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

V. V. Flambaum, I. B. Samsonov and H. B. Tran Tan

Physical Review A 98, 043408
Physical Review A 98, 053437
Physical Review A 99, 013430
ArXiv:1904.07609

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Key points

- **Measurement of nuclear Electric Dipole Moment (EDM) → test of CP-violation theories.**
- Schiff theorem: nuclear EDM is completely screened, d E=0
- Oscillating external electric field E(t) is not completely screened → use for probing nuclear EDM.
- In **atom**: resulting field proportional to ω^2 and polarizability.
- In **molecule**: enhancement due to the factor $M_{nuc}/m_e \geq 10^4$, small energy denominators and large polarizability.
- In resonance there is a big enhancement.
- Similar effect: oscillating nuclear EDM induced by axion dark matter is not completely screened.
- Molecules: large enhancements and small energy → good for axion search.

Extended Schiff theorem - ions and molecules in static electric field

- Schiff theorem: in static external field E, $E_N = 0$ for neutral systems → E_Nd=0, nuclear EDM d is unobservable.
- Extension for ions and molecules:

Ion acceleration $a_{ion} = \frac{Z_i eE}{M}$,

Nucleus acceleration $a_N = \frac{ZeE_N}{M}$,

$$\Rightarrow E_N = \frac{Z_i}{Z} E.$$

- In molecules screening is stronger: $a_{ion} = \frac{Z_i eE}{M+m} \Longrightarrow E_N = \frac{Z_i}{Z} \frac{M}{M+m} E.$

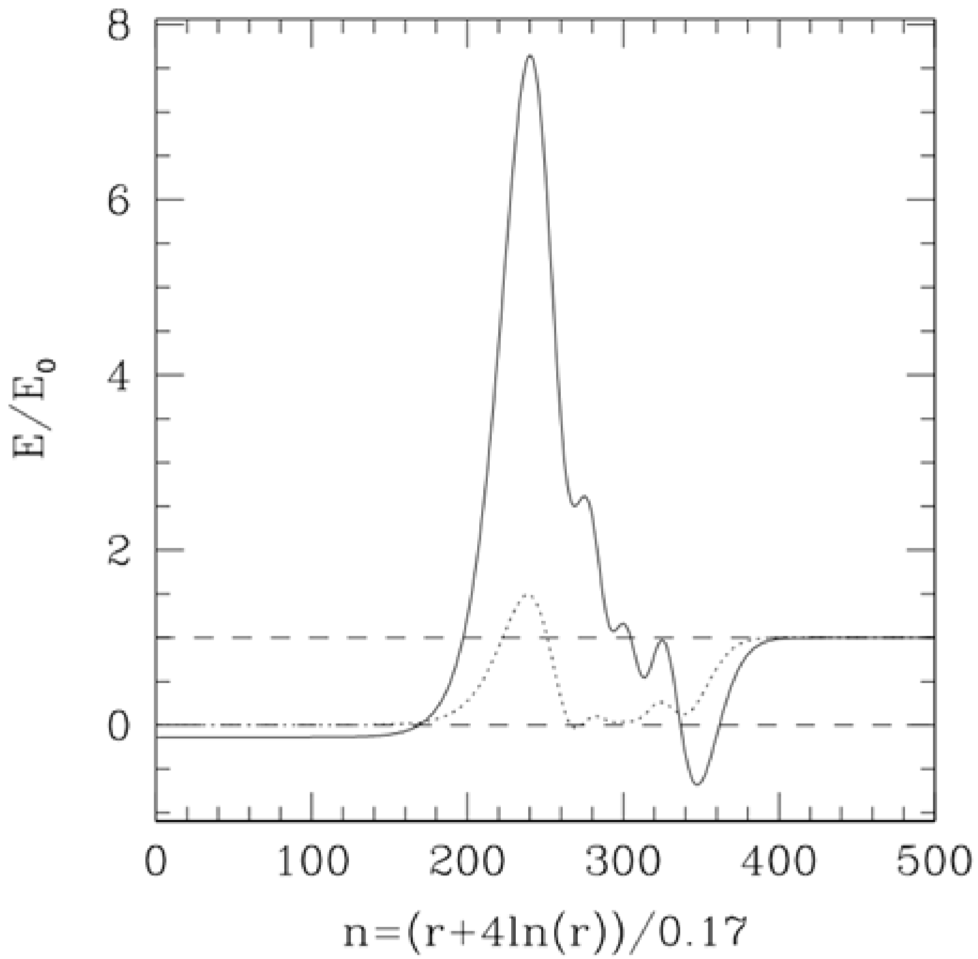
Extended screening theorem - atoms in oscillating electric field

- Oscillating field $E = E_0 \cos(\omega t)$: incomplete screening!
- In **atom** (V. F. - PRA 98, 043408): $E_N = -\frac{\omega^2 \alpha_{zz}}{Z} E$.
- In light atoms E$_N$ is larger (recall static case $Z_i \;/Z \quad$).
- In resonance: $E_N = A \sin \varsigma t \cos \omega t$ where,

  $\varsigma = 2eE_0 \langle 0|D_z|n\rangle$ is the Rabi oscillation frequency,

  $A = \frac{\omega^2 D_z}{Z}$ is the amplitude of the electric field on the nucleus in atomic units of electric field $\sim 5.14 \times 10^9 V/cm$.
- Nuclear EDM effect E$_N$d may be strongly enhanced near resonance.

Screening of static and oscillating electric field in Xe, graph of $E(r)/E_0$, $\omega = 0.3$ a.u.



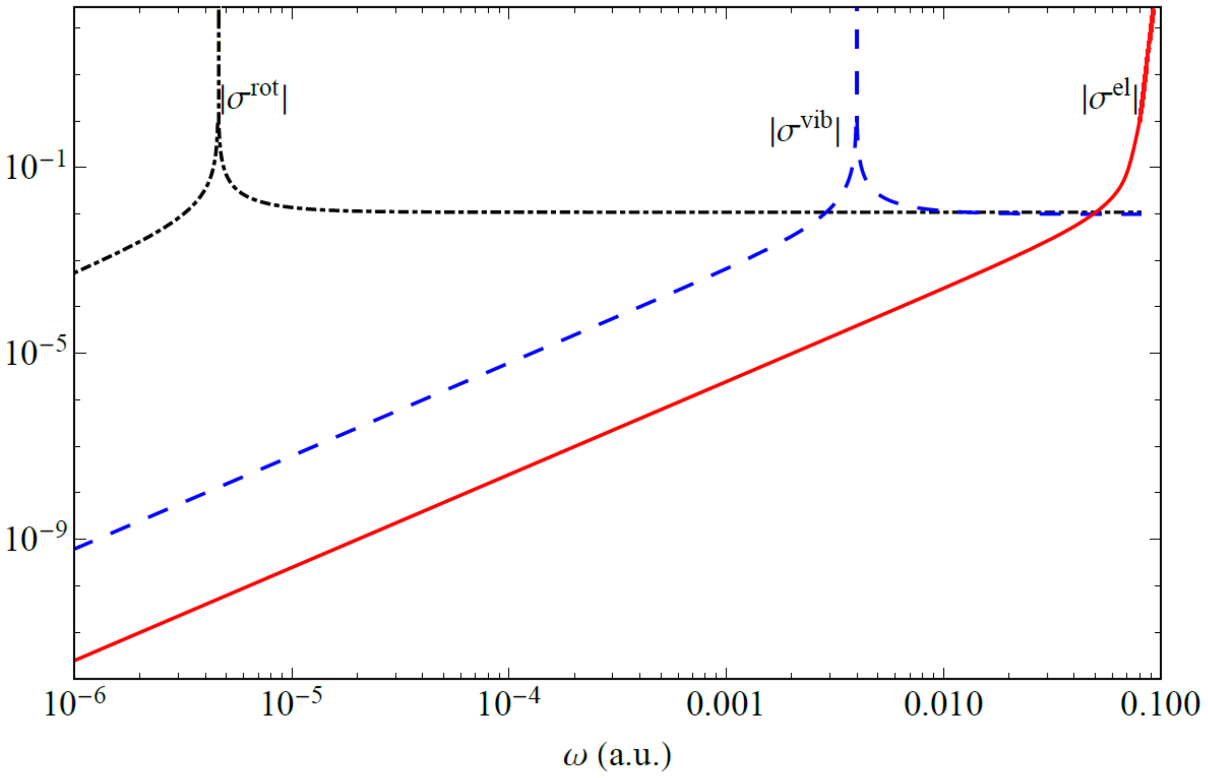
- Static field is zero inside the nucleus.
- Oscillating field is not zero inside the nucleus, -0.14 E_0. Enhancement outside the nucleus.
- E/E_0=1 outside the atom

V. Dzuba, and V. F.
arxiv: 1805.04989

Extended screening theorem - molecules in oscillating electric field

- In **diatomic molecule** (V. F. , I. Samsonov and H. B. Tran Tan – Phys. Rev. A 99, 013430):
  - ✓ $\frac{E_1}{E} = \sigma^{rot}, \sigma^{rot} = -\frac{2\omega^2\mu}{3Z_1}\frac{\bar{\omega}\bar{S}\bar{d}}{\bar{\omega}^2-\omega^2}$ if ω is in the rotational regime, E_1 is the field on the nucleus 1, E is the external field. Light nucleus dominate.
  - ✓ $\frac{E_1}{E} = \sigma^{rot} + \sigma^{vib}, \sigma^{vib} = -\frac{2\omega^2\mu}{3Z_1}\sum_{vib\ states}\frac{\omega_{0n}S_0^n d_0^n}{\omega_{0n}^2-\omega^2}$ if ω is in the vibrational regime,
  - ✓ $\frac{E_1}{E} = \sigma^{rot} + \sigma^{vib} + \sigma^{el}, \sigma^{el} = -\frac{\omega^2 M_1}{3(M_1+M_2)Z_1}(\alpha_{\parallel}^{el} + 2\alpha_{\perp}^{el})$ if ω is in the electronic regime.
- $\frac{E_1}{E} = \sigma^{rot}$ has large coefficient $\frac{\mu}{m_e}\sim 10^4$ (μ is the reduced nuclear mass). Nuclei moves slowly and do not provide efficient screening of oscillating field E. Small rotational energy denominator gives additional enhancement factor $\frac{\mu}{m_e}\sim 10^4$. Resonance gives an additional enhancement.

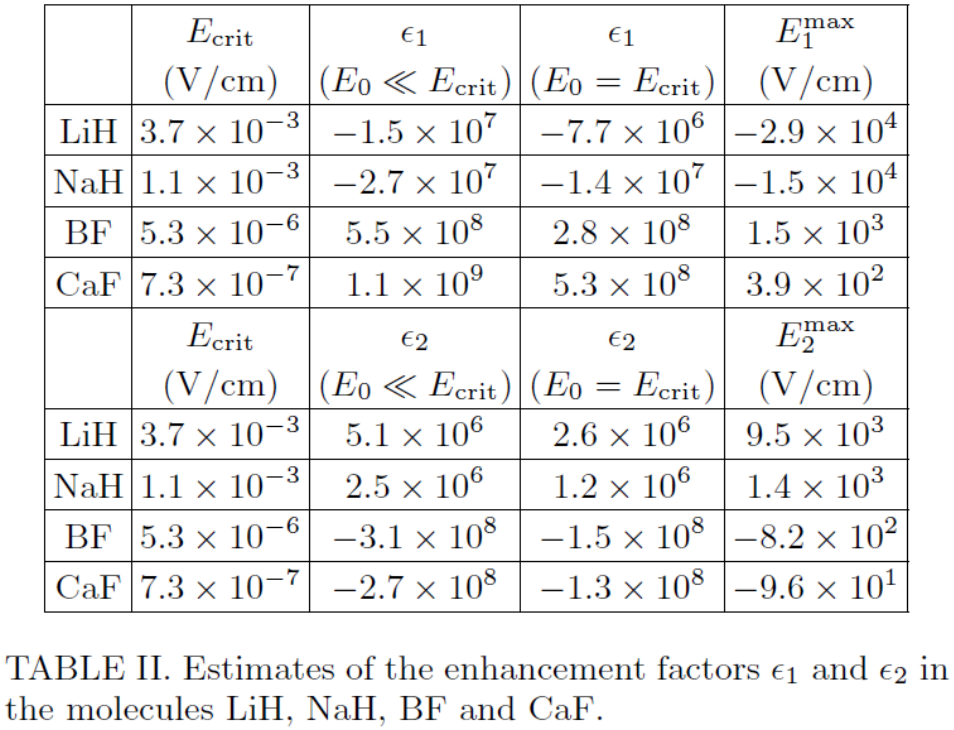
Screening/enhancement factor σ of oscillating electric field in molecules



- Contributions of σ^{rot}, σ^{vib} and σ^{el} to the ratio E_1/E as one goes up the energy scale.
- The resonance peaks are clearly visible. The height of these peaks is $10^7{\sim}10^8$.

Resonance enhancement of oscillating electric field

- In **resonance** with the lowest rotational level $\omega = \bar{\omega}$:
- ✓ $\left|\frac{E_1}{E}\right| = \varepsilon_1 \equiv \frac{4\mu\bar{\omega}^5 \bar{S}\bar{d}}{Z_1\left(8\bar{\omega}^6\bar{d}^2+9E_0^2\right)}$.
- ✓ $\varepsilon_1 \sim 10^6 - 10^9$.
- Maximum value of E_1 between $10^3 - 10^5$ V/cm.
- Can measure energy shift (nuclear spin rotation) $E_1 d$ produced by nuclear EDM d in electric field
- Test of unification theories
- Screening/enhancement affects nuclear reactions: E1 transitions, radiative capture, laser-induced neutron capture



	$E_{\rm crit}$ (V/cm)	ϵ_1 ($E_0 \ll E_{\rm crit}$)	ϵ_1 ($E_0 = E_{\rm crit}$)	$E_1^{\rm max}$ (V/cm)
LiH	3.7×10^{-3}	-1.5×10^7	-7.7×10^6	-2.9×10^4
NaH	1.1×10^{-3}	-2.7×10^7	-1.4×10^7	-1.5×10^4
BF	5.3×10^{-6}	5.5×10^8	2.8×10^8	1.5×10^3
CaF	7.3×10^{-7}	1.1×10^9	5.3×10^8	3.9×10^2
	$E_{\rm crit}$ (V/cm)	ϵ_2 ($E_0 \ll E_{\rm crit}$)	ϵ_2 ($E_0 = E_{\rm crit}$)	$E_2^{\rm max}$ (V/cm)
LiH	3.7×10^{-3}	5.1×10^6	2.6×10^6	9.5×10^3
NaH	1.1×10^{-3}	2.5×10^6	1.2×10^6	1.4×10^3
BF	5.3×10^{-6}	-3.1×10^8	-1.5×10^8	-8.2×10^2
CaF	7.3×10^{-7}	-2.7×10^8	-1.3×10^8	-9.6×10^1

TABLE II. Estimates of the enhancement factors ϵ_1 and ϵ_2 in the molecules LiH, NaH, BF and CaF.

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

Y. Stadnik, V. Flambaum, et al.

Physical Review Letters 118, 142501 (2017)

Physical Review Letters 116, 023201 (2016)
Physical Review Letters 117, 271601(2016)
Physical Review Letters 115, 201301 (2015)
Physical Review Letters 114, 161301 (2015)
Physical Review Letters 113, 151301 (2014)
Physical Review Letters 113, 081601 (2014)
Physical Review D 89, 043522 (2014)
Physical Review D 90, 096005 (2014)

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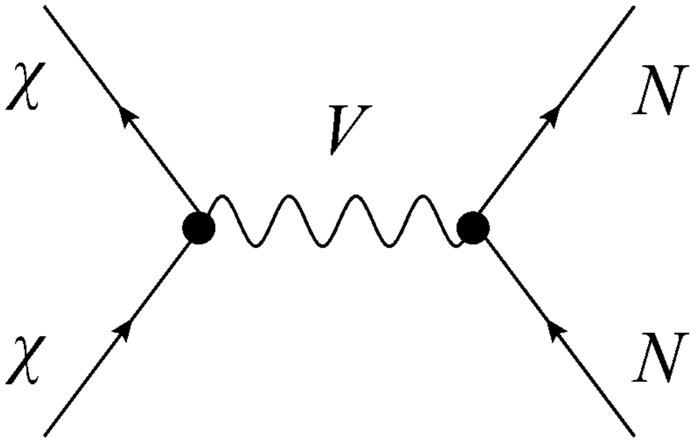
Nature Physics 12, 465 (2016)

Motivation

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



$$\mathcal{M} \propto (e')^2$$

$$=> \frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 \propto (e')^4$$

Problem: Observable is **quartic** in the interaction constant e', which is extremely small ($e' << 1$)!

We consider **linear** effects. Enormous advantage!

Low-mass Spin-0 Dark Matter

- *Low-mass spin-0 particles* form a *coherently oscillating classical* field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ GeV/cm^3)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{\mathrm{dB},\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = "Cosmic maser"
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV <=> 10^{-8} Hz $\leq f \leq 10^{13}$ Hz

$\lambda_{\mathrm{dB},\varphi} \leq L_{\text{dwarf galaxy}} \sim 1$ kpc

Classical field

- $m_\varphi \sim 10^{-22}$ eV <=> $T \sim 1$ year

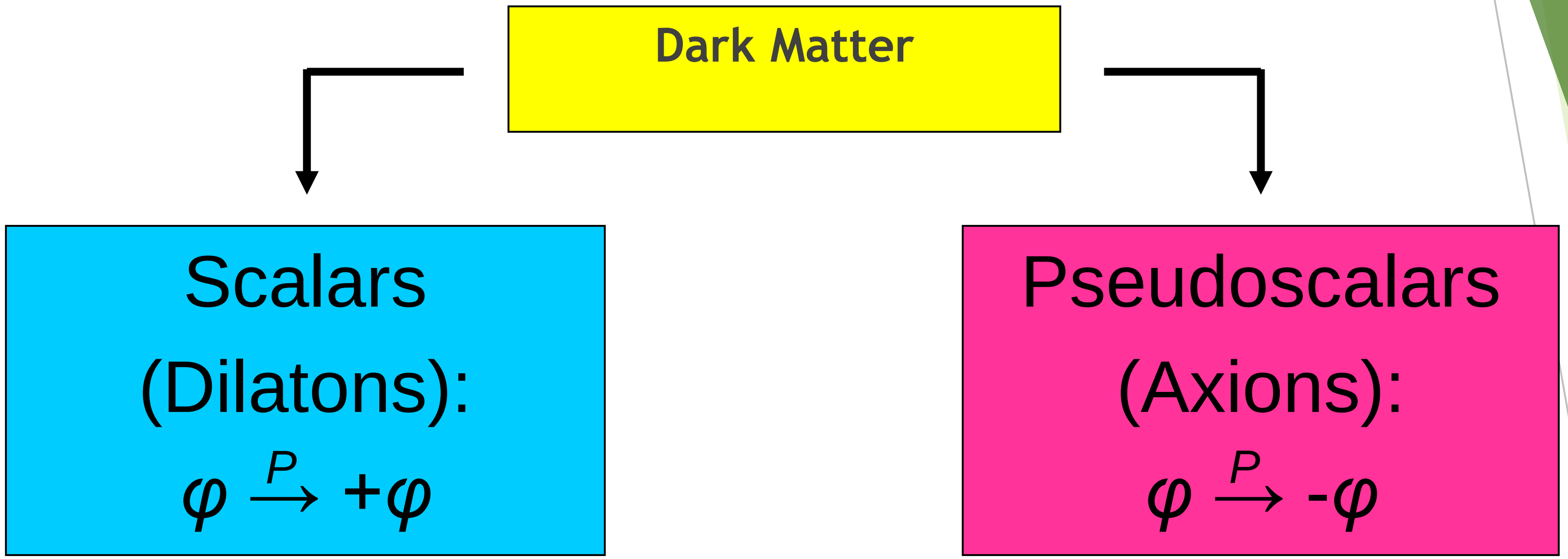
Coherence of Galactic DM

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

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

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

Low-mass Spin-0 Dark Matter



Dark Matter

Scalars (Dilatons): $\varphi \xrightarrow{P} +\varphi$

Pseudoscalars (Axions): $\varphi \xrightarrow{P} -\varphi$

⟶ Time-varying fundamental constants

10^{15} improvement

⟶ Time-varying spin-dependent effects, EDM

10^{3} improvement

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

$\varphi \xrightarrow{P} -\varphi$

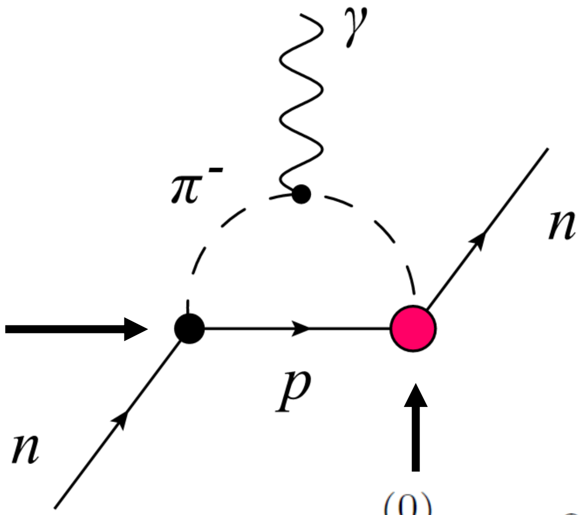
QCD axion resolves strong CP problem, most popular dark matter candidate

→ Time-varying spin-dependent effects, oscillating EDM

Axion-Induced Oscillating Neutron EDM

- Axion dark matter field → oscillating nucleon EDM (static neutron EDM: Crewther, Di Vecchia, Veneziano, Witten - *PLB* 88, 123, 1979; Pospelov, Ritz - *PRL* 83, 2526, 1999; axion-induced neutron EDM Graham, Rajendran-*PRD* 84,055013,2011)

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



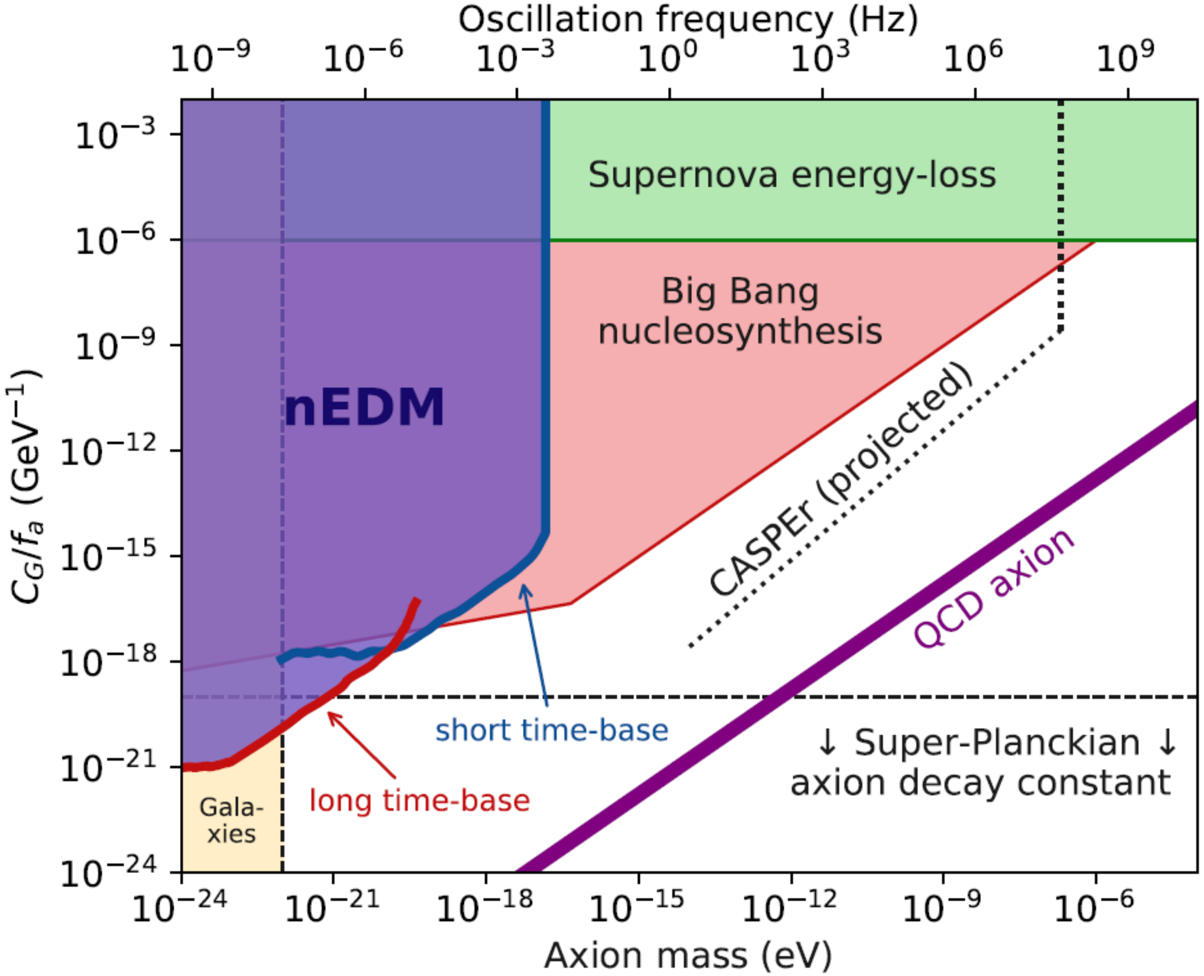
$g_{\pi NN} = 13.5$

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

Constraints on Interaction of Axion Dark Matter with Gluons (n and Hg EDM)

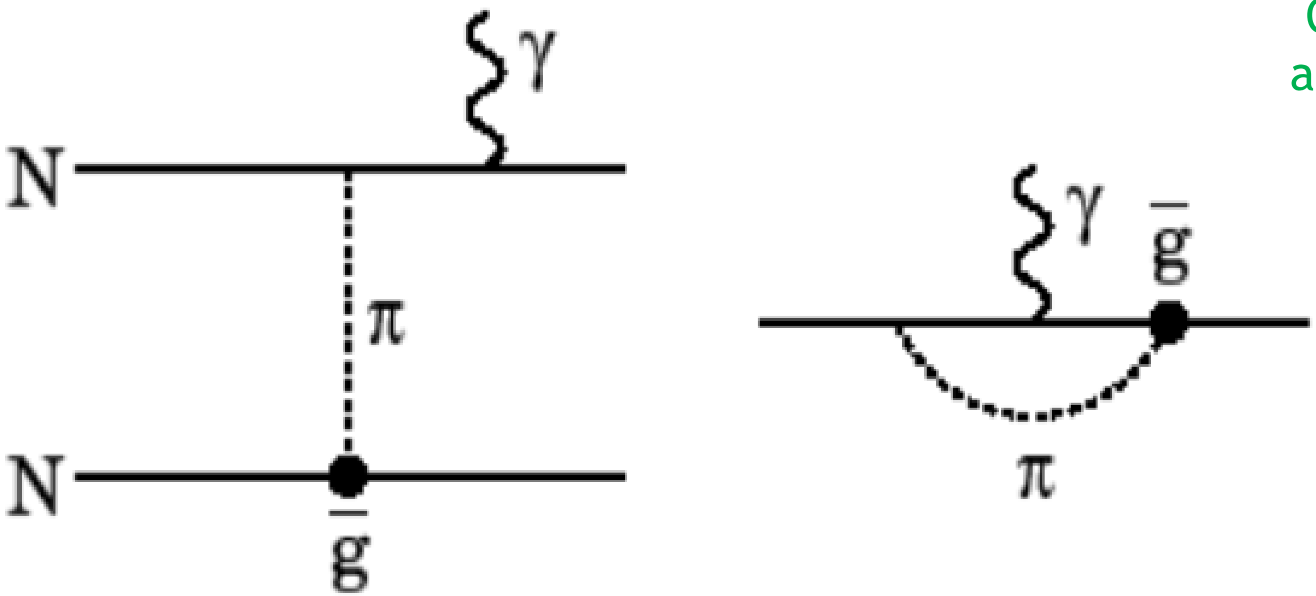
nEDM constraints: [nEDM collaboration, Phys. Rev. X 7, 041034, 2017]

3 orders of magnitude improvement!



Nuclear EDM: T,P-odd NN interaction

gives~ **40** times larger contribution than nucleon EDM, × 10 in deformed nuclei due to close levels of opposite parity



O. Sushkov, V. F. and I. Khriplovich - *JETP* 60, 873, 1984

Axion-Induced oscillating Nuclear, Atomic and Molecular EDMs

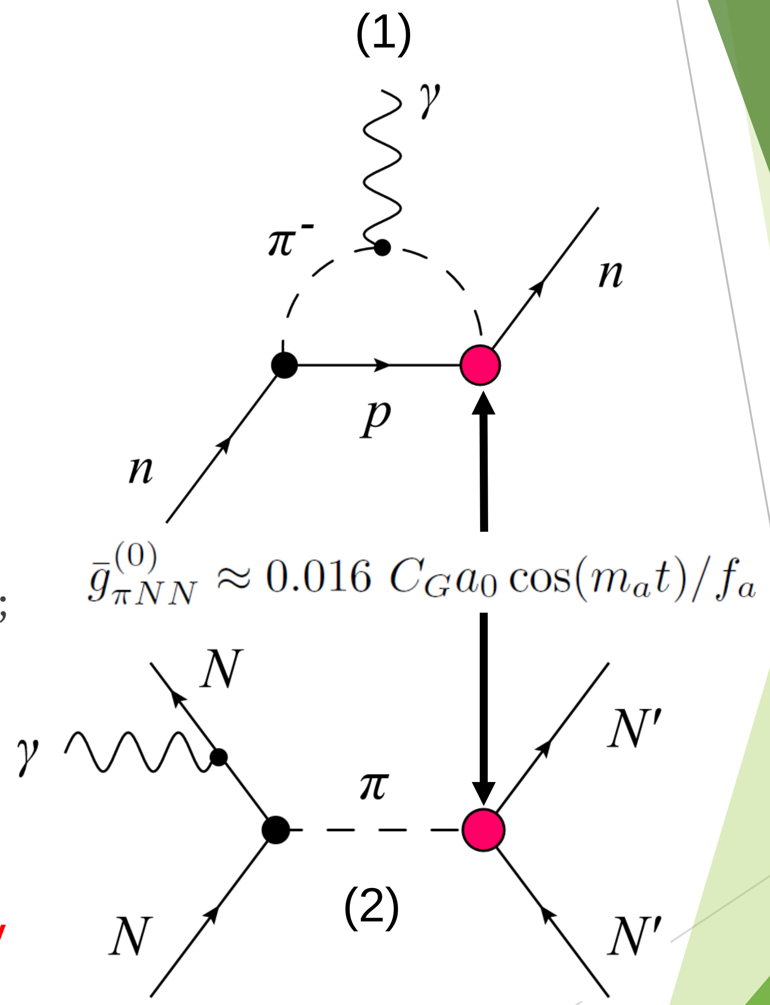
- Static nuclear EDM (O. Sushkov, V.F. and I. Khriplovich - *JETP* 60, 873, 1984),
- Oscillating nuclear EDM (Y. Stadnik and V.F. - *PRD* 89, 043522, 2014).
- Induced through *hadronic mechanisms*:

✓ Oscillating nuclear EDM and nuclear Schiff moments ($I \geq 1/2$ → $J \geq 0$)

✓ Oscillating nuclear magnetic quadrupole moments ($I \geq 1$ → $J \geq 1/2$; *magnetic* → no Schiff screening)

- Underlying mechanisms:

1. Intrinsic oscillating nucleon EDMs (1-loop level)
2. Oscillating *P*,*T*-violating intra-nuclear forces (*tree level* → **larger by $\sim 4\pi^2 \approx 40$**; up to **extra 1000-fold enhancement** in deformed nuclei)



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

Oscillating nuclear EDM - $d_N = d_0 \cos\omega t$

- Static nuclear EDM is completely screened in a neutral system.
- Axion-induced nuclear EDM oscillates → not screened (V. F. and H. B. Tran Tan - arxiv:1904.07609).
- In **atom**: $d_{atom} = -\frac{\omega^2 \alpha_{zz}}{Z} d_N$.
- In **diatomic molecule**: $\vec{d}_{mol} = -\frac{\omega^2 \mu}{\sqrt{Z_1 Z_2}}\left(\alpha\vec{\Delta} + \beta\vec{\delta}\right)$,

$$\alpha = 2\sum_n \frac{E_{n0}\langle 0|\vec{D}|n\rangle\langle n|\vec{D}|0\rangle}{E_{n0}^2 - \omega^2} \qquad \beta = 2\sum_n \frac{E_{n0}\langle 0|\vec{X}|n\rangle\langle n|\vec{D}|0\rangle}{E_{n0}^2 - \omega^2}$$

$$\vec{\Delta} = \frac{Z_2 M_1 \vec{d}_1 + Z_1 M_2 \vec{d}_2}{M_1 M_2 \sqrt{Z_1 Z_2}} \qquad \vec{\delta} = \frac{Z_2 \vec{d}_1 - Z_1 \vec{d}_2}{\sqrt{Z_1 Z_2}}$$

Oscillating nuclear EDM - $d_N = d_0 \cos\omega t$ Small frequency behavior

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

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

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

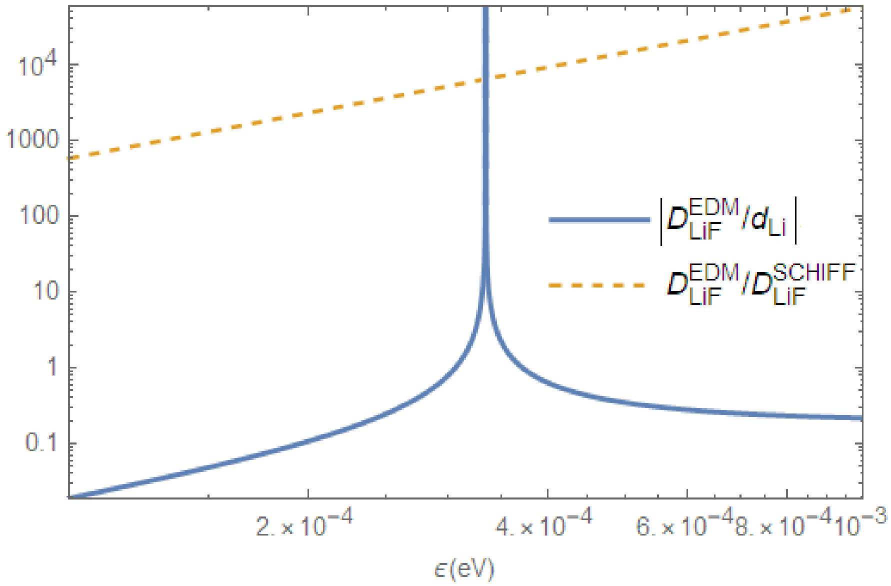
- In resonance $\omega = \overline{\omega}$: $\vec{d}_{mol} \approx -\frac{2\bar{d}}{3Z_1\bar{X}}\frac{\overline{\omega}}{\Gamma}\vec{d}_1$ where

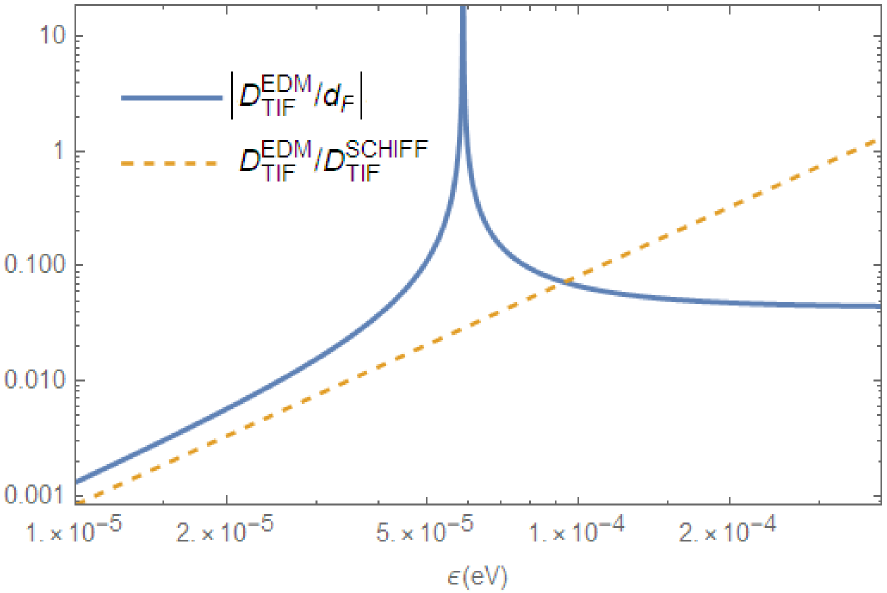
$$\frac{\Gamma}{\overline{\omega}} \approx \frac{\langle v^2\rangle}{c^2} \sim 10^{-6}$$

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

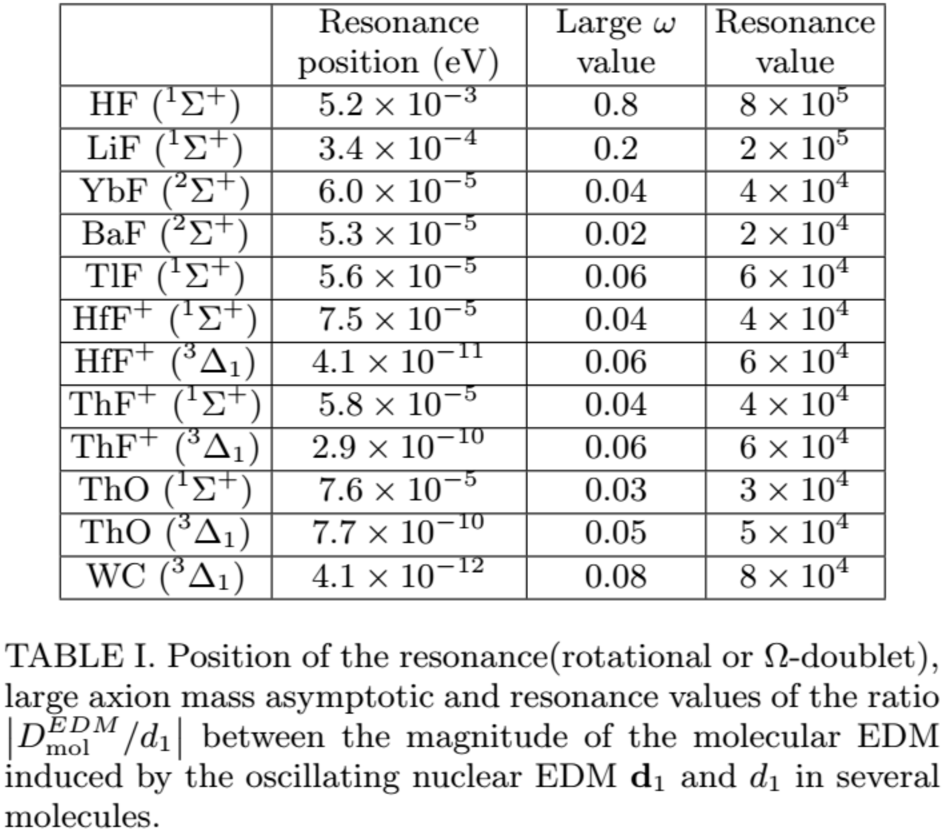
Ratio of oscillating molecular and nuclear EDM - Examples: LiF and TlF

- Solid line: ratio of induced molecular EDM and nuclear EDM (V. F. and H. B. Tran Tan - arXiv:1904.07609).
- Dashed line: ratio between induced molecular EDM produce by nuclear EDM and by oscillating nuclear Schiff moment (O. Sushkov, V. F. and I. Khriplovich - *JETP* 60, 873, 1984; Y. Stadnik and V.F. - PRD 89, 043522, 2014; V. F. and H. B. Tran Tan - arXiv:1904.07609).
- Resonance enhancement $10^4 \sim 10^5$.





Ratio of oscillating molecular and nuclear EDM - More examples



	Resonance position (eV)	Large ω value	Resonance value
HF ($^1\Sigma^+$)	5.2×10^{-3}	0.8	8×10^5
LiF ($^1\Sigma^+$)	3.4×10^{-4}	0.2	2×10^5
YbF ($^2\Sigma^+$)	6.0×10^{-5}	0.04	4×10^4
BaF ($^2\Sigma^+$)	5.3×10^{-5}	0.02	2×10^4
TlF ($^1\Sigma^+$)	5.6×10^{-5}	0.06	6×10^4
HfF$^+$ ($^1\Sigma^+$)	7.5×10^{-5}	0.04	4×10^4
HfF$^+$ ($^3\Delta_1$)	4.1×10^{-11}	0.06	6×10^4
ThF$^+$ ($^1\Sigma^+$)	5.8×10^{-5}	0.04	4×10^4
ThF$^+$ ($^3\Delta_1$)	2.9×10^{-10}	0.06	6×10^4
ThO ($^1\Sigma^+$)	7.6×10^{-5}	0.03	3×10^4
ThO ($^3\Delta_1$)	7.7×10^{-10}	0.05	5×10^4
WC ($^3\Delta_1$)	4.1×10^{-12}	0.08	8×10^4

TABLE I. Position of the resonance(rotational or Ω-doublet), large axion mass asymptotic and resonance values of the ratio $|D_{\mathrm{mol}}^{EDM}/d_1|$ between the magnitude of the molecular EDM induced by the oscillating nuclear EDM $\mathbf{d}_1$ and d_1 in several molecules.

- Sub-eV resonance energy:
- ✓ $10^{-5} \sim 10^{-3}$ eV if rotational,
- ✓ $10^{-12} \sim 10^{-10}$ eV if Ω-doublet.
- Reasonable large energy asymptotic value.
- Large resonance enhancement $10^4 \sim 10^6$.
- Tuning by magnetic or electric field to resonance with axion energy mc^2

Why are molecules good?

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

Interference-assisted resonance detection of axions and dark photons

Tran Tan, V.F., Samsonov, Stadnik, Budker, Physics of Dark Universe 24, 100272 (2019),

Axions are produced from photons in magnetic field B_1, photons and axions travel to detection area where they are captured by an atom. Interference between the axion and photon capture amplitudes is the first order effect in the axion-electron interaction constant g_{ae}.

V.F., Samsonov, Tran Tan PRD 2019

Similar for dark photon

Coherent axion-photon transformation in the forward scattering on atoms

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

Forward scattering is always coherent, production or capture of axions is proportional to L^2 , L is the length, similar to the production or detection of axions in magnetic field. We calculated effective magnetic and electric fields for the photon-axion transformation in M0 and M1 atomic transitions, $L_{eff}=g_{ae}a(EB_{eff}+BE_{eff})$

Diamagnetic atoms and molecules:
Source of static atomic EDM-nuclear Schiff moment

Schiff moment 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 (our 1984 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.

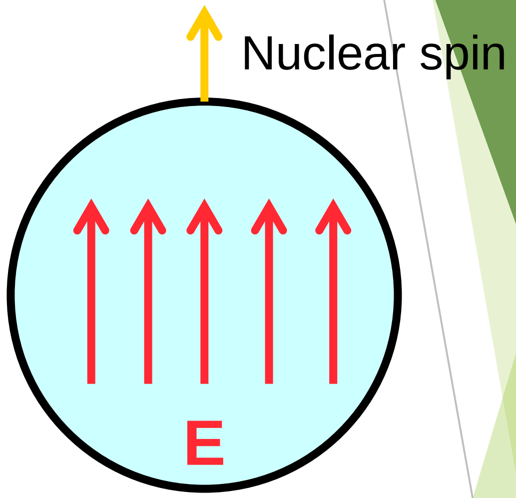
V.F. and J.Ginges:
L=S(1 – c Z^2 α^2)

$$\phi(\mathbf{R}) = -\frac{3L \bullet \mathbf{R}}{B}\rho(R)$$

where

$$B = \int \rho(R) R^4 dR$$

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

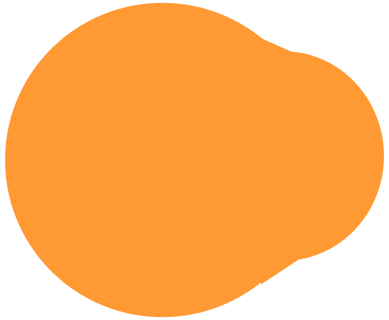


This potential has no singularities and may be used in relativistic calculations.
SM electric field polarizes atom and produces EDM.
Calculations of nuclear SM: Sushkov, V.F. and Khriplovich ;Brown et al, V.F. et al
Dmitriev et al,Auerbach et al,Engel et al, Liu et al,Sen’kov et al, Ban et al.
Atomic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

Nuclear enhancement

Auerbach, V.F. and Spevak 1996

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

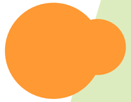


Intrinsic Schiff moment:

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

$\beta_2 \approx 0.2$ - quadrupole deformation

$\beta_3 \approx 0.1$ - octupole deformation



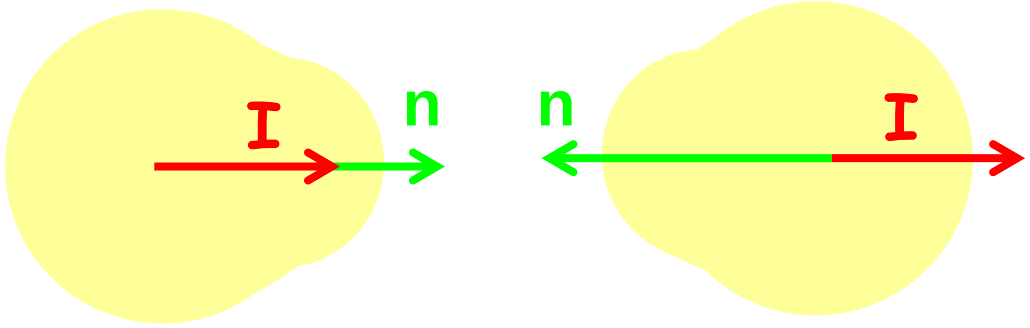
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

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

Simple estimate

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

Two factors of enhancement:

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

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

^{225}Ra EDM experiment – Argon lab, ^{223}Rn TRIUMF. Short lifetime – 15 Days for ^{225}Ra
^{229}Th 8000 years, EDM exceeds that of ^{225}Ra and ^{223}Rn. Molecules ThO, ThF$^+$, ThOH$^+$
Polar molecules have close opposite parity rotational levels (doublets), very strong internal electric field to measure EDM

Atomic EDM produced by nuclear magnetic quadrupole moment

Magnetic interaction is not screened! MQM produced by nuclear T,P-odd forces and proton and neutron EDM

Collective enhancement in deformed nuclei

Mechanism: T,P-odd nuclear interaction produces spin hedgehog-correlation (s r)

Spherical – magnetic monopole forbidden

Deformed- collective magnetic quadrupole

Nuclear and molecular calculations of MQM effects

- V.F., DeMille, Kozlov PRL 2014

Nuclear and molecular estimates for TaN, ThO, BaF, HgF, YbF, HfF+ ,TaO+, WN+

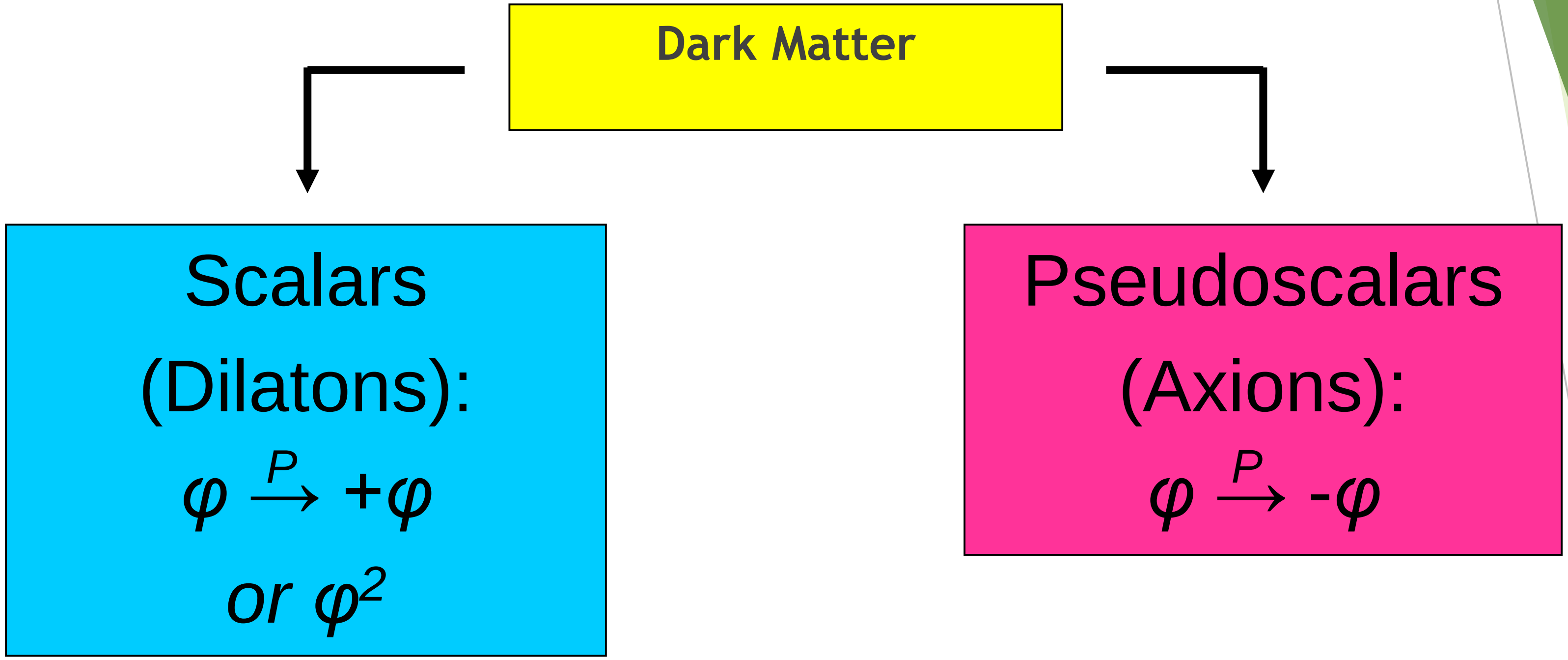
Accurate molecular calculations

- ThO: Skripnikov, Petrov, Titov, and V.F. PRL 2014
- TaN: Skripnikov, Petrov, Mosyagin, Titov, and V.F 2015,
- HfF+ Skripnikov,Titov, and V.F. 2017,
- YbOH Maison, Skripnikov, and V.F. 2019
- Nuclear calculations Lackenby and V.F. 2018

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

- 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. If there are close opposite parity levels with J_1-J_2=2, the only enhanced contribution is that of the weak quadrupole moment
- W_T mixes very close levels of opposite parity (omega=+1,-1 doublet) in molecules ThO, TaN, ThF+, HfF+, PbO, WC, TaO+, WN+ used to measure electron EDM. Enhancement of W_T
- In the Standard model neutron weak charge -1, proton weak charge 0.08. So, we measure NQM.

Low-mass Spin-0 Dark Matter



Dark Matter

Scalars (Dilatons):

$\varphi \xrightarrow{P} +\varphi$

or φ^2

→ Time-varying fundamental constants

10^{15} improvement

Pseudoscalars (Axions):

$\varphi \xrightarrow{P} -\varphi$

→ Time-varying spin-dependent effects

10^{3} improvement

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Consider an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, that interacts with SM fields (e.g. a fermion *f*) via *quadratic couplings* in φ.

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

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

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

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, and V.F. *PRL* 114, 161301 (2015); *PRL* 115, 201301 (2015)]

Fermions:

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

Photon:

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

W and *Z* Bosons:

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

Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* 91, 015015 (2015)], [Stadnik and V.F., *PRL* 114, 161301 (2015)]

$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_X \left(K_{X,1} - K_{X,2}\right)\cos\left(\omega t\right)$$

$\omega = m_\varphi$ (linear portal) or $\omega = 2m_\varphi$ (quadratic portal)

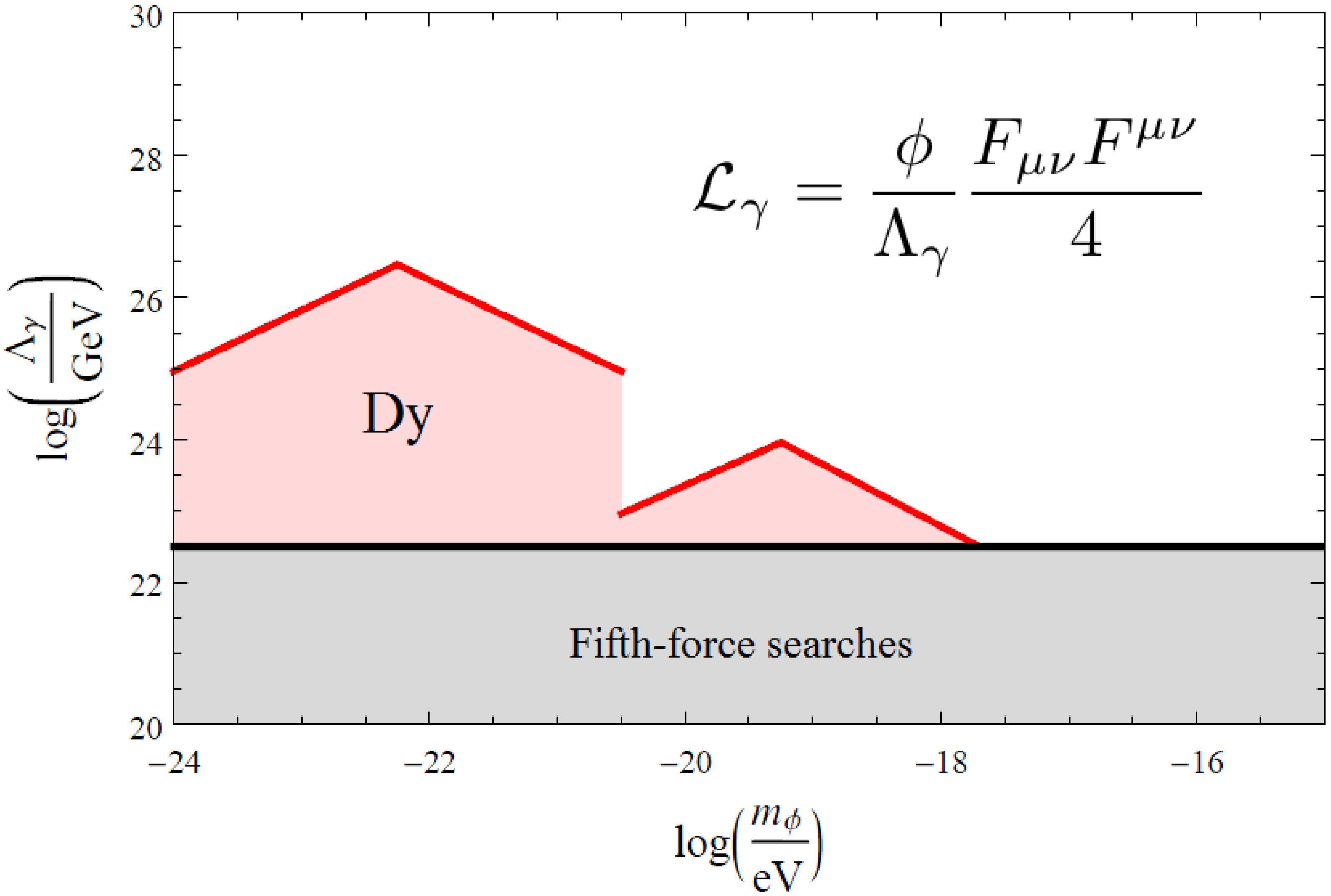
- Precision of optical clocks approaching ~10^{-19} fractional level,
- Sensitivity coefficients K_X calculated by our group ,1998 – …

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

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

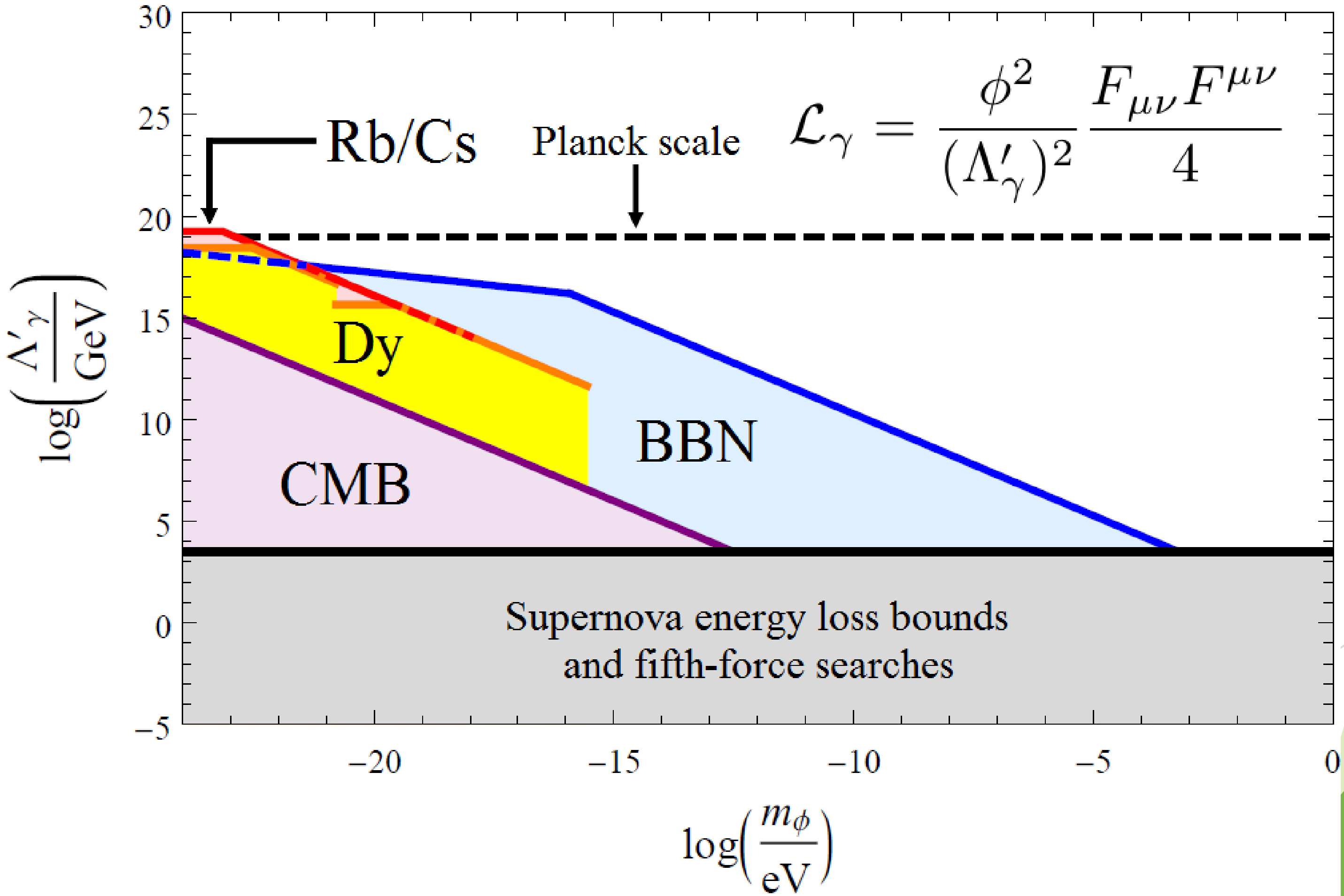
Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

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



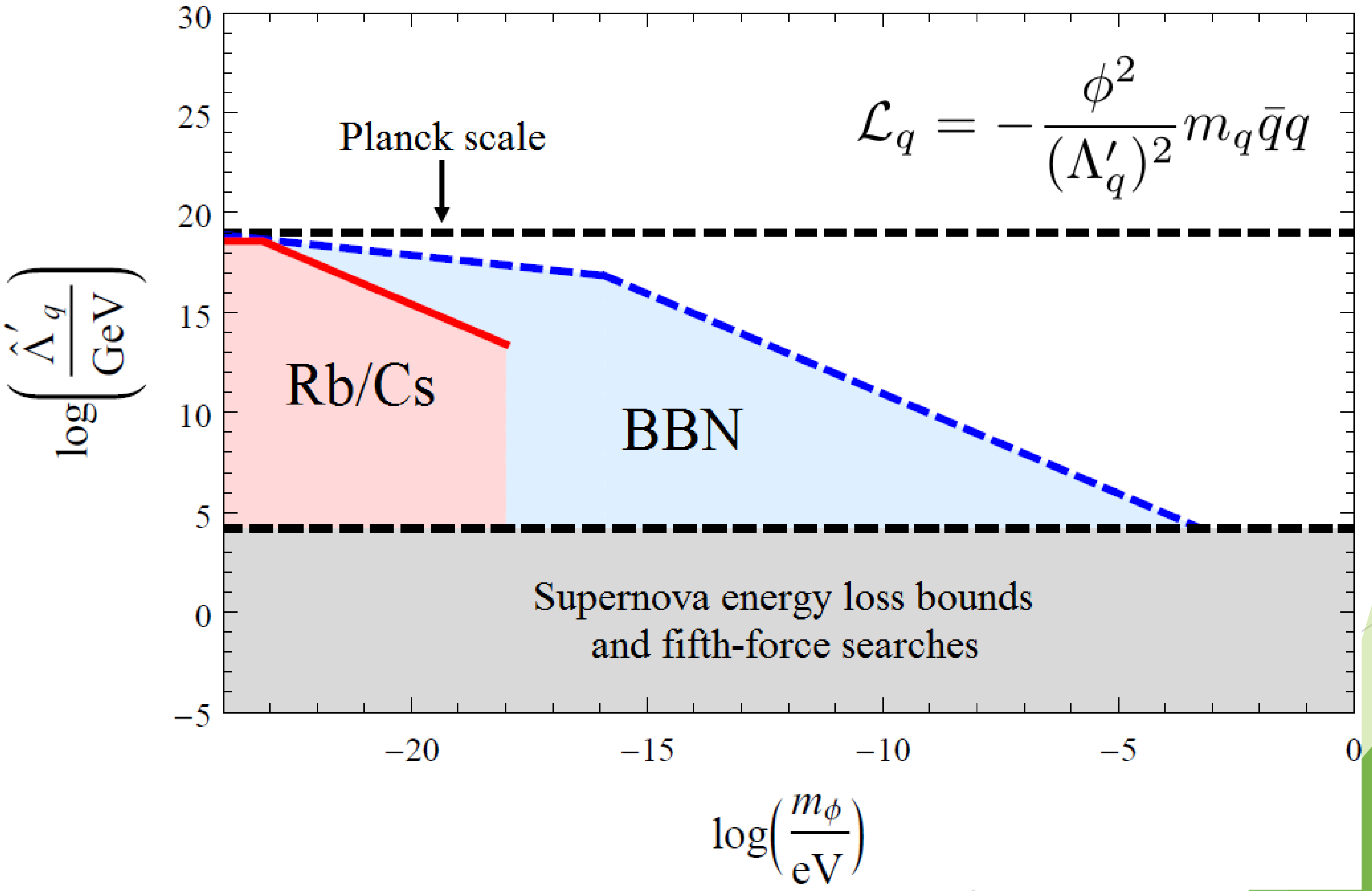
Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:
[Stadnik and V.F., *PRL* 115, 201301 (2015) + Phys. Rev. D 2016]
15 orders of magnitude improvement!



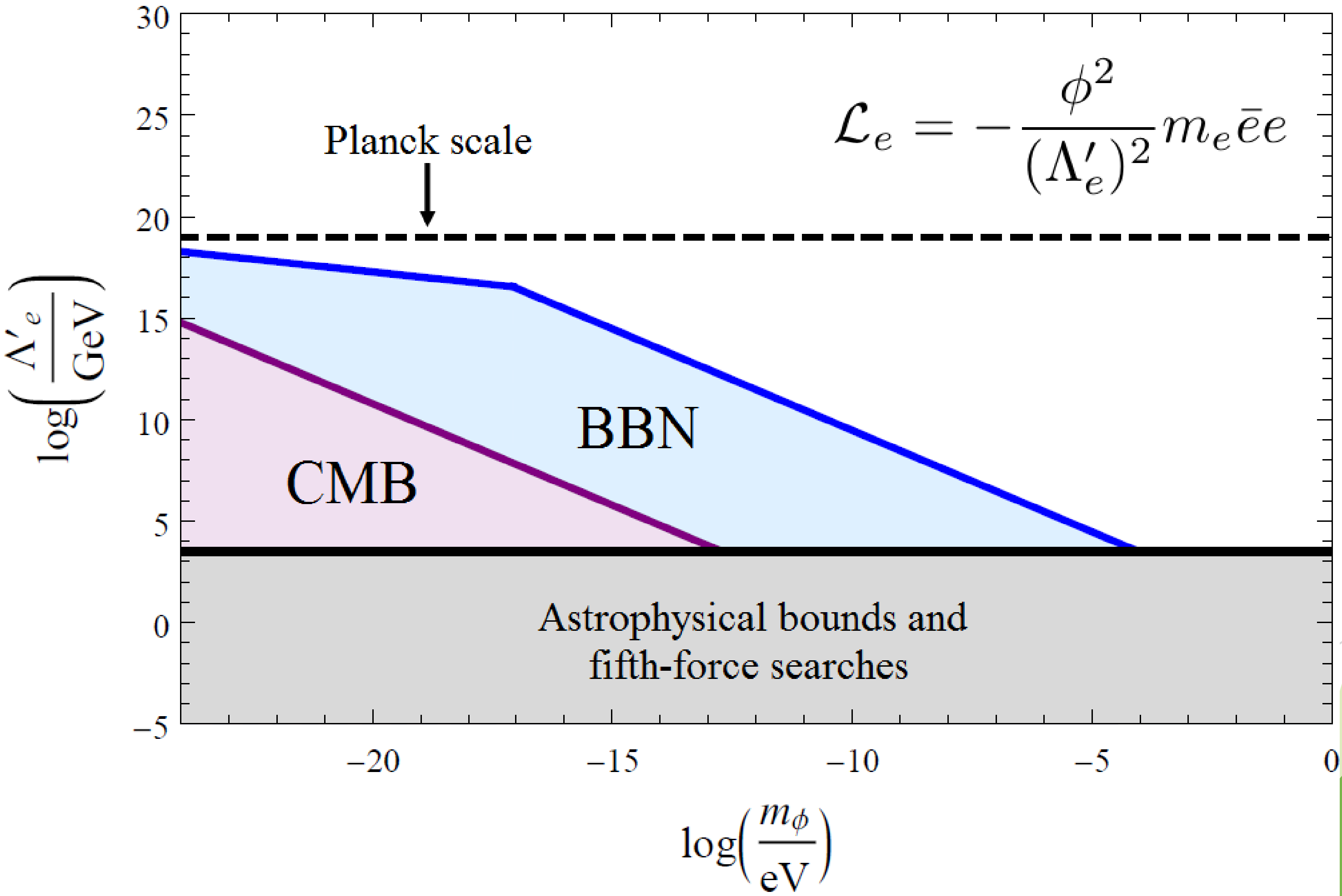
Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints:
[Stadnik and V.F., *PRL* 115, 201301 (2015) + Phys. Rev. D 2016]



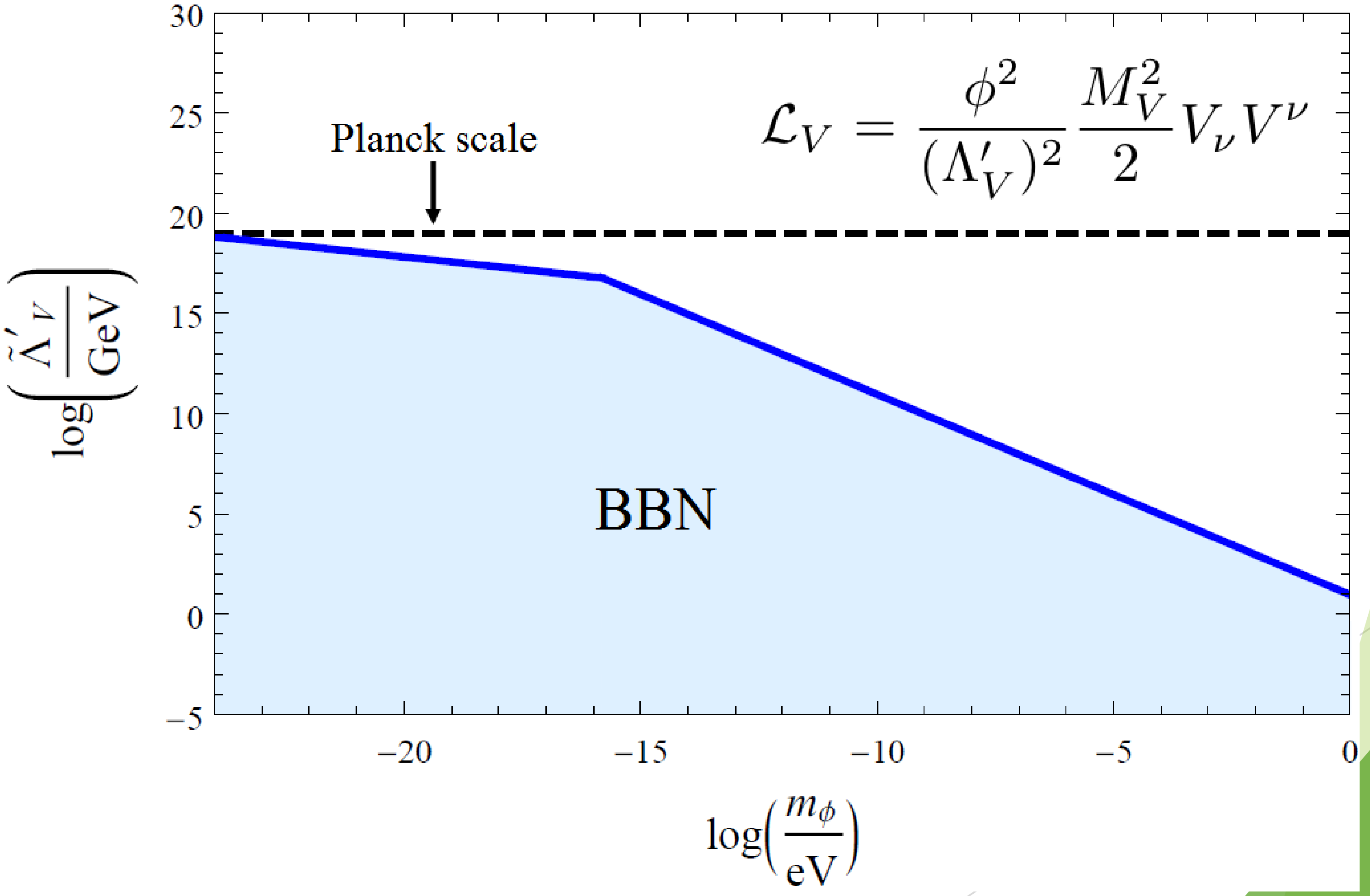
Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

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



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

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

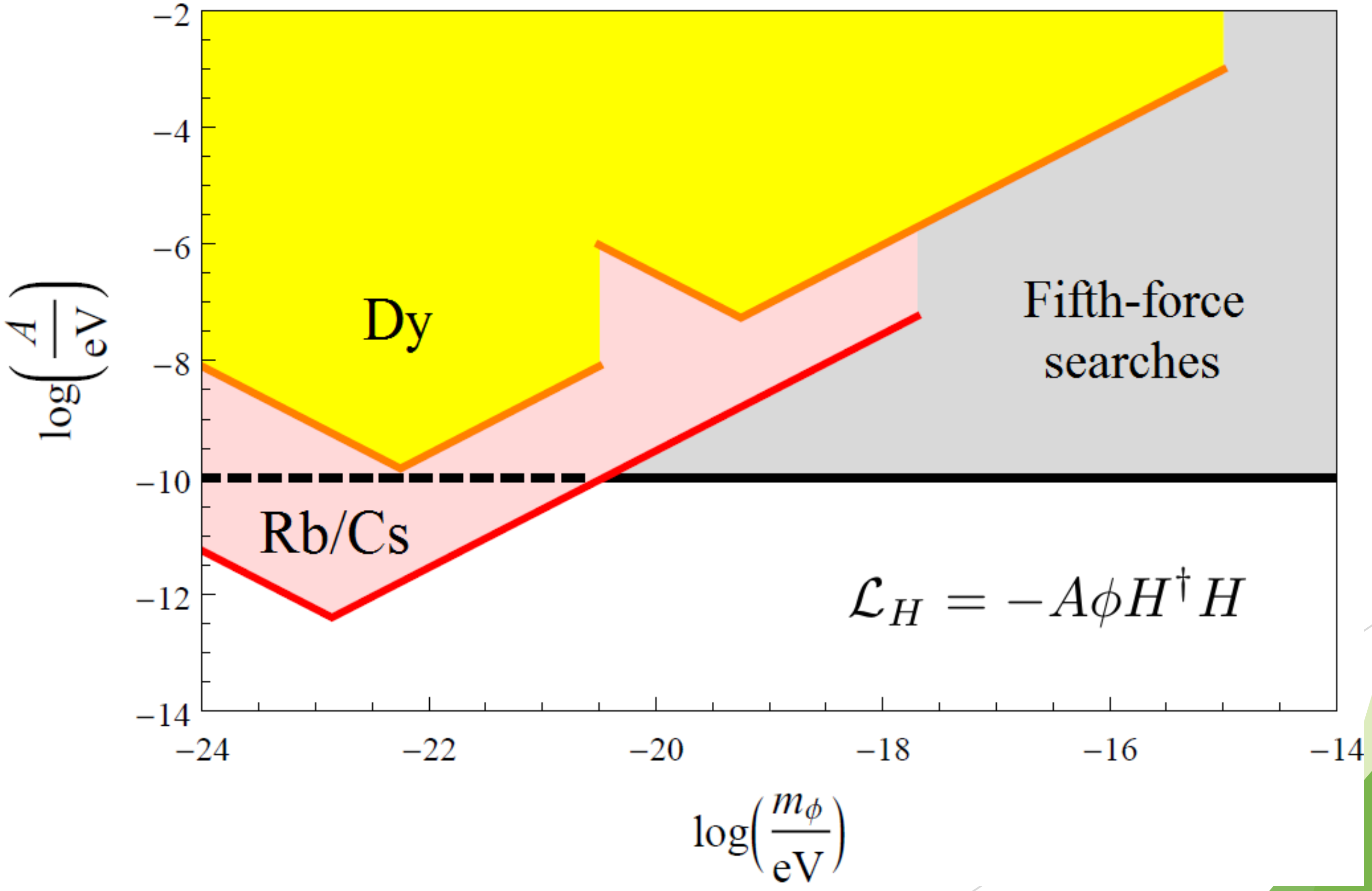


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

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

2 – 3 orders of magnitude improvement!



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