April 7, 2014

Sensitivity Considerations for a Short-range Test of the Gravitational Inverse-square Law

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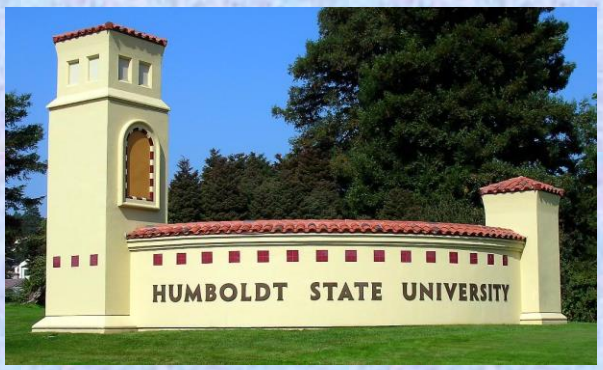
Dave Smith



American Physical Society

April Meeting 2014

Savannah, GA

April 5-8

Gravitational Physics Laboratory

PI: Dr. C.D. Hoyle

Undergraduate Researchers:

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- D. Smith
- C. Cardenas
- E. Guerrero
- M. A. Leitner

Primary Research Areas

*WEP *ISL

At Short Range

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Gravity is Well Tested

Newtonian Inverse-Square Law for Point Masses

$$F = -G\frac{m_1 m_2}{r^2}$$

The Weak Equivalence Principle

"The trajectory of a point mass in a gravitational field depends only on its initial position and velocity and is independent of its composition"

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…But Lots to Learn

- GR Inconsistent with Standard Model
- String Theory – "Extra Dimensions"
- Dark Energy—Property of Gravity?
- Short-Range Forces—Exotic Particles
- WEP Violations Due to Composition
  - Baryon Number
  - Lepton Number

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Newtonian Potential Energy with Yukawa Addition

$$V(r) = -\frac{Gm_1m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

λ = Length Scale of Deviation

α = Dimensionless Strength of Deviation

As $|\alpha| \to 0 \Rightarrow$ GR Confirmed

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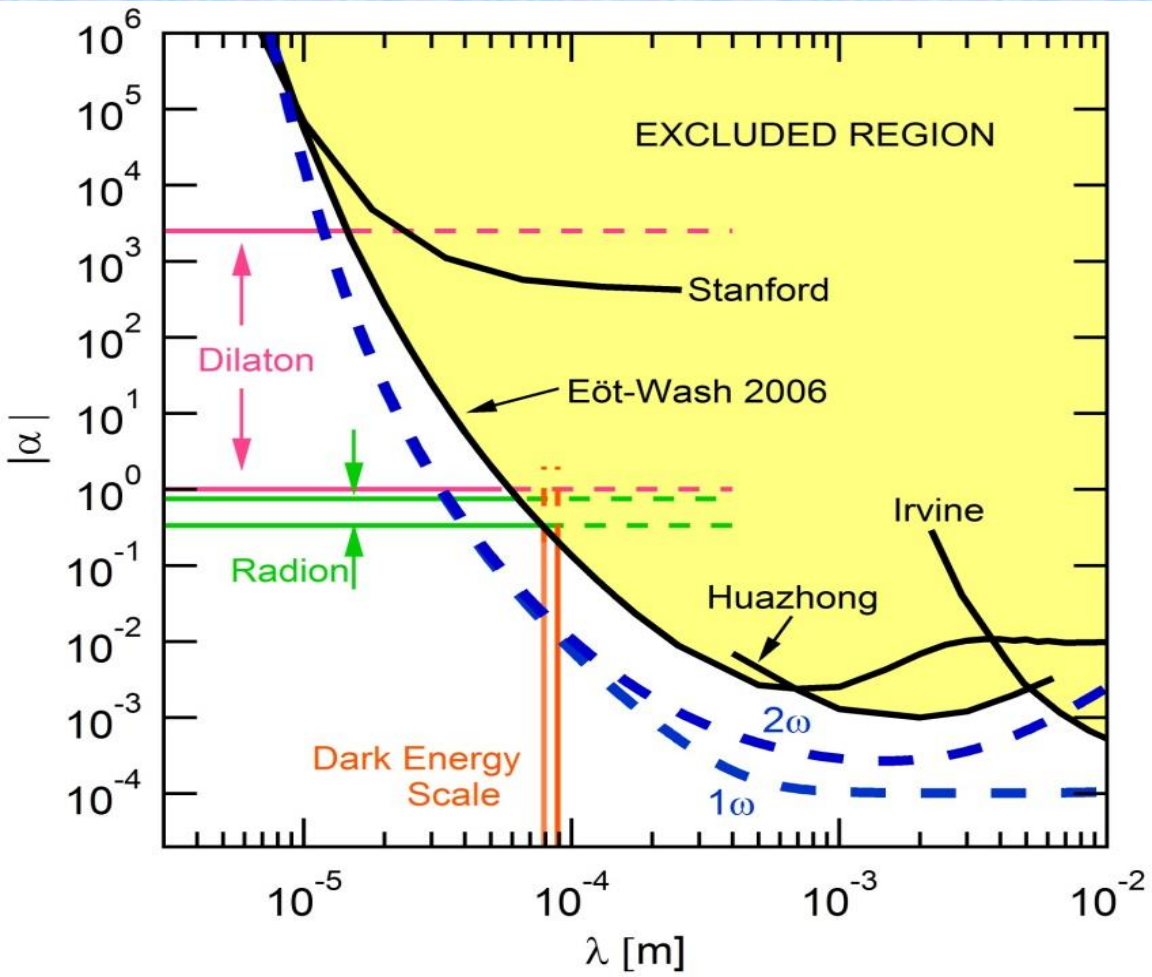
Current Precision/Expectations-ISL



ISL tested to about 55 microns

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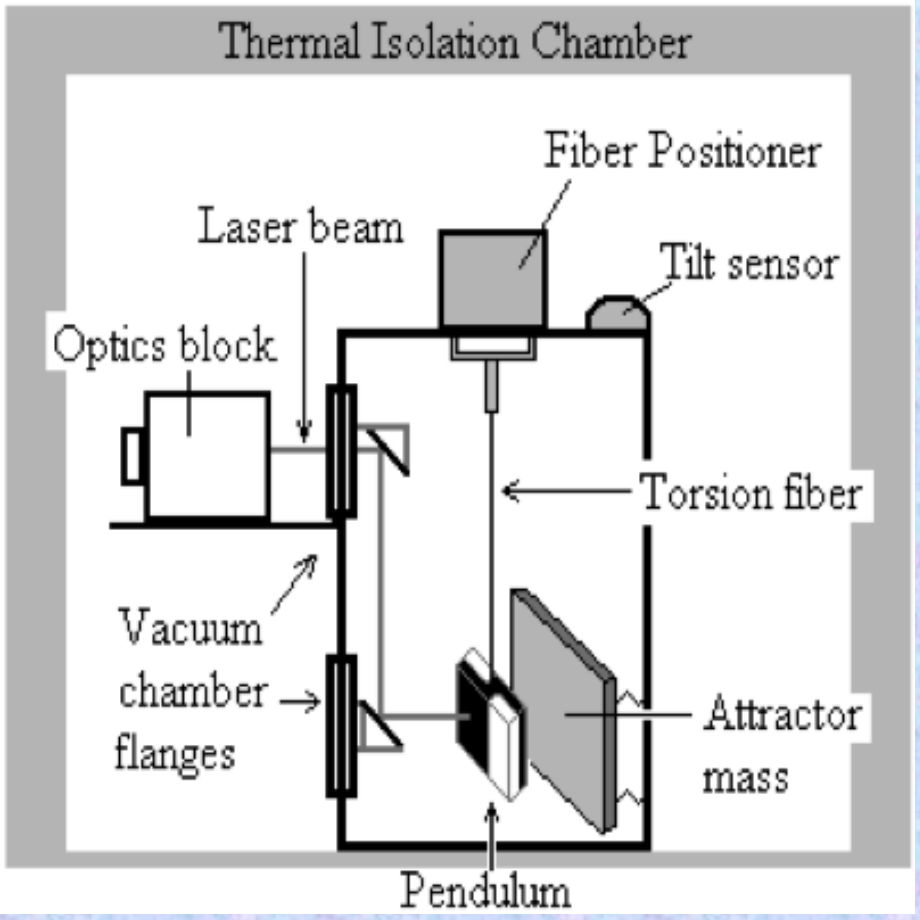
Vertical Plate Step Pendulum



Uniform Field—Any Torque May Indicate New Physics

Shaded area of pendulum represents area of different density

- Largely insensitive to Newtonian torque
- Highly sensitive to short-range effects
- Excellent Null Experiment

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Gauss's Law for Gravity

$$\oint \boldsymbol{g} \cdot \hat{\boldsymbol{n}} dA = -4\pi G M_A$$

Spherical Symmetry:

$$\boldsymbol{g} = \frac{-GM_A}{r^2}$$

Linear Symmetry:

$$\boldsymbol{g} = \frac{-2GM_A}{Lr}$$

Infinite Slab/Plane:

$$\boldsymbol{g} = \frac{-2GM_A}{A} \Rightarrow \boldsymbol{g}\ is\ constant$$

$$\boldsymbol{g} = constant \Rightarrow \boldsymbol{F_g} = constant$$

Dependence on distance of separation

- Highly sensitive to Newtonian torque
- Difficult to separate short-range effects

No dependence on distance of separation

- Attractor mass **not** infinite plane
- Some Newtonian torque present
- Very small

Where M_A is the Attractor Mass

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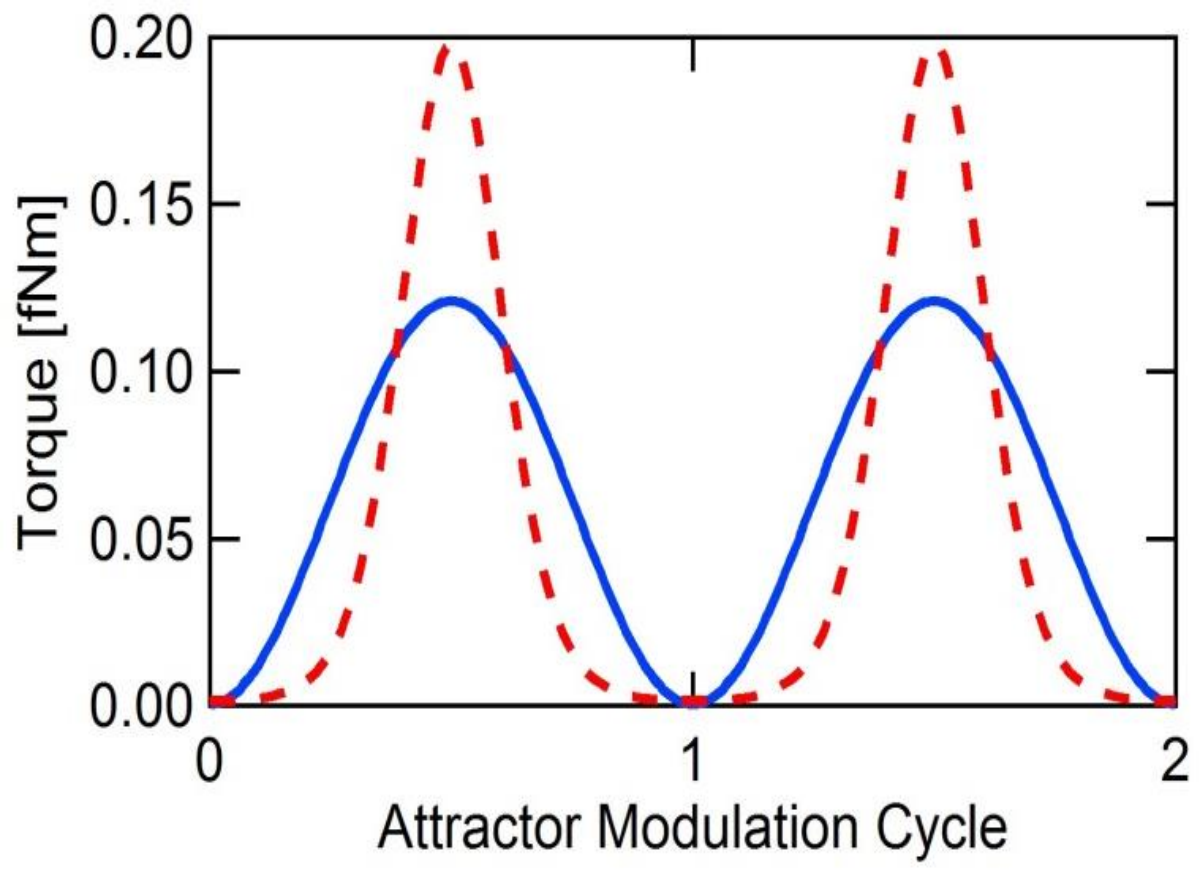

Harmonic Torque Amplitudes [fNm]

	Newtonian	Yukawa
1ω	0.0605	0.0816
2ω	0.0004	0.0415
3ω	0.0000	0.0154
4ω	0.0000	0.0005
5ω	0.0000	0.0001

Note Harmonic Torque Amplitude of 1ω vs 2ω

Assumed Parameters:

$$\lambda = 100\mu m$$
$$\alpha = 1$$

- Blue Curve: Newtonian Torque Due to Finite Plate (Pure Sine Wave)
- Red Curve: Potential Yukawa Torque

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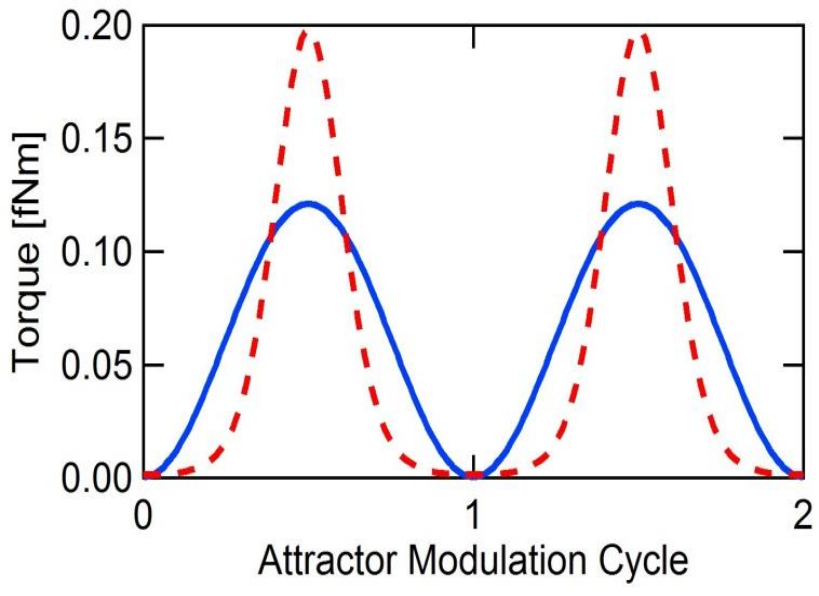

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1ω: Strong Newtonian and Yukawa Signals

2ω: Strong Yukawa Signal, Weak Newtonian

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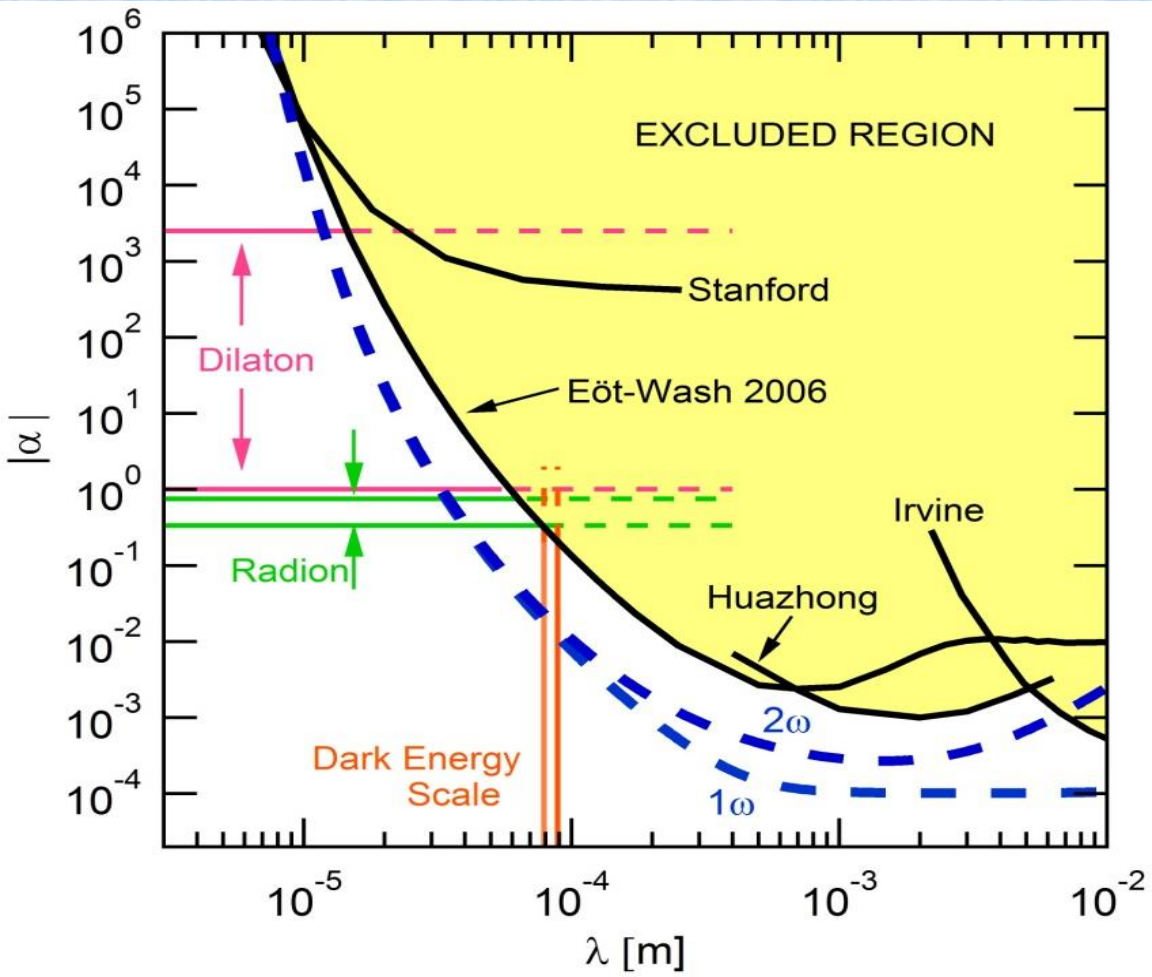
Current Precision/Expectations-ISL



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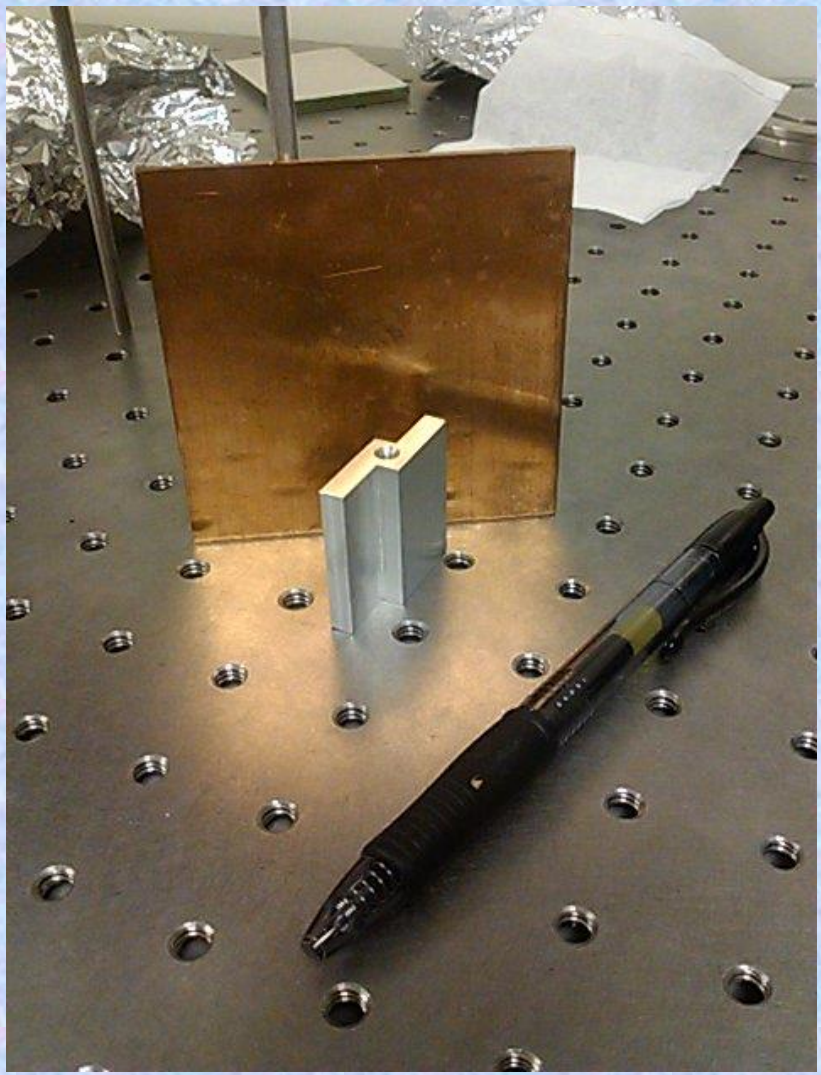
Prototypes of Attractor Mass and Step Pendulum



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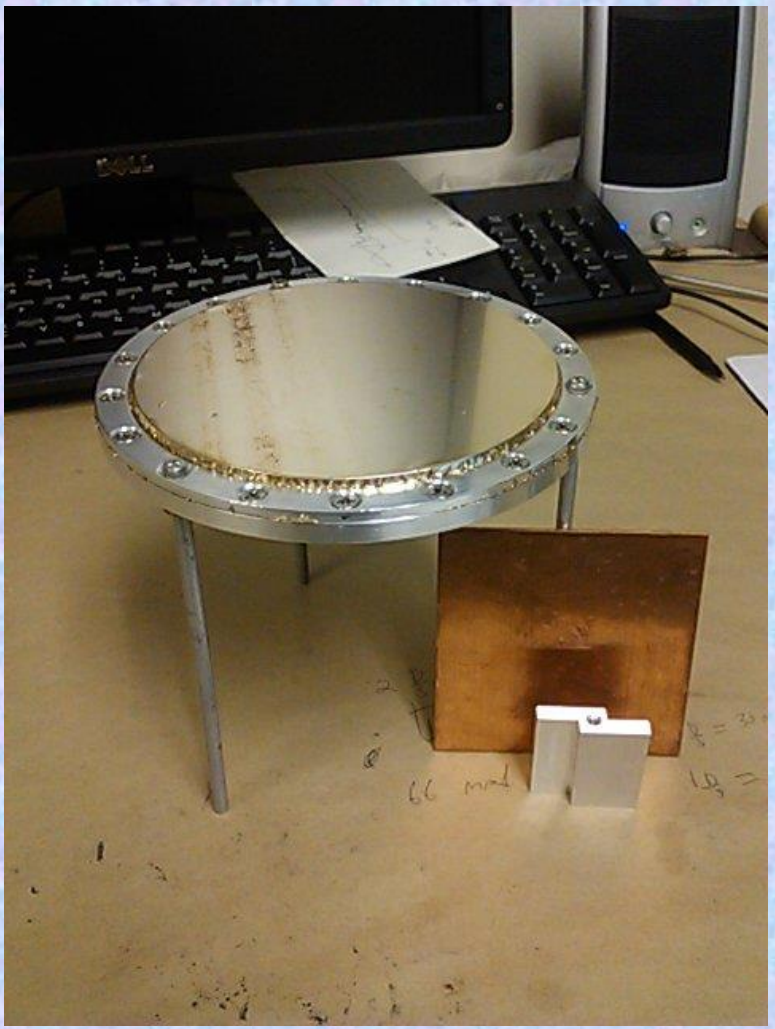
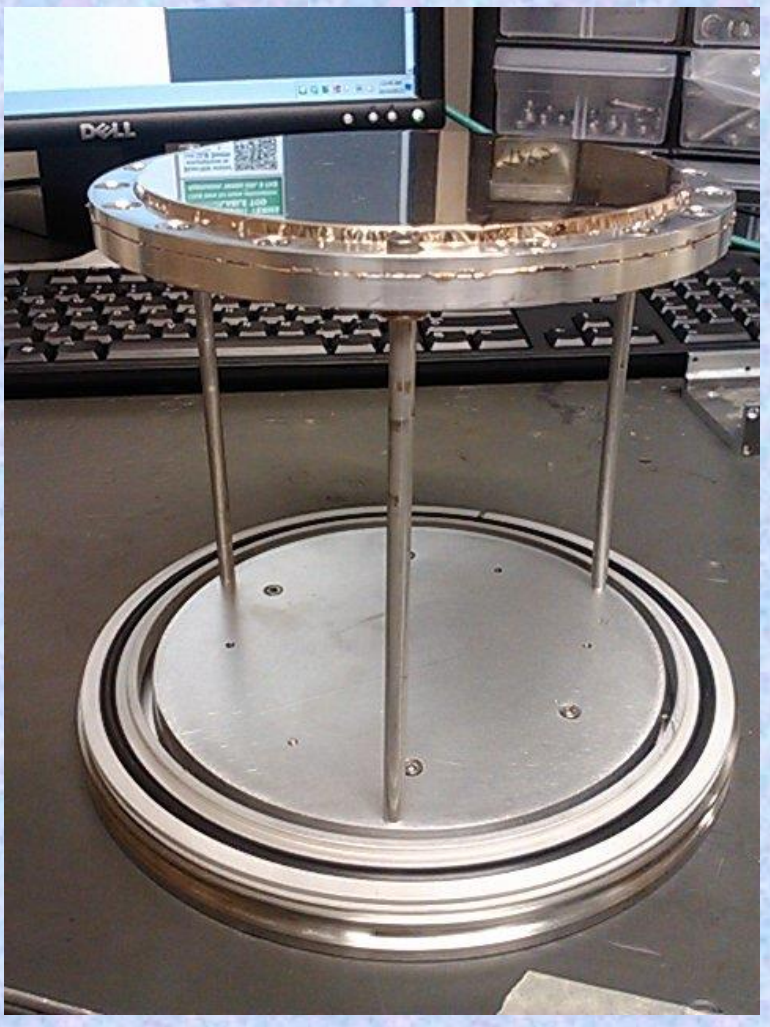


Electrostatic Membrane, AM, Pendulum



ESM Support Structure

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Credits/Sources

Special Thanks to CD Hoyle

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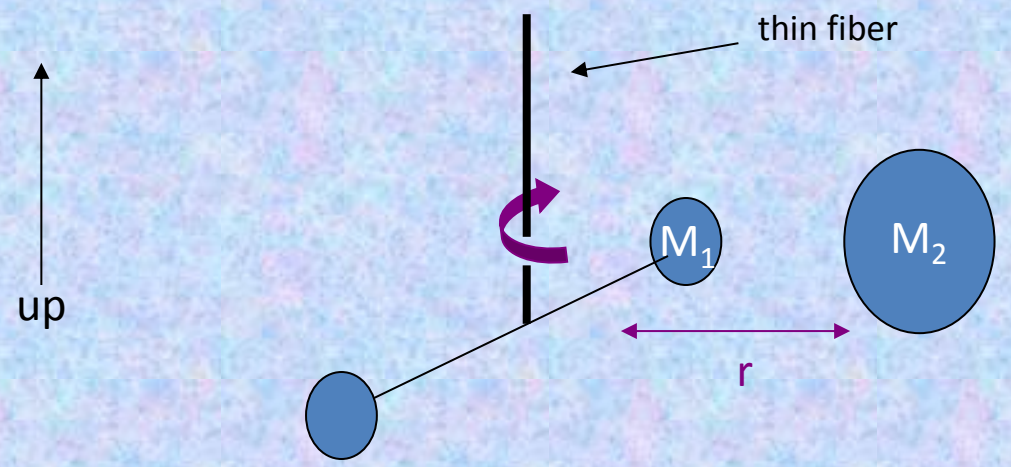
Torsion Pendulum



- Vary distance between M_1 and M_2
- Force on M_1 due to M_2 causes pendulum to twist
- Measure twist angle
- Compare with GR prediction
- Highly sensitive to Newtonian Torque

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Yukawa Force on High-Density Step is Approximated by

$$F_Y = 2\pi\alpha G\rho_1\rho_a A\lambda^2\left[1-e^{-t_1/\lambda}\right]\left[1-e^{-t_a/\lambda}\right]e^{-s/\lambda}$$

ρ_1 = Mass Density of Pendulum Step

ρ_a = Mass Density of Attractor Mass

t_1 = *Step Thickness*

t_a = *Attractor Mass Thickness*

A = Area of Pendulum Step

s = Separation Distance, Pendulum Step and Attractor Mass

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Short-Range Yukawa Torque on Entire Pendulum is Approximated by

$$N_Y \approx \pi \alpha G \rho_a R A \left(\rho_1 - \rho_2 \right) \lambda^2 e^{-s/\lambda}$$

ρ_a = Mass Density of Attractor Mass
ρ_1 = Mass Density of Pendulum Step
ρ_2 = Mass Density of Lighter Step

R = Width of Step
A = Area of Pendulum Step
s = Separation Distance, Pendulum Step and Attractor Mass

Assumed Parameters:

λ very small

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