New Probes of Ultra-Low-Mass Dark Matter and Dark Sectors

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Collaborators (Theory):

Victor Flambaum group (UNSW)

Peter Wolf group (SYRTE)

Collaborators (Experiment):

Dmitry Budker group (Mainz)

nEDM collaboration at PSI and Sussex

BASE collaboration at CERN and RIKEN

General Seminar, INFN Frascati, February 2019

Low-Mass Dark Bosons (m << 100 GeV)

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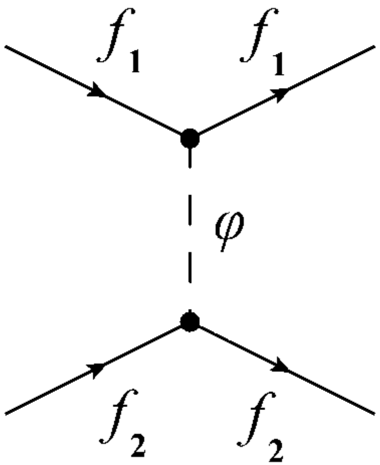

New forces

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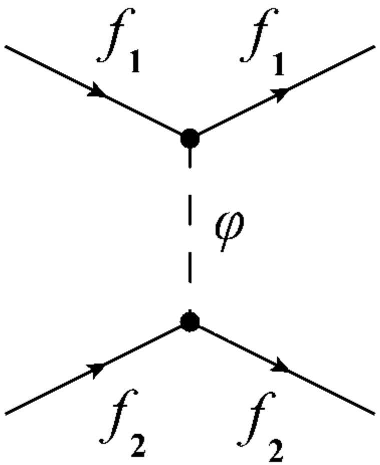

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Atomic spectroscopy:

Leefer, Gerhardus, Budker, Flambaum, Stadnik, *PRL* **117**, 271601 (2016)

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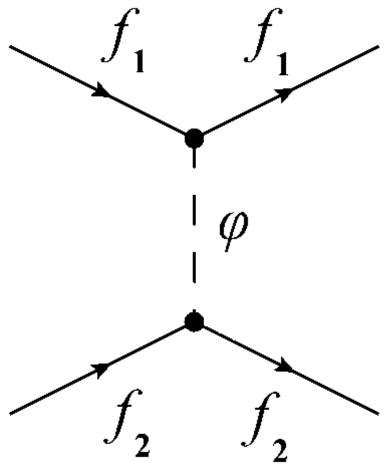

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Potentials revisited:

Fadeev, Stadnik, Ficek, Kozlov, Flambaum, Budker, *PRA* **99**, 022113 (2019)

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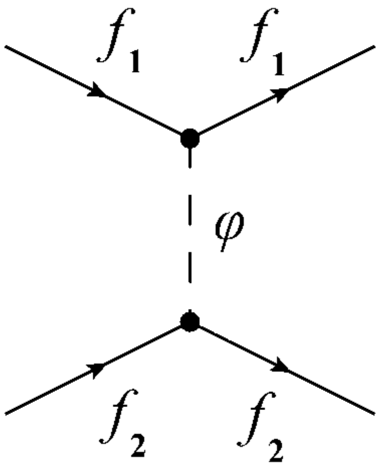

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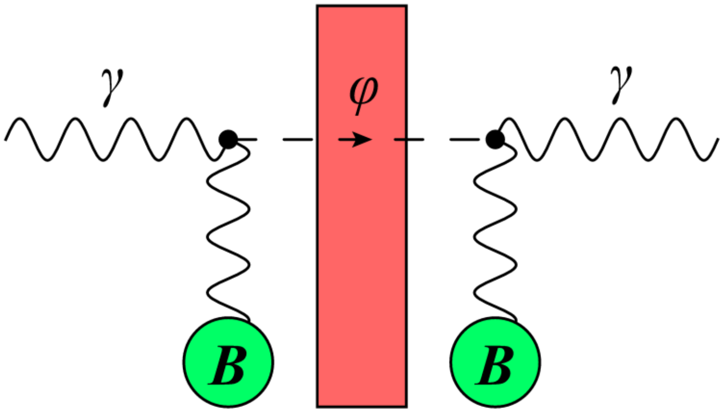

Interconversion with ordinary particles

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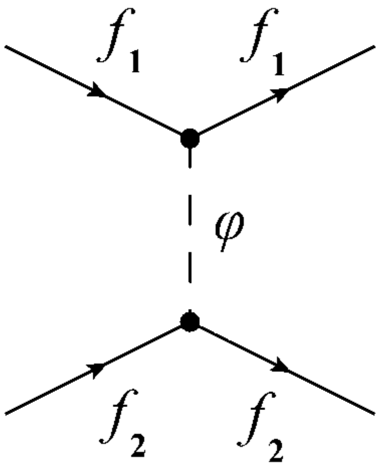

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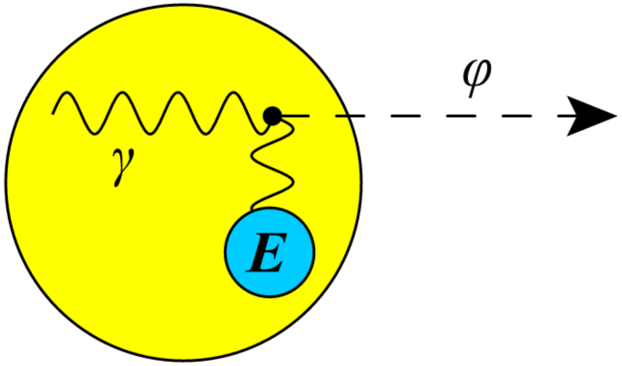
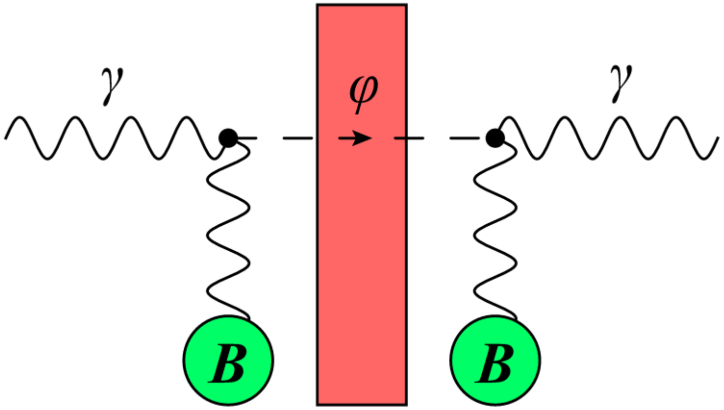


Stellar emission



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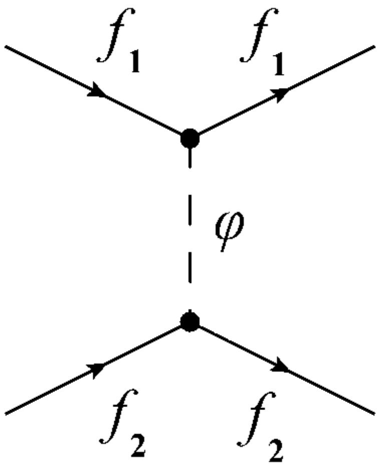

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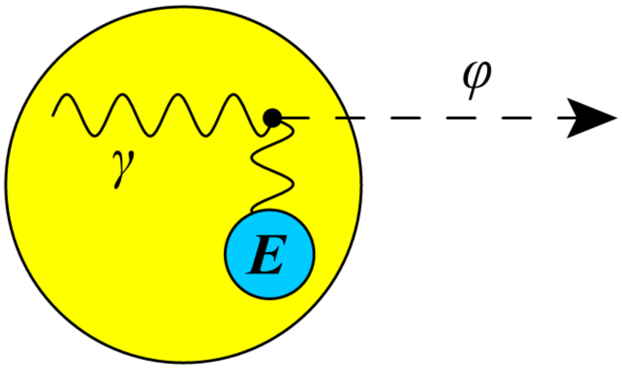

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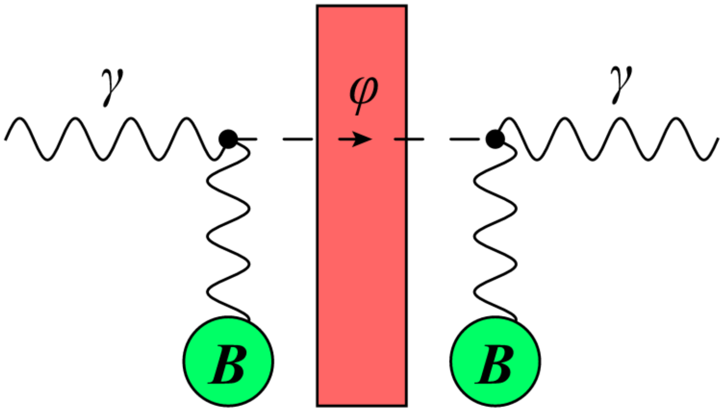

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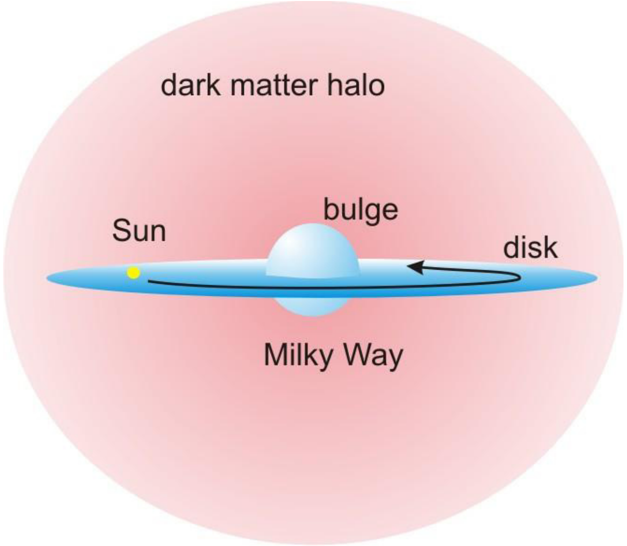

Dark matter

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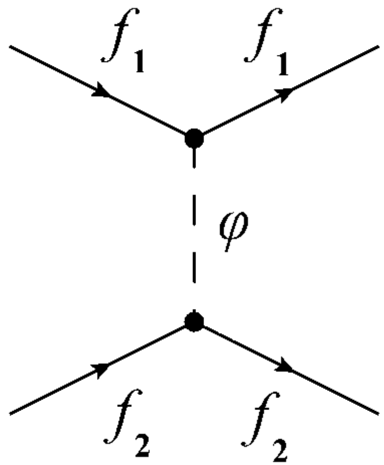

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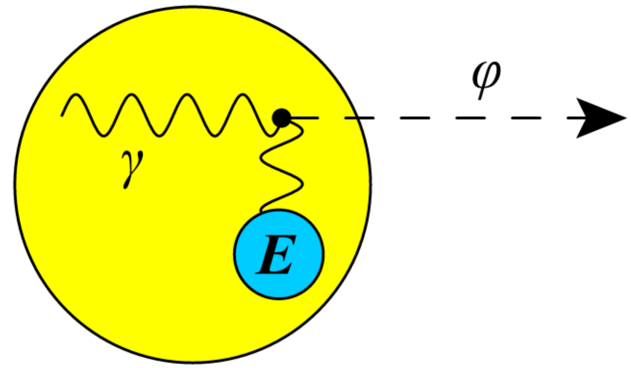

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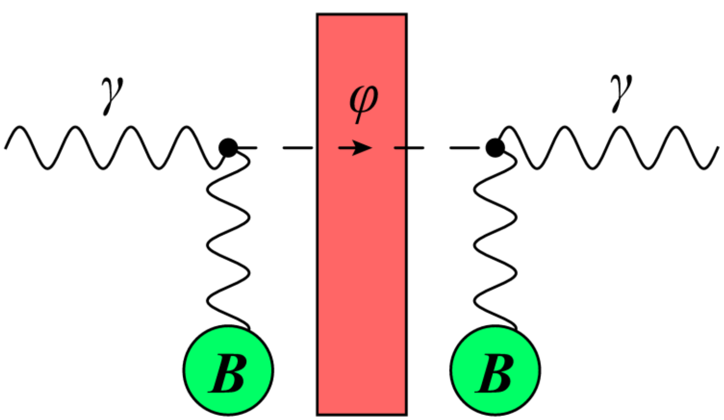

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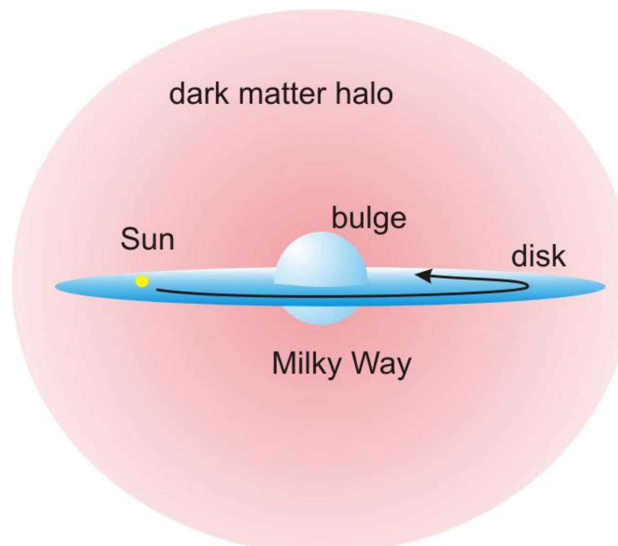


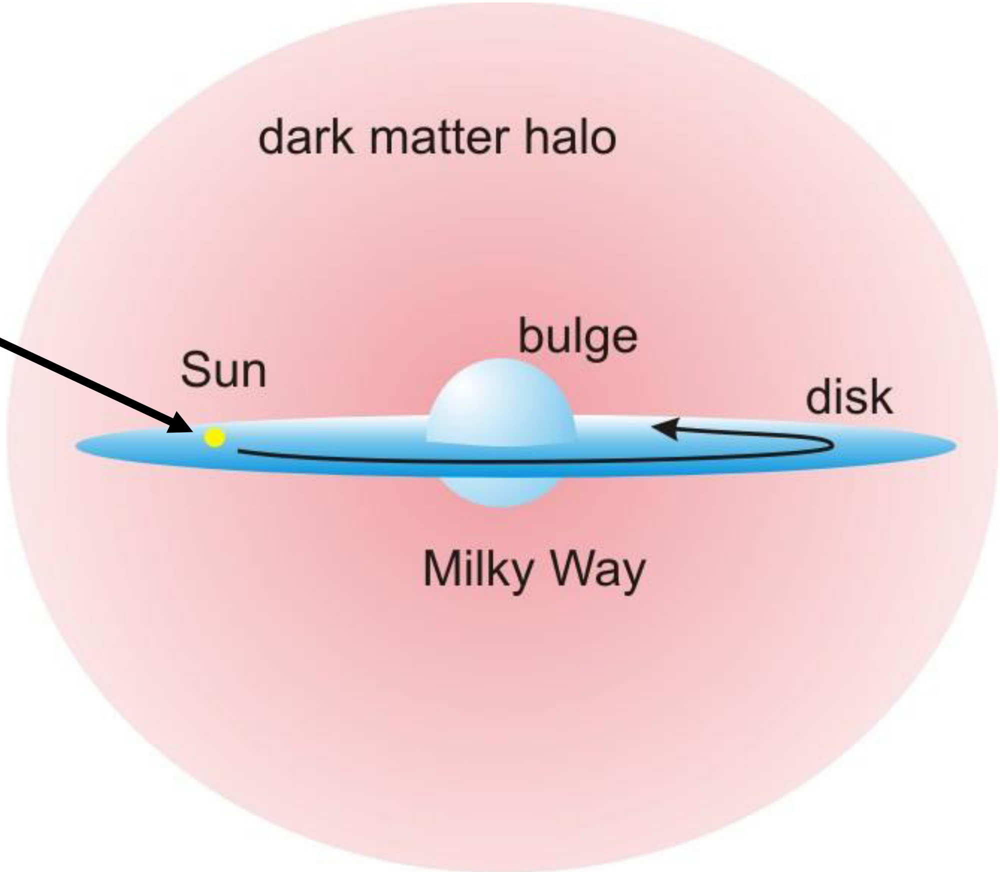
Dark matter

Motivation

Strong 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



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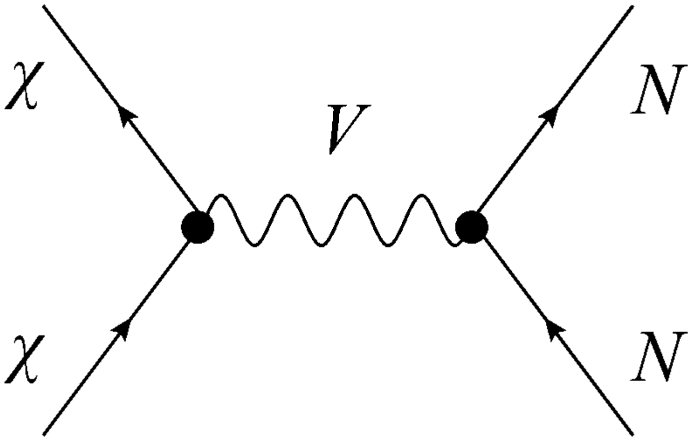
Traditional "scattering-off-nuclei" searches for heavy WIMP dark matter particles ($m_\chi \sim$ GeV) have not yet produced a strong positive result.



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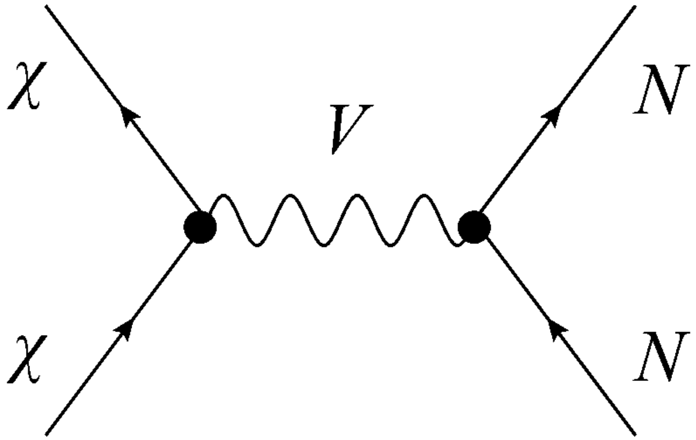

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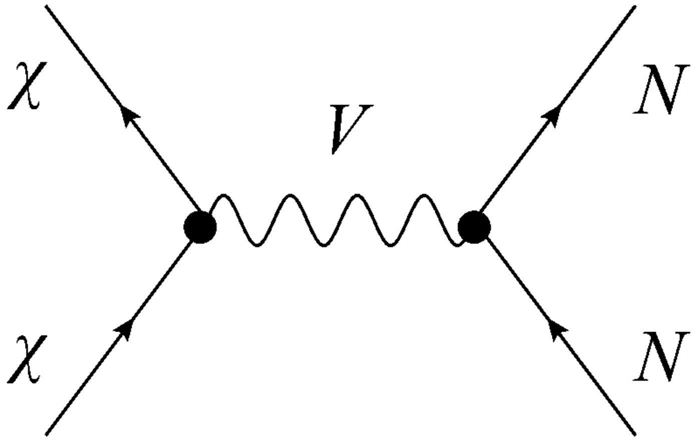

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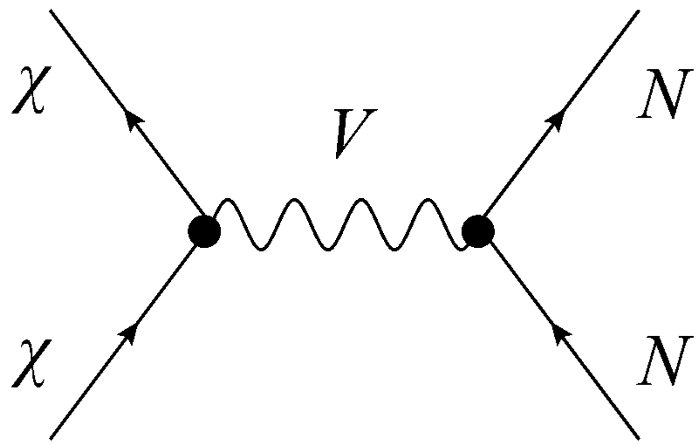

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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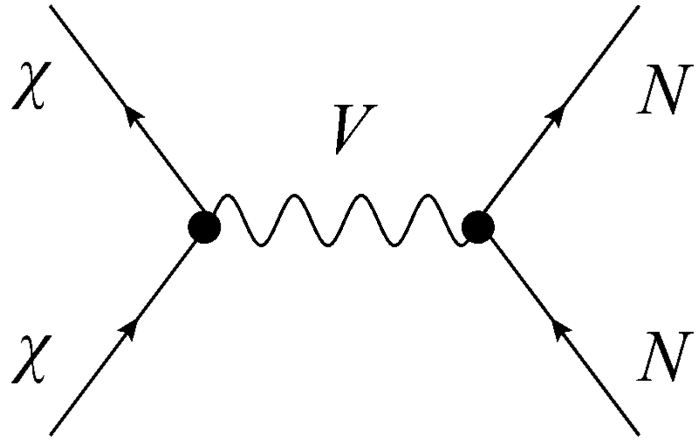

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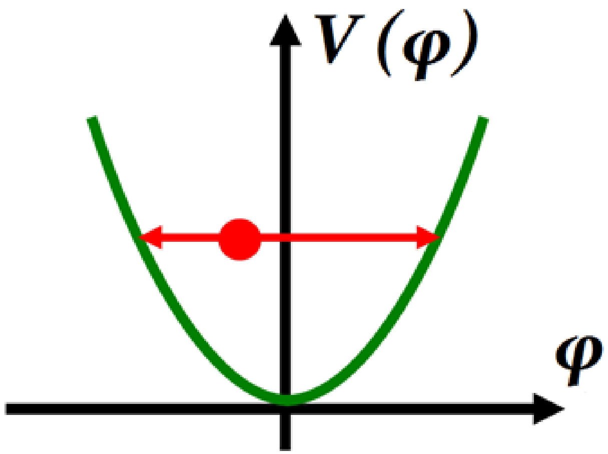
Question: *Can we instead look for effects of dark matter that are **first power** in the interaction constant?*

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)



$$V(\phi) = \frac{m_\phi^2 \phi^2}{2}$$

$$\tau_{\mathrm{coh}} \sim \frac{2\pi}{m_\phi \langle v_{\mathrm{DM}}^2 \rangle} \sim 10^6 T_{\mathrm{osc}}$$

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- 10^{-22} eV $\lesssim m_\varphi \ll 1$ eV <=> 10^{-8} Hz $\lesssim f \ll 10^{14}$ Hz

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

Classical field

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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):

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

$\longrightarrow$ Time-varying fundamental constants

- Atomic clocks
- Optical cavities
- Fifth-force searches
- Astrophysics (e.g., BBN)

$\longrightarrow$ Time-varying spin-dependent effects

- Co-magnetometers
- Nuclear magnetic resonance
- Torsion pendula

Low-mass Spin-0 Dark Matter

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"Thou shall measure frequency."

Low-mass Spin-0 Dark Matter

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→ Time-varying fundamental constants

→ Time-varying spin-dependent effects

- Atomic clocks

- Co-magnetometers

$f \sim 10^{15}$ Hz, $\Delta f \sim 10^{-3}$ Hz, $\Delta f/f \sim 10^{-18}$

$f \sim 100$ Hz, $\Delta f \sim 10^{-9}$ Hz, $\Delta f/f \sim 10^{-11}$

Low-mass Spin-0 Dark Matter

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(Dilatons):

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fundamental constants

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Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

Consider ***quadratic couplings*** of an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.*

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

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Oscillating variations
[Laboratory (high precision)]

Fifth Forces: Linear vs Quadratic Couplings

[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

Consider the effect of a massive body (e.g., Earth) on the scalar DM field

Fifth Forces: Linear vs Quadratic Couplings

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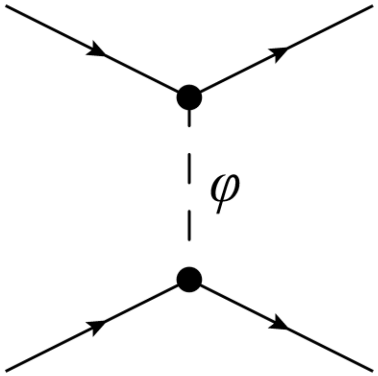

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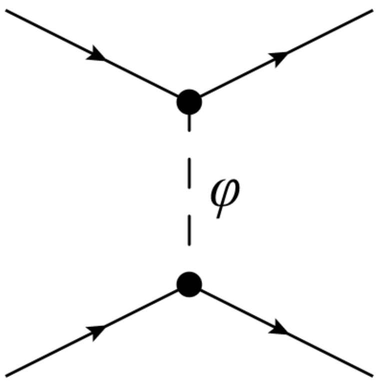

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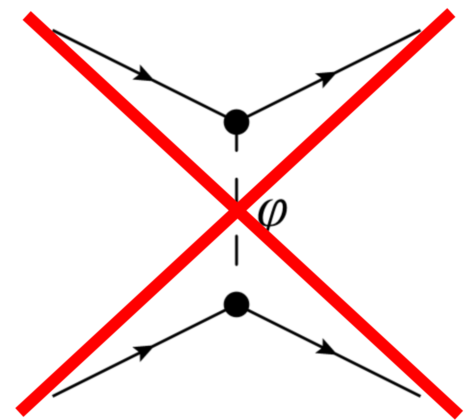

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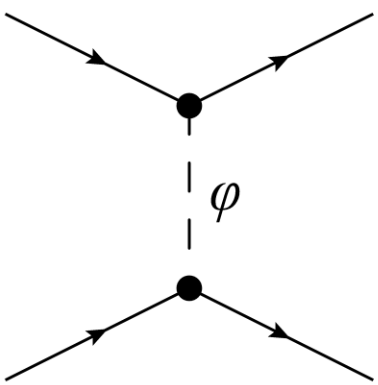

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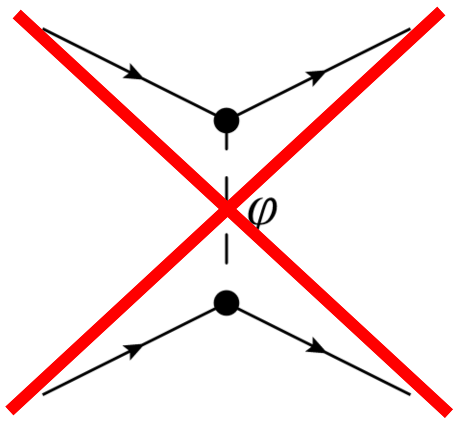

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Gradients + screening/amplification

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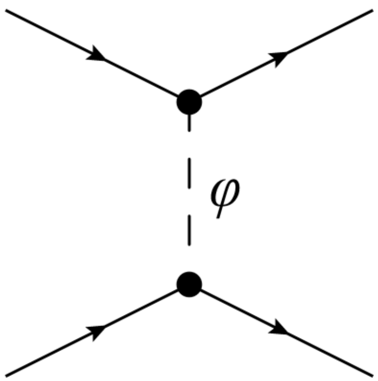

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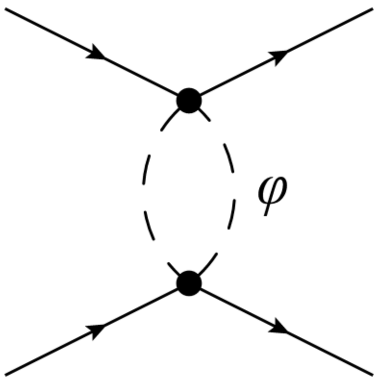

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Gradients + screening/amplification

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

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik, Flambaum, *PRL* **114**, 161301 (2015)]

$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_{X=\alpha, m_e/m_p, \ldots} \underbrace{\left(K_{X,1} - K_{X,2}\right)}_{\text{Sensitivity coefficients}} \cos\left(\omega t\right)$$

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

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- Precision of optical clocks approaching ~10^{-18} fractional level

Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Gravitational-wave detector (LIGO/Virgo), *L* ~ 4 km

Small-scale cavity, *L* ~ 0.2 m

Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

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- Compare $L \sim N a_\mathrm{B}$ with λ
- For a "usual" atomic optical transition and in the non-relativistic limit:*

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

* For numerical calculations, including (small) relativistic effects, see [Pasteka, Hao, Borschevsky, Flambaum, Schwerdtfeger, arXiv:1809.02863].

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- Multiple reflections of light beam enhance the effect ($N_{eff} \sim 10^5$ in small-scale interferometers with highly reflective mirrors; c.f. $N_{eff} \sim 100$ in LIGO/Virgo)

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Experiments

Clock/clock comparisons: 10^{-23} eV < m_φ < 10^{-16} eV

- **Dy/Cs (Mainz):** [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]
- **Rb/Cs (SYRTE):** [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]
- **Rb/Cs (GPS network)*:** [Roberts *et al.*, *Nature Commun.* **8**, 1195 (2017)]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ (NIST + JILA):** [Hume, Leibrandt *et al.*, In preparation]
- **Yb^+(E3)/Sr (PTB):** [Huntemann, Peik *et al.*, In preparation]

Clock/cavity comparisons: 10^{-20} eV < m_φ < 10^{-15} eV

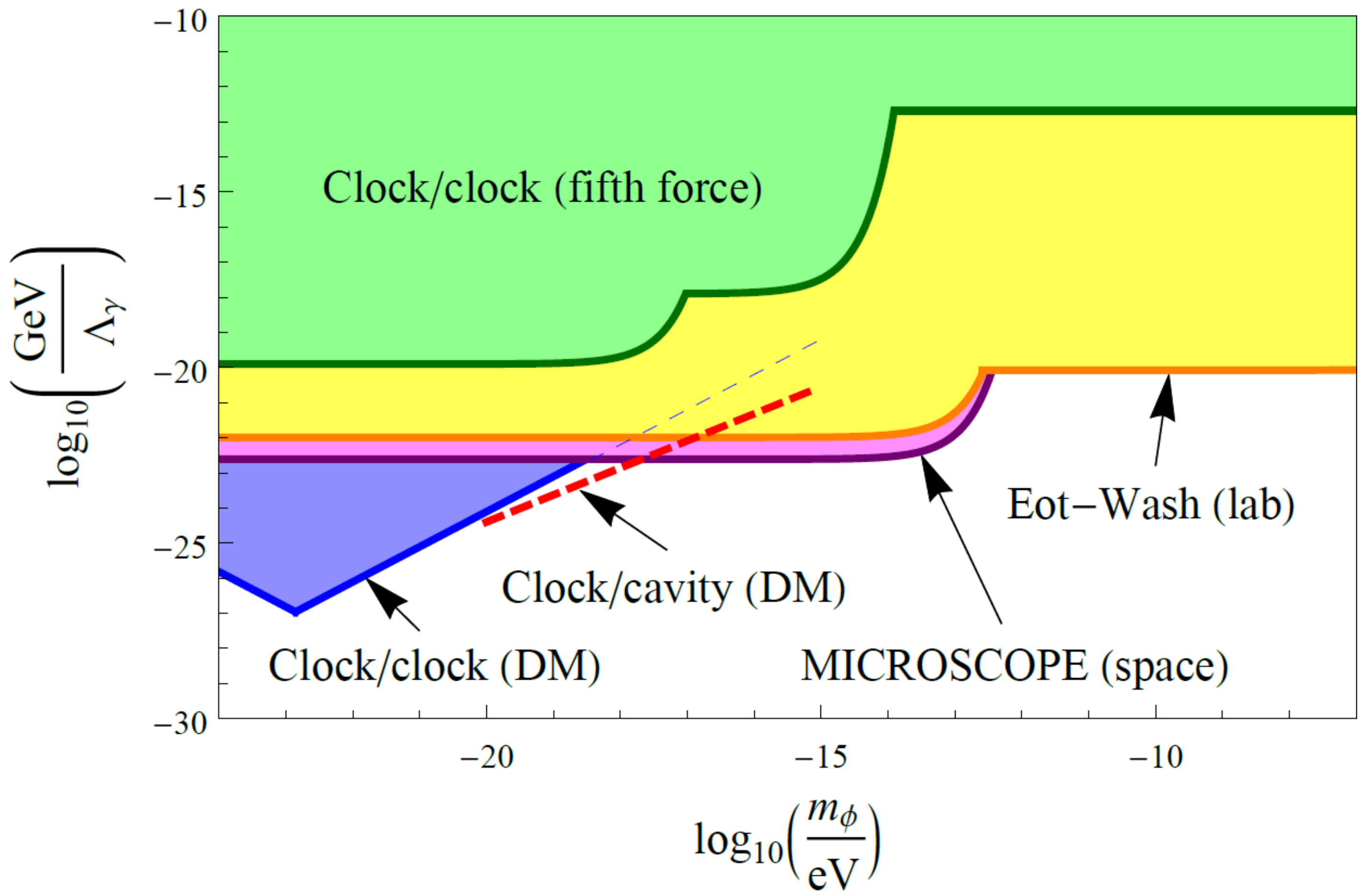
- **Sr/ULE cavity (Torun)*:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Sr/Si cavity (JILA):** [Robinson, Ye *et al.*, In preparation]

* Searches for domain wall dark matter.

Constraints on Linear Interaction of Scalar Dark Matter with the Photon

Clock/clock (DM) constraints: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Hees *et al.*, *PRL* **117**, 061301 (2016)]; **Clock/clock (fifth force) constraints:** [Leefer *et al.*, *PRL* **117**, 271601 (2016)]

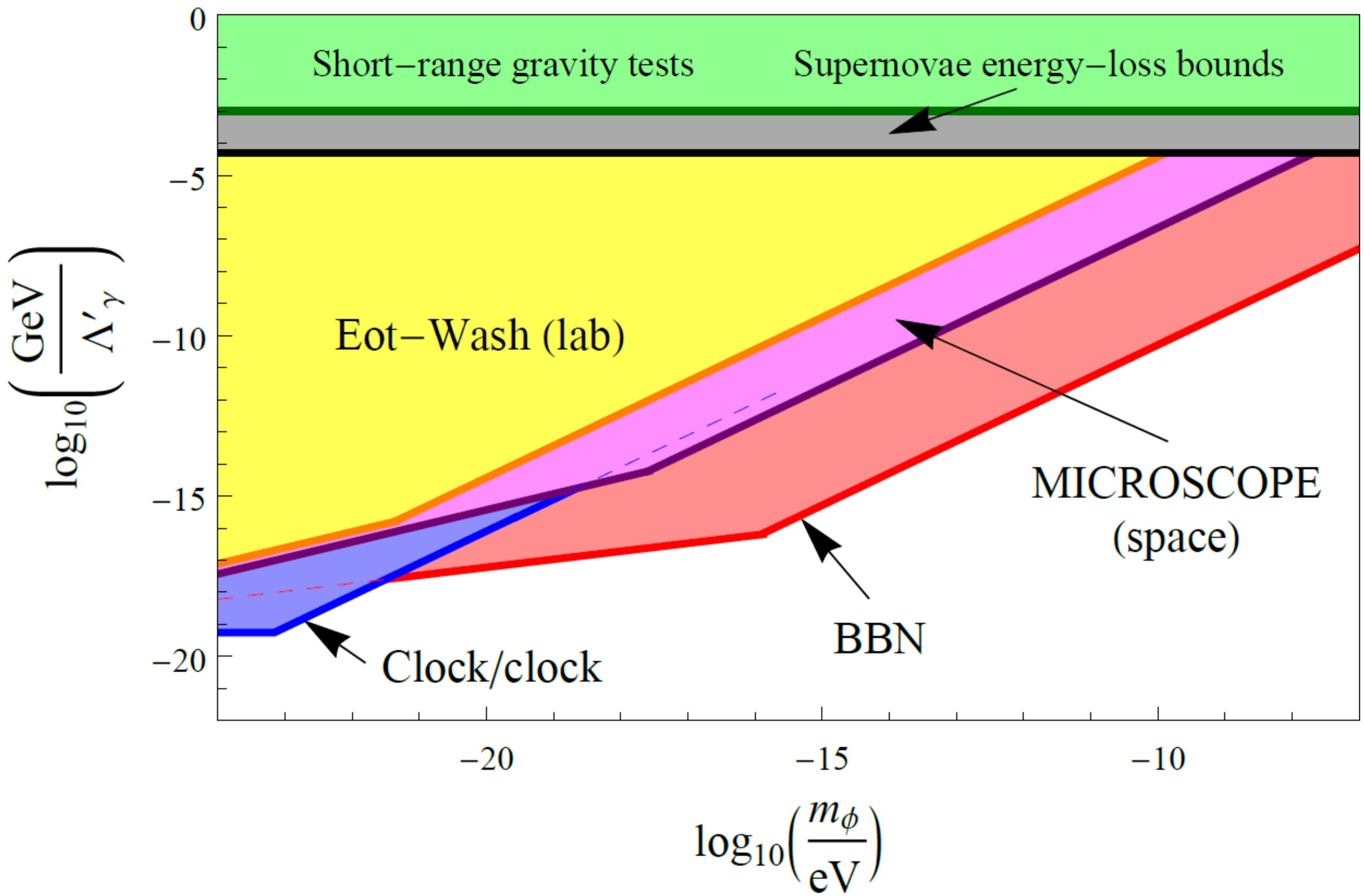
4 orders of magnitude improvement!



Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

Clock/clock + BBN constraints: [Stadnik, Flambaum, *PRL* **115**, 201301 (2015); *PRA* **94**, 022111 (2016)]; **MICROSCOPE + Eöt-Wash constraints:** [Hees *et al*., *PRD* **98**, 064051 (2018)]

15 orders of magnitude improvement!



Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

QCD axion resolves strong CP problem

→ Time-varying spin-dependent effects

- Co-magnetometers
- Nuclear magnetic resonance
- Torsion pendula

"Axion Wind" Spin-Precession Effect

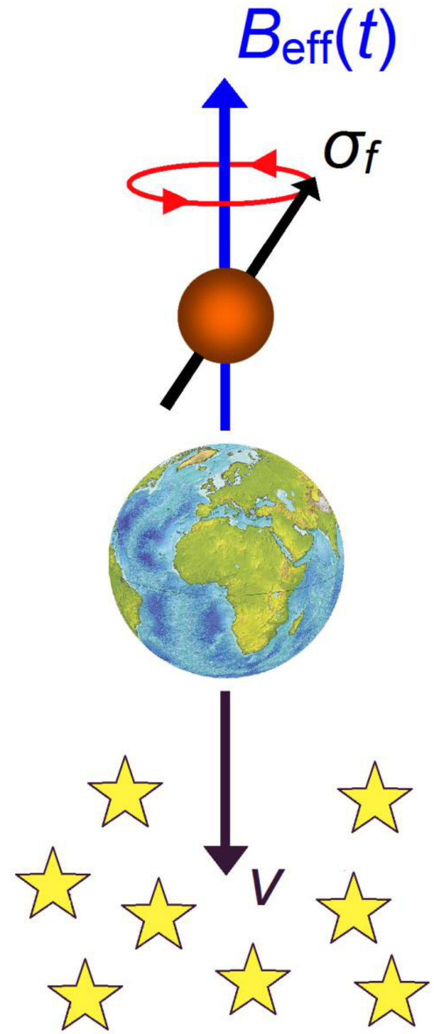
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field** *

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



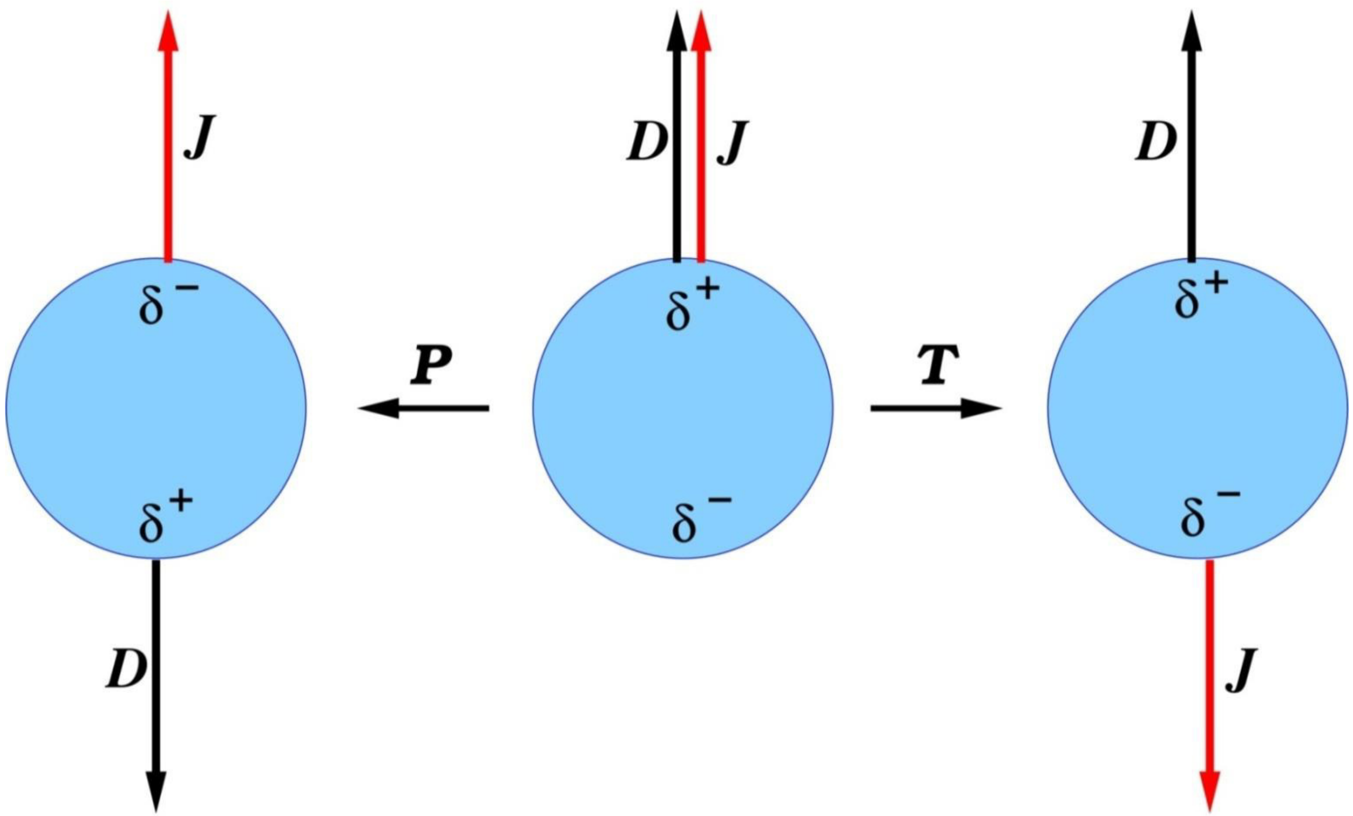
* Compare with usual magnetic field: $H = -\boldsymbol{\mu}_f\cdot\boldsymbol{B}$

Oscillating Electric Dipole Moments

Nucleons: [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

Electric Dipole Moment (EDM) = parity (P) and time-reversal-invariance (T) violating electric moment



Searching for Spin-Dependent Effects

Proposals: [Flambaum, talk at *Patras Workshop*, 2013; Stadnik, Flambaum, *PRD* **89**, 043522 (2014); arXiv:1511.04098; Stadnik, PhD Thesis (2017)]

Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

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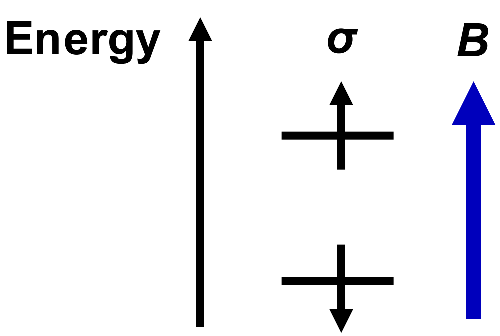
$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left| \frac{\mu_n B}{\mu_{\mathrm{Hg}} B} \right| + R(t)$$

***B*-field effect**

Axion DM effect



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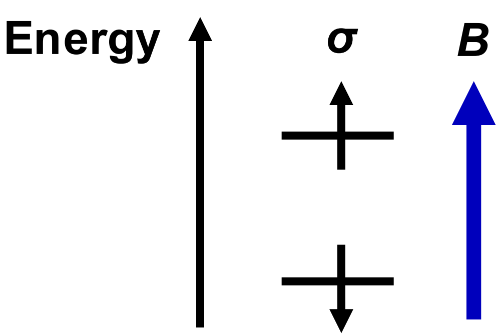

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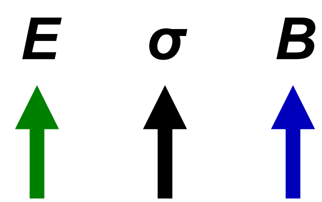

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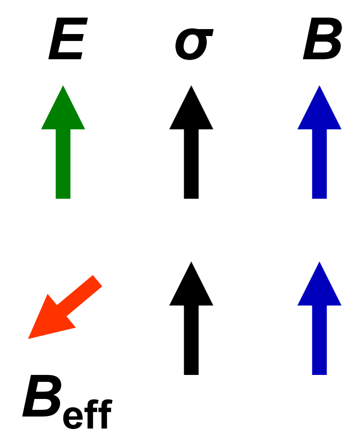
$$R_{\mathrm{wind}}(t) \propto \sum_{i=1,2,3} A_i \sin(\omega_i t)$$



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

Earth's rotation

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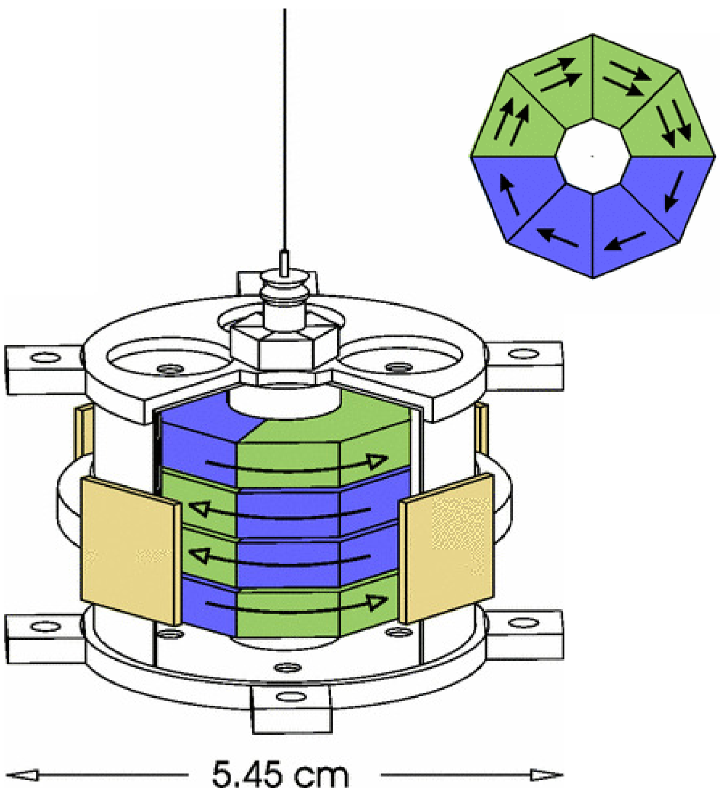

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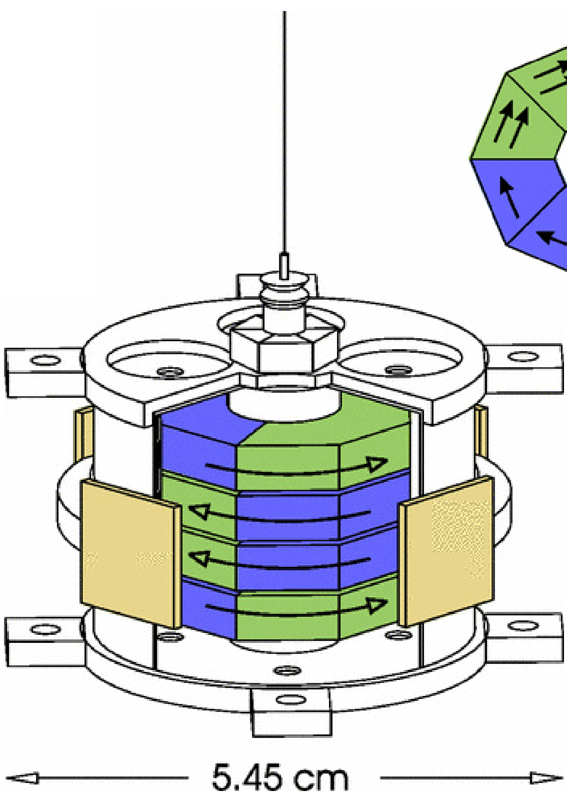

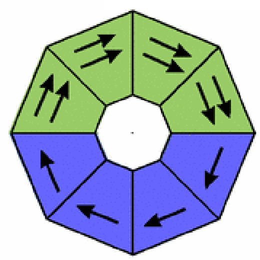

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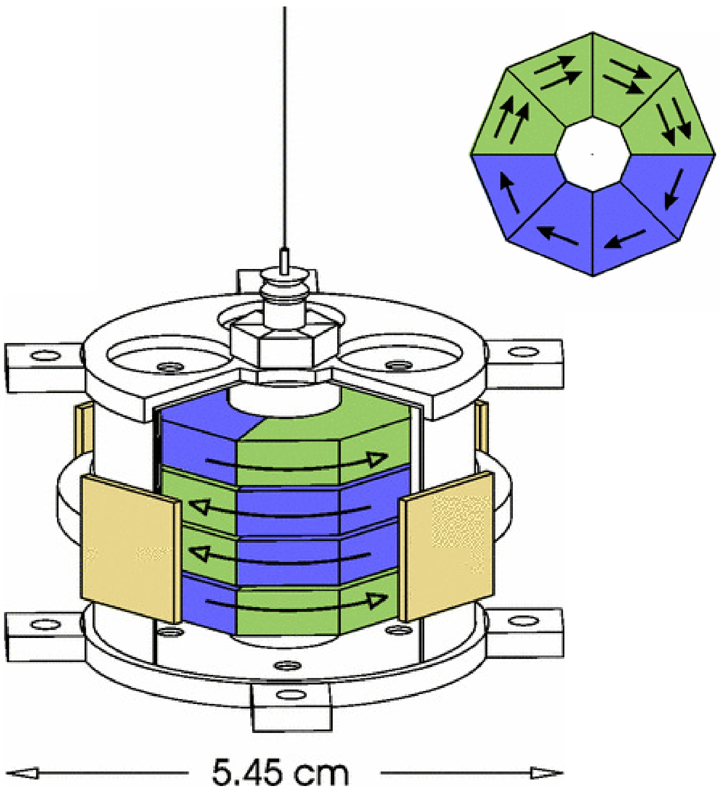

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$$\boldsymbol{\tau}(t) \propto (\boldsymbol{\sigma}_e)_{\text{pendulum}} \times \boldsymbol{B}_{\text{eff}}(t)$$

Searching for Spin-Dependent Effects

Proposals: [Garcon *et al*., *Quantum Sci. Technol.* **3**, 014008 (2018)]

Use *nuclear magnetic resonance* (“sidebands” technique)

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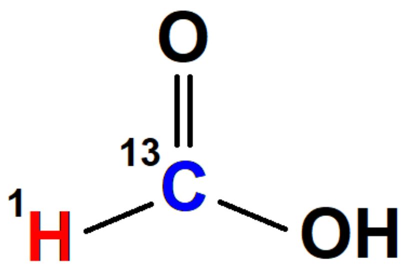

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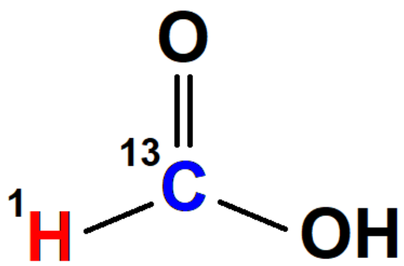

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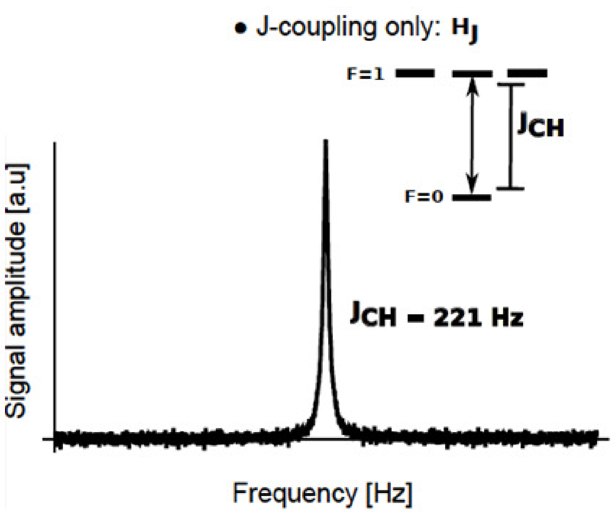

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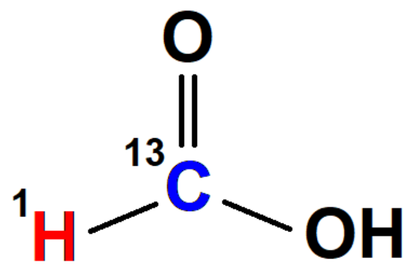

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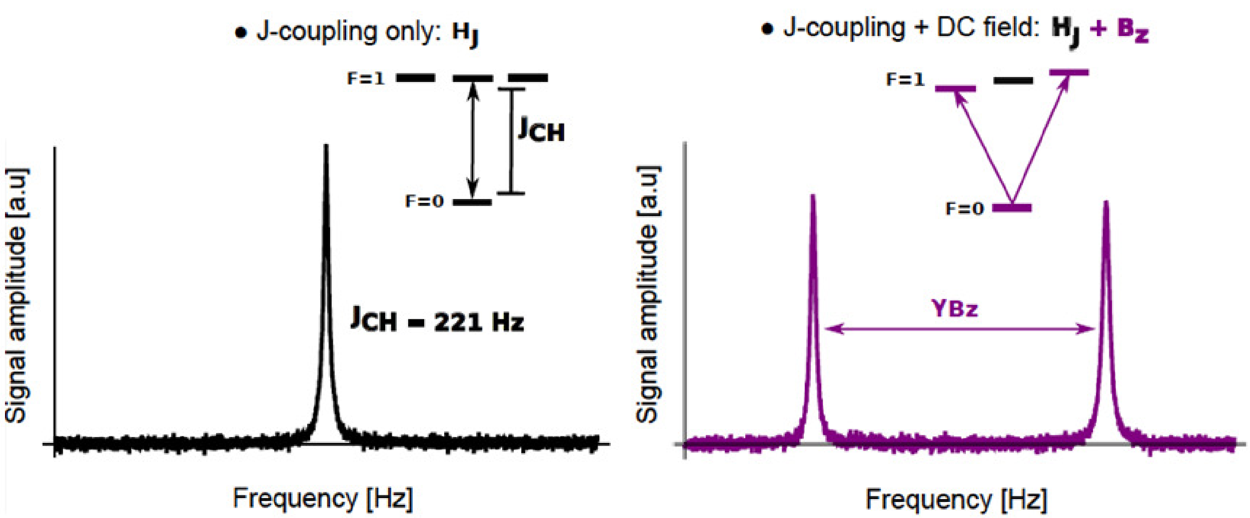

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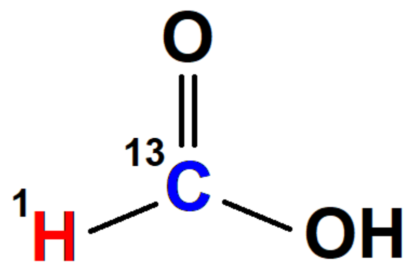

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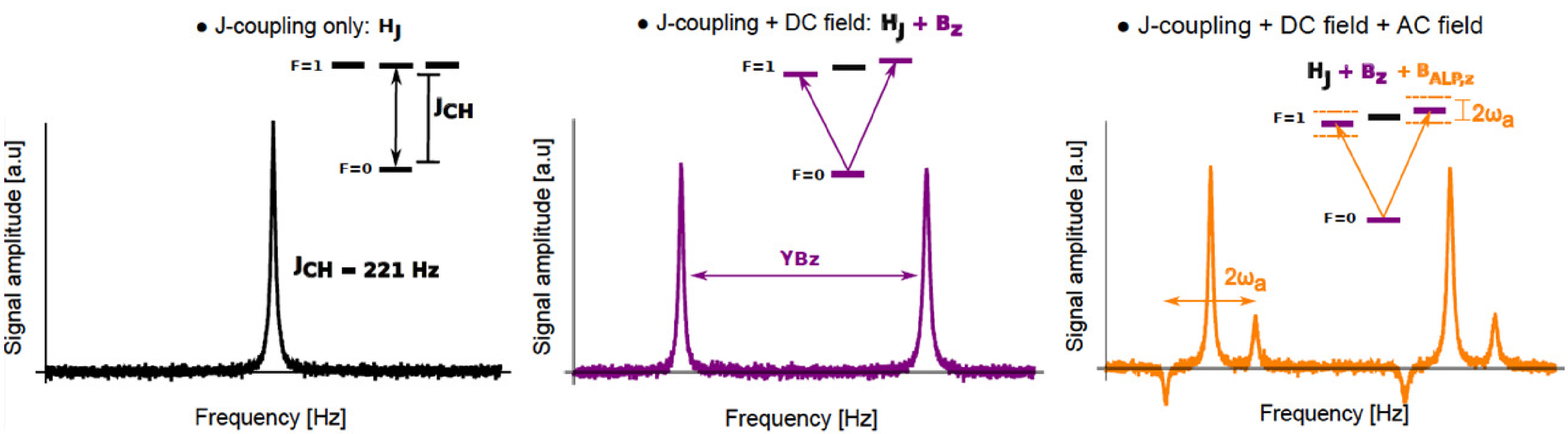

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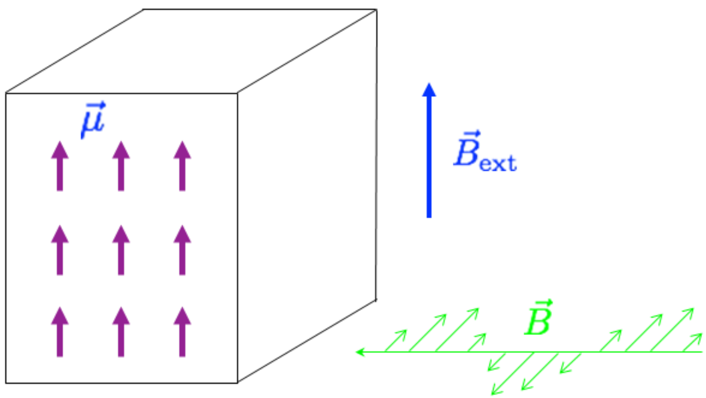
Traditional NMR



Resonance: $2\mu B_{\rm ext} = \omega$

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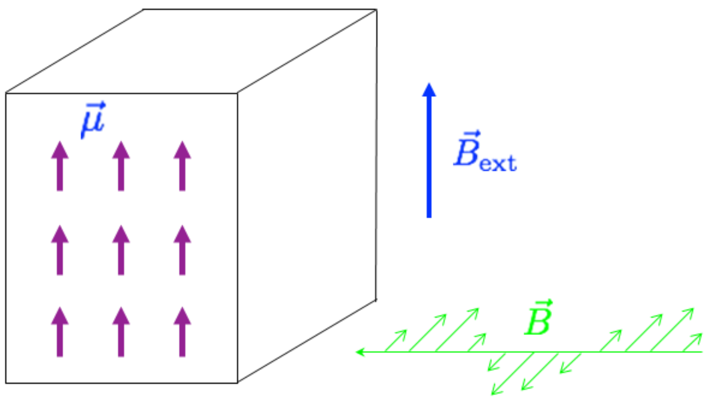

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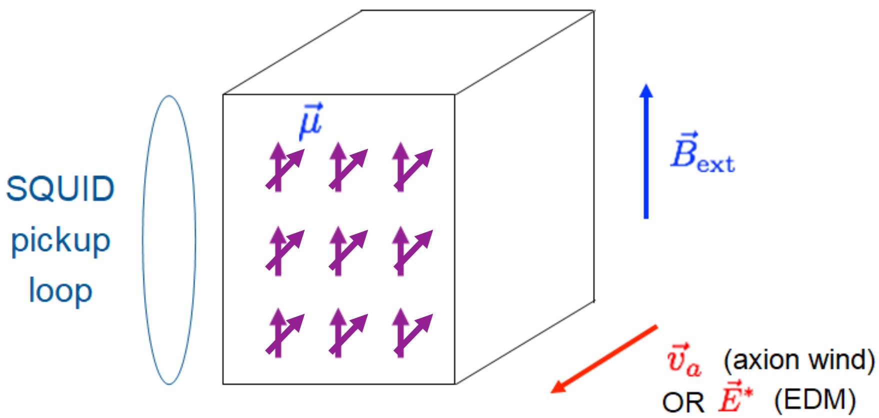
Dark-matter-driven NMR



Resonance: $2\mu B_{\text{ext}} \approx m_a$

Measure transverse magnetisation

Experiments

Co-magnetometry: 10^{-23} eV < m_a < 10^{-17} eV

- **n/Hg (PSI):** [nEDM collaboration, *PRX* **7**, 041034 (2017)]
- **Acetonitrile (Mainz):** [Wu *et al*., arXiv:1901.10843]

Torsion pendulum: 10^{-23} eV < m_a < 10^{-18} eV

- **Alnico/$SmCo_5$ (Seattle):** [Terrano *et al*., arXiv:1902.04246]

"Sidebands" NMR: 10^{-16} eV < m_a < 10^{-13} eV

- **Formic acid (Mainz):** [Garcon *et al*., arXiv:1902.04644]

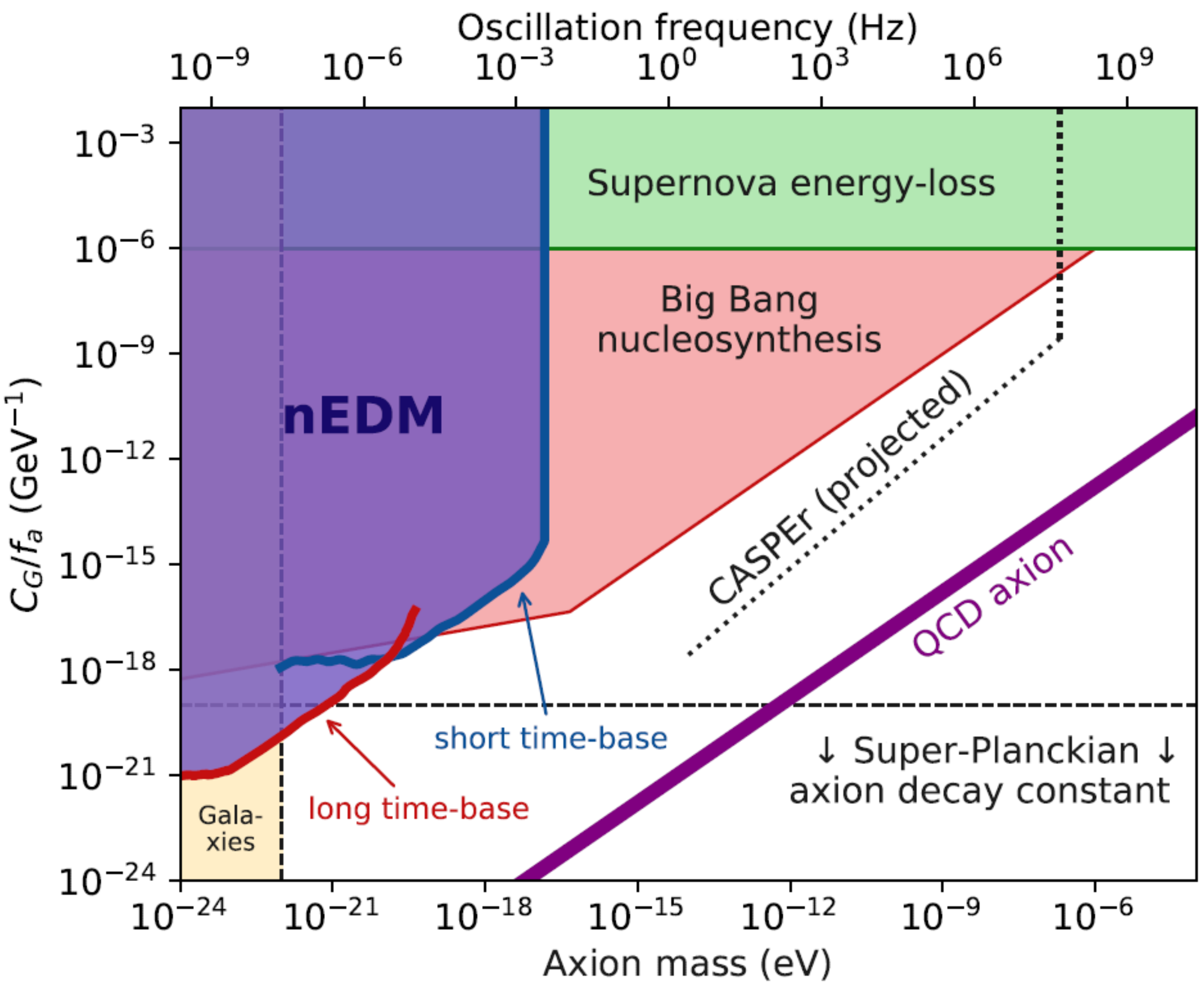
"Normal" NMR: 10^{-14} eV < m_a < 10^{-7} eV

- **Liquid Xe (Mainz)**
- **Pb in ferroelectric medium (Boston)**

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

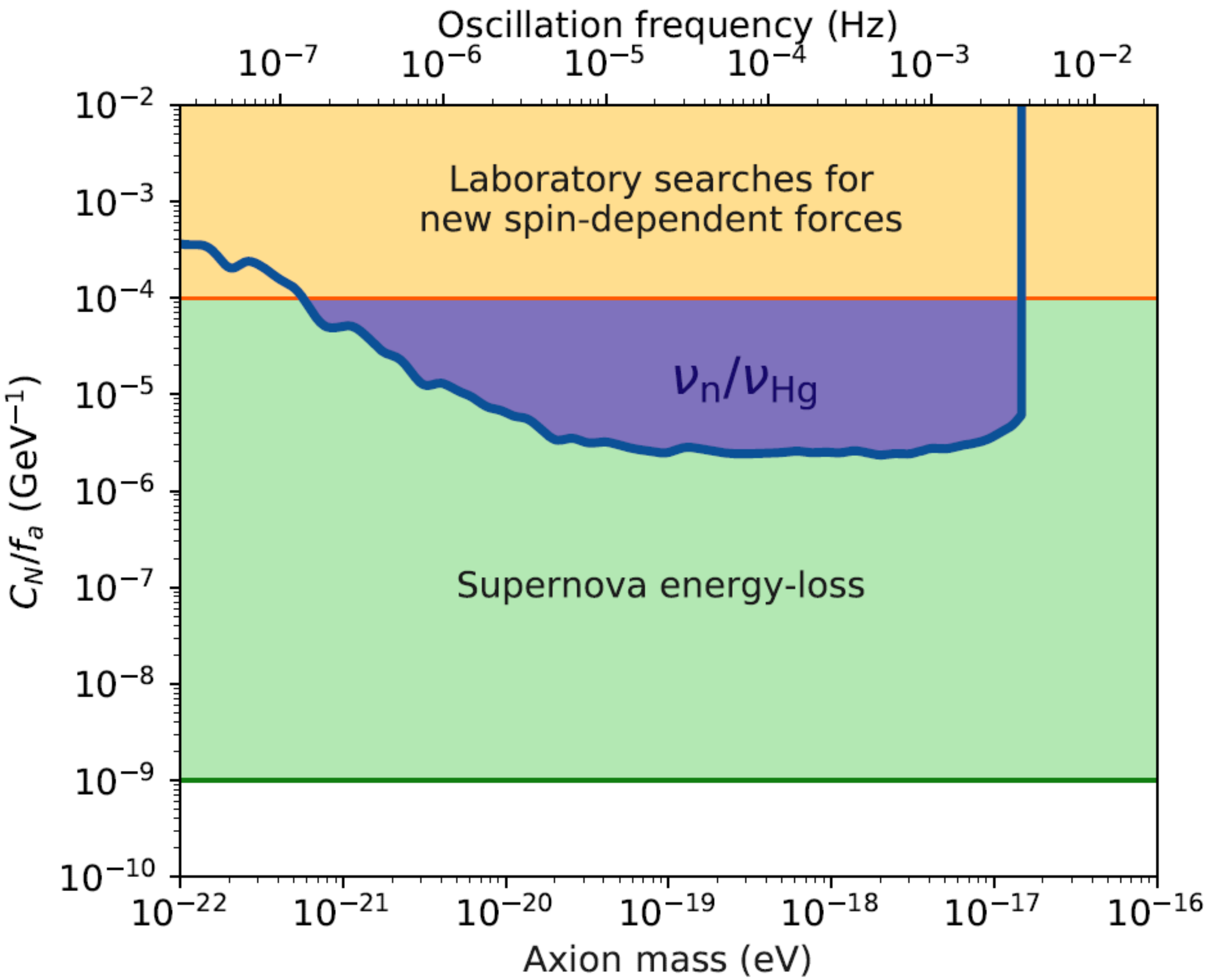
3 orders of magnitude improvement!



Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

40-fold improvement (laboratory bounds)!

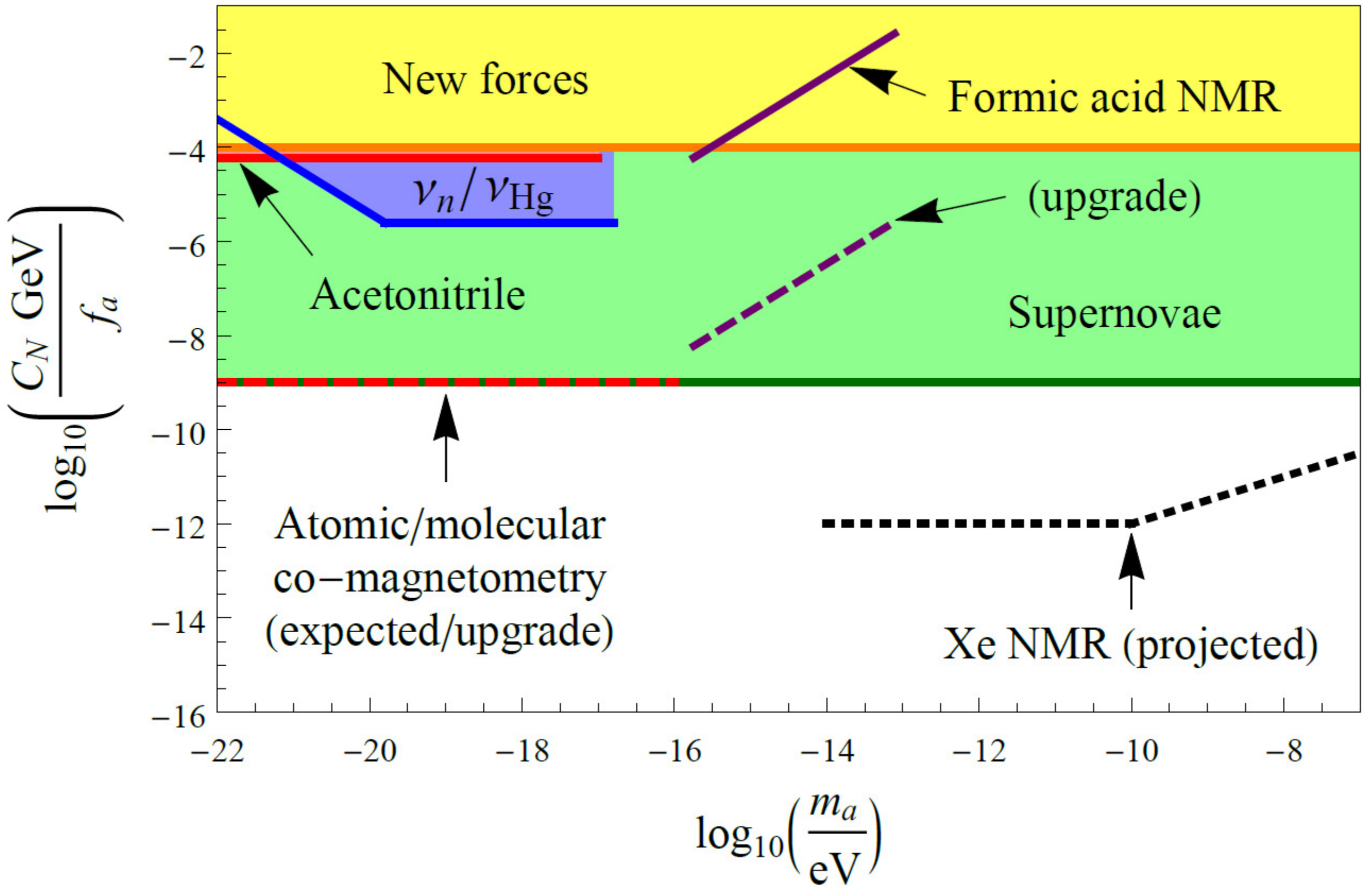


Constraints on Interaction of Axion Dark Matter with Nucleons

ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

Acetonitrile constraints: [Wu *et al*., arXiv:1901.10843]

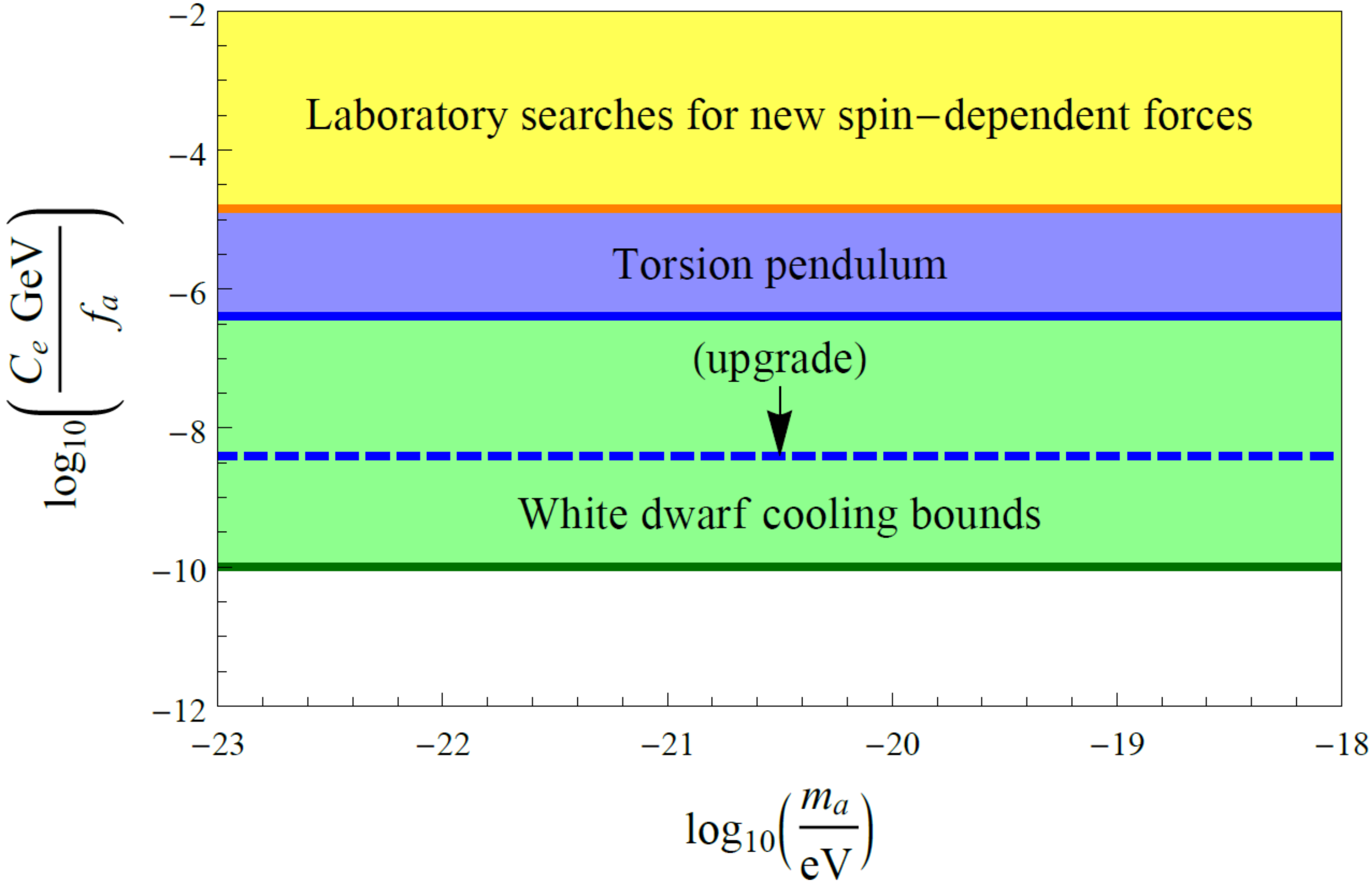
Formic acid NMR constraints: [Garcon *et al*., arXiv:1902.04644]



Constraints on Interaction of Axion Dark Matter with the Electron

Torsion pendulum constraints: [Terrano *et al.*, arXiv:1902.04246]

35-fold improvement (laboratory bounds)!



Summary

- New classes of dark matter effects that are **first power** in the underlying interaction constant => Up to **15 orders of magnitude improvement** with low-energy probes:
  - Spectroscopy
  - Cavities and interferometry
  - Magnetometry
  - Torsion pendula

⋮

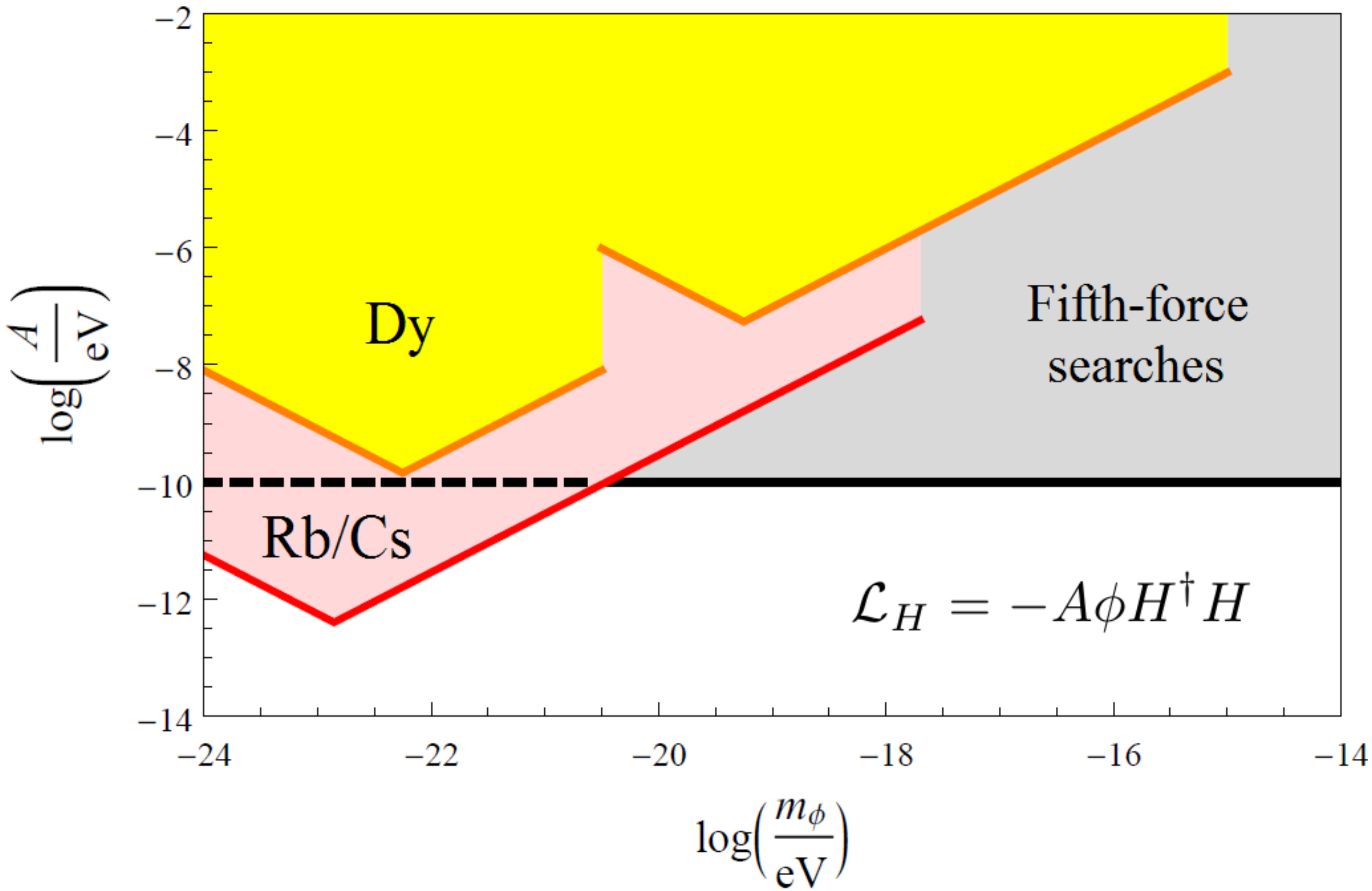
Back-up Slides

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

Rb/Cs constraints:

[Stadnik, Flambaum, *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!



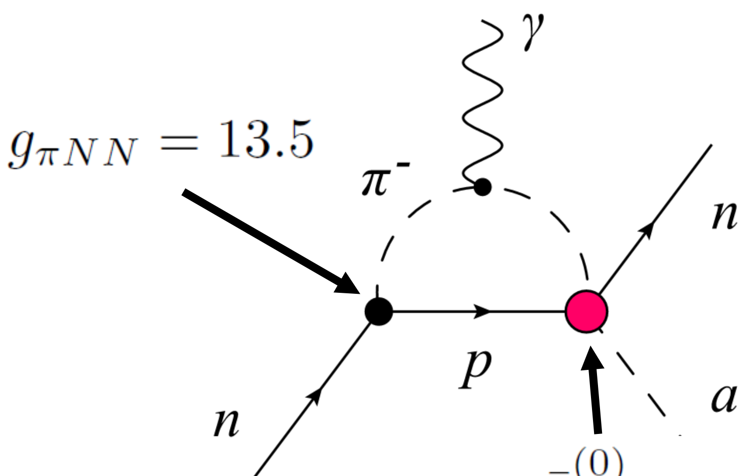
Oscillating Electric Dipole Moments

Nucleons: [Graham, Rajendran, *PRD* **84**, 055013 (2011)]

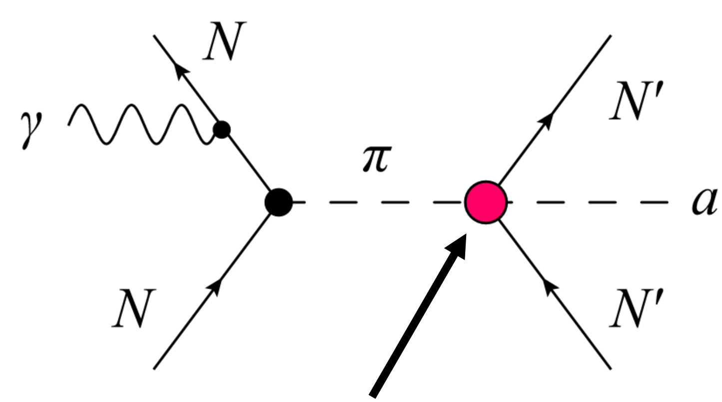
Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

Nucleon EDMs



***CP*-violating intranuclear forces**



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

In nuclei, <u>tree-level</u> *CP*-violating intranuclear forces dominate over <u>loop-induced</u> nucleon EDMs (loop factor = $1/(8\pi^2)$).

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

[Stadnik, Flambaum, *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)

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

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

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

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

Back-Reaction Effects in BBN

[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]