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
1. Electroweak Phenomena

2. Electric Dipole Moments

Outline

1. Electroweak Phenomena

2. Electric Dipole Moments

EW Phenomena in Atoms (PNC)

Electromagnetic

$e \leftrightarrow e$

$\gamma$

$N \leftrightarrow N$

Parity conserving,
long range
Electromagnetic
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\[ e \rightarrow \gamma \rightarrow e \]

Weak neutral current
Parity violating,
short range (~10^{-18} m)

\[ e \rightarrow Z \rightarrow e \]
EW Phenomena in Atoms (PNC)

\[ \Gamma_{\pm} = \pm 2 \]

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\[ [E \cdot (\varepsilon \times B)](\varepsilon \cdot B) \]

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Parity conserving, long range

Parity violating, short range \((\sim 10^{-18} \text{ m})\)

Flip sign by reversing a P-odd invariant, e.g. 
\[ [E \cdot (\varepsilon \times B)](\varepsilon \cdot B) \]

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

\[ \Rightarrow \text{Determine nuclear weak charge } Q_W = -N + Z [1 - 4\sin^2(\theta_W)] \approx -N \]
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:

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

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Bounds on new physics:

Extra standard-type \( Z \) boson: \( M_{Z'} > 700 \) GeV

[Dzuba, Berengut, Flambaum, Roberts, PRL 109, 203003 (2012)]

Extra generic spin-1 boson:

\[ |g^A_e g^V_N| < 3 \times 10^{-14}, \quad M_V < 1 \text{ keV}; \quad |g^A_e g^V_N|/M^2_V < 4 \times 10^{-8} \text{ GeV}^{-2}, \quad M_V > 200 \text{ keV} \]

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\[ H_{\text{anapole}} = e \alpha \cdot a \delta(r) \]

Measure nuclear-spin-dependent PNC amplitude
Nuclear Anapole Moments (PNC)

So far, only observation of nuclear anapole moment in caesium beam experiment in Boulder:

\[ \kappa_a (^{133}\text{Cs})_{\text{exp}} = 0.36(6) \quad \text{cf.} \quad \kappa_a (^{133}\text{Cs})_{\text{theory}} = 0.27(8) \]

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New experiments targeting observation of anapole moments in odd-neutron nuclei (mainly sensitive to $g_n$): $^{137}\text{BaF, }^{171,173}\text{Yb}$
Ground-state hyperfine interval in muonium (e⁻μ⁺ bound state):

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

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

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[Hides, *PRA* 53, 2953 (1996)]

New experiments and calculations targeting $\sim \mathcal{O}(10)$ 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

In 4-Fermi approximation:

\[ V_\nu(r) \sim \frac{G_F^2}{r^5} + \text{spin-dependent terms} \]
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No centrifugal barrier!

No hadronic nucleus => lower cutoff length scale is \( \sim \lambda_Z \), instead of \( \sim R_{\text{nucl}} \)
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\( \Rightarrow \) clean system

\[ F_\nu \propto (R^3)^2/r^6 \leq R^0 \Rightarrow \text{no penalty in small systems, cf. } F_{\text{grav}} \propto (R^3)^2/r^2 \leq R^4 \]
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\[ (G_{\text{eff}}^2)_{\mu\text{onium}} < 10^2 G_F^2 \quad \text{cf.} \quad (G_{\text{eff}}^2)_{\text{macroscopic}} < 10^{20} G_F^2 \]
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Motivation for EDM Experiments

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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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\[ \psi = + \xi = \implies |\psi|^2 = \]
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\[ h\nu_i = 2|\mu_i B \pm d_i E| \]

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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)]

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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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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*. 
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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Small magnetic moment in $^3\Delta_1$ ThO state: $|\mu_{\text{ThO}}(^3\Delta_1)| \sim 10^{-2} \mu_B$

$\Rightarrow$ Less sensitive to (stray) magnetic fields
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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

\[ \mathcal{O}(m_{\pi}^{-2}) \] (LO)

\[ \mathcal{O}(m_{\pi}^{-1}) \] (NLO)

\[ \mu - d: \mathcal{O}[\ln(A)/p_F] \]
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**LO:** $\mathcal{O}(m^{-2}_\pi)$

**NLO:** $\mathcal{O}(m^{-1}_\pi)$

**$\mu - d$:** $\mathcal{O}[\ln(A)/p_F]$  

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

$p, n$ contributions: *same sign*

Example $- \theta_{QCD}$ term:

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

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

|θ|_{ThO} < 3 \times 10^{-8}
|θ|_{n} < 2 \times 10^{-10}
|θ|_{Hg} < 1.5 \times 10^{-10}

|d_{p}|_{ThO} < 2 \times 10^{-23} \text{ e cm}
|d_{p}|_{Hg} < 2 \times 10^{-25} \text{ e cm}
|d_{p}|_{Xe} < 3 \times 10^{-22} \text{ e cm}

|\bar{g}_{\pi NN}^{(1)}|_{ThO} < 4 \times 10^{-10}
|\bar{g}_{\pi NN}^{(1)}|_{n} < 1 \times 10^{-10}
|\bar{g}_{\pi NN}^{(1)}|_{Hg} < 1 \times 10^{-12}
|\bar{g}_{\pi NN}^{(1)}|_{Xe} < 7 \times 10^{-8}
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Current bounds from molecules are ~10–100 times weaker than from Hg & n, but are ~10–100 times stronger than bounds from Xe

*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. $\tilde{d}_{u} - \tilde{d}_{d}$)*
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Motivation

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

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

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

- Dark matter density: \( \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \)
- Dark matter velocity: \( v_{DM} \approx 300 \text{ km/s} \)

Ultra-low-mass bosons
  - WIMPs

Particle mass
  - Ultralow: \( 10^{-21} \text{ eV} \)
  - eV
  - GeV
  - TeV
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Ultra-low-mass bosons

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WIMPs

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10^{-21} \text{ eV} \quad \text{eV} \quad \text{GeV} \quad \text{TeV}
Low-mass Spin-0 Dark Matter

- Low-mass spin-0 particles form a coherently oscillating classical field $\phi(t) = \phi_0 \cos(m\phi c^2t/\hbar)$, with energy density $\langle \rho_\phi \rangle \approx m_\phi^2 \phi_0^2/2$ ($\rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3$)

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

\[
\ddot{\phi} + m_\phi^2 \phi \approx 0
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  \[ <\rho_\phi> \approx m_\phi^2 \phi_0^2/2 \left( \rho_{\text{DM,local}} \approx 0.4 \ \text{GeV/cm}^3 \right) \]

- **Coherently oscillating field, since cold** \((E_\phi \approx m_\phi c^2)\)

- \(\Delta E_\phi /E_\phi \sim <v_\phi^2>/c^2 \sim 10^{-6} \Rightarrow \tau_{\text{coh}} \sim 2\pi/\Delta E_\phi \sim 10^6 T_{\text{osc}}\)
Low-mass Spin-0 Dark Matter

• Low-mass spin-0 particles form a coherently oscillating classical field \( \phi(t) = \phi_0 \cos(m_{\phi}c^2t/\hbar) \), with energy density
  \( <\rho_\phi> \approx m_{\phi}^2\phi_0^2/2 \) (\( \rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3 \))

• Coherently oscillating field, since cold \( (E_\phi \approx m_{\phi}c^2) \)

• \( \Delta E_\phi /E_\phi \sim <v_{\phi}^2>/c^2 \sim 10^{-6} \Rightarrow \tau_{\text{coh}} \sim 2\pi/\Delta E_\phi \sim 10^6 T_{\text{osc}} \)

• Classical field for \( m_{\phi} \lesssim 1 \text{ eV} \), since \( n_{\phi}(\lambda_{\text{dB,}\phi}/2\pi)^3 \gg 1 \)
Low-mass Spin-0 Dark Matter

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- Coherently oscillating field, since cold ($E_\phi \approx m_\phi c^2$)

- $\Delta E_\phi / E_\phi \sim <v_\phi^2>/c^2 \sim 10^{-6} \Rightarrow \tau_{coh} \sim 2\pi/\Delta E_\phi \sim 10^6 T_{osc}$

- Classical field for $m_\phi \leq 1 \text{ eV}$, since $n_\phi(\lambda_{dB,\phi}/2\pi)^3 \gg 1$

- $10^{-21} \text{ eV} \leq m_\phi \leq 1 \text{ eV} \iff 10^{-7} \text{ Hz} \leq f \leq 10^{14} \text{ Hz}$

Lyman-α forest measurements [suppression of structures for $L \leq \mathcal{O}(\lambda_{dB,\phi})$]
Low-mass Spin-0 Dark Matter

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- *Classical* field for $m_\phi \lesssim 1 \text{ eV}$, since $n_\phi (\lambda_{\text{dB,}\phi}/2\pi)^3 \gg 1$

- $10^{-21} \text{ eV} \lesssim m_\phi \lesssim 1 \text{ eV} \iff 10^{-7} \text{ Hz} \lesssim f \lesssim 10^{14} \text{ Hz}$

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

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (Dilatons):
\[ \phi \rightarrow +\phi \]

Pseudoscalars (Axions):
\[ \phi \rightarrow -\phi \]

→ Time-varying fundamental constants
- Atomic clocks
- Cavities and interferometers
- Fifth-force searches
- Astrophysics (e.g., BBN)

→ Time-varying spin-dependent effects
- Co-magnetometers
- Nuclear magnetic resonance
- Torsion pendula
Low-mass Spin-0 Dark Matter

Scalors (Dilatons):
\[ \phi \xrightarrow{P} +\phi \]

Pseudoscalars (Axions):
\[ \phi \xrightarrow{P} -\phi \]

→ Time-varying fundamental constants
  - Atomic clocks
  - Cavities and interferometers
    - Fifth-force searches
  - Astrophysics (e.g., BBN)

→ Time-varying spin-dependent effects
  - Co-magnetometers
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• fifth-force searches
• astrophysics (e.g., BBN)
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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\[ \mathcal{L}_\gamma = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \Rightarrow \frac{\delta \alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma} \]
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\]

\[
\mathcal{L}_f = -\frac{\phi}{\Lambda_f} m_f \bar{f} f \implies \frac{\delta m_f}{m_f} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_f}
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[Stadnik, Flambaum, *PRL* 114, 161301 (2015); *PRA* 93, 063630 (2016)]

Solid material

\[L \sim N a_B = N/(m_e \alpha)\]
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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\]

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

Solid material

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

\[
L \sim N_{a_B} = N/(m_{e\alpha})
\]
Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter


Solid material

$L_{\text{free}} \sim N\alpha_B = N/(m_e\alpha)$
Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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

Solid material

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

Electronic transition

$\Delta E = \hbar \omega_{\text{atom}}$

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

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

$\Rightarrow \frac{\delta \Phi}{\Phi} \approx \frac{\delta \alpha}{\alpha}$
Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter


Solid material

![Solid material](image)

Electronic transition

![Electronic transition](image)

$\Delta E = \hbar \omega_{\text{atom}}$

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

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

- **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

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

Freely-suspended mirrors

cf.

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

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

$\Phi \propto L_{\text{free}} \propto a_B \implies \frac{\delta \Phi}{\Phi} \approx -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e}$
Cavity-Based Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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

Solid material

\[ L_{\text{free}} \sim N a_B = N / (m_e \alpha) \]

Freely-suspended mirrors

\[ L_{\text{fixed}} \approx \text{const.} \]

\[ \Phi \propto L_{\text{free}} \propto a_B \implies \frac{\delta \Phi}{\Phi} \approx -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e} \]

cf.

\[ \frac{\delta \Phi}{\Phi} \approx \frac{\delta \alpha}{\alpha} \]
Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

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

Michelson interferometer (GEO 600)
Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter


- Geometric asymmetry from beam-splitter: \( \delta(L_x - L_y) \sim \delta(nI) \)
Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter


- 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

• 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)

\[
N_{\text{eff}} \sim \text{few} \times 10^2
\]

\[
\delta(L_x - L_y)_{BS} \sim \delta(nl) / N_{\text{eff}}
\]
Michelson vs Fabry-Perot-Michelson Interferometers

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

\[ \delta(L_x - L_y) \approx \delta(\Delta w) \]

[Grote, Stadnik, Phys. Rev. Research 1, 033187 (2019)]
Linear Interaction of Scalar Dark Matter with the Electron

Logarithmic plot showing the interaction of scalar dark matter with the electron. The plot includes regions labeled as Fifth-force searches (non-DM), LIGO, and Holometer. The y-axis is labeled as $\log_{10} \left( \frac{\text{GeV}}{\Lambda_e} \right)$ and the x-axis is labeled as $\log_{10} \left( \frac{m_\phi}{\text{eV}} \right)$. The plot compares different experimental setups, including GEO 600.
Linear Interaction of Scalar Dark Matter with the Electron
Linear Interaction of Scalar Dark Matter with the Electron

- Fifth-force searches (non-DM)
- LIGO (modified)
- Holometer (narrowband)
- Cross-correlation between pair of detectors

Graph showing \( \log_{10} \left( \frac{m_\phi}{\text{eV}} \right) \) vs. \( \log_{10} \left( \frac{\text{GeV}}{\Lambda_e} \right) \) with curves for GEO 600 and other detectors.
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

   - **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 \( \phi(t) = \phi_0 \cos(m_\phi c^2 t/\hbar) \), with energy density \( \langle \rho_\phi \rangle \approx m_\phi^2 \phi_0^2/2 \) (\( \rho_{DM,\text{local}} \approx 0.4 \text{ GeV/cm}^3 \))

- \( \Delta E_\phi/E_\phi \sim \langle v_\phi^2 \rangle/c^2 \sim 10^{-6} \Rightarrow \tau_{coh} \sim 2\pi/\Delta E_\phi \sim 10^6 T_{osc} \)
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)]

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

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

\[
\phi = \phi_0 \cos(m_\phi t - \mathbf{p}_\phi \cdot \mathbf{x}) \quad \Rightarrow \quad F \propto \mathbf{p}_\phi \sin(m_\phi t)
\]

\[
\left\{ \begin{array}{l}
\mathcal{L}'_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \\
\mathcal{L}'_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f
\end{array} \right. 
\quad \Rightarrow \quad \frac{\delta \alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \delta \rho_\phi
\]

\[
F \propto \nabla \rho_\phi
\]
Consider quadratic couplings of an oscillating classical scalar field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, with SM fields.

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

\[
\Rightarrow \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\varphi t) = \begin{cases} \frac{\phi_0^2}{2(\Lambda'_f)^2} & \text{red} \\ \frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2m_\varphi t) & \text{blue} \end{cases}
\]

\[
\rho_\varphi = \frac{m_\varphi^2 \phi_0^2}{2} \implies \phi_0^2 \propto \rho_\varphi
\]
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, \( \phi(t) = \phi_0 \cos(m_\phi t) \), with SM fields.

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

\[
\Rightarrow \quad \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \frac{\phi_0^2}{2(\Lambda'_f)^2} + \frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2m_\phi t)
\]

`Slow' drifts [Astrophysics (high \( \rho_{DM} \)): BBN, CMB]

+ Gradients [Fifth forces]

Oscillating variations [Laboratory (high precision)]
Consider the effect of a massive body (e.g., Earth) on the scalar DM field.

**Linear couplings** $(\phi \bar{\chi} \chi)$

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

**Quadratic couplings** $(\phi^2 \bar{\chi} \chi)$

\[ \phi = \phi_0 \cos(m_\phi t) \left(1 - \frac{B}{r}\right) \]

Gradients + screening/amplification
Fifth Forces: Linear vs Quadratic Couplings

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

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

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

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

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

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

Gradients + screening/amplification
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 ($\phi \dot{X} X$)

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

Quadratic couplings ($\phi^2 \ddot{X} X$)

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

Motional gradients: $\phi_0 \cos(m_\phi t - \mathbf{p}_\phi \cdot \mathbf{x})$

“Fifth-force” experiments: torsion pendula, atom interferometry

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!

\[
\mathcal{L}_H = -A\phi H^\dagger H
\]
BBN Constraints on ‘Slow’ Drifts in Fundamental Constants due to Dark Matter

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

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

\[
p + e^- \iff n + \nu_e
\]

\[
n + e^+ \iff p + \bar{\nu}_e
\]

\[
n \rightarrow p + e^- + \bar{\nu}_e
\]
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**

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