Search for ultra-light dark matter using cold atoms

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Probing the dark sector and general relativity at all scales

CERN, 14-25 August 2017

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Menu

- 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 in linear model
- Results in other models
- Limits on mass range
- Conclusion and Outlook

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

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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 [e.g. Guéna et al., PRL 2012].
• 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

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

- 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.

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

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

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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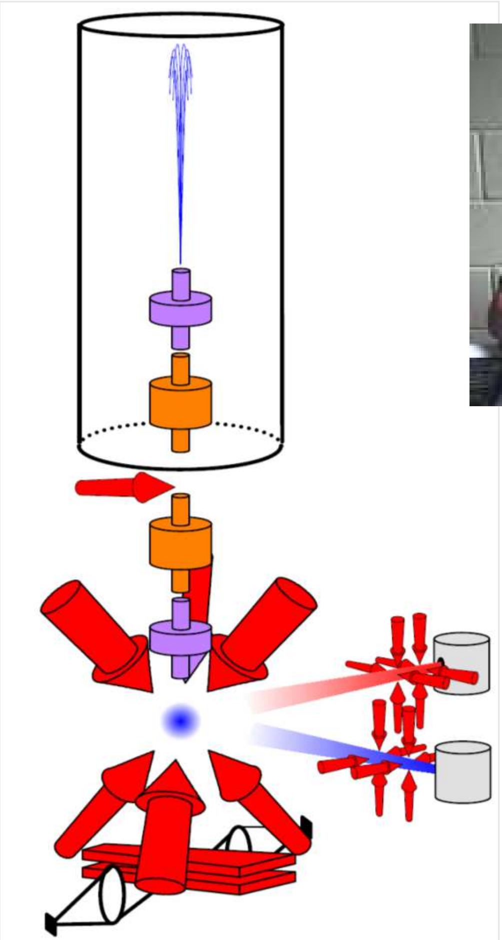
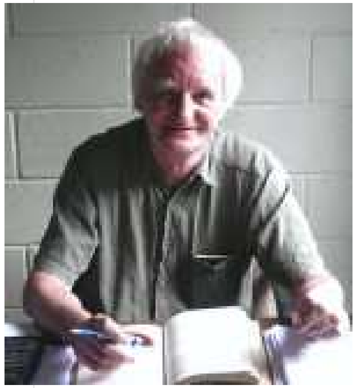
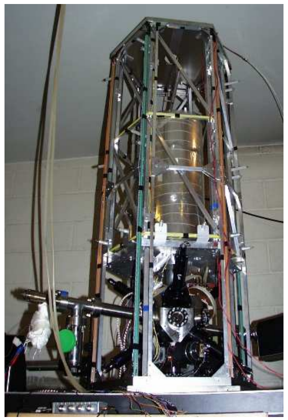
The SYRTE dual Rb-Cs fountain FO2





André Clairon
1947 - 2015



- Built in early 2000s by André Clairon and co-workers.
- Operates simultaneously on laser cooled (μK) ^{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, PRL 2012].
- All systematics are evaluated and corrected during operation.

[Guéna et al. 2010, 2012, 2014]

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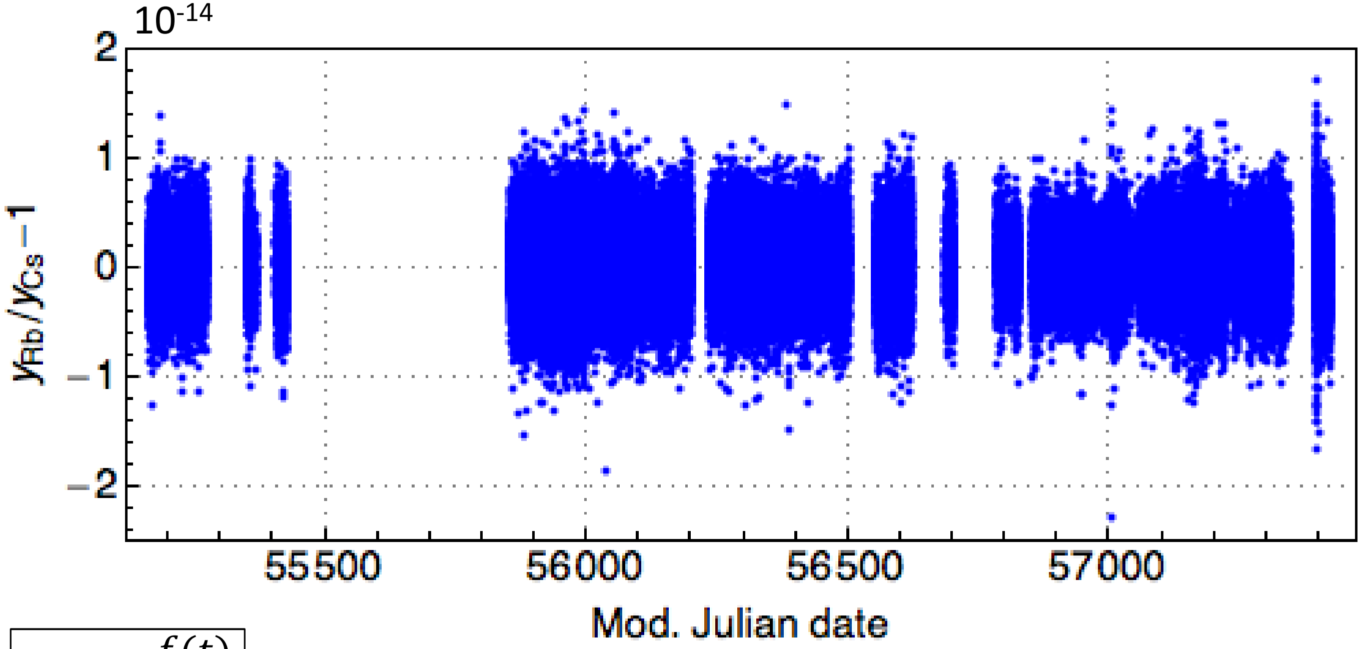
FO2 Rb/Cs raw data



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

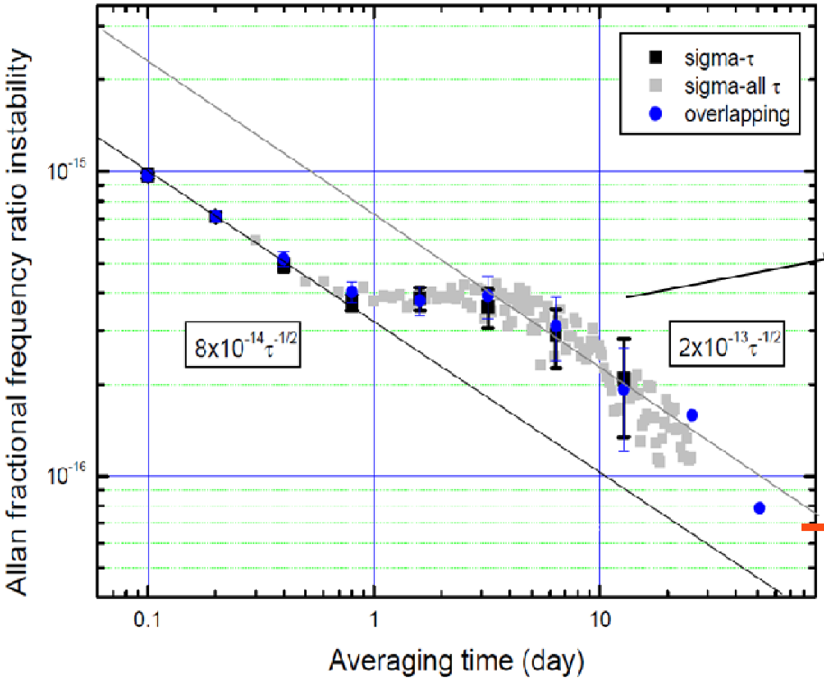
- Nov 2009 – Feb 2016
- Averaged to 100 points/day
- 100814 points in total
- ≈ 45% duty cycle with gaps due to maintenance and investigation of systematics
- Standard deviation = 3×10^{-15}

Noise model

FO2-Rb/Cs comparison over 6 months

Allan standard deviation of the Rb/Cs frequency ratio

effective duration 130 days



Bump well understood: correction of collision shift by HD/LD measurements interleaved introduce another timescale at 5 days

Resolution below 10^{-16}

- Noise level is a function of Fourier frequency:

$$\sigma_o^2(\omega) = 4.6\times10^{-29}, \quad \text{for } \omega \le 9.0\times10^{-6} \text{ rad/s}$$

$$\sigma_o^2(\omega) = 9.3\times10^{-30}, \quad \text{for } \omega \ge 4.5\times10^{-5} \text{ rad/s}$$

$$\sigma_o^2(\omega) = 4.2\times10^{-34}/\omega, \quad \text{otherwise},$$

See Guéna et al., *Metrologia,* **51**, 108, (2014) for details

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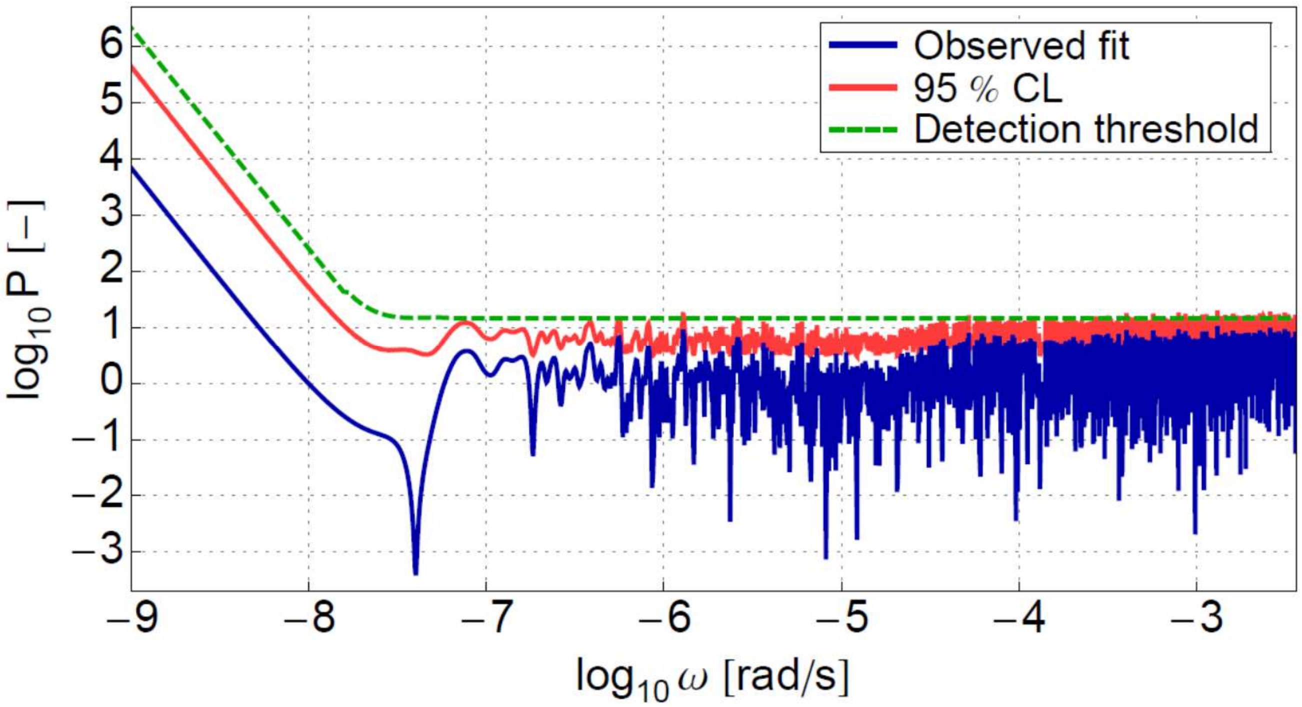
Normalized power



- 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 $P_\omega = \frac{N}{4\sigma_0^2(\omega)}(C_\omega^2 + S_\omega^2)$.
- Use different methods (LSQ + MC, Bayesian MCMC) to determine confidence limits.

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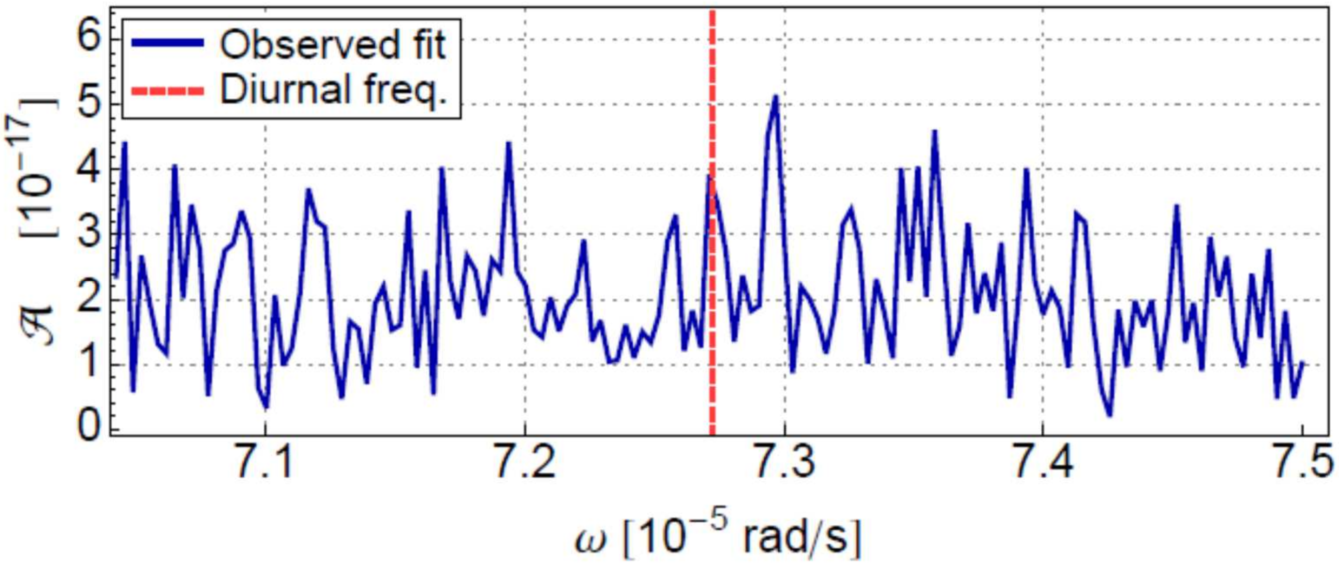
Systematic Effects



- Detailed and repeated analysis of systematic effects (Guéna 2012, 2014) estimates uncertainty on absolute determination of Rb and Cs hyperfine frequency to 3.2×10^{-16} and 2.1×10^{-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).

$\Rightarrow$ Our results are limited by statistics rather than systematic uncertainties.

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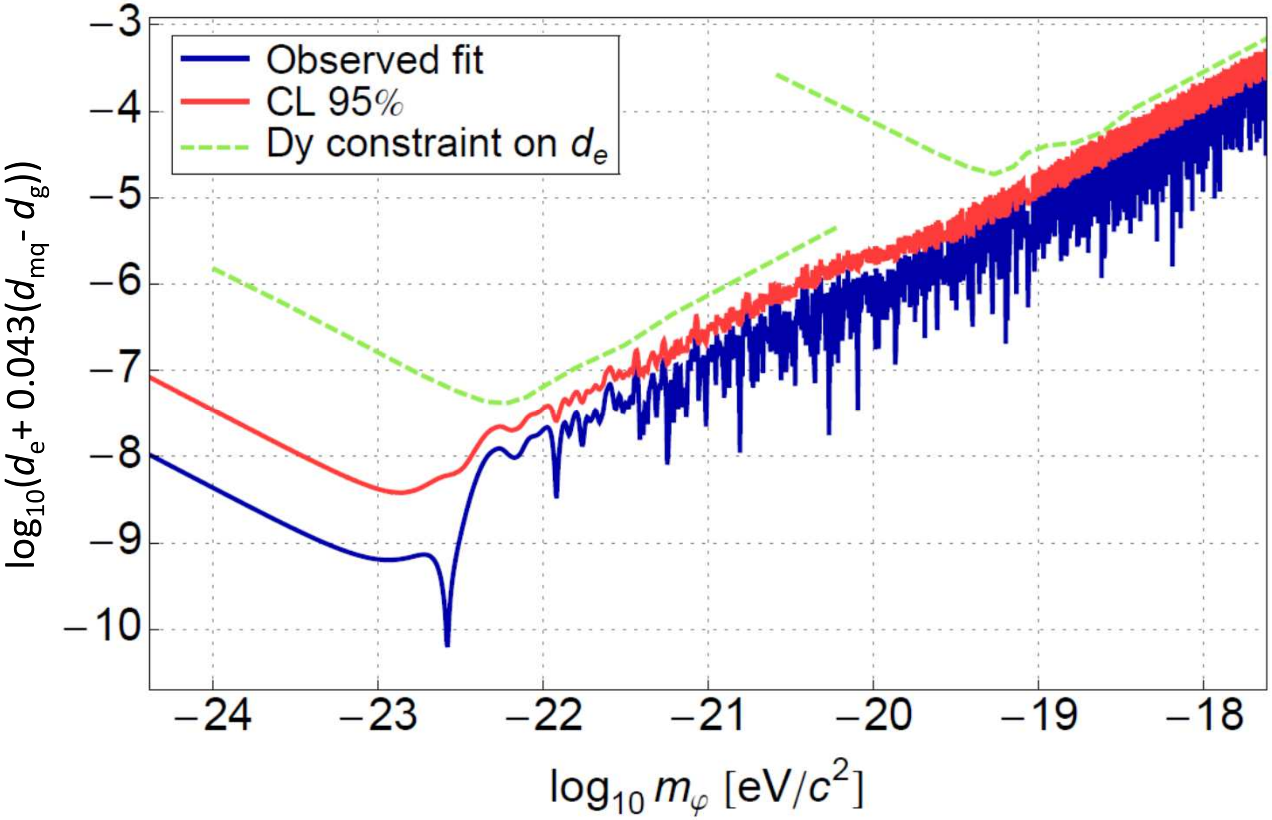
Results in linear model



- 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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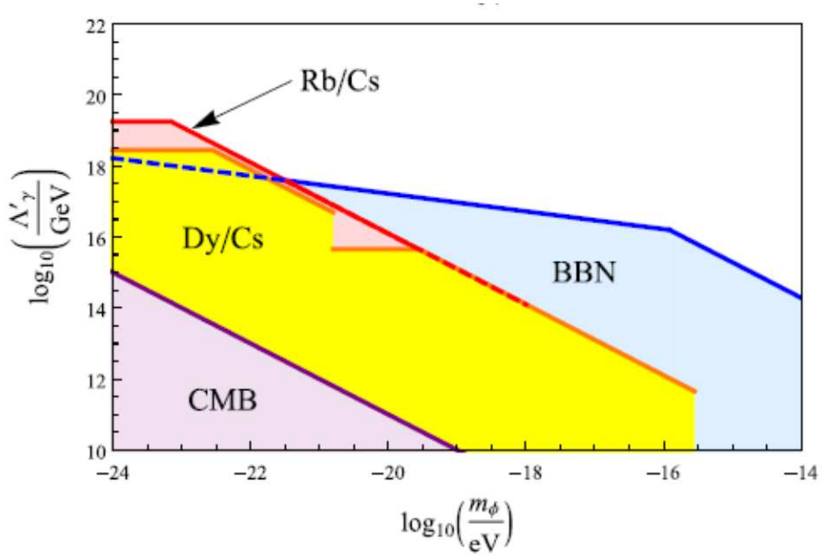
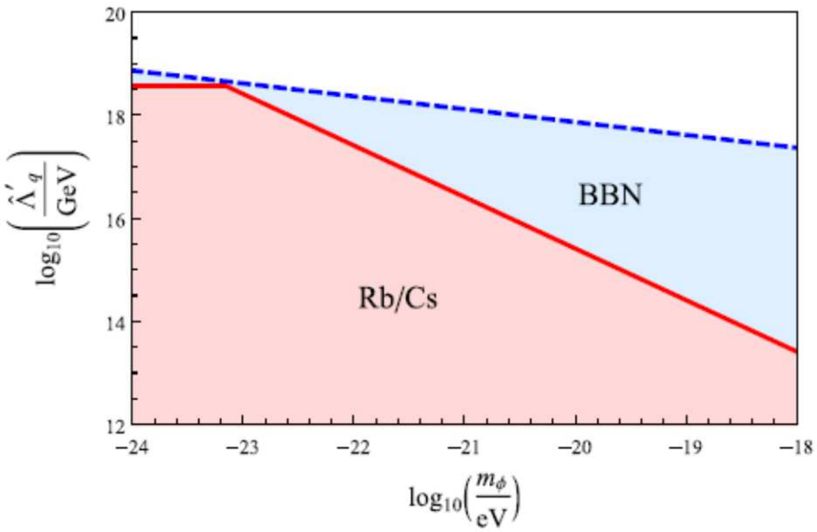
Results in other models





$$\mathcal{L}_{\mathrm{int}}^{\mathrm{quad}} = -\sum_f \frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f + \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4}$$

Note the different parametrization of the scalar field: $\varphi = \sqrt{4\pi G/c\hbar}\phi = \sqrt{4\pi}\phi/M_{\mathrm{Pl}}$.

[From Stadnik & Flambaum, PRA **94**, 022111 (2016)]

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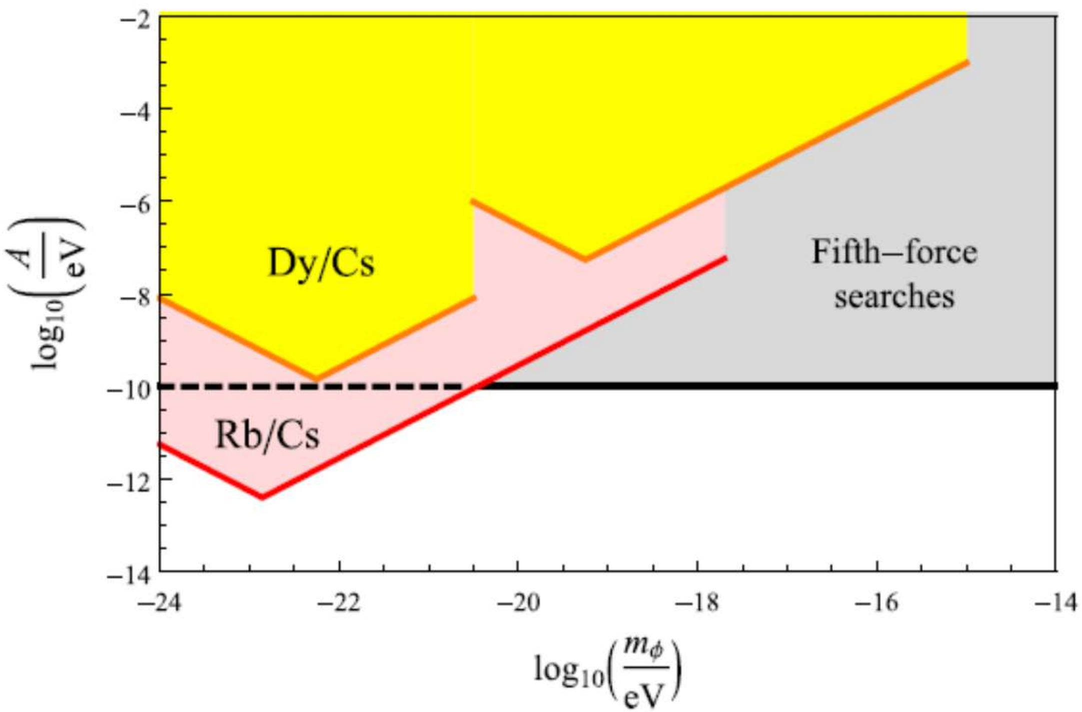
Results in other models



$$\mathcal{L}_{\text{int,eff}}^{\text{Higgs}} = \frac{A\langle h\rangle}{m_h^2}\phi\left(\sum_f g_{hff}\bar{f}f + \frac{g_{h\gamma\gamma}}{\langle h\rangle}F_{\mu\nu}F^{\mu\nu}\right), \qquad (7)$$

where $m_h = 125$ GeV is the mass of the Higgs boson, $g_{hff} = m_f/\langle h\rangle$ for couplings of the Higgs to elementary fermions (leptons and quarks), $g_{hNN} = bm_N/\langle h\rangle$ with $b \sim 0.2$–0.5 [24] for couplings of the Higgs to nucleons, and $g_{h\gamma\gamma} \approx \alpha/8\pi$ for the radiative coupling of the Higgs to the electromagnetic field

[From Stadnik & Flambaum, PRA **94**, 022111 (2016)]

Limits on mass range

A lower limit on plausible DM masses is obtained by requiring that $\lambda = h/mv <$ smallest dwarf galaxy ($\approx$ 1 kpc $\approx 3\text{x}10^{19}$ m). With $v \approx 10^{-3}\,c$ this gives a minimum mass of about 10^{-23} eV.

- Our upper limit is due to our data being averaged to 100 points/day, imposing a Nyquist limit at $5.8\text{x}10^{-4}$ Hz corresponding to m $\approx 2.4\text{x}10^{-18}$ eV.
- But our basic measurement cycle time is 2 s, so we will analyze some high frequency data to extend our search up to 10^{-15} eV.
- It is possible to search at even higher masses, at the expense of sensitivity [see e.g. Kalaydzhyan & Yu, arXiv 2017]. Limited when DM coherence time = h/mv^2 (assuming virialized DM) becomes shorter than clock cycle (2 s). Then $m \leq 2\text{x}10^{-9}$ eV.

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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, and competitive with, previous searches in several different DM models.

- We expect to extend the reach of our search to masses as high as 10^{-9} eV in the near future.
- We expect that with the advent of new and better atomic clocks this type of search will be further improved and expanded in the future.
- Although not discussed in this presentation, searching for topological scalar DM with atomic clocks is a new and interesting field. Could be the subject of future work.

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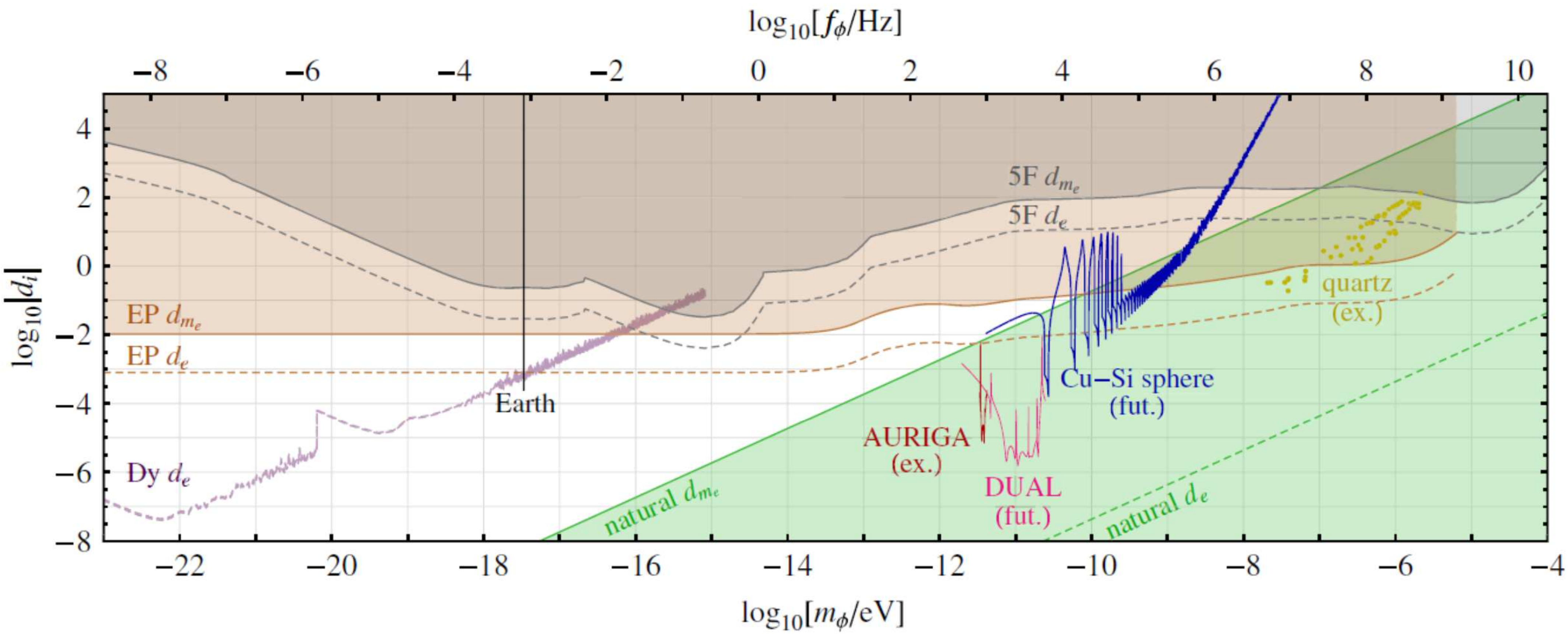
Post-doctoral position

Searching for Dark Matter with a network of atomic clocks

directed by : Pacôme Delva and Peter Wolf
Observatoire de Paris, CNRS, Université Pierre et Marie Curie, LNE
Systèmes de Référence Temps-Espace SYRTE, Paris

For details see: https://syrte.obspm.fr/spip/stages-theses/
Open until filled (max. March 2018)

Backup Slides



Arvanitaki, et al. PRL 2016

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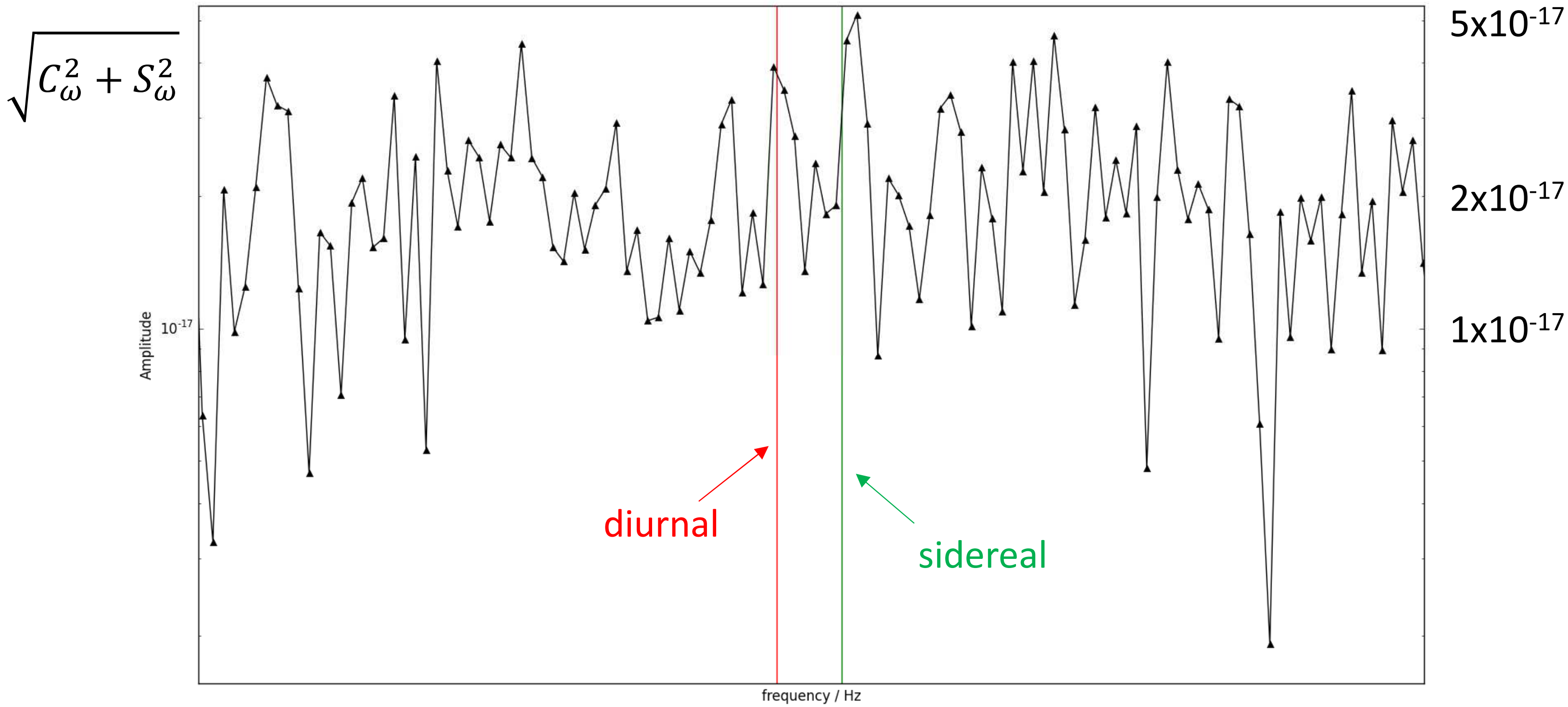

- Detailed and repeated analysis of systematic effects (Guéna 2012, 2014) estimates uncertainty on absolute determination of Rb and Cs hyperfine frequency to 3.2×10^{-16} and 2.1×10^{-16}.
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- No evidence for systematic effect at most likely frequency (diurnal).
- Our results are certainly limited by statistics rather than systematic uncertainties.

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Coherence time:

$$\hbar\omega = mc^2 + \frac{mv^2}{2} \Rightarrow \frac{\delta\omega}{\omega} \approx \frac{v\delta v}{c^2} \approx 10^{-6}$$

for $\delta v \approx v \approx 10^{-3}\, c$

$$\delta\omega\, \tau_{coh} = 2\pi$$

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

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Minimum mass:

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

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