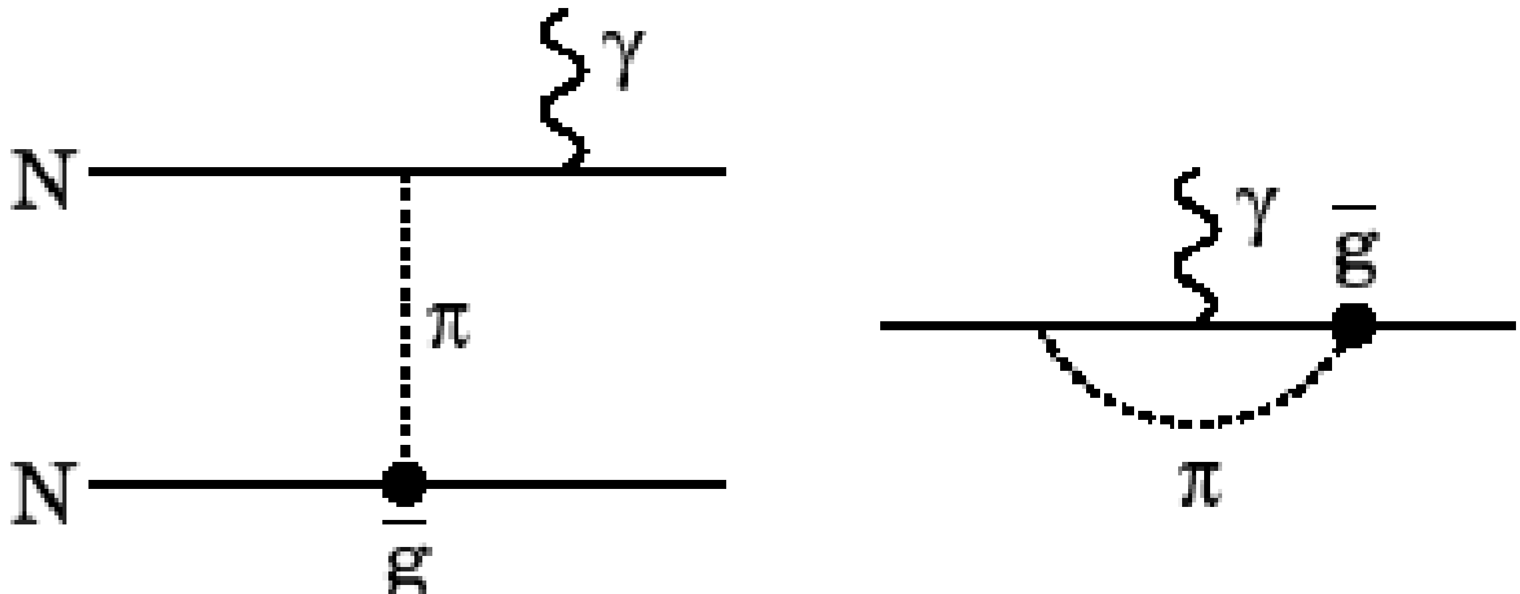
$$\mathcal{L}_{agg} = \frac{a_0 \cos(m_{\rm a} t)}{f_{\rm a}} \frac{g^2}{32\pi^2} G\tilde{G} \qquad d_n(t) \approx 2.4 \times 10^{-16} \frac{a_0}{f_a} \cos(m_a t)\; e \cdot \mathrm{cm}$$



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

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

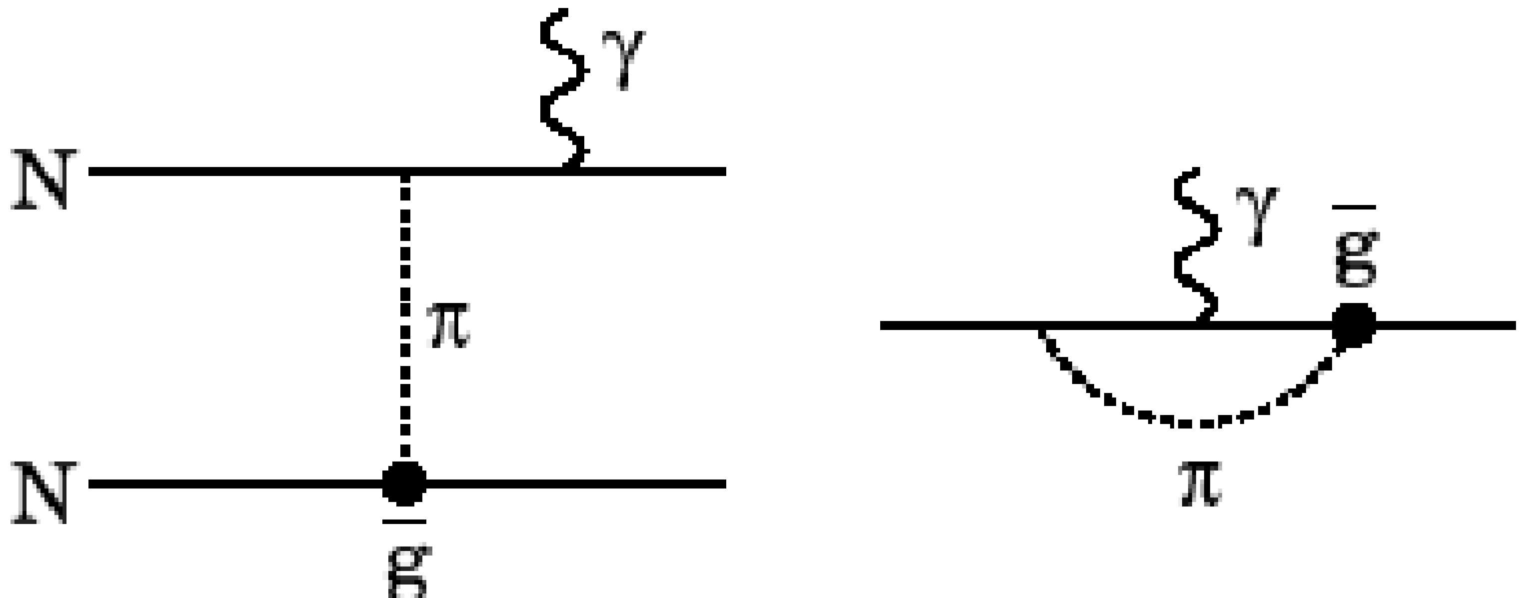
[Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]



Haxton, Henley 1983, Flambaum, Khriplovich, Sushkov 1984, 1986 calculations of nuclear EDM, Schiff moments, magnetic quadrupoles, atomic and molecular EDMs. Collective effects in deformed nuclei: further enhancement 10-1000 times, magnetic quadrupole(Flambaum), Schiff moment (Auerbach, Flambaum, Spevak)

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

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



Flambaum, Khriplovich, Sushkov JETP1984 and NPA1986 calculations of T,P-odd πNN and NN constants, nuclear Schiff moments and atomic EDMs in Standard model – 4 orders of magnitude gap with new Hg EDM experiment.
Collective effects in deformed nuclei: further enhancement 10-1000 times, magnetic quadrupole, Schiff moment

Nuclear EDM-screening: d_N E_N

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

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

Nucleus acceleration $a=Z\, eE_N/M$

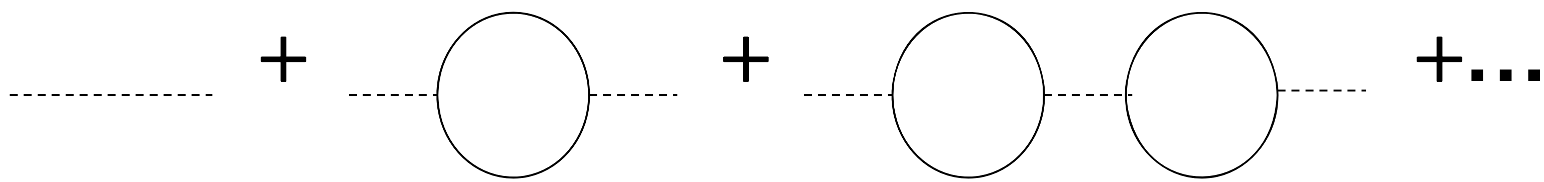
$$E_N=E\, Z_i/Z$$

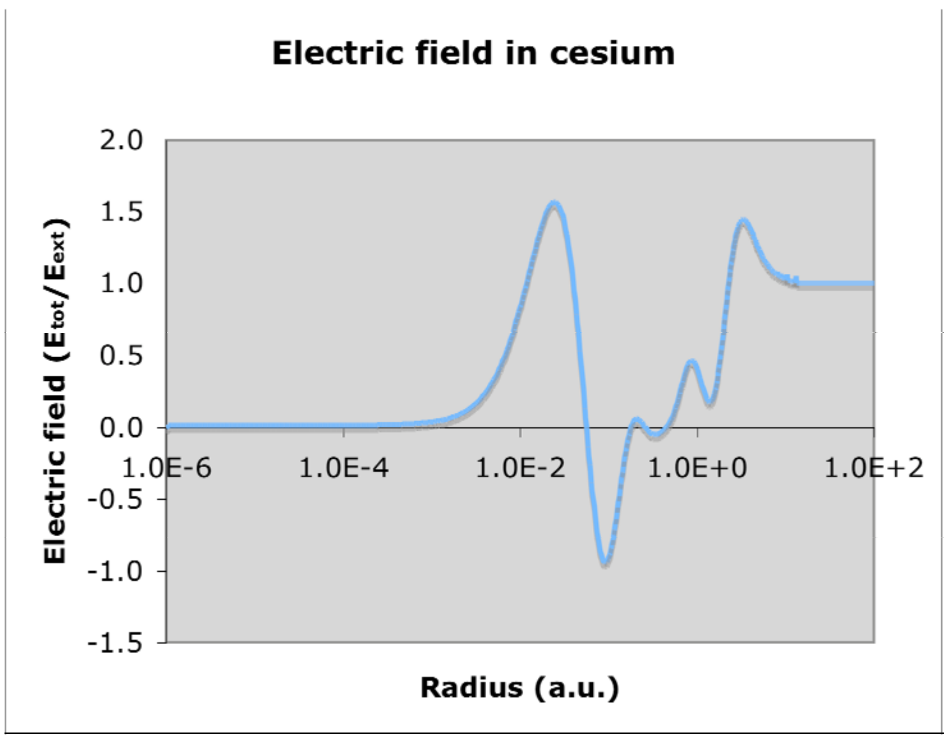
In molecules screening is stronger:

$a= Z_i\, eE/(M+m)$, $E_N= E\, (Z_i/Z)(M/(M+m))$

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):

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

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

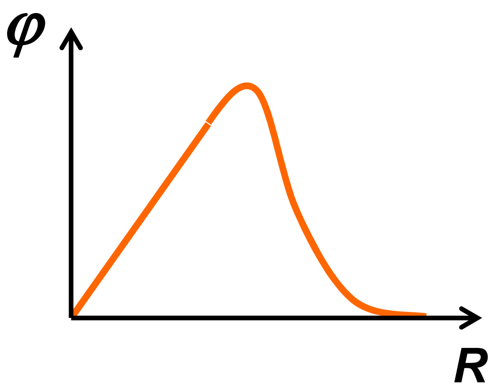
$\varphi(\mathbf{R})$ in multipole expansion is reduced to $\varphi(\mathbf{R}) = 4\pi \mathbf{S} \bullet \nabla \delta(\mathbf{R})$

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.

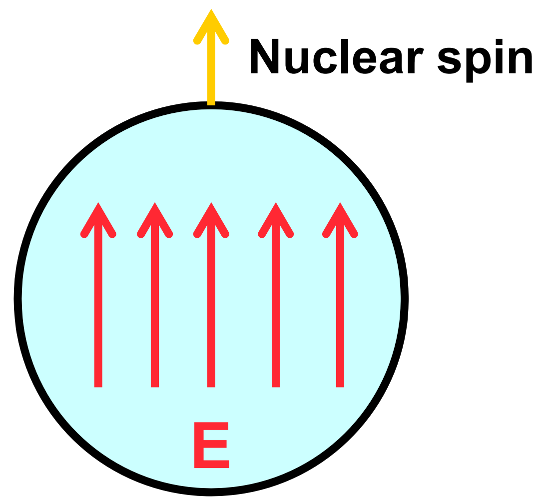
This expression is not suitable for relativistic calculations.

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.

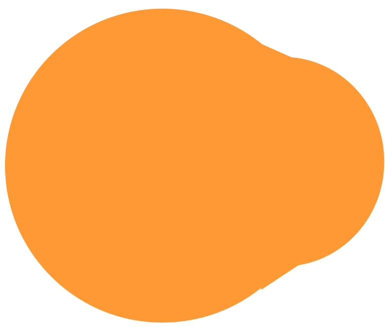
Calculations of nuclear SM: Sushkov,Flambaum,Khriplovich ;Brown et al,Flambaum et al Dmitriev et al,Auerbach et al,Engel et al, Liu et al,Sen'kov et al, Ban et al.
Atomic EDM: Sushkov,Flambaum,Khriplovich; Dzuba,Flambaum,Ginges,Kozlov.

Best limits from Hg EDM measurement in Seattle, also Xe, Yb, TlF
Crucial test of modern theories of CP violation (supersymmetry, etc.)

Nuclear enhancement of Schiff moment

Auerbach, Flambaum, Spevak 1996

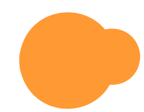
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



Intrinsic Schiff moment:

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

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

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

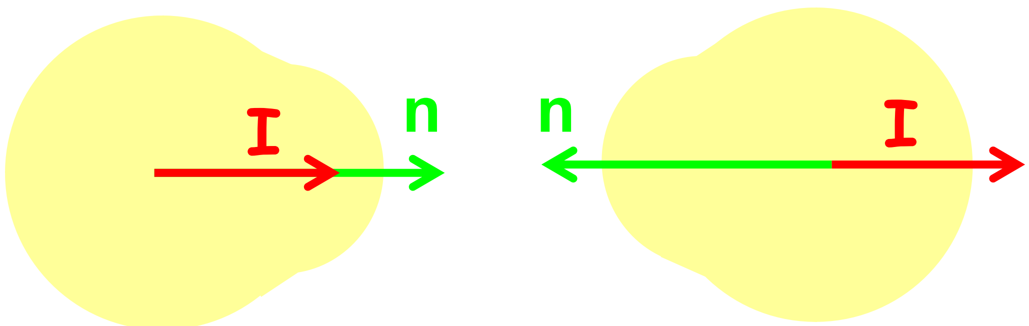
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

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

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

Octupole deformation (Auerbach, Flambaum, Spevak):

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

Two factors of enhancement of the Schiff moment:

1. **Large collective Schiff 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

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 Henly,Haxton;Khriplovich,Sushkov,Flamb

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 moleculesThO,TaN,YbF,

HfF+ (Flambaum. DeMille. Kozlov)

Enhancement of electron EDM

- Sandars: atomic EDM induced by interaction of electron EDM with atomic electric field increases as $Z^{3.}$. Enhancement >100

Flambaum: Enhancement factor in atoms $3 Z^3 \alpha^2 R(Z\alpha)$

Numerical calculations in atoms: Tl enhancement $d(Tl)= -582\, d_e$

Tl EDM Experiment – Berkeley; also Cs, Fr, Xe*,

- Molecules –close rotational levels, huge enhancement of electron EDM: $Z^3 \alpha^2 R(Z\alpha) M/m_e$ Sushkov,Flambaum 1978

$\Omega = 1/2$	10^7	YbF	London
$\Omega=1$	10^{10}	PbO,ThO	Yale, Harvard
		HfF^+ ThF+	Boulder
		WC	

Weak electric field is sufficient to polarise the molecule. Molecular electric field is several orders of magnitude larger than external field (Sandars)

2013 ThO : dramatic impovement > 10 times!

Electron-nucleus T,P scalar-pseudoscalar and tensor-pseudotensor interactions

Atomic EDMs

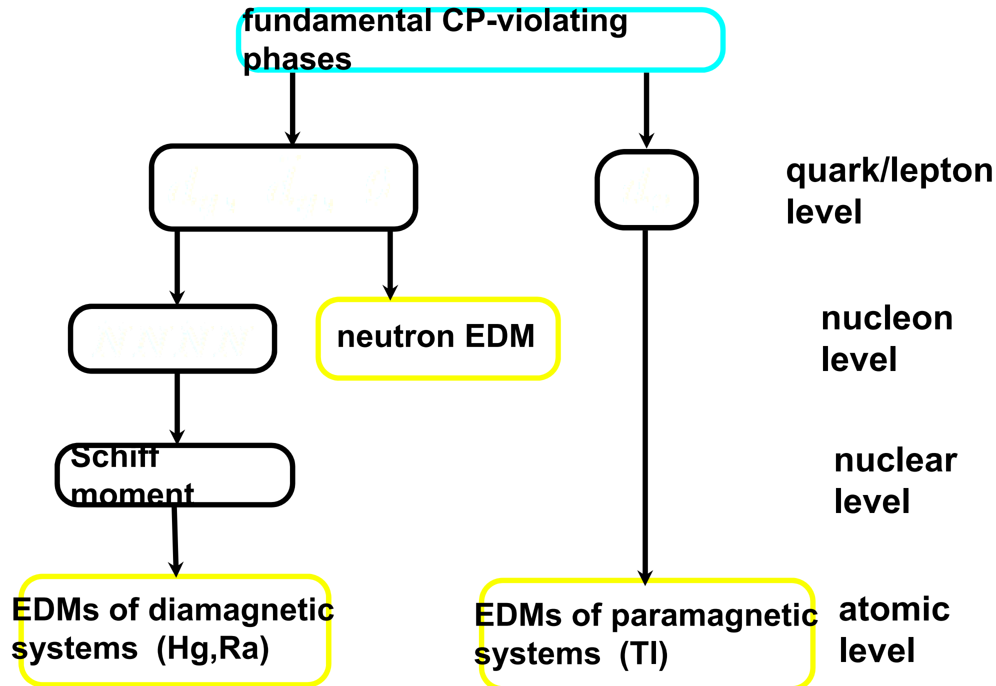
Best limits

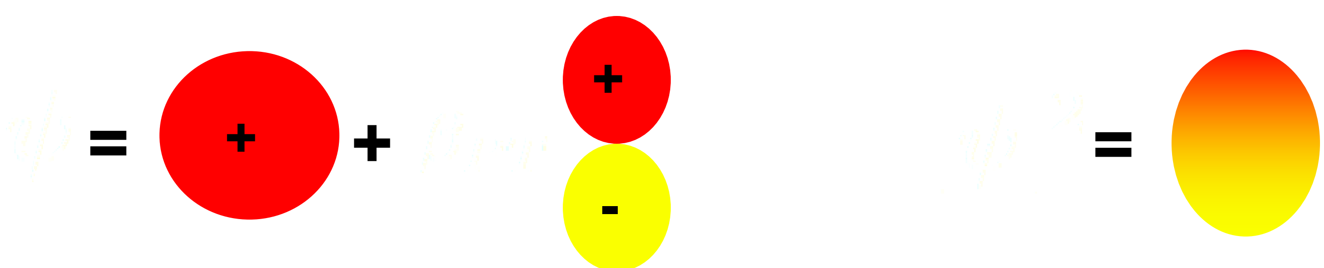
$|d(^{199}\text{Hg})| < 10^{-29}$ *e* cm
(95% c.l., Seattle, 2016)

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

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

Leading mechanisms for EDM generation





Axion-Induced Oscillating Atomic and Molecular EDMs

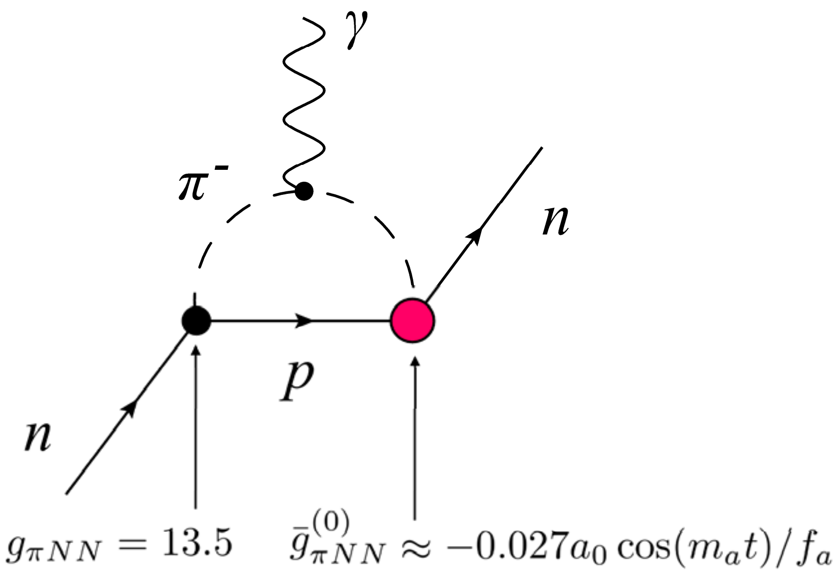
[Stadnik, Flambaum, *PRD* **89**, 043522 (2014)] CASPEr

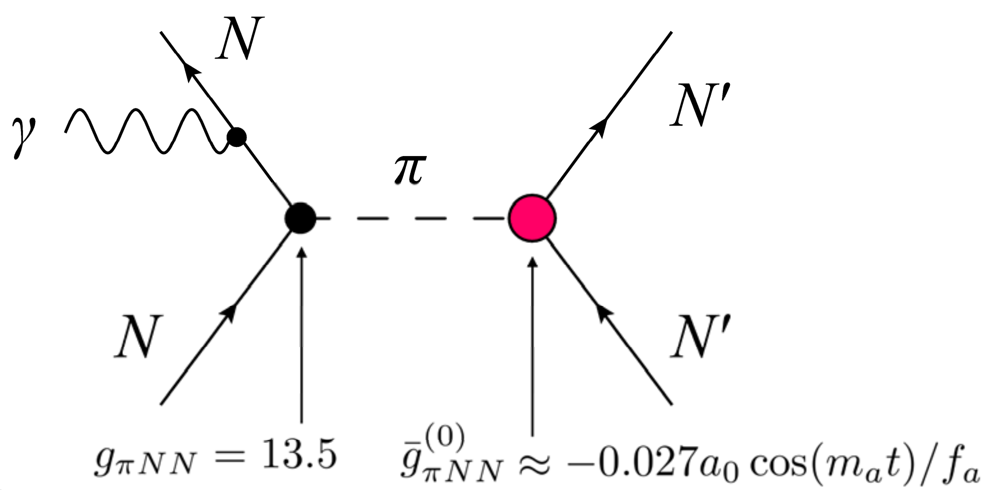
Oscillating atomic and molecular EDMs are induced through oscillating Schiff ($J \geq 0$) and oscillating magnetic quadrupole ($J \geq 1/2$, **no Schiff screening**) moments of nuclei, which arise from *intrinsic oscillating nucleon EDMs* and *oscillating P,T-violating intranuclear forces* (**larger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

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

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

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



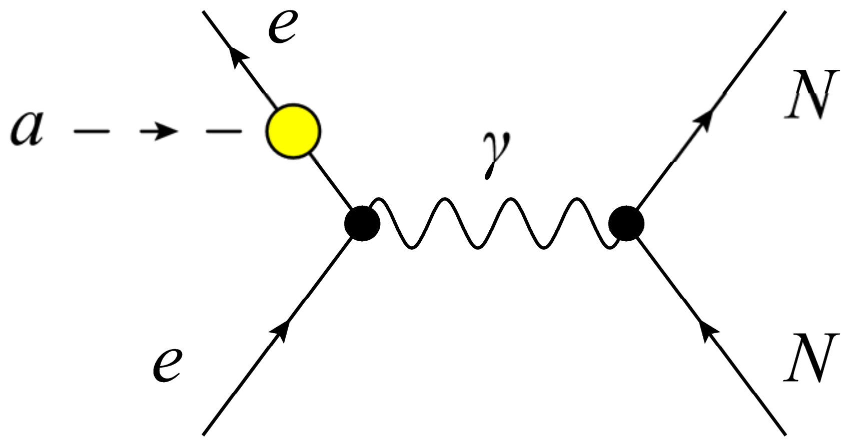


Axion-Induced Oscillating EDMs of Paramagnetic Atoms and Molecules

[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.

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



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

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

Interaction of the oscillating axion field with atomic/molecular electrons mixes opposite-parity states, producing **oscillating PNC effects in atoms and molecules**.

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

Axion-induced oscillating atomic PNC effects are determined entirely by relativistic corrections (in the non-relativistic approximation, $K_{\mathrm{PNC}} = 0$)*.

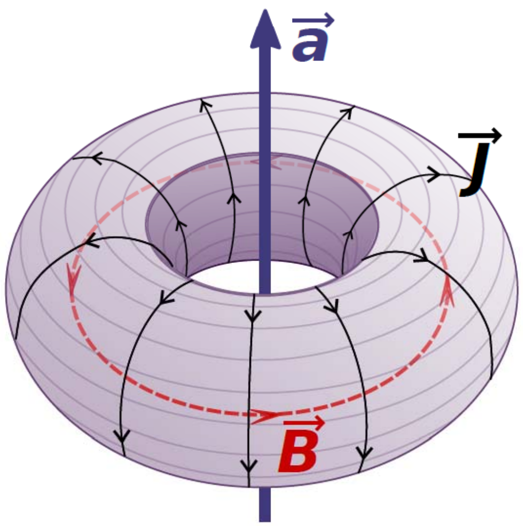
* Compare with the Standard Model *static* atomic PNC effects in atoms, which are dominated by Z^0-boson exchange between atomic electrons and nucleons in the nucleus, where the effects arise already in the non-relativistic approximation.

Axion-Induced Oscillating Nuclear Anapole Moments

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

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

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



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

Search for Axion Dark Matter with Ultracold Neutrons and Hg atoms

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

- Ongoing search for "axion wind" spin-precession effect and axion-induced oscillating neutron EDM by the nEDM collaboration at PSI and Sussex, using a dual neutron/^{199}Hg co-magnetometer to measure the weighted combination of Larmor precession frequencies:

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

- Exact frequency of oscillation is unknown: $\omega = m_a$ (10^{-22} eV ≤ m_a ≤ 0.1 eV => 10^{-8} Hz ≤ f ≤ 10^{13} Hz), with $\Delta f/f \sim 10^{-6}$.
- Need to search over a broad range of frequencies.

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.

t,W,Z bags and bariogenesis, Flambaum,Shuryak PRD2010

The pressure of the Higgs walls collects over 100 of heavy particles t,W,Z into Higgs h=0 areas, compresses and heats the gas of t,W,Z until mechanical equilibirium is reached: pressure of hot gas compensates pressure of the walls P=v forming metastable bags. Masses $m_{t,W,Z}$ =0 inside!

Finite size h=0 sphaleron produces barion number violation inside the bags. The barrier is 2 TeV only (instead of 14 TeV for <h>=v).

Possible role of W, Z, top quark bags in bariogenesis (Standard model, no new particles!) Flambaum, Shuryak PRD82, 073019 (2010)

1. Heavy particles W,Z,t were rapidly produced by Higgs field and massless in Higgs field h=0. Moving walls between new phase h=v and h=0 phase collect ~1000 W,Z,t into small pockets of h=0 where they are massless. Pressure of the Higgs walls compresses and heats gas of W,Z,t until mechanical equilibrium is reached.

Free zero mass W,Z,t are stable. Calulations of W,Z, t energy levels and their lifetimes in the bag and the bag stabilization by the t,W,Z gas pressure. Flambaum, Kuchiev, Shuryak. PRD 78,077502(2008); D82 073018 (2010); D84, 114024 (2011); Phys. Lett. B693, 485(2010); EPL 97, 51001 (2012).

2. Barrier for the barion number changing transition (finite size COS sphaleron) inside these h=0 bags is E= 2 TeV instead of 14 TeV for for h=v. Rate exp(-E/T), ~0.03 transitions per bag.

t-quarks are already in the bag. Inclusion of t-quarks enhances the sphaleron rate by another factor of 20 (3 to 9, instead of 0 to 12).

No significant suppression of the barion number violation.

4. CP violation and bariogenesis within the Standard Kobayashi-Maskawa model ? Calculations of effective CP-violating operators with W,Z fields. Asymmetric t-penetration, t-decay and sphaleron rate.

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

Parity Violation to measure quadrupole moments of neutron distribution (NQM)

- Sushkov, Flambaum 1978: Nuclear quadrupole moment generates tensor weak interaction $W_T=W_{ik}I_iI_k$ which mixes opposite parity electron energy levels up to J_1-J_2=2. In atoms this contribution may be separated by measurements of PV on different hyperfine components

  Cs, Ba, Yb, Dy, Fr, Ra+,…
- W_T mixes very close levels of opposite parity (omega=+1,-1 doublet) in molecules ThO, TaN, ThF+, HfF+, PbO, WC used to measure electron EDM. Huge enhancement of W_T
- In the Standard model neutron weak charge -1, proton weak charge 0.08. So, we measure NQM.
- NQM is calculated using deformed oscillator model for all nuclei of experimental interest, PRL 2016

Acknowledgements

We would like to thank the following people for helpful discussions:

Bruce Allen, Francois Bondu, Julian Berengut, Dmitry Budker, Vladimir Dzuba, Gleb Gribakin, Hartmut Grote, Nils Huntemann, Sergey Klimenko, Nathan Leefer, David Marsh, Guenakh Mitselmakher, Ekkehard Peik, Maxim Pospelov, Surjeet Rajendran, Fritz Riehle, Benjamin Roberts, Ken Van Tilburg, Yvonne Wong and Jun Ye

References (Scalar Dark Matter)

Y. V. Stadnik and V. V. Flambaum. *Can Dark Matter Induce Cosmological Evolution of the Fundamental Constants of Nature*? Physical Review Letters **115**, 201301 (2015). arXiv:1503.08540.

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. *Improved limits on interactions of low-mass spin-0 dark matter from atomic clock spectroscopy*. arXiv:1605.04028.

Y. V. Stadnik and V. V. Flambaum. *Enhanced effects of variation of the fundamental constants in laser interferometers and application to dark matter detection*. arXiv:1511.00447.

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.

References (Axion Dark Matter)

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.

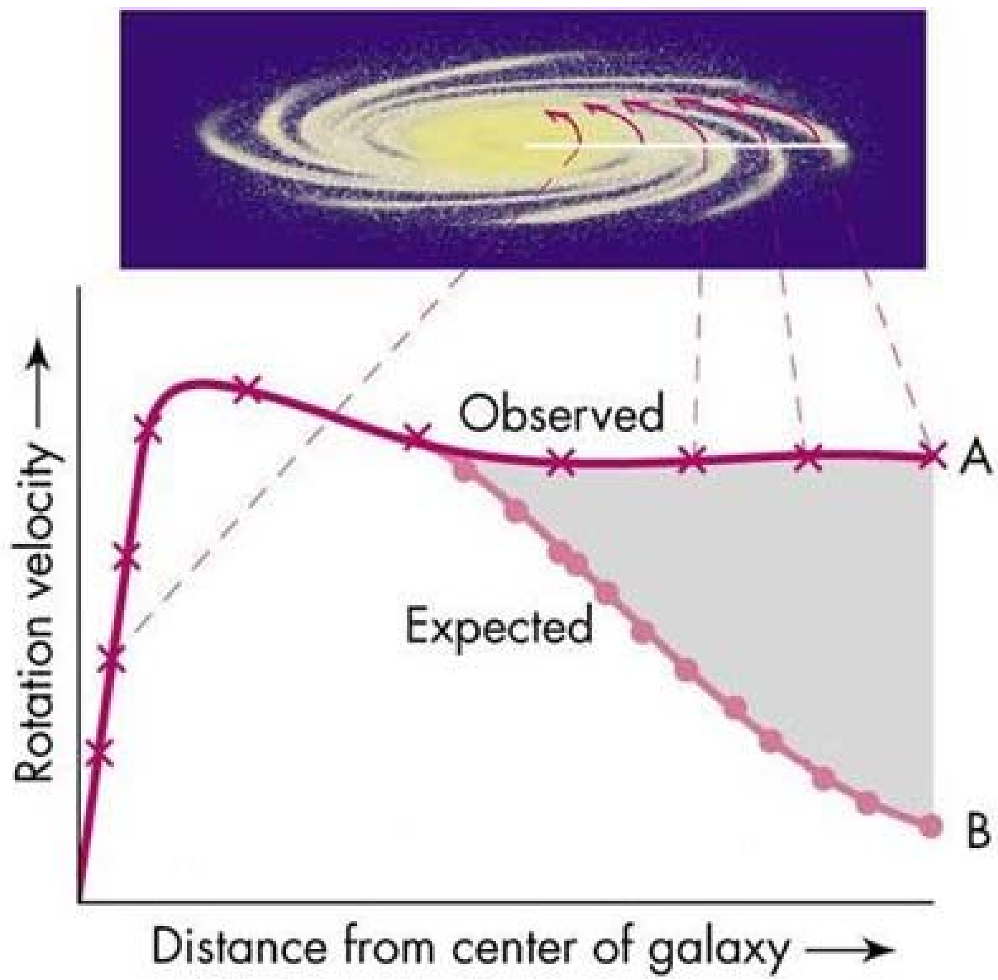
B. M. Roberts, Y. V. Stadnik, V. A. Dzuba, V. V. Flambaum, N. Leefer and D. Budker. *Limiting P-odd interactions of Cosmic Fields with Electrons, Protons and Neutrons*. Physical Review Letters **113**, 081601 (2014). arXiv:1404.2723.

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.

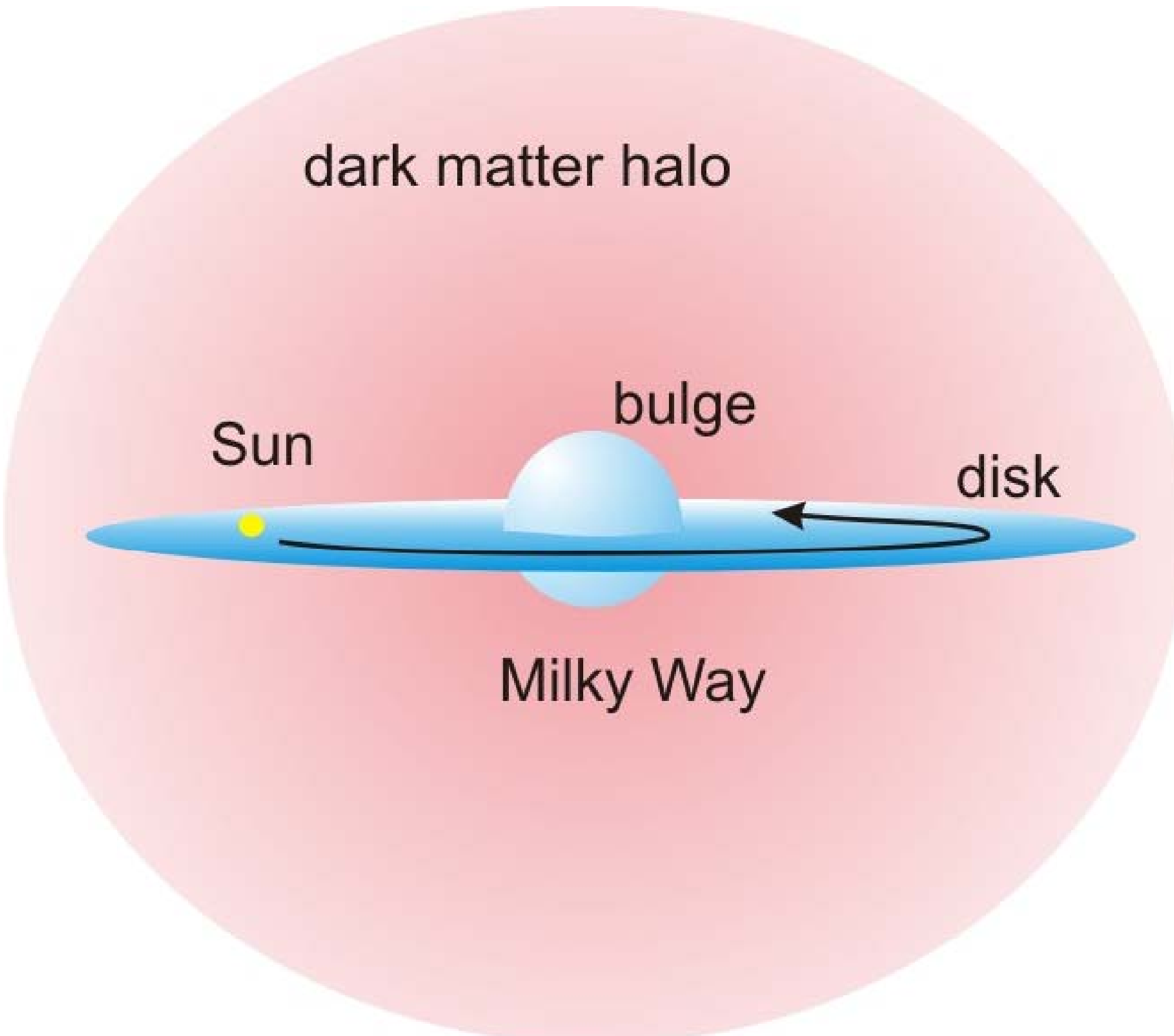
Y. V. Stadnik and V. V. Flambaum. *Nuclear spin-dependent interactions: searches for WIMP, axion and topological defect dark matter, and tests of fundamental symmetries*. European Physical Journal C **75**, 110 (2015). arXiv:1408.2184.

Motivation

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



Motivation



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 $t_{\text{weak}} \approx 1\text{s}$ until $t_{\text{BBN}} \approx 3$ 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 $t_{\text{weak}} \approx 1\text{s}$ ($T_{\text{weak}} \approx 0.75$ MeV).

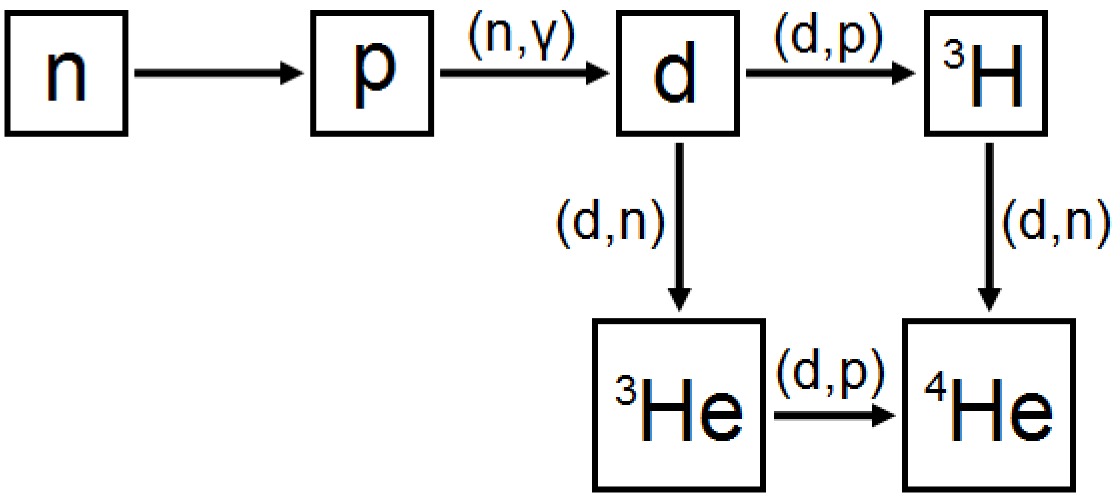
$$p + e^- \rightleftharpoons n + \nu$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

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

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 $t_{\rm BBN} \approx 3$ min ($T_{\rm BBN} \approx 60$ keV).



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

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

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

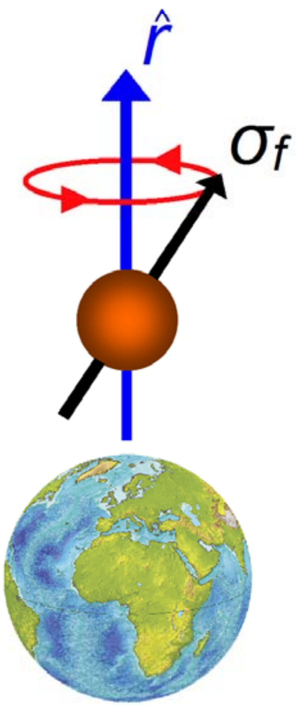
- Weaker astrophysical constraints come from CMB measurements (lower ρ_{DM}).
- Variations in α and m_e at the time of electron-proton recombination affect the ionisation fraction and Thomson scattering cross section, $\sigma_{Thomson} = 8\pi\alpha^2/3m_e^2$, changing the mean-free-path length of photons at recombination and leaving distinct signatures in the CMB angular power spectrum.

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

Axion-Induced Oscillating Spin-Gravity Coupling

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

Distortion of axion field by gravitational field of Sun or Earth induces **oscillating spin-gravity couplings**.



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

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

Spin-axion momentum and axion-induced oscillating spin-gravity couplings to nucleons may have isotopic dependence ($C_p \neq C_n$) – calculations of proton and neutron spin contents for nuclei of experimental interest have been performed, see, e.g., [Stadnik, Flambaum, *EPJC* **75**, 110 (2015)].

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

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

Interaction of the oscillating axion field with atomic/molecular electrons mixes opposite-parity states, producing **oscillating PNC effects in atoms and molecules**.

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

Axion-induced oscillating atomic PNC effects are determined entirely by relativistic corrections (in the non-relativistic approximation, $K_{\rm PNC} = 0$)*.

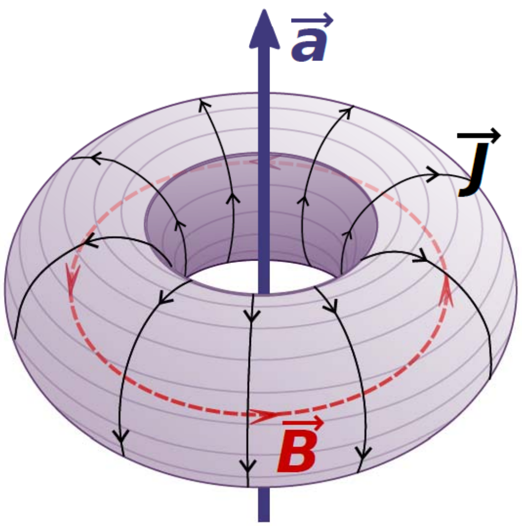
* Compare with the Standard Model *static* atomic PNC effects in atoms, which are dominated by Z^0-boson exchange between atomic electrons and nucleons in the nucleus, where the effects arise already in the non-relativistic approximation.

Axion-Induced Oscillating Nuclear Anapole Moments

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

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

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



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

Topological Defect Dark Matter

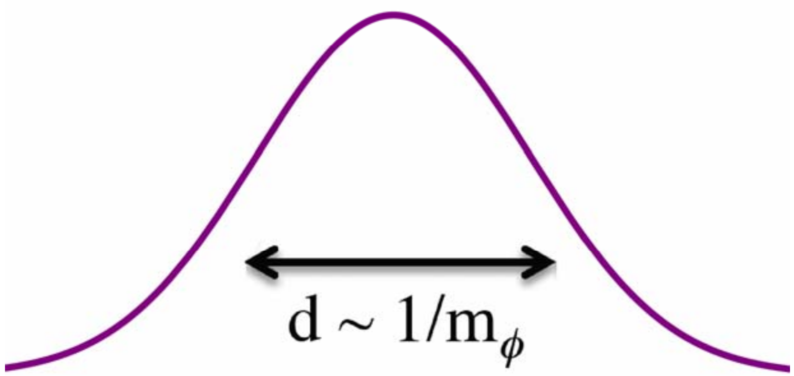
Take a simple scalar field and give it a *self-potential*, e.g. $V(\varphi) = \lambda(\varphi^2 - v^2)^2$. If $\varphi = -v$ at $x = -\infty$ and $\varphi = +v$ at $x = +\infty$, then a stable **domain wall** will form in between, e.g. $\varphi(x) = v \tanh(x m_\varphi)$ with $m_\varphi = \lambda^{1/2}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

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); arXiv:1511.00447]