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

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Outline

1. Electroweak Phenomena

2. Electric Dipole Moments

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EW Phenomena in Atoms (PNC)

Electromagnetic

Parity conserving, long range
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**Electromagnetic**

Parity conserving, long range

\[ e \rightarrow e \]

\[ N \rightarrow N \]

**Weak neutral current**

Parity violating, short range (~$10^{-18}$ m)

\[ e \rightarrow e \]

\[ N \rightarrow N \]

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

\[ \Gamma_\pm = \begin{pmatrix}
  \text{Electromagnetic} \\
  e \quad e \\
  N \quad N \\
\end{pmatrix} + \begin{pmatrix}
  \text{Weak neutral current} \\
  e \quad e \\
  N \quad N \\
\end{pmatrix} \pm \begin{pmatrix}
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$\Gamma_{\pm} = \pm$ Flip sign by reversing a P-odd invariant, e.g. $[\mathbf{E} \cdot (\mathbf{\varepsilon} \times \mathbf{B})](\mathbf{\varepsilon} \cdot \mathbf{B})$
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Flip sign by reversing a P-odd invariant, e.g. $[E \cdot (\varepsilon \times B)](\varepsilon \cdot B)$

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

=> Determine nuclear weak charge $Q_W = -N + Z[1 - 4\sin^2(\theta_W)] \approx -N$
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[Barkov, Zolotorev, JETP Lett. 27, 357 (1978); Pis’ma Zh. Eksp. Teor. Fiz. 27, 379 (1978)]

Current “gold standard” – caesium beam experiment in Boulder:

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

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

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Bounds on new physics:

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


**Extra generic spin-1 boson:**

\[
\left| g_e^A g_N^V \right| < 3 \times 10^{-14}, \ M_V < 1 \text{ keV}; \quad \left| g_e^A g_N^V \right|/M_V^2 < 4 \times 10^{-8} \text{ GeV}^{-2}, \ M_V > 200 \text{ keV}
\]

Nuclear Anapole Moments (PNC)

Parity-violating toroidal moment:

\[ \mathbf{a} = -\pi \int d^3r \, r^2 \, \mathbf{j}(\mathbf{r}) \propto \kappa_a \mathbf{l} \]
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\[ H_{\text{anapole}} = e \, \mathbf{a} \cdot \mathbf{a} \, \delta(\mathbf{r}) \]

Measure

nuclear-spin-dependent

PNC amplitude
Nuclear Anapole Moments (PNC)

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

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

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[Dzuba, Flambaum, Stadnik, PRL 119, 223201 (2017)]

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

Ground-state hyperfine interval in muonium (e−μ+ bound state):

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

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

Experiment: [Liu et al., PRL 82, 711 (1999)]

Theory (summary): [CODATA, Rev. Mod. Phys. 88, 035009 (2016)]
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![Diagram](image)

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[\text{Eides, PRA 53, 2953 (1996)}]

New experiments and calculations targeting \( \mathcal{O}(10) \text{ Hz} \) 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

\begin{align*}
V_\nu(r) & \sim \frac{G_F^2}{r^5} + \text{spin-dependent terms}
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In 4-Fermi approximation:
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\delta \nu \sim \frac{a_B}{\lambda_Z} (G_F^2/a_B^5) \sim \text{Hz}
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No hadronic nucleus => lower cutoff length scale is \(\sim \lambda_Z\), instead of \(\sim R_{\text{nucl}}\)

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\[F_\nu \propto \left(\frac{R^3}{r^6}\right) \leq R^0 \Rightarrow \text{no penalty in small systems, cf. } F_{\text{grav}} \propto \left(\frac{R^3}{r^2}\right) \leq R^4\]
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\( \left( G_{\text{eff}}^2 \right)_{\text{muonium}} < 10^2 G_F^2 \) \hspace{1em} \text{cf.} \hspace{1em} \left( G_{\text{eff}}^2 \right)_{\text{macroscopic}} < 10^{20} G_F^2 \]
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1. Electroweak Phenomena

2. Electric Dipole Moments

Motivation for EDM Experiments

- Observed predominance of matter over antimatter in Universe
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Motivation for EDM Experiments

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• In hot big bang model, require sources of CP violation to produce this asymmetry

• Known sources of CP violation in the standard model ($\delta_{\text{CKM}}$ and $\theta_{\text{QCD}} \approx 0$) insufficient

• EDM experiments are high-precision low-energy probes of possible new sources of CP violation
Atomic Electric Dipole Moments
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\[ \psi = \begin{array}{l}
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\end{array} \begin{array}{l}
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Atomic Electric Dipole Moments

\[ h\nu_i = 2|\mu_i B \pm d_i E| \]

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Flip sign by reversing the P,T-odd invariant \( \mathbf{E} \cdot \mathbf{B} \)

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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)],

**Illustrative example:** \[ \mathcal{L}_{\theta_{\text{QCD}}} = \theta \frac{g^2}{32\pi^2} G\tilde{G} \]
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**Nucleon EDMs**

**CP-violating intranuclear forces**

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


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Classical explanation for nuclear EDM: A neutral atom does not accelerate in 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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$\Rightarrow$ 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

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

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

$\mu - d$: $\mathcal{O}[\ln (A)/p_F]$
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\( \pi^0, \eta \) contributions: \textit{opposite sign}

\( p, n \) contributions: \textit{same sign}

Example – \( \theta_{\text{QCD}} \) term:

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

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

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|\theta|_{\text{ThO}} < 3 \times 10^{-8} \\
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*Clean* bound on \(g^{(1)}_{\pi NN}\), unlike from Hg Schiff moment (where *nuclear uncertainties can formally nullify sensitivity* to \(g^{(1)}_{\pi NN}\) and derived quantities, e.g. \(\tilde{d}_u - \tilde{d}_d\)).
Motivation

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

\[ \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \]
\[ \nu_{DM} \sim 300 \text{ km/s} \]
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Ultra-low-mass bosons

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$\nu_{DM} \sim 300 \text{ km/s}$
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 $\langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2 / 2$ ($\rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3$)

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

$$\ddot{\varphi} + m_\varphi^2 \varphi \approx 0$$
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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 \( \langle \rho_\varphi \rangle \approx m_\varphi^2 \varphi_0^2/2 \) (\( \rho_{\text{DM,local}} \approx 0.4 \text{ GeV/cm}^3 \))

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

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

• *Coherently* oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)

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

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

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

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

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

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

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

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

• $\Delta E_\phi / E_\phi \sim \langle v_\phi^2 \rangle / c^2 \sim 10^{-6} \Rightarrow \tau_{\text{coh}} \sim 2\pi/\Delta E_\phi \sim 10^6 T_{\text{osc}}$

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

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

  ↑

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

• *Wave-like* signatures [cf. *particle-like* signatures of WIMP DM]
Low-mass Spin-0 Dark Matter

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**Dark Matter**

**Scalars (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
- Nuclear magnetic resonance
- Torsion pendula
Low-mass Spin-0 Dark Matter

Dark Matter

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

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

Pseudoscalars (Axions):
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Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, Flambaum, *PRL* 114, 161301 (2015); *PRL* 115, 201301 (2015)],
[Hees, Minazzoli, Savalle, Stadnik, Wolf, *PRD* 98, 064051 (2018)]
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[Stadnik, Flambaum, *PRL* 114, 161301 (2015); *PRL* 115, 201301 (2015)],
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\[ L_{\gamma} = \frac{\phi}{\Lambda_{\gamma}} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \implies \frac{\delta \alpha}{\alpha} \approx \frac{\phi_0 \cos(\frac{m_{\phi} t}{\Lambda_{\gamma}})}{\Lambda_{\gamma}} \]
Dark Matter-Induced Cosmological Evolution of the Fundamental Constants


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\mathcal{L}_\gamma = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \implies \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 \implies \frac{\delta m_f}{m_f} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_f}
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Dark Matter-Induced Cosmological Evolution of the Fundamental Constants


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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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\]


Solid material

\[
L \sim N a_B = N/(m_e \alpha)
\]
Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

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

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

Solid material

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

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

\[ L_{\text{free}} \sim N a_B = N/(m_e \alpha) \]
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[Stadnik, Flambaum, *PRL* 114, 161301 (2015); *PRA* 93, 063630 (2016)]

**Solid material**

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

**Electronic transition**

\[ \Delta E = \hbar \omega_{\text{atom}} \]

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

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

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


Solid material

Electronic transition

\[
\Delta E = \hbar \omega_{\text{atom}}
\]

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

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

- Sr/Si cavity (JILA): [Robinson, Ye et al., *Bulletin APS*, H06.00005 (2018)]
- Sr\(^+\)/ULE cavity (Weizmann): [Aharony et al., arXiv:1902.02788]
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

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

Freely-suspended mirrors

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

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


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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


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


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


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


Michelson interferometer  
(GEO 600, Fermilab holometer)

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

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

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

\[ N_{\text{eff}} \sim \text{few} \times 10^2 \]
Michelson vs Fabry-Perot-Michelson Interferometers


Michelson interferometer
(GEO 600, Fermilab holometer)

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

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

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

Change thickness of arm mirrors by amount \(\Delta w\)
Linear Interaction of Scalar Dark Matter with the Electron

\[ \log_{10}\left(\frac{\text{GeV}}{\Lambda_e}\right) \]

Fifth-force searches (non-DM)

LIGO

Holometer

GEO 600
Linear Interaction of Scalar Dark Matter with the Electron

\[ \text{log}_{10} \left( \frac{\text{GeV}}{\Lambda_e} \right) \]

\[ \text{log}_{10} \left( \frac{m_\phi}{\text{eV}} \right) \]

- Fifth-force searches (non-DM)
- LIGO (modified)
- Holometer (narrowband)

GEO 600
Linear Interaction of Scalar Dark Matter with the Electron

\[
\log_{10}\left(\frac{\text{GeV}}{\Lambda_e}\right)
\]
\[
\log_{10}\left(\frac{m_\phi}{\text{eV}}\right)
\]

Fifth-force searches (non-DM)

LIGO (modified)

Holometer (narrowband)

Cross-correlation between pair of detectors

GEO 600
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** \( \varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar) \), with energy density
  \[ <\rho_\varphi> \approx m_\varphi^2 \varphi_0^2/2 \ (\rho_{DM,\text{local}} \approx 0.4 \text{ GeV/cm}^3) \]

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

![Evolution of \( \varphi_0 \) with time](image1)

![Probability distribution function of \( \varphi_0 \)](image2)
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)]

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

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

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

\[ \begin{aligned} 
\mathcal{L}'_\gamma &= \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \\
\mathcal{L}'_f &= -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f 
\end{aligned} \]

\[ \Rightarrow \quad \frac{\delta \alpha}{\alpha} \propto \frac{\delta m_f}{m_f} \propto \delta \rho_\phi \]

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

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

\[
\implies \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m\varphi t) = \frac{\phi_0^2}{2(\Lambda'_f)^2} + \frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2m\varphi t)
\]

\[
\rho_\varphi = \frac{m^2_\varphi \phi_0^2}{2} \implies \phi_0^2 \propto \rho_\varphi
\]
Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Consider \textit{quadratic couplings} of an oscillating classical scalar field, \( \phi(t) = \phi_0 \cos(m_\phi t) \), with SM fields.

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

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

\textbf{‘Slow’ drifts} [Astrophysics (high \( \rho_{DM} \)): BBN, CMB]

\textbf{+ Gradients} [Fifth forces]

\textbf{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** \((\phi \bar{X} X)\)

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

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

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

Gradients + screening/amplification
Consider the effect of a massive body (e.g., Earth) on the scalar DM field

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

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

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

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

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 ($\phi \ddot{X}X$)

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

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: $\phi_0 \cos(m_\phi t - p_\phi \cdot x)$

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

Gradients + screening/amplification
Constraints on Linear Interaction of Scalar Dark Matter with the Electron

![Graph showing constraints on scalar dark matter interactions with the electron. The graph plots \( \log_{10} \left( \frac{m_\phi}{eV} \right) \) against \( \log_{10} \left( \frac{\Lambda}{eV} \right) \). The graph includes regions for fifth-force searches (non-DM), LIGO (modified), Holometer (narrowband), and technical naturalness (\( \Lambda \sim 10 \text{ TeV} \)).]
Quartic Self-Interaction of Scalar

![Graph of Quartic Self-Interaction of Scalar]

- Structures (DM)
- Black Holes

Graph axes:
- $\log_{10} |\lambda_\phi|$
- $\log_{10}\left(\frac{m_\phi}{\text{eV}}\right)$
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 $\rho_{\text{DM}}$)
- 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)

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

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

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

\[
n \to p + e^- + \bar{\nu}_e
\]
Back-Reaction Effects in BBN

[Sörensen, Sibiryakov, Yu, PRELIMINARY – In preparation]
Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon


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

\[ g_{\pi NN} = 13.5 \]

\[ g_{\pi NN}^{(0)} \approx 0.016 \frac{C_G a_0 \cos(m_a t)}{f_a} \]

CP-violating intranuclear forces

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