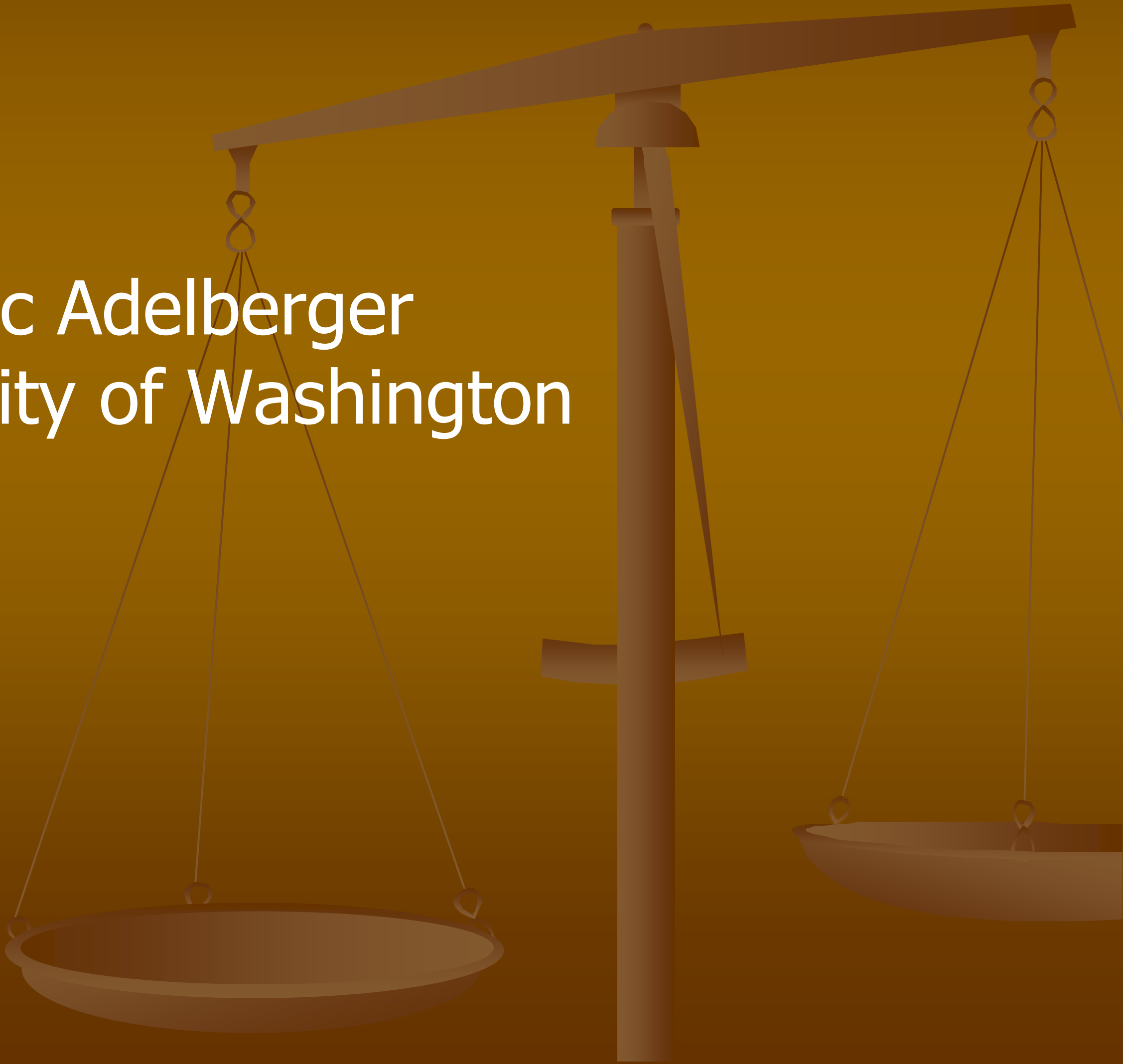
Laboratory tests of gravity from micron to galactic scales



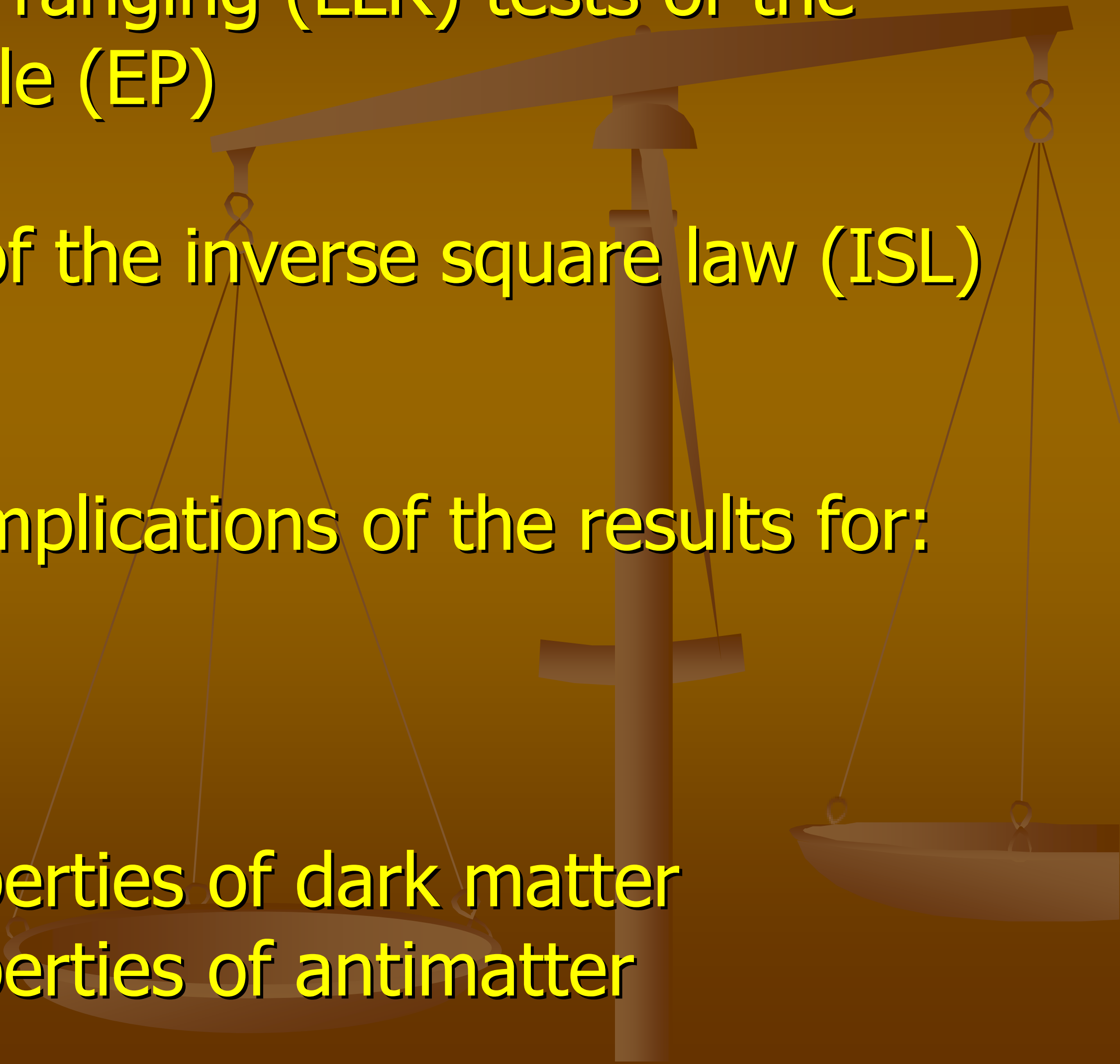
Eric Adelberger
University of Washington

will review techniques, status, future prospects of experimental results for:

- lab and lunar laser ranging (LLR) tests of the equivalence principle (EP)
- lab and LLR tests of the inverse square law (ISL)

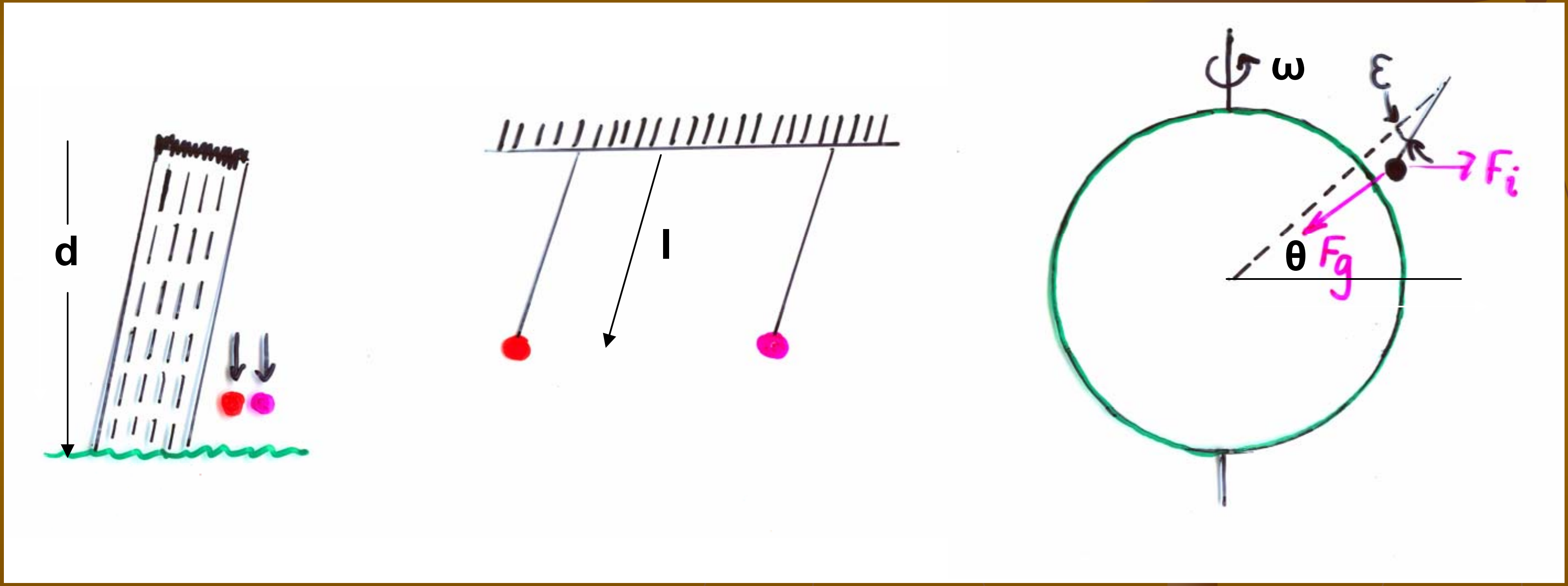
will discuss some implications of the results for:

- strong EP
- G-dot/G
- gravitational properties of dark matter
- gravitational properties of antimatter



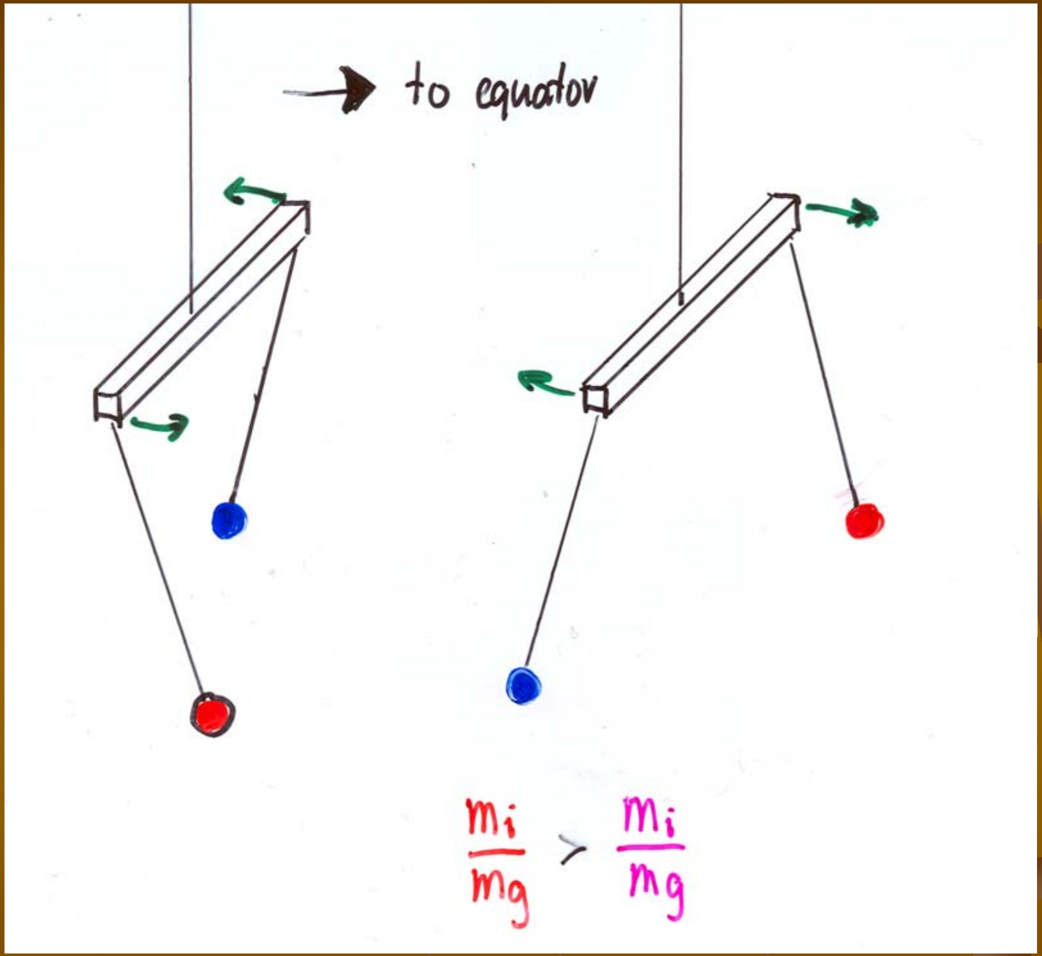
A brief history of Equivalence Principle tests:

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?
$T=\sqrt{(2d/g\,(m^i/m^g))}$	$T=2\pi\sqrt{(l/g\,(m^i/m^g))}$	$\varepsilon=\omega^2 R\sin 2\theta/(2g)\,(m^i/m^g)$
$\Delta a/a \leq 0.1$	$\Delta a/a \leq 10^{-4}$	$\Delta a/a \leq 10^{-9}$

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

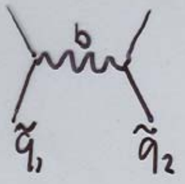
2 WAYS TO THINK ABOUT EP TESTS

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

  is $m_i = m_g$?

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

any quantum exchange force will violate the EP



$$F_{12} \propto \tilde{q}_1 \tilde{q}_2 \frac{1}{r^2}\left(1+\frac{r}{\lambda}\right) e^{-r/\lambda}$$

$$\lambda = \frac{\hbar}{m_b c}$$

$$a_1 = \frac{F_{12}}{m_1} \propto \boxed{\frac{\tilde{q}_1}{m_1}}$$

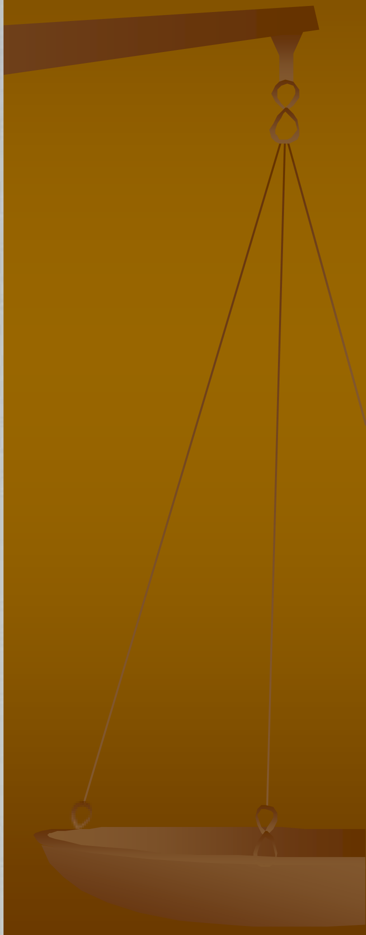
"charge"-to-mass ratio cannot be exactly the same for all objects!

recall EM

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

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

  e.g. string theory dilaton



Parameterizing EP-violating effects of quantum vector exchange forces

gravity couples to mass

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

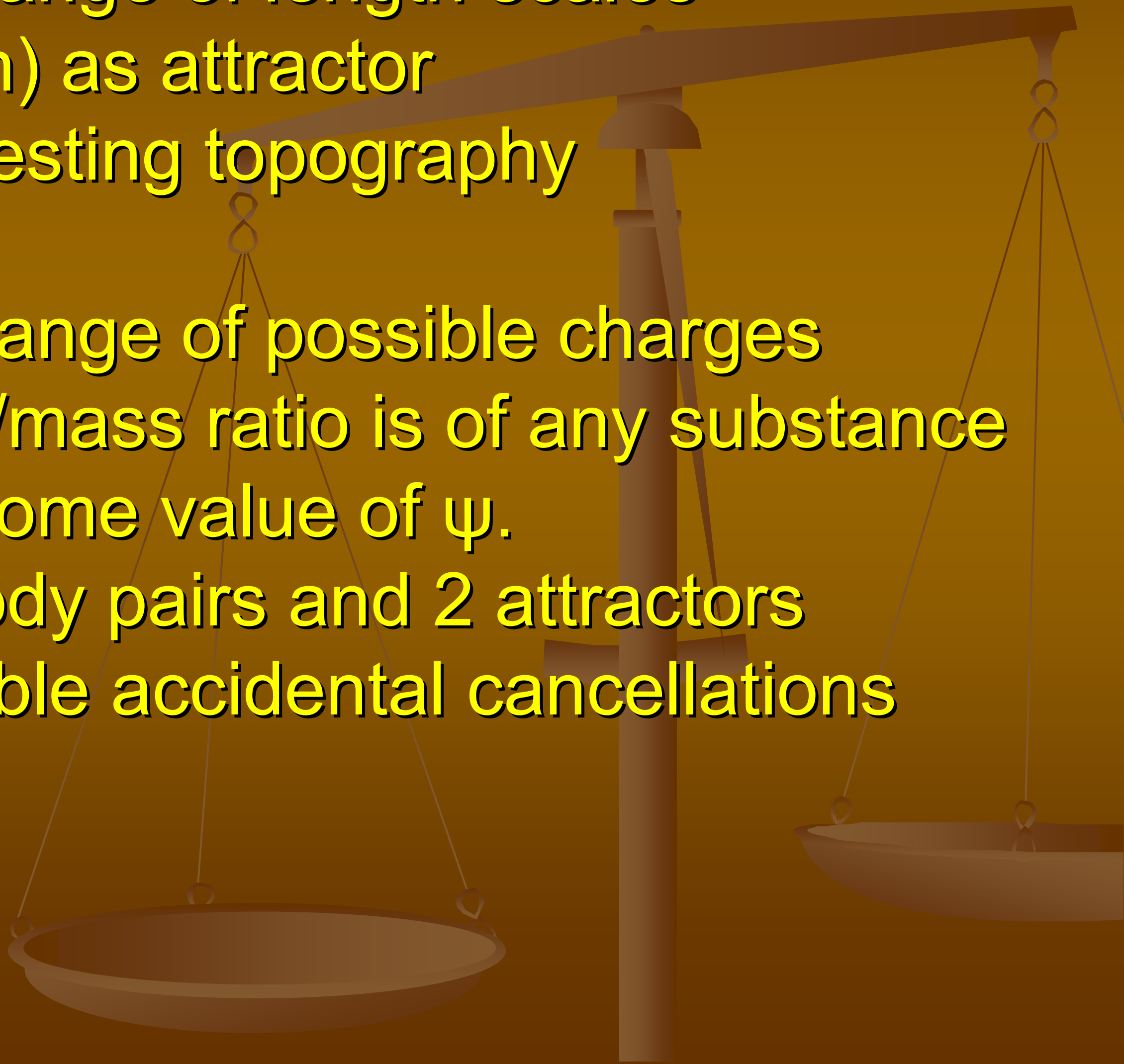
quantum exchange forces couple to “charges”

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

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

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

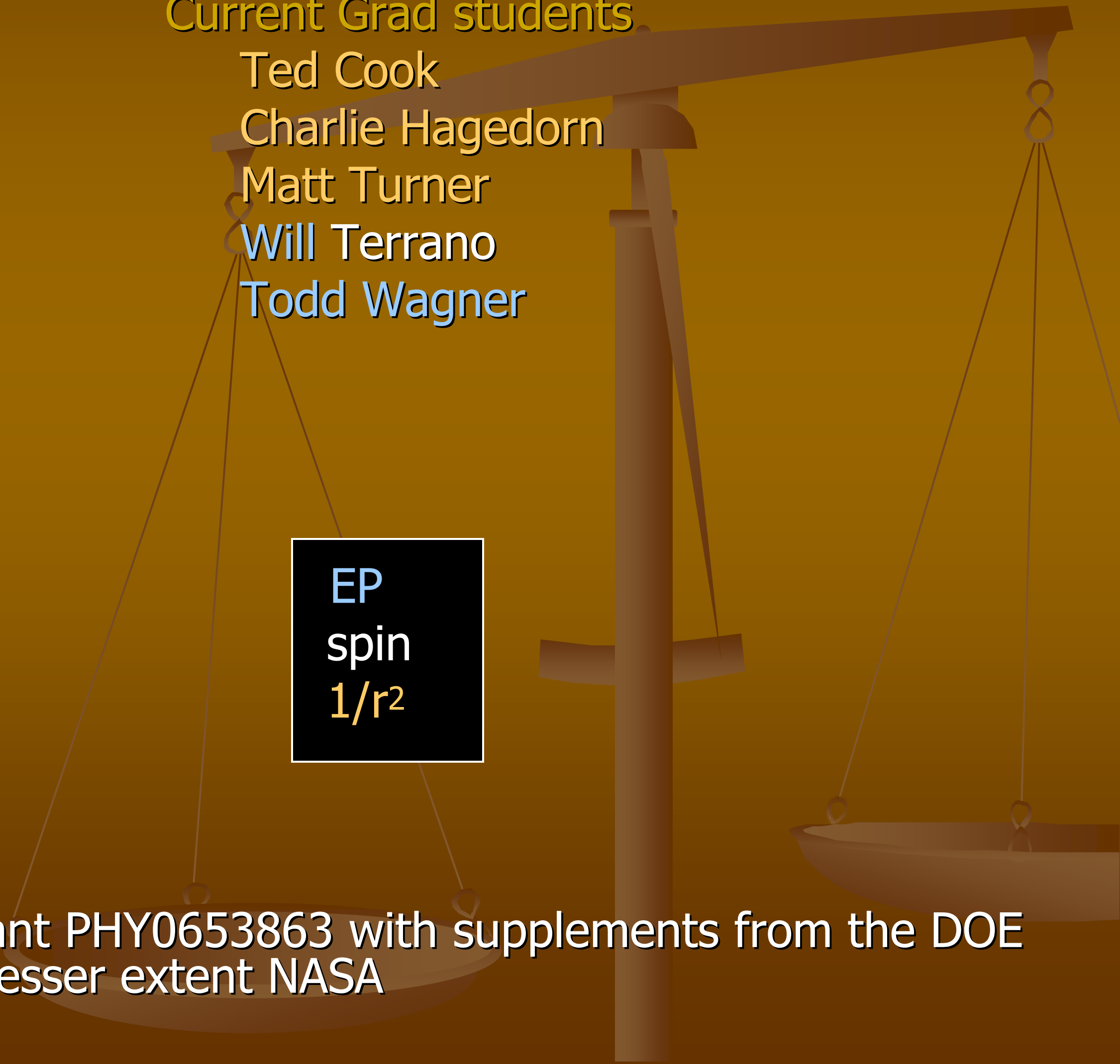
the Eöt-Wash® group in experimental gravitation

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

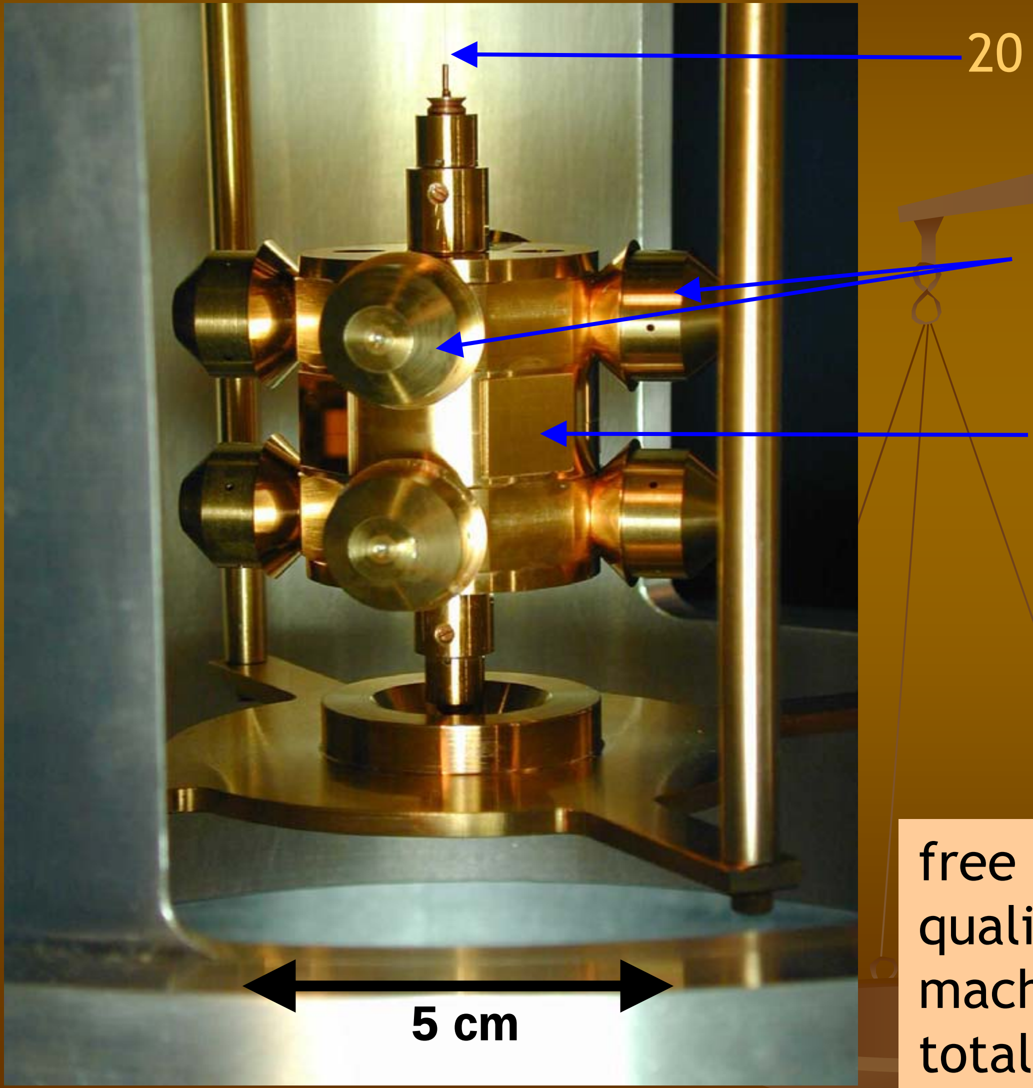


EP
spin
$1/r^2$

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.

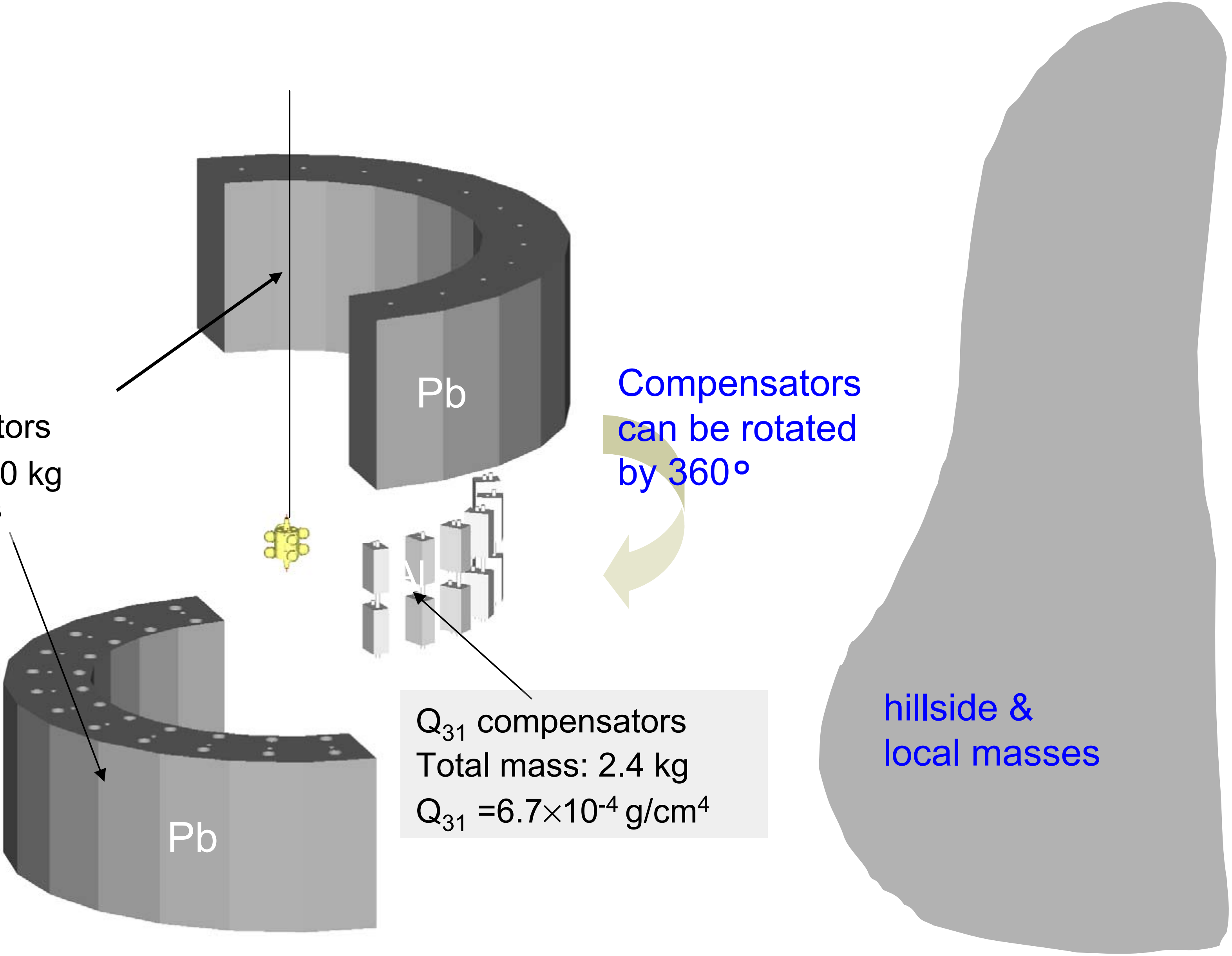
free osc freq:	1.261 mHz
quality factor:	4000
machining tolerance:	5 μm
total mass :	70 g

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



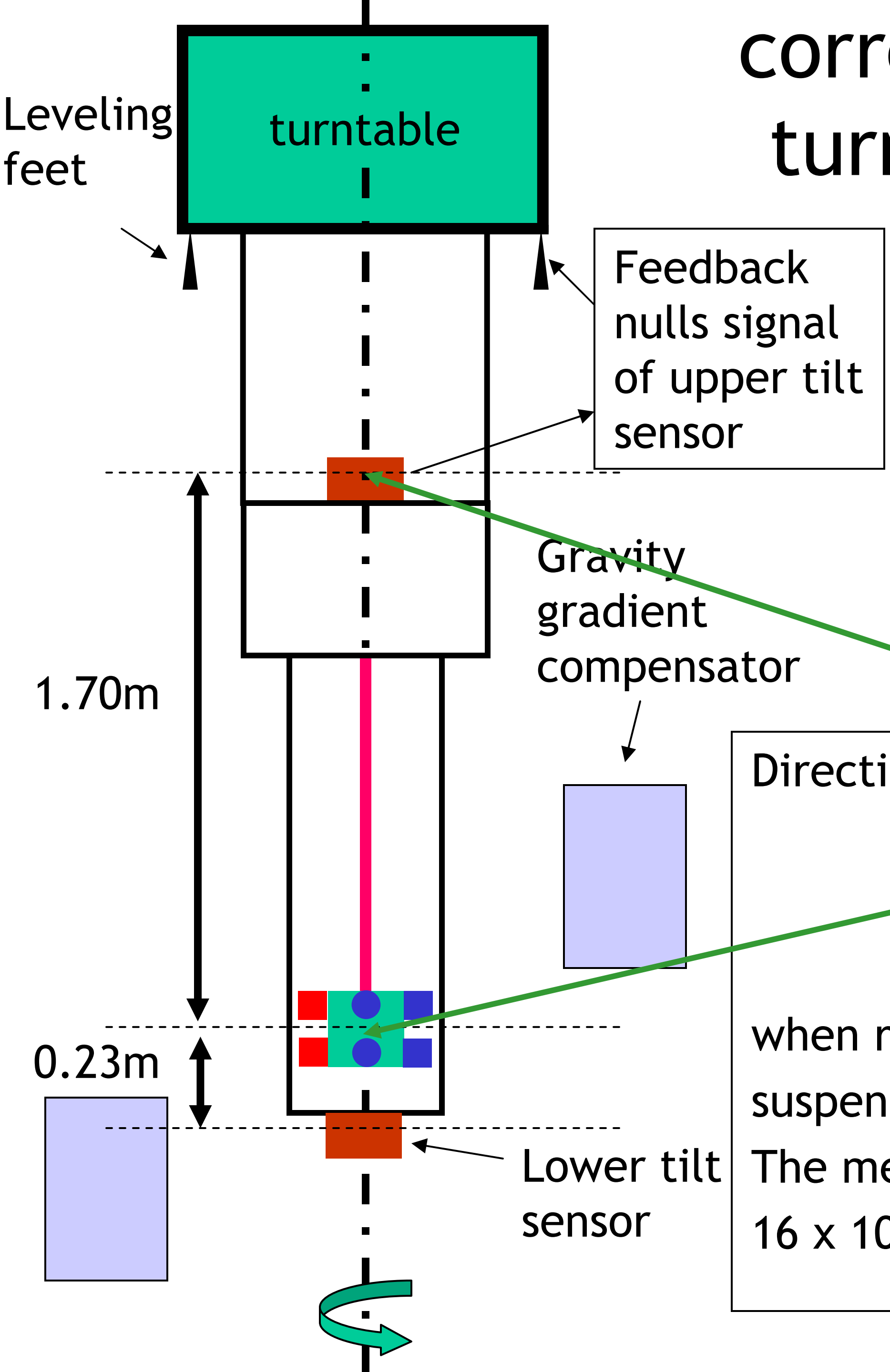
Q_{21} compensators
Total mass: 880 kg
Q_{21}= 1.8 g/cm^3

Compensators can be rotated by 360°

Q_{31} compensators
Total mass: 2.4 kg
Q_{31} =6.7×10^{-4} g/cm^4

hillside &
local masses

correction for tilt of the turntable rotation axis



Leveling feet

turntable

Feedback nulls signal of upper tilt sensor

Gravity gradient compensator

1.70m

0.23m

Lower tilt sensor

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

Direction of down here and here differs by 50 nrad

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

The measured correction for this is

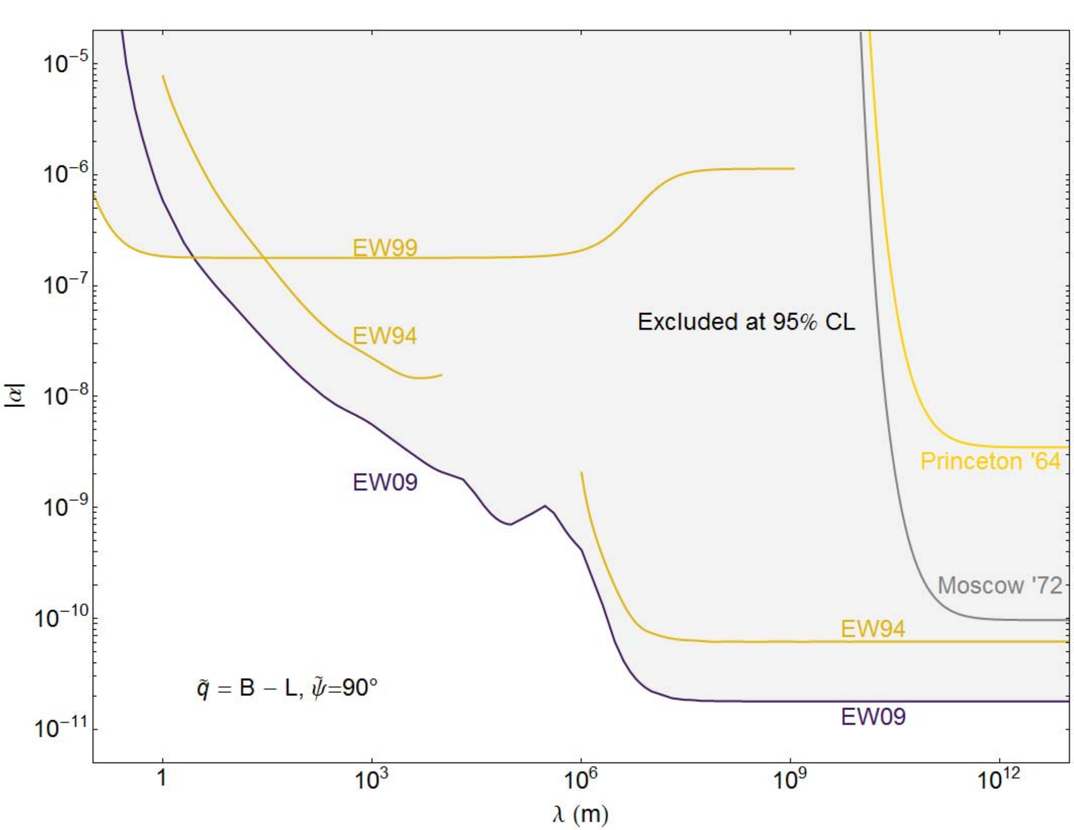
16×10^{-13} cm/s^2

1σ statistical + systematic uncertainties from the EP experiment with Be and Al test bodies; Be and Ti data are similar

Source	Δa (cm/s^2)	$\Delta a/a_{source}$
Earth	$(-1.2 \pm 2.2) \times 10^{-13}$	$(-0.7 \pm 1.3) \times 10^{-13}$
Sun	$(-3.1 \pm 2.4)\times10^{-13}$	$(-5.2 \pm 4.0)\times10^{-13}$
Milky Way	$(-1.2 \pm 2.6)\times10^{-13}$	$(-6.5 \pm 8.6)\times10^{-6}$
CMB	$(-3.0 \pm 2.4)\times10^{-13}$	$(-3.4 \pm 2.7)\times10^{-4}$

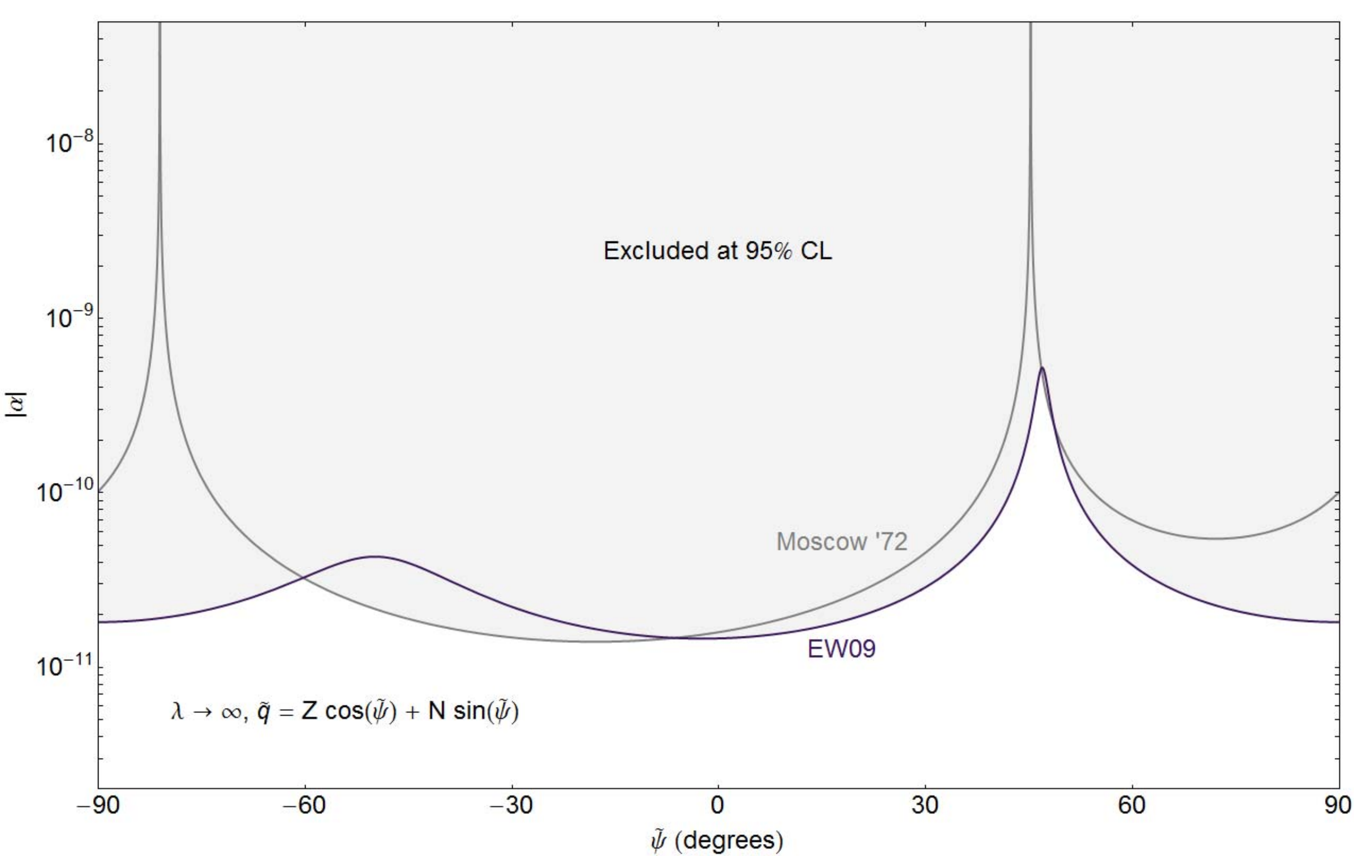
PhD project of Todd Wagner

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



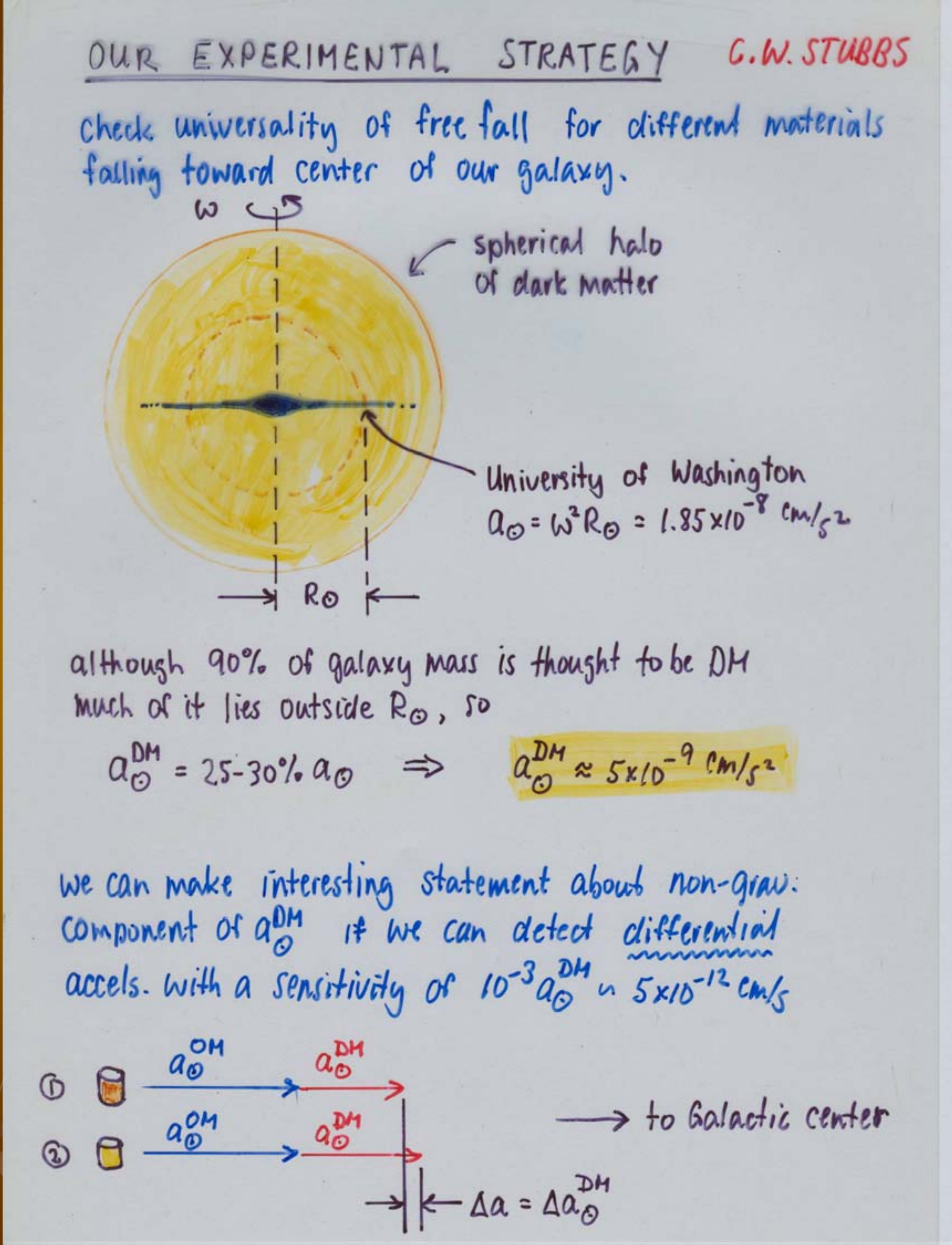
Yukawa attractor integral based on:	
0.5m<λ<5m	lab building and its major contents
1m< λ<50km	topography
5km< λ<1000km	USGS subsurface density model
1000km< λ<10000km	PREM earth model

95% confidence level constraints on an infinite-range interaction as a function of its presumed charge



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?



OUR EXPERIMENTAL STRATEGY

C.W. STUBBS

Check universality of free fall for different materials falling toward center of our galaxy.

University of Washington

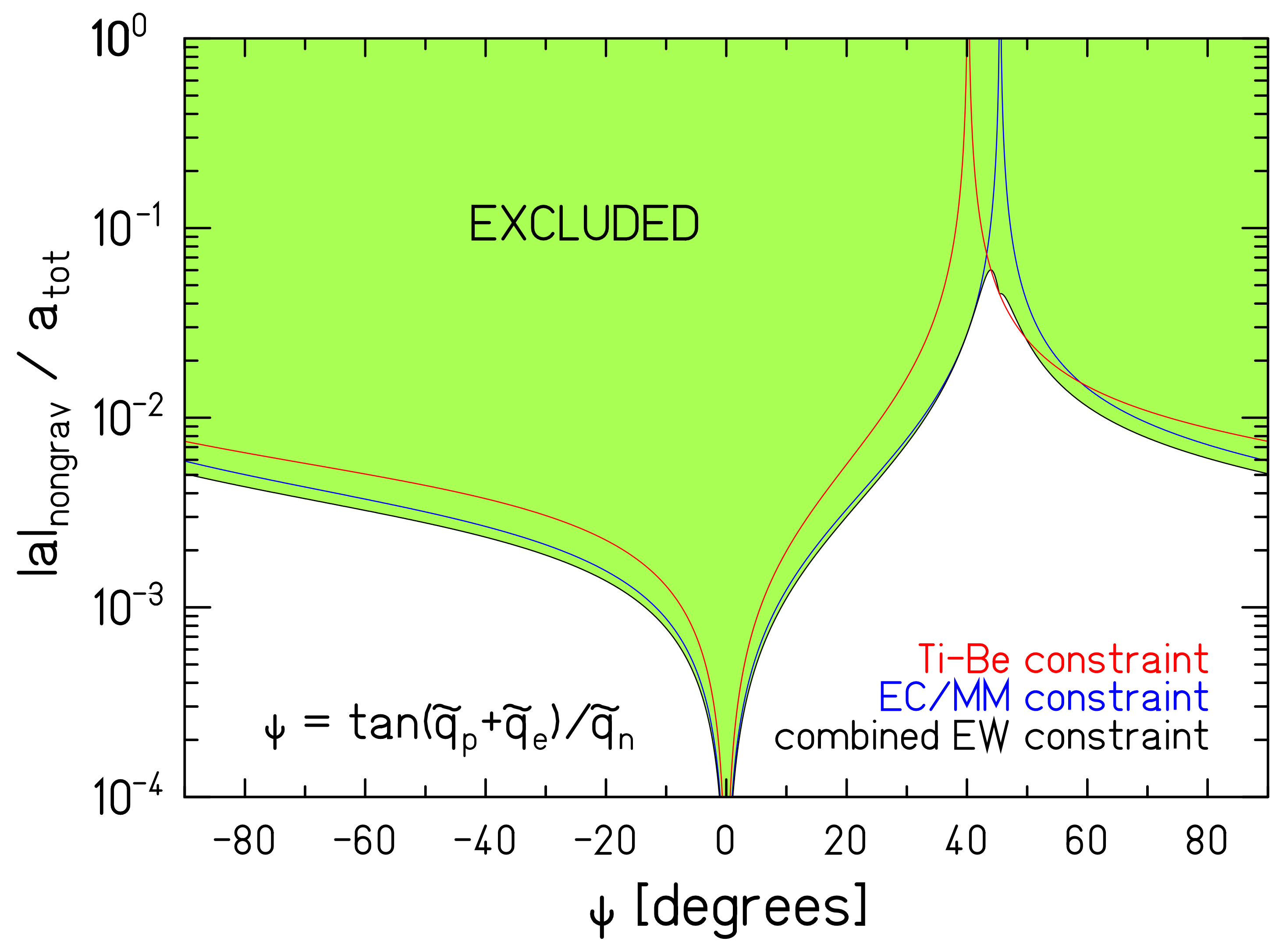
$a_\odot = \omega^2 R_\odot = 1.85 \times 10^{-8}\ \mathrm{cm/s^2}$

although 90% of galaxy mass is thought to be DM much of it lies outside $R_\odot$, so

$$a_\odot^{DM} = 25\text{-}30\%\ a_\odot \Rightarrow a_\odot^{DM} \approx 5 \times 10^{-9}\ \mathrm{cm/s^2}$$

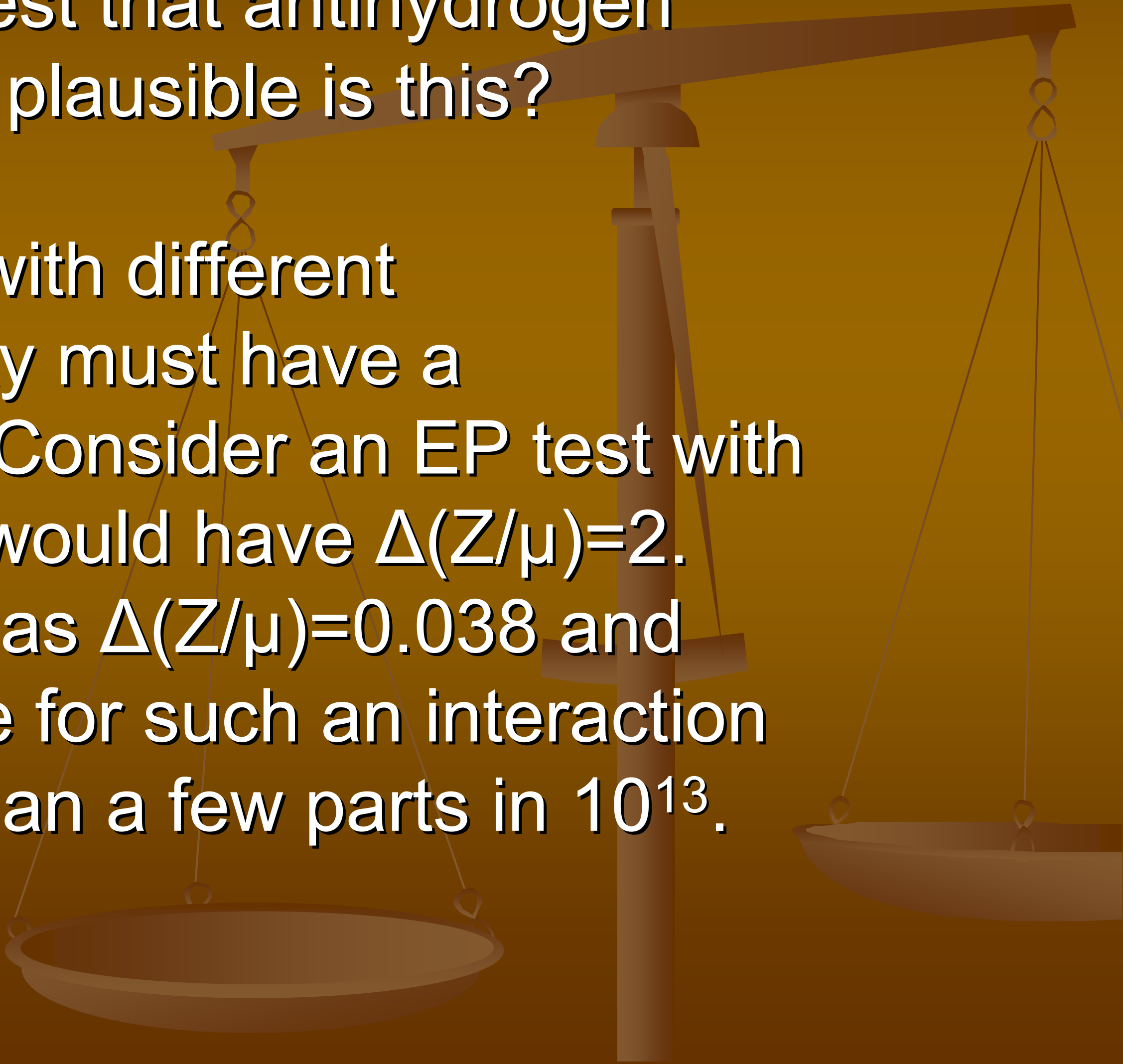
we can make interesting statement about non-grav. component of $a_\odot^{DM}$ if we can detect differential accels. with a sensitivity of $10^{-3} a_\odot^{DM} \sim 5 \times 10^{-12}$ cm/s

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



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

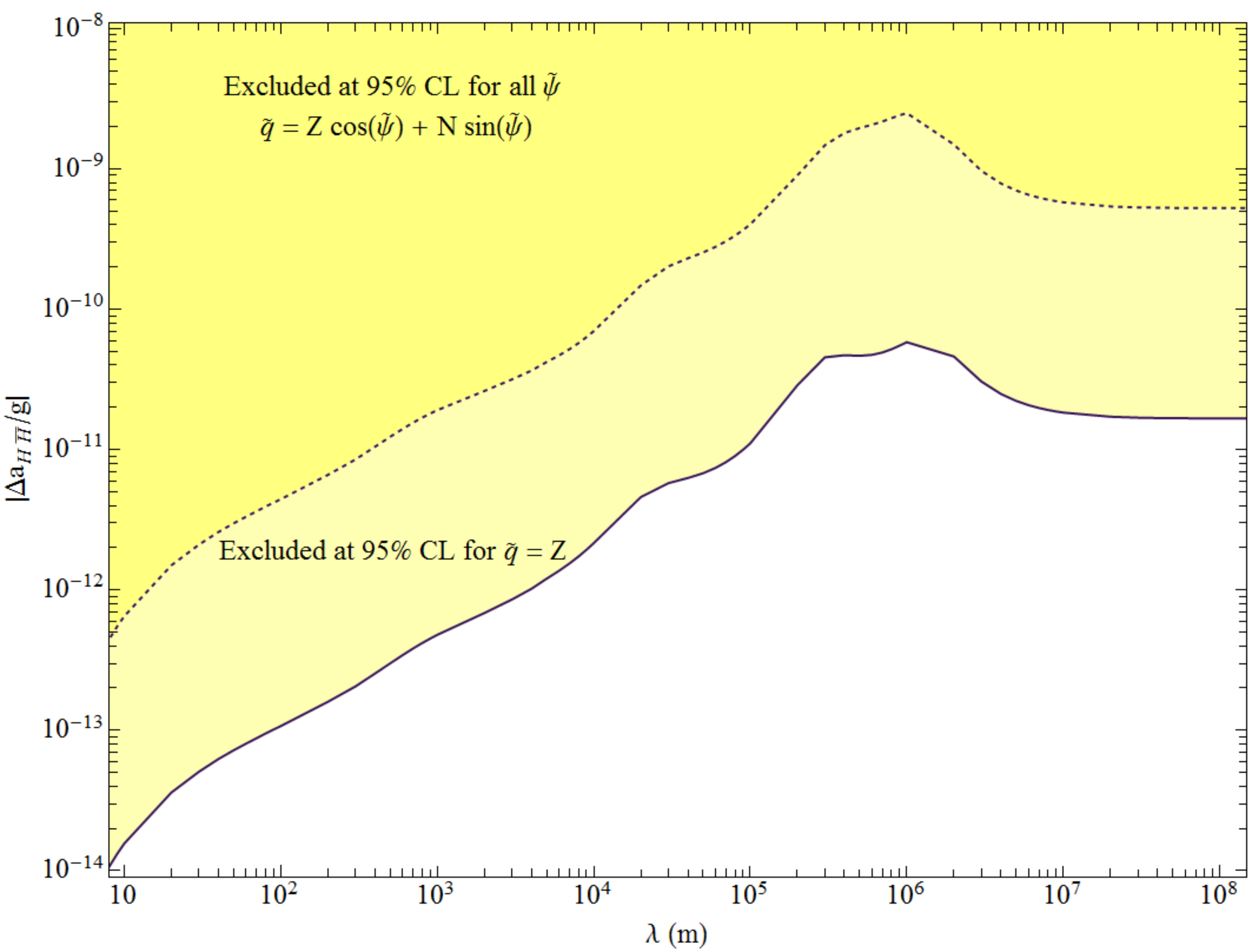
gravitational properties of antimatter



Some people suggest that antihydrogen could fall up! How plausible is this?

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 $\Delta(Z/\mu)=0.038$ and we see no evidence for such an interaction with $\Delta g/g$ greater than a few parts in 10^{13}.

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

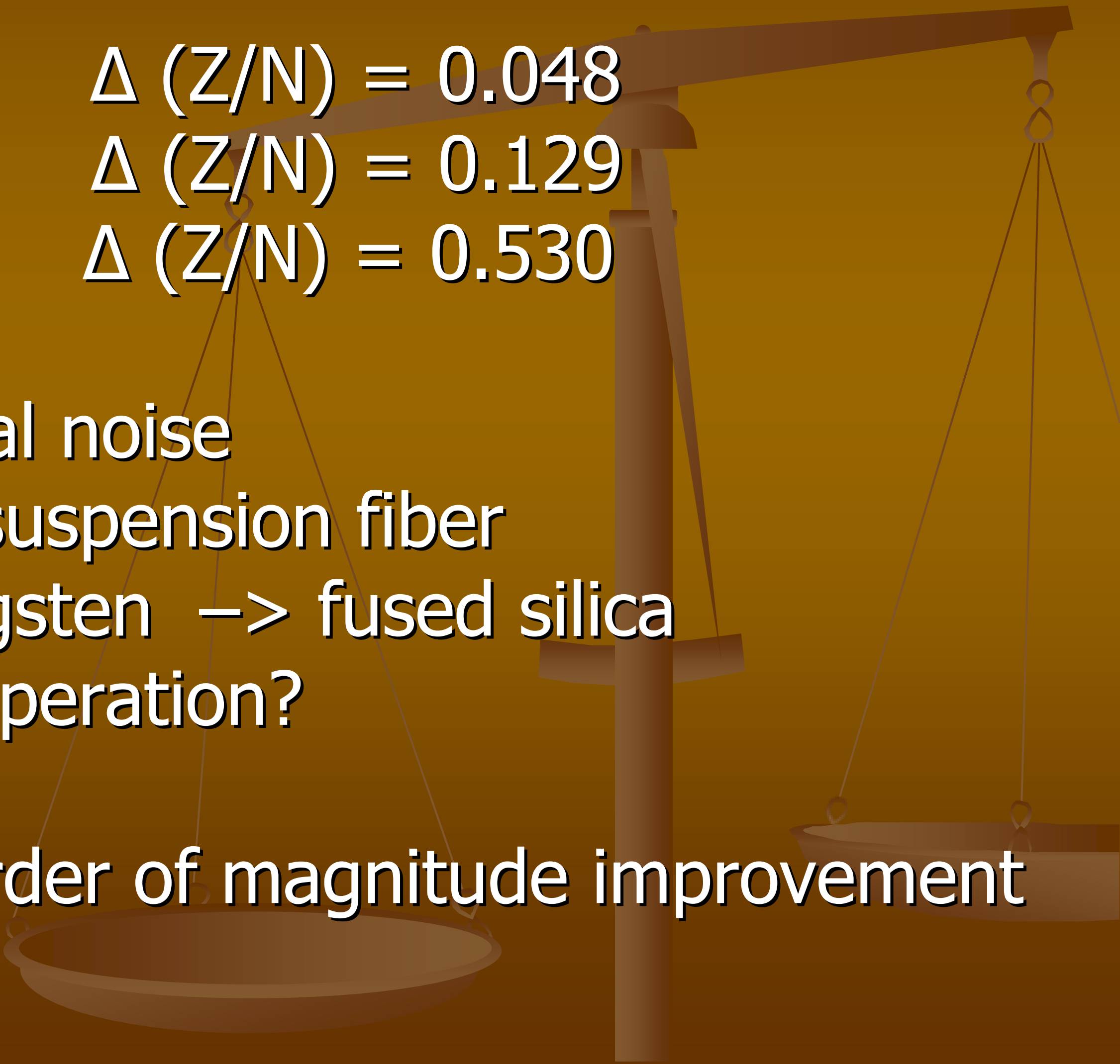


an amusing number

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

Prospects for higher EP sensitivity



- make test bodies more different

Ti – Be $\Delta\,(Z/N) = 0.048$
Al – Be $\Delta\,(Z/N) = 0.129$
→ CH_2 – Be $\Delta\,(Z/N) = 0.530$

- reduce thermal noise
  lower loss suspension fiber
  tungsten –> fused silica
  cryogenic operation?

- should give order of magnitude improvement

Planned atom interferometry Equivalence Principle test by the Kasevich group at Stanford

Co-falling ^{85}Rb and ^{87}Rb ensembles

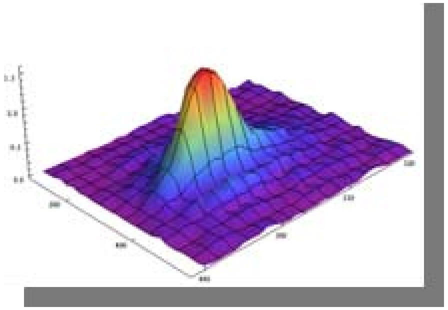
Evaporatively cool to < 1 μK to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

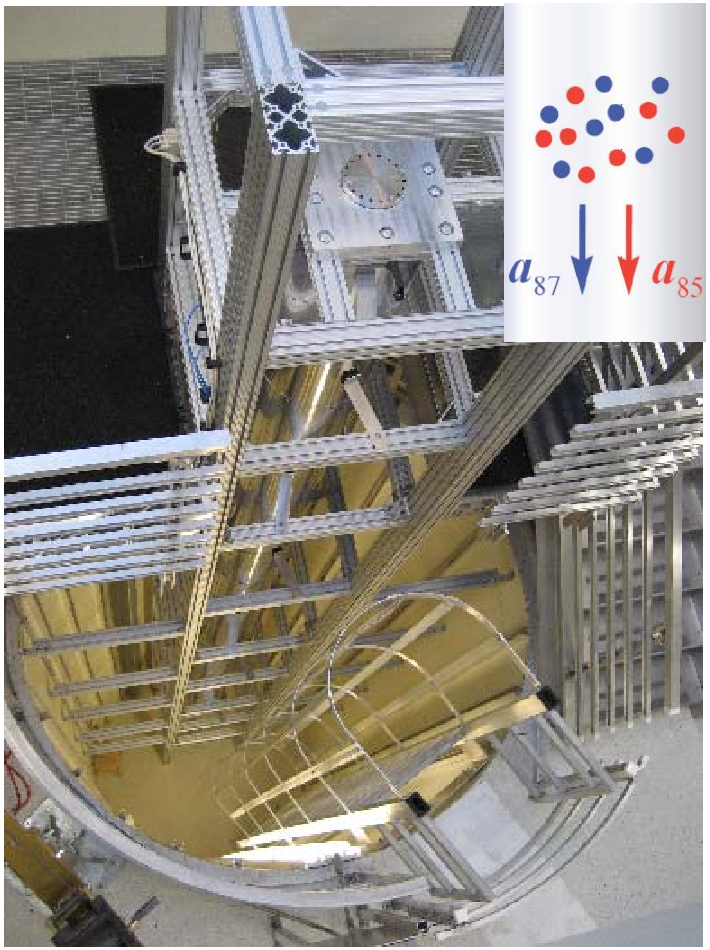
$\delta g \sim 10^{-15}$ g with 1 month data collection

Systematic uncertainty

$\delta g \sim 10^{-16}$ g limited by magnetic field inhomogeneities and gravity anomalies.

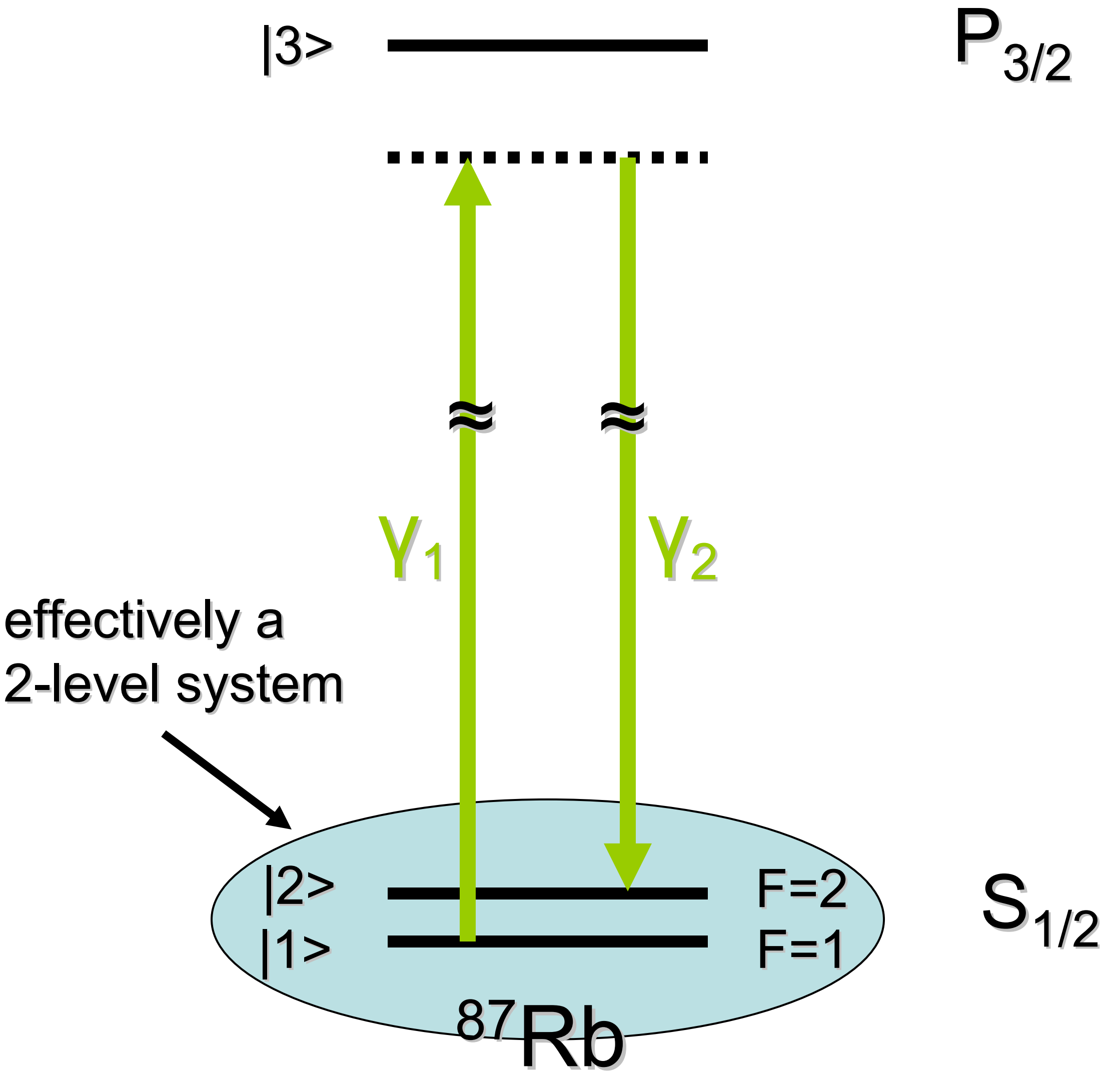


Evaporatively cooled atom source



10 m drop tower

Kasevich-Chu atom interferometer uses stimulated Raman transitions

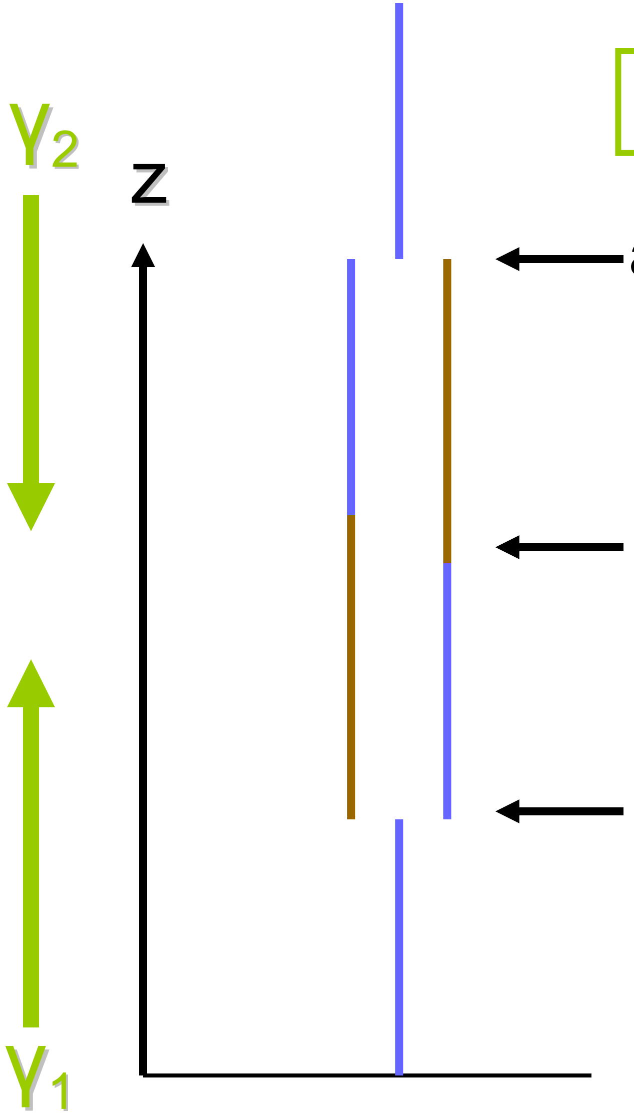


γ_1 is absorbed
γ_2 is stimulated
so atom gets
a momentum
kick $\hbar(k_1+k_2)$

Principle of Kasevich-Chu atom interferometer

If we neglect gravity phase diff of 2 arms $\Delta\varphi=0$ and all atoms end up in state 1

laser fields γ_1 and γ_2 are pulsed



apply $\pi/2$ pulse at $t=2T$

apply π pulse at $t=T$

apply $\pi/2$ pulse at $t=0$

hyperfine state 1

hyperfine state 2

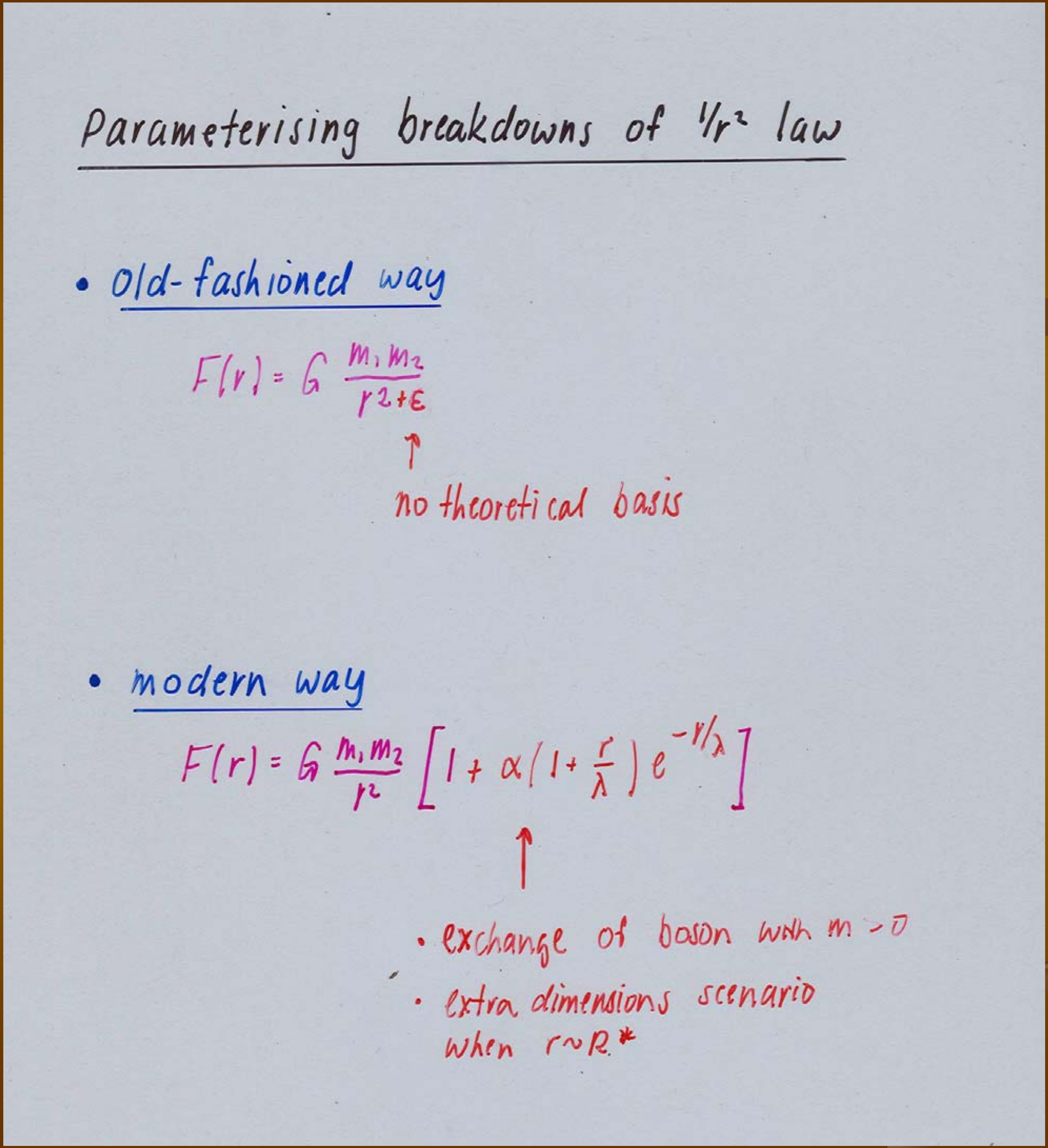
EP => local effects of gravity disappear in freely falling frame so expect $\Delta\varphi = 0$.

In the real world the atoms fall freely but the optical system accelerates upward at g so the atoms interact with laser fields at different vertical positions.
This gives a phase difference

$$\Delta\varphi = g\, k_{eff}\, T^2 \qquad k_{eff} = k_{\gamma 1} + k_{\gamma 2}$$

A 1 m high fountain has $\Delta\varphi \approx 10^8$ radians making the atom interferometer an extraordinarily sensitive absolute accelerometer.

Gravity gradients in Galileo experiments are a smaller problem than in Eötvös experiments, because the signal is 1000 times bigger. But one needs to know the gradients along the entire path, rather at just one point.



Parameterising breakdowns of $1/r^2$ law

- Old-fashioned way

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

↑

no theoretical basis

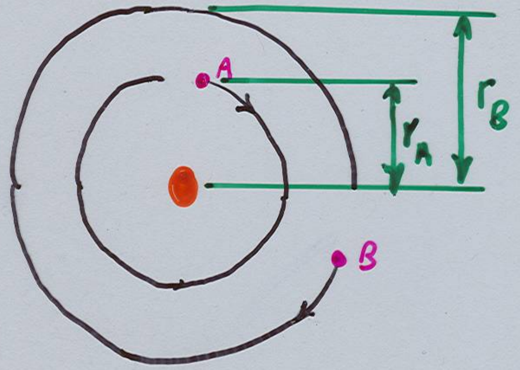
- modern way

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

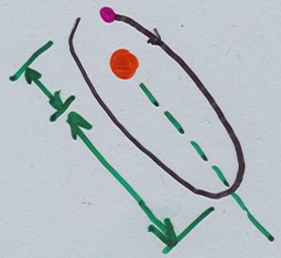
↑

- 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



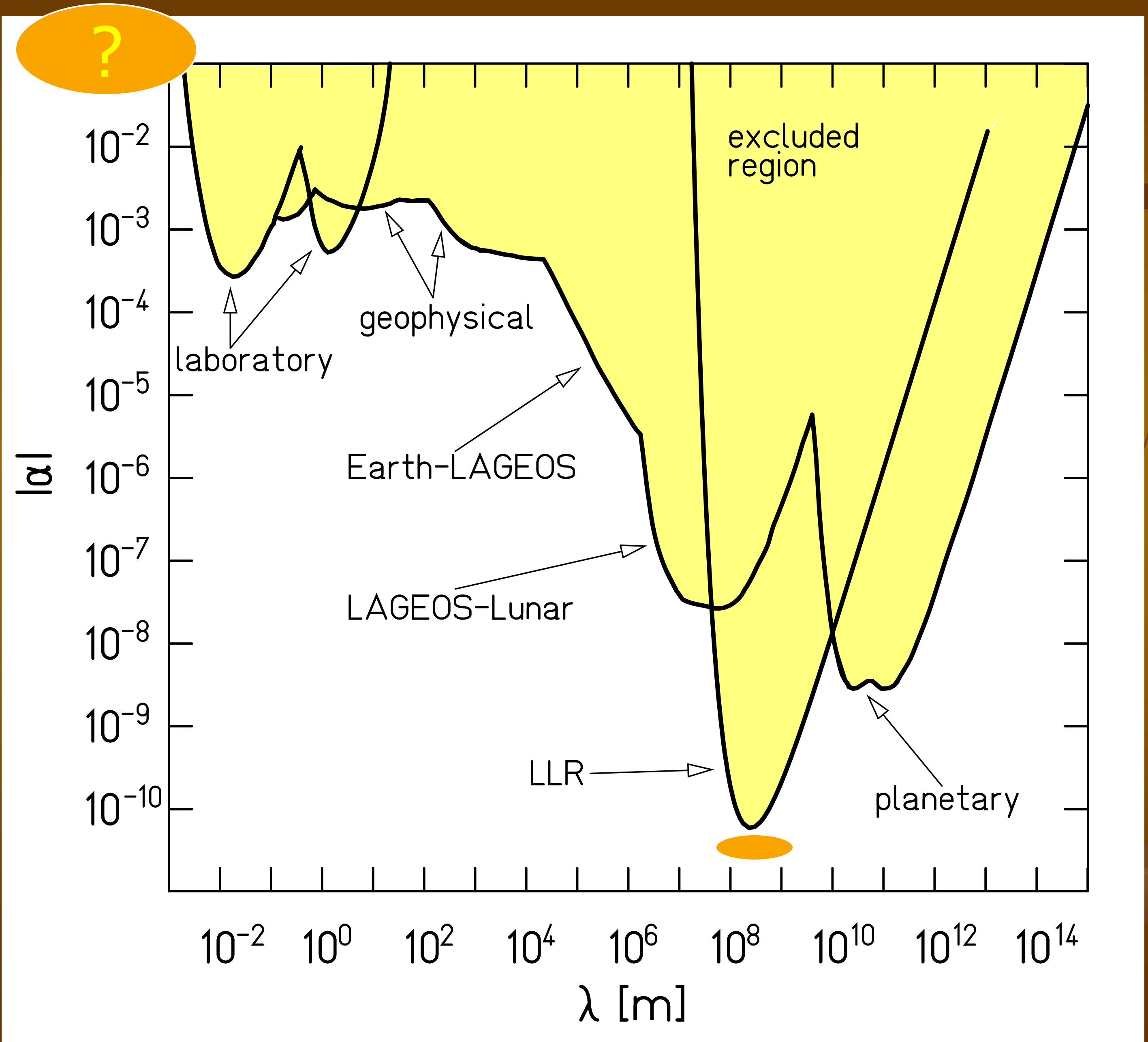
$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \; ?$$



precession of perigee ?

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

95% confidence ISL limits as of 2000



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

- untested regime
- probes the dark-energy length scale

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

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

- searches for proposed new phenomena

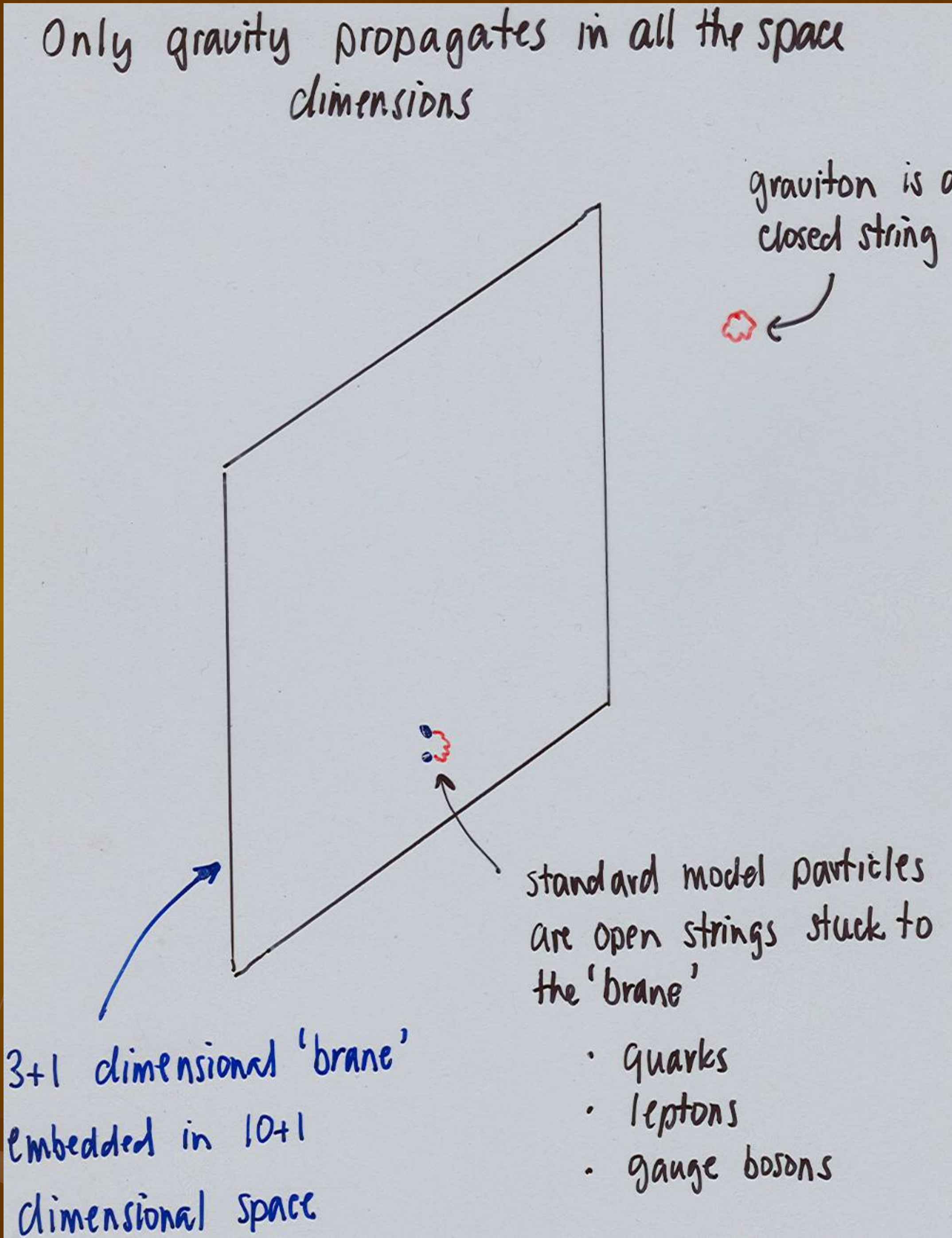
→ large extra dimensions

chameleons

“fat gravitons”

Arkani-Hamed, Dimopoulos and Dvali’s brane-world explanation for the extreme weakness of gravity:

gravity isn’t actually so weak, we simply think it is because most of its strength has leaked off into the extra dimensions. This could lower the Planck mass M* to TeV scale



Gauss’s Law and extra dimensions

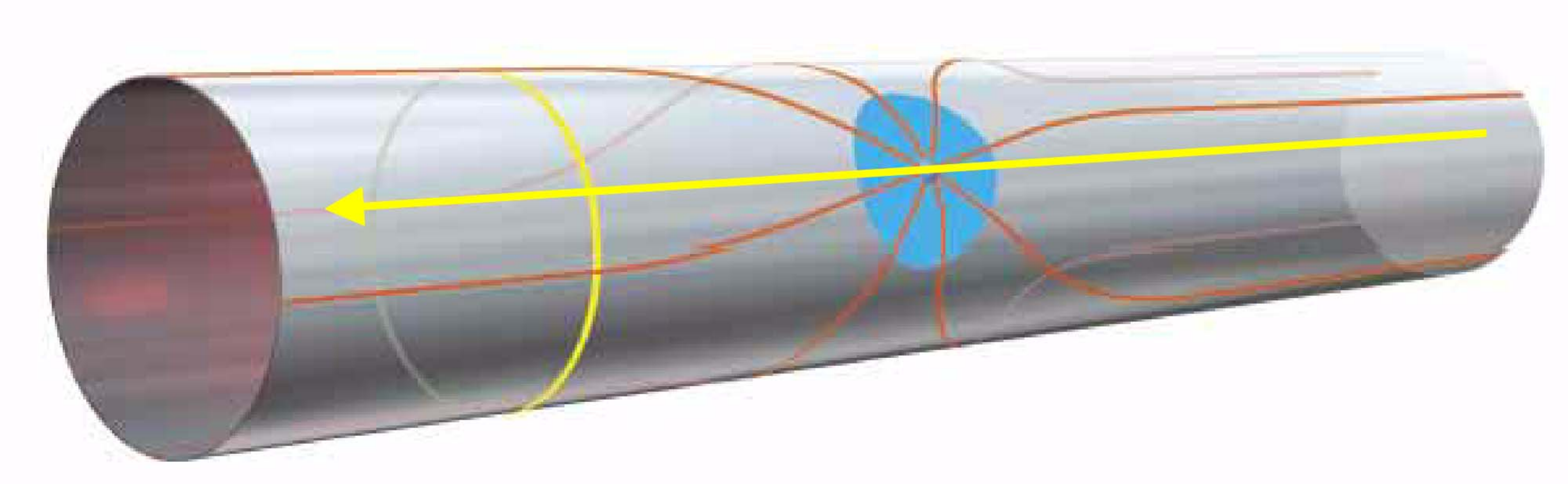
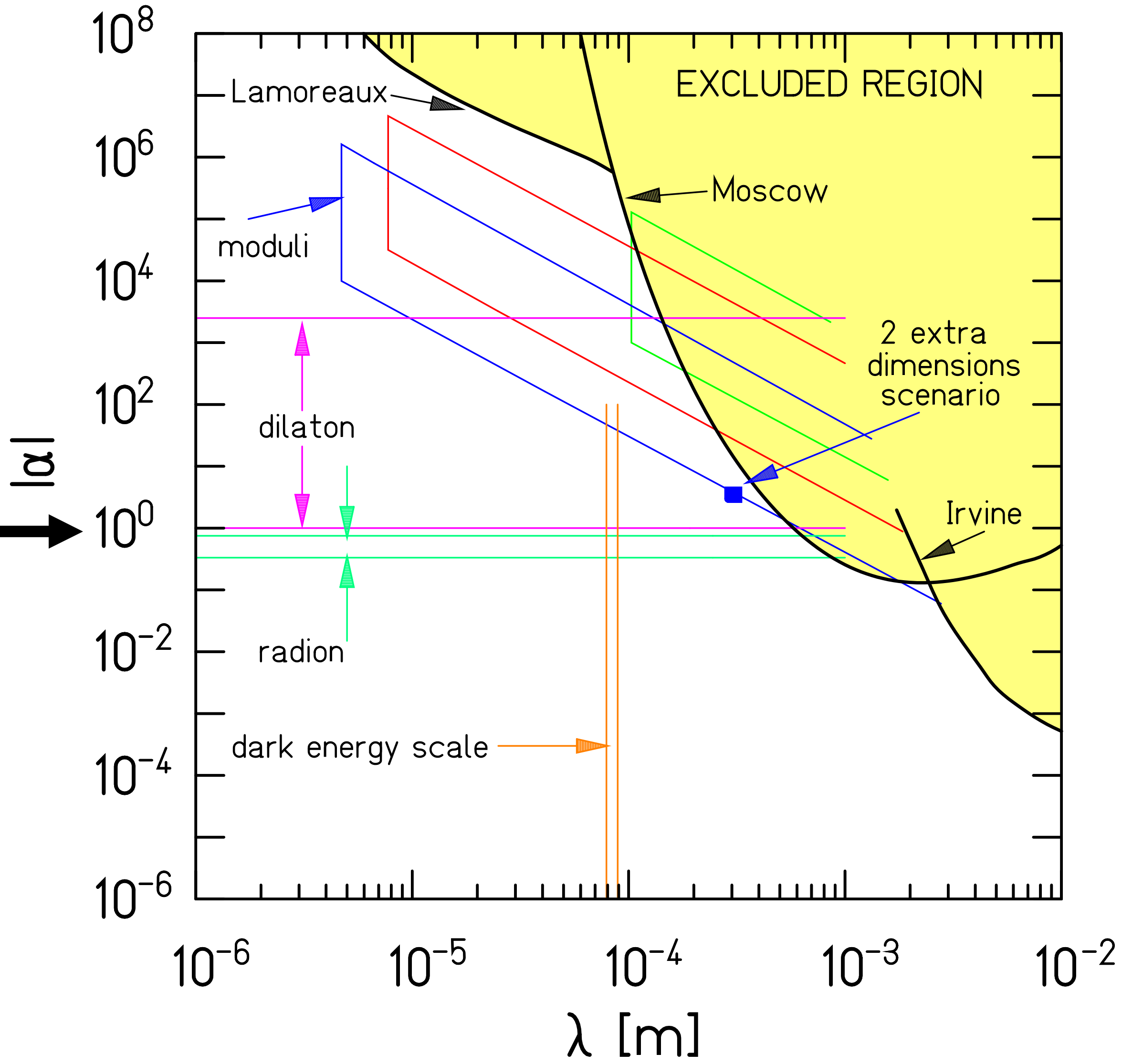


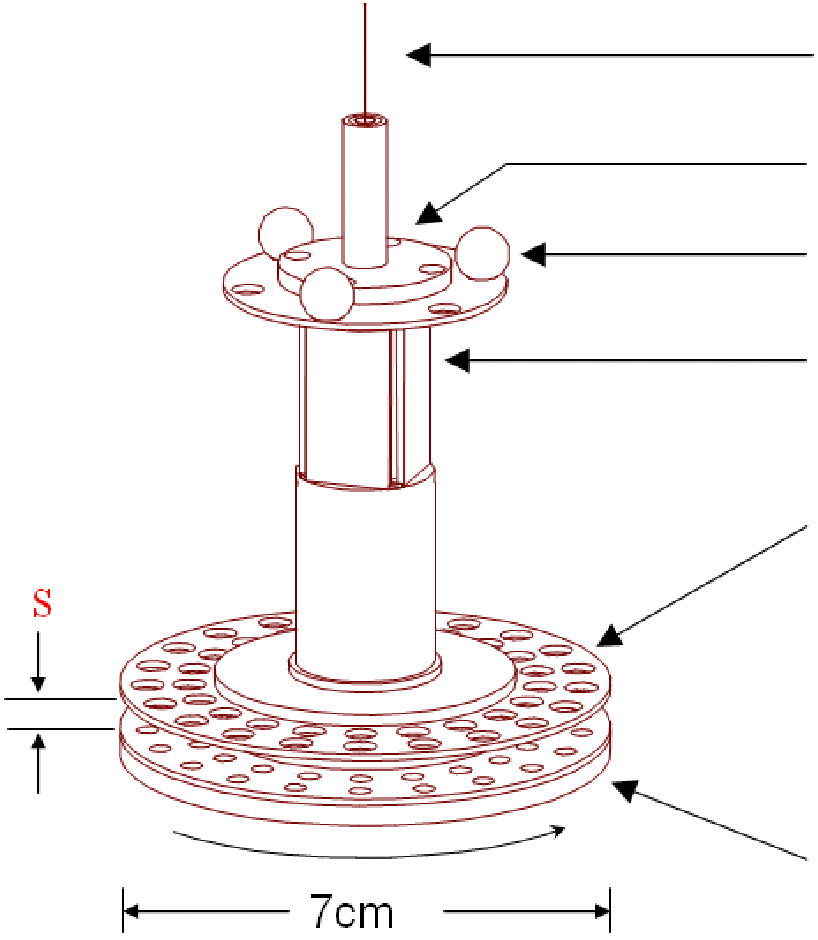
illustration from Savas Dimopoulos

95% confidence limits as of 2000

strength of gravity →



the 42-hole Eöt-Wash ISL pendulum



tungsten fiber, 20μm diameter, 80cm length

leveling mechanism

3 aluminum calibration spheres

4 mirrors for tracking angle of deflection

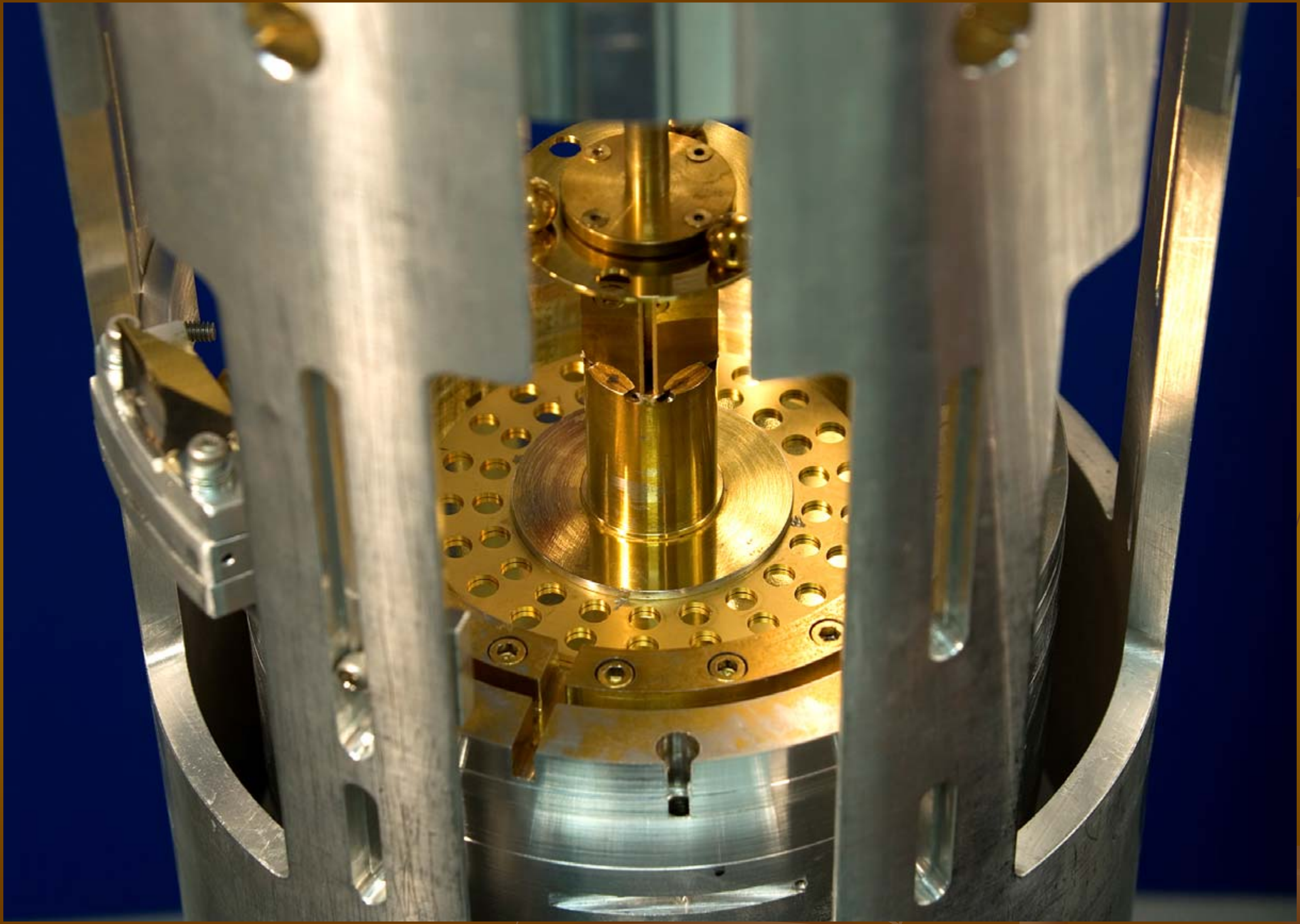
detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry

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)

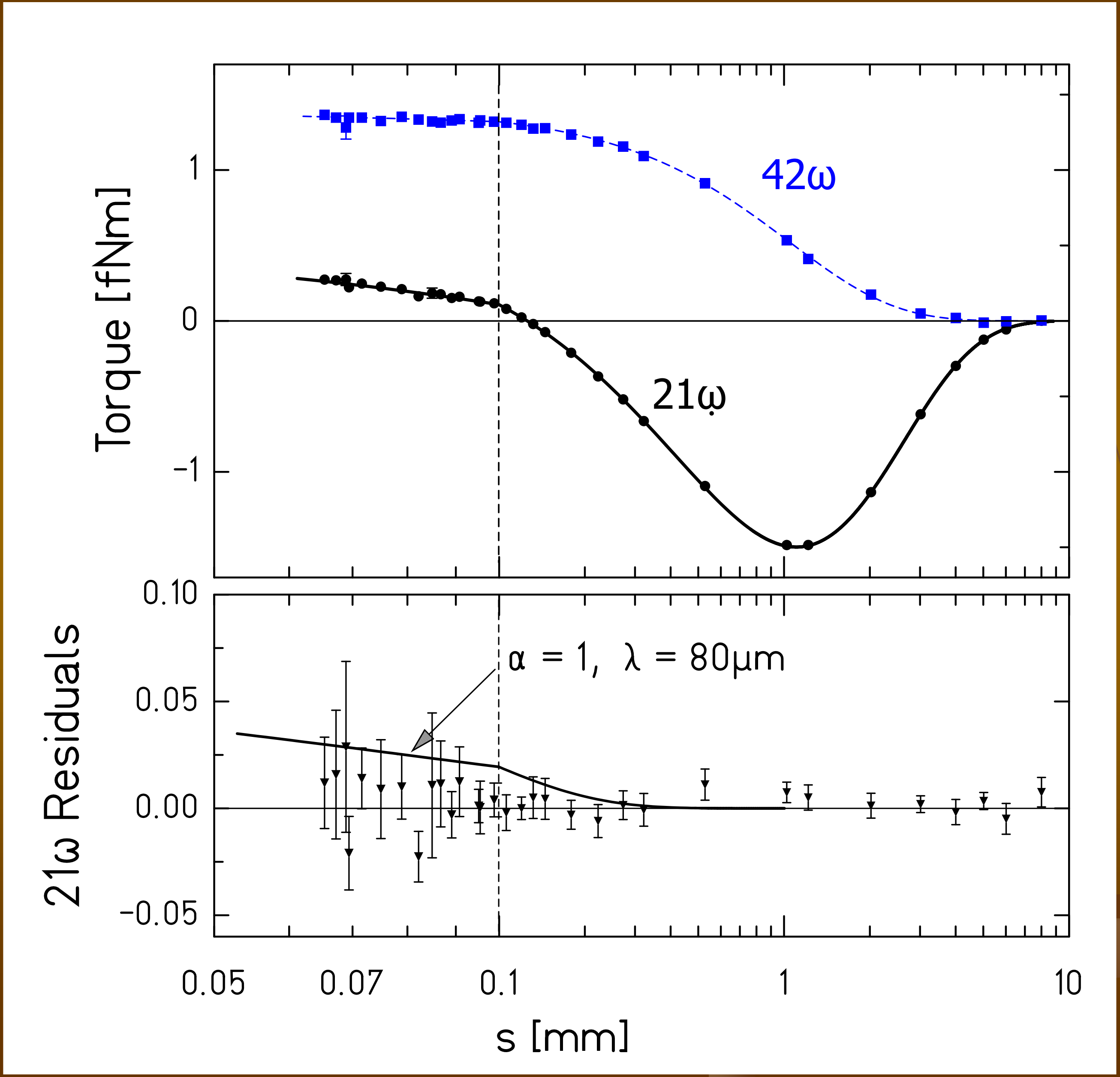
The 42-hole ISL pendulum



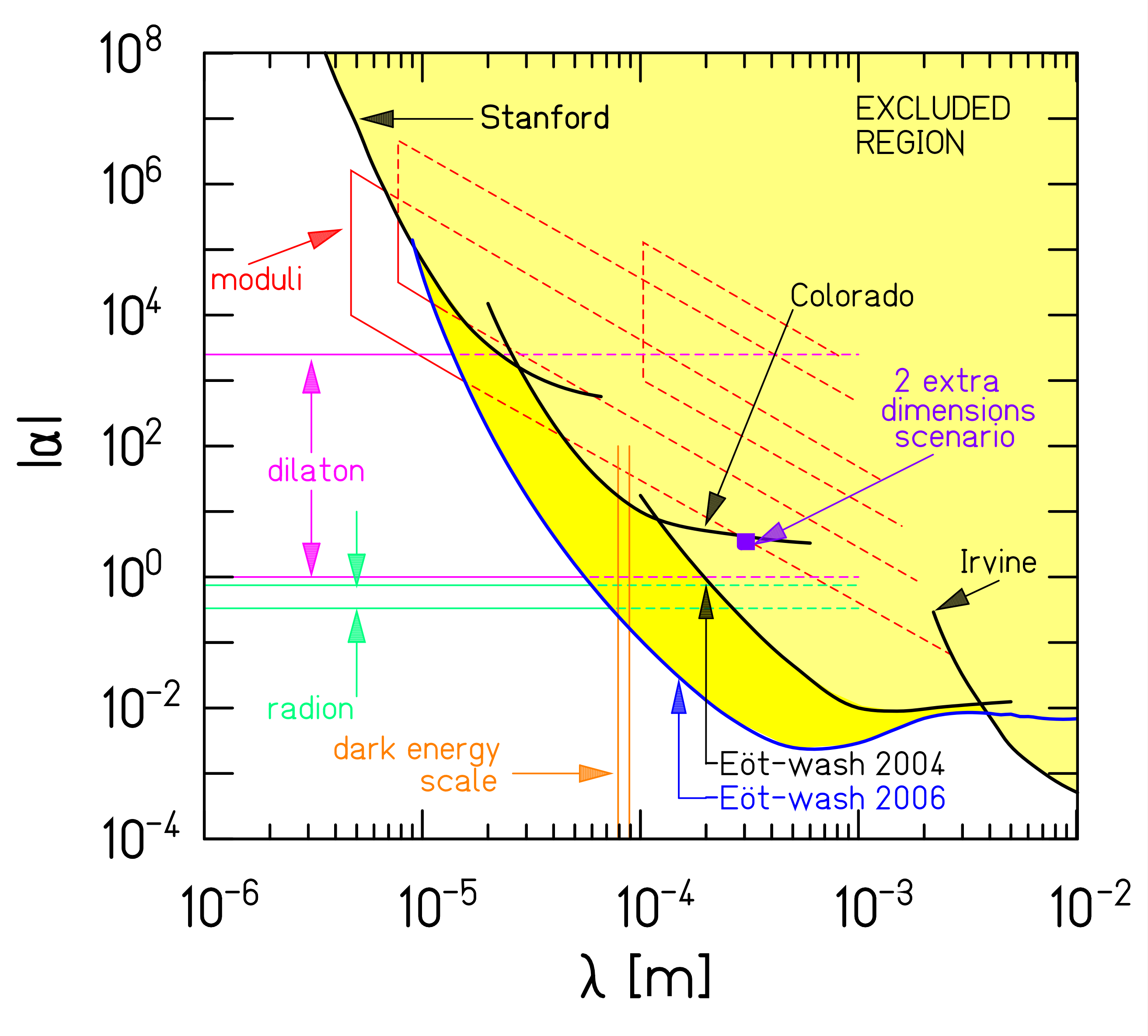
Mary Levin photo

data from 42-hole Experiment II

we did 3 separate experiments, making small changes to the apparatus—attractor thicknes, pendulum coating, etc.



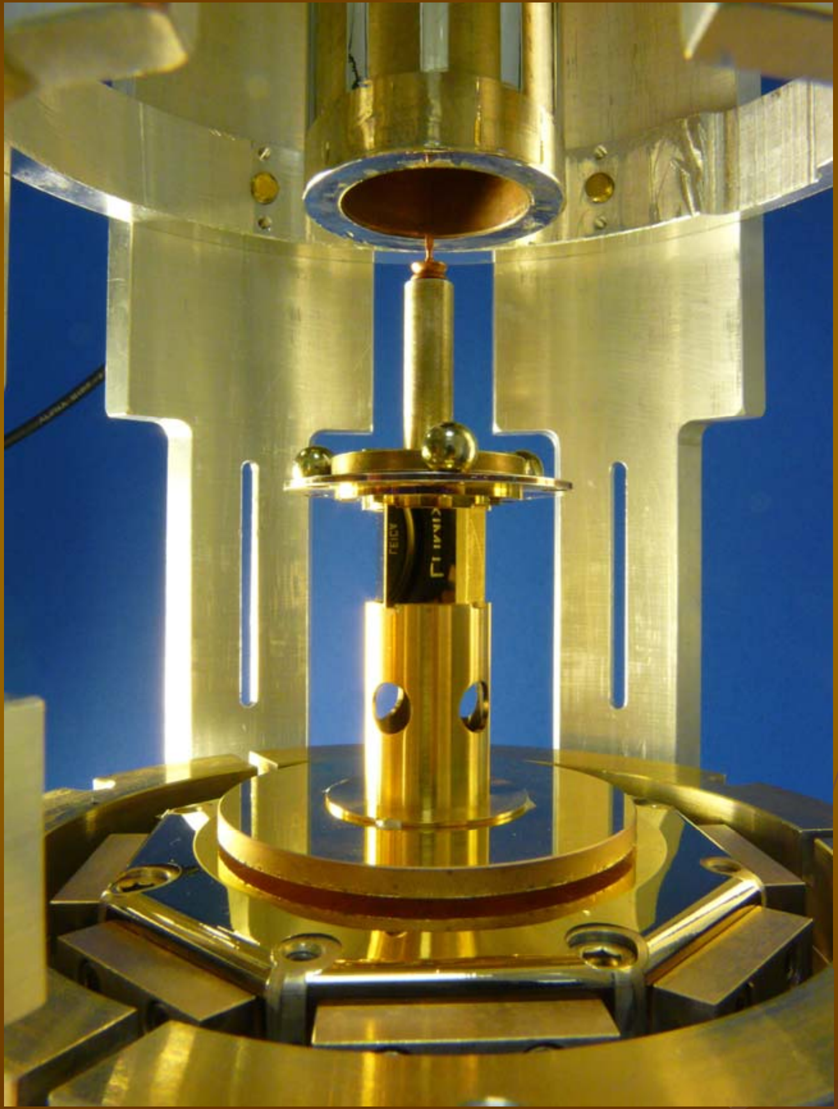
95% confidence upper limits on ISL violation (uses data from all 3 experiments)



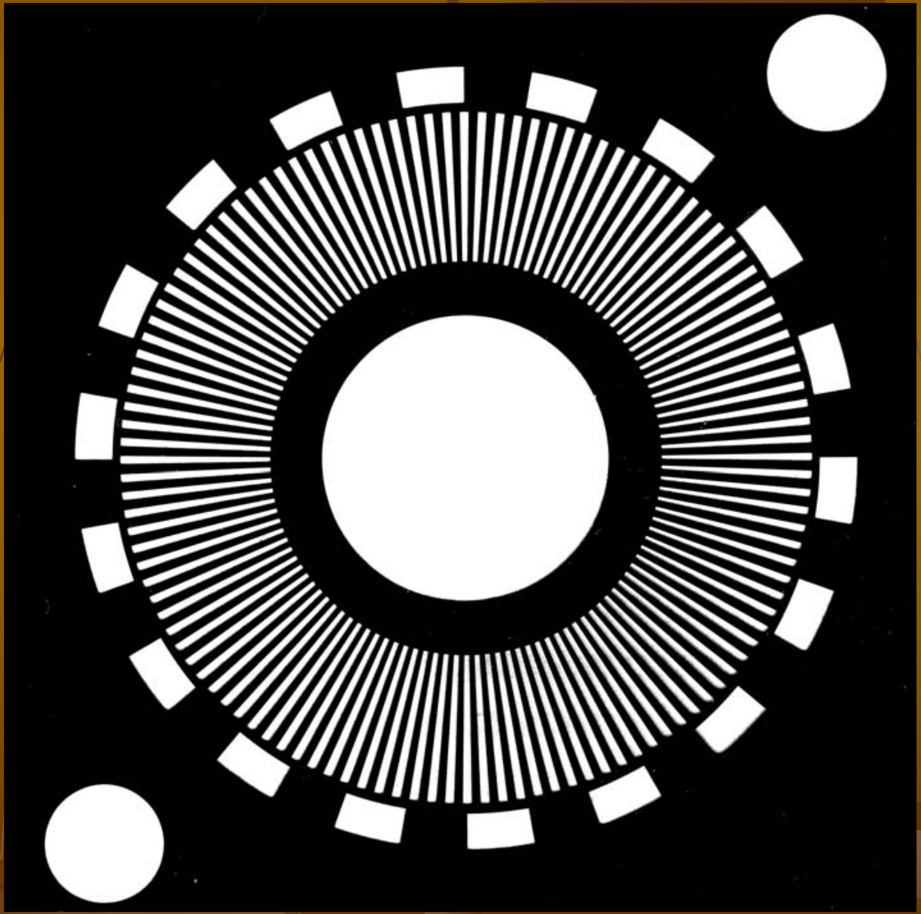
some 2σ implications of the data

- inverse-square law holds down to 56 microns
- largest possible size of an extra dimension is $R = \lambda(\alpha = 8/3)$ = 44 microns (~1/2 the diameter of a hair)
- dilaton must have mass $mc^2 \geqslant 3.5$ meV
- in ADD's 2 equal extra dimensions scenario the unification scale is $M^* \geqslant 3.4$ TeV/c^2

the Fourier-Bessel pendulum

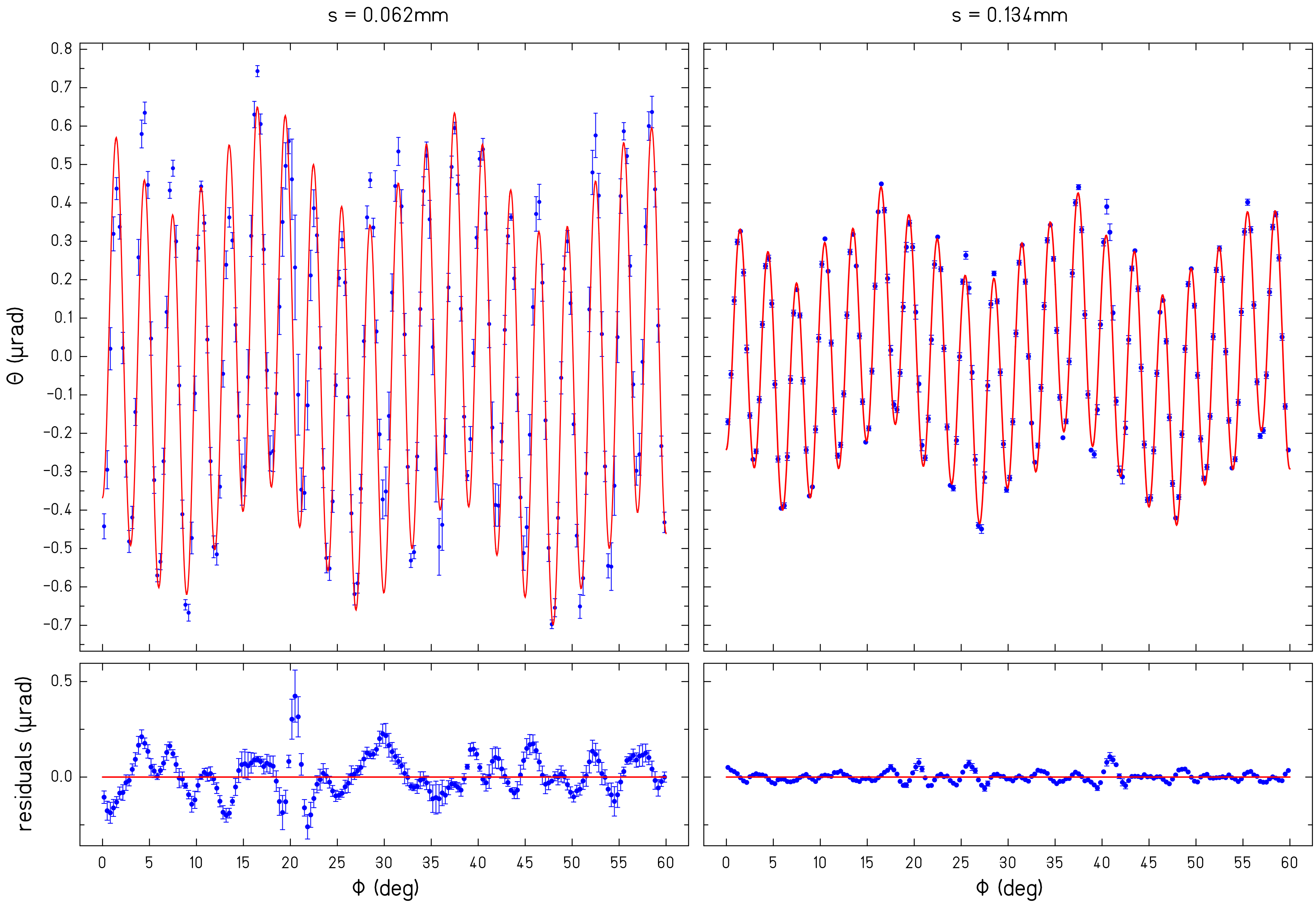


pendulum & attractor are 50μm thick W foils glued to glass plates



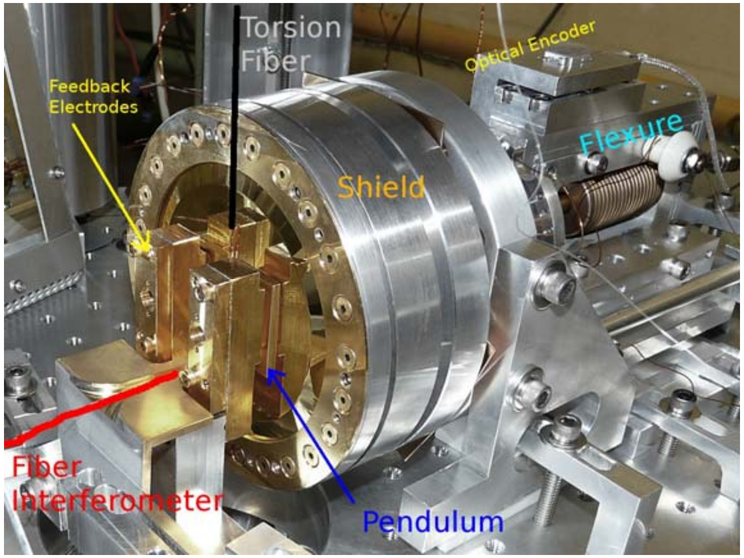
PhD project of Ted Cook

observed Fourier-Bessel signals

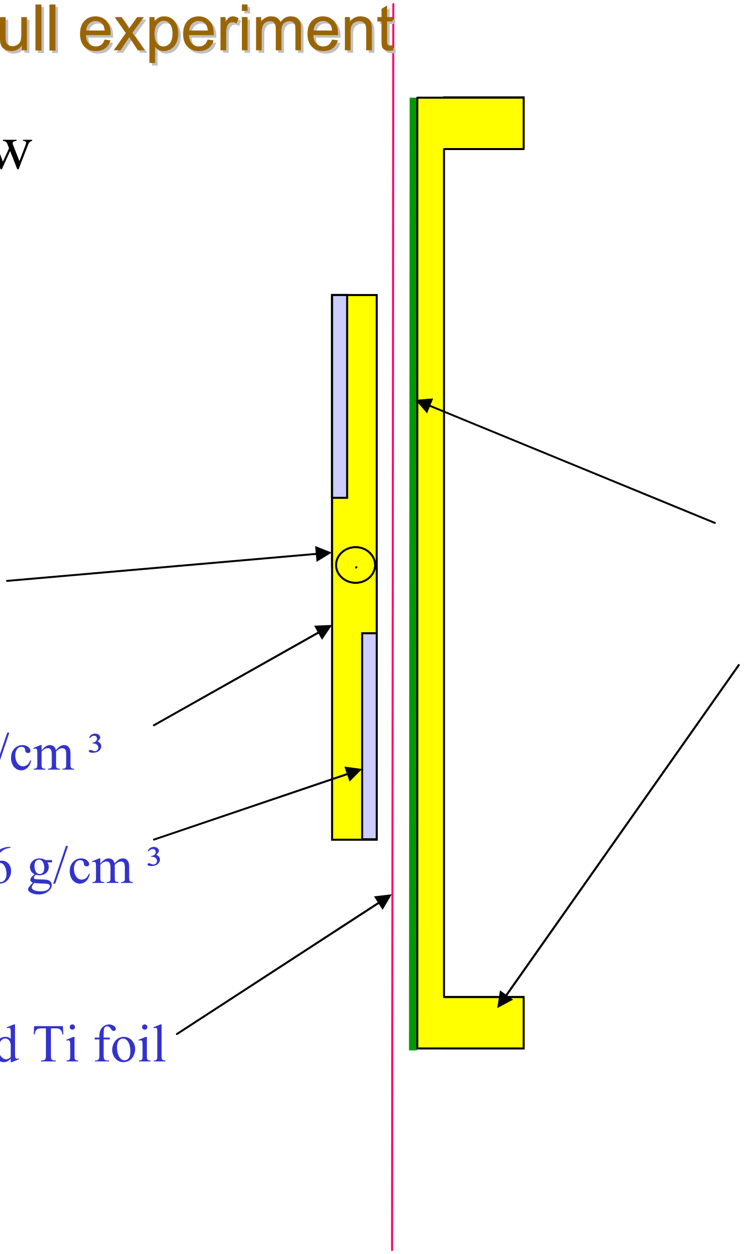


parallel-plate ISL pendulum

a null experiment



top view



torsion pendulum

Ti, ρ= 4.6 g/cm ^{3}

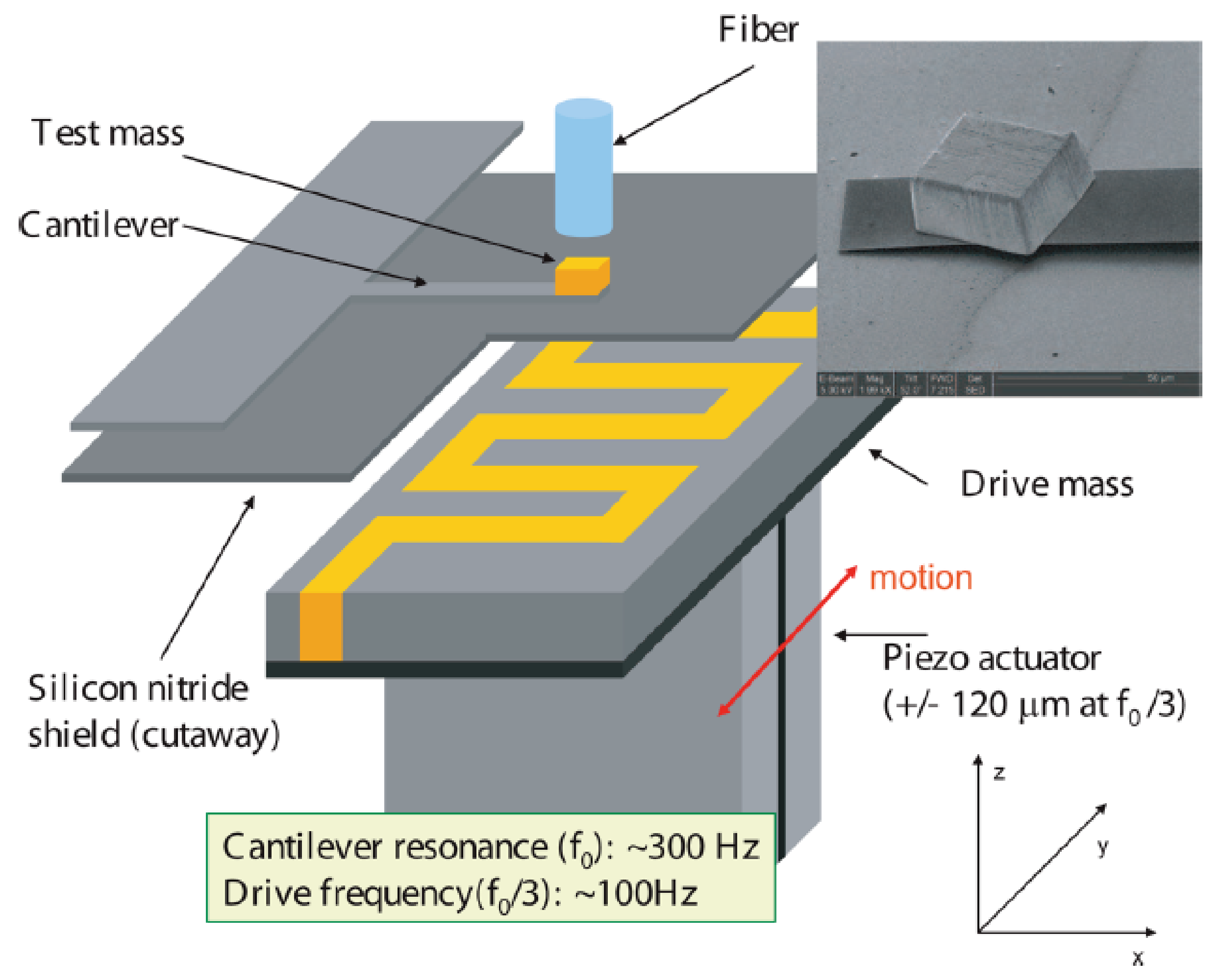
Ta, ρ= 16.6 g/cm ^{3}

stretched Ti foil
4 μm

Thin Pt attractor sheet,
backing made from Ti:
a rim makes the finite
attractor look "infinite":
homogenous gravity field

PhD project
of Charlie Hagedorn

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

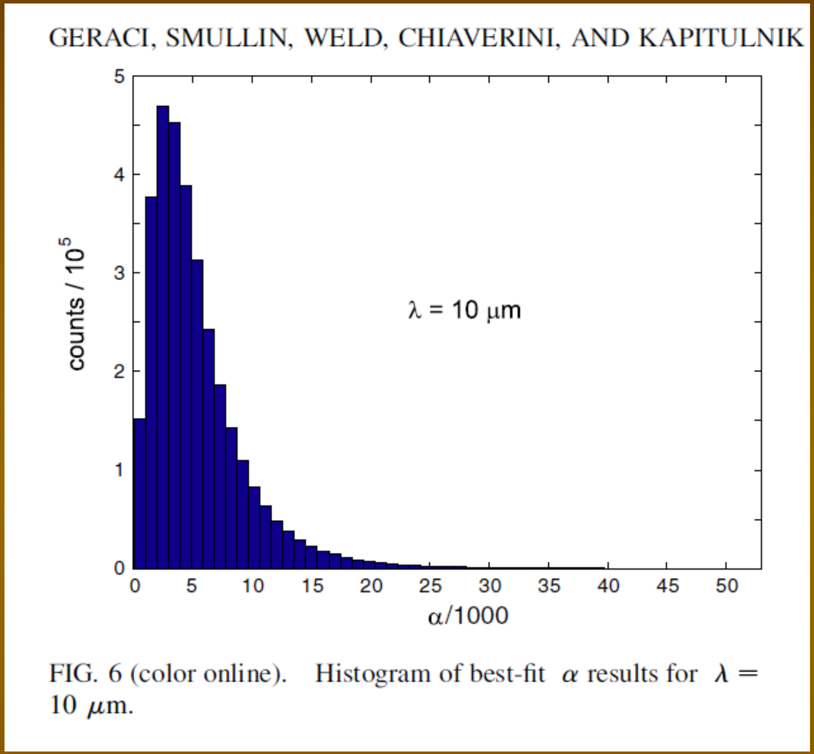


Cantilever has 1.5 μg Au test Mass with Q~10,000 at

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 $\lambda = 10\ \mu\text{m}$.

statistical error dominated by thermal noise in the cantilever

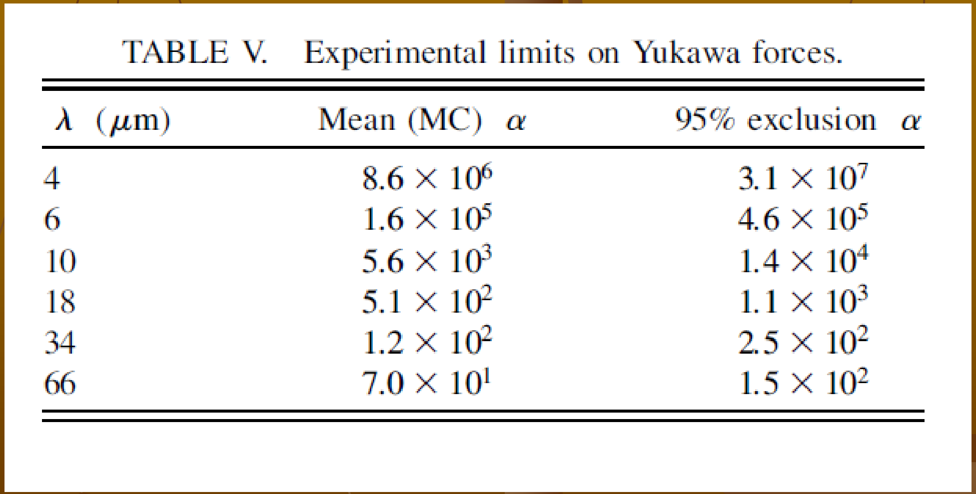


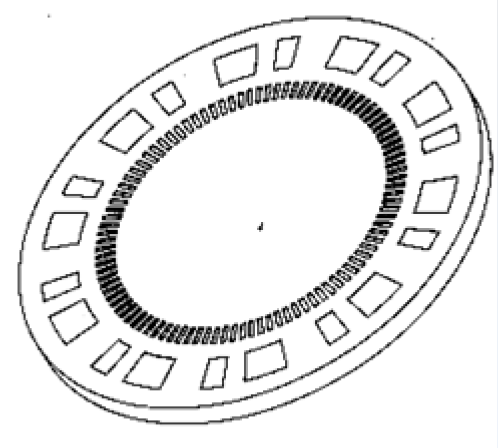
TABLE V. Experimental limits on Yukawa forces.

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

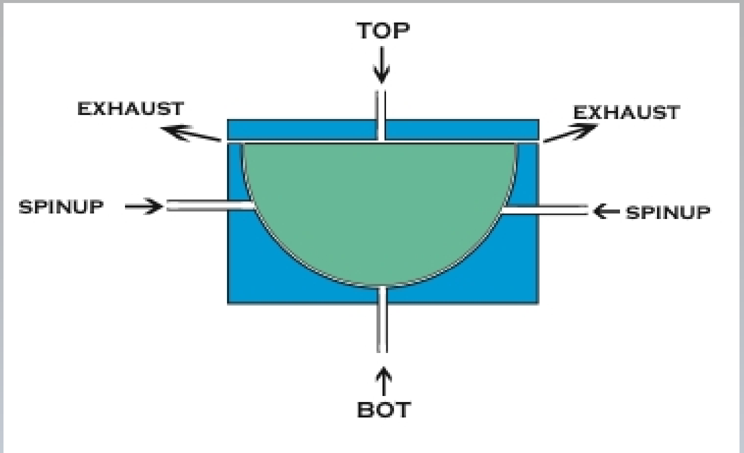
gravity signal is not resolved

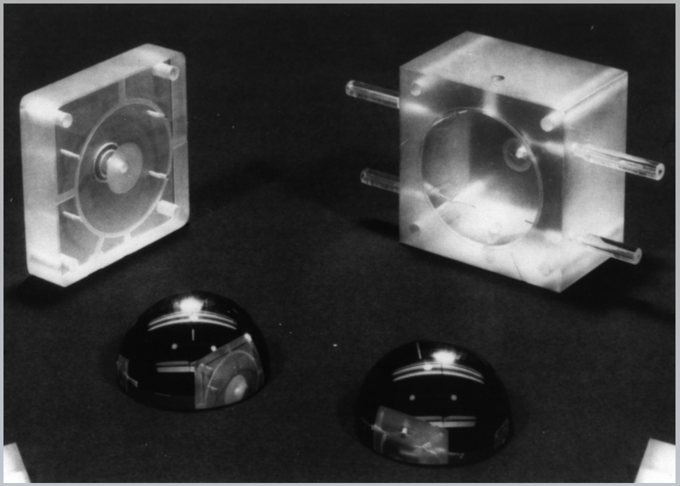
future plans of the Stanford group: rotational drive

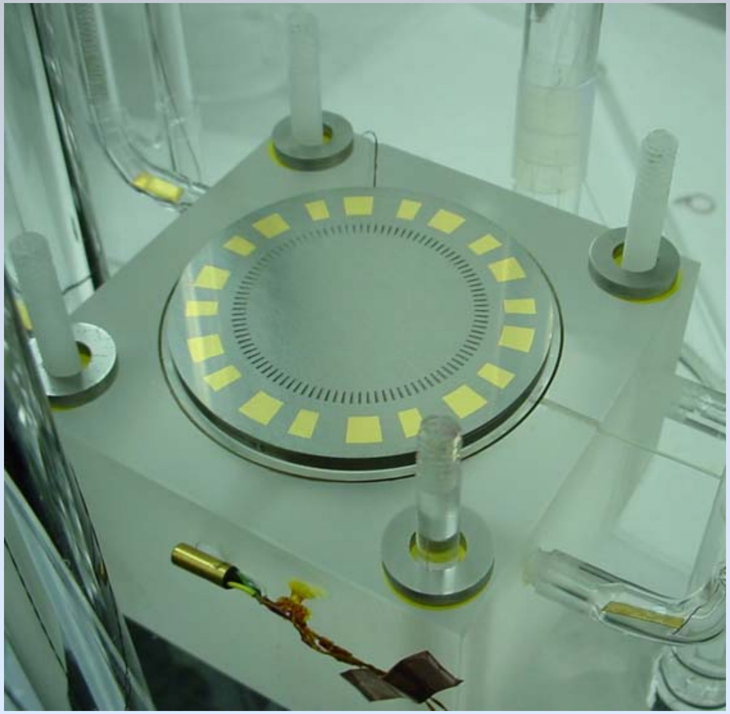
- Much larger area drive mass possible
  - ➔ 250-fold increase in force signal
- Most efficient way to modulate mass
  - ➔ Maximum force modulation at chosen harmonic
- Removes the need for alignment
  - ➔ Simplified experimental procedure
- Much higher frequency multiplier (100x)
  - ➔ Reduced vibrational problems
- No piezoelectric elements
  - ➔ Eliminates spurious effects due to piezo nonlinearity, high voltage
- Gas bearings ideal for low-temperature actuation
  - ➔ Stiff, low clearance, proven technology

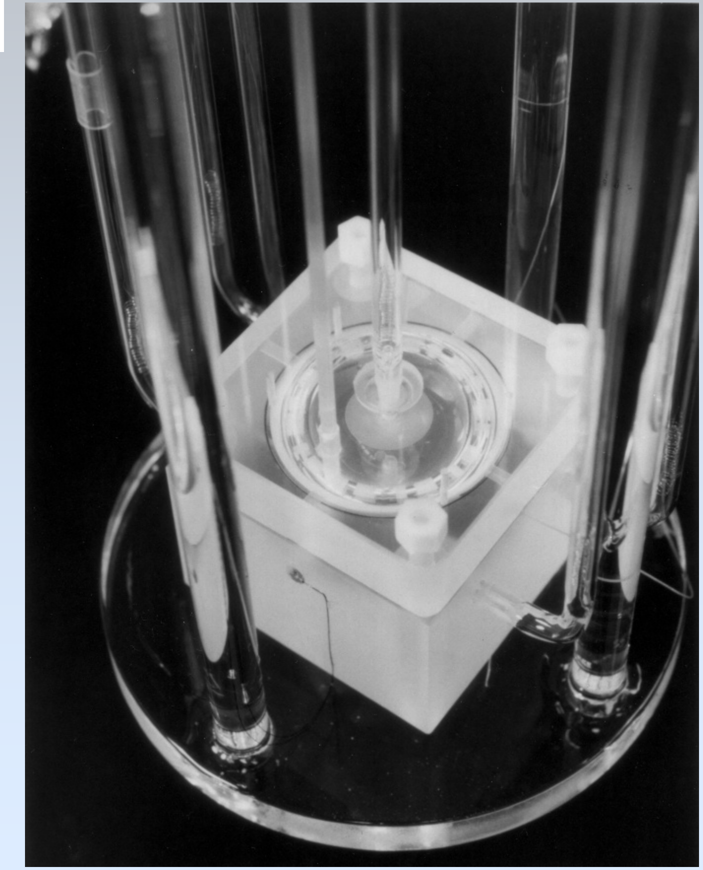


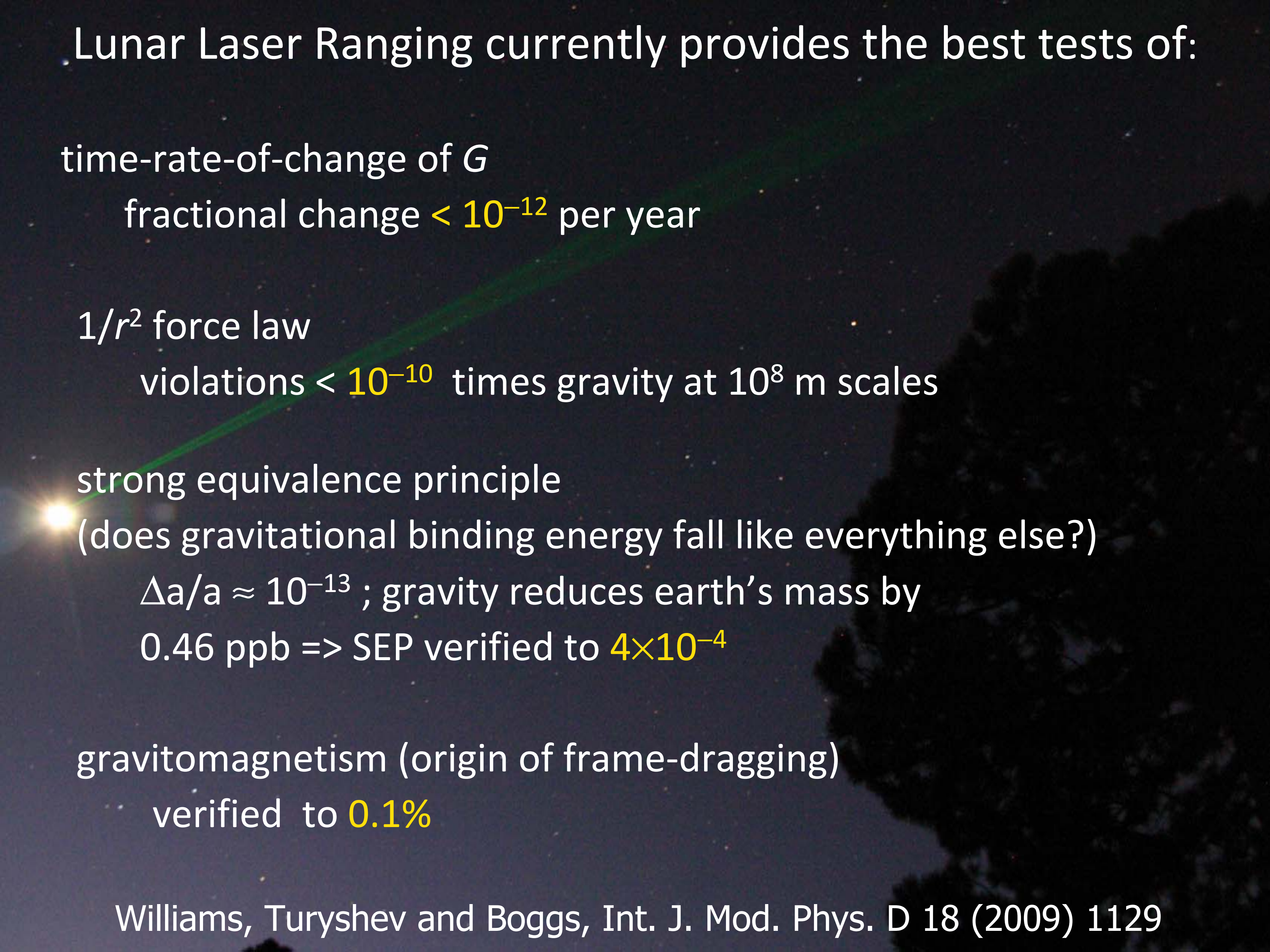
Drive mechanism and rotor











Lunar Laser Ranging currently provides the best tests of:

time-rate-of-change of *G*

fractional change $< 10^{-12}$ 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

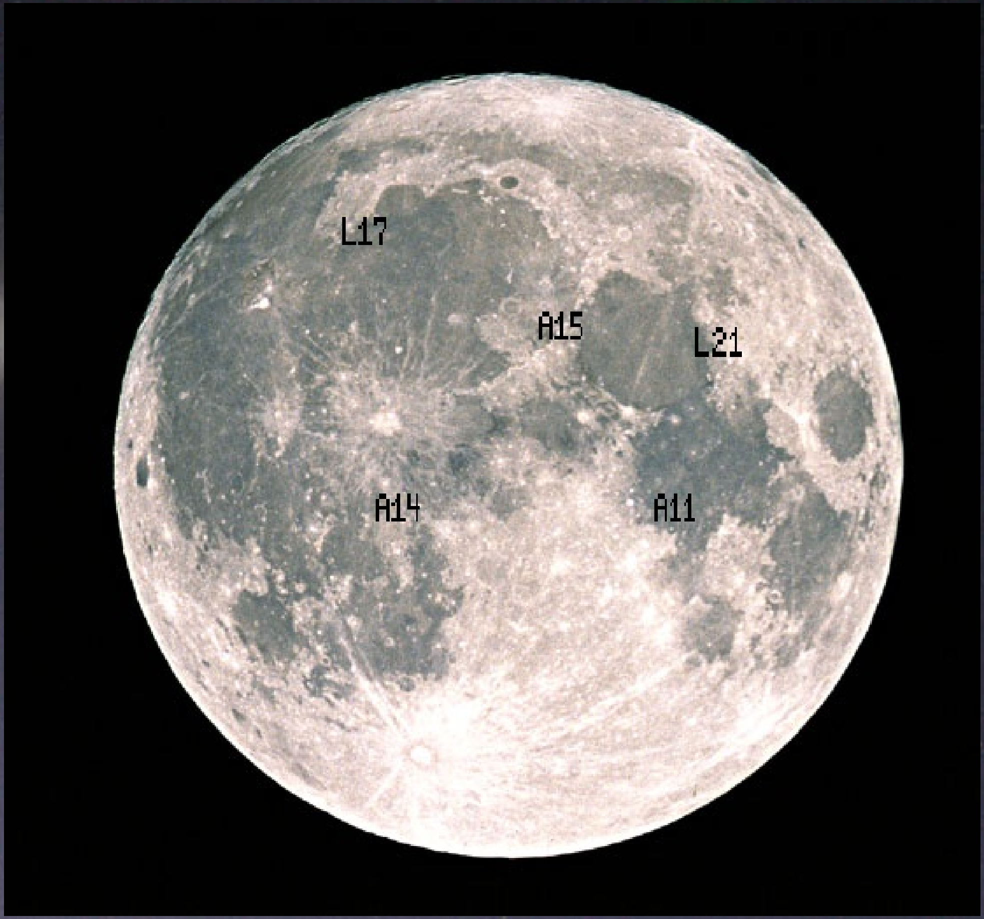
0.46 ppb => SEP verified to 4×10^{-4}

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.

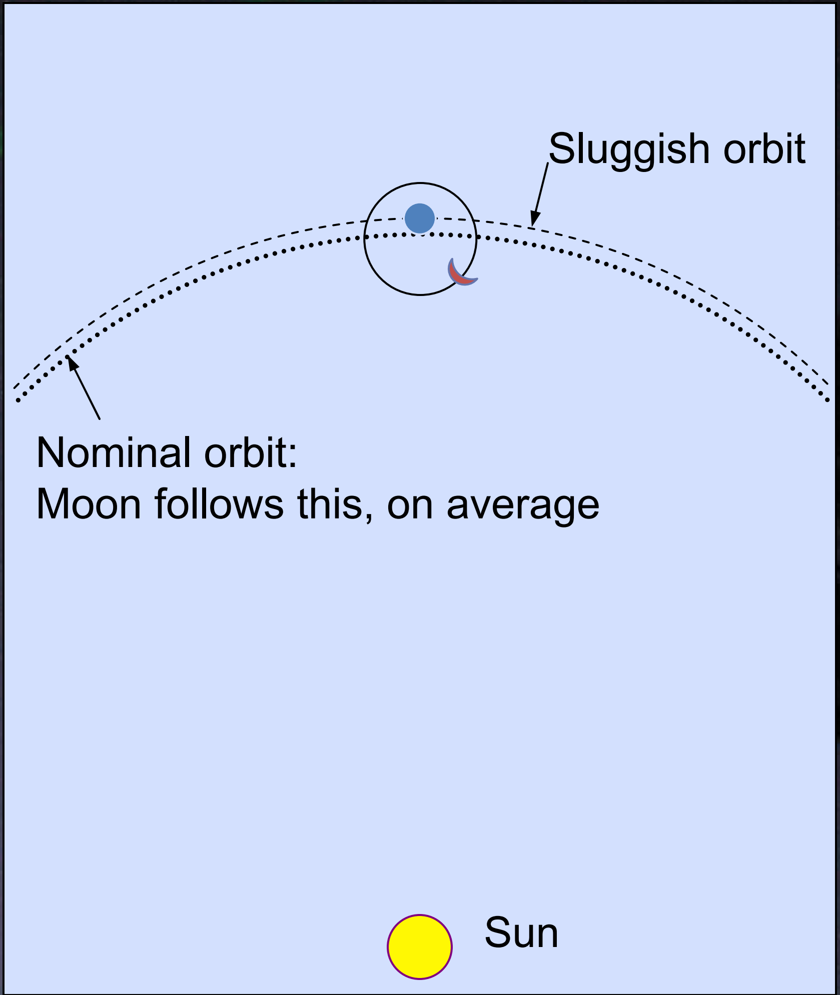
Signal loss is huge:

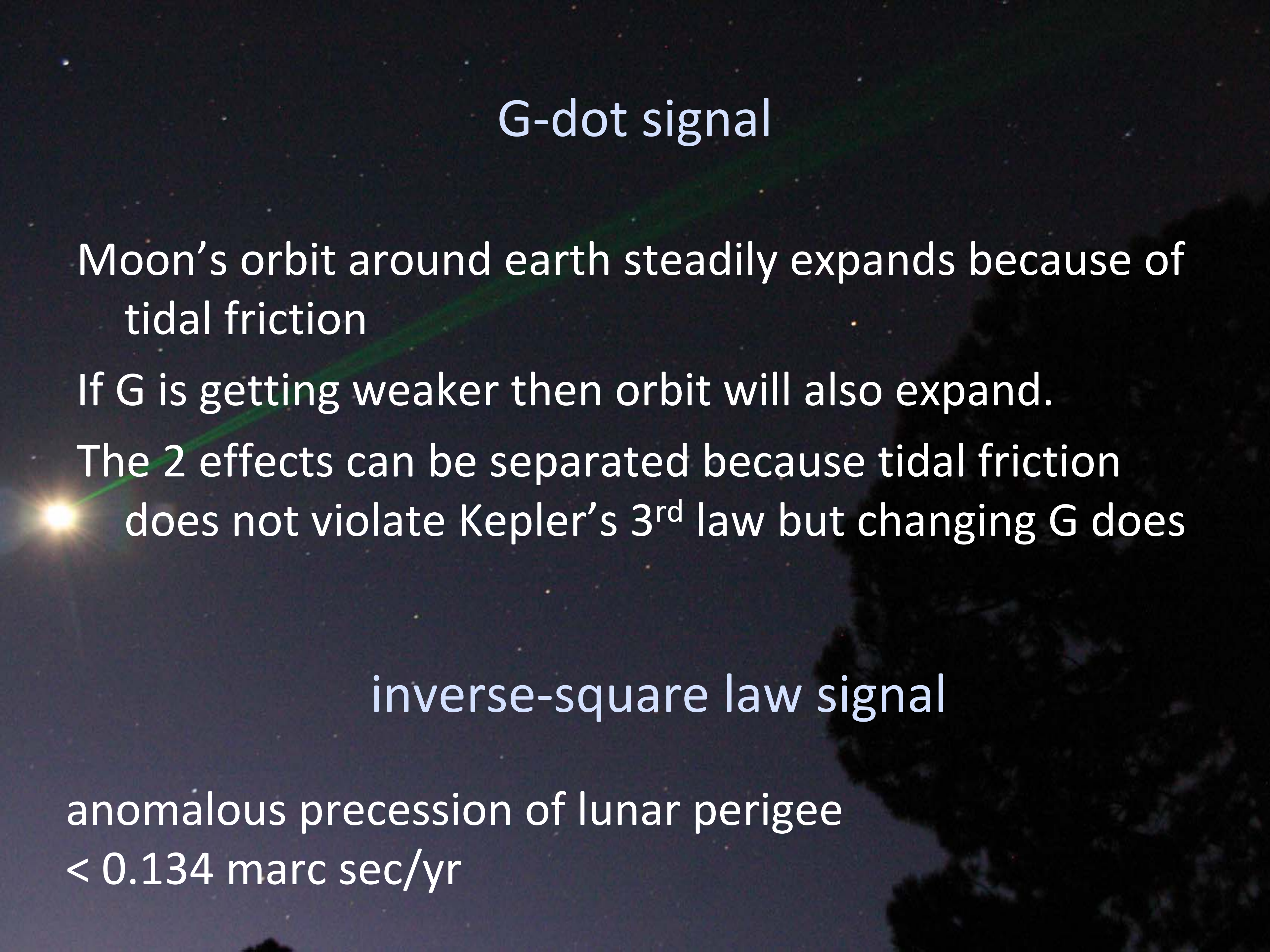
- ≈10^{-8} of photons launched find reflector (atmospheric seeing)
- ≈10^{-8} of returned photons find telescope (reflector diffraction)
- >10^{17} loss considering other optical/detection losses.

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.

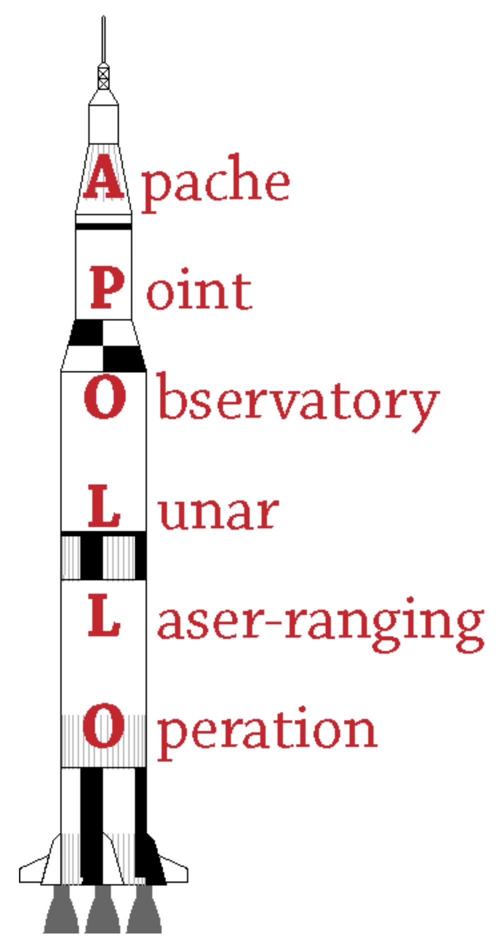
The 2 effects can be separated because tidal friction does not violate Kepler’s 3rd law but changing G does

inverse-square law signal

anomalous precession of lunar perigee
< 0.134 marc sec/yr

APOLLO: a next-generation LLR facility

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

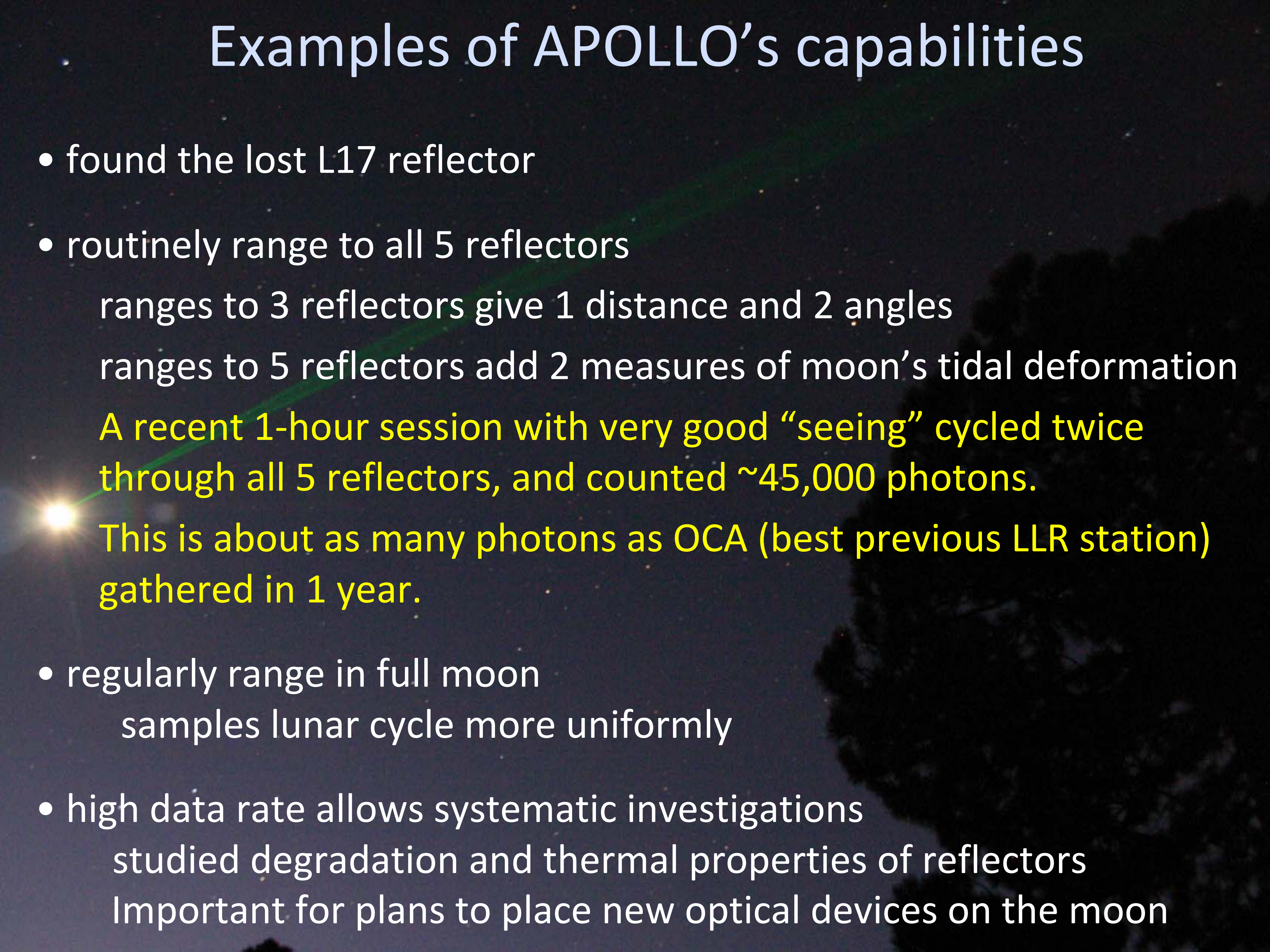


APOLLO provides factor of 10 improvement in range precision (from cm to mm) and

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

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.

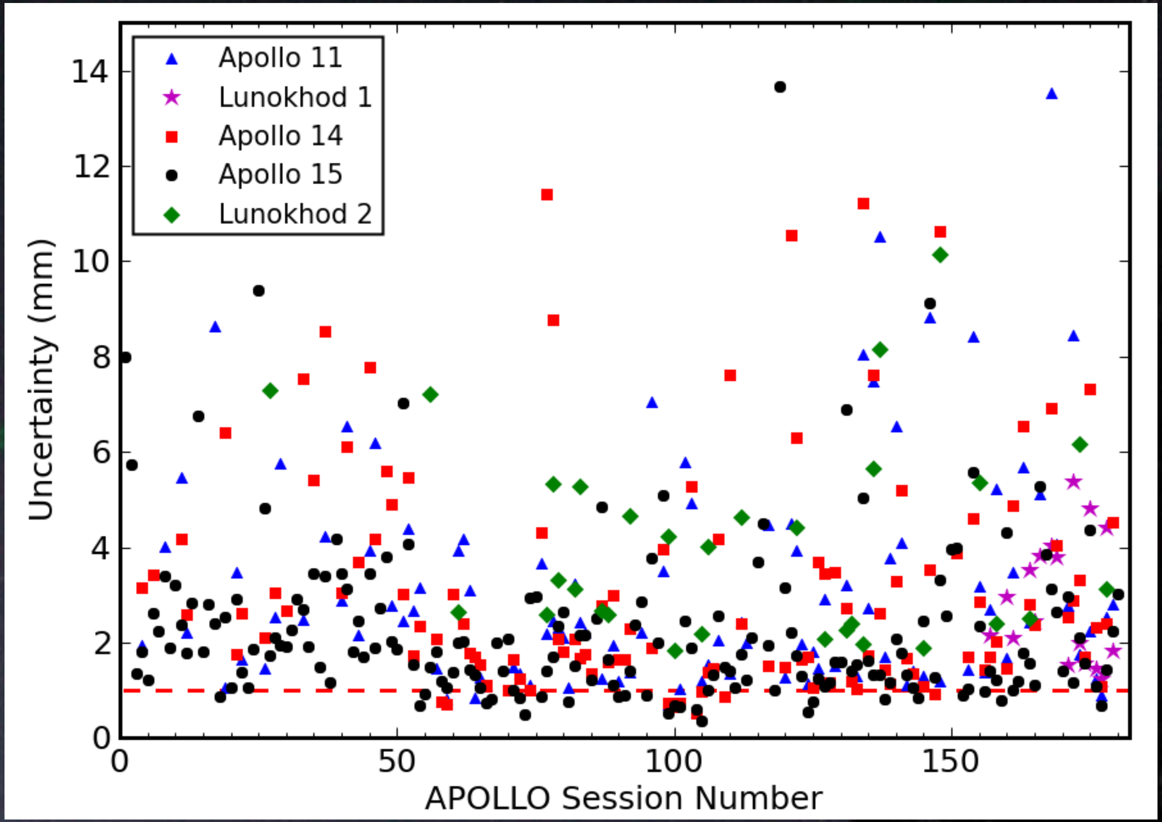
  This is about as many photons as OCA (best previous LLR station) gathered in 1 year.
- regularly range in full moon

  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

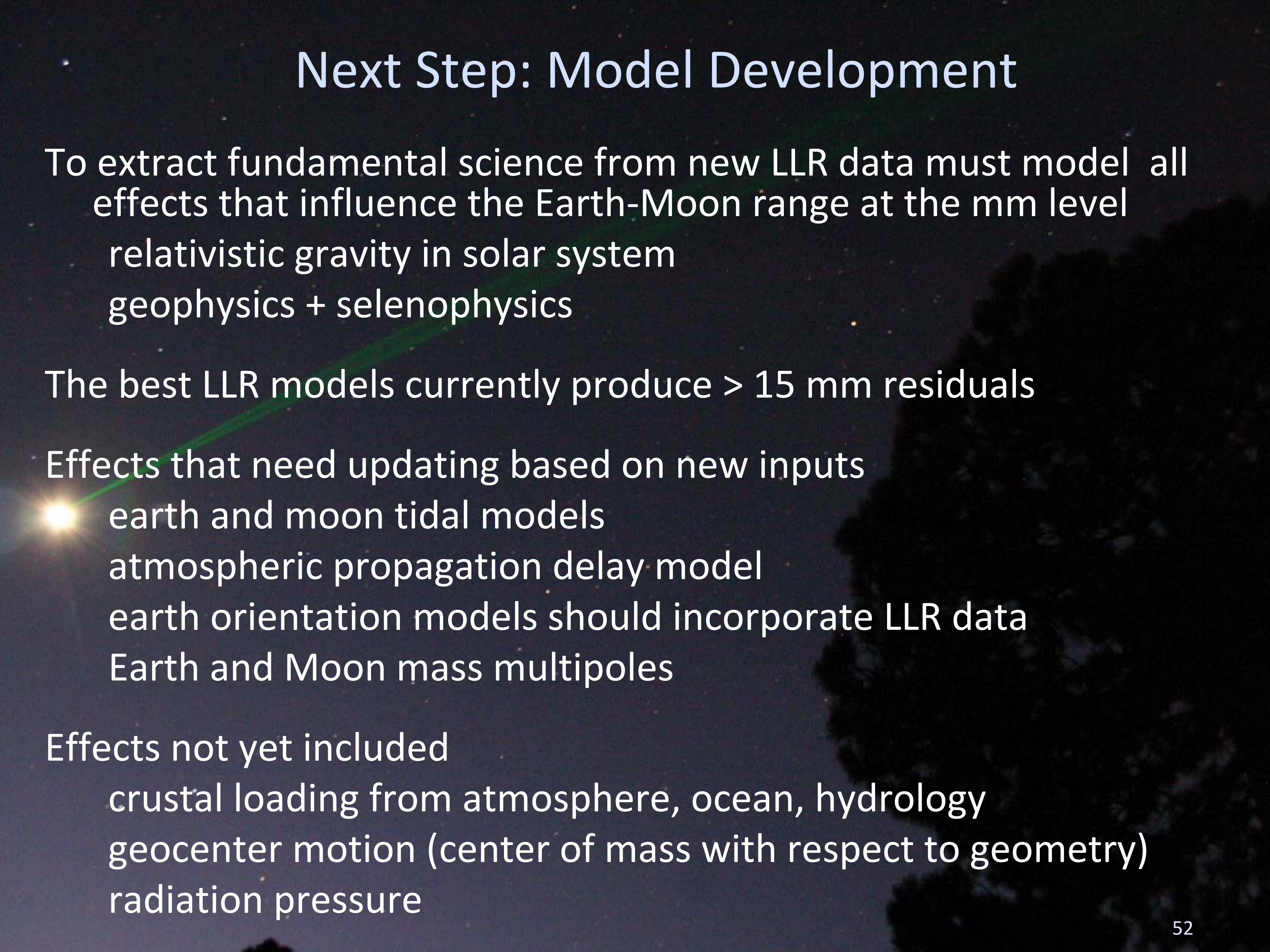
APOLLO’s range precision



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

pre-APOLLO data were rarely better than 10 mm

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

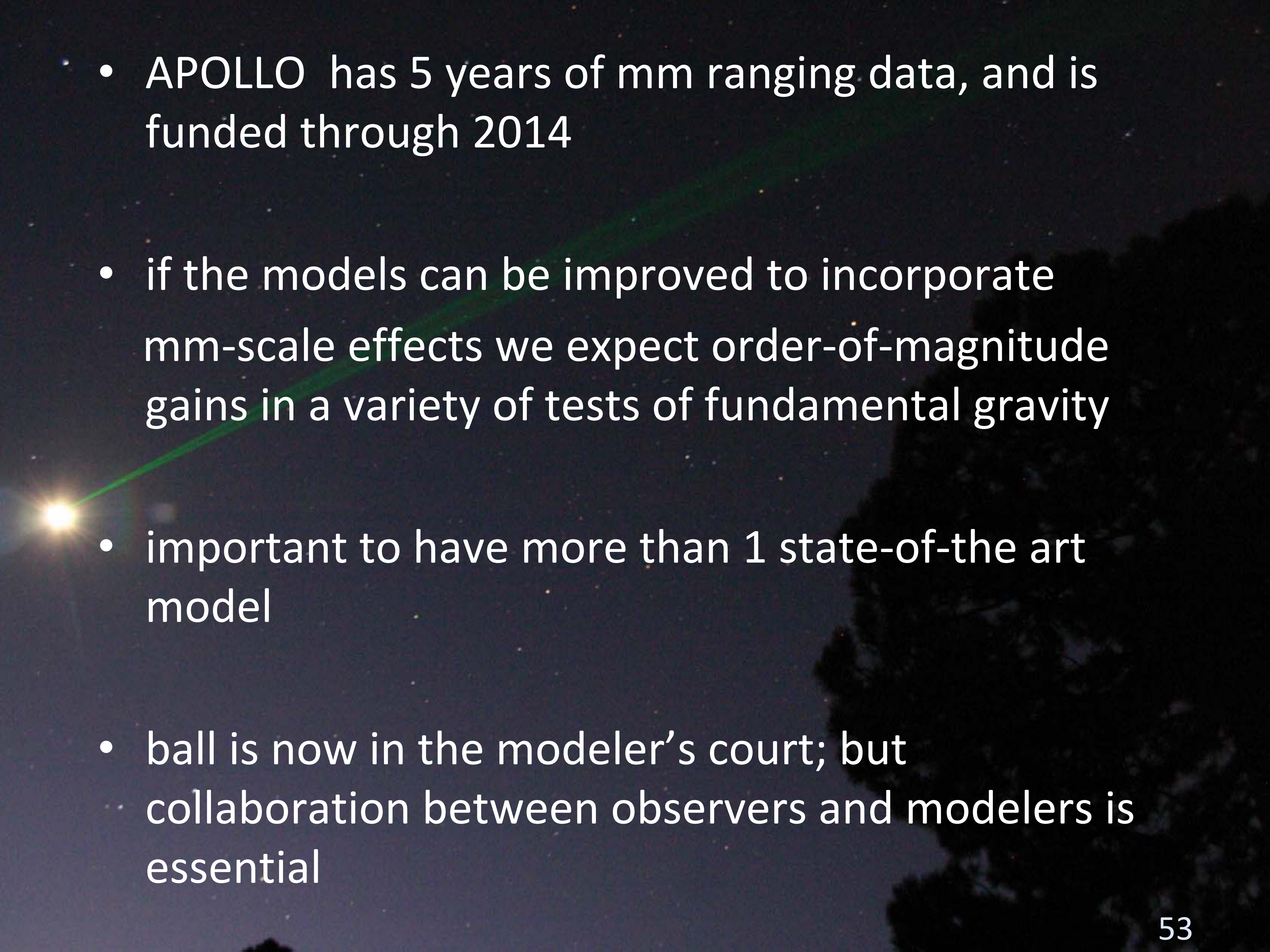
The best LLR models currently produce > 15 mm residuals

Effects that need updating based on new inputs

- 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

some references

- Recent general review of torsion balance experiments

E Adelberger, J. Gundlach, B. Heckel, S. Hoedl, and
S. Schlamminger, PPNP 62, 102 (2009)

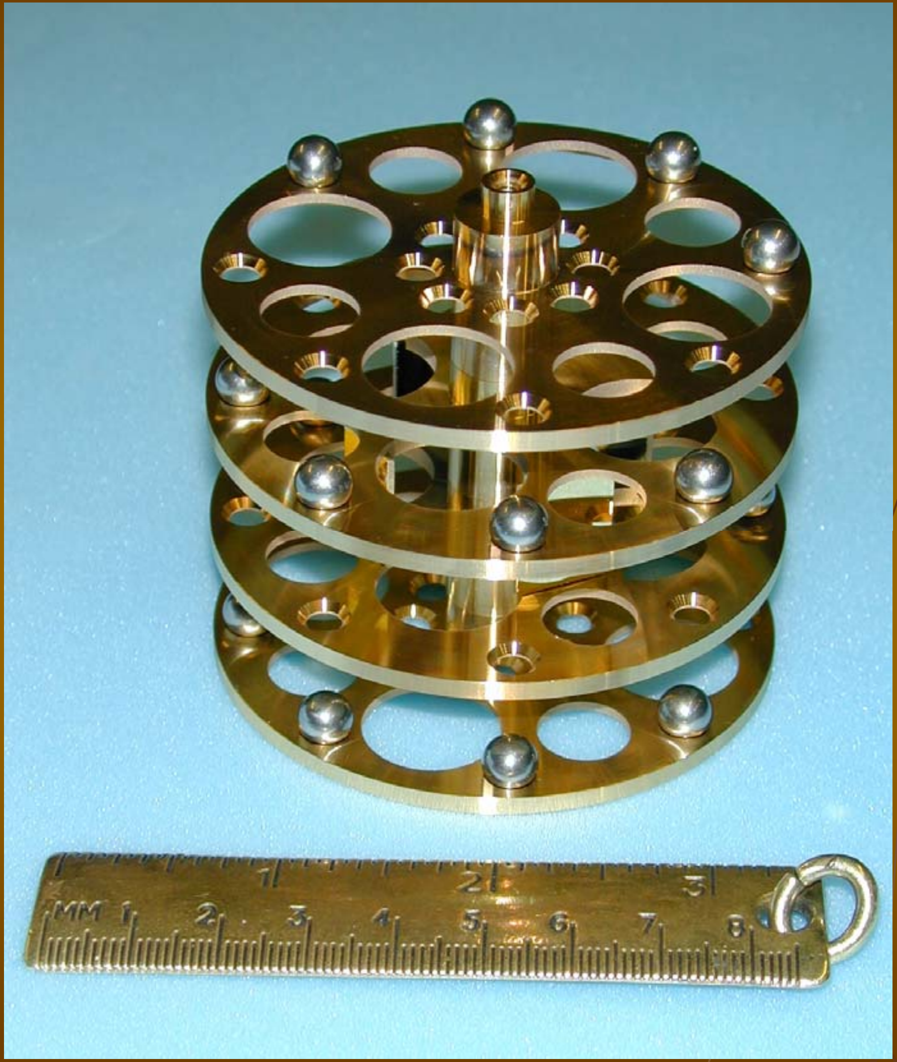
- Atom interferometer accelerometers

M. Kasevich and S. Chu, Appl. Phys. B 54, 321 (1992)

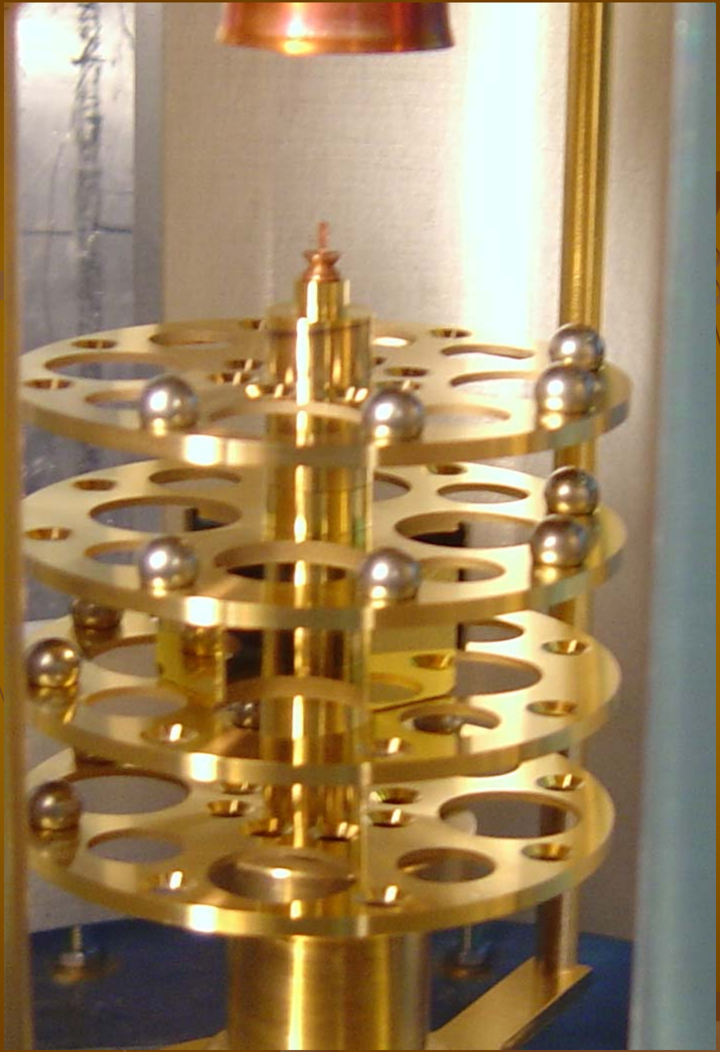
- APOLLO

J.B.R. Battat et al., Pub. Astr. Soc. Pacific 121, 29 (2009)
T.W. Murphy et al., Icarus 211, 1103 (2011)

gravity-gradiometer pendulums

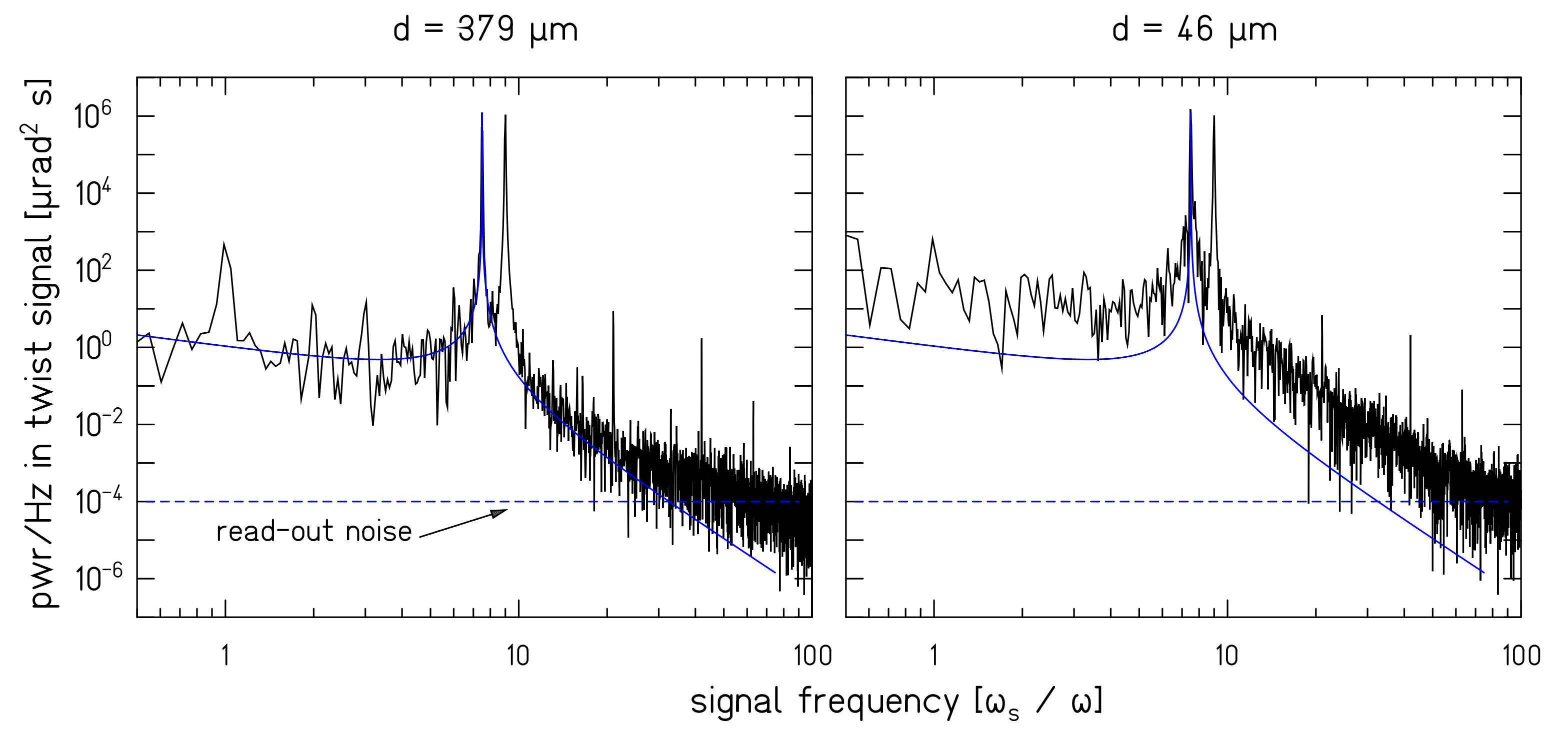


q_{41} configuration on a table



q_{21} configuration installed

power spectral density of twist signal

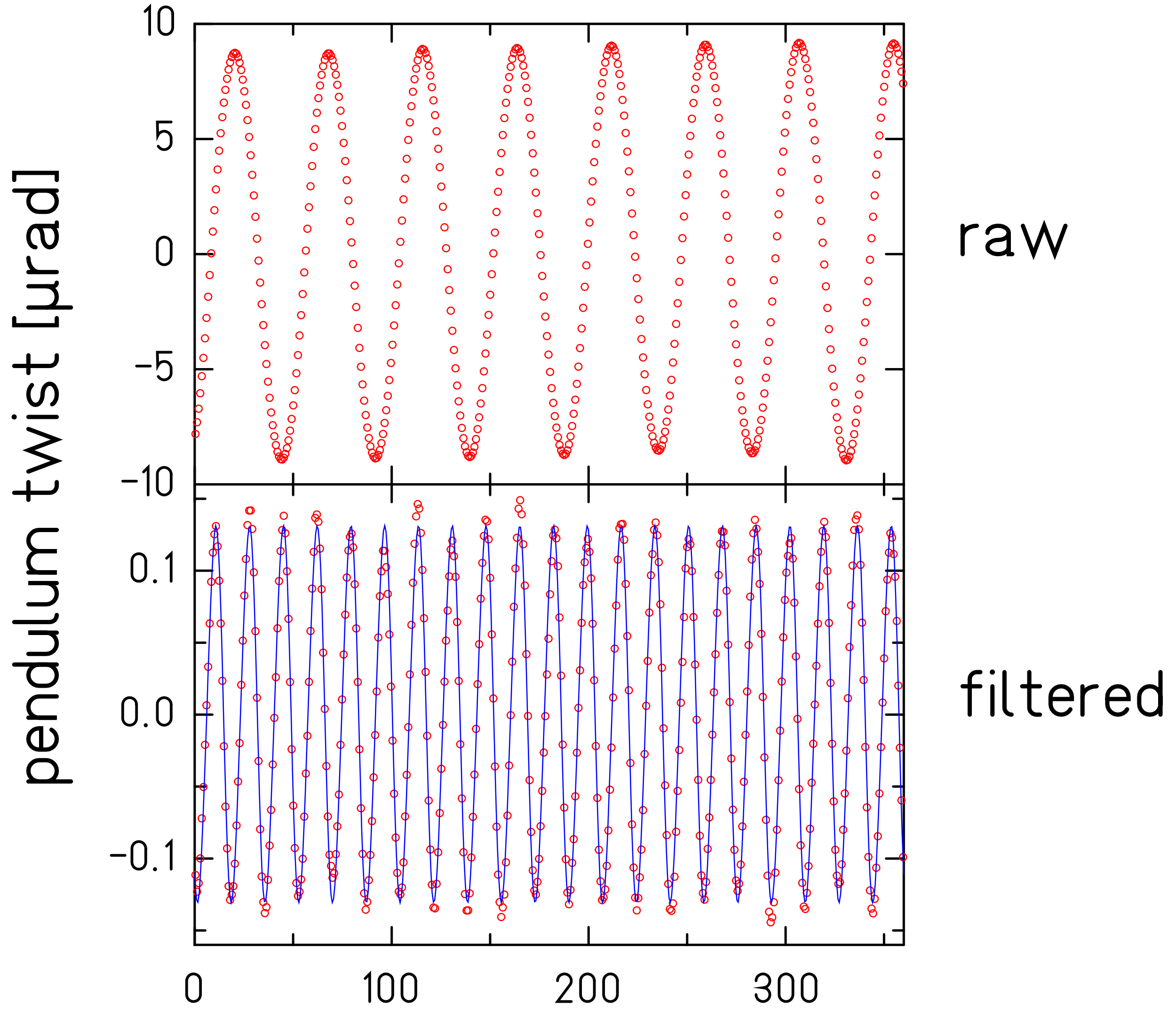


d = detector/foil separation

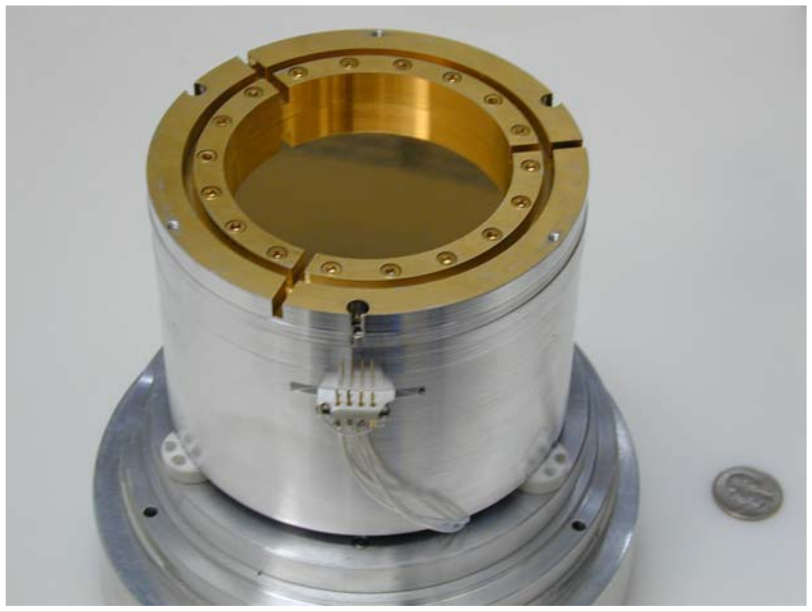
area under smooth curves is k_BT

signal processing

these data
were taken
with the
calibration
turn-table
stationary

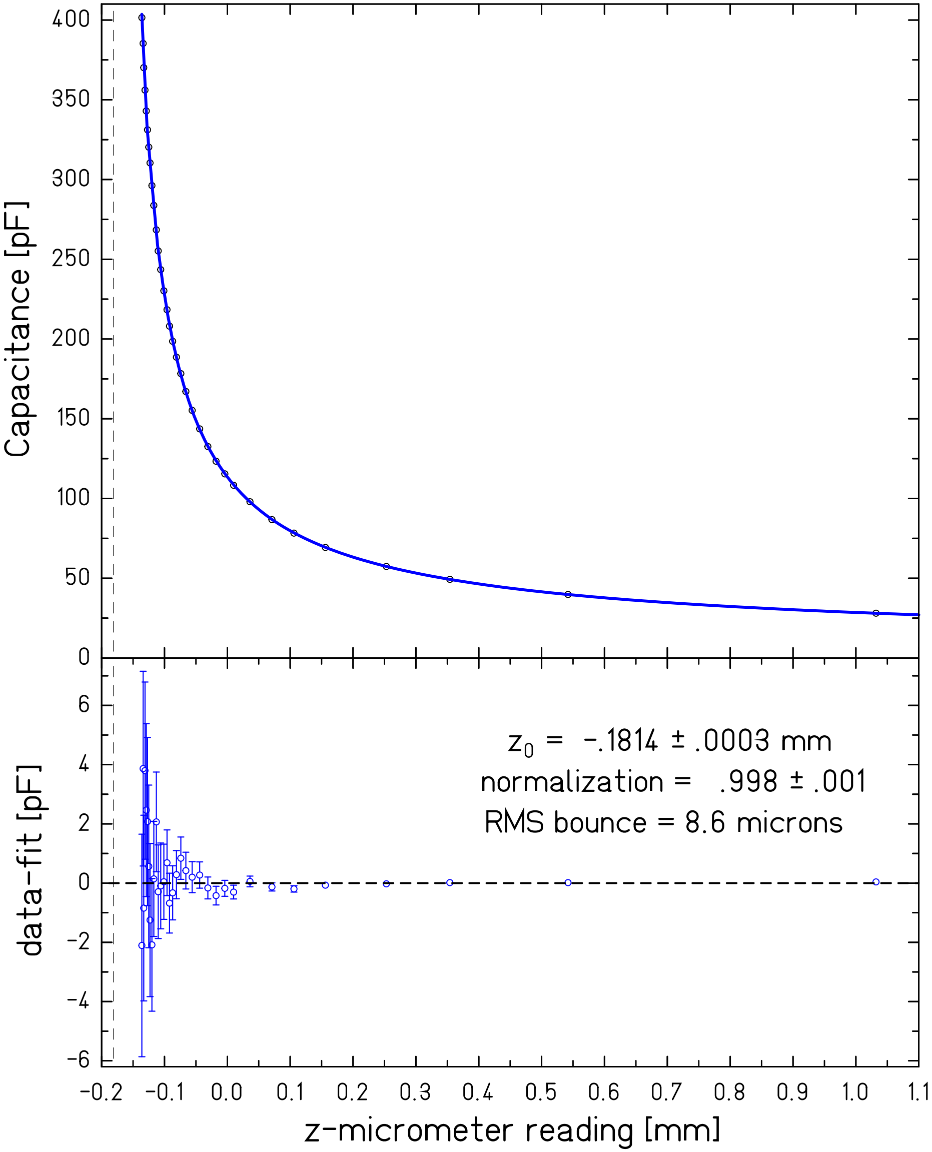


rotating attractor and its electrostatic shield



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

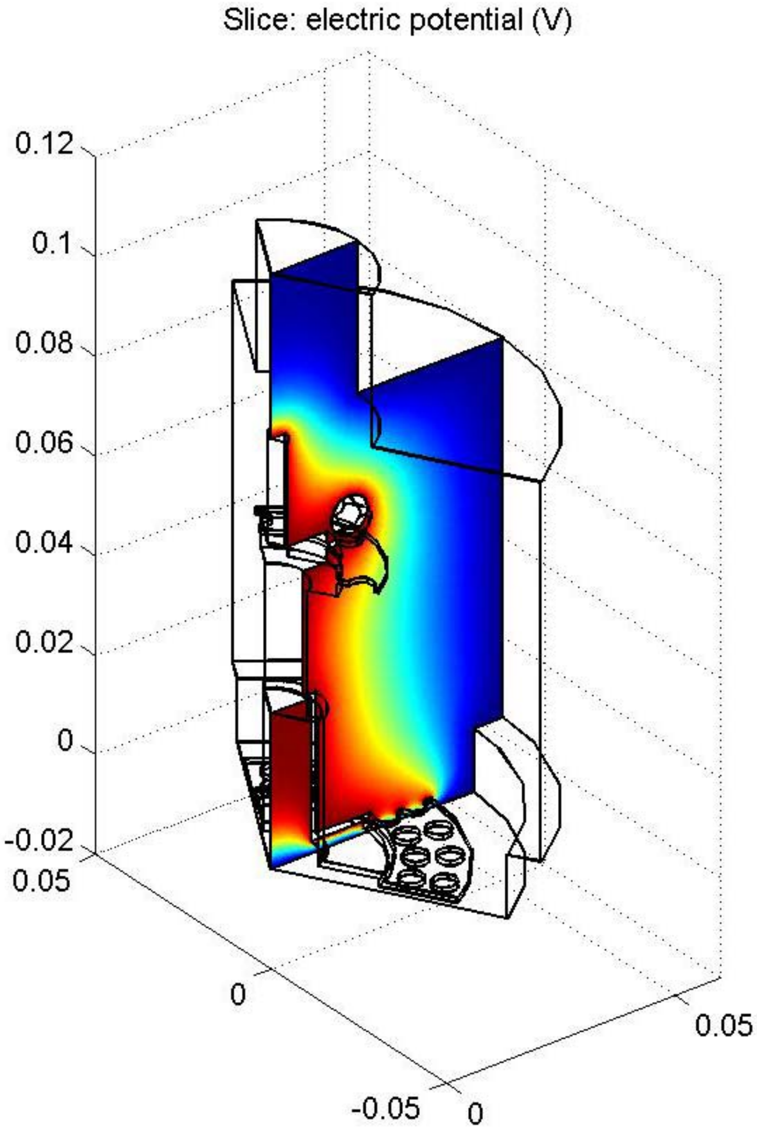
measuring the detector-membrane separation



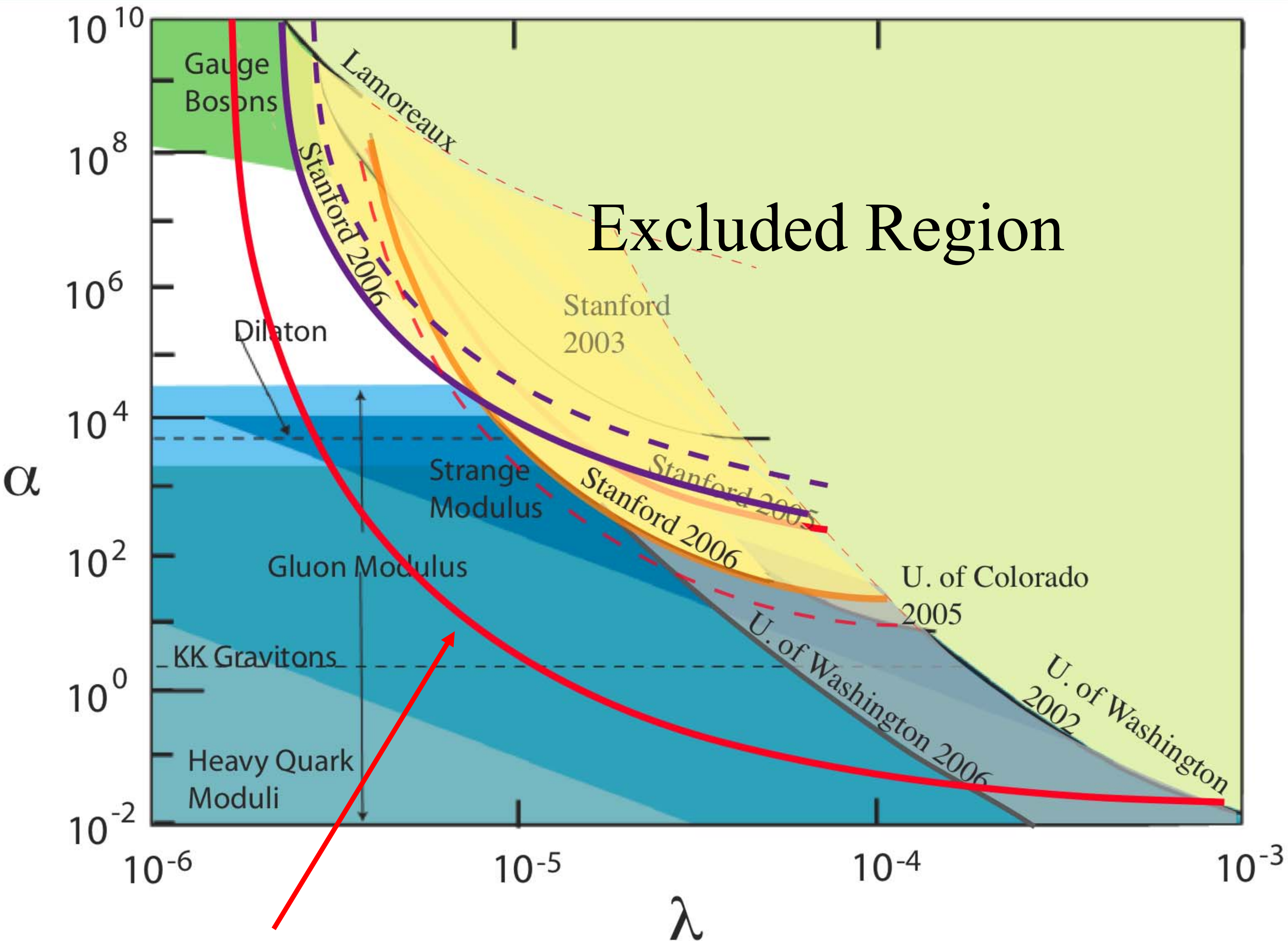
z_0 = -.1814 ± .0003 mm

normalization = .998 ± .001

RMS bounce = 8.6 microns

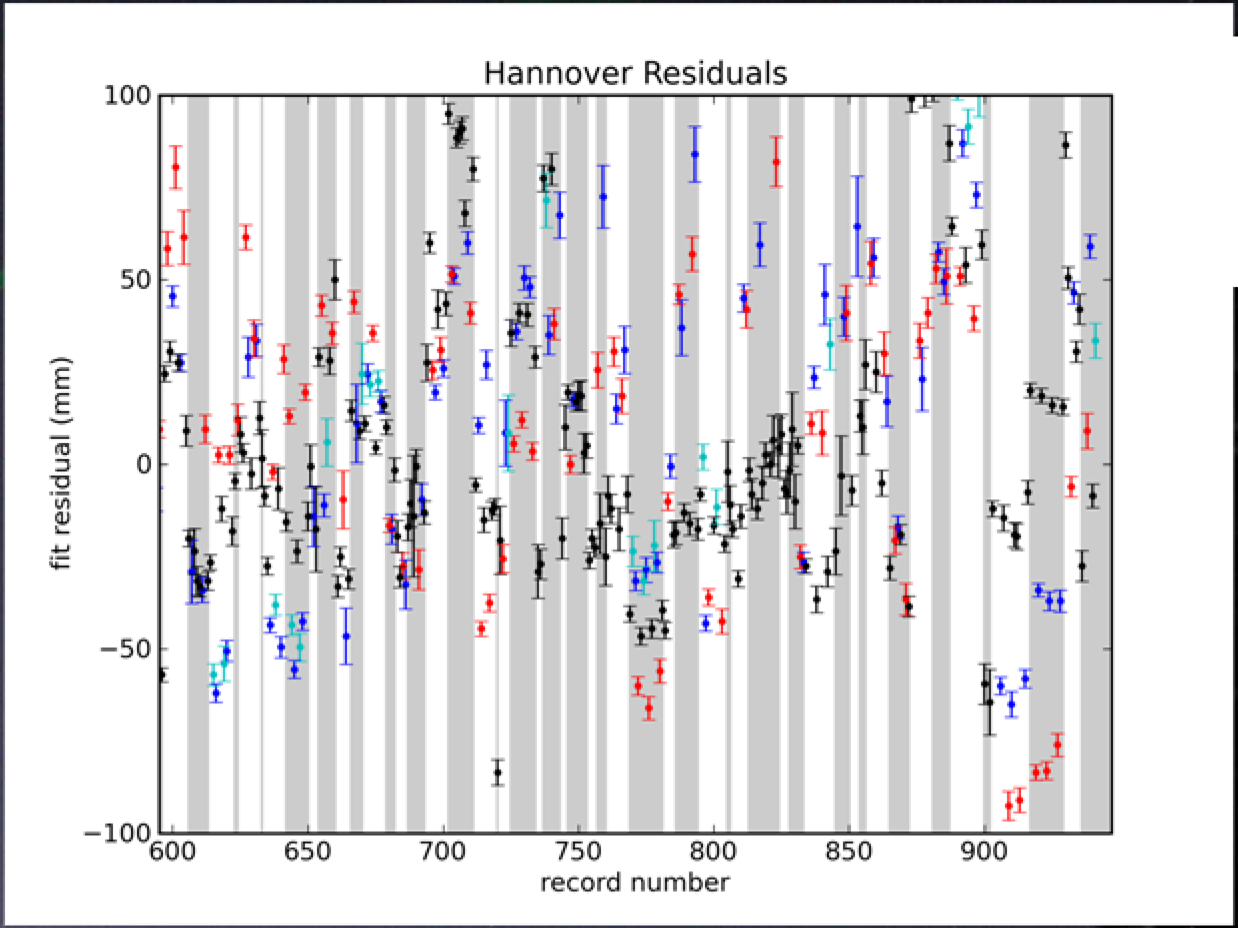


Future plans of Stanford group:



their goal

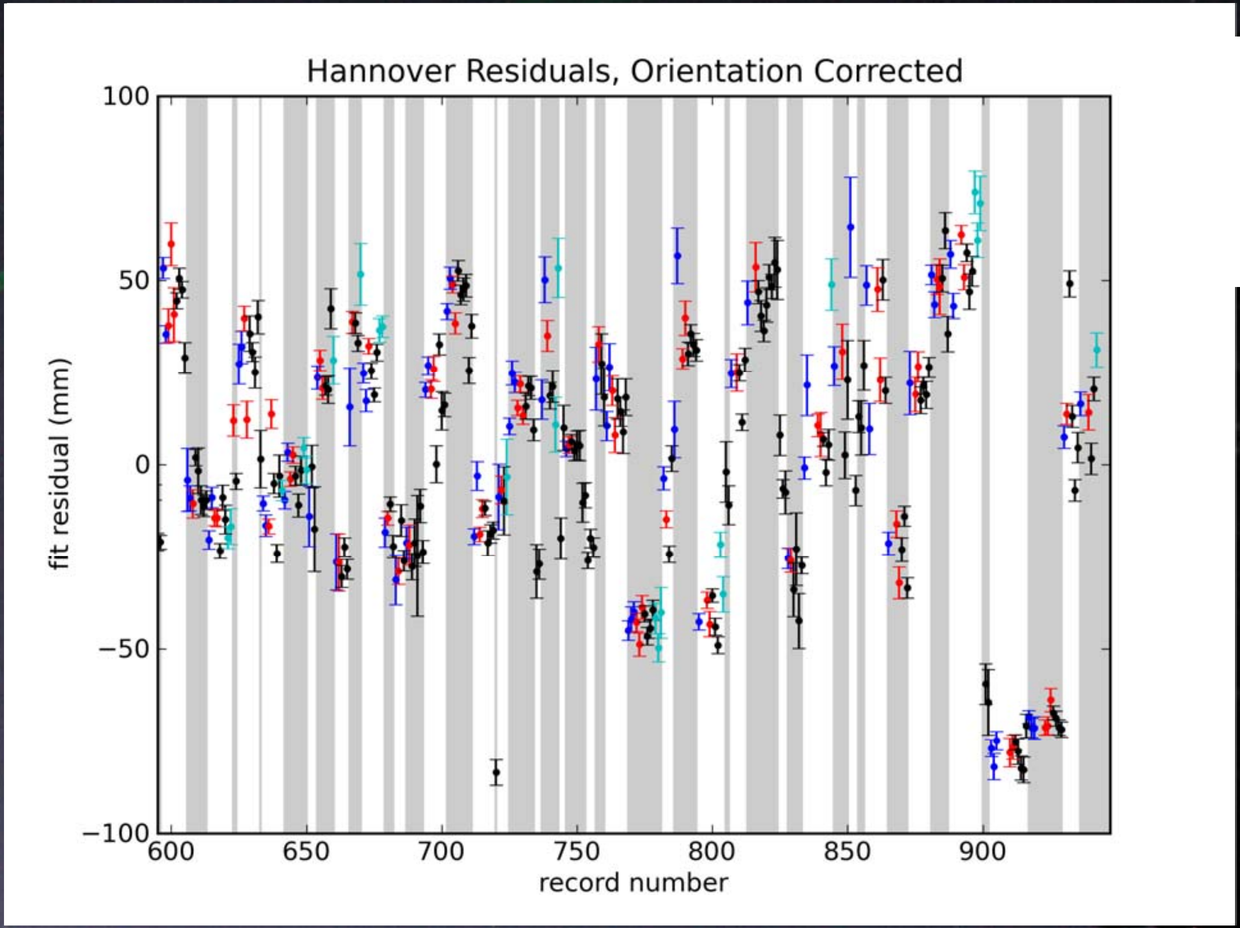
APOLLO data clearly call for nightly adjustment of lunar orientation



- Apollo 11
- Apollo 14
- Apollo 15
- Lunokhod 2

(vertical bands show individual nights)

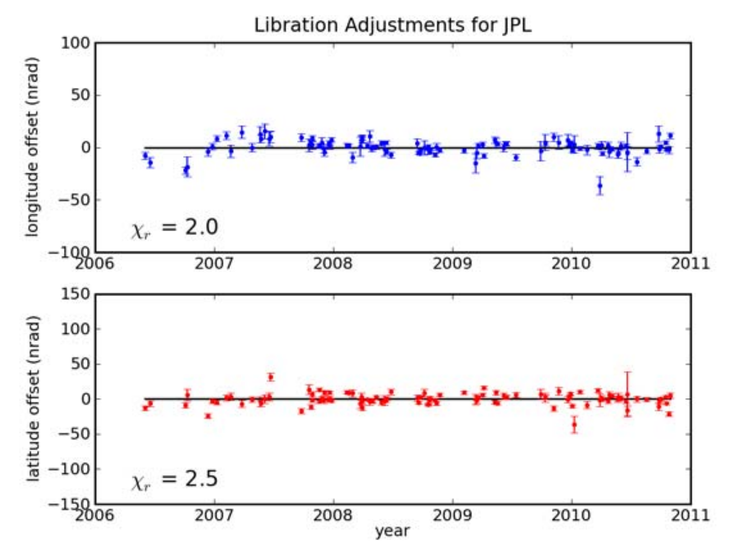
APOLLO data clearly call for nightly adjustment of lunar orientation

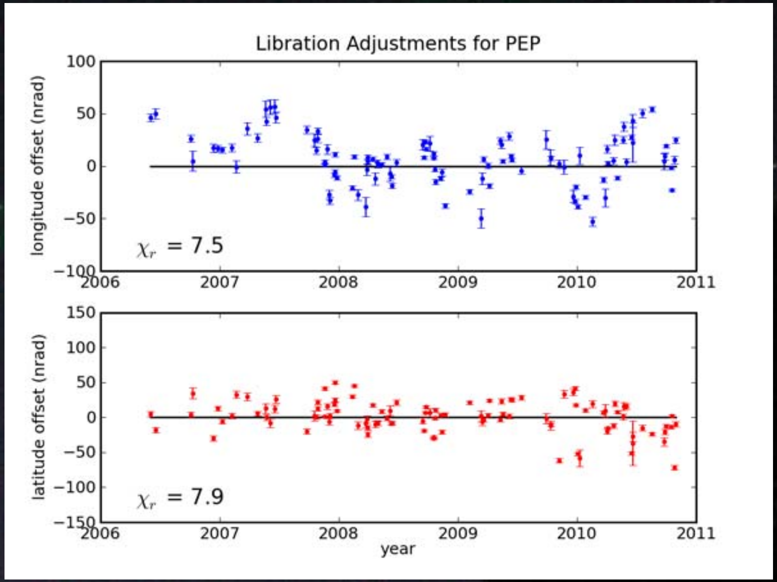


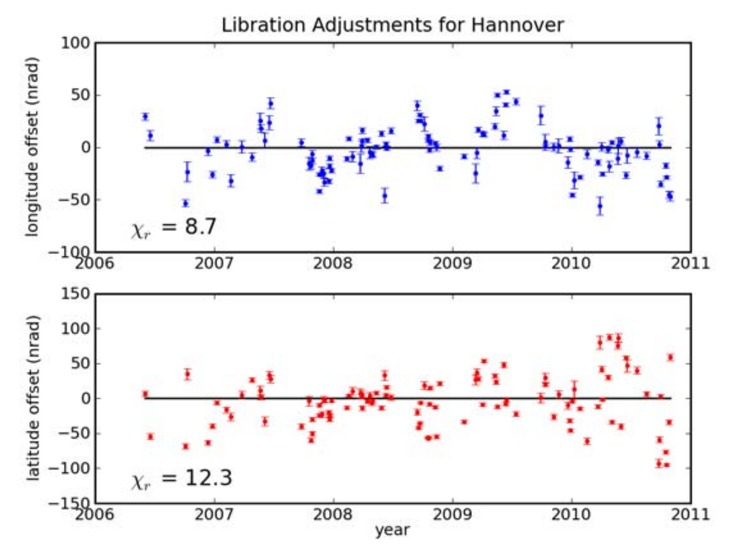
- Apollo 11
- Apollo 14
- Apollo 15
- Lunokhod 2

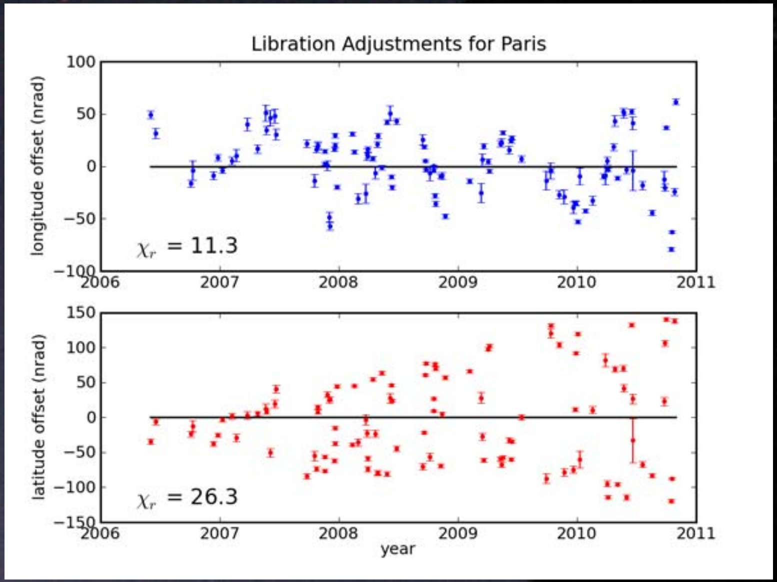
(vertical bands show individual nights)

adjusting moon orientation to fit APOLLO data









Ranges are very sensitive to lunar orientation; 1 nrad is 1.7 mm at moon’s surface. Here we tweaked lunar orientation each night to minimize the spread between residuals for different reflectors

predicted signals for the Fourier-Bessel instrument