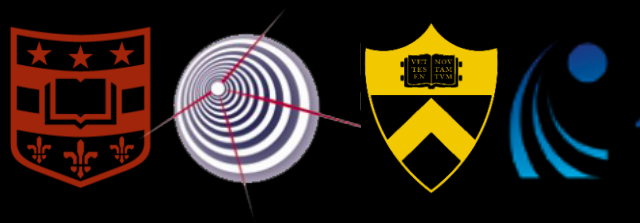


$G^{\epsilon\epsilon}$ Lab's Equivalence Principle Experiment

Kasey Wagoner: kwagoner@princeton.edu

R. Cowsik, D. Huth, M. Jeyakumar, M Abercrombie,
A. Archibald, T. Madziwa-Nussinov, N. Krishnan

Equivalence Principles

Weak Equivalence Principle

all bodies fall equally in a gravitational field

Einstein's Equivalence Principle

all *non-gravitational* laws of physics should take on their SR form in a FF reference frame

Strong Equivalence Principle

all laws of physics should take on their SR form in a FF reference frame

Exciting time for EP Tests

Torsion Balances

Atomic Interferometers

Antimatter

Lunar Laser Ranging

Satellites

Astrophysics

Why do we care?

Pillar of General Relativity

Unification?

GR is Foundation of ΛCDM

- Dark Energy = ???
- H_0 measurement tension

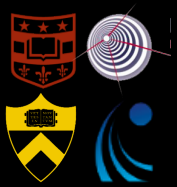
Characterizing EP Violation

New fields have potential energy characterized as

$$V(r) = \frac{G m_1 m_2}{r}\left(1 + \alpha_{12} e^{-r/\lambda}\right)$$

EP tests quantified through Eötvös parameter

$$\eta_{1,2} = 2\frac{a_1 - a_2}{a_1 + a_2} = 2\frac{\left(m_g/m_i\right)_1 - \left(m_g/m_i\right)_2}{\left(m_g/m_i\right)_1 + \left(m_g/m_i\right)_2}$$



$\eta_{(t)}$

Eötvös [1919]	$\eta < 4\times10^{-9}$
Princeton [1964]	$\eta = [1.3 \pm 1.0]\times10^{-11}$
Eöt-Wash [2012]	$\eta = [-0.7 \pm 1.3]\times10^{-13}$
Wuhan [2018]	$\eta = [-1.2 \pm 2.8_{\text{stat}} \pm 3.0_{\text{syst}}]\times10^{-13}$
MicroSCOPE [2017]	$\eta = [-1 \pm 9_{\text{stat}} \pm 9_{\text{syst}}]\times10^{-15}$
$G^{\epsilon\epsilon}$ Lab [goal]	$\eta\sim5\times10^{-14}$

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G^{ee} Lab

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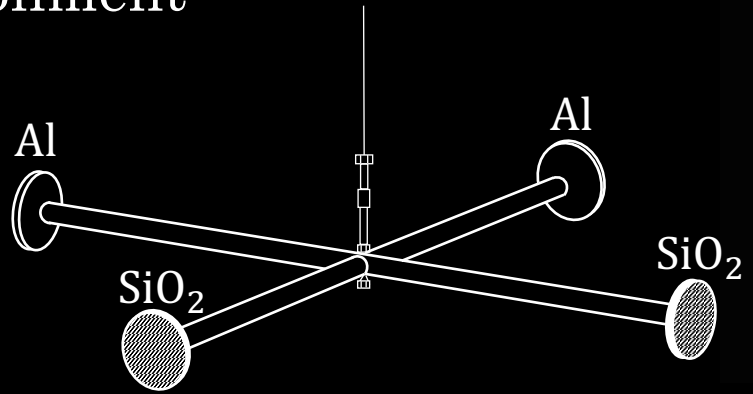
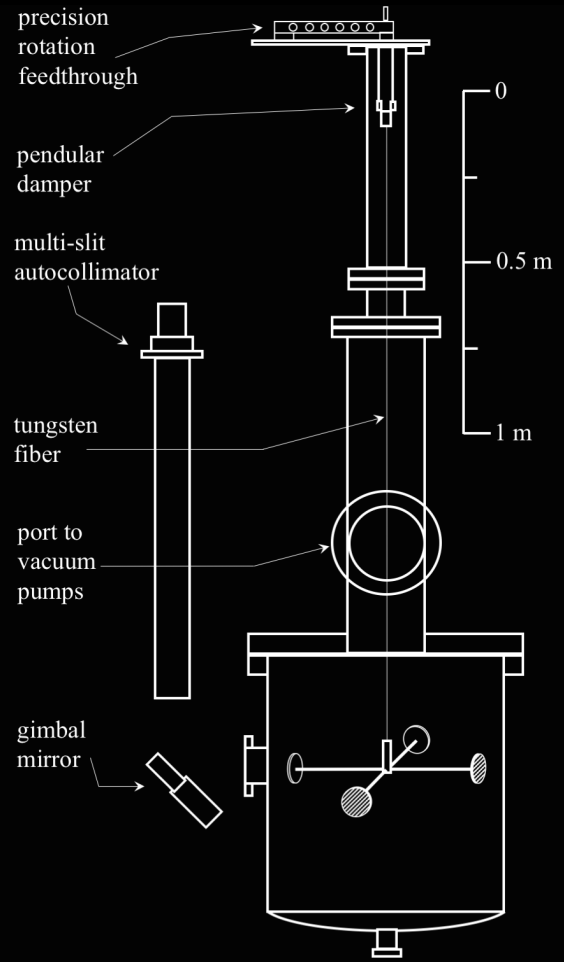
$G^{\epsilon\epsilon}$ Lab's Instrument

Dicke-Braginsky torsion balance

Angular orientation monitored by autocollimating optical lever

Passively isolated from environment





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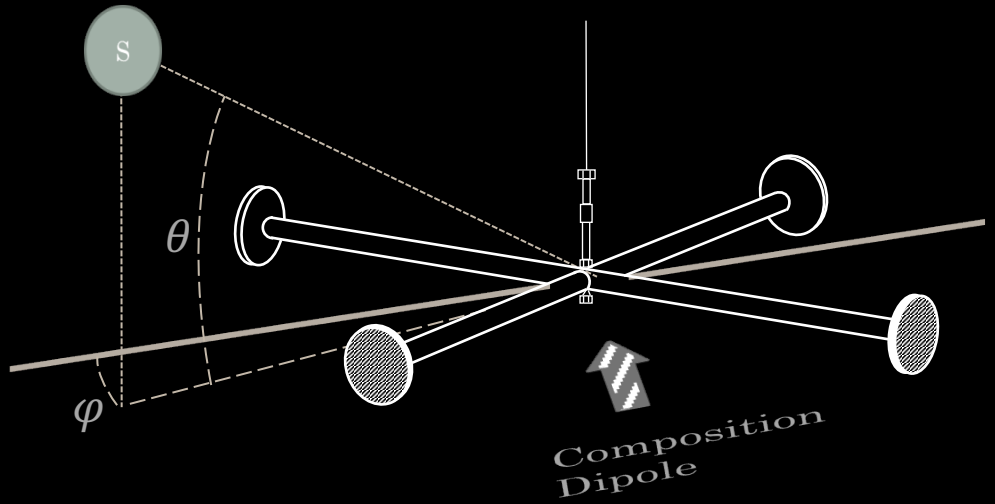
The signal



$$\tau(t) = \left[\left(\frac{m_g}{m_i}\right)_1 - \left(\frac{m_g}{m_i}\right)_2 \right] \frac{G M_S}{R^2} r \cos\theta_{(t)} \cos\varphi_{(t)}$$

Our Home

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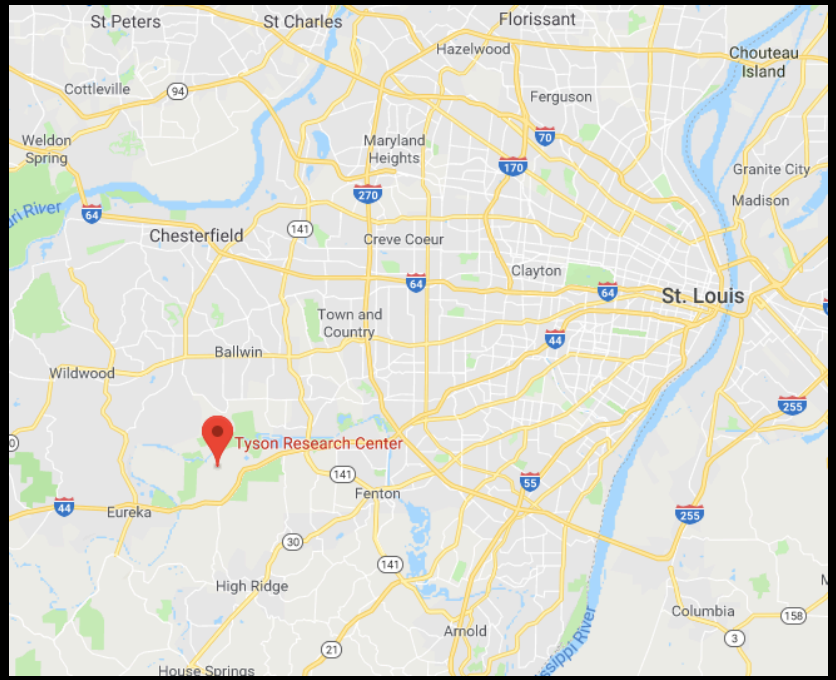
10/20

Our Home



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Our Home

Tyson Research Center

- protected area outside St. Louis, MO, USA
- low auto and foot traffic

Ammunition bunker

- thick concrete walls
- partially buried in hillside

Remotely operated

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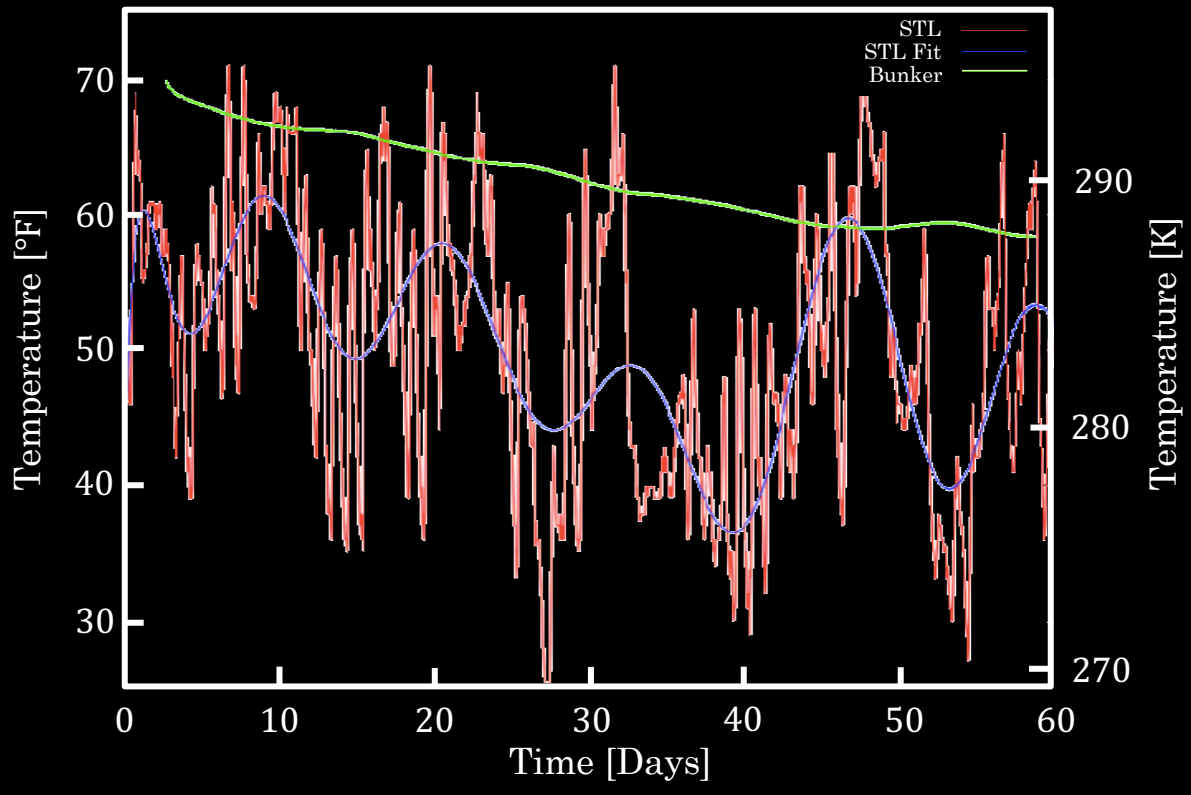
Temperature Variations



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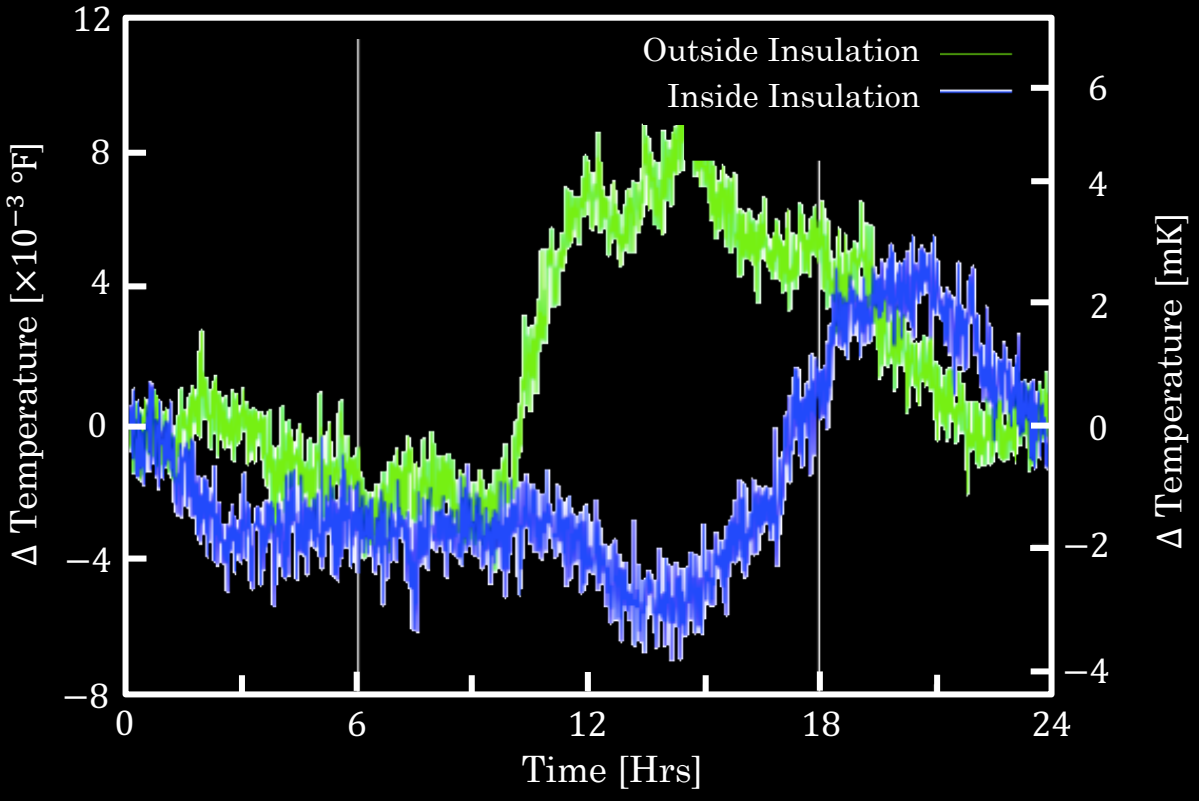
Daily Temperature Variations



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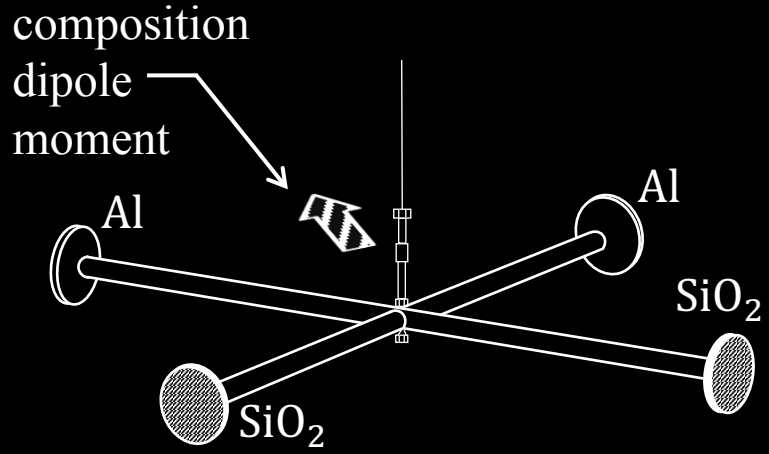
Long-Period Torsion Balance

Al and SiO_2 masses create a compositional dipole with four-fold azimuthal symmetry

75% of total mass couples to EP-violating forces

SiO_2 masses are mirrored for observation



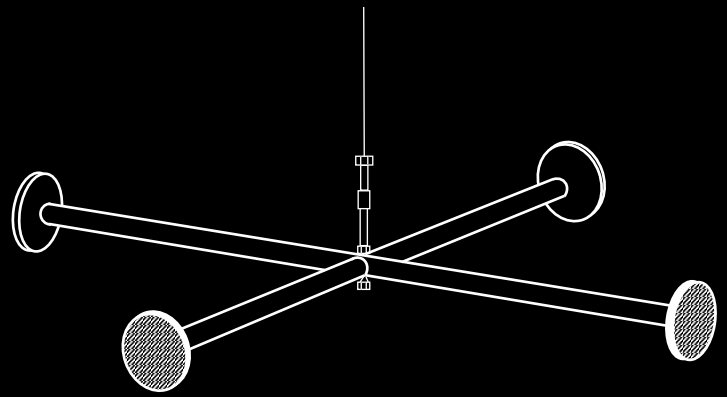
Long-Period Torsion Balance

4-fold mass symmetry, each $m = 14.33$ g

$$I = 3.75 \times 10^{-3}\ \mathrm{kg\,m^2}$$

Suspended from $\emptyset = 18\ \mu$m tungsten fiber

Long period, $T \approx 3.5$ hrs



Long-Period Torsion Balance

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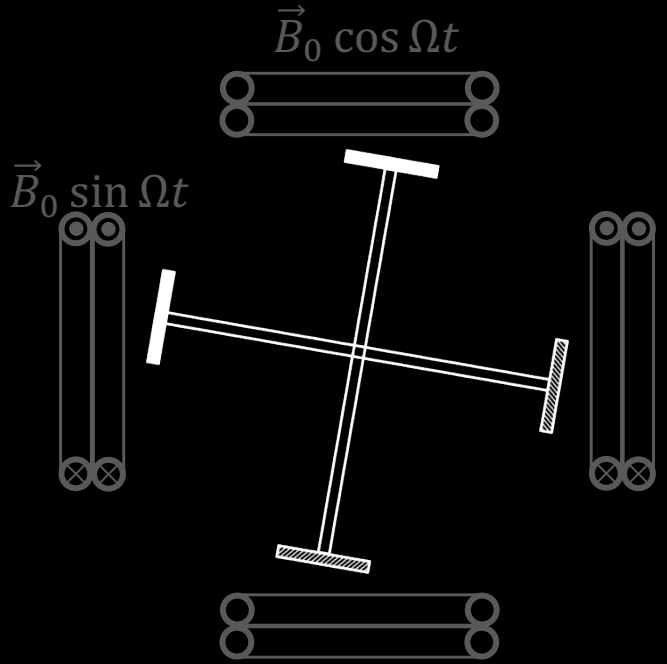
Magnetic Induction Control System

Two sets of Helmholtz coils 90° out of phase

- $\vec{B}$ field induces magnetic dipole, $\vec{\mu}_{ind}$
- Torque aligns $\vec{\mu}_{ind}$ with $\vec{B}$
- Rotating $\vec{B}$ rotates torque

Remote control of electronics allows control of balance



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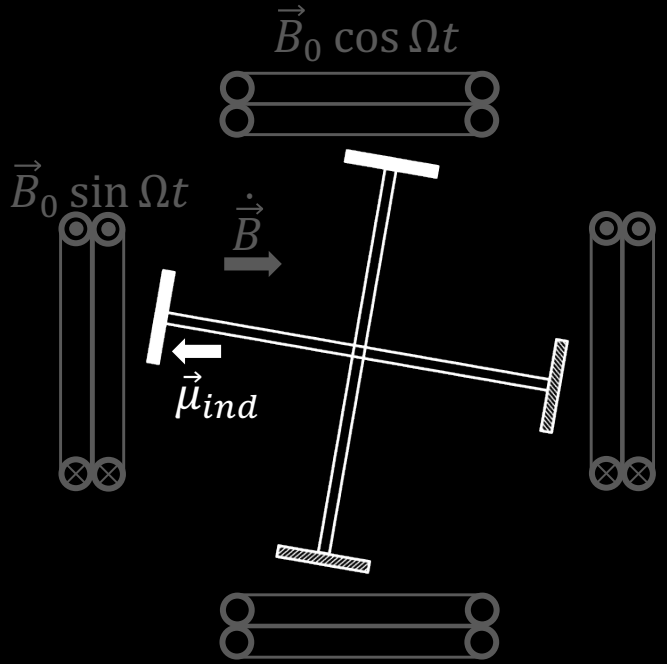

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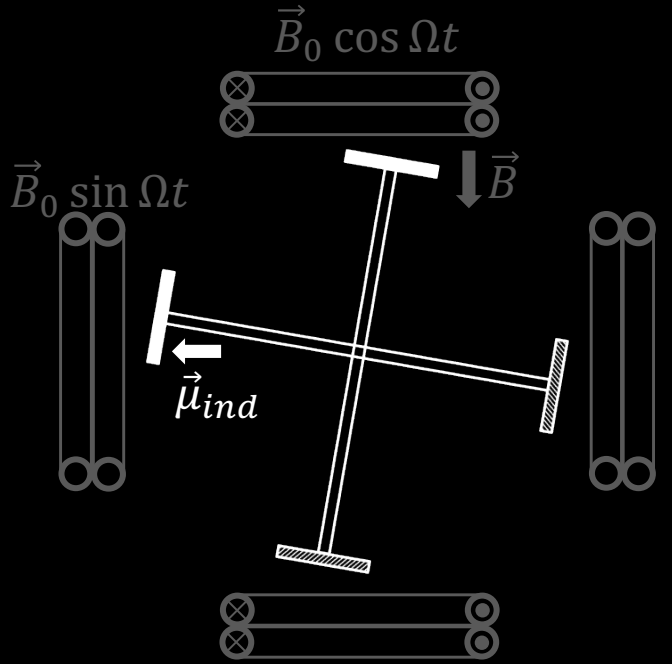

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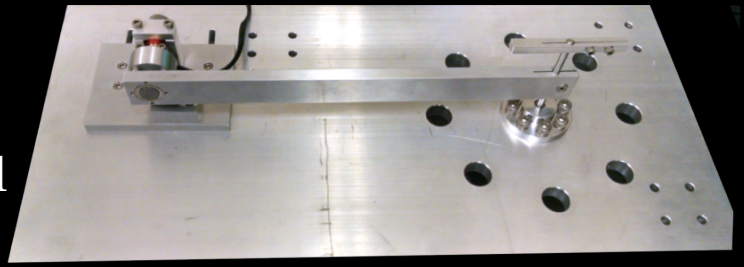
Fiber Connections

Rotary Feedthrough

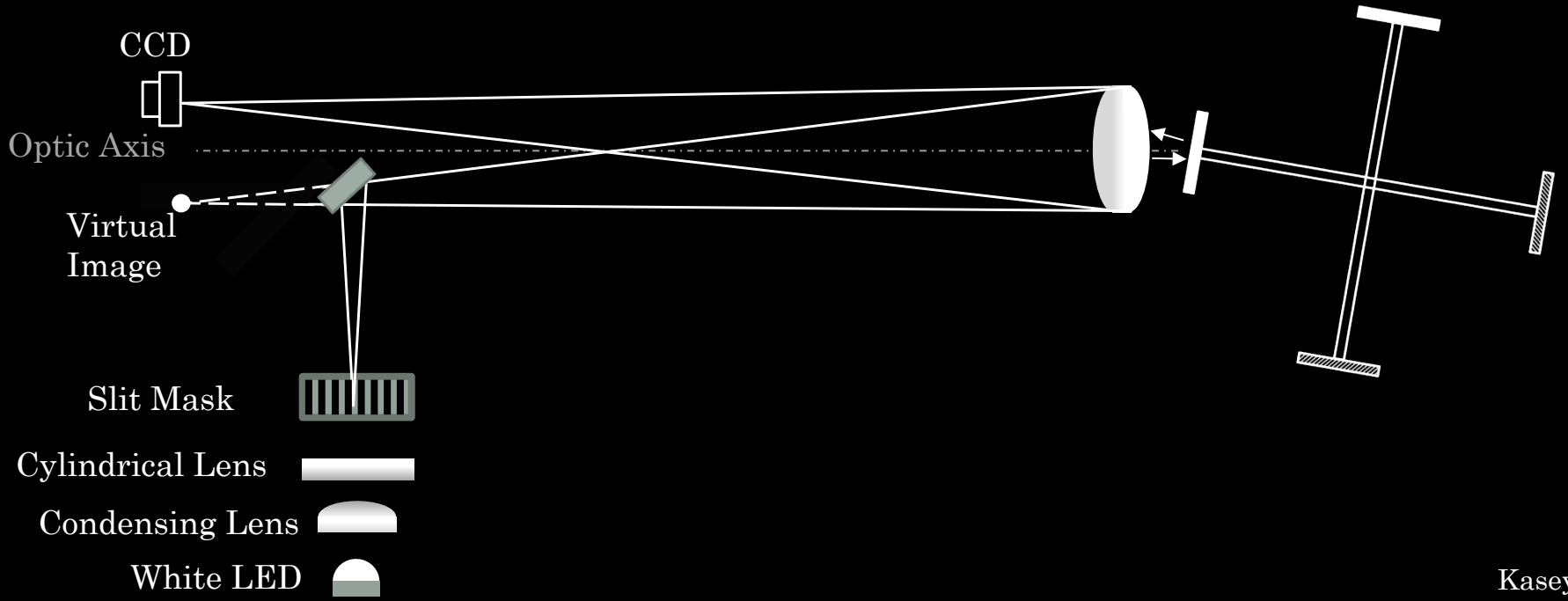
allows for active damping on site or remotely through a computer controlled picomotor



Pendular Damper

passive damping of pendular motion through the dissipation of eddy currents

Autcollimating Optical Lever



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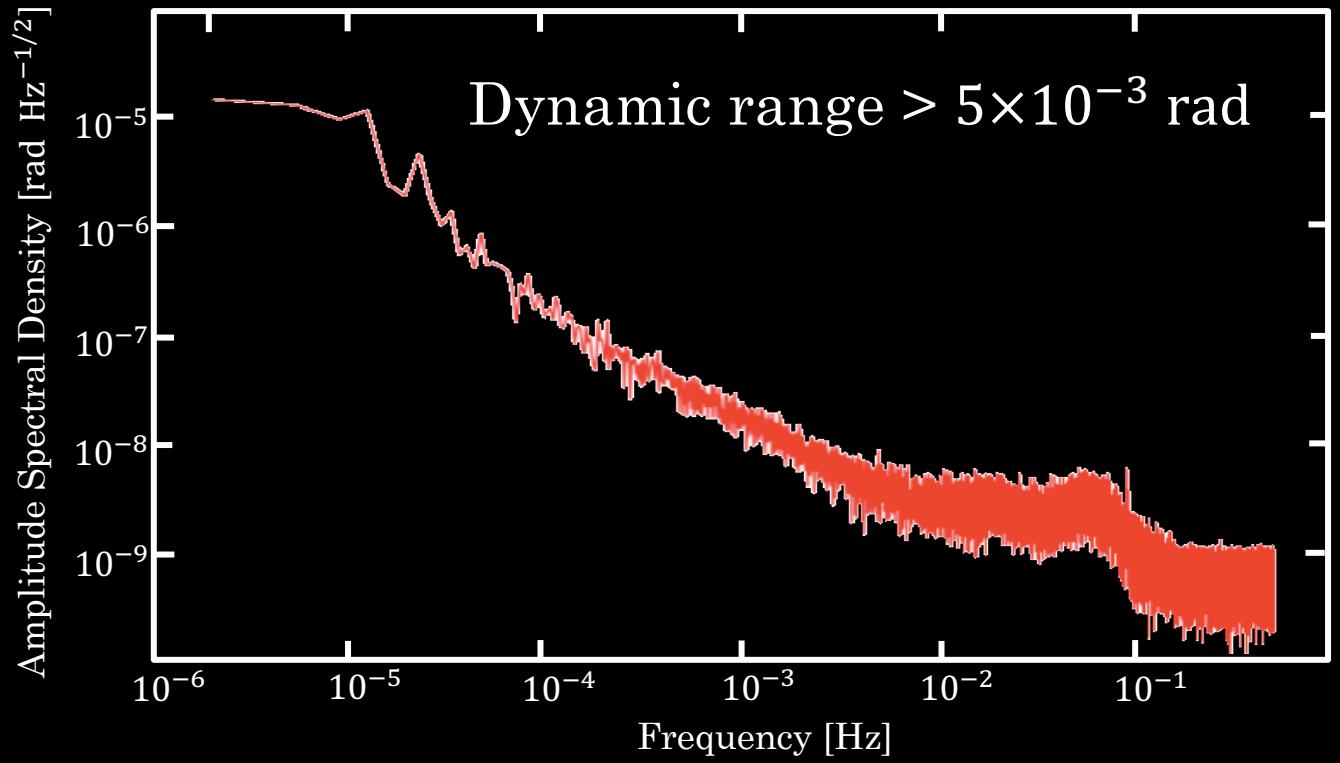
Optical Lever Response



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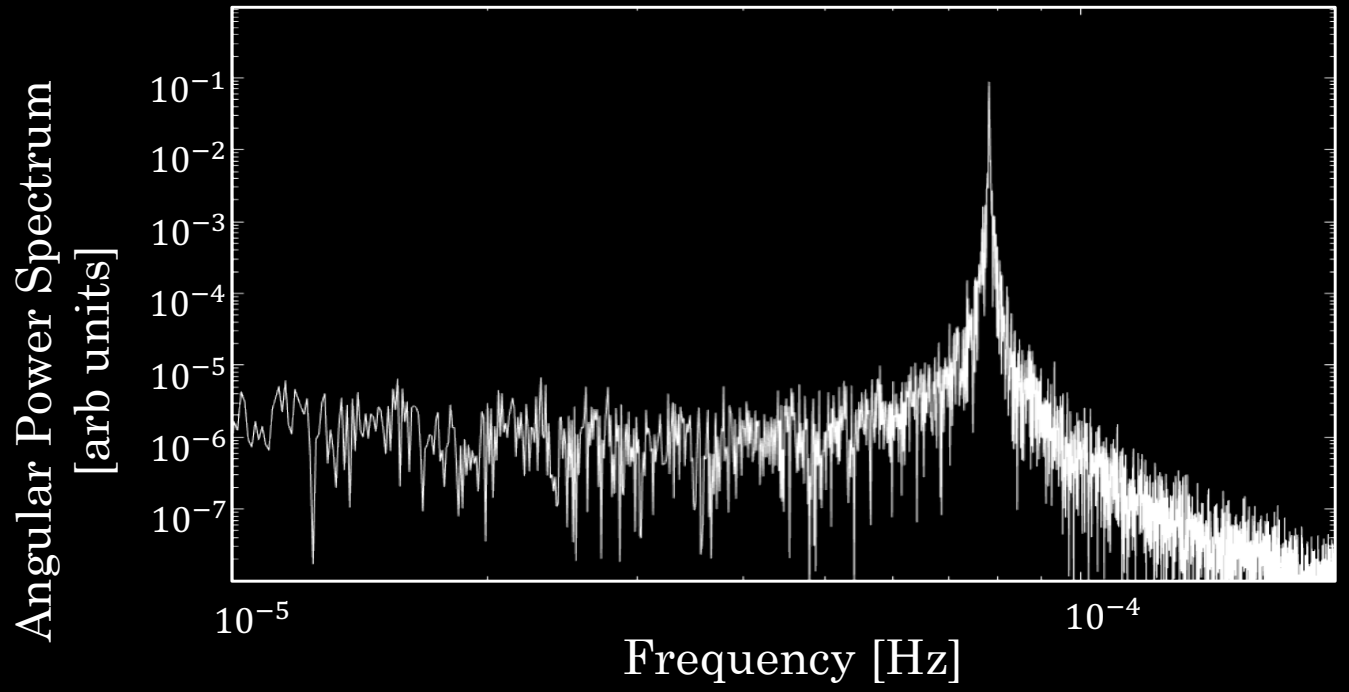
The Data

Fully integrated, remote controlled instrument

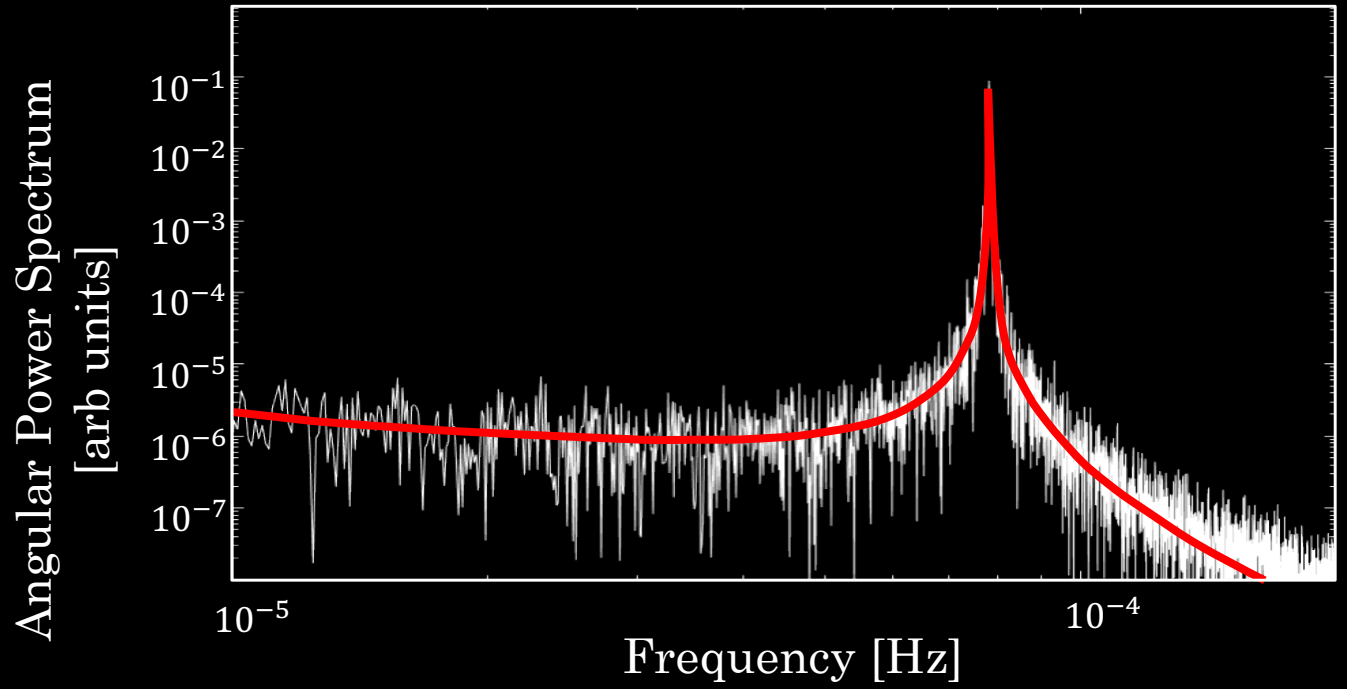
115 days of uninterrupted data

- Start: 00:00:00, 19/01/2018
- End: 06:58:19, 14/05/2018

The Data


Angular Power Spectrum
[arb units]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-5}
10^{-4}
Frequency [Hz]

The Data



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Lessons Learned for Future

Improve pendular damper

Improve thermal isolation

Improve magnetic shielding

Improve environmental monitoring

Improve robustness of induction control system

Summary

Eötvös's legacy lives on in this exciting time

torsion balances still have a lot to say!

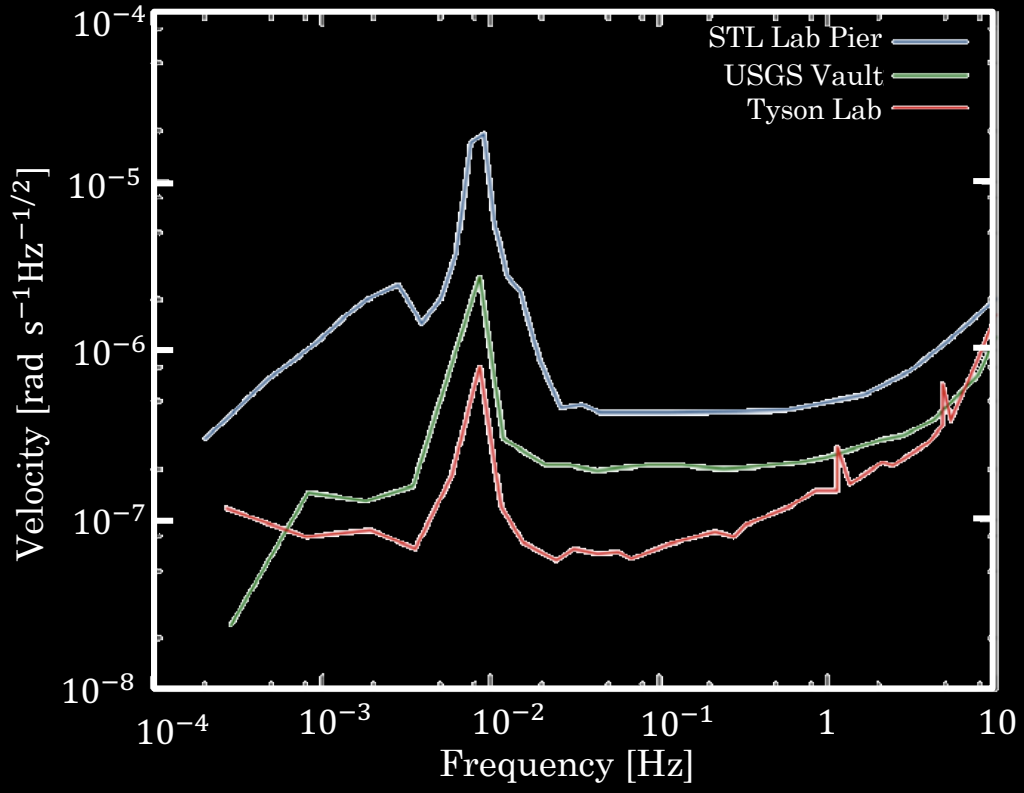
Long-period torsion balances are promising instruments

$G^{\epsilon\epsilon}$ Lab's experiment is off and running.

Washington University in St. Louis
McDonnell Center for the Space Sciences
Princeton University
Tata Institute for Fundamental Research

Backup

Seismic Background



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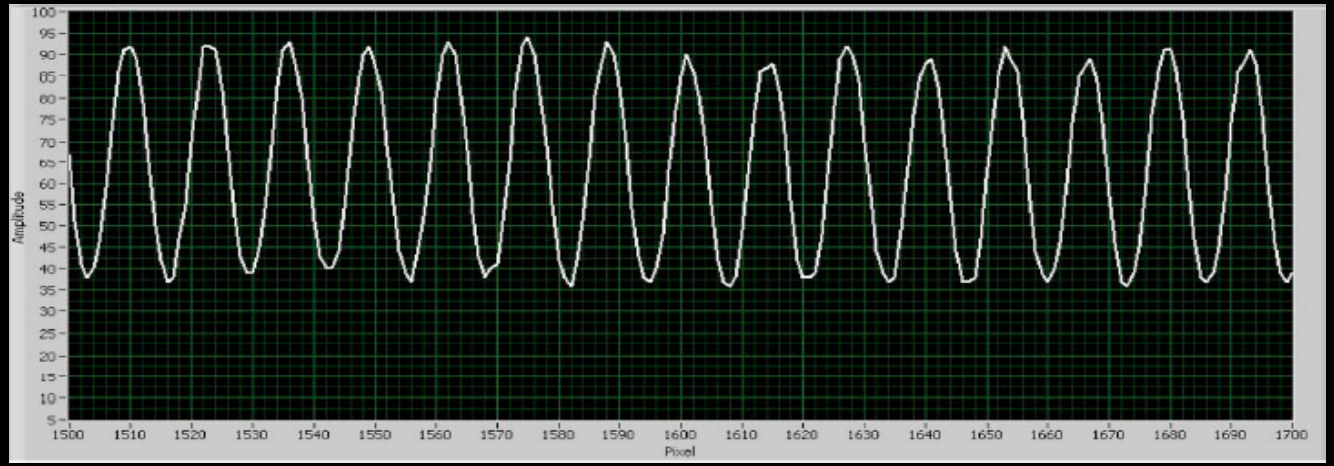
backup

Autcollimating Optical Lever



Dynamic range > 5×10^{-3} rad

Resolution ≈ 3×10^{-10} rad/Hz$^{-1/2}$ above 0.1 Hz

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backup