Violation of the Fundamental Symmetries, Variations of Fundamental Constants and Search for Dark matter

Victor Flambaum

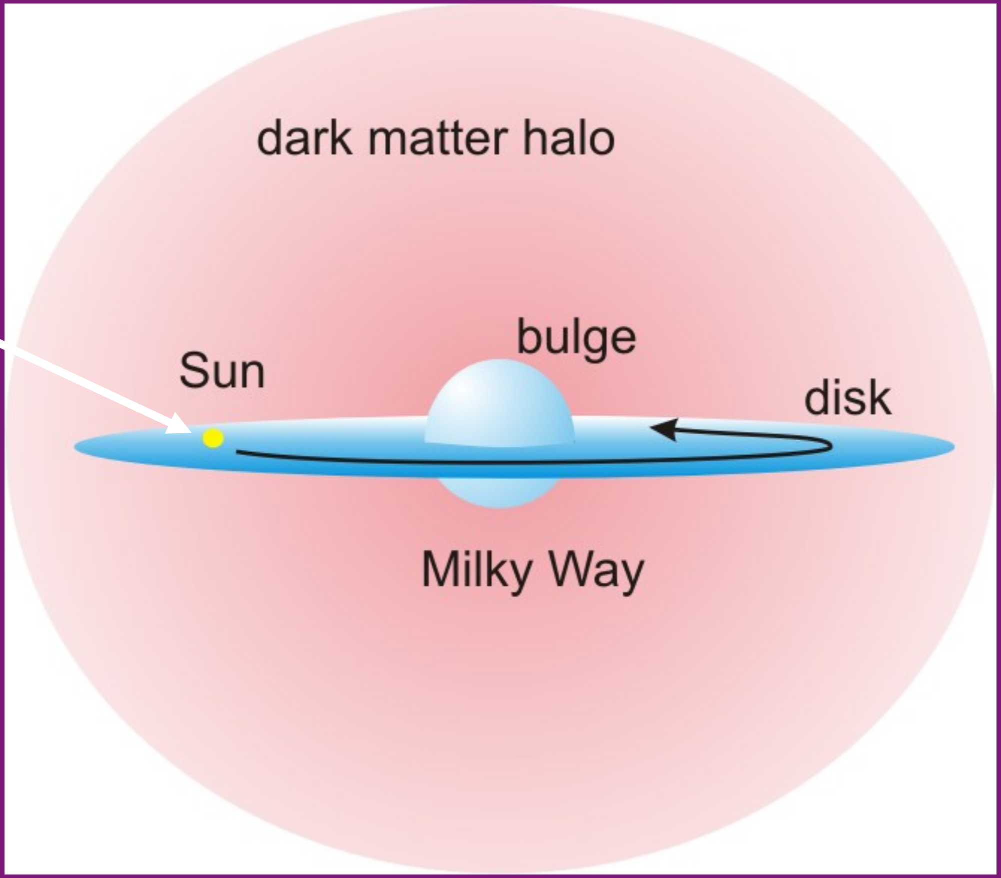
Co-authors: I.Khriplovich, O.Sushkov, V.Dzuba, P.Silvestrov, N.Auerbach, Spevak, J.Ginges, M.Kuchiev, M.Kozlov, A.Brown, A.Derevianko, S.Porsev, J. Berengut, Y. Stadnik, B. Roberts, A. Borschevsky, M.Ilias, K.Beloy, P.Schwerdtfeger, C. Harabati, Y, L. Skripnikov, A. Petrov, A. Titov, et al.

Motivation

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

$\rho_{DM} \approx 0.4$ GeV/cm^3

$v_{DM} \sim 300$ km/s



Test of unification theories

- *Parity Violation (PV) in atoms*

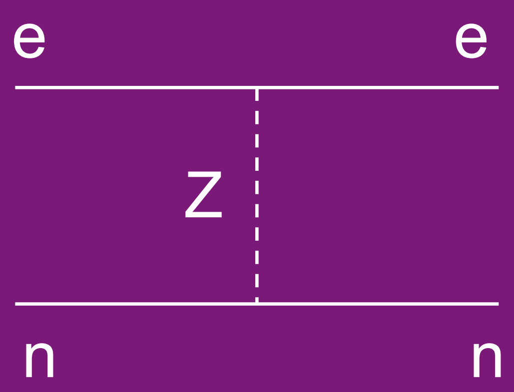
  - nuclear weak charge –test of Standard Model and beyond
  - nuclear anapole moment
  - tensor weak interaction due to weak quadrupole and quadrupole in neutron distribution,

- *Time reversal violation (T), atomic electric dipole moments (EDM) - test of CP violation theories*

- Enhancement in molecules

- T,P- violating Nuclear Magnetic Quadrupole: Enhancement in deformed nuclei and in molecules,
- Apparent violation of fundamental symmetries produced by dark matter - oscillating variation of the fundamental constants, oscillating EDM, oscillating pseudomagnetic field

Atomic parity violation



- Dominated by Z-boson exchange between electrons and nucleons

$$H = \frac{G}{\sqrt{2}}\left[C_{1p}\bar{e}\gamma_\mu\gamma_5 e\bar{p}\gamma^\mu p + C_{1n}\bar{e}\gamma_\mu\gamma_5 e\bar{n}\gamma^\mu n\right]$$

Standard model tree-level couplings: $C_{1p} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)\ ;\ \ C_{1n} = -\frac{1}{2}$

- In atom with Z electrons and N neutrons obtain effective Hamiltonian parameterized by “nuclear weak charge” Q_W

$$h_{PV} = \frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

$$Q_W = 2(NC_{1n} + ZC_{1p}) \approx -N + Z(1 - 4\sin^2\theta_W) \approx -N$$

- PV amplitude $E_{PV} \propto Z^3$ [Bouchiat,Bouchiat]

Discovered in 1978 Bi; Tl, Pb, Cs –accuracy 0.4-1%

Our calculations in 1975-1989 Bi 11%,Pb 8%,Tl 3%,Cs1%

Calculations of observable effects

- APV

$$E_{PV}(1 \to 2) = \sum_n \left[\frac{\langle 2 | H_{PV} | n \rangle \langle n | D | 1 \rangle}{E_2 - E_n} + \frac{\langle 2 | D | nP \rangle \langle n | H_{PV} | 1 \rangle}{E_1 - E_n} \right] = \zeta Q_W$$

- Atomic EDM

$$d_{atom}(1) = 2 \sum_n \frac{\langle 1 | D_z | N \rangle \langle N | H_{PT} | 1 \rangle}{E_1 - E_N} = \xi S$$

H_{PV} is due to electron-nucleon P-odd interactions and nuclear anapole,
H_{PT} is due to nucleon-nucleon, electron-nucleon PT-odd interactions, electron, proton or neutron EDM.

Atomic wave functions need to be good at *all* distances!

We check the quality of our wave functions by calculating:

- hyperfine structure constants and isotope shift
- energies
- E1 transition amplitudes

and comparing to measured values.
Also, estimates of higher order diagrams.

Ab initio methods of atomic calculations

N_{ve}	Method	Accuracy
0	Rel. Hartree-Fock+RPA	~ 10%
1	RHF+MBPT All-orders sums	0.1-1%
2-8	RHF+MBPT+CI	1-10%
2-15	Configuration interaction	10-20%

N_{ve} - number of valence electrons

These methods cover all periodic table of elements

PV in Cs (1997 -1999 JILA experiments).

Calculations V.Dzuba, V.F., and J.Ginges 2002

$\rightarrow \quad Q_W - Q_W^{SM} = 1.1\,\sigma$

$$E_{PV} = -0.897(1 \pm 0.5\%) \times 10^{-11}\ iea_B(-Q_W/N)$$

Porsev, Beloy, Derevianko 2009 $\quad Q_W - Q_W^{SM} = 0\,\sigma.$

Dzuba et al 2012 found correction to this result which brings Porsev, Beloy, Derevianko result into agreement with our number.

$Q_W - Q_W^{SM} \sim 1\,\sigma$

Tightly constrains possible new physics.

E_{PV} includes -0.8% shift due to strong-field QED self-energy / vertex corrections to weak matrix elements W_{sp}

[Kuchiev and V.F; Milstein, Sushkov,Terekhov]

$$E_{PV} = \sum_p \frac{W_{sp} E1_{ps}}{E_s - E_p}$$

A complete calculation of QED corrections to PV *amplitude* includes also

- QED corrections to energy levels and E1 amplitudes

[V.F, and Ginges; Shabaev,Pachuki,Tupitsyn,Yerokhin]

Calculations and experiments in Cs analogues

Our calculations and calculations of other groups

Ba^+

Fr, Ra^+, Ac^{2+}, Th^{3+} PNC effects 15 times larger

Experiments in Seattle (Ba^+),

TRIUMF (Fr), Groningen (Ra^+)

PV : Chain of isotopes

V. Dzuba, V.F, I. Khriplovich

Rare-earth atoms:

- close opposite parity levels-enhancement
- Many stable isotopes

Ratio of PV effects gives ratio of weak charges. Uncertainty in atomic calculations cancels out. Experiments:

Berkeley-Mainz: Dy and Yb; PV amplitude 100 x Cs!

Ra^+ - Groningen, Fr- TRIUMF, (Ra Argonne?)

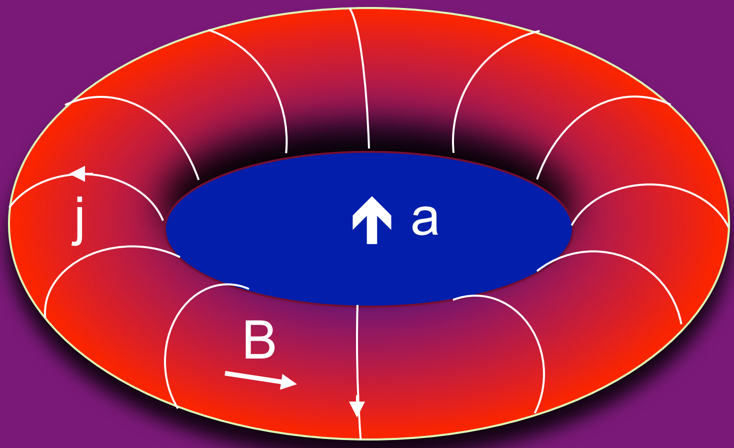
Fortson,Pang,Wilets - neutron distribution problem

Test of Standard model or neutron distribution?

A.Brown, A. Derevianko, and V.F. 2009. Uncertainties in neutron distributions cancel in differences of PV effects in isotopes of the same element. Measurements of ratios of PV effects in isotopic chain can compete with other tests of Standard model!

Nuclear anapole moment

- Source of nuclear spin-dependent PV effects in atoms
- Nuclear magnetic multipole violating parity
- Arises due to parity violation inside the nucleus



- Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

$$h_a = e\vec{\alpha}\cdot\vec{A} \propto \kappa_a \vec{\alpha}\cdot\vec{I}\rho(r)\,, \quad \kappa_a \propto A^{2/3}$$

[V.F. , I. Khriplovich, O. Sushkov]

$E_{PV} \propto Z^2 A^{2/3}$ measured as difference of PV effects for transitions between hyperfine components

JILA Cs: |6s,F=3> – |7s,F'=4> and |6s,F'=4> – |7s,F=3>

Probe of weak nuclear forces via atomic experiments!

Nuclear anapole moment is produced by PV nuclear forces. Measurements +our calculations give the strength constant g.

- Boulder Cs: g=6(1) in units of Fermi constant

  Seattle Tl: g=-2(3)

More accurate calculations V.F. and C. Hanhart; Haxton,Liu,Ramsey-Musolf; Auerbach, Brown; Dmitriev, Khriplovich,Telitsin:

problem remains.

Experiments and proposals: Fr (TRIUMF),

10^3 enhancement in Ra atom due to close opposite parity state; Dy,Yb,…(Berkeley)

Enhancement of nuclear anapole effects in molecules

10^5 enhancement of the anapole contribution in diatomic molecules due to mixing of close rotational levels of opposite parity.

Theorem: only nuclear-spin-dependent (anapole) contribution to PV is enhanced (L. Labzovsky; O. Sushkov, and V.F 1978).

Weak charge can not mix opposite parity rotational levels and $\Lambda-$doublet. Anapole can.

Ω=1/2 terms: $\Sigma_{1/2}$, $\Pi_{1/2}$. Heavy molecules, effect $Z^2 A^{2/3} R(Z\alpha)$

YbF,BaF, PbF,LuS,LuO,LaS,LaO,HgF,…Cl,Br,I,…BiO,BiS,…

.

Molecular experiments : Yale, Groningen, NWU.

Accurate molecular calculations

- T.A.Isaev, S. Hoekstra, R.Berger.
- M.G.Kozlov, A,V.Titov, N.S. Mosyagin, P.V. Souchko et al.
- M.N.Nayak, B.Das, et al.
- Many molecules and molecular ions: Borschevsky, Ilias, Beloy, Dzuba, Flambaum, Schwerdtfeger

Experimental proposals: DeMille et al; T.A.Isaev, S. Hoekstra, R.Berger.

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

- Sushkov, Flambaum 1978, Khriploviich, Pospelov 1991: 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 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.
- NQM is calculated using deformed oscillator model for all nuclei of experimental interest, V.F. PRL 117, 072501, 2016. Flambaum, Lackenby 2017

Atomic calculations: Flambaum, Dzuba, Harabati 2017, enhanced effects in rare-earth atoms −close levels

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+ Jayich at UCSB) 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.

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

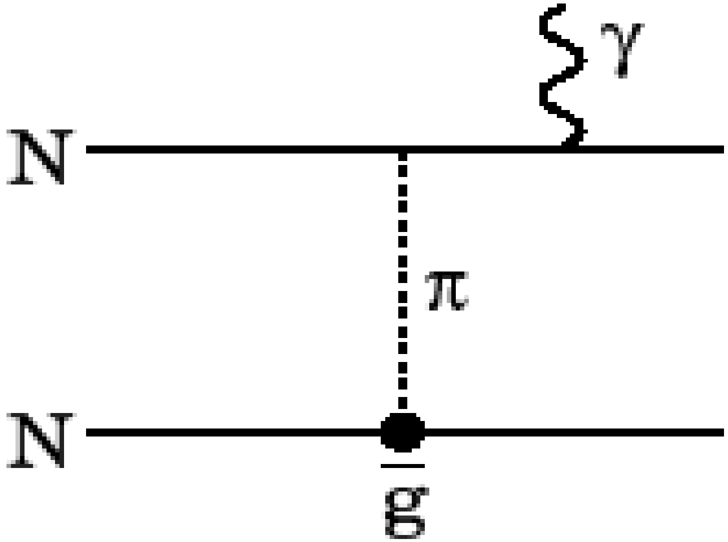
- Sushkov, Flambaum 1978, Khriploviich, Pospelov 1991: Nuclear quadrupole moment generates tensor weak interaction $W_T = W_{ik} I_i I_k$ which mixes opposite parity electron energy levels up to $J_1 - J_2 = 2$. If there are close opposite parity levels with $J_1 - J_2 = 2$, the only enhanced contribution 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 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.
- NQM is calculated using deformed oscillator model for all nuclei of experimental interest, V.F. PRL 117, 072501, 2016. Flambaum, Lackenby 2017

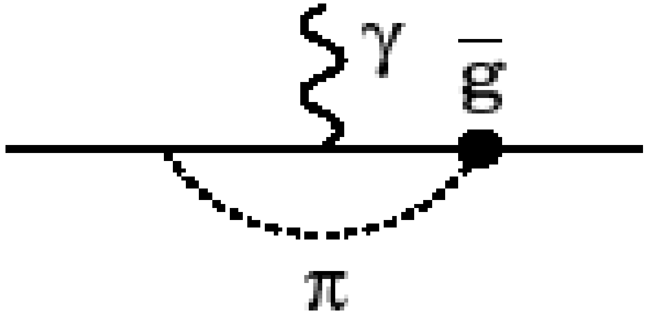
Atomic calculations: Flambaum, Dzuba, Harabati 2017, enhanced effects in rare-earth atoms −close levels

Calculation of the tensor weak interaction in HfF+

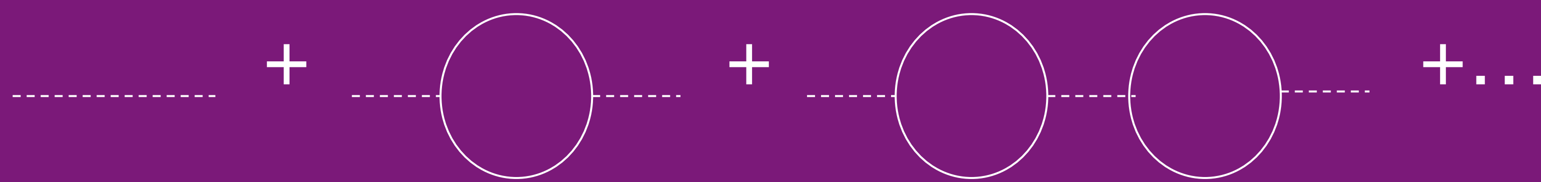
- L.Skripnikov,A.Petrov, A.Titov, and V. F W_T = i 0.3 10^{-2} Hz
- Nuclear calculations of the weak quadrupole moments – V.F., PRL 117, 072501 (2016); V.F. and Lackenby, arxiv: 1705.02642
- Atomic calculations – V.F. , Dzuba, Harabati, PRA A 96, 012516 (2017)

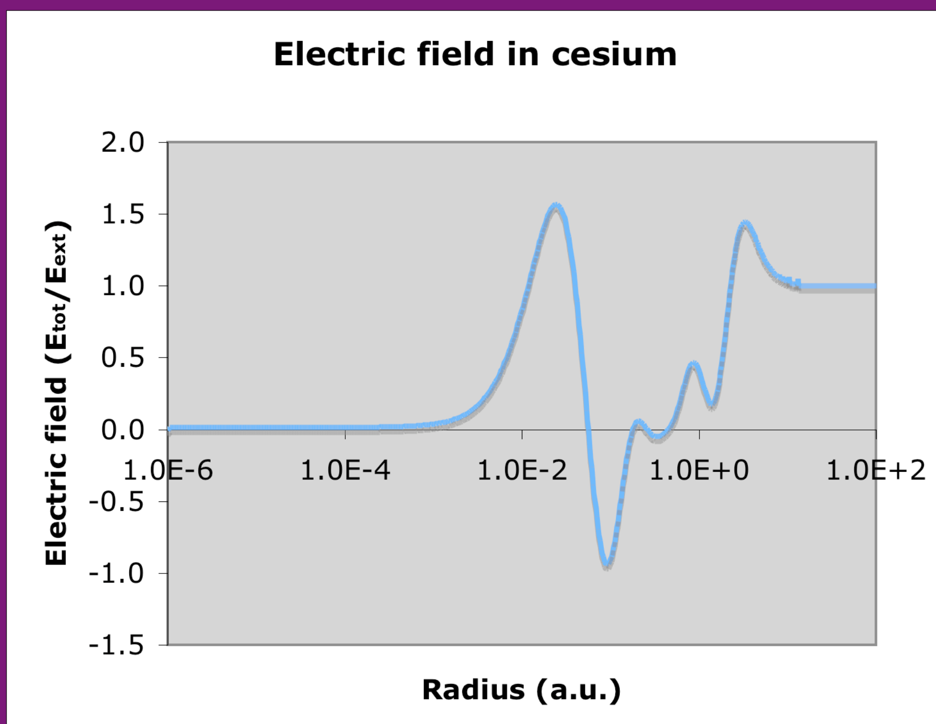
Nuclear Electric Dipole Moment: T,P-odd NN interaction gives 40 times larger contribution than nucleon EDM. O.Sushkov, V.F. and I. Khriplovich 1984, x 10^1 - 10^3 in deformed nuclei





Screening of external electric field in atoms-our calculation





Nuclear EDM-screening: d_N E_N

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

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:

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

Oscillating field: incomplete screening!

V.F. arxiv:1804.08898 $E_N=-E\, \varpi^2\, \alpha_{zz}{}^2/Z$

Nuclear EDM-screening: d_N E_N

- Oscillating field: incomplete screening!

V.F. arxiv:1804.08898 $E_N = -E\, \varpi^2\, \alpha_{zz}{}^2/Z$

In resonance $E = A \sin \varsigma t\ \cos \varpi t$

$\varsigma = 2eE_0 <0|D_z|n>$ is Rabi osvillation frequency

$A = \varpi^2 D_z$ x $5.14\ 10^9$ V/cm

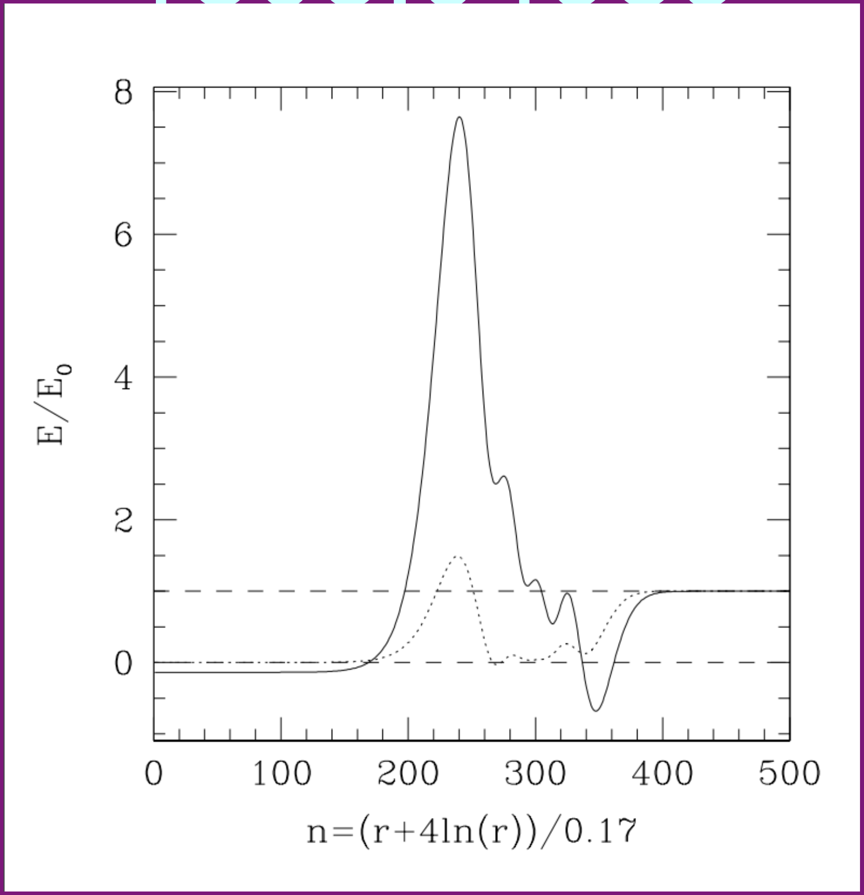
Schiff: Incomplete sctreening in neutral atoms

- Hyperfine interaction: atomic EDM is proportional to nuclear EDM times nuclear magnetic moment –low Z, ~ Z
- Finite nuclear size –high Z.

Effect due to nuclear Schiff moment, $\sim Z^2 R$

We performed calculations of both effects for all atoms of experimental interest.Sushkov,Flambaum,Khriplovich, Dzuba, Ginges, Kozlov, …

Screened field in Xe Dzuba and V.F. arxiv: 1805.04989



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 (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

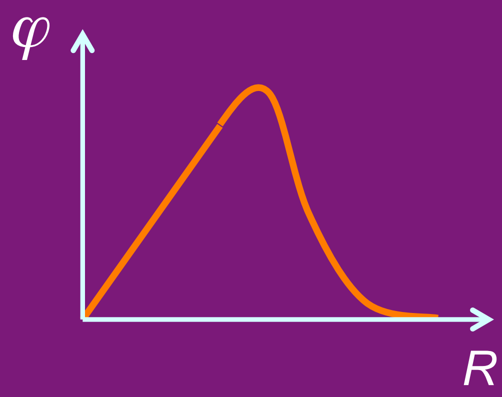
φ(**R**) in multipole expansion is reduced to $\varphi(\mathbf{R}) = 4\pi\mathbf{S}\bullet\nabla\delta(\mathbf{R})$

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.

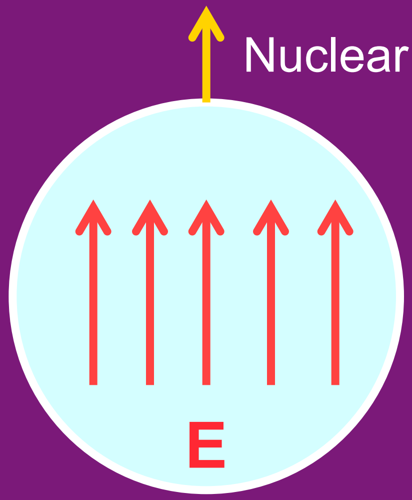
This expression is not suitable for relativistic calculations.

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

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

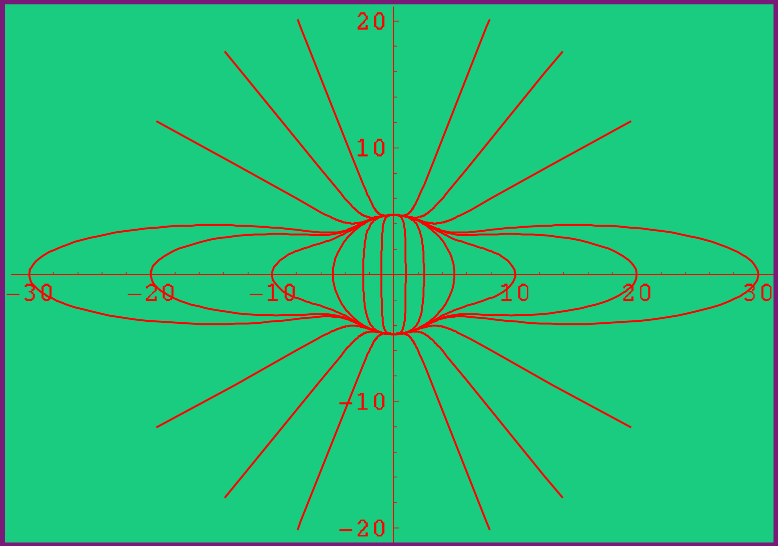


Electric field induced by T,P-odd nuclear forces which influence proton charge density



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.)

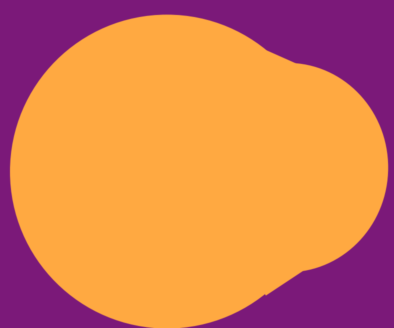
Electric field of Schiff moment (exponentially small outside nucleus, zero at two poles)



Nuclear enhancement

Auerbach, V.F. and Spevak 1996

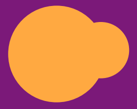
The strongest enhancement is due to octupole deformation (Rn,Ra,Fr,…)



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 

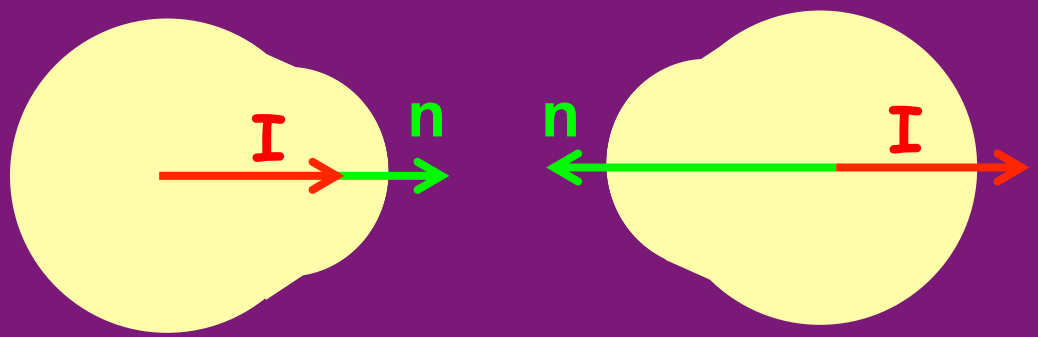
No T,P-odd forces are needed for the Schiff moment and EDM in intrinsic reference frame

However, in laboratory frame S=d=0 due to rotation

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

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

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



$K = \langle \mathbf{I} \cdot \mathbf{n} \rangle$

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

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

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

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

^{225}Ra EDM experiment − Argon lab

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

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

^{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,

EDMs of atoms of experimental interest

Z	Atom	[*S*/(e fm3)]*e* cm	[10^{-25} η] *e* cm	Expt.
2	^{3}He	0.00008	0.0005	
54	^{129}Xe	0.38	0.7	Seattle, Ann Arbor, Princeton
70	^{171}Yb	-1.9	3	Bangalore,Kyoto
80	^{199}Hg	-2.8	4	Seattle
86	^{223}Rn	3.3	3300	TRIUMF
88	^{225}Ra	-8.2	2500	Argonne,KVI
88	^{223}Ra	-8.2	3400	

Standard Model $\eta = 0.3\ 10^{-8}$ $d_n = 5 \times 10^{-24}\ e$ cm η, $d(^{199}Hg)/\ d_n = 10^{-1}$

RaO molecule

Enhancement factors

- Biggest Schiff moment
- Highest nuclear charge
- Close rotational levels of opposite parity

(strong internal electric field)

Largest T,P-odd nuclear spin-axis interaction κ(I n), RaO= 200 TlF

Flambaum 2008; Kudashov, Petrov, Skripnikov,Mosyagin, Titov, Flambaum 2013

Enhancement in nuclei with quadrupole deformation

Close level of opposite parity

- Haxton, Henley –EDM, MQM
- Sushkov, Flambaum, Khriplovich –Schiff and magnetic quadrupole moments

Magnetic interaction is not screened!

Khriplovich, Sushkov, Flambaum- MQM produces EDM in atoms and molecules

Enhancement in nuclei with quadrupole deformation

Close level of opposite parity

- Haxton, Henley –EDM, MQM
- Sushkov, Flambaum, Khriplovich –Schiff moment
- V.F. - spin hedgehog and collective magnetic quadrupole are produced by T,P-odd interaction which polarises spins along radius, correlation $(r\sigma)$

Magnetic interaction is not screened!

Khriplovich, Sushkov, Flambaum- MQM produces EDM in atoms and molecules

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+ Jayich at UCSB)

Accurate molecular calculations

- ThO: Skripnikov, Petrov, Titov, and V.F. PRL 2014
- TaN: Skripnikov, Petrov, Mosyagin, Titov, and V.F 2015, HfF+ 2017

Enhancement of electron EDM

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

V.F.: Enhancement factor in atoms 3 $Z^3 \alpha^2 R(Z\alpha)$

Tl enhancement d(Tl)= -500 d_e . Tl experiment – Berkeley;

Cs, Fr, Xe*,

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

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

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

2013 ThO : dramatic impovement > 10 times! 2017 HfF+ JILA

Atomic EDMs

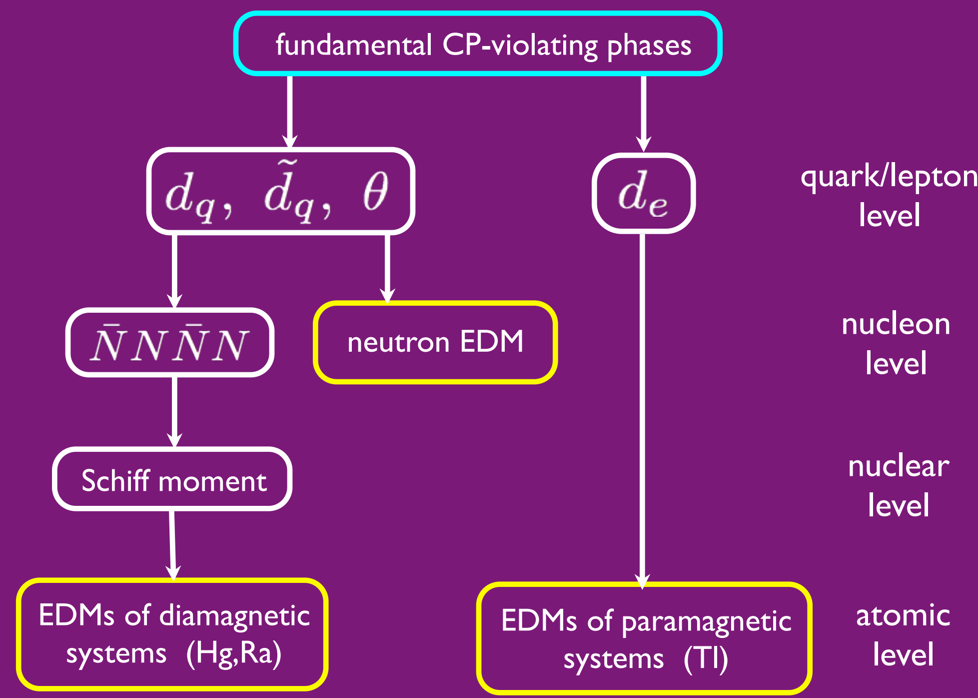
Atomic limits

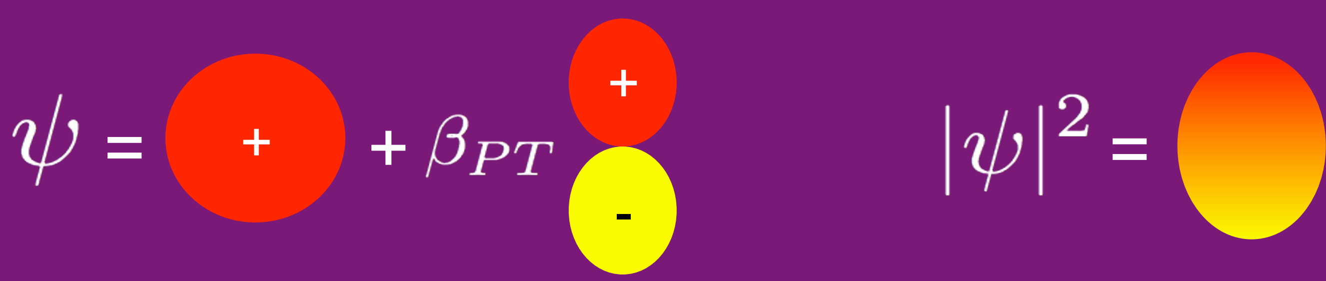
$|d(^{199}\text{Hg})| < 10^{-29}\ e$ cm
(95% c.l., Seattle, 2016)

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

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

Leading mechanisms for EDM generation





Atomic EDM produced by electron-nucleus T,P-odd interaction

We performed accurate many-body calculations in diamagnetic and paramagnetic atoms and molecules

- Sushkov, Flambaum 1980 predicted million times enhancement of parity violation effects in p-wave compound resonances in neutron reactions: confirmed by numerous experiments in JINR (Dubna), LINP,IAE, ITEP (Russia), KEK (Japan), Los Alamos. Strength of the weak interaction in heavy nuclei is extracted from data for 100 resonances
- Bunakov, Gudkov: Similar enhancement for T,P-volating effects
- Flambaum, Vorov: new statistical theory to calculate P-odd and T,P-odd effects

Origin of chaotic eigenstates

- Interval between energy levels in a system with many active electrons is exponentially small (distribution of n electrons over m orbitals gives exponentially large number of combinations   m!/[n!(m-n)!] - millions!
- Residual interaction between electrons significantly exceeds this interval and mixes thousands of Hartree-Fock configurations into chaotic eigentstate

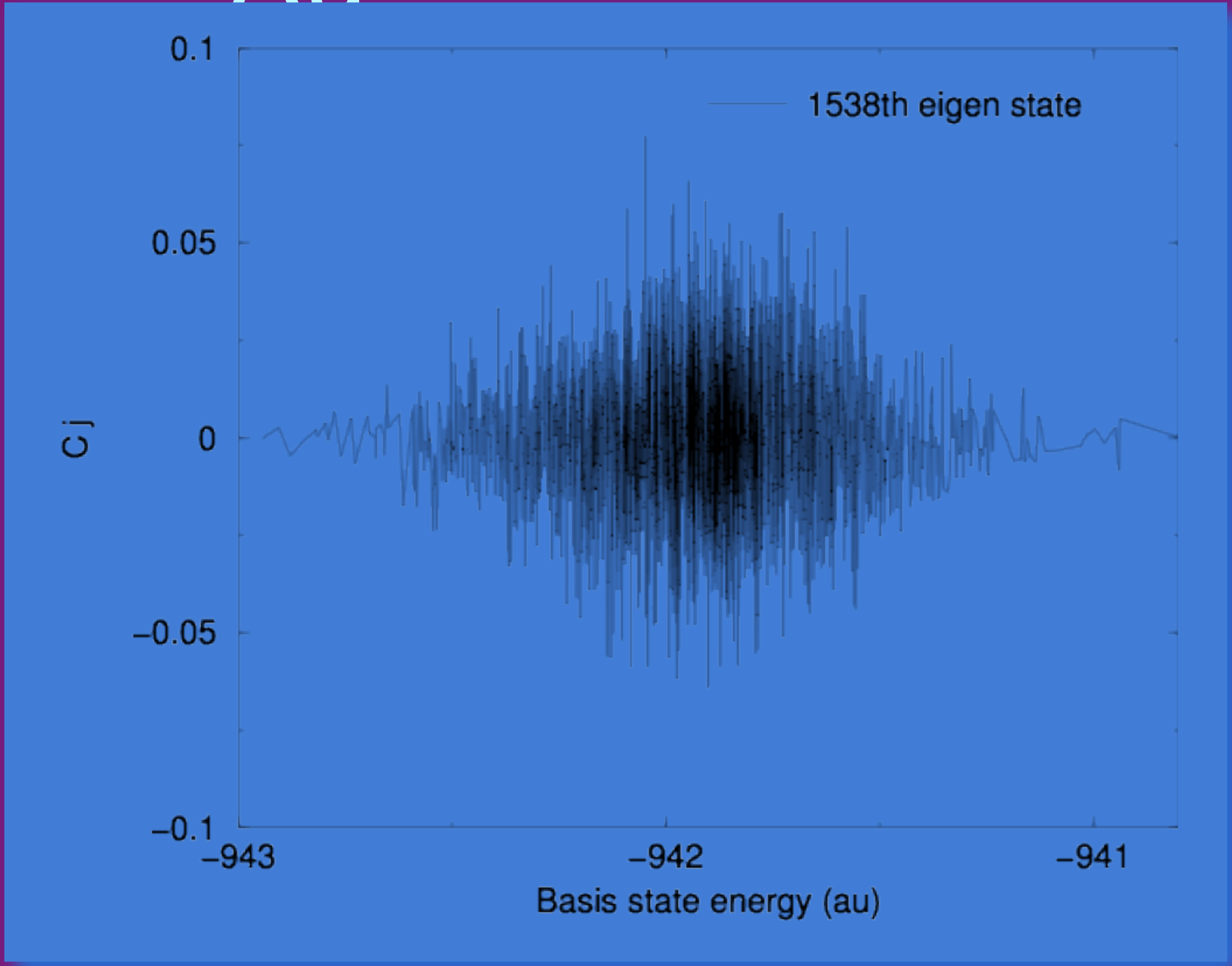
Typical eigenstate in excited Au^{24+}

Graph shows eigen-state components

$$|\Psi_\nu\rangle = \sum_j C_j^{(\nu)} |\Phi_j\rangle$$

as a function of the basis-state energies

$$E_j = \langle \Phi_j | H | \Phi_j \rangle$$



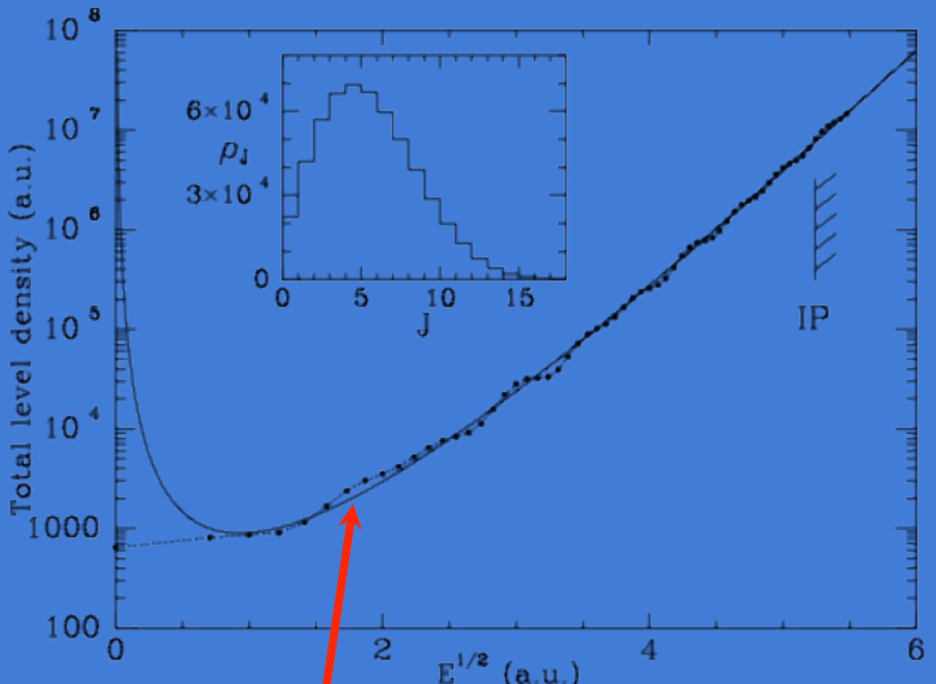
- Components fluctuate (are uncorrelated - "quantum chaos"). Random variables, $\langle C_j \rangle = 0$
- Systematic dependence on $E_j - E_\nu$

Many-excited-electron states in Au^{24+} and W^{+19}

Construction of the spectrum

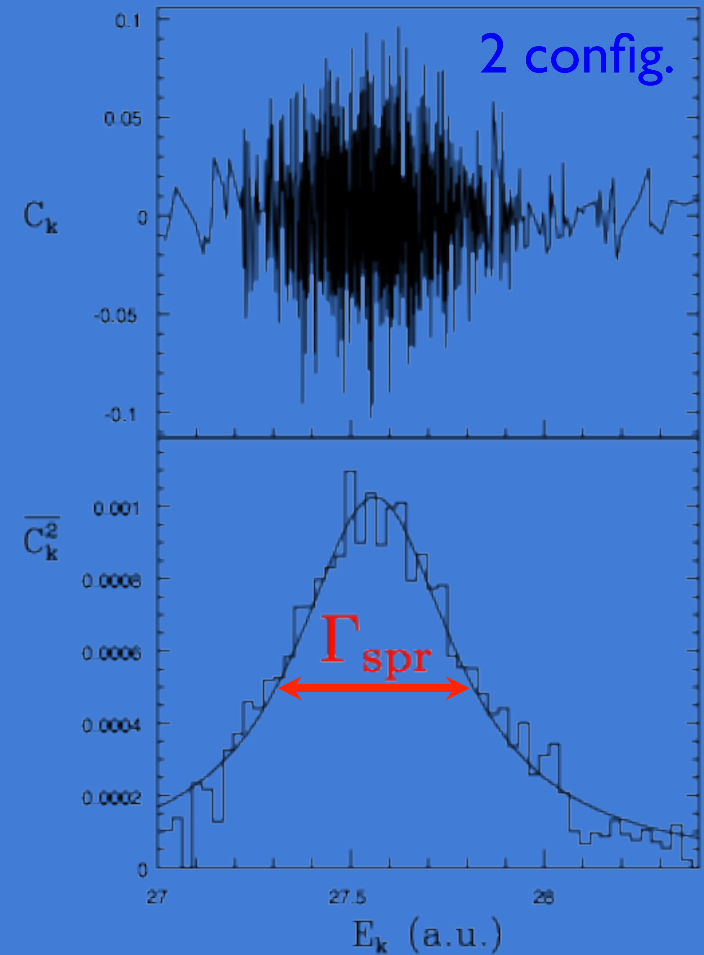
$$E_i = E_{core} + \sum_a \epsilon_a n_a + \sum_{a\le b} \frac{n_a(n_b - \delta_{ab})}{1+\delta_{ab}} U_{ab} ,$$

$$N_i = \prod_a \frac{g_a!}{n_a!(g_a - n_a)!} , \qquad g_a = 2j_a + 1$$



Fermi-gas ansatz $\rho(E) = AE^{-\nu}\exp(a\sqrt{E})$

Examining the eigenstates



$$C_k^2(E) = \frac{1}{N} \frac{\Gamma_{spr}^2/4}{(E_k - E)^2 + \Gamma_{spr}^2/4}$$

$\langle C_i \rangle = 0$. Diagonal matrix elements contain $\langle C_i^2 \rangle$.

$$|\Psi_\nu\rangle = \sum_j C_j^{(\nu)} |\Phi_j\rangle$$

$$C_k^2(E) = \frac{1}{N} \frac{\Gamma_{\rm spr}^2/4}{(E_k - E)^2 + \Gamma_{\rm spr}^2/4}$$

partition function

Average value of non-diagonal matrix elements is zero since $\langle C_i \rangle = 0$. Calculate product of matrix elements containing $\langle C_i^2 \rangle$

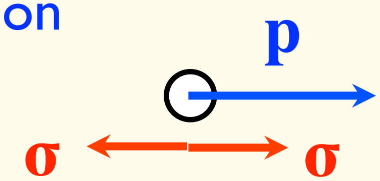
Accurate calculations possible

1. Simple systems (small configuration mixing) – standard many body approaches.
2. Chaotic systems – statistical theory.

- Statistical theory produces results averaged over small energy interval containing many compound states.
- Calculations in nuclei and atoms: orbital occupation numbers, electromagnetic amplitudes, scattering, 10^6 enhanced P-odd and T,P-odd effects, 10^3 enahncement of electron recombination,

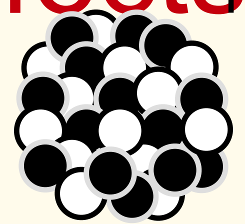
10^6 Enhancement of parity violation effects

Neutron scattering and spin rotation



I_+

nucleus



Weak interaction admixes strong s-wave resonance to weak p-wave resonance: 10^3 enhancement

Relative strength in nuclei

$$G_F m_\pi^2 = 2 \times 10^{-7} \quad \begin{array}{|l} m_W = 80 \text{ GeV} \\ m_\pi = 0.14 \text{ GeV} \end{array}$$

Hamiltonian

$$H_W \propto \boldsymbol{\sigma} \cdot \mathbf{p}$$

spin momentum

Parity violation

Asymmetry $P = \dfrac{I_+ - I_-}{I_+ + I_-}$

$$P \sim \frac{\langle + | H_W | - \rangle}{E_+ - E_-}$$

Denominator $E_+ - E_- \sim D \propto 1/N$

Numerator $\langle + | H_W | - \rangle \propto 1/\sqrt{N}$

Effect $P \sim \dfrac{H_W}{\Gamma_{\text{spr}}} \sqrt{N}$ $\sqrt{N} \sim 10^3$

O. P. Sushkov and V.V. Flambaum, Pis'ma Zh. Eksp. Teor. Fiz., **32**, 377 (1980) [JETP Lett., **32**, 353 (1980)]

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)

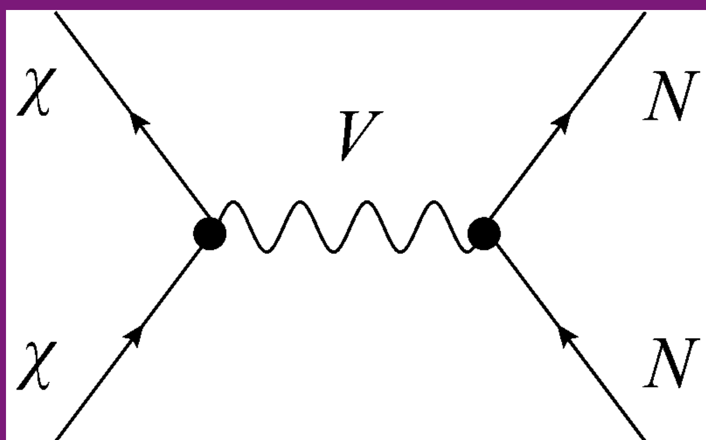
Physical Review Letters 116, 023201 (2016)
Physical Review Letters 117, 271601(2016)
Physical Review Letters 115, 201301 (2015)
Physical Review Letters 114, 161301 (2015)
Physical Review Letters 113, 151301 (2014)
Physical Review Letters 113, 081601 (2014)
Physical Review D 89, 043522 (2014)
Physical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

University of New South Wales, Sydney, Australia

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

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

Classical field

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons): $\varphi \xrightarrow{P} +\varphi$	Pseudoscalars (Axions): $\varphi \xrightarrow{P} -\varphi$
$\rightarrow$ Time-varying fundamental constants	$\rightarrow$ Time-varying spin-dependent effects
10^{15} improvement	10^{3} improvement

Variation of fundamental constants (fine structure constant α, α_s , masses) due to Dark matter

" Fine tuning" of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

Variation of coupling constants in space provide natural explanation of the "fine tuning": we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

Source of the variation: Dark matter?

We performed calculations to link change of atomic transition frequencies to change of fundamental constants:

optical transitions: atomic calculations _for quasar absorption spectra and for atomic clocks transitions in Al II, Ca I, Sr I, Sr II, In II, Ba II, Dy I, Yb I, Yb II, Yb III, Hg I, Hg II, Tl II, Ra II, Th III, highly charged ions,

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

Nuclear clock ^{229}Th ,

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

We performed atomic, QCD and nuclear calculations.

Molecular calculations

Evidence for spatial variation of the fine structure constant

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

Quasar spectra

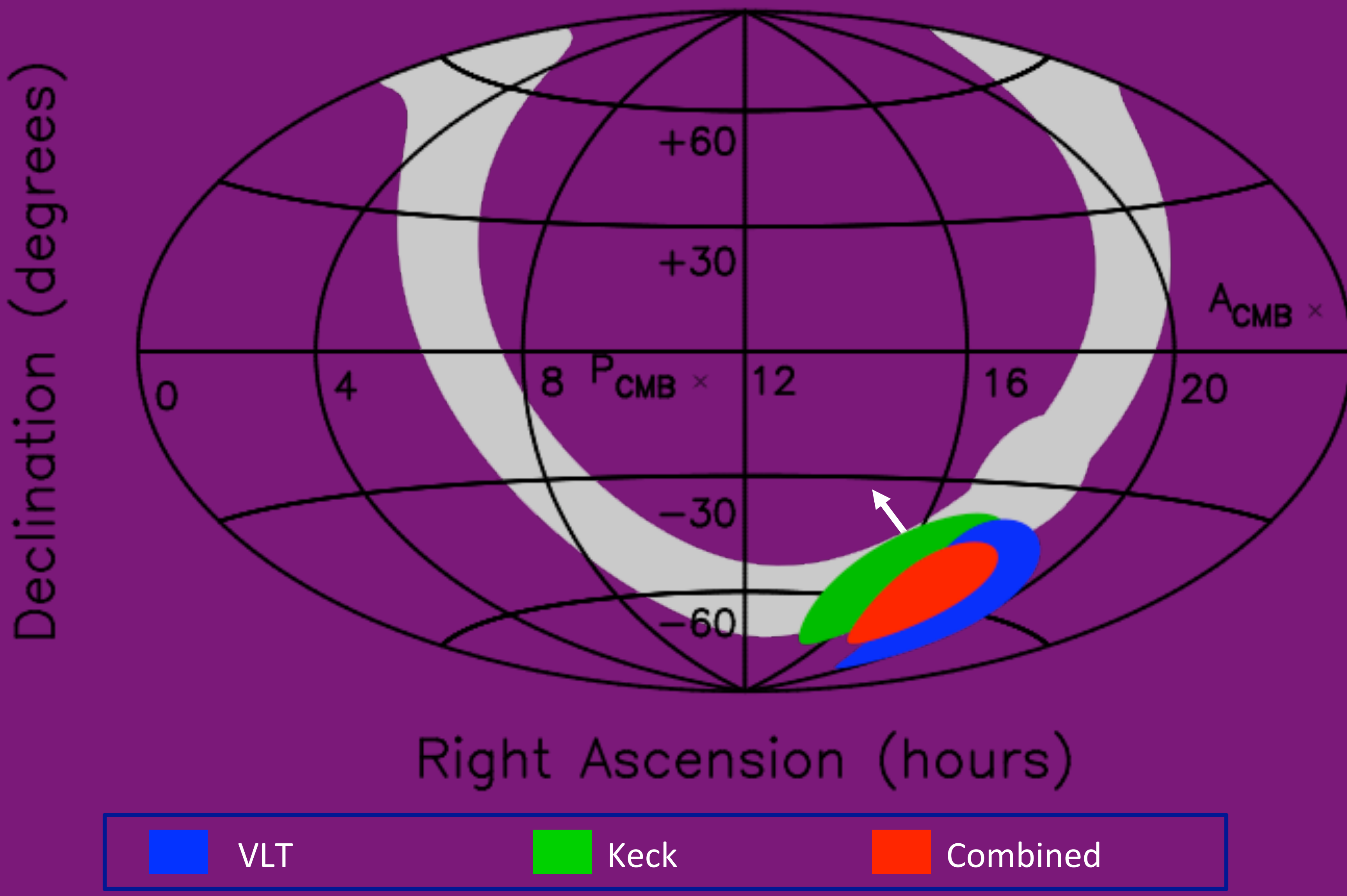
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

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

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

Reconciles all measurements of the variation

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.

Berengut et al. Limits on dependence of alpha on gravity from white dwarf spectra $Fe4+$,$Ni4+$ 4.2(1.6) 10^{-5}.   Accurate laboratory spectra needed.

Results for variation of fundamental constants: Clocks

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} $-0.1(1.0) \times 10^{-16}\ yr^{-1}$

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:

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

Photon:

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

W and *Z* Bosons:

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

BBN Constraints on 'Slow' Drifts in Fundamental Constants due to Dark Matter

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

- Largest effects of DM in early Universe (highest ρ_{DM})
- Big Bang nucleosynthesis ($t_{weak} \approx 1s$ – $t_{BBN} \approx 3$ min)
- Primordial ^{4}He abundance sensitive to n/p ratio (almost all neutrons bound in ^{4}He after BBN)

$$\frac{\Delta Y_p(^4\mathrm{He})}{Y_p(^4\mathrm{He})} \approx \frac{\Delta(n/p)_{\mathrm{weak}}}{(n/p)_{\mathrm{weak}}} - \Delta\left[\int_{t_{\mathrm{weak}}}^{t_{\mathrm{BBN}}} \Gamma_n(t)\,dt\right]$$

$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

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)

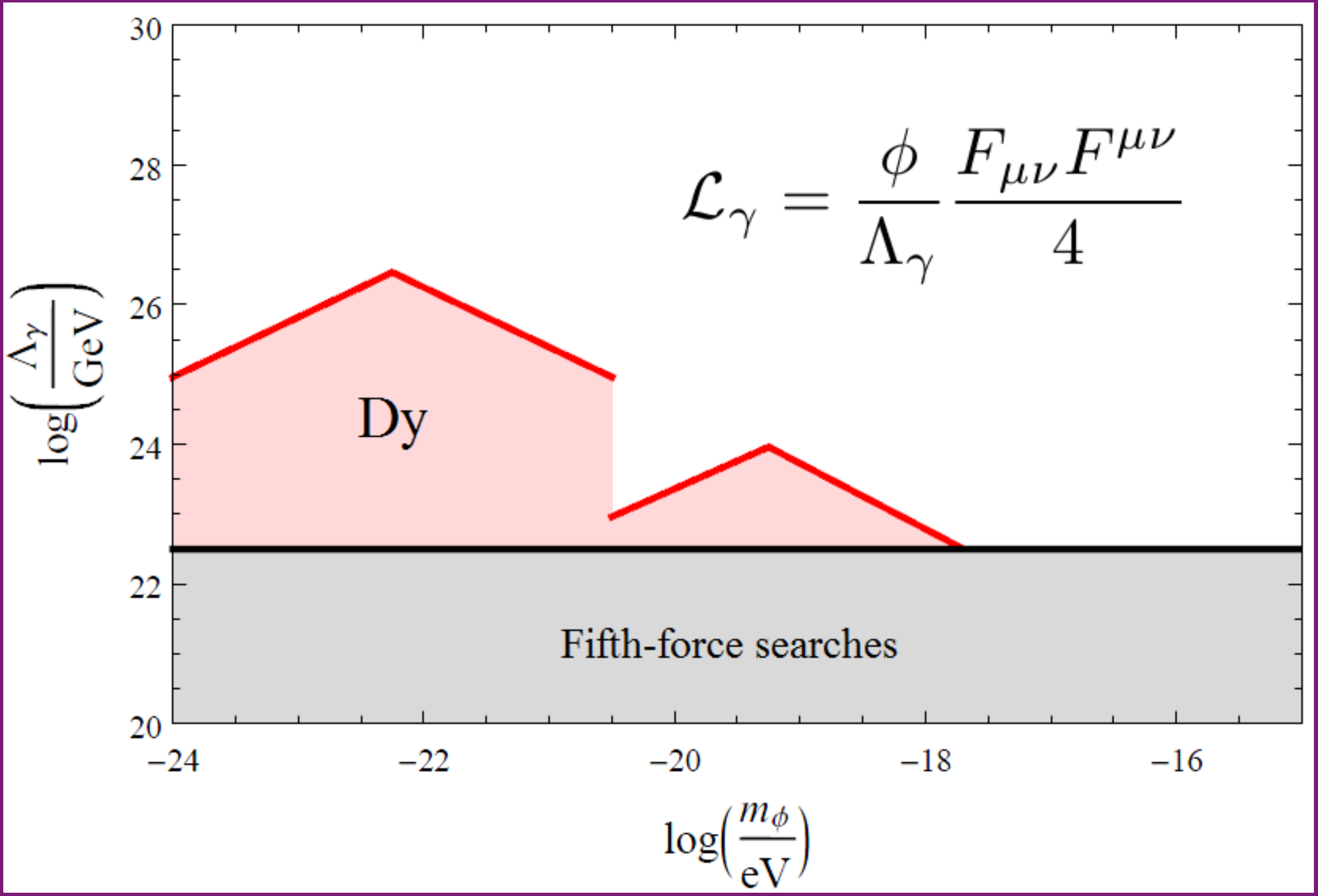
- Precision of optical clocks approaching ~10^{-19} fractional level, Jun Ye group
- Sensitivity coefficients K_X calculated by our group ,1998 – ⋯

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

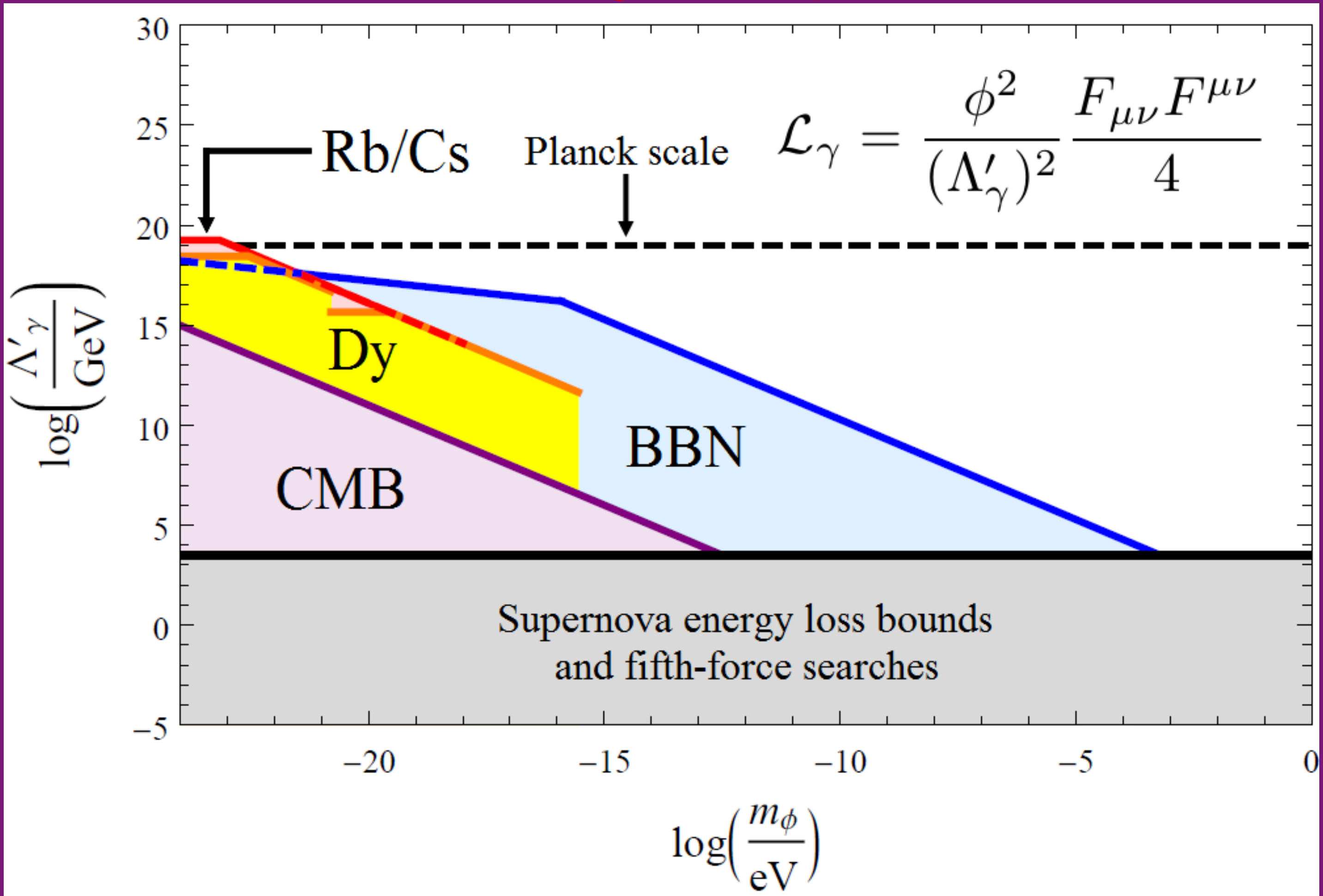
[Van Tilburg, Leefer, Bougas, Budker, *PRL* 115, 011802 (2015)]



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]

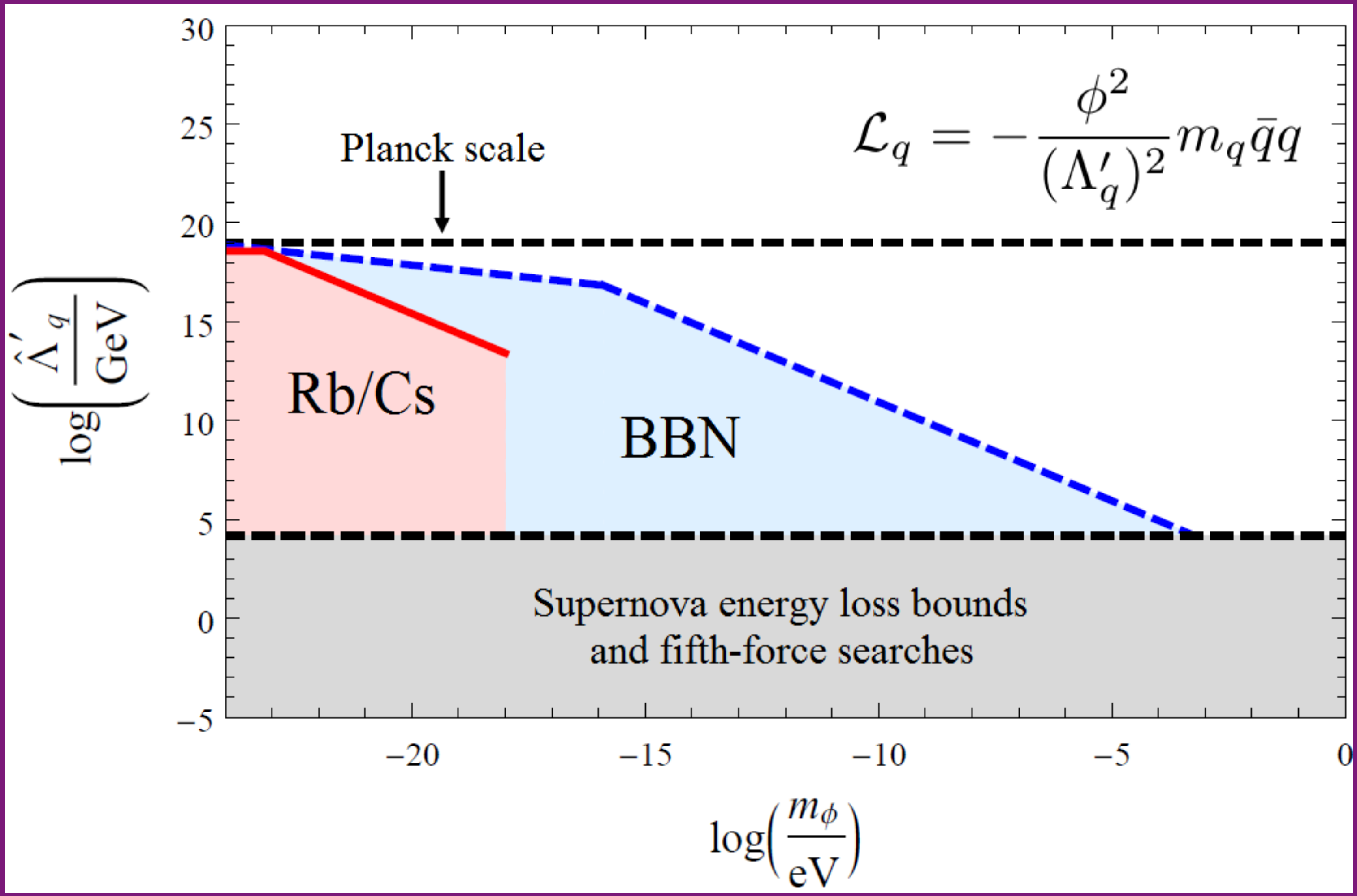
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

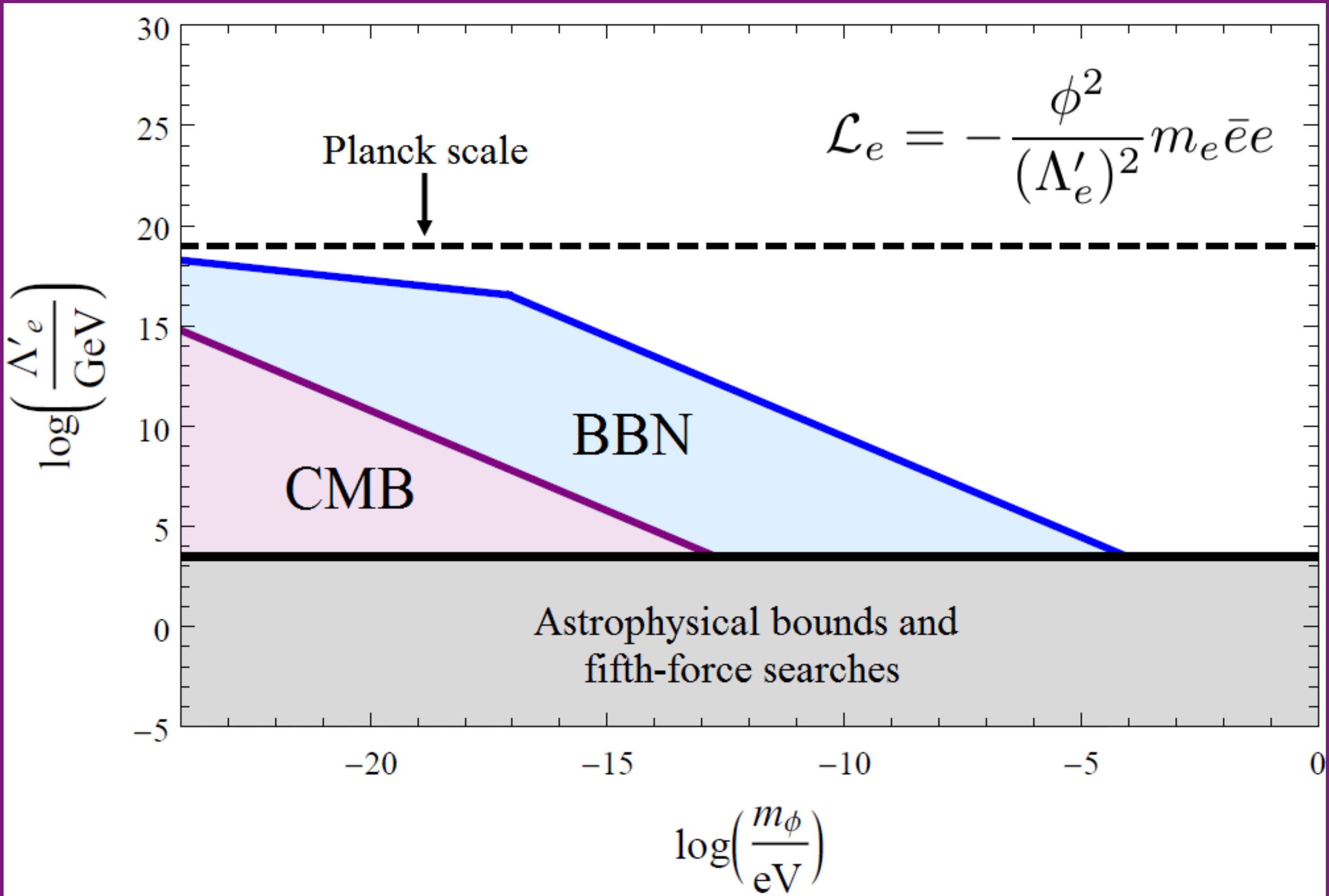
BBN and Rb/Cs constraints:

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



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

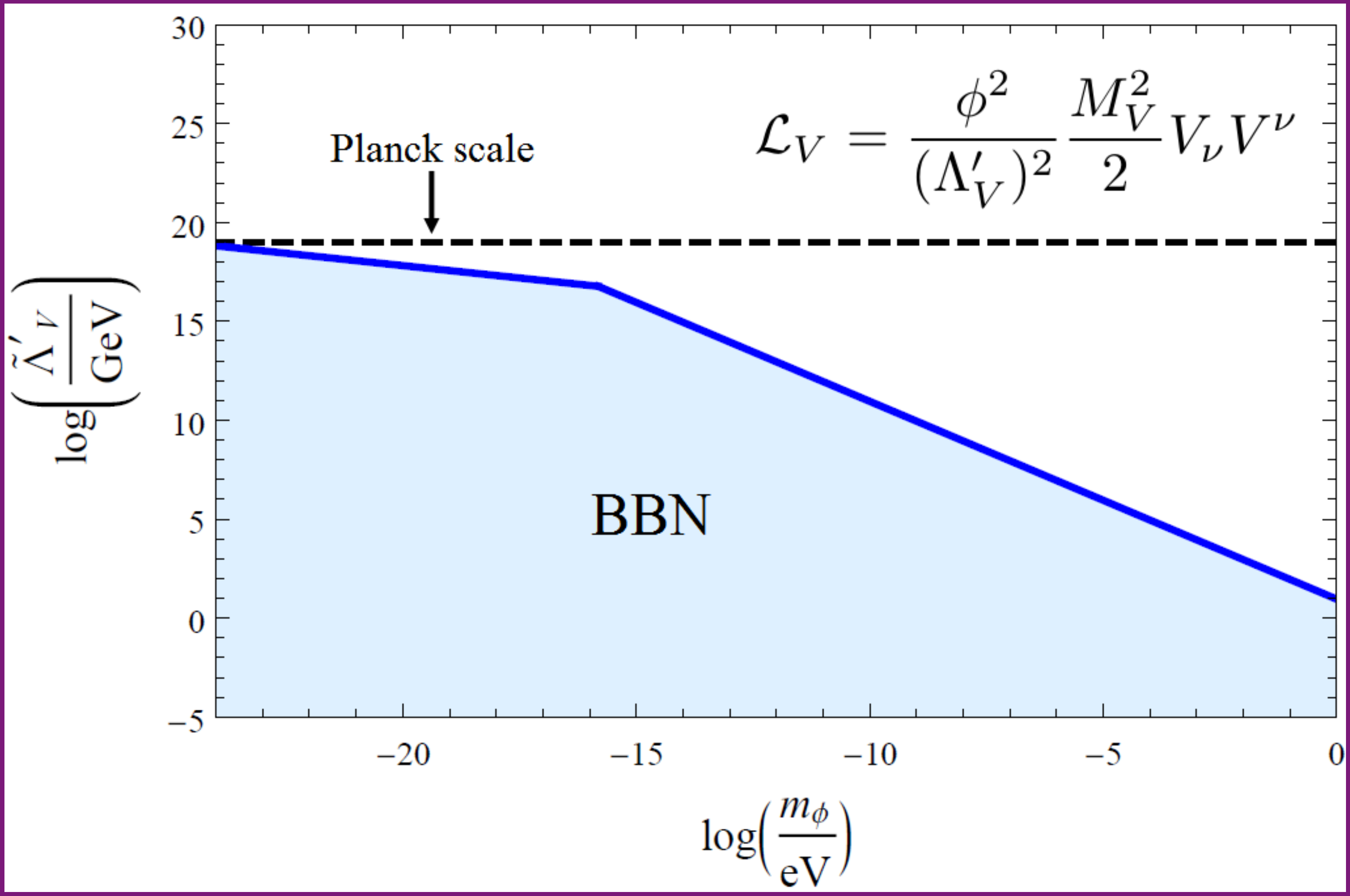
BBN and CMB constraints:
[Stadnik and V.F., *PRL* 115, 201301 (2015)]



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

BBN constraints:

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

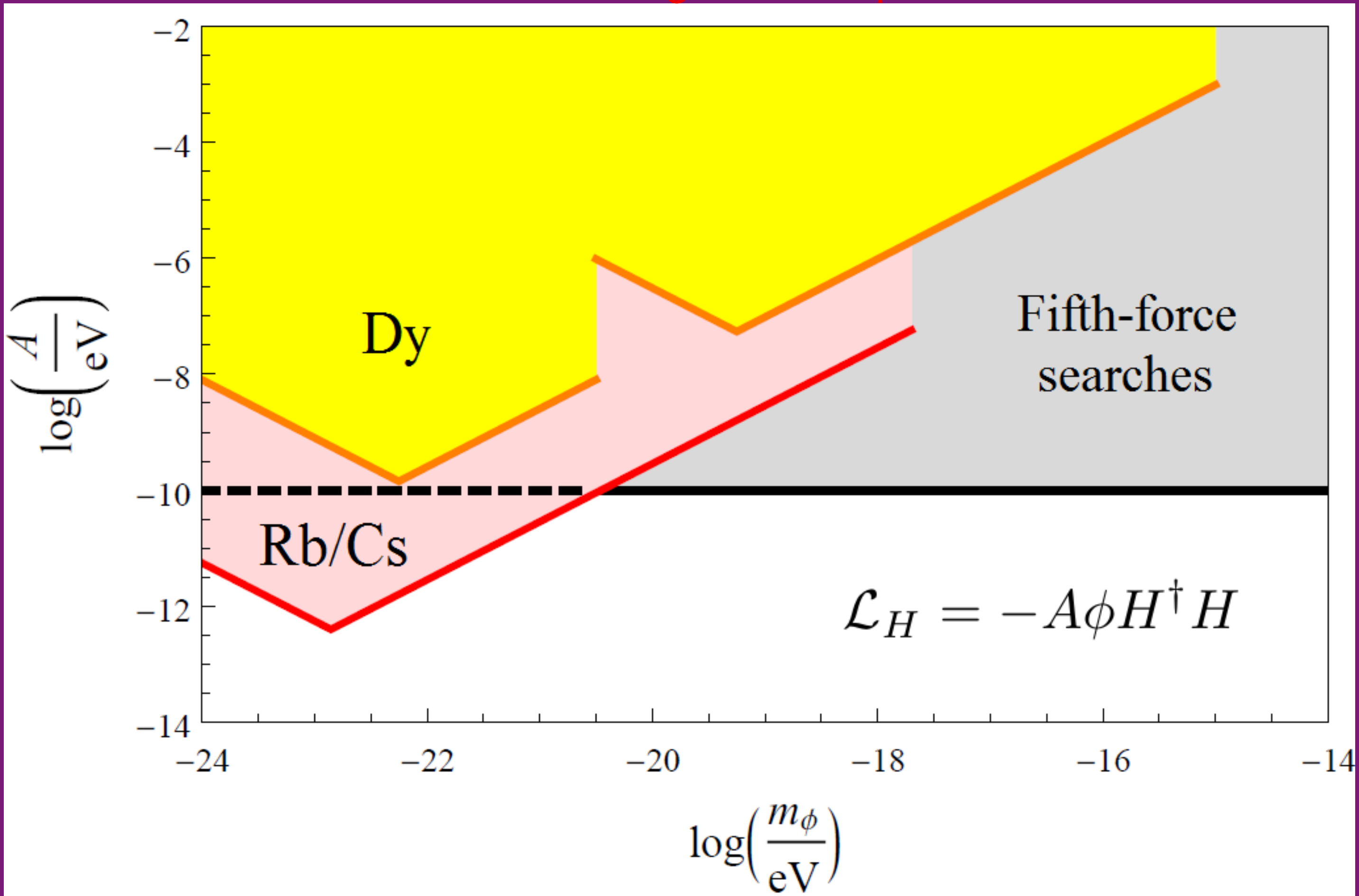


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

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

2 – 3 orders of magnitude improvement!



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.

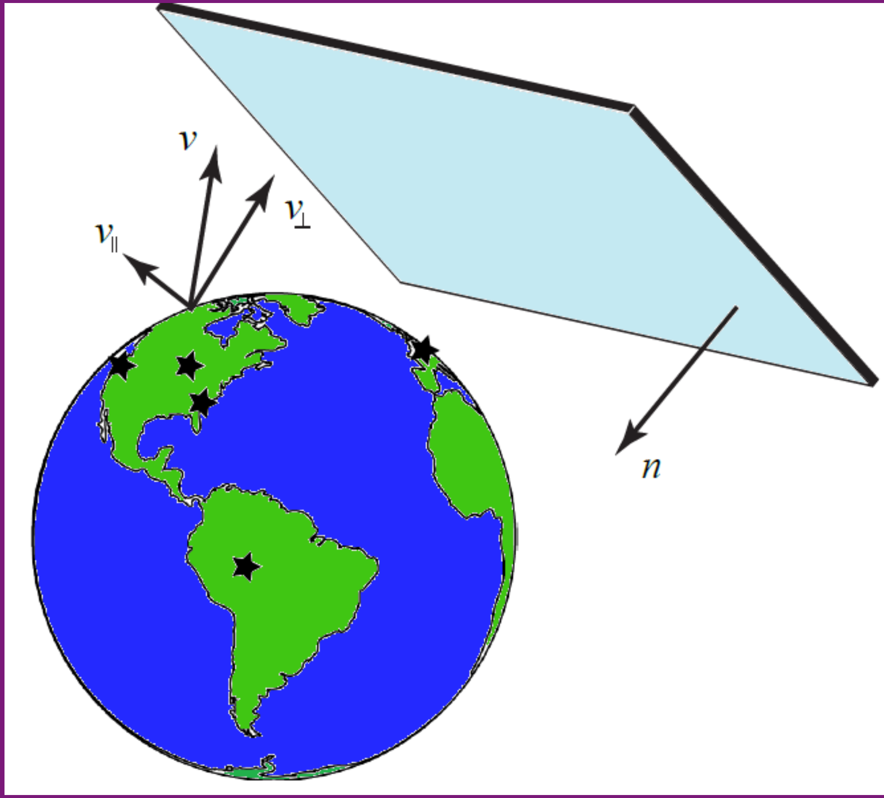
Recent proposals include:

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

Pulsar Timing [Stadnik and V.F, *PRL* 113, 151301 (2014)]

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

Laser Interferometers [Stadnik and V.F., *PRL* 114, 161301 (2015); arXiv:1511.00447]



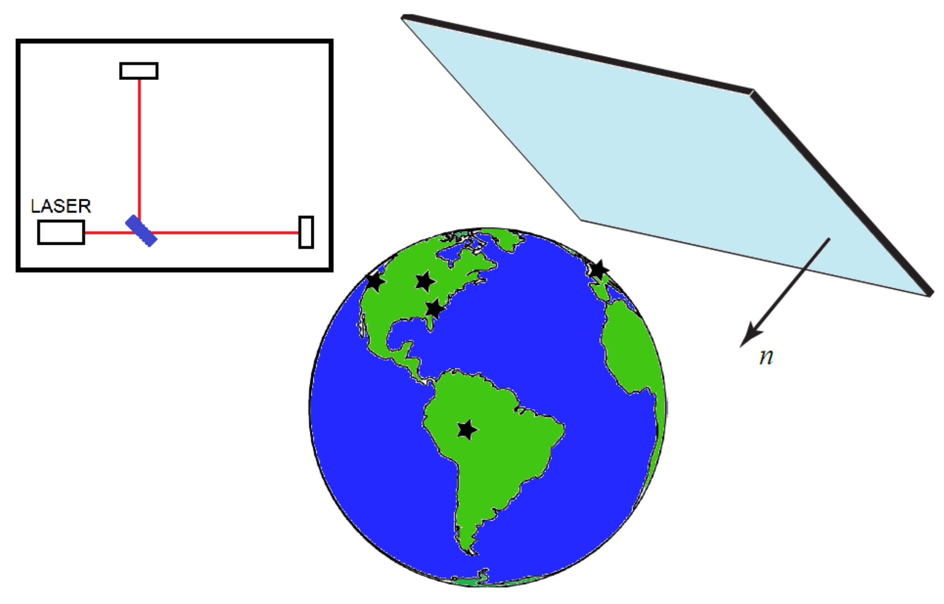
Global Network of Laser/Maser Interferometers (LIGO, Virgo, GEO600, TAMA300)

Stadnik and V.F., Phys. Rev.Lett. 2015 + Ongoing collaboration with LIGO and VIRGO

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

$$\mathcal{L}_{\text{int}}^{\gamma} = \left(\frac{\phi}{\Lambda'_\gamma}\right)^2 \frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

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

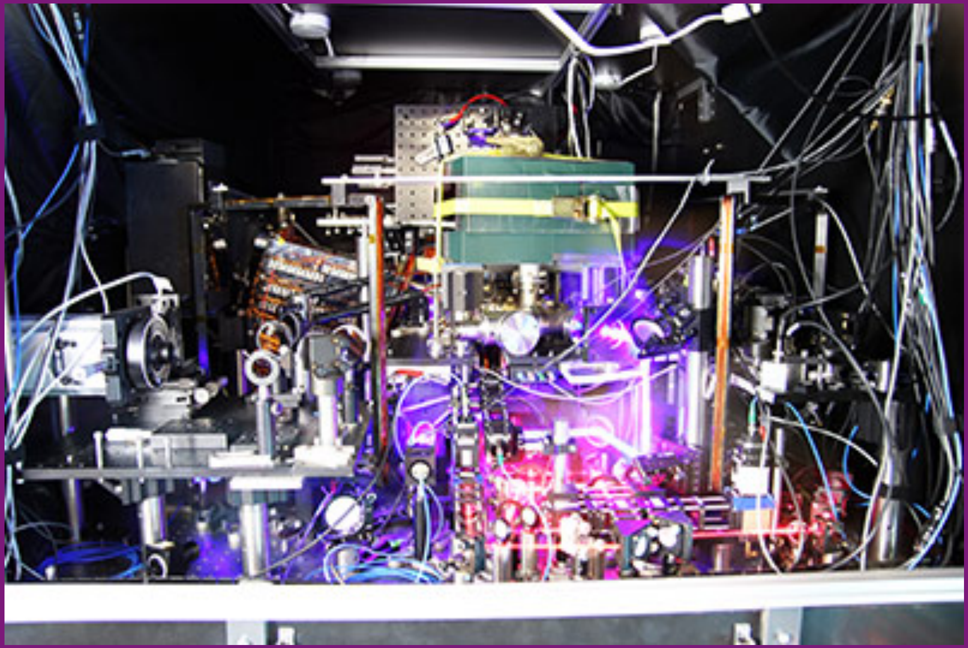


Laser Interferometry (smaller-scale)

[Stadnik and V.F., *PRL* 114, 161301 (2015); PRA 93, 063630 2016]

.

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 Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik and V.F., *PRL* 114, 161301 (2015); *PRA* 93, 063630 (2016)]

- Compare $L \sim Na_B$ with λ

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

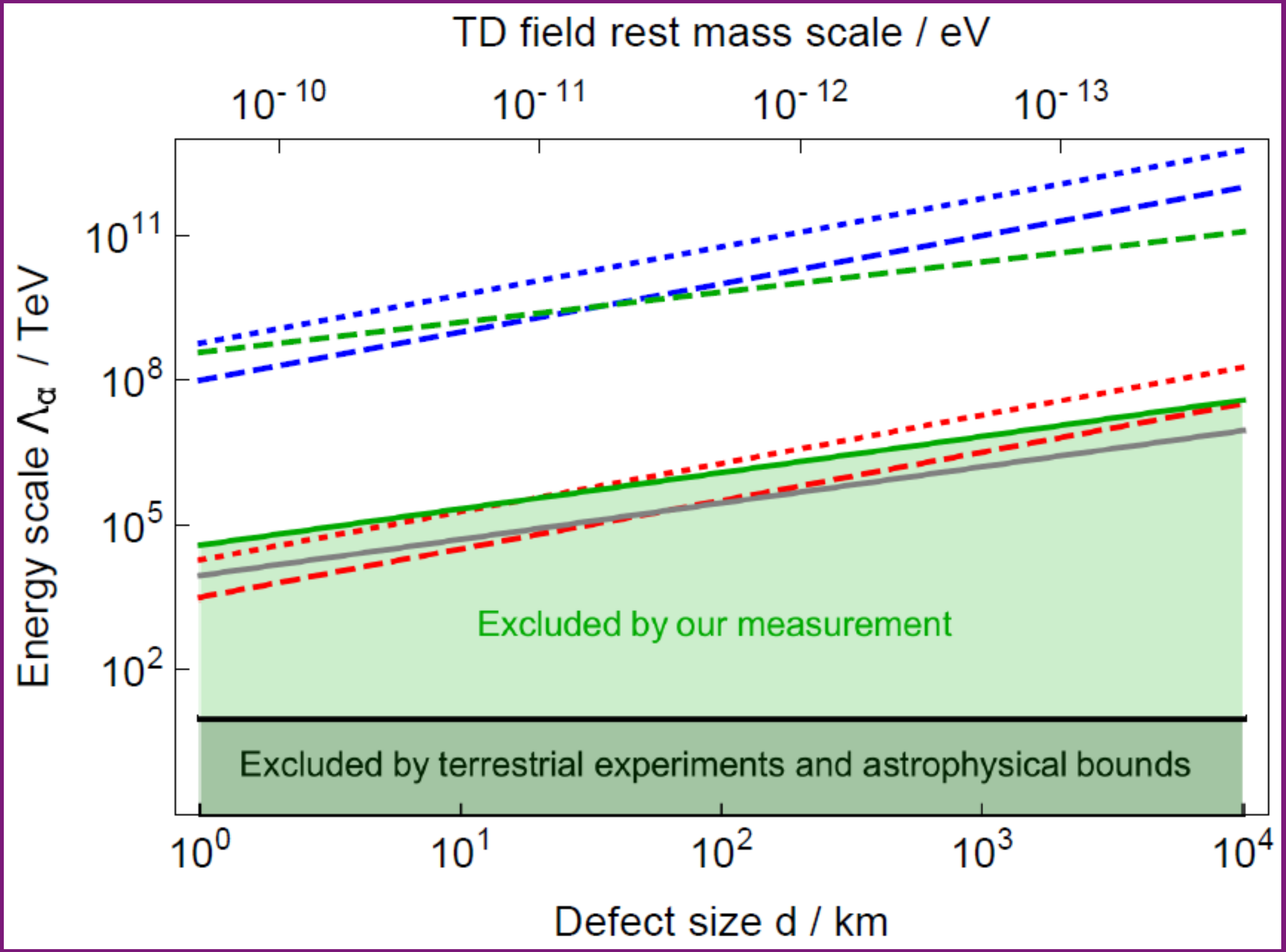
Multiple reflections of light beam enhance effect ($N_{eff} \sim 10^5$ in small-scale interferometers with highly reflective mirrors).

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\, \delta\alpha/\alpha = 10^7\, \delta\alpha/\alpha$ single passage, $10^{12}\, \delta\alpha/\alpha$ for maximal number of reflections

Sr/Cavity (Domain wall DM): [Wcislo *et al.*, *Nature Astronomy* 1, 0009 (2016)]

Recent Search for Topological Defects with Strontium Clock – Silicon Cavity System

[Wcislo *et al.*, *Nature Astronomy* 1, 0009 (2016)]



Variation of Fundamental Constants Induced by a Massive Body

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* 117, 271601 (2016)]

Varying the distance away from a massive body hence alters the fundamental constants, in the presence of Yukawa-type interactions:

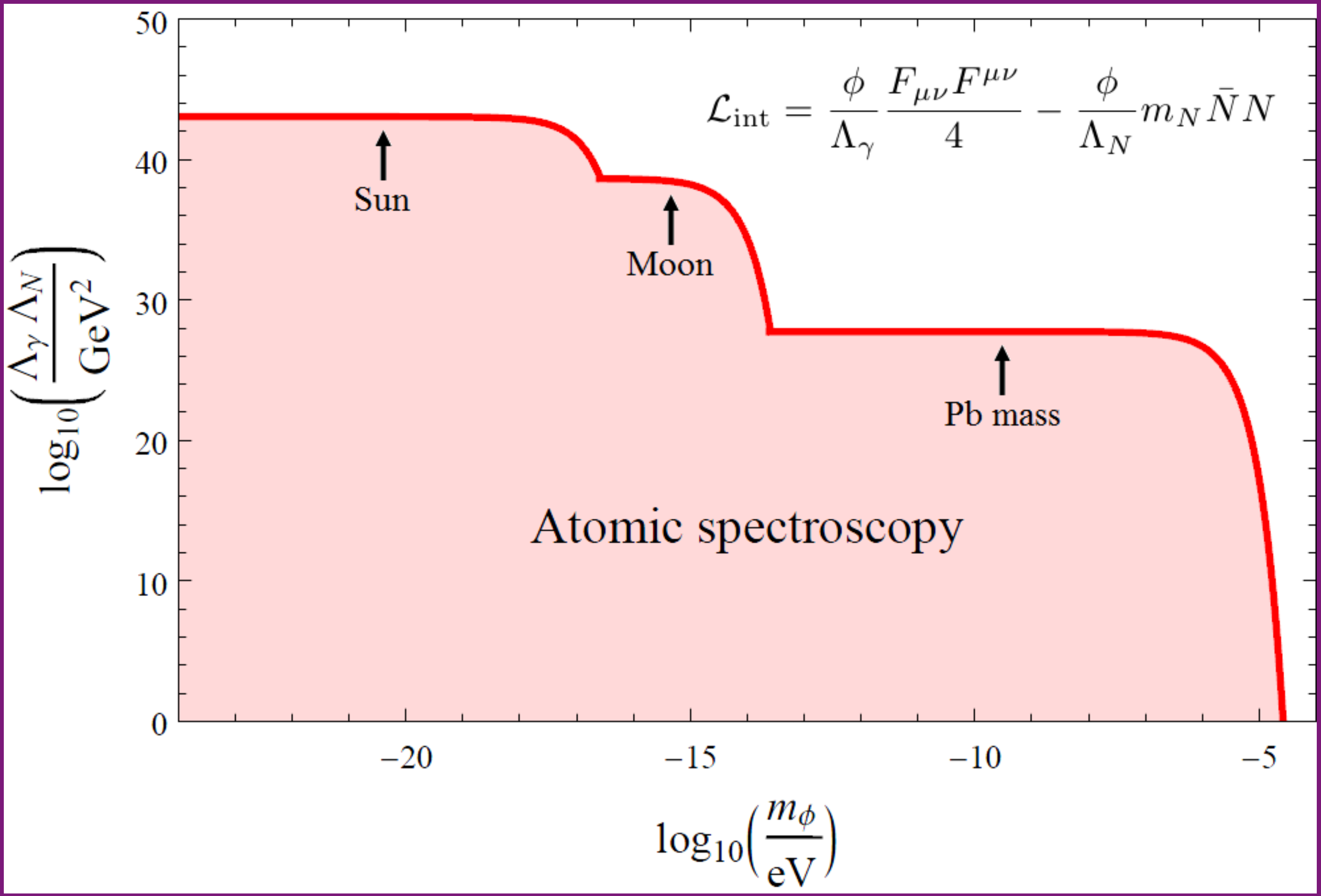
$$\frac{\delta m_f}{m_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \propto \frac{e^{-m_\phi r}}{r}$$

We can search for such alterations in the fundamental constants, using clock frequency comparison measurements (ω_1/ω_2 => *scalar* quantities), in the presence of a massive body at two different distances away from the clock pair:

- Sun (elliptical orbit, e = 0.0167)
- Moon ($e \approx 0.05$, with seasonal variation and effect of finite Earth size)
- Massive objects in the laboratory (e.g., moveable 300kg Pb mass)

Constraints on a Combination of Linear Yukawa Interactions of a Scalar Boson

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* 117, 271601 (2016)]



Low-mass Spin-0 Dark Matter

Dark Matter

QCD axion resolves strong CP problem

Pseudoscalars (Axions):

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

$\rightarrow$ Time-varying spin-dependent effects

"Axion Wind" Spin-Precession Effect

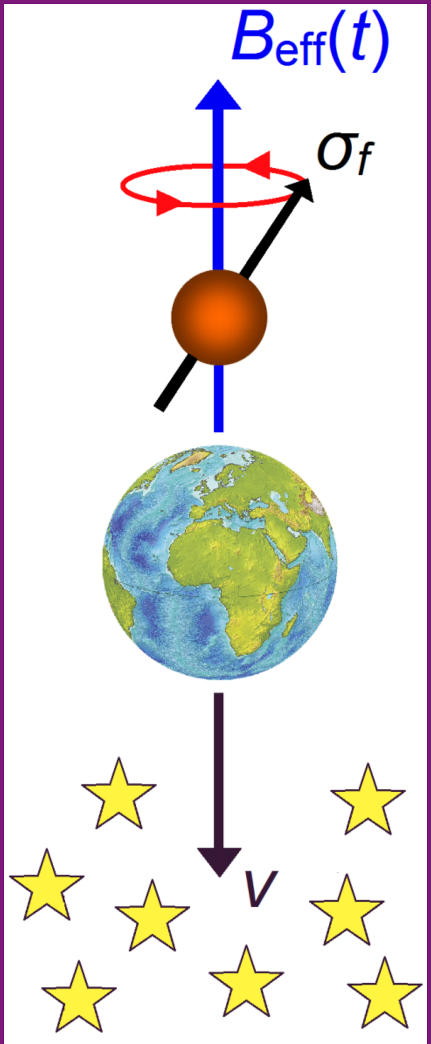
[V.F., talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* 88, 035023 (2013)], [Stadnik and V.F., *PRD* 89, 043522 (2014)]

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

$$=> \quad H_{\text{eff}}(t) \simeq \boldsymbol{\sigma}_f \cdot \boldsymbol{B}_{\text{eff}}\sin(m_a t)$$

Pseudo-magnetic field

$$\boldsymbol{B}_{\text{eff}} \propto \boldsymbol{v}$$



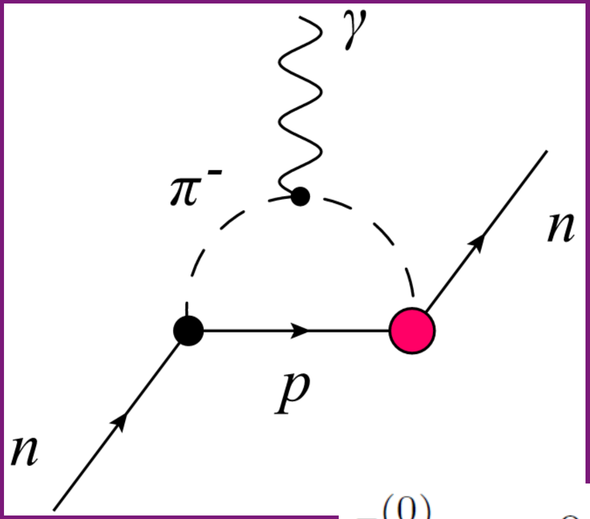
Axion-Induced Oscillating Neutron EDM

[Crewther, Di Vecchia, Veneziano, Witten, *PLB* 88, 123 (1979)],
[Pospelov, Ritz, *PRL* 83, 2526 (1999)], [Graham, Rajendran, *PRD* 84, 055013 (2011)]

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

$$=> \quad d_n(t) \propto \cos(m_a t)$$

$$g_{\pi NN} = 13.5$$



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

Axion-Induced Oscillating Atomic and Molecular EDMs

[O. Sushkov, V.F., Khriplovich, *JETP* 60, 873 (1984)],
[Stadnik and V.F., *PRD* 89, 043522 (2014)]

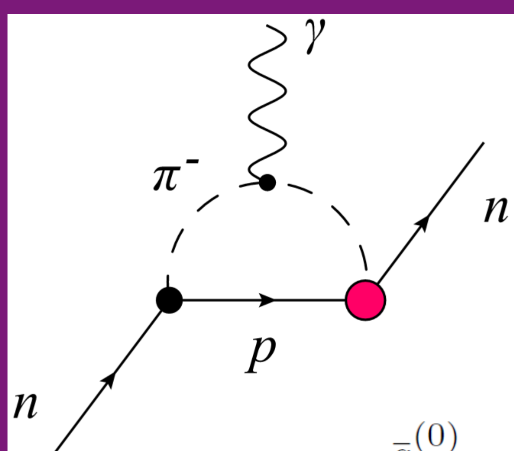
Induced through *hadronic mechanisms*:

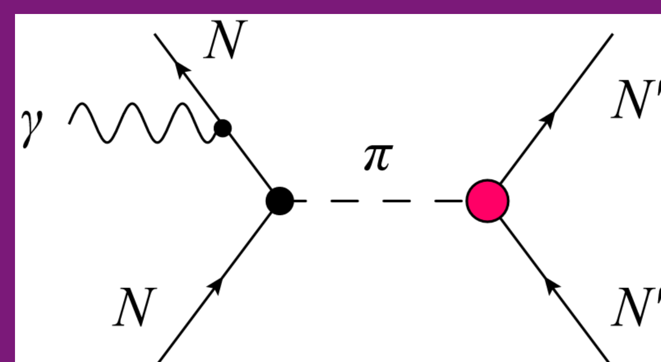
- Oscillating nuclear Schiff moments (*I* ≥ 1/2 => *J* ≥ 0)
- Oscillating nuclear magnetic quadrupole moments (*I* ≥ 1 => *J* ≥ 1/2; *magnetic* => no Schiff screening)

Underlying mechanisms:

(1) Intrinsic oscillating nucleon EDMs (1-loop level)

(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~$4\pi^2 \approx 40$**; up to **extra 1000-fold enhancement** in deformed nuclei)





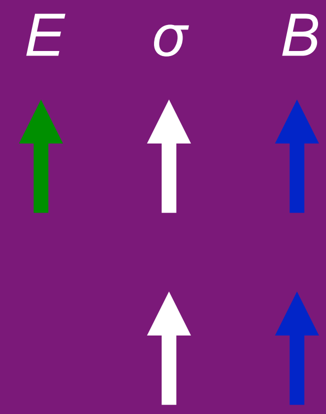
$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

Searching for Spin-Dependent Effects

Need spin-polarised sources!

n/Hg: [nEDM collaboration, arXiv:1708.06367]

$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left| \frac{\gamma_n \cancel{B}}{\gamma_{\mathrm{Hg}} \cancel{B}} \right| + R(t)$$



$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$

$$R_{\mathrm{wind}}(t) \propto \sum_{i=1,2,3} A_i \sin(\omega_i t)$$

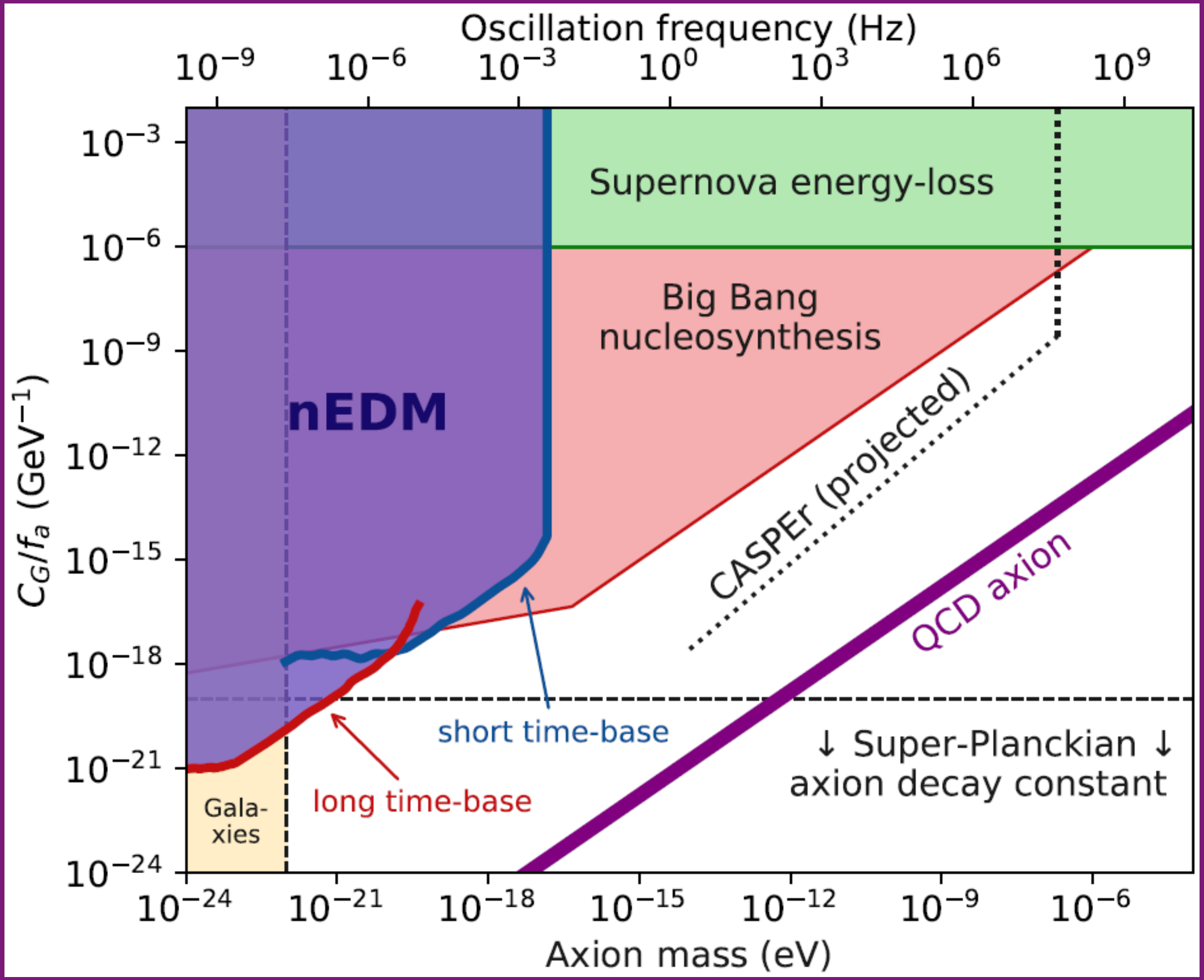
$$\omega_1 = m_a,\ \omega_2 = m_a + \Omega_{\mathrm{sidereal}},\ \omega_3 = |m_a - \Omega_{\mathrm{sidereal}}|$$

Earth's rotation

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, arXiv:1708.06367]

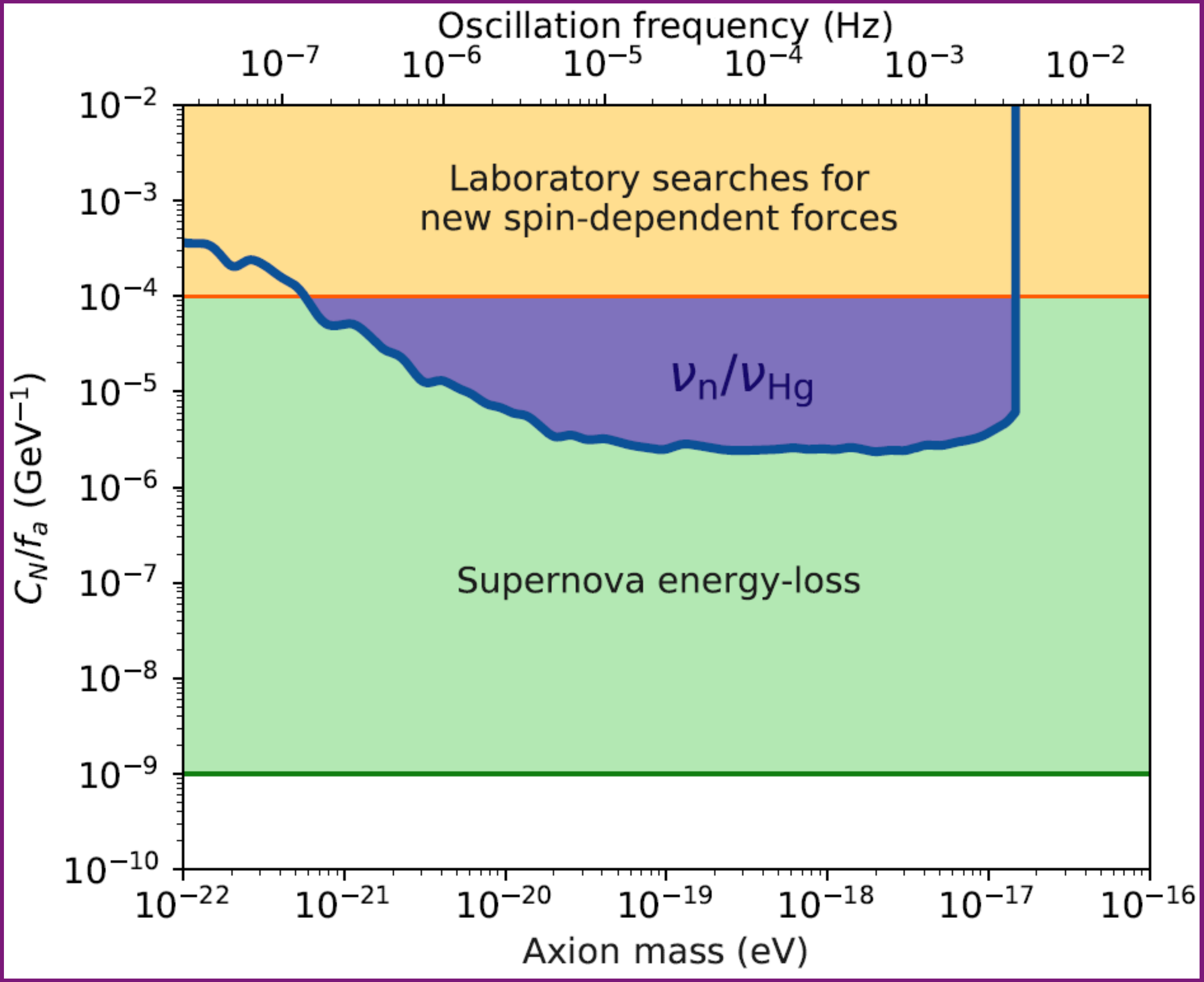
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, arXiv:1708.06367]

40-fold improvement!



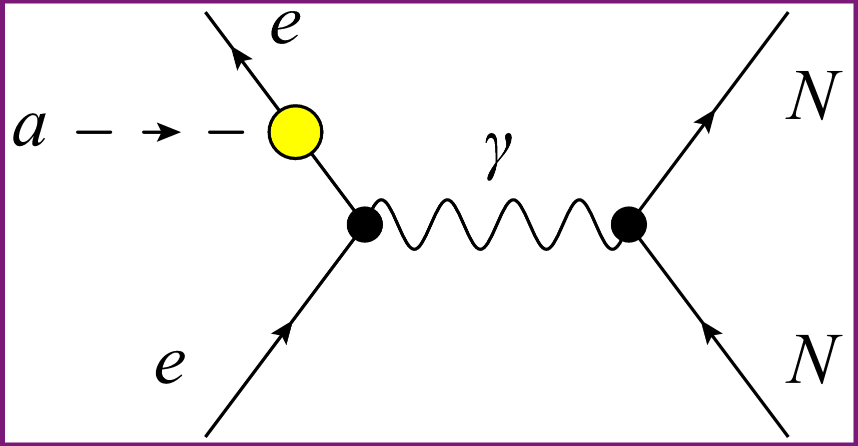
Axion-Induced Oscillating EDMs of Paramagnetic Atoms and Molecules

[Stadni and V.F., *PRD* 89, 043522 (2014)], [Roberts, Stadnik, Dzuba, V.F. , Leefer, Budker, *PRL* 113, 081601 (2014) + *PRD* 90, 096005 (2014)]

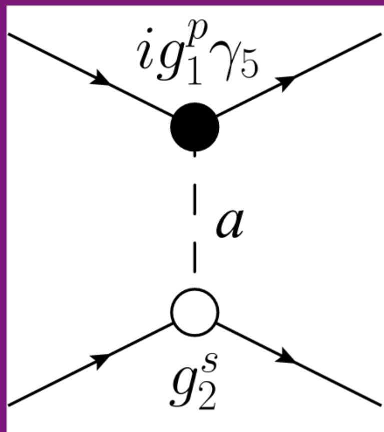
In *paramagnetic* atoms and molecules, such as HfF^+, oscillating EDMs are also induced through *mixing of opposite-parity states* via the interaction of the oscillating axion field with atomic/molecular electrons.

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

$$d_{\mathrm{atomic}}(t) \sim -\frac{C_e a_0 m_a^2 \alpha_s}{f_a e}\cos(m_a t)$$



Non-Cosmological Sources of Exotic Bosons



$$\mathcal{L}_{aff} = a \sum_f \bar{f}\left(g_f^s + i g_f^p \gamma_5\right) f$$

$$V_{12}(r) \approx \frac{g_1^p g_2^s}{8\pi m_1}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{r}}\left(\frac{m_a}{r}+\frac{1}{r^2}\right)e^{-m_a r}$$

- Macroscopic fifth-forces [Moody, Wilczek, *PRD* 30, 130 (1984)]

- *P*,*T*-violating forces => Atomic and Molecular EDMs

[Stadnik, Dzuba, and V.F, arXiv:1708.00486]

Atomic EDM experiments: Cs, Tl, Xe, Hg

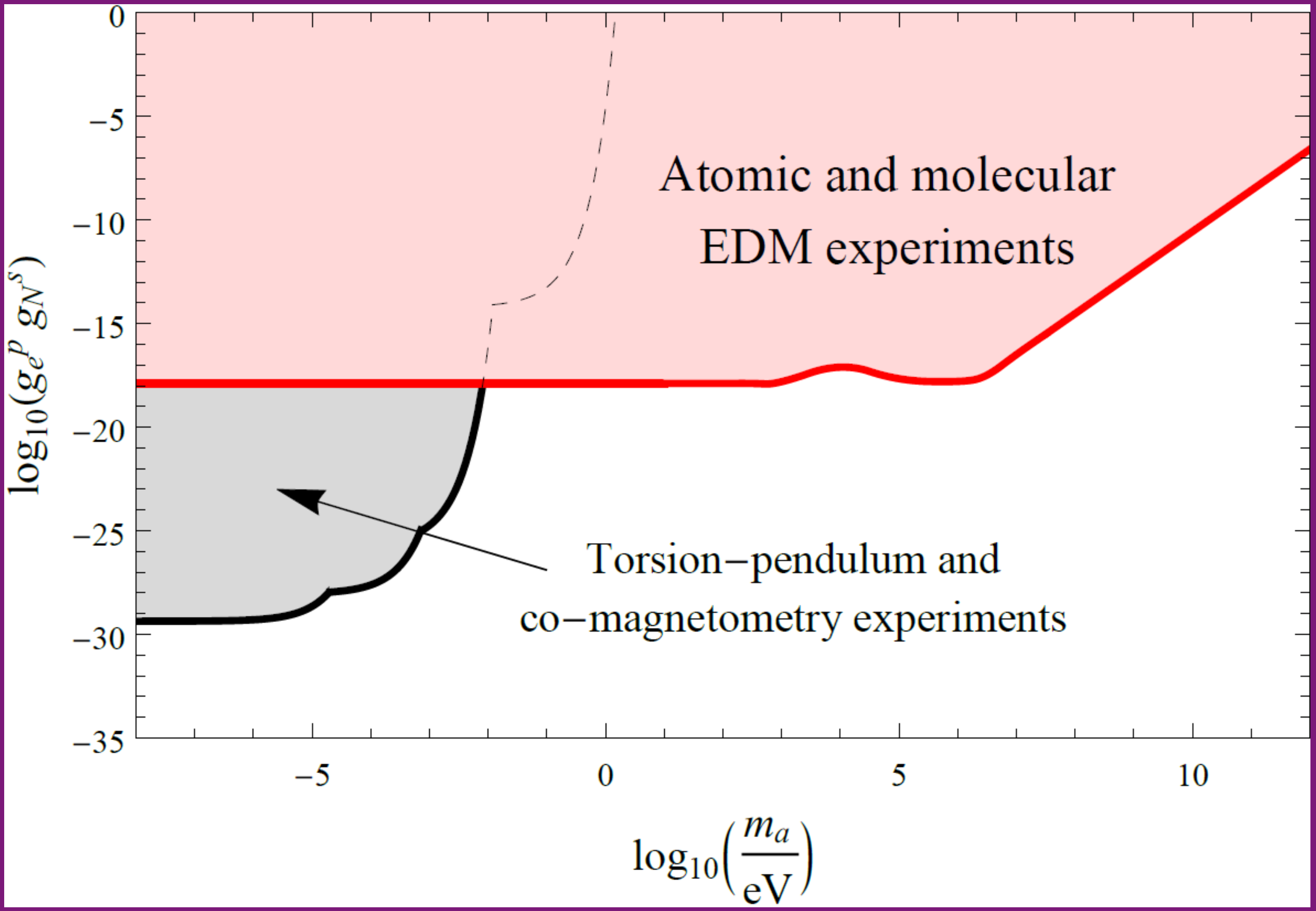
Molecular EDM experiments: YbF, HfF^+, ThO

HfF+ gives best limits for small axion masses

Constraints on Scalar-Pseudoscalar Nucleon-Electron Interaction

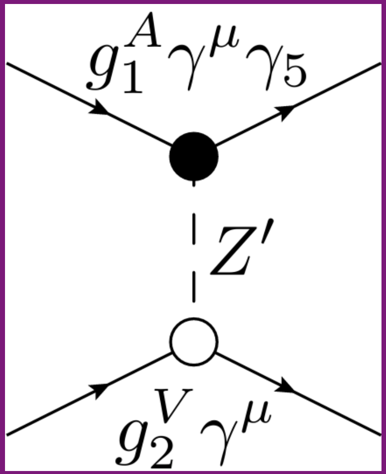
EDM constraints: [Stadnik, Dzuba and V.F., arXiv:1708.00486]

Many orders of magnitude improvement!



Non-Cosmological Sources of Exotic Bosons

Z' boson [Dzuba, V.F., Stadnik, *PRL* 119, 223201 (2017)]



$$\mathcal{L}_{\text{int}} = Z'_\mu \bar{f} \gamma^\mu \left(g_f^V + g_f^A \gamma_5 \right) f$$

$$V(r) \approx -\frac{g_1^A g_2^V}{8\pi m_1} \left\{ \boldsymbol{\sigma} \cdot \boldsymbol{p}, \; \frac{e^{-m_{Z'} r}}{r} \right\}$$

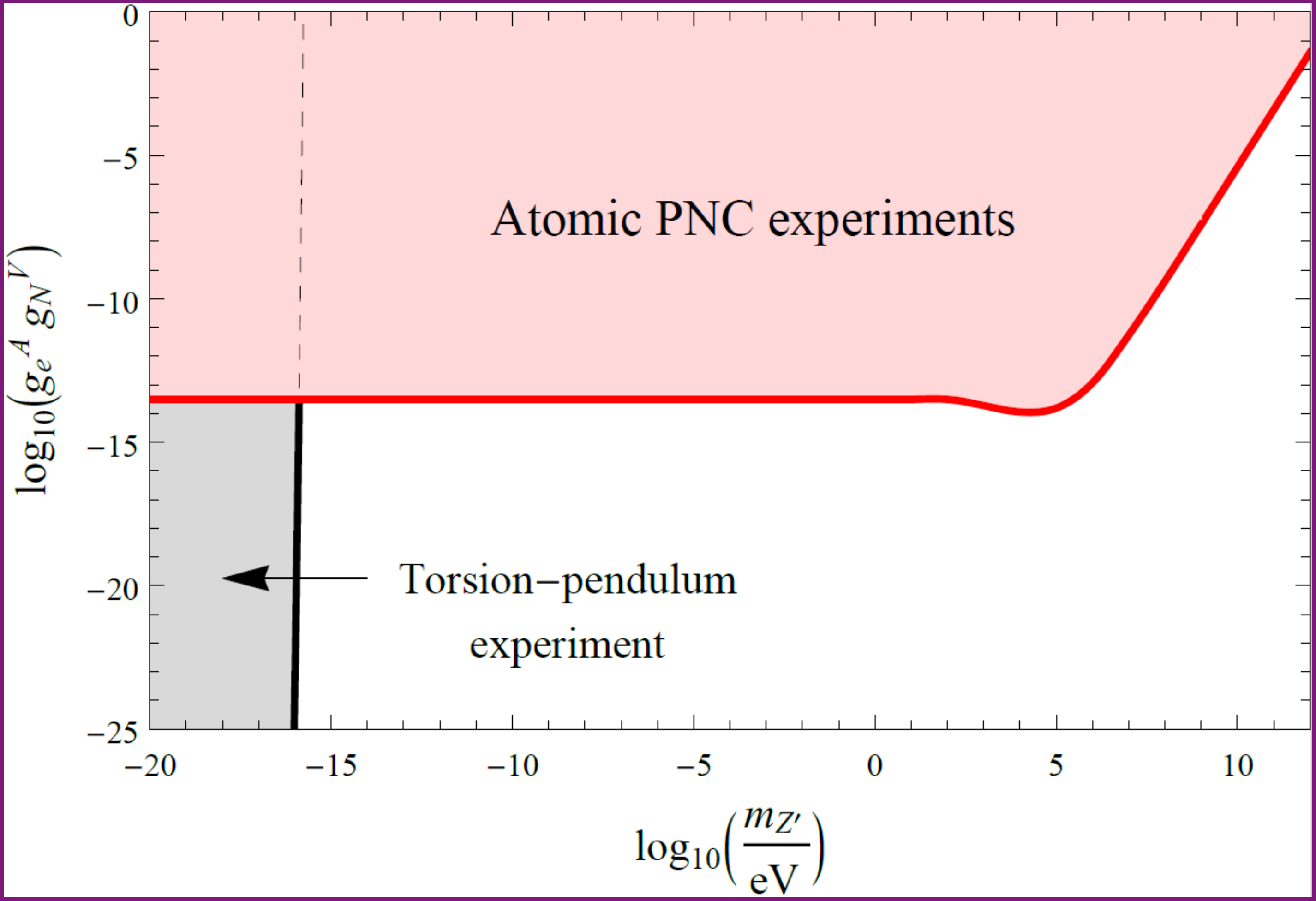
P-violating forces => Atomic parity-nonconserving effects and nuclear anapole moments

Atomic PNC experiments: Cs, Yb, Tl

Constraints on Vector-Pseudovector Nucleon-Electron Interaction

PNC constraints: [Dzuba, V.F. , Stadnik, *PRL* 119, 223201 (2017)]

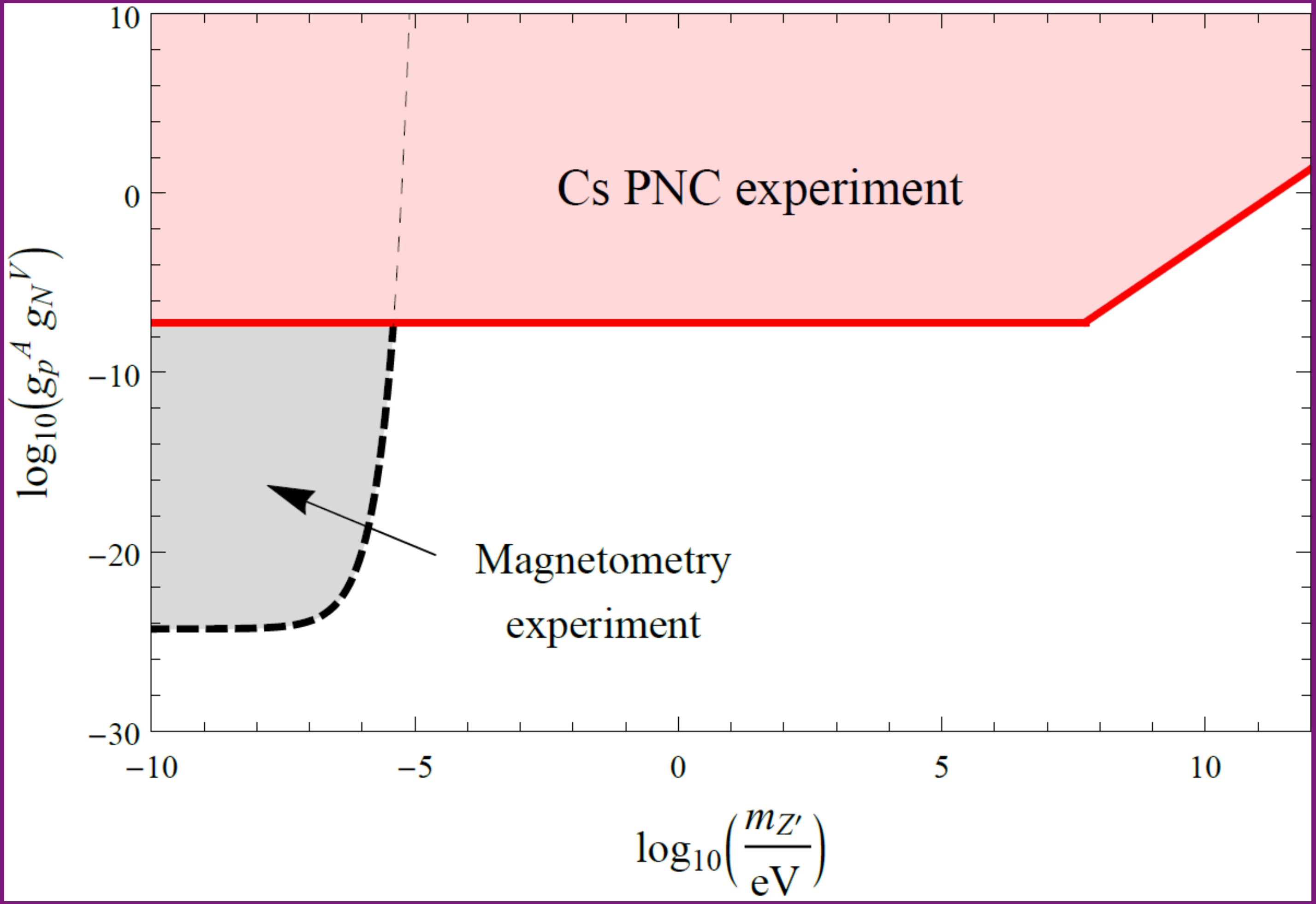
Many orders of magnitude improvement!



Constraints on Vector-Pseudovector Nucleon-Proton Interaction

PNC constraints: [Dzuba,V.F., Stadnik, *PRL* 119, 223201 (2017)]

Many orders of magnitude improvement!



Effect of photon mass on Galaxy rotational curve instead of dark matter

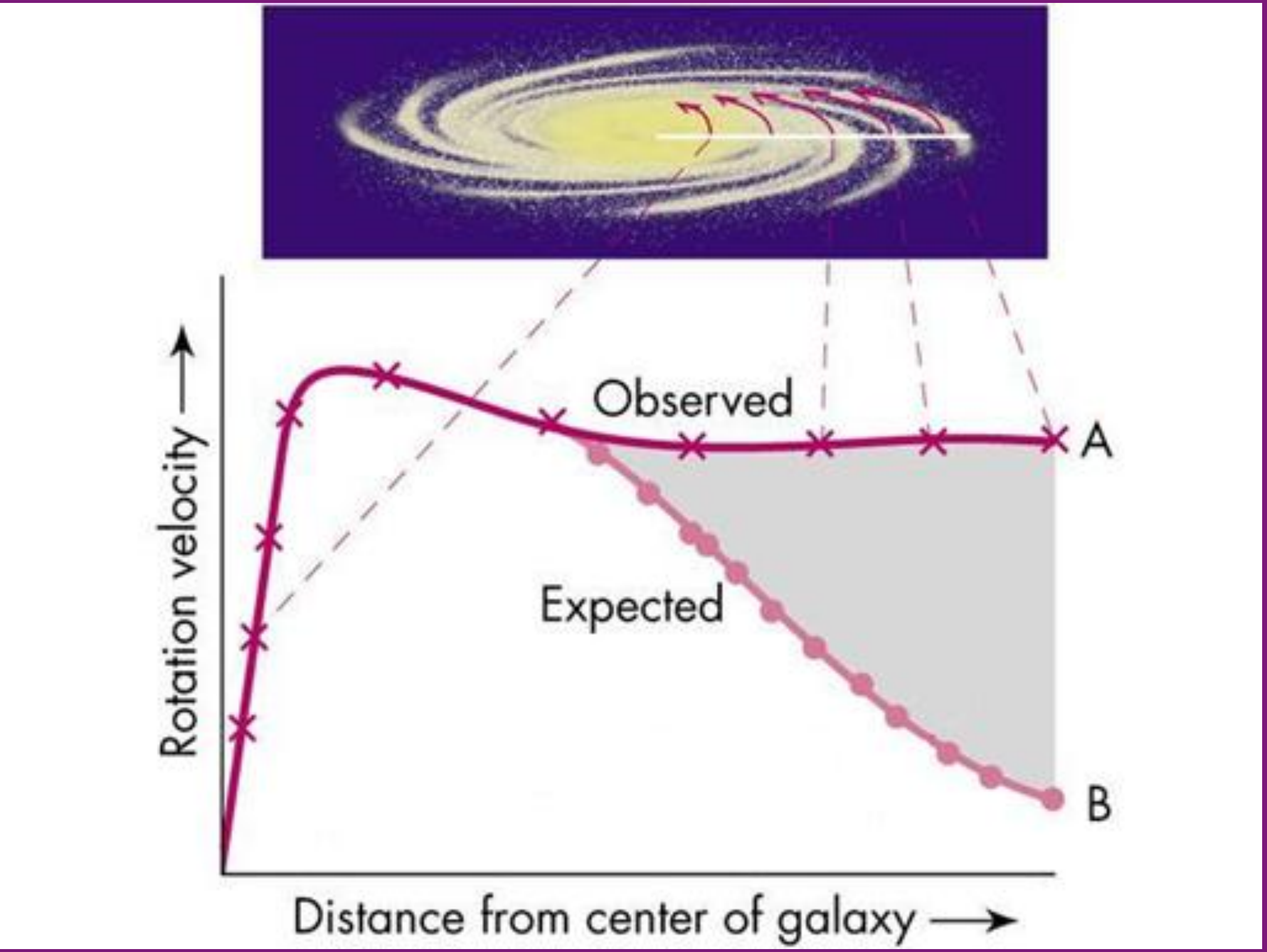
- *Negative pressure inside Galactic plasma* p= $-\varepsilon/3$ (similar to dark energy). Magnetic force imitates gravity!

A hypothetical effect of Maxwell-Proca electromagnetic stresses on galaxy rotation curve

D.Ryutov, D. Budker, V.Flambaum, arxiv:1708.09514

Motivation

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



Effect of Photon Mass on Galaxies?

Key points:

•Sufficiently strong forces to explain galactic rotation curves without dark matter

•The effect of mass is through Magnetic HydroDynamics (MHD)

Maxwell-Proca Equations

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t};$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A};$$

$$\nabla \times \boldsymbol{B} + \frac{\boldsymbol{A}}{\lambda^2} = \frac{4\pi}{c}\boldsymbol{j} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t};$$

$$\nabla \cdot \boldsymbol{E} + \frac{\varphi}{\lambda^2} = 4\pi\rho;$$

Quasistatic case $\nabla \cdot A = 0$

No gauge invariance! Vector-potential is defined by the Maxwell-Proca equations

Effect of photon mass on Galaxy rotational curve instead of dark matter

D.Ryutov, D. Budker, V.Flambaum, arxiv:1708.09514

- Slowly varying random magnetic field B permeates Galactic plasma, B~A/L, A is the vector potential, L is the correlation length.
- Maxwell-Proca equation for photon with mass m:
  curl $B+m^2A=j$, $B=$curl A
- **Lorentz force**
  jxB= -(B x curl B)+m^2(A x curl A), note opposite sign for mass term
- **Maxwell stress tensor**:
  energy density T_{00} $=\varepsilon=(B^2+m^2A^2)/2=B^2(1+m^2L^2)/2$
- **Space components averaged over directions**:
  pressure T_{ii}=p= $(B^2-m^2A^2)/6=B^2(1-m^2L^2)/6$
- If m=0 then $p=\varepsilon/3$, usual relation for massless particles
- $m^2L^2>>1$ *Negative pressure inside plasma* $p=-\varepsilon/3$ (similar to dark energy). Imitates gravity!

Effect of photon mass on Galaxy rotational curve instead of dark matter

- *Negative pressure inside plasma* $p = -\varepsilon/3$ (similar to dark energy). Gradient of pressure produces attraction towards Centre of the Galaxy and Galaxy plane, imitates gravity.
- Small photon mass m instead of dark matter? Data for Galactic magnetic field give correlation length L=1- 10 pc.
  We need $m^2L^2=600$ to reproduce Galaxy rotation curve. This gives photon mass $m=10^{-24}$ eV, 6 orders of magnitude smaller than the current limit on the photon mass $m < 10^{-18}$ eV
- Magnetic field is everywhere in the Universe − cosmological effects
- Tully-Fisher relation − rotation velocity V in different galaxies is function of total barionic mass M (sum of gas and stars), $M= \text{const}\ V^x$, x=3.5- 4. Different from Kepler law, there is an extra contribution to the attractive force.
- Mass of dark matter is a function of barionic mass M?
  Non-gravitational contribution to the attraction (the effect of photon mass)?

Finite photon mass

- Negative pressure of galactice magnetic field, P=-E/3, imitates gravity. May replace dark matter?
- Intergalactic magnetic field- dark energy???
- A hypothetical effect of the Maxwell-Proca electromagnetic stresses on galaxy rotation curves. D. D. Ryutov, D. Budker, and V. F.,arxiv:1708.09514,

Summary

- Precision atomic physics can be used to probe fundamental interactions
  - unique test of the standard model through APV, now agreement
  - Nuclear anapole, probe of PV weak nuclear forces (in APV)
  - Tensor weak interaction- to measure neutron quadrupole
  - EDM, unique sensitivity to physics beyond the standard model.

  1-2 orders improvement may be enough to reject or confirm popular models of CP violation, e.g. supersymmetric models

  Dark matter produces oscillating effects.
- A new generation of experiments with enhanced effects is underway in atoms, diatomic molecules, nuclei and solids

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

Cs PNC: conclusion and future directions

- Cs PNC is still in perfect agreement with the standard model
- Theoretical uncertainty is now dominated by correlations (0.5%)
- Improvement in precision for correlation calculations is important. Derevianko aiming for 0.1% in Cs.
- Similar measurements and calculations can be done for Fr, Ba+, Ra+

Summary

- Precision atomic physics can be used to probe fundamental interactions
  - EDMs (existing): Xe, Tl, Hg
  - EDMs (new): Xe, Ra, Yb, Rn
  - EDM and APV in metastable states: Ra, Rare Earth
  - Nuclear anapole: Cs, Tl, Fr, Ra, Rare Earth
  - APV (Q_W): Cs, Fr, Ba+, Ra+
- Atomic theory provides reliable interpretation of the measurements

Atoms as probes of fundamental interactions

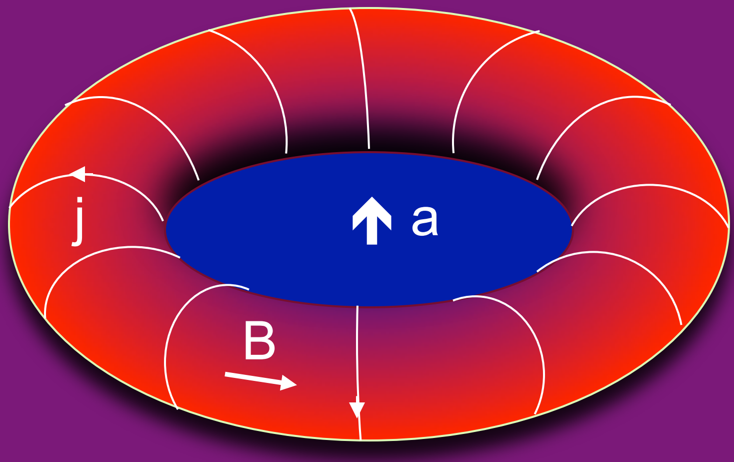
- T,P and P-odd effects in atoms are strongly enhanced:
  - Z^3 or Z^2 electron structure enhancement (universal)
  - Nuclear enhancement (mostly for non-spherical nuclei)
    - Close levels of opposite parity
    - Collective enhancement
    - Octupole deformation
  - Close atomic levels of opposite parity (mostly for excited states)

- A wide variety of effects can be studied:

Schiff moment, MQM, nucleon EDM, e^- EDM via atomic EDM
Q_W, Anapole moment via *E(PNC)* amplitude

Nuclear anapole moment

- Source of nuclear spin-dependent PV effects in atoms
- Nuclear magnetic multipole violating parity
- Arises due to parity violation inside the nucleus



- Interacts with atomic electrons via usual magnetic interaction (PV hyperfine interaction):

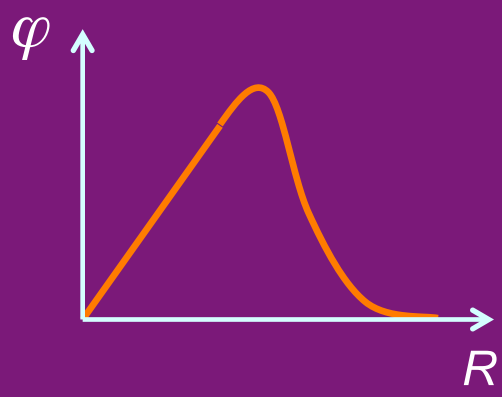
$$h_a = e\vec{\alpha}\cdot\vec{A} \propto \kappa_a \vec{\alpha}\cdot\vec{I}\rho(r)\ , \quad \kappa_a \propto A^{2/3}$$

[Flambaum,Khriplovich,Sushkov]

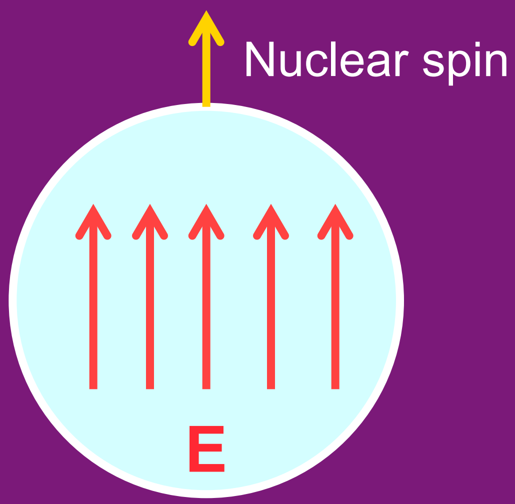
$E_{PV} \propto Z^2 A^{2/3}$ measured as difference of PV effects for transitions between hyperfine components

- Boulder Cs: **g= 6(1)** (in units of Fermi constant)
- Seattle Tl: **g=-2(3)**

Flambaum, Ginges, 2002: $\varphi(\mathbf{R}) = -\frac{3\mathbf{S}\bullet\mathbf{R}}{B}\rho(R)$ 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. Schiff moment electric field polarizes atom and produce EDM.

Relativistic corrections originating from electron wave functions can be incorporated into *Local Dipole Moment* (**L**)

$$\mathbf{L} = \sum_{k=1}^{\infty} \mathbf{S}_k$$

$$\varphi(\mathbf{R}) = 4\pi\mathbf{L}\bullet\nabla\delta(\mathbf{R})$$

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
- Electric octupole moment – modified by screening
- Magnetic quatrupole moment – not significantly affected

Nuclear electrostatic potential with screening:

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

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.

Extra enhancement in excited states: Ra

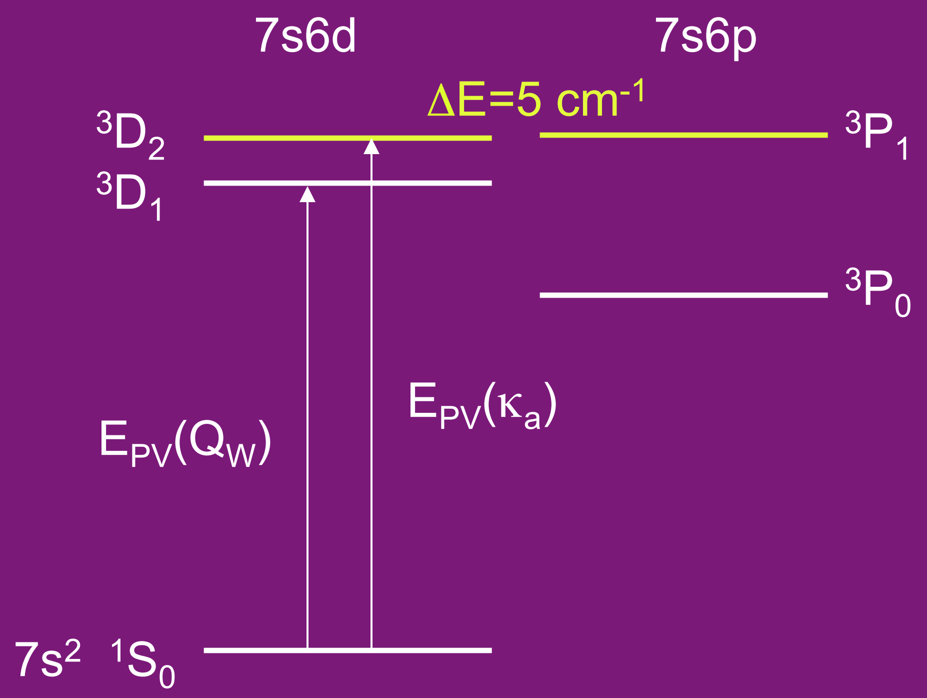
$$d_{atom}(1) = 2\sum_N \frac{\langle 1|D_z|N\rangle\langle N|H_{PT}|1\rangle}{E_1 - E_N}$$

- Extra enhancement for EDM and APV in metastable states due to presence of close opposite parity levels

  [Flambaum; Dzuba,Flambaum,Ginges]

$d(^3D_2) \sim 10^5 \times d(\mathrm{Hg})$

$E_{PV}(^1S_0\text{-}^3D_{1,2}) \sim 100 \times E_{PV}(\mathrm{Cs})$



Matrix elements: $<\psi_a|h+\delta V+\delta\Sigma|\psi_b>$

$\psi_{a,b}$ - Brueckner orbitals: $(H^{HF} - \varepsilon_a + \Sigma)\psi_a = 0$

h – External field

$<\psi_a|\delta V|\psi_b>$ - Core polarization

$<\psi_a|\delta\Sigma|\psi_b>$ - Structure radiation

Example: PNC $E(6s\text{-}7s)$ in ^{133}Cs [$10^{-11} i e a_B(-Q_W/N)$]

E_{PNC} = 0.91(1) (Dzuba, Sushkov, Flambaum, 1989)

E_{PNC} = 0.904(5) (Dzuba, Flambaum, Ginges, 2002)

Close states of opposite parity in Rare-Earth atoms

Z	Atom	Even	Odd	ΔE [cm^{-1}]	ΔJ	What
60	Nd II	$^{6}G_{11/2}$	$^{6}L_{13/2}$	8	1	S,M
62	SM I	$4f^{6}5d6s$	$4f^{6}6s6p$	5	0	S,E,M
62	SM I	$^{7}D_{4}$	$^{9}G_{5}$	10	1	S,M
64	Gd I	$^{11}F_{5}$	$^{9}P_{3}$	0	2	A,M
66	Dy I	$4f^{10}5d6s$	$4f^{10}6s6p$	1	1	A,S,M
66	Dy I	$4f^{10}5d6s$	$4f^{9}5d^{2}6s$	0	0	A,E,S,M
67	Ho I	$^{8}K_{21/2}$	$4f^{10}6s^{2}6p$	10	1	S,M

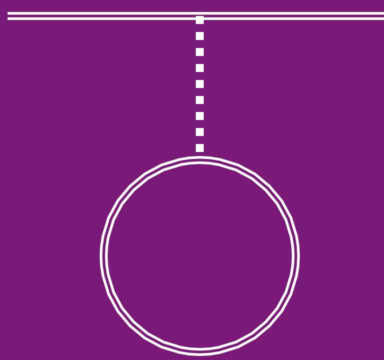
S = Schiff Moment, A = Anapole moment, E = Electron EDM,
M = Magnetic quadrupole moment

Radiative potential for QED

$$\Phi_{\text{rad}}(r) = \Phi_U(r) + \Phi_g(r) + \Phi_f(r) + \Phi_l(r) + \frac{2}{3}\Phi_{WC}^{simple}(r)$$

$$\Phi_g(r) + \Phi_f(r) + \Phi_l(r) =$$

$$\Phi_U(r) + \frac{2}{3}\Phi_{WC}^{simple}(r) =$$



$\Phi_g(r)$ – magnetic formfactor
$\Phi_f(r)$ – electric formfactor
$\Phi_l(r)$ – low energy electric formfactor
$\Phi_U(r)$ – Uehling potential
$\Phi_{WC}(r)$ – Wichmann-Kroll potential

$\Phi_f(r)$ and $\Phi_f(r)$ have free parameters which are chosen to fit QED corrections to the energies (Mohr, et al) and weak matrix elements (Kuchiev,Flambaum; Milstein,Sushkov,Terekhov; Sapirstein et al)

QED corrections to E_{PV} in Cs

$$E_{PV} = \sum_p \frac{W_{sp} E1_{ps}}{E_s - E_p}$$

- QED correction to weak matrix elements leading to δE_{PV} (Kuchiev, Flambaum, '02; Milstein, Sushkov, Terekhov, '02; Sapirstein, Pachucki, Veitia, Cheng, '03)

  δE_{PV} = (0.4-0.8)% = -0.4%

- QED correction to δE_{PV} in effective atomic potential (Shabaev *et al*, '05)

  δE_{PV} = (0.41-0.67)% = -0.27%

- QED corrections to *E1* and ΔE in radiative potential, QED corrections to weak matrix elements are taken from earlier works (Flambaum, Ginges, '05)

  δE_{PV} = (0.41-0.73)%=-0.32%

- QED correction to δE_{PV} in radiative potential with full account of many-body effects (Dzuba, Flambaum, Ginges, '07)

  δE_{PV} = -0.20%

Overview

- Atoms as probes of fundamental interactions
  - *atomic electric dipole moments (EDMs)*
  - *atomic parity violation (APV)*

    - nuclear anapole moment
    - nuclear weak charge
- Nuclear Schiff moment (SM)
- High-precision atomic many-body calculations
- EDMs of diamagnetic atoms
- Strong enhancement of SM in deformed nuclei
- Strong enhancement of EDMs and APV due to close levels of opposite parity
- Summary