Searching for ultra-light dark matter with atomic spectroscopy

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Could we not use atomic clocks to detect Dark Matter?
DM effects on clocks and oscillators

1. DM fields interacting with the spin of the electrons or nuclei in the atoms.  
⇒ Effect on spin dependent transitions (Hyperfine transitions, Zeeman states, ...).  

2. DM scalar field with non-universal scalar couplings to SM fields.  
⇒ Apparent violations of the equivalence principle  
⇒ Space-time variation of fundamental constants  
⇒ Differential effect on different atomic transitions  
⇒ Effects on oscillators (cavities) – access to higher frequency/mass  
[Hees, Guéna, Abgrall, Bize, Wolf, PRL 117, 061301, 2016]  
[Hees, Minazzoli, Savalle, Stadnik, Wolf, PRD 98, 064051, 2018]  

See the DAMNED poster by E. Savalle.
Dark Matter (1)

- “Evidence” for DM is purely gravitational, but of several types e.g.:
  - Galaxy rotation curves
  - Gravitational lensing
  - Cosmic Microwave Background
  - Structure formation
  - ...

- We “know” that:
  - It is cold ($v \ll c$)
  - Forms a galactic halo
  - Has virialized in the galaxy ($\delta v \approx 10^{-3} c$, $\langle v \rangle \approx 0$)
  - It’s energy density in the solar system is $\approx 0.4$ GeV/cm$^3$ and $\langle v \rangle \approx 10^{-3} c$

- We hope that:
  - More gravitational evidence will be obtained to constrain its properties
  - DM interacts other than gravitationally with standard model fields
  - Someone will detect it locally
  - New physics will be learned
Dark Matter (2)


- Spans 90 orders of magnitude in mass!
- Here we will concentrate on low masses (< 10 keV).
- In that region standard collisional (recoil based) detection techniques fail.
Ultralight DM

\[ N_{occ} = \frac{n}{n \delta v} \approx \frac{3\pi^2 \hbar^3 \rho}{4m^4 \delta v^3} \]

\( N_{occ} = 1 \) in our galaxy for \( m \approx 10 \text{ eV} \).

- For \( N_{occ} > 1 \) the DM field can be treated as a classical field. It is likely to oscillate at its Compton frequency \( \omega = mc^2/\hbar \) and may form “clumps” e.g. topological defects.
- For \( N_{occ} < 1 \) it must be quantized i.e. treated as a particle.
- Fermions cannot have \( N_{occ} > g \) (\( g \) = number of internal degrees of freedom).
- Fermionic DM mass must be \( > \text{eV} \).
- Bosonic DM can be treated as a classical field for mass below 10 eV or so.
DM interacting with SM spins

- \( m_\chi \ll m_{At} \Rightarrow \) no momentum exchange
- “See” effects proportional to \( S_{At} \cdot S_\chi \) or \( S_{At} \cdot v_\chi \)
- When varying \( S_{At} \) (e.g. using a magnetic field) the effect is modulated
Interaction types

- Example: EFT model with contact interaction
- Generalized to a model with a dynamical mediator.
- Also considered interactions with axial scalar (axion) or axial vector boson.


\[ L_{\text{int}} = - \int d^3x \left( G^{\tau}_e e^{\tau} \bar{e} \mathcal{J}_\chi + \sum_{q=u,d} G^{\tau}_q \bar{q} \Gamma^q q \mathcal{J}_\chi \right) \equiv - \int d^3x \sum_{\psi} G^{\tau}_\psi \mathcal{J}^{\tau}_\psi \times \mathcal{J}^{\tau}_\chi \]

\begin{tabular}{|c|c|c|c|c|}
\hline
\( T \) & \( \psi = e, u, d \) & DM & Scalar & Fermion & Vector Boson \\
\hline
Ax. vector & \( \mathcal{J}_\psi : \bar{\psi} \gamma^\mu \gamma_5 \psi \) & \( \mathcal{J}_\chi : i \chi^\dagger \partial_\mu \chi + \text{h.c.} \), \( \bar{\chi} \gamma^\mu \chi \), \( i \chi^\dagger \gamma^\nu \partial_\mu \chi^\nu + \text{h.c.} \) & \( \bar{\chi} \gamma^\mu \gamma_5 \chi \) & \text{--} \text{--} \text{--} \text{--} \\
\hline
Tensor & \( \mathcal{J}_\psi : \bar{\psi} \sigma^{\mu\nu} \psi \) & \( \mathcal{J}_\chi : \text{--} \) & \( \bar{\chi} \sigma^{\mu\nu} \chi \), \( \chi^\dagger (\Sigma_{\mu\nu})^\alpha \beta \chi^\alpha \beta \). & \text{--} \text{--} \text{--} \text{--} \\
\hline
\end{tabular}
Observables (ex. hyperfine atomic clock)

Consider hyperfine transition in Rb or Cs clocks. The effect is akin to frequency shifts due to collisions with background gases [Gibble, PRL 110, 180802, 2013]. For a detailed derivation see [Wolf, Alonso, Blas, arXiv:1810.01632]:

\[ \delta \omega \simeq \frac{2\pi \rho \chi \hbar}{m^2 \chi} \text{Re} [f_1(0) - f_2(0)] \]

\( f_i(0) = \) forward scattering amplitudes in the two clock states \(|1\) and \(|2\):
- \( f_1(0) - f_2(0) \) depends **linearly** on \( G_{e/q} S_{At} \cdot S_\chi \) or \( G_{e/q} S_{At} \cdot v_\chi \)
- When operating the clock on spin polarized states (using a quantization magnetic field \( B \)) the frequency shift varies as the orientation of \( B \) varies.
- Additionally, may have modulations at Compton frequency of \( m_\chi \)
- To control magnetic field fluctuations use differential measurement between different species e.g. Rb and Cs in clocks (see later) or He and Xe in magnetometers.
Sensitivity estimate examples

- Coupling to neutron.
- Sensitivity estimates, not bounds!
- Assume μHz uncertainty for Rb/Cs hyperfine clocks, sub-nHz for He/Xe magnetometers.
- Provides an indication of parameter space that can be explored.
Axion field coupling to electron or neutron

- Much lower mass region than many other axion experiments (e.g. ADMX)
- Not quite able to reach astrophysical (stellar cooling) bounds
- Price to pay is that QCD axion is much lower ($C_n/f_a \approx 10^{-24}$ @ $10^{-15}$ eV)
Axial vector boson coupling to $e^{-}$ or n

\[ H_A = 2g^A_{\psi} \frac{\sqrt{2} \rho_X}{m_A} \bar{\lambda}_\psi \cdot \text{Re}[\bar{\epsilon} e^{-i m_A t + i \phi_0}] \]

- Dominated by longitudinal polarization mode
**DArk Matter from Non Equal Delays (DAMNED)**

- See poster by Etienne Savalle and [Savalle, Roberts, Frank, Pottie, McAllister, Dailey, Derevianko, Wolf, arXiv:1902.07192, 2019]
- Based on ultra-stable optical cavity that is “compared to itself in the past”.
- Aiming at high frequency (10-100 kHz i.e. DM mass around $10^{-10}$ eV)

\[
\Delta \phi(t) = \omega_0 T_0 + 2 \frac{\omega_0}{\omega_m} \left( \frac{\delta T}{T_0} + \frac{\delta \omega}{\omega_0} \right) \sin \left( \frac{\omega_m T_0}{2} \right) \sin (\omega_m t + \Phi)
\]

Ignores resonant effects of the cavity (ongoing work).
**DArk Matter from Non Equal Delays (DAMNED)**

\[
\frac{\delta T}{T_0} + \frac{\delta \omega}{\omega_0} \approx \frac{\omega_0}{n_0} \frac{\partial n}{\partial \omega} \left( d_{m_c}^{(1)} - d_{e}^{(1)} - \frac{1}{2} \left( d_{m_c}^{(1)} - d_{g}^{(1)} \right) + 0.024 \left( d_{m_q}^{(1)} - d_{g}^{(1)} \right) \right) \varphi_0 + \mathcal{O} \left( 10^{-4} \varphi_0 d_{i}^{(1)} \right)
\]

- 50 km fibre, tens of mW on diode
- Shot noise limited just above the cavity noise.

[arXiv:1902.07192, 2019]
Thank you for your attention!