Sub-millimeter tests of the gravitational $1/r^2$ law

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outline

- motivations
- history
- experimental techniques
  - Eöt-Wash ←
  - Colorado
  - Stanford
- results
- conclusions

the University of Washington

EÖT-WASH® GROUP

in experimental gravitation

faculty

$1/r^2$ → Eric Adelberger
$1/r^2$ → Blayne Heckel
Jens Gundlach ← EP

professional staff

Erik Swanson

post docs

Seth Hoedl
$1/r^2$ → CD Hoyle
Stephan Schlamminger ← EP

grad students

K-Y Choi ← EP
$1/r^2$ → Ted Cook
$1/r^2$ → Dan Kapner
Frank Marcoline

undergrads

→ Rogan Carr · Caleb Hotchkiss

Questions about gravity (the first fundamental force, understood by Newton ~300 yrs ago) are again at the frontier of physics! Why?

- have very successful theory of gravity
  Einstein's general relativity
- have very successful theory of all the other forces
  quantum field theory

that have passed all experimental tests.

What, then, is the problem?

the two theories are inconsistent with each other

- quantum field theory can't describe gravity
- general relativity can't describe the center of black holes

Some motivations for precision tests of the familiar laws of gravity

- discovery of cosmic acceleration – expansion of universe is apparently speeding up!
- candidate theory for unifying gravity with the rest of physics embodies fundamentally new features
  - new particles ← EP and $1/r^2$ law
  - 11 dimensions ← $1/r^2$ law
- there are vast unexplored regions in gravity

3 FAMOUS PROBLEMS WITH GRAVITY

- WHY IS GRAVITY SO WEAK?

  comparison of electrical & gravitational attractions of e and p at a given separation r.

  $$F_e = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2} \qquad F_g = G\frac{m_1 m_2}{r^2}$$

  $$\frac{F_e}{F_g} = 2\times10^{39}$$

- WHY IS THE COSMOLOGICAL CONSTANT SO SMALL?
  - Einstein's biggest blunder?
  - discovery of cosmic acceleration (Type 1A supernovae)
  - particle-physics predictions for Λ (vacuum energy)

  $\sim 10^{120}$ larger than observed value!

  ↖ $\sim 10^{60}$ if supersymmetry is just around the corner

- WHAT IS THE DARK MATTER?

  we know that most of the "gravitational" effects in the universe are not produced by normal matter

The hierarchy problem

- mass scale of gravity

$$V_N(r) = G\frac{mm}{r} = \frac{\hbar c}{M_P^2}\frac{mm}{r}$$

$$\longrightarrow M_P = \sqrt{\hbar c/G} \sim 10^{16}\ \text{TeV}$$

- mass scale of particle physics

$$\longrightarrow M_{SM} \sim 1\ \text{TeV}$$

- Arkani-Hamed et al. solution to the problem

  Phys. Lett. B 429 (1998) 263

  assume that:

  - gravity propagates in all of the 7 extra dimensions of string theory
  - SM particles are confined to a 4-dim "brane"
  - some of the 7 extra dimensions are "large" while the remainder are "curled up" at the Planck scale $R_P = \sqrt{G\hbar/c^3} = 1.6\times10^{-33}\,\text{cm}$

Arkani-Hamed et al. solution to 1st hierarchy problem

Phys. Lett. B 429 (1998) 263

- gravity actually isn't so weak,
  we just think it is

- their argument

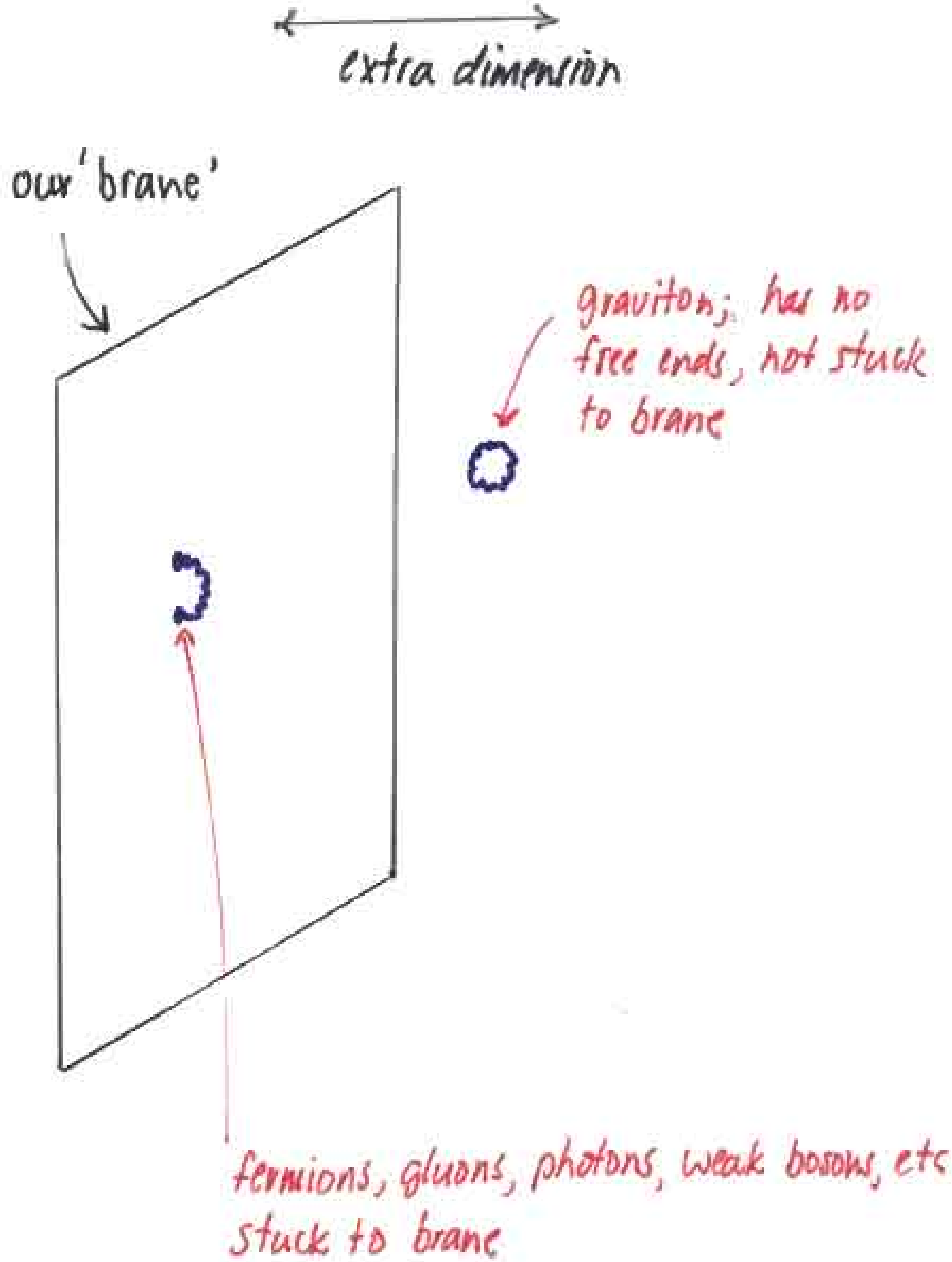
  - suppose some of the 7 extra dimensions of string theory are not curled up at the Planck length

    $$R_p = \sqrt{G\hbar/c^3} \sim 10^{-33}\,\text{cm}$$

    but have a "large size" $R^* \gg R_p$

  - suppose only gravity can spread out in the extra dimensions, everything else ('particle physics, etc.) is confined to a 3+1 dimensional "brane"

  - then gravity can be just as strong as everything else, but we wouldn't know it until we can measure the strength of gravity as separations $s < R^*$


extra dimension
our 'brane'
graviton; has no free ends, not stuck to brane
fermions, gluons, photons, weak bosons, etc stuck to brane

can make gravity the same strength as the other 3 forces if

$D = 3 + 1$	$F \propto \frac{1}{r^3}$	$s \sim 10^{11}\,m$
$D = 3 + 2$	$F \propto \frac{1}{r^4}$	$s \sim 0.3\,mm$
$D = 3 + 3$	$F \propto \frac{1}{r^5}$	$s \sim 10^{-9}\,m$
$D = 3 + 4$	$F \propto \frac{1}{r^6}$	$s \sim 3 \times 10^{-12}\,m$
⋮	⋮	

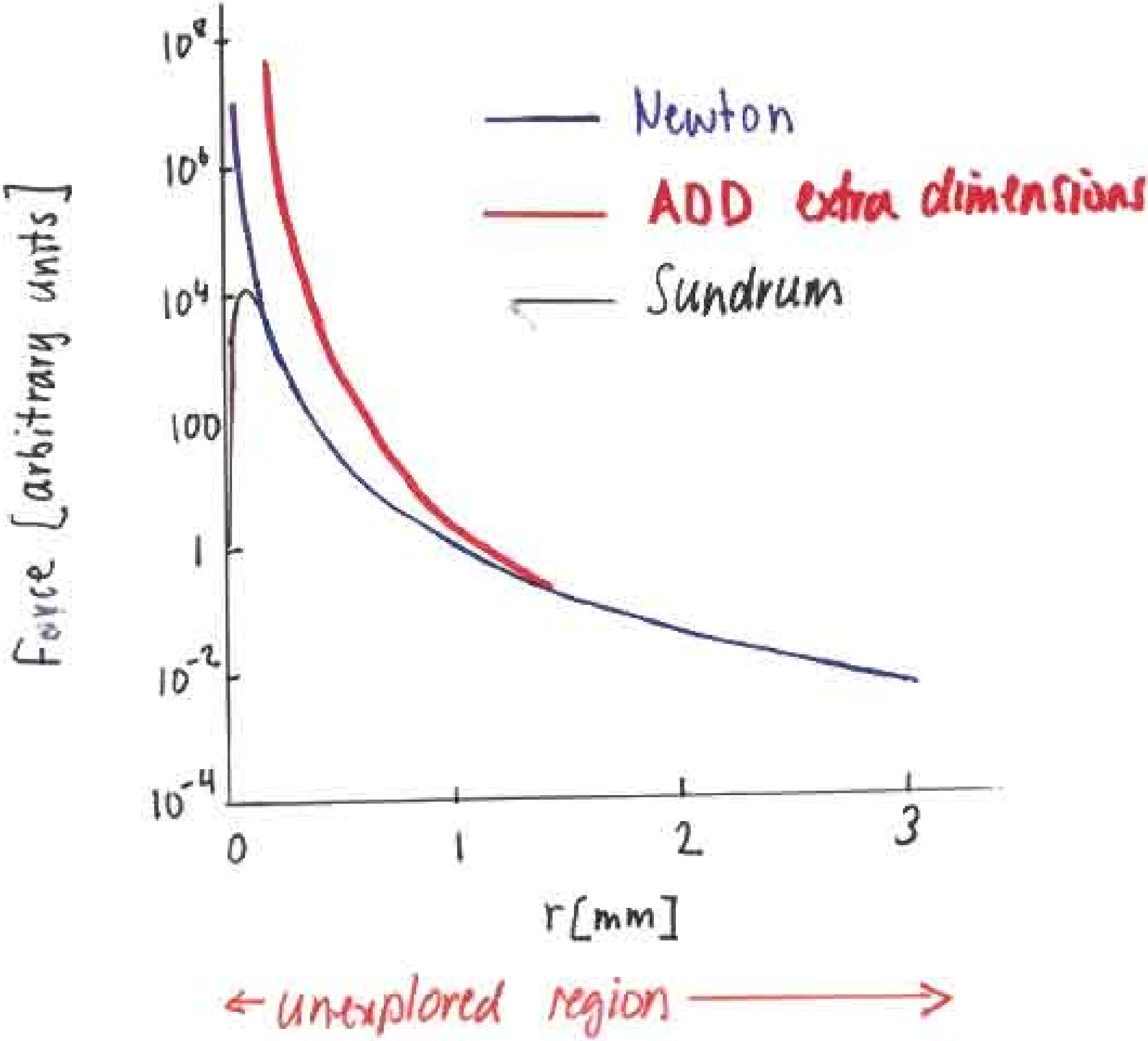
↑ number of large extra dimensions

↑ size of the large extra dimensions

Why might gravity get weak at separations less than 0.1 mm?

- the repulsive "gravity" deduced from cosmological data indicates that empty space has an energy of $\rho = 4\,\text{keV}/\text{cm}^3$.
- this corresponds to a length scale
  $d = \sqrt[4]{\hbar c/\rho} \sim 0.1\,\text{mm}$
- Sundrum's suggestion: the graviton string has a size of 0.1 mm. this prevents it from "seeing" the short-distance physics that produces most of the predicted vacuum energy
- prediction: gravity gets very weak at separations less than 0.1 mm

PREDICTIONS FOR 1/r² LAW BREAKDOWNS



MOTIVATION FOR TESTING $1/r^2$ LAW AT SHORTEST POSSIBLE LENGTH SCALES

- model-independent probe of the geometry of the Universe
  - requires sensitivity at gravitational strength $\alpha = 1$
  - great theoretical interest in extra dimensions
- very sensitive to exchange forces from exchange of new scalar or vector particles
  - string theory predicts lots of them!
- unexpected discovery of "dark energy" sparked interest in testing gravity at length scale corresponding to Λ (~ 0.1 mm)
- many predictions for revolutionary effects but very little data

Parameterising breakdowns of $1/r^2$ law

- Old-fashioned way

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

↑ no theoretical basis

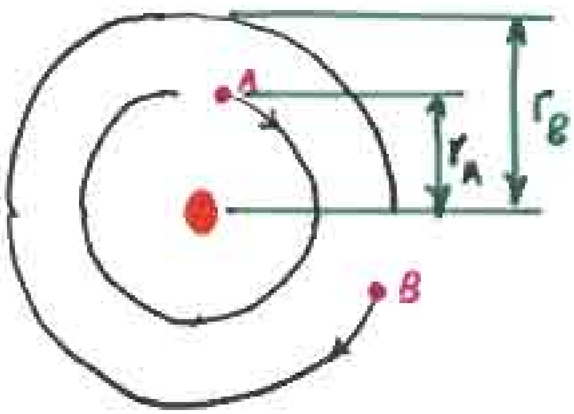
- modern way

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

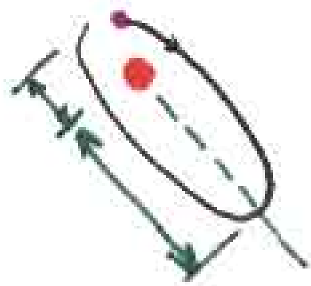
↑

- exchange of boson with $m \neq 0$
- 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



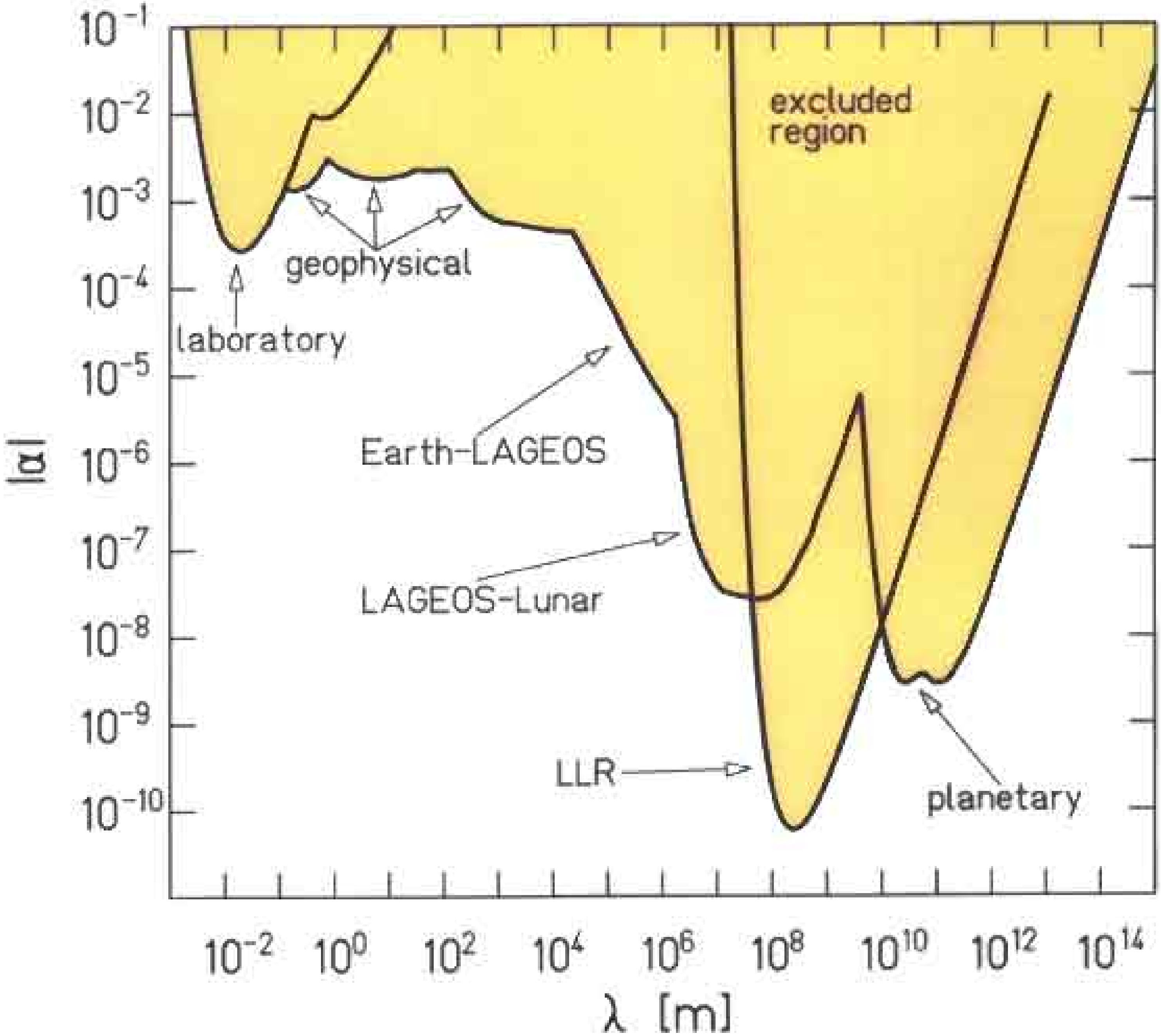
$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \ ?$$

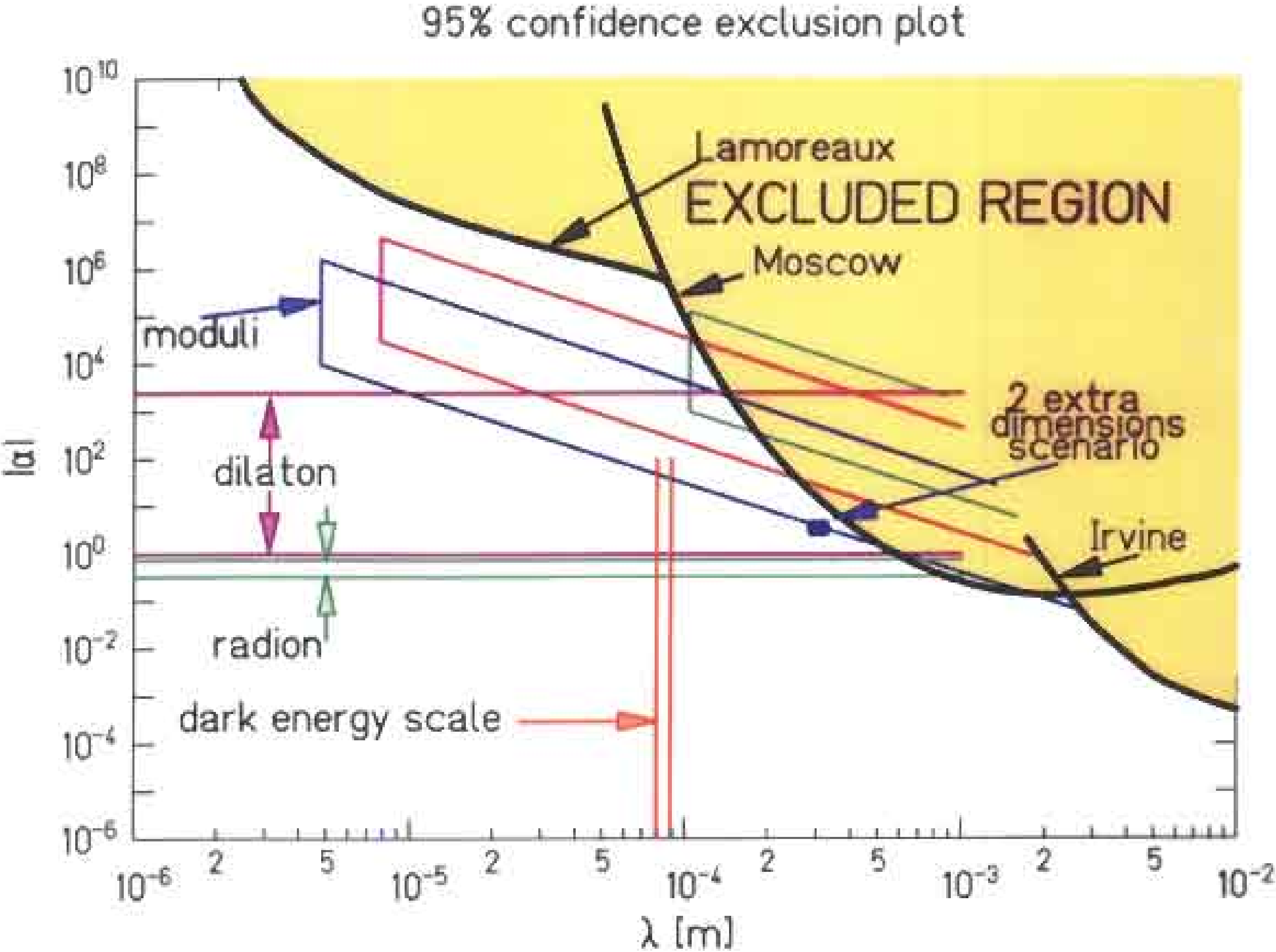


precession of perigee?

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

95% confidence limits

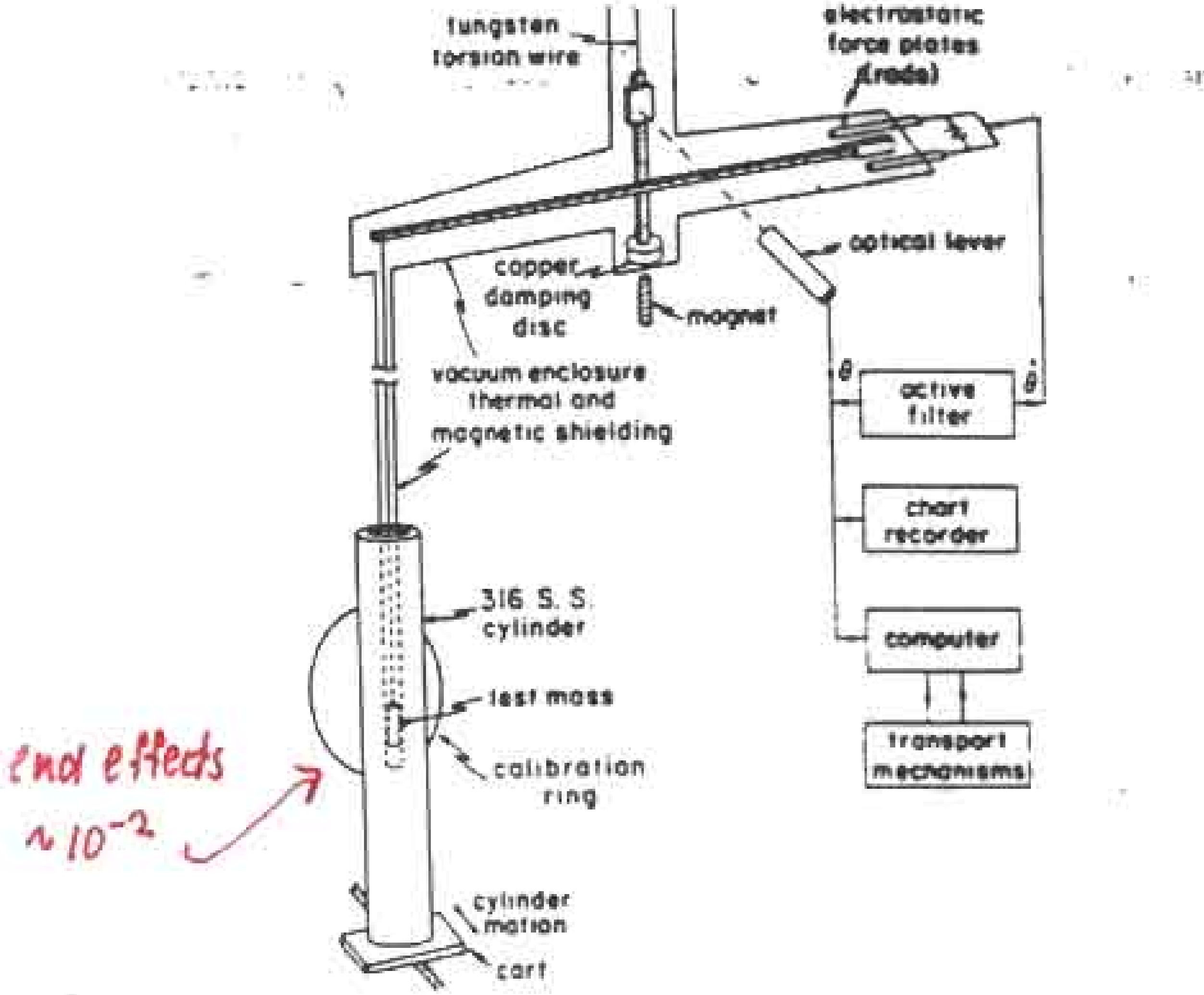




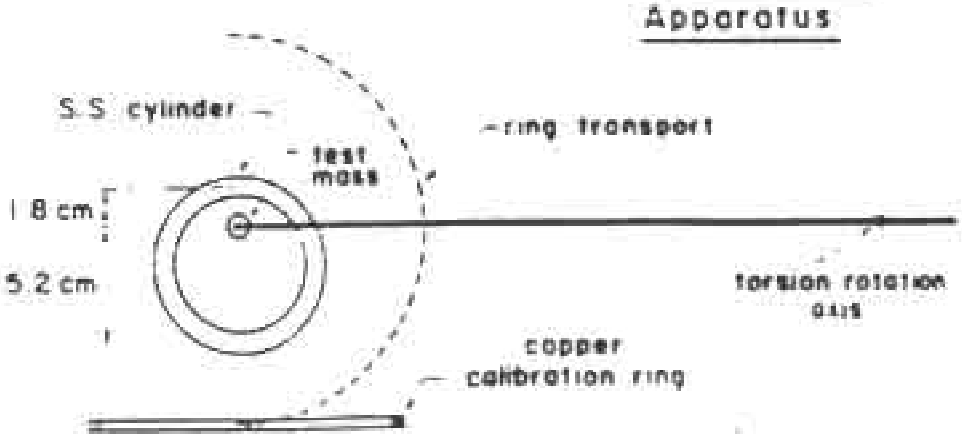
95% confidence exclusion plot
Lamoreaux
EXCLUDED REGION
Moscow
moduli
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
|α|
λ [m]

The UC Irvine test of $1/r^2$ law

Hoskins et al., Phys. Rev. D 32 (1985) 3084

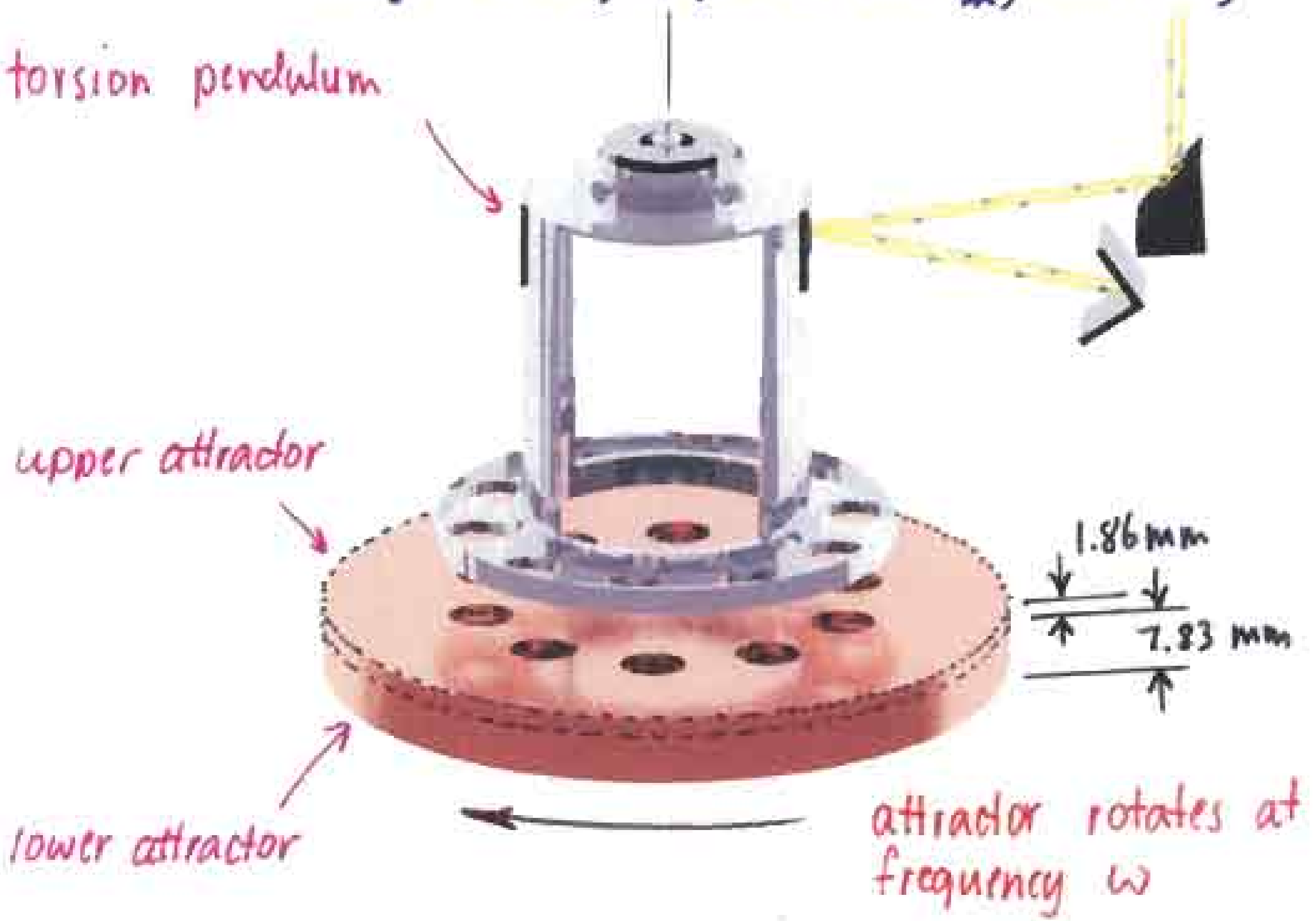


Top View of Apparatus

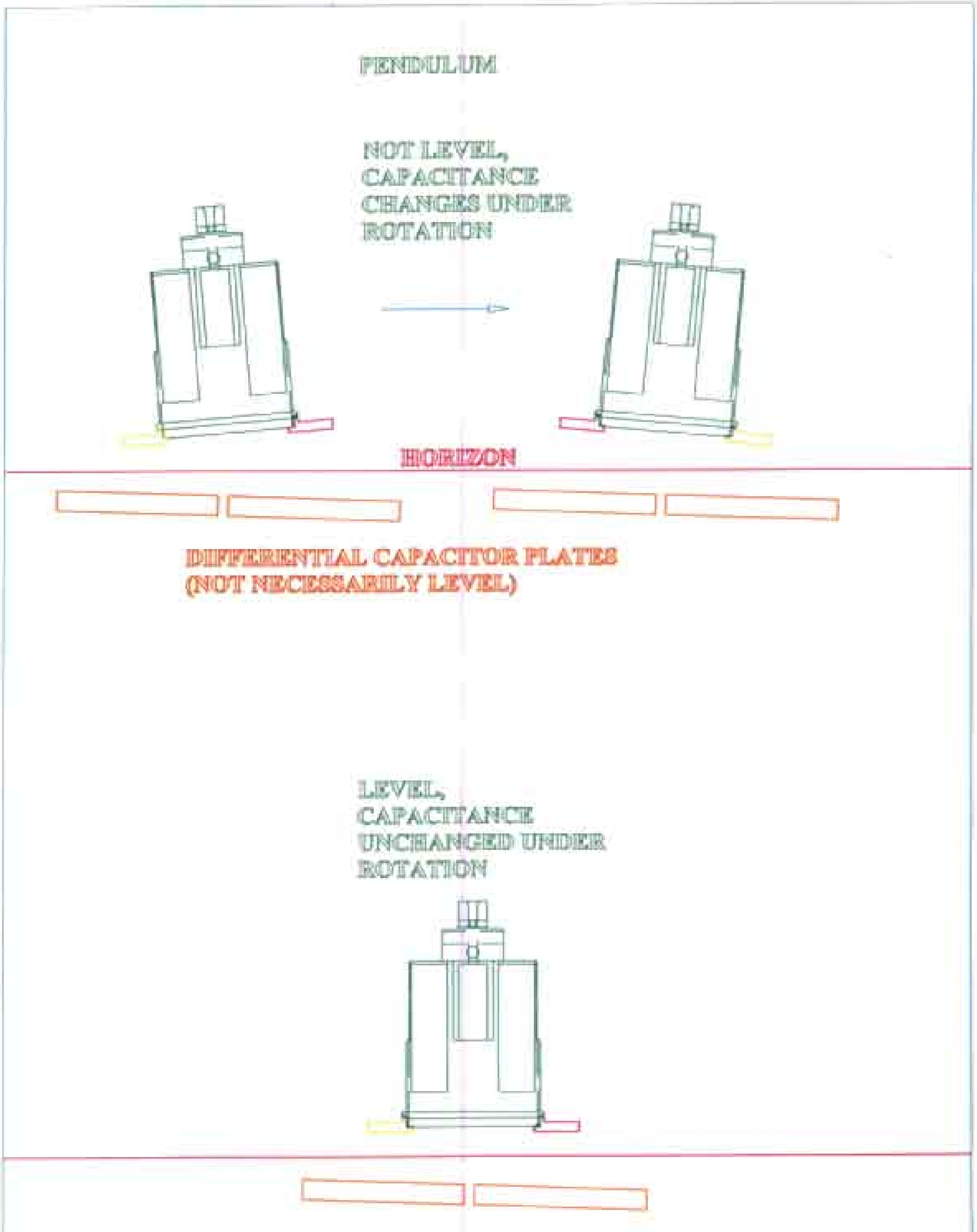


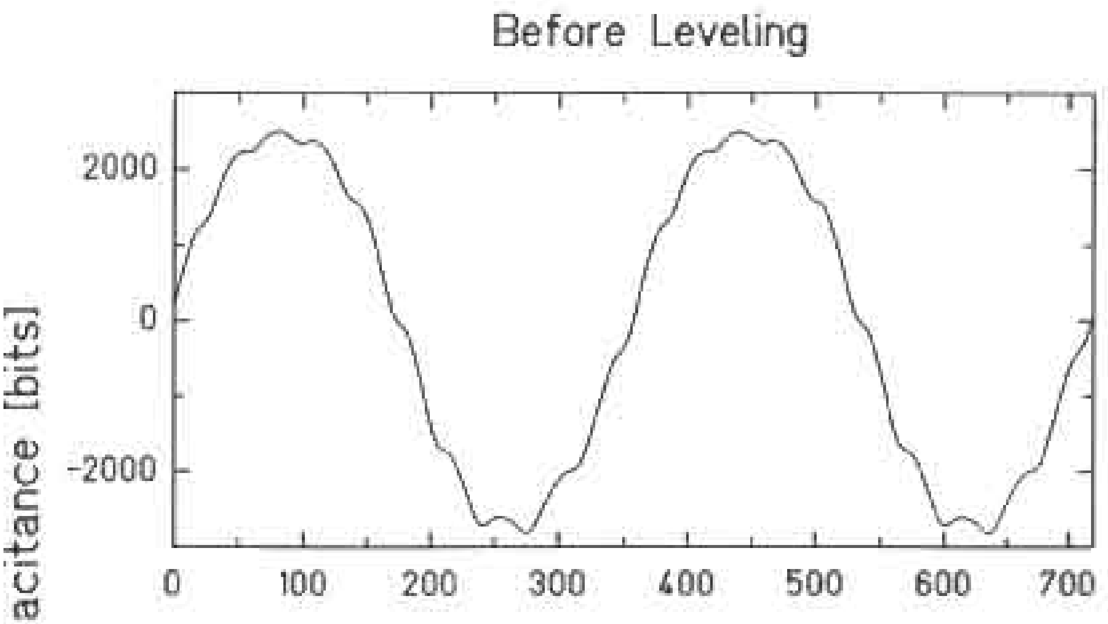
Washington short-range instrument

Hoyle et al., Phys. Rev. Lett. 86, 1418 (2001)



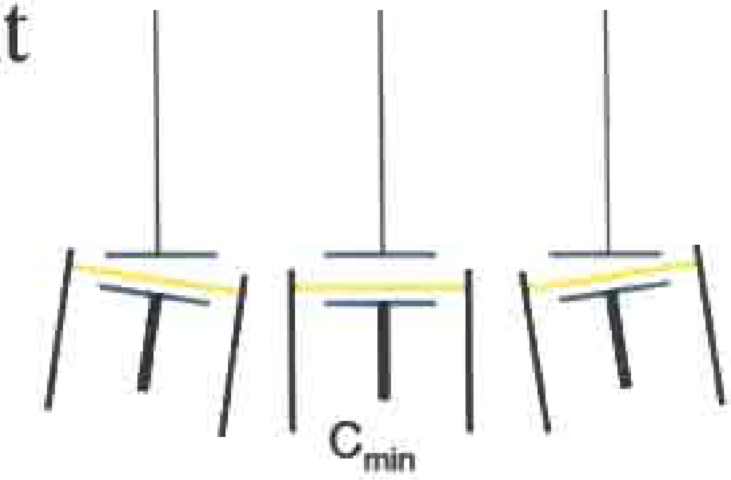
- the 10 holes in the lower attractor are "out of phase" with the holes in the upper attractor.
- this cancels Newtonian gravity torque by a factor of ~20, but has little effect on torque from short-range force
- measure z-dependence of torque signals at 10ω, 20ω and 30ω

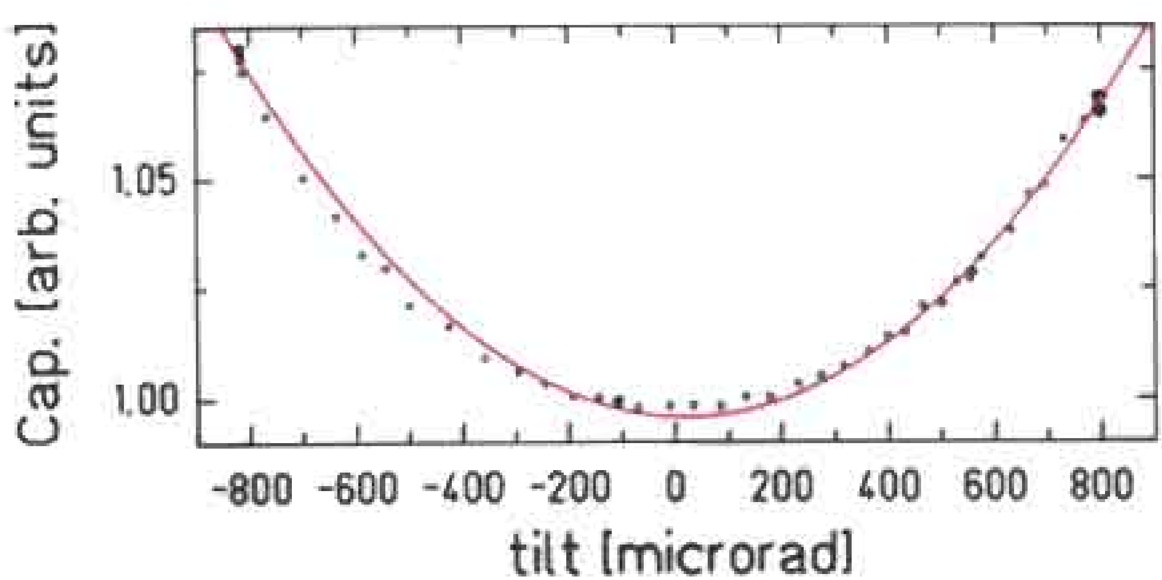

PENDULUM
NOT LEVEL,
CAPACITANCE
CHANGES UNDER
ROTATION
HORIZON
DIFFERENTIAL CAPACITOR PLATES
(NOT NECESSARILY LEVEL)
LEVEL,
CAPACITANCE
UNCHANGED UNDER
ROTATION


Before Leveling
acitance [bits]
2000
0
-2000
0
100
200
300
400
500
600
700

Alignment

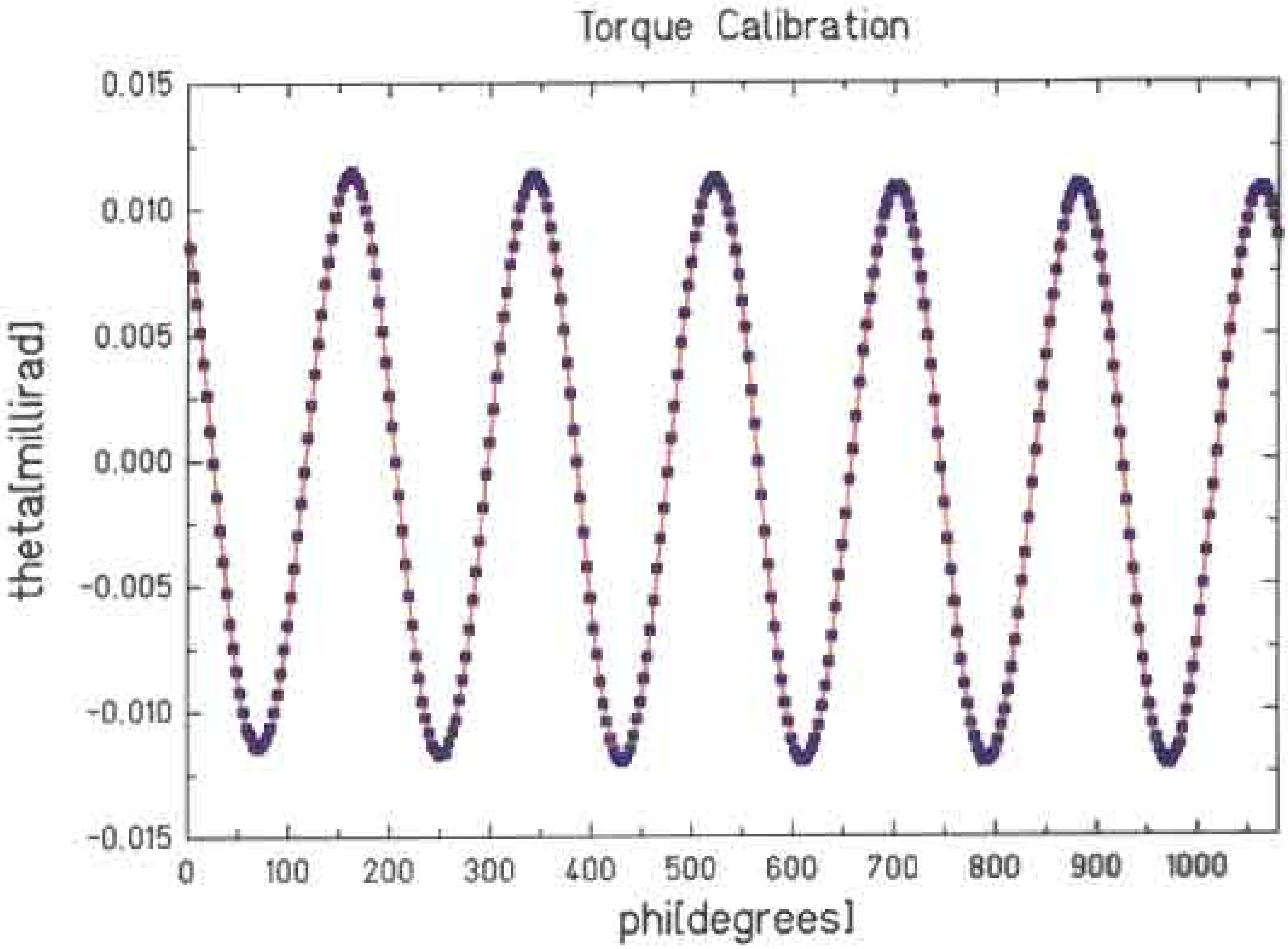
- Attractor/shield to pendulum :
  - measured using pendulum-shield capacitance, tilt sensors
  - adjusted with leveling legs of apparatus





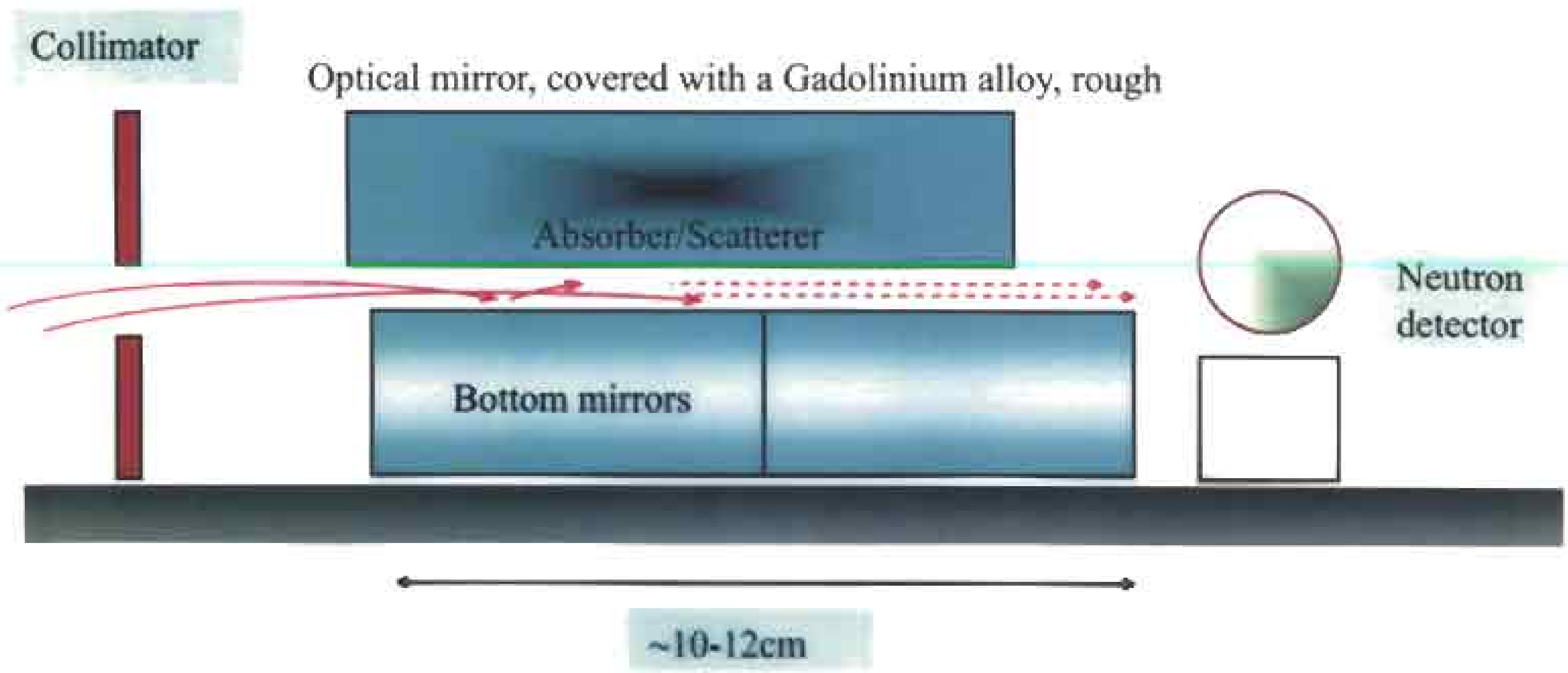
total attractor-pendulum misalignment

< 120 μrad

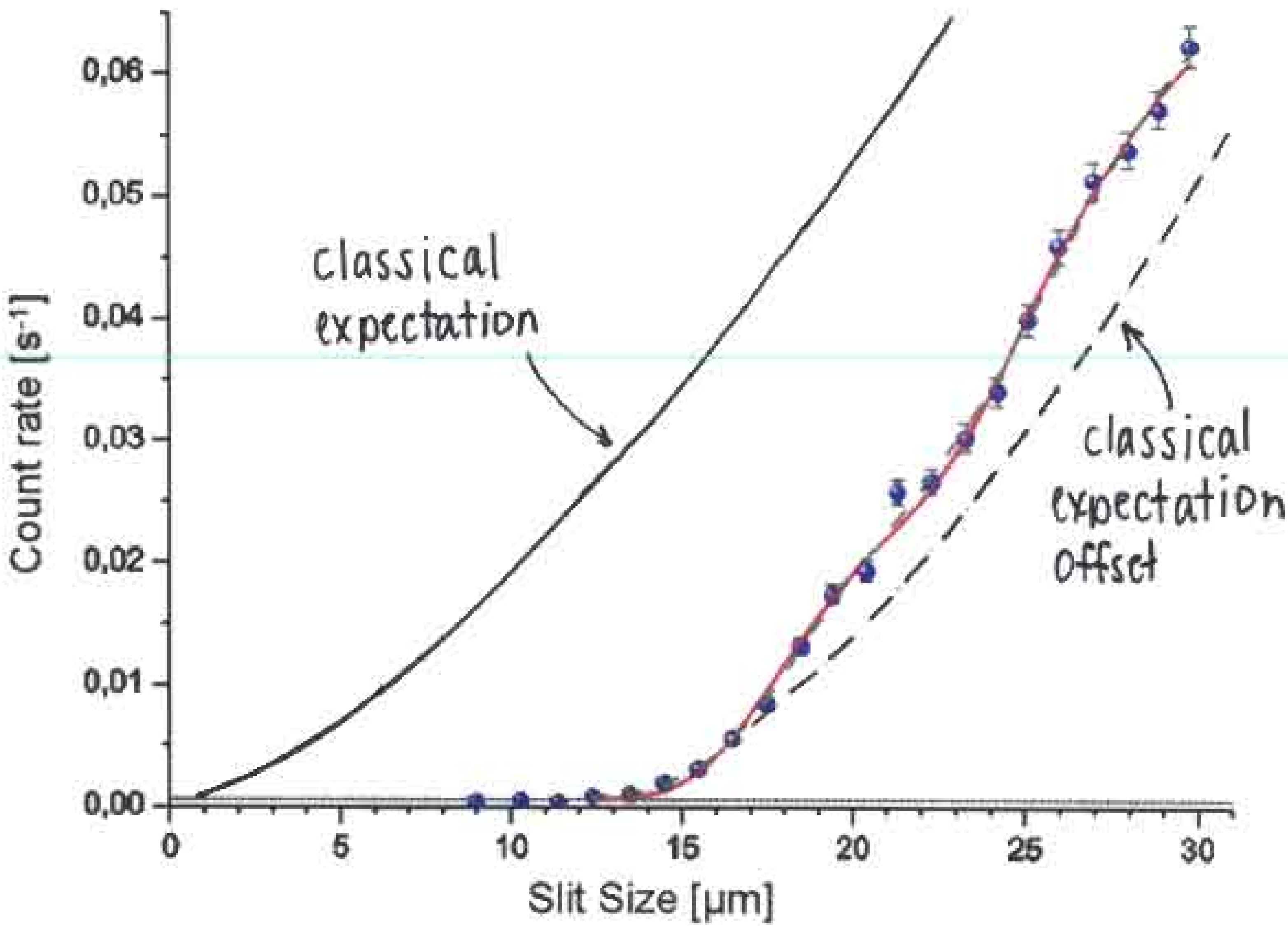


a(2ω) = 11.557 ± 0.010 μrad

GRENOBLE, GATCHINA, HEIDELBERG, MOSCOW EXPERIMENT WITH ULTRA-COLD NEUTRONS

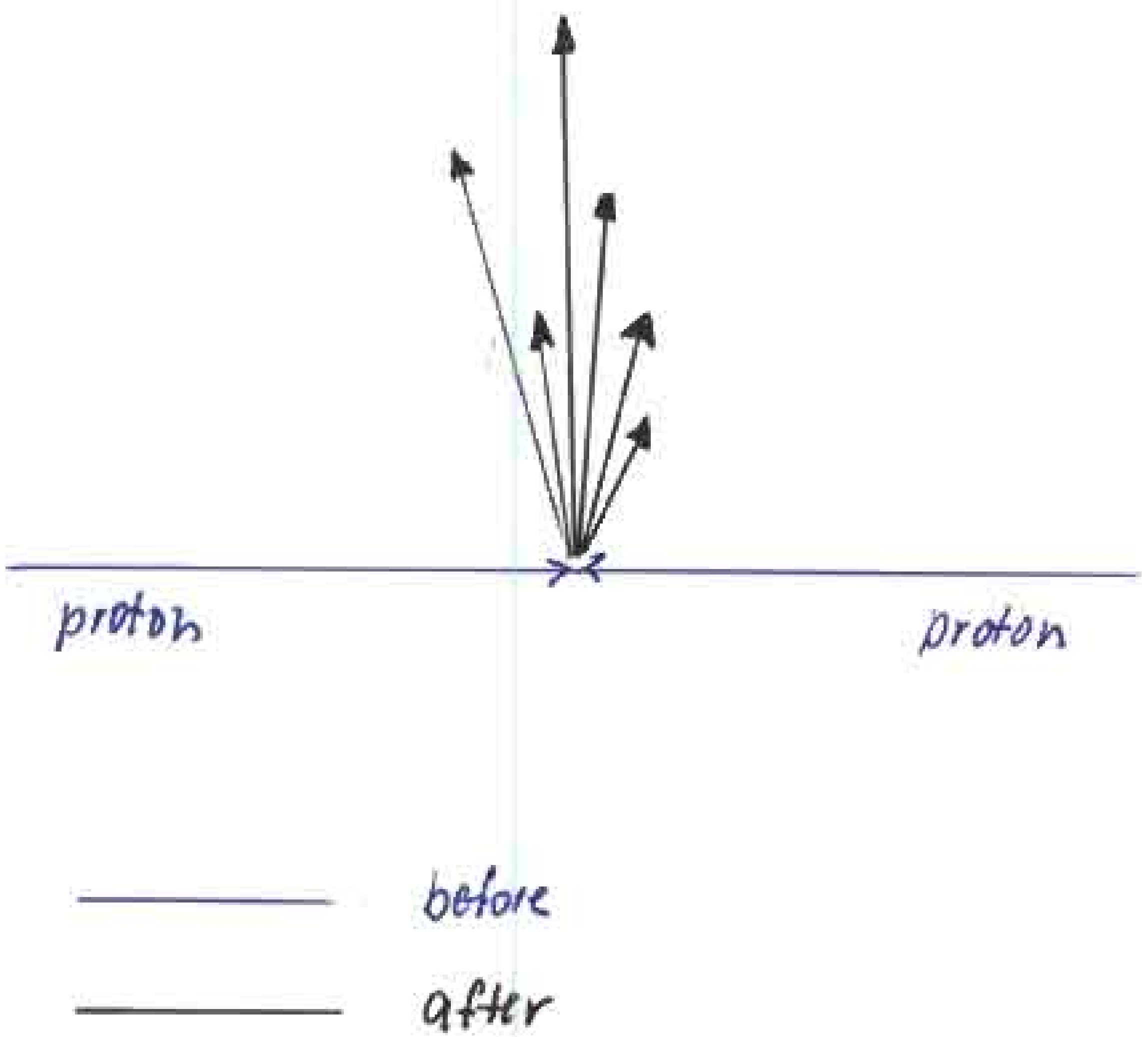


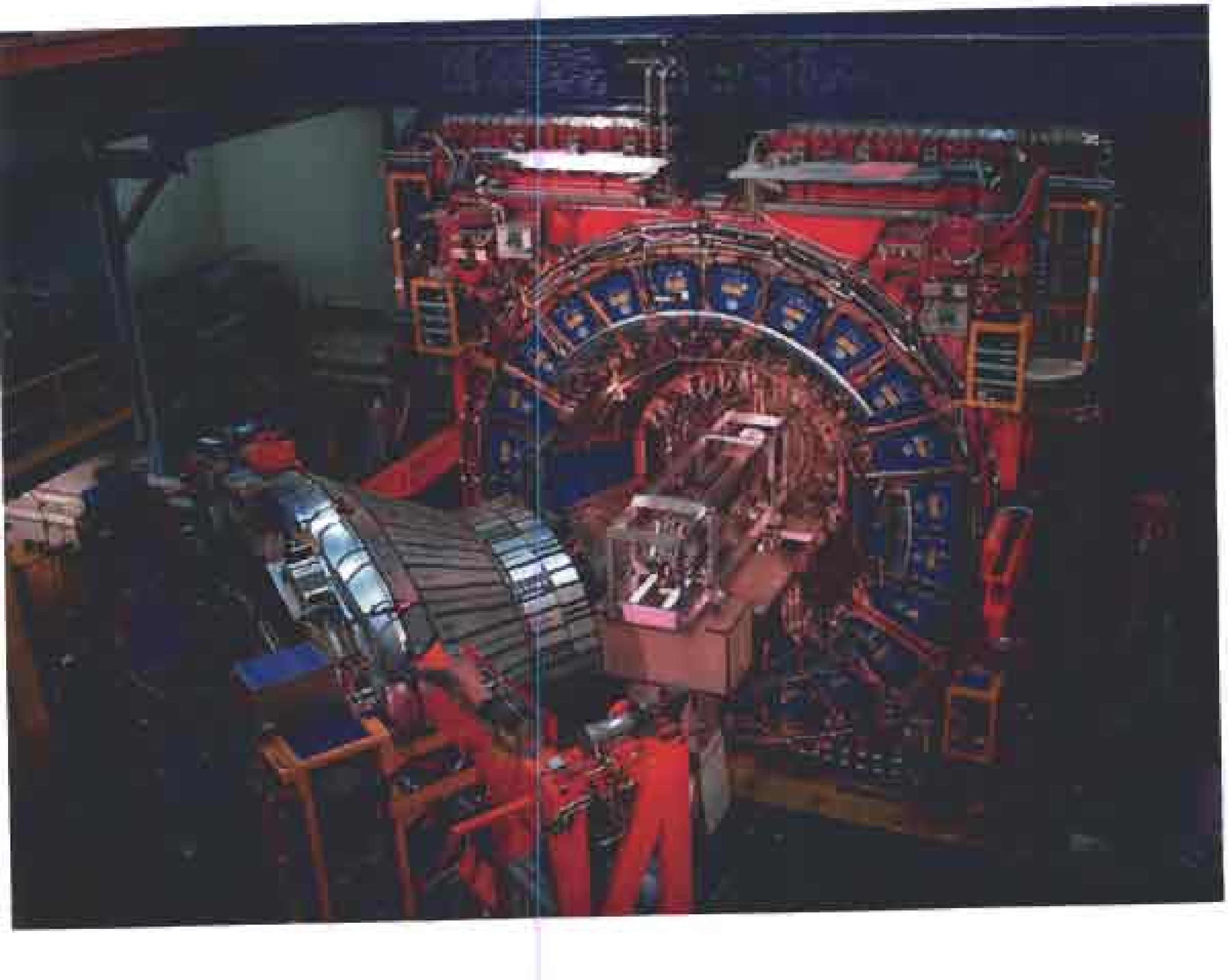
Transmission vs. Slit Size (preliminary data, 2002)



S. Baessler

brane-world effects in ultra-high energy collisions





CONCLUSIONS

- no firm evidence yet for a breakdown of $1/r^2$ law
- entirely possible that we live on a 3+1 dimensional brane
- $1/r^2$ experiments are probing interesting regime

  these tests sensitive to scenarios with varying number of "large" extra dimensions
- hints of anomalies are intriguing
- speculations abound
- experiments not yet limited by fundamental considerations
- it is a very exciting time!

Experimental Citations

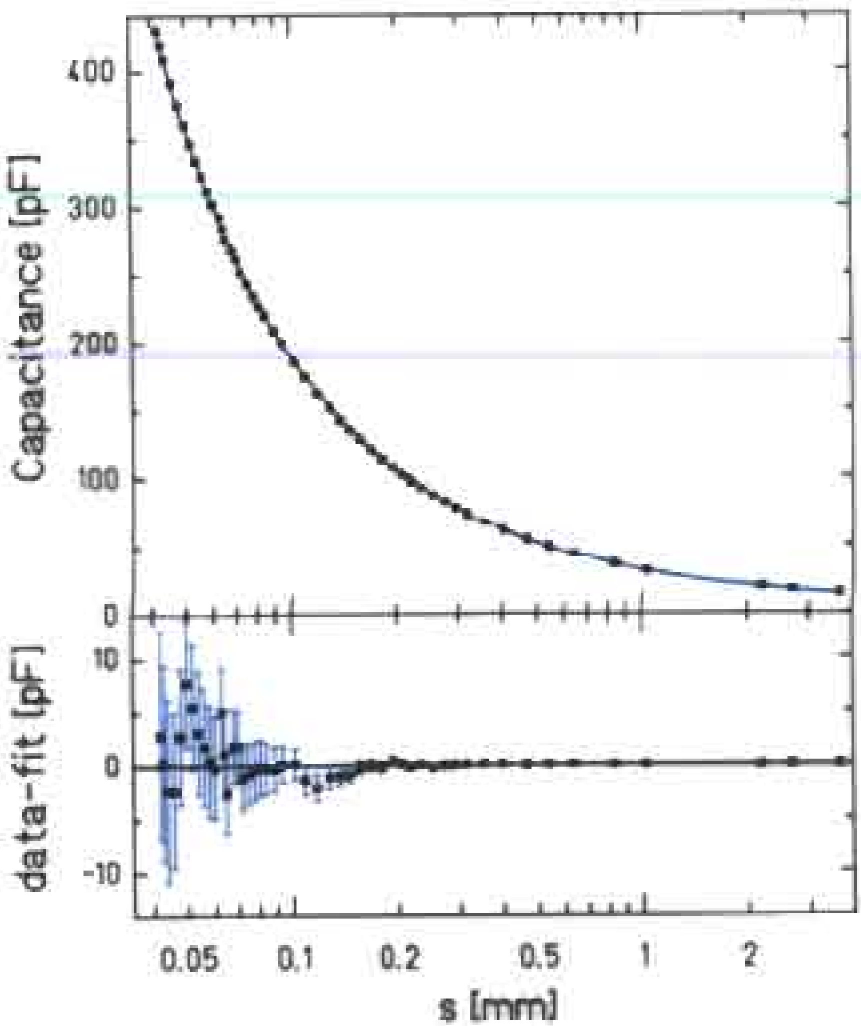
- C.D. Hoyle et al., PRL **86**, 1418 (2001).
- V. Nesvizhevsky et al., Nature **415**, 297 (2002).
- J.C. Long et al., Nature **421**, 922 (2003)
- J. Chiaverini et al., PRL **90**, 15101 (2003).
- C.D Hoyle et al., PRD **70**, 042004 (2004).

Reviews

- E.G. Adelberger, B.R. Heckel & A.E. Nelson
  Ann. Rev. Nucl. Part. Sci. (2003) p.77
  hep-ph/0307284 (2003)
- J. Hewitt & M. Spiropulu.
  Ann. Rev. Nucl. Part. Sci. (2002) **52**, 397
- R. Sundrum
  hep-th/0306106 (2003)
  PRD **69**, 044014 (2004)

Eöt-Wash Mark II short-range instrument

Positioning



x,y,z read out to +/- 1μm

C vs. z compared to finite element calculation.

Error bars dominated by 1 μm uncertainty in z at short distances.

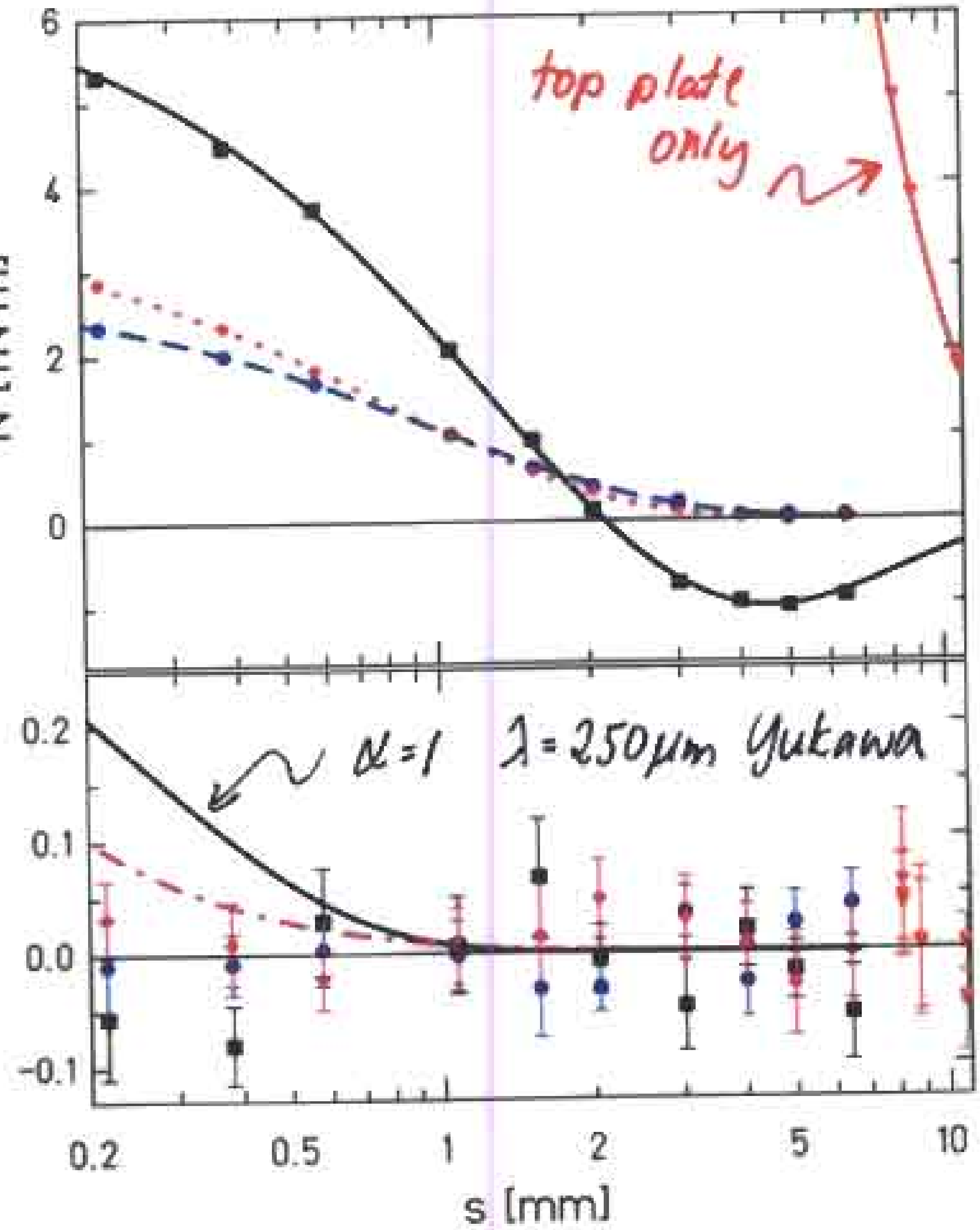
C tells us distance to screen reliably at short distances. Indicator suffices for larger distances.

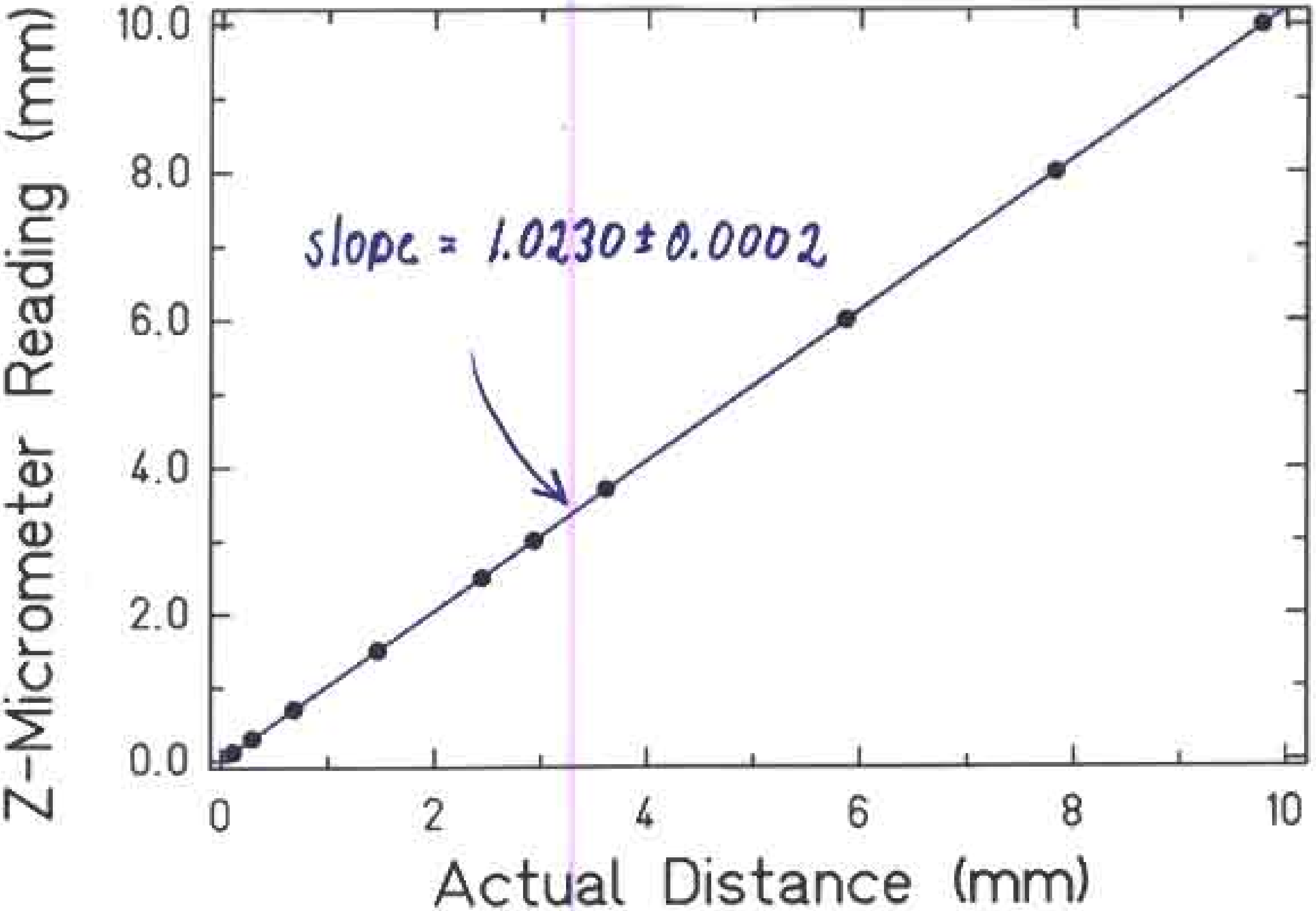
Hoyle et al. 10-hole data

— 10 w torque

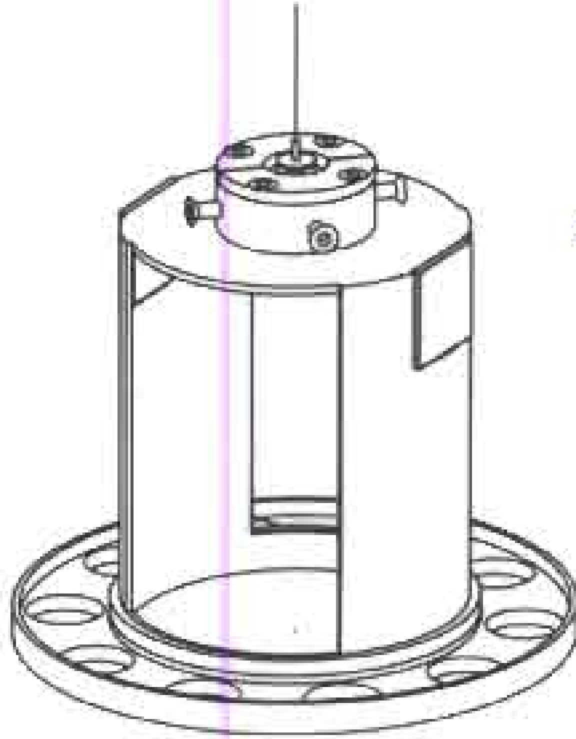
- - - 20 w torque

• • • • 30 w torque

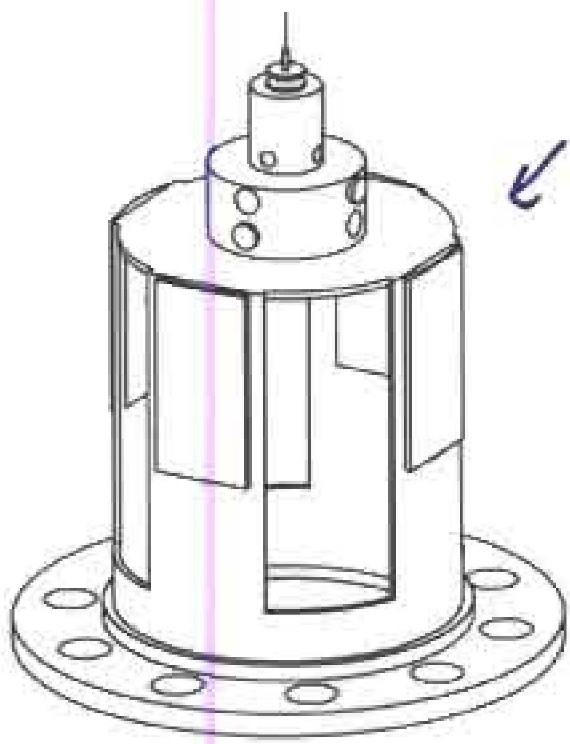




slope = 1.0230±0.0002
Z-Micrometer Reading (mm)
0.0
2.0
4.0
6.0
8.0
10.0
0
2
4
6
8
10
Actual Distance (mm)



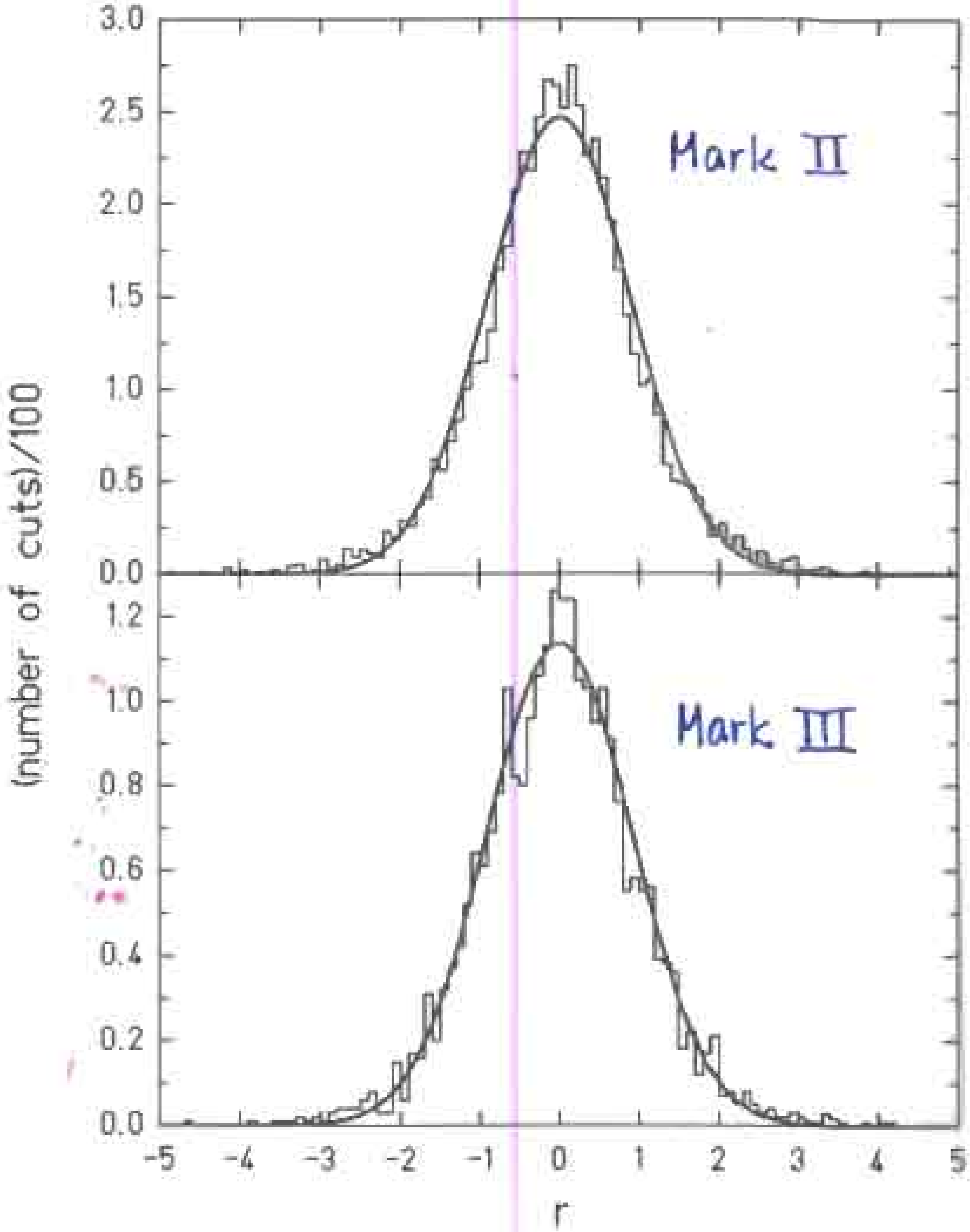
Mark II

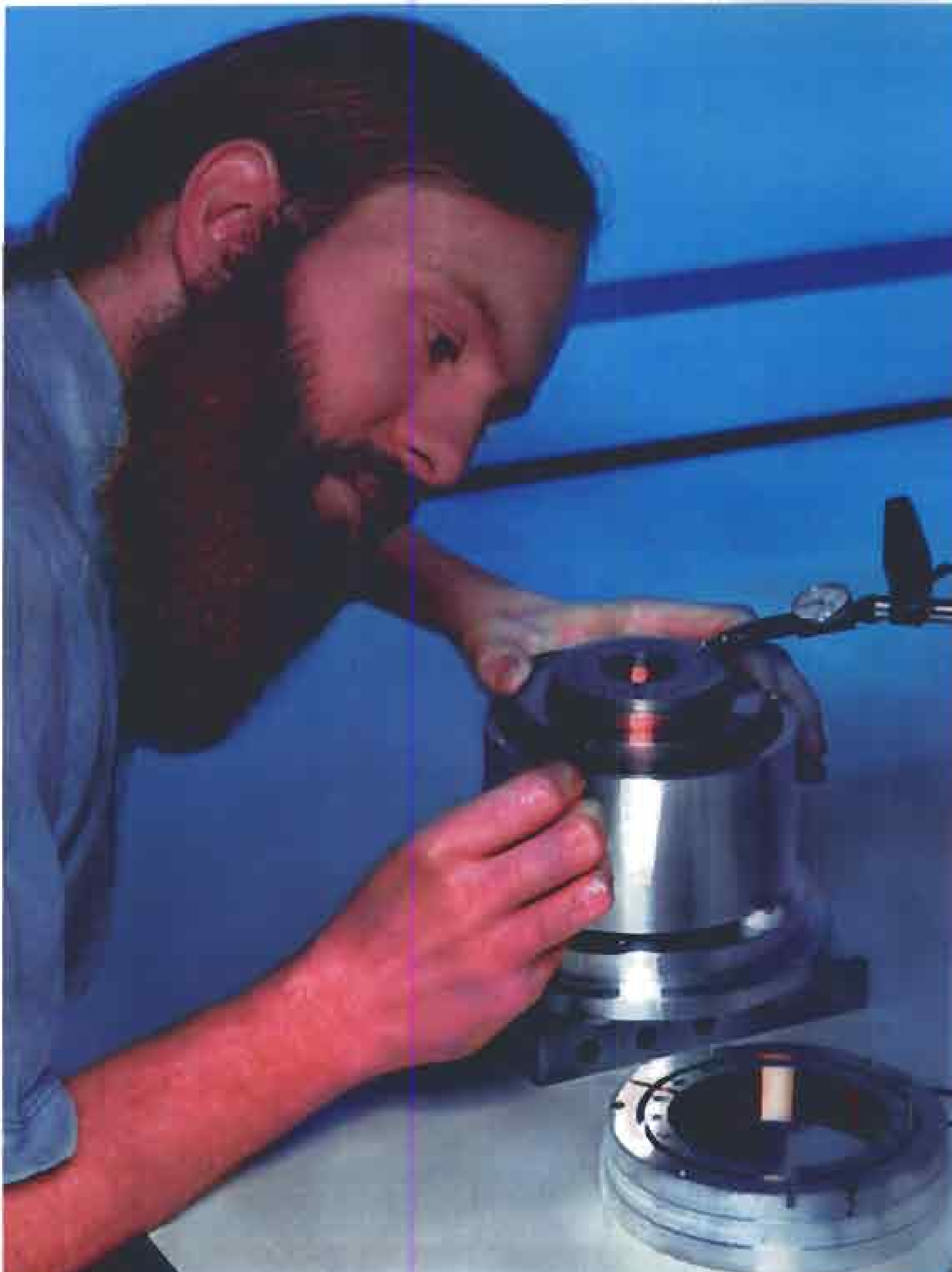


Mark III

Distribution of the Individual Torque Measurements

$$\sum_{run} \sum_{i} \frac{T_i(run) - \overline{T}(run)}{\Delta T(run)}$$





Hi Eric,

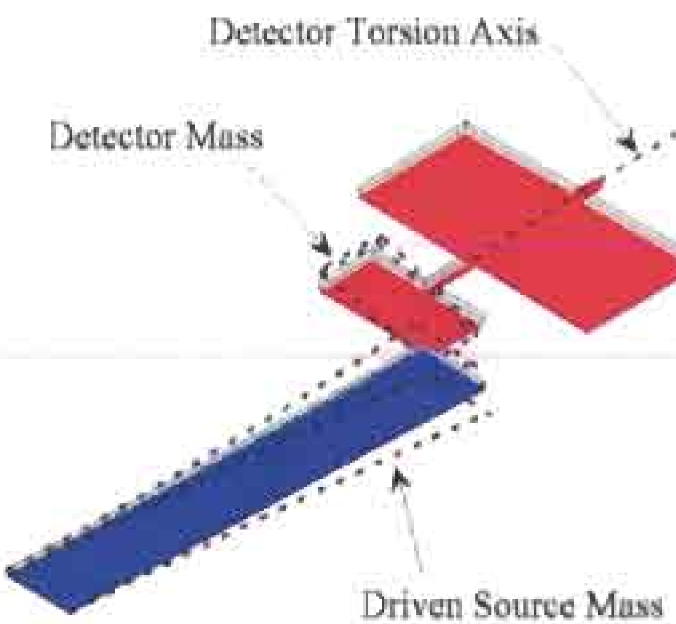
The brochure we have been making had 2 month long delay due to a bureaucratic problem getting the purchase order written. During that time we have been showing the brochure to the non-physicist public. The most common complaint has concerned the long-bearded student in the photo of your apparatus. This photo appears in a very prominent place, and many people found it very distracting.

As a person with a beard, I am quite embarrassed to raise this matter with you. Nonetheless our group would like to find a solution. There are several possibilities:
1) The artist can make the beard much shorter in Photoshop.
2) You can take a new photo with a new person (perhaps a woman).
3) The artist can insert another person.
To be honest, solution 2 is the preferred solution.

I know this is an unpleasant matter, but I am appealing for your help. This brochure is intended to sell physics (at a time of crisis in funding). Under any other circumstances I wouldn't think of changing the photo, but we have to deal with the public reaction we have actually observed.

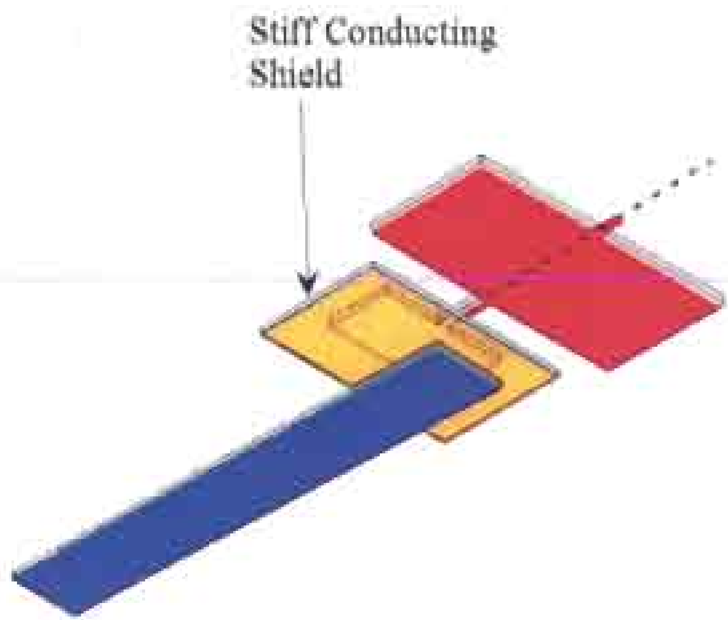
Long et al., Nature 421, 922 (2003)

Planar Geometry



$F_Y(\alpha=1, \lambda=100\,\mu m) \approx 1\times10^{-14}\,N$

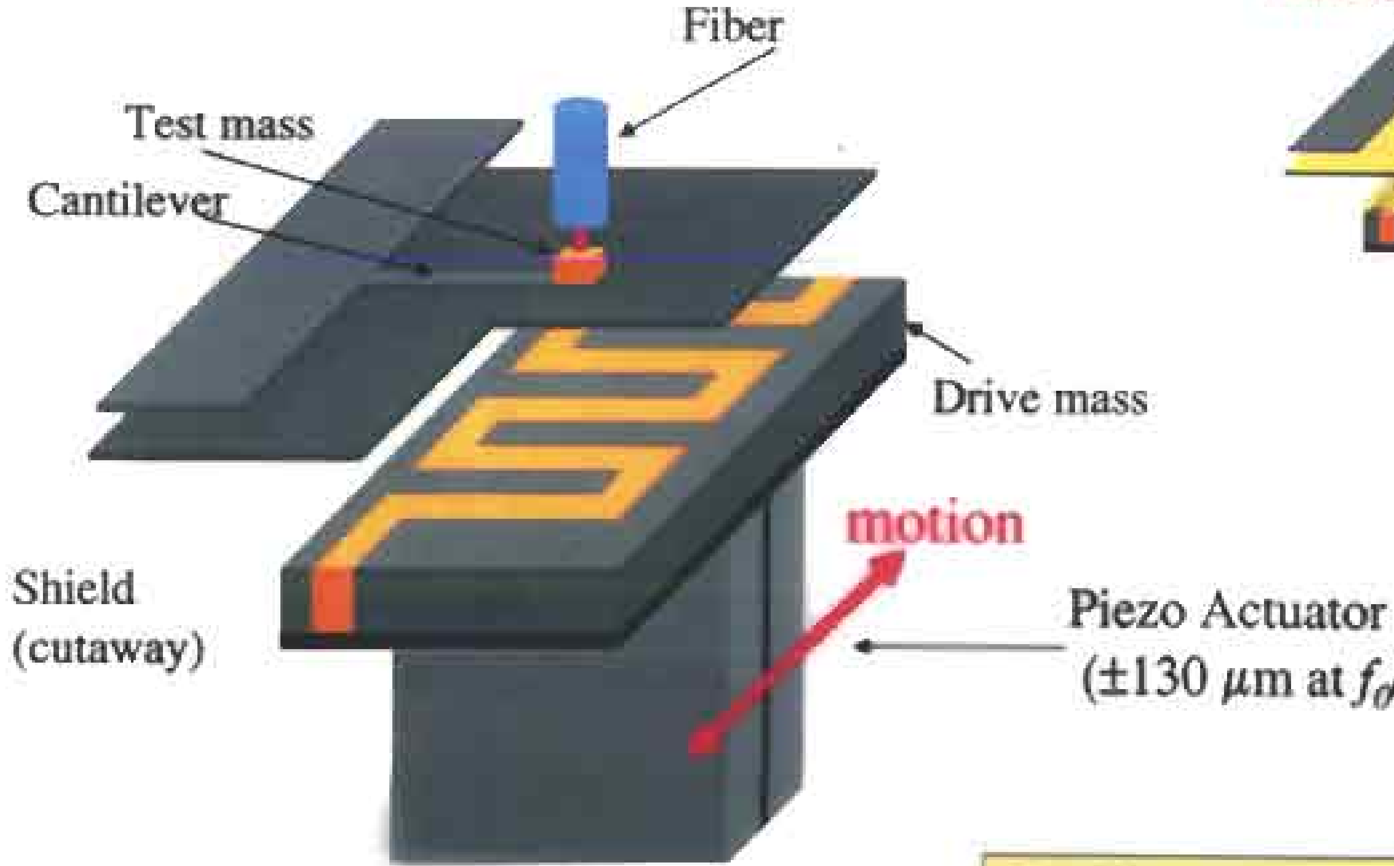
Source and Detector Oscillators

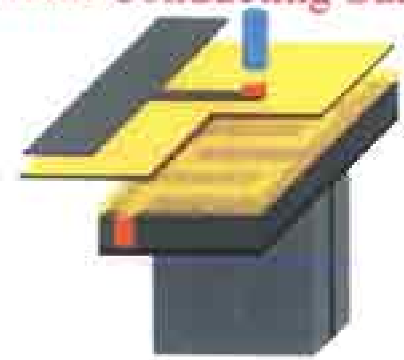


Shield for Background Suppression

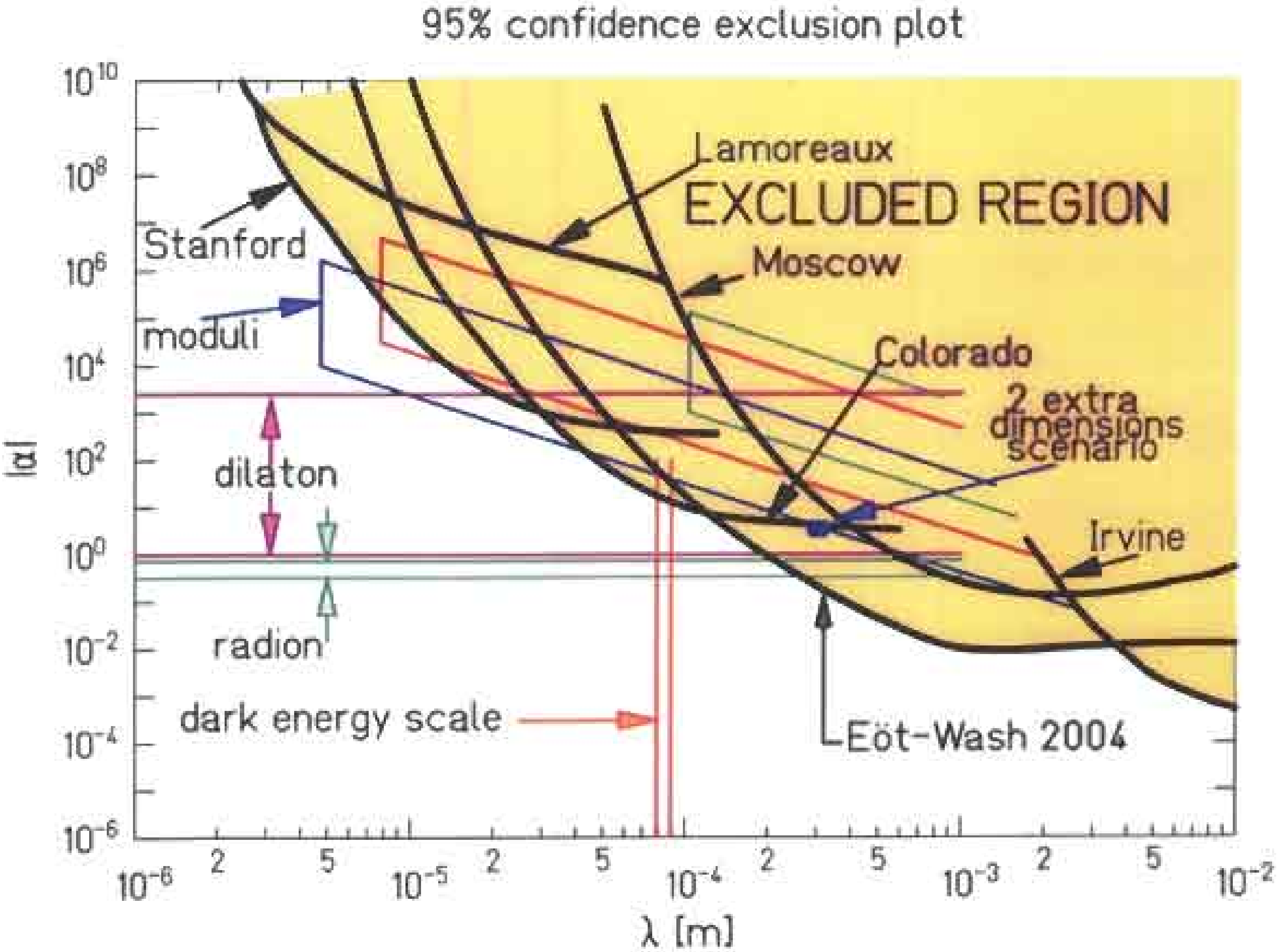
Stanford's Experiment

Chiaverini et al., Phys. Rev. Lett. 90, 151101 (2003)



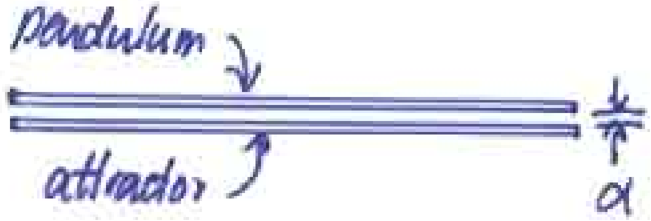


Cantilever resonance (f_0): ~300 Hz
Drive frequency($f_0/3$): ~100Hz


95% confidence exclusion plot
EXCLUDED REGION
Lamoreaux
Stanford
Moscow
moduli
Colorado
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
Eöt-Wash 2004
|α|
λ [m]

Scaling relations for detector sensitivity to new short-range physics

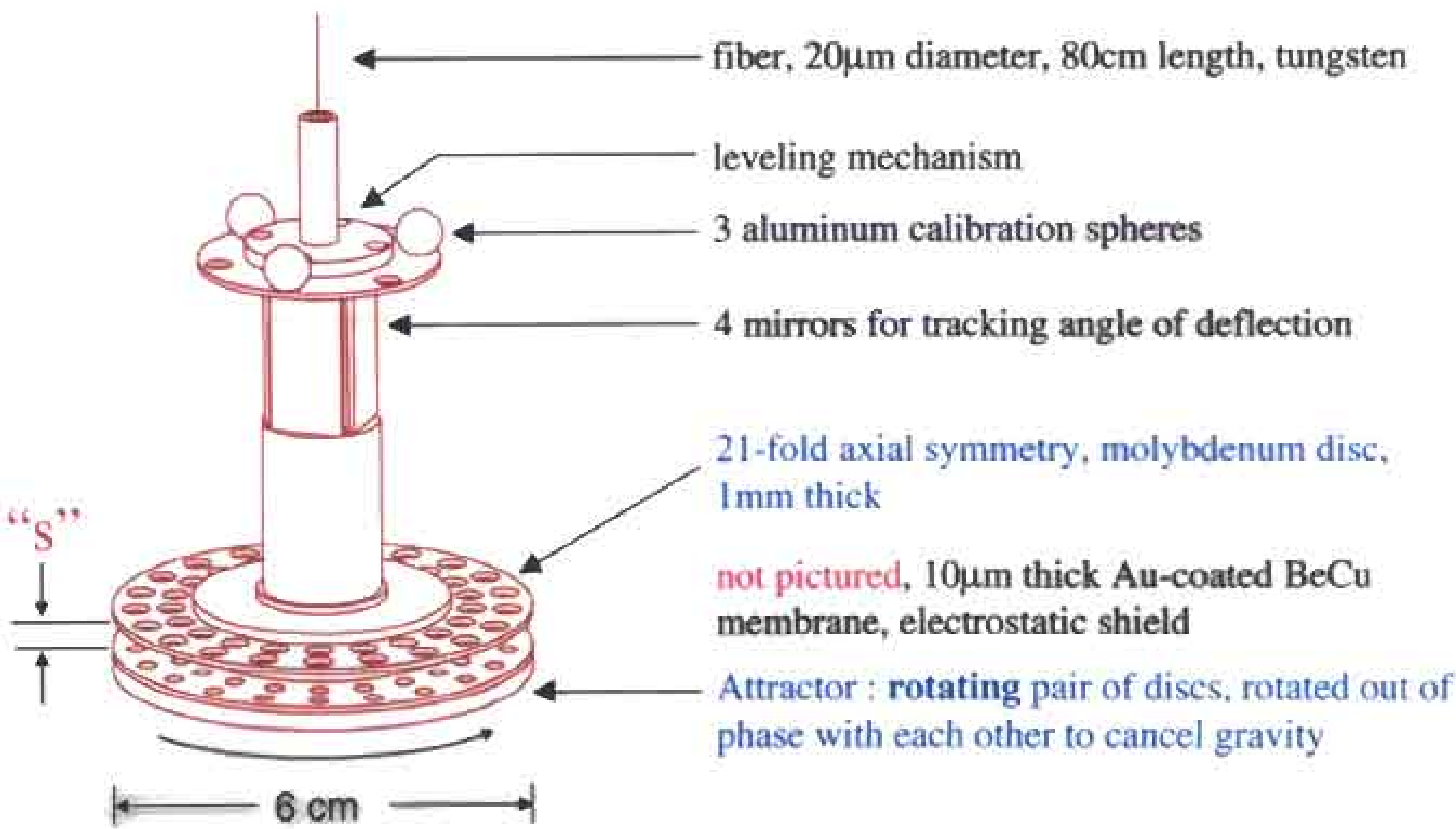
$$\text{torque} = N_{s.r.} = \frac{\Delta E_{s.r}}{\Delta \theta}$$



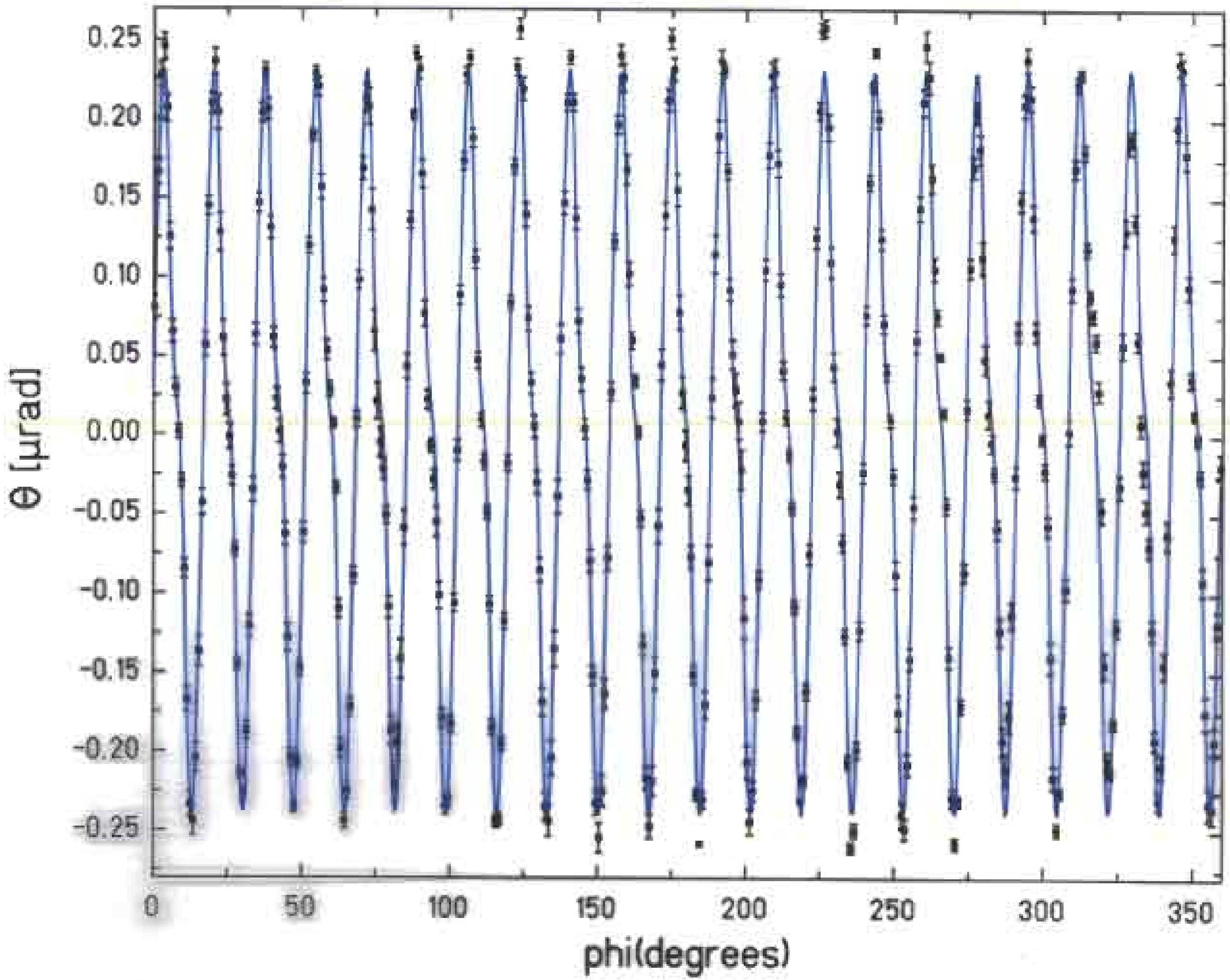
$$E_{s.r} = A \rho_1 \rho_2 \lambda^3 e^{-d/\lambda}$$

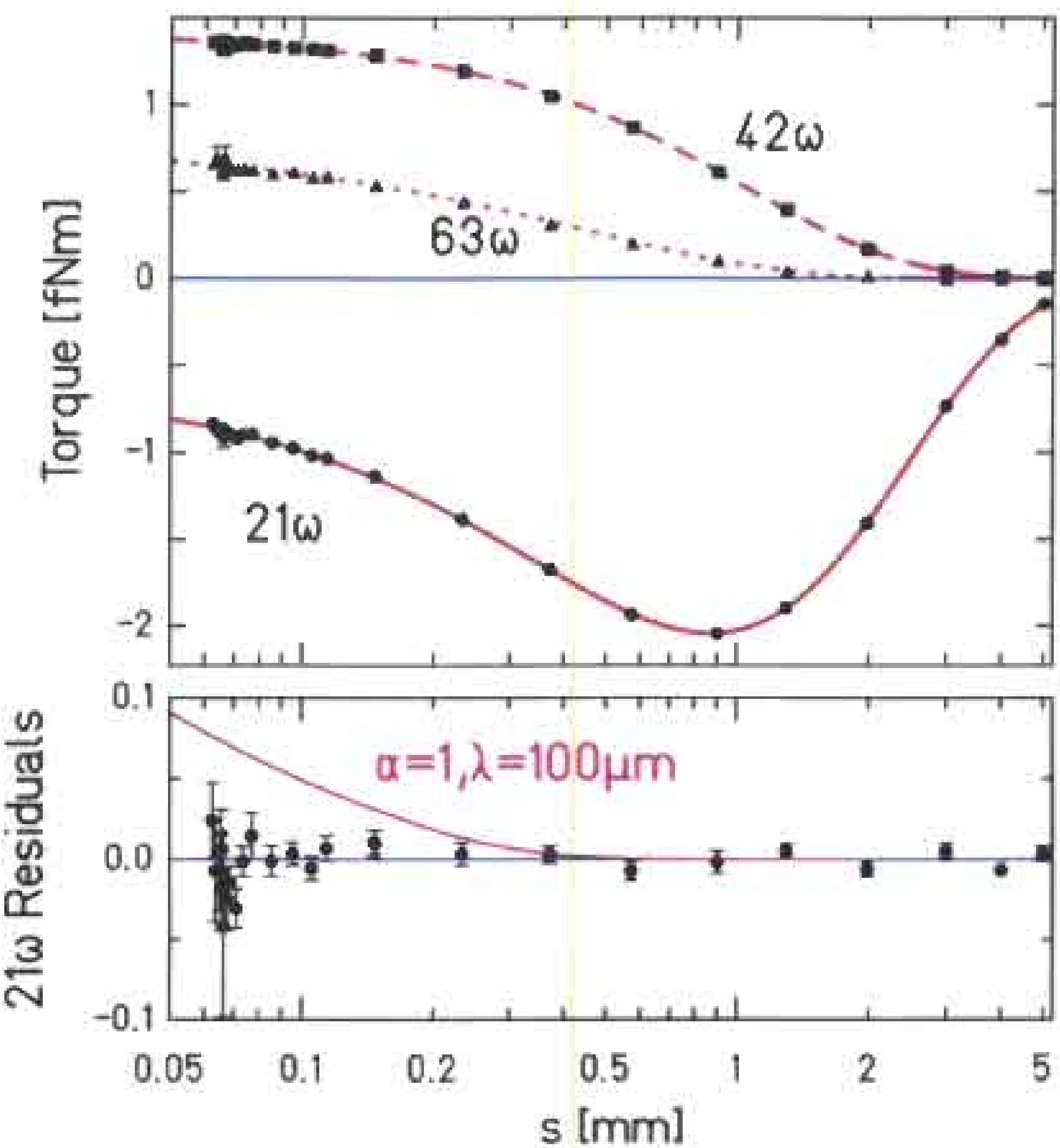
$$N_{s.r} = \frac{\Delta A}{\Delta \theta} \rho_1 \rho_2 \lambda^3 e^{-d/\lambda}$$

21-Hole Torsion Pendulum

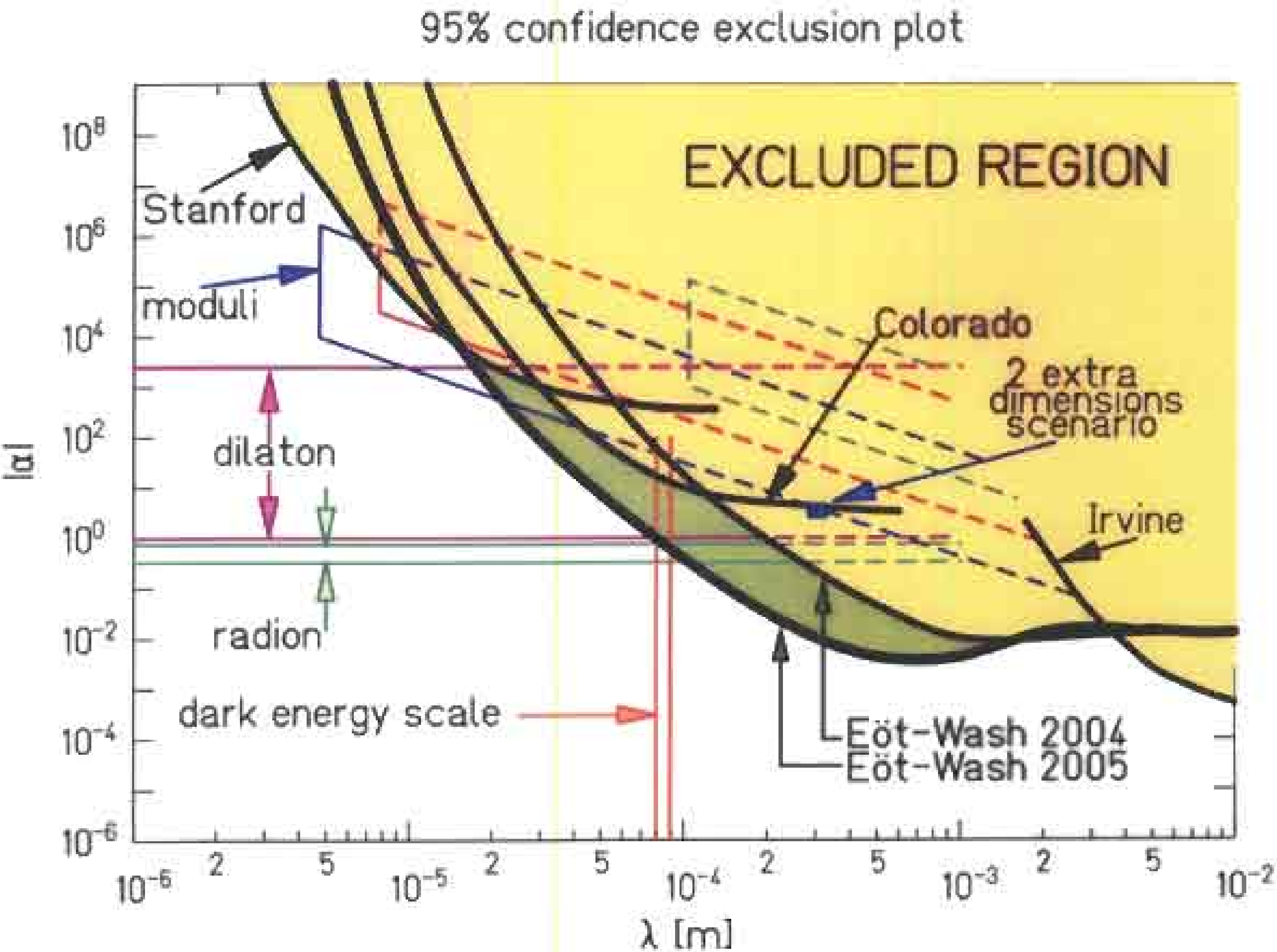


42-hole data taken at a separation of 75 μm





Torque [fNm]
1
0
-1
-2
42ω
63ω
21ω
21ω Residuals
0.1
0.0
-0.1
α=1,λ=100μm
0.05
0.1
0.2
0.5
1
2
5
s [mm]


95% confidence exclusion plot
EXCLUDED REGION
Stanford
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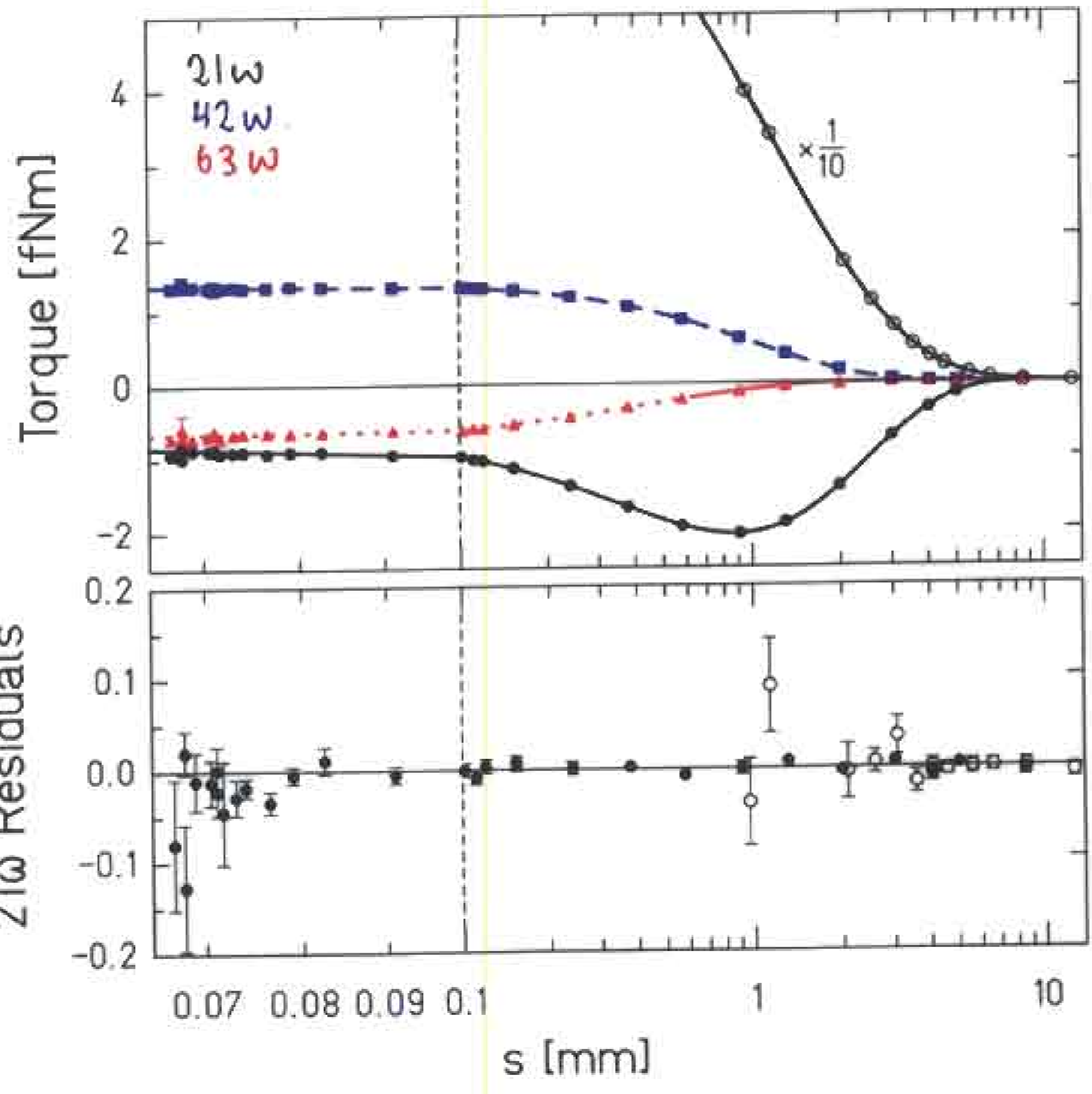
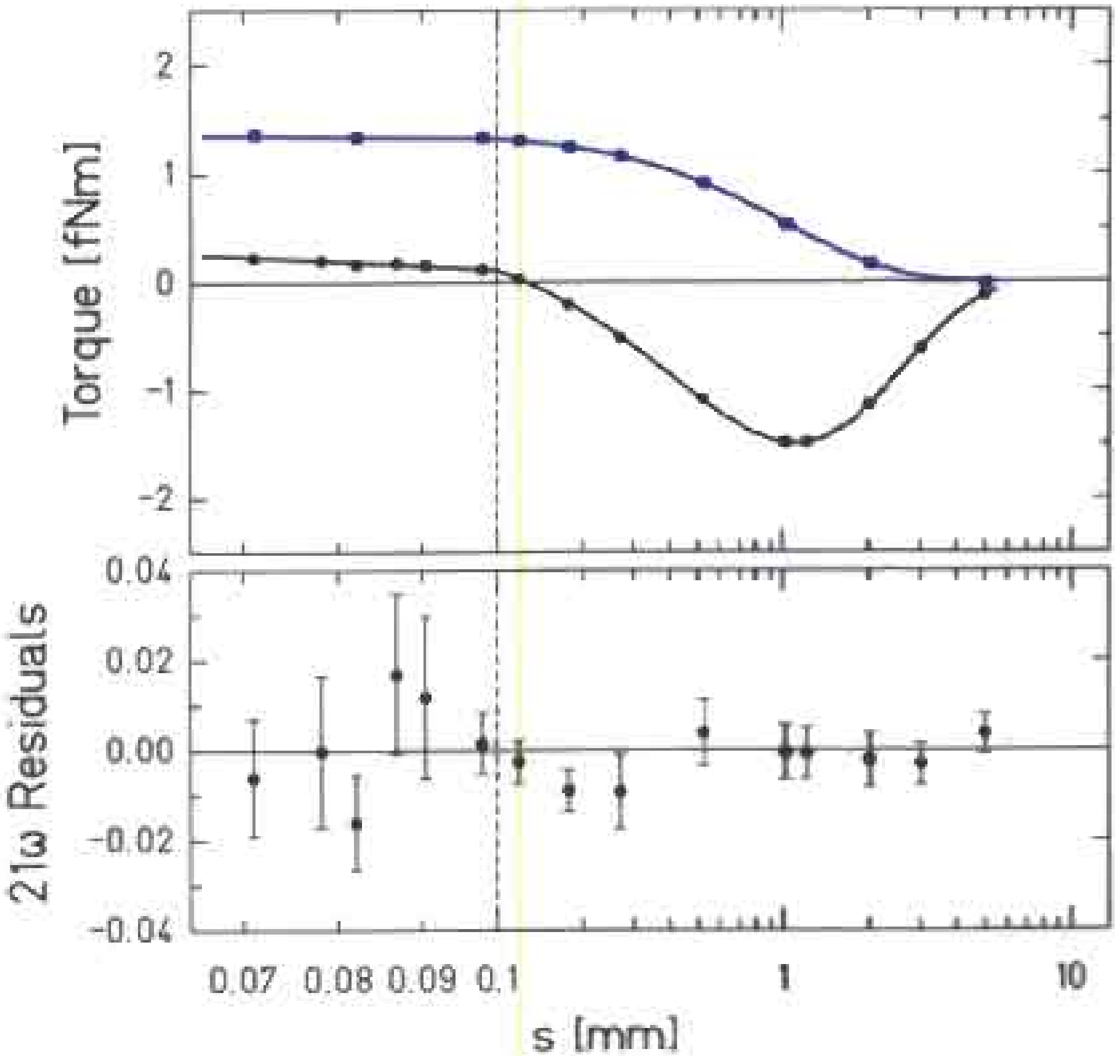
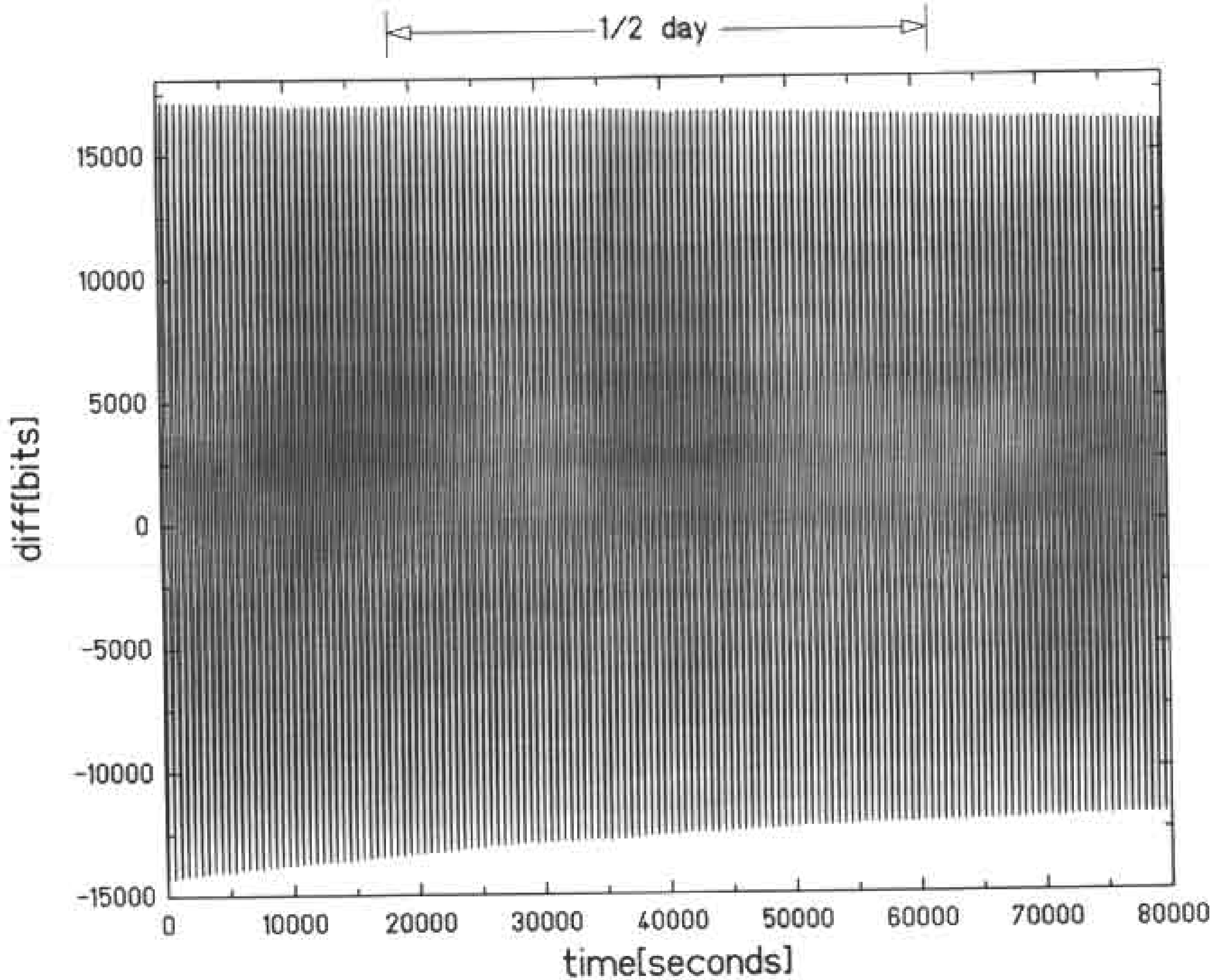
dark energy scale
Colorado
2 extra dimensions scenario
Irvine
Eöt-Wash 2004
Eöt-Wash 2005
|α|
λ [m]

data taken with $\omega = \frac{\omega_0}{28}$

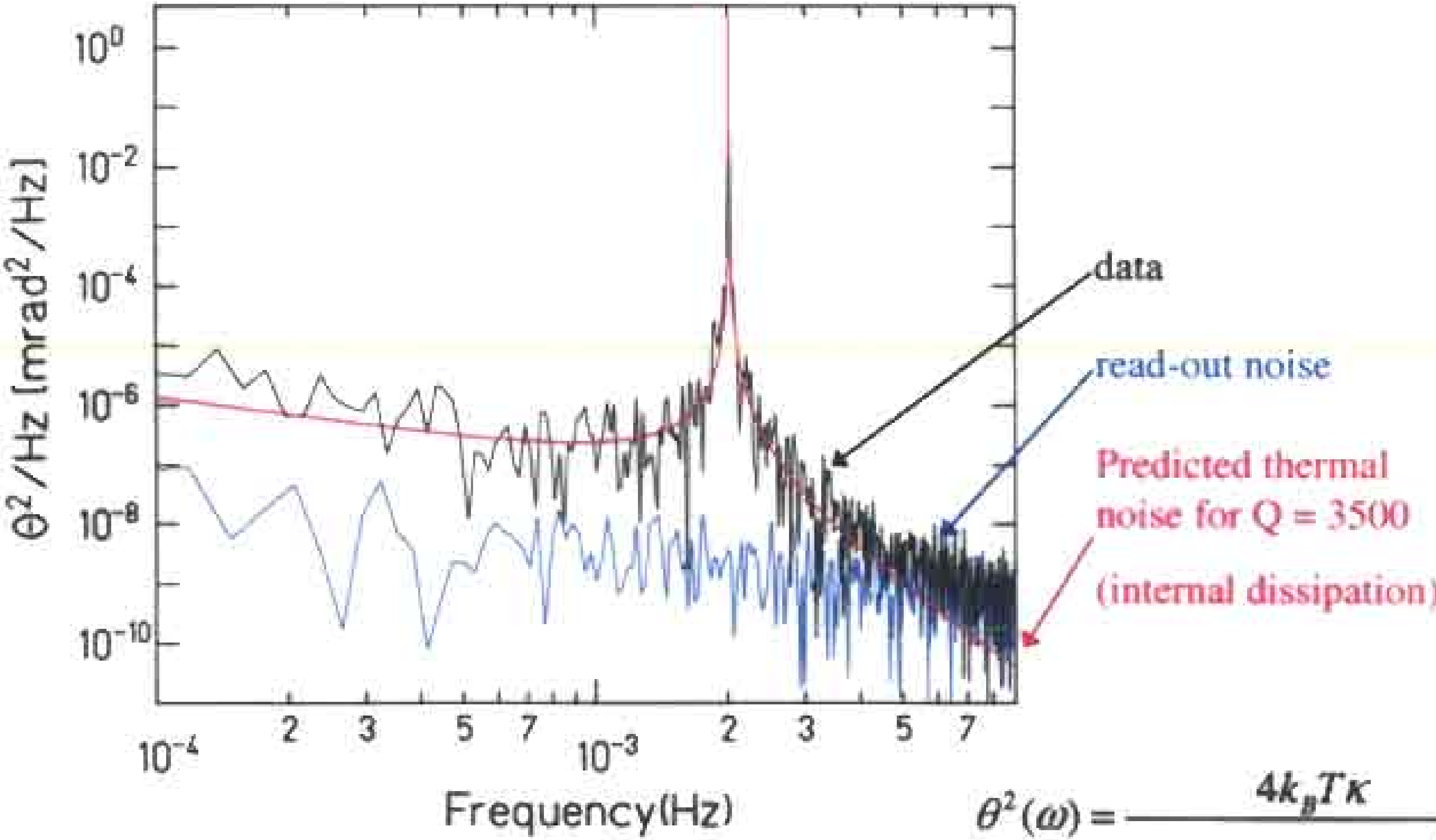




Torque [fNm]
2
1
0
−1
−2
21ω Residuals
0.04
0.02
0.00
−0.02
−0.04
0.07
0.08
0.09
0.1
1
10
s [mm]


1/2 day
diff[bits]
15000
10000
5000
0
-5000
-10000
-15000
0
10000
20000
30000
40000
50000
60000
70000
80000
time[seconds]

Noise



$$\theta^2(\omega) = \frac{4k_B T\kappa}{Q\omega[(\kappa - I\omega^2)^2 + \frac{\kappa^2}{Q^2}]}$$

- We see an apparent deviation at small distances ($s < 100\mu m$)

- Is this real?

  - check for experimental artifact by shaving 140 μm off lower attractor plate

    greatly reduces Newtonian 21ω torque, but has essentially no effect on short-range interaction

  - if anomaly persists, must distinguish between new 'gravitational' physics & subtle EM effect

    replace Mo detector ring with Al ring of same dimensions

    gravity force reduced by ρ_{Al}/ρ_{Mo}

    but EM effects virtually unchanged

SOME INTERESTING NUMBERS

- typical torque in our 42-hole experiments ~ 1 fN-m, with statistical uncertainty of ~ 0.006 fN-m
- corresponding gravitation force is $\sim (40 \pm 0.24)$ fN

can get an idea how small this is by cutting a postage stamp into 10^{12} equal pieces

typical force in 21-hole experiment is 60x weight of one of those pieces

statistical error is $\sim \frac{1}{3}$ weight of one of those pieces

Wedge Pendulum

120 Fold Symmetric
~~Tungsten~~ Pendulum
(50μm Thick)

Rhenium

(Preliminary Design)

SUMMARY

- to probe the <u>true</u> geometry of the Universe must study gravity
- this is done most directly by testing the $1/r^2$ law
- our tests have shown that $1/r^2$ law holds down to $\lambda \sim 80\,\mu m$ ($|\alpha| = 1$) at 95% confidence
  - $\Rightarrow$ largest extra dimension must have size $R_* \leq 63\,\mu m$ ($\alpha = 8/3$)
  - $\Rightarrow$ 2 equal extra dimensions require $R_* \leq 53\,\mu m$ ($\alpha = 16/3$) and a unification scale $M_* \geq 2.4$ TeV
- we do see anomalies at shorter length scales (apparent weakening of gravity or new repulsive force)
- we are currently running experiments to track down the source of the anomaly.

  experimental artifact ?

  suble EM effect ?

  new physics ?