Title: Fundamental physics with low-frequency mechanical oscillators

Date: Aug 25, 2017 02:00 PM

URL: http://pirsa.org/17080038

Abstract:

I’d like to thank the organizers for inviting me to hear about all the beautiful and sophisticated modern approaches to experimental physics. In fact, I’m embarrassed to talk about a very old technique (torsion balances) with a long (and mostly glorious) history of being used by famous people to address important issues :

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Cavendish 1797 -- Newton's constant

Eőtvős 1922 -- equivalence principle

Einstein & de Haas 1915 – g factor of the electron

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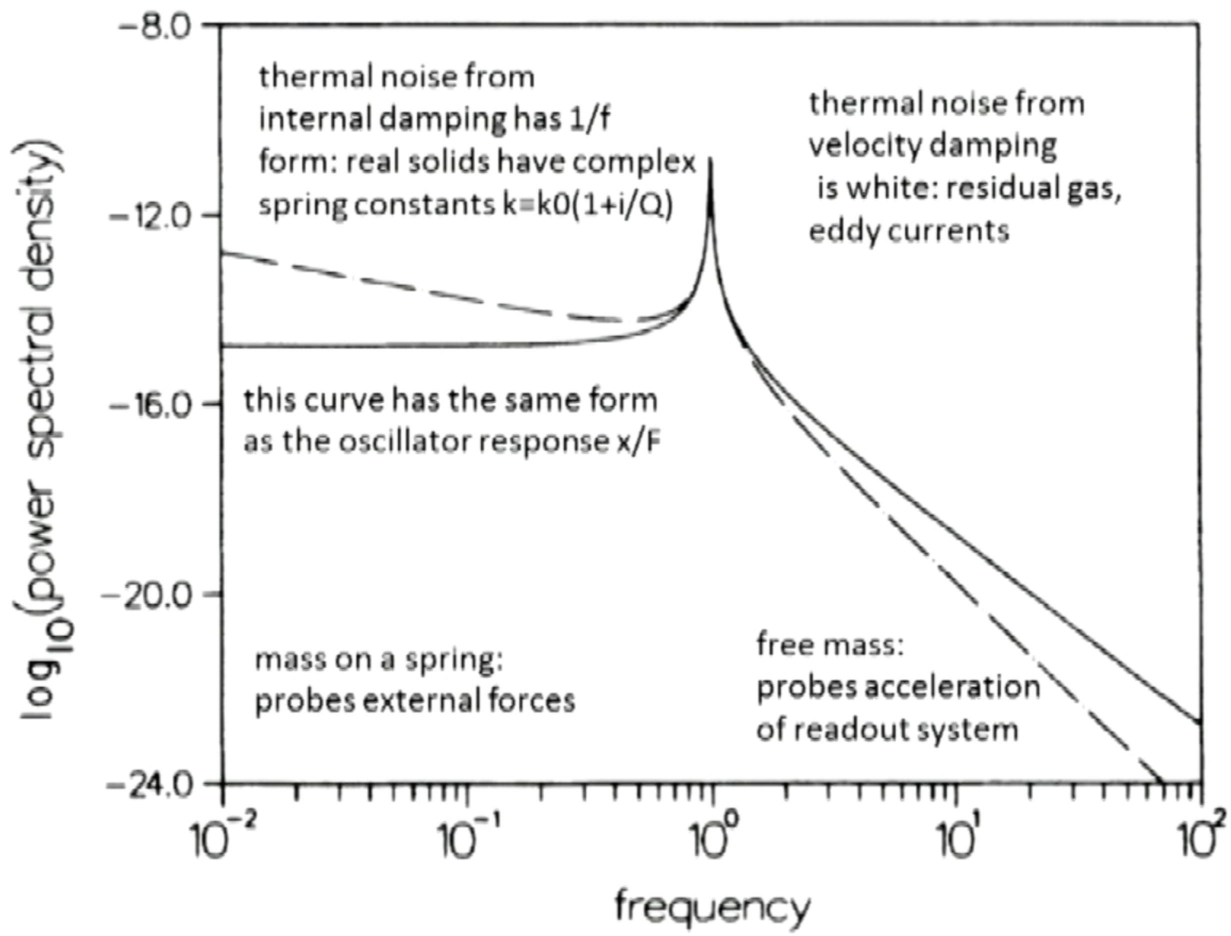
Fundamental physics with low-frequency mechanical oscillators

E. G. Adelberger
University of Washington

will discuss experimental principles, results, limiting factors and realistic prospects for improvements:

- equivalence-principle tests
- ~~short-range inverse-square law-tests~~
- pseudo-Goldstone bosons and new global symmetries
- ultralow-mass bosonic dark matter
- absolute rotation sensors

Elementary properties of an oscillator



Some consequences:

Putting signal at the free resonance only helps if you do not have the displacement sensitivity to see the actual displacement. If the displacement sensitivity is good enough it is better to run off resonance. Best S/N often occurs far enough above resonance until readout noise is comparable to the thermal noise and technical noise from acceleration of the readout system.

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Historical lesson from gravitational experiments:

They are seldom limited by fundamental considerations typically shown in plots of how well they are expected to do.

Gravity is weak compared to EM so it's hard to eliminate fake effects. Short-distance gravity is especially hard because as test bodies get smaller their surface (EM) /volume(gravity) ratio gets worse.

Earth's gravity is complicated:
- not uniform: gradients
- time-varying: tides, weather, seismic activity, "cultural influences", etc.

Building a highly symmetrical apparatus is a very good idea

the Eöt-Wash® group

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Current and recent grad students
- Michael Ross
- John Lee
- Erik Shaw
- Will Terrano

Staff scientist
- Erik Swanson

Sabbatical Visitor
- Andy Kim

Postdocs
- Krishna Venkateswara (LIGO)
- Charlie Hagedorn

Current undergrad
- Carson Blinn

EP
1/r2
spin
technology

Primary support from NSF Gravitational Physics

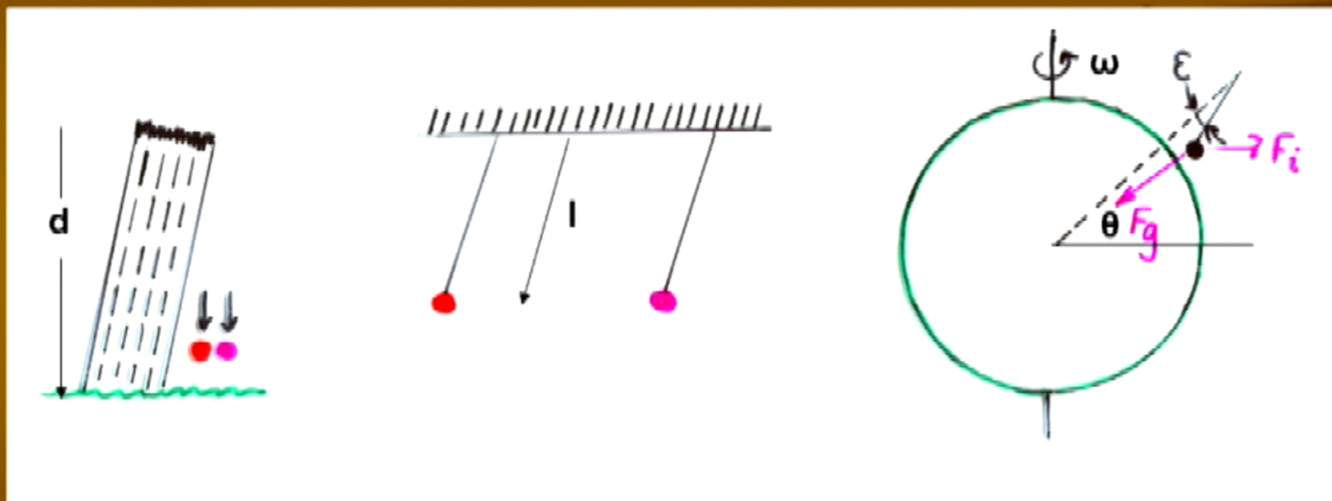
two ways to test gravity:

1) watch things fall down (Galileo)
    a) obvious
    b) long history
    c) revived with new technology: atoms,space

2) watch things fall sideways (Eötvös)
    a) not so obvious
    b) currently provides the most sensitive tests but Microscope satellite will have higher precision

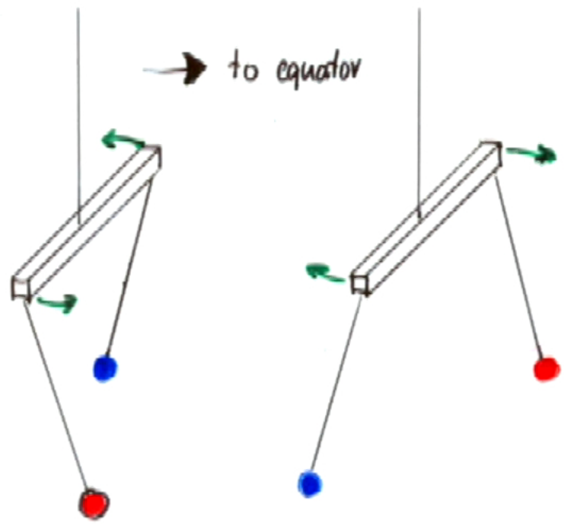
a brief history of weak Equivalence Principle tests: do all materials have the same m^i/m^g?

Galileo test | Newton-Bessel test | Eötvös test



Galileo test	Newton-Bessel test	Eötvös test
are fall times equal?	are periods equal?	are angles equal?
$T=\sqrt{(2d/g\ (m^i/m^g))}$	$T=2\pi\sqrt{(l/g\ (m^i/m^g))}$	$\varepsilon=\omega^2 R \sin 2\theta/(2g)\ (m^i/m^g)$
$\Delta a/a \sim 0.1$	$\Delta a/a \sim 10^{-4}$	$\Delta a/a \sim 10^{-9}$

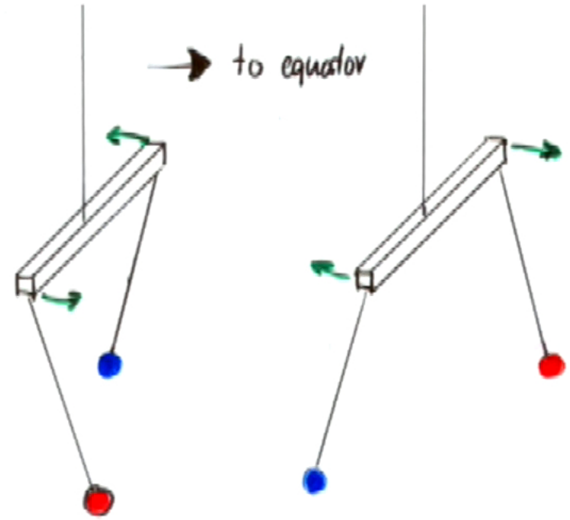
Testing the WEP by watching things fall sideways



$$\frac{m_i}{m_g} > \frac{m_i}{m_g}$$

beam only twists if force vectors are not parallel
i.e. if down is not a unique direction
occurs if EP is violated or if gravity field is not uniform

Testing the WEP by watching things fall sideways



$$\frac{m_i}{m_g} > \frac{m_i}{m_g}$$

beam only twists if force vectors are not parallel
i.e. if down is not a unique direction
occurs if EP is violated or if gravity field is not uniform

brief history of WEP tests in the 20th century:

1910-20's   Eötvös
watched things falling in
earth's field and turned balance manually

1950-60's   Dicke and later Bragisky
watched things falling toward sun and let
earth's rotation turn their instruments

1980's onward   Eöt-Wash
watched things fall in fields of earth, sun, galaxy
and in the rest frame defined by the CMB
using balances on high-performance turntables

Eötvös's instrument for comparing sideways acceleration of things falling towards the center of the earth

Eötvös first tested the EP in 1889. His most famous work was done between 1904 and 1909

Eötvös et al studied a range of materials and claimed $\Delta a/a < 5\times10^{-9}$

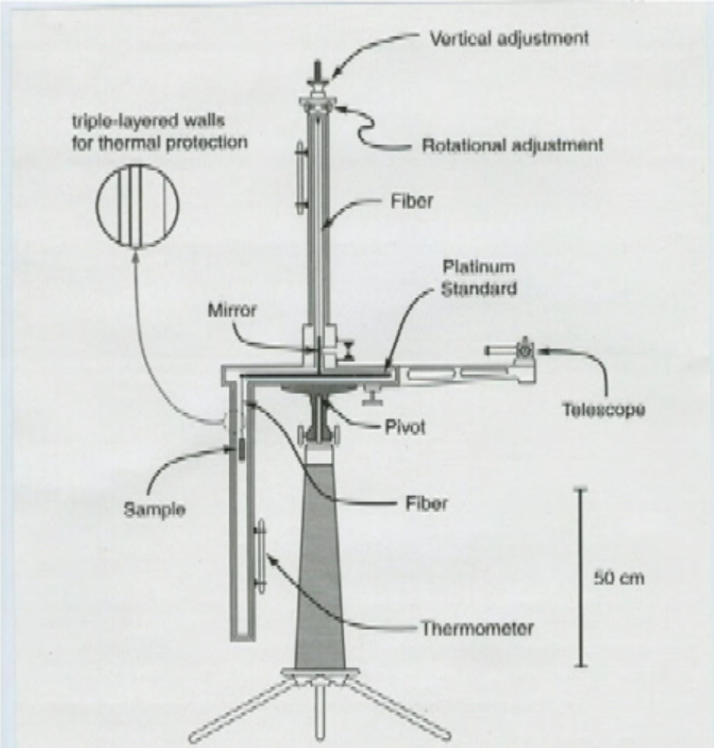
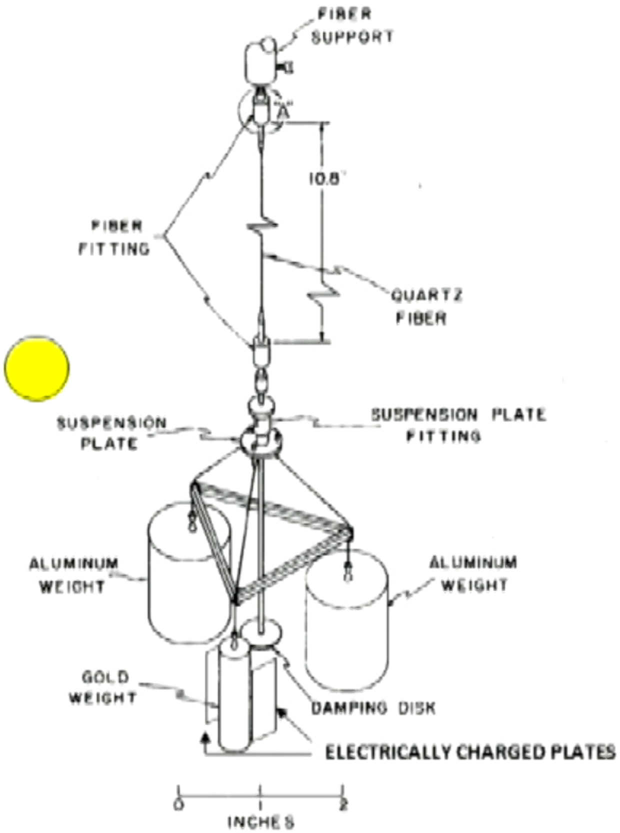


Figure 4.6: Single-arm torsion balance used by Eötvös, Pekár, and Fekete.

Note: this instrument was originally a gravity gradiometer

Roll, Krotkov and Dicke's instrument
for watching things fall toward the sun



Roll, Krotkov and Dicke,
Ann. Phys. 26, 442 (1964)

1 sigma result $\Delta a/a=(1.0\pm1.5)\times10^{-11}$
only 280 times more precise than Eotvos
Dicke was surprised and expressed concern
about effects of temperature variations
and the gravity field of Eötvös himself

two ways to think about WEP tests:

classical (Newtonian) way:

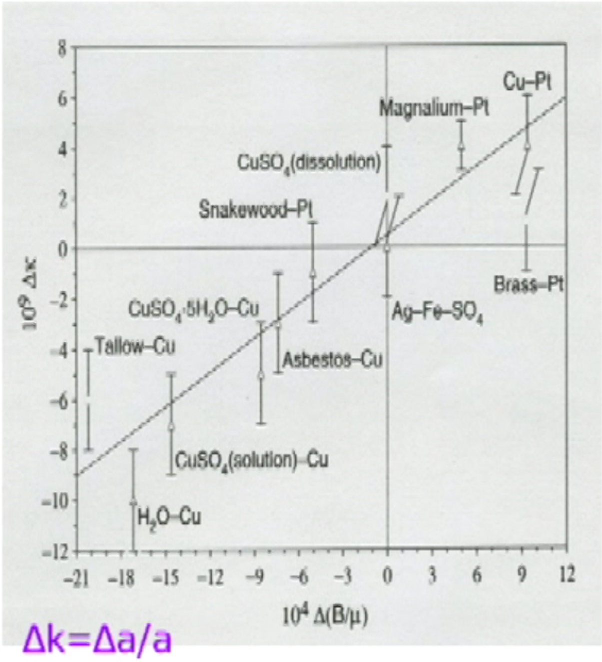
is $m_g = m_i$ exact?

new way (popularized by E. Fischbach):

a broad-gauge way to search for ultra-feeble long-range quantum-exchange forces that may lie hidden underneath "normal" gravity

The modern era in EP tests was ushered in by Fischbach's reanalysis of Eötvös's results

Fischbach at el., PRL 56, 3 (1986)



$\Delta k = \Delta a / a$

This reanalysis along with measurements of gravity in mines was taken as evidence for a "5th force"

$$V_{12}(r) \propto B_1 B_2 \frac{1}{r} e^{-r/\lambda}$$

where
B = # of neutrons + protons (the baryon number)
and the force range λ was between 30m and 1000m

because λ is much less than distance to the sun this force could not have been seen in the classic experiments

Parameterizing EP-violating effects of quantum vector exchange forces

gravity couples to mass

$$V_{\rm G}(r) = G_{\rm N}\frac{m_1\,m_2}{r}$$

quantum exchange forces couple to "charges"

$$V_{\rm OBE}(r) = \mp\frac{\tilde{g}^2}{4\pi}\frac{\tilde{q}_1\tilde{q}_2}{r}\exp(-r/\lambda)$$

$$V_{1,2} = V_{\rm G} + V_{\rm OBE} = V_{\rm G}(r)\left(1 + \tilde{\alpha}\left[\frac{\tilde{q}}{\mu}\right]_1\left[\frac{\tilde{q}}{\mu}\right]_2\exp(-r/\lambda)\right) \ .$$

vector "charge" of electrically neutral objects

$$[\tilde{q}/\mu] = [Z/\mu]\cos\tilde{\psi} + [N/\mu]\sin\tilde{\psi} \quad \text{with} \quad \tan\tilde{\psi} \equiv \frac{\tilde{q}_n}{\tilde{q}_e + \tilde{q}_p} \ .$$

Suppose we have no preconceptions about the nature of EP violation and want unbiased tests:

this requires:

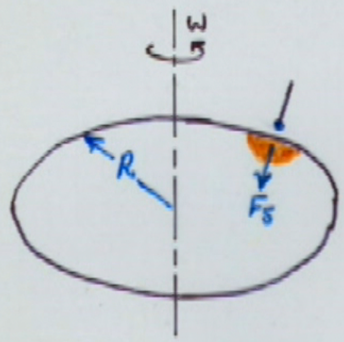
•sensitivity to wide range of possible charges
vector charge/mass ratio of any composition
monopole or dipole vanishes for some value of ψ.

need 2 test body pairs and 2 attractors
to avoid possible accidental cancellations

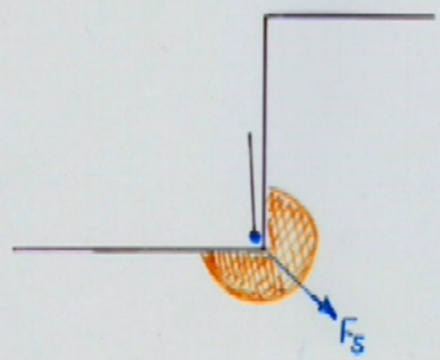
•sensitivity to wide range of length scales

need earth (not sun) as attractor
and a site with interesting topography

to have reasonable sensitivity for $\lambda \ll R_{earth}$
put instrument in lab excavated from hillside



smooth earth gives no sensitivity for $\lambda \ll R$



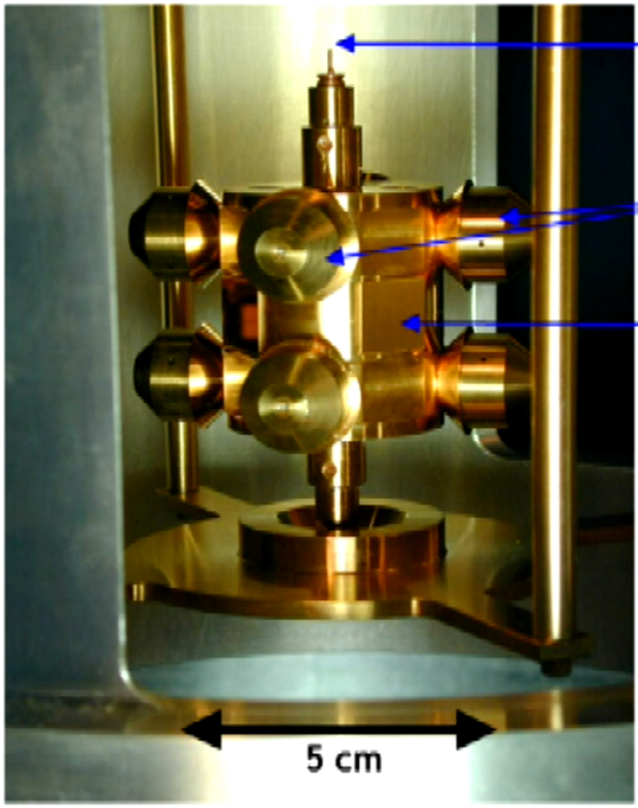
big cliff gives high sensitivity to short ranges

This Grand Canyon site has excellent topology but poor experimental conditions.

We put our instrument on the UW campus in a lab carved out of a hillside beside a deep lake.

torsion pendulum of the recent WEP test

T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)



20 μm diameter, 1 m long tungsten fiber

eight 4.84 g test bodies (4 Be & 4 Ti) or (4 Be & 4 Al)

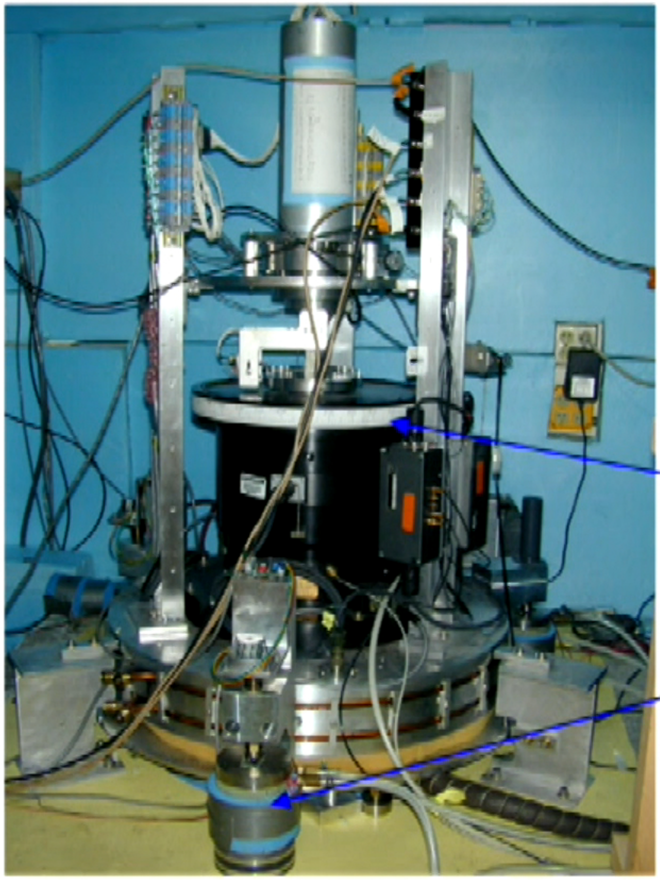
4 mirrors for measuring pendulum twist

symmetrical design suppresses false effects from gravity gradients, etc.

free osc freq:	1.261 mHz
quality factor:	4000
machining tolerance:	5 μm
total mass :	70 g

Pendulum twist is measured by a laser autocollimator system. The twists are really tiny: our twist angles are measured in nanoradians. A nanoradian is about 1/5 of a milliarcsecond.

Eöt-Wash torsion balance hangs from turntable that rotates with a ~ 20 min period



Advantage: signal is boosted from a period of 1 day (terrible) to much lower noise regions

Disadvantage: the turntable must be very good: constant rotation rate, rotation axis precisely vertical

air-bearing turntable with eddy-current motor

thermal expansion feet fedback to keep turntable rotation axis level

Examples of two kinds of systematic errors

suspension system tilt

fibers are not perfectly round; twist readout imperfections let horizontal movement of pendulum produce a small apparent twist

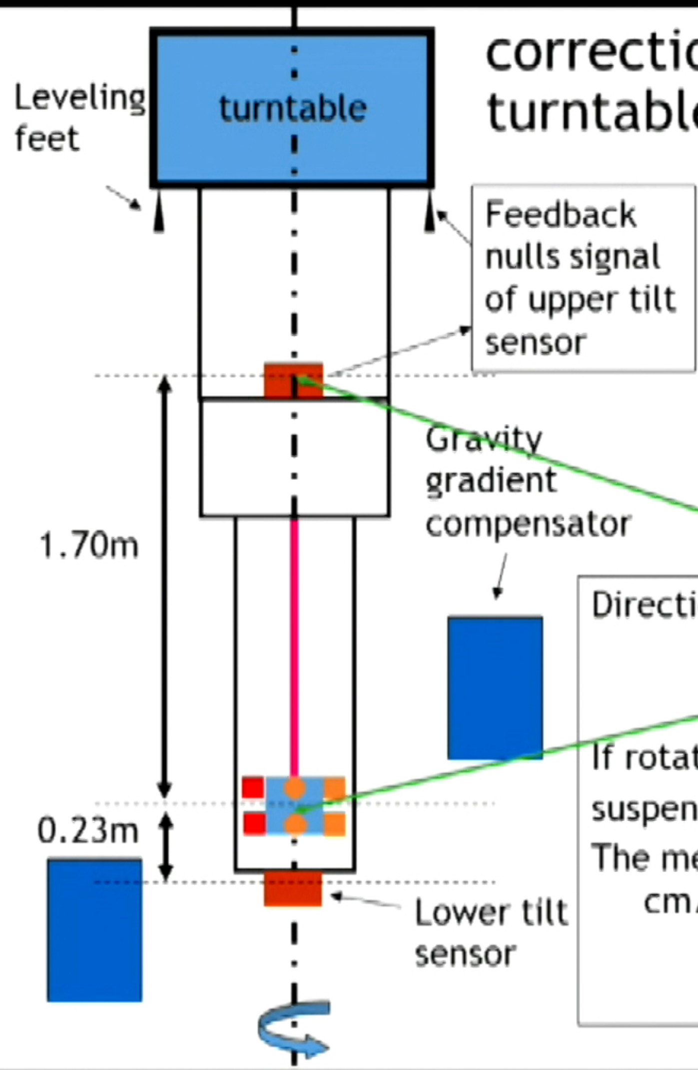
gravity gradients

particularly important because we chose to operate in a place with interesting topography

Our strategy for evaluating systematic errors:

1) continuously monitor the "driving terms"
2) in systematic checks deliberately exaggerate the "driving terms" and measure their effects on the twist signal
3) use these measured "feedthroughs" to find systematic effect and its uncertainty in the science data

correction for tilt of the turntable rotation axis



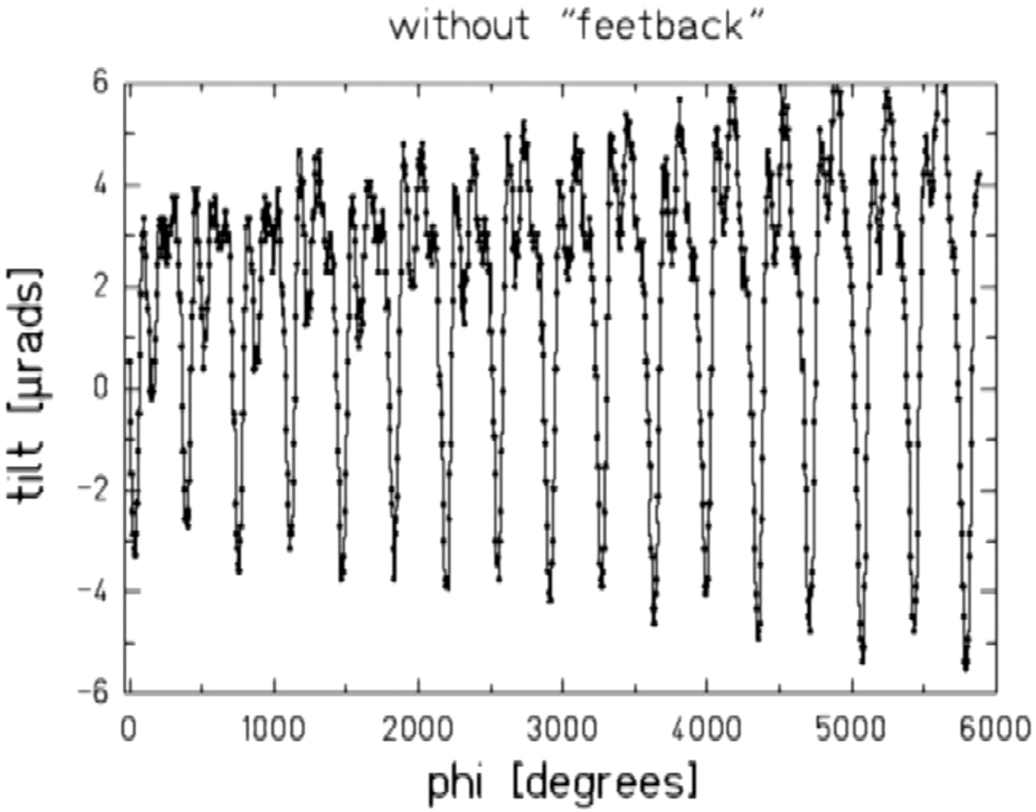
- Feedback removes tilt at upper tilt sensor
- However, local vertical varies with height
  - gives a spurious deflection of the pendulum due to residual tilt

Directions of down here and here differ by 50 nrad

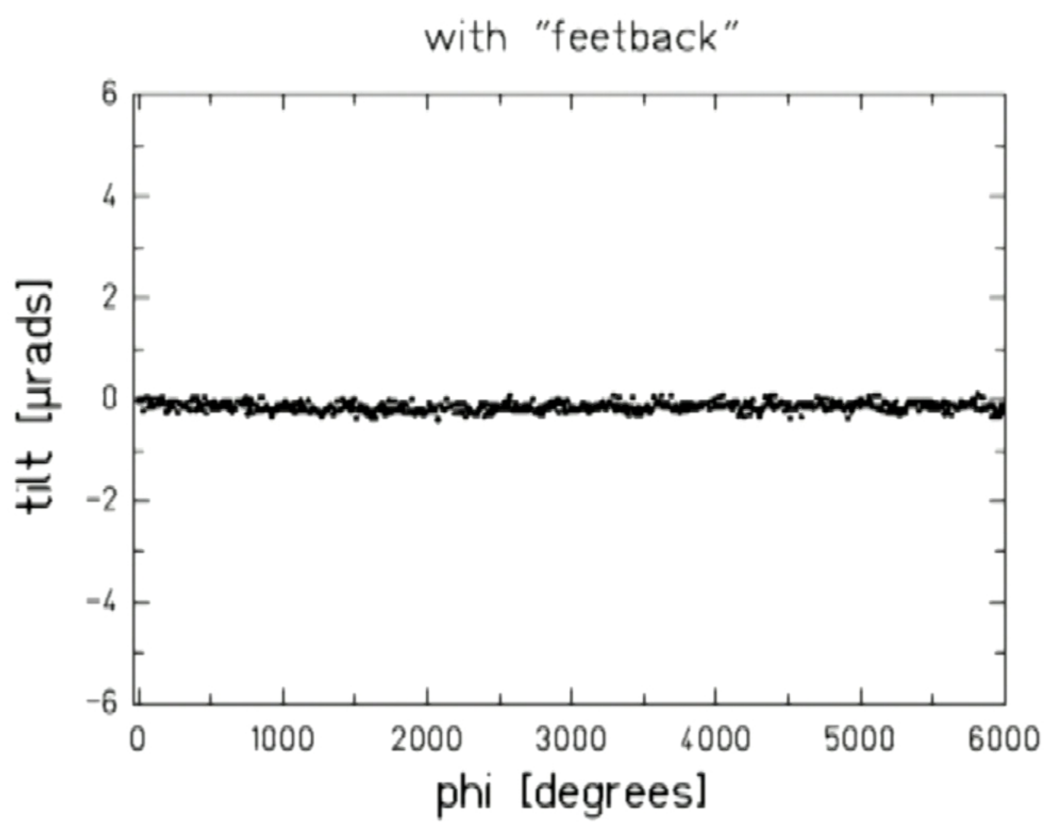
If rotation axis is down at the upper sensor, the suspension fiber experiences 50 nrad of "tilt".

The measured correction for this is 16×10^{-13} cm/s^2

The tilt of the lab floor drifts around by microradians



These data taken with an older ball-bearing turntable


with "feetback"
tilt [μrads]
6
4
2
0
-2
-4
-6
0
1000
2000
3000
4000
5000
6000
phi [degrees]

Analyze gravity gradient effects using spherical multipole formalism:
Gravitational torque on pendulum as a function of turntable rotation frequency

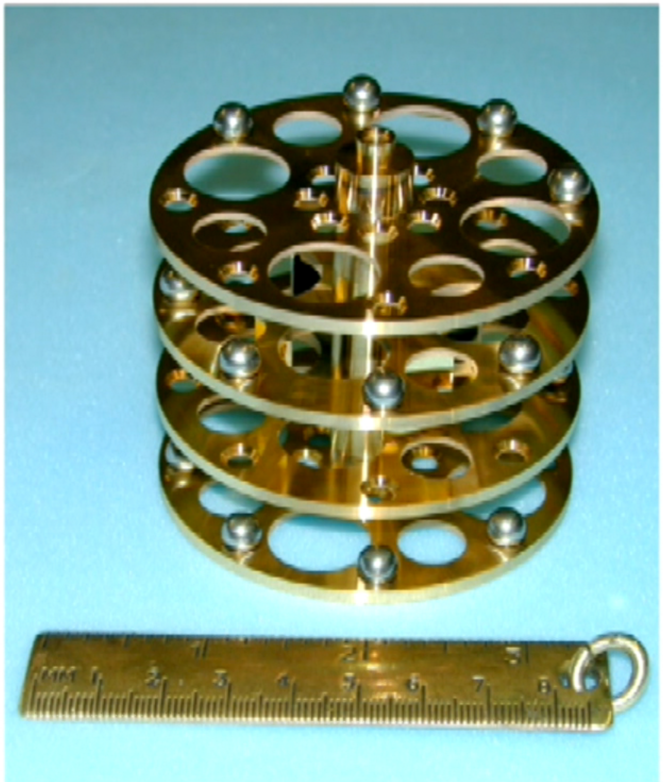
$$T_g = -\frac{\partial W}{\partial \phi} = -4\pi i G \sum_{l=0}^{\infty} \frac{1}{2l+1} \sum_{m=-l}^{+l} m \bar{q}_{lm} Q_{lm} \times e^{-im\omega t},$$

$$q_{lm} = \int \rho_p(\vec{r}) r^l Y^*_{lm}(\hat{r}) d^3 r$$ inner moments of pendulum

$$Q_{lm} = \int \rho_s(\vec{r}') r'^{-(l+1)} Y_{lm}(\hat{r}') d^3 r'$$ outer moments of environment

Pendulum "cocks" so that its CM is directly below the fiber attachment. This guarantees that its q_{1m} moments vanish and that the leading order gradient is q_{2m}; the q_{21} and q_{2-1} moments will mimic an EP-violation signal.

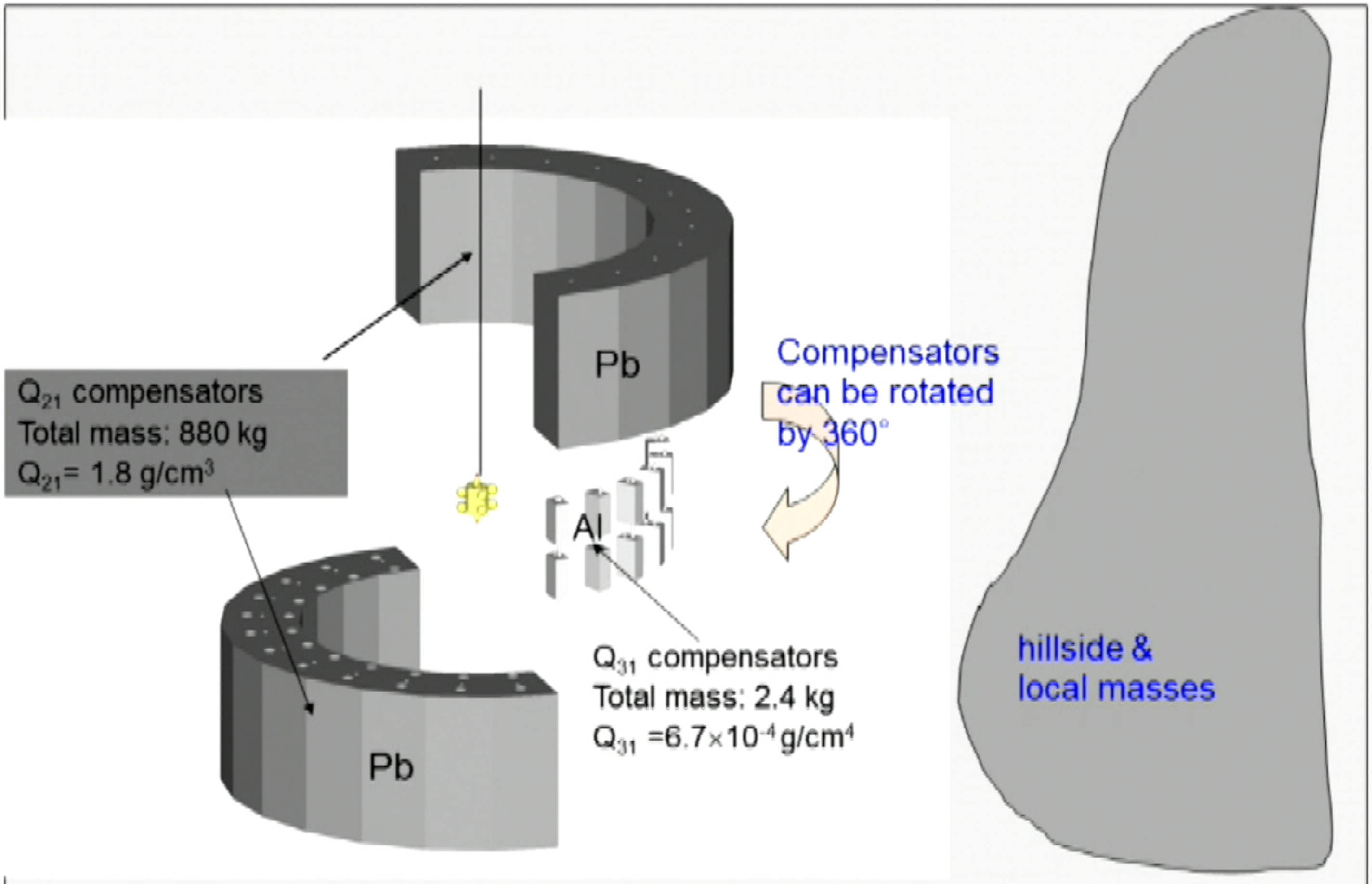
gravity-gradiometer pendulums



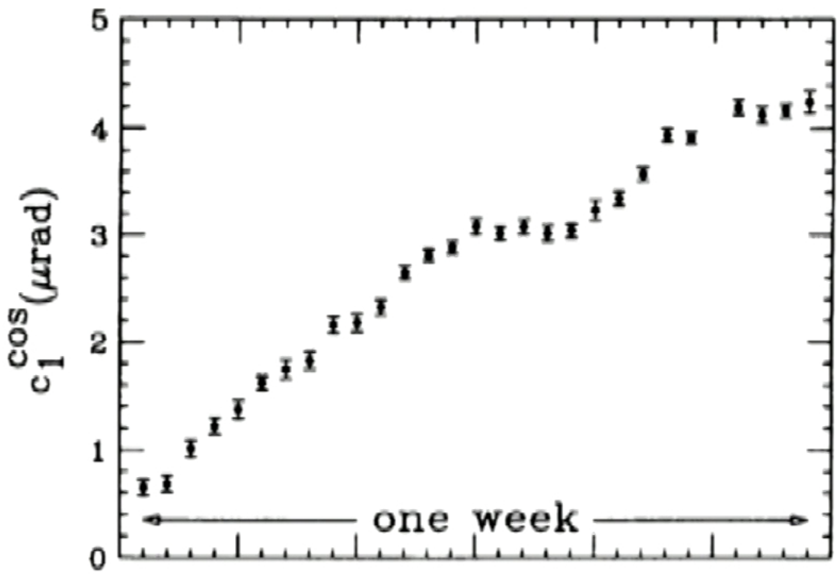
q_{41} configuration on a table

q_{21} configuration installed

gravity-gradient compensation

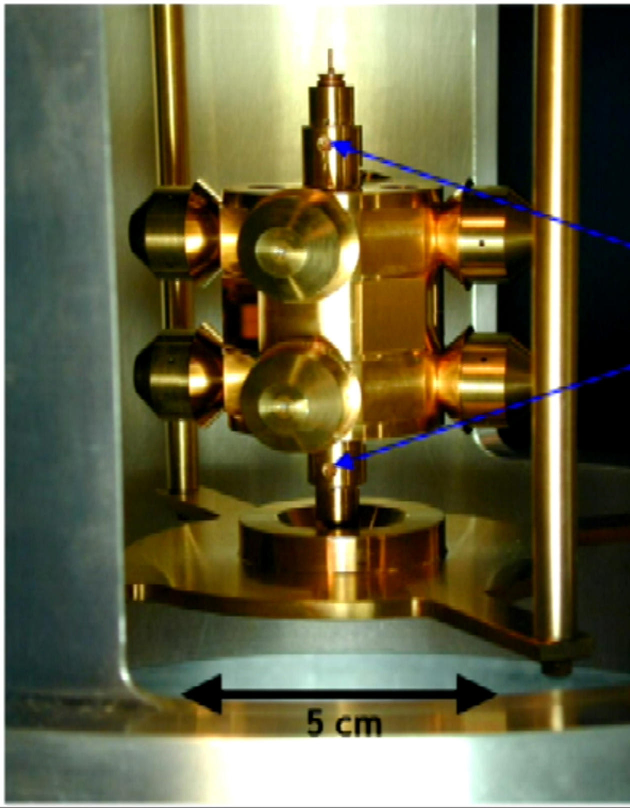


limitations on gradient cancellation



these data were taken in early November

We can’t stop the weather, but we can rotate the compensators by 180 degrees to make a large known gradient and then tune away the pendulum’s residual gravity moments

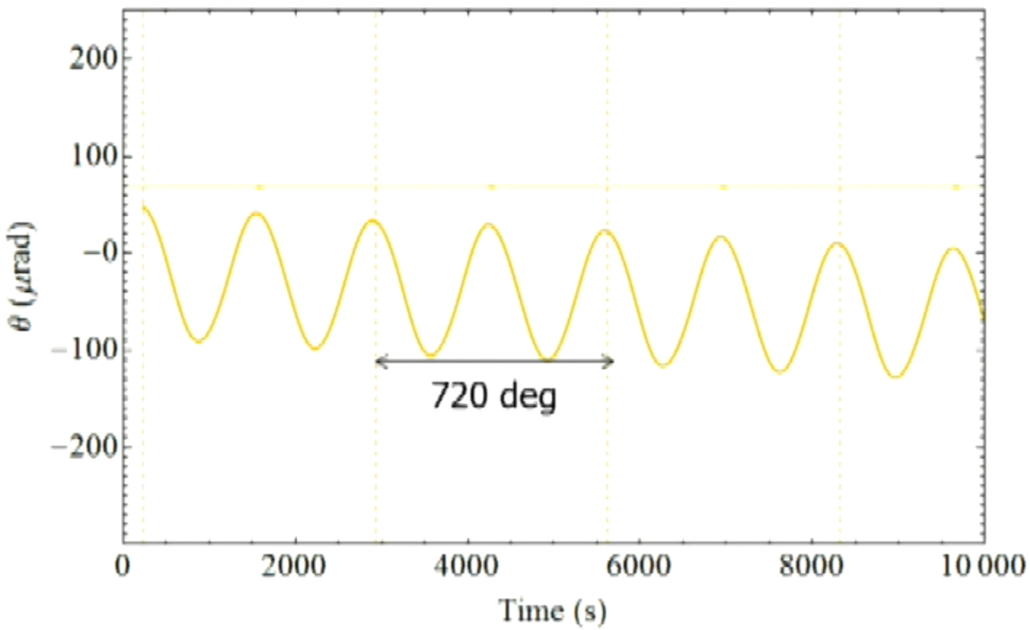


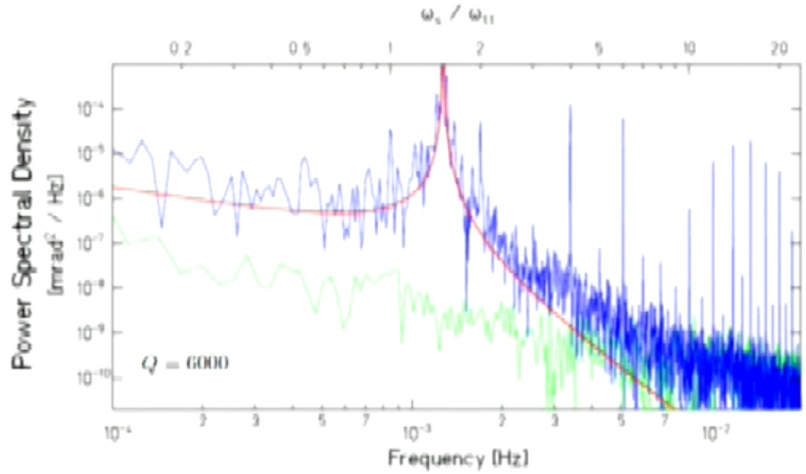
8 tiny screws used to minimize residual gravity moments

this requires a patient grad student with good hands

Twist data are cut into segments containing exactly 2 turntable revolutions. Segments are fitted with harmonic series in the turntable angle plus polynomial "drift". EP signal is at fundamental frequency. Repeat analysis resegmenting the data with starting points shifted by $\pi/2$, π, $3\,\pi/2$ and average the 4 results (removes effects of non orthogonality of polynomial and harmonic terms).

This example shows gravity-gradient data





daily reversal of pendulum orientation with respect to turntable rotor canceled turntable imperfections.

Test bodies were interchanged after data set 4 to cancel asymmetries in the pendulum body and suspension fiber. Each data point represents about 2 weeks of data

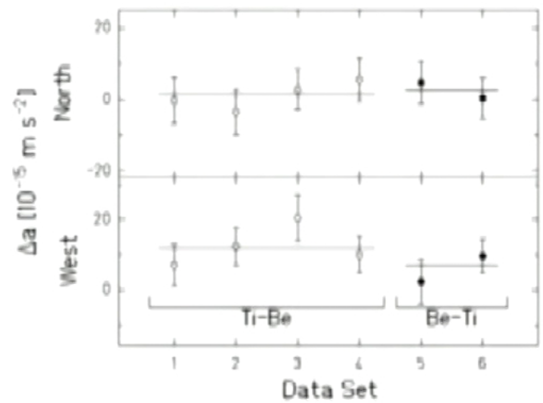


Figure 5. Data collected in the Ti-Be (first 4 runs) and Be-Ti (last 2 runs) configurations of the pendulum. The final result is in the difference between the means of the two configurations (shown as solid lines).

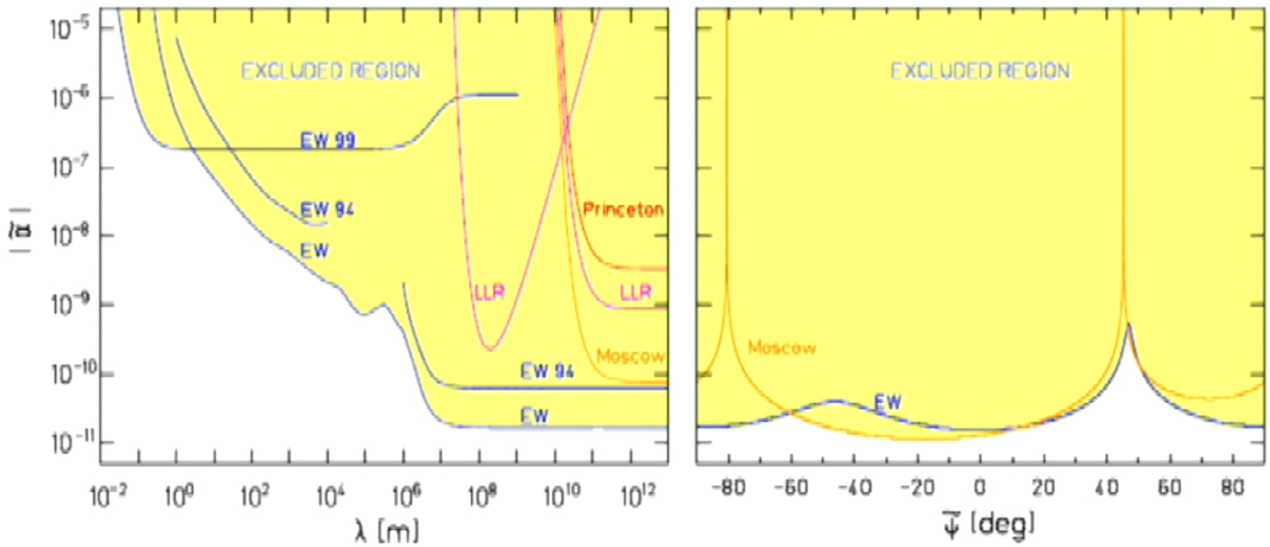
WEP results using the earth, the sun and the galaxy as attractors and their 1σ statistical + systematic uncertainties

		Be-Ti	Be-Al
Δa_{N}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	0.6 ± 3.1	-1.2 ± 2.2
Δa_{W}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.5 ± 3.5	0.2 ± 2.4
$\Delta a_{\odot}$	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-1.8 ± 2.8	-3.1 ± 2.4
Δa_{g}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.1 ± 3.1	-1.2 ± 2.6
$\eta_{\oplus}$	(10^{-13})	0.3 ± 1.8	-0.7 ± 1.3
$\eta_{\odot}$	(10^{-13})	-3.1 ± 4.7	-5.2 ± 4.0
η_{DM}	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

Table 2. Error budget for the lab-fixed Be-Ti differential accelerations. Corrections were applied for gravitational gradients and tilt, only upper limits were obtained on the magnetic and temperature effects. All uncertainties are 1 σ.

Uncertainty source	$\Delta a_{\mathrm{N,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$	$\Delta a_{\mathrm{W,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$
Statistical	3.3 ± 2.5	-2.4 ± 2.4
Gravity gradients	1.6 ± 0.2	0.3 ± 1.7
Tilt	1.2 ± 0.6	-0.2 ± 0.7
Magnetic	0 ± 0.3	0 ± 0.3
Temperature gradients	0 ± 1.7	0 ± 1.7

95% confidence level exclusion plot for interactions coupled to B-L



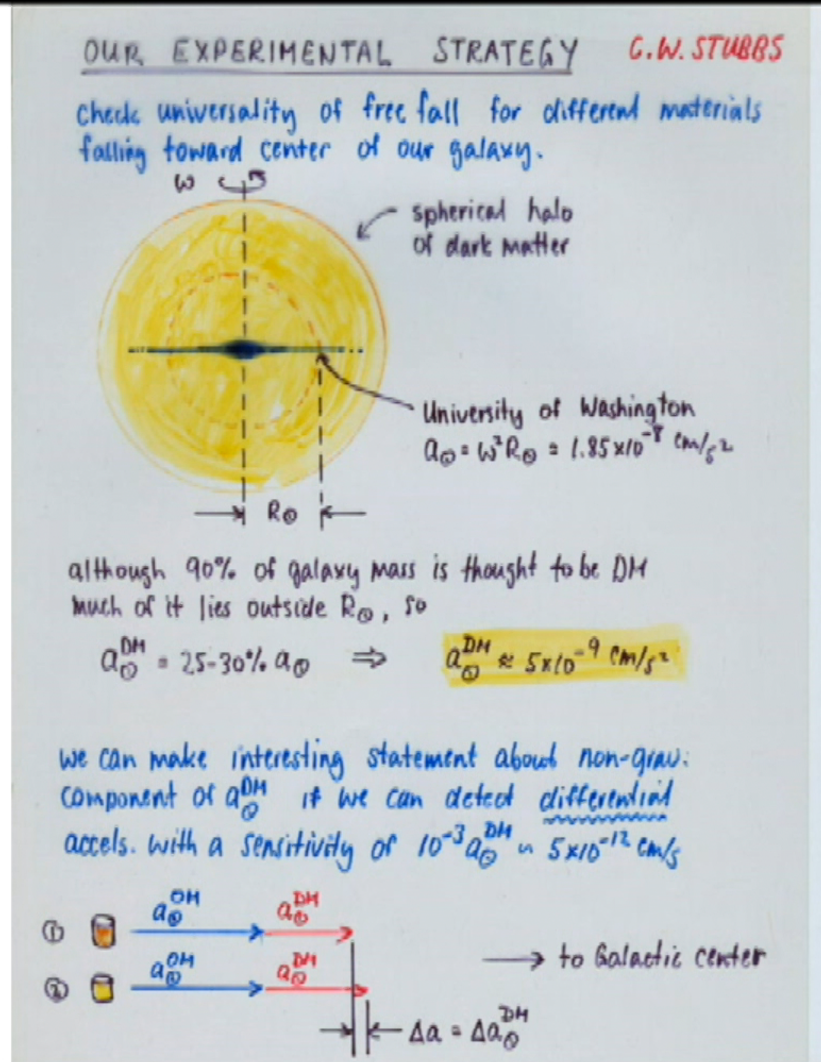
Yukawa attractor integral based on:

0.5m<λ<5m	lab building and its major contents
1m< λ<50km	topography
5km< λ<1000km	USGS subsurface density model
1000km< λ<10000km	PREM earth model

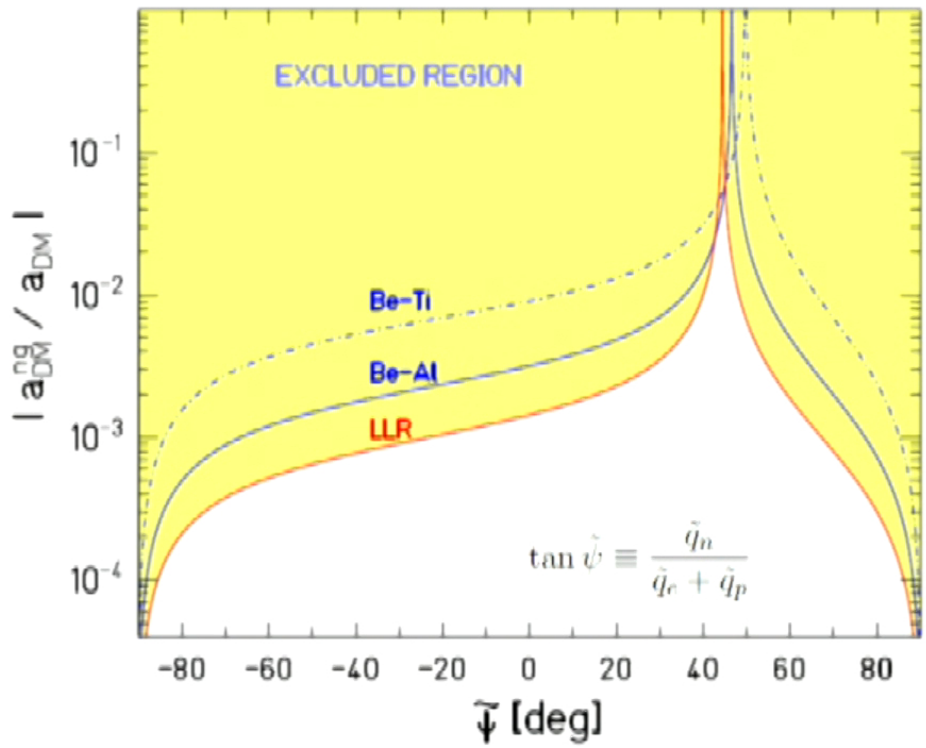
T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)

Is gravity the only long-range force between dark and luminous matter?

Could there be a long-range scalar interaction that couples dark-matter & standard-model particles?



95% confidence limits on non-gravitational acceleration of hydrogen by galactic dark matter



at most 6% of the acceleration can be non-gravitational

an amusing number

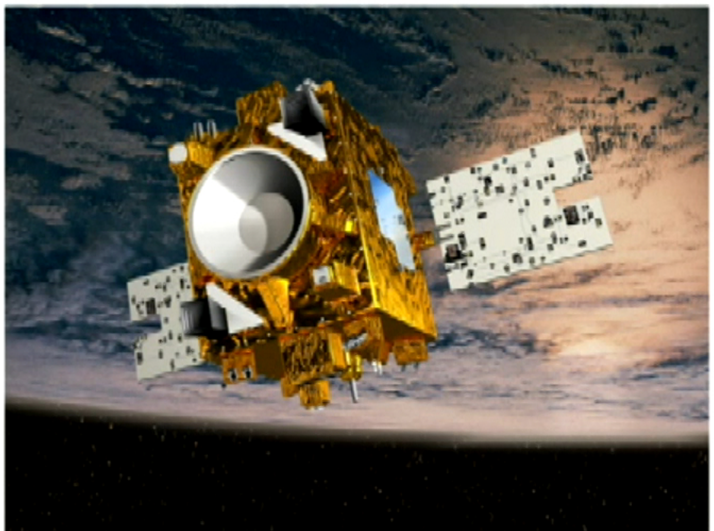
our differential acceleration resolution

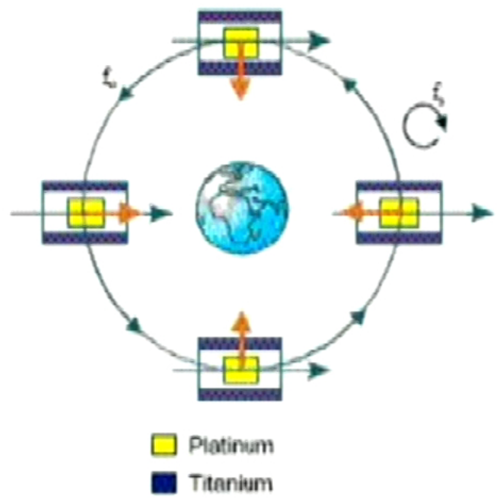
$\Delta a \approx 3\times 10^{-13}$ cm/s^2

is comparable to the difference in g between 2 spots in this room separated vertically by $\approx$ 1 nm

Microscope: French-German collaboration to test the WEP to 1 part in 10^{15} with a Ti/Pt EP test and a Pt/Pt null comparison in a drag-free satellite operated in both inertial and rotating modes. This Galileo-type experiment was launched on April 2016 and has been successfully commissioned and is now running in rotating mode.

advantages: signal 1000× larger, grav. gradients much smaller and stable
disadvantages: can't make changes if one finds an unexpected problem





- Two masses of different materials maintained on the same orbit ($< 10^{-11}$ m) by electrostatic forces
- An EP violation is indicated by a difference between the required forces
- Circular and heliosynchronous orbit ($e < 5 \times 10^{-3}$)
  - Thermal stability
  - Earth gravity gradient stability
  - 730 km altitude
- Two test modes:
  - Inertial: $f_{ep} = f_{orb} = 1.7 \times 10^{-4}$ Hz
  - Spin: $f_{ep} = f_{orb} + f_{spin} = 7.8 \times 10^{-4}$ Hz

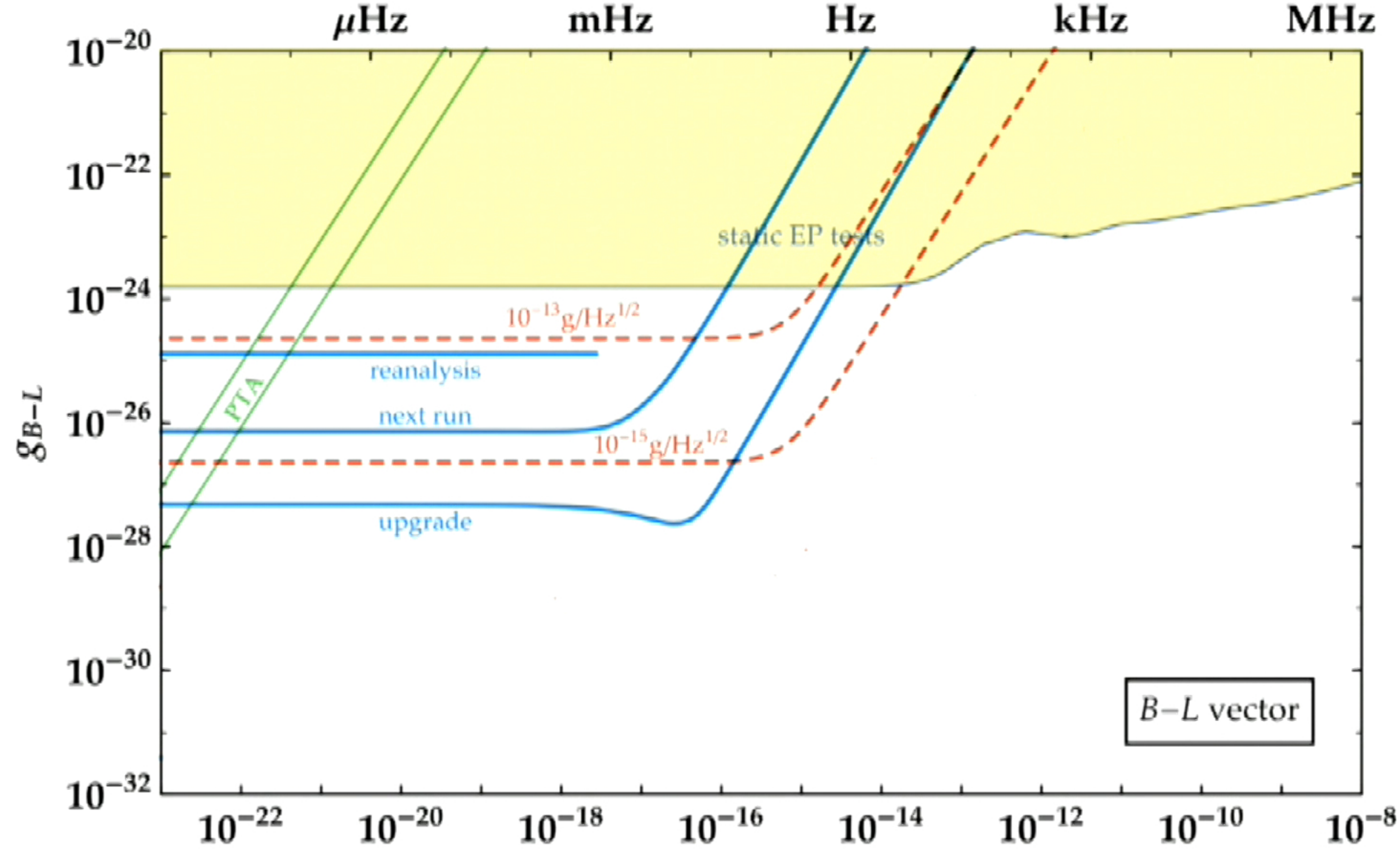
Several talks have given nice discussions about the intriguing topic of low-mass bosonic dark. Eőt-Wash has two projects in this area:

1) Vector DM that couples to B-L with Be-Al pendulum on stationary balance

2) Axion-like DM with Compton frequencies between 10^{-8} and 10^{-4} Hz spin pendulum (see below) on rotating torsion balance.
Sensitive to f_a at PeV scale

↑

don't have time to talk about this



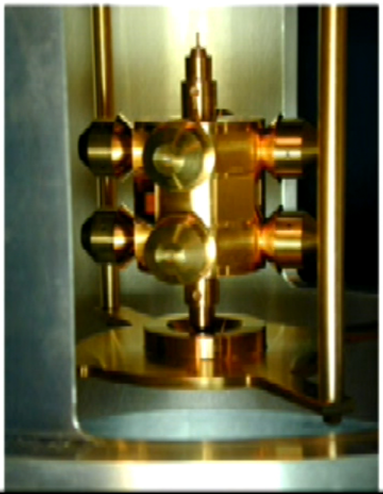
P.W. Graham et al. PRD 93, 075029 (2016)

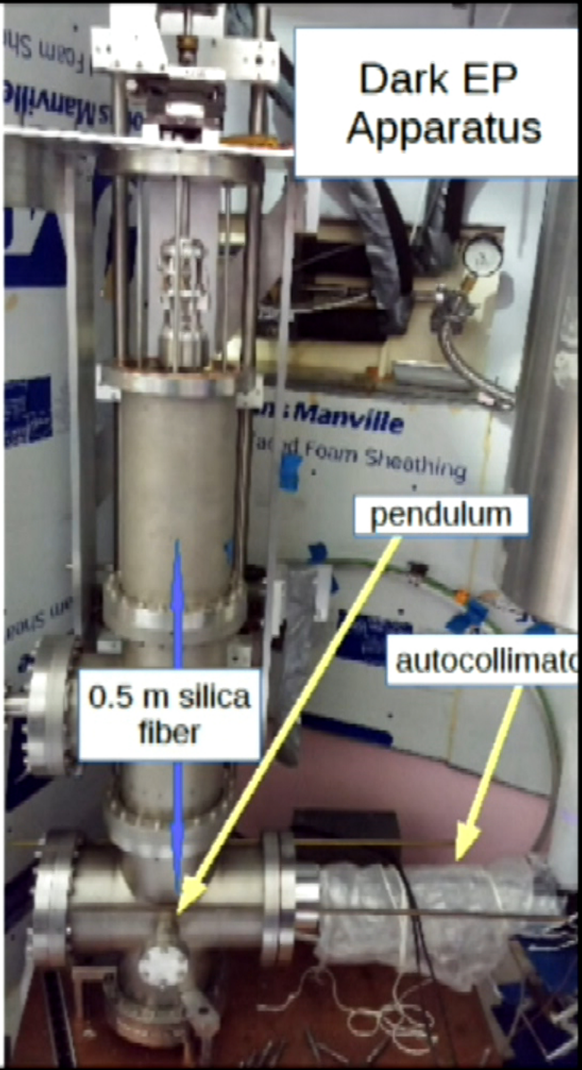
DarkEP: a new experiment sensitive to ultra-low mass dark-matter vector bosons coupled to B-L

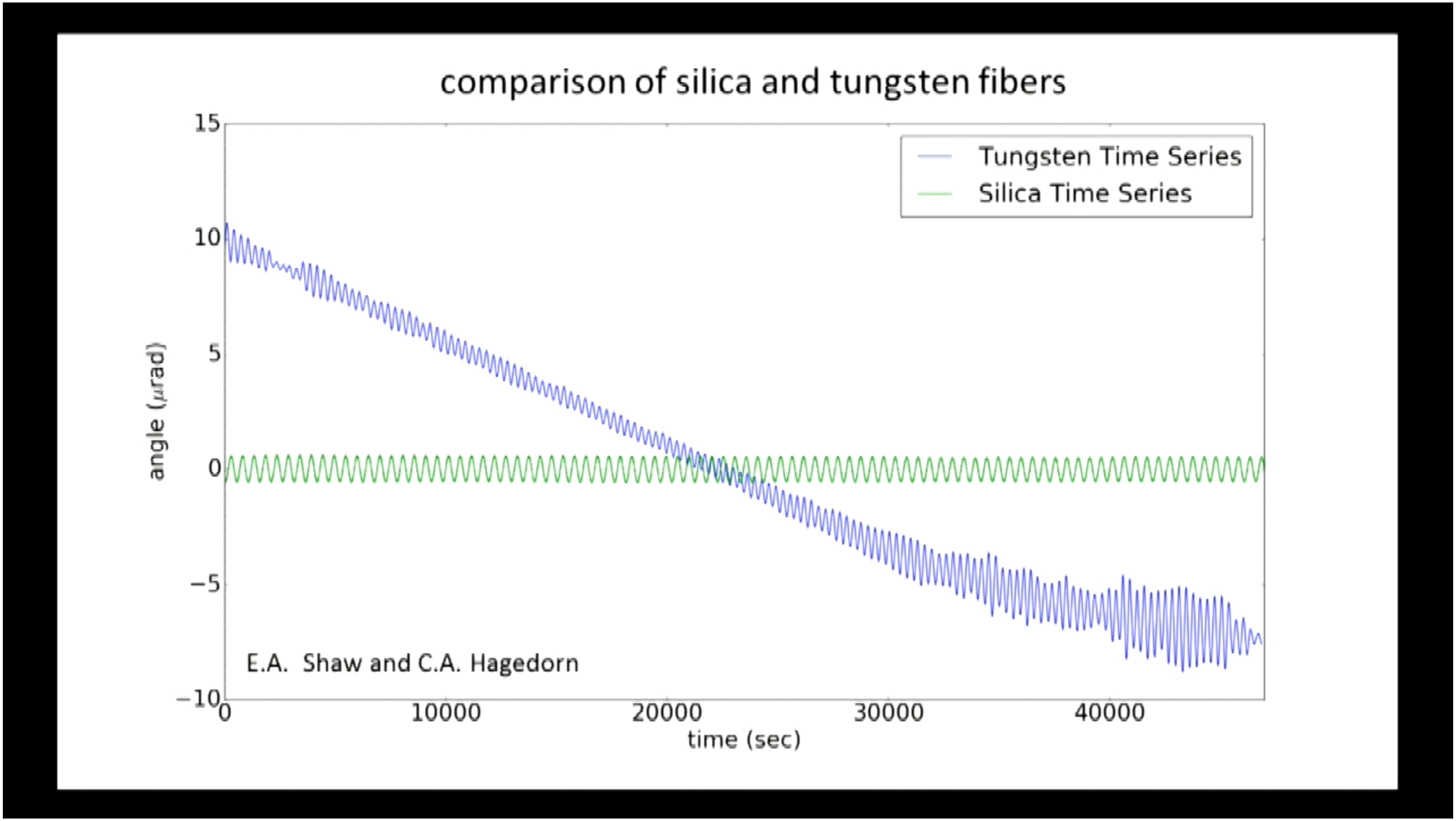
work by Charlie Hagedorn and Erik Shaw

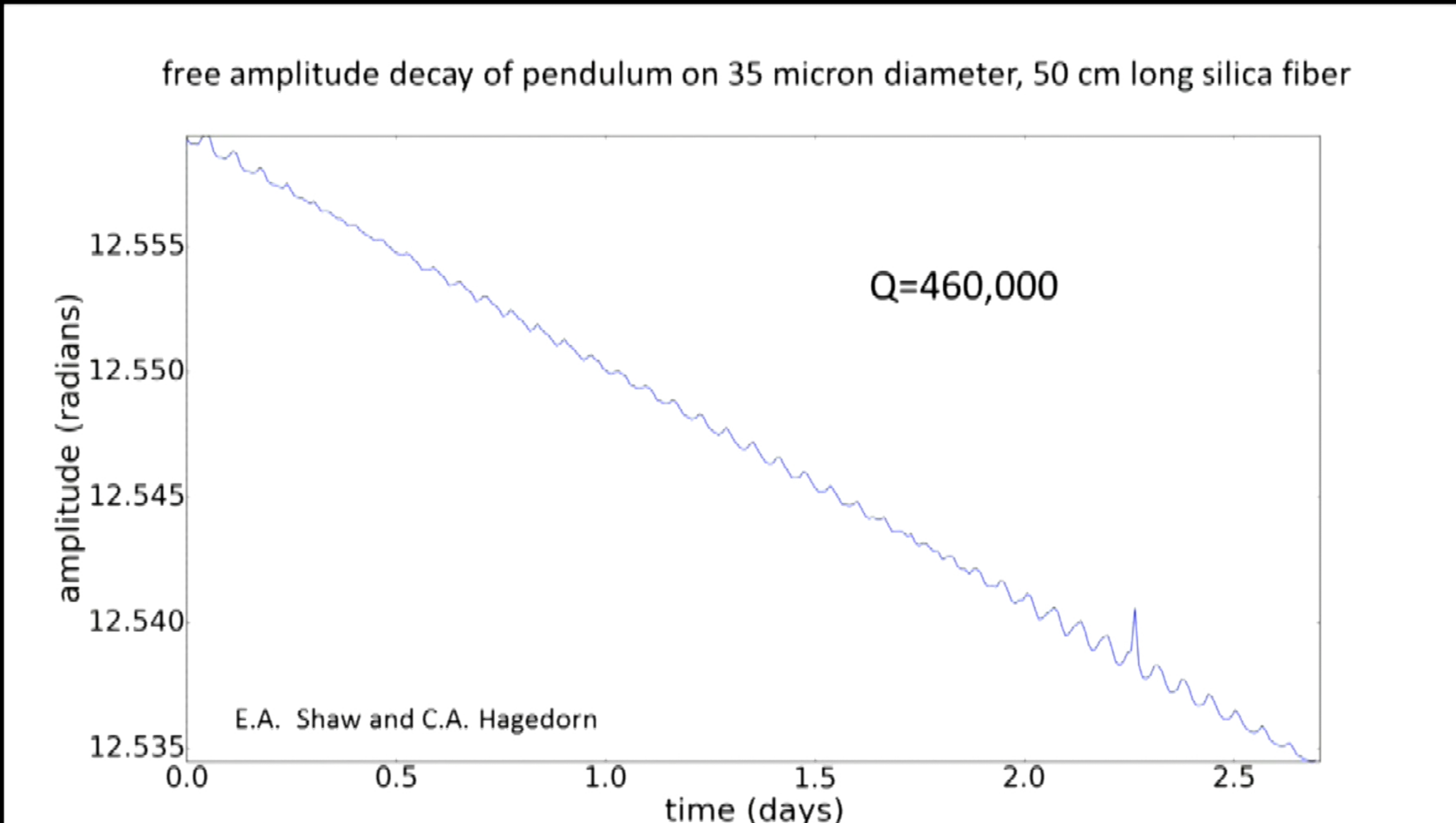
features:

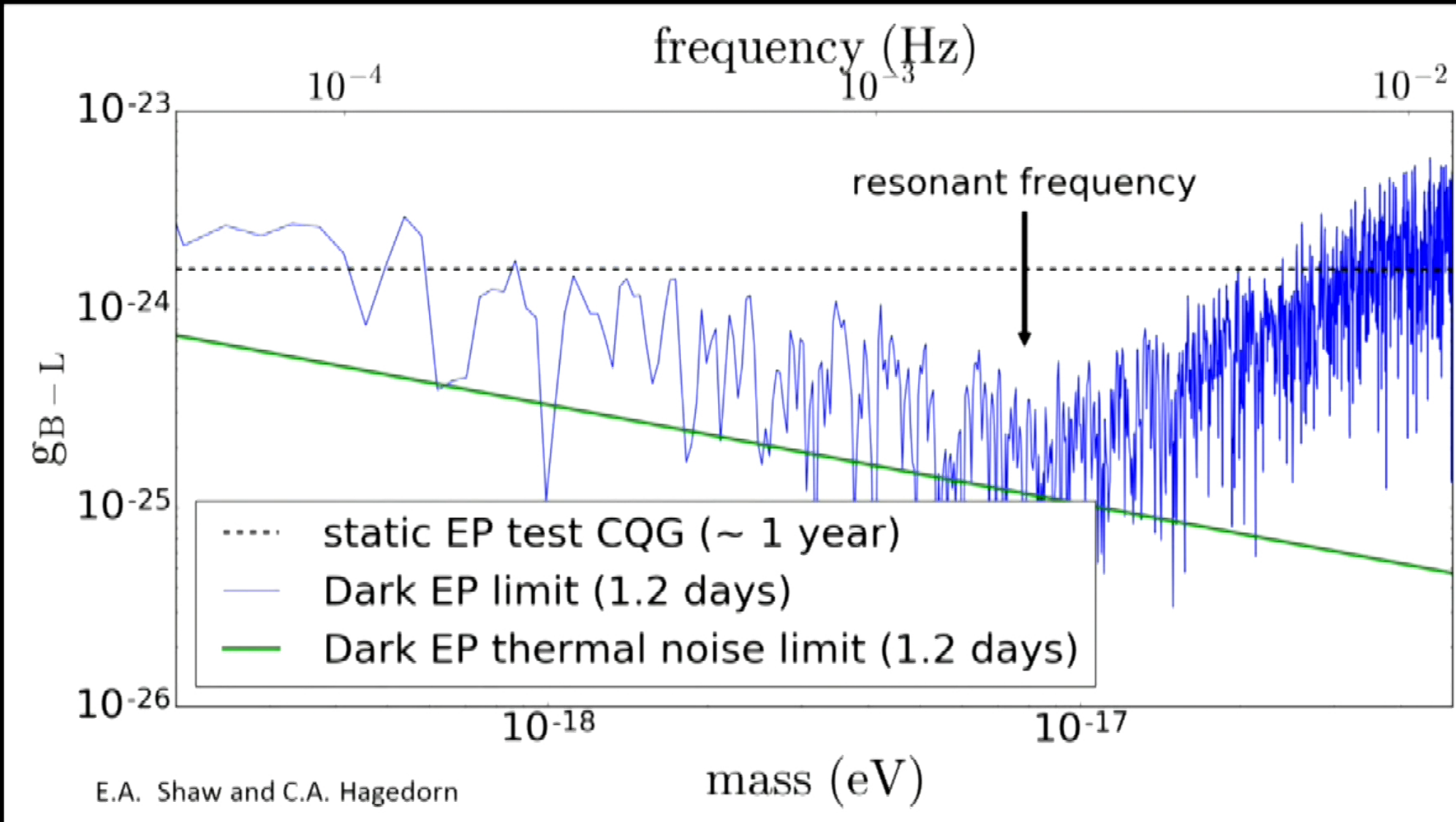
- stationary balance
- Be-Al pendulum for high B-L sensitivity
- high-Q low-noise quartz fiber
- look for periodic signals modulated by Earth's sidereal rotation and boson Compton frequency






comparison of silica and tungsten fibers
Tungsten Time Series
Silica Time Series
angle (μrad)
15
10
5
0
−5
−10
0
10000
20000
30000
40000
time (sec)
E.A. Shaw and C.A. Hagedorn


free amplitude decay of pendulum on 35 micron diameter, 50 cm long silica fiber
Q=460,000
E.A. Shaw and C.A. Hagedorn
amplitude (radians)
12.555
12.550
12.545
12.540
12.535
0.0
0.5
1.0
1.5
2.0
2.5
time (days)



frequency (Hz)
10^{-4}
10^{-3}
10^{-2}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
g_{B-L}
resonant frequency
static EP test CQG (~ 1 year)
Dark EP limit (1.2 days)
Dark EP thermal noise limit (1.2 days)
10^{-18}
10^{-17}
mass (eV)
E.A. Shaw and C.A. Hagedorn

Lab EP tests in the post-MICROSCOPE era

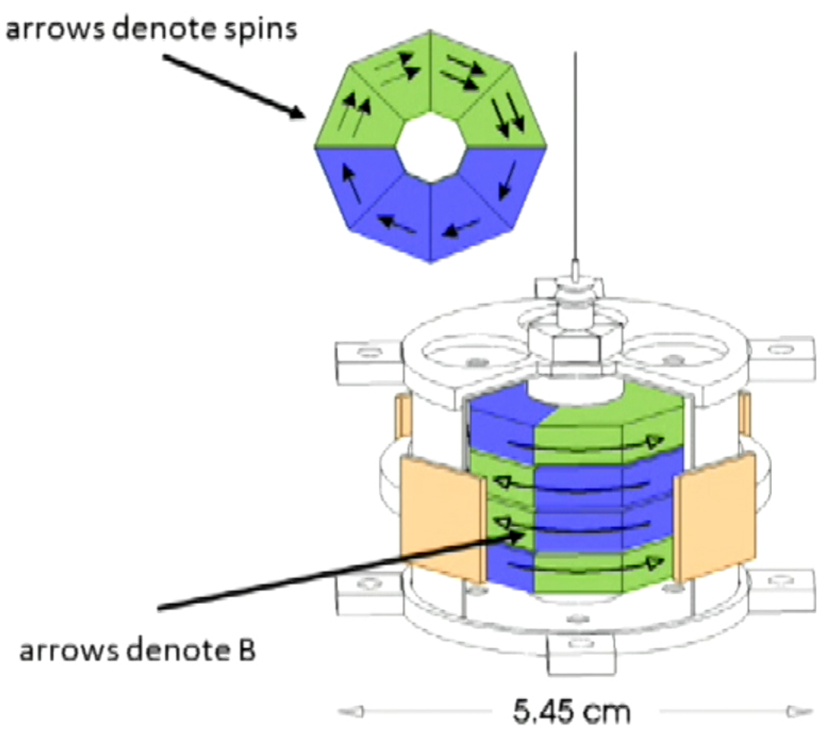
We can do things MICROSCOPE cannot:

it cannot probe interactions with $\lambda \leq 5\times10^5$ m

it has a single composition dipole so there is a charge parameter $\tilde{\psi}$ for which it has no sensitivity

With silica fibers we will have 10 times lower statistical noise.
Can we reduce systematic errors by a corresponding factor?
It will be challenging and requires R&D.

the Eöt-Wash spin pendulum



- 9.8×10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within octagons
- negligible external B field

- Alnico: all B comes from electron spin: spins point opposite to B

- $SmCo_5$: Sm 3^+ ion spin points along total B and its spin B field is nearly canceled by its orbital B field--so B of $SmCo_5$ comes almost entirely from the Co's electron spins

- therefore the spins of Alnico and Co form a closed loop and pendulum's net spin comes from the Sm. Because $B_{Sm} \propto 2S_{Sm} + L_{Sm} \approx 0$ we find $J_{Sm} = - S_{Sm}$

our spin experiments exploit the properties of 2 different magnetic materials:

Alnico – a soft ferromagnet with high spin density:
magnetization comes from pairs of aligned electron spins

$SmCo_5$ – a hard ferromagnet with low spin density:
Sm magnetization has large spin and orbital angular contributions that essentially cancel

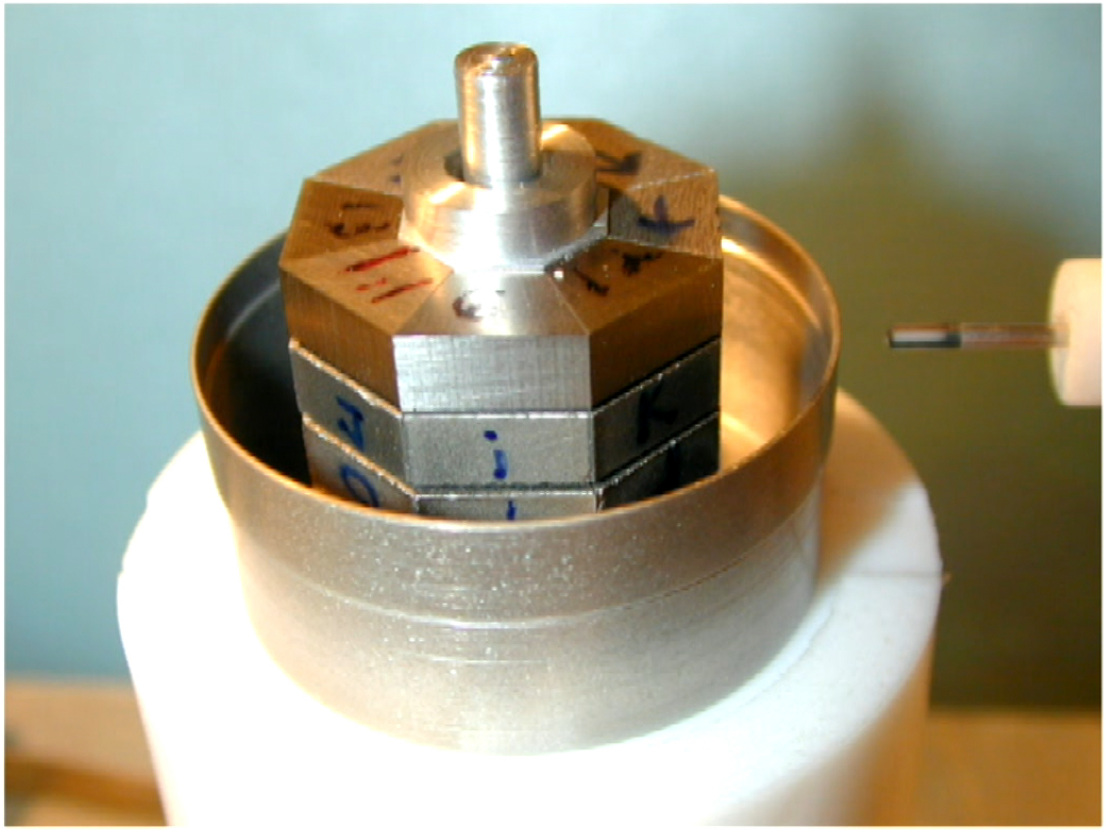
Simplified explanation for remarkable properties of $SmCo_5$:

The Sm in $SmCo_5$ crystal exists in a 3+ ionic state with 5 valence f electrons.
The repulsive e-e interaction forces the space function to be maximally antisymmetric.
m_L = (+3) + (+2) + (+1) + (0) + (-1) = 5 i.e. L=5

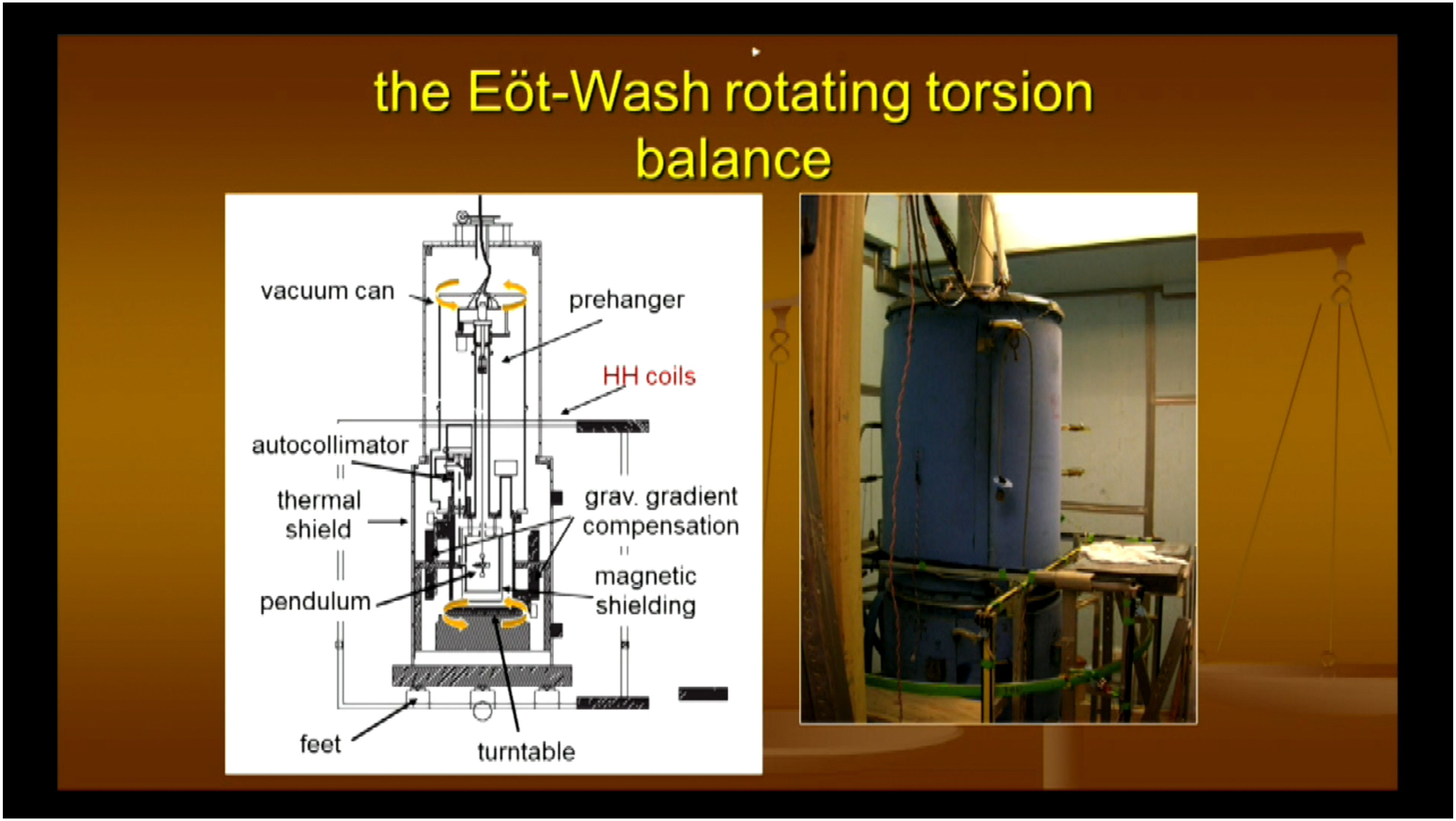
The spin function must be maximally symmetric i.e. S=5/2 .
Therefore the spin and orbital contributions to the Sm magnetic moment are equal.
Hund's Rule says that at beginning of a shell the two contributions cancel.

Hence the magnetic moment of $SmCo_5$ comes almost entirely from the 10 polarized Co electrons, but the spin moment of $SmCo_5$ is S=10-5=5, i.e. roughly ½ of that in a typical ferromagnet

measuring the stray magnetic field of the spin pendulum



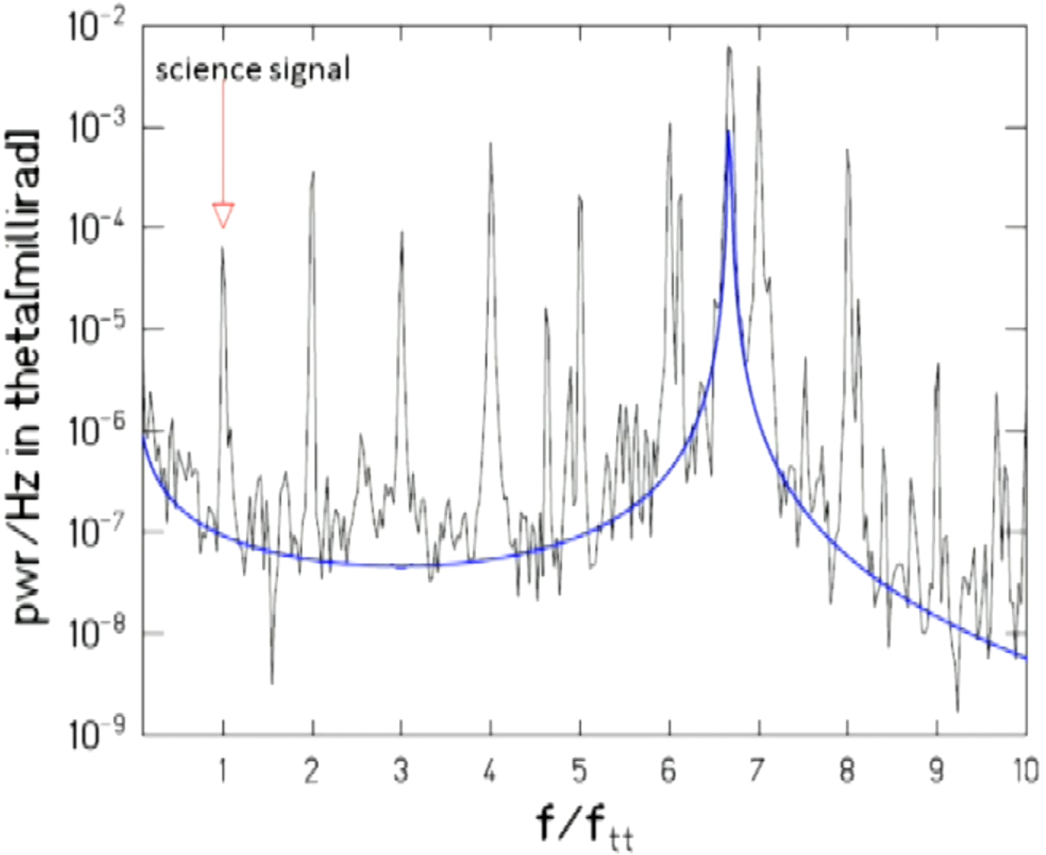
B inside = 9.6±0.2 kG   B outside ≈ few mG


the Eöt-Wash rotating torsion balance
vacuum can
prehanger
HH coils
autocollimator
thermal shield
grav. gradient compensation
magnetic shielding
pendulum
feet
turntable

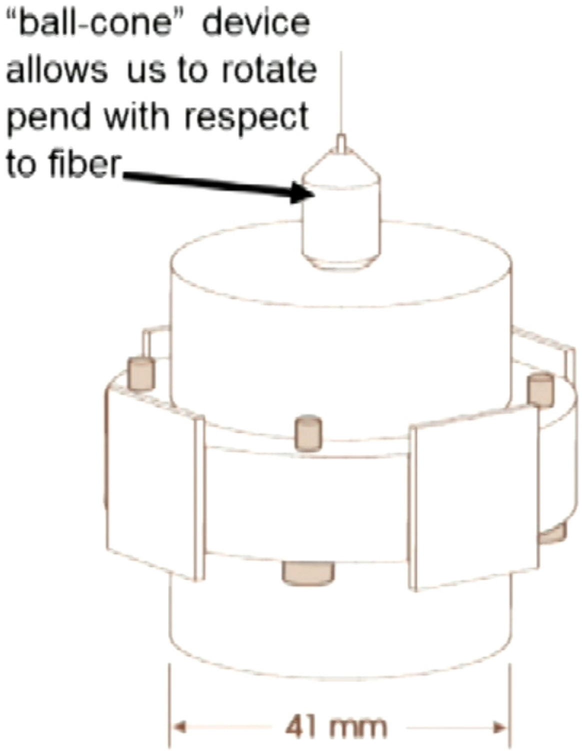
power spectrum of the spin-pendulum twist

Peaks are due to repeatable irregularities in the turntable rotation rate. Odd multiples are eliminated by combining data with two opposite orientations of the pendulum or by looking for astronomical modulation of the science signal.

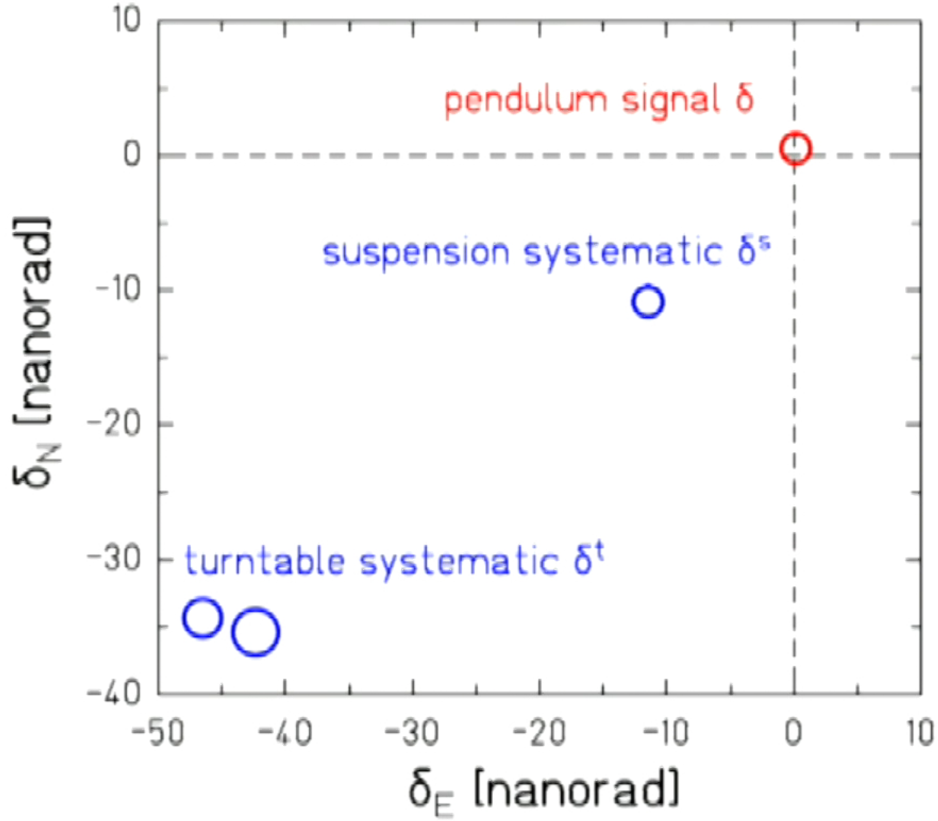
Note that the noise background Is thermal.



Early spin-dipole pendulum data taken with rotating turntable showed a well-resolved non-zero effect that was not canceled by taking data with 2 opposite orientations of pendulum wrt. the turntable. Was it something weird about the pendulum or some effect we had not known about?

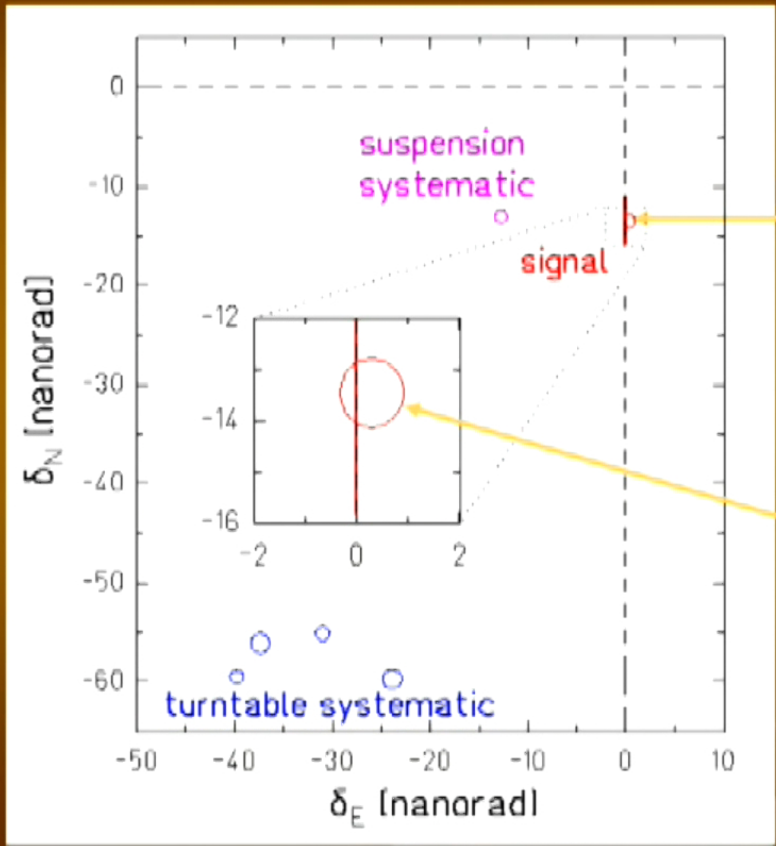


aluminum "zero-moment" pendulum



data with 4 orthogonal orientations of pend. wrt. turntable & 2 opposite orientations of pend. wrt. suspension

lab-fixed spin pendulum signal



gyrocompass effect:
The vertical bar shows expected effect based on 2 previous discordant measurements of $SmCo_5$ spin density

The ellipse shows our result when we use the Coriolis effect to calibrate the spin density rather than previous polarized neutron and X-ray scattering data.

The gyrocompass

Anschütz's gyrocompass.

Anschuetz-Kaempfe and Sperry separately patented gyrocompasses in UK and US. In 1915 Einstein ruled that Anschütz's patent was valid.

conventional gyrocompass

angular momentum J of a spinning flywheel in a lossy gimbal will eventually point true North where the gimbals do not dissipate energy

our gyrocompass.

Earth's rotation Ω acting on J of pendulum produces a steady torque along suspension fiber

$| \Omega \times J \cdot n |$ where n is unit vector along local vertical. Because $S = -J$ this is equivalent to $\boldsymbol{\beta}_N = -\ 1.616 \times 10^{-20}$ eV

new spontaneously-broken symmetries?

Spontaneously broken global symmetries always generate massless pseudoscalar Goldstone bosons that couple to fermions with $g_p = m_f / F$ where F is the symmetry-breaking energy scale.

If the symmetry is explicitly broken as well the resulting pseudo Goldstone bosons acquire a mass $m_b = \frac{\Lambda^2}{F}$.

Sensitive searches for the fermionic interactions of these bosons can probe for new hidden symmetries broken at very high scales.

familiar example of a pseudo-Goldstone boson (pGb):
the pion from spontaneous breaking of chiral symmetry

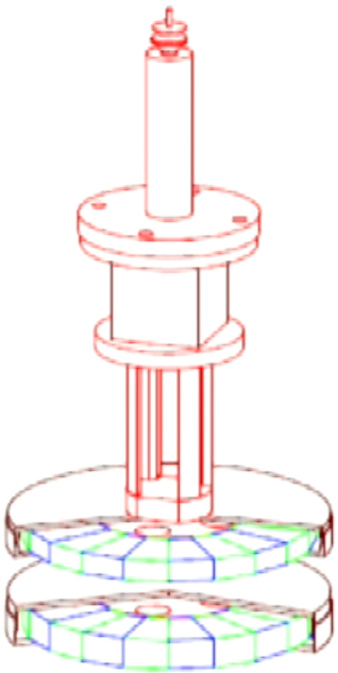
Speculations about additional pGb's:

- axions
- familons
- majorons
- closed-string axions
- accidental pGb's

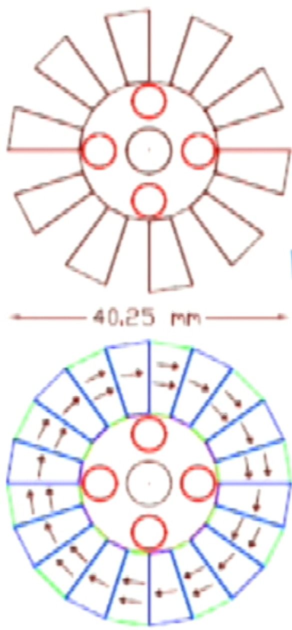
see A. Ringwald, arXiv:1407.0546 for a nice review

Eöt-Wash pseudo-Goldstone boson detector

developed by Will Terrano (PhD 2015)



unpolarized mass attractor



polarized spin attractor

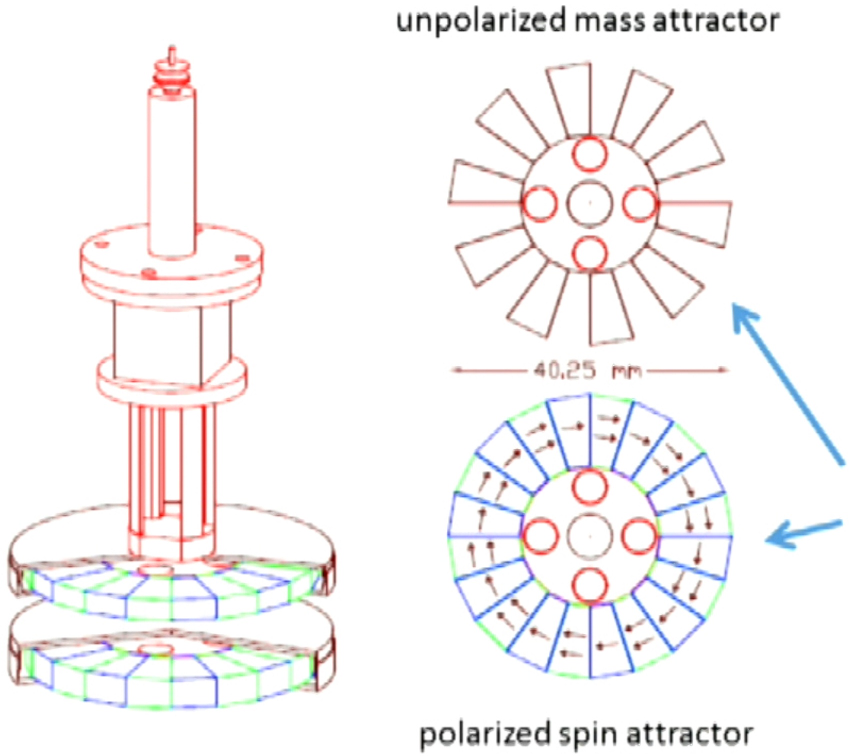
stationary pendulum- rotating attractor instrument with 20-pole azimuthal symmetry

compact setup with sophisticated magnetic shielding

we probed both monopole-dipole & dipole-dipole interactions

Eöt-Wash pseudo-Goldstone boson detector

developed by Will Terrano (PhD 2015)



stationary pendulum- rotating attractor instrument with 20-pole azimuthal symmetry

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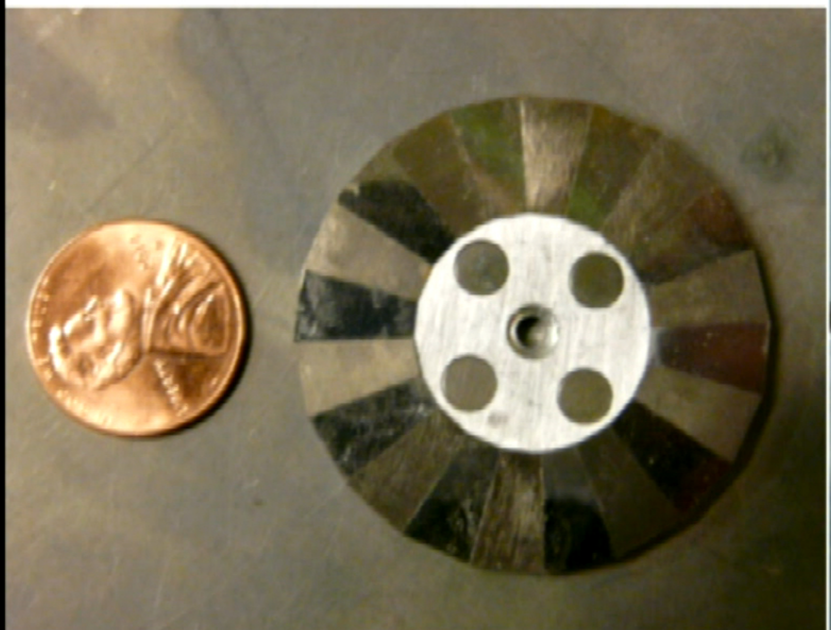
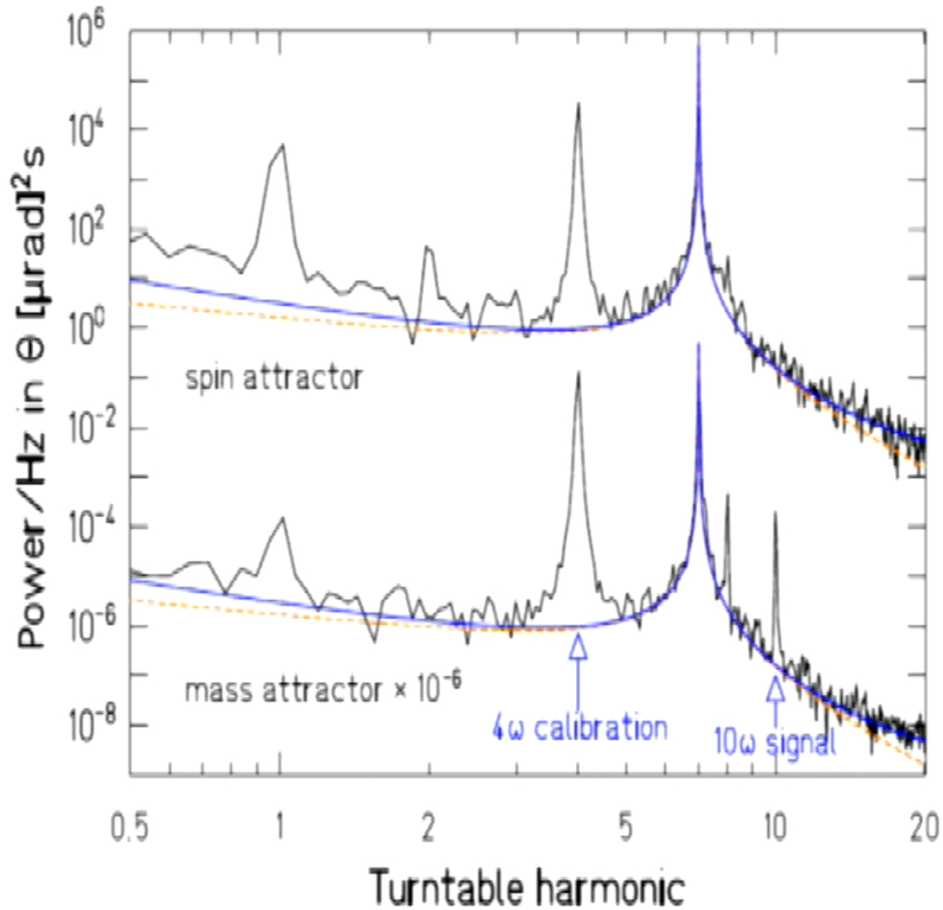


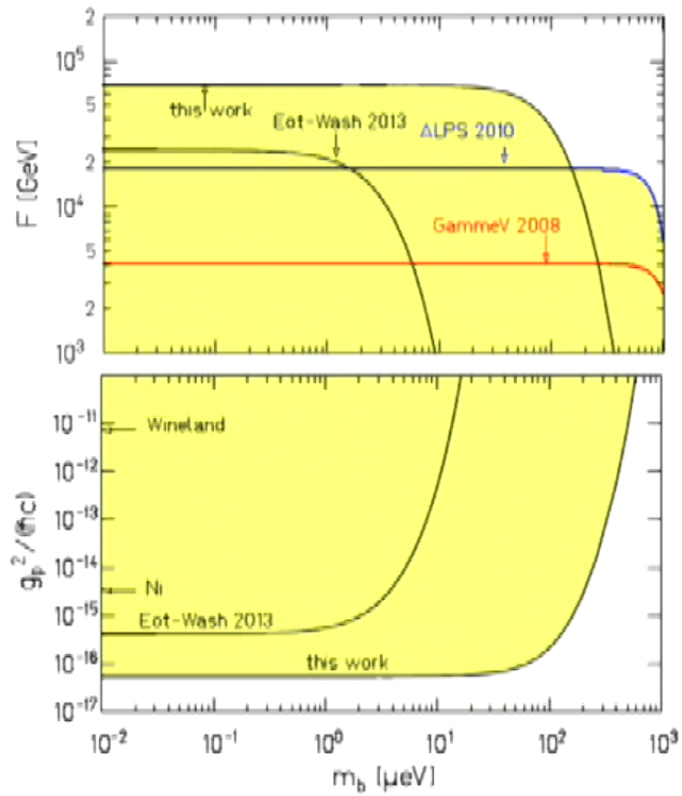
the 4 circles are tungsten cylinders that provided a continuous L=4 gravitational calibration unprecedented aN m torque sensitivity

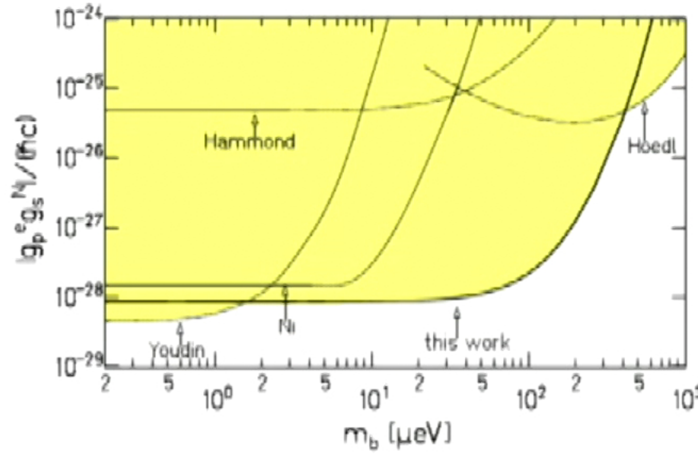
TABLE I. Observed 4ω and 10ω torques. Amplitudes A are in units of aN m, phases ϕ are in degrees, and separations s are in millimeters. The 1σ uncertainties do not include systematic effects. If $V_{\rm md} = 0$, we expect $\Delta\phi = \phi_{10\omega} - \phi_{4\omega} = -9.0°$.

Attractor	$T_{\rm att}/T_0$	$A_{4\omega}$	$A_{10\omega}$	$\phi_{10\omega} - \phi_{4\omega}$
Spin: $s = 4.12$	7	2855 ± 5	0.7 ± 2.9	$+3 \pm 25$
Spin: $s = 4.12$	6	2863 ± 4	2.9 ± 2.8	-7.9 ± 5.5
Spin: $s = 4.12$	$6 + 7$	2860 ± 3	1.3 ± 2.0	-6.1 ± 8.6
Mass: $s = 1.98$	7	5611 ± 8	344 ± 4	-9.47 ± 0.08



95% confidence exclusion limits from the pseudo-Goldstone boson detector

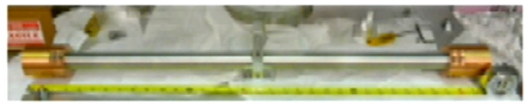




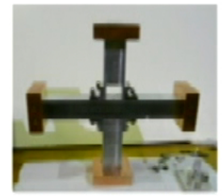
ALPS and GammeV are light shining thru wall expts at DESY and FermiLab

W.A. Terrano et al., PRL 115, 201801 (2015)

BRS-X



BRS-Y



c-BRS

Beam Rotation Sensors for LIGO

03/14/2017

Krishna Venkateswara
for
UW - Michael Ross, Charlie Hagedorn, and Jens Gundlach
SEI – J. Warner, H. Radkins, J. Kissel, T. J. Shaffer, B. Lantz, R. Mittleman, R. Schofield, C. Mow-Lowry, A. Pele and others
Newtonian Noise – M. Coughlin, J. Harms, J. Driggers

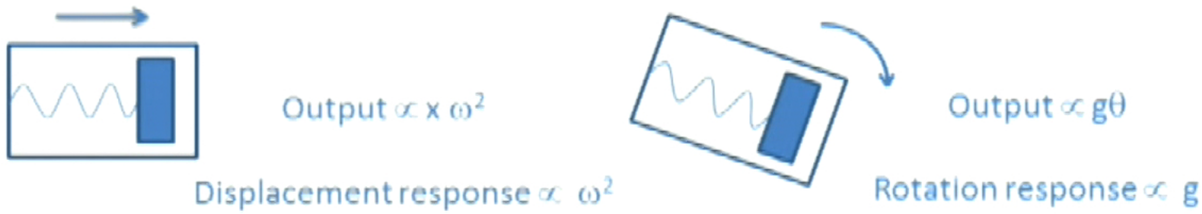
LIGO-G1600451

Ground motion (seismic, wind, etc.) at frequencies below the resonances of the suspended interferometer optical elements would make it impossible to keep the aLIGO interferometer locked. This is handled by using seismometers to feed forward to cancel the ground motion allowing the interferometer to stay locked.

However, there is a problem.

Rotation versus Horizontal displacement

- Conventional seismometers and tiltmeters cannot differentiate between horizontal displacement and ground rotation.

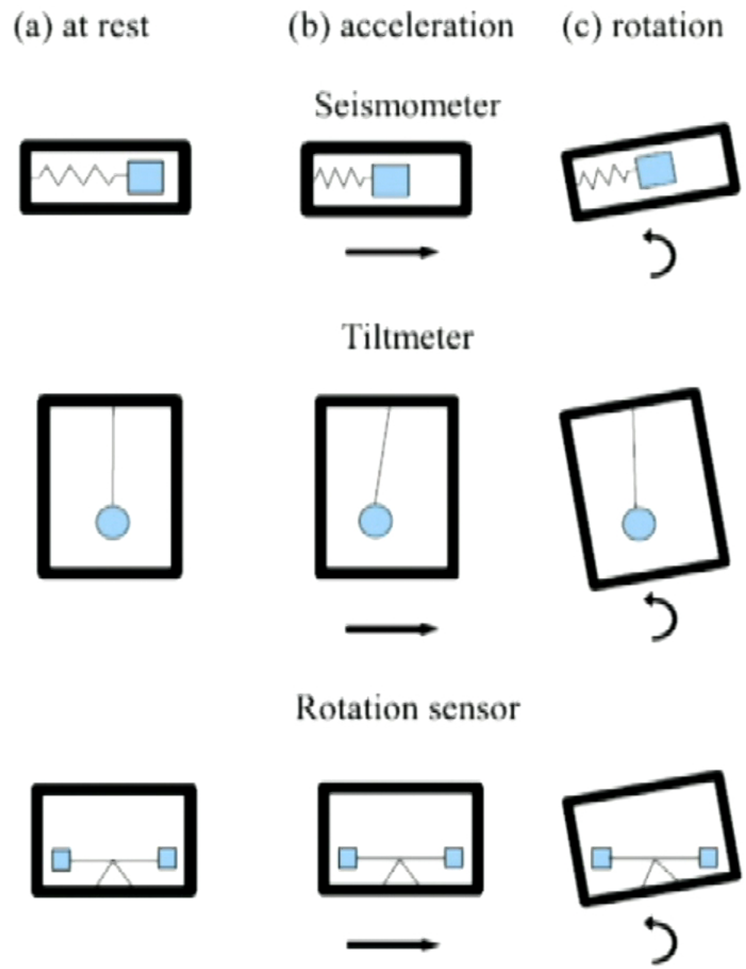


Rotation response to horizontal displacement response for <u>all</u> seismometers = $-g/\omega^2$

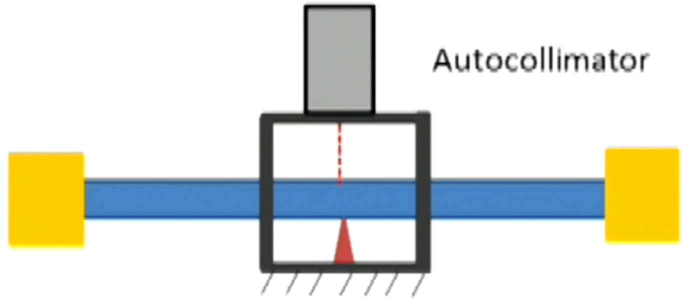
$\Rightarrow$ Rotation is confused with horizontal motion at low frequencies (below ~ 0.1 Hz).

<u>Solution</u>: Inertial rotation sensors, Tilt-free seismometers or ring-laser gyroscopes...

Credit: K. Venkateswara


(a) at rest
(b) acceleration
(c) rotation
Seismometer
Tiltmeter
Rotation sensor

BRS Concept



Principle:

- Ground rotation is measured by measuring angle between ground and low frequency beam balance.
- Horizontal acceleration can be rejected by locating center of mass at the pivot.

Credit: K. Venkateswara

Venkateswara, Krishna, et al. "A high-precision mechanical absolute-rotation sensor." Review of Scientific Instruments 85.1 (2014): 015005.

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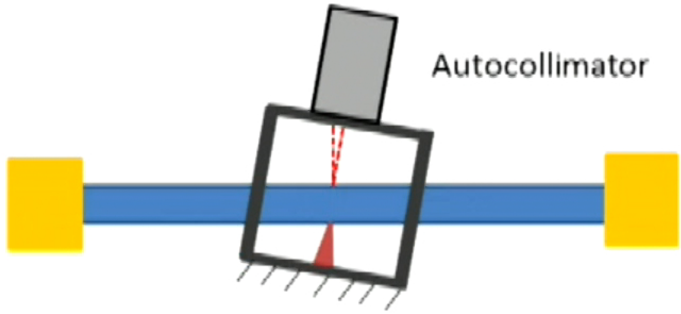
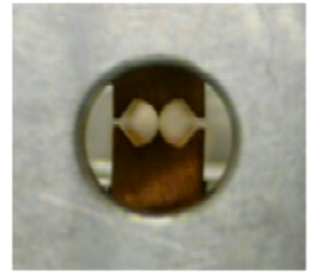
BRS Concept





10-20 μm-thick,
1.6 mm radius
Cu-Be Flexures

Principle:

- Ground rotation is measured by measuring angle between ground and low-frequency beam balance ($f_0 \approx 8$ mHz).
- Horizontal acceleration can be rejected by locating center of mass at the pivot.

$$Translation\ rejection = \frac{Md}{I} \approx 10^{-5}\text{rad/m}$$

Credit: K. Venkateswara

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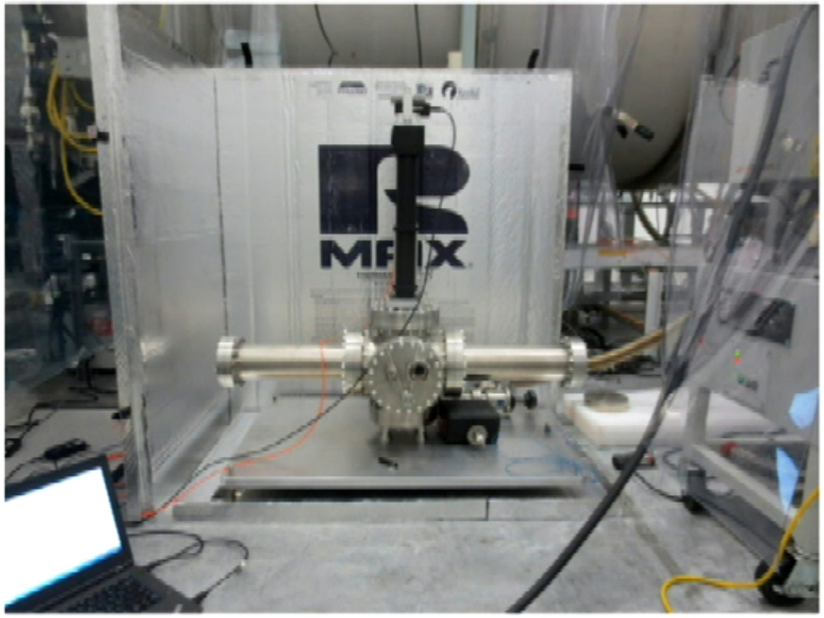
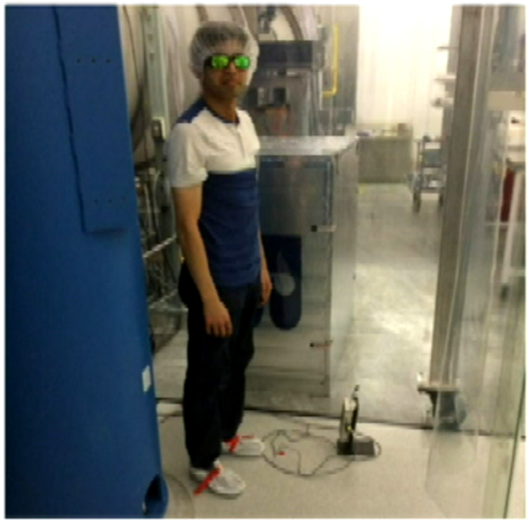
BRS-X Installation at LHO EX

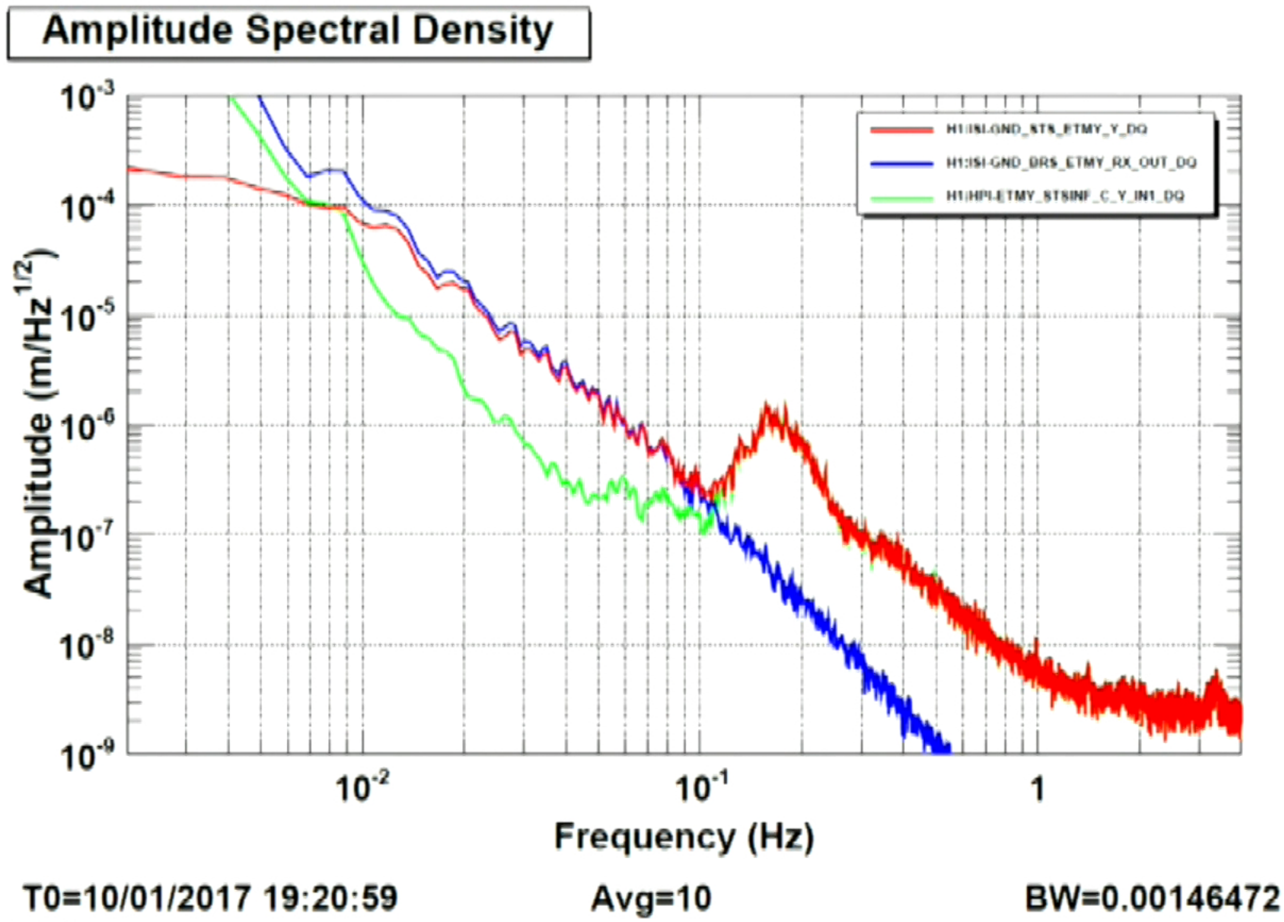




Credit: K. Venkateswara

Rotation-subtraction during ~15 mph winds

tilts ≈3-10 nrad



Credit: K. Venkateswara

BRS Performance at LHO

- Is part of the <u>default</u> seismic configuration at LHO in Observation Run 2 of Advanced LIGO.

Effect of Environment on Duty Cycle (as of ~March 10, 2017)

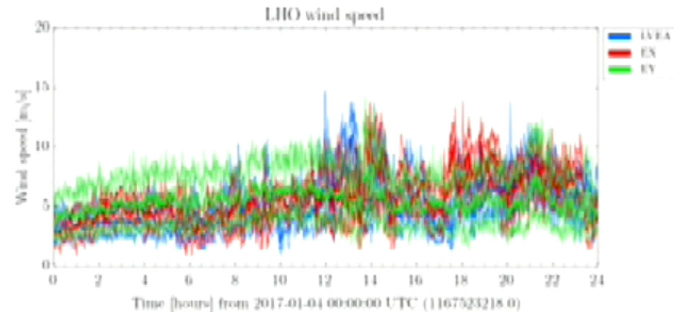
		Hours (lost)
no BRS	Wind	108.9
	Seismic	1.9
	Microseism	69.3
	Earthquake	72.8

Observation Run 1

		Hours (lost)
with BRS	Wind	1.7
	Seismic	1.0
	Microseism	2.6
	Earthquake	57.4

Observation Run 2

- 50 Solar mass black hole merger* observed at LHO on Jan 4, 2017 despite ~ 20 mph winds!



Only possible because of our rotation sensor

* 'GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2', Phys. Rev. Lett. **118**, 221101 (2017).

Thanks for your attention.

I'm sure you will all join me in congratulating the organizers, the Perimeter Institute, and the other participants for a very stimulating and productive meeting.

Let's do it again!