Sub-millimeter tests of the gravitational $1/r^2$ law: a search for "large extra dimensions"

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Outline

- motivation
- previous work
- new results from the Eöt-Wash group

What might be special about gravity at ≲ 1 mm?

- mass scale of gravity

  $M_p = \sqrt{\hbar c / G} \sim 10^{16}$ TeV

  can be unified with mass scale of particle physics

  $M_{part} \sim 1$ TeV

  if 2 of the extra dimensions are large and have size ~ 1 mm

- cosmological constant from distant supernovae

  $\Lambda \sim 3 \; \mathrm{keV/cm^3}$

  corresponds to a length of ~ 0.1 mm

- essentially nothing is known about gravity at small separations ≲ mm

These notions have sparked a flowering of ideas in theory & experiment

The hierarchy problem

- mass scale of gravity

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

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

- mass scale of particle physics

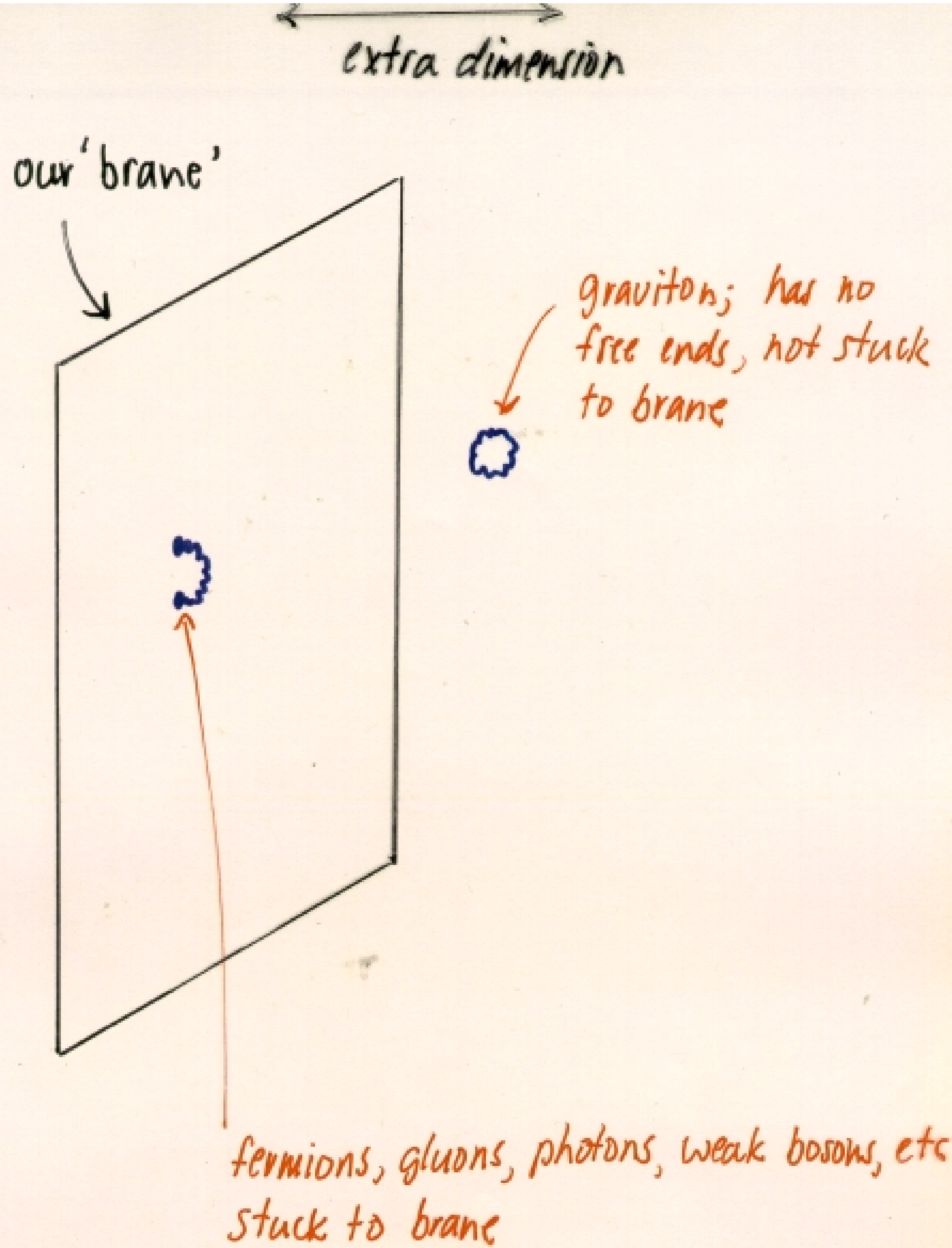
$\longrightarrow M_{SM} \sim 1$ TeV

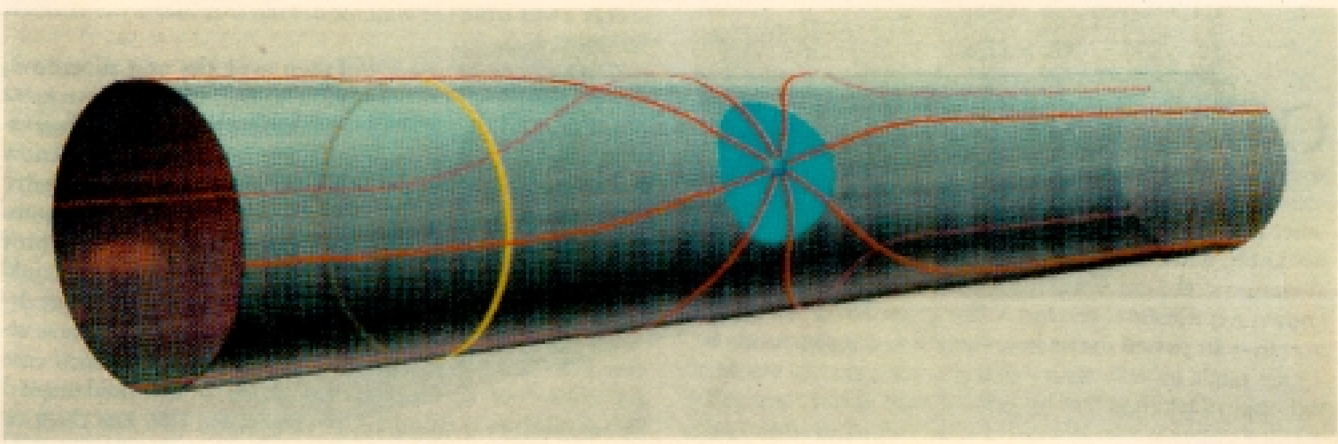
- Arkani-Hamed et al. solution to the problem

  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 $R_p = \sqrt{G\hbar/c^3} = 1.6 \times 10^{-33}$ cm


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



- Suppose there are n "large" extra dimensions of size R^*

- then at distances $r \ll R^*$

  gravity would obey Gauss' Law in n+3 space dimensions

$$V_{4+n}(r) = \frac{(\hbar c)^{n+1}}{(M^*)^{n+2}\, c^{2n}} \; \frac{m\,m}{r^{n+1}}$$

  where M^* is the true mass scale of gravity

- while at distances $r \gg R^*$

  gravity obeys the usual Gauss' Law in 3 dimensions

$$V_4(r) = \frac{\hbar c}{M_p^2} \; \frac{m\,m}{r}$$

  and now M_p is no longer a fundamental scale

- equating $V_{4+n}(R) = V_4(R)$ we find

$$(M^*)^{n+2} = \left(\frac{\hbar}{cR^*}\right)^n M_p^{\,2}$$

$$\hookrightarrow \; R^* = \frac{\hbar c}{M^* c^2} \left(\frac{M_p}{M^*}\right)^{2/n}$$

  by picking R^* and n can make $M^* = M_{SM}$

"solving" hierarchy problem by letting $M^* = 1$ TeV we find

for $n = 1$

$R^* \sim 10^{15}$ cm

↑ ruled out by astronomical observations of orbit precessions

for $n = 2$

$R^* \sim 2$ mm

↑ not inconsistent with existing data!

why not?

gravity is very, very weak.

for $n > 2$

R^* so small it cannot be detected in mechanical experiments

but may be detected in collider experiments

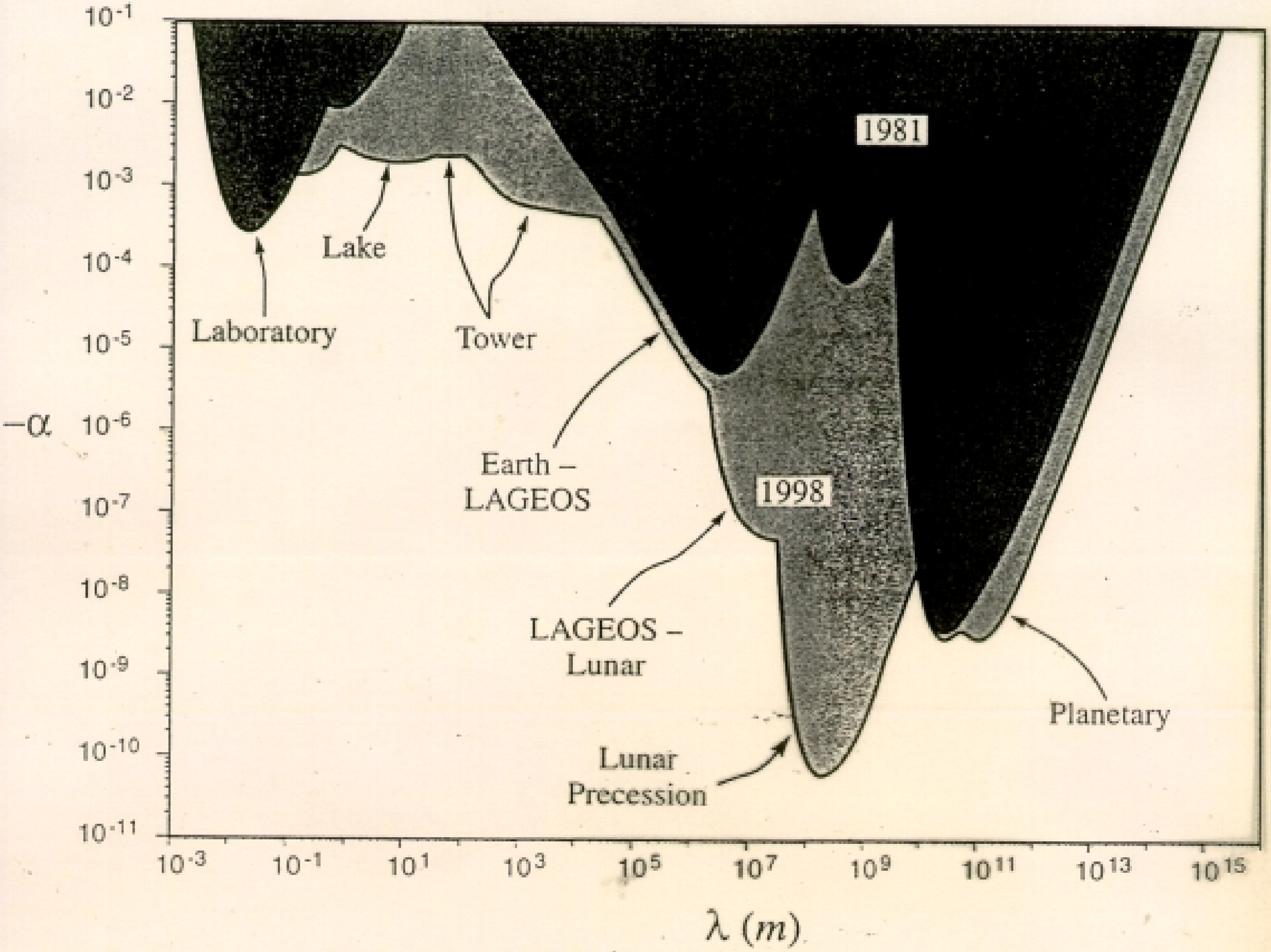
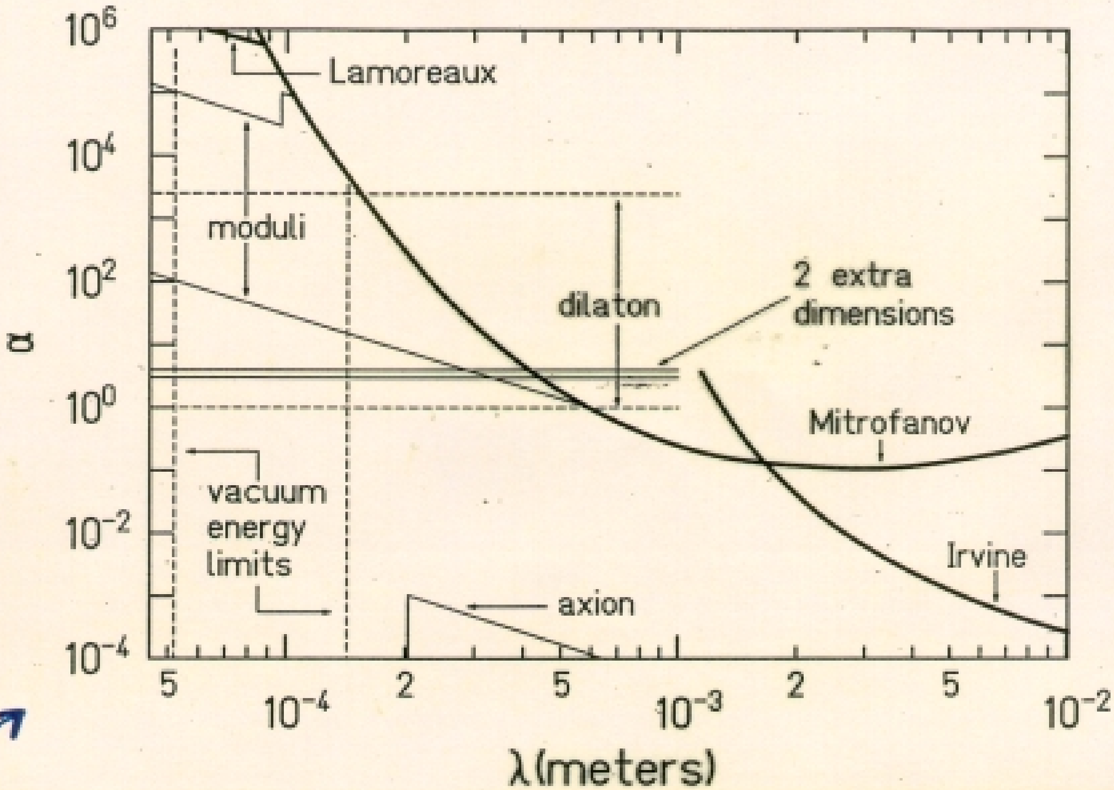


Figure 2.13: Constraints on the coupling constant α as a function of the range λ from composition-independent experiments. The dark shaded area indicates the status as of 1981, and the lighter region gives the current limits. Note that only the most sensitive results are exhibited in each regime in λ, and that all limits are quoted at the 2σ level. For references to the earlier experiments which contribute to the curves, see [TALMADGE, 1988] and [DERUJULA, 1986].

2σ limits on inverse-square law violating interaction of the form

$$V(r) = \alpha \frac{Gmm}{r} e^{-r/\lambda}$$

$$V(r) = -G\frac{mm}{r}\left(1+\alpha e^{-r/\lambda}\right)$$



taken from Long, Chan + Price, Nucl. Phys B 539 (1999) 23

- moduli - theoretical speculation by Dimopoulis & Guidice, Phys. Lett B 379 (1996) 105
- dilaton - theory argument by Kaplan & Wise hep-ph 000811
- axion - region allowed by neutron EDM + astrophysical constraints

the University of Washington

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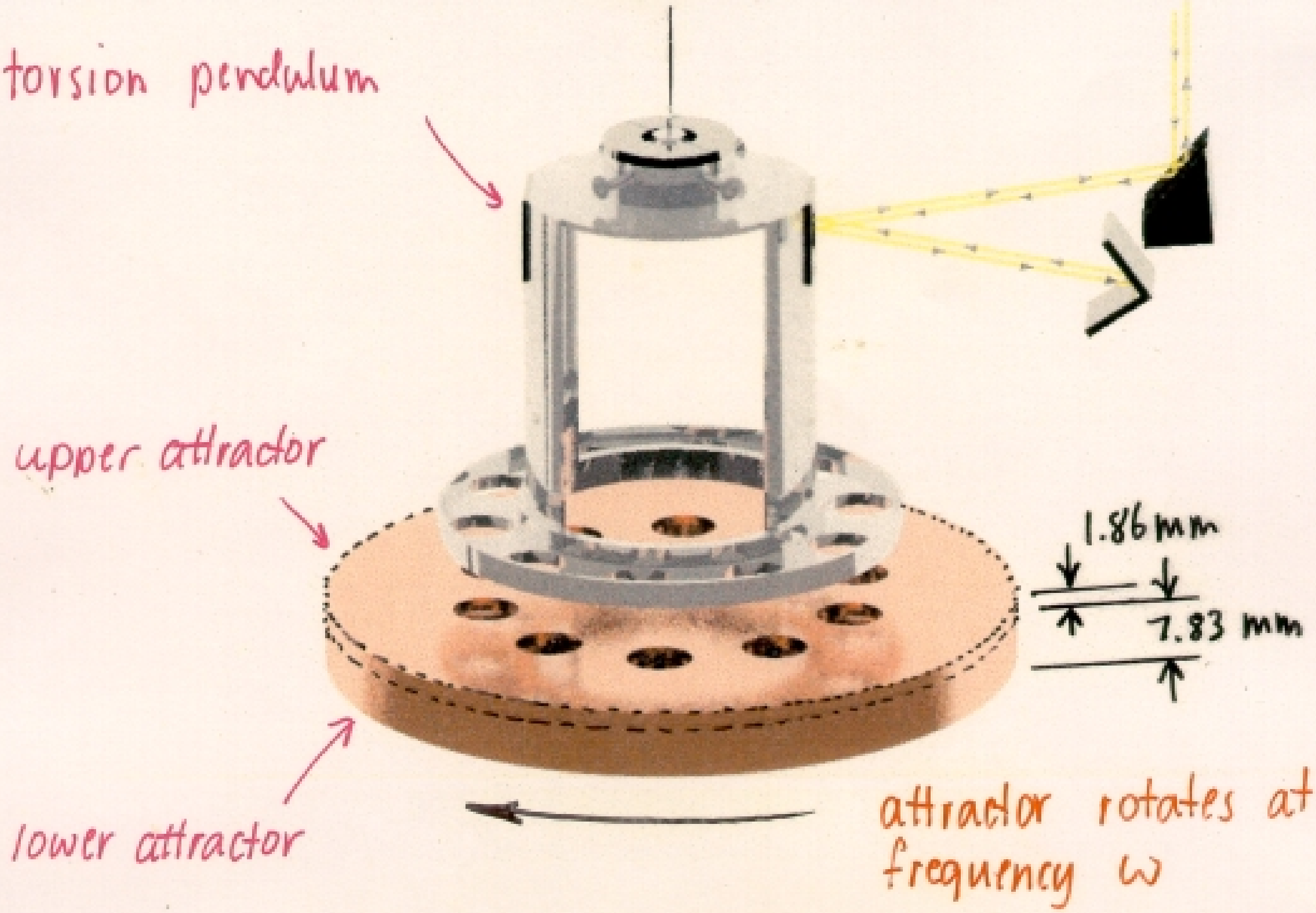
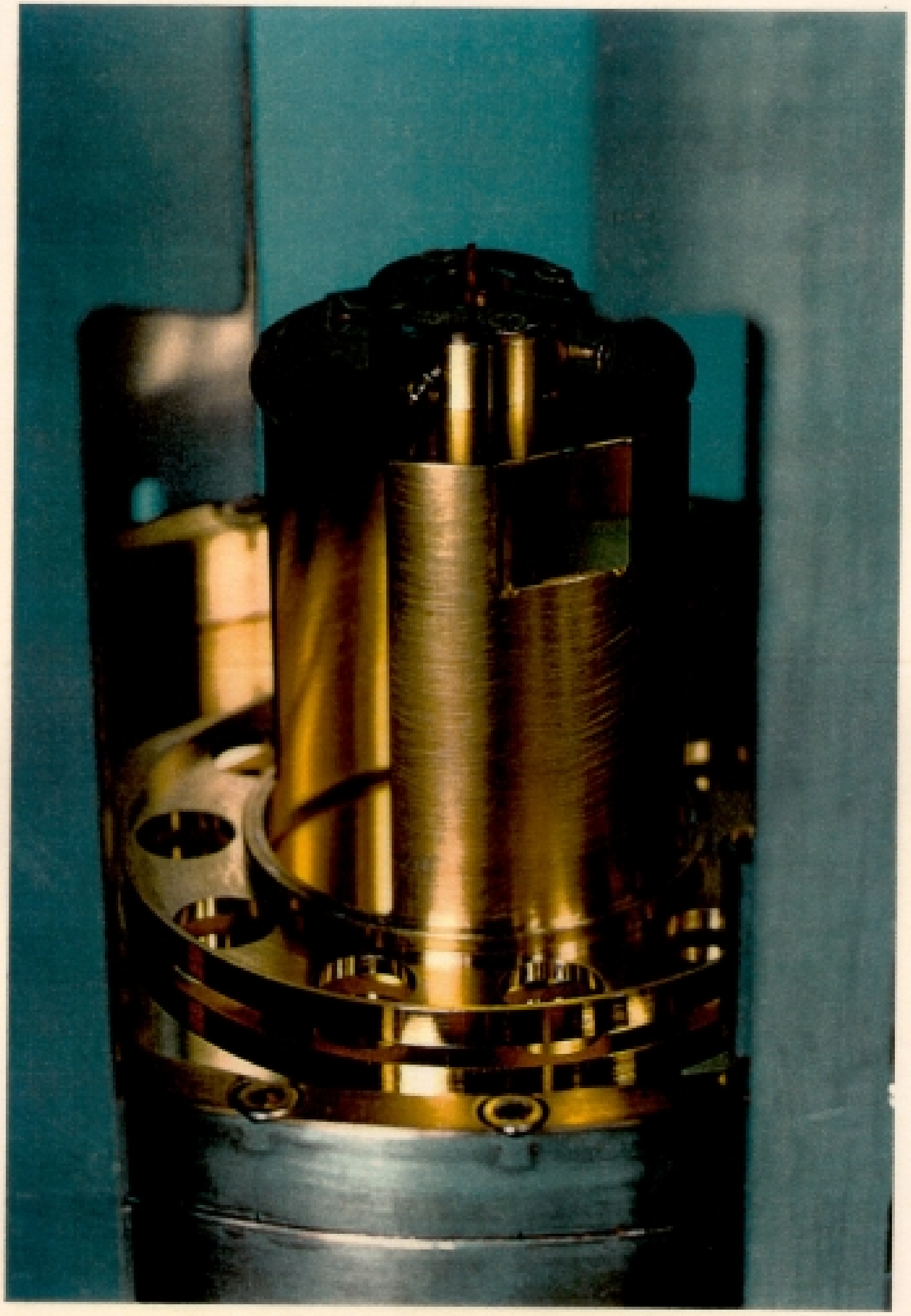
NSF DOE NASA

Mark II short-range instrument

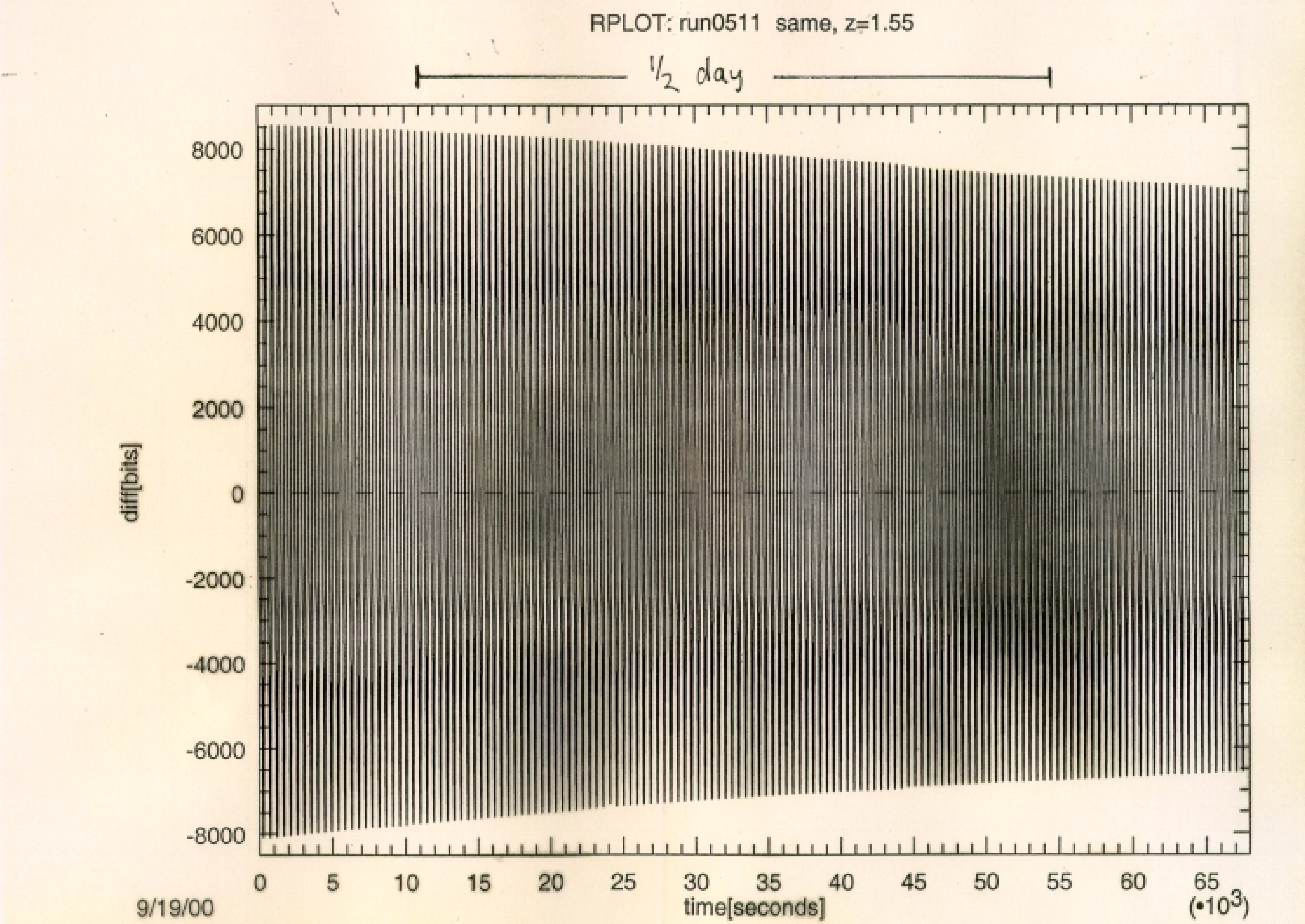


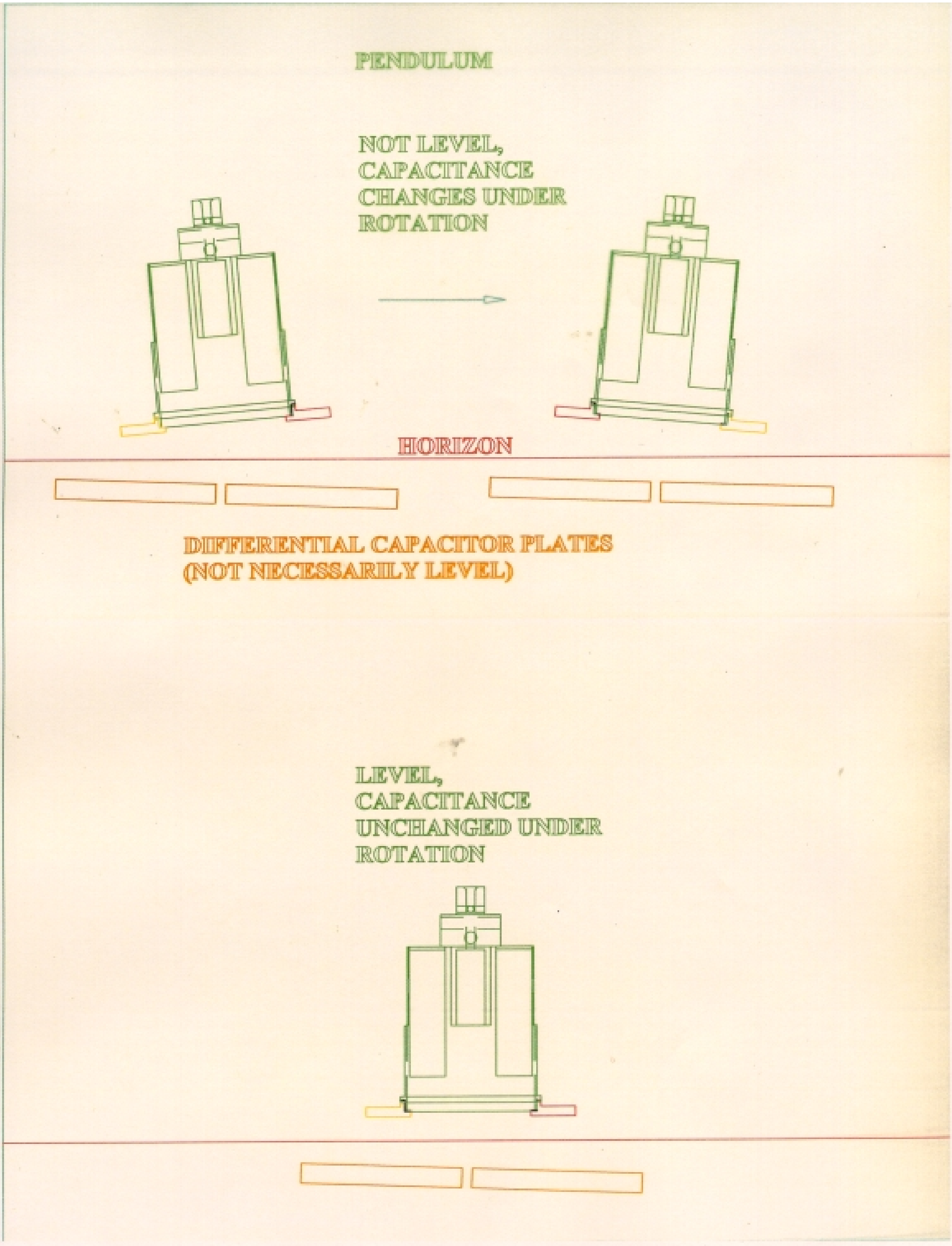
- the 10 holes in the lower attractor are "out of phase" with the holes in the upper attractor.
- this cancels Newtonian gravity torque by a factor of ~ 20, but has little effect on torque from short-range force
- measure z-dependence of torque signals at 10ω, 20ω and 30ω

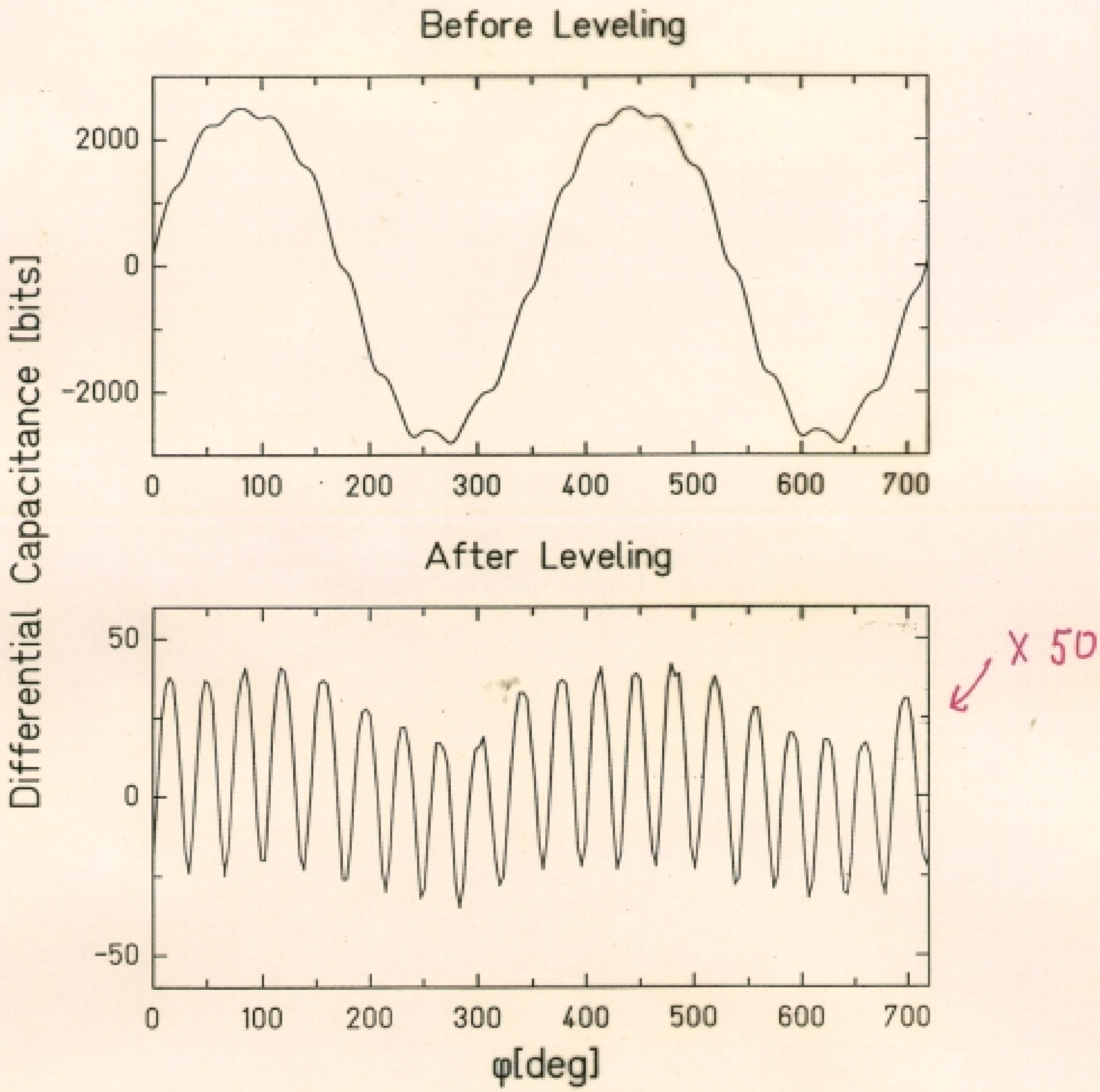
Eöt-Wash Mark II short-range instrument



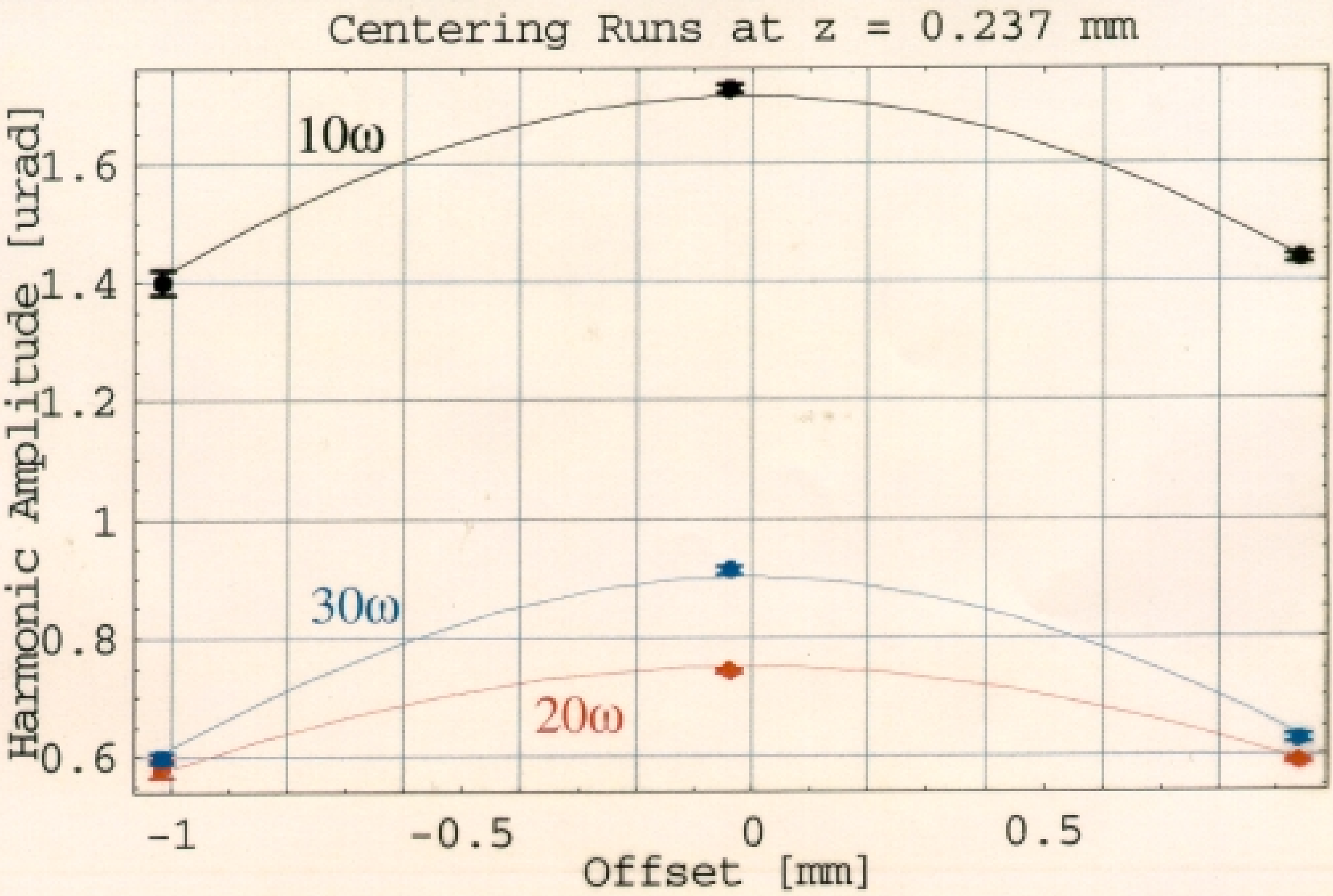
Free oscillations of the torsion oscillator




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

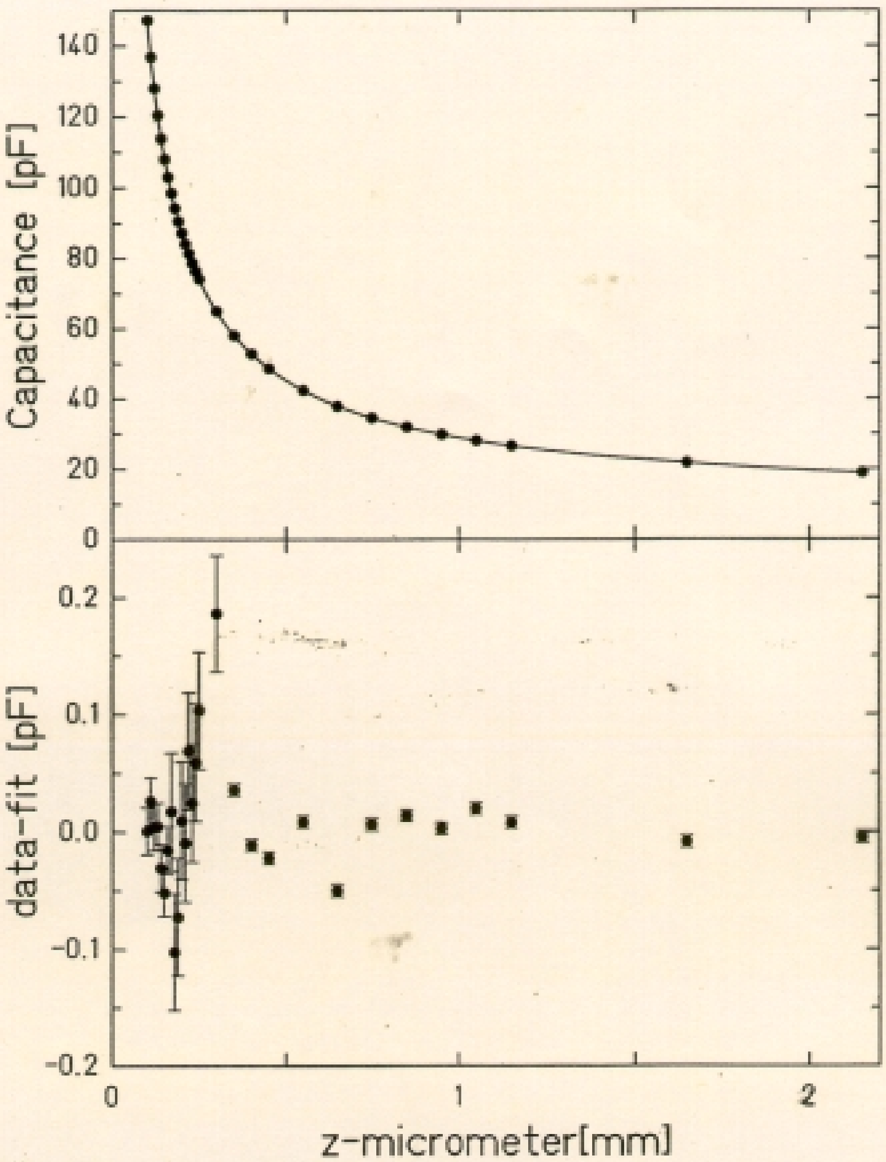


Before Leveling
2000
0
-2000
0
100
200
300
400
500
600
700
After Leveling
50
0
-50
0
100
200
300
400
500
600
700
φ[deg]
Differential Capacitance [bits]
X 50

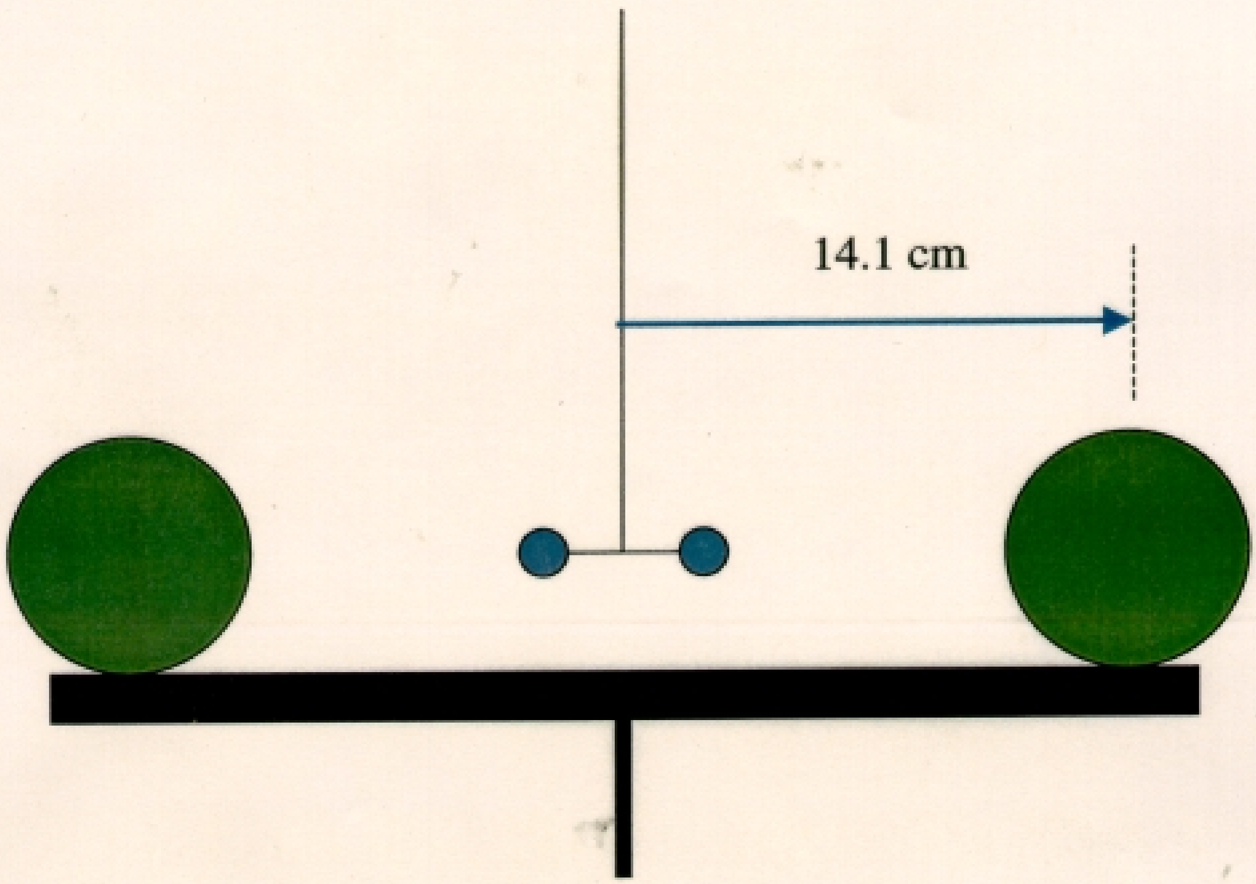


Centering Runs at z = 0.237 mm
Harmonic Amplitude [urad]
Offset [mm]
10ω
30ω
20ω
1.6
1.4
1.2
1
0.8
0.6
-1
-0.5
0
0.5

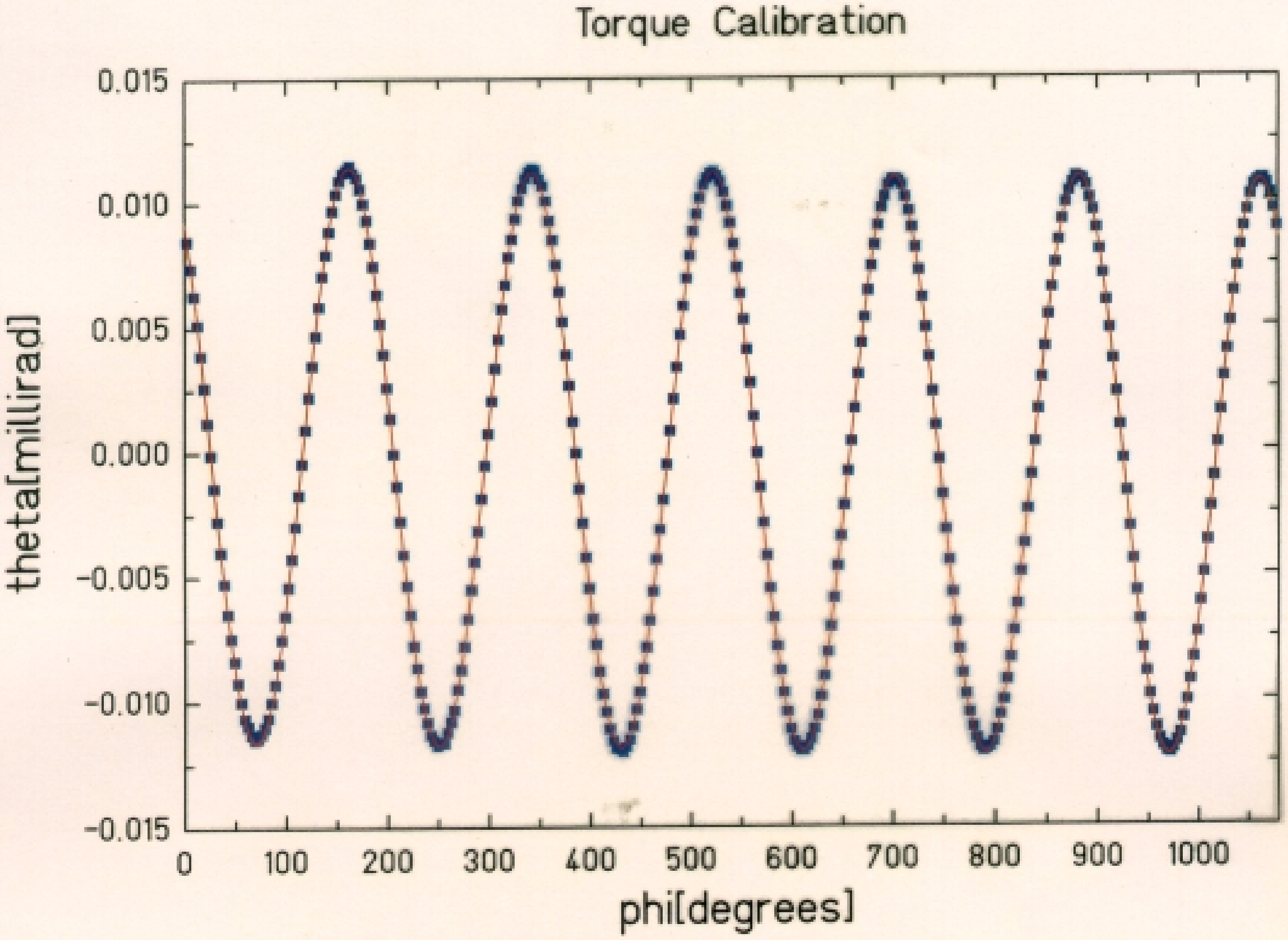
capacitance measurement of the separation



Calibration

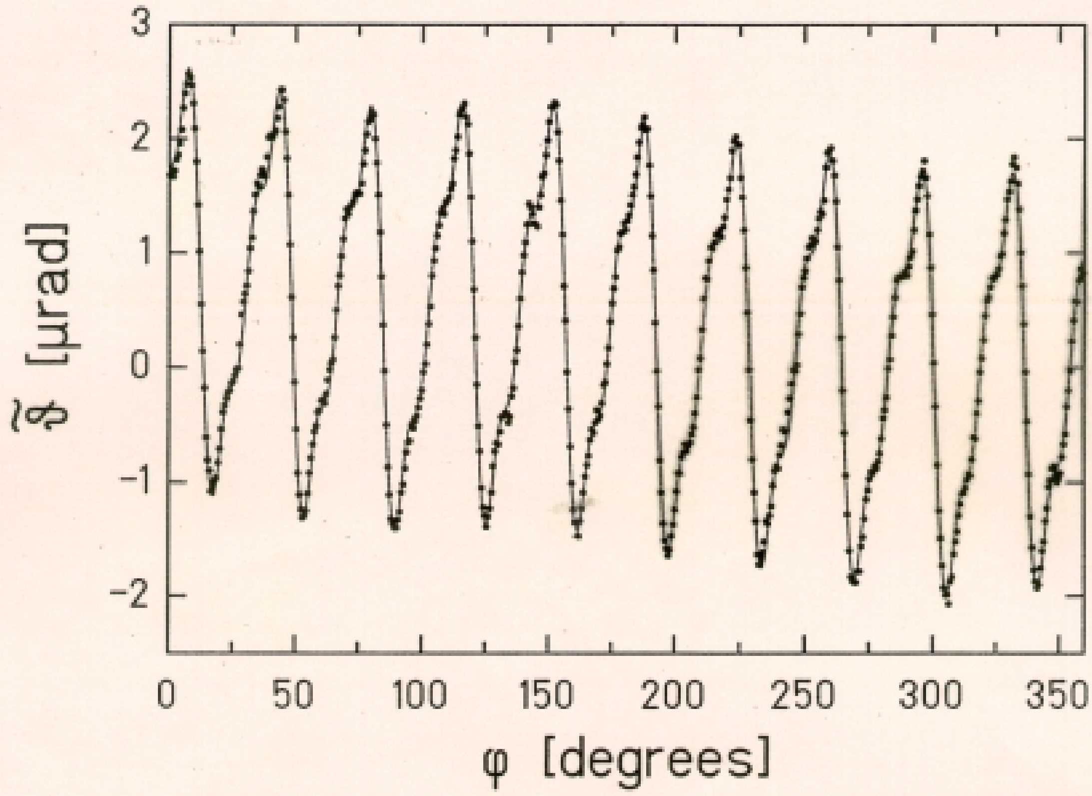


- Gravitational force between spheres is simple to calculate.
- Large sphere separation eliminates effects from short-range interactions
- 2ω torque = $4.007 \pm 0.001 \times 10^{-7}$ dyne-cm

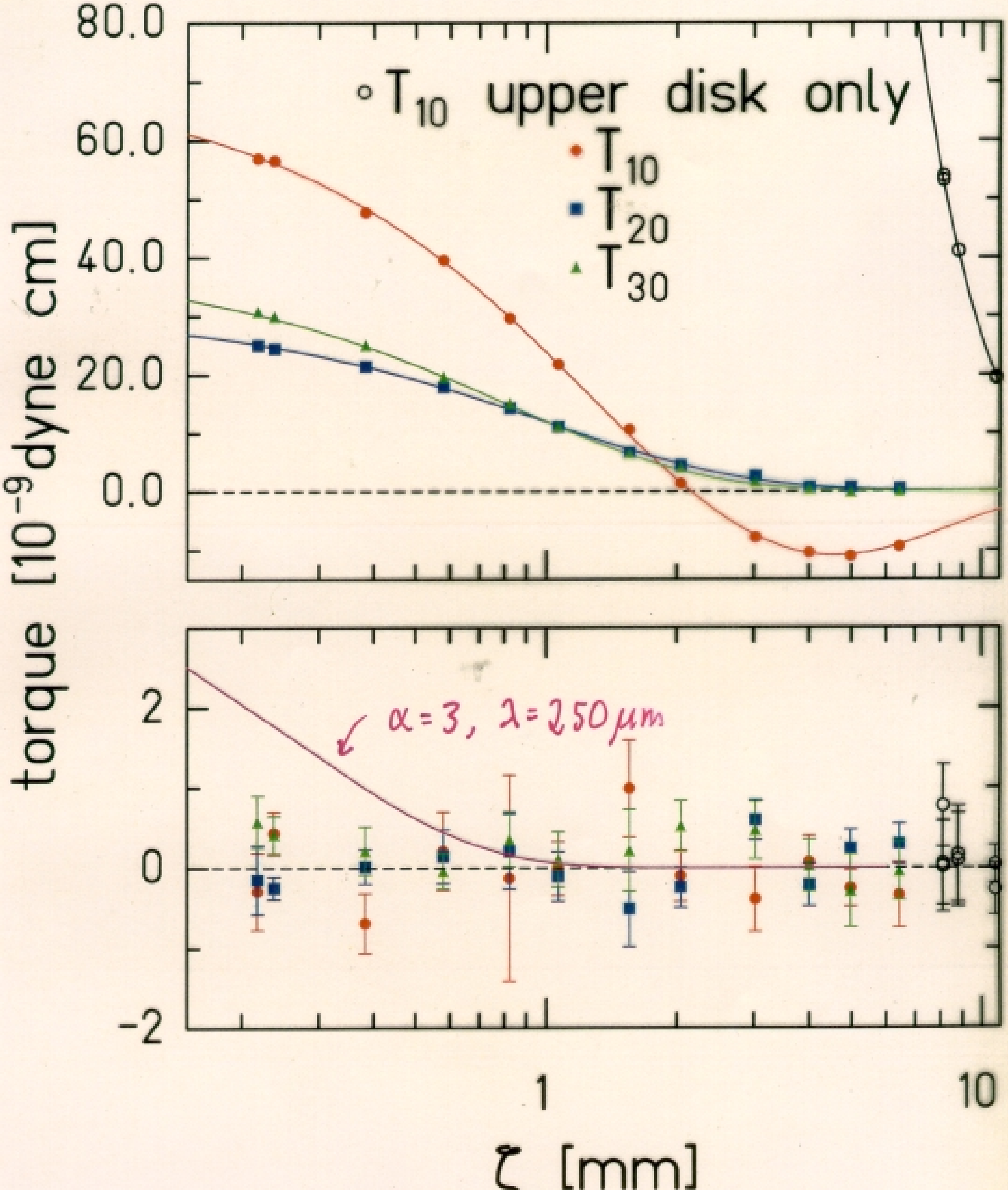


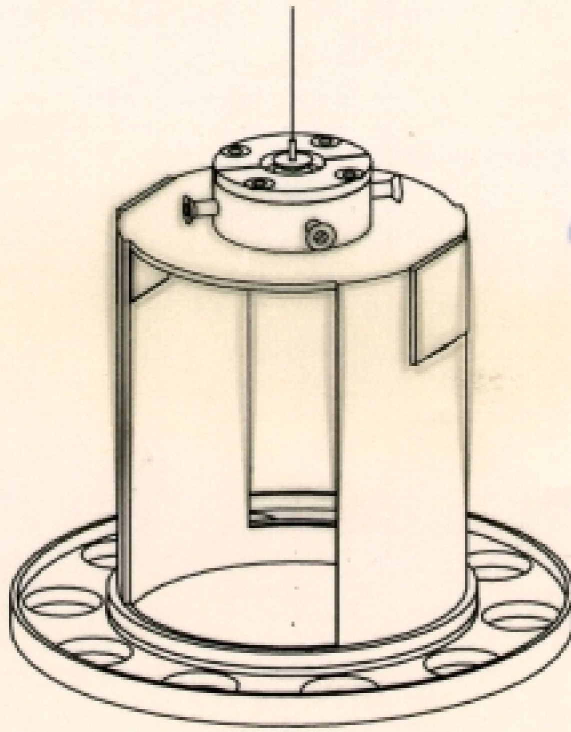
$a(2\omega) = 11.557 \pm 0.010\ \mu rad$

signal at a separation of 237 μm

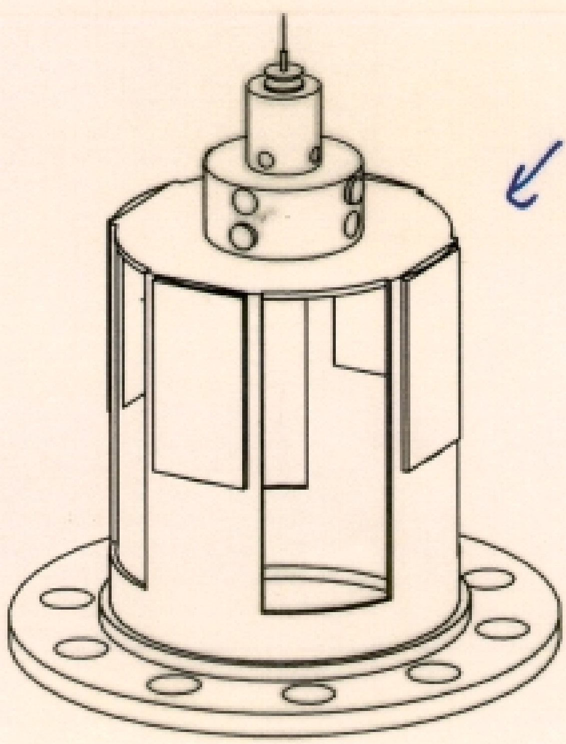


hep-ph/0011014

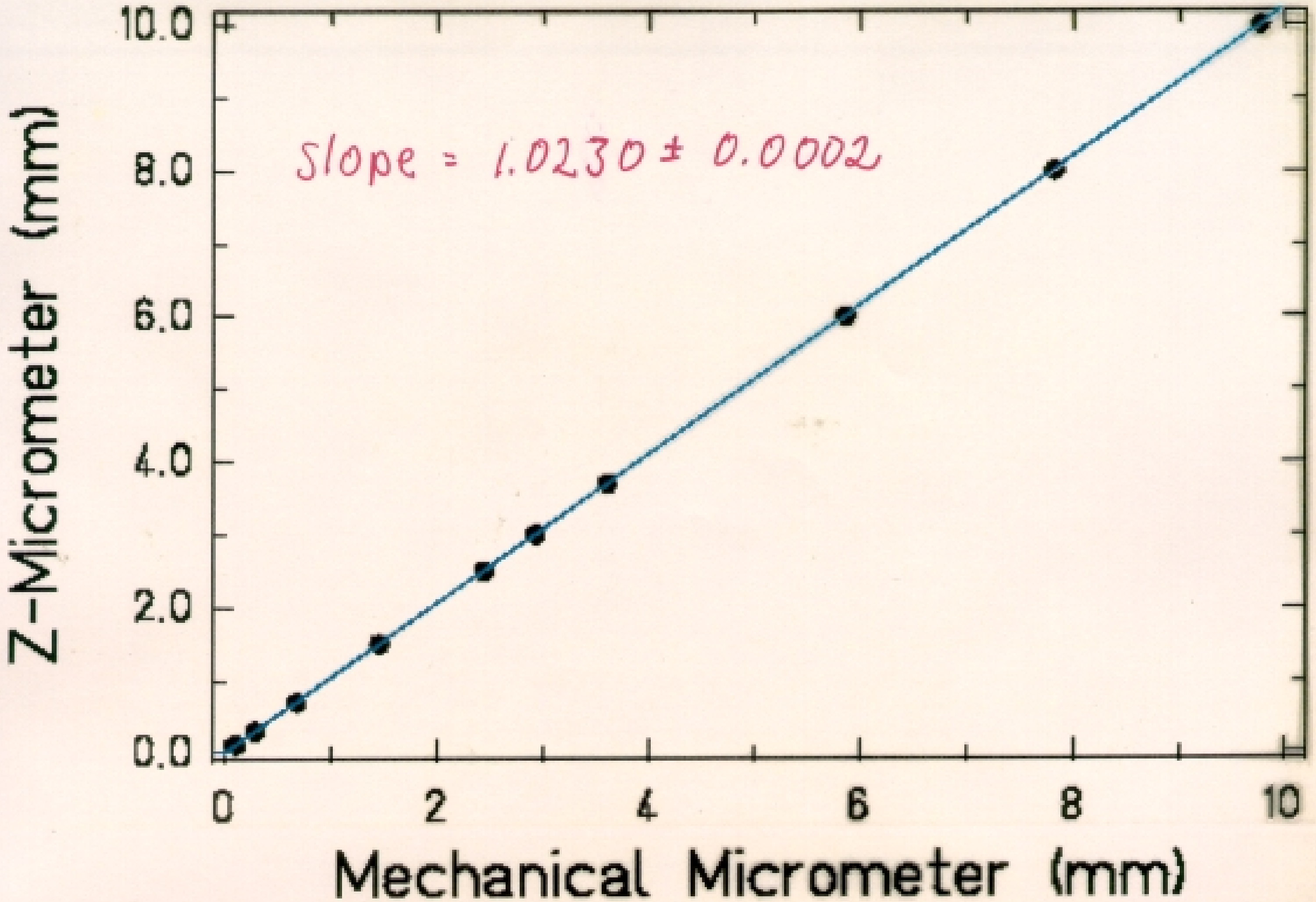




Mark II



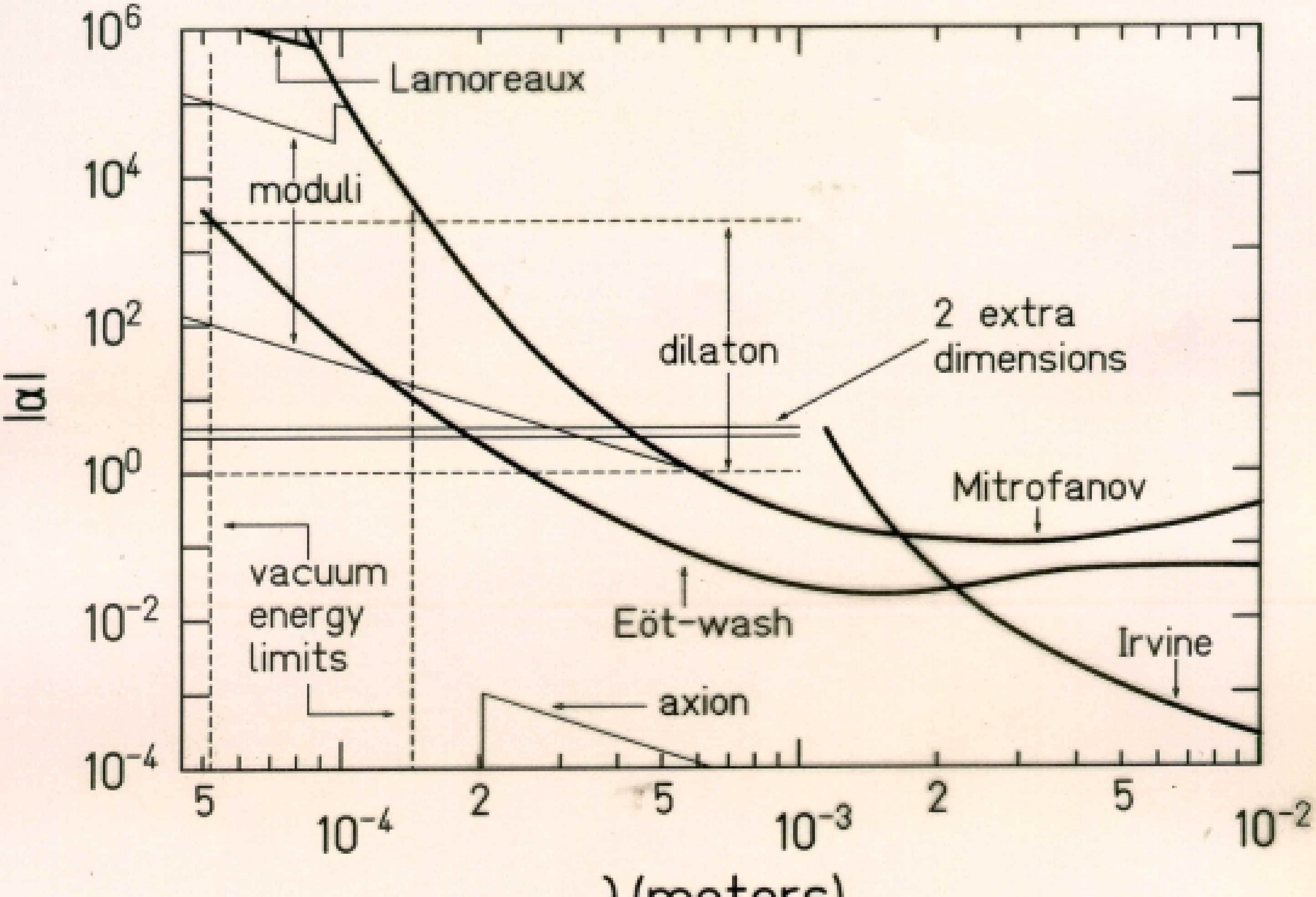
Mark III



Slope = 1.0230 ± 0.0002
Z-Micrometer (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
Mechanical Micrometer (mm)

(Feb 19, 2001 PRL)

Eöt-Wash Mark II short-range constraints



2 large extra dimensions scenario predicts

$\alpha = 3$ ← compactification on sphere

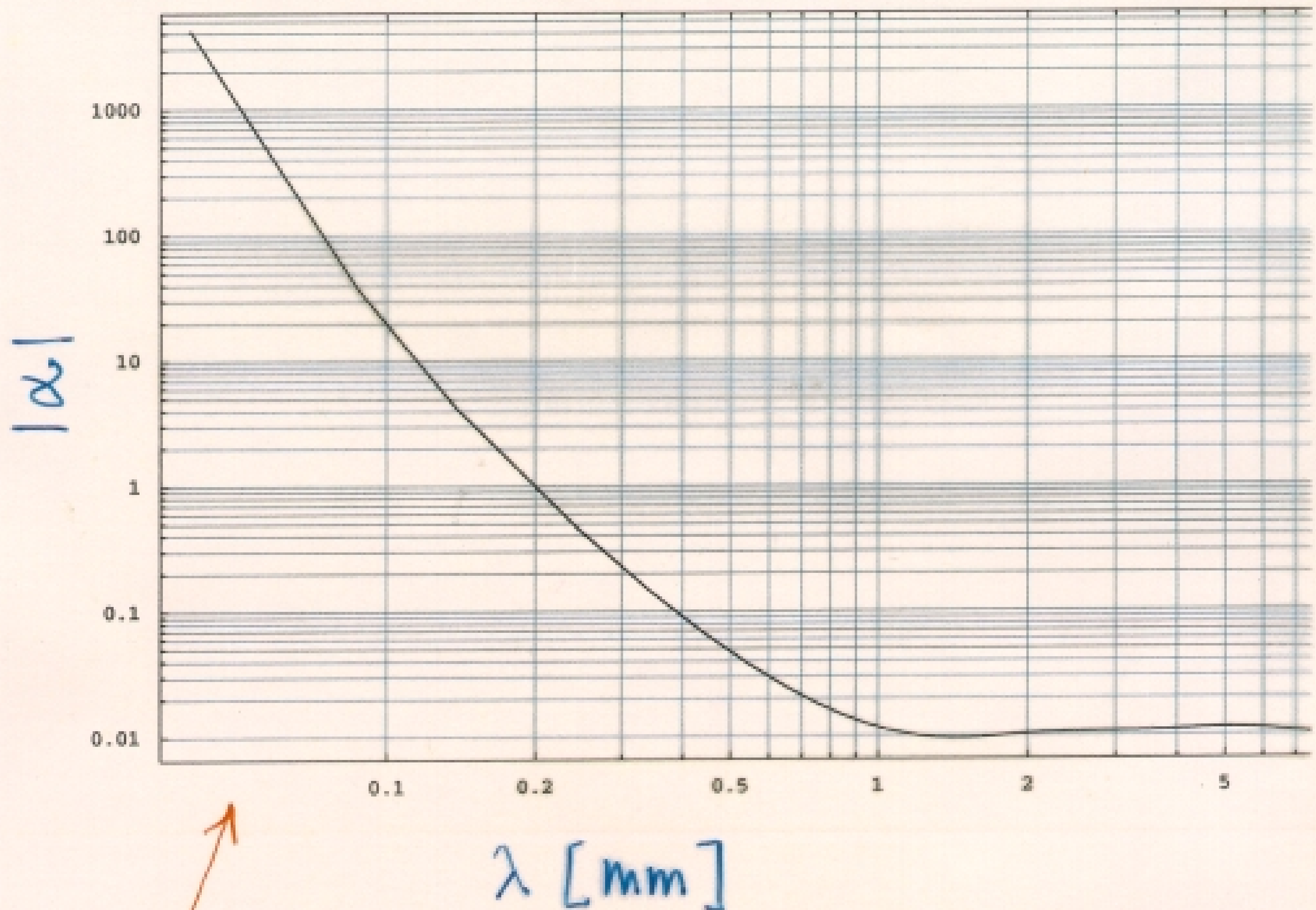
$\alpha = 4$ ← " " torus

Our Mark II results are inconsistent with

$\alpha \gtrsim 3$ for $\lambda \gtrsim 190\ \mu m$

at 95% confidence ⇒ $M^* \gtrsim 3.5$ TeV

95% confidence constraints on |α|

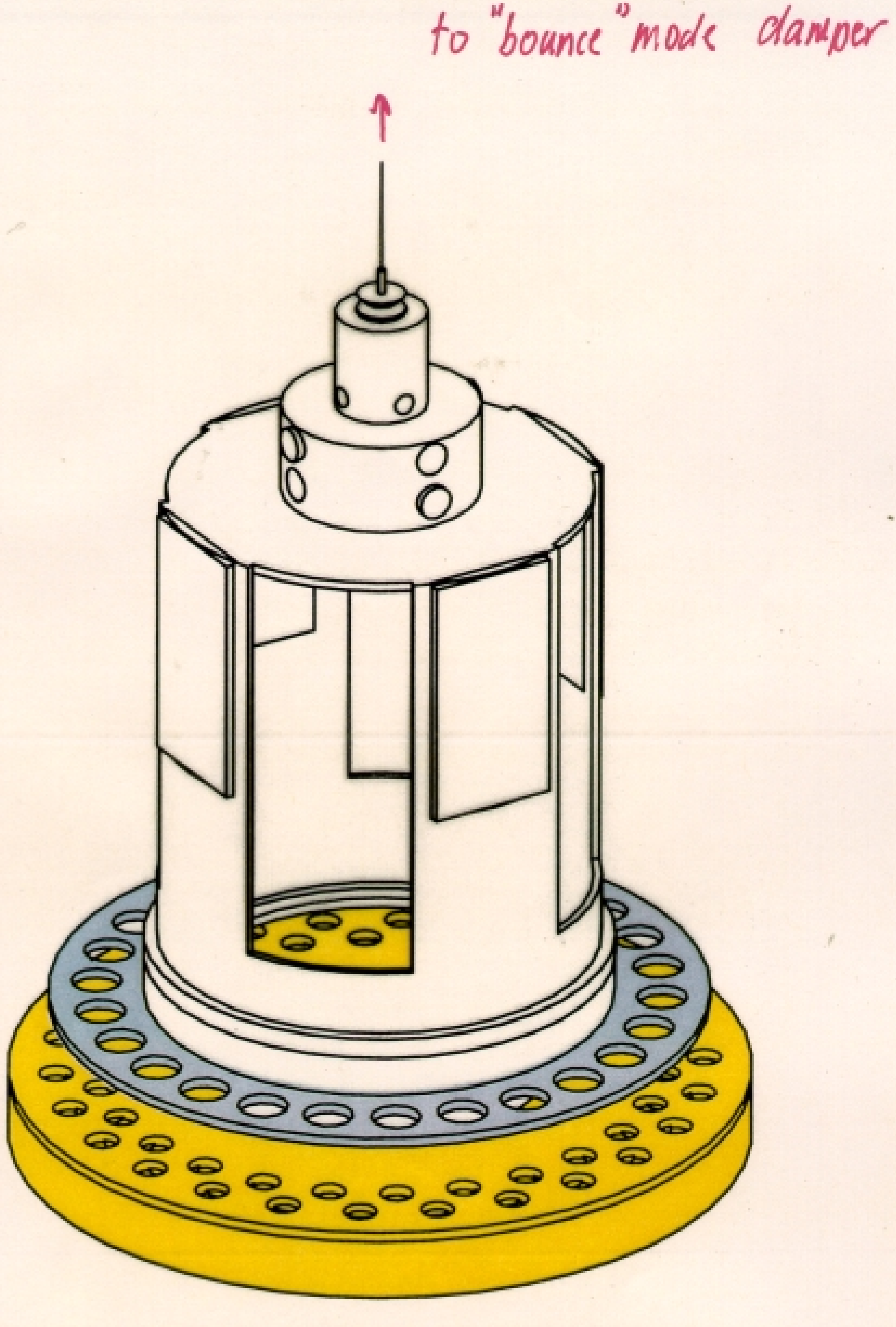


new analysis combining results from Mark II + Mark III instruments

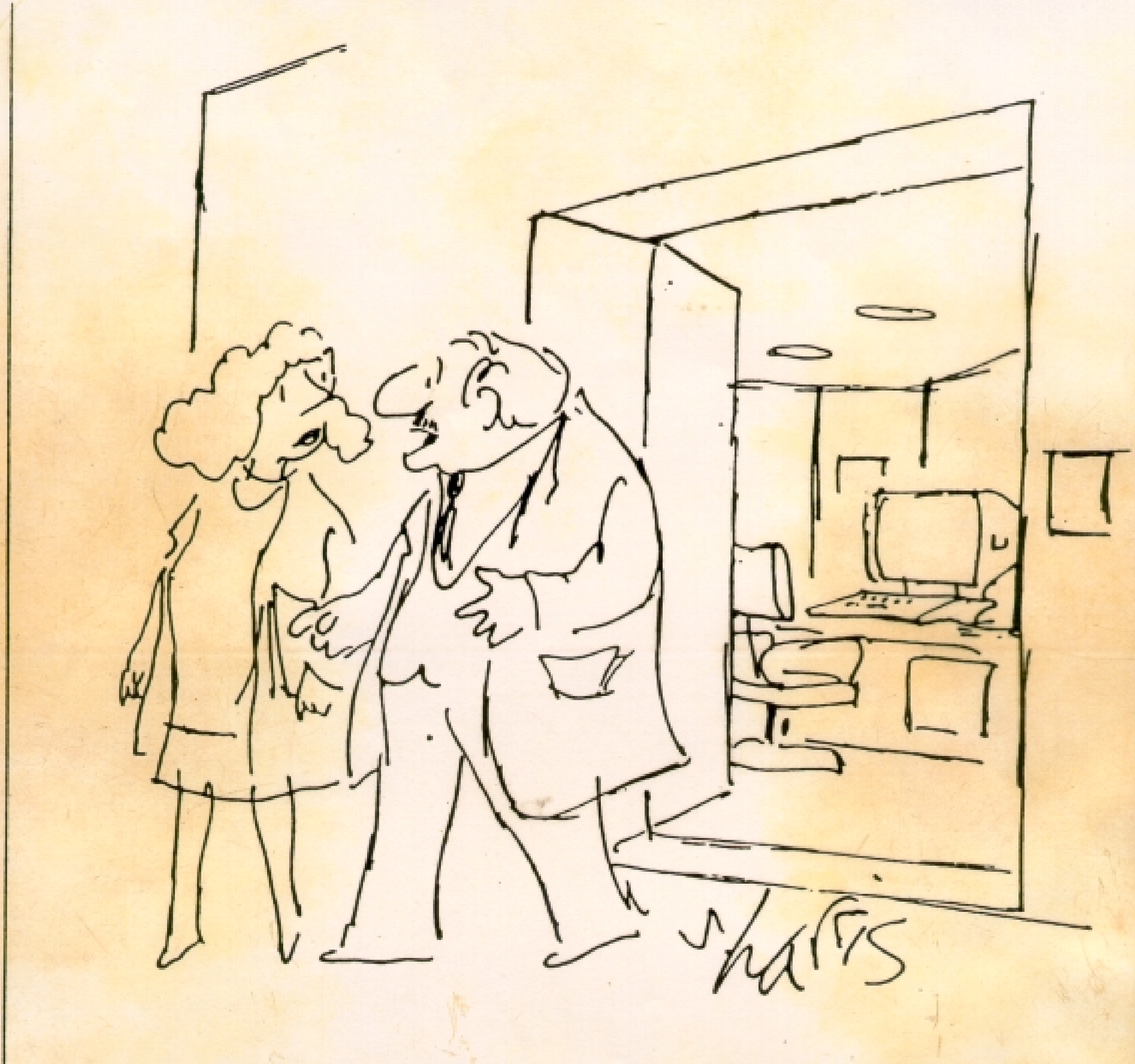
$\alpha < 3$ for $\lambda \geq 150\,\mu m$ ← 2 large extra dim. scenario

$\alpha < 1$ for $\lambda > 300\,\mu m$

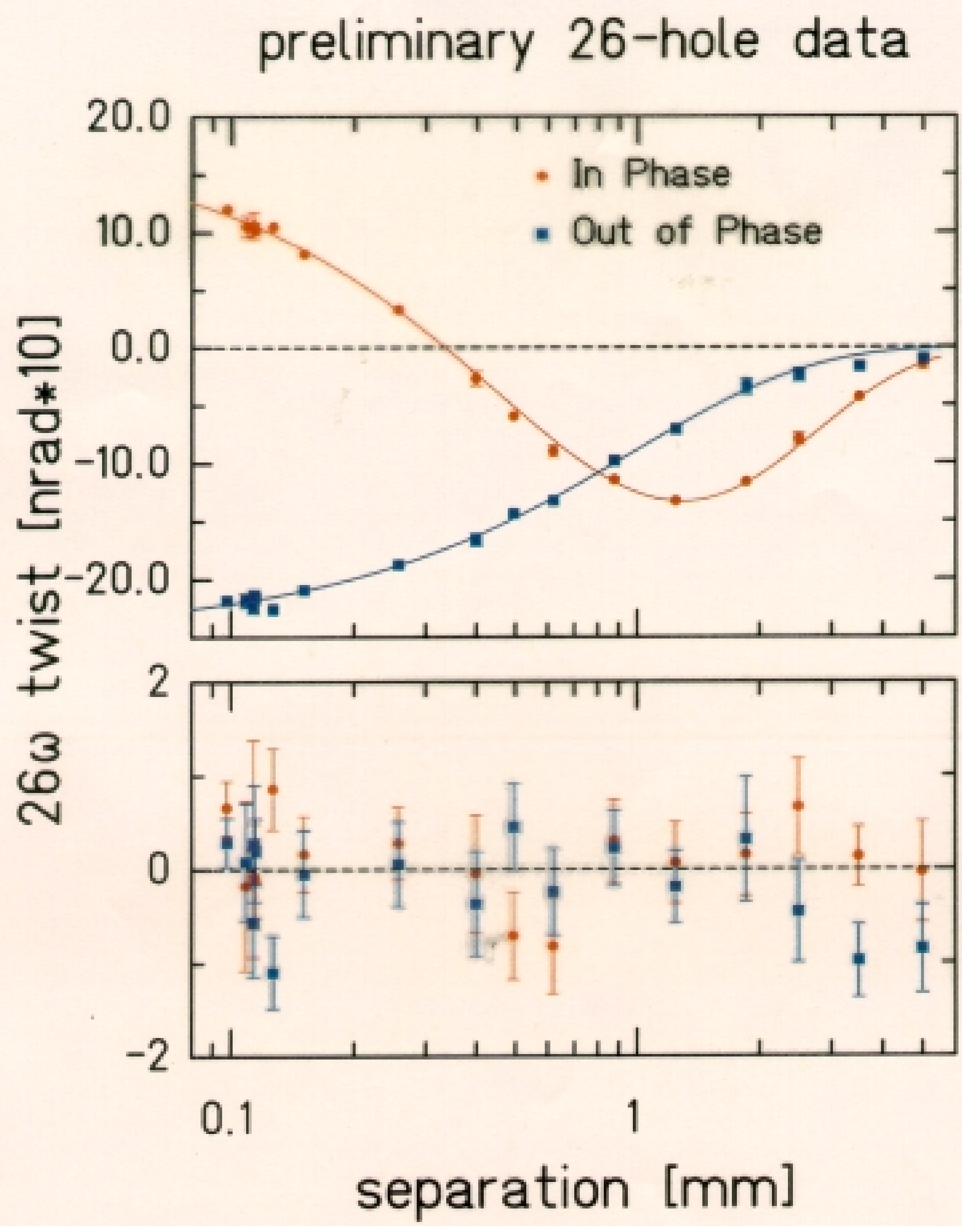
↖ upper limit on size of the largest extra dimension



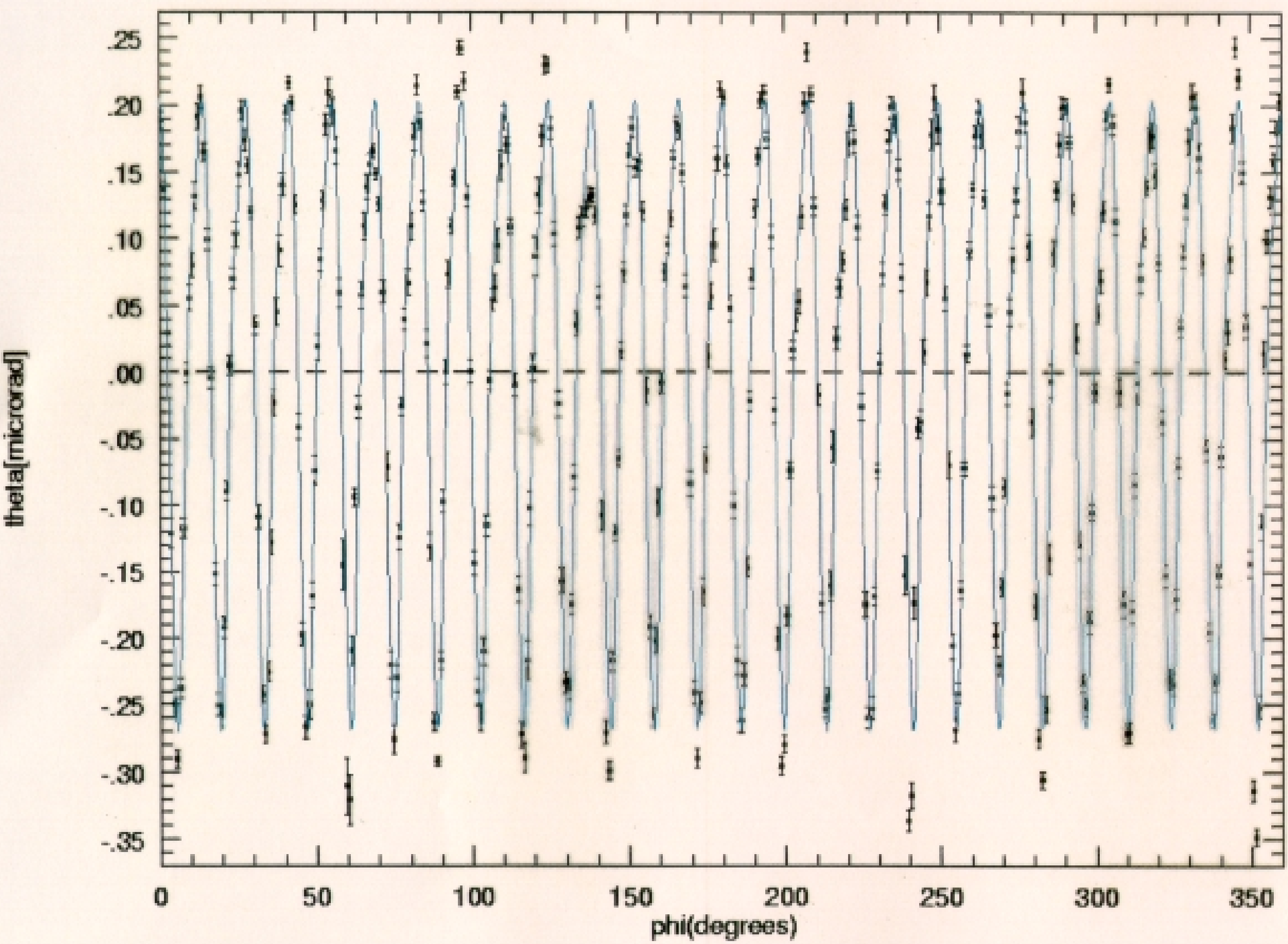
we hope to probe down to $\lambda \approx 50 \mu m$ with this instrument



"I had a better grasp of things when physics dealt mostly with falling bodies."



preliminary 26-hole data
20.0
10.0
0.0
-10.0
-20.0
In Phase
Out of Phase
2
0
-2
0.1
1
26ω twist [nrad*10]
separation [mm]


theta[microrad]
.25
.20
.15
.10
.05
.00
-.05
-.10
-.15
-.20
-.25
-.30
-.35
0
50
100
150
200
250
300
350
phi(degrees)

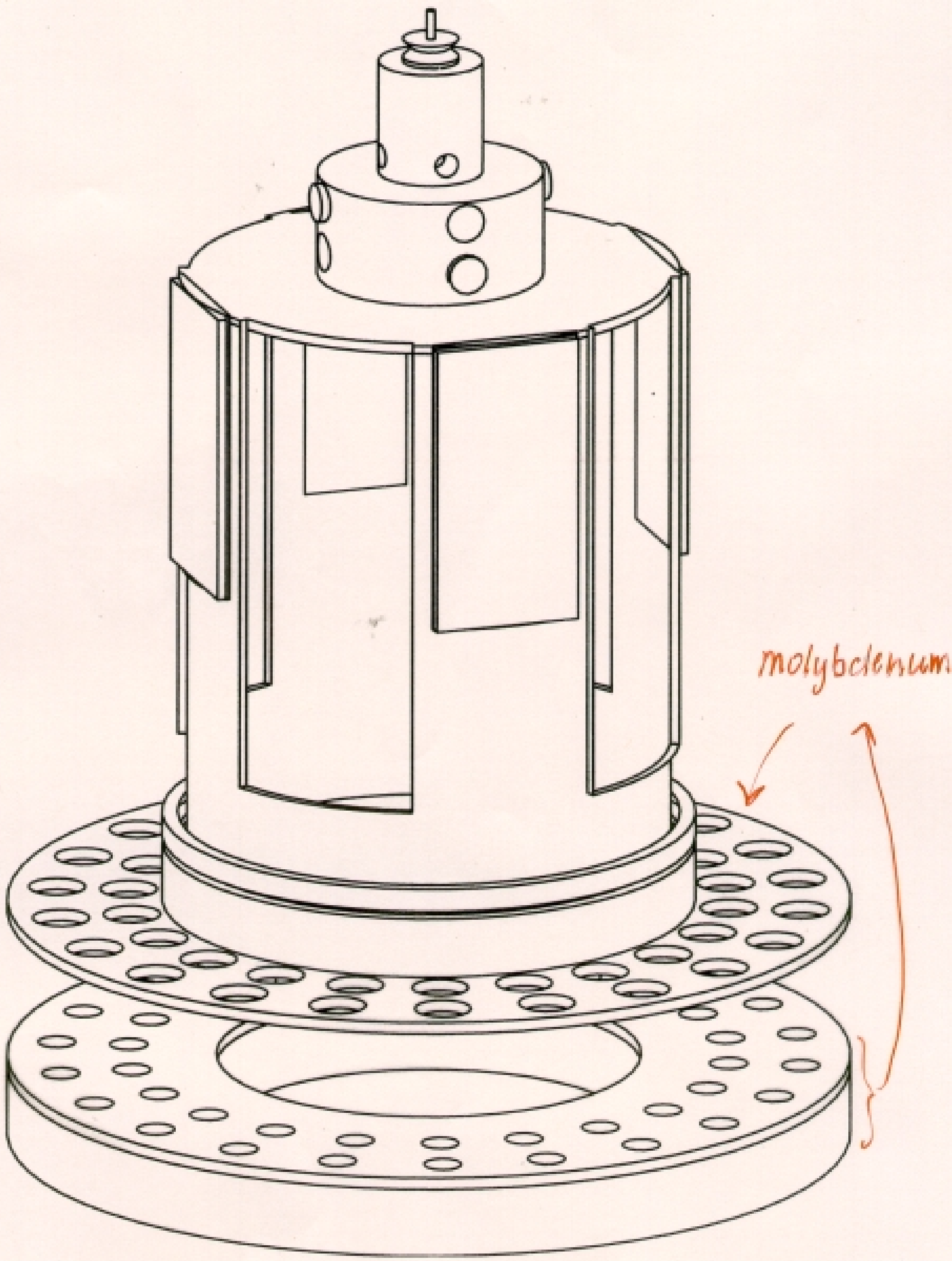
Some improvements in the 44-hole instrument

- better cancellation of Newtonian gravity
- bigger Yukawa signal
  - higher densities   Mo + Mo → $\rho_p \rho_a$ 4.5× greater
  - power pushed into fundamental
- 2× thinner conducting membrane
- "bounce mode" damper   6× reduction in mean bounce
- 6× lower torque noise
- minimum separation 2× closer

  have data at $z = 98\mu m$
  with prototype system

44- hole pendulum with 22-fold azimuthal symmetry

design goal: probe down to $\lambda \sim 50\mu m$



magnetic "glitches"