Particle Physics with Torsion Pendulums: WISPs and Axions

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6th Patras Workshop on Axions, WIMPs and WISPs
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The Eöt-Wash® Group

Six instruments devoted to probing gravitational strength physics.
One instrument devoted to technology development.

Faculty	Postdocs	Grad Students
Eric Adelberger	Frank Fleischer	Ted Cook
Jens Gundlach	Seth Hoedl	Charlie Hagedorn
Blayne Heckel	Stephan Schlamminger*	Matt Turner
		Todd Wagner
		Will Terrano

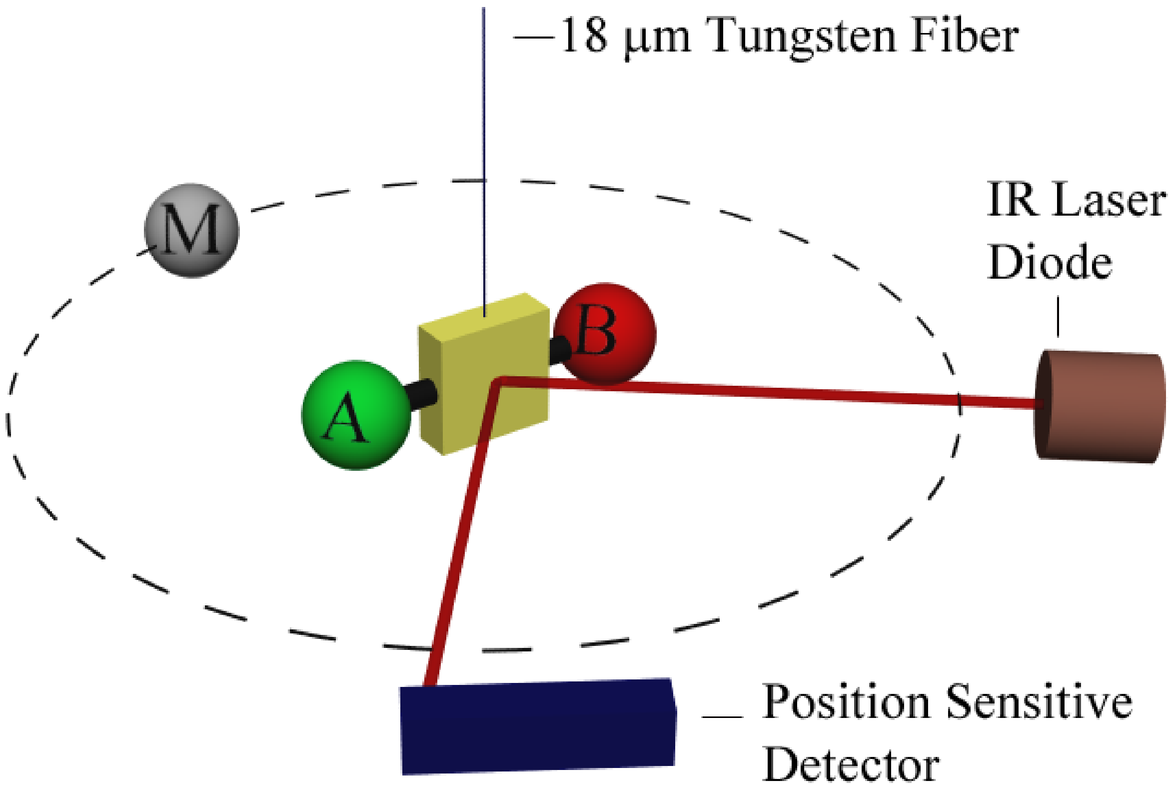
*Phd from UZH

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

Toy model of a torsion balance to test the equivalence principle

By converting a differential acceleration of A and B towards M into an oscillating twist angle…

…and by confining the motion of 10^{23} atoms to one degree of freedom…



Unprecedented sensitivity to small forces… and new physics.

Eöt-Wash torsion pendulums operate at the thermal (300K) noise limit.

Angular Resolution:

- ~1 nano-radian/√day
- *~10 mm deflection over distance between Seattle and Zurich*

Torque :

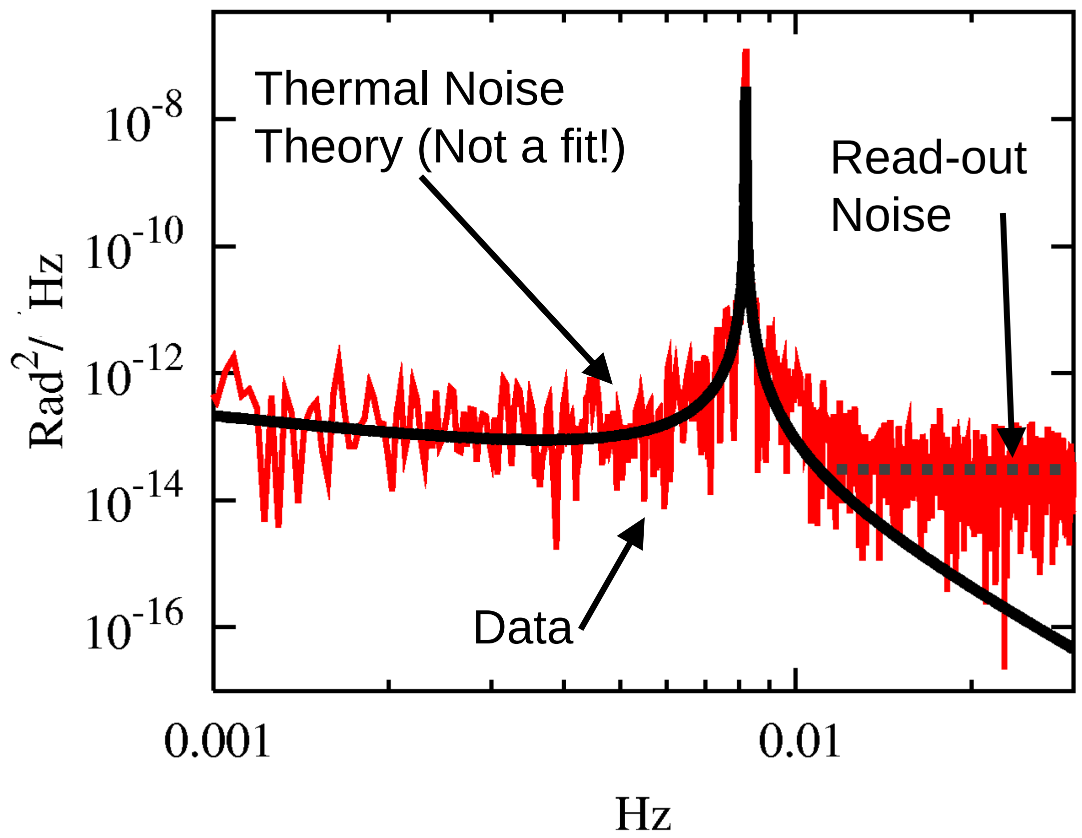
- 2×10^{-11} ergs or *10 eV/√day*

Force:

- 0.1 femto-N or

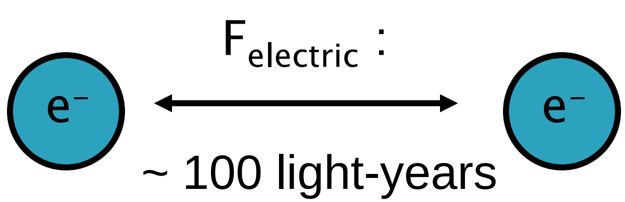
  1 postage stamp / 10^{12}

Power Spectral Density in rotation signal



Force / Atom :

- 0.1 femto-N $/(N_a)^2$ or

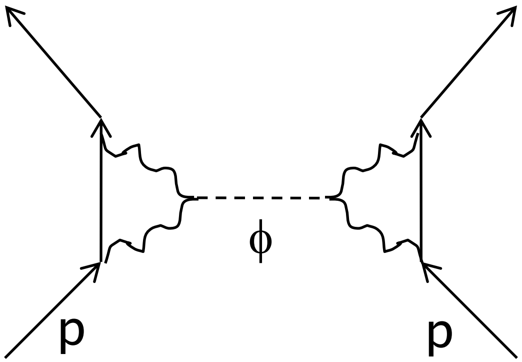


Eöt-Wash torsion pendulums probe profound questions in particle physics:

- Are there forces much weaker than gravity?
- Is there a force that couples to B-L?
- Is there a non-gravitational force between luminous matter and dark matter?
- Are there “large” extra-dimensions?
- Is there a preferred frame in space?
- Are the light scalar particles of string theory hidden by a self-interaction process (chameleons)?
- Are there weakly interacting scalars or pseudoscalars (WISPs or Axions)?

Are there sub-eV scalars that couple to two photons?

A. Dupays *et al* PRL **98**, 131802 (2007)



Through a second order interaction, a ***scalar*** WISP could mediate a Yukawa force between two protons.

This force modifies Newtonian gravity:

$$V_G(r) = -G\frac{m_1 m_2}{r}\left(1 + (g_{\phi\gamma\gamma})^2 \frac{9\alpha^2}{16\pi^3 G}\left[\frac{Z}{A}\right]_1\left[\frac{Z}{A}\right]_2 \cdot e^{-r/\lambda_\varphi}\right)$$

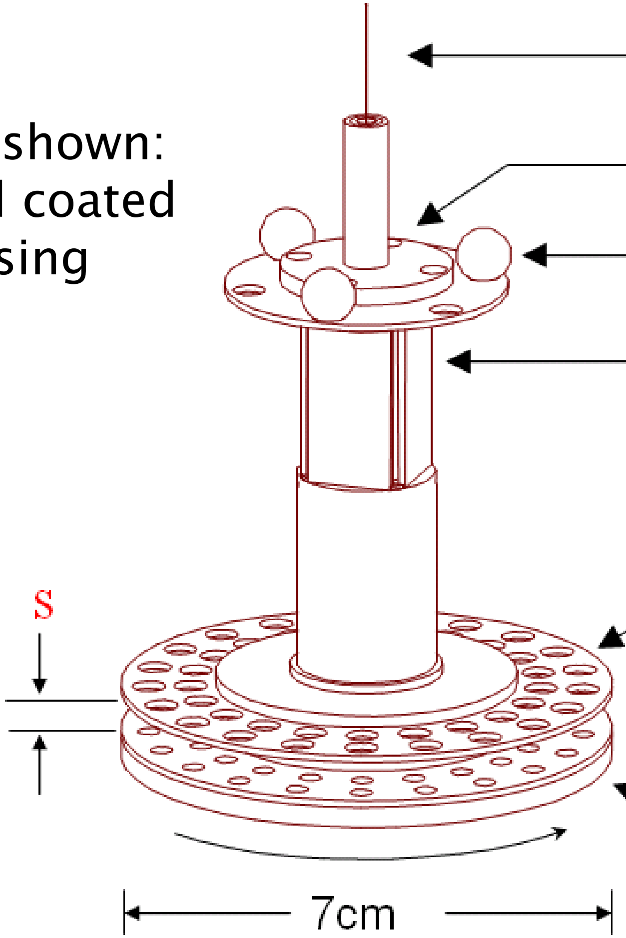
Tests of Newton's Inverse Square Law are sensitive to such a force!

Note: A low energy form-factor with scale μ suppresses the yukawa force by $(\mu/m_p)^2$

Most recent published Inverse Square Law pendulum

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

Not shown: gold coated housing



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

4 mirrors for tracking angle of deflection

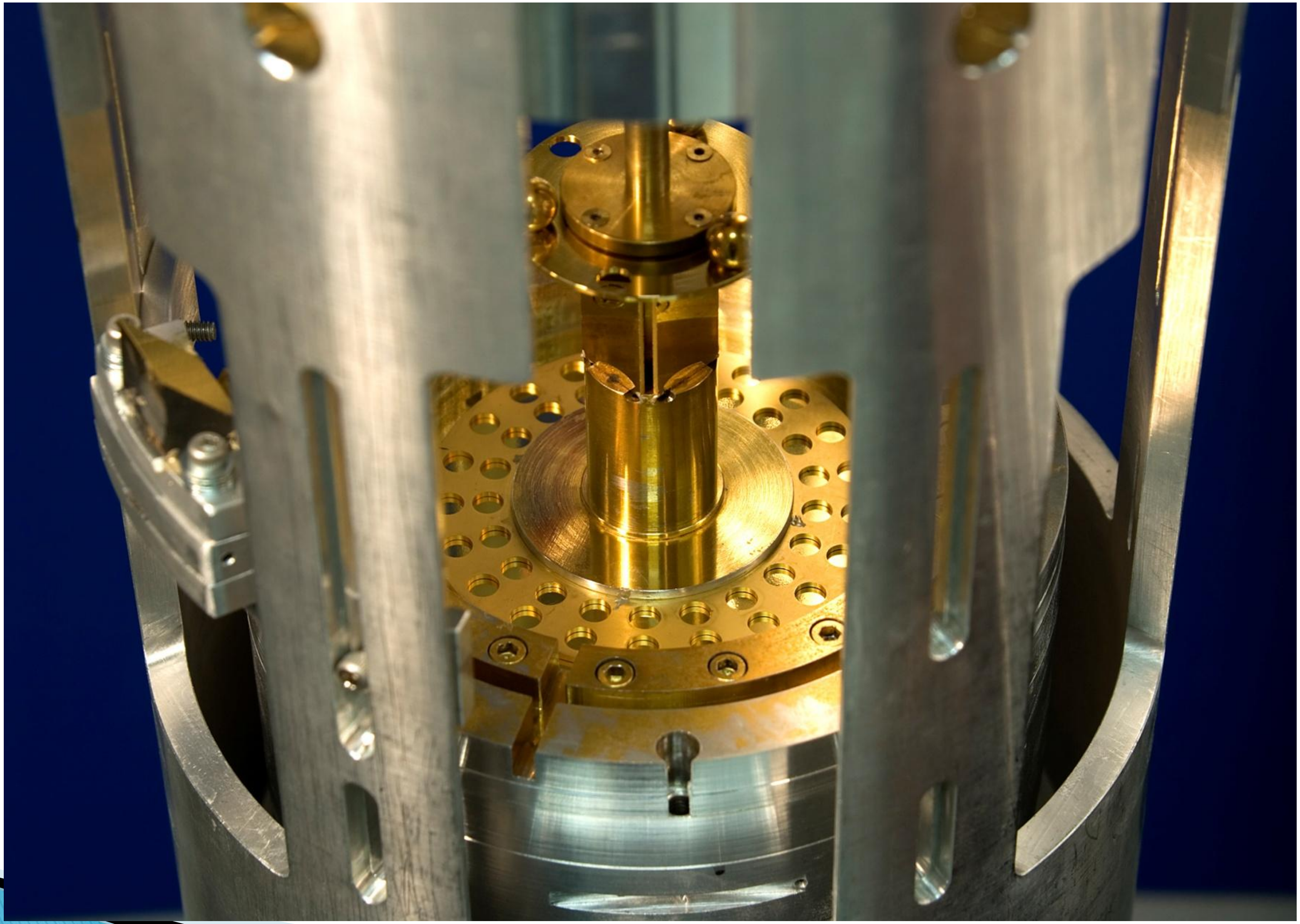
detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

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**

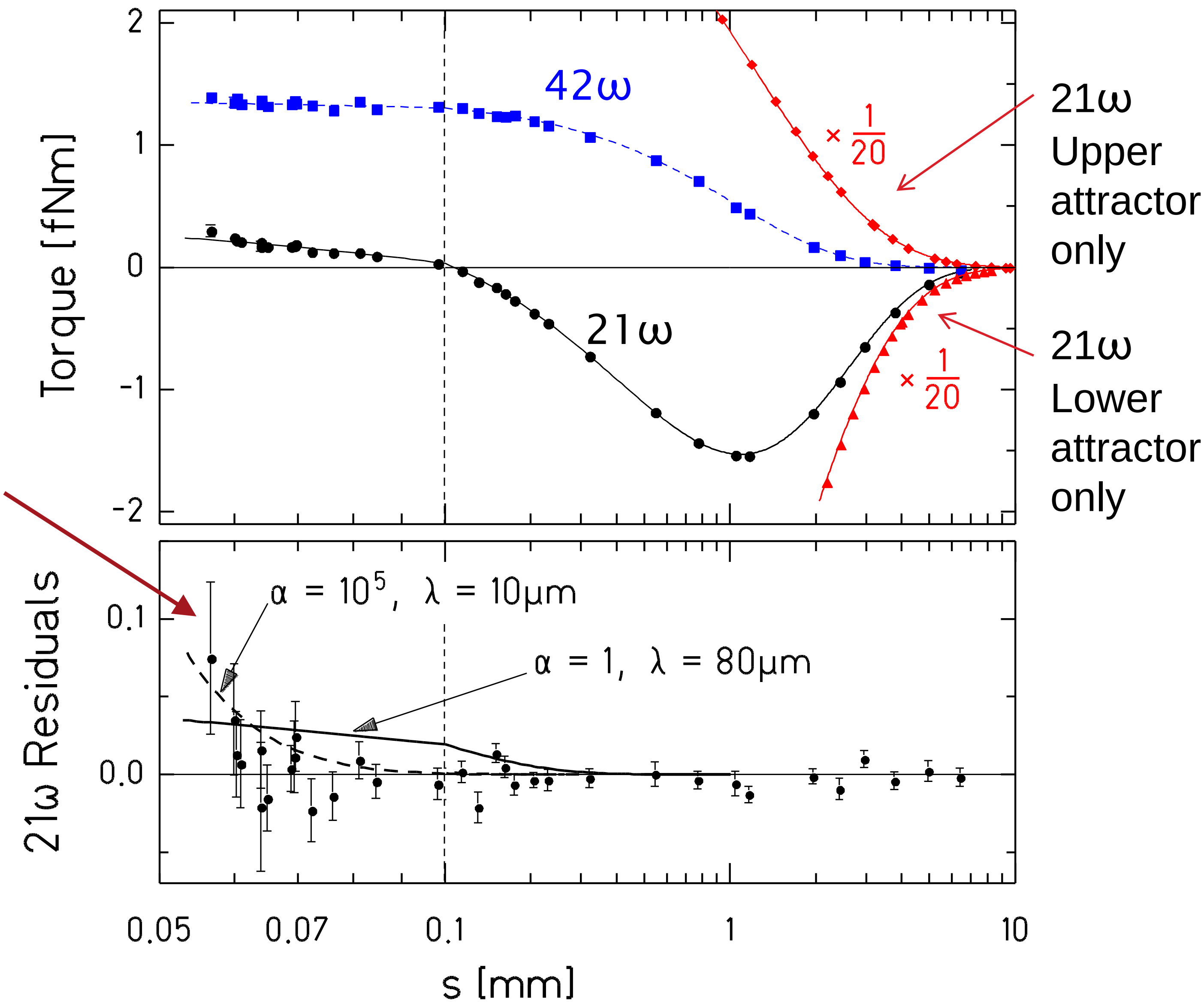
Key features: Planar geometry maximizes mass. Signal at high multiple of disturbance frequency prevents spurious 1- ω signals and maximizes S/N.

The ISL pendulum with upper shield removed



Typical Data from Inverse Square Law Pendulum

Anomalies at short distances are not reproducible.

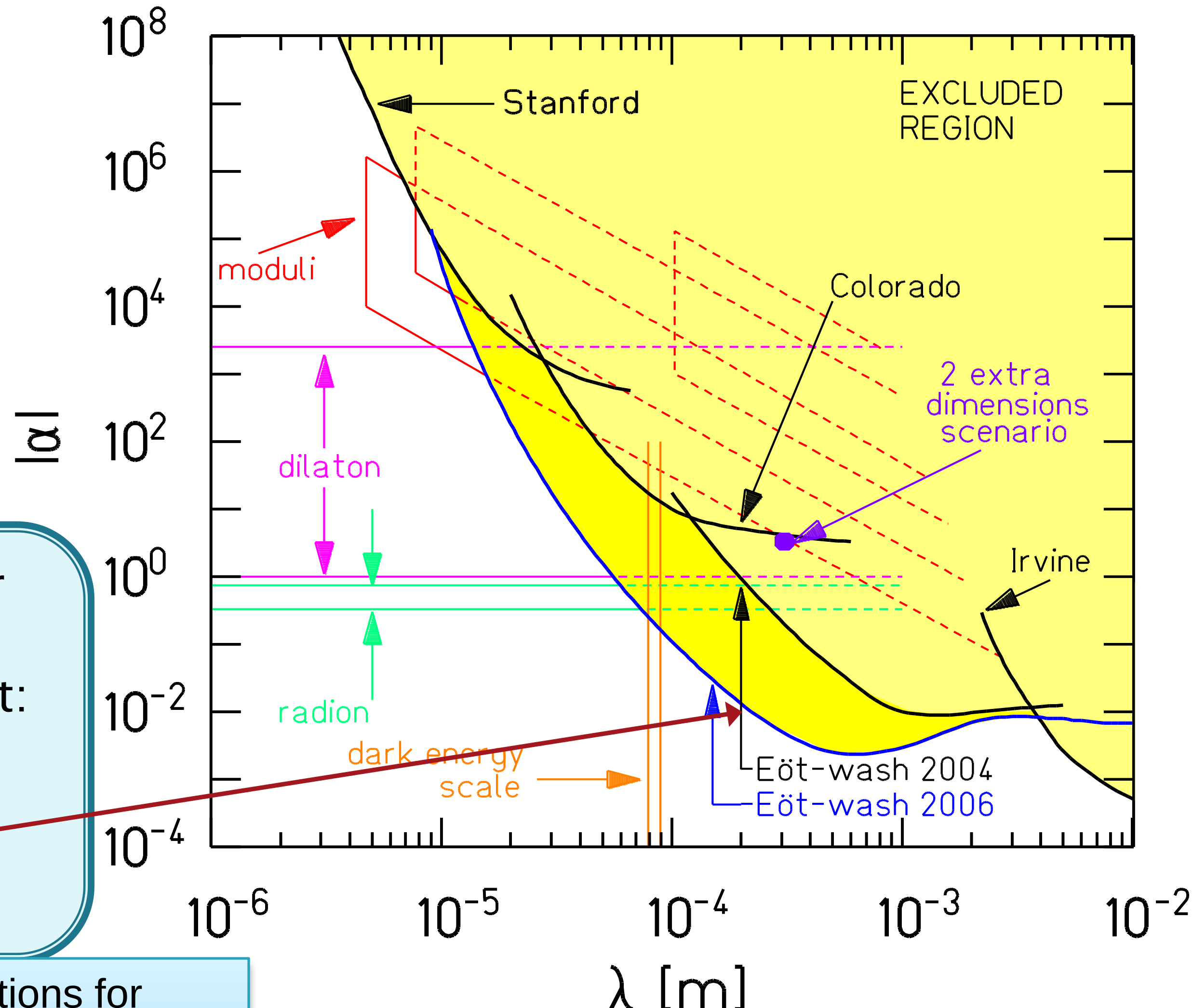


Most recent published results from 42-hole ISL pendulum

$$V_G(r) = -G\frac{m_1 m_2}{r}\left(1+\alpha\cdot e^{-r/\lambda}\right)$$

For $|\alpha| = 1$, $\lambda < 56\ \mu m$

2-σ exclusion plot on non-gravitational forces



In Dupays' model for scalar WISPs,
our result gives the 2σ limit:

$$g_{\phi\gamma\gamma} \le 1.6\times10^{-17}\ \mathrm{GeV}^{-1}$$

for

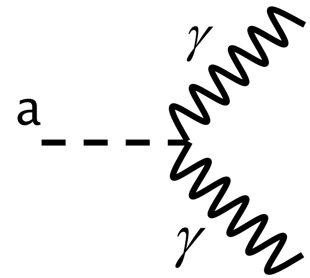
$$m_\varphi = 1\,\mathrm{meV}$$

For thorough discussion of implications for particle physics see:
E.G. Adelberger *et al.*, PRL **98**, 131104 (2007)

Are there axions or axion-like particles?

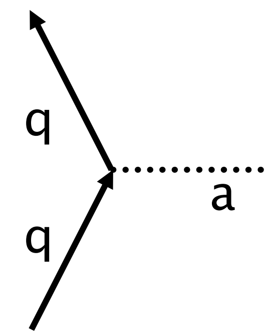
Most experiments look for ALPs that couple to photons:

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

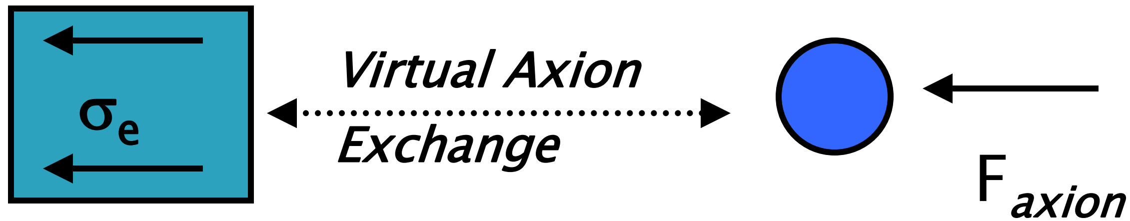


ALPs will also couple to fermions:

$$\mathcal{L}_{aq} = C_q \frac{m_q}{2 f_a}\overline{\psi}_q\gamma^5\psi_q a \quad \text{And…} \quad \overline{\theta}\,\frac{C_q}{f_a}\overline{\psi}_q\psi_q a$$

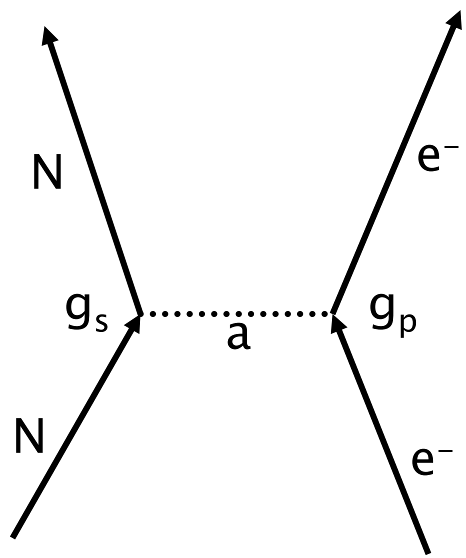


ALPS will mediate a CP violating macroscopic force



Polarized Matter
(Magnetized Iron)

Unpolarized
Matter



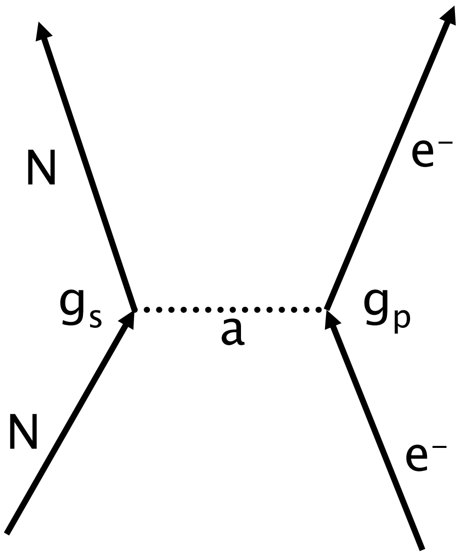
$$V(r) = (30\mathrm{MeV}) \underbrace{\frac{\theta_{QCD}}{f_a} \frac{m_e}{f_a}}^{g_s g_p} \frac{\hat{\sigma} \cdot \hat{r}}{8\pi\, m_e} \left(\frac{1}{\lambda_a r} + \frac{1}{r^2} \right) e^{-r/\lambda_a}$$

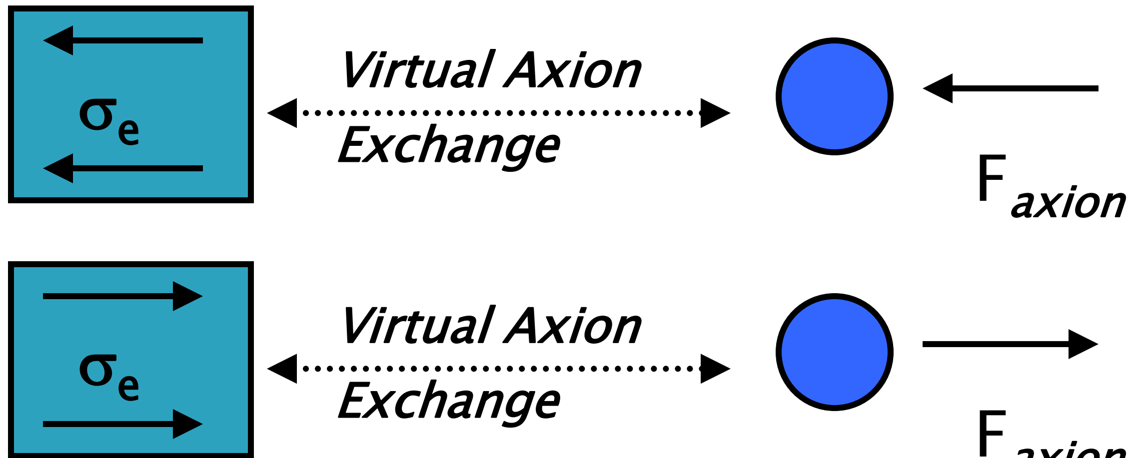
Disadvantage: Coupling proportional to θ_{QCD}.

Advantage: Does not depend on cosmology or astrophysics.

Moody and Wilczek PRD **30** 130 (1984)

ALPS will mediate a CP violating macroscopic force





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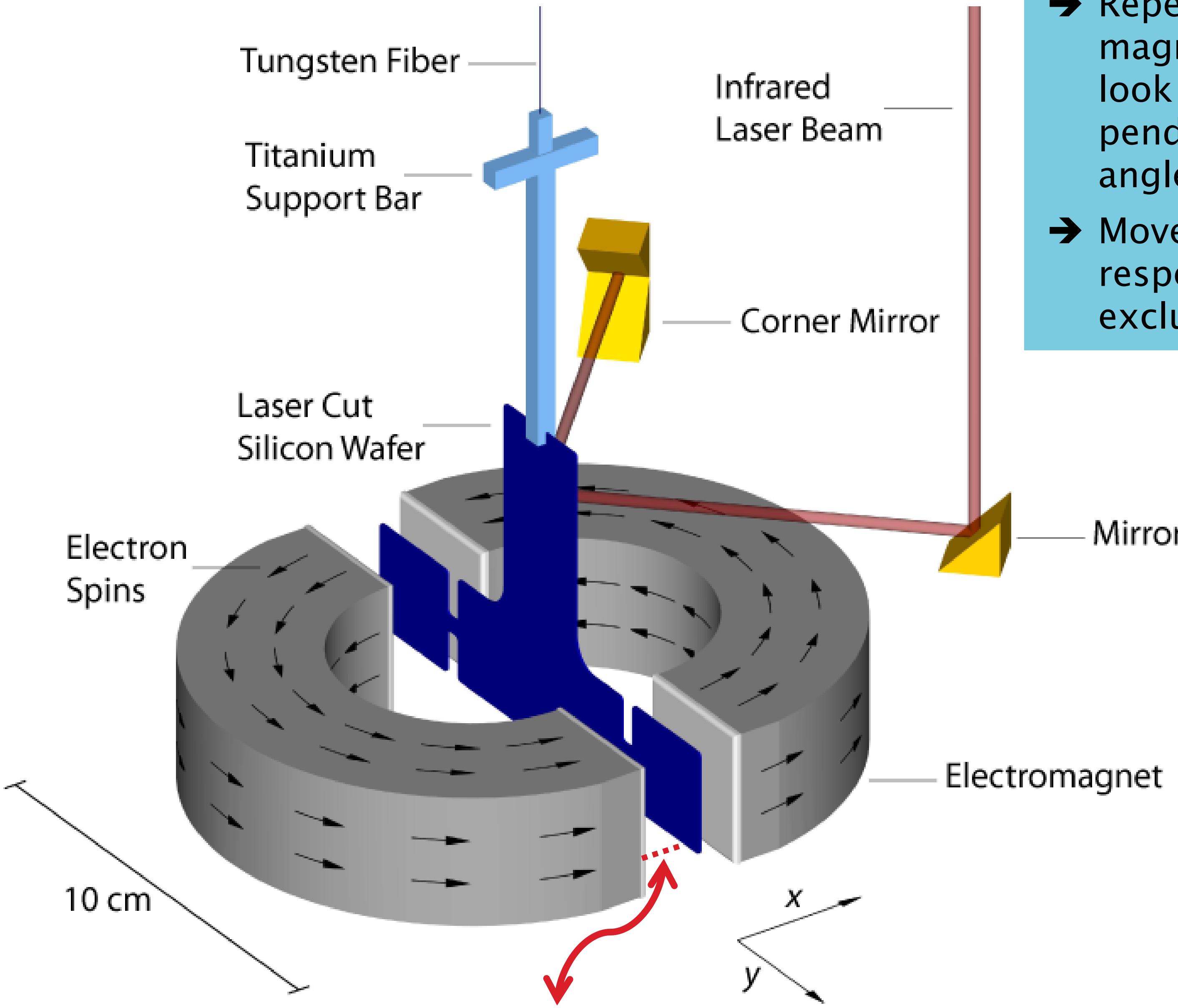
Our Axion Detector



Strategy:

- ➔ Repeatedly change the magnet polarization and look for a change in the pendulum equilibrium angle.
- ➔ Move pendulum with respect to pole faces to exclude systematic errors.

Virtual Axion Exchange

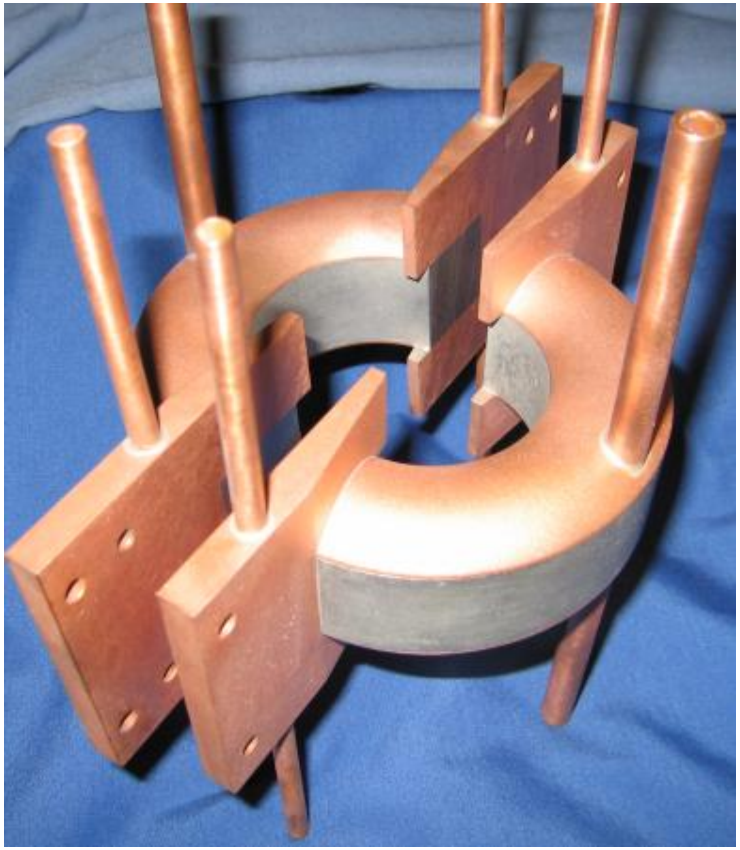
A lot of effort to turn this idea into a working apparatus…

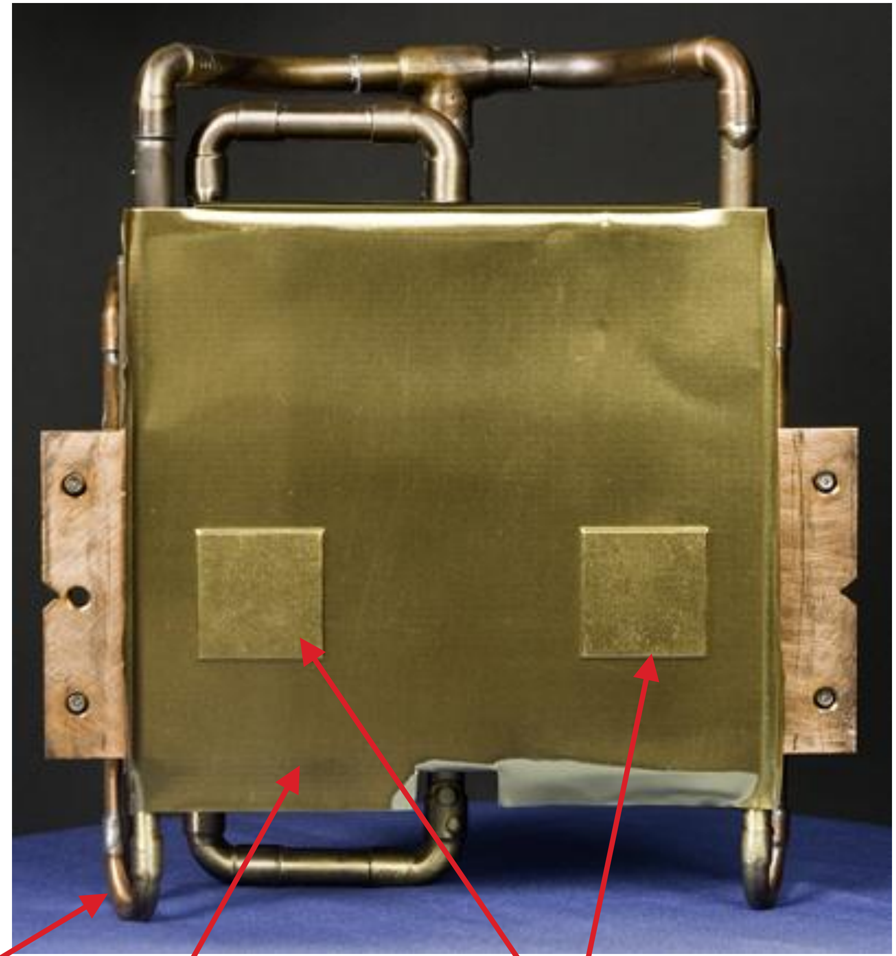
The challenge…

- No one has ever operated a torsion pendulum in a strong magnetic field.

Systematic errors are ***very*** difficult.

The magnet





Water cooling lines

Gold coated electrostatic shield

Pole pieces & Electrodes for electrostatic feedback control

At 8A (24W), 3mm gap:

- 3.1kG
- Symmetric to 1 part in 10^5.
- Temperature stabilized to 0.01°C.

The Pendulum

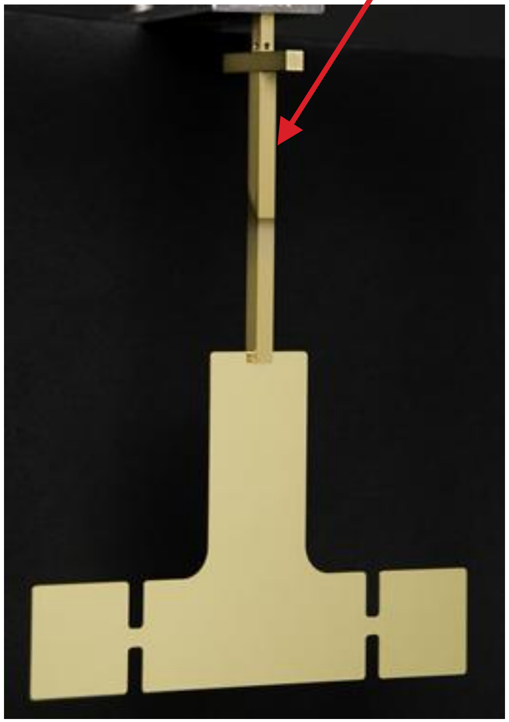
Sensitive to 20 femto-grams (2×10^8 atoms) of polarized Iron.

- Pendulum made of single crystal silicon (pure to 1 part in 10^{10}).
- Never contacts metal tools (laser cut).
- Carefully cleaned with RCA1 and RCA2 protocols.

Coated with 300Å of paramagnetic terbium to cancel the diamagnetism of silicon.

Fiber attaches here

Ultra-pure titanium support bar



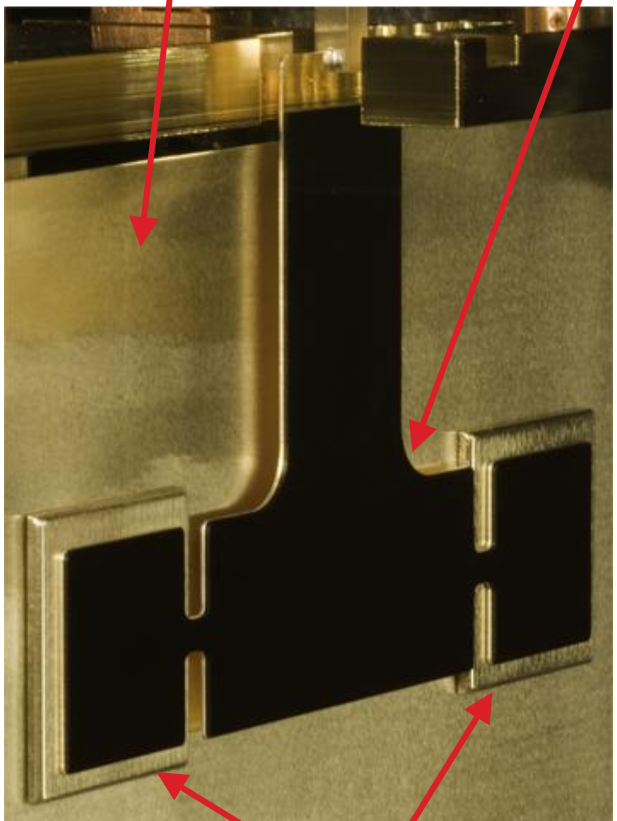
7.3cm

11.3cm

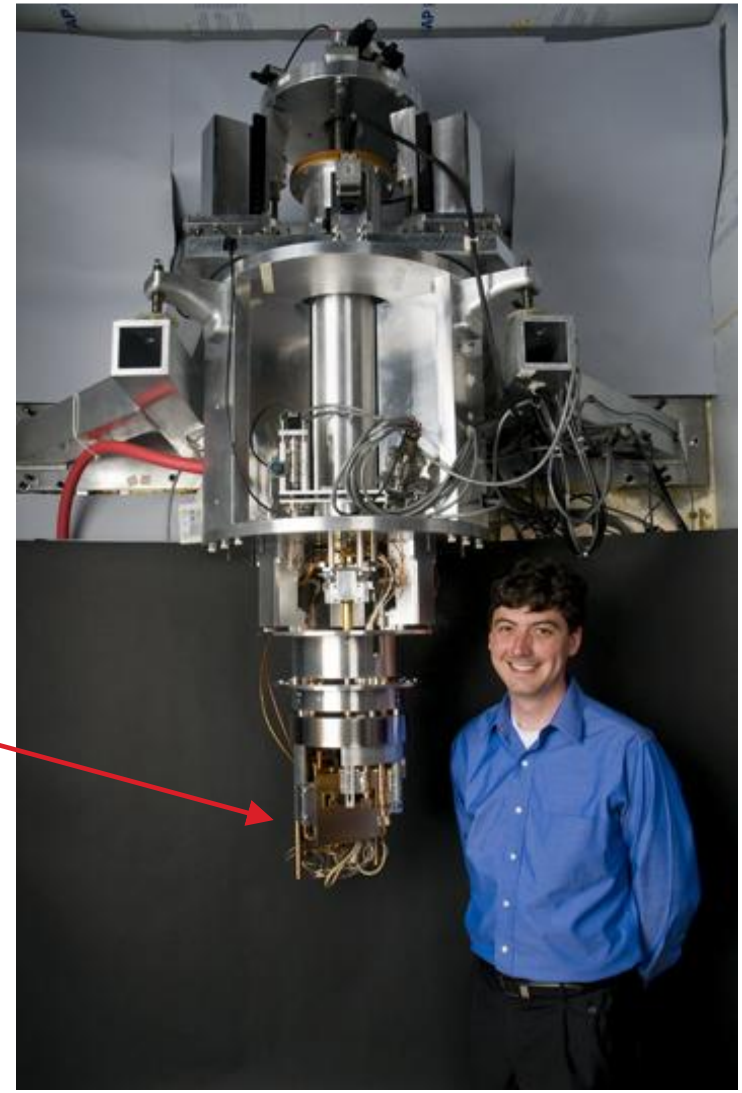
Assembly

Electrostatic Shield

Pendulum



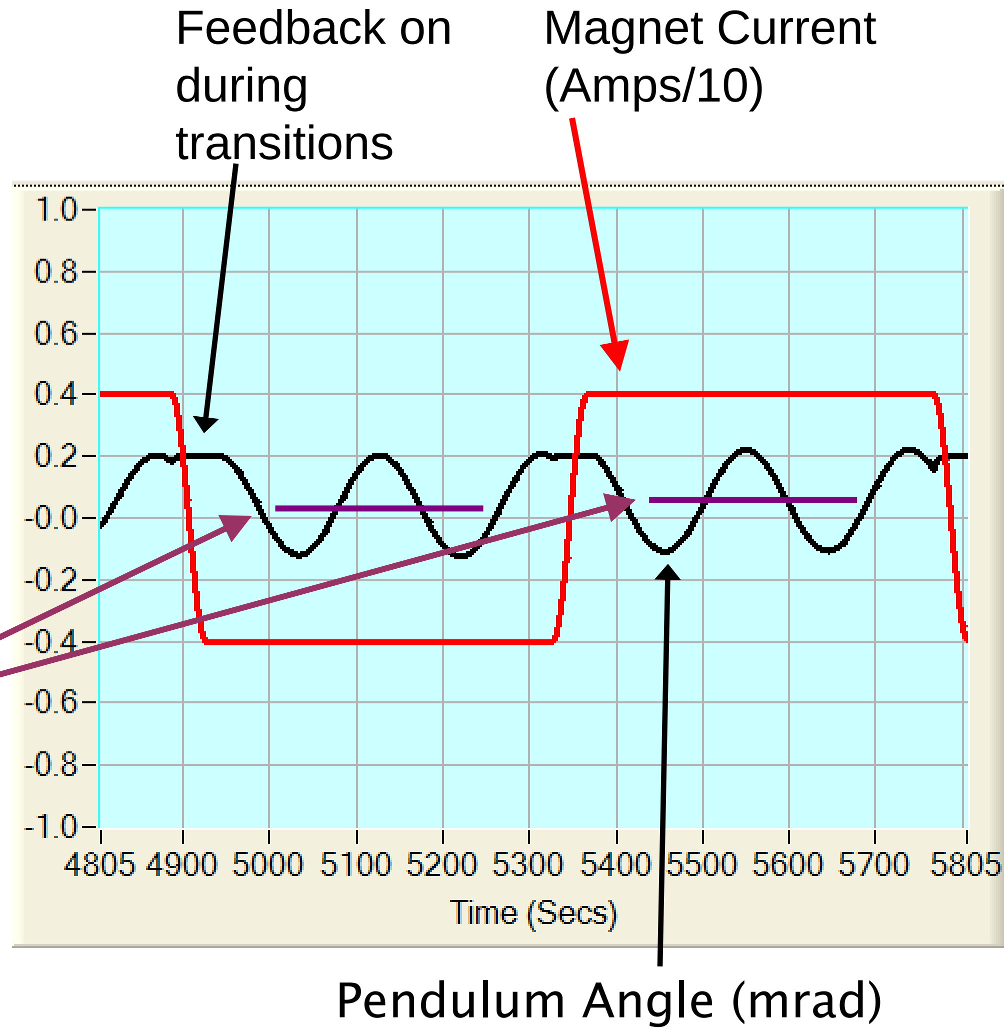
Magnet Poles &
Feedback electrodes



The measurement strategy

Tricky because the diamagnetic silicon seeks a magnetic field minimum. Thus, the B field acts as a strong torsion spring.

For each magnet state, we fit for the equilibrium angle, amplitude, frequency and phase.

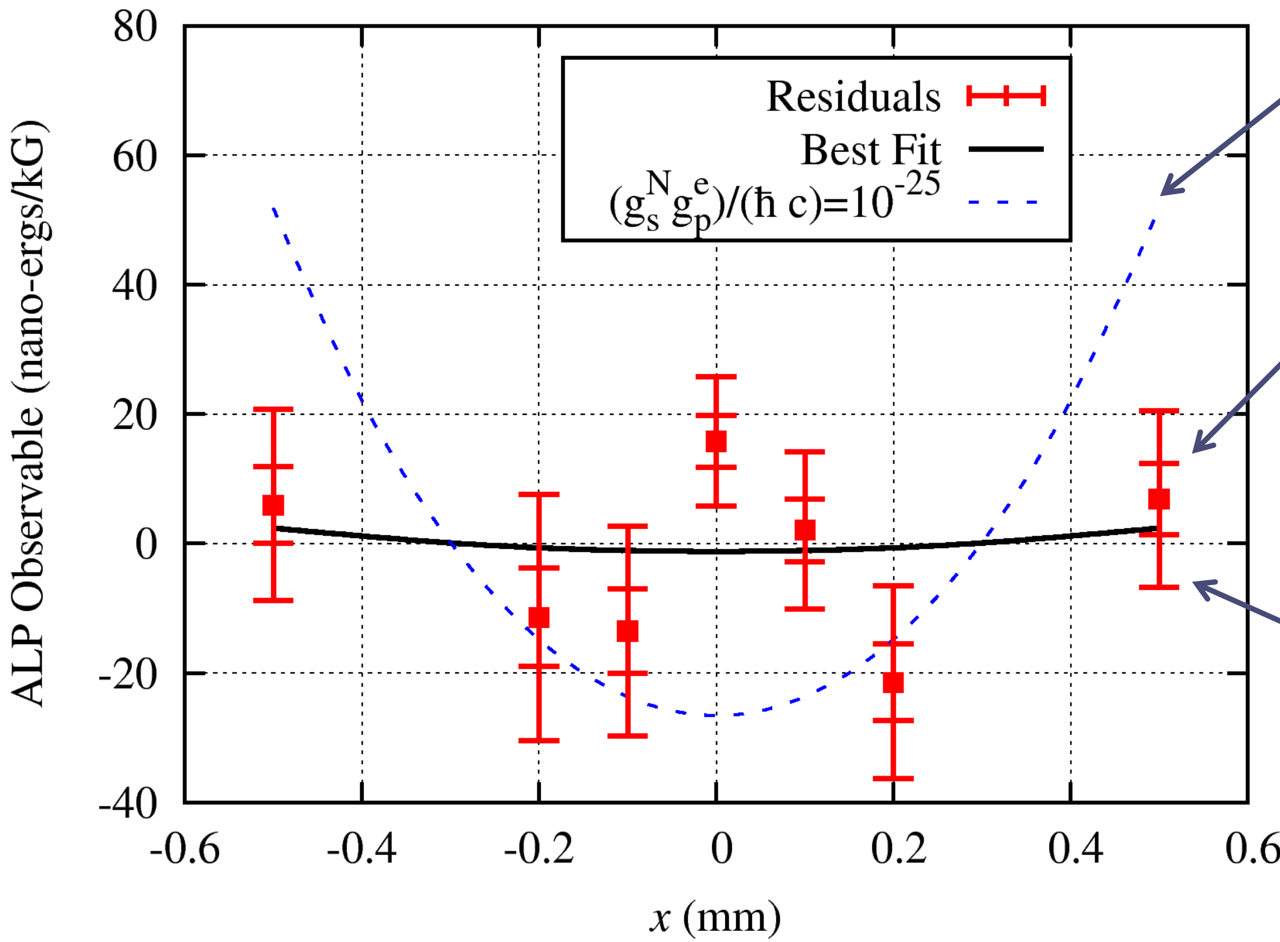


The axion signal is the equilibrium angle difference between the positive and negative magnet states

Observe ~1 micro-radians.
~(100 nano-erg/kG)

Is it an axion?

Fit residuals from planar model for ALP with $\lambda_a = 0.5$mm



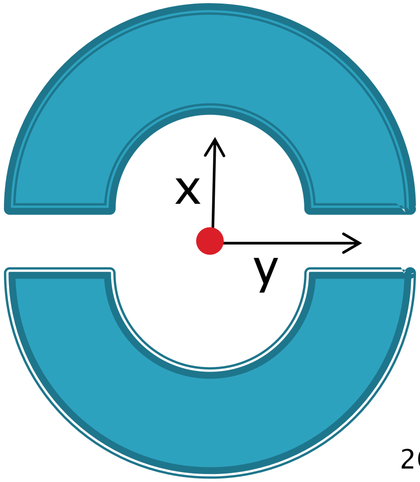
Example ALP signal

Original error bars from residuals scatter, typically ~5 nano-ergs/kG.

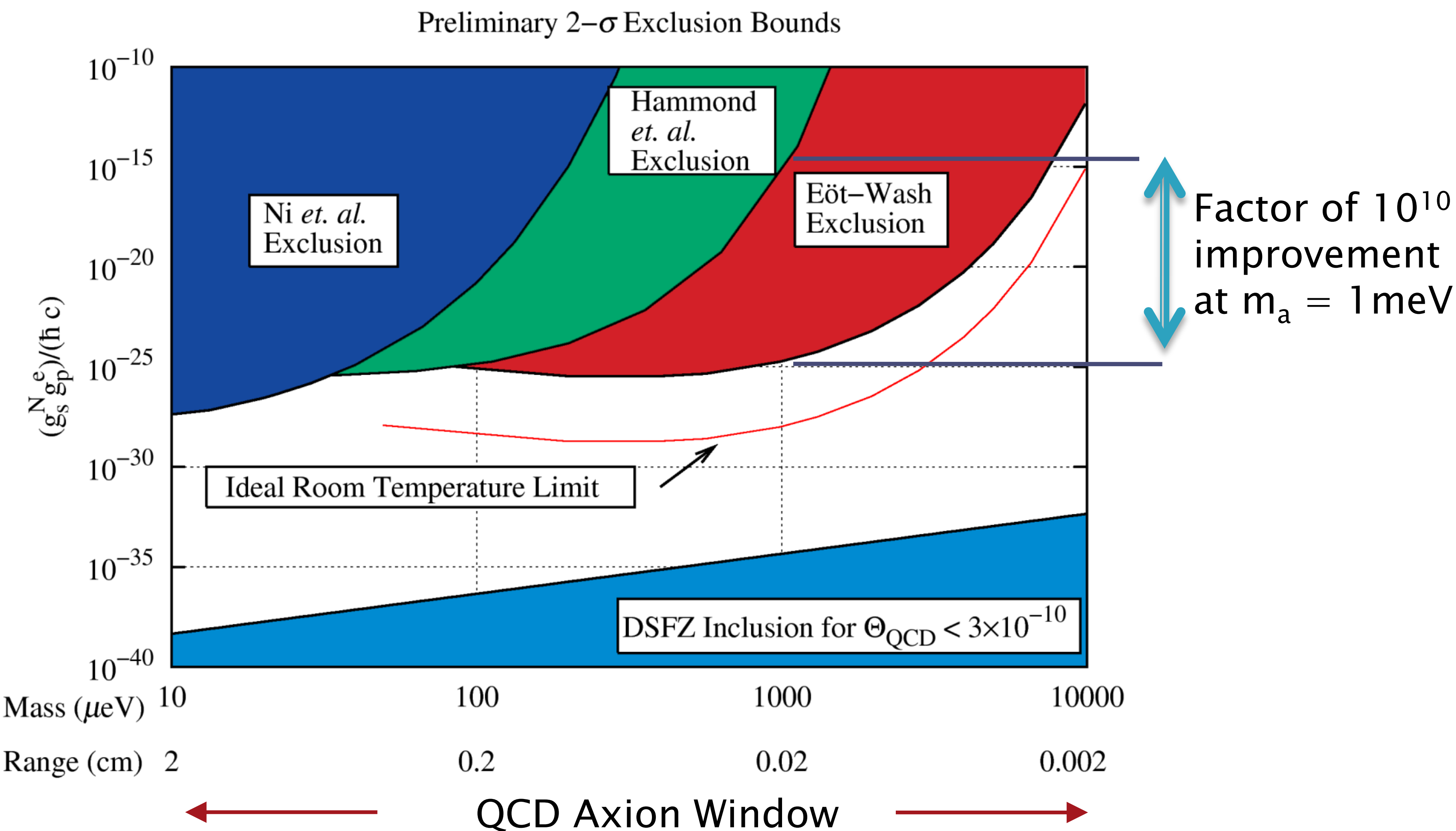
Scaled error bars, typically ~14 nano-ergs/kG

For λ = 0.5mm:

$$g_s g_p / \hbar c = (0.5 \pm 1.6) \times 10^{-26}$$



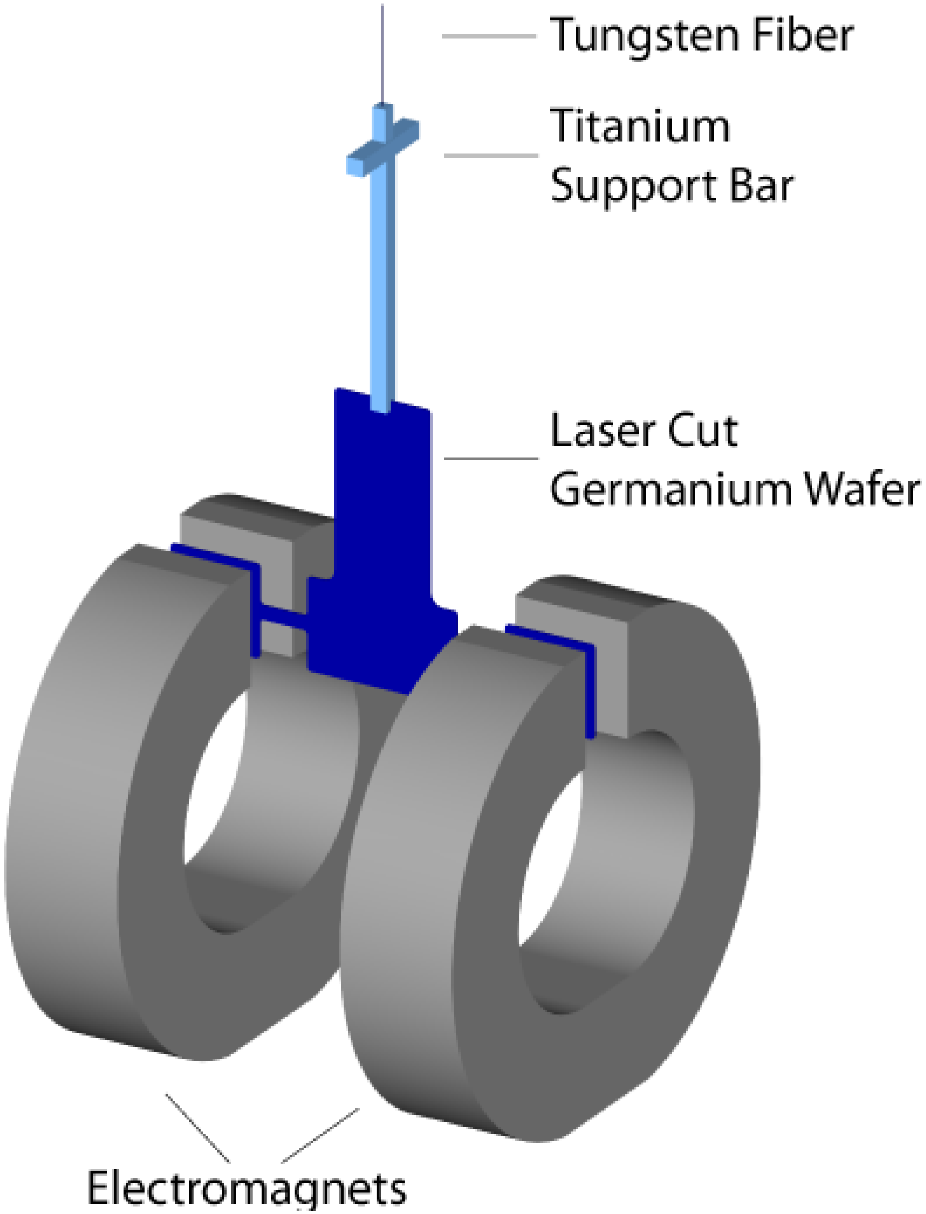
Preliminary exclusion plot



Future Improvements

- *Bigger Gap –In progress.*
- Iron/Nickel alloy ($\times$100?).
- Laminate ($\times$10?).
- Germanium ($\times$2).
- New Geometry.

Maybe thermal noise limited in the next iteration?

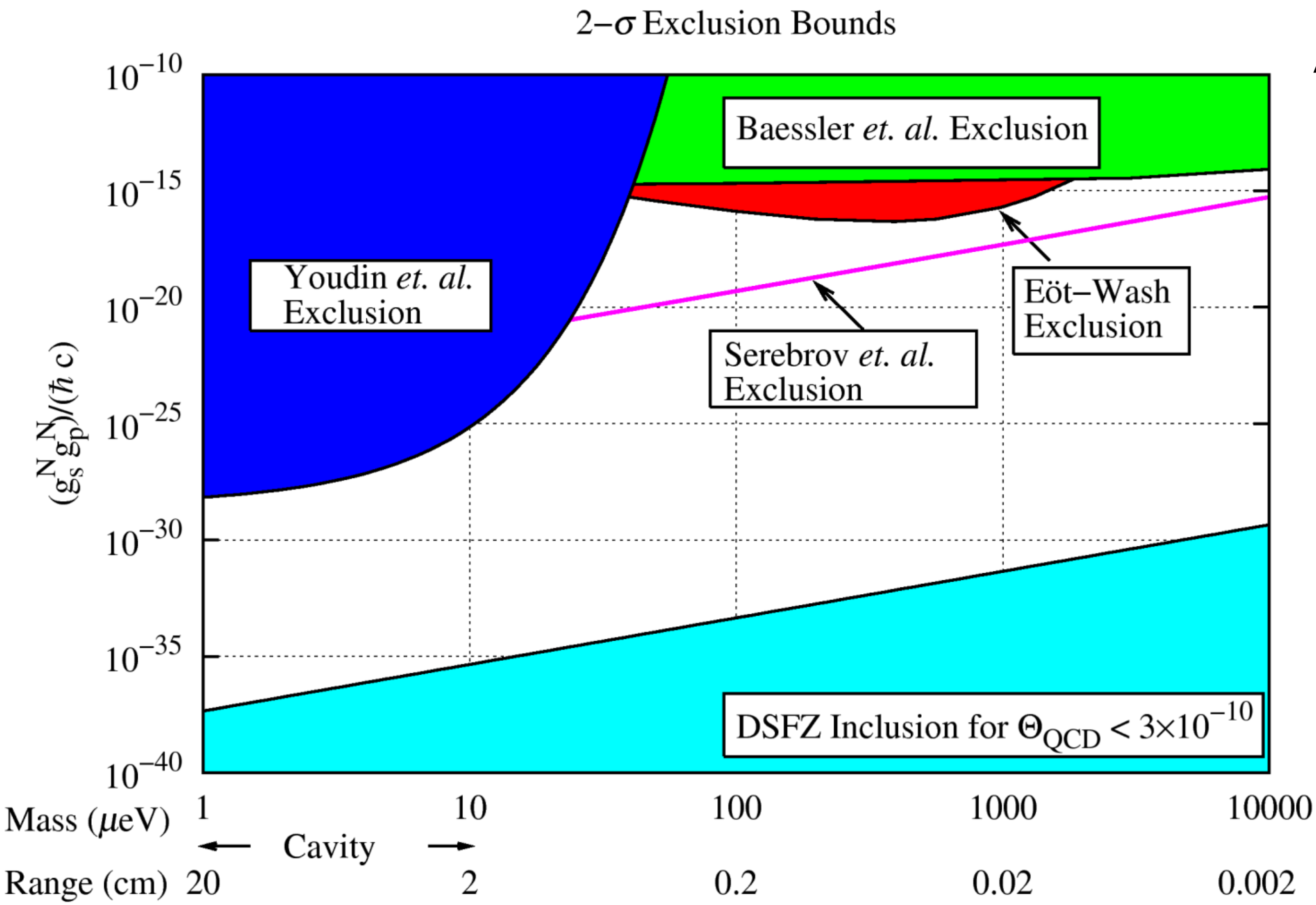


Summary

- Torsion pendulum experiments can make many interesting statements about gravitational scale particle physics.
- We have constrained the scalar coupling of the simplest WISP to two photons to be $g_{\phi\gamma\gamma} \leq 10^{-17}$ GeV^{-1}.
- The axion torsion pendulum has improved the bound on a macroscopic parity and time violating force by more than a factor of 10^{10} for axions or ALPs heavier than 1 meV.
- Future improvement is likely.
- Opened a path for other methods of searching for heavy axion-like particles.

Extra Slides

Preliminary exclusion plot on nucleon–nucleon ALP force

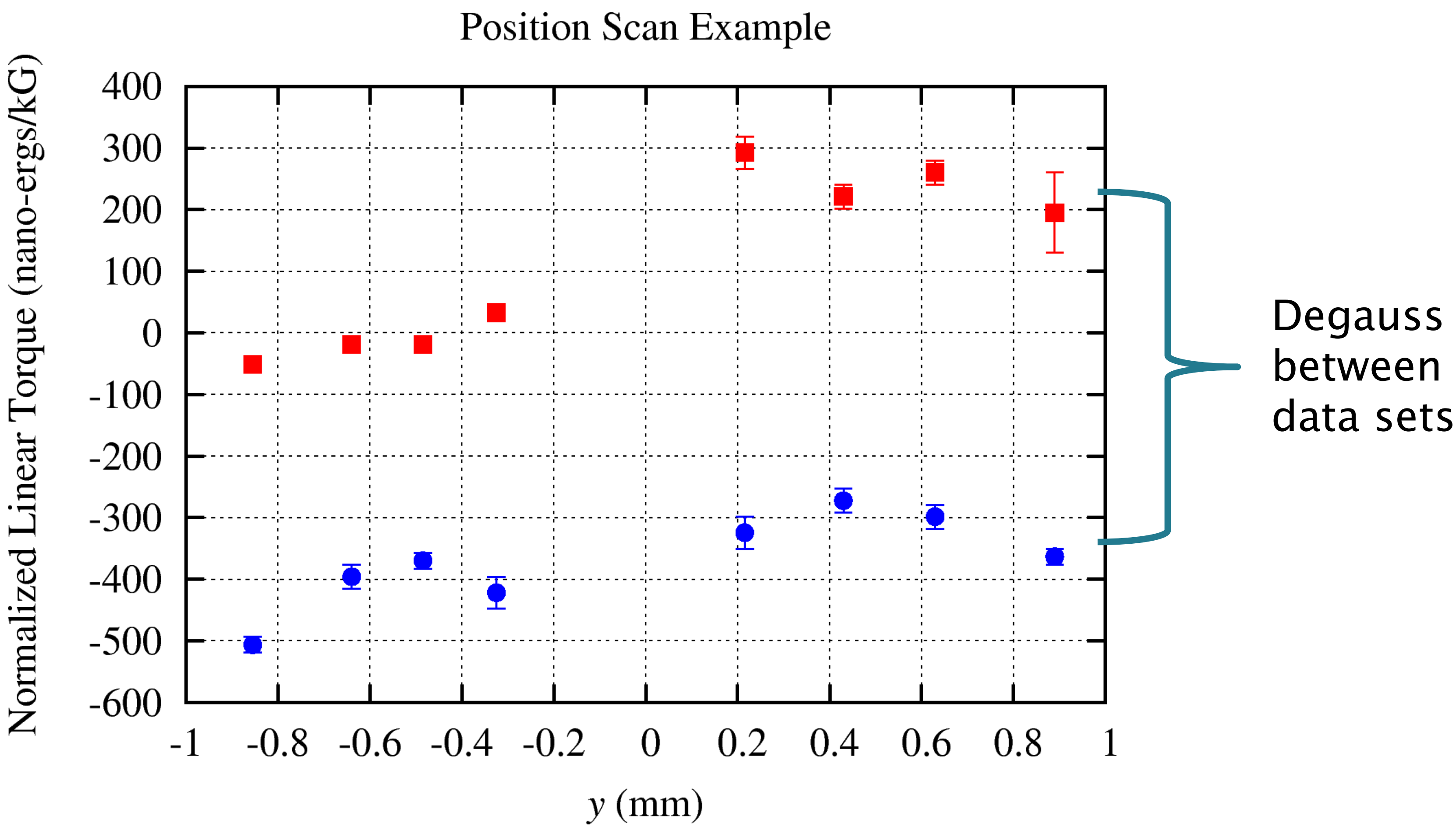


Assumes:

$P_{nuclear} = \mu_N B/k_B T.$
$= 1.2\times10^{-7}$ / kG

1.7×10^{-8} moles/cm^3

Degauss generated changes at different pendulum positions are correlated



The Recent Eöt-Wash Equivalence Principle Test

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

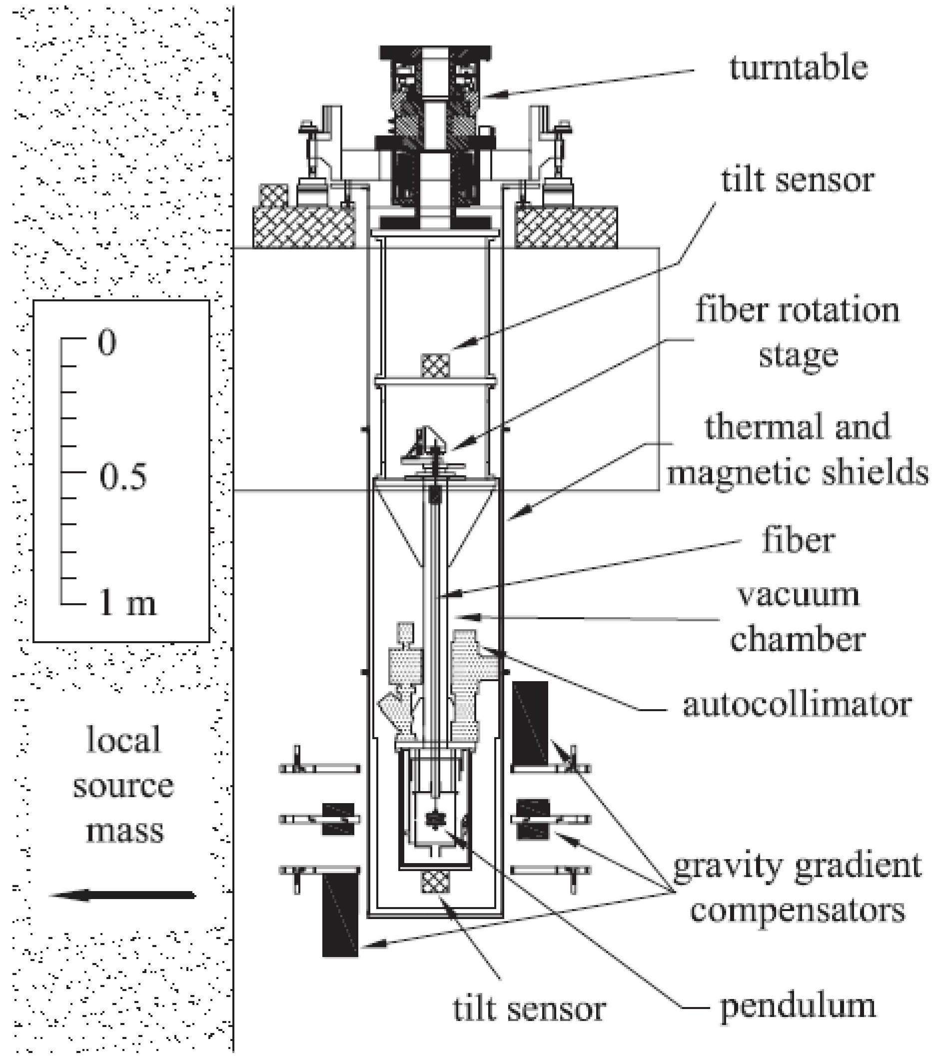
In this case we rotate instrument instead of attractor.

Rotation provided by

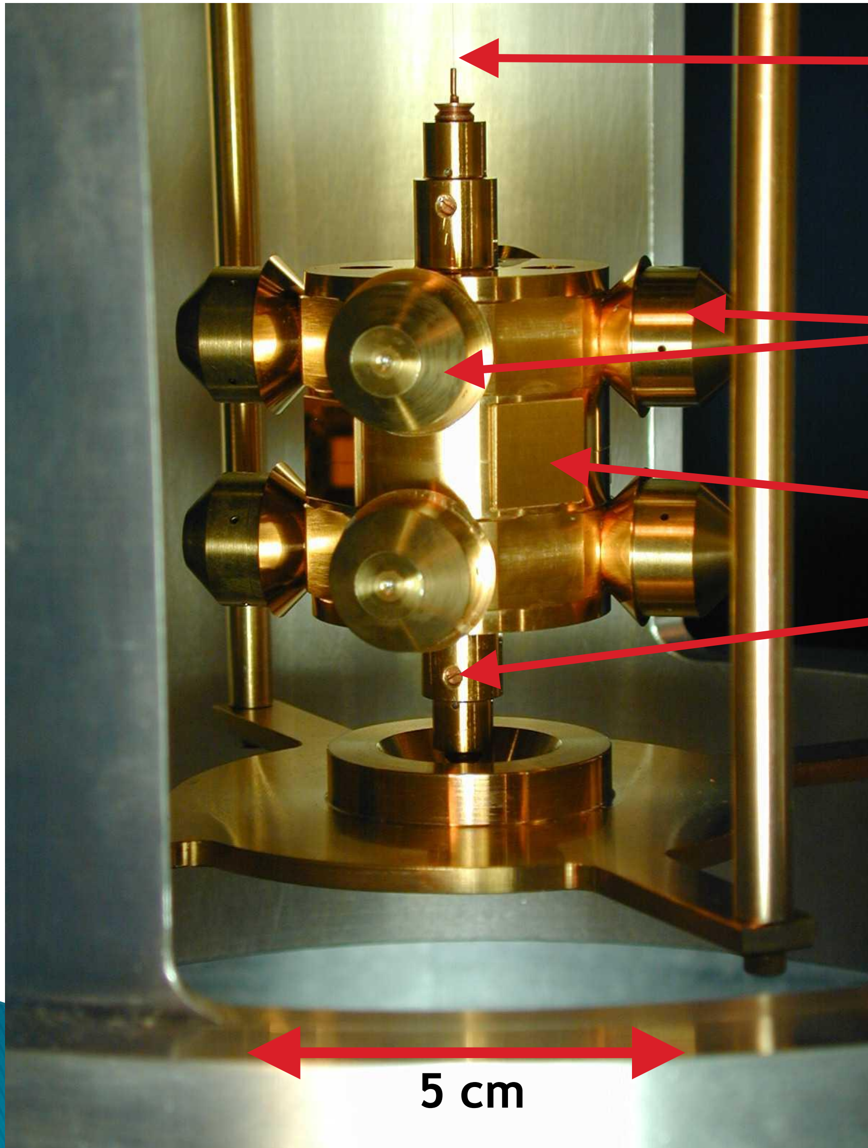
- Earth.

  And, most importantly,

- Air bearing turntable with 20 min rotation period.



Recent Eöt-Wash EP test torsion pendulum



20 μm diameter
108 cm long tungsten fiber

Eight 4.84 g test masses
(4 Be & 4 Ti) or (4 Be & 4 Al)
Mass matched to within 1 part in 10^5.
Mass moments minimized to $l = 6$.

4 mirrors

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

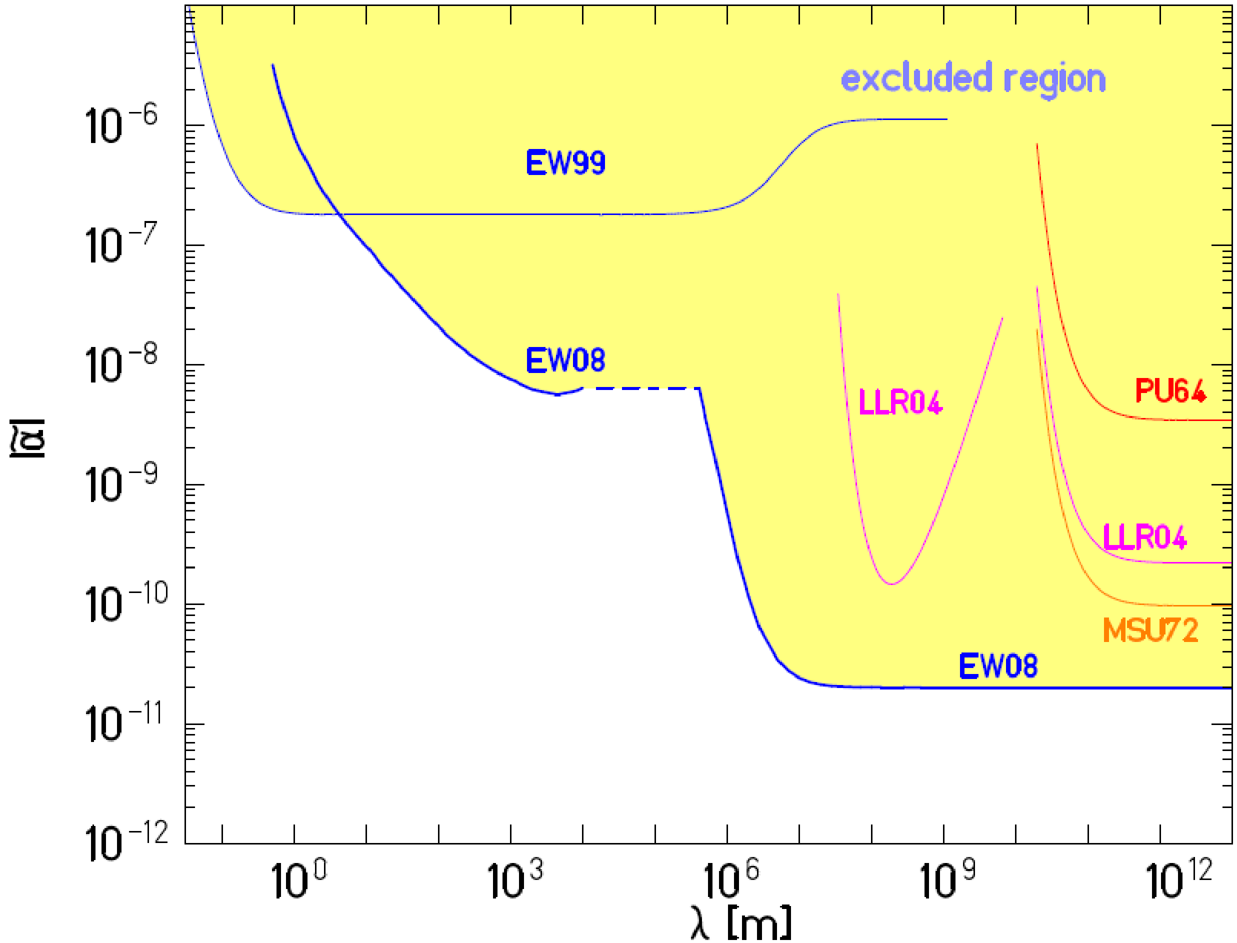
free osc freq:	1.261 mHz
quality factor:	4000
decay time:	11d 6.5 hrs
machining tolerance:	5 μm
total mass :	70 g

Constraint on a new force coupled to B-L

In Grand Unified Theories, Baryon-Lepton number is exactly conserved.

One expects neutron rich matter to be attracted towards distant objects differently than neutron poor matter.

2-σ exclusion plot for interactions coupled to B-L



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

Why is gravity so much weaker than the other forces?

Perhaps gravity is just as strong as the other forces – ***but*** – in our 4 dimensional world it appears much weaker because most of its strength acts in *n* other dimensions.

N. Arkani-Hamed *et al*. Phys. Lett. B 436 p.257 (1998).

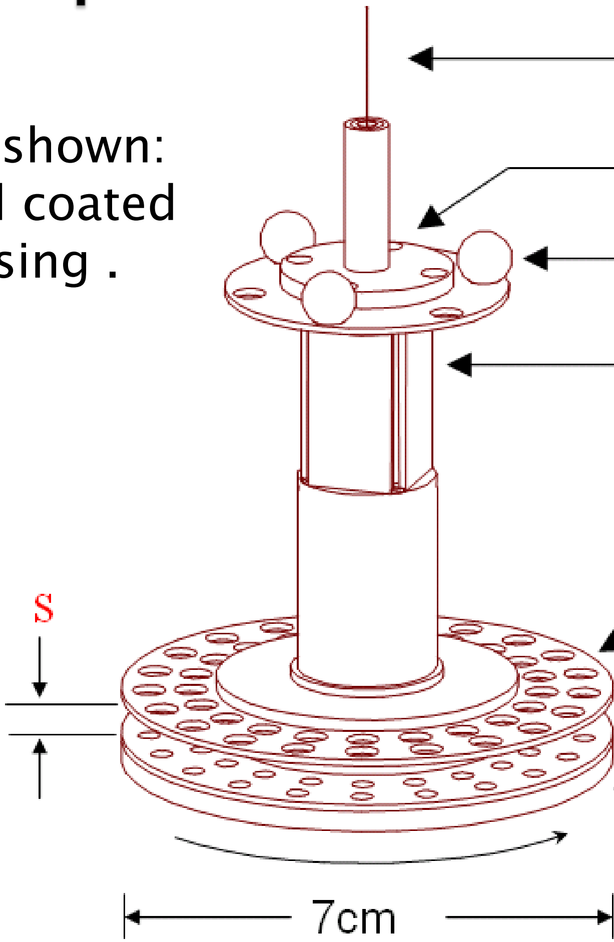
- Expect that gravity strengthens at scales comparable to the largest extra dimension.

Tests of the gravitational inverse square law at sub-mm distances are an excellent test of such theories.

Most recent published Inverse Square Law experiment

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

Not shown: gold coated housing .



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

4 mirrors for tracking angle of deflection

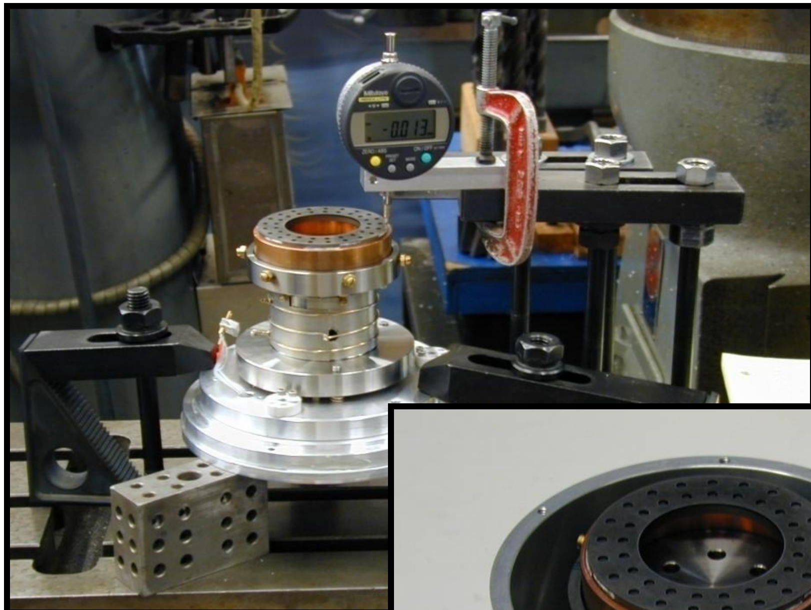
detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

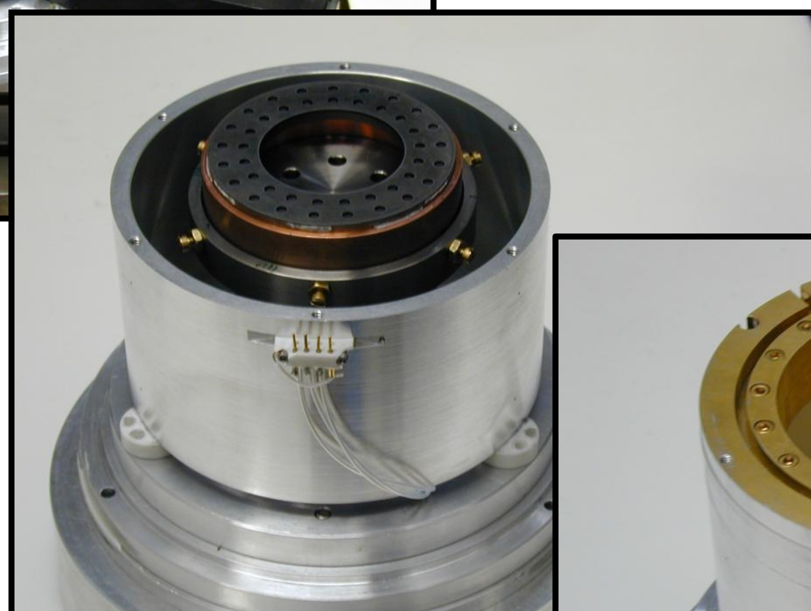
not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

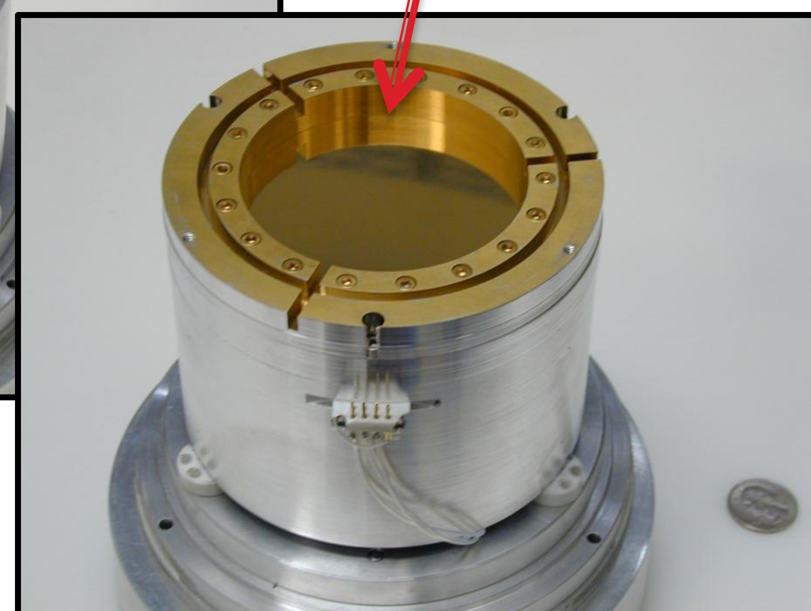
attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

Key features: Planar geometry maximizes mass. Signal at high multiple of disturbance frequency prevents spurious 1- ω signals and maximizes S/N.

Rotating attractor and its electrostatic shield

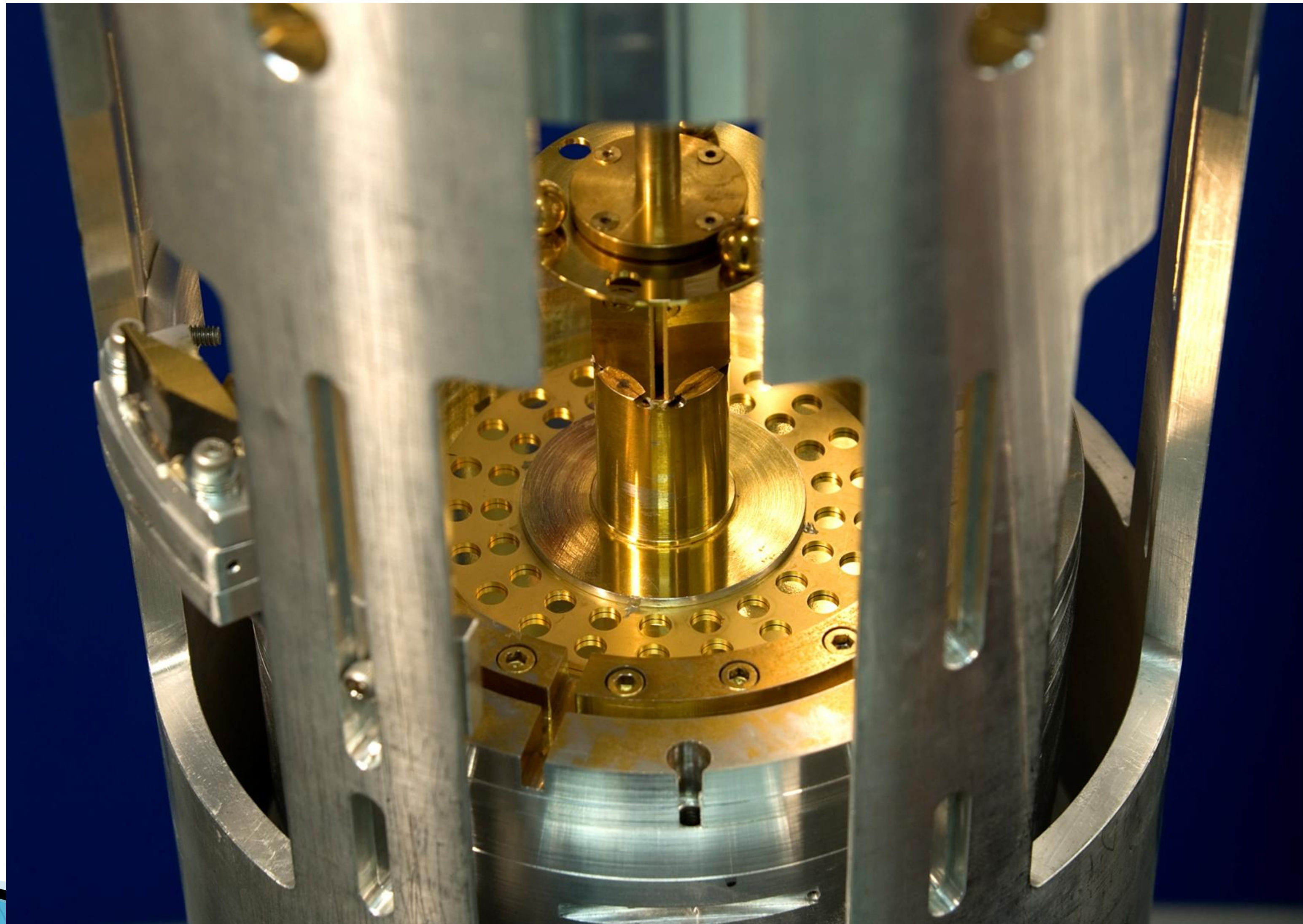






• Tightly stretched, 10-μm thick, Au-coated BeCu foil, 12 μm above rotating attractor, shields electrostatic effects.

The ISL pendulum with upper shield removed



Most recent published results from 42-hole ISL pendulum

$$V_G(r) = -G\frac{m_1 m_2}{r}\left(1+\alpha\cdot e^{-r/\lambda}\right)$$

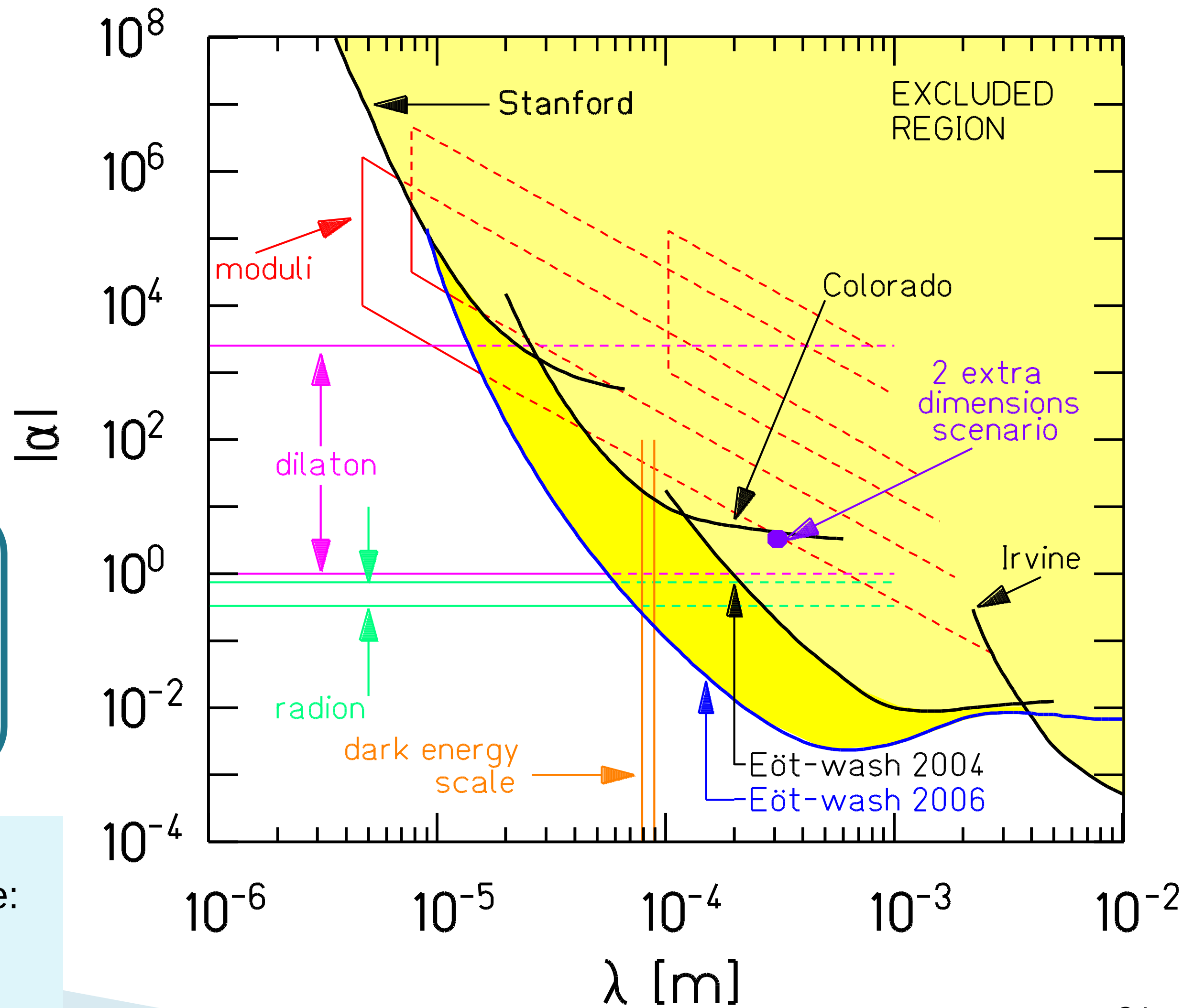
For $|\alpha| = 1$, $\lambda < 56\ \mu\text{m}$

Our 2-σ exclusion bounds imply that the maximum size of any extra dimension must be less than 44μm.

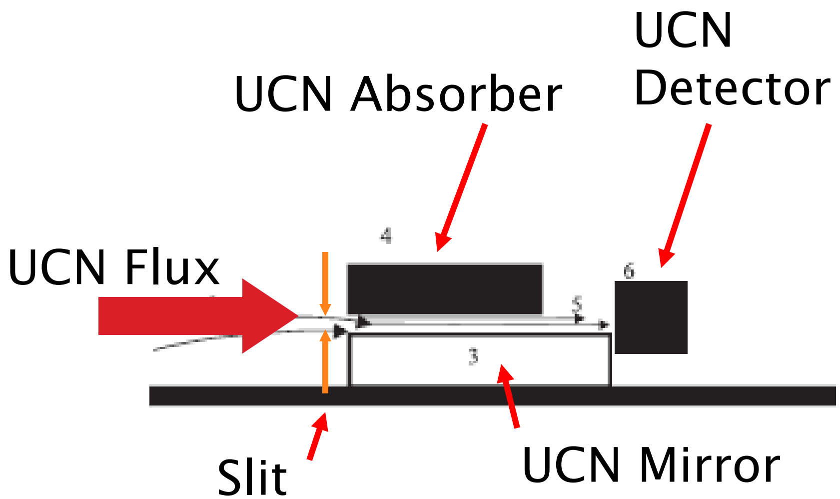
For thorough discussion of implications for particle physics see:

E.G. Adelberger *et al*., PRL **98**, 131104 (2007)

2-σ exclusion plot on non-gravitational forces

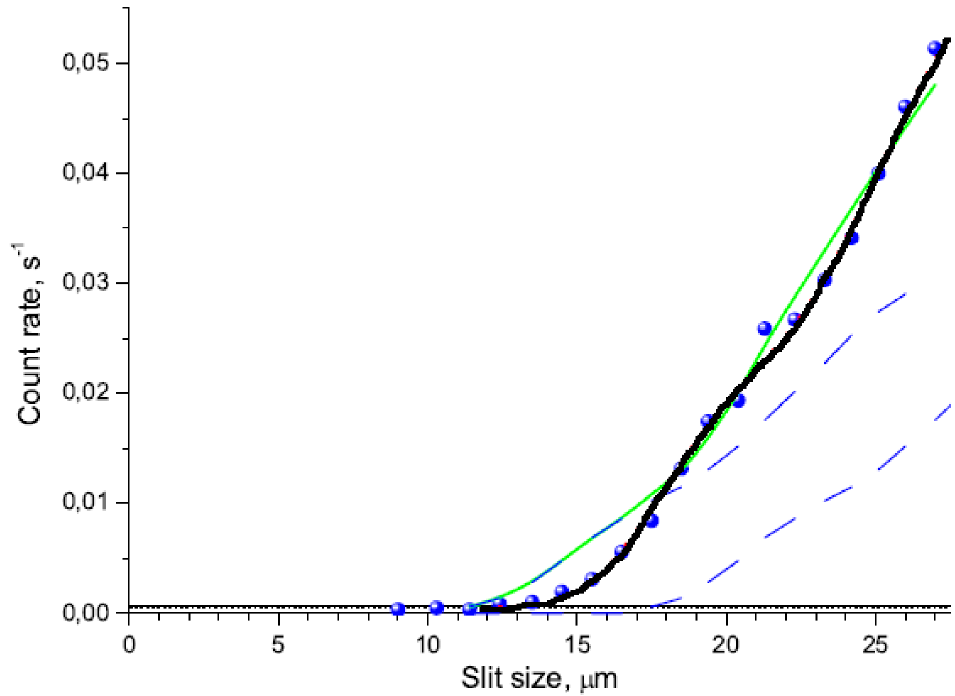


Probing axions with Ultra-Cold Neutrons



S. Baeßler *et al* PRD **75**, 075006 (2007)

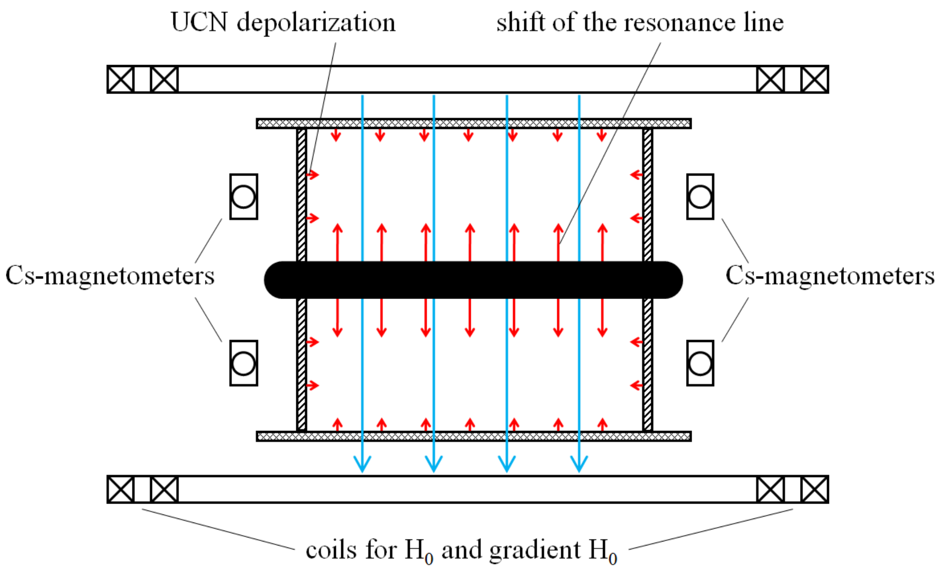
ALP force would change the energy levels of gravitational bound states.



$$g_s g_p / \hbar c < 2 \times 10^{-15}$$

For nucleon-nucleon ALP force.

Probing axions with Ultra-Cold Neutrons, part 2



Serebrov *et. al.* JETP Lett. **91**, 6 (2010)

ALP force acts as a "pseudo-magnetic" field, that would change UCN precession frequency.

Note: UCN are only sensitive to a nucleon-nucleon APL force.

What could it be?

A "Frozen" Ferromagnetic Impurity? $\vec{\mu} \cdot \vec{B}$

An asymmetry in the magnetic field? $\Delta\theta_m \kappa_m$

An asymmetry in the spring constant and a steady torque? $\left(\frac{\Delta\kappa}{\bar{\kappa}}\right)\kappa_f \bar{\theta}_{diff}\left(\frac{1}{1-\kappa_f/\bar{\kappa}}\right)$

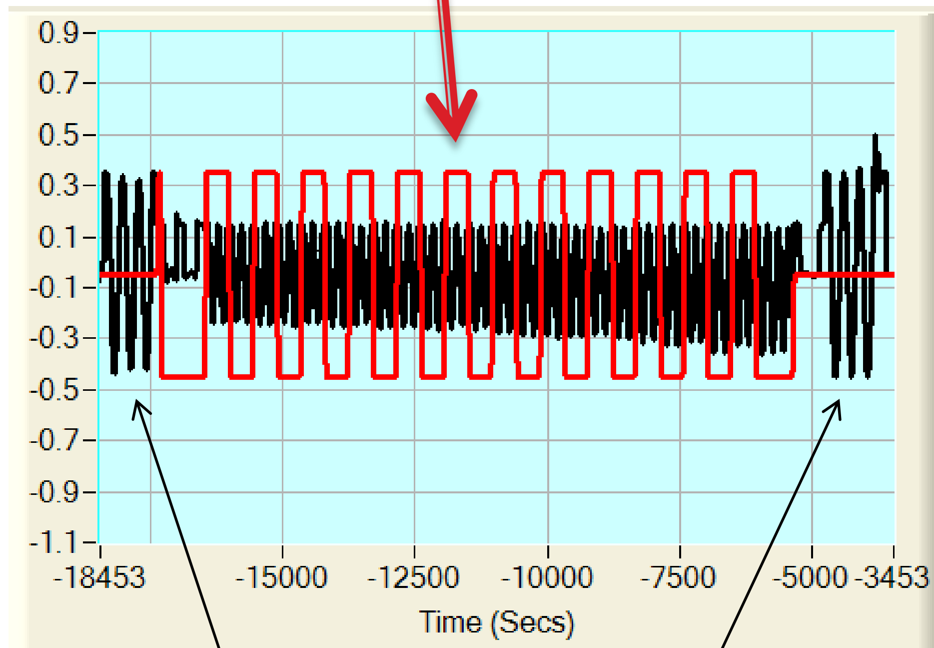
Some other asymmetry? $\Delta\theta_f \kappa_f$

An axion or ALP?

Approach: Fix apparatus asymmetries that generate false signals.
Correct for spring constant asymmetry.
Move pendulum to distinguish an ALP signal from other effects.
Explore how small asymmetries could mimic an ALP.

Torsion constant asymmetry correction…

Flip magnet current for 12 cycles.



Magnet torsion spring constant is typically a little different in the two magnet states (1 part in 10^3).

This asymmetry will generate a false signal by coupling to a steady torque.

Record free running period and equilibrium angle before and after magnet cycles.

We correct for this false effect.

Typically,
$\tau \sim 100 \pm 20$ nano-ergs/kG.
Correction < 8 nano-ergs/kG.

Torsion constant asymmetry is not source of signal

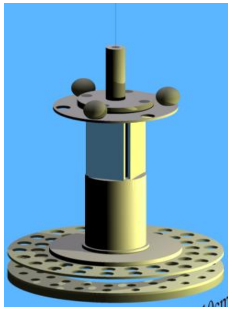
To exclude a ferromagnetic impurity and other false effects we must move the pendulum. But there are two complications…

Statistical Error Budget

Statistical Error	1-σ Uncertainty At $\lvert x \rvert = 0.50$ mm (nano-ergs/kG)	For $\lambda = 0.50$mm $g_s g_p / \hbar c$
Degauss Scatter	3.6	5.52×10^{-27}
Fit Scatter	1.9	2.87×10^{-27}
Spring Asymmetry Correction	0.2	3.72×10^{-28}
Thermal Noise	0.1	1.09×10^{-28}
Total Statistical Uncertainty	4.1	1.55×10^{-26}

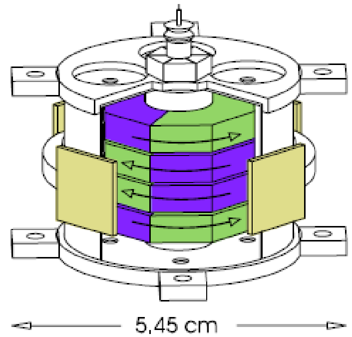
Planar Model Uncertainty = 9.2 nano-ergs/kG

Eöt-Wash torsion pendulums presently explore new physics…



"Short-Range"

- Best sub-mm test of gravity.
- ISL holds to 56 μm.
- PRL **98**, 021101 (2007)
- T. Cook, D. Kapner, C.D. Hoyle

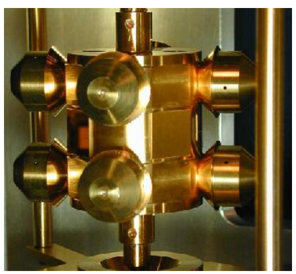


"Spin-Pendulum"

- Best limit on anisotropy of space:

$$\vec{\sigma}\cdot\vec{B}_{eff} < 5\times10^{-21} eV$$

- PRL **97** 021603 (2006).
- C. Cramer



"New-Wash"

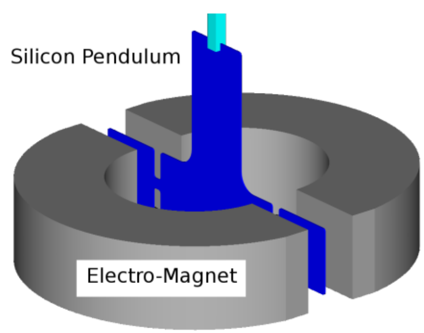
- Best test of the Equivalence Principle.
- $\Delta a < 3\times10^{-15}$ m/s^2
- PRL **100** 041101 (2008)
- S. Shlamminger, T. Wagoner, K.Y. Choi

"Plate-Wash"

- New Sub-mm gravity test.
- C. Hagedorn

"Cryo-Wash"

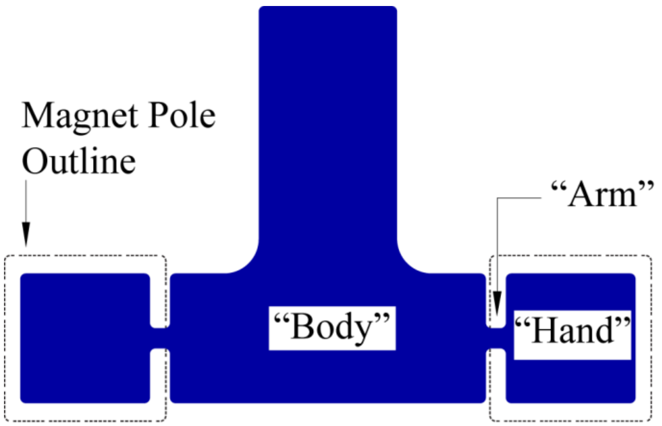
- Cryogenic test of Equivalence Principle
- F. Fleischer



"Axion Pendulum"

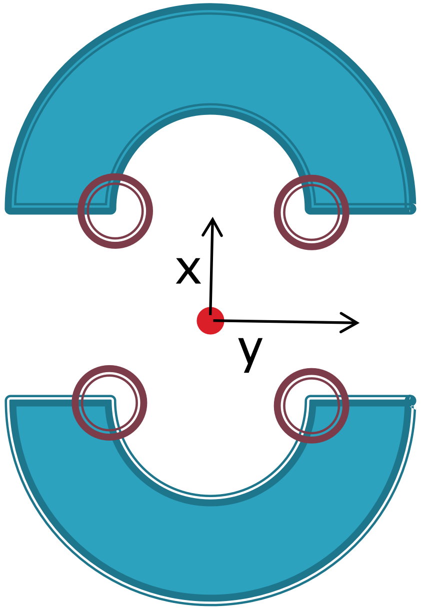
- Searching for axions or axion-like particles.
- This talk.

What explains this behavior?



A pico-gram of polarized iron on the pendulum:

- Would generate a 100 nano-erg/kG torque.
- But, it would have to be located only on ***both*** pendulum "arms" or edge of the "body" and ***not*** on pendulum "hands" in order to explain linear *y* dependence.



Alternatively, a magnetic material inhomogeneity at pole face edges:

- Generates a fixed field or gradient that does not follow electric current.
- Would explain the linear *y* dependence.
- Is likely to change after each degauss.

Strategy

- Degauss
- Measure linear torque at 8 positions in horizontal plane.
- Fit planar model to each "position scan" and calculate residuals.
- Average residuals at each position: the ALP Observable

For each ALP range, λ:

- Calculate best fit ALP signal.
- Scale error bars so that $\chi^2/\nu = 1$.
- Estimate 95% uncertainty by calculating contour where $\Delta\chi^2 = 3.95$ with scaled error bars.

Could a systematic error mimic an axion?

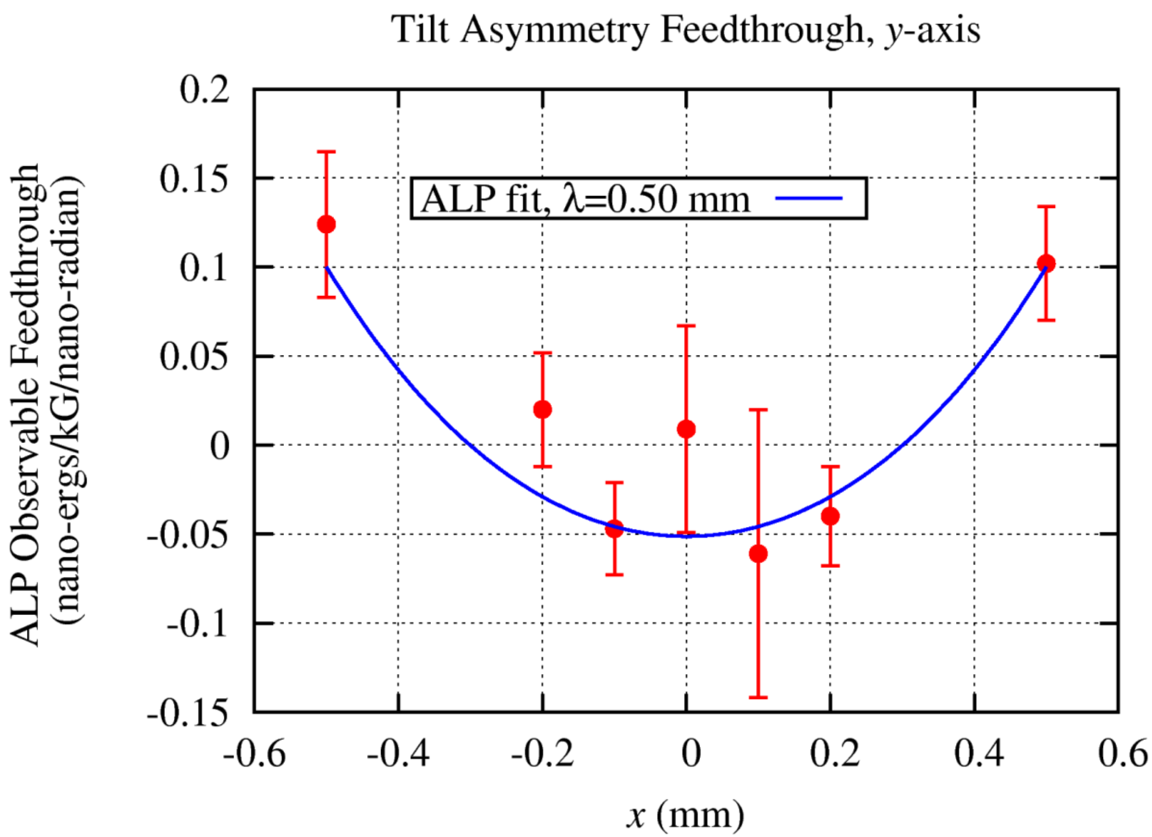
If the position dependence of the pendulum's response to any asymmetry in the apparatus scales like cosh(x), then a false ALP signal will be observed or a true ALP signal hidden.

We explored the position dependence of five different types of asymmetries:

- Magnet temperature.
- Apparatus tilt.
- Absolute value of the magnetic field.
- Laboratory magnetic field.
- Laboratory magnetic field gradient.

- For each systematic error we:
  - Measure "Feedthrough" at each pendulum position.
  - Fit with the planar model and calculate "ALP Observable feedthrough."
  - Fit these ALP Observables to ALP model.
  - Multiply best fit ALP force strength by size of the asymmetry to calculate correction.

Greatest systematic error: Magnetic field dependent Tilt about y-axis.



Y-Axis Tilt Asymmetry: $+2.20 \pm 3.30$ nano-radians

Correction at $|x| = 0.5$ mm: $+0.24 \pm 0.37$ nano-ergs/kG

Other asymmetries generate even smaller false ALP signals.

Systematic Error Budget

Systematic Error	Correction: At $\lvert x \rvert = 0.50$ mm (nano-ergs/kG)	Correction: For $\lambda = 0.50$mm $g_s g_p / \hbar c$
Tilt Y-Axis	0.2433 ± 0.3691	$(4.25 \pm 6.43)\times 10^{-28}$
Tilt X-Axis	-0.0122 ± 0.1798	$-(0.23 \pm 3.73)\times 10^{-28}$
Magnetic Field Asymmetry 4A	0.0195 ± 0.1263	$-(0.00 \pm 1.86)\times 10^{-28}$
Temperature Asymmetry	-0.0467 ± 0.0506	$-(9.60 \pm 9.53)\times 10^{-29}$
Magnetic Field Asymmetry 8A	0.0133 ± 0.0145	$(3.24 \pm 3.32)\times 10^{-29}$
External Parallel Field	0.0066 ± 0.0078	$(1.39 \pm 1.18)\times 10^{-29}$
External Perpendicular Gradient	-0.0004 ± 0.0056	$(-0.81 \pm 8.81)\times 10^{-30}$
External Perpendicular Field	0.0019 ± 0.0045	$(1.73 \pm 7.04)\times 10^{-30}$
External Parallel Gradient	-0.0006 ± 0.0010	$-(1.05 \pm 1.72)\times 10^{-30}$
Total Systematic Correction	0.2258 ± 0.4329	$(3.51 \pm 7.73)\times 10^{-28}$

Largest

Smallest

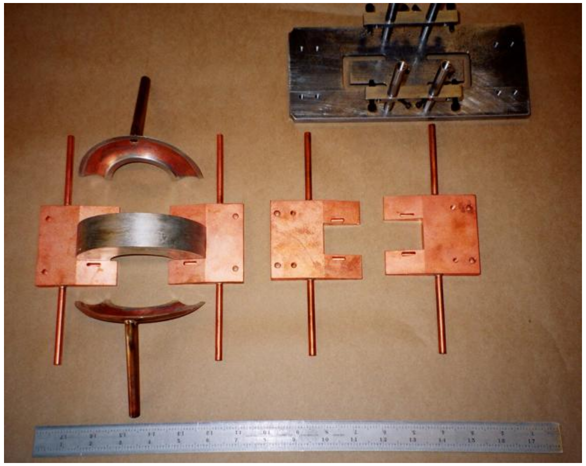
Compare with planar model uncertainty of ~9 nano-ergs/kG

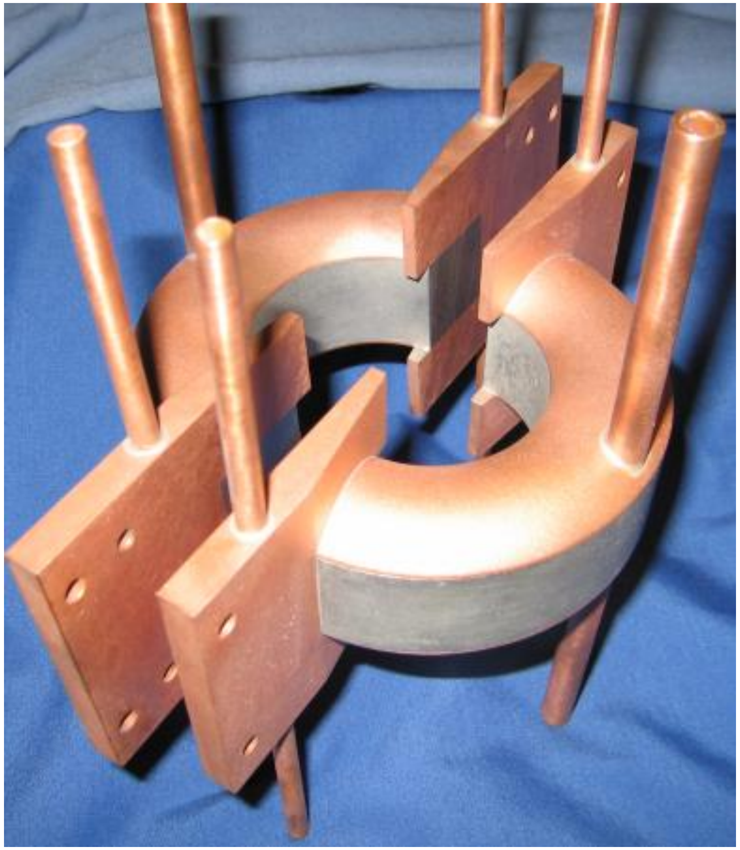
Safely ignore all systematic errors
…for now.

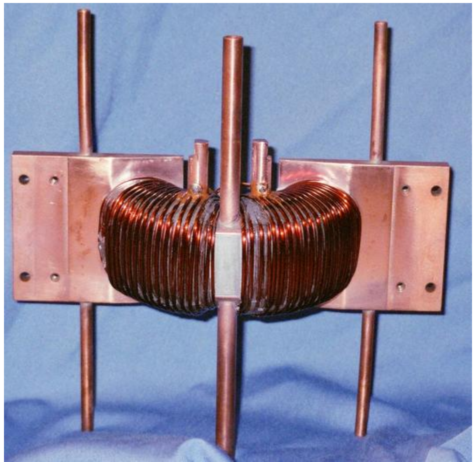
The Homemade Magnet

Needs to be:

- Temperature stabilized.
- Vacuum compatible.
- Minimal histersis.





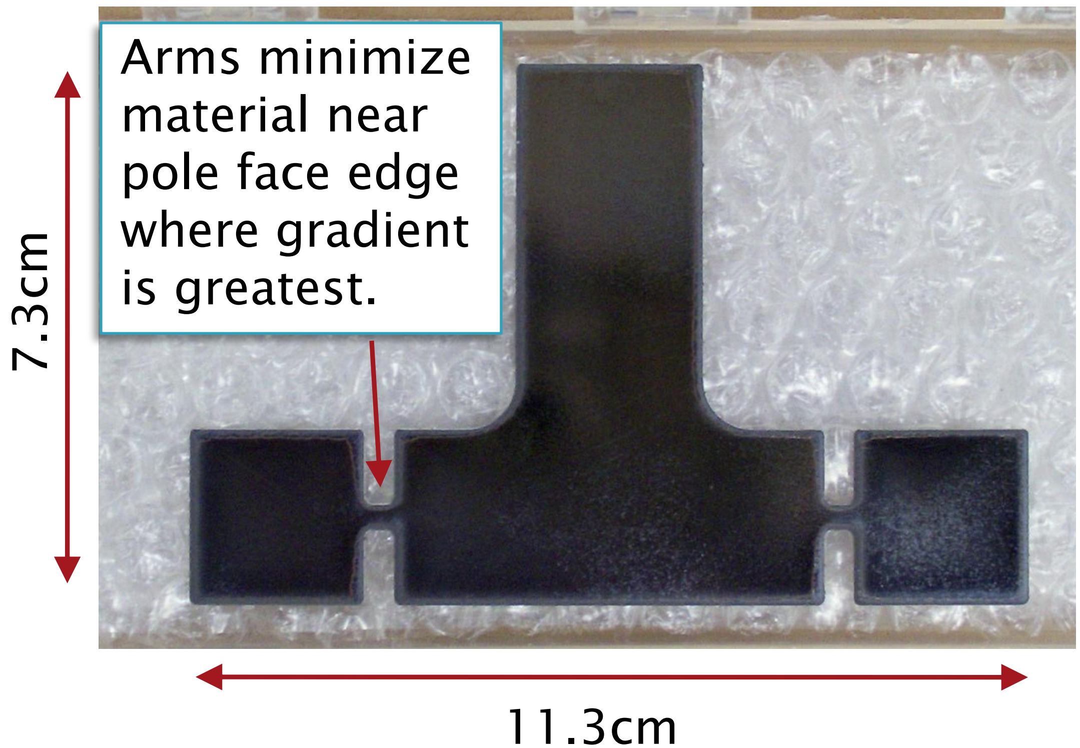


At 8A (24W), 3mm gap:

- 3.1kG
- Symmetric to 1 part in 10^5.
- Temperature stabilized to 0.01°C.

Fabricating the Pendulum…

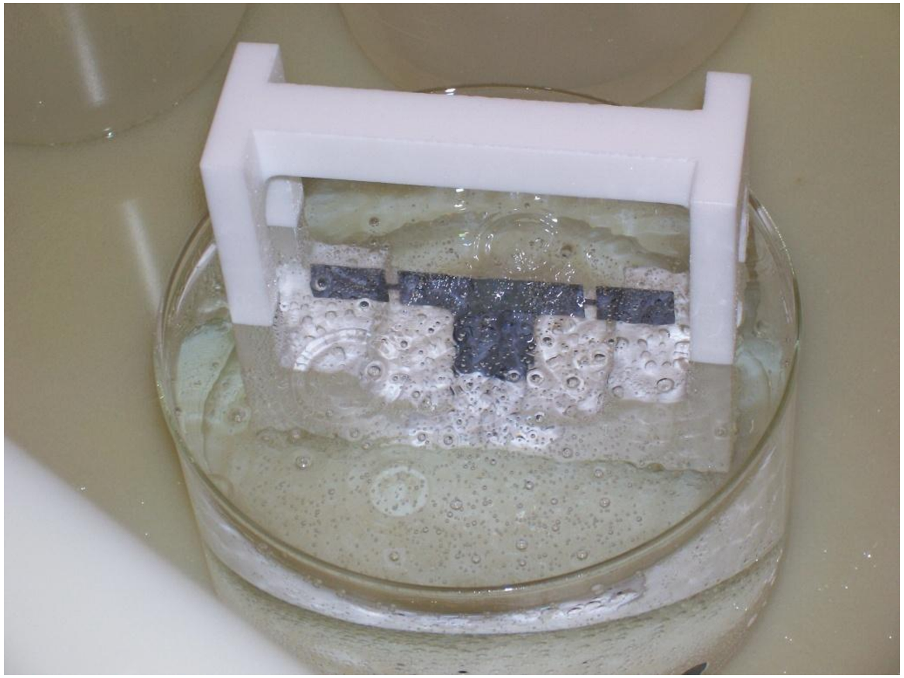
Shape chosen to minimize effect of magnetic field.



Sensitive to 20 femto-grams of polarized Iron.

- Pendulum made of single crystal silicon (pure to 1 part in 10^{10}).
- Never contacts metal tools (laser cut).
- Carefully cleaned.

Cleaning a Pendulum…

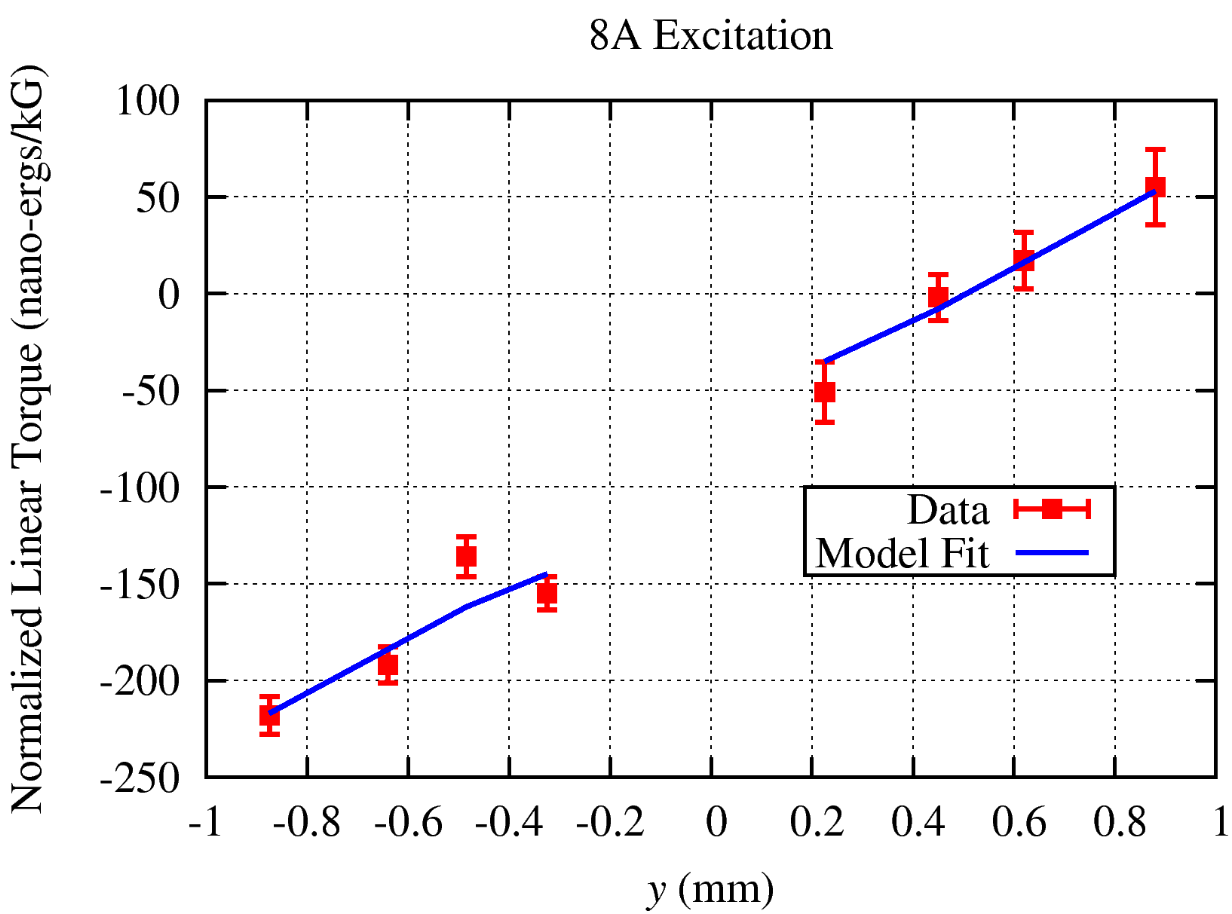


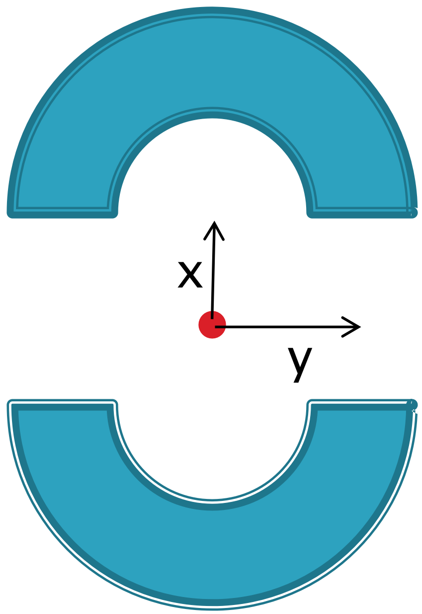
Three Step Process:

- Strong Solvent
- Boiling NH_4OH/H_2O_2 (RCA1)
- Boiling HCl/H_2O_2 (RCA2)

< 10^{10} Fe atoms/cm2
< 10 pico-grams

Linear torque depends on position parallel to pole face…

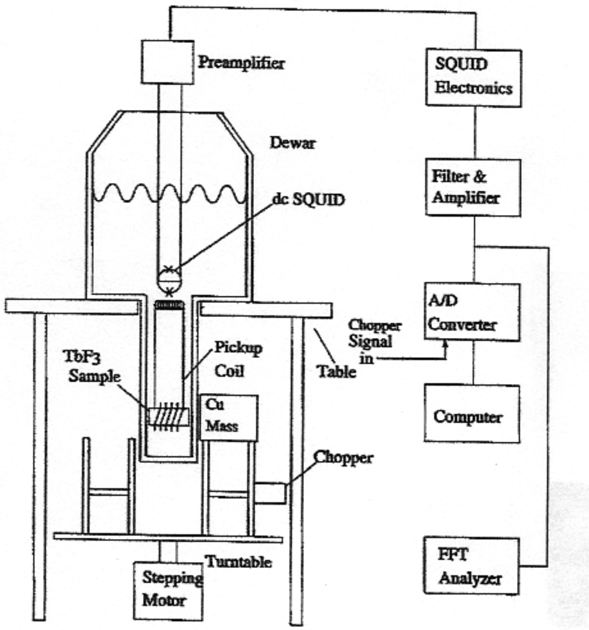




Planar Model: $\tau = k + a \cdot y + b \cdot x$

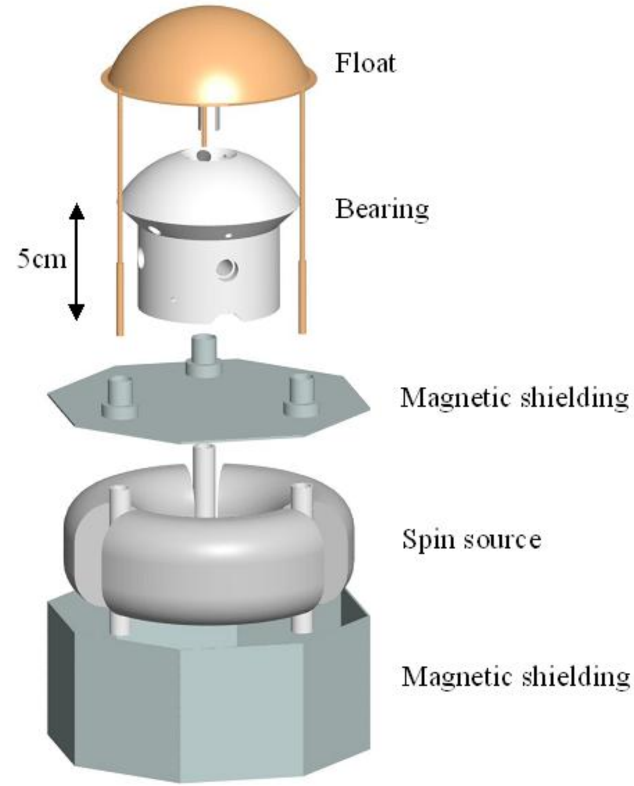
Not an Axion!

Most recent short-range macroscopic force tests



W.T. Ni *et al* PRL **82,** 2439 (1999)

Measured the induced magnetization of a paramagnetic salt as a function of the position of a copper mass.



Hammond *et al* PRL **98** 081101 (2007)

Measured torsion angle of levitating pendulum as polarization of adjacent magnet flipped.

Note that Ultra-Cold Neutron experiments are also sensitive to an ALP mediated nucleon-nucleon force.

Are there forces weaker than gravity?

String or M theory provides a promising framework to unify gravity with other forces in nature. Predicts 100's of massless scalar particles with composition dependent gravitational strength couplings.

The Equivalence Principle,

All objects, independent of composition, fall at the same rate in a ***uniform*** gravitational field.

is an ideal test of such forces.

The Recent Eöt-Wash Equivalence Principle Test

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

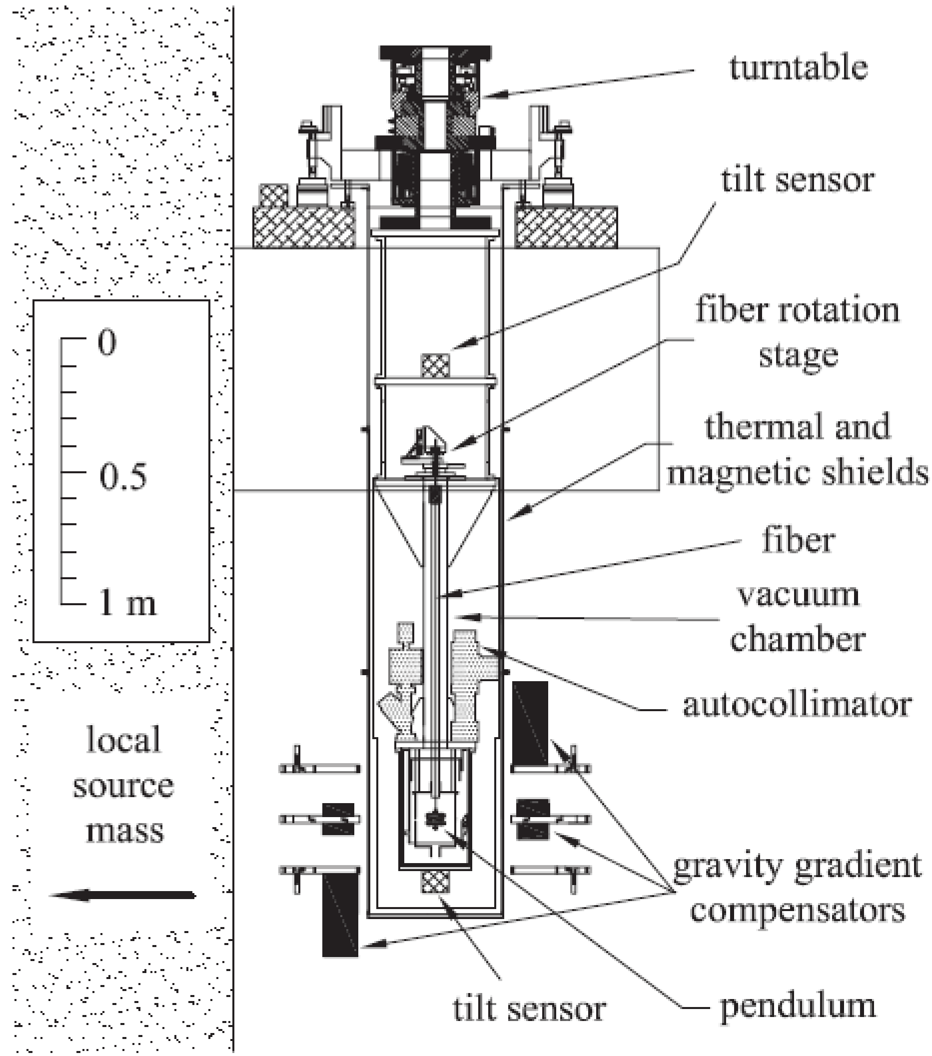
In this case we rotate instrument instead of attractor.

Rotation provided by

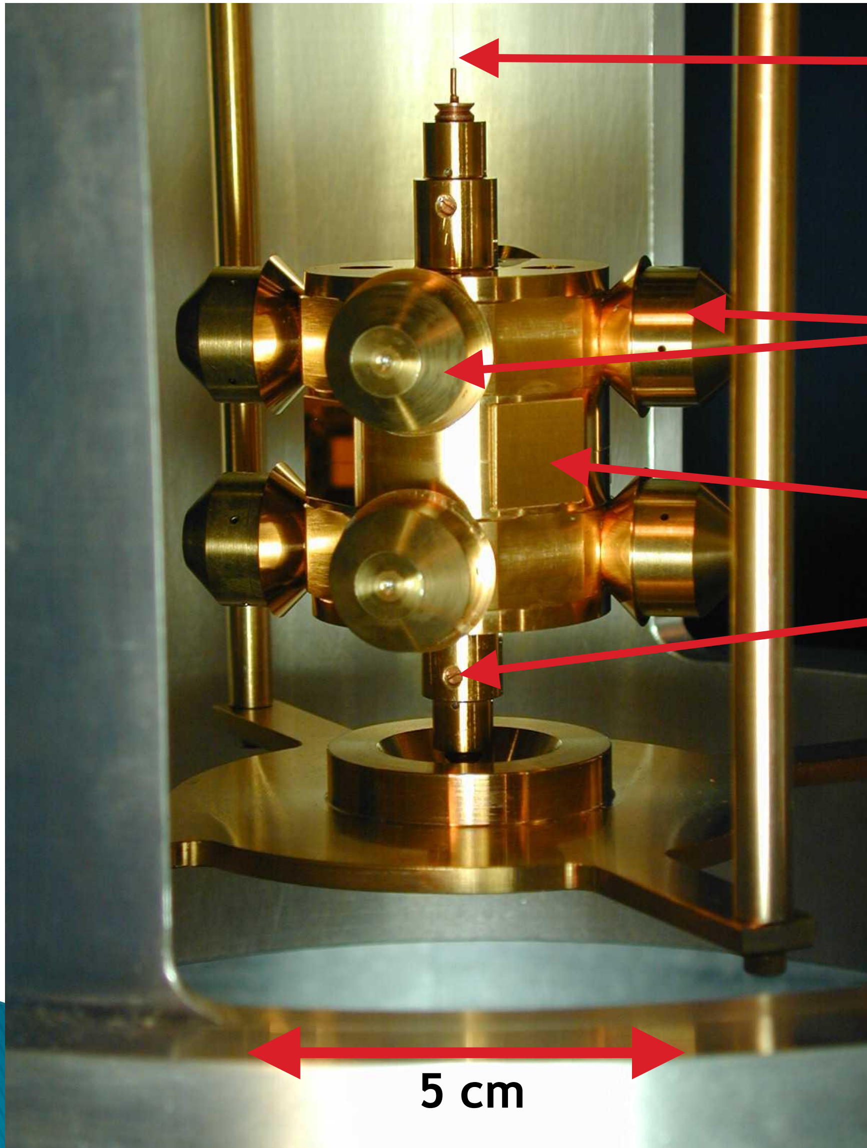
- Earth.

  And, most importantly,

- Air bearing turntable with 20 min rotation period.



Recent Eöt-Wash EP test torsion pendulum



20 μm diameter
108 cm long tungsten fiber

Eight 4.84 g test masses
(4 Be & 4 Ti) or (4 Be & 4 Al)
Mass matched to within 1 part in 10^5.
Mass moments minimized to l = 6.

4 mirrors

4 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

Most Recent EP test results for Ti/Be materials

Source	Δa (cm/s^2)	$\Delta a/a_{source}$
Earth	$(+0.6 \pm 3.1)\times 10^{-13}$	$(+0.3 \pm 1.8)\times 10^{-13}$
Sun	$(-2.4 \pm 2.8)\times 10^{-13}$	$(-4.0 \pm 4.7)\times 10^{-13}$
Milky Way	$(-2.1 \pm 3.1)\times 10^{-13}$	$(-1.1 \pm 1.6)\times 10^{-5}$
CMB	$(-2.9 \pm 2.7)\times 10^{-13}$	$(-2.1 \pm 1.9)\times 10^{-3}$

1-σ uncertainties dominated by thermal noise in fiber (statistical) and residual gravity gradients (systematic).

- Our differential acceleration resolution is comparable to the difference in g between 2 spots in this room separated vertically by $\approx$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.

Are there weak forces coupled to B–L ?

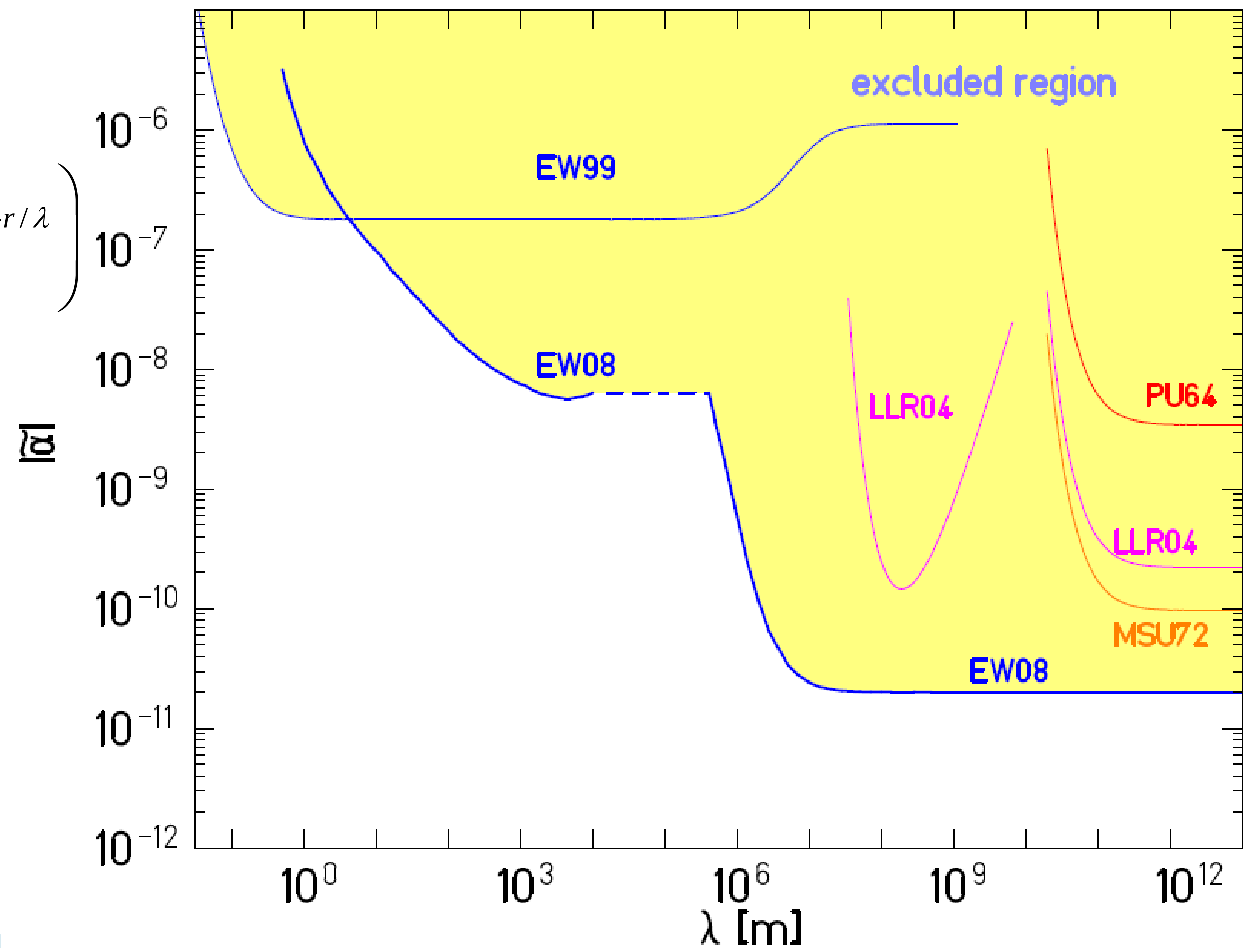
In GUTs, B–L is exactly conserved, thus one expects yukawa couplings to B–L.

2-σ exclusion plot for interactions coupled to B-L

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

$$\tilde{\alpha} = \pm\frac{\tilde{g}^2}{4\pi\, G u^2}$$

For electrically neutral matter, B–L coupling implies: $\tilde{q} = N$



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

Most of the galaxy (90%) is thought to be dark matter.

At the Earth's location,

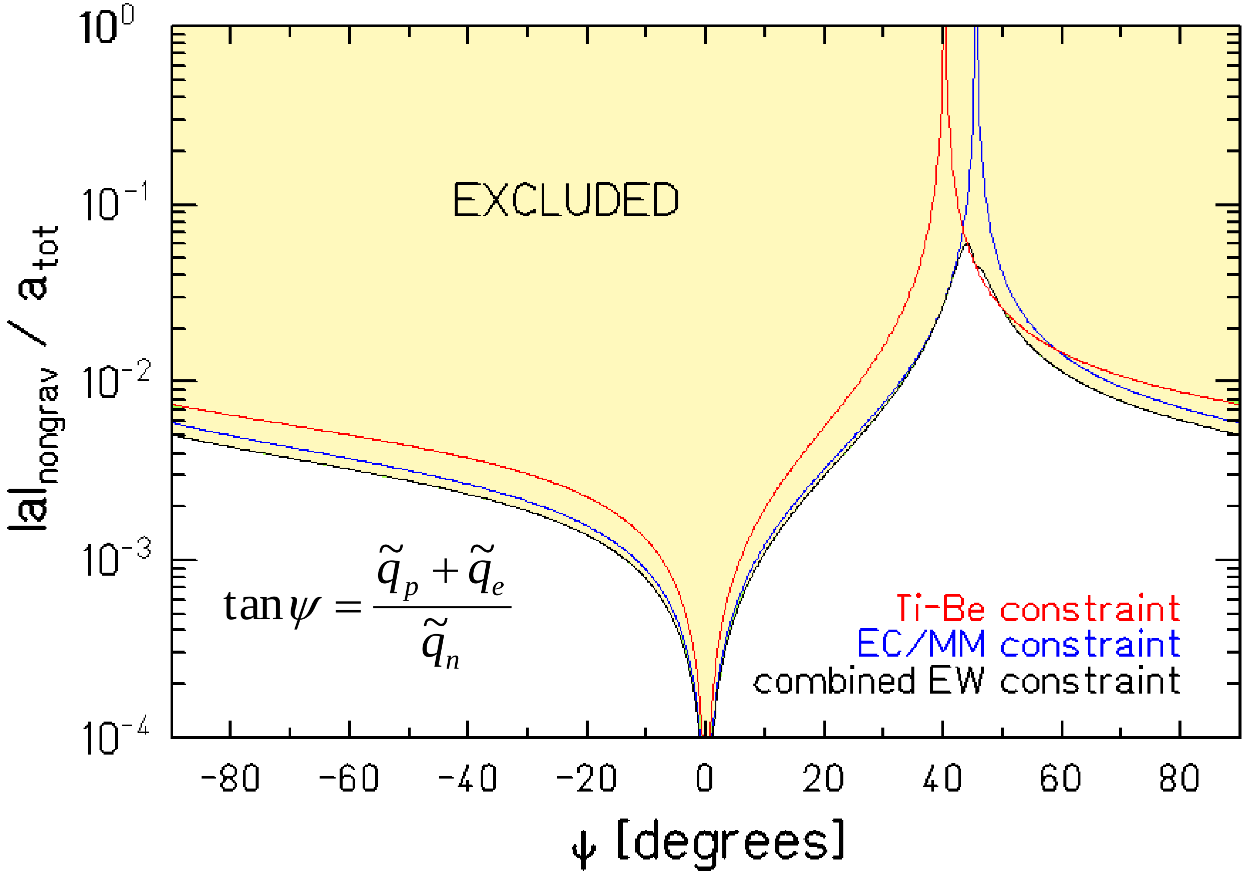
$$a_{gal} \approx \tfrac{3}{4}\, a_{matter} + \tfrac{1}{4}\, a_{dm}$$

$$a_{dm} \approx 5\times10^{-9}\ \mathrm{cm/s^2}$$

By looking for an EP violation towards the center of the galaxy, we can constrain the differential acceleration of different elements to dark matter.

C.W. Stubbs, PRL 70, 119 (1993)

2-σ exclusion limits on non-gravitational acceleration of hydrogen towards galactic dark matter



At most 5% of the acceleration towards dark matter can be non-gravitational

Could there be “large” extra dimensions?

Extra dimensions could solve the hierarchy problem. Gravity may be just as strong as the other forces – ***but*** – in our 4 dimensional world it appears much weaker because most of its strength acts in *n* other dimensions.

N. Arkani-Hamed *et al*. Phys. Lett. B 436 p.257 (1998).

- Expect that gravity strengthens at scales comparable to the largest extra dimension.
- Our 2-σ exclusion bounds imply that the maximum size of any extra dimension must be less than 44μm.
- If there are two extra dimensions, our result implies that $M^* \geq 3.2 TeV/c^2$.

In string theory, the size of the compactified extra dimensions is dynamic, and stabilized by radions, that mediate additional yukawa forces.

- Our limit implies that for 6 extra dimensions $M^* \geq 6.4$ TeV/c^2.

Can the strong bounds on gravitationaly coupled scalars be evaded?

- String theory predicts gravitationally coupled low mass scalars.
- EP/ISL tests place very strong limits.
- These experimental bounds can be circumvented if scalars are self-interacting, i.e., chameleon's:

$$V_{\rm eff}(\phi,\vec{x}) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\gamma}{4!}\phi^4 - \frac{\beta}{M_{\rm Pl}}\rho(\vec{x})\phi$$

In presence of matter, they acquire an effective mass:

$$m_{\rm eff}(\rho) = \frac{\hbar}{c}\left(\frac{9}{2}\right)^{1/6}\gamma^{1/6}\left(\frac{\beta\rho}{M_{\rm Pl}}\right)^{1/3}$$

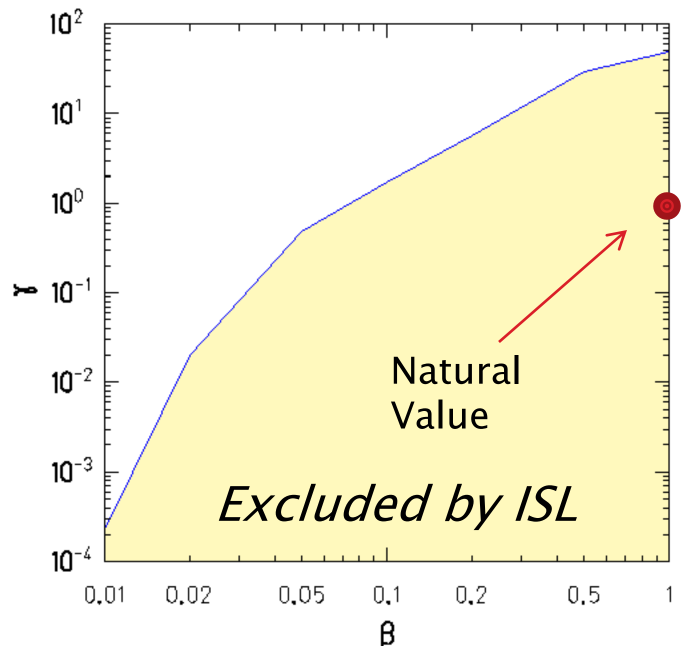
Thus, only a thin skin of material,

$$\lambda_s \sim O(\hbar / m_{eff}\, c)$$

can generate long-range fields.

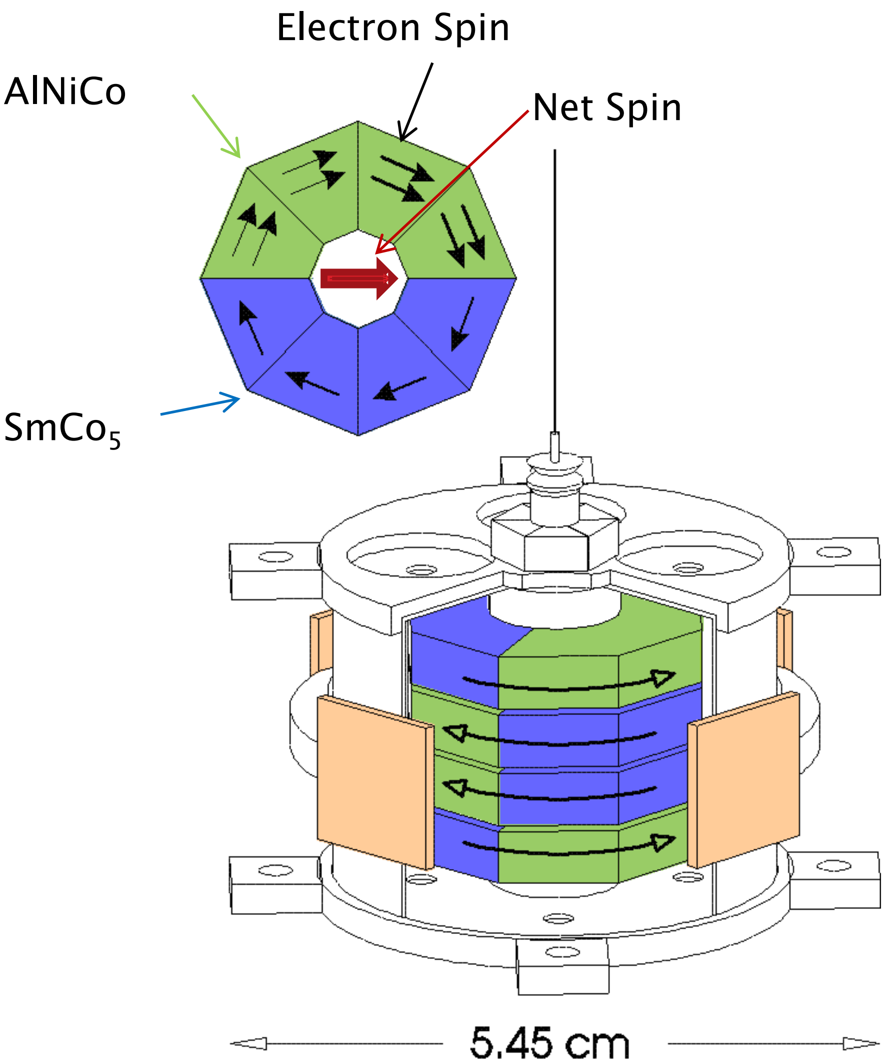
For Mo, λ_s~60μm

2-σ bounds on Chameleon parameters



J.Khoury and A. Weltman PRL 93, 171104 (2004)
A. Upadhye *et al* PRD 74 104024 (2006)

The Eöt-Wash spin pendulum



- Key point:
  - AlNiCo: almost all B generated by electron spin.
  - $SmCo_5$: half of B generated by net spin, half by orbital motion.

- Net spin (9.8 x 10^{22} polarized electrons)

- Negligible mass asymmetry
- Negligible composition asymmetry
- Flux of B confined within octagons
- Negligible external B field

- Sensitive to preferred frames
- Pseudoscalar exchange (axion-like particles).

$$V(r) \propto (\hat{\sigma} \cdot \hat{r}) \left(\frac{1}{\lambda_a r} + \frac{1}{r^2} \right) e^{-r/\lambda_a}$$

Non-commutative space-time geometry

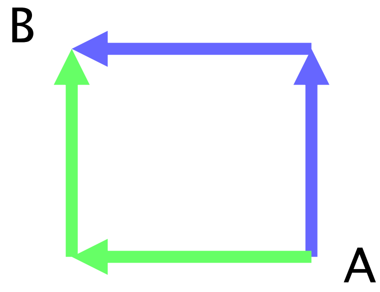
string theorists have suggested that the space-time coordinates may not commute, i.e. that

$$[\widehat{x}_\mu, \widehat{x}_\nu] = i\theta_{\mu\nu}$$

where Θ_{ij} has units of area and represents the minimum observable patch of area, just as the commutator of x and p_x represents the minimum observable product of $\Delta x\ \Delta p_x$

Non-commutative geometry is equivalent to a "pseudo-magnetic" field and thus couples to spins

$$\mathcal{L}_{eff} = \frac{3}{4} m\Lambda^2 \left(\frac{e^2}{16\pi^2}\right)^2 \theta^{\mu\nu}\overline{\psi}\sigma_{\mu\nu}\psi$$

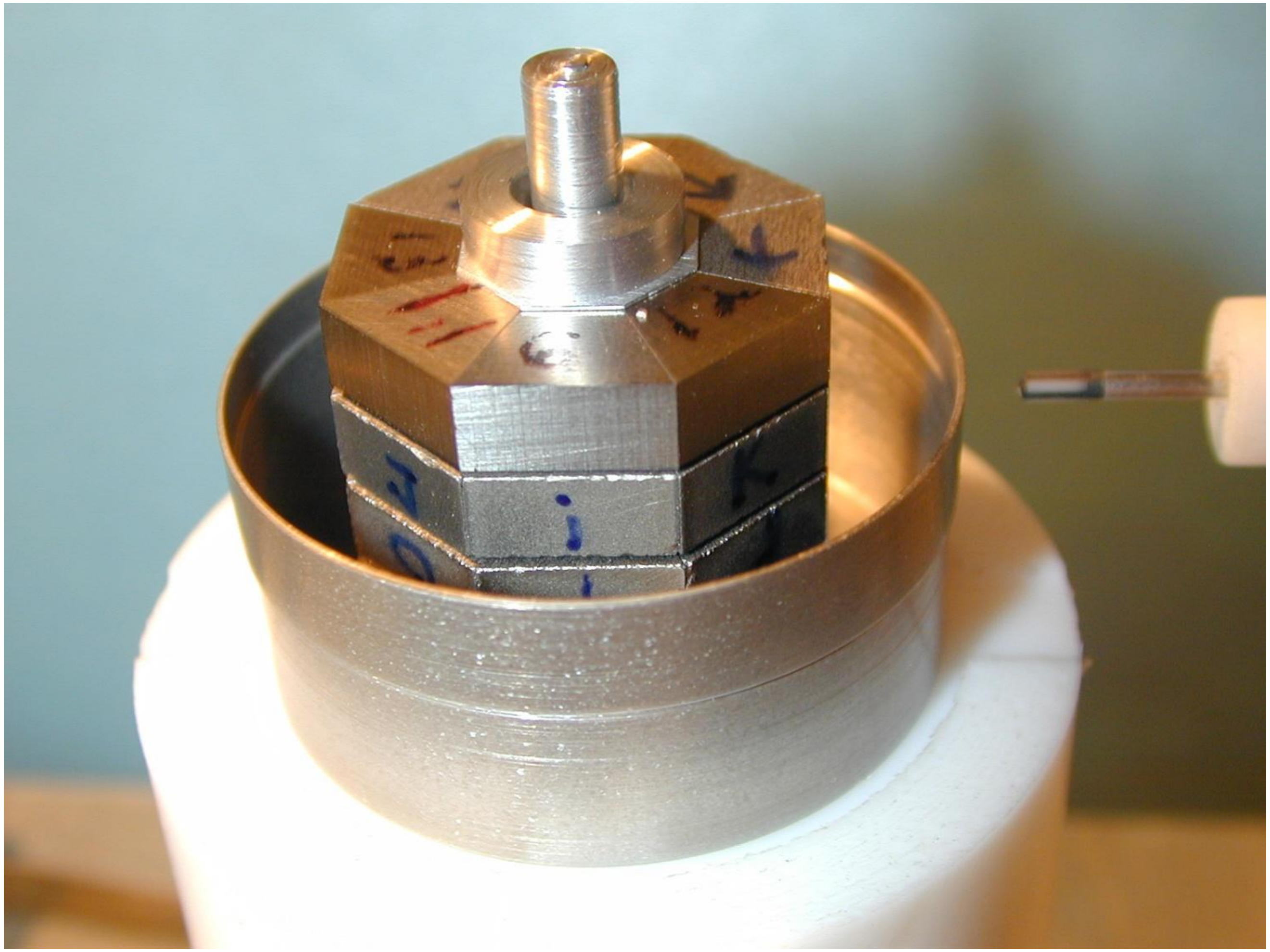


Λ~TeV

If the commutator is the same over the space/time of the experiment, then this effect also defines a preferred frame for the spin pendulum.

I. Hinchliffe, N Kersting and Y.L. Ma hep-ph/0205040
Anisimov, Dine, Banks and Graesser PRD 65, 085032 (2002)

measuring the stray magnetic field of the spin pendulum



B inside = 9.6±0.2 kG   B outside ≈ few mG

Lorentz-symmetry violating rotation parameters

TABLE IX: 1σ constraints on the Lorentz-symmetry violating $\tilde{b}^e$ parameters. Units are 10^{-22} eV.

parameter	electron	proton	neutron
	our work		
$\tilde{b}_X$	-0.67 ± 1.31	$\leq 2 \times 10^4$	0.22 ± 0.79
$\tilde{b}_Y$	-0.18 ± 1.32	$\leq 2 \times 10^4$	0.80 ± 0.95
$\tilde{b}_Z$	-4 ± 44		

Cane et al, PRL 93(2004) 230801

Phillips et al, PRD 63(2001) 111101

These should be compared to the benchmark value $m_e^2/M_{\text{Planck}} = 2 \times 10^{-17}$ eV.

Our limit is comparable to the electrostatic energy of two electrons separated by ~ 90 astronomical units