Table-top Tests of Gravity and probes for new ultra-weak forces.

Eric Adelberger
University of Washington

outline:

1) weak and strong equivalence principle tests

2) short-distance inverse-square law tests

3) exotic Goldstone boson searches

two ways to test gravity:

1) watch things fall down (Galileo)

- obvious
- long history
- revived with new technology

2) watch things fall sideways (Eȍtvȍs)

- not so obvious
- currently the most sensitive tests

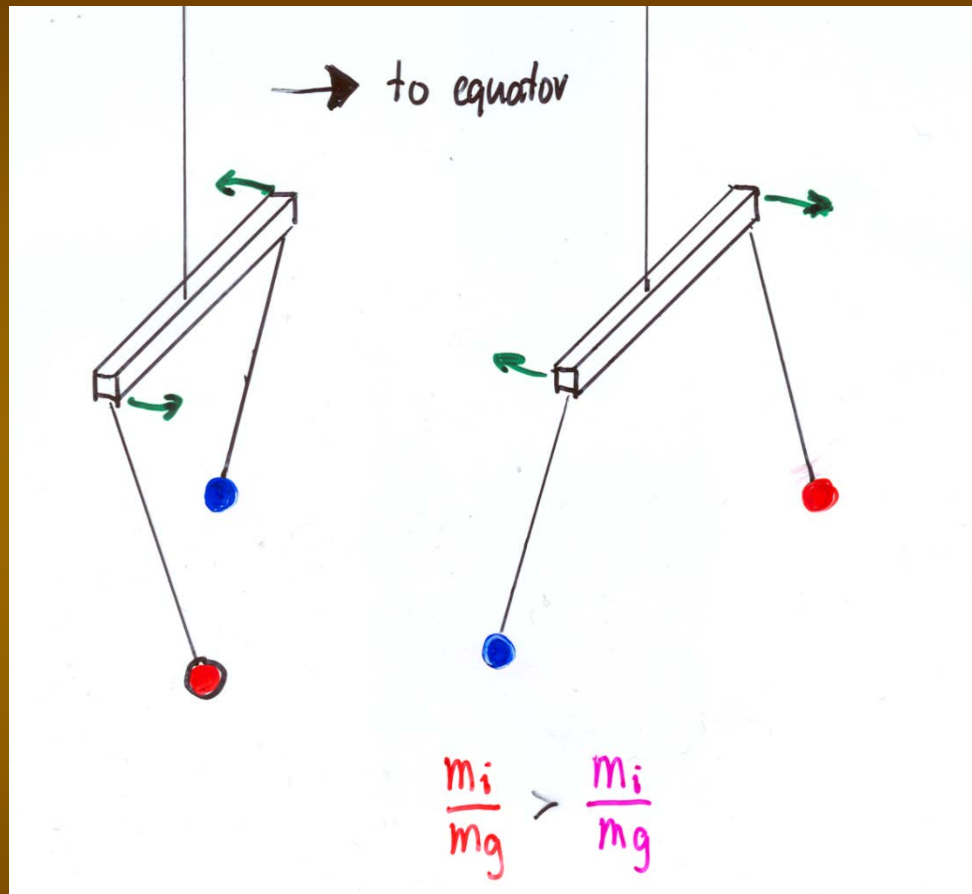
Weak equivalence principle (WEP):

All laboratory sized test bodies (objects with negligible gravitational binding energy) fall with the same acceleration in a uniform gravitational field. All metric theories predict that the WEP is exact. Quantum gravity models allow violation.

Strong equivalence principle (SEP):

Extends the WEP to include objects so large that gravitational binding energy is significant. This probes the non-linear nature of gravity. SEP is violated by some metric theories. Quantum gravity models allow violation.

Testing the WEP by watching things fall sideways



beam only twists if force vectors are not parallel
down is not a unique direction
if EP is violated or if gravity field is not uniform

two ways to think about WEP tests:

old way:

is $m_g = m_i$ exact?

new way (popularized by E. Fischbach):

a broad-gauge way to search for ultra-feeble long-range boson-exchange forces that may lie hidden underneath gravity

brief history of WEP tests in the 20th century:

1910-20’s Eötvös
watched things falling in
earth’s field and turned balance manually

1950-60’s Dicke and later Bragisky
watched things falling toward sun and let
earth’s rotation turn the instrument

1980’s onward Eöt-Wash
watched things fall in fields of earth, sun, galaxy
and in the rest frame defined by the CMB
using balances on high-performance turntables

the Eöt-Wash® group

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel
- Svenja Fleischer

Current Grad students
- Charlie Hagedorn
- John Lee
- Erik Shaw
- Will Terrano
- Matt Turner

Staff scientist
- Erik Swanson

Postdoc
- Krishna Venkateswara (LIGO)

EP
$1/r^2$
spin
technology

Current undergrad
- Alex Zderic

Primary support from NSF Gravitational Physics

Parameterizing EP-violating effects of quantum vector exchange forces

gravity couples to mass

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

quantum exchange forces couple to "charges"

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

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

vector "charge" of electrically neutral objects

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

Suppose we have no preconceptions about the nature of EP violation and want unbiased tests:

this requires:

- sensitivity to wide range of length scales
  - need earth (not sun) as attractor
  - and a site with interesting topography

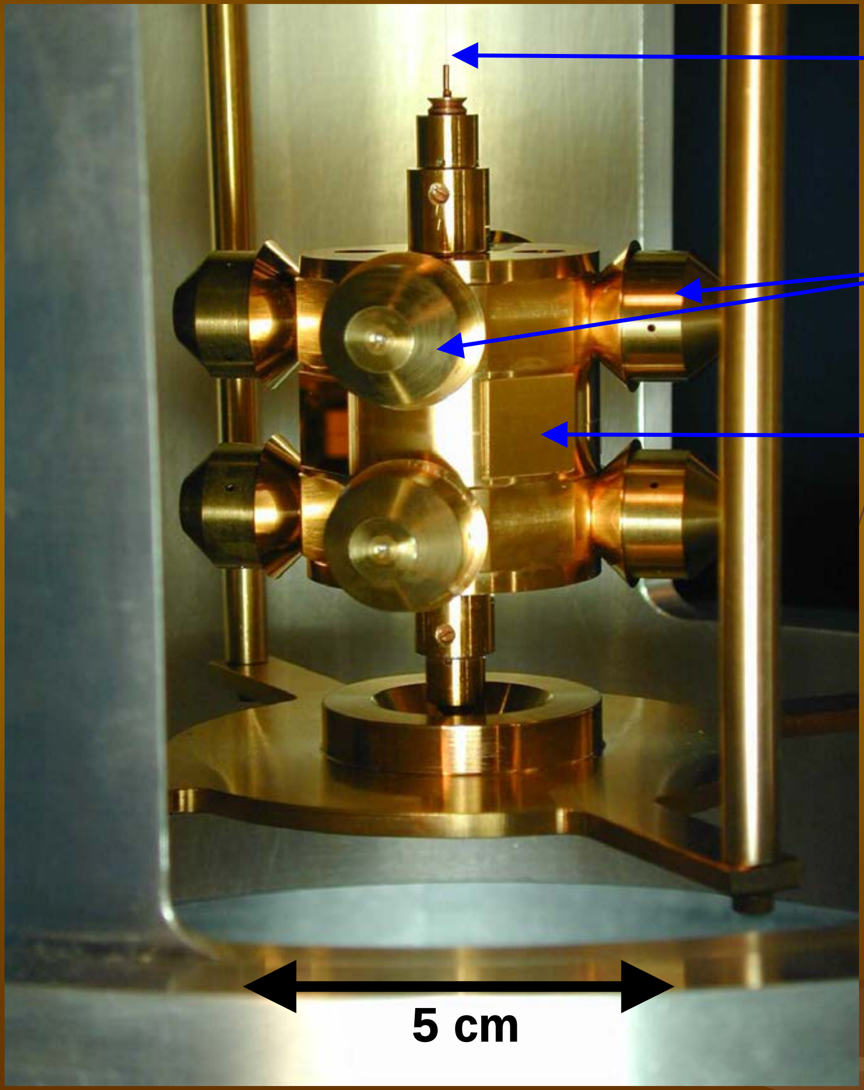
- sensitivity to wide range of possible charges

vector charge/mass ratio of any composition monopole or dipole vanishes for some value of ψ.

- need 2 test body pairs and 2 attractors
- to avoid possible accidental cancellations

torsion pendulum of the recent WEP test

T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)



20 μm diameter tungsten fiber

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

4 mirrors for measuring
pendulum twist

symmetrical design
suppresses false effects
from gravity gradients, etc.

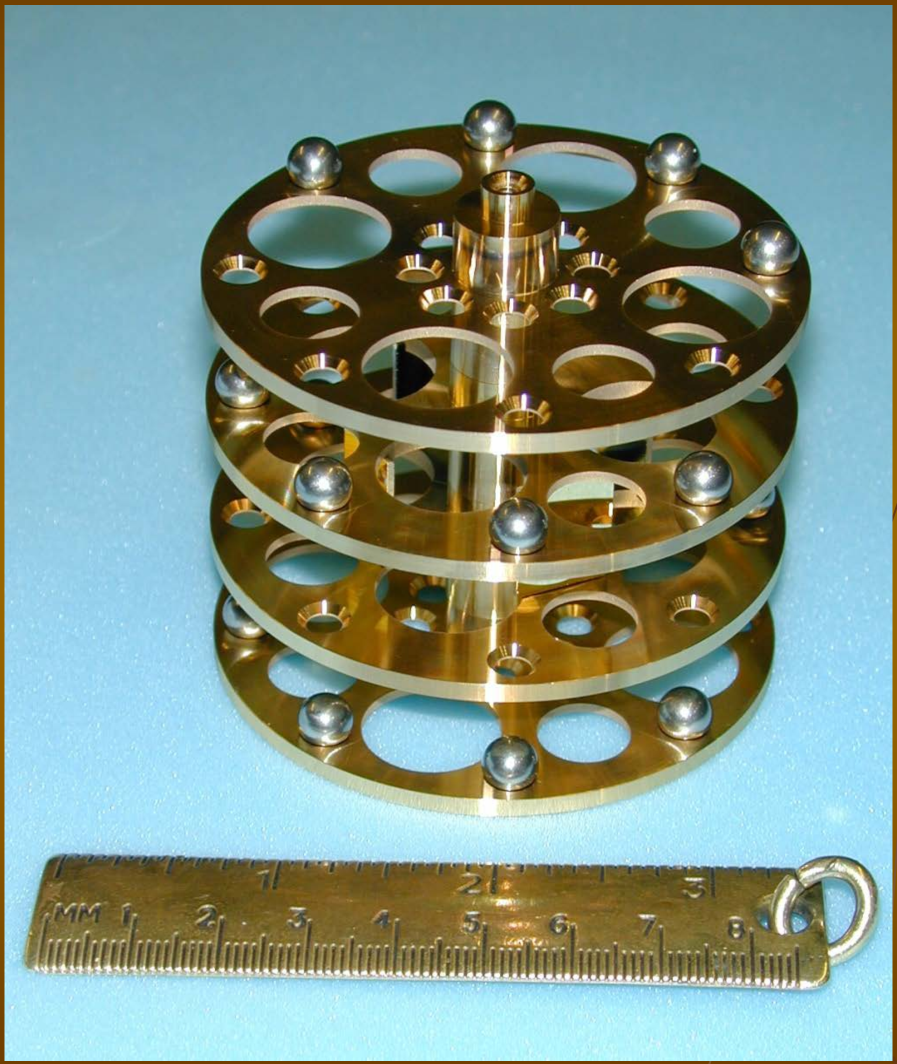
free osc freq:	1.261 mHz
quality factor:	4000
machining tolerance:	5 μm
total mass :	70 g

Eöt-Wash torsion balance hangs from turntable that rotates with a ~ 20 min period

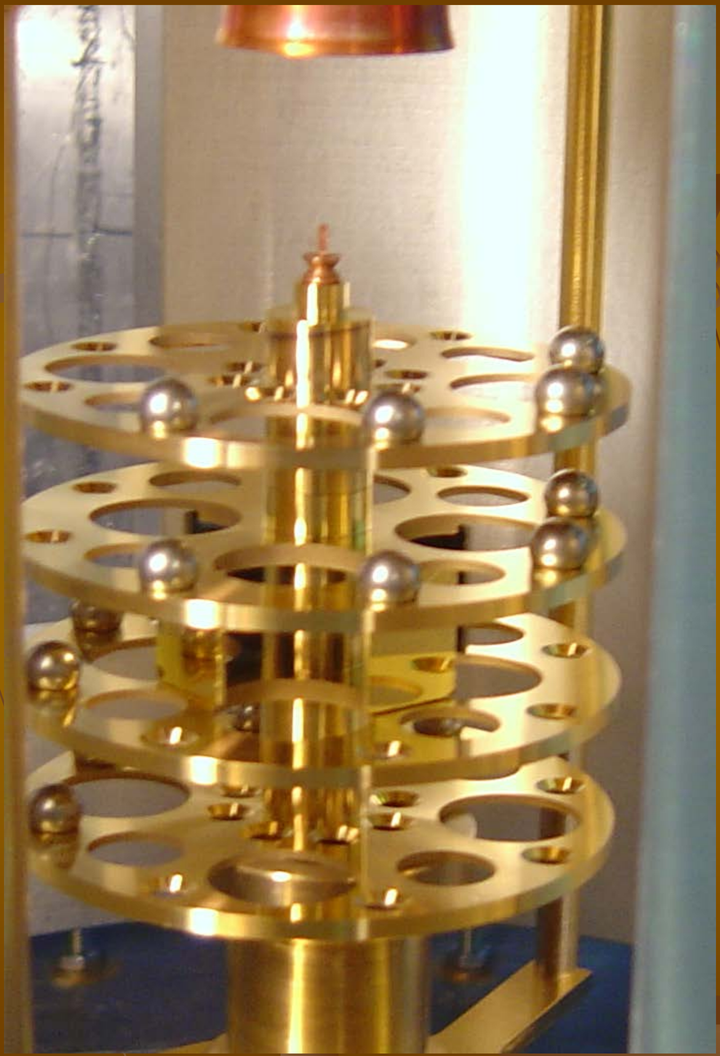
air-bearing turntable

thermal expansion feet fedback to keep turntable rotation axis level

gravity-gradiometer pendulums



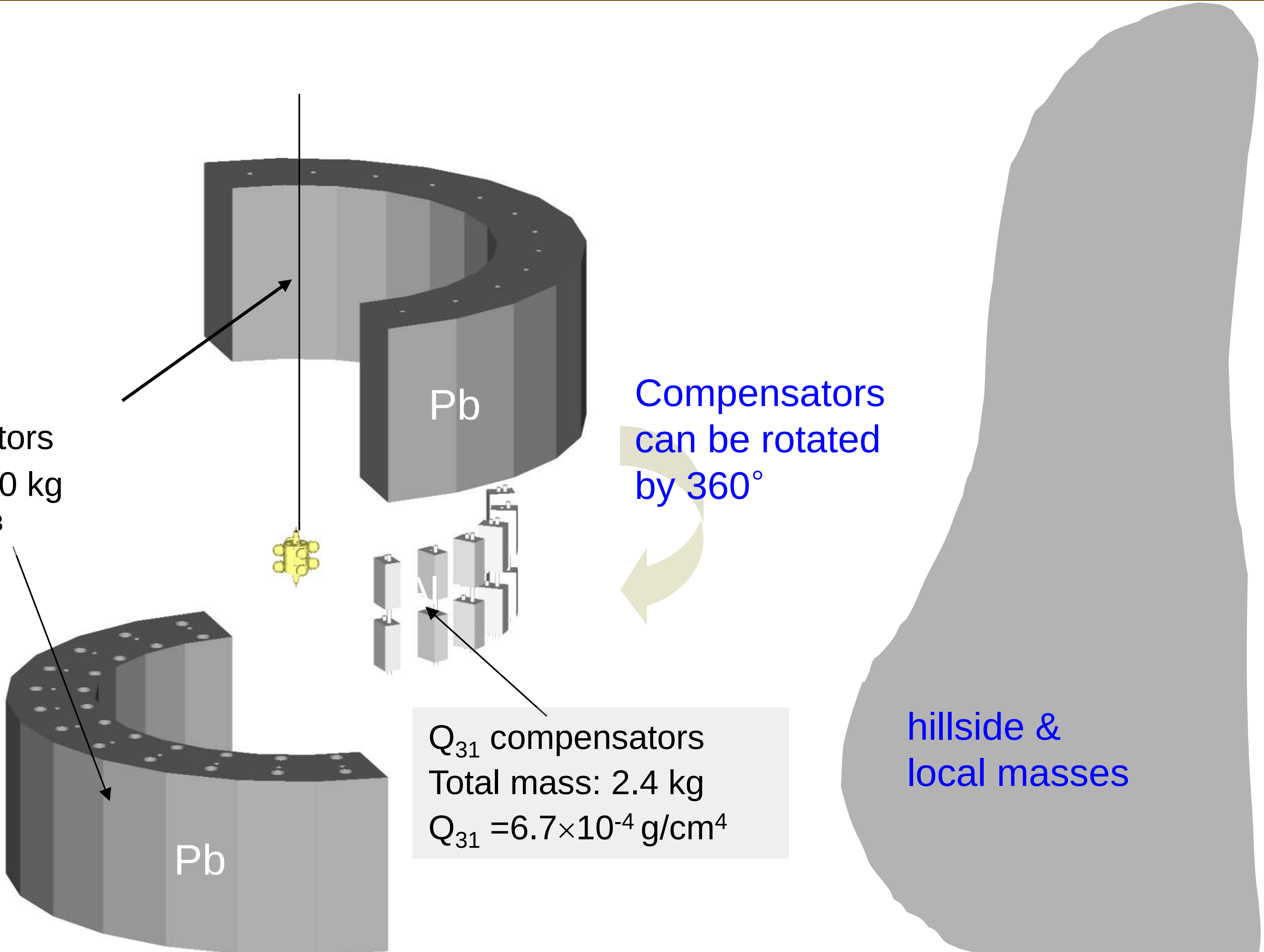
q_{41} configuration on a table



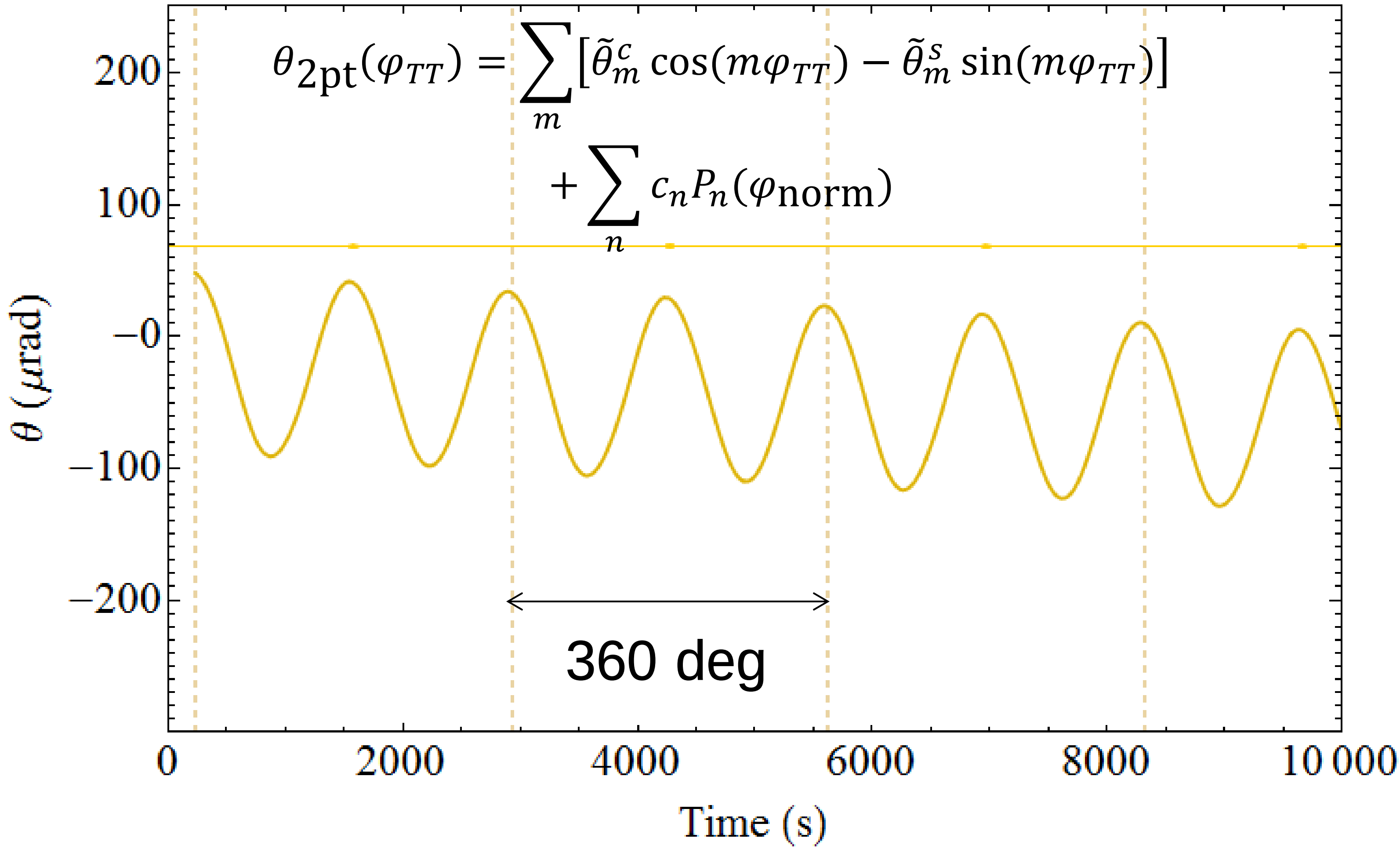
q_{21} configuration installed

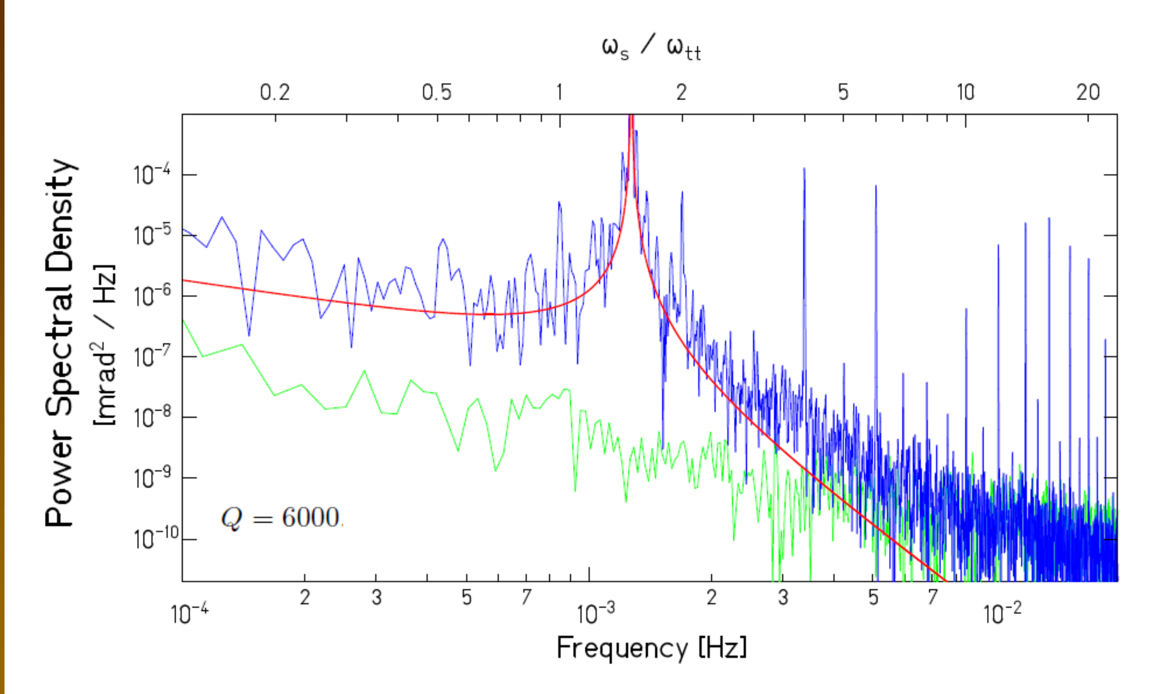
gravity-gradient compensation

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



Segment data and fit segments to find the signal at the turntable rotation frequency. (this example shows gravity-gradient data)





daily reversal of pendulum orientation with respect to turntable rotor canceled turntable imperfections.

Test bodies were interchanged after data set 4 to cancel asymmetries in pend body and suspension fiber. Each data point represents about 2 weeks of data

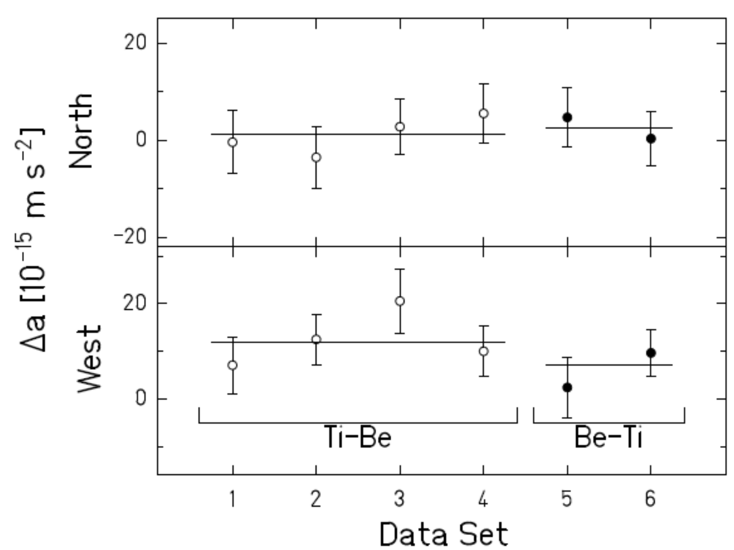
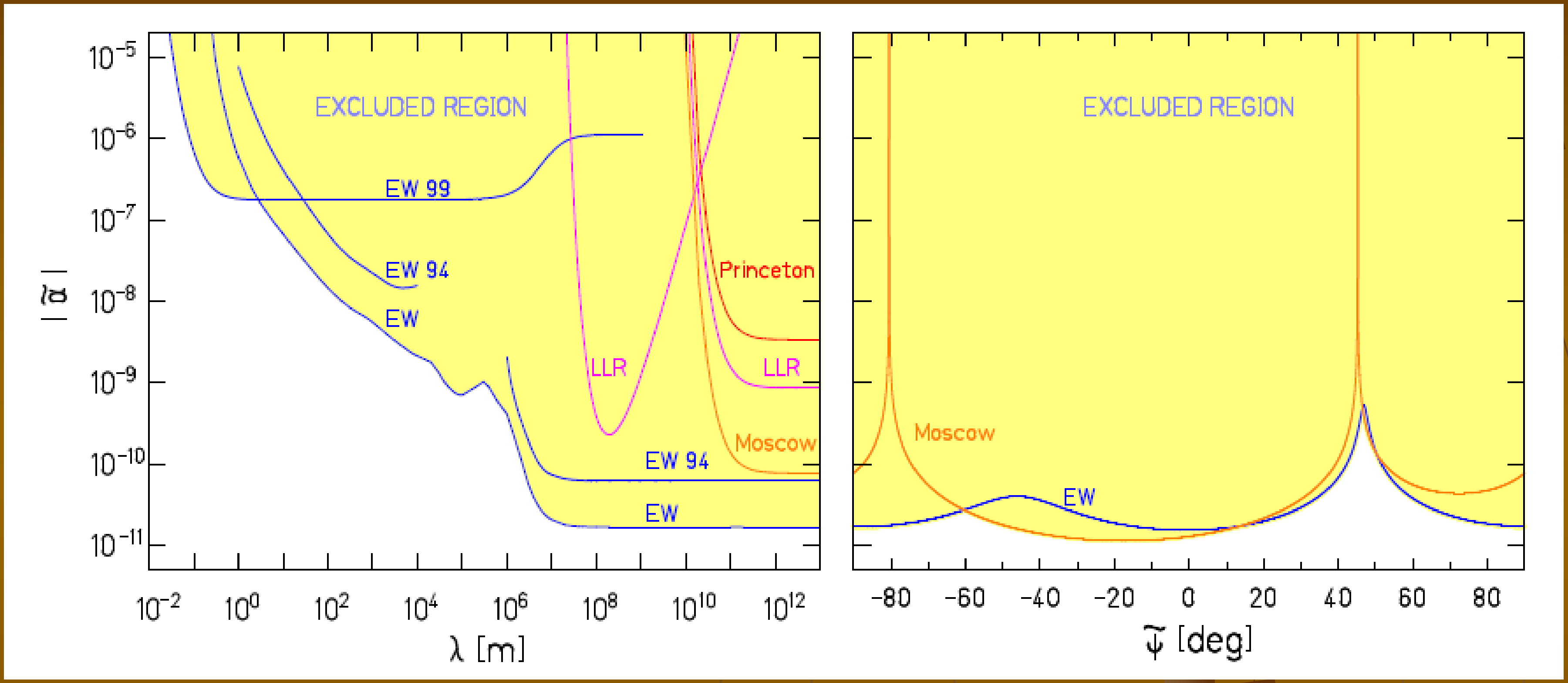


Figure 5. Data collected in the Ti-Be (first 4 runs) and Be-Ti (last 2 runs) configurations of the pendulum. The final result is in the difference between the means of the two configurations (shown as solid lines).

WEP results using the earth, the sun and the galaxy as attractors and their 1σ statistical + systematic uncertainties

		Be-Ti	Be-Al
Δa_{N}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	0.6 ± 3.1	-1.2 ± 2.2
Δa_{W}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.5 ± 3.5	0.2 ± 2.4
$\Delta a_{\odot}$	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-1.8 ± 2.8	-3.1 ± 2.4
Δa_{g}	$(10^{-15}\ \mathrm{m\ s^{-2}})$	-2.1 ± 3.1	-1.2 ± 2.6
$\eta_{\oplus}$	(10^{-13})	0.3 ± 1.8	-0.7 ± 1.3
$\eta_{\odot}$	(10^{-13})	-3.1 ± 4.7	-5.2 ± 4.0
η_{DM}	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

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



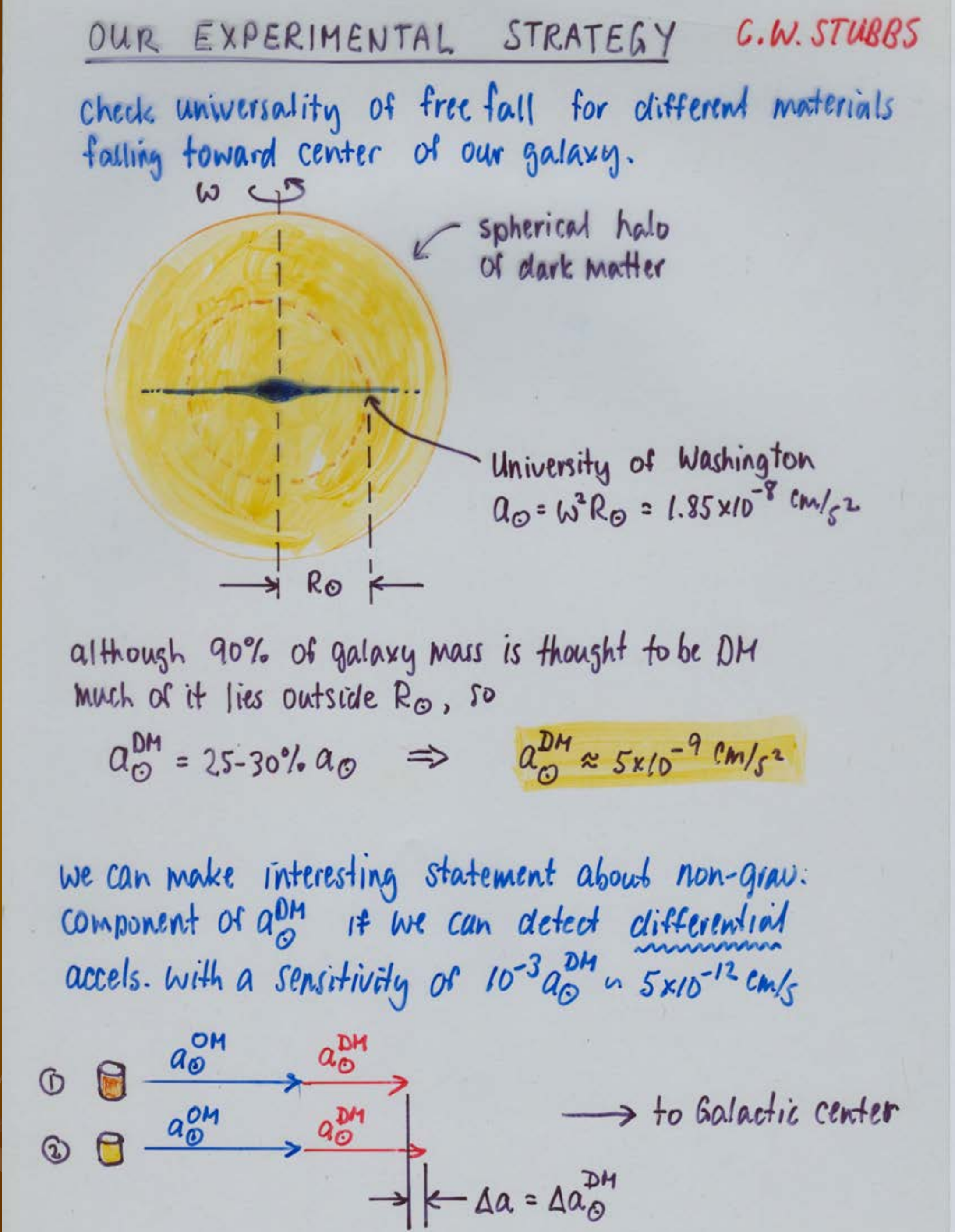
Yukawa attractor integral based on:

0.5m<λ<5m	lab building and its major contents
1m< λ<50km	topography
5km< λ<1000km	USGS subsurface density model
1000km< λ<10000km	PREM earth model

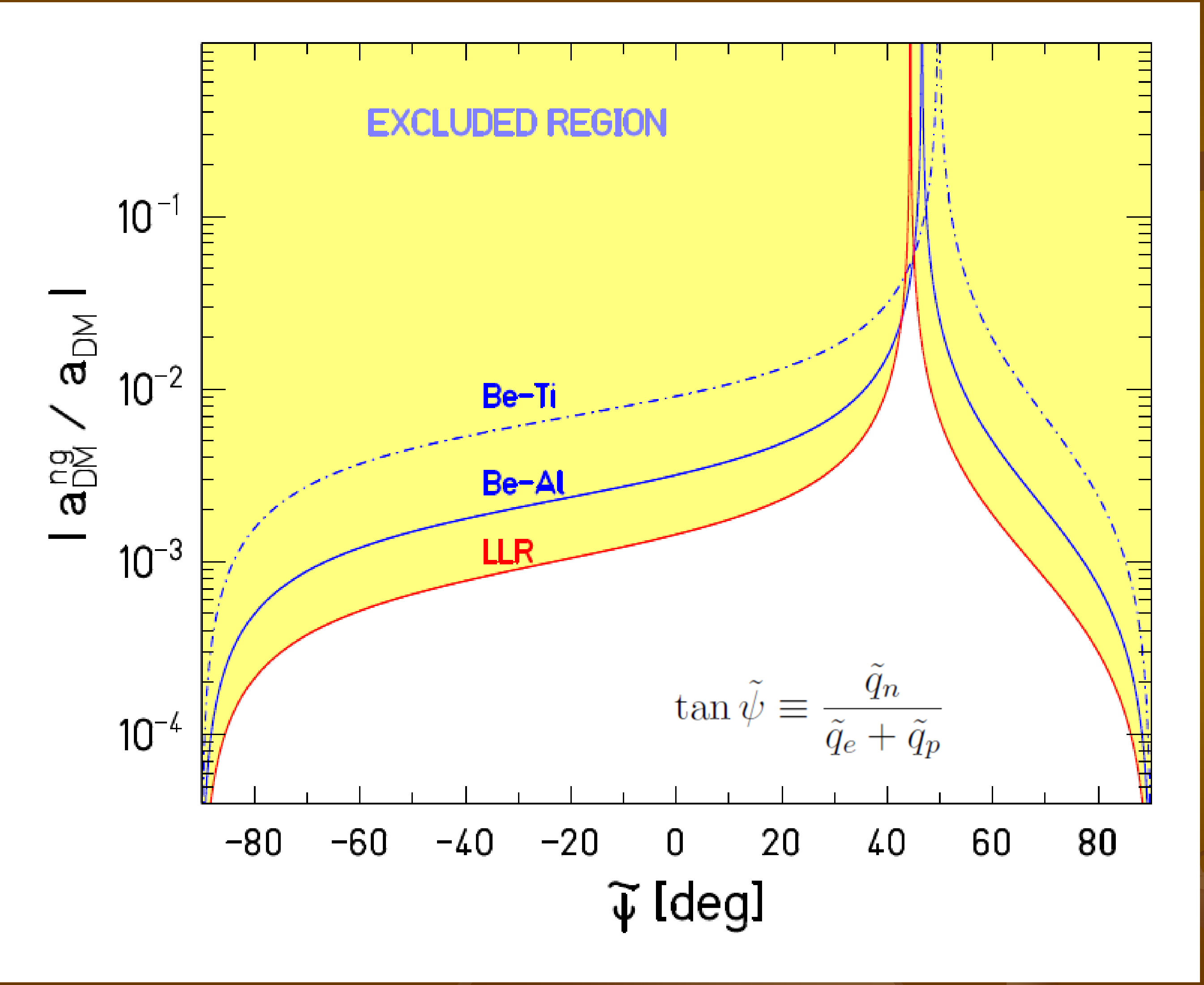
T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)

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

Could there be a long-range scalar interaction that couples dark-matter & standard-model particles?



95% confidence limits on non-gravitational acceleration of hydrogen by galactic dark matter



at most 6% of the acceleration can be non-gravitational

gravitational properties of antimatter

Some people suggest that antimatter could
could fall up with acceleration -g! They propose
to test this by dropping antihydrogen, a very difficult
and challenging experiment. How plausible is this
scenario?

If antimatter falls up:

1) photons (their own antiparticles) should not fall

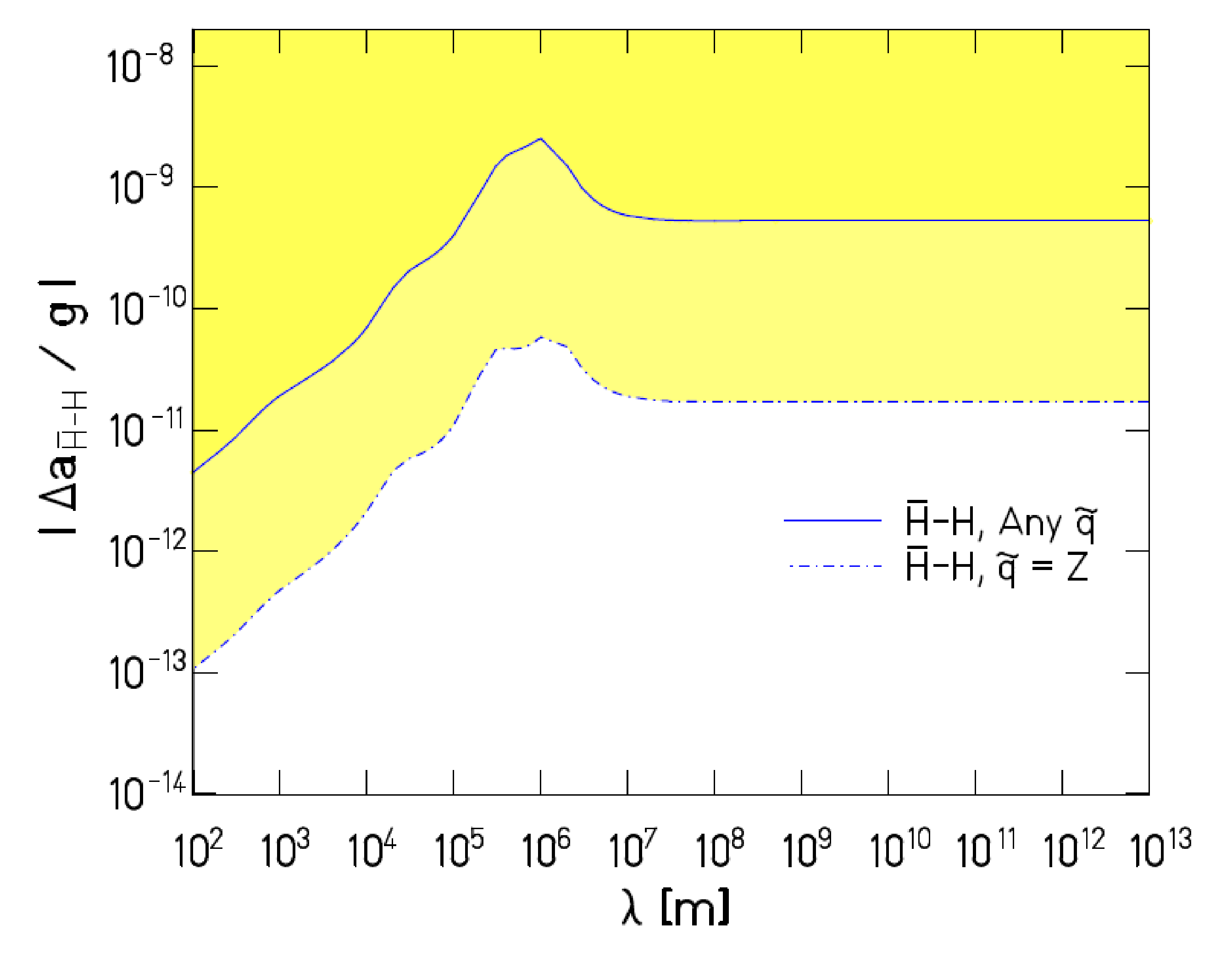
2) nucleons (~99% of their mass consists of glue & anti-glue) should fall with ~100 times smaller accelerations than electrons

gravitational properties of antimatter (quantitative argument)

If H and anti-H fall with different accelerations gravity must have a vector component. Consider an EP test with H and anti-H. This would have $\Delta(Z/\mu)=2$. Our Be/Al WEP test has $\Delta(Z/\mu)=0.0382$ and we see no evidence for such an interaction with $\Delta g/g$ greater than a few parts in 10^{13}.

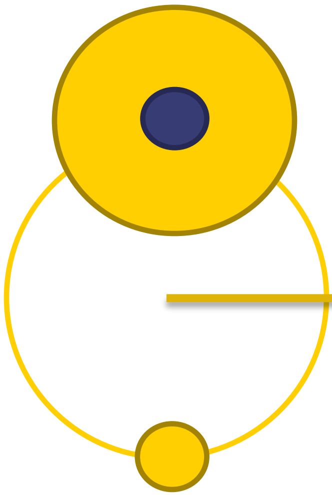
The following plot assumes only CPT invariance and the impossibility of exact cancellation between V and S interactions

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



T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)

Combining LLR data and a laboratory WEP test to make a loophole-free test of the SEP



$E_{grav}/(M_{\odot}c^2) = -4.6 \times 10^{-10}$

Earth has a massive Fe core.

Earth and Moon test bodies differ in both composition and gravitational binding energy

$E_{grav}/(M_{\oplus}c^2) = -0.2 \times 10^{-10}$

Moon does not have massive Fe core

Only composition differs.

A loophole-free test of the Strong EP

- Lunar laser ranging:

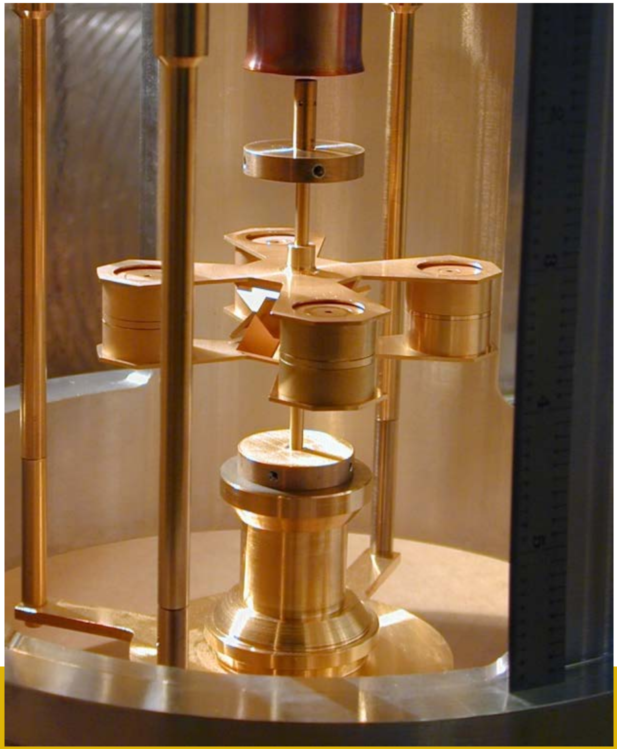
  $\eta_{SEP} + \eta_{CD} = (-0.8 \pm 1.3) \times 10^{-13}$

  (goal of $\eta_{LLR} \sim 10^{-14}$)

- Our measurement:

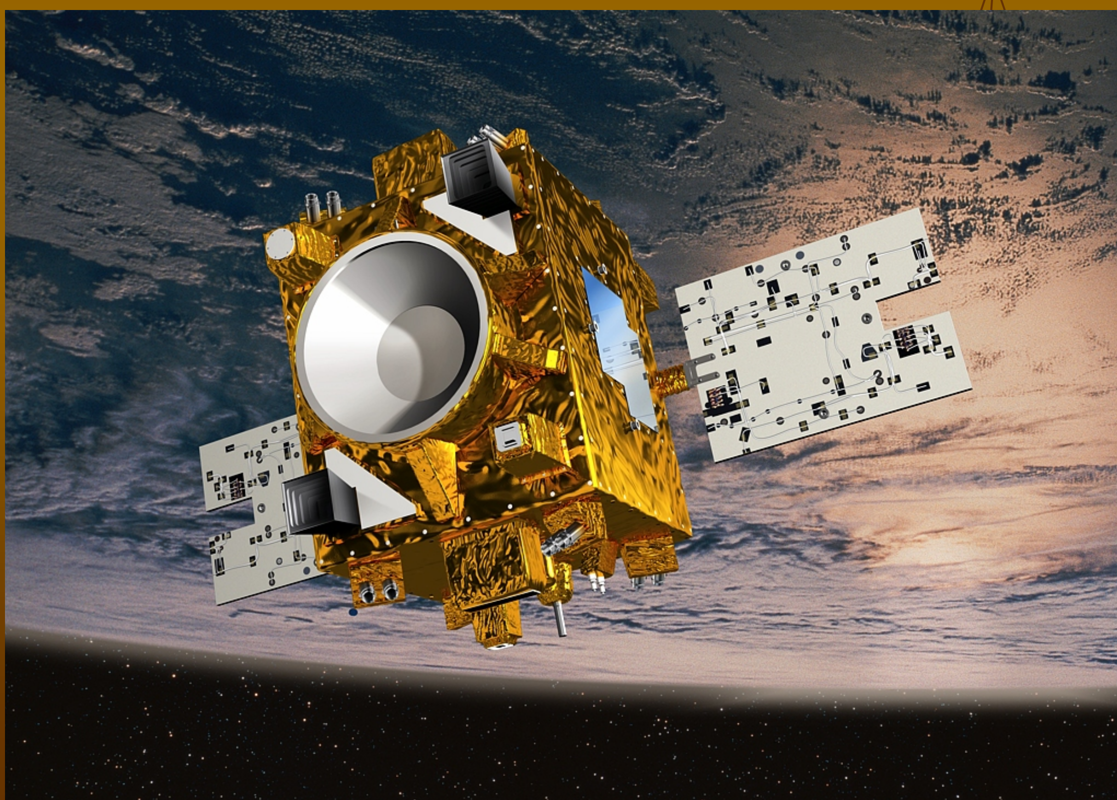
  $\eta_{CD} = (1.2 \pm 1.1) \times 10^{-13}$

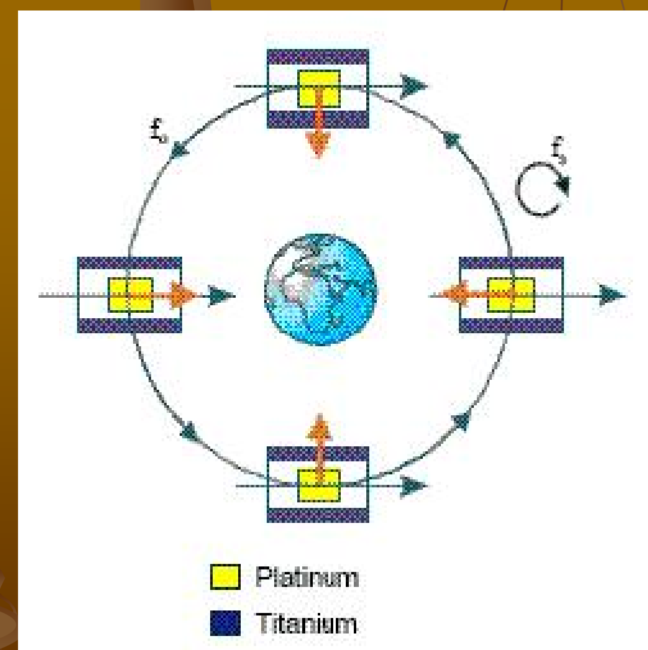
- $|\eta|_{SEP} < 6 \times 10^{-4}$ at 1σ



Microscope: French-German collaboration to test the WEP to 1 part in 10^{15} using Ti-Pt test bodies and a Pt/Pt null comparison in a drag-free satellite operated in both inertial and rotating modes.

Expected to be launched in 2016





motivations for sub-millimeter tests of the inverse-square law (ISL)

- explore an untested regime
- probe the dark-energy length scale

$$\rho_{\rm d} \approx 3.8 \ {\rm keV/cm^3}$$
$$\lambda_{\rm d} = \sqrt[4]{\hbar c/\rho_{\rm d}} \approx 85 \ \mu{\rm m}$$

- search for proposed new phenomena
  - large extra dimensions: why is gravity so weak?
  - chameleons: what happened to the stringy scalars?

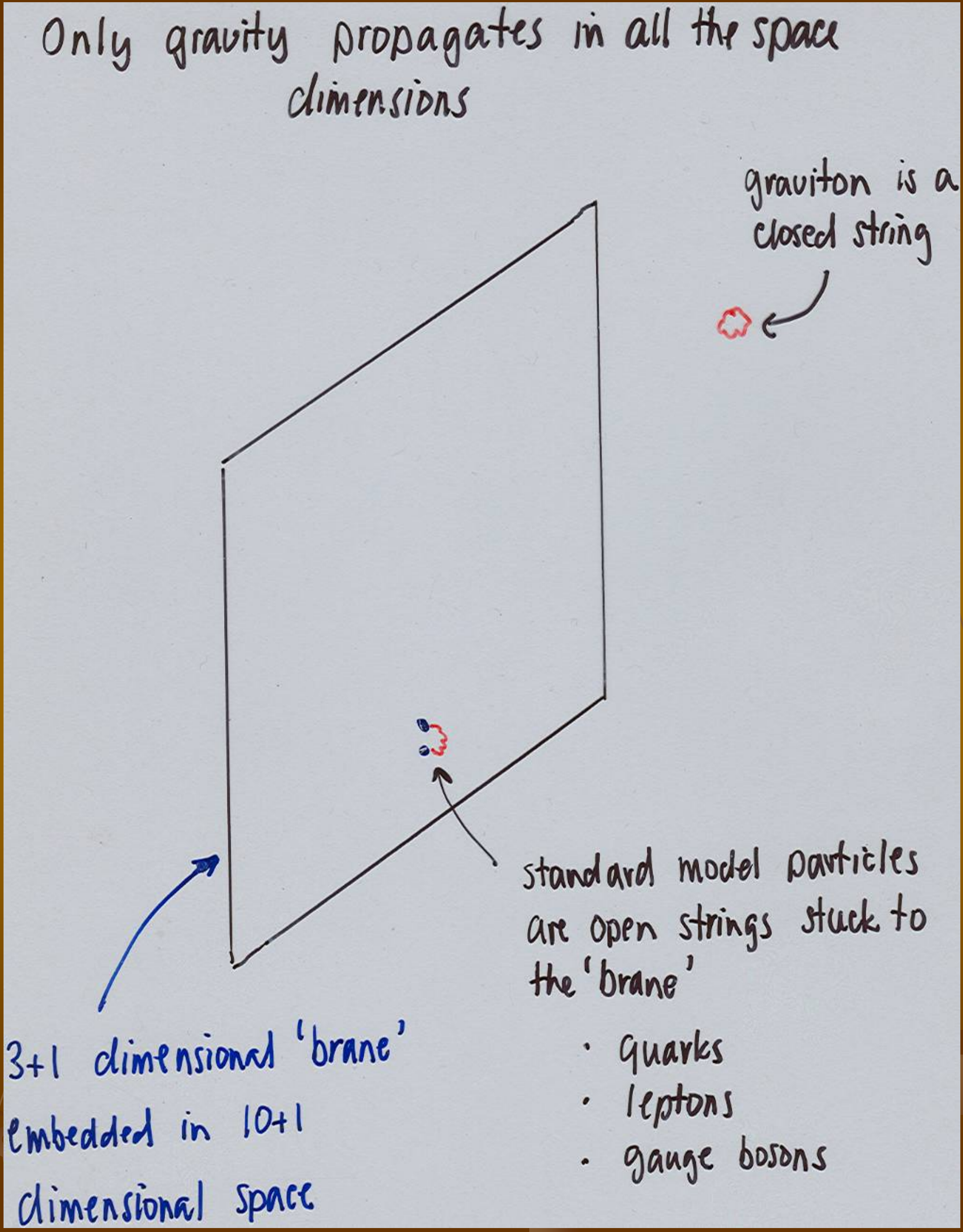
Parameterizing ISL violating effects

$$V(r) = V_g(r)[1 + \alpha \exp(-r/\lambda)]$$

this Yukawa form is exact for one-boson exchange and a good approximation for extra dimensions as long as $r < R$ where R is the size of the largest extra dimension.

Note that $\alpha \neq \tilde{\alpha}$. For a given Yukawa interaction, the ISL-violating signal α, which reflects the full strength of a new interaction, is much larger than the EP-violating signal, $\tilde{\alpha}$, which describes only its composition-dependent piece.

“large” extra dimensions could explain why gravity is so weak:
most of its strength has leaked off into places we cannot go



Gauss's Law and extra dimensions

Moral: to see the true strength of gravity you have to get really close

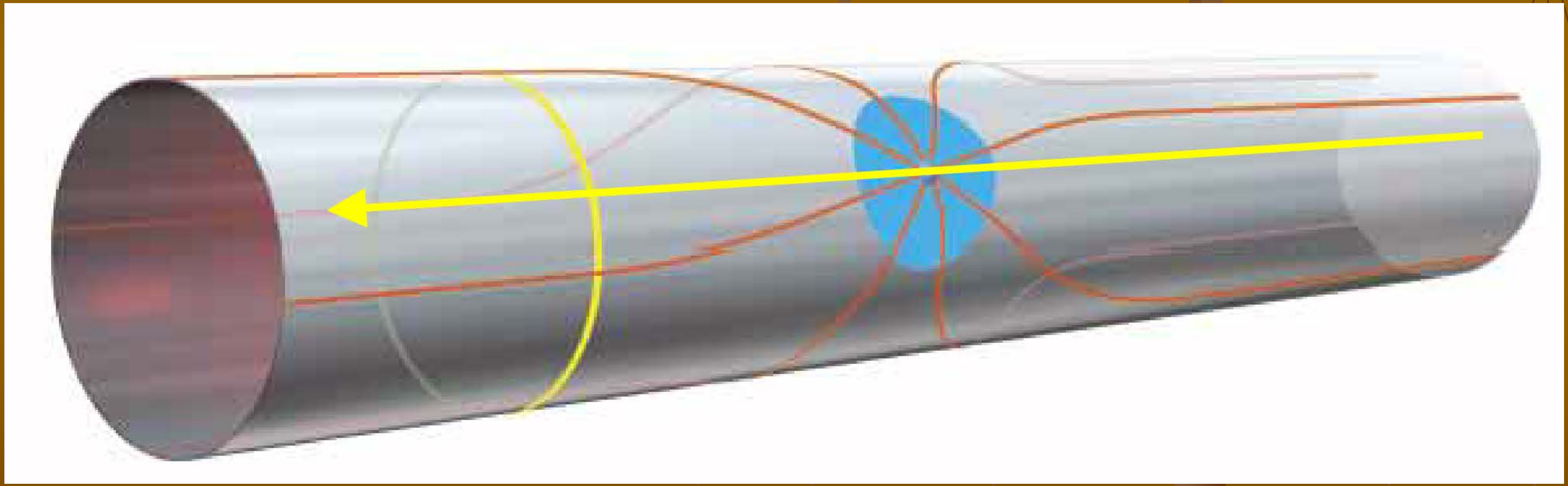


illustration from Savas Dimopoulos

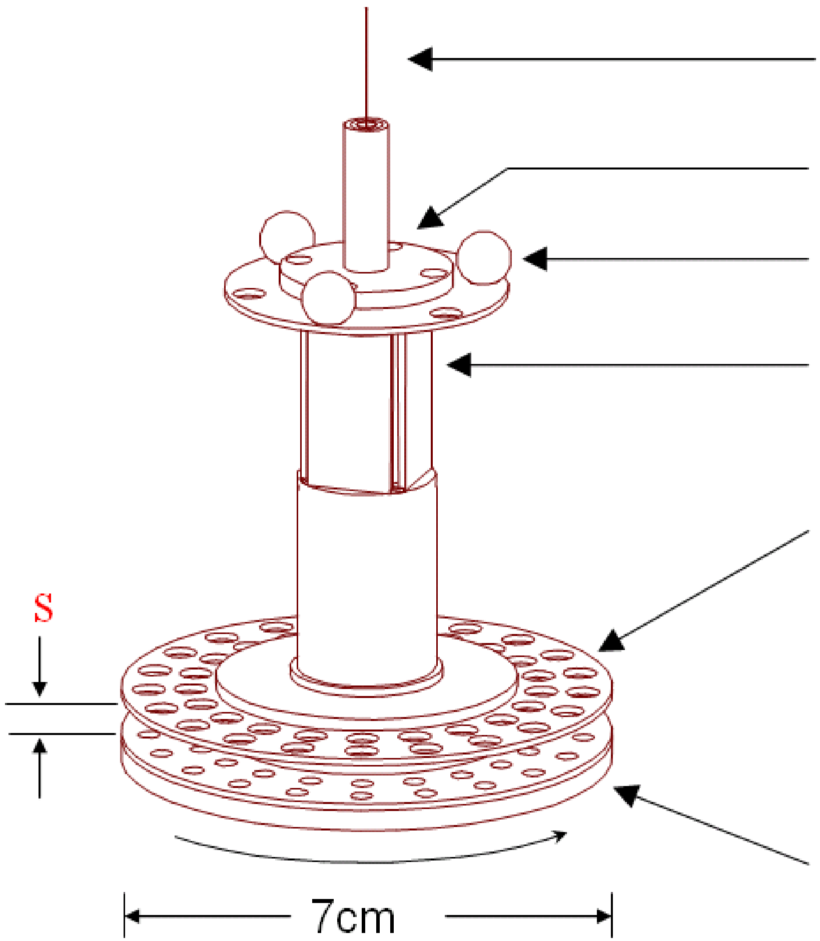
chameleons

Chameleons circumvent experimental evidence against gravitationally-coupled low-mass scalars by adding a self-interaction term to their effective potential density.

This gives massless chameleons an effective mass in presence of matter so that a test body’s external field comes entirely from a thin skin of material of thickness $\sim 1/m_{eff}$. For a density of 10 g/cm^3 and natural values of the chameleon couplings this skin is ~ 60 µm thick; making such particles very hard to detect.

Khoury and Weltman, PRD 69, 0444026 (2004)
Gubser and Khoury, PRD 70, 104001 (2004)

the 42-hole test of the ISL

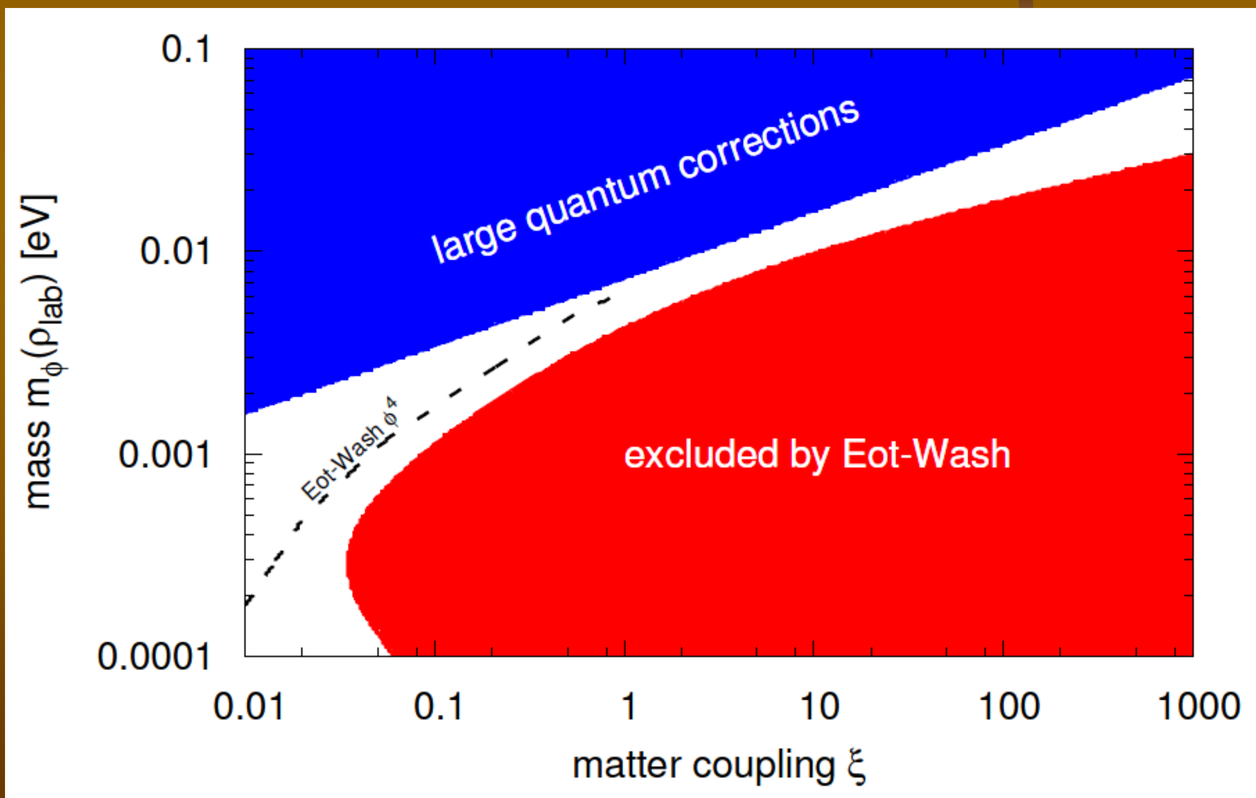


PhD project of Dan Kapner

D.J. Kapner et al., Phys. Rev. Lett. 98 021101 (2007)

Some implications of Kapner et al.' s ISL results:

largest extra dimension < 44μm
dilaton mass > 3.5 meV
strong constraints on generic chameleons

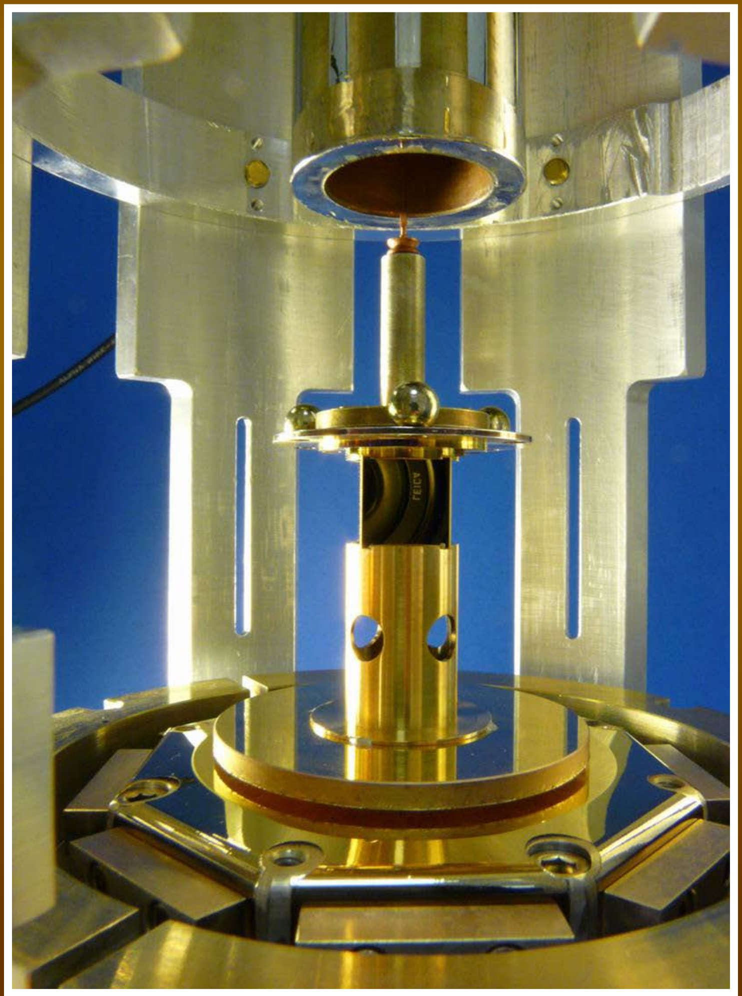


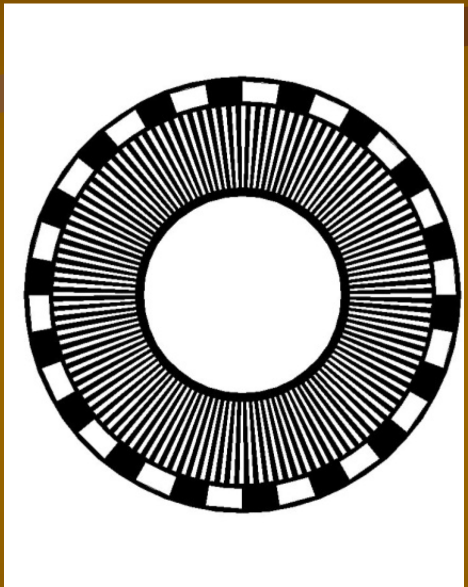
Upadhye, Hu and Khoury, PRL 109, 041301 (2012)

"natural value" of ξ is 1

UW Fourier-Bessel ISL instrument

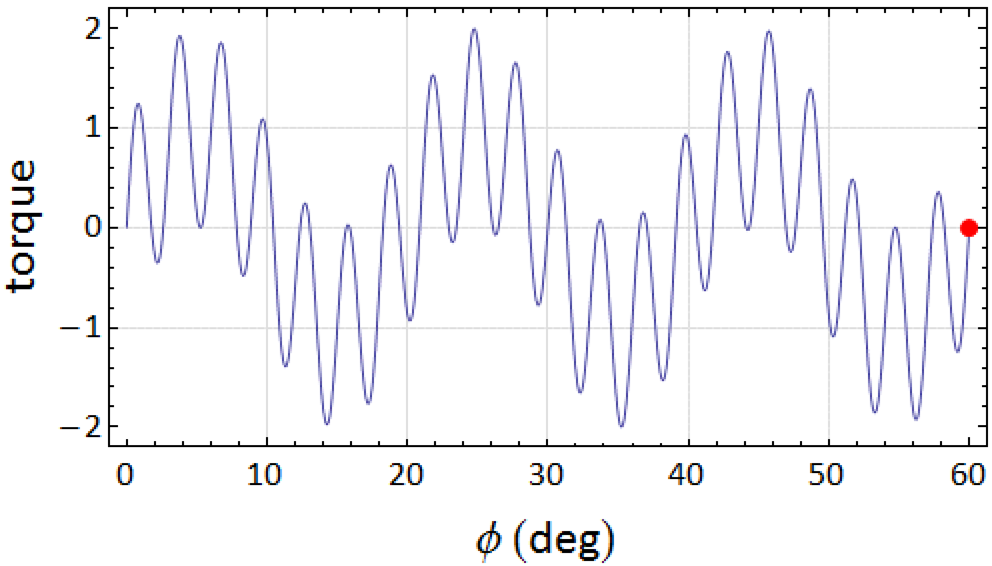
Ted Cook's 2013 PhD project. Now being upgraded by Svenja Fleischer and John Lee.

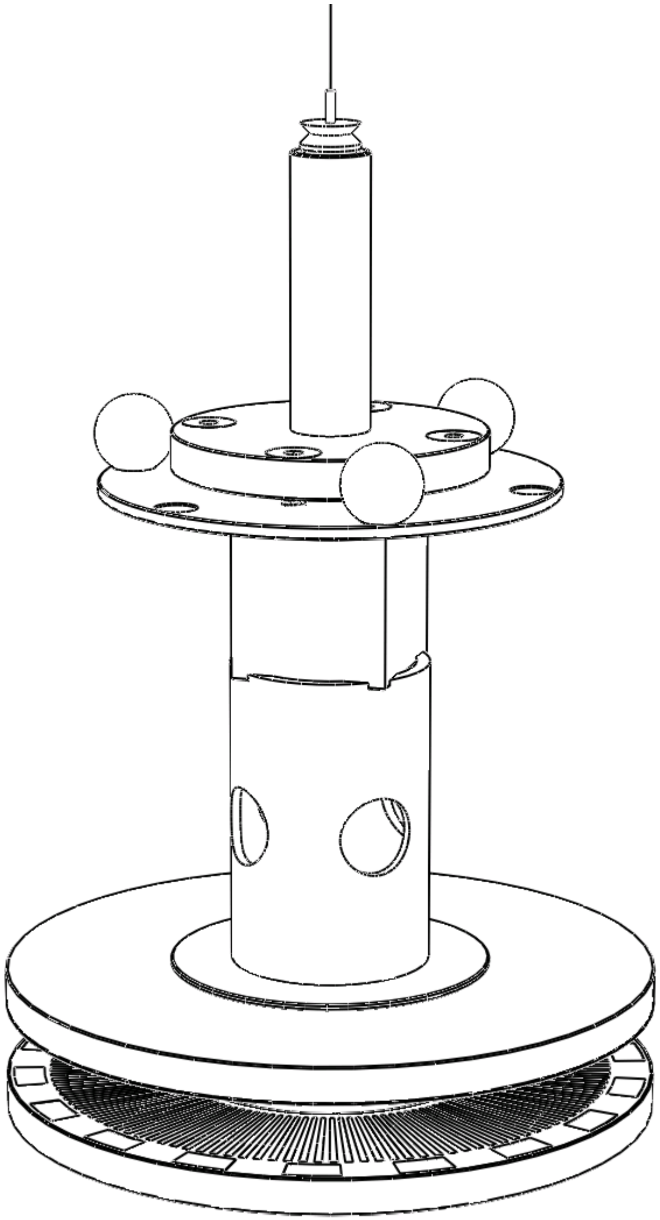




Active elements of pendulum and rotating attractor are cut from 50 micron W (Pt) foils. F-B expansion gives analytic solution for Newtonian and Yukawa torques

Cook et al.'s Experiment

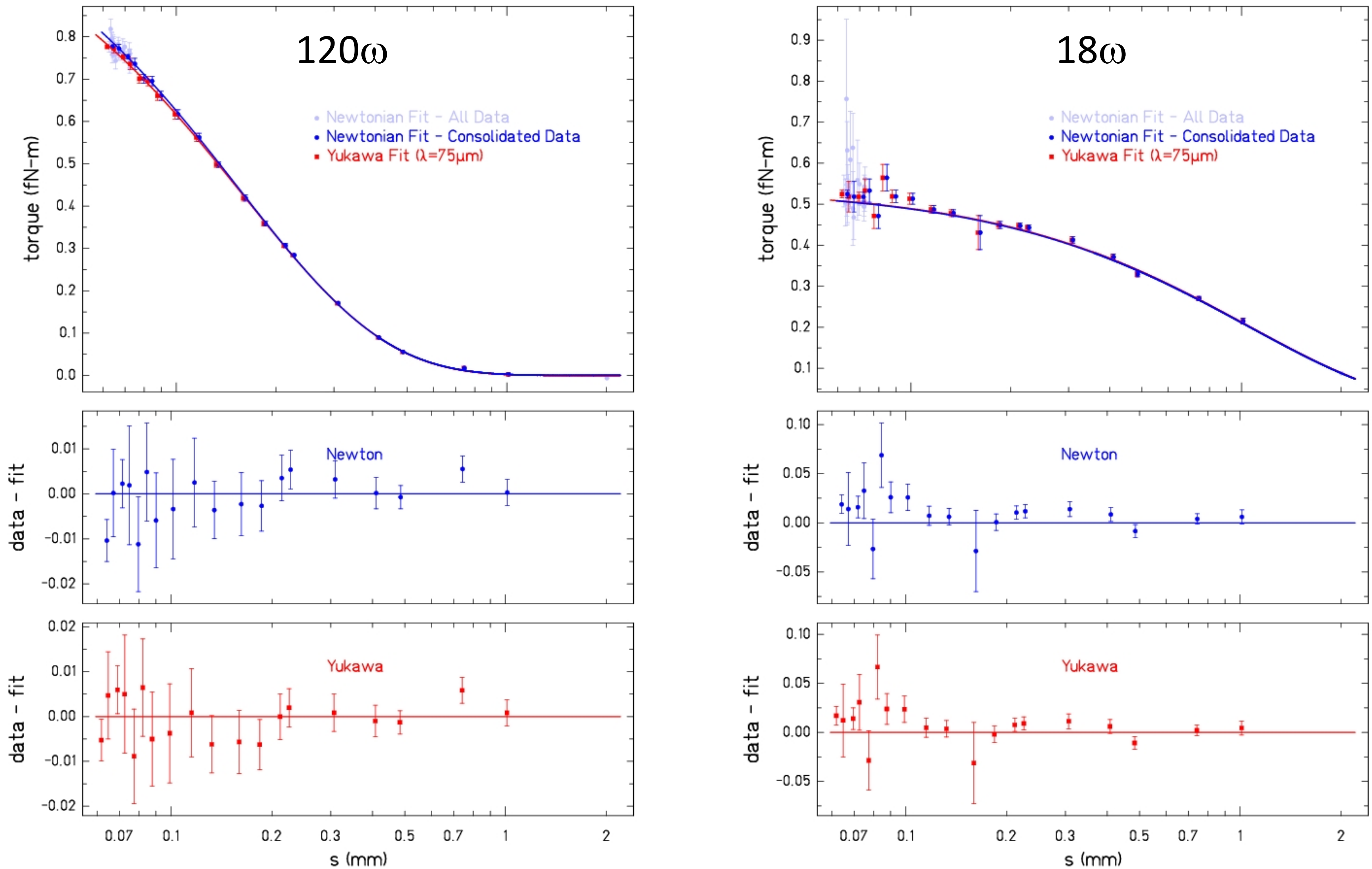




simulation is speeded up by factor of ≈1000

Data Fit

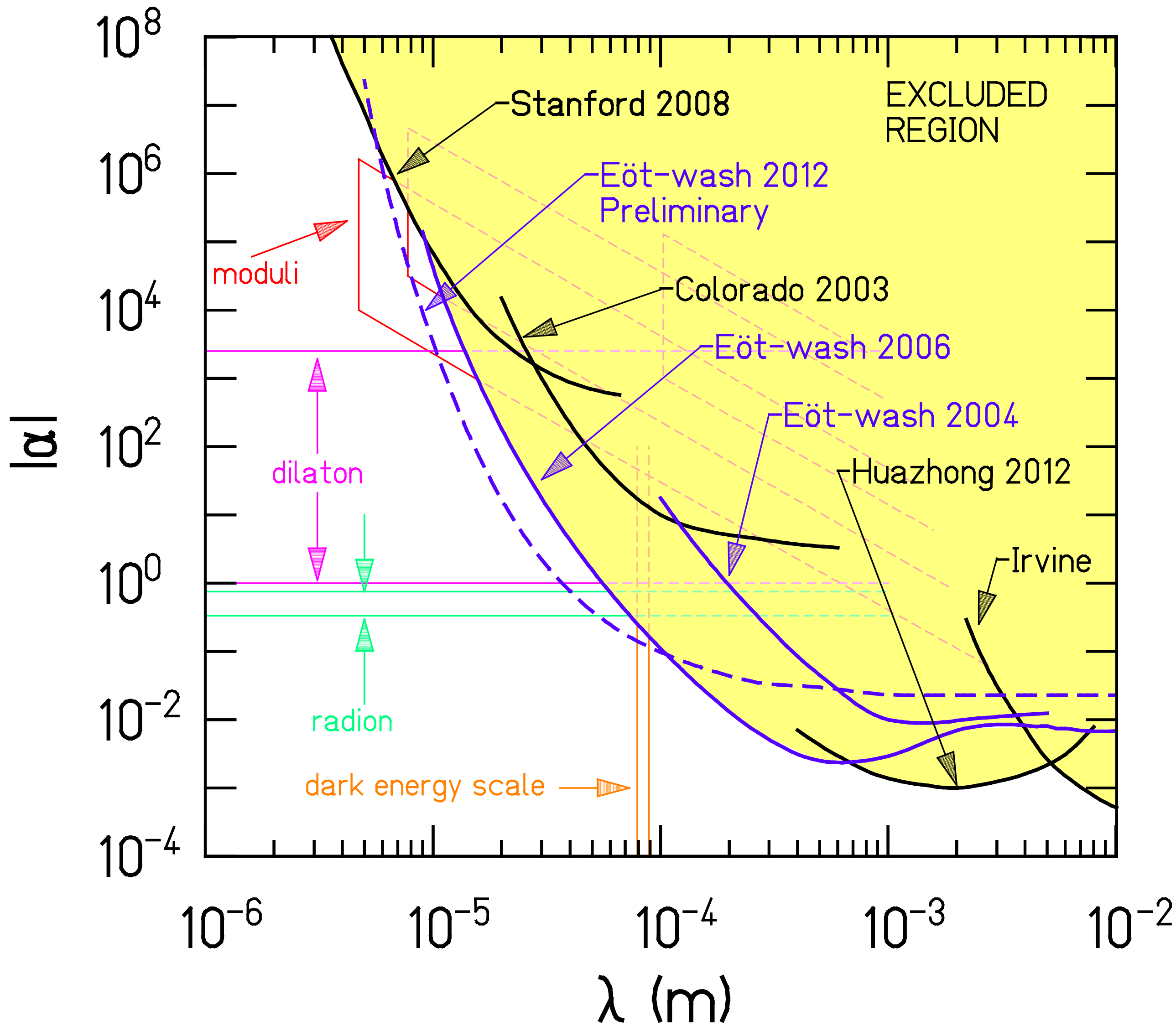
$\lambda = 75\ \mu m$; $\alpha = -0.16 \pm 0.05$



Cook's preliminary 95% C.L. results

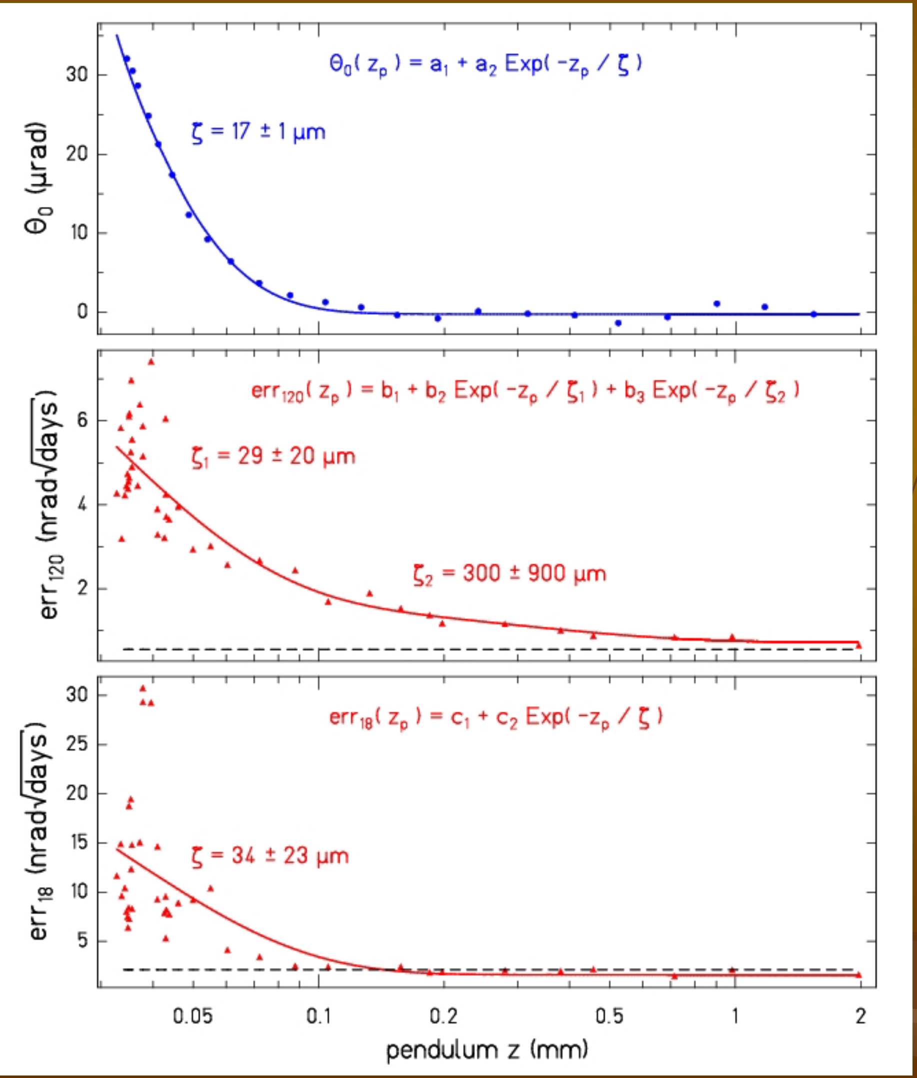
order of magnitude higher sensitivity than Kapner et al. below 40 µm:

We hope to do significantly better by major upgrade of Cook's device.



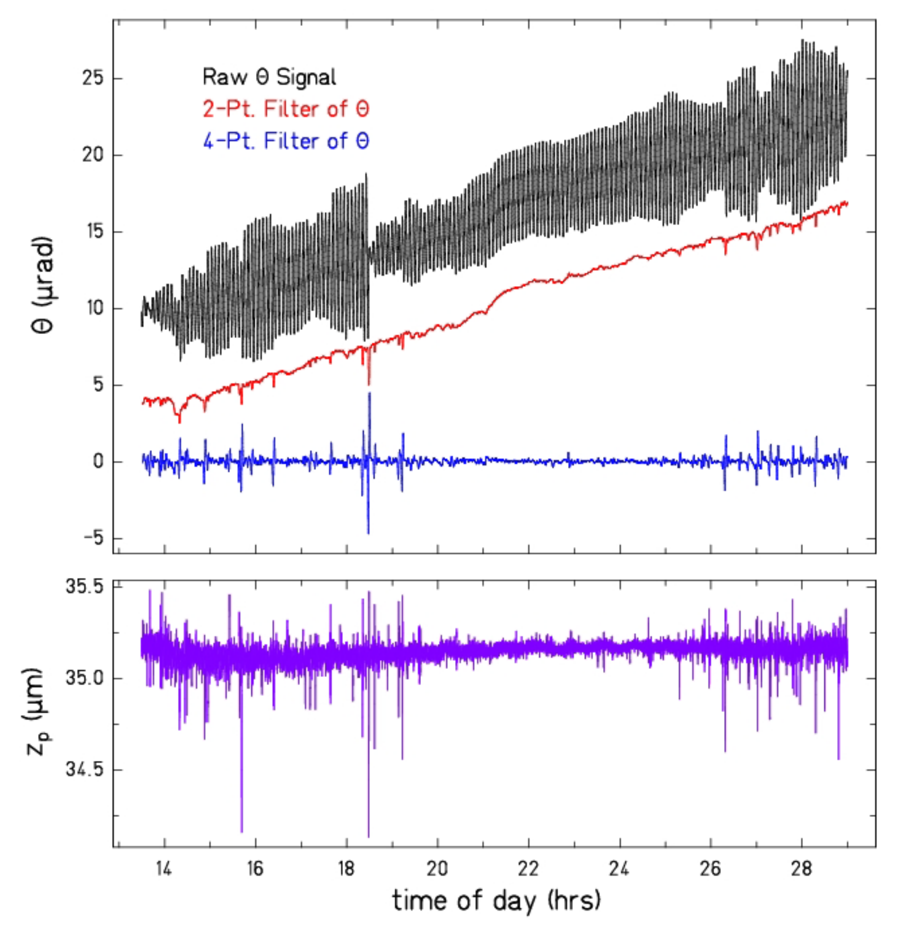
patch fields

patch field potential minimum
not aligned with fiber minimum



vibrations

almost sleepless in Seattle



(attractor not turning)

EP and short-distance ISL tests are tough:

- weak signals (WEP & ISL)
- tricky alignment (ISL)
- changing gravity gradients (WEP)
- patch electrostatic fields (ISL)
- sensitivity to vibrations (ISL)

But there is still room for improvements:

- new test-body materials (WEP & ISL)
- lower-loss suspension fibers (WEP)
- improved vibration damping (ISL)

But the achieved sensitivities are impressive

the differential acceleration resolution achieved in our WEP tests is
$\Delta a \approx 3 \times 10^{-13}$ cm/s^2

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

But there is still some room for improvements:

new test-body materials (WEP)

proton-rich test bodies

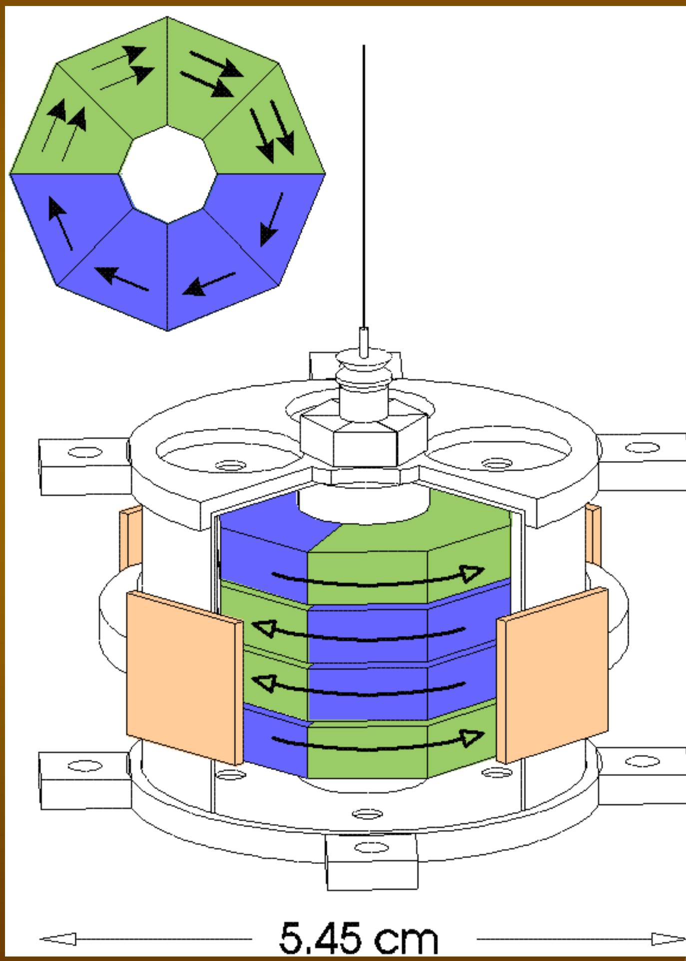
lower-loss suspension fibers (WEP)

fused silica suspension fibers

improved vibration damping (ISL)

better dampers for unwanted pendulum modes

Eöt-Wash spin-dipole pendulum



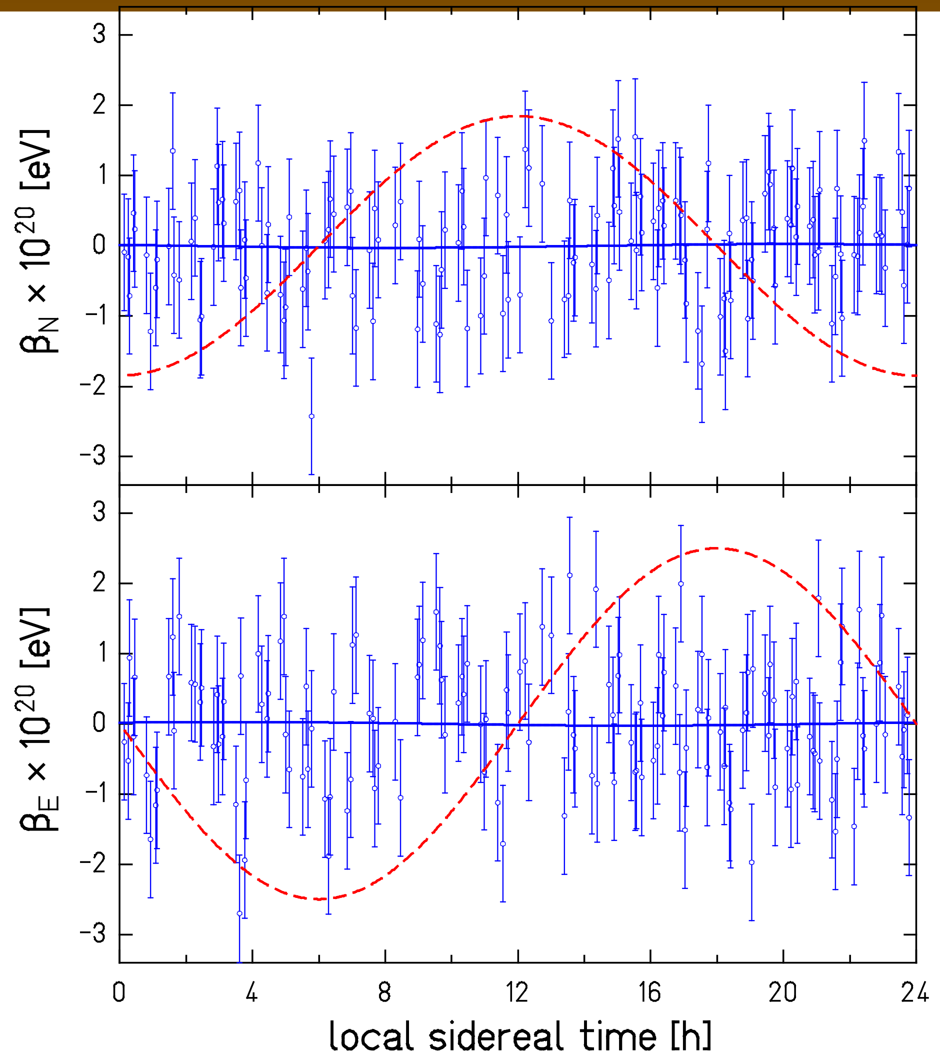
- 9.8×10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within magnets
- negligible external B field

- Alnico: all B comes from electron spin: spins point <u>opposite</u> to B

- $SmCo_5$: Sm 3^+ ion has spin pointing <u>along</u> total B and its spin B field is nearly canceled by its orbital B field--so B of $SmCo_5$ comes almost entirely from the Co's electron spins

- therefore the spins of Alnico and Co cancel and pendulum's net spin comes from the Sm and J = [illegible] S

spin-pendulum data span a period of 46 months between 8/2004 and 6/2008 a 113 hour stretch is shown below



definition of **β:**
$E_{pend}=$ □ $N_p\ \boldsymbol{\beta\cdot\sigma}$

simulated signal from assumed $b_x=2.5\times10^{-20}$ eV

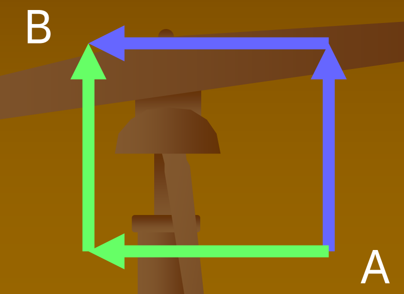
best fit out-of-phase sine waves--corresponds to preferred-frame signal:
$b_x=(-0.20\pm0.76)$□10^{-21} eV
$b_y=(-0.23\pm0.76)$□10^{-21} eV

an amusing number

- our upper limit on the energy required to invert an electron spin about an arbitrary axis fixed in inertial space is ~10^{-22} eV
- this is comparable to the electrostatic energy of two electrons separated by ~ 90 astronomical units

effect of non-commutative geometry on a spin

non-commutative geometry is equivalent to a “pseudo-magnetic” field and thus couples to spins



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

Anisimov, Dine, Banks and Graesser
Phys Rev D 65, 085032 (2002)
 is a cutoff assumed to be 1TeV

constraint on non-commutative geometry

If electrons are point-like up to $\Lambda = 1$ TeV , this corresponds to a minimum observable area

$$|\theta^{\mu\nu}| \leq 6 \times 10^{-58}\ \mathrm{m}^2$$

$6 \times 10^{-58}\ \mathrm{m}^2 \sim (10^6\ L_P)^2$
where L_P is the Planck Length = $\sqrt{\hbar G/c^3} = 1.6 \times 10^{-35}$ m

or $\sim (10^3\ L_U)^2$
where L_U is the GUT scale = $\hbar c / 10^{16}$ GeV

but 10^{13} GeV is not too shabby for a table-top instrument

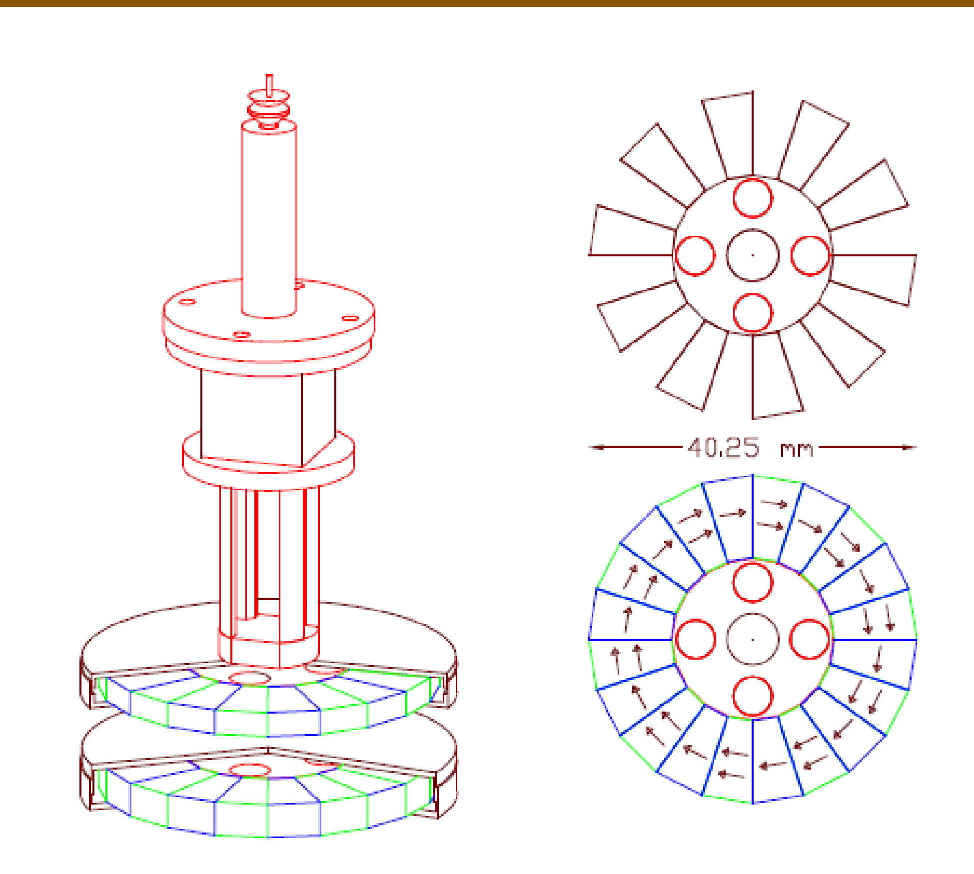
Is QCD the only spontaneously broken fundamental symmetry?

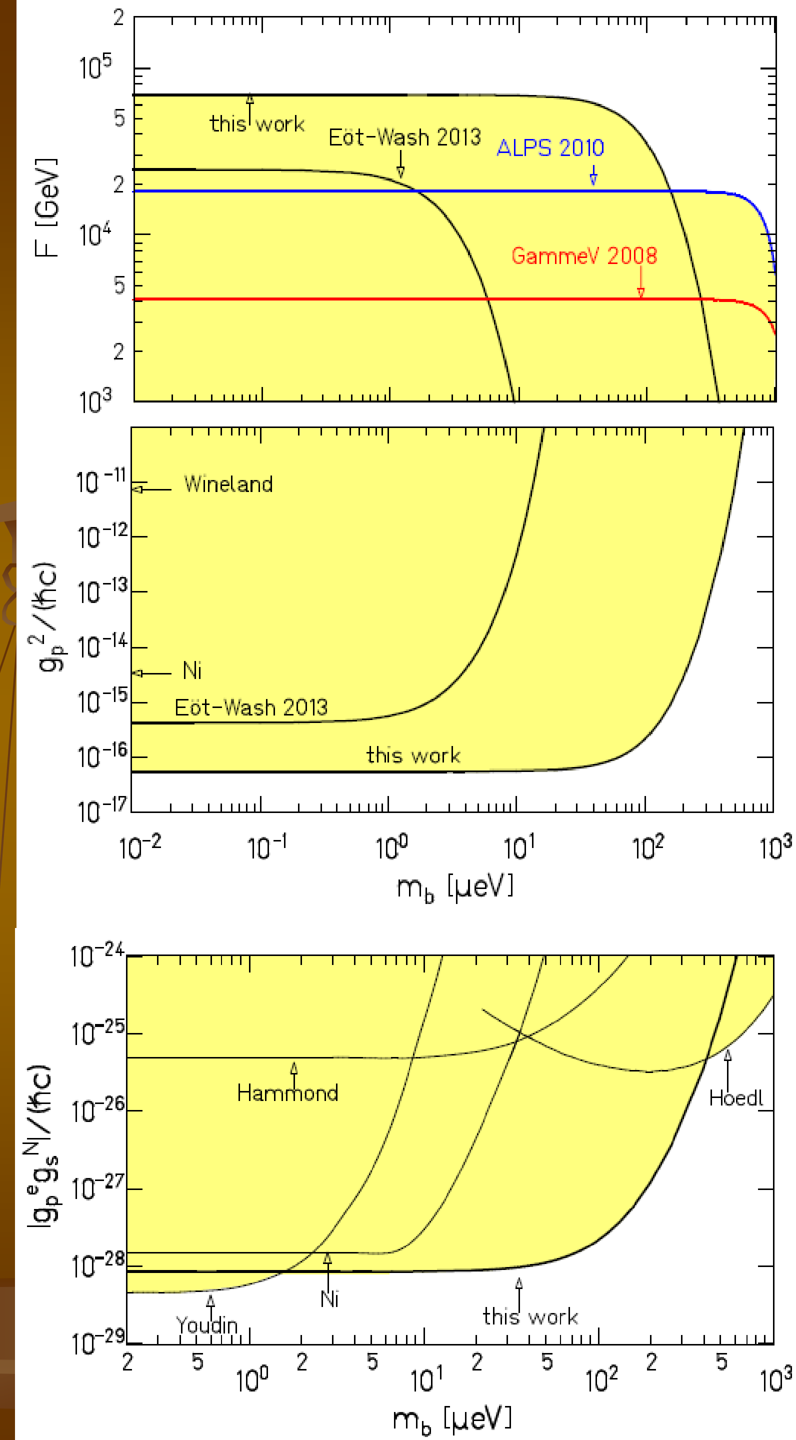
Lots of theoretical suggestions for new symmetries
axions and ALPS, majorans, familons, etc

Generic signature: pseudo-scalar Goldstone bosons whose fermionic couplings are inversely proportional to symmetry-breaking scale F

These couplings are purely spin-dependent so traditional 5th force expts have no tree-level sensitivity

20-pole "pseudo-Goldstone boson detector" probes dipole-dipole & monopole-dipole interactions





W. Terrano 2015 thesis

Current “hot” topic in AMO and gravity:

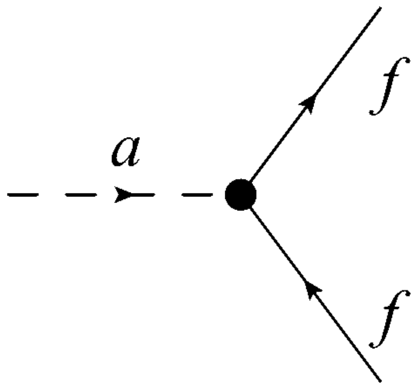
The “WIMP miracle” is getting ever less miraculous

Testing proposals for a new kind of axionic or scalar dark matter candidate

axion could solve 2 mysteries at once the strong-CP and the dark matter puzzles

“Axion Wind” Effect (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]



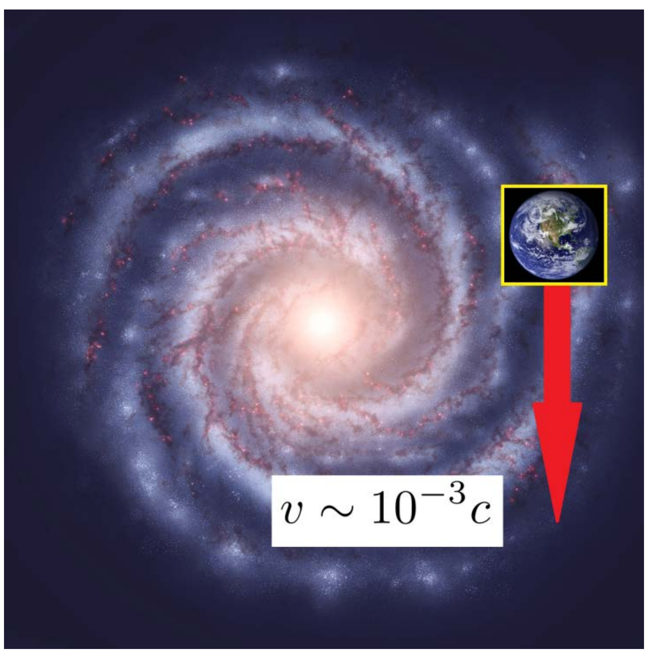
$$\mathcal{L}_{aff} = -\frac{C_f}{2f_a}\partial_i[a_0 \cos(\varepsilon_a t - p_a \cdot r)]\bar{f}\gamma^i\gamma^5 f$$

$$=> \quad H_{\text{eff}}(t) \simeq \frac{C_f a_0}{2f_a}\sin(m_a t)\ p_a \cdot \sigma_f$$

$$a_0\vec{p}_a = \vec{v}_a\sqrt{2\rho_{\text{DM}}}$$

$$v_a \approx 10^{-3}$$

$$H_{\text{eff}}(t) \simeq \sqrt{\rho_{\text{DM}}/2}\ \frac{C_f}{f_a}\sin(m_a t + \phi_a)\vec{v}_a \cdot \vec{\sigma}_f$$



τ_0	200 s	$m_a = 2.1 \times 10^{-17}$ eV
τ_{cut}	2700 s	$m_a = 1.5 \times 10^{-18}$ eV
1 y	$\pi \times 10^7$ s	$m_a = 1.3 \times 10^{-22}$ eV

"Axion Wind" Effect (Axion and ALPs)

[Flambaum, *Patras Workshop*, 2013], [Stadnik, Flambaum, *PRD* **89**, 043522 (2014)]

There are two distinct spin-precession frequencies:

$$H_{\rm eff}(t) \simeq \frac{C_f a_0}{2 f_a} \sin(m_a t) \; \boldsymbol{p}_a \cdot \boldsymbol{\sigma}_f$$

$$\omega_1 \approx \frac{m_a c^2}{\hbar} \qquad \omega_2 = \frac{2\pi}{T_{\rm sidereal}}$$

Spin-axion momentum couplings can be sought for with **atomic co-magnetometer** and **torsion pendulum experiments**.

take-away messages:

High-sensitivity table-top gravitational expts probe really interesting issues

Getting sufficient sensitivity is not so difficult

The hard part is eliminating all the systematic errors

References:

EP

T. A. Wagner, S. Schlamminger, J. H. Gundlach and E. G. Adelberger, Class Quant Grav 29, 184002 (2012)

T.A. Wagner, PhD thesis (2014)

ISL

D.J. Kapner et al., Phys. Rev. Lett. 98 021101 (2007)

E.G. Adelberger et al., Phys. Rev. Lett. 98, 131104 (2007)

T.E. Cook, PhD thesis (2013)

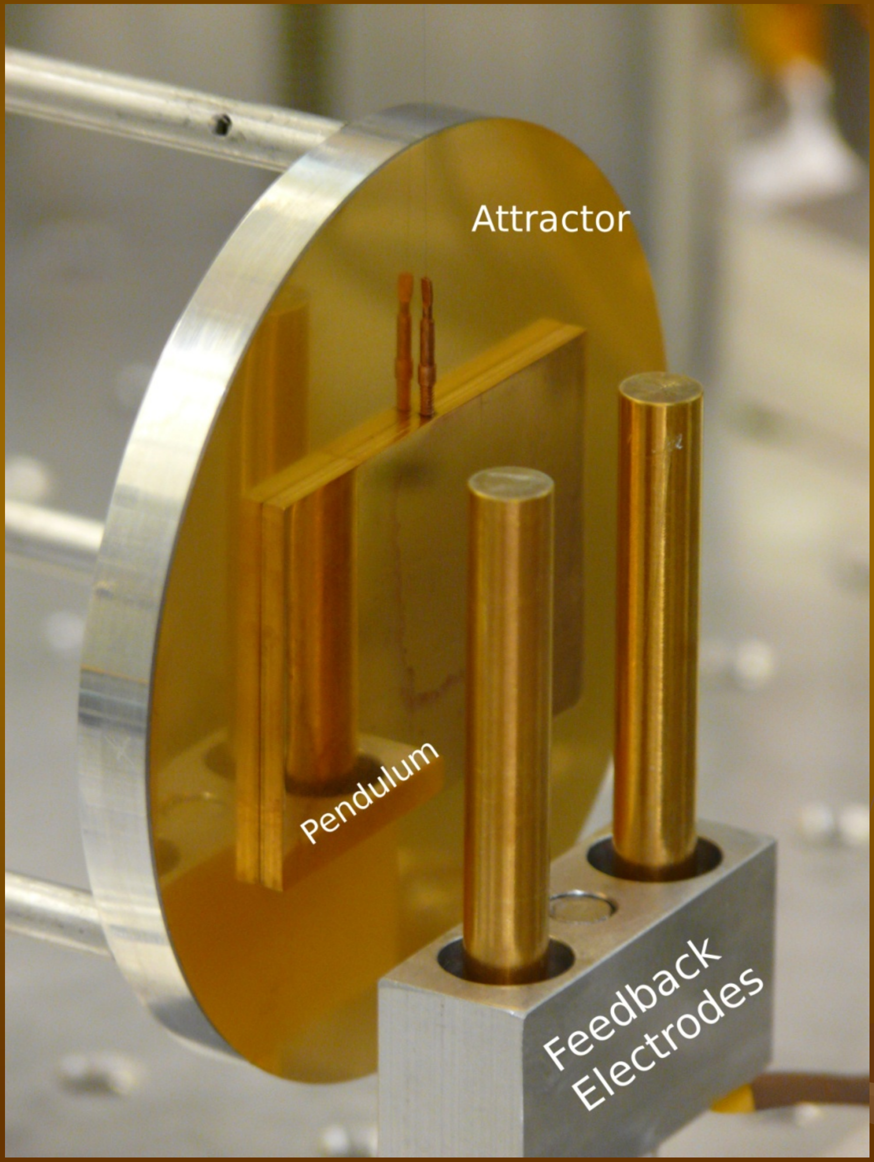
SPIN

B.R. Heckel et al., Phys. Rev. D 78, 092006 (2008)

REVIEW

E.G. Adelberger, J.H. Gundlach, B.R. Heckel, S. Hoedl and S. Schlamminger, Progress in Particle and Nuclear Physics 62, 102 (2009).

Parallel-plate ISL instrument

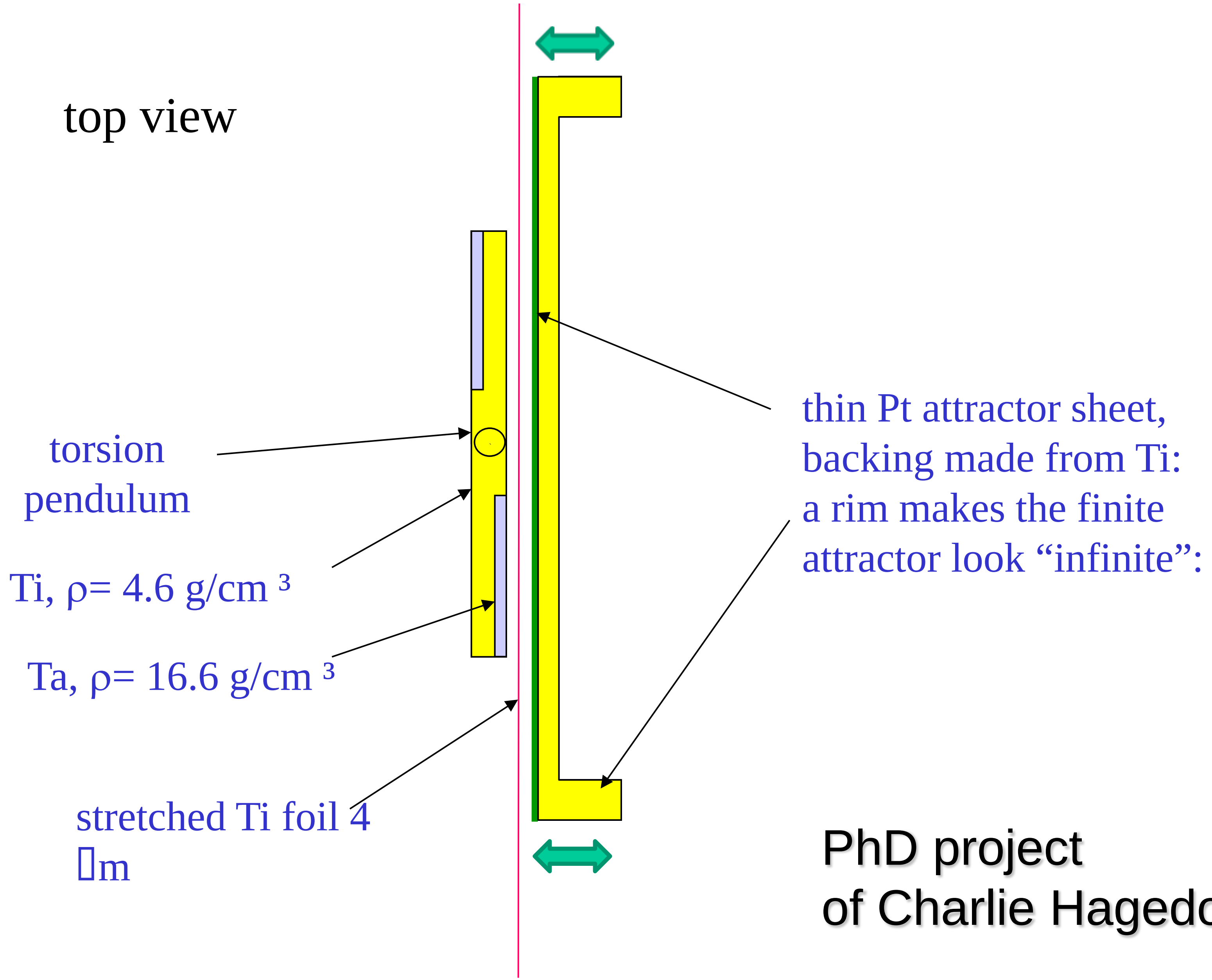


attractor is mounted on a pneumatically-driven flexure

Charlie is doing a sophisticated blind analysis of his data. He is brave and will “open the envelope” during his upcoming thesis defense.

the electrostatic shield between pend and moving attractor was removed for this photo. Its position is monitored by 3 fiber interferometers

Parallel-plate null test of the ISL



PhD project
of Charlie Hagedorn