Searching for an oscillating massive scalar field as a dark matter candidate using atomic hyperfine frequency comparisons

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Outline

• Introduction
• Scalar fields with non-universal coupling
• Link to dark matter
• Relation to atomic spectroscopy
• Searching in the SYRTE FO2 Rb/Cs spectroscopy data
• Results
• Conclusion and Outlook

[Hees et al., PRL 117, 061301, 2016]
Introduction

• General Relativity (GR) is a classical theory, difficult to reconcile with quantum field theory and the Standard Model of particle physics (SM).
• Dark Energy and Dark Matter (DM) may indicate deviations from GR and/or SM.

• Many modified gravitational theories and corresponding cosmological models contain long range scalar fields. Higgs boson is the first known fundamental scalar field (short range).
• If such scalar fields are massive and pressureless they could be DM candidates. Under quite general assumptions they will oscillate at frequency $f = \frac{m_\varphi c^2}{h}$.
• Scalar fields might be non-universally coupled to SM-fields, leading to violations of the equivalence principle e.g. non-universality of free fall or space-time variations of fundamental constants.
• Comparing different atomic transitions allows searching for such variations.
• We analyze ≈ 6 yrs of Rb/Cs hyperfine frequency measurements to search for such massive scalar fields at very low mass $\approx 10^{-24} – 10^{-18}$ eV.
Non-universally coupled scalar fields

\[ S = \frac{1}{c} \int d^4 x \sqrt{-g} \left[ R - 2g^{\mu \nu} \partial_\mu \varphi \partial_\nu \varphi - V(\varphi) \right] + \frac{1}{c} \int d^4 x \sqrt{-g} \left[ \mathcal{L}_{\text{SM}}(g_{\mu \nu}, \Psi) + \mathcal{L}_{\text{int}}(g_{\mu \nu}, \varphi, \Psi) \right] \]

With five dimensionless coupling constants \( d_x \)

- From Damour & Donoghue (2010).
- Fundamental constants (\( \alpha, \Lambda_3, m_i \)) are functions of \( \varphi \), and vary if \( \varphi \) varies.
- Quadratic couplings treated in Stadnik & Flambaum (2014). Leads to similar phenomenology.

\[ \mathcal{L}_{\text{int}} = \varphi \left[ \frac{d_e}{4\mu_0} F^2 - \frac{d_g \beta_g}{2g_3} (F^A)^2 - c^2 \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right] \]

\[ \alpha(\varphi) = \alpha (1 + d_e \varphi) , \]
\[ m_i(\varphi) = m_i (1 + d_{m_i} \varphi) \]
\[ \Lambda_3(\varphi) = \Lambda_3 (1 + d_g \varphi) \]

[Damour & Donoghue 2010]
[Stadnik & Flambaum 2014,2015]
Evolution of the scalar field

\[ V(\varphi) = 2\frac{c^2}{\hbar^2} m^2 \varphi^2 \]

\[ \ddot{\varphi} + 3H \dot{\varphi} + \frac{m^2 c^4}{\hbar^2} \varphi = \frac{4\pi G}{c^2} \frac{\partial L_{\text{int}}}{\partial \varphi} \]

\[ \varphi = \frac{4\pi G \sigma \hbar^2}{m^2 c^6} + \varphi_0 \cos(\omega t + \delta) \]

- Assume a quadratic potential for \( \varphi \).
- Embed action in FLRW metric.
- Varying with respect to \( \varphi \) gives a KG equation for its evolution (\( \sigma = \frac{\partial L_{\text{int}}}{\partial \varphi} \)).
- The solution oscillates at \( \omega = \frac{m^2 c^2}{\hbar} \) with negligible “Hubble damping” for \( m^2 \gg \frac{\hbar^2}{c^2} \), well satisfied for our mass range.
The cosmological density (+) and pressure (-) of \( \varphi \) are given by
\[
\frac{c^2}{8\pi G} \left( \dot{\varphi}^2 \pm \frac{V(\varphi)c^2}{2} \right).
\]

It turns out that the oscillating part of \( \varphi(t) \) has zero average pressure and is therefore a candidate for Dark Matter.

Equating its average density with the DM density (\( \approx 0.4 \text{ GeV/cm}^3 \)) fixes the amplitude of the oscillation \( \varphi_0 \cos(\omega t + \delta) \).

That oscillation translates into an oscillation of the fundamental constants that can be searched for in a 6 parameter space (\( m_\varphi, d_x \)).

The mass \( m_\varphi \) is given by the frequency of oscillation, the coupling constants \( d_x \) by the amplitude.

[Stadnik & Flambaum 2014, 2015]
[Arvinataki, Huang, Van Tilburg 2015]
• Different atomic transition frequencies depend differently on three dimensionless fundamental constants: $\alpha$, $m_e/m_p$, $m_q/\Lambda_3$, with $m_q = (m_u+m_d)/2$.
• If one or several of those constants vary in time/space you can search for that variation by monitoring ratios of atomic transition frequencies in atomic clocks.
• The dependence of different frequency ratios on the fundamental constants has been calculated in great detail by Flambaum and co-workers [2006, 2008, 2009].
• Generally optical transitions are sensitive to variations of $\alpha$ only, hyperfine transitions to linear combinations of all three. Thus ideally at least 3 different frequency ratios are required to independently search for a possible variation of either of the 3 constants.

$$d\ln(X) = k_\alpha d\ln(\alpha) + k_\mu d\ln(\mu) + k_q d\ln(m_q/\Lambda_{QCD})$$

TABLE I. Sensitivity coefficients $k_\alpha$, $k_\mu$, and $k_q$ of atomic transition frequencies used in current atomic clocks to a variation of $\alpha$ [23,24], of $\mu = m_e/m_p$ and of $m_q/\Lambda_{QCD}$ [16,17]. These transitions are hyperfine transitions for $^1\text{H}_{\text{hfs}}$, $^{87}\text{Rb}$, $^{133}\text{Cs}$, and optical transitions for $^1\text{H}(1S-2S)$ and all others except Dy. For Dy, the rf transition between two closely degenerated electronic levels of opposite parity is used in the two 162 and 163 isotopes [10,11,25].

<table>
<thead>
<tr>
<th>Element</th>
<th>$k_\alpha$</th>
<th>$k_\mu$</th>
<th>$k_q$</th>
</tr>
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<tbody>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>2.34</td>
<td>1</td>
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</tr>
<tr>
<td>$^{133}\text{Cs}$</td>
<td>2.83</td>
<td>1</td>
<td>0.002</td>
</tr>
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<td>$^1\text{H}_{\text{hfs}}$</td>
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<td>1</td>
<td>-0.100</td>
</tr>
<tr>
<td>$^1\text{H}(1S-2S)$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{199}\text{Hg}^+$</td>
<td>-2.94</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{87}\text{Sr}$</td>
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<td>0</td>
</tr>
<tr>
<td>$^{162}\text{Dy} - ^{163}\text{Dy}$</td>
<td>$1.72 \times 10^7$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$^{27}\text{Al}^+$</td>
<td>0.008</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The SYRTE dual Rb-Cs fountain FO2

- Built in early 2000s by André Clairon and co-workers.
- Operates simultaneously on $^{87}\text{Rb}$ and $^{133}\text{Cs}$ since 2008 (common mode systematics).
- Most accurate and stable Rb/Cs frequency ratio measurement world-wide (and longest duration).
- Contributes continuously to TAI with both Rb and Cs.
- Previously used to constrain linear drifts of fundamental constants, and variations proportional to $U/c^2$ i.e. annual variations [Guéna 2012].
- All systematics are evaluated and corrected during operation.


André Clairon
1947 - 2015
FO2 Rb/Cs raw data

- Nov 2009 – Feb 2016
- Averaged to 100 points/day
- 100814 points in total
- ≈ 45% duty cycle with gaps due to maintenance and investigation of systematics
- Standard deviation = 3x10^{-15}

\[ y(t) = \frac{f(t)}{f_0} \]
Results: Scargle filter

- Fit $A + C_\omega \cos(\omega t) + S_\omega \sin(\omega t)$ to data for each independent $\omega$.
- Search for a peak in normalized power $P_\omega = \frac{N}{4\sigma^2} (C_\omega^2 + S_\omega^2)$.
- Use different methods (LSQ + MC, Bayesian MCMC) to determine confidence limits.
Results: upper limit on couplings

- Complementary to previous searches (Dy) that are sensitive to $d_e$ only.
- When assuming only $d_e \neq 0$, improve Dy limits significantly.
- Also complementary to WEP tests ($\approx 10^{-3}$ for only $d_e \neq 0$). But those are limiting at $m_{\psi} = 0$ (no link to DM).

$log_{10} \left( \frac{d_e + 0.043(d_{mq} - d_g)}{d_g} \right)$ vs. $log_{10} m_{\psi}$ [eV/c²]

[Damour & Donoghue 2010]
[Van Tilburg et al. 2015]
A massive scalar field $\varphi$ may oscillate at frequency $f = m_\varphi c^2 / h$.

If non-universally coupled to SM fields it will lead to a corresponding oscillation of fundamental constants, that can be searched for with atomic clocks.

It may also be a candidate for pressureless DM, that continues to elude direct detection.

We analyze $\approx 6$ yrs of Rb/Cs hyperfine frequency measurements to search for such massive scalar fields at very low mass $\approx 10^{-24} – 10^{-18}$ eV.

We see no evidence for such a scalar field.

Our results are complementary to previous searches as they test other combinations of coupling constants.

When assuming that $\varphi$ only couples to electro-magnetism we improve previous limits by over an order of magnitude.

We expect that with the advent of new and better atomic clocks this type of search will be further improved and expanded in the near future.
Backup Slides
Arvanitaki, et al. PRL 2016
• Detailed and repeated analysis of systematic effects (Guéna 2012, 2014) estimates uncertainty on absolute determination of Rb and Cs hyperfine frequency to $3.2 \times 10^{-16}$ and $2.1 \times 10^{-16}$.
• The uncertainty on the difference is expected to be significantly less due to common mode.
• Periodic variations at any frequency are again expected to be below that level.
• No evidence for systematic effect at most likely frequency (diurnal).
• Our results are certainly limited by statistics rather than systematic uncertainties.
FO2-Rb/Cs comparison over 6 months

Allan standard deviation of the Rb/Cs frequency ratio

Coherence time:
\[ \hbar \omega = mc^2 + \frac{mv^2}{2} \Rightarrow \frac{\delta \omega}{\omega} \approx \frac{v \delta v}{c^2} \approx 10^{-6} \text{ for } \delta v \approx v \approx 10^{-3} c \]

\[ \delta \omega \tau_{coh} = 2\pi \]

For our highest frequency (\( \omega_{\text{max}} = \frac{\pi}{864 \text{ s}} \)) this gives a minimum \( \tau_{coh} \approx 55 \text{ years} \), much longer than our data.

Minimum mass:

- \( mv = h/\lambda \), but \( \lambda \) needs to be smaller than smallest dwarf galaxy (\( \approx 1 \text{ kpc} \approx 3 \times 10^{19} \text{ m} \))
- With \( v \approx 10^{-3} c \) this gives a minimum mass of about \( 10^{-23} \text{ eV} \).