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Detection of Ultralight Dark Matter and Spatial Variation of Fundamental Constants with Space Quantum Sensors

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ABSTRACT:
We propose a clock-comparison space mission with two clocks on board, in orbits near the Sun, to search for an ultralight dark matter halo bound to the Sun, partly motivated by the NASA Deep Space Atomic Clock and Parker Solar Probe. We show that the projected sensitivities of space-based clocks exceed the reach of Earth-based clocks by orders of magnitude, probing dark matter motivated by the naturalness of the Higgs mass. Another primary goal of our proposal is to test the potential spatial variations of fundamental constants, improving the Earth-based limits by two orders of magnitude.

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1 Introduction

In this proposal, we present an exciting new avenue of probing ultralight dark matter with future high-precision atomic, molecular, and nuclear clocks in space, and testing the spatial variation of fundamental constants [1]. The oscillations of the ultralight dark matter field can induce a time-varying contribution to fundamental constants, including the electron mass and fine-structure constant [2, 3]. Exceptional enhancements of dark matter density that can be enabled by the bound halos present an opportunity for direct dark matter detection with clocks [4, 5].

Space quantum technologies provide near-future crucial applications, including linking Earth optical clocks [6], the auto-navigation of spacecraft [7], secure quantum communications [8], and relativistic geodesy [9]. The NASA Deep Space Atomic Clock (DSAC) mission and other recent missions [7, 10] have demonstrated significant stability, with a factor of 10 or better improvements over previous space-based clocks. Missions such as the NASA Parker Solar Probe (PSP) show the viability of space missions in orbits close to the Sun [11].

We propose a clock-comparison space mission with two clocks on board to search for a dark matter halo bound to the Sun. We show that the projected sensitivity of space-based clocks for detecting Sun-bound dark matter halo exceeds the reach of Earth-based clocks by orders of magnitude. We consider the projected bounds for the existing cutting-edge clocks, as well as the novel nuclear and molecular clocks under development.

Another primary goal of this proposal is to test the spatial variations of fundamental constants under the change in the gravitational potential [12, 13]. We show that using space-based quantum clocks, one can improve the precision by two orders of magnitudes for this measurement in comparison to similar tests on Earth [13].

2 Solar System Halos

Ultralight dark matter (ULDM), with particle mass m_ϕ in the range 10^{-22} eV$\lesssim m_\phi \lesssim$ eV, is a compelling solution to the dark matter problem of our universe [14–16]. ULDM states bound to objects in the solar system are an intriguing possibility, with possible large enhancements to the local dark matter density that could allow more weakly-coupled ULDM candidates to be potentially detectable [4, 5, 17]. Furthermore, these bound objects are typically much colder (lower energy per particle) than the background density of dark matter, implying a longer timescale of coherent oscillations that is also advantageous to experimental searches. There are hints in the literature that such bound states should form, both from numerical simulations of

ULDM halos [18] as well as studies of adiabatic contraction during star formation [17]. Current constraints on these bound states arise from local gravity measurements, including solar system ephemerides [19].

In this proposal, we study the scenario of ULDM particles bound to the sun, in a bound state sometimes referred to as a ULDM *solar halo*. We focus on the prospect of a future space quantum clock mission to probe a high-density ULDM solar halo around the Sun, with the unique possibility of discovery for solar halos with radius < 1 AU, which would not be possible in terrestrial searches [4].

3 Quantum Clock Searches for Ultralight Dark Matter

Ultralight dark matter gives rise to novel oscillatory signals in atomic physics systems, including clocks [2–5]. These signals arise from couplings to the Standard Model particles, and can be parameterized by

$$\begin{aligned} \mu(\phi) \simeq \mu_0\left(1+d_{m_e}\kappa\phi\right), \qquad \alpha(\phi) \simeq \alpha_0\left(1-d_\alpha\kappa\phi\right) \\ \left(\frac{m_q}{\Lambda_{\rm QCD}}\right)(\phi) \simeq \left(\frac{m_q}{\Lambda_{\rm QCD}}\right)_0\left(1-d_g\kappa\phi\right), \end{aligned} \tag{3.1}$$

where μ, α, and $m_q/\Lambda_{\rm QCD}$ are the electron-proton mass ration m_e/m_p, fine-structure constant, and quark mass m_q relative to the Quantum Chromodynamics (QCD) energy scale $\Lambda_{\rm QCD}$ (respectively), and $\kappa = \sqrt{4\pi}/M_P$ with $M_P = 1.2 \times 10^{19}$ GeV the Planck mass. The interaction strength is dictated by the dimensionless coupling constants d_{m_e} (for ULDM coupling to electrons), d_α (for coupling to photons), and d_g (for coupling to gluons), as well as the field value ϕ, which oscillates around a central value ϕ_0 at a fixed frequency proportional to the ULDM particle mass m_ϕ.

The field value ϕ is dictated by the ULDM density ρ at the position of the experiment, as $\phi_0 = \sqrt{2\rho/m_\phi}$. Typically it is assumed that the local density is dictated by the spherical dark matter halo distribution, virialized in the Milky Way galaxy, which implies $\rho = \rho_{\rm local} = 0.4$ GeV/cm^3. However, large dark matter overdensities in the solar system are possible, and consistent with all known constraints, when the dark matter is gravitationally bound to the Sun (see Section 2) [4, 5]. For terrestrial searches, the direct constraints imply that $\rho \lesssim 10^4\rho_{\rm local}$ at most, but the constraints are much weaker when considering orbits much nearer to the Sun than 1 AU, which implies the potential to probe even smaller values of the coupling constants d_{m_e}, d_α, and d_g (defined above) than would be possible with a terrestrial search. In our estimation, we use the complete set of local constraints, as outlined in [1].

4 Sensitivities from Atomic, Molecular, and Nuclear Clocks

To detect ultralight dark matter with high-precision clocks, one measures a frequency ratio of two clocks with different sensitivities to the variation of fundamental constants over a period of time [2]. The discrete Fourier transform of the resulting time series then allows the extraction of a peak at the dark matter Compton frequency, with an asymmetric lineshape [2, 20, 21]. If such a signal is not detected, one can obtain limits on the dark matter parameter space. It is also possible to carry out such a measurement with a single clock by comparing the frequency of atoms to the frequency of the local oscillator (i.e., cavity) [22, 23]. For further details, see [1].

The coupling constants d_{m_e}, d_α, and d_g in Eq. (3.1) can be probed using different clock technologies. It is important to note that detection of the signal proposed here would require a pair of co-located clocks on a space probe, although a wide variety of clocks could be selected for this purpose. A detailed discussion of possible mission clocks can be found in [1]. In brief, on the basis of the present literature, an optical, molecular, or nuclear clock would each be well-suited to one or more of these couplings. Molecular or optical clocks can realistically achieve a future sensitivity to oscillations on the order of $(\delta X/X)_{\rm exp} \simeq 10^{-18}$, with $X = \mu, \alpha$ [24–27], whereas a future nuclear clock may be capable of achieving $(\delta X/X)_{\rm exp} \simeq 10^{-23}$ for $X = \alpha$, $m_q/\Lambda_{\rm QCD}$ [28, 29].

5 Estimation of the Sensitivity Reach

Using the benchmarks described above (see [1] for further details), we can estimate the sensitivity of a future space-based atomic clock to oscillating ULDM signals. In Figure 1, we illustrate the potential sensitivity to coupling constants d_{m_e} (panel a), d_α (b), and d_g (c). In panels (a) and (b), we estimate the experimental reach assuming a sensitivity to oscillation of fundamental constants at the level of $(\delta X/X)_{\rm exp} = 10^{-15}$ (solid lines) or 10^{-18} (dashed lines) (with $X = \mu, \alpha$), which are achievable in near-future terrestrial clock systems [24–27] and could be optimized for a space mission. In panels (b) and (c), we also include a projection for a nuclear clock with sensitivity at the level of $(\delta X/X)_{\rm exp} = 10^{-23}$ for $X = \alpha, m_q/\Lambda_{\rm QCD}$ [28, 29]. The gray and yellow shaded regions represent contraints from equivalence principle tests [31–33] and atomic physics probes of the local dark matter density ρ_{DM} [3, 23, 34, 35] (respectively).

For each of the three couplings considered, we observe in Figure 1 that a clock mission in some inner solar orbit can achieve a very high degree of sensitivity to ULDM signals. The sensitivity is greatest in the range 10^{-14} eV$\lesssim m_\phi \lesssim 3 \times 10^{-13}$ eV, and has the potential to probe well-motivated theory targets, below the burgundy and green lines, motivated by naturalness and by relaxion theories [36, 37].

6 Spatial Variation of Fundamental Constants

Variations of fundamental constants can also be tested by a clock-comparison experiment in an inner solar orbit, due to the change in the gravitational potential. Such

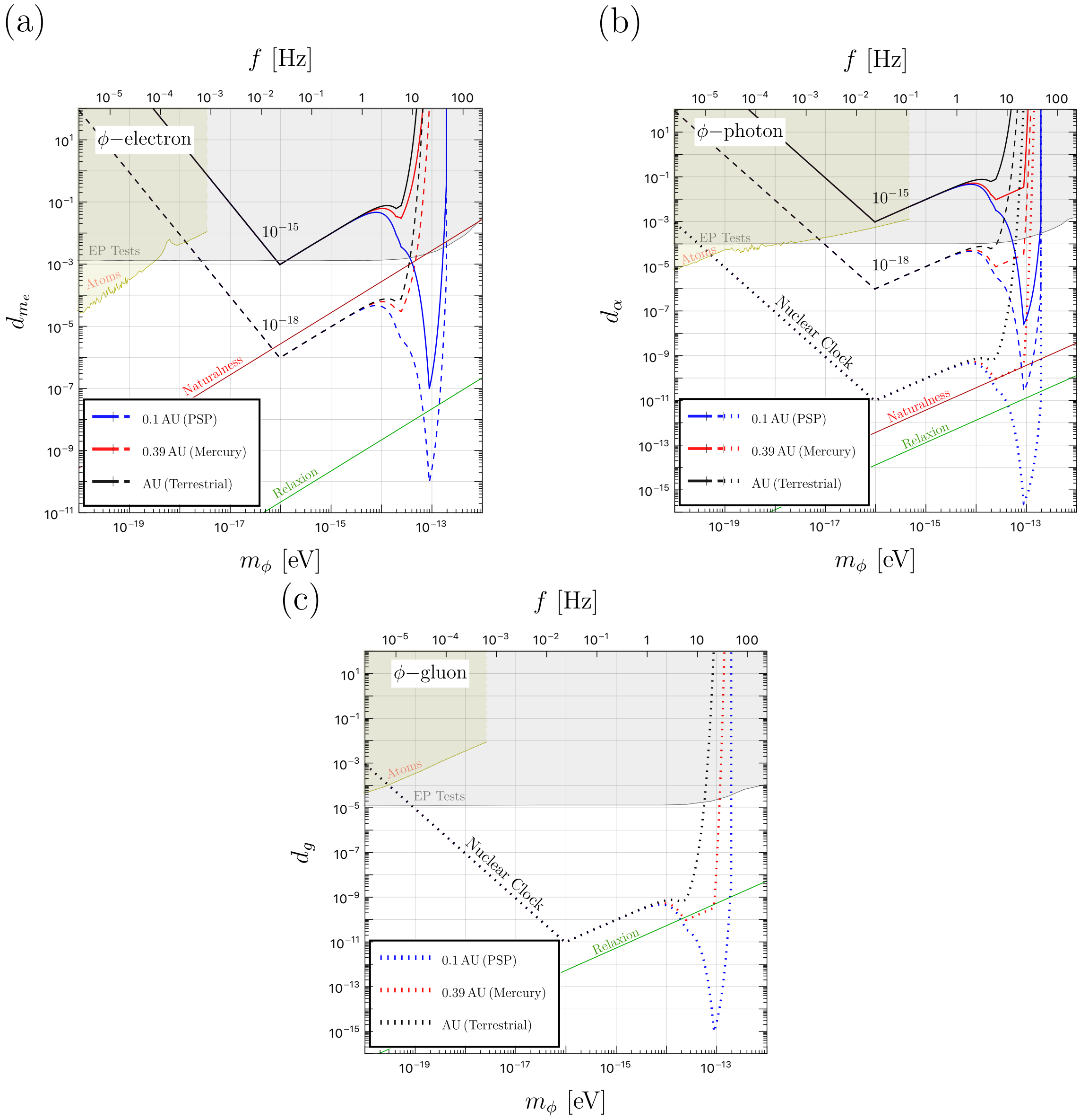

Figure 1. Estimated sensitivity reaches for ultralight dark matter bound to the sun, using couplings described in Eq. (3.1). The blue, red, and black denote sensitivity for probes at the distance of 0.1 AU, probes at the orbit of Mercury, and for terrestrial clocks, respectively; note that distances of $r < 0.1$ AU have already been reached by the NASA Parker Solar Probe (PSP) mission, reaching 0.06 AU on its most recent perihelion and aiming to reach 0.045 AU at its closest approach [30]. We illustrate the projected bounds for the variations of the electron-proton mass ratio μ (panel a), the fine structure constant α (panel b), and ratio $m_q/\Lambda_{\rm QCD}$ (panel c). The thick (dashed) lines correspond to assumed experimental sensitivity of 10^{-15} (10^{-18}) for panels (a) and (b). The dotted lines in panels (b) and (c) represent the projection for a clock-comparison experiment at the 10^{-19} level involving a nuclear clock and assuming a 10^4 sensitivity factor [29].

new physics is usually parameterized as [12, 13]

$$k_X \equiv c^2 \frac{\delta X}{X\,\delta U}, \tag{6.1}$$

with $X = \alpha$, μ, or m_q/Λ_{QCD}, and δU is the change in gravitational potential between the positions of two clock measurements. Such experiments are referred to as "null" experiments in [38], and essentially measure differential redshift. Monitoring ratio of clocks as the satellite moves deeper in the solar system can set constrain k_X, via the relation $(k_X)_{\text{exp}} = (\delta X/X)_{\text{exp}}\, c^2/\delta U$.

The current constraints on k_X arise from studies that utilize the seasonal variation of Earth's orbital distance to the Sun, where the variation of gravitational potential is on the order of $\delta U/c^2 \simeq 3.3 \times 10^{-10}$ [13]. On the other hand, a space probe at a distance of 0.1 AU would see a change in potential of $\delta U/c^2 \sim 9 \times 10^{-8}$, relative to 1 AU. This implies that a space quantum clock with the same intrinsic uncertainty on measuring $\delta X/X$ can more strongly constrain k_X, by a factor of nearly 300, relative to terrestrial clocks (barring additional systematic uncertainties).

Our present proposal does not require an optical link enabling comparing the satellite and Earth-based clocks. If such a link can be achieved, one can also directly test general relativity and provide a direct bound on the anomalous gravitational redshift exceeding present bounds by orders of magnitude [38–40].

7 Implementation

The Parker Solar Probe (PSP) has achieved near-solar orbital fly-by distances on the level we consider in this work, $r \simeq 0.1$ AU. The present mission can be integrated into a future solar probe or be a part of a mission sequence to deploy high-precision clocks in space. The clocks on the mission package will depend on the progress in the development of new clocks with high sensitivity to the variation of fundamental constants (such as a nuclear clock) and the development of space-ready clocks. Possible clock combinations for this mission were explored in [1].

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