Tabletop Probes of Ultra-Low-Mass Bosonic Dark Matter

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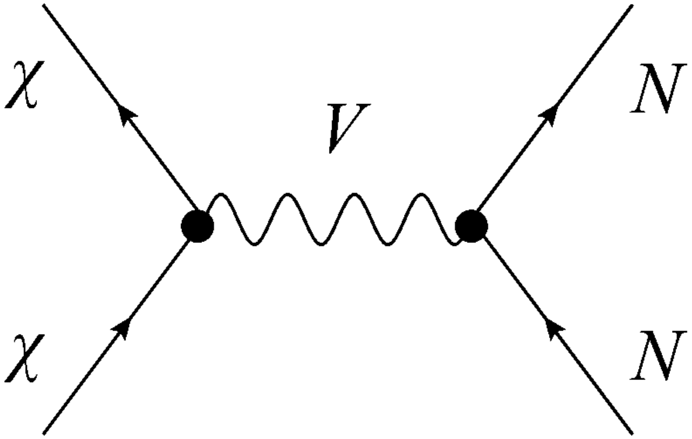
Motivation

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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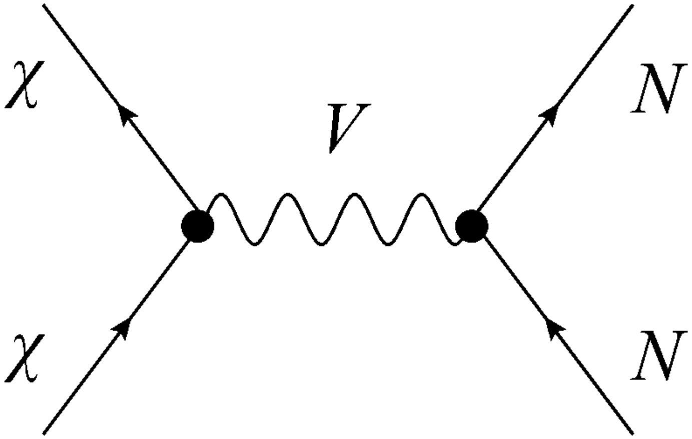

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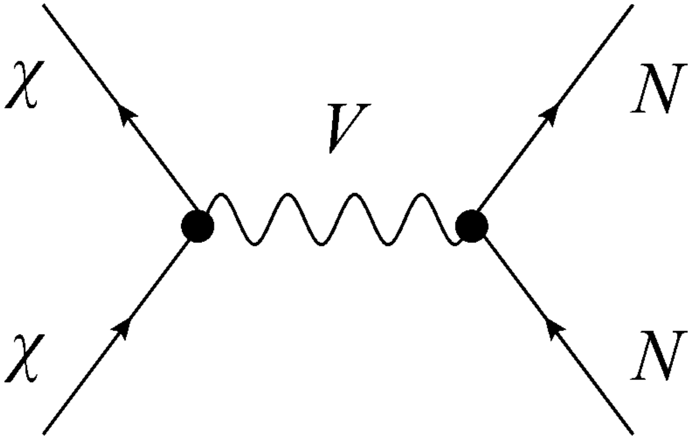

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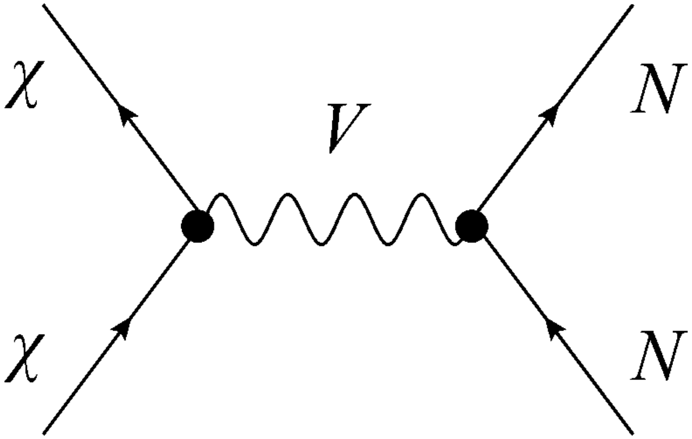

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Challenge: Observable is **fourth power** in a small interaction constant ($e' << 1$)!

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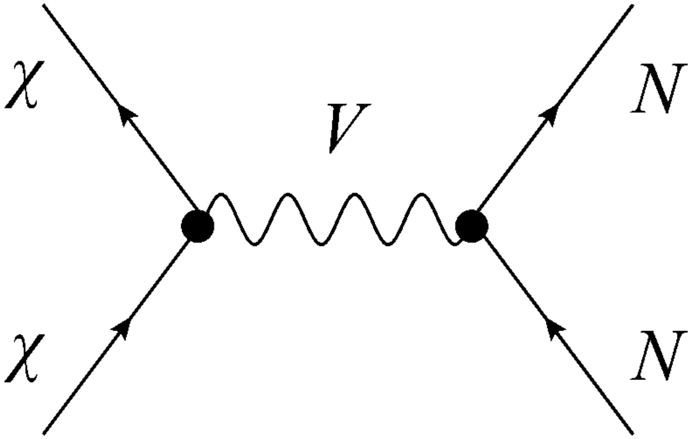

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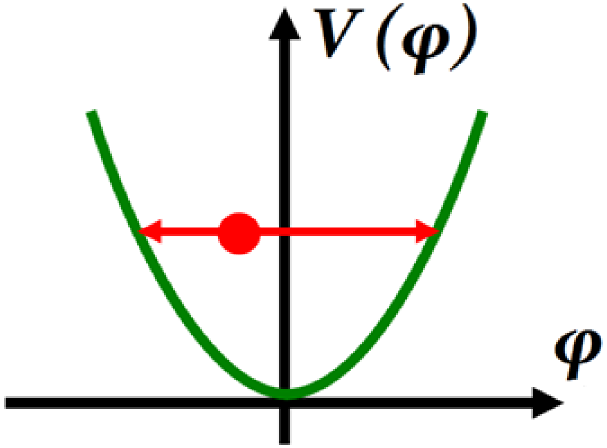
Question: *Can we instead look for effects of dark matter that are* ***first power*** *in the interaction constant?*

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 $<\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ 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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Classical field

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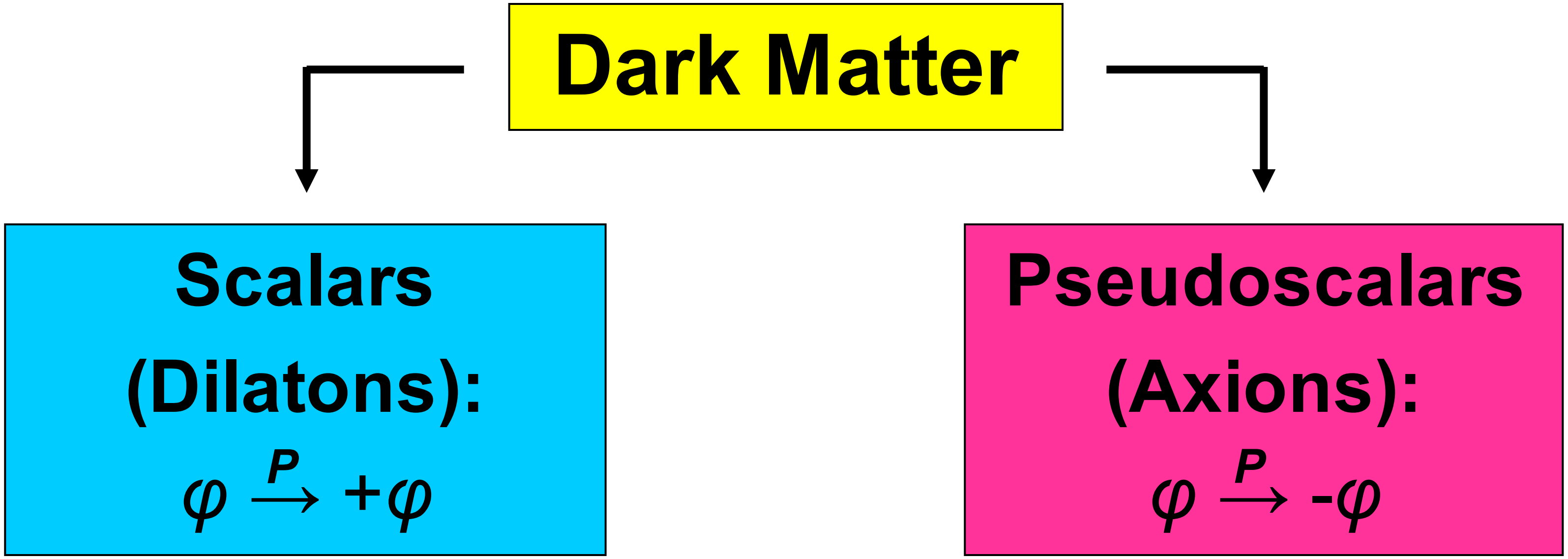
Classical field

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

Low-mass Spin-0 Dark Matter



Dark Matter

Scalars (Dilatons):

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

Pseudoscalars (Axions):

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

→ 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

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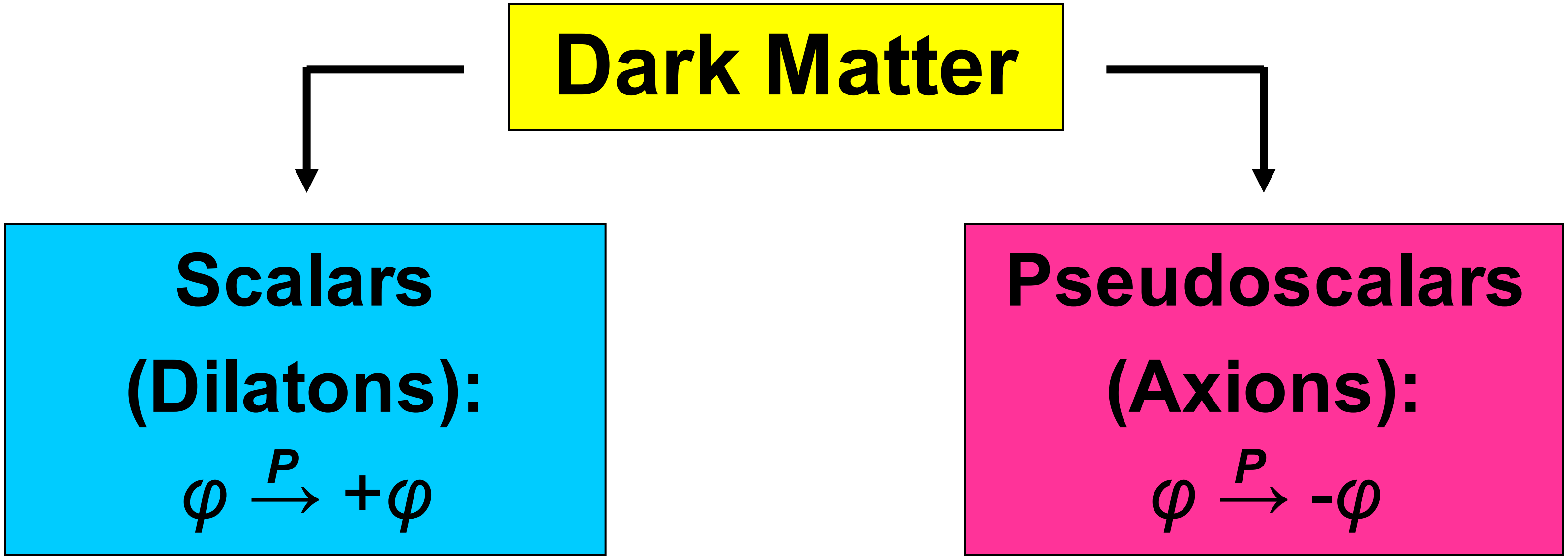

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"Thou shall measure frequency."

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

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

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- $N \sim 10^5 - 10^{13}$ (or even 1!) [cf. $N \sim 10^{21} - 10^{29}$ (traditional "bulk" detectors)]

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- $N \sim 10^5 - 10^{13}$ (or even 1!) [cf. $N \sim 10^{21} - 10^{29}$ (traditional “bulk” detectors)]
- Search for *wave-like* signatures [cf. traditional *particle-like* recoil signatures]

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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)]

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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

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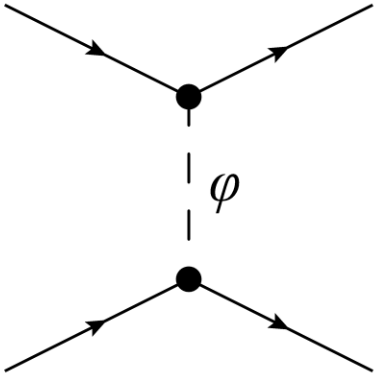

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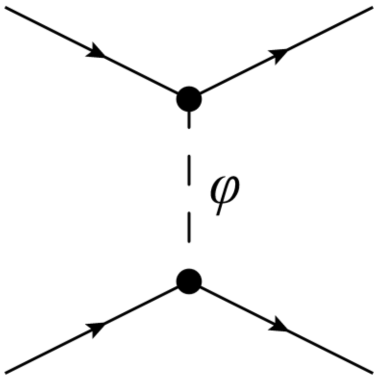

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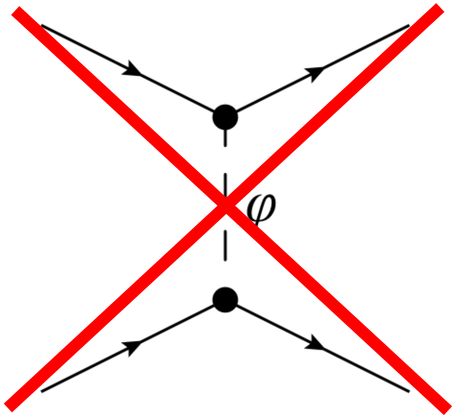

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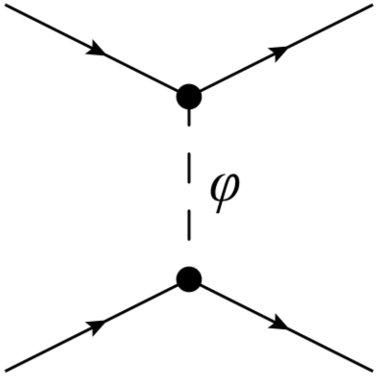

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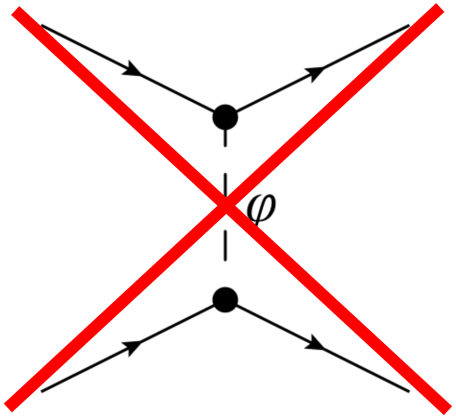

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↓

Gradients + screening/amplification

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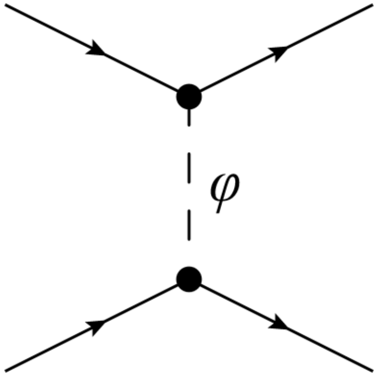

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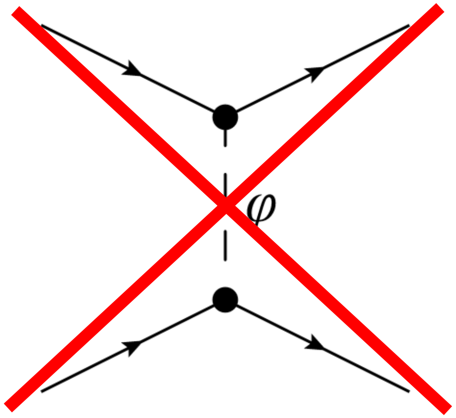
Many different (classical) signatures in “fifth-force” experiments

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



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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)]

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

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

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)]

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

Sensitivity coefficients

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

- Precision of optical clocks approaching ~10^{-18} fractional level
- Sensitivity coefficients K_X calculated extensively by Flambaum group and co-workers (1998 – present), see the reviews

  [Flambaum, Dzuba, *Can. J. Phys.* **87**, 25 (2009); *Hyperfine Interac.* **236**, 79 (2015)]

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

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

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

- Compare $L \sim N a_B$ with λ (or a 2nd L)

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- Compare $L \sim Na_B$ with λ (or a 2nd L)
- For a "usual" atomic optical transition and in the non-relativistic limit:

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

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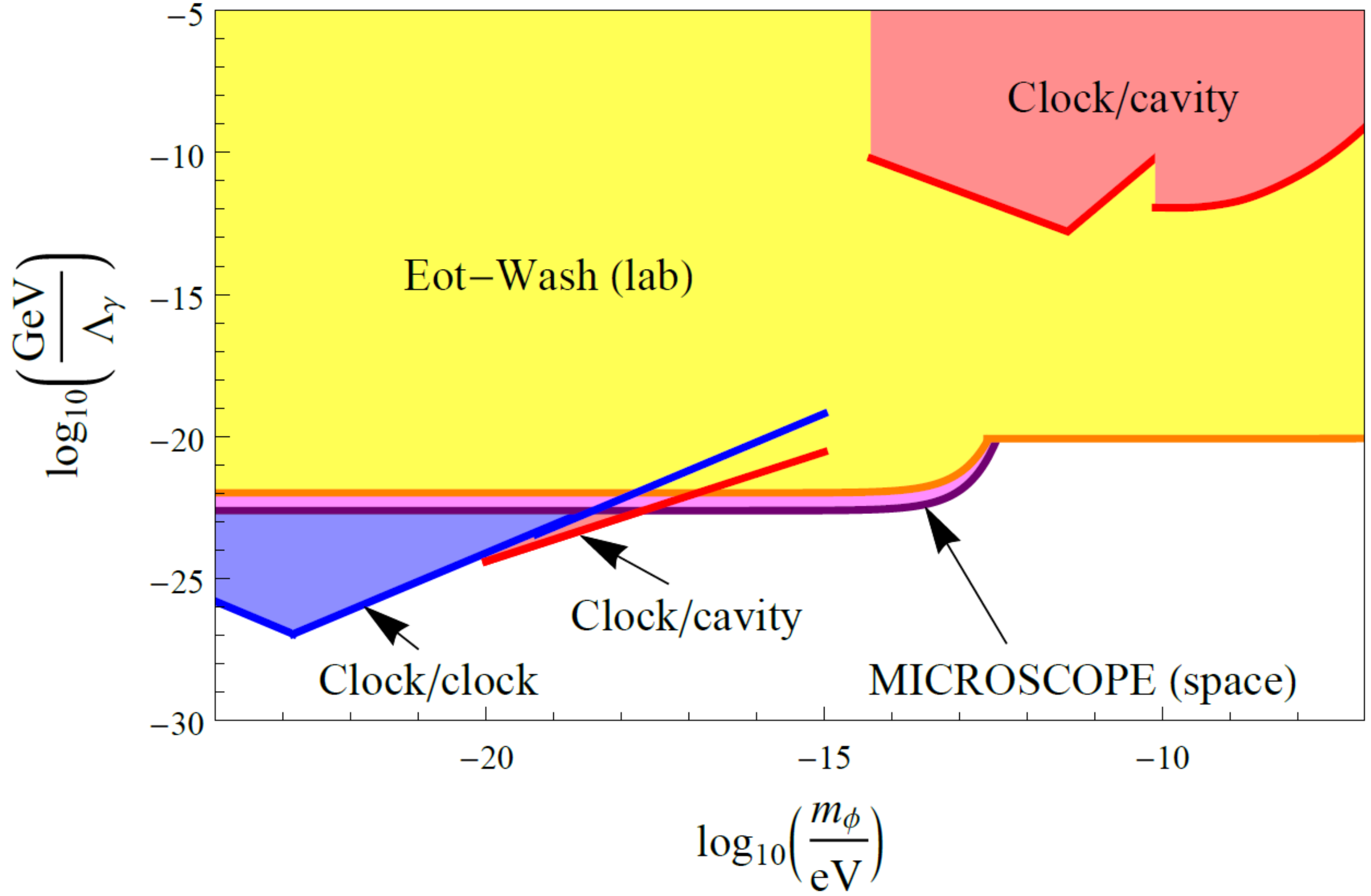
- Multiple reflections of light beam enhance the effect ($N_{\mathrm{eff}} \sim 10^5$ in small-scale interferometers with highly reflective mirrors; c.f. $N_{\mathrm{eff}} \sim 100$ in LIGO/Virgo)

Constraints on Linear Interaction of Scalar Dark Matter with the Photon

Clock/clock constraints: [Van Tilburg *et al*., *PRL* **115**, 011802 (2015)], [Hees *et al*., *PRL* **117**, 061301 (2016)]; **Clock/cavity constraints:** [Robinson, Ye *et al*., *Bulletin APS*, H06.00005 (2018)], [Aharony *et al*., arXiv:1902.02788], [Antypas *et al*., arXiv:1905.02968]

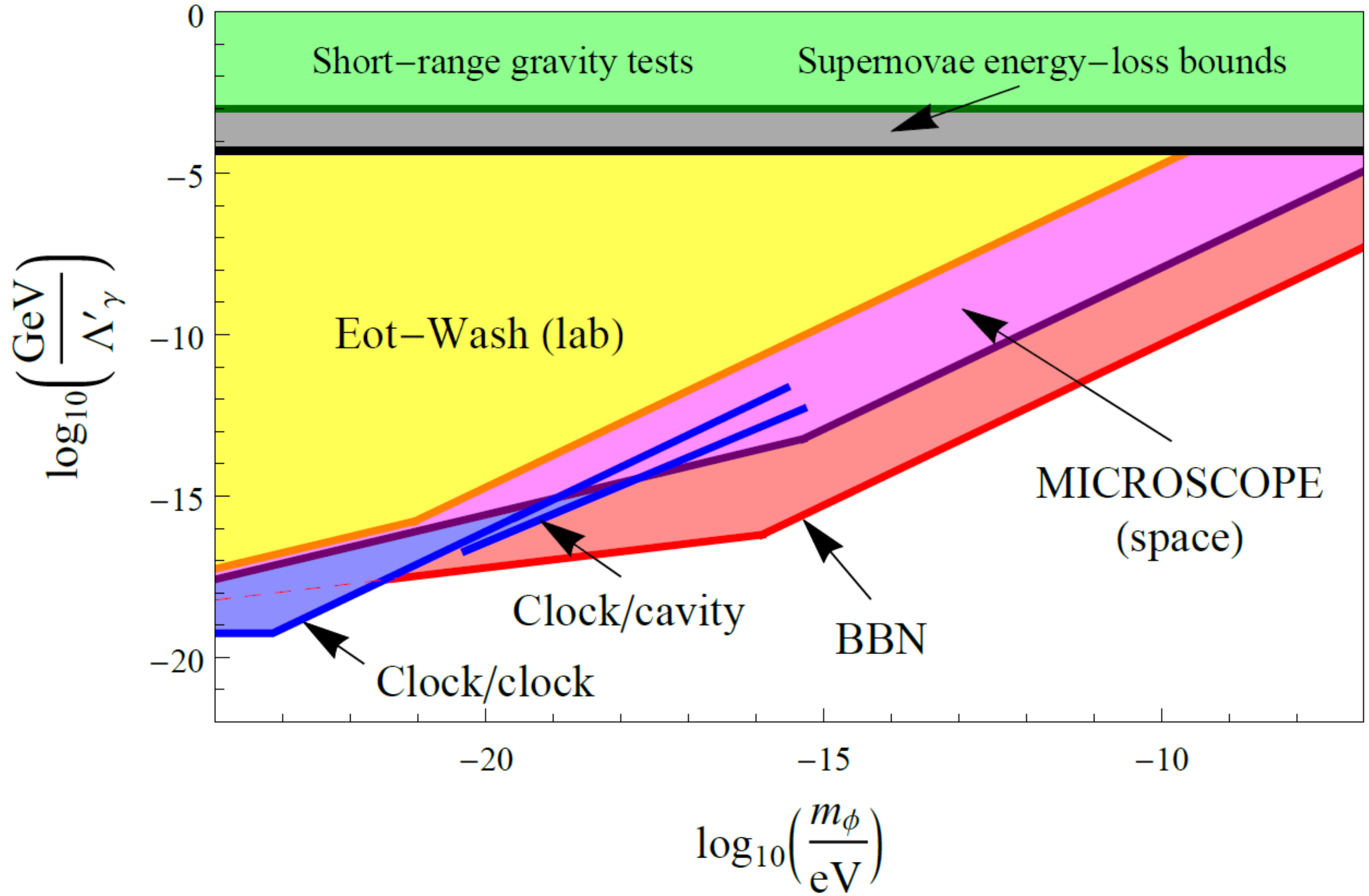
4 orders of magnitude improvement!



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

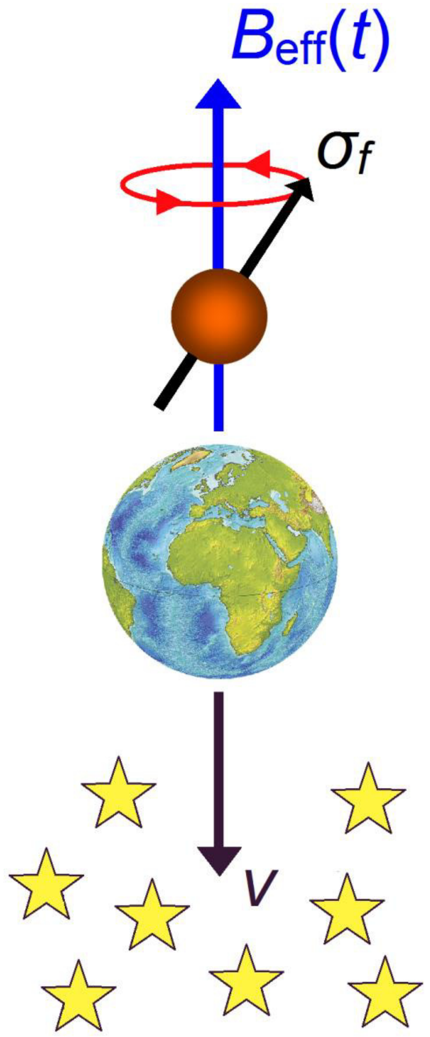
[Flambaum, talk at *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field** *

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



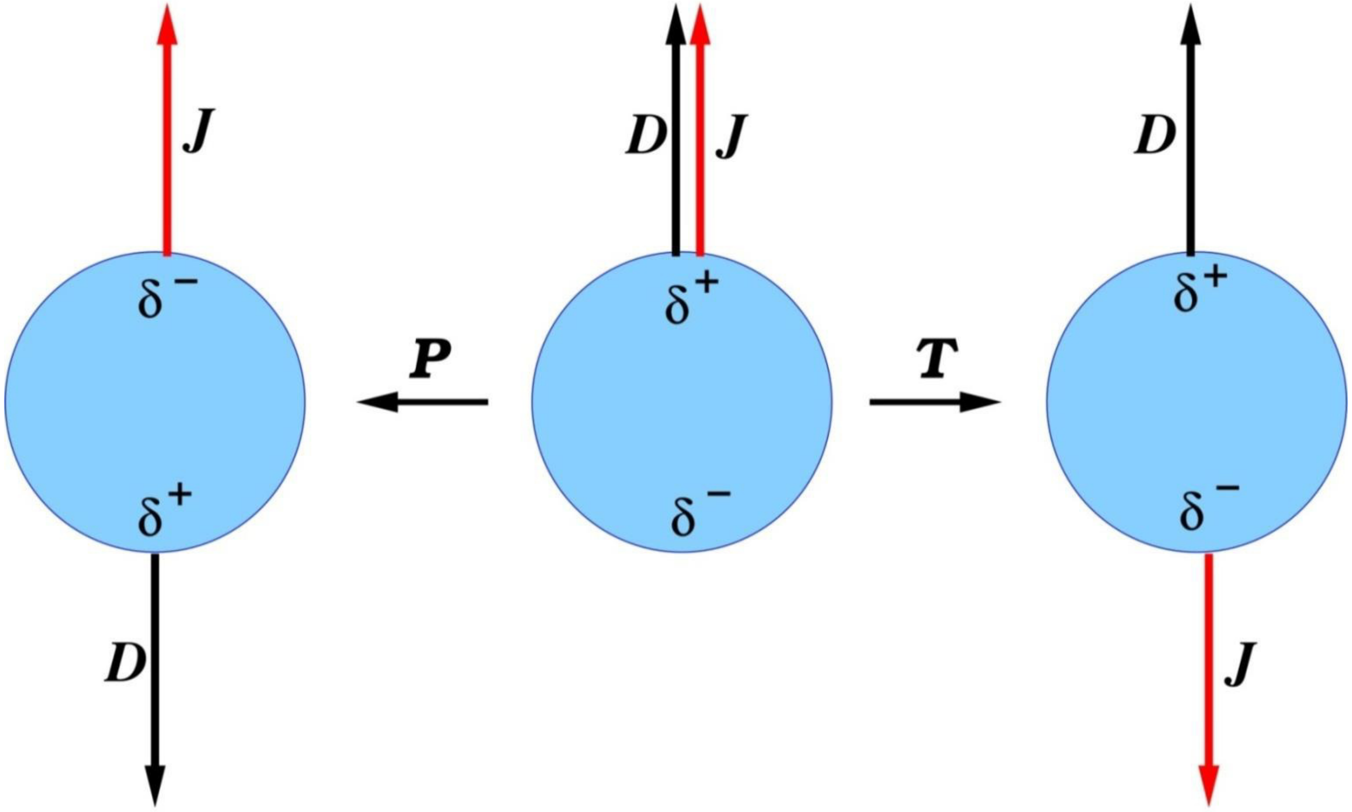
* Compare with usual magnetic field: $H = -\boldsymbol{\mu}_f \cdot \boldsymbol{B}$

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); Stadnik, thesis (Springer, 2017)]

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

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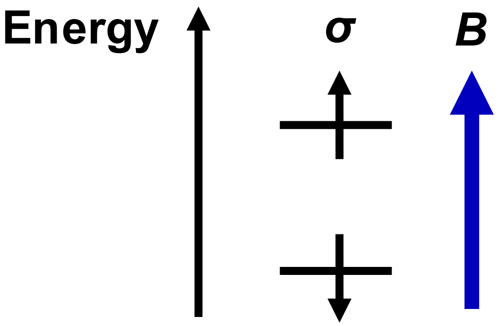
Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]

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



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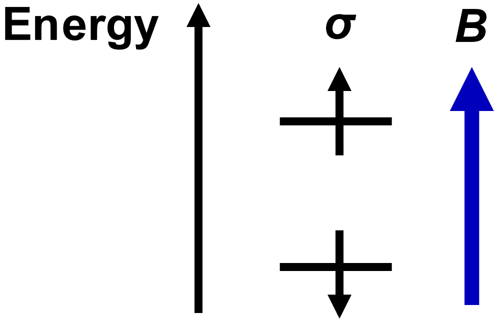
***B*-field effect**

Axion DM effect



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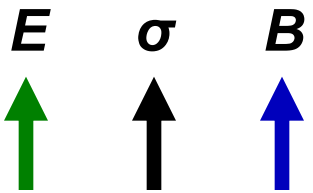
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$



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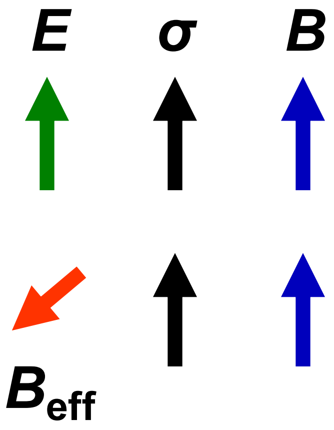
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$

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



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

Searching for Spin-Dependent Effects

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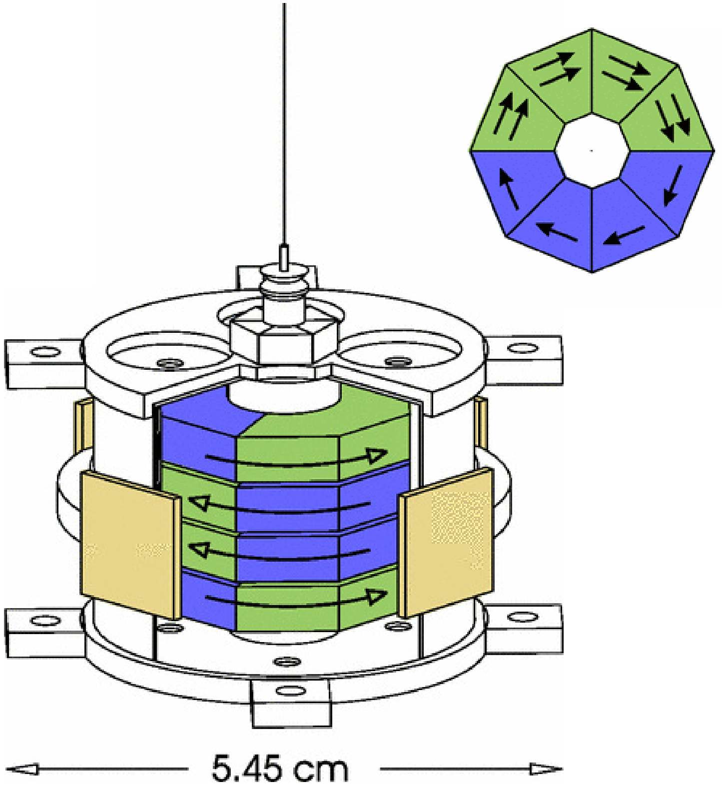
Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

Experiment (Alnico/SmCo$_5$): [Terrano *et al.*, arXiv:1902.04246; *PRL* (In press)]



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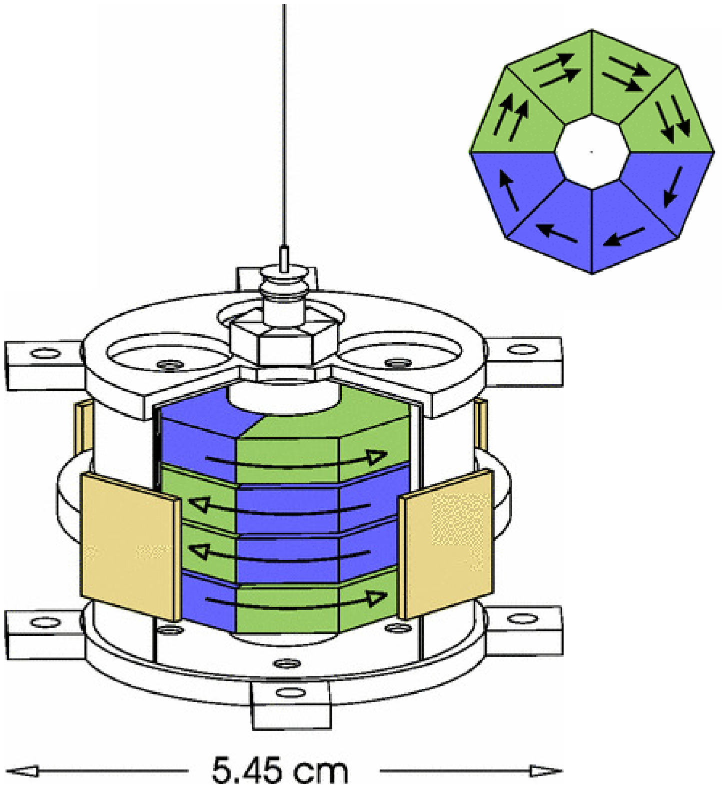

$$\boldsymbol{\mu}_{\mathrm{pendulum}} \approx \mathbf{0}$$

$$(\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \neq \mathbf{0}$$

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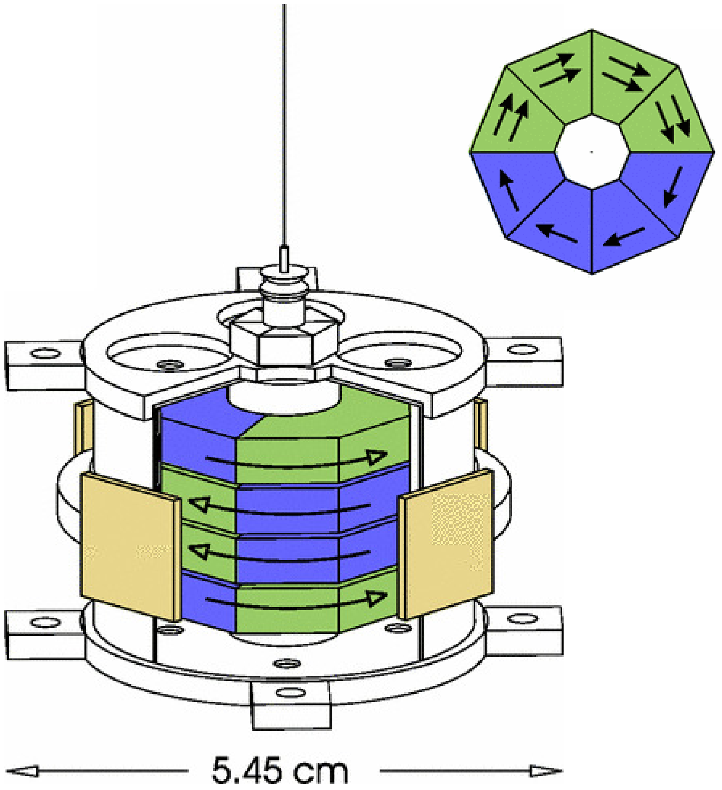


$$\boldsymbol{\mu}_{\text{pendulum}} \approx \mathbf{0}$$

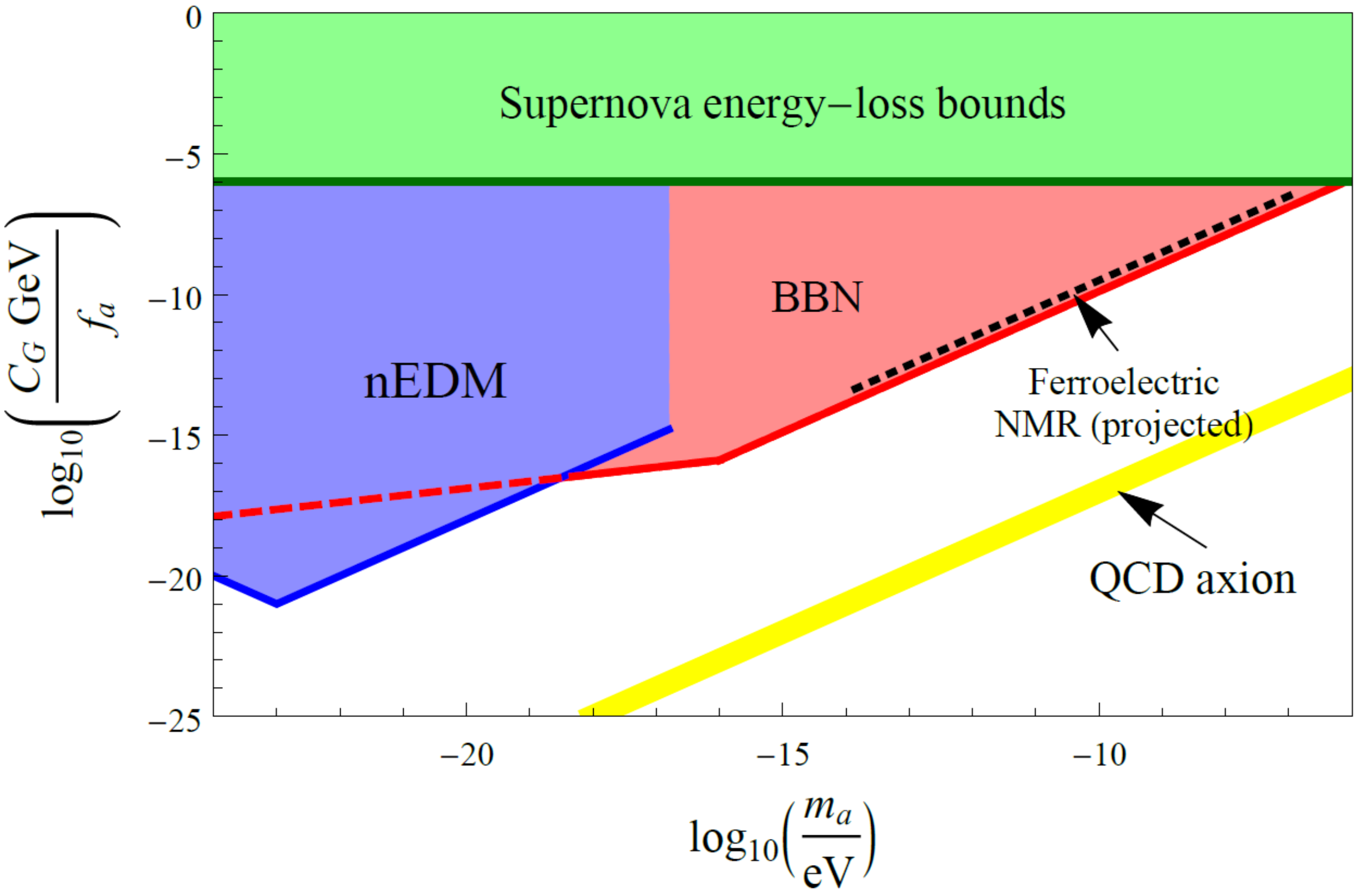
$$(\boldsymbol{\sigma}_e)_{\text{pendulum}} \neq \mathbf{0}$$

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

Constraints on Interaction of Axion Dark Matter with Gluons

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

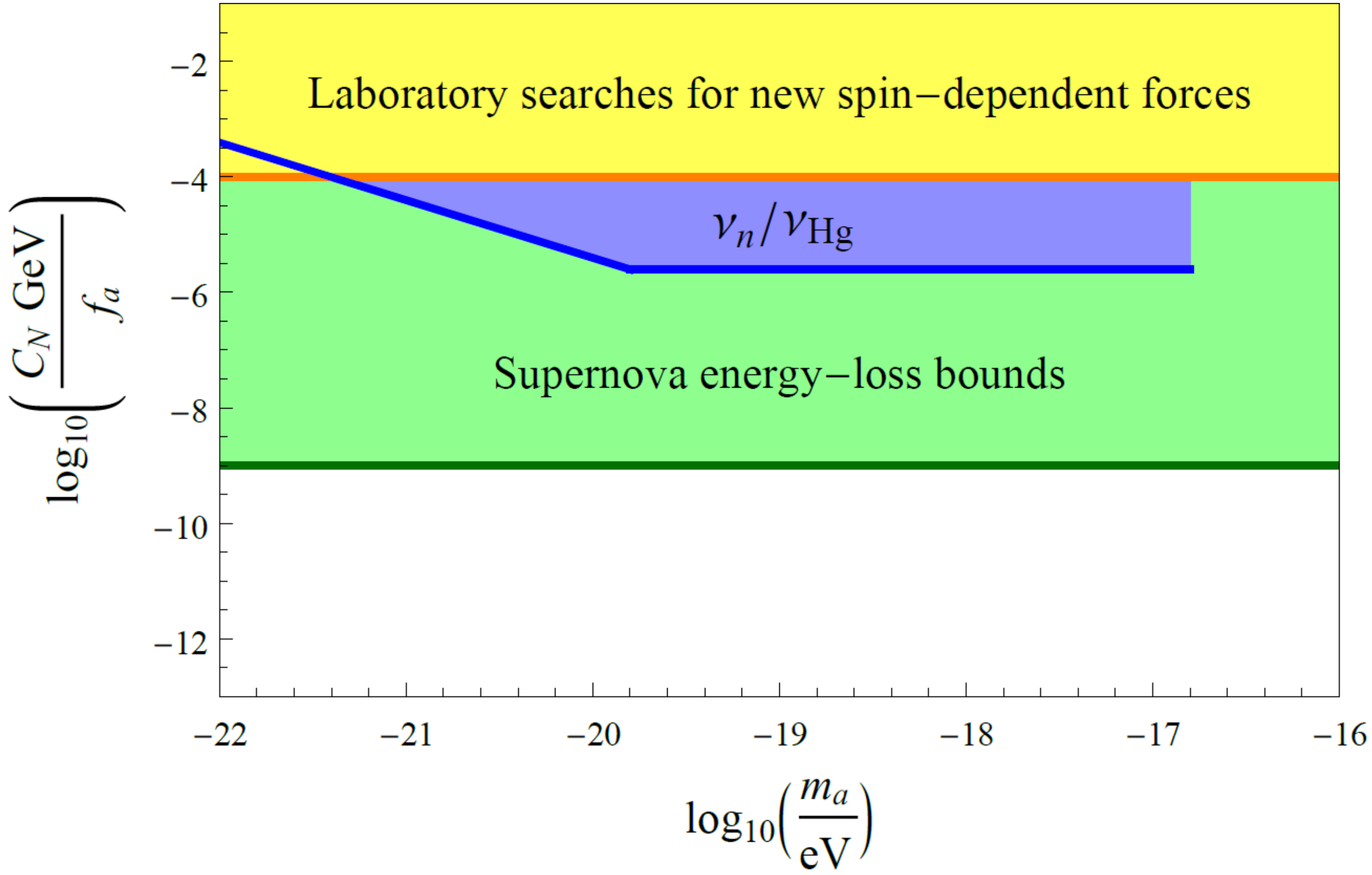
3 orders of magnitude improvement!



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)!



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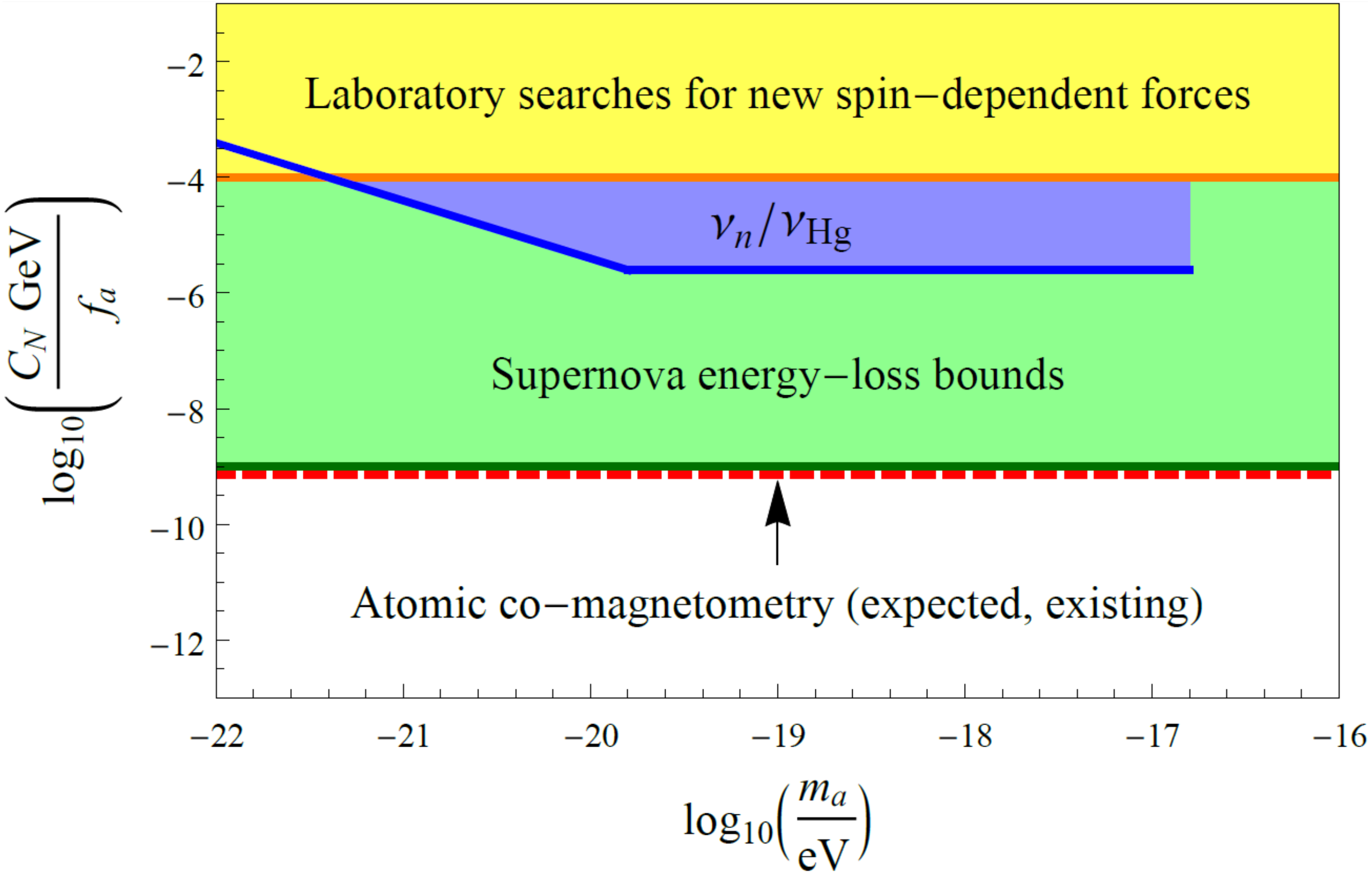
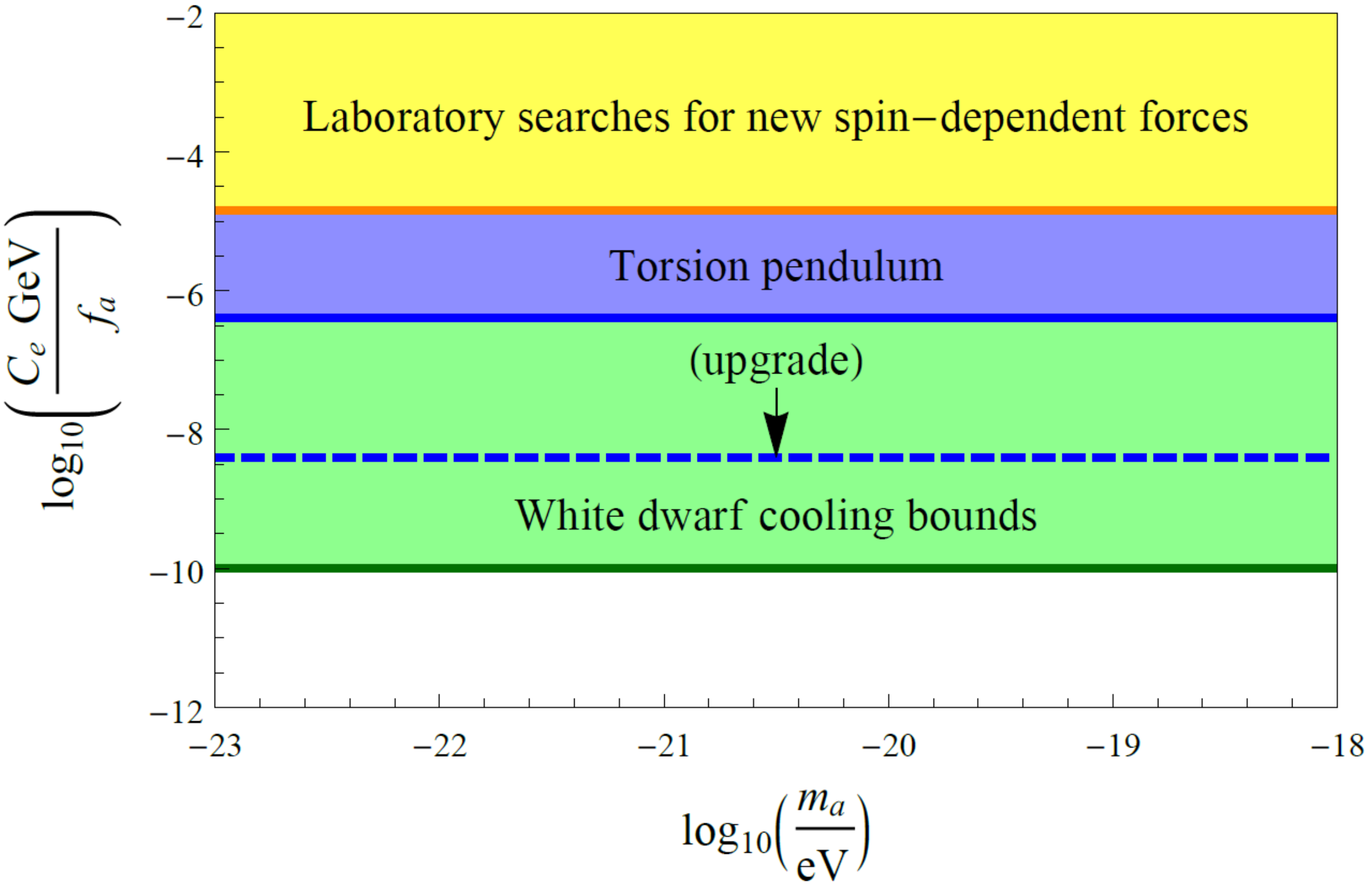


Constraints on Interaction of Axion Dark Matter with the Electron

Torsion pendulum constraints: [Terrano *et al*., arXiv:1902.04246; *PRL* (In press)]

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 precision, low-energy, table-top experiments:
  - Spectroscopy (clocks)
  - Cavities and interferometry
  - Magnetometry
  - Torsion pendula

⋮

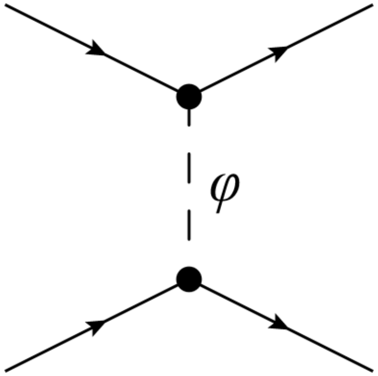
Back-up Slides

Fifth Forces: Linear vs Quadratic Couplings

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

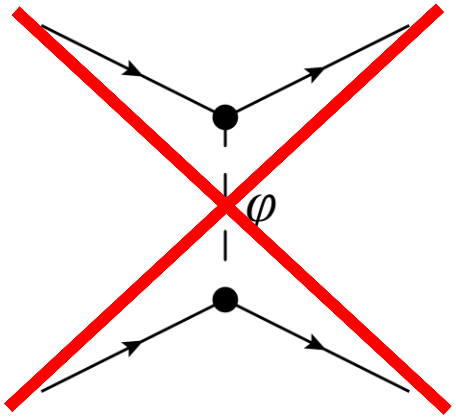
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

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



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

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



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

Gradients + screening/amplification

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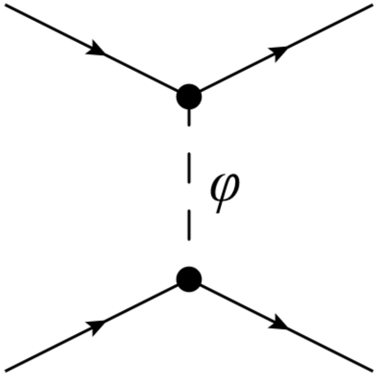

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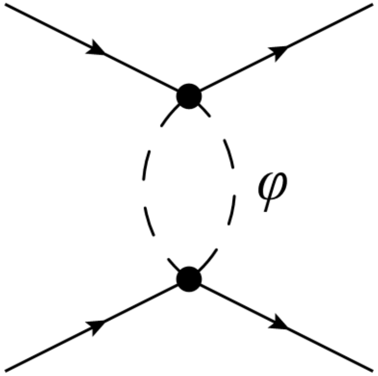


$$\phi = \phi_0 \cos(m_\phi t)\left(1 - \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

Gradients + screening/amplification

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)

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

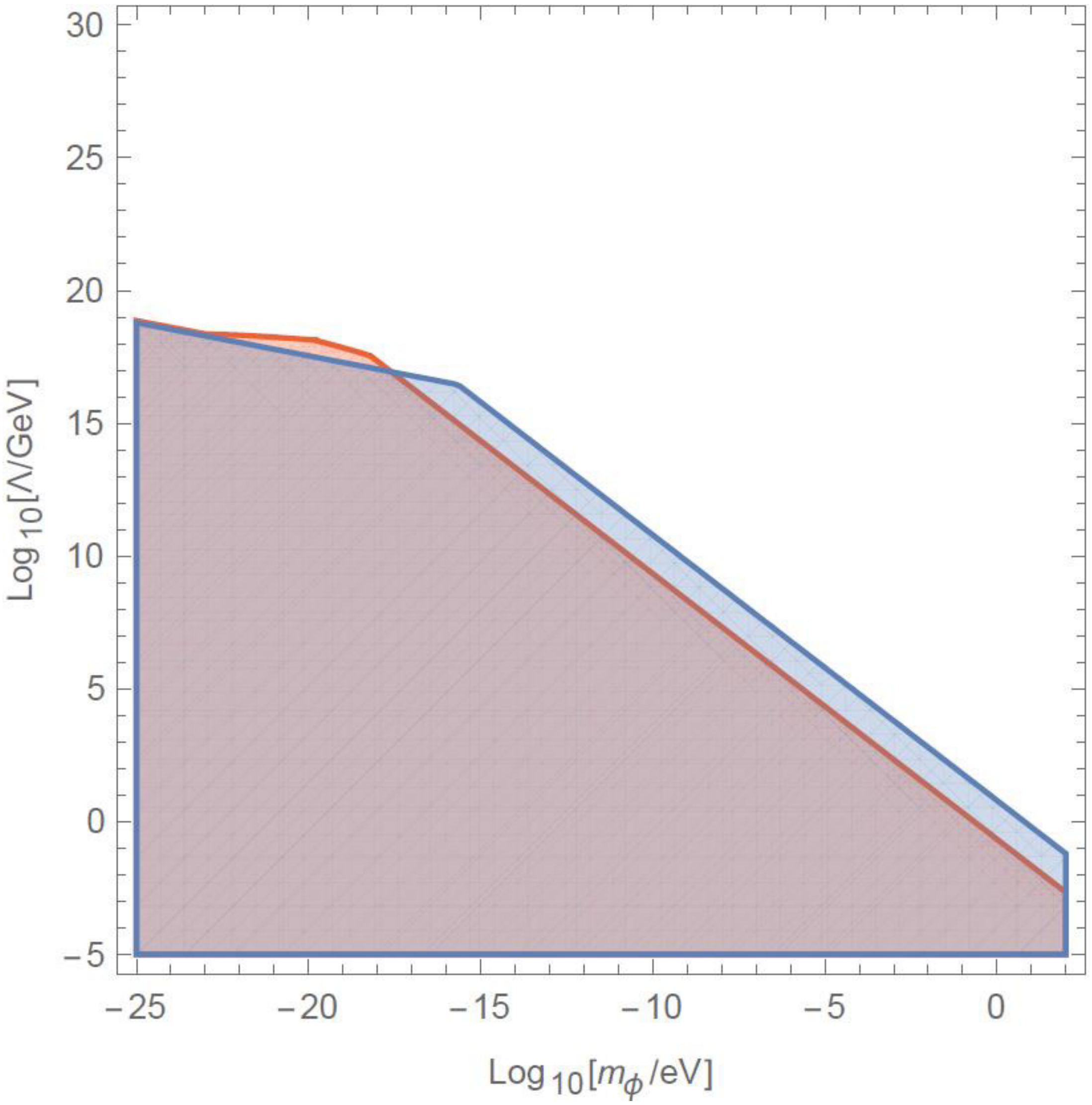
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN

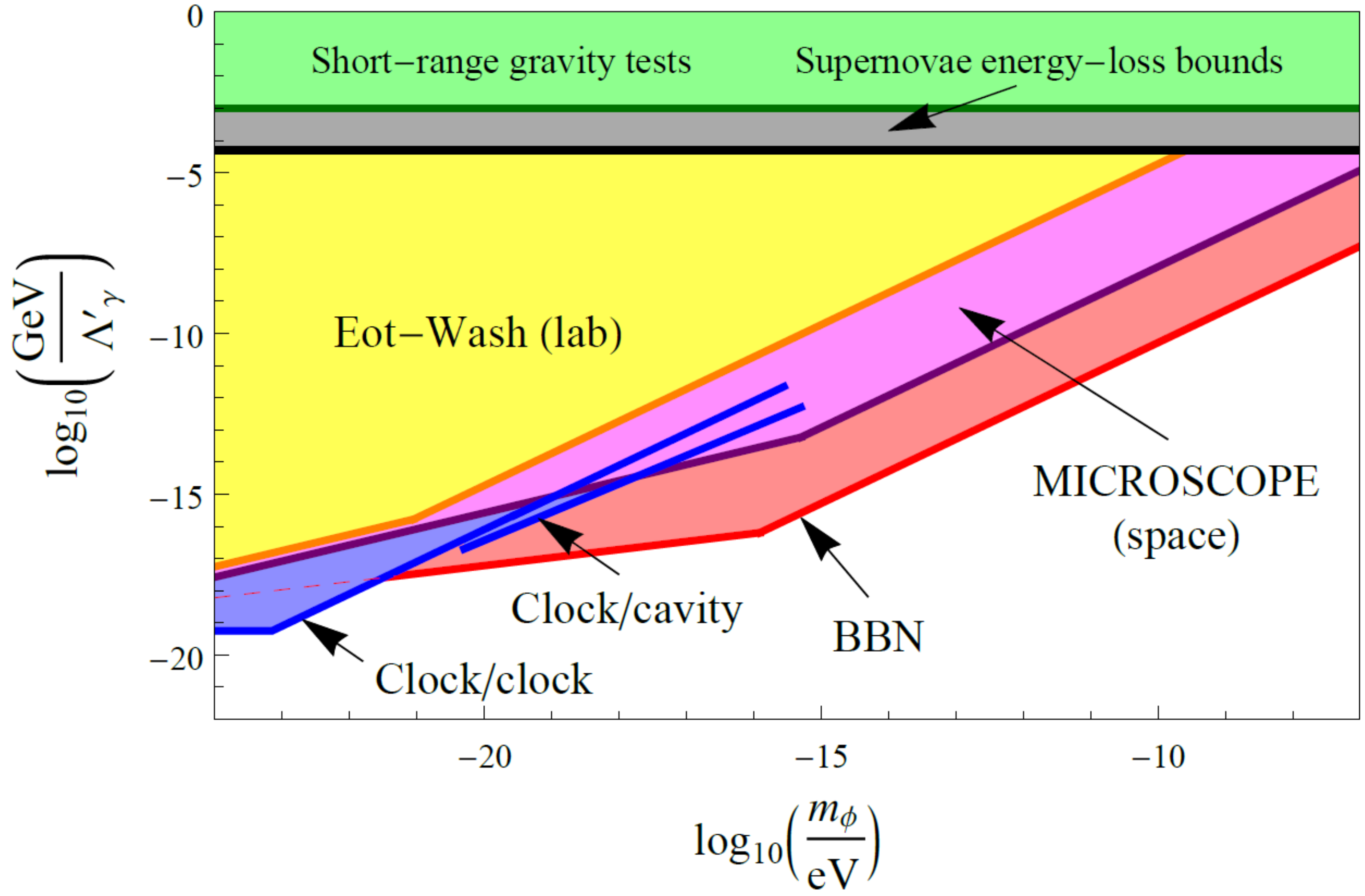
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



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!

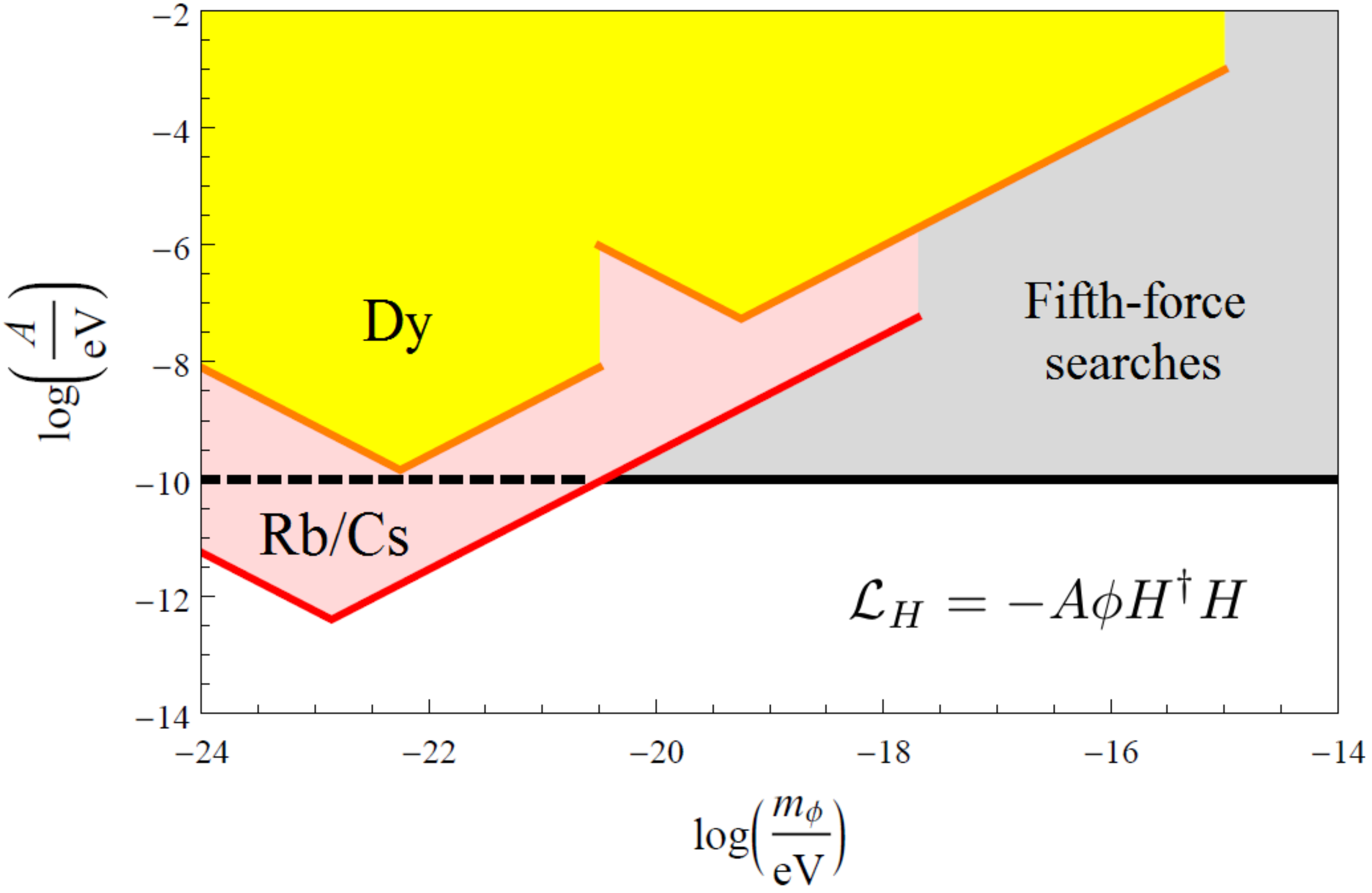


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

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

2 – 3 orders of magnitude improvement!



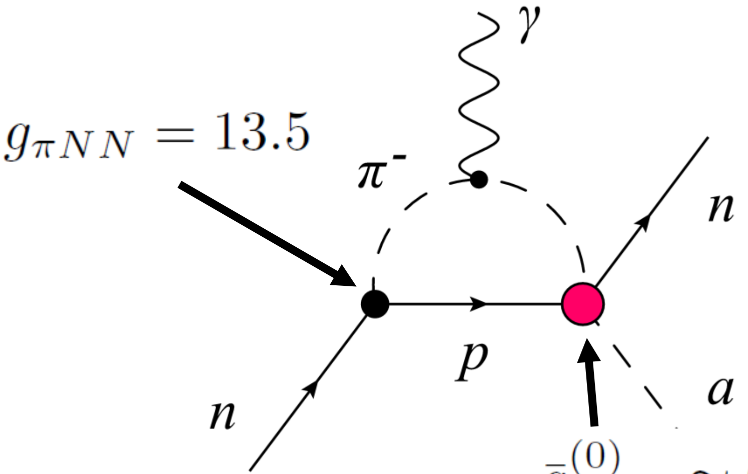
Oscillating Electric Dipole Moments

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

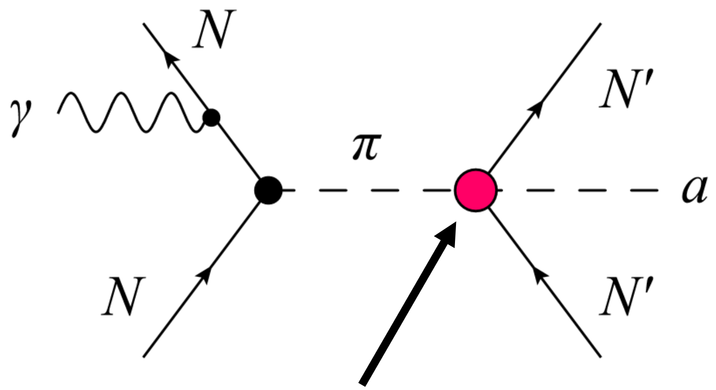
Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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