Precision tests of Newton's inverse-square law and Einstein's equivalence principle

results are interesting because of the extraordinary sensitivity of our mechanical experiments to tiny forces

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University of Washington

will discuss experimental principles
and the motivations for, results from, and implications of,
the following experimental tests:

- Equivalence Principle (universality of free fall)
  - broad-gauge search for exotic Yukawa forces
  - gravitational properties of dark matter
  - gravitational properties of antimatter

- Inverse-square law at short distances (completely unknown)
  - broad-scale search for new meV-scale physics
  - extra dimensions
  - chameleons

the Eöt-Wash® group in experimental gravitation

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

Staff scientist
- Erik Swanson

Current & recent postdocs
- Andreas Kraft
- Stephan Schlamminger
- Krishna Venkateswara

Current Grad students
- Charlie Hagedorn
- Michael Ingber
- John Lee
- Will Terrano
- Matt Turner
- Todd Wagner

EP
spin
$1/r^2$

Primary support from NSF Grant PHY0969199 with supplements from the DOE Office of Science and to a lesser extent NASA

unifying gravity with the other forces in physics is the central problem in fundamental science

string or M theory provides the only known framework
for doing this but it inherently contains features that have to be hidden from experiment:

10 or 11 dimensions
100s of massless scalars with “gravitational” couplings

and it doesn’t naturally account for the extreme weakness
of gravity or the observed “dark energy”

many scenarios have been invented to address this;
some of these predict new features could show up in equivalence principle and/or inverse-square law tests

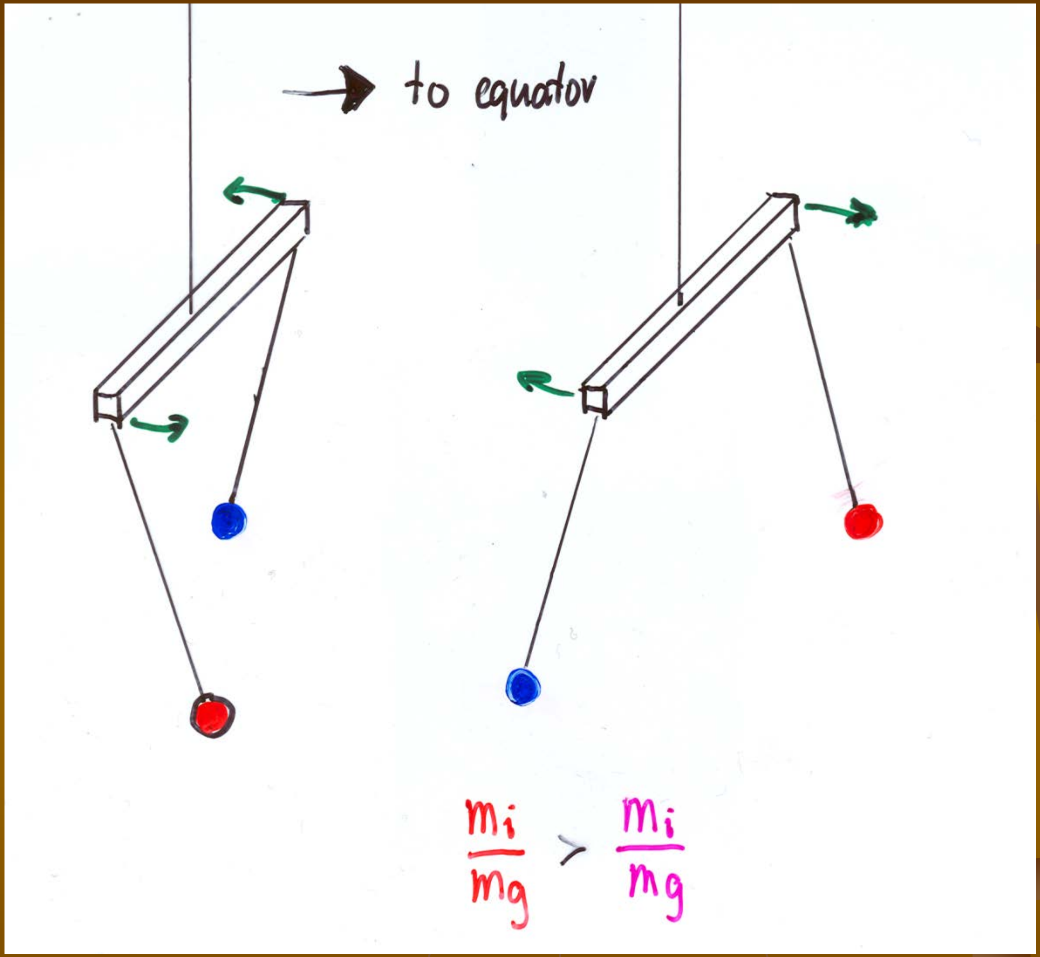
Einstein used the equivalence principle to develop his relativistic theory of gravity.

Statements of Einstein's equivalence principle:

- acceleration is locally equivalent to gravity
- local effects of gravity disappear in freely falling frames
- in Newtonian terms $mg = mi$

The most precisely tested manifestion of the EP is the universality of free fall (WEP)

testing the WEP by watching things fall sideways



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

brief history of EP tests in the 20th century:

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

1950-60’s Dicke
watched things falling toward sun and let
earth’s rotation turn his 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

two ways to think about WEP tests:

old way:

is $mg = mi$ exactly true?

new way (popularized by E. Fischbach):

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

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”

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

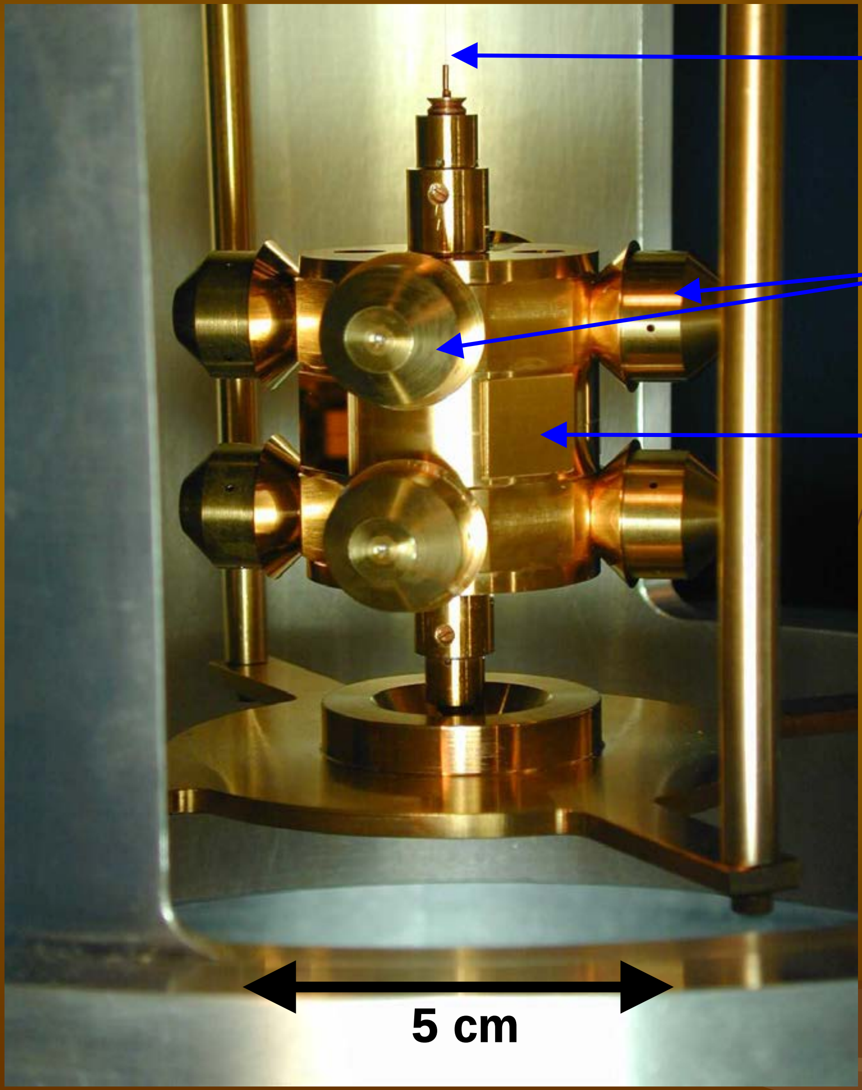
$$V_{1,2} = V_{\mathrm{G}} + V_{\mathrm{OBE}} = V_{\mathrm{G}}(r) \left(1 + \tilde{\alpha} \left[\frac{\tilde{q}}{\mu}\right]_1 \left[\frac{\tilde{q}}{\mu}\right]_2 \exp(-r/\lambda) \right)$$

general vector charge of electrically neutral objects

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

torsion pendulum of our recent EP 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

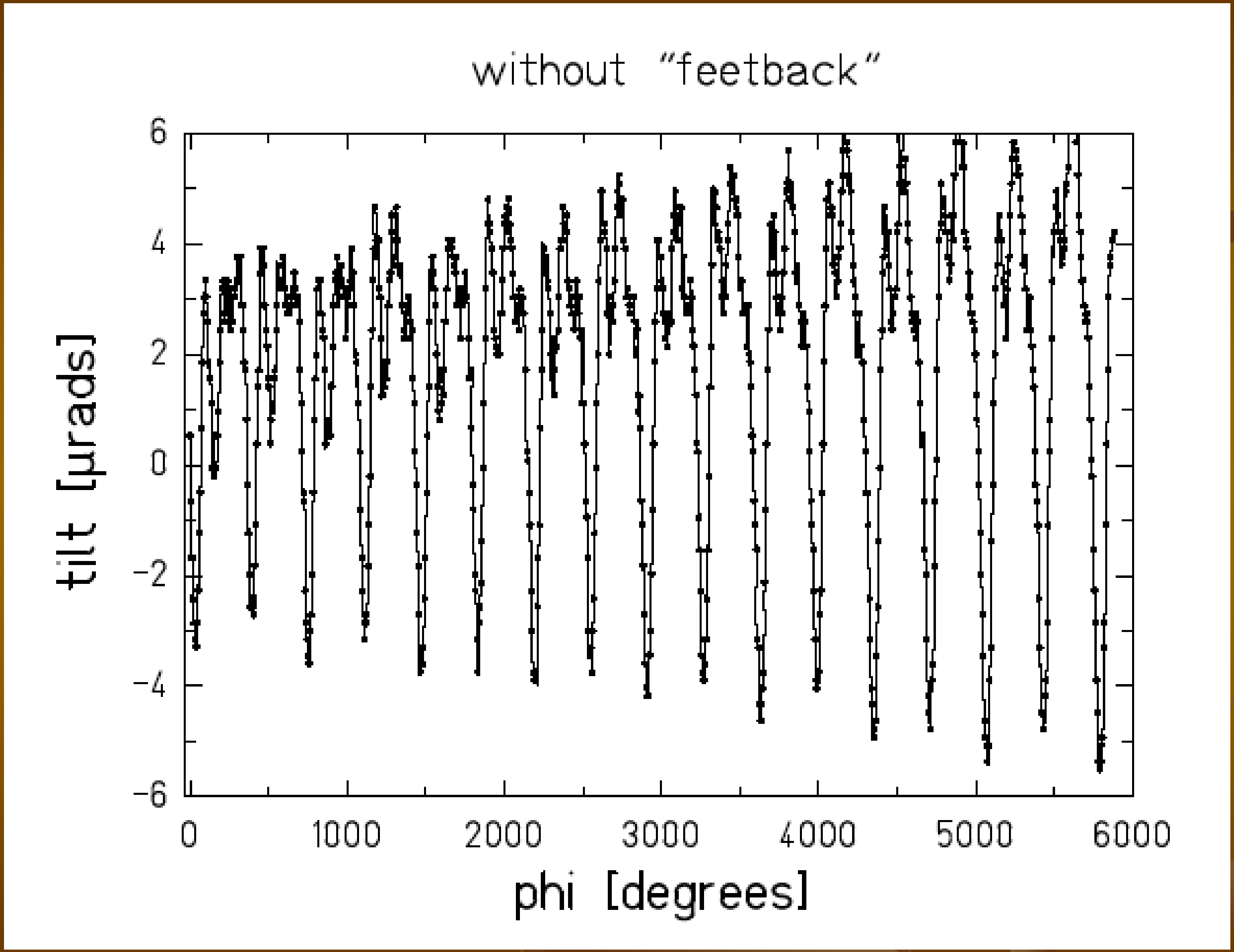
Eöt-Wash torsion balance hangs from turntable that rotates at about 0.833 mHz

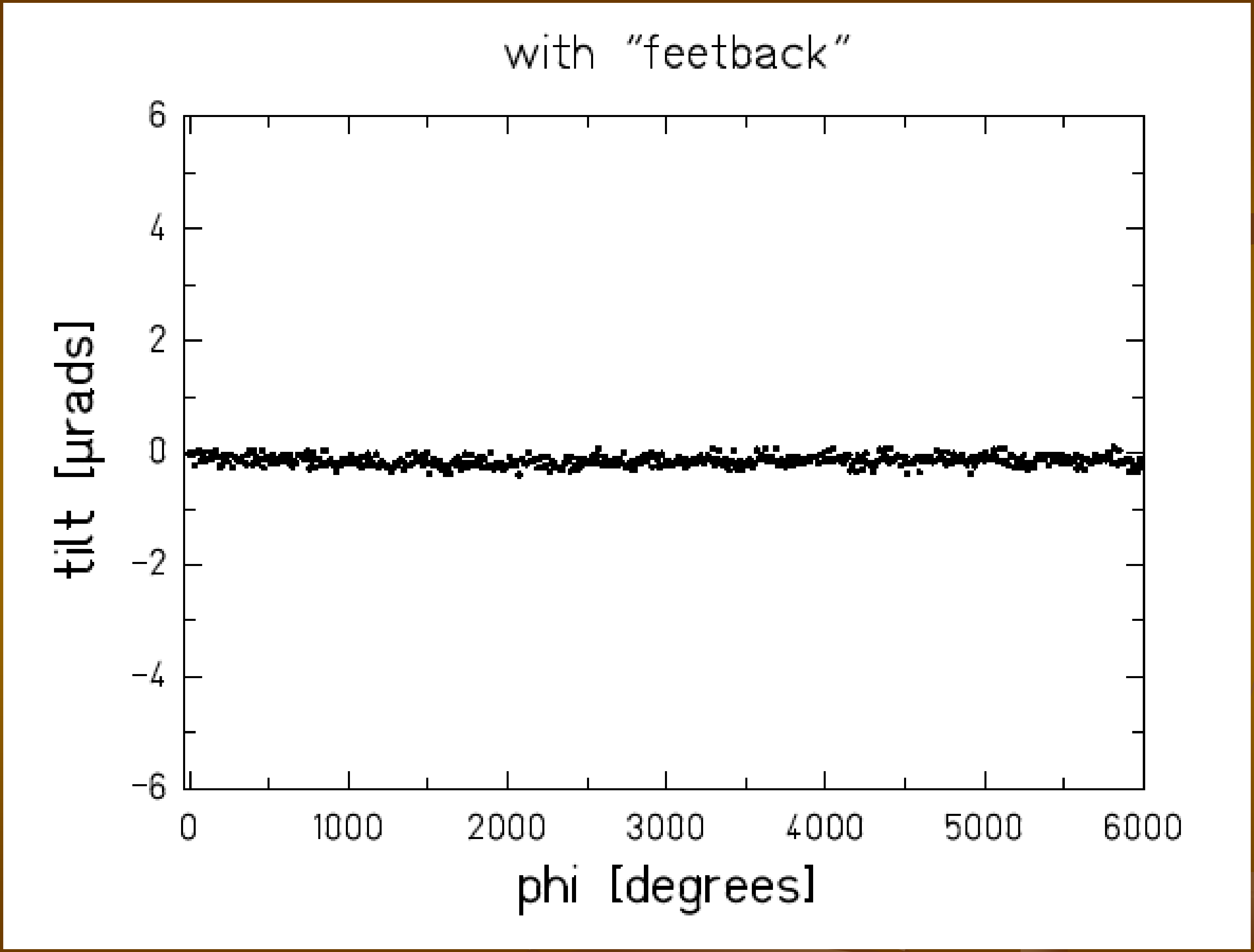
turntable requirements:

1) constant rotation rate
2) rotation axis must be along the suspension fiber

air-bearing turntable

thermal expansion feet fedback to keep turntable rotation axis level


without "feetback"
tilt [μrads]
6
4
2
0
−2
−4
−6
0
1000
2000
3000
4000
5000
6000
phi [degrees]


with "feetback"
tilt [μrads]
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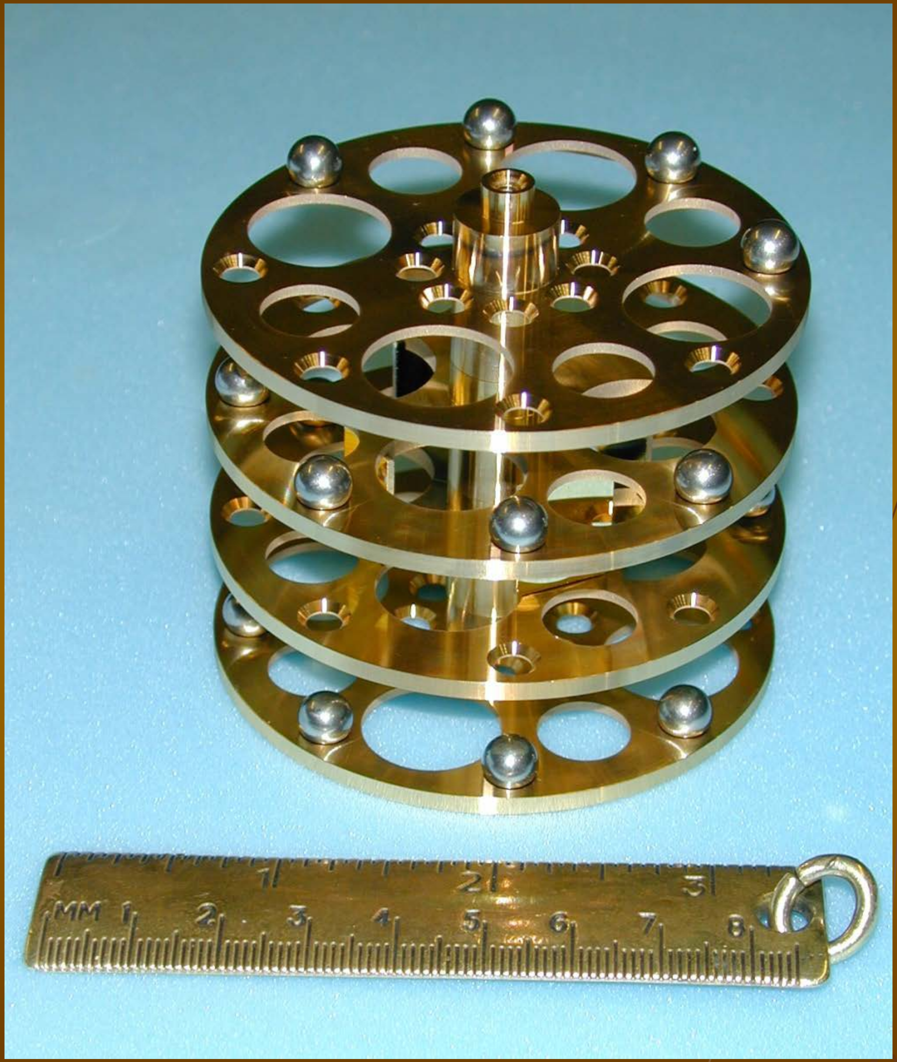
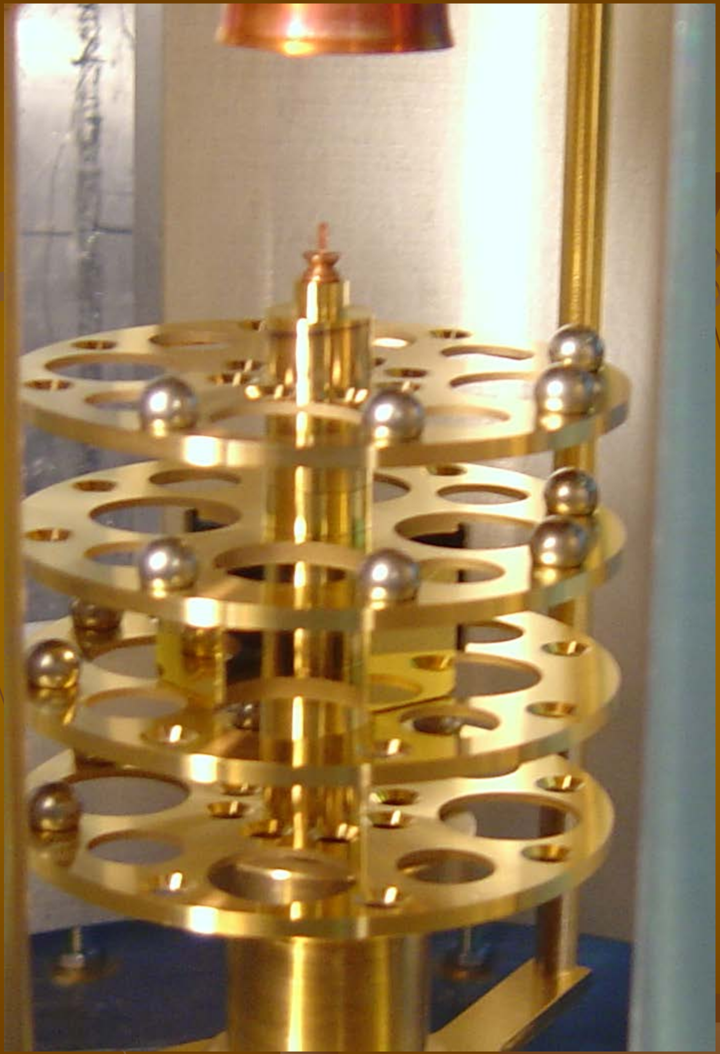
6000
phi [degrees]

gravity-gradiometer pendulums

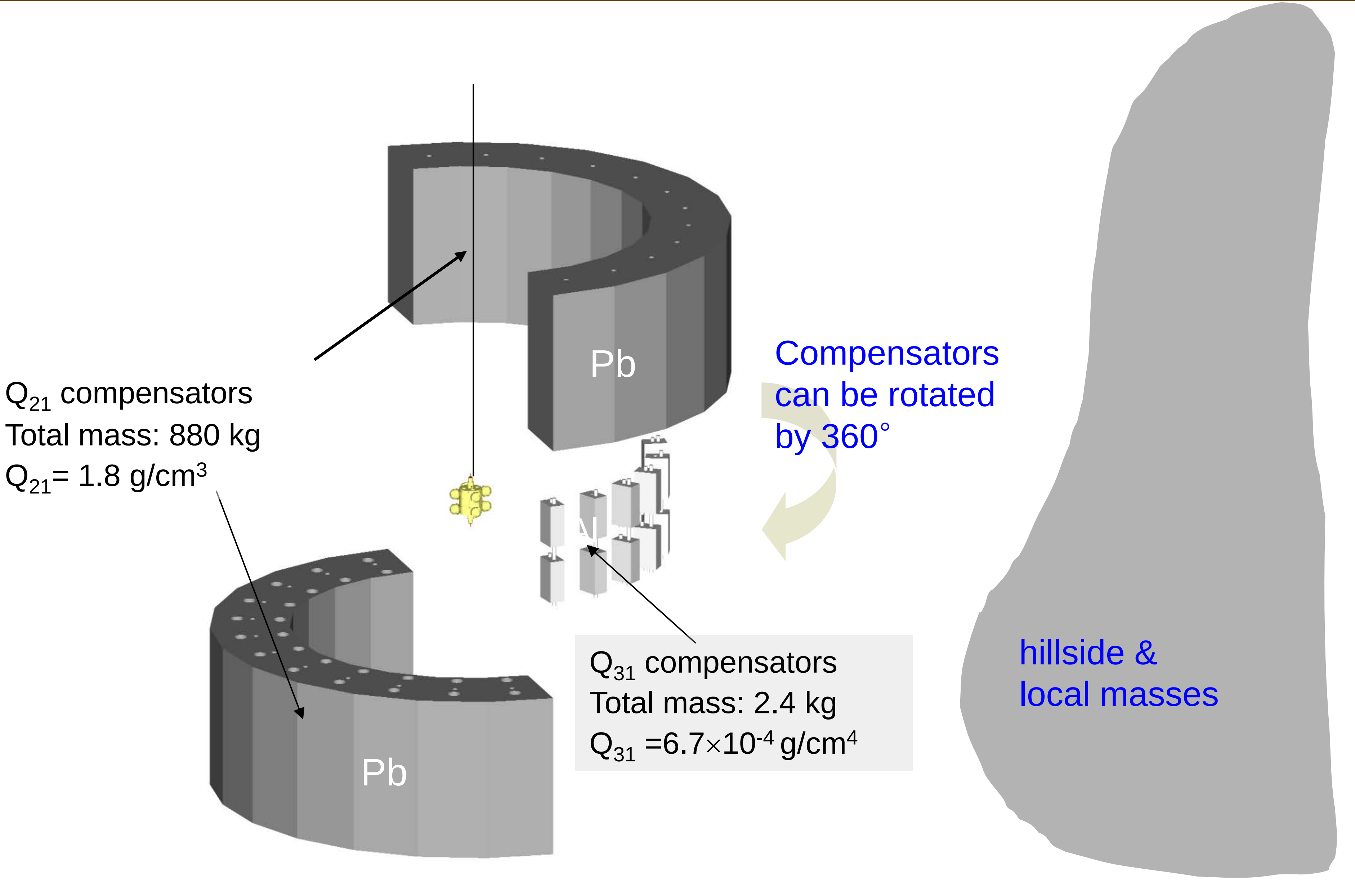


q_{41} configuration on a table

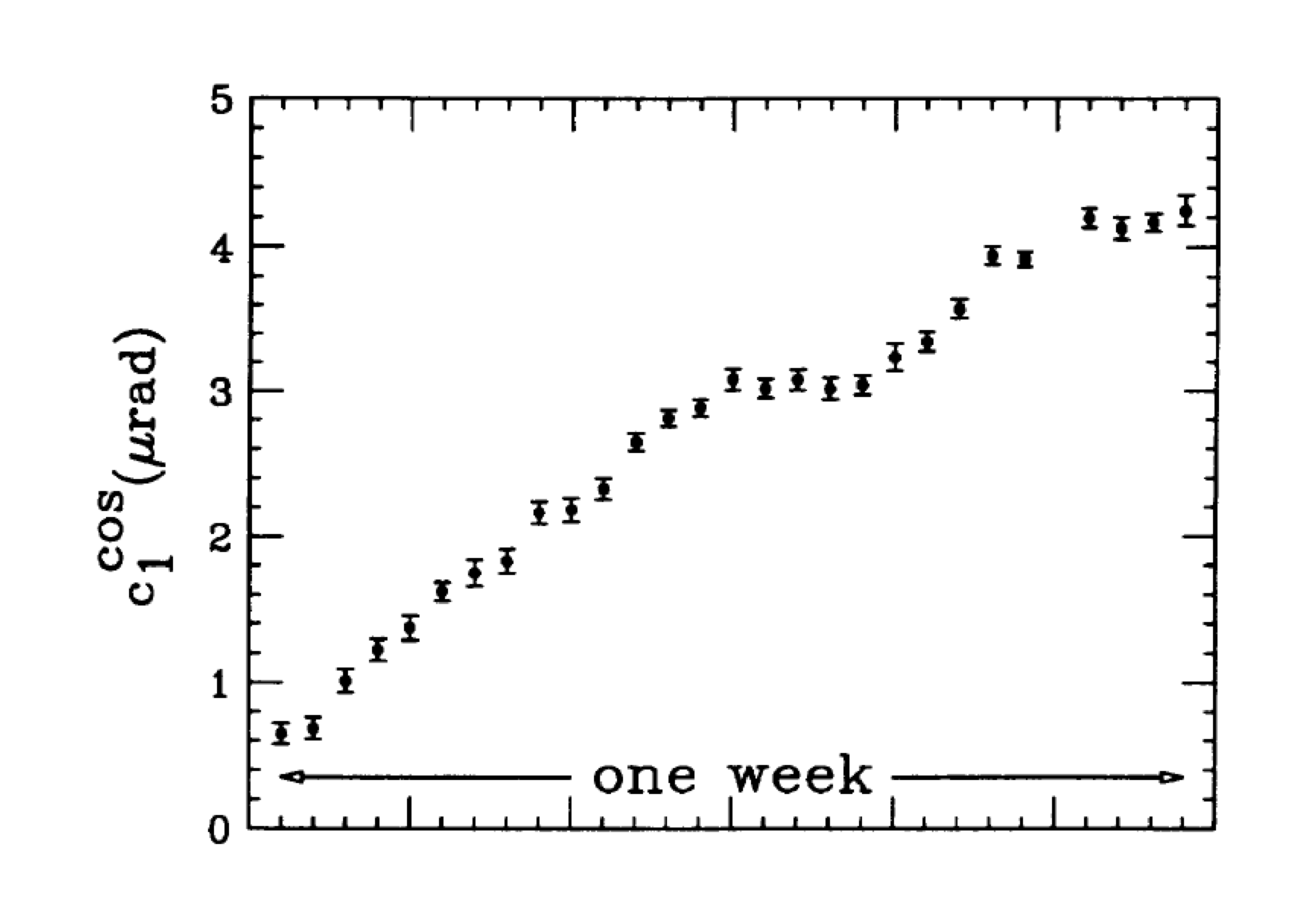


q_{21} configuration installed

gravity-gradient compensation



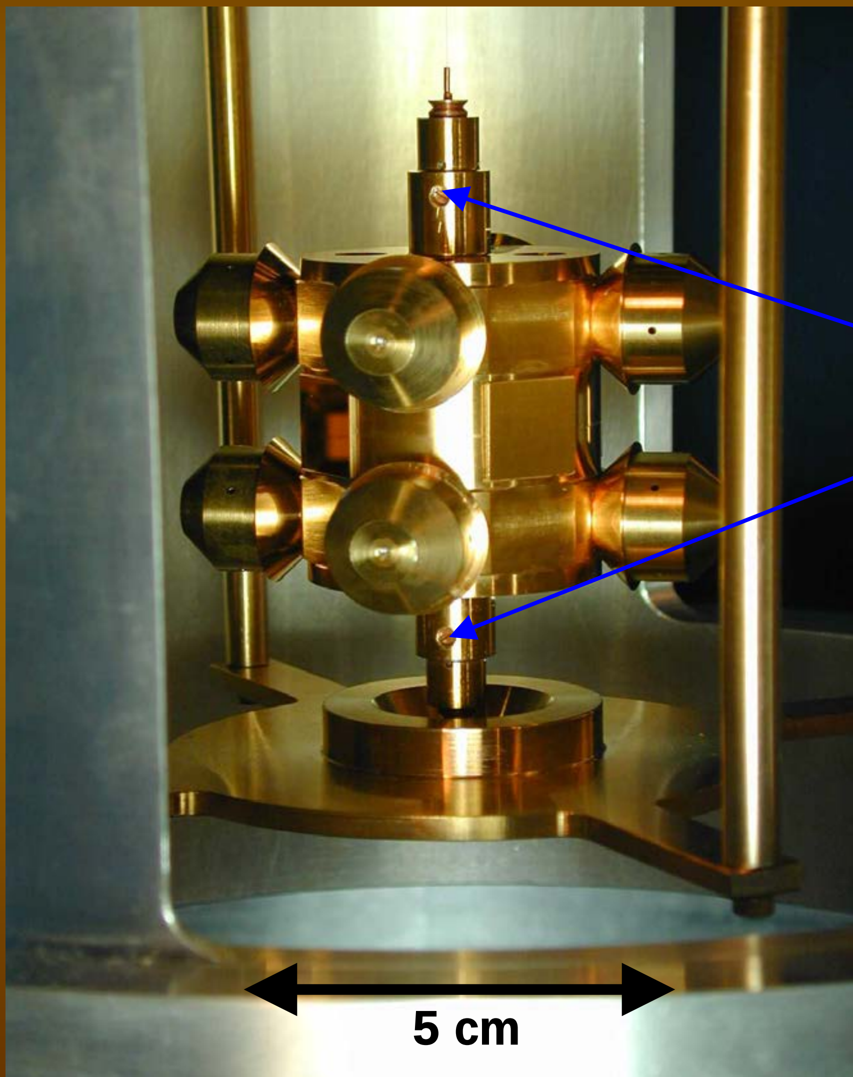
limitations on gradient cancellation



these data were taken in early November

torsion pendulum of our recent EP test

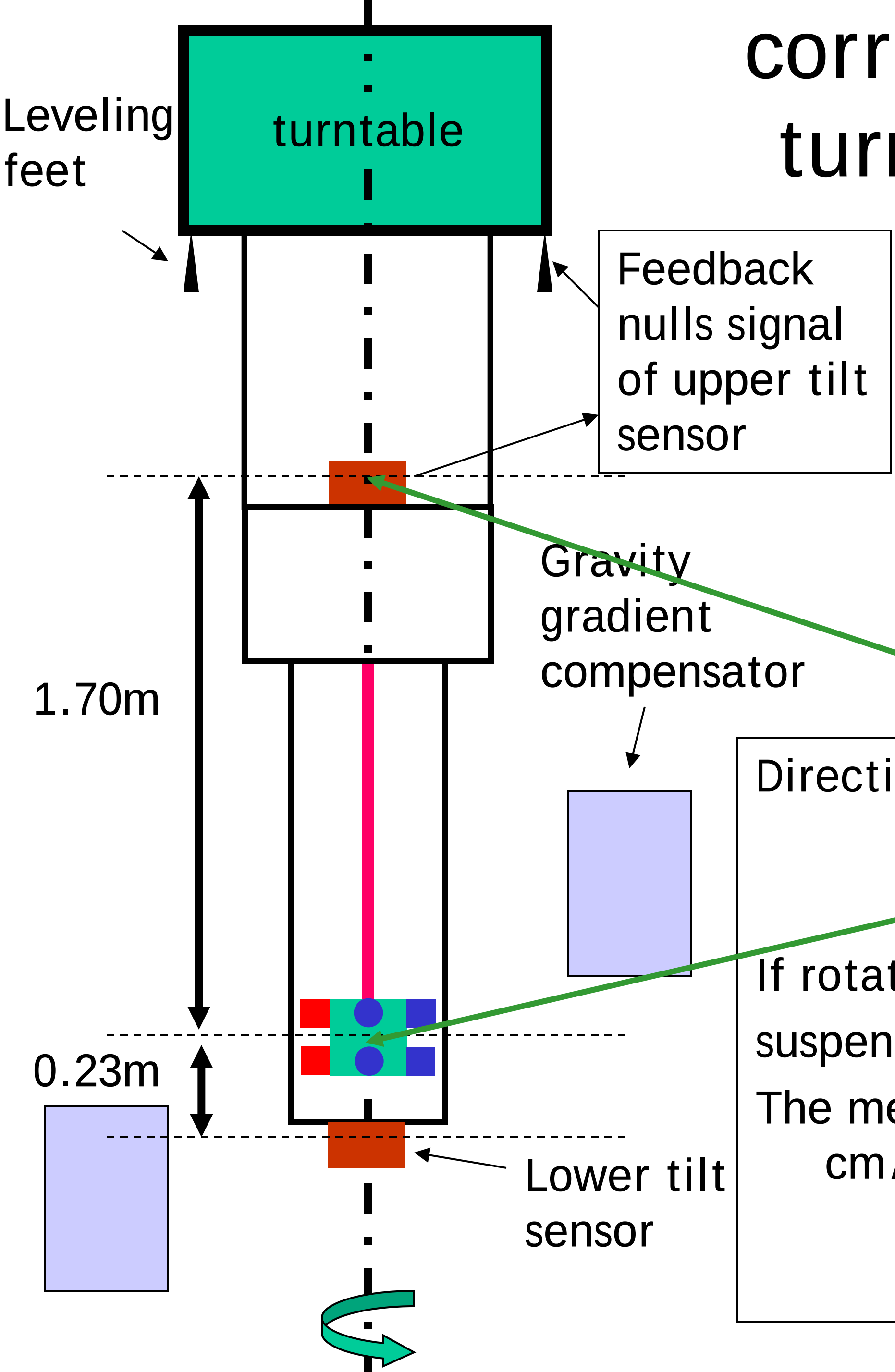
T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)



8 tiny screws that grad students painstakingly adjust to null out leading mass multipole term (q21) and reduce sensitivity to changing gravity gradients

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

correction for tilt of the turntable rotation axis

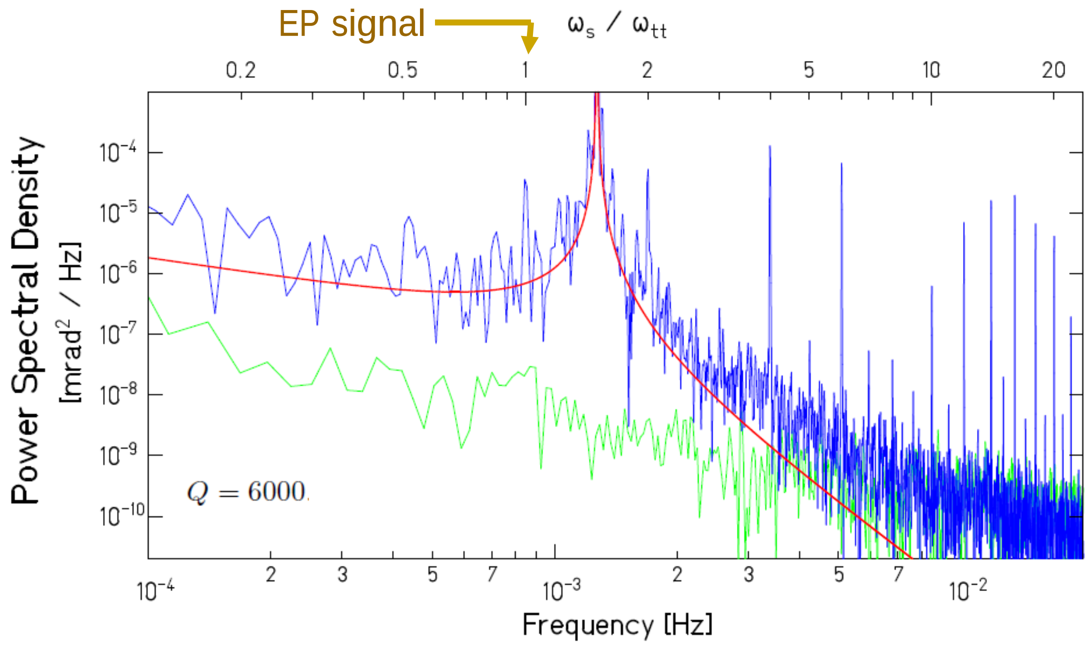


- Feedback removes tilt at upper tilt sensor
- However, local vertical varies with height
  - gives a spurious deflection of the pendulum due to residual tilt

Directions of down here and here differ by 50 nrad

If rotation axis is down at the upper sensor, the suspension fiber experiences 50 nrad of “tilt”.

The measured correction for this is 16×10^{-13} cm/s^2



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

data points show the difference of 2 opposite pendulum orientations in 2 week long runs; the difference in the solid lines is due only to the test bodies themselves

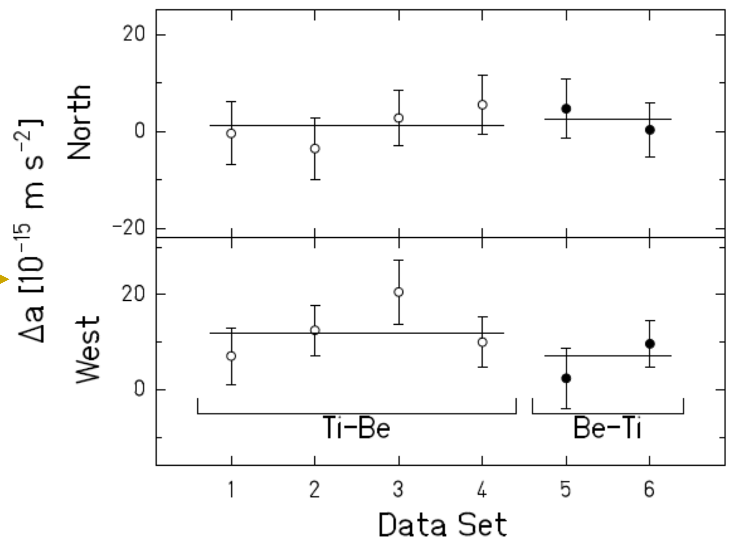


Figure 5. Data collected in the Ti-Be (first 4 runs) and Be-Ti (last 2 runs) configurations of the pendulum. The final result is in the difference between the means of the two configurations (shown as solid lines).

results with 1σ 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

Table 2. Error budget for the lab-fixed Be-Ti differential accelerations. Corrections were applied for gravitational gradients and tilt, only upper limits were obtained on the magnetic and temperature effects. All uncertainties are $1\,\sigma$.

Uncertainty source	$\Delta a_{\mathrm{N,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$	$\Delta a_{\mathrm{W,Be-Ti}}$ $(10^{-15}\ \mathrm{m\ s^{-2}})$
Statistical	3.3 ± 2.5	-2.4 ± 2.4
Gravity gradients	1.6 ± 0.2	0.3 ± 1.7
Tilt	1.2 ± 0.6	-0.2 ± 0.7
Magnetic	0 ± 0.3	0 ± 0.3
Temperature gradients	0 ± 1.7	0 ± 1.7

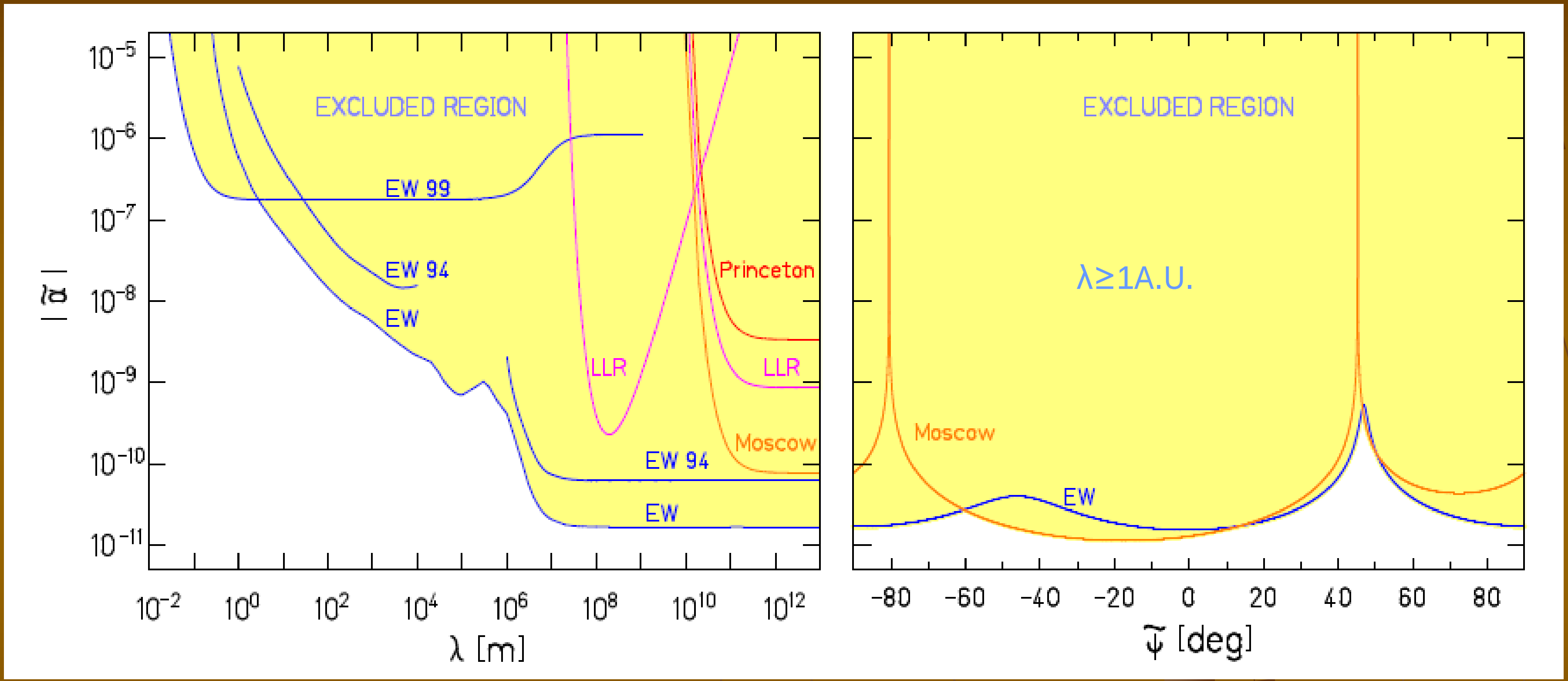
PhD project of Todd Wagner

an amusing number

our differential acceleration resolution $\Delta a \approx 3 \times 10^{-13}$ cm/s^2

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

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



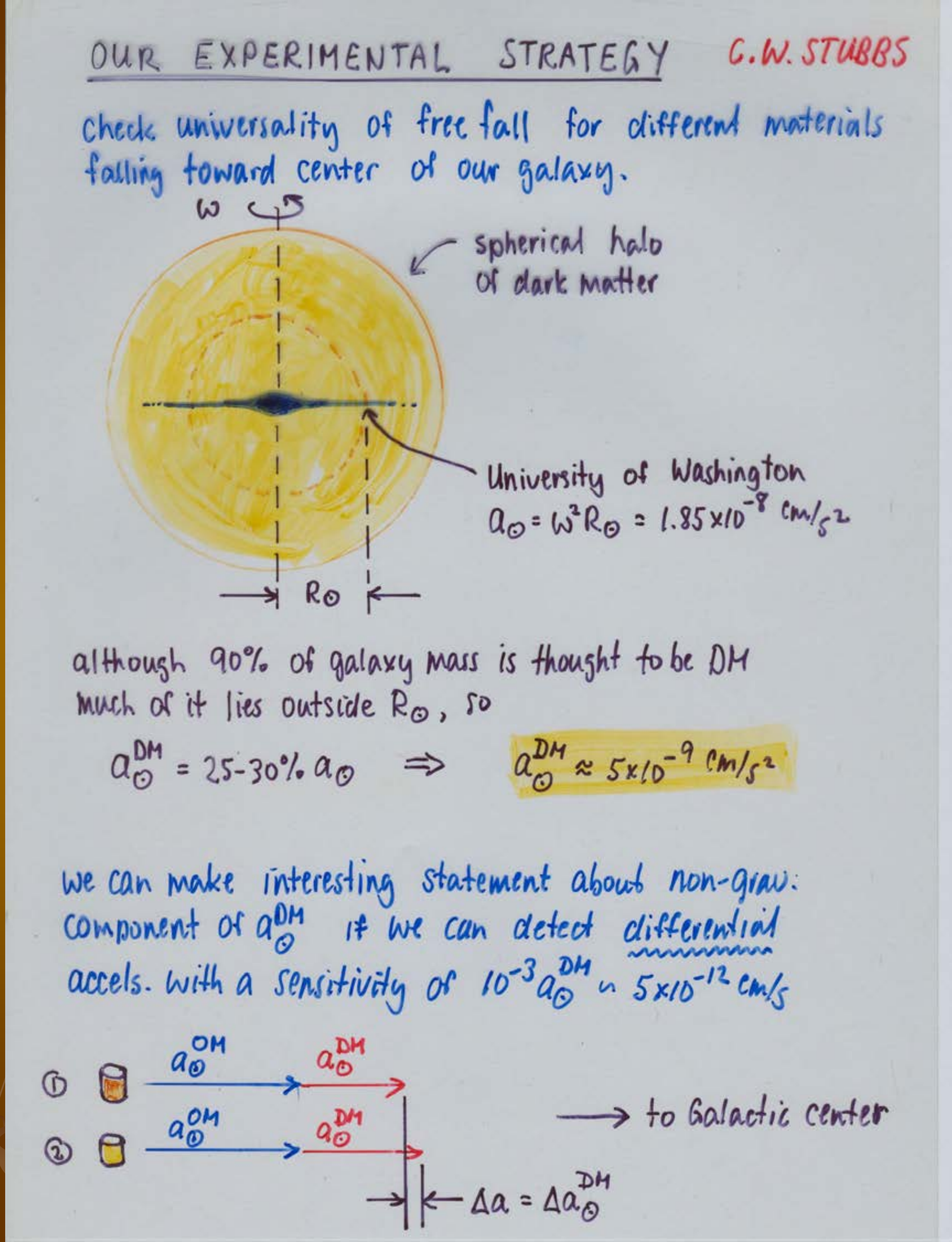
Yukawa attractor integral based on:

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

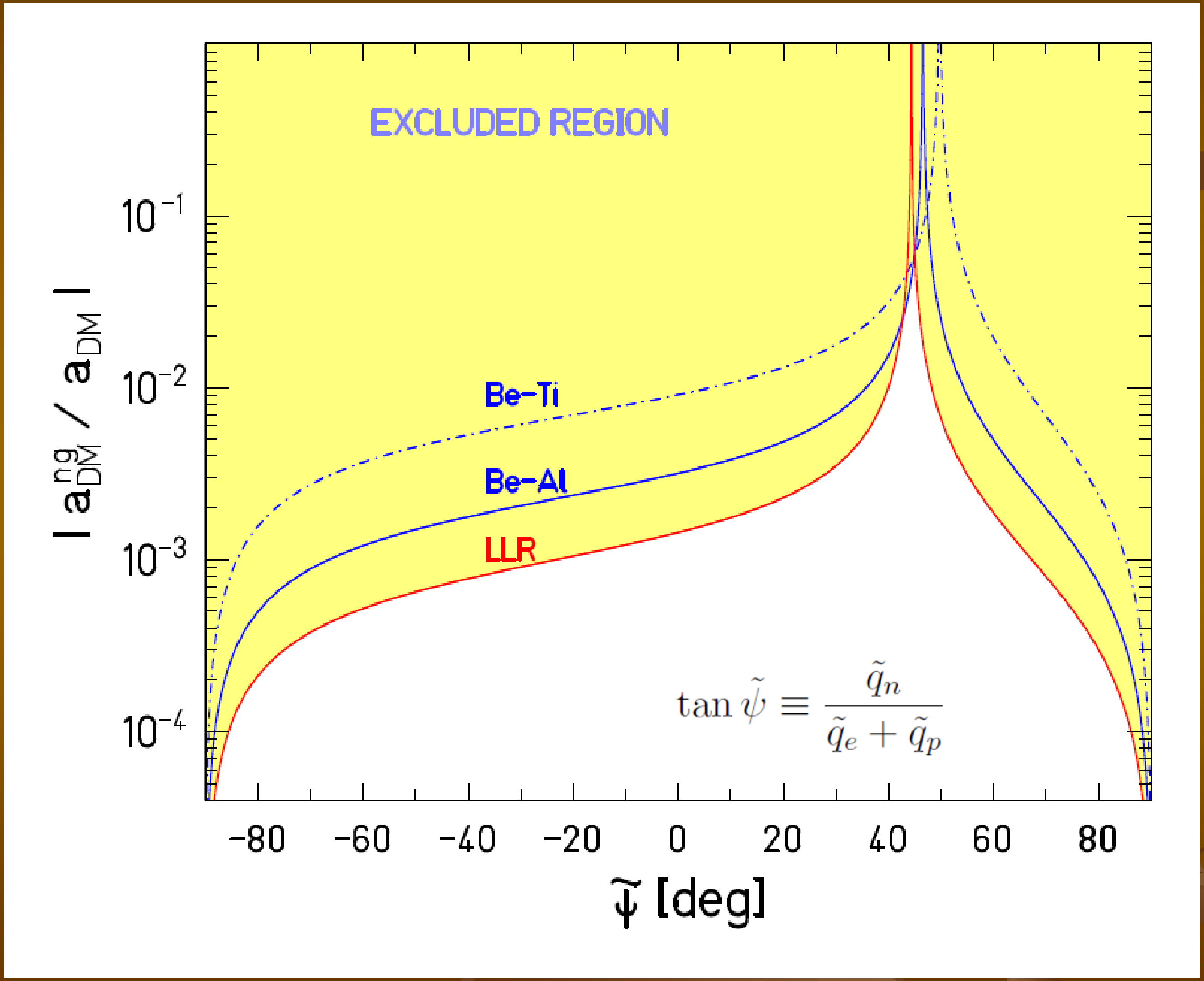
T. A. Wagner et al., Class. Quant. Grav. 29, 184002 (2012)

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

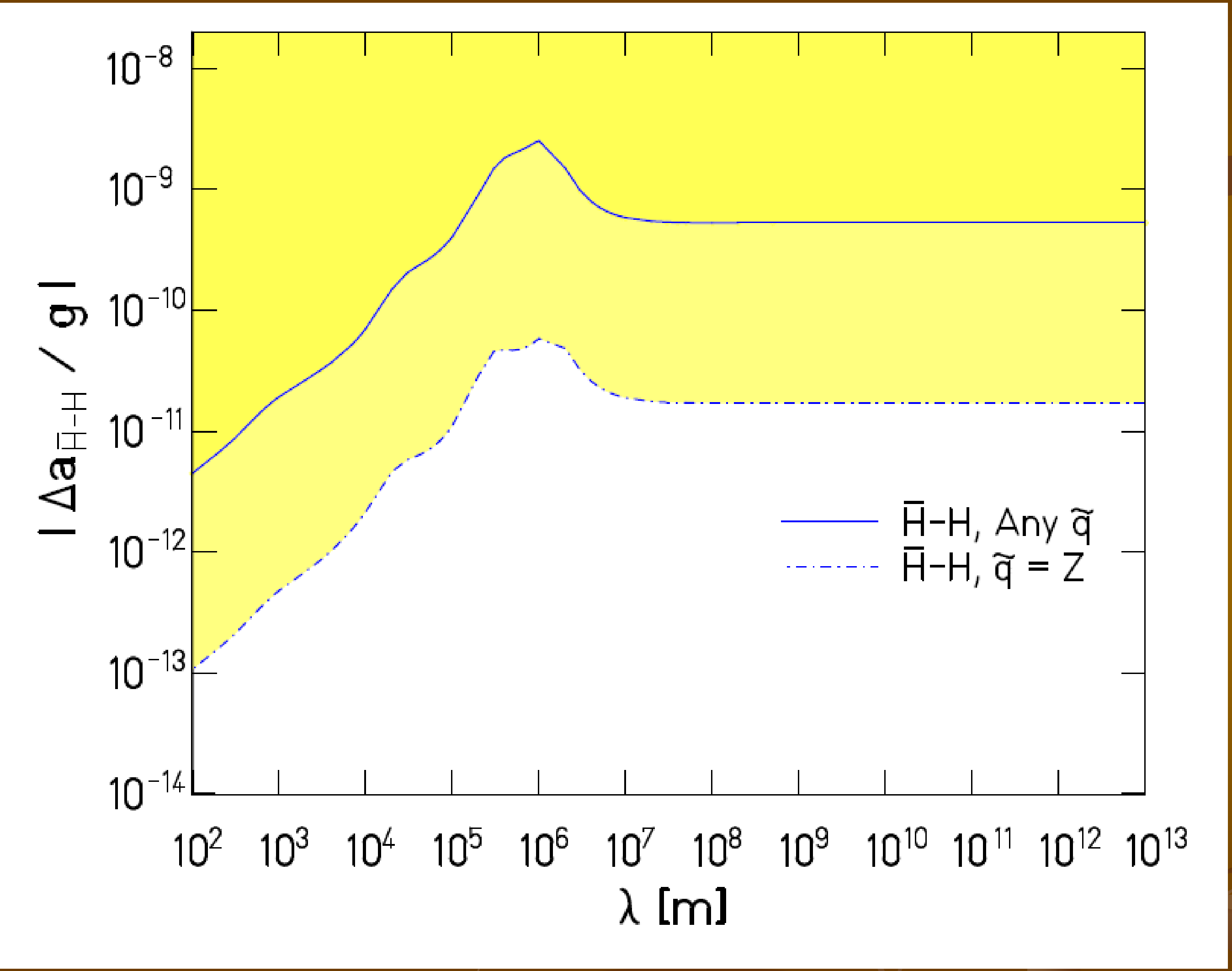
2) nucleons (~99% of their mass consists of glue & antiglue) should fall with ~100 times smaller accelerations than electrons

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 EP 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)

motivations for sub-millimeter tests of the inverse-square law

- explore an untested regime

- probe the dark-energy length scale

$$\rho_{\mathrm{d}} \approx 3.8 \ \mathrm{keV/cm^3}$$

$$\lambda_{\mathrm{d}} = \sqrt[4]{\hbar c/\rho_{\mathrm{d}}} \approx 85 \ \mu\mathrm{m}$$

- search for proposed new phenomena

  large extra dimensions: why is gravity so weak?

  chameleons: what happened to the stringy scalars?

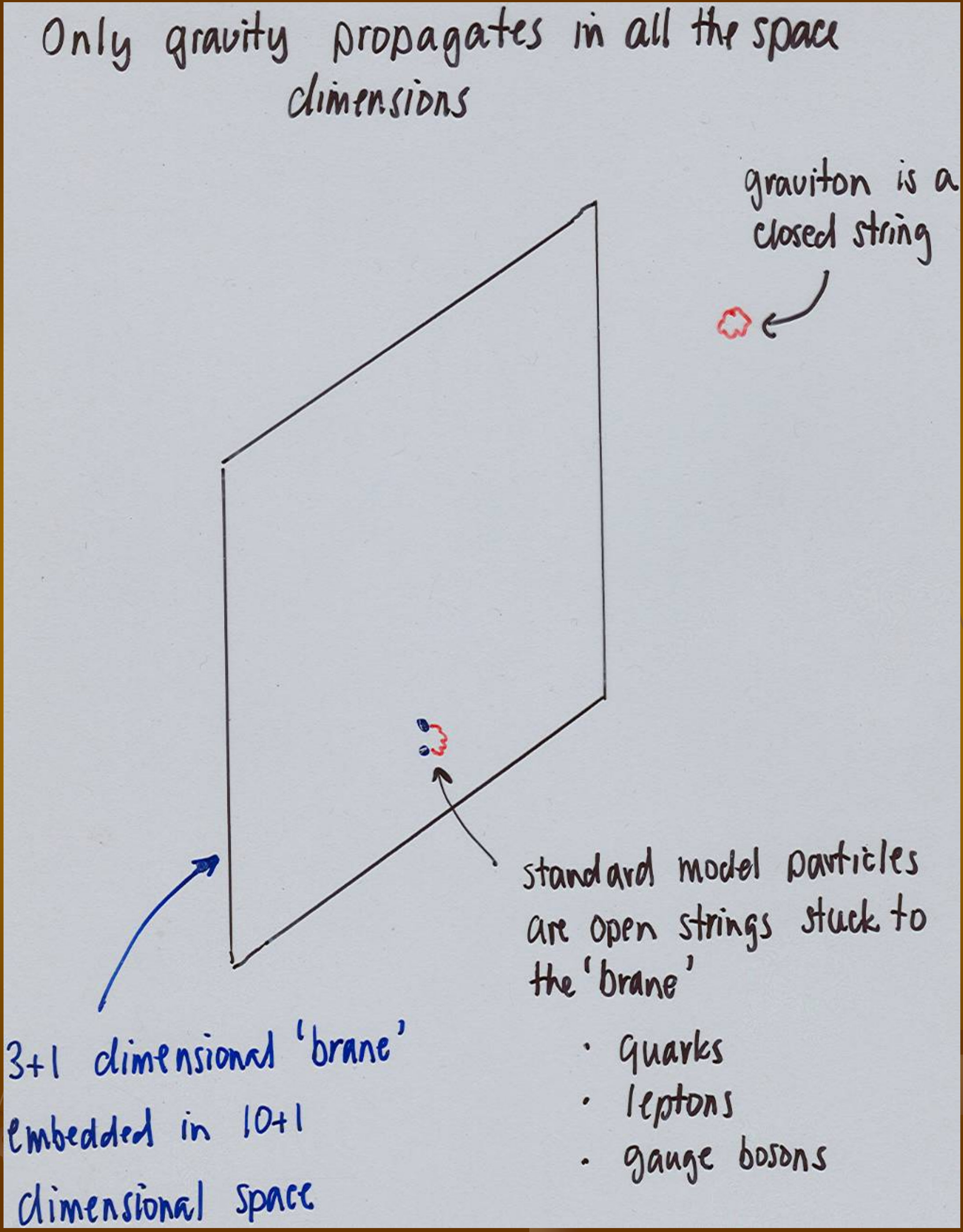
Parameterizing ISL violating effects

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

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

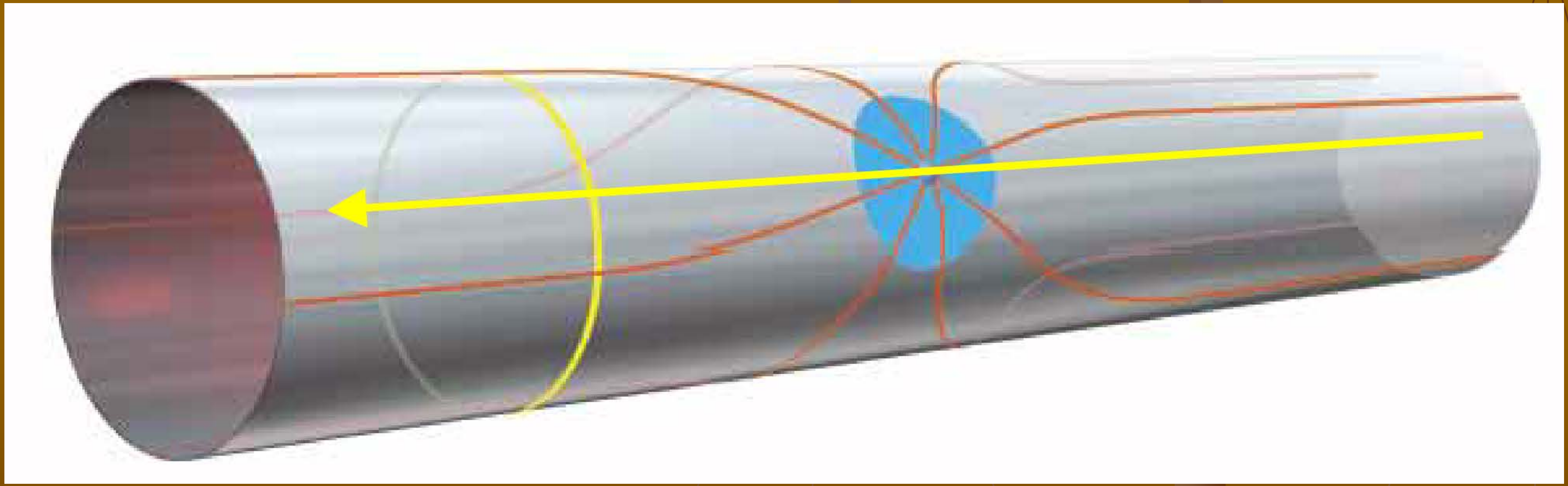


illustration from Savas Dimopoulos

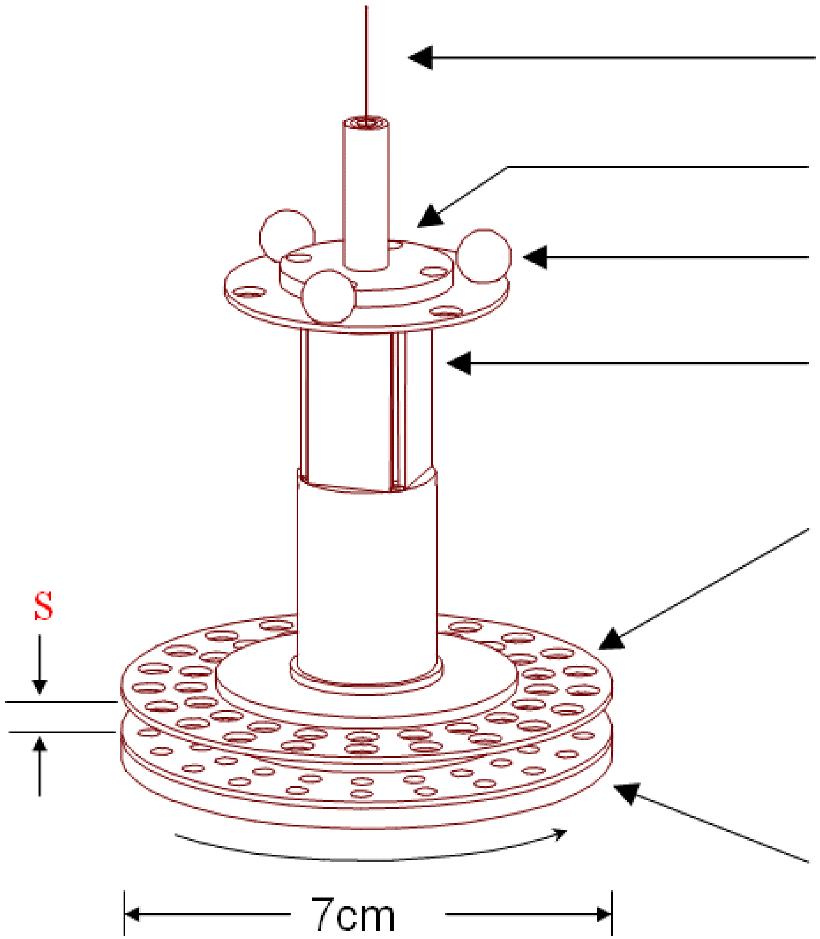
chameleons

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 ~ $1/m_{eff}$. 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 ISL pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

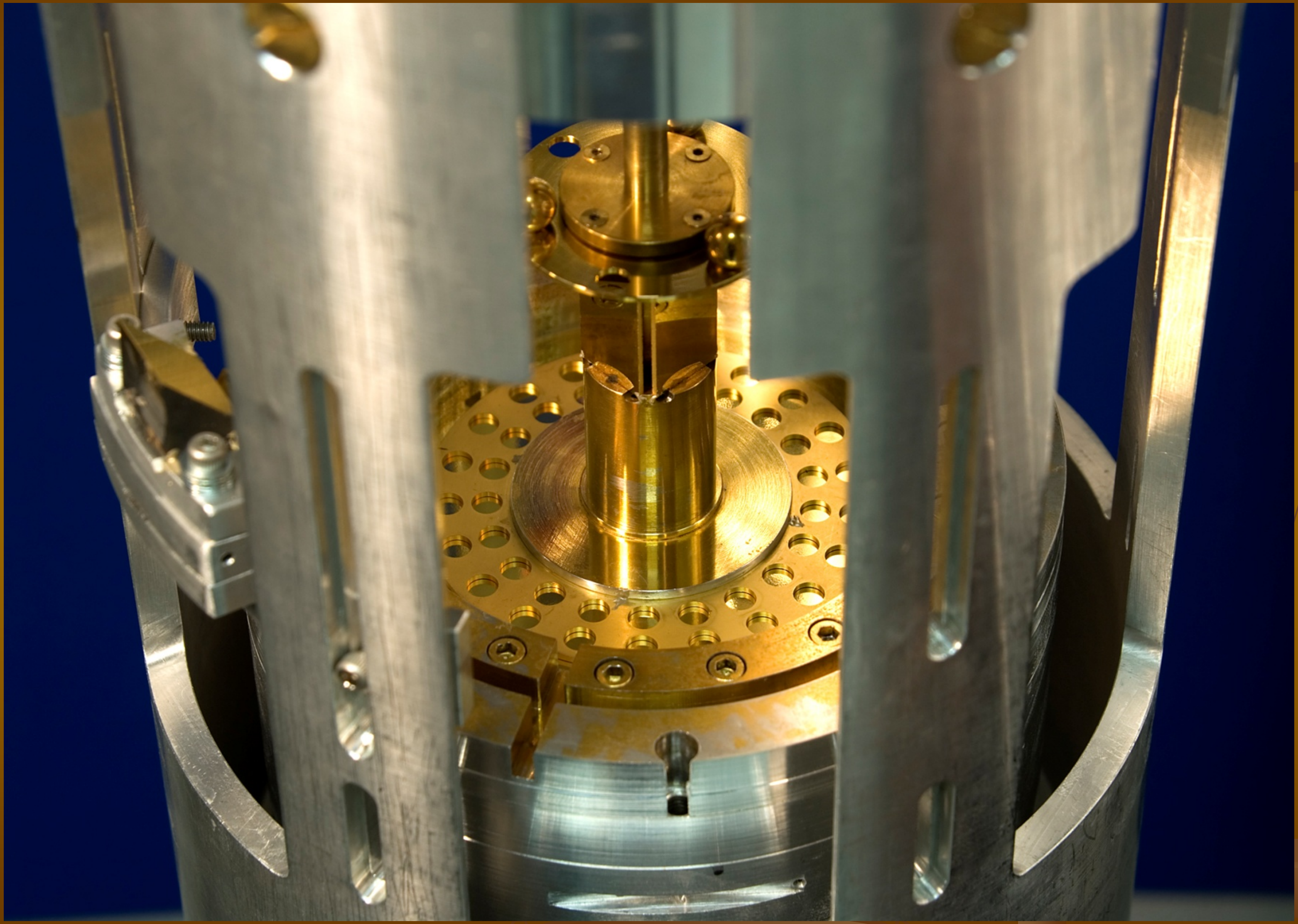
4 mirrors for tracking angle of deflection

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

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

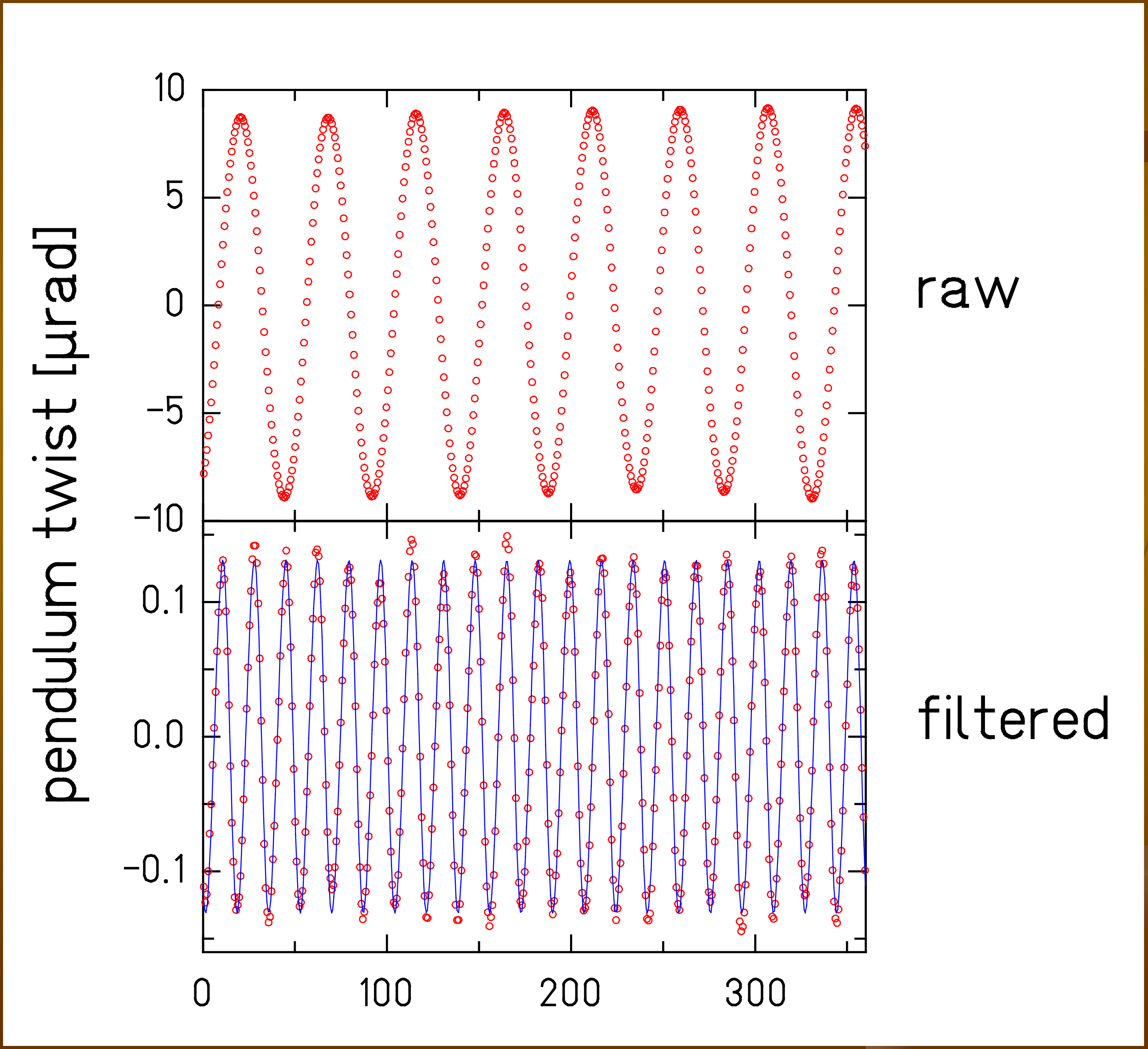
attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

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

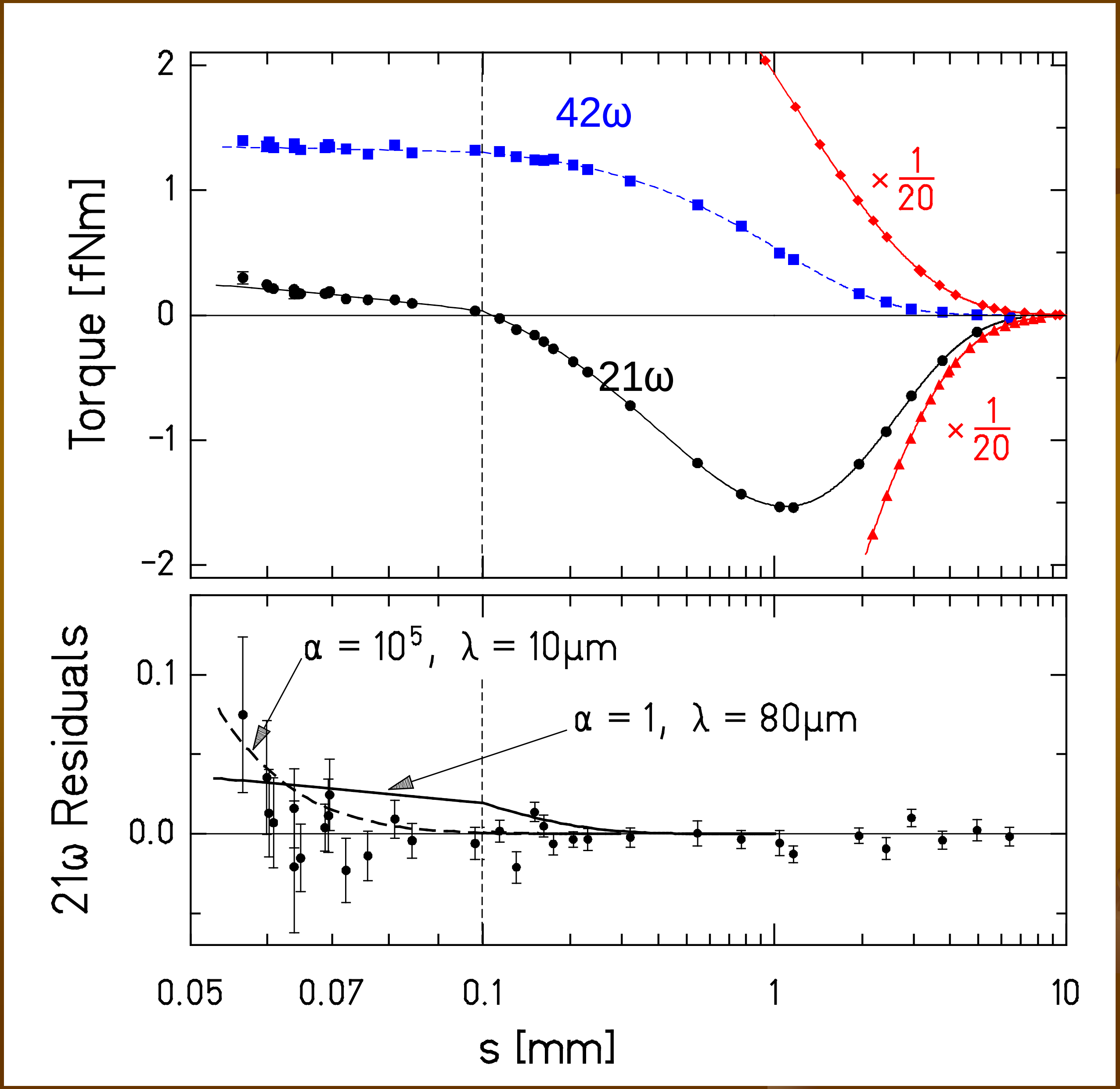

Mary Levin photo

signal processing

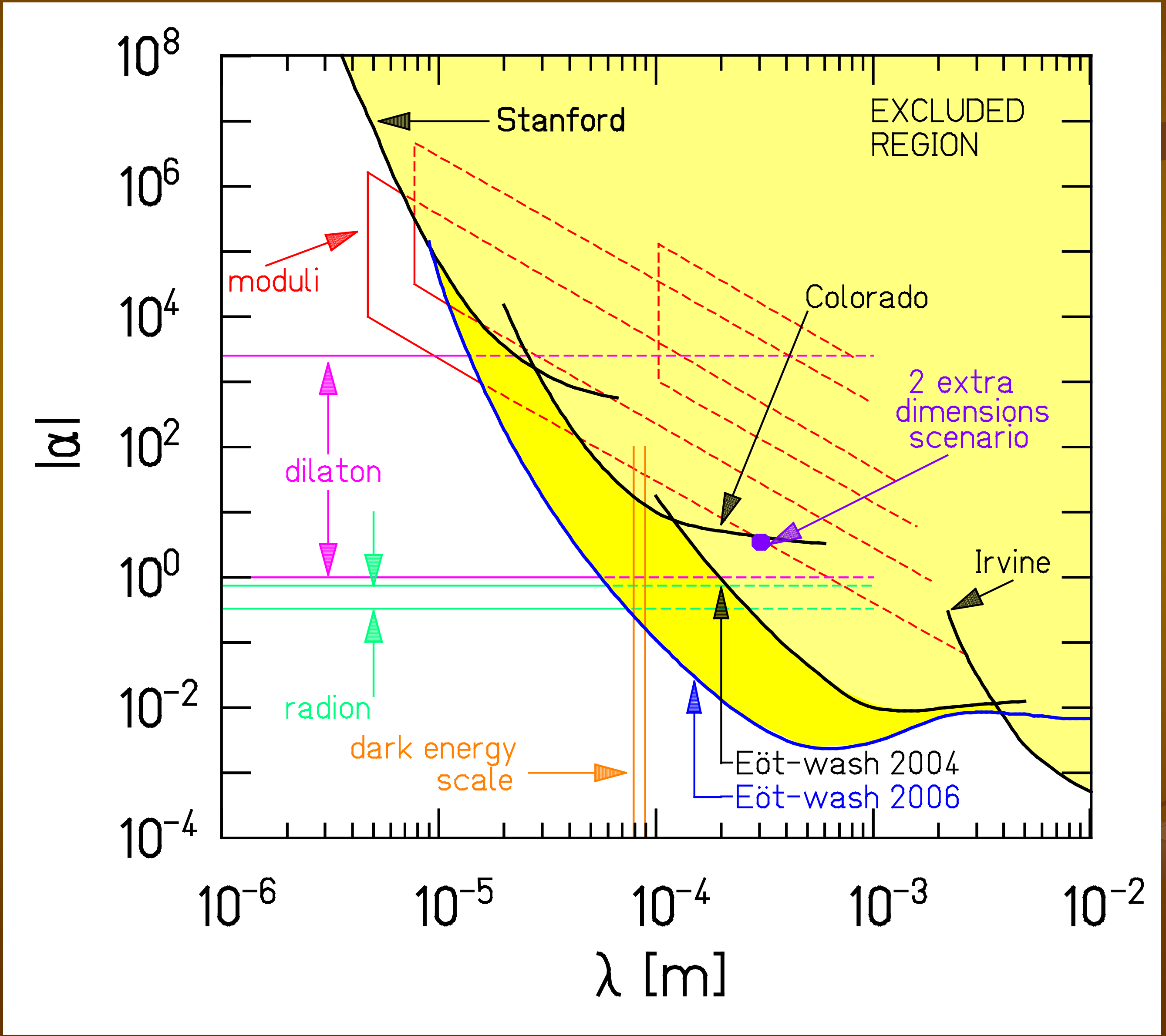
these data were taken with the calibration turn-table stationary



data from 42-hole experiment III

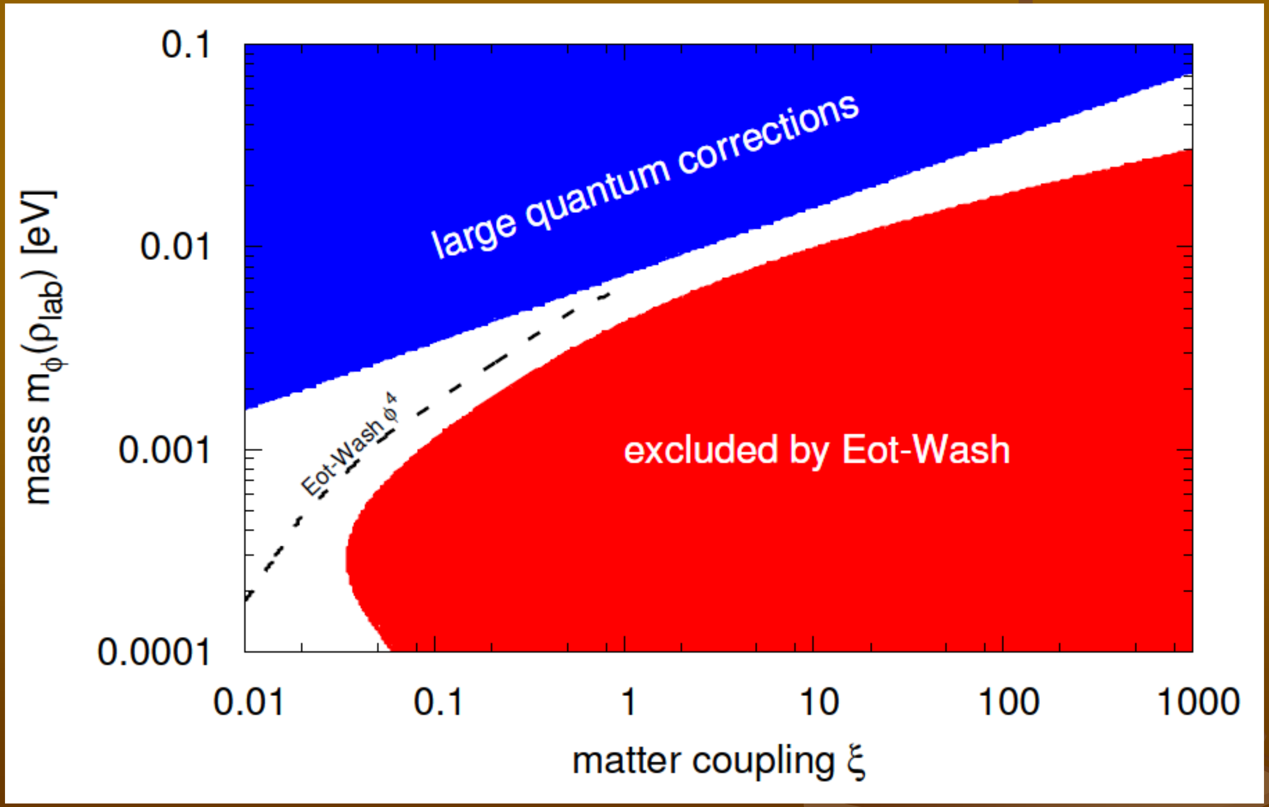


95% confidence upper limits on ISL violation as of 2008



Some implications if the 42-hole results:

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

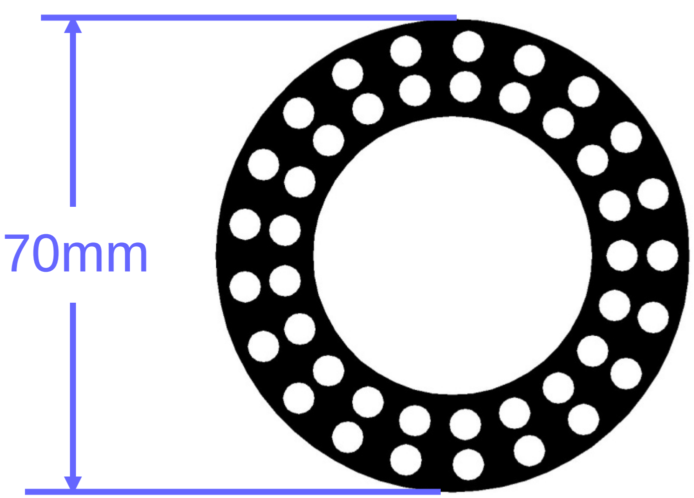


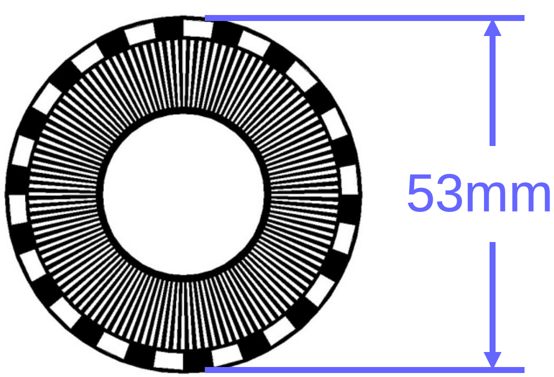
Upadhye, Hu and Khoury, PRL 109, 0413012012)

our next-generation short-range instrument

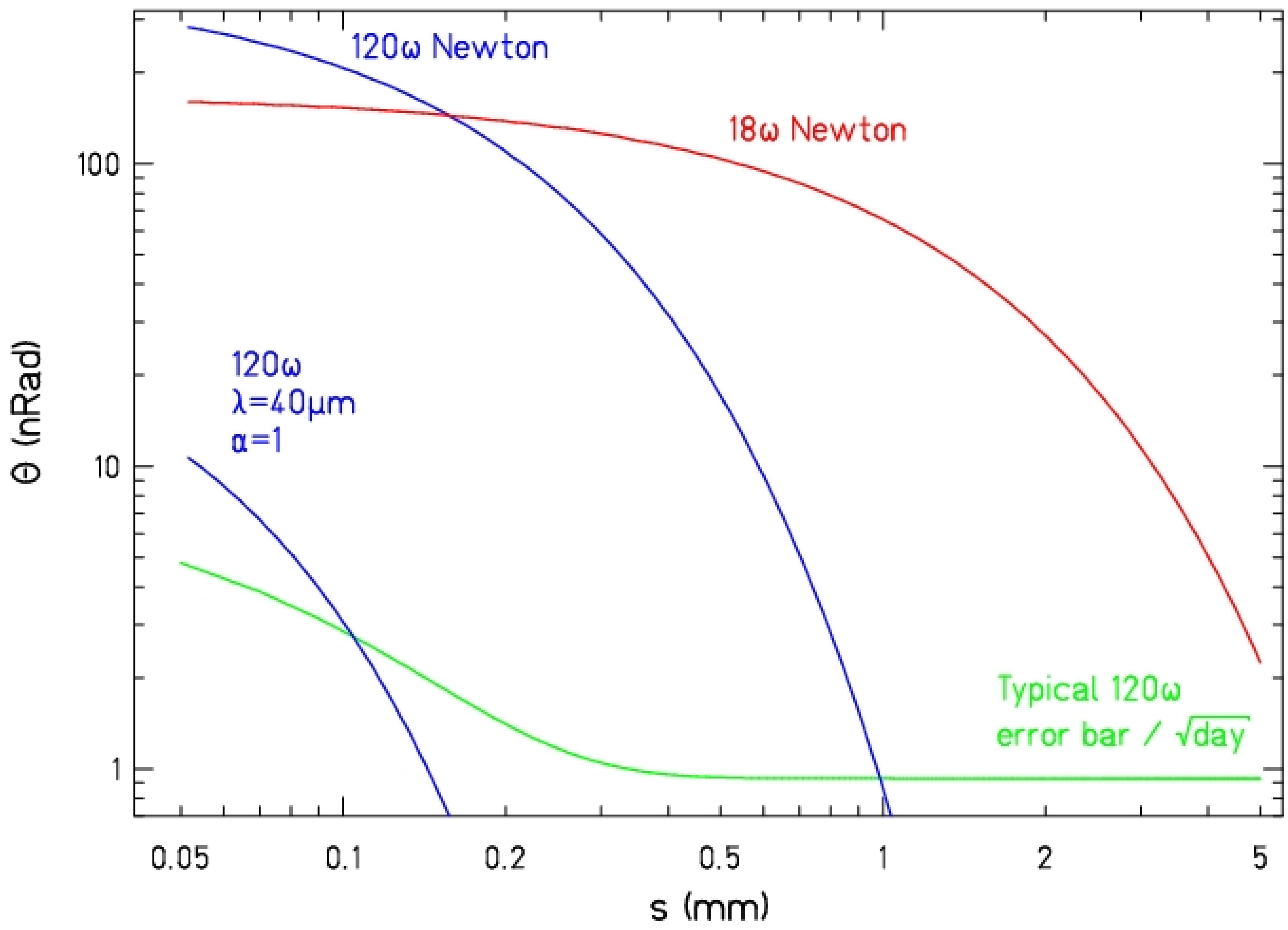
$$N_Y = \frac{\partial E_Y}{\partial \phi} \approx 2\pi\alpha G\lambda^3 \rho_D \rho_A \frac{\Delta A}{\Delta \phi} \exp(-\frac{s}{\lambda})$$

	Kapner et al.	Cook et al.
symmetry:	21	120 & 18
material:	molybdenum (10.3 g/cm^3)	tungsten (19.3 g/cm^3)
thickness:	1 mm	0.05 mm
attractor:	2 pieces	1 piece

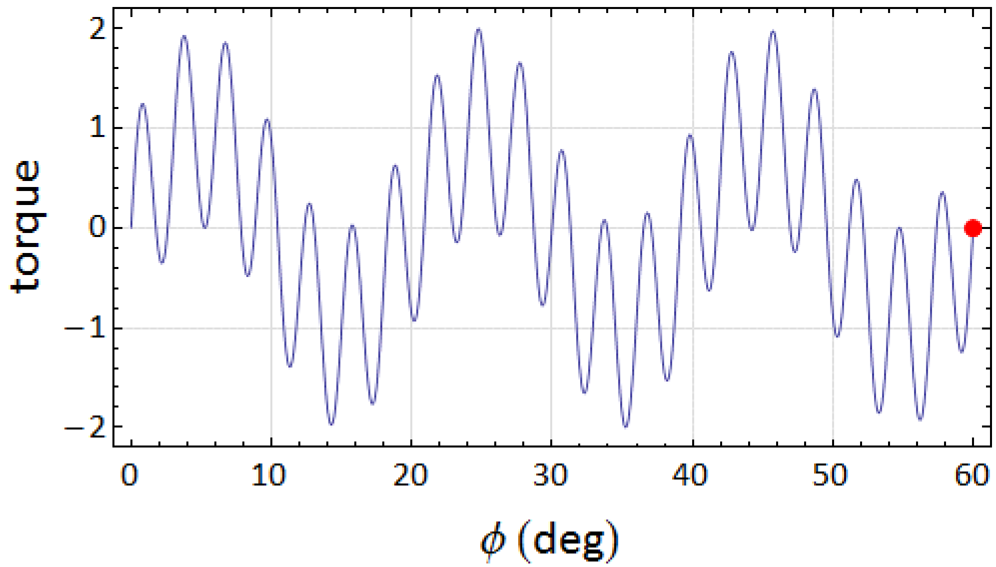


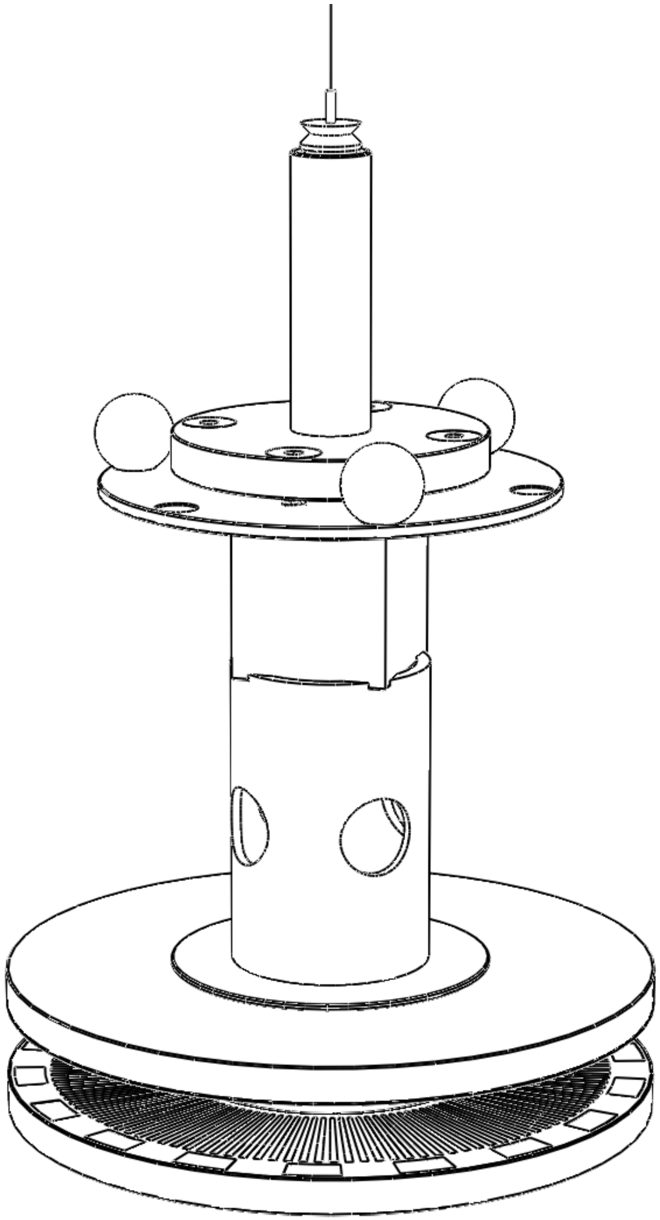


expected twist signals



Cook et al.'s Experiment

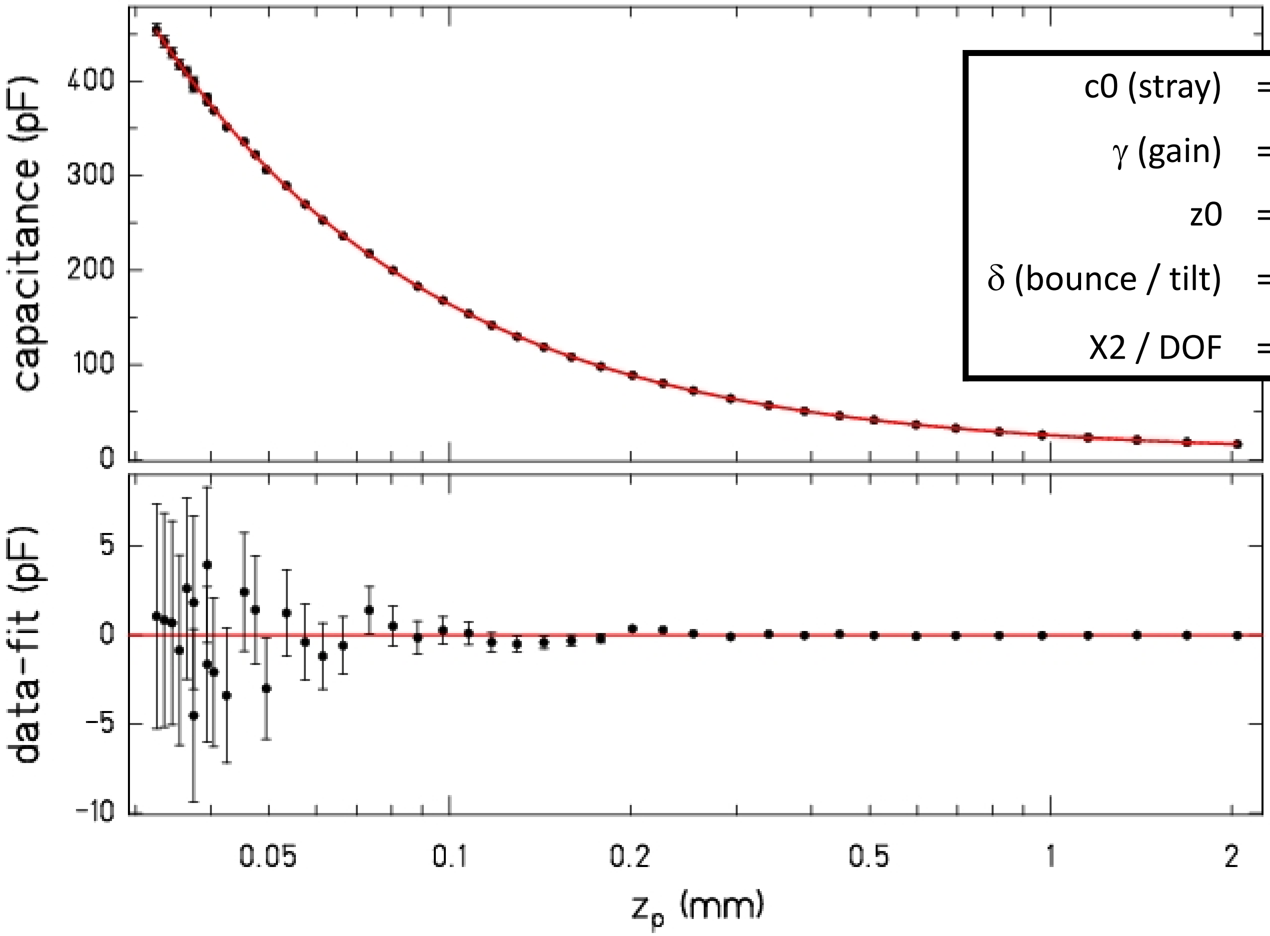




simulation is speeded up by factor of ≈1000

Pendulum-Screen Separation

$$\overline{C}(z_p) = c0 + \gamma\left(C(z_p - z0) + \frac{1}{2}\delta^2 C''(z_p - z0) \right)$$

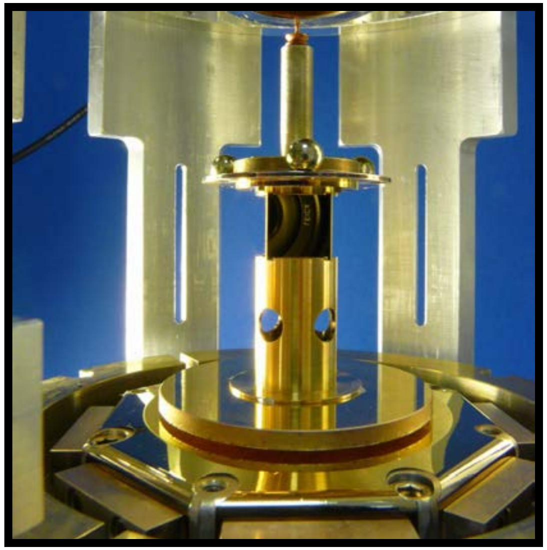


c0 (stray)	=	2.10 ± 0.003 pF
γ (gain)	=	1.012 ± 0.0001
z0	=	20.5 ± 0.1 μm
δ (bounce / tilt)	=	6.2 ± 0.5 μm
X2 / DOF	=	38.7 / 40

cleanliness is next to godliness

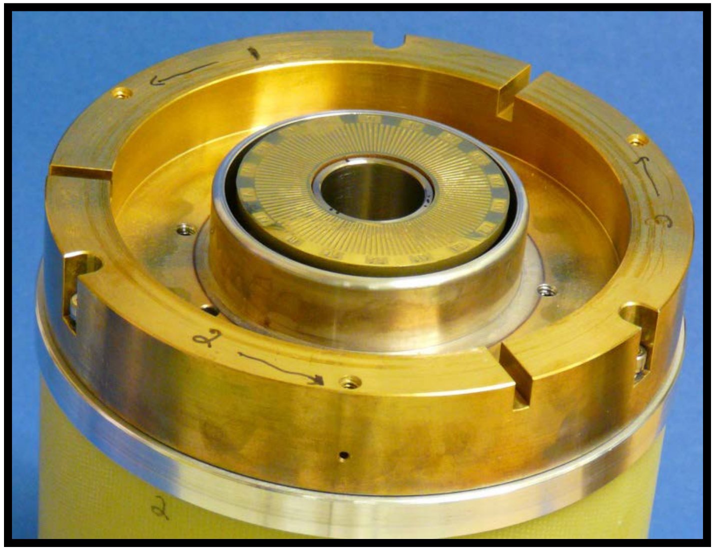
Pendulum

- Clear dust with 0.003” broom
- Pendulum kicked when touches debris

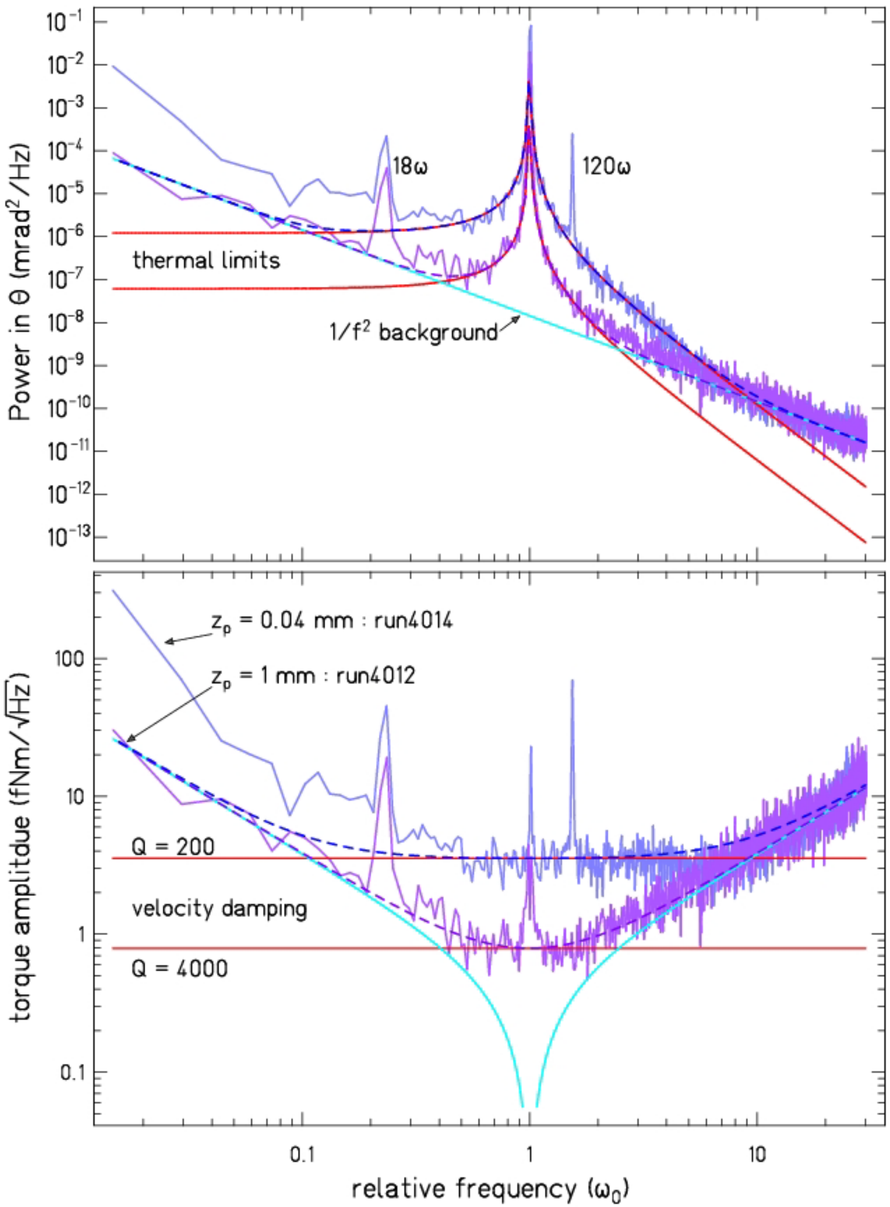


Attractor

- Clear dust with lint-free cloth
- Large dust visible through foil
- Touching can short-circuit attractor-screen capacitance
- Touching or dust can modulate pendulum-screen capacitance



Noise



Sources of Noise

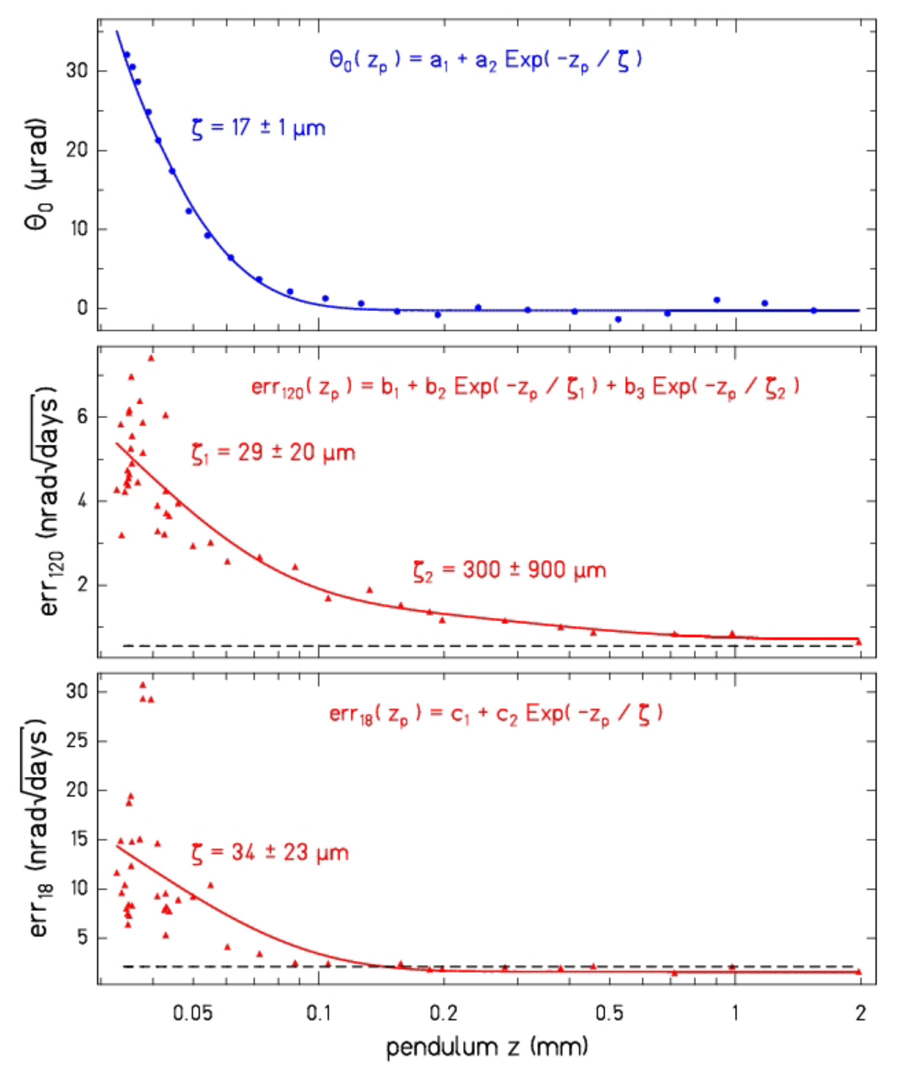
- Internal damping from fiber (σ_i)
- Velocity damping from residual gas and eddy currents (σ_v)

$$\sigma_i = \sqrt{\frac{4kT\kappa}{Q\omega}}\ ; \qquad \sigma_v = \sqrt{\frac{4kT\kappa}{Q\omega_0}}$$

- Seismic bounce coupled to patch fields ($d\theta/dz$)
- Autocollimator noise (high f)
- Temperature drifts (low f)

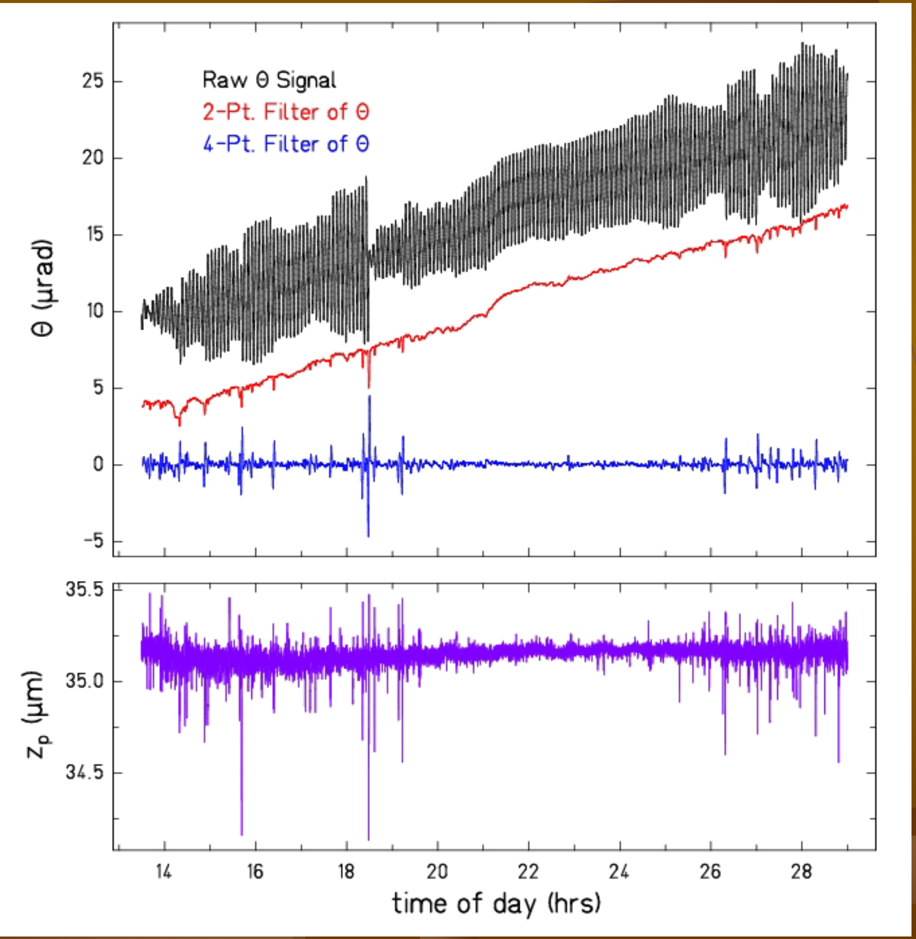
patch fields

patch field potential minimum
not aligned with fiber minimum



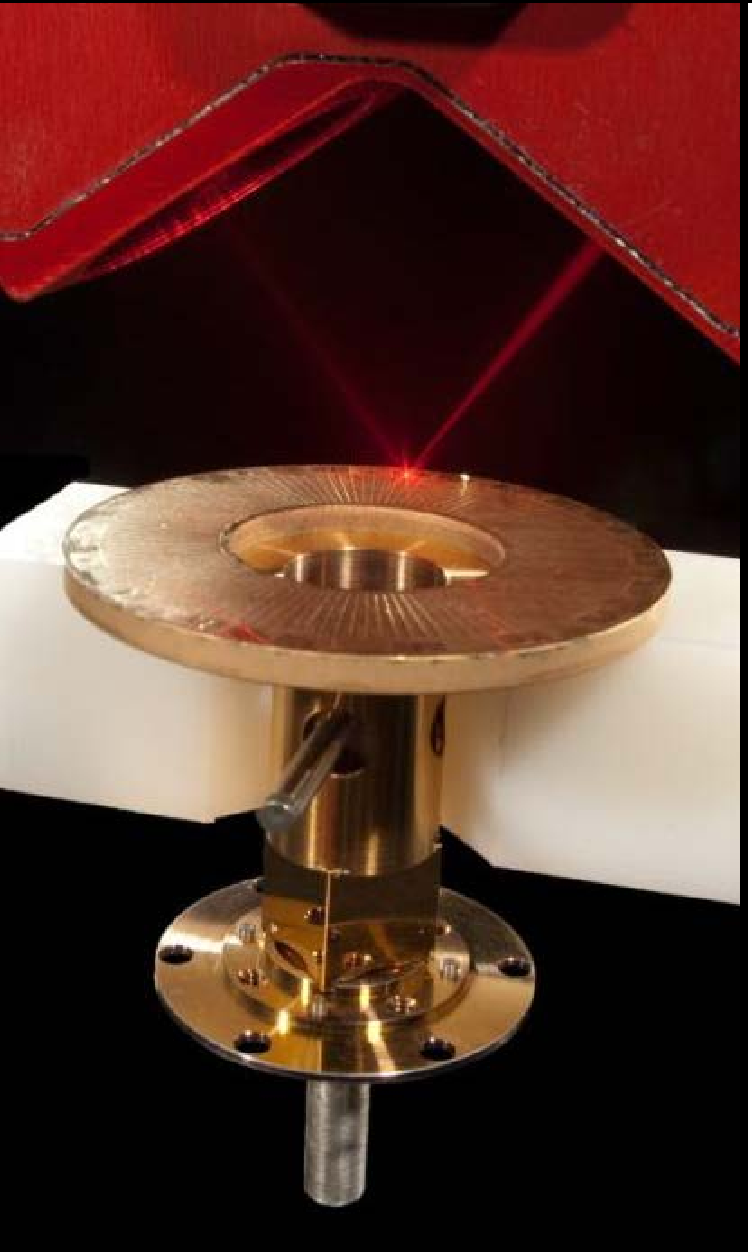
vibrations

almost sleepless in Seattle

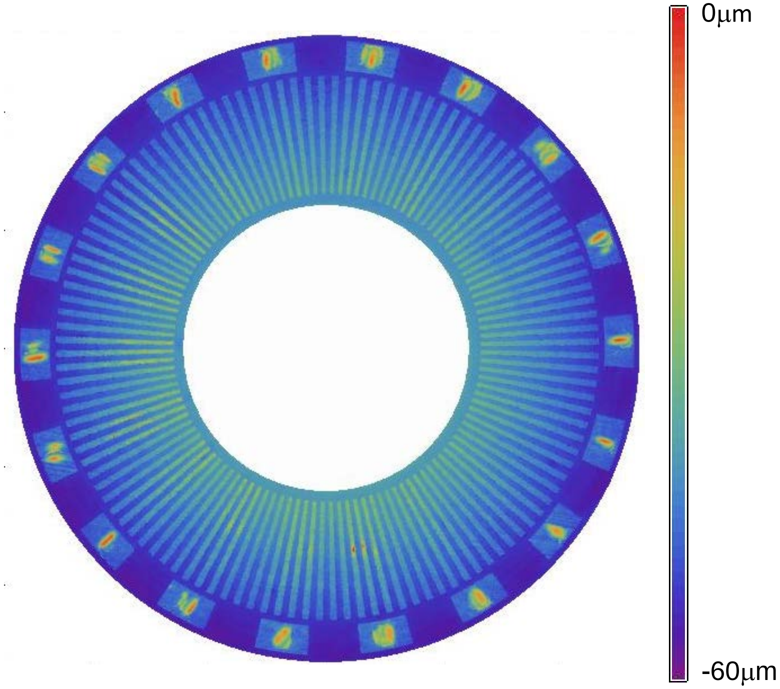


(attractor not turning)

:: Mapping the pendulum & attractor geometries ::

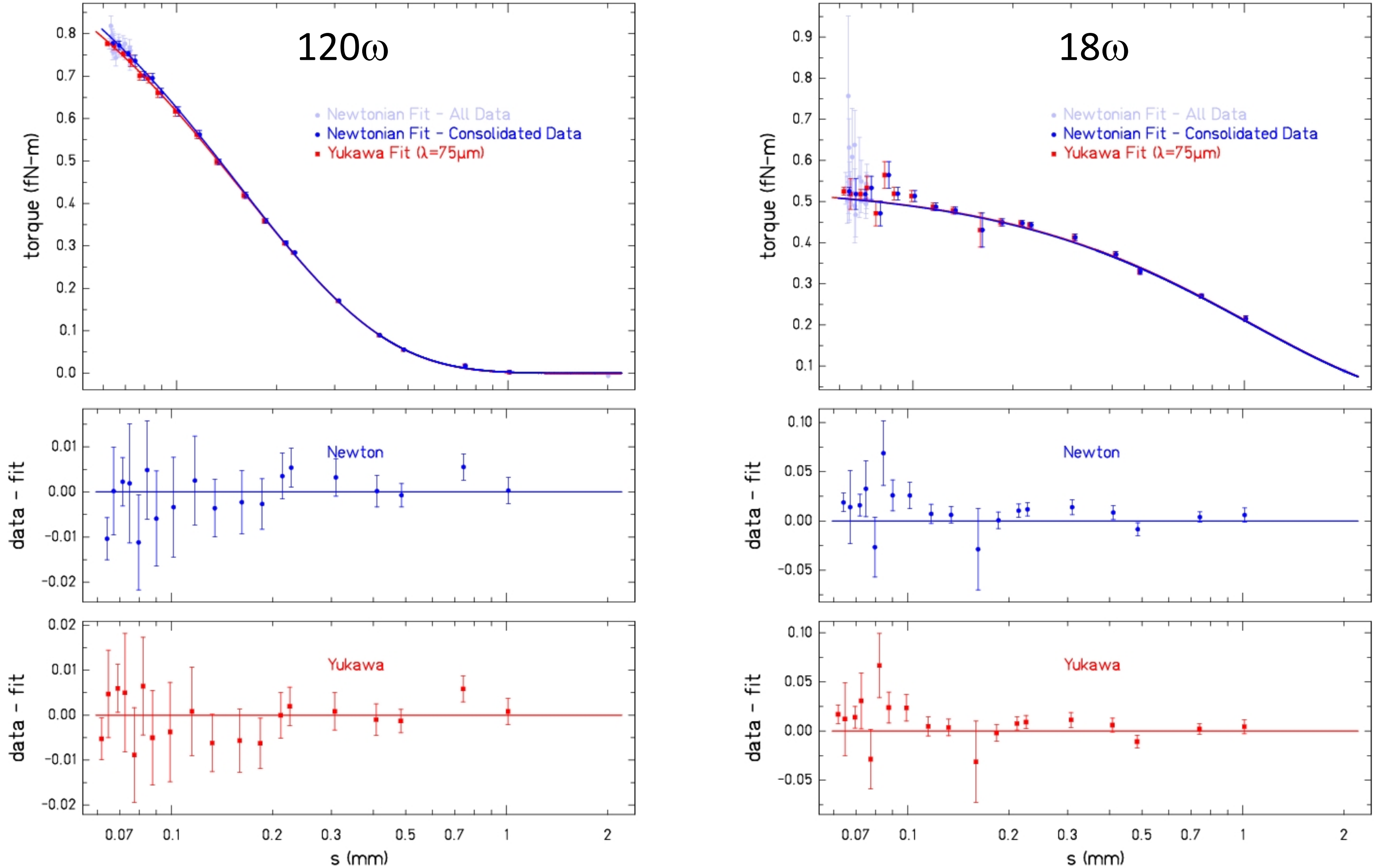


Need precise model of the mass distribution of the tungsten and the glue



Data Fit

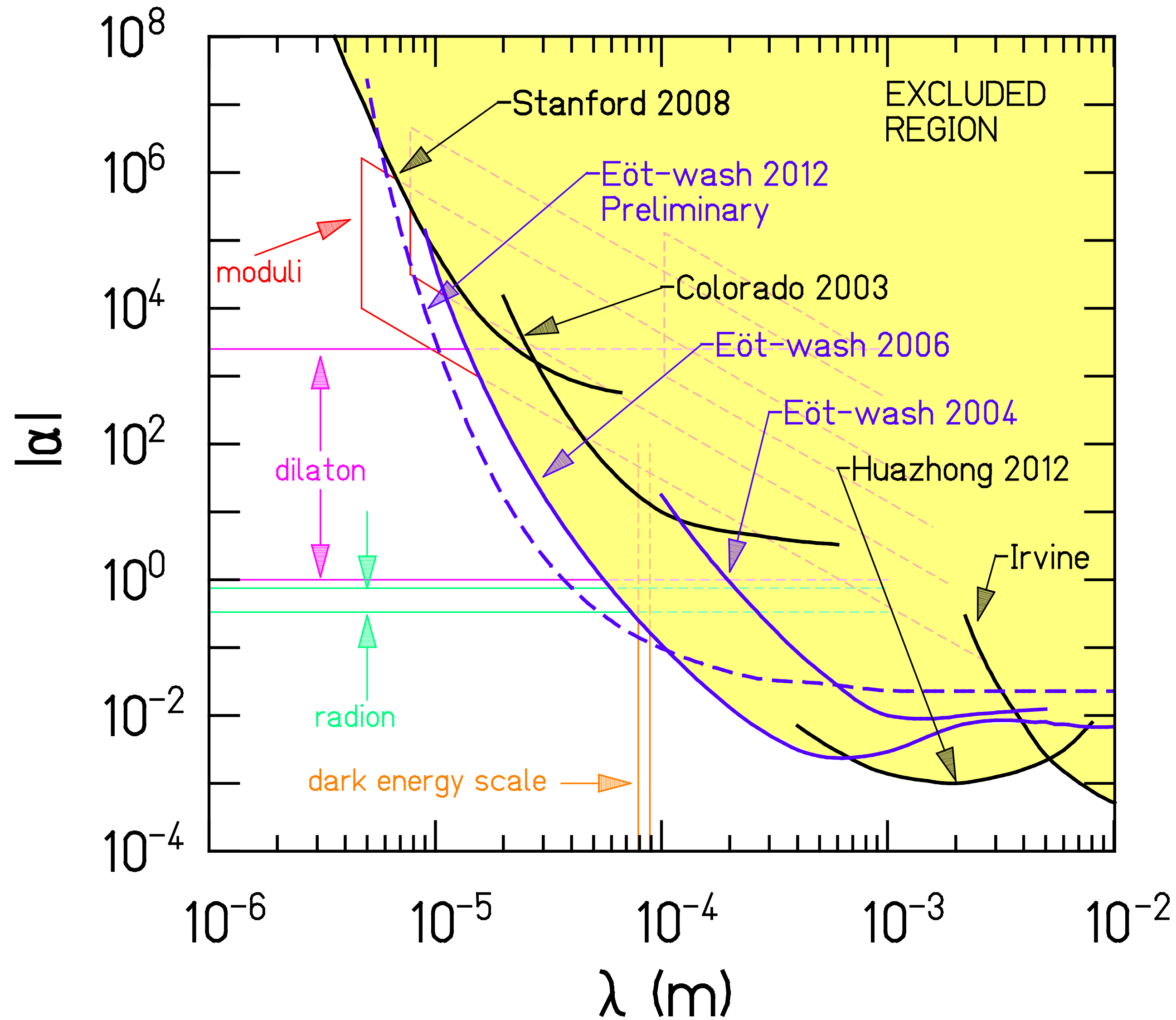
$\lambda = 75\ \mu m;\ \alpha = -0.16 \pm 0.05$



Cook's preliminary 95% C.L. results

order of magnitude higher sensitivity below 40 µm:

We hope to do significantly better in the an improved iteration of Cook's device



Is Lorentz symmetry broken at the Planck scale?

The Universe defines a frame in which the CMB is essentially isotropic. Could there be other, more fundamental, preferred frame effects defined by the Universe?

Kostelecky et al. developed a scenario where vector and axial-vector fields were spontaneously generated in the early universe and then inflated to enormous extents;

particles couple to these preferred-frame fields in Lorentz-invariant manners.

This “Standard Model Extension” predicts many new observables some of which violate CPT. One observable is $E = \sigma_e \cdot \tilde{b}_e$ where $\tilde{b}_e$ is fixed in inertial space - its benchmark value is $m_e^2 / M_{Planck} \approx 2 \times 10^{-17}$ eV

do space-time coordinates commute?

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

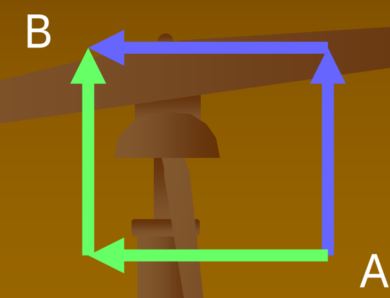
$$[\widehat{x}_{\mu}, \widehat{x}_{\nu}] = i\theta_{\mu\nu}$$

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

“Review of the Phenomenology of Noncommutative Geometry”
I. Hinchliffe, N Kersting and Y.L. Ma
hep-ph/0205040

effect of non-commutative geometry on a spin

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

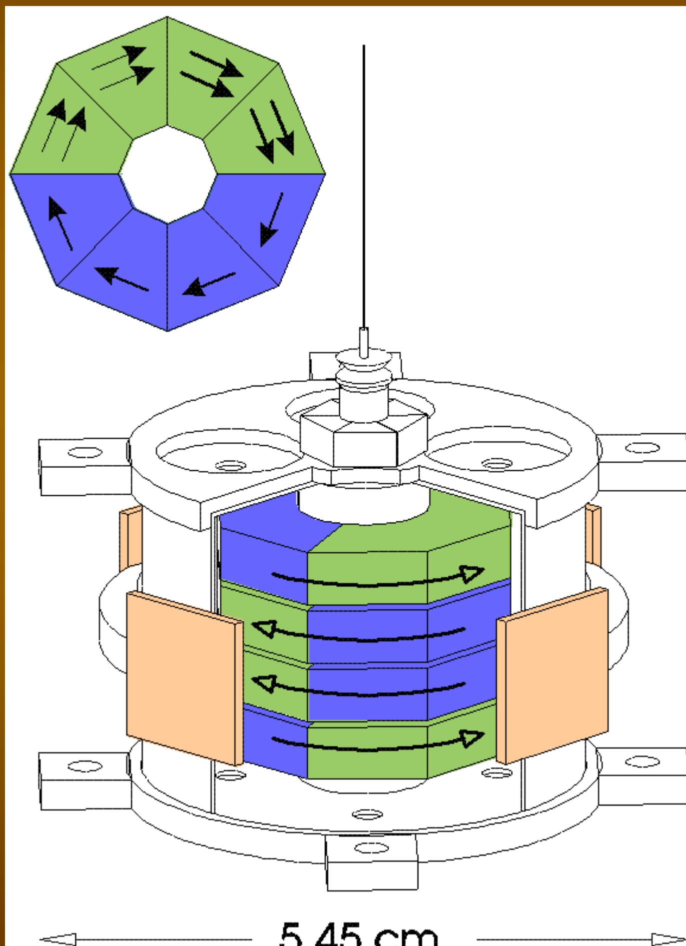


$$\mathcal{L}_{eff} = \frac{3}{4} m\Lambda^2 \left(\frac{e^2}{16\pi^2}\right)^2 \theta^{\mu\nu}\overline{\psi}\sigma_{\mu\nu}\psi$$

Anisimov, Dine, Banks and Graesser
Phys Rev D 65, 085032 (2002)

Λ is a cutoff assumed to be 1TeV

the Eöt-Wash spin pendulum



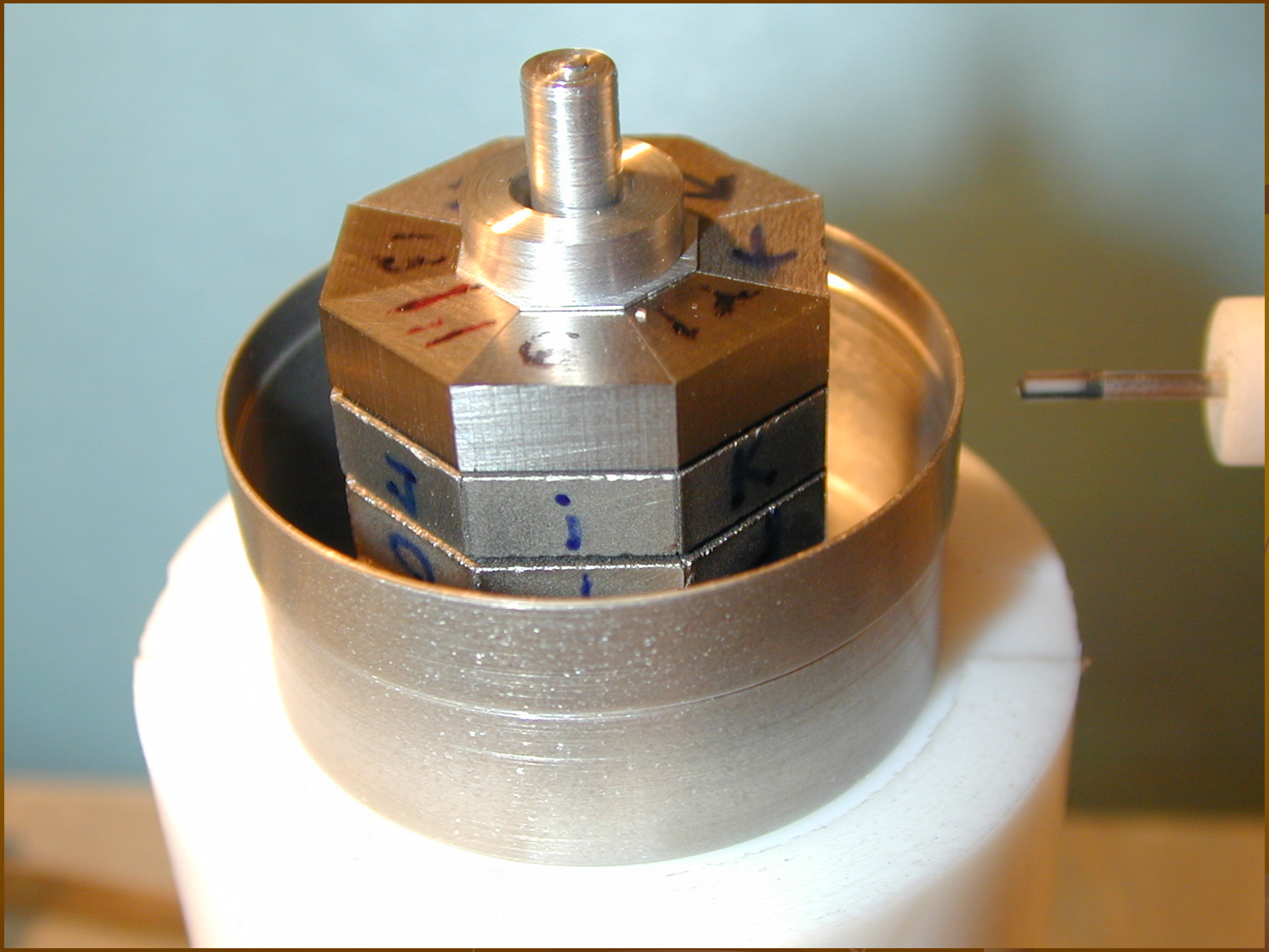
- 9.8×10^{22} polarized electrons
- negligible mass asymmetry
- negligible composition asymmetry
- flux of B confined within magnets
- negligible external B field

- Alnico: all B comes from electron spin: spins point opposite to B

- $SmCo_5$: Sm 3^+ ion has spin pointing along 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 $J = \hbar S$

measuring the spin pendulum's stray B field



B inside = 9.6±0.2 kG

B outside ≈ few mG

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

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.

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

References:

EP

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

ISL

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

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

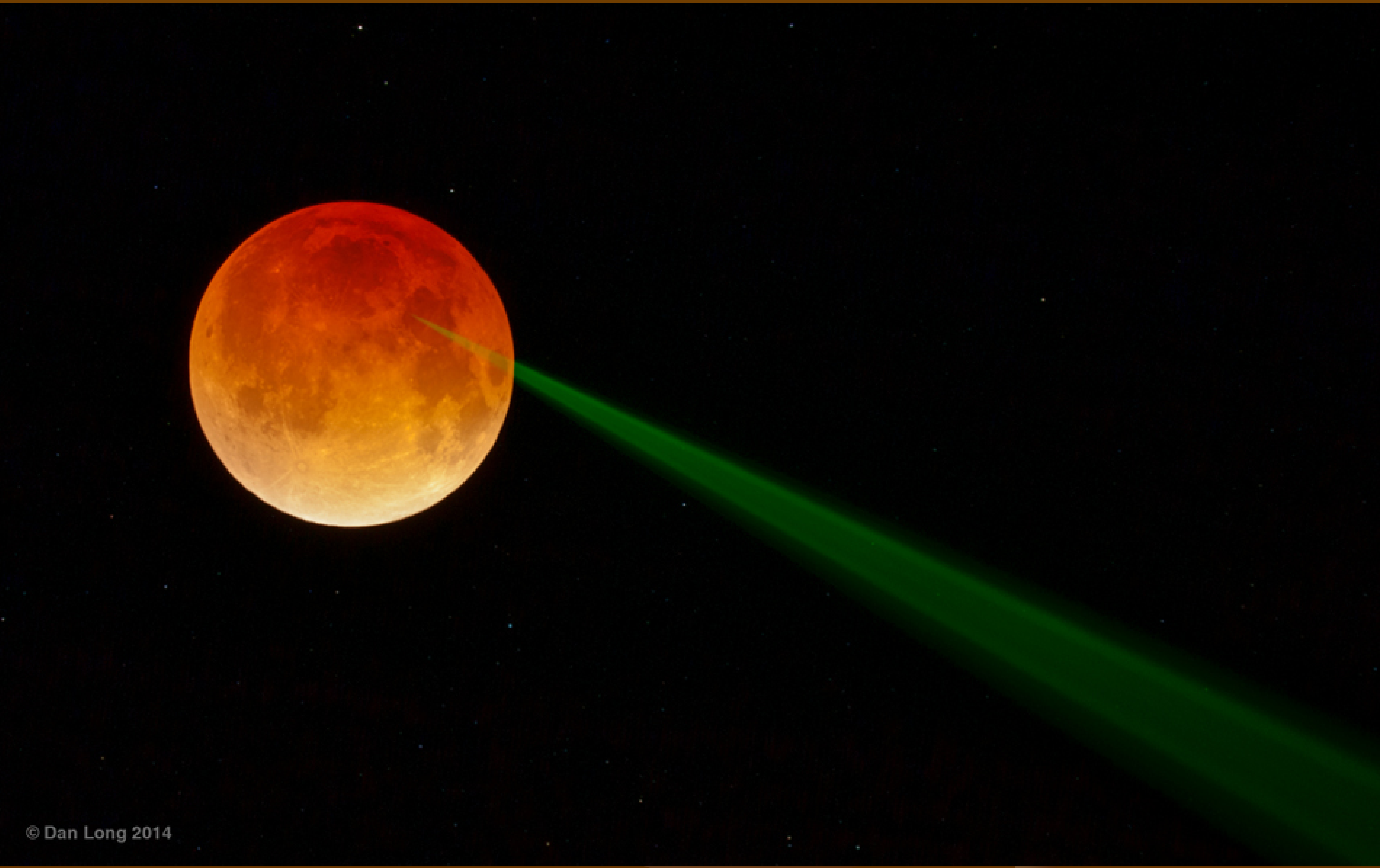
SPIN

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).

APOLLO ranging to A15 during 4/18/2014 lunar eclipse



Following slides are for answering questions

the chameleon mechanism

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

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

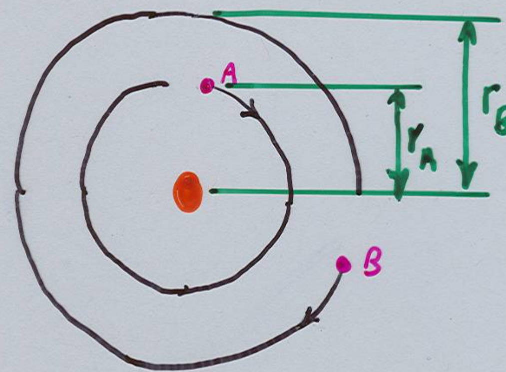
natural values of □ and □ are 1

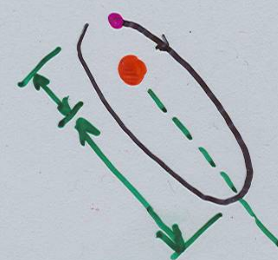
in presence of matter this gives massless chameleons an effective mass

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

so that a test body's external field comes only from a thin skin of material of thickness ~ $1/m_{\text{eff}}$

Any given test of the $1/r^2$ law is sensitive to a restricted range of length scales





$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \;?$$

precession of perigee ?

∴ need many different approaches to cover a wide range of length scales

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

this requires:

•sensitivity to wide range of length scales

earth (not sun) as attractor

site with interesting topography

•sensitivity to wide range of possible charges

vector charge/mass ratio is of any substance

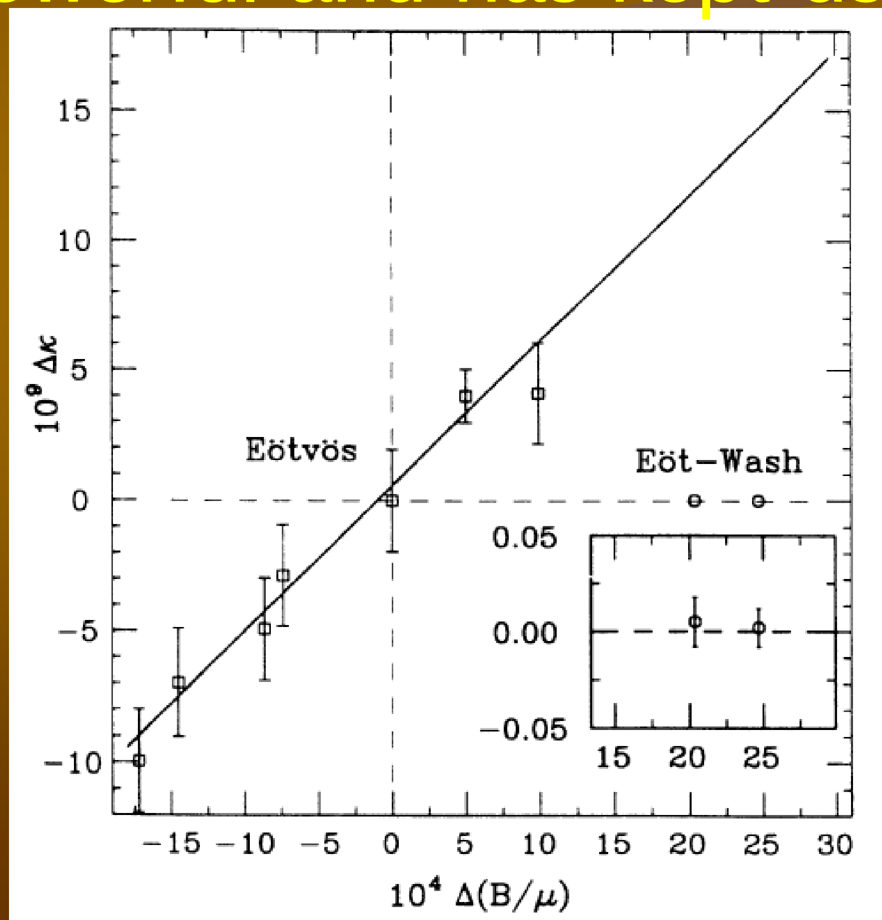
vanishes for some value of ψ.

need 2 test body pairs and 2 attractors

to avoid possible accidental cancellations

Although we found no evidence for a 5th force, we were very lucky because Fischbach's idea of using EP data to probe new physics turned out t be very powerful and has kept us busy for years

Fischbach et al. 1986 analysis



our 1994 result