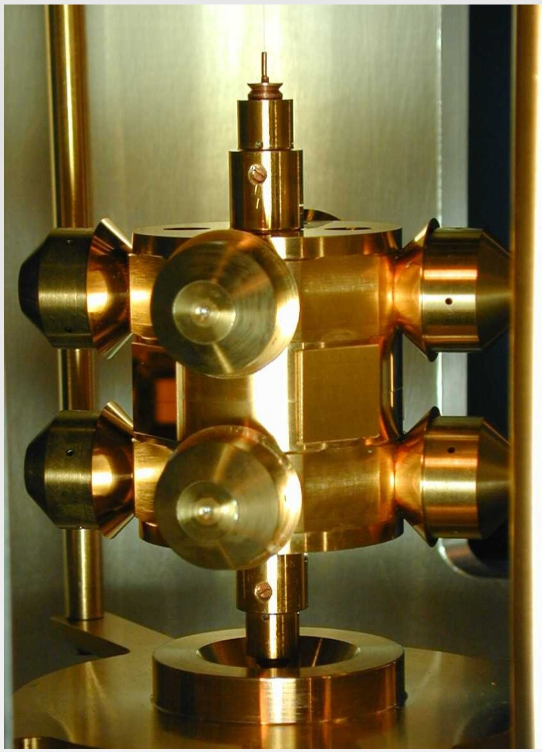
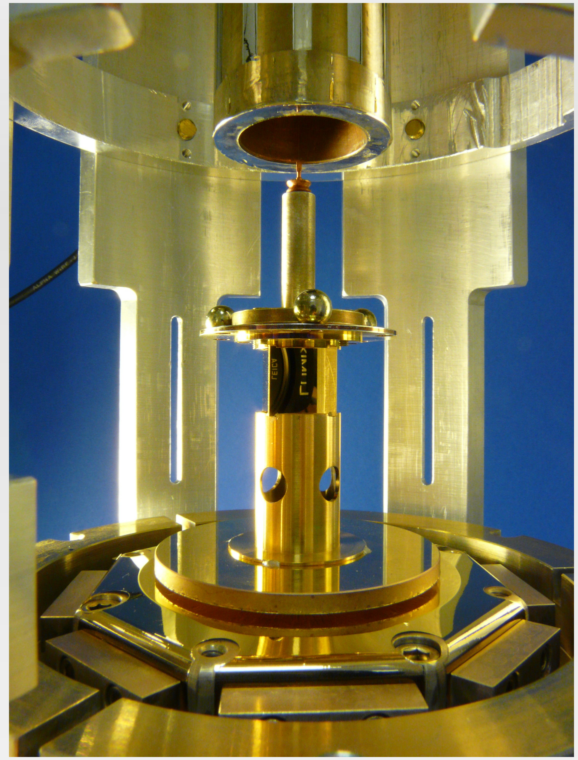
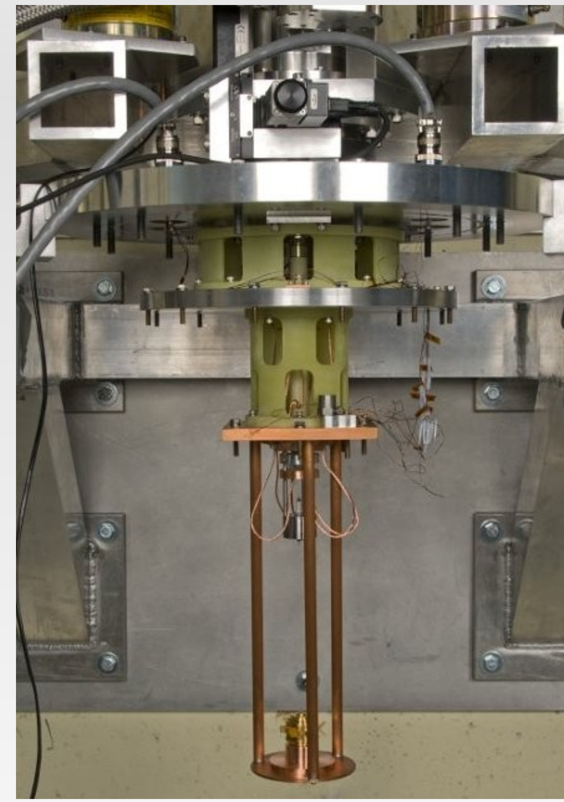
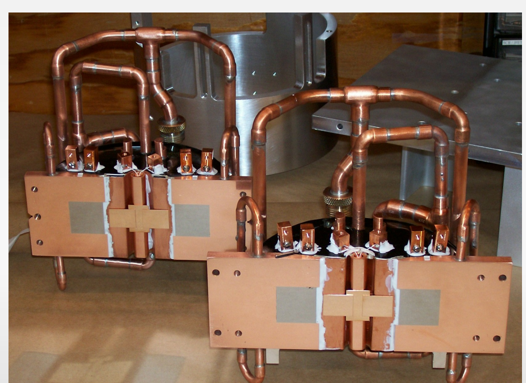
Searching for new Interactions and Particles Using Torsion Balances









18 May 2012

Frank Fleischer,
University of Washington

Physics with torsion balances

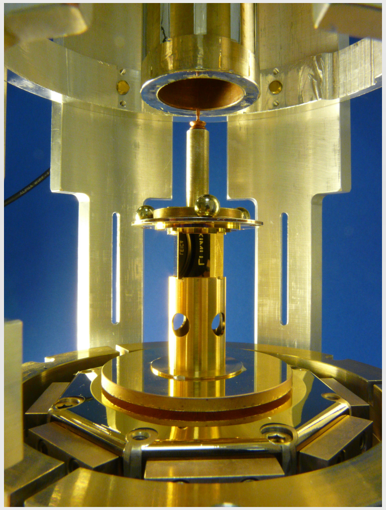
•Torsion balances can test regions of parameter space totally inaccessible to high energy physics experiments.

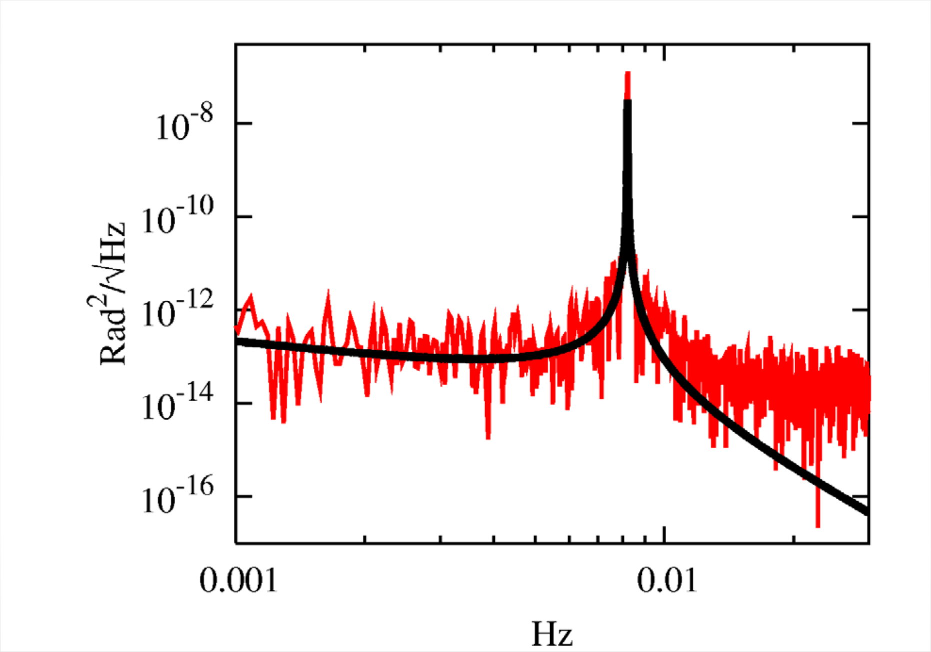
I will talk about:

- Tests of the equivalence principle
- Tests of the inverse-square law
- Searching for macroscopic parity and time-reversal violating forces

Torsion balances

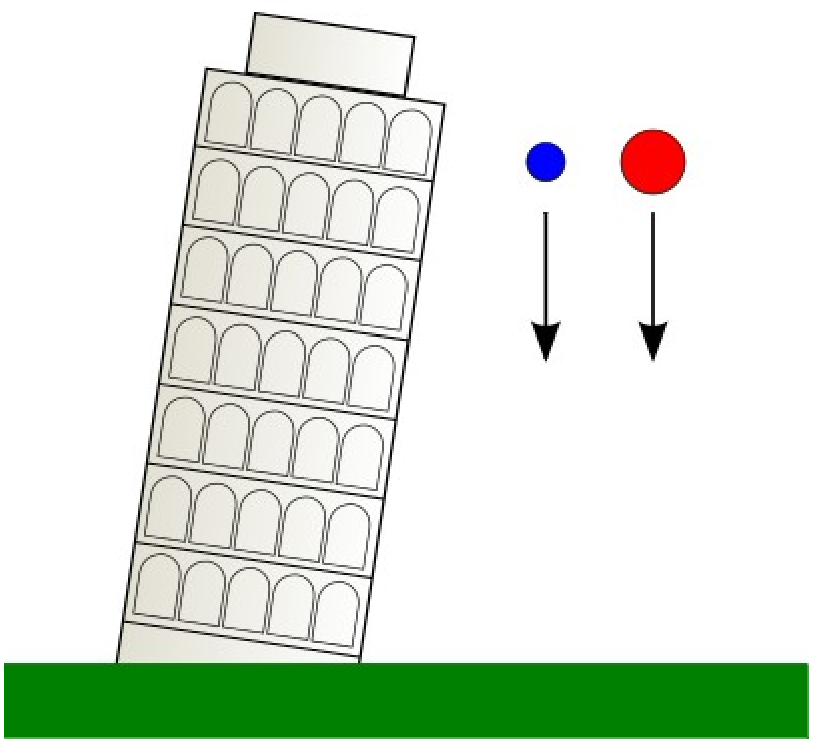
Our torsion balances can measure a force equivalent to the weight of a trillionth of a postage stamp!





- Enormous sensitivity due to having ~10^{23} particles interacting.
- Despite being macroscopic pendula, in many cases we can run them at the thermal noise limit.
- Can detect extremely small torques: ~fNm!
- Very low energy physics, giving great complementary information to high energy results.

The equivalence principle (EP)

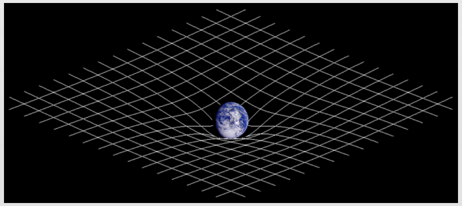


$$m_g = m_i$$

- Fundamental assumption of general relativity
- *locally* a homogenous gravitational field looks the same as a uniform acceleration of the frame
- usually tested via the universality of free fall (UFF)

EP tests as searches for new interactions

- Test the foundation of general relativity

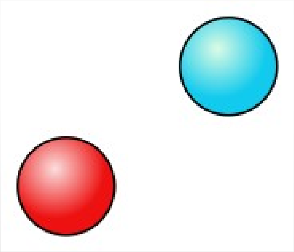


- Or assume the EP is exact for classical gravity:

→ use EP tests as extremely sensitive probes for new scalar or vector interactions!

- Many ideas for physics beyond the standard model introduce such interactions.

→ Torsion balance experiments provide stringent limits on such models!



New forces?

- New vector or scalar forces will show up as an equivalence principle violation.
- parameterization:

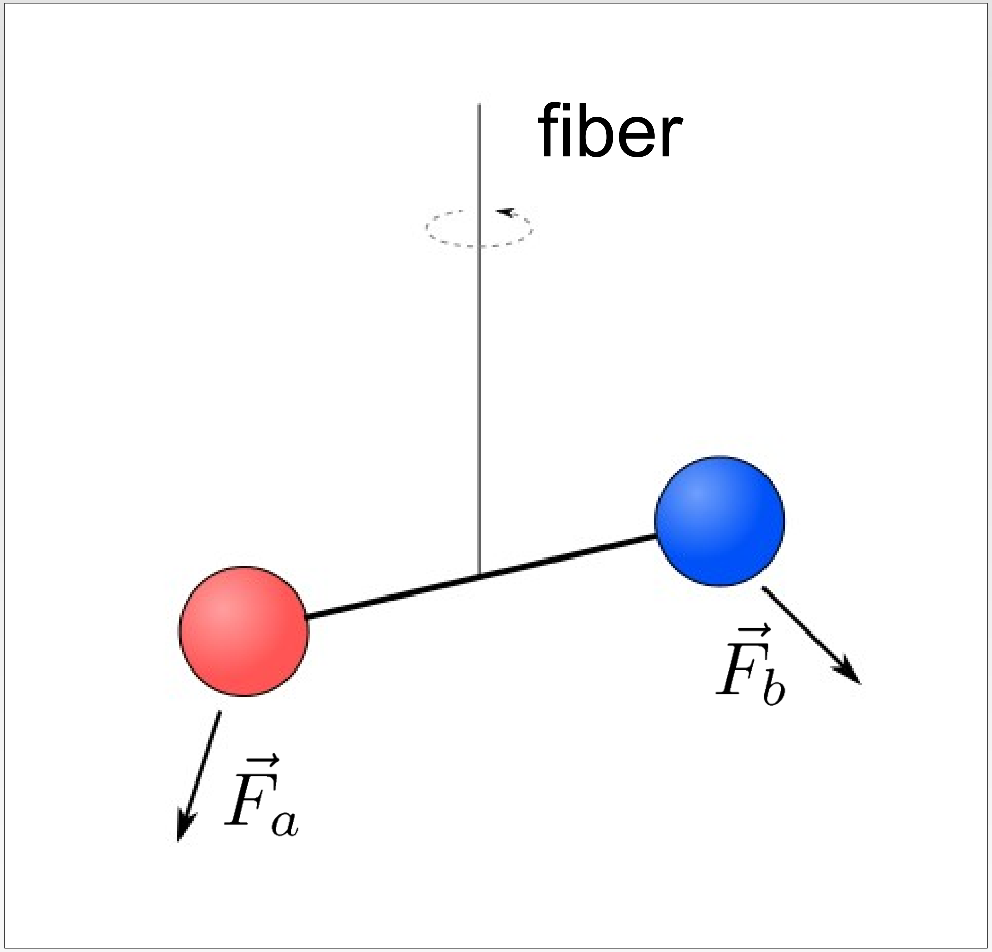
$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \tilde{\alpha}\left[\frac{\tilde{q}}{\tilde{g}\mu}\right]_1\left[\frac{\tilde{q}}{\tilde{g}\mu}\right]_2 e^{-r/\lambda}\right)$$

with a hypothetical ”charge”

$$\tilde{q} = \tilde{g}(Z\cos\tilde{\psi} + N\sin\tilde{\psi})$$

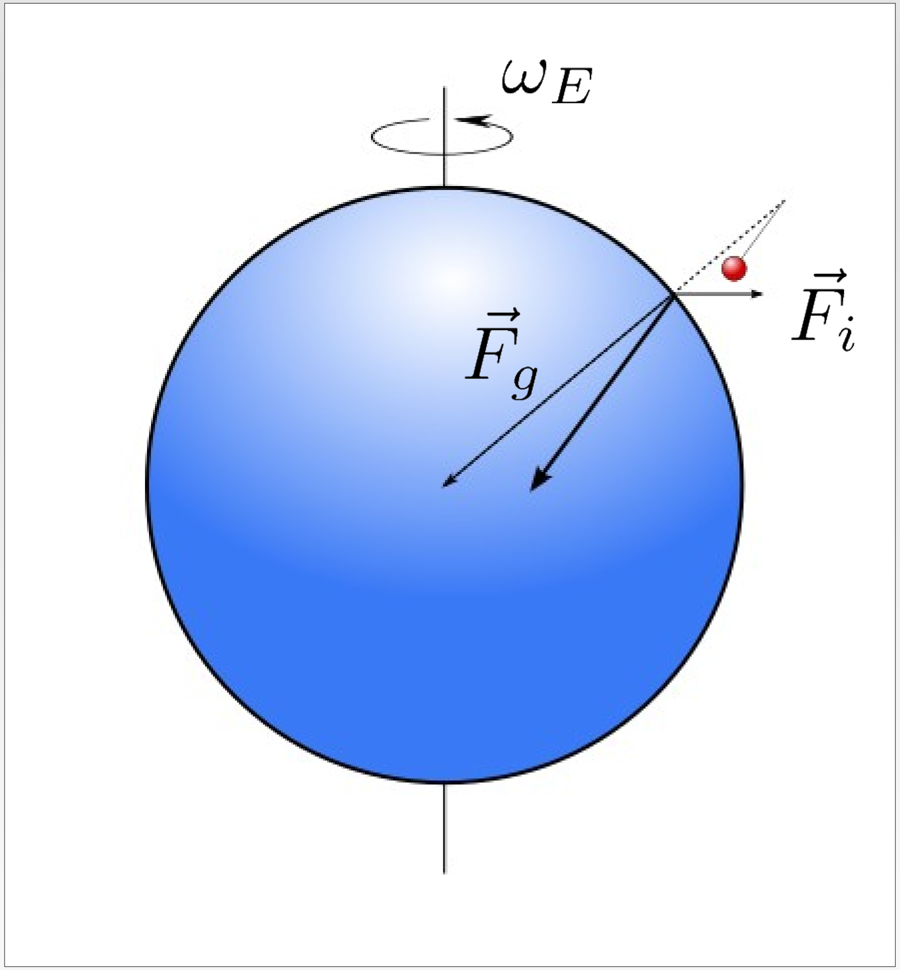
- This parameterization is exact for vector charges, scalar charges are more complicated – but we can expect this to work approximately even then.

EP test torsion balances



- Simplified model of a pendulum for EP tests
  - Balance twists if the two force vectors are not parallel, i.e. if EP is violated or gravitational field is not uniform.
- Modulation: rotate balance or use the earth's rotation.

Using the earth as a source mass



Can only use the horizontal component.

- If the EP is violated, ”down” is not a unique direction!

→ depends on the ratio of gravitational and inertial mass!

Choice of test body materials

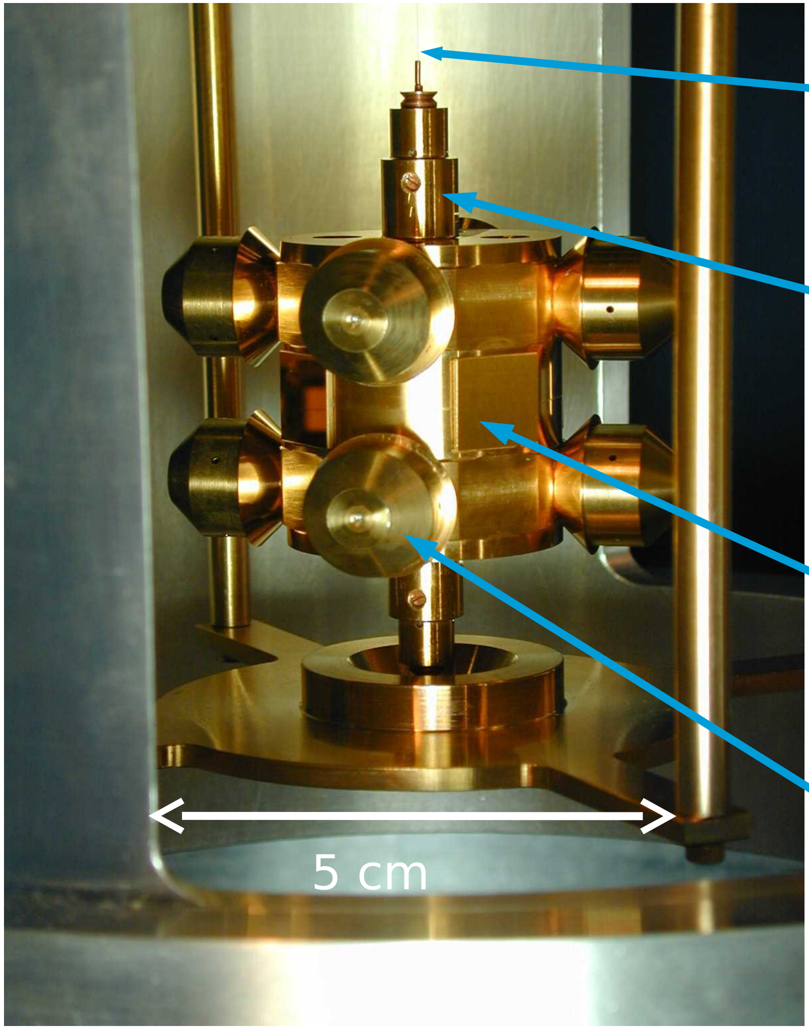
- Practical constraints: solid, non-magnetic
- For complete coverage of the parameter space, more than one test-body pair / attractor combination is necessary.
- Generally, large differences in number of neutrons and nuclear binding energy give greater sensitivity.

$x10^{-2}$	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	

Orange: $\Delta(Z/\mu)$

Blue: $\Delta(N/\mu)$

The EP test pendulum



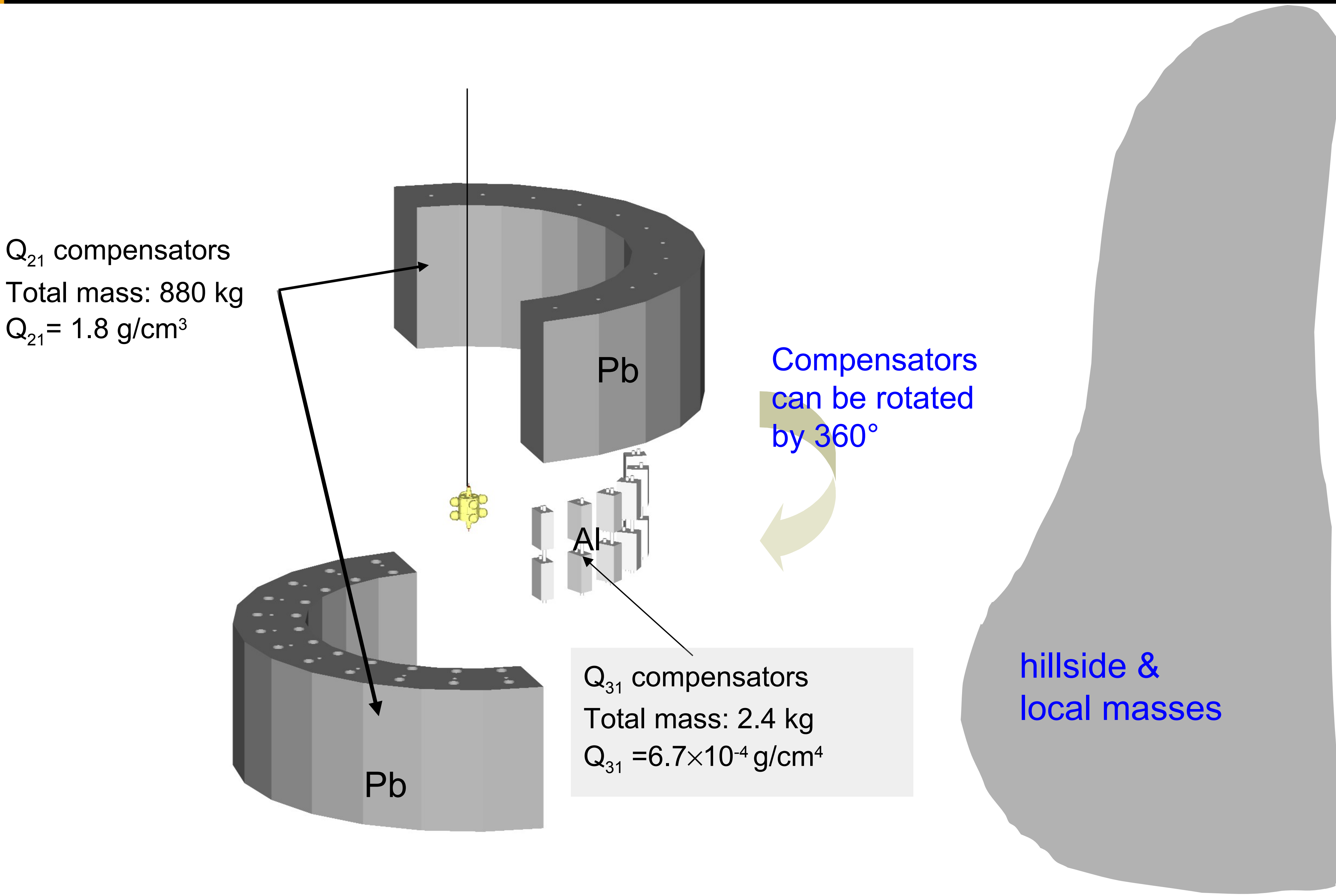
70g pendulum,
suspended by a 20μm thick,
1.08 m long tungsten fiber

Screws to reduce residual coupling to gravitational gradients

Design minimizes coupling to gravitational gradients:
4-fold azimuthal symmetry and top-bottom reflection symmetry

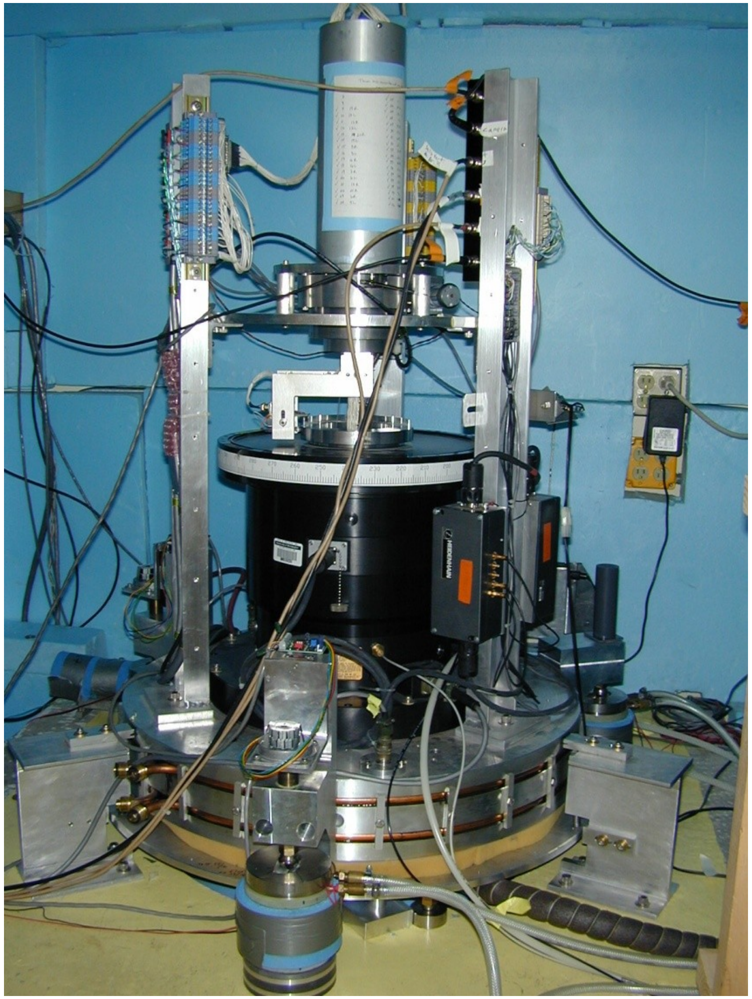
Eight test bodies
(4 Be & 4 Ti) or (4 Be & 4 Al)
4.84g each

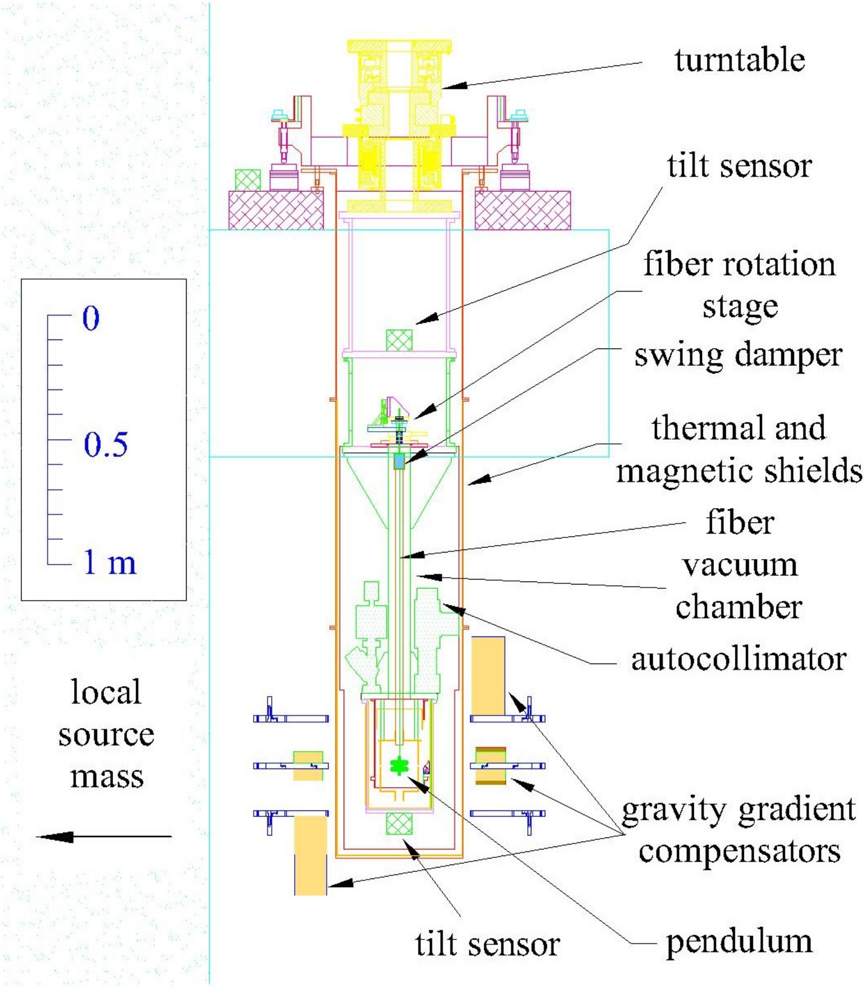
Gravity gradients



The turn table

High precision turn table for continuous smooth rotation.



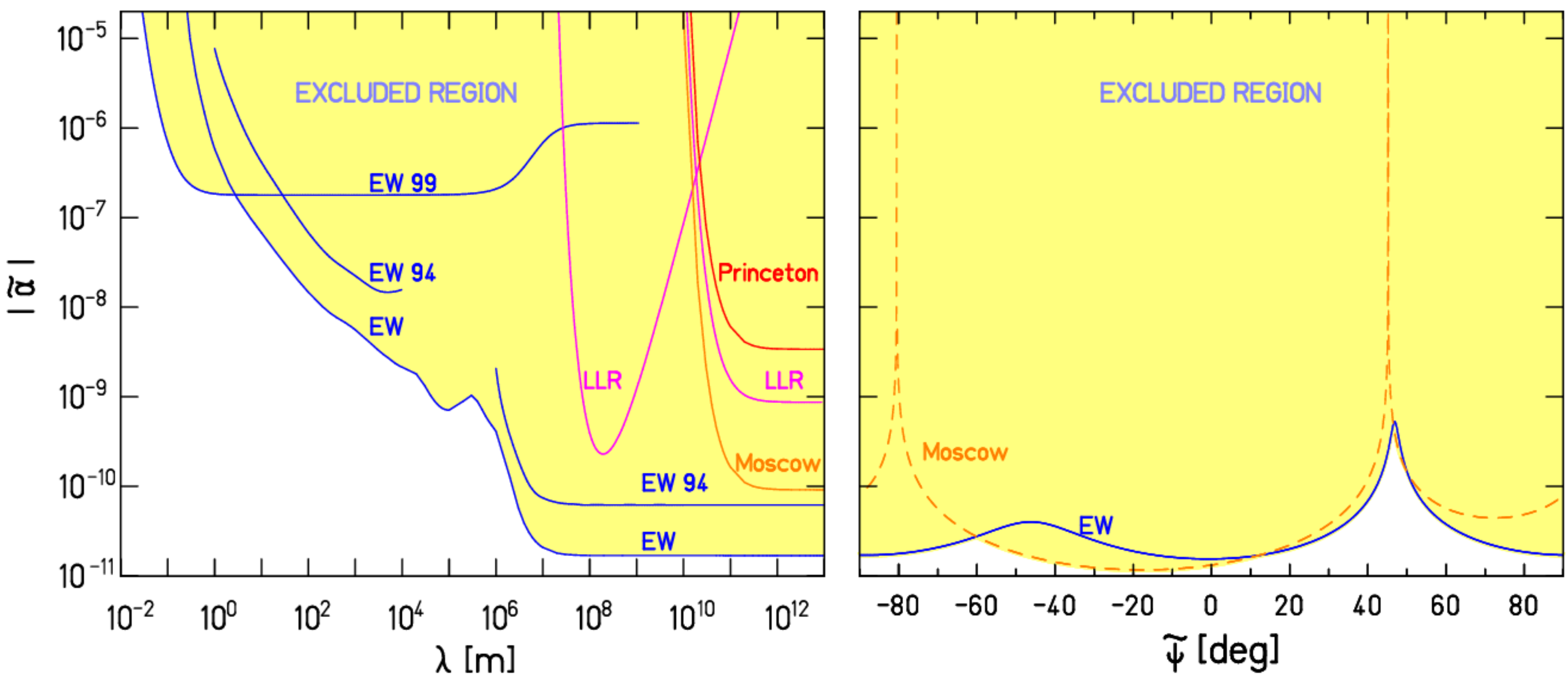


Current results

Eotvös parameter $\eta = \frac{\Delta a_\perp}{g_\perp}$

$$\eta(\mathrm{Be,Ti}) = (0.3 \pm 1.8) \cdot 10^{-13}$$
$$\eta(\mathrm{Be,Al}) = (-0.7 \pm 1.3) \cdot 10^{-13}$$

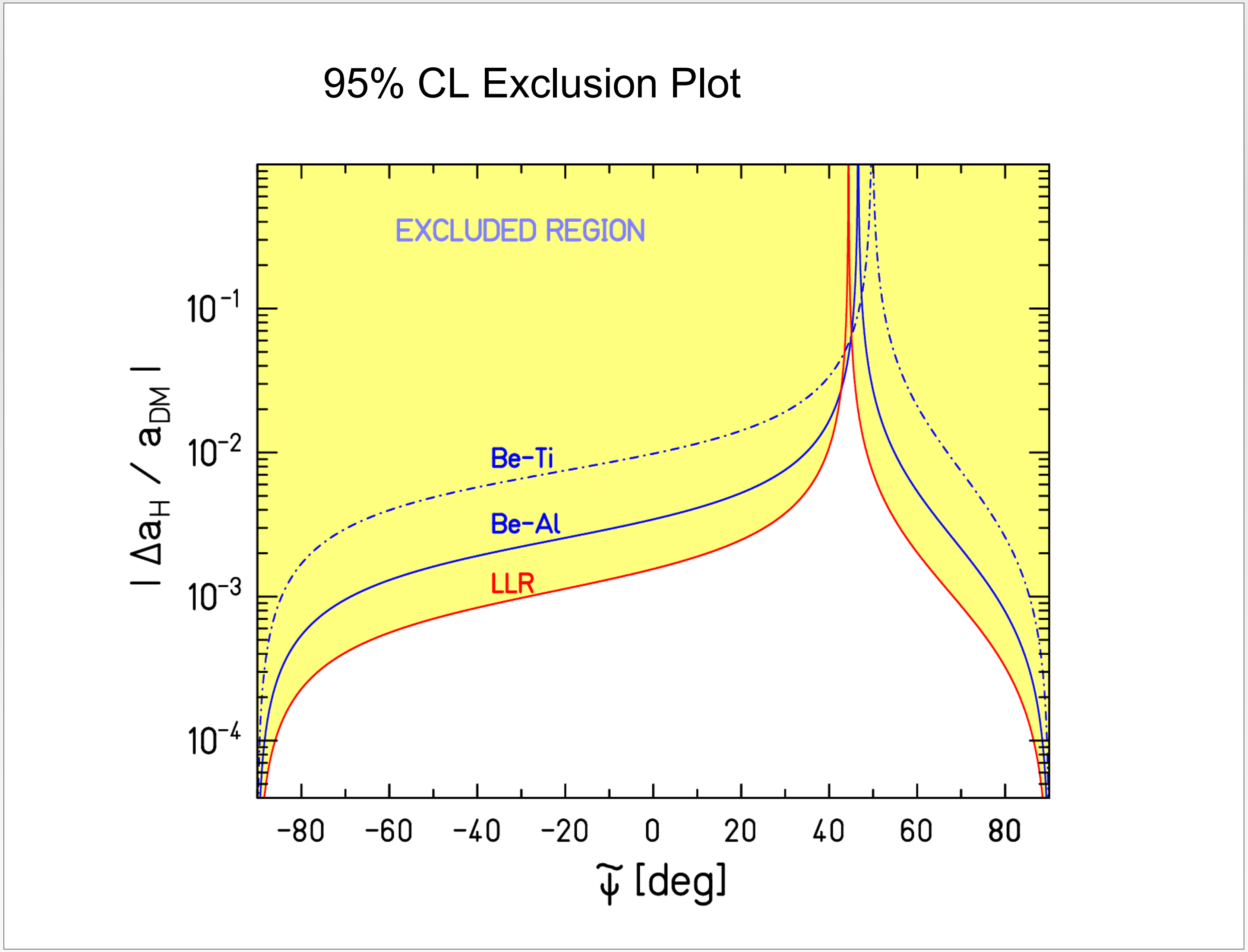
95% CL Exclusion Plots



Is gravity the only force acting between matter and dark matter?

We don't know what dark matter is, and so far the only evidence is gravitational.

Although a large fraction of the total dark matter in our galaxy is located farther out than our solar system, we can set limits on any non-gravitational force between matter and dark matter.



At most 6% of the acceleration could be non-gravitational!

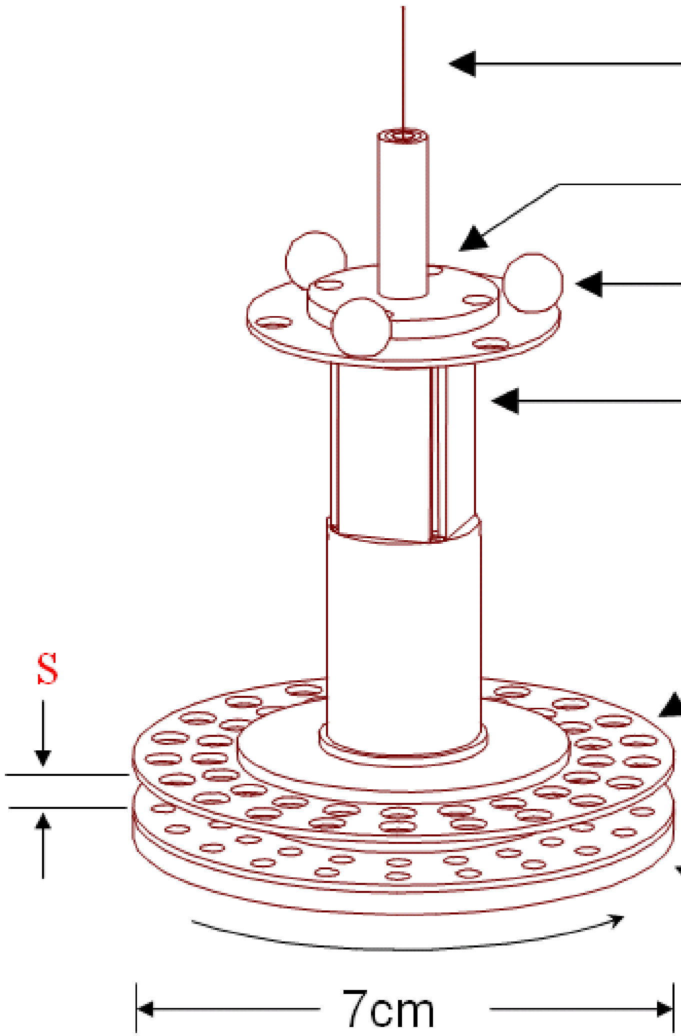
Next generation EP tests

- Basically two ways forward to push the limits of torsion balance experiments for EP tests:
    - Increase the signal by using more sensitive test body material pairs, for example Be - PE
    - Reduce the noise floor: quartz fibers, cryogenic torsion balance
- Significant (order of magnitude) improvements over our current limits are possible.

Testing the inverse-square law

- We seem to be missing something big in terms of understanding gravity!
- Hierarchy problem
- Dark energy
- Extra dimensions?
- Fat graviton hypothesis
- Dilaton
- Chameleons
- ...

The 42-hole pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

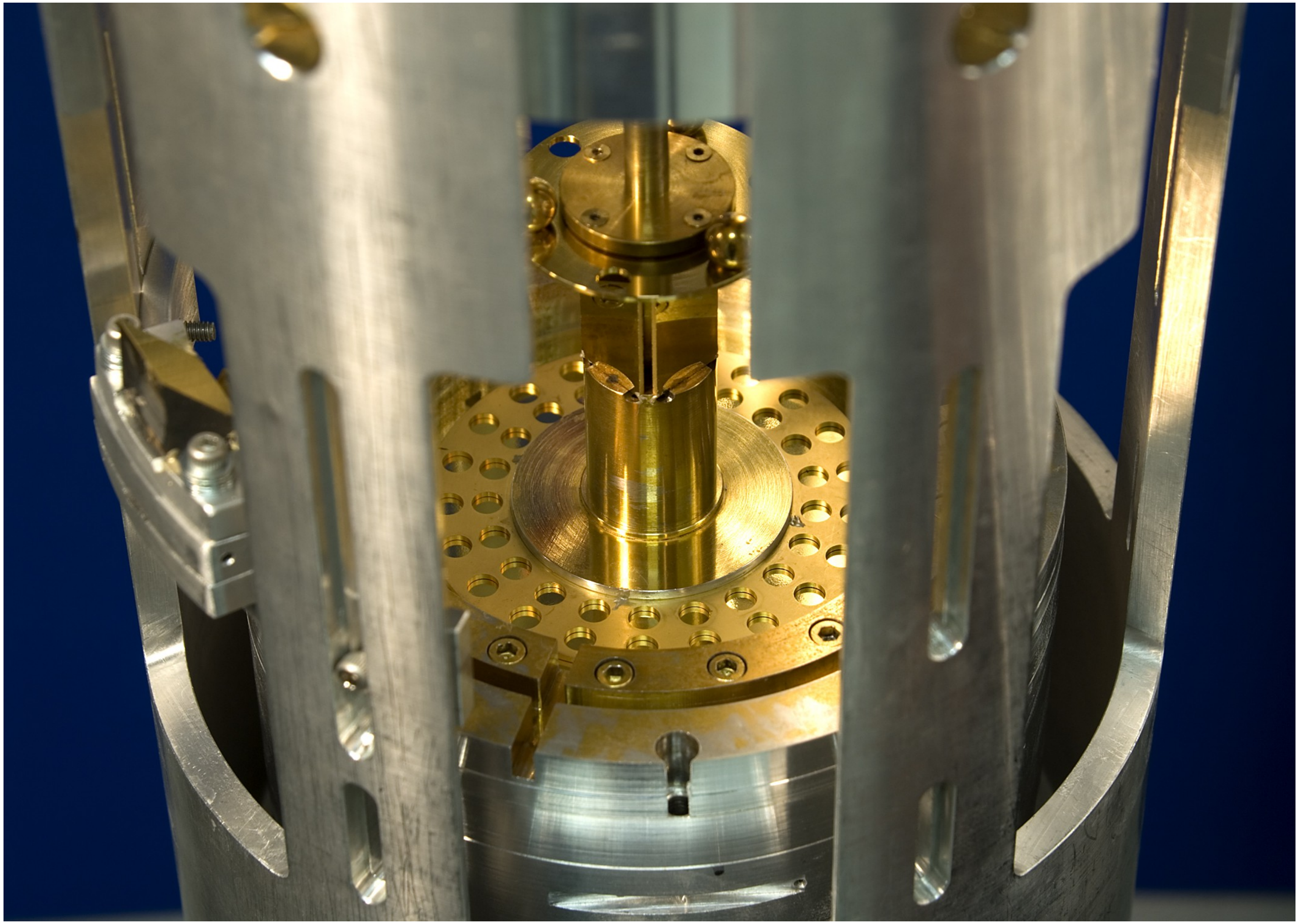
4 mirrors for tracking angle of deflection

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

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

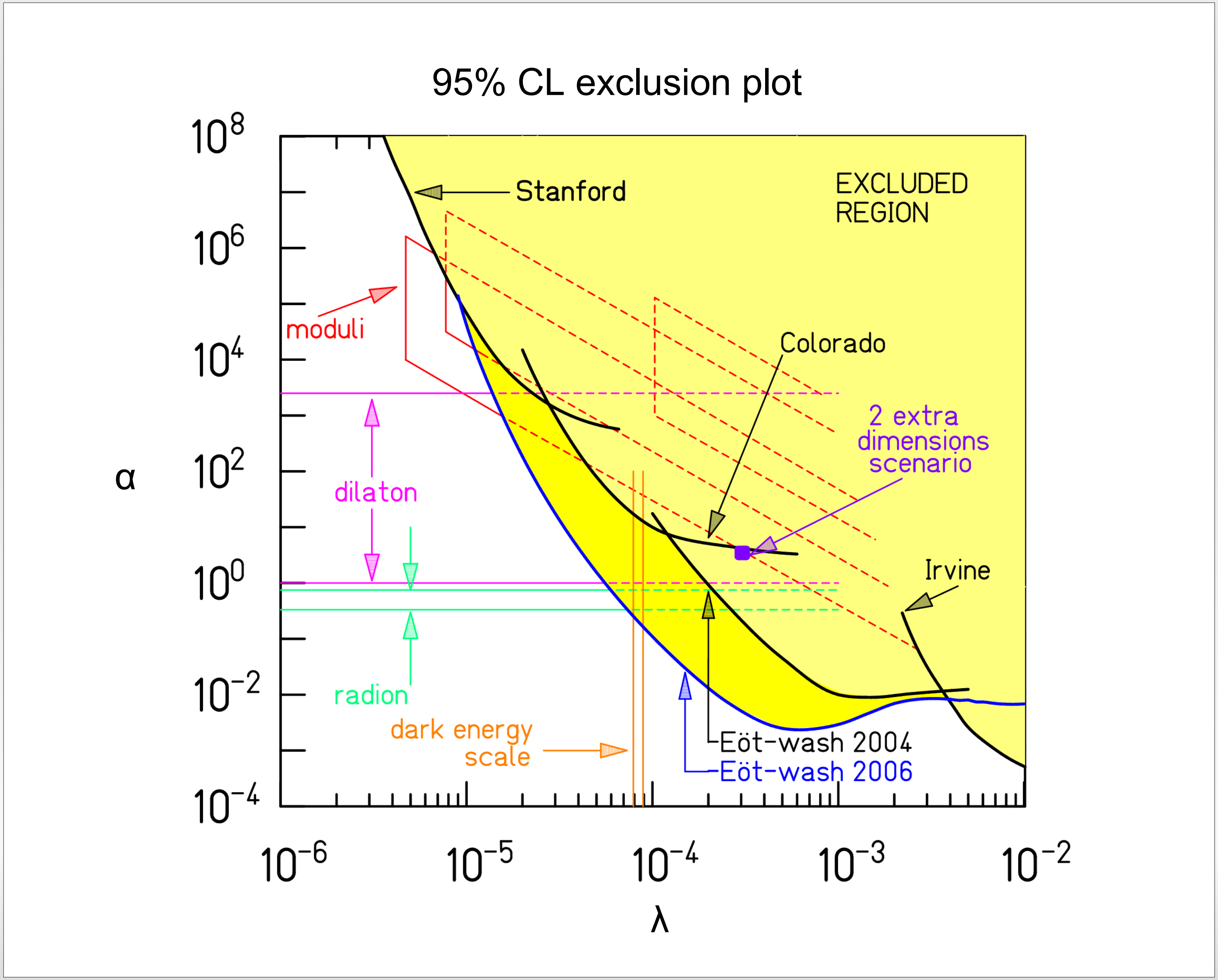
attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

The 42-hole pendulum

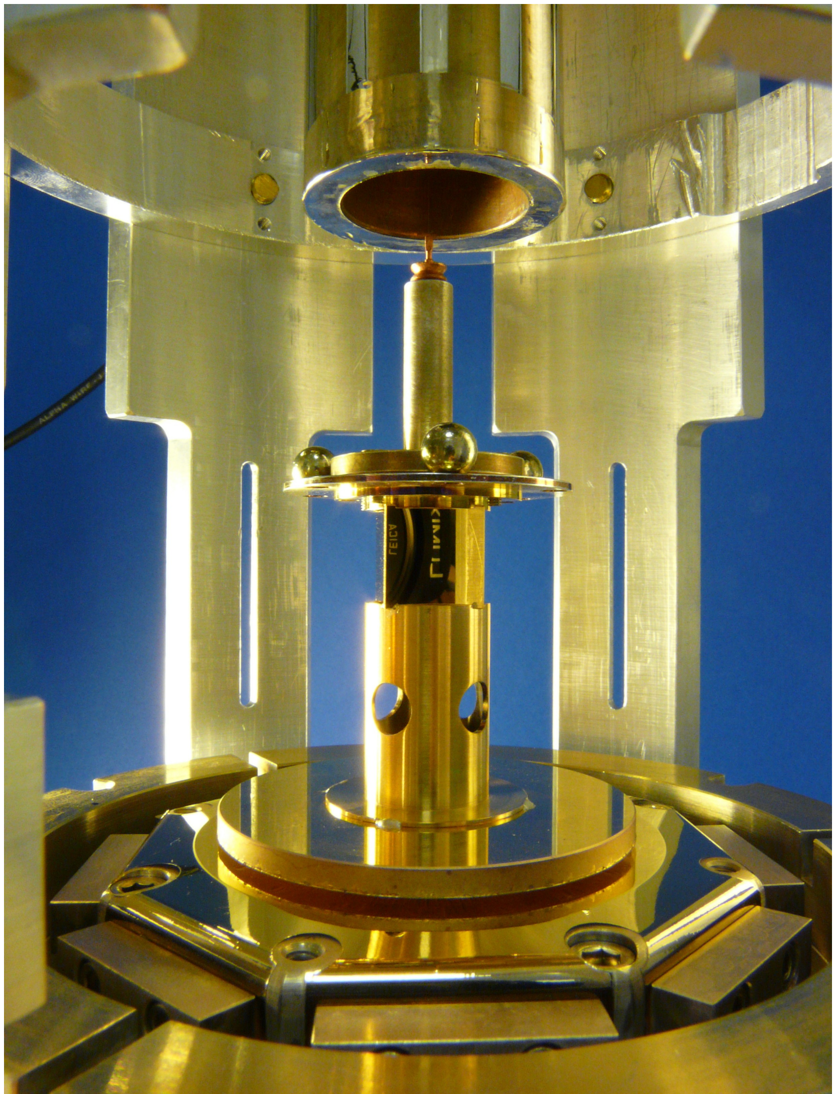


Mary Levin photo

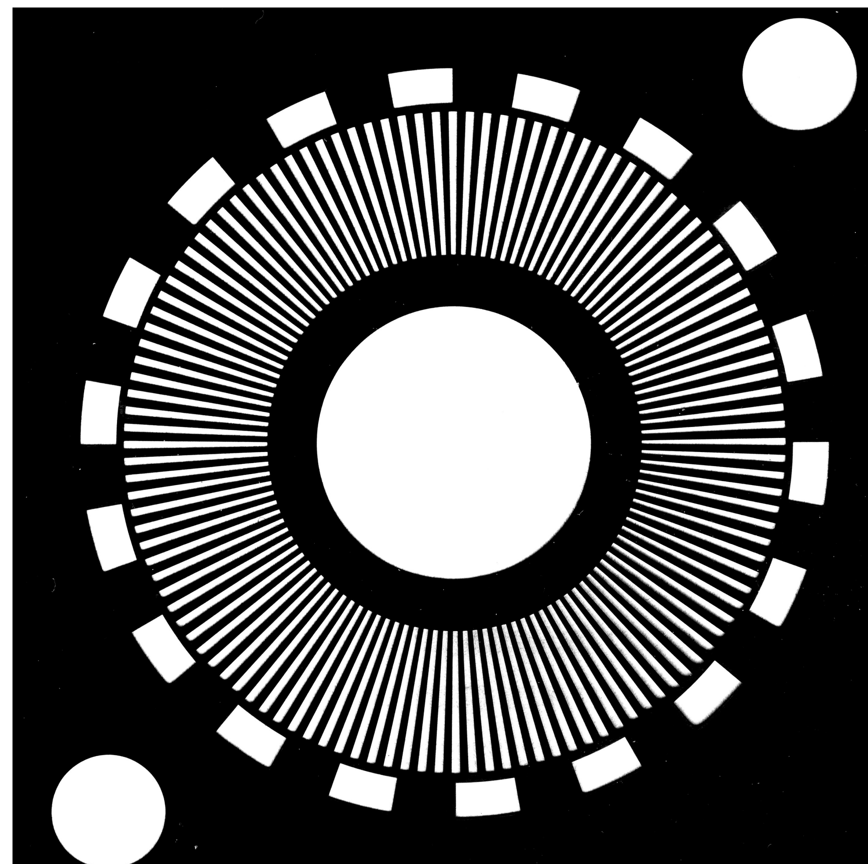
Results


95% CL exclusion plot
α
λ
10^8
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-5
10^-4
10^-3
10^-2
Stanford
EXCLUDED REGION
moduli
Colorado
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
Eöt-wash 2004
Eöt-wash 2006

Upgrade: Fourier-Bessel pendulum



pendulum & attractor are 50μm thick tungsten foils glued to glass plates



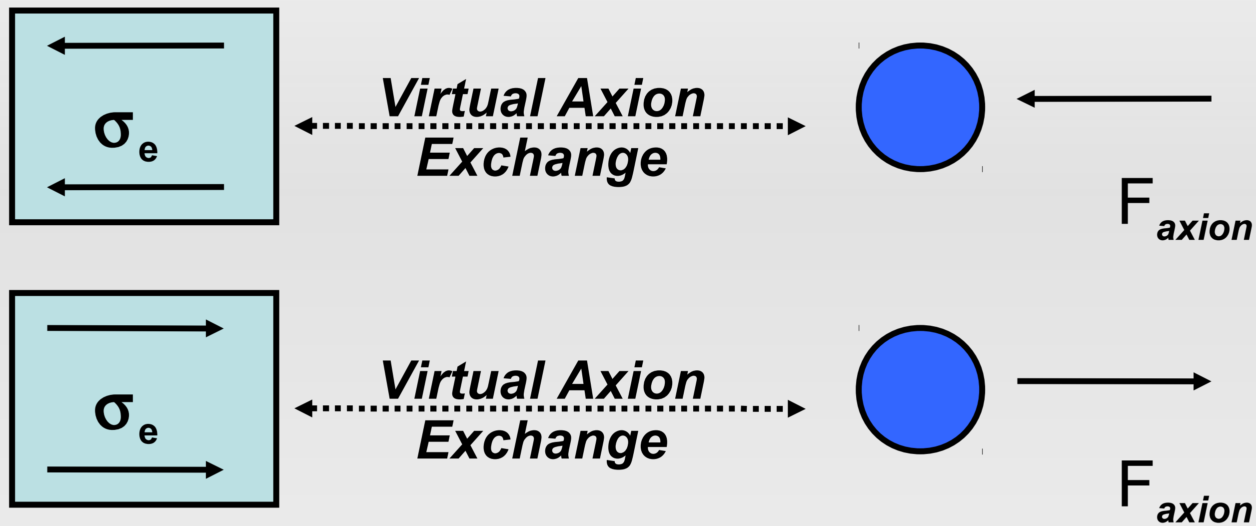
PhD project of Ted Cook

A macroscopic parity and time-reversal violating force?

Virtual axions mediate a ***macroscopic*** P,T violating force between polarized electrons and unpolarized nucleons

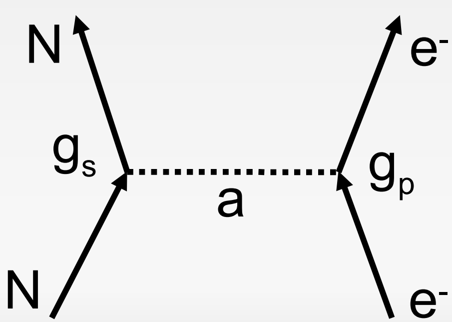
Moody and Wilczek

PRD **30** 130 (1984)



Polarized Matter (Magnetized Iron)

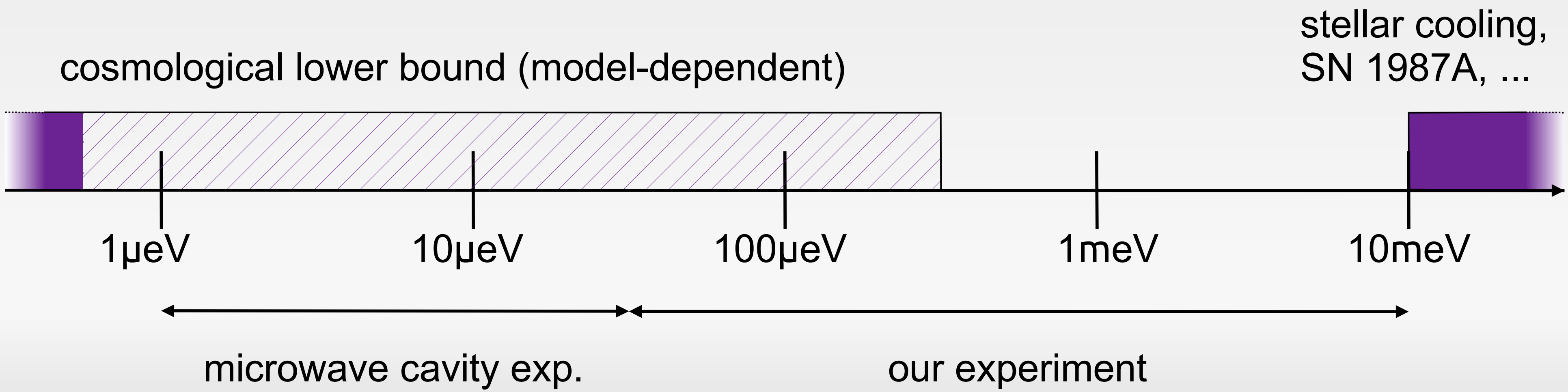
Unpolarized Matter



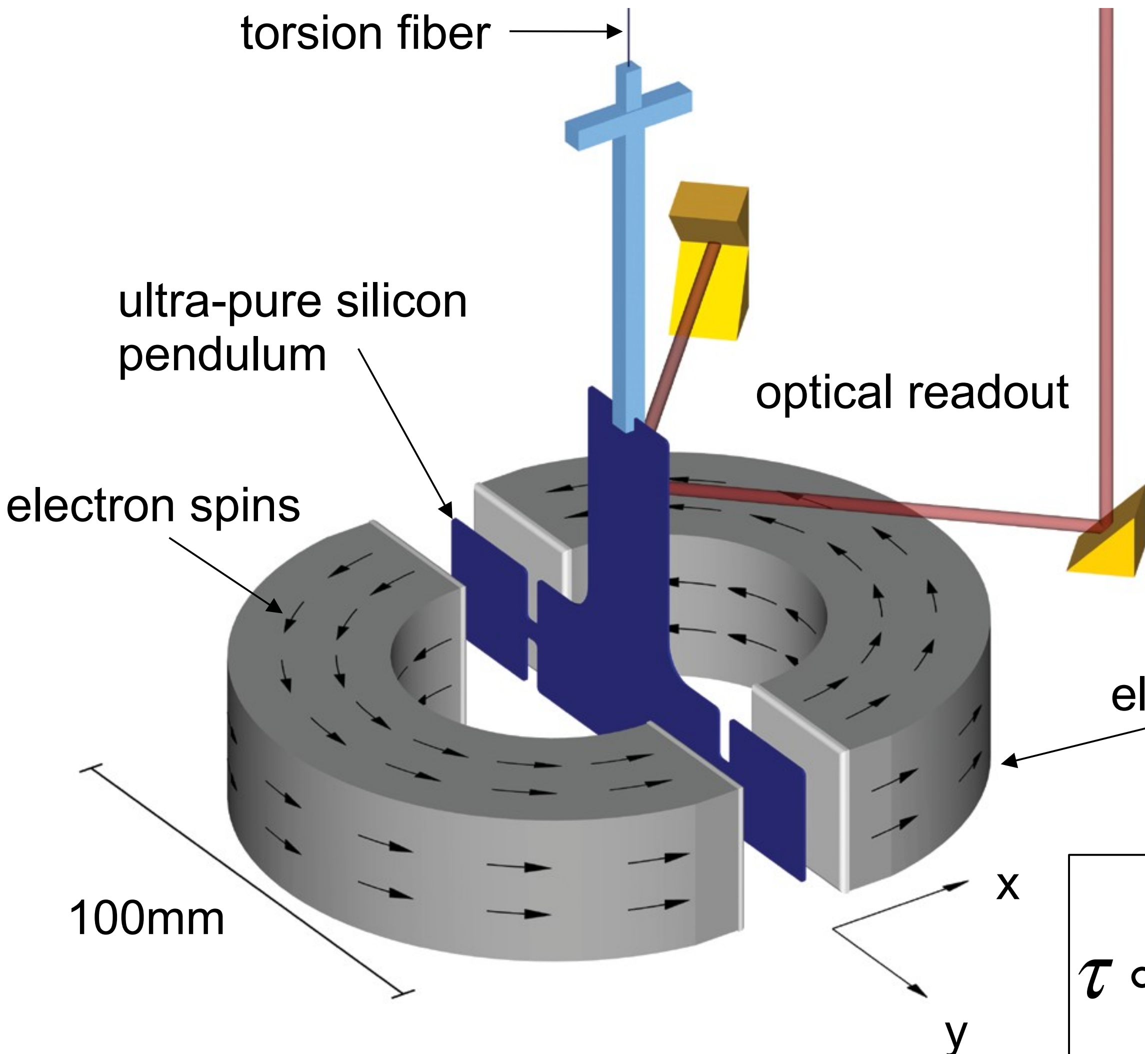
$$V(r) = (30\,\mathrm{MeV})\overbrace{\frac{\bar{\theta}}{f_a}\frac{m_e}{f_a}}^{g_s g_p}\frac{\hat{\sigma}\cdot\hat{r}}{8\pi m_e}\left(\frac{1}{\lambda_a r}+\frac{1}{r^2}\right)e^{-r/\lambda_a}$$

The „axion window“

- upper limits on axion mass:
  - stellar lifetimes
  - SN 1987A
- lower limit:
  - too many axions produced in the early universe if mass is small – depends on cosmological models



The axion torsion balance

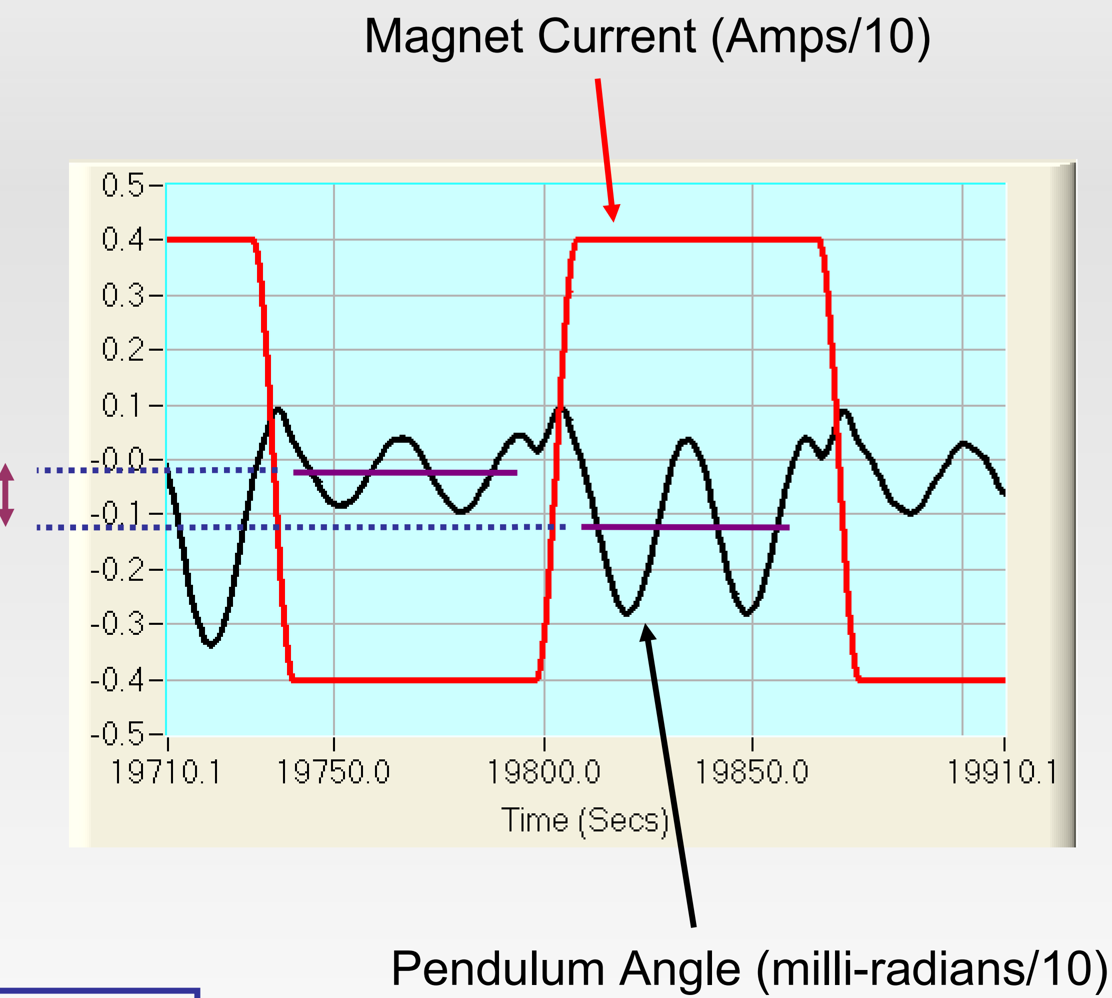


Axion-like particles will create a torque on the pendulum, depending on spin orientation and distance to the magnet's pole faces.

Torque acting on the pendulum:

$$\tau \propto g_s g_p \lambda_a e^{-g/\lambda_a}(1-e^{-t/\lambda_a})$$

Measurement strategy

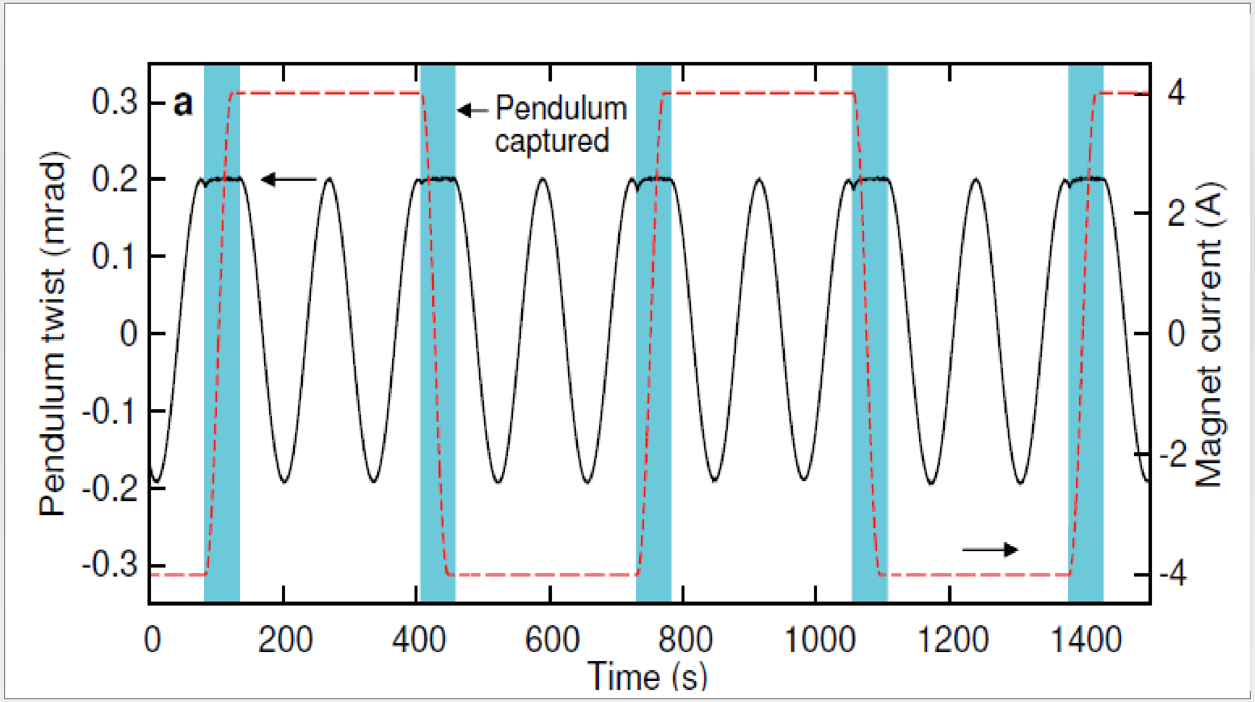


Signal is offset difference between positive and negative magnet states

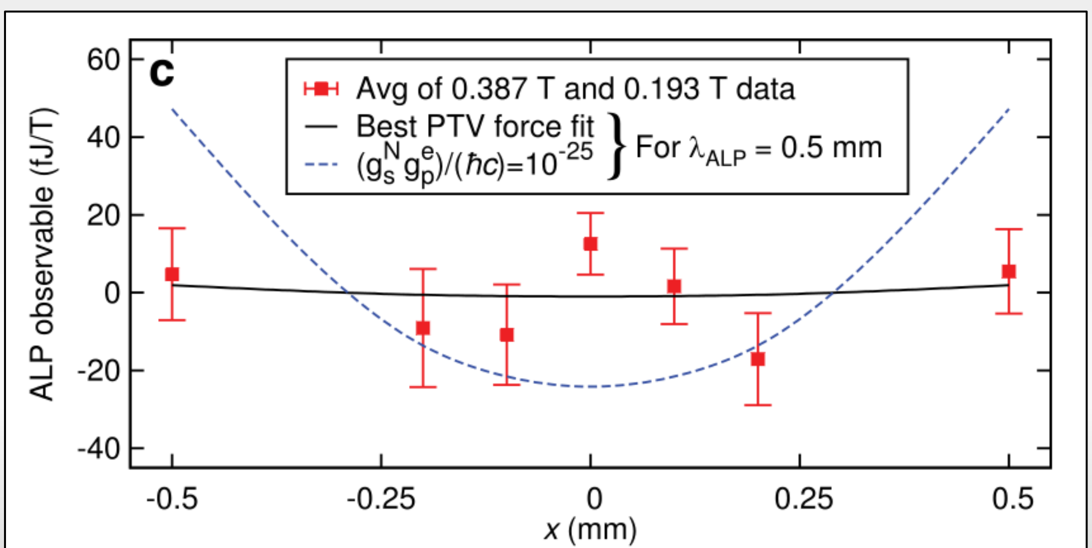
(here strongly exaggerated)

For each magnet state, we fit for the frequency, offset and phase.

Real data

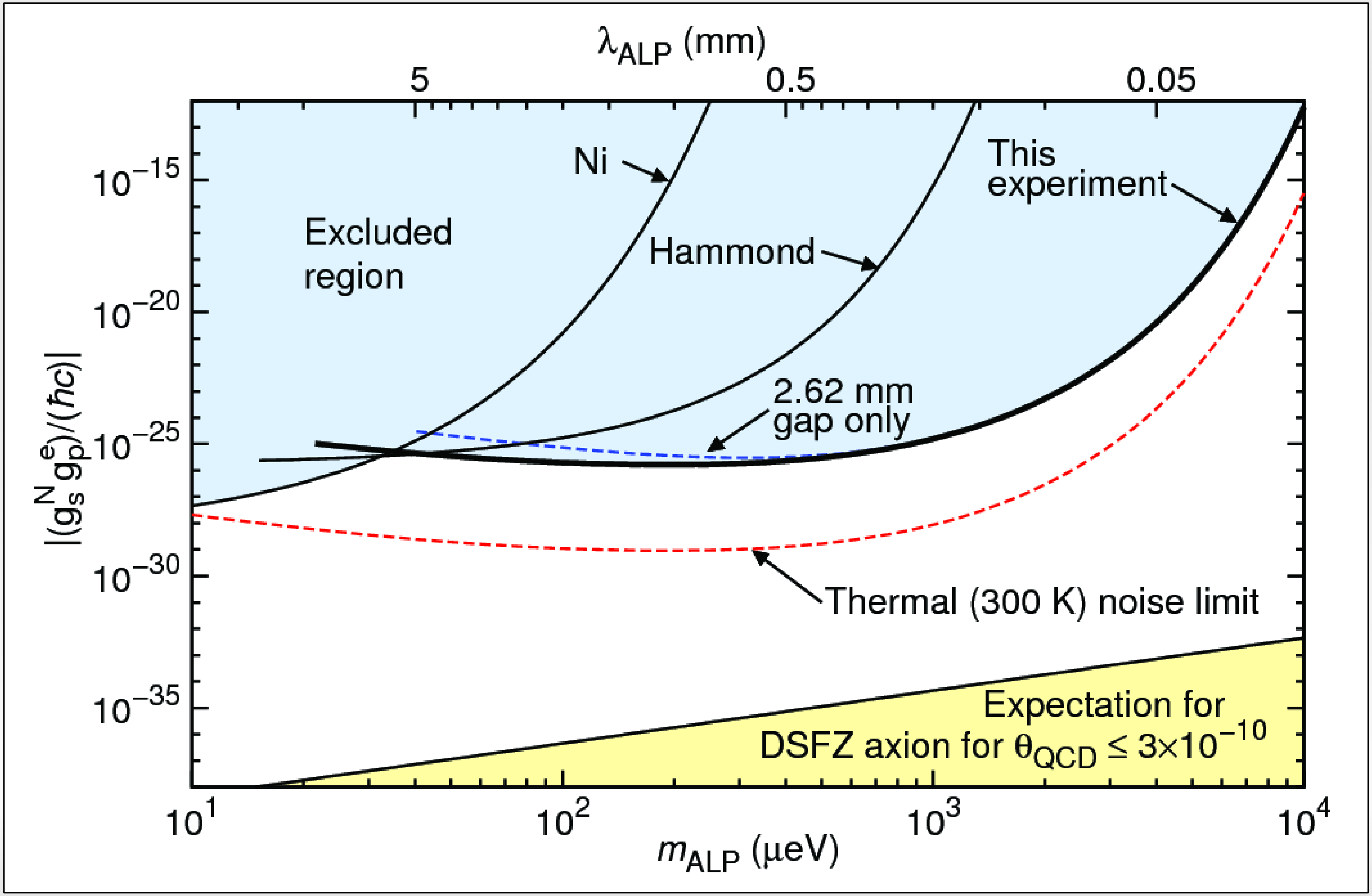


a few cycles of typical data



an axion-mediated force has a specific dependence on the distance to the magnet pole faces

Results



λ_{ALP} (mm)
5
0.5
0.05
Ni
Excluded region
Hammond
This experiment
2.62 mm gap only
Thermal (300 K) noise limit
Expectation for DSFZ axion for $\theta_{QCD} \leq 3\times10^{-10}$
$|(g_s^N g_p^e)/(\hbar c)|$
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^1
10^2
10^3
10^4
m_{ALP} (μeV)

Summary

- Torsion balances are enormously sensitive probes of new forces with sub-gravitational strength.
- They can provide access to regions of parameter space inaccessible to high energy experiments.
- We are actively working on pushing the limits towards more and more sensitive tests of the equivalence principle and the inverse-square law!
- This allows to set limits on many theories including new scalar, vector or pseudoscalar particles.

The EotWash group

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William Terrano
Matt Turner
Todd Wagner
John Lee

Undergraduate students
Sasha
Trevor

Primary support from NSF with supplement from the DOE

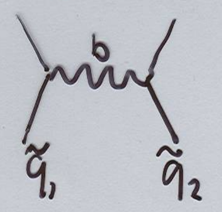
Thank you for your attention!

2 WAYS TO THINK ABOUT EP TESTS

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

  is $m_i = m_g$?

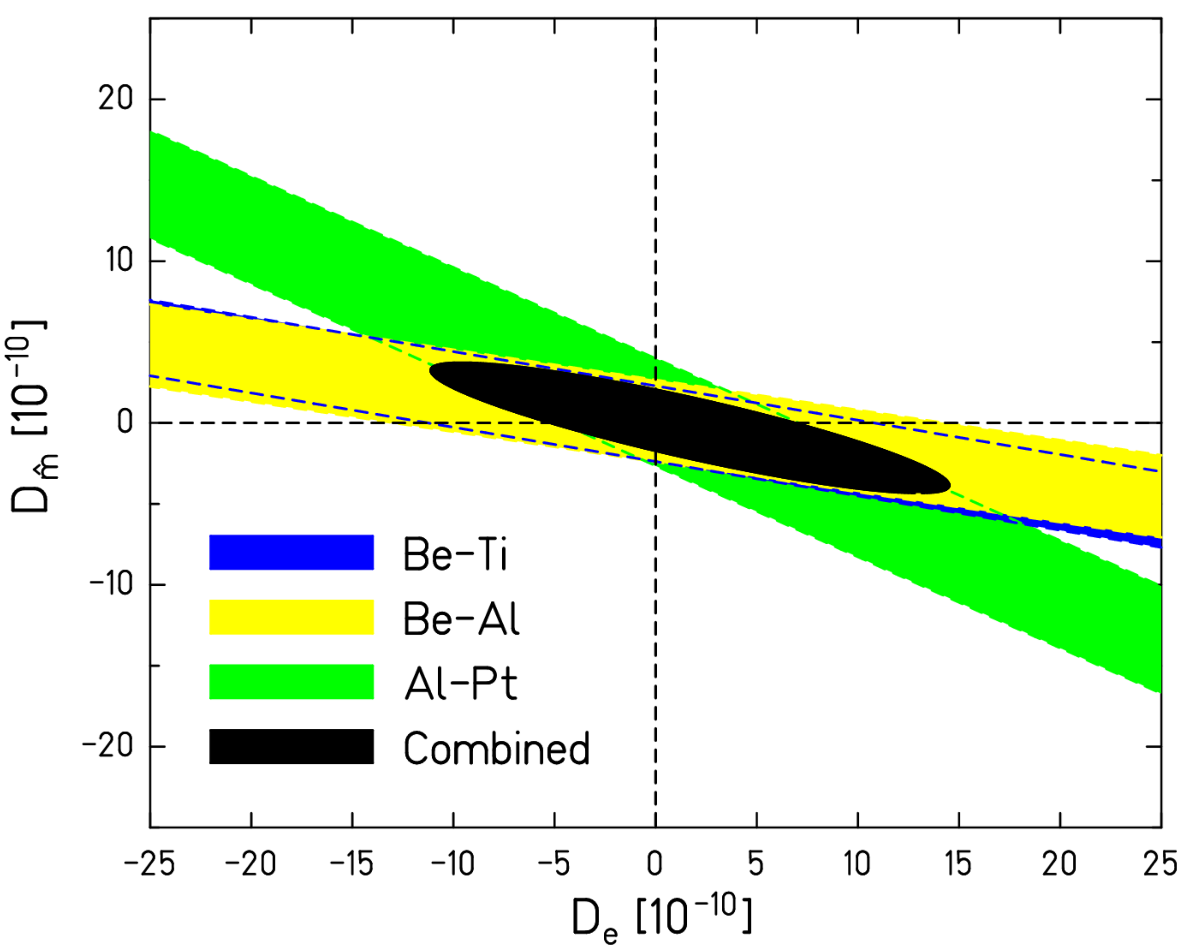
- assume EP is exact for gravity; use tests to probe for new quantum exchange forces even weaker than gravity

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

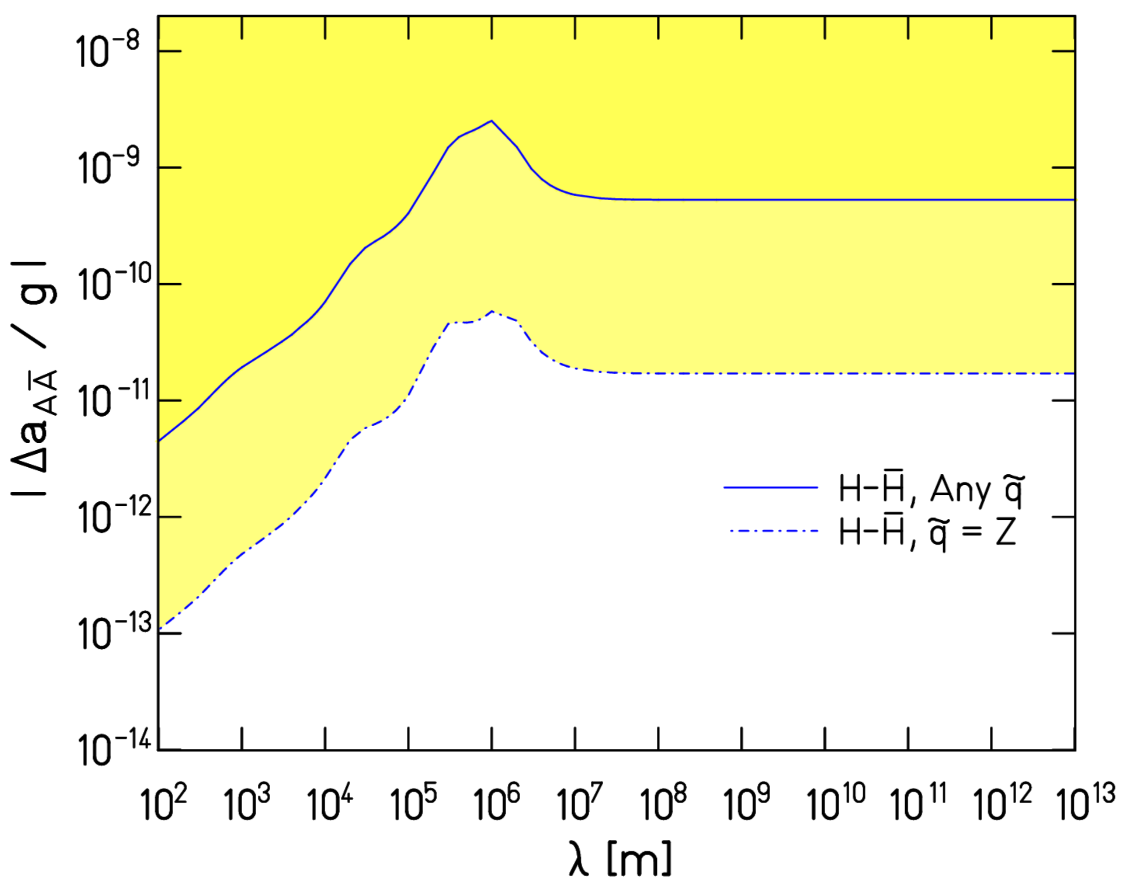
- most of the ideas for solving the big problems in physics predict effects that could show up in EP tests

  e.g. string theory dilaton

Dilaton limits



Implications for the free fall of anti-hydrogen



State of the art

- Our group at UW started looking for EP violations after a reanalysis of the Eötvös data by Fischbach et al., claiming evidence of a ”fifth force” with finite range.
- Most recent published result*:
  - rotating torsion balance
  - employing different source masses
    - local topography
    - earth
    - sun
    - galaxy
  - sensitive to forces with λ from ~1m upward

* Schlamminger *et al.* 2009

Increasing the sensitivity

- Significant gain in sensitivity possible with a ”hydrogen-rich” test body
- Promising material: UHMWPE – Ultra-High Molecular Weight PolyEthylene

$x10^{-2}$	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	

$\Delta(Z/\mu)$ (orange, upper triangle)

$\Delta(N/\mu)$ (blue, lower triangle)

Reducing the noise

- An inherent limitation for torsion balance experiments is thermal noise

$$\tau^2(\omega) \propto 4\frac{kT}{\kappa Q\omega}$$

cooling to 4K: factor ~60

factor ~100

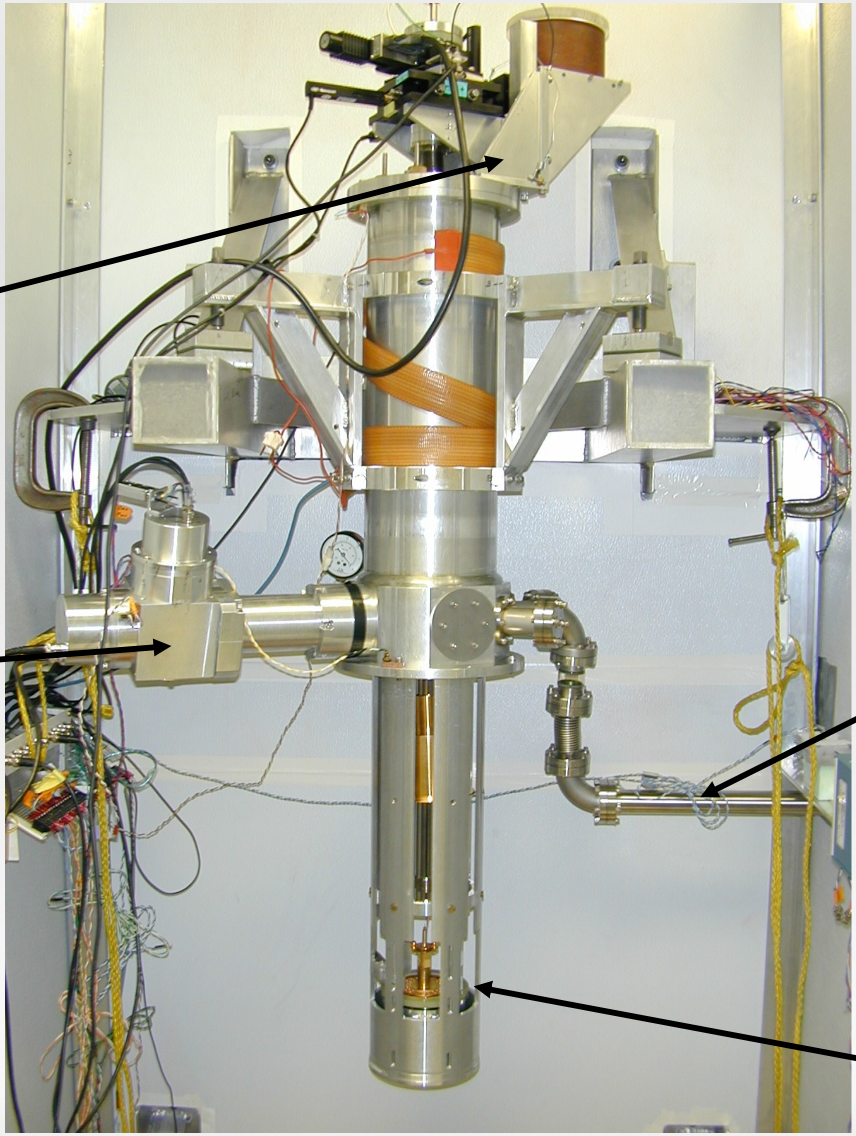
- Cooling helps in two respects:
  - lower temperature *T*
  - Higher values of *Q* possible at low temperatures: values of order 10^5 reported with metal fibers at 4.2K

→ **Build a cryogenic torsion balance to investigate operation at low temperature!**

The apparatus

suspension fiber attached here

optical system for measuring pendulum twist

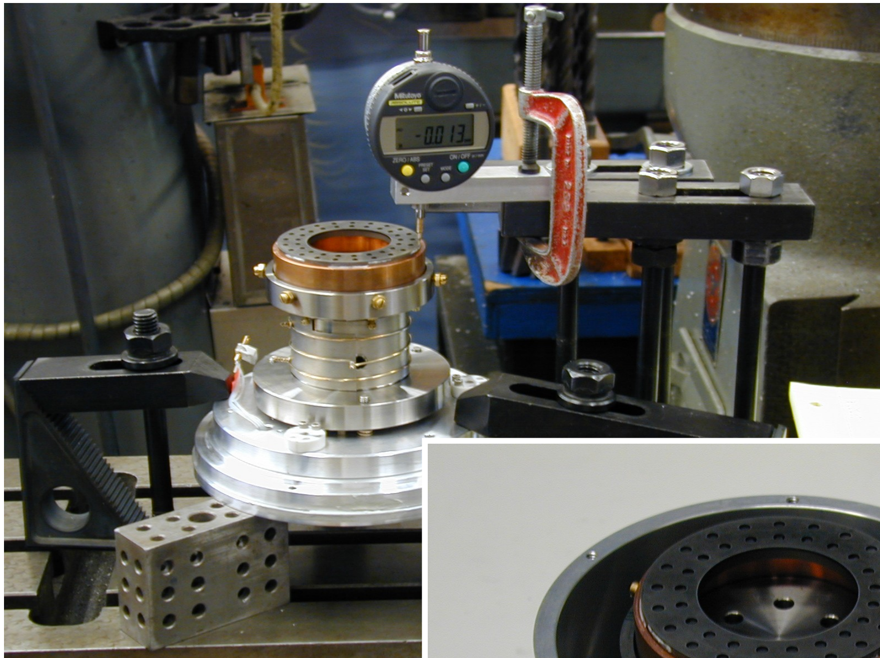


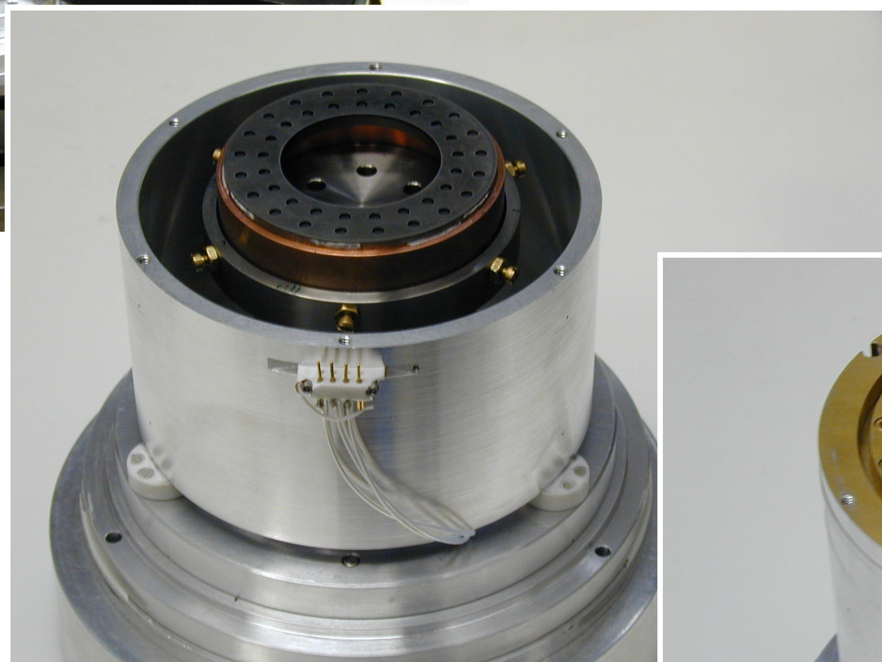
The whole instrument is located inside a temperature-controlled box.

to vacuum pump

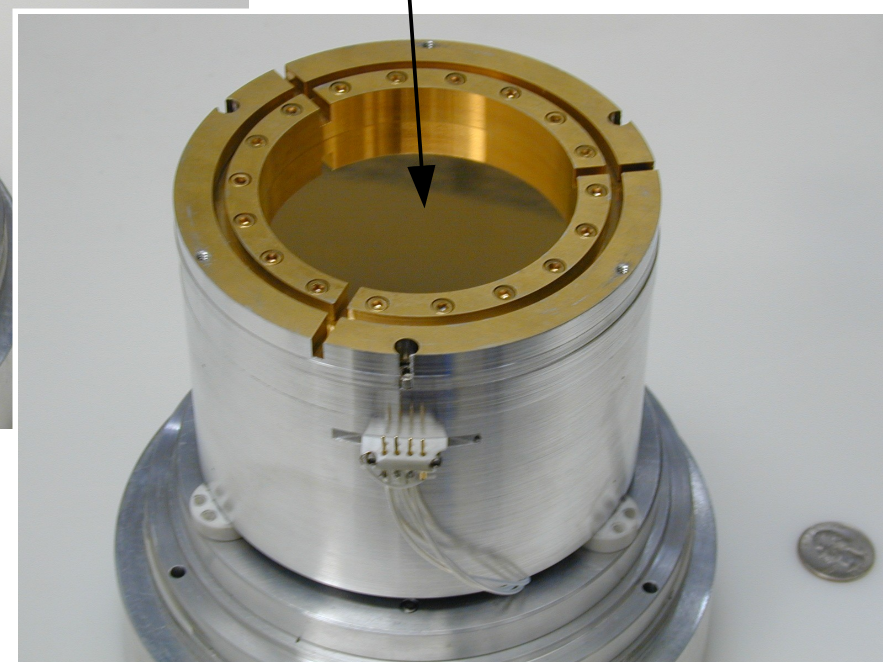
torsion pendulum

rotating attractor and its electrostatic shield

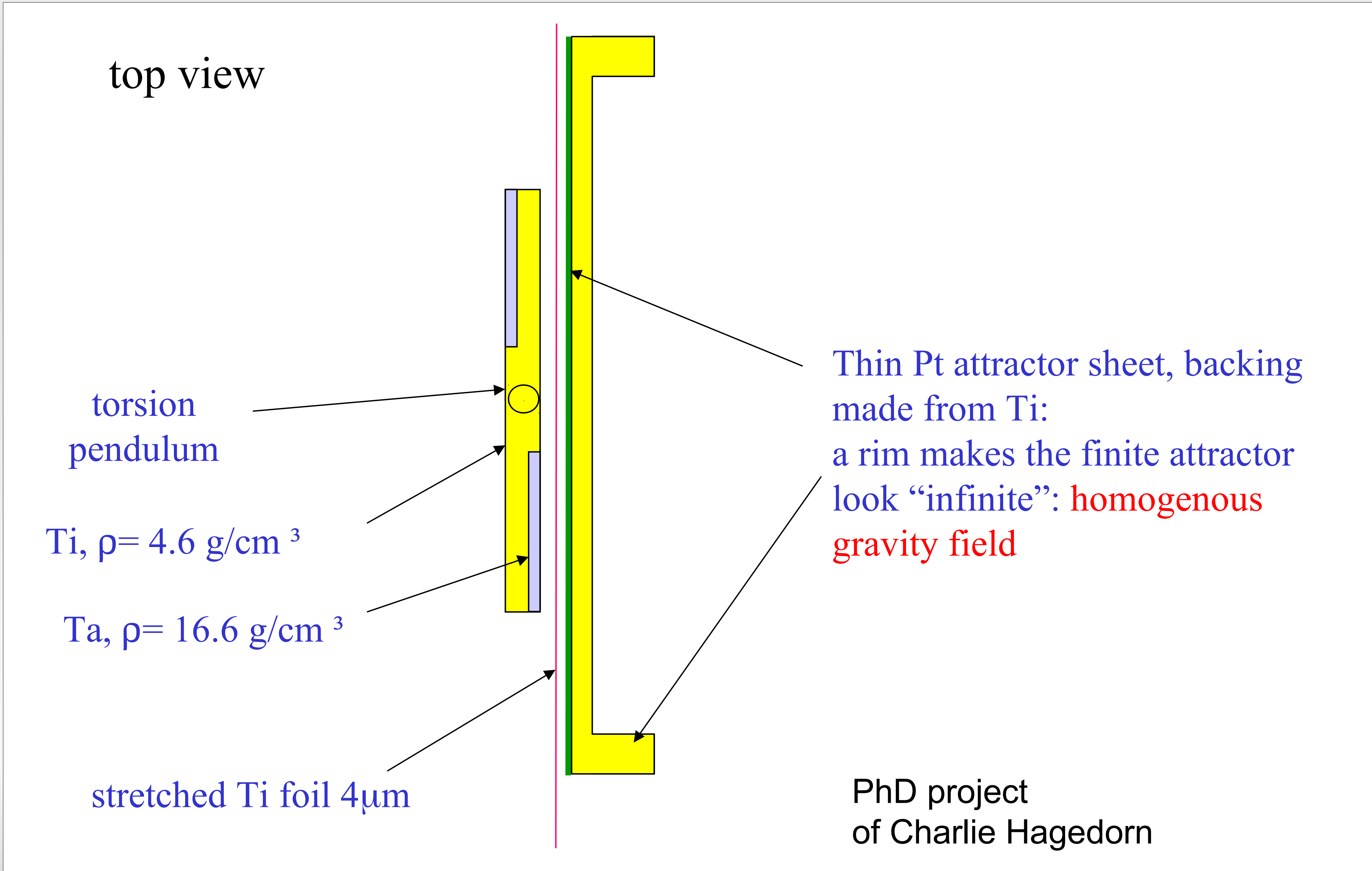




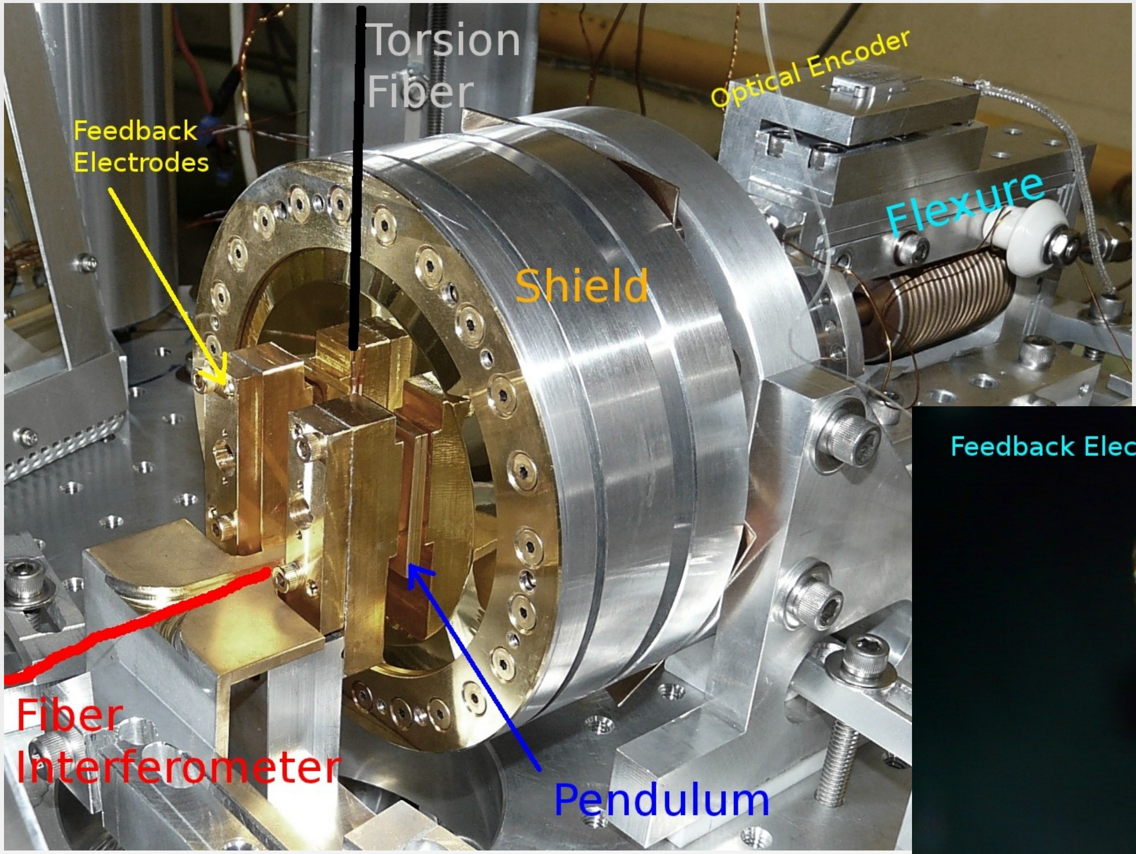
Tightly stretched gold-coated BeCu foil (12 micron above the attractor) provides shielding from electrostatic interactions.

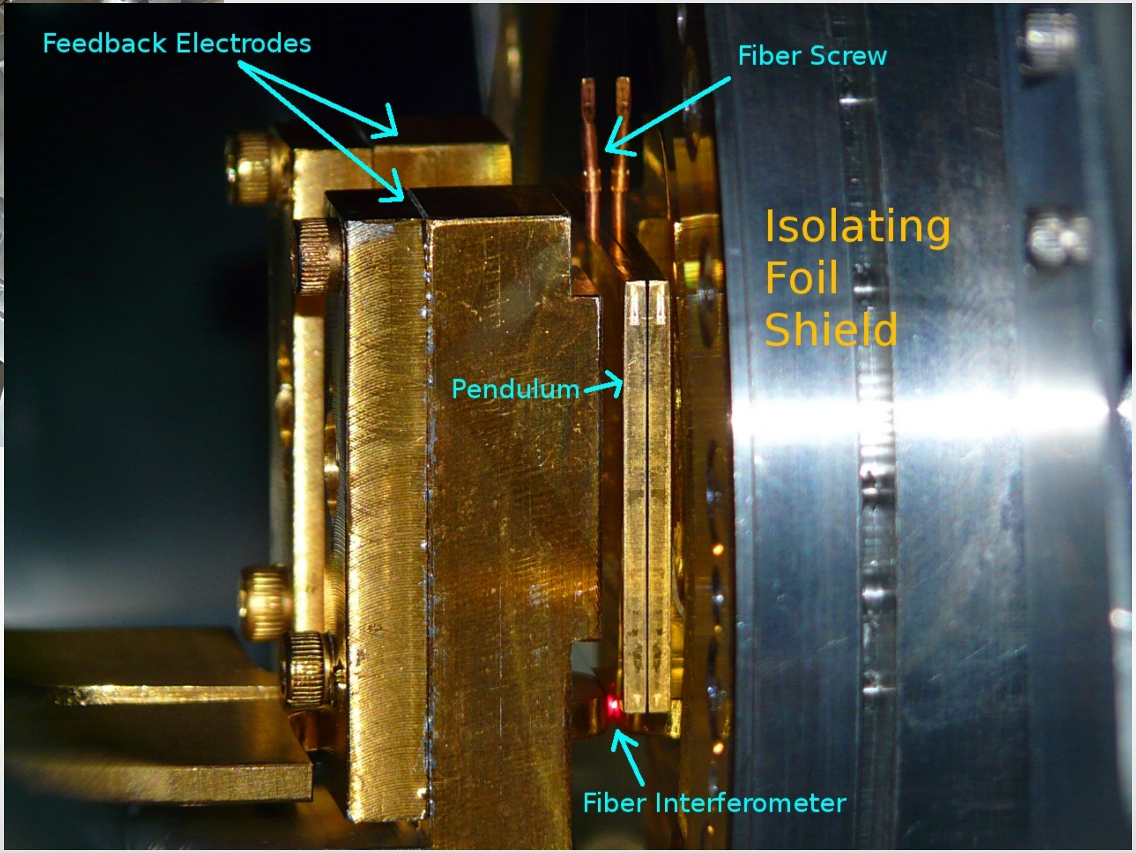


A different approach I



A different approach II

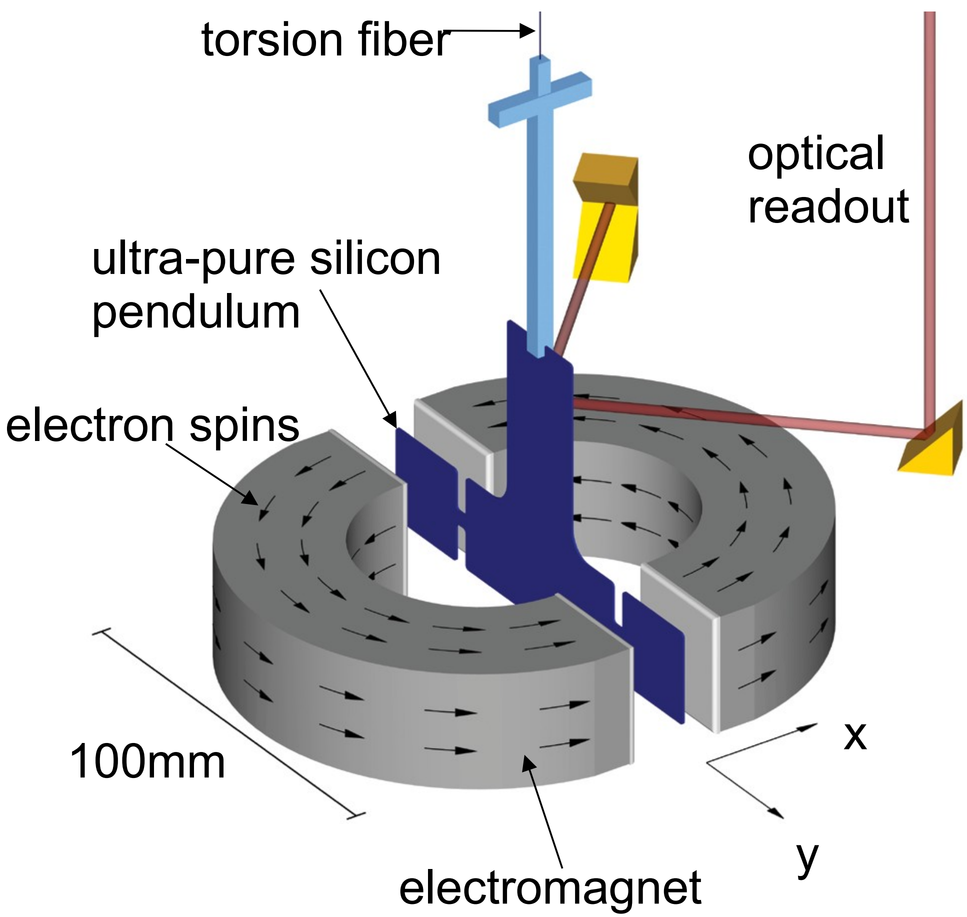


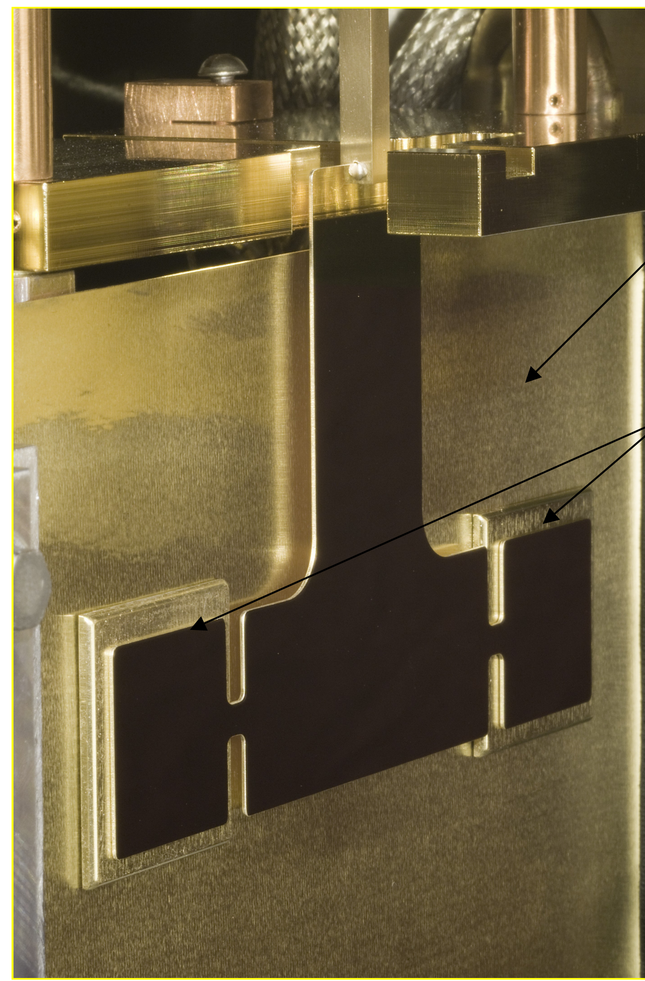


Exchange of virtual axions mediates a monopole-dipole force

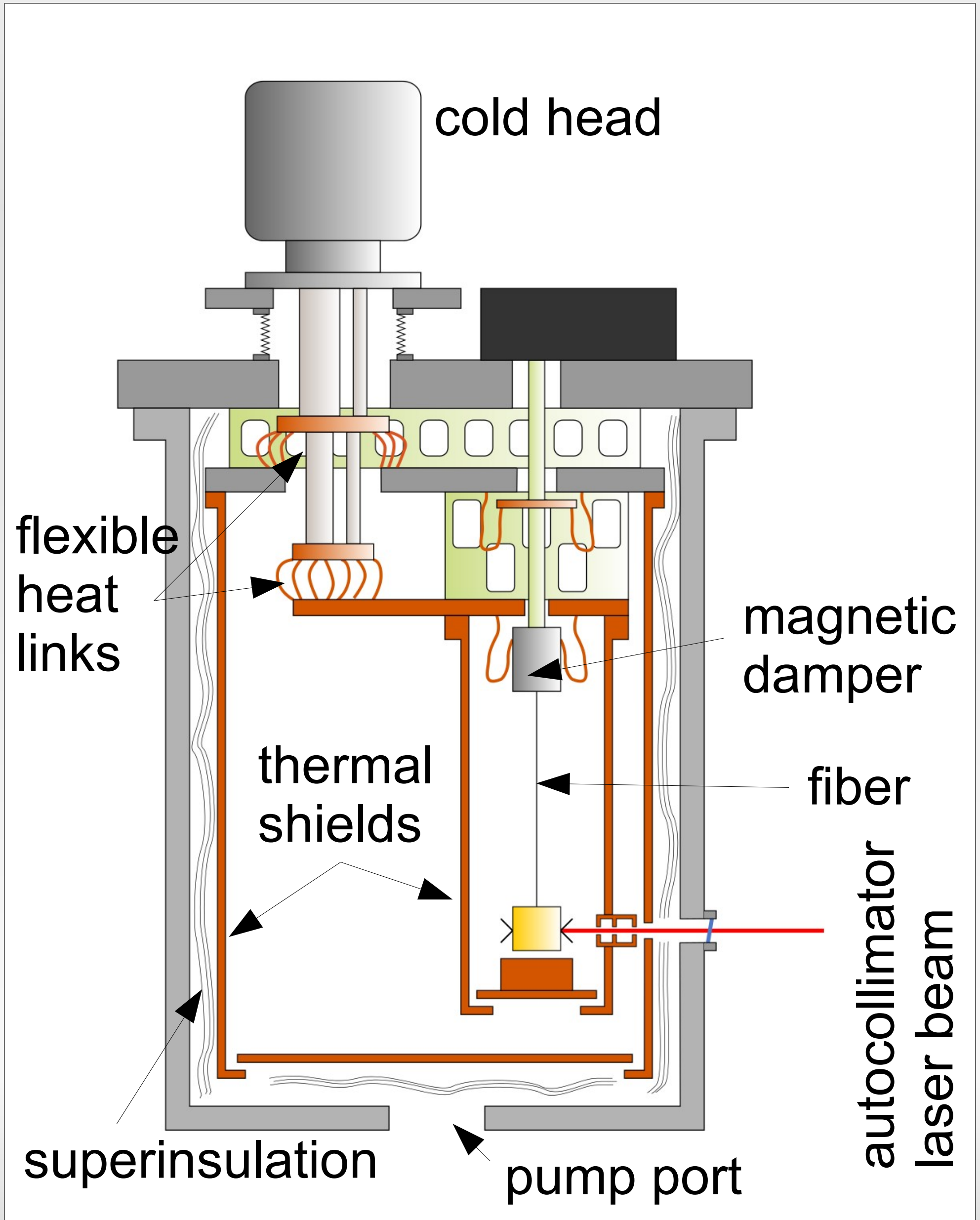
$$V(\hat{\sigma}, r) = \frac{\hbar^2 (\hat{\sigma} \cdot \hat{r})}{8\pi m_e} \left(\frac{g_s^a g_p^e}{\hbar c} \right) \left(\frac{1}{r \lambda_{\mathrm{ALP}}} + \frac{1}{r^2} \right) e^{-r/\lambda_{\mathrm{ALP}}}$$

where g_s^a is proportional to Θ_{QCD}





A cryogenic torsion balance



Use a pulse tube cooler for cooling to cryogenic temperatures

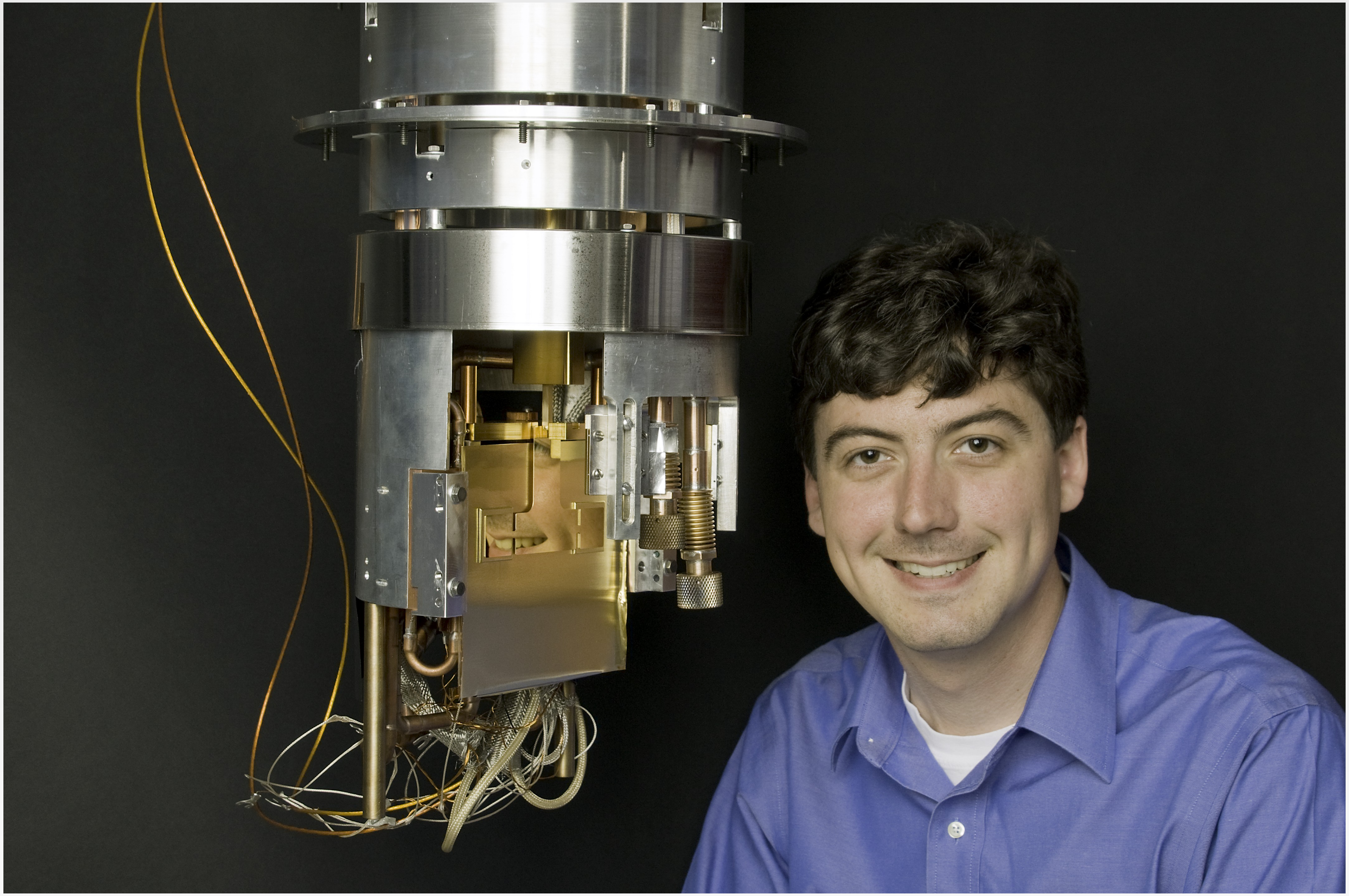
Early torsion balance experiments

- Loránd Eötvös (1922):
  - various test-body pairs in the field of the earth
  - e.g. $\eta(\mathrm{Cu}, \mathrm{Pt}) = (4 \pm 2) \cdot 10^{-9}$
- Roll, Krotkov, Dicke (1964):
  - sun as attractor, feedback
  - $\eta(\mathrm{Au}, \mathrm{Al}) = (1.3 \pm 1.5) \cdot 10^{-11}$
- Braginsky, Panov (1972):
  - sun as attractor, no feedback
  - $\eta(\mathrm{Al}, \mathrm{Pt}) = (3 \pm 4) \cdot 10^{-13}$

Reminder:

$$\eta = \frac{\Delta a_\perp}{g_\perp}$$

The axion torsion balance



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