Implications of equivalence principle data for the predicted anomalous gravitational properties of antimatter

Eric G. Adelberger
University of Washington

based on PhD thesis of Todd Wagner

the Eöt-Wash® group in experimental gravitation

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Staff
- Erik Swanson

Postdocs
- Frank Fleischer
- Seth Hoedl
- Stephan Schlamminger
- Krishna Venkateswara

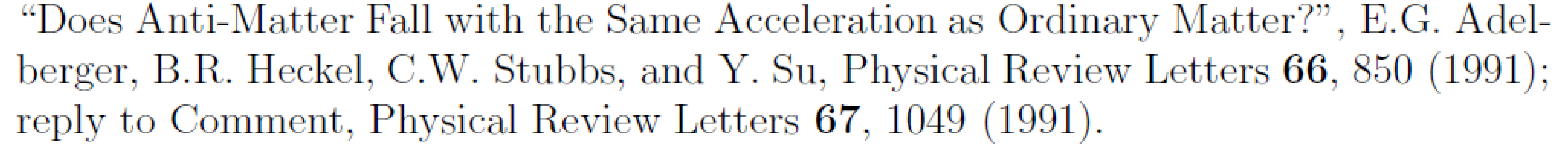
Current Grad students
- Ted Cook
- Charlie Hagedorn
- Matt Turner
- Will Terrano
- Todd Wagner

$1/r^2$
EP
spin

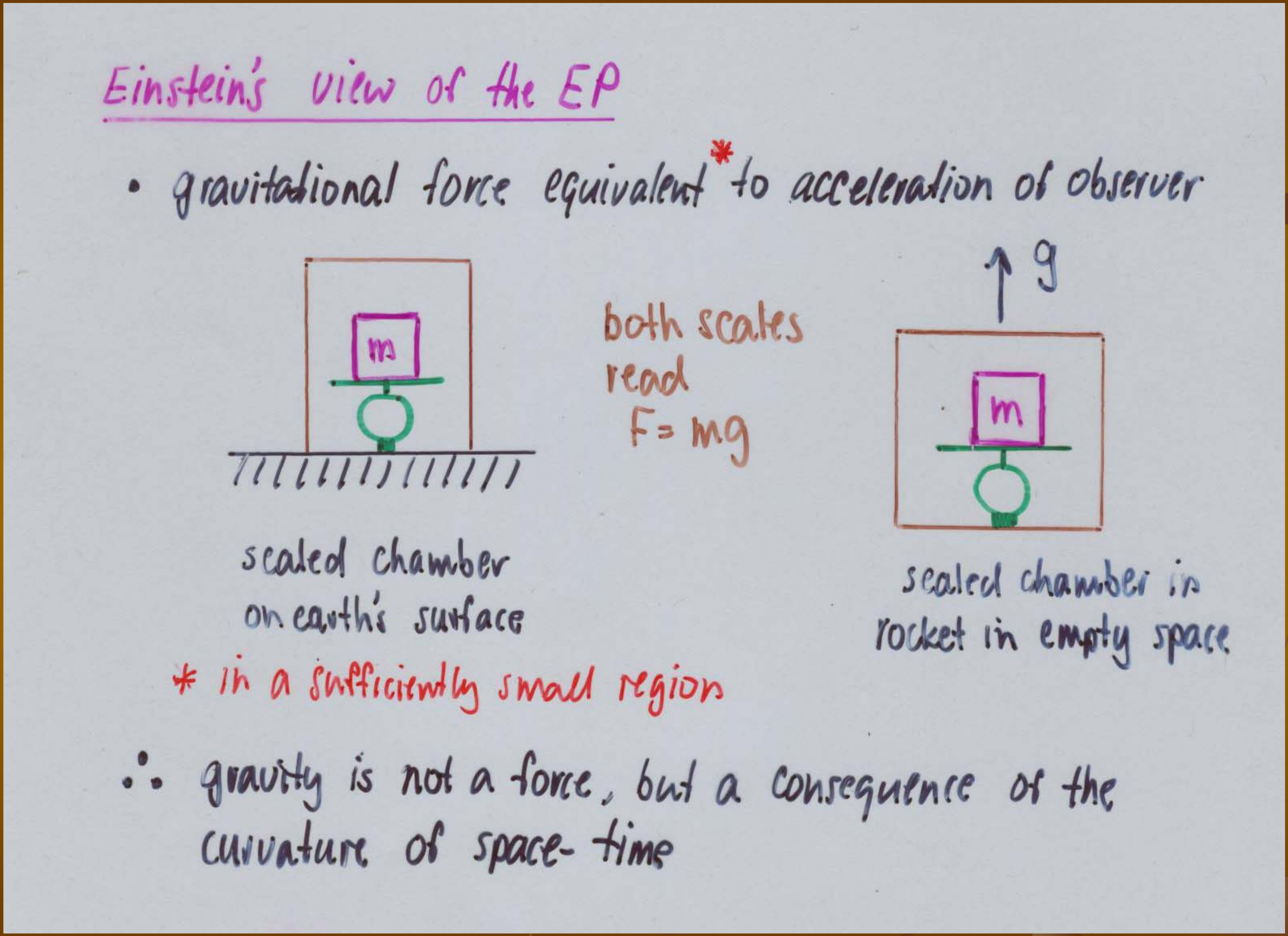
Primary support from NSF Grant PHY0653863 with supplements from the DOE Office of Science and to a lesser extent NASA

This talk is an update of ideas originally given in


“Constraints on Proposed Spin-0 and Spin-1 Partners of the Graviton,” C.W. Stubbs, E.G. Adelberger and C. Gregory, Physical Review Letters **61**, 2409 (1988).


“Does Anti-Matter Fall with the Same Acceleration as Ordinary Matter?”, E.G. Adelberger, B.R. Heckel, C.W. Stubbs, and Y. Su, Physical Review Letters **66**, 850 (1991); reply to Comment, Physical Review Letters **67**, 1049 (1991).

EP was Einstein's "happiest idea" and the foundation of GR



Einstein's view of the EP

- gravitational force equivalent* to acceleration of observer

both scales read $F = mg$

sealed chamber on earth's surface

sealed chamber in rocket in empty space

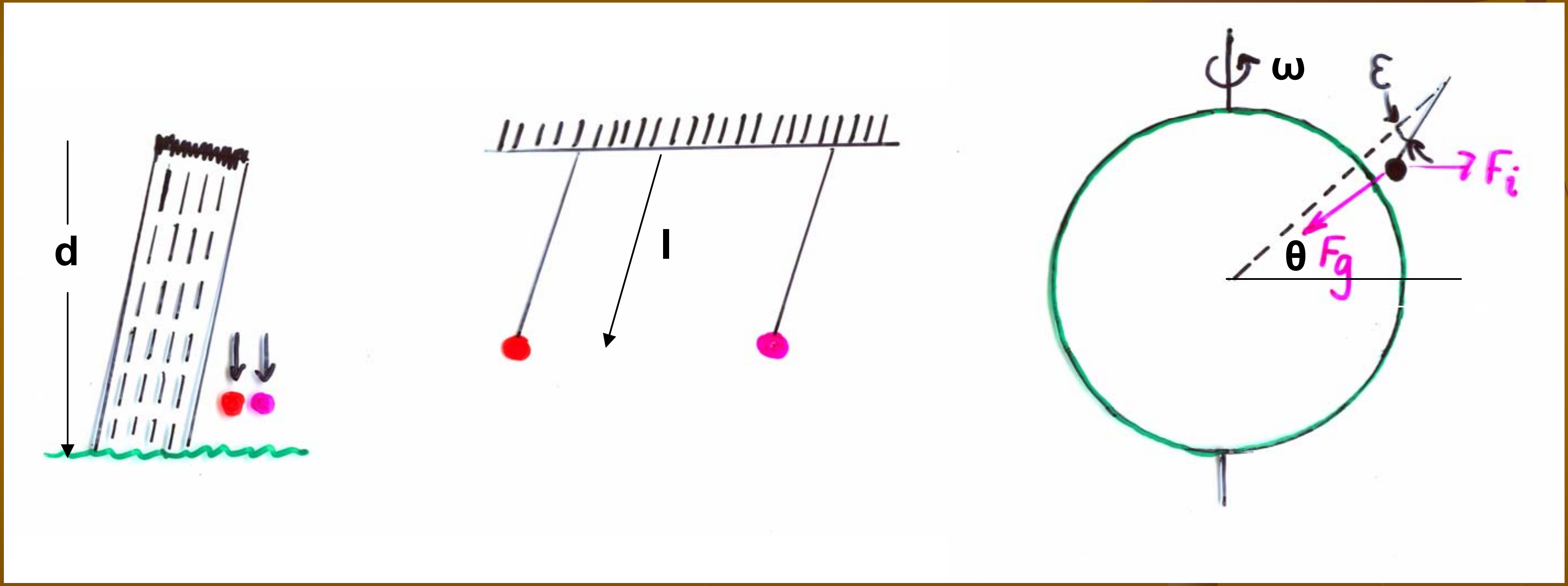
* in a sufficiently small region

∴ gravity is not a force, but a consequence of the curvature of space-time

EP => local effects of gravity disappear in a freely falling frame

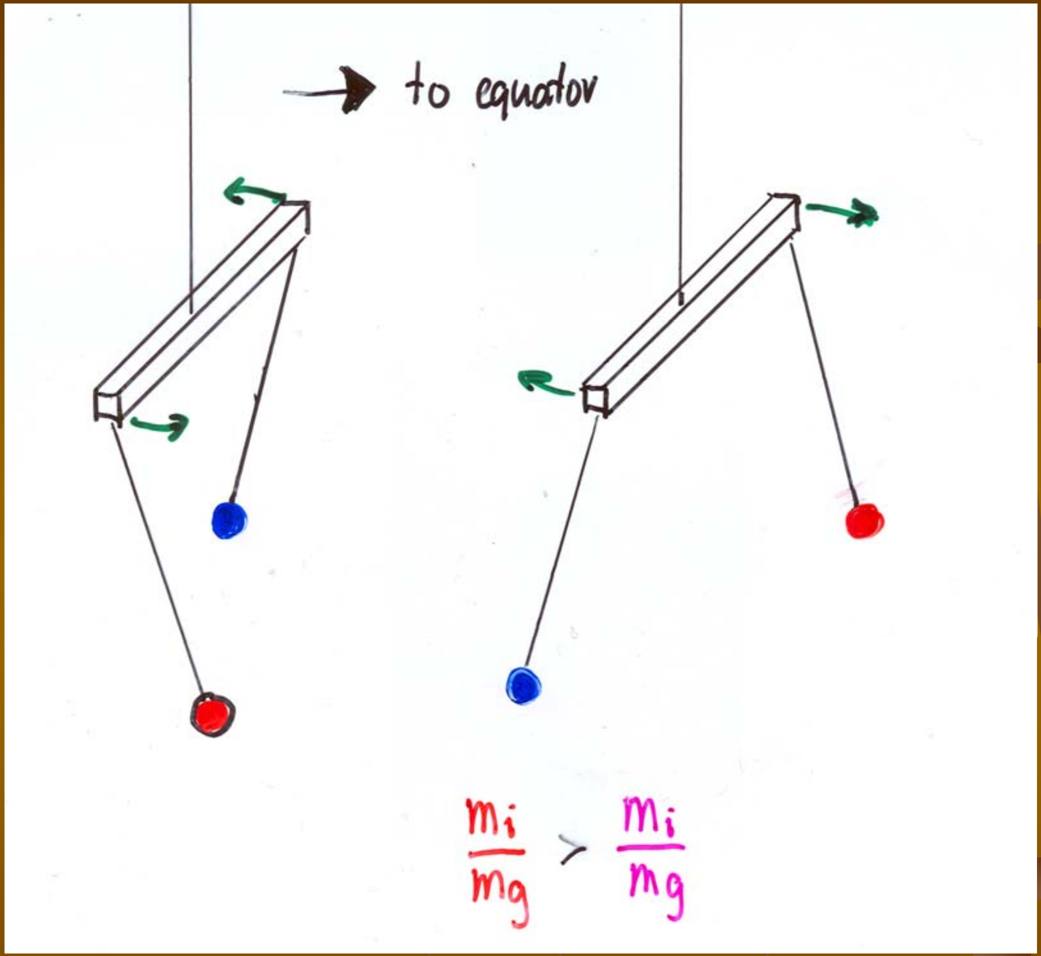
A brief history of Equivalence Principle tests: classic view: do all materials have the same m^i/m^g ?

Galileo **test** | Newton-Bessel test | Eötvös test



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

implementation as a null experiment



if the EP is violated down is not a unique direction

balance twists only if force vectors are not parallel
i.e. if EP is violated or if gravity field is not uniform

How can such a simple thing get precision of 10^{-13} when no part has a precision as good as 10^{-6} ?

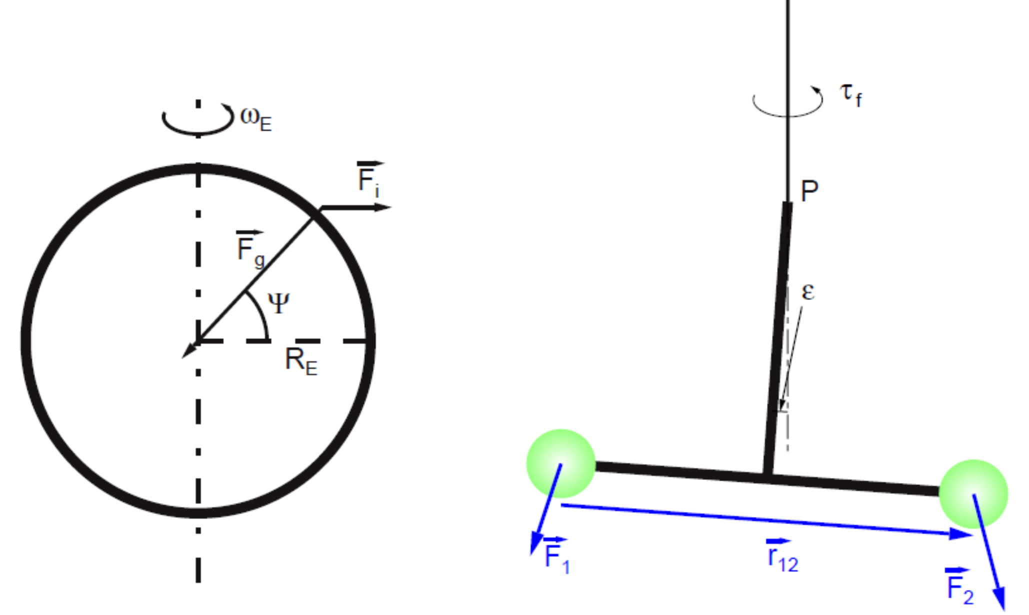


Figure 1: The left graph shows the inertial and gravitational forces on a test-body mounted at a latitude $\Psi = 47°$. The ratio of the forces is exaggerated by a factor 200. The right figure shows the forces on a simplified torsion pendulum where m_2 is greater than m_1. The pendulum tips by an angle ϵ so that the center of mass lies vertically below P.

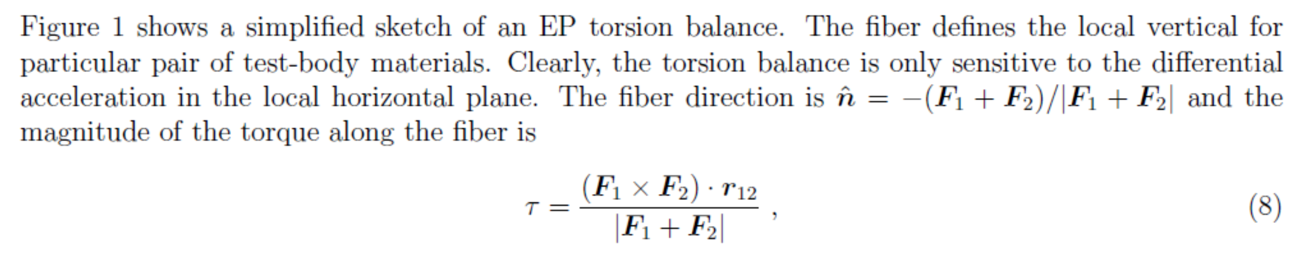


Figure 1 shows a simplified sketch of an EP torsion balance. The fiber defines the local vertical for particular pair of test-body materials. Clearly, the torsion balance is only sensitive to the differential acceleration in the local horizontal plane. The fiber direction is $\hat{\boldsymbol{n}} = -(\boldsymbol{F}_1 + \boldsymbol{F}_2)/|\boldsymbol{F}_1 + \boldsymbol{F}_2|$ and the magnitude of the torque along the fiber is

$$\tau = \frac{(\boldsymbol{F}_1 \times \boldsymbol{F}_2) \cdot \boldsymbol{r}_{12}}{|\boldsymbol{F}_1 + \boldsymbol{F}_2|} \,, \tag{8}$$

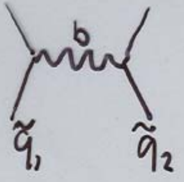
2 WAYS TO THINK ABOUT EP TESTS

- test a key prediction of Einstein's theory of gravity

  is $m_i = m_g$?

- assume EP is exact for gravity; use tests to probe for new quantum exchange forces even weaker than gravity

any quantum exchange force will violate the EP



$$F_{12} \propto \tilde{q}_1 \tilde{q}_2 \frac{1}{r^2}\left(1+\frac{r}{\lambda}\right) e^{-r/\lambda}$$

$$\lambda = \frac{\hbar}{m_b c}$$

$$a_1 = \frac{F_{12}}{m_1} \propto \boxed{\frac{\tilde{q}_1}{m_1}} \leftarrow$$

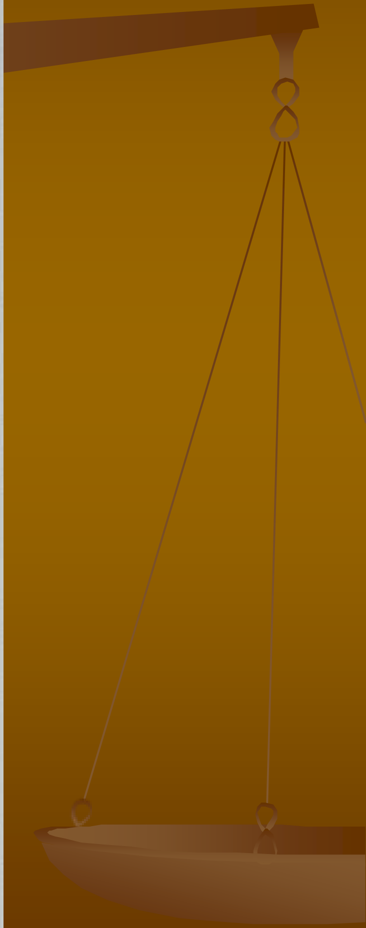
"charge"-to-mass ratio cannot be exactly the same for all objects!

recall EM

$$(q/m)_{electron} = -(q/m)_{positron} \approx -2000\,(q/m)_{proton}$$

- most of the ideas for solving the big problems in physics predict effects that could show up in EP tests

  e.g. string theory dilaton



reasons why $\tilde{q}/m$ cannot be universal constant

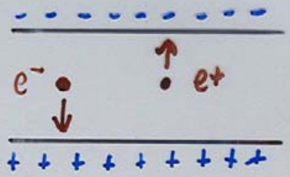
- interactions mediated by vector bosons

$$\tilde{q}_{particle} = -\tilde{q}_{antiparticle}$$

$$\tilde{q}\,(\text{binding energy}) = 0$$

$$\therefore\ \tilde{q}\,(\text{object}) = \sum \tilde{q}\,(\text{constituents})$$

$$m\,(\text{object}) \neq \sum m\,(\text{constituents})$$



- interactions mediated by scalar bosons

$$\tilde{q}_{particle} = \tilde{q}_{antiparticle}$$

$$\tilde{q}\,(\text{binding energy}) \neq 0$$

$$\tilde{q} = \int \tilde{\rho}_s\, d^3x \rightarrow \frac{1}{\gamma}\int \tilde{\rho}_s\, d^3x'$$

Lorentz scalar density

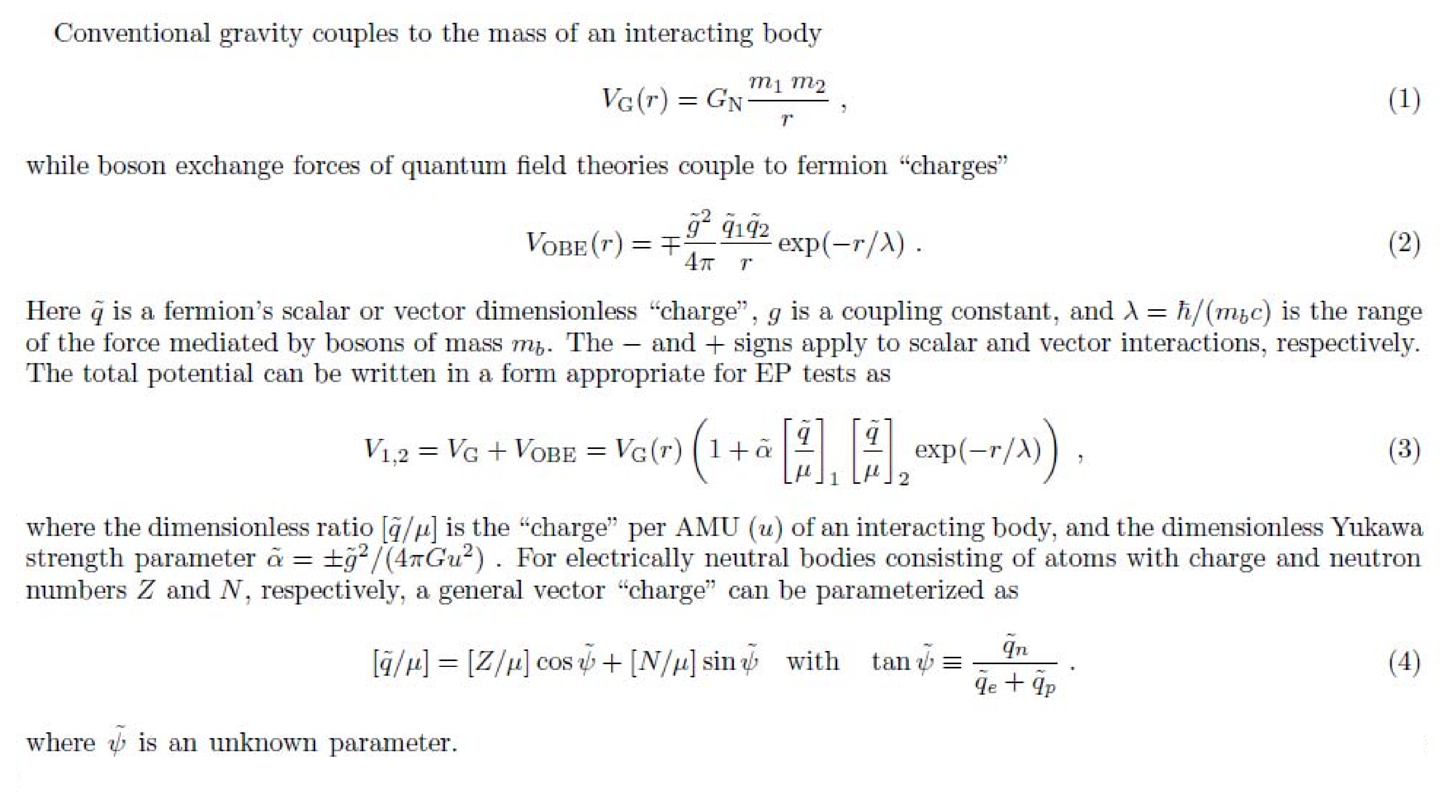
$$\hat{q}_{object} \neq \sum \tilde{q}\,(\text{constituents})$$

inner atomic electrons have $\gamma - 1 \simeq \frac{1}{2}(Z\alpha)^2 \sim 2\times10^{-2}$

nucleons in nucleus have $\gamma - 1 \sim 4\times10^{-2}$

quarks in nucleon have $\gamma - 1 > 1$

Parameterizing EP-violating effects of quantum vector exchange forces in terms of α, λ and ψ



Conventional gravity couples to the mass of an interacting body

$$V_{\rm G}(r) = G_{\rm N}\frac{m_1\, m_2}{r}\ , \tag{1}$$

while boson exchange forces of quantum field theories couple to fermion "charges"

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

Here $\tilde{q}$ is a fermion's scalar or vector dimensionless "charge", g is a coupling constant, and $\lambda = \hbar/(m_b c)$ is the range of the force mediated by bosons of mass m_b. The $-$ and $+$ signs apply to scalar and vector interactions, respectively. The total potential can be written in a form appropriate for EP tests as

$$V_{1,2} = V_{\rm G} + V_{\rm OBE} = V_{\rm G}(r)\left(1 + \tilde{\alpha}\left[\frac{\tilde{q}}{\mu}\right]_1\left[\frac{\tilde{q}}{\mu}\right]_2\exp(-r/\lambda)\right)\ , \tag{3}$$

where the dimensionless ratio $[\tilde{q}/\mu]$ is the "charge" per AMU (u) of an interacting body, and the dimensionless Yukawa strength parameter $\tilde{\alpha} = \pm\tilde{g}^2/(4\pi G u^2)$. For electrically neutral bodies consisting of atoms with charge and neutron numbers Z and N, respectively, a general vector "charge" can be parameterized as

$$[\tilde{q}/\mu] = [Z/\mu]\cos\tilde{\psi} + [N/\mu]\sin\tilde{\psi} \quad \text{with} \quad \tan\tilde{\psi} \equiv \frac{\tilde{q}_n}{\tilde{q}_e + \tilde{q}_p}\ . \tag{4}$$

where $\tilde{\psi}$ is an unknown parameter.

Unbiased tests of the EP require:

- sensitivity to wide range of length scales
  requires variety of attractors:
  local topography, entire earth, sun, galaxy

- sensitivity to wide range of possible charges
  vector charge/mass ratio of electrically
  neutral atoms is specified by a single
  number: the ratio (Z/μ) / (N/μ)
  need 2 test body pairs and 2 attractors
  to avoid possible cancellations

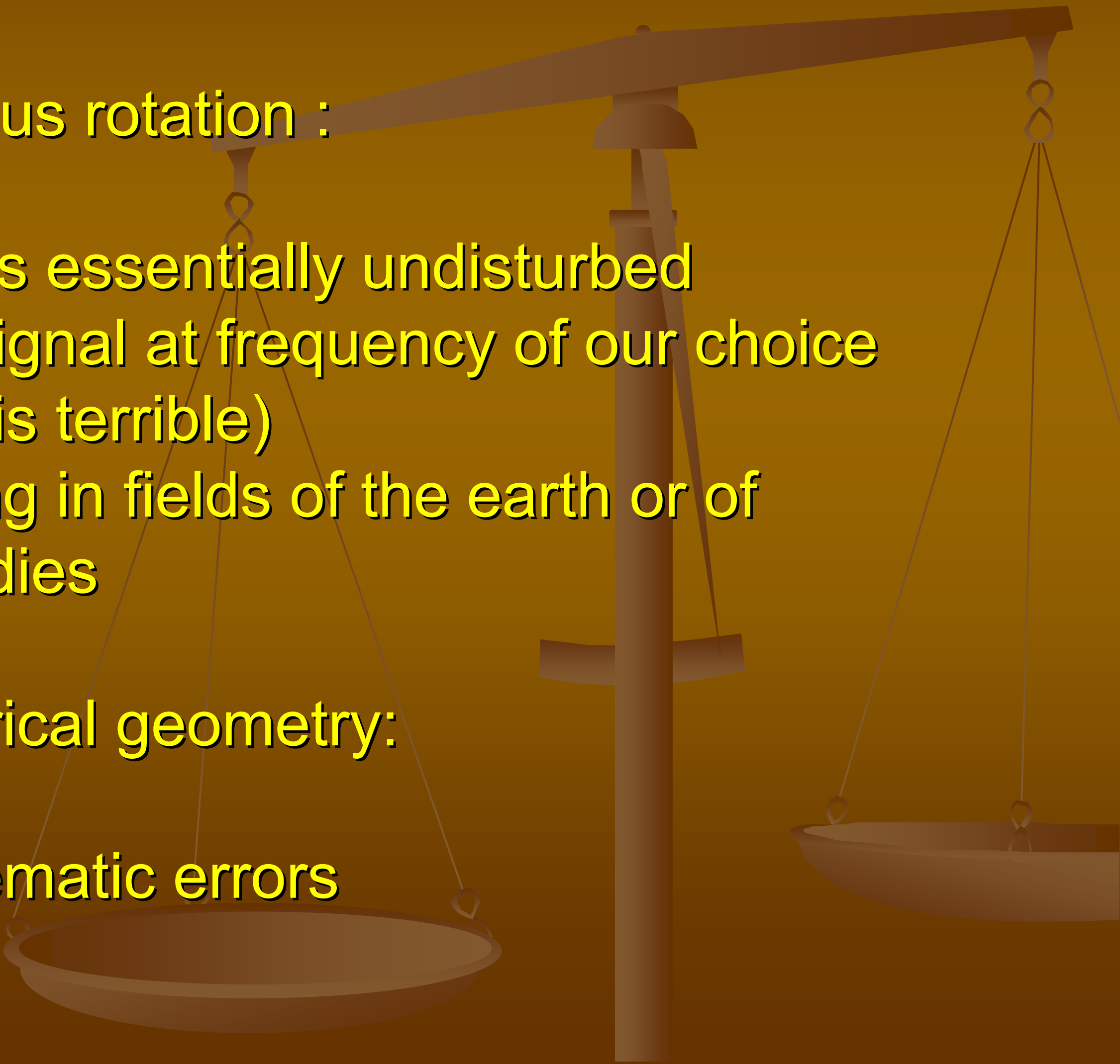
We decided to do this by developing continuously rotating torsion balance instruments with high degrees of symmetry.

advantages of continuous rotation :

- the instrument remains essentially undisturbed
- produces sinusoidal signal at frequency of our choice (period of 1 day is terrible)
- can watch things falling in fields of the earth or of astronomical bodies

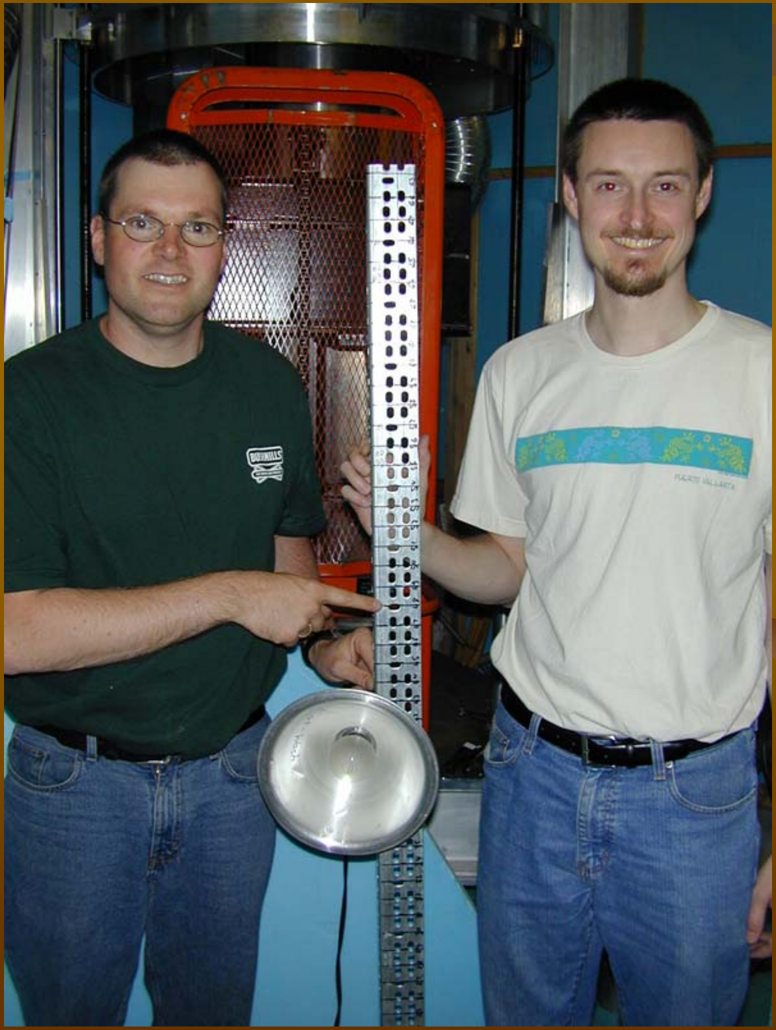
advantages of symmetrical geometry:

- minimizes many systematic errors



principal people in our current EP test as they tested for thermal systematics using heat from a light bulb.

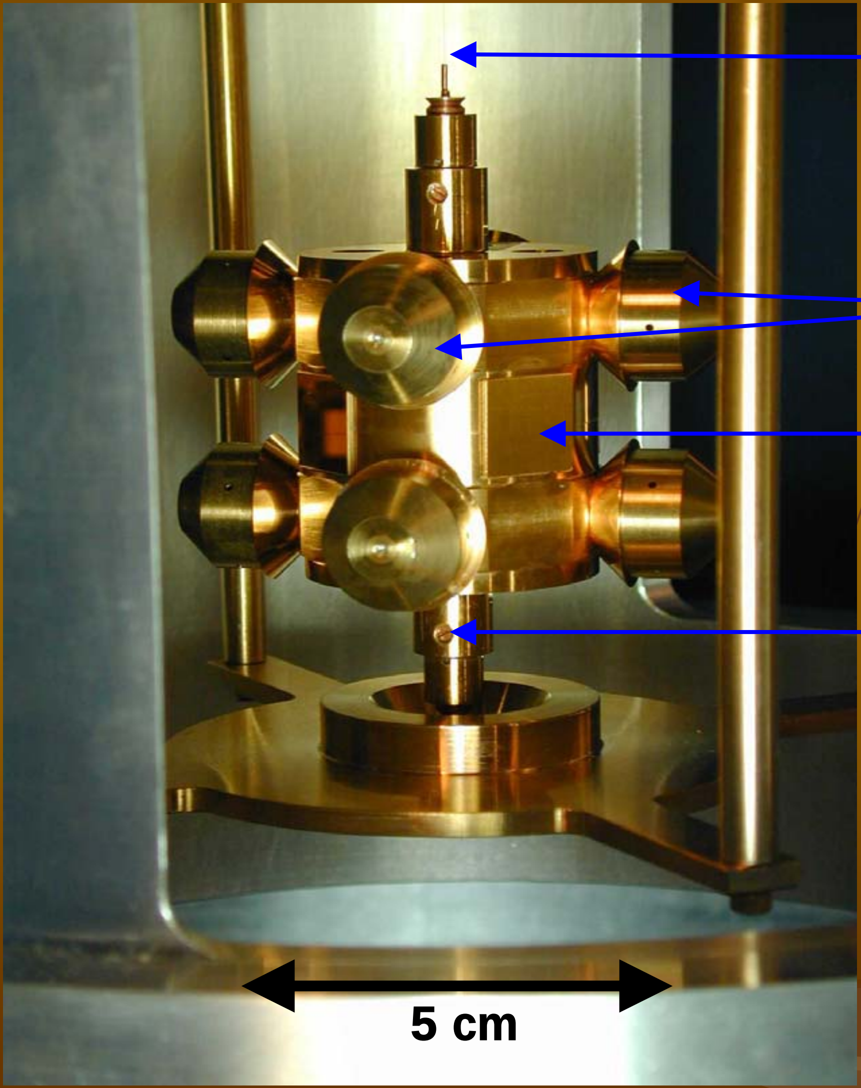
Stephan
Schlamminger
(now at NIST)



Todd Wagner
(now finishing
his PhD)

torsion pendulum of the recent Eöt-Wash EP test

S. Schlamminger et al., PRL 100, 041101 (2008)



20 μm diameter 108 cm long tungsten fiber

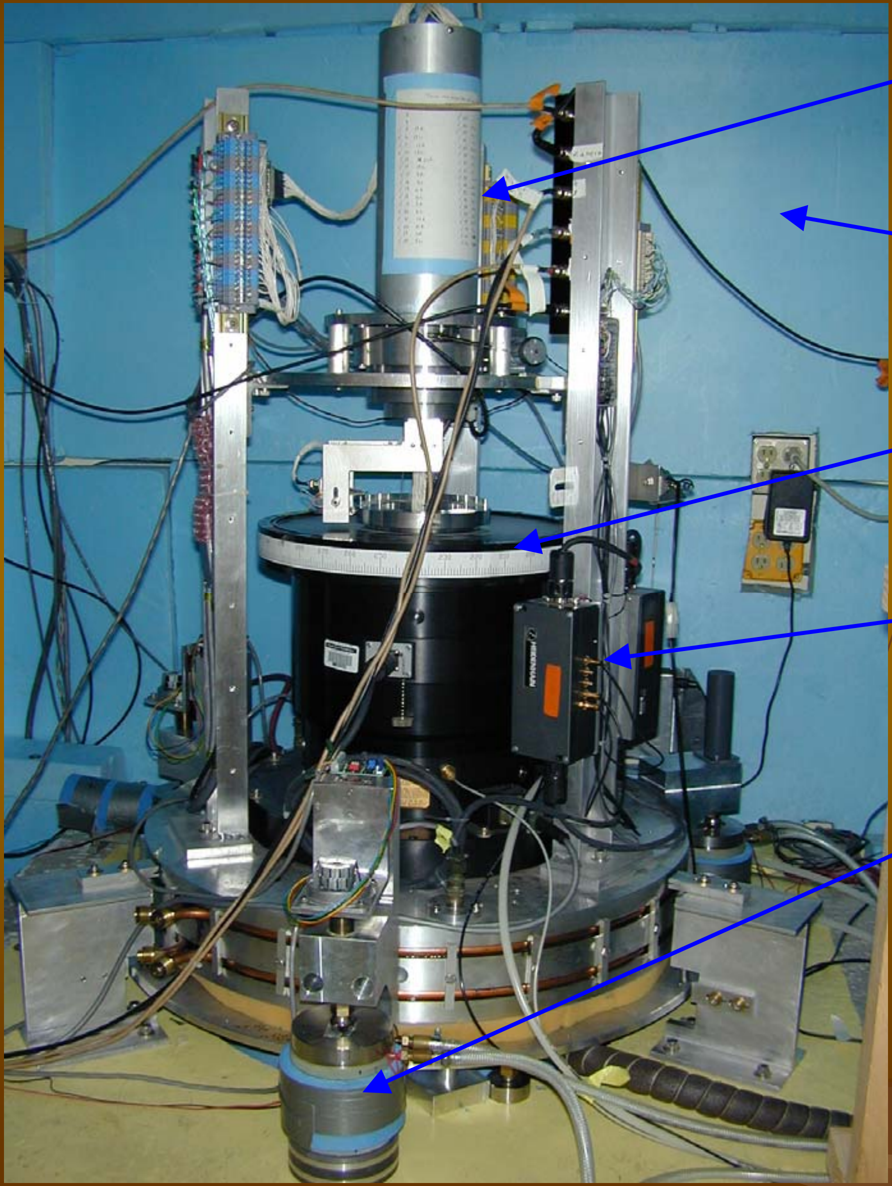
eight 4.84 g test masses (4 Be & 4 Ti) or (4 Be & 4 Al)

4 mirrors

tuning screws adjust the mass multipole moments & minimize sensitivity to gravity gradients

free osc freq:	1.261 mHz
quality factor:	4000
decay time:	11d 6.5 hrs
machining tolerance:	5 μm
total mass :	70 g

turntable of the new EP balance



servoed rotary contactor
for electric signals

thermal insulation

air-bearing turntable

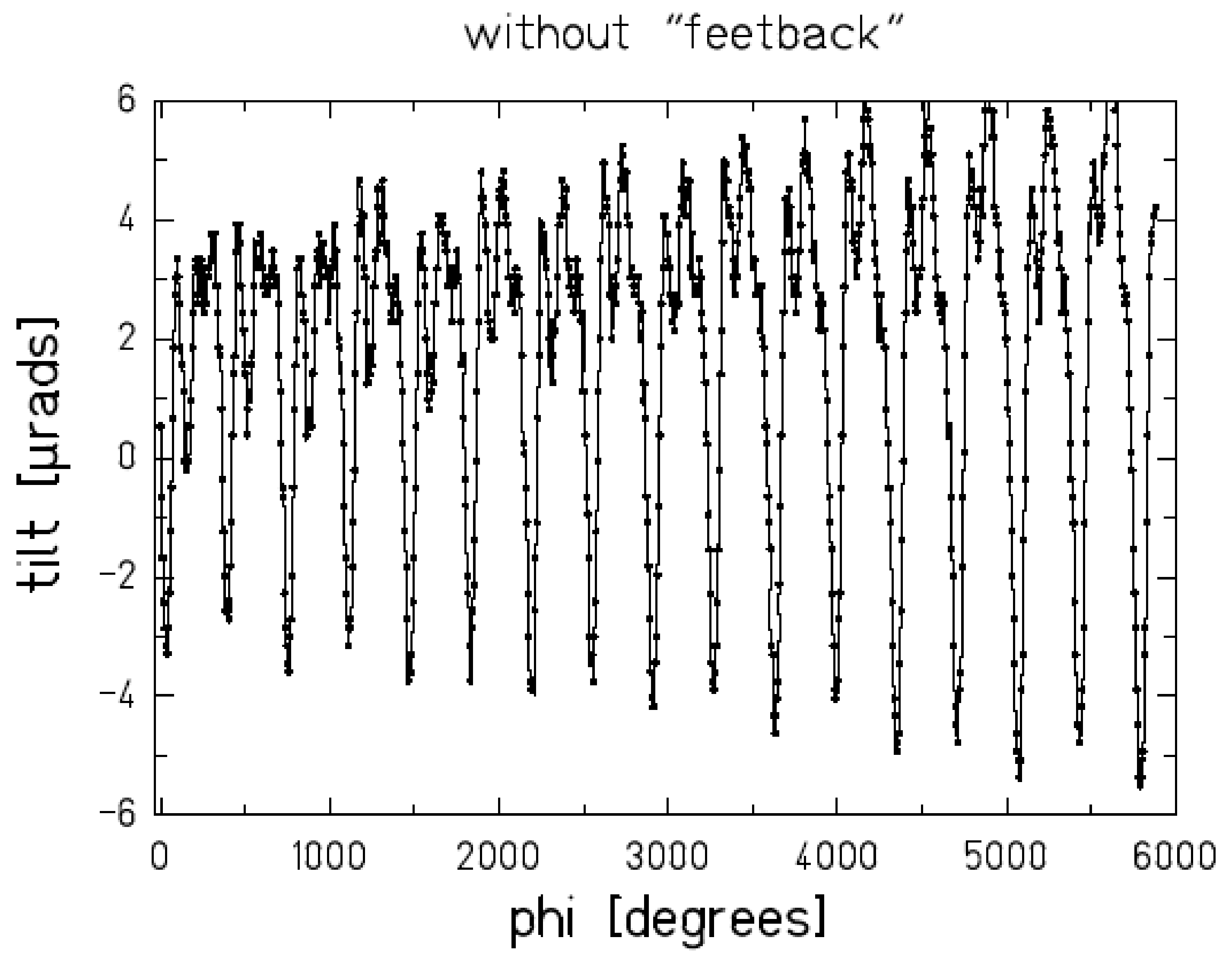
angle encoder electronics

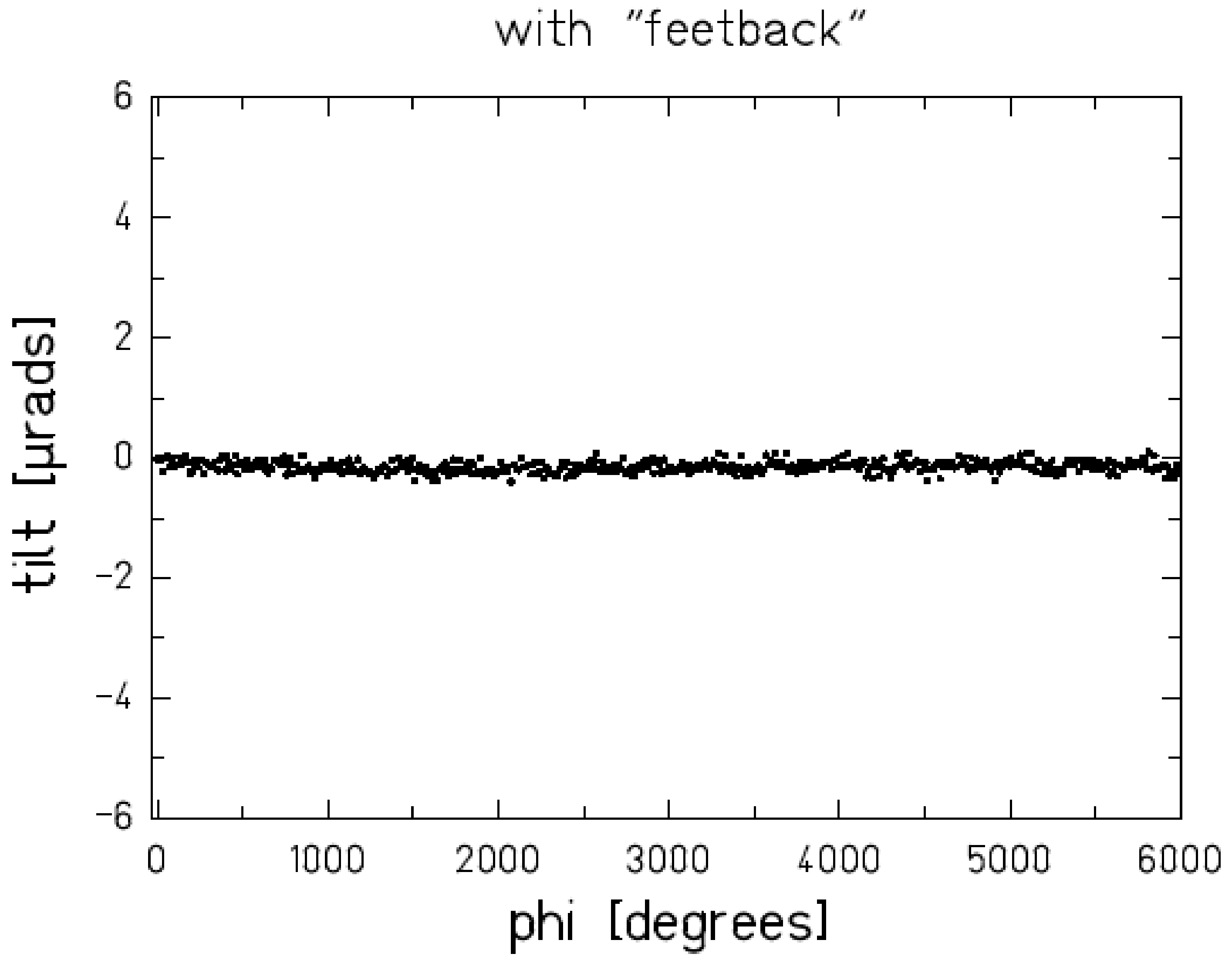
thermal expansion feet
fedback to keep turntable
rotation axis level

torsion balance hangs
from the bearing which
rotates at 0.833 mHz

the “feetback” leveling system

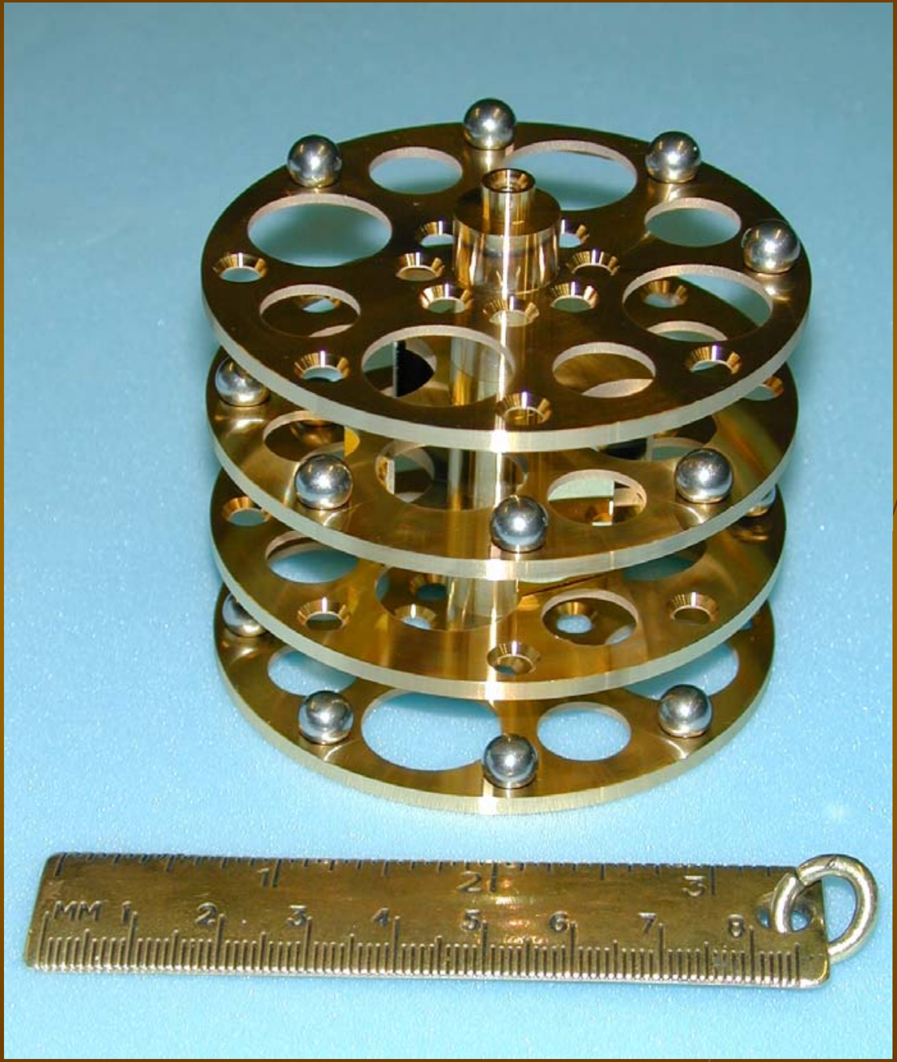
- orthogonal rotating electronic tilt sensors continuously measure the tilt of the rotating instrument, correcting for varying tilt of the lab floor and imperfections in the turntable itself
- this information is fed to Peltier elements controlling the temperature of the feet and causes them to expand or shrink by a few μm
- developed by Ulrich Schmidt


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

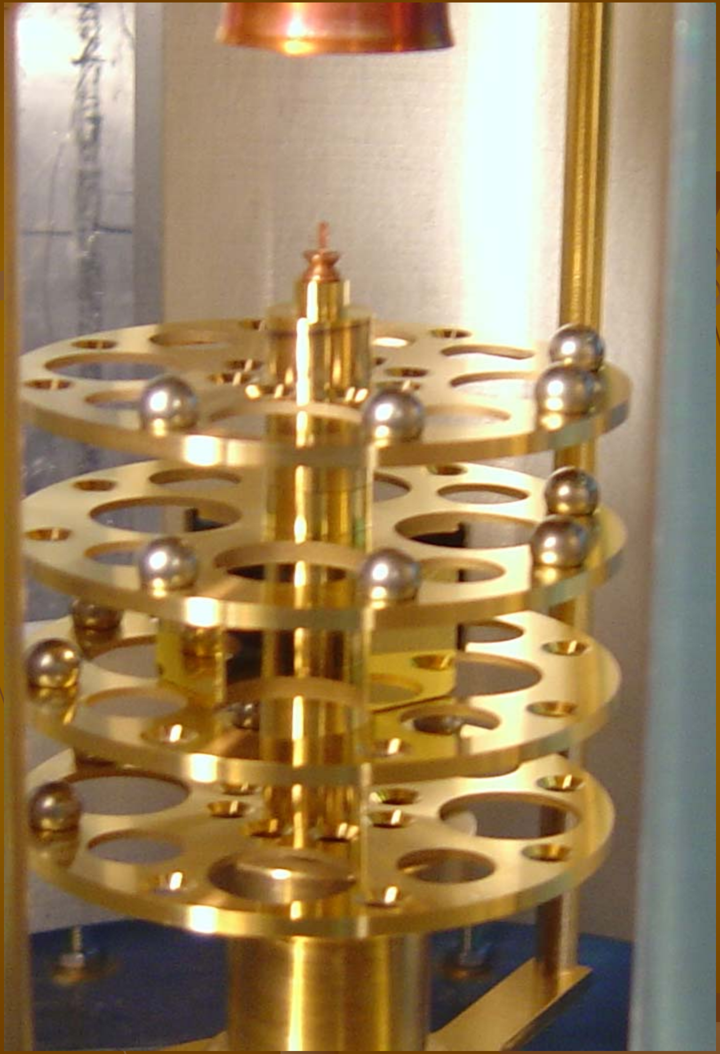


with “feetback”

gravity-gradiometer pendulums

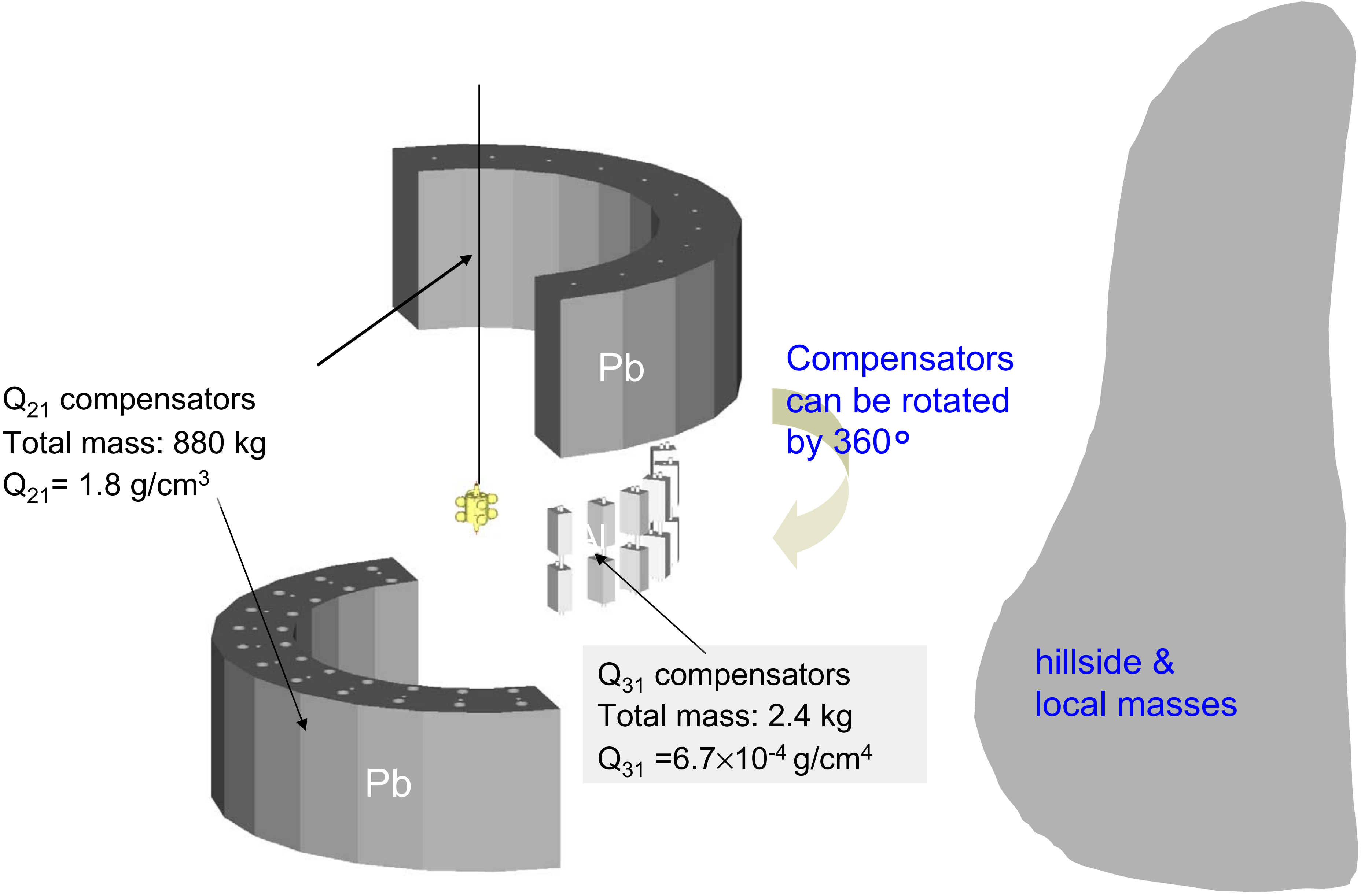


q_{41} configuration on a table



q_{21} configuration installed

gravity-gradient compensation



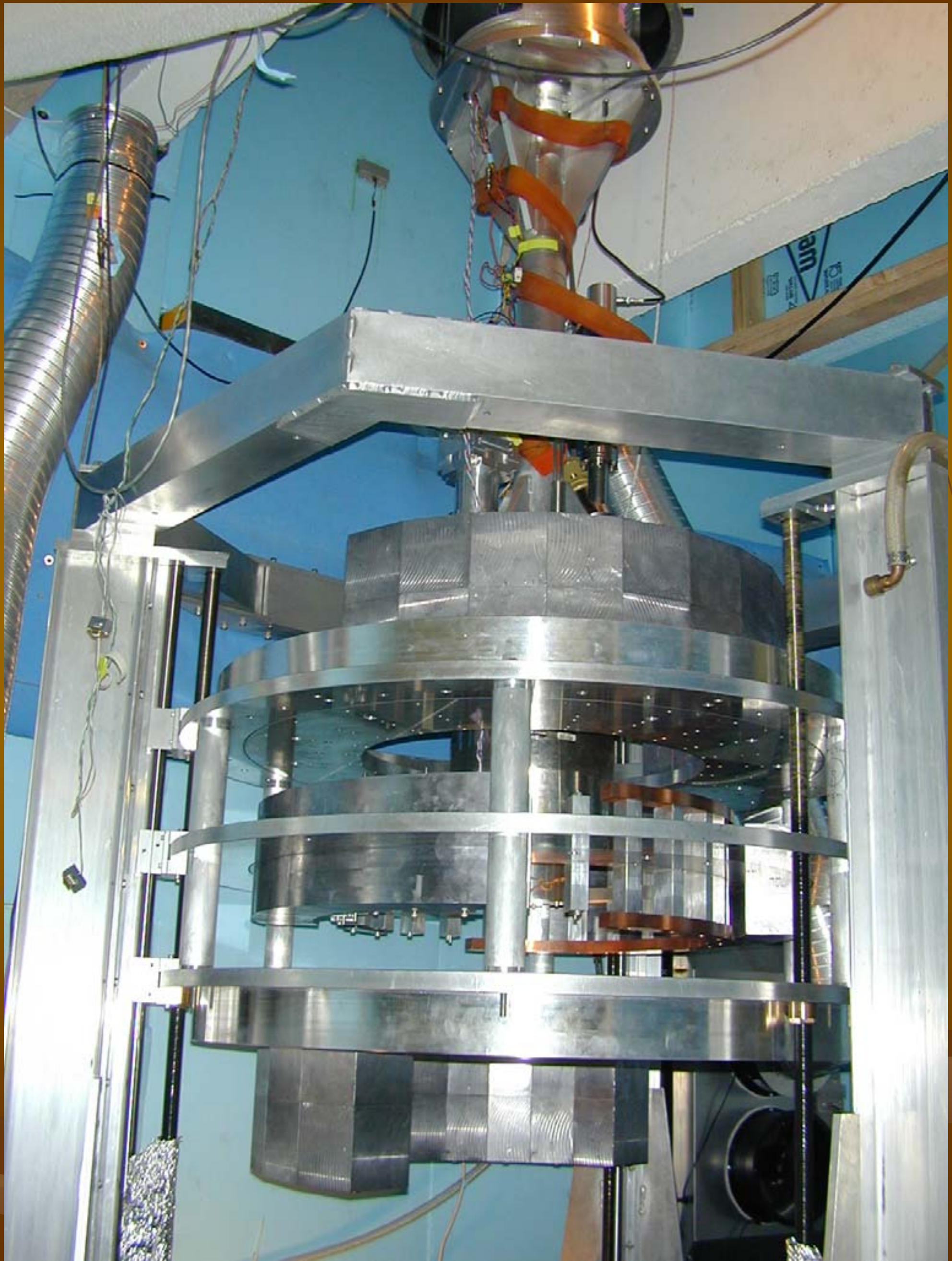
Q_{21} compensators
Total mass: 880 kg
Q_{21}= 1.8 g/cm^3

Compensators can be rotated by 360°

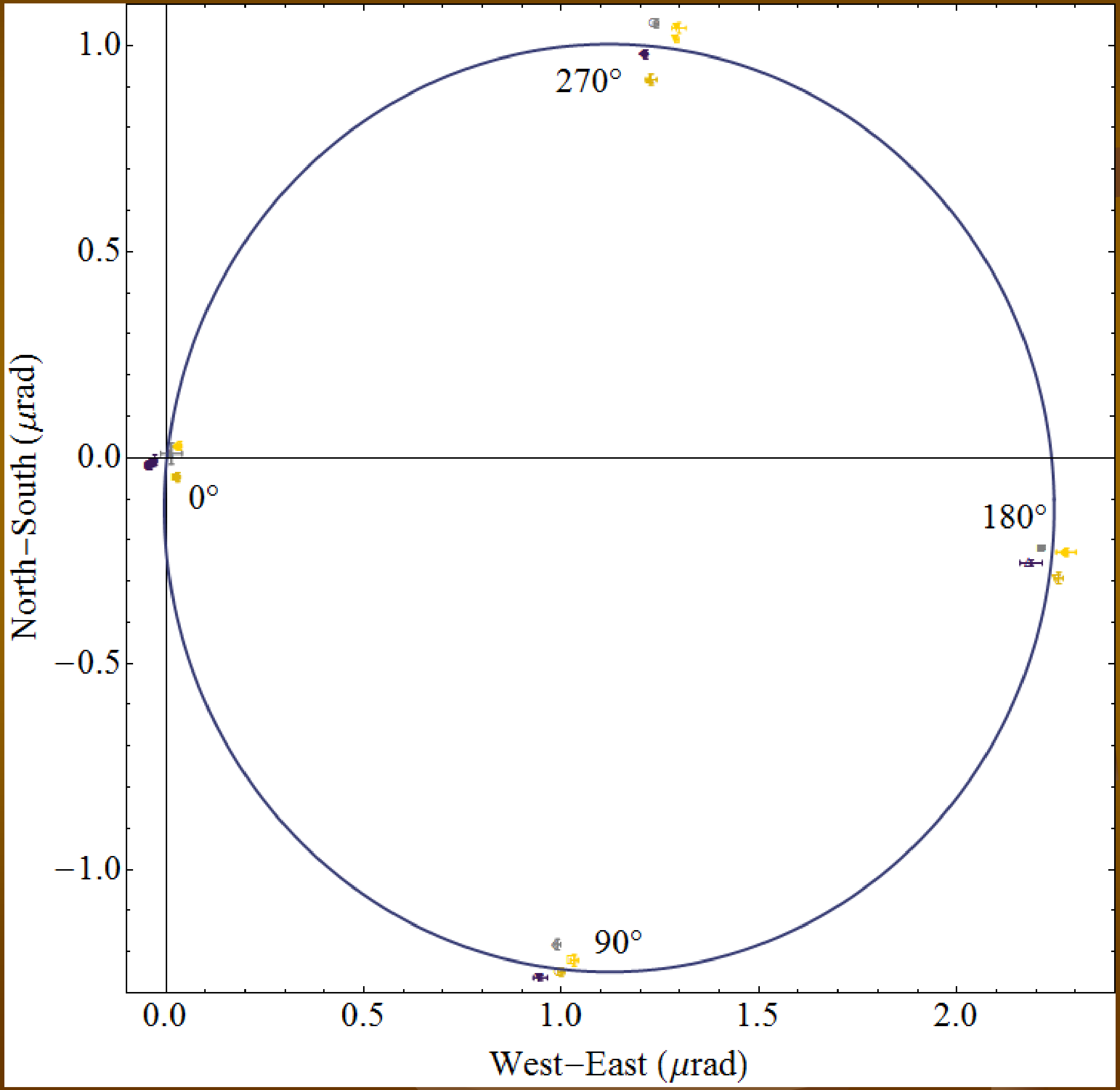
Q_{31} compensators
Total mass: 2.4 kg
Q_{31} =6.7×10^{-4} g/cm^4

hillside &
local masses

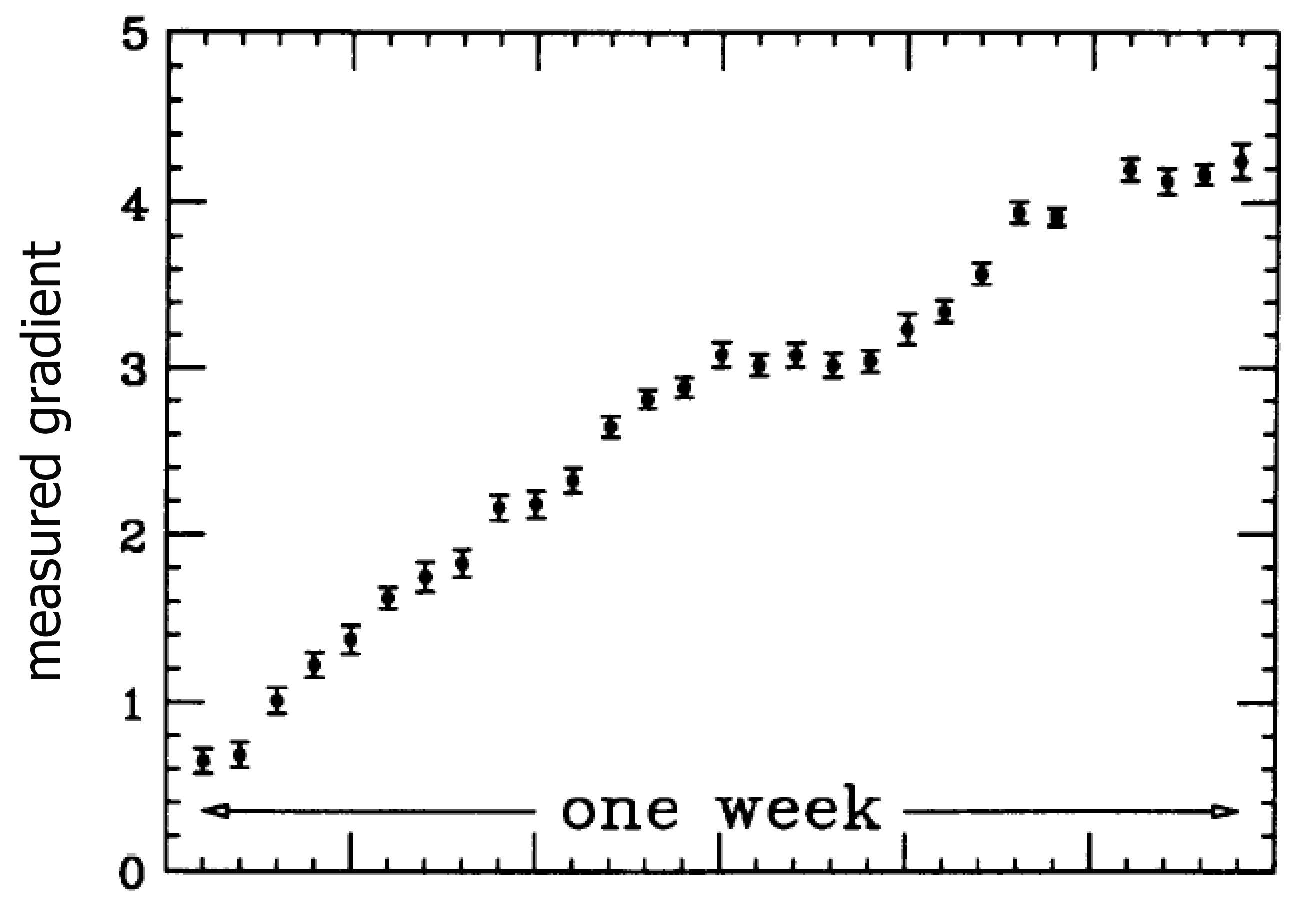
gravity-gradient compensators are on a turntable so they can be rotated to double the gradient rather than cancel it



effect of rotating the Q_{31} compensator

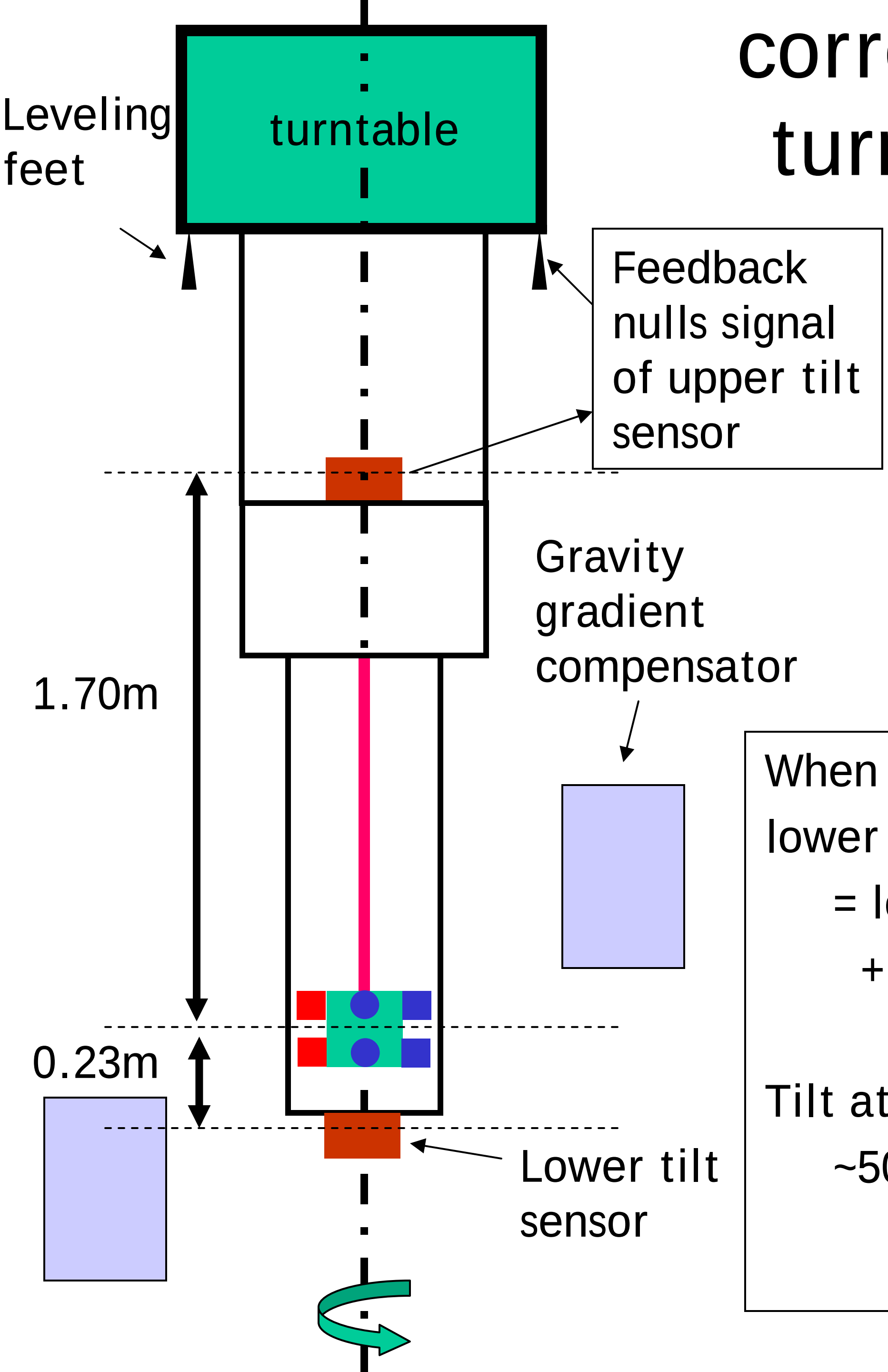


but there is a limit on how well the gradient can be cancelled



these data were taken in early November

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

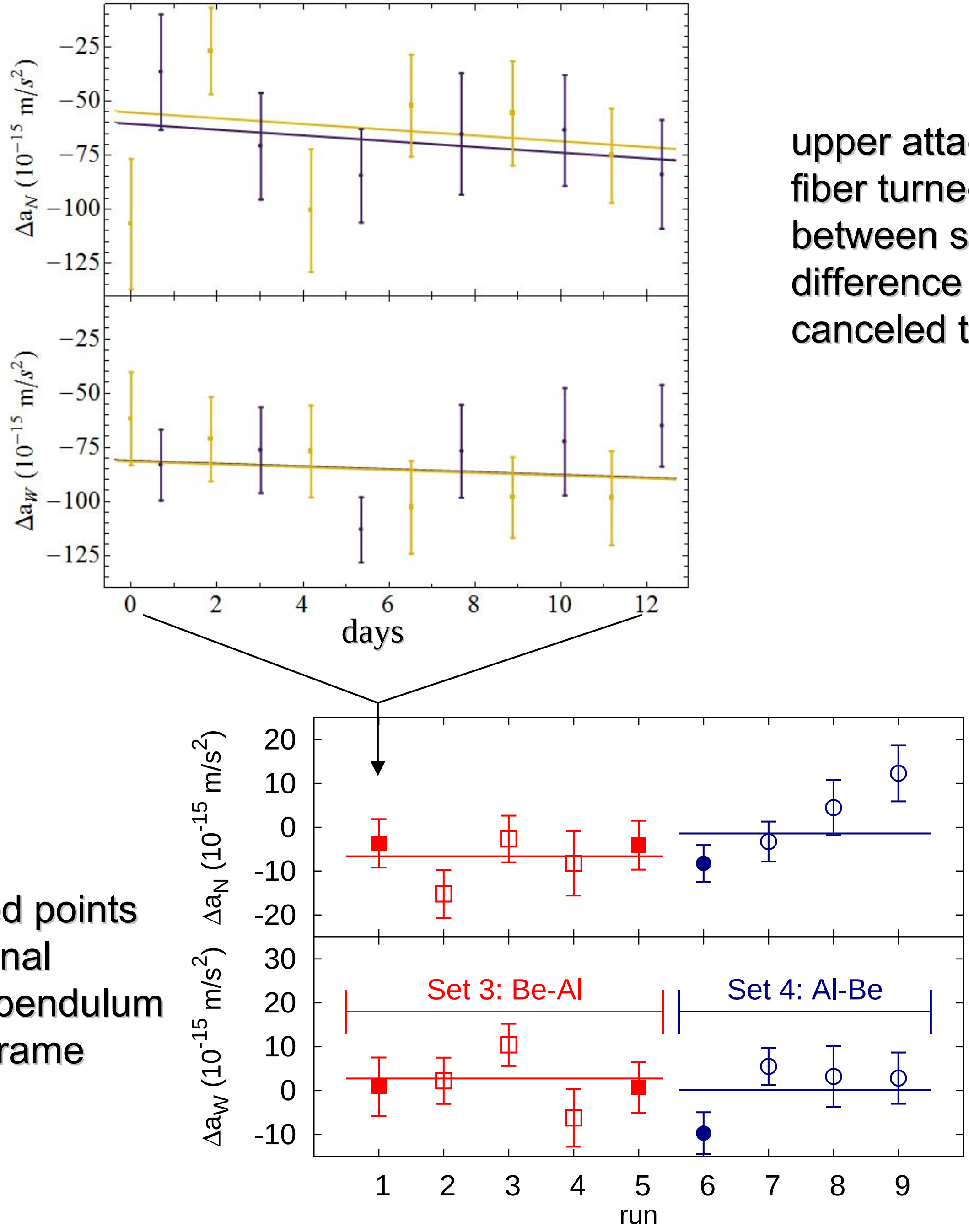
When tilt is nulled at upper sensor, the lower sensor measures a tilt of ~45 nrad!

= local earth field (~60 nrad)

+ off-center compensator field (~ –15 nrad)

Tilt at pendulum is only due to local earth field:

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



upper attachment of suspension fiber turned by 180 degrees between successive days -- the difference in measured Δa's canceled turntable imperfections

red & blue points show the results of interchanging test bodies on the pendulum frame

open and closed points denote orthogonal orientations of pendulum in the rotating frame

1σ statistical + systematic uncertainties from our Equivalence Principle experiment with beryllium and aluminum test bodies; beryllium and titanium data are similar

Source	Δa (cm/s^2)	$\Delta a/a_{source}$
Earth	(-1.2 ± 2.2) x 10^{-13}	(-0.7 ± 1.3) x 10^{-13}
Sun	$(-3.1 \pm 2.4)\times10^{-13}$	$(-5.2 \pm 4.0)\times10^{-13}$
Milky Way	$(-1.2 \pm 2.6)\times10^{-13}$	$(-6.5 \pm 8.6)\times10^{-6}$
CMB	$(-3.0 \pm 2.4)\times10^{-13}$	$(-3.4 \pm 2.7)\times10^{-4}$

PhD project of Todd Wagner

Suppose in addition to the normal tensor gravitation there was an additional gravi-vector field.

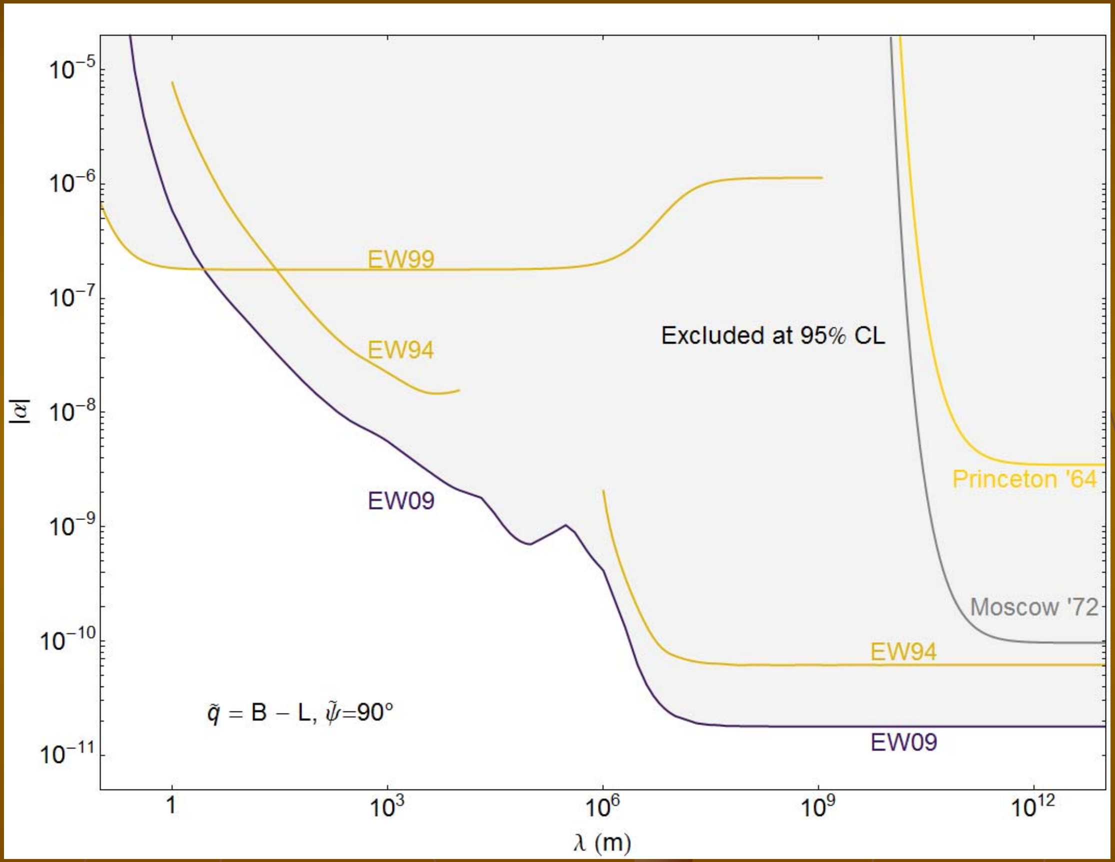
This would have following experimental consequences:

anti-H would fall with greater acceleration than H because anti-H would feel an additional attractive gravi-vector acceleration to protons in the earth.

it would produce a compositon-dependent force in EP tests

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

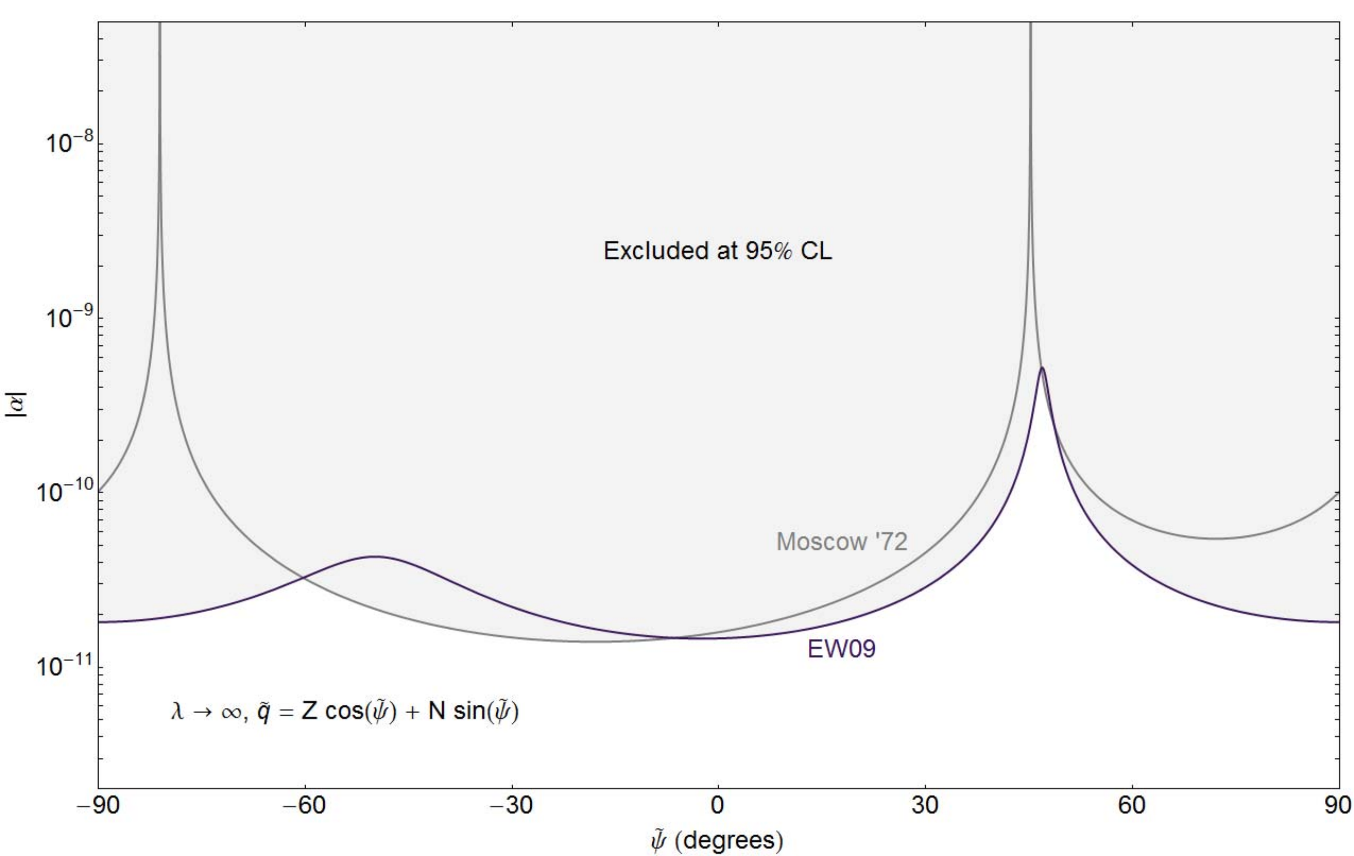
α is full interaction strength compared to gravity. The charge-dependent part we detect is about 500 times smaller



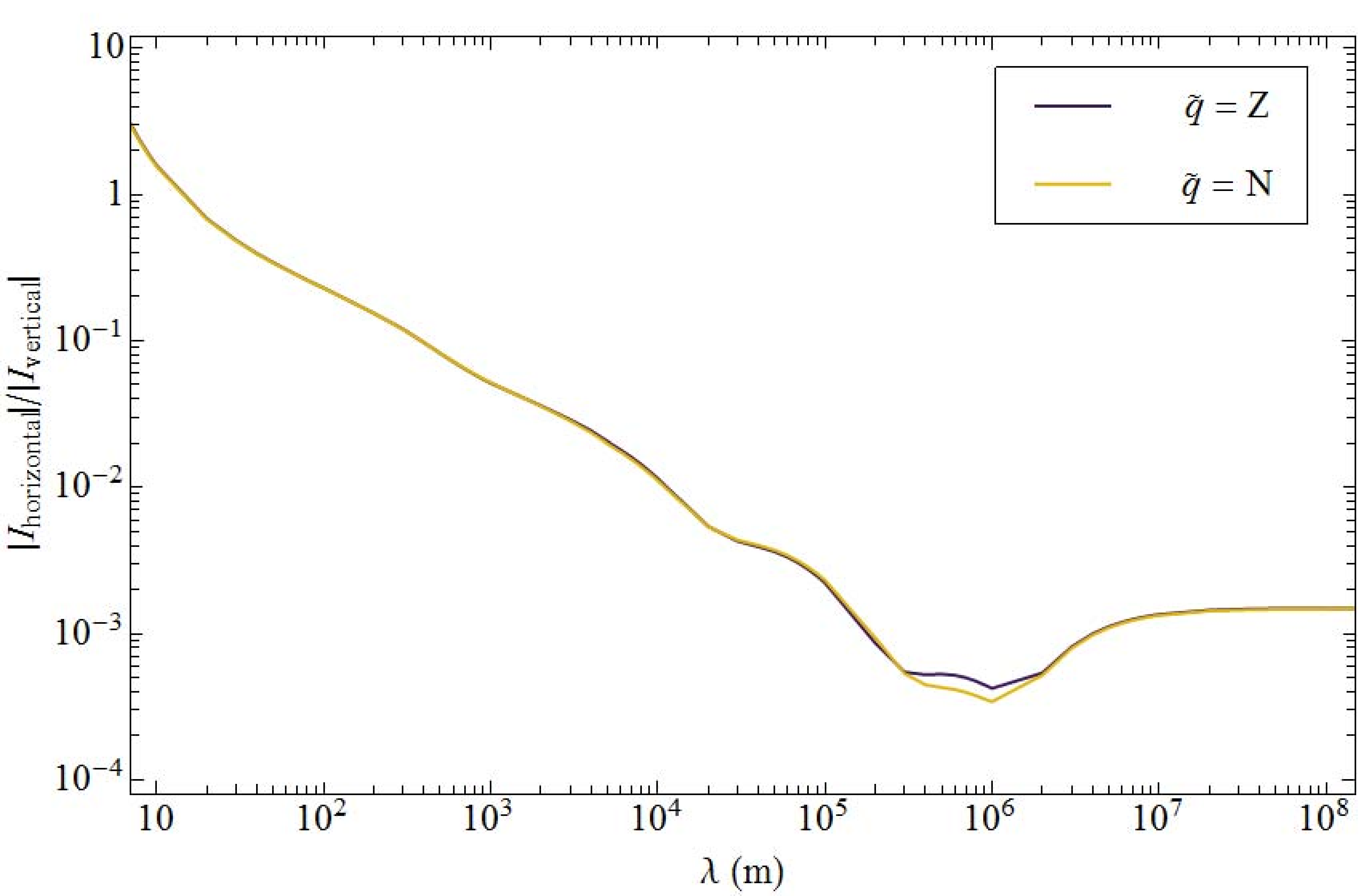
horizontal Yukawa source integral is based on:

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

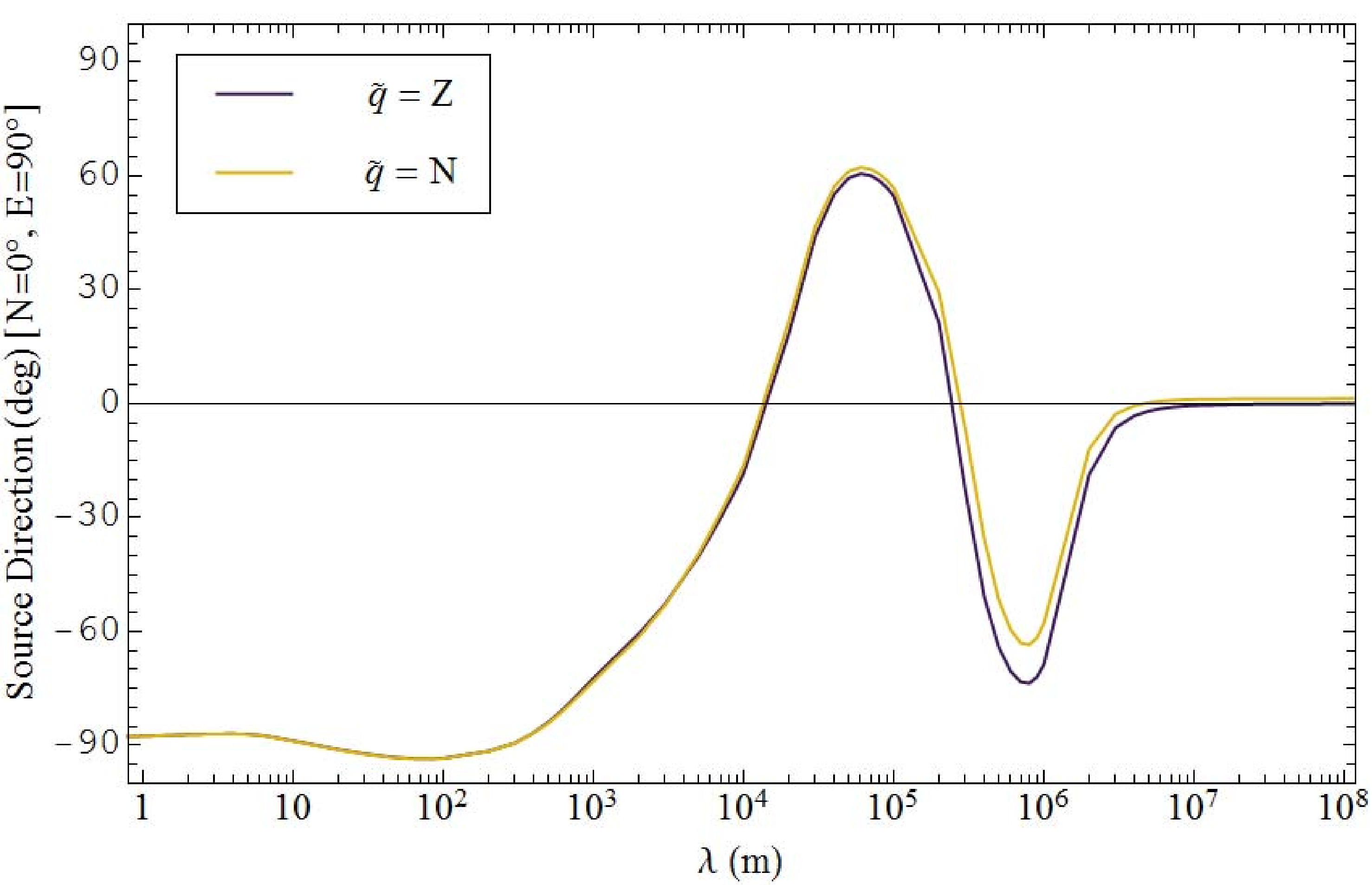
95% confidence level constraints on an infinite-range interaction as a function of its presumed charge



ratio of vertical (Galilean) to horizontal (Eötvös) Yukawa source integrals for our site

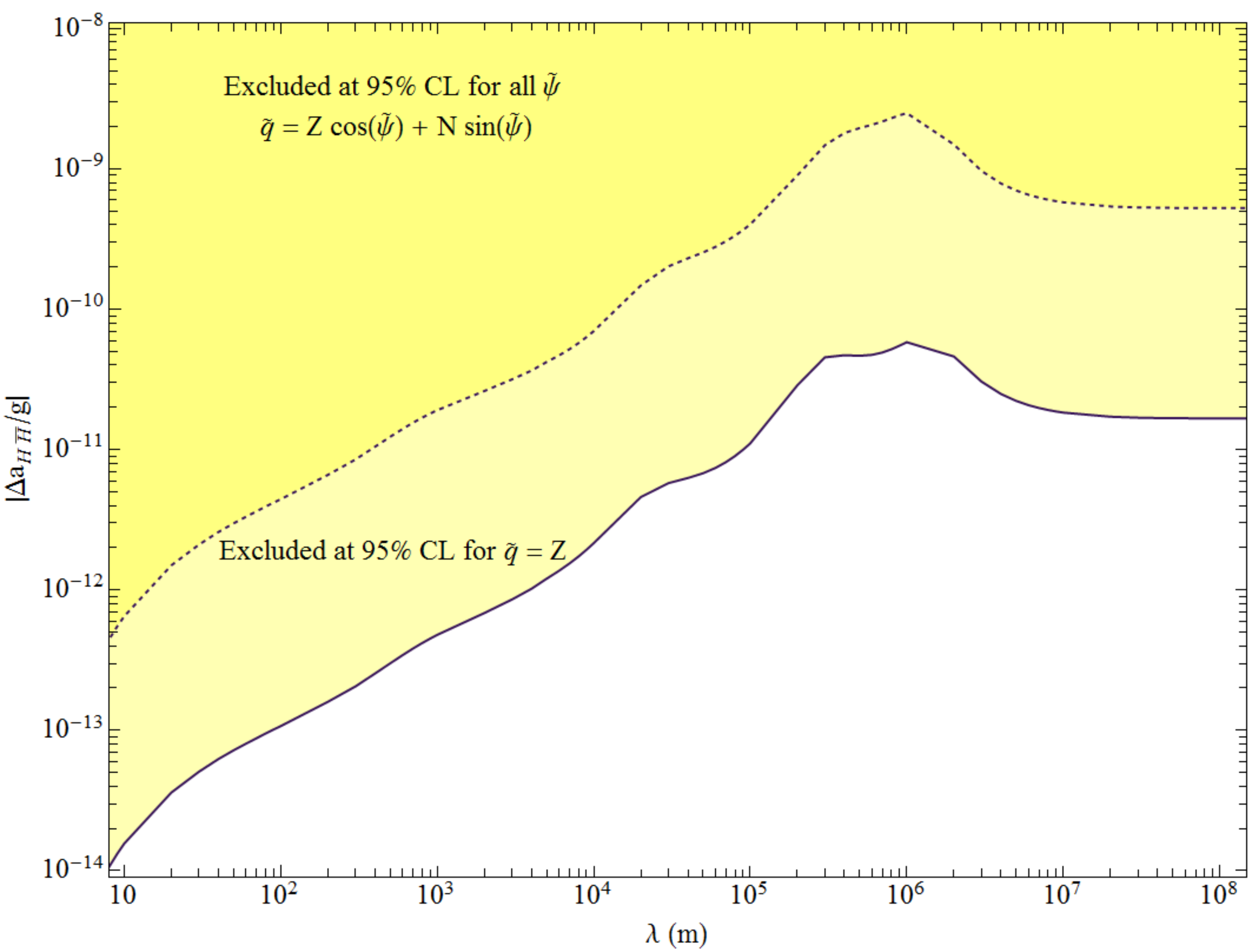


direction of our horizontal source integral is a strong function of lambda

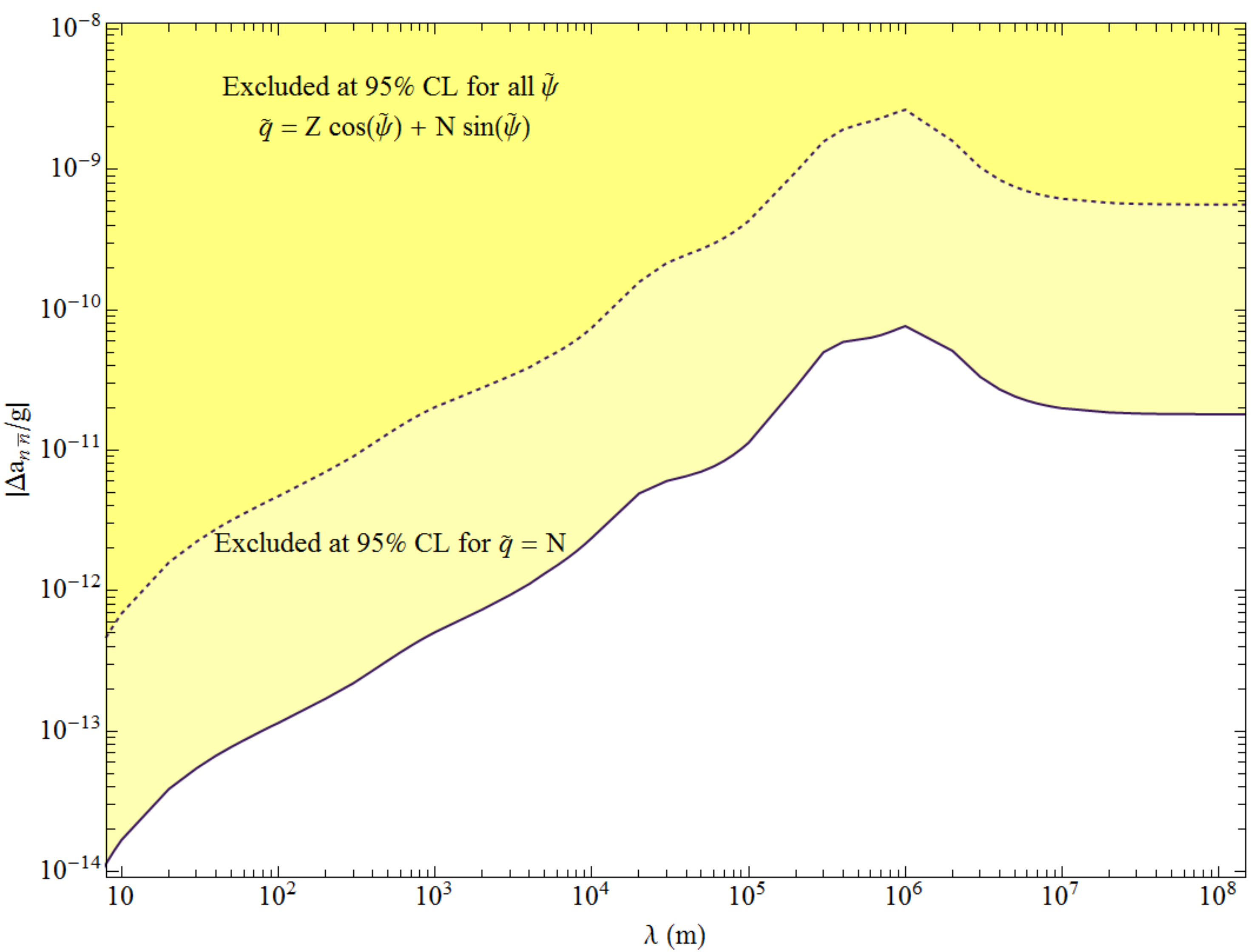


this differs from the corresponding plot in PRL 61, 2409 (1988) because that was made for a different location on our lab

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



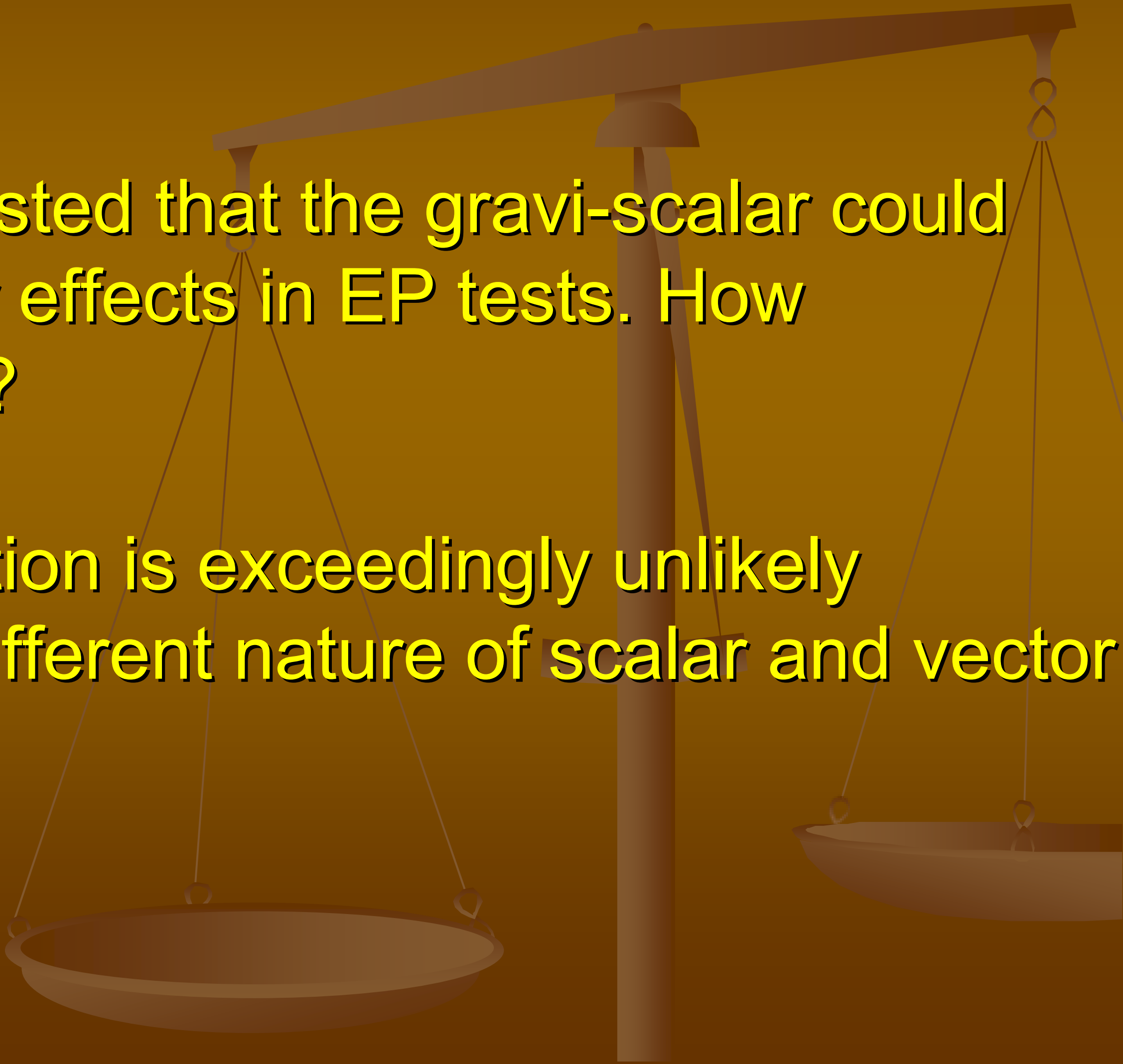
constraints on gravi-vector difference in free-fall accelerations of anti-neutrons and neutrons



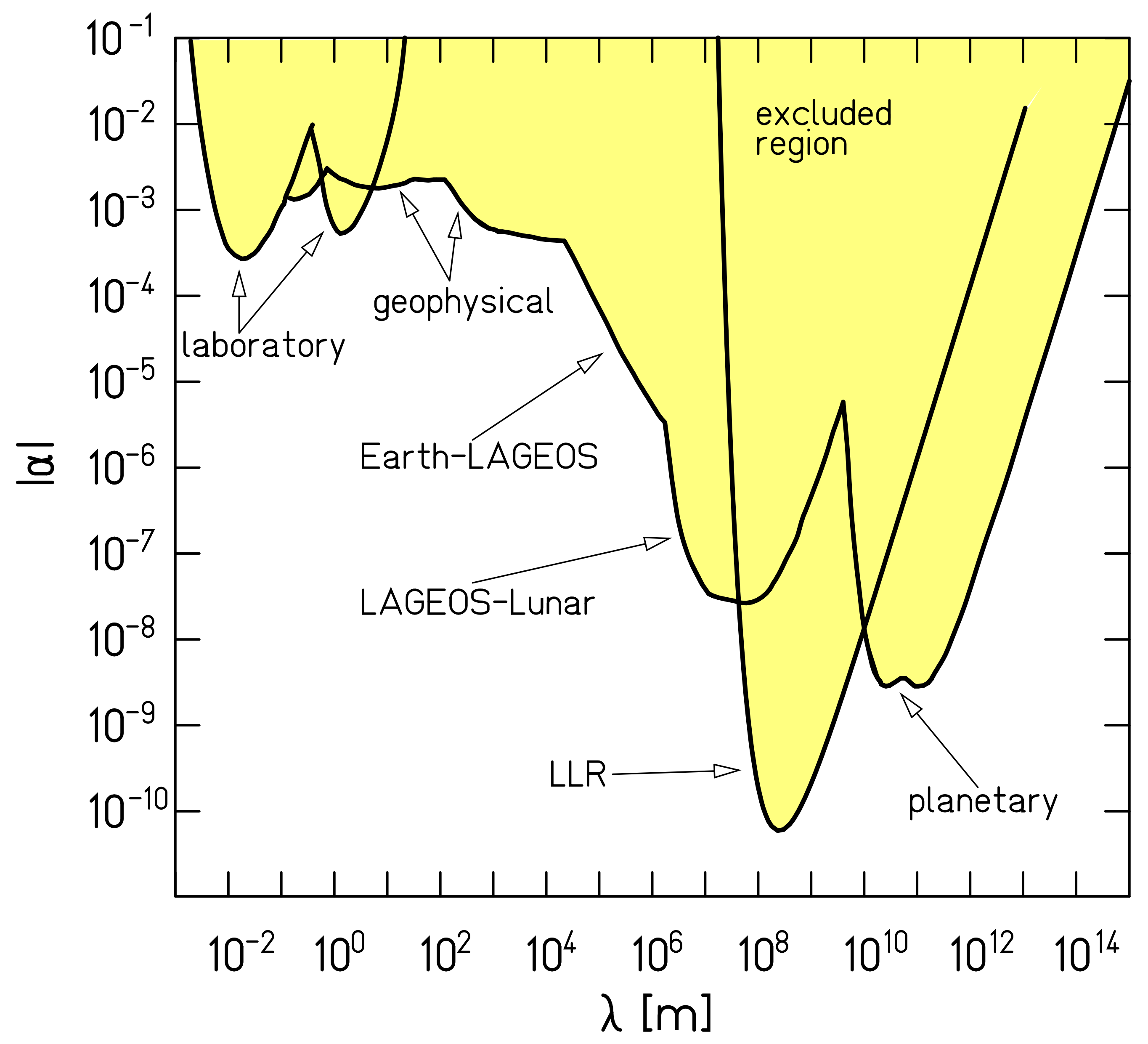
Now suppose there was in addition to the gravi-vector field also a gravi-scalar field. This would not change the difference in free fall accelerations of anti-H and H.

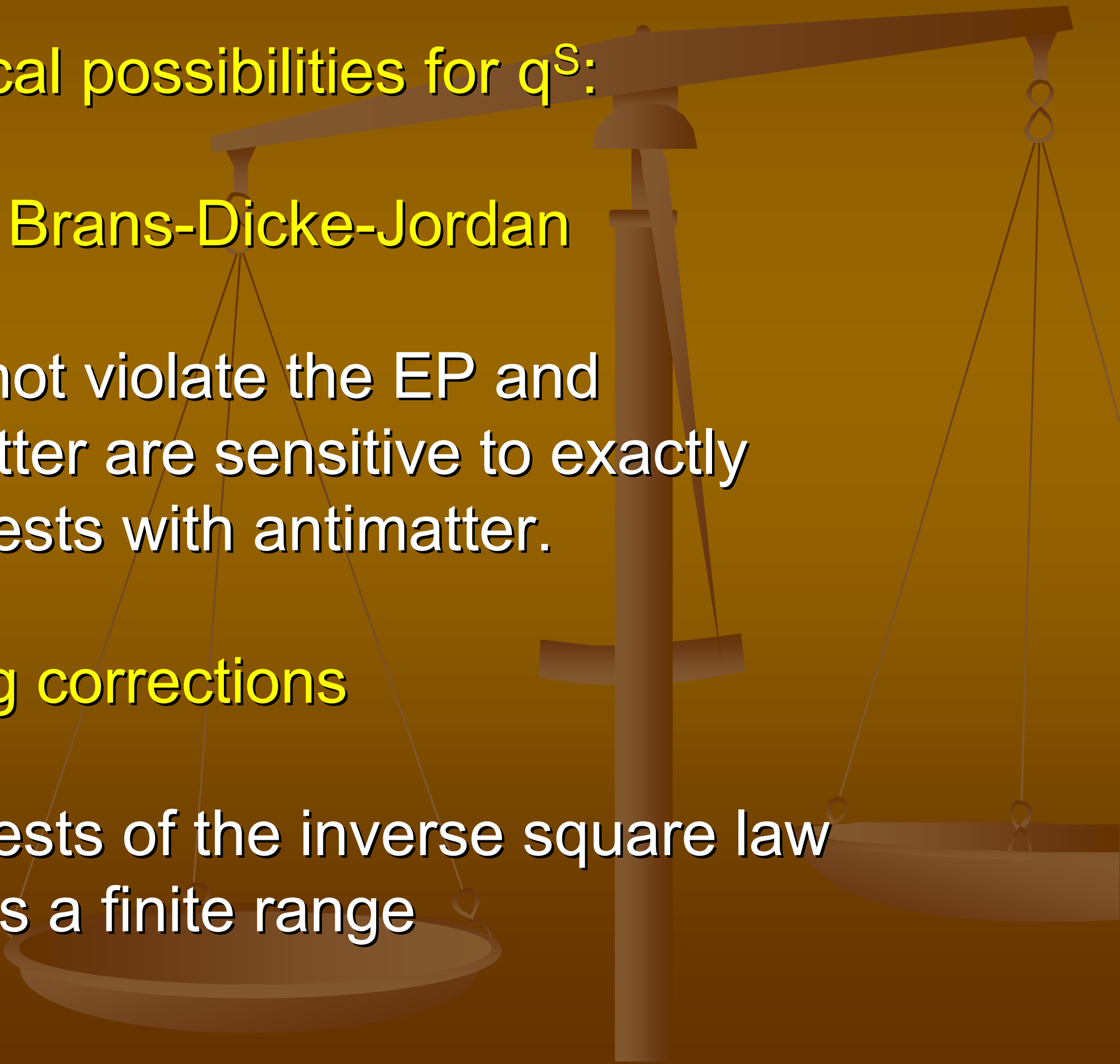
But it has been suggested that the gravi-scalar could “hide” the gravi-vector effects in EP tests. How plausible Is this claim?

Near-perfect cancellation is exceedingly unlikely because of the very different nature of scalar and vector charges



95% confidence limits as of 2000





Computing an atom's scalar charge q_S from a fundamental theory requires complex calculations that account for details of the atomic (QED) and nuclear structure (QCD).

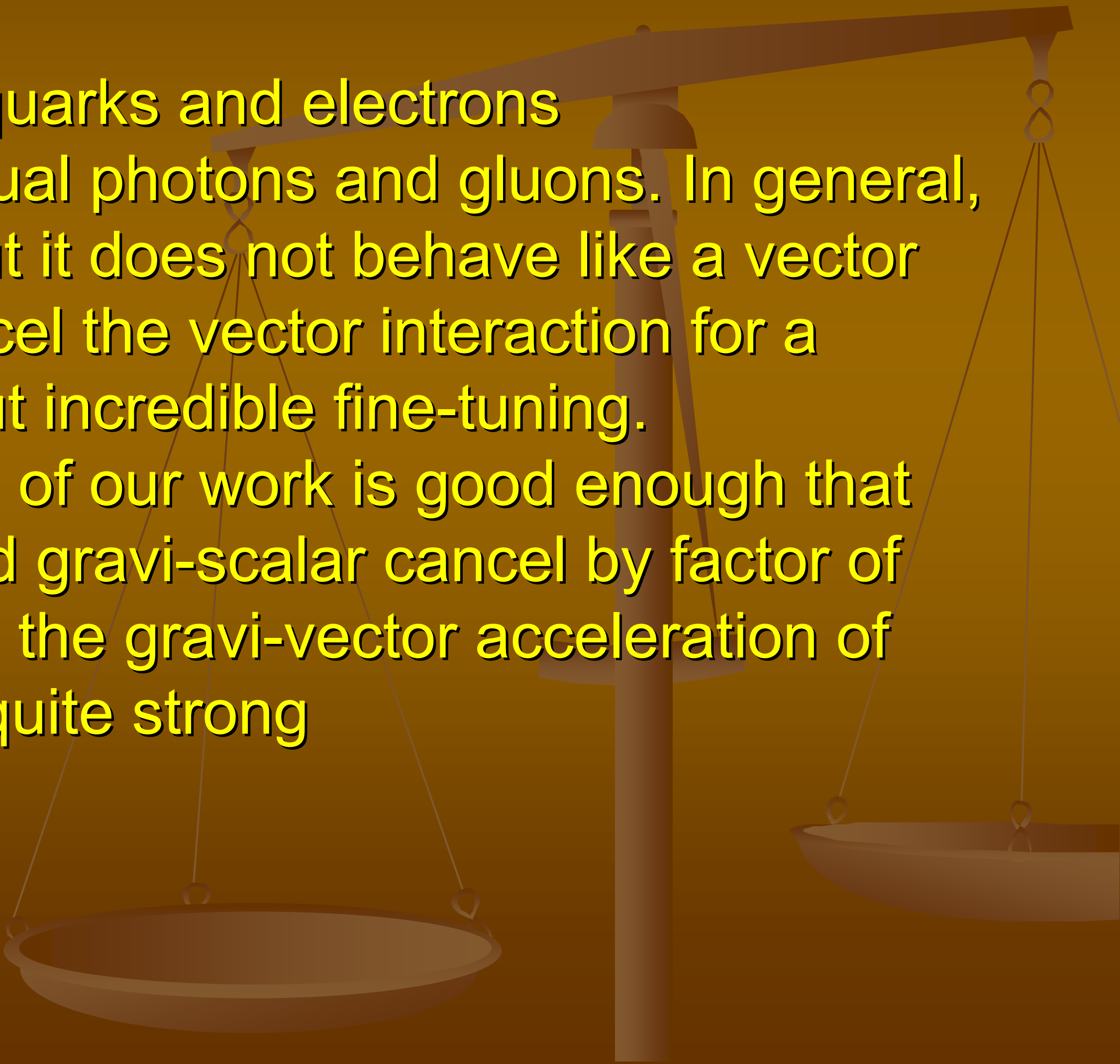
Consider phenomenological possibilities for q^S:

$q^S = \mu$ (mass or $T_\mu{}^\mu$) Brans-Dicke-Jordan

then scalar couplings do not violate the EP and
EP tests with ordinary matter are sensitive to exactly
the same physics as EP tests with antimatter.

$q^S = \mu$ + small EP-violating corrections

then it would show up in tests of the inverse square law
if the scalar interaction has a finite range



On the other hand, a field-theoretic calculation would give
$q^S = \sum (q^S/\gamma)_i + \sum q^S{}_j$
where i runs over the quarks and electrons
and j runs over the virtual photons and gluons. In general, this violates the EP, but it does not behave like a vector charge, so cannot cancel the vector interaction for a variety of atoms without incredible fine-tuning.
Experimental precision of our work is good enough that even if gravi-vector and gravi-scalar cancel by factor of 100, the constraints on the gravi-vector acceleration of anti-hydrogen remain quite strong

Cancellation in Eötvös experiments requires:

- Scalar and vector accelerations must have the same magnitude

  definite relation between coupling strengths and ranges

- Scalar and vector accelerations must have the same direction

  $\lambda_S = \lambda_V$ or $\lambda_S , \lambda_V > 10^7$ m

- Cancellation must occur for all test-bodies and attractors

Be-Al, Be-Ti, Be-Cu	earth sun galaxy
Cu-Pb	^{238}U
MM-EC	sun

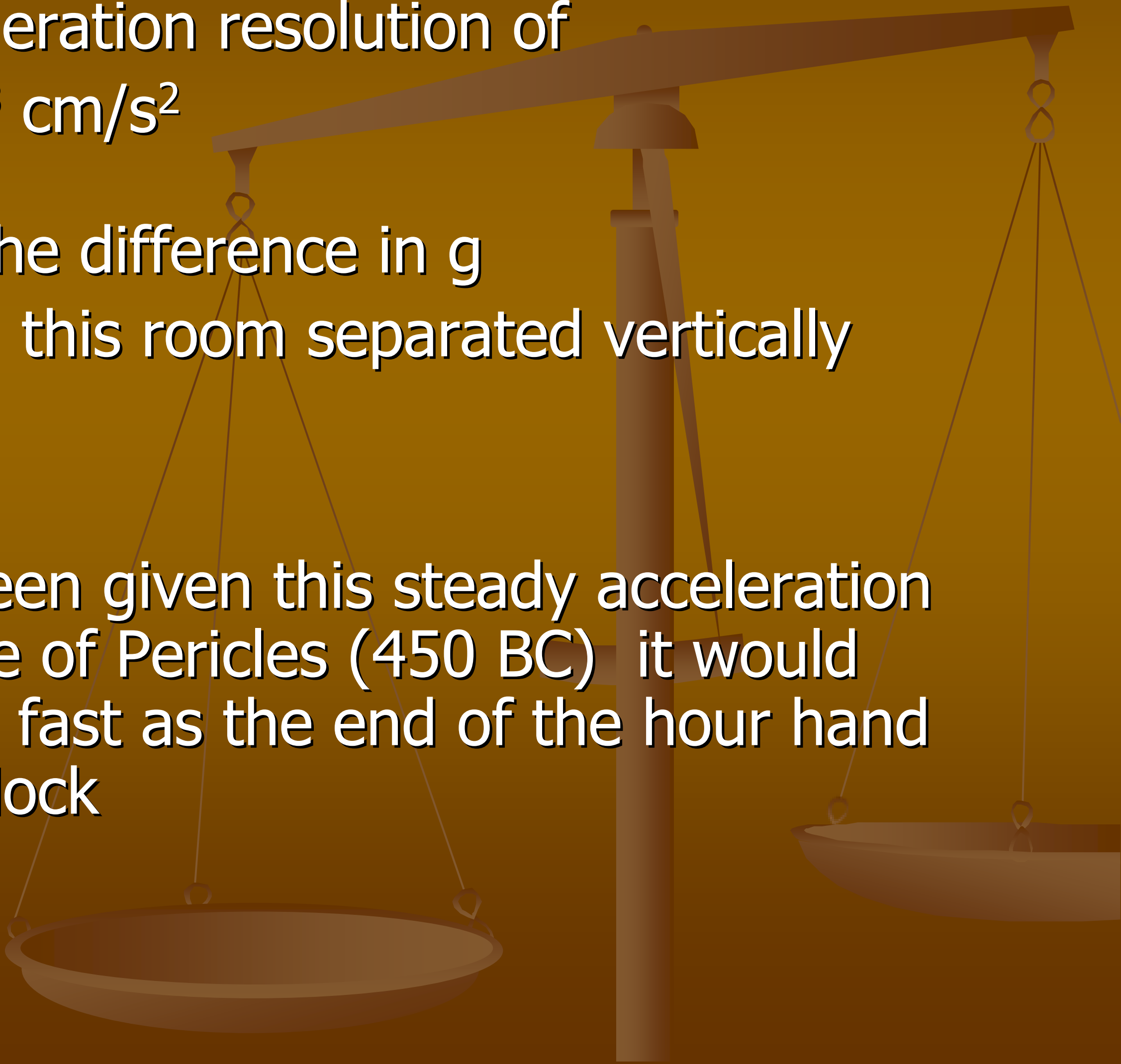
MM = Mg + SiO_2 EC = Fe + Ni + Cr

Conclusion:

Theories involving gravi-vector fields are tightly constrained by conventional EP results, probably at a more sensitive level than is likely to come from first generation of anti-hydrogen free-fall experiments

But EP tests with antihydrogen provide an opportunity to test if gravitational mass obeys CPT symmetry as our arguments based on EP tests with ordinary matter assume CPT symmetry.

some amusing numbers



our differential acceleration resolution of

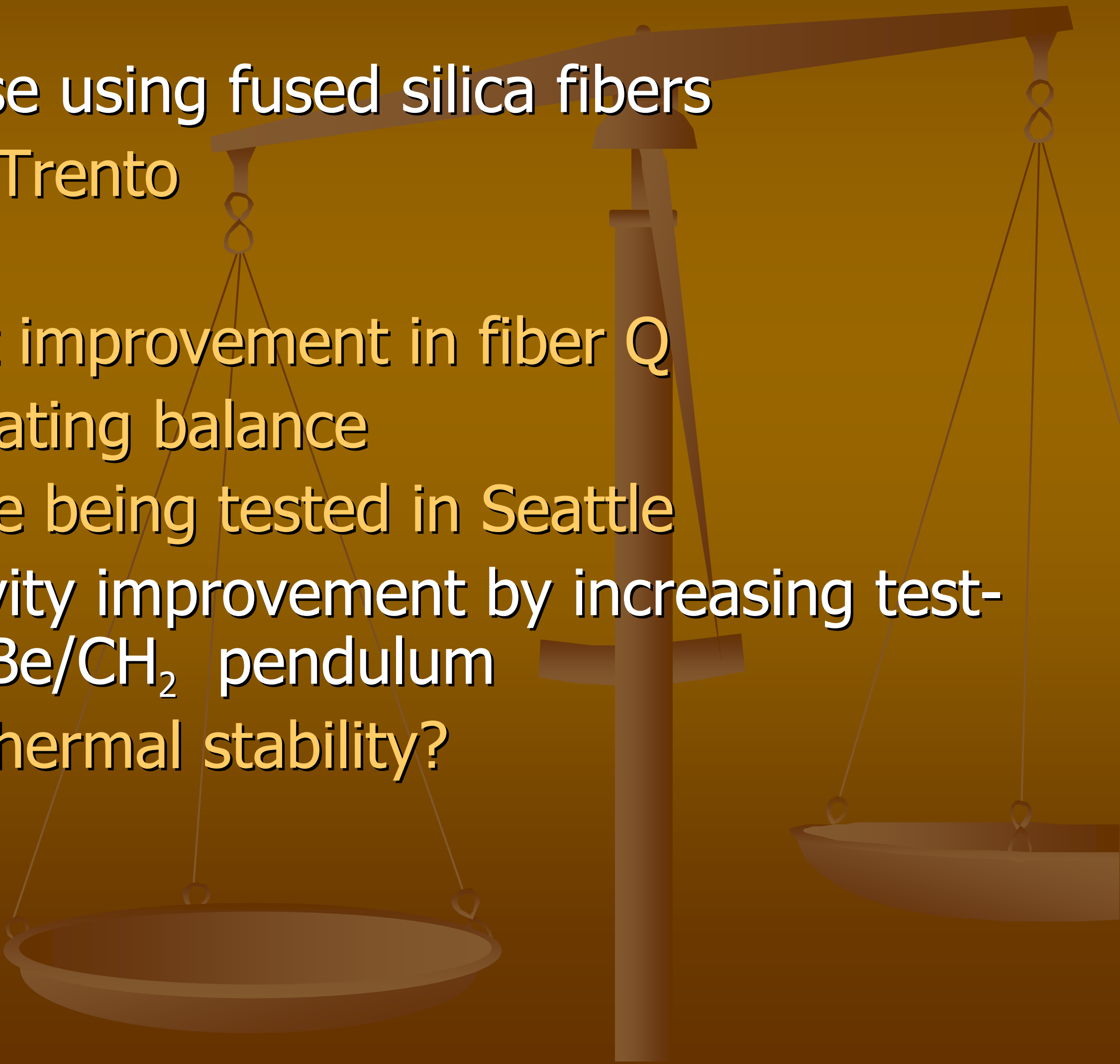
$$\Delta a \approx 3\times10^{-13}\ \mathrm{cm/s^2}$$

- is comparable to the difference in g between 2 spots in this room separated vertically by ≈ 1 nm

- if an object had been given this steady acceleration starting in the time of Pericles (450 BC) it would now be moving as fast as the end of the hour hand on a typical wall clock

prospects for further EP improvements

sensitivity ~ Δa / test-body difference



- decrease thermal noise using fused silica fibers
  - demonstrated at Trento
- operate at 4 K
  - expect significant improvement in fiber Q
  - hard to do on rotating balance
  - stationary balance being tested in Seattle
- obtain 10-fold sensitivity improvement by increasing test-body difference with Be/CH_2 pendulum
  - mechanical and thermal stability?
- atom interferometers

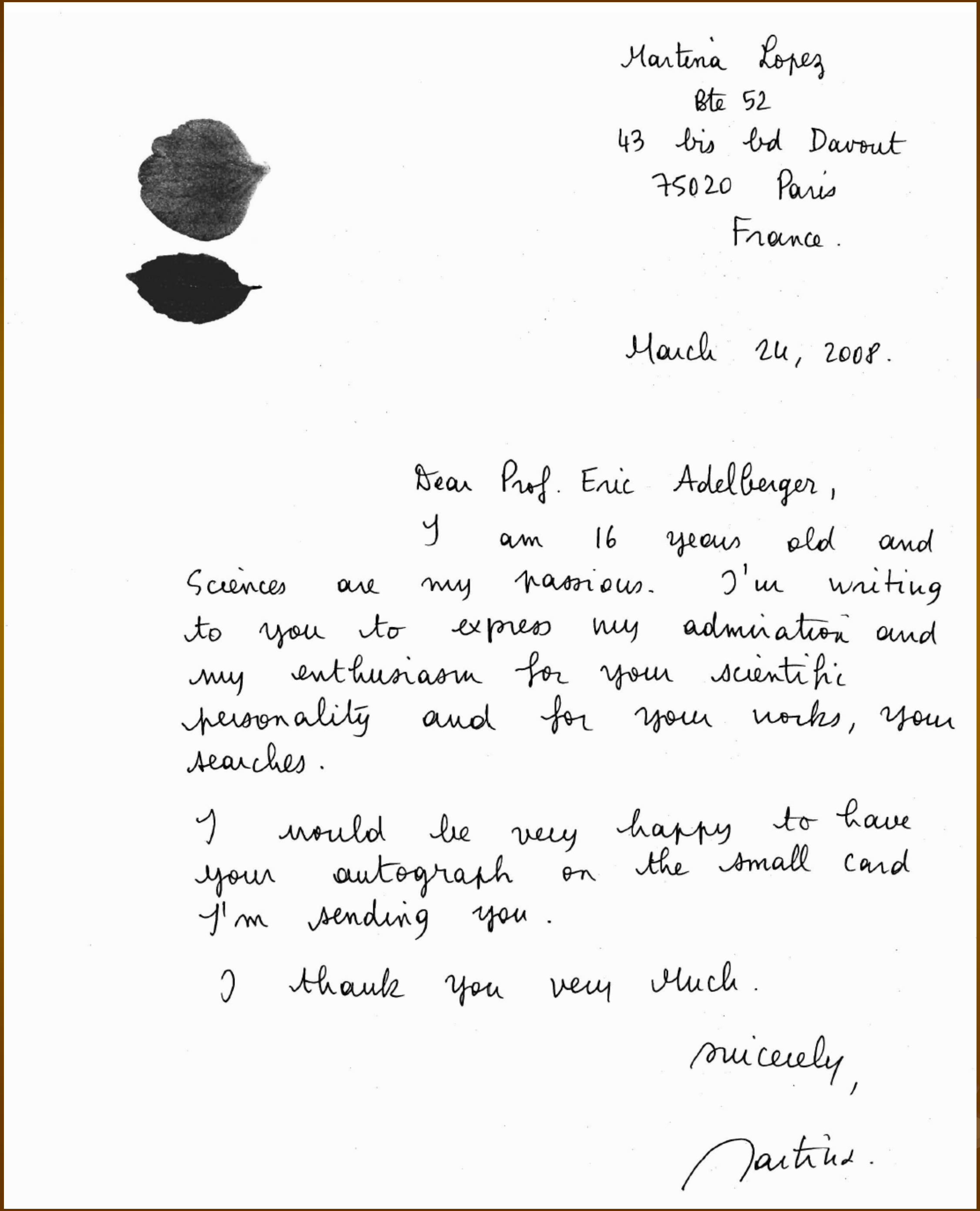
Improving EP sensitivity with new test body materials

- large differences in neutron/proton ratio and nuclear binding energy give high EP sensitivity.
- Be-polyethylene test bodies improve sensitivity by factor of about ten

x10^{-2}	Be	PE	Al	Ti	Cu	Pt
Be		-12.65	-3.80	-1.58	-1.25	4.40
PE	-12.63		8.85	11.07	11.40	17.05
Al	-3.59	9.03		2.22	2.54	8.20
Ti	-1.33	11.29	2.26		0.32	5.98
Cu	-1.01	11.62	2.59	0.33		5.65
Pt	4.55	17.18	8.15	5.89	5.56	

🟧 $\Delta(Z/\mu)$

🟦 $\Delta(N/\mu)$



Martina Lopez
Bte 52
43 bis bd Davout
75020 Paris
France.

March 24, 2008.

Dear Prof. Eric Adelberger,

I am 16 years old and Sciences are my passions. I'm writing to you to express my admiration and my enthusiasm for your scientific personality and for your works, your searches.

I would be very happy to have your autograph on the small card I'm sending you.

I thank you very much.

sincerely,

Martina.