# Modern tests of Einstein's Equivalence Principle

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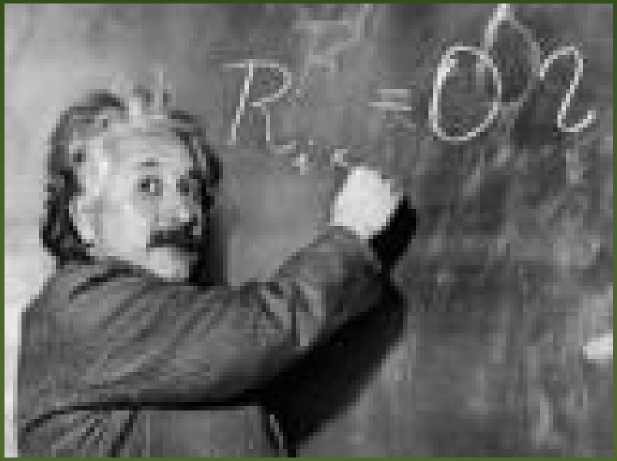
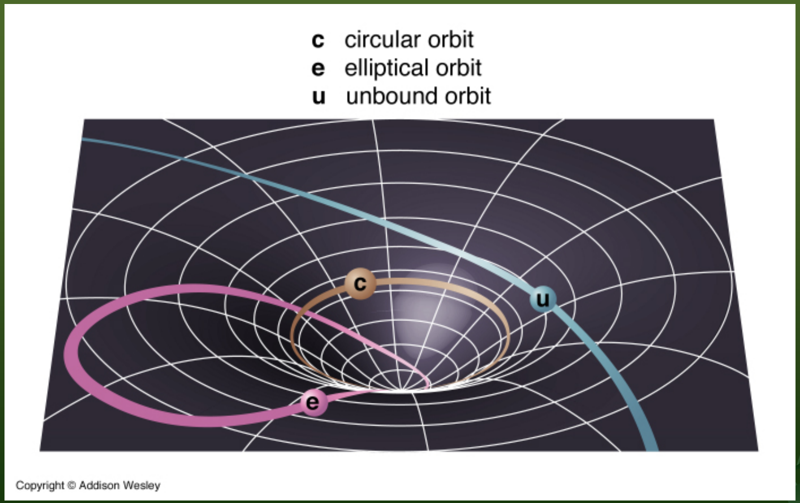
# outline

- a brief account of a long history
- motivations old and new
- experimental techniques
- modern results
- what next?

# Einstein's relativistic gravity

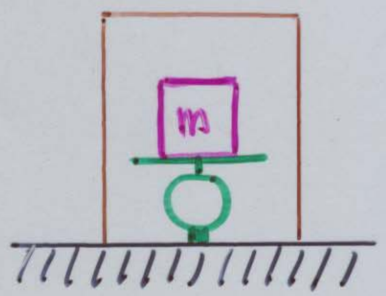





- Einstein equivalence principle (EP) his "happiest idea"
  in Newtonian terms $m^i \equiv m^g$
- gravity=space-time curvature
- local inertial frames
- no preferred frame (my third talk)
- constancy of constants G and $\alpha$
- $1/r^2$ gravity: a consequence of 3 space dimensions (my second talk)
- has passed all experimental tests
- classical theory i.e. not quantized

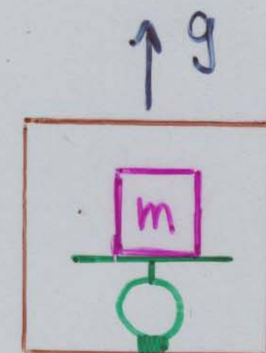
## Einstein's view of the EP

- gravitational force equivalent* to acceleration of observer




sealed chamber
on earth's surface

both scales read
$F = mg$

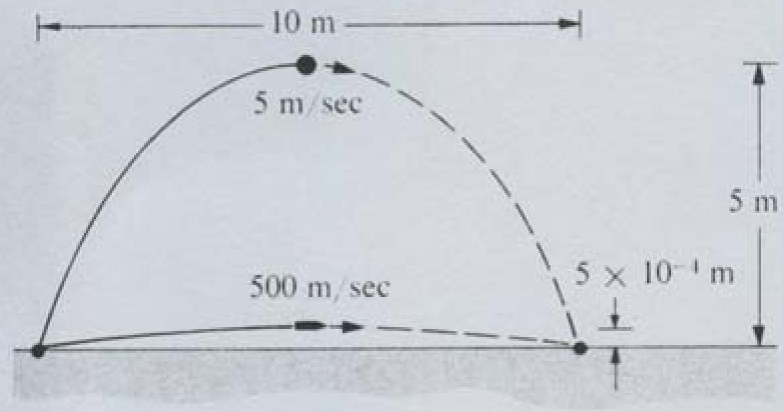



sealed chamber in
rocket in empty space

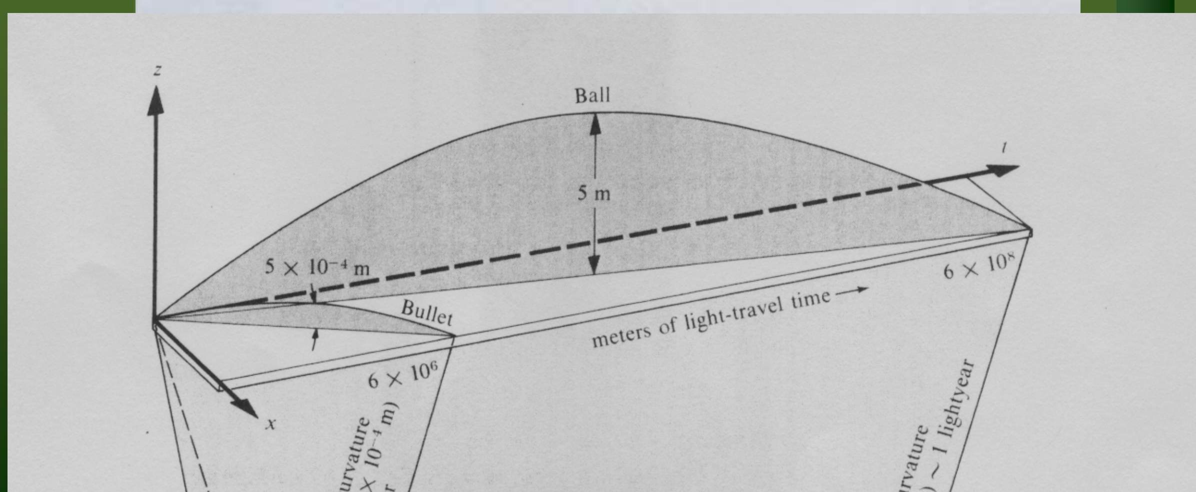
* in a sufficiently small region

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

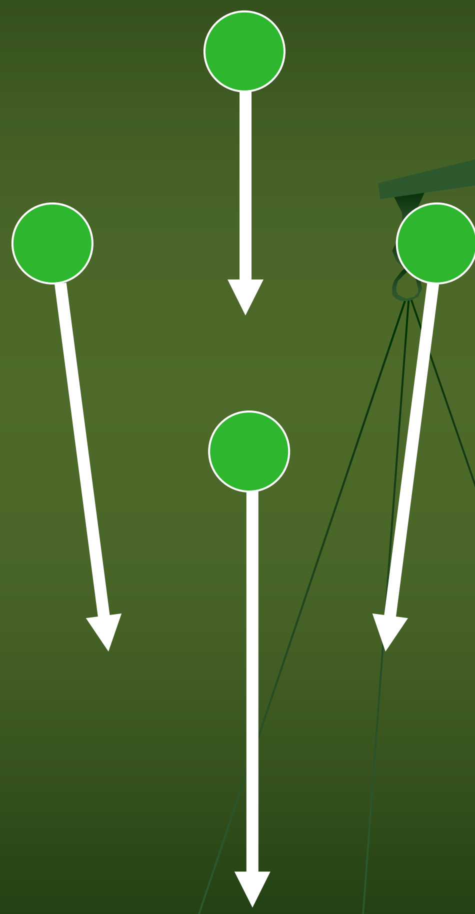
# How can the different trajectories of a bullet and a ball both be due to spacetime curvature?




B. Tracks of ball and bullet through space as seen in laboratory have very different curvatures.



but gravity is equivalent to acceleration only locally i.e. in a very small region



This is a huge effect at current levels of precision

# string theory and the unification of gravity with the rest of physics

- replaces point particles with 1-dimensional strings and higher dimensional “branes”
- first viable candidate for a quantum theory of gravity that unifies it with the rest of physics
- string theory triumphs
  - predicts the graviton, gives black holes, etc.
- string theory problems
  - actually ~ $10^{500}$ different theories
  - nobody knows how to solve it yet
  - requires 10 or 11 dimensions
  - predicts large number of light scalar particles that will violate the EP
- but these new features provide motivations for experimenters to look for new gravitational phenomena

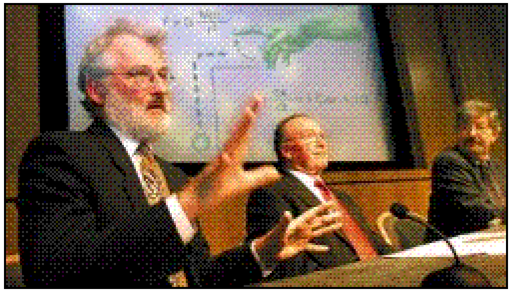
# But fortunately we have a simpler theoretical alternative

the ONION

## Evangelical Scientists Refute Gravity With New 'Intelligent Falling' Theory

August 17, 2005 | **Issue 41•33**

KANSAS CITY, KS—As the debate over the teaching of evolution in public schools continues, a new controversy over the science curriculum arose Monday in this embattled Midwestern state. Scientists from the Evangelical Center For Faith-Based Reasoning are now asserting that the long-held "theory of gravity" is flawed, and they have responded to it with a new theory of Intelligent Falling.



Rev. Gabriel Burdett (left) explains Intelligent Falling.

"Things fall not because they are acted upon by some gravitational force, but because a higher intelligence, 'God' if you will, is pushing them down," said Gabriel Burdett, who holds degrees in education, applied Scripture, and physics from Oral Roberts University.

Burdett added: "Gravity—which is taught to our children as a law—is founded on great gaps in understanding. The laws predict the mutual force between all bodies of mass, but they cannot explain that force. Isaac Newton himself said, 'I suspect that my theories may all depend upon a force for which philosophers have searched all of nature in vain.' Of course, he is alluding to a higher power."

Founded in 1987, the ECFR is the world's leading institution of evangelical physics, a branch of physics based on literal interpretation of the Bible.

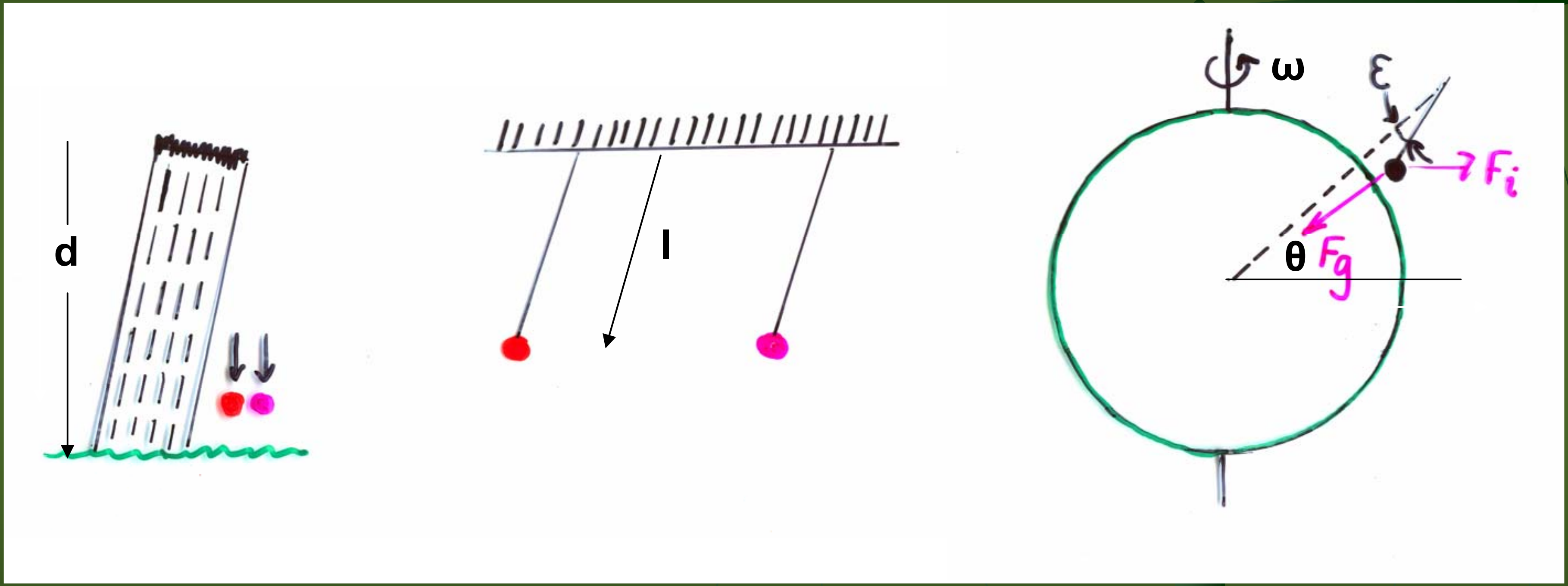
According to the ECFR paper published simultaneously this week in the *International Journal Of Science* and the adolescent magazine *God's Word For Teens!*, there are many phenomena that cannot be explained by secular gravity alone, including such mysteries as how angels fly, how Jesus ascended into Heaven, and how Satan fell when cast out of Paradise.

The ECFR, in conjunction with the Christian Coalition and other Christian conservative action groups, is calling for public-school curriculums to give equal time to the Intelligent Falling theory. They insist they are not asking that the theory of gravity be banned from schools, but only that students be offered both sides of the issue "so they can make an informed decision."

"We just want the best possible education for Kansas' kids," Burdett said.

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

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




are fall times equal?

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

$\Delta a/a \leq 0.1$

are periods equal?

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

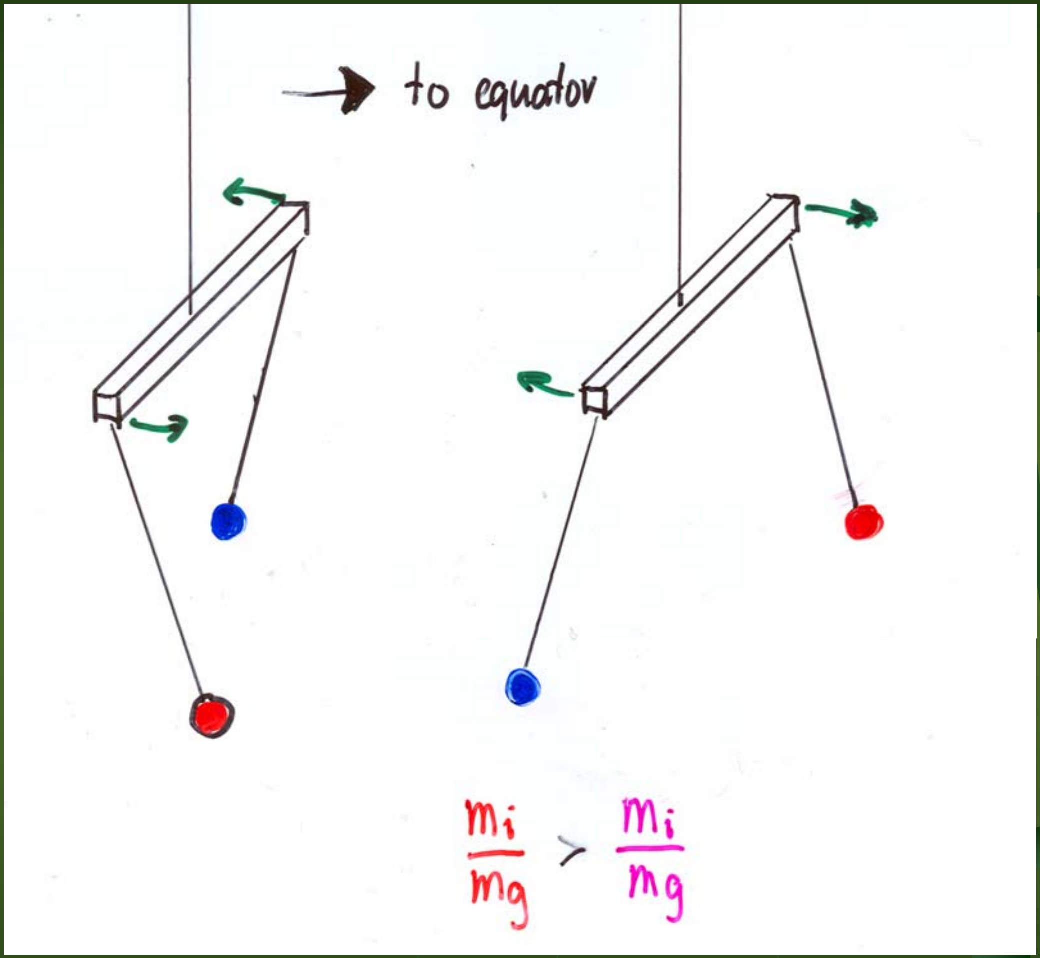
$\Delta a/a \leq 10^{-4}$

are angles equal?

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

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

# implementation as a null experiment

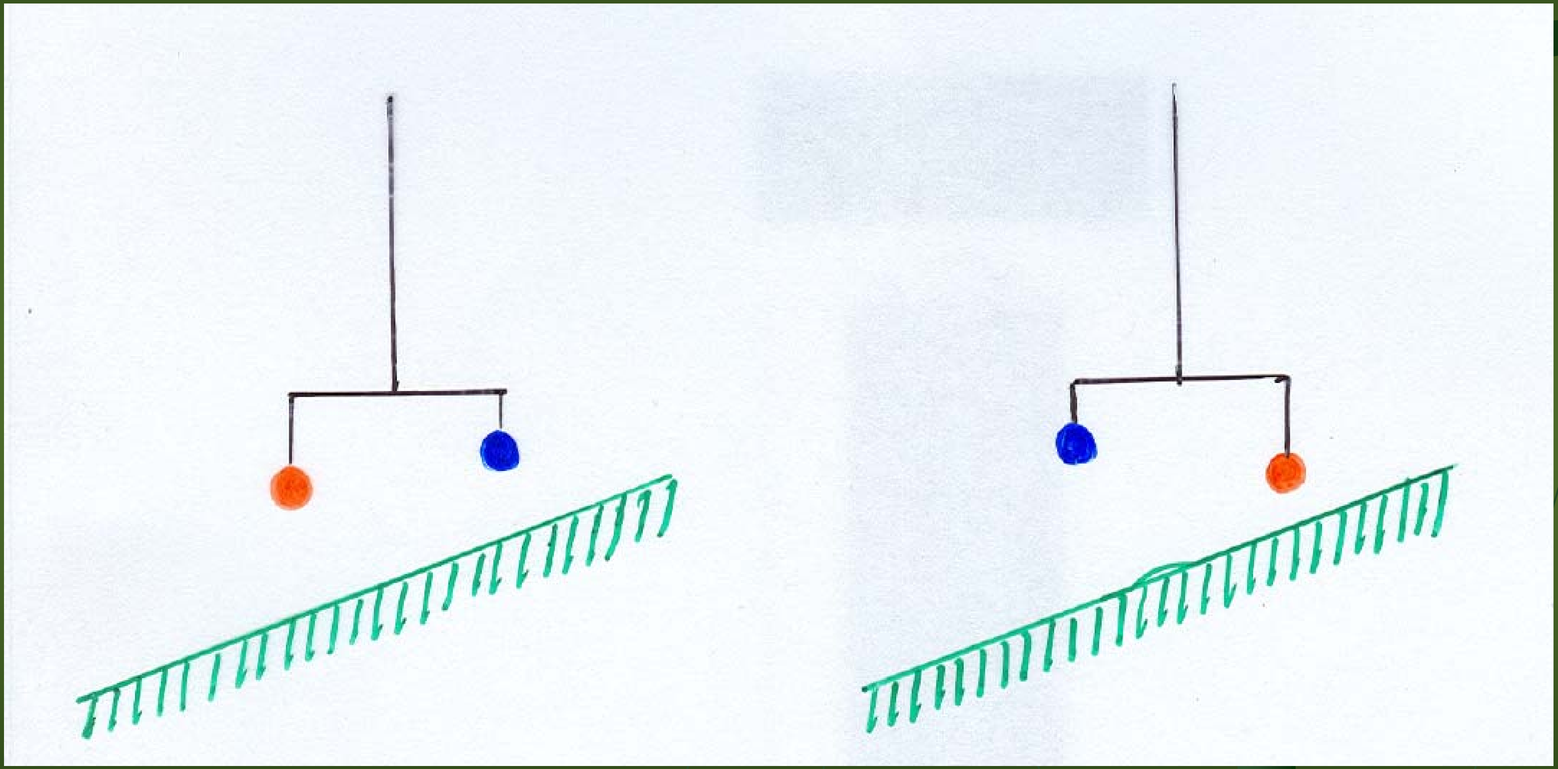



Torsion balance twists only if force vectors are not parallel!

if the EP is violated down is not a unique direction

# False signals from gravity gradients

Suppose one test body is lower than the other and that the apparatus is located on a hillside



This orientation is less bound gravitationally

This orientation is more bound gravitationally

This gravity-gradient effect looks like EP violation

# Eötvös's instrument

Eötvös first used torsion balance to test the EP In 1889. His most famous work was done between 1904 and 1909

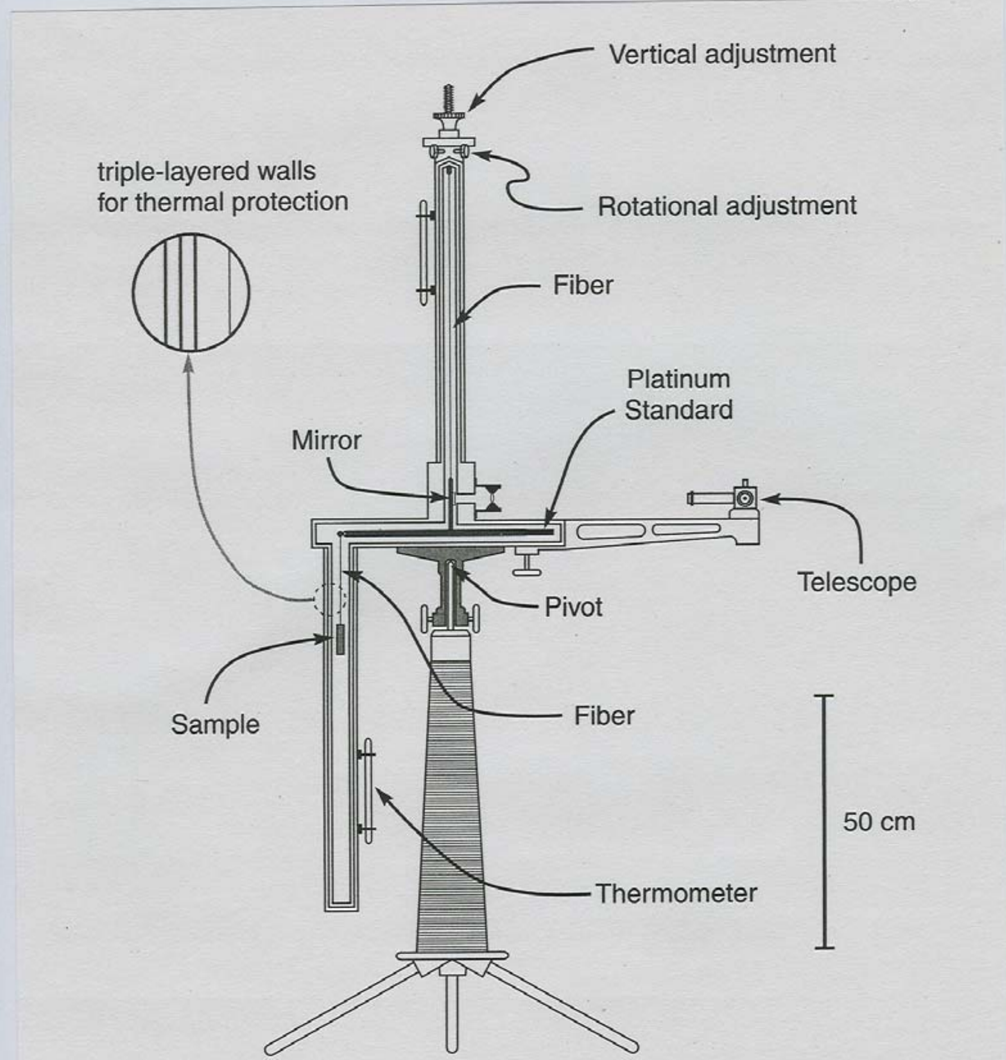



**Figure 4.6**: Single-arm torsion balance used by Eötvös, Pekár, and Fekete.

Eötvös et al claimed $\Delta a/a < 5\times10^{-9}$

# The classic EP experiments (from the 60s and 70s) used the sun as the attracting object

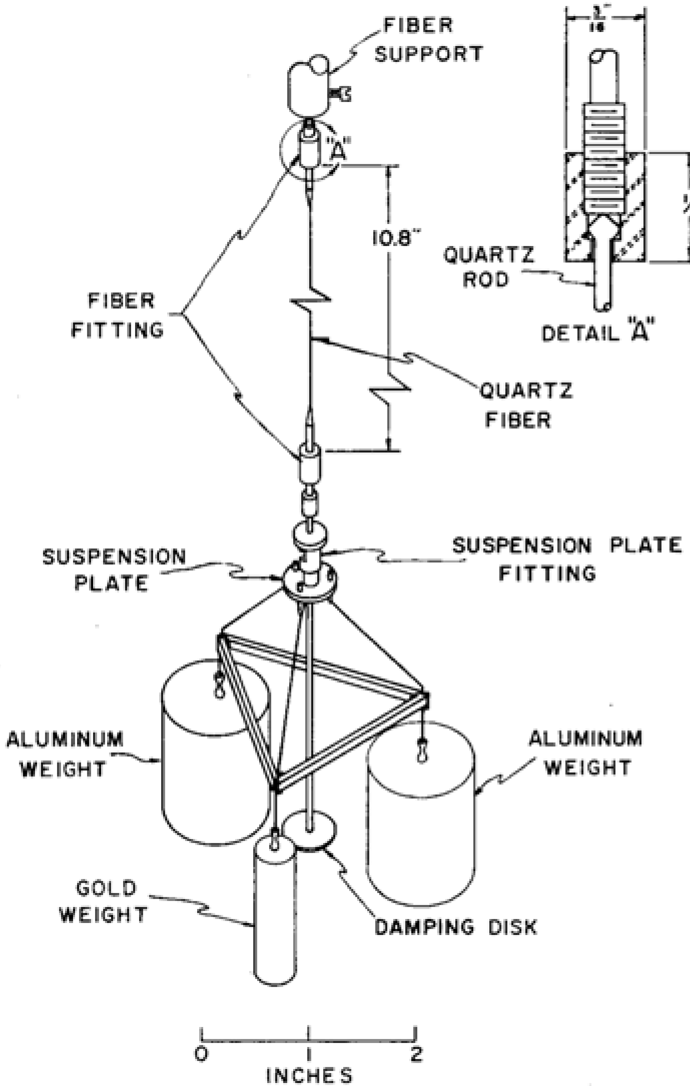
## advantages of using the sun as a source

- the apparatus is rotated very smoothly and periodically
- gravity gradients and B fields from sun are negligible
- signal is only decreased by factor of ≈ 2.7

## disadvantages of using the sun as a source

- once per day is a terrible frequency
- cannot see forces with range < 1 AU

# Dicke's instrument



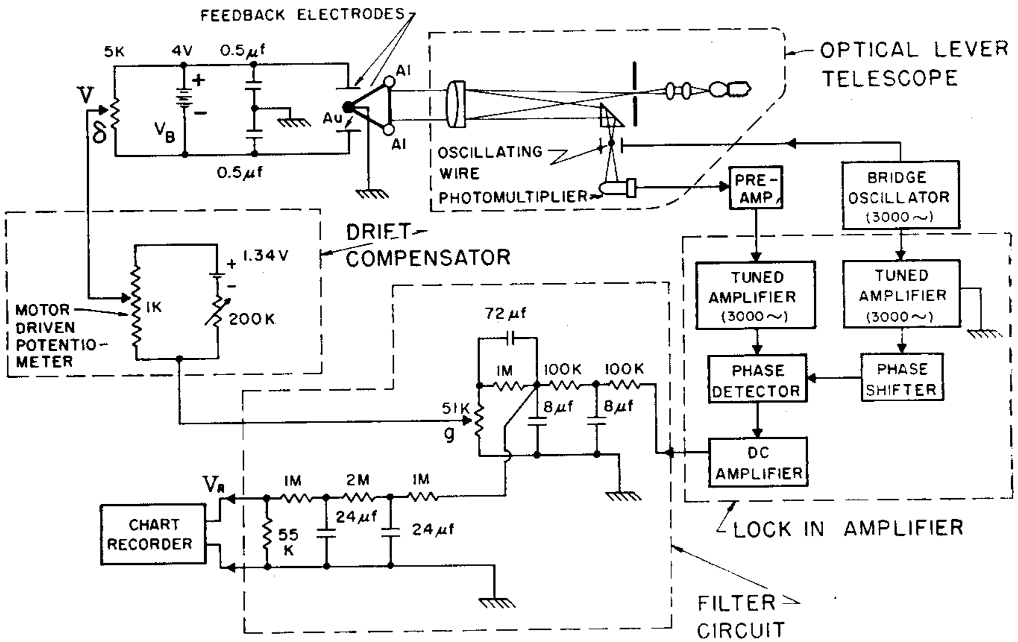



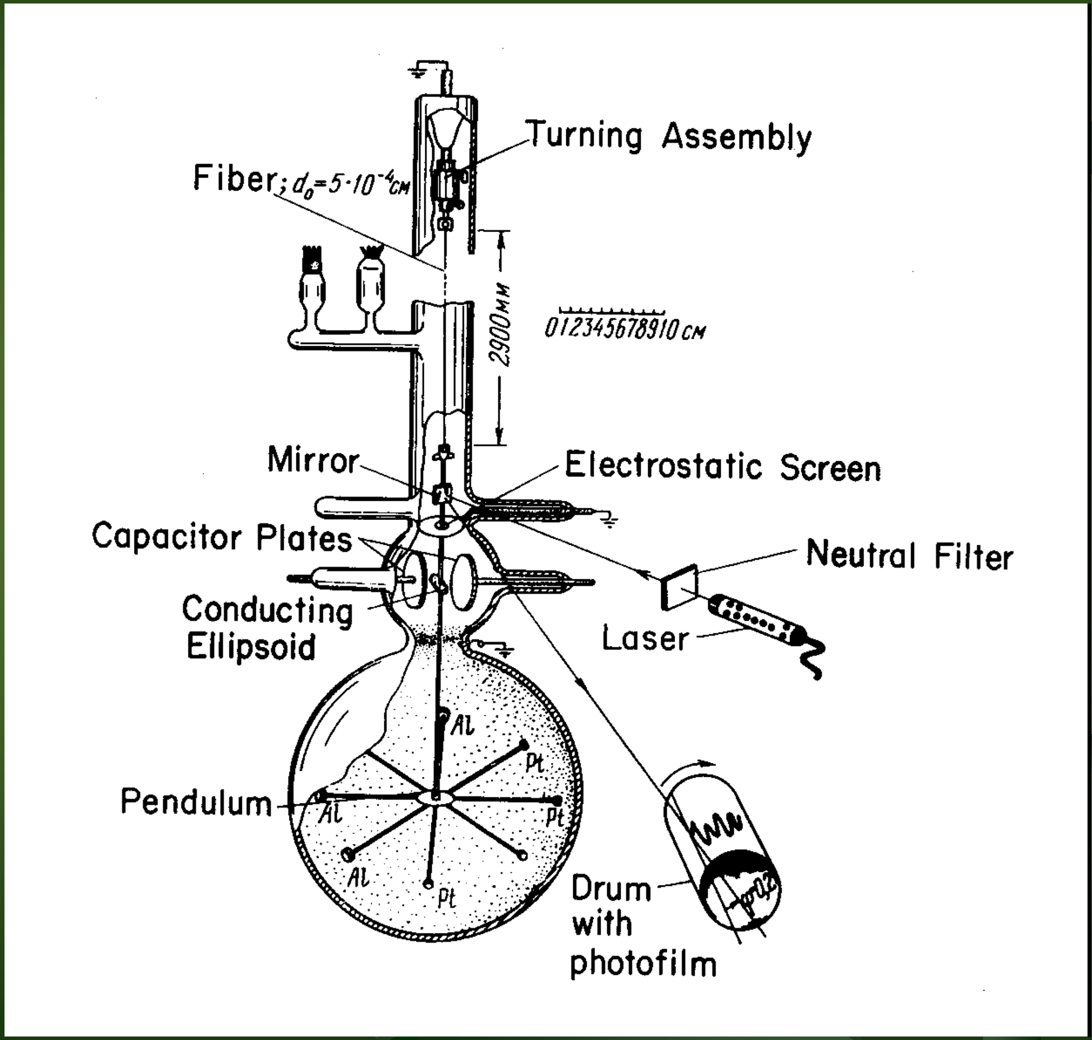

Fig. 6. Block diagram of the optical lever detection system

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

1 sigma result $\Delta a/a=(1.0\pm1.5)\times10^{-11}$

# Braginsky and Panov's instrument

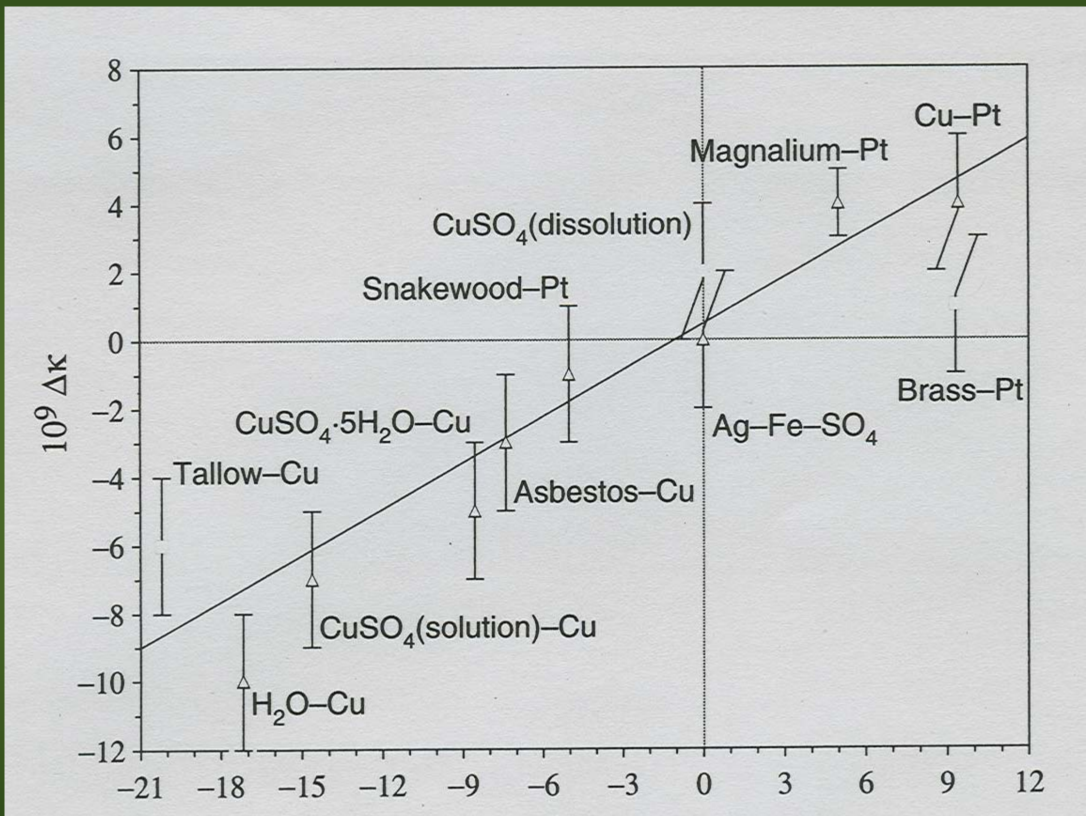
Braginsky and Panov, Sov. Phys. JETP 34, 463 (1972)




1 sigma result $\Delta a/a=(-0.3\pm0.45)\times10^{-12}$

# 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 result along with geophysical measurements was taken as evidence for a "5th force"

$$V(r) = V_{\mathrm{N}}\left(1 + \tilde{\alpha}\left[\frac{B}{u}\right]\left[\frac{B}{u}\right]\right)\exp(-r/\lambda)$$

with

$\alpha \approx .01$

$30\text{m} \leq \lambda \leq 1000\text{m}$

A scientific moral:

A wrong result* can lead to scientific progess

Examples:

$\mu \rightarrow e\ \gamma$ why is lepton number conserved?

5th force understand EP tests as a search new Yukawa interations that could have any range and couple to any sorts of “charge”

Weber’s gravity wave “detection” started a new field

* that gets corrected

# The Eöt-Wash® group in experimental gravitation

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Staff
- Erik Swanson

Postdocs
- Frank Fleischer
- Seth Hoedl
- Stephan Schlamminger

Current Grad students
- Ted Cook
- Charlie Hagedorn
- William Terrano
- Todd Wagner

Primary support from NSF Grant PHY0355012 with supplements from the DOE Office of Science and to a lesser extent NASA

# the Eöt-Wash strategy

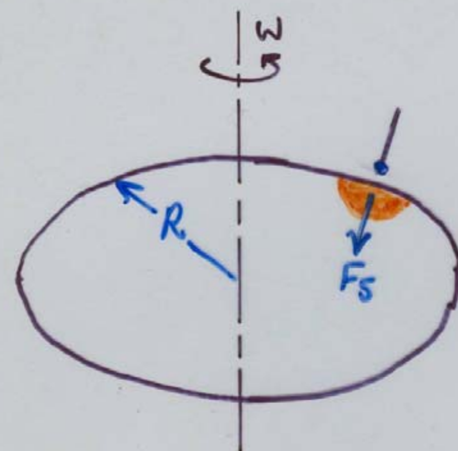
build a continuously rotating torsion balance

design with high symmetry so only gravity knows which test body is which

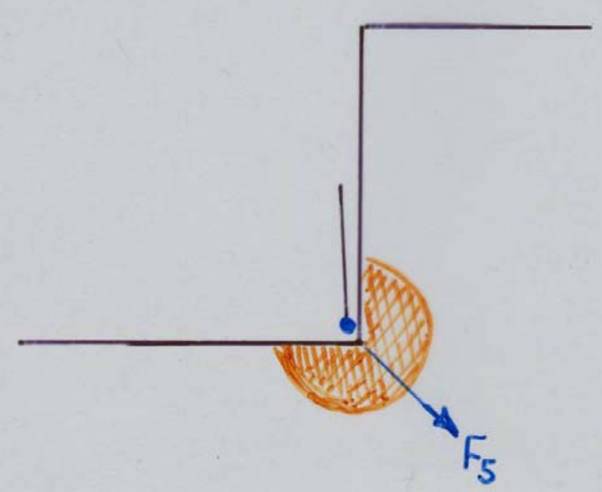
use 4 interchangeable test bodies

recruit really good grad students

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

# our first torsion balance circa 1986

Test bodies designed to look for interaction coupled to B

The result
$\Delta a/a=(2.4\pm2.7)\times10^{-7}$

required

$\alpha \leq .001$
$30\text{m} \leq \lambda \leq 1000\text{m}$

Stubbs et al., PRL 58, 1070 (1987)

# modern version of the Galileo test

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

gave roughly comparable limits on Yukawa interactions

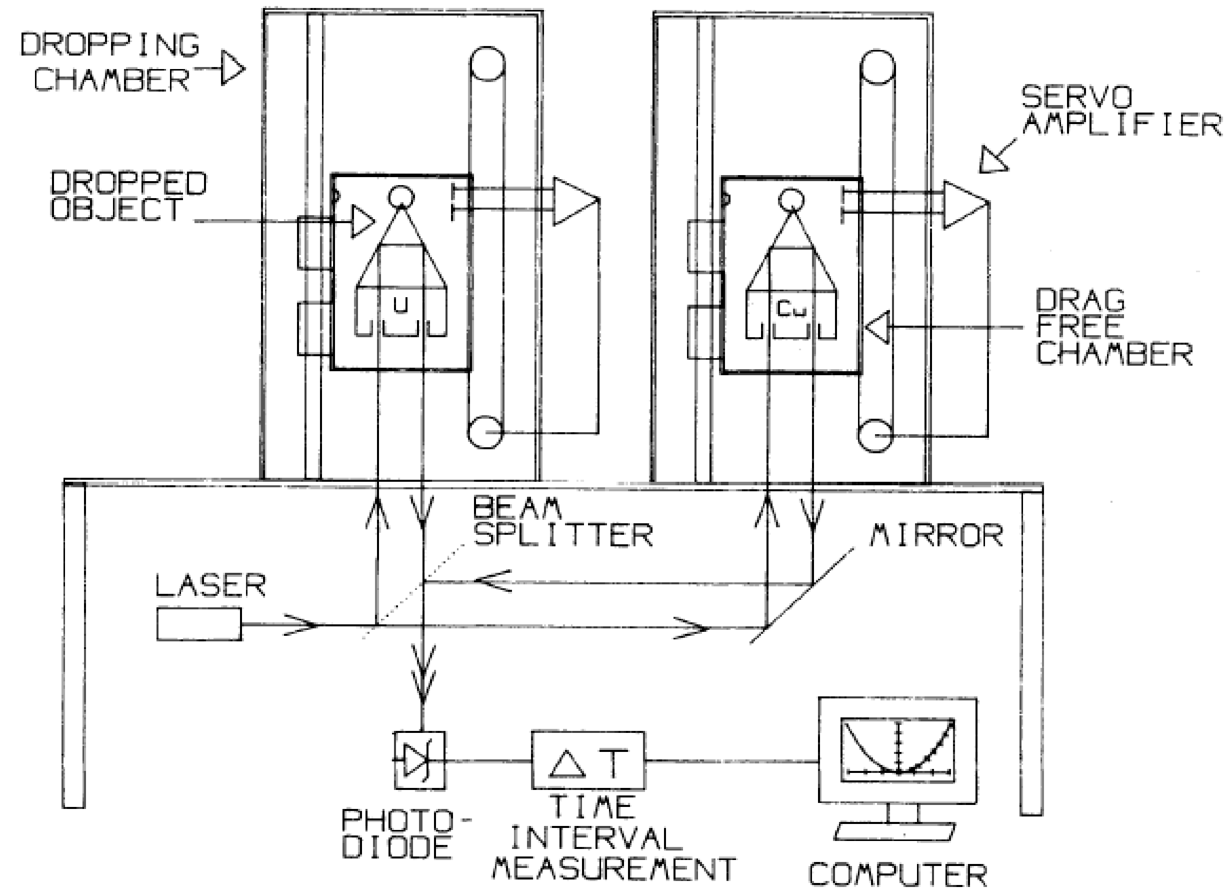



**FIG. 1.** Schematic diagram of the apparatus used in Joint Institute for Laboratory Astrophysics for the Galilean experiment.

Niebauer, McHugh and Faller, PRL 59 609 (1987)

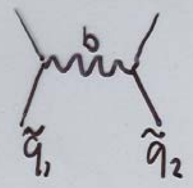
# 2 WAYS TO THINK ABOUT EP TESTS

- 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




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

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

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

"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

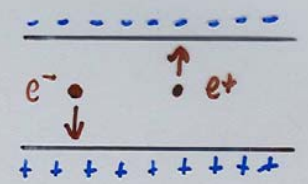
- interactions mediated by vector bosons

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

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

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

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




- 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

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

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 $\gamma - 1 > 1$

# Parameterization of scalar or vector Yukawa interactions

$$\tilde{V}_{1A}(r) = \mp \frac{1}{4\pi} \tilde{q}_1 \tilde{q}_A \frac{e^{-r/\lambda}}{r}, \tag{1}$$

where $\tilde{q}_A$ and $\tilde{q}_1$ are the scalar or vector "charges" of the attractor and the test body respectively. The interaction range is given by the Compton wavelength $\lambda = \hbar/m_b c$ of the exchanged boson. The upper$(-)$ and lower$(+)$ signs apply to scalar and vector interactions, respectively. For electrically neutral bodies consisting of atoms with charge and neutron numbers $Z$ and $N$, the "charge" can be written as

$$\tilde{q} = \tilde{g}[Z \cos \tilde{\psi} + N \sin \tilde{\psi}] \tag{2}$$

where $\tilde{g}$ is a coupling constant and $\tilde{\psi}$ (which in principle can have any value between $-\pi/2$ and $\pi/2$) is a parameter that specifies the details of the charges

$$\tan \tilde{\psi} \equiv \frac{\tilde{q}_n}{\tilde{q}_e + \tilde{q}_p} \ . \tag{3}$$

For example an interaction coupled to $B$ ($\tilde{q}_p = \tilde{q}_n = \tilde{g}$, $\tilde{q}_e = 0$) corresponds to $\tilde{\psi} = \pi/4$ while $\tilde{\psi} = 0$ corresponds to a coupling to lepton number $L$. An interaction coupled to $B - L$ is especially interesting because in Grand Unified Theories $B - L$ is conserved although $B$ and $L$ are not conserved individually. In this case the charges are $\tilde{q}_p = \tilde{q}_n = \tilde{g}$ and $\tilde{q}_e = -\tilde{g}$, which corresponds to $\tilde{\psi} = \pm\pi/2$.

Equation 1 can be re-expressed in a form that makes manifest its connection to EP experiments

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \tilde{\alpha}\left[\frac{\tilde{q}}{\tilde{g}\mu}\right]_1 \left[\frac{\tilde{q}}{\tilde{g}\mu}\right]_2 e^{-r/\lambda}\right) , \tag{5}$$

where $\mu$ is a test body mass in units of atomic mass unit $u$, and

$$\tilde{\alpha} = \pm\tilde{g}^2/(4\pi G u^2) . \tag{6}$$

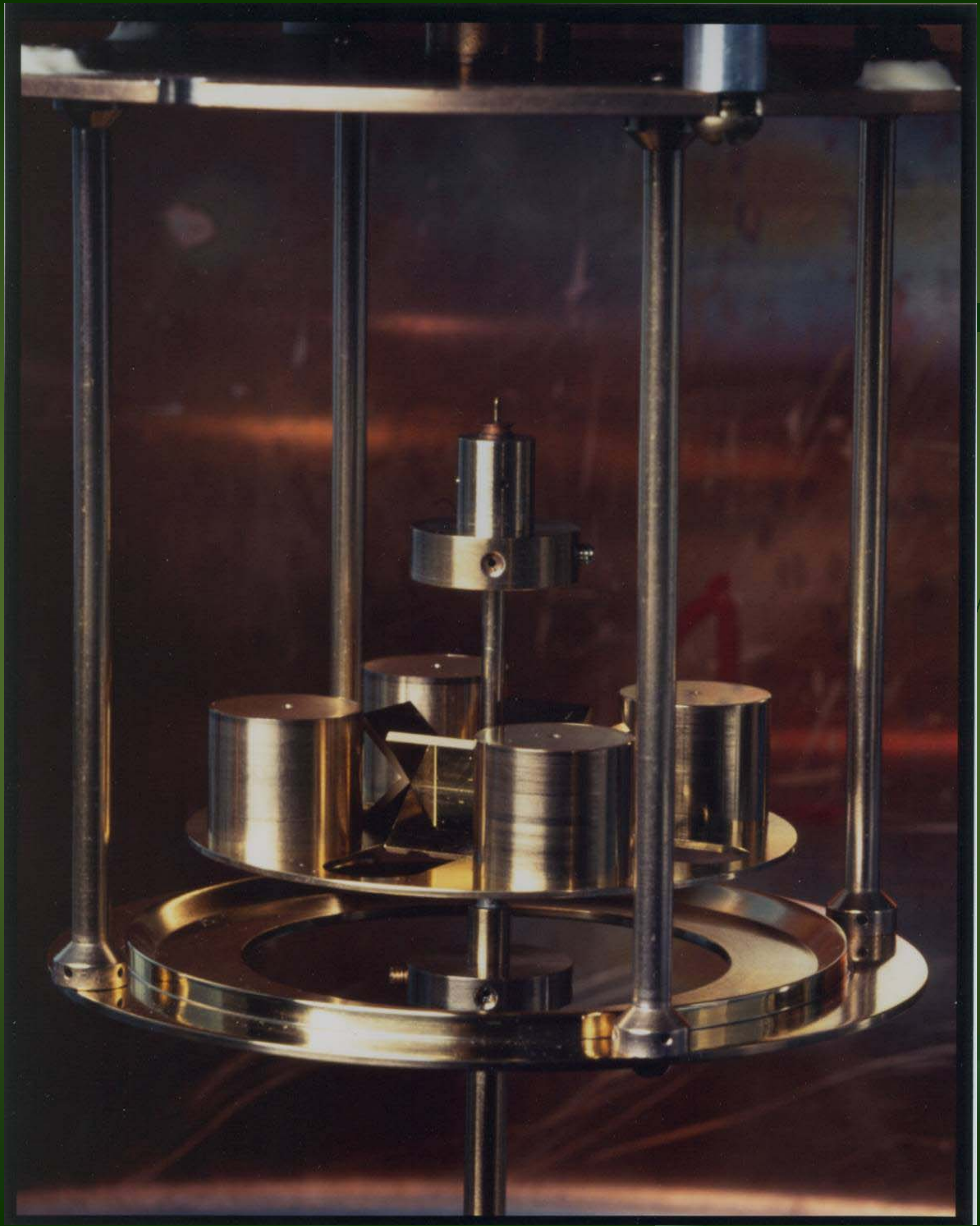
# Torsion pendulum used in our 1994 test of the EP

Su et al., PRD 50, 3614 (1994)

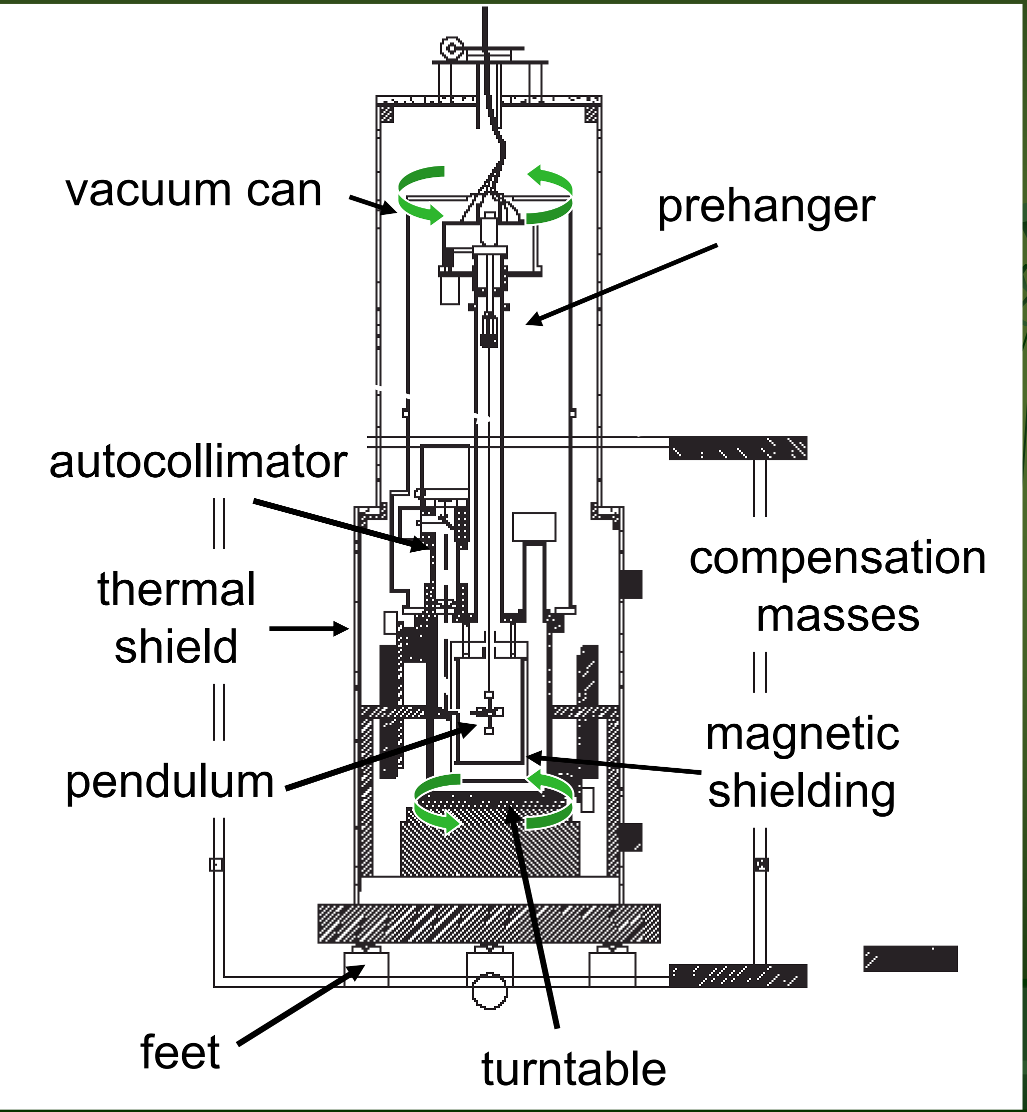
Test bodies have identical masses and outside dimensions and vanishing mass quadrupole moments

Quadrupole moment of entire pendulum is tiny

Gravity gradients cancelled



# The torsion balance apparatus:




# Gravity gradients

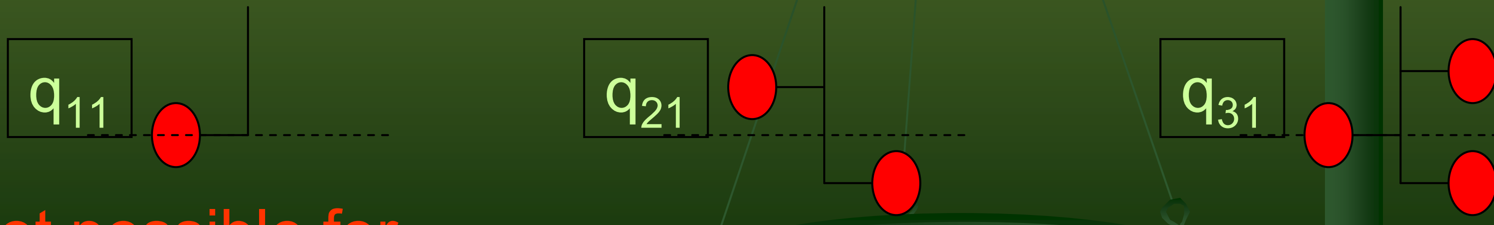
Gravitational potential energy between the pendulum and the attractor is given by

$$\boxed{\mathrm{w} = -4\pi G \sum_{l=0}^{\infty} \frac{1}{2l+1} \sum_{m=-l}^{l} Q_{lm}\, q_{lm}\, e^{-im\phi}}$$

$$Q_{lm} = \int d^3r' \rho_{\mathrm{source}}(\vec{r}\,')\, r'^{-(l+1)}\, Y_{lm}(\hat{r}')$$ gravity gradient field

$$q_{lm} = \int d^3r\, \rho_{\mathrm{pend}}(\vec{r})\, r^{l}\, Y_{lm}^{*}(\hat{r})$$ gravity multipole moment

Torque for 1ω (m=1) signal: $$N = 8\pi G \sum_{l} \frac{1}{2l+1} |q_{l1}|\, |Q_{l1}|$$




not possible for a torsion pendulum

# gravity-gradient compensation

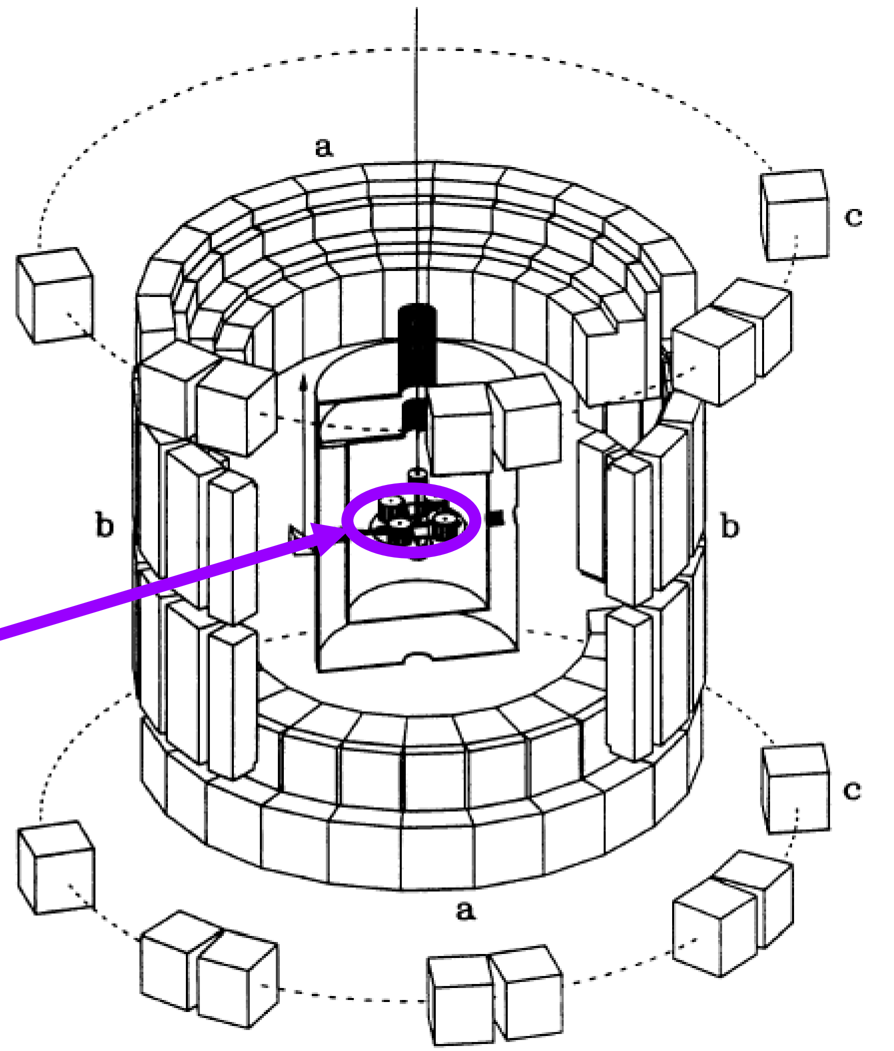
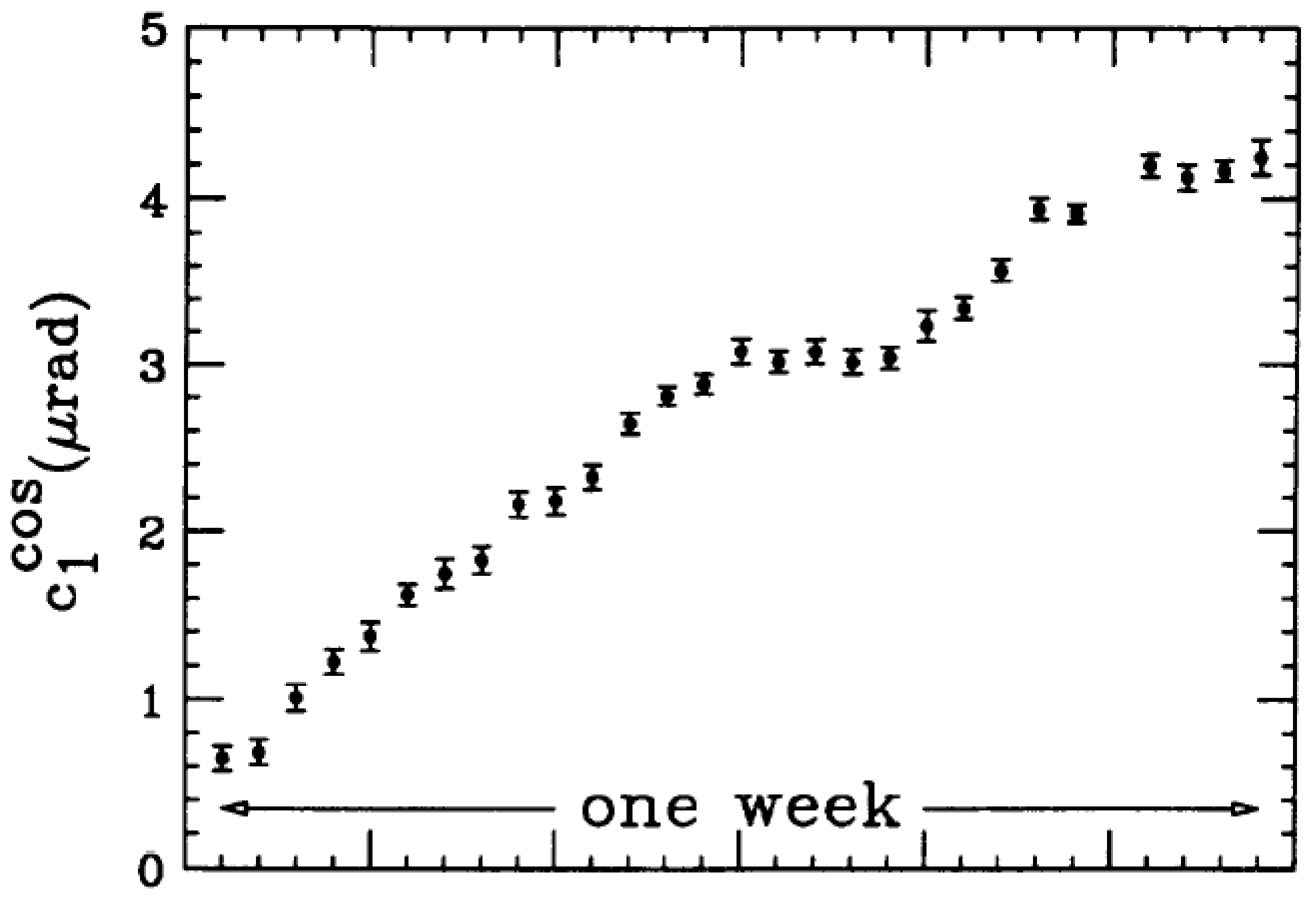


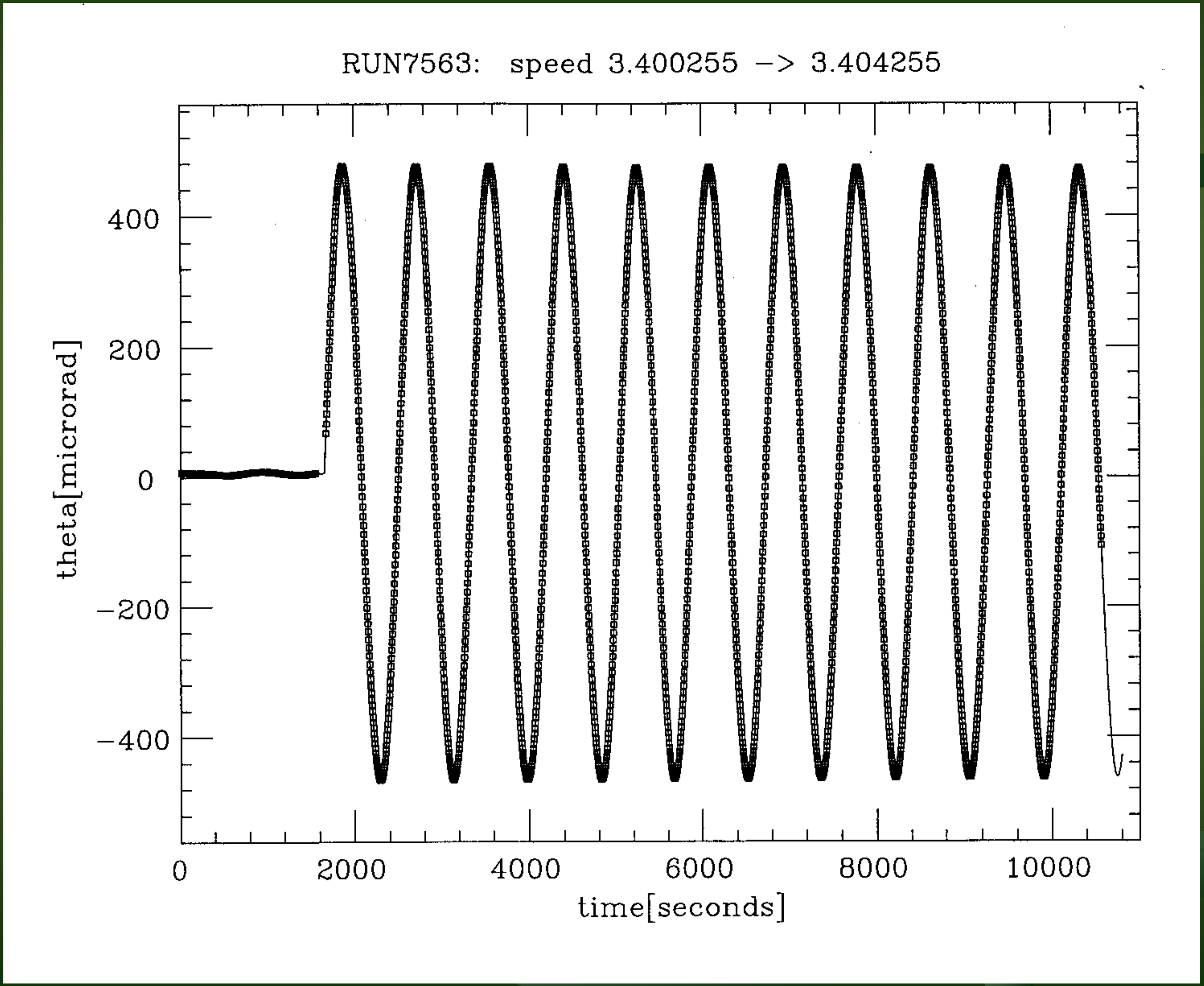

FIG. 8. Gravity-gradient compensators used to "flatten" the local gravitational field: *a*: $Q_{21}$ compensator, *b*: $Q_{22}$ compensator, *c*: $Q_{31}$ compensator.

The most uniform field on earth?

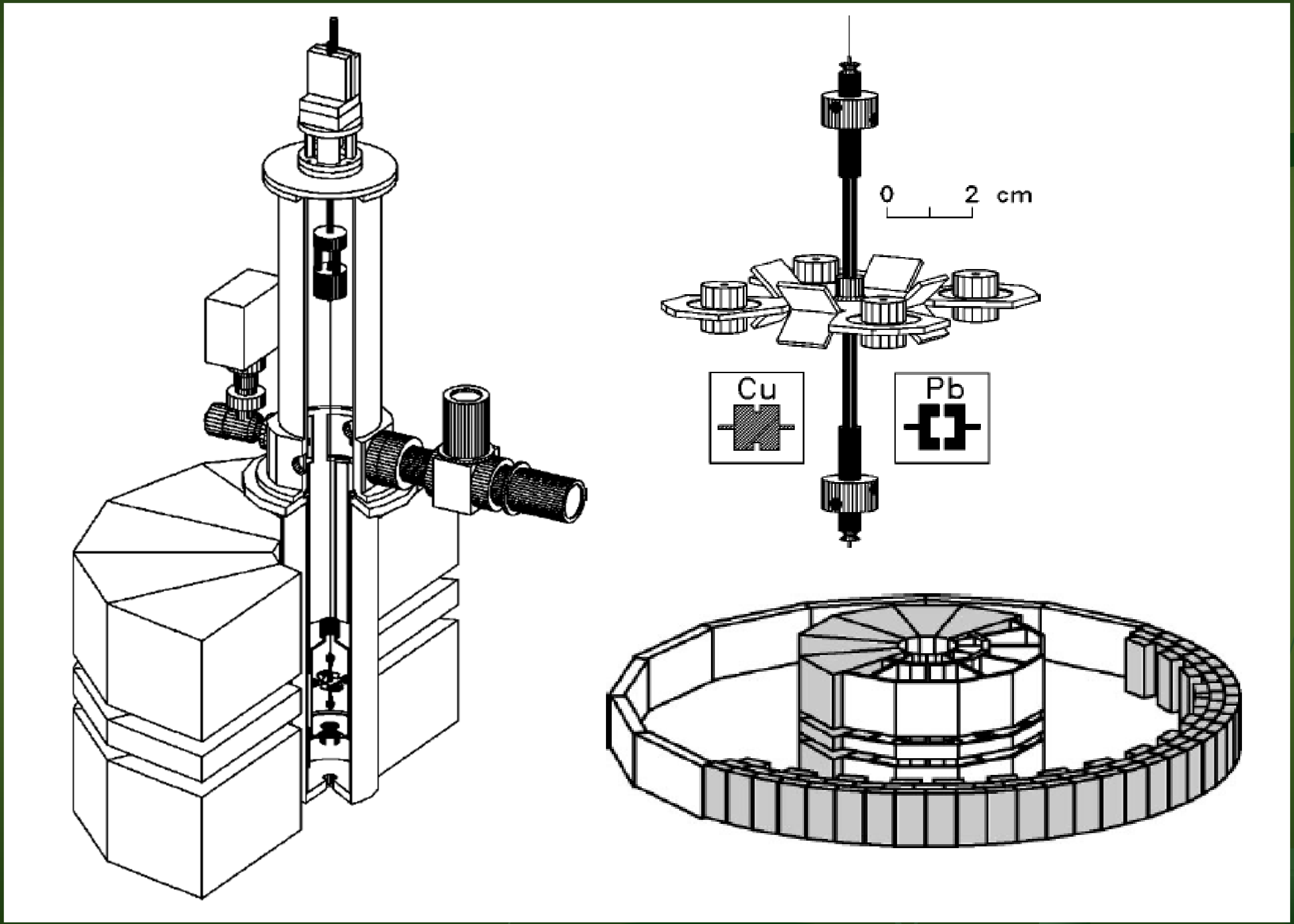
# but there is a limit how well it can be done



# calibration of pendulum response

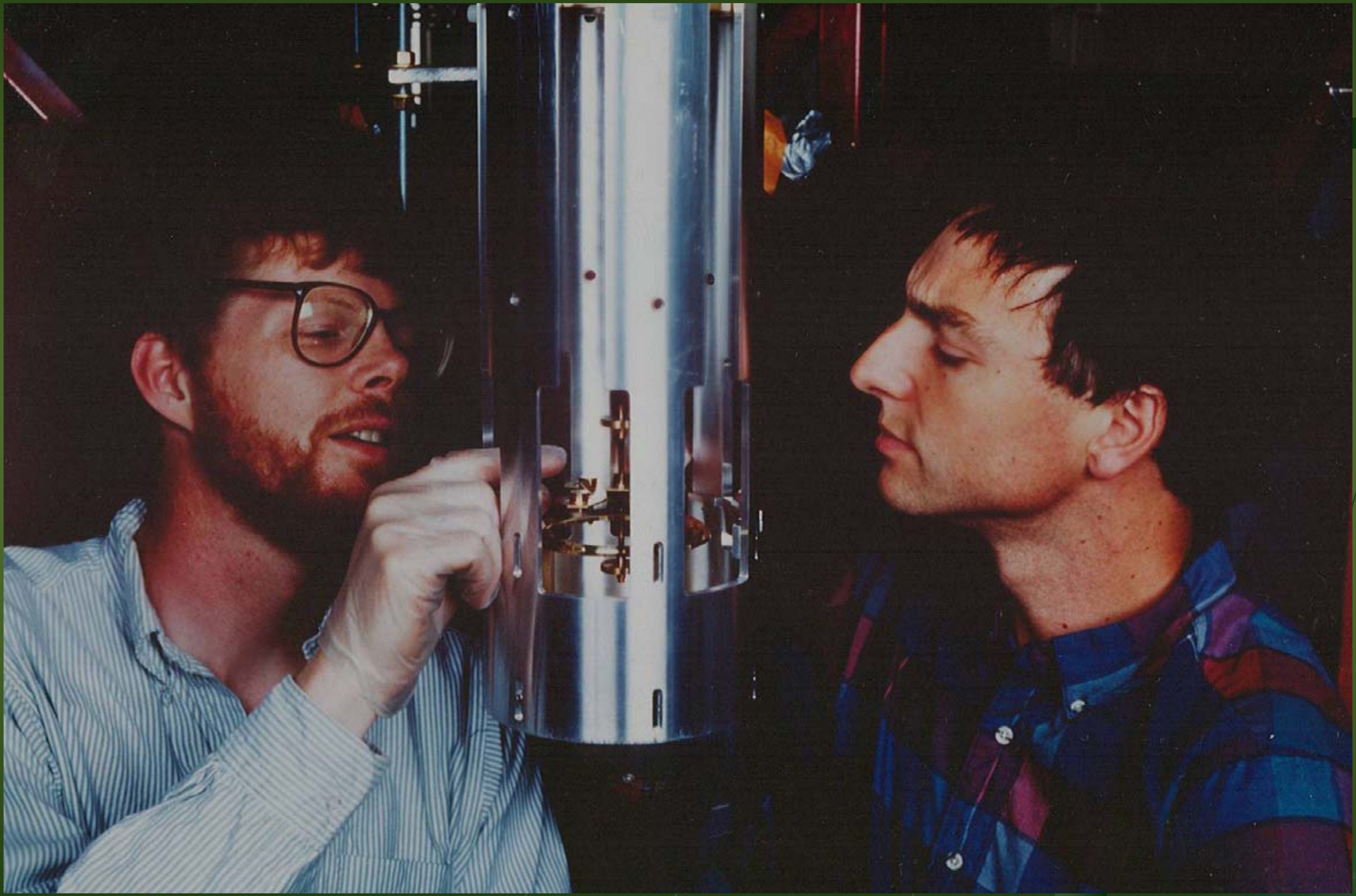


# The Rot-Wash short-range test of the EP



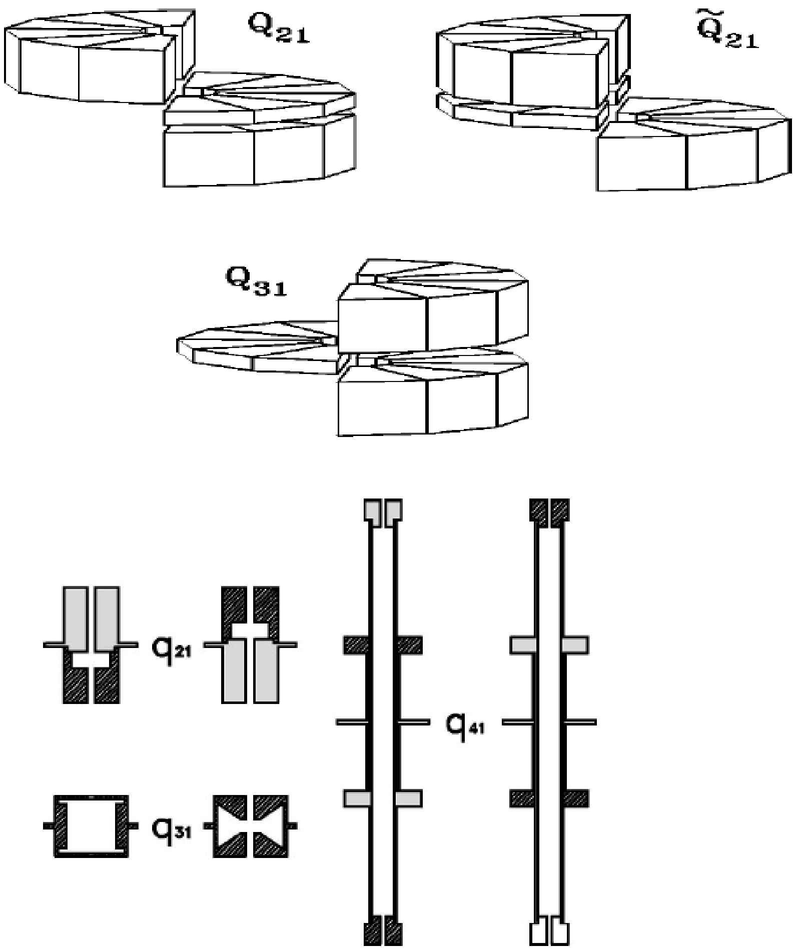

rotating 3-ton $^{238}U$ attractor

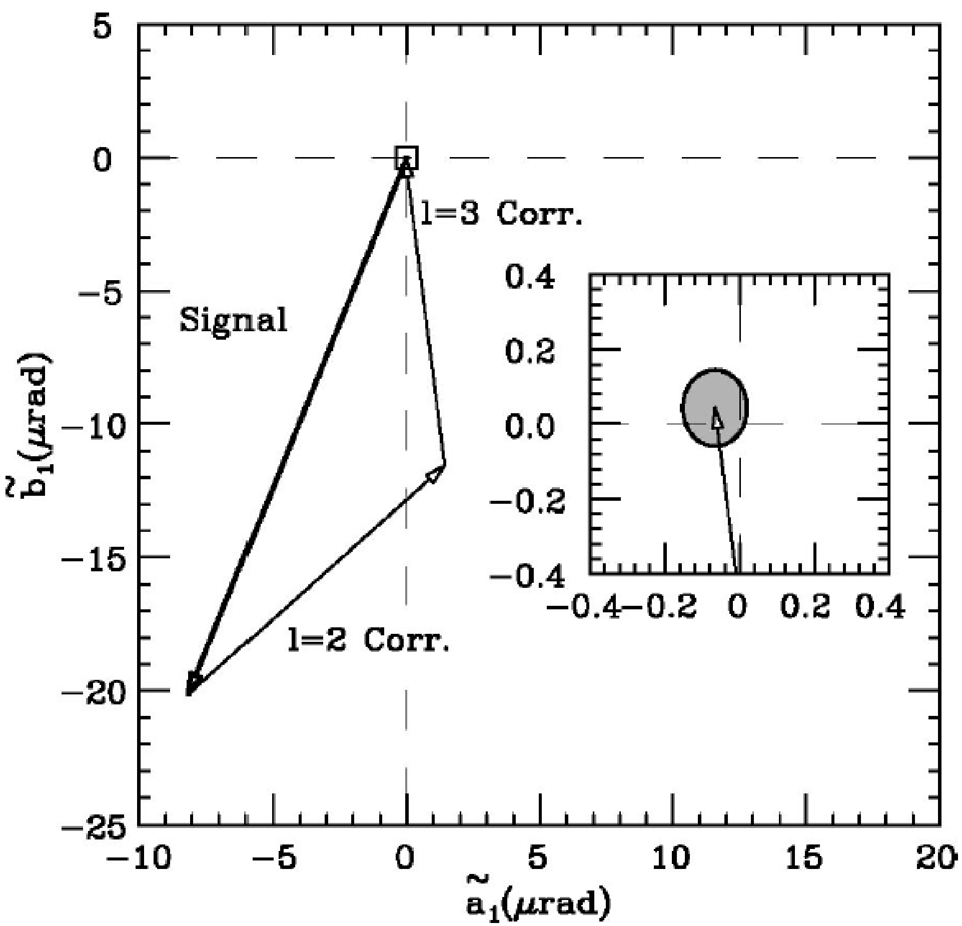
# A short-range test of the Equivalence Principle



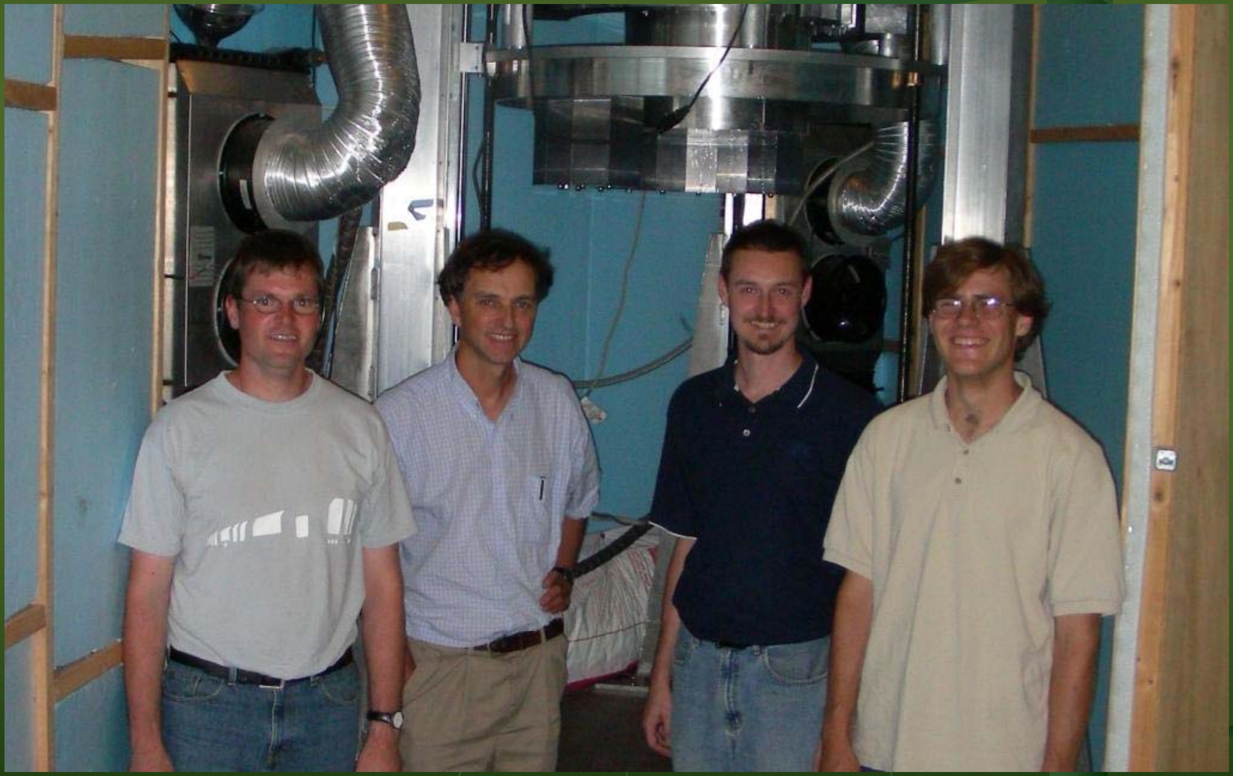
Smith et al., PRD 61, 022001 (2000)

# gravity gradients: a major challenge for the Rot-Wash experiment



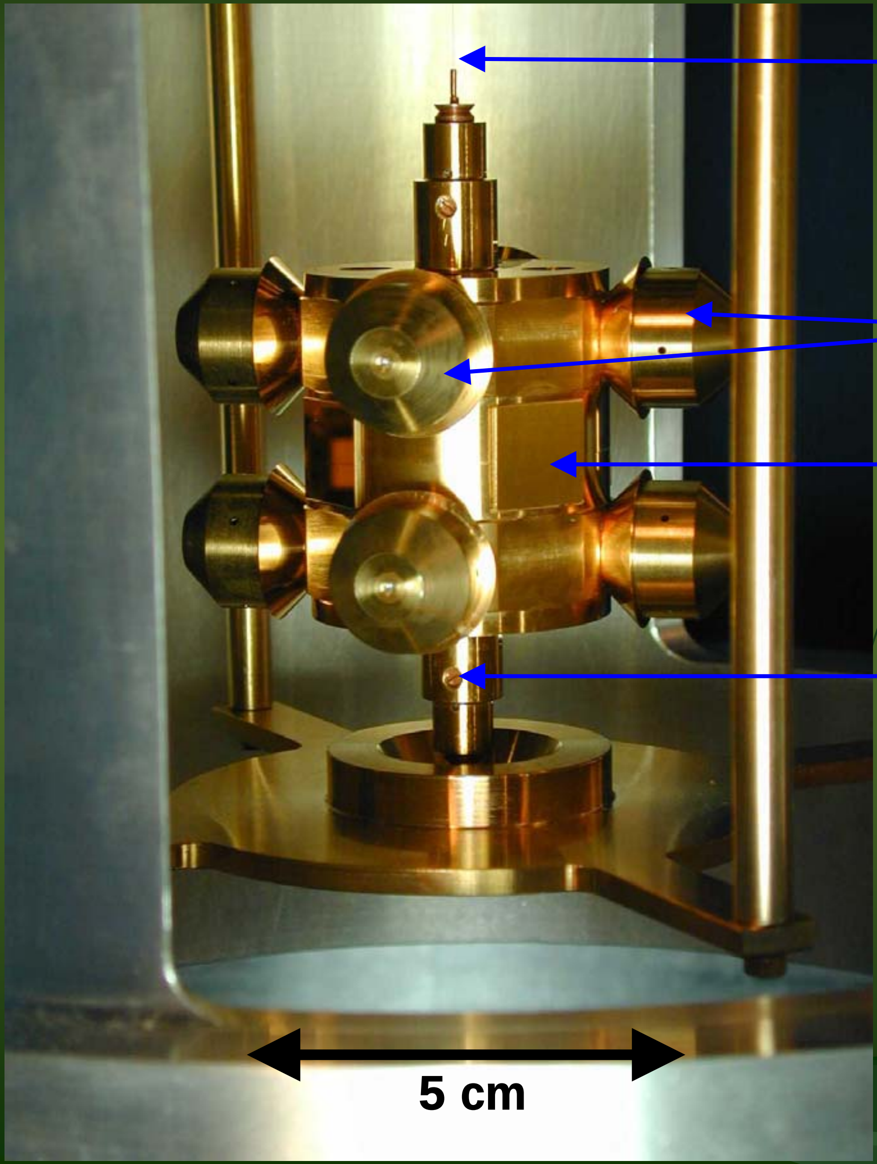



# The new Eöt-Wash test of the EP



Stephan Schlamminger, Jens Gundlach, Todd Wagner, Charlie Hagedorn

# Torsion Pendulum of the new EP test




20 μm diameter tungsten fiber
(length: 108 cm)

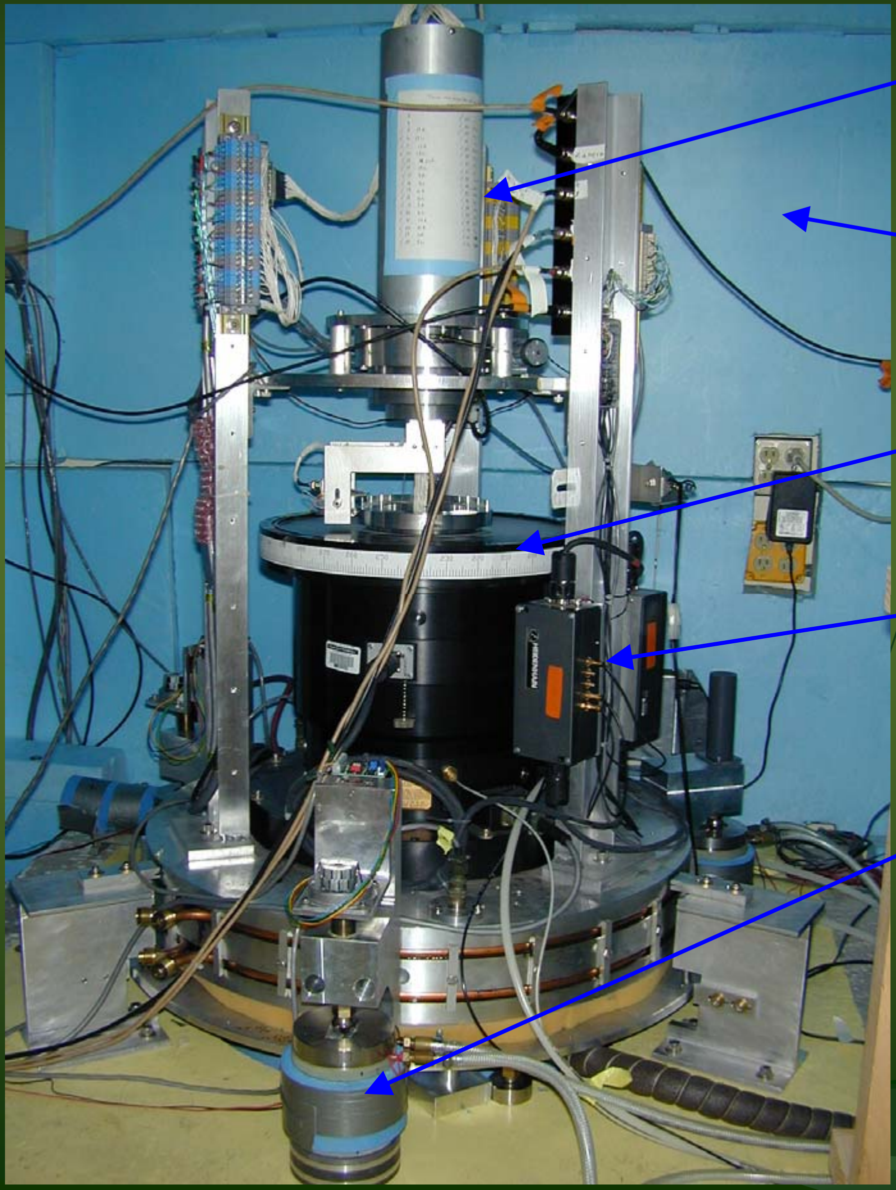
8 test masses (4 Be & 4 Ti )
4.84 g apiece

4 mirrors

tuning screws for adjusting
gravity multipole moments
to null the gravitational coupling

| | |
|---|---|
| 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 feedthrough for electric signals

thermal insulation

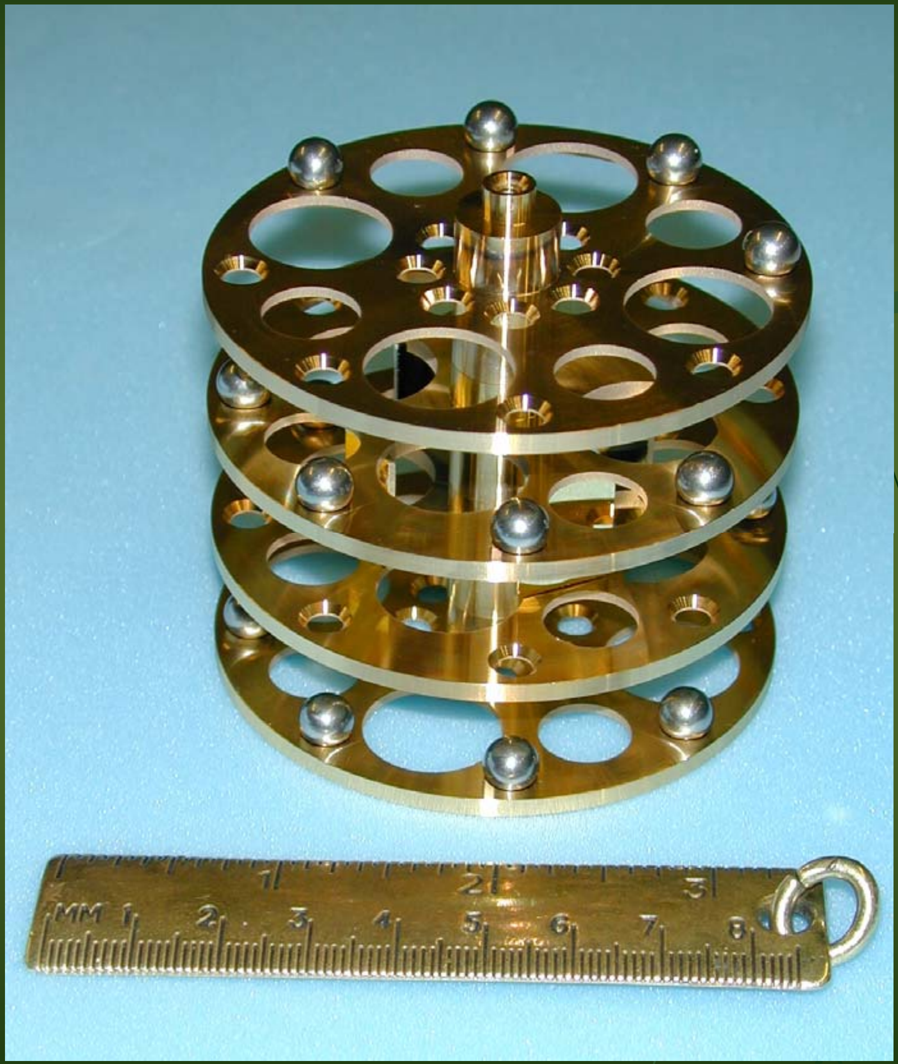
air-bearing turntable

angle encoder electronics

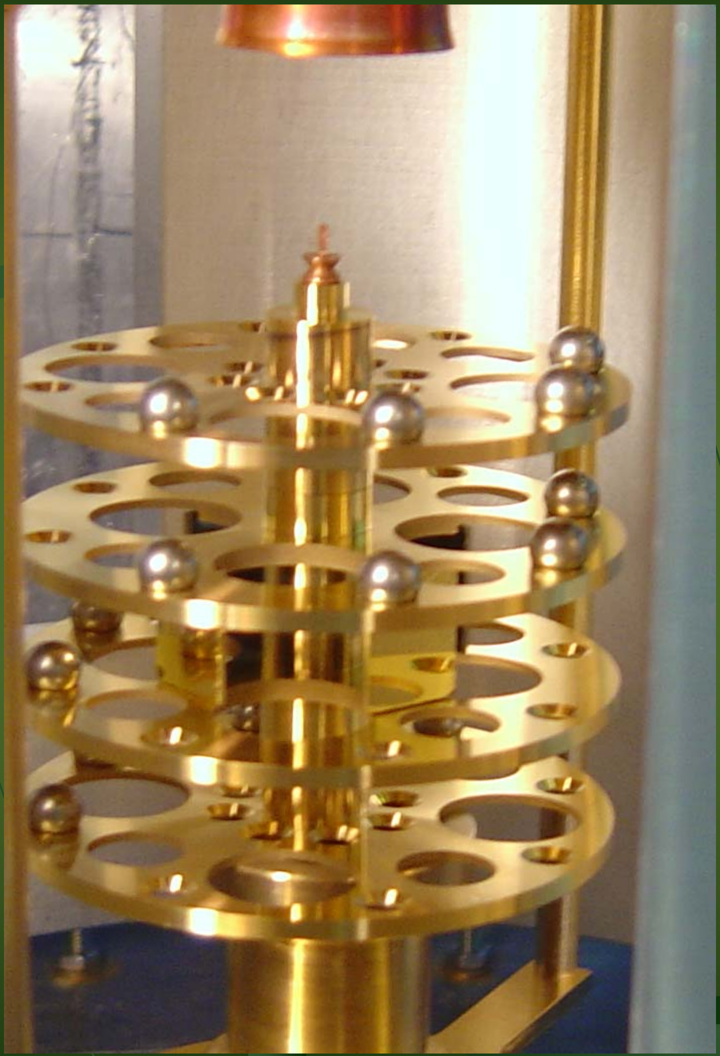
thermal expansion feet fedback to keep turntable level

torsion balance hangs from the bearing which rotates at 0.833 mHz

# gravity-gradiometer pendulums

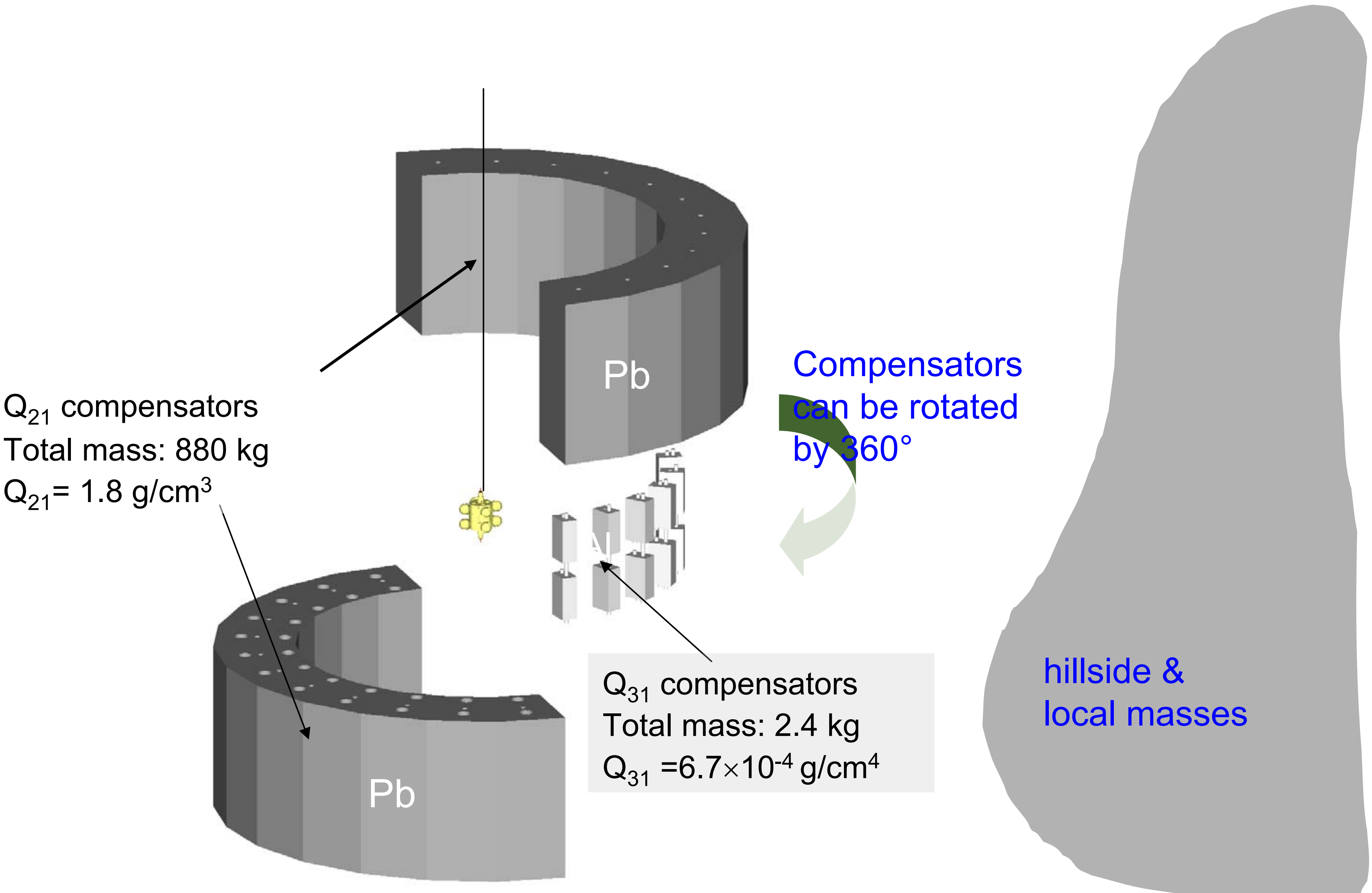



$q_{41}$ configuration on a table



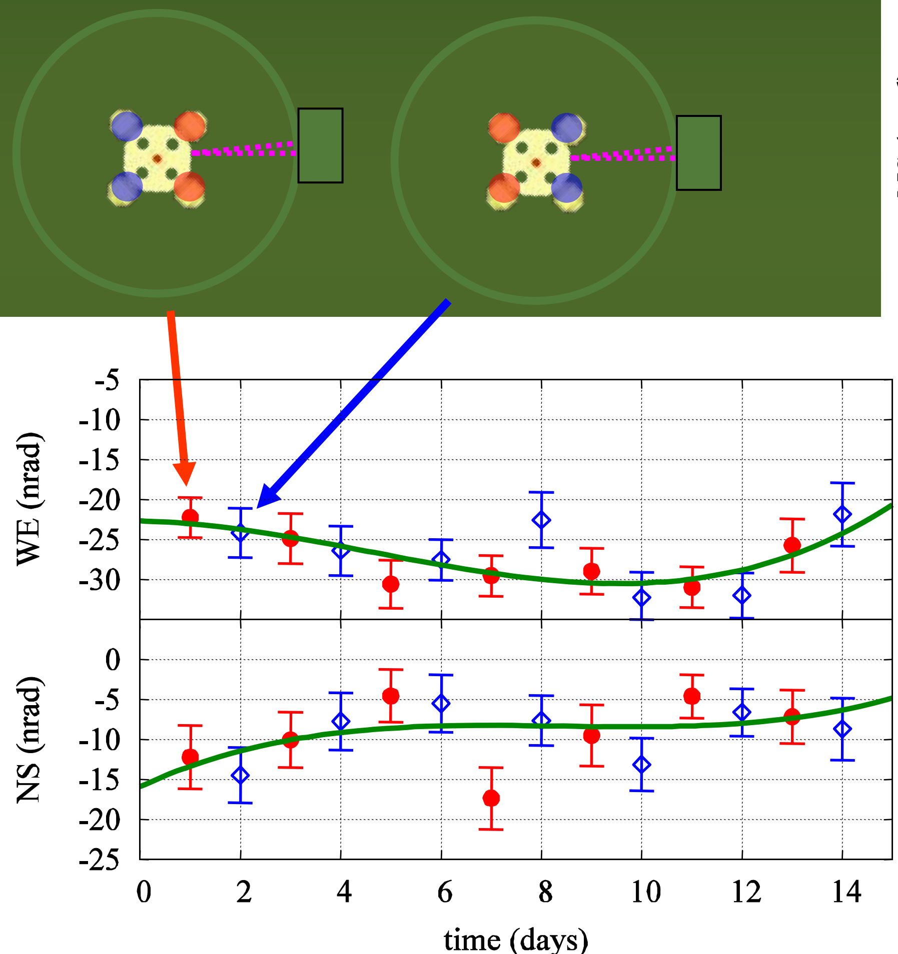
$q_{21}$ configuration installed

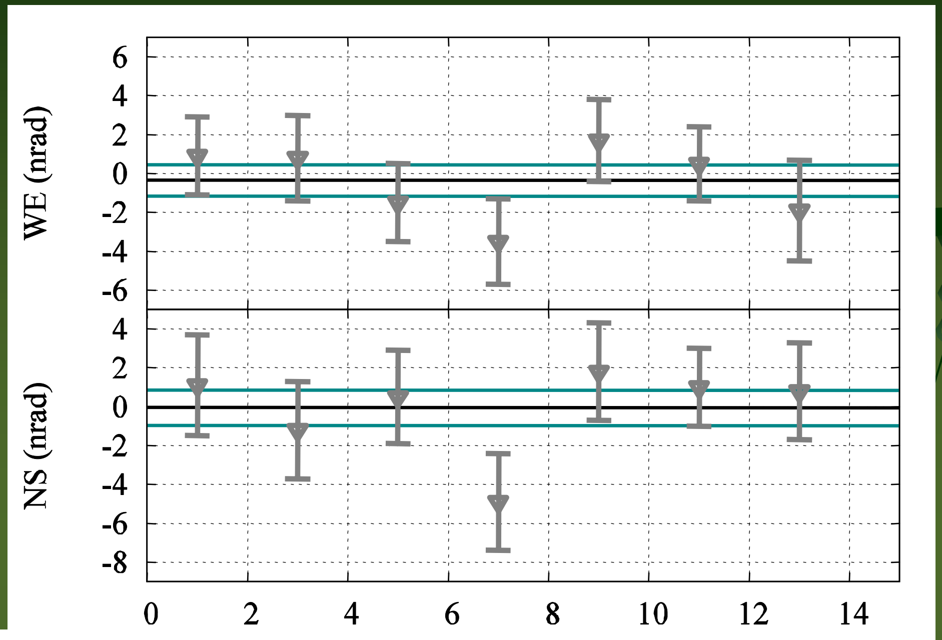
# gradient compensation in New-EP experiment



# data taking sequence 1

We reverse the dipole orientation with respect to the readout once each day

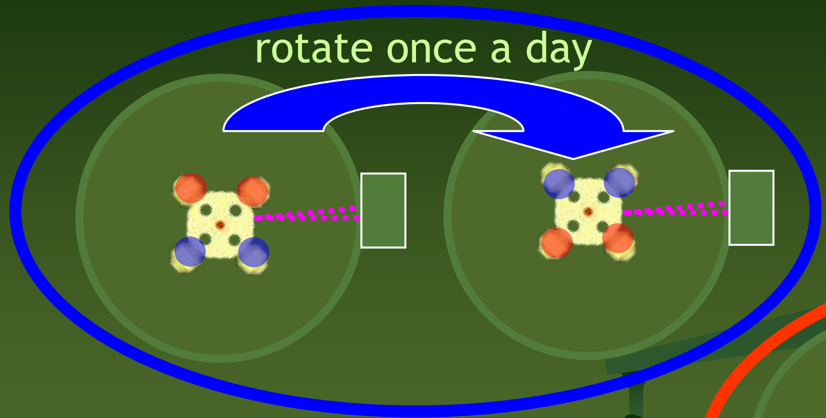


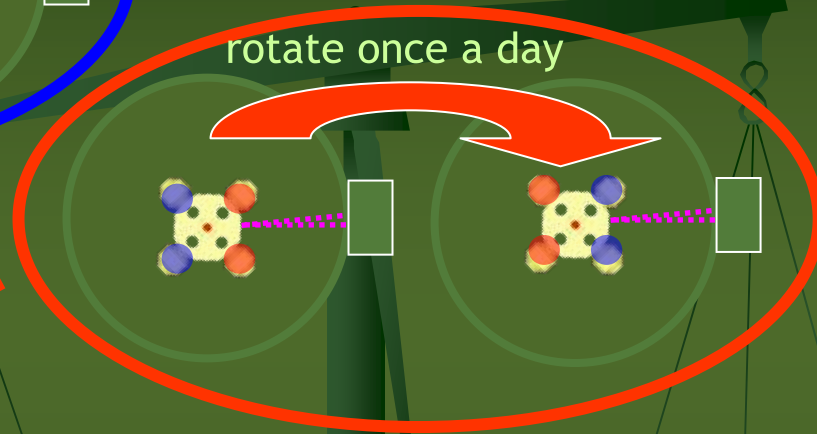

The data shows the measured twist. It is dominated by effects of the turntable (offset + slow drifts). By taking the difference between successive points, we isolate the EP signal.

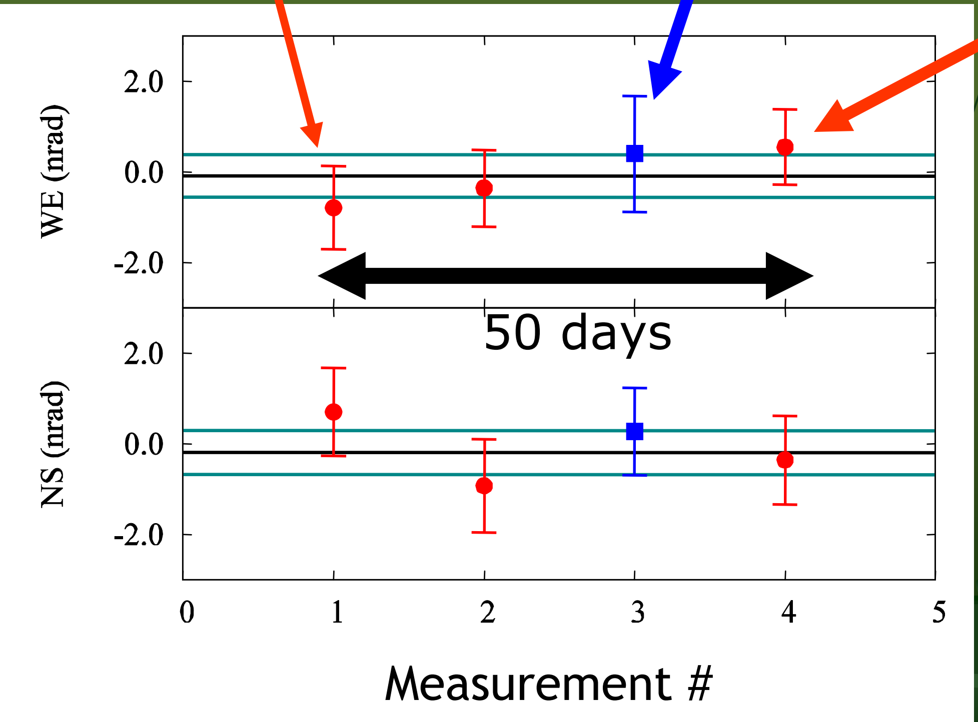
# data taking sequence 2

The 12 days of data from the previous slide are condensed into a single point.




Dipole is **orthogonal** to readout.




Dipole is (anti-) **parallel** to readout.

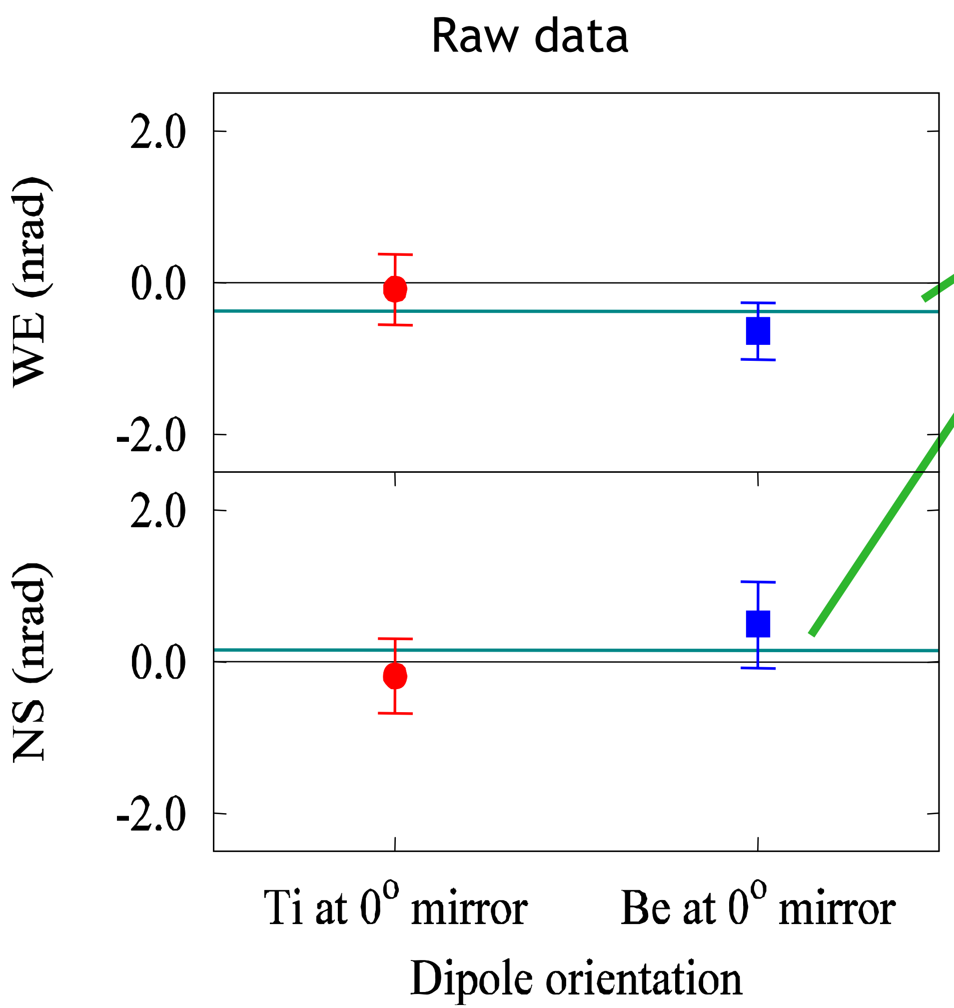
A resolved amplitude, must be corrected for:

(a) Tilt-feed-through

(b) Gravitational coupling

# data taking sequence 3

Finally we exchanged the test bodies with respect to the pendulum frame. Ideally the tilt-feedthrough is unchanged but an EP-violating effect reverses so we can extract a true EP-violating signal.



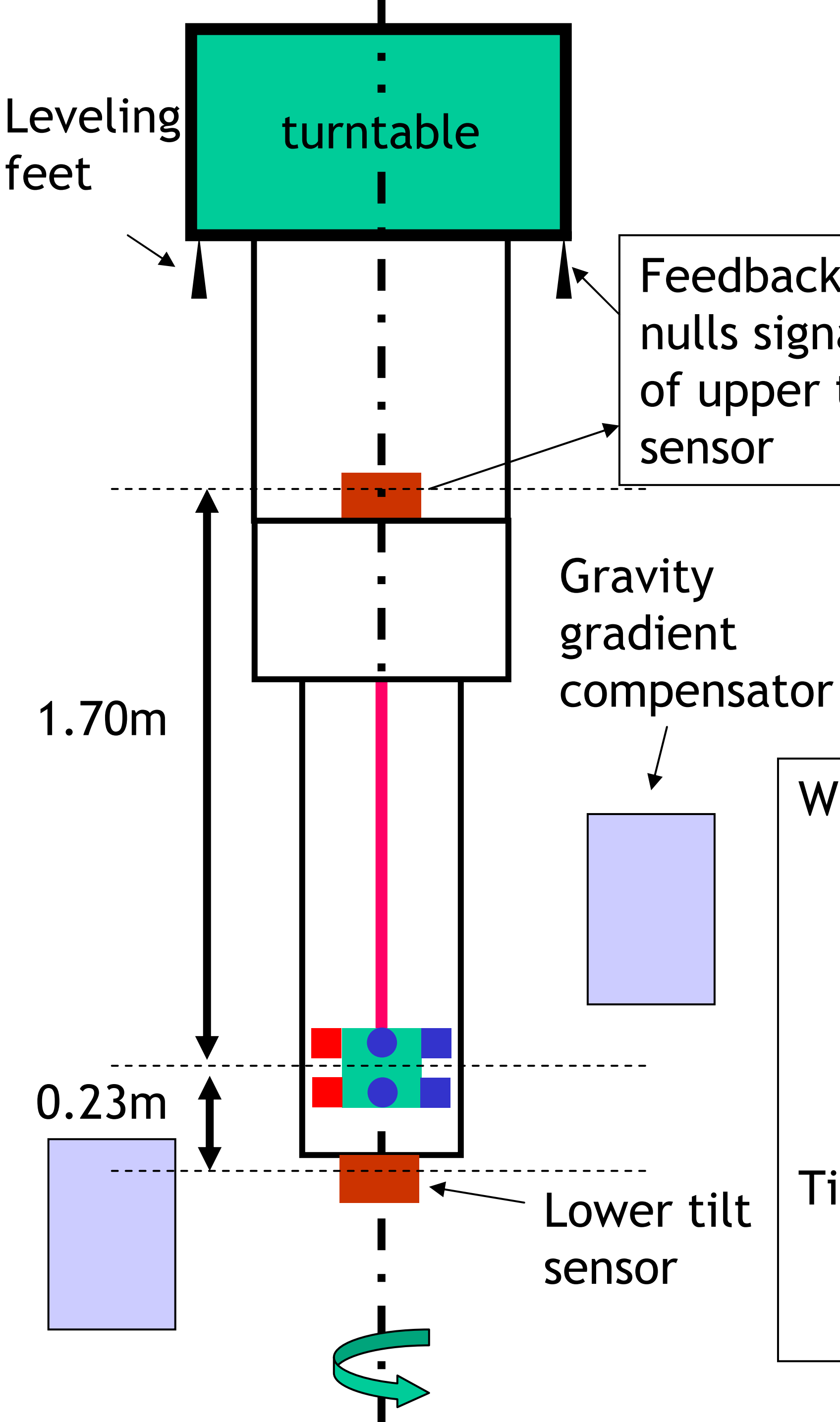

Average value of blue & red points due to un-modeled systematic effects

Science-signal is the difference between red and blue points

After correcting for the measured gravitational coupling, we obtain:

| Direction | signal (nrad) | differential acc. ($10^{-13}$ cm/s$^2$) |
|---|---|---|
| NS | -0.13±0.38 | -0.8±2.4 |
| WE | 0.08±0.39 | -0.5±2.5 |

# Correction for the Tilt Feedthrough




- 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

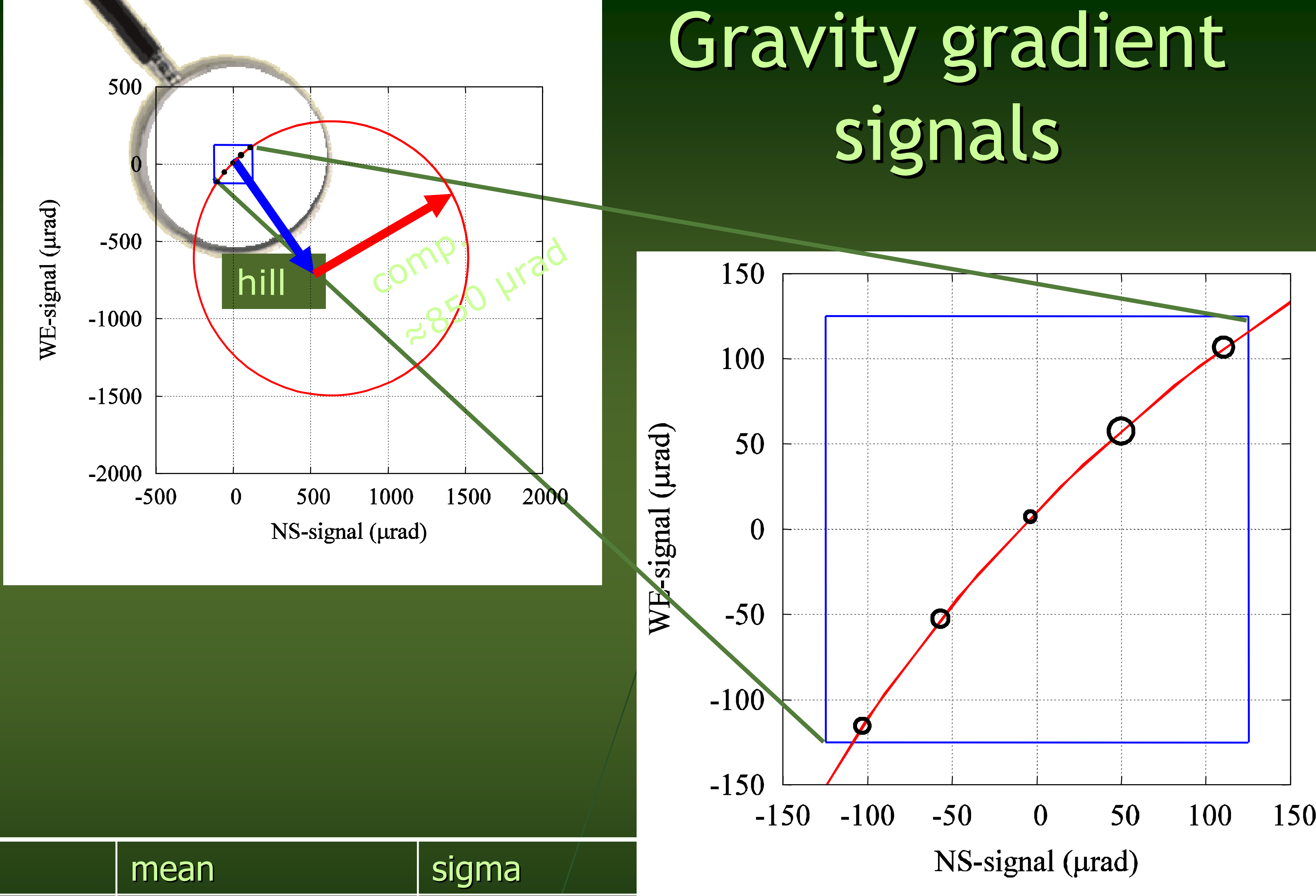
local earth field (~60 nrad) plus the off-axis

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

# Gravity gradient signals




| | mean | sigma |
|---|---|---|
| EW | -0.10 nrad | 0.25 nrad |
| NS | -0.21 nrad | 0.17 nrad |

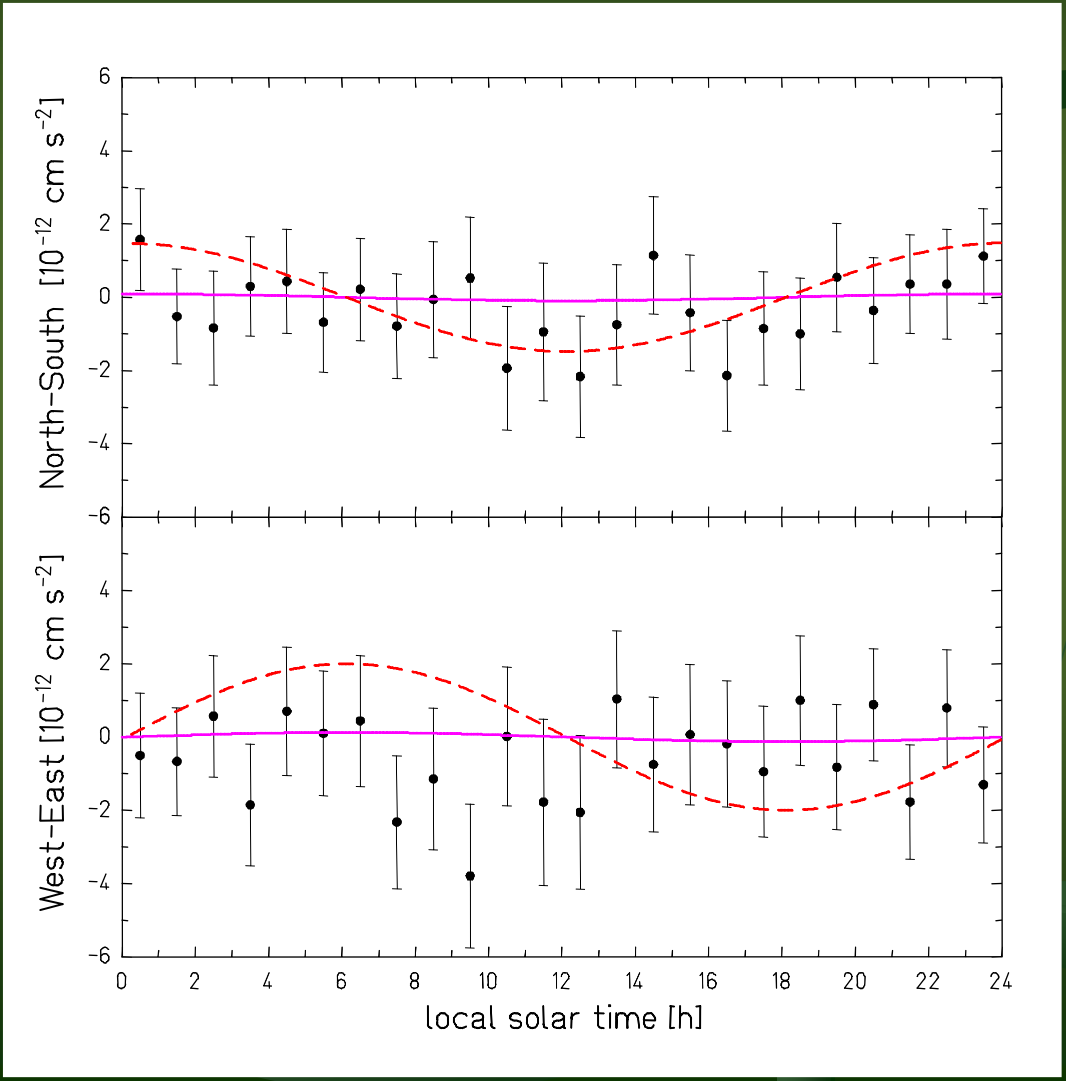
# Uncertainty Budget for the lab-fixed EP-test

| Source | Signal (nrad) | Differential acc. ($10^{-13}$ cm/s$^2$) |
|---|---|---|
| Tilt | 0.40 | 2.6 |
| Statistical uncertainty | 0.39 | 2.5 |
| Temperature | 0.38 | 2.4 |
| Gravity Gradient | 0.14 | 0.9 |
| Magnetics | 0.04 | 0.3 |
| **Sum** | **0.69** | **4.4** |

The shaded items contribute only to the lab-fixed result.

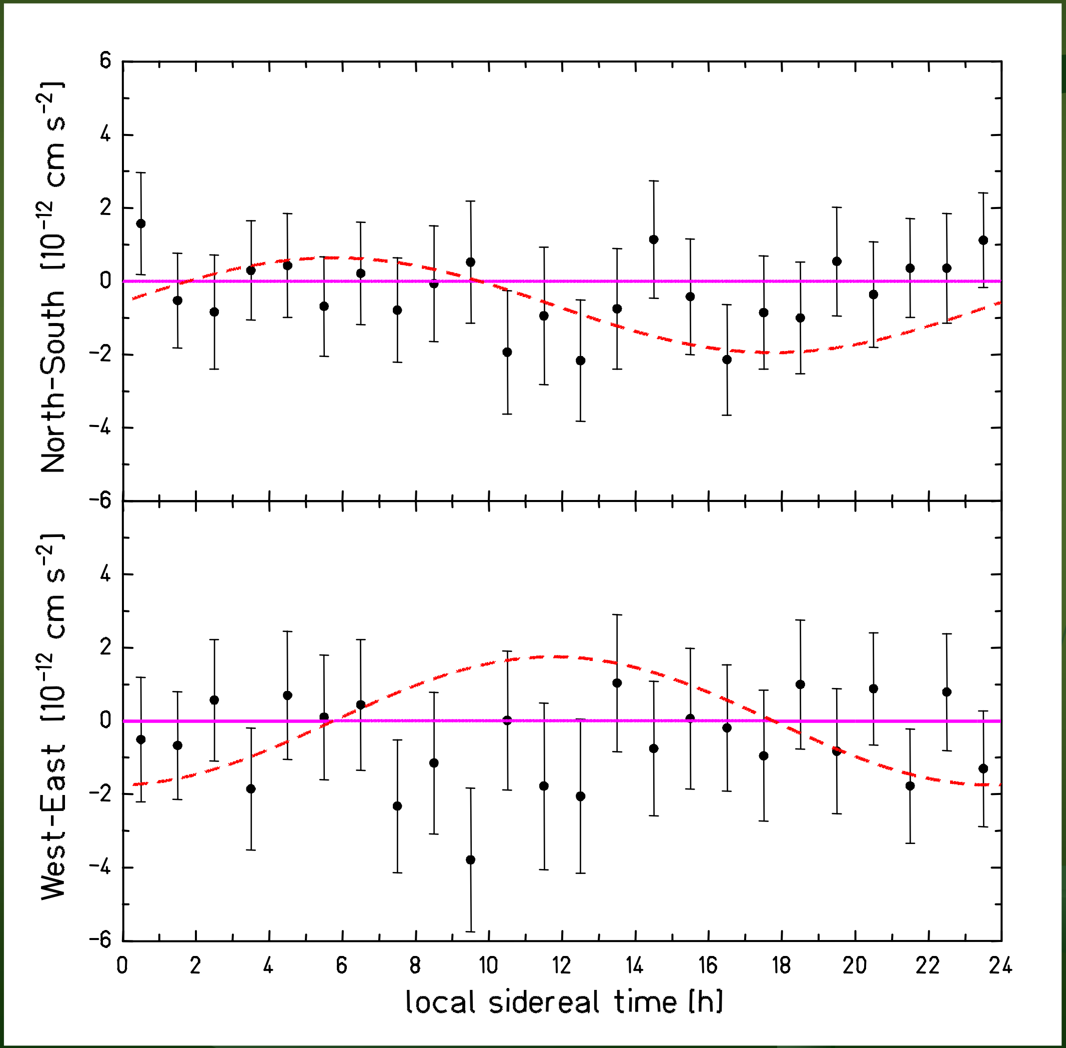
# Differential Acceleration of Ti-Be Toward the Sun

- Data points represent 1825 hours of data taken over 220 days
- Lab fixed offsets have been subtracted from data points
- Solid line represents best fit signal of $(1.24\pm2.66)\times10^{-13}$ cm/s$^2$
- Dashed line illustrates a signal of $2.00\times10^{-12}$ cm/s$^2$ toward the sun on the vernal equinox



# Differential Acceleration of Ti-Be Toward the Center of the Milky Way

- Data points represent 1825 hours of data taken over 220 days
- Lab fixed offsets have been subtracted from data points
- Solid line represents best fit signal of $(0.02 \pm 2.95) \times 10^{-13}$ cm/s$^2$
- Dashed line illustrates a signal of $2.00 \times 10^{-12}$ cm/s$^2$ toward the center of the galaxy



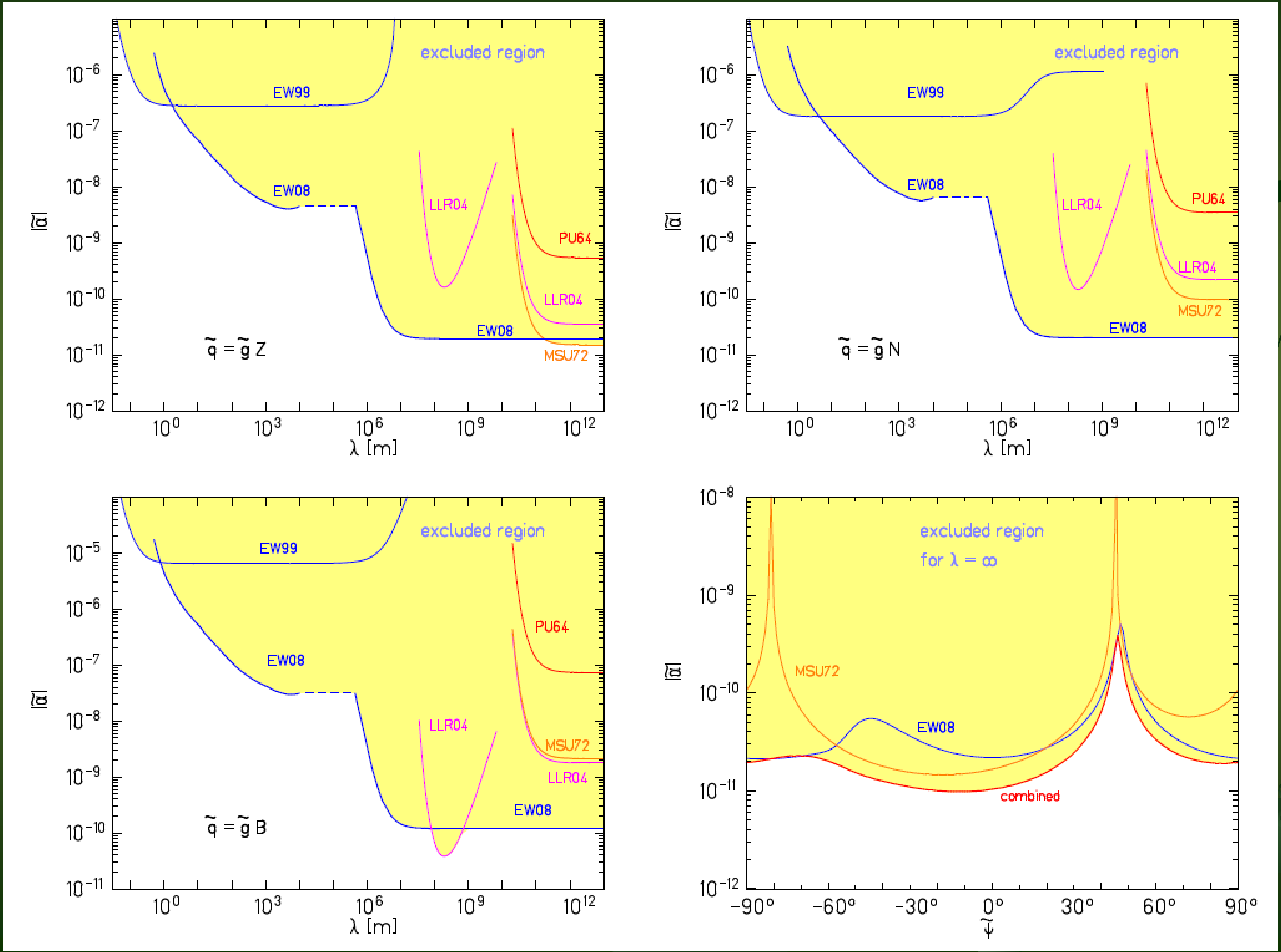
# Properties of some of our test bodies

$$\text{EP test sensitivity} = \frac{\Delta a/a \leftarrow \text{few} \times 10^{-13}}{\text{relevant test body difference}}$$

SOME RELEVANT DIFFERENCES OF OUR TEST BODIES

| T.B. pair | quanitity | value |
|---|---|---|
| Al - Be | $\Delta\left(\frac{p}{\mu}\right) = \Delta\left(\frac{e}{\mu}\right)$ | $3.80 \times 10^{-2}$ |
| Al - Be | $\Delta\left(\frac{n}{p}\right)$ | $-1.73 \times 10^{-1}$ |
| Al - Be | $\Delta\left(\frac{B-L}{\mu}\right)$ | $-3.59 \times 10^{-2}$ |
| Cu - Be | $\Delta\left(\frac{p+n}{\mu}\right)$ | $2.47 \times 10^{-3}$ |
| Cu - Be | $\Delta\left(\frac{E_{strong}}{\mu}\right)$ | $-2.47 \times 10^{-3}$ |
| Cu - Be | $\Delta\left(\frac{E_{coul}}{\mu}\right)$ | $1.98 \times 10^{-3}$ |
| Cu - Be | $\Delta\left(\frac{E_{weak}}{\mu}\right)$ | $5.6 \times 10^{-11}$ |
| Earth-Moon | $\Delta\left(\frac{E_{grav}}{M}\right)$ | $-4.4 \times 10^{-10}$ |

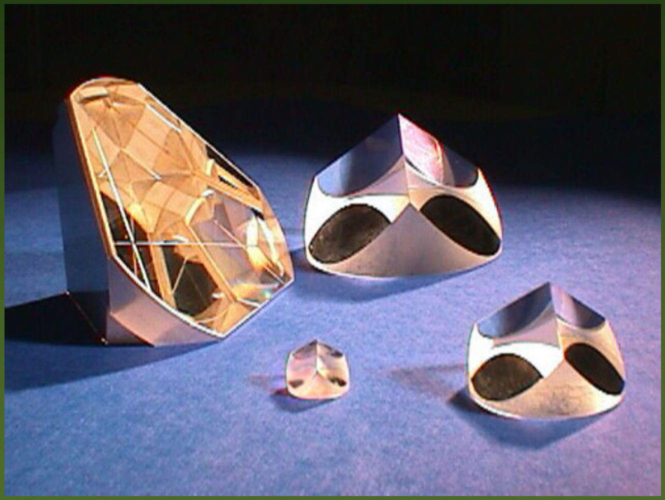
# 95% conf. level exclusion plots



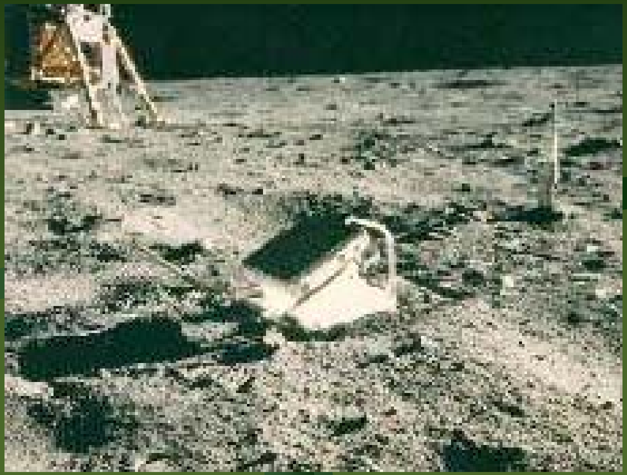
# What is the weight of gravity itself?

A test of the Strong Equivalence Principle

# Lunar Retroreflector Arrays

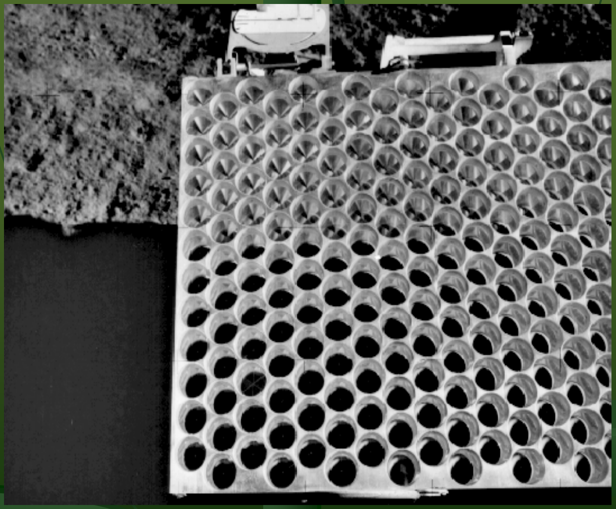


Corner cubes



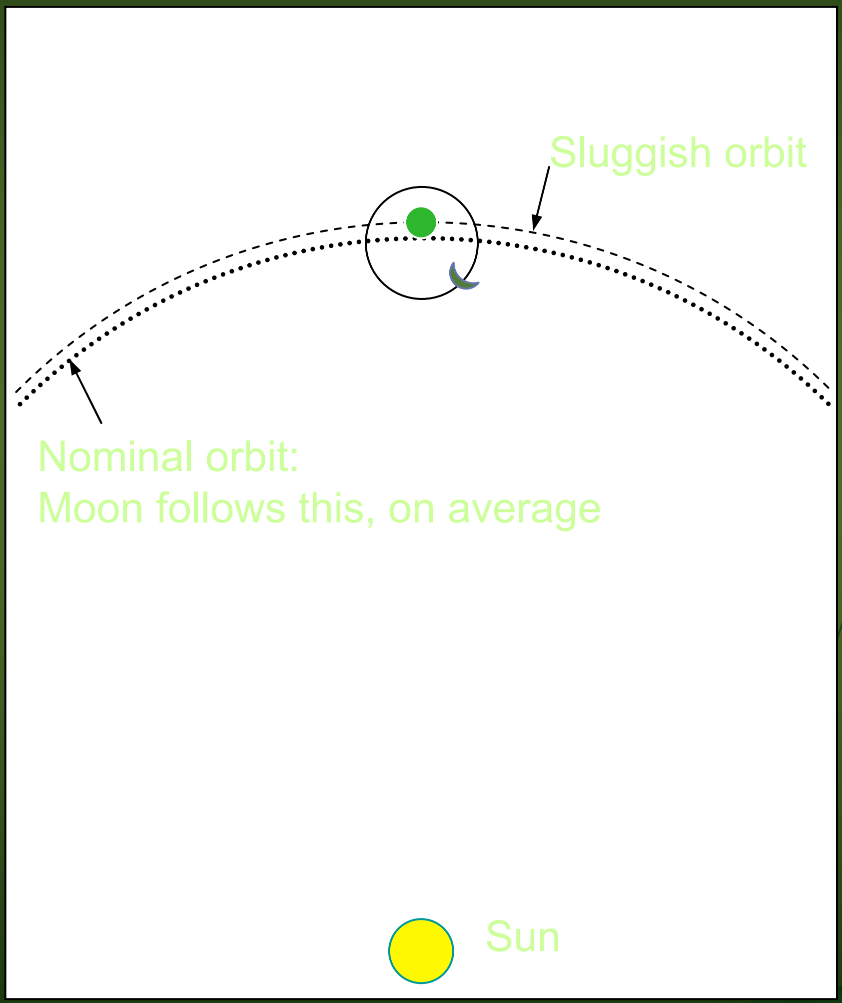
Apollo 11 retroreflector array

Apollo 14 retroreflector array



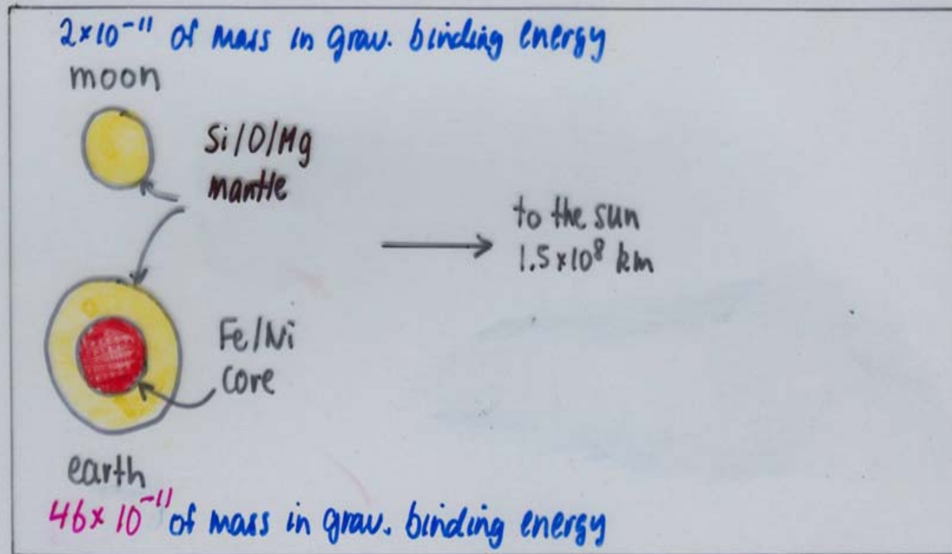
Apollo 15 retroreflector array

# Equivalence-Principle Signal

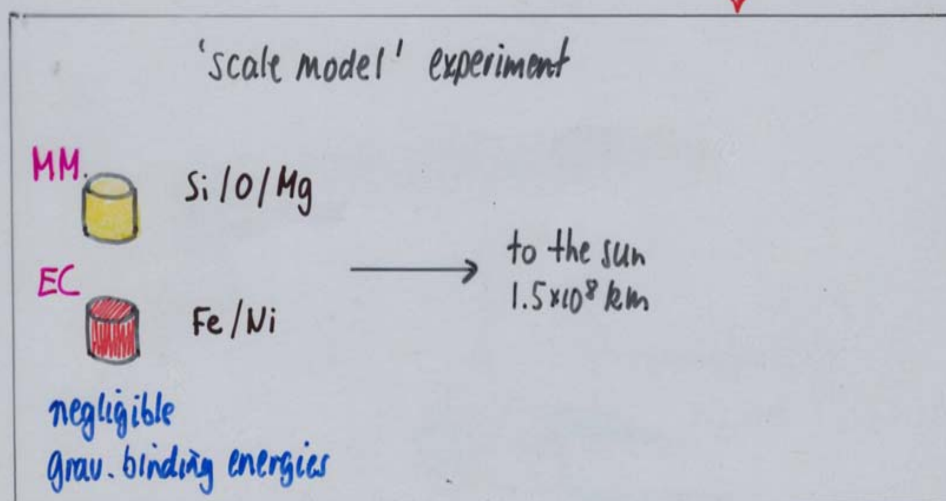



- If, for example, Earth has greater $m_i/m_g$ than the moon
  - the Earth falls to the Sun more slowly than the Moon
  - its orbit has a larger radius than does the Moon's
  - appears that Moon's orbit is *shifted* toward sun: $\cos D$ signal
- How do Earth and Moon test bodies differ?
  - Earth's mass reduced by 4.6 parts per billion by gravitational self-energy (GSE), Moon's mass only by 0.2 ppb
  - Earth has massive Fe/Ni core, Moon does not

# 'Model-independent' test of equivalence principle for gravitational binding energy




composition-dependent accelerations the same in both cases



## UNAMBIGUOUS TESTS OF THE SEP

$$\eta_{SEP} = \left.\frac{\Delta a}{a}\right|_{SEP} \frac{1}{(46-2)\times 10^{-11}}$$

$$\left.\frac{\Delta a}{a}\right|_{SEP} = \left.\frac{\Delta a}{a}\right|_{LLR} - \left.\frac{\Delta a}{a}\right|_{CD}$$

- new result

$$\left.\frac{\Delta a}{a}\right|_{LLR} = (-0.7 \pm 1.5)\times 10^{-13}$$

Anderson & Williams, Class. Quant. Grav. 18, 2447 (2001)

$$\left.\frac{\Delta a}{a}\right|_{CD} = (-1.3 \pm 1.3)\times 10^{-13}$$

U. Schmidt et al., unpublished

$$\eta_{SEP} = (1.4 \pm 4.3)\times 10^{-4}$$

<4 mm deformation of Moon's orbit

# The APOLLO Collaboration: a next-generation LLR facility

**UCSD:**
Tom Murphy (PI)
Eric Michelsen
Adam Orin
Eric Williams
Philippe LeBlanc
Evan Million

**U Washington:**
Eric Adelberger
C. D. Hoyle
Erik Swanson

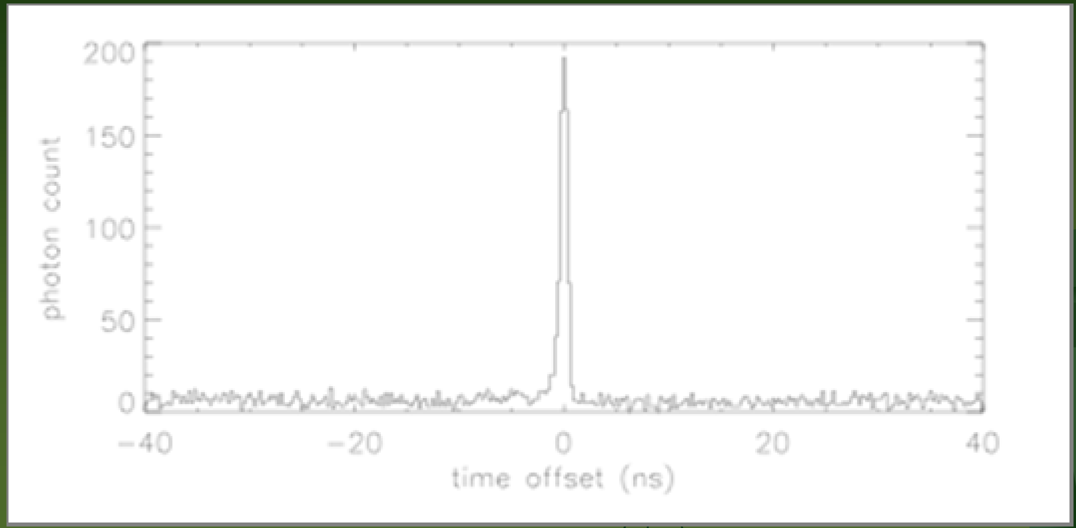
**Harvard:**
Chris Stubbs
James Battat

**JPL:**
Jim Williams
Slava Turyshev
Dale Boggs
Jean Dickey

**Northwest Analysis:**
Ken Nordtvedt

**Lincoln Labs:**
Brian Aull
Bob Reich

# APOLLO's first photon returns




- Oct. 19, 2005:
  - 2,400 returned photons in 20 minutes
  - peak rate of 0.25 photons/pulse (5/sec) over one minute
  - taken at full moon phase
  - now achieving 1 mm range precision
- Comparison:
  - McDonald station detected 2,317 photons total in three-year period from 2000–2002
  - ~ 2 cm precision

# non-grav interactions of between dark and luminous matter

Let the electron, proton, neutron and dark matter particles have "charges" $\tilde{q}_e$, $\tilde{q}_p$, $\tilde{q}_n$, and $\tilde{q}_{\rm DM}$, respectively. Depending on the nature of the interaction, electrically neutral normal matter will have a "charge"

$$\tilde{q} = B\cos\psi + L\sin\psi \tag{1}$$

where $\psi$ can range between $-\pi$ and $+\pi$. (The "charge" of hydrogen vanishes at $\psi = -\pi/4$.) The anomalous acceleration of a particle $p$ in the field of an attractor $a$ is

$$\frac{\tilde{a}}{a_g} = \pm \left[\frac{\tilde{q}}{u}\right]_p \left[\frac{\tilde{q}}{u}\right]_a K \tag{2}$$

where the $+$ and $-$ signs apply to scalar and vector interactions, respectively, and $K = 1/(4\pi G\hbar c u^2)$. Our EP results for luminous matter yield

$$\left[\frac{\tilde{q}}{u}\right]^2_{\rm LM} K < 10^{-10} \ . \tag{3}$$

For vector interactions, stability of dark matter halos requires

$$\left[\frac{\tilde{q}}{u}\right]^2_{\rm DM} K < 1 \ . \tag{4}$$

Therefore, a general *vector* interaction between dark and luminous matter can at most give an acceleration

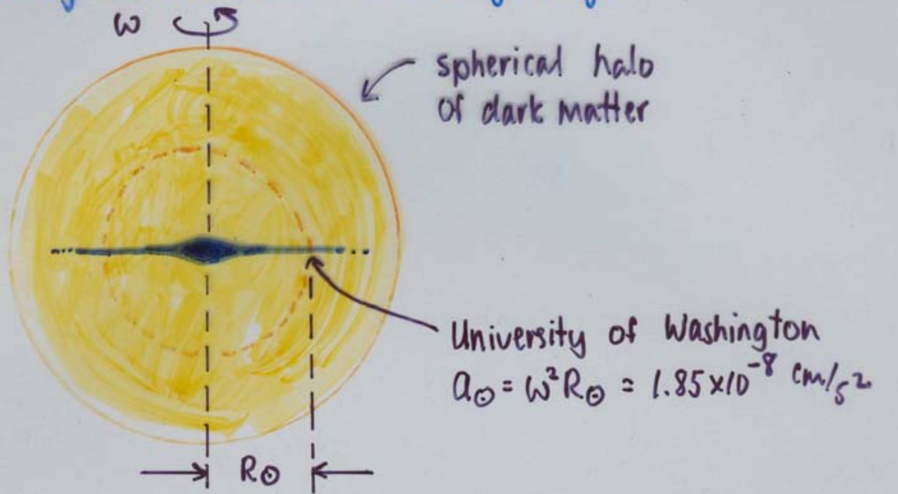
$$\frac{\tilde{a}}{a_g} < 10^{-5} \ . \tag{5}$$

However, for *scalar* interactions we do not have a strong constraint from the stability of halos.

# OUR EXPERIMENTAL STRATEGY

C.W. STUBBS

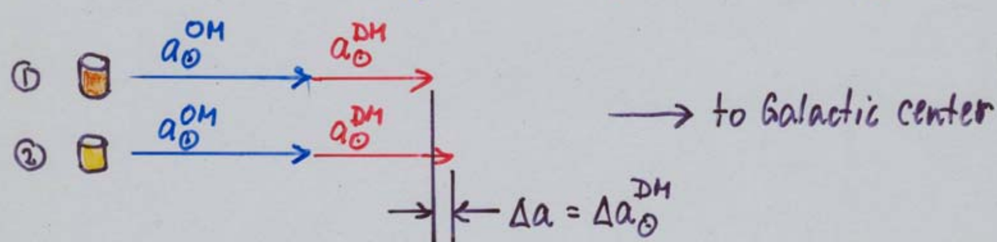
Check universality of free fall for different materials falling toward center of our galaxy.



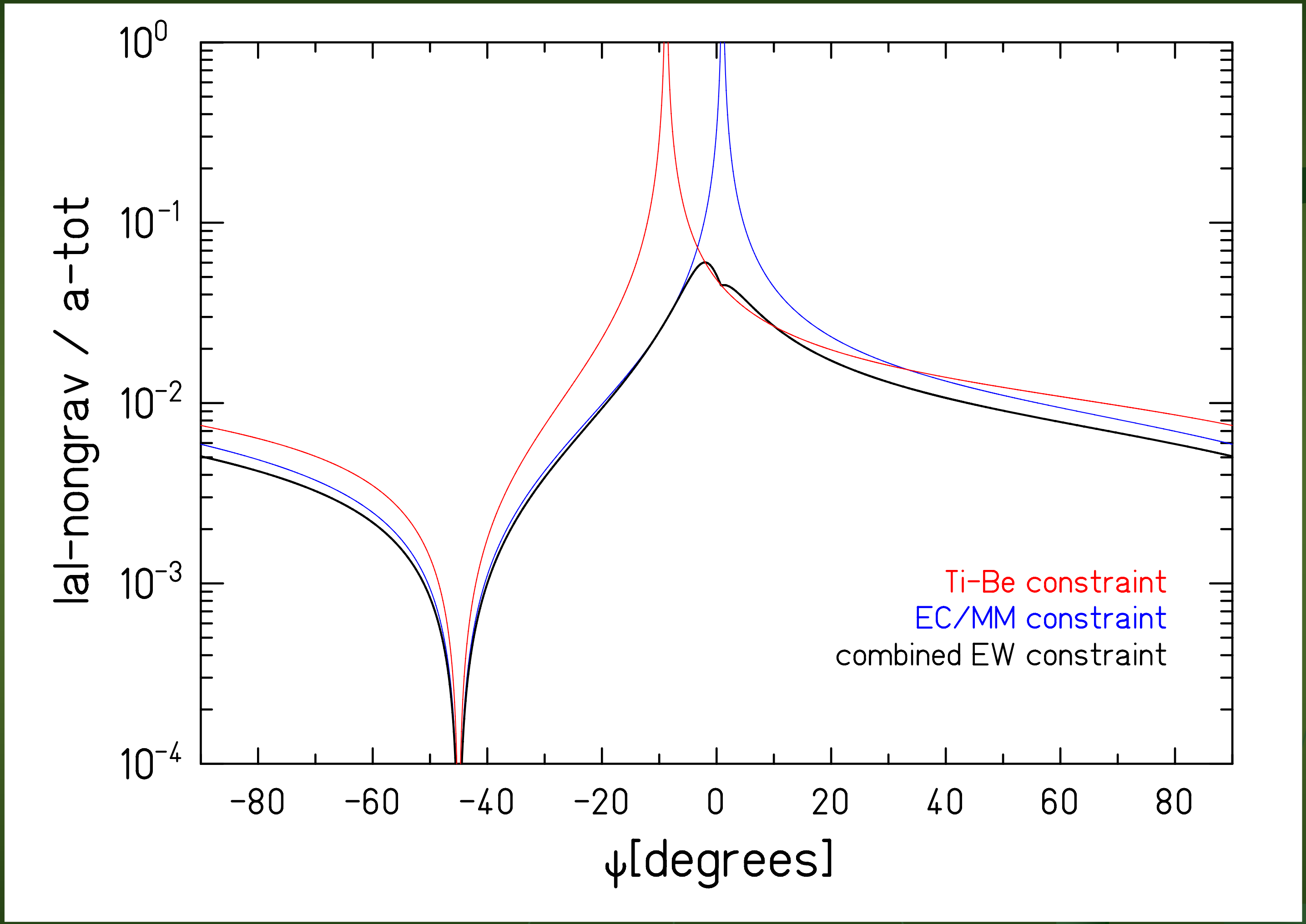

although 90% of galaxy mass is thought to be DM much of it lies outside $R_\odot$, so

$$a_\odot^{DM} = 25\text{-}30\%\ a_\odot \quad \Rightarrow \quad \boxed{a_\odot^{DM} \approx 5\times10^{-9}\ cm/s^2}$$

we can make interesting statement about non-grav. component of $a_\odot^{DM}$ if we can detect differential accels. with a sensitivity of $10^{-3} a_\odot^{DM} \sim 5\times10^{-12}$ cm/s



# 95% confidence limits on non-grav interactions between dark matter and hydrogen




at most 5% of the acceleration can be nongravitational

# some interesting numbers

- Our differential acceleration resolution is $\approx 2\times10^{-13}$ cm/s$^2$

- This is the change in g caused by a vertical dispacement of 0.6 nm in Earth's field

- If, at the time of Pericles (450 BC), you started an object from rest and gave it an acceleration $2\times10^{-13}$ cm/s$^2$, it would now be moving as fast as the end of the hour hand on a typical wall clock

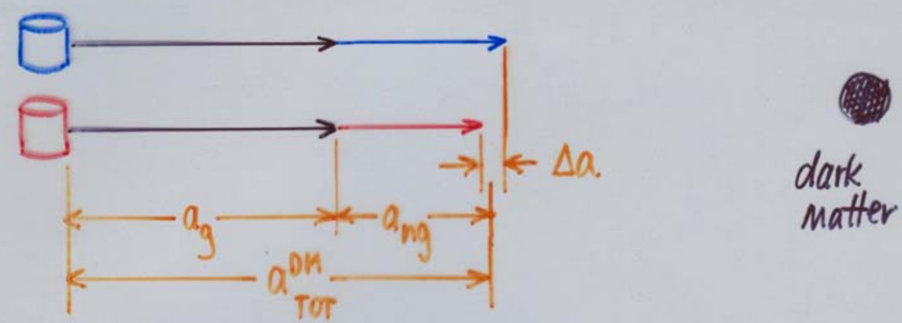
# conclusions

- The EP is one of the most precisely tested principles in all of physics with many broad implications
- Most scenarios for new physics predict EP violation at some level
- No evidence yet for a breakdown of the EP. For example:
  - the weight of gravity agrees with Einstein's prediction to better than 1 part in $10^3$
  - assuming CPT symmetry, anti-H falls with the same acceleration as H to within 2 parts in $10^{10}$
  - laboratory proof that gravity is the dominant long-range force between dark and luminous matter
- Existing experimental results constrain many theoretical speculations
- Plans exist for new types of EP experiments
  - satellites, balloons, cold-atom fountains
- The physics of falling bodies remains a non-trivial and profound subject

# Some references to our work

- Y. Su et al., PRD 50, 3614 (1994)
- S. Baessler et al., PRL 83, 3585 (1999)
- G.L. Smith et al., PRD 61, 22001 (2000)
- S. Schlamminger et al., PRL 100, 041101 (2008)

# Accelerations due to dark matter




$$\eta^{DM} \equiv \frac{\Delta a}{a^{DM}_{TOT}}$$

analyse Eöt-Wash data spanning ~ 2 yrs for signal pointing toward galactic center

find:

$$\eta^{DM}(\text{Be-Al}) = (+1.8 \pm 1.4) \times 10^{-3}$$
$$\eta^{DM}(\text{Be-Cu}) = (-1.3 \pm 0.9) \times 10^{-3}$$
$$\eta^{DM}(\text{Si/Al-Cu}) = (+0.7 \pm 1.0) \times 10^{-3}$$

$$a_{ng} = a^{DM}_{TOT} \, \eta^{DM} \underbrace{\frac{\langle q_5/\mu \rangle}{\Delta(q_5/\mu)}}_{\text{property only of detector dipole}}$$

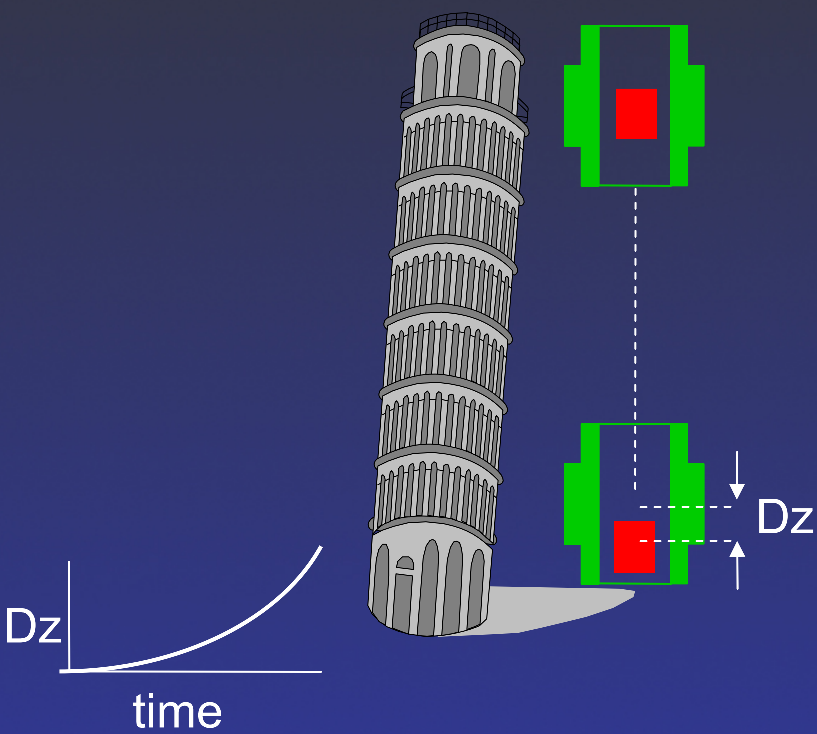
simple tree-level estimate

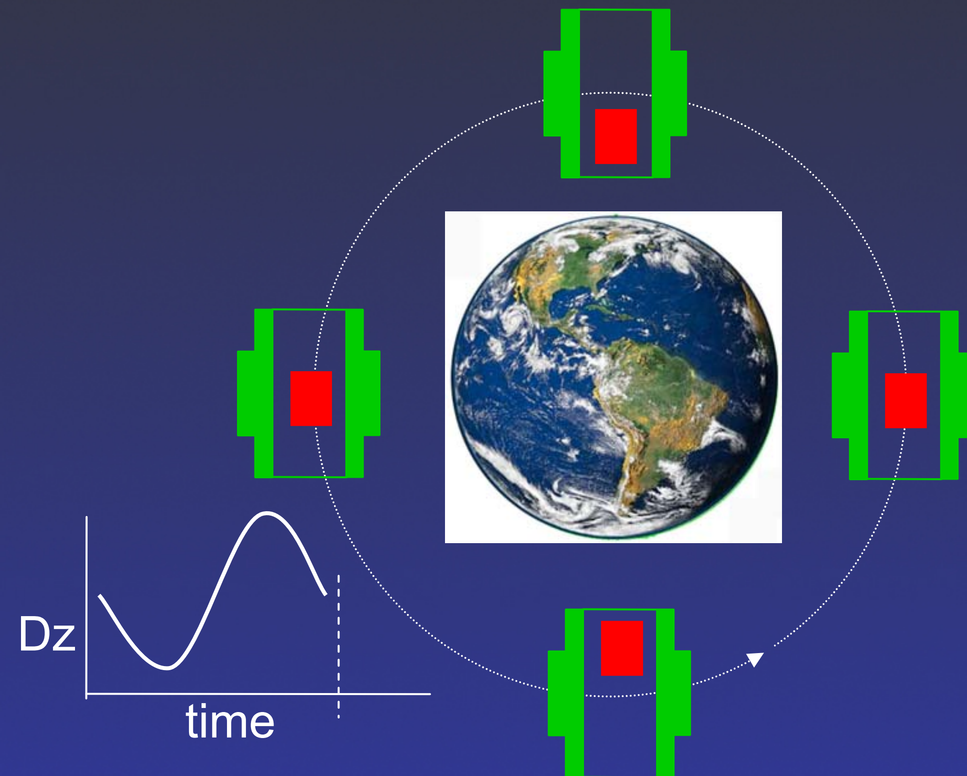
$$\frac{\langle q_5/\mu \rangle}{\Delta(q_5/\mu)} = \frac{(q_5^e + q_5^p)\langle Z/\mu \rangle + q_5^n \langle N/\mu \rangle}{(q_5^e + q_5^p)\Delta(Z/\mu) + q_5^n \Delta(N/\mu)}$$

# STEP

## Satellite Test of the Equivalence Principle

Newton's Mystery { $F = ma$ mass - the receptacle of inertia
$F = GMm/r^2$ mass - the source of gravitation




Orbiting drop tower experiment {
* More time for separation to build
* Periodic signal