Topical: Search for dark matter with orbiting atomic clocks

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Abstract

This a short review of opportunities for NASA in searches for ultralight dark matter with orbiting atomic clocks and cavities. If dark matter drives minute variation of fundamental constants, resonance frequencies of atomic clocks and cavities would be affected in a manner consistent with dark matter models. Orbiting constellations of atomic clocks can probe these models. These can be, for example, a dedicated relatively inexpensive constellation of CubeSats housing miniature optical clocks. Dark matter search can be also carried out with satellites housing high-performance optical clocks, such as in the proposed FOCOS mission. These ideas can be extended to other quantum sensors, such as magnetometers that are sensitive to one of the popular DM candidate, axions.

Multiple astrophysical observations suggest that the ordinary (luminous or baryonic) matter contributes only $\sim 5\%$ to the total energy density budget of the Universe. Exacting the nature of the two other constituents, dark matter (DM) and dark energy (DE), is a grand challenge to the contemporary state of knowledge. It is believed that dark matter is required for galaxy formations, while dark energy leads to the accelerated expansion of the Universe [3, 9, 11, 13, 21]. Below we primarily focus on DM, although some aspects of the discussion would also apply to hypothetical DE fields.

All the evidence for DM (galactic rotation curves, gravitational lensing, peaks in the cosmic microwave background spectra, etc) comes from galactic scale observations. The challenge lies in extrapolating down from the ~ 10 kpc distances to the laboratory scales. This is a truly vast extrapolation scale and a large number of theoretical models can fit the observations. The prevailing view is that all the theoretical constructs have to conform to the cold dark matter paradigm [4]: DM constituents move with velocities $\ll c$. Our galaxy, the Milky Way, is embedded into a DM halo and rotates through the halo. Astrophysical simulations provide estimates of DM properties in the Solar system (see, e.g., [12]). The DM energy density in the vicinity of Solar system is estimated to be $\rho_{\mathrm{DM}} \approx 0.3\,\mathrm{GeV/cm^3}$. Further, in the DM halo reference frame, the velocity distribution of DM objects is nearly Maxwellian with the dispersion of $v_{\mathrm{vir}} \sim 270\,\mathrm{km/s}$ (virial velocity) and a sharp cut-off at the galactic escape velocity $v_{\mathrm{esc}} \approx 650\,\mathrm{km/s}$. Solar system travels through the DM halo at galactic velocities $v_{\mathrm{g}} \approx 230\,\mathrm{km/s}$ towards the Cygnus constellation.

"Dark" universe does not absorb or emit electromagnetic radiation and all the evidence is based on the gravitational interaction between the dark and luminous matter. Thereby, the gravitational interaction between DM and ordinary matter is a given. But the gravity is weak on laboratory scales, so one generically introduces additional interactions ("portals") in order to make DM detectable by our instruments. Below we review a class of couplings to DM sector ("portals") that translates into either transient or oscillating variations of fundamental constants. Such variations can affect atomic and cavity frequencies that are detectable by atomic clocks.

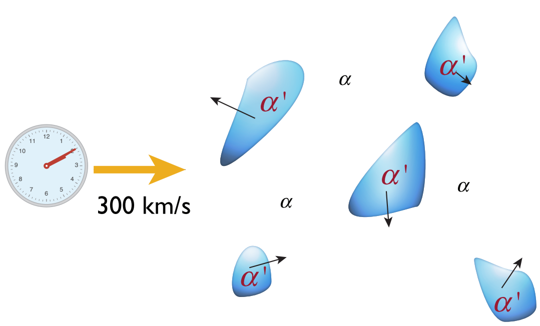

Figure 1: An atomic clock sweeps through the dark matter halo at galactic velocities. DM is assumed to be composed of extended objects (or clumps). If there the difference of fundamental constants (such as the fine-structure constant α in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [5]. From Ref. [6].

Considering a wide variety of DM models, we generically split them into two classes: "wavy" and "clumpy" DM. These two classes lead to distinct DM signatures, illustrated in Figs. 1 and 2. The early theoretical proposals [2, 5] on DM detection with atomic clocks led to experimental DM searches with atomic clocks [10, 15, 16, 18–20], both terrestrial and with clocks onboard GPS satellites (GPS.DM collaboration).

Fig. 1 depicts encounters of extended DM objects (or DM clumps) with an atomic clock

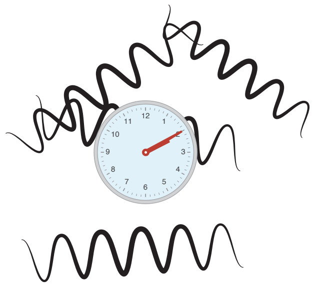

Figure 2: Ultra-light fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [2]. Generically, the oscillations are of stochastic nature [7]. From Ref. [6].

traveling through the DM halo at galactic velocities. It is assumed that DM clumps effectively change the values of fundamental constants [5] (such as the fine structure constant α and/or masses of elementary particles). In the DM model of Ref. [5] the clumps are identified with topological defects (TD) formed due to the self-interaction of ultralight fields. DM clumps can be formed in other models as well, so the TD model is not required *per se*. We can pose a general question: can atomic clocks or other sensors detect our motion through the "preferred" DM halo reference frame?

Another possibility (see Fig. 2) is DM composed of non-self-interacting ultralight fields [2] (wavy DM). Masses of these DM candidates span many orders of magnitude below 10 eV down to 10^{-22} eV, where the particle de Broglie wavelength is comparable to the size of dwarf galaxies. These particles have large mode occupation numbers and behave like a classical field. Such fields can lead to oscillating fundamental constants at the Compton frequency of the field. By Fourier-transforming a time series of clock frequency measurements, one could hunt for peaks in the power spectrum and potentially identify DM presence. Ref. [7] built on this idea taking into account the stochastic nature of such fields and provided more informative spectral profile of the expected DM signal.

Dark matter-induced variation of fundamental constants – A systematic phenomenological approach to DM-SM (Standard Model) sector couplings, is that of the so-called portals [8]. We focus on the portals in the form of the linear ($k = 1$, or dilaton) and quadratic ($k = 2$) scalar portals,

$$\mathcal{L}^{(2)}_{\text{clock}} = -\phi(\boldsymbol{r}, t)^k \sum_X \Gamma^{(k)}_X \, \mathcal{L}^X_{\text{SM}}, \tag{1}$$

where $\mathcal{L}^X_{\text{SM}}$ are various pieces of the SM Lagrangian weighted with coupling constants $\Gamma^{(k)}_X$ and $\phi(\boldsymbol{r}, t)$ is a dark matter field of DM particle mass m_ϕ. Most relevant are $\mathcal{L}^\alpha_{\text{SM}} = -F^2_{\mu\nu}/4$ ($F_{\mu\nu}$ is the electromagnetic field tensor) and $\mathcal{L}^f_{\text{SM}} = \sum_f m_f \bar{\psi}_f \psi_f$ (for atoms, the relevant fermions are electron and protons). Linear portals were considered in Ref. [2], while quadratic portals — in Ref. [5]. $\Gamma^{(k)}_X$ are constrained by terrestrial experiments and astrophysical bounds. Combining the portals (1) with the QED Lagrangian governing atomic physics leads to the modulation of fundamental constants by DM fields ($\alpha = e^2/\hbar c$):

$$m^{\text{eff}}_{e,p} = m_{e,p} \times \left(1 + \Gamma^{(k)}_{m_{e,p}} \phi(\boldsymbol{r}, t)^k\right), \quad \alpha^{\text{eff}} \approx \alpha \times \left(1 + \Gamma^{(k)}_\alpha \phi(\boldsymbol{r}, t)^k\right). \tag{2}$$

What are the implications of these equations? For clumpy DM, outside the clump, by assumption, $\phi \to 0$ and these portals renormalize masses and couplings only when the clump overlaps with the quantum device. This, via Eq.(2), leads to *transient* variation of fundamental constants as the clump passes through the device. The ultra-light fields oscillate at the Compton frequency, $\phi(\boldsymbol{r}, t) = A\cos(m_\phi c^2 t - k_\phi \cdot \boldsymbol{r} + \cdots)$, where m_ϕ is the mass associated with the field and k_ϕ is the wave-vector of the field. Thereby, Eq. (2) leads to *oscillating* fundamental constants.

Atomic clocks operate by comparing the frequency of an atomic transition with the resonance frequency of a local oscillator, typically a reference optical or microwave cavity. The atoms are interrogated with laser or microwave pulses outcoupled from the cavities, whose frequency is kept in resonance with the atomic transition via a feedback loop. Atomic frequencies are primarily affected by the induced variation of the Rydberg constant, $\mathcal{R}_\infty = m_e c^2 \alpha^2$. Microwave clocks operate on hyperfine transitions and are hence affected by the variation in the quark masses, m_q and the strong coupling constant. In addition, the variation in the Bohr radius $a_0 = \alpha^{-1}\hbar/(m_e c)$ affects the cavity length $L \propto a_0$ and, thereby, the cavity resonance frequencies $\propto c/L$.

Relation to dark-matter models – While the on-going particle physics DM searches focus on particles with masses $\sim 1 - 10^3\,\mathrm{GeV}$, here we consider an alternative: ultralight fields. Depending on the initial field configuration at early cosmological times, light fields could lead to DM oscillations about the minimum of their potential, or form stable spatial configurations due self-interaction potentials. The former possibility leads to fields oscillating at Compton frequency (dilaton-type DM [2]) and the latter to the formation of topological defects (TD) such as domain walls, strings and monopoles ("clumpy" DM [5]). The maximum values of portal couplings (1) depend on the DM field amplitudes A; these can related to the dark-matter energy density in the Solar system neighborhood in the assumption that such models individually saturate the DM energy density.

Dark matter signatures – Inevitable clock noise (especially flicker noise) for a single clock can mimic an encounter with a DM clump. In the "clumpy" DM searches, the solution [5] is to rely on a geographically distributed clock *network* which seeks synchronous propagation of clock "glitches" at galactic velocities through the network. This approach is similar to the magnetometer GNOME network [14] or gravitational wave detection [1]. In the context of clocks, two spatially-separated and initially-synchronized identical clocks are expected to exhibit a distinct de-synchronization and re-synchronization pattern, Fig. 3. The duration of the characteristic "hump" is given by $\Delta t = l/v$, with l being the distance between the clocks and v being the relative velocity of the encounter. If $v \sim v_g$, $\Delta t \sim 3\,\mathrm{s}$ for a trans-continental network ($l \sim 1,000\,\mathrm{km}$) and $\Delta t \sim 150\,\mathrm{s}$ for clocks onboard GPS satellites ($l \sim 50,000\,\mathrm{km}$).

Similarly, for wavy DM, an oscillating signal by itself is not a "smoking-gun" signature, as cavities can exhibit multiple peaks in the their power spectral densities. One of possibilities is to rely on predicted spectral profiles [7] and another is to use the network of clocks.

If the DM events are not observed, it could mean that either the DM model and/or assumed portals are incorrect, or that the clocks are not sensitive enough to measure the effects. In the latter case, setting signal-to-noise ratio ~ 1 establishes the limits on the coupling constants entering the portals (1). This has be the case so far with all reported experimental DM searches [10, 15, 16, 18–20].

Potential space missions – First of all, GPS.DM collaboration (of which A.D. is a part of) is already using atomic clocks on-board GPS satellites to search for clumpy DM [16].

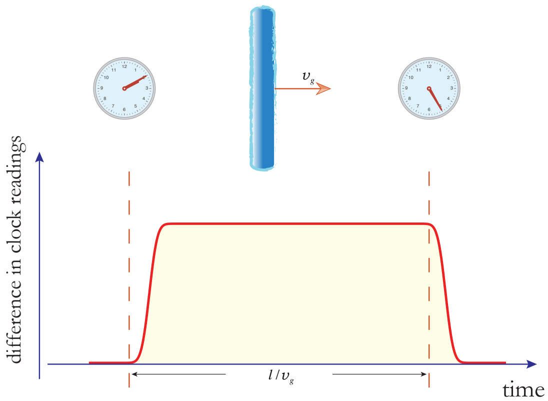

Figure 3: Spatially-separated and initially-synchronized identical clocks are expected to exhibit a distinct de-synchronization and re-synchronization pattern due to an encounter with a dark matter clump. From Ref. [5].

There are several deficiencies with the existing publicly-available GPS data:

1. GPS data comes from terrestrial geodetic GPS receivers and it is polluted with ionospheric disturbances affecting the GPS microwave signals. For example, solar wind (electron fluxes) perturbs the index of refraction of ionosphere and, thereby, the GPS microwave signals. Solar wind has characteristic velocities of propagation comparable to those of DM sweeps. As such, solar wind perturbations lead to systematic effects that mimic sweeps by DM clumps. Ultimately the GPS.DM sensitivity to DM is not determined by the intrinsic clock noise, but rather by the solar activity.

2. Low sampling rate — GPS data is recorded in the public database only every 30 seconds.

3. Convoluted "black box" processing of GPS data - the atomic clock data are provided by the JPL data center. To some extent, JPL data processing is a black box based on proprietary codes, and it is not immediately obvious if the potential DM events are discarded during data processing (although the GPS.DM collaboration was assured that it is not the case).

4. The geodetic receivers are a subject to multiple path interference effects (GPS microwave signals reflecting off of surfaces) that also can mimic DM events.

5. GPS atomic clock data is biased to a reference clock, complicating the search and reducing sensitivity.

All of these deficiencies with the GPS data can be remedied by collecting clock data directly from dedicated satellites at a much faster rate. This can be done with a constellation of relatively inexpensive CubeSats housing compact optical clocks (these have a better noise floor compared to the GPS microwave clocks), see relevant whitepaper. The clock data can be time-stamped on the satellites using the ubiquitous GPS time scale. Then it can be uploaded for processing and DM search analysis. This proposed mission solves all of the enumerated deficiencies of the GPS-based DM search by removing systematic effects and improving sensitivity to DM fields.

How would this CubeSat mission compare with terrestrial networks of high-performance atomic clocks? A CubeSats constellation would have a better spatial coverage and a continuous mode of operation. Further, for quadratic portals and certain signs of couplings $\Gamma_X^{(2)}$, the DM field can be drastically attenuated by the atmosphere and the Earth [17]. Then the terrestrial networks are effectively screened out from DM fields. Orbiting clocks would remain sensitive to DM "clump" encounters even in that case.

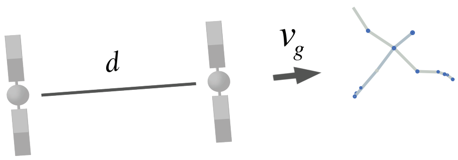

Figure 4: Satellite mission for probing wavy DM correlation function; both the distance between the satellites and the angle between galactic velocity $\mathbf{v}_g$ and separation $\mathbf{d}$ vectors can be varied. Adopted from [7].

At to the the *wavy* DM, it would drive an oscillating-in-time DM signal at a given spatial location. In addition, because these are waves, DM signals at different locations have a fixed phase relation, i.e., the signals are correlated. Based on this observation, Ref. [7] argued that a wider discovery reach can be gained by sampling the DM wave at several locations via a network of precision quantum sensors, such as atomic clocks. Further, based on the standard halo model, the DM field is composed out of interfering waves traveling at different speeds and in different directions. Then the problem of relating signals at different space-time locations requires cross-node spatio-temporal correlation function for DM fields, derived in Ref. [7].

The wavy DM cross-node correlation function depends on the direction of motion of Solar system through DM halo (towards Cygnus constellation), separation between the satellites and DM parameters. Then by varying the angle between galactic velocity $\mathbf{v}_g$ and satellite separation $\hat{\mathbf{d}}$ vectors and also the distances d between the satellites, the DM correlation function can be probed, see Fig. 4. This mission was proposed in Ref. [7] and it can be adopted to FOCOS mission, see relevant whitepaper. The FOCOS mission uses a satellite housing high-performance atomic clock in a strongly elliptic orbit and compares it to a terrestrial clock. Both the distance d between the clocks and relative orientation vector $\hat{\mathbf{d}}$ in galactic reference frame vary during the natural dynamics of orbiting satellite.

We have proposed two satellite-based dark matter searches with atomic clocks. These can be extended to other quantum sensors, such as magnetometers that are sensitive to one of the popular DM candidate, axions. Evaluation of sensitivity, feasibility, and data analysis strategies can be carried out with NASA support.

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