Searching for Dark Matter with Magnetic Resonance and Atomic Clocks

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Collaborators (Theory):

Victor Flambaum group (UNSW)

Peter Wolf group (SYRTE)

Collaborators (Experiment):

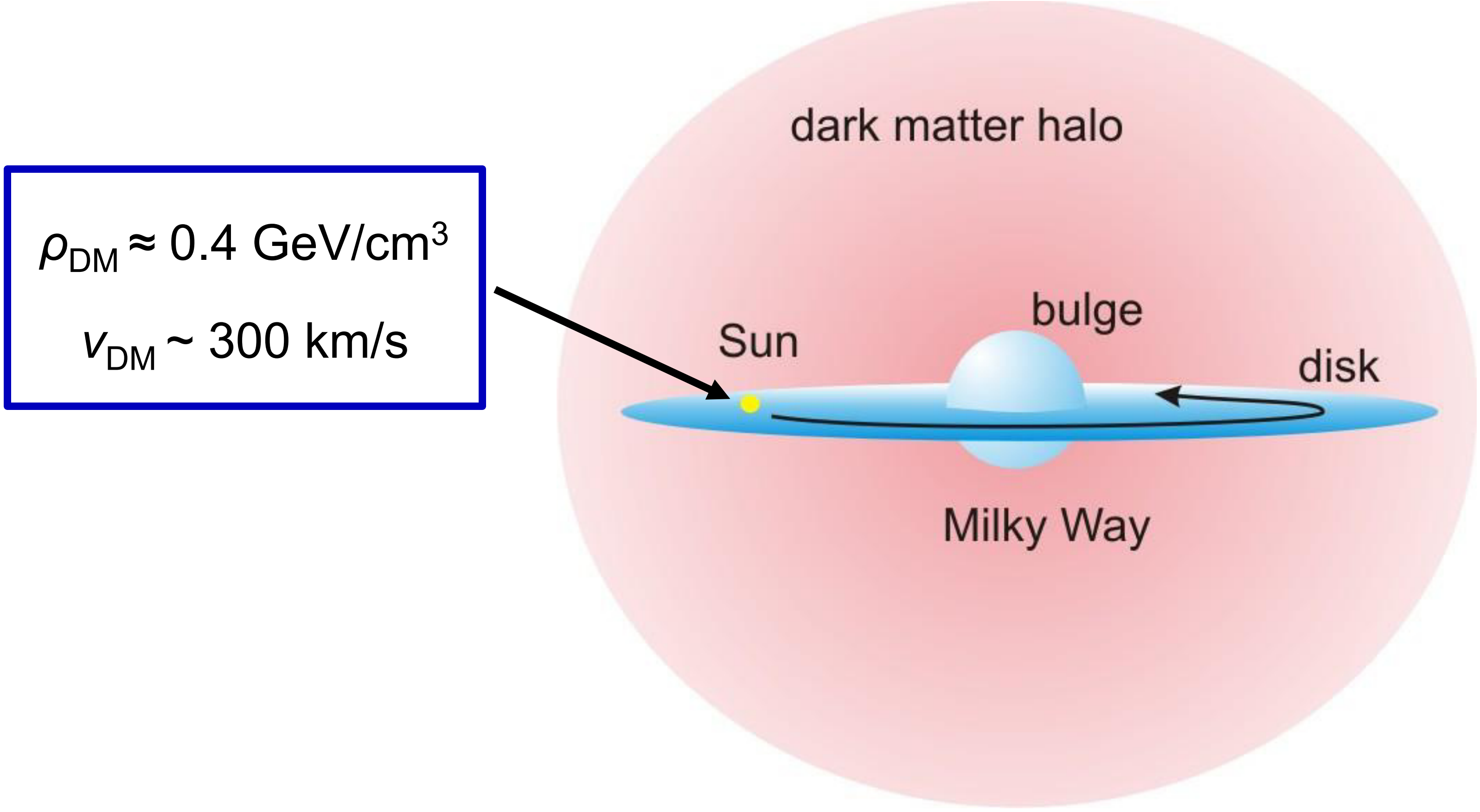
Dmitry Budker group (Mainz)

nEDM collaboration at PSI and Sussex

Quantum Sensors for Fundamental Physics, Oxford, October 2018

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

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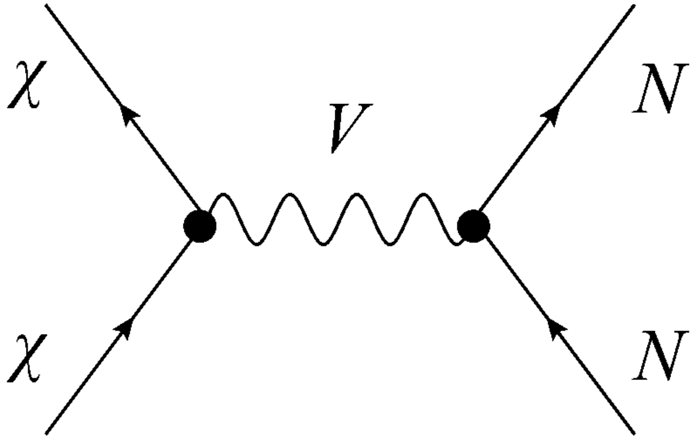
Traditional “scattering-off-nuclei” searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



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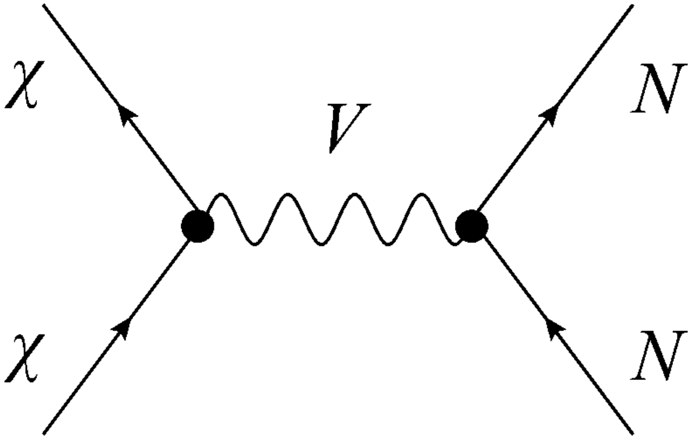

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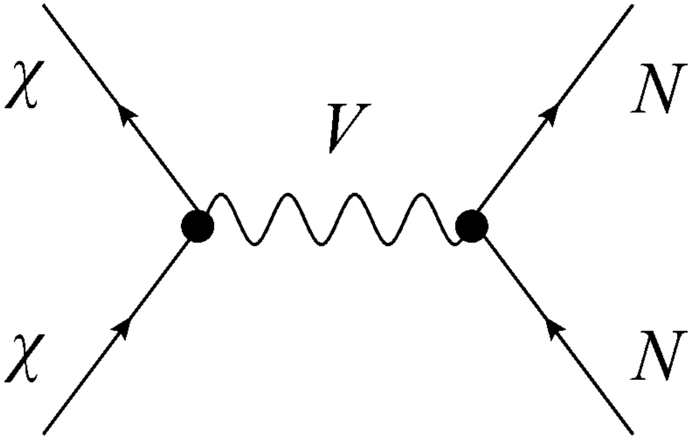

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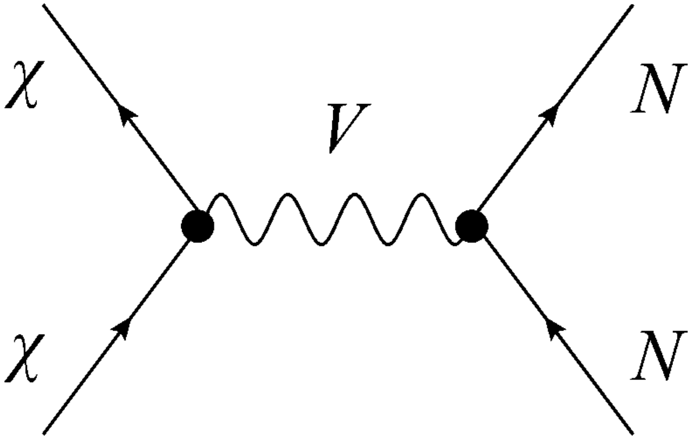

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Challenge: Observable is **fourth power** in a small interaction constant (e' << 1)!

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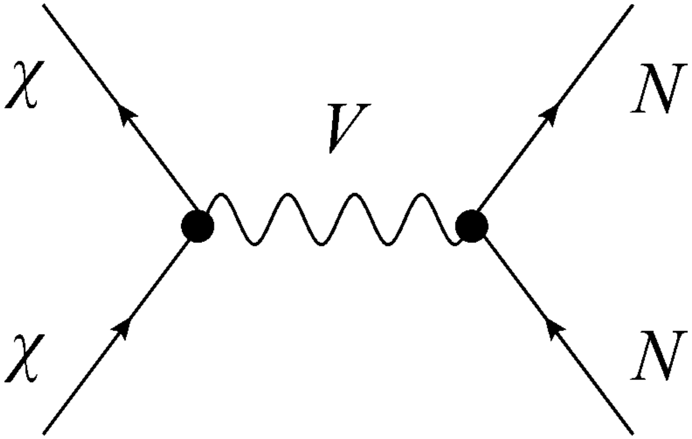

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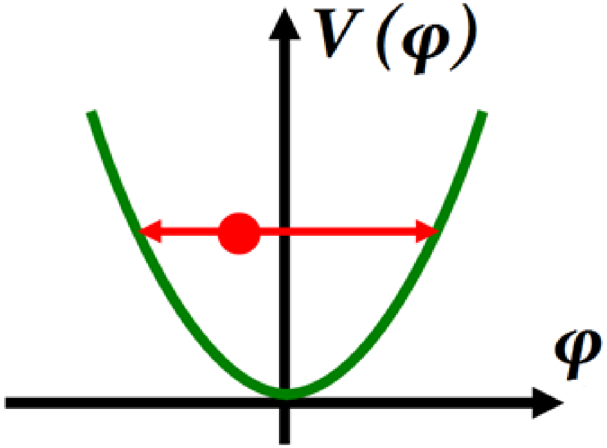
Question: *Can we instead look for effects of dark matter that are **first power** in the interaction constant?*

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 $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4\ \mathrm{GeV/cm^3}$)



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

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

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

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

Classical field

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

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

→ Time-varying fundamental constants

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

→ Time-varying spin-dependent effects

- Co-magnetometers
- Nuclear magnetic resonance
- Torsion pendula

Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

QCD axion resolves strong CP problem

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"Axion Wind" Spin-Precession Effect

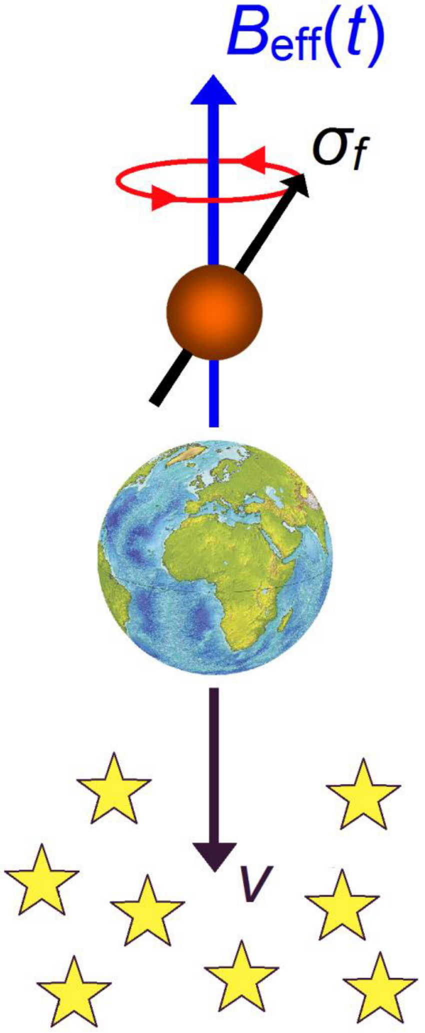
[Flambaum, talk at *Patras Workshop*, 2013], [Graham, Rajendran, *PRD* **88**, 035023 (2013)], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field** *

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



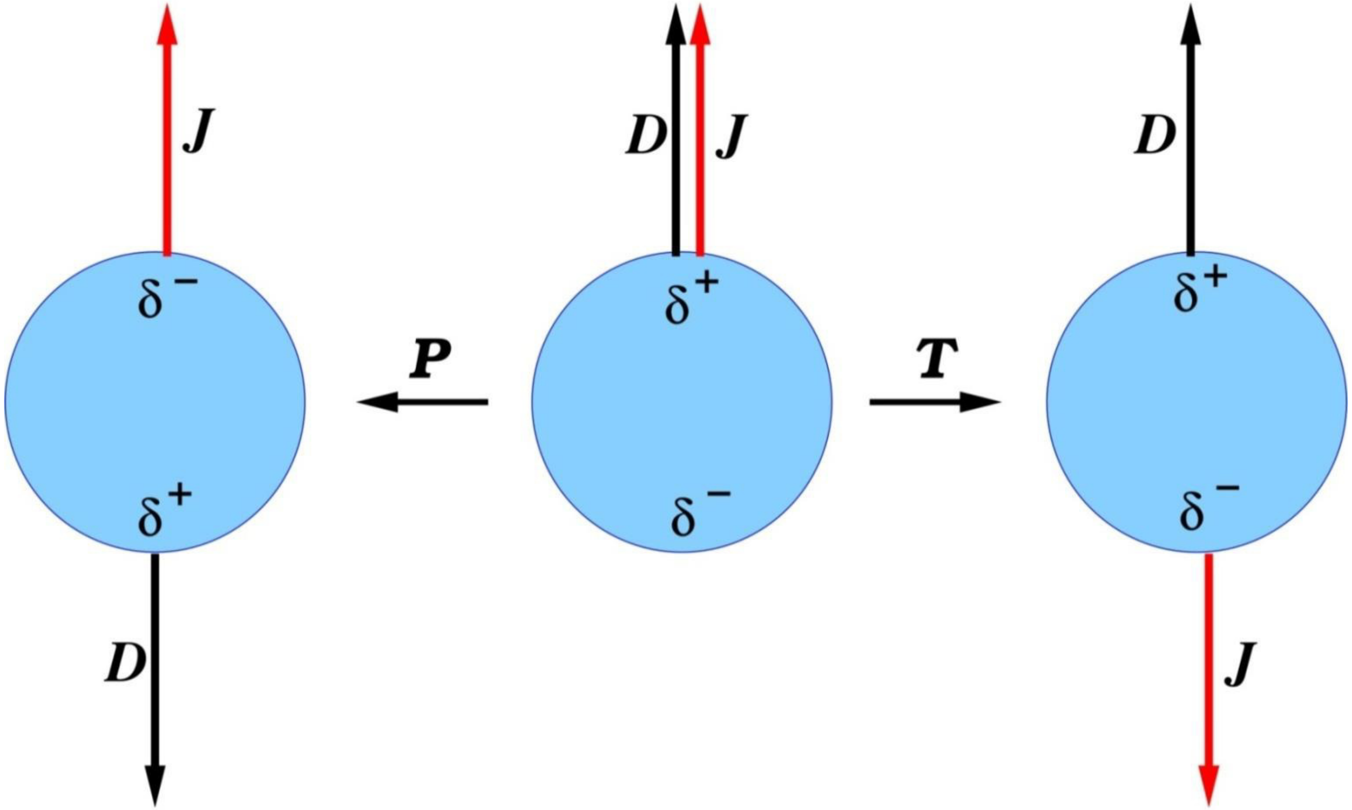
* Compare with usual magnetic field: $H = -\boldsymbol{\mu}_f \cdot \boldsymbol{B}$

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



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

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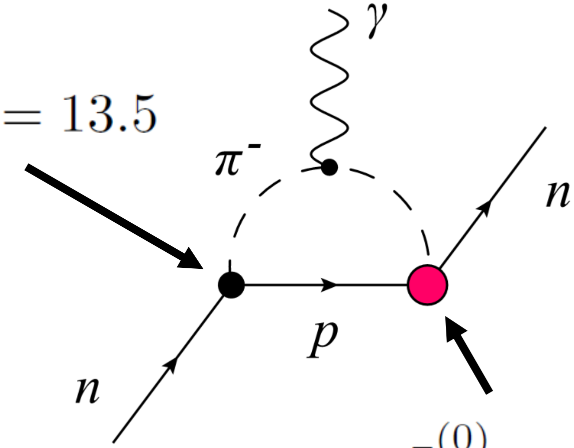

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$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$

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CP-violating intranuclear forces

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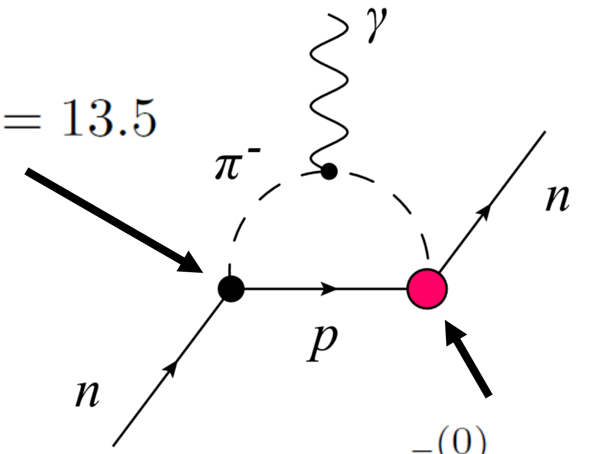

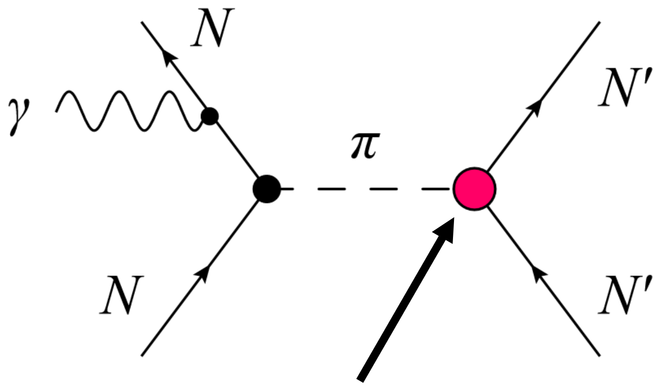

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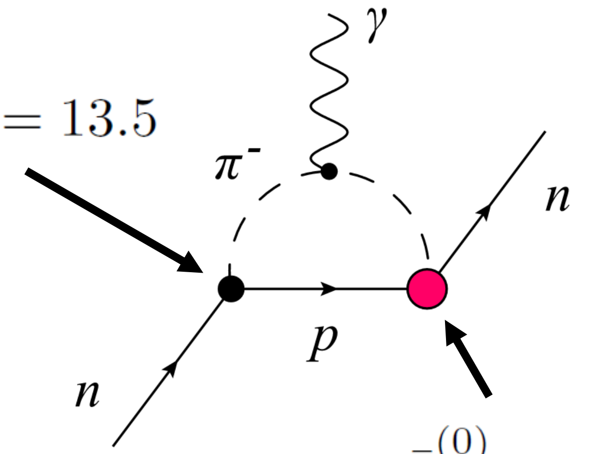
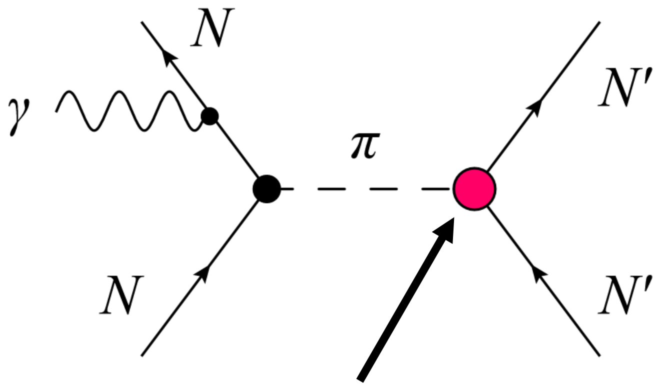


***CP*-violating intranuclear forces**



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

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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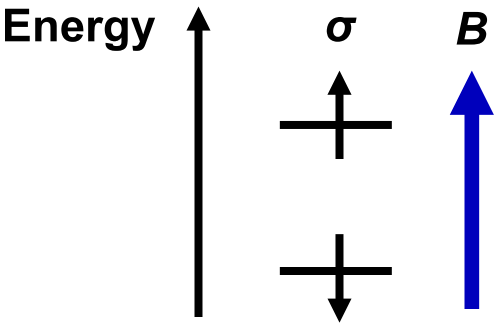
$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \underbrace{\left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right|}_{\textbf{\textit{B}}\text{-field effect}} + \underbrace{R(t)}_{\text{Axion DM effect}}$$



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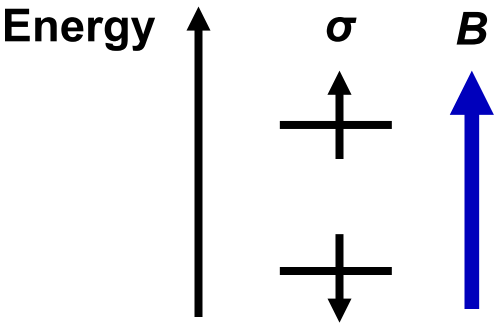
***B*-field effect**

Axion DM effect



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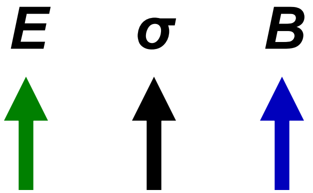

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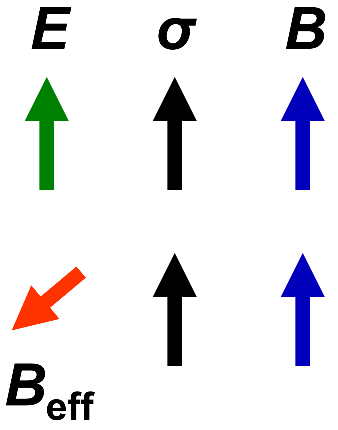
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$

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



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

Earth's rotation

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Use *nuclear magnetic resonance* ("sidebands" technique)

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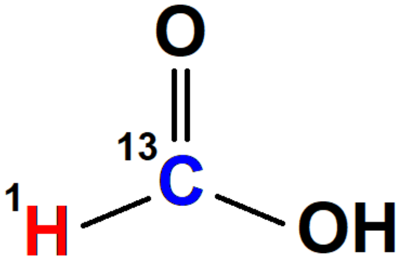

$$H_J \sim J\,\boldsymbol{I}_{\mathrm{H}}\cdot\boldsymbol{I}_{\mathrm{C}}$$

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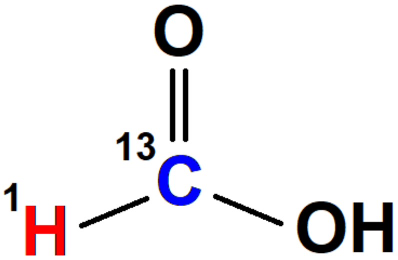

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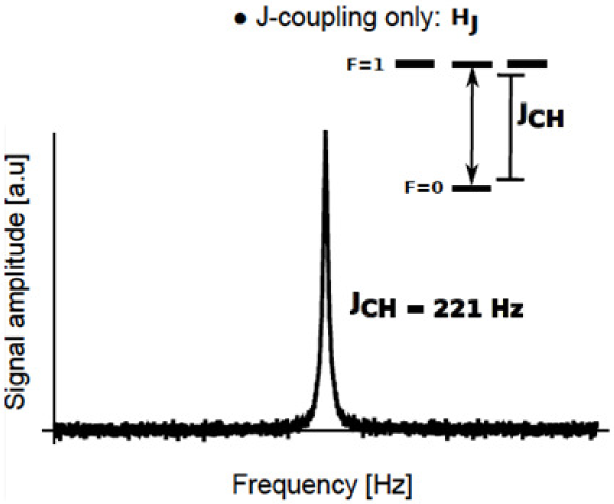

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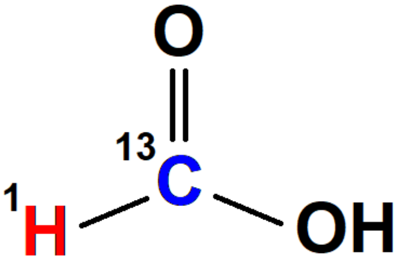

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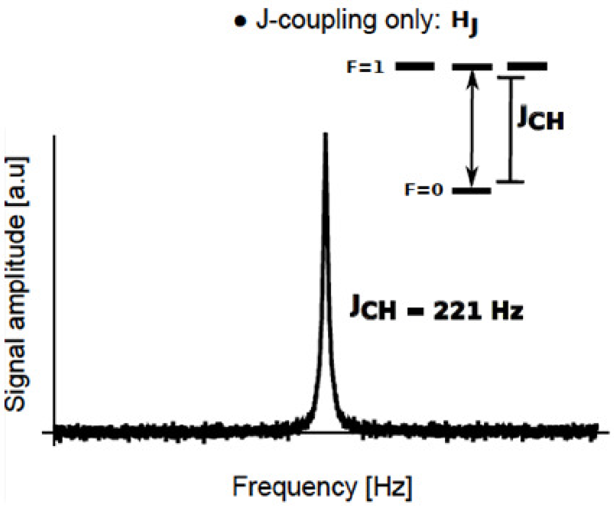

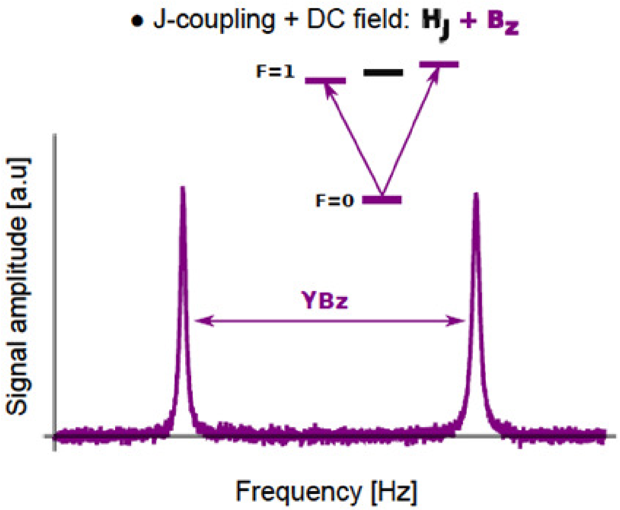

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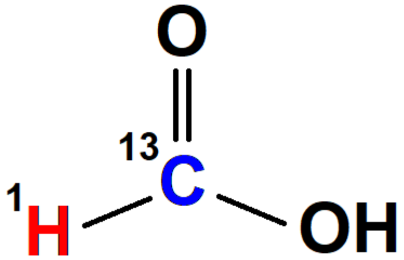

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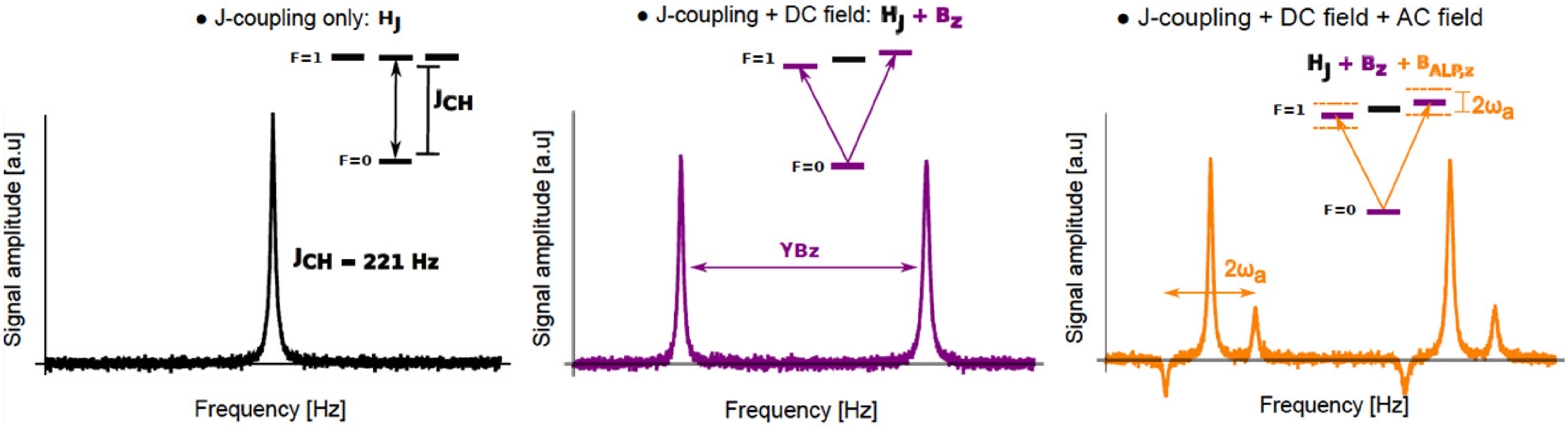

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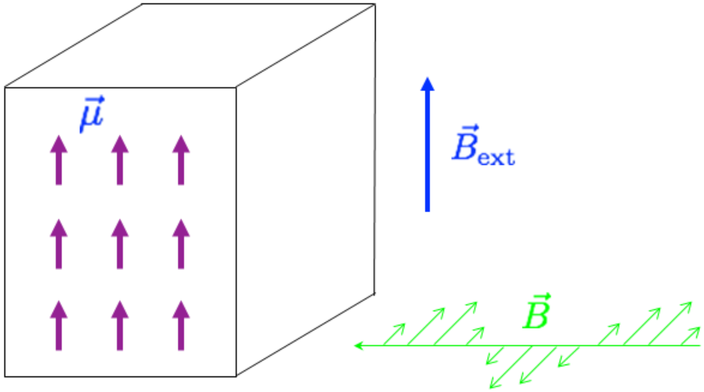
Traditional NMR



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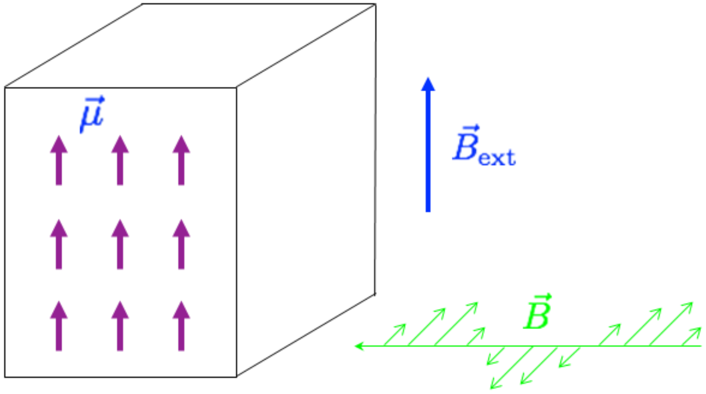

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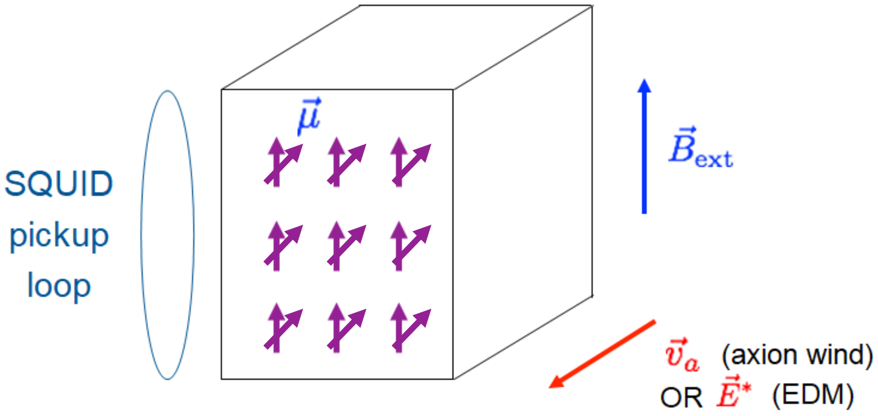
Dark-matter-driven NMR



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)]

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

- **Formic acid (Mainz):** [CASPEr collaboration, In preparation]

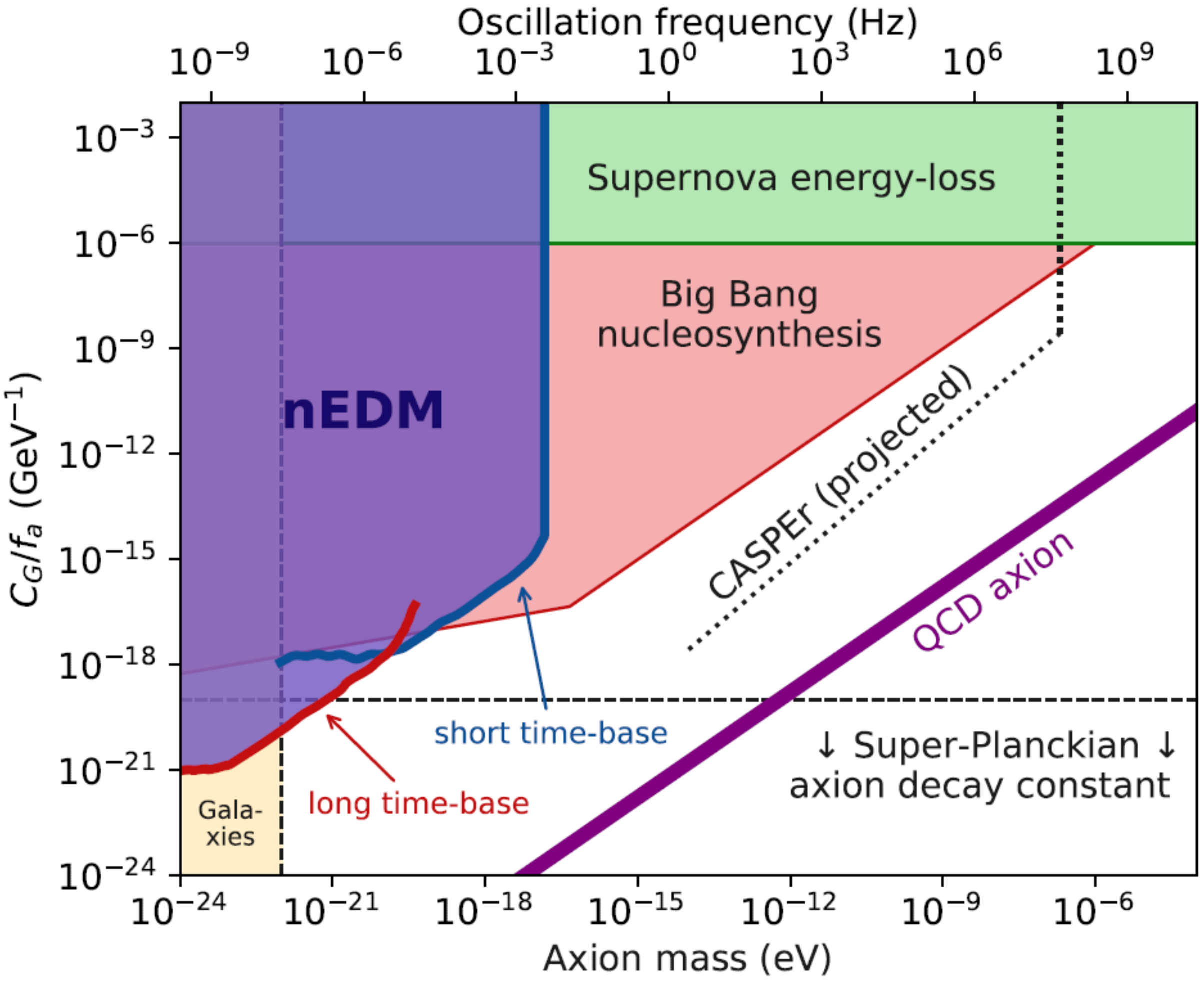
“Normal” NMR: 10^{-14} eV < m_a < 10^{-7} eV

- **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!

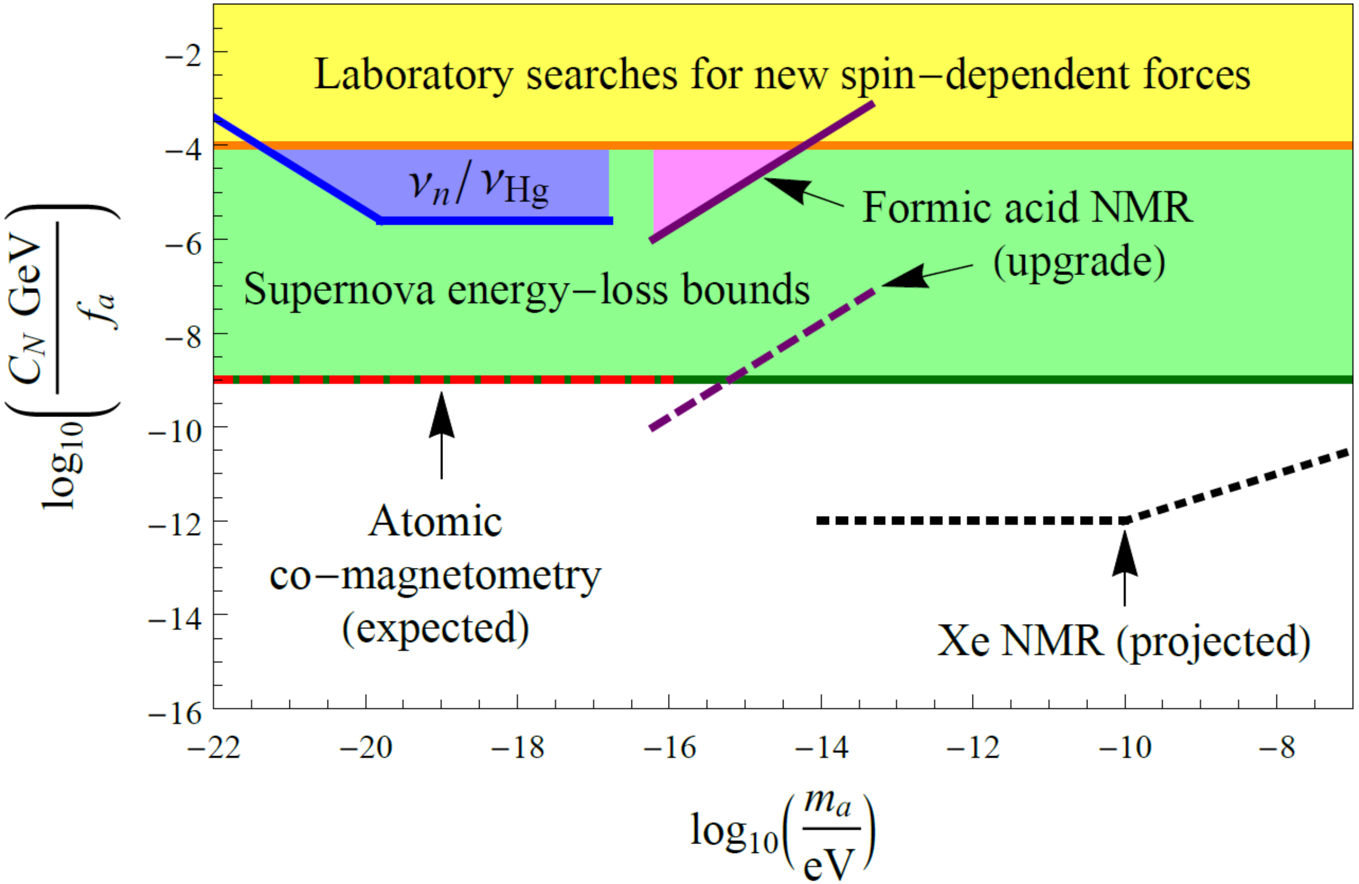


Constraints on Interaction of Axion Dark Matter with Nucleons

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

Formic acid NMR constraints (preliminary): [CASPEr collaboration, In preparation]

2 orders of magnitude improvement (laboratory bounds)!



Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

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

→ Time-varying fundamental constants

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

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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$$\rho_\phi = \frac{m_\phi^2 \phi_0^2}{2} \quad => \quad \phi_0^2 \propto \rho_\phi$$

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‘Slow’ drifts [Astrophysics
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Oscillating variations
[Laboratory (high precision)]

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)]

$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_{X=\alpha,m_e/m_p,\ldots} \left(\underset{\big\uparrow}{K_{X,1}} - \underset{\big\uparrow}{K_{X,2}}\right)\cos\left(\omega t\right)$$

Sensitivity coefficients

$\omega = m_\varphi$ (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

nature photonics

OCTOBER 2012 VOL 6 NO 10
www.nature.com/naturephotonics

X-RAY FELS
Self-seeding success

SPIN-WAVE EMISSION
Directional control by light

SILICON NANOPHOTONICS
Bridging mid-infrared gap

Ultrastable silicon Fabry–Pérot cavity

Small-scale cavity, *L* ~ 0.2 m

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

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

* 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 ($N_{\mathrm{eff}} \sim 10^5$ in small-scale interferometers with highly reflective mirrors; c.f. $N_{\mathrm{eff}} \sim 100$ 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):** [Hume, Leibrandt, Wineland *et al.*, In prep.]
- **Yb^+(E3)/Sr (PTB):** [Huntemann, Peik *et al.*, In preparation]

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

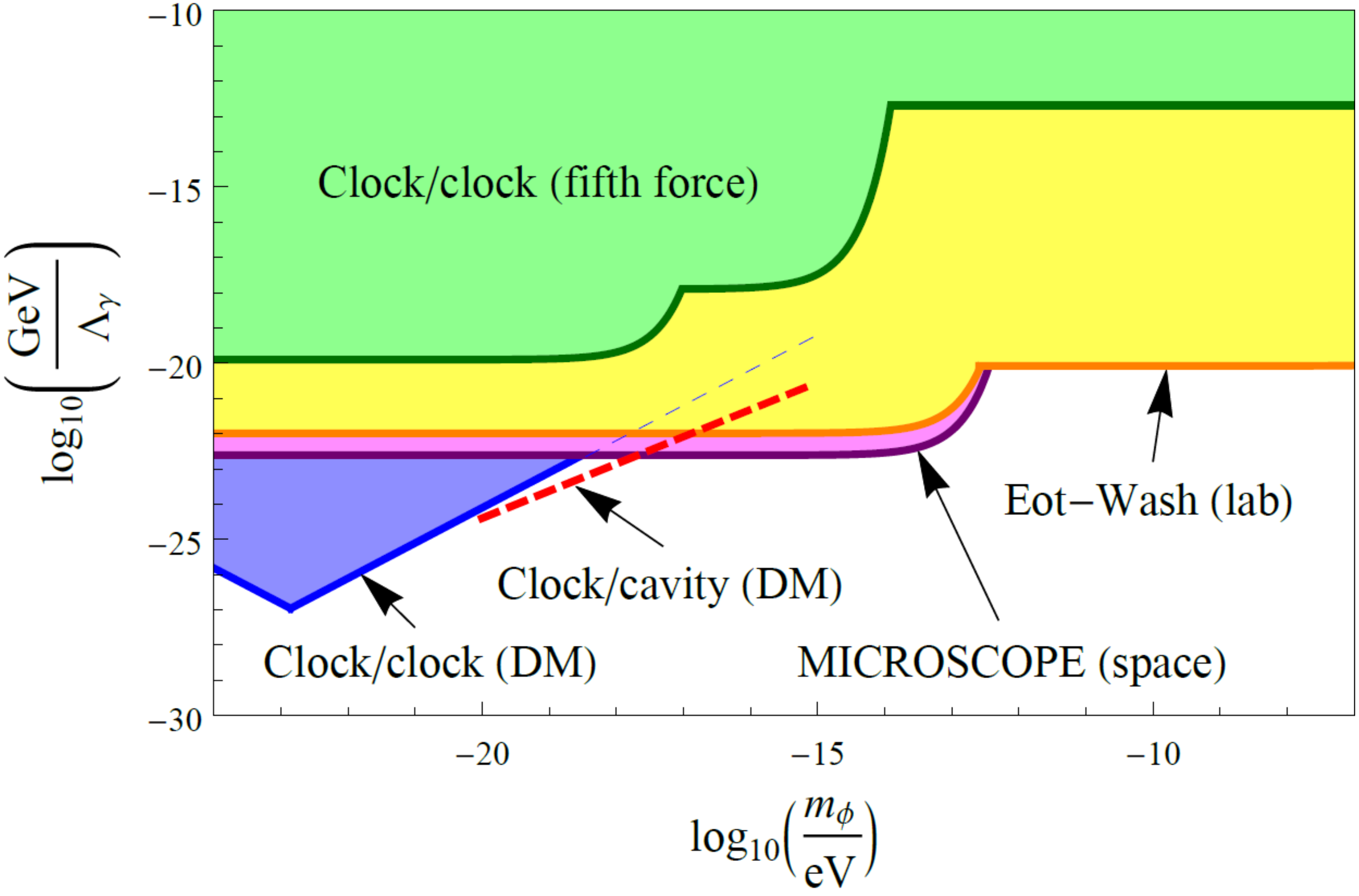
- **Sr/ULE cavity (Torun)*:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Sr/Si cavity (JILA):** [Robinson, Ye *et al.*, In preparation]

* 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)]

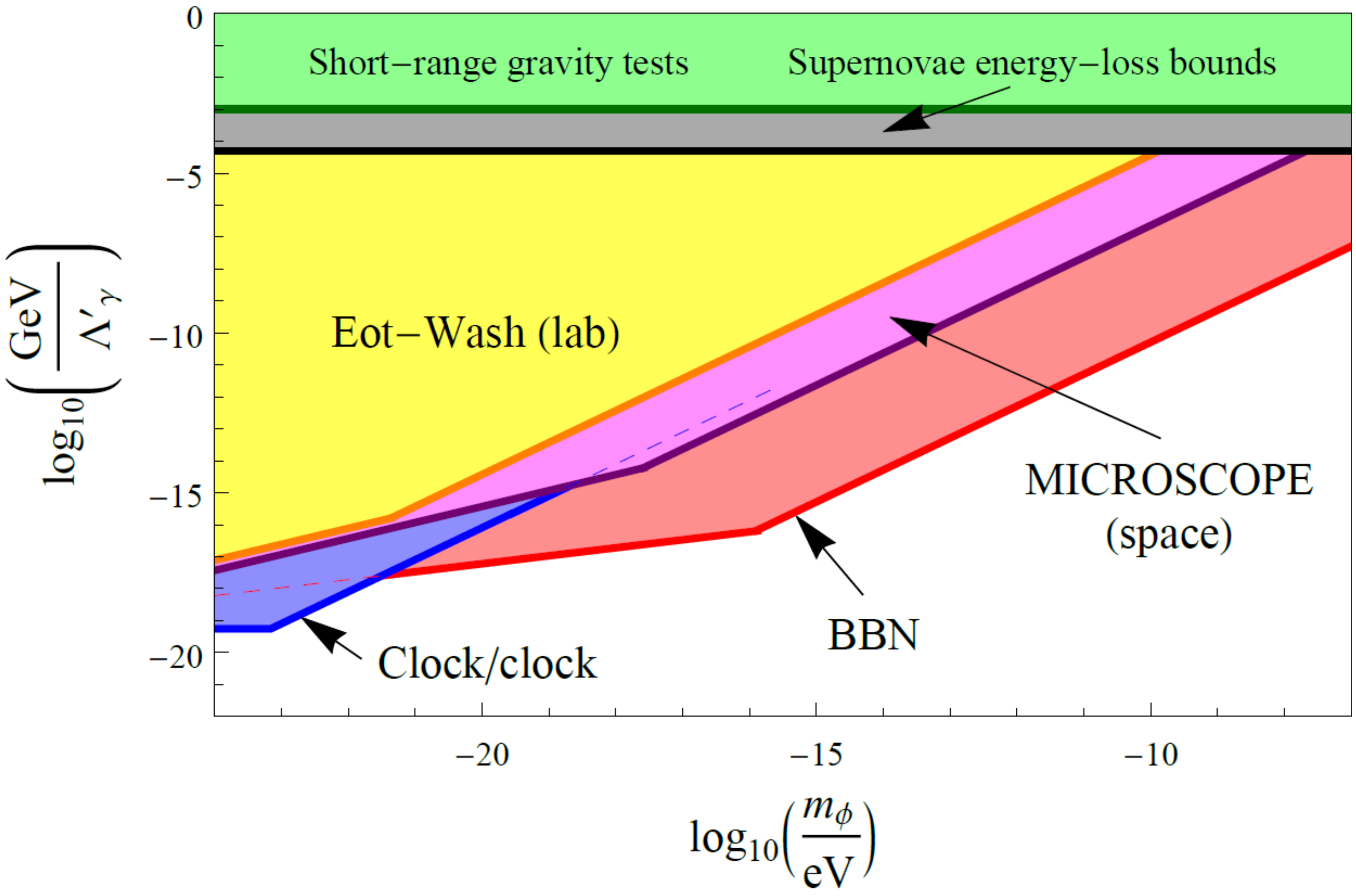
4 orders of magnitude improvement!



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!



Summary

- New classes of dark matter effects that are **first power** in the underlying interaction constant => Up to **15 orders of magnitude improvement** with experiments based on magnetic resonance and atomic clock spectroscopy

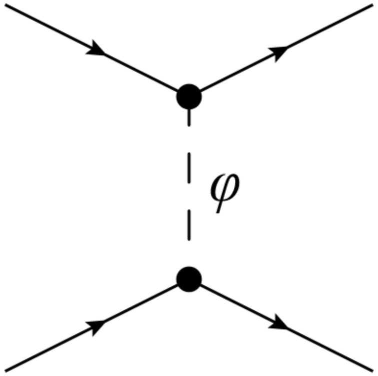
Back-up Slides

Linear vs Quadratic Couplings

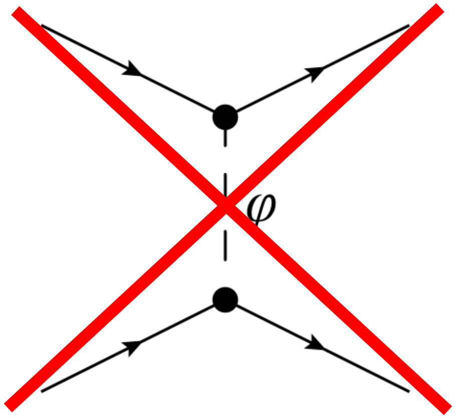
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

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

Linear couplings ($\varphi \bar{X} X$)



Quadratic couplings ($\varphi^2 \bar{X} X$)



$$\phi = \phi_0 \cos(m_\phi t) - A \frac{e^{-m_\phi r}}{r}$$

$$\phi = \phi_0 \cos(m_\phi t) \left(1 - \frac{B}{r} \right)$$

↓

Gradients + screening/amplification

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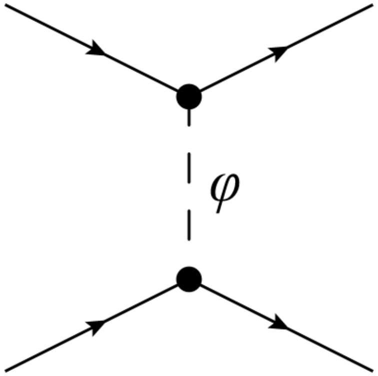

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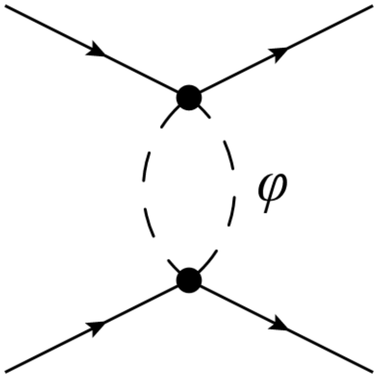


$$\phi = \phi_0 \cos(m_\phi t)\left(1 - \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

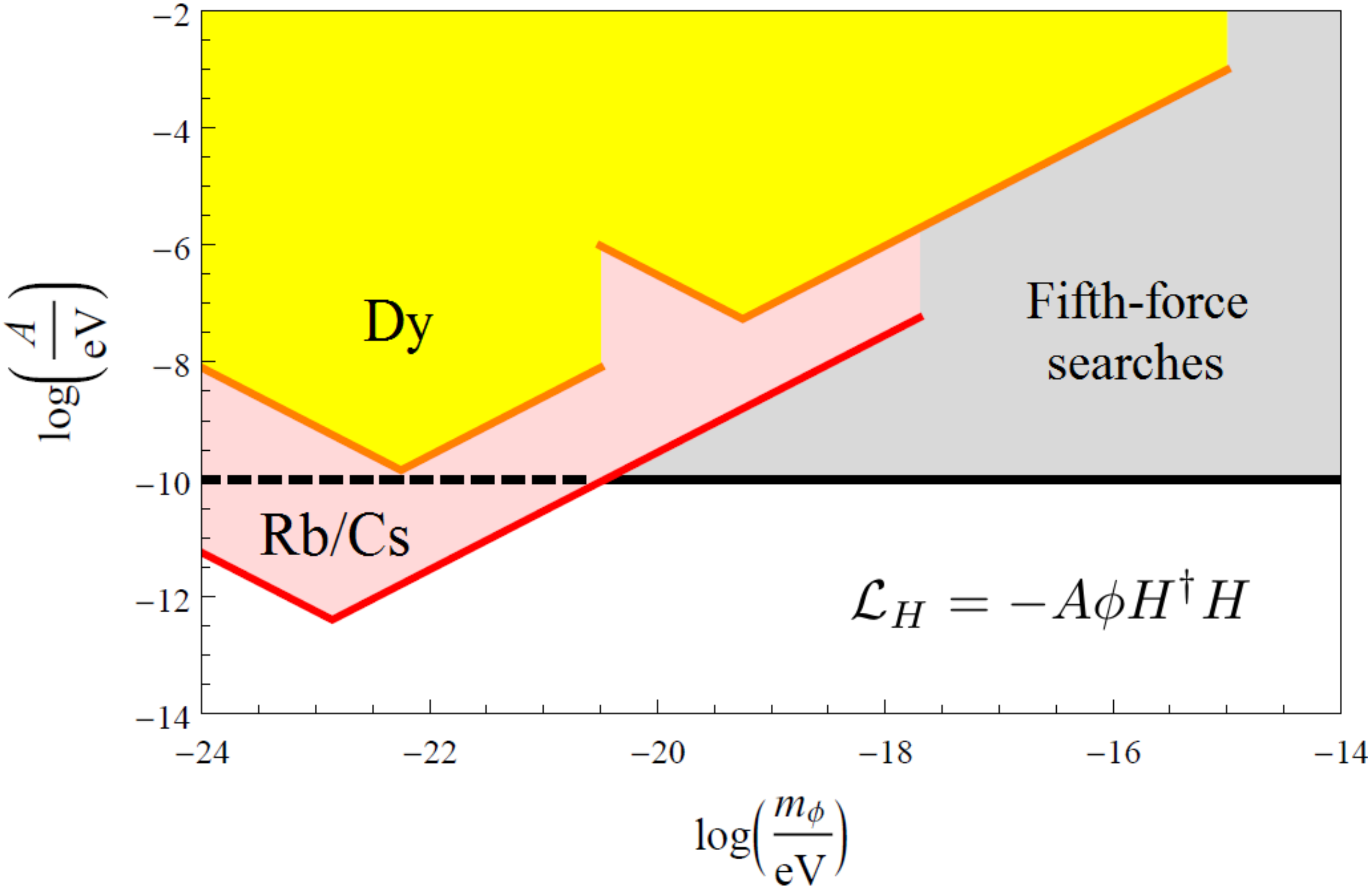
Gradients + screening/amplification

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!



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 ($t_{\mathrm{weak}} \approx$ 1s – $t_{\mathrm{BBN}} \approx$ 3 min)
- Primordial ^{4}He abundance sensitive to *n*/*p* ratio (almost all neutrons bound in ^{4}He after BBN)

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

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

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

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

Back-Reaction Effects in BBN

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