Tests of Newton's Inverse-square Law probing the true geometry of the Universe

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Outline

- Sub-millimeter tests
  - motivation
  - techniques
  - results
- long-range tests
  - LLR technique & results
- Summary of constraints on Yukawa interactions (including Equivalence Principle test results)

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

Yukawa forces from boson exchange

$$V_{12} \propto \frac{\tilde{q}_1 \tilde{q}_2}{r} e^{-r/\lambda} \qquad \lambda = \frac{\hbar}{m_b c}$$

$\tilde{q}_1 \tilde{q}_2$ → violates EP

$e^{-r/\lambda}$ → violates $1/r^2$ force law

$$\vec{a}_1 = -\frac{1}{m_1}\frac{\partial V_{12}}{\partial r} \propto -\left(\frac{\tilde{q}}{m}\right)_1 \tilde{q}_2 \vec{\nabla} \frac{e^{-r/\lambda}}{r}$$

$\tilde{q}/m$ cannot be identical for different materials;

this gives in effect in EP tests

REASON:

vector interactions

- $\tilde{q}_V$ conserved $\quad \tilde{q}_V = \int j_V \, d^3x \rightarrow q_V'$
- binding energy has $\tilde{q}_V = 0$ $\quad f$ & $\bar{f}$ have opposite $\tilde{q}_V$'s
- easy to compute q_V/m for a given vector interaction using measured atomic masses

scalar interactions

- $\tilde{q}_S$ not conserved $\quad \tilde{q}_S = \int j_S \, d^3x \rightarrow \frac{1}{\gamma} \tilde{q}_S'$
- binding energy has $\tilde{q}_S \neq 0$ $\quad f$ & $\bar{f}$ have same $\tilde{q}_S$'s
- difficult to compute $\tilde{q}_S/m$ for a given scalar interaction, but in general expect variations of order 10^{-3} (binding energy differences)

3 FAMOUS PROBLEMS WITH GRAVITY

- ## WHY IS GRAVITY SO WEAK?

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

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

$$\frac{F_e}{F_g} = 2\times 10^{39}$$

- ## 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

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

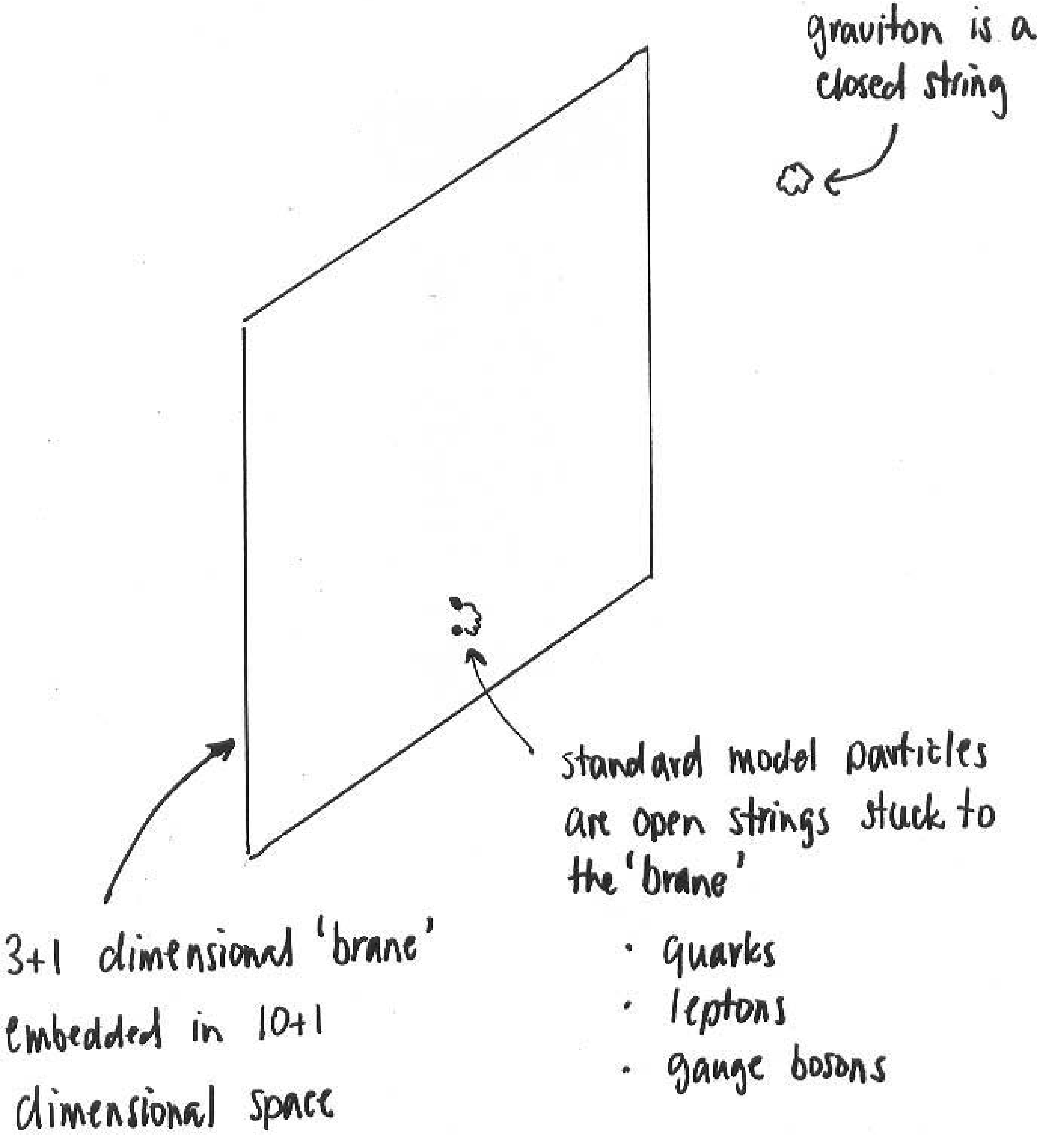
Phys. Lett. B 429 (1998) 263

- 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

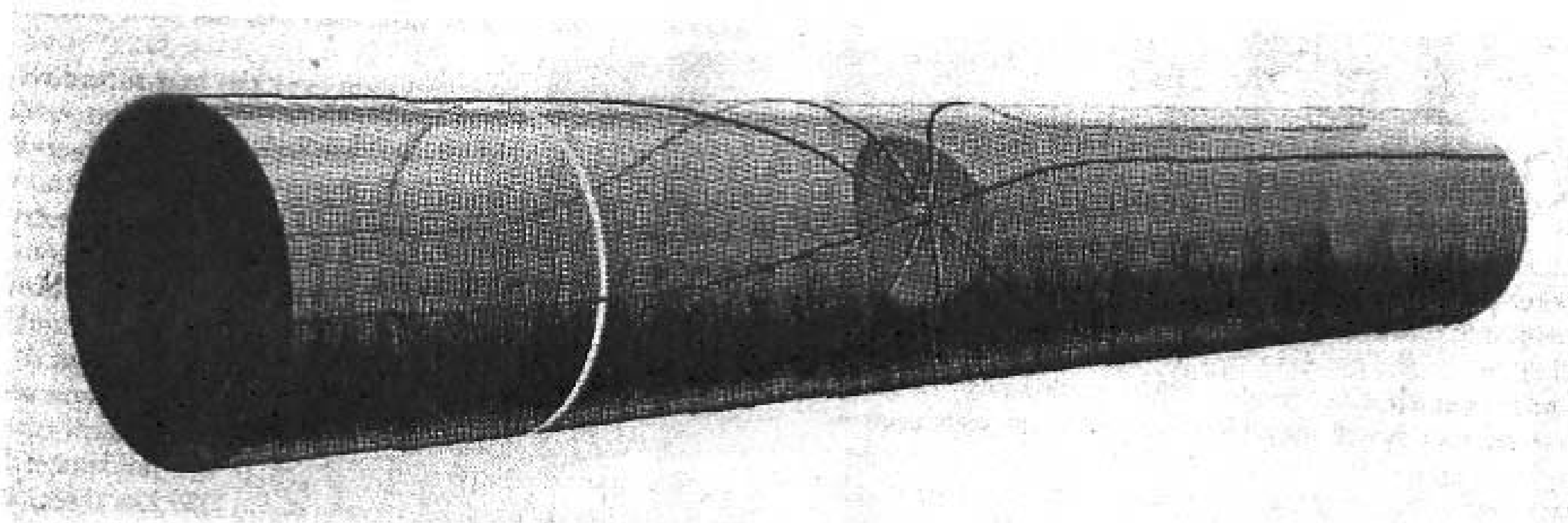
    $$R_P = \sqrt{G\hbar/c^3} \sim 10^{-33}\,\text{cm}$$

    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 $s < R^*$

Only gravity propagates in all the space dimensions



Arkani-Hamed, Dimopoulis & Dvali



from August 2000 Scientific American article
" The Universe's Unseen Dimensions

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 $\rho = 4\,\mathrm{keV/cm^3}$.

- this corresponds to a length scale
  $d = \sqrt[4]{\hbar c/\rho} \sim 0.1\,\mathrm{mm}$

- 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

Parameterising breakdowns of $1/r^2$ law

- <u>old-fashioned way</u>

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

↑ no theoretical basis

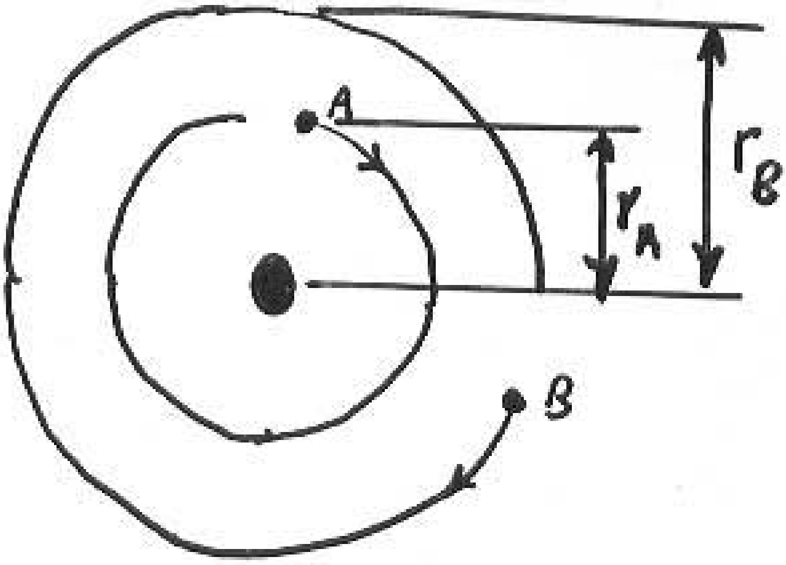
- <u>modern way</u>

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

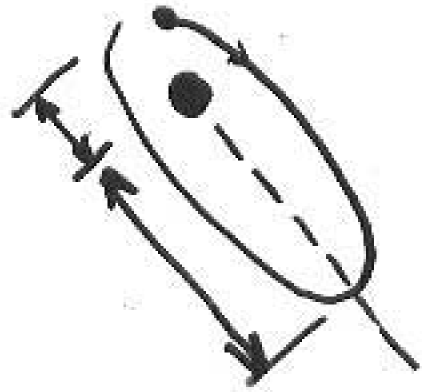
↑

- 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

Fischbach & Talmadge "The Search for Non-Newtonian Gravity"

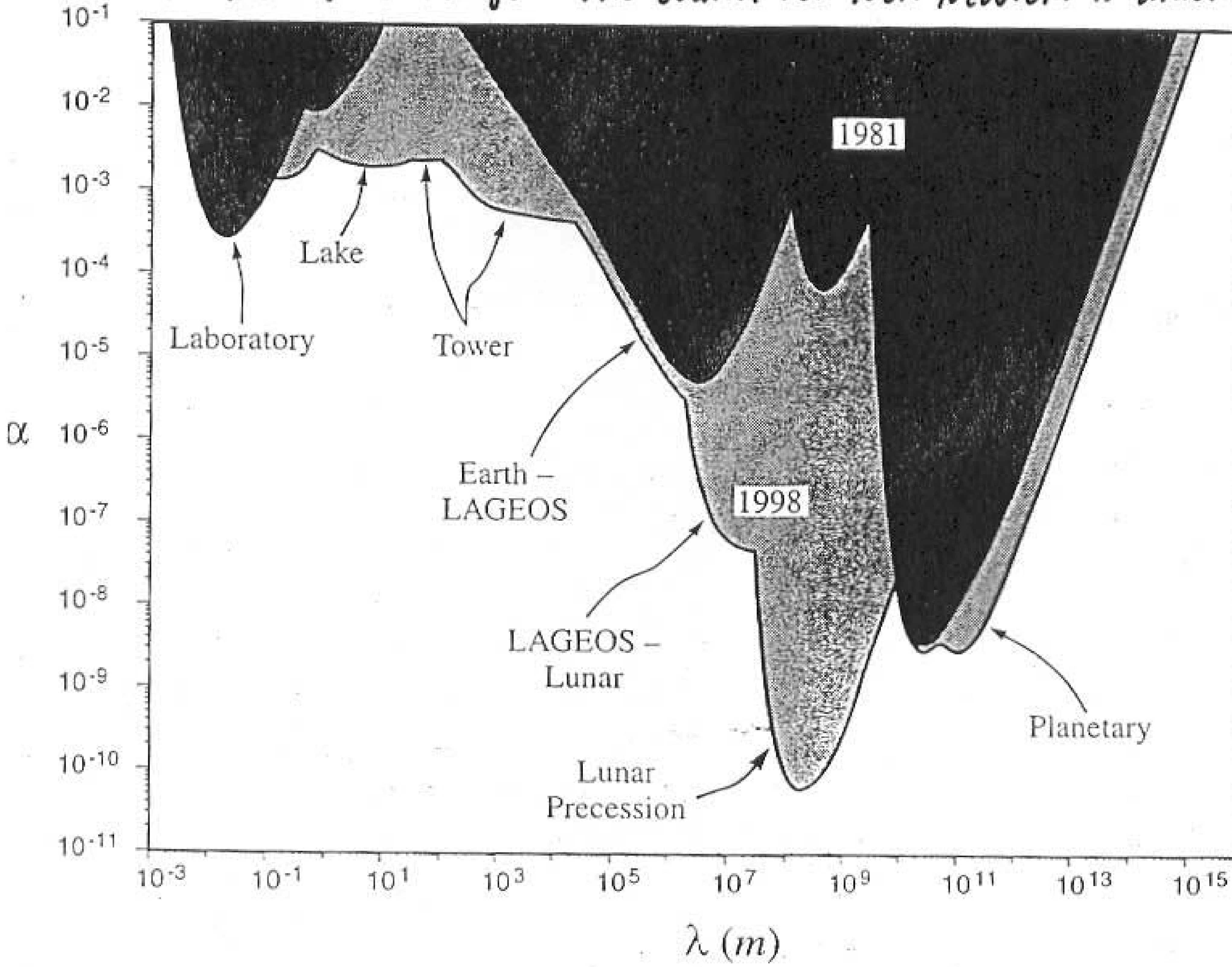
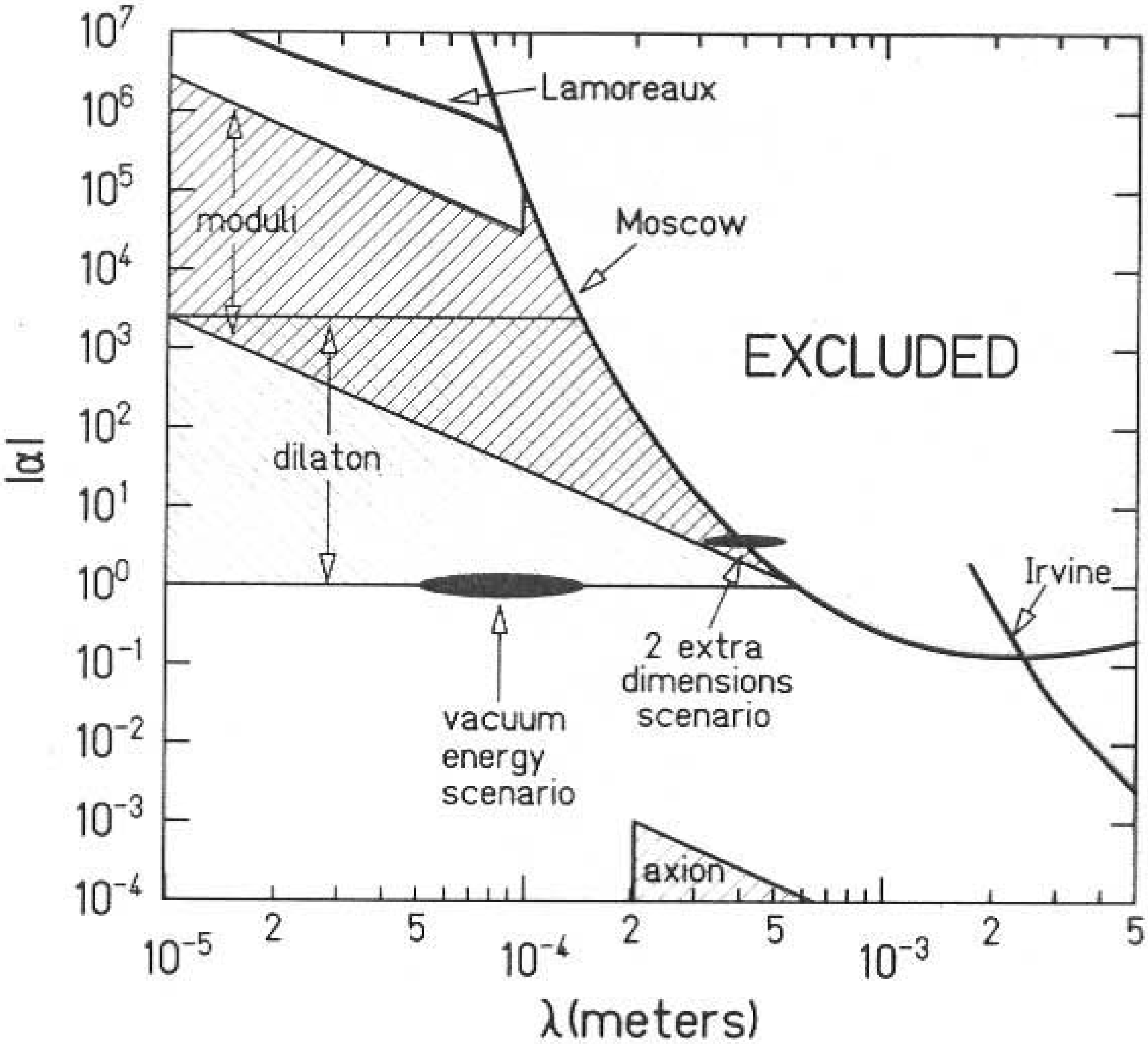


Figure 2.13: Constraints on the coupling constant α as a function of the range λ from composition-independent experiments. The dark shaded area indicates the status as of 1981, and the lighter region gives the current limits. Note that only the most sensitive results are exhibited in each regime in λ, 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

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

$$V(r) = V_N\{1 + \alpha\ e^{-r/\lambda}\}$$

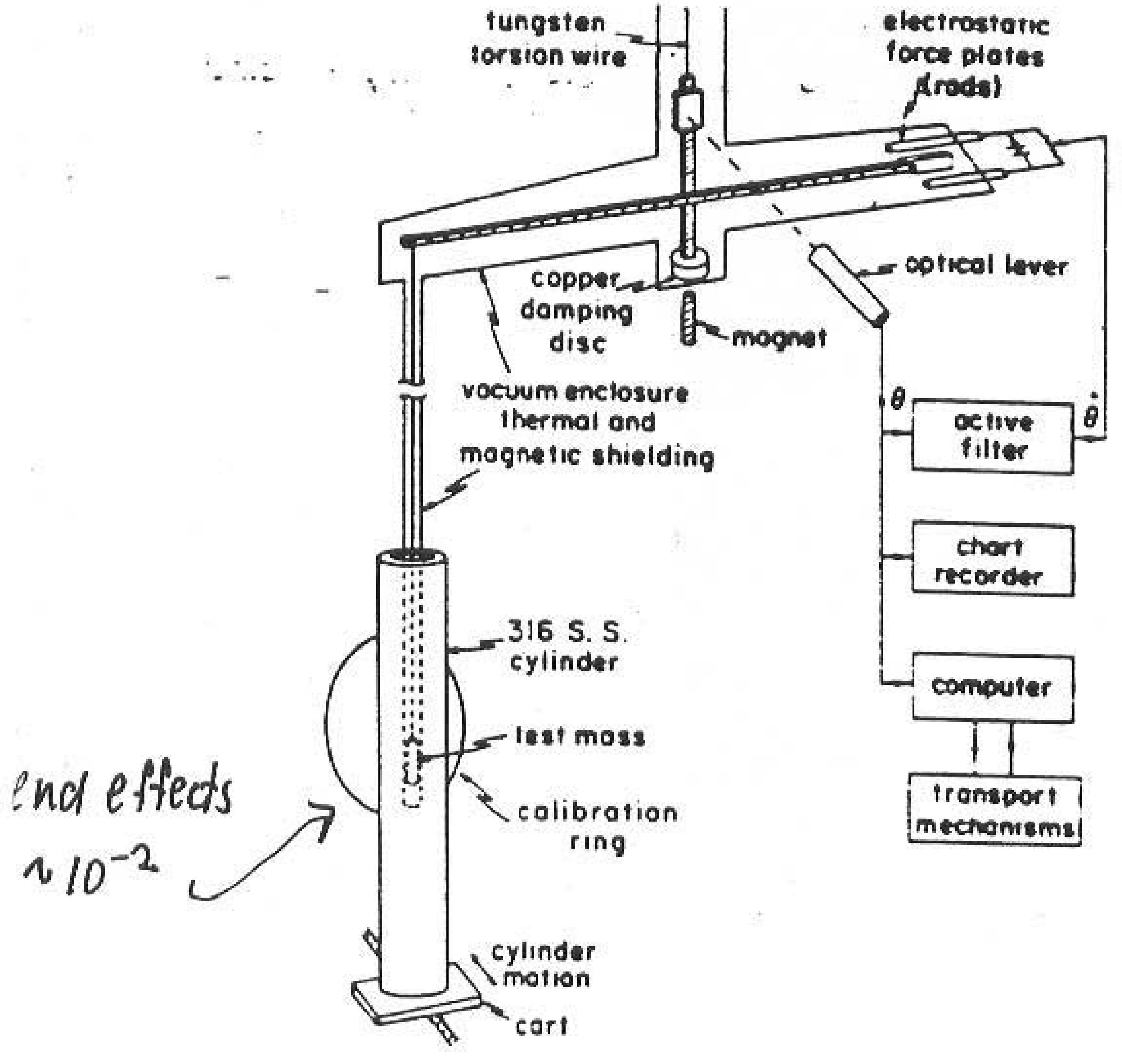


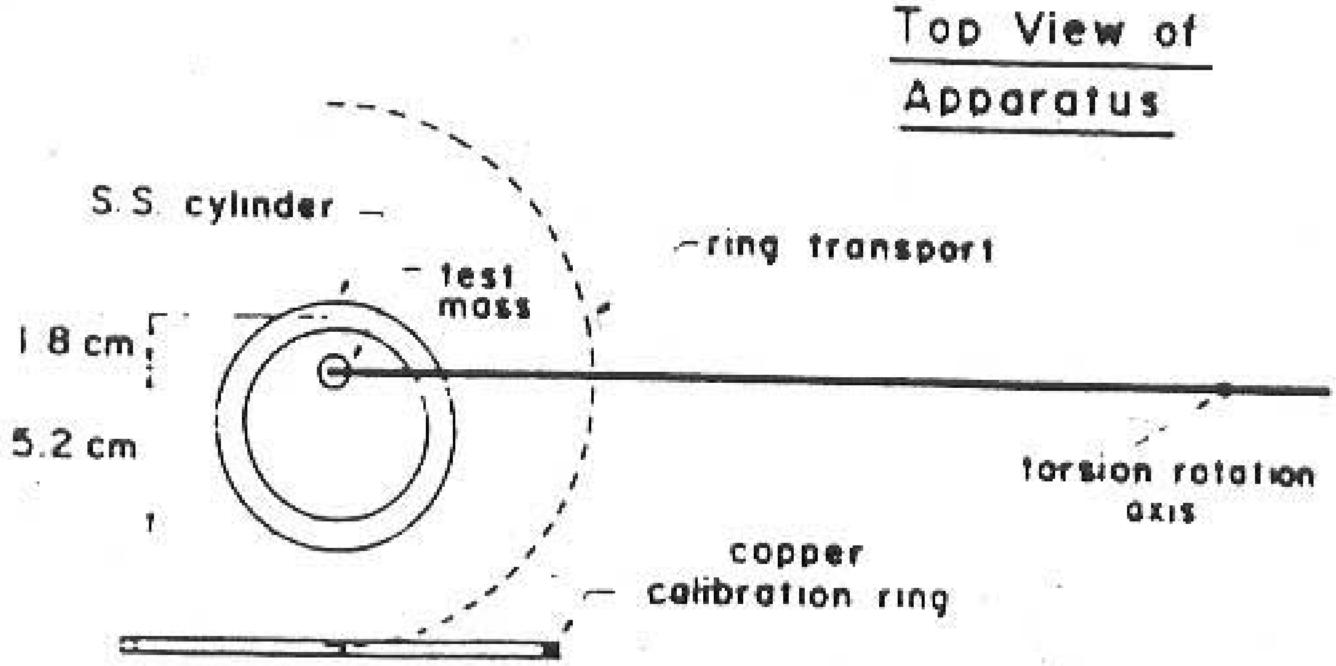
taken from Long, Chan, & Price, Nucl. Phys. B 529 (1999) 23

- moduli - theoretical speculation by Dimopoulis & Guidice, Phys. Lett. B 379 (1966) 105
- dilaton - theory argument by Kaplan & Wise hep-ph 0008116
- axion - region allowed by neutron EDM & astrophysical constraints

The UC Irvine test of 1/r² law

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





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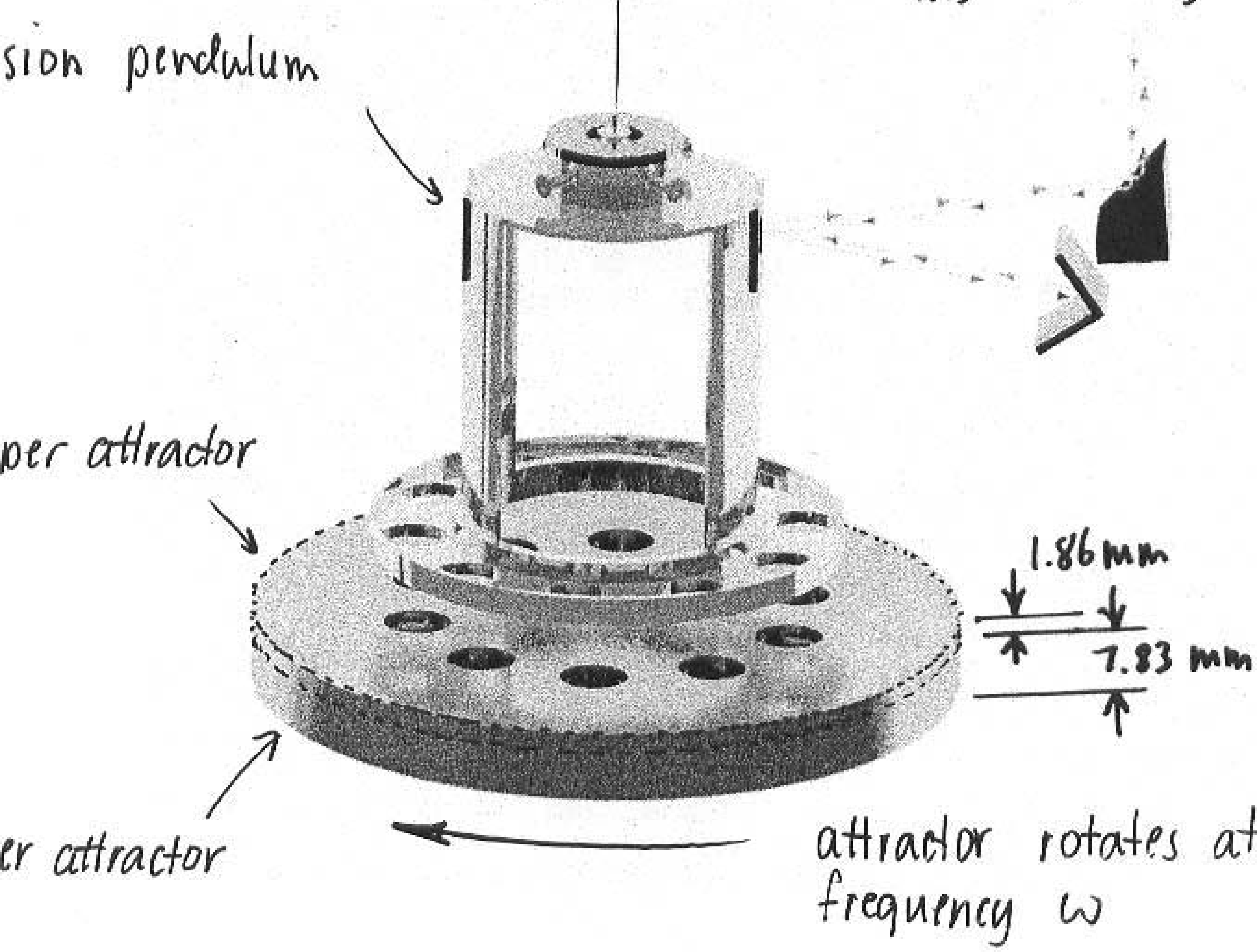
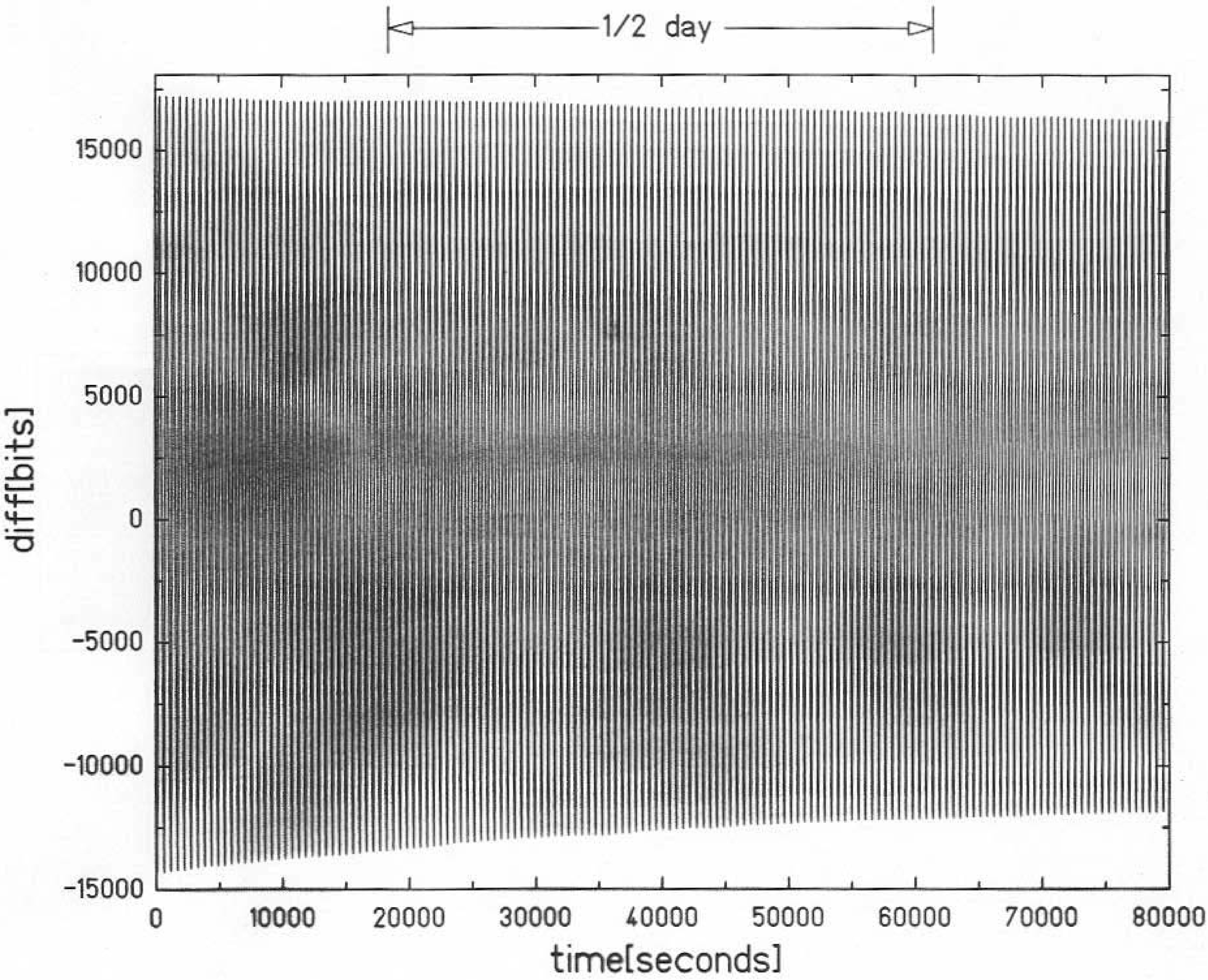
NSF DOE NASA

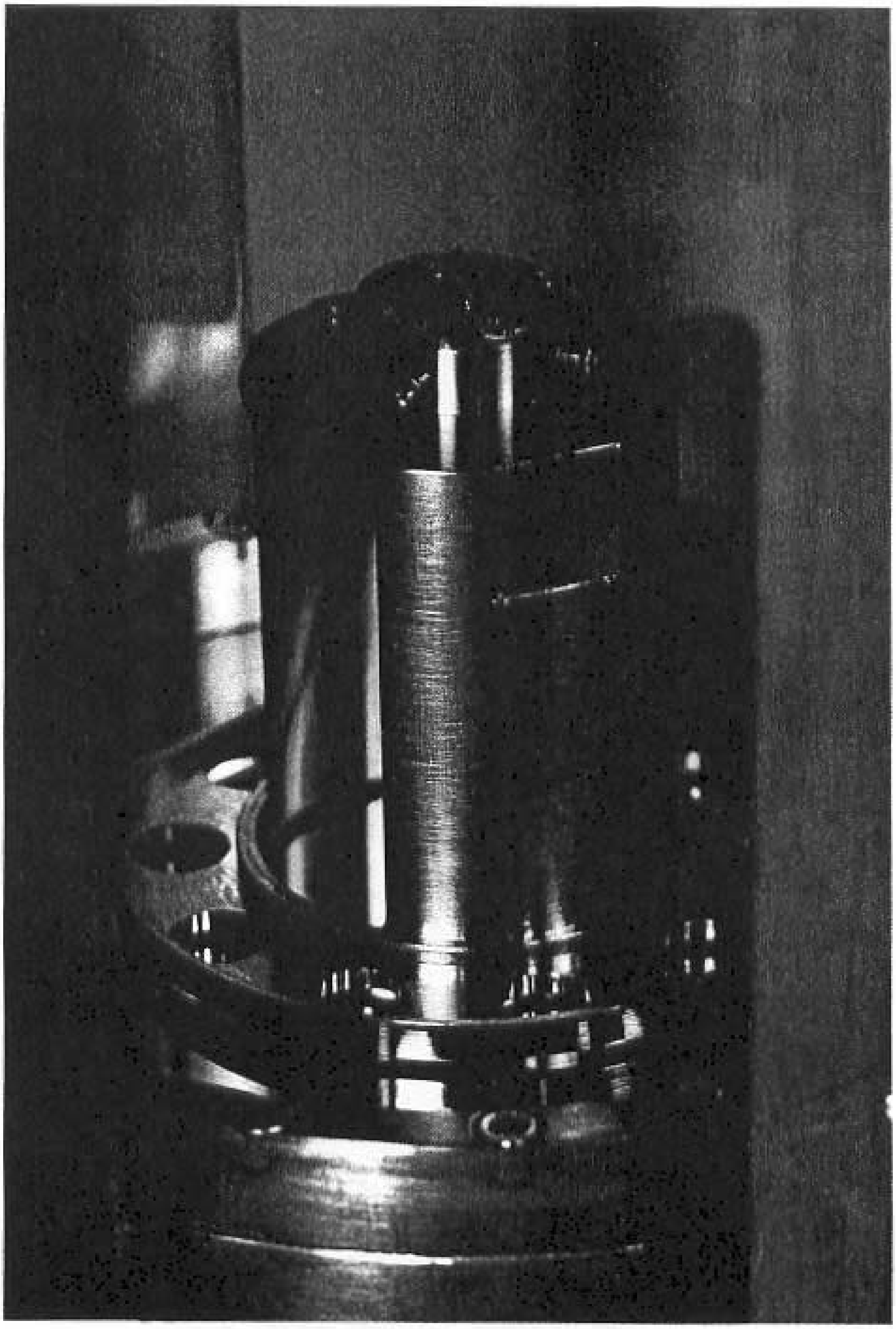
Hoyle et al., Phys. Rev. Lett. 86, 1418 (2001)



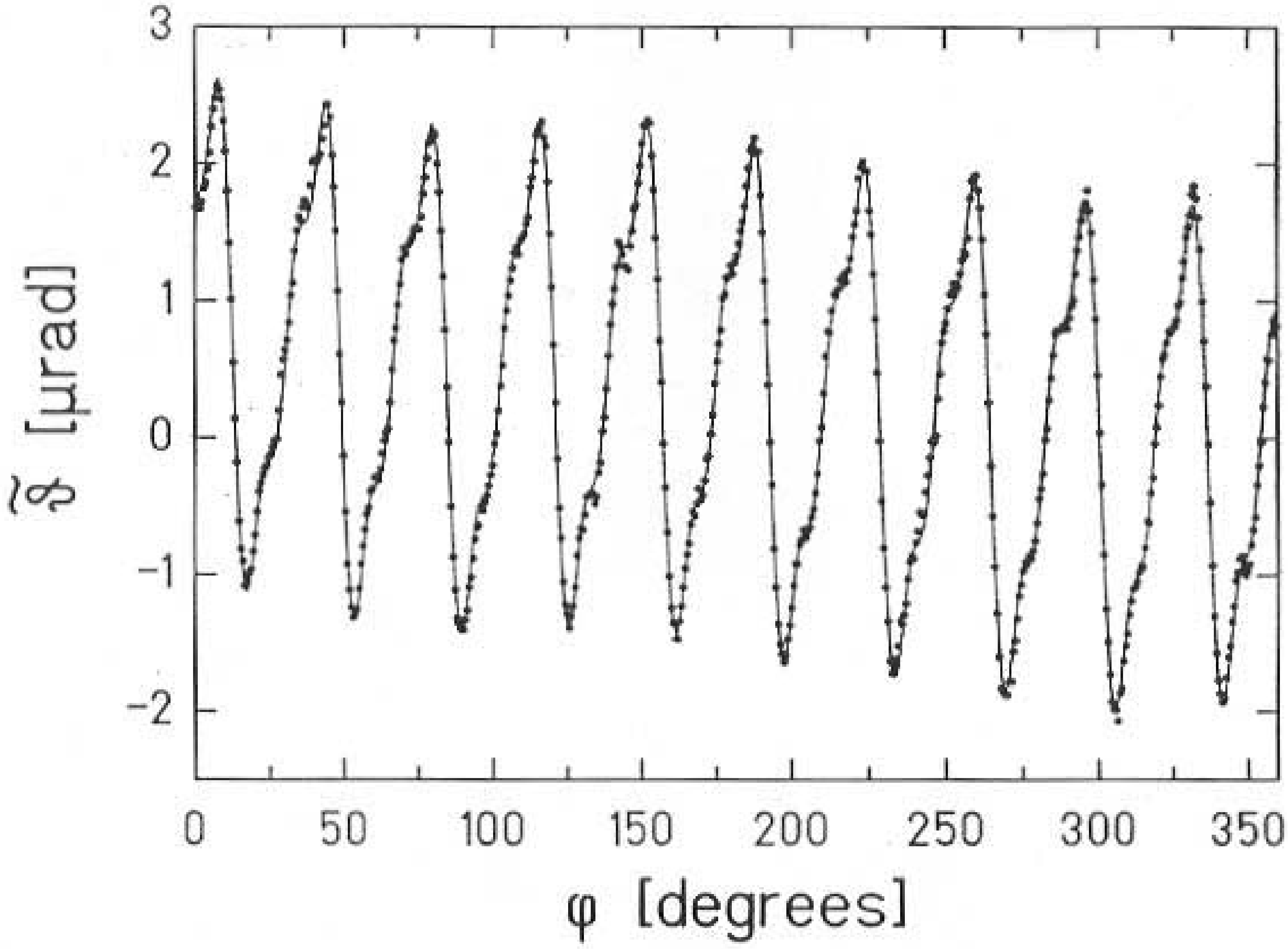
- the 10 holes in the lower attractor are "out of phase" with the holes in the upper attractor.
- this cancels Newtonian gravity torque by a factor of ~ 20, but has little effect on torque from short-range force
- measure z-dependence of torque signals at 10ω, 20ω and 30ω


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

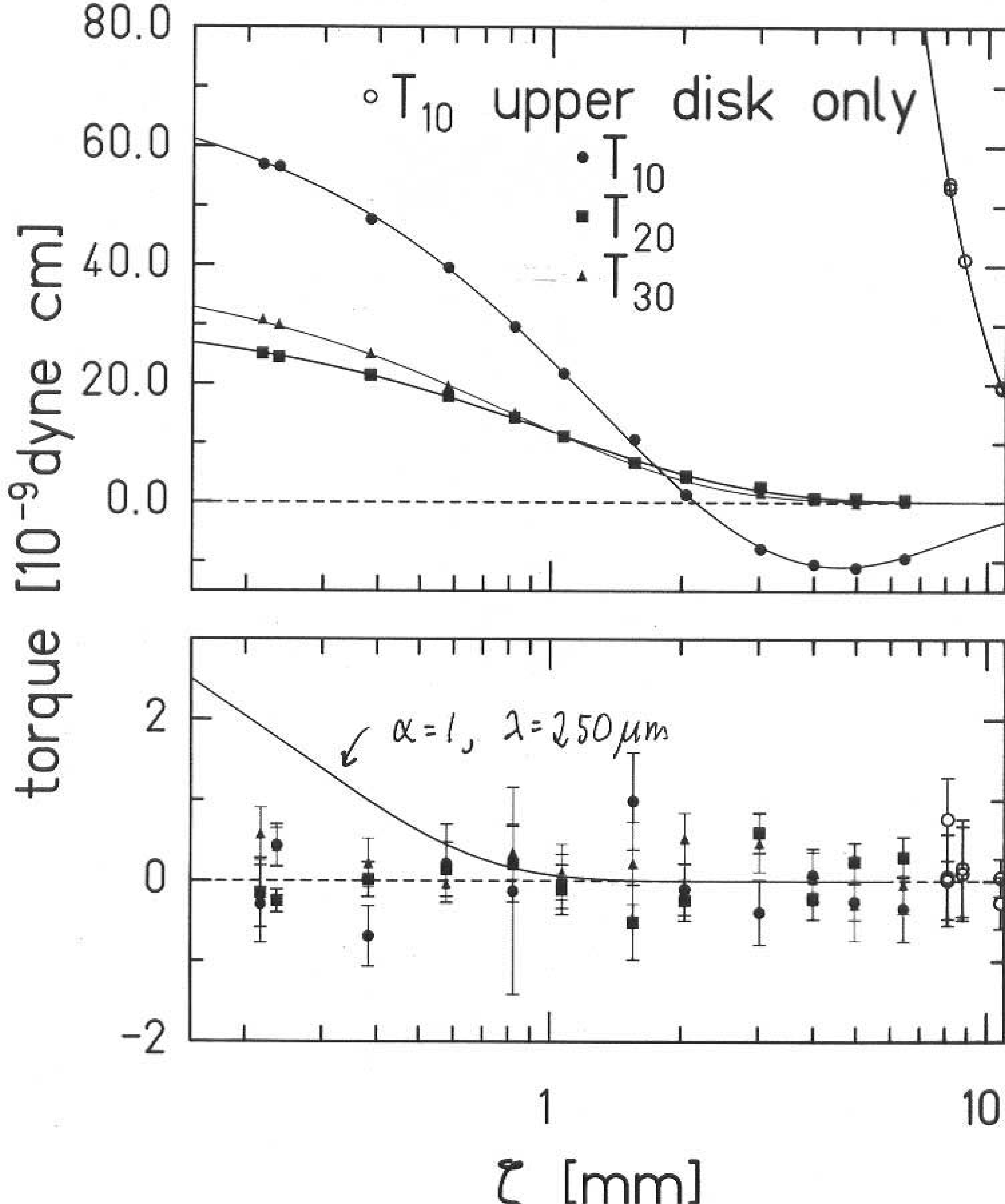
Eöt-Wash Mark II short-range instrument



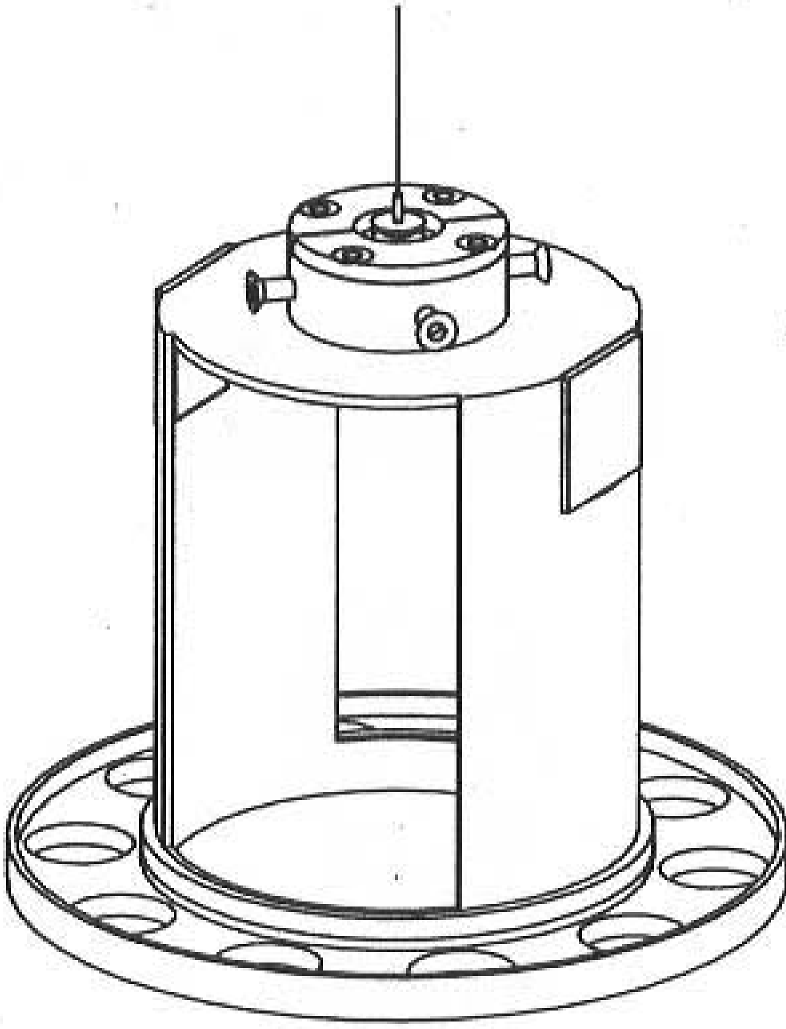
signal at a separation of 237 μm



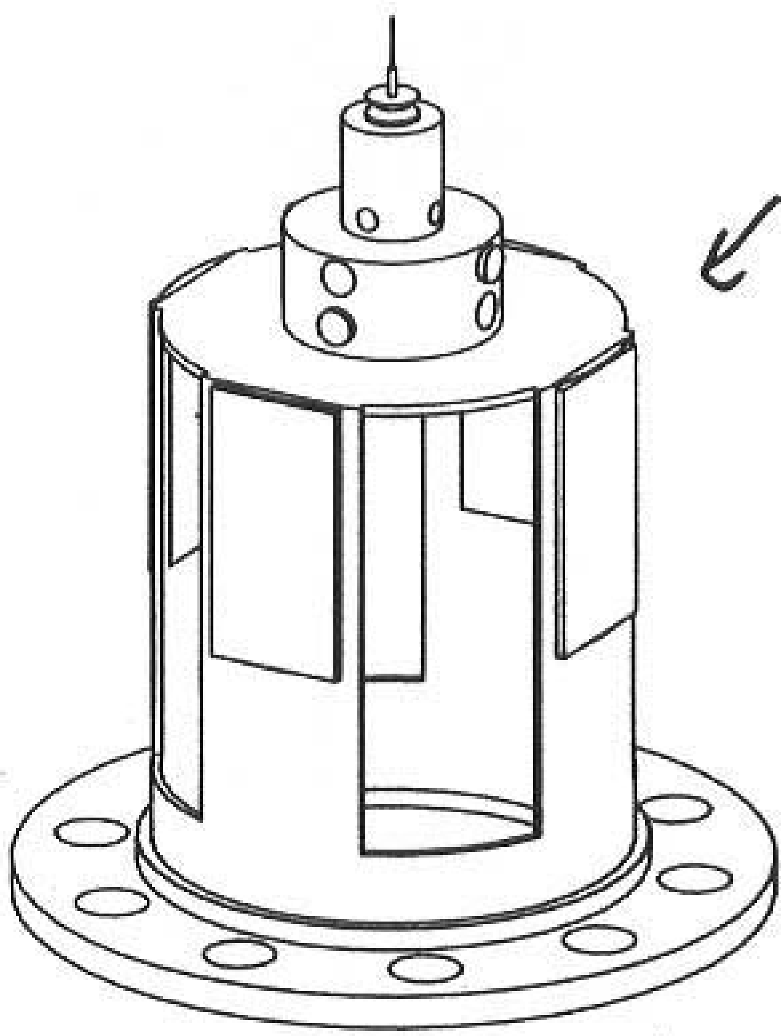
hep-ph/0011014

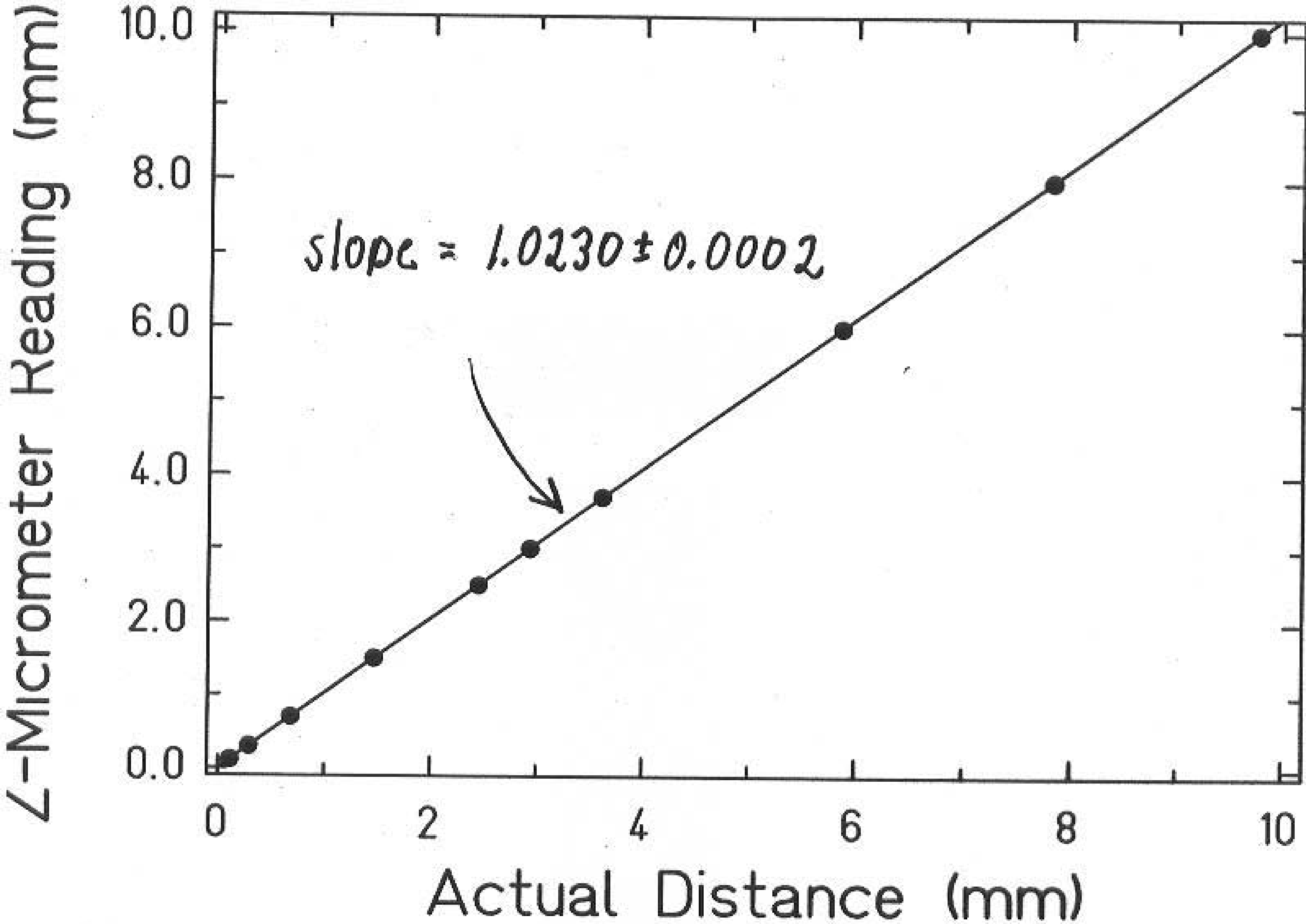


Mark II



Mark III





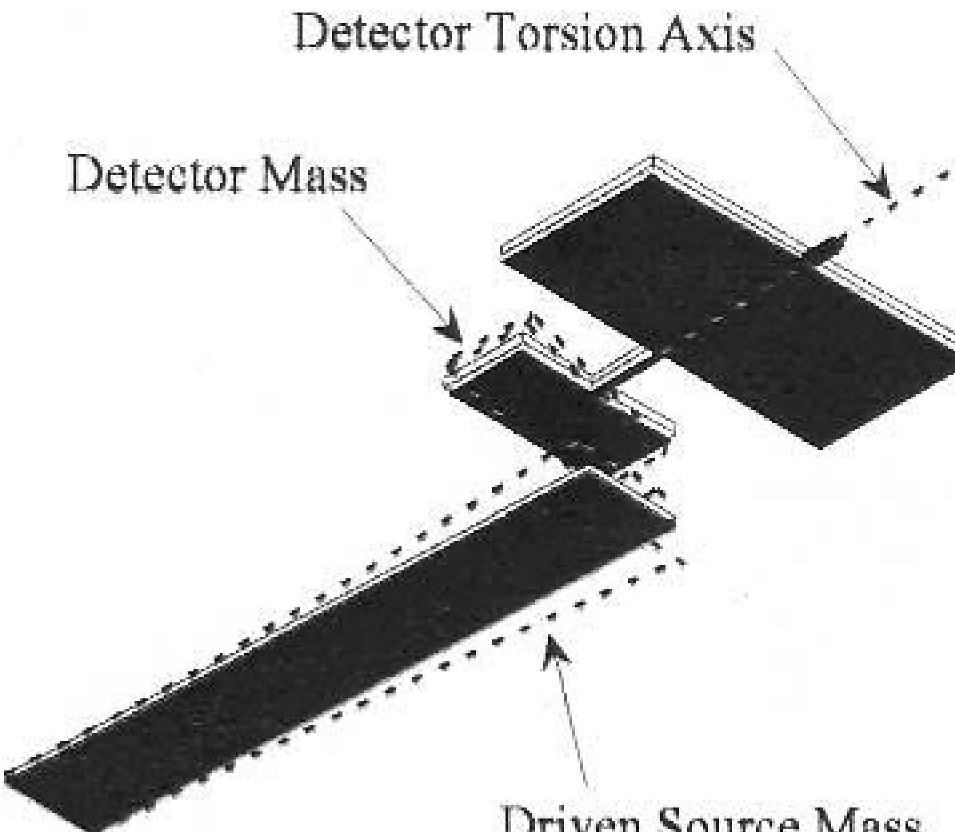
Z-Micrometer Reading (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
2
4
6
8
10
Actual Distance (mm)
slope = 1.0230 ± 0.0002

SOME INTERESTING NUMBERS

- typical torque measured in our 10-hole experiments ~ 4 fN·m with statistical uncertainty of 0.04 fN·m
- this corresponds to a gravitational force of ~(140 ± 1.4) fN
- to get an idea of how small this is, cut a postage stamp into 10^{12} equal pieces
- typical force in 10-hole experiment is ~ 200x weight of one of those pieces
  uncertainty in force ~ 2x weight of one of those pieces
- current measurement errors are ~10x smaller!

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

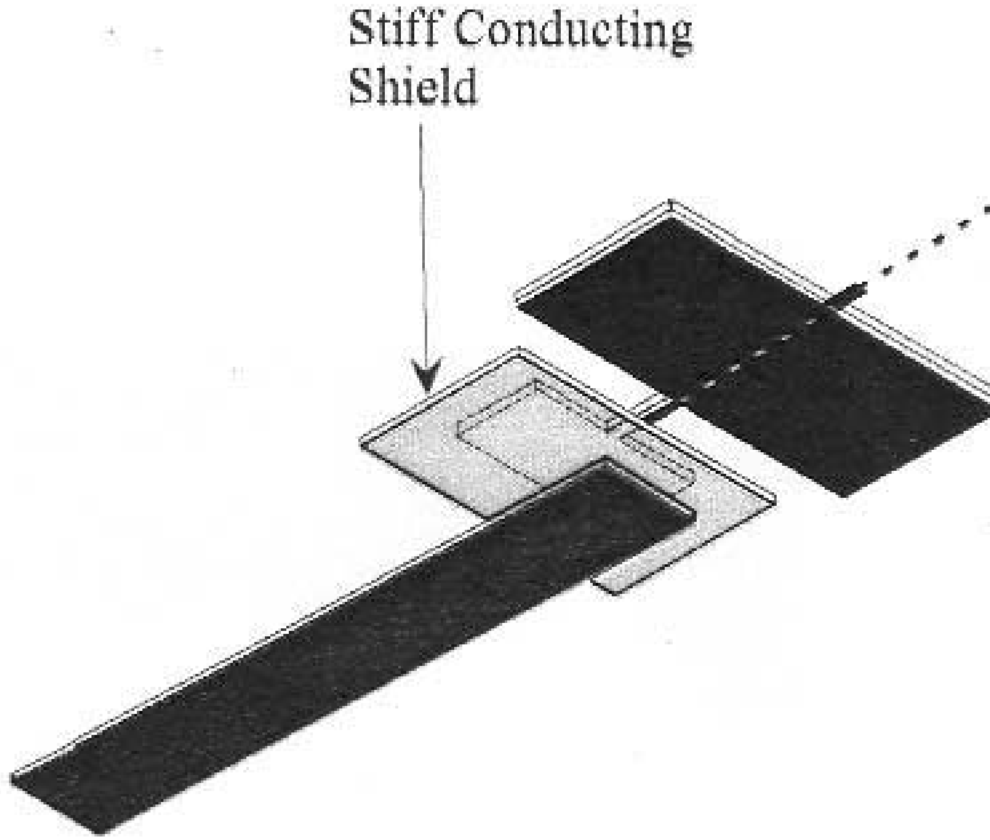
Planar Geometry



$F_Y(\alpha = 1, \lambda = 100\,\mu m)$

$\approx 1 \times 10^{-14}$ N

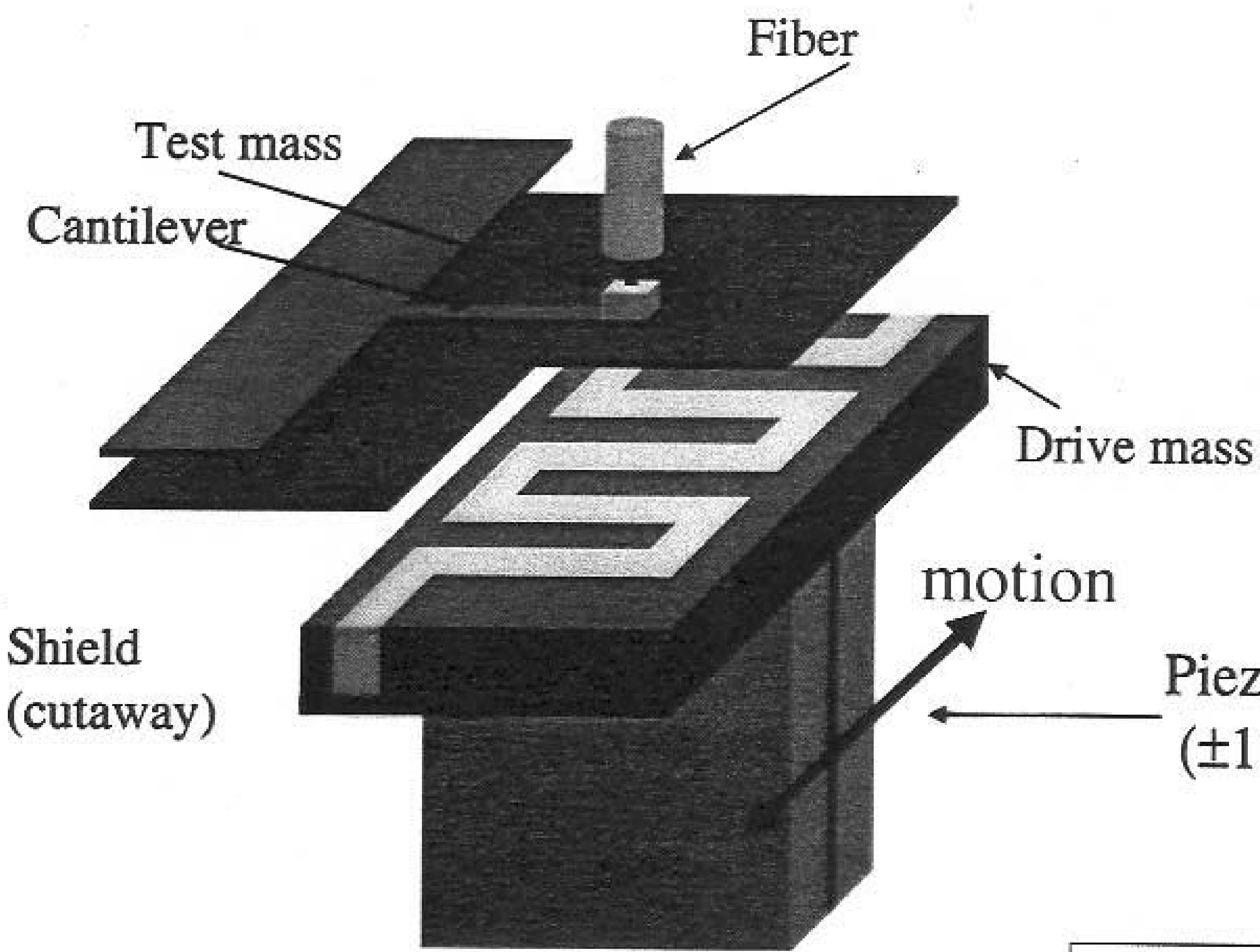
Source and Detector Oscillators

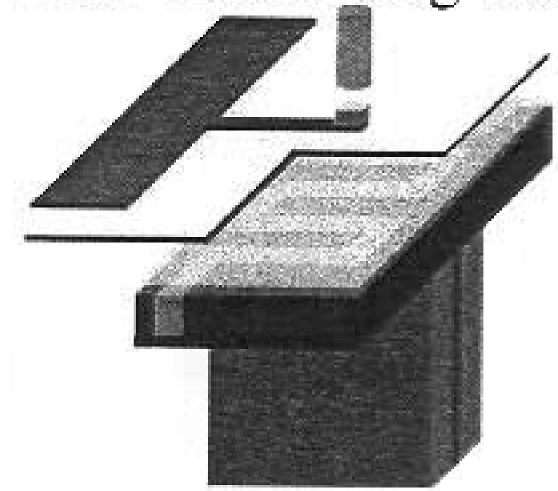


Shield for Background Suppression

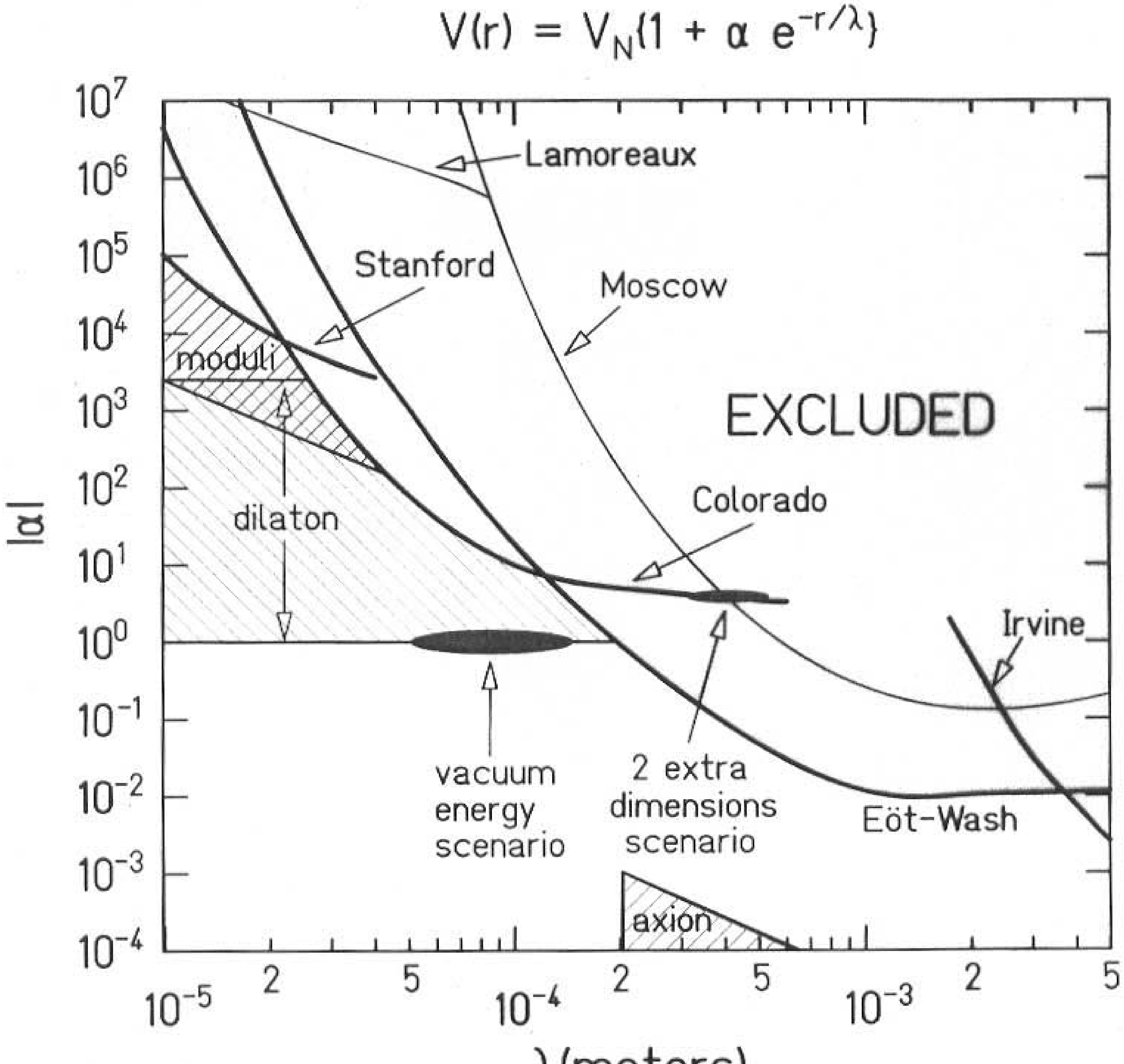
Stanford's Experiment

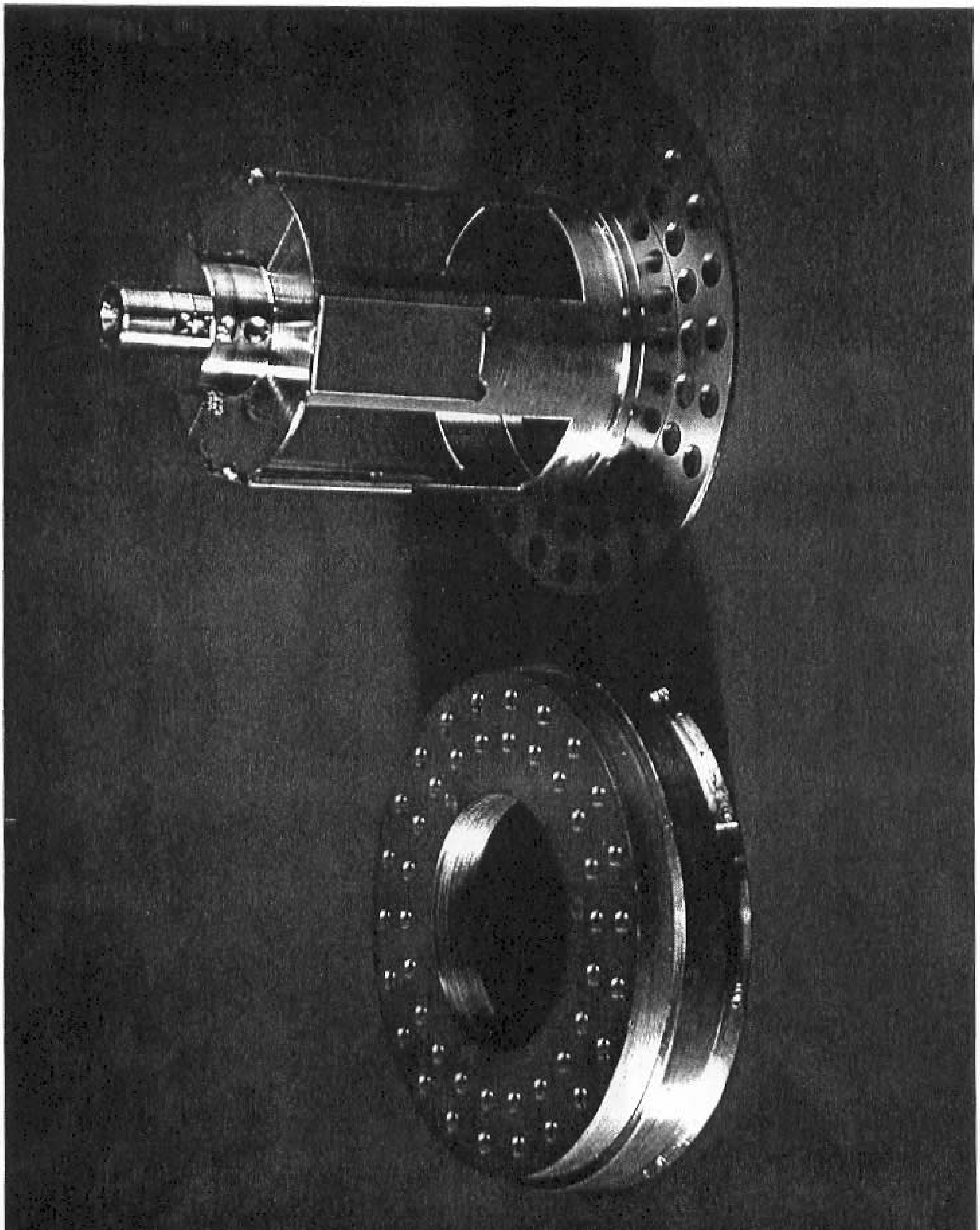
Chiaverini et al., Phys. Rev. Lett. 90, 151101 (2003)

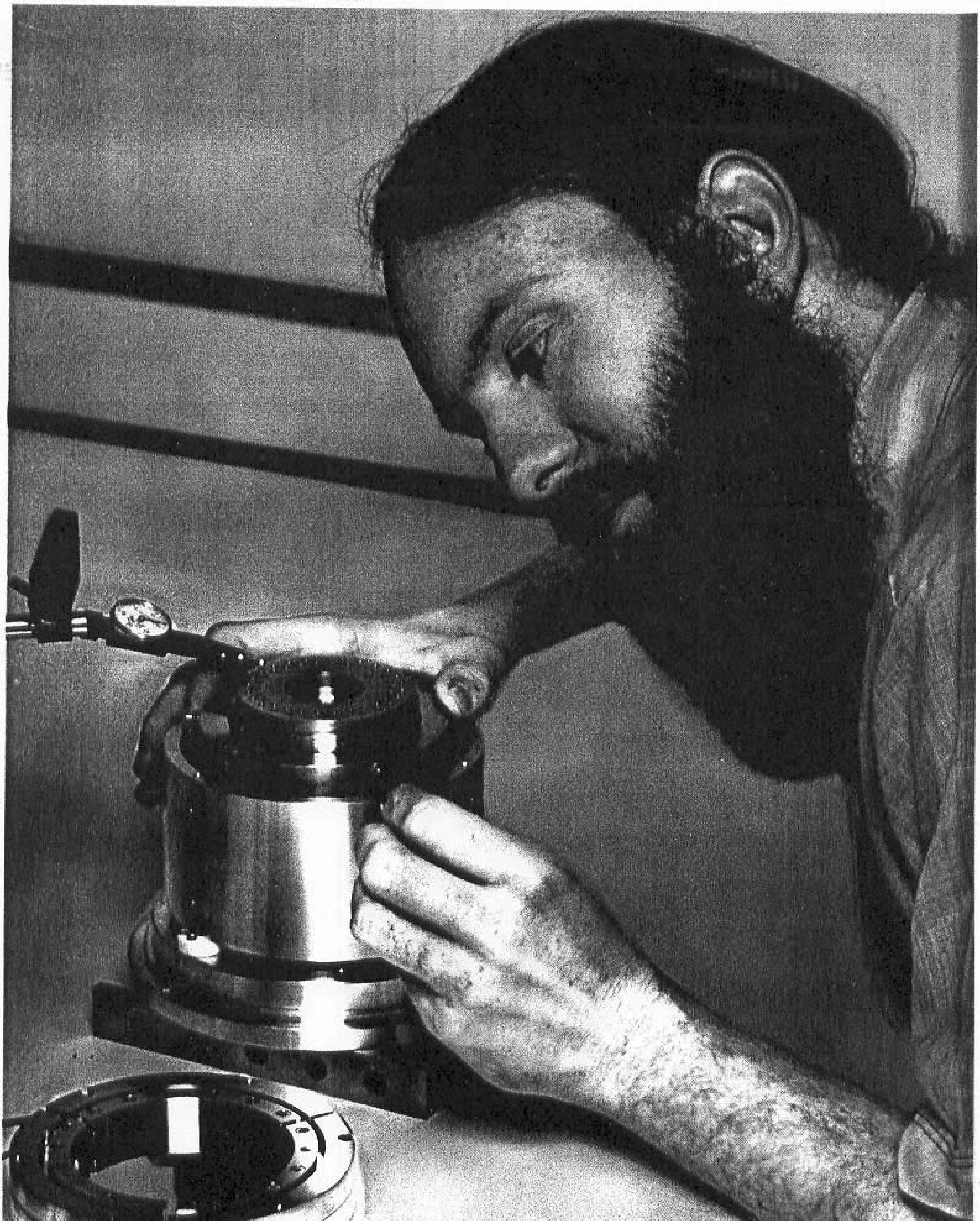




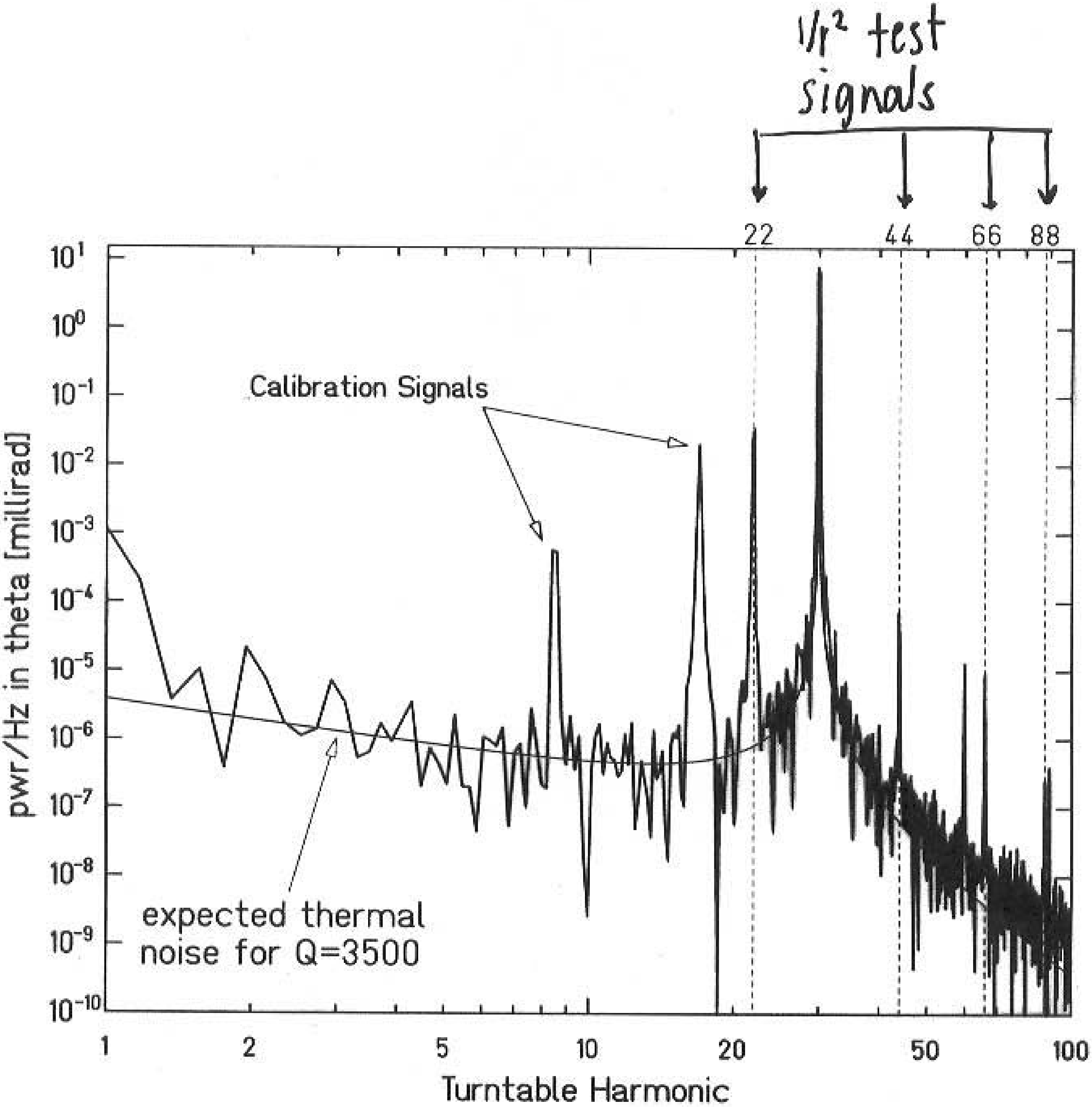
Cantilever resonance (f_0): ~300 Hz
Drive frequency($f_0/3$): ~100Hz

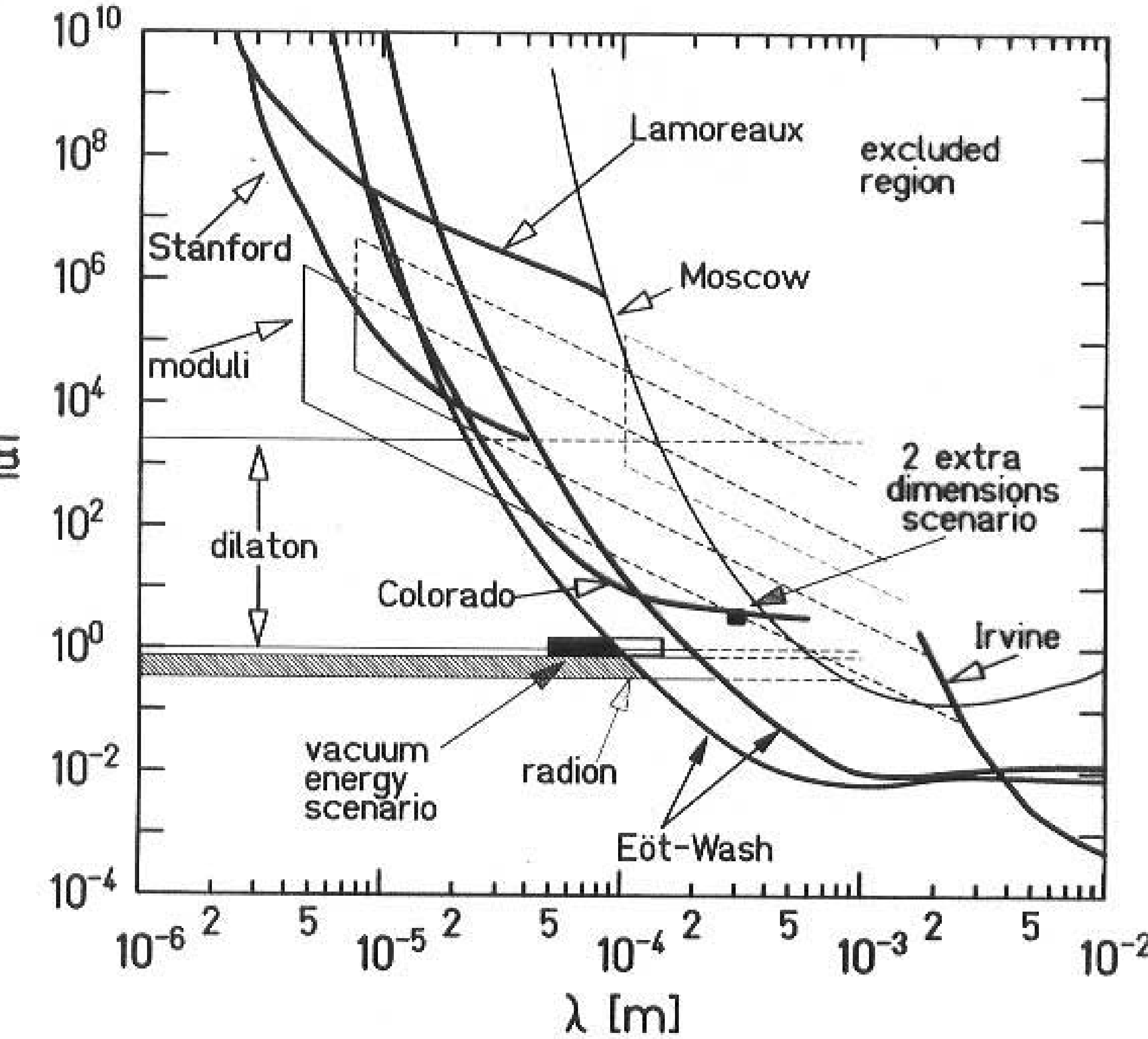

V(r) = V_N{1 + α e^{-r/λ}}
|α|
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Lamoreaux
Stanford
Moscow
moduli
EXCLUDED
Colorado
dilaton
Irvine
vacuum energy scenario
2 extra dimensions scenario
Eöt-Wash
axion
10^-5
2
5
10^-4
2
5
10^-3
2
5
λ(meters)





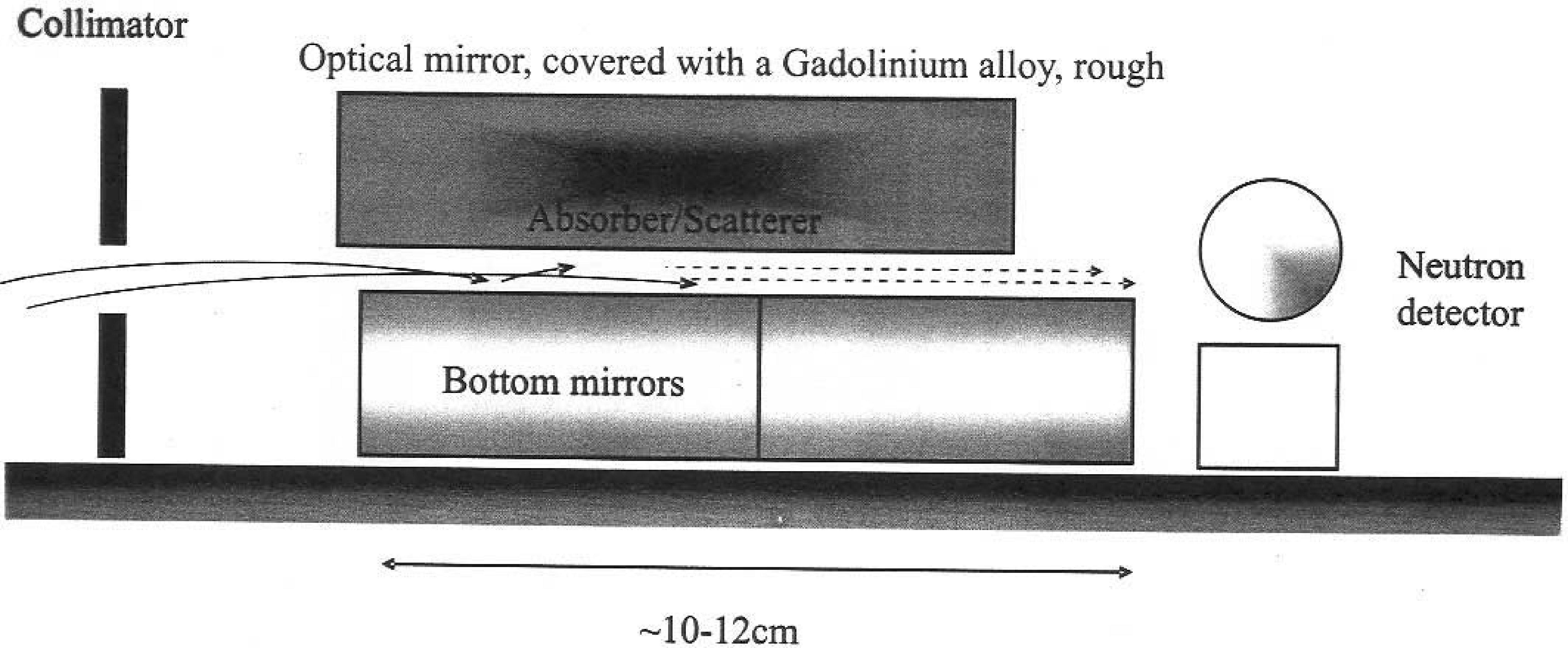
Power spectrum of the twist signal in the 44-hole experiment



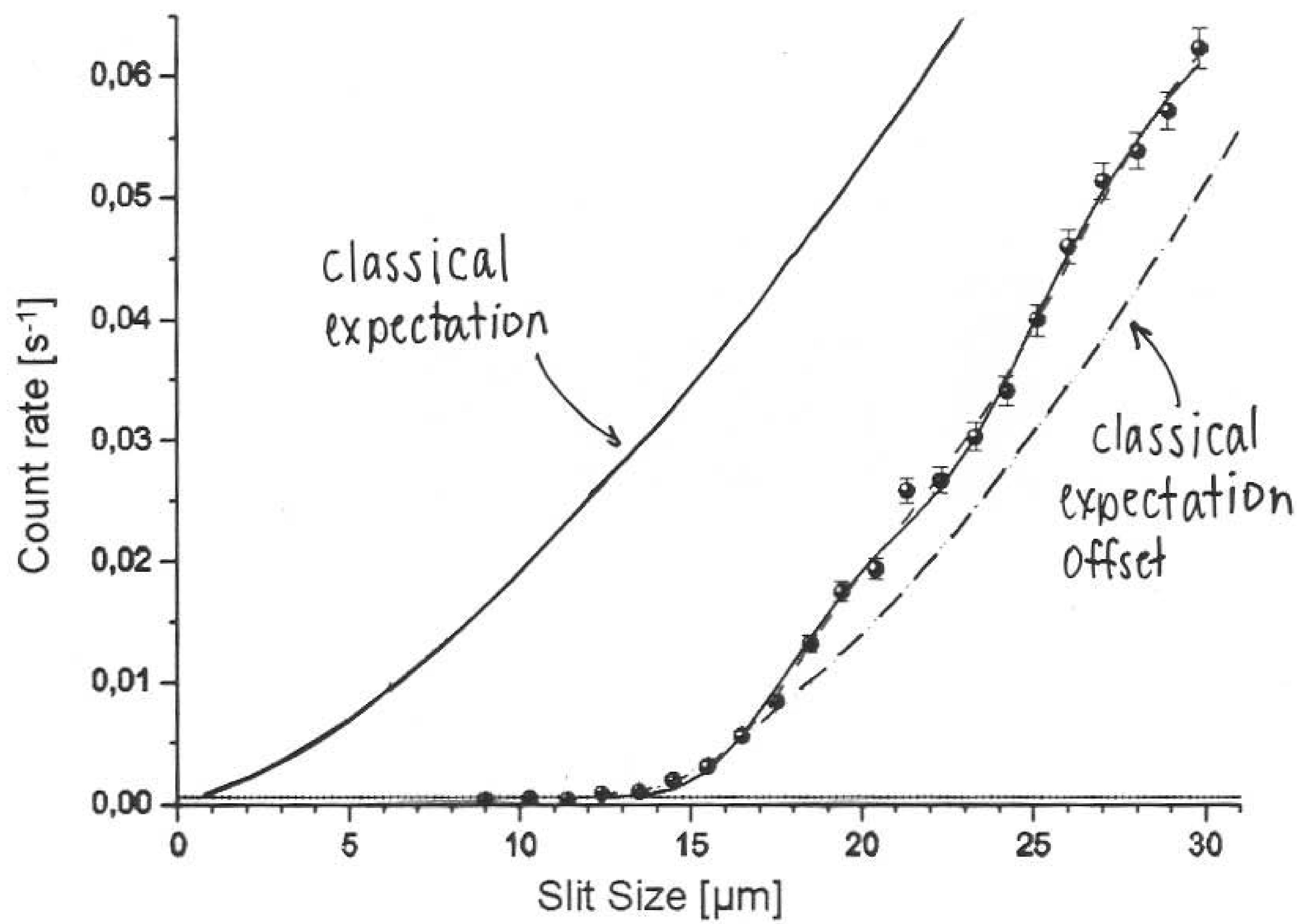


Lamoreaux
excluded region
Stanford
Moscow
moduli
2 extra dimensions scenario
dilaton
Colorado
Irvine
vacuum energy scenario
radion
Eöt-Wash
|α|
λ [m]

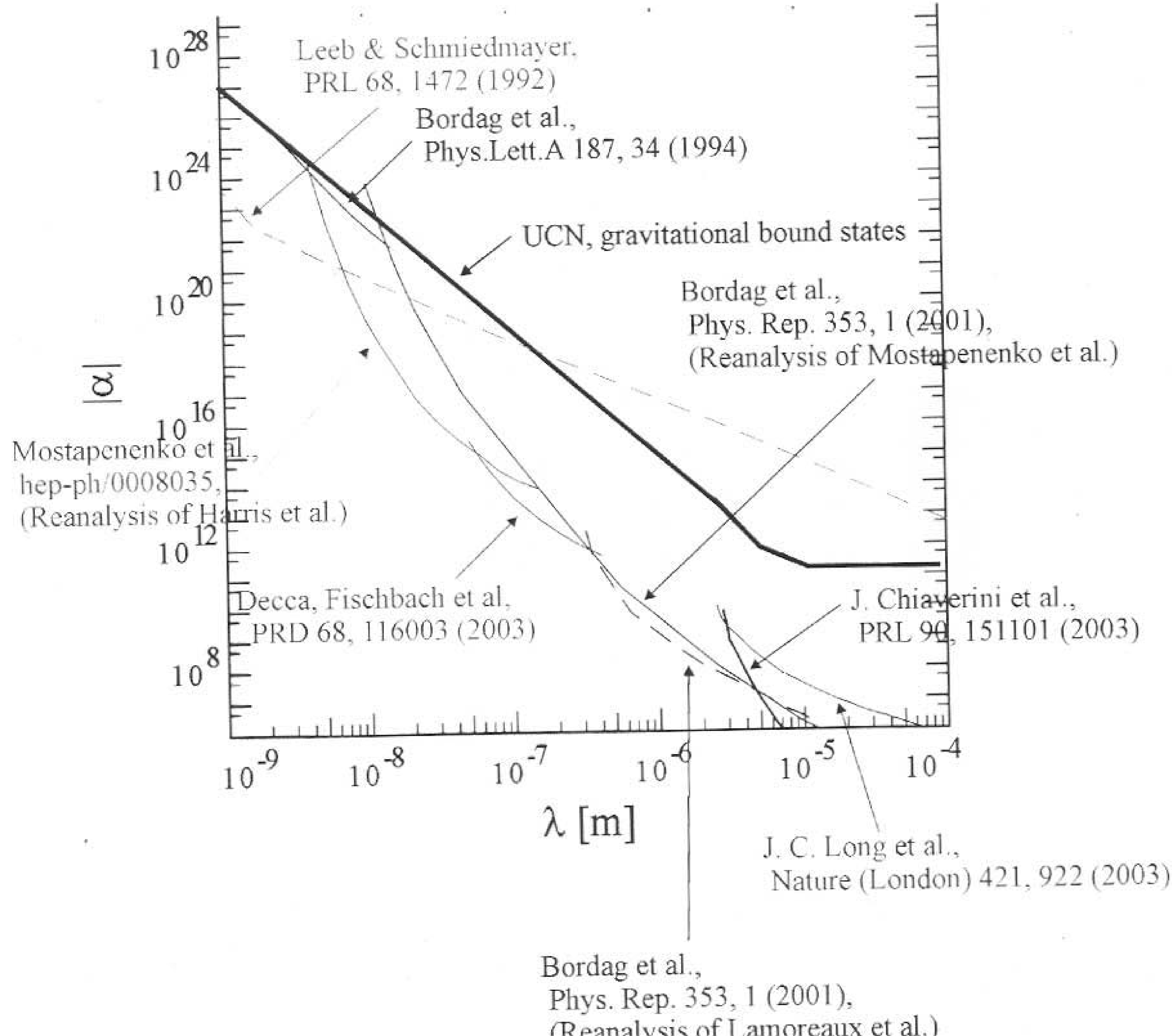
GRENOBLE, GATCHINA, HEIDELBERG, MOSCOW EXPERIMENT WITH ULTRA-COLD NEUTRONS



Transmission vs. Slit Size (preliminary data, 2002)



S. Baessler


Leeb & Schmiedmayer,
PRL 68, 1472 (1992)
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(Reanalysis of Mostapenenko et al.)
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Decca, Fischbach et al,
PRD 68, 116003 (2003)
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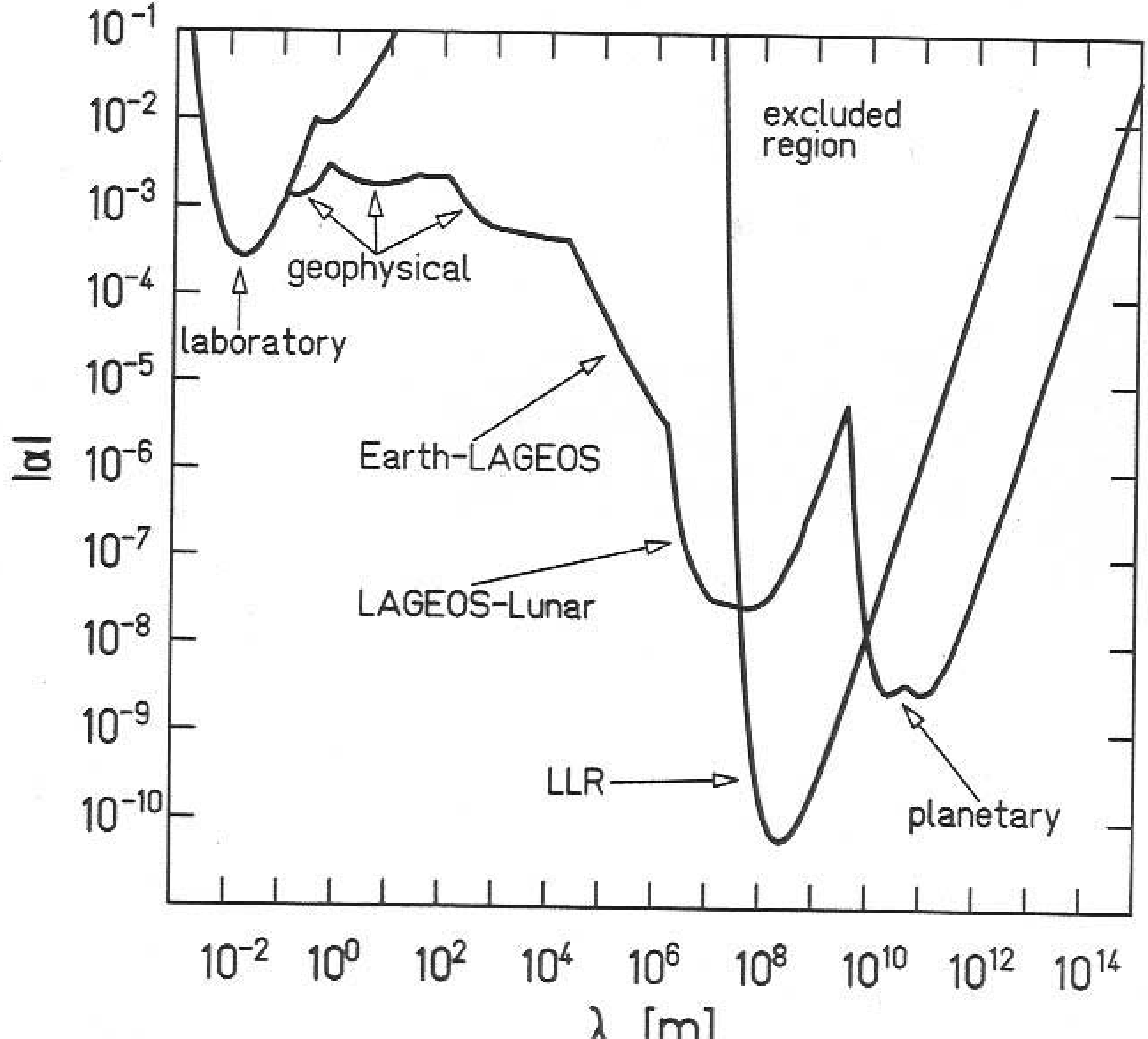
PRL 90, 151101 (2003)
J. C. Long et al.,
Nature (London) 421, 922 (2003)
Bordag et al.,
Phys. Rep. 353, 1 (2001),
(Reanalysis of Lamoreaux et al.)
|α|
λ [m]
10^28
10^24
10^20
10^16
10^12
10^8
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4

Constraints on Long-Range Yukawa Forces



A BRIEF HISTORY OF LLR

1969 • first reflector placed on moon by Apollo 11 astronauts (DW)

1969 • 2.7m McDonald Observatory telescope launches laser beam at moon & gets photons back

1971 • 2 more reflectors placed on moon by Apollo astronauts

1973 • French reflector placed by Soviet unmanned lander

⋮

1984 • Haleakala & CERGA facilities begin ranging

1985 • McDonald Observatory replaced by 0.6m dedicated telescope

1990 • Haleakala stops LLR

⋮

• little apparent degradation of reflectors in 35 y !

2003 • hope to have new APOLLO facility on-line

LLR Science

Gravitational Physics:

- The *best* test available of the strong equivalence principle (EP)
- A *leading* test of the weak (composition-dependent) EP
- The *best* test of time-variation of Newton's constant, G
- The *best* test of gravitomagnetism ($\cos D$ term)
- Currently the *best* probe of relativistic geodetic precession
- The *most sensitive* test of $1/r^2$ law

By-products:

- Lunar interior
- Coordinate systems
- Geophysics

What is the Weight of Gravity?

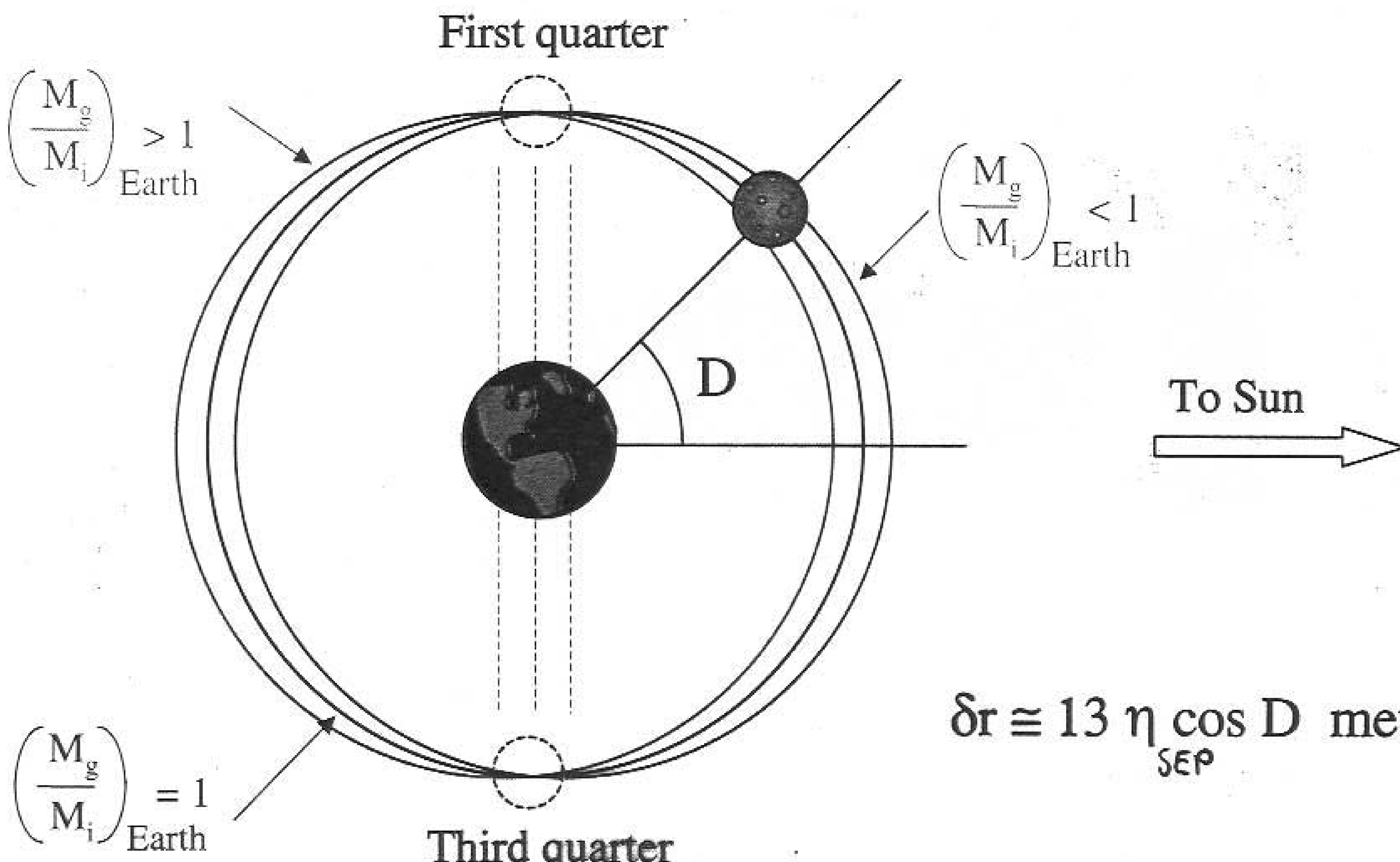
Testing the EP for gravitational self-energy (GSE)

- No experiment using laboratory-sized test-bodies can test if gravity itself gravitates
  - i.e., cannot check non-linear aspects of the theory
- GR predicts that GSE obeys the EP, but other metric theories (such as scalar-tensor) predict violations
- Best test of the EP for GSE
  - LLR comparison of earth and moon accelerations toward the sun
  - fractional contribution of GSE to masses of:

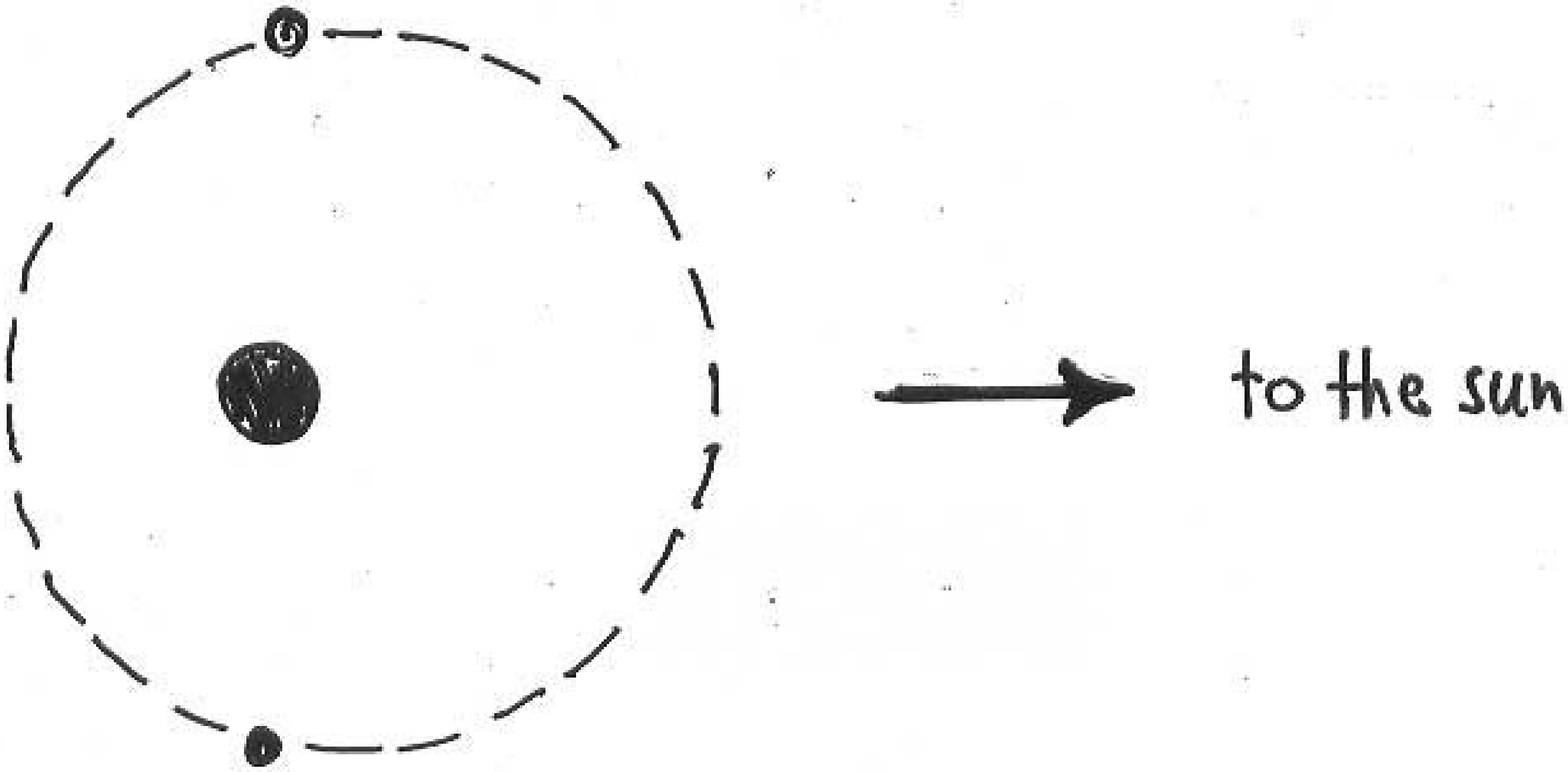
    earth: -4.6×10^{-10}
    moon: -0.2×10^{-10}

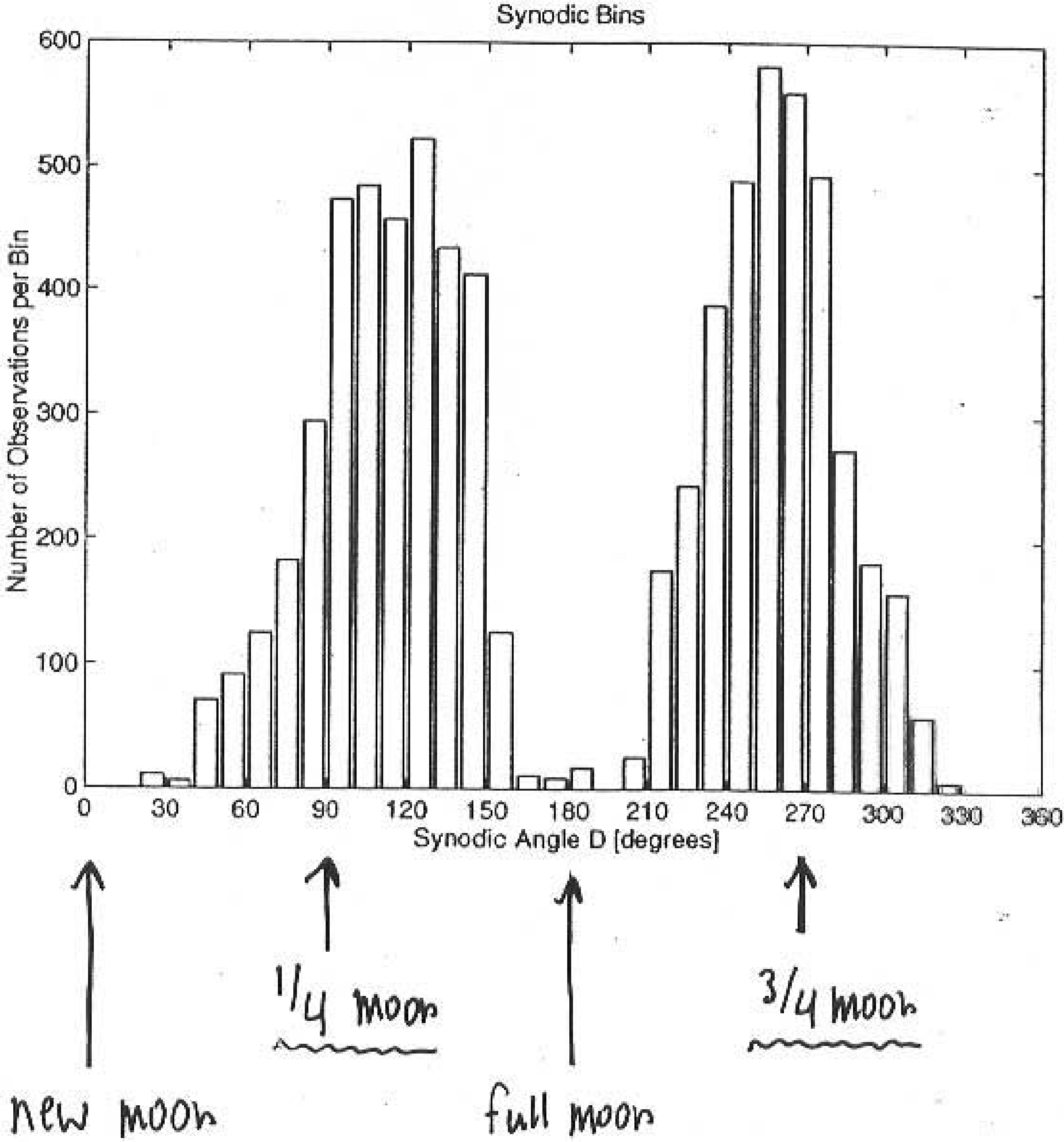
- LLR sets $\Delta a/a < 1.4 \times 10^{-13}$
  - yields upper limit of 4 mm on $\cos D$ distortion of lunar orbit
  - corresponds to $\omega > 2500$

Orbital Perturbations



$$\delta r \cong 13\, \eta_{SEP} \cos D \ \text{meters}$$





Müller & Nordtvedt Phys Rev D 58 (1998) 062001

- *Question*: Doesn't the Hulse-Taylor binary pulsar provide a better test of the Strong EP than LLR?

  - gravitational self energy is

    10^{-1} of neutron star mass

    4×10^{-10} of earth's mass

  - timing measurements so good that the GR prediction for power radiated into gravitational waves is verified to $\sim 1/3\%$!

- *Answer*: No

  - two objects in binary pulsar are almost identical

    neutron stars with $m \sim 1.4 M_\odot$

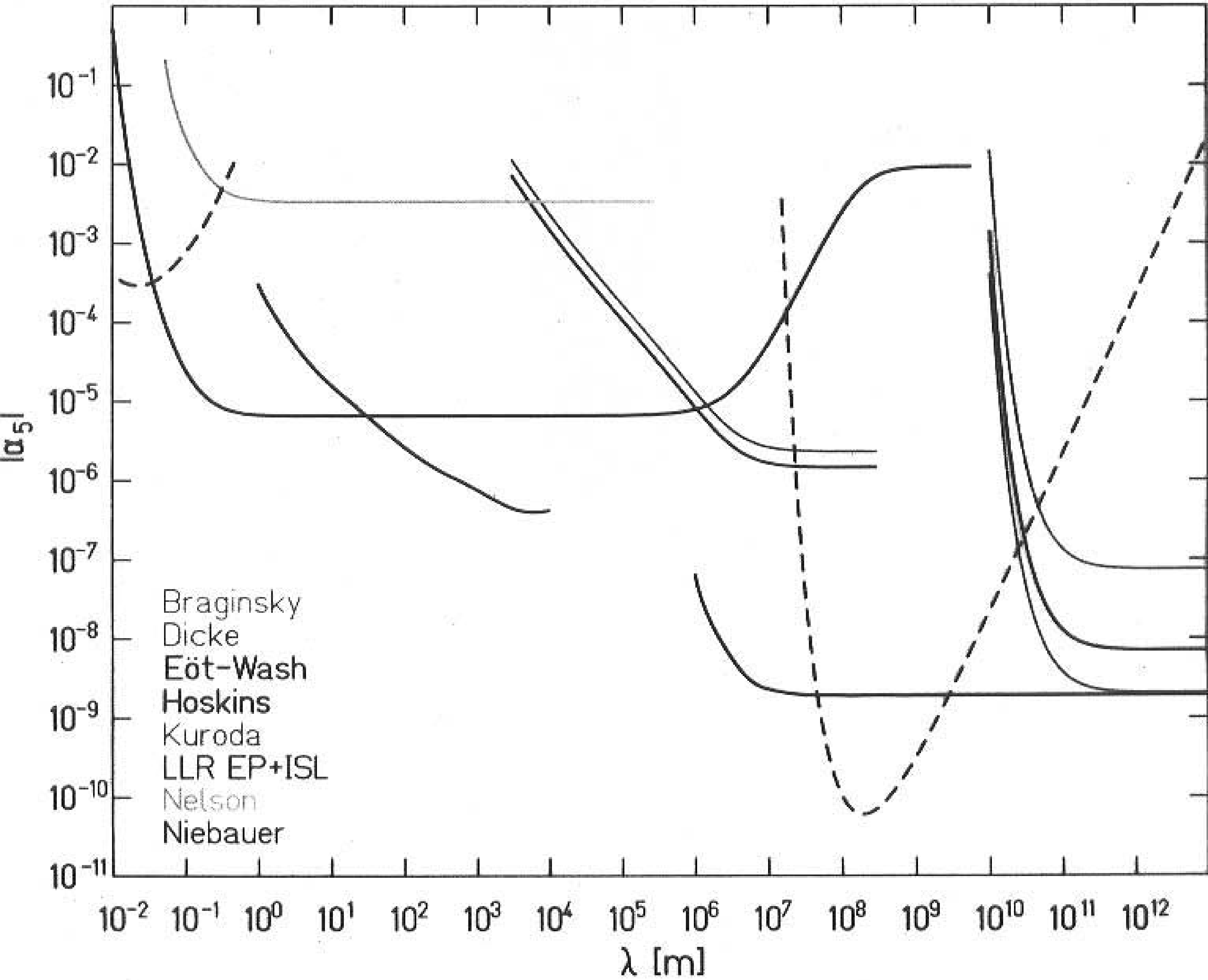
- *the Holy Grail*

  - find an *isolated* neutron star-black hole binary system

— from EP tests

--- from $1/r^2$ tests

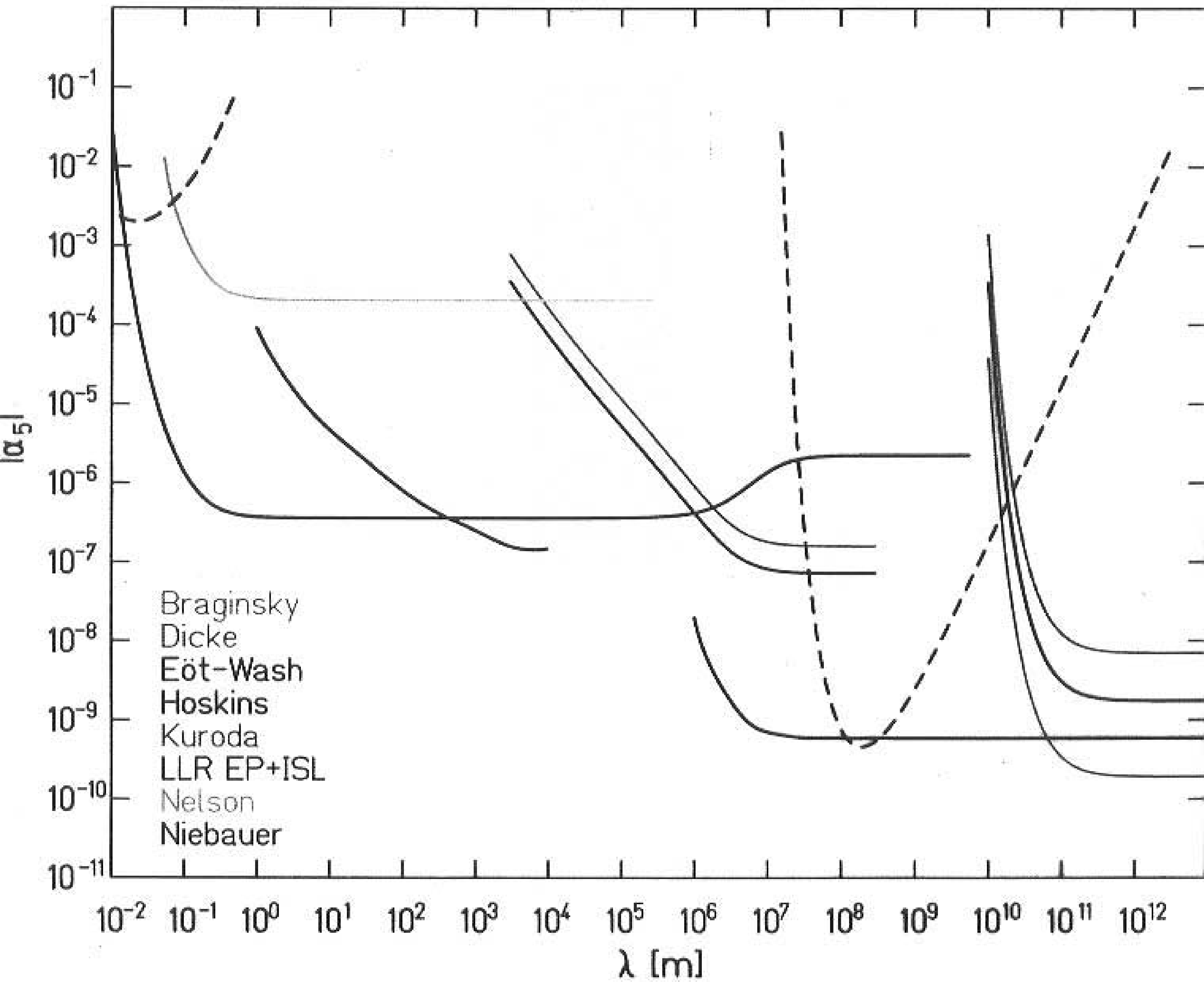
95% c.l. upper limits on $V_5 = -\alpha_5\ (B/\mu)_1\ (B/\mu)_2\ m_1 m_2/r\ e^{-\lambda/r}$



—— from EP tests

---- from $1/r^2$ tests

95% c.l. upper limits on $V_5 = -\alpha_5\,(q_5/\mu)_1\,(q_5/\mu)_2\,m_1 m_2/r\;e^{-\lambda/r}$ q_5 = B–L



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

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)
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Reviews

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