Testing the Standard Model and Probing New Physics with Low-Energy Atomic, Molecular and Optical Experiments

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“New Physics on the Low-Energy Precision Frontier”, CERN, January 2020

Outline

1. **Electroweak Phenomena**

2. **Electric Dipole Moments**

3. **Ultra-Low-Mass Dark Matter**

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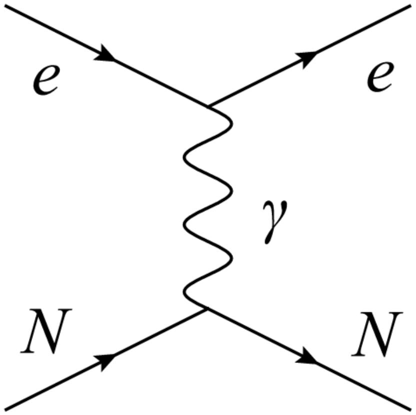
2. **Electric Dipole Moments**

3. **Ultra-Low-Mass Dark Matter**

EW Phenomena in Atoms (PNC)

Electromagnetic



Parity conserving,
long range

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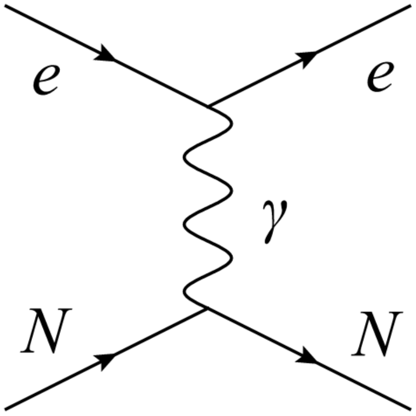

Parity conserving,
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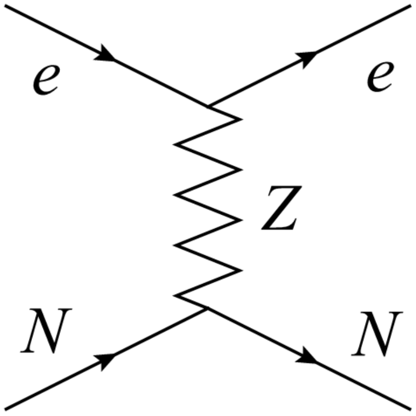
Weak neutral current



Parity violating,
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$\Gamma_{\pm} = \Big|$

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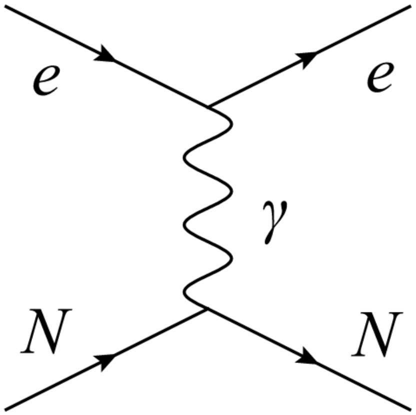

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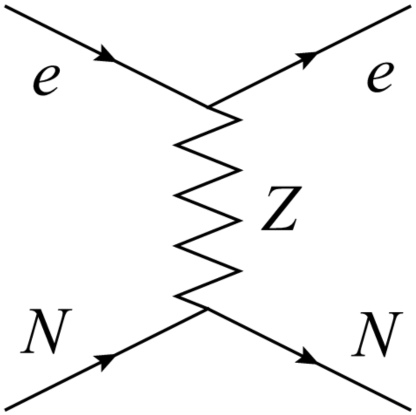

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$\Gamma_{\pm} =$ | **Electromagnetic** ± **Weak neutral current** $|^2$

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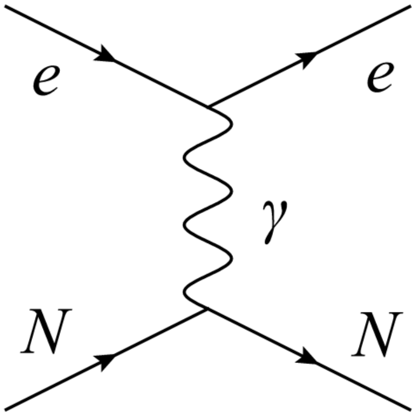

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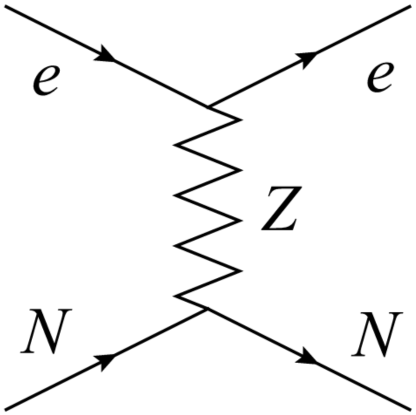

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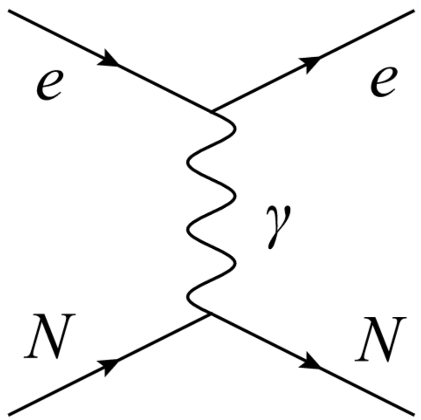

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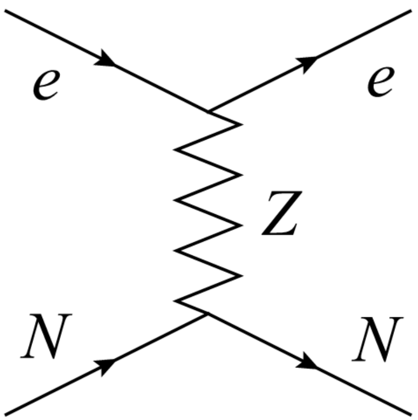

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Measure parity-nonconserving amplitude $E_{PNC} = \Gamma_{+} - \Gamma_{-}$

=> Determine nuclear weak charge $Q_W = -N + Z\,[1 - 4\sin^2(\theta_W)] \approx -N$

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Parity violation in weak neutral current interactions first discovered in bismuth optical rotation experiments in Novosibirsk

[Barkov, Zolotorev, *JETP Lett.* **27**, 357 (1978); *Pis'ma Zh. Eksp. Teor. Fiz.* **27**, 379 (1978)]

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Current "gold standard" – caesium beam experiment in Boulder:

$Q_W\,(^{133}\mathrm{Cs}) = -72.58(29)_{\mathrm{exp}}(32)_{\mathrm{theory}}$ cf. $Q_W\,(^{133}\mathrm{Cs})_{\mathrm{SM}} = -73.23(2)$

Experiment: [Wood *et al*., *Science* **275**, 1759 (1997)]

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Bounds on new physics:

Extra standard-type *Z* boson: $M_{Z'} > 700$ GeV

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$|\,g_e^A g_N^V\,| < 3\times10^{-14}$, $M_V < 1$ keV; $|\,g_e^A g_N^V\,|/M_V^2 < 4\times10^{-8}\ \mathrm{GeV}^{-2}$, $M_V > 200$ keV

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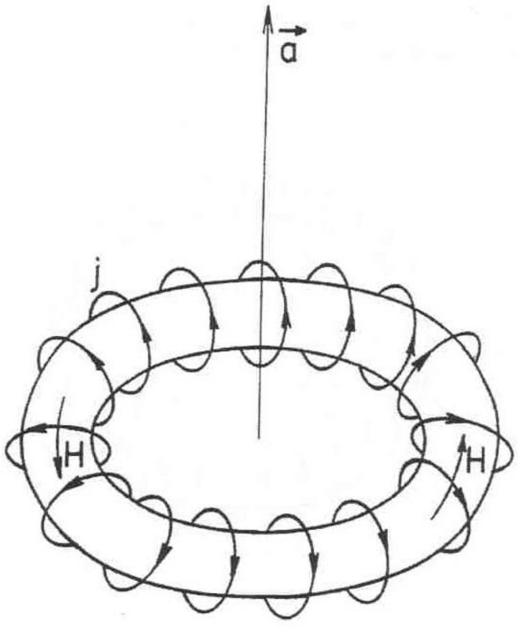
Nuclear Anapole Moments (PNC)



Parity-violating toroidal moment:

$$\mathbf{a} = -\pi \int d^3r\, r^2\, \mathbf{j}(\mathbf{r}) \propto \kappa_a \mathbf{I}$$

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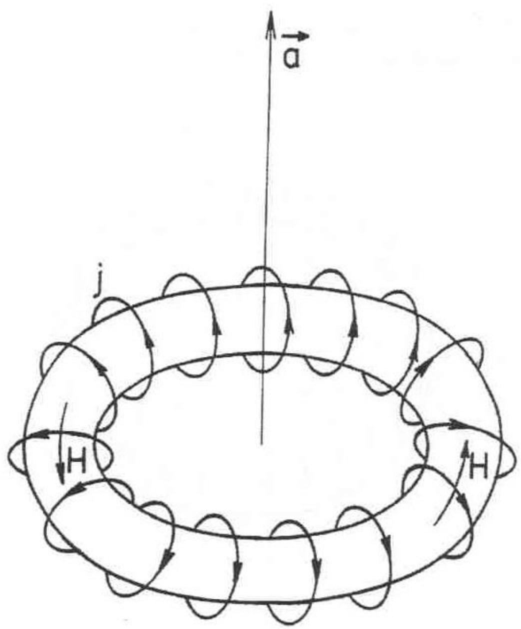

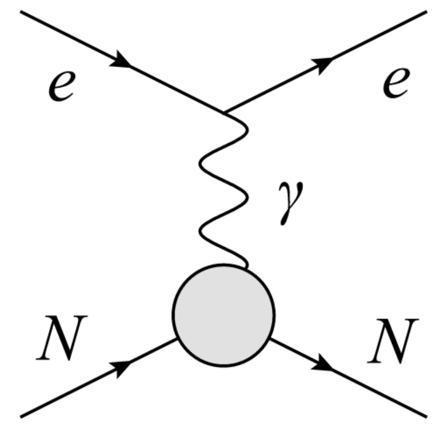

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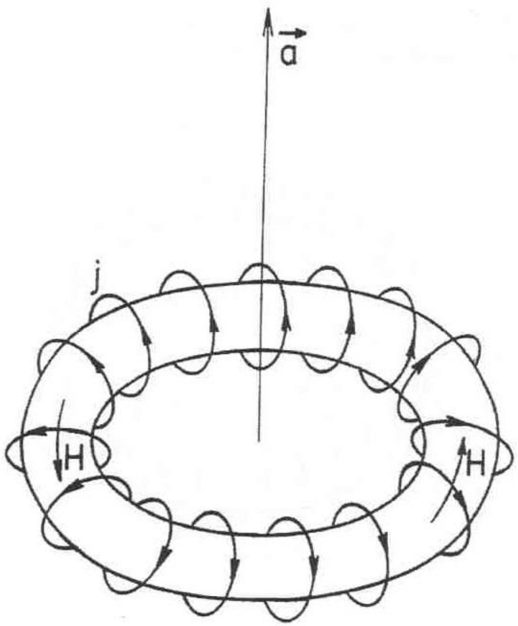

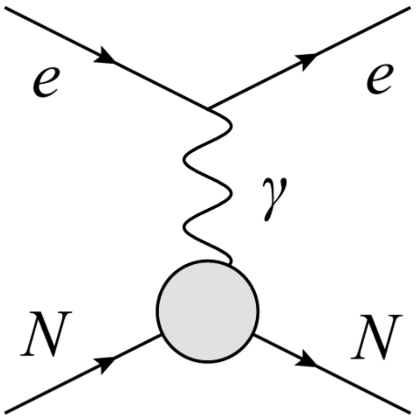

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$$H_{anapole} = e\, \boldsymbol{\alpha} \cdot \mathbf{a}\, \delta(\mathbf{r})$$

Measure *nuclear-spin-dependent* PNC amplitude

Nuclear Anapole Moments (PNC)

So far, only observation of nuclear anapole moment
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$$\kappa_a\,(^{133}\mathrm{Cs})_{exp} = 0.36(6) \quad \text{cf.} \quad \kappa_a\,(^{133}\mathrm{Cs})_{theory} = 0.27(8)$$

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New experiments targeting observation of anapole moments in odd-neutron nuclei (mainly sensitive to g_n): ^{137}BaF, ^{171,173}Yb

EW Phenomena in Atoms (PC)

Ground-state hyperfine interval in muonium ($e^- \mu^+$ bound state):

$$\nu_{exp} = 4463302776(51)\ \text{Hz} \quad \text{cf.} \quad \nu_{theory} = 4463302868(271)^*\ \text{Hz}$$

***** $u[\nu_{theory}(m_e/m_\mu)] \approx 260$ Hz, $u[\nu_{theory}(4^{th}\text{-order QED})] \approx 85$ Hz, $u[\nu_{theory}(\text{others})] \lesssim \mathcal{O}(\text{Hz})$

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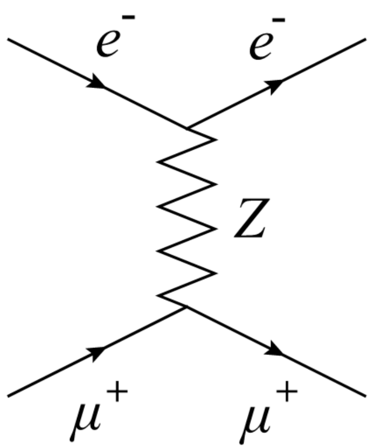

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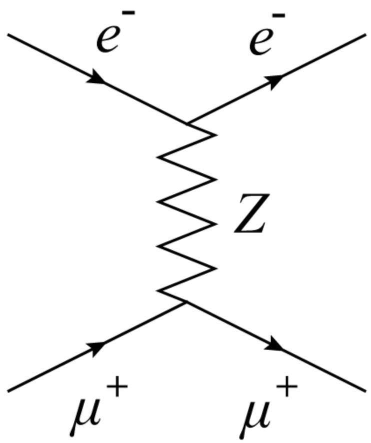

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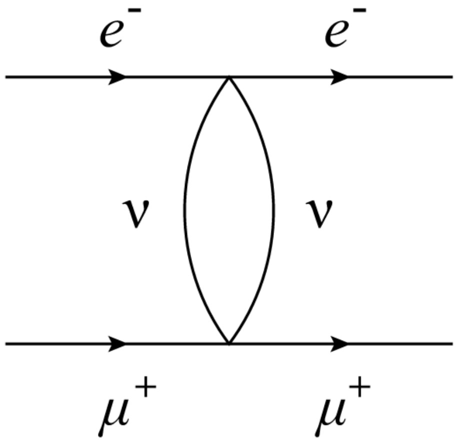
New experiments and calculations targeting ~ $\mathcal{O}(10)$ Hz precision level

Enhanced Sensitivity to Highly-Singular Parity-Conserving Forces in Muonium

[Stadnik, *PRL* **120**, 223202 (2018)]

Illustrative example – SM predicts “long range” neutrino-mediated forces



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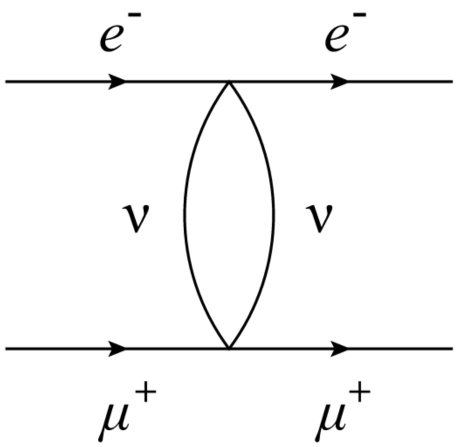

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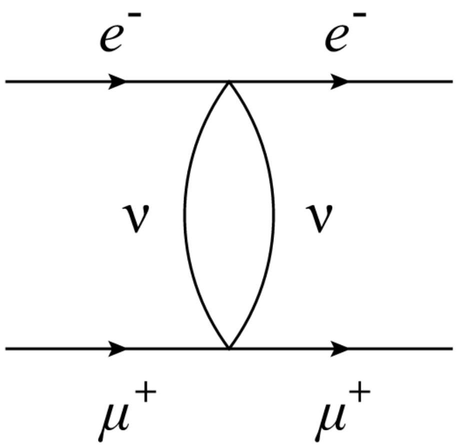

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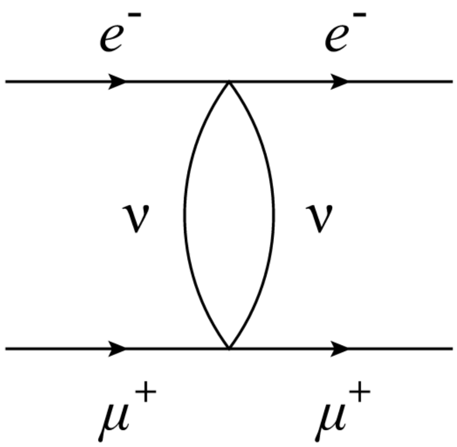

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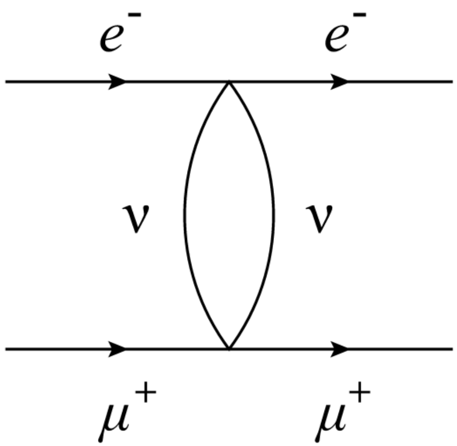

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$$\left(G_{\text{eff}}^2\right)_{\text{muonium}} < 10^2 G_F^2 \quad \text{cf.} \quad \left(G_{\text{eff}}^2\right)_{\text{macroscopic}} < 10^{20} G_F^2$$

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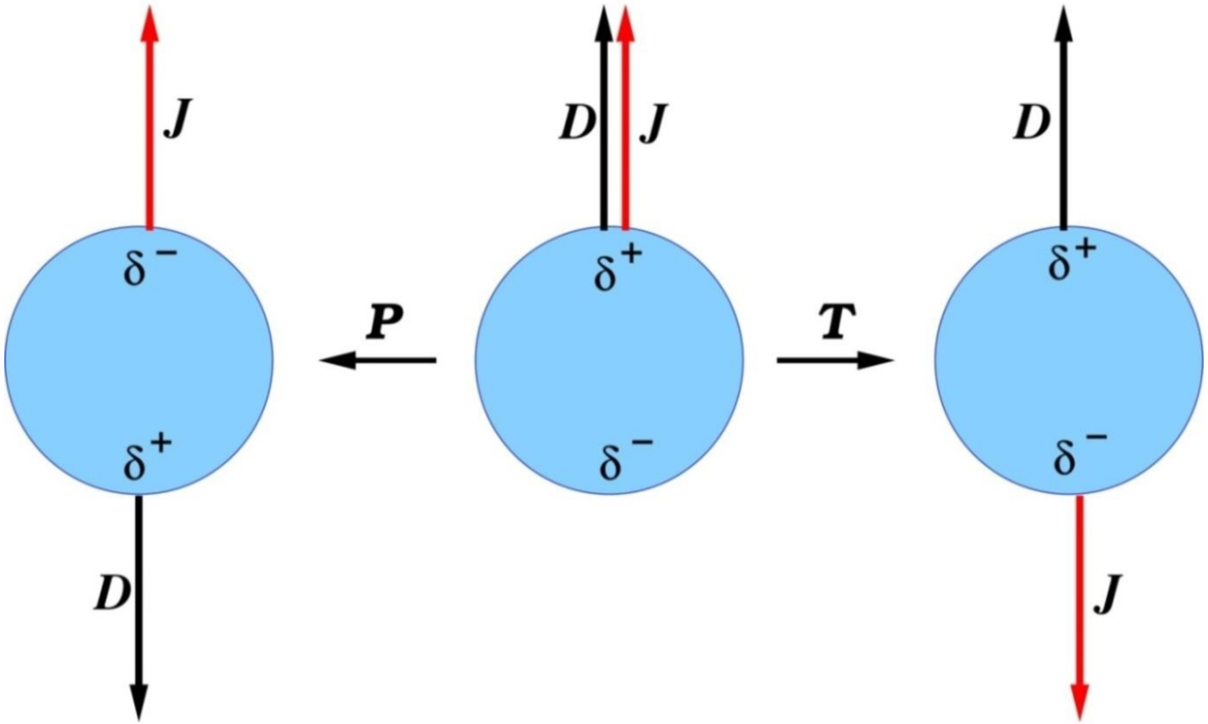
- EDM experiments are high-precision low-energy probes of possible new sources of CP violation

Atomic Electric Dipole Moments



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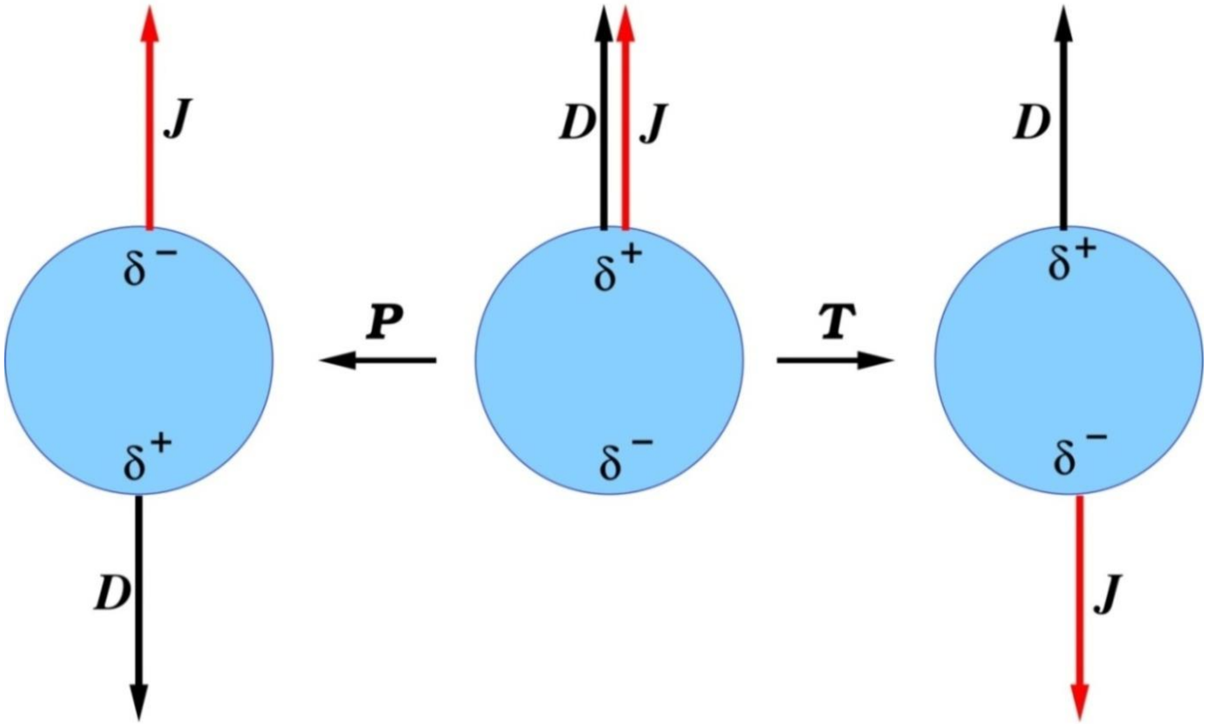

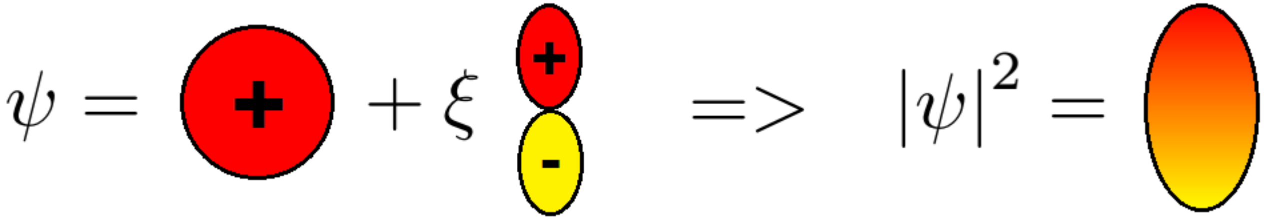

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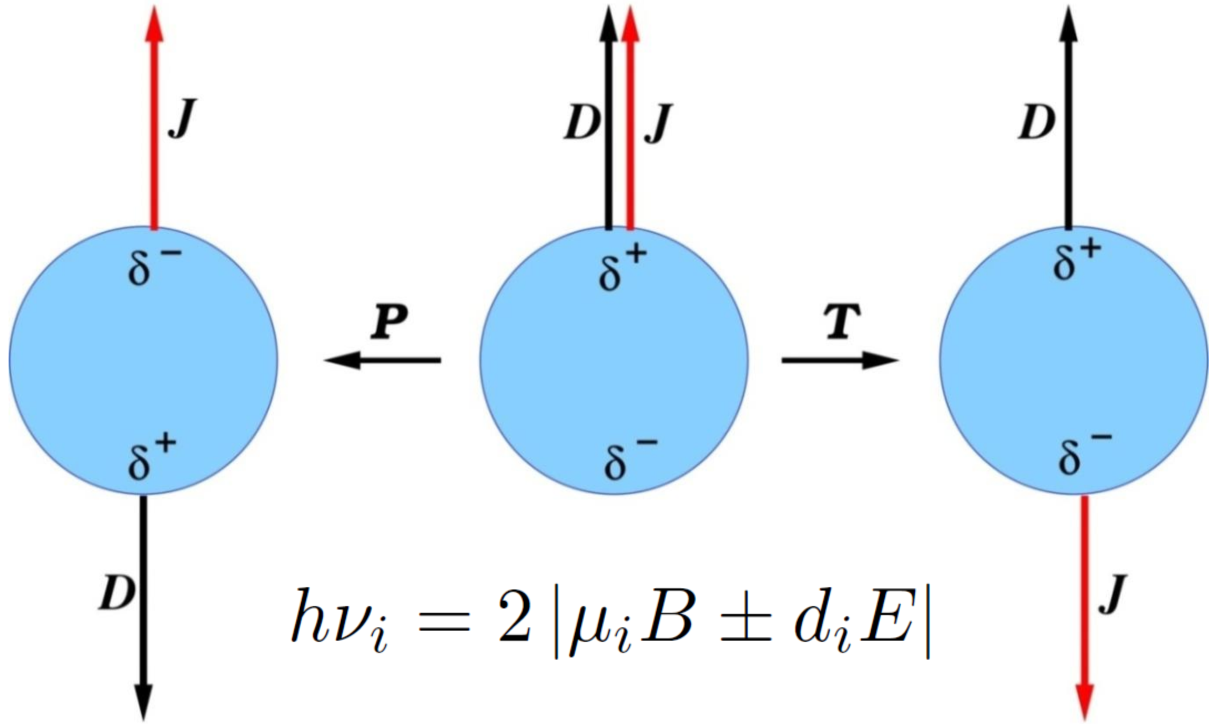
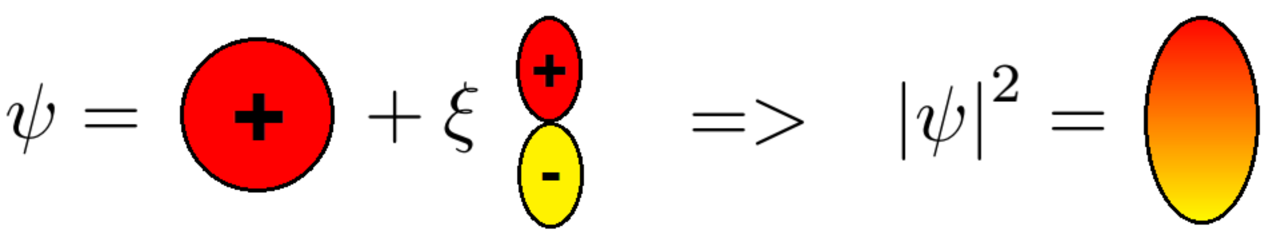


$$h\nu_i = 2\,|\mu_i B \pm d_i E|$$



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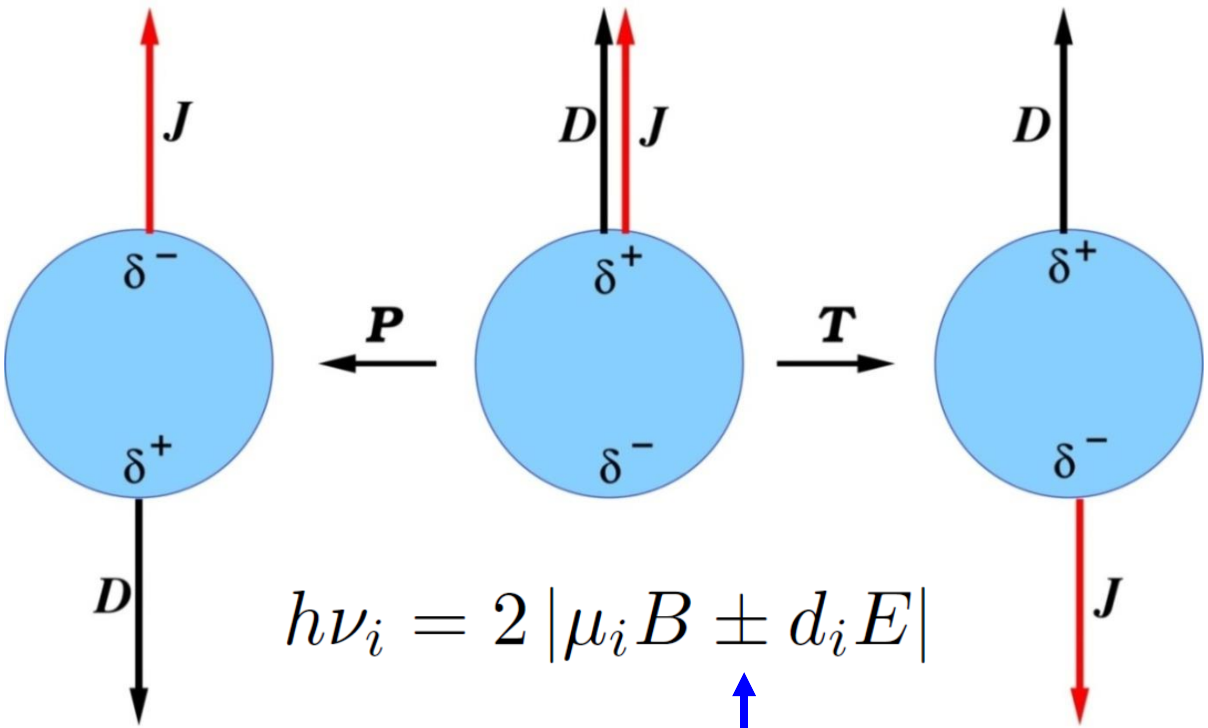

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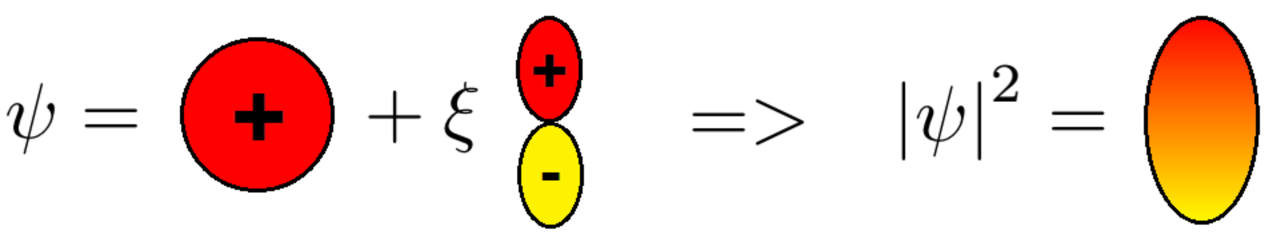

Hadronic CP Violation in Diamagnetic Atoms

Nucleon EDMs: [Crewther, Di Vecchia, Veneziano, Witten, *PLB* **88**, 123 (1979)]

Intranuclear forces: [Haxton, Henley, *PRL* **51**, 1937 (1983)],

[O. Sushkov, Flambaum, Khriplovich, *JETP* **60**, 873 (1984)]

Illustrative example: $$\mathcal{L}_{\theta_{\mathrm{QCD}}} = \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

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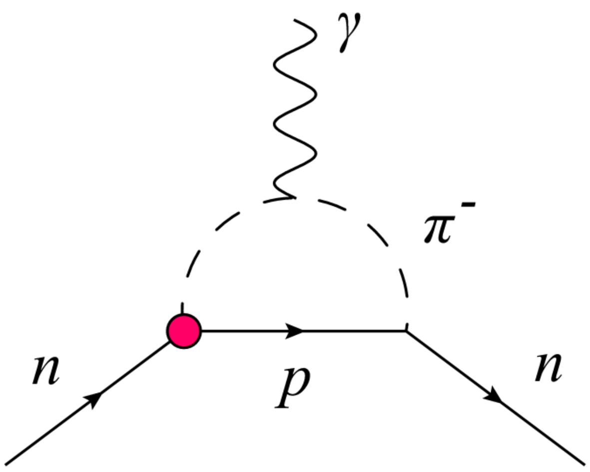

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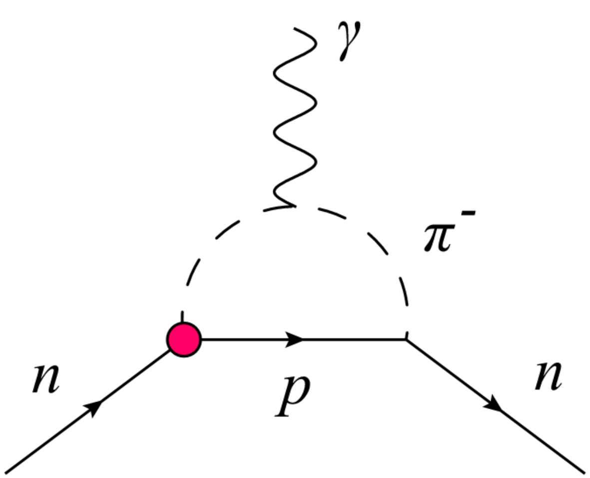
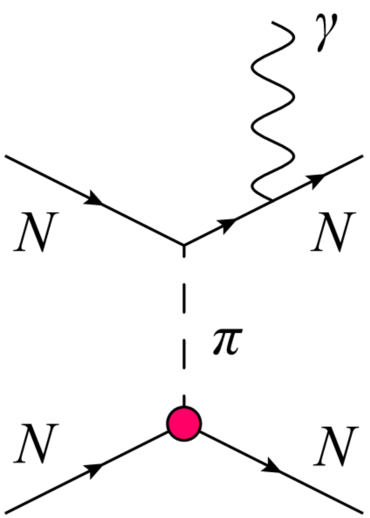


CP-violating intranuclear forces

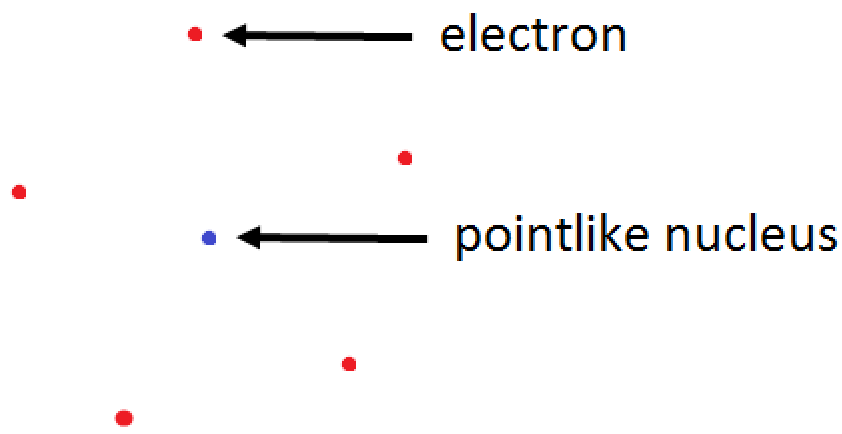


In nuclei, *tree-level* CP-violating intranuclear forces dominate over *loop-induced* nucleon EDMs [loop factor = $1/(8\pi^2)$].

Screening of Hadronic CP Violation in Atoms

[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."



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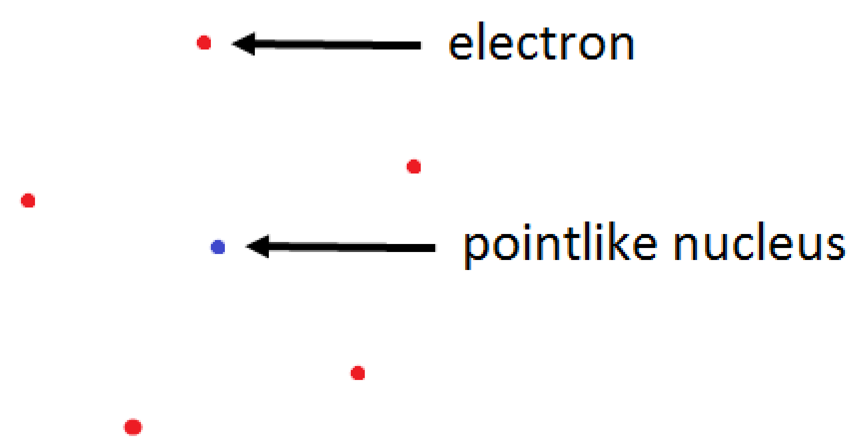

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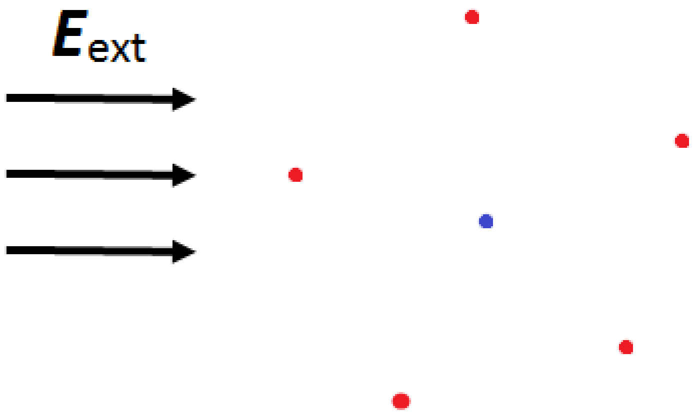

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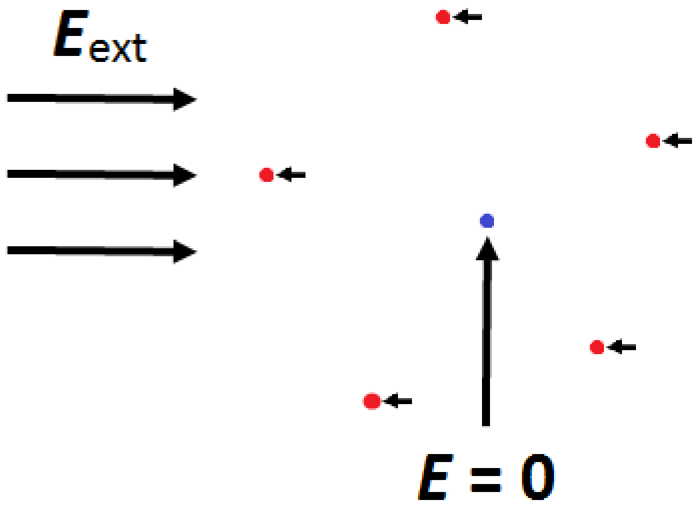

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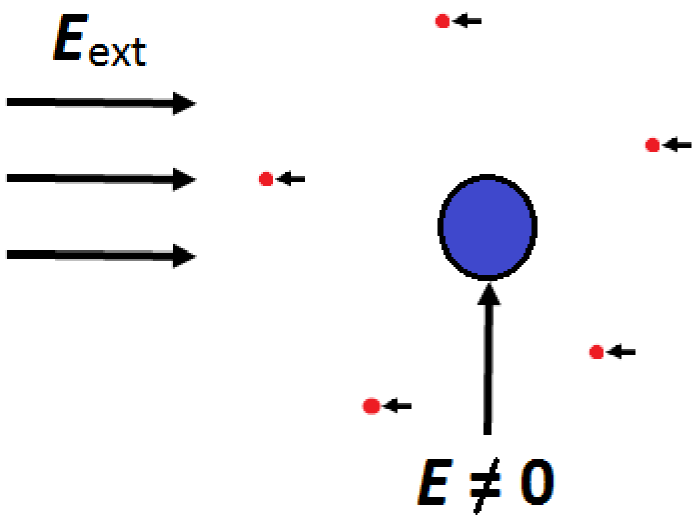
Lifting of Schiff's Theorem

[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*.



Leptonic CP Violation in Paramagnetic Molecules

Over the past decade, molecular experiments have improved sensitivity to electron EDM d_e by more than 100-fold:

ThO bound: $|d_e| < 10^{-29}$ *e* cm

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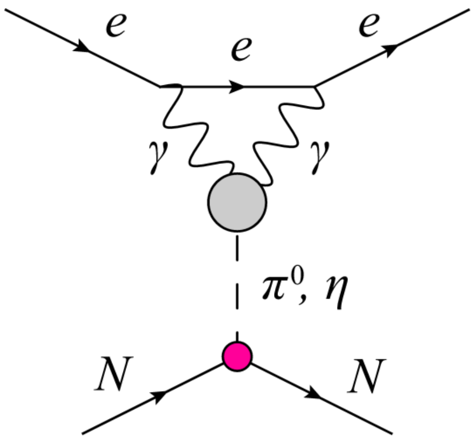
What about sensitivity to hadronic CP violation?

Hadronic CP Violation in Paramagnetic Molecules

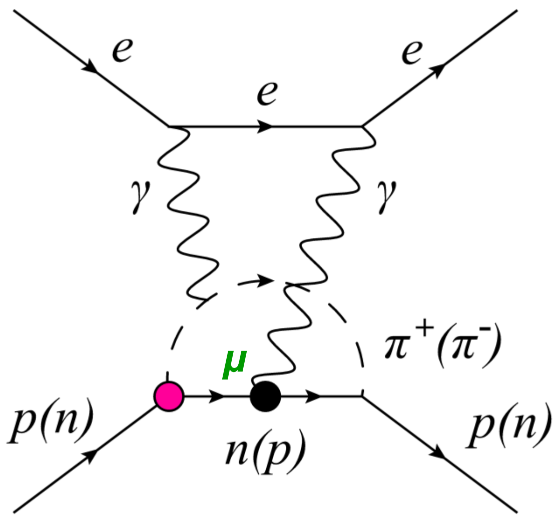
[Flambaum, Pospelov, Ritz, Stadnik, arXiv:1912.13129]

Hadronic CP-violating effects arise at 2-loop level

LO: $\mathcal{O}(m_\pi^{-2})$



NLO: $\mathcal{O}(m_\pi^{-1})$



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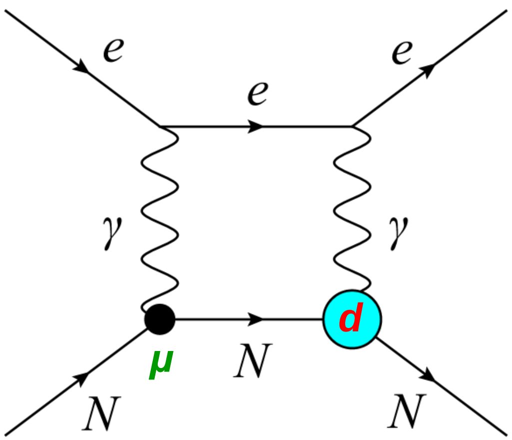

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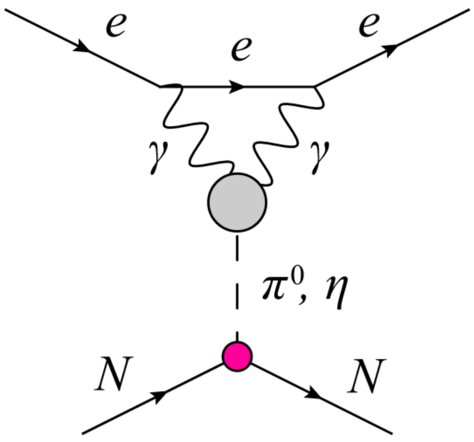

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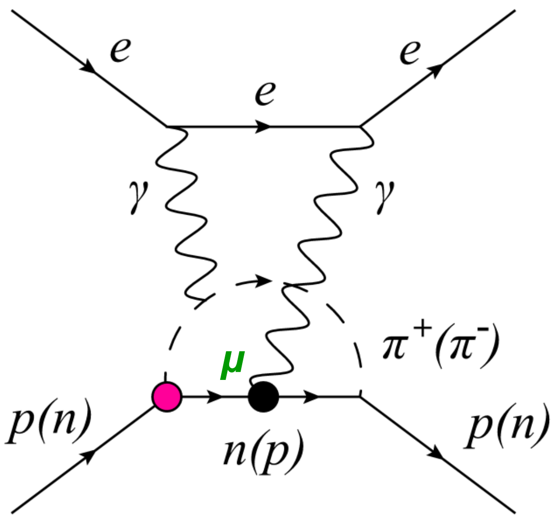

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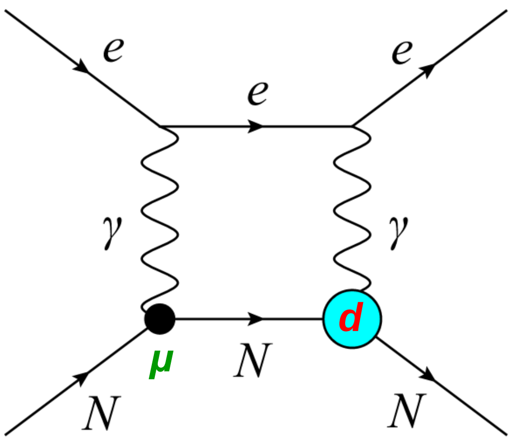

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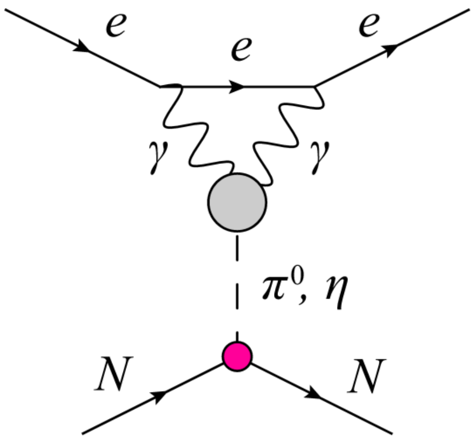

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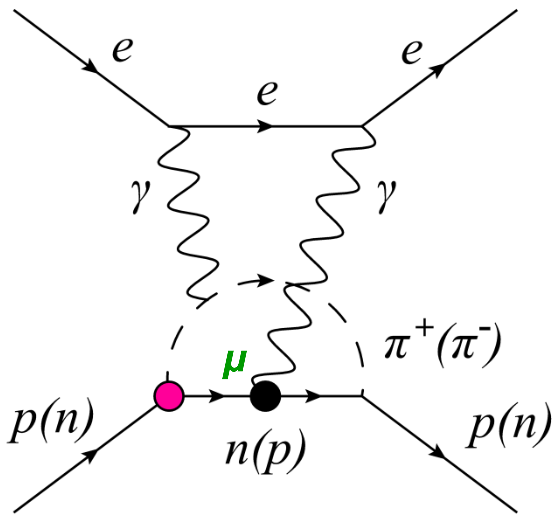

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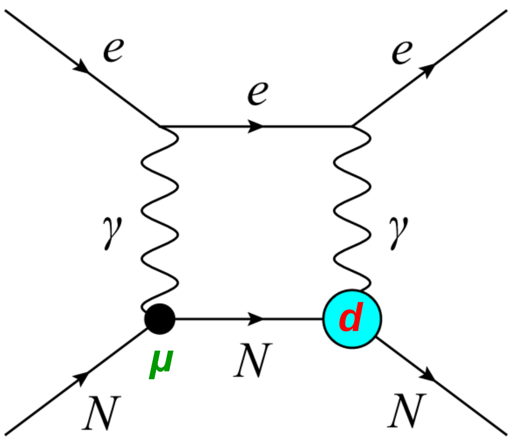

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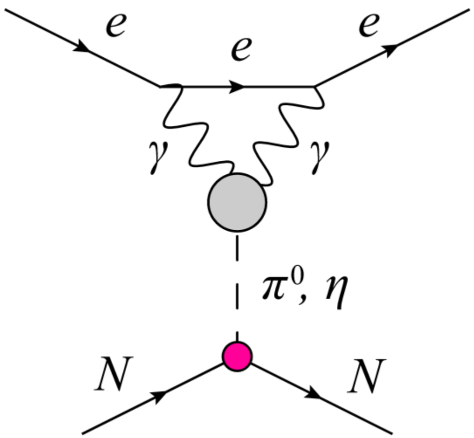

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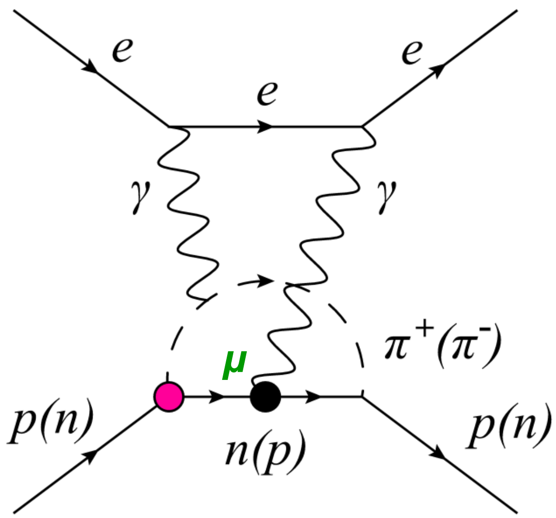

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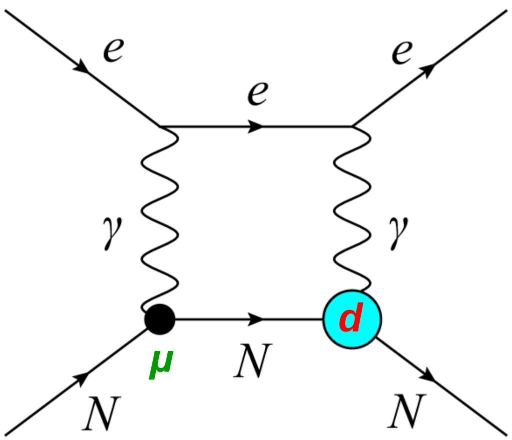

π^0,η contributions: *opposite sign*

p,n contributions: *same sign*

Example – θ_{QCD} term:

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

Bounds on Hadronic CP Violation Parameters

ThO bounds: [Flambaum, Pospelov, Ritz, Stadnik, arXiv:1912.13129]

$|\theta|_{\mathrm{ThO}} < \mathbf{3 \times 10^{-8}}$

$|\theta|_{n} < 2 \times 10^{-10}$

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Clean bound on $\bar{g}_{\pi NN}^{(1)}$, unlike from Hg Schiff moment (where *nuclear uncertainties can formally nullify sensitivity* to $\bar{g}_{\pi NN}^{(1)}$ and derived quantities, e.g. $\tilde{d}_u - \tilde{d}_d$)

Outline

1. Electroweak Phenomena

2. Electric Dipole Moments

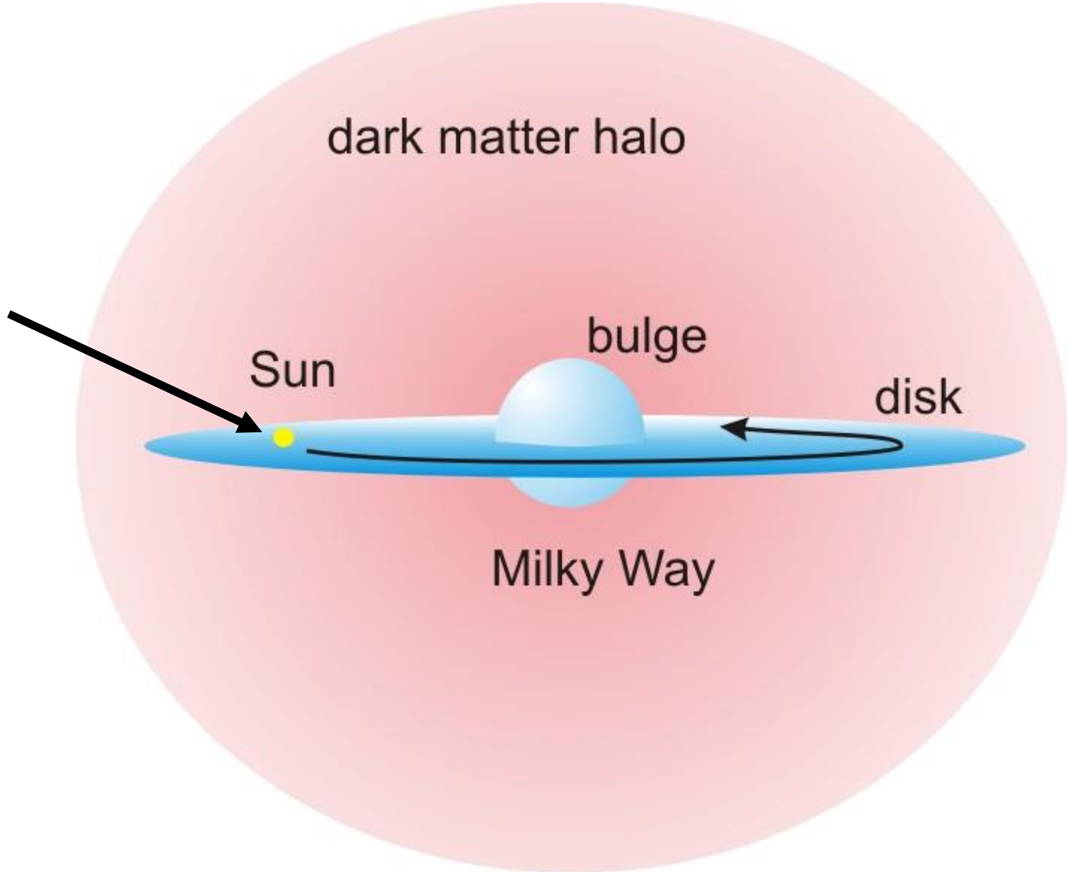
3. **Ultra-Low-Mass Dark Matter**

Motivation

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



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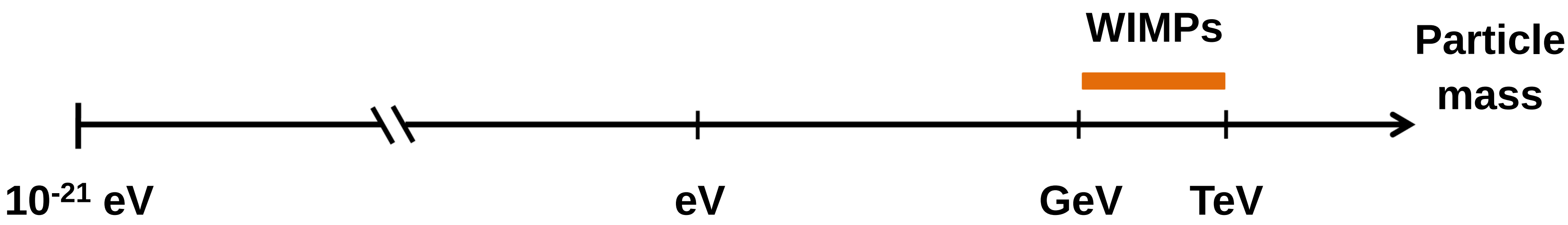

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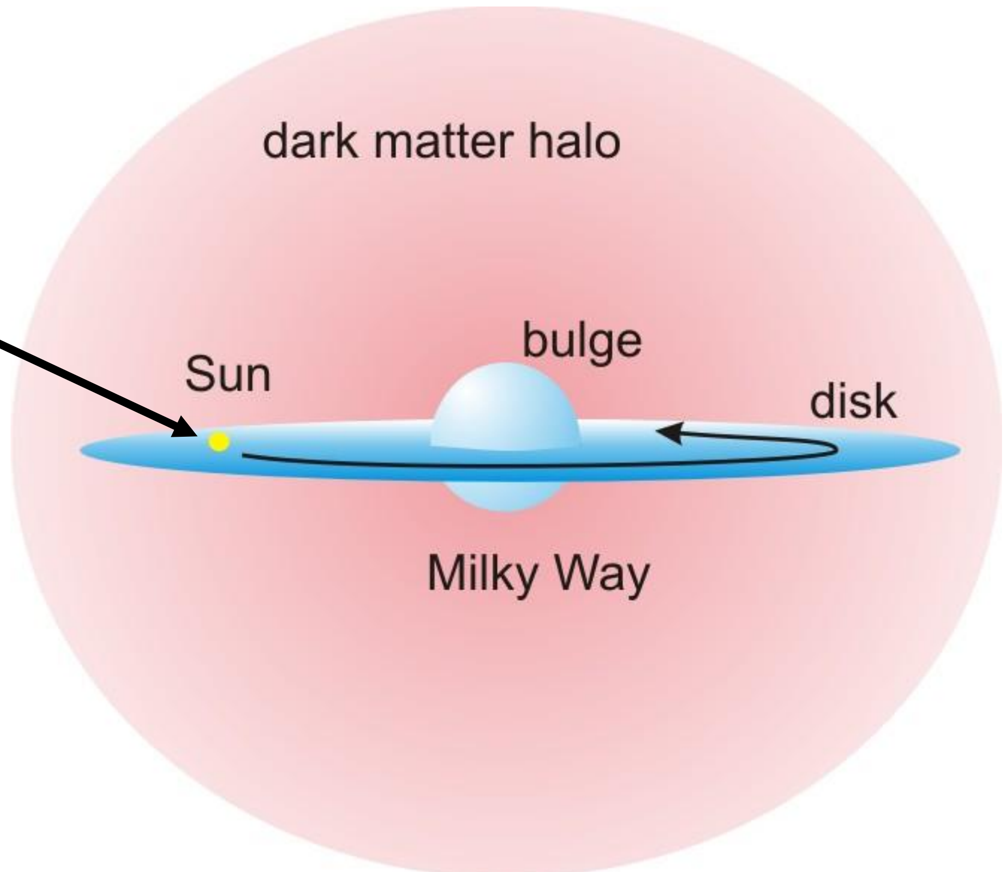

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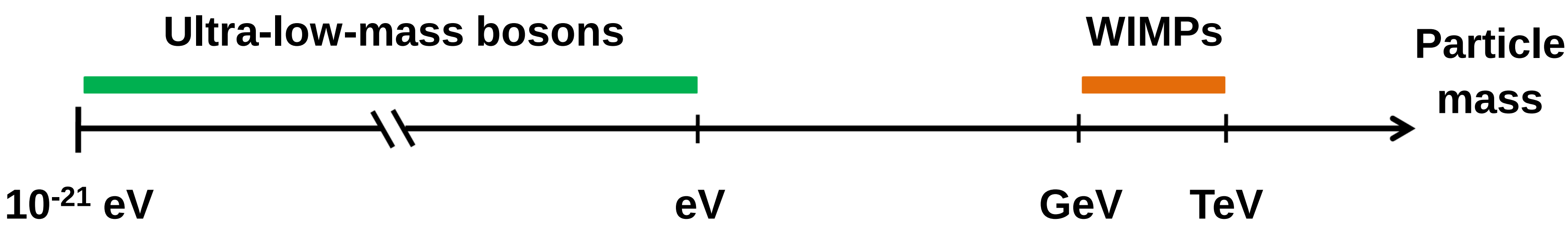

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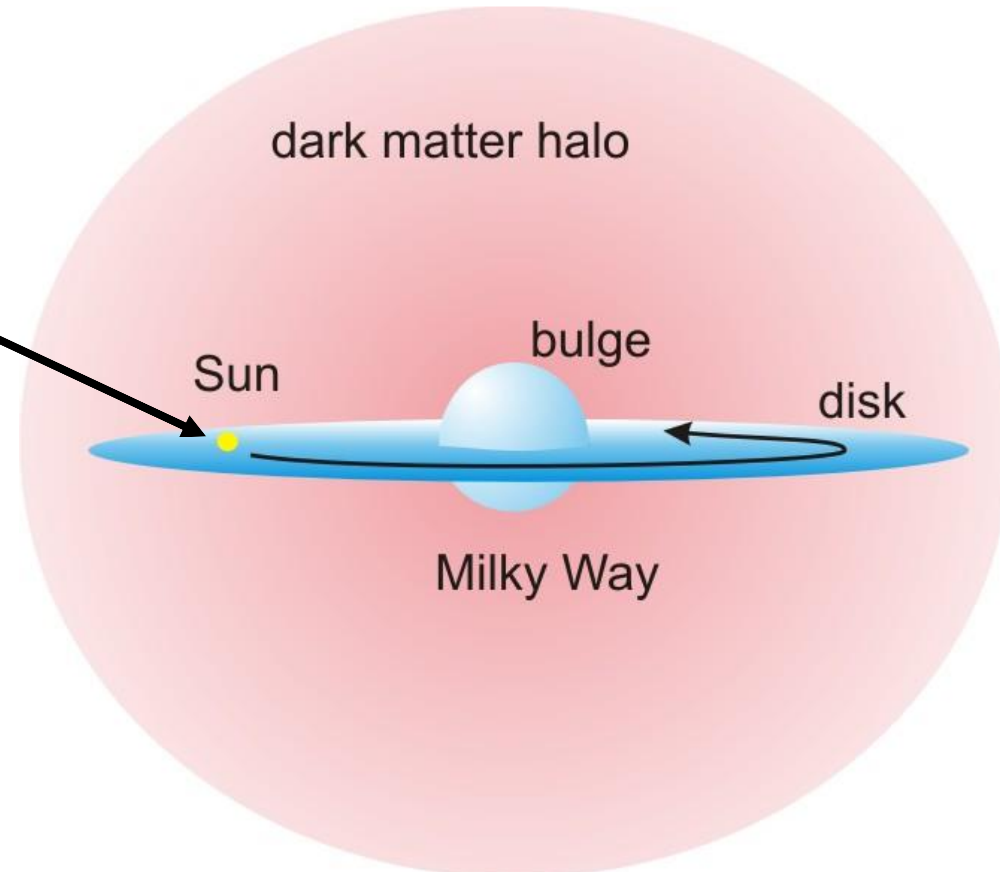
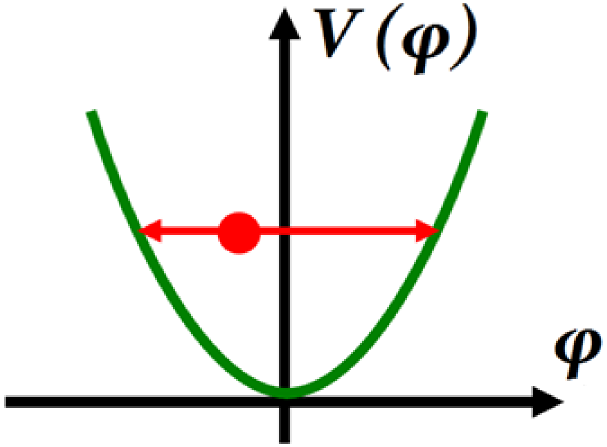


Low-mass Spin-0 Dark Matter

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



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

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

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

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

Low-mass Spin-0 Dark Matter

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Scalars (Dilatons):	**Pseudoscalars (Axions):**
$\varphi \xrightarrow{P} +\varphi$	$\varphi \xrightarrow{P} -\varphi$

→ Time-varying fundamental constants

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

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Solid material

$L \sim Na_B = N/(m_e\alpha)$

$$\frac{\delta L(t)}{L} \approx -\frac{\delta\alpha(t)}{\alpha} - \frac{\delta m_e(t)}{m_e}$$

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

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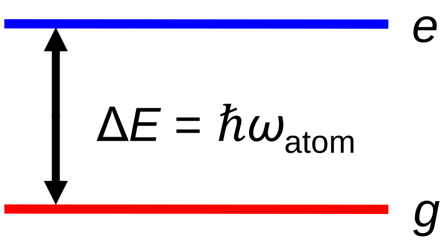
Electronic transition



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

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

$$\Rightarrow \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

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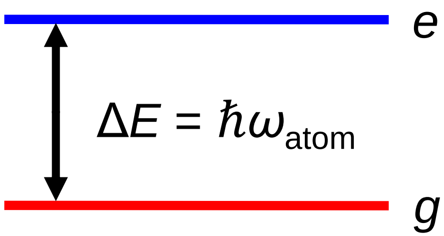
cf.

Electronic transition

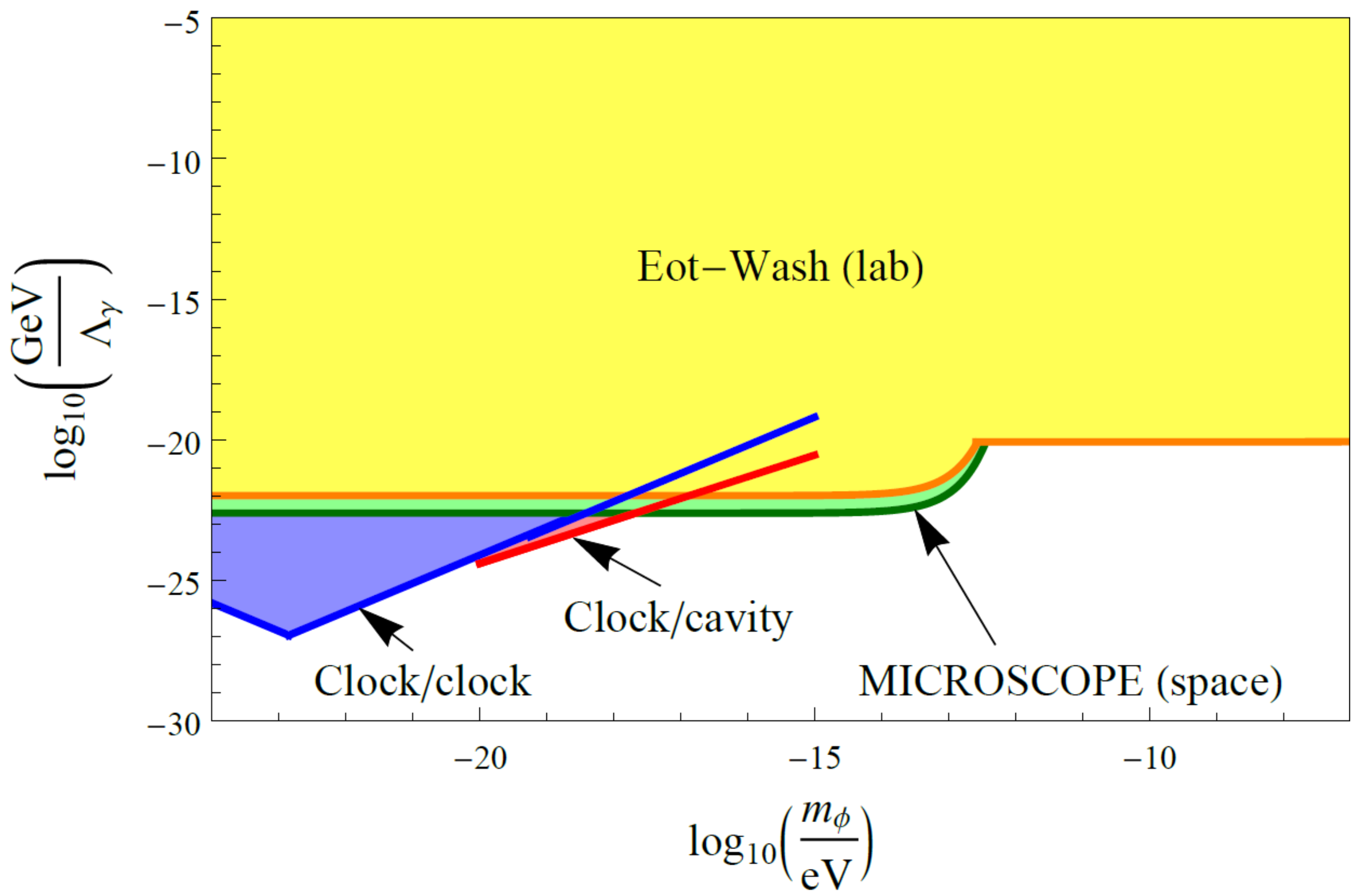


$\hbar \omega_{\text{atom}} \sim e^2/a_{\text{B}}$

- **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)]

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)]



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

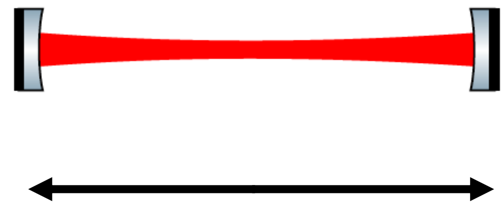
[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Solid material

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

cf.

Freely-suspended mirrors



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

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

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

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

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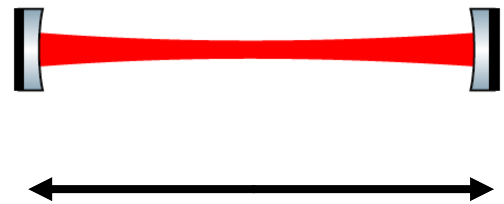

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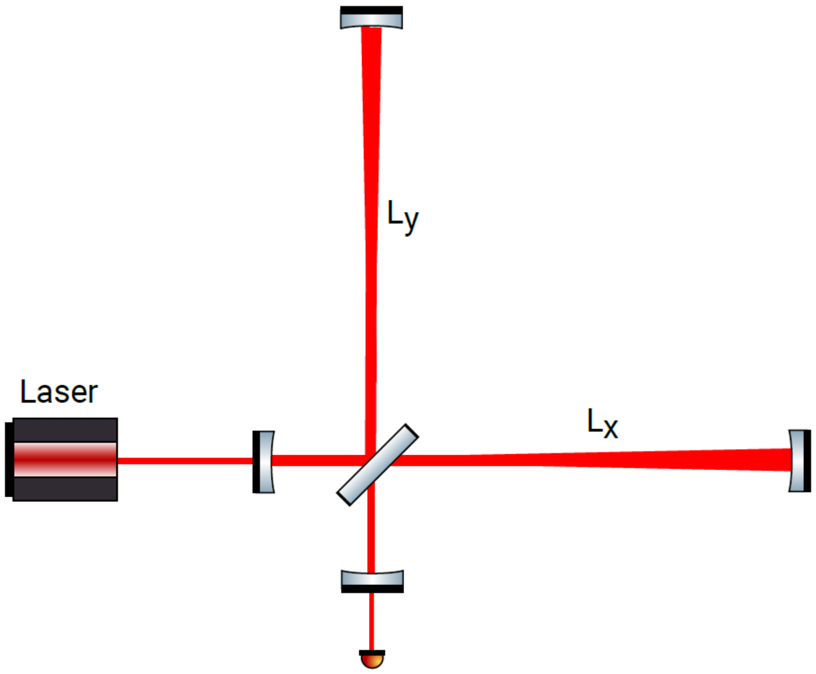
cf. $$\frac{\delta \Phi}{\Phi} \approx \frac{\delta \alpha}{\alpha}$$

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

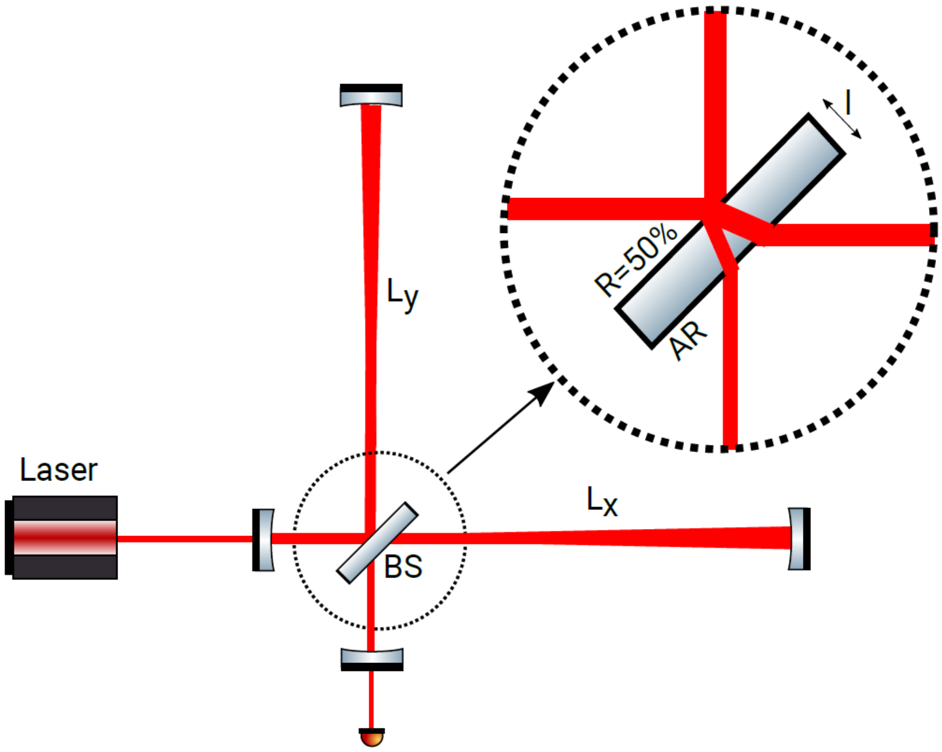
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



Michelson interferometer (GEO 600)

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

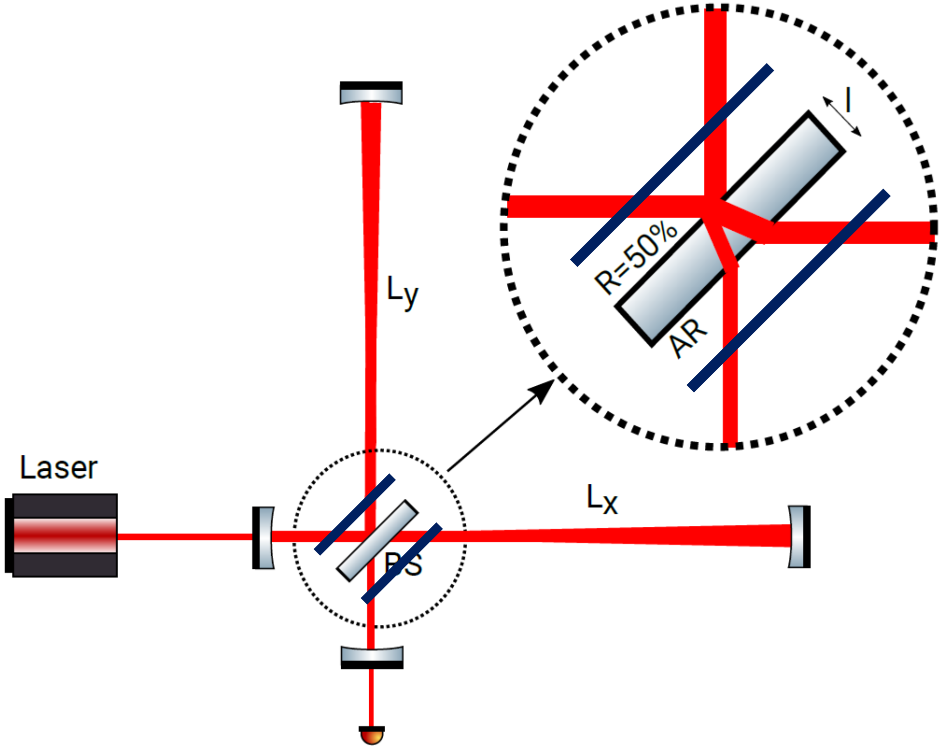
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]



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

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

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



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

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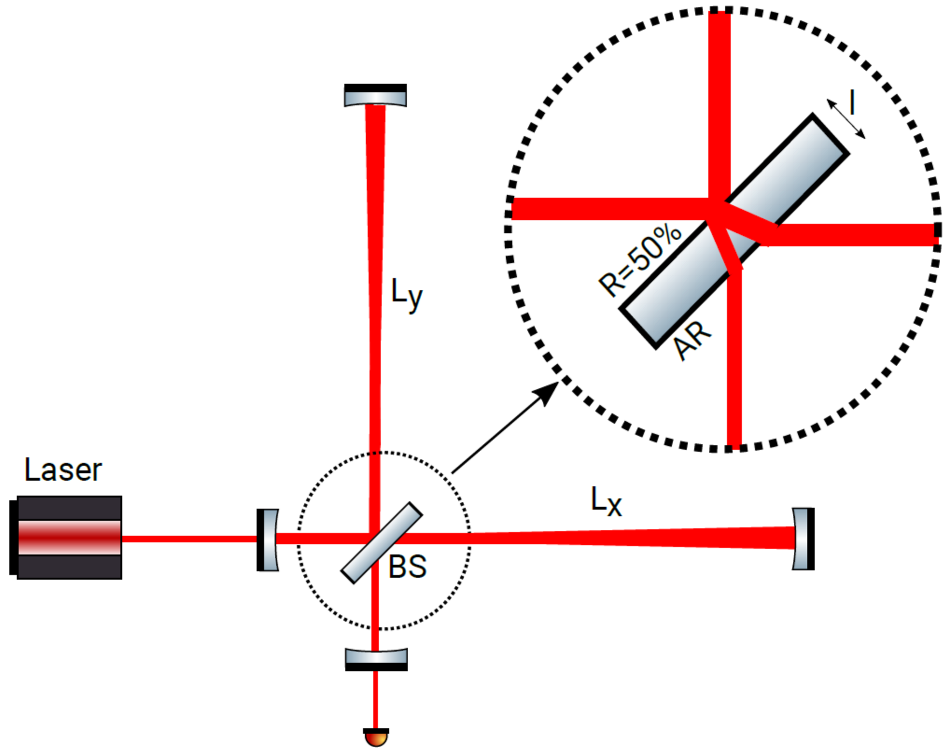
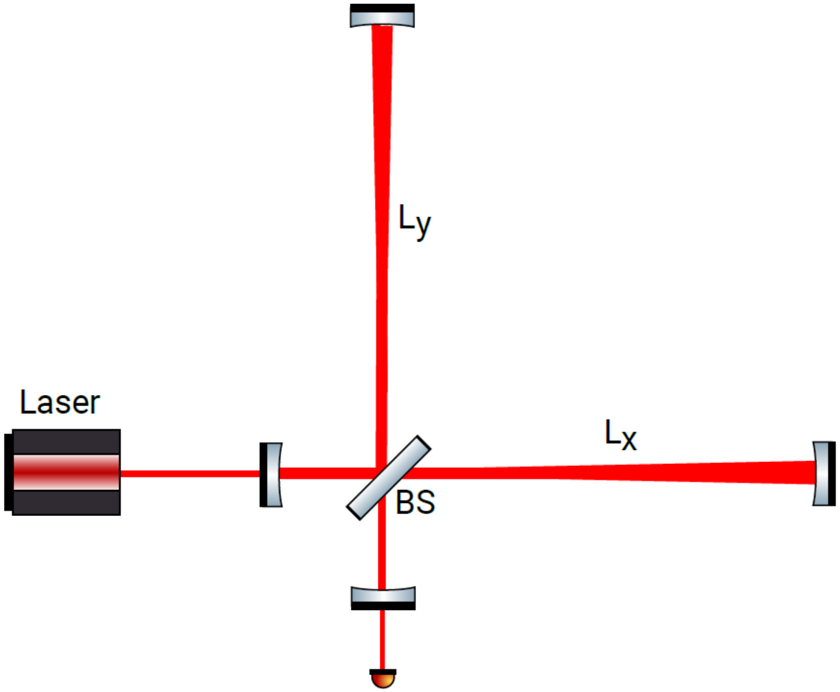


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{DM} \approx f_{vibr,BS} \sim v_{sound}/l$, $Q \sim 10^6$ enhancement

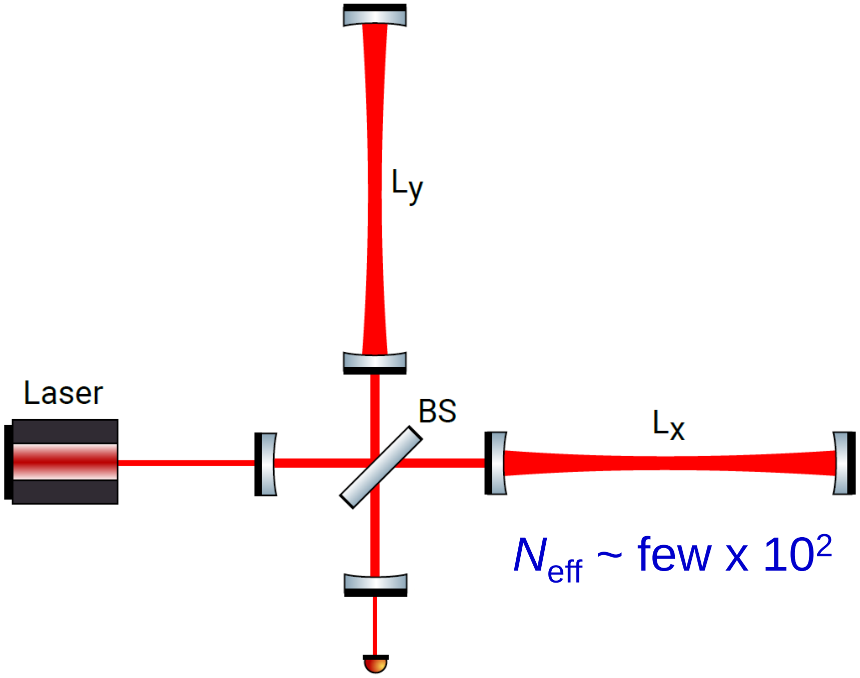
Michelson vs Fabry-Perot-Michelson Interferometers

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

Michelson interferometer
(GEO 600, Fermilab holometer)



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



$N_{\mathrm{eff}} \sim$ few x 10^2

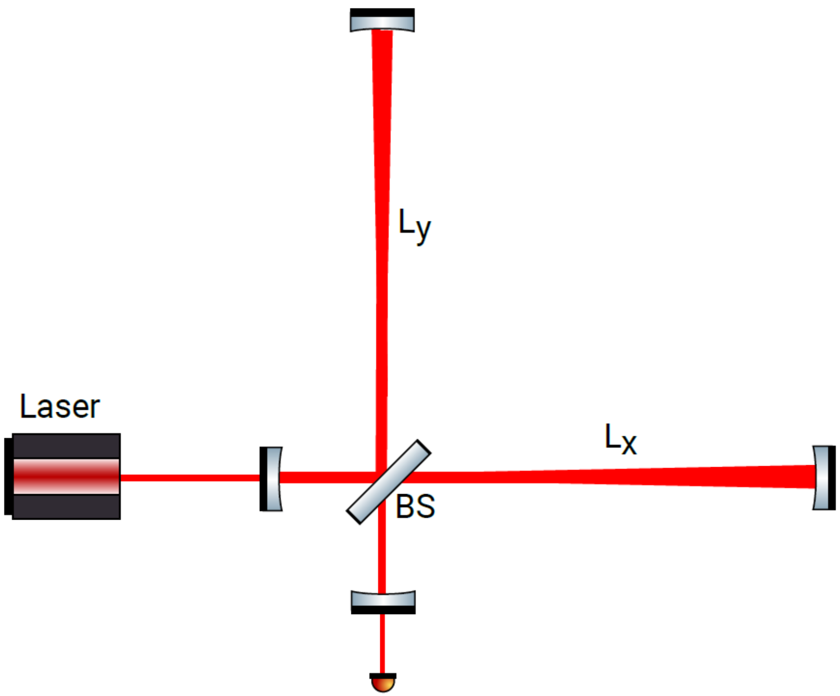
$\delta(L_x - L_y)_{\mathrm{BS}} \sim \delta(nl)$

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

Michelson vs Fabry-Perot-Michelson Interferometers

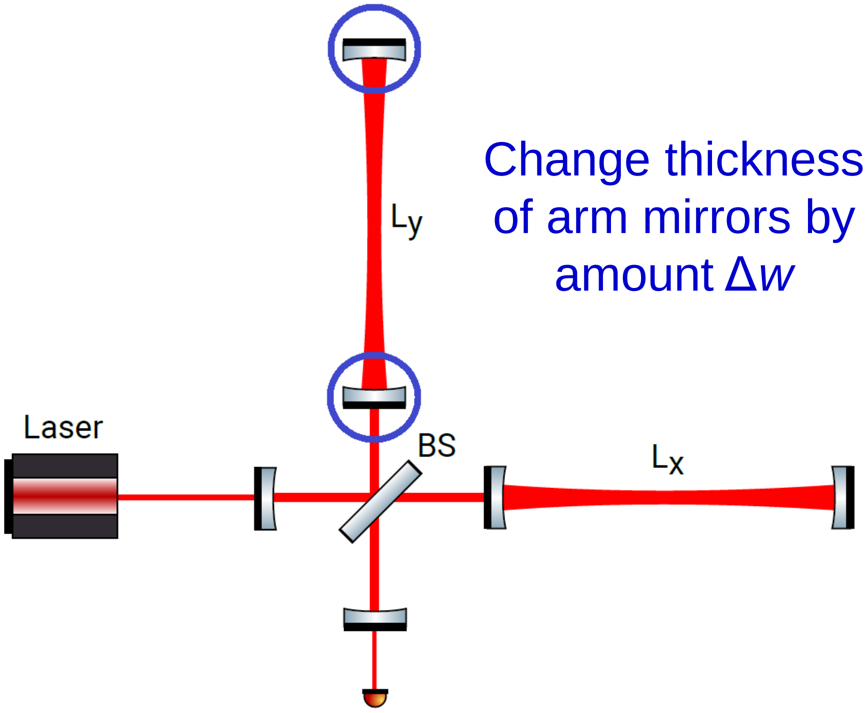
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

Michelson interferometer
(GEO 600, Fermilab holometer)



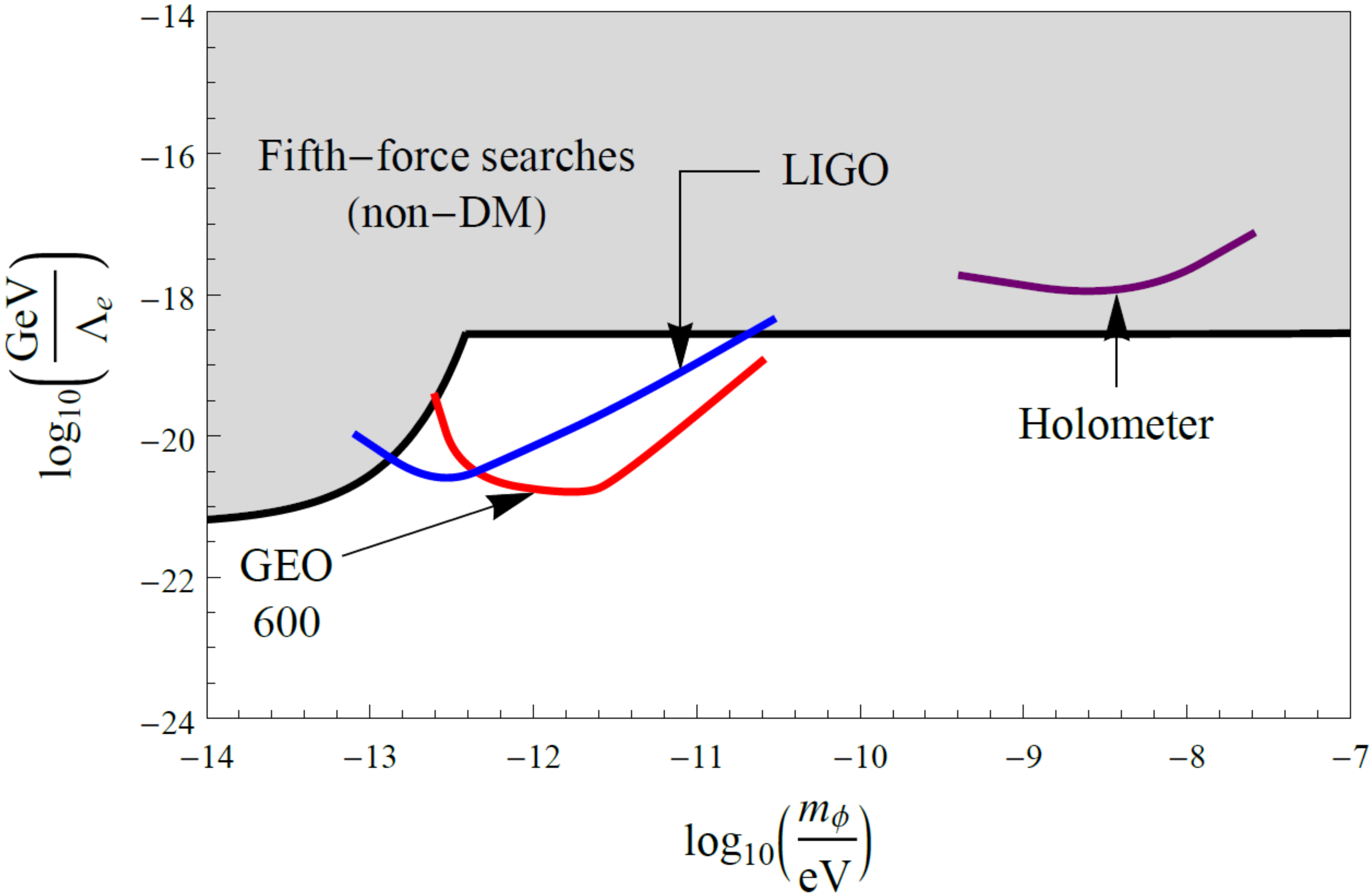
$$\delta(L_x - L_y)_{BS} \sim \delta(nl)$$

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

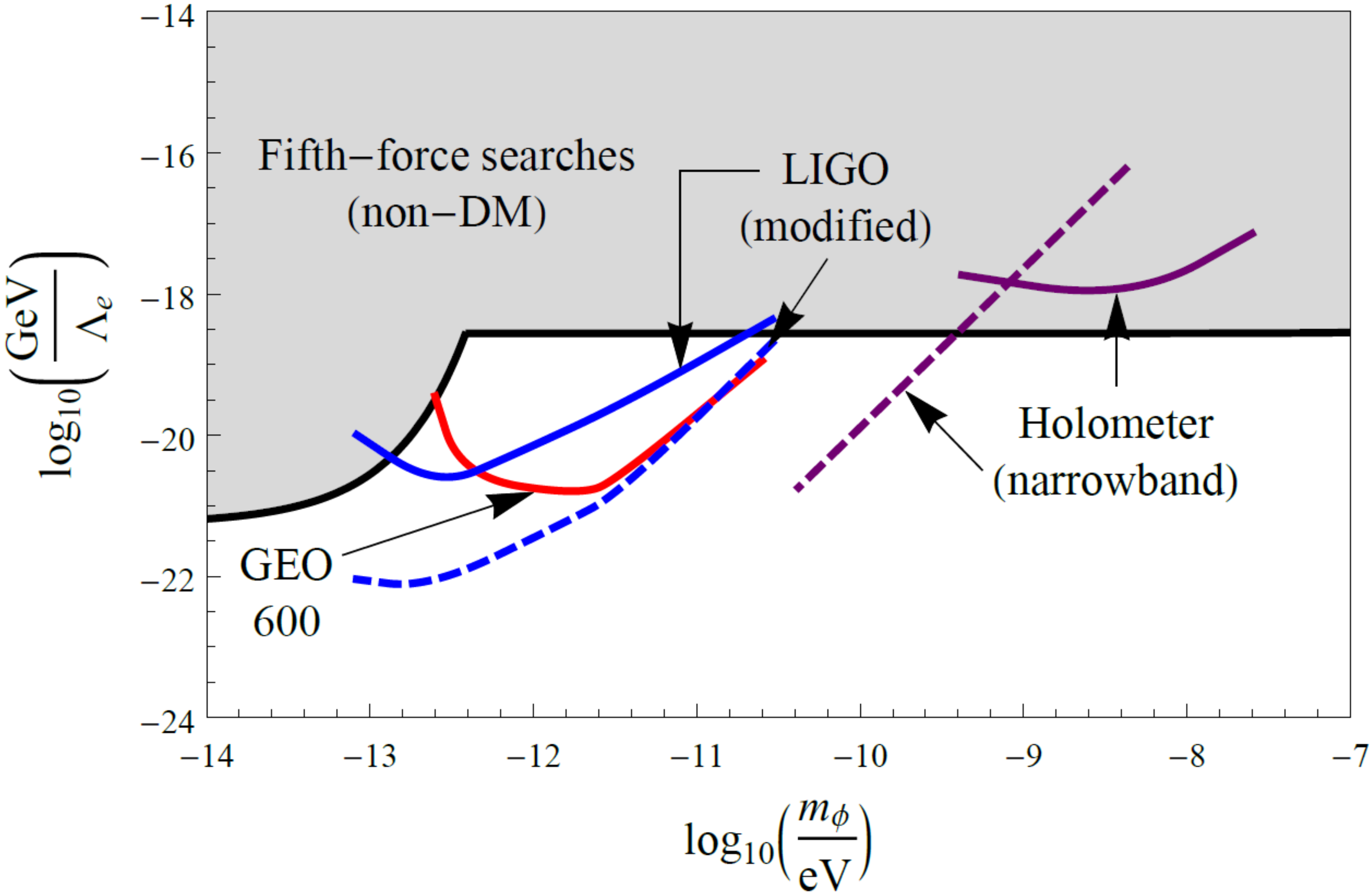


$$\delta(L_x - L_y) \approx \delta(\Delta w)$$

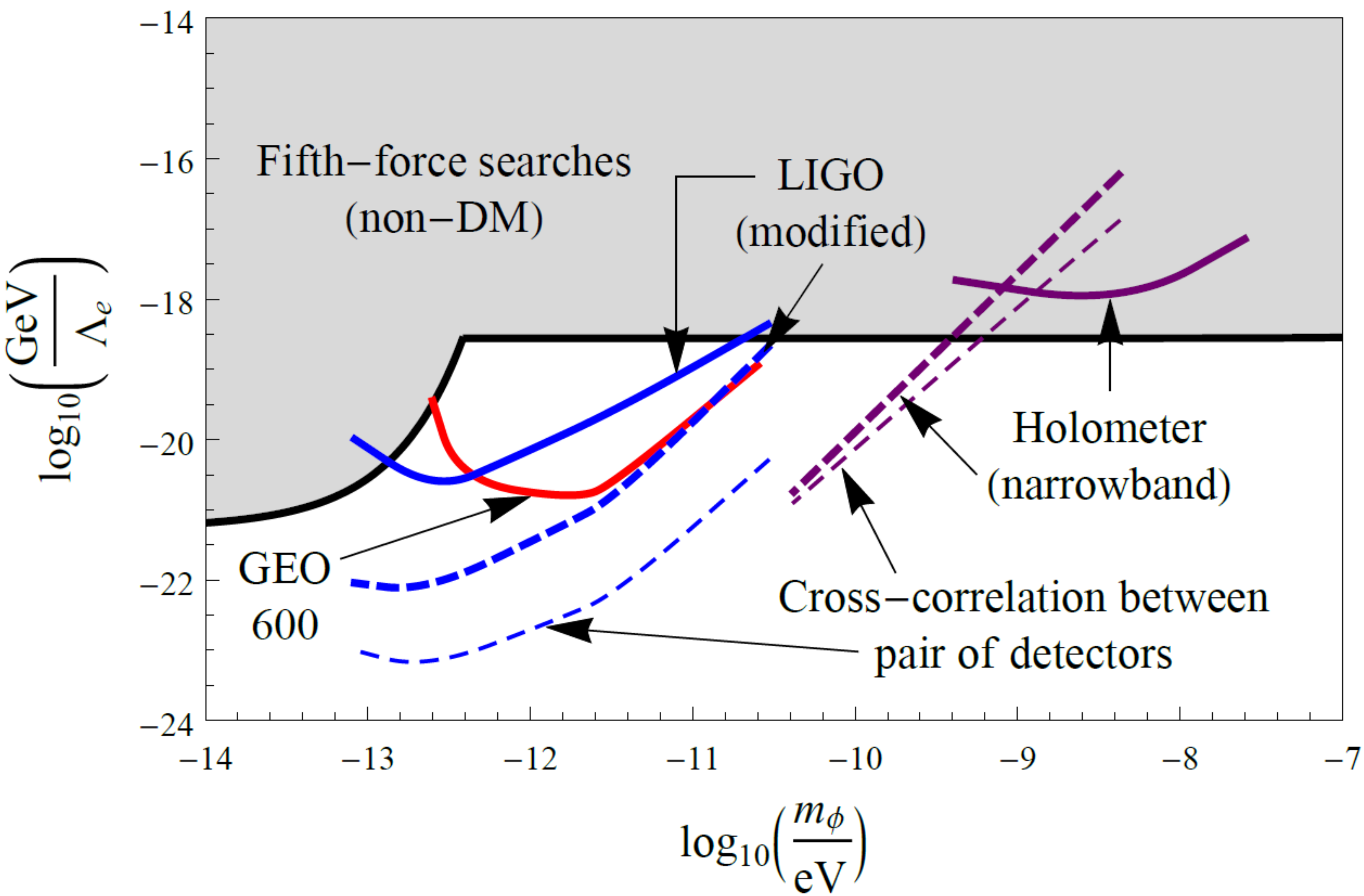
Linear Interaction of Scalar Dark Matter with the Electron



Linear Interaction of Scalar Dark Matter with the Electron



Linear Interaction of Scalar Dark Matter with the Electron



Summary

1. Electroweak Phenomena

- *Cs PNC experiments:* electroweak theory (PNC effects), nuclear anapole moments, new Z-like bosons
- *Muonium hyperfine ground-state spectroscopy:* electroweak theory (PC effects), highly-singular PC forces

2. Electric Dipole Moments

- *EDM experiments in paramagnetic molecules:* sensitive probes of hadronic CP violation, in addition to leptonic CP violation

3. Ultra-Low-Mass Dark Matter

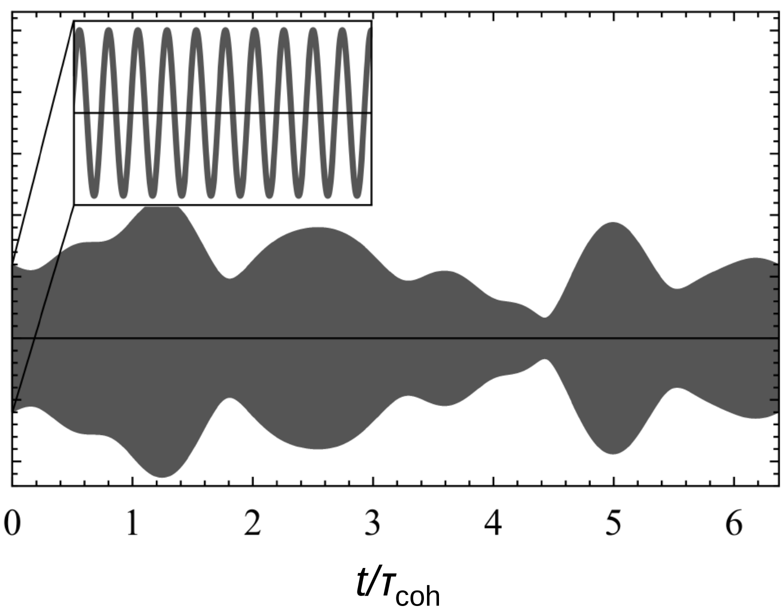
- *Optical interferometers and cavities:* sensitive probes of apparent oscillations in α and m_e induced by oscillating scalar DM field

Back-Up Slides

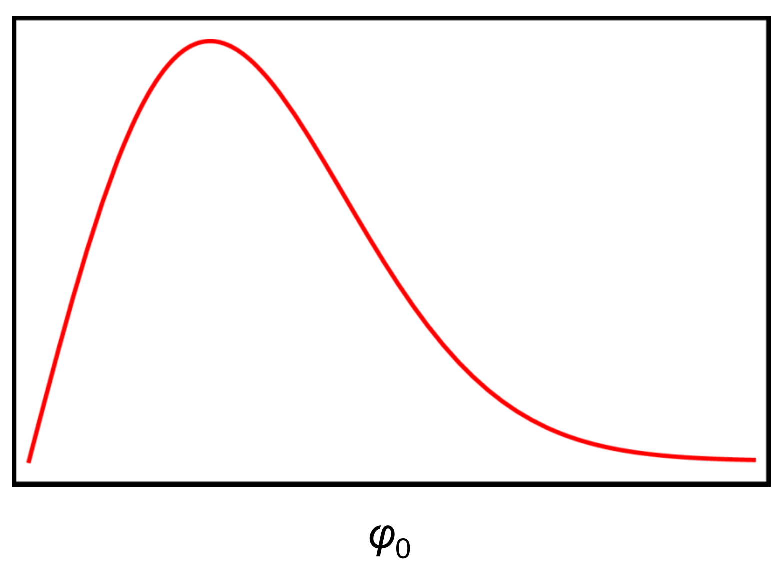
Temporal Coherence

- *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 $<\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{DM,local} \approx 0.4$ GeV/cm^3)
- $\Delta E_\varphi / E_\varphi \sim <v_\varphi^2>/c^2 \sim 10^{-6}$ => $\tau_{coh} \sim 2\pi/\Delta E_\varphi \sim 10^6 T_{osc}$

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)]

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

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

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

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

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

[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 $\rho_{\rm DM}$): BBN, CMB]
+ Gradients [Fifth forces]

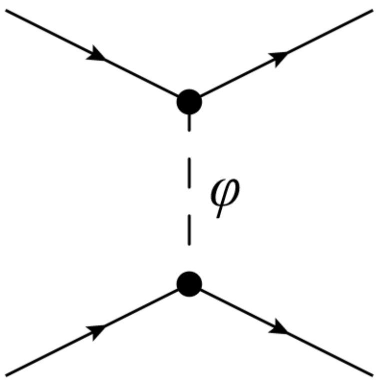
Oscillating variations
[Laboratory (high precision)]

Fifth Forces: Linear vs Quadratic Couplings

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

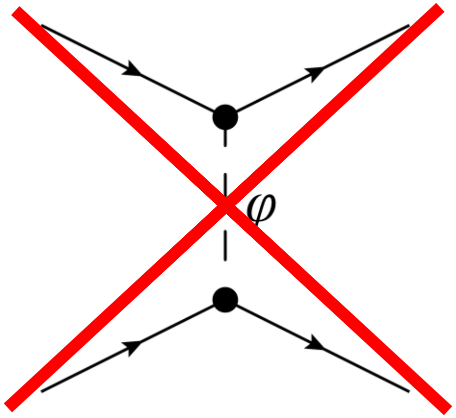
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

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

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

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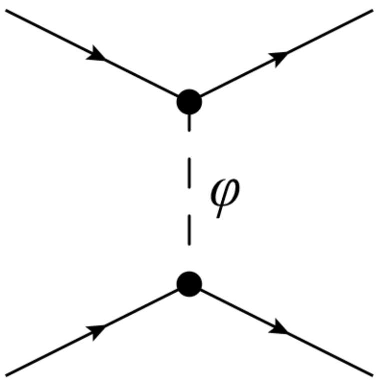

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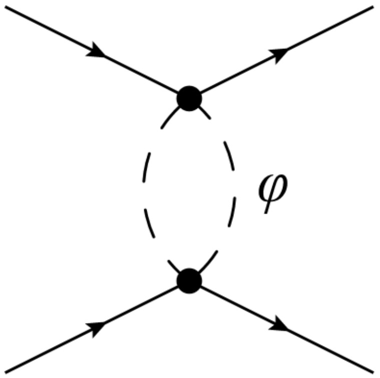

$$\phi = \phi_0 \cos(m_\phi t) \left(1 - \frac{B}{r}\right) - C \frac{e^{-2 m_\phi r}}{r^3}$$

Gradients + screening/amplification

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

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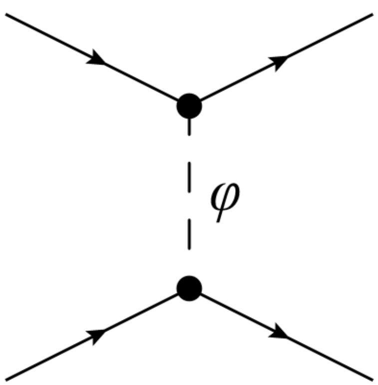
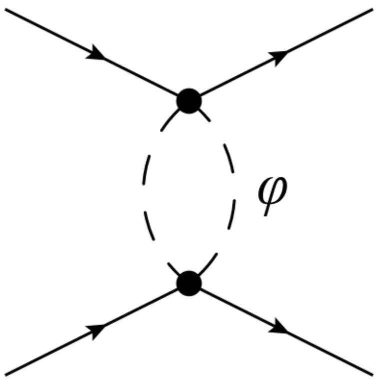


$$\phi = \underline{\phi_0 \cos(m_\phi t)} - A \frac{e^{-m_\phi r}}{r}$$

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

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

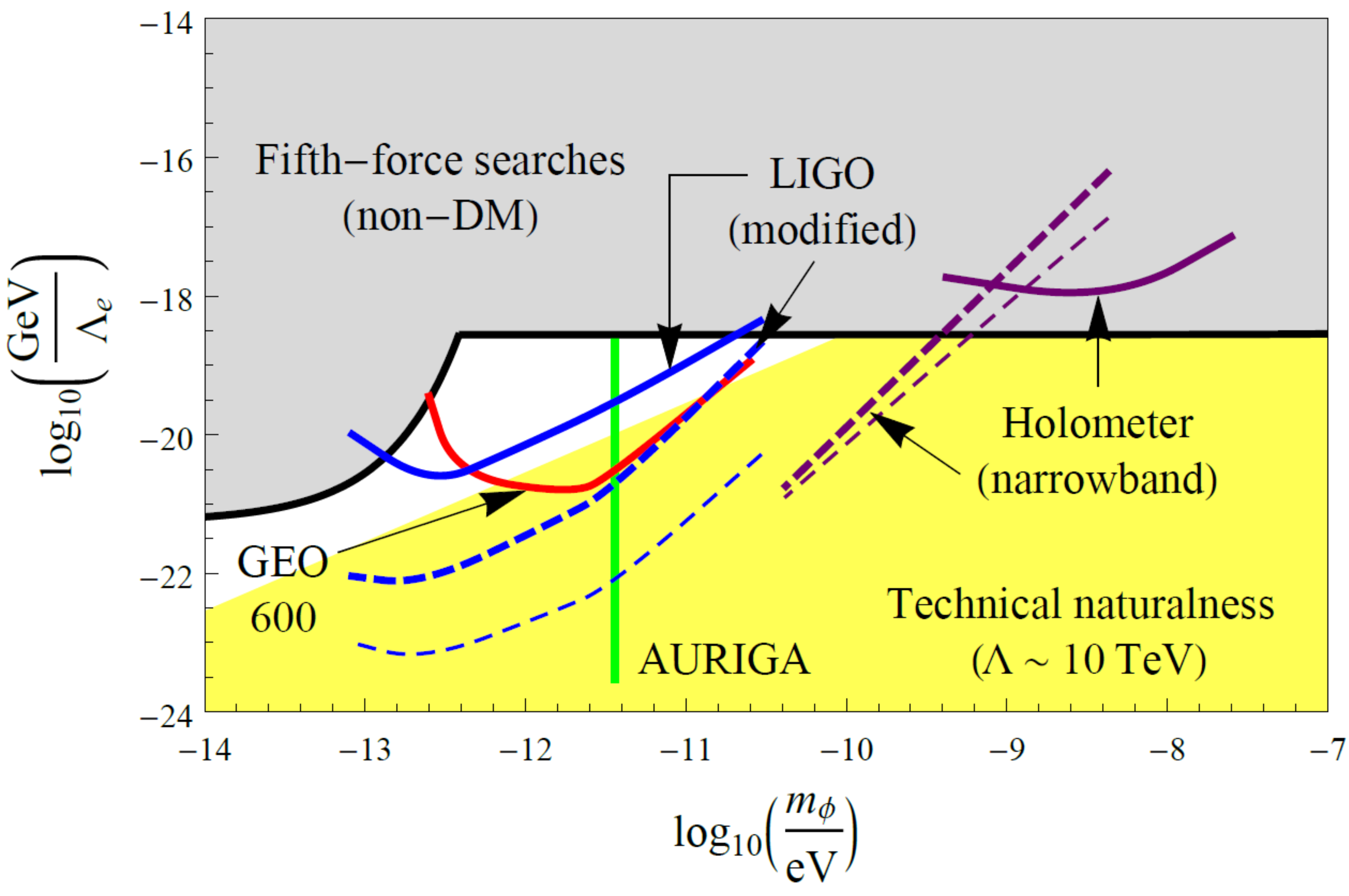
Quadratic couplings ($\varphi^2 \bar{X} X$)



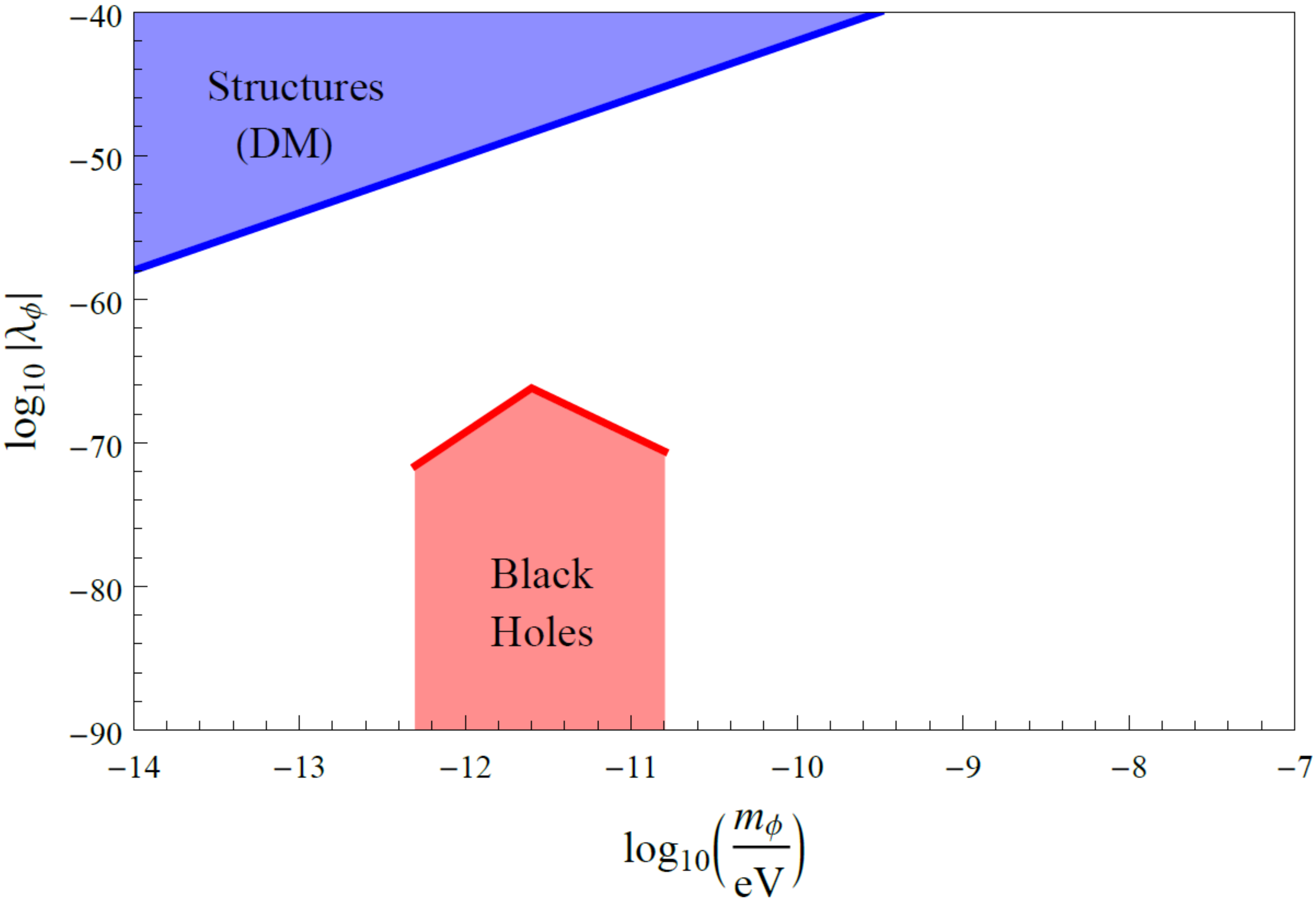
$$\phi = \underline{\phi_0 \cos(m_\phi t)} \left(1 - \frac{B}{r}\right) - C \frac{e^{-2m_\phi r}}{r^3}$$

Gradients + screening/amplification

Constraints on Linear Interaction of Scalar Dark Matter with the Electron



Quartic Self-Interaction of Scalar

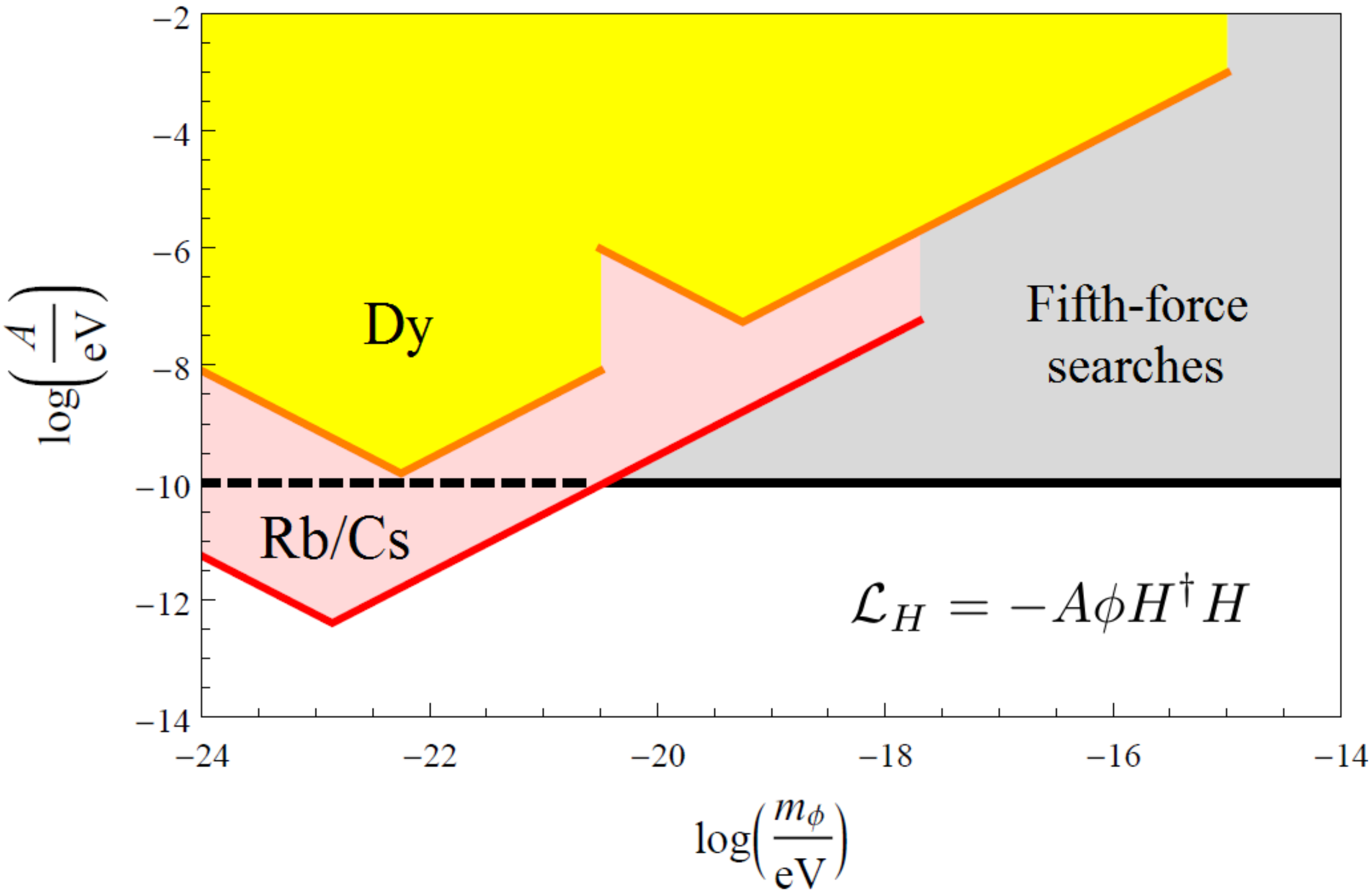


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

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

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

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

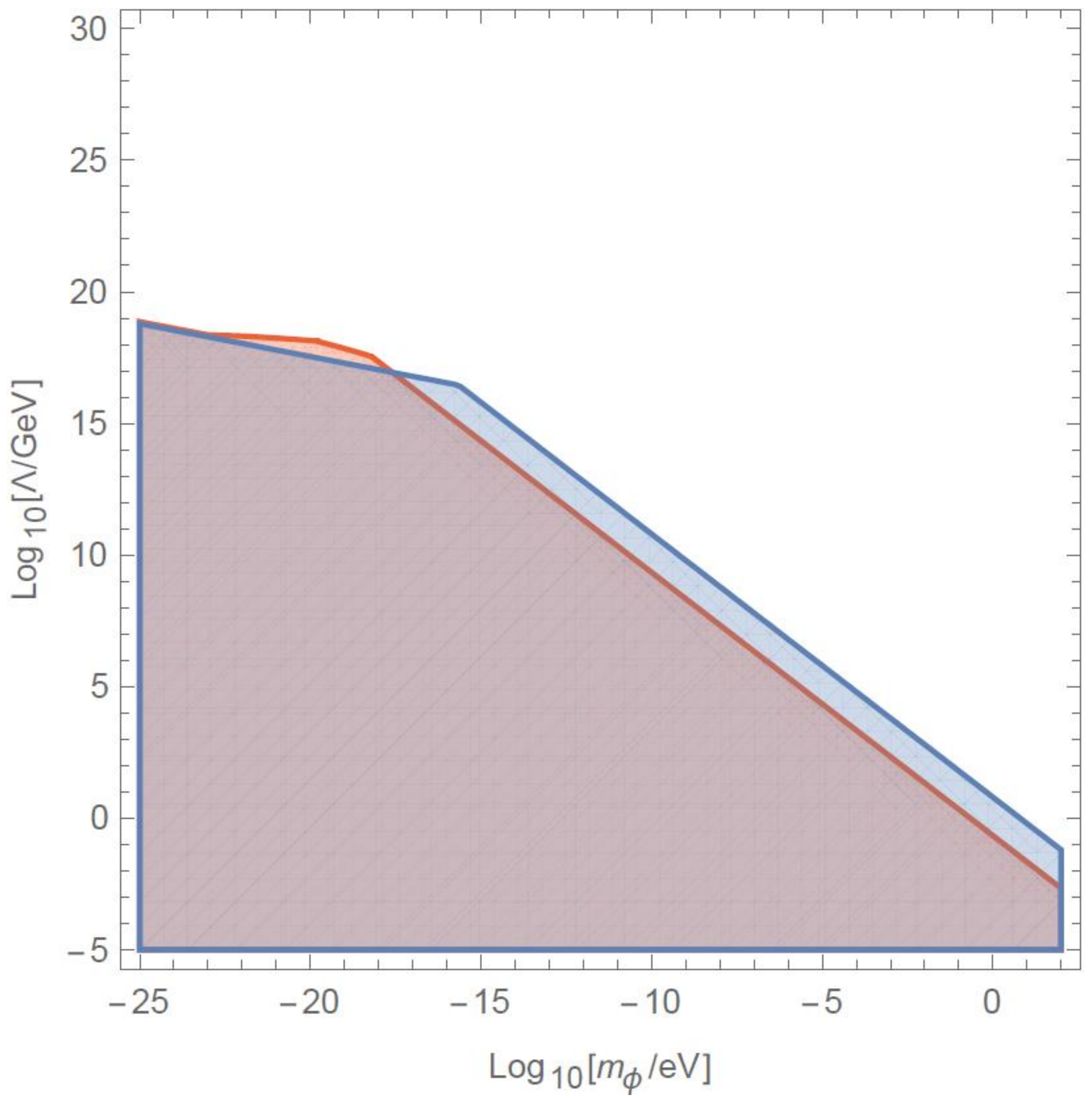
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

Back-Reaction Effects in BBN

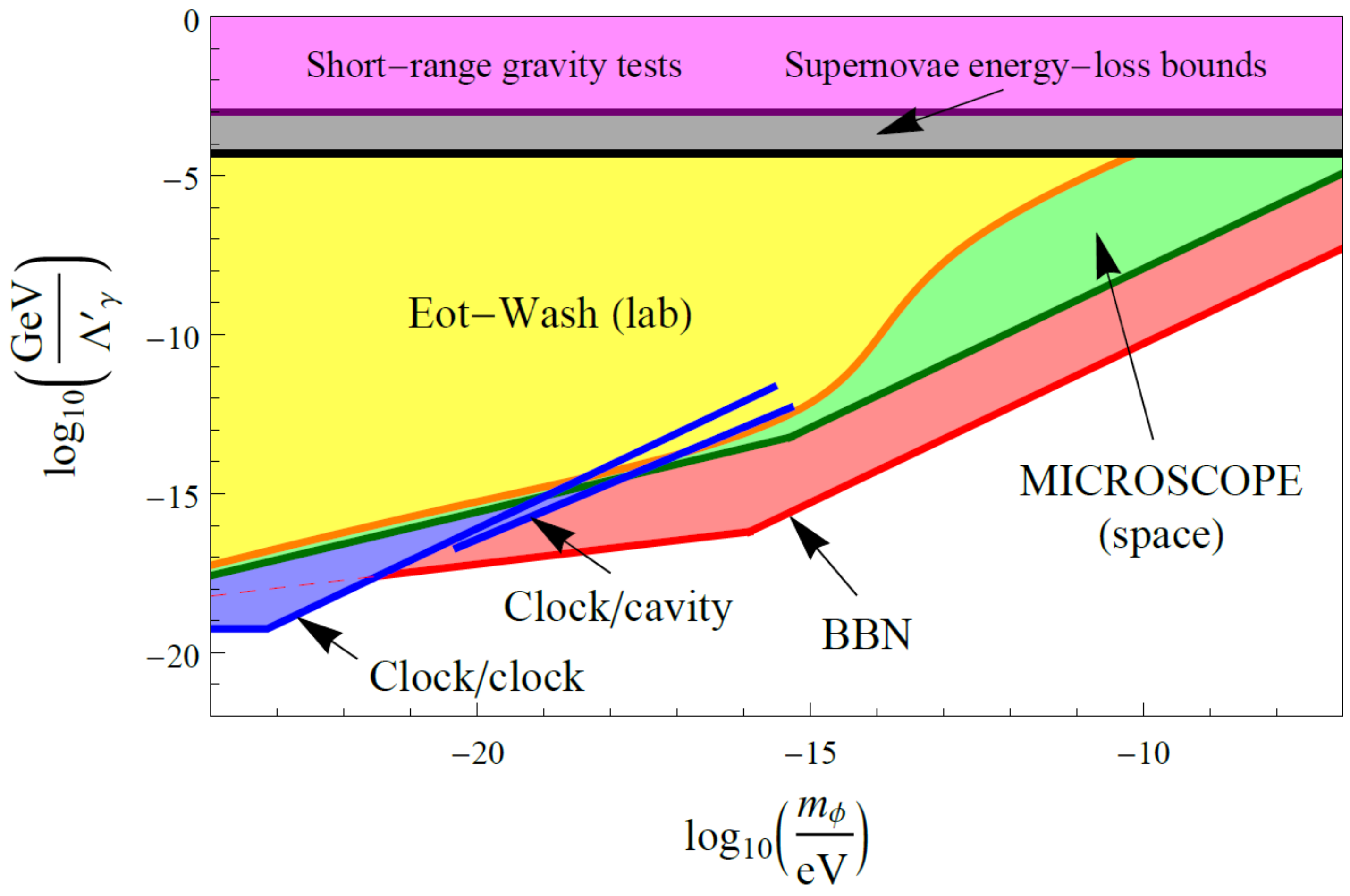
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



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!



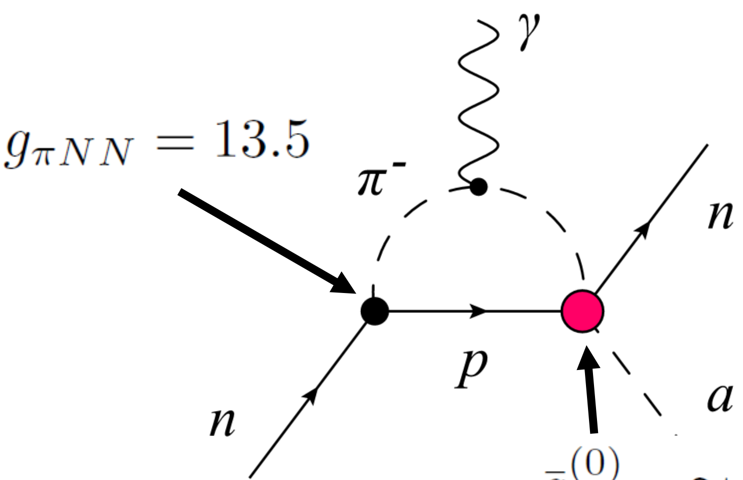
Oscillating Electric Dipole Moments

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

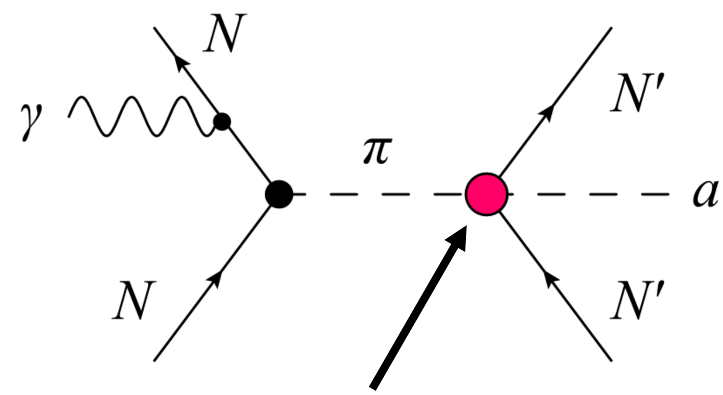
Atoms and molecules: [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

Nucleon EDMs



***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)].