# 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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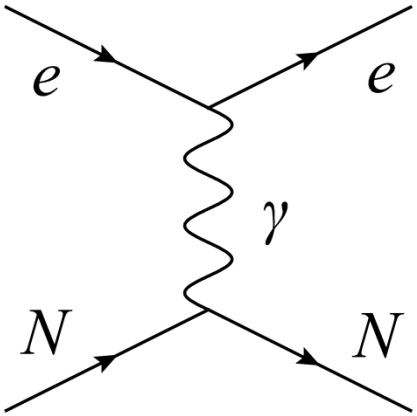
2. **Electric Dipole Moments**

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

# EW Phenomena in Atoms (PNC)

**Electromagnetic**

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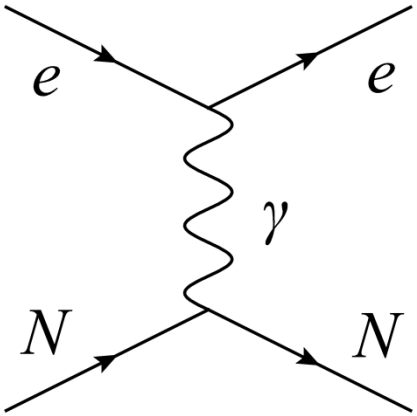


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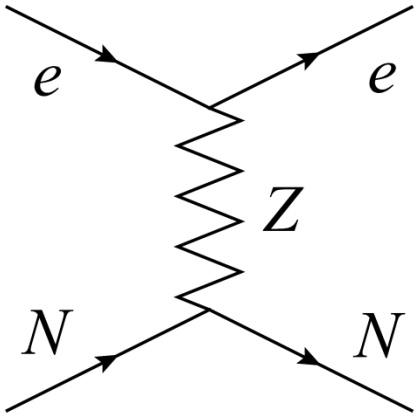


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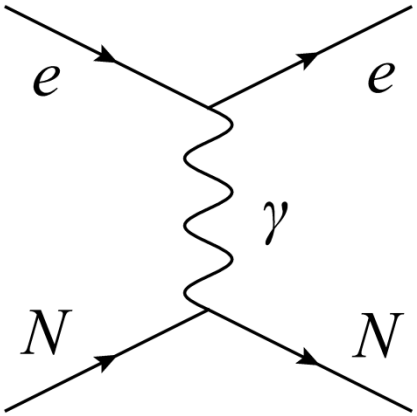


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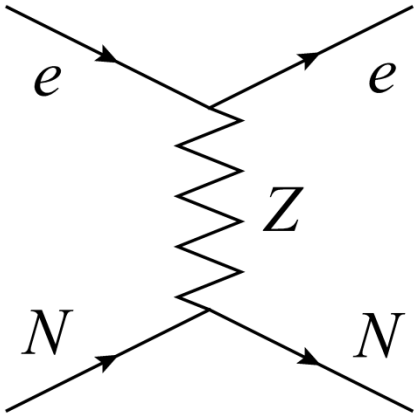


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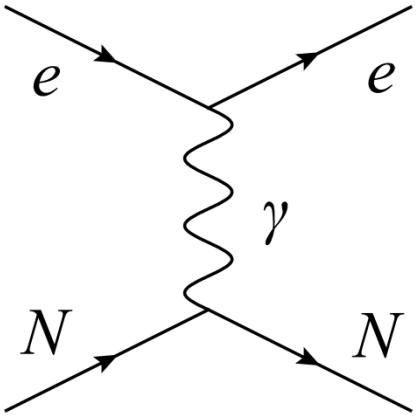


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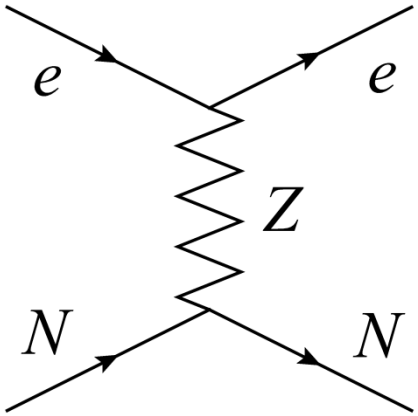


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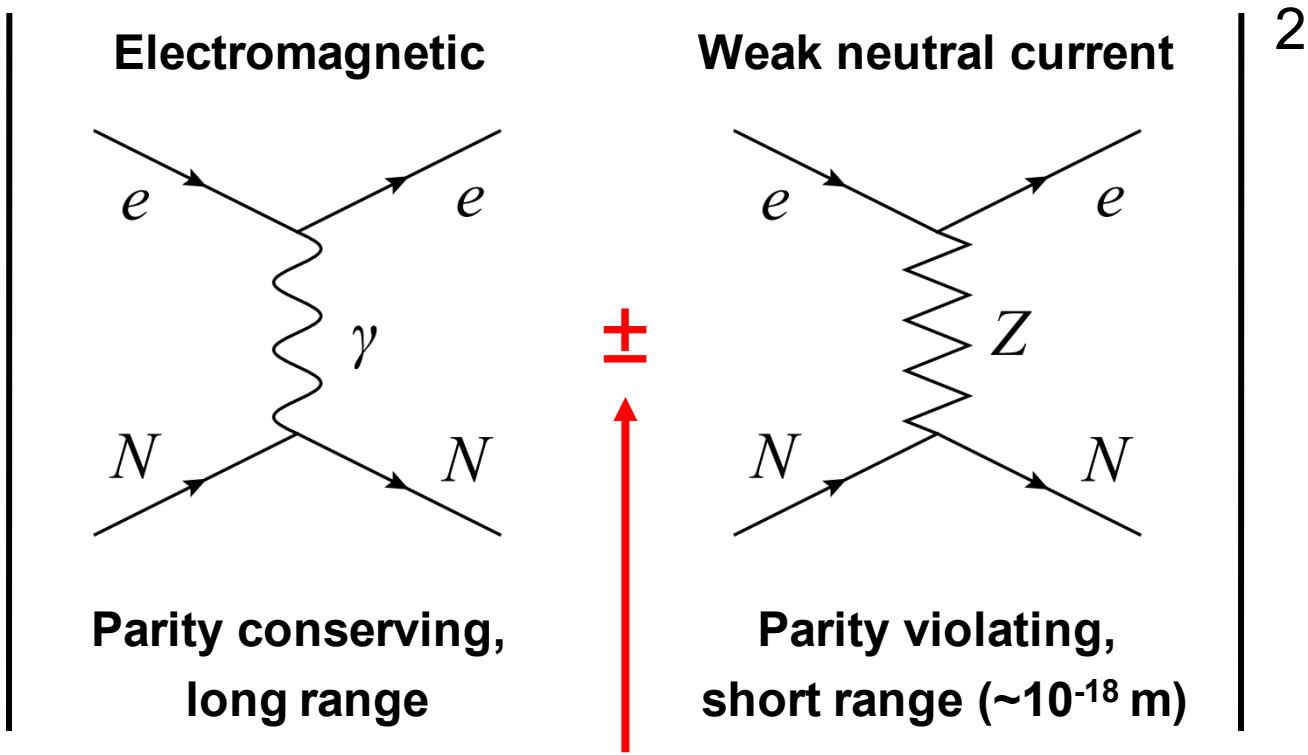


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Measure parity-nonconserving amplitude $E_{PNC} = \Gamma_{+} - \Gamma_{-}$

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

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

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

**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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**Extra generic spin-1 boson:**

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

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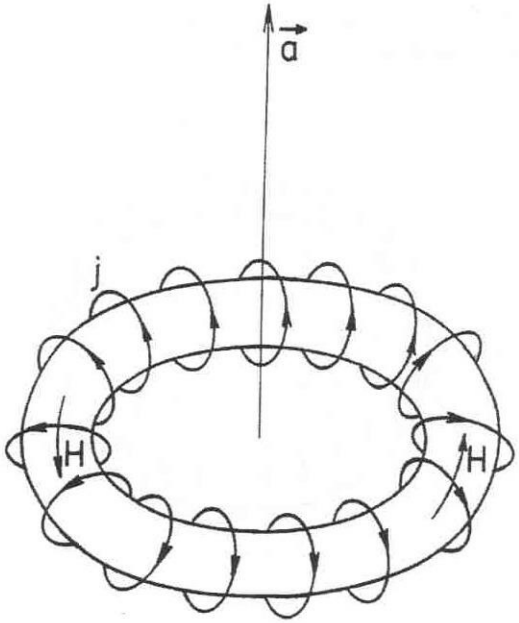
# Nuclear Anapole Moments (PNC)

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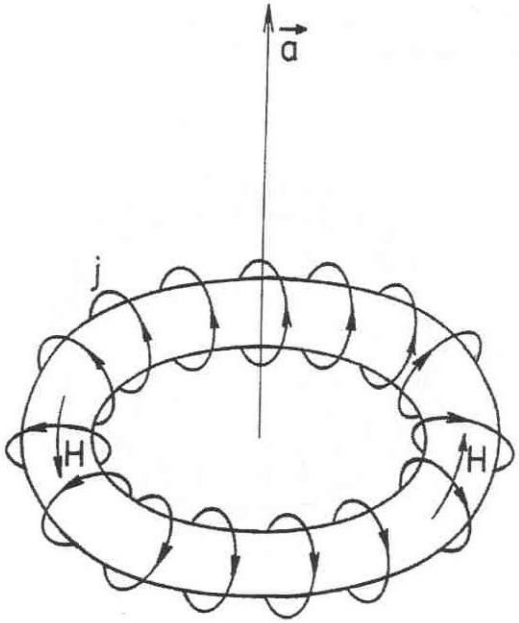


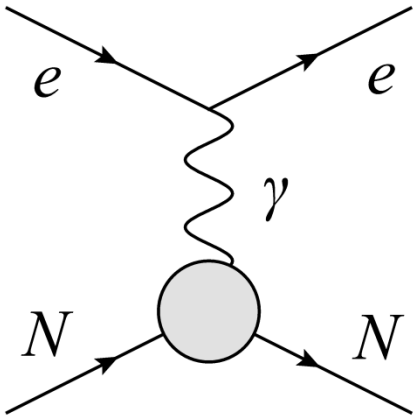


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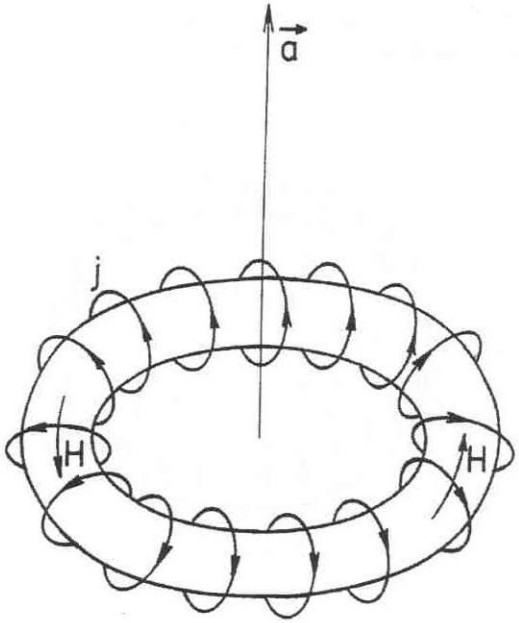


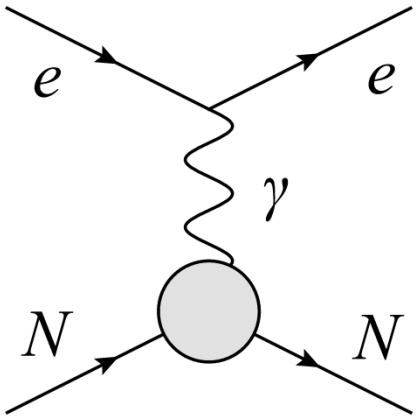


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$$H_{anapole} = e\, \boldsymbol{\alpha} \cdot \mathbf{a}\, \delta(\mathbf{r})$$

Measure *nuclear-spin-dependent* PNC amplitude

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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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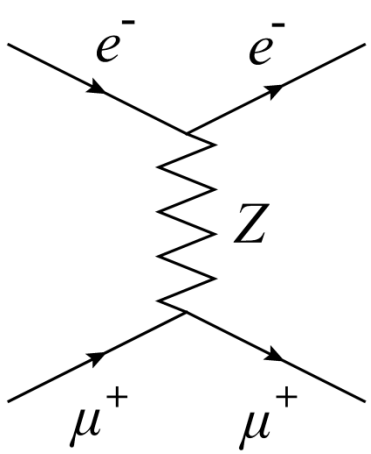


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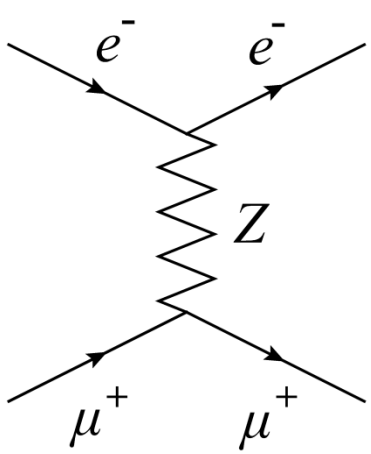


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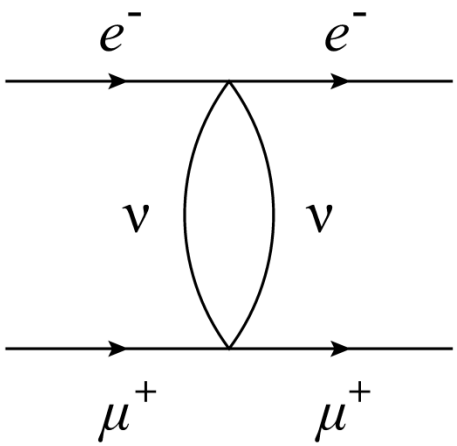
New experiments and calculations targeting ~ $\mathcal{O}(10)$ Hz precision level

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

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

<u>Illustrative example</u> – SM predicts "long range" neutrino-mediated forces

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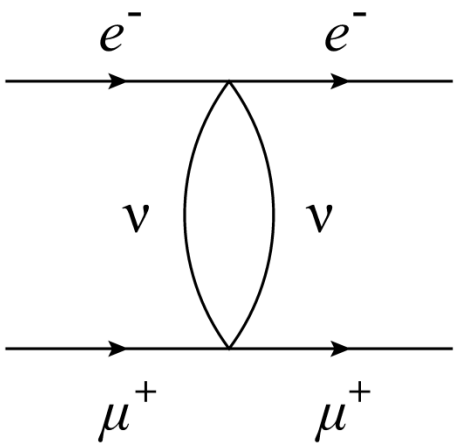


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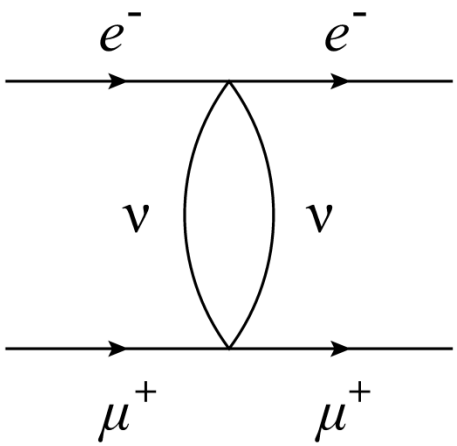


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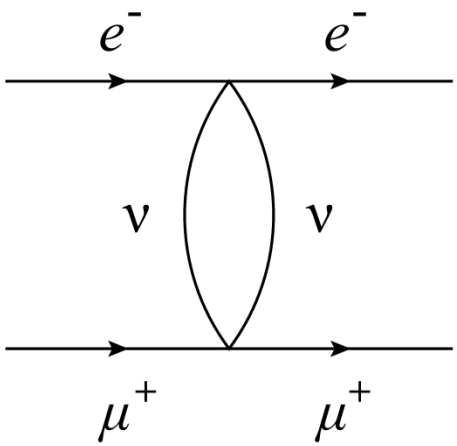


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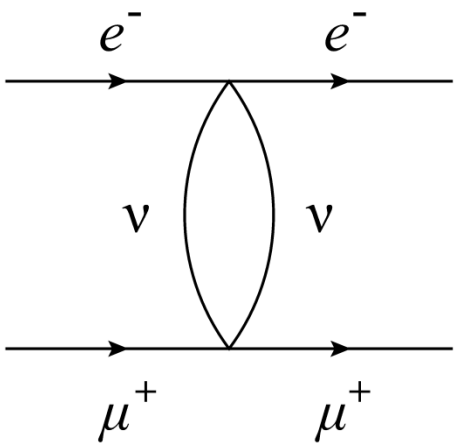


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- EDM experiments are high-precision low-energy probes of possible new sources of CP violation

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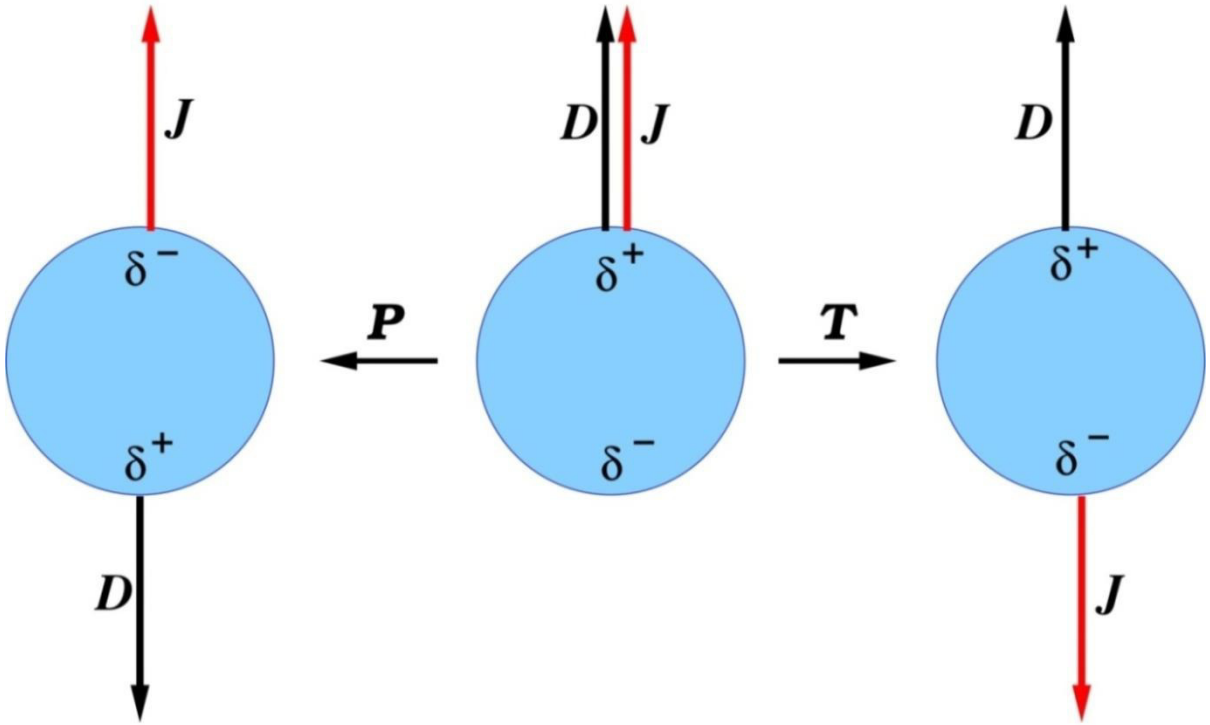

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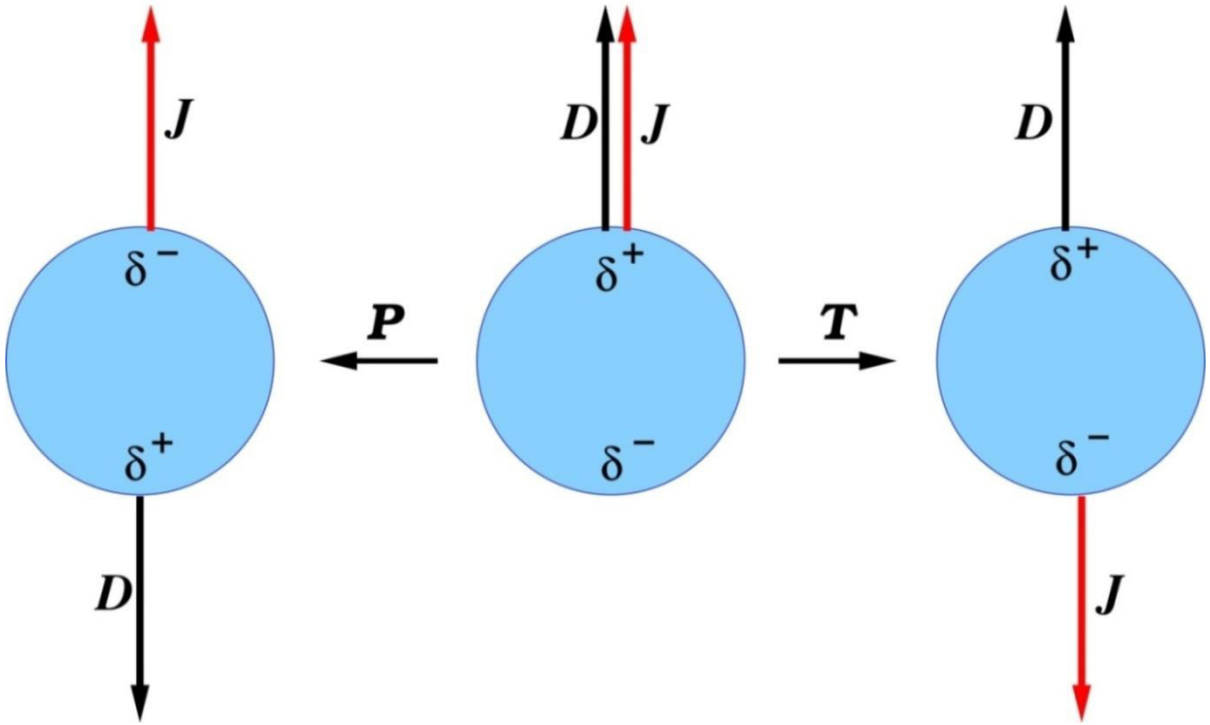


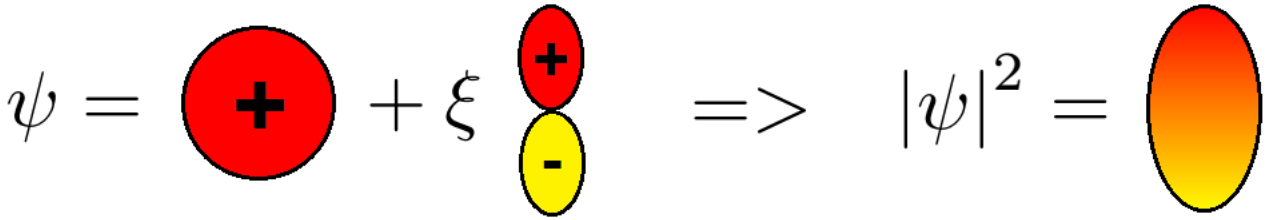

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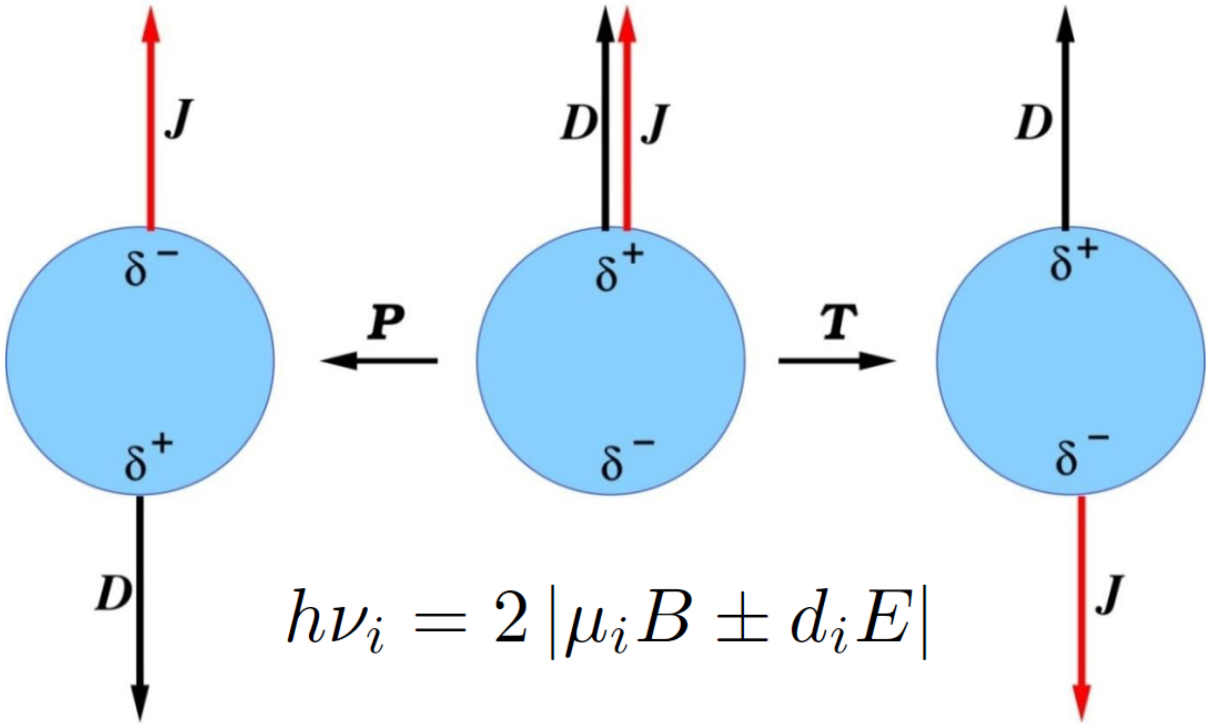
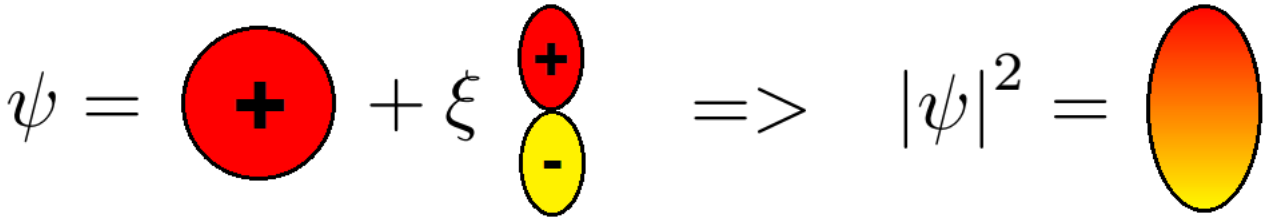



$$h\nu_i = 2\left|\mu_i B \pm d_i E\right|$$



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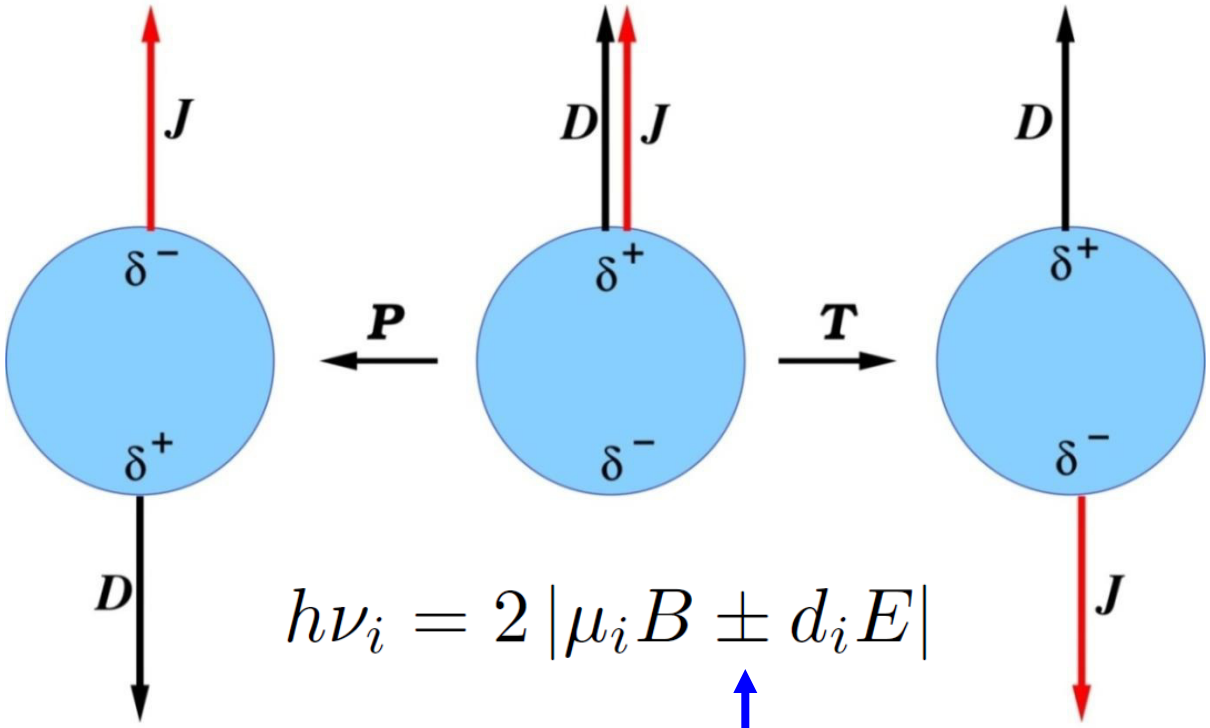


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Flip sign by reversing the P,T-odd invariant **E · B**

$$\psi = \; + \; + \xi \; \begin{matrix} + \\ - \end{matrix} \quad => \quad |\psi|^2 =$$

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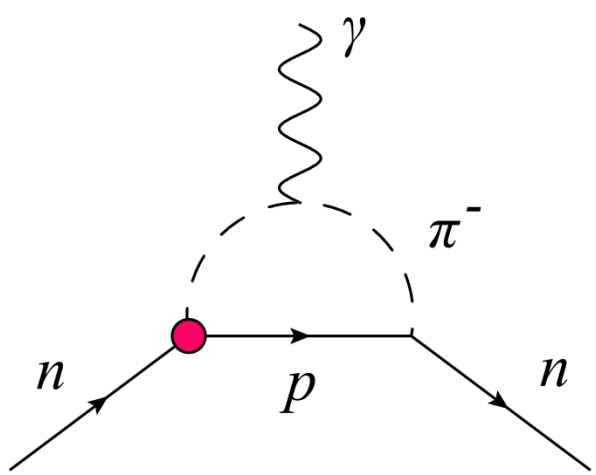

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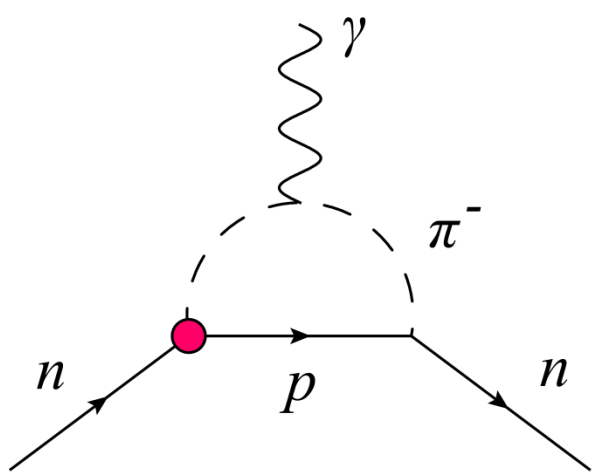
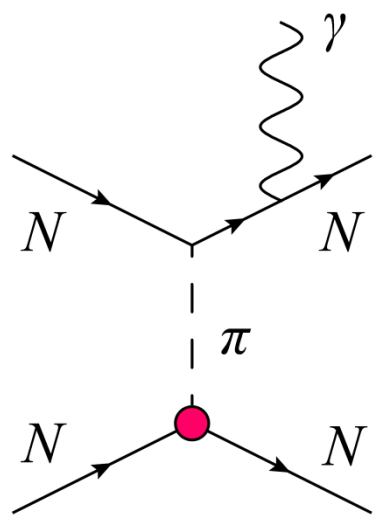
Illustrative example: $$\mathcal{L}_{\theta_{\rm QCD}} = \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

**Nucleon EDMs**




**CP-violating intranuclear forces**

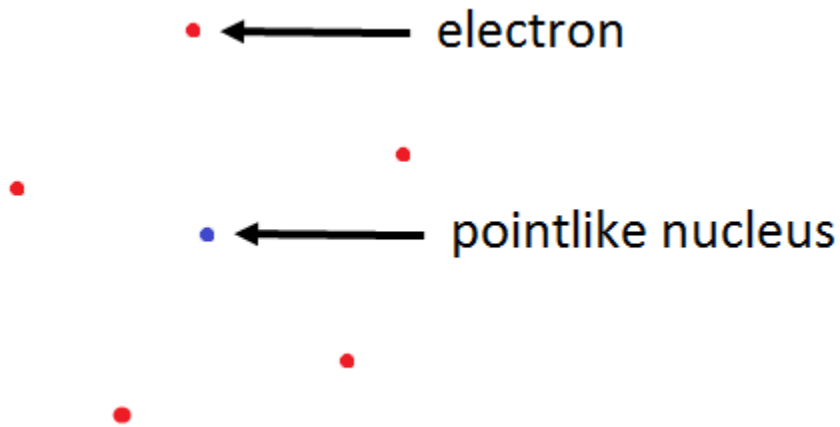



In nuclei, *tree-level* CP-violating intranuclear forces dominate over *loop-induced* nucleon EDMs [loop factor = $1/(8\pi^2)$].

# 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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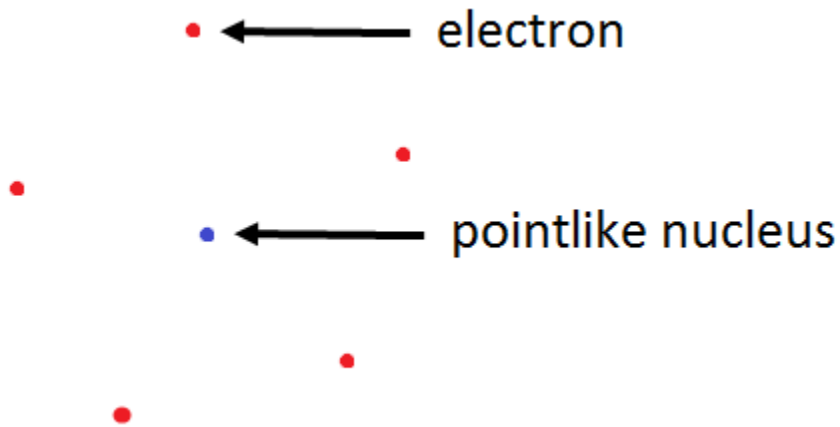


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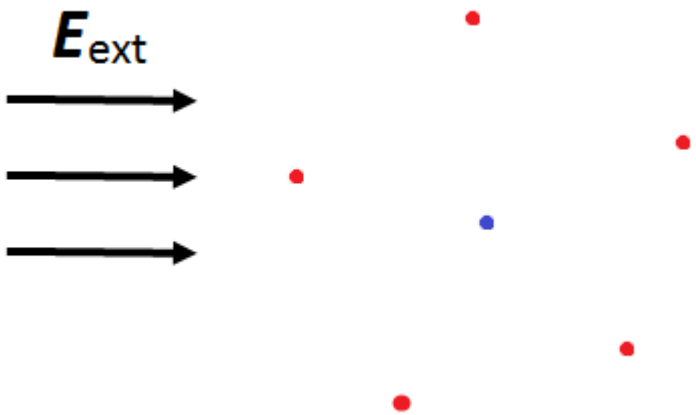


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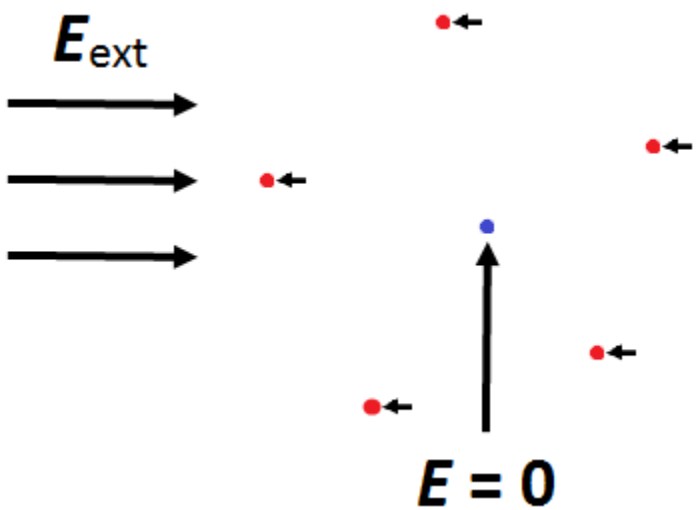


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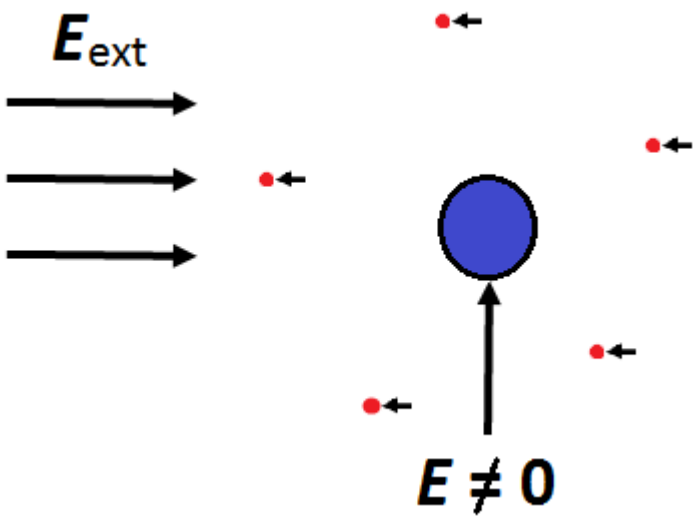
# Lifting of Schiff's Theorem

[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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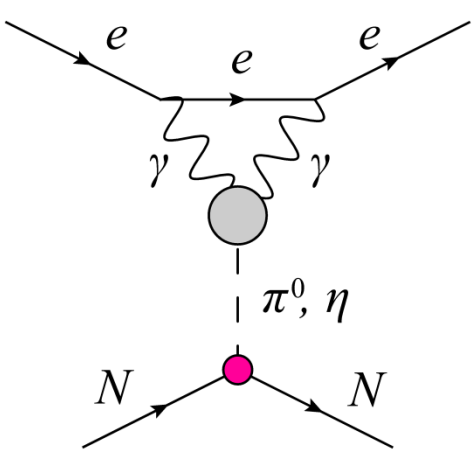
**What about sensitivity to hadronic CP violation?**

# Hadronic CP Violation in Paramagnetic Molecules

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

Hadronic CP-violating effects arise at 2-loop level

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

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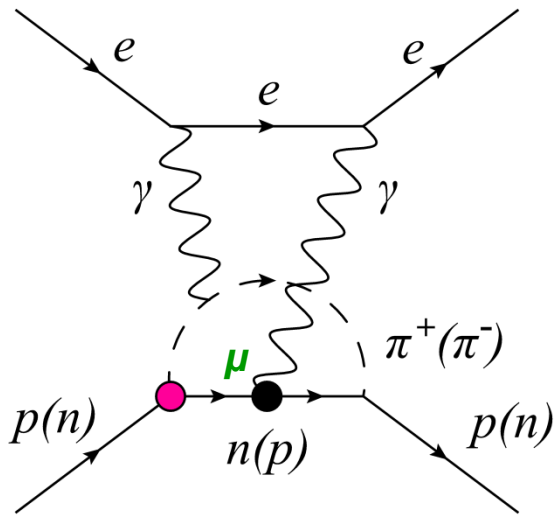


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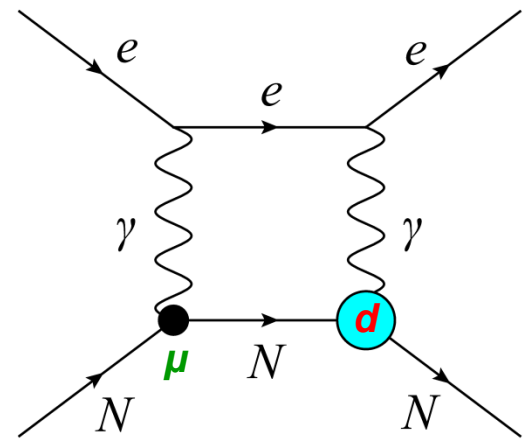

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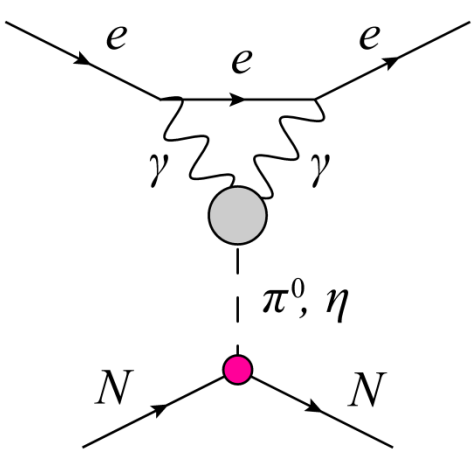


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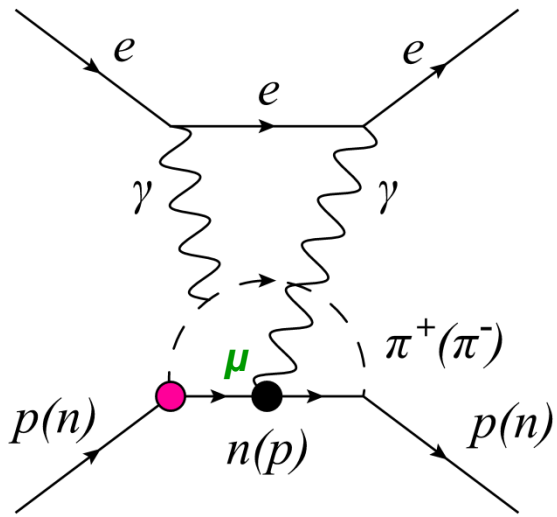


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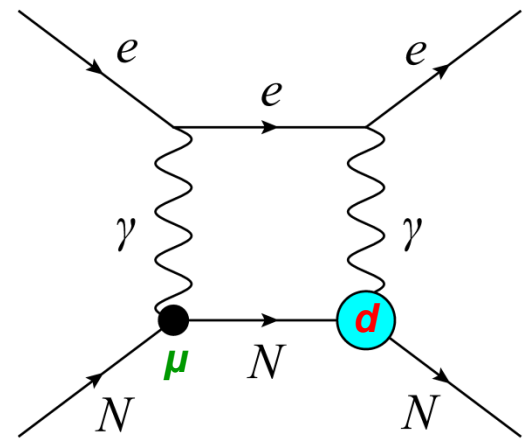

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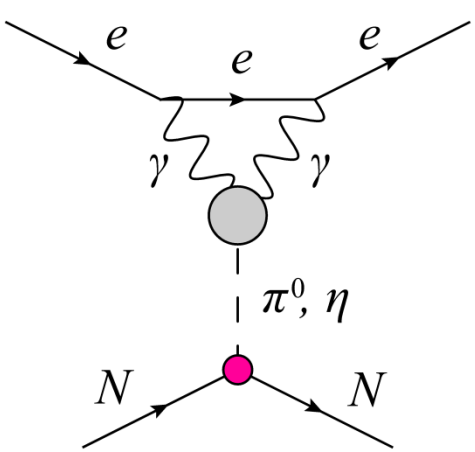


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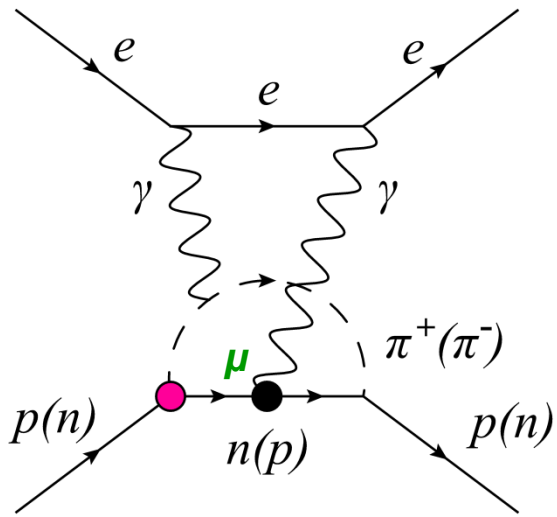


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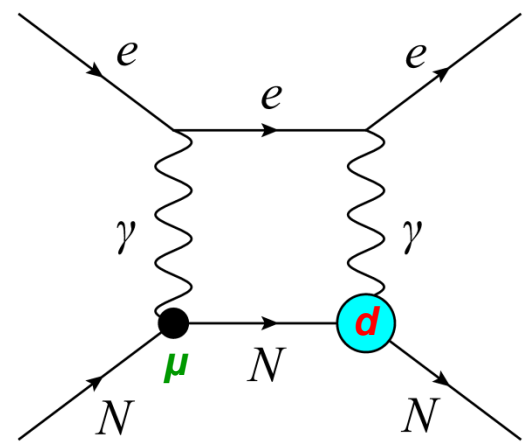

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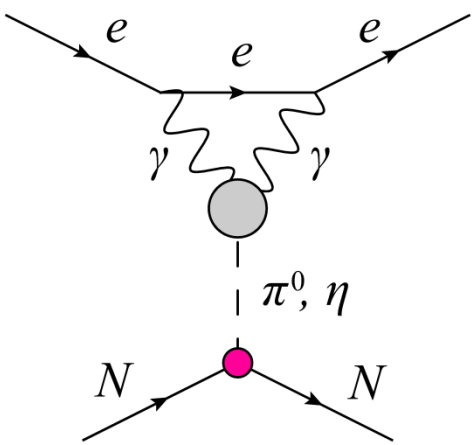


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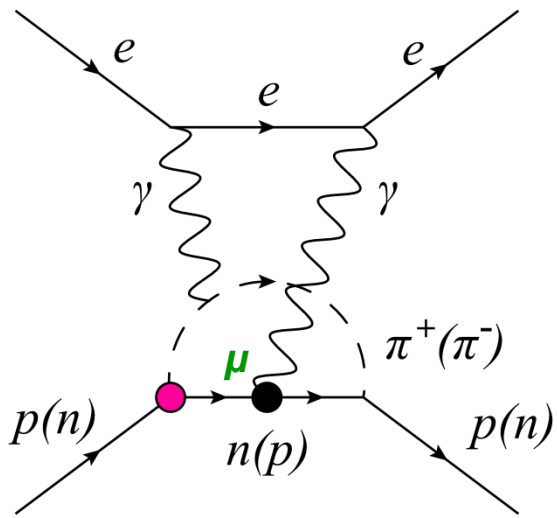


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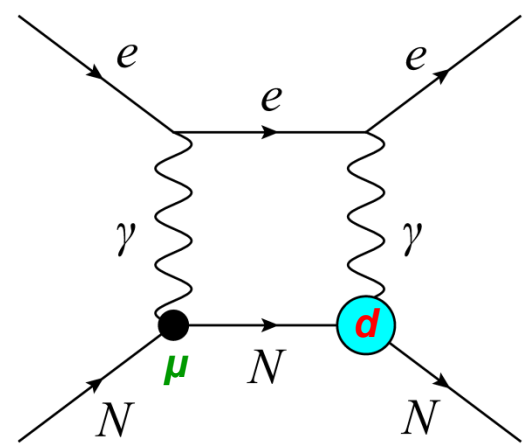


$\pi^0$,η contributions: *opposite sign*

p,n contributions: *same sign*

<u>Example</u> – $\theta_{QCD}$ 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]

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

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

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$|d_p|_{ThO} < \mathbf{2 \times 10^{-23}}\ \boldsymbol{e}\ \mathbf{cm}$

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$|\bar{g}^{(1)}_{\pi NN}|_{ThO} < \mathbf{4 \times 10^{-10}}$

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

# Outline

1. Electroweak Phenomena

2. Electric Dipole Moments

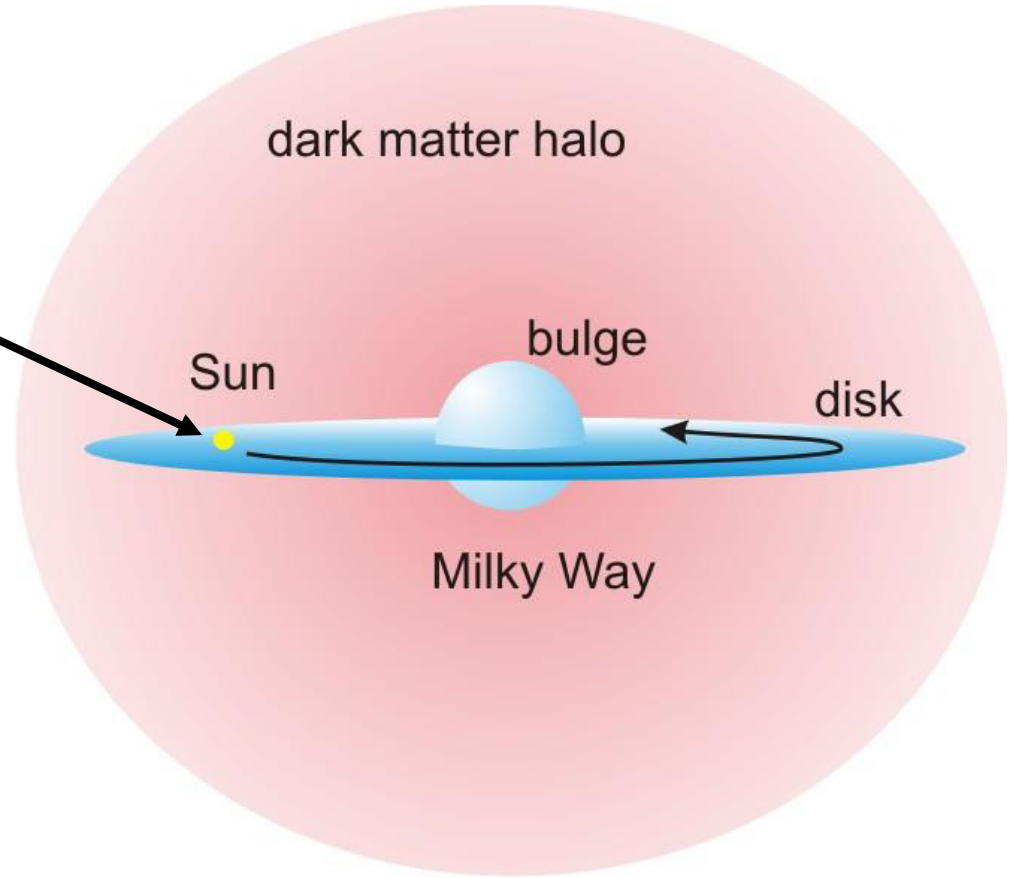
3. **Ultra-Low-Mass Dark Matter**

# 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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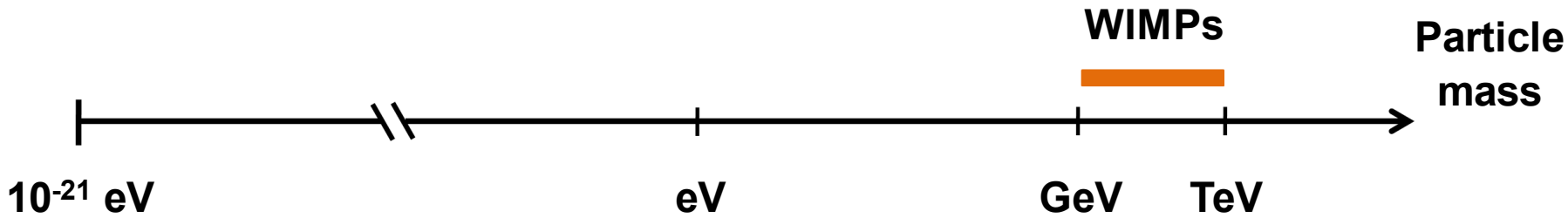


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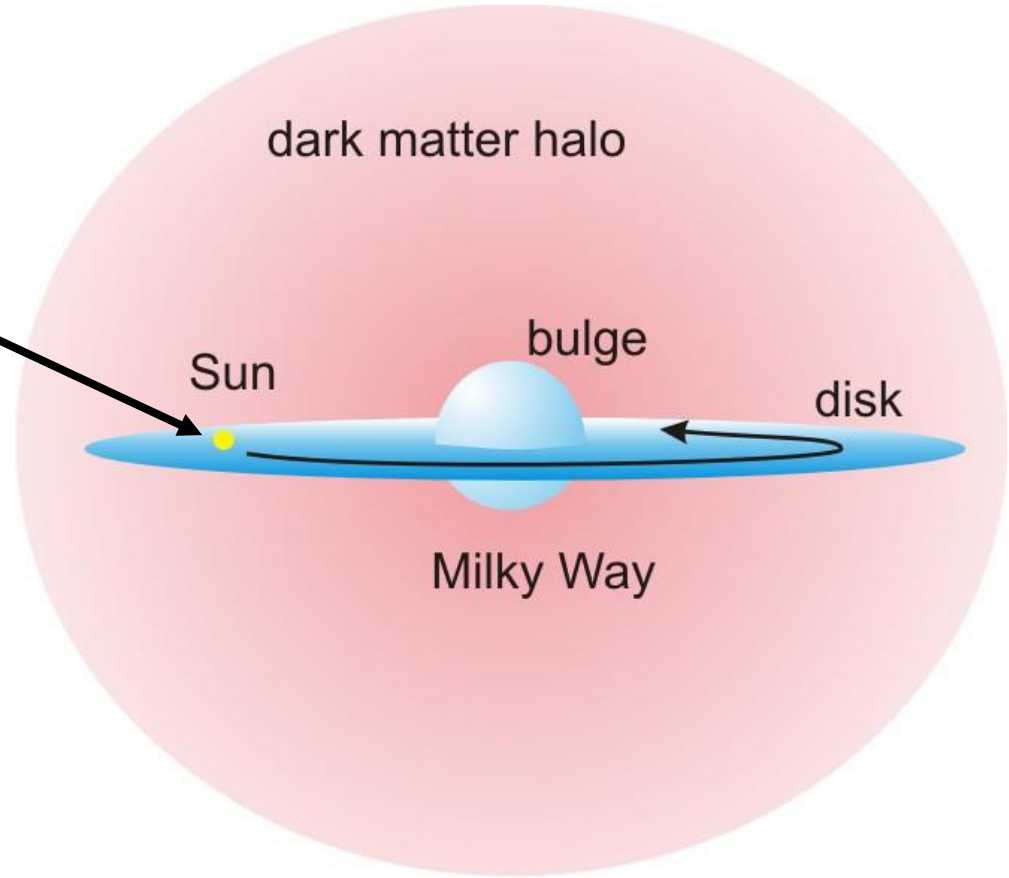

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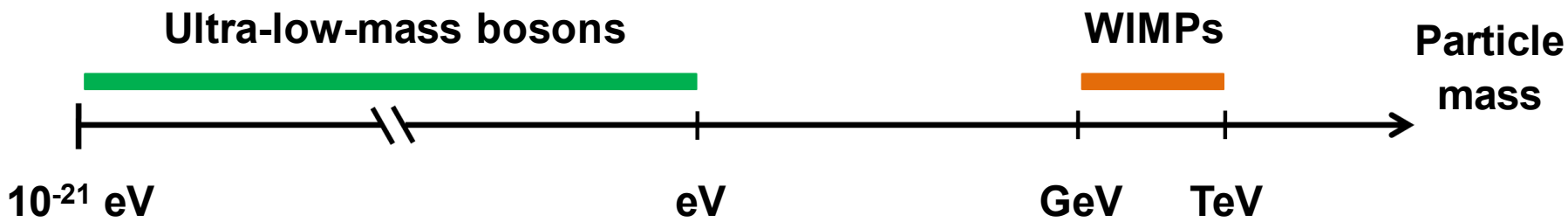


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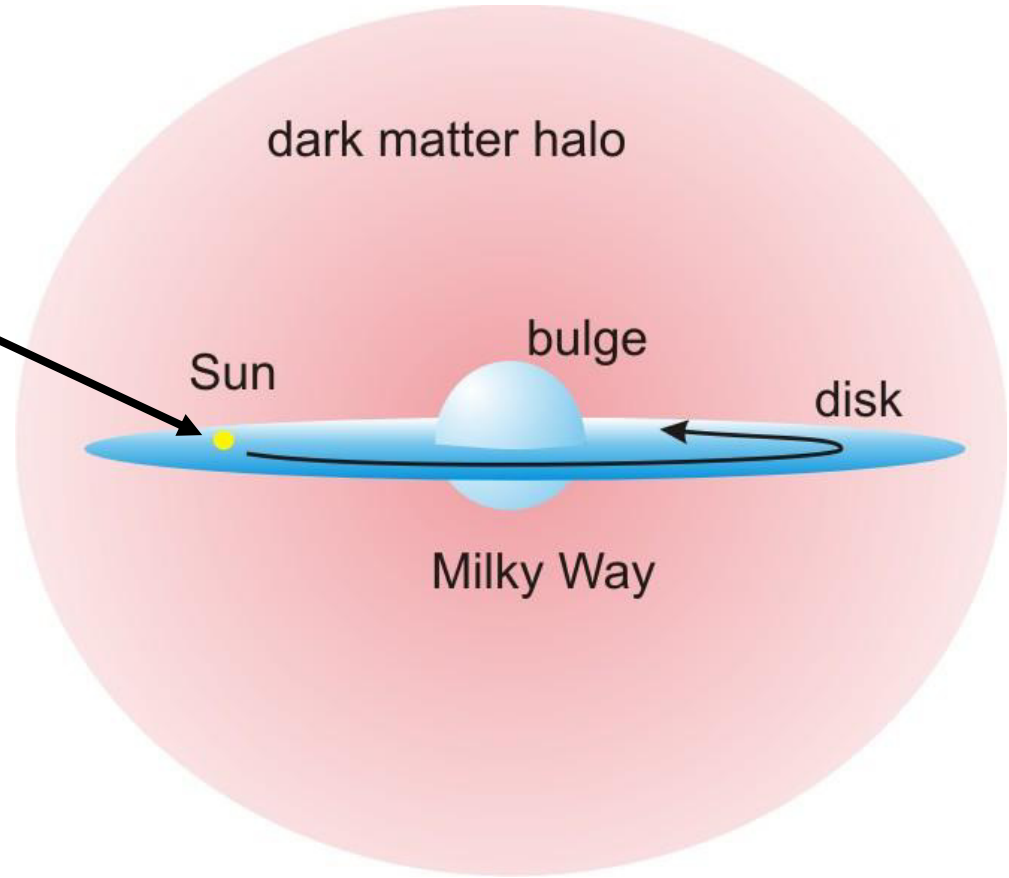

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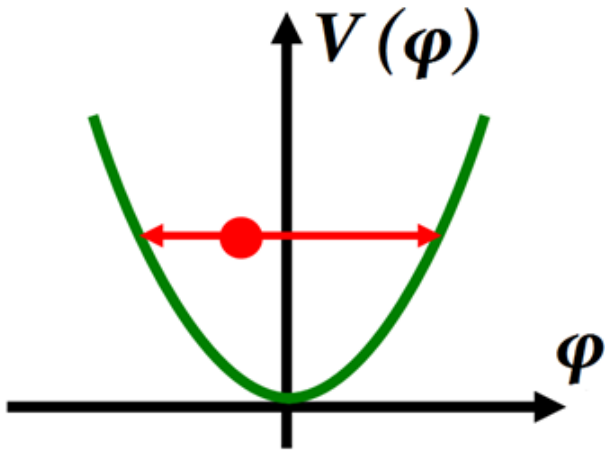
- Low-mass spin-0 particles form a coherently oscillating classical field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{\mathrm{DM,local}} \approx 0.4$ GeV/cm$^3$)




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

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

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

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

**Pseudoscalars (Axions):**

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

# Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
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[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

**Solid material**

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

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

**Solid material**

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

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

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

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

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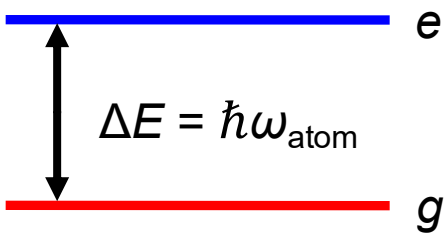
cf.

**Electronic transition**




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

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

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

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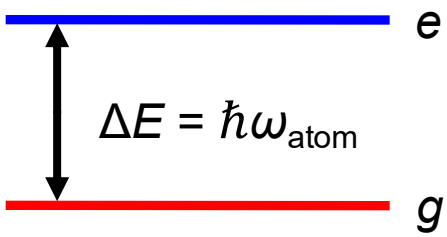
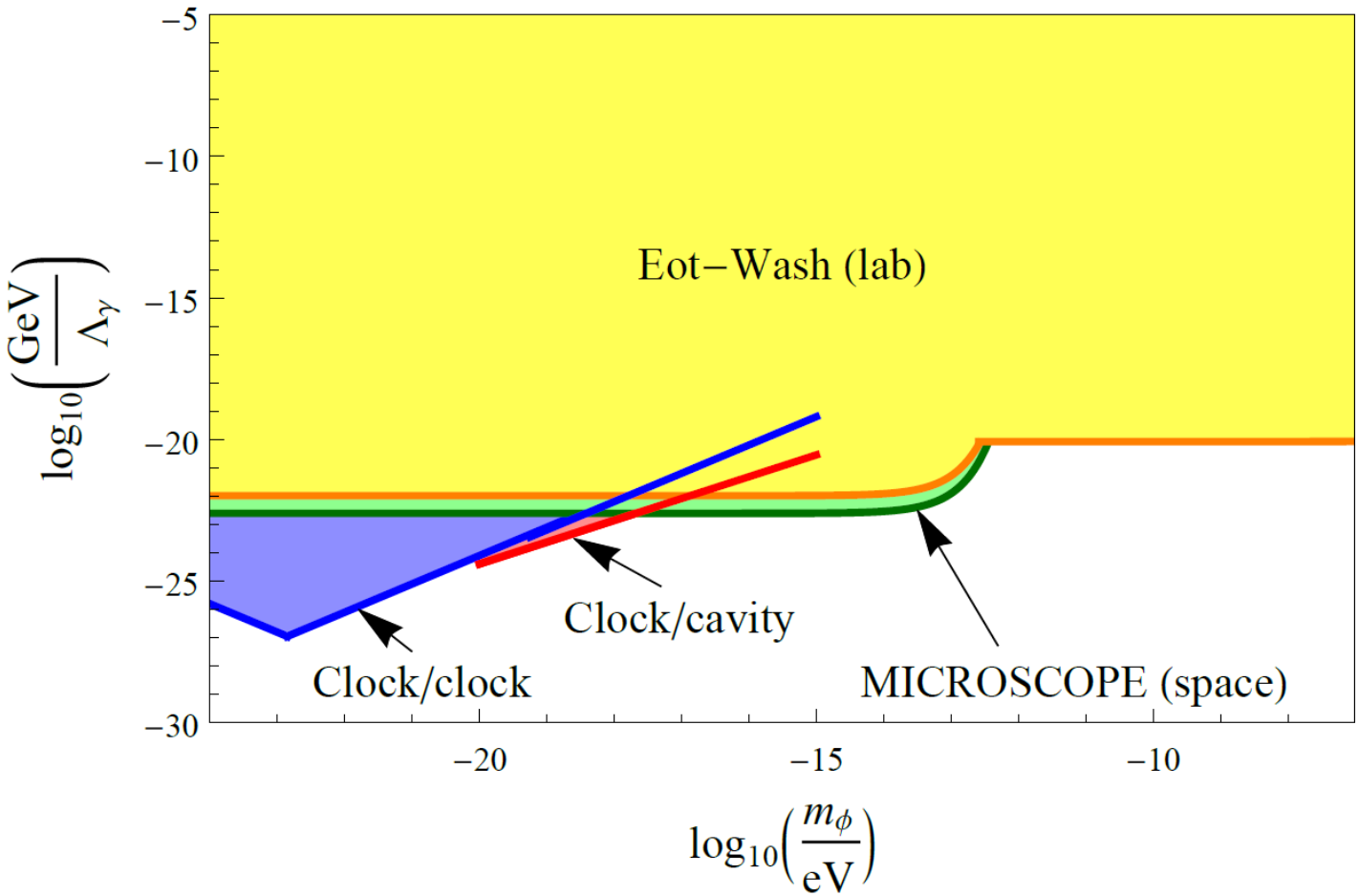



$\hbar\omega_{\text{atom}} \sim e^2/a_B$

- **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)]

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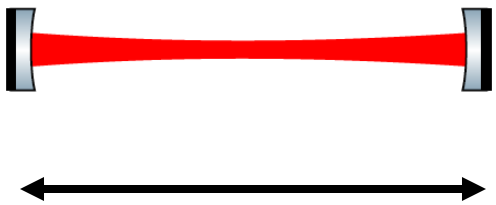
cf.

**Freely-suspended mirrors**



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

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

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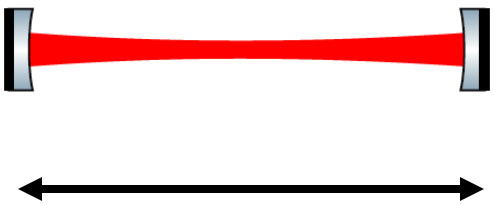

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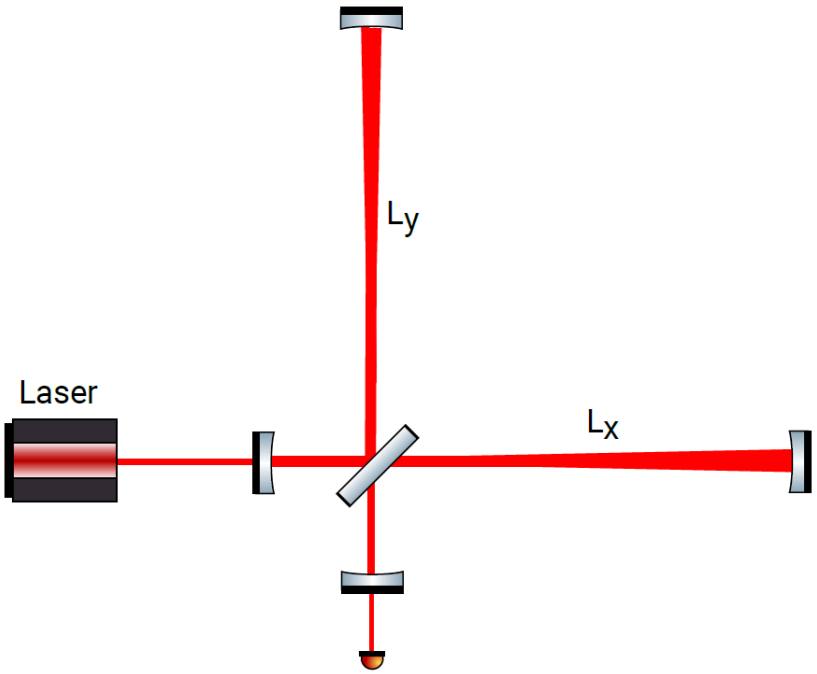
cf. $$\frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

# 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

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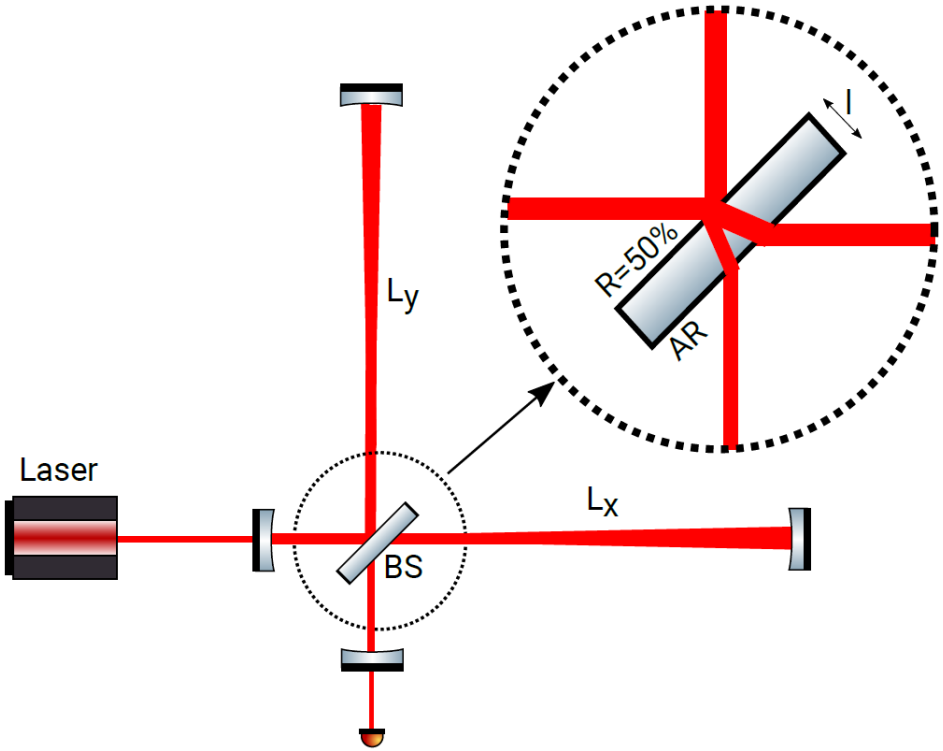


- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$

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

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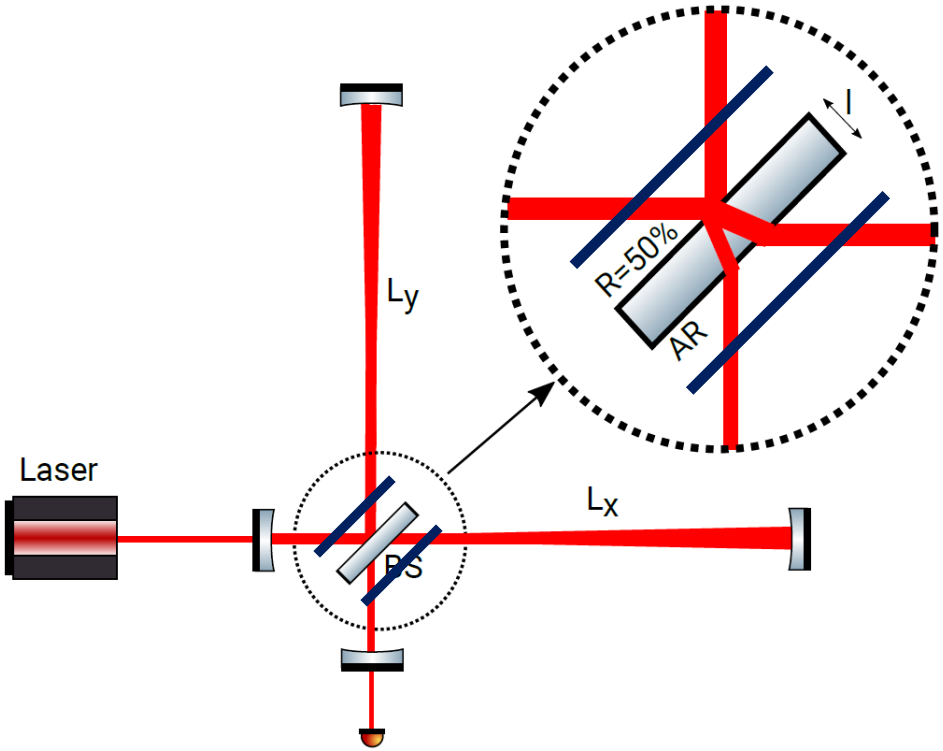


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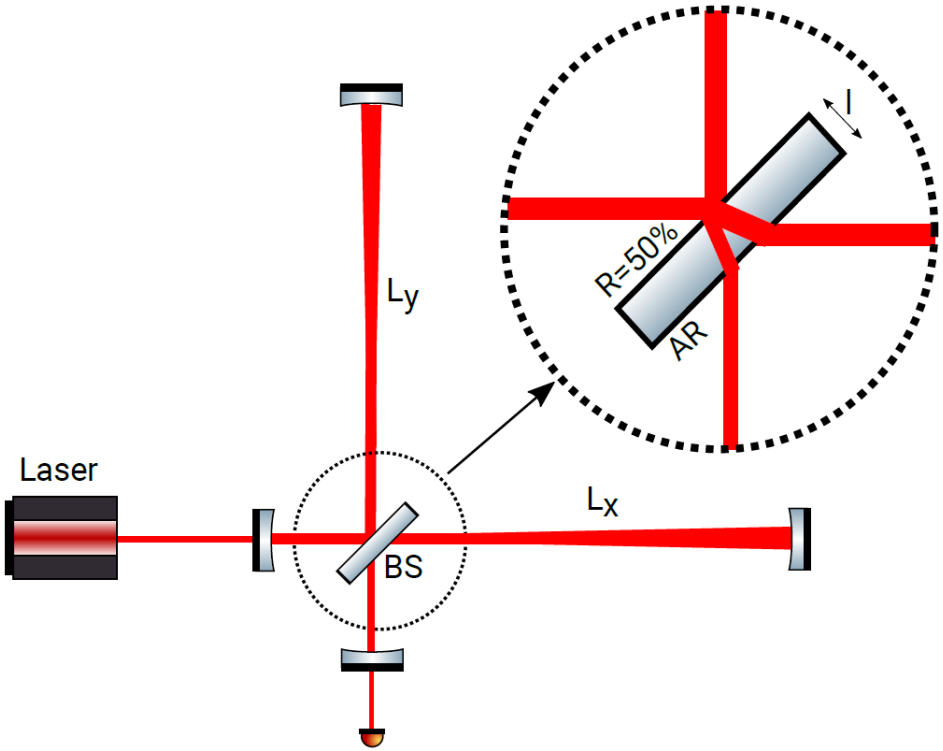
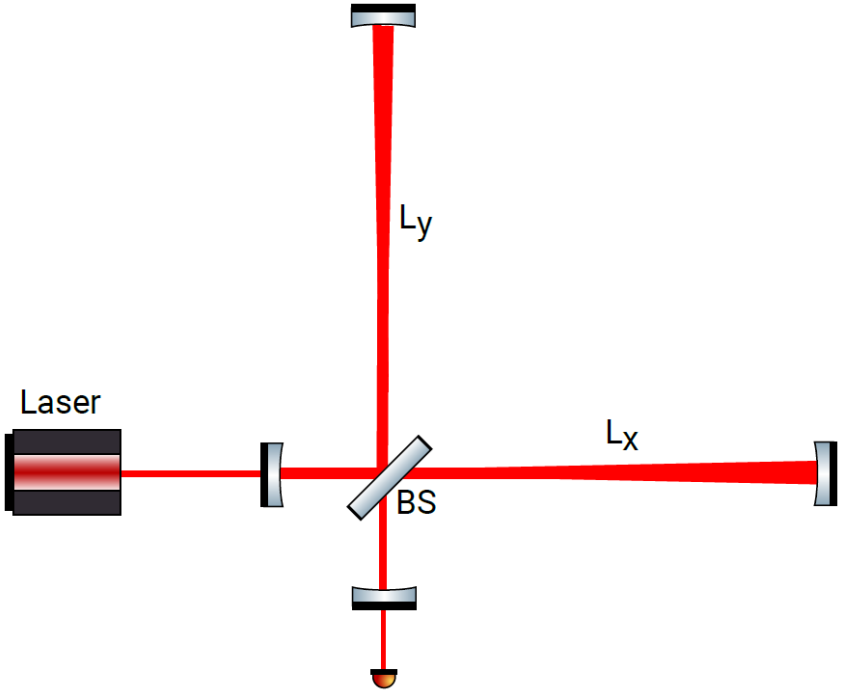



- Geometric asymmetry from beam-splitter: $\delta(L_x - L_y) \sim \delta(nl)$
- Both broadband and resonant narrowband searches possible: $f_{DM} \approx f_{vibr,BS} \sim v_{sound}/l$, $Q \sim 10^6$ enhancement

# Michelson vs Fabry-Perot-Michelson Interferometers

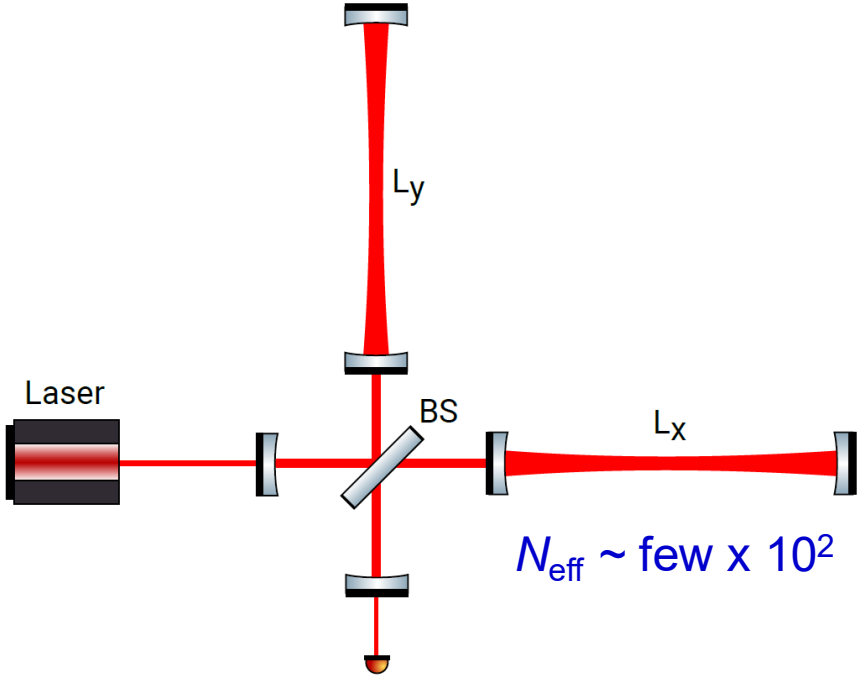
[Grote, Stadnik, *Phys. Rev. Research* **1**, 033187 (2019)]

**Michelson interferometer**
**(GEO 600, Fermilab holometer)**




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

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




$N_{eff}$ ~ few x $10^2$

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

# Michelson vs Fabry-Perot-Michelson Interferometers

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

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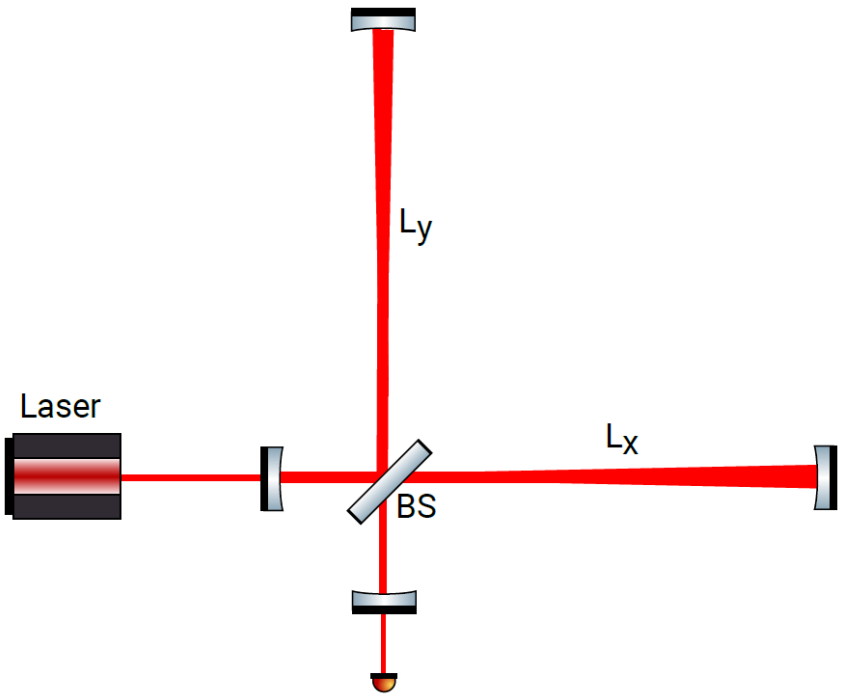


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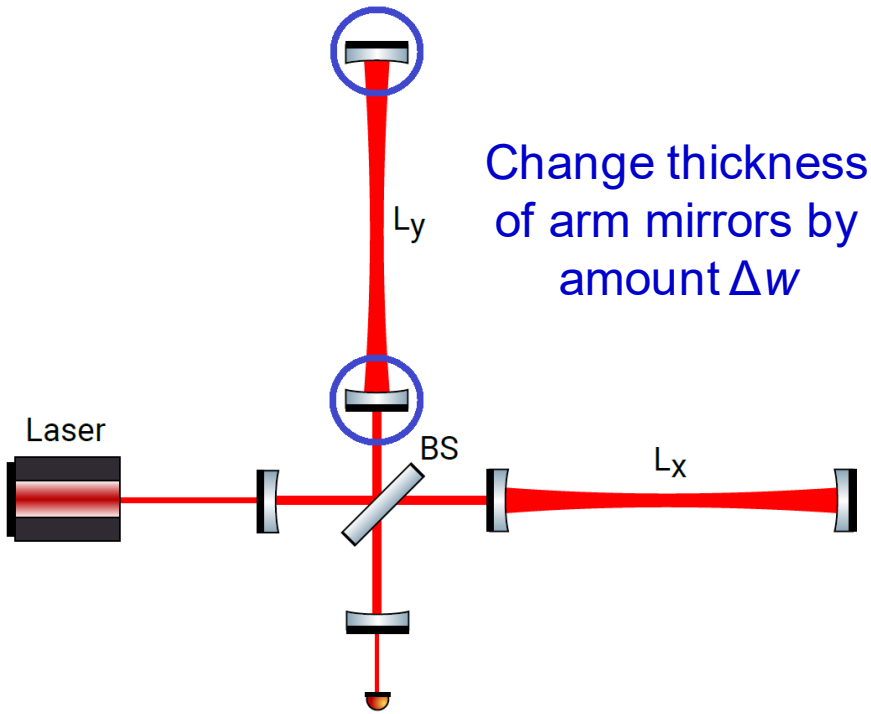
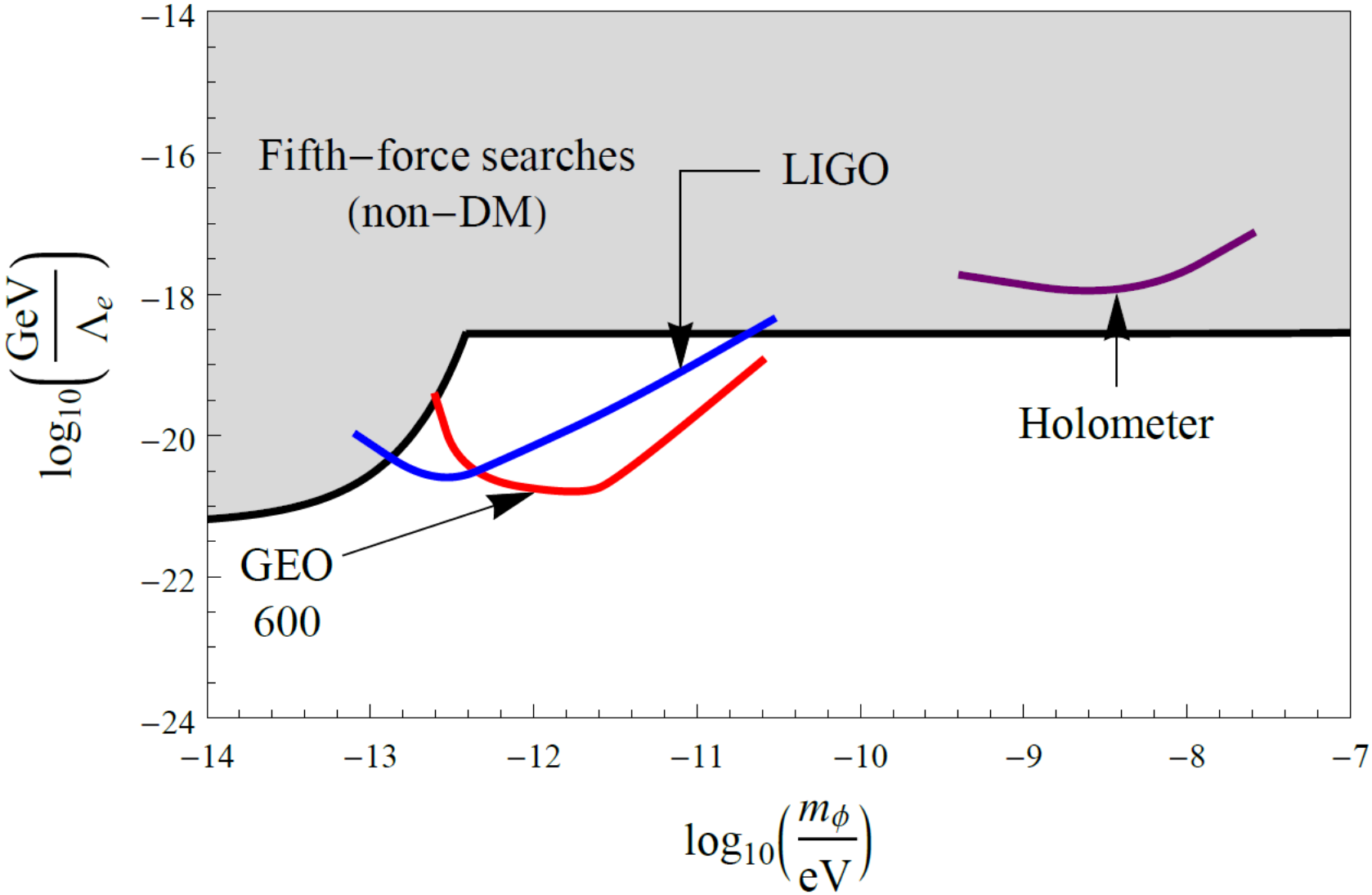



Change thickness of arm mirrors by amount $\Delta w$

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

# Linear Interaction of Scalar Dark Matter with the Electron



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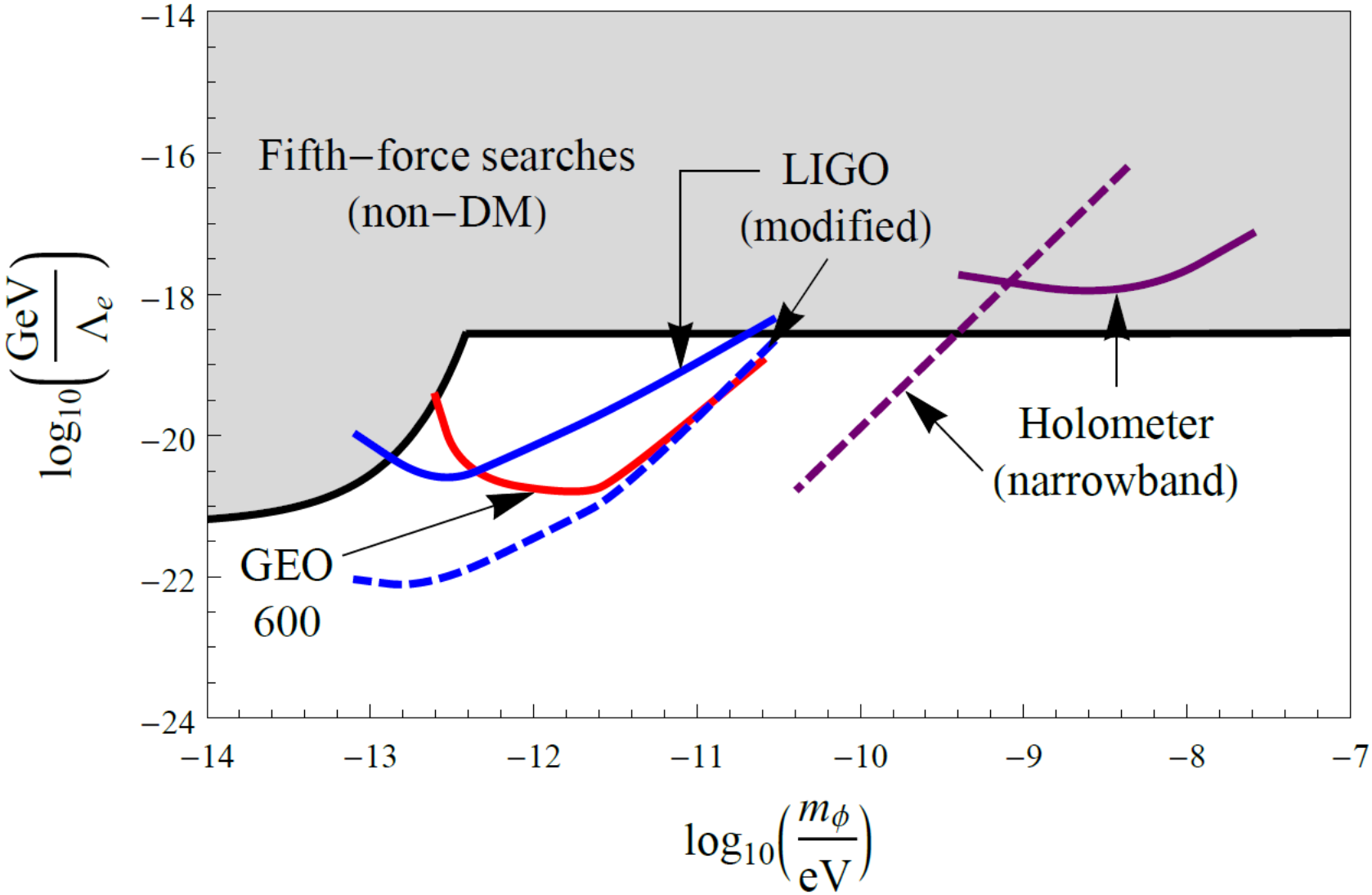

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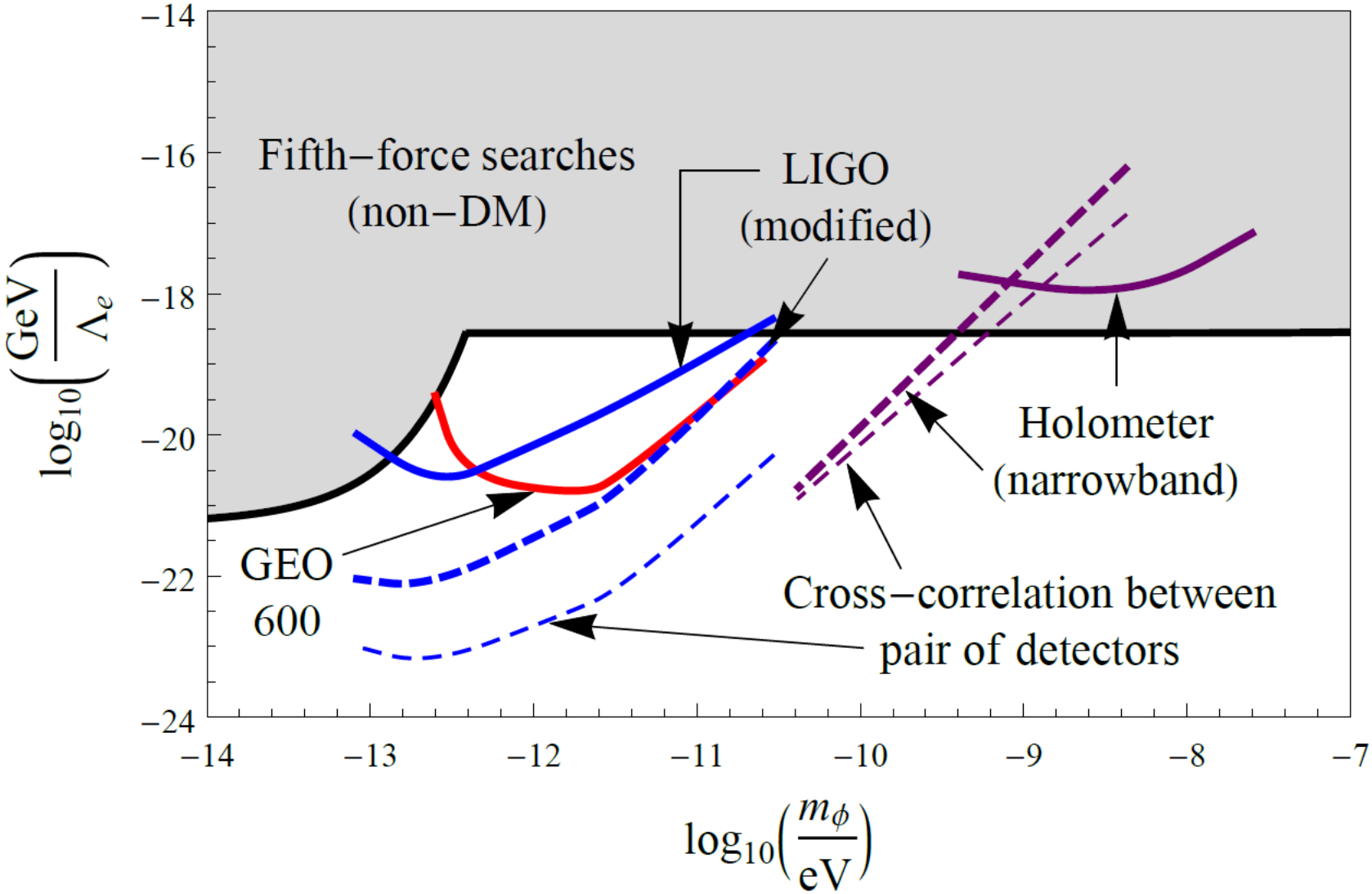


# Summary

## 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

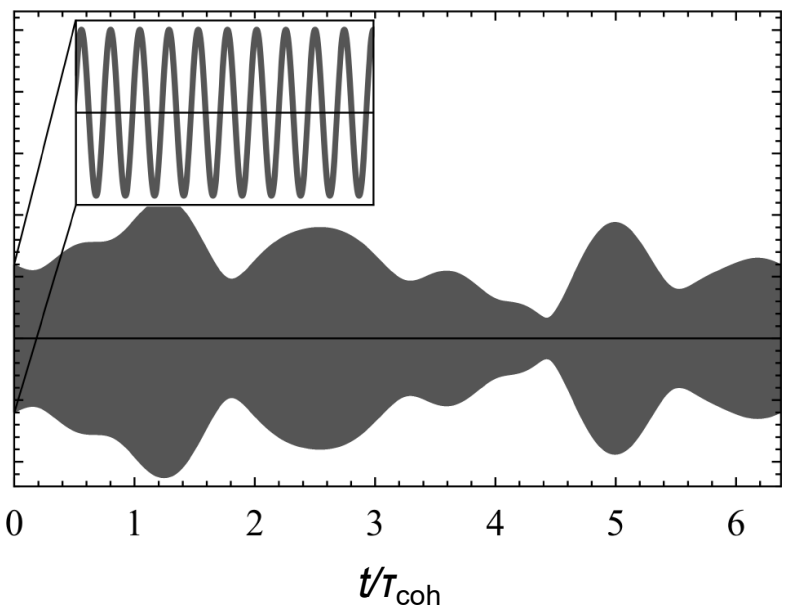
- *Optical interferometers and cavities:* sensitive probes of apparent oscillations in $\alpha$ and $m_e$ induced by oscillating scalar DM field

# Back-Up Slides

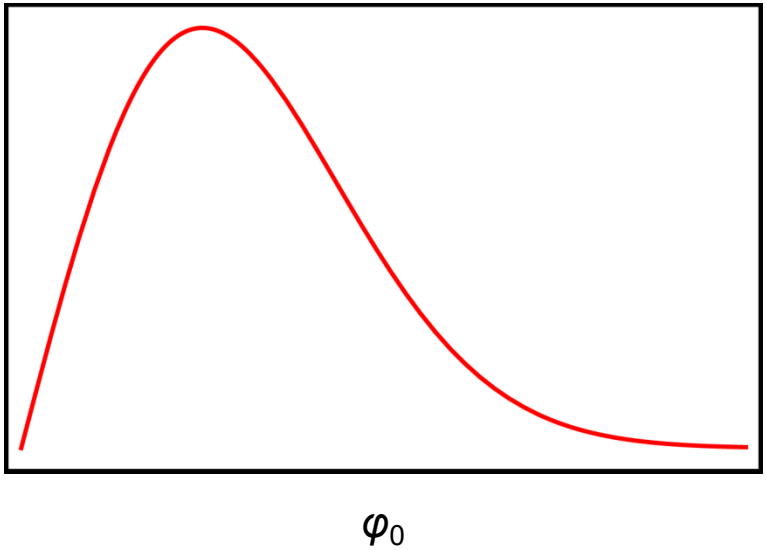
# Temporal Coherence

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

Evolution of $\varphi_0$ with time




Probability distribution function of $\varphi_0$



# Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)],
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$$\mathcal{L}_f = -\frac{\phi}{\Lambda_f}m_f\bar{f}f \quad => \quad \frac{\delta m_f}{m_f} \approx \frac{\phi_0\cos(m_\phi t)}{\Lambda_f}$$

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

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

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Consider *quadratic couplings* of an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.

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

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

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

# Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

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**'Slow' drifts** [Astrophysics (high $\rho_{\rm DM}$): BBN, CMB]
**+ Gradients** [Fifth forces]

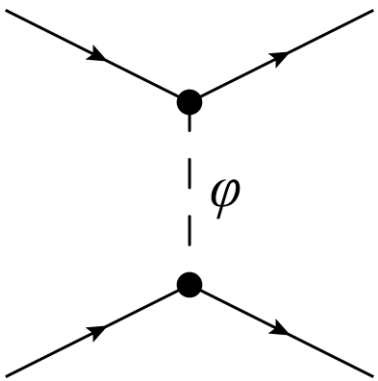
**Oscillating variations**
[Laboratory (high precision)]

# Fifth Forces: Linear vs Quadratic Couplings

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

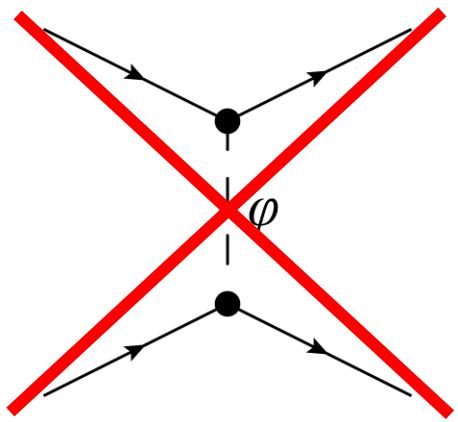
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

**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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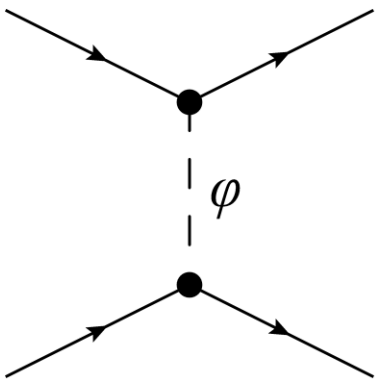


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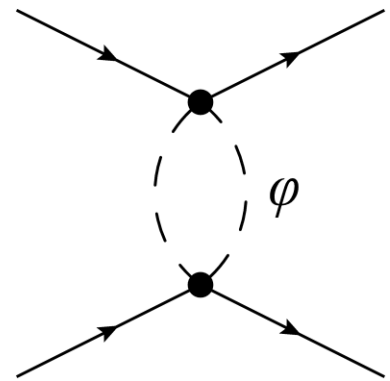


$$\phi = \phi_0 \cos(m_\phi t)\left(1 - \frac{B}{r}\right) - C\frac{e^{-2m_\phi r}}{r^3}$$

↓

**Gradients + screening/amplification**

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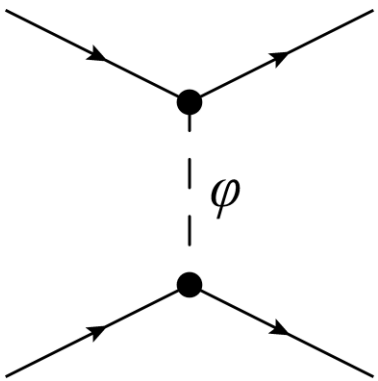
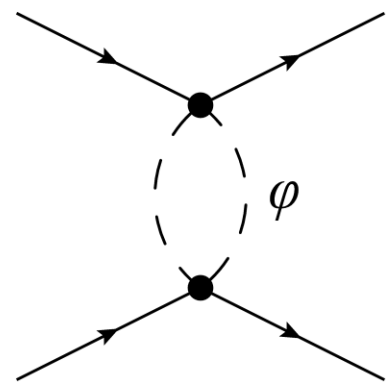



$$\phi = \underline{\phi_0 \cos(m_\phi t)} - A\frac{e^{-m_\phi r}}{r}$$

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

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

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

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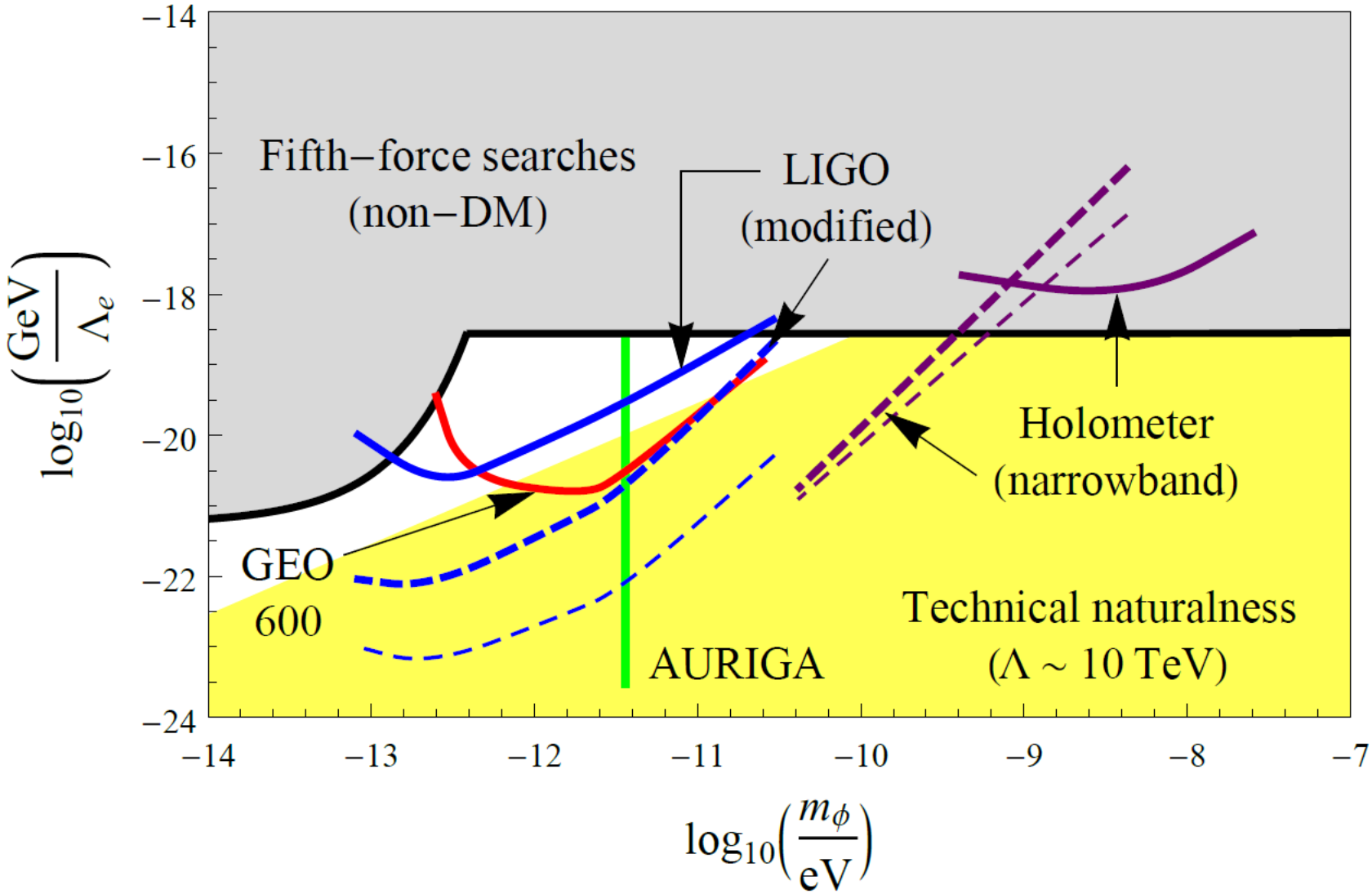
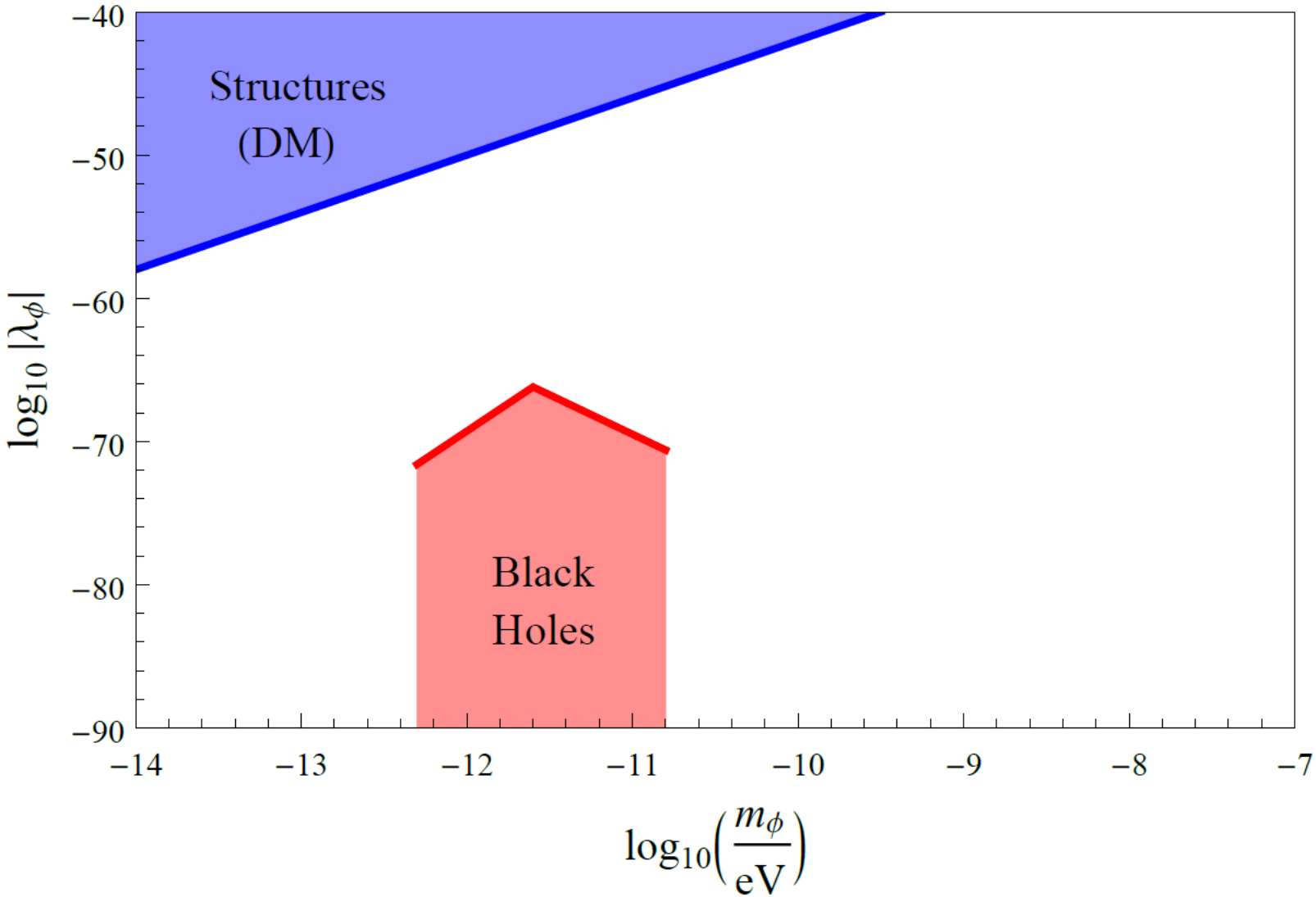
↓

**Gradients + screening/amplification**

# Constraints on Linear Interaction of Scalar Dark Matter with the Electron



# Quartic Self-Interaction of Scalar

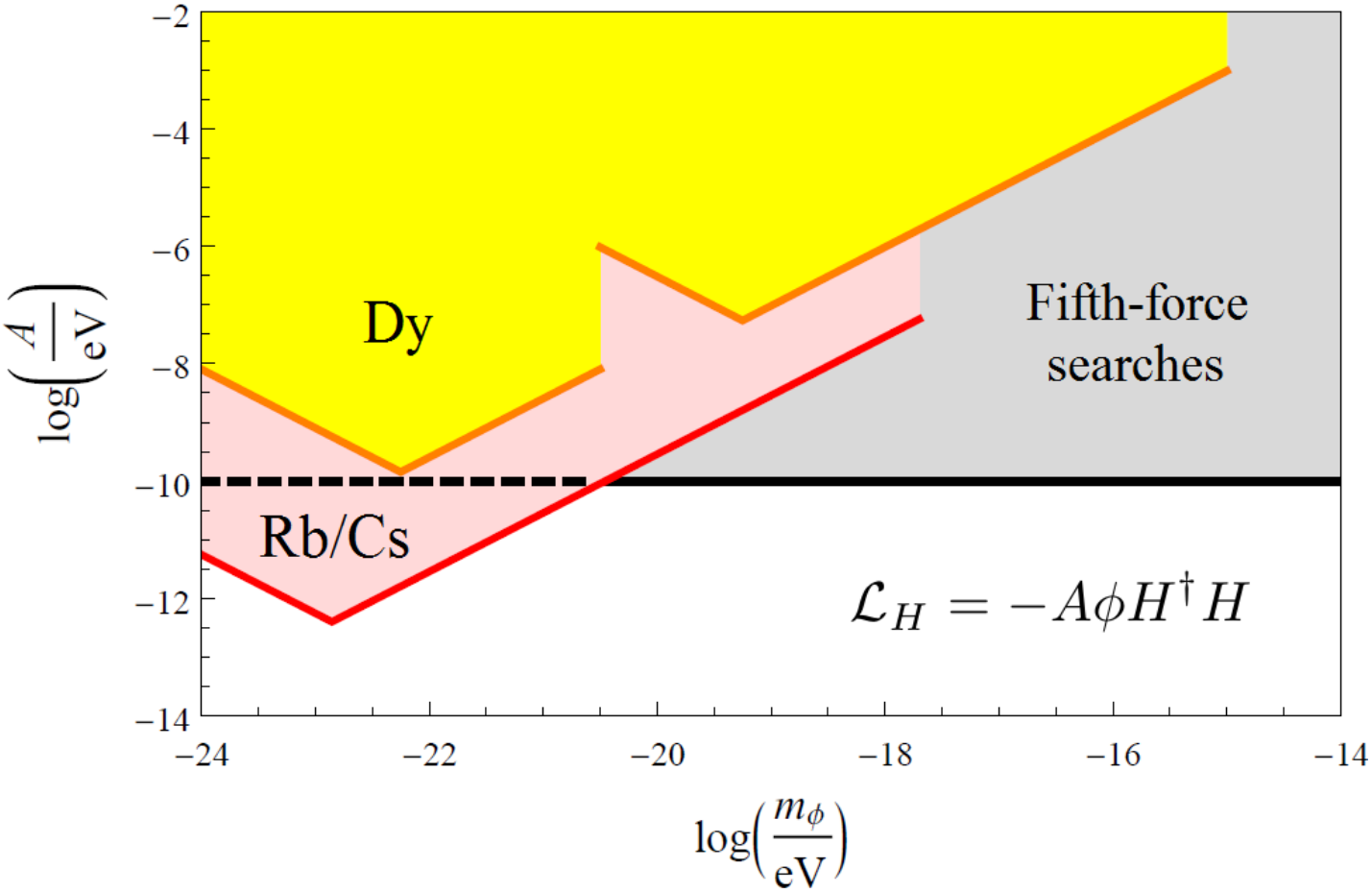


# Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

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

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

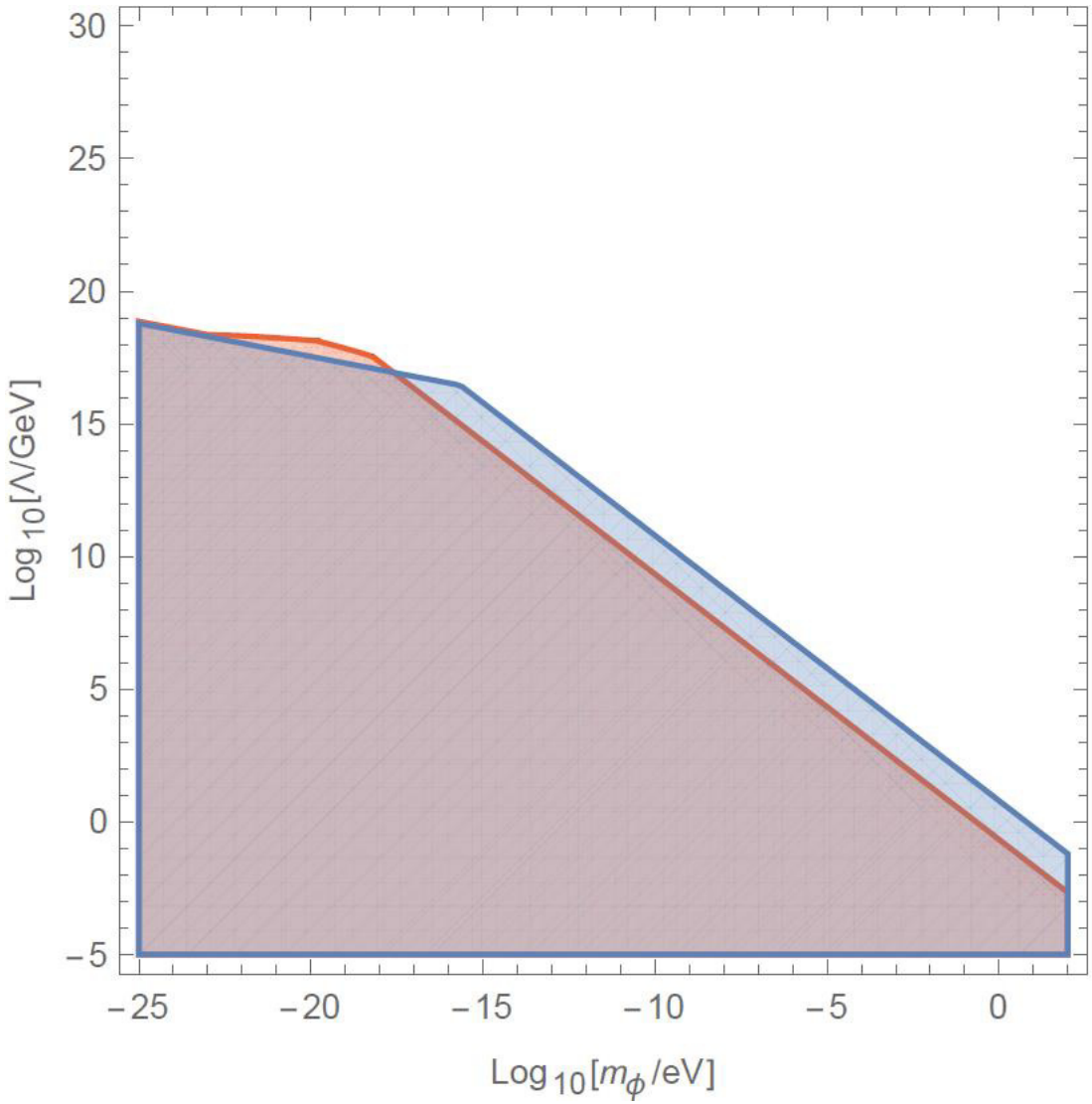
$$p + e^- \rightleftharpoons n + \nu_e$$

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

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

# Back-Reaction Effects in BBN

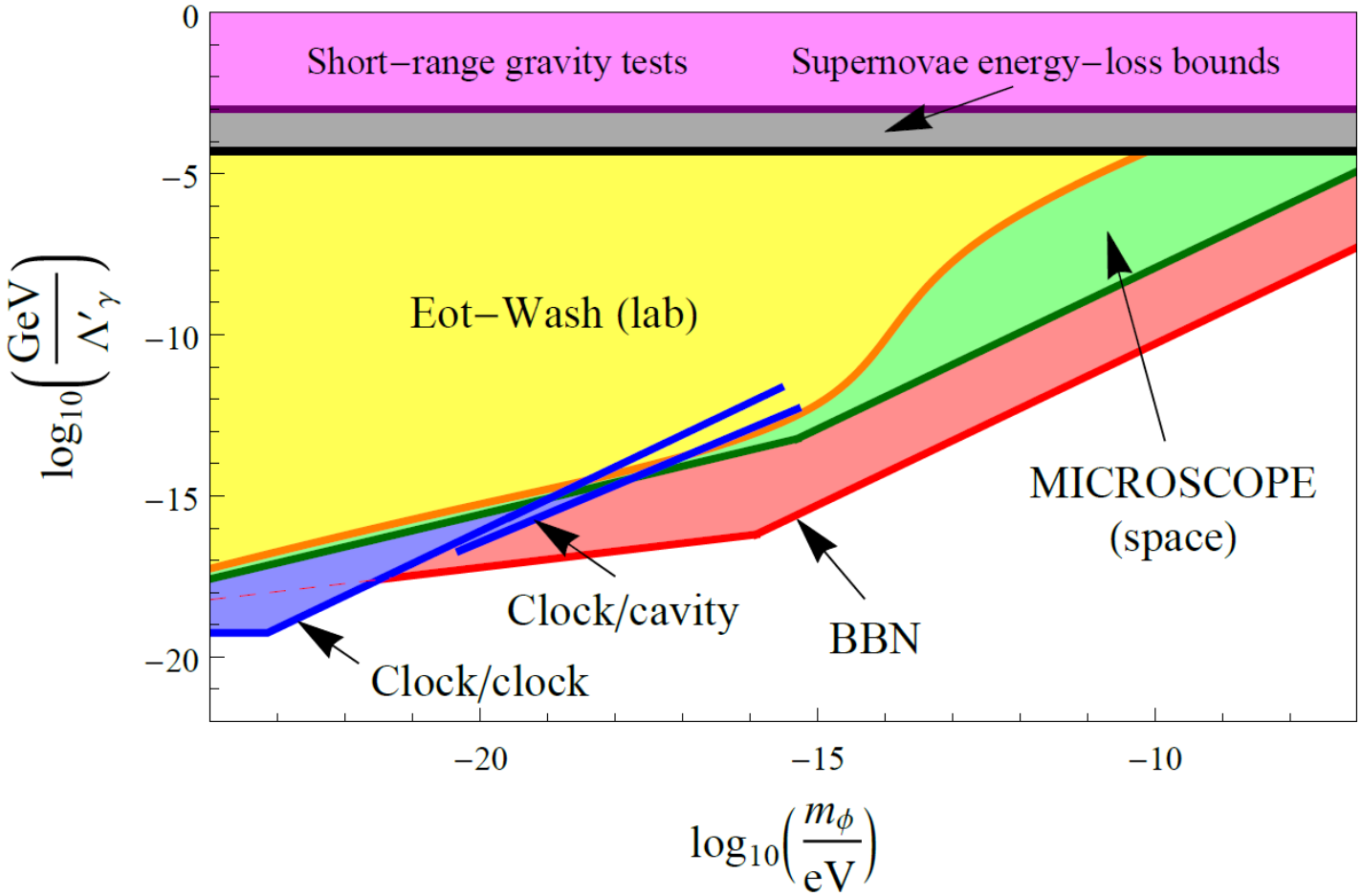
[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]



# 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!**



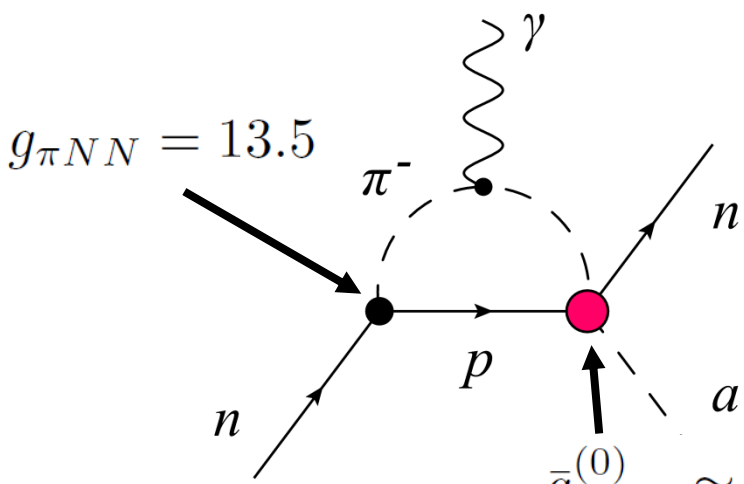
# Oscillating Electric Dipole Moments

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

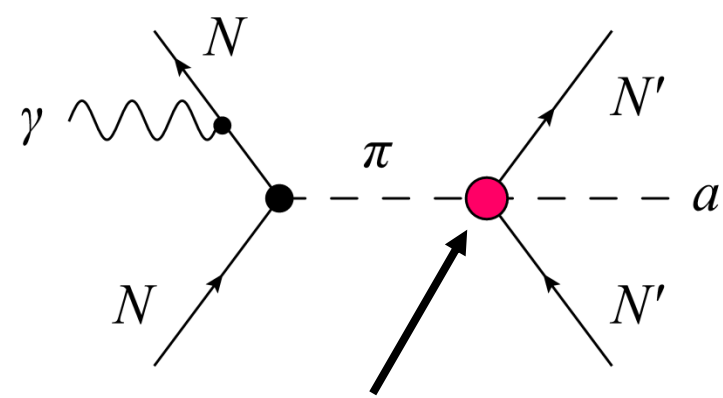
**Atoms and molecules:** [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

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

**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 = $1/(8\pi^2)$].