Recent tests of the equivalence principle and of the gravitational inverse-square law

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- will review techniques, status, future prospects of experimental results

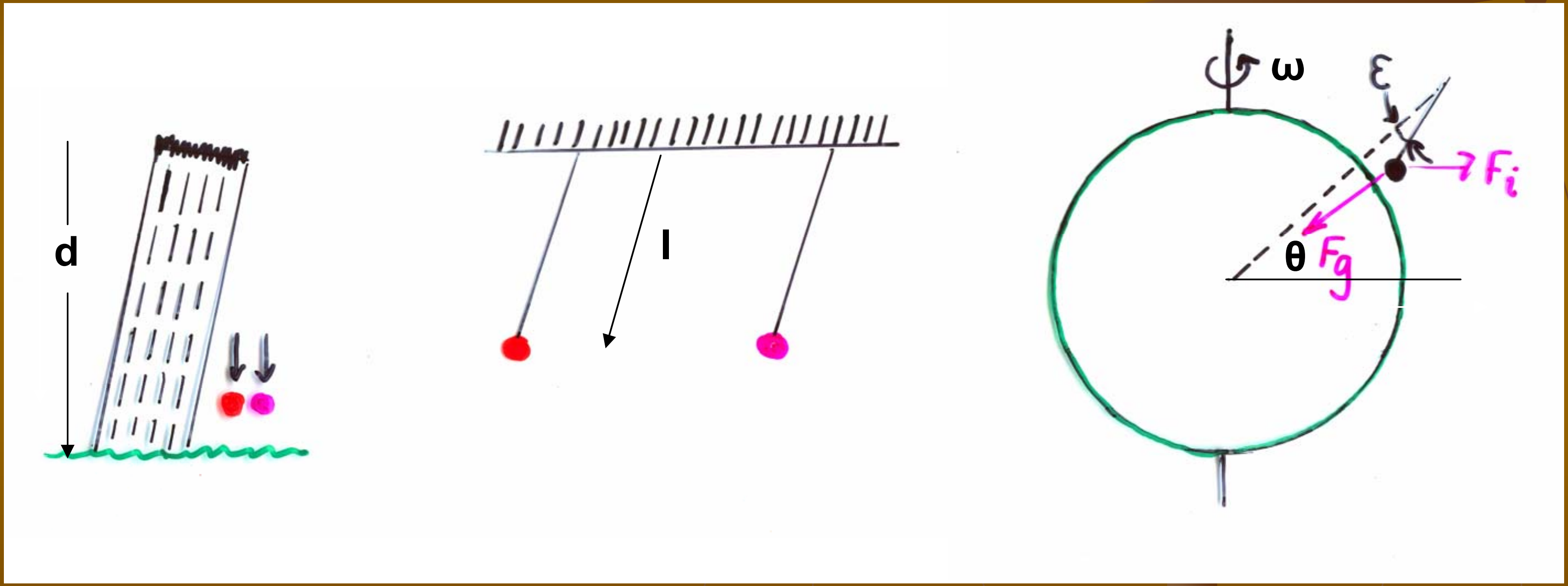
- will discuss some implications of the results for:

  5th forces
  gravitational properties of dark matter
  gravitational properties of gravitational energy
  G-dot/G
  extra dimensions
  chameleons

A brief history of Equivalence Principle tests:

classic view: do all materials have the same m^i/m^g ?

Galileo **test** | Newton-Bessel test | Eötvös test



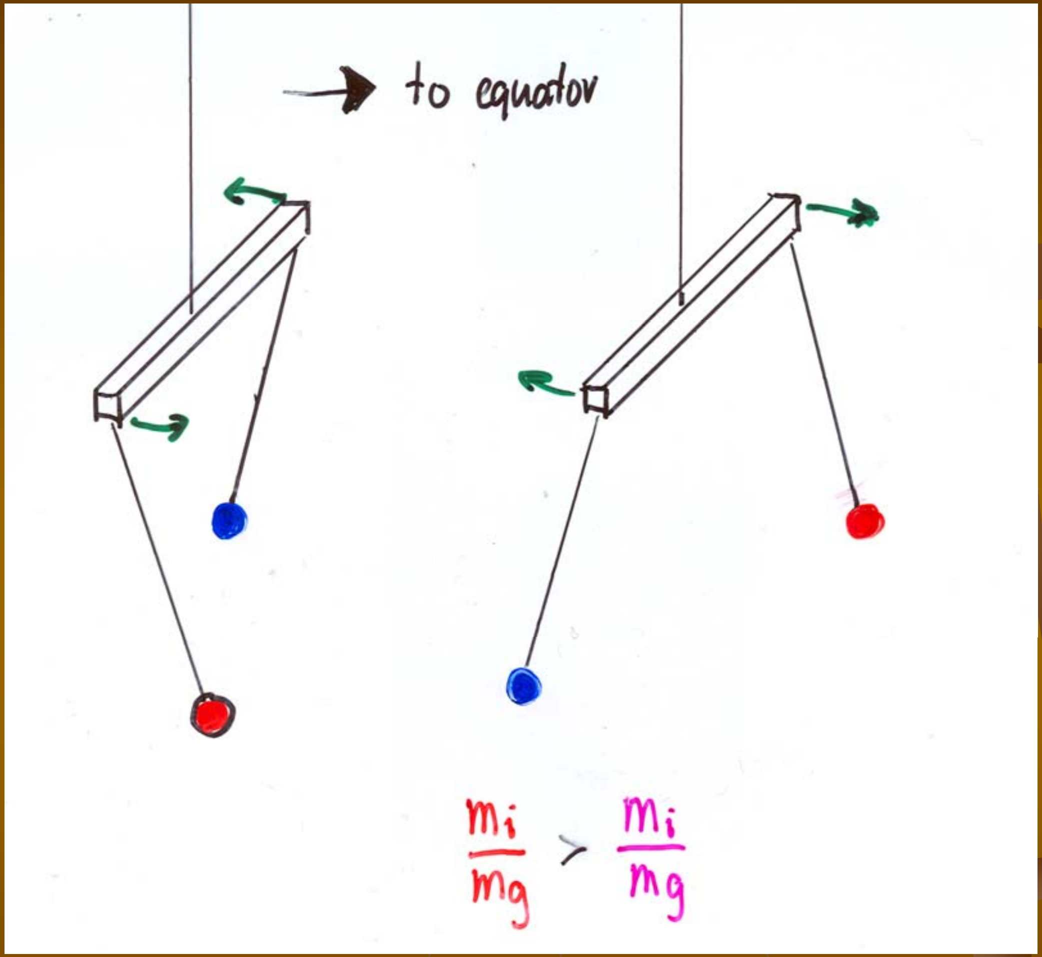
are fall times equal? | are periods equal? | are angles equal?

$T=\sqrt{(2d/g\ (m^i/m^g))}$ $\Delta a/a \leq 0.1$

$T=2\pi\ \sqrt{(l/g\ (m^i/m^g))}$ $\Delta a/a \leq 10^{-4}$

$\varepsilon=\omega^2 R \sin 2\theta/(2g)\ (m^i/m^g)$ $\Delta a/a \leq 10^{-9}$

implementation as a null experiment



balance 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

Parameterizing EP-violating effects of quantum vector exchange forces in terms of α, λ and ψ

gravity couples to mass

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

quantum exchange forces couple to "charges"

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

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

vector charge of electrically neutral objects

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

Unbiased tests of the EP require:

- 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

the Eöt-Wash® group in experimental gravitation

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

Staff scientist
- Erik Swanson

Current & recent postdocs
- Seth Hoedl
- Stephan Schlamminger
- Krishna Venkateswara

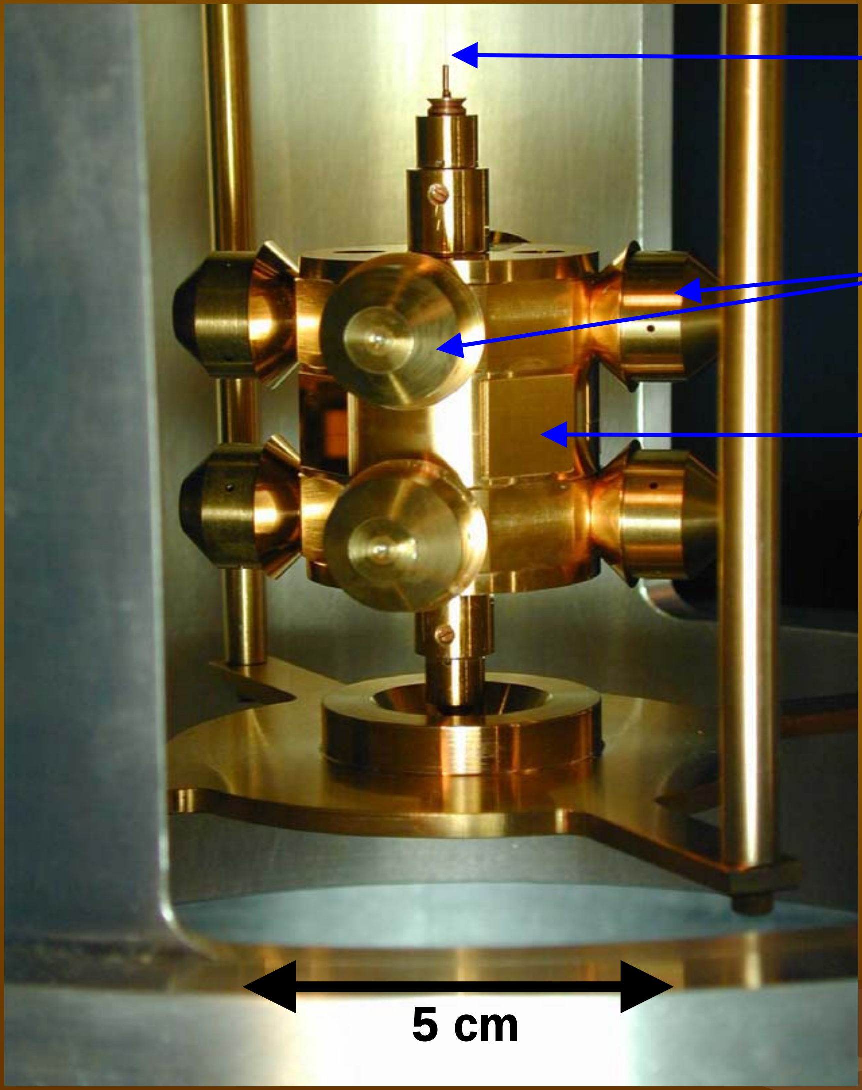
Current Grad students
- Ted Cook
- Charlie Hagedorn
- Matt Turner
- Will Terrano
- Todd Wagner

EP
spin
$1/r^2$

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

torsion pendulum of the recent EP test

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



20 μm diameter tungsten fiber

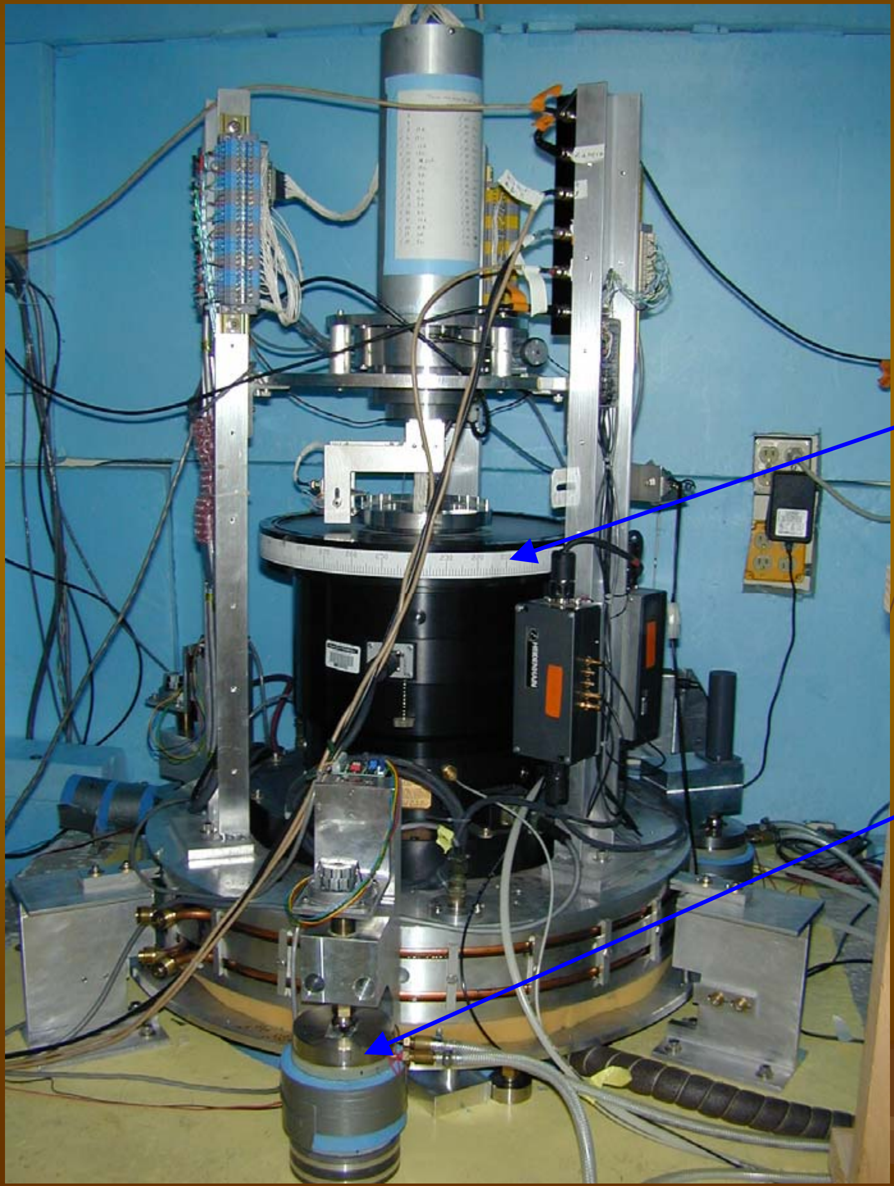
eight 4.84 g test bodies
(4 Be & 4 Ti) or (4 Be & 4 Al)

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 0.833 mHz

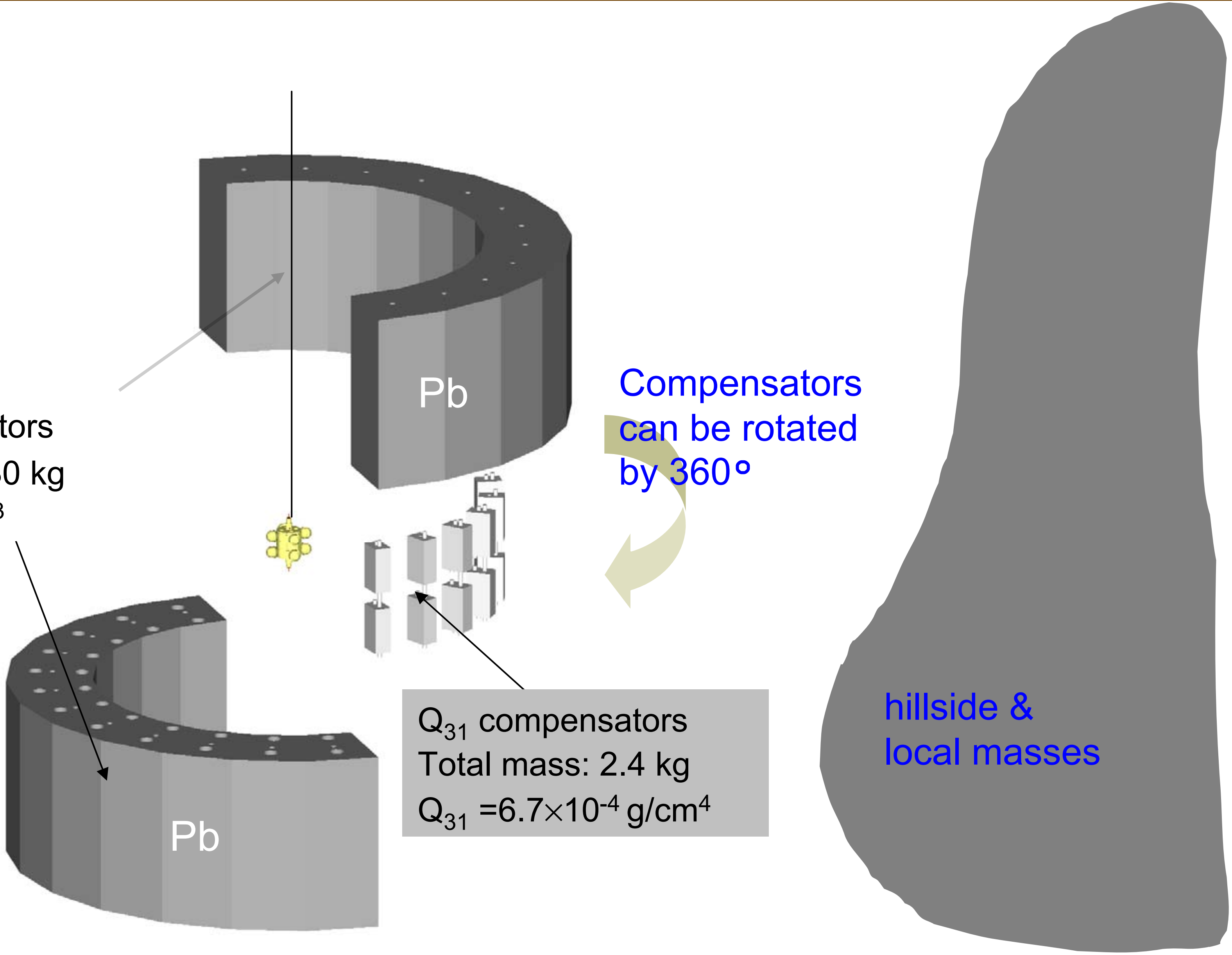


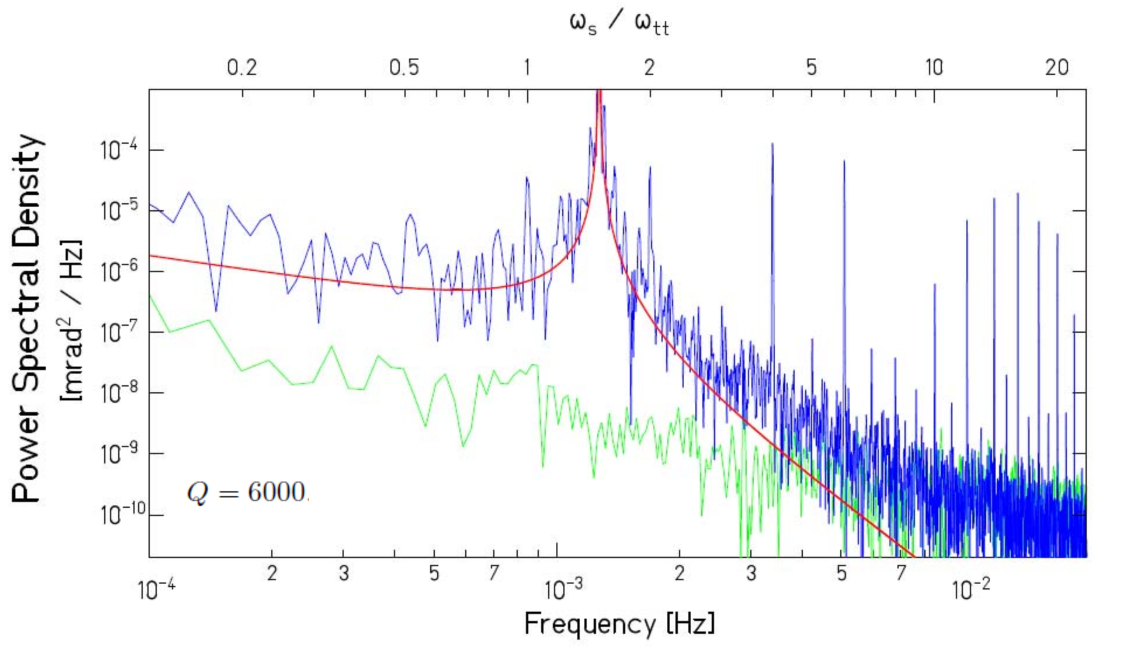
air-bearing turntable

thermal expansion feet fedback to keep turntable rotation axis level

gravity-gradient compensation

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





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

each data point represents about 2 weeks of data

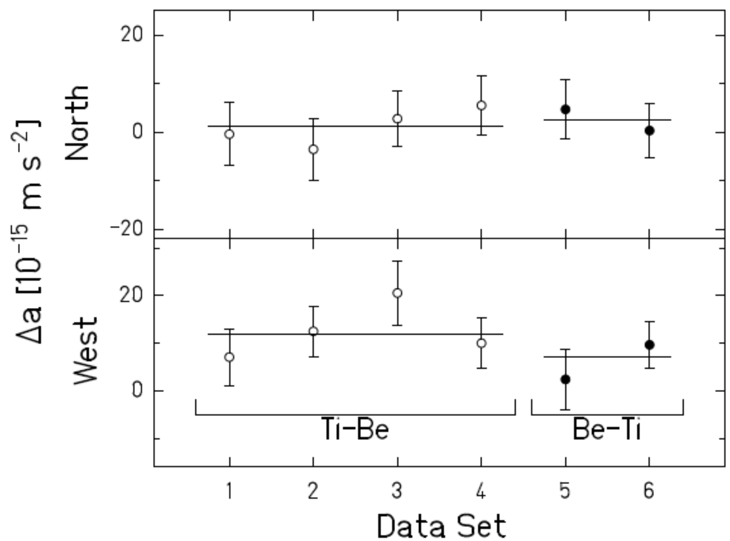


Figure 5. Data collected in the Ti-Be (first 4 runs) and Be-Ti (last 2 runs) configurations of the pendulum. The final result is in the difference between the means of the two configurations (shown as solid lines).

1σ statistical + systematic uncertainties

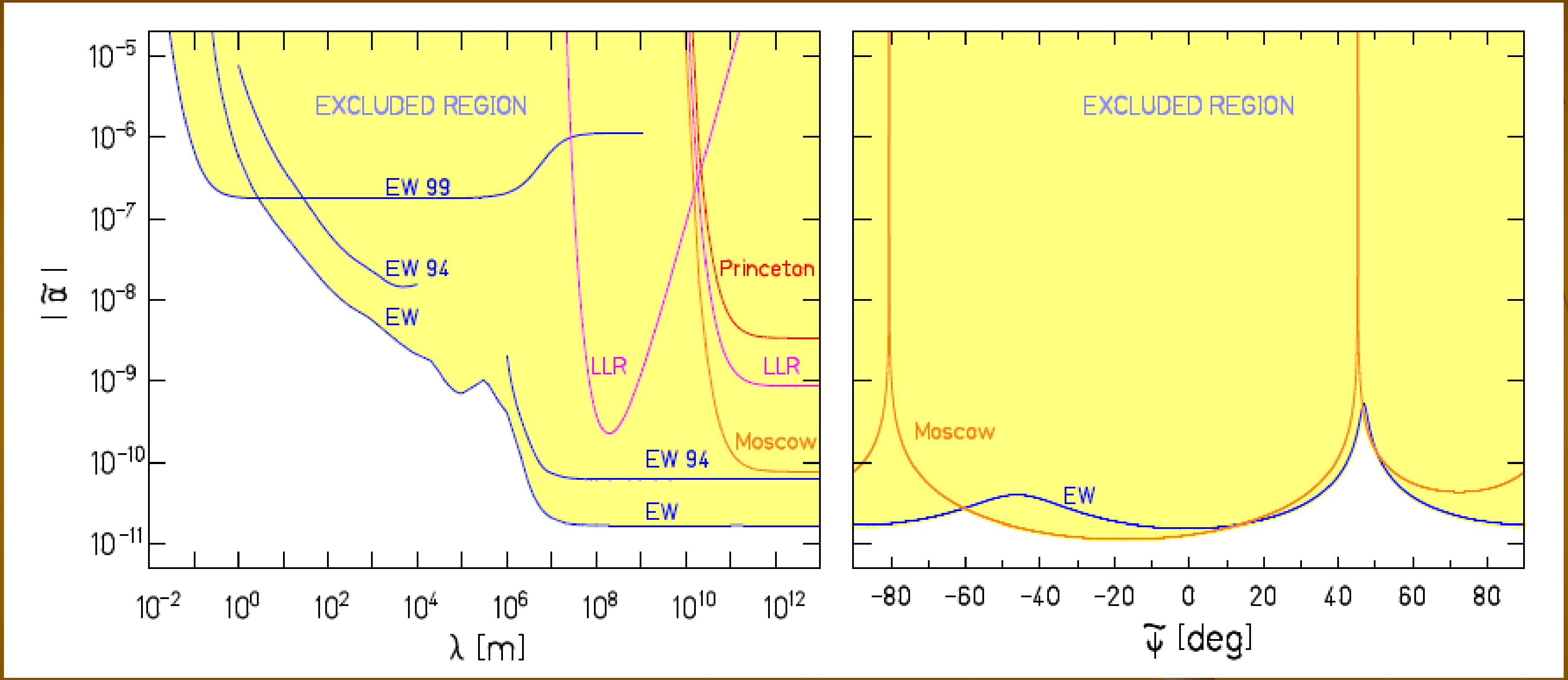
Table 2. Error budget for the lab-fixed Be-Ti differential accelerations. Corrections were applied for gravitational gradients and tilt, only upper limits were obtained on the magnetic and temperature effects. All uncertainties are $1\,\sigma$.

Uncertainty source	$\Delta a_{\mathrm{N,Be-Ti}}$ (10^{-15} m s^{-2})	$\Delta a_{\mathrm{W,Be-Ti}}$ (10^{-15} 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

		Be-Ti	Be-Al
Δa_{N}	(10^{-15} m s^{-2})	0.6 ± 3.1	-1.2 ± 2.2
Δa_{W}	(10^{-15} m s^{-2})	-2.5 ± 3.5	0.2 ± 2.4
$\Delta a_{\odot}$	(10^{-15} m s^{-2})	-1.8 ± 2.8	-3.1 ± 2.4
Δa_{g}	(10^{-15} 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

PhD project of Todd Wagner

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

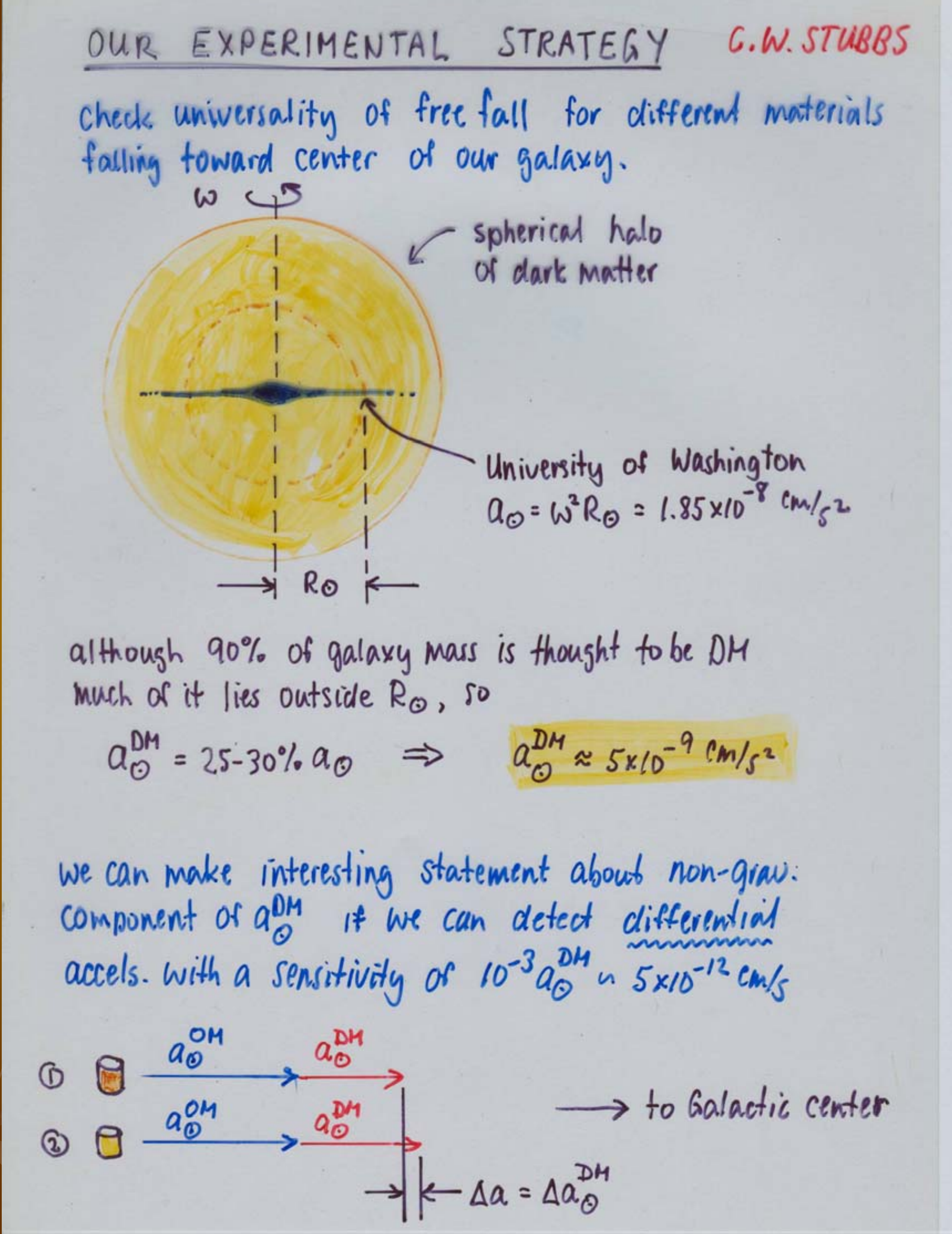


Yukawa attractor integral based on:

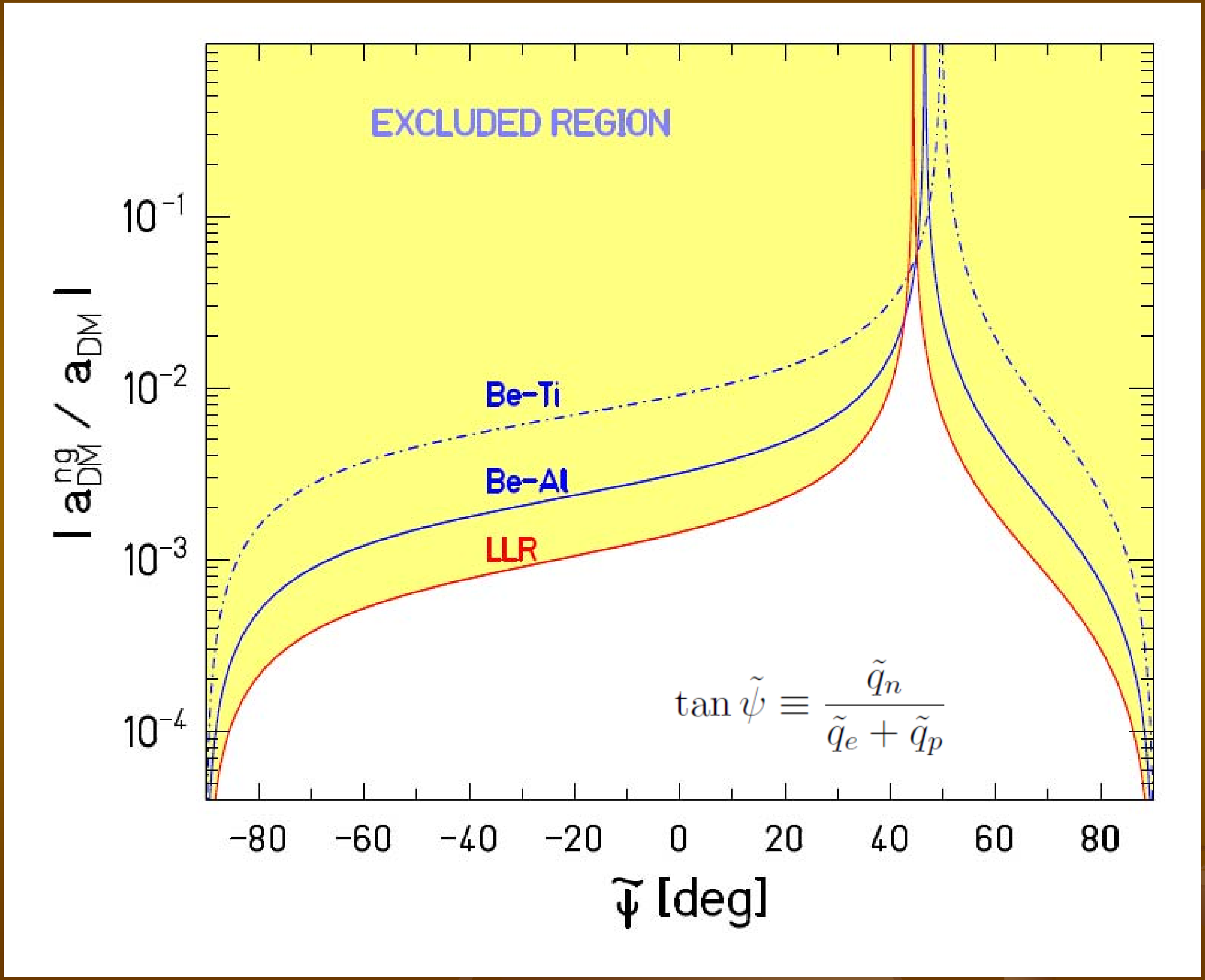
0.5m<λ<5m	lab building and its major contents
1m< λ<50km	topography
5km< λ<1000km	USGS subsurface density model
1000km< λ<10000km	PREM earth model

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

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 $\approx$ 1 nm

Now working on an upgrade that we hope will give order of magnitude improvement:

- fused silica suspension fiber
- Be/CH2 test bodies
- continuous measurement of gravity gradients

Lunar Laser Ranging currently provides the best tests of:

time-rate-of-change of G

fractional change $< 10^{-12}$ per year

recent analysis of Mueller et al. $<3\text{x } 10^{-13}$ per year

$1/r^2$ force law

violations $< 10^{-10}$ times gravity at 10^8 m scales

strong equivalence principle

(does gravitational binding energy fall like everything else?)

$\Delta a/a \approx 10^{-13}$; gravity reduces earth's mass by

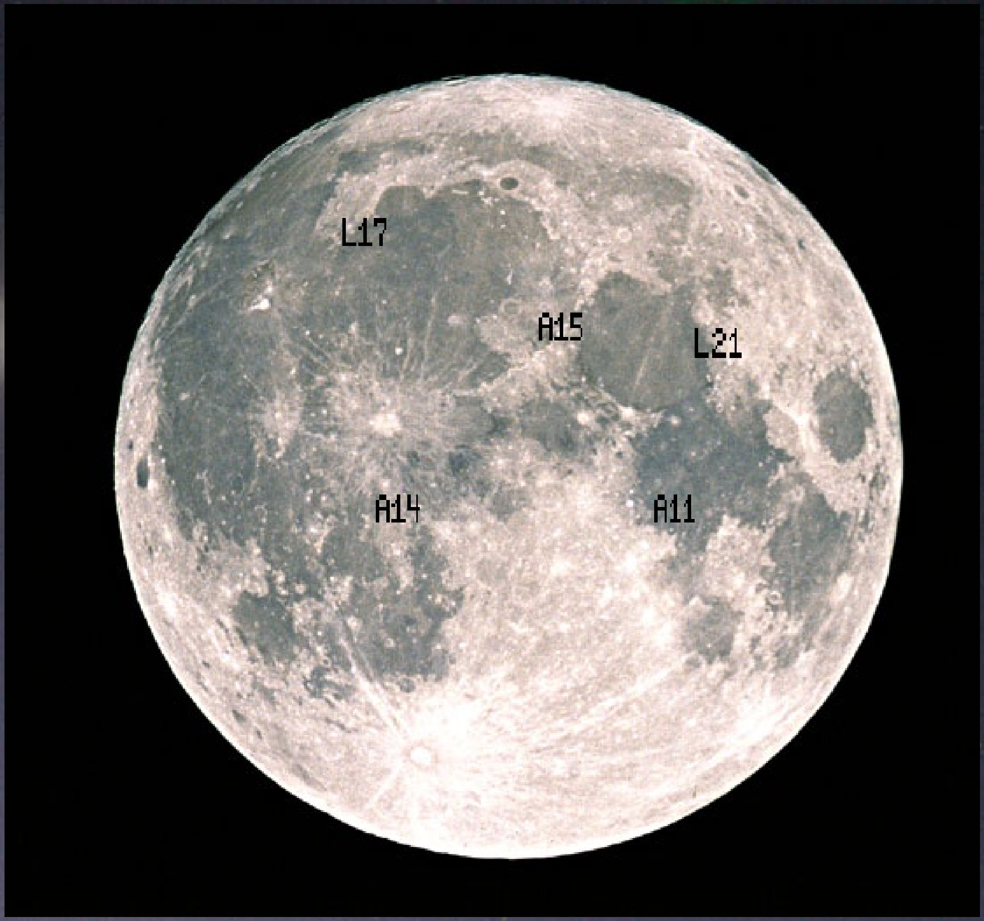
0.46 ppb => SEP verified to 4×10^{-4}

gravitomagnetism (origin of frame-dragging)

verified to 0.1%

Williams, Turyshev and Boggs, Int. J. Mod. Phys. D 18 (2009) 1129

the lunar reflector arrays



A11, A14, and A15 were deployed by APOLLO astronauts arrays

L17 and L21 were deployed by Soviet Lunokhod rovers. No documented ranges to L17 until it was found in 2010.

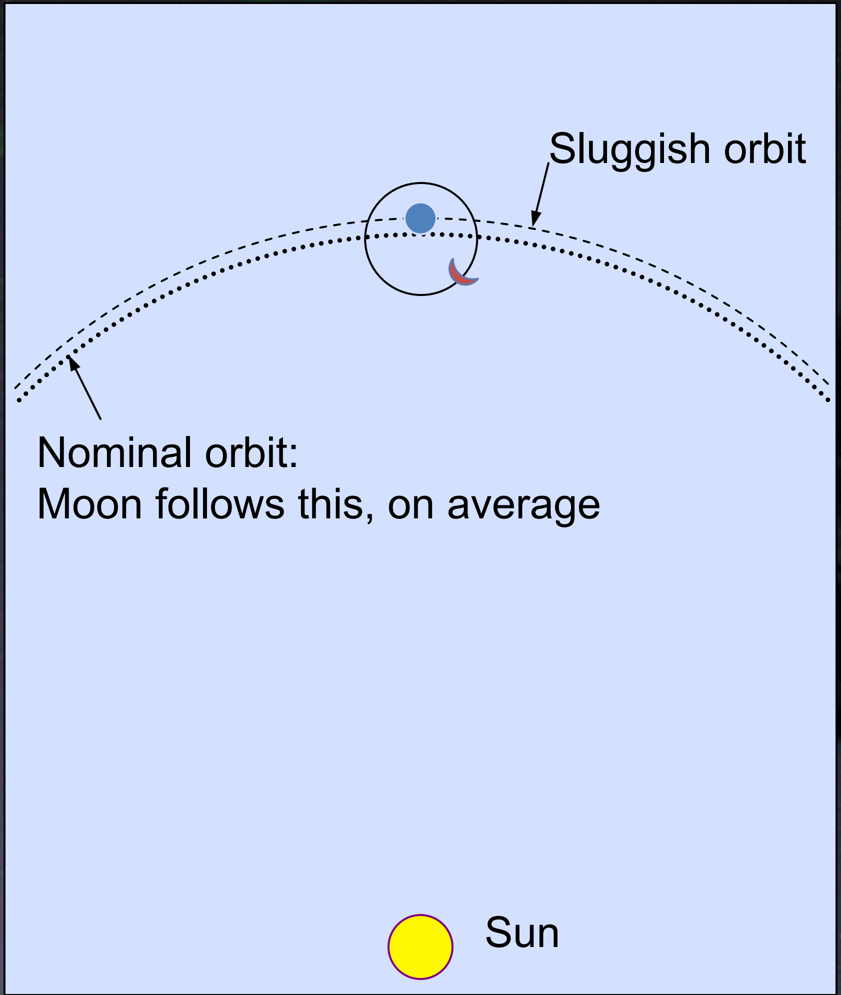
Signal loss is huge:

- $\approx 10^{-8}$ of photons launched find reflector (atmospheric seeing)
- $\approx 10^{-8}$ of returned photons find telescope (reflector diffraction)
- $>10^{17}$ loss considering other optical/detection losses.

Most data were taken on A15 (the brightest reflector), lesser amounts on A11 and A14. Data were concentrated on ¼ and ¾ moon.

equivalence principle signal

- If earth had smaller gravitational to inertial mass ratio than the moon, the earth's orbit around sun would have larger radius than the moon's. It would appear that moon's orbit is *shifted* toward sun



G-dot signal

Moon's orbit around earth steadily expands because of tidal friction

If G is getting weaker then orbit will also expand.

The 2 effects can be separated because tidal friction does not violate Kepler's 3rd law but changing G does

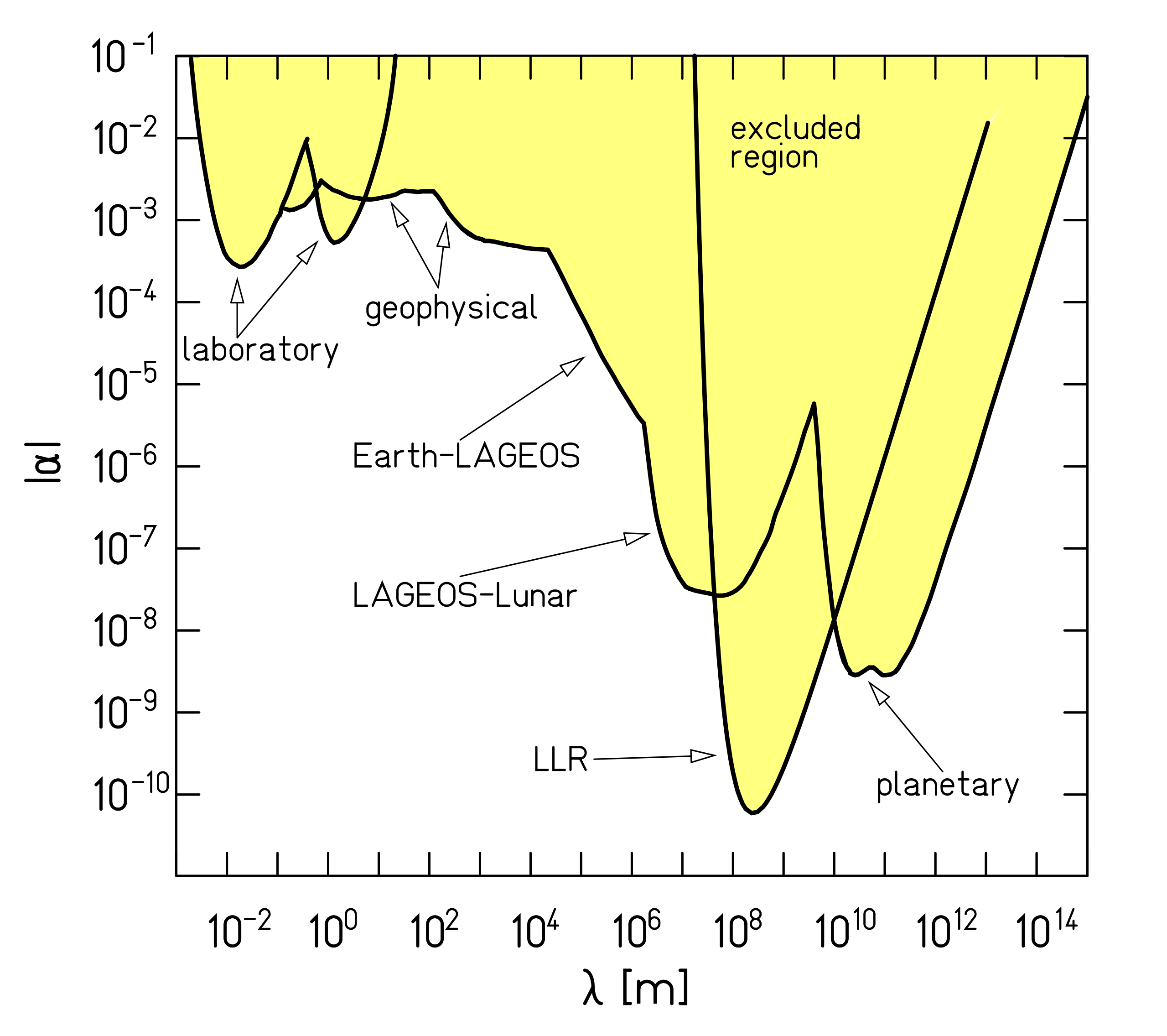
inverse-square law signal

anomalous precession of lunar perigee

< 0.134 marc sec/yr

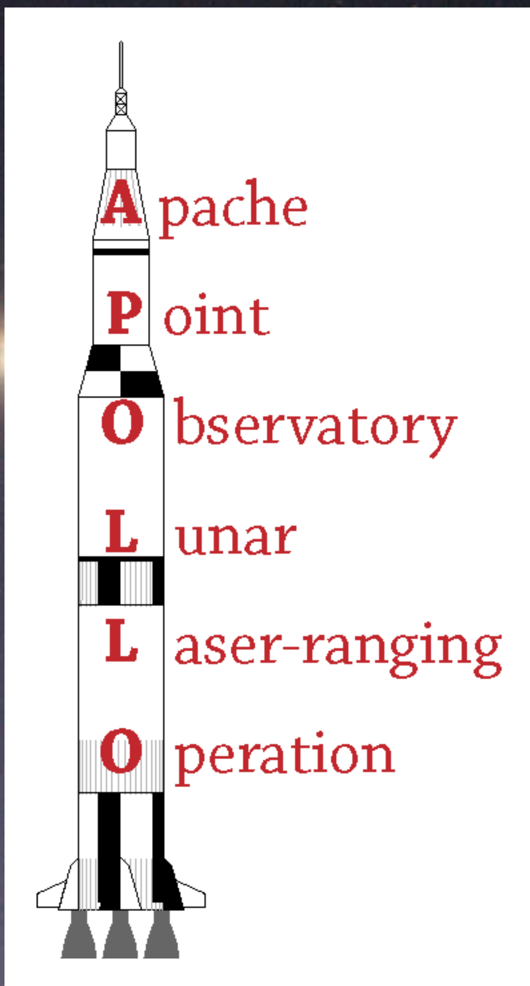
95% confidence ISL limits as of 2000

LLR constraint inferred from anomalous precession of lunar orbit



APOLLO: a next-generation LLR facility

UCSD, APO, Washington, Harvard, Humboldt State, Northwest Analysis collaboration led by Tom Murphy and funded by NASA & NSF



APOLLO provides factor of 10 improvement in range precision (from cm to mm) and

factor of 100 improvement in data rates by:

- using a 3.5 meter telescope with good seeing
- firing 20 pulses/sec
- gathering multiple photons/shot with 16 element detector array

APO 3.5 m, New Mexico, 2800 m elevation

Examples of APOLLO's capabilities

- found the lost L17 reflector
- routinely range to all 5 reflectors

  ranges to 3 reflectors give 1 distance and 2 angles

  ranges to 5 reflectors add 2 measures of moon's tidal deformation

  A recent 1-hour session with very good "seeing" cycled twice through all 5 reflectors, and counted ~45,000 photons.

  This is about as many photons as OCA (best previous LLR station) gathered in 1 year.

- regularly range in full moon

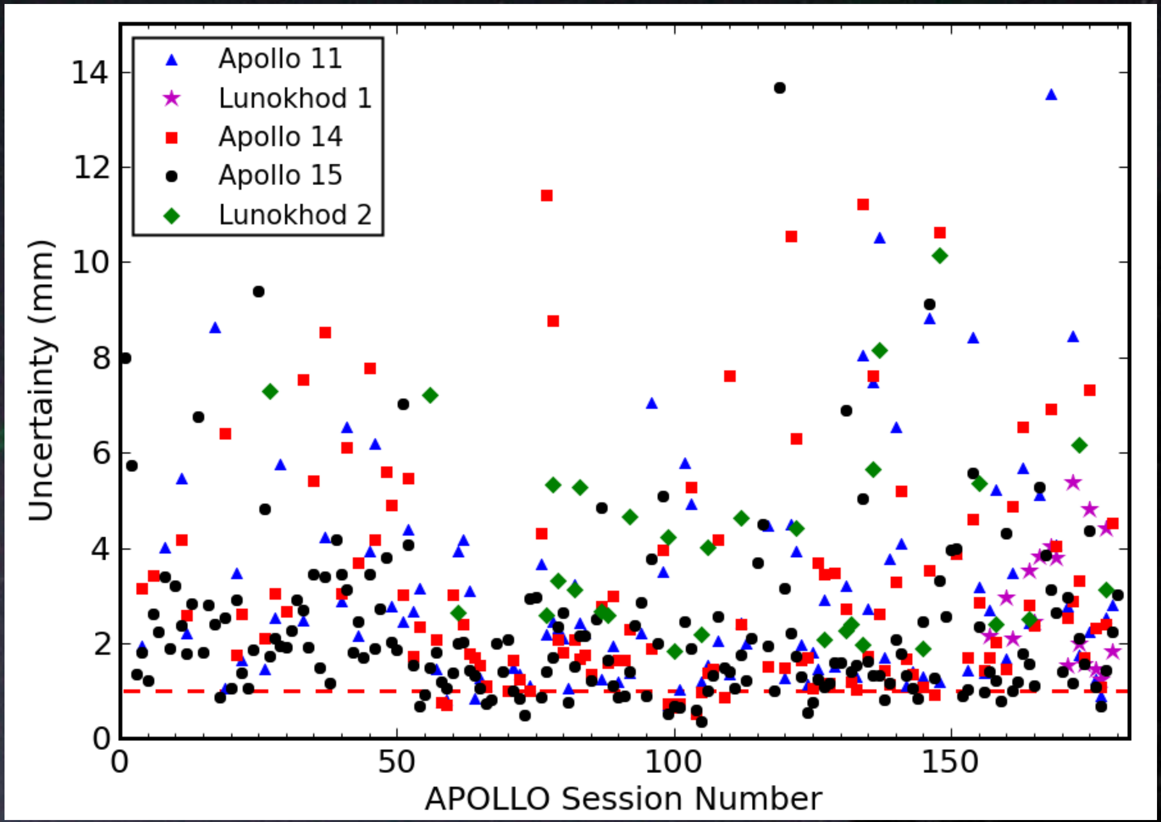
  samples lunar cycle more uniformly

- high data rate allows systematic investigations

  studied degradation and thermal properties of reflectors

  Important for plans to place new optical devices on the moon

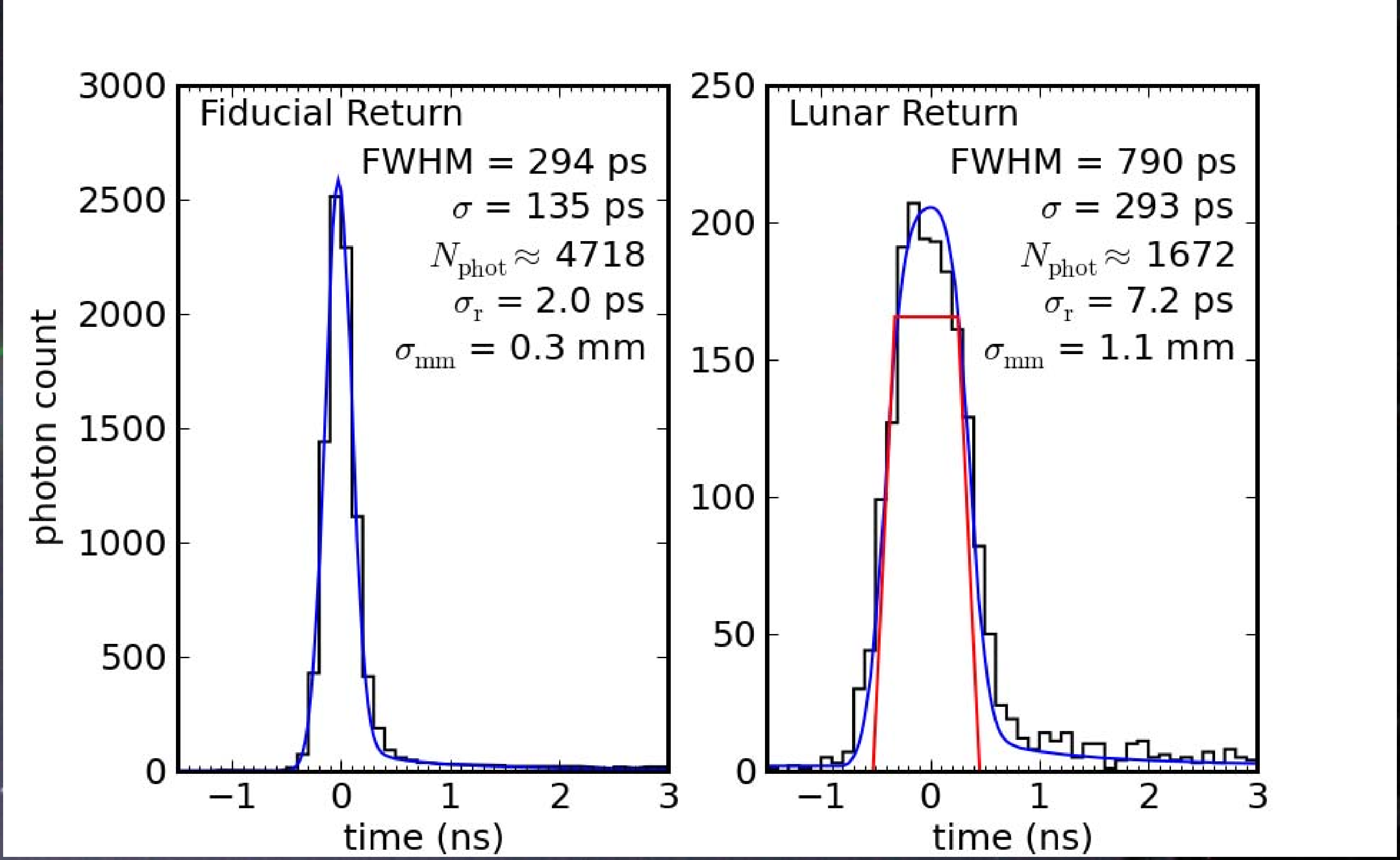
APOLLO's range precision



uncertainties are per night, per reflector; combined nightly median range error is 1.4 mm

pre-APOLLO data were rarely better than 10 mm

Fitting the Return & Reflector Trapezoid



Next Step: Model Development

To extract fundamental science from new LLR data must model all effects that influence the Earth-Moon range at the mm level

- relativistic gravity in solar system
- geophysics + selenophysics

The best LLR models currently produce > 15 mm residuals

Effects that need updating based on new inputs

- site displacement phenomena
- earth and moon tidal models
- atmospheric propagation delay model
- earth orientation models should incorporate LLR data
- Earth and Moon mass multipoles

Effects not yet included

- crustal loading from atmosphere, ocean, hydrology
- geocenter motion (center of mass with respect to geometry)
- radiation pressure

- APOLLO has 5 years of mm ranging data, and is funded through 2014
- if the models can be improved to incorporate mm-scale effects we expect order-of-magnitude gains in a variety of tests of fundamental gravity
- important to have more than 1 state-of-the art model
- ball is now in the modeler’s court; but collaboration between observers and modelers is essential

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

- untested regime
- probes the dark-energy length scale

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

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

- searches for proposed new phenomena
  - large extra dimensions
  - chameleons
  - “fat gravitons”

Motivation 1:

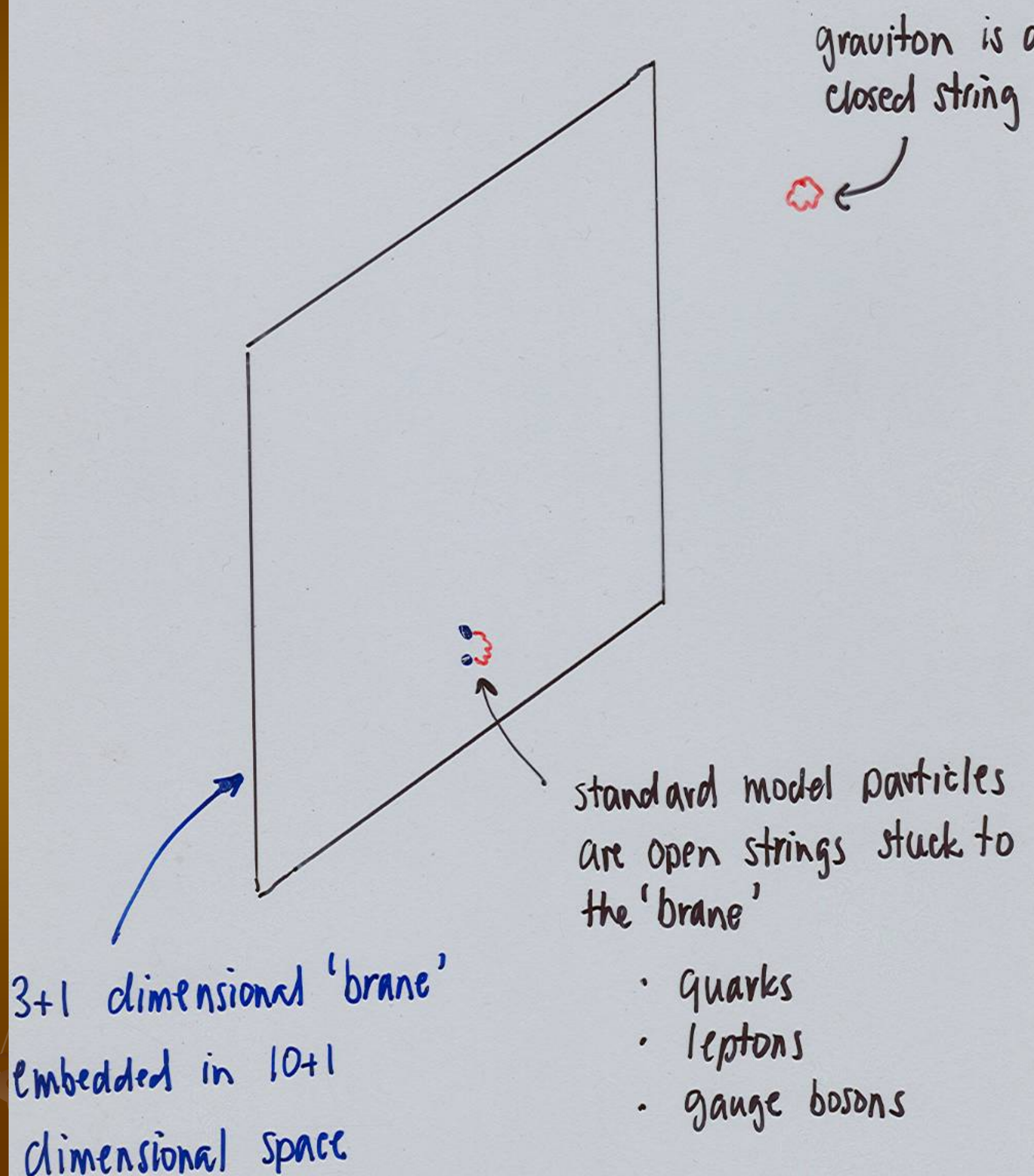
brane-world explanation for gravity's weakness

String theory is not just a theory of strings but it also contains "branes"

Brane-world solution to the hierarchy problem

Gravity isn't actually terribly weak—
we just cannot see its full strength
because most of it has leaked off into
the extra dimensions

Only gravity propagates in all the space dimensions



Gauss's Law and extra dimensions

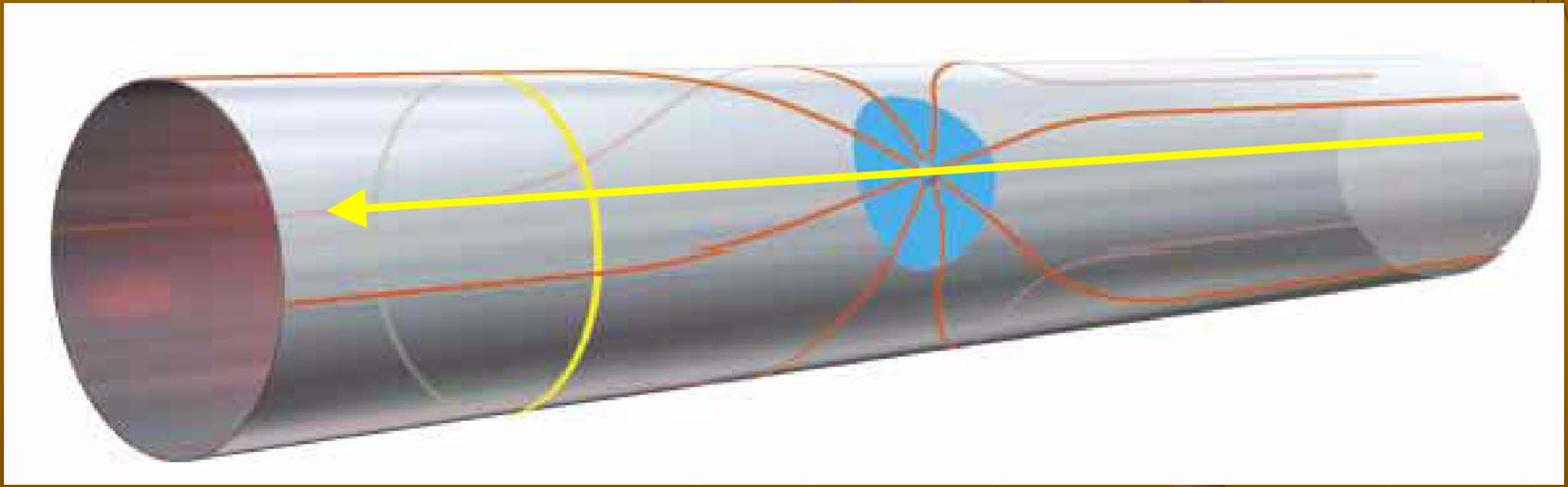
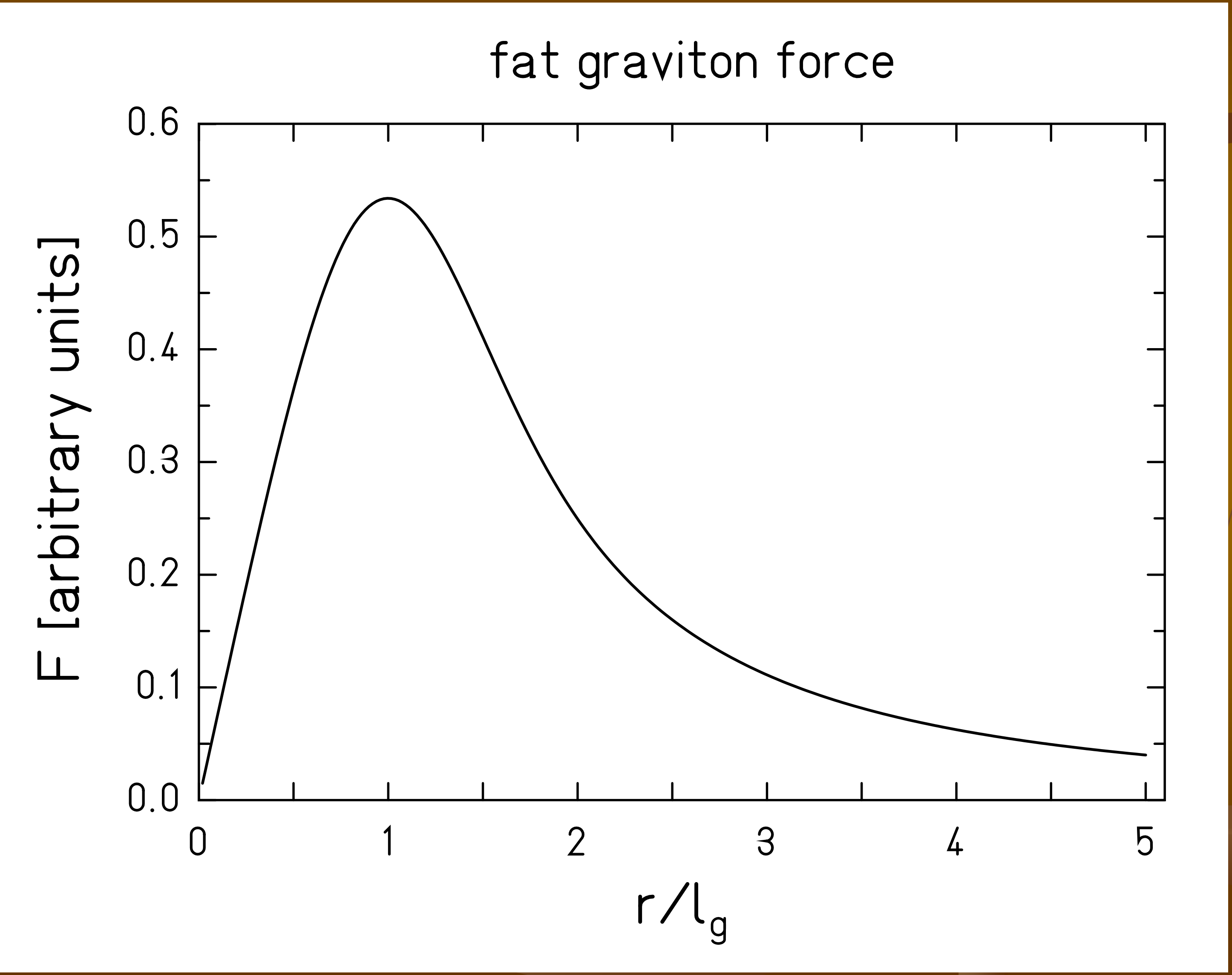


illustration from Savas Dimopoulos

Motivation 2:

Sundrum’s “fat graviton” explanation for observation that repulsive gravity of vacuum energy is 120 orders of magnitude weaker than predicted by GR plus QM

Sundrum's "fat graviton" force



Motivation 3: the chameleon mechanism

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

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

natural values of β and γ are 1

in presence of matter this gives massless chameleons an effective mass

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

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

Parameterising breakdowns of $1/r^2$ law

- Old-fashioned way

$$F(r) = G\frac{m_1 m_2}{r^{2+\epsilon}}$$

↑ no theoretical basis

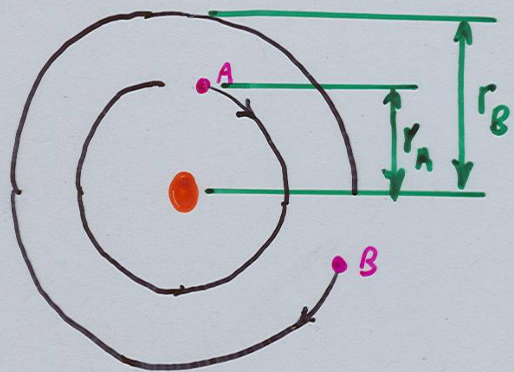
- modern way

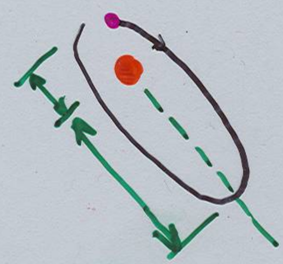
$$F(r) = G\frac{m_1 m_2}{r^2}\left[1 + \alpha\left(1+\frac{r}{\lambda}\right)e^{-r/\lambda}\right]$$

↑

- exchange of boson with $m > 0$
- extra dimensions scenario when $r \sim R^*$

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





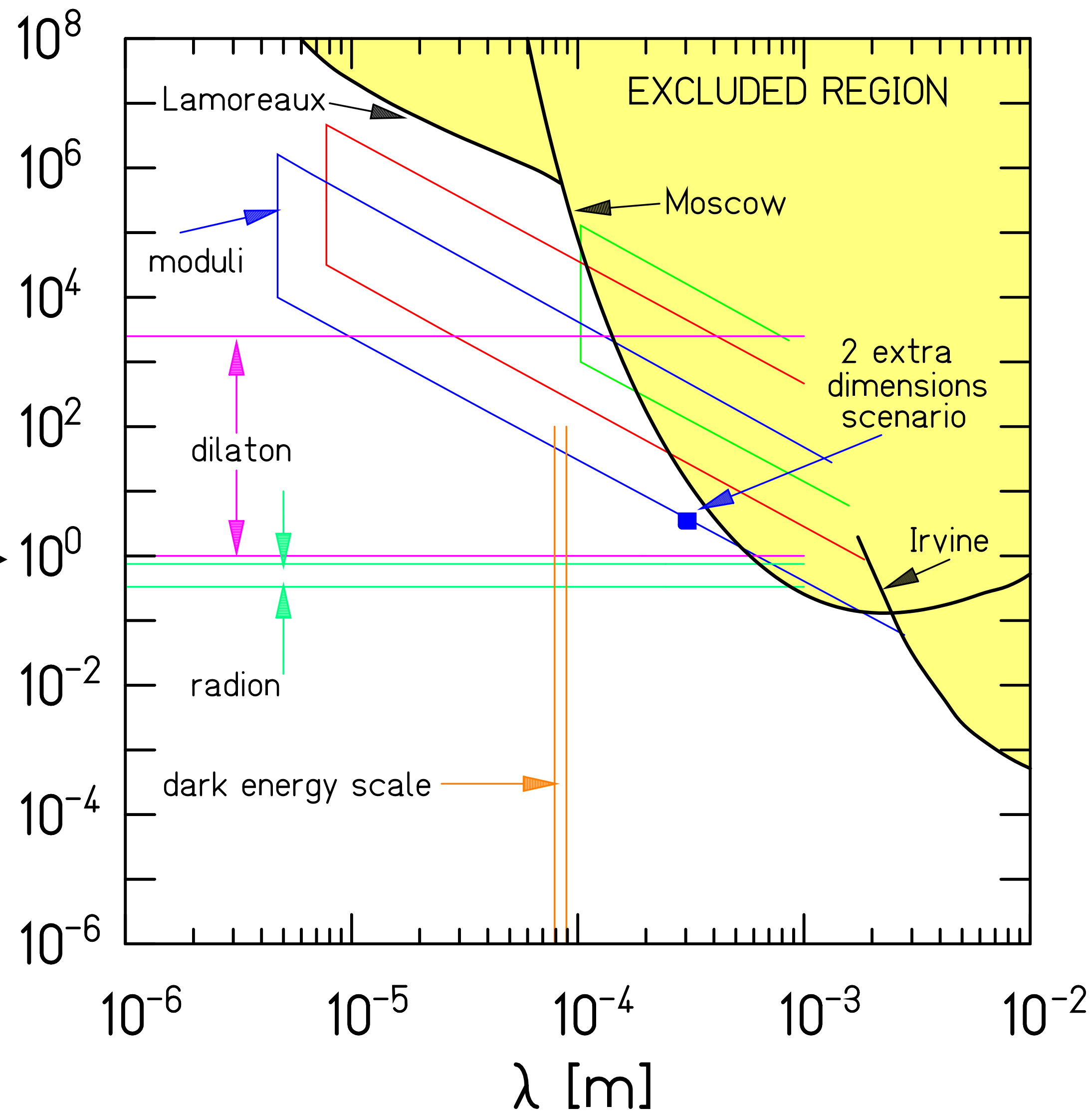
$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \ ?$$

precession of perigee ?

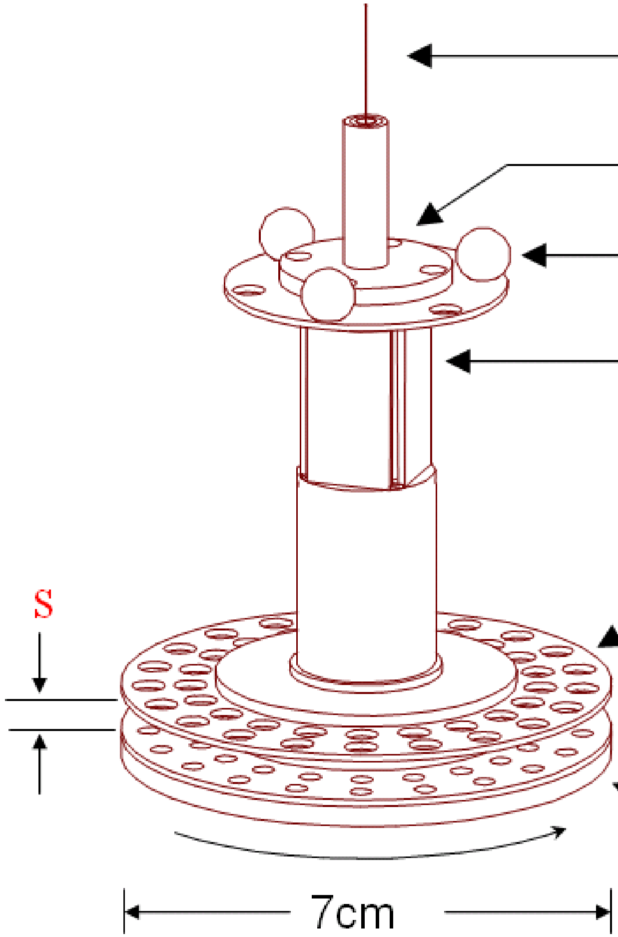
∴ need many different approaches to cover a wide range of length scales

95% confidence limits as of 2000

strength of gravity →



the 42-hole ISL pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

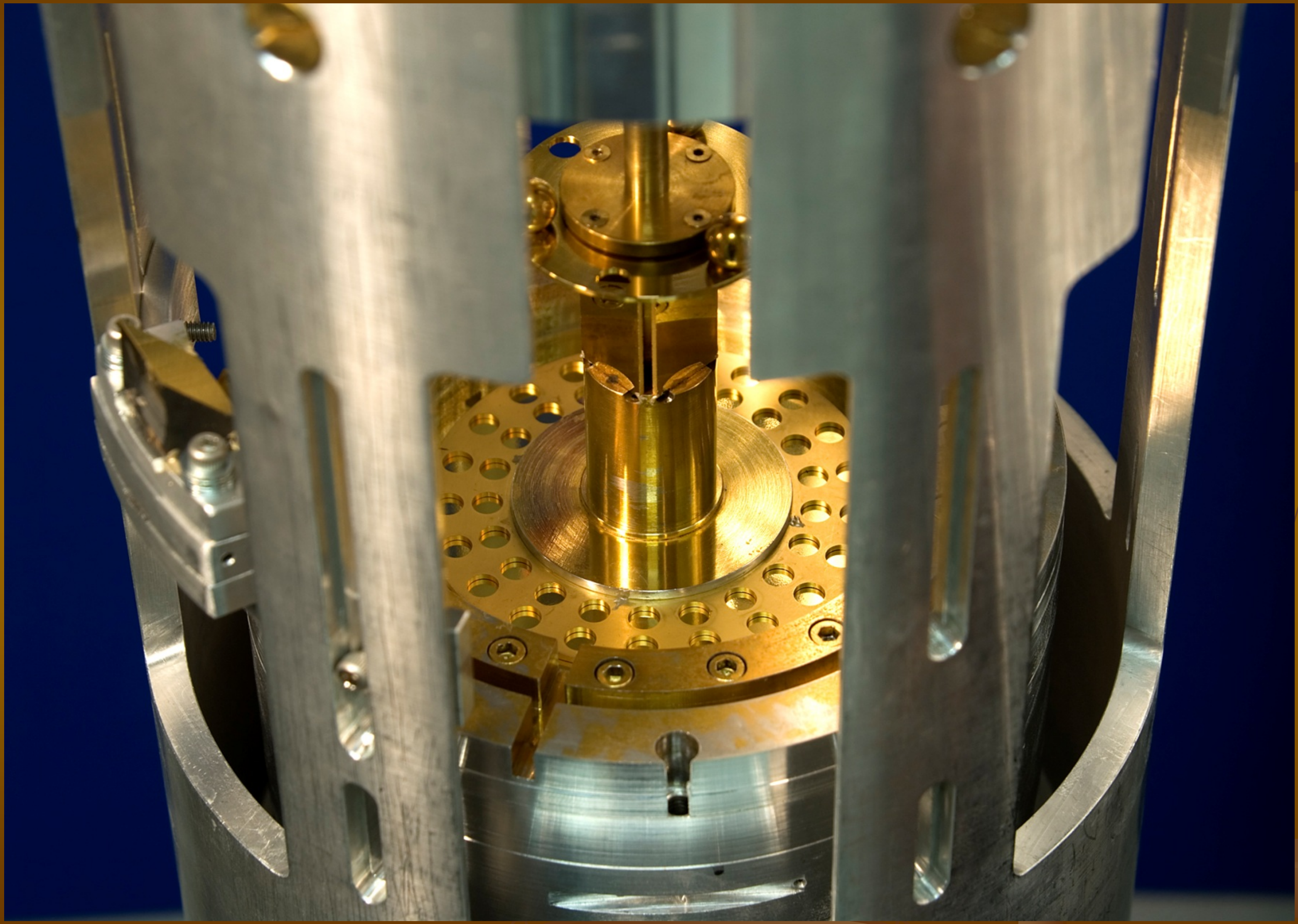
4 mirrors for tracking angle of deflection

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

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

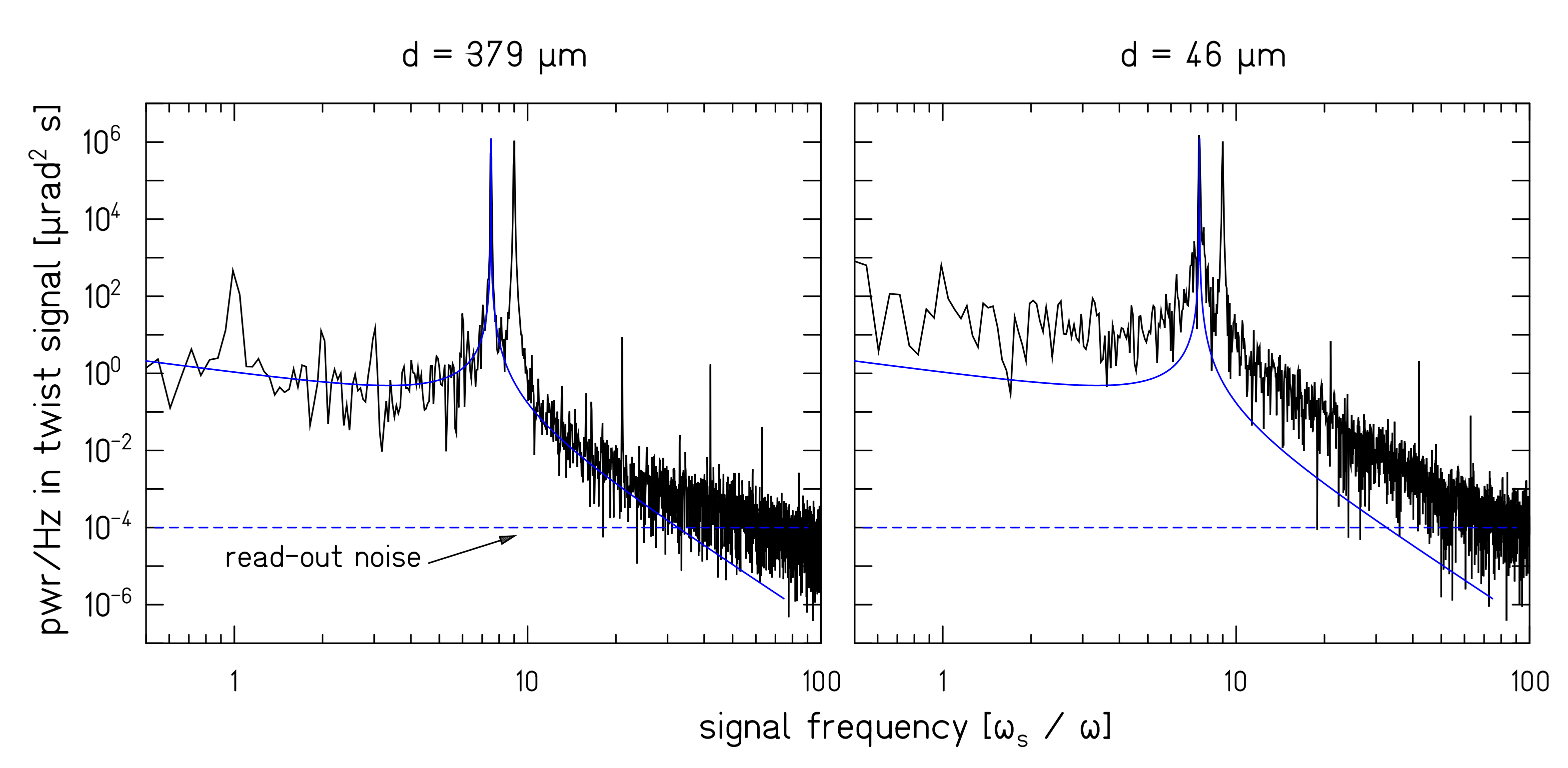
attractor : **rotating pair** of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to **cancel Newtonian gravity**

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



Mary Levin photo

power spectral density of twist signal

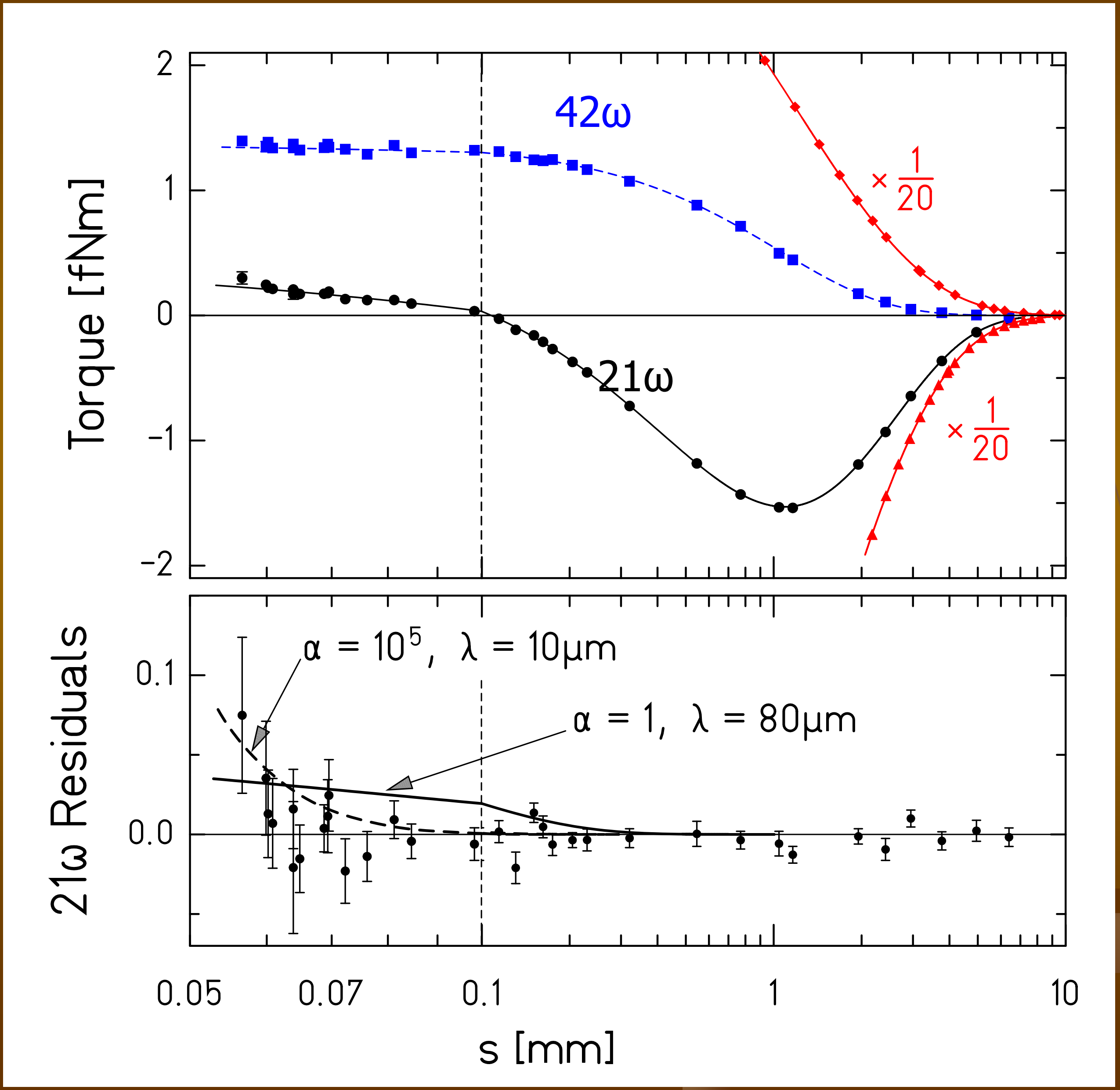


d = detector/foil separation

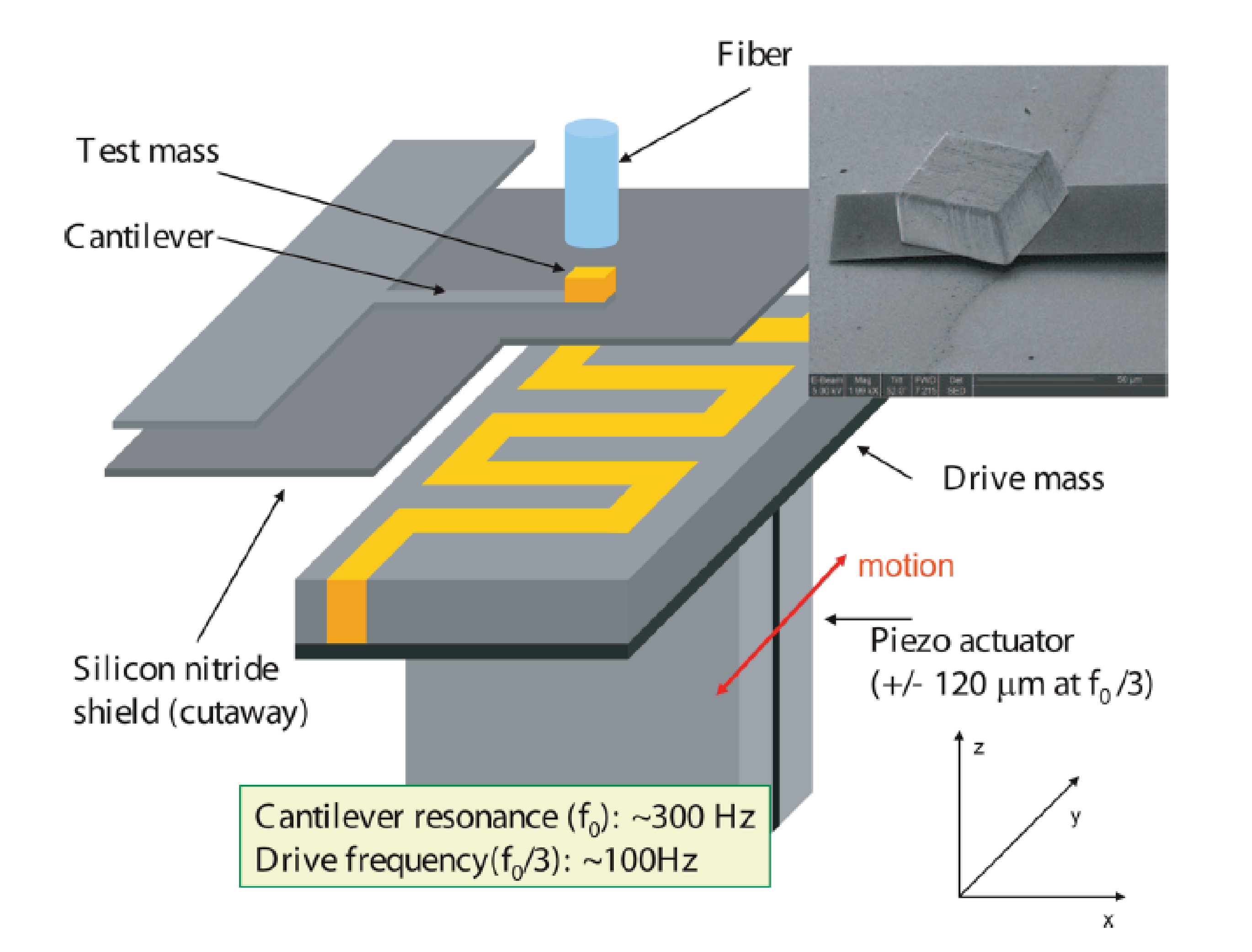
area under smooth curves is $k_B T$

data from 42-hole experiment III

We did 3 experiments, making small changes to the instrument: reducing thickness of the lower attractor, after replacing the gold coatings on the detector and membrane, etc. All 3 experiments showed small anomalies for s < 60 microns. Our constraints are based on all the data.



Kapitulnik group at Stanford does complementary work using low-temperature micro-cantilevers



cantilever has 1.5 μg Au test mass with Q~10,000 at

T_{eff} ~ 2 – 3 K

A. A. Geraci et al., Phys. Rev. D78, 022002 (2008).

data from Geraci et al.'s experiment

GERACI, SMULLIN, WELD, CHIAVERINI, AND KAPITULNIK

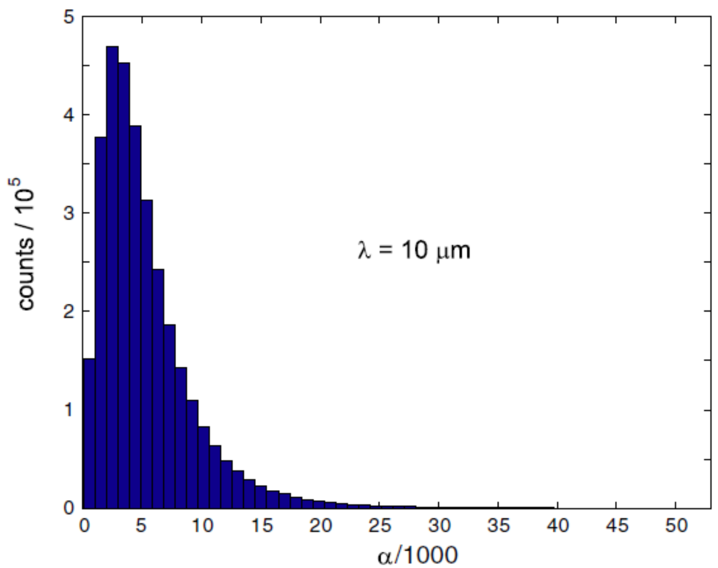


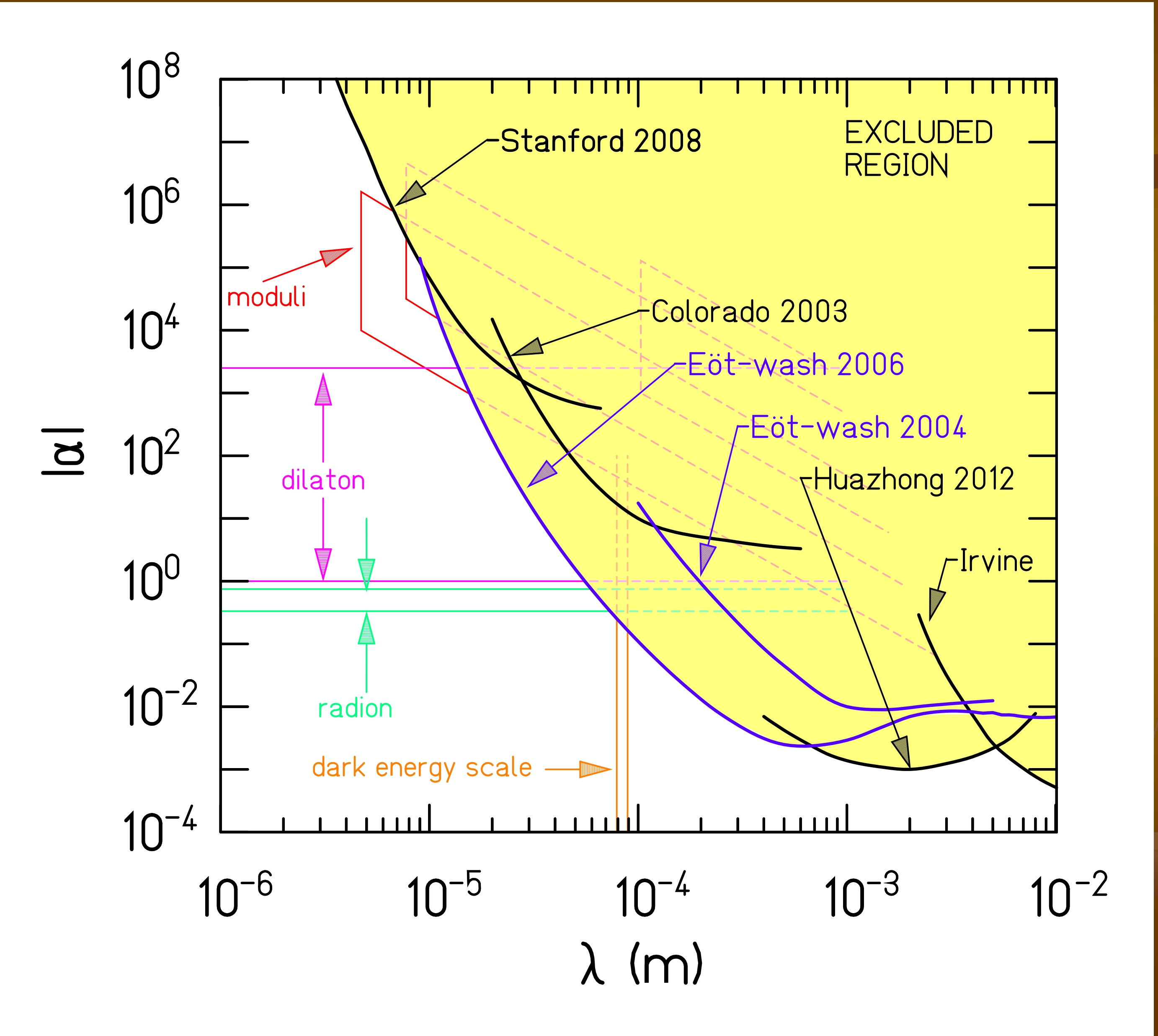
FIG. 6 (color online). Histogram of best-fit α results for $\lambda = 10\ \mu$m.

TABLE V. Experimental limits on Yukawa forces.

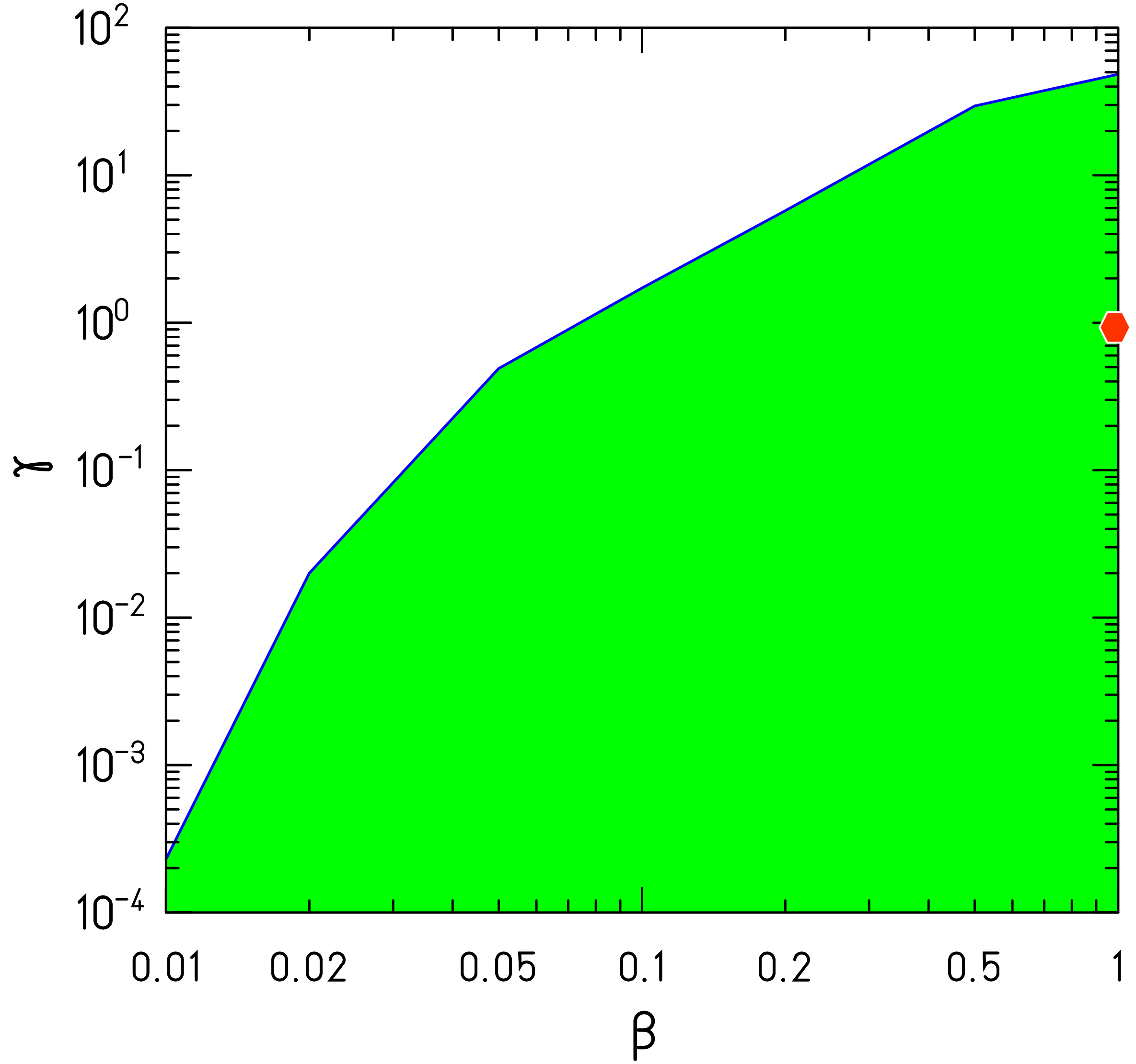
λ (μm)	Mean (MC) α	95% exclusion α
4	8.6×10^6	3.1×10^7
6	1.6×10^5	4.6×10^5
10	5.6×10^3	1.4×10^4
18	5.1×10^2	1.1×10^3
34	1.2×10^2	2.5×10^2
66	7.0×10^1	1.5×10^2

statistical error predominantly from thermal noise in the cantilever

published 95% C.L. results on mm-scale ISL violation

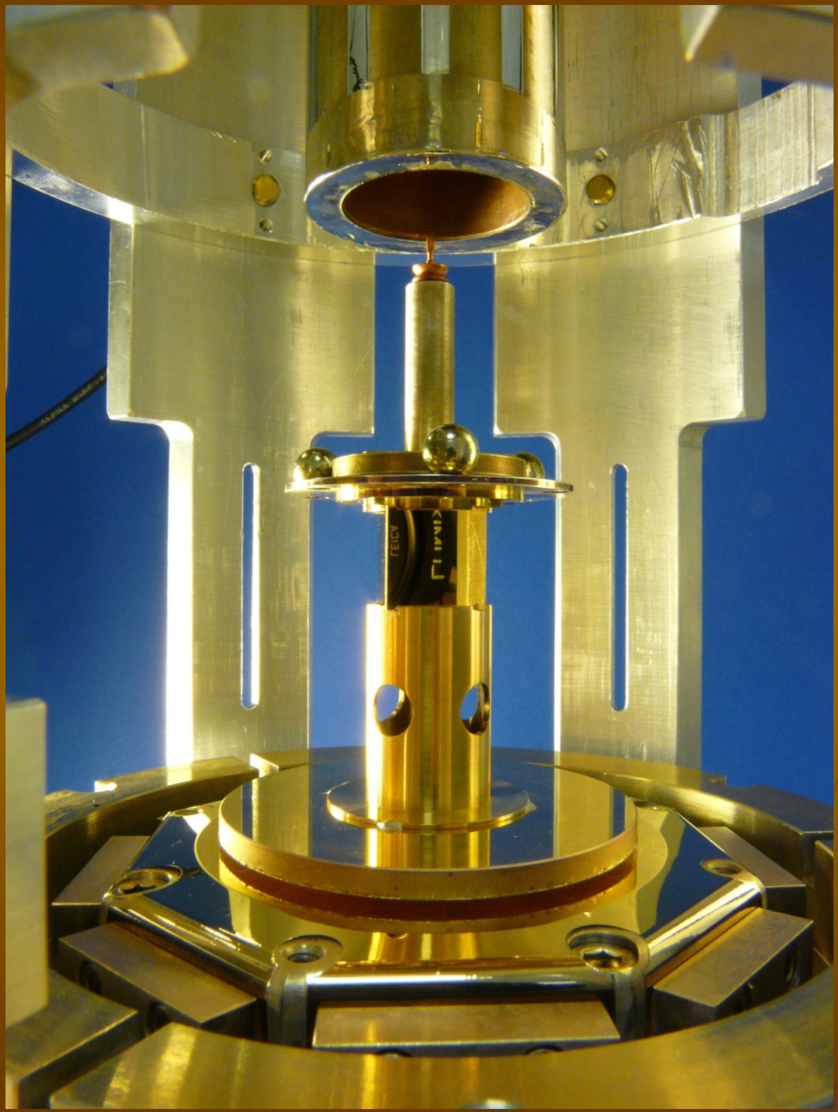


2σ chameleon constraints

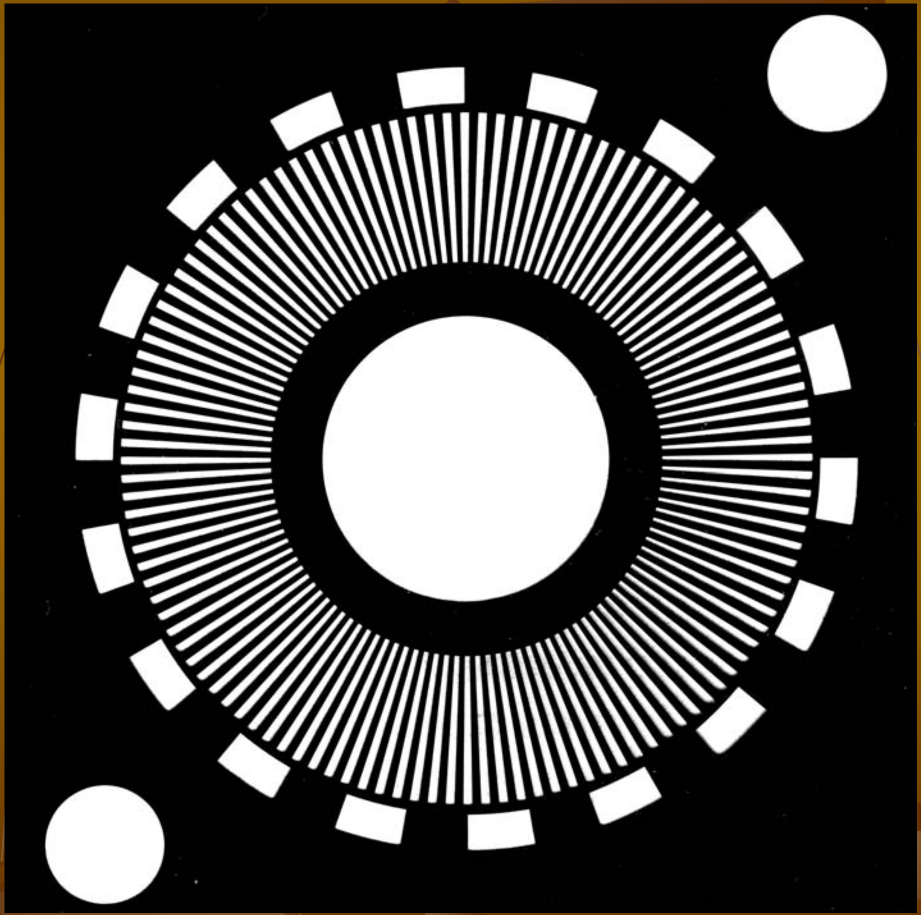


natural value

the Fourier-Bessel pendulum

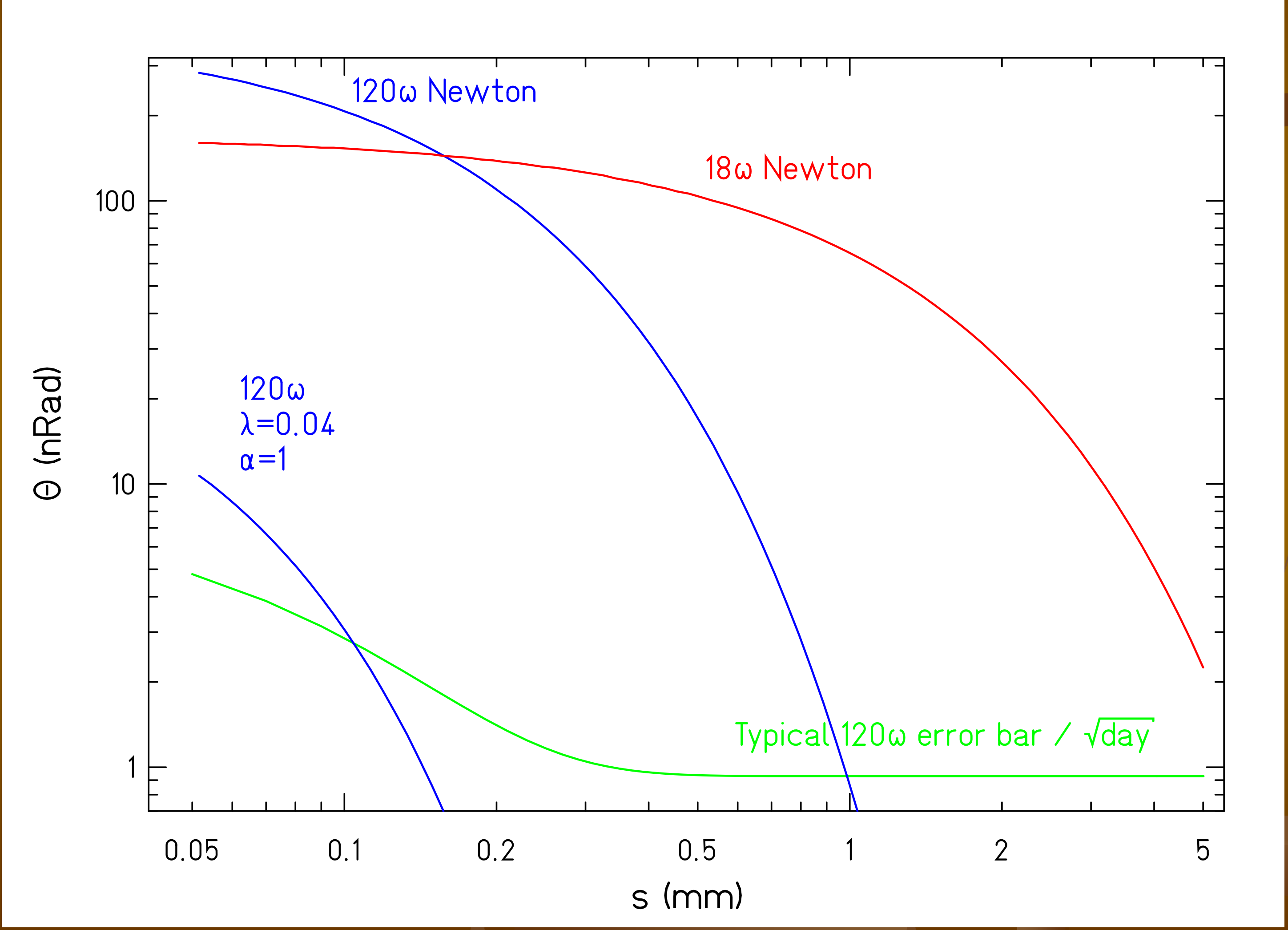


pendulum & attractor are 50μm thick W foils glued to glass plates

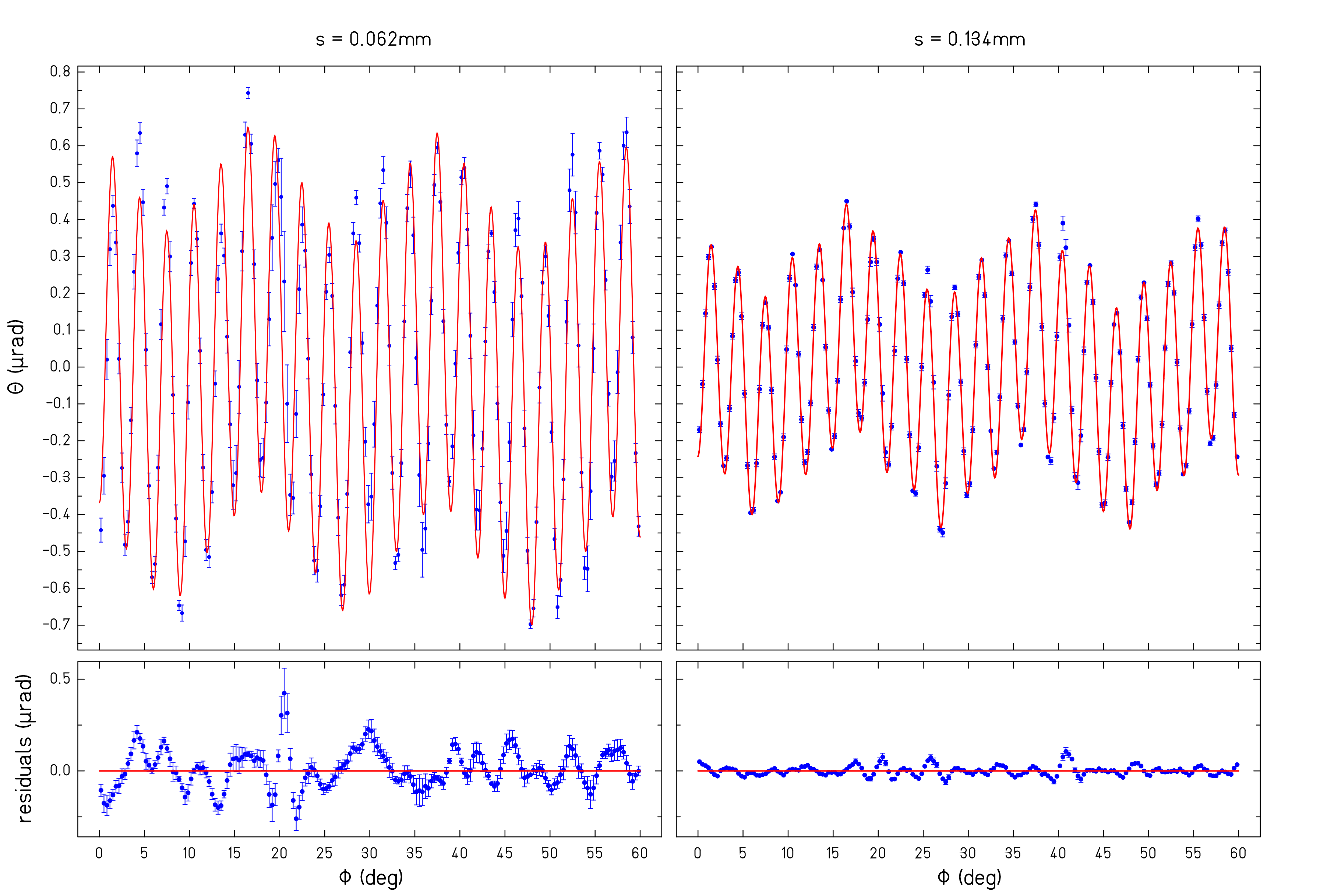


PhD project of Ted Cook

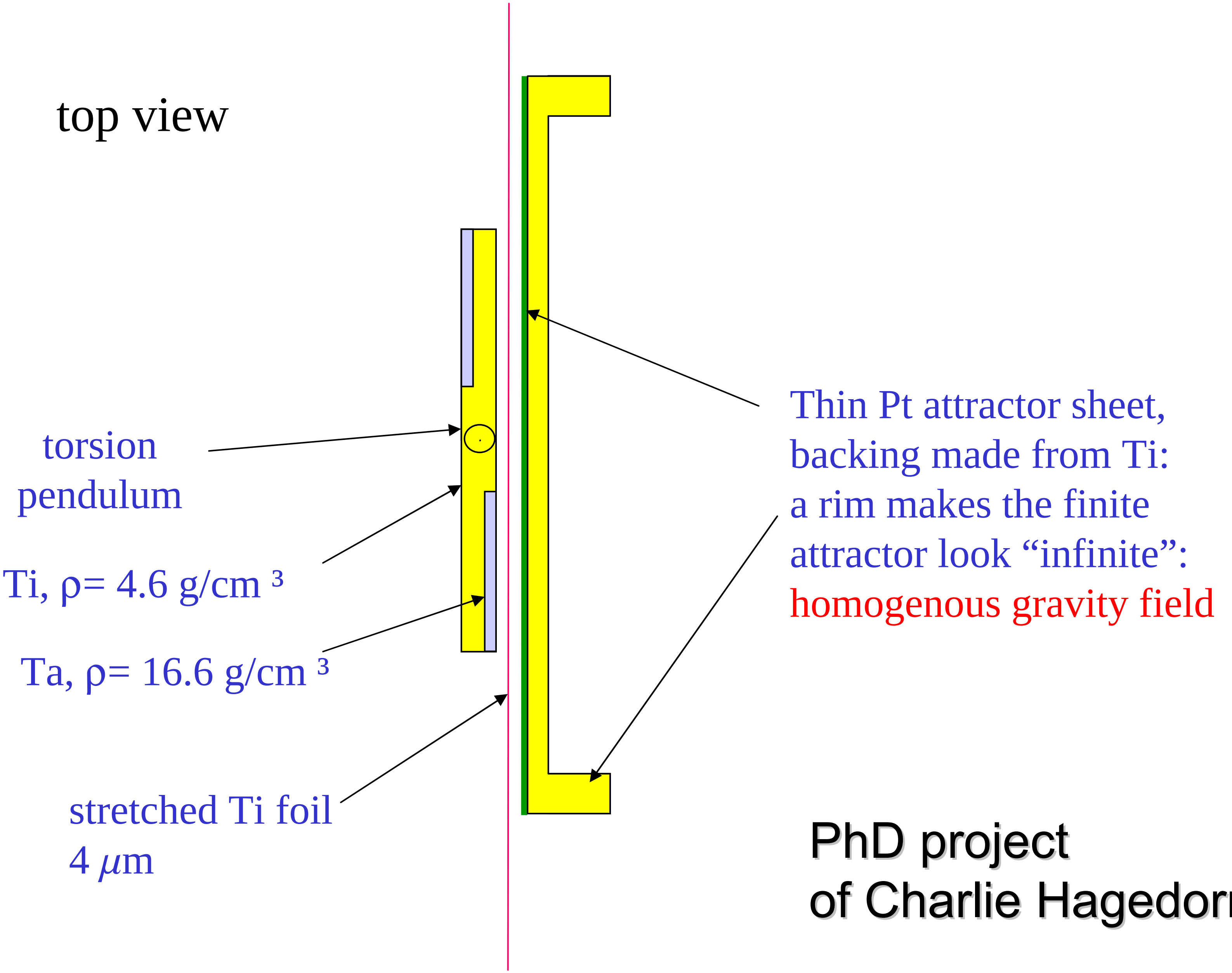
predicted signals for the Fourier-Bessel instrument



observed Fourier-Bessel signals



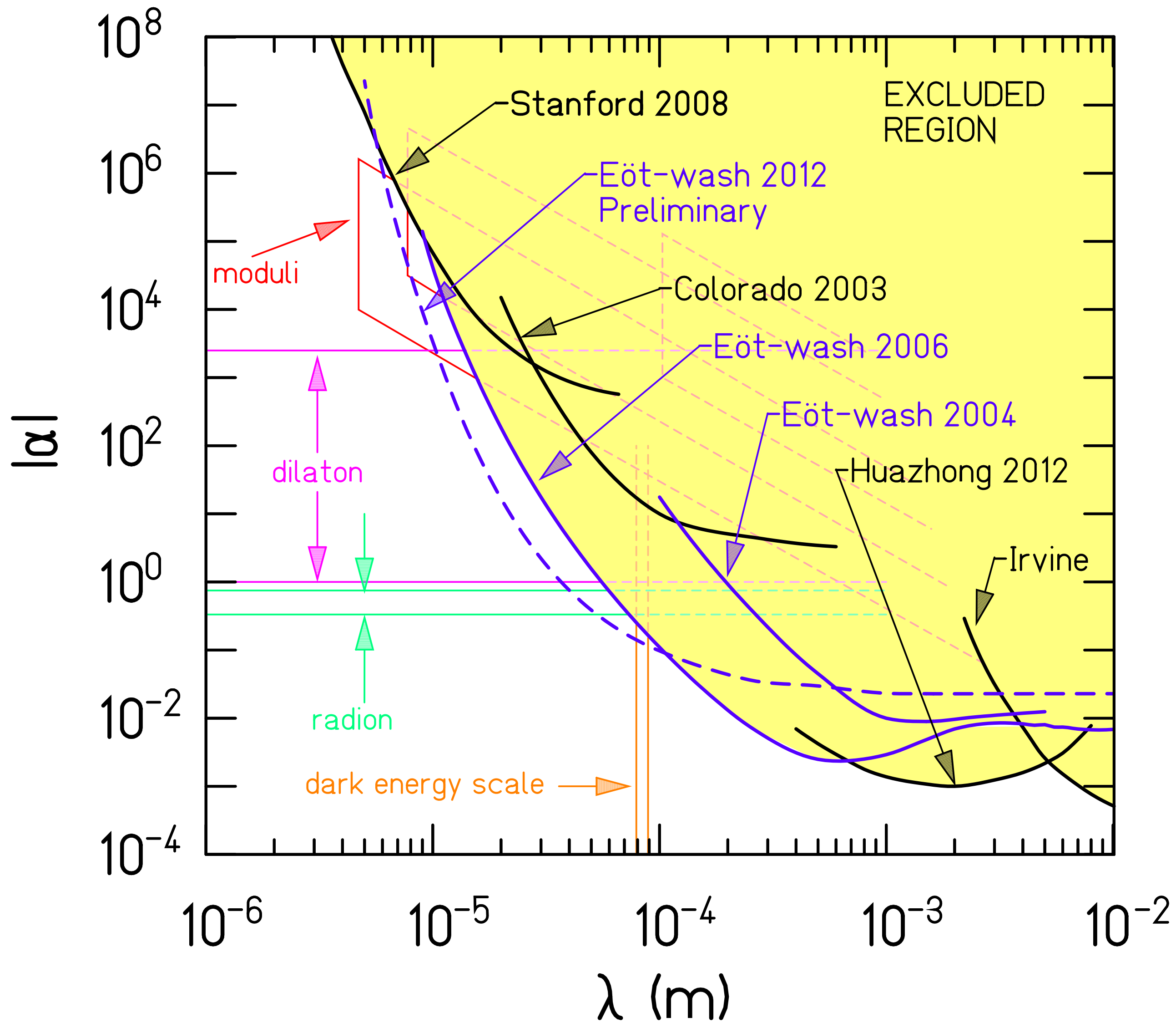
The parallel-plate pendulum



PhD project
of Charlie Hagedorn

Cook's preliminary 95% C.L. results

order of magnitude higher sensitivity below 40 μm: based on 1/3 of his data



some references

- Eöt-Wash test of the EP

  T. Wagner, S. Schlamminger, J. Gundlach and E. Adelberger,
  Class. Quant. Gravity (to be published)

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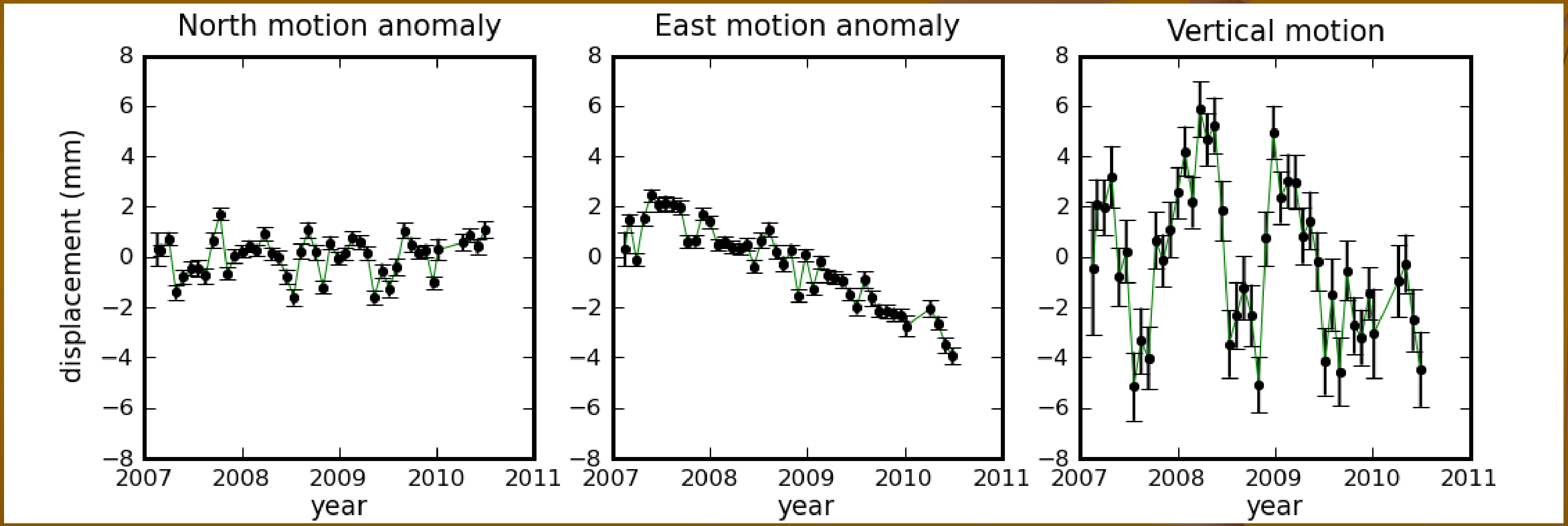
local GPS station motion relative to North American plate



Local GPS station is part of Plate Boundary Observatory and Earthscope

data from on-site superconducting gravimeter