CLOCK COMPARISON AND DISTRIBUTION BEACON AT CISLUNAR ORBITS. J. R. Williams and N. Yu, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 298-103B, Pasadena, CA, 91109. Jason.R.Williams.Dr@jpl.nasa.gov (818) 354-8872.

Introduction: We propose to deploy an advanced space optical clock system (ASOCS) on a Deep Space Gateway Station (DSG) and establish a high-precision time and frequency beacon to Earth and into deep space. ASOCS will operate a space-based clock at unprecedented fractional frequency stability of 1×10^{-18} [1], which can be disseminated via microwave and/or optical links. Clock comparison measurements to existing clocks on Earth will provide opportunities for direct detection of ultra-light dark matter (DM) fields [2,3,4]; tests of gravity-induced frequency shifts and time delays for fundamental physics measurements [5,6]; and precision one-way spacecraft Doppler tracking and ranging in deep space. The high-performance clock and link asset at DSG will also enable future clock-based gravitational wave detections when properly linked to another high-performance clock in deep space [7,8].

Background: There has been tremendous and rapid advancement in the development of high-performance atomic clocks in the form of *optical clocks* (OC). Optical atomic clocks utilize ensembles of laser-cooled atoms, with technologies similar to those at the heart of the ISS-based Cold Atom Laboratory (CAL), but confined in optical lattice potentials for unprecedented insensitivity to interactions, thermal effects, and environmental perturbations. The clock signal is derived from a stable laser frequency-locked to a metastable optical transition at 100s of THz, which has recently achieved record fractional frequency stabilities at 10^{-18} (2.2×10^{-16} at 1 second) [1]. Operating an OC aboard the DSG would provide unique opportunities for a range of applied and fundamental physics applications via unprecedented long-baseline clock comparison experiments between Earth and DSG. The demonstrated optical clocks now reach sufficient precisions for gravitational wave detections using clocks directly.

Objectives: The primary science objectives include:

1) Searching for direct evidence of dark matter, thereby providing insight into the widely unknown nature of DM and/or testing the validity of contemporary DM theories with stringent bounds.
2) Improving the test of clock time dilation described by Einstein's general relativity of space-time, often known as the gravitational redshift, by several orders of magnitude over the current limit.
3) Seeking a violation of Lorentz invariance (LI) with unprecedented precision in the framework of Einstein's special relativity [6].
4) Demonstrating the utilities of the clock asset at cislunar orbits for deep space time and frequency dissemination and for possible gravitational wave detection similar to those by the Cassini Doppler-tracking gravitation detection experiments.

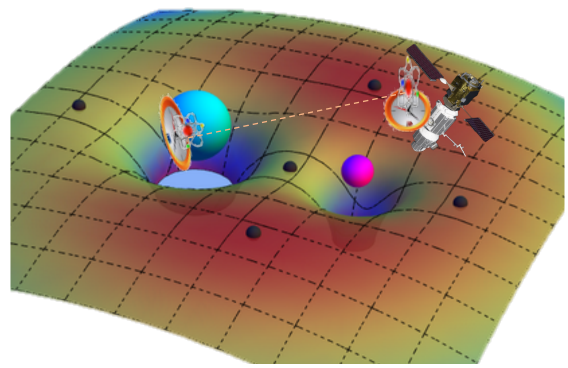

Figure 1: High-precision time and frequency comparisons between DSG-based and terrestrial optical clocks enable novel searches of ultralight DM and high-precision tests of Einsten's general relativity.

Searching for signatures of DM: Determining the composition and properties of dark matter is one of the grand challenges in astrophysics and cosmology today. The challenge lies in the range of uncertainty of the mass of dark matter fields. While the range of massive particles is mostly investigated in high energy accelerator physics, ultra-light dark matter can be probed through precision measurements using clocks [2,3,4].

It is known that the DM coupling to the standard model fields results in changes of fundamental constants such as the fine structure constant. A change in these fundamental constants affects atomic transition frequencies and, therefore, atomic clock ticking rate. By comparing atomic clocks of different species or separated by a distance, we would be able to detect the presence and dynamics of DM fields, which can be in the forms of sinusoidal waves [4], clumps of topologic defects [2,3], or stochastic backgrounds.

Figure 2 gives existing constraints on the DM energy-coupling-scale ($\Lambda\alpha$) for topological DM defects from clock-cavity comparisons [3], and astrophysical measurements [9], as well as projected sensitivities that may be achieved using trans-continental networks of GPS and OC. Comparisons with OC onboard DSG and terrestrial clocks promise to increase bounds on the $\Lambda\alpha$, increase the measurable defect size, as well as extend the bounds to lower masses for DM waves. A network of three clocks can also detect stochastic backgrounds through cross-correlation measurements [10].

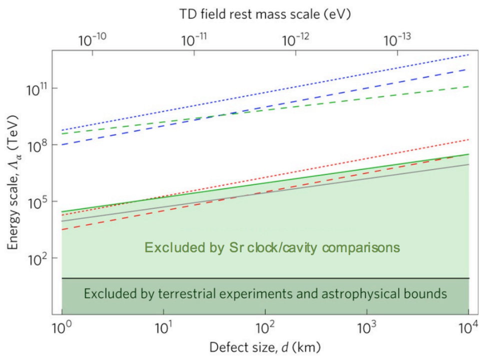

Figure 2. Constraints on the DM energy-coupling scale (Λ_α) for topological defect dark matter. The region below the solid green line corresponds to constraints from Sr clock/optical cavity comparison measurements [4]. The region below the solid black line corresponds to constraints from fifth-force searches and astrophysical measurements [5]. The dashed red and blue lines correspond to the sensitivities that may be achieved using a trans-continental network of GPS clocks and Sr clocks, respectively [3].

Test of gravitational redshift of clocks: Einstein's general theory of relativity offers the most elegant description of gravity and so far, the most successful theory in fundamental physics. However, there are compelling reasons to believe that the gravity theory is not complete. A violation could exist at some scales. General relativity predicts the slowing down of a clock in a gravitational field, the gravitation redshift. This effect was validated by the Gravity Probe A experiment in 1979 by Vessot [9]. ASOCS at cislunar orbits of nearly zero gravity can be compared with clocks on the ground at the full Earth gravity, offering the opportunity to perform the most precise test of general relativity, and improve the violation limit by 10,000, and potential for new discovery [5].

Test of Lorentz Invariance: Special Relativity relies on the assumption that Lorentz Invariance is a fundamental symmetry of nature. However, several theoretical frameworks predict that LI may not hold at all energy scales [2]. The highest-precision constraint of the LI violating terms is given by a comparison campaign of strontium OC in different locations throughout Europe [6]. Here, the clocks travels at different velocities (varying by up-to 22m/s in the inertial geocentric frame) due to their different positions on the Earth. By utilizing a DSG-based OC and undergoing similar clock-comparison campaigns with terrestrial OC worldwide, it will be possible to perform similar experiments with more than two orders of magnitude increased precision. The DSG orbits provide access to diverse speed and orientation changes for these measurements.

Instrument Concept:
The advanced space optical clock system will consist of an optical clock and a hybrid optical-microwave link for time transfer. The optical link provides high-performance frequency and time links with other clocks on Earth, for high precision clock comparison experiments, while the microwave link is intended for demonstrating time signal reference covering an appropriate omnidirectional antenna and receiver while also providing frequency references for lunar and interplanetary missions.

The experiment concepts take advantage of the nearly zero gravity potential at DSG relative to that on Earth, large simultaneous ground coverage, and greater range of orientation and velocity changes. The very long baseline of cislunar orbits from Earth also increase the dark matter signal strength for ultra-light particle fields with long wavelengths. The main payload can be either inside or outside, the antenna needs to be outside. Multiple ground stations are assumed. Quiet EMI and vibration environments are preferred. Similar to ISS environment is acceptable.

Size, Weight, and Power: The clock payload will be < 200 kg, including antennas, dependent on the functionality and capability requirements, < 1 m^3, < 500 W. Stable temperature and vibration environment is desired

Preferred Orbits: Constant earth viewing, with varying gravity that passes through zero potential point of L1 is preferred.

Astronaut Involvement: No.

Cost Estimate: $100M WAG is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

References: [1] T. Nicholson *et al.*, Nature Communications **6**, 6896 (2015). [2] A. Derevianko and M. Pospelov, Nature Phys. **10**, 933 (2014). [3] P. Wcislo et al., Nature Astronomy 1, 0009 (2016). [4] T. Kalaydzhyan and N. Yu, Phys. Rev. D 96, 075007 (2017). [5] S. Turyshev et al., Intl J of Modern Phys. D 16, 1879-1925 (2007). [6] P. Delva *et al.,* Phys. Rev. Lett. **118**, 221102 (2017). [7] S. Kolkowitz et al., Phys. Rev. D 94, 124043 (2016). [8] J. Su et al. arXiv:1711.07730v1 (2017). [9] K. A. Olive and M. Pospelov, Phys. Rev. D 77, 043524 (2008). [10] T. Kalaydzhyan and N. Yu, in preparation. [11] R. F. C. Vessot et al., Phys. Rev. Lett. 45, 2081–2084 (1980).