Search for ultra-light dark matter using cold atoms

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[Hees et al., PRL 117, 061301, 2016]
• 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 \( f = \frac{m_\phi c^2}{h} \).
• 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 \( \approx 6 \) yrs of Rb/Cs hyperfine frequency measurements to search for such massive scalar fields at very low mass \( \approx 10^{-24} \ldots 10^{-18} \text{ eV} \).
Non-universally coupled scalar fields

- 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.

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

With five dimensionless coupling constants $d_x$

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

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

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

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

\[ \varphi = \frac{4\pi G \sigma \hbar^2}{m_\varphi^2 c^6} + \varphi_0 \cos(\omega t + \delta) \]
The cosmological density (+) and pressure (-) of $\phi$ are given by
\[ \frac{c^2}{8\pi G} \left( \phi^2 \pm \frac{V(\phi)c^2}{2} \right). \]

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

Equating its average density with the DM density ($\approx 0.4$ GeV/cm$^3$) fixes the amplitude of the oscillation $\phi_0 \cos(\omega t + \delta)$.

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

The mass $m_\phi$ is given by the frequency of oscillation, the coupling constants $d_x$ by the amplitude.

\[
\rho_\phi = \frac{c^2}{4\pi G} \omega^2 \phi_0^2 = \frac{c^6}{4\pi G \hbar^2} \frac{m_\phi^2 \phi_0^2}{2}
\]

[Stadnik & Flambaum 2014, 2015]
[Arvinataki, Huang, Van Tilburg 2015]
Relation to Atomic Spectroscopy

- Different atomic transition frequencies depend differently on three dimensionless fundamental constants: $\alpha$, $m_e/\Lambda_{\text{QCD}}$, $m_q/\Lambda_{\text{QCD}}$, 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 $\alpha$ only, while 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>
<thead>
<tr>
<th>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 $m_q/\Lambda_{\text{QCD}}$ [16,17]. These transitions are hyperfine transitions for $^{1}H_{\text{hfs}}$, $^{87}$Rb, $^{133}$Cs, and optical transitions for $^{1}H(1S-2S)$ 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].</th>
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<tbody>
<tr>
<td>$^{87}$Rb</td>
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<tr>
<td>$k_\alpha$</td>
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<td>$k_\mu$</td>
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<td>$k_q$</td>
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[Guéna et al. 2012]
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.

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 = $3 \times 10^{-15}$

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

FO2-Rb/Cs comparison over 6 months
Allan standard deviation of the Rb/Cs frequency ratio

- Noise level is a function of Fourier frequency:

\[
\begin{align*}
\sigma_0^2(\omega) &= 4.6 \times 10^{-29}, \quad \text{for } \omega \leq 9.0 \times 10^{-6} \text{ rad/s} \\
\sigma_0^2(\omega) &= 9.3 \times 10^{-30}, \quad \text{for } \omega \geq 4.5 \times 10^{-5} \text{ rad/s} \\
\sigma_0^2(\omega) &= 4.2 \times 10^{-34}/\omega, \quad \text{otherwise,}
\end{align*}
\]

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

Resolution below $10^{-16}$

- 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 $P_\omega = \frac{N}{4\sigma_\delta^2(\omega)} (C^2_\omega + S^2_\omega)$.
- Use different methods (LSQ + MC, Bayesian MCMC) to determine confidence limits.
Systematic Effects

- Detailed and repeated analysis of systematic effects (Guéna 2012, 2014) estimates uncertainty on absolute determination of Rb and Cs hyperfine frequency to $3.2 \times 10^{-16}$ 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 limited by statistics rather than systematic uncertainties.
• 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).

Results in linear model

$\log_{10}(d_e + 0.043(d_{mq} - d_g))$

$\log_{10} m_\varphi [\text{eV}/c^2]$

[Damour & Donoghue 2010]
[Van Tilburg et al. 2015]
**Results in other models**

Note the different parametrization of the scalar field:

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

\[
\varphi = \sqrt{4\pi G/c^2} \phi = \sqrt{4\pi \phi/M_{Pl}}
\]

[From Stadnik & Flambaum, PRA 94, 022111 (2016)]
Results in other models

\[ L_{\text{int,eff}}^{\text{Higgs}} = \frac{A(h)}{m_h^2} \phi \left( \sum_f g_{hff} f \bar{f} + \frac{g_{h\gamma\gamma}}{\langle h \rangle} F_{\mu\nu} F^{\mu\nu} \right), \]  

where \( m_h = 125 \text{ GeV} \) 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), \( g_{hNN} = bn_N/\langle h \rangle \) 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)]
A lower limit on plausible DM masses is obtained by requiring that $\lambda = \frac{h}{mv} < $ 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 $10^{-23} \text{ eV}$.

- Our upper limit is due to our data being averaged to 100 points/day, imposing a Nyquist limit at $5.8 \times 10^{-4} \text{ Hz}$ corresponding to $m \approx 2.4 \times 10^{-18} \text{ eV}$.
- But our basic measurement cycle time is 2 s, so we will analyze some high frequency data to extend our search up to $10^{-15} \text{ eV}$.
- 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 $= \frac{h}{mv^2}$ (assuming virialized DM) becomes shorter than clock cycle (2 s). Then $m \leq 2 \times 10^{-9} \text{ eV}$. 
Conclusion and Outlook

- 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, 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.
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
• 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.
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 \((\omega_{max} = \frac{\pi}{864 \text{s}})\) this gives a minimum \(\tau_{coh} \approx 55\) 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 \(10^{-23}\) eV.