Searches for Very-Low-Mass FIPs (Atomic Physics, Quantum Technology)

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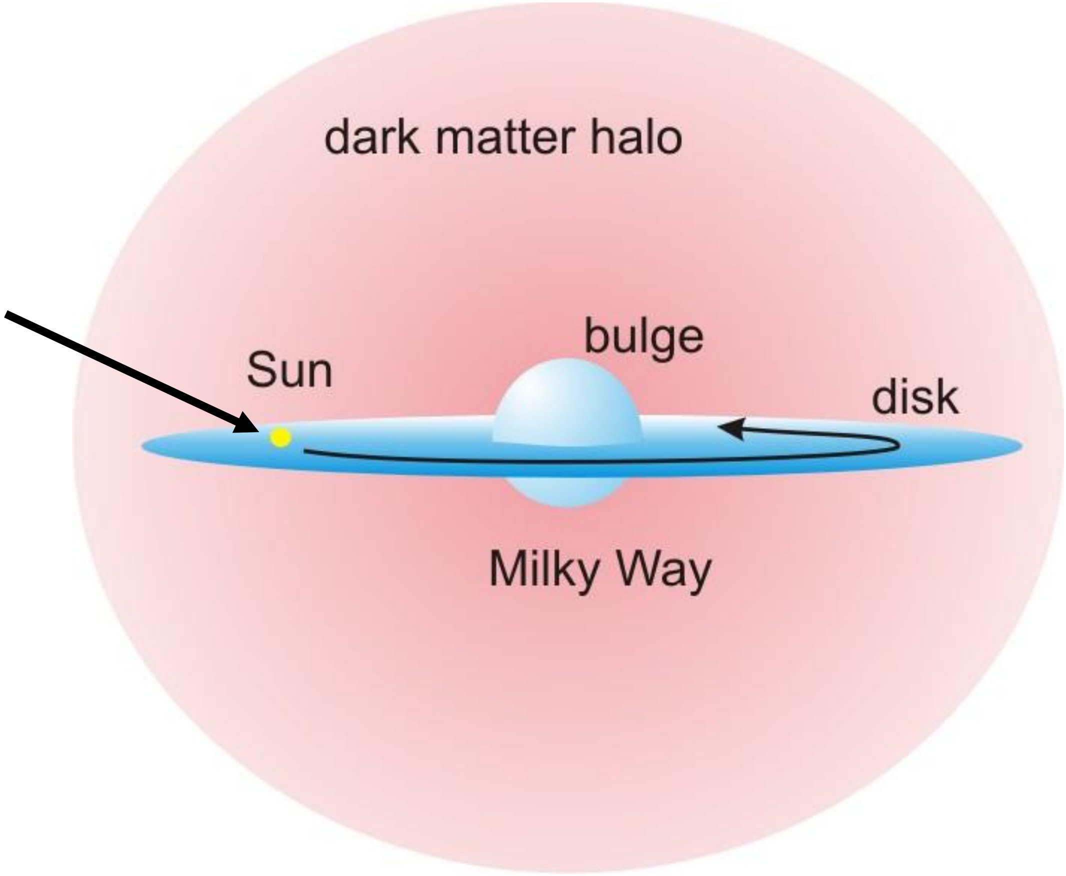
Workshop on Feebly-Interacting Particles, CERN, August 2020

Dark Matter

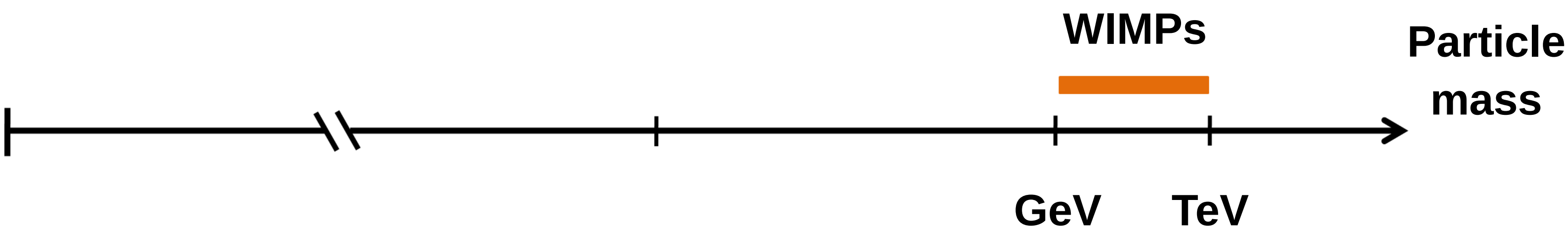
Strong astrophysical evidence for existence of **dark matter** (~5 times more dark matter than ordinary matter).

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

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



Dark Matter



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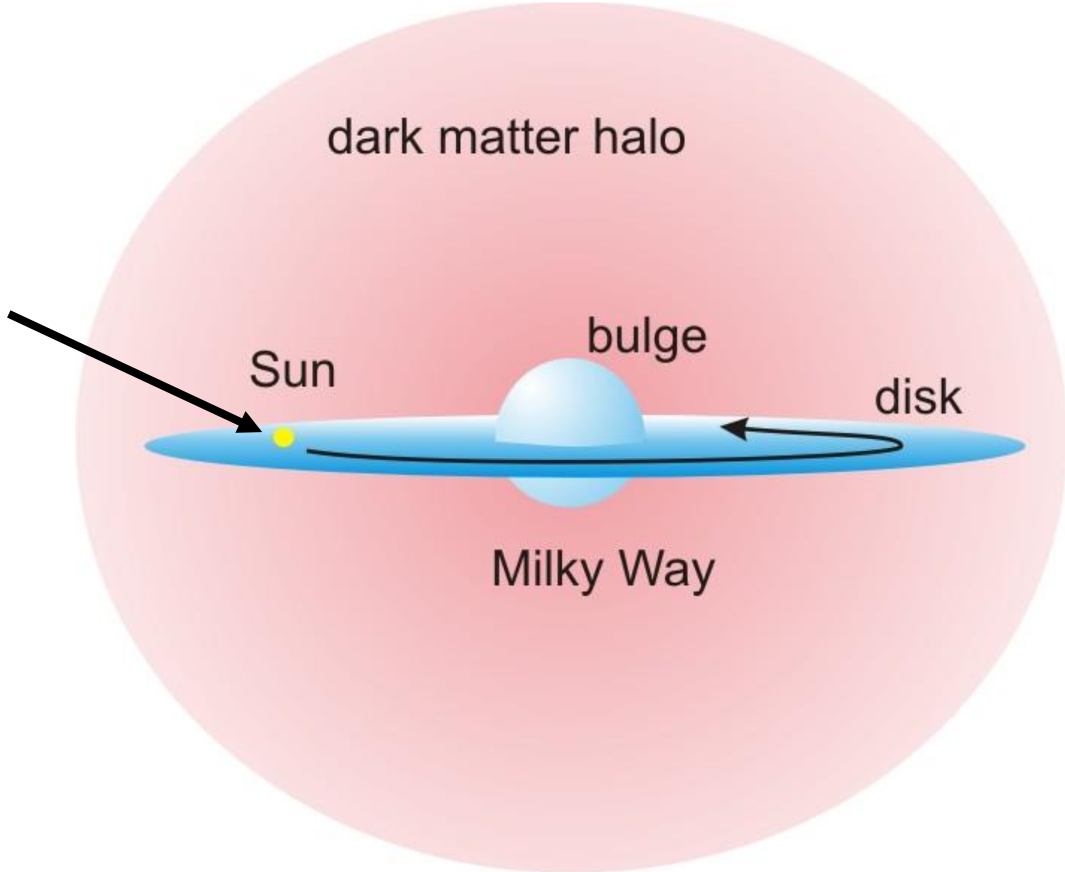

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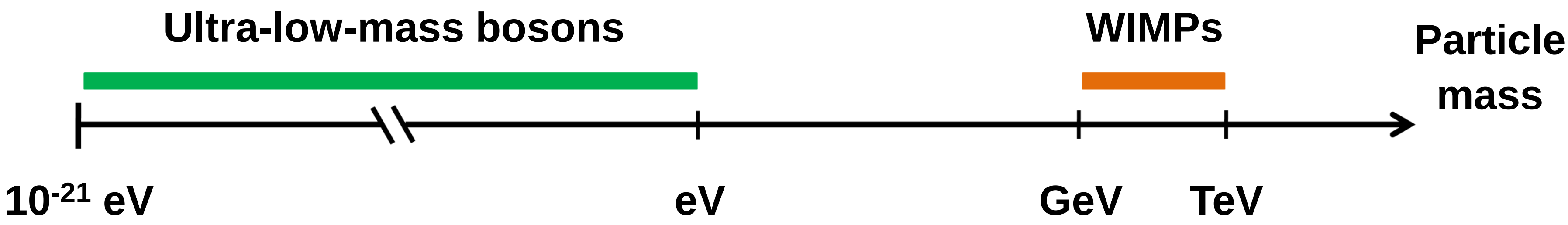

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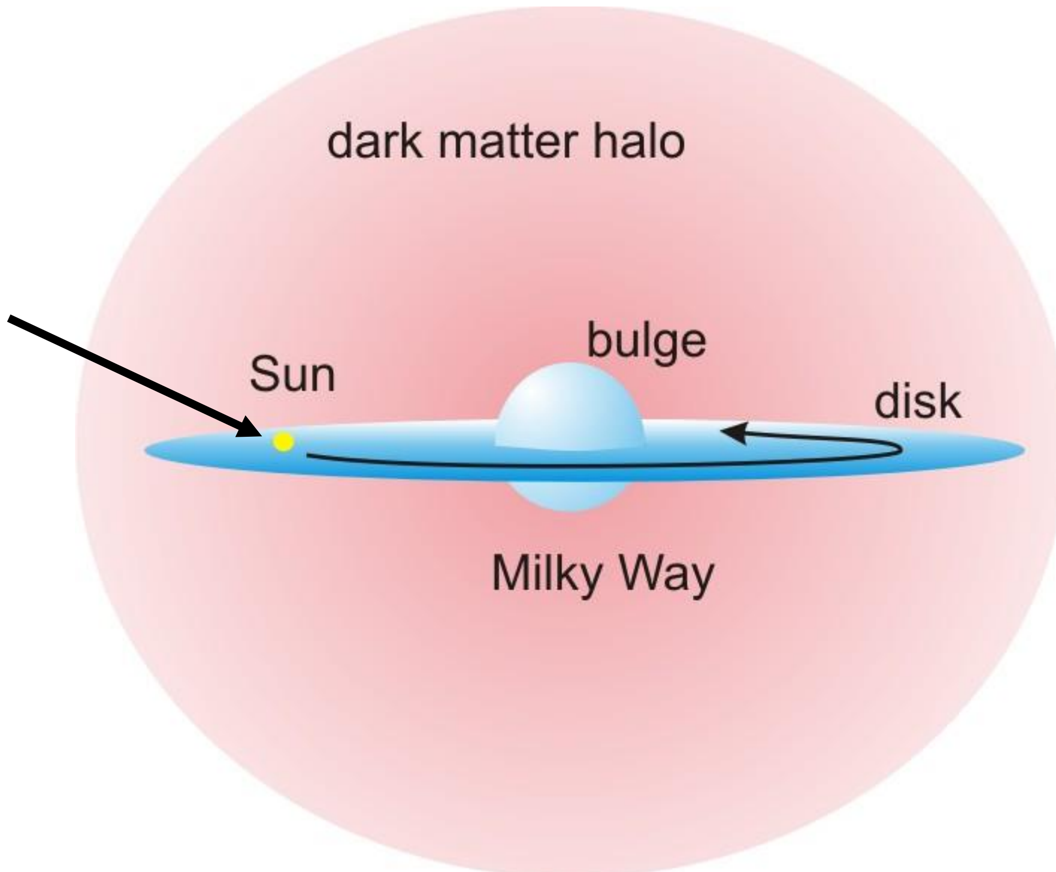
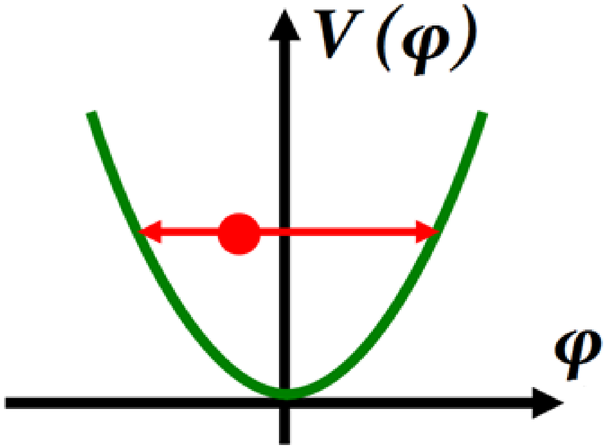


Low-mass Spin-0 Dark Matter

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



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

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

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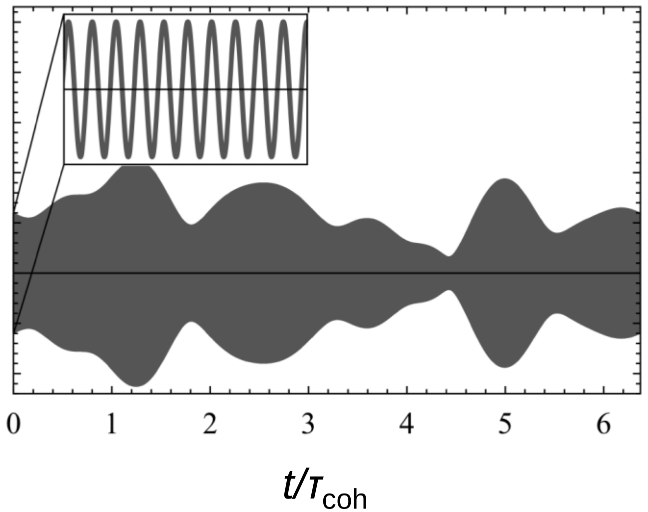
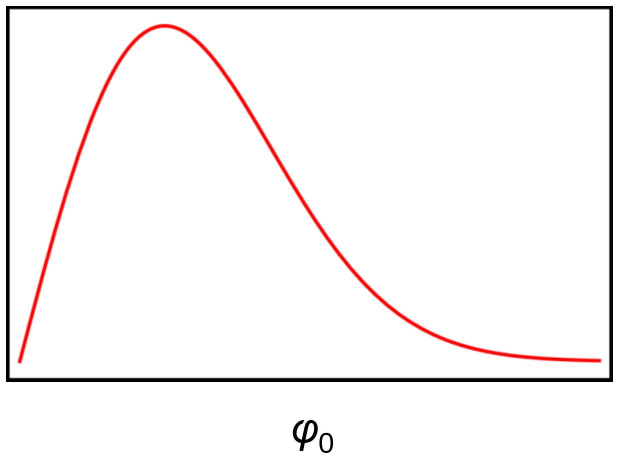
Evolution of φ_0 with time



Probability distribution function of φ_0 (e.g., Rayleigh distribution)



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- 10^{-21} eV $\lesssim m_\varphi \lesssim 1$ eV <=> 10^{-7} Hz $\lesssim f \lesssim 10^{14}$ Hz

$T_{\mathrm{osc}} \sim 1$ month IR frequencies

↑

Lyman-α forest measurements [suppression of structures for $L \lesssim \mathcal{O}(\lambda_{\mathrm{dB},\varphi})$]

[cf. $\lambda_{\mathrm{dB},\varphi}/2\pi \lesssim L_{\mathrm{dwarf\ galaxy}} \sim 1$ kpc $\Rightarrow m_\varphi \gtrsim 10^{-22}$ eV]

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- *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
- Torsion pendula
- Astrophysics (e.g., BBN)

Pseudoscalars (Axions):

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

→ Time-varying spin-dependent effects

- Co-magnetometers
- Particle g-factors
- Spin-polarised torsion pendula
- Spin resonance (NMR, ESR)

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):

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

$\longrightarrow$ **Time-varying fundamental constants**

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

Solar System (and lab) move through stationary dark matter halo

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φ^2 interactions also exhibit the same oscillating-in-time signatures as above, as well as …

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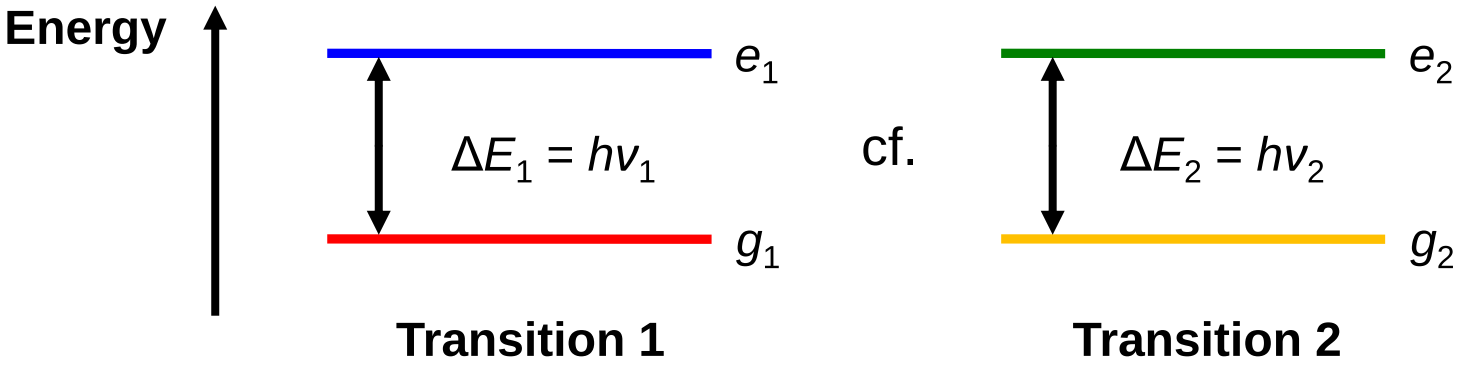
Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter



$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} = (K_{X,1} - K_{X,2})\frac{\delta X}{X} \; ; \; X = \alpha, m_e/m_N, \ldots$$

Atomic spectroscopy (including clocks) has been used for decades to search for "slow drifts" in fundamental constants

Recent overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

"Sensitivity coefficients" K_X required for the interpretation of experimental data have been calculated extensively by Flambaum group

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

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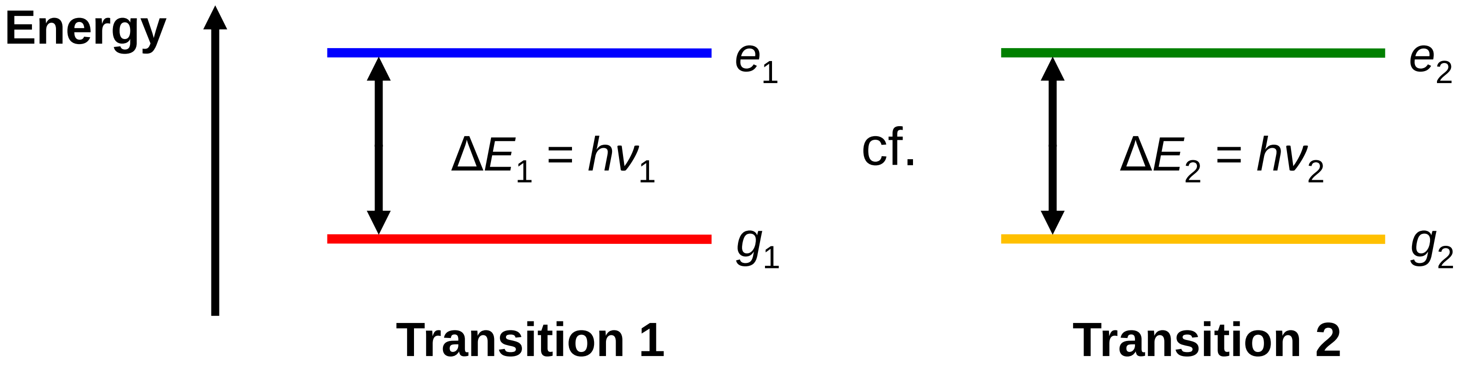
[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik, Flambaum, *PRL* **114**, 161301 (2015)]



$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} \propto \sum_{X=\alpha, m_e/m_N, \ldots} (K_{X,1} - K_{X,2}) \cos(\omega_\phi t) \;\; ; \;\; \omega_\phi = m_\phi \text{ or } 2m_\phi$$

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

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

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

$\Rightarrow \nu_{\mathrm{free}} \propto 1/L_{\mathrm{free}} \propto m_e \alpha$

(adiabatic regime)

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

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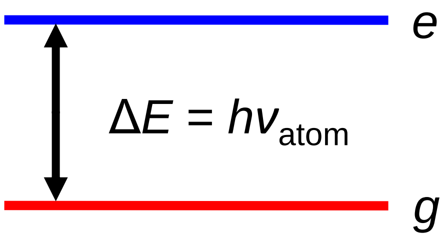
Solid material

cf.

Electronic transition



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

$\Rightarrow \nu_{free} \propto 1/L_{free} \propto m_e \alpha$

$h\nu_{atom} \sim m_e \alpha^2$

$$\frac{\nu_{atom}}{\nu_{free}} \propto \alpha$$

- **Sr/ULE cavity [Torun]:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Sr/H/Si cavity [JILA + PTB]:** [Kennedy *et al.*, *BAPS*, H06.00005 (2018); arXiv:2008.08773]
- **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)]

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$\Rightarrow \nu_{\mathrm{free}} \propto 1/L_{\mathrm{free}} \propto m_e \alpha$

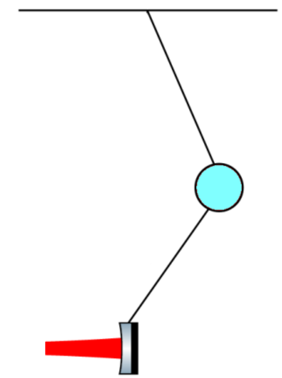
cf.

Freely-suspended mirrors

$L_{\mathrm{fixed}} \approx$ const. for $f > f_{\mathrm{natural}}$

$\Rightarrow \nu_{\mathrm{fixed}} \approx$ constant

Double-pendulum suspensions



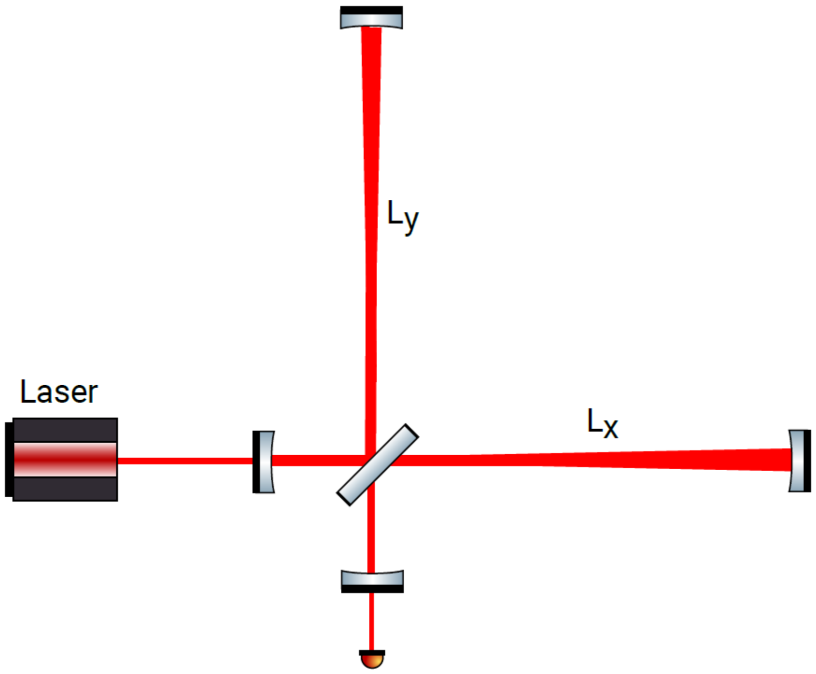
$$\frac{\nu_{\mathrm{free}}}{\nu_{\mathrm{fixed}}} \propto m_e \alpha$$

cf.

$$\frac{\nu_{\mathrm{atom}}}{\nu_{\mathrm{free}}} \propto \alpha$$

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

[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO 600)

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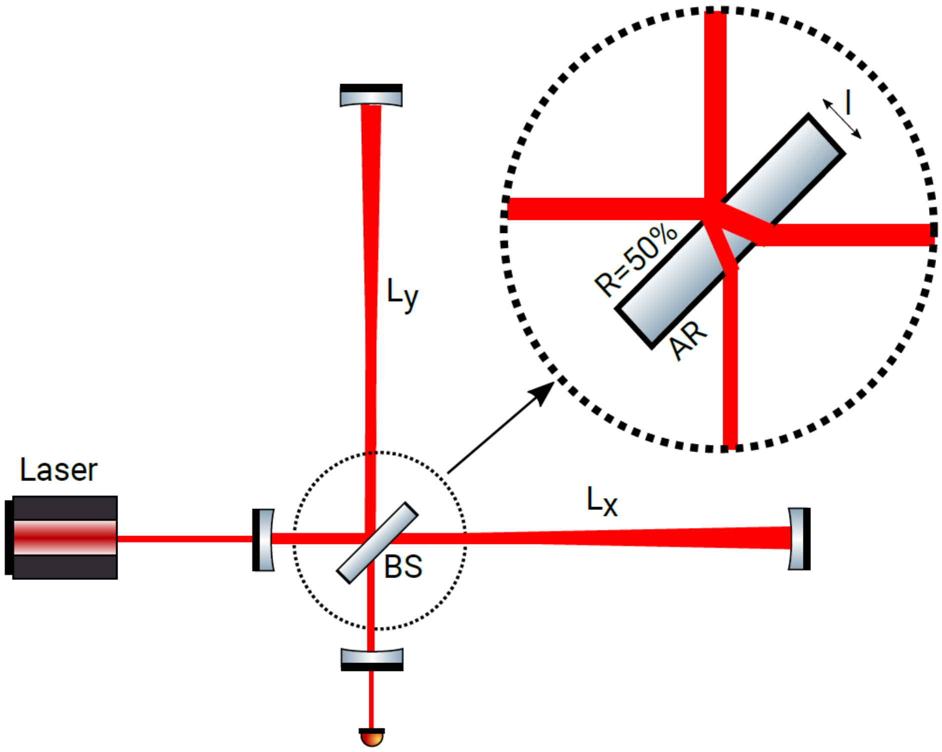

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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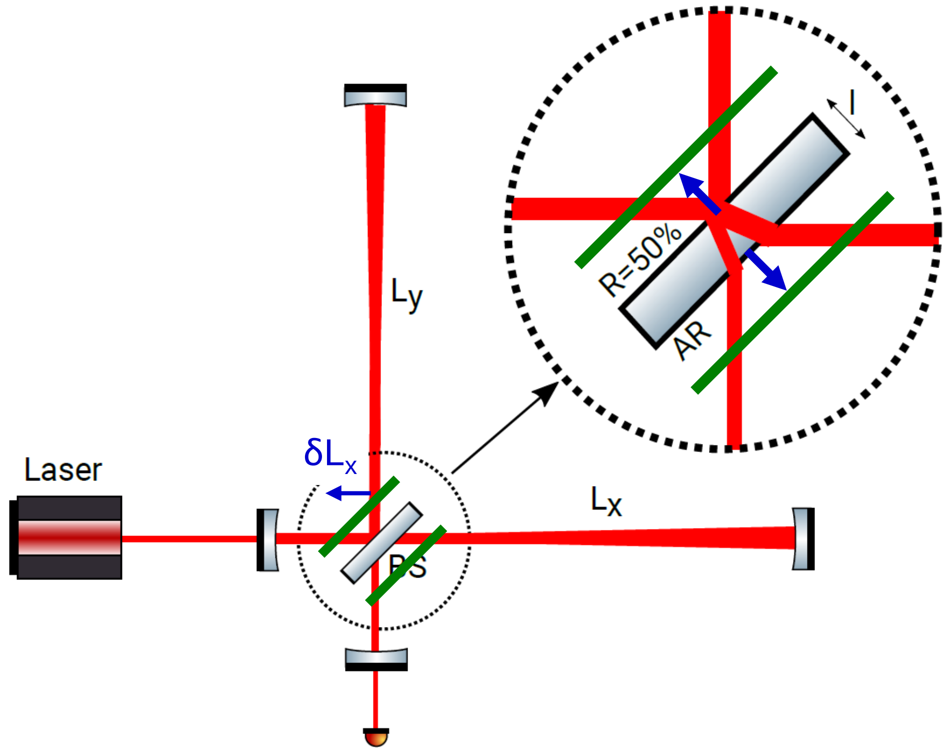

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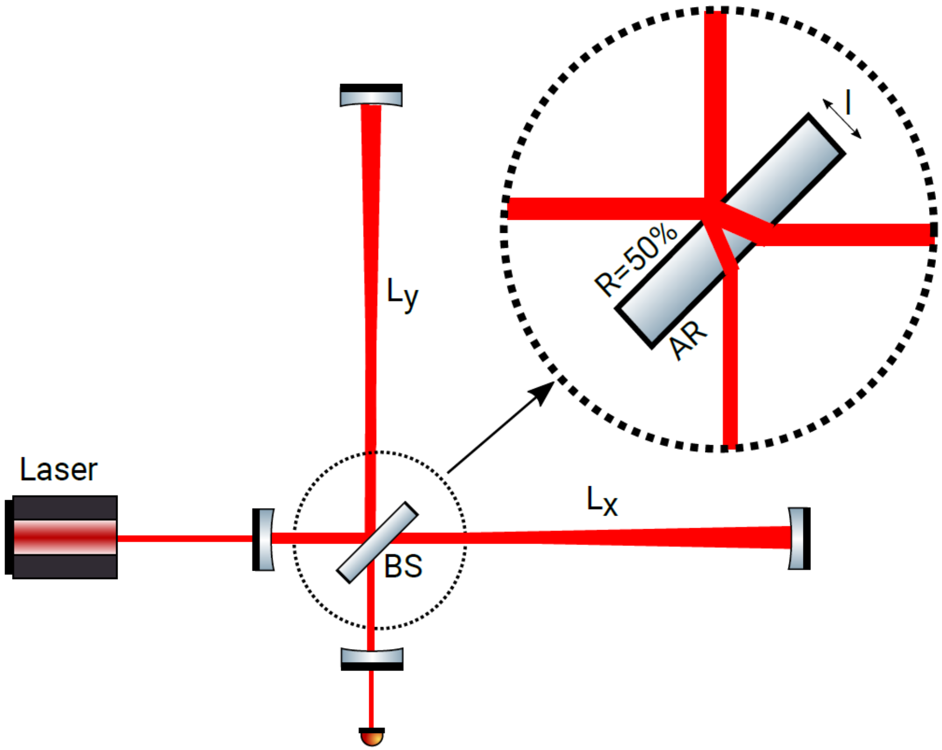
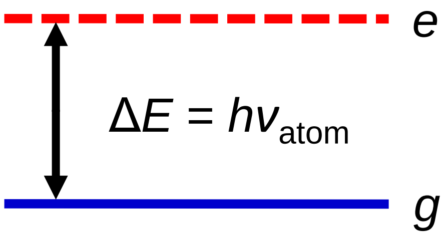


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{DM} \approx f_{vibr,BS}(T) \sim v_{sound}/l$, $Q \sim 10^6$ enhancement

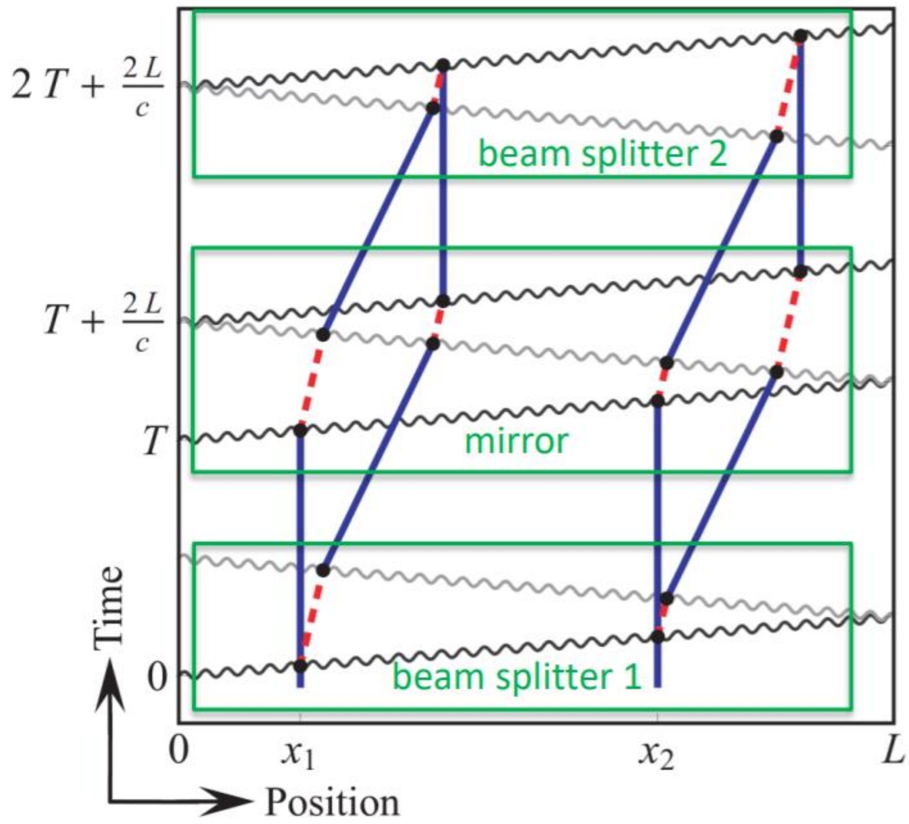
Atom Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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

Electronic transition



$h\nu_{atom} \sim m_e \alpha^2$

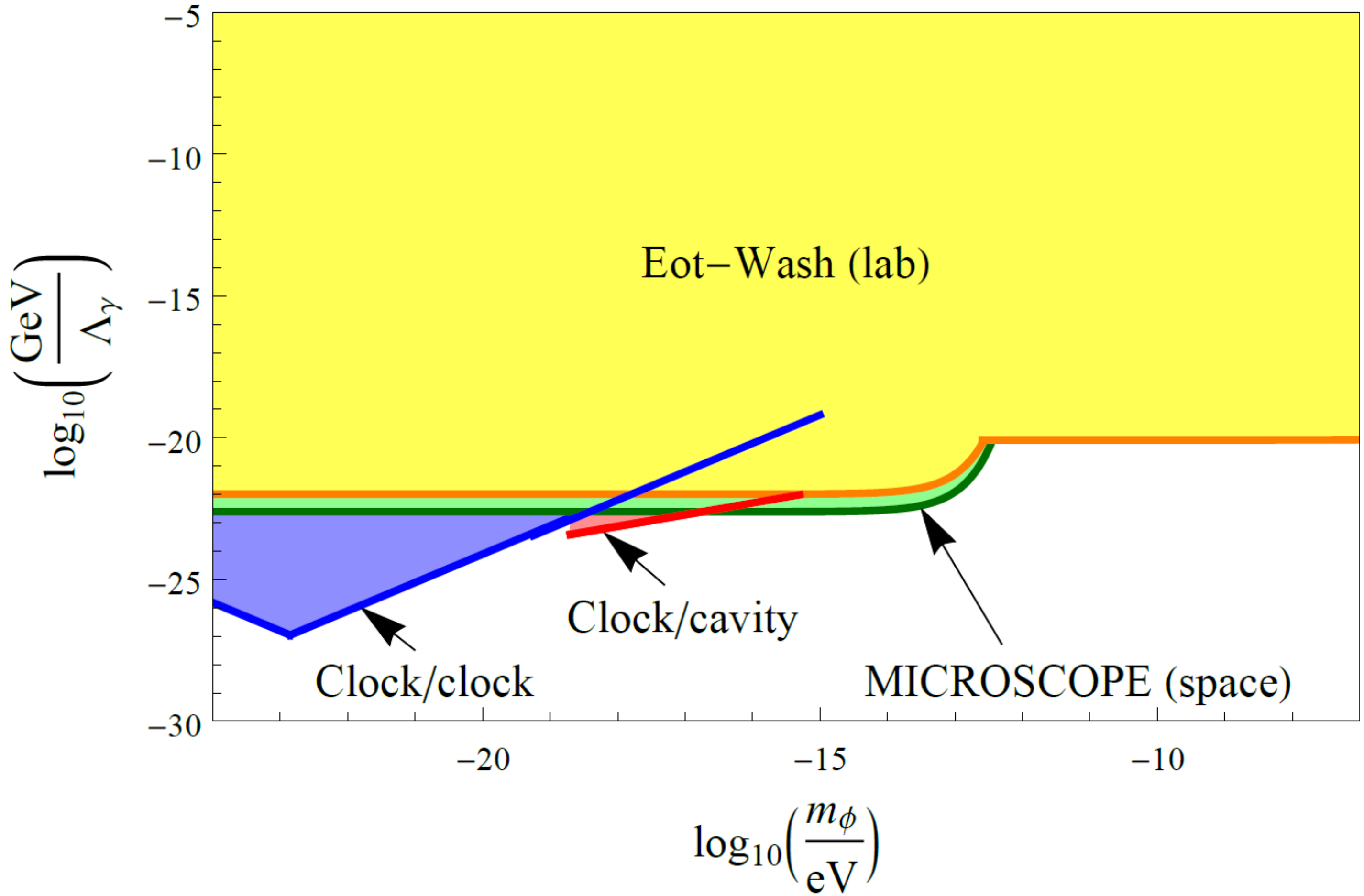


Phase shift between the two separated atom interferometers is maximised when $T_{osc} \sim 2T$: $\delta(\Delta\Phi)_{max} \sim \delta\nu_{atom} \cdot T_{osc}$

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:** [Kennedy *et al.*, arXiv:2008.08773]

4 orders of magnitude improvement!



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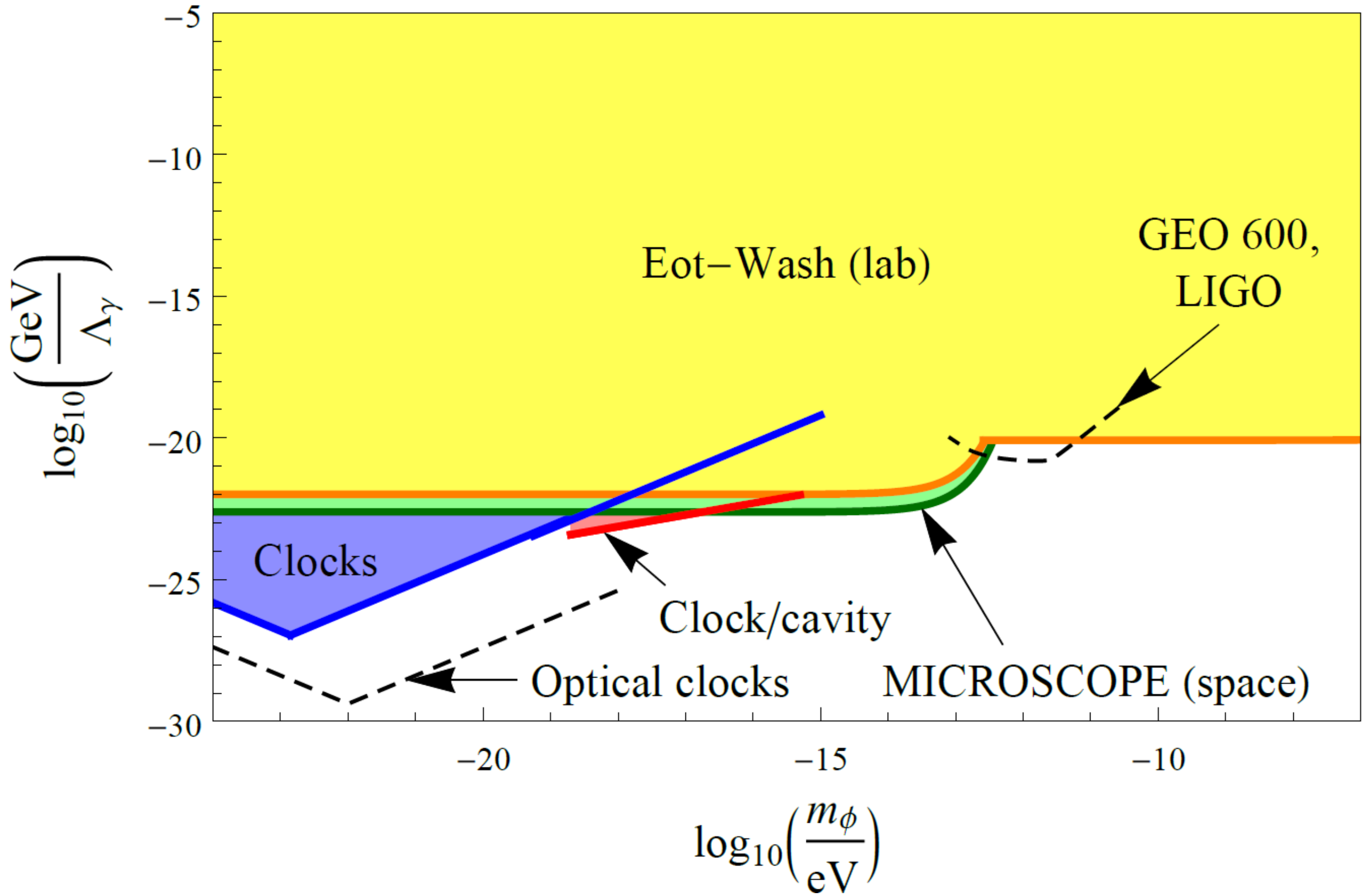

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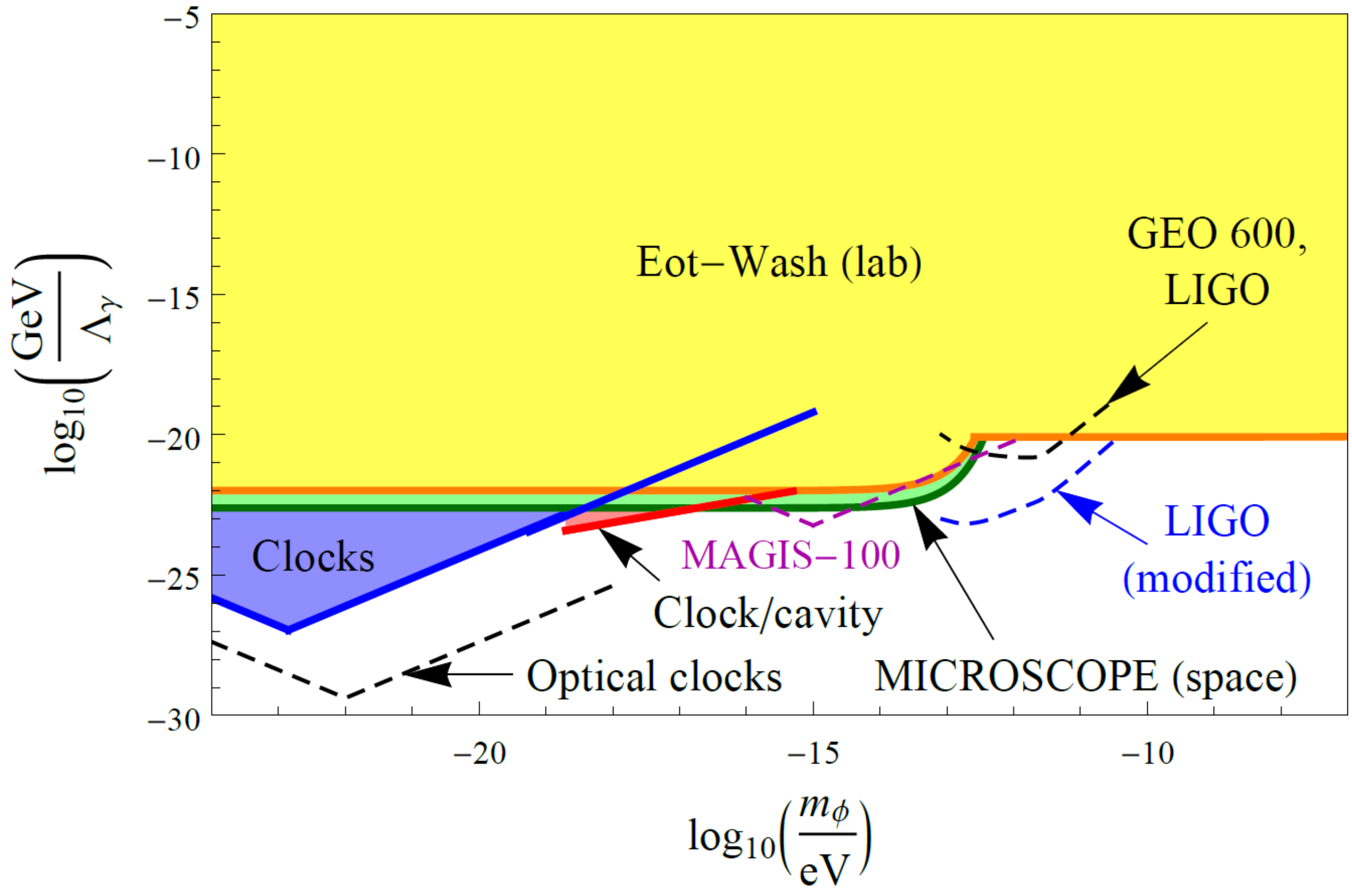

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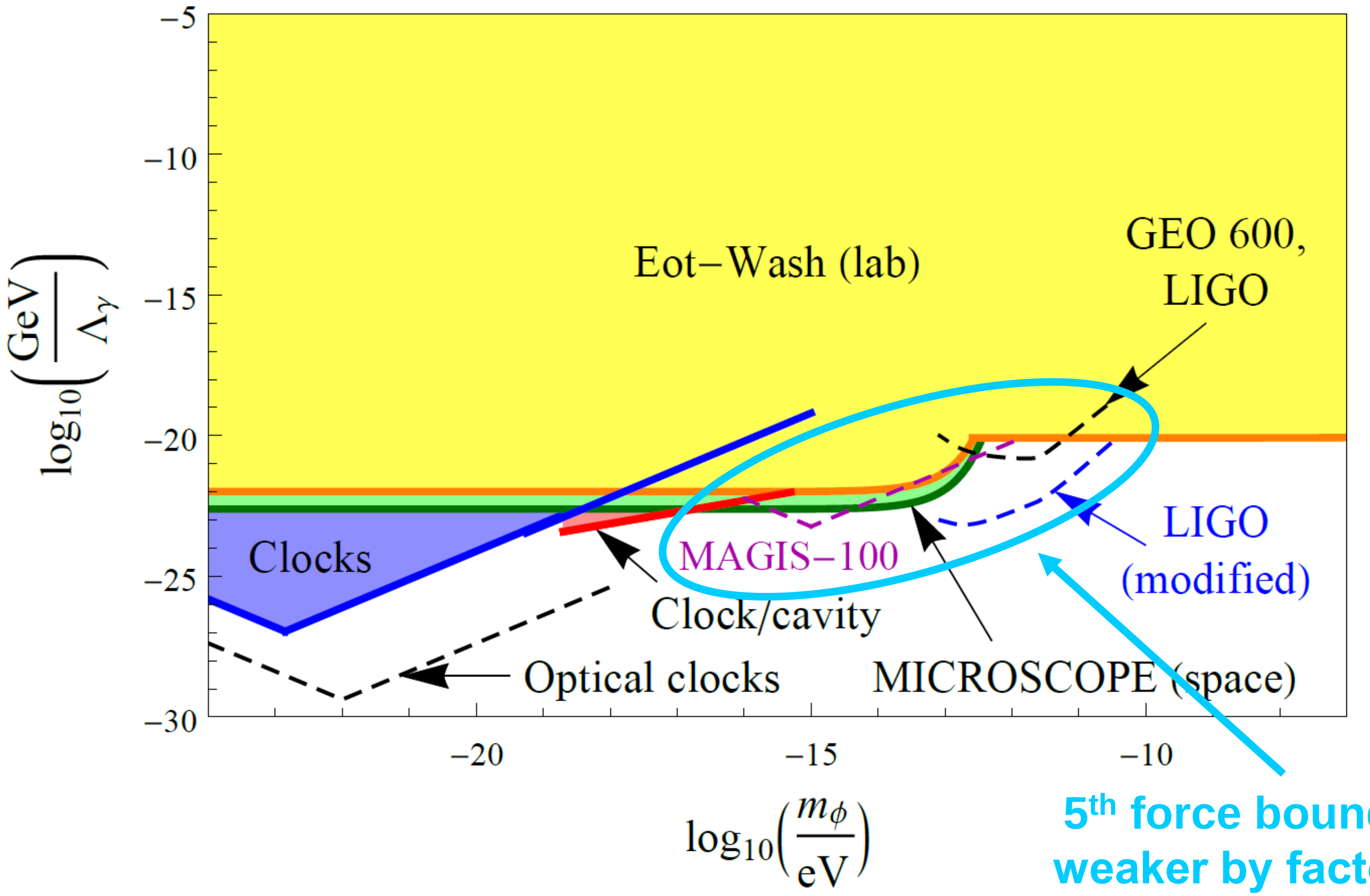
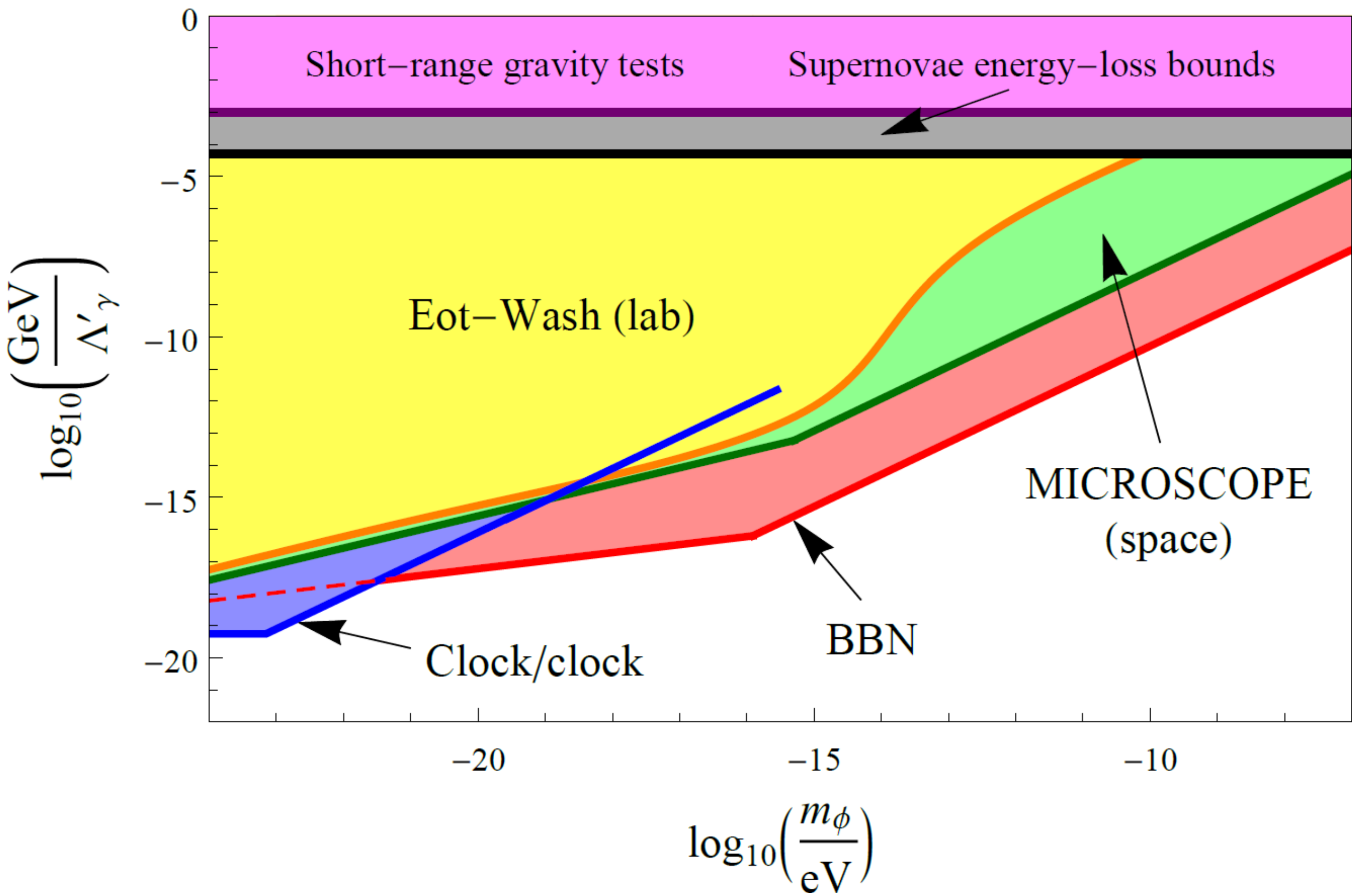


5^{th} force bounds on Λ_e weaker by factor of ≈20

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):

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

More traditional axion detection methods tend to focus on the ***electromagnetic*** *coupling – see, e.g., talks on Thursday by Andreas Ringwald and Igor Irastorza*

I will focus on relatively new detection methods based on ***non-electromagnetic*** *couplings* →

Time-varying spin-dependent effects

- Co-magnetometers
- Particle g-factors
- Spin-polarised torsion pendula
- Spin resonance (NMR, ESR)

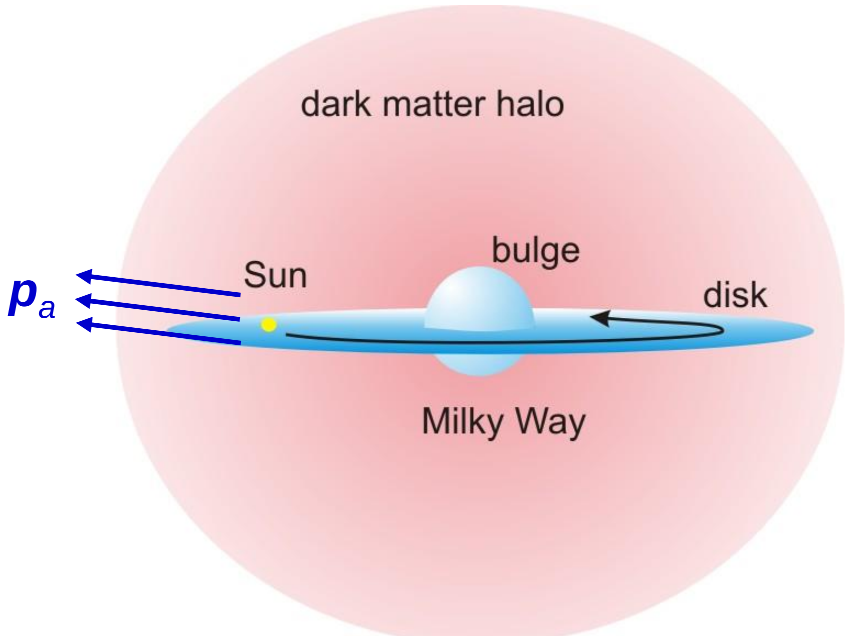
Dark Matter-Induced Spin-Dependent Effects

"Axion Wind" Spin-Precession Effect

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

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

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



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Oscillating Electric Dipole Moments

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

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

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

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

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

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*, *cold/ultracold particles*, *torsion pendula*

Similar to previous searches for Lorentz-invariance violation

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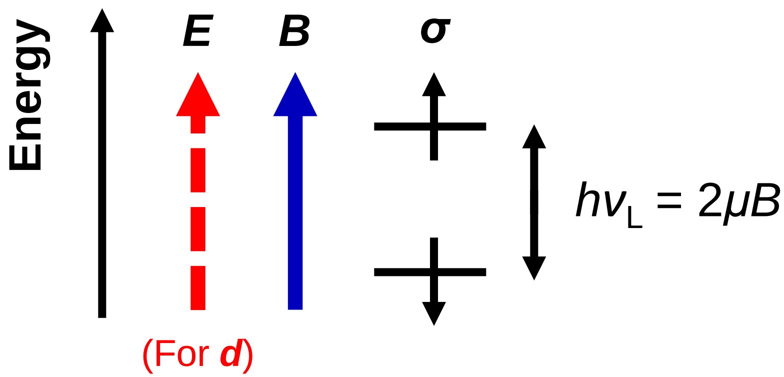
Experiment (n/Hg): [nEDM collaboration, *PRX* **7**, 041034 (2017)]



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

↑

***B*-field effect**

Searching for Spin-Dependent Effects

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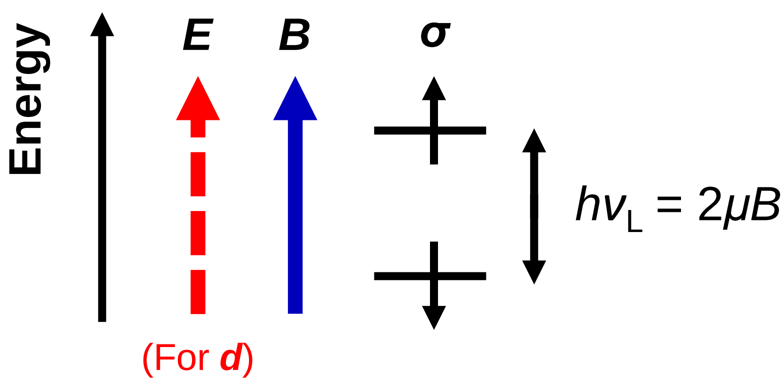

$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}}\right| + R(t)$$

***B*-field effect**

DM effect (*non-magnetic* coupling to ***σ*** or ***d***)

Searching for Spin-Dependent Effects

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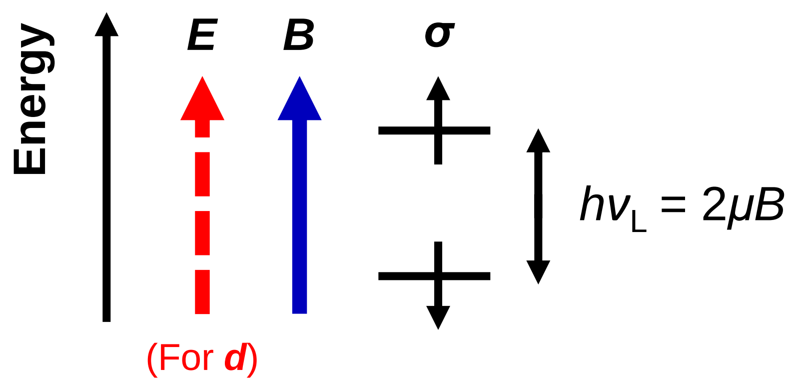
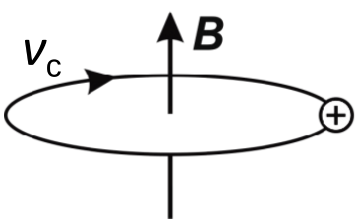


$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right| + R(t)$$

***B*-field effect**

DM effect (*non-magnetic* coupling to ***σ*** or ***d***)

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



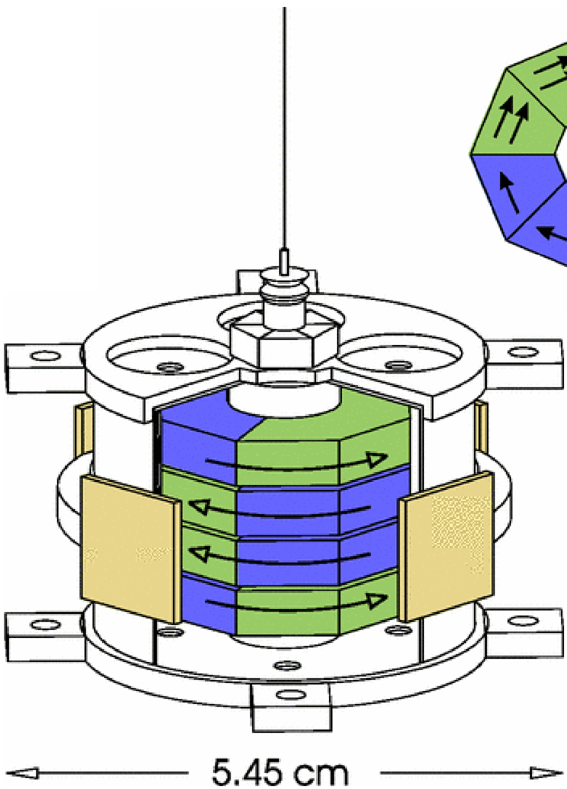
$$\left(\frac{\nu_{\mathrm{L}}}{\nu_{\mathrm{c}}}\right)_{\bar{\mathrm{p}}} = \frac{|g_{\bar{\mathrm{p}}}|}{2} + R(t)$$

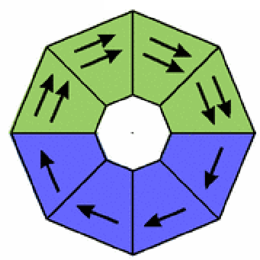
Searching for Spin-Dependent Effects

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

Use spin-polarised sources: Atomic magnetometers, cold/ultracold particles, <u>*torsion pendula*</u>

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





$\boldsymbol{\mu}_{\text{Alnico}}$ →
← $\boldsymbol{\mu}_{SmCo_5}$

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

$(\boldsymbol{\sigma}_e)_{\text{Alnico}}$ →
← $(\boldsymbol{\sigma}_e)_{SmCo_5}$

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

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

Searching for Spin-Dependent Effects

At higher axion masses, resonant narrowband approaches with $Q \sim 10^6$ enhancement become possible

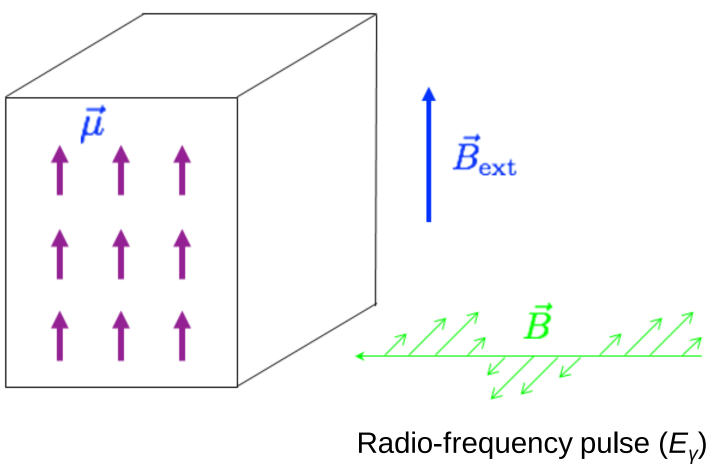
Searching for Spin-Dependent Effects

At higher axion masses, resonant narrowband approaches with $Q \sim 10^6$ enhancement become possible

For nucleon and gluon couplings, <u>*nuclear magnetic resonance (NMR)*</u>

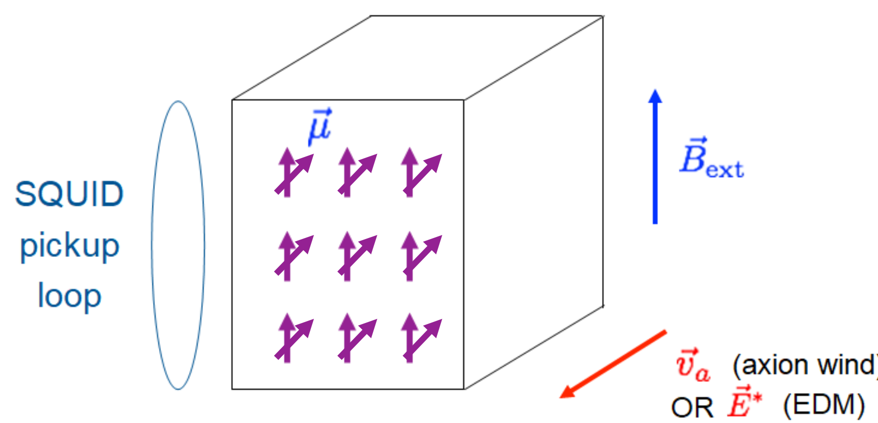
[Budker, Graham, Ledbetter, Rajendran, A. O. Sushkov, *PRX* **4**, 021030 (2014)]

Traditional NMR



Resonance: $2\mu B_{\text{ext}} = E_\gamma$

Dark-matter-driven NMR



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

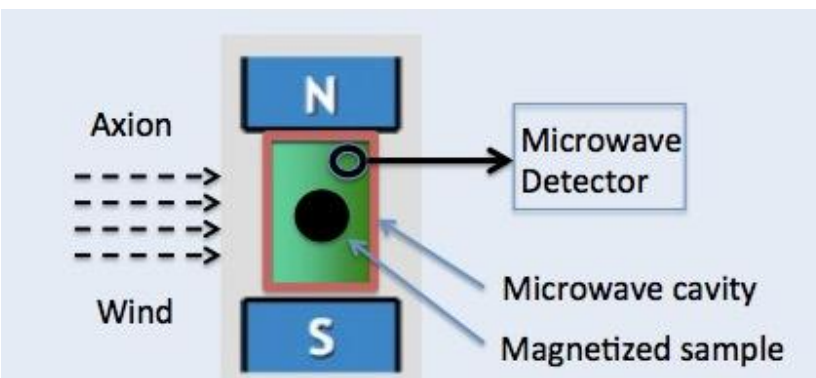
Measure transverse magnetisation

Searching for Spin-Dependent Effects

At higher axion masses, resonant narrowband approaches with $Q \sim 10^6$ enhancement become possible

For the electron coupling, *electron spin resonance (ESR)*

Proposals: [Krauss, Moody, Wilczek, Morris, HUTP-85/A006 (1985)], [Raffelt, MPI-PAE/PTh 86/85 (1985)], [Barbieri, Cerdonio, Fiorentini, Vitale, *PLB* **226**, 357 (1989)], [Caspers, Semertzidis, *Proceedings of the Workshop on Cosmic Axions*, 1990], [Kakhidze, Kolokolov, *Sov. Phys. JETP* **72**, 598 (1991); Vorob′ev, Kakhidze, Kolokolov, *Phys. Atom. Nuclei* **58**, 959 (1995)], [Barbieri *et al*., *Phys. Dark Universe* **15**, 135 (2017)]



Resonance: $2\mu B_{\mathrm{ext}} \approx E_{\mathrm{res,cav}} \approx E_{\pm} \approx m_a$

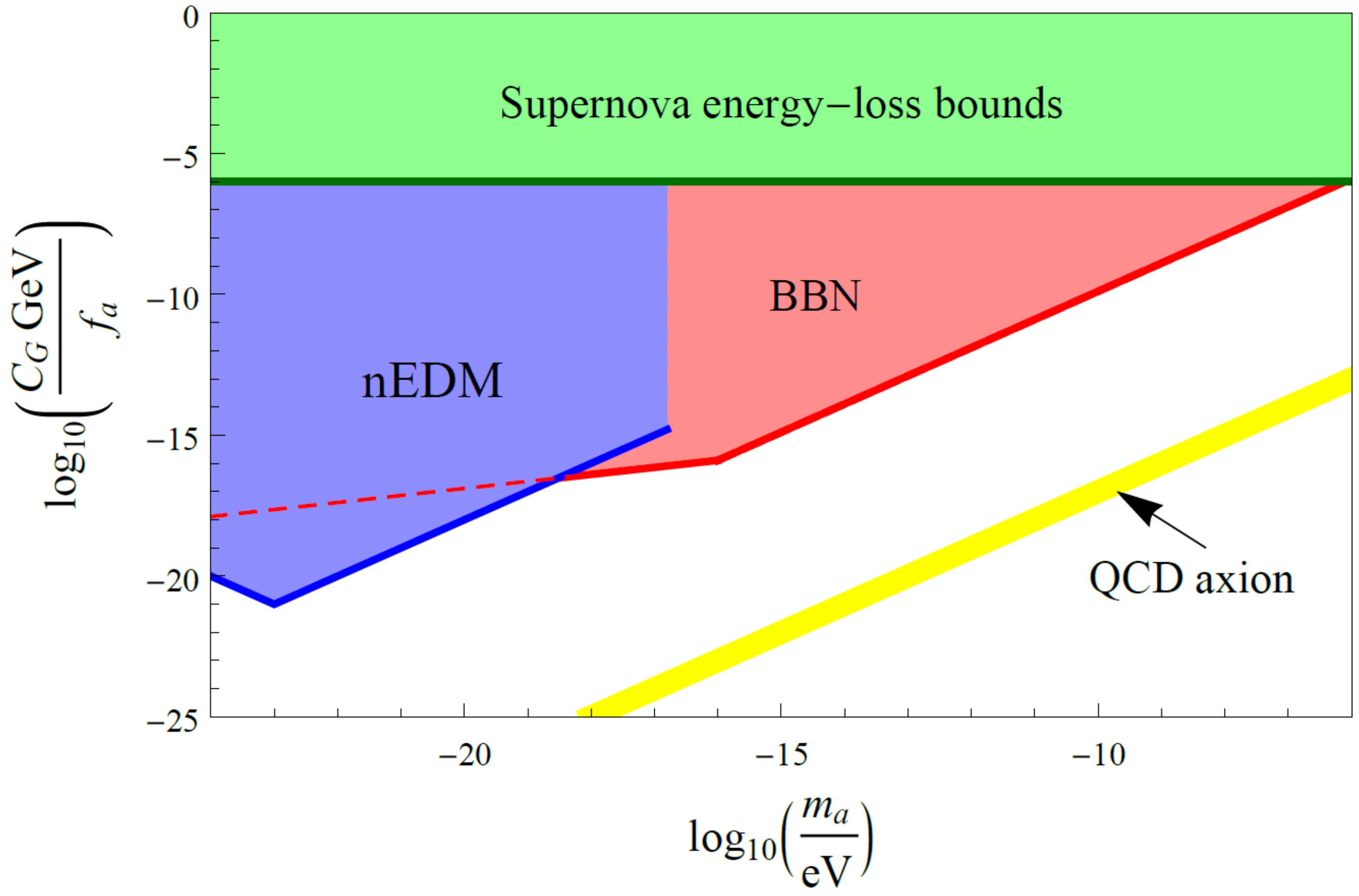
Measure photons resulting from axion-to-polariton conversion (hybridised cavity-magnon mode)

- **YIG [INFN]:** [Crescini *et al*., *EPJ C* **78**, 702 (2018); *PRL* **124**, 171801 (2020)]
- **YIG [UWA]:** [Flower, Bourhill, Goryachev, Tobar, *Phys. Dark Universe* **25**, 100306 (2019)]

Constraints on Interaction of Axion Dark Matter with Gluons

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

3 orders of magnitude improvement!



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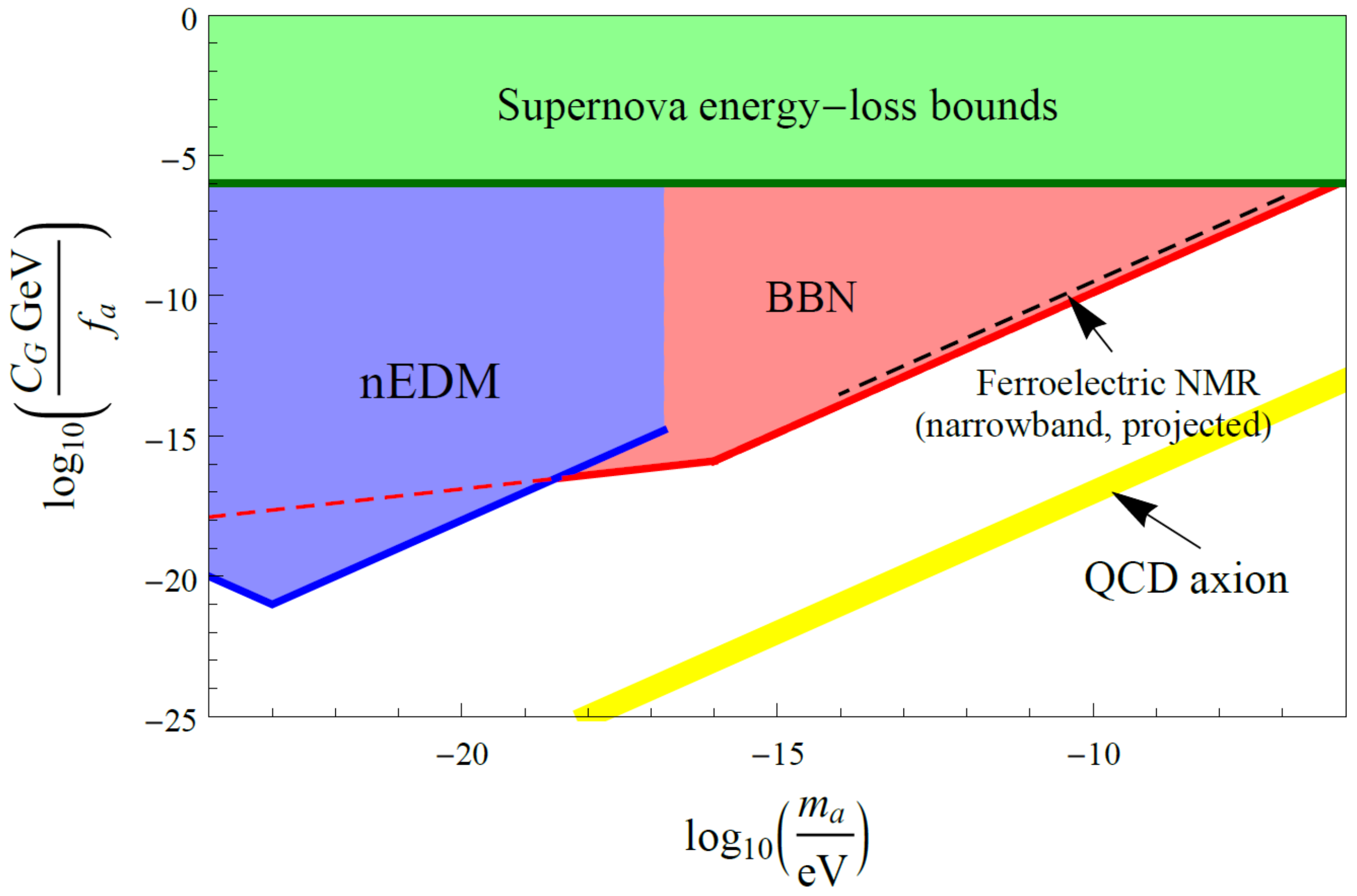

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ν_n/ν_{Hg} constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

Acetonitrile constraints: [Wu *et al*., *PRL* **122**, 191302 (2019)]

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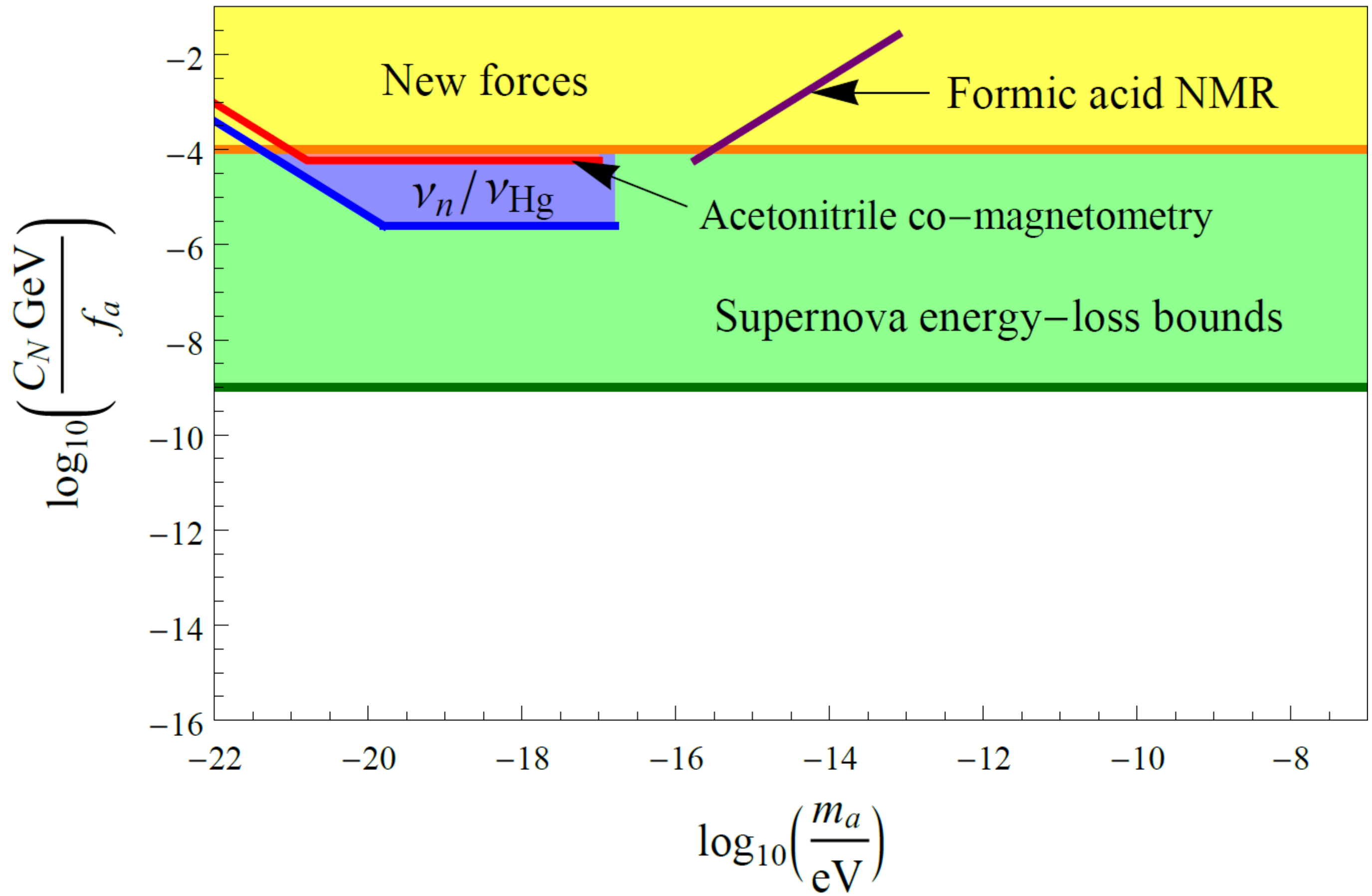

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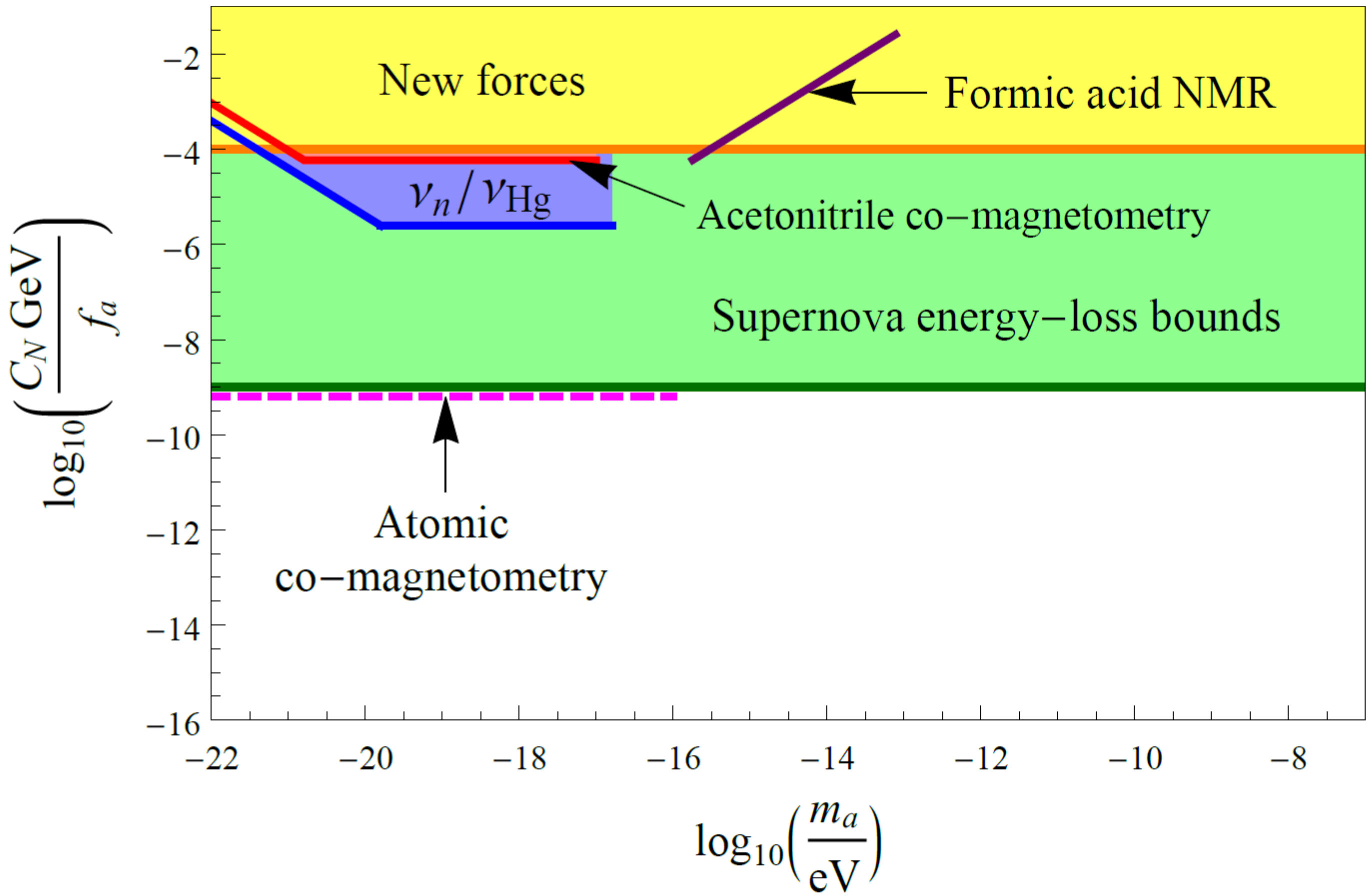

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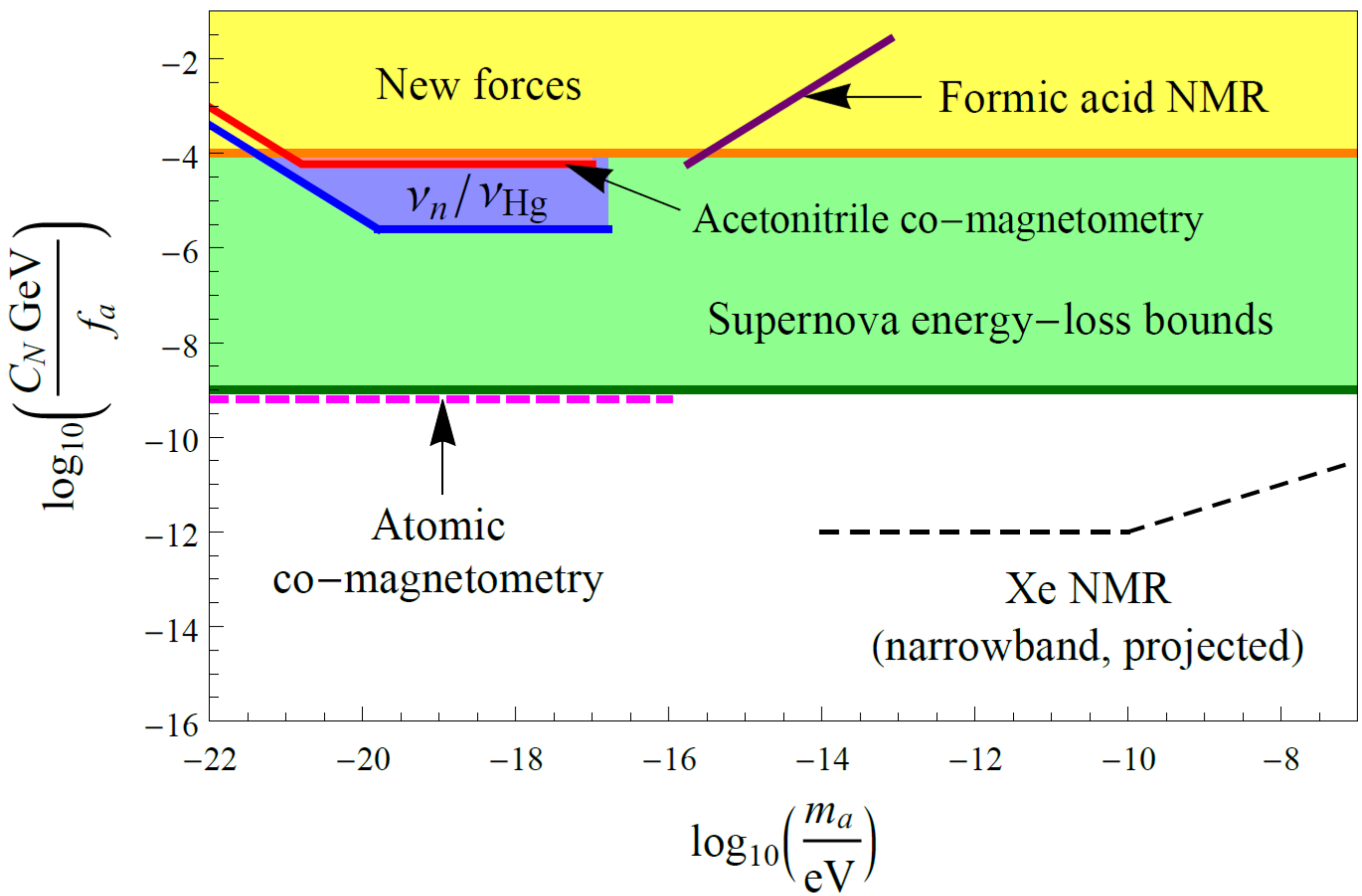

Constraints on Interaction of Axion Dark Matter with the Electron

Spin-polarised torsion pendulum constraints: [Terrano *et al*., *PRL* **122**, 231301 (2019)]

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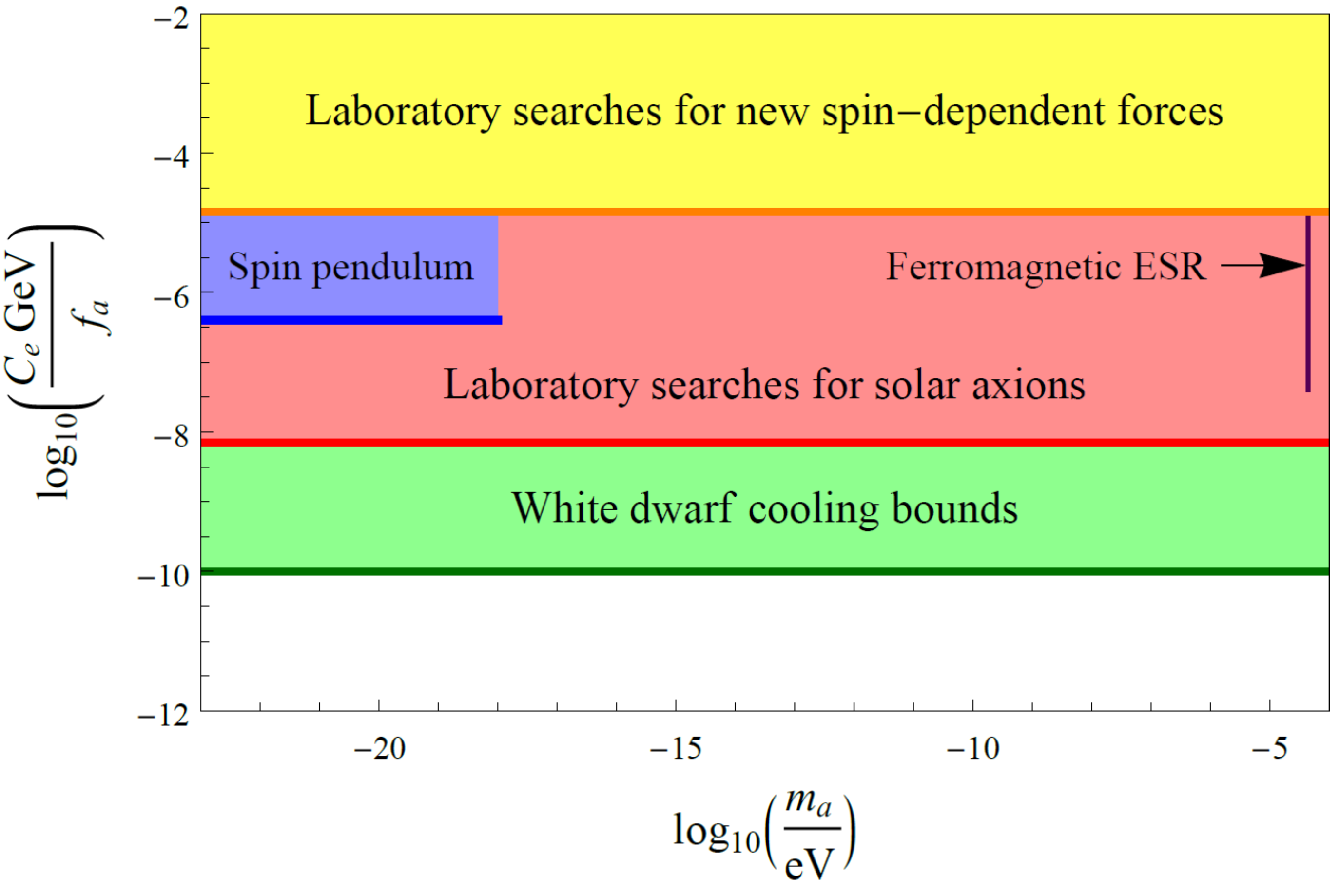

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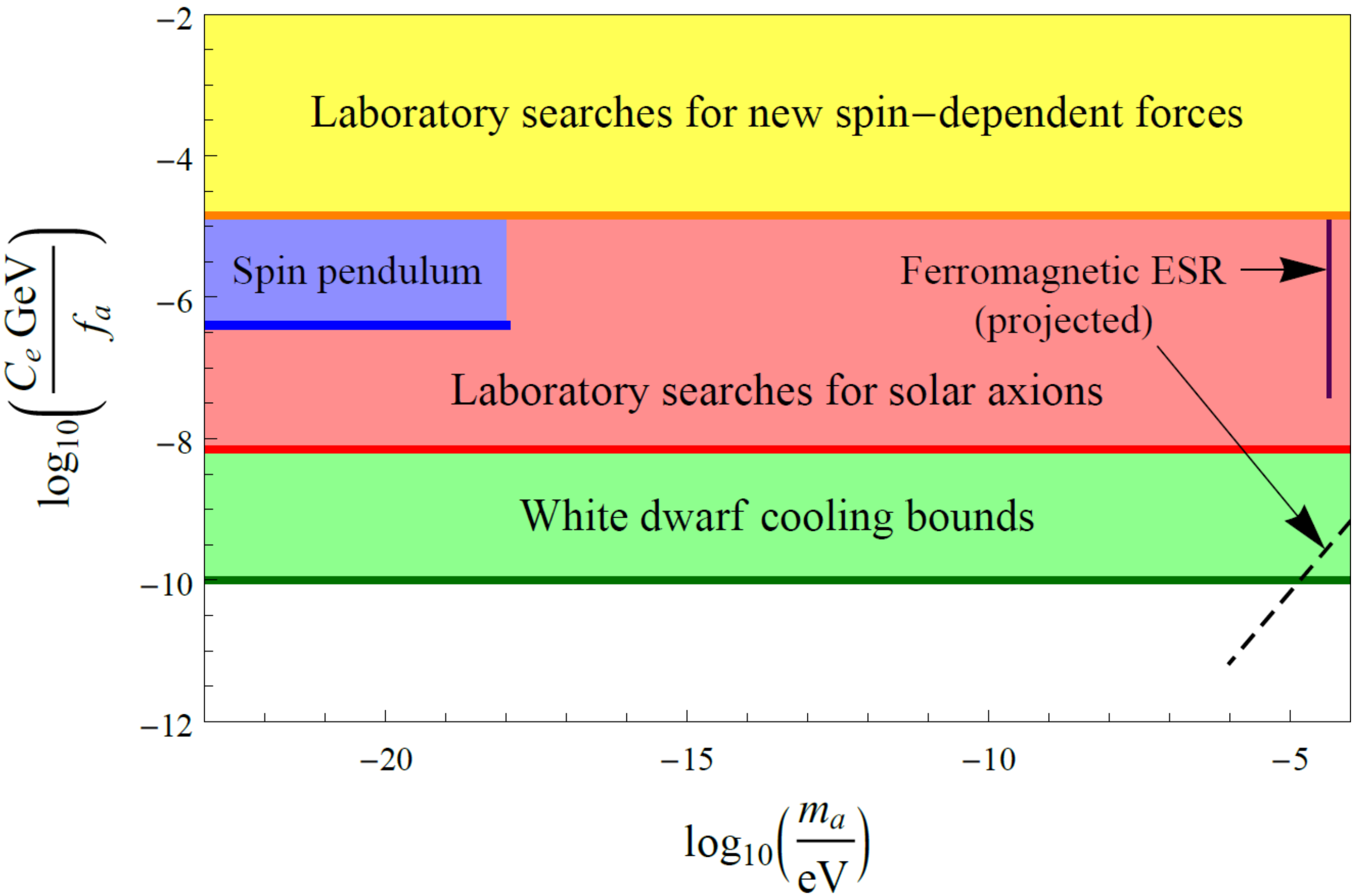
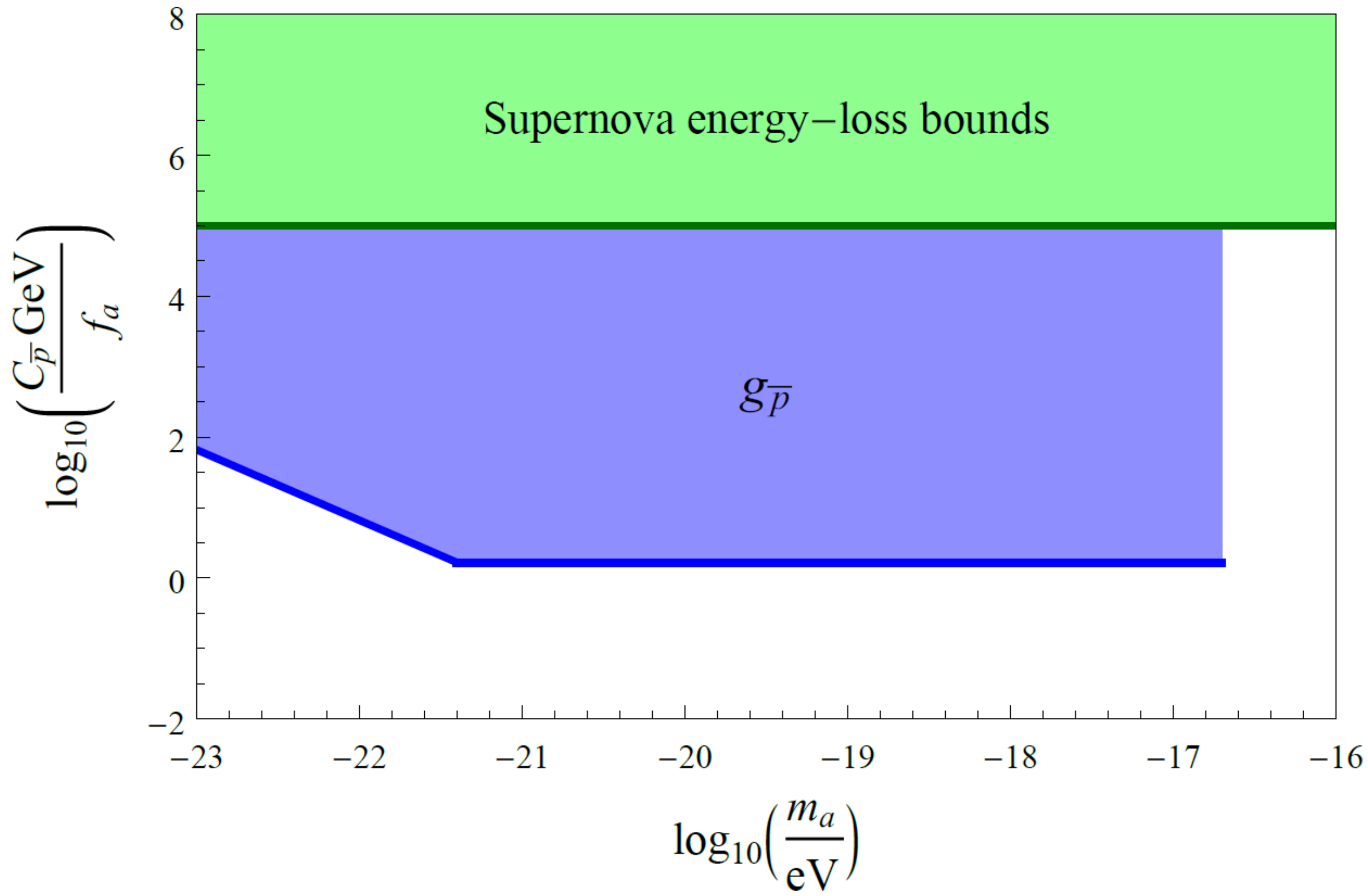


Constraints on Interaction of Axion Dark Matter with the Antiproton

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

5 orders of magnitude improvement!



Summary

- There are a plethora of new opportunities to search for very-low-mass feebly-interacting particles with atomic physics and quantum technology approaches, with improvement by up to **15 orders of magnitude** already demonstrated

  - Scalar dark matter:
    - *Atomic clocks and optical cavities*
    - *Optical and atom interferometers*

  - Pseudoscalar dark matter:
    - *Co-magnetometers*
    - *Particle g-factors*
    - *Spin-polarised torsion pendula*
    - *Nuclear magnetic resonance and electron spin resonance*

Back-Up Slides

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)]

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

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

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

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

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
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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

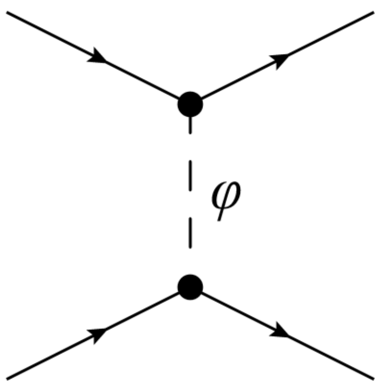
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

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

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

$$\Box\phi + m_\phi^2\phi = \mp\kappa\rho$$

Source term

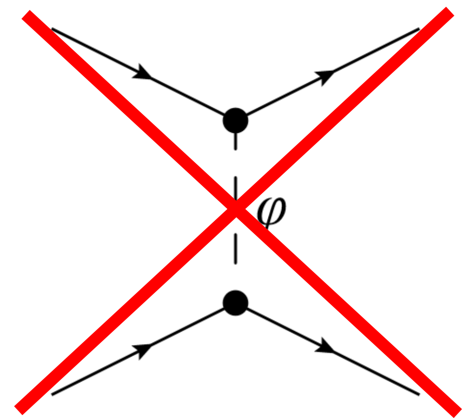


$$\phi = \phi_0\cos(m_\phi t) - A\frac{e^{-m_\phi r}}{r}$$

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

$$\Box\phi + m_\phi^2\phi = \mp\kappa'\rho\phi$$

Potential term



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

Gradients + screening/amplification

Fifth Forces: Linear vs Quadratic Couplings

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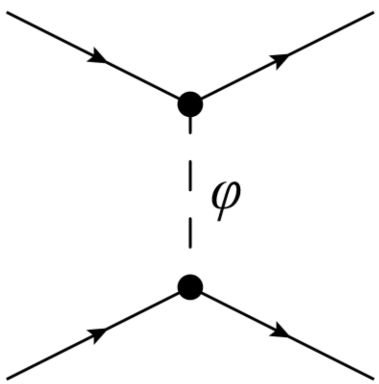
Linear couplings ($\varphi\bar{X}X$)

$$\Box\phi + m_\phi^2\phi = \mp\kappa\rho$$ **Source term**



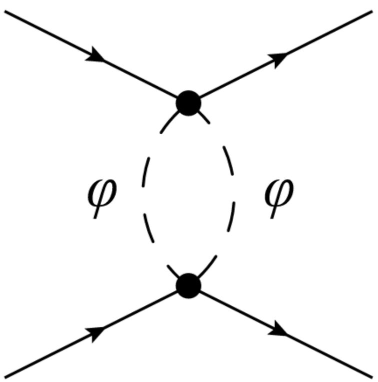
$$\phi = \underline{\phi_0\cos(m_\phi t)} - A\frac{e^{-m_\phi r}}{r}$$

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

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

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

$$\Box\phi + m_\phi^2\phi = \mp\kappa'\rho\phi$$ **Potential term**



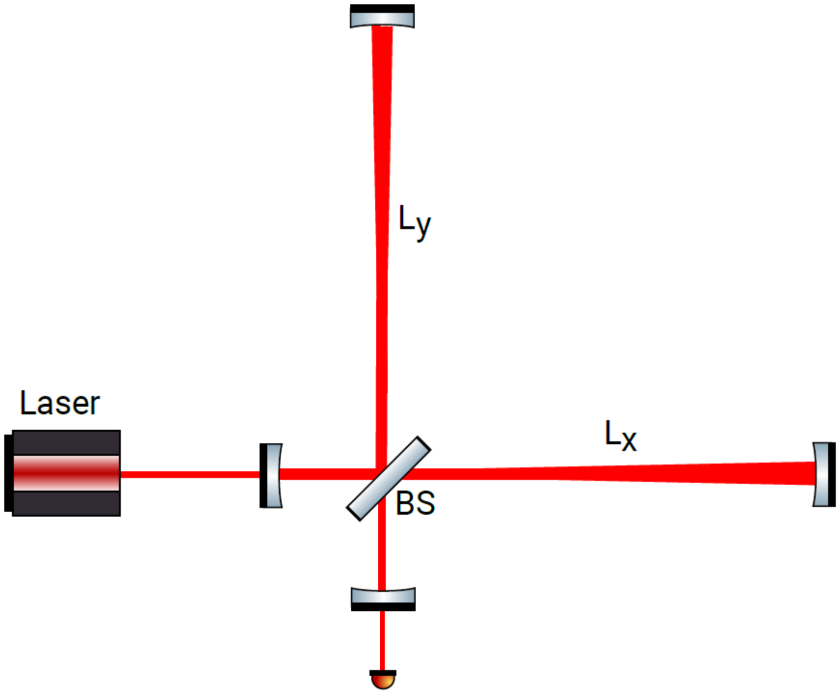
$$\phi = \underline{\phi_0\cos(m_\phi t)}\left(1 \mp \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

Gradients + screening/amplification

Michelson vs Fabry-Perot-Michelson Interferometers

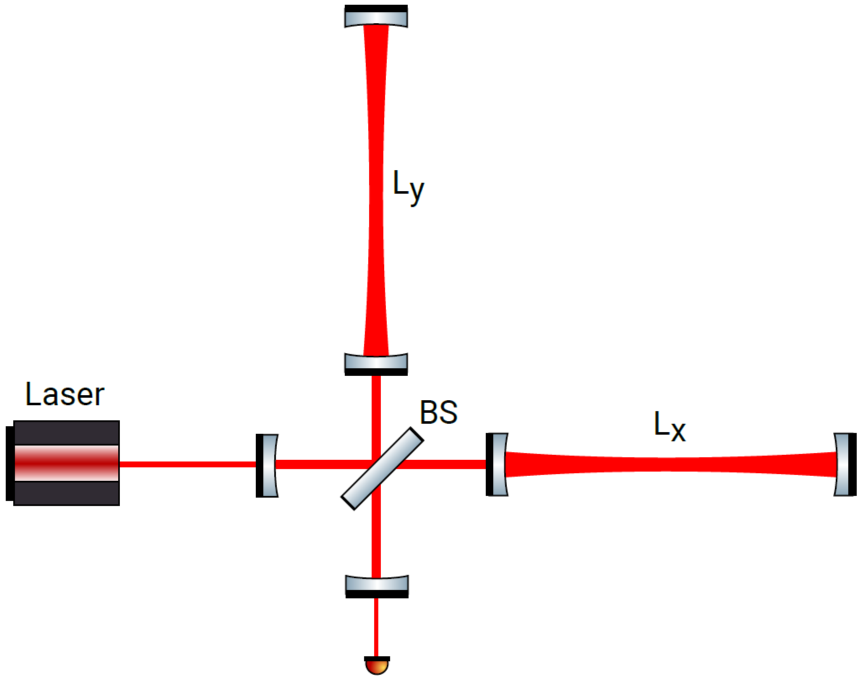
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)

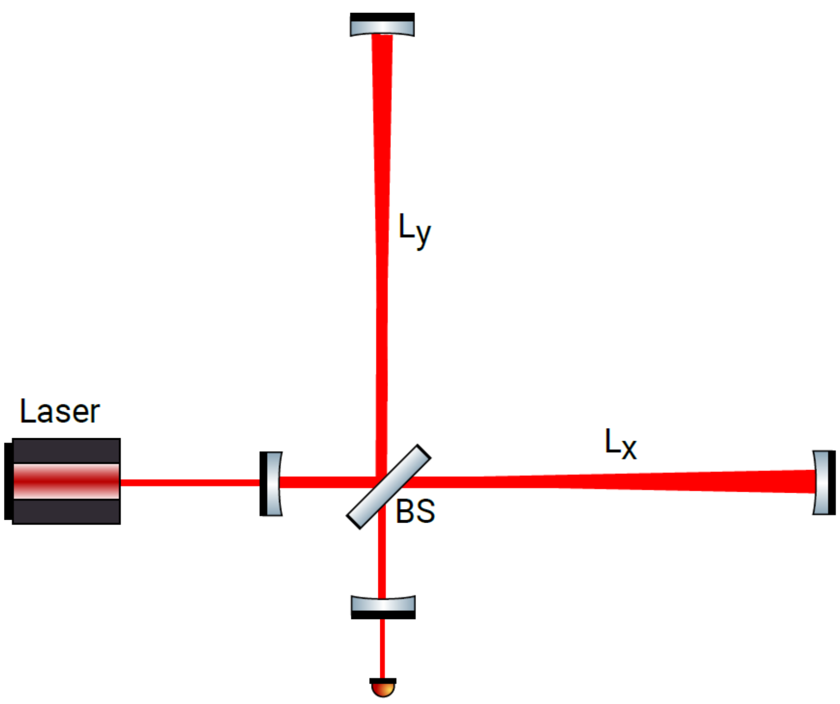


$\delta(L_x - L_y)_{BS} \sim \delta(nl)/N_{eff}$

Michelson vs Fabry-Perot-Michelson Interferometers

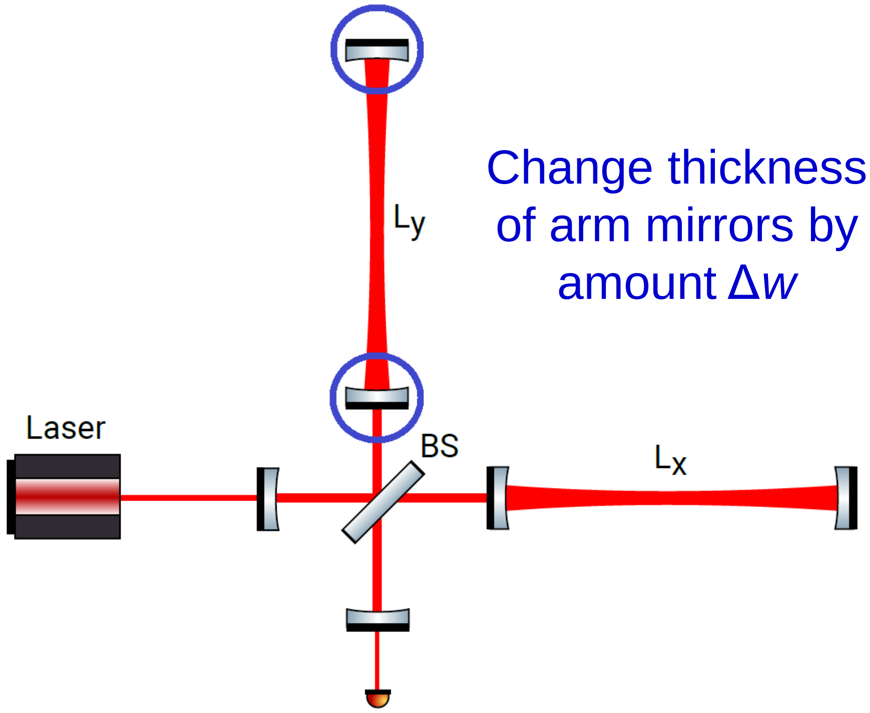
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

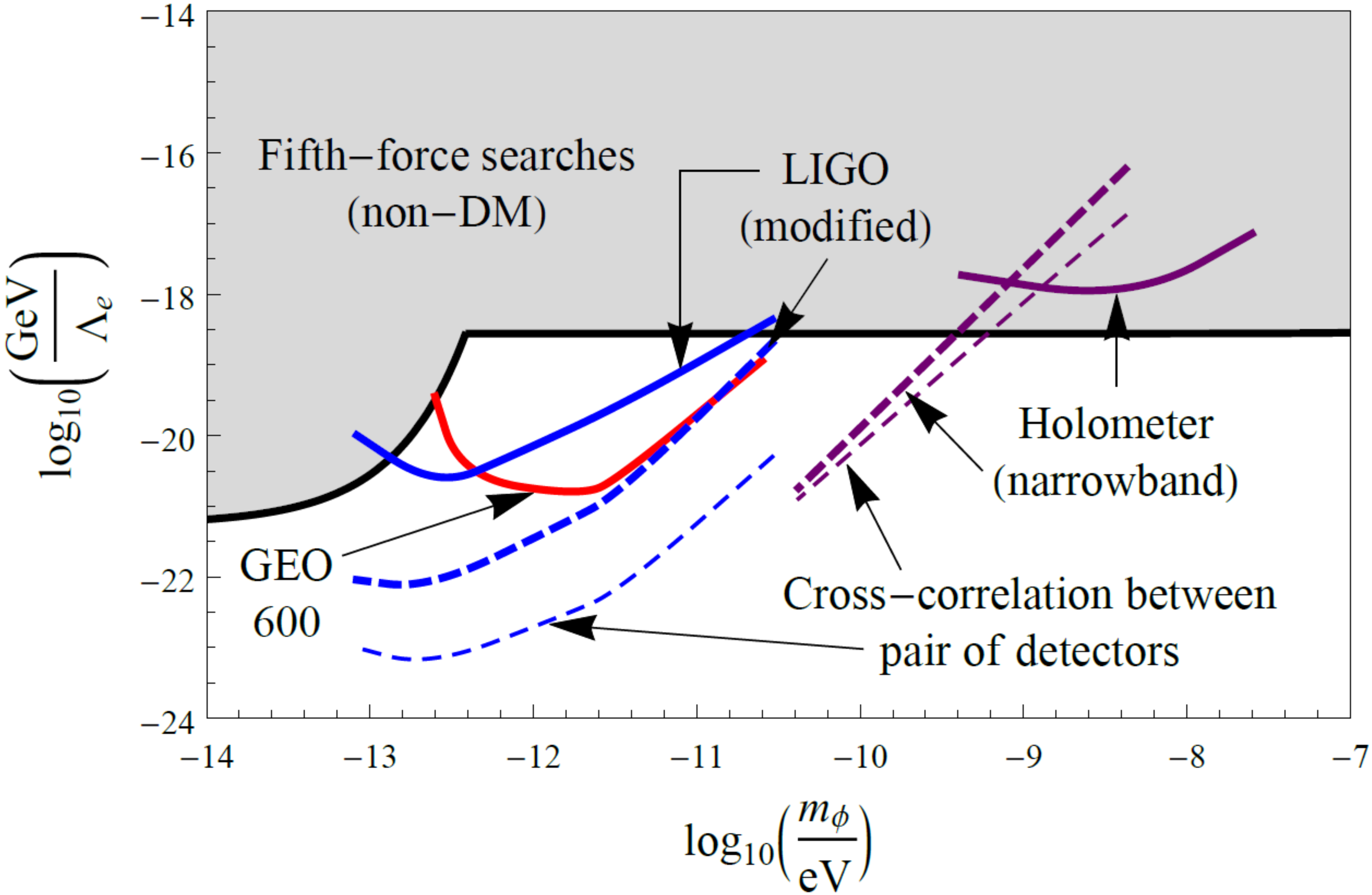
Fabry-Perot-Michelson interferometer (LIGO)



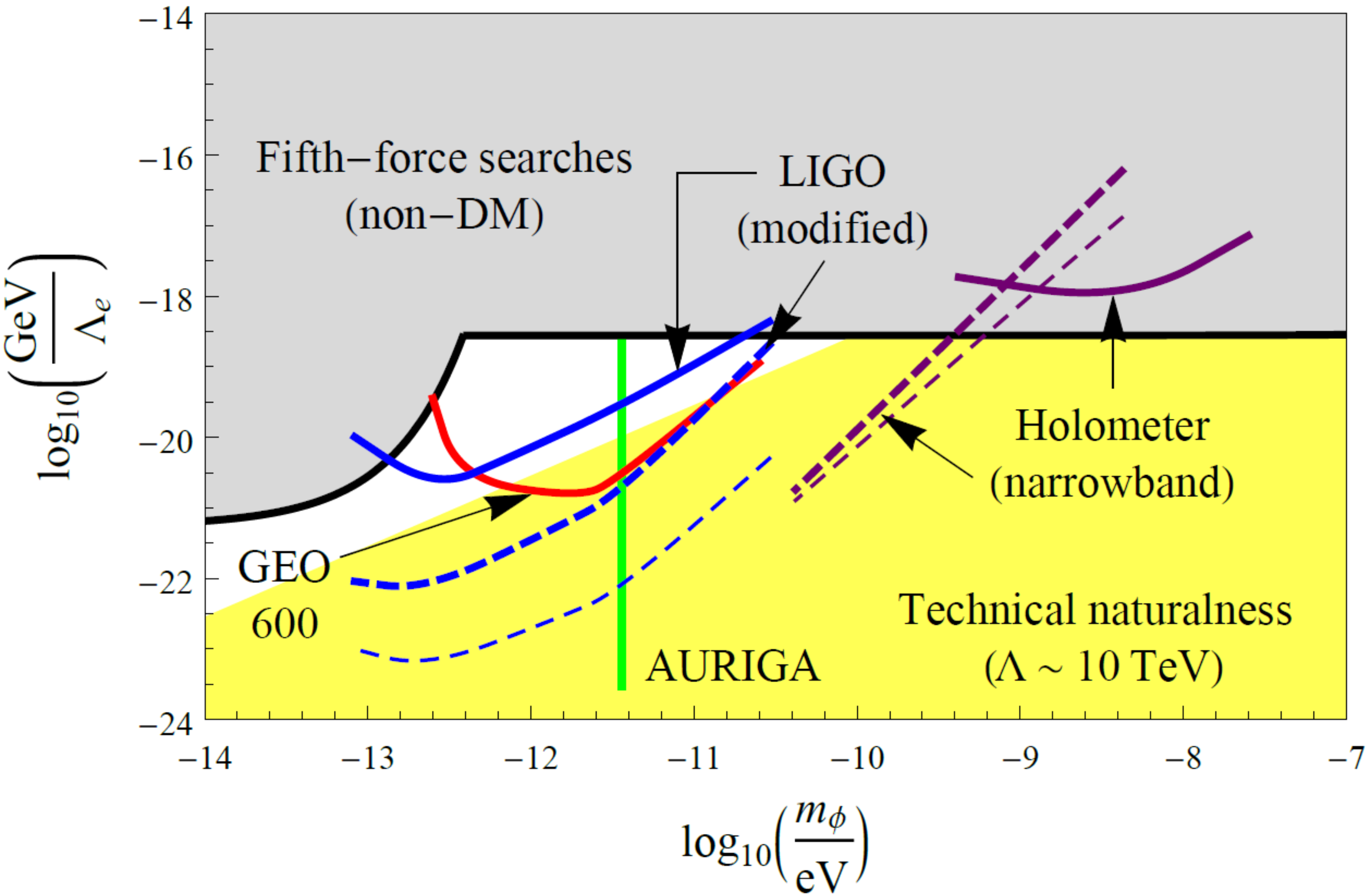
Change thickness of arm mirrors by amount Δw

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

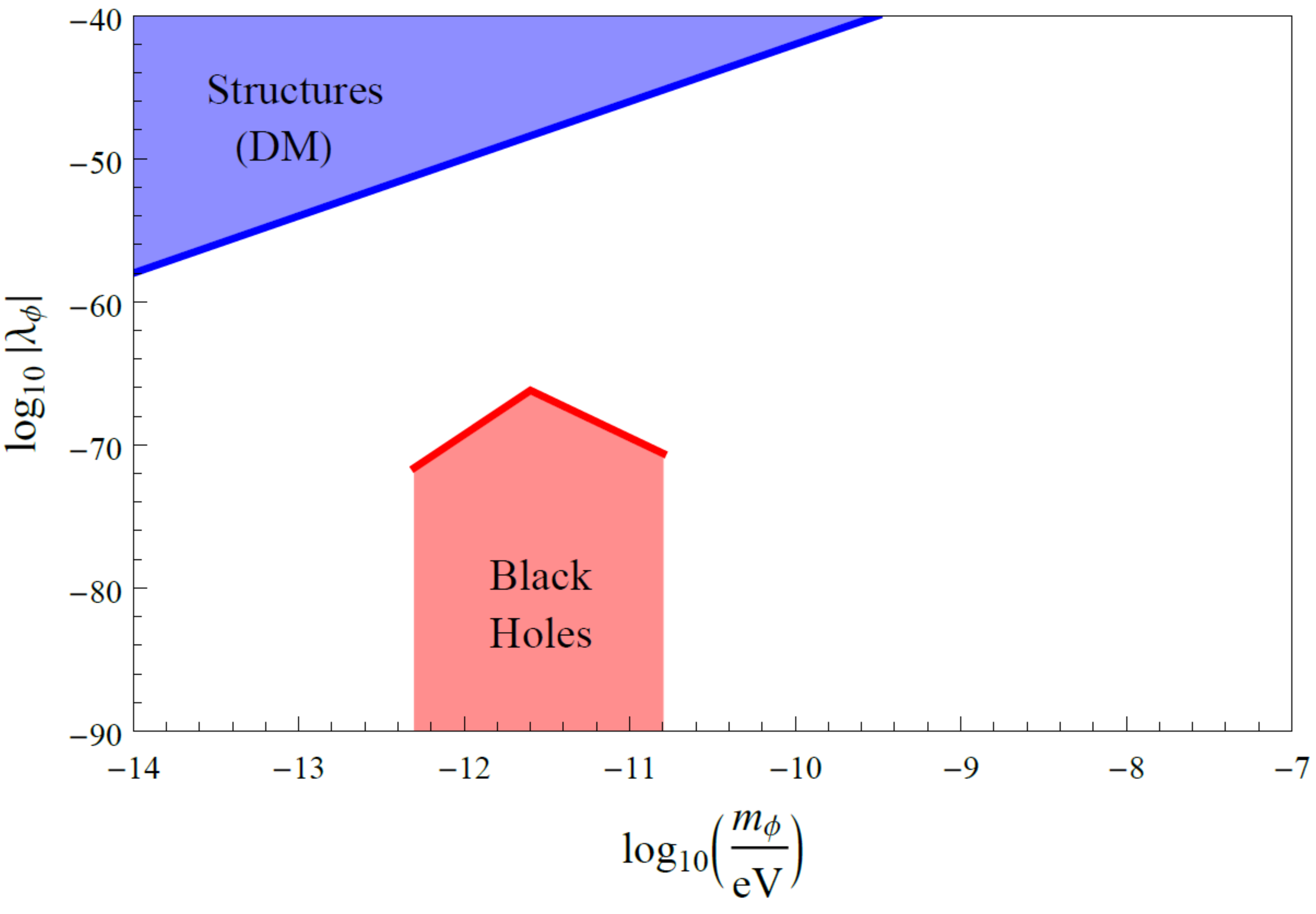
Linear Interaction of Scalar Dark Matter with the Electron



Constraints on Linear Interaction of Scalar Dark Matter with the Electron



Quartic Self-Interaction of Scalar

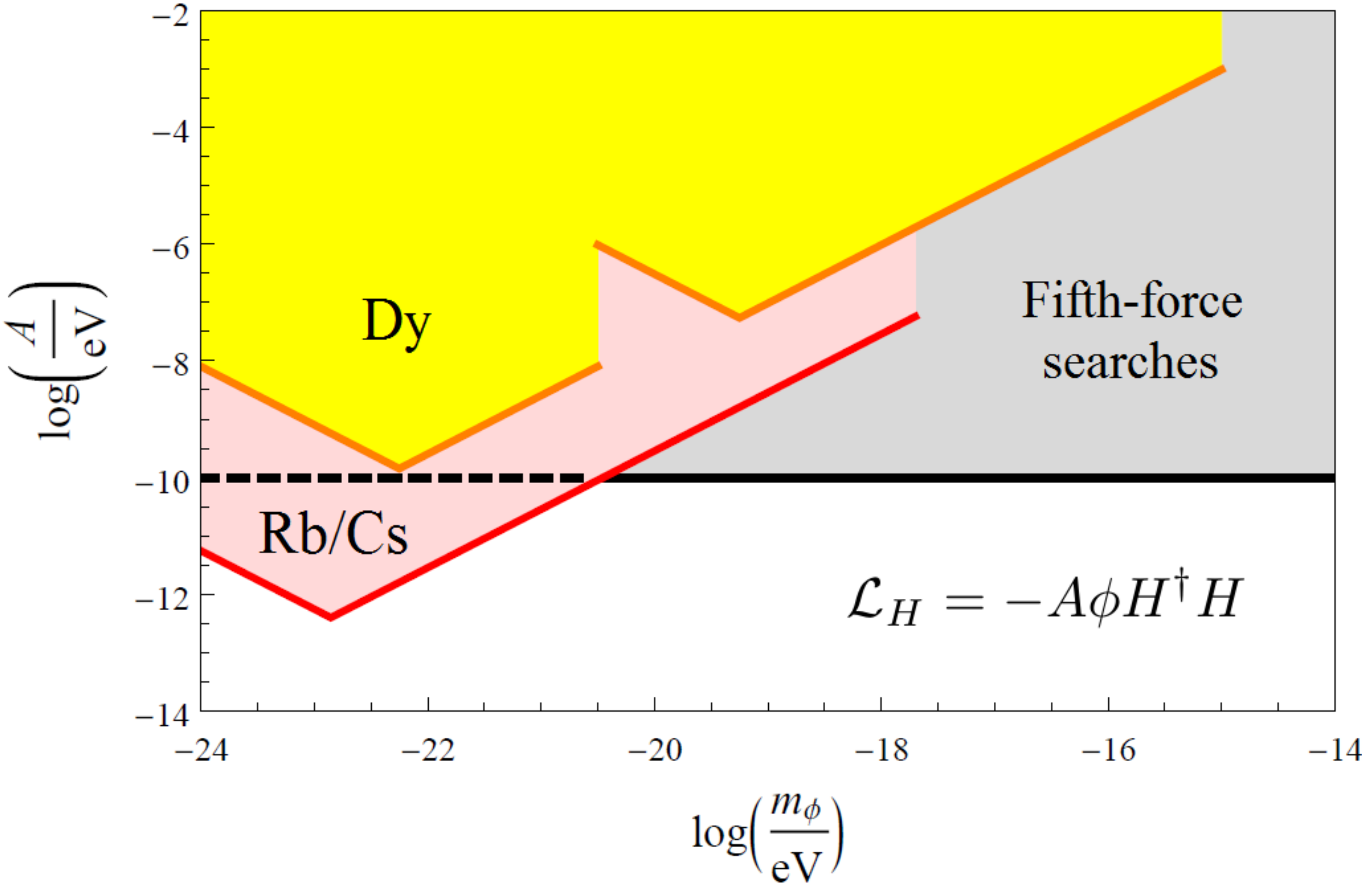


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

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 ($t_{weak} \approx$ 1s – $t_{BBN} \approx$ 3 min)
- Primordial ^{4}He abundance sensitive to n/p ratio

  (almost all neutrons bound in ^{4}He after BBN)

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

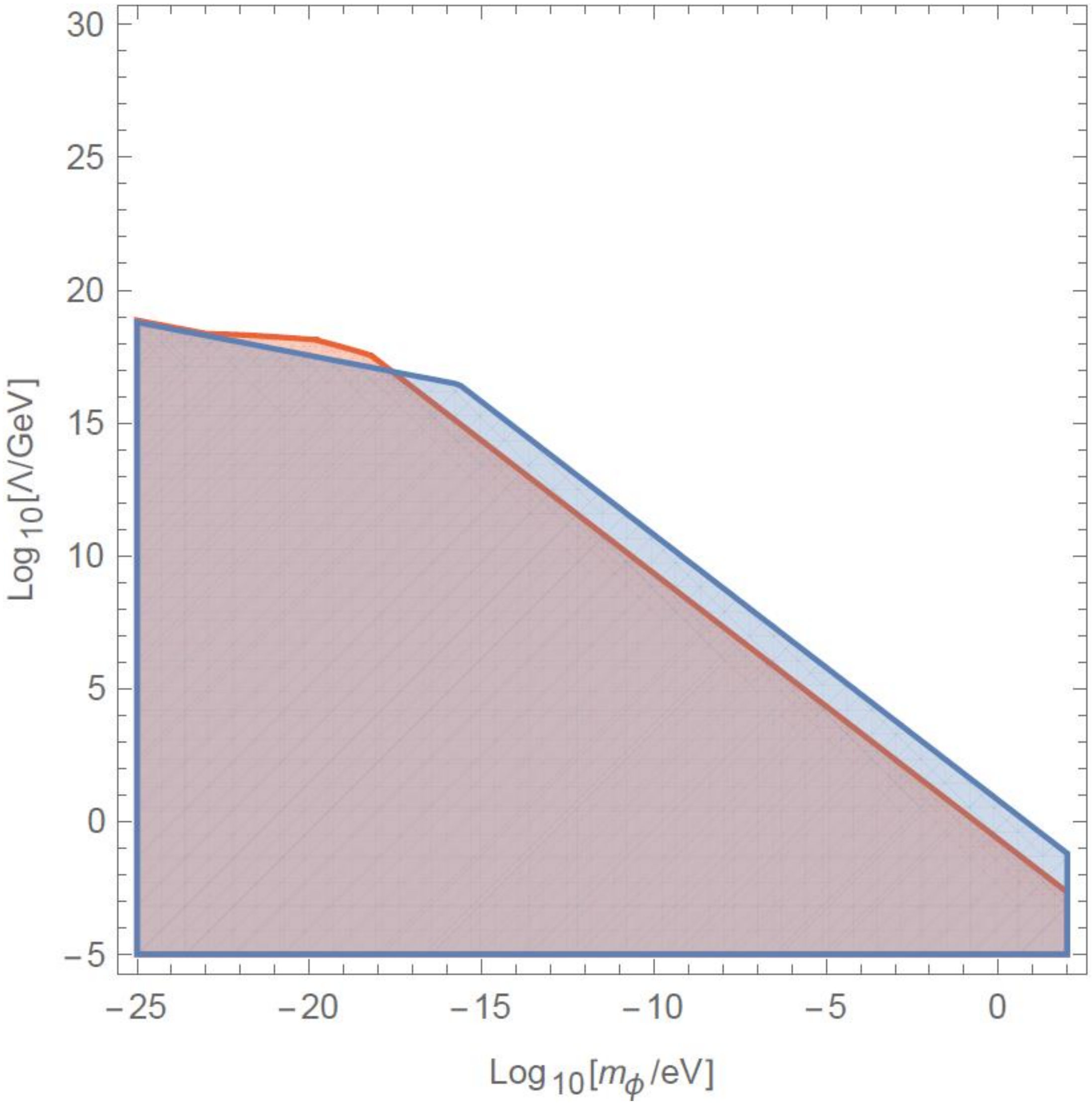
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN

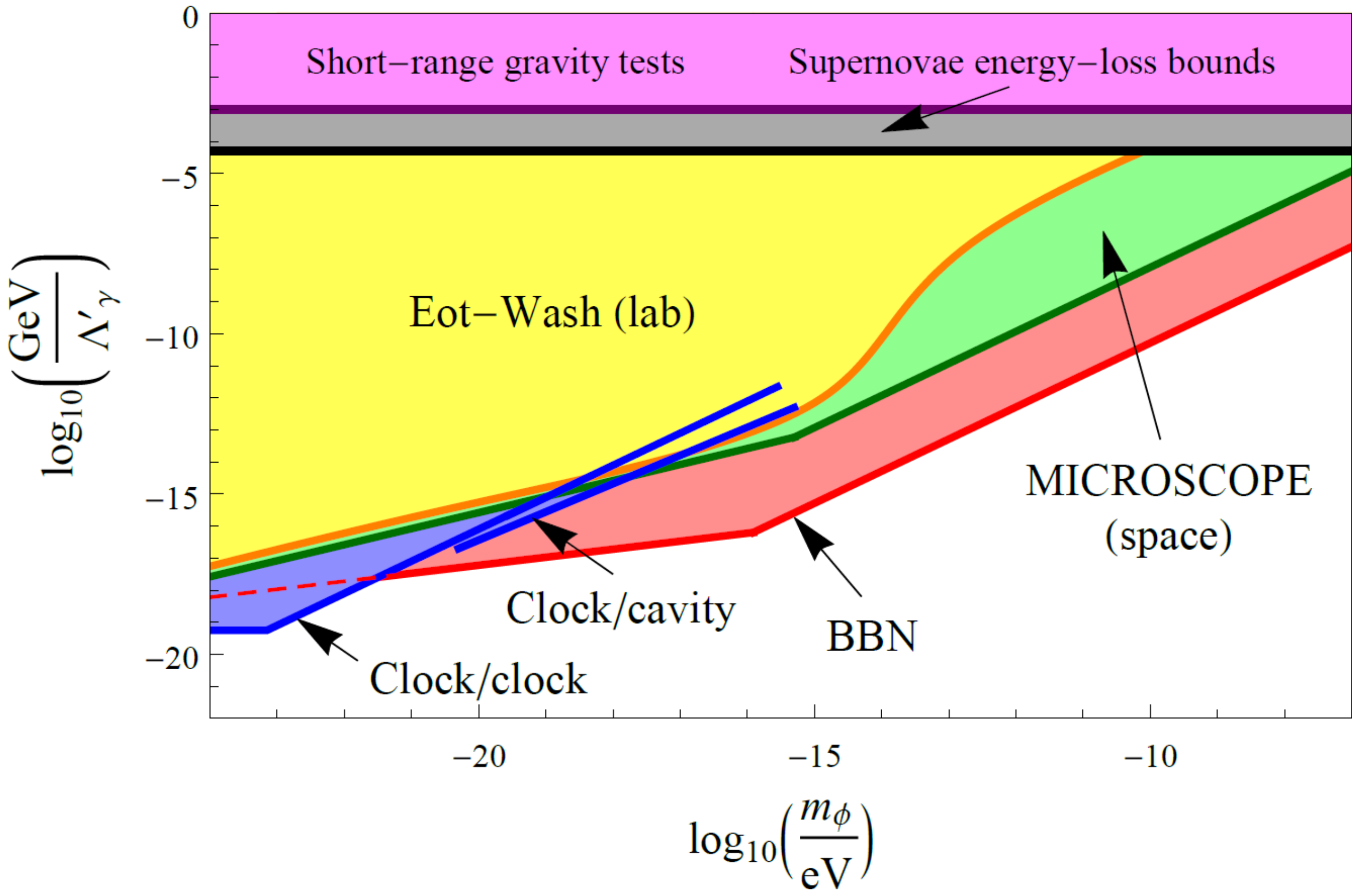
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



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!



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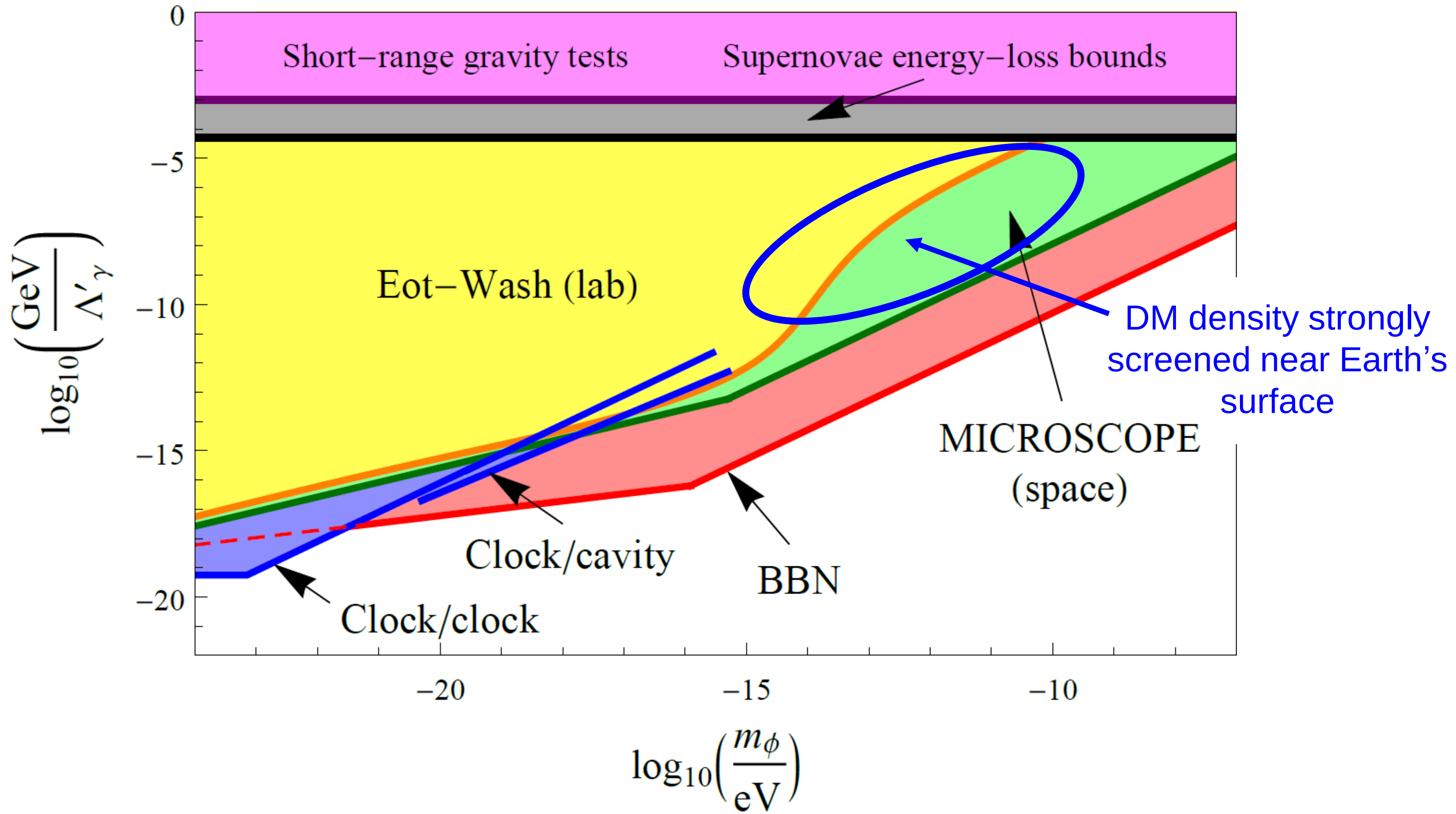
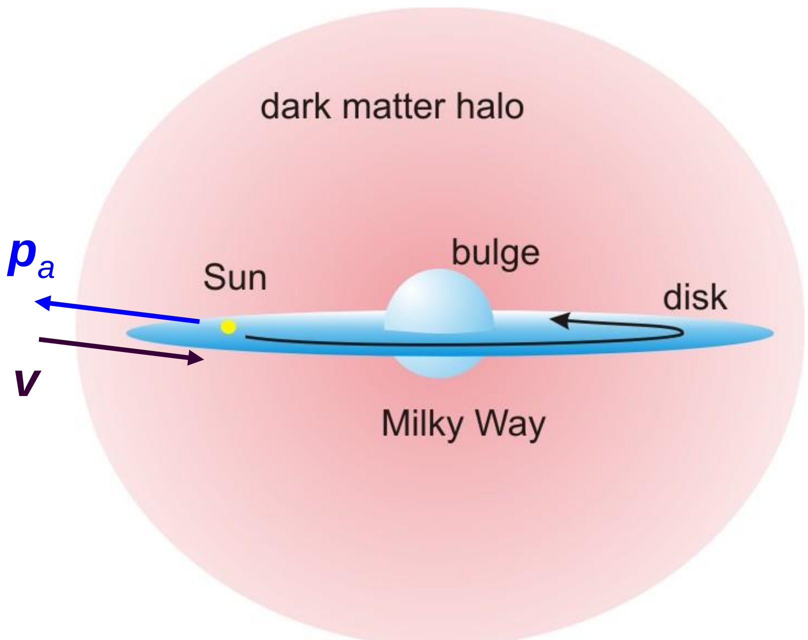


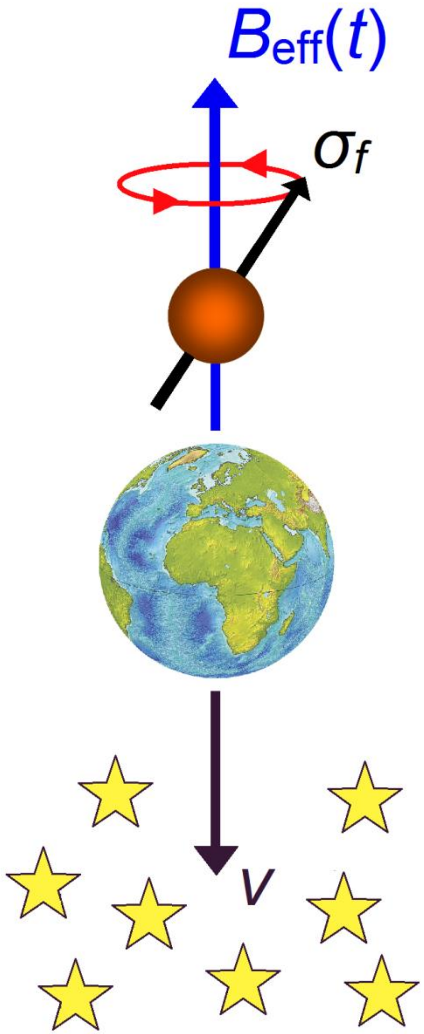
"Axion Wind" Spin-Precession Effect

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

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

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



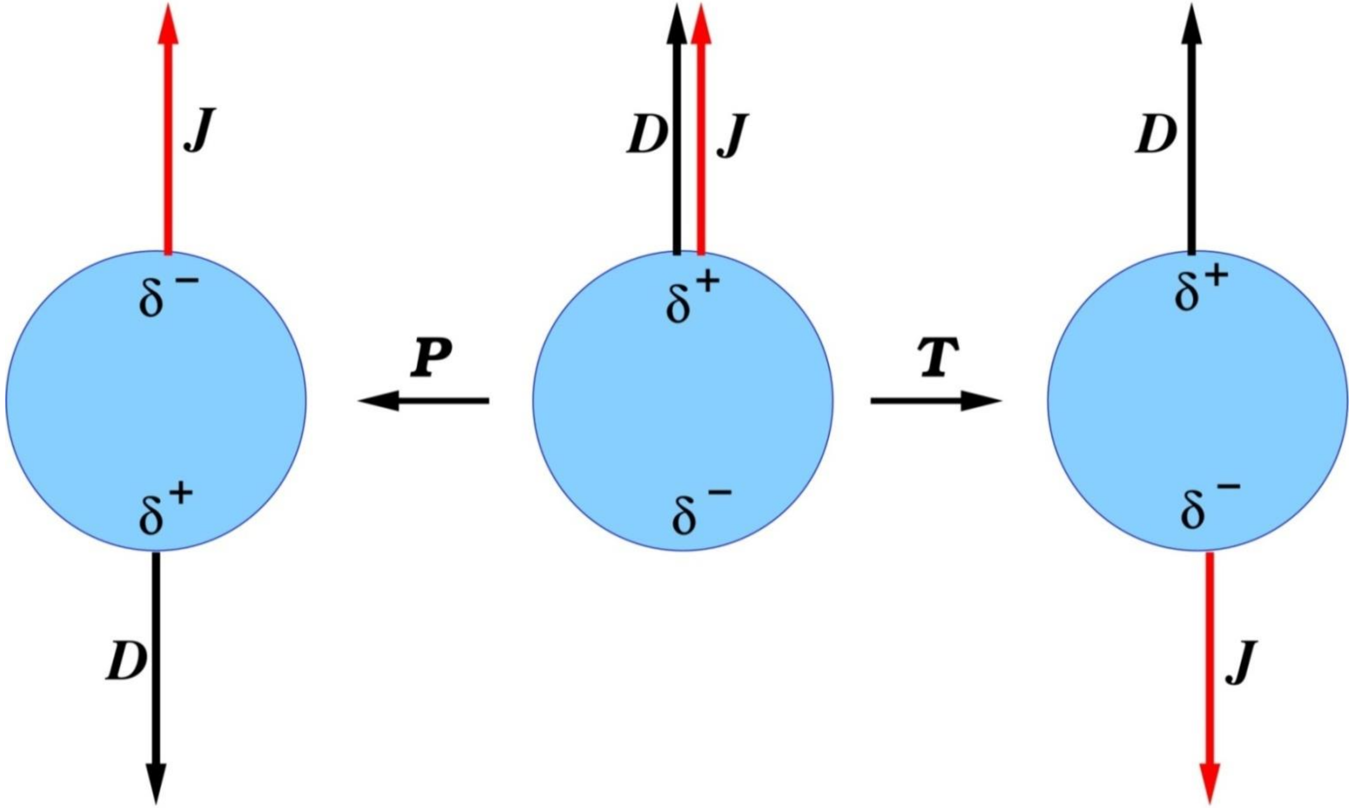


Oscillating Electric Dipole Moments

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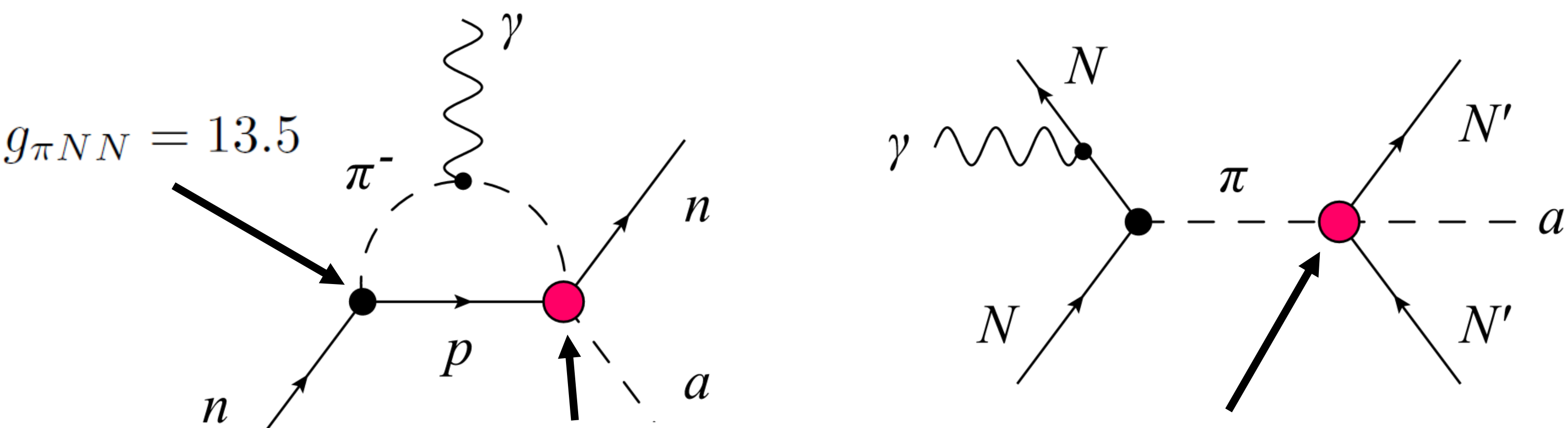
$$\mathcal{L}_g = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G\tilde{G}$$

Nucleon EDMs | ***CP*-violating intranuclear forces**



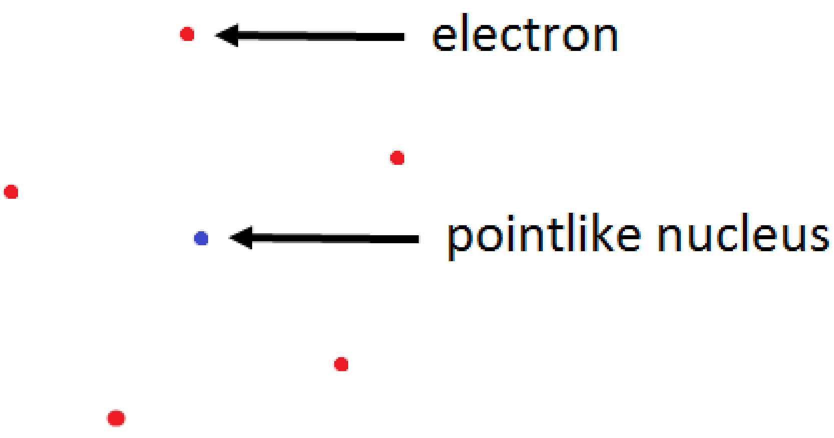
$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\, C_G a_0 \cos(m_a t)/f_a$$

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

Schiff's Theorem

[Schiff, *Phys. Rev.* **132**, 2194 (1963)]

Schiff's Theorem: "In a neutral atom made up of point-like non-relativistic charged particles (interacting only electrostatically), the constituent EDMs are screened from an external electric field."



Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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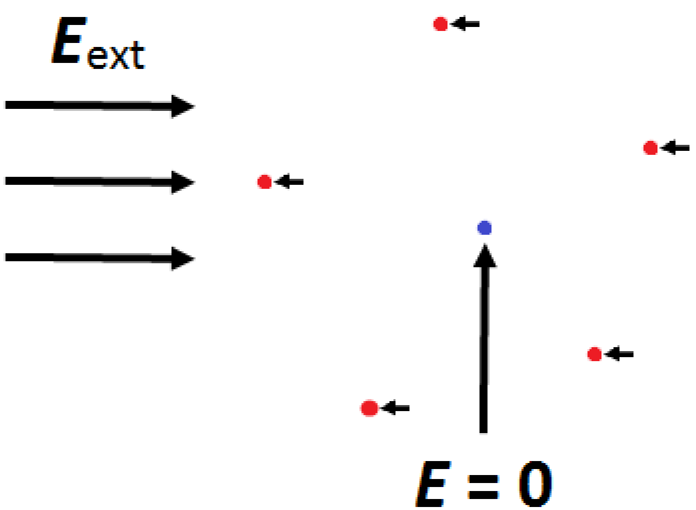
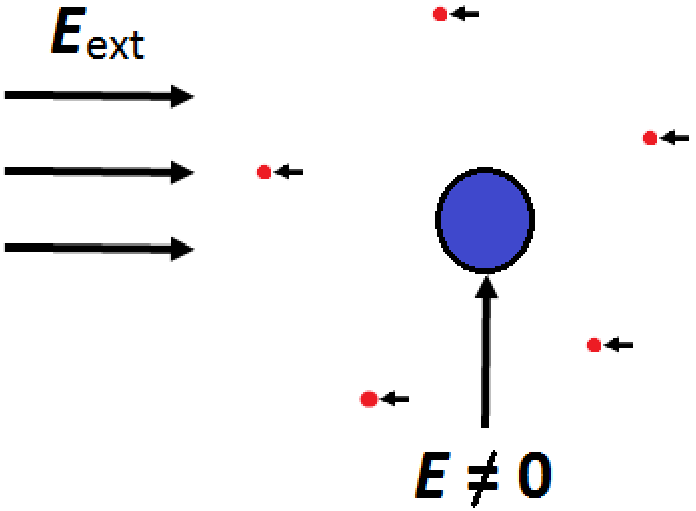


Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

Lifting of Schiff's Theorem

[Sandars, *PRL* **19**, 1396 (1967)],
[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

In real (heavy) atoms: Incomplete screening of external electric field due to finite nuclear size, parametrised by *nuclear Schiff moment*.



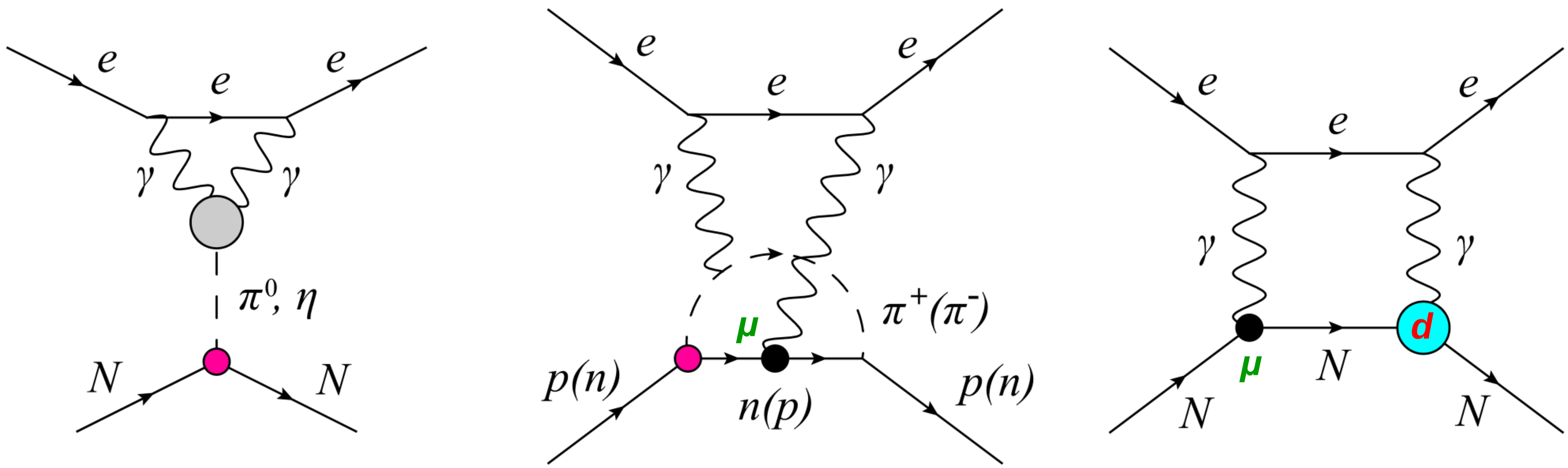
Hadronic CP Violation in Paramagnetic Molecules

[Flambaum, Pospelov, Ritz, Stadnik, *PRD* **102**, 035001 (2020)]

Hadronic CP-violating effects arise at 2-loop level, $\mathcal{O}$(A) enhanced

Interaction of one of photons with nucleus is *magnetic* => no Schiff screening

LO: $\mathcal{O}(m_\pi^{-2})$ **NLO:** $\mathcal{O}(m_\pi^{-1})$ ***μ* – *d*:** $\mathcal{O}[\ln(A)/p_F]$



π^0,η contributions: *opposite sign*

p,n contributions: *same sign*

Example – θ_{QCD} term [$\theta \leftrightarrow C_G a_0 \cos(m_a t)/f_a$]:

For Z ~ 80, A ~ 200: $C_{SP}(\theta) \approx [0.1_{LO} + 1.0_{NLO} + 1.7_{(\mu d)}] \times 10^{-2}\,\theta \approx 0.03\,\theta$