Tests of the equivalence principle and the inverse-square law

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outline:

A little bit of history plus current status of:

weak and strong equivalence principle tests
Einstein's "happiest idea"

short-distance inverse-square law tests
Kant's number of space dimensions

Two versions of the Equivalence Principle

Weak equivalence principle (WEP):

All laboratory-sized test bodies (i.e. objects with negligible gravitational binding energy) fall with the same acceleration in a uniform gravitational field. All metric theories predict that the WEP is exact. Quantum gravity models allow violation.

Strong equivalence principle (SEP):

Extends the WEP to include objects so large that gravitational binding energy is significant. This probes the non-linear nature of gravity. Some metric theories violate the SEP. Quantum gravity models allow violation..

two ways to test gravity:

1) watch things fall down (Galileo)

obvious

long history

revived with new technology: atoms, space

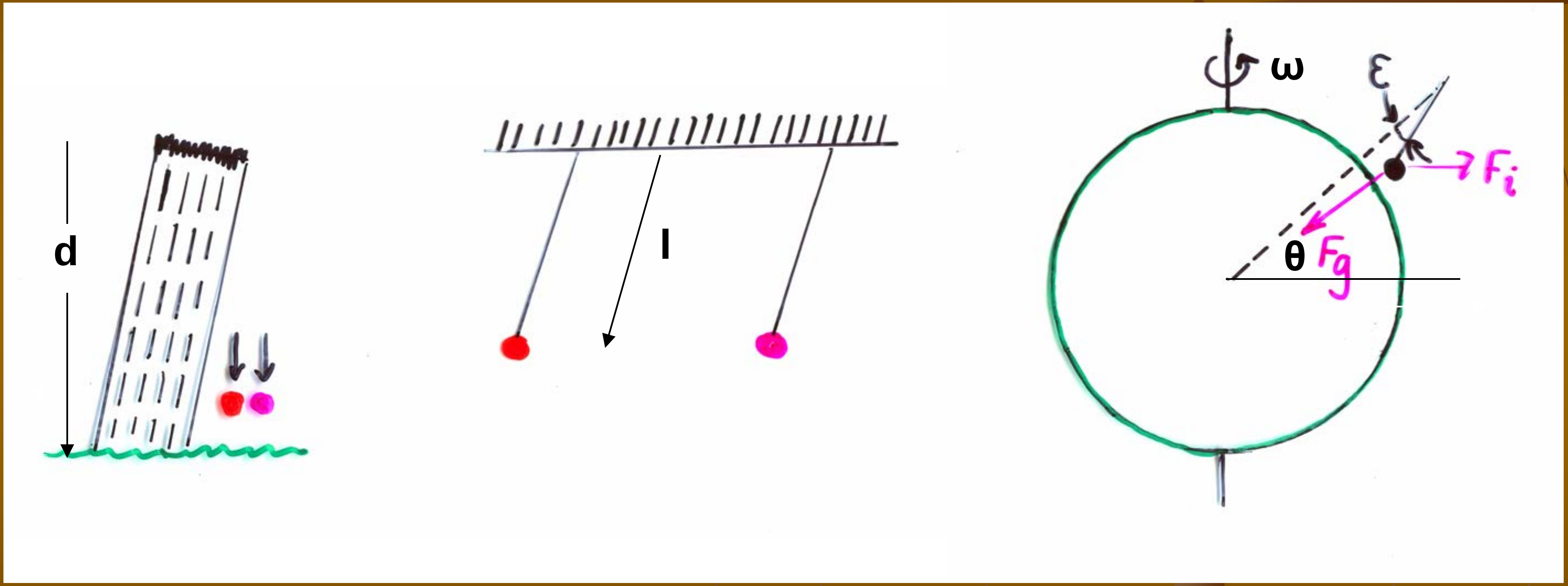
2) watch things fall sideways (Eötvös)

not so obvious

currently provides the most sensitive tests

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



are fall times equal?

$T=\sqrt{(2d/g\ (m^i/m^g))}$

$\Delta a/a \sim 0.1$

are periods equal?

$T=2\pi\sqrt{(l/g\ (m^i/m^g))}$

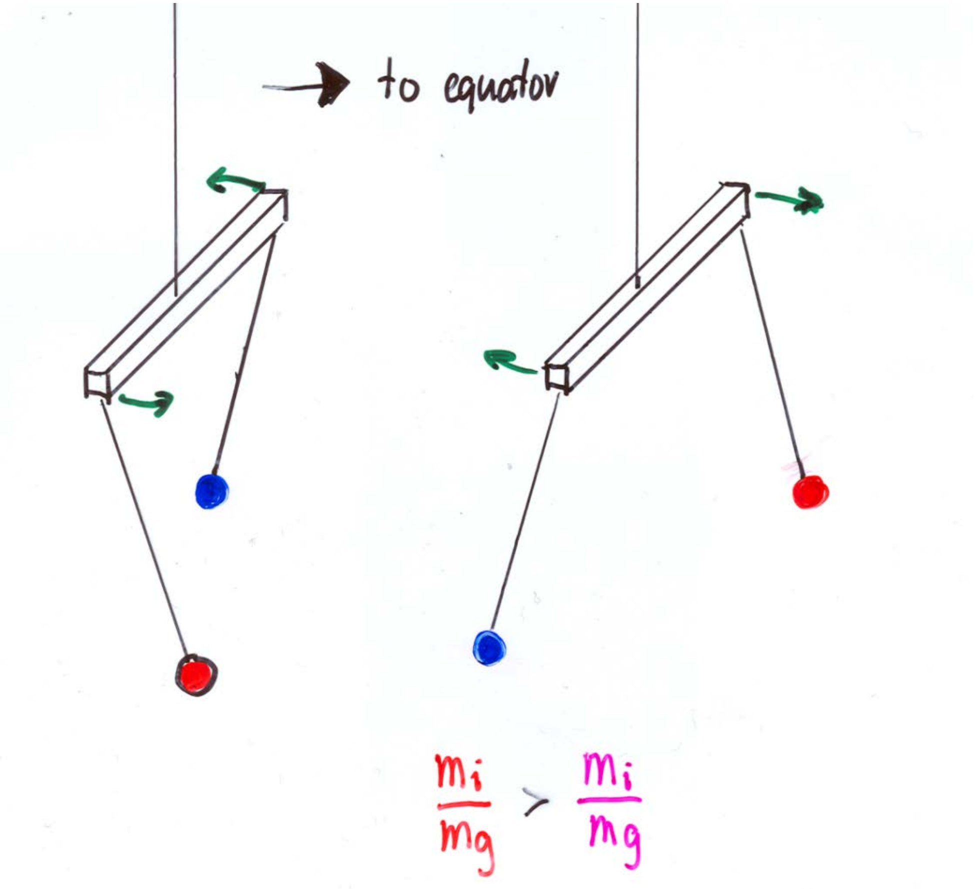
$\Delta a/a \sim 10^{-4}$

are angles equal?

$\varepsilon=\omega^2 R \sin 2\theta/(2g)\ (m^i/m^g)$

$\Delta a/a \sim 10^{-9}$

Testing the WEP by watching things fall sideways



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 $\Delta a/a < 5 \times 10^{-9}$

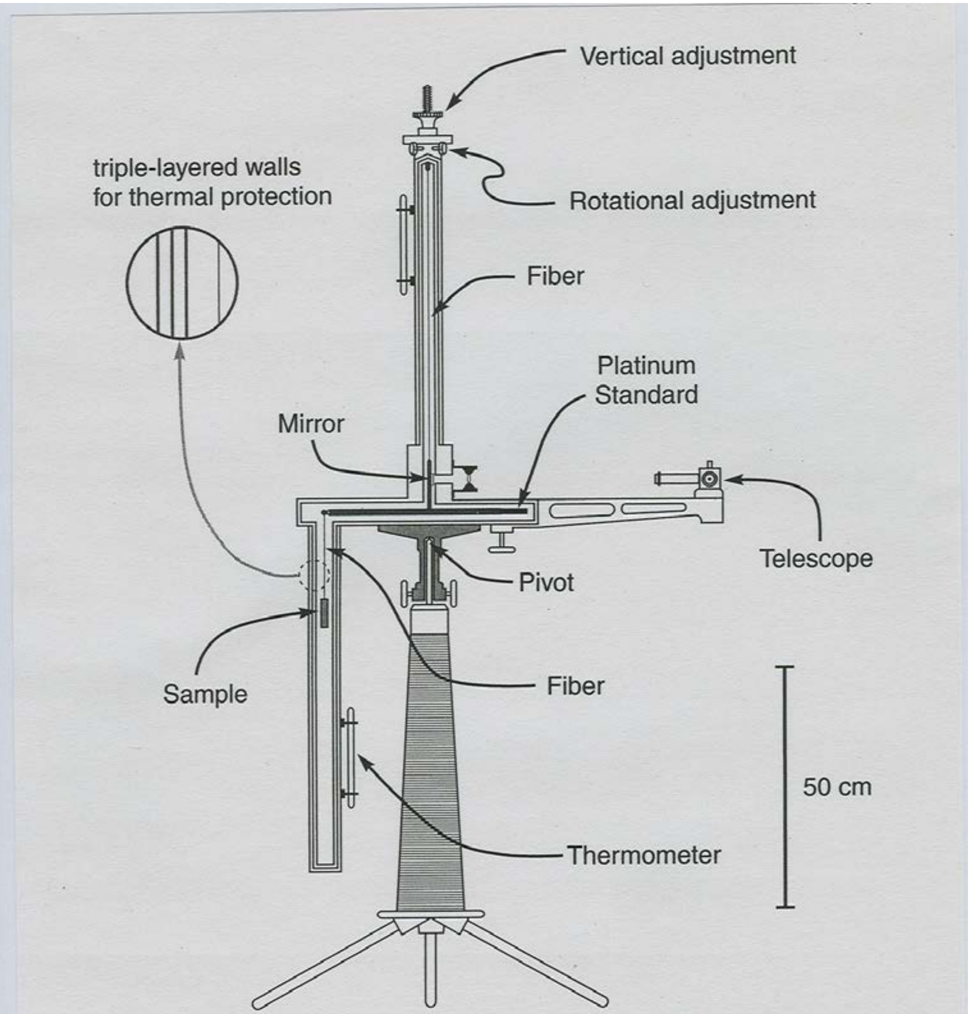
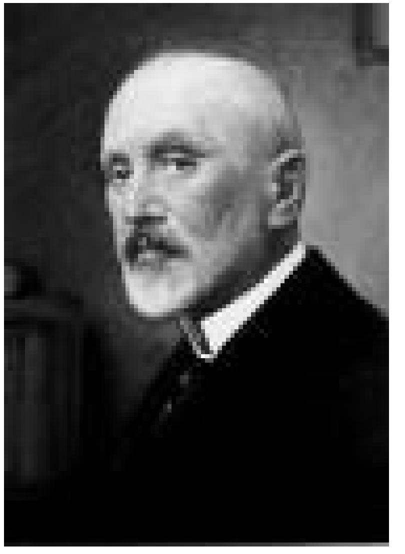
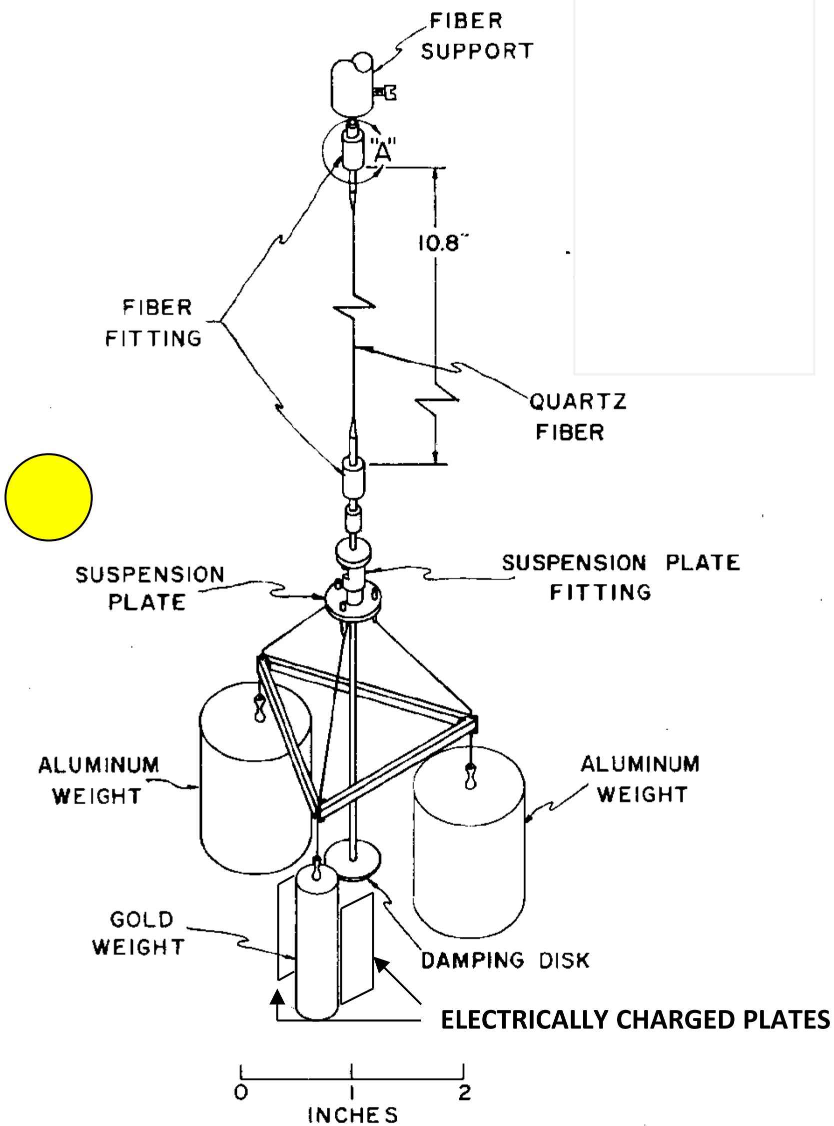


Figure 4.6: Single-arm torsion balance used by Eötvös, Pekár, and Fekete.



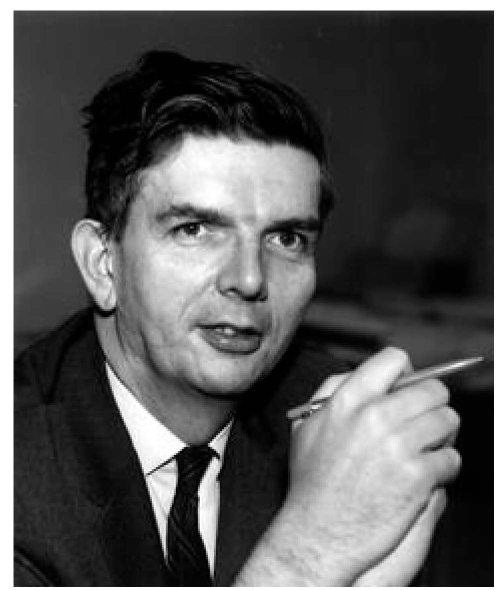
Note: this instrument was originally a gravity gradiometer

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 $\Delta a/a=(1.0\pm 1.5)\times 10^{-11}$
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:

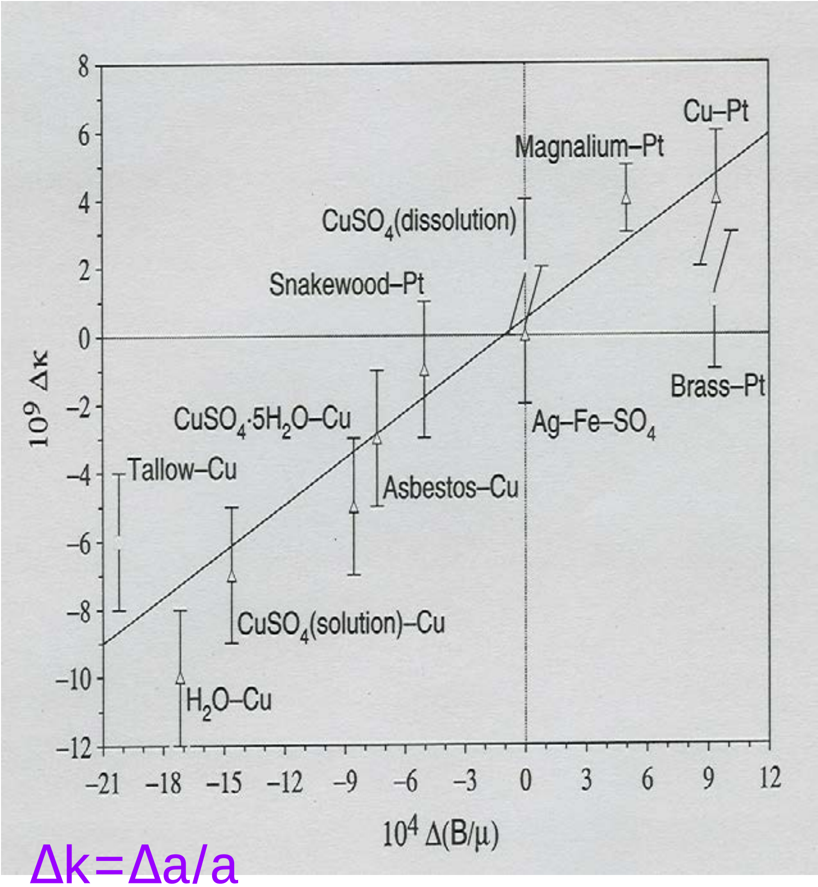
is $m_g = m_i$ exact?

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)



Δk=Δa/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

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

quantum exchange forces couple to "charges"

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

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

vector "charge" of electrically neutral objects

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

the Eöt-Wash® group

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Staff scientist
- Erik Swanson

Postdocs
- Krishna Venkateswara (LIGO)
- Charlie Hagedorn

Current undergrad
- Michael Ross

Current Grad students
- John Lee
- Erik Shaw
- Will Terrano

EP
$1/r^2$
spin
technology

Primary support from NSF Gravitational Physics

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

this requires:

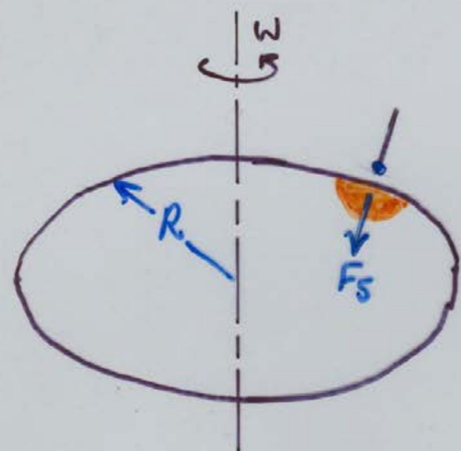
•sensitivity to wide range of possible charges
vector charge/mass ratio of any composition
monopole or dipole vanishes for some value of ψ.

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

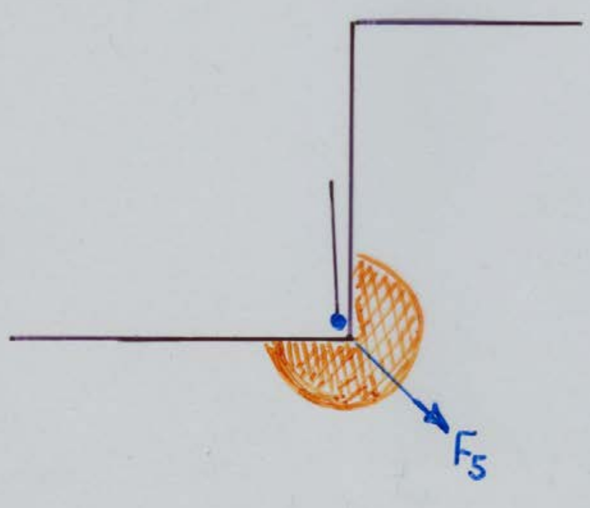
•sensitivity to wide range of length scales

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 $\lambda \ll R$



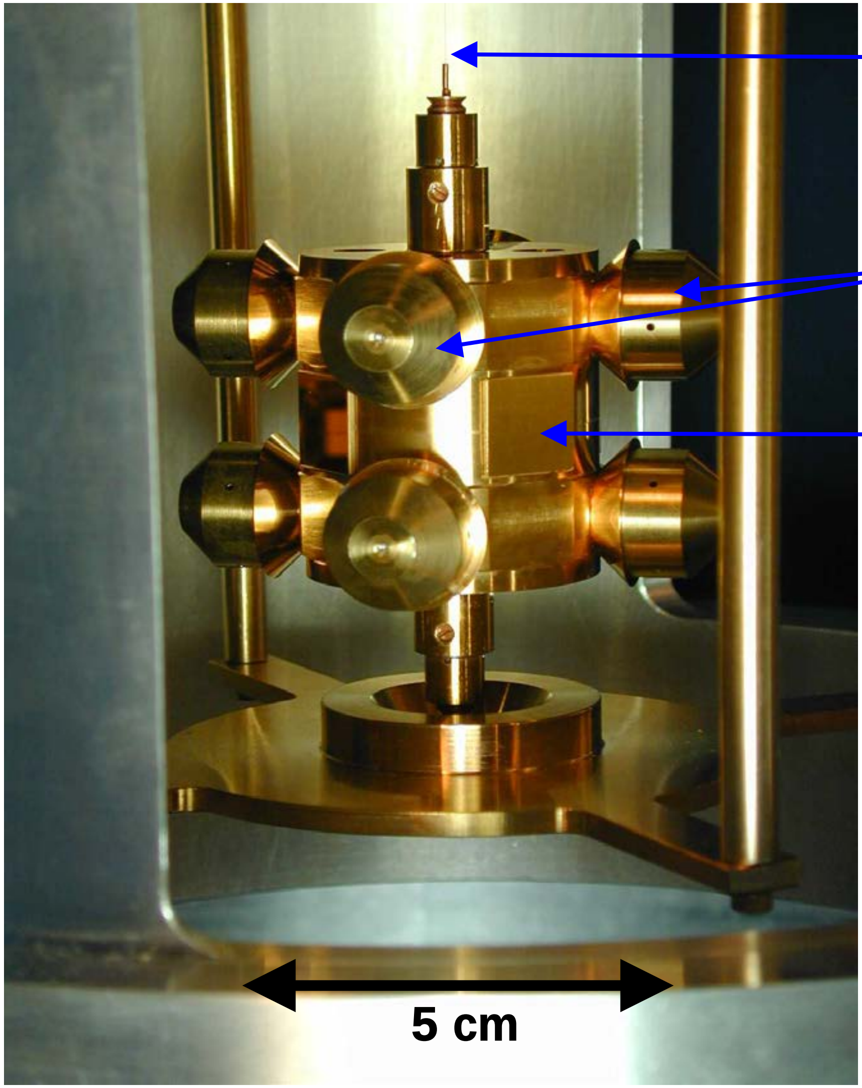
big cliff gives high sensitivity to short ranges

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 tungsten fiber

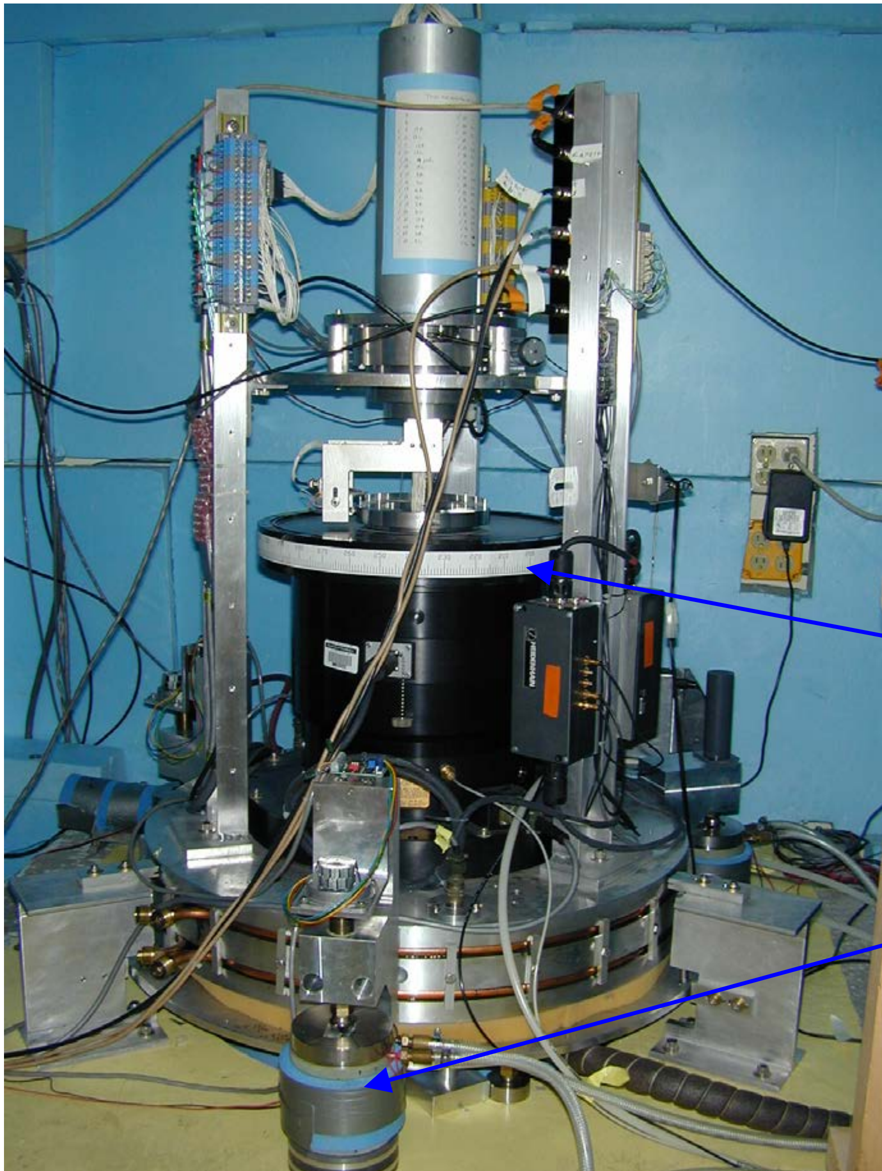
eight 4.84 g test bodies
(4 Be & 4 Ti) or (4 Be & 4 Al)

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

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



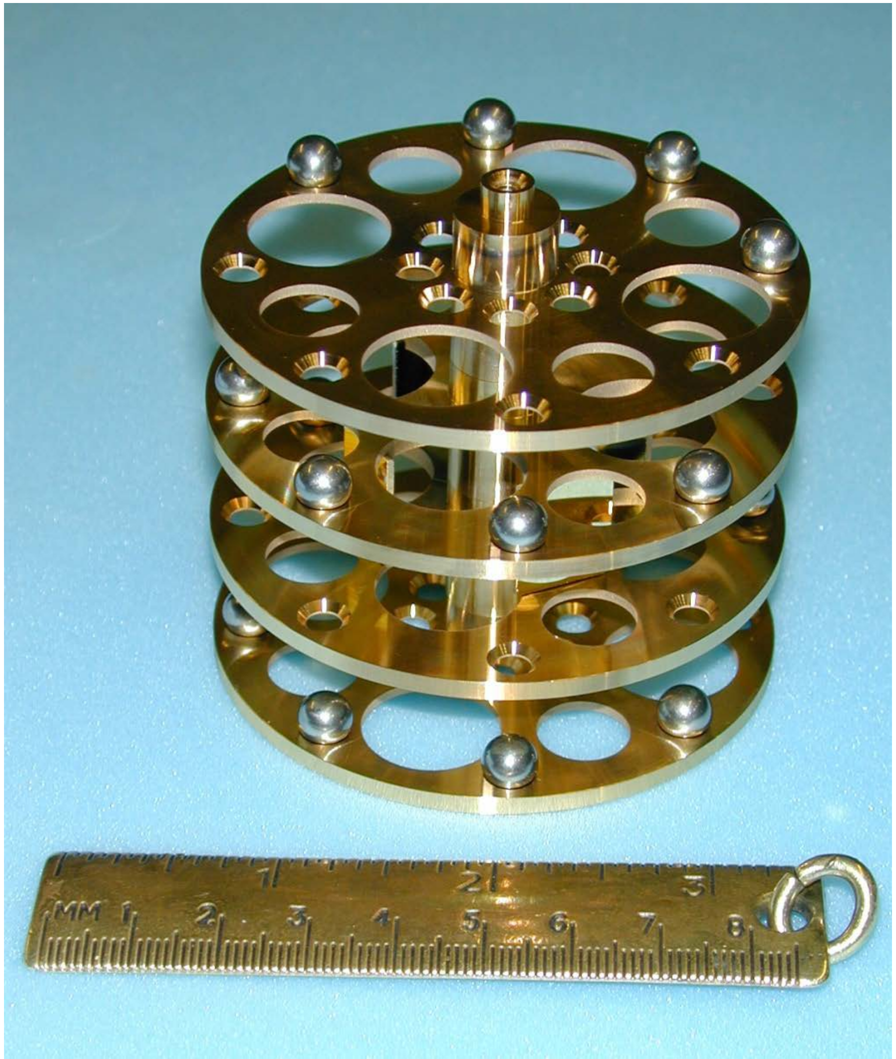
Advantage: signal is boosted from a period of 1 day (terrible) to much lower noise regions

Disadvantage: the turntable must be <u>very</u> good.

air-bearing turntable

thermal expansion feet fedback to keep turntable rotation axis level

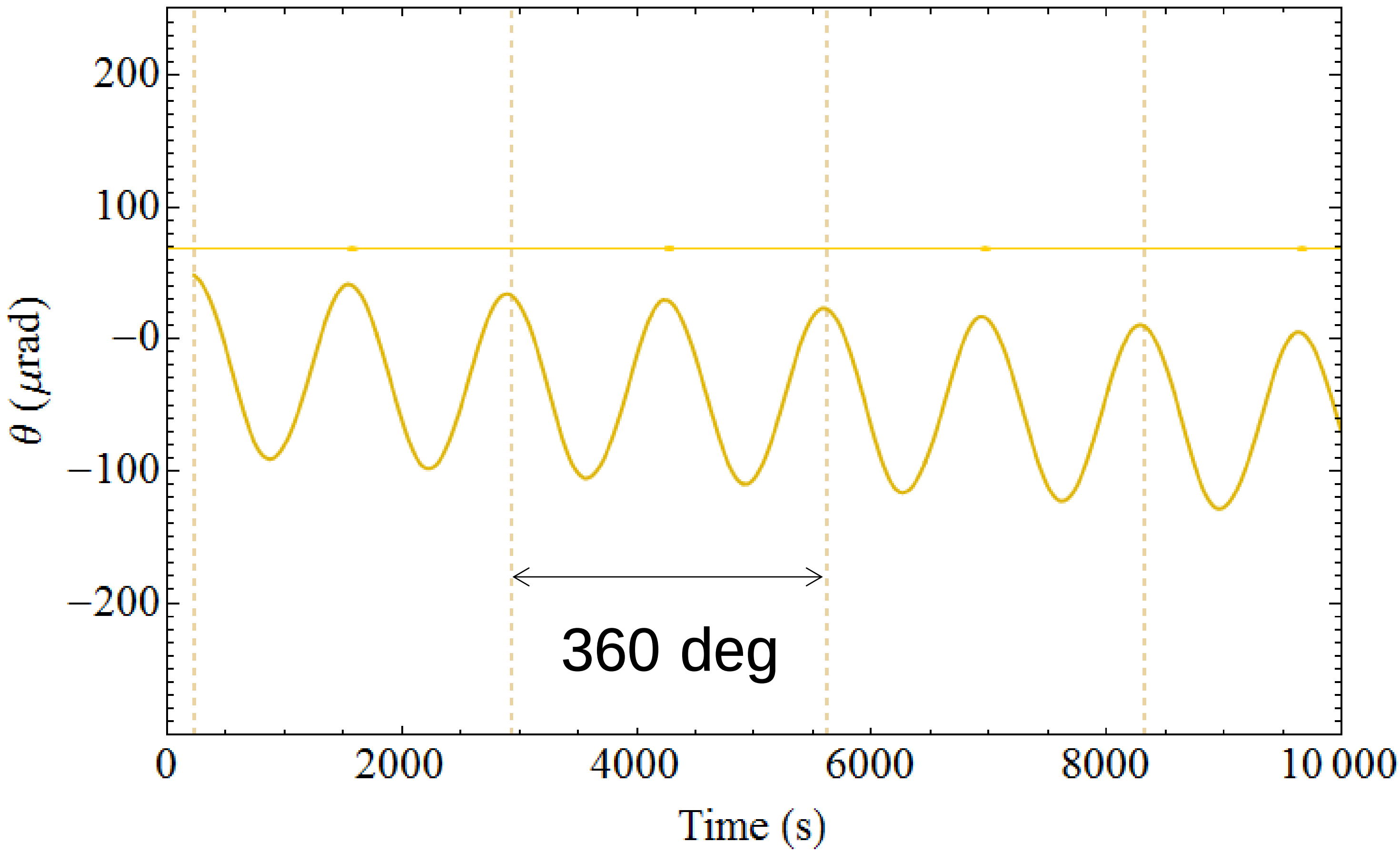
gravity-gradiometer pendulums



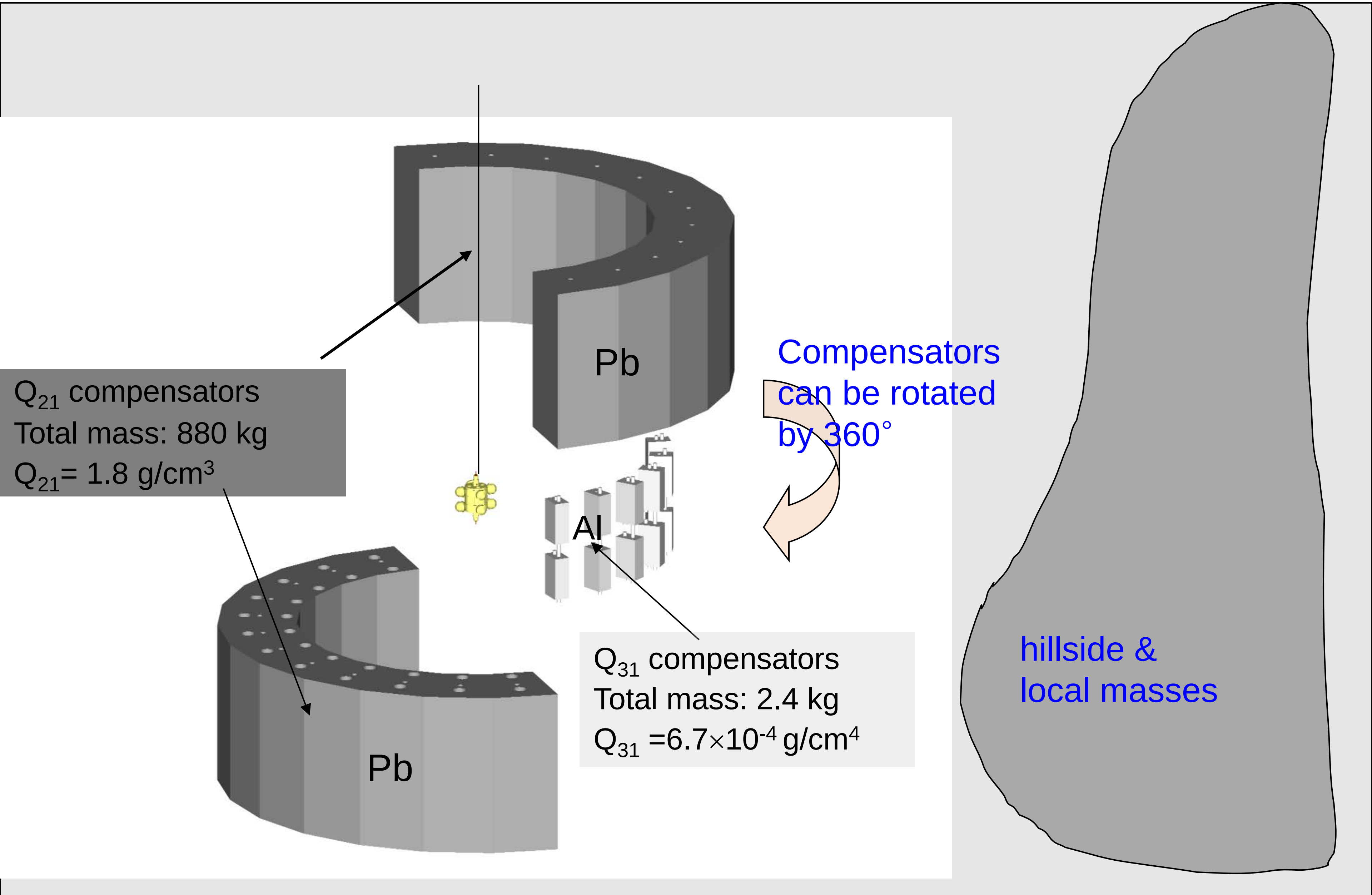
q_{41} configuration on a table

q_{21} configuration installed

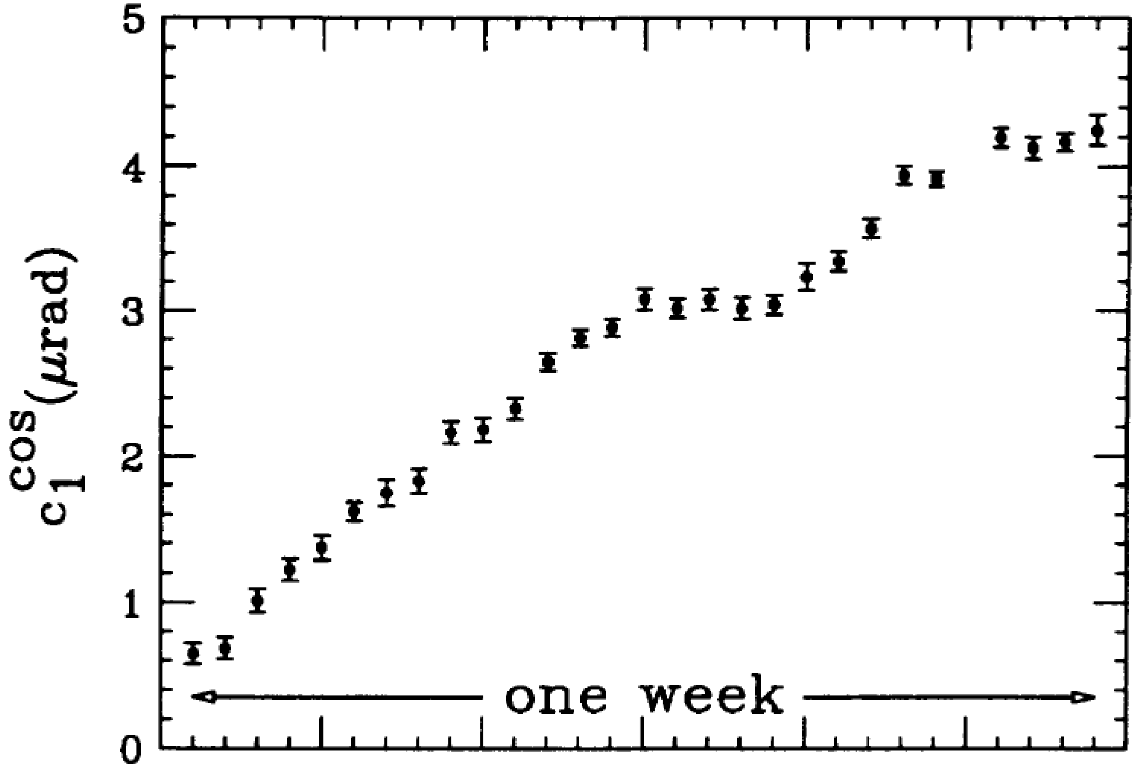
Segment data and fit segments to find the signal at the turntable rotation frequency.
(this example shows gravity-gradient data)



gravity-gradient compensation

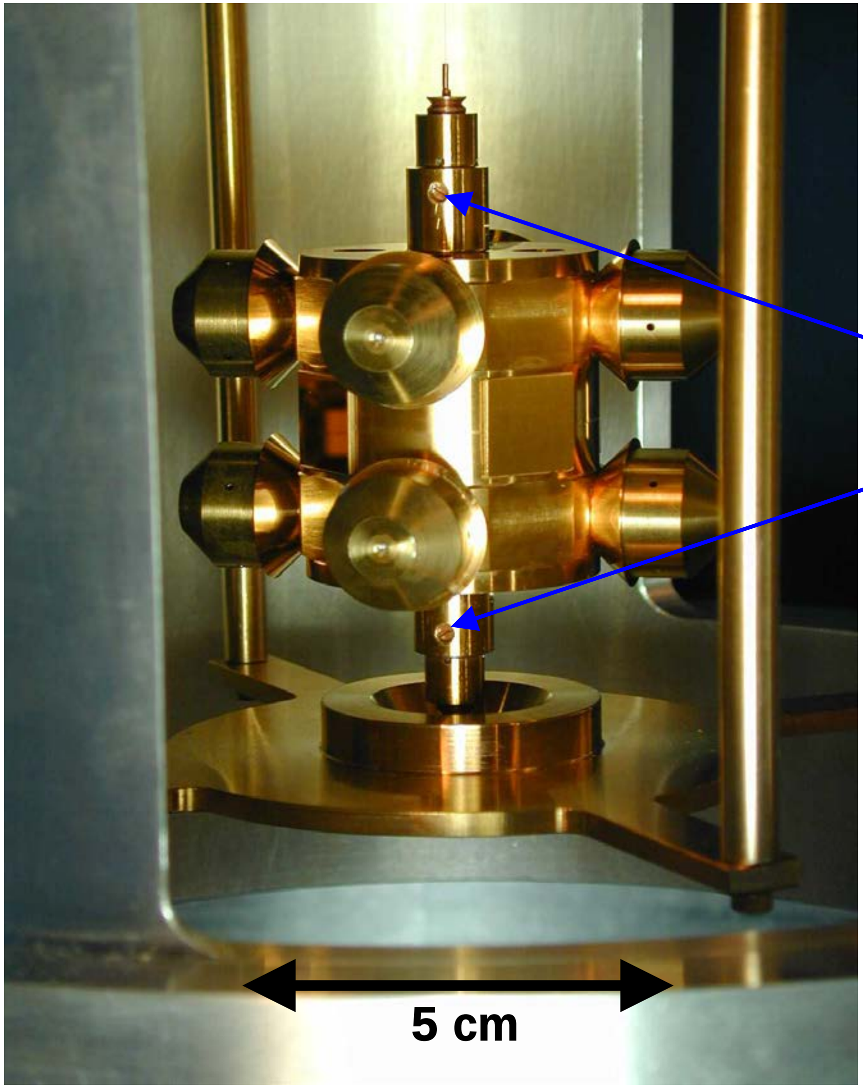


limitations on gradient cancellation



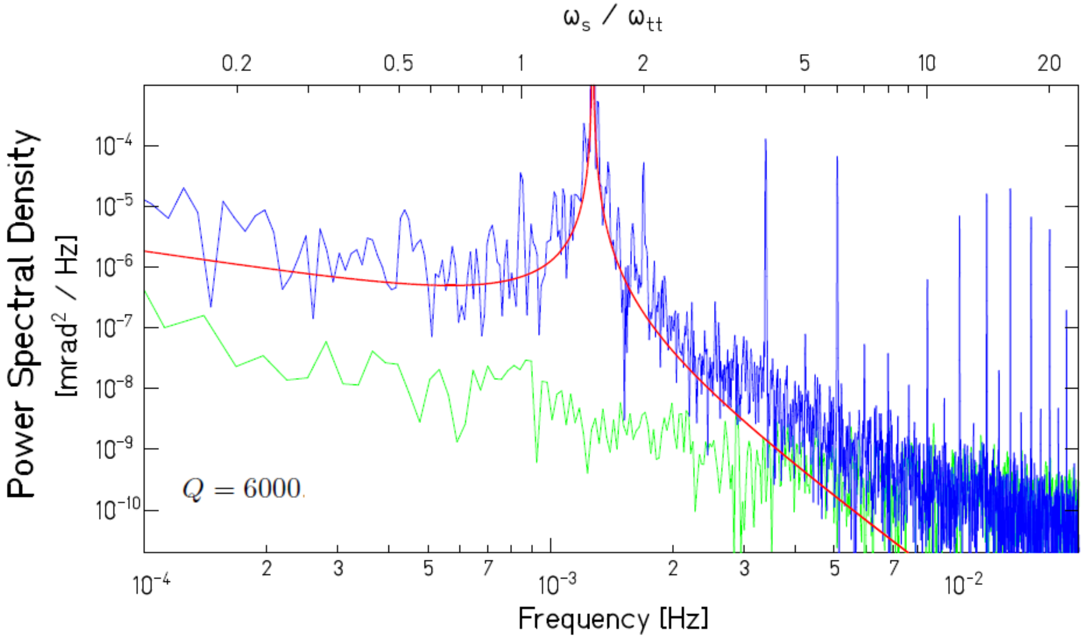
these data were taken in early November

We can’t stop the weather, but we can tune away residual gravity moments



8 tiny screws used to minimize residual gravity moments

this requires a patient grad student with good hands



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

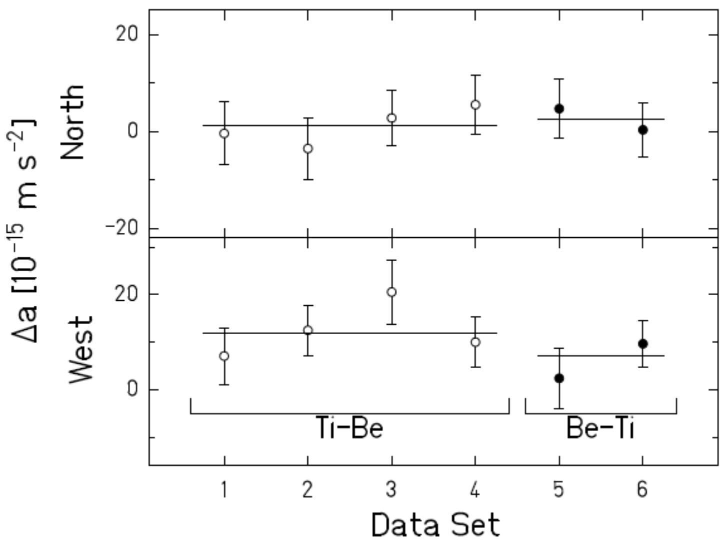
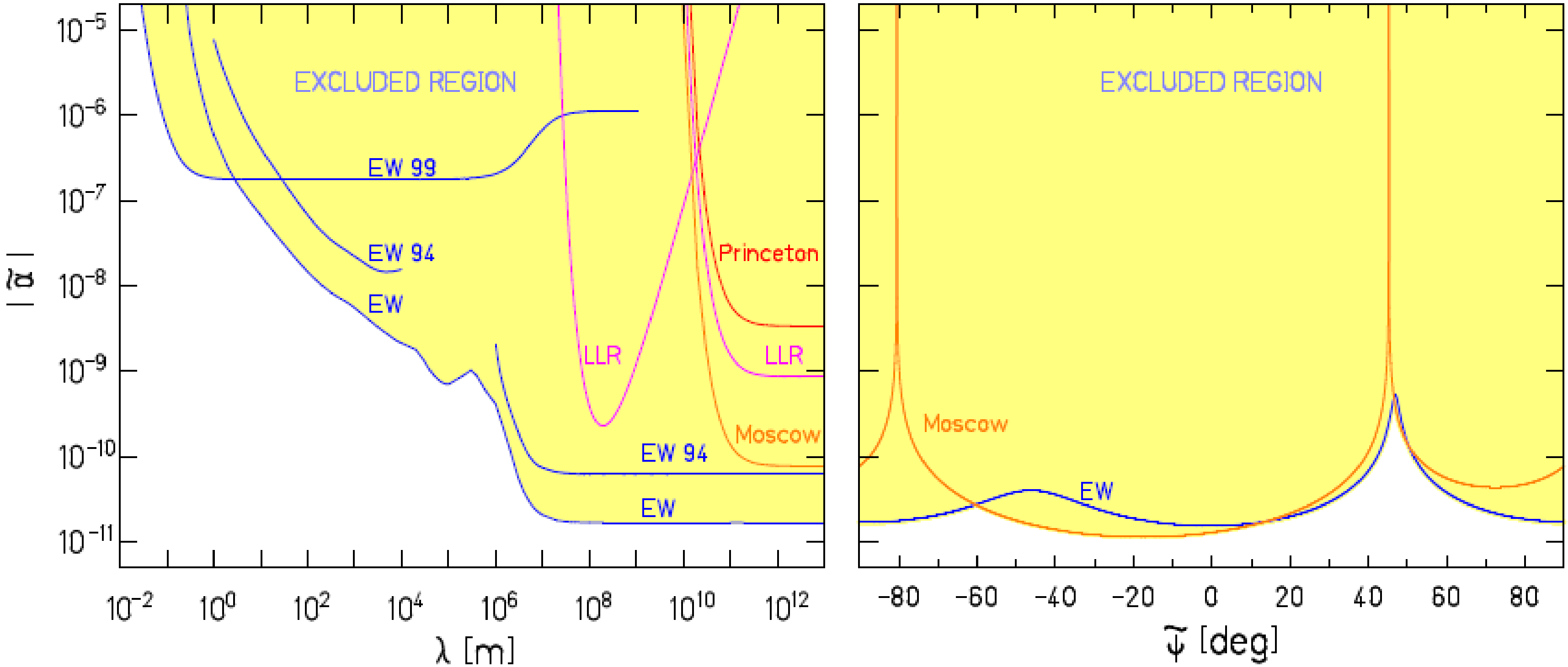


Figure 5. Data collected in the Ti-Be (first 4 runs) and Be-Ti (last 2 runs) configurations of the pendulum. The final result is in the difference between the means of the two configurations (shown as solid lines).

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

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)

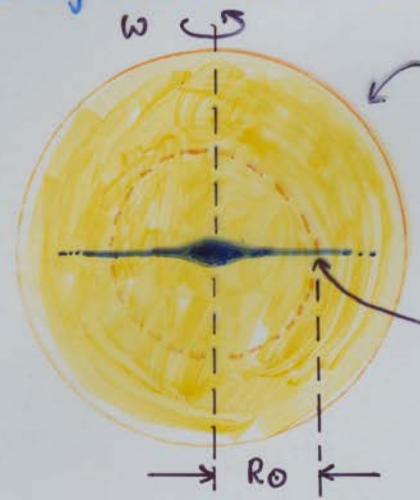
Is gravity the only long-range force between dark and luminous matter?

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

OUR EXPERIMENTAL STRATEGY

C.W. STUBBS

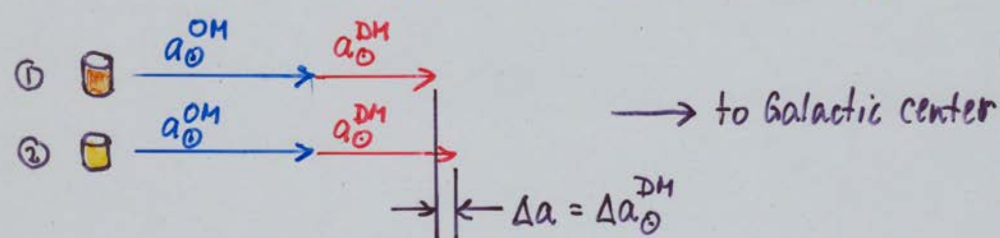
Check universality of free fall for different materials falling toward center of our galaxy.



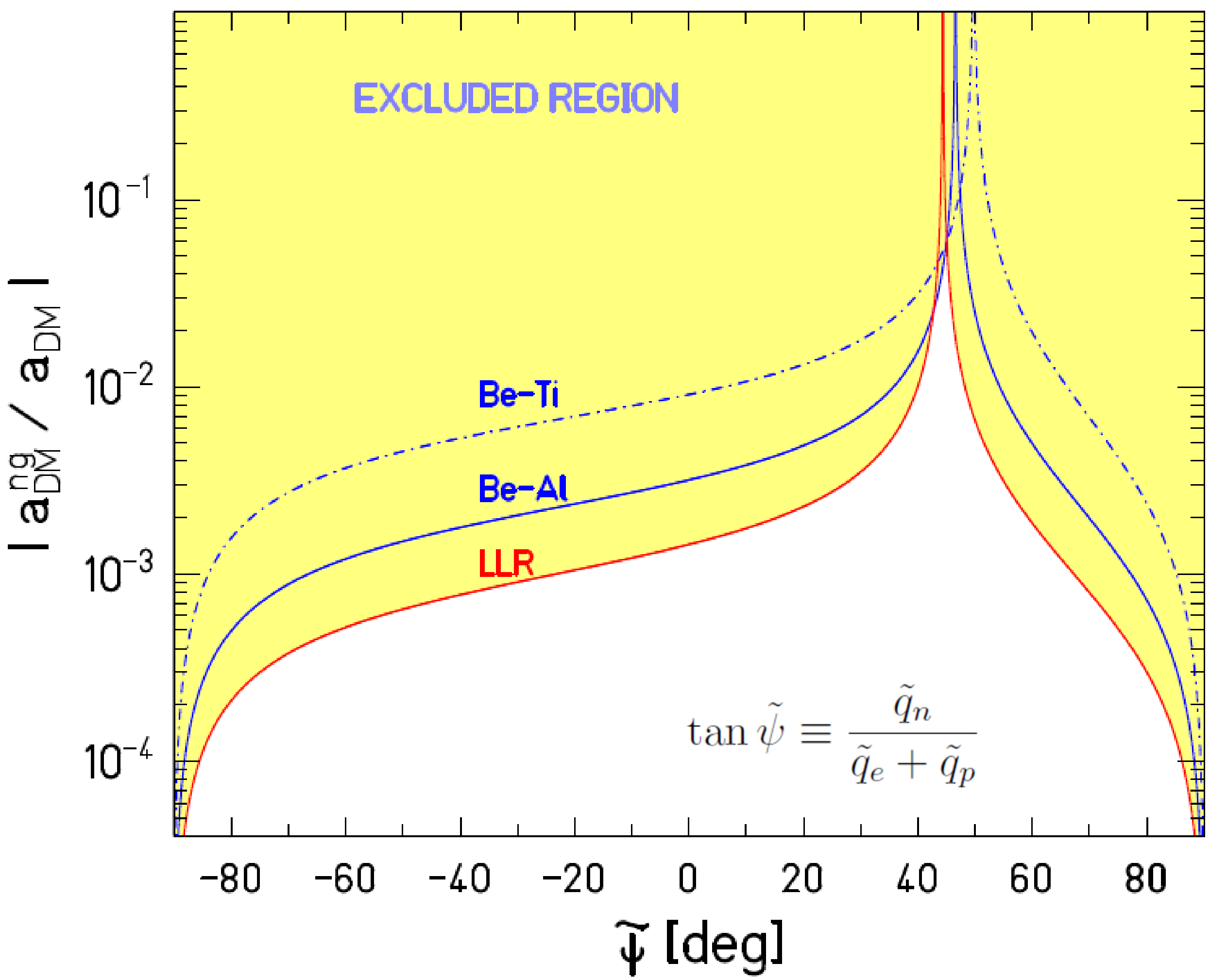
although 90% of galaxy mass is thought to be DM much of it lies outside $R_\odot$, so

$$a_\odot^{DM} = 25\text{-}30\%\ a_\odot \Rightarrow \boxed{a_\odot^{DM} \approx 5 \times 10^{-9}\ \mathrm{cm/s^2}}$$

we can make interesting statement about non-grav. component of $a_\odot^{DM}$ if we can detect differential accels. with a sensitivity of $10^{-3} a_\odot^{DM} \sim 5 \times 10^{-12}\ \mathrm{cm/s}$



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



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

gravitational properties of antimatter

Some people suggest that antimatter could
could fall up with acceleration -g! They propose
to test this by dropping antihydrogen, a very difficult
and challenging experiment. How plausible is this
scenario?

If antimatter falls up:

1) photons (their own antiparticles) should not fall

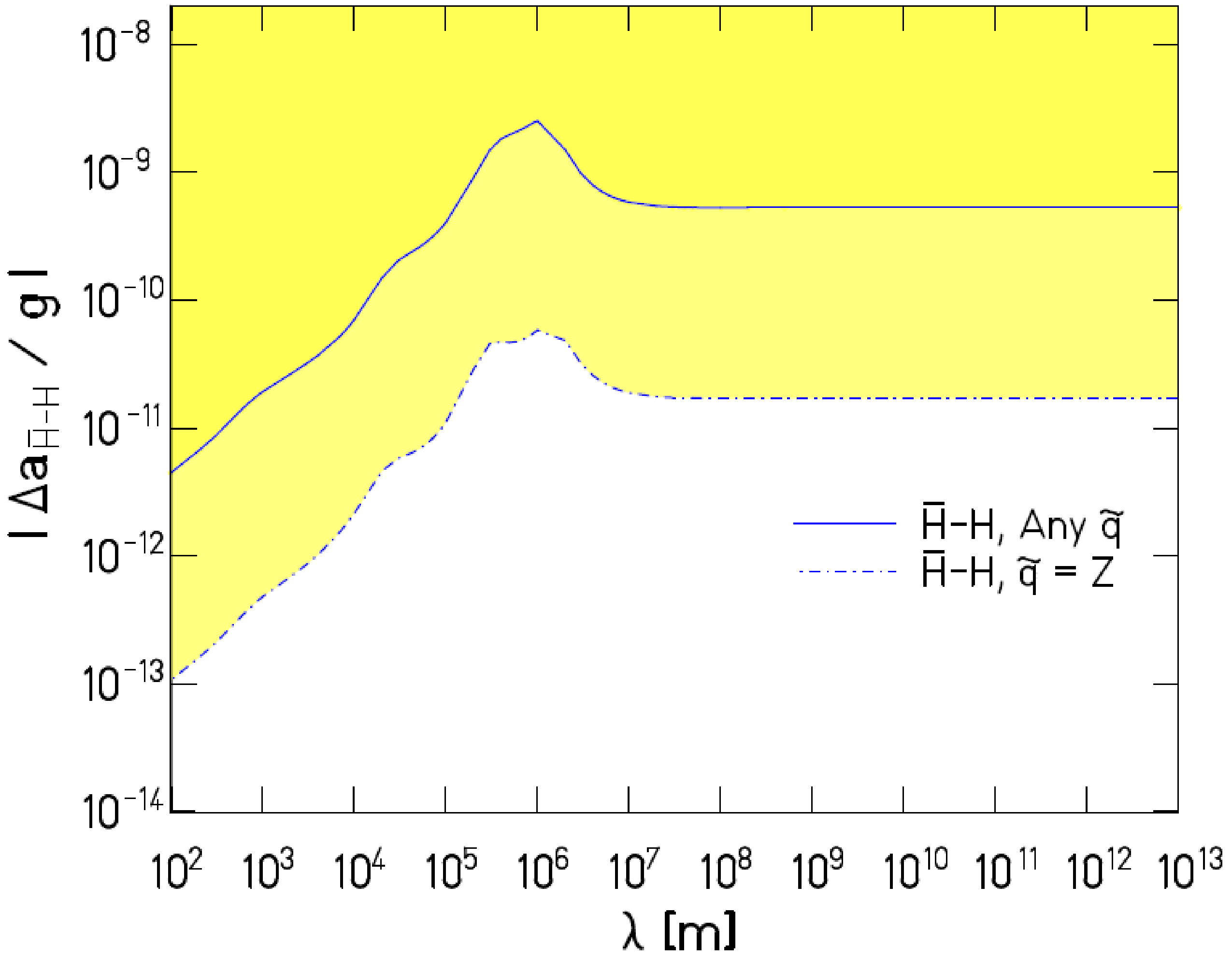
2) nucleons (~99% of their mass consists of glue & anti-glue) should fall with ~100 times smaller accelerations than electrons

gravitational properties of antimatter (quantitative argument)

If H and anti-H fall with different accelerations gravity must have a vector component. Consider an EP test with H and anti-H. This would have $\Delta(Z/\mu)=2$. Our Be/Al WEP test has $\Delta(Z/\mu)=0.0382$ and we see no evidence for such an interaction with $\Delta g/g$ greater than a few parts in 10^{13}.

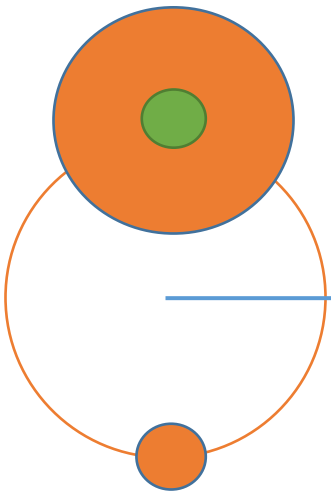
The following plot assumes only CPT invariance and the impossibility of exact cancellation between V and S interactions

95 CL constraints on gravi-vector difference in free-fall accelerations of anti-H and H



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

Combining LLR data and a laboratory WEP test to make a loophole-free test of the SEP



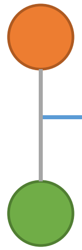
$E_{grav}/(M_{\odot}c^2) = -4.6 \times 10^{-10}$

Earth has a massive Fe core.

Earth and Moon test bodies differ in both composition and gravitational binding energy

$E_{grav}/(M_{\oplus}c^2) = -0.2 \times 10^{-10}$

Moon does not have massive Fe core



Only composition differs.

A loophole-free test of the Strong EP

- Lunar laser ranging:

  $\eta_{SEP} + \eta_{CD} = (-0.8 \pm 1.3) \times 10^{-13}$

  (goal of $\eta_{LLR} \sim 10^{-14}$)

- Our result from comparing accelerations of moon-mantle and earth-core test bodies toward the sun

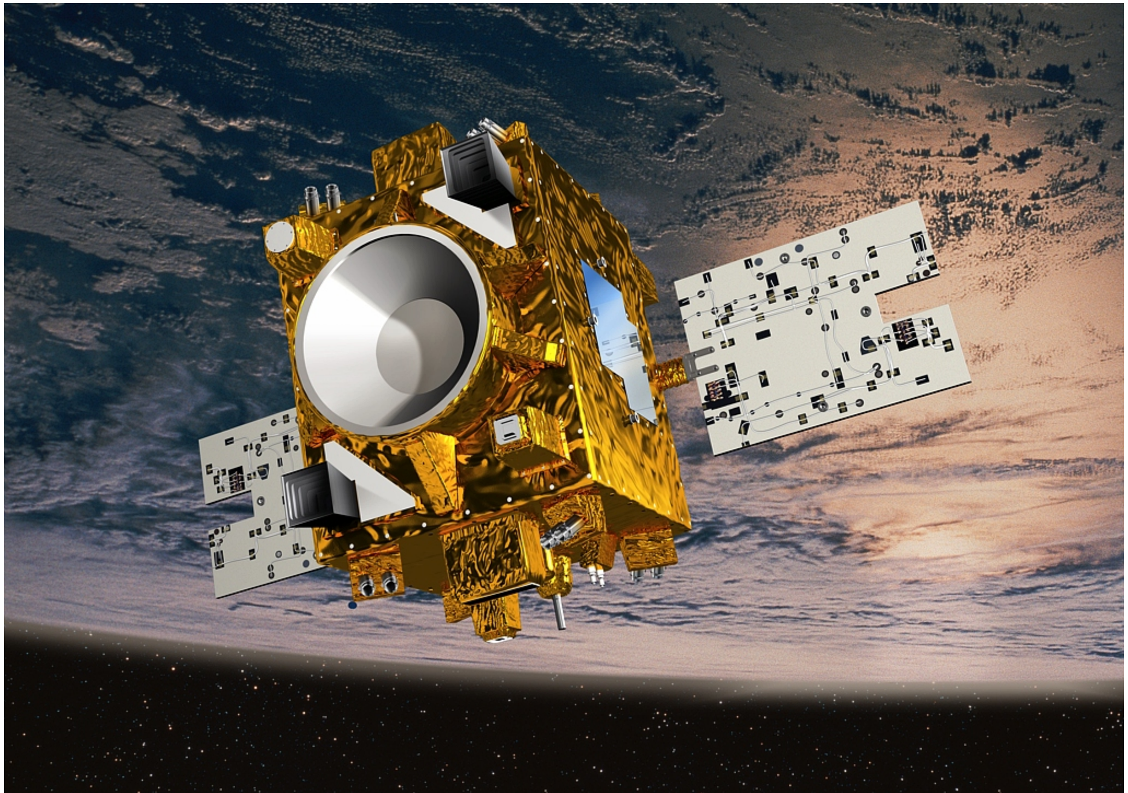
  $\eta_{CD} = (1.2 \pm 1.1) \times 10^{-13}$

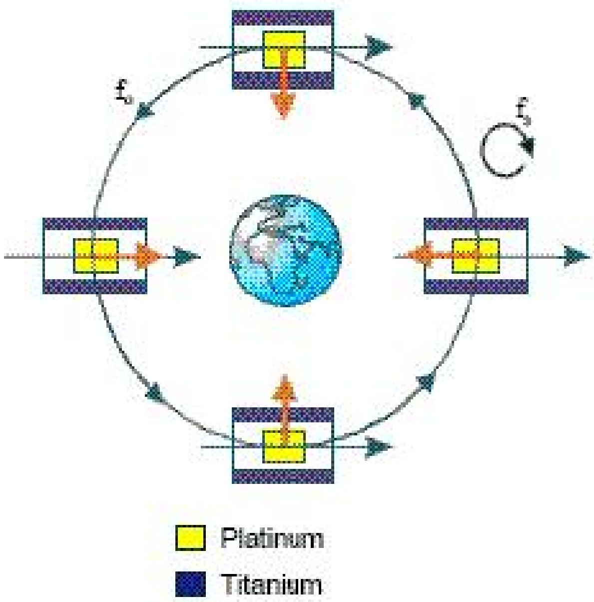
- Combined result

  $|\eta|_{SEP} < 6 \times 10^{-4}$ at 1σ

Microscope: French-German collaboration to test the WEP to 1 part in 10^{15} using Ti/Pt-Rh test bodies and a Pt-Rh/Pt-Rh null comparison in a drag-free satellite operated in both inertial and rotating modes. This Galileo-type experiment will be launched in spring 2016

Advantages: signal 1000× larger, grav. gradients much smaller





motivations for sub-millimeter tests of the inverse-square law (ISL)

- explore an untested regime

- probe the dark-energy length scale

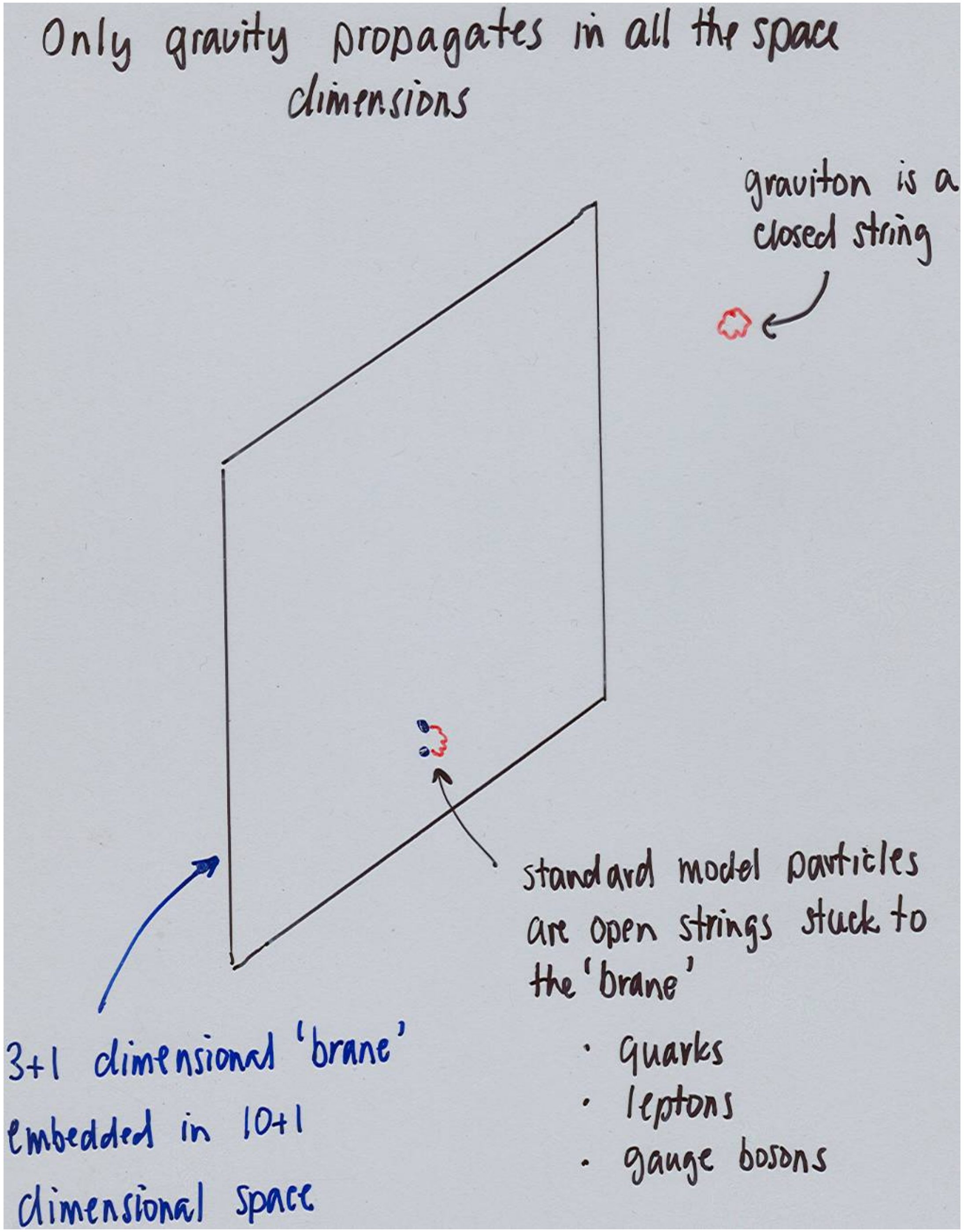
$$\rho_{\rm d} \approx 3.8 \ {\rm keV/cm^3}$$
$$\lambda_{\rm d} = \sqrt[4]{\hbar c/\rho_{\rm d}} \approx 85 \ \mu{\rm m}$$

- search for proposed new phenomena

  large extra dimensions: why is gravity so weak?

  chameleons: why don't we see the many "gravitationally" coupled particles of string theory?

"large" extra dimensions could explain why gravity is so weak:
most of its strength has leaked off into places we cannot go



Gauss's Law and extra dimensions

moral: to see the true strength of gravity you have to get really close

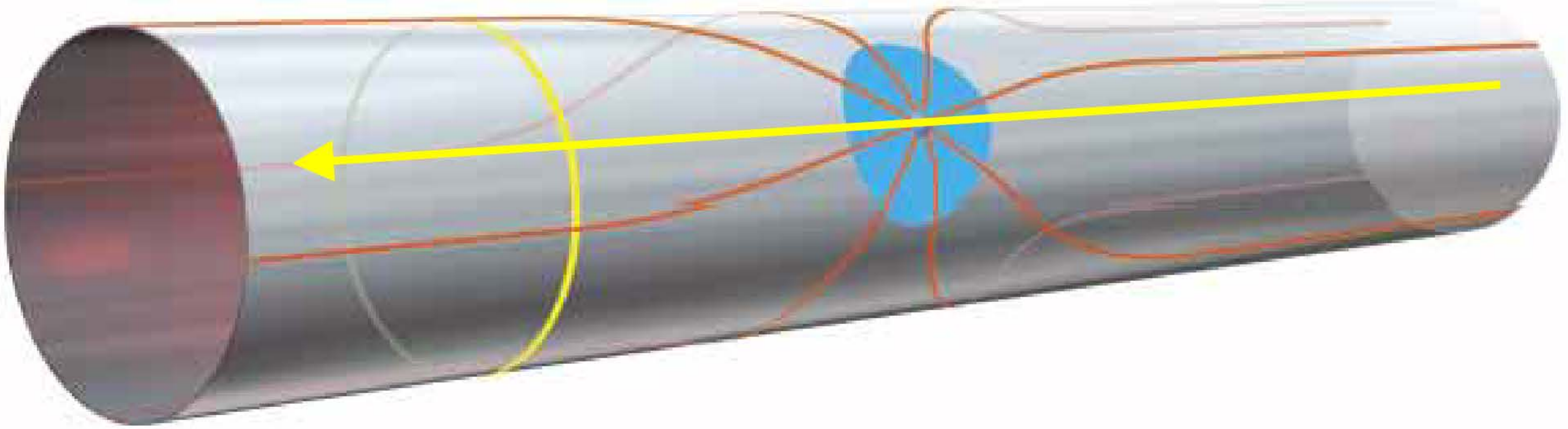


illustration from Savas Dimopoulos

Chameleons and the ISL

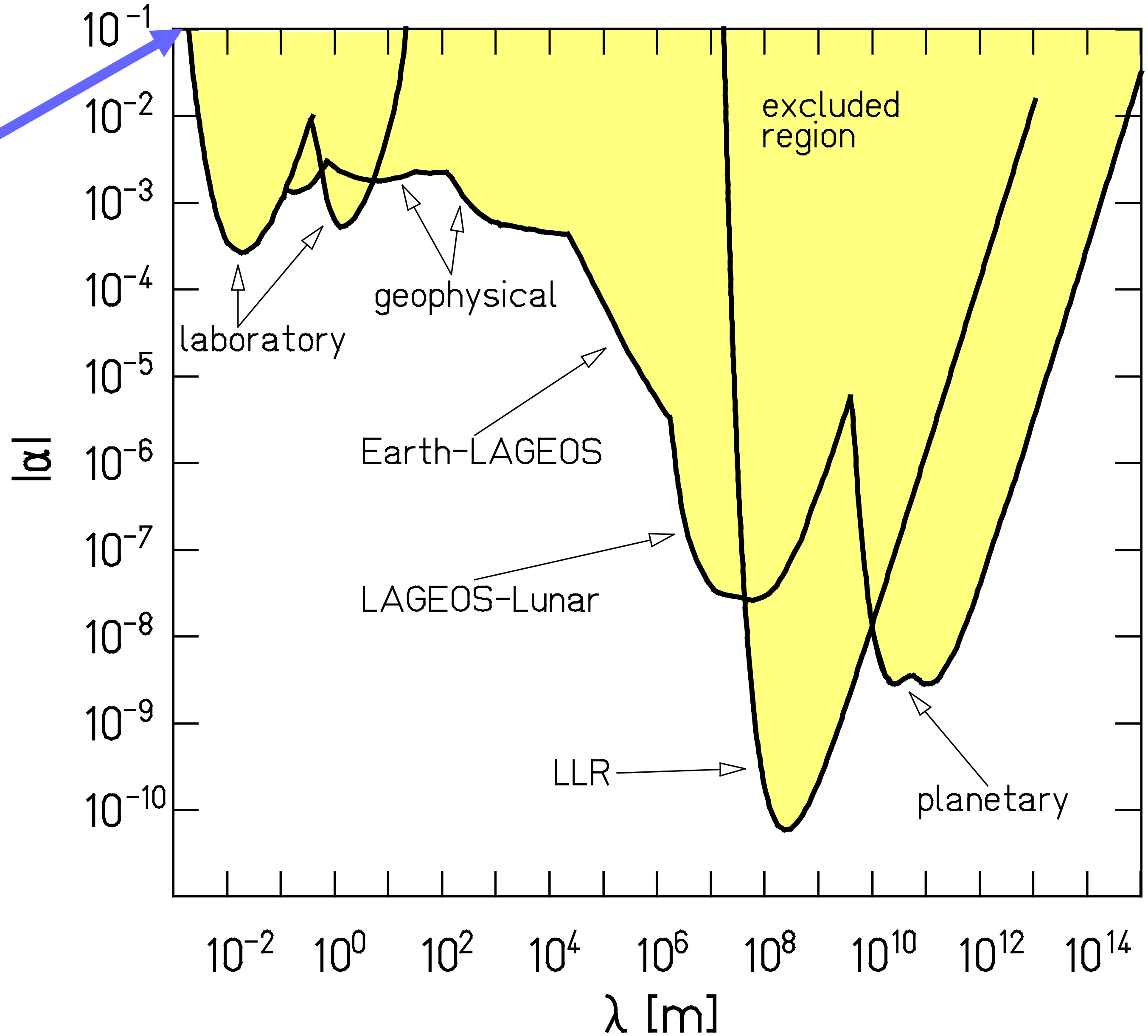
Chameleons circumvent experimental evidence against gravitationally-coupled low-mass scalar particles by adding a self-interaction term to their effective potential density.

This gives massless chameleons an effective mass in presence of matter so that a test body's external field comes entirely from a thin skin of material of thickness ~ $1/m_{eff}$. An object with ρ=10 g/cm^3 and natural values of the chameleon couplings has a skin thickness of ~ 60 μm; making its chameleon field very weak and hard to detect.

Khoury and Weltman, PRD 69, 0444026 (2004)
Gubser and Khoury, PRD 70, 104001 (2004)

95% confidence limits on ISL violation as of 2000

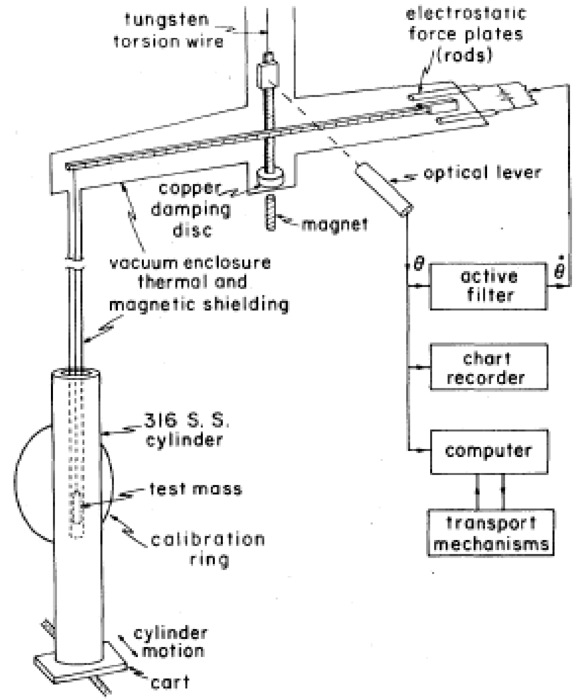
what happens here? Could there be new physics?

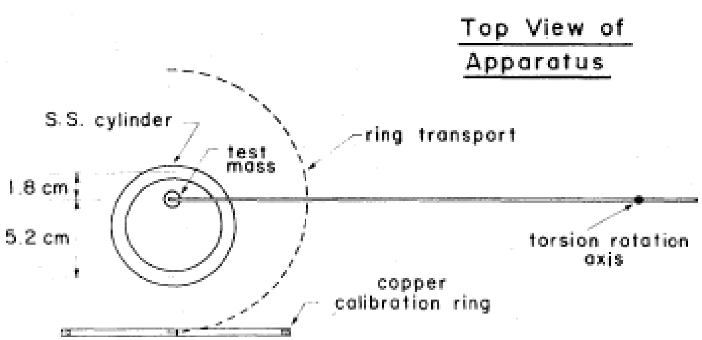


Irvine null test of the ISL

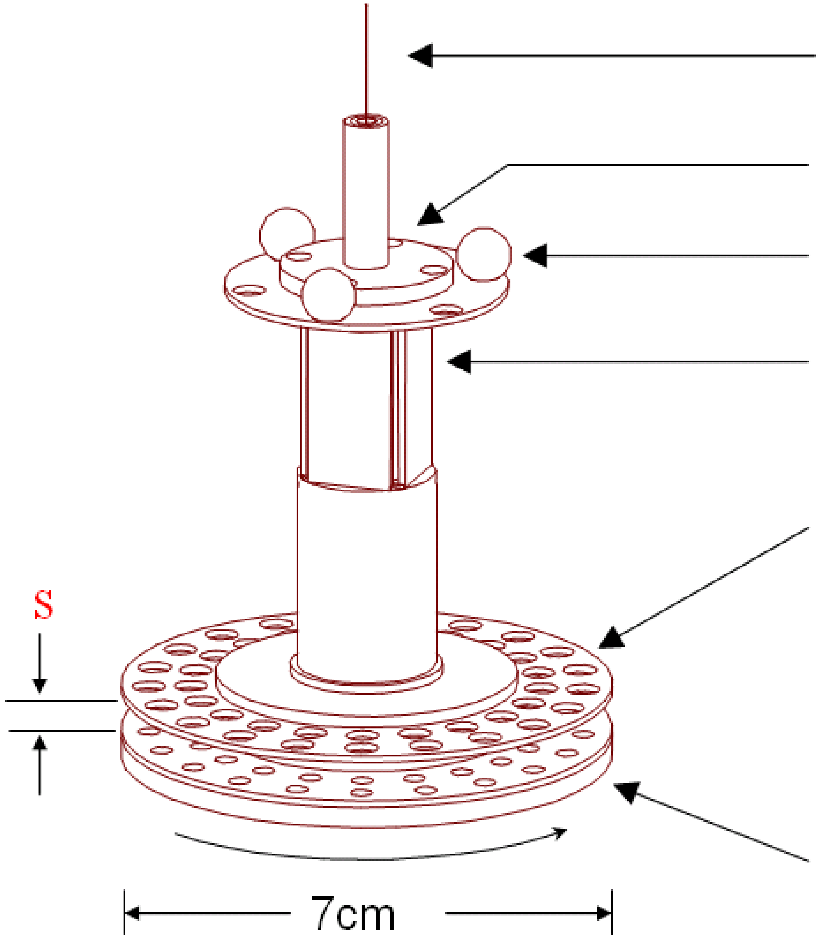
Hoskins et al. PRD 32, 3084 (1985)

Does a cylinder inside an "infinitely long" cylindrical shell feel a force?

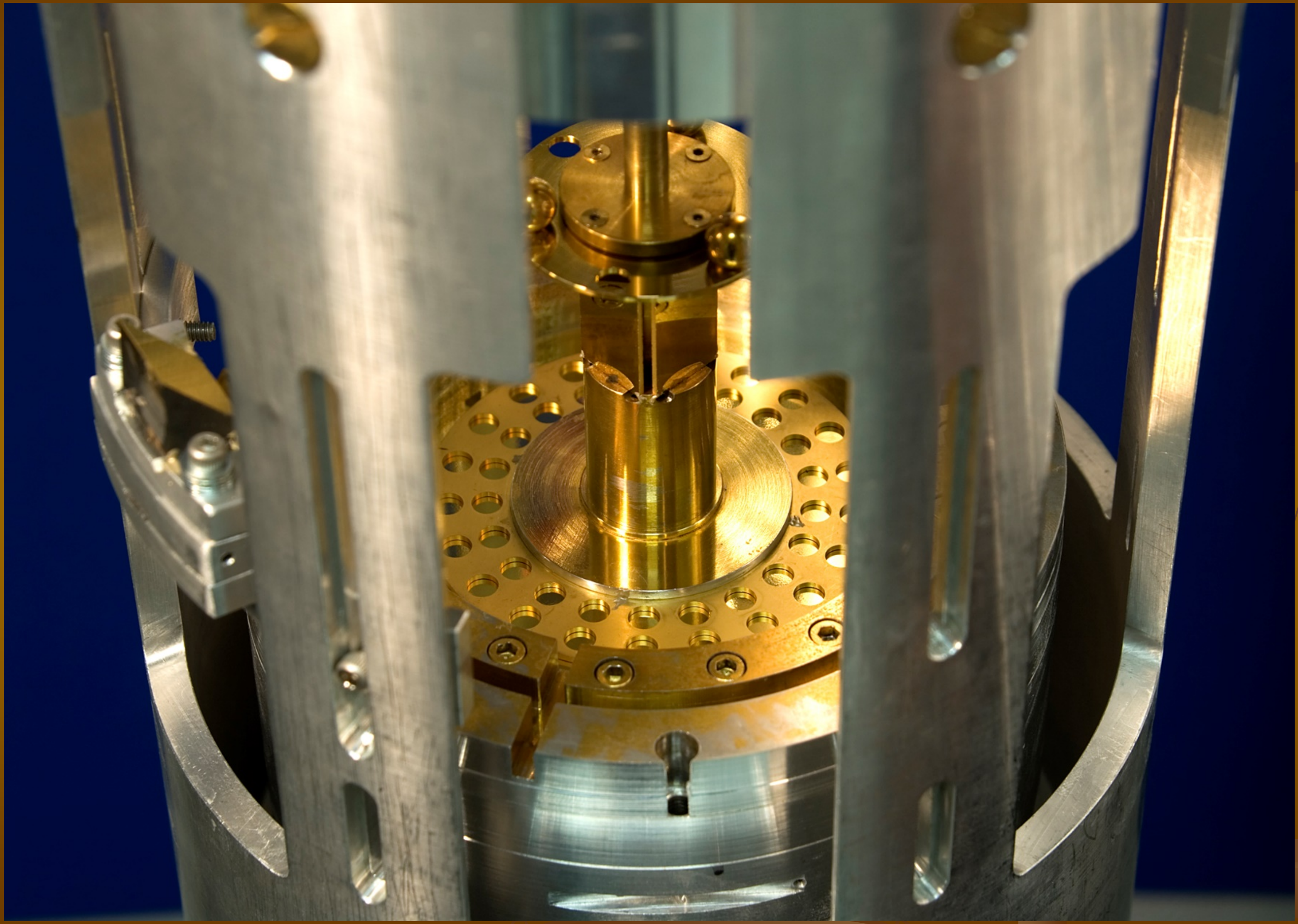




the 42-hole partial-null test of the ISL



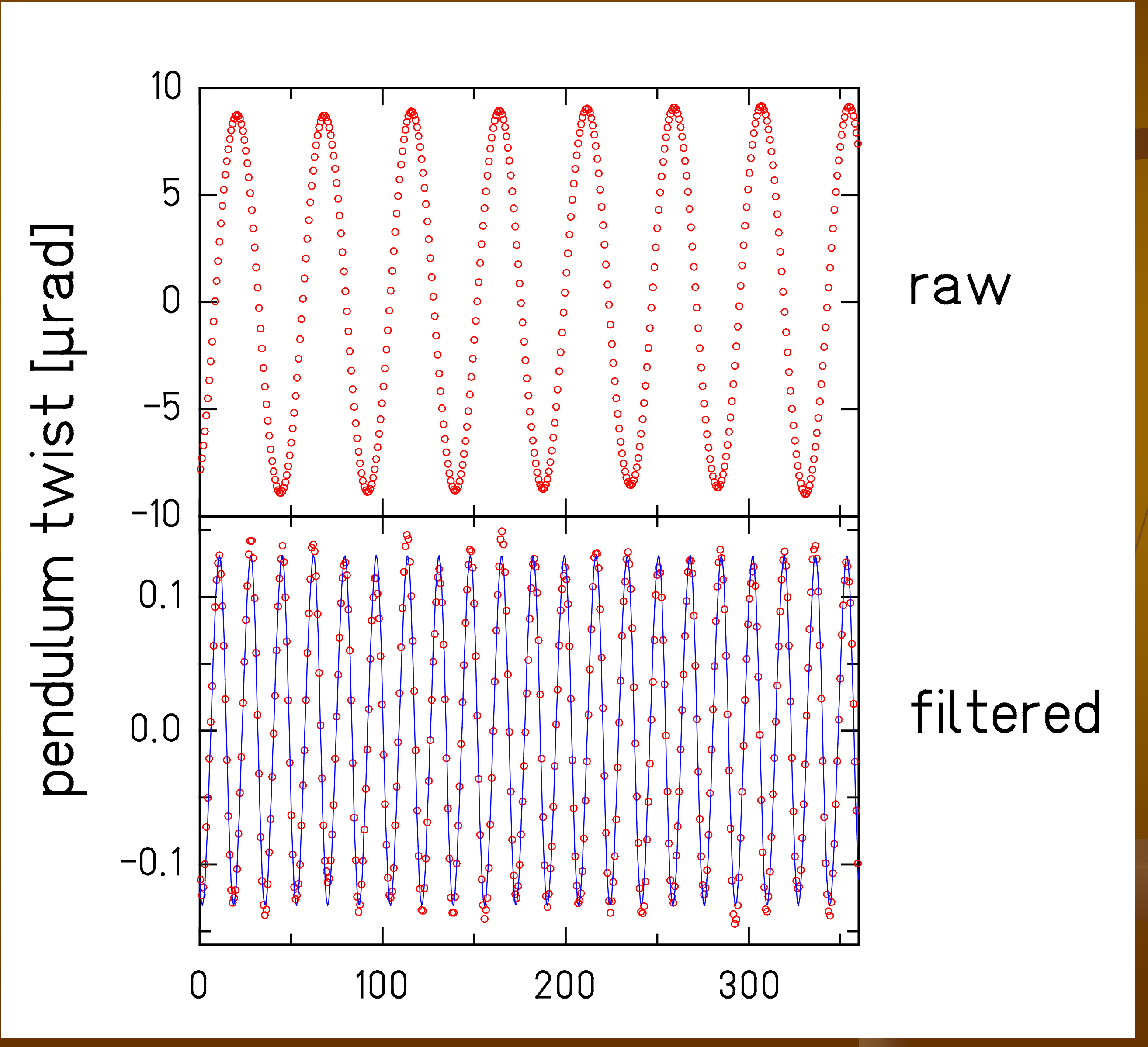
D.J. Kapner et al., PRL 98, 021101(2007)



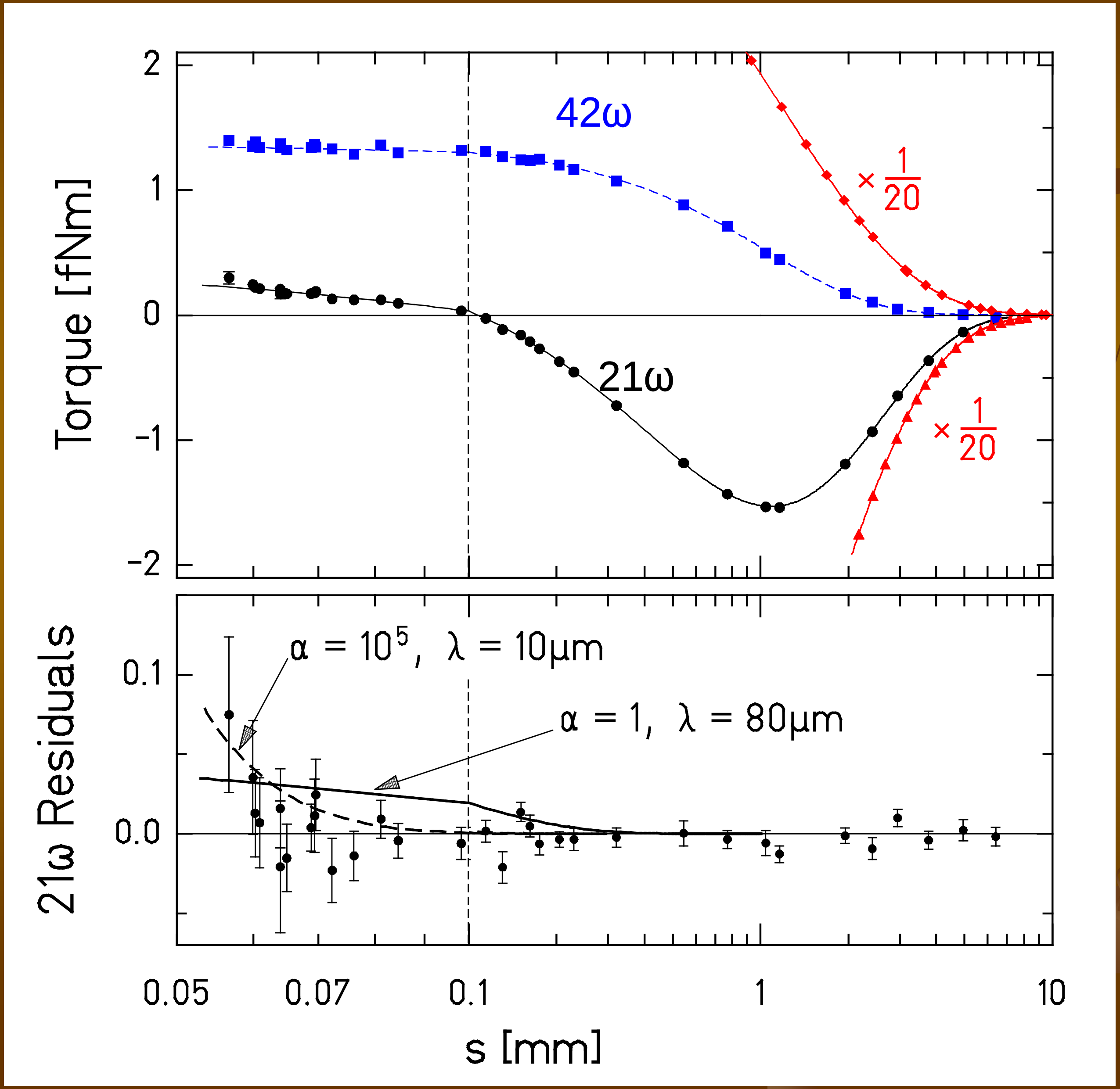
Mary Levin photo

signal processing

these data were taken with the calibration turn-table stationary

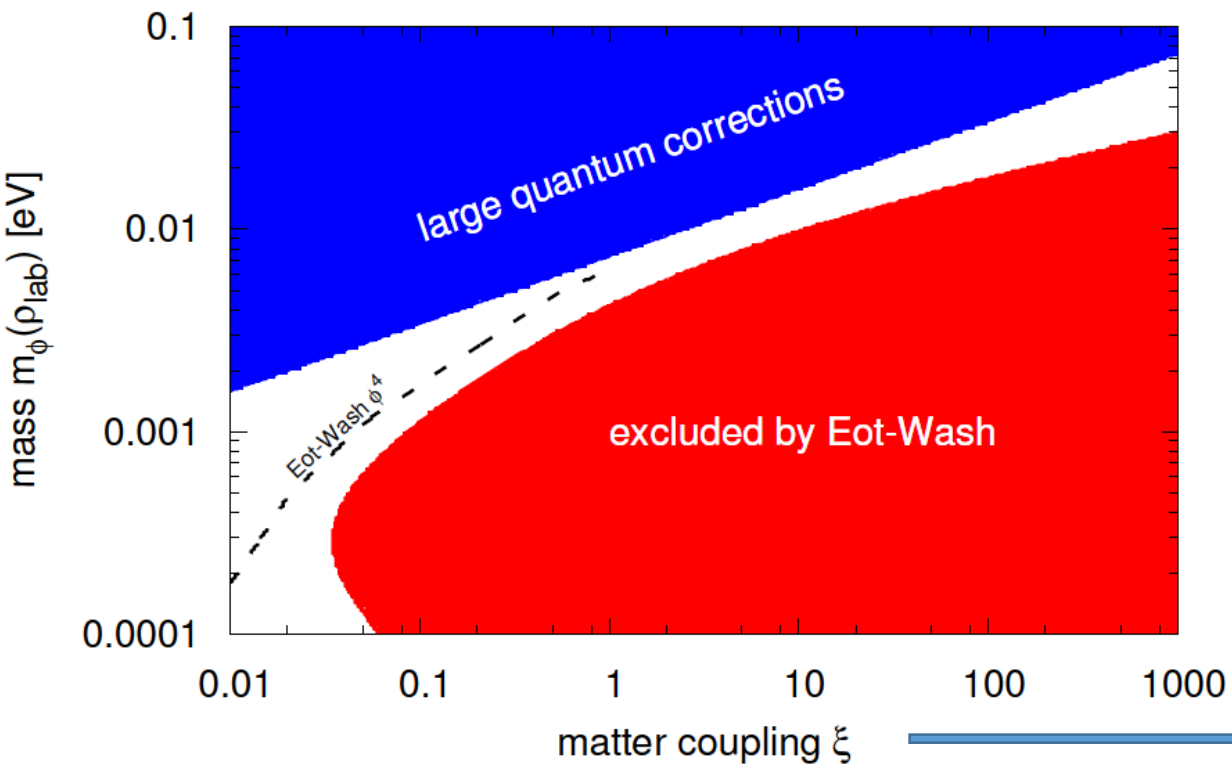


data from 42-hole experiment III



Some implications of Kapner et al.' s ISL results:

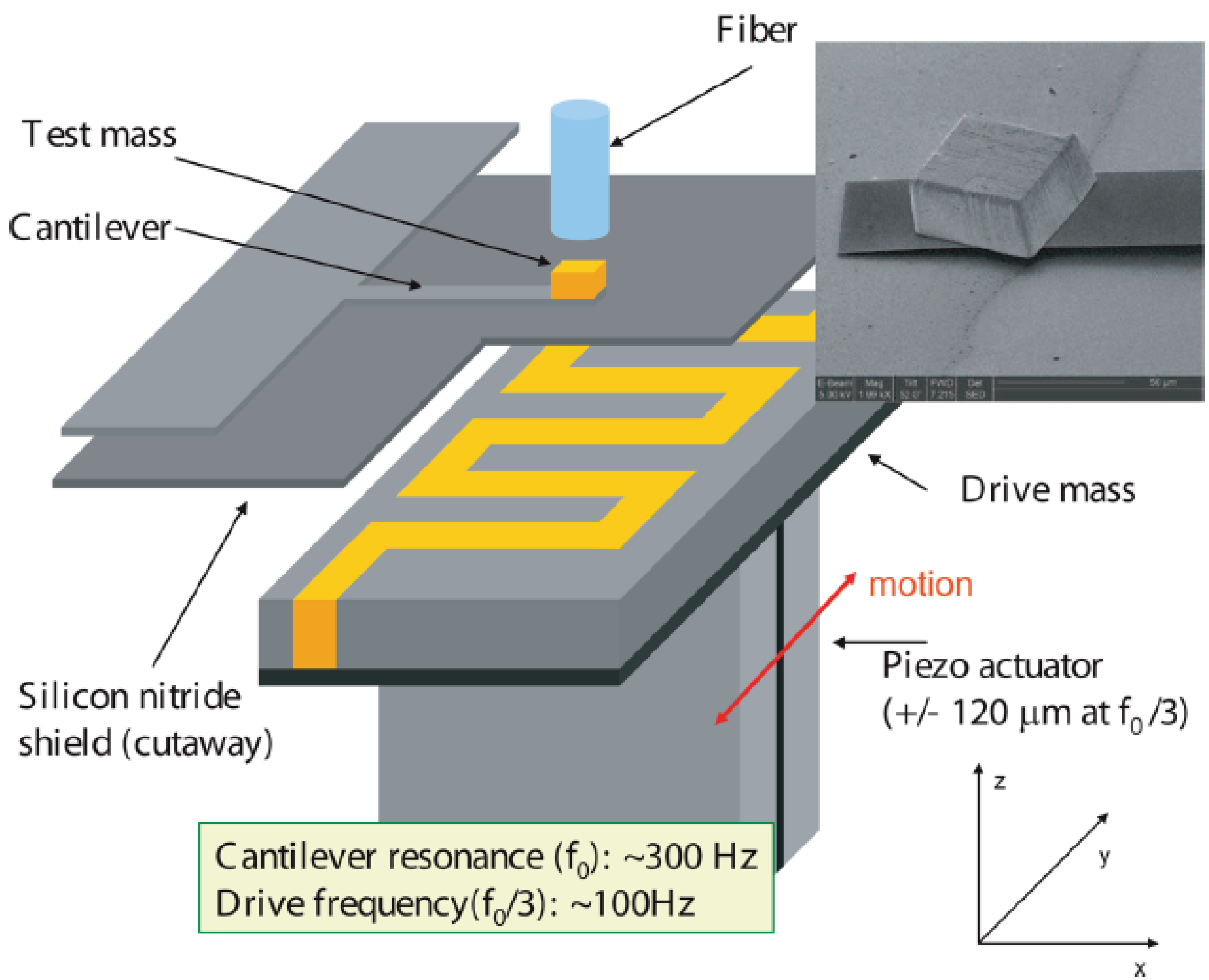
largest extra dimension has r < 44µm
dilaton mass > 3.5 meV
strong constraints on generic chameleons



"natural value" of ξ is 1

Upadhye, Hu and Khoury, PRL 109, 041301 (2012)

Kapitulnik group at Stanford probes shorter ranges with low-temperature micro-cantilevers



cantilever has 1.5 μg Au test mass with Q~10,000 at T_{eff} ~ 2 – 3 K

A. A. Geraci et al., Phys. Rev. D78, 022002 (2008).

data from Geraci et al.'s experiment

GERACI, SMULLIN, WELD, CHIAVERINI, AND KAPITULNIK

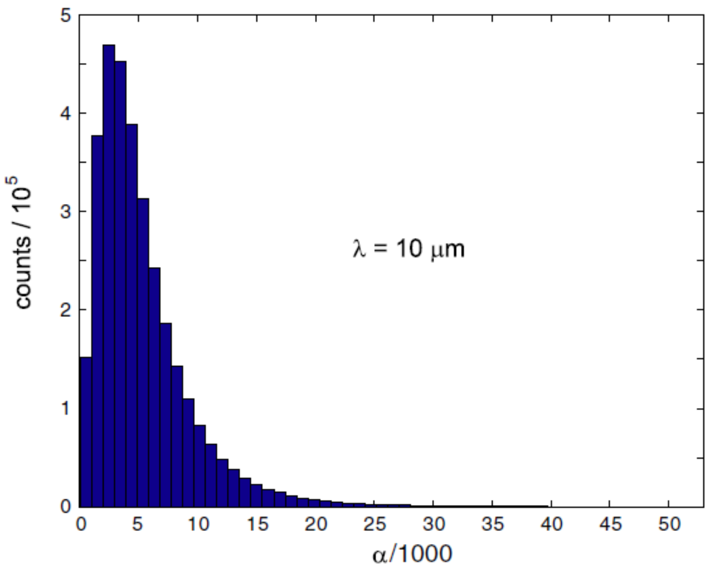


FIG. 6 (color online). Histogram of best-fit α results for $\lambda = 10\ \mu$m.

statistical error dominated by thermal noise in the cantilever

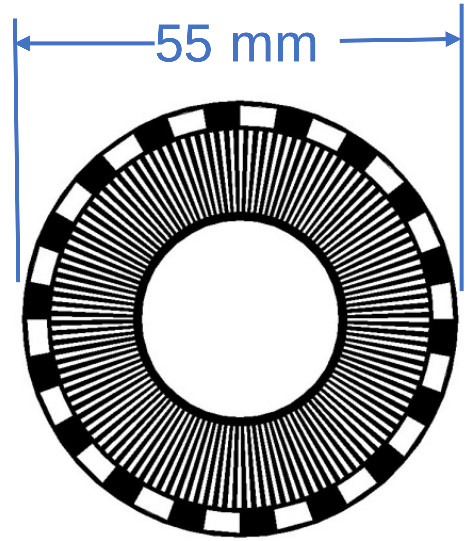
sensitivity was sufficient to exclude proposed forces much stronger than gravity but not yet high enough to see gravity itself

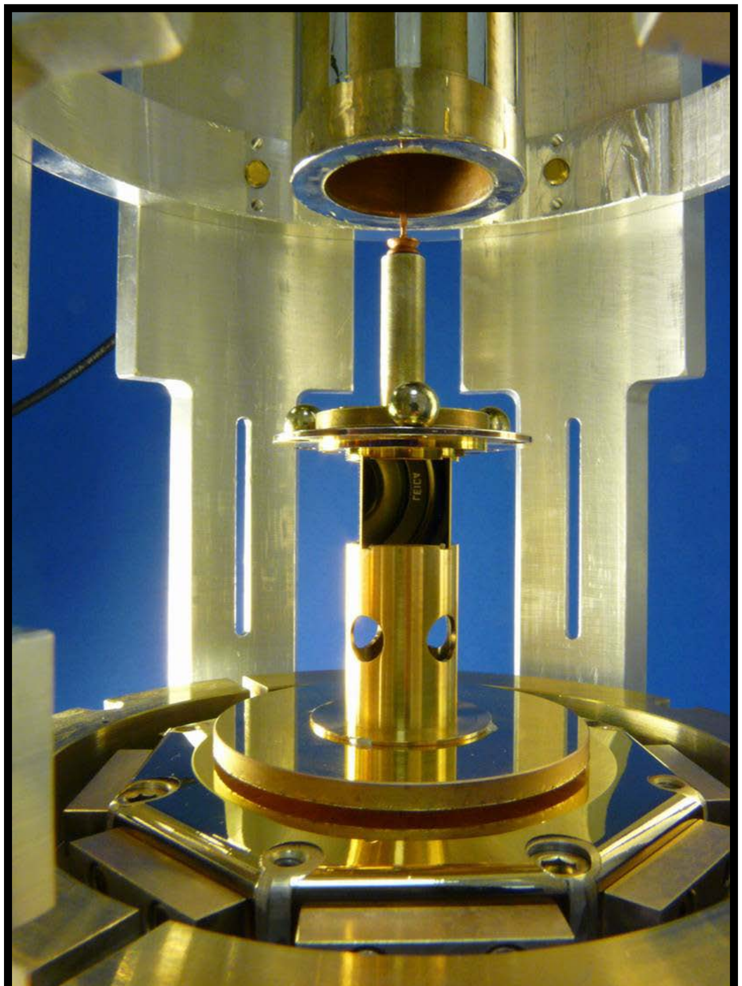
TABLE V. Experimental limits on Yukawa forces.

λ (μm)	Mean (MC) α	95% exclusion α
4	8.6×10^6	3.1×10^7
6	1.6×10^5	4.6×10^5
10	5.6×10^3	1.4×10^4
18	5.1×10^2	1.1×10^3
34	1.2×10^2	2.5×10^2
66	7.0×10^1	1.5×10^2

UW Fourier-Bessel ISL instrument

Ted Cook's 2013 PhD project. Now being upgraded by John Lee.





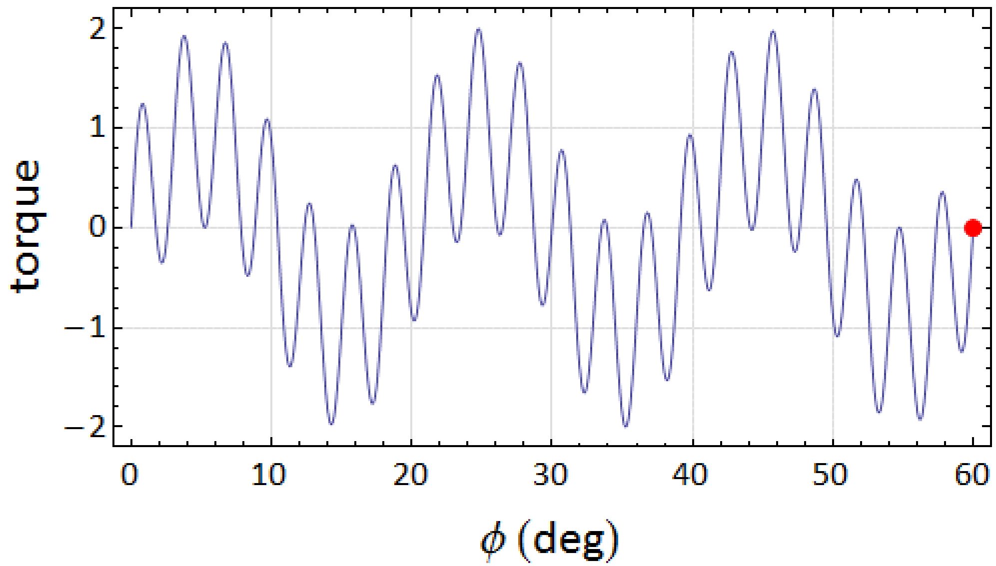
Active elements of pendulum and rotating attractor are cut from 50 micron W (Pt) foils. Have both 18-fold and 120-fold azimuthal symmetries.

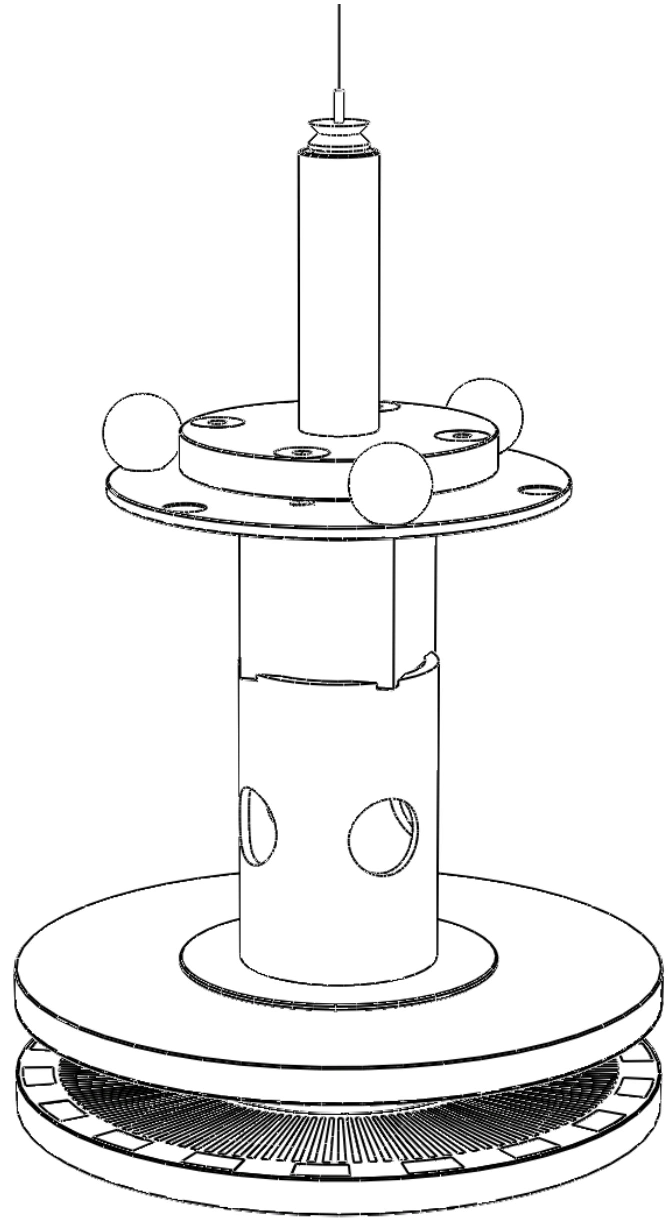
18-fold mass=214 mg,

120-fold mass= 627 mg

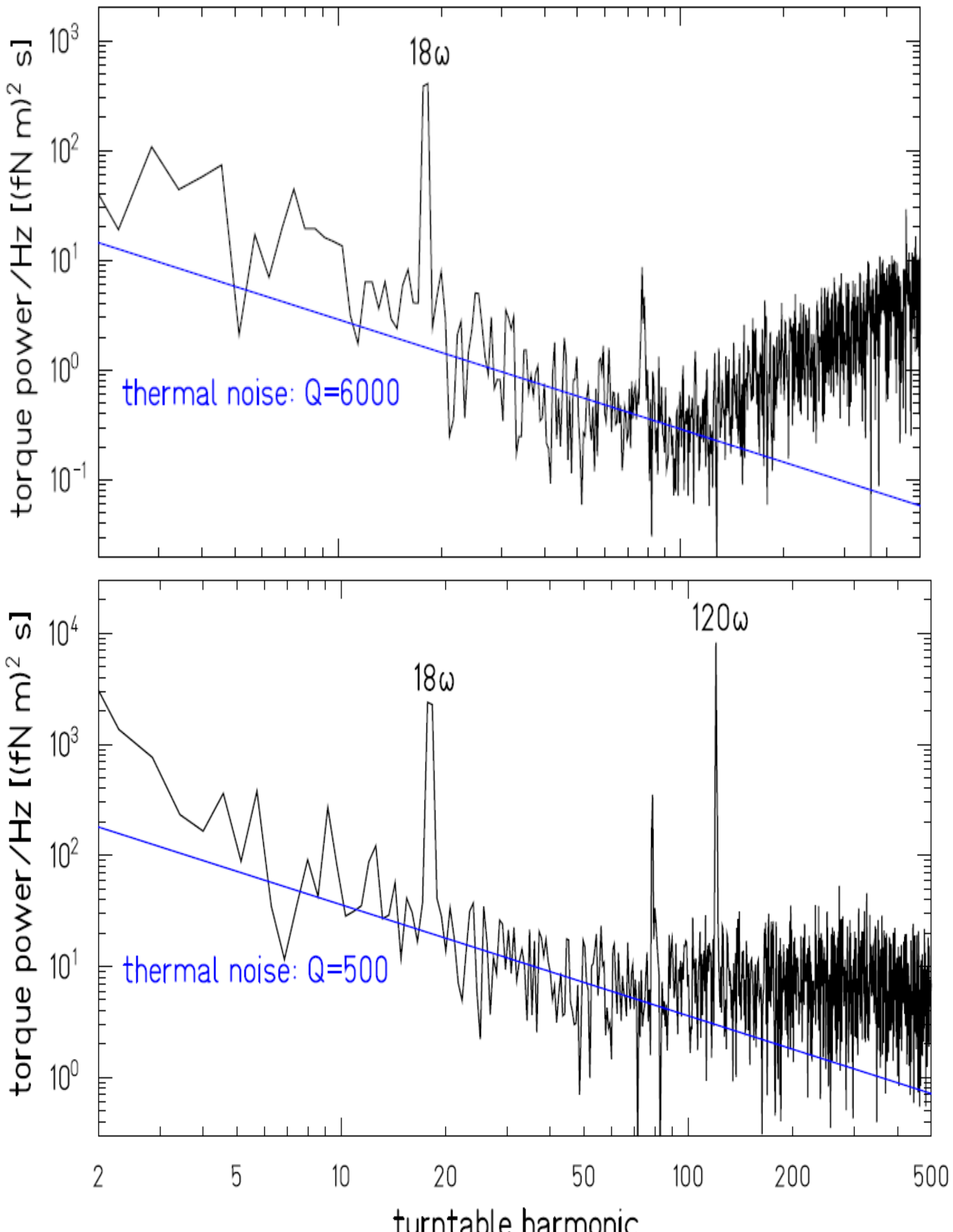
F-B expansion gives analytic solution for Newtonian and Yukawa torques.

Cook et al.'s Experiment





simulation is speeded up by factor of ≈1000 z=1.0 mm

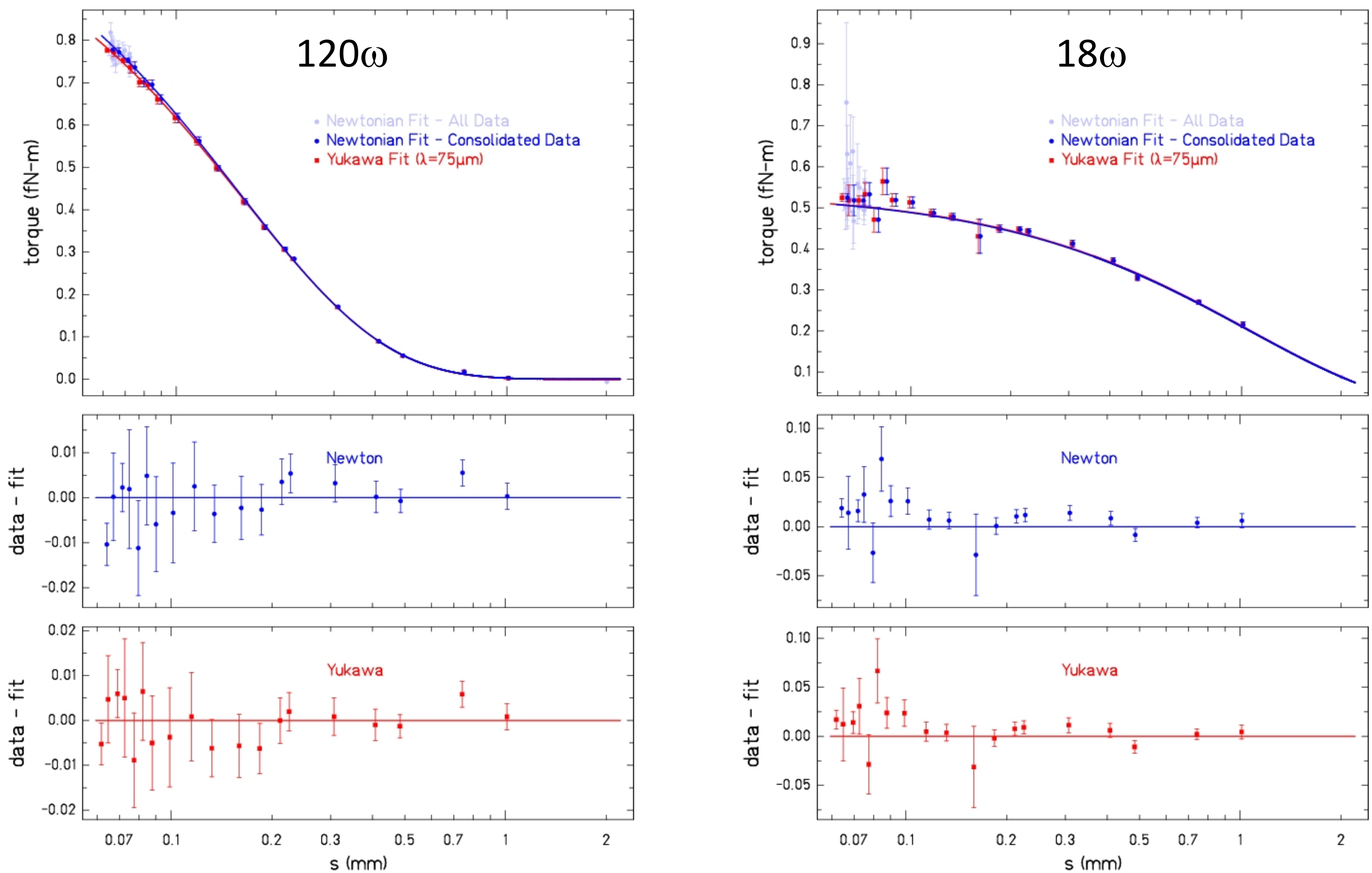


z=0.04 mm

z = pendulum-screen separation

Cook's fit for Newton and Newton + Yukawa

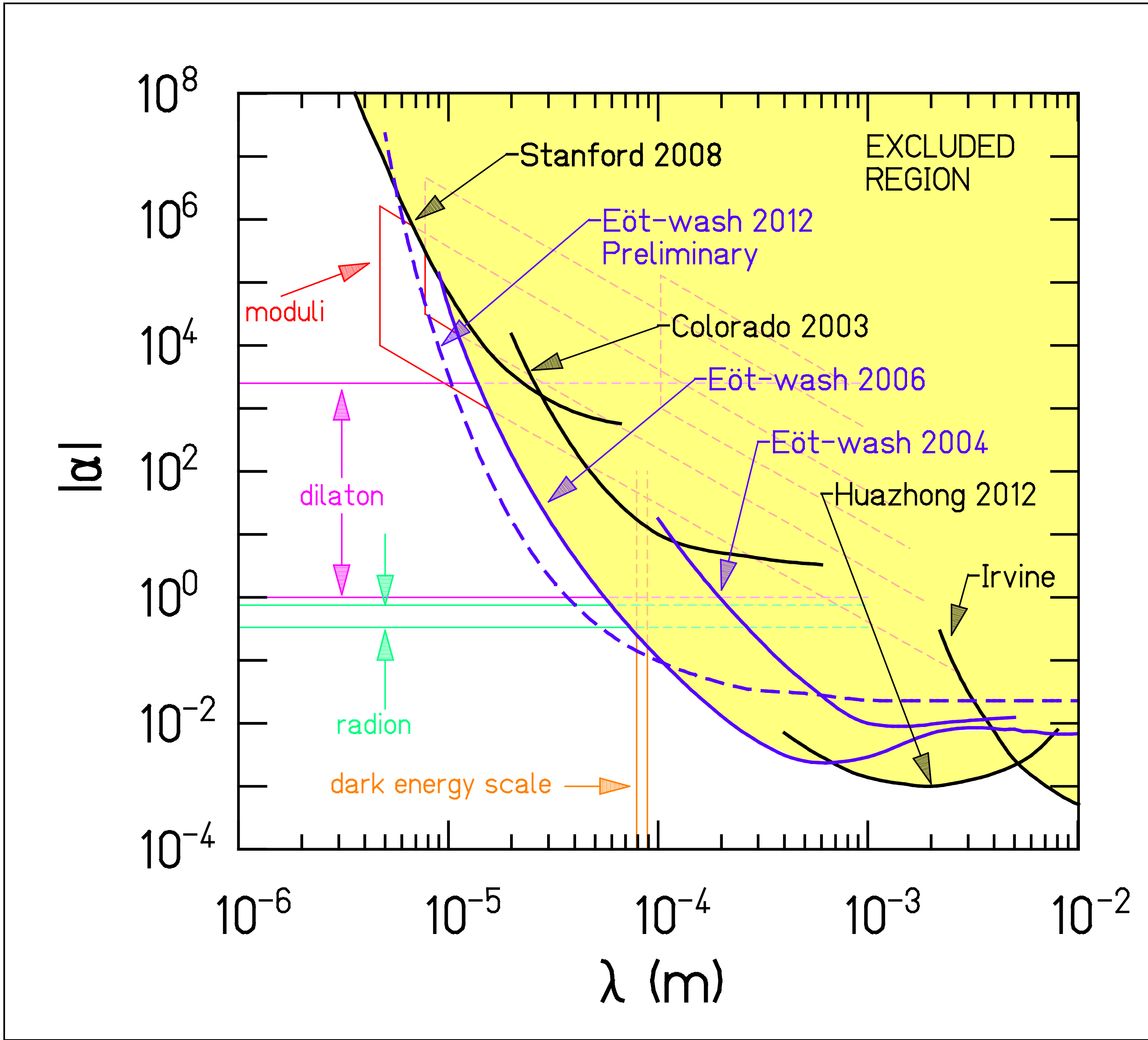
λ = 75 μm; α = -0.16 $\pm$ 0.05



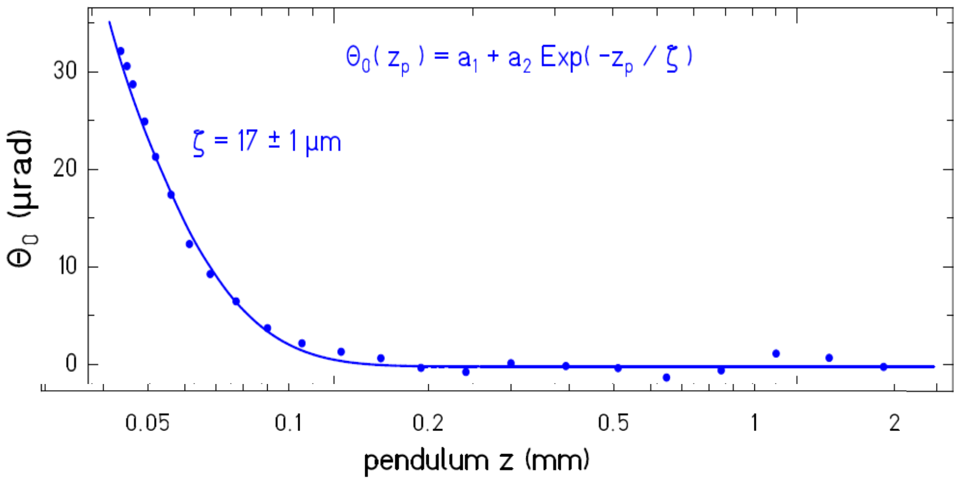
Cook’s preliminary 95% C.L. results

order of magnitude higher sensitivity than Kapner et al. below 40 µm:

We hope to do significantly better with major upgrade of Cook’s device: flatter test bodies, smaller separations, improved vibration damping.

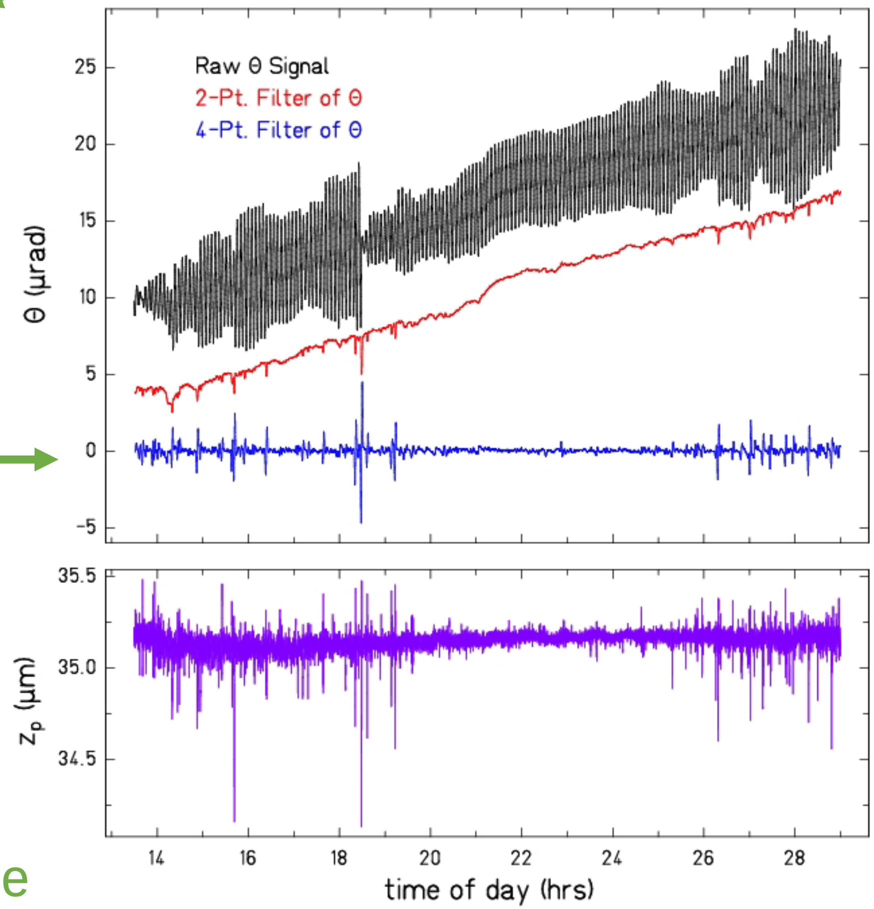


Limiting factor of our ISL tests: electrostatic pendulum-foil interactions



twist angle varies with z

induced pendulum twist



seismic vibrations make pendulum bounce

EP and short-distance ISL tests are very challenging:

weak signals (WEP & ISL)
tricky alignment (ISL)
changing gravity gradients (WEP)
patch electrostatic fields (ISL)
sensitivity to vibrations (ISL)

But the achieved sensitivities are impressive:

the differential acceleration resolution in our WEP tests
is $\Delta a \approx 3 \times 10^{-13}$ cm/s^2
which is comparable to the difference in g
between 2 spots in this room separated vertically by ≈ 1 nm

We and many other experimenters have tried very hard to find some evidence that Einstein's 100 year old theory of gravity breaks down. So far, despite much experimental effort, all of us have all been entirely unsuccessful.

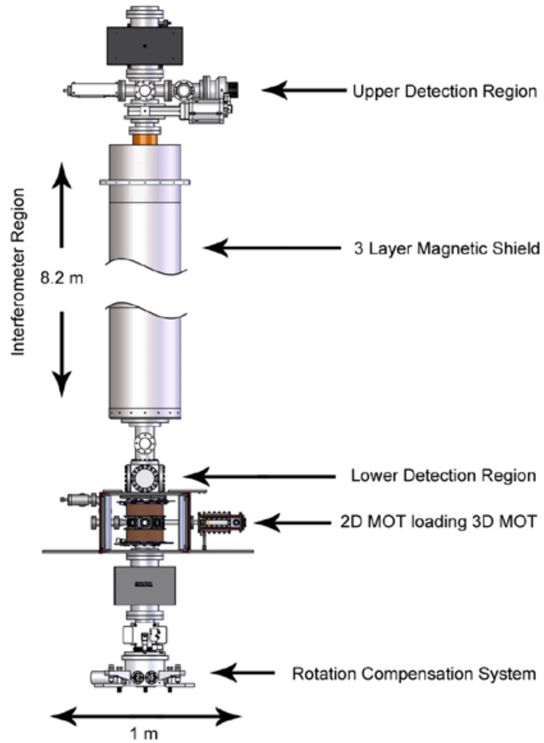
So the score is:

Einstein	4
Experimenters	0

But all is not lost: there is still room for near-term improvements in these conventional tests:

- new test-body materials
  - proton-rich test bodies (WEP)
  - Pt instead of W foils (ISL)
- uncertainty from gravity gradients (WEP)
  - real-time in situ monitor (laboratory)
  - go into space (Microscope)
- lower-loss suspension fibers (WEP)
  - fused silica suspension fibers
- improved vibration damping (ISL)
  - better dampers for unwanted pendulum modes

Groups around the world are making <u>very rapid progress</u> in atomic fountain interferometers. These provide absolute accelerometers with ultra-high sensitivity for WEP tests.

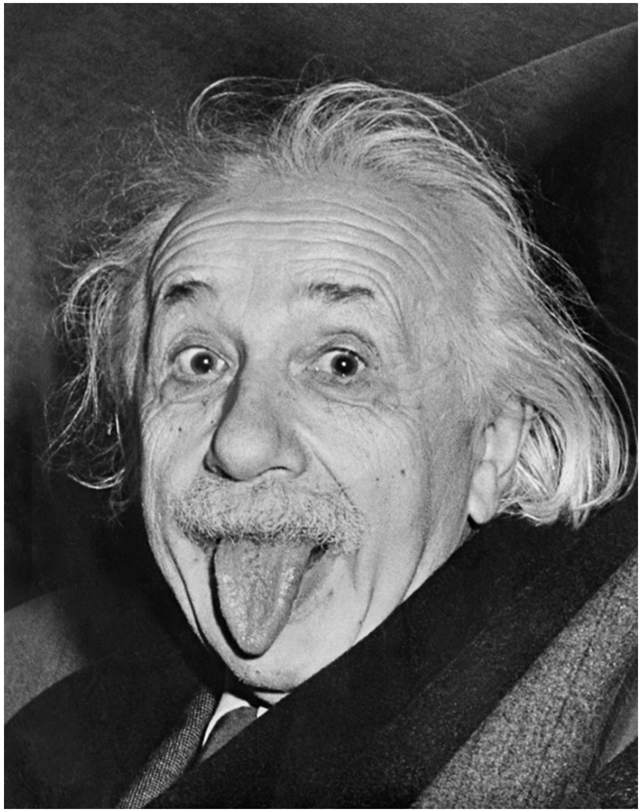


Stanford's Kasevich group proposed comparison of 85Rb/87Rb

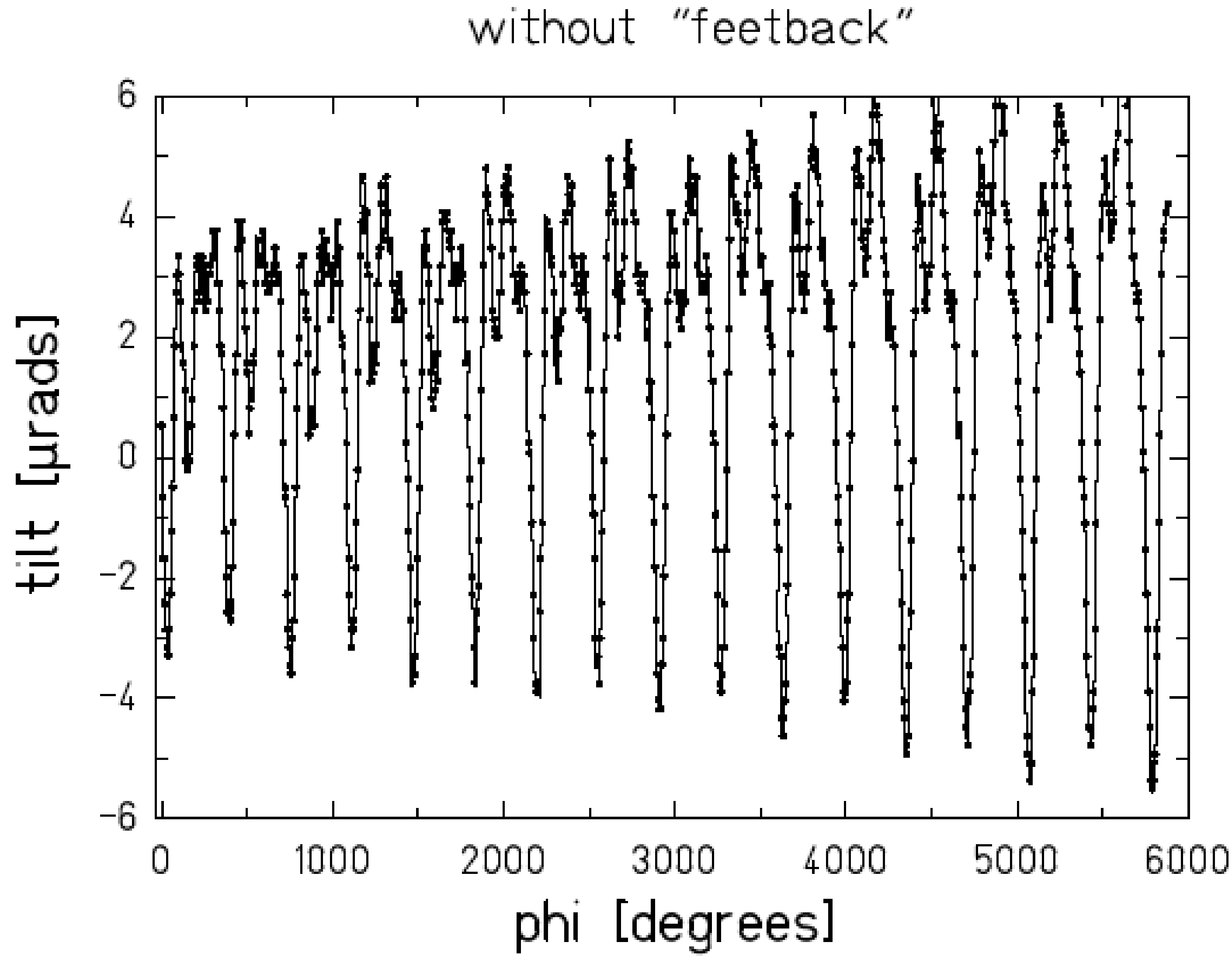
www.2physics.com/2013/09/atom-interferometry-in-10-meter-atomic.html

My guess: such tests may be limited by same issues that plague conventional lab experiments—not sensitivity but gravity gradients, etc.

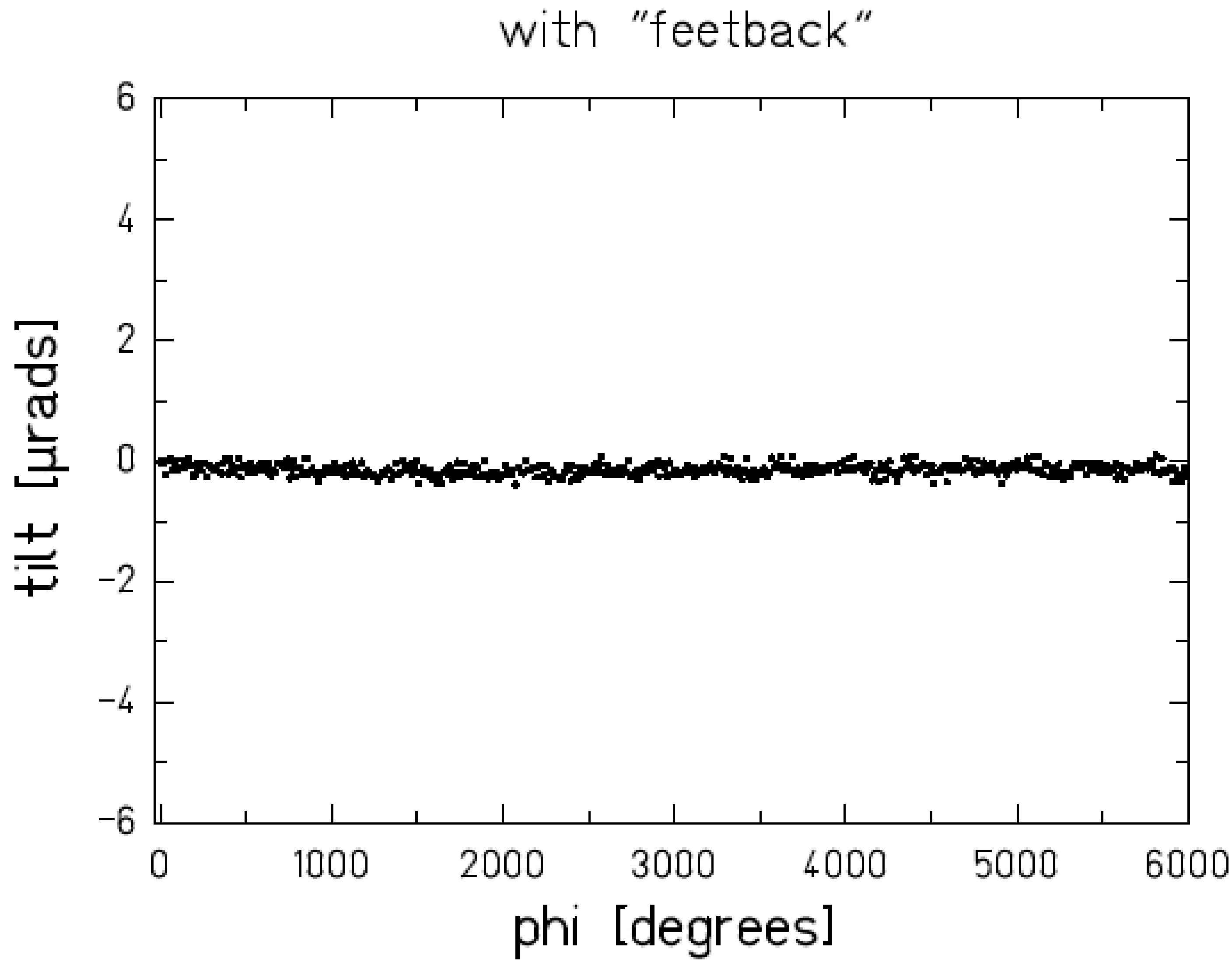
I doubt Einstein would have been surprised that his beautiful theory still reigns supreme 100 years later



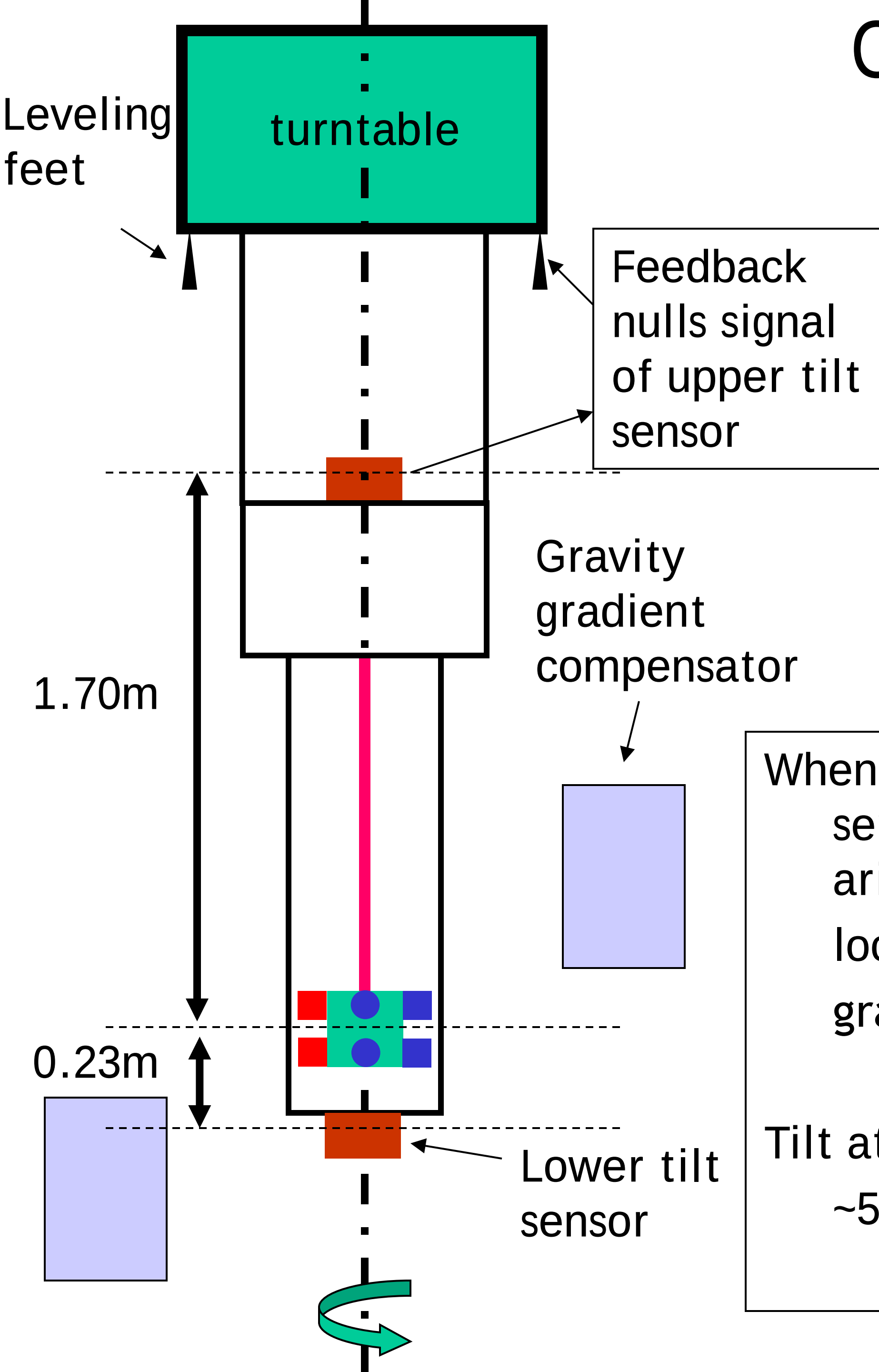
But for many of us, the fact that his classical theory has not been supplanted is one of the biggest mysteries of all.



without "feetback"
tilt [µrads]
phi [degrees]
6
4
2
0
−2
−4
−6
0
1000
2000
3000
4000
5000
6000


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

Correction for the Tilt Effect



- Feedback removes tilt at upper tilt sensor
- However, local vertical varies with height and we need to remove tilt at the pendulum to eliminate the tilt systematic

When tilt is nulled at upper sensor, the lower sensor measures a tilt of ~45 nrad which arises from

local earth field (~60 nrad) plus the off-axis gravity gradient compensator (~ —15 nrad)

Tilt at pendulum is only due to local earth field:

~50 nrad of tilt → ~2.5 nrad correction to pendulum signal