Novel Probes of Ultra-Low-Mass Bosonic Dark Matter

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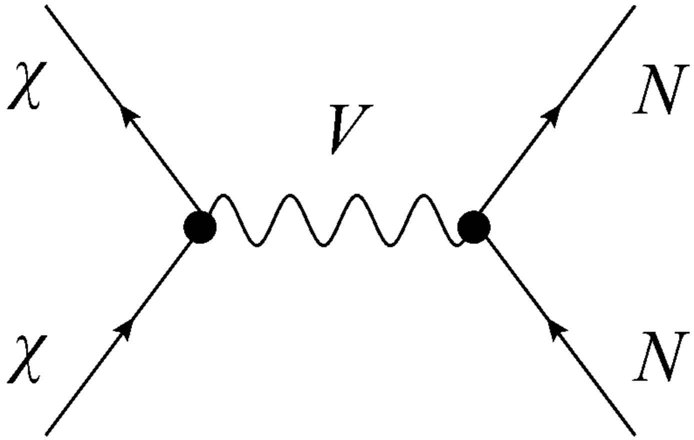
Seminar, June 2019

Motivation

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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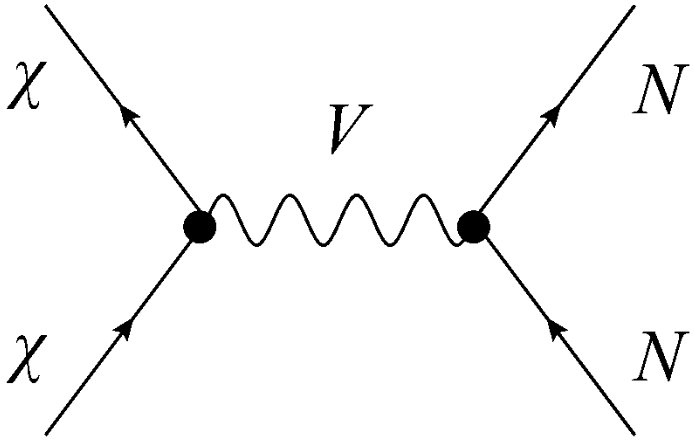

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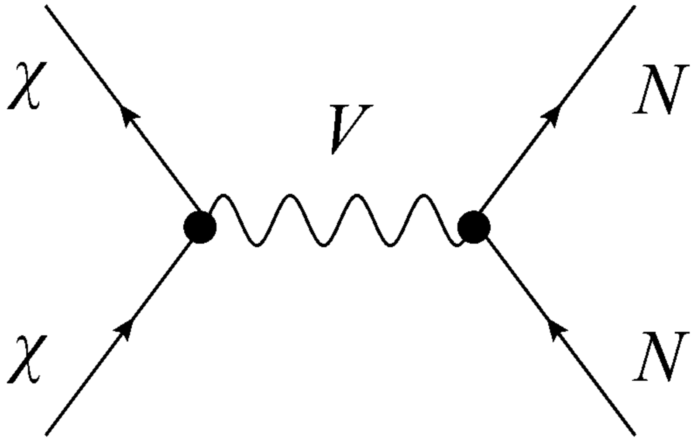

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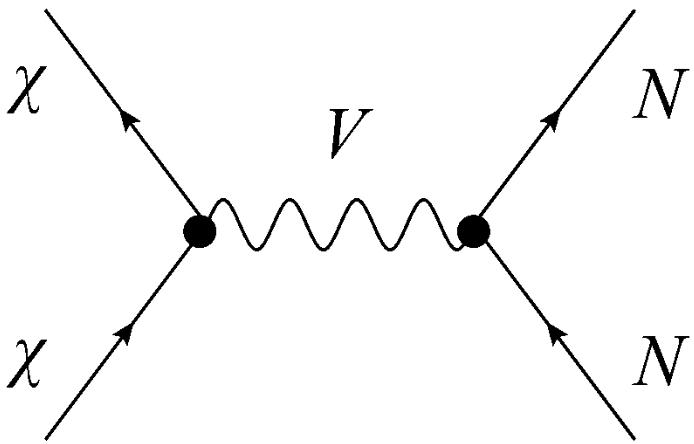

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Challenge: Observable is **fourth power** in a small interaction constant ($e' \ll 1$)!

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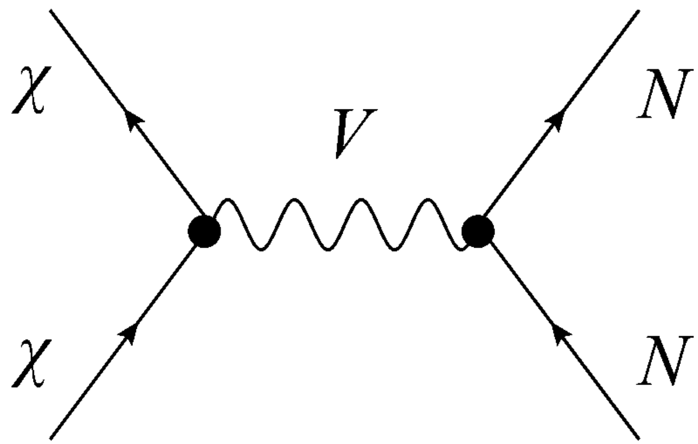

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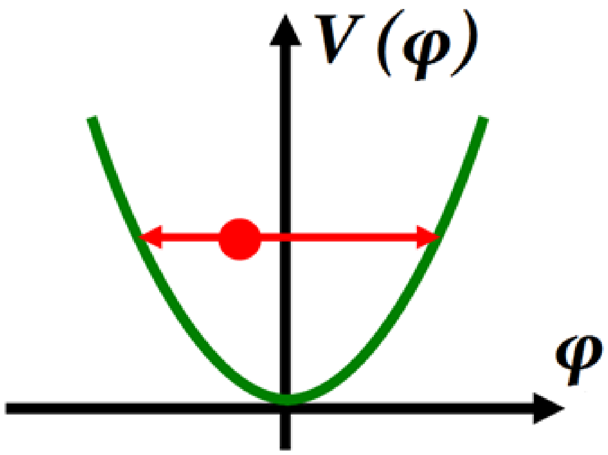
Question: *Can we instead look for effects of dark matter that are **first power** in the interaction constant?*

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



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

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

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$\lambda_{\mathrm{dB},\varphi}/2\pi \lesssim L_{\mathrm{dwarf\ galaxy}} \sim 1$ 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):	**Pseudoscalars (Axions):**
$\varphi \xrightarrow{P} +\varphi$	$\varphi \xrightarrow{P} -\varphi$
$\rightarrow$ **Time-varying fundamental constants**	$\rightarrow$ **Time-varying spin-dependent effects**
• Atomic clocks • Cavities and interferometers • Fifth-force searches • Astrophysics (e.g., BBN)	• Co-magnetometers • Nuclear magnetic resonance • Torsion pendula

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"Thou shall measure frequency."

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- Atomic clocks

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

→ Time-varying spin-dependent effects

- Co-magnetometers

$f \sim 100$ 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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- Cavities and interferometers
- Fifth-force searches
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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.*

* Linear couplings may be eliminated by a Z_2 symmetry (invariance under $\varphi \to -\varphi$)

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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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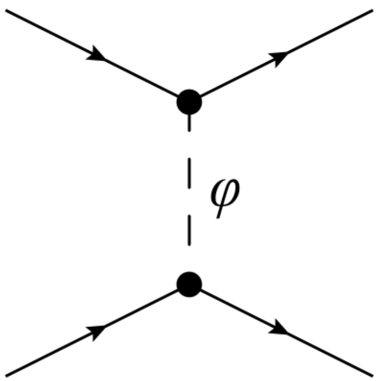

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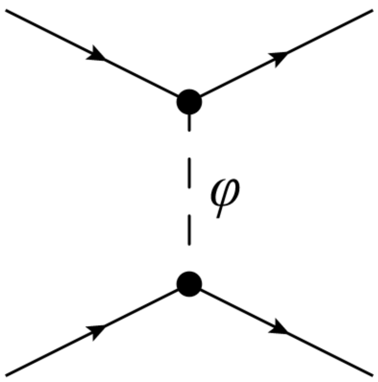

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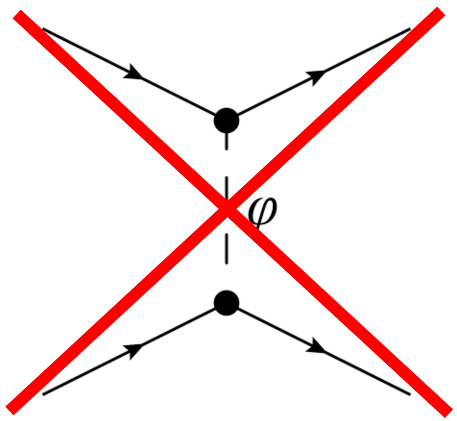

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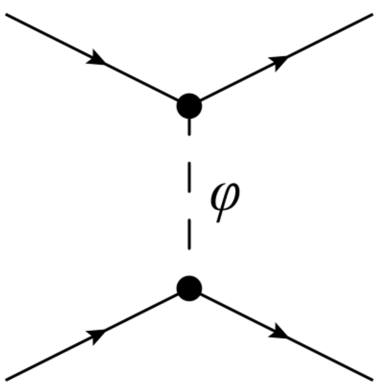

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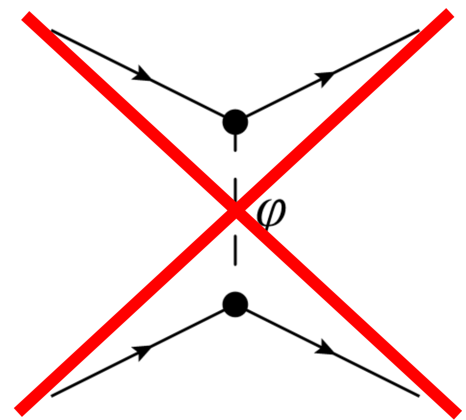

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Gradients + screening/amplification

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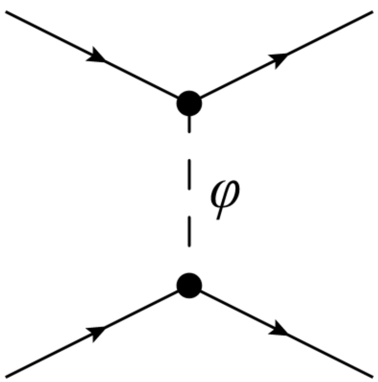

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Many different (classical) signatures in "fifth-force" experiments

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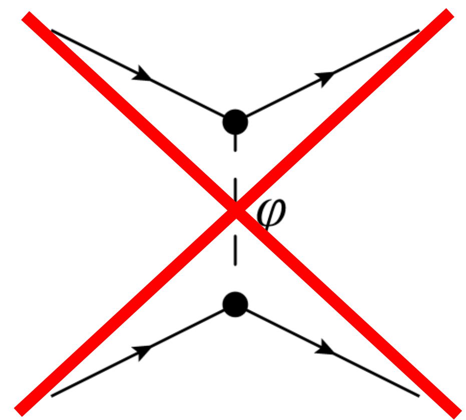

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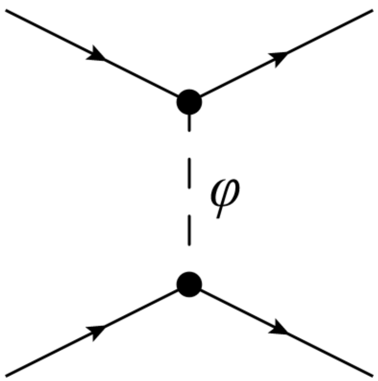

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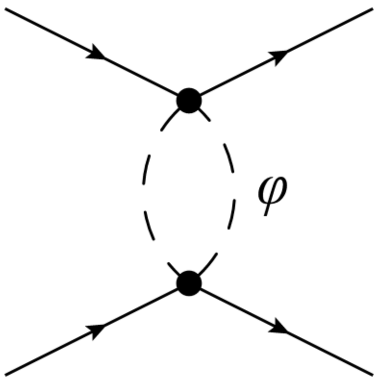

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Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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

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

Sensitivity coefficients

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

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- Precision of optical clocks approaching $\sim 10^{-18}$ 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)]

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

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)],
[Grote, Stadnik, arXiv:1906.06193]

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)]

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

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

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

- Compare $L \sim Na_{\mathrm{B}}$ with λ (or a 2nd L)
- For a cavity compared against a "usual" atomic optical transition, in the non-relativistic limit:

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

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

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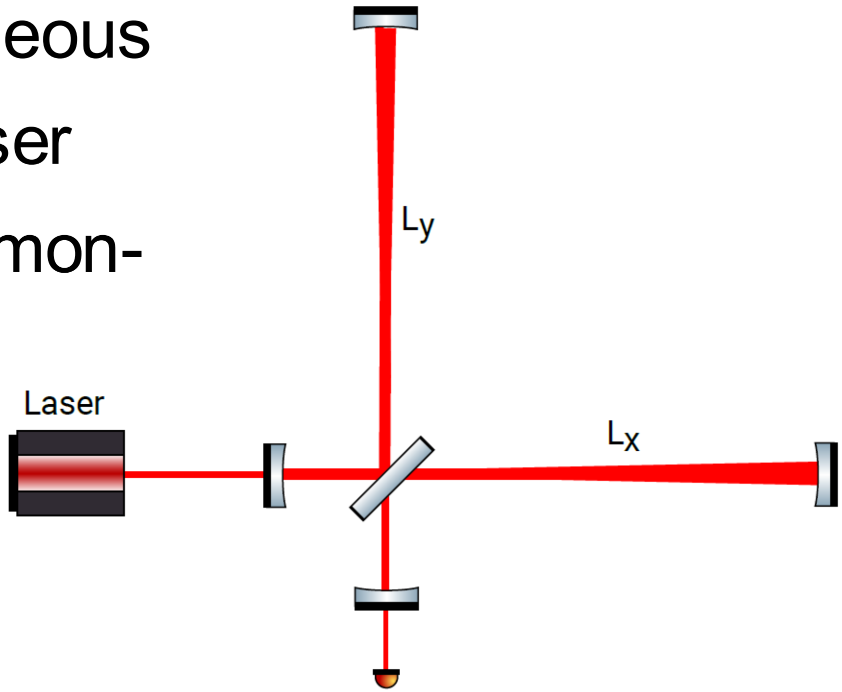
- Multiple reflections of light beam enhance the effect ($N_{\mathrm{eff}} \sim 10^5$ in small-scale interferometers with highly reflective mirrors; c.f. $N_{\mathrm{eff}} \sim 100$ in LIGO/Virgo)

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

[Grote, Stadnik, arXiv:1906.06193]

- Most effects of homogeneous DM fields on two-arm laser interferometers are common-mode suppressed



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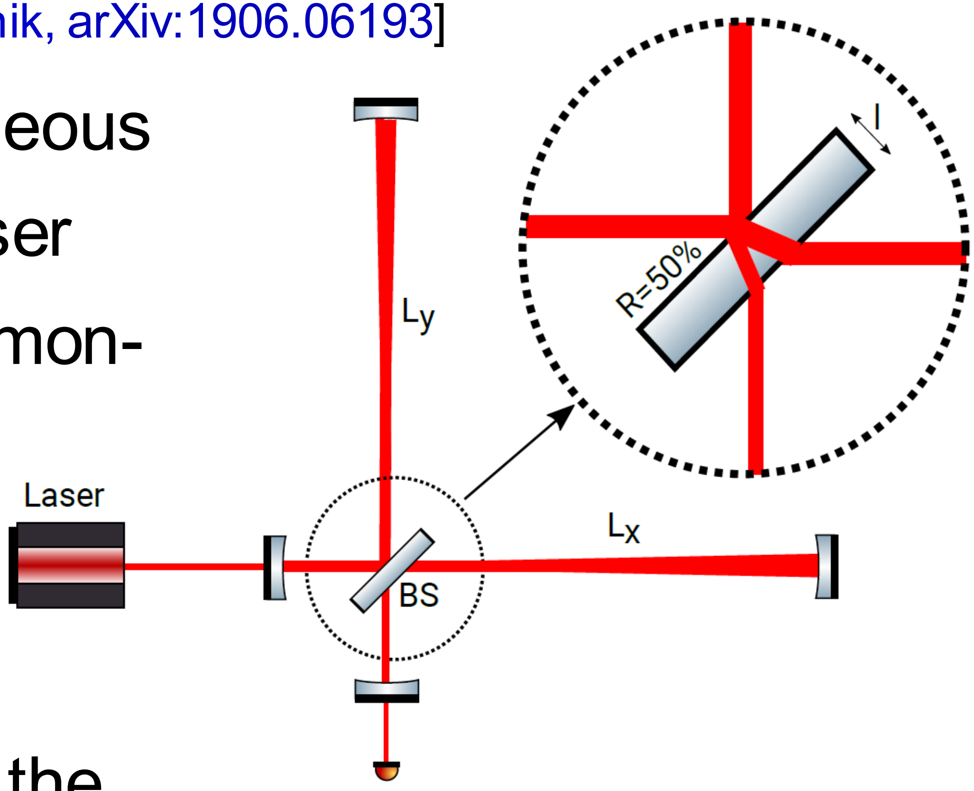
- However, the beam-splitter creates a geometric asymmetry in the detector: $\delta(L_x - L_y) \sim \delta(nl)$



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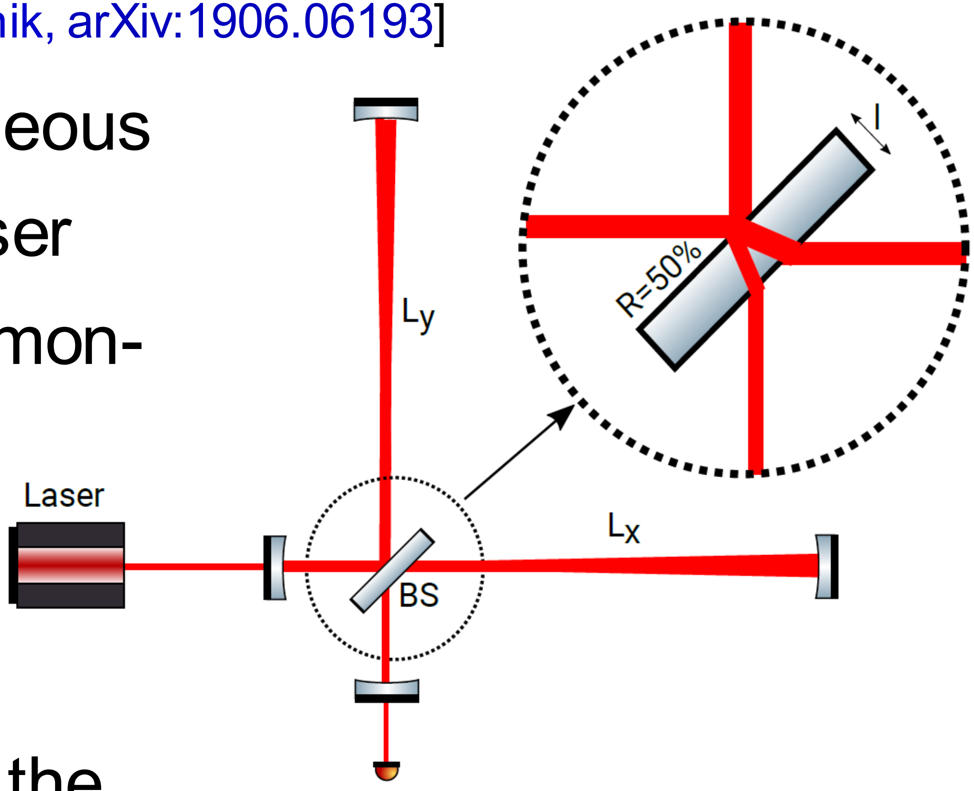
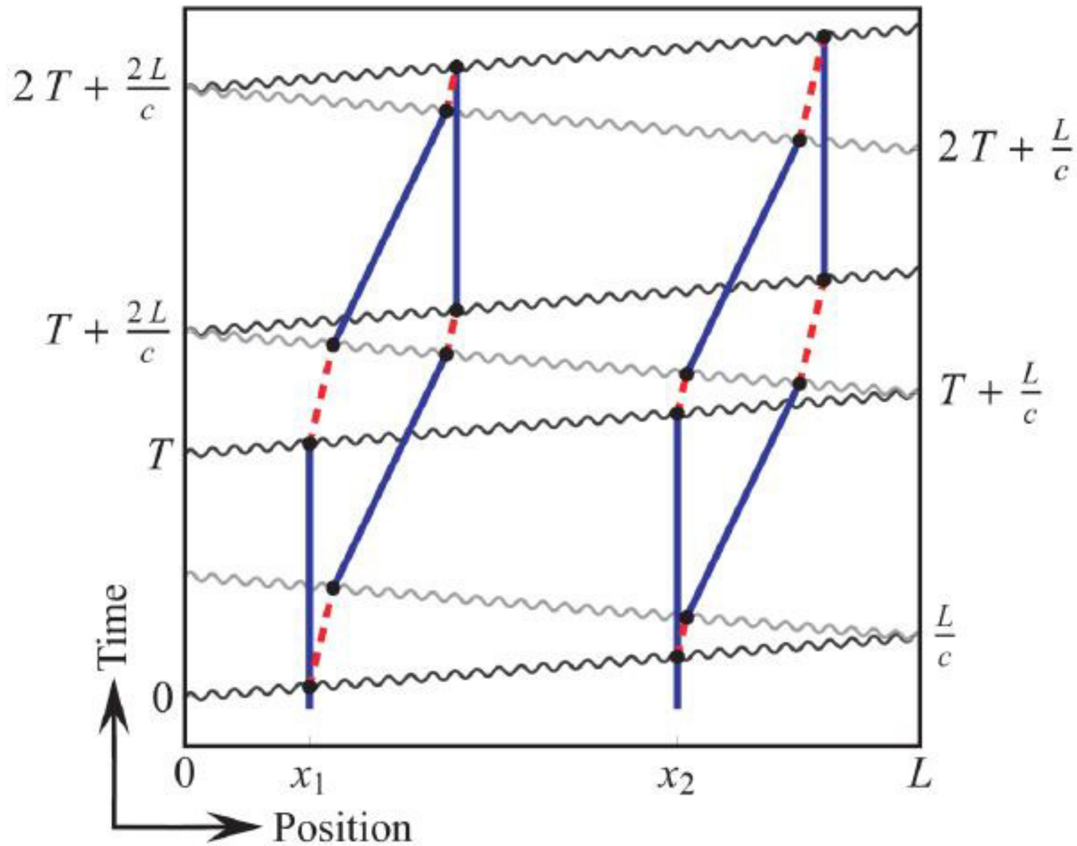


- Most effects of homogeneous DM fields on two-arm laser interferometers are common-mode suppressed
- However, the beam-splitter creates a geometric asymmetry in the detector: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}} \sim v_{\mathrm{sound}}/l$, $Q \sim 10^6$ (best case)

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

[Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg, *PRD* **97**, 075020 (2018)]



- Phase shift between the two separated interferometers maximised when $T_{osc} \sim 2T$: $\delta(\Delta\Phi)_{max} \sim 2T(\delta\omega_{atomic})_{max}$

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

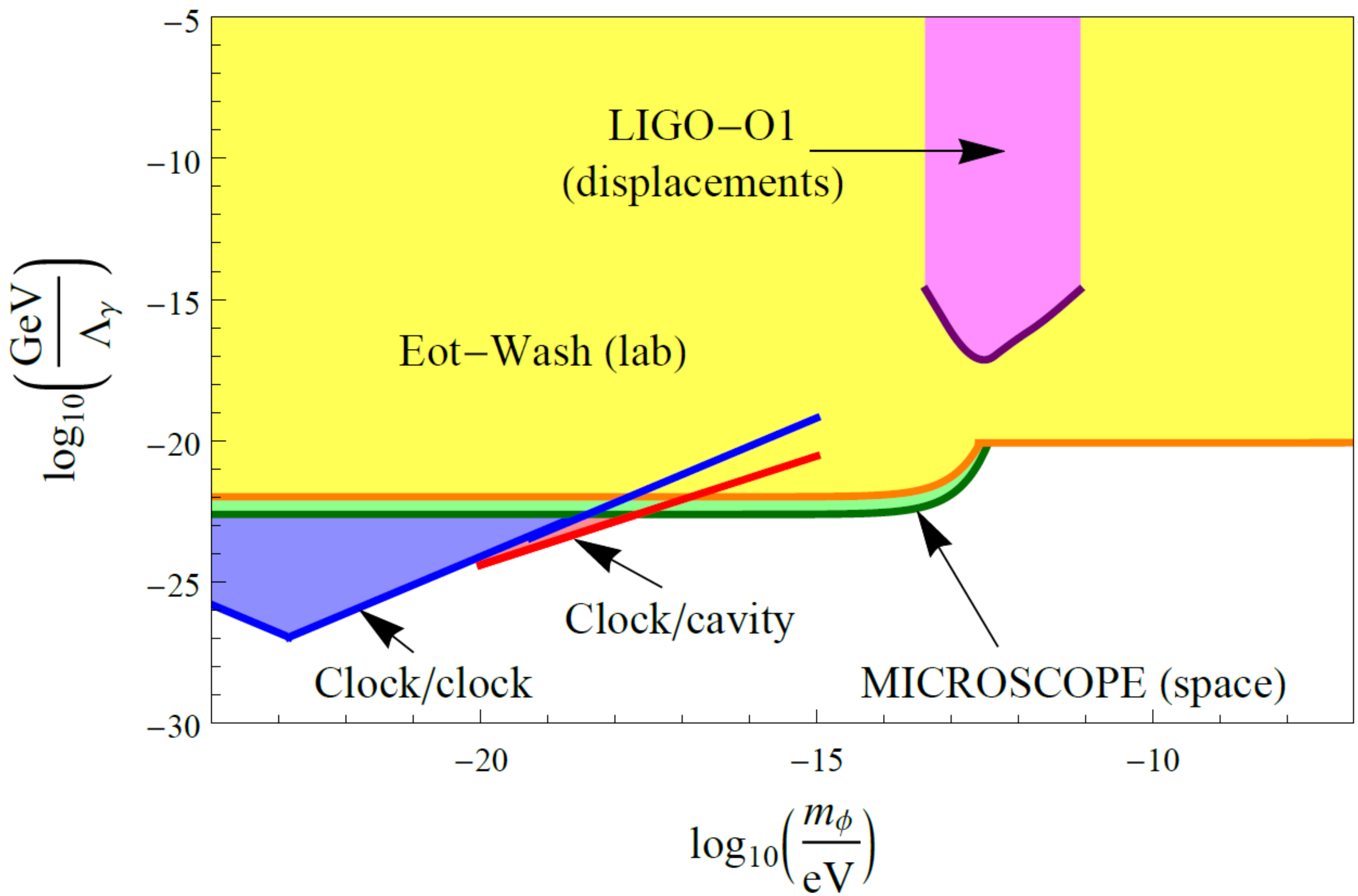
- **Sr/ULE cavity (Torun)*:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Sr/Si cavity (JILA):** [Robinson, Ye *et al.*, *Bulletin APS*, H06.00005 (2018)]
- **Sr^+/ULE cavity (Weizmann):** [Aharony *et al.*, arXiv:1902.02788]
- **Cs/cavity (Mainz):** [Antypas *et al.*, arXiv:1905.02968]

* Searches for domain wall dark matter.

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)]; **LIGO-O1 (displacements) constraints:** [Grote, Stadnik, arXiv:1906.06193]

4 orders of magnitude improvement!



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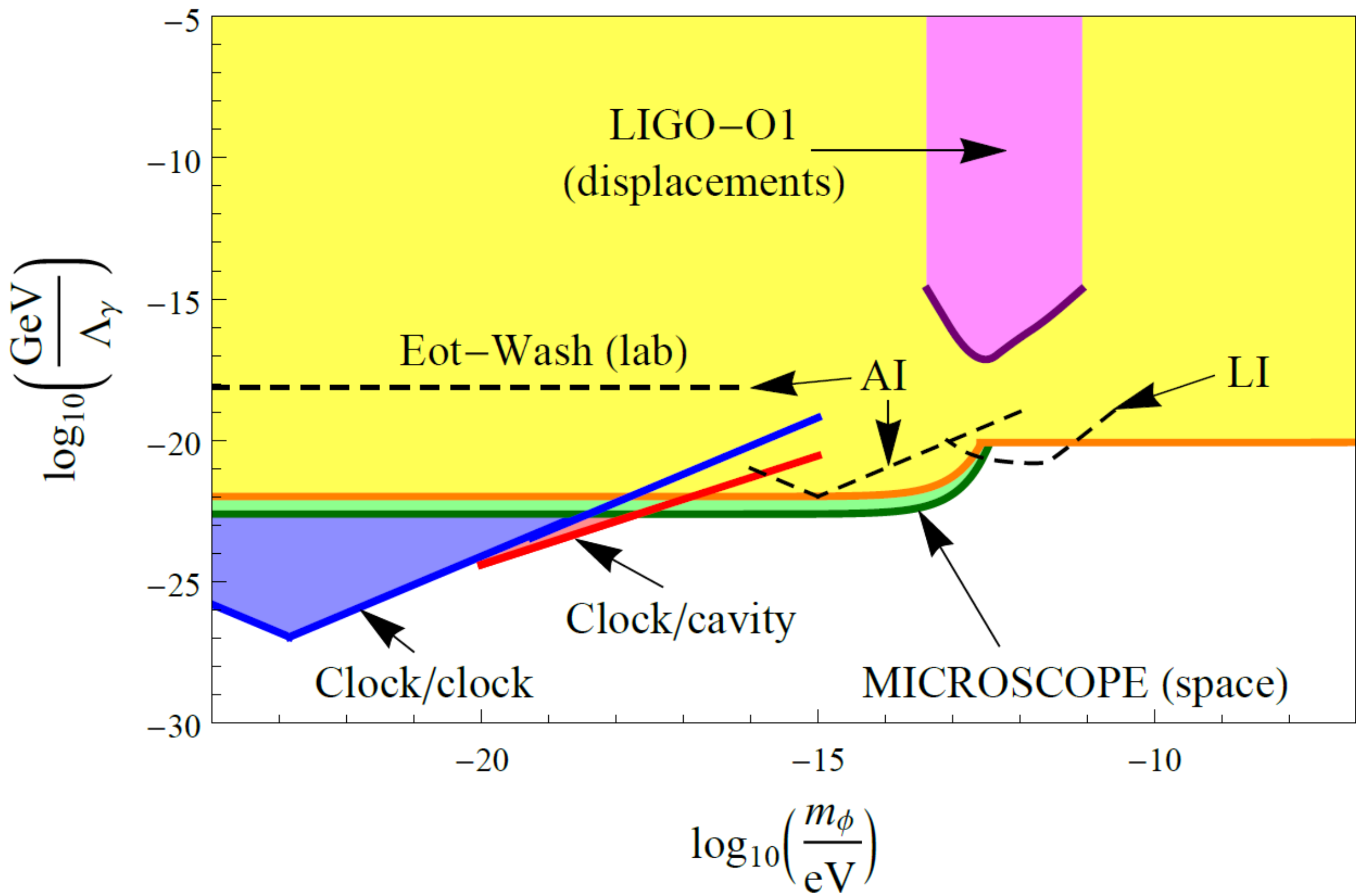
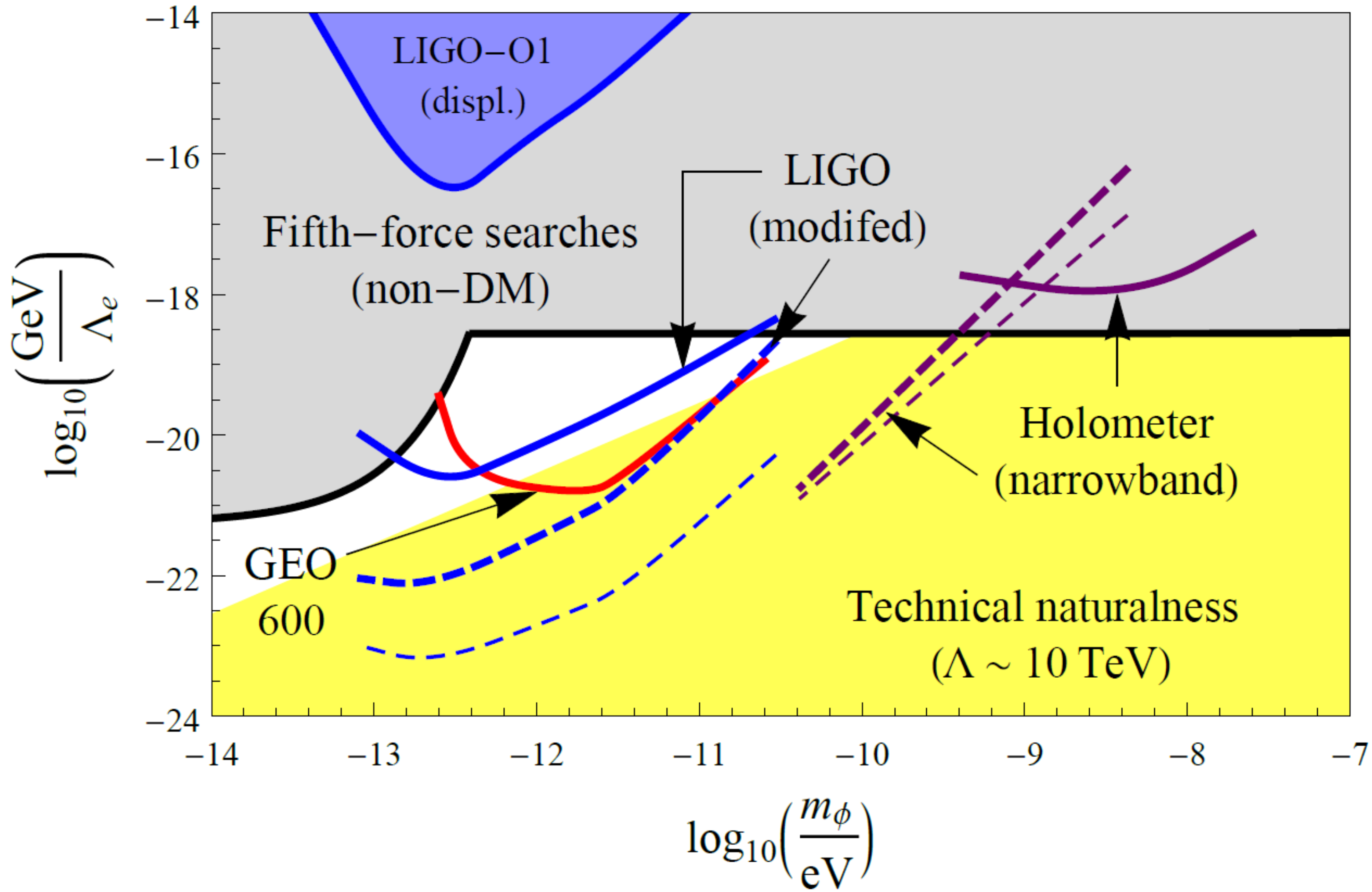


Constraints on Linear Interaction of Scalar Dark Matter with the Electron

Laser interferometry sensitivity estimates and LIGO-O1 (displ.) constraints:

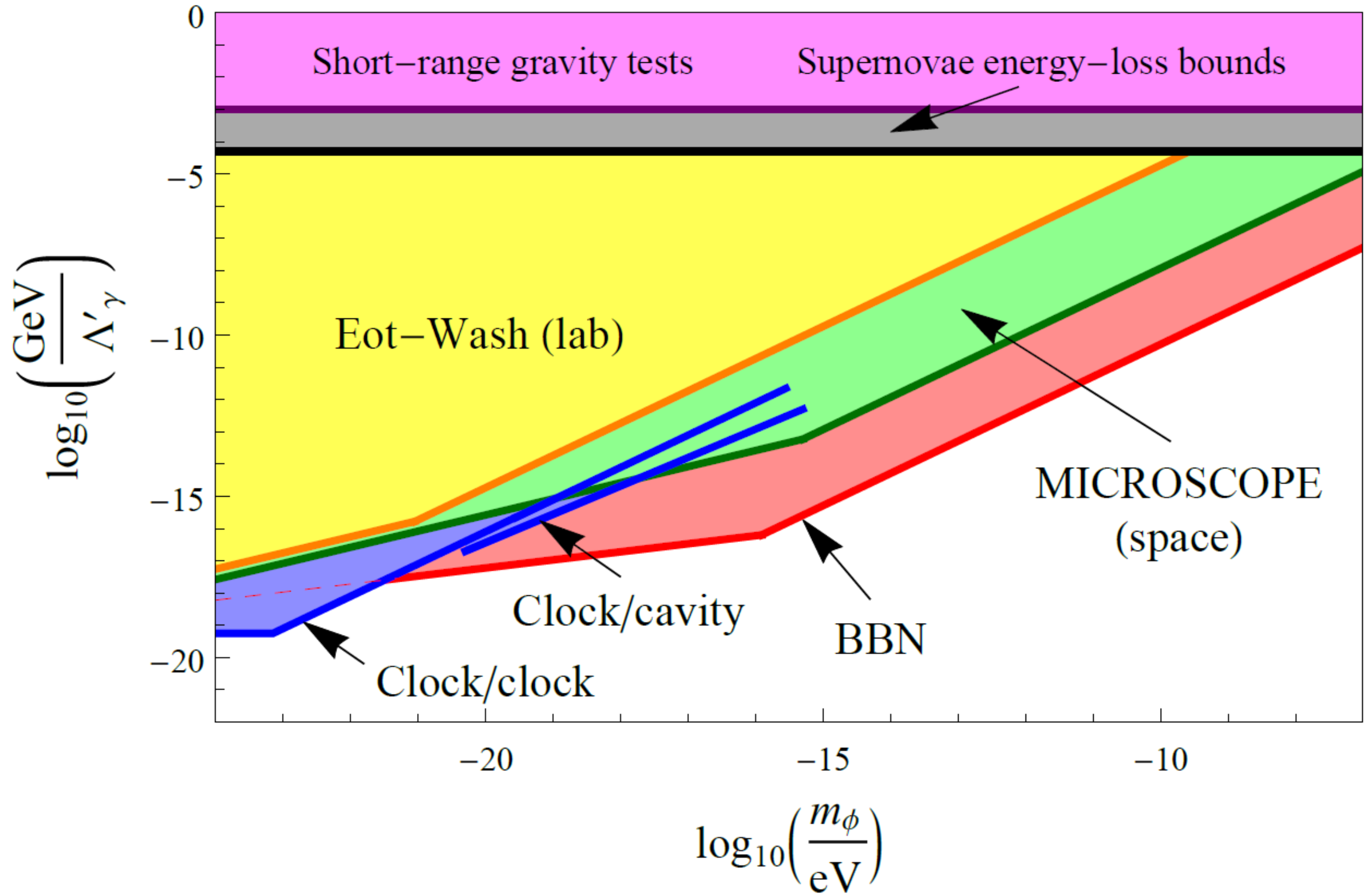
[Grote, Stadnik, arXiv:1906.06193]



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

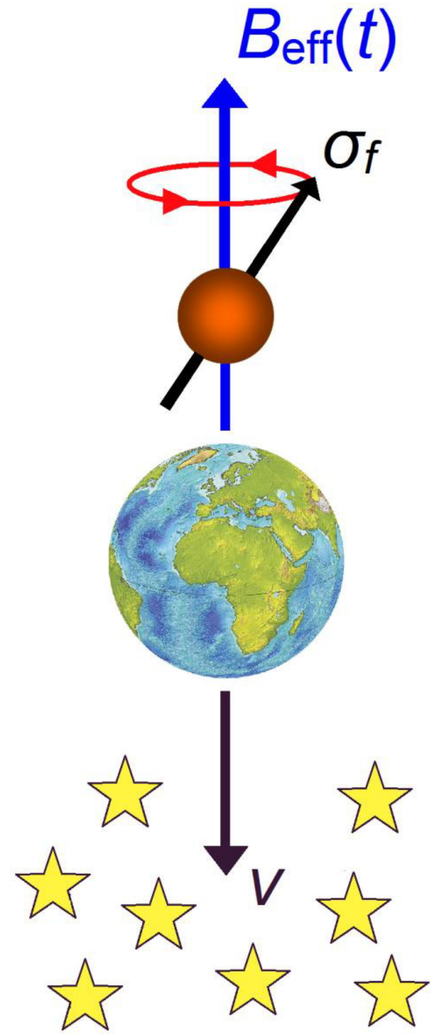
[Flambaum, talk at *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

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

***Pseudo*-magnetic field** *

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



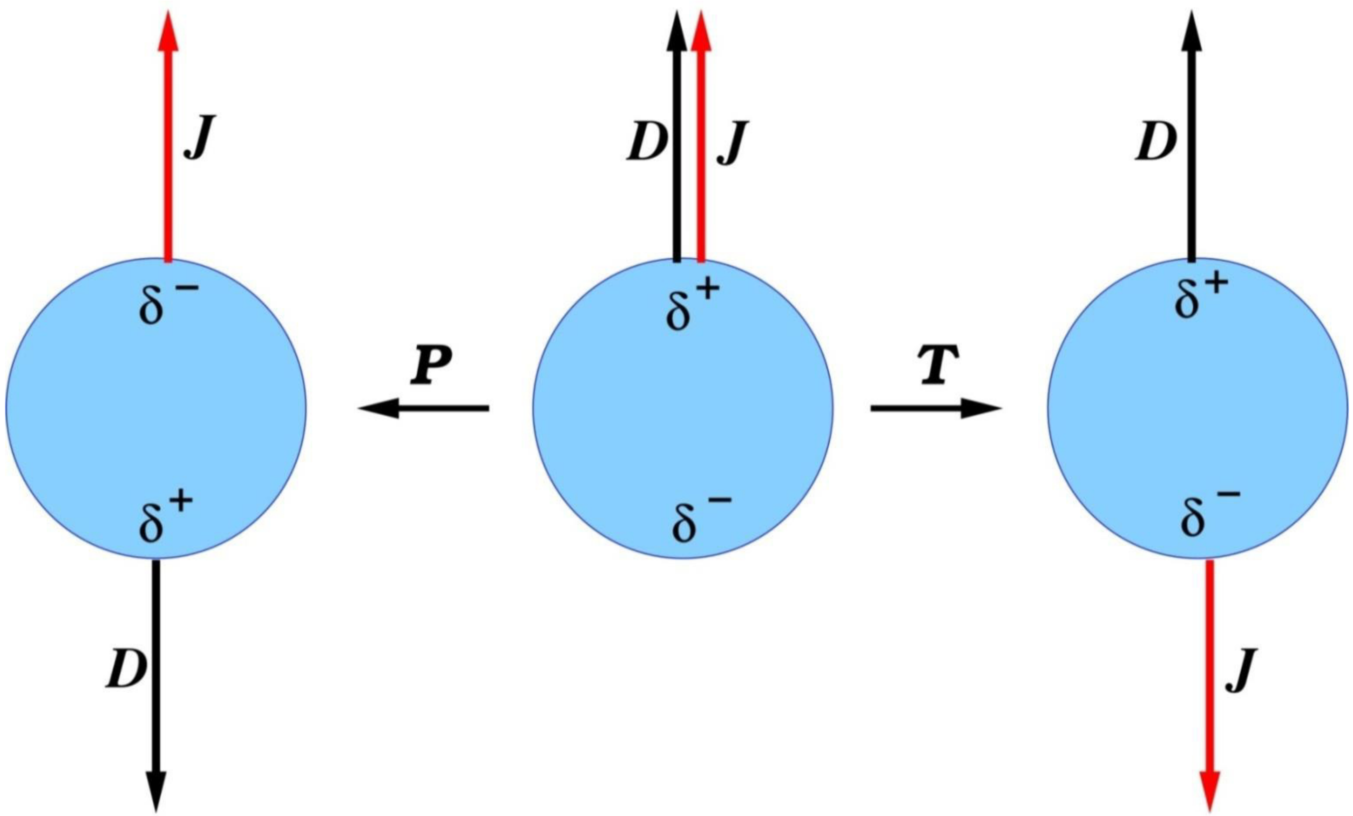
* Compare with usual magnetic field: $H = -\boldsymbol{\mu}_f\cdot\boldsymbol{B}$

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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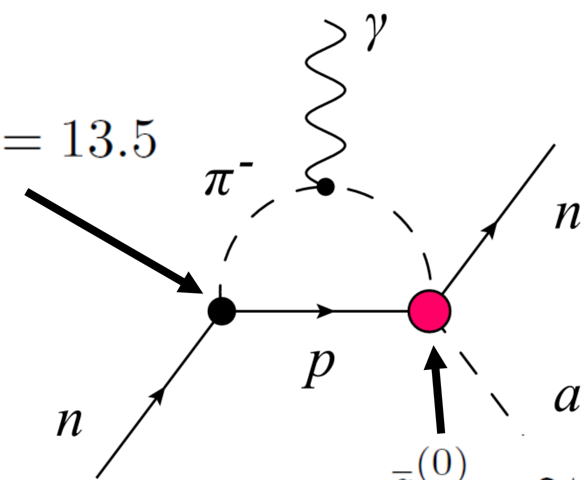
Nucleon EDMs

$g_{\pi NN} = 13.5$



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

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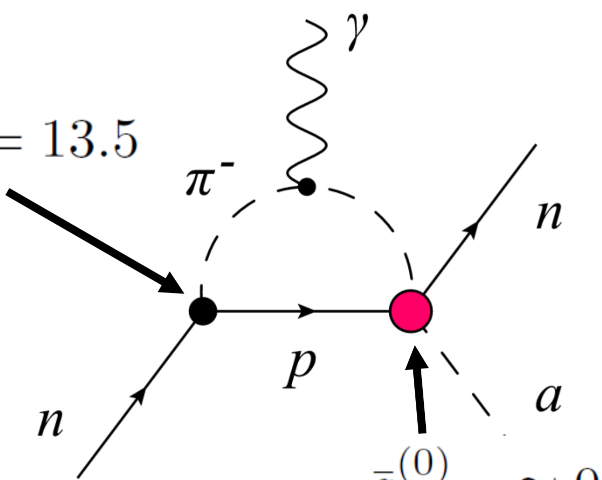
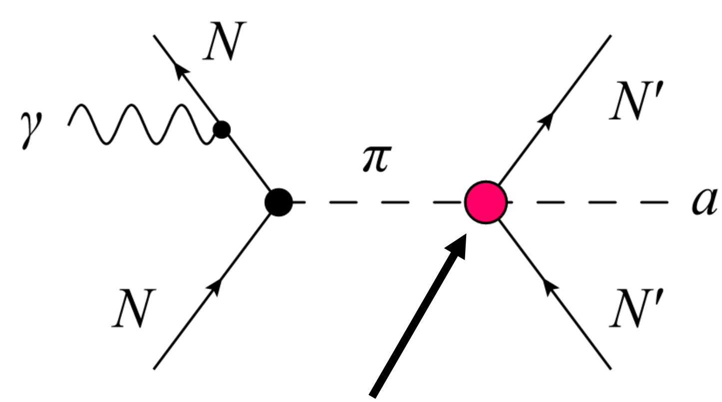


CP-violating intranuclear forces



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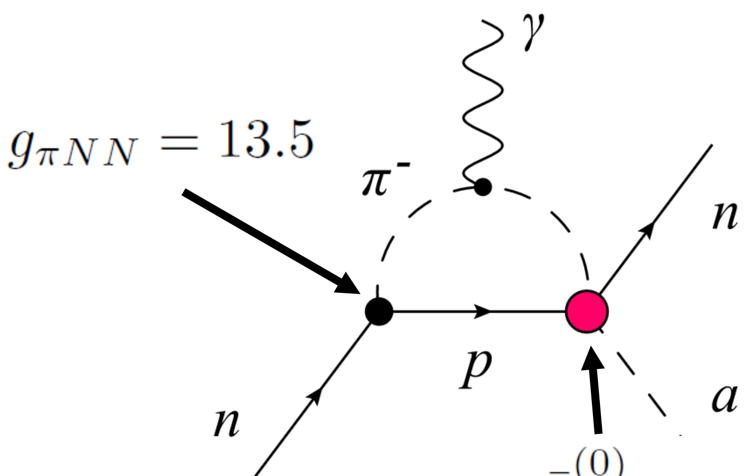
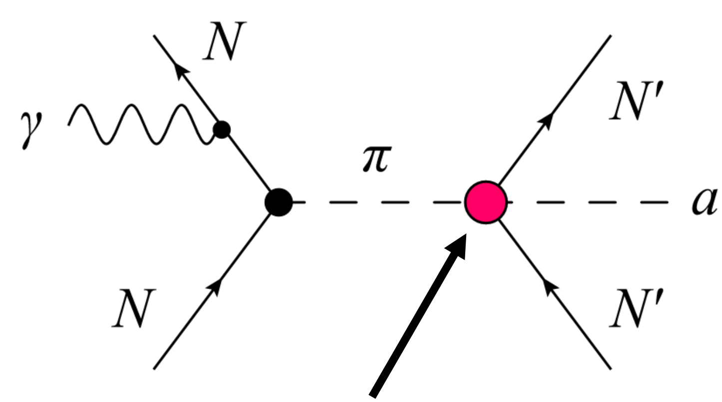


***CP*-violating intranuclear forces**



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

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

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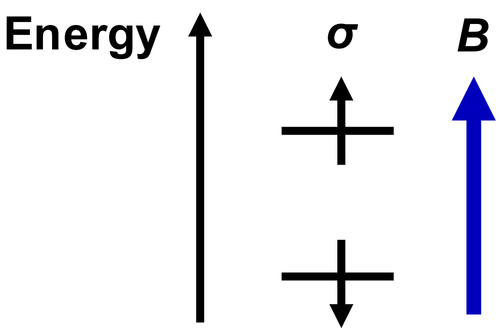
Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]

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

***B*-field effect** · Axion DM effect



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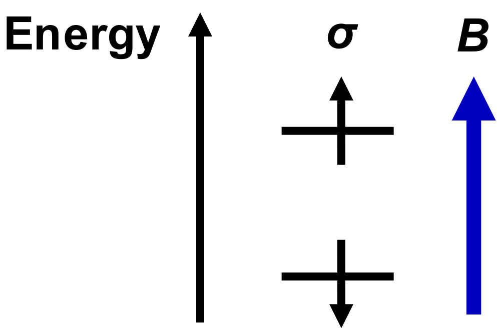
***B*-field effect**

Axion DM effect



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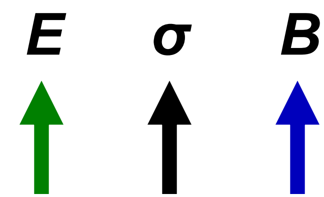
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$



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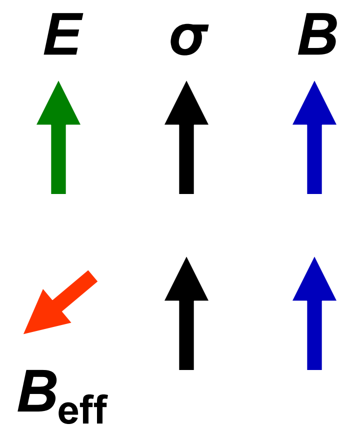
$$R_{\mathrm{EDM}}(t) \propto \cos(m_a t)$$

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



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

Earth's rotation

Searching for Spin-Dependent Effects

Proposals: [Flambaum, talk at *Patras Workshop*, 2013;
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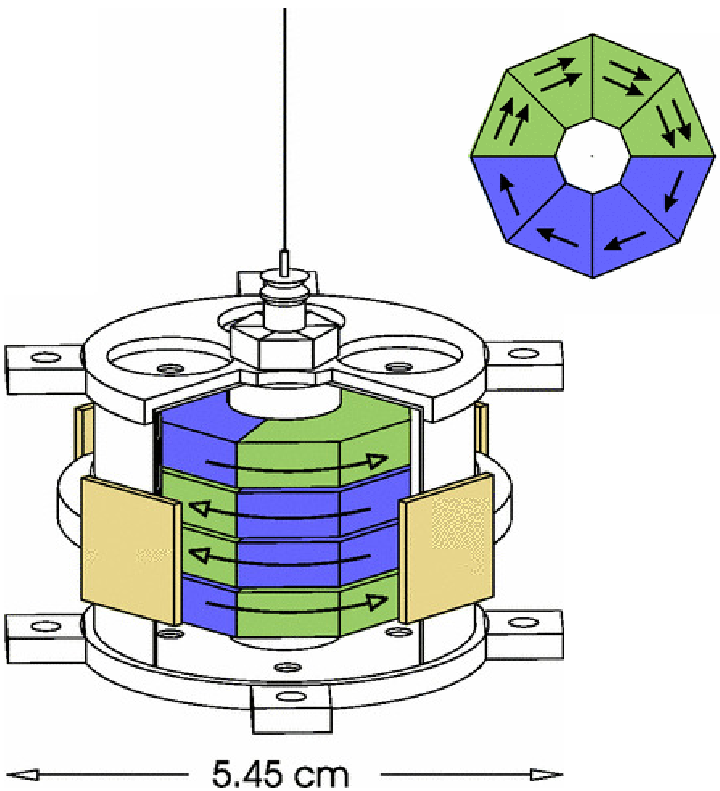
Use *spin-polarised sources*: Atomic magnetometers, ultracold neutrons, torsion pendula

Experiment (Alnico/$SmCo_5$): [Terrano *et al.*, *PRL* **122**, 231301 (2019)]



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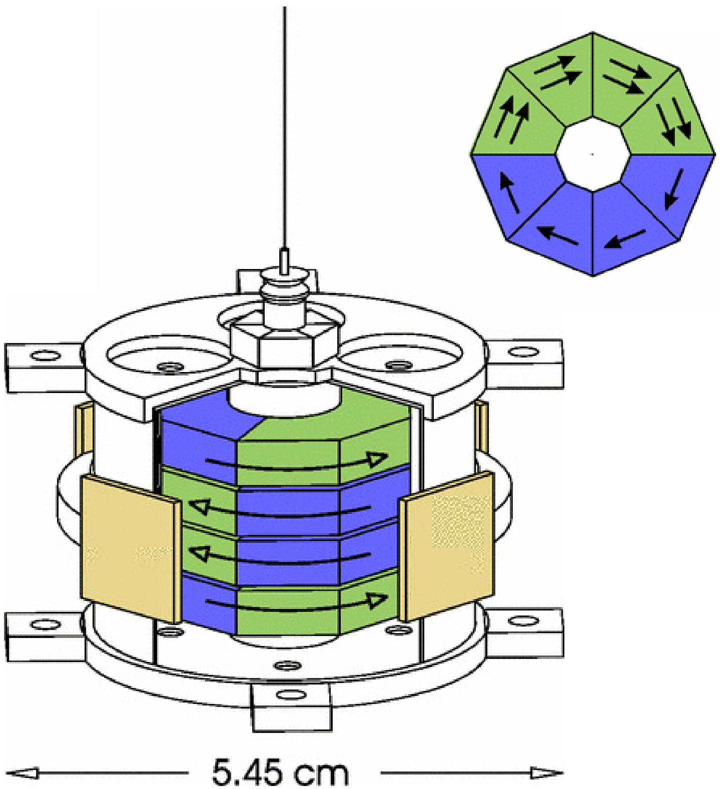

$$\boldsymbol{\mu}_{\text{pendulum}} \approx \mathbf{0}$$

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

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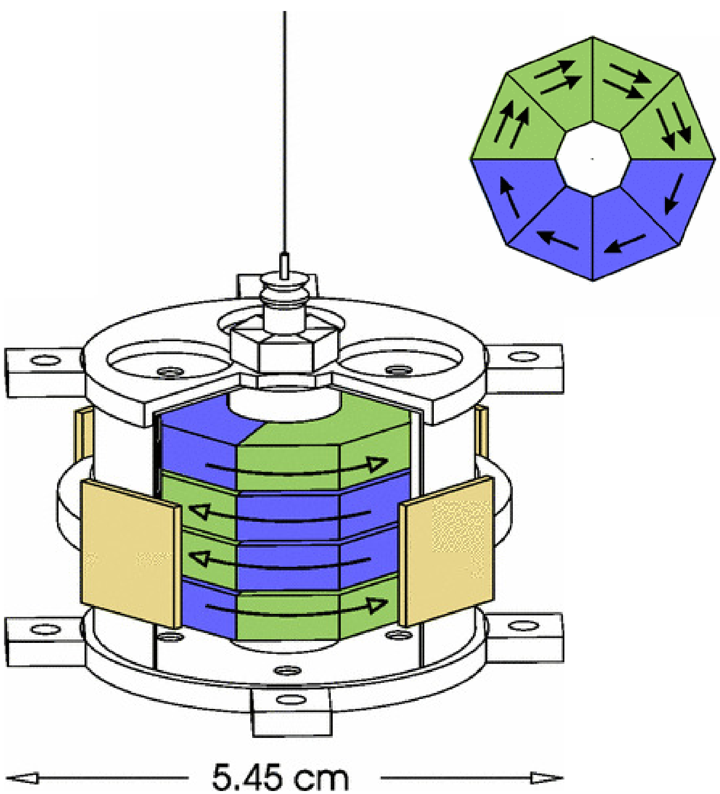


$$\boldsymbol{\mu}_{\rm pendulum} \approx \mathbf{0}$$

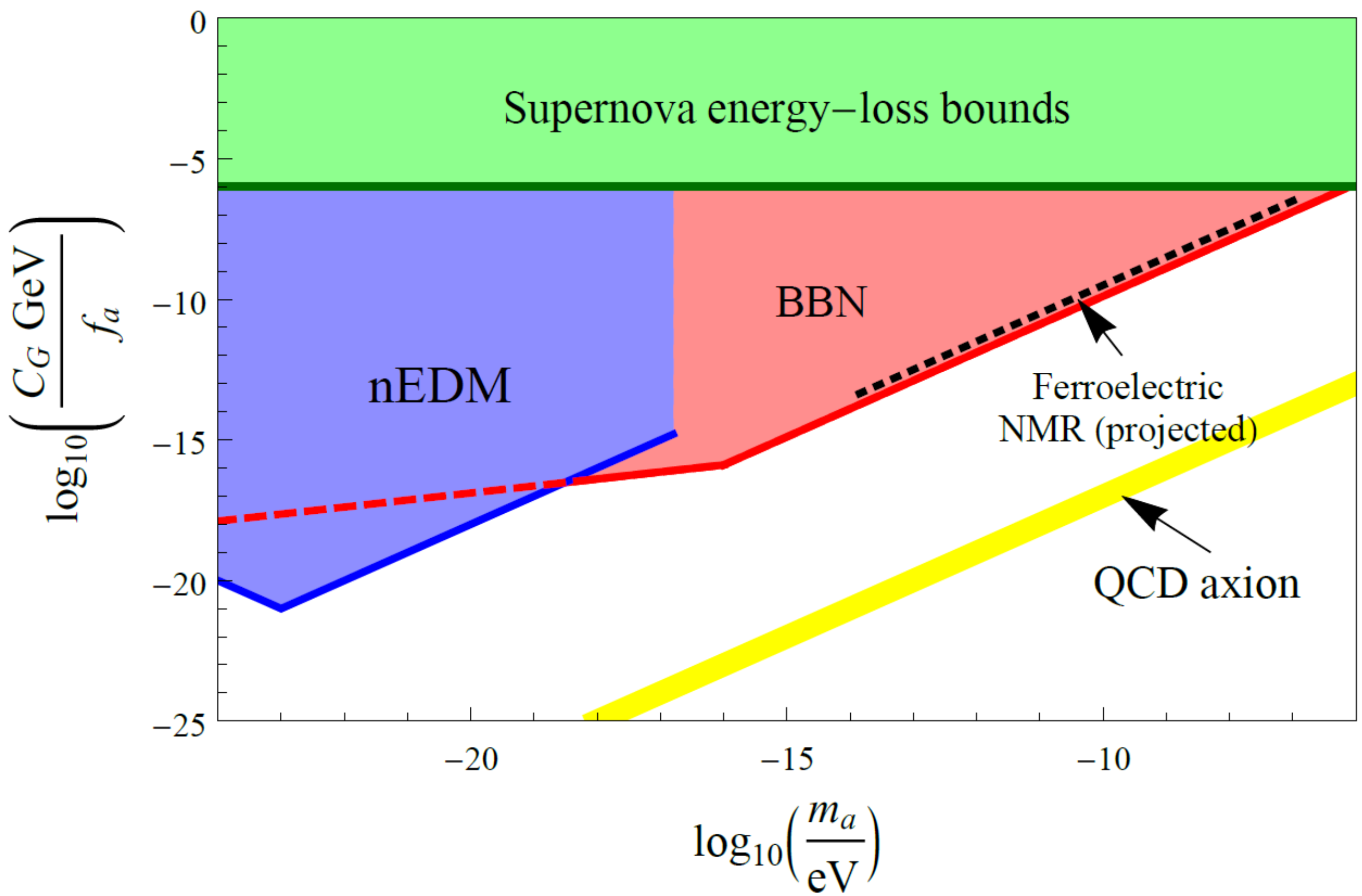
$$(\boldsymbol{\sigma}_e)_{\rm pendulum} \neq \mathbf{0}$$

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

Constraints on Interaction of Axion Dark Matter with Gluons

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

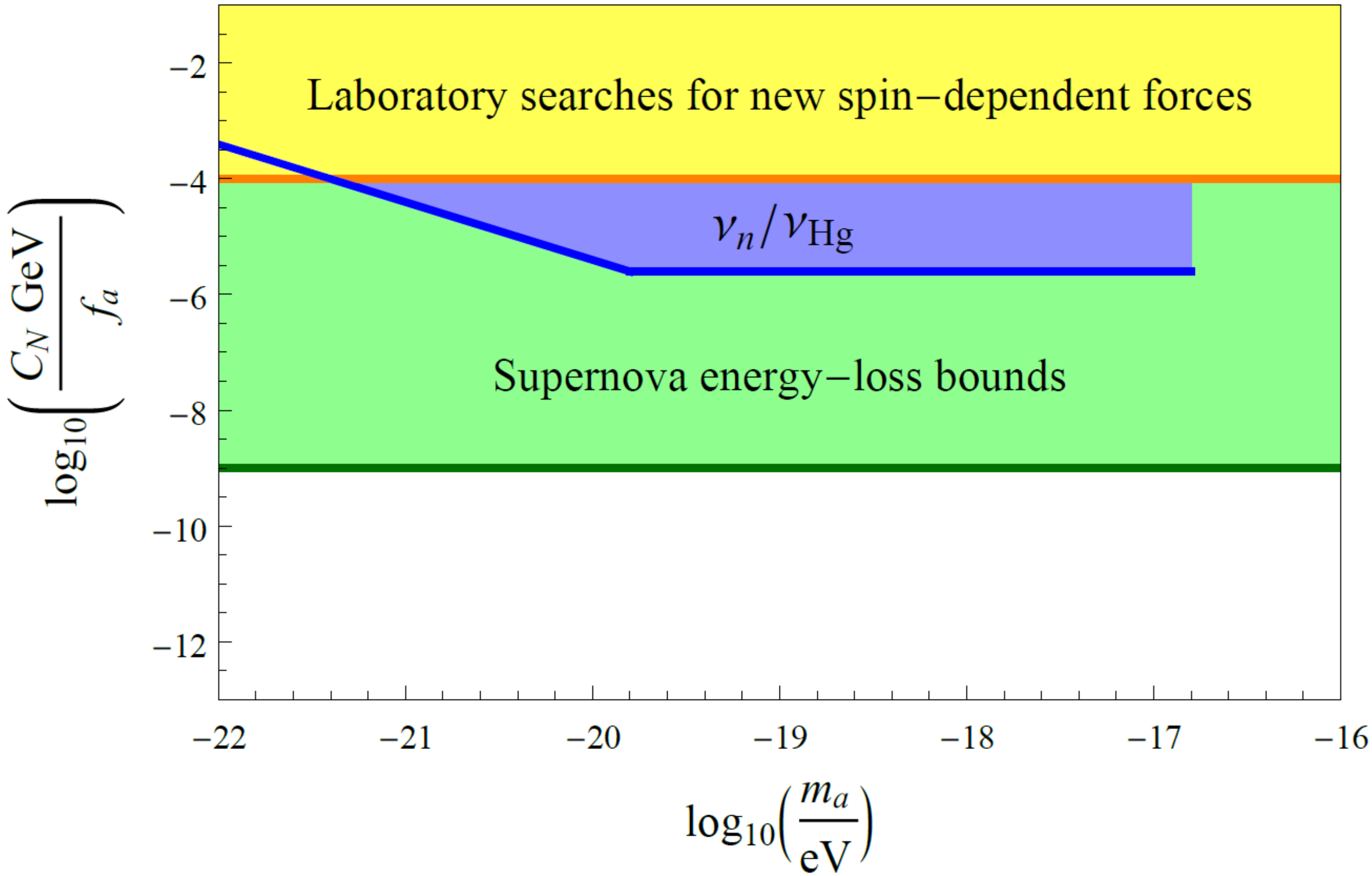
3 orders of magnitude improvement!



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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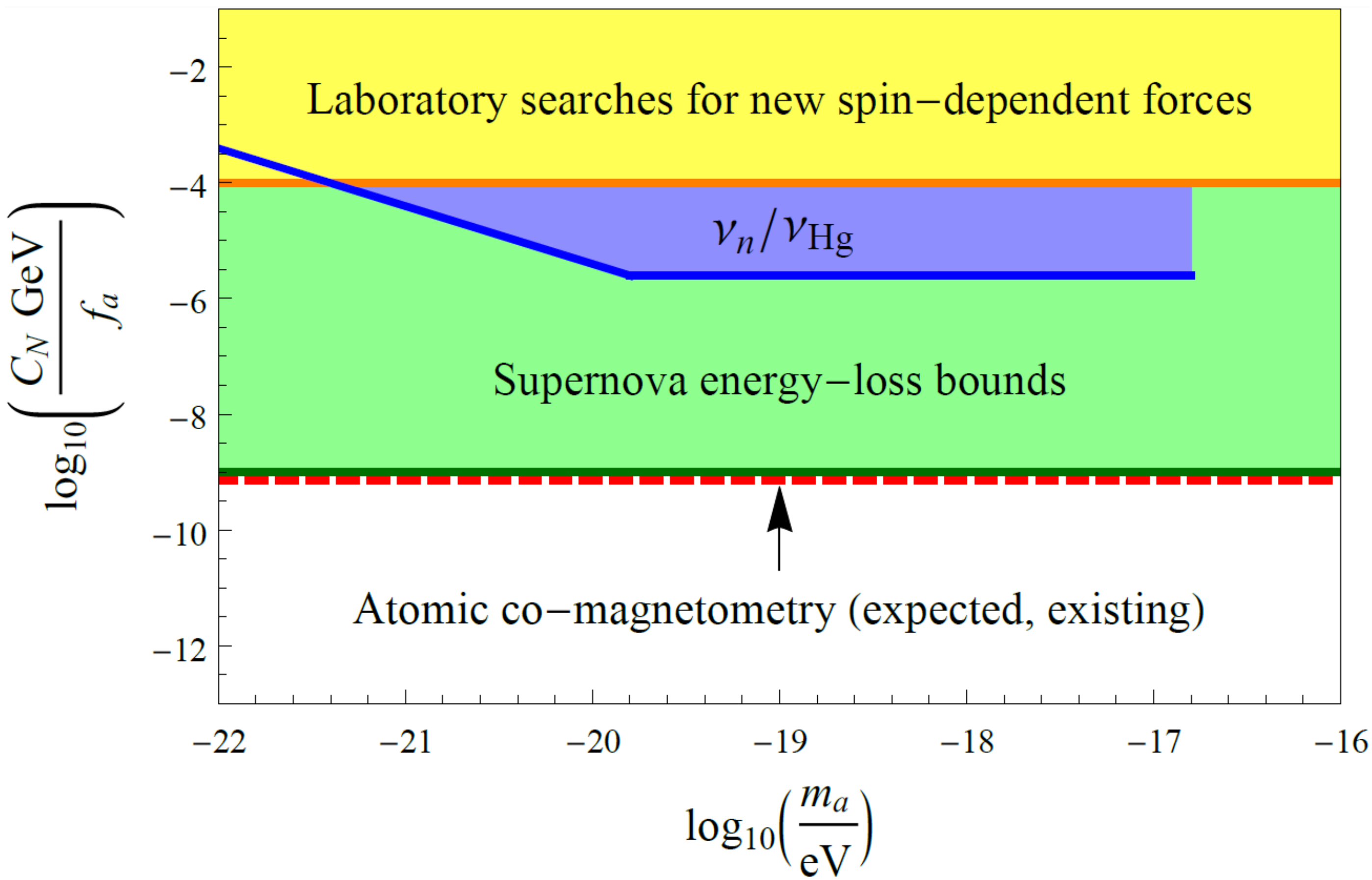
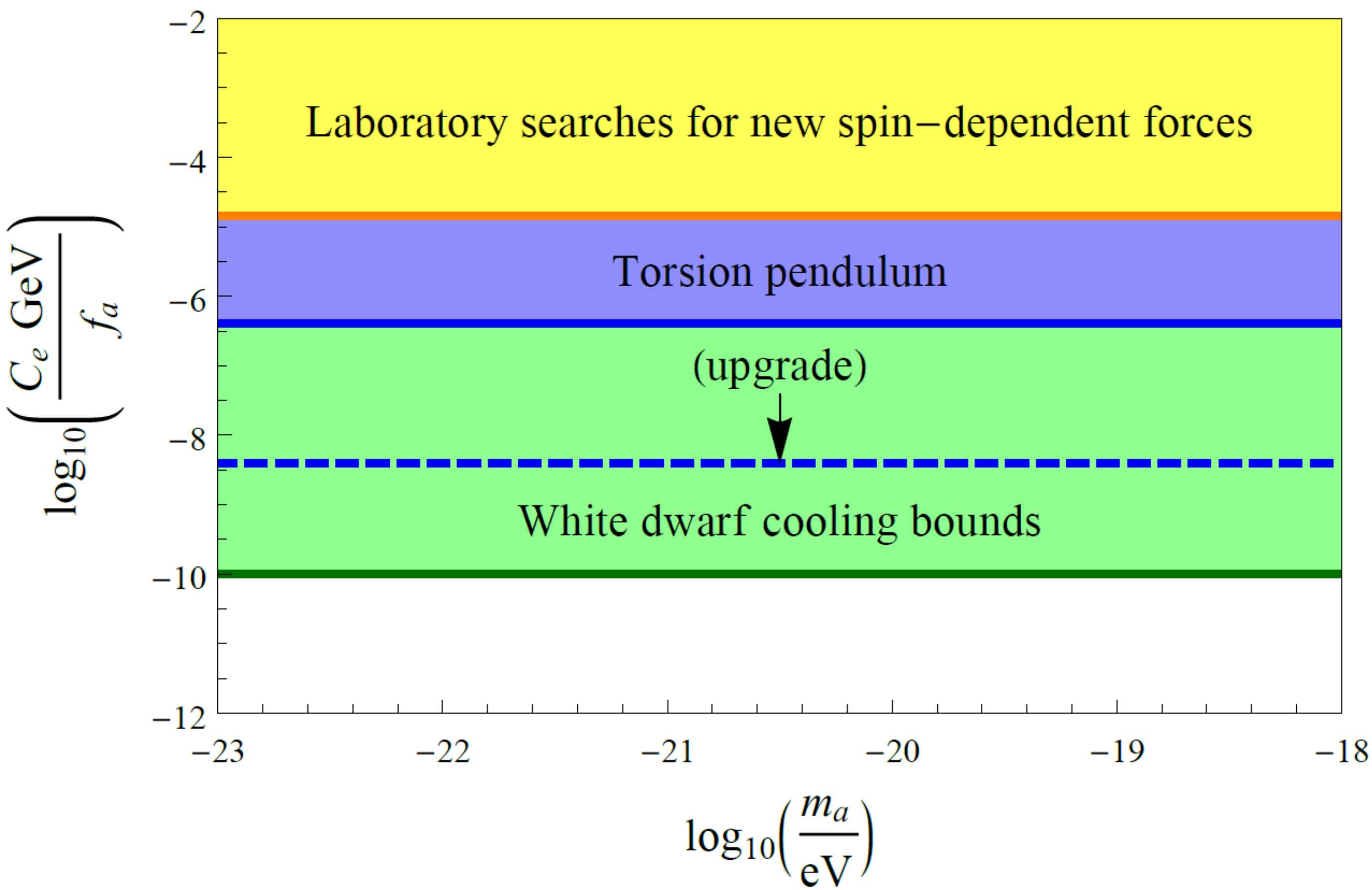


Constraints on Interaction of Axion Dark Matter with the Electron

Torsion pendulum constraints: [Terrano *et al*., *PRL* **122**, 231301 (2019)]

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 (and often) table-top experiments:

    - Spectroscopy (clocks)
    - Cavities and interferometry
    - Magnetometry
    - Torsion pendula

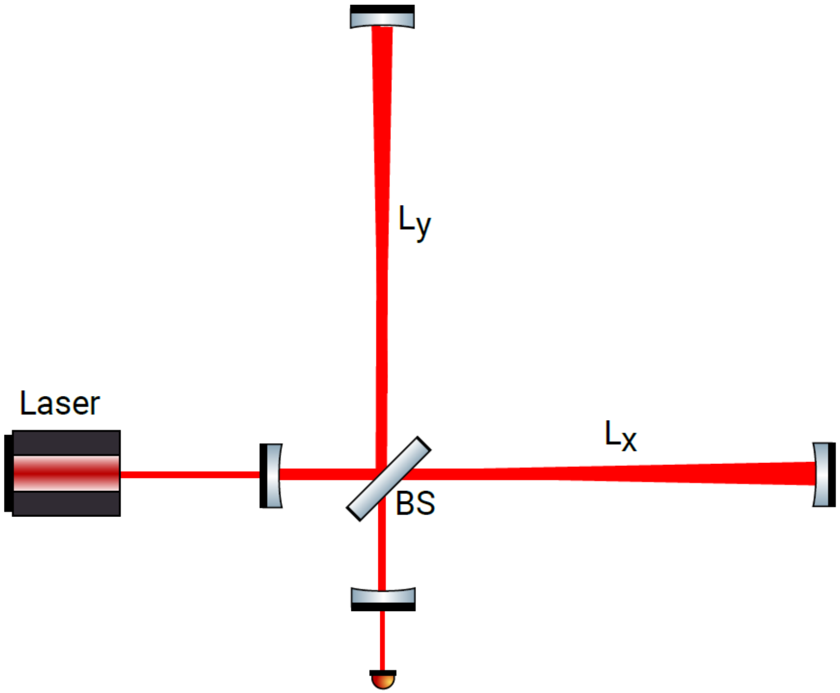
    ⋮

Back-up Slides

Michelson vs Fabry-Perot-Michelson Interferometers

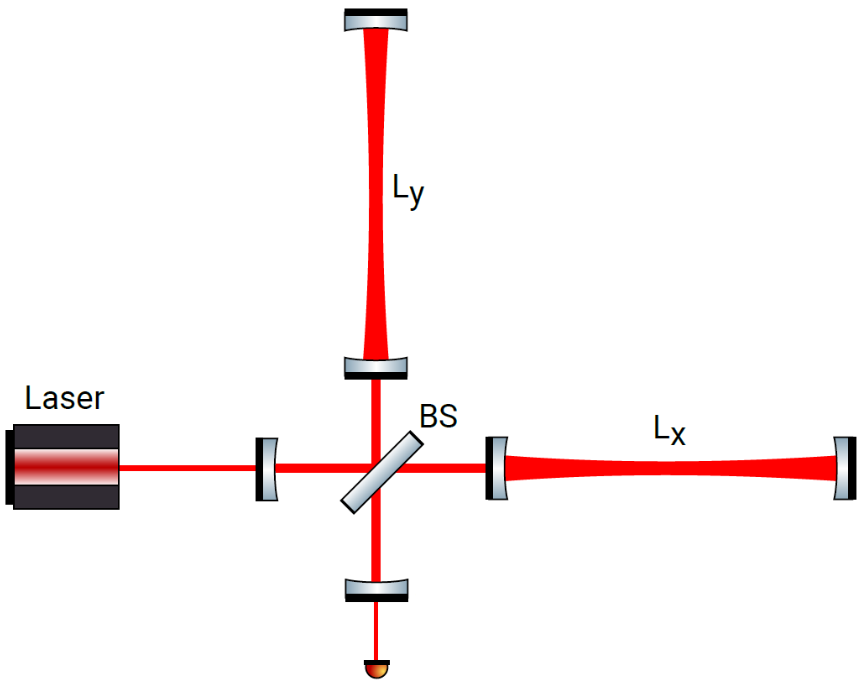
[Grote, Stadnik, arXiv:1906.06193]

Michelson interferometer (GEO 600)



$$\delta(L_x - L_y)_{BS} \sim \delta(nl)$$

Fabry-Perot-Michelson interferometer (LIGO)



$$\delta(L_x - L_y)_{BS} \sim \delta(nl)/N_{eff}$$

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

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

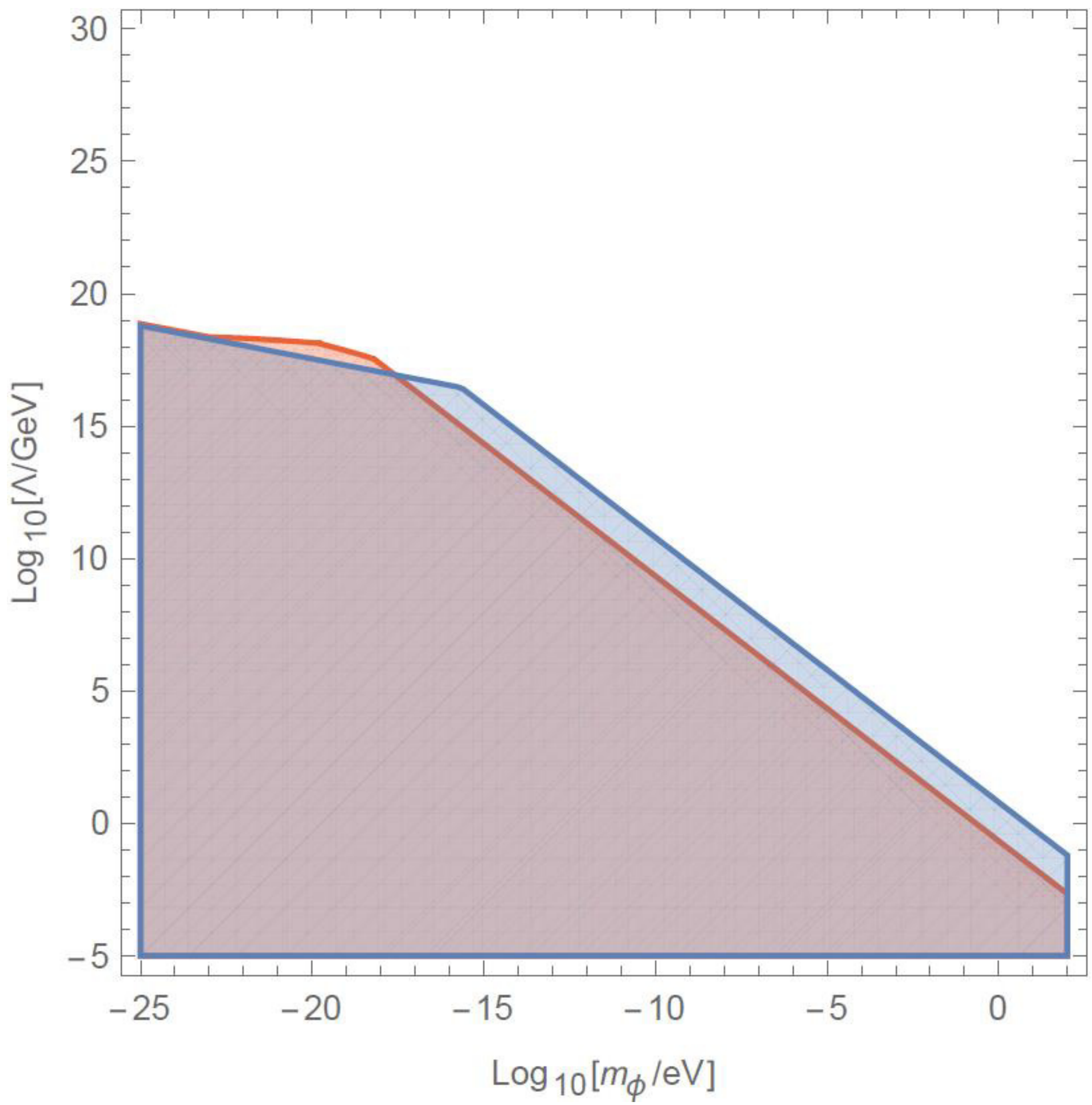
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN

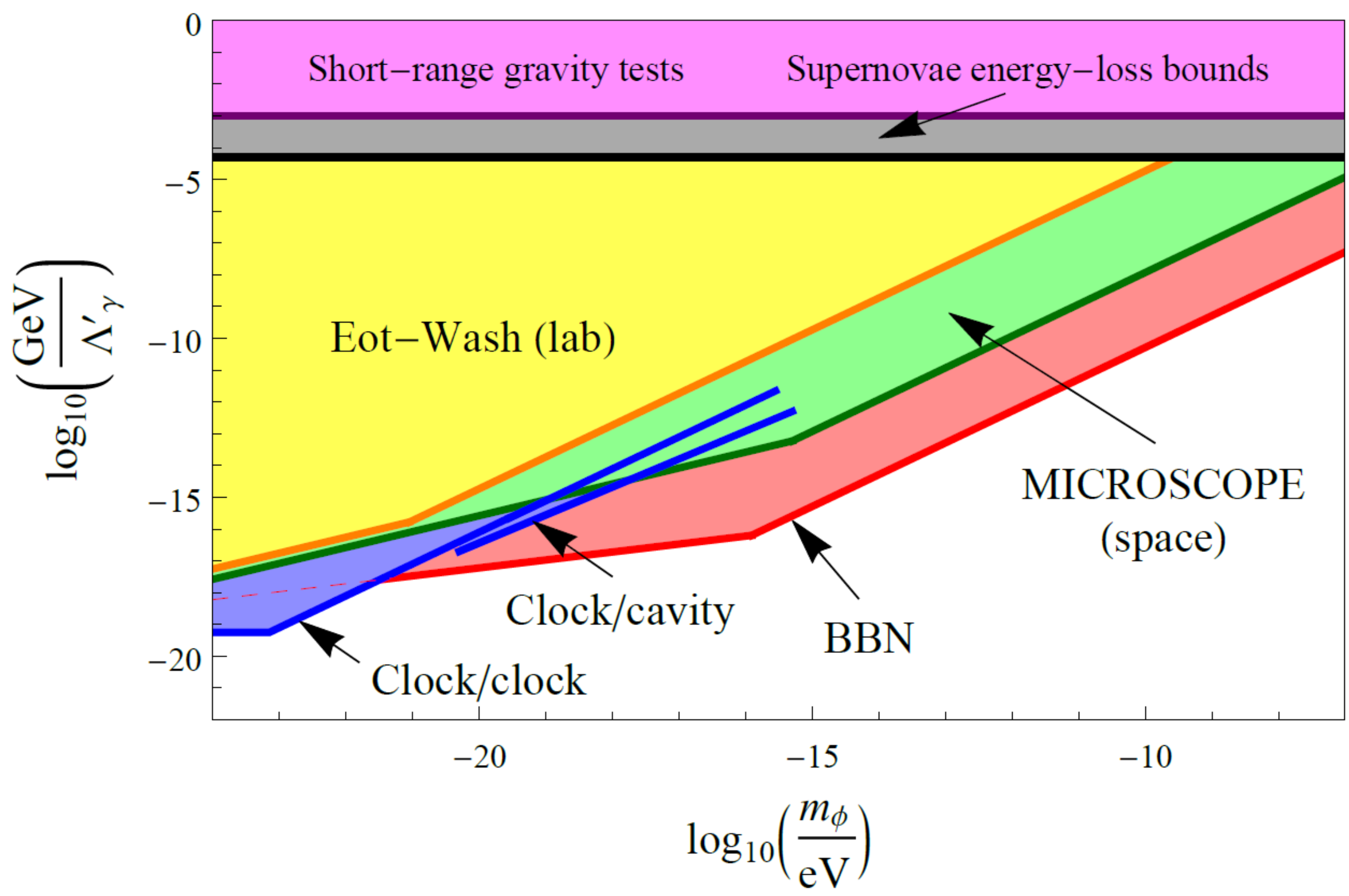
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



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!