Direct and indirect torsion-balance constraints on monopole-dipole forces from axion-like particles

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Outline:

- discuss the 2 most recent direct lab results:
  try to get sensitivity to high-mass “home made” ALPs
  challenging experiments with
  simple interpretation

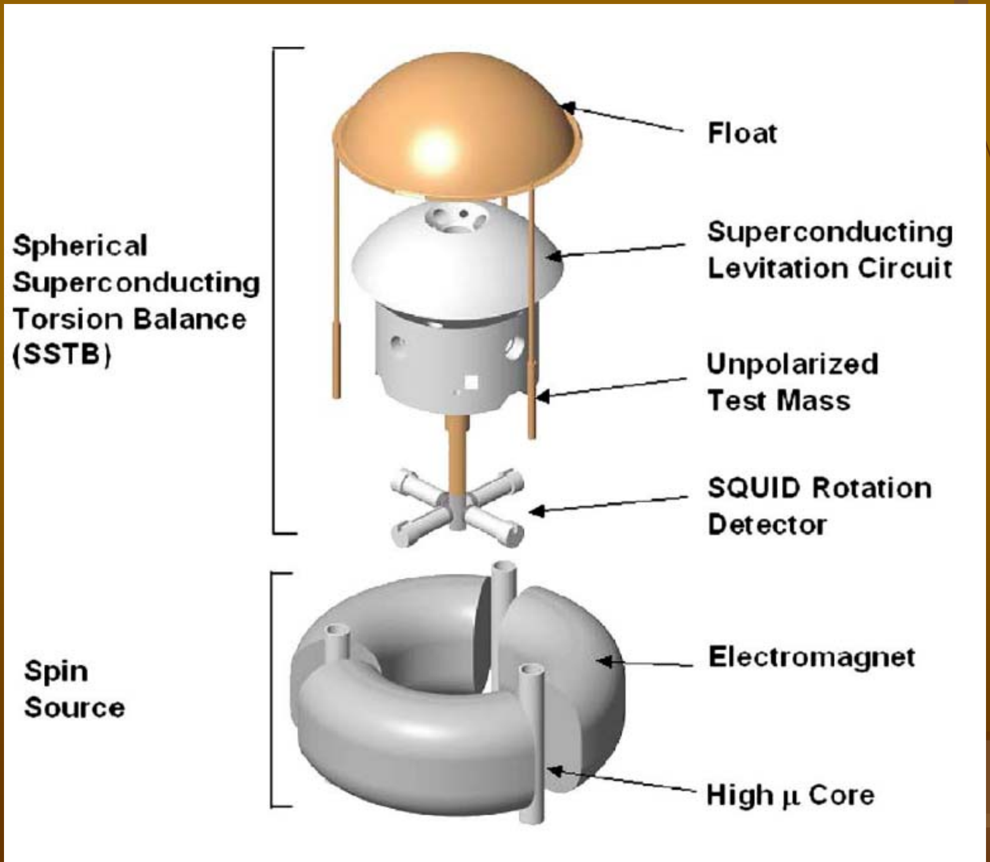
- indirect lab results (see Raffelt’s talk)
  get $g_s(N)$ from ISL and WEP tests
    very sensitive experiments but
    some subtleties in interpretation
  get $g_p(e)$ from spin-spin experiments
    5 orders of magnitude less sensitive than
    astrophysical limits

- Is it worth pushing a 2nd generation of direct experiments?

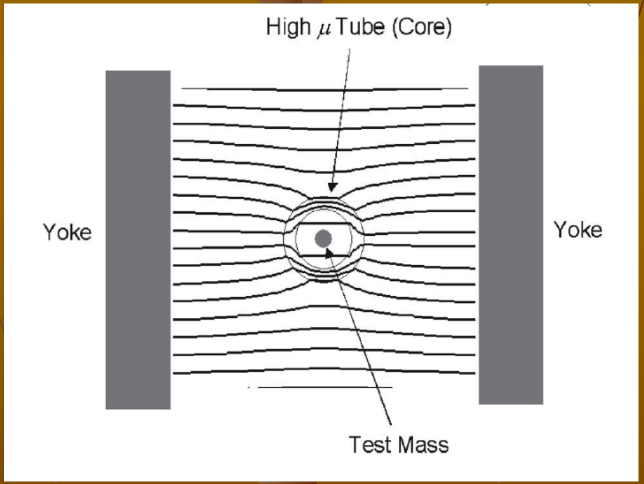
innovative, high-tech Birmingham / Imperial College spin-bulk experiment

G D Hammond et al, PRL 98, 081101 (2007)
PRD 77, 036005 (2008)

the challenge: align a lot of electron spins in close proximity to a test body while minimizing magnetic effects on the unpolarized test body

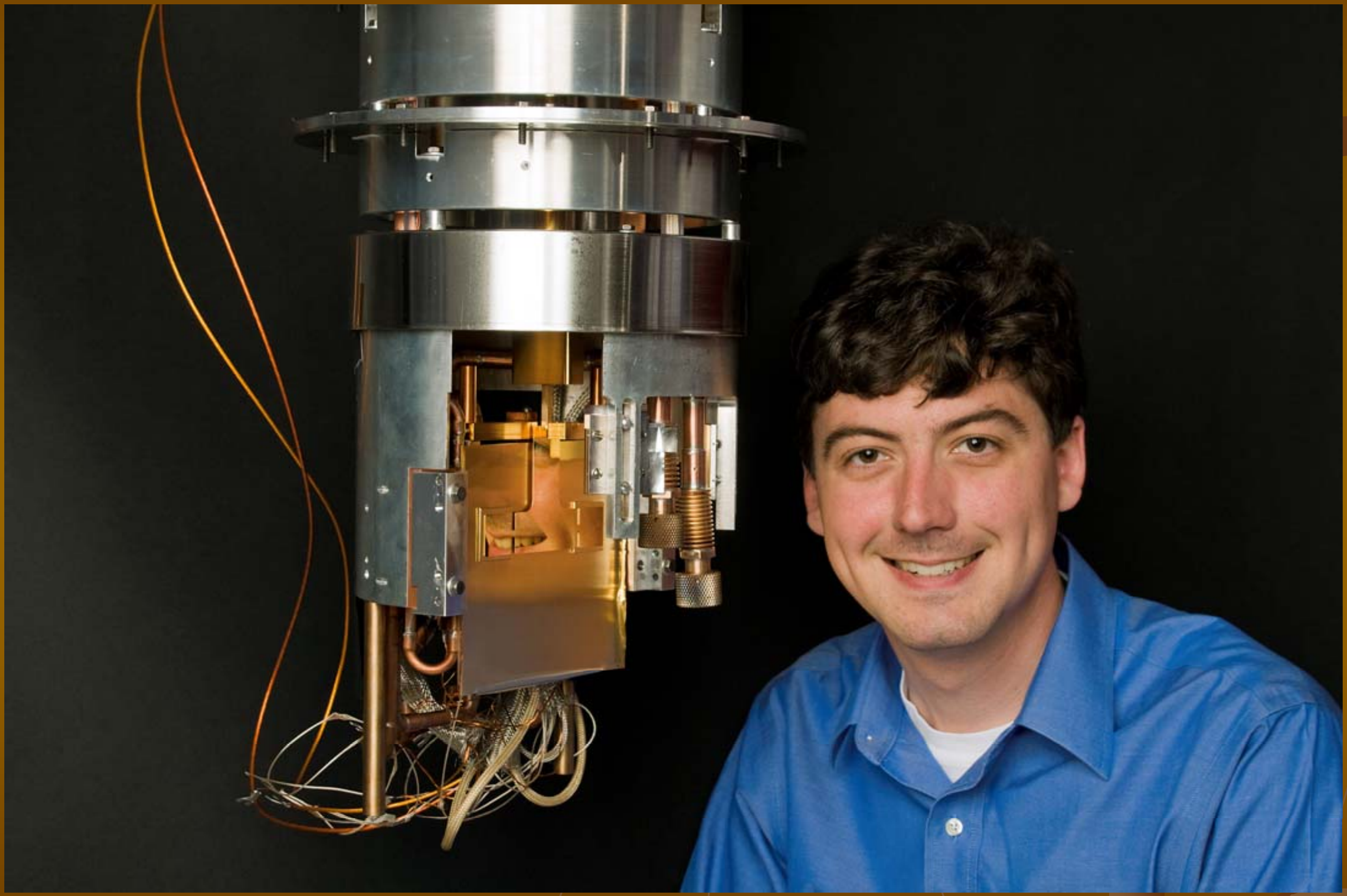


top view of test body in a core



Mu-Metal core:
r_{inner} = 4.5 mm, h=80 mm
OFHC test body:
r=0.5 mm, h=30 mm

Eöt-Wash spin-bulk experiment

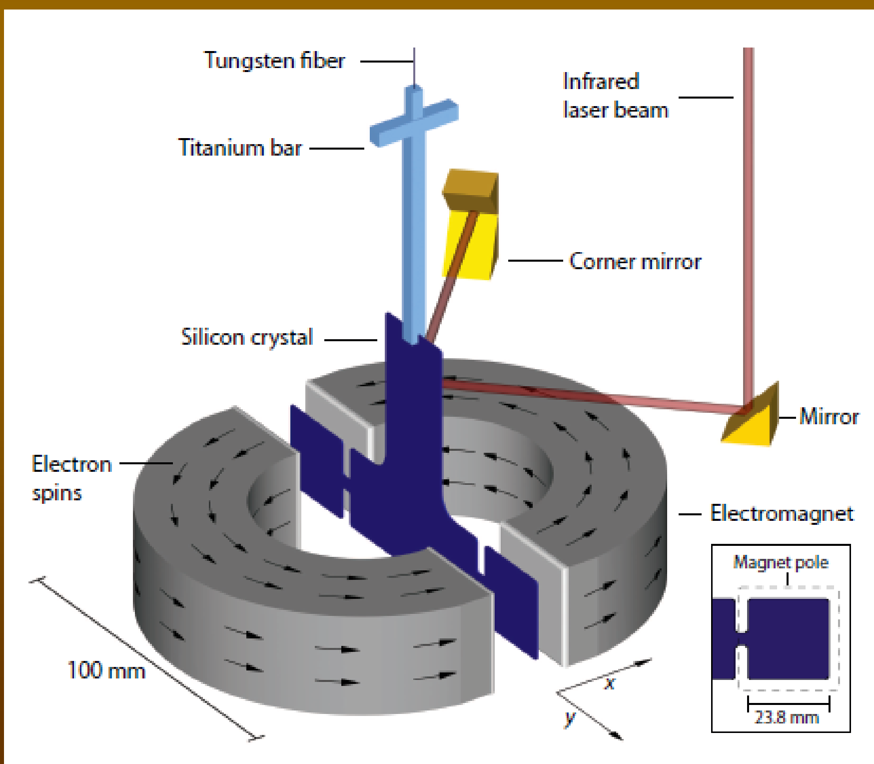


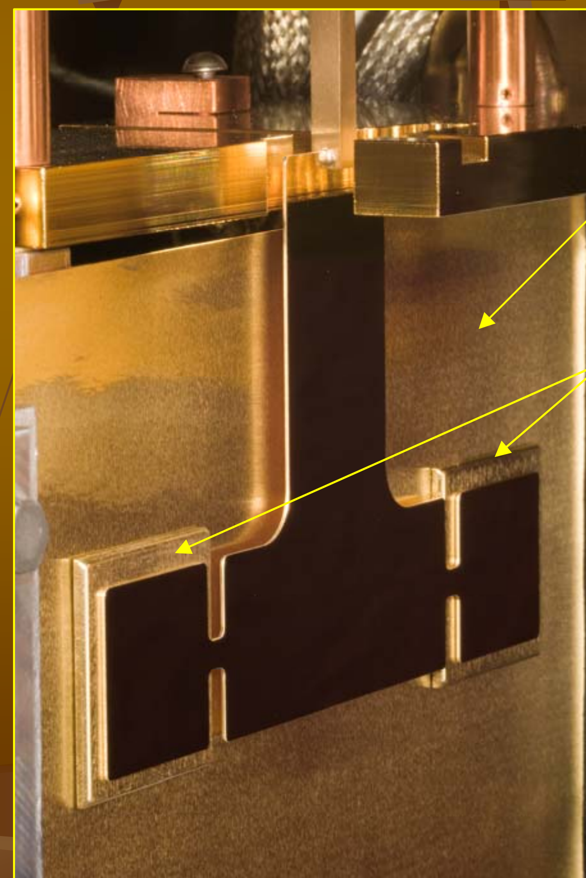
"Improved Constraints on Axion-mediated Forces", S. Hoedl, F. Fleischer, E. G. Adelberger and B. R. Heckel, Physical Review Letters **106**, 041801 (2011).

Exchange of virtual axions mediates a monopole-dipole force

$$V(\hat{\sigma}, \boldsymbol{r}) = \frac{\hbar^2(\hat{\sigma}\cdot\hat{r})}{8\pi m_e}\left(\frac{g_s^a g_p^e}{\hbar c}\right)\left(\frac{1}{r\lambda_{\mathrm{ALP}}}+\frac{1}{r^2}\right)e^{-r/\lambda_{\mathrm{ALP}}}$$

where g_s^a is proportional to Θ_{QCD}





electrostatic shield

electrically isolated magnet poles used to lock pendulum when reversing B

Tb coating canceled Si diamagnetism to within 5%

This experiment was very brave: we got sensitivity to higher axion masses by using an unshielded test body

our pendulums are normally shielded from electrical and magnetic fields and very little power is dissipated inside the instrument to avoid temperature variations.

In this case pendulum is subjected reversing kG fields and magnets windings dissipate ~30 W

pendulum is slightly paramagnetic (a weak-field seeker) and so is subject to a “magnetic torsional spring” that is much stronger than the fiber spring

B must be reversed very precisely and any stray B fields carefully minimized to keep the magnet spring constant

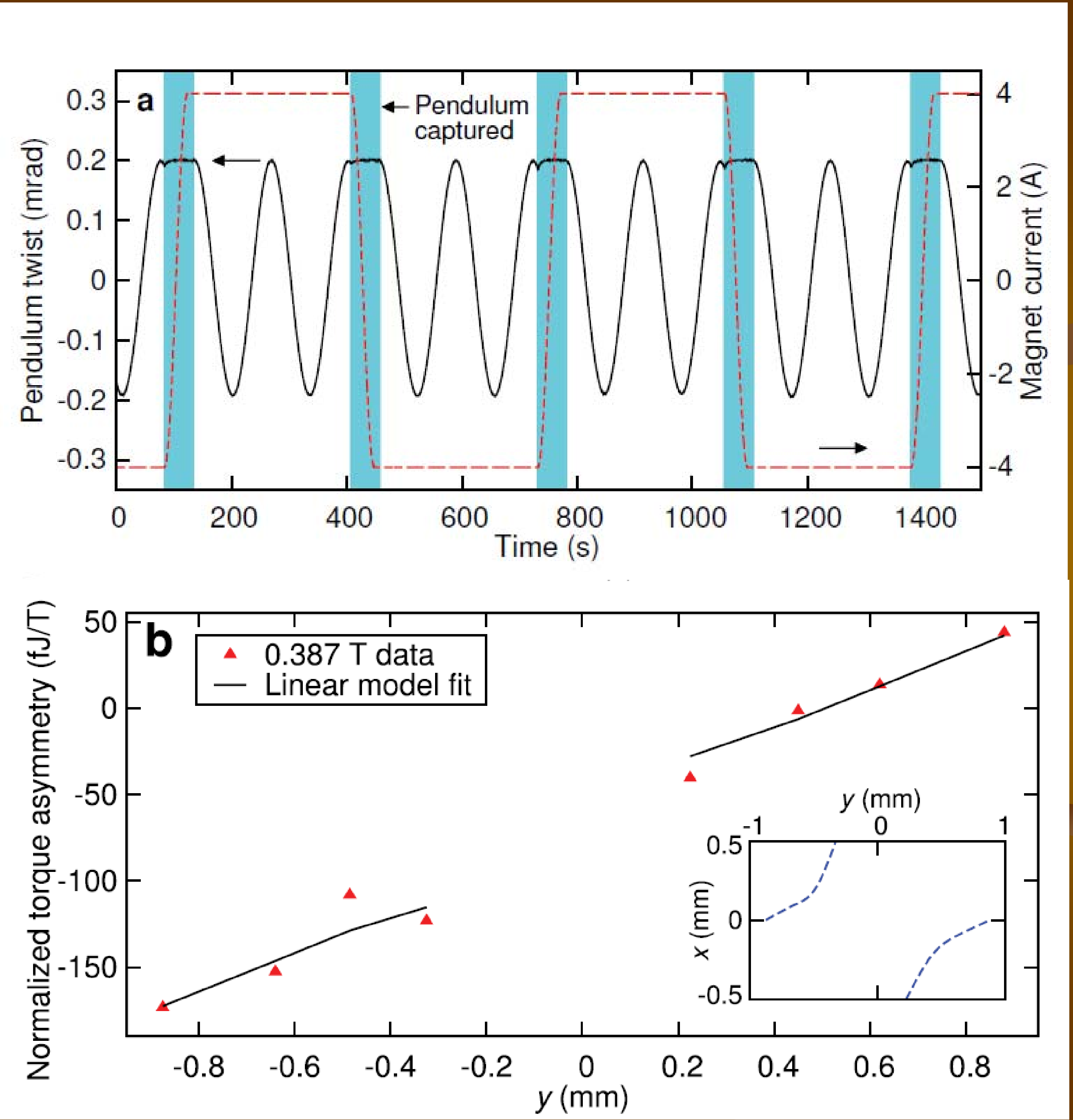
our experiment is most sensitive for axions (ALPs) at the high end of the allowed axion mass window

The pendulum:

- hi-purity single-Xtal Si
  - (vol mag susceptability -3.7x10-6)
- coated with 30 nm of Tb
  - (vol mag susceptability .112, Curie point 222K)
- finish coat of Au

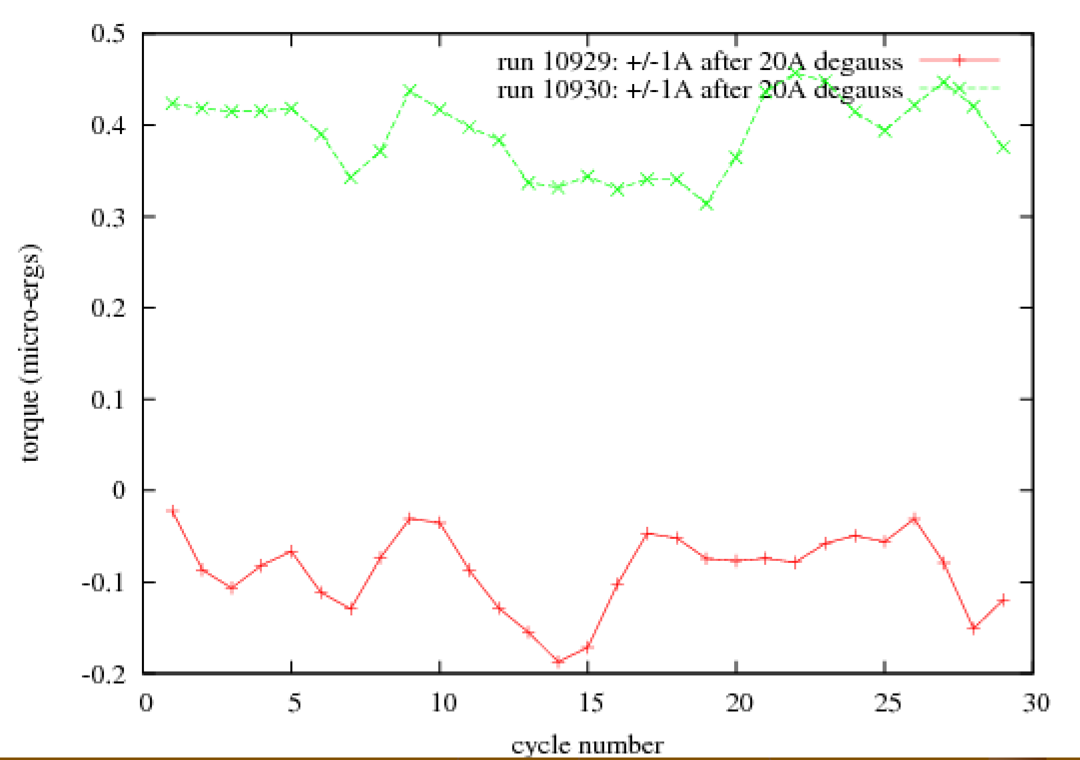
The magnet:

- core of magnet iron
- temp controlled by coolant in direct contact with iron
  - $\Delta T=(-.32 +- .27)$mK
- potted in heat conducting exoxy
- electrically insulated pole shims
  - improved B field uniformity
  - used to capture pendulum during B reversals
- surrounded by 2 layers of mu-metal shielding

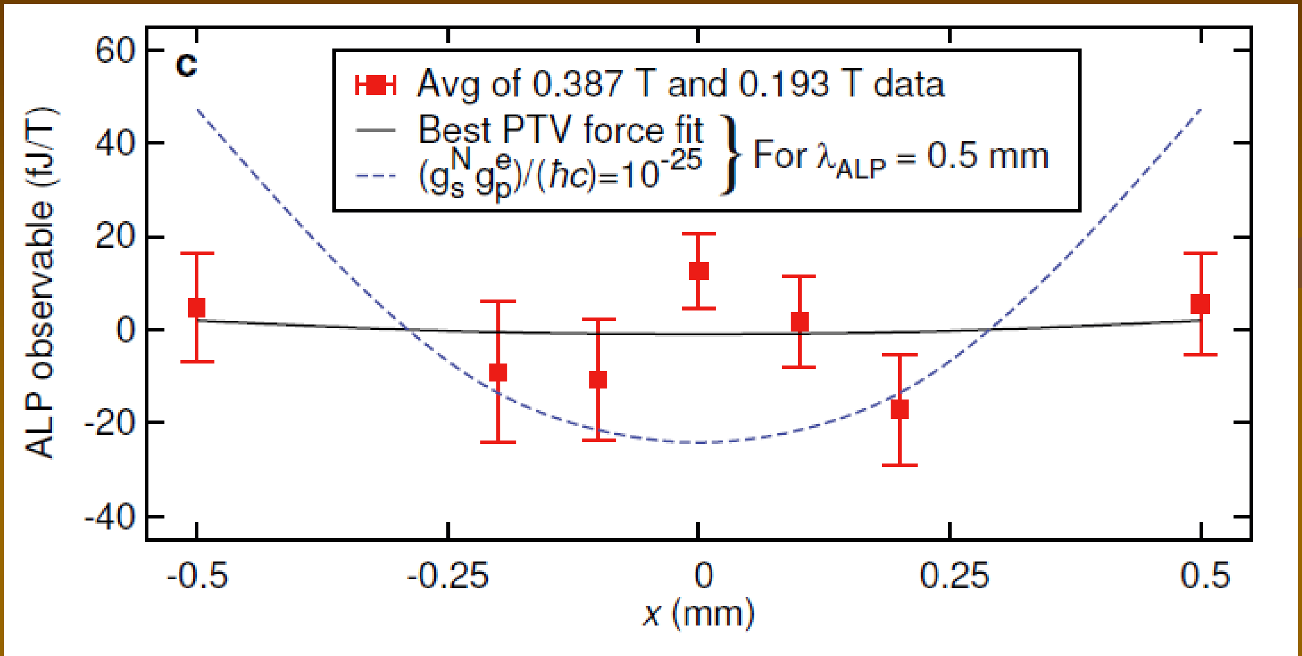


a run consisted of 12 cycles of +/- magnetic-field reversals

a scan consisted of a magnet degauss followed by runs taken with pendulum at 8 positions within the magnet gap uncertainties were dominated by “degauss scatter” that is an order magnitude larger than scatter within a run



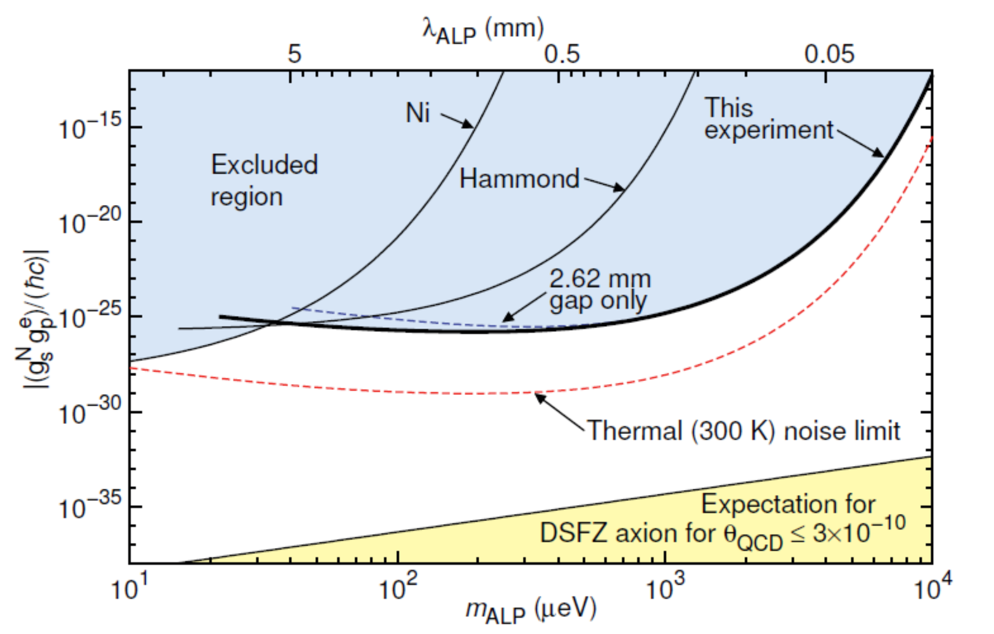
we suspect the effect arises from inhomogeneities in the magnetic iron



20 scans

we exploited the
finite range of the monopole-dipole force by varying the distance between pendulum and pole

Constraints on couplings of axions (ALPs) in the allowed mass range



experimental 95% confidence upper limit on $|g_s^N g_p^e/\hbar c|$.

We improved direct constraints on ALPs with masses >1meV by more than a factor of 10^{10}

The upgrade path for our experiment:

replace magnet core with laminated hi-mu material (Conetic AA)
- lower saturation B
- much smaller coercive force

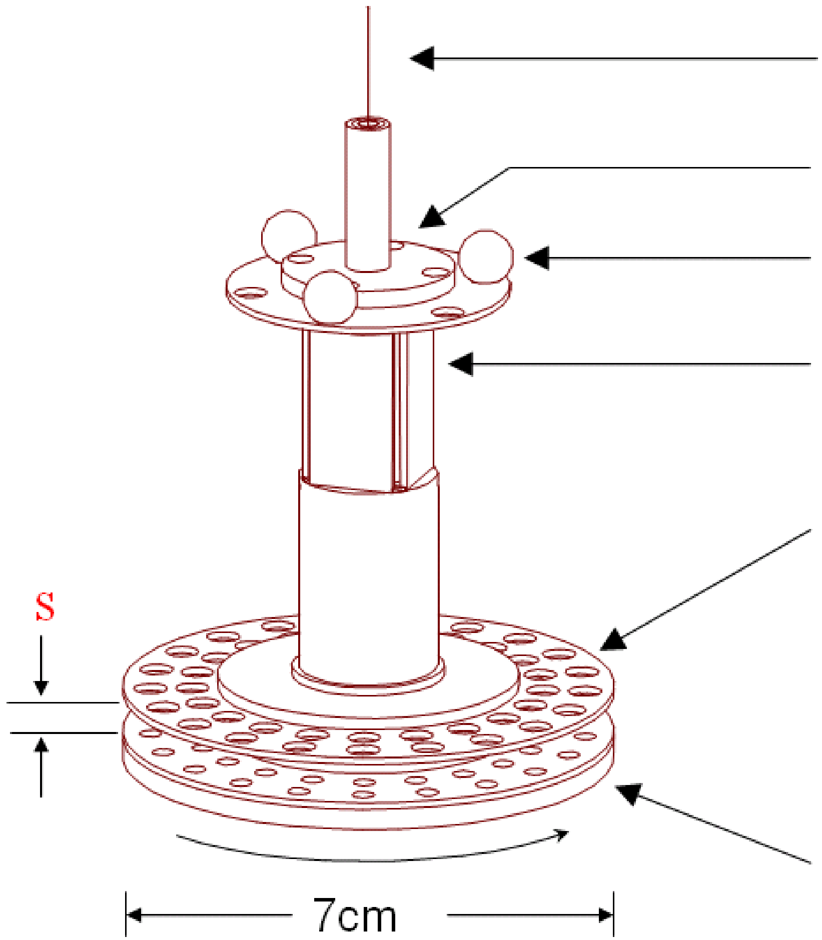
replace pendulum
- Ge instead of Si
- reduce susceptibility with conventional paramagnetic coating
- much larger “cutouts” don’t try to cancel magnetic spring

Now review some of the lab experiments that Raffelt uses for indirect constraints on the monopole-dipole force:

get $g_s(N)$ from
- ISL tests
- WEP tests

assume deviations prop to $| g_s(N) |^2$

Eöt-Wash 42-hole inverse-square law pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

4 mirrors for tracking angle of deflection

detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

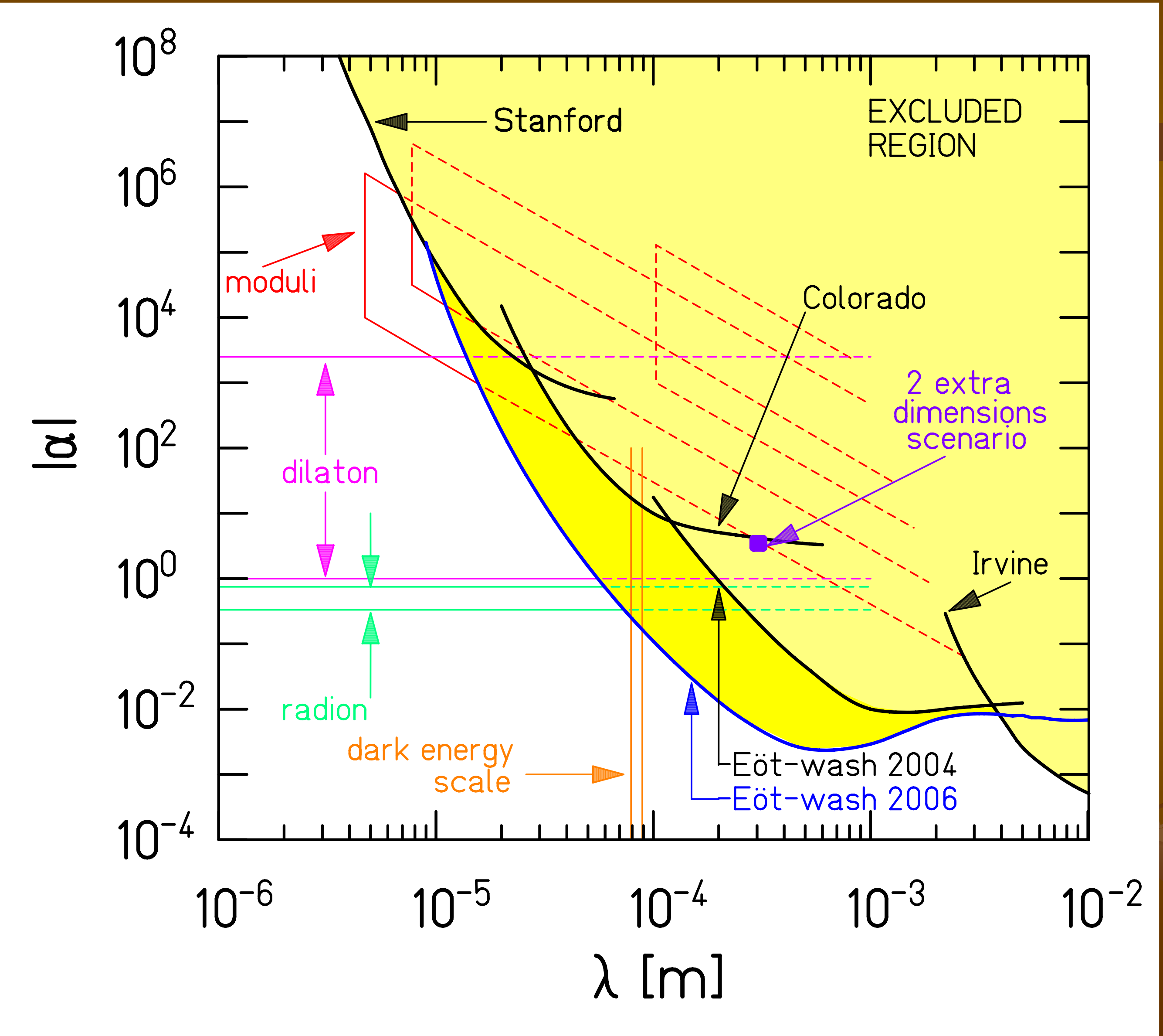
not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

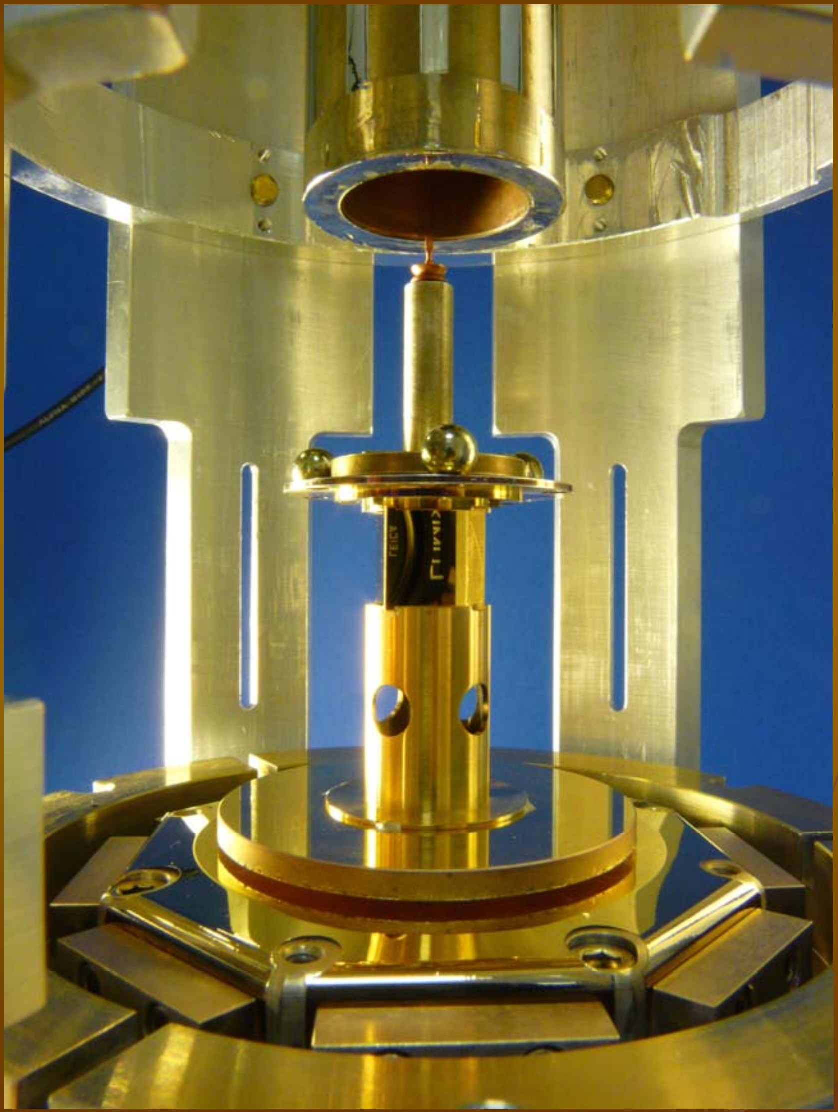
PhD project of Dan Kapner, PRL 98, 021101(2007)

95% confidence upper limits on ISL violation

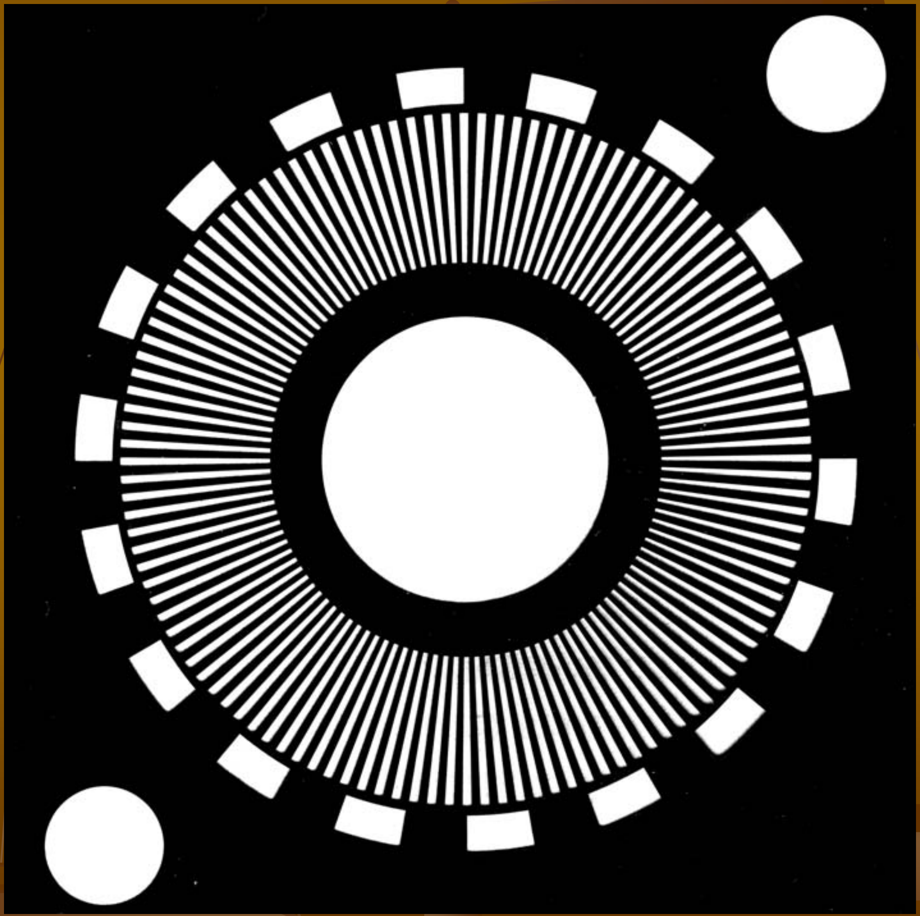
D J Kapner et al., PRL 98, 021101 (2007)



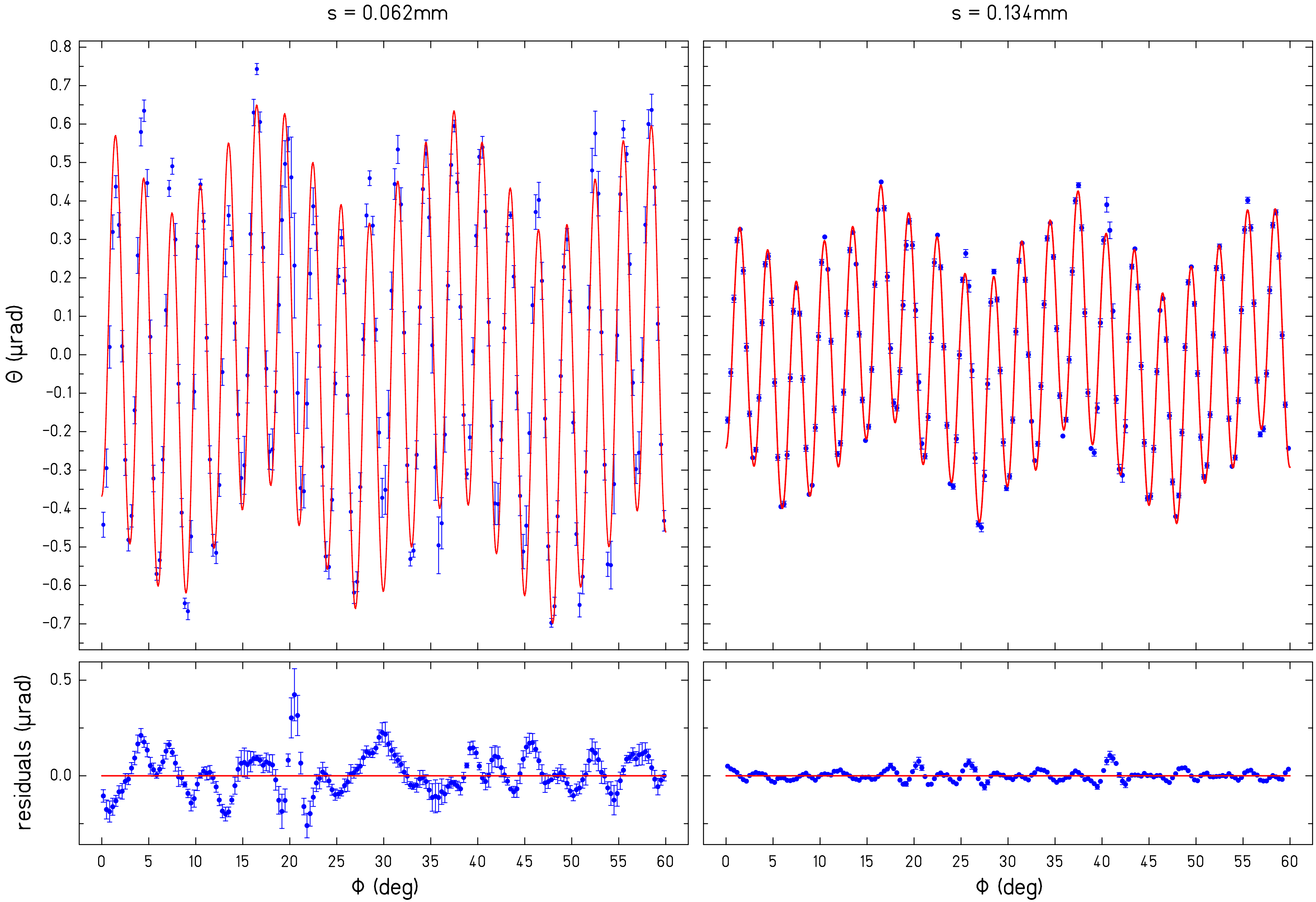
the Fourier-Bessel pendulum



pendulum & attracter are 50μm think W foils glued to glass plates



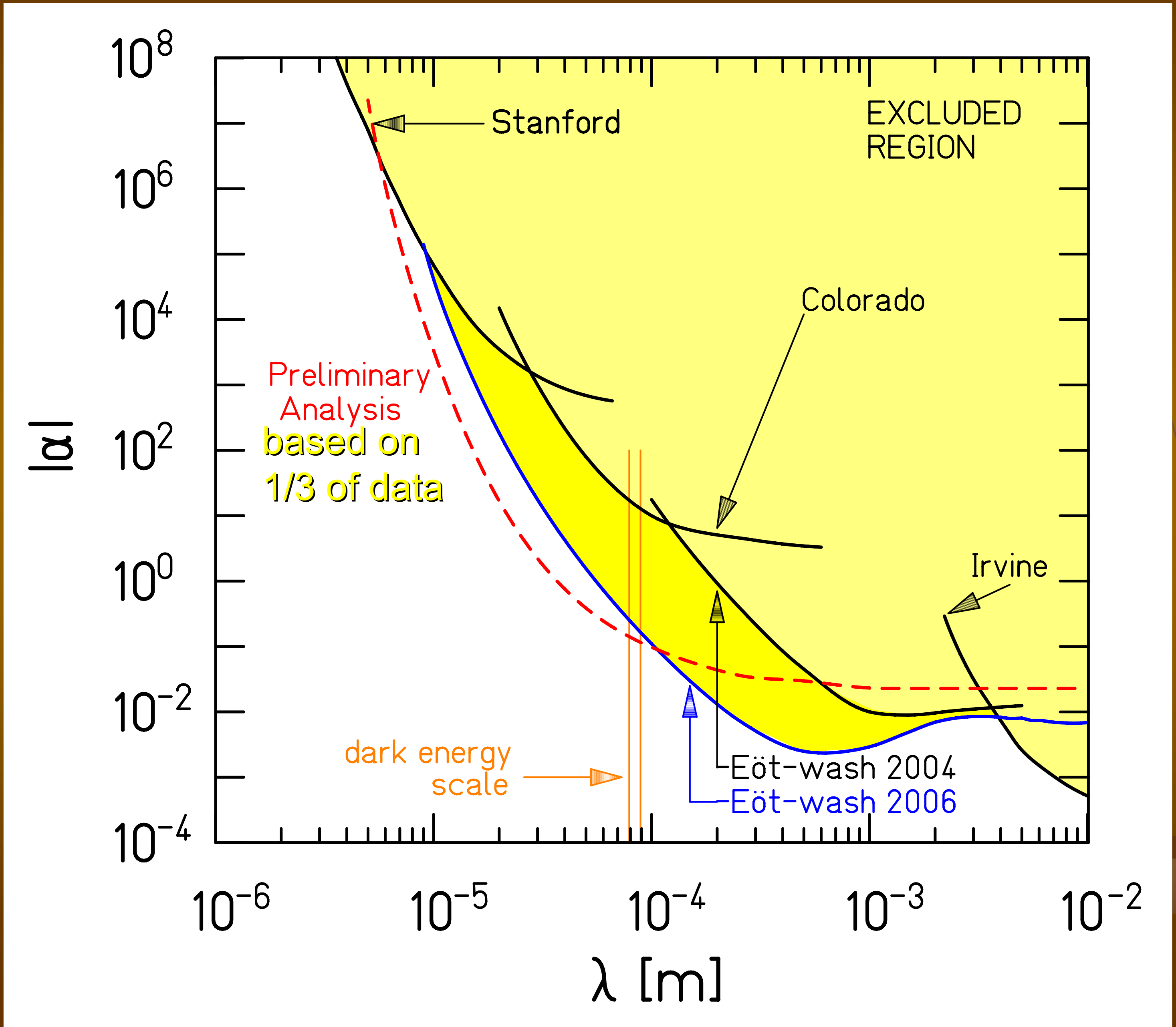
PhD project of Ted Cook



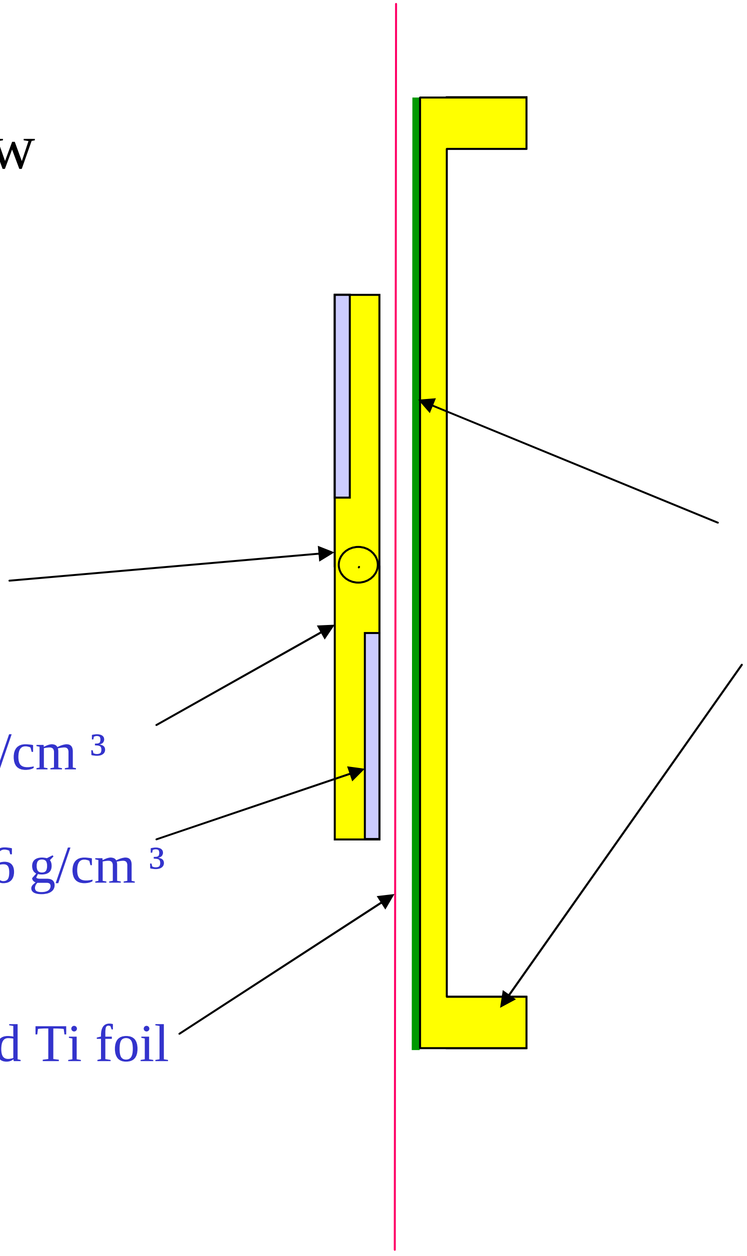
s = 0.062mm
s = 0.134mm
Θ (μrad)
residuals (μrad)
Φ (deg)
Φ (deg)

Preliminary 95% CL limits from Cook's expt.

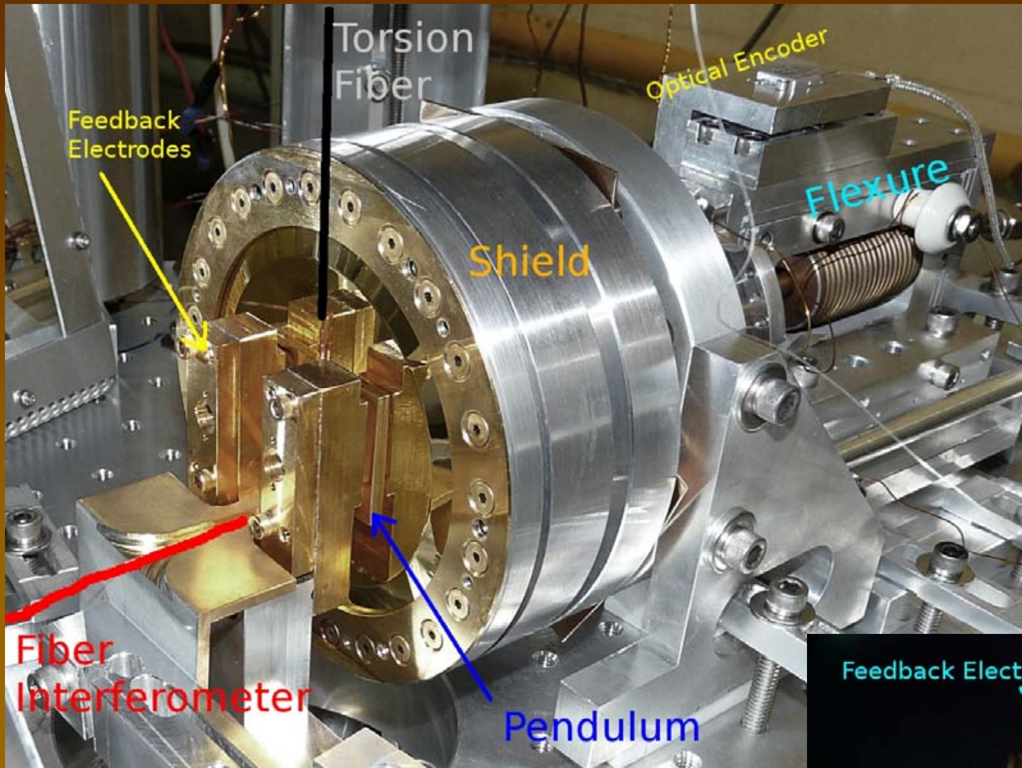
10 x improvement for masses of 10 meV

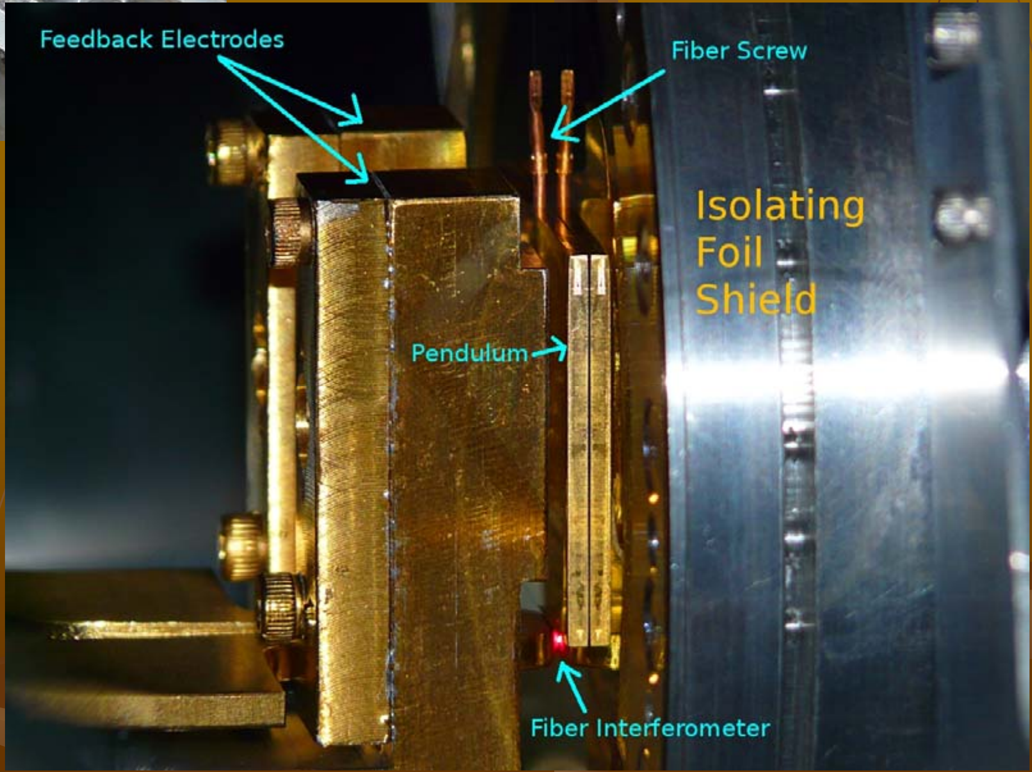


The parallel-plate pendulum



PhD project
of Charlie Hagedorn


Torsion Fiber
Optical Encoder
Feedback Electrodes
Flexure
Shield
Fiber Interferometer
Pendulum

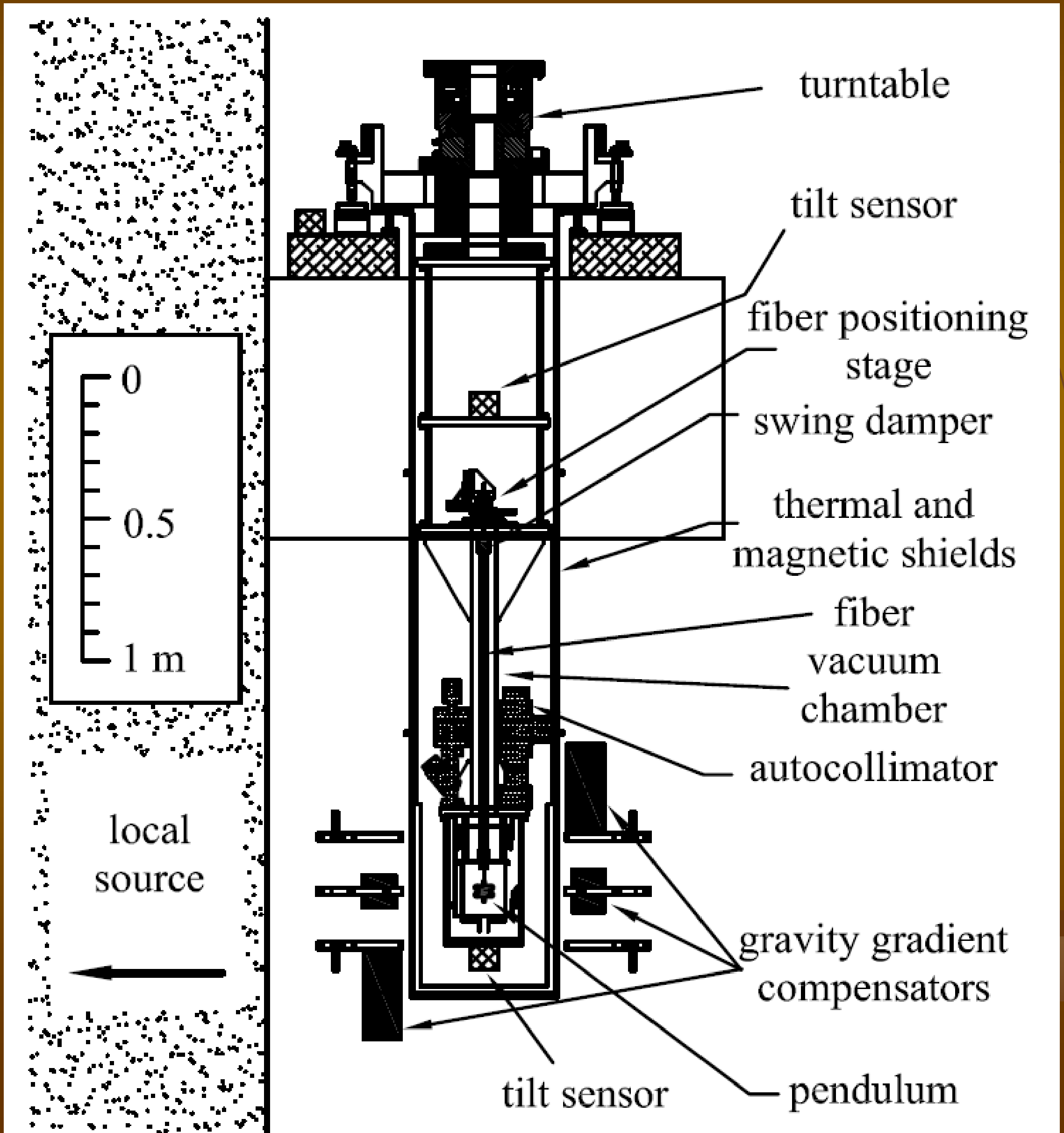

Feedback Electrodes
Fiber Screw
Isolating Foil Shield
Pendulum
Fiber Interferometer

Limiting factor in Fourier-Bessel ISL test:

excess electrostatic noise for separations less than 100 microns

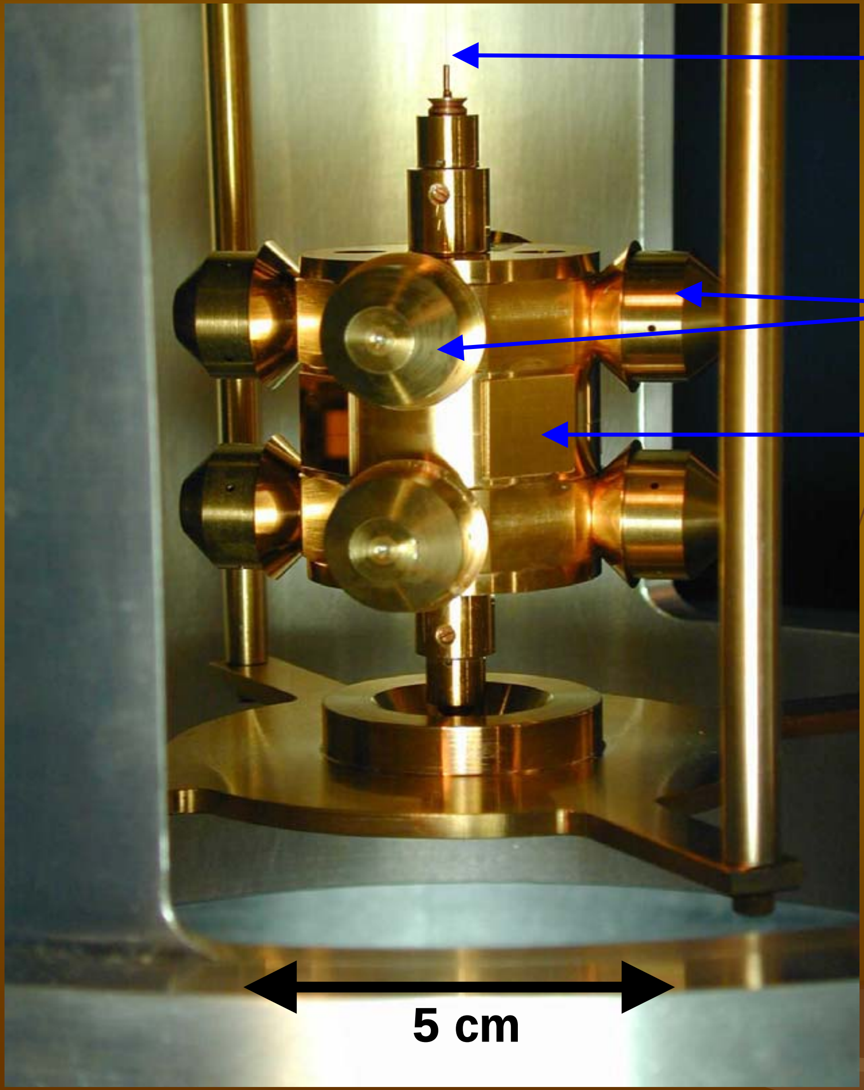
Eöt-Wash WEP test with a rotating torsion balance

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



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

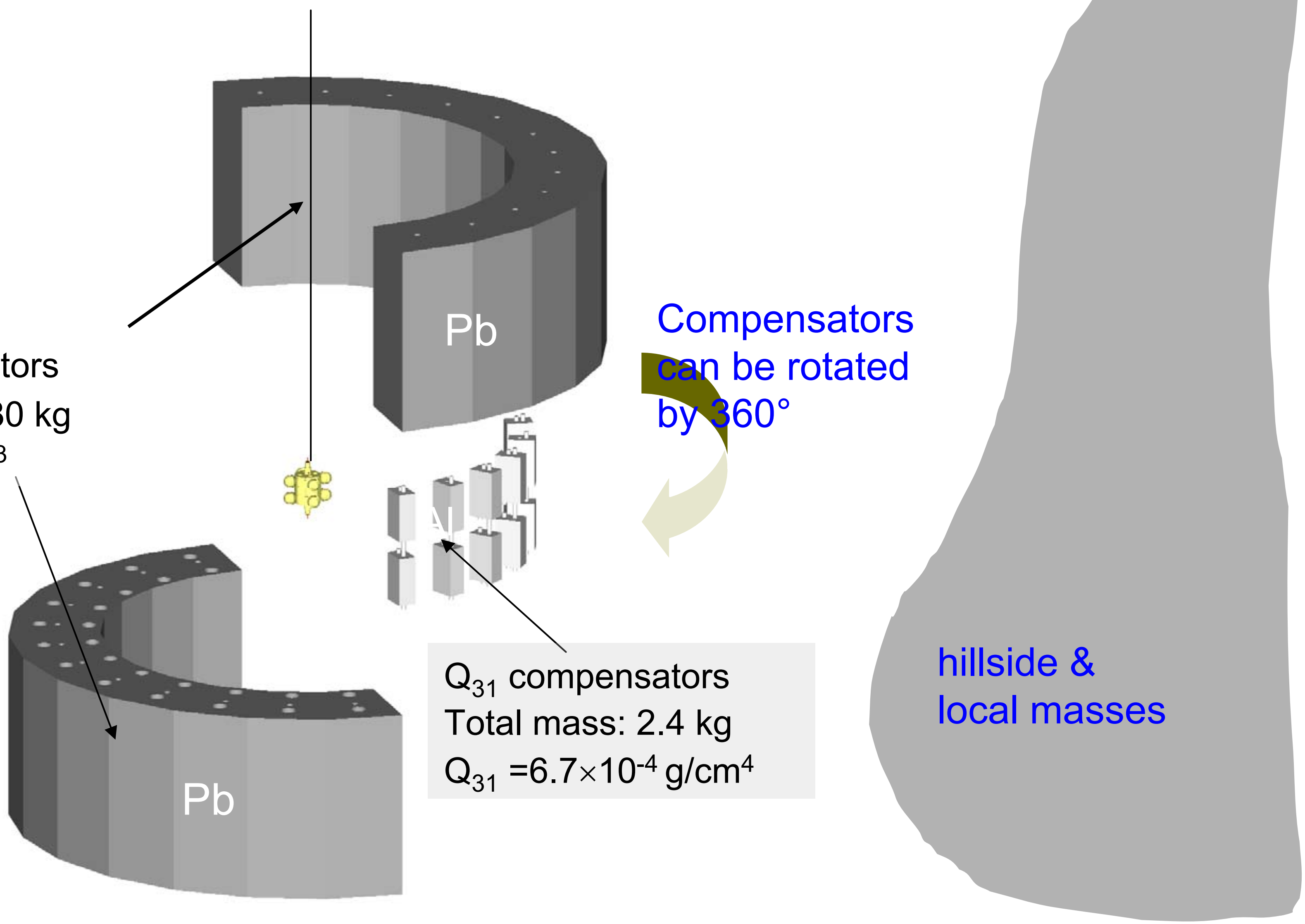
eight 4.84 g test masses (4 Be & 4 Ti) or (4 Be & 4 Al)

4 mirrors

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

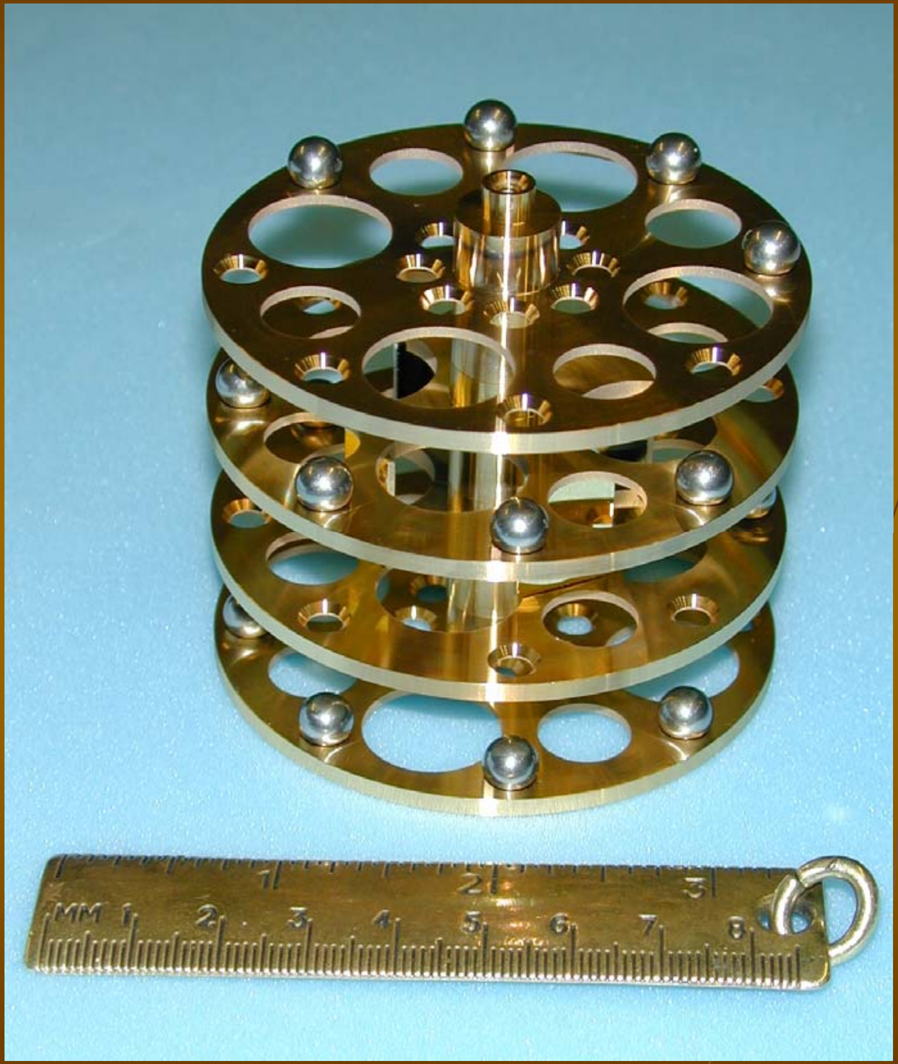
gravity-gradient compensation

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

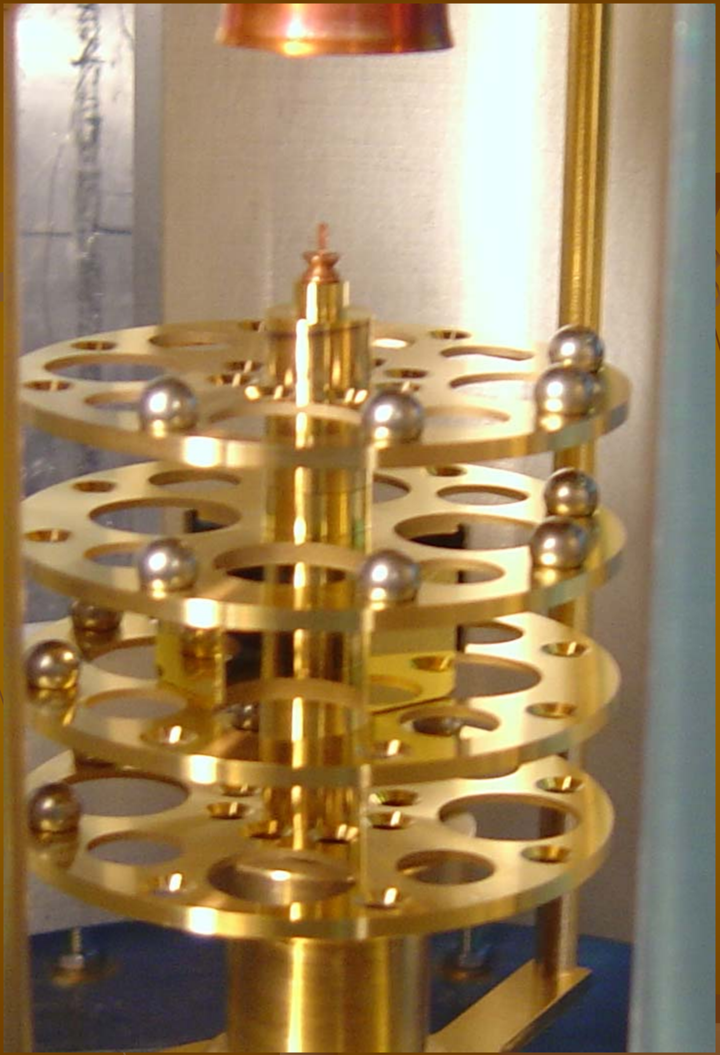


Q_{31} compensators
Total mass: 2.4 kg
Q_{31} =6.7×10^{-4} g/cm^4

gravity-gradiometer pendulums



q_{41} configuration on a table



q_{21} configuration installed

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

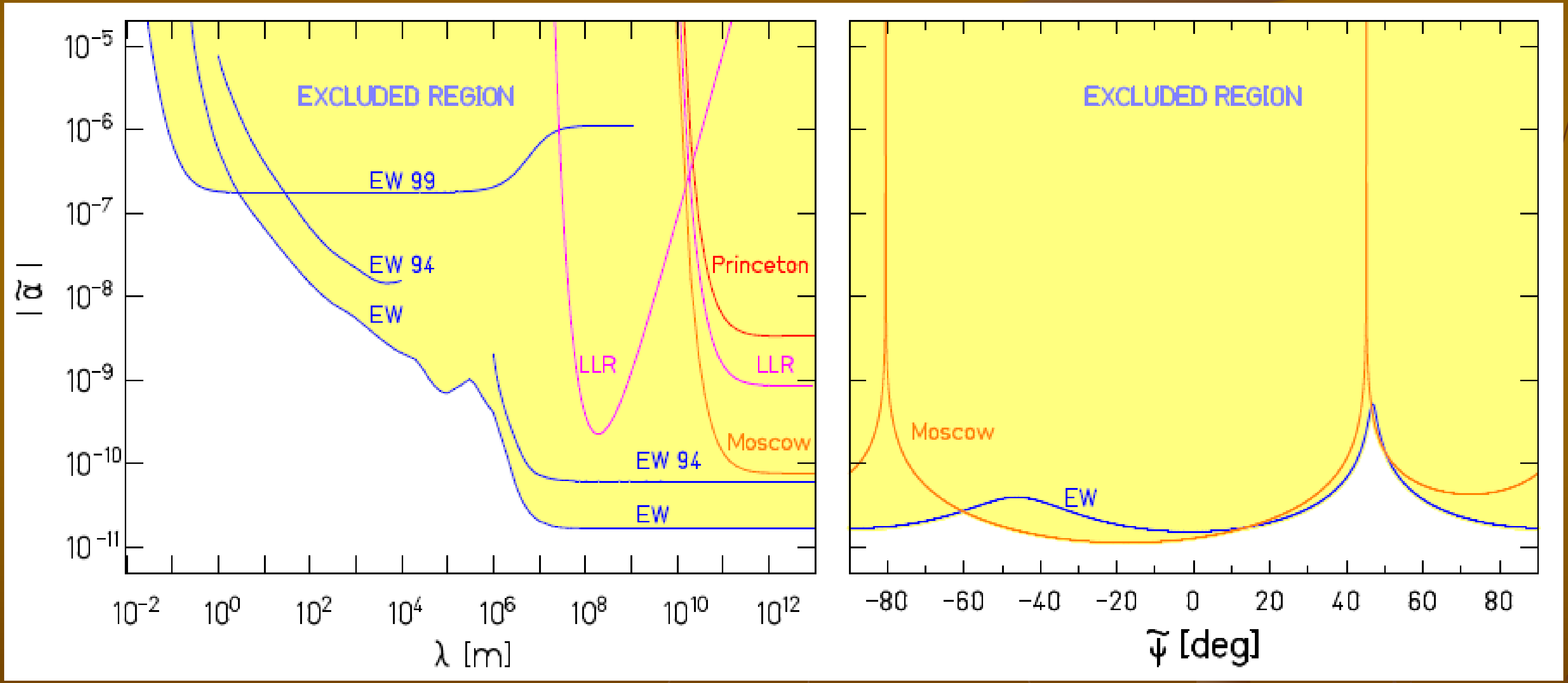
Source	Δa (cm/s^2)	$\Delta a/a_{source}$
Earth	$(-1.2 \pm 2.2) \times 10^{-13}$	$(-0.7 \pm 1.3) \times 10^{-13}$
Sun	$(-3.1 \pm 2.4)\times10^{-13}$	$(-5.2 \pm 4.0)\times10^{-13}$
Milky Way	$(-1.2 \pm 2.6)\times10^{-13}$	$(-6.5 \pm 8.6)\times10^{-6}$
CMB	$(-3.0 \pm 2.4)\times10^{-13}$	$(-3.4 \pm 2.7)\times10^{-4}$

PhD project of Todd Wagner

95% CL constraints on coupling to vector charges

assumes charge =B-L

shows how constraint depends on assumed charge



Note that gap for ranges between 10^4 m and 10^6 m has been filled in by improved geophysical models

T. A Wagner el al., CQG in press

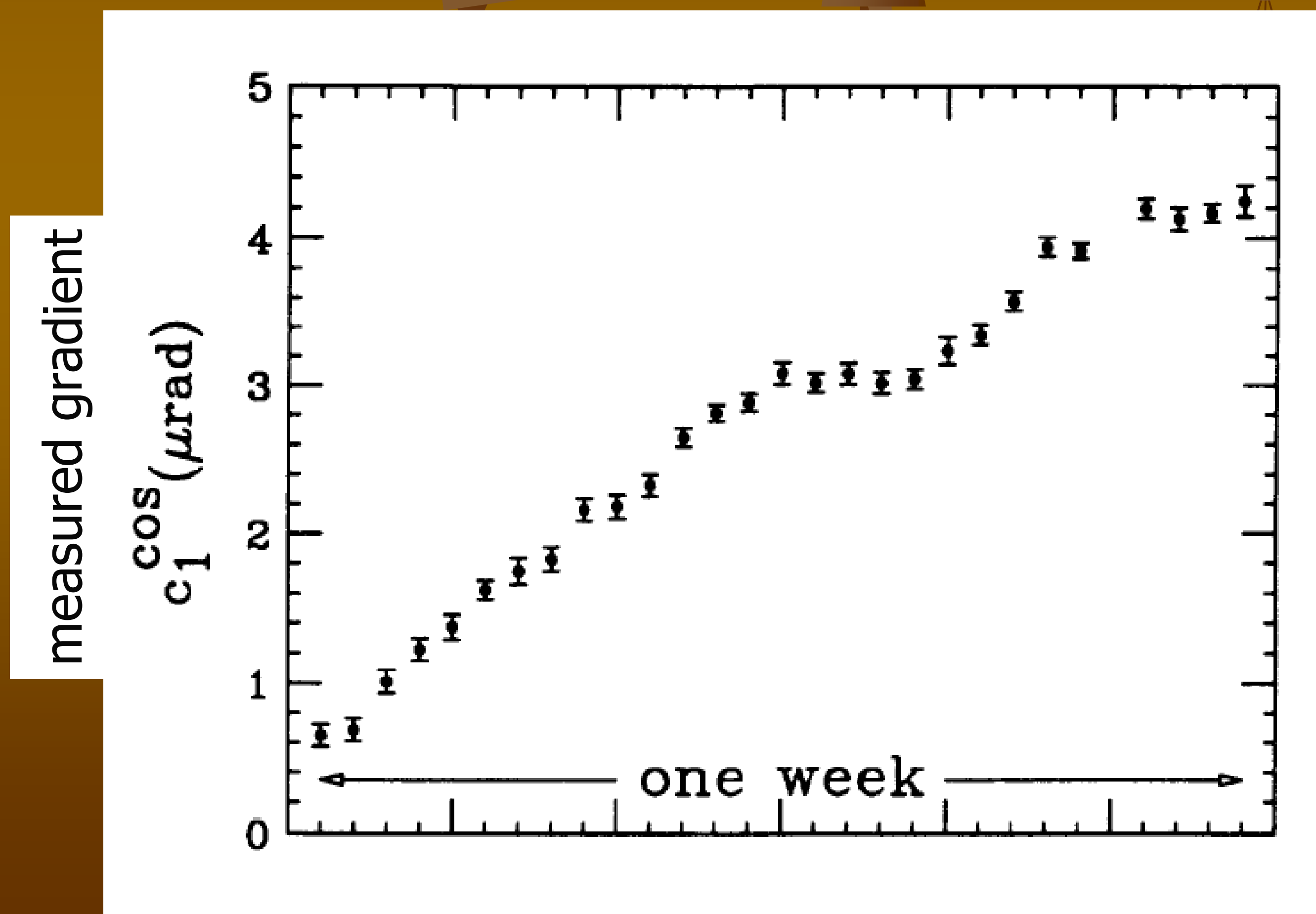
Limiting factors in our WEP tests:

thermal noise in suspension fiber

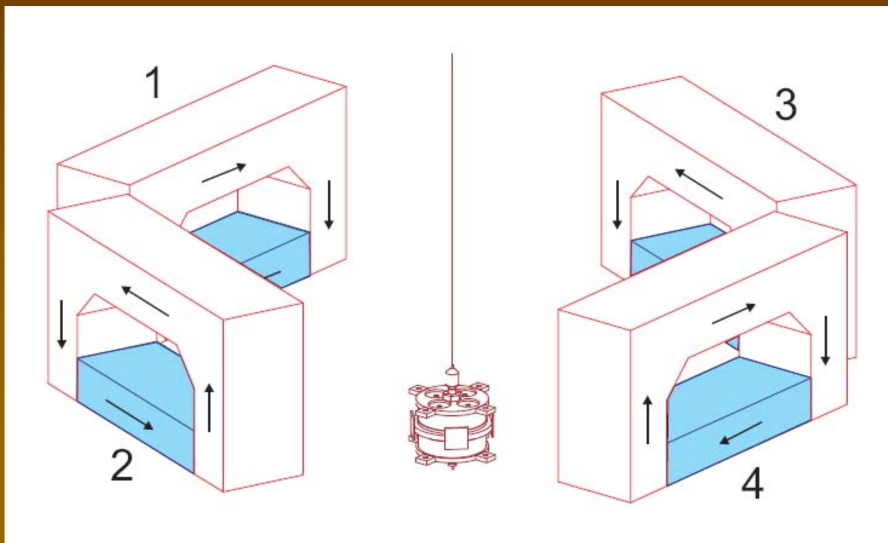
replace W fibers with fused silica

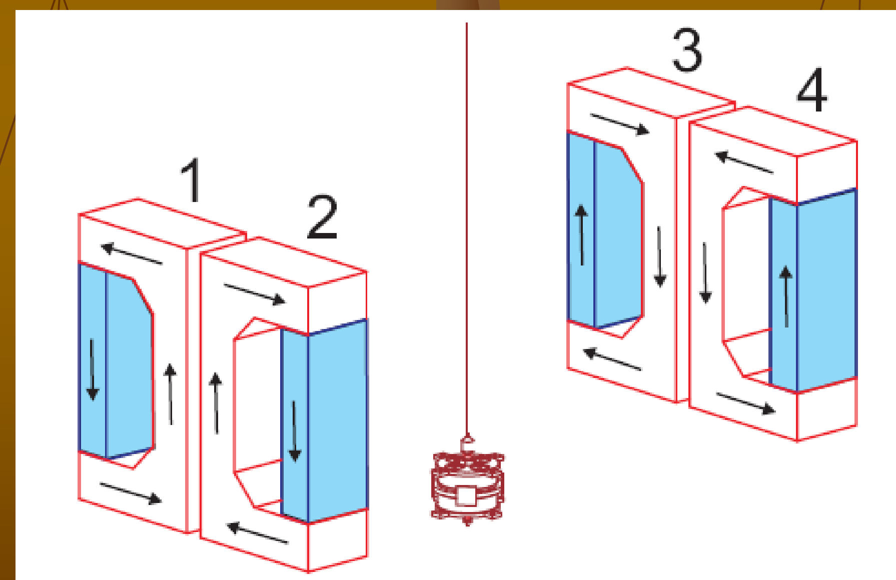
time-varying gravity gradients

measure gradients continuously



The Eöt-Wash spin-spin experiments





BR Heckel, EGA and WA Terrano,
to be published

$$V_1 = \frac{g_A^2}{4\pi r}(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2) e^{-r/\lambda} \quad \text{and}$$

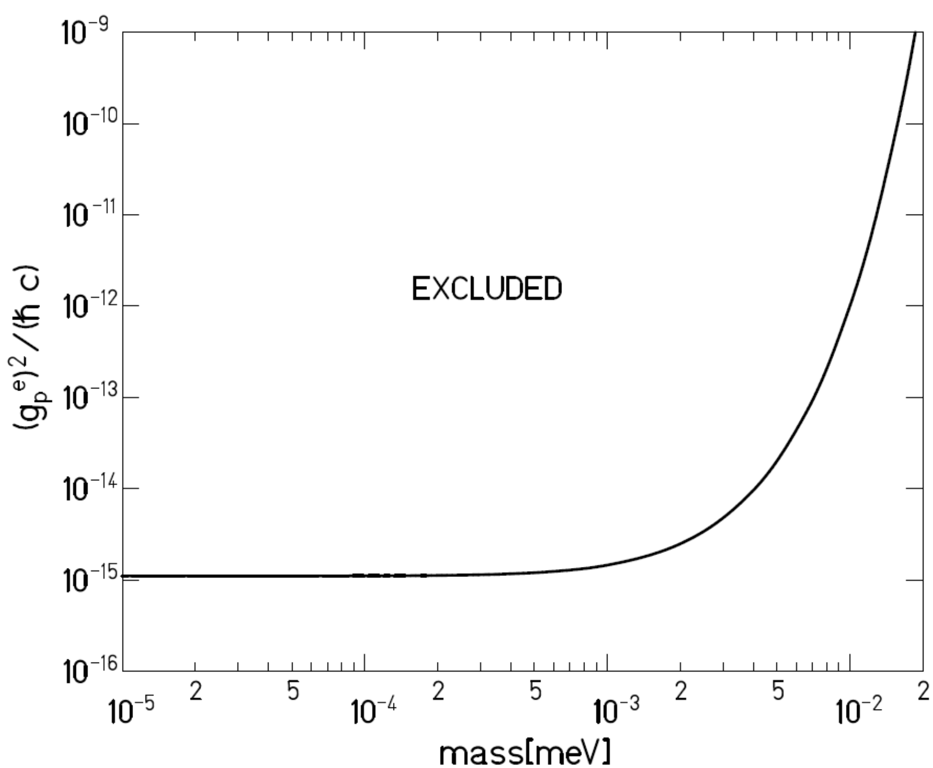
$$V_2 = -\frac{g_A g_V \hbar}{4\pi m_e c r^2}(\hat{\boldsymbol{\sigma}}_1 \times \hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}}) \left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda}$$

$$V_3 = -\frac{g_P^2 \hbar^2}{16\pi m_e c^2 r^3} \left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2) \left(1 + \frac{r}{\lambda}\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}}) \left(3 + \frac{3r}{\lambda} + \frac{r^2}{\lambda^2}\right) \right] e^{-r/\lambda} \;;$$

obtain high sensitivity for V1, V2 and V3 using horiz and vert source configs

preliminary 2σ constraint on V3

5 orders of magnitude weaker than Raffelt astrophysical bound



The big question:

Is it worth pursuing 2nd generation monopole-dipole experiments?

recent review articles:

Torsion balance experiments: a low-energy frontier of particle physics
EGA et al, PPNP 62, 102 (2009)

Torsion-balance tests of the Weak Equiv. Principle
T. A. Wagner et al, CQG (in press)