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

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[Hees et al. 2016, arXiv: 1604.08514]

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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 $f = m_{\varphi} c^2 / h$.
• 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 ≈ $10^{-24} – 10^{-18}$ eV.

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Non-universally coupled scalar fields

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

- From Damour & Donoghue (2010).
- Fundamental constants (α, Λ_3, m_i) are functions of φ, and vary if φ varies.
- Quadratic couplings treated in Stadnik & Flambaum (2014). Leads to similar phenomenology.

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

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

With five dimensionless coupling constants d_x

[Damour & Donoghue 2010]
[Stadnik & Flambaum 2014,2015]

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Evolution of the scalar field

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

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{m_\varphi^2 c^4}{\hbar^2}\varphi = \frac{4\pi G}{c^2}\sigma$$

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

- Assume a quadratic potential for φ.
- Embed action in FLRW metric.
- Varying with respect to φ gives a KG equation for its evolution ($\sigma = \partial \mathcal{L}_{int}/\partial\varphi$).
- The solution oscillates at $\omega = m_\varphi c^2/\hbar$ with negligible "Hubble damping" for $m_\varphi \gg \frac{\hbar H}{c^2}$, well satisfied for our mass range.

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Link to Dark Matter

$$\rho_{\tilde{\varphi}} = \frac{c^2}{4\pi G}\frac{\omega^2\varphi_0^2}{2} = \frac{c^6}{4\pi G\hbar^2}\frac{m_\varphi^2\varphi_0^2}{2}$$

- The cosmological density (+) and pressure (-) of φ 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 (≈ 0.4 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_φ, d_x).
- The mass m_φ is given by the frequency of oscillation, the coupling constants d_x by the amplitude.

[Stadnik & Flambaum 2014, 2015]
[Arvinataki, Huang, Van Tilburg 2015]

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Relation to Atomic Spectroscopy

- Different atomic transition frequencies depend differently on three dimensionless fundamental constants: α, m_e/Λ_{QCD}, m_q/Λ_{QCD}, 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 α 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.

TABLE I. Sensitivity coefficients k_α, k_μ, and k_q of atomic transition frequencies used in current atomic clocks to a variation of α [23,24], of $\mu = m_e/m_p$ and of m_q/Λ_{QCD} [16,17]. These transitions are hyperfine transitions for $^1H_{hfs}$, ^{87}Rb, ^{133}Cs, and optical transitions for $^1H(1S-2S)$ 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].

[Guéna et al. 2012]

	^{87}Rb	^{133}Cs	$^1H_{hfs}$	$^1H(1S-2S)$	$^{171}Yb^+$	$^{199}Hg^+$	^{87}Sr	(^{162}Dy–^{163}Dy)	$^{27}Al^+$
k_α	2.34	2.83	2.0	~0	1.0	−2.94	0.06	1.72×10^7	0.008
k_μ	1	1	1	0	0	0	0	0	0
k_q	−0.019	0.002	−0.100	0	0	0	0	0	0

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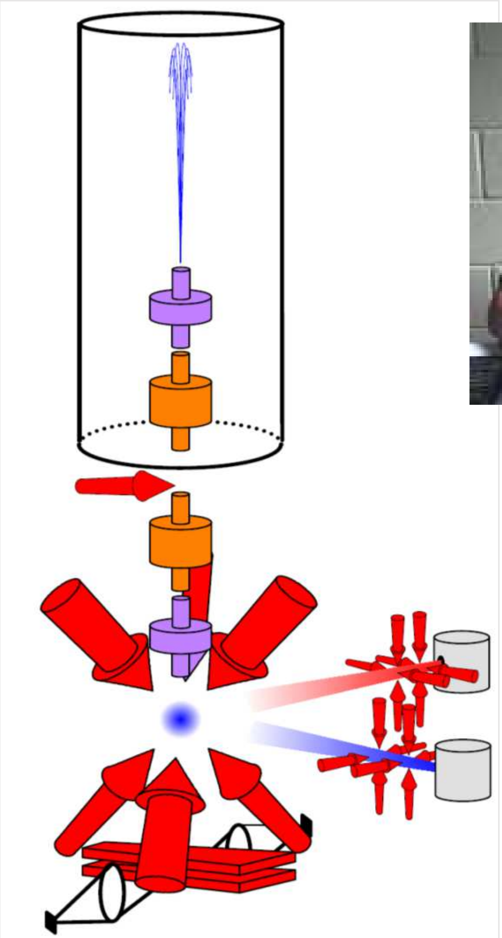
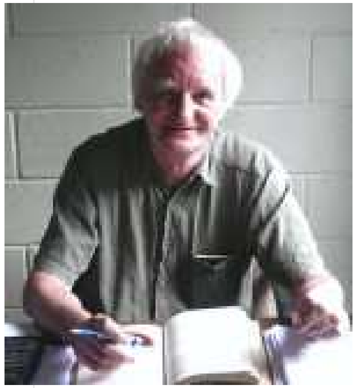
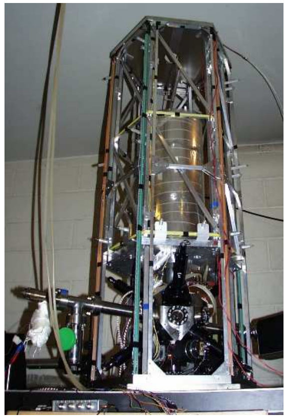
The SYRTE dual Rb-Cs fountain FO2





André Clairon
1947 - 2015



- Built in early 2000s by André Clairon and co-workers.
- Operates simultaneously on ^{87}Rb and ^{133}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.

[Guéna et al. 2010, 2012, 2014]

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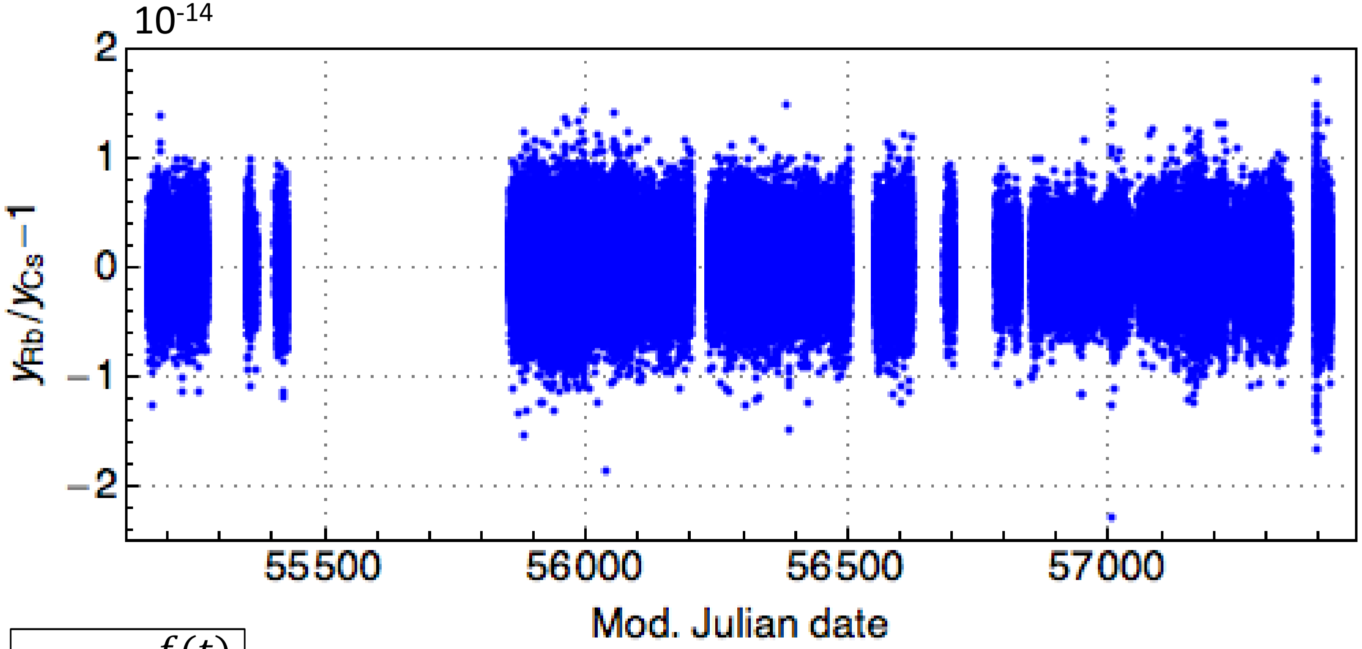
FO2 Rb/Cs raw data



$$y(t) = \frac{f(t)}{f_0}$$

- 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 = 3×10^{-15}

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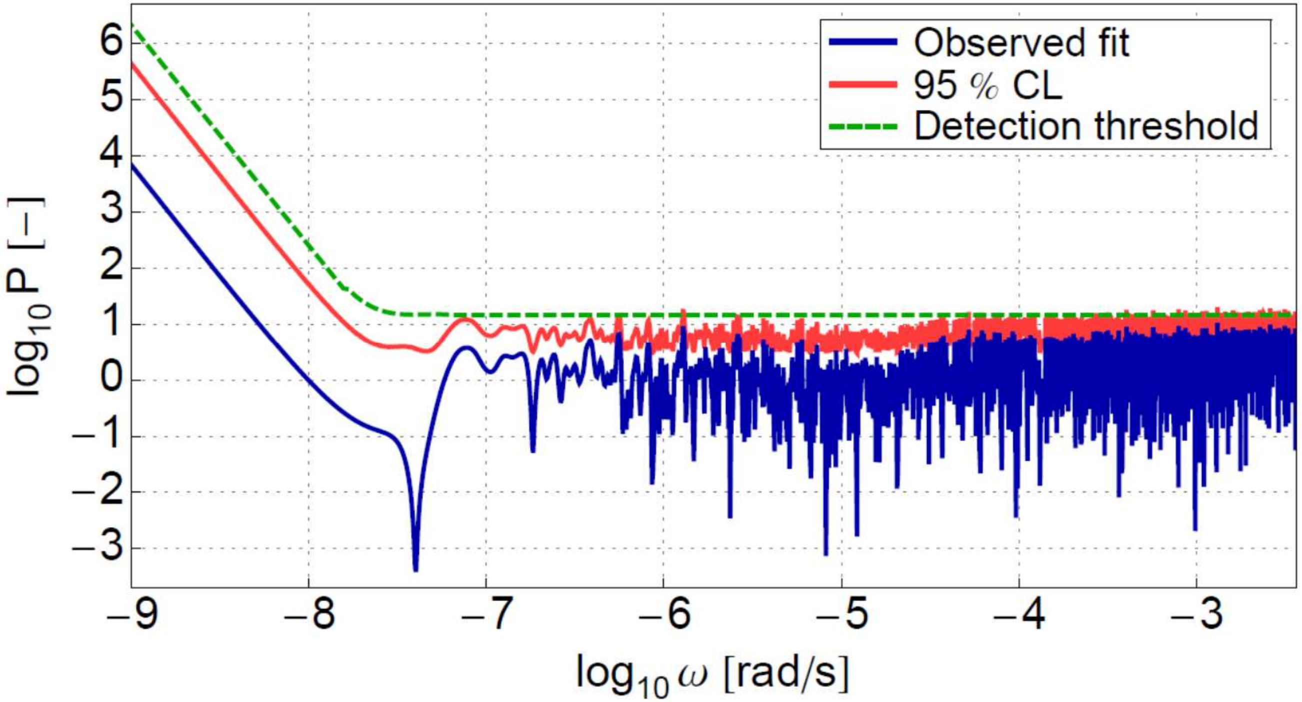
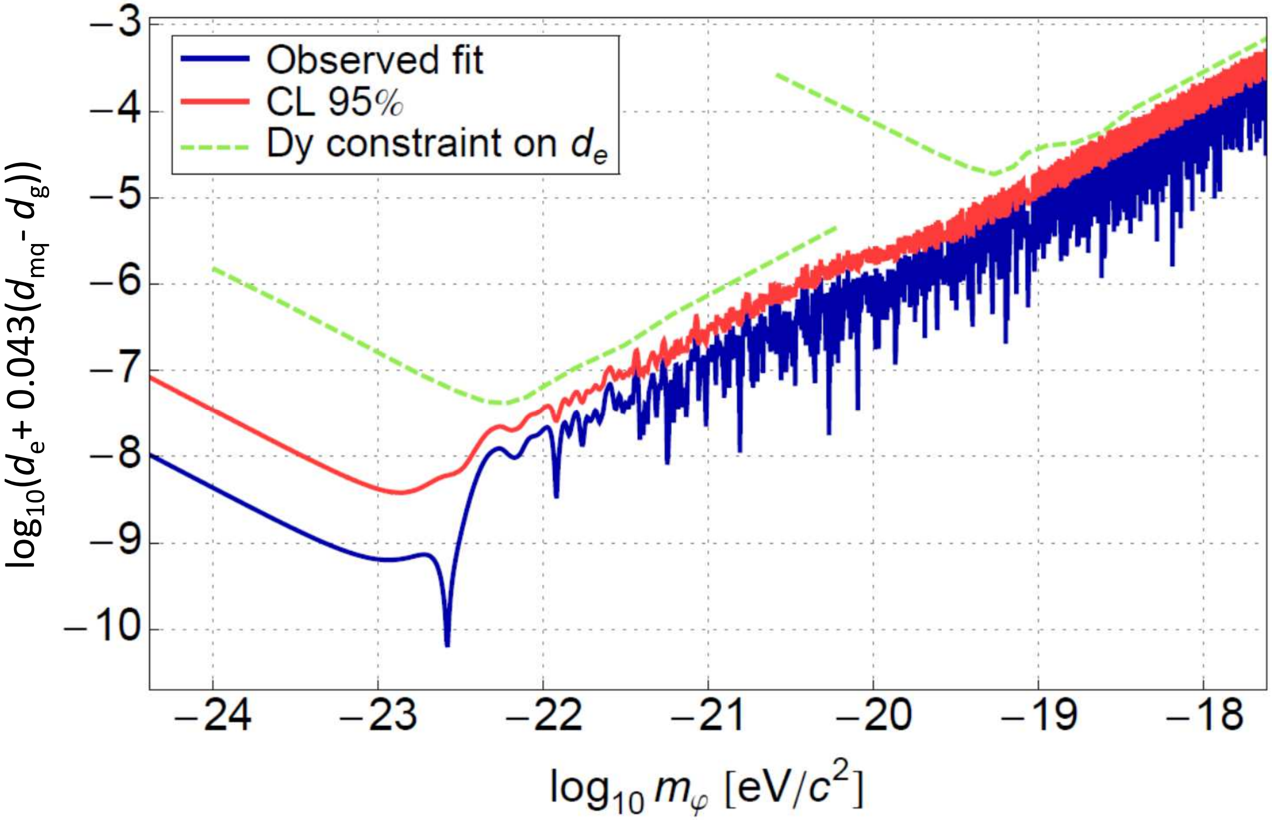
Results



- Fit $A + C_\omega \cos(\omega t) + S_\omega \sin(\omega t)$ to data for each independent ω.
- 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



- 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 $m_\varphi = 0$ (no link to DM).

[Damour & Donoghue 2010]
[Van Tilburg et al. 2015]

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Conclusion and Outlook

- A massive scalar field φ 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 ≈ 6 yrs of Rb/Cs hyperfine frequency measurements to search for such massive scalar fields at very low mass ≈ 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 φ 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.

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