Novel Approaches to Dark Matter Detection with Atomic, Molecular and Optical Experiments

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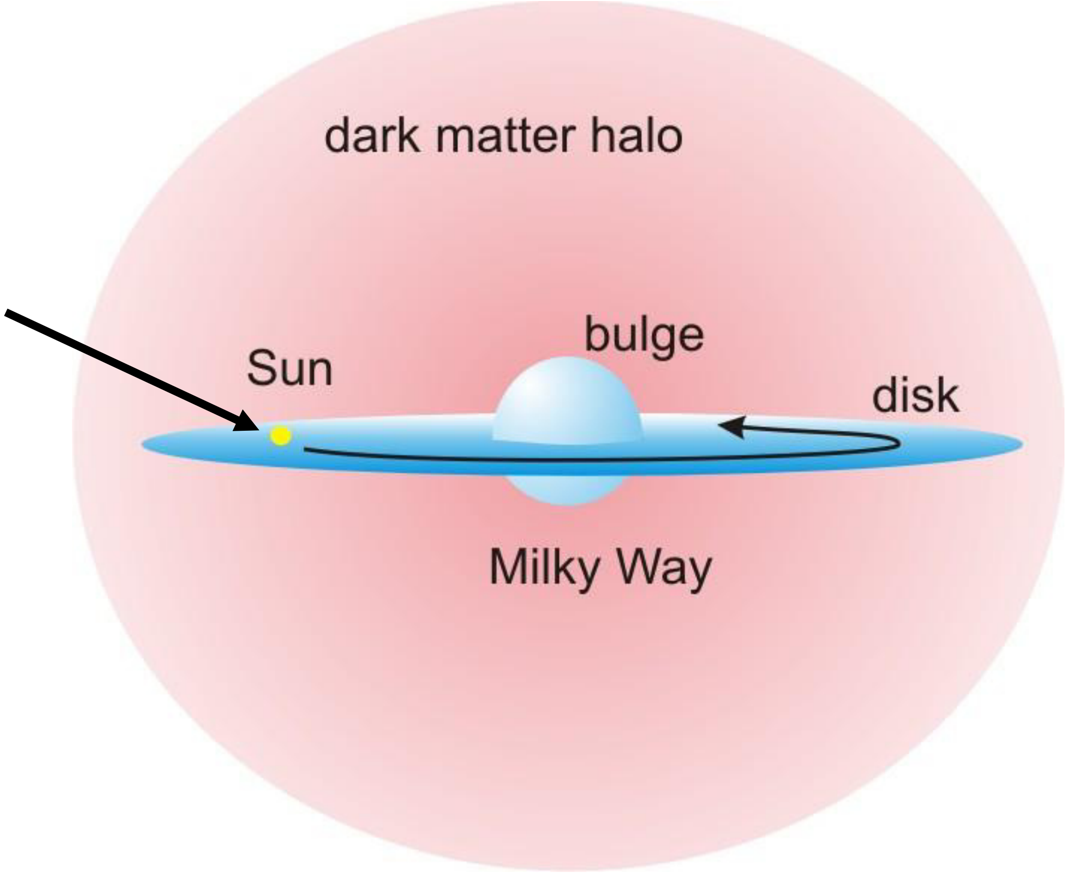
Motivation

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

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

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



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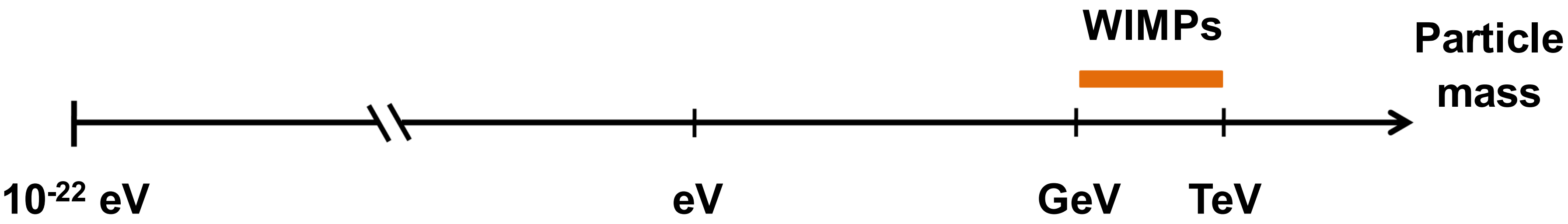

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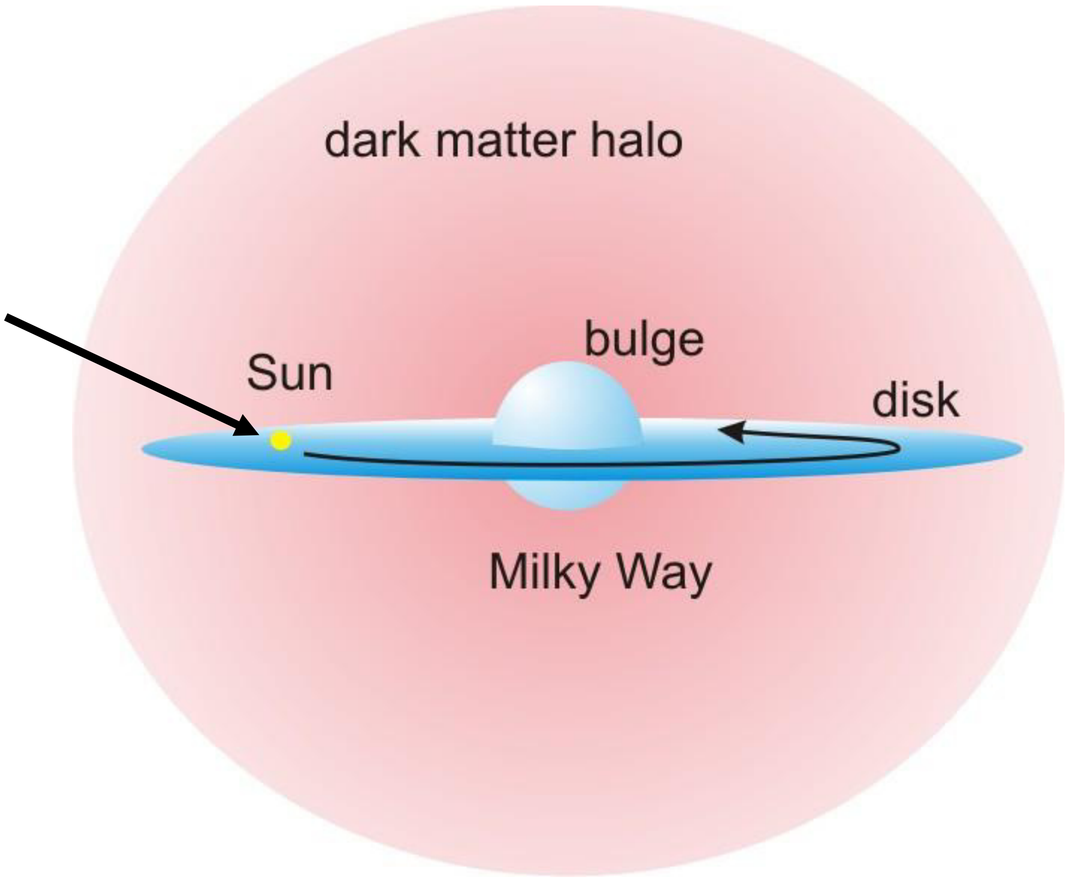

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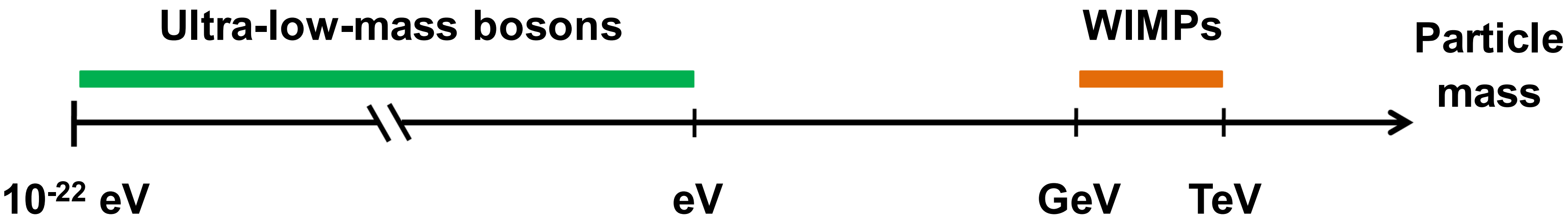

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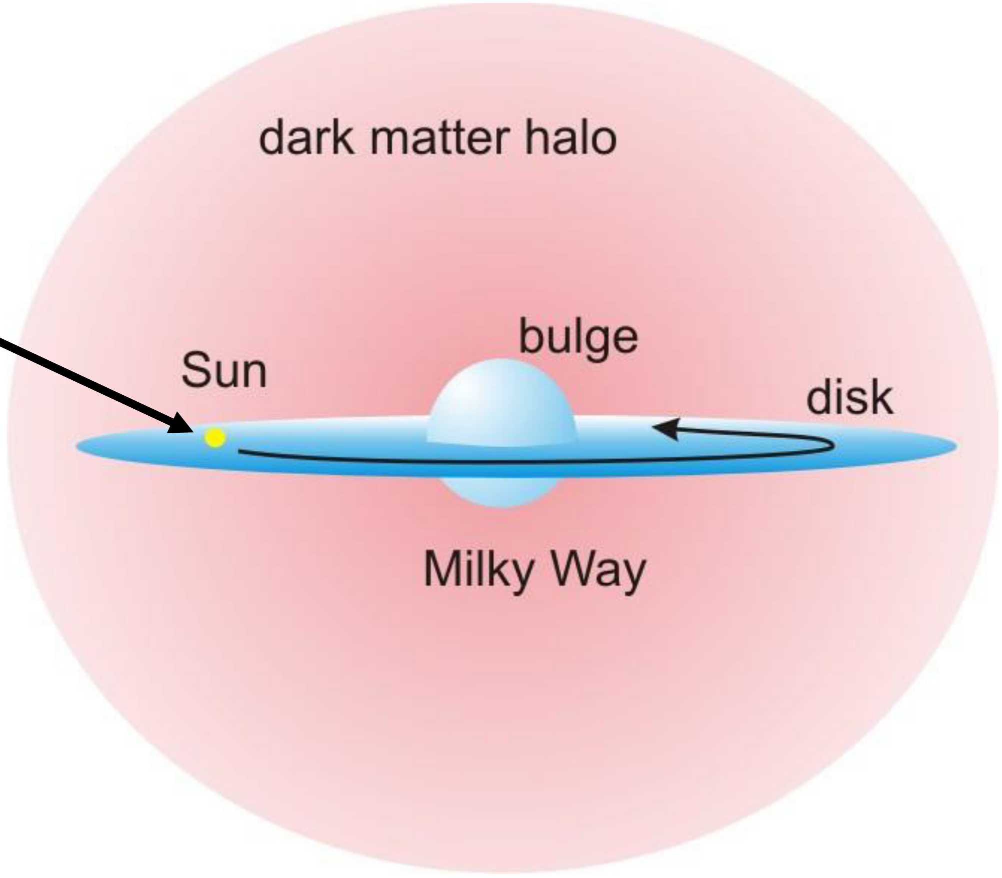
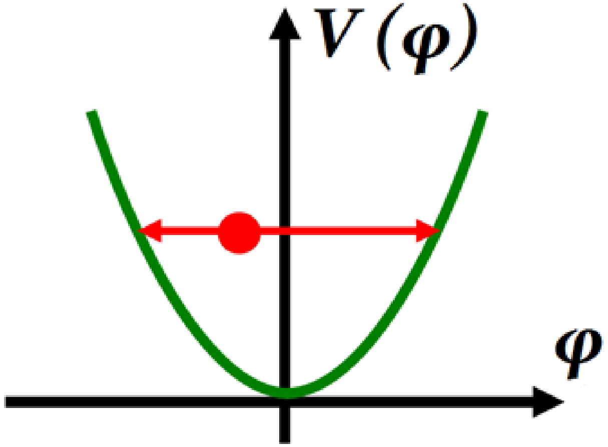


Low-mass Spin-0 Dark Matter

- 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)



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

$$\ddot{\phi} + m_\phi^2 \phi \approx 0$$

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

$\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\mathrm{dwarf\ galaxy}} \sim 1$ kpc

Classical field

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Classical field

- *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

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

→ Time-varying fundamental constants

- Atomic clocks
- Cavities and interferometers
- Fifth-force searches
- Astrophysics (e.g., BBN)

Pseudoscalars (Axions):

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

→ Time-varying spin-dependent effects

- Co-magnetometers
- Nuclear magnetic resonance
- Torsion pendula

Low-mass Spin-0 Dark Matter

Dark Matter

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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)]

$$\mathcal{L}_\gamma = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \quad => \quad \frac{\delta\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}$$

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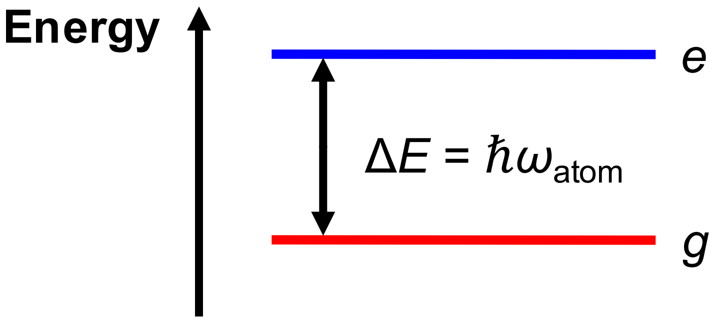
Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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



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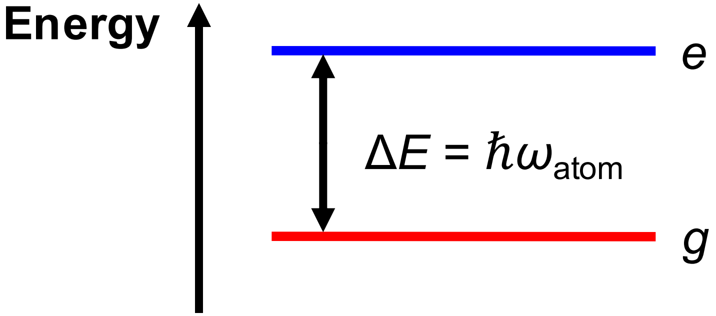


$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_{X=\alpha, m_e/m_p, \ldots} \left(\underset{\uparrow}{K_{X,1}} - \underset{\uparrow}{K_{X,2}}\right)\cos\left(\omega_\phi t\right)$$

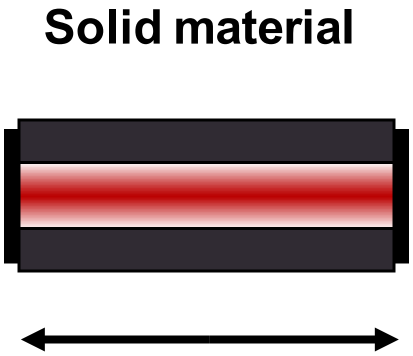
Sensitivity coefficients *

$\omega_\varphi = m_\varphi$ (linear-in-φ coupling) or $\omega_\varphi = 2m_\varphi$ (quadratic-in-φ coupling)

* Sensitivity coefficients K_X calculated extensively by Flambaum group, see the reviews [Flambaum, Dzuba, *Can. J. Phys.* **87**, 25 (2009); *Hyperfine Interac.* **236**, 79 (2015)]

Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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



$L_{\mathrm{free}} \sim Na_{\mathrm{B}} = N/(m_e\alpha)$

Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

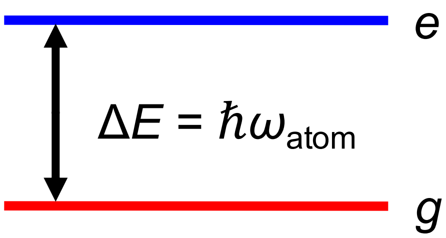
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

$L_{\text{free}} \sim Na_B = N/(m_e\alpha)$

cf.

Electronic transition



$\hbar\omega_{\text{atom}} \sim e^2/a_B$

$$\Phi = \frac{\omega_{\text{atom}} L_{\text{free}}}{c} \propto \left(\frac{e^2}{a_B \hbar}\right)\left(\frac{N a_B}{c}\right) = N\alpha$$

$$=> \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

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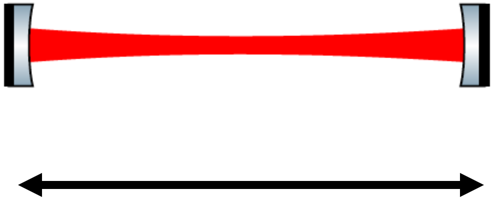
Solid material

$L_{\mathrm{free}} \sim N a_{\mathrm{B}} = N/(m_e \alpha)$

cf.

Freely-suspended mirrors

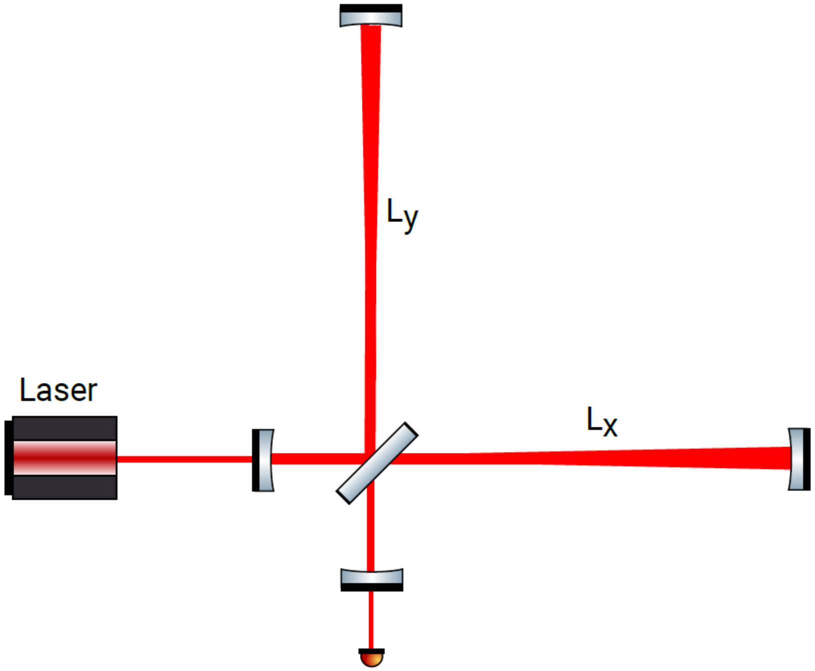


$L_{\mathrm{fixed}} \approx$ const.

$$\Phi \propto L_{\mathrm{free}} \propto a_{\mathrm{B}} \;\; => \;\; \frac{\delta \Phi}{\Phi} \approx -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e}$$

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

[Grote, Stadnik, arXiv:1906.06193; *Phys. Rev. Research* (In press)]



Michelson interferometer (GEO 600)

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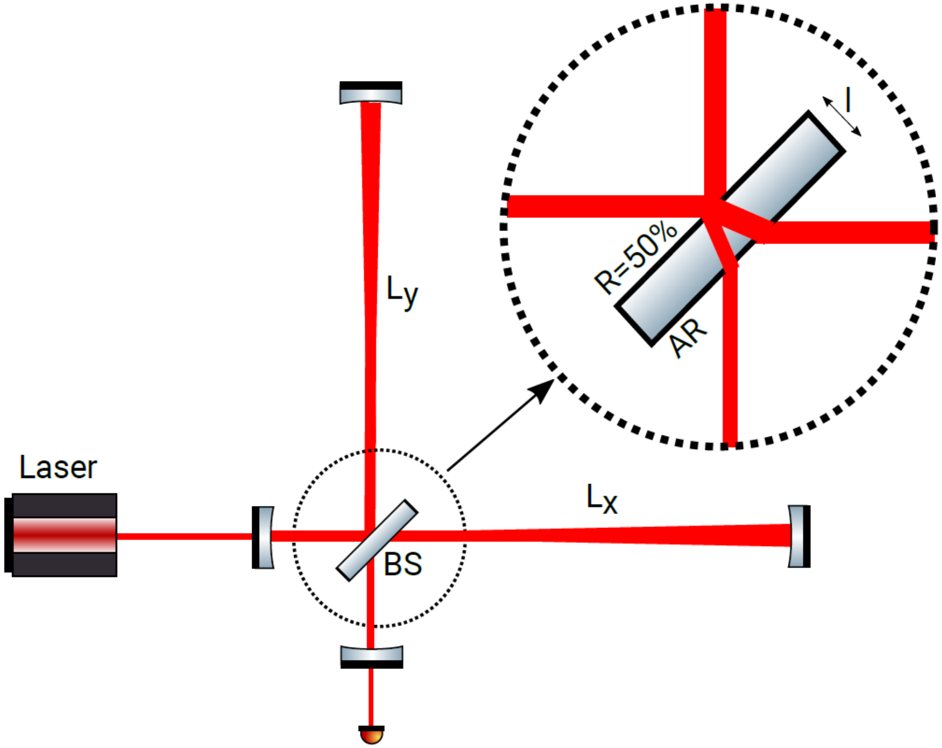

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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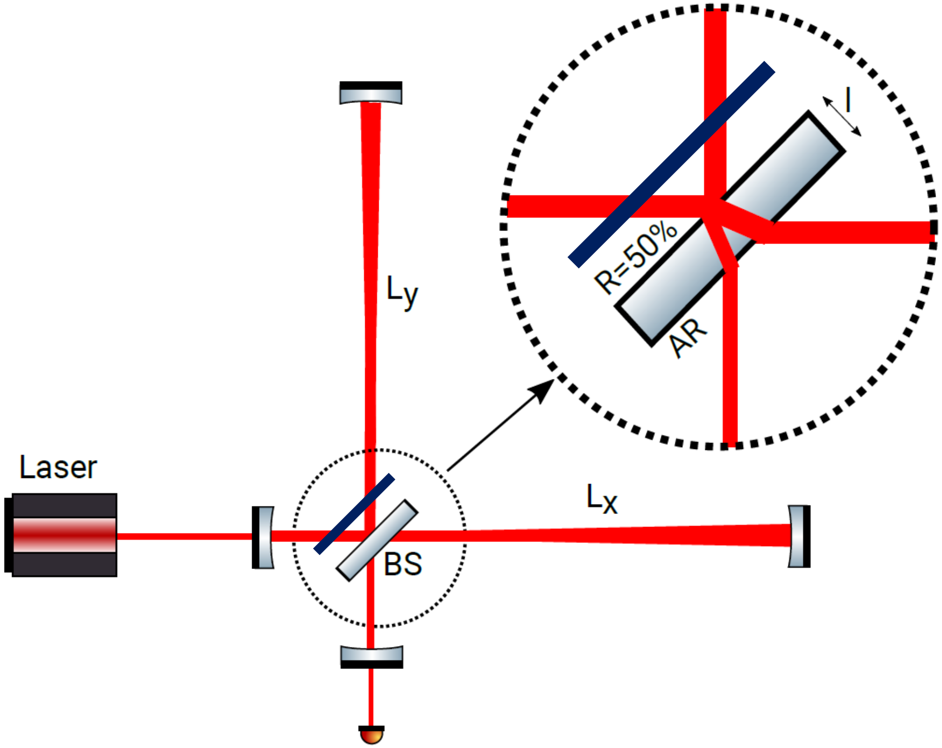

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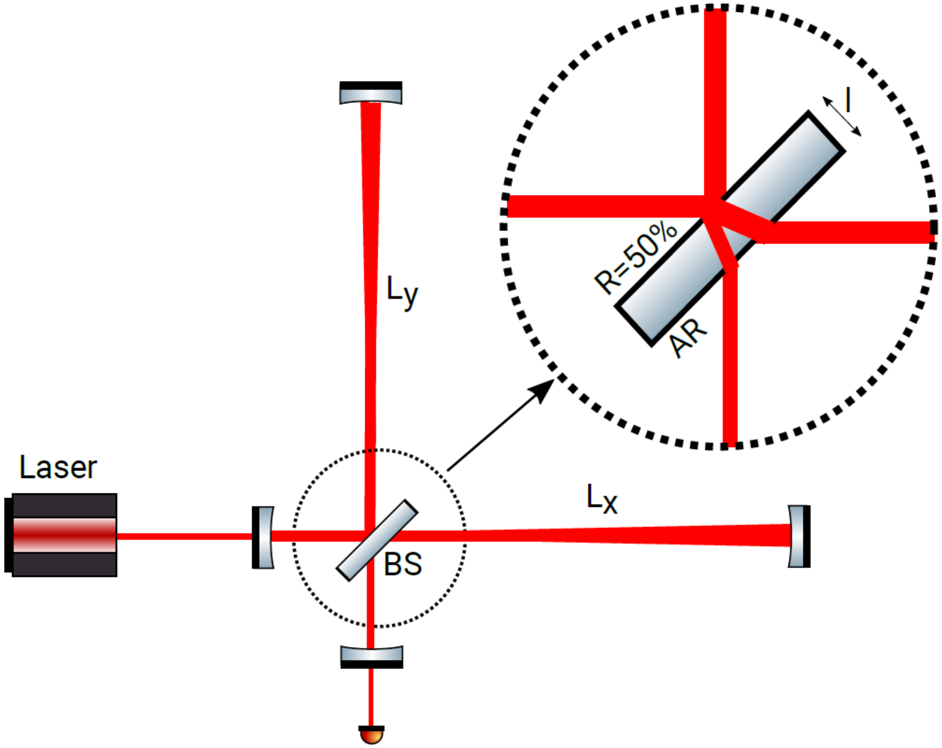
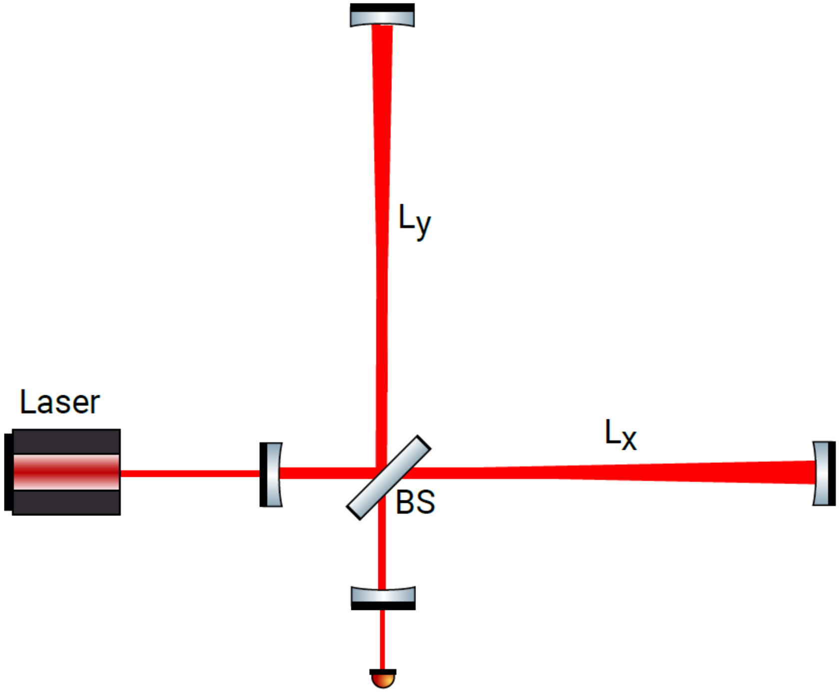


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{DM} \approx f_{vibr,BS} \sim v_{sound}/l$, $Q \sim 10^6$ enhancement

Michelson vs Fabry-Perot-Michelson Interferometers

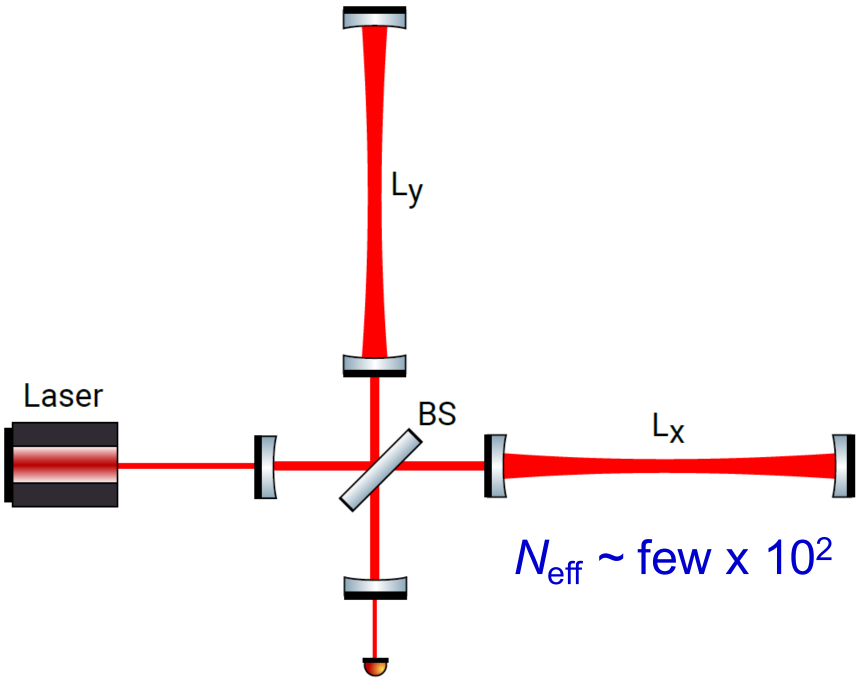
[Grote, Stadnik, arXiv:1906.06193; *Phys. Rev. Research* (In press)]

Michelson interferometer
(GEO 600, Fermilab holometer)



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

Fabry-Perot-Michelson interferometer
(LIGO, VIRGO, KAGRA)



N_{eff} ~ few x 10^2

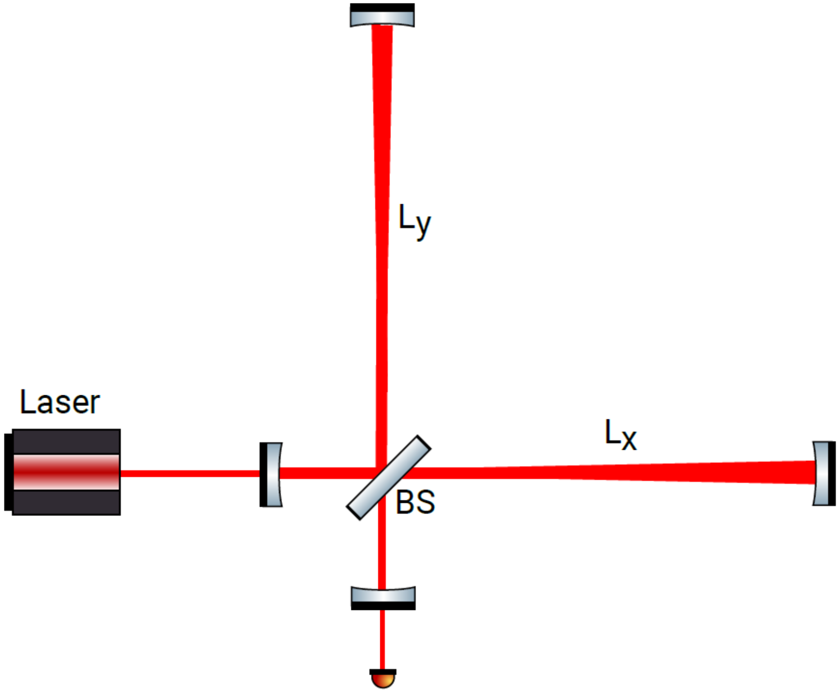
$$\delta(L_x - L_y)_{BS} \sim \delta(nl)/N_{eff}$$

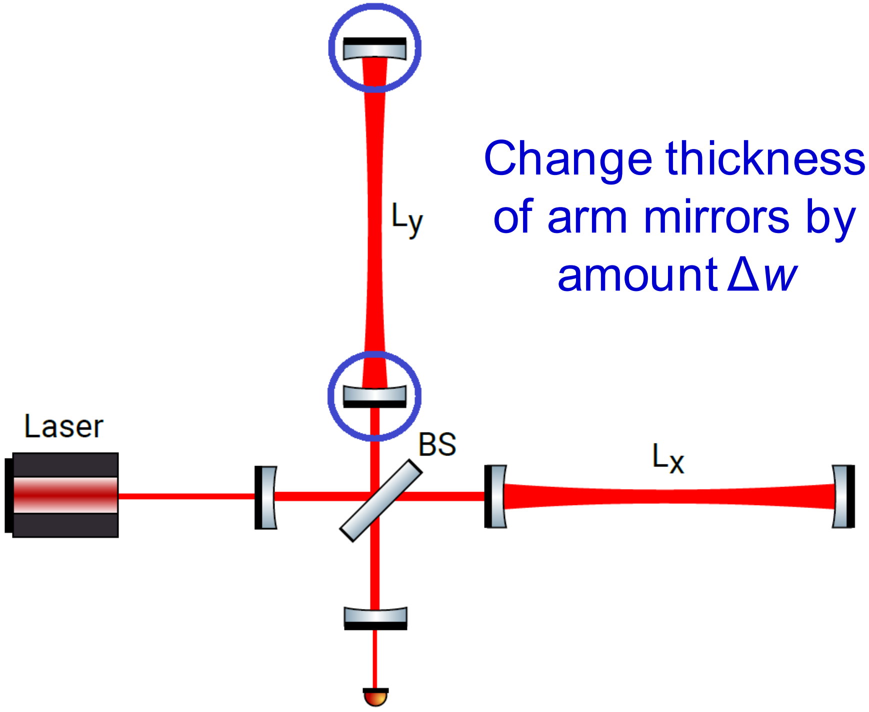
Michelson vs Fabry-Perot-Michelson Interferometers

[Grote, Stadnik, arXiv:1906.06193; *Phys. Rev. Research* (In press)]

Michelson interferometer
(GEO 600, Fermilab holometer)

Fabry-Perot-Michelson interferometer
(LIGO, VIRGO, KAGRA)





Change thickness of arm mirrors by amount Δw

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

$$\delta(L_x - L_y) \approx \delta(\Delta w)$$

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)]
- **Yb^+(E3)/Sr (PTB):** [Huntemann, Peik *et al.*, In preparation]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ (NIST + JILA):** [Hume, Leibrandt *et al.*, In preparation]

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

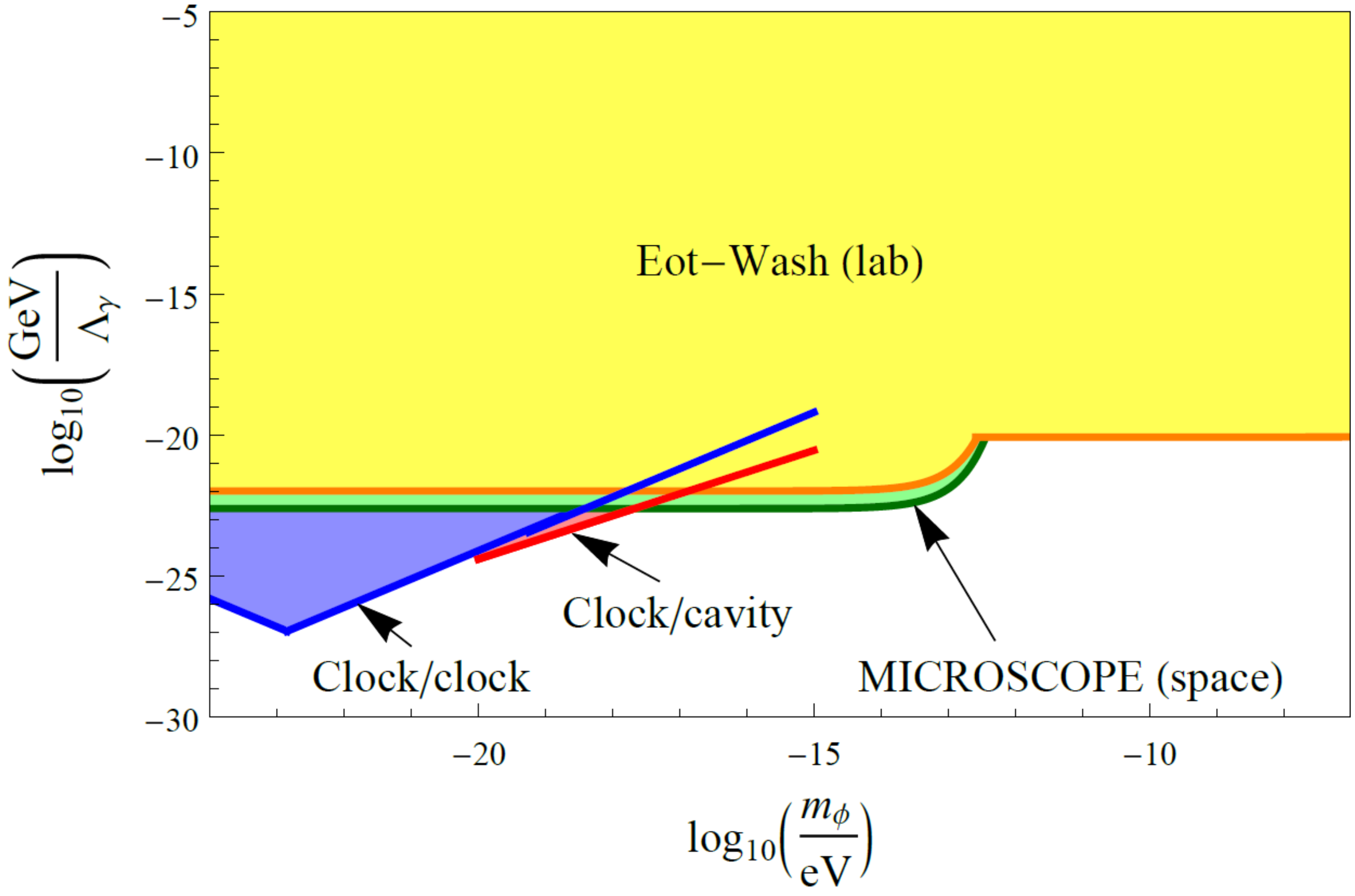
- **Sr/ULE cavity (Torun)*:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Sr/Si cavity (JILA):** [Robinson, Ye *et al.*, *Bulletin APS*, H06.00005 (2018)]
- **Various (global network):** [Wcislo *et al.*, *Sci. Adv.* **4**, eaau4869 (2018)]
- **Sr^+/ULE cavity (Weizmann):** [Aharony *et al.*, arXiv:1902.02788]
- **Cs/cavity (Mainz):** [Antypas *et al.*, *PRL* **123**, 141102 (2019)]

* 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)]

4 orders of magnitude improvement!



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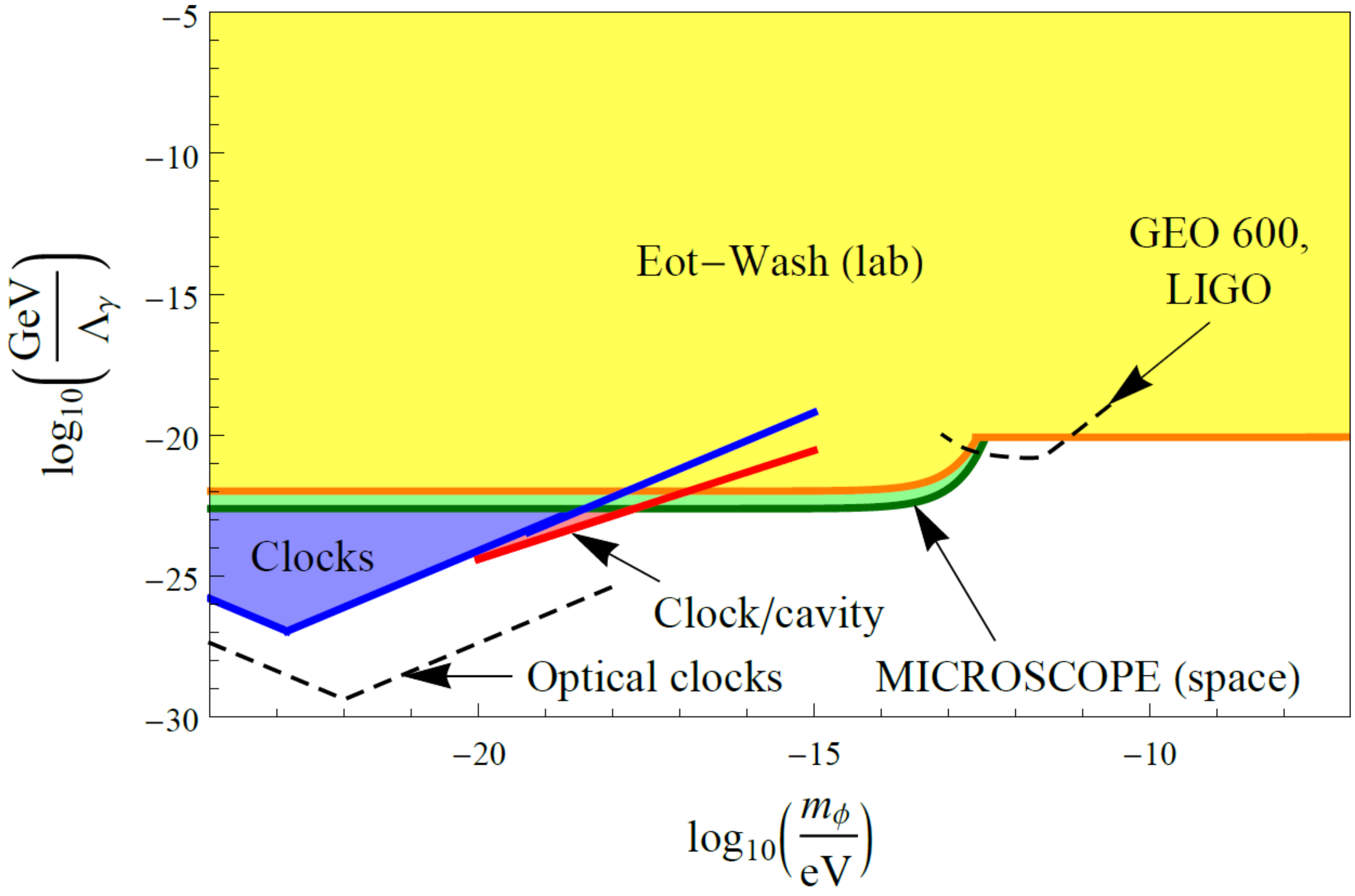
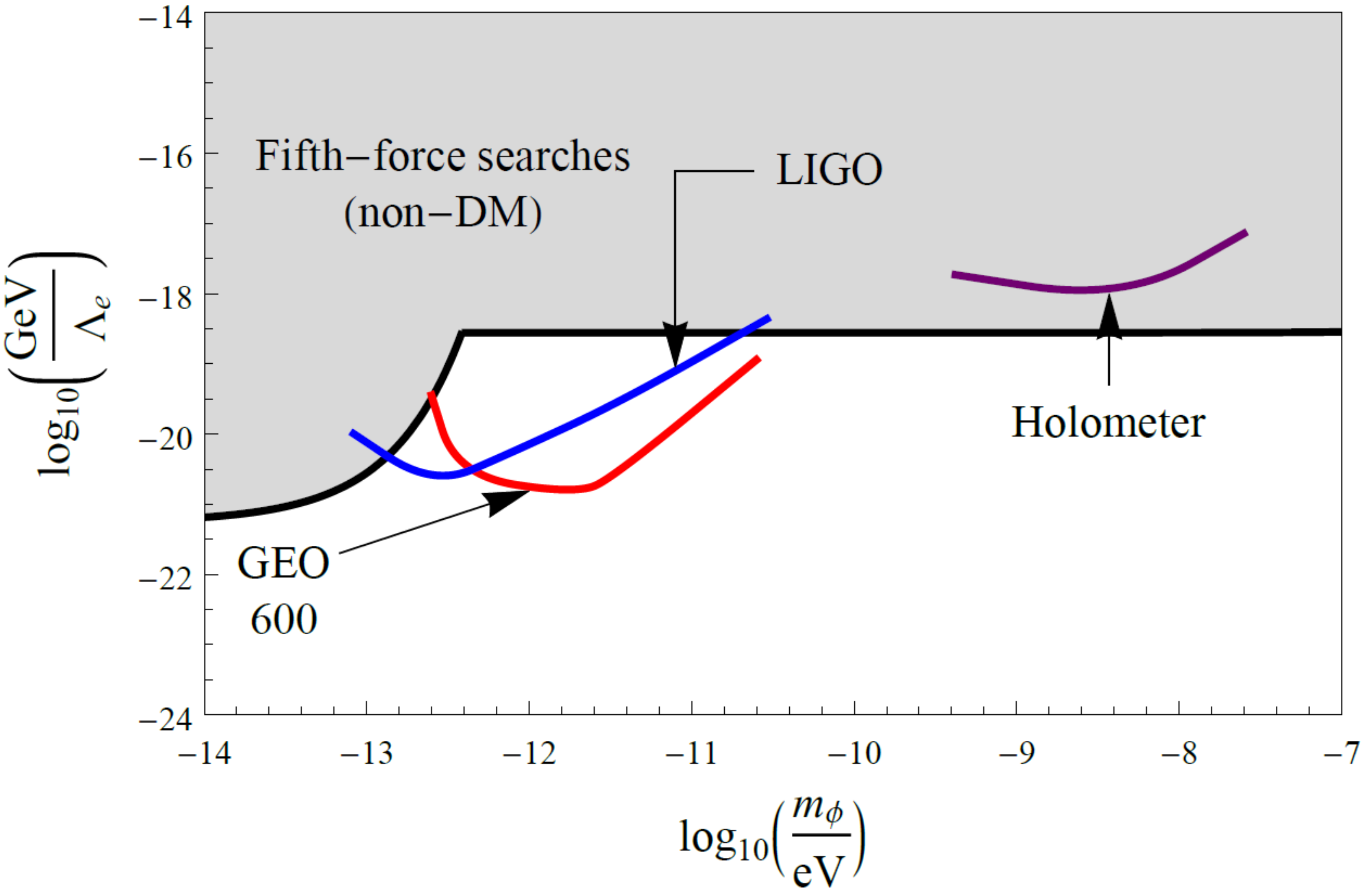


Linear Interaction of Scalar Dark Matter with the Electron



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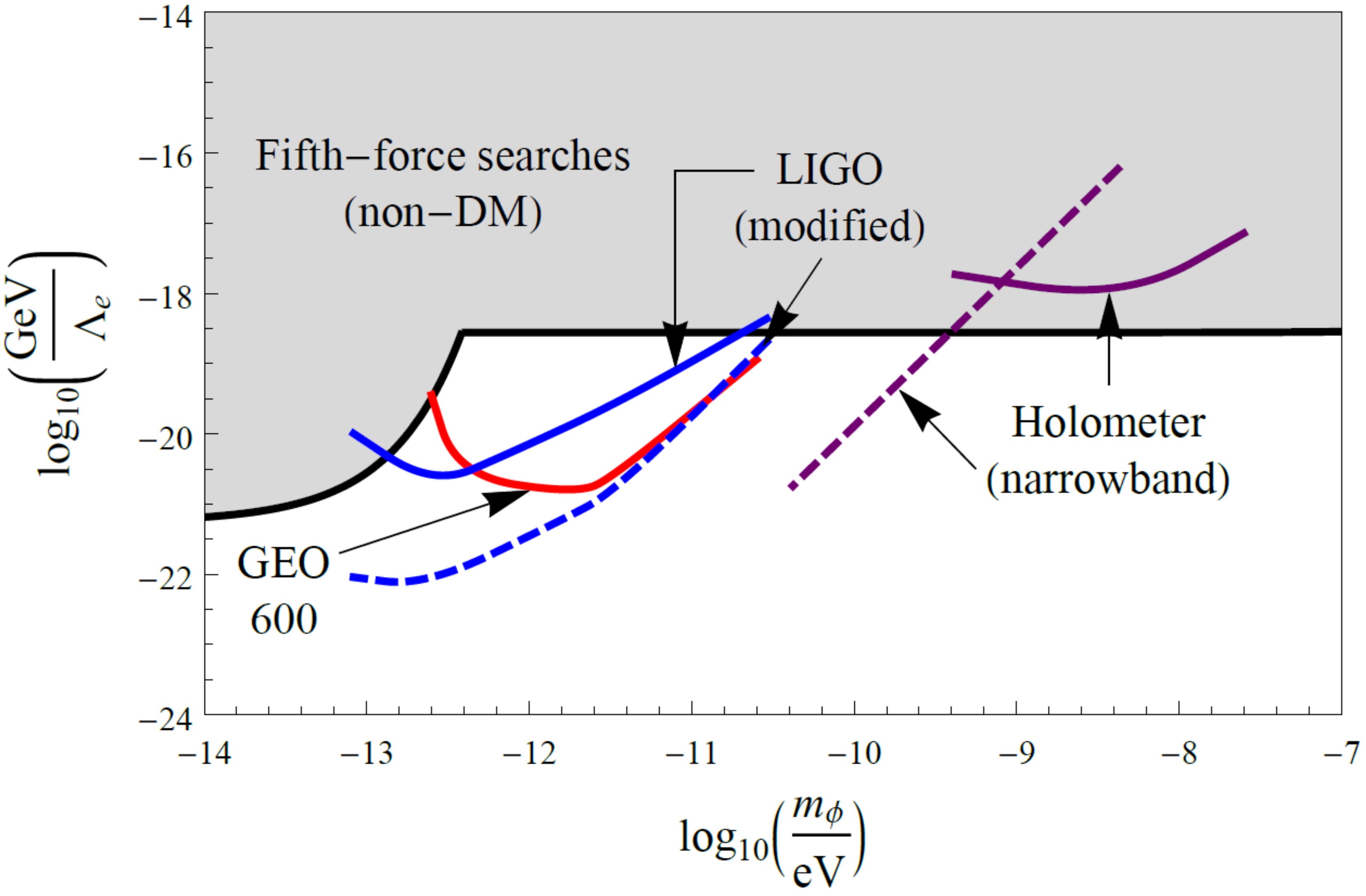
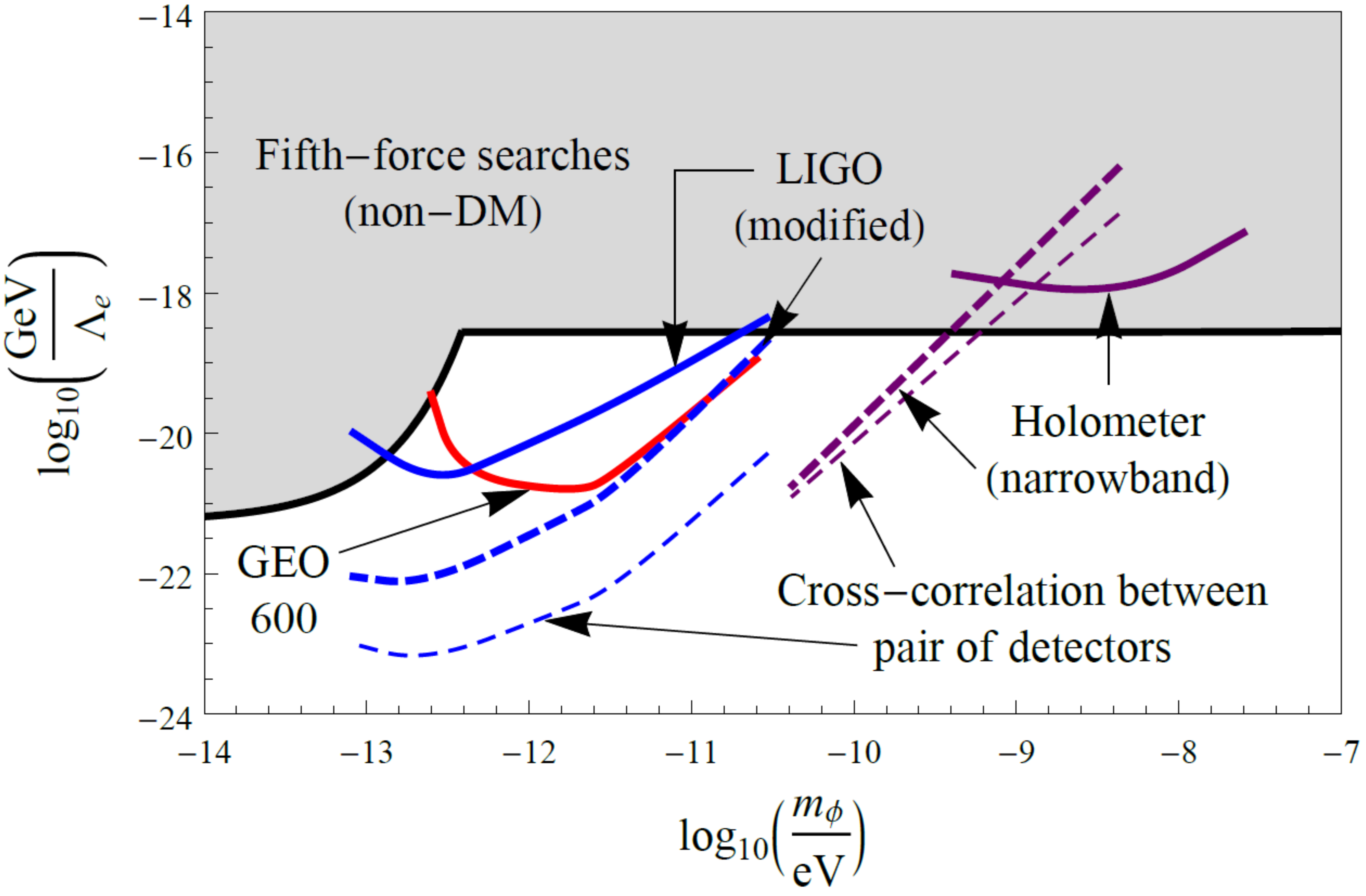


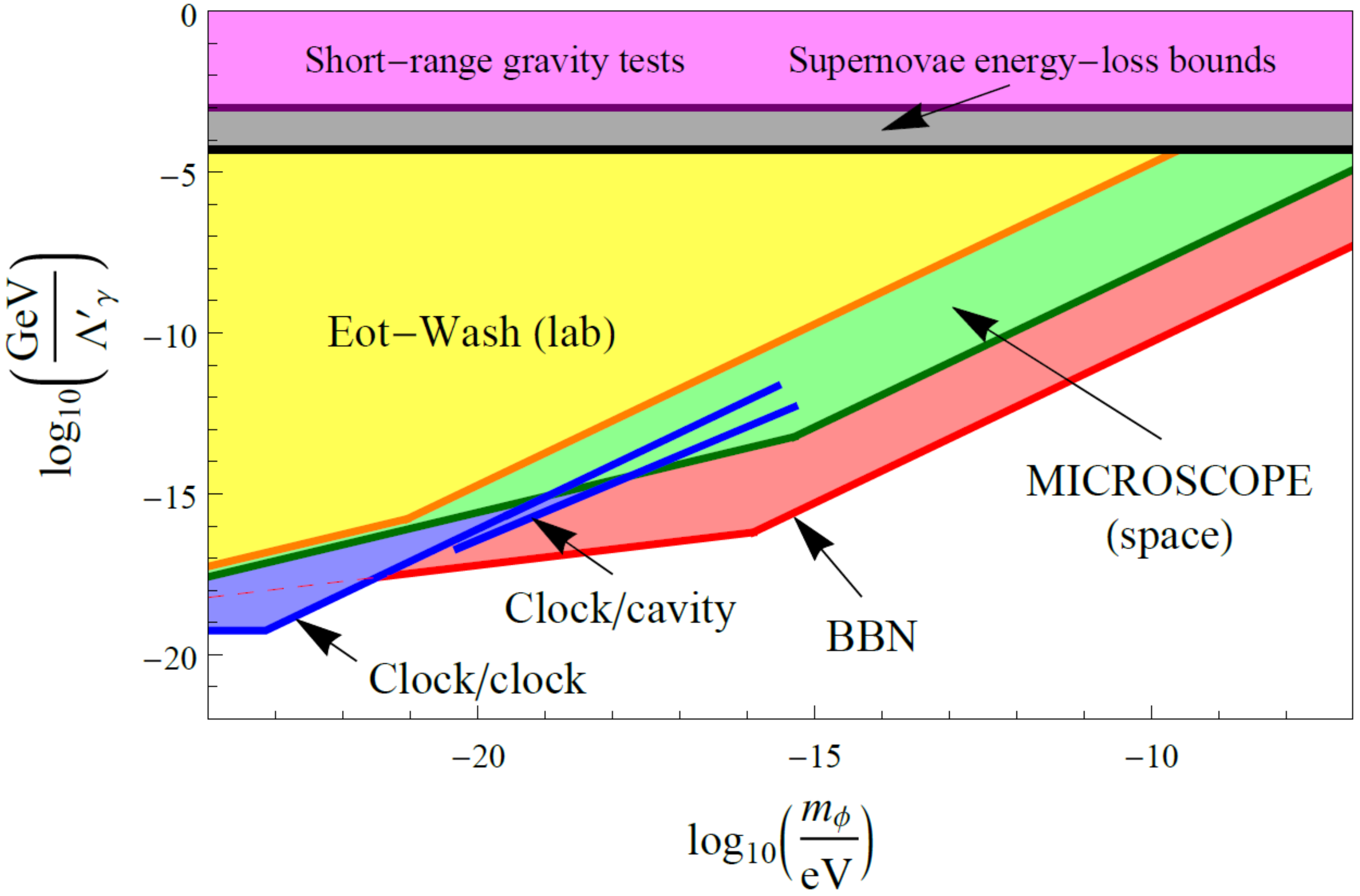
Linear Interaction of Scalar Dark Matter with the Electron



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

Dark Matter-Induced Spin-Dependent Effects

“Axion Wind” Spin-Precession Effect

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

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

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

Dark Matter-Induced Spin-Dependent Effects

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Oscillating Electric Dipole Moments

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

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

$$\mathcal{L}_g = \frac{C_G a_0\cos(m_a t)}{f_a}\frac{g^2}{32\pi^2}G\tilde{G}$$

$$=> \quad H_{\mathrm{EDM}}(t) = \boldsymbol{d}(t)\cdot\boldsymbol{E},\ \ \boldsymbol{d}(t) \propto \boldsymbol{J}\cos(m_a t)$$

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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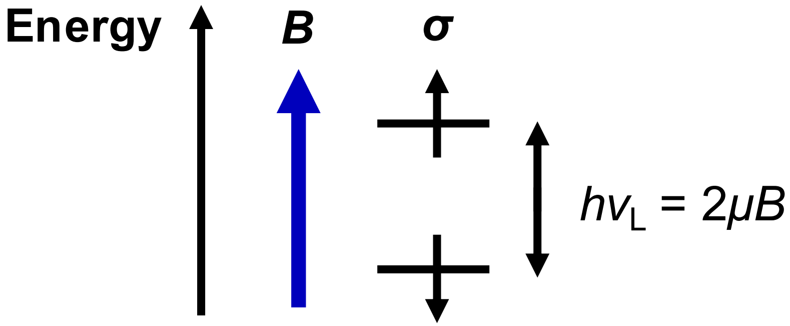

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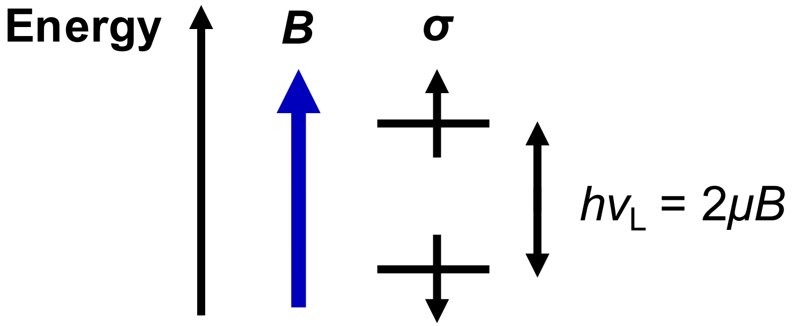

$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left| \frac{\mu_n B}{\mu_{\mathrm{Hg}} B} \right| + R(t)$$

B-field effect

Searching for Spin-Dependent Effects

Proposals: [Flambaum, talk at *Patras Workshop*, 2013;
Stadnik, Flambaum, *PRD* **89**, 043522 (2014); Stadnik, thesis (Springer, 2017)]

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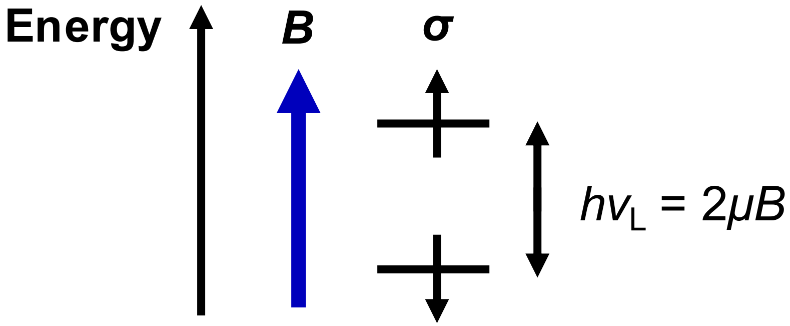

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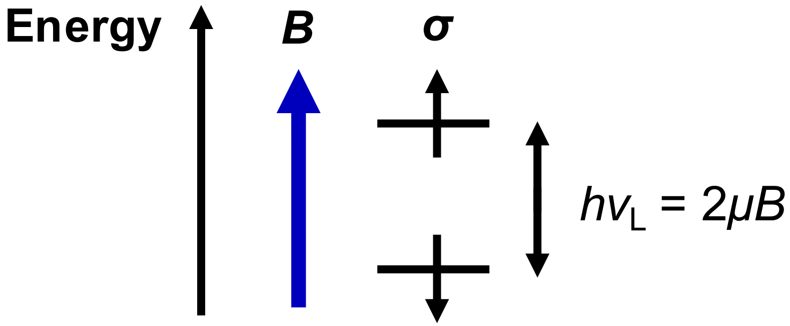

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***B*-field effect**

DM effect (non-magnetic)

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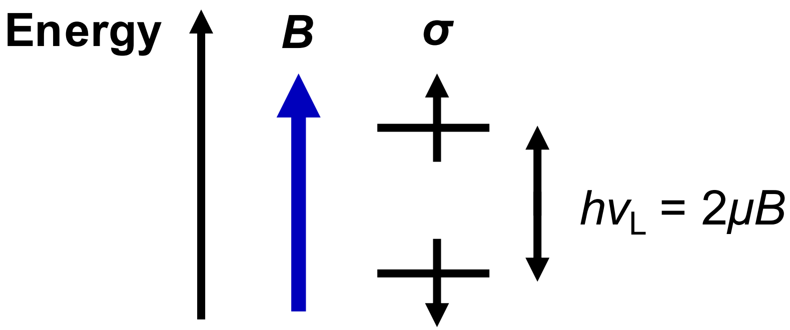


$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}}\right| + R(t)$$

***B*-field effect**

DM effect (non-magnetic)

Proposal + Experiment (p̄): [BASE collaboration, *Nature* **575**, 310 (2019)]

Cold antiprotons

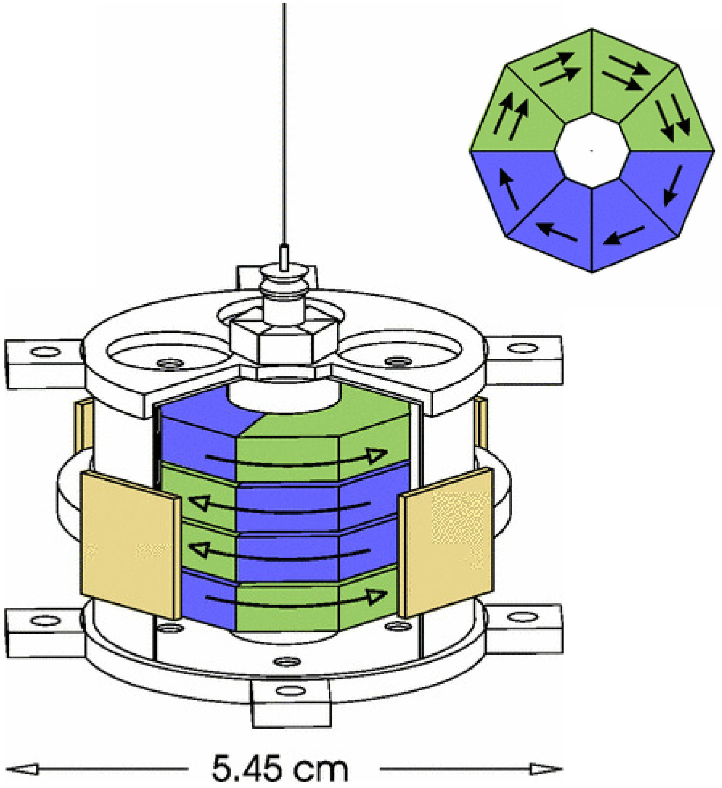
$$\left(\frac{\nu_{\mathrm{L}}}{\nu_{\mathrm{c}}}\right)_{\bar{\mathrm{p}}} = \frac{|g_{\bar{\mathrm{p}}}|}{2} + R(t)$$

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

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



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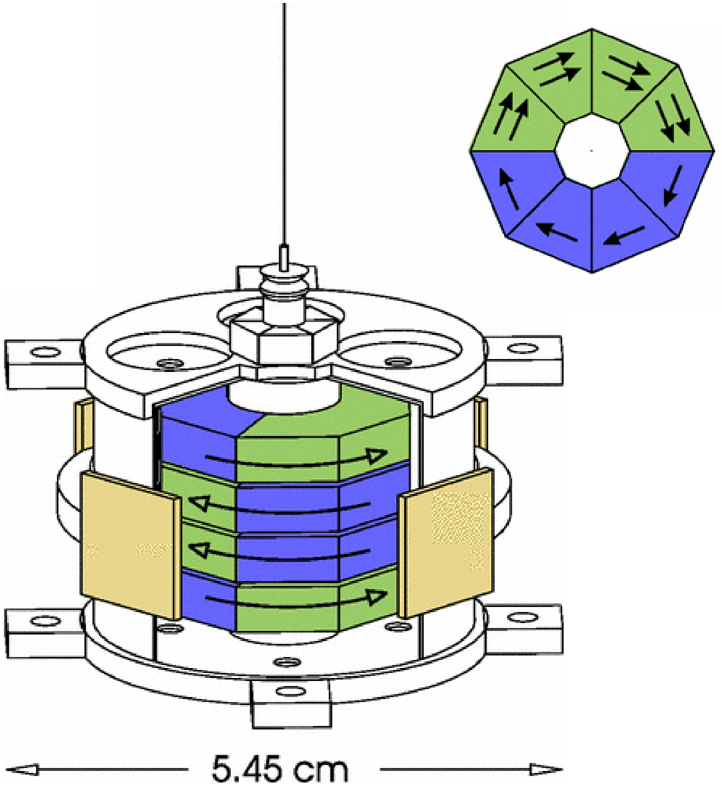

$$\boldsymbol{\mu}_{\text{pendulum}} \approx \mathbf{0}$$

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

Searching for Spin-Dependent Effects

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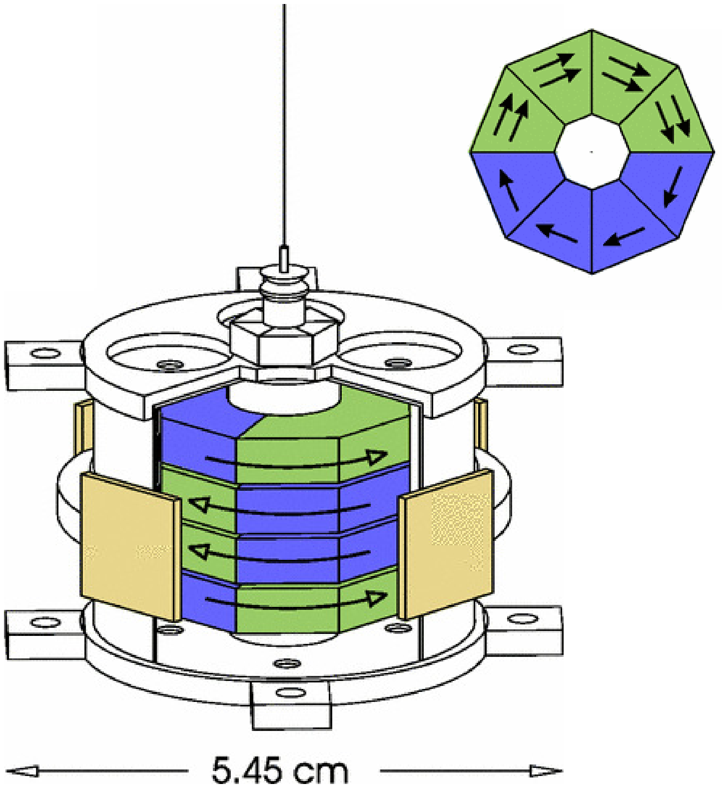


$$\boldsymbol{\mu}_{\mathrm{pendulum}} \approx \mathbf{0}$$

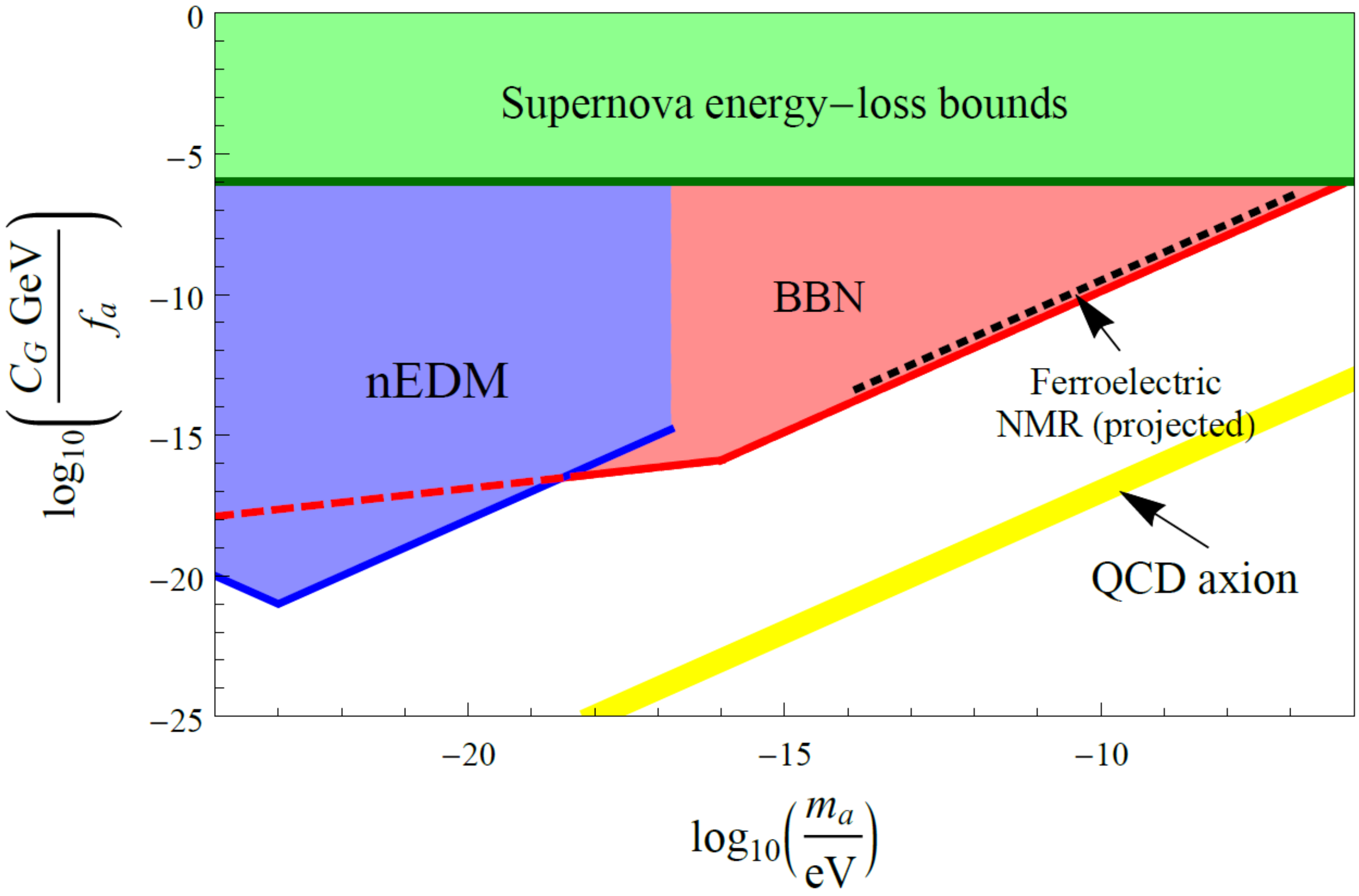
$$(\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \neq \mathbf{0}$$

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

Constraints on Interaction of Axion Dark Matter with Gluons

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

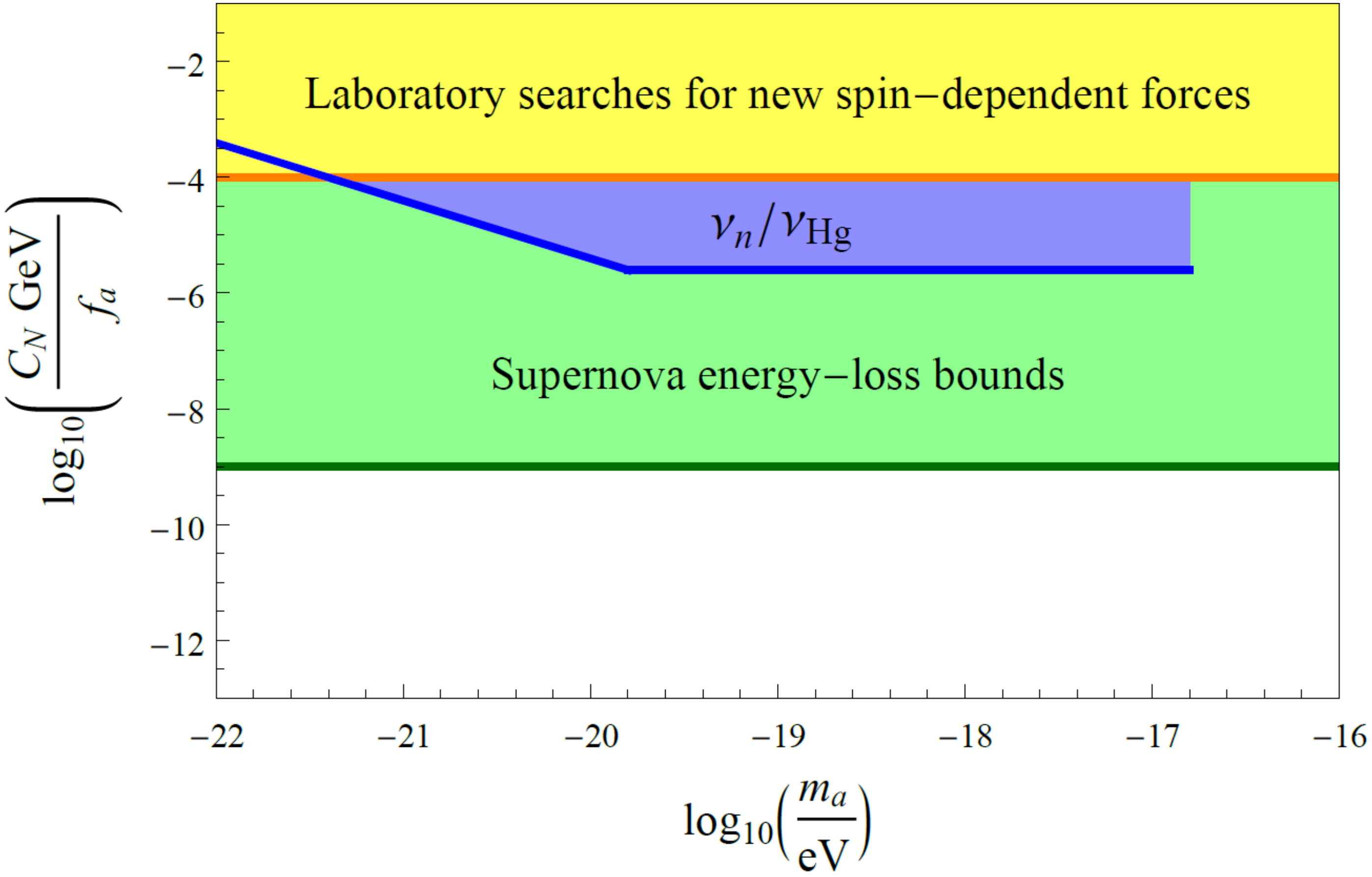
3 orders of magnitude improvement!



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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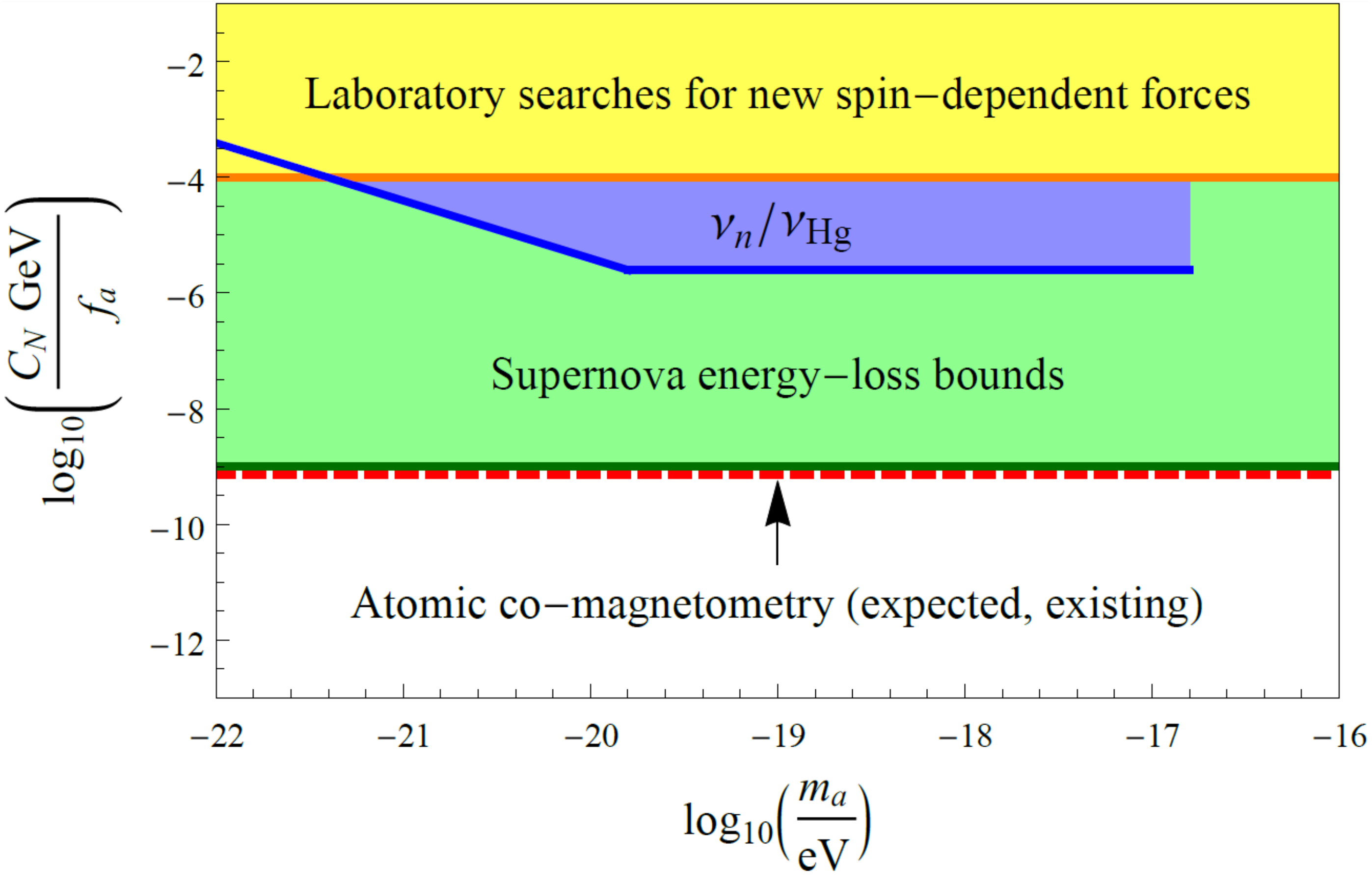
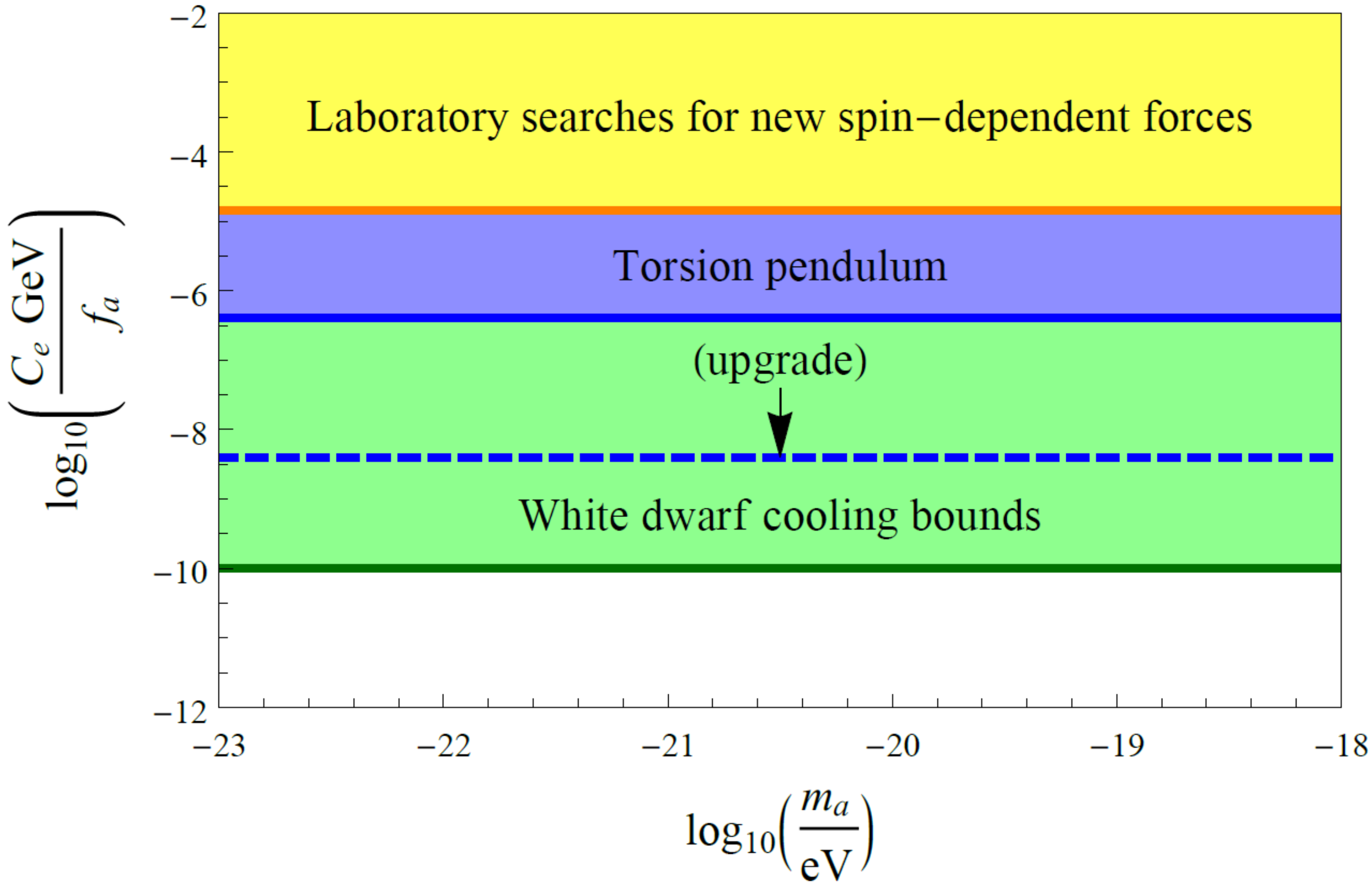
40-fold improvement (laboratory bounds)!



Constraints on Interaction of Axion Dark Matter with the Electron

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

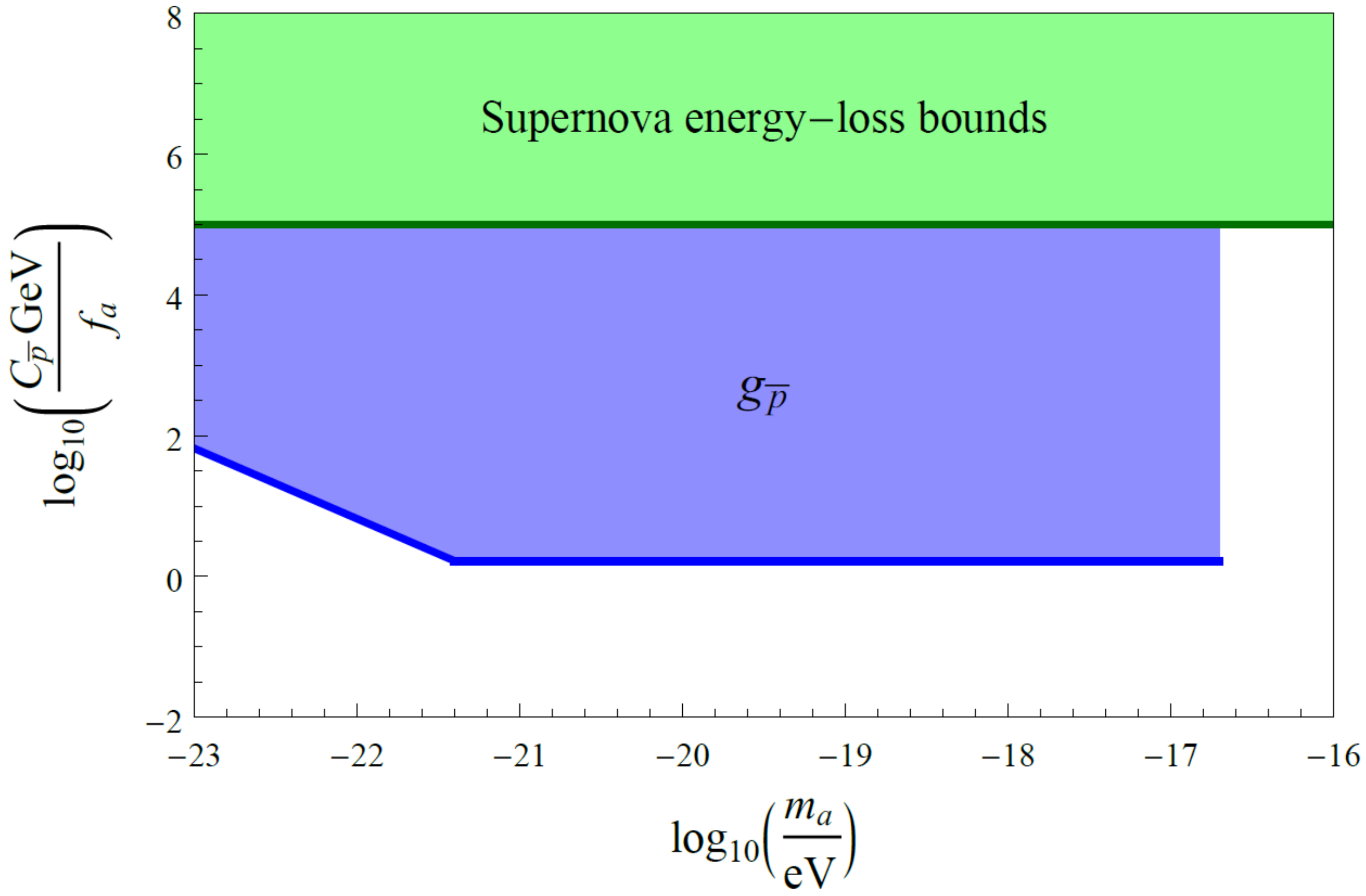
35-fold improvement (laboratory bounds)!



Constraints on Interaction of Axion Dark Matter with the Antiproton

Antiproton constraints: [BASE collaboration, *Nature* **575**, 310 (2019)]

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

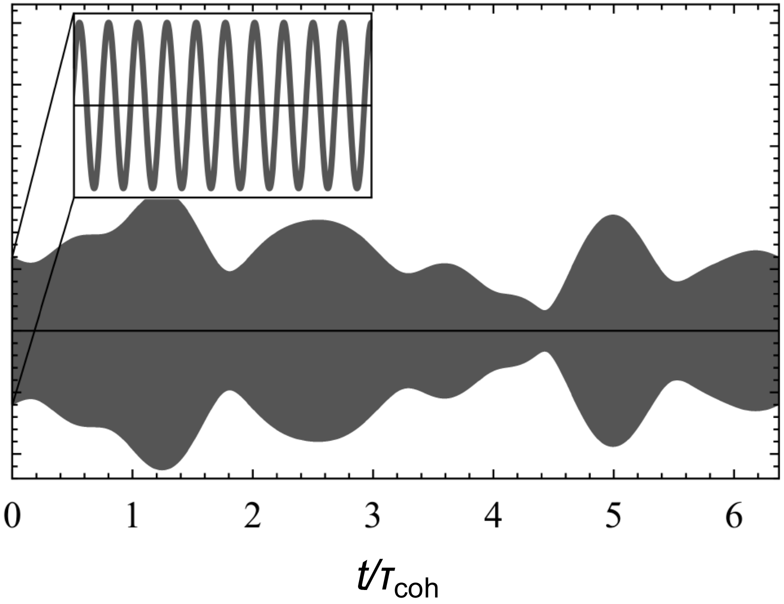
⋮

Back-Up Slides

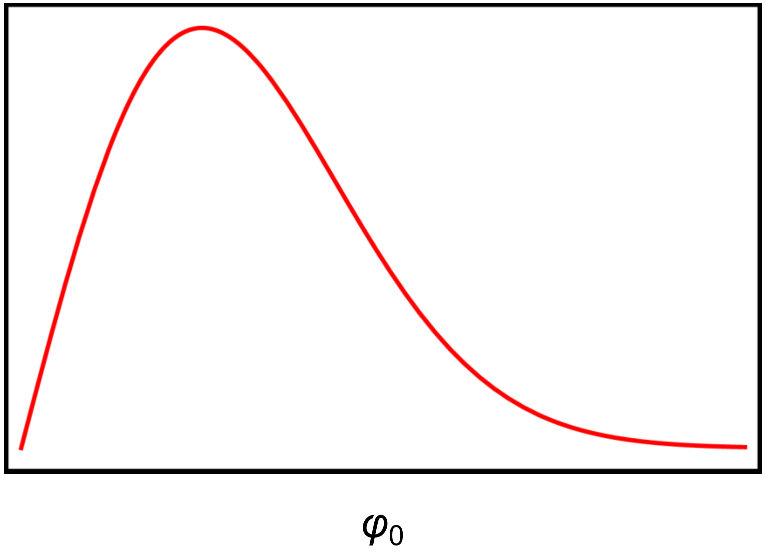
Temporal Coherence

- *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)
- $\Delta E_\varphi / E_\varphi \sim <v_\varphi^2>/c^2 \sim 10^{-6}$ => $\tau_{\mathrm{coh}} \sim 2\pi/\Delta E_\varphi \sim 10^6 T_{\mathrm{osc}}$

Evolution of φ_0 with time



Probability distribution function of φ_0



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)]

$$\mathcal{L}_\gamma = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad => \quad \frac{\delta\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}$$

$$\mathcal{L}_f = -\frac{\phi}{\Lambda_f} m_f \bar{f} f \quad => \quad \frac{\delta m_f}{m_f} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_f}$$

$$\phi = \phi_0 \cos(m_\phi t - \underline{\boldsymbol{p}_\phi \cdot \boldsymbol{x}}) \quad => \quad \underline{\boldsymbol{F} \propto \boldsymbol{p}_\phi \sin(m_\phi t)}$$

$$\left.\begin{aligned} \mathcal{L}'_\gamma &= \frac{\phi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \\ \mathcal{L}'_f &= -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \end{aligned}\right\} \quad => \quad \begin{gathered} \frac{\delta\alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \delta\rho_\phi \\ \boldsymbol{F} \propto \boldsymbol{\nabla}\rho_\phi \end{gathered}$$

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.

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

$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

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

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
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'Slow' drifts [Astrophysics (high ρ_{DM}): BBN, CMB]
+ Gradients [Fifth forces]

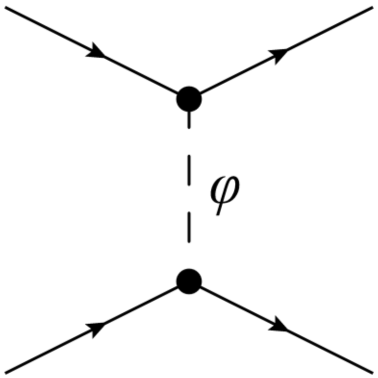
Oscillating variations
[Laboratory (high precision)]

Fifth Forces: Linear vs Quadratic Couplings

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

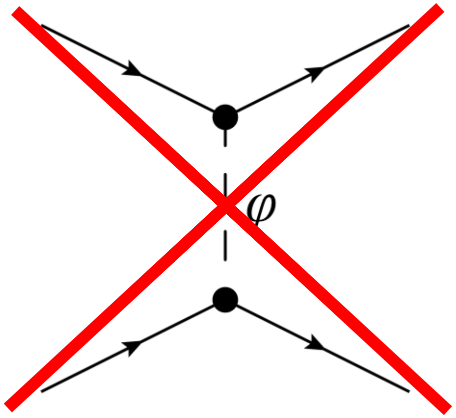
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

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

Fifth Forces: Linear vs Quadratic Couplings

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

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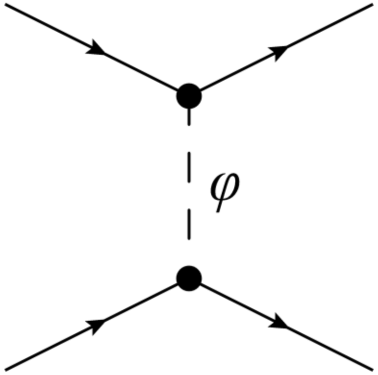

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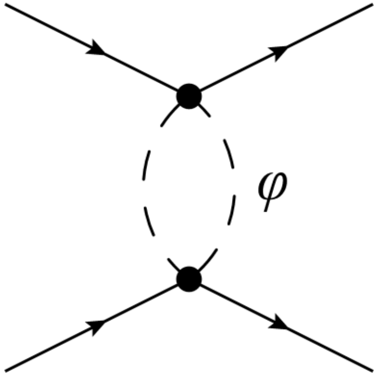

$$\phi = \phi_0 \cos(m_\phi t)\left(1 - \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

Gradients + screening/amplification

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

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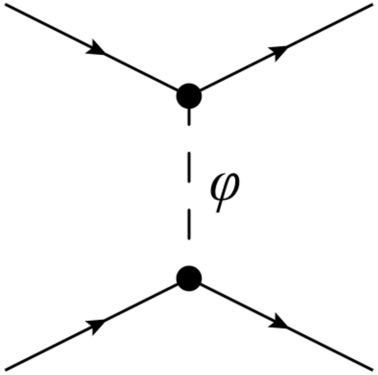
Linear couplings ($\varphi \bar{X} X$)

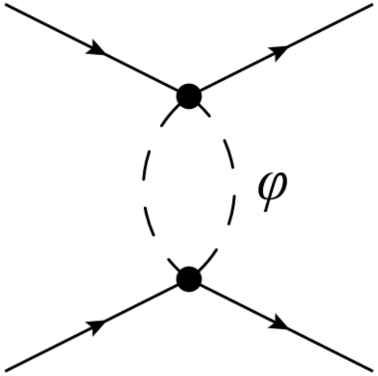


$$\phi = \underline{\phi_0 \cos(m_\phi t)} - A\frac{e^{-m_\phi r}}{r}$$

Motional gradients: $\varphi_0 \cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x})$

"Fifth-force" experiments: torsion pendula, atom interferometry

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

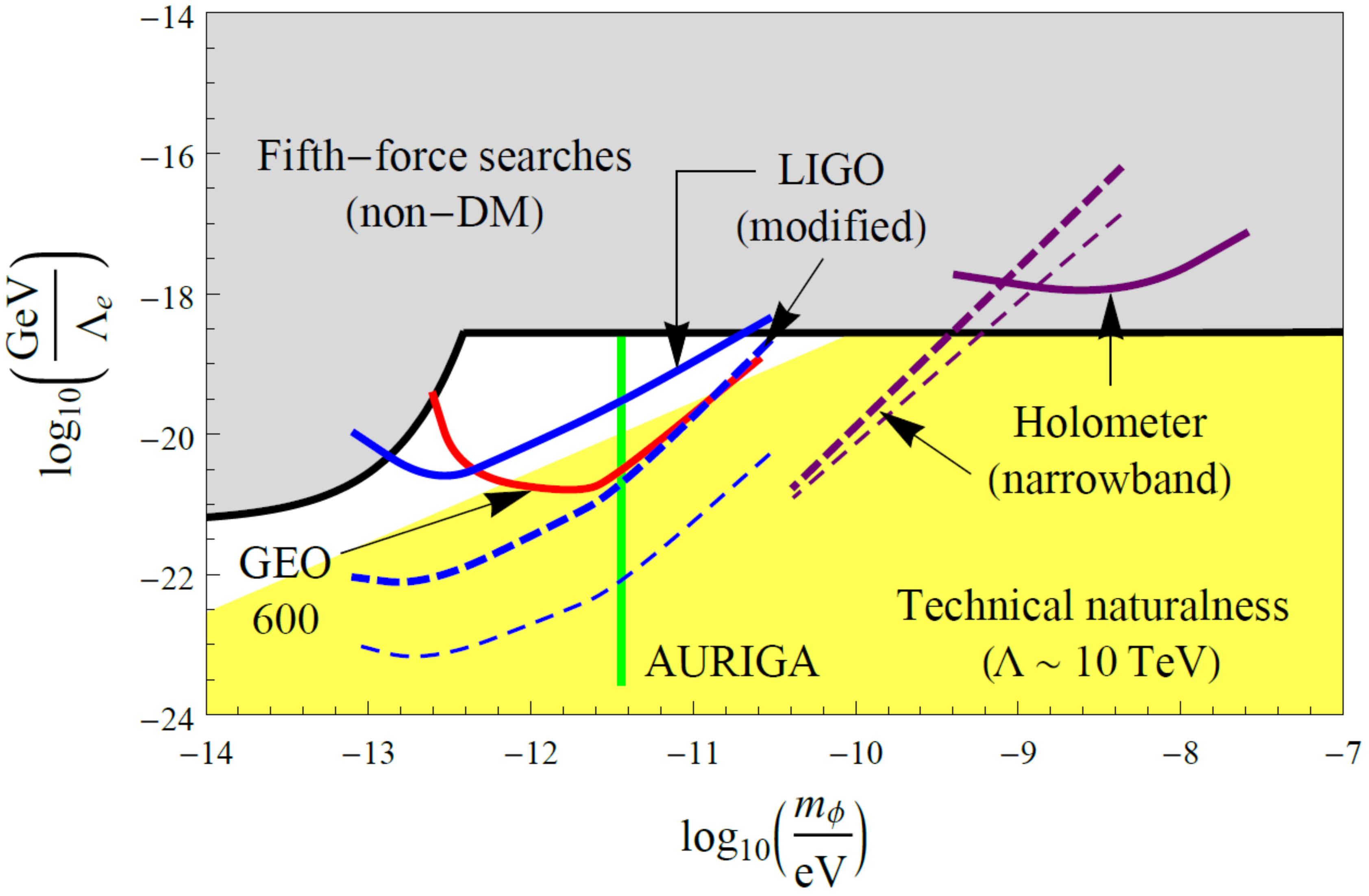


$$\phi = \underline{\phi_0 \cos(m_\phi t)}\left(1 - \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

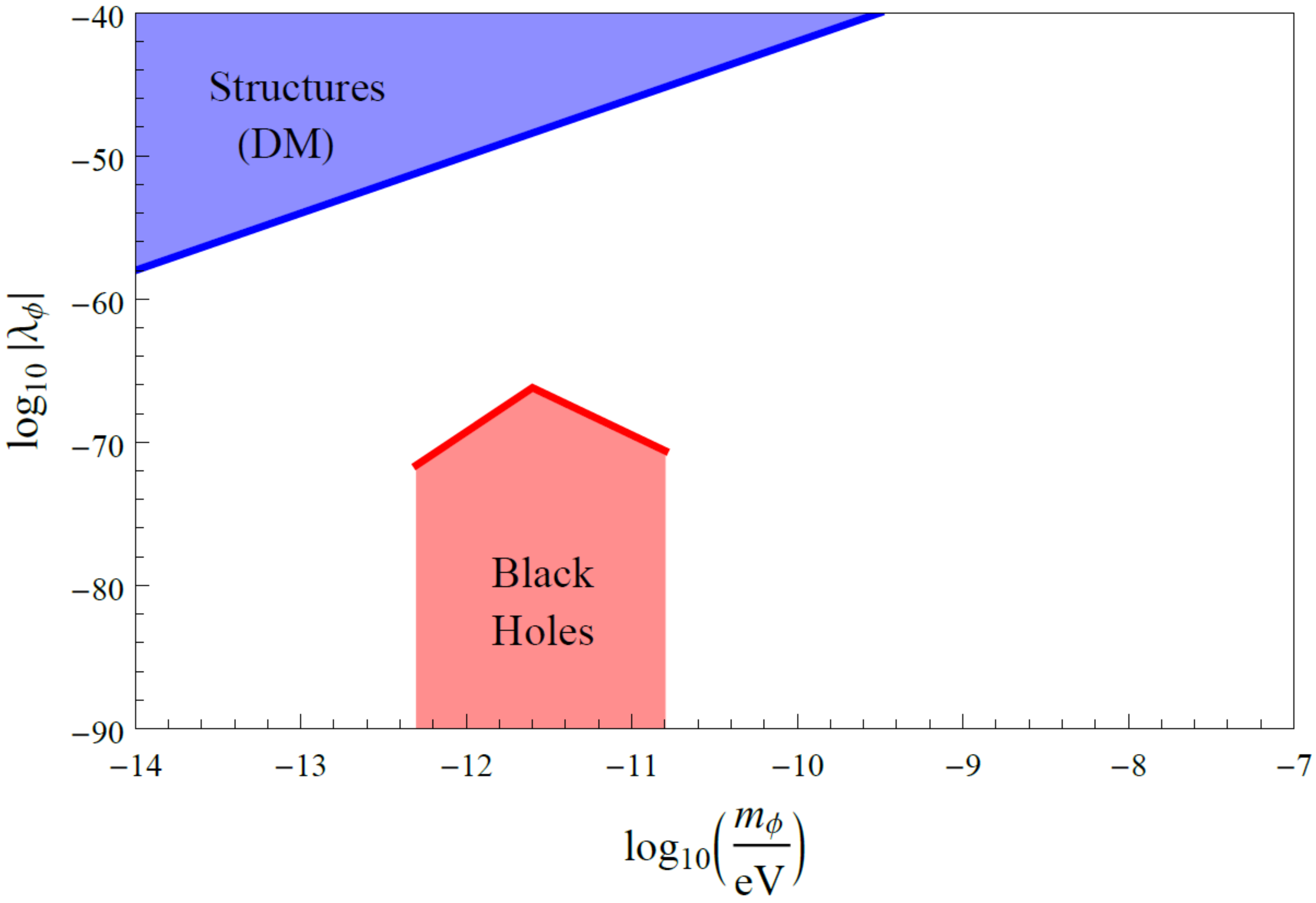
$$\Big\downarrow$$

Gradients + screening/amplification

Constraints on Linear Interaction of Scalar Dark Matter with the Electron



Quartic Self-Interaction of Scalar

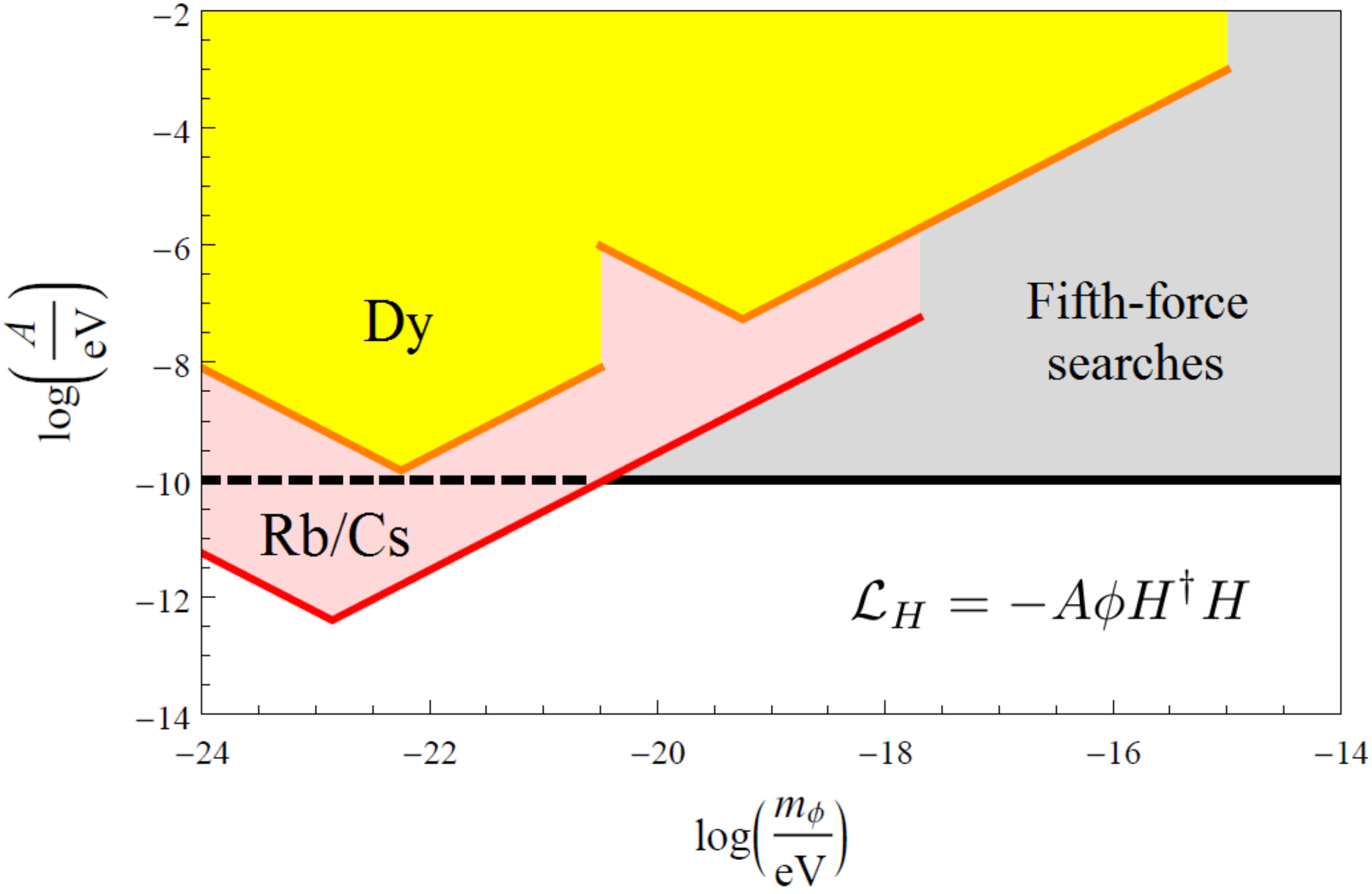


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

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

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

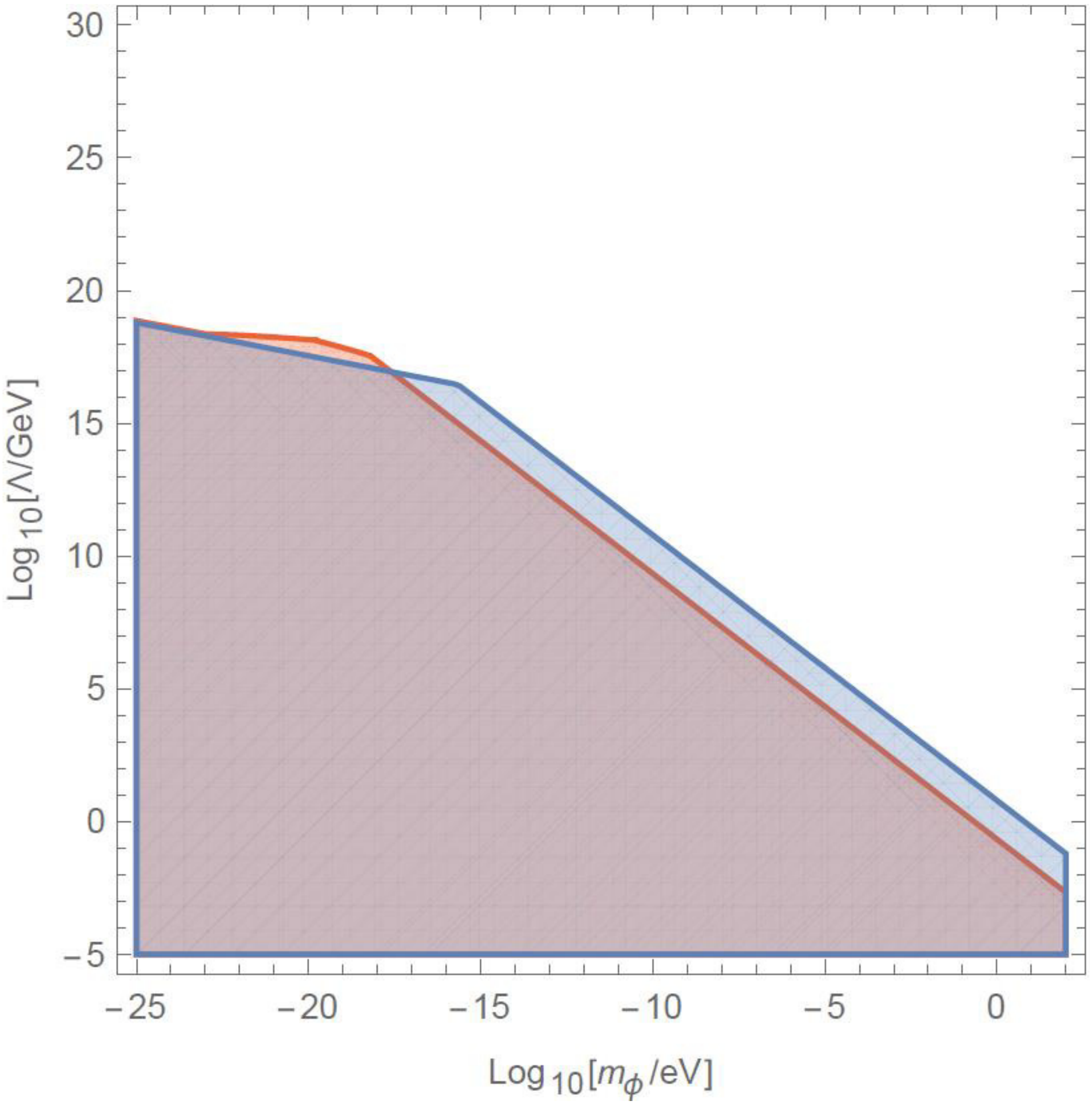
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN

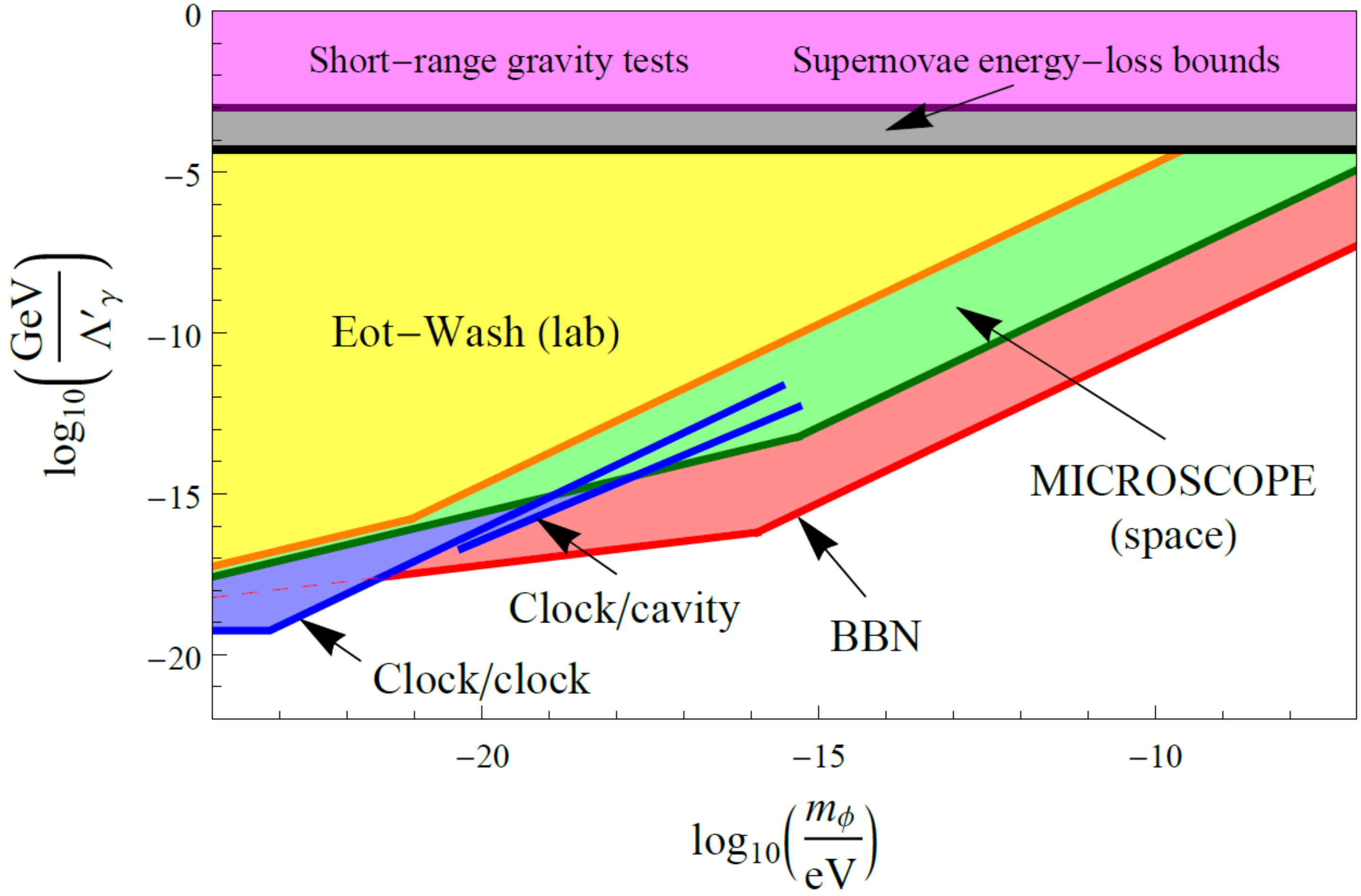
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



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!



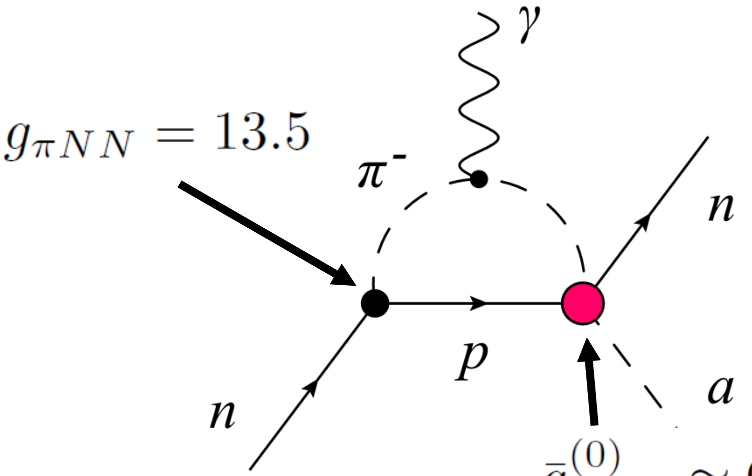
Oscillating Electric Dipole Moments

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

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

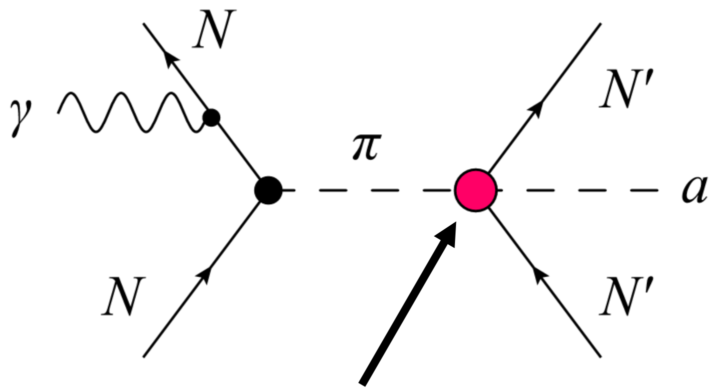
$$\mathcal{L}_g = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G\tilde{G}$$

Nucleon EDMs



$g_{\pi NN} = 13.5$

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/(8π²)].