Searches for Ultra-Low-Mass Dark Matter

Yevgeny Stadnik

Kavli IPMU, University of Tokyo, Japan

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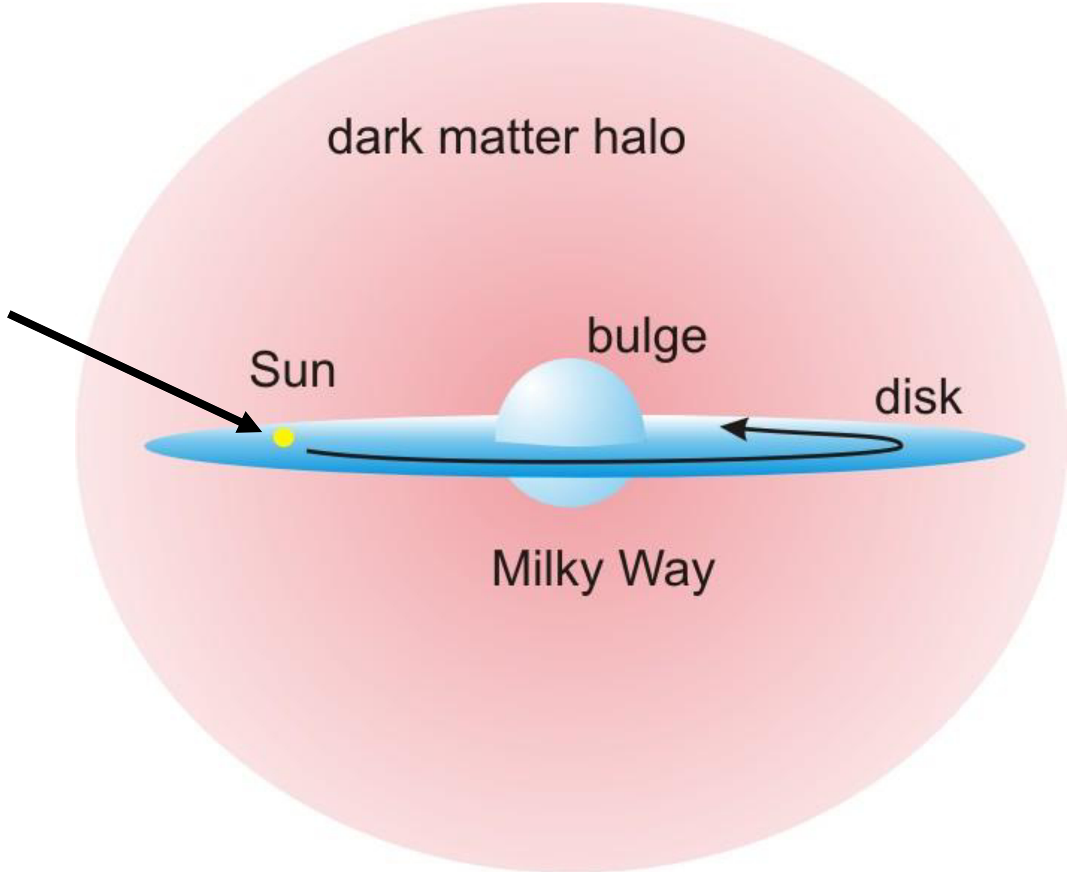
Dark Matter

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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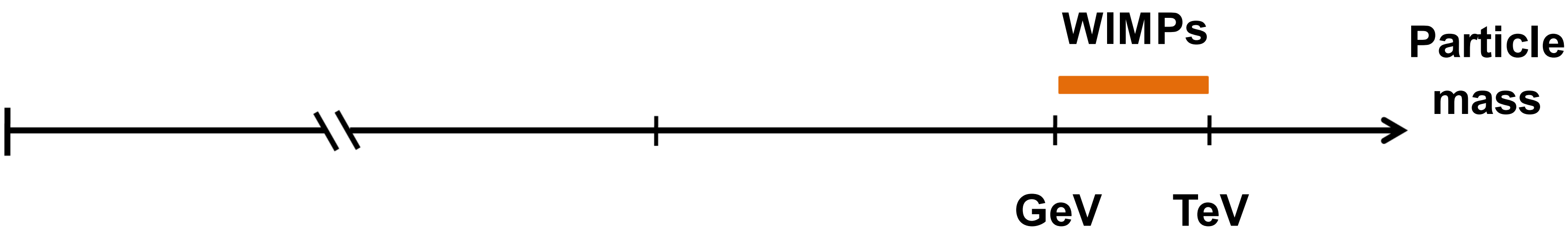

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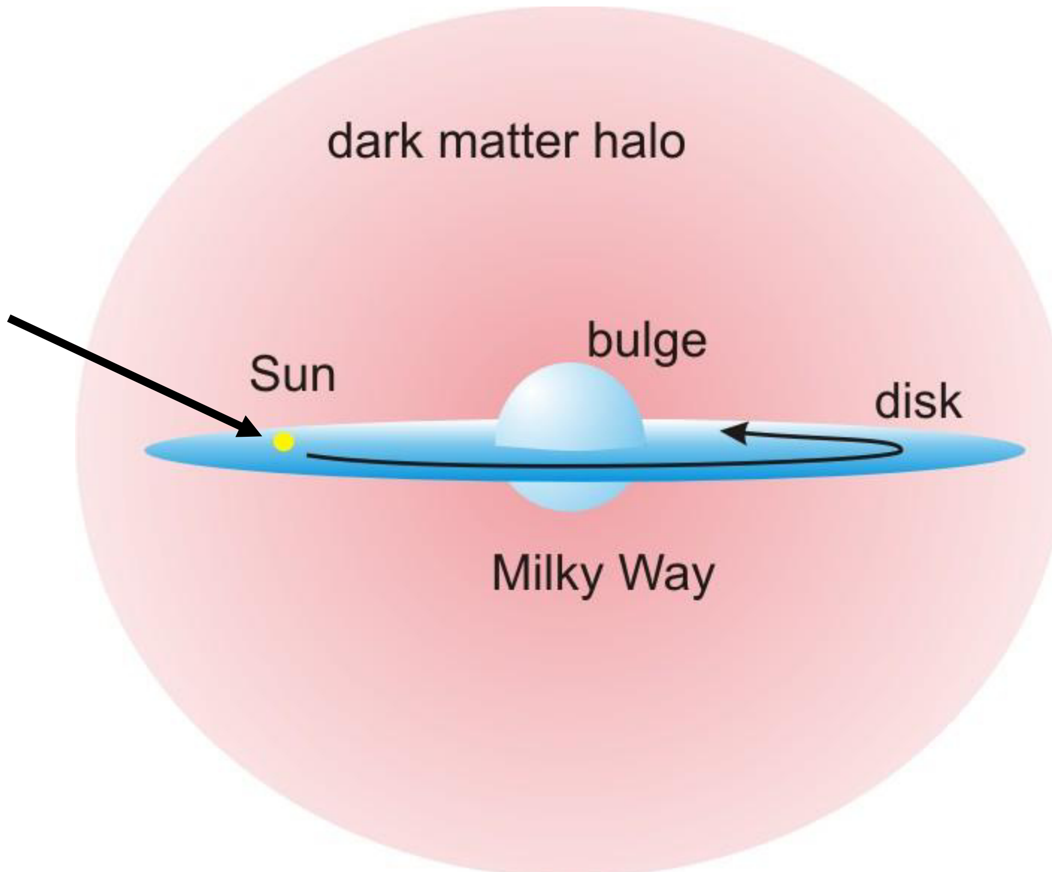

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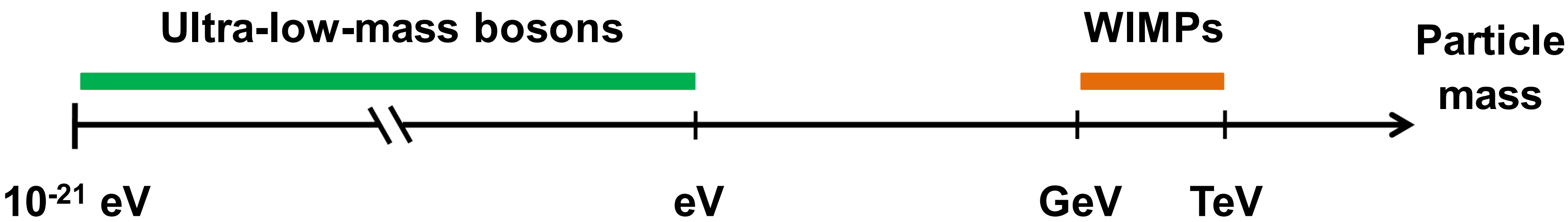

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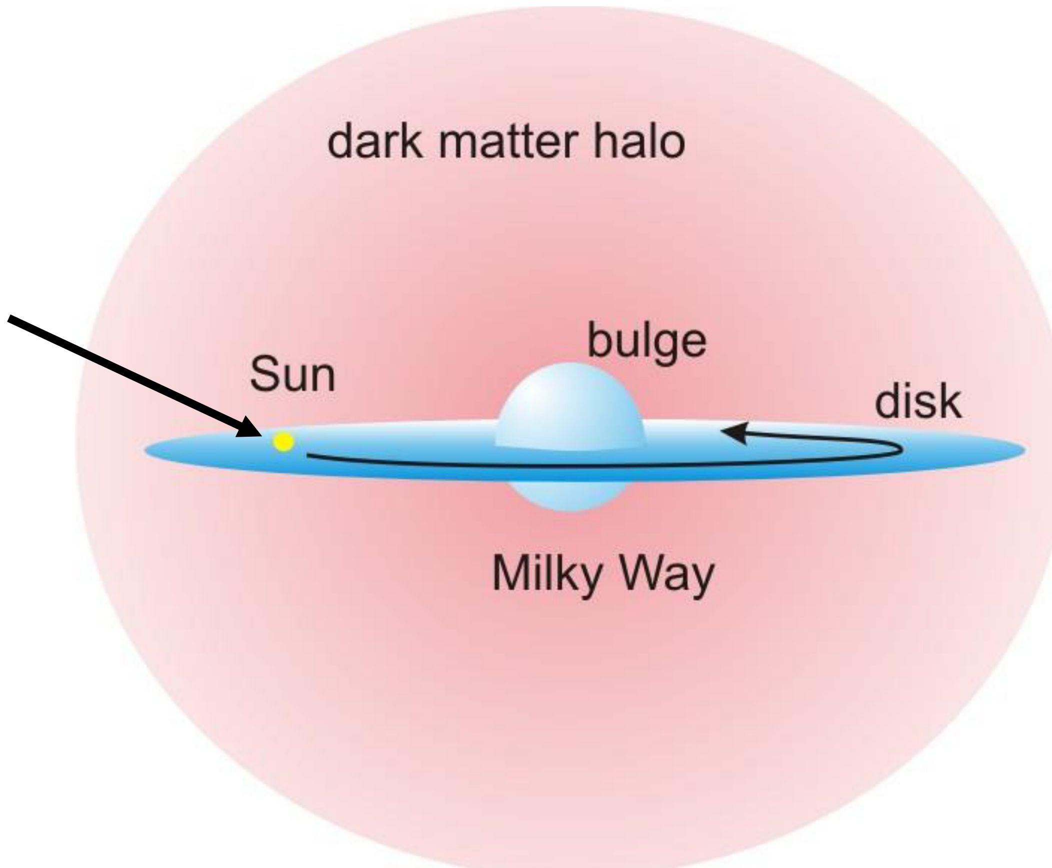
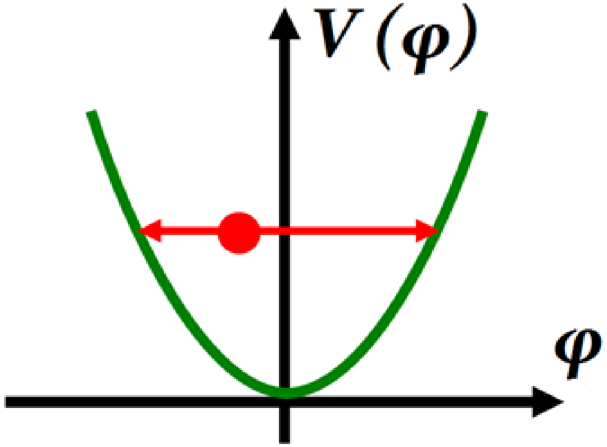


Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos\left(m_\varphi c^2 t/\hbar\right)$, with energy density $\langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2/2$ $\left(\rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3\right)$



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

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

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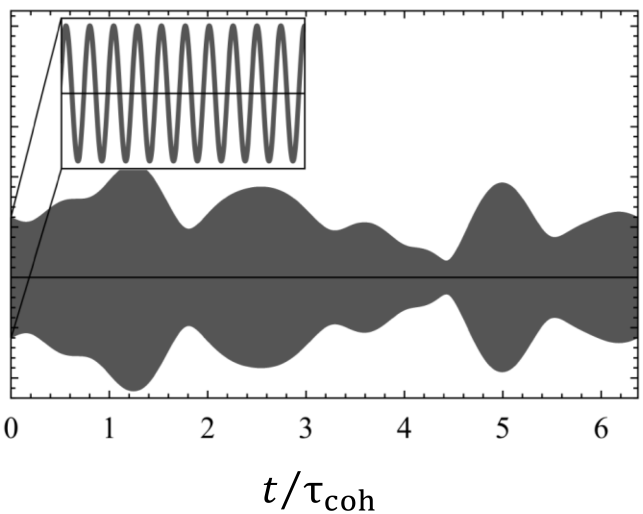
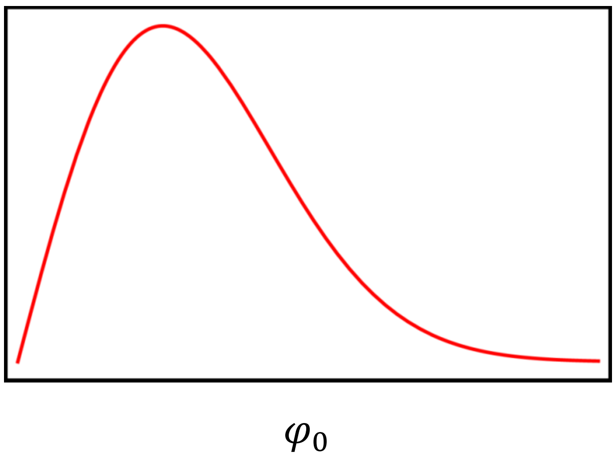
Evolution of φ_0 with time



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



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- $10^{-21}\ \mathrm{eV} \lesssim m_\varphi \lesssim 1\ \mathrm{eV} \;\; \Leftrightarrow \;\; 10^{-7}\ \mathrm{Hz} \lesssim f_{\mathrm{DM}} \lesssim 10^{14}\ \mathrm{eV}$

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

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

[Related figure-of-merit: $\lambda_{\mathrm{dB},\varphi}/2\pi \leq L_{\mathrm{dwarf\,galaxy}} \sim 100\ \mathrm{pc} \;\; \Rightarrow \;\; m_\varphi \gtrsim 10^{-21}\ \mathrm{eV}$]

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):	**Pseudoscalars (Axions):**
$\varphi \xrightarrow{P} +\varphi$	$\varphi \xrightarrow{P} -\varphi$
→ Time-varying fundamental constants	**→ Time-varying spin-dependent effects**
• Atomic clocks	• Co-magnetometers
• Cavities and interferometers	• Particle *g*-factors
• Torsion pendula	• Spin-polarised torsion pendula
• Astrophysics (e.g., BBN)	• Spin resonance (NMR, ESR)

Low-mass Spin-0 Dark Matter

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Dark-Matter-Induced Variations of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* **98**, 064051 (2018)]

$$\mathcal{L}_\gamma = \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \approx \frac{\varphi_0 \cos(m_\varphi t)}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad \Rightarrow \quad \frac{\delta\alpha}{\alpha} \approx \frac{\varphi_0 \cos(m_\varphi t)}{\Lambda_\gamma}$$

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$$\varphi = \varphi_0 \cos(m_\varphi t - \boldsymbol{p}_\varphi \cdot \boldsymbol{x}) \Rightarrow \boldsymbol{F} \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$$

Lab frame

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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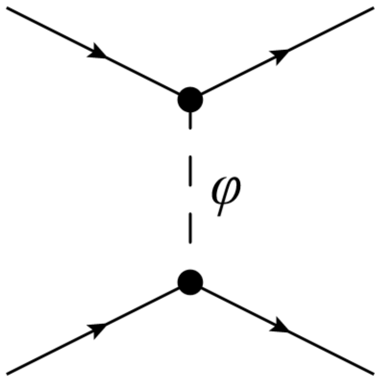
Fifth Forces: Linear vs Quadratic Couplings

[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 ($\varphi \bar{X} X$)

$\Box\varphi + m_\varphi^2 \varphi = \pm\kappa\rho$ **Source term**



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Profile outside of a spherical body

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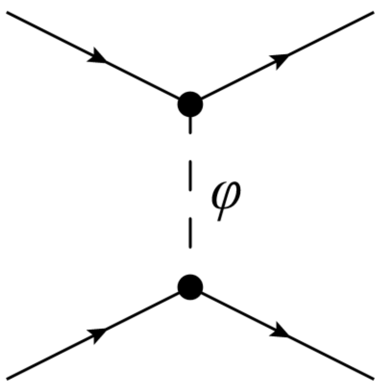

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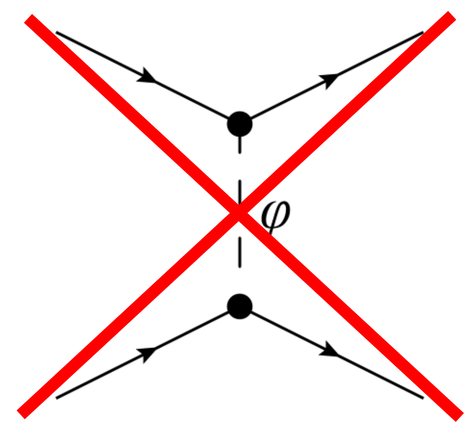

$$m_{\text{eff}}^2(\rho) = m_\varphi^2 \mp \kappa' \rho$$

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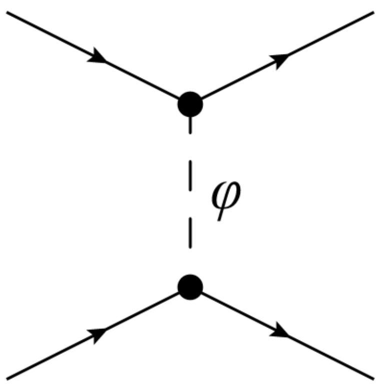

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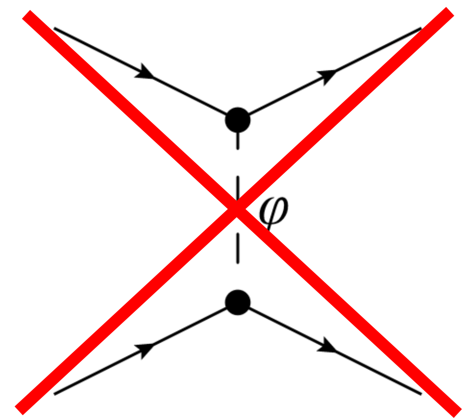

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Gradients + amplification/screening

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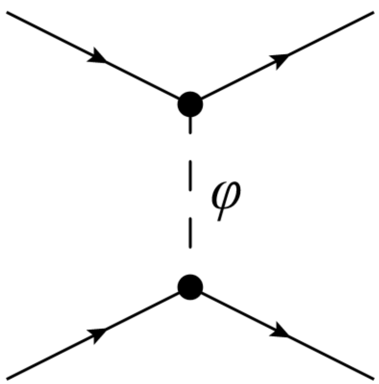

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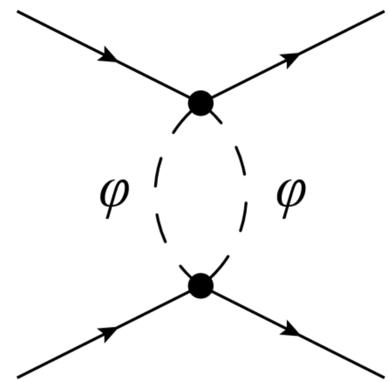

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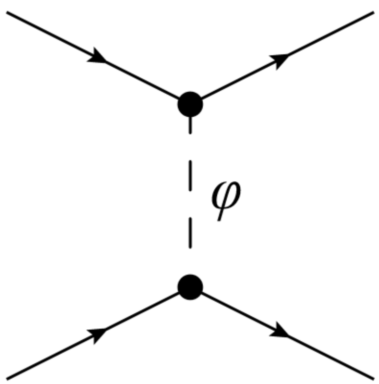

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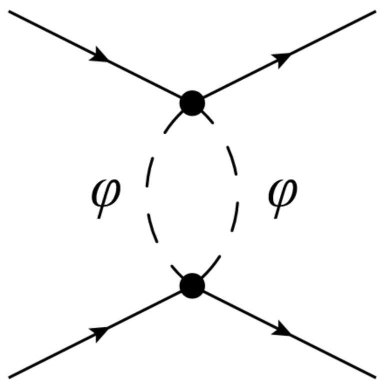

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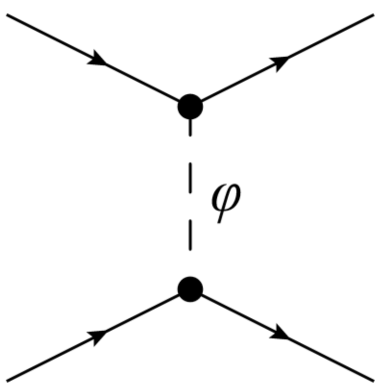

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"Fifth-force" experiments: torsion pendula, atom interferometry

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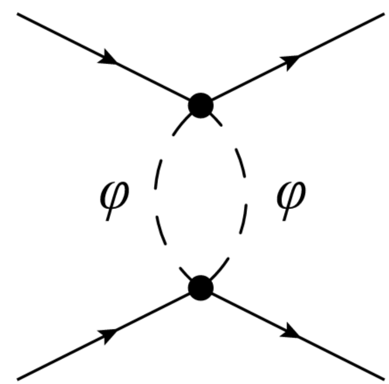

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↓

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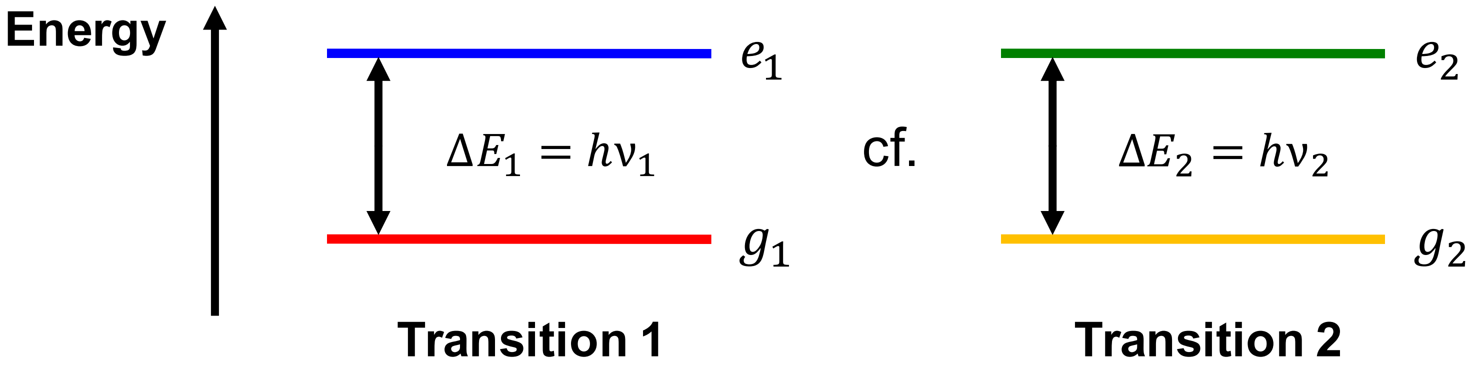
Atomic Spectroscopy Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter



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

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

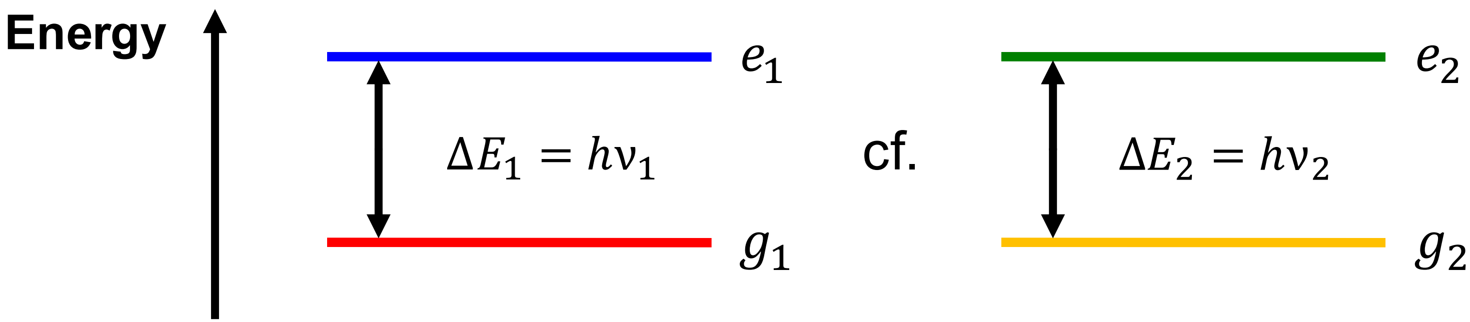
Recent overview: [Ludlow, Boyd, Ye, Peik, Schmidt, *Rev. Mod. Phys.* **87**, 637 (2015)]

"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)]

Atomic Spectroscopy Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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



Transition 1 **Transition 2**

$$\frac{\delta(\nu_1/\nu_2)}{\nu_1/\nu_2} \propto \sum_{X=\alpha, m_e/m_N, \ldots} \left(K_{X,1} - K_{X,2}\right) \cos(2\pi f_{\mathrm{DM}} t) \; ; \; 2\pi f_{\mathrm{DM}} = m_\varphi \text{ or } 2m_\varphi$$

- **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.*, Ongoing]
- **Al^+/Yb, Yb/Sr, Al^+/Hg^+ [NIST + JILA]:** [Hume, Leibrandt *et al.*, Ongoing]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

$L_{\text{solid}} \propto a_{\text{B}} = 1/(m_e \alpha)$

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

(adiabatic regime)

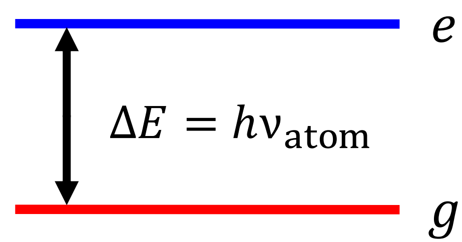
Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

cf.

Electronic transition



$L_{\mathrm{solid}} \propto a_{\mathrm{B}} = 1/(m_e \alpha)$

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

$\nu_{\mathrm{atom}} \propto \mathrm{Ry} \propto m_e \alpha^2$

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

- **Sr vs Glass cavity [Torun]:** [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]
- **Various combinations [Worldwide]:** [Wcislo *et al.*, *Science Advances* **4**, eaau4869 (2018)]
- **Cs vs Steel cavity [Mainz]:** [Antypas *et al.*, *PRL* **123**, 141102 (2019)]
- **Sr^+ vs Glass cavity [Weizmann]:** [Aharony *et al.*, arXiv:1902.02788]
- **Sr/H vs Silicon cavity [JILA + PTB]:** [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]
- **H vs Sapphire/Quartz cavities [UWA]:** [Campbell *et al.*, arXiv:2010.08107]

Cavity-Based Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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

Solid material

$L_{\text{solid}} \propto a_{\text{B}} = 1/(m_e \alpha)$

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

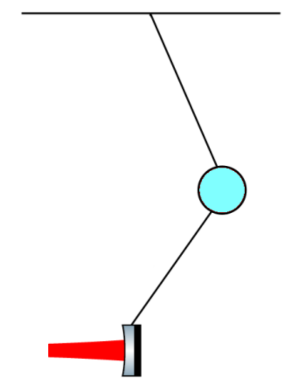
cf.

Freely-suspended mirrors

$L_{\text{free}} \approx \text{const. for } f_{\text{DM}} > f_{\text{natural}}$

$\Rightarrow \ \nu_{\text{free}} \approx \text{constant}$

Double-pendulum suspensions



$$\frac{\nu_{\text{solid}}}{\nu_{\text{free}}} \propto m_e \alpha$$

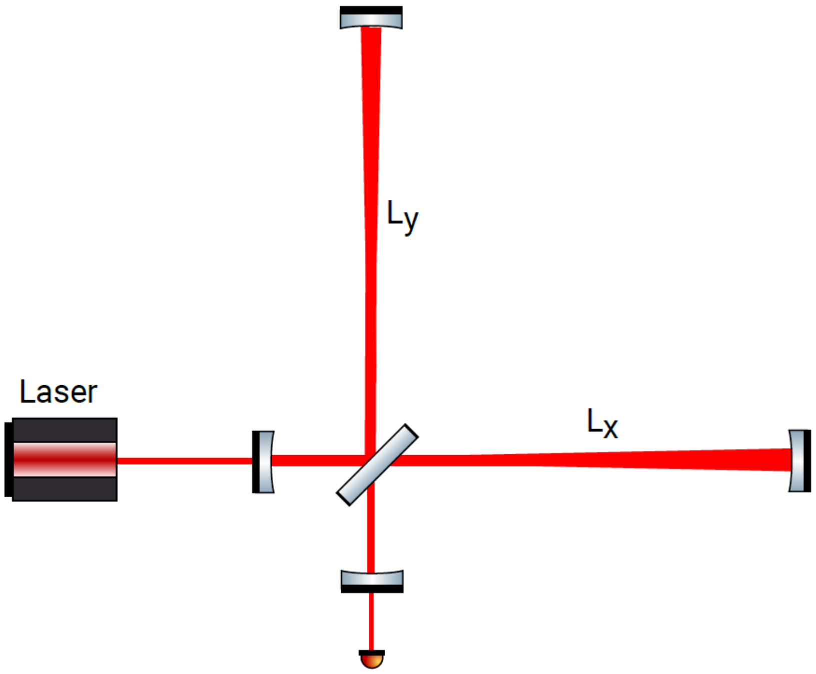
cf.

$$\frac{\nu_{\text{atom}}}{\nu_{\text{solid}}} \propto \alpha$$

Small-scale experiment currently under development at Northwestern University

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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



Michelson interferometer (GEO600)

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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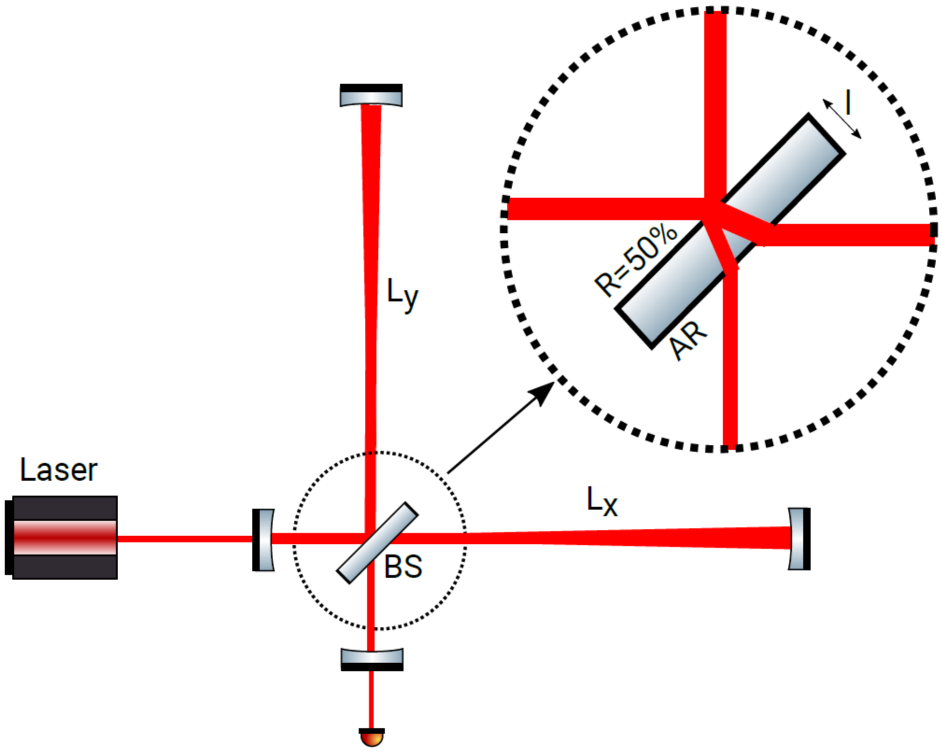

- Geometric asymmetry from beam-splitter

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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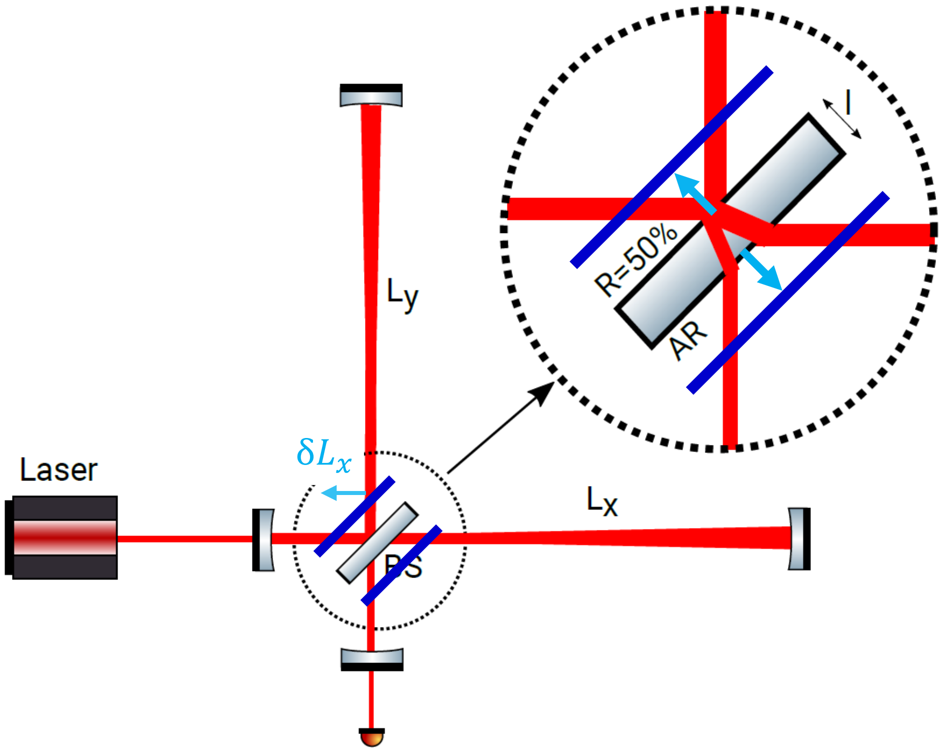

- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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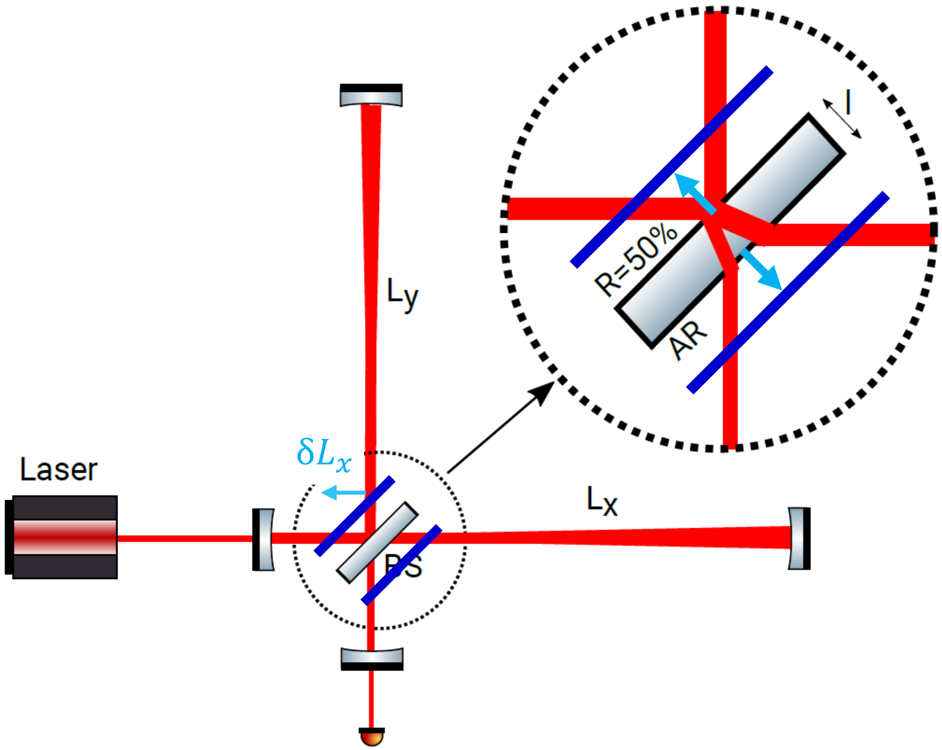
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



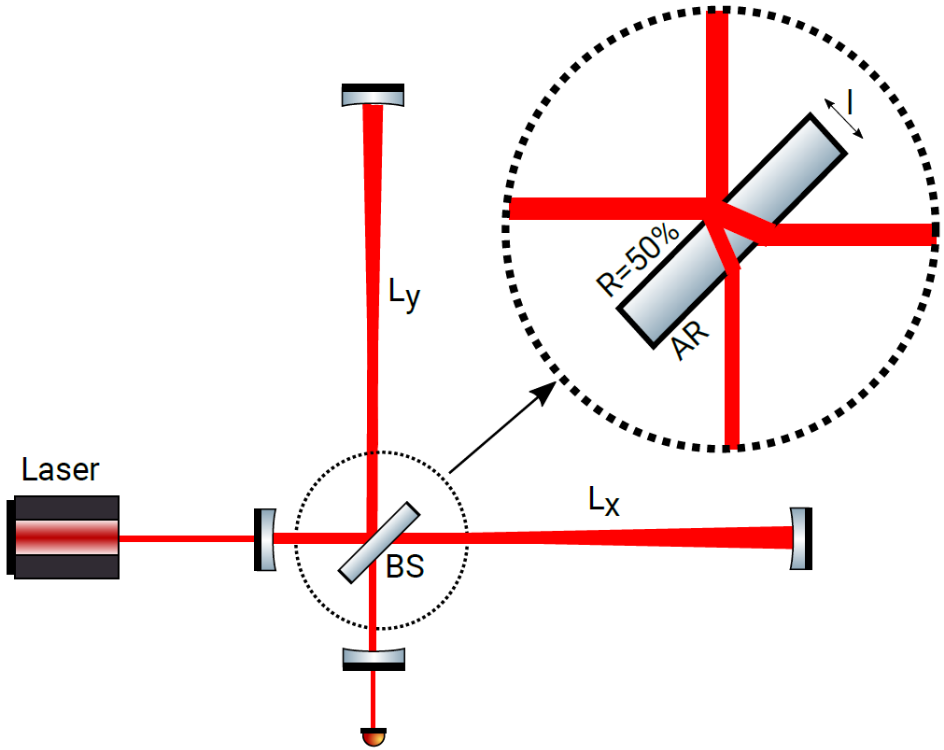
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

First results recently reported using GEO600 data:

[Vermeulen *et al.*, arXiv:2103.03783]

Laser Interferometry Searches for Oscillating Variations of Fundamental Constants induced by Dark Matter

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



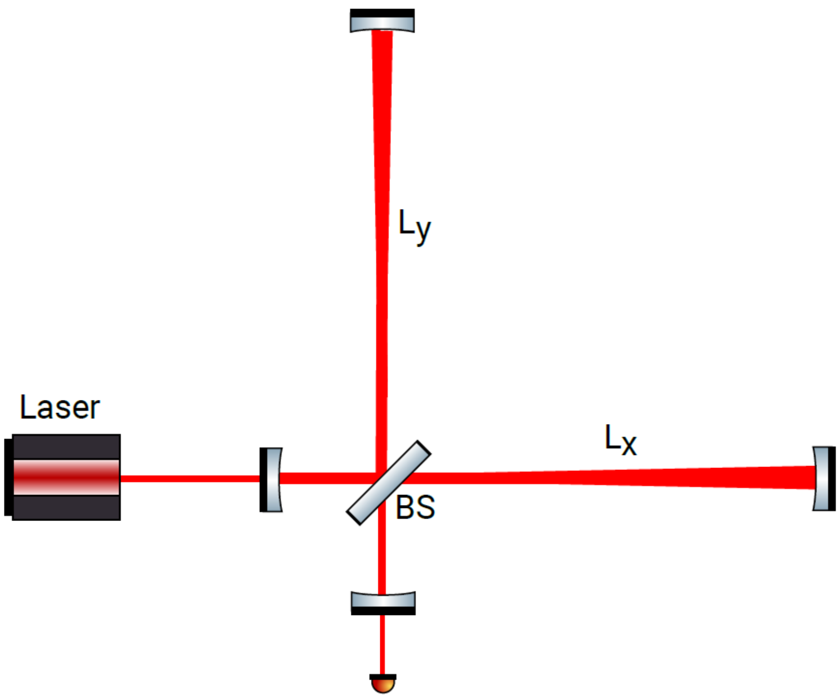
- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible:

$$f_{\mathrm{DM}} \approx f_{\mathrm{vibr,BS}}(T) \sim v_{\mathrm{sound}}/l \;\Rightarrow\; Q \sim 10^6 \text{ enhancement}$$

Michelson vs Fabry-Perot-Michelson Interferometers

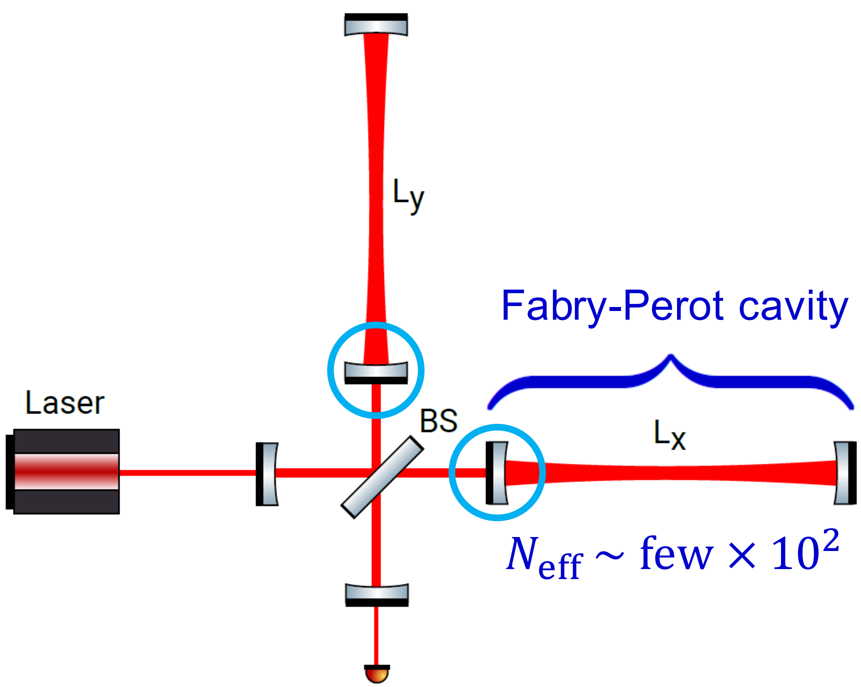
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)

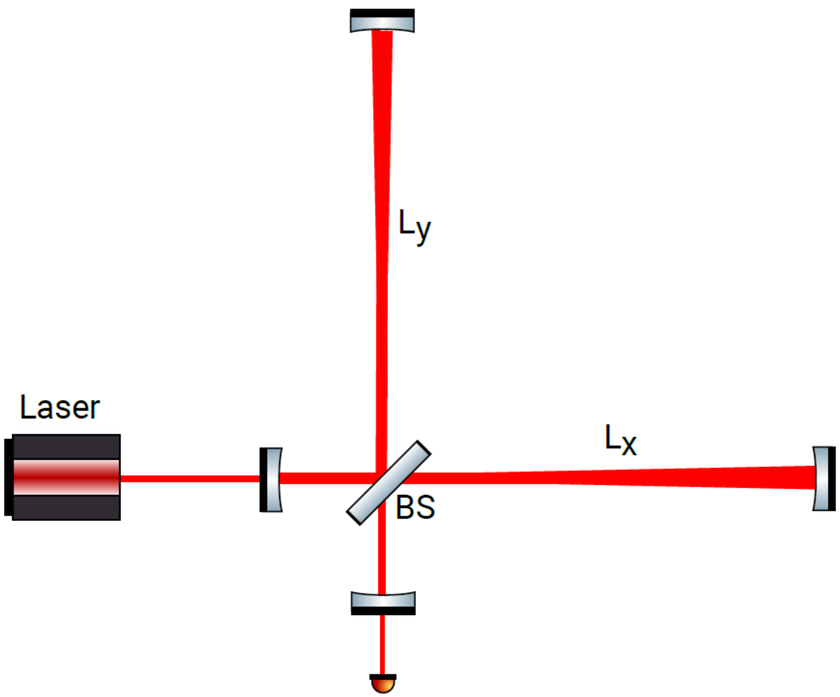


$$\delta\left(L_x - L_y\right)_{\mathrm{BS}} \sim \delta(nl)/N_{\mathrm{eff}}$$

Michelson vs Fabry-Perot-Michelson Interferometers

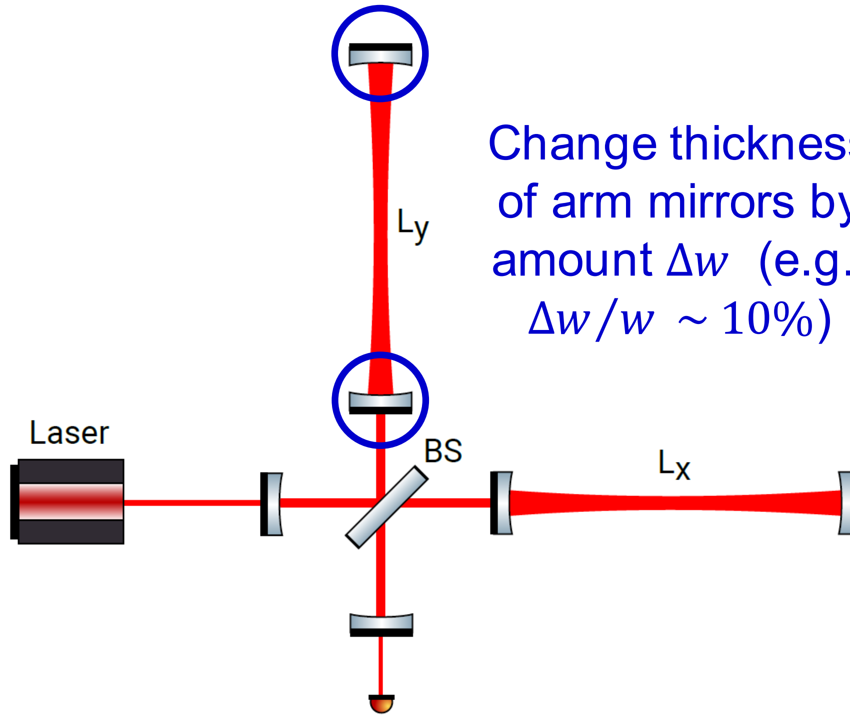
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer (GEO 600)



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

Fabry-Perot-Michelson interferometer (LIGO)



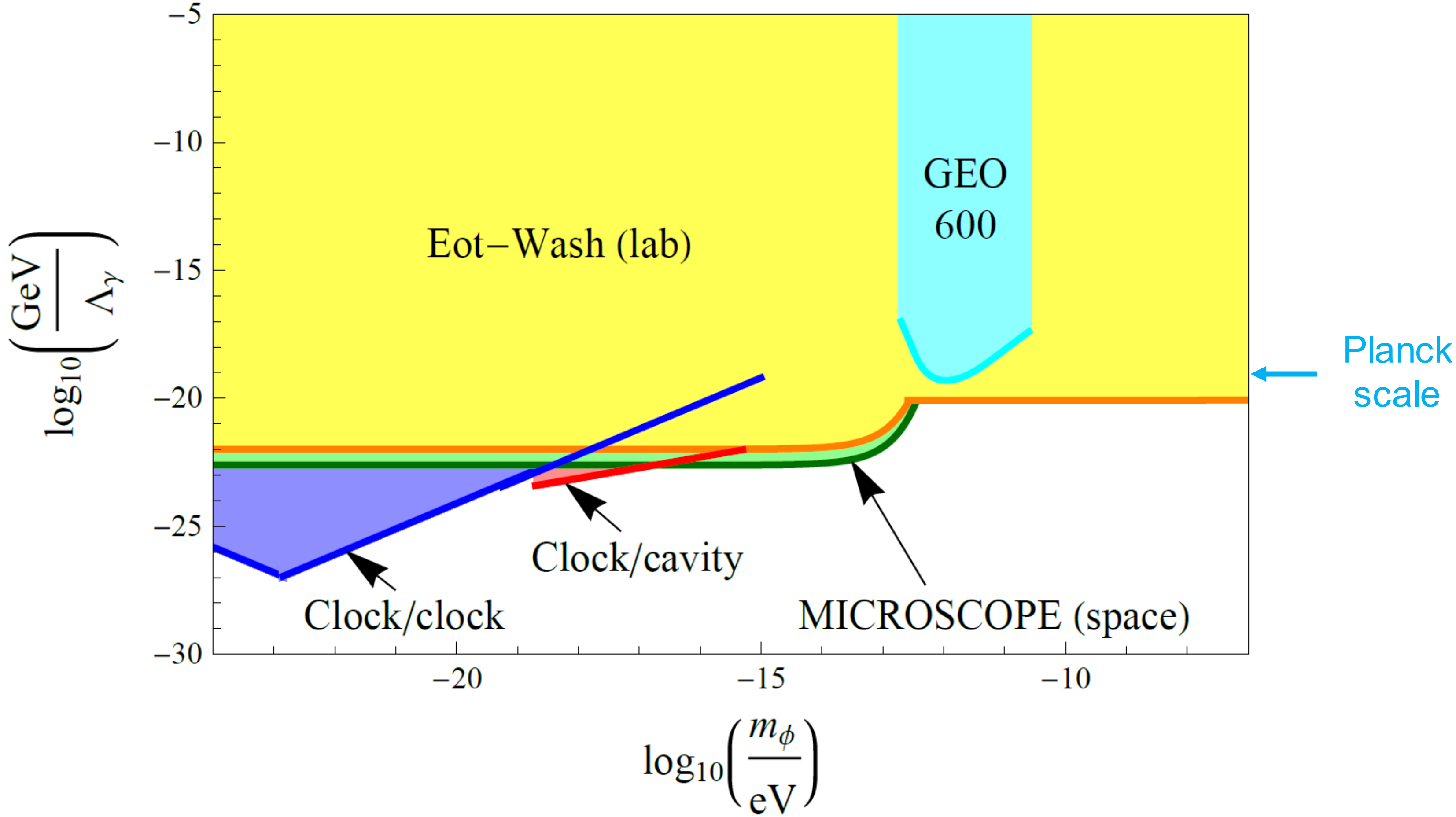
Change thickness of arm mirrors by amount Δw (e.g., $\Delta w / w \sim 10\%$)

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

Constraints on Linear Interaction of Scalar Dark Matter with the Photon

Clock/clock: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Hees *et al.*, *PRL* **117**, 061301 (2016)];
Clock/cavity: [Kennedy *et al.*, *PRL* **125**, 201302 (2020)]; **GEO600:** [Vermeulen *et al.*, arXiv:2103.03783]

4 orders of magnitude improvement!



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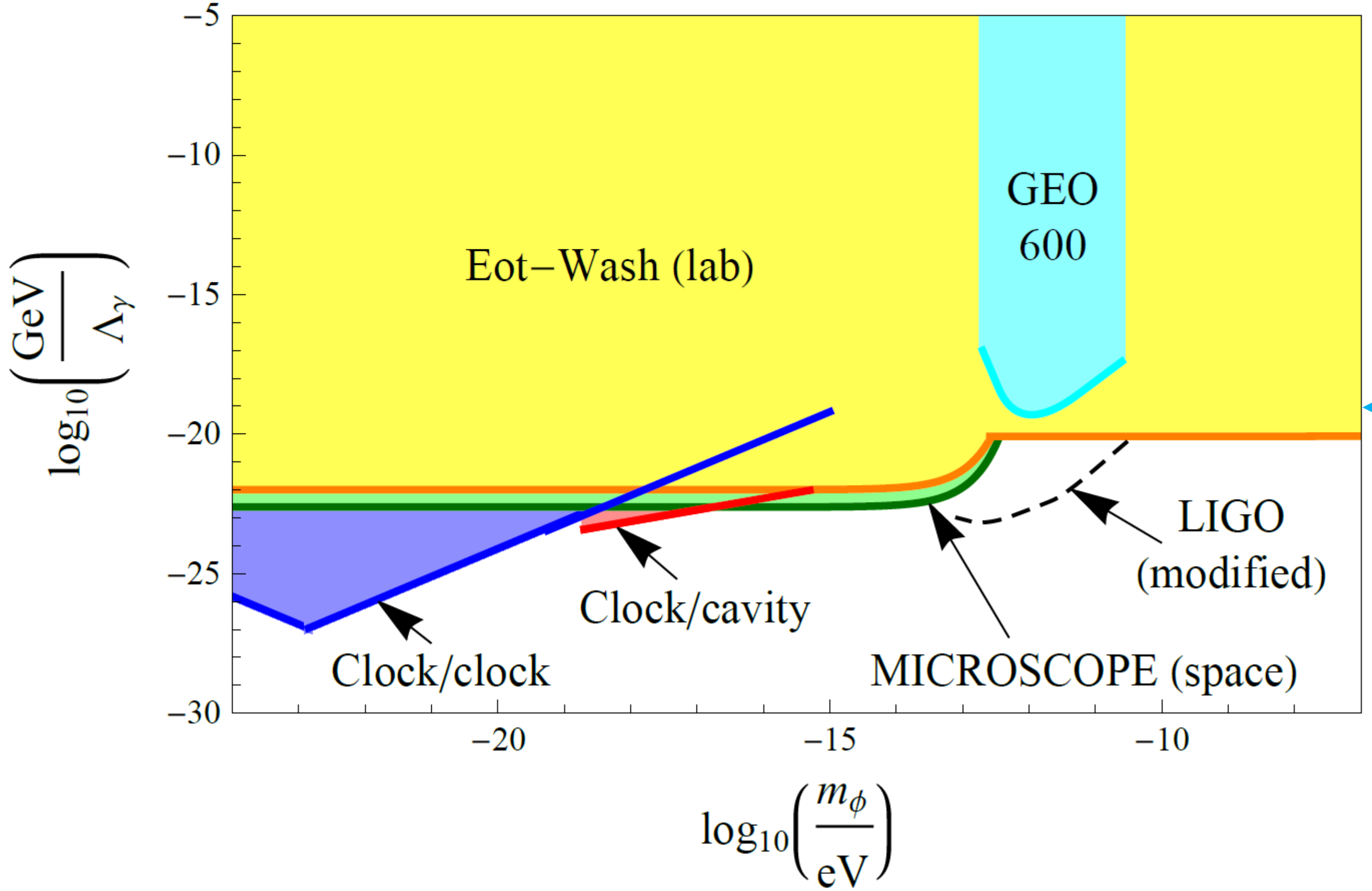

Planck scale

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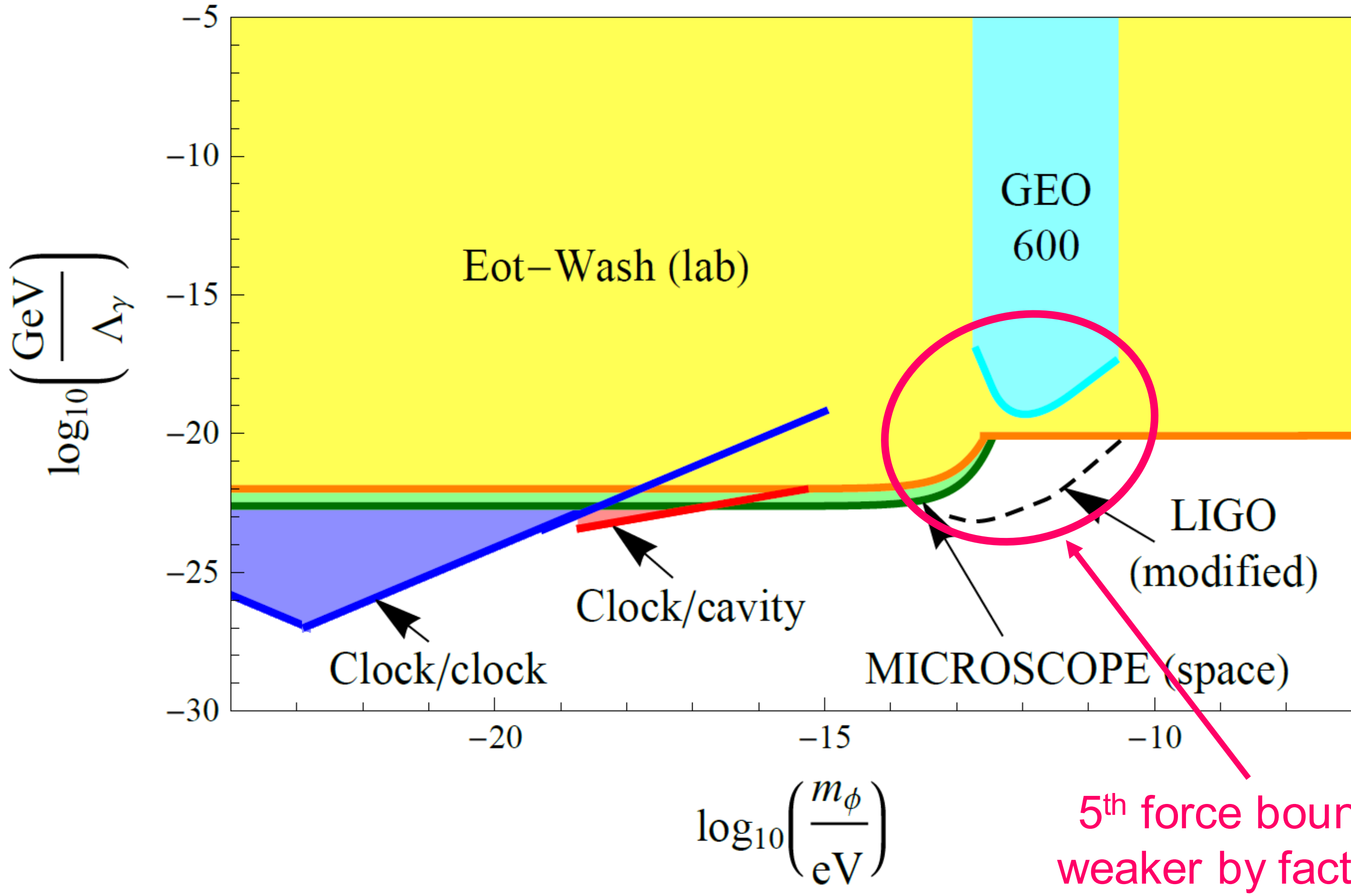


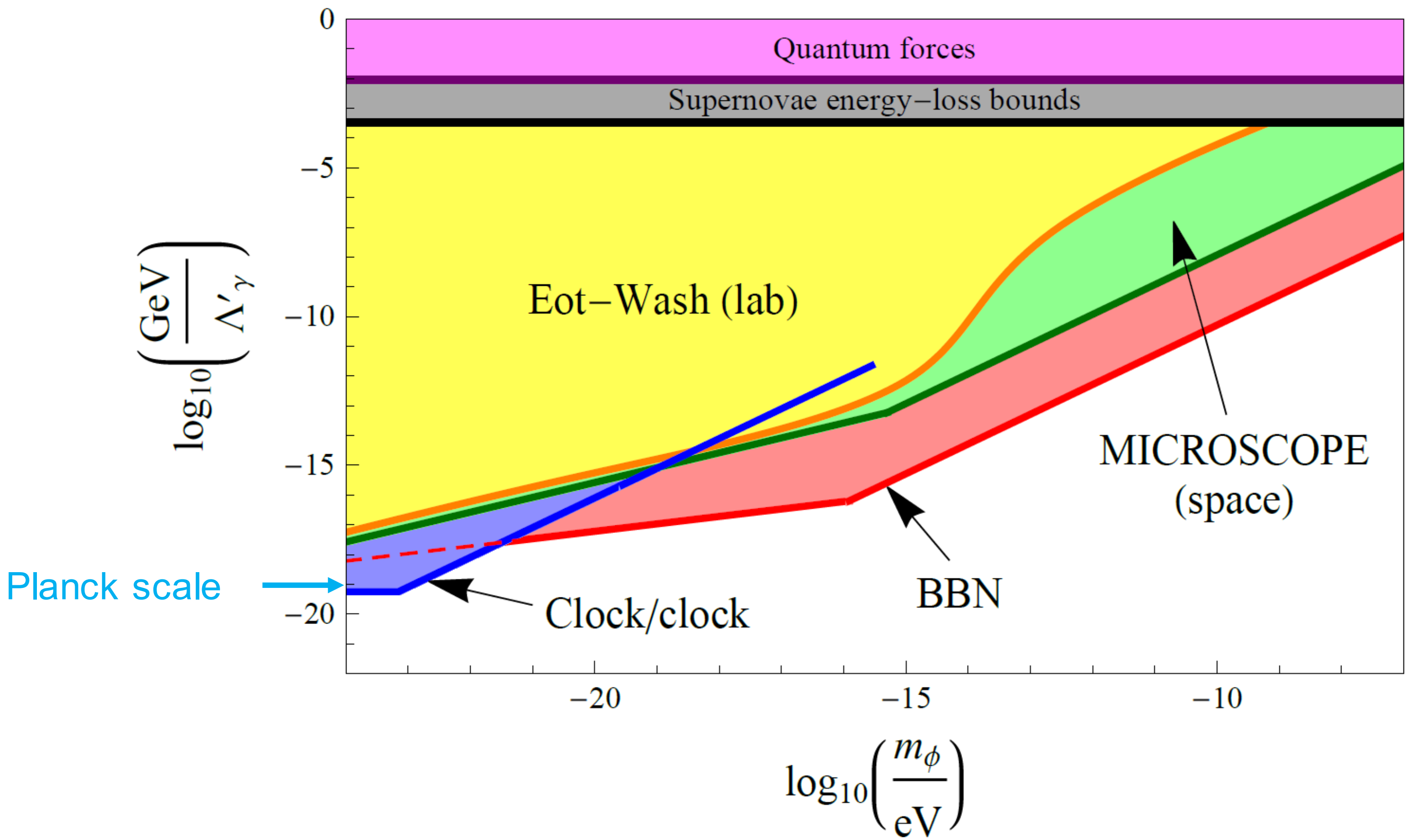
Planck scale

5th 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!



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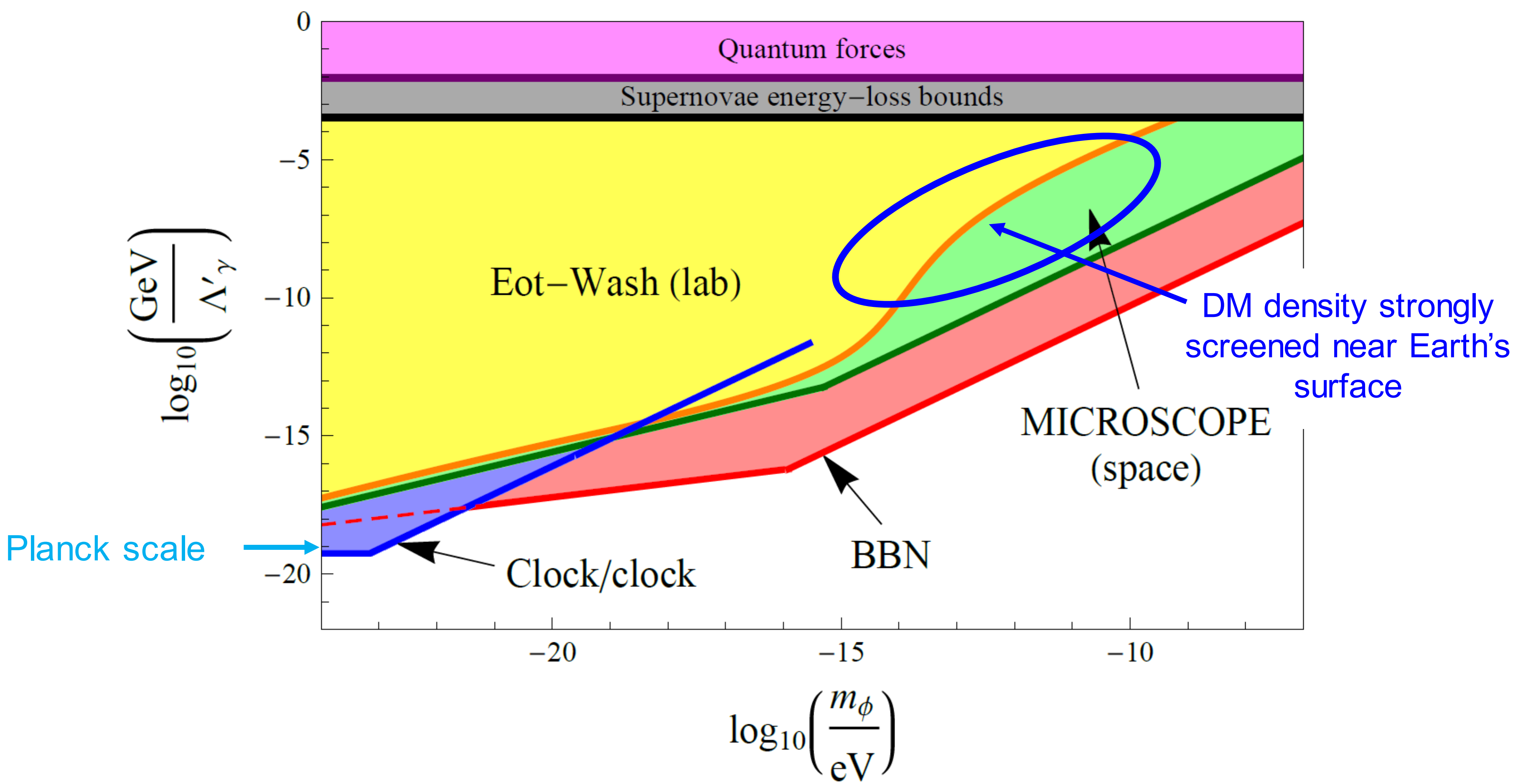


Low-mass Spin-0 Dark Matter

Dark Matter

Pseudoscalars (Axions):

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

More traditional axion detection methods tend to focus on the ***electromagnetic*** *coupling*

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

Time-varying spin-dependent effects

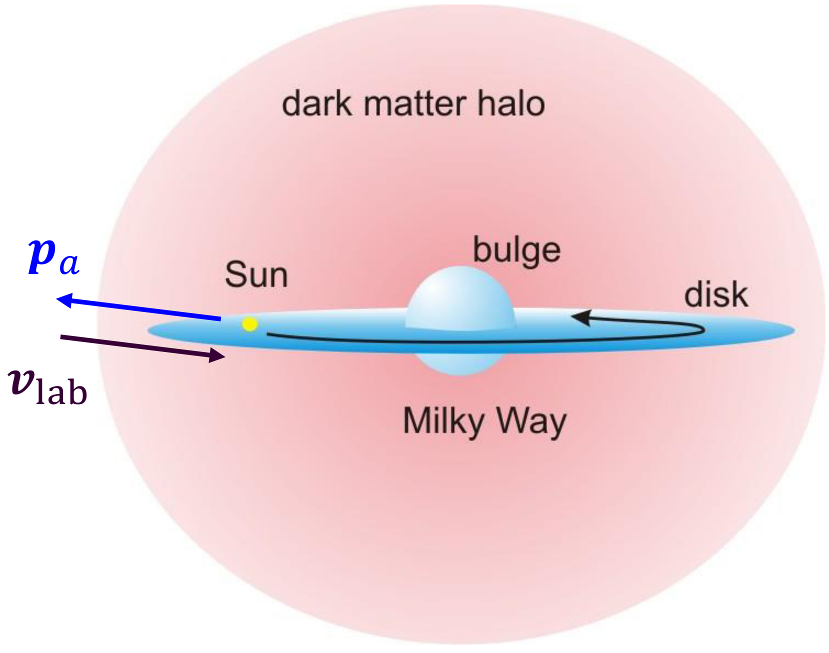
- Co-magnetometers
- Particle *g*-factors
- Spin-polarised torsion pendula
- Spin resonance (NMR, ESR)

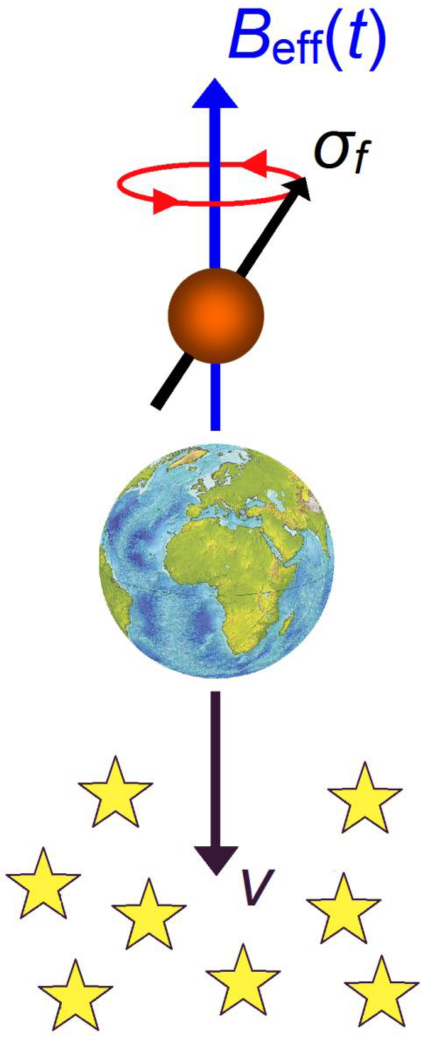
"Axion Wind" Spin-Precession Effect

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

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

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



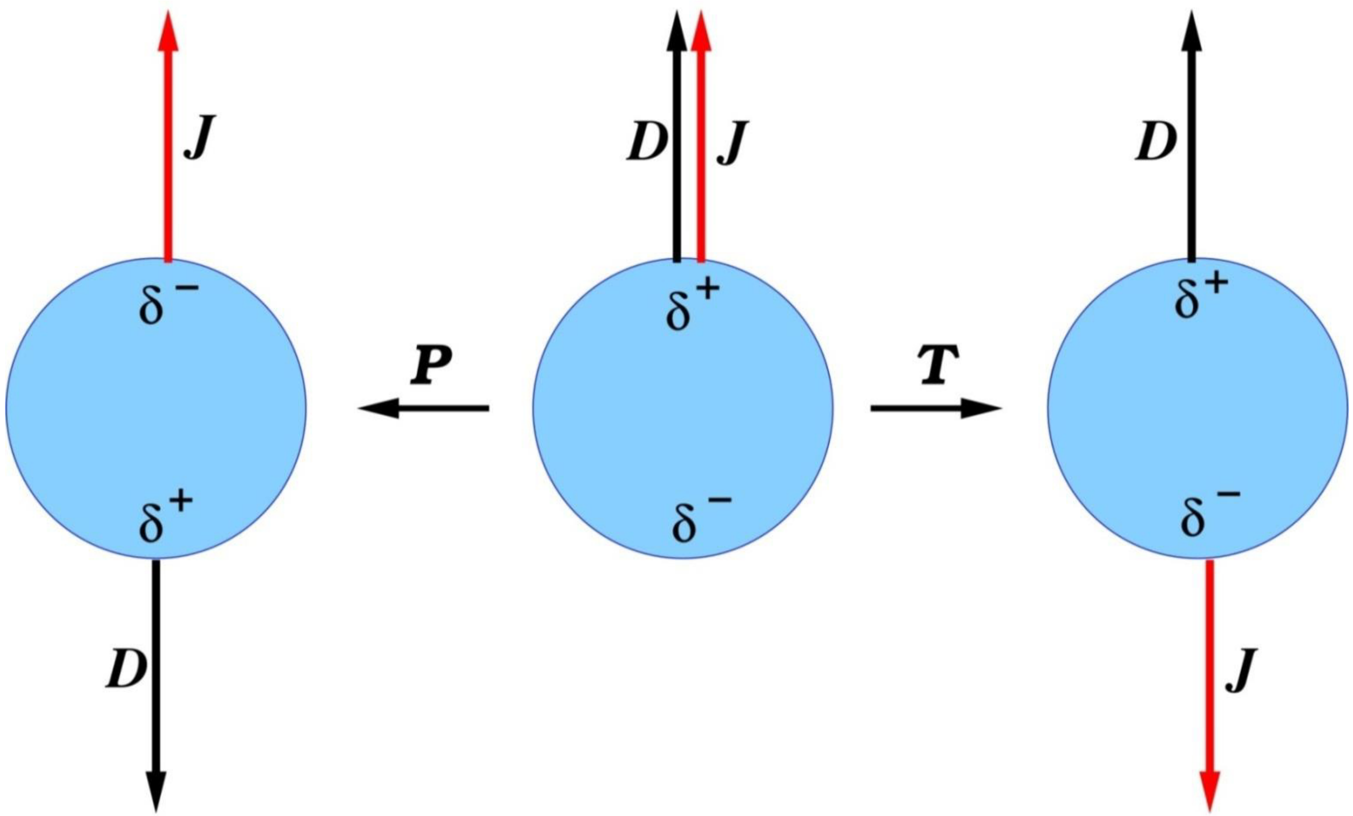


Oscillating Electric Dipole Moments

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



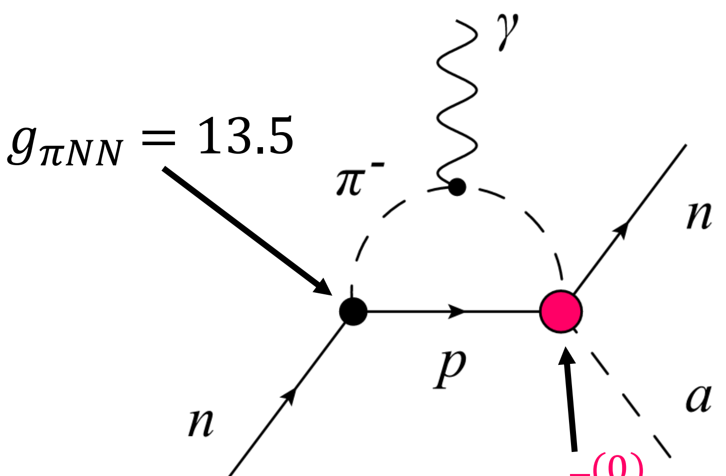
Oscillating Electric Dipole Moments

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

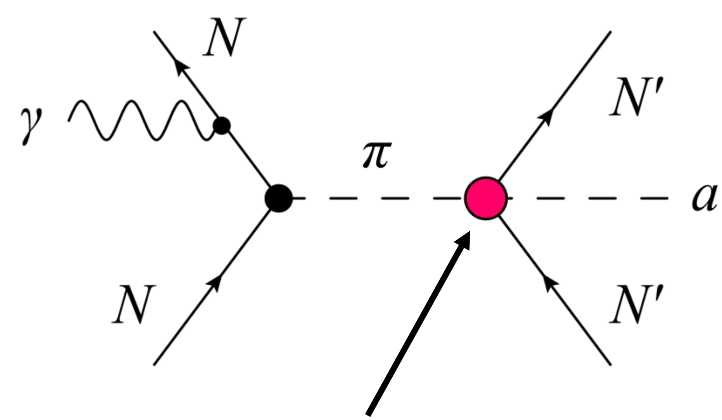
Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

$$\mathcal{L}_G = \frac{C_G g^2}{32\pi^2 f_a} a_0 \cos(m_a t) G\tilde{G} \;\Rightarrow\; H_{\mathrm{EDM}}(t) = \boldsymbol{d}(t) \cdot \boldsymbol{E}, \quad \boldsymbol{d}(t) \propto \boldsymbol{J} \cos(m_a t)$$

Nucleon EDMs



***CP*-violating intranuclear forces**



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

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

Similar to previous searches for Lorentz-invariance violation

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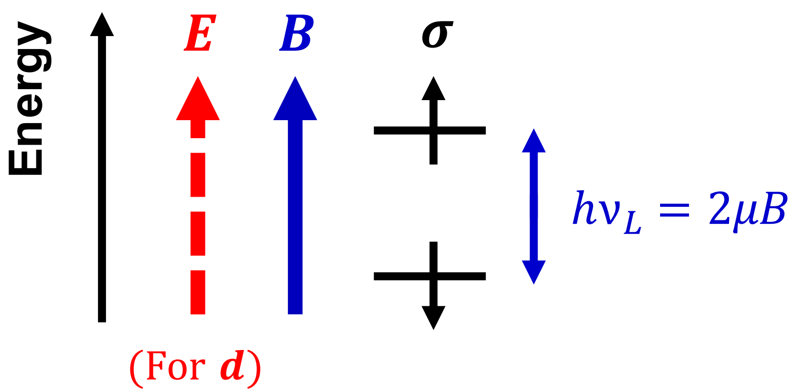
Use spin-polarised sources: *Atomic magnetometers*, *cold/ultracold particles*, *torsion pendula*

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



$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left|\frac{\mu_n B}{\mu_{\mathrm{Hg}} B}\right|$$

B-field effect

Searching for Spin-Dependent Effects

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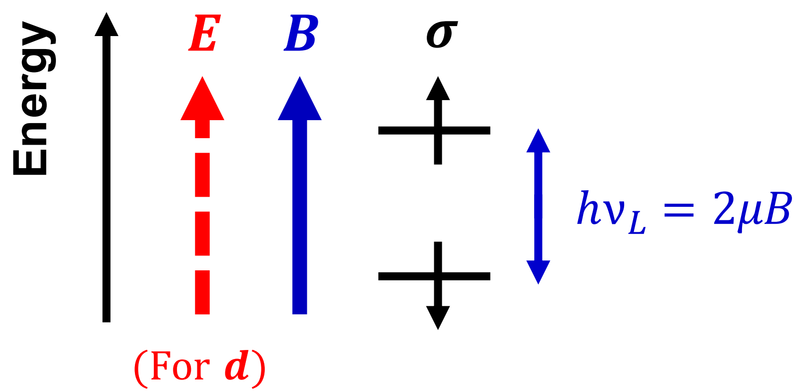

$$\frac{\nu_n}{\nu_{\text{Hg}}} = \left| \frac{\mu_n \cancel{B}}{\mu_{\text{Hg}} \cancel{B}} \right|$$

↑

B-field effect

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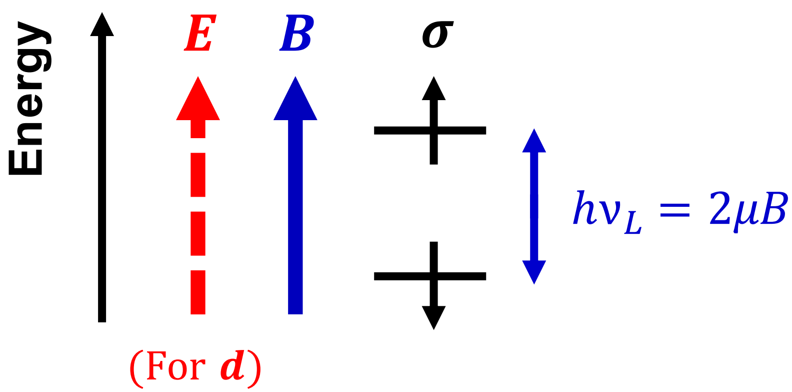

$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left| \frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}} \right| + R(t)$$

$\boldsymbol{B}$-field effect

DM effect (*non-magnetic* coupling to $\boldsymbol{\sigma}$ or $\boldsymbol{d}$)

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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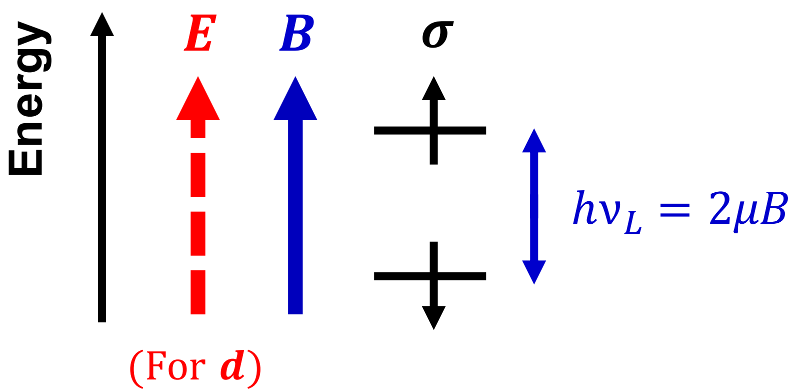
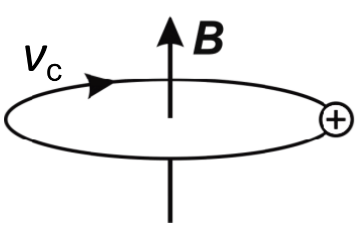


$$\frac{\nu_n}{\nu_{\mathrm{Hg}}} = \left| \frac{\mu_n \cancel{B}}{\mu_{\mathrm{Hg}} \cancel{B}} \right| + R(t)$$

B-field effect

DM effect (*non-magnetic* coupling to $\boldsymbol{\sigma}$ or $\boldsymbol{d}$)

Proposal + Experiment ($\bar{p}$): [BASE collaboration, *Nature* **575**, 310 (2019)]



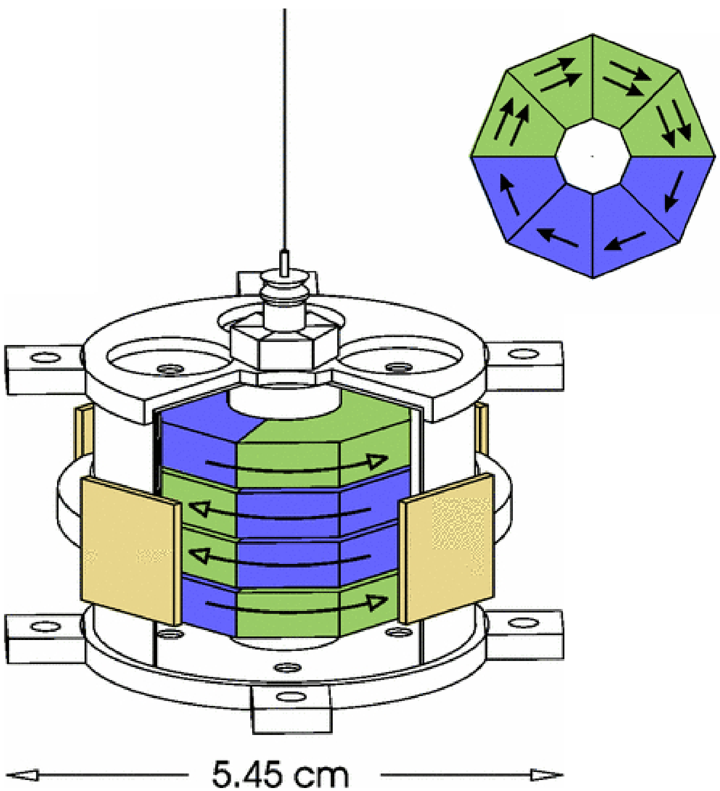
$$\left(\frac{\nu_L}{\nu_c} \right)_{\bar{p}} = \frac{|g_{\bar{p}}|}{2} + R(t)$$

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, *torsion pendula*

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



$\boldsymbol{\mu}_{\mathrm{Alnico}}$ →

← $\boldsymbol{\mu}_{\mathrm{SmCo_5}}$

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

$(\boldsymbol{\sigma}_e)_{\mathrm{Alnico}}$ →

← $(\boldsymbol{\sigma}_e)_{\mathrm{SmCo_5}}$

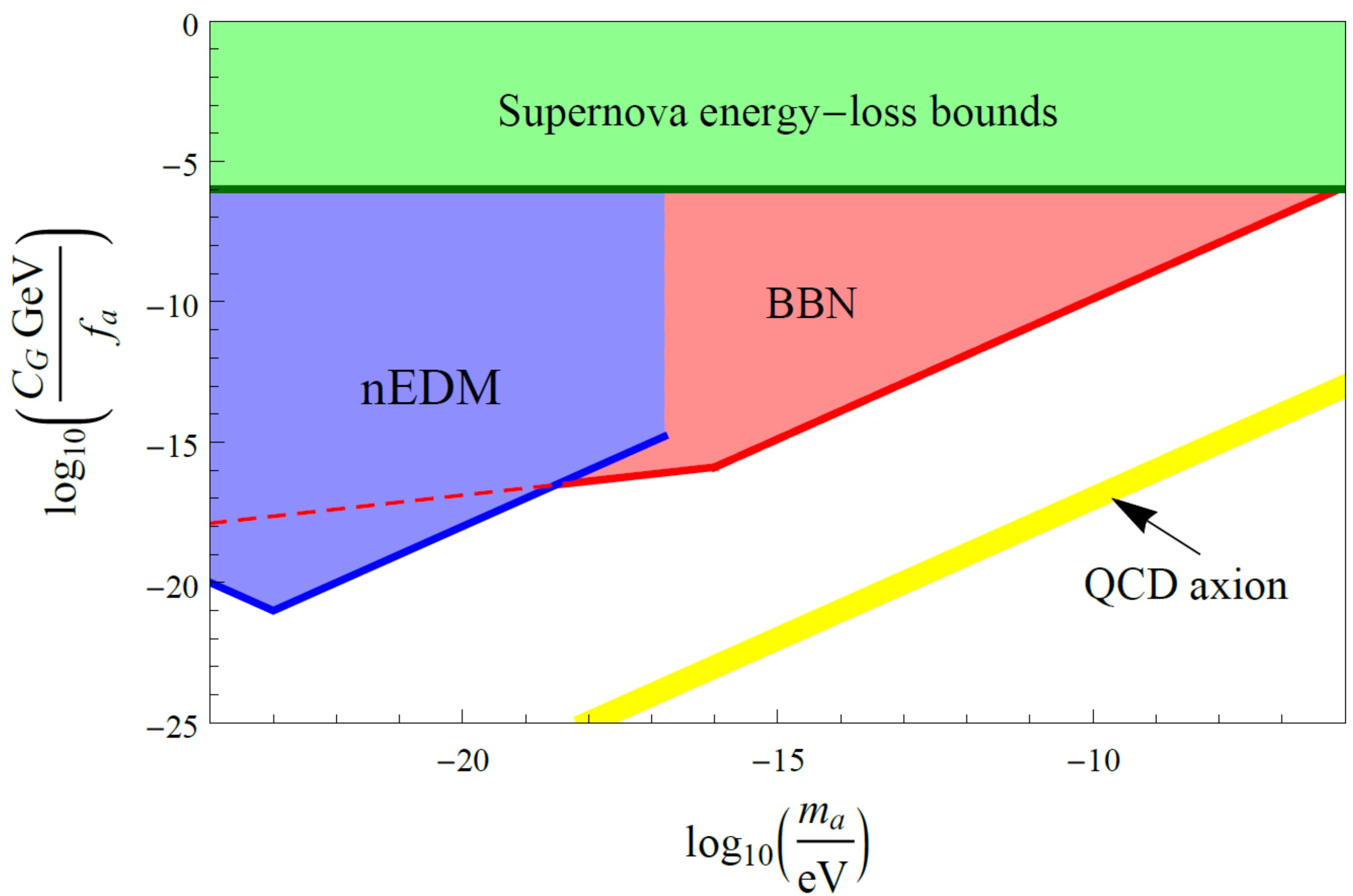
$$(\boldsymbol{\sigma}_e)_{\mathrm{pendulum}} \neq \mathbf{0}$$

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

Constraints on Interaction of Axion Dark Matter with Gluons

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

3 orders of magnitude improvement!



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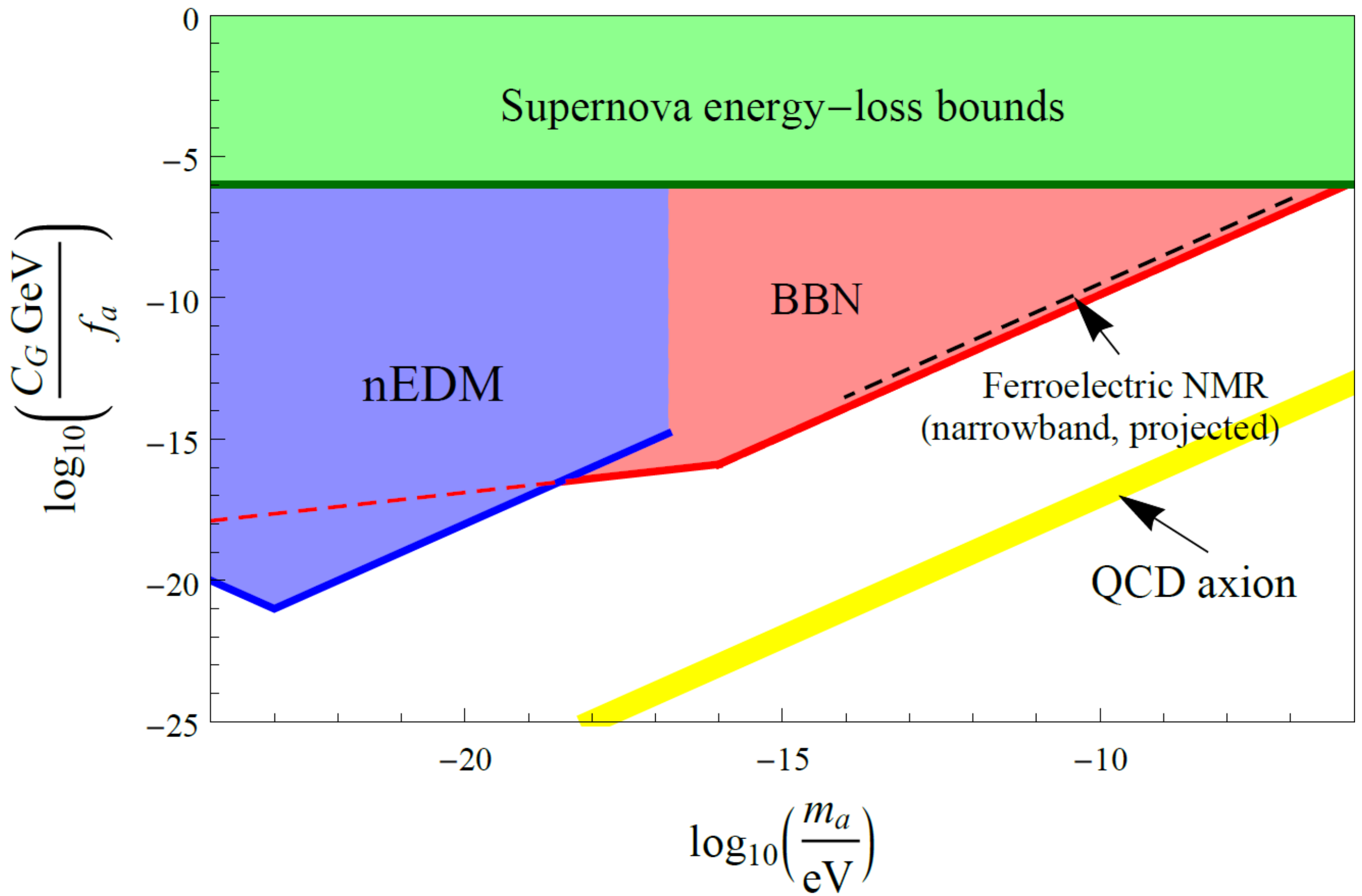
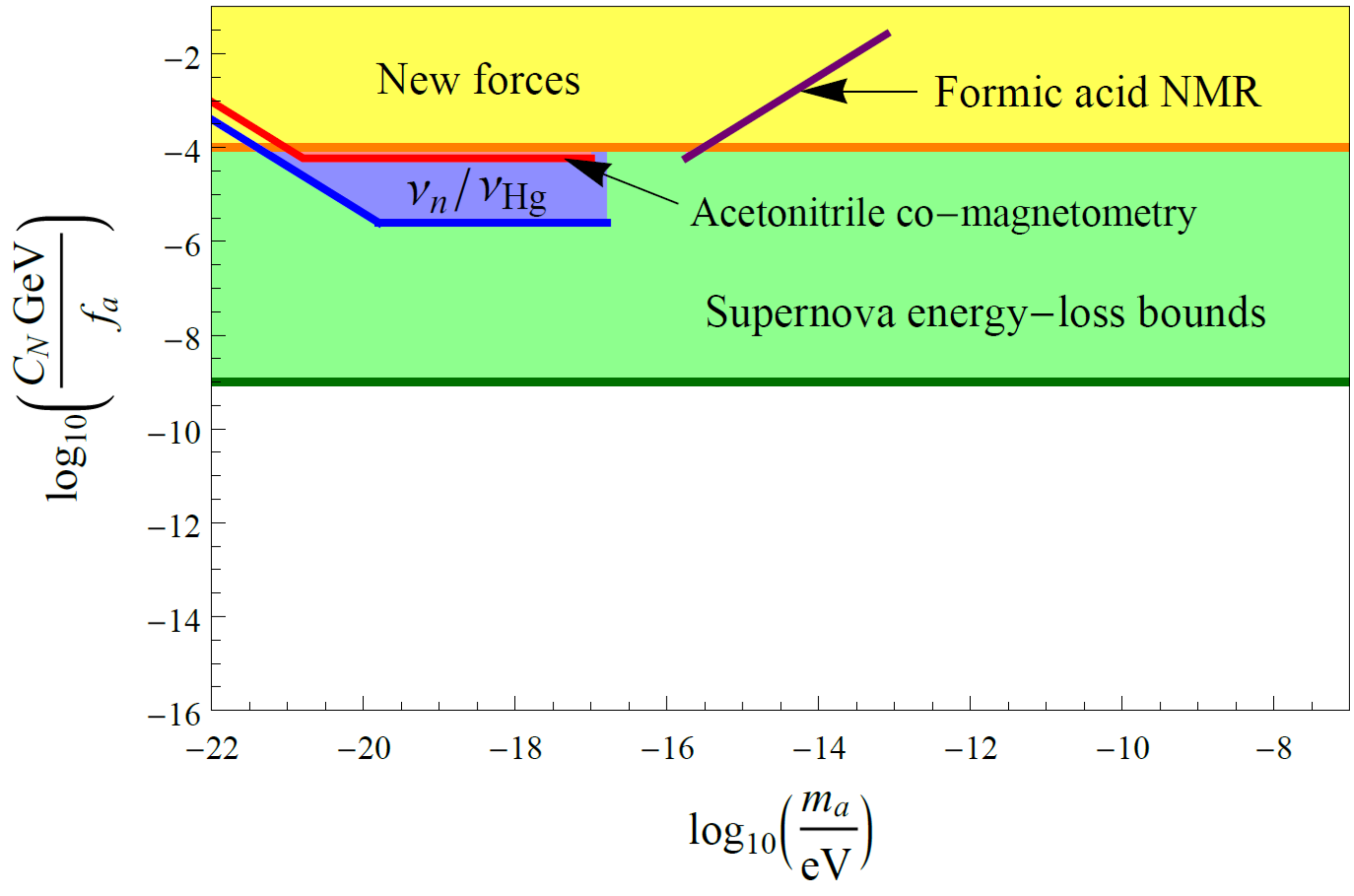


Constraints on Interaction of Axion Dark Matter with Nucleons

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

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

Formic acid NMR constraints: [Garcon *et al*., *Sci. Adv.* **5**, eaax4539 (2019)]



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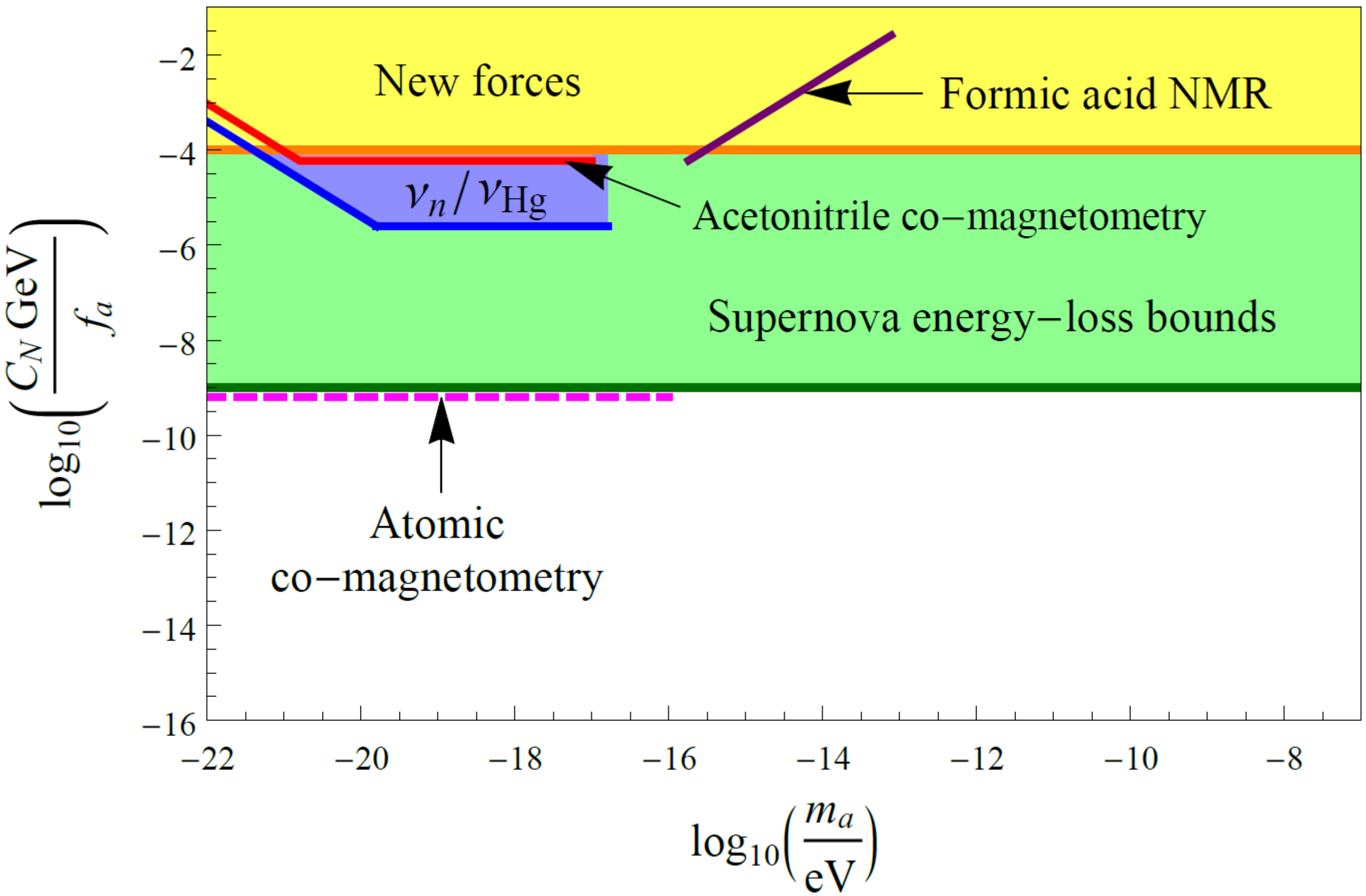

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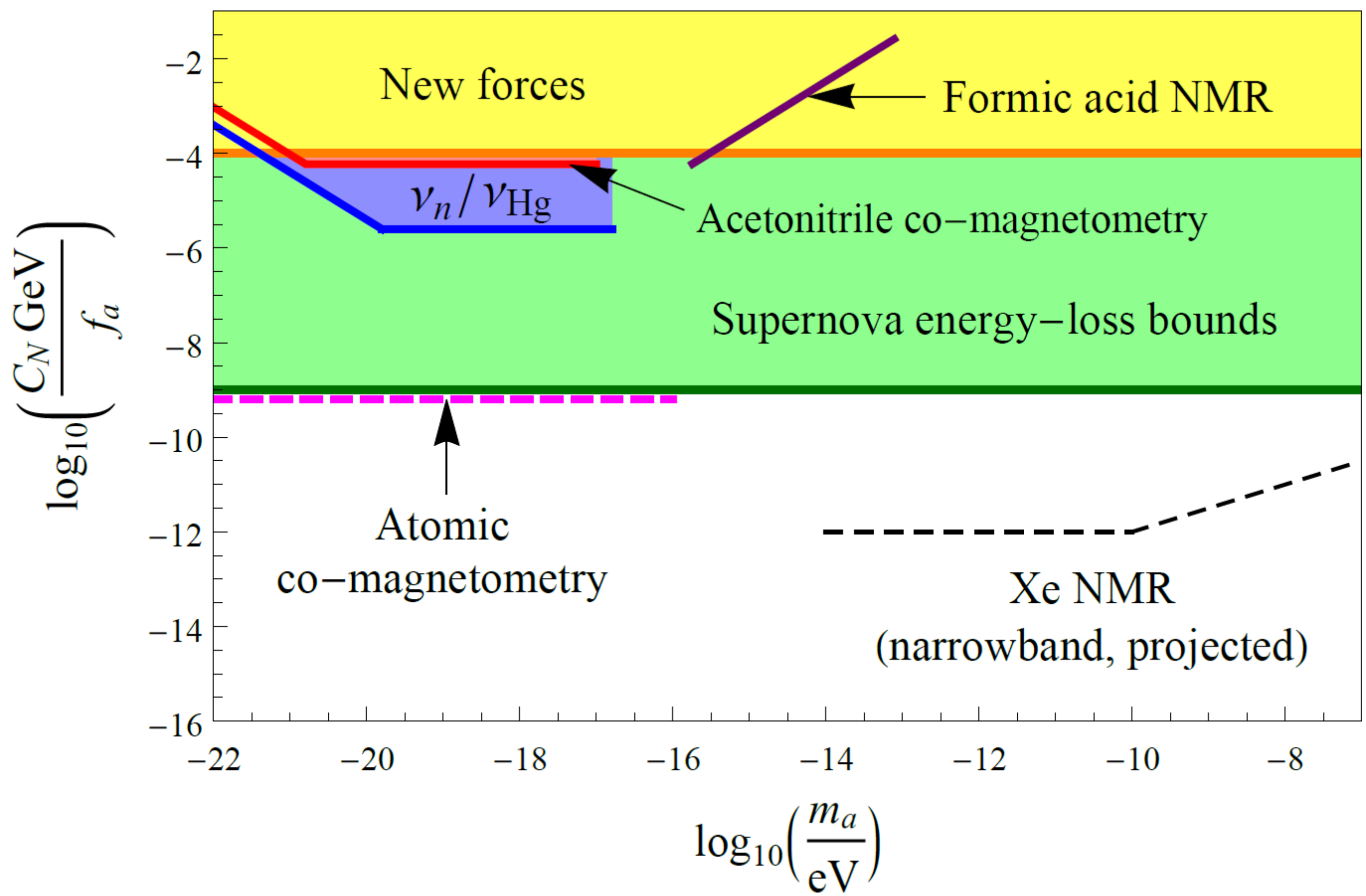
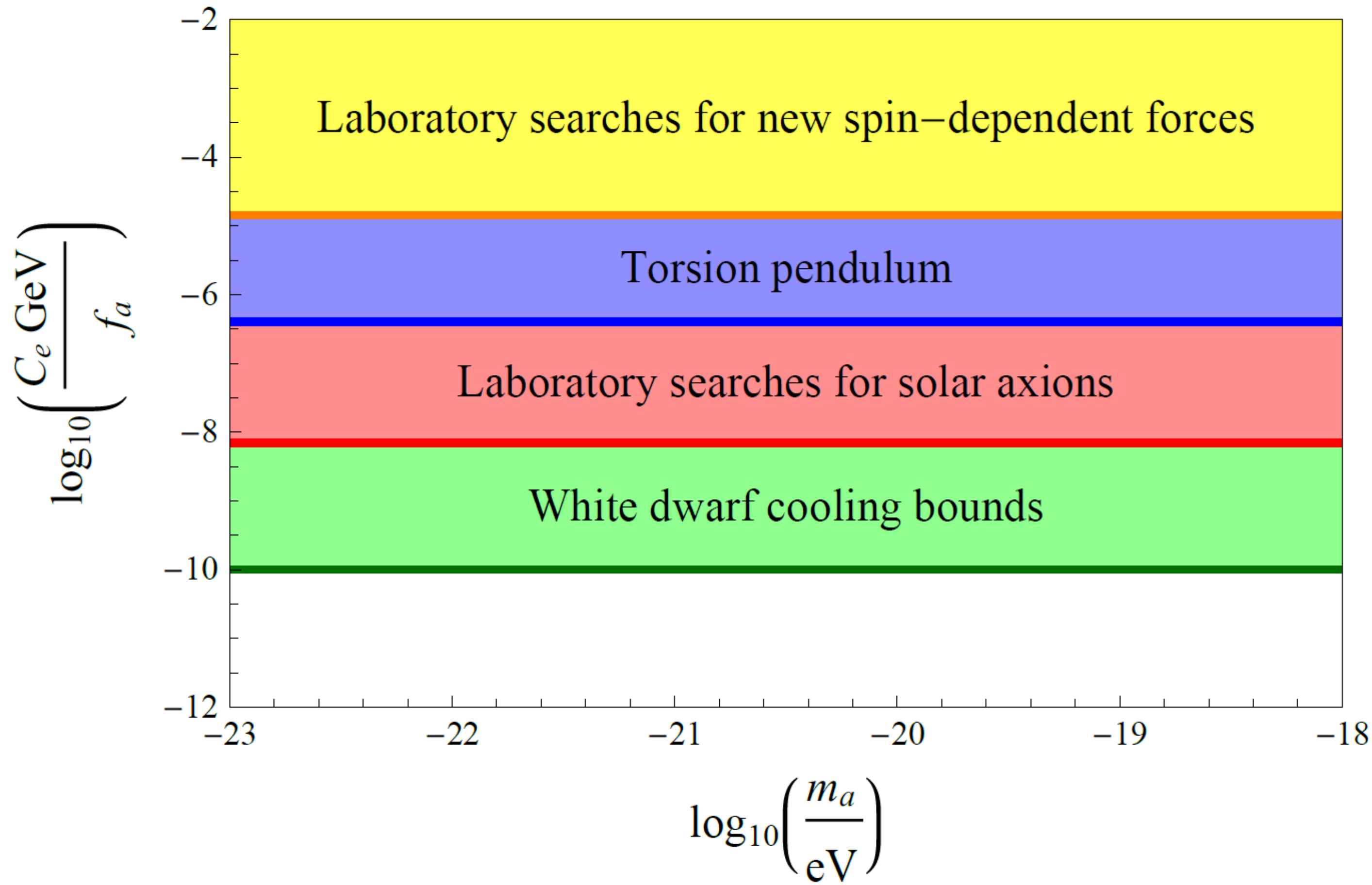


Constraints on Interaction of Axion Dark Matter with the Electron

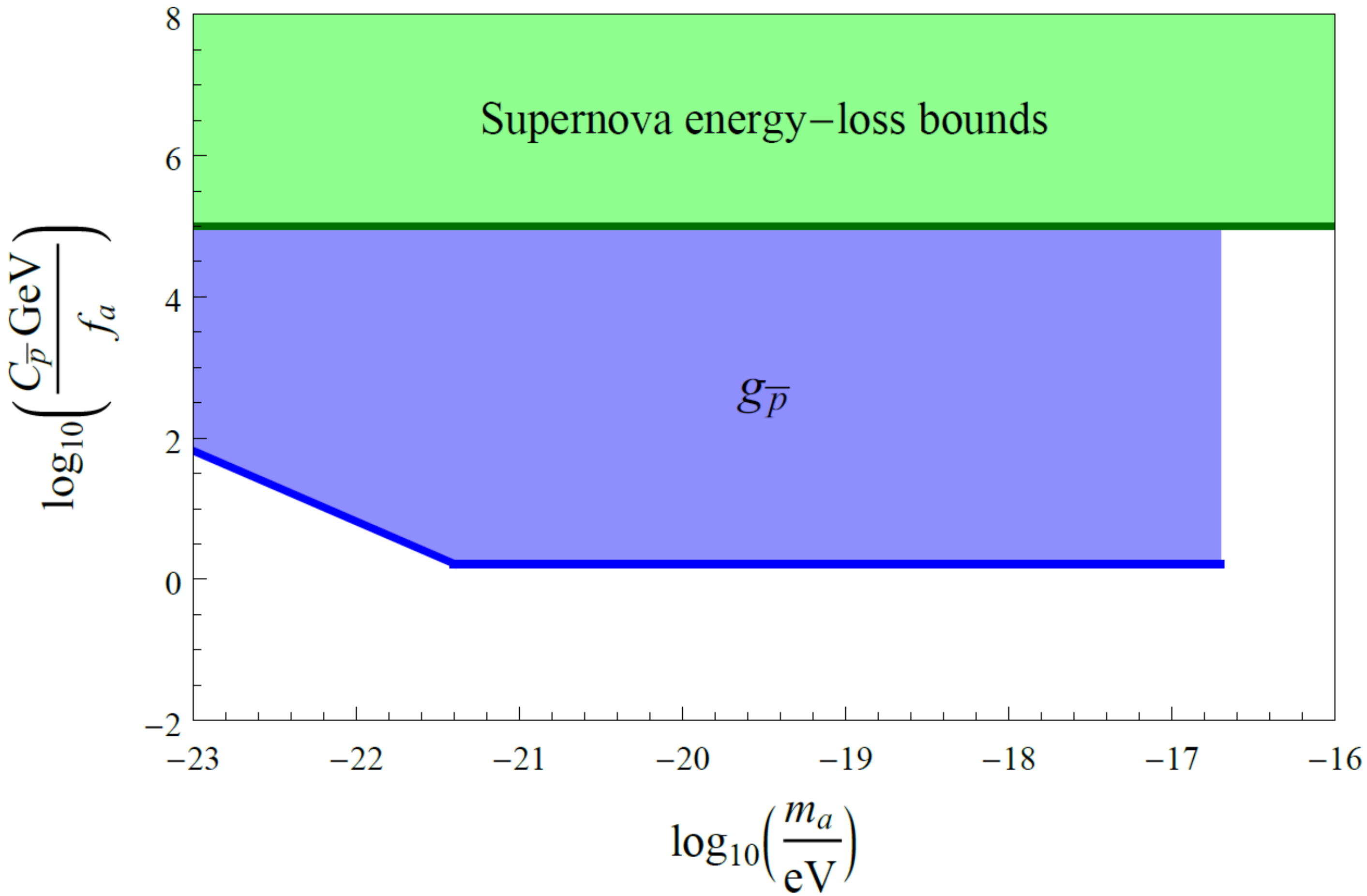
Torsion pendulum constraints: [Terrano *et al.*, *PRL* **122**, 231301 (2019)]



Constraints on Interaction of Axion Dark Matter with the Antiproton

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

5 orders of magnitude improvement!



Summary

- We have identified new signatures of ultra-low-mass dark matter that have allowed us and other groups to improve the sensitivity to underlying interaction strengths by up to **15 orders of magnitude**
- Novel approaches based on precision low-energy experiments (often "table-top scale"):
  - Spectroscopy (clocks) [Scalars]
  - Optical cavities and interferometry [Scalars]
  - Magnetometry and particle *g*-factors [Pseudoscalars]
  - Torsion pendula [Scalars and pseudoscalars]

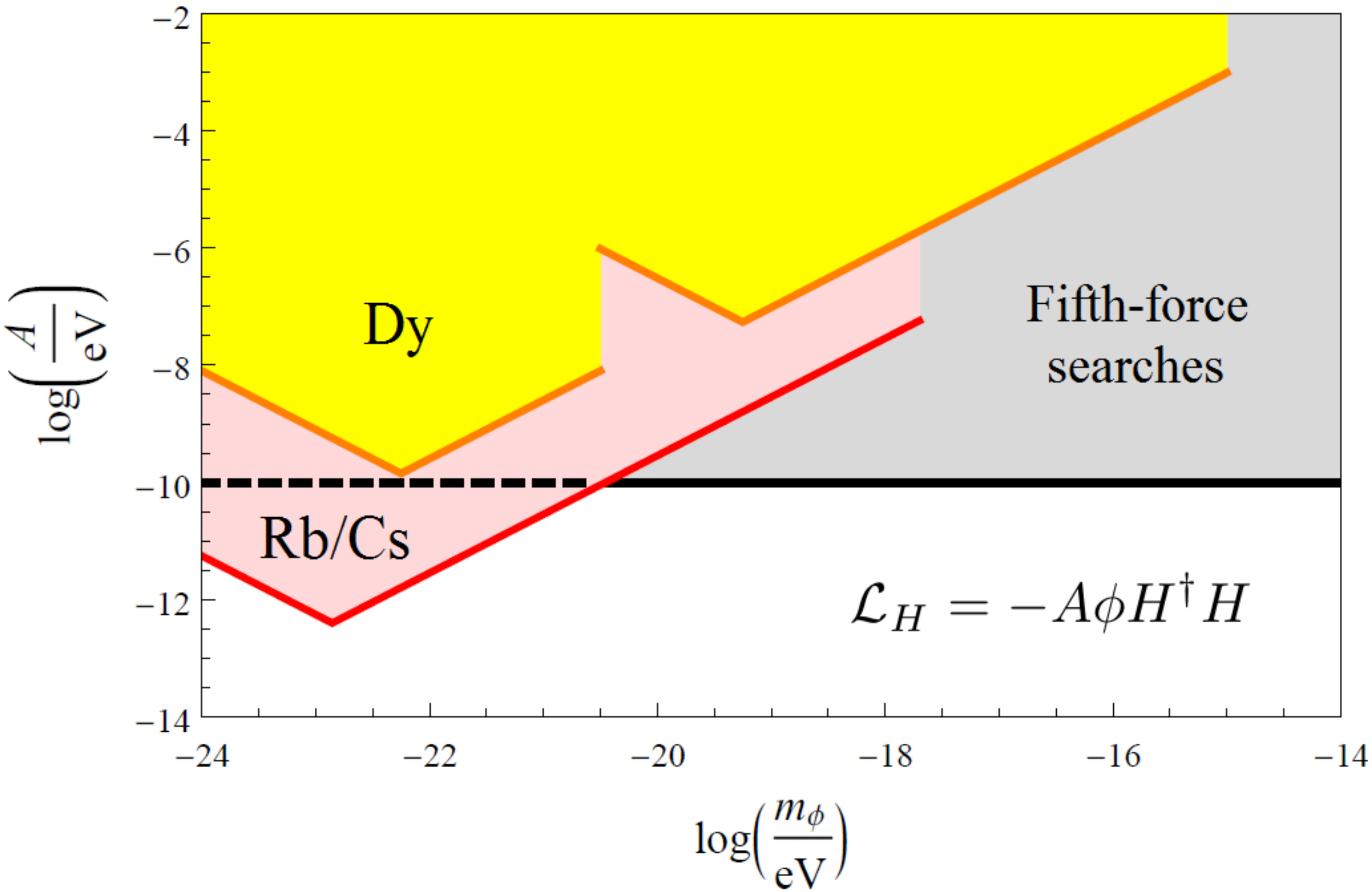
Back-Up Slides

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

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

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

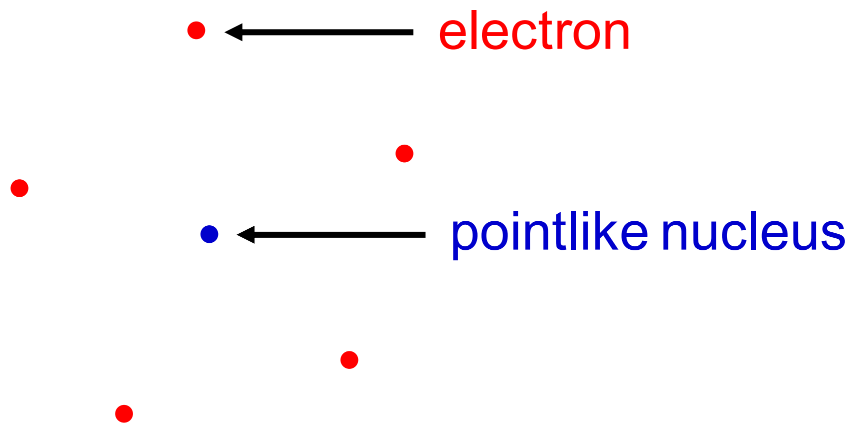
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

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

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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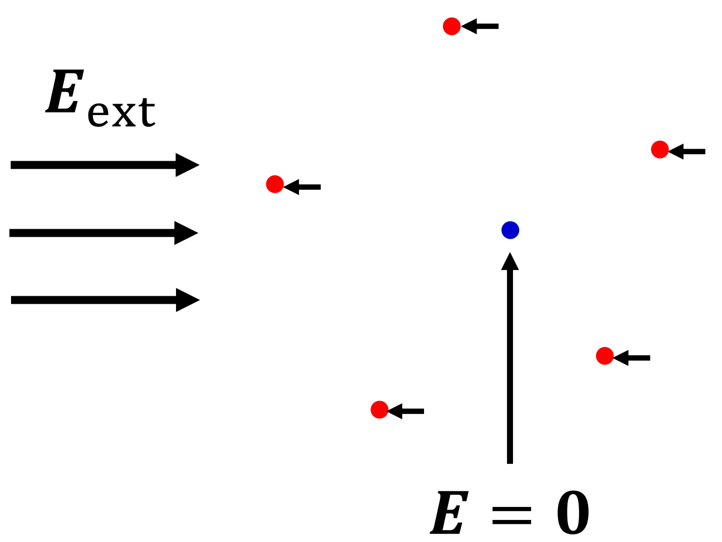


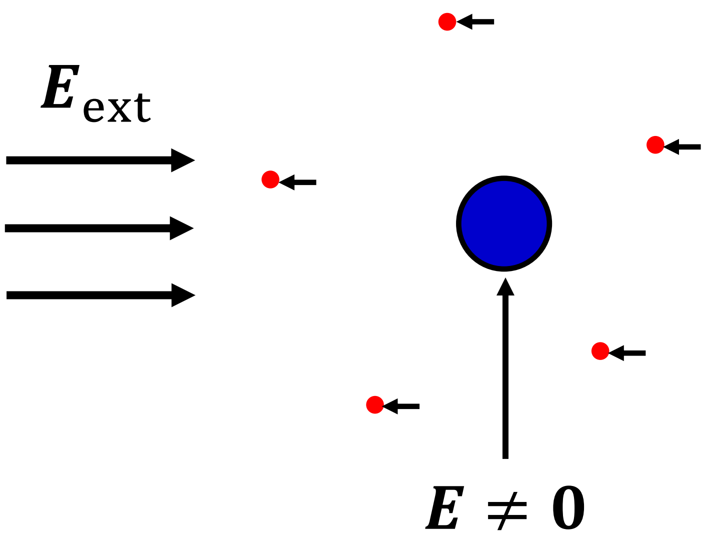
Classical explanation for nuclear EDM: A neutral atom does not accelerate in an external electric field!

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*.



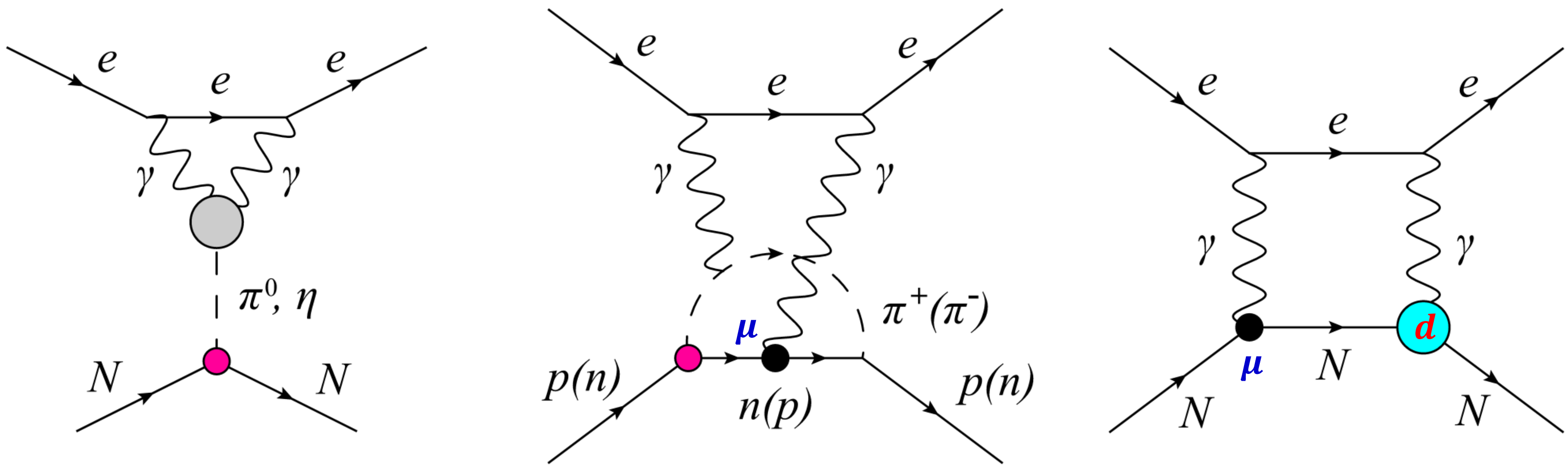
Hadronic CP Violation in Paramagnetic Molecules

[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* $\Rightarrow$ no Schiff screening

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



π^0, η contributions: *opposite sign*

p, n contributions: *same sign*

<u>Example</u> – $\bar{\theta}_{\mathrm{QCD}}$ term [$\bar{\theta} \leftrightarrow C_G a_0 \cos(m_a t)/f_a$]:

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

Bounds on Hadronic CP Violation Parameters

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

System	$\left|\bar{g}_{\pi NN}^{(1)}\right|$	$\left|\tilde{d}_u - \tilde{d}_d\right|$ (cm)	$\left|d_p\right|$ (e cm)	$\left|\bar{\theta}\right|$
ThO	$\mathbf{4 \times 10^{-10}}$	$\mathbf{2 \times 10^{-24}}$	$\mathbf{2 \times 10^{-23}}$	$\mathbf{3 \times 10^{-8}}$
n	1.1×10^{-10}	5×10^{-25}	—	2.0×10^{-10}
Hg	1×10^{-12}	5×10^{-27}	2.0×10^{-25}	1.5×10^{-10}
Xe	6.7×10^{-8}	3×10^{-22}	3.2×10^{-22}	3.2×10^{-6}

* These limits can formally be null within nuclear uncertainties

Current bounds from molecules are $\sim 10 - 100$ times weaker than from Hg & n, but are $\sim 10 - 100$ times stronger than bounds from Xe