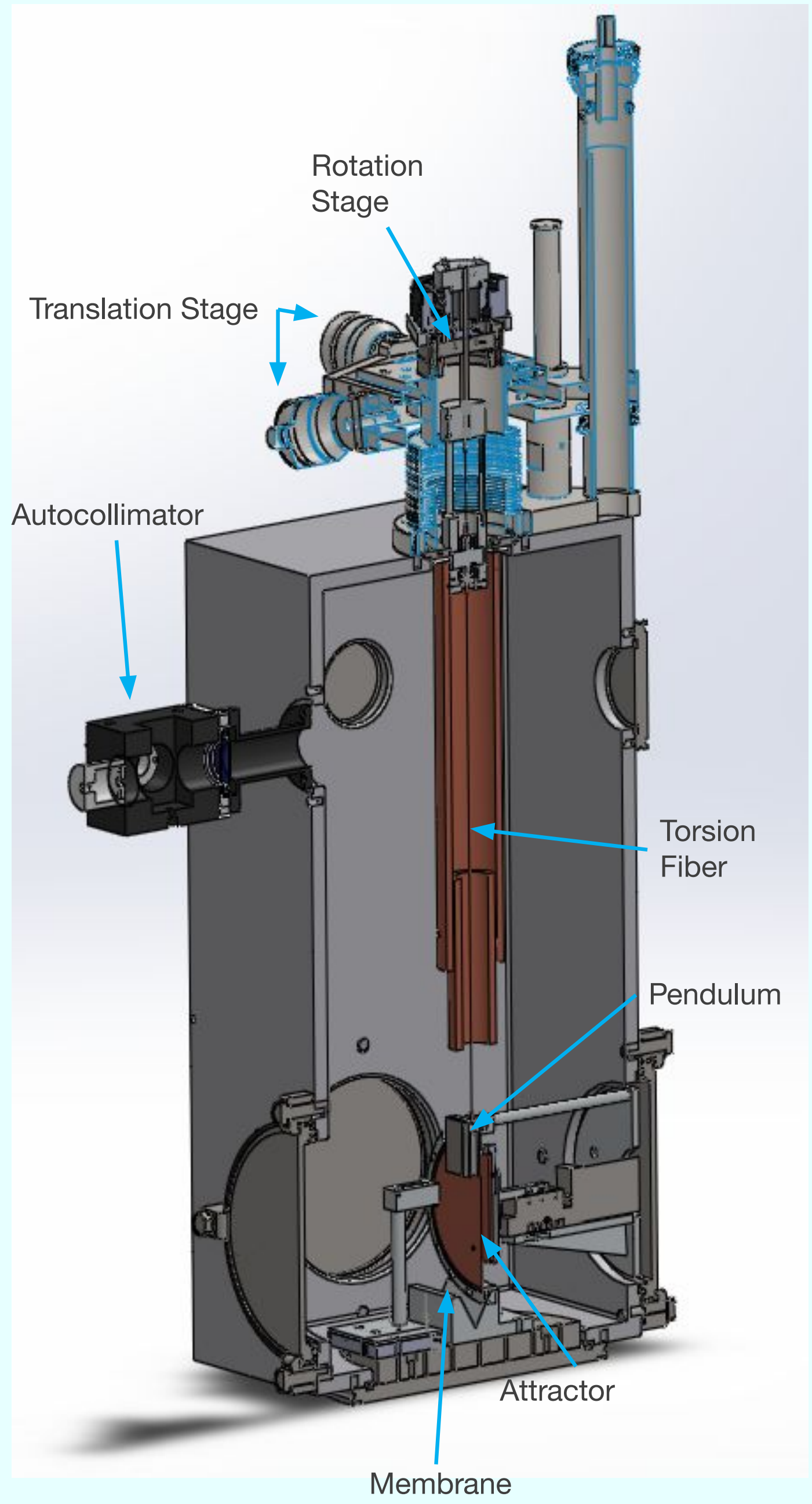
Novel Tests of Gravity Below Fifty Microns

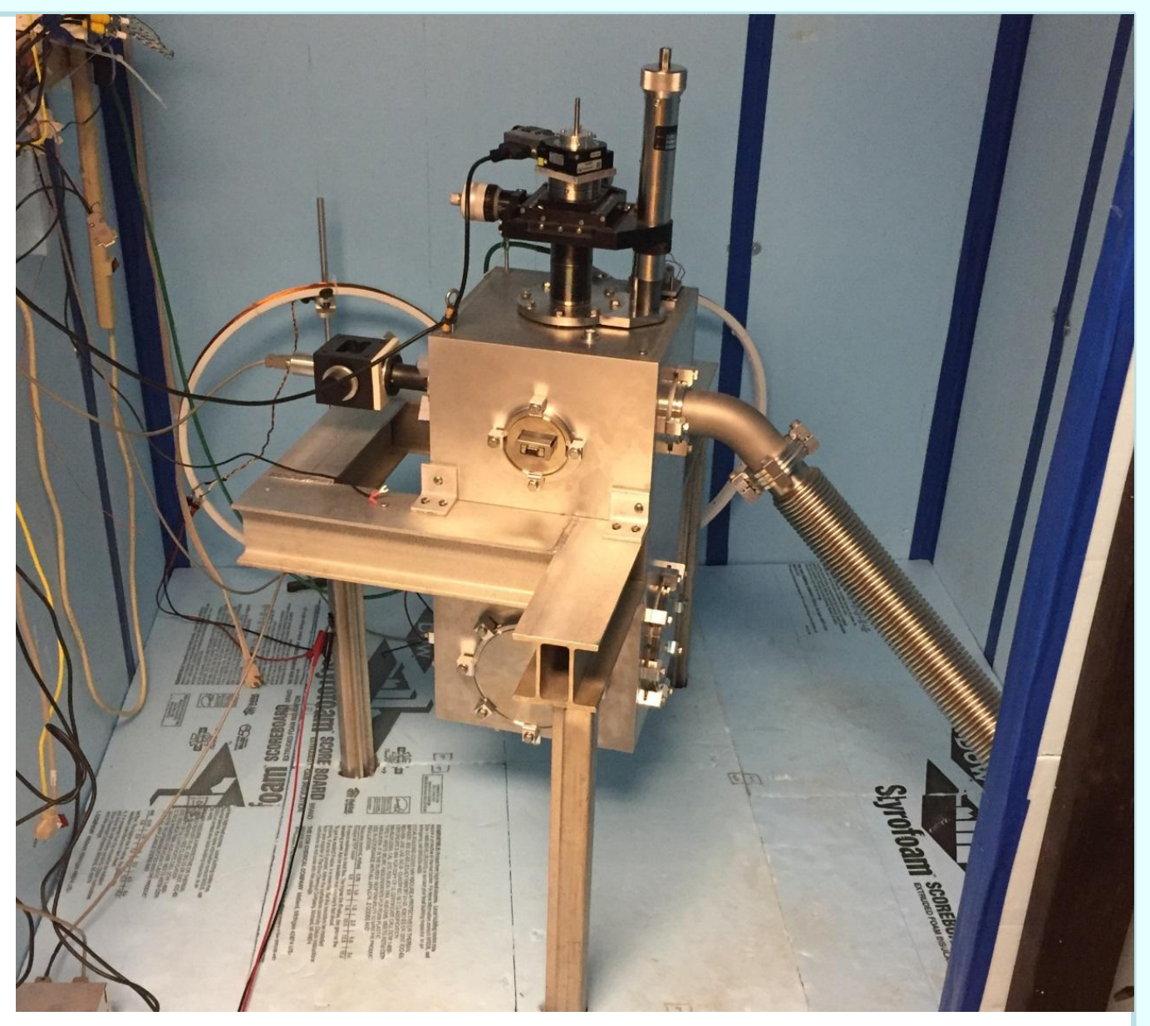
C.J. Rogers, J.P. Mendez, T.B. Hooven, K. Chung, A.M. Johnson, A.G. Papesh, and C.D. Hoyle
Department of Physics and Astronomy
Humboldt State University, 1 Harpst Street, Arcata, California 95521

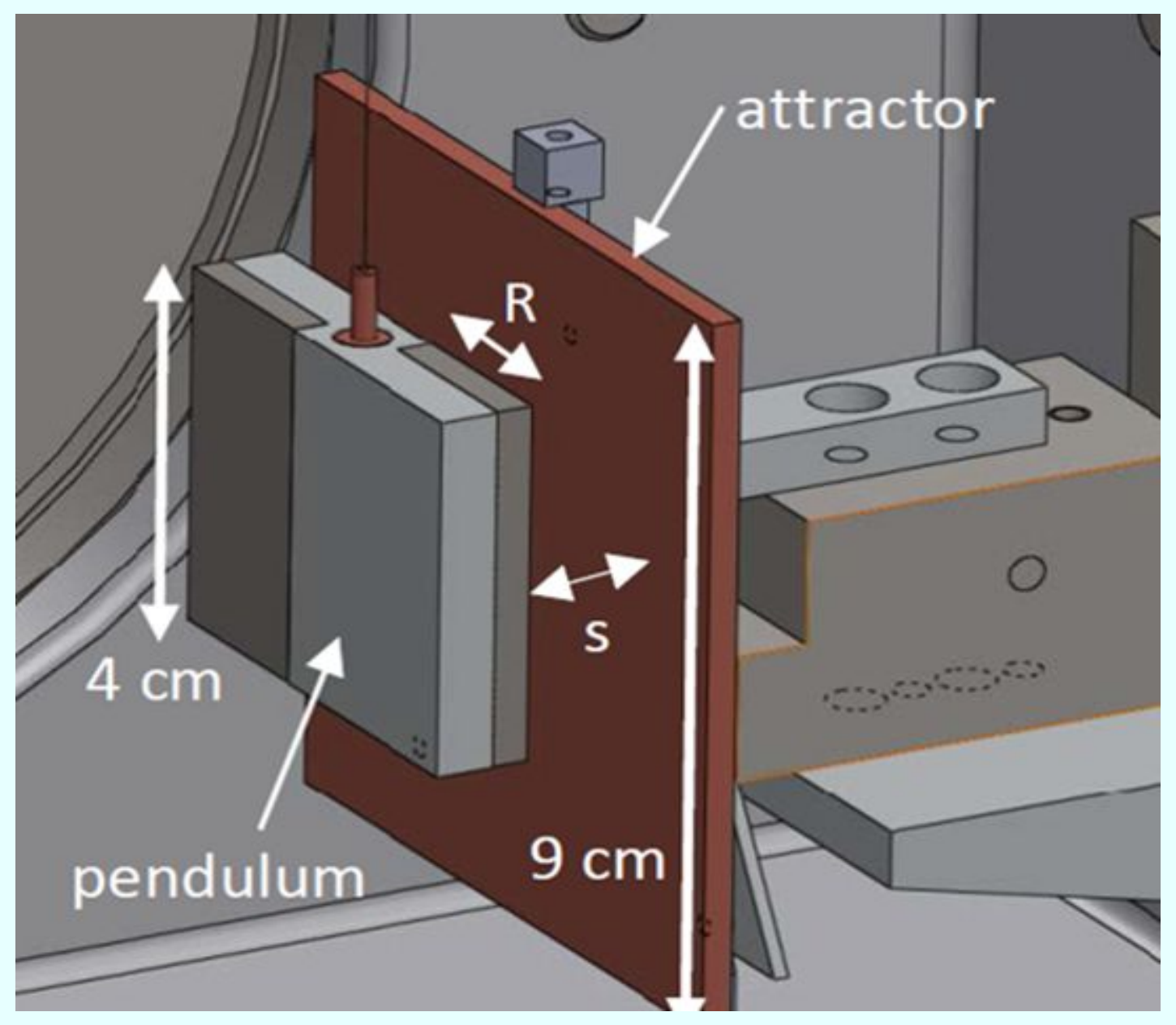
Motivation

Physical processes regarding gravity are well understood on the scale of planetary distances but pose challenges in measurements at very short distances. Theories such as the Inverse Square Law (ISL) and Einstein's Weak Equivalence Principle (WEP) of General Relativity have been tested over distance scales from 1 cm to infinity [1]. Reliable measurements of gravitational forces at scales smaller than a centimeter carry significant challenges. The non-gravitational forces that are generally negligible at the scale of everyday objects have a much more substantial effect in the sub-centimeter regime.

Some gravity models predict alterations of the gravitational ISL at sub-millimeter distances [1 - 3]. Others predict a violation of the WEP at some level due to interactions coupled to quantities other than mass, or modifications of gravity itself. Humboldt State University (HSU) experiments will have unprecedented sensitivity to search for deviations from Newtonian gravity in the 20-50 micron range.







Experimental Methods

The experiment essentially consists of a parallel-plate torsion pendulum and an attractor mass oscillating nearby at an angular frequency ω (the distance s, shown in the bottom right image in the figure above, is varied sinusoidally). As the attractor mass oscillates, the twist in the pendulum is measured and read out to the lab computers in real-time using an autocollimator.

An autocollimator combines a laser and a position-sensitive photodiode detector to measure tiny variations in the pendulum's angle. The laser emitted from the autocollimator follows a path to the pendulum, then reflects off it and traces its way back to the photodiode detector. As the pendulum twists, the motion gets mirrored by the laser onto the photodiode detector. The measured amount of twist indicates a torque on the pendulum and will be compared to the Newtonian ISL prediction to search for deviations from expected behavior.

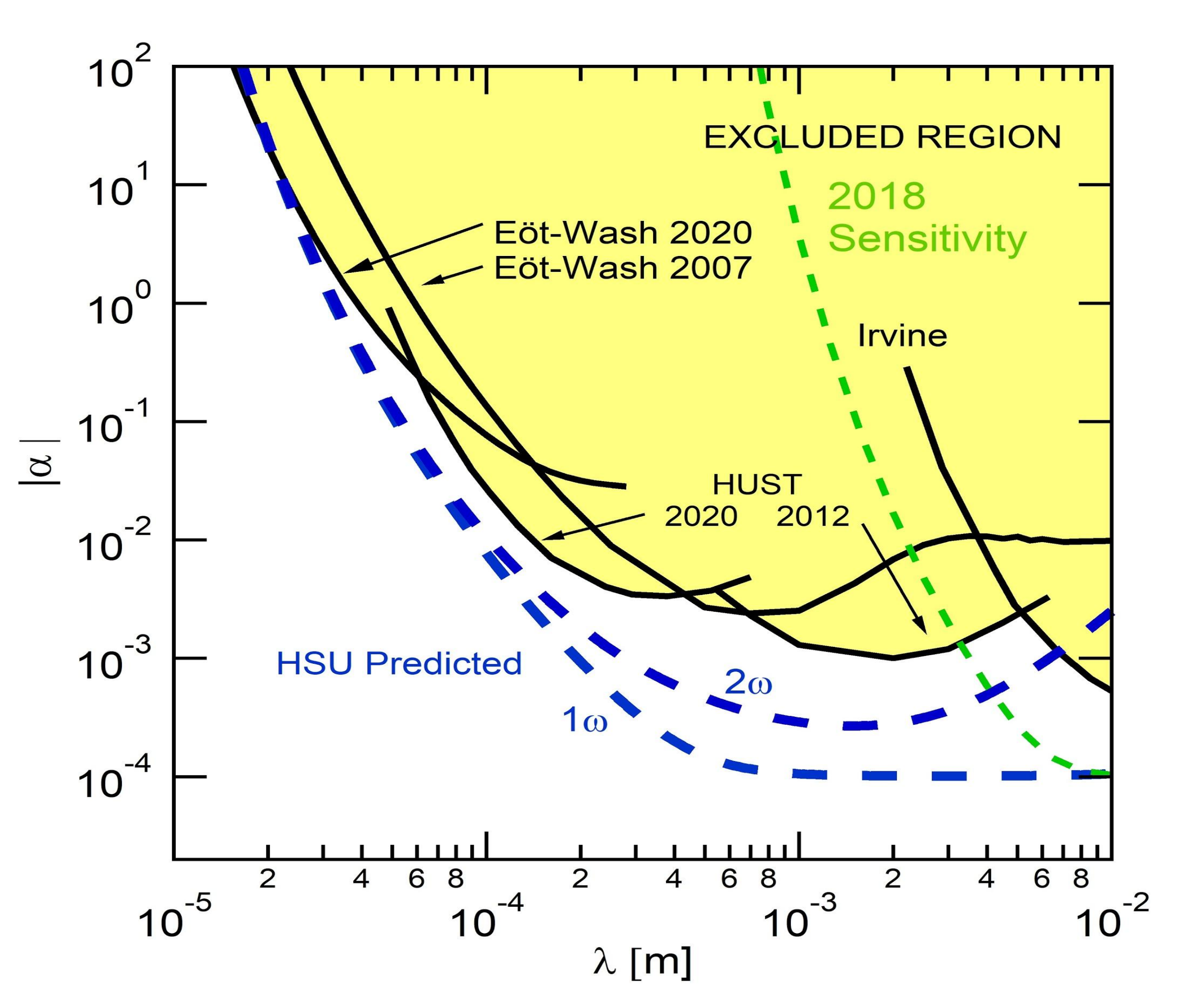
The WEP is tested through the pendulum's composition by constructing the parallel plate pendulum out of two different materials with equal masses. In this context, it might help to think of the WEP as the Einstein equivalent to the Galilean assumption that a hammer and a feather would experience the same acceleration in freefall (astronauts on the moon verified this [4]). By making the pendulum out of two materials, it is made into a "composition dipole" that is sensitive to violations of the WEP as well as the ISL.

Inverse-square Law

One way to model deviations from the ISL is to add a Yukawa addition to the standard Newtonian potential energy [3] :

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

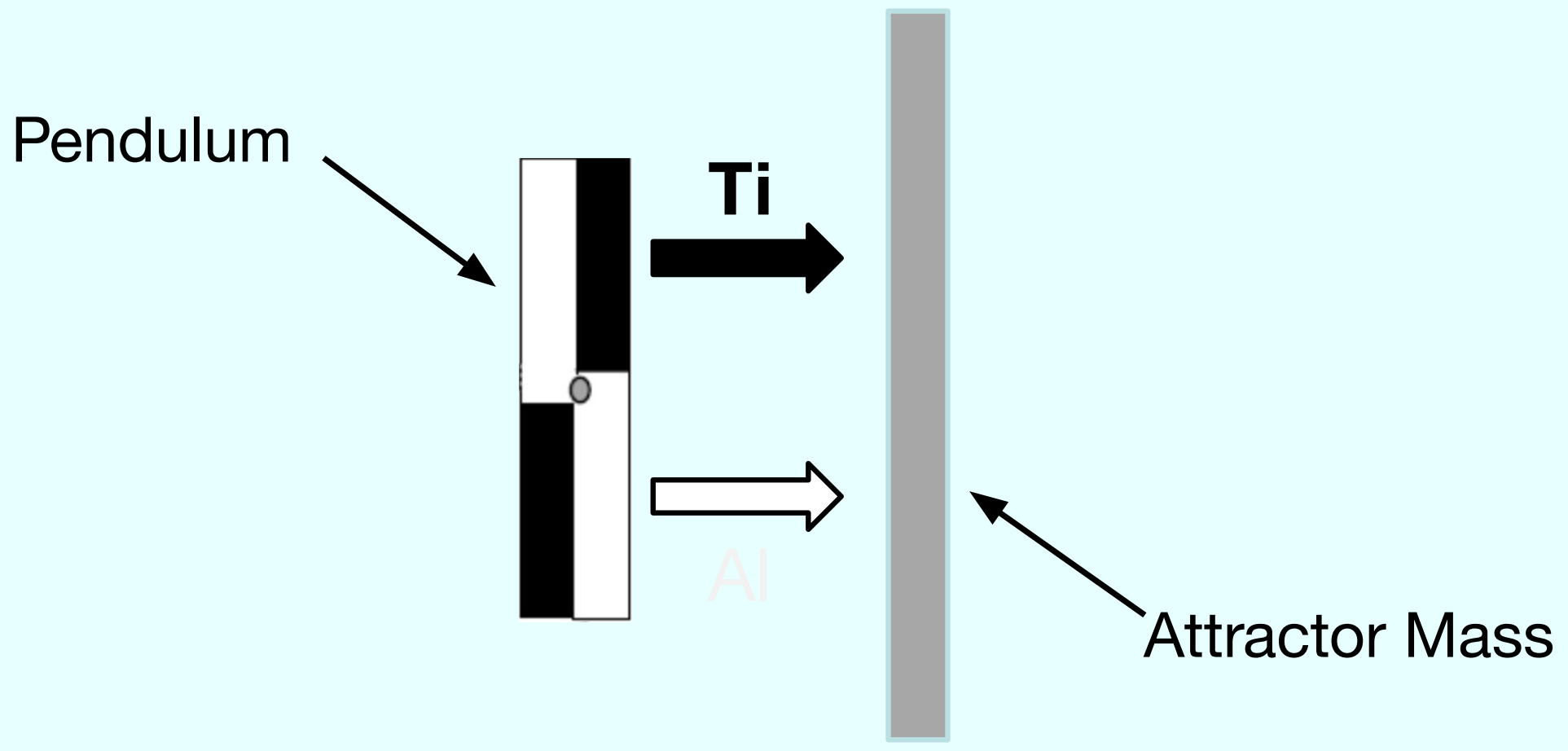
λ - Length scale where a deviation from the ISL might occur
α - Strength of the potential deviation



Above: Results from previous experiments, shown by the curves labeled Eöt-Wash [5,6], HUST [7, 8], and Irvine [9], produce the region in yellow which is excluded at the 95% confidence level. Each blue dashed line shows the predicted sensitivity of this apparatus for independent analyses of the first (1ω) and second (2ω) harmonic torque amplitudes. Improved constraints may be obtained by analyzing multiple harmonics together. The green dashed line is the current expected sensitivity of the apparatus. Note that for certain values of λ, an improvement by a factor of approximately 20 is obtained over previous efforts. The dashed curve crosses α = 1 at λ = 29 μm.

Weak Equivalence Principle

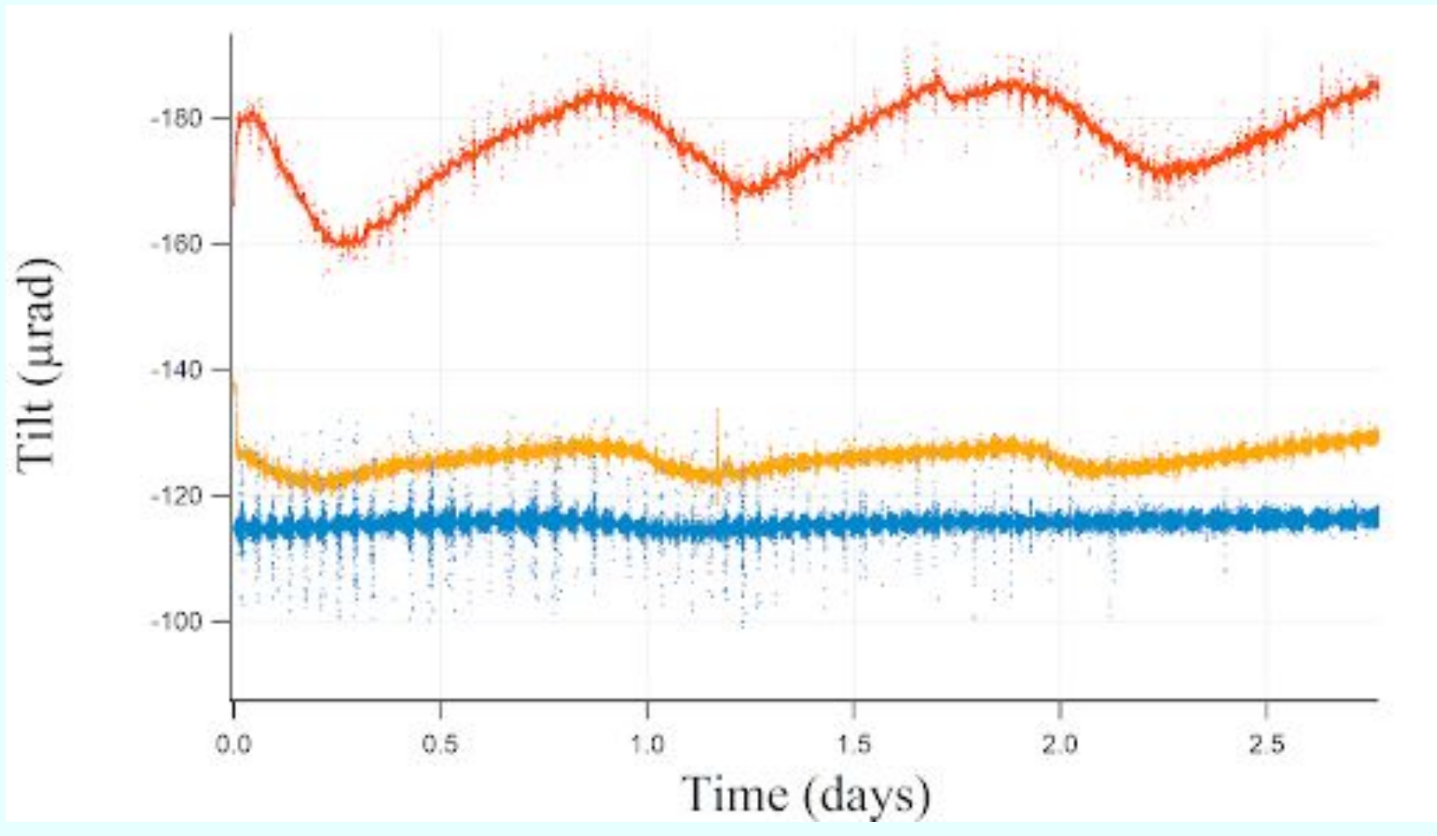
The WEP will be tested at short range using a composition dipole pendulum as shown below.



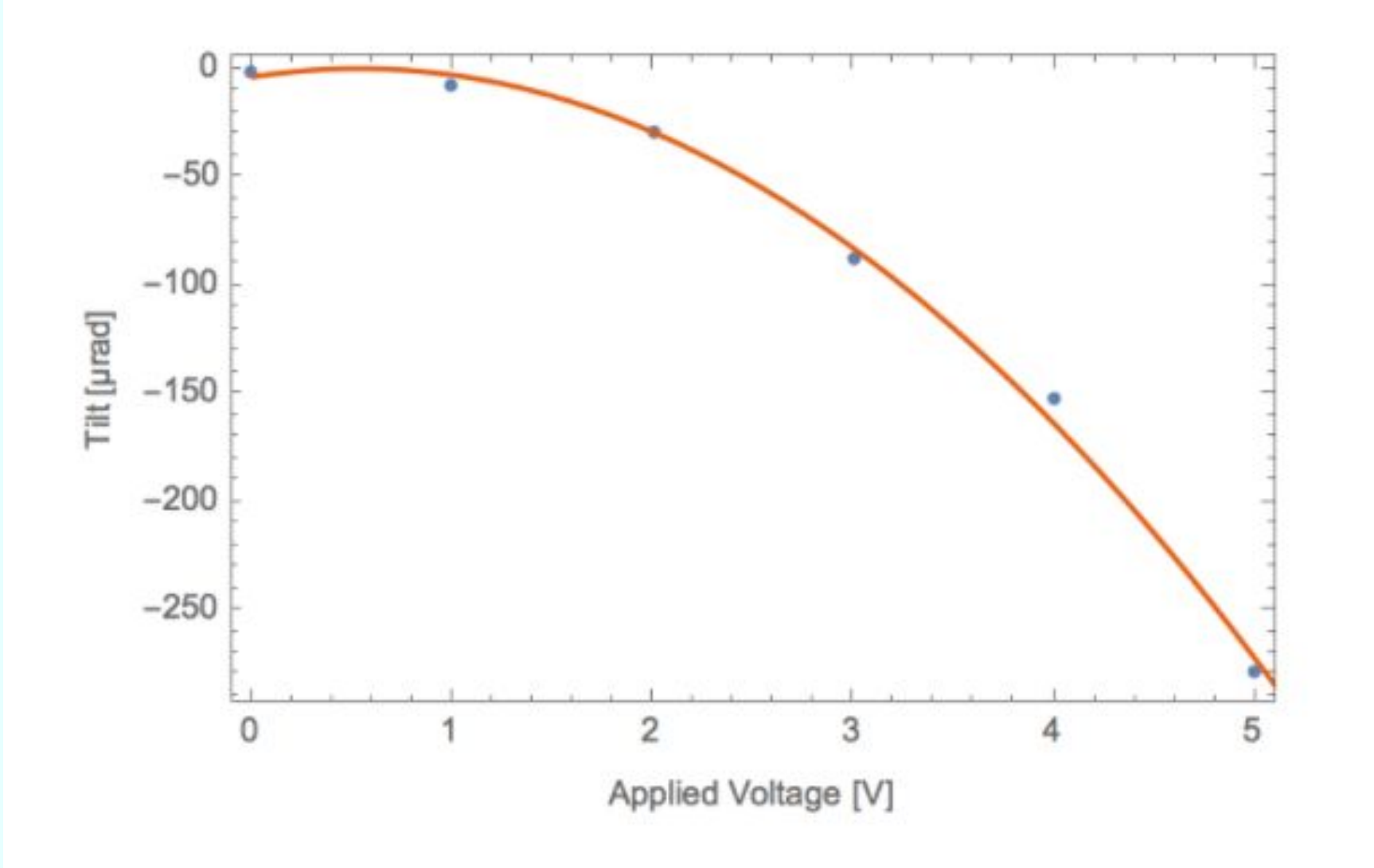
As the attractor mass is oscillated, any interaction dependent on the composition difference of the right half of the pendulum would result in a modulation of the twist, and could be evidence of a short-range violation of the WEP.

Current Projects

- The Tilt Control group has been working on canceling out the tilt due to the daily movement of Science A. The tilt of the building throughout a day varies by up to 50 microradians, making it a large source of noise. We wrote a LabView program to measure the current tilt of the apparatus and send out a tilt correction voltage calculated by a PID loop to bring the tilt back to a set point. This voltage is sent to a resistor on one of the legs of the apparatus and thermally expands the table let to tilt back to the set point. We also deliberately modulated the tilt to measure the pendulum's response and found that the pendulum twist is altered by about 2 microradians per microradian of tilt.
- The Magnetic Moment group performed experiments to discover by what magnitude the pendulum was affected by magnetic fields in order to reduce extraneous noise on the experiment. After constructing a Helmholtz coil to generate and apply a precisely modulated magnetic field onto the pendulum, the group was able to calculate the upper limit of magnetic torque affecting the pendulum, approximately (9.68 ± 0.07)×10^{-16} Nm. Ultimately, we are able to use this data to filter out potential interference resulting from magnetic fields with specialized data analysis software.



The red curve shows the natural tilt of Science A varying across three days by about 20 microradians. The yellow curve shows the tilt of the apparatus with only the proportional term of the tilt control PID loop active. The blue curve shows the tilt of the apparatus with both the proportional and derivative terms of the tilt control PID loop active.



The orange curve shows the capacity of our tilt correction system to help keep the experiment level with a tilt range of 300 microradians as our applied voltage varies from 0 to 5V.

Acknowledgements

We extend a special thanks to Tyler Hooker, and all of the current and former students who have contributed to the HSU Gravitational Physics Laboratory.

HSU gravitational physics research is supported by the National Science Foundation (NSF) grants PHY-1065697, PHY-1306783, PHY-1606988, PHY-1908502, Research Corporation grant CC6839, and internally by the HSU College of Natural Resources and Sciences, Sponsored Programs Foundation, and President's Office. CSU-LSAMP is funded through the NSF under grant HRD-1302873 and the Chancellor's Office of the California State University.

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