Tests of the Gravitational $1/r^2$ Law at the Dark Energy length scale

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outline

- motivations
- history
- new results
    - techniques
    - challenges
    - results
- conclusions

Rationale for testing the gravitational $1/r^2$ law

- probes the geometry of the universe

  $1/r^2 \rightarrow$ 3 space dimensions

- broad-gauge probe for any new Yukawa forces mediated by particles with $m \leq 0.1$ eV
  - string theory predicts lots of nominally massless scalar particles
  - effects not surpressed by $\Delta(\tilde{q}/m)$ factors

- no evidence (as of 2000) for its validity at separations below 1 mm

  Contrast to EM where we know QED works down to $\sim 10^{-16}$ cm from
  $e^+e^- \rightarrow \mu^+\mu^-$

Parameterising breakdowns of $1/r^2$ law

- **Old-fashioned way**

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

$\uparrow$

no theoretical basis

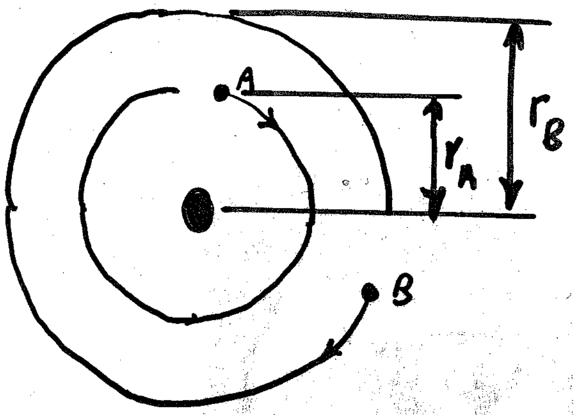
- **modern way**

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

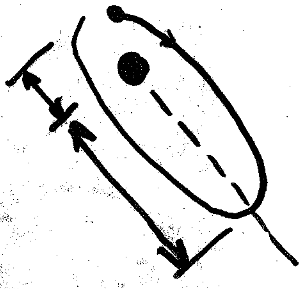
$\uparrow$

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



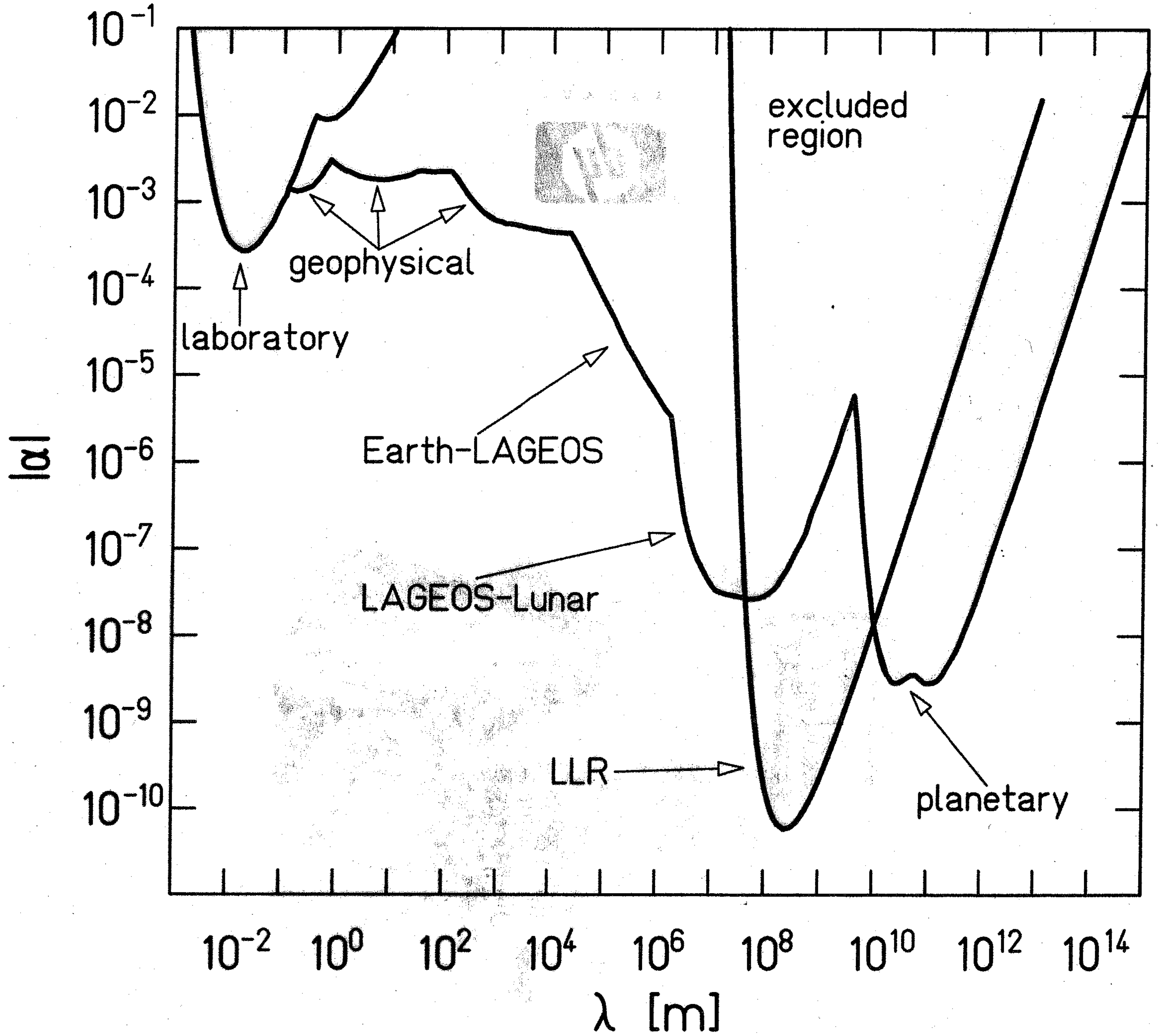
$$\frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \;?$$



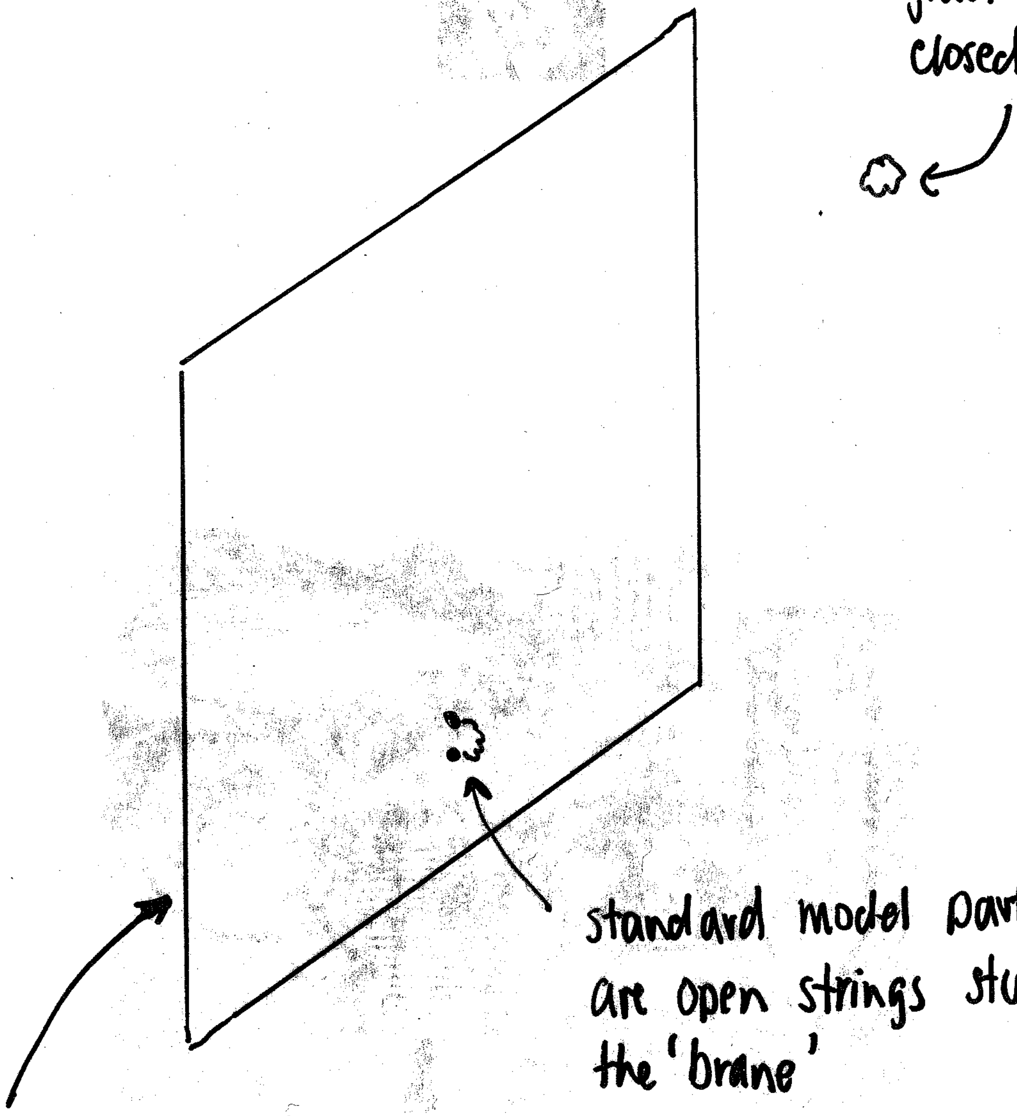
precession of perigee ?

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

95% confidence limits



Only gravity propagates in all the space dimensions

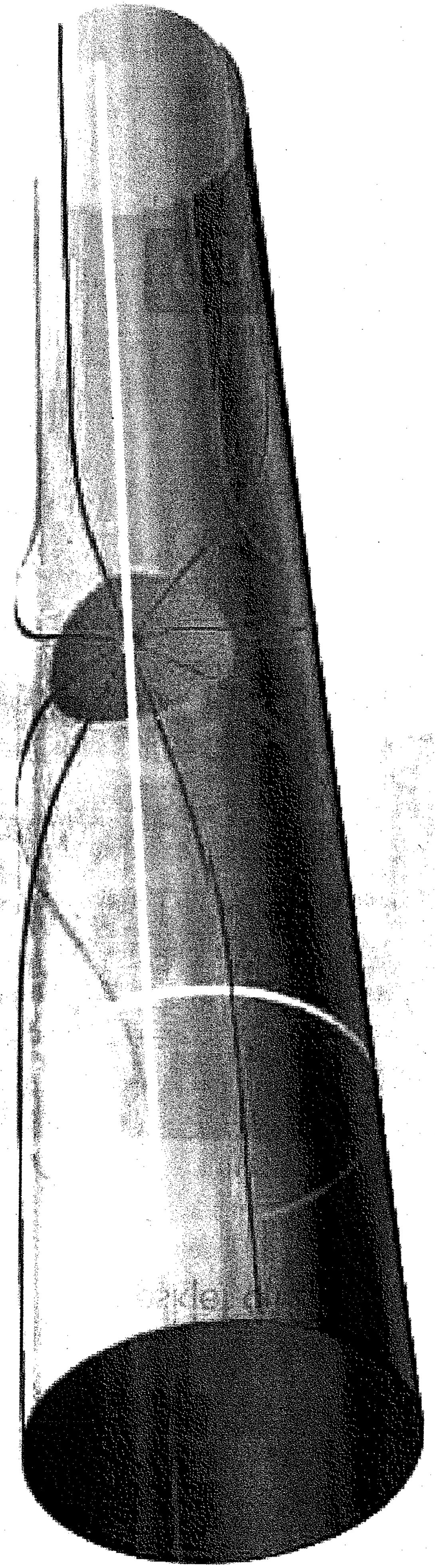


graviton is a closed string

standard model particles are open strings stuck to the 'brane'

- quarks
- leptons
- gauge bosons

3+1 dimensional 'brane' embedded in 10+1 dimensional space



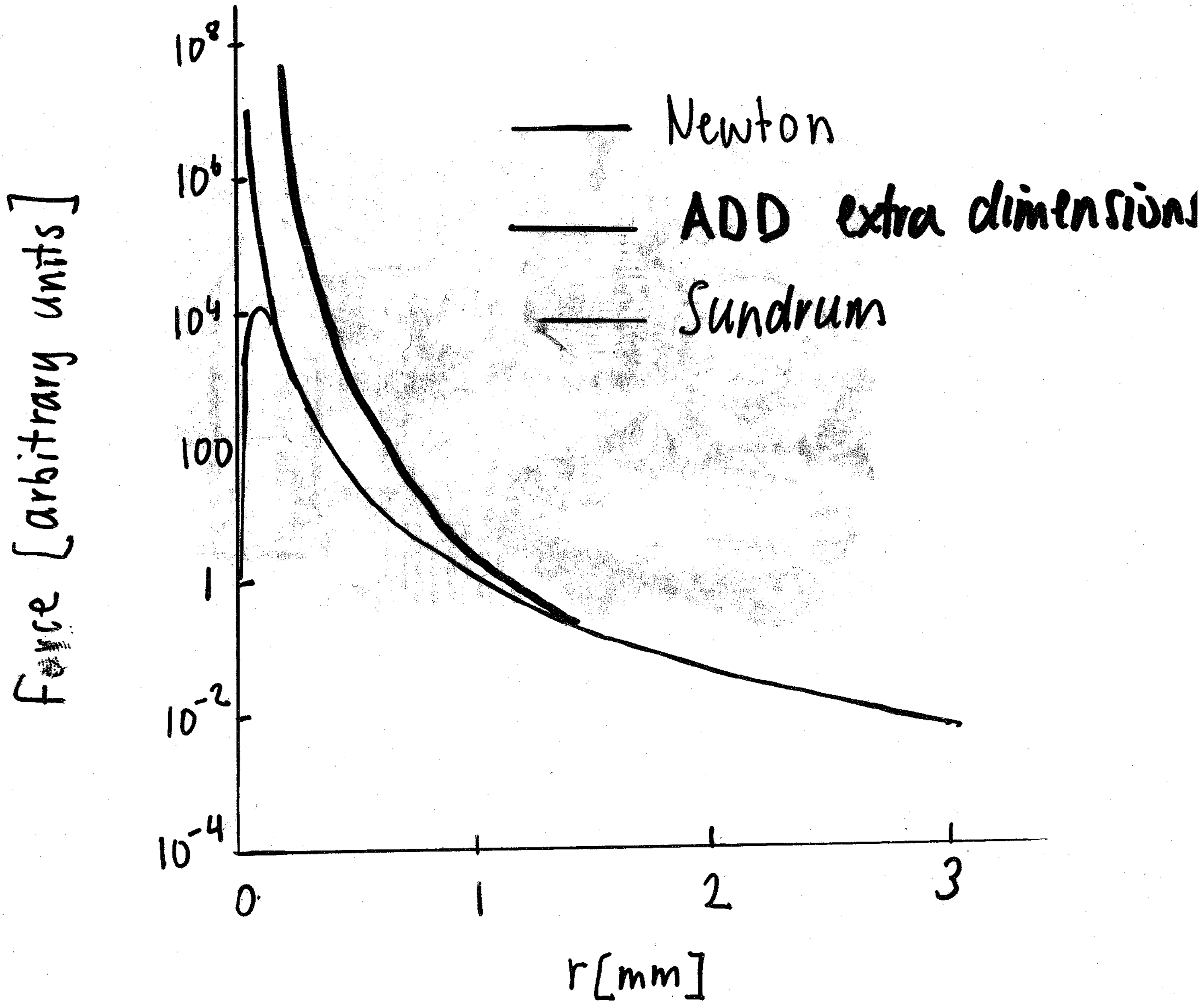
Why might gravity get weak at separations less than 0.1 mm?

- 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

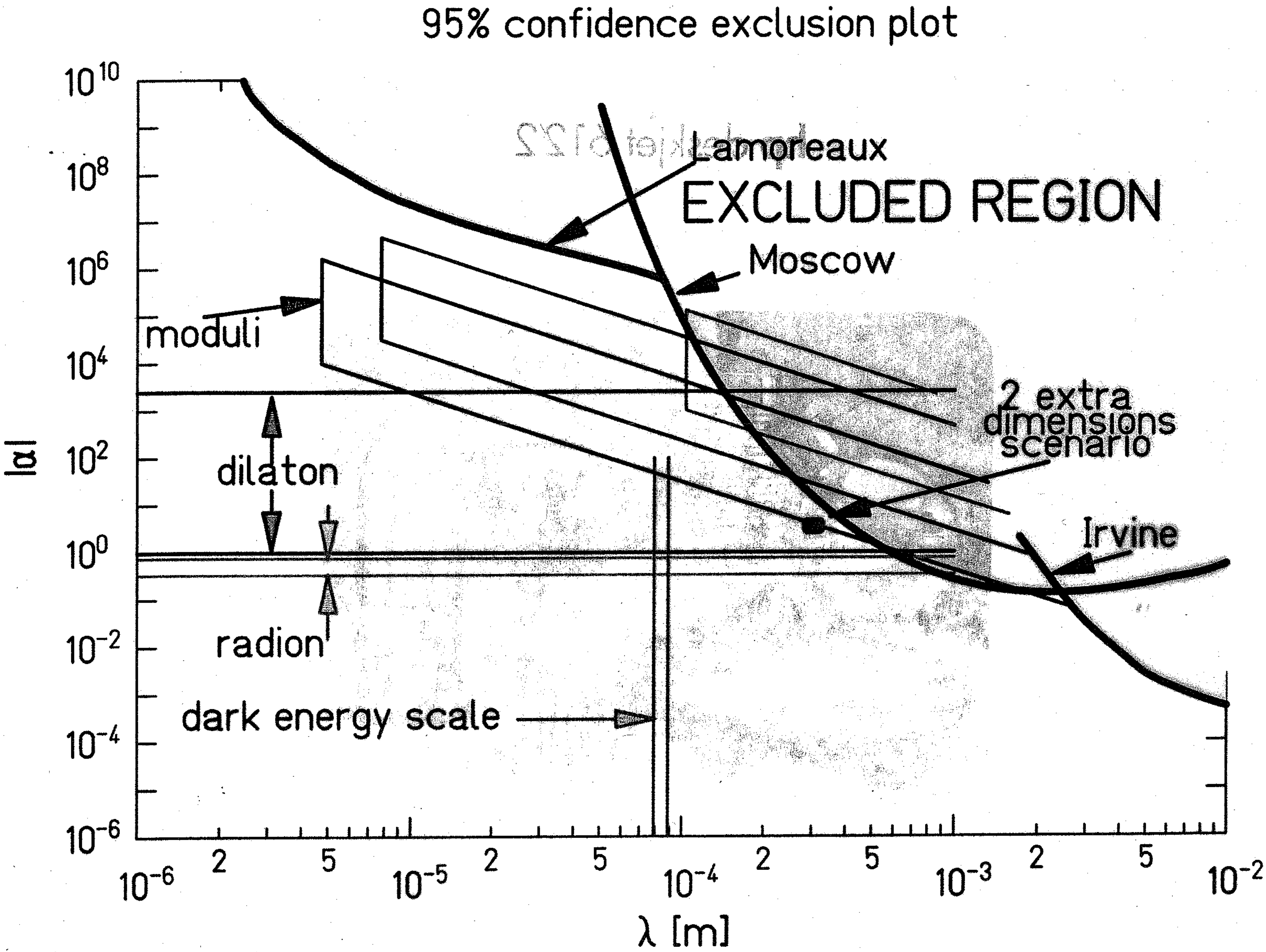
  $$d = \sqrt[4]{\hbar c/\rho} \sim 0.1\,\mathrm{mm}$$

- 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

PREDICTIONS FOR $1/r^2$ LAW BREAKDOWNS

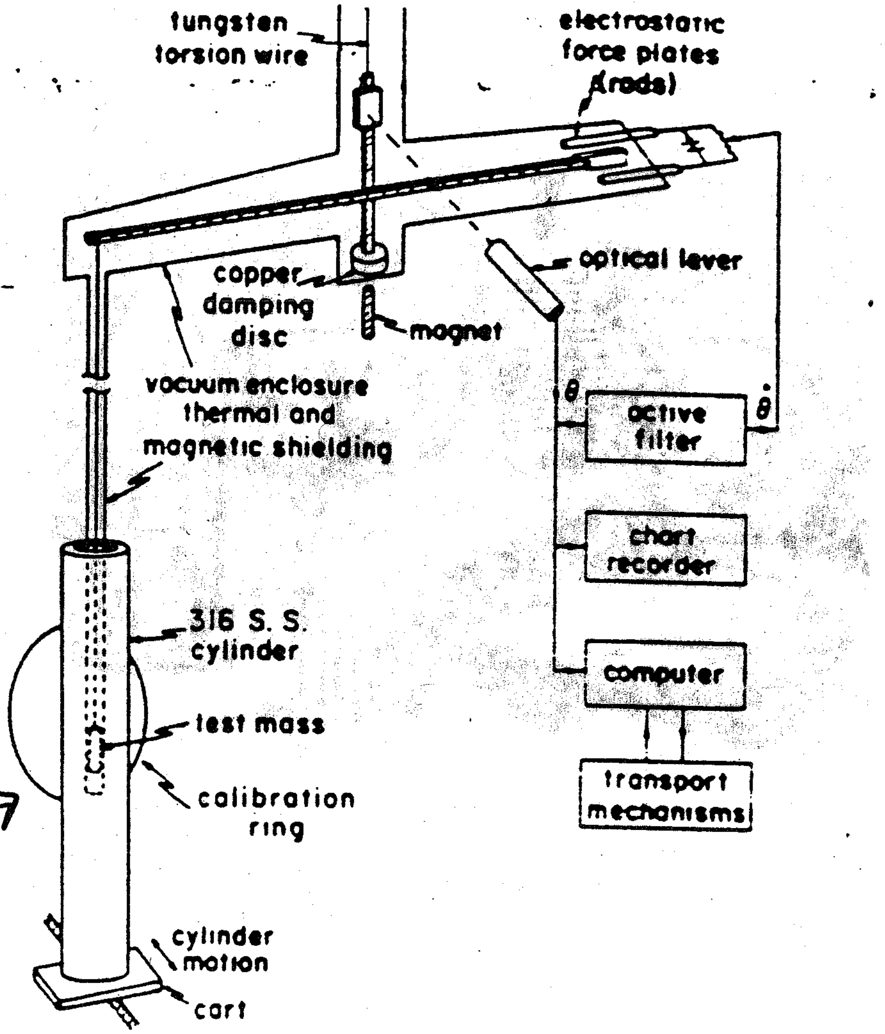


← unexplored region →


95% confidence exclusion plot
EXCLUDED REGION
Lamoreaux
Moscow
moduli
2 extra dimensions scenario
Irvine
dilaton
radion
dark energy scale
|α|
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-6}
2
5
10^{-5}
2
5
10^{-4}
2
5
10^{-3}
2
5
10^{-2}
λ [m]

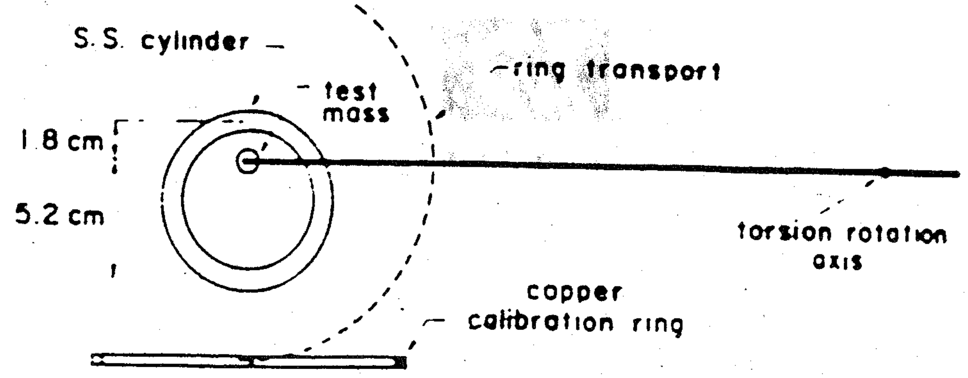
The UC Irvine test of $1/r^2$ law

Hoskins et al., Phys. Rev. D $\underset{\sim}{32}$ (1985) 3084



end effects $\sim 10^{-2}$

Top View of Apparatus



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

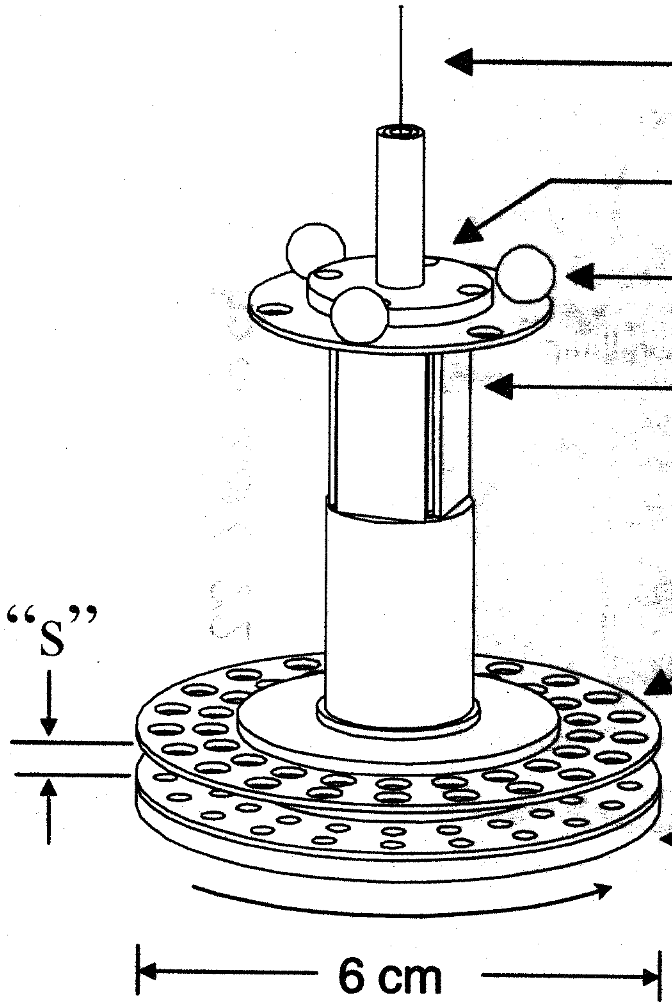
grad students

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

undergrads

→ Rogan Carr · Caleb Hotchkiss

21-Hole Torsion Pendulum



fiber, 20μm diameter, 80cm length, tungsten

leveling mechanism

3 aluminum calibration spheres

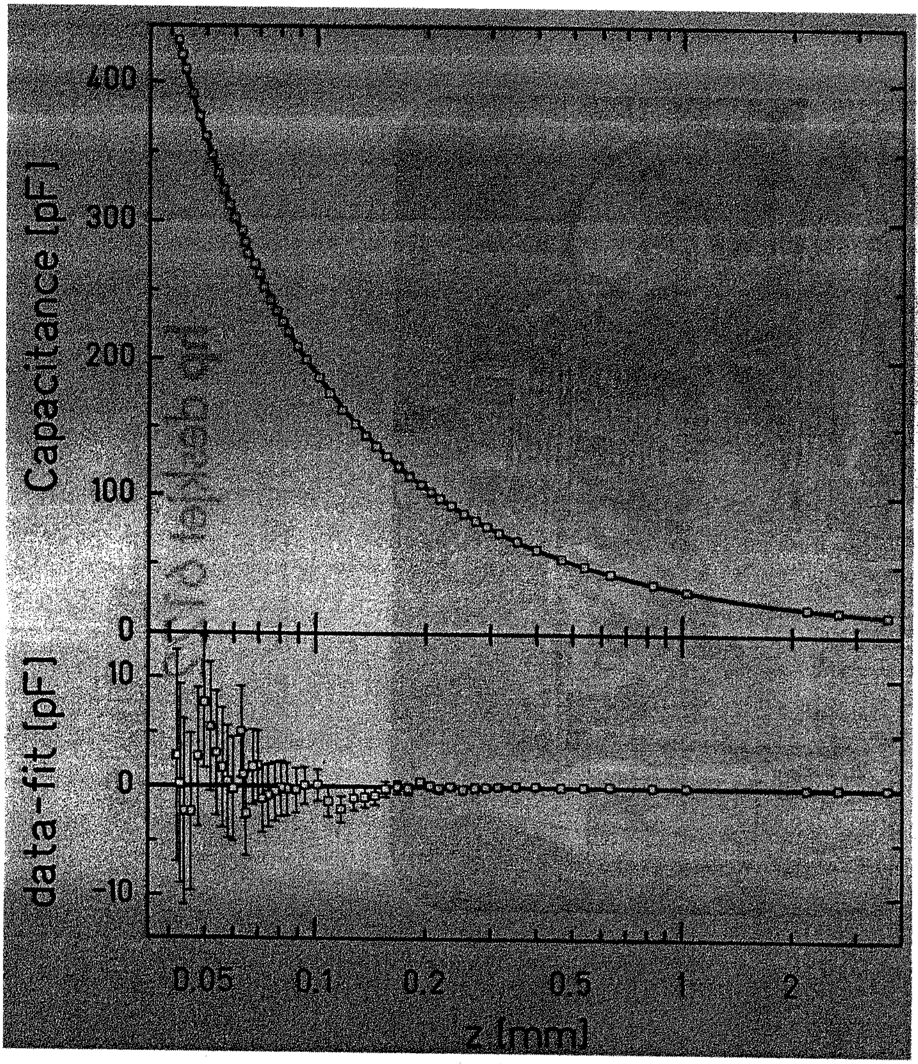
4 mirrors for tracking angle of deflection

21-fold axial symmetry, molybdenum disc, 1mm thick

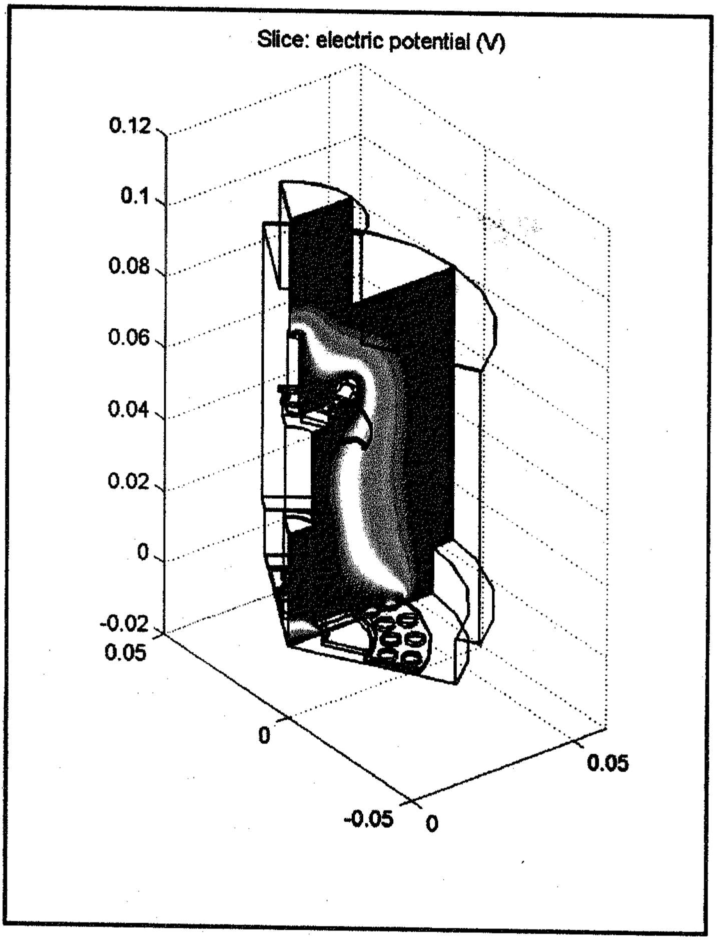
not pictured, **10μm thick Au-coated BeCu membrane, electrostatic shield**

Attractor : **rotating** pair of discs, rotated out of phase with each other to cancel gravity

Pendulum-to-shield separation is a key parameter



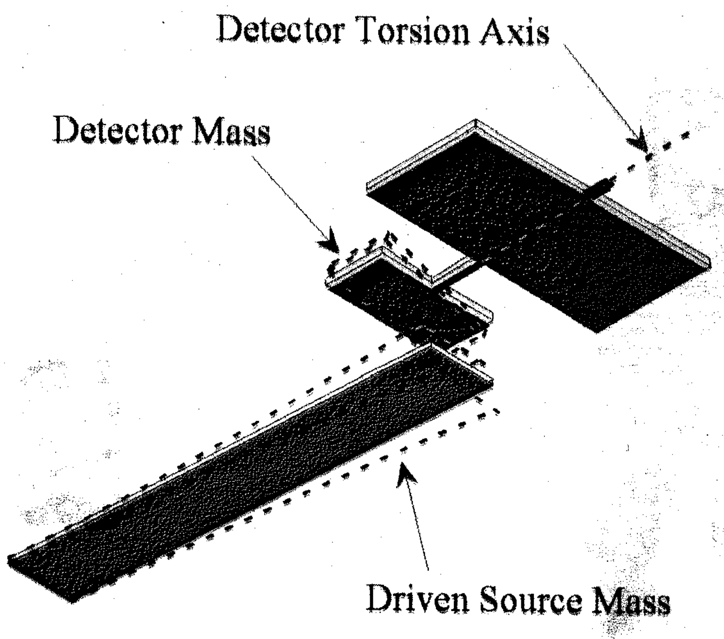
separation determined by fitting capacitance vs. *z* to a finite-element calculation



gives separation to better than 1 micron

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

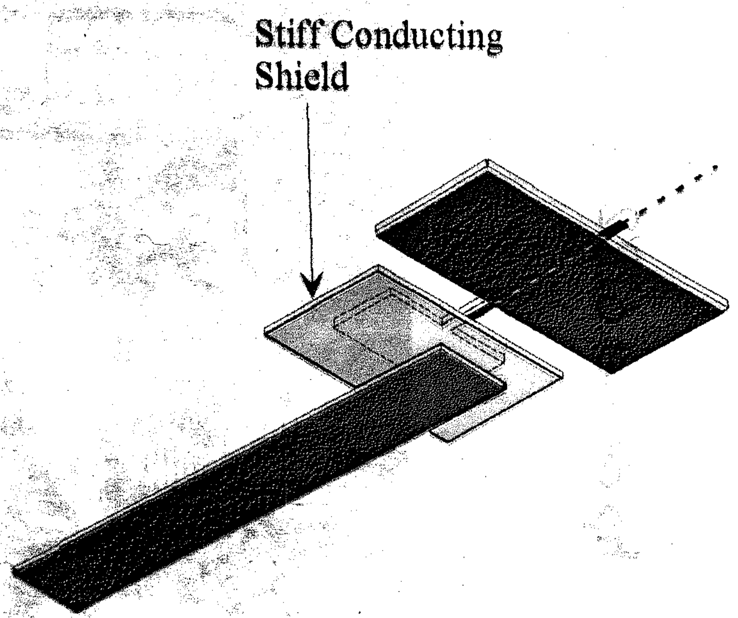
Planar Geometry



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

$\approx 1\times10^{-14}\ N$

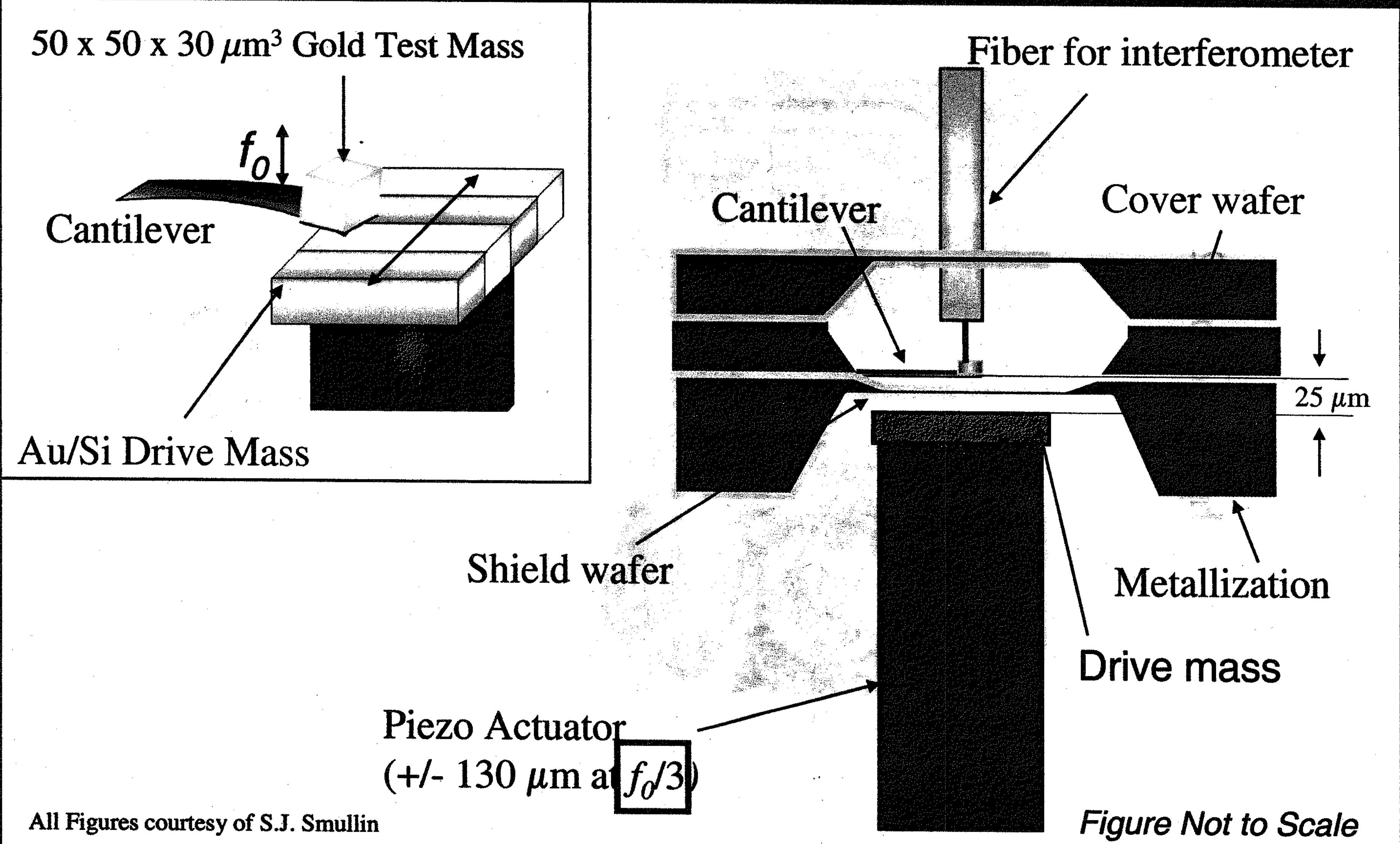
Source and Detector Oscillators



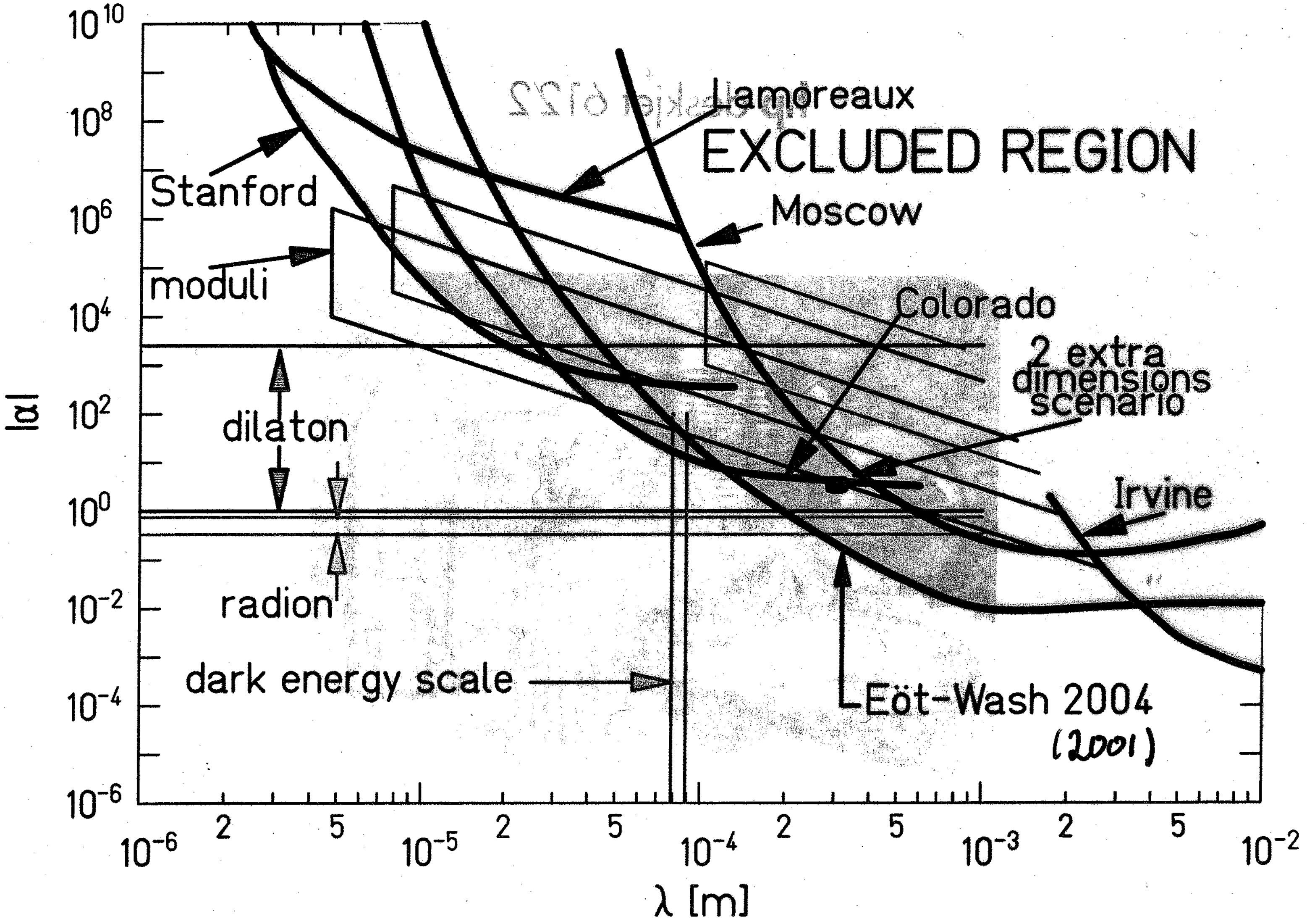
Shield for Background Suppression

Stanford Experiment (A. Kapitulnik, *et al.*)

- Low-temperature micro-cantilevers:



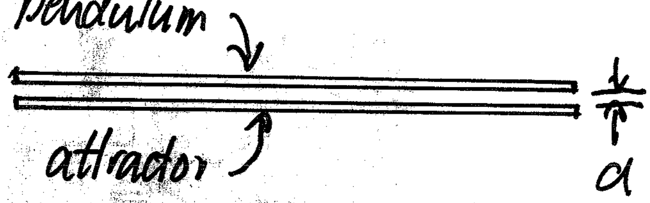
All Figures courtesy of S.J. Smullin



95% confidence exclusion plot

Scaling relations for detector sensitivity to new short-range physics

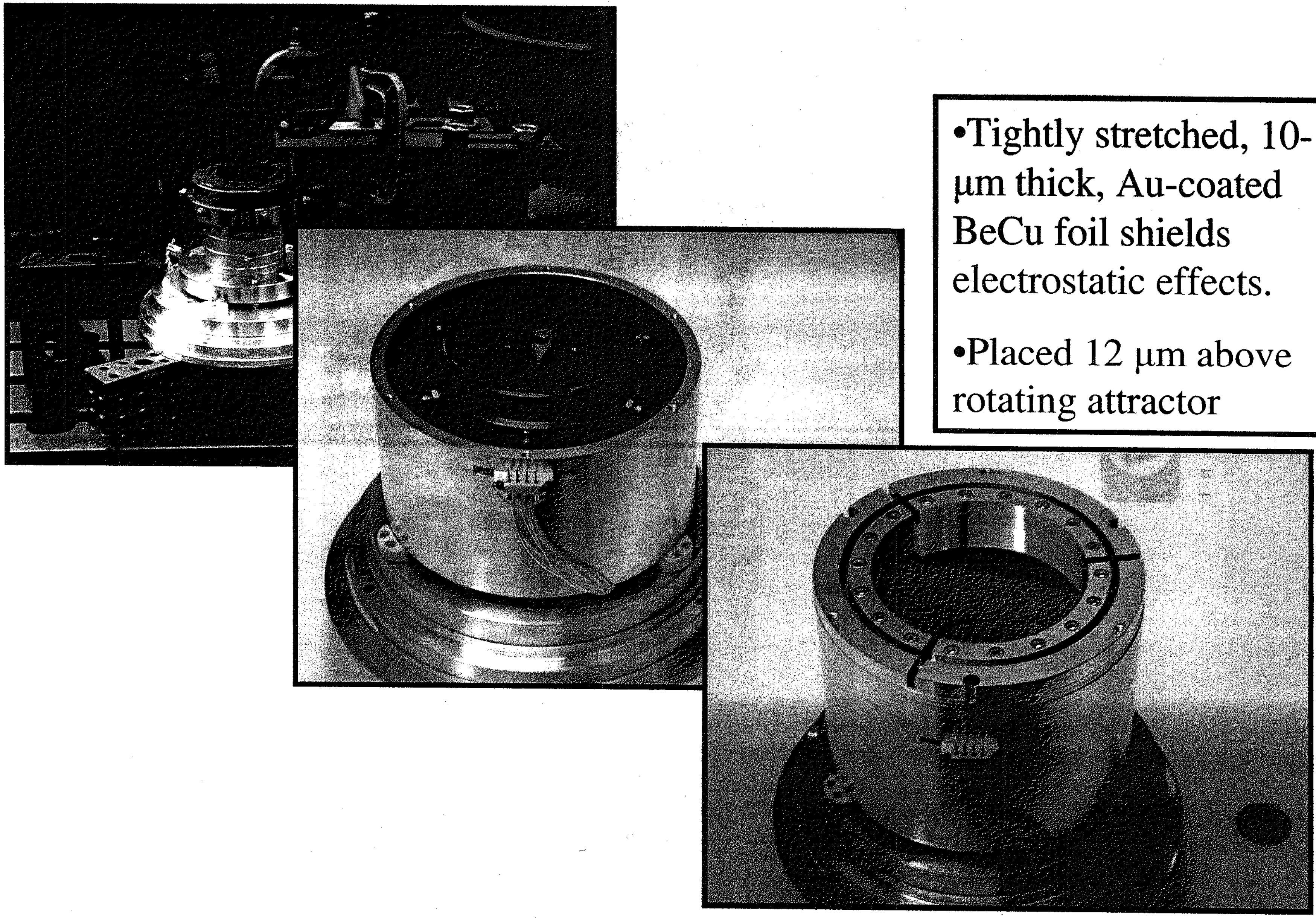
torque $= N_{s.r.} = \dfrac{\Delta E_{s.r}}{\Delta \theta}$



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

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

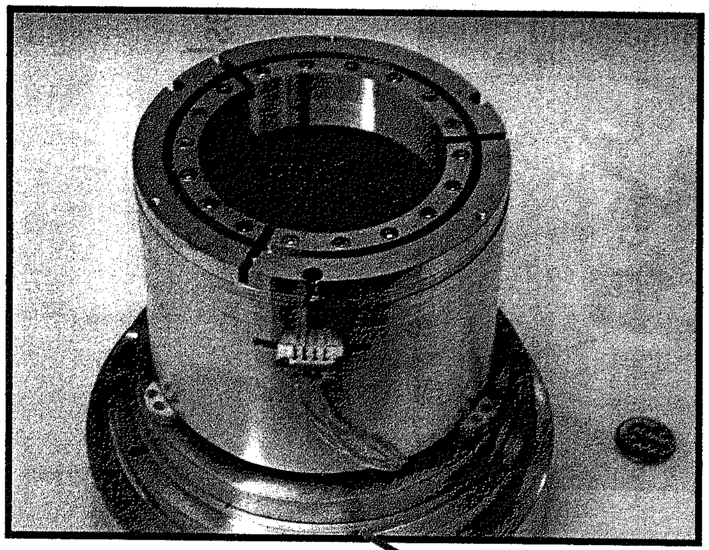
Rotating attractor and its electrostatic shield

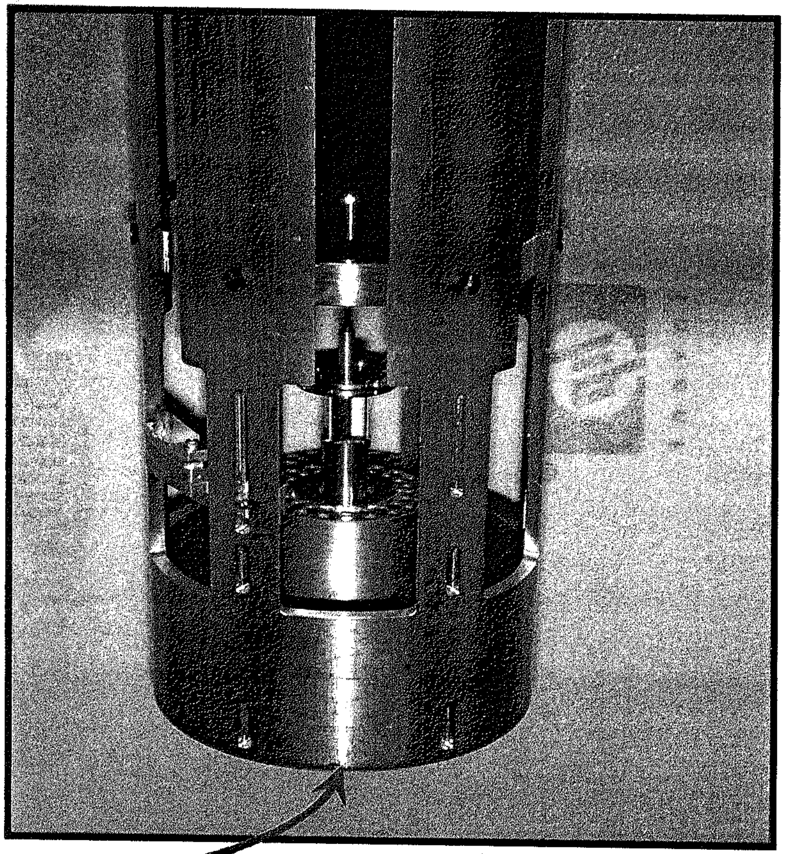


- Tightly stretched, 10-μm thick, Au-coated BeCu foil shields electrostatic effects.
- Placed 12 μm above rotating attractor

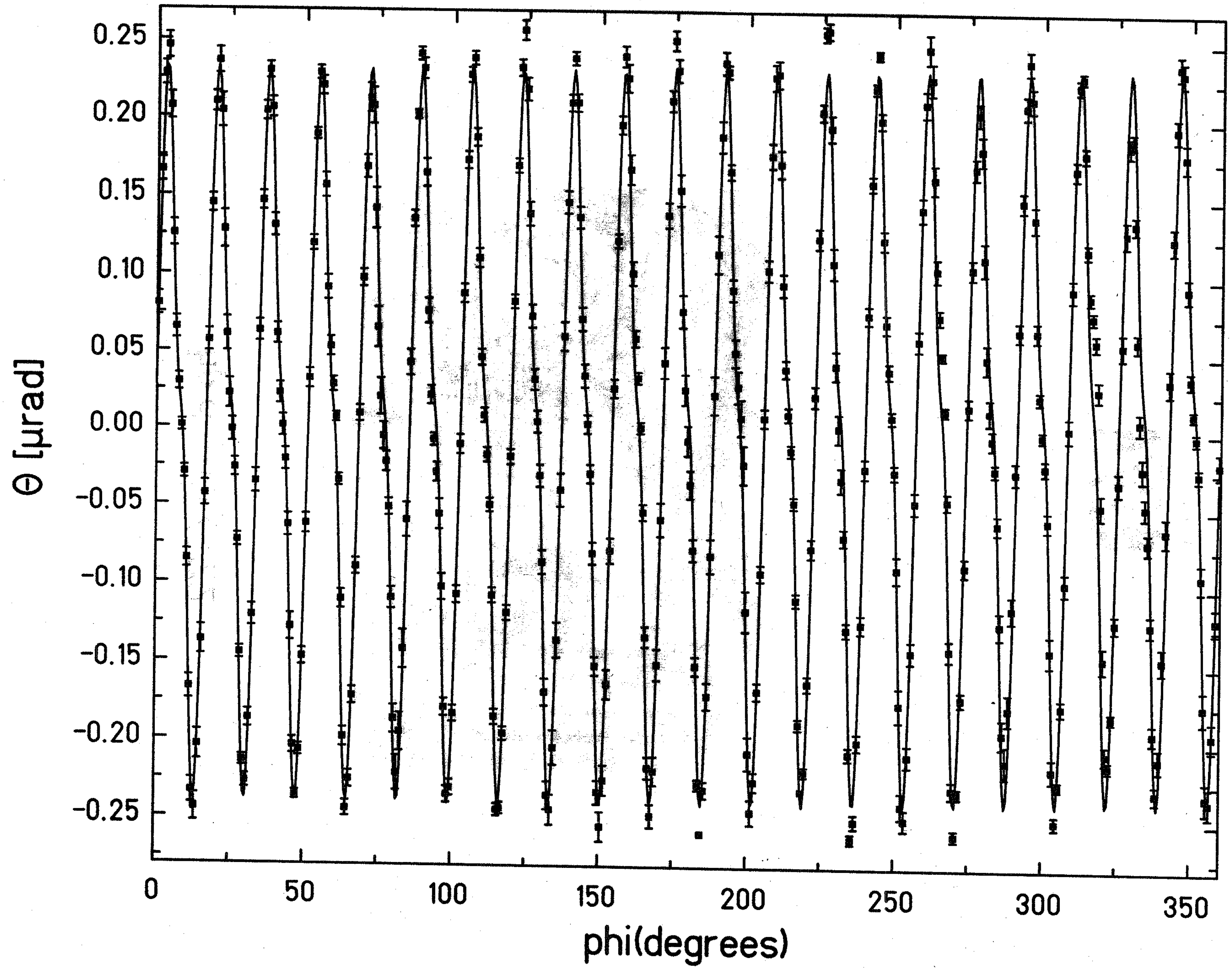
assembling the pendulum and attractor

Pendulum is Au-coated; conducting membrane and Au-coated magnetic shield (not shown) surround it to minimize electrostatic interactions.

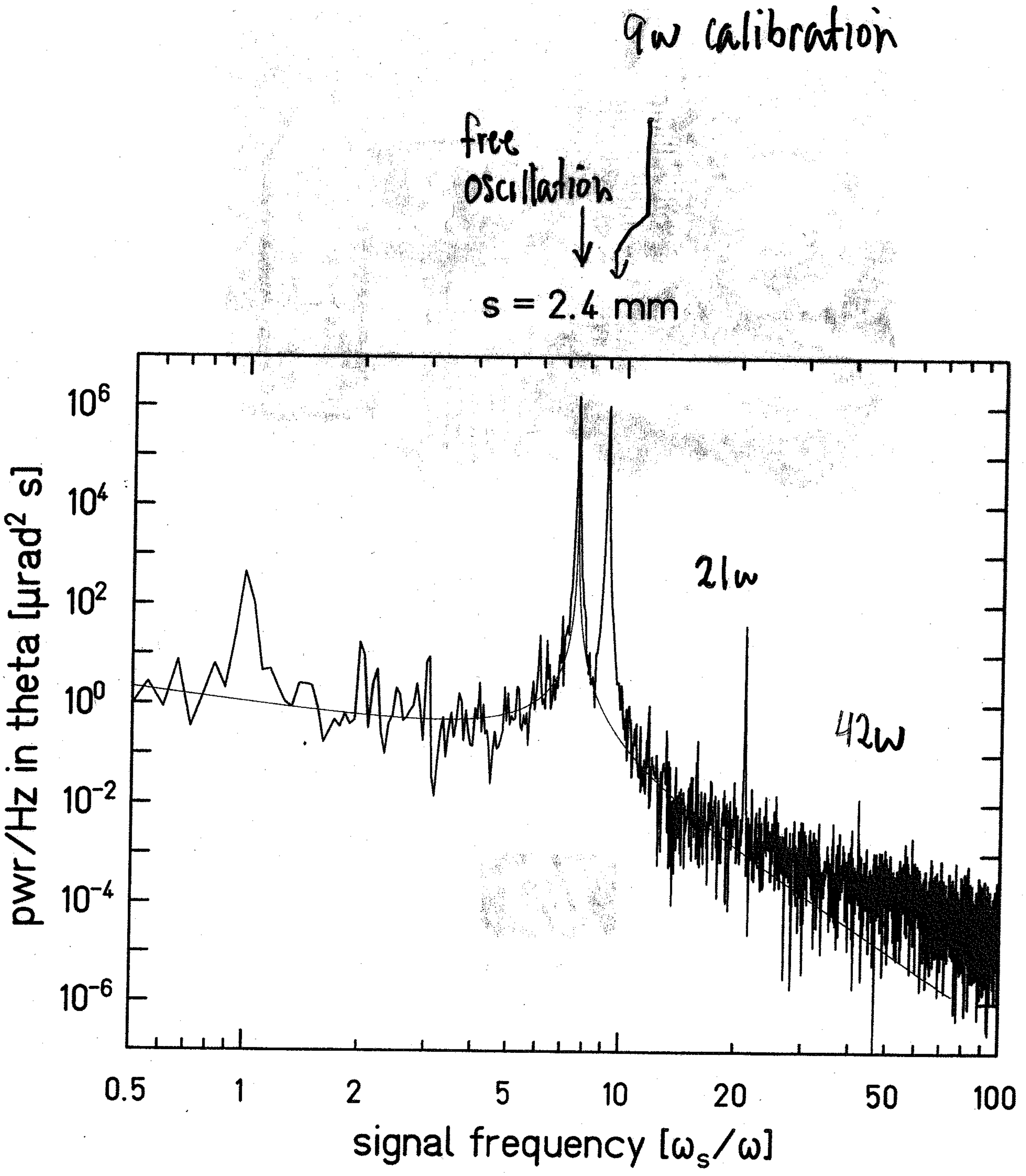


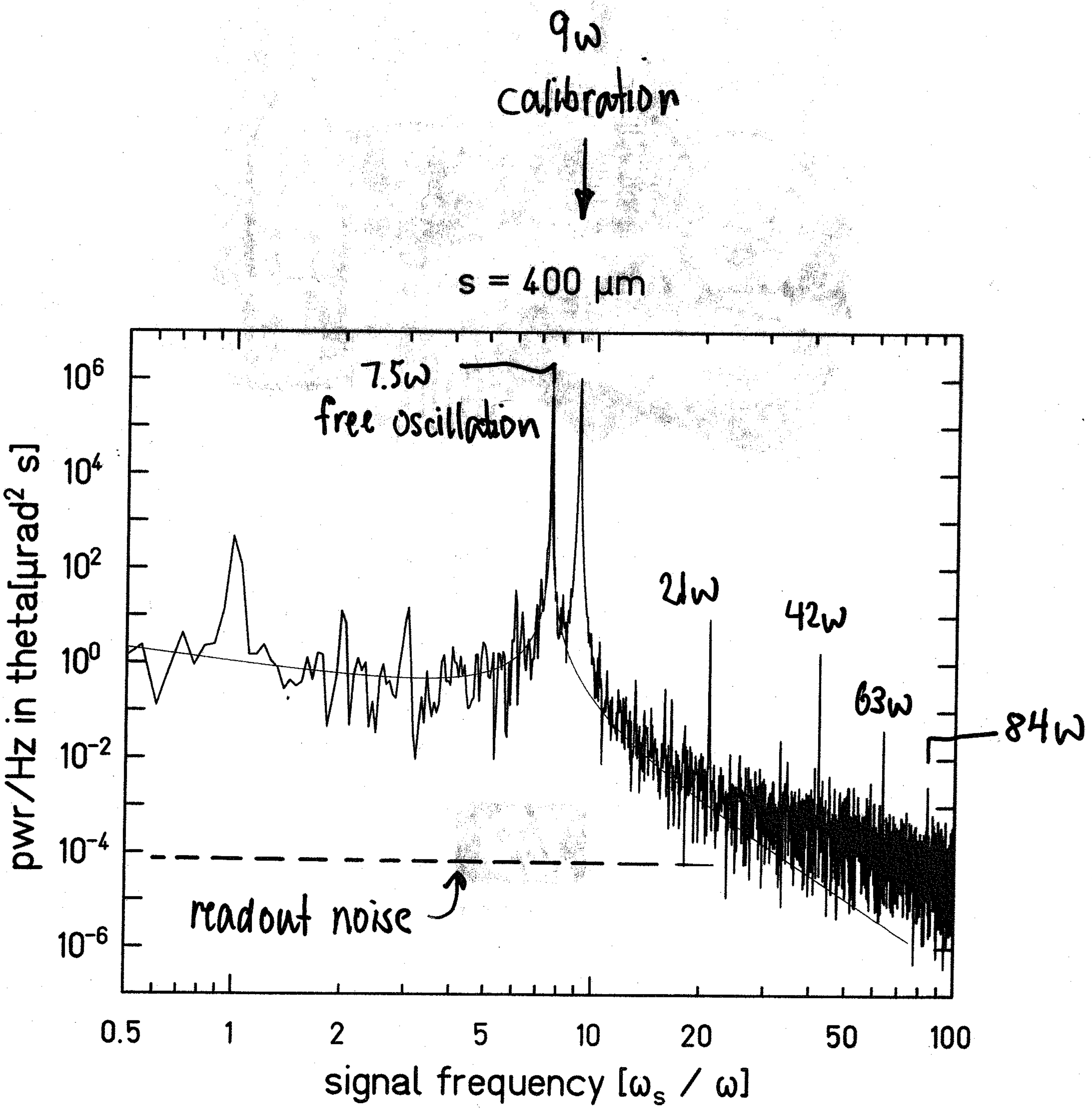


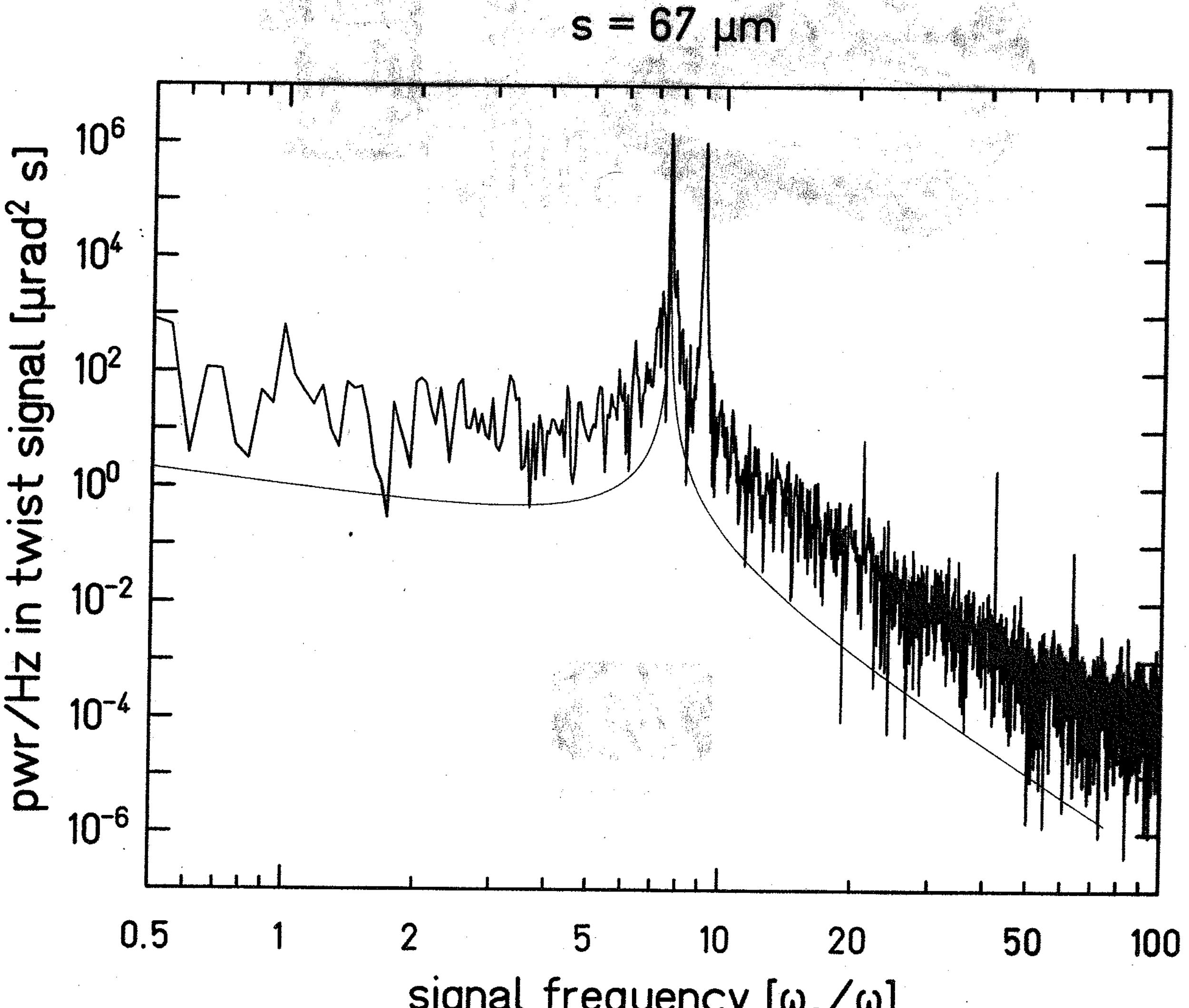
42-hole data taken at a separation of 75 μm

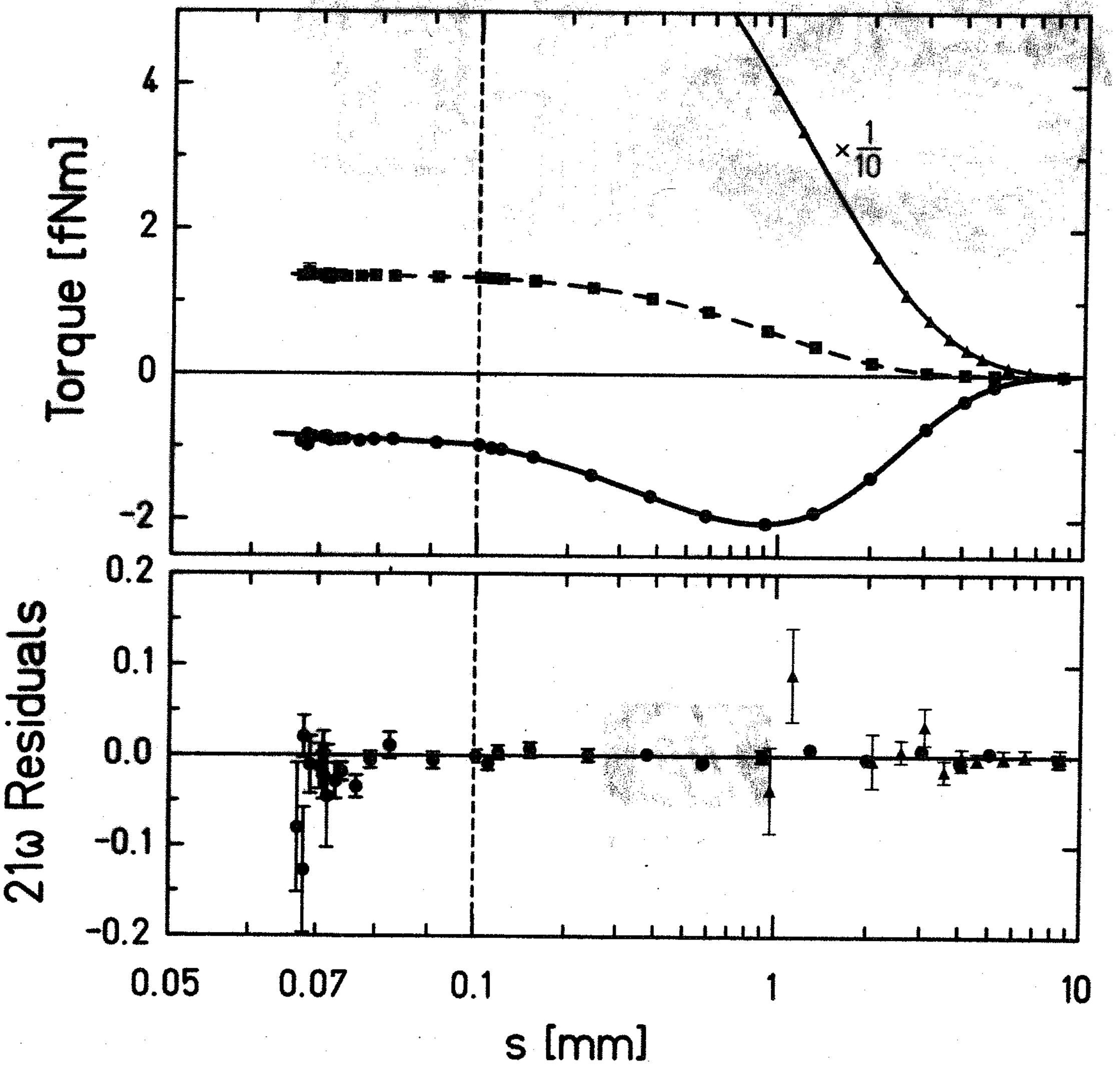


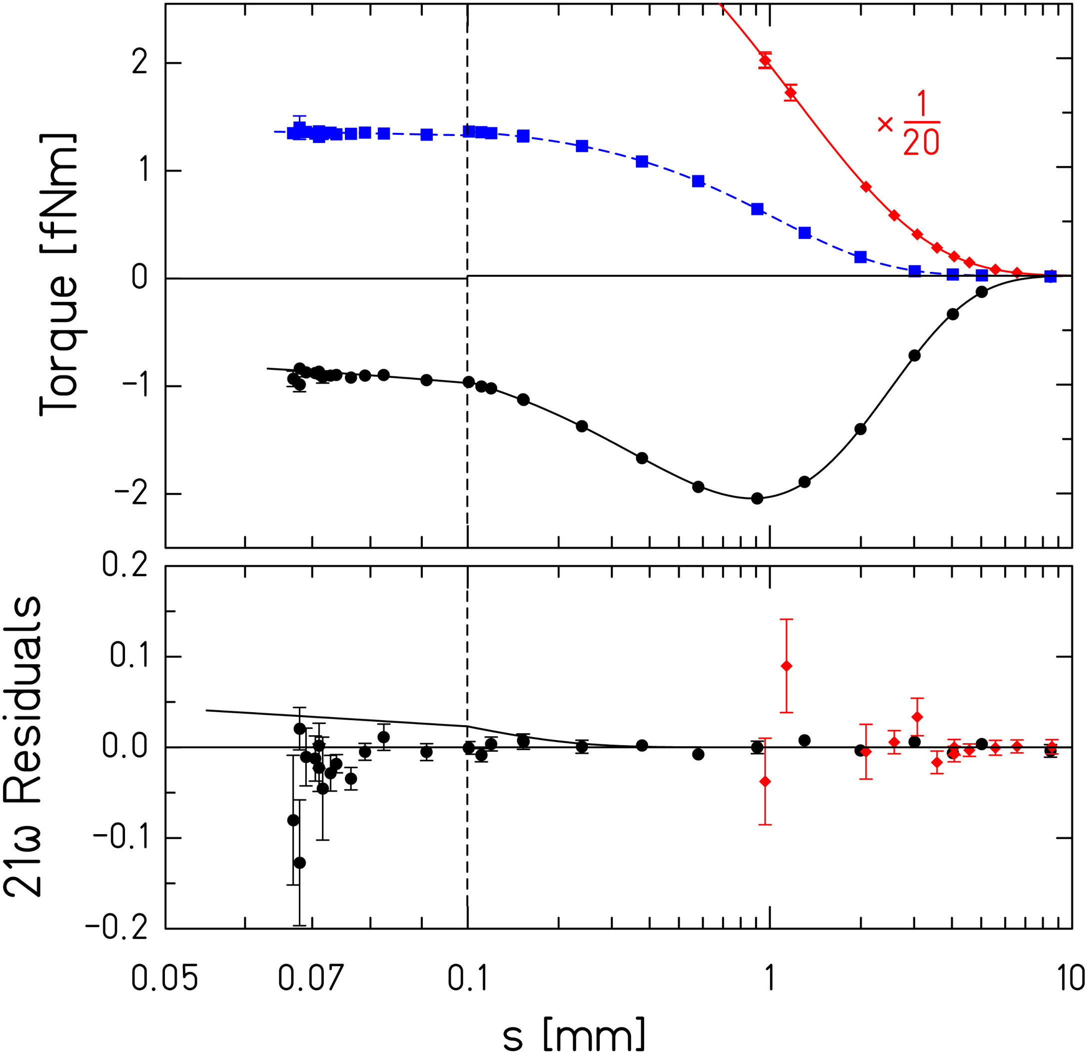
(free torsional oscillations suppressed by digital filter)

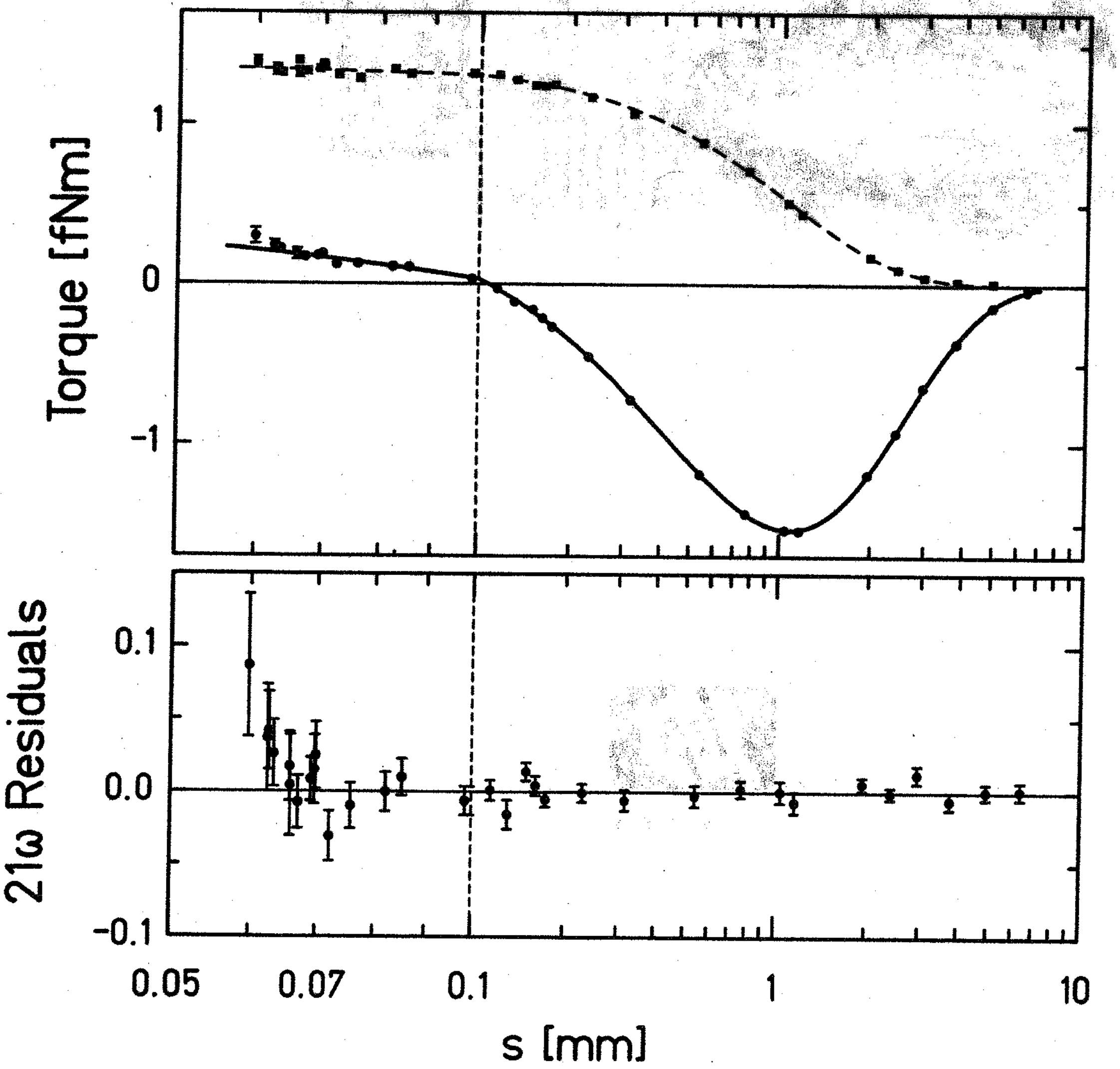

9w calibration
free oscillation
s = 2.4 mm
21w
42w
pwr/Hz in theta [μrad^2 s]
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0.5
1
2
5
10
20
50
100
signal frequency [ω_s/ω]

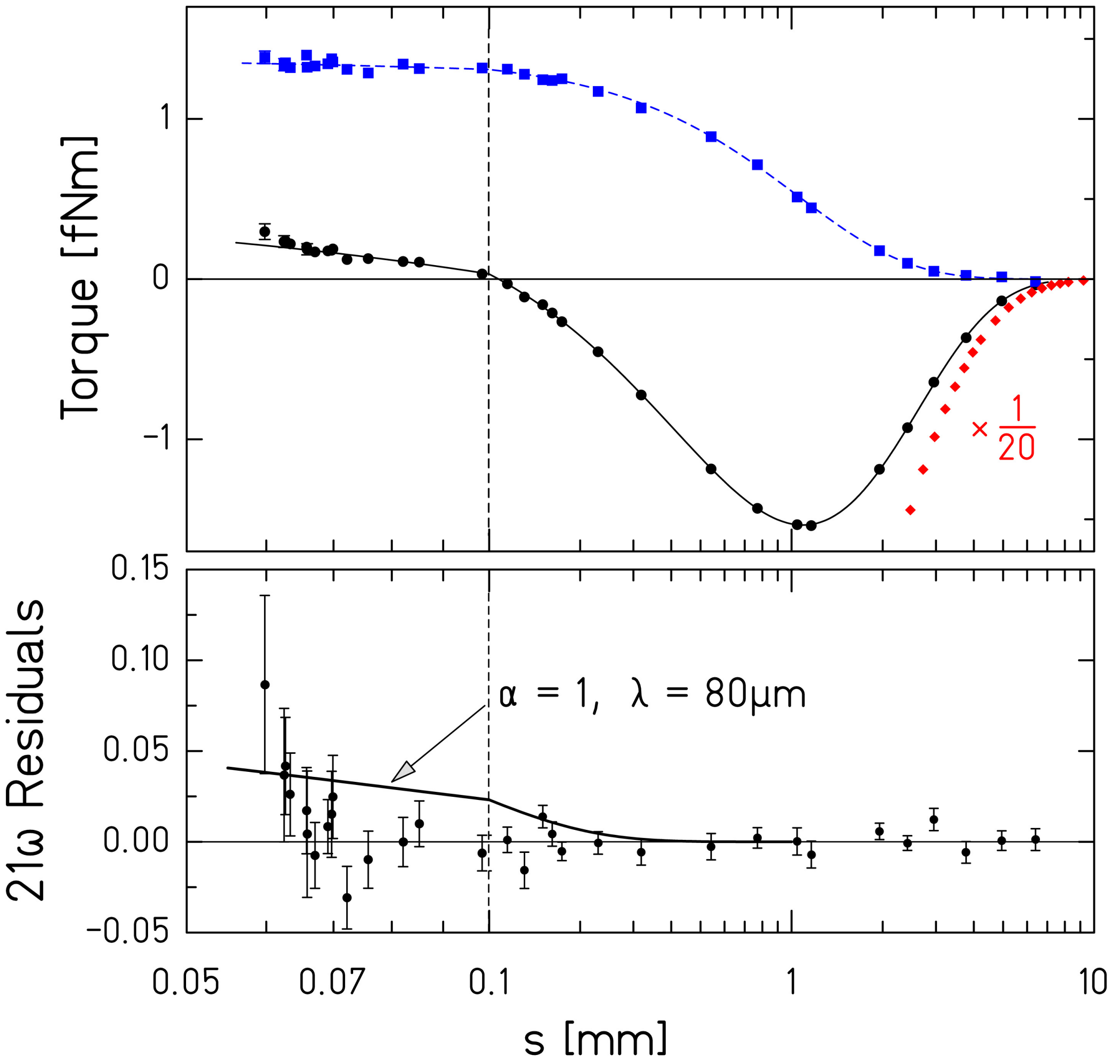

9w
calibration
s = 400 µm
7.5w
free oscillation
21w
42w
63w
84w
readout noise
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
pwr/Hz in theta[µrad^2 s]
0.5
1
2
5
10
20
50
100
signal frequency [ωs / ω]


s = 67 μm
pwr/Hz in twist signal [μrad^2 s]
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0.5
1
2
5
10
20
50
100
signal frequency [ω_s/ω]

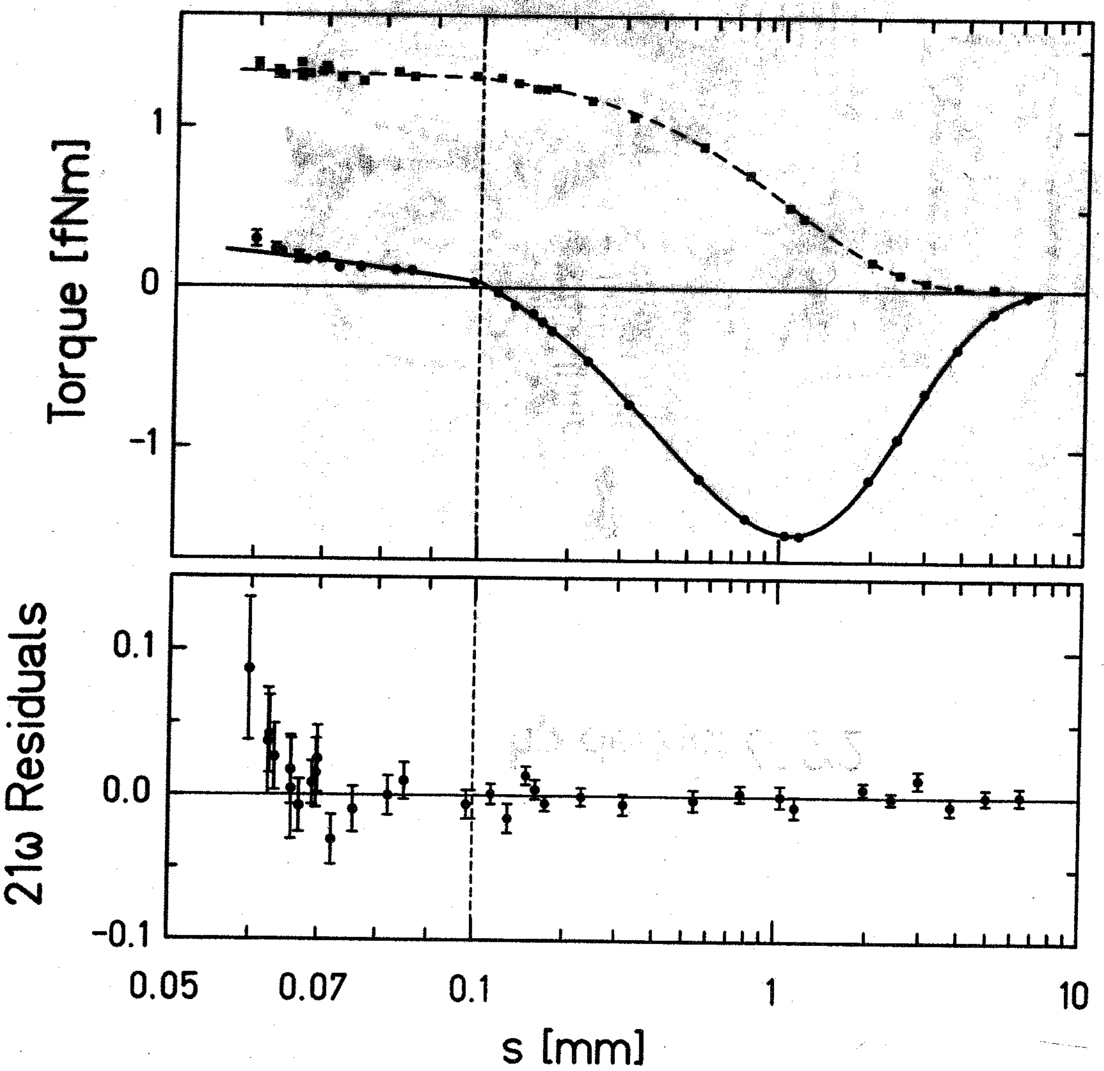

Torque [fNm]
4
2
0
-2
$\times \frac{1}{10}$
21ω Residuals
0.2
0.1
0.0
-0.1
-0.2
0.05
0.07
0.1
1
10
s [mm]

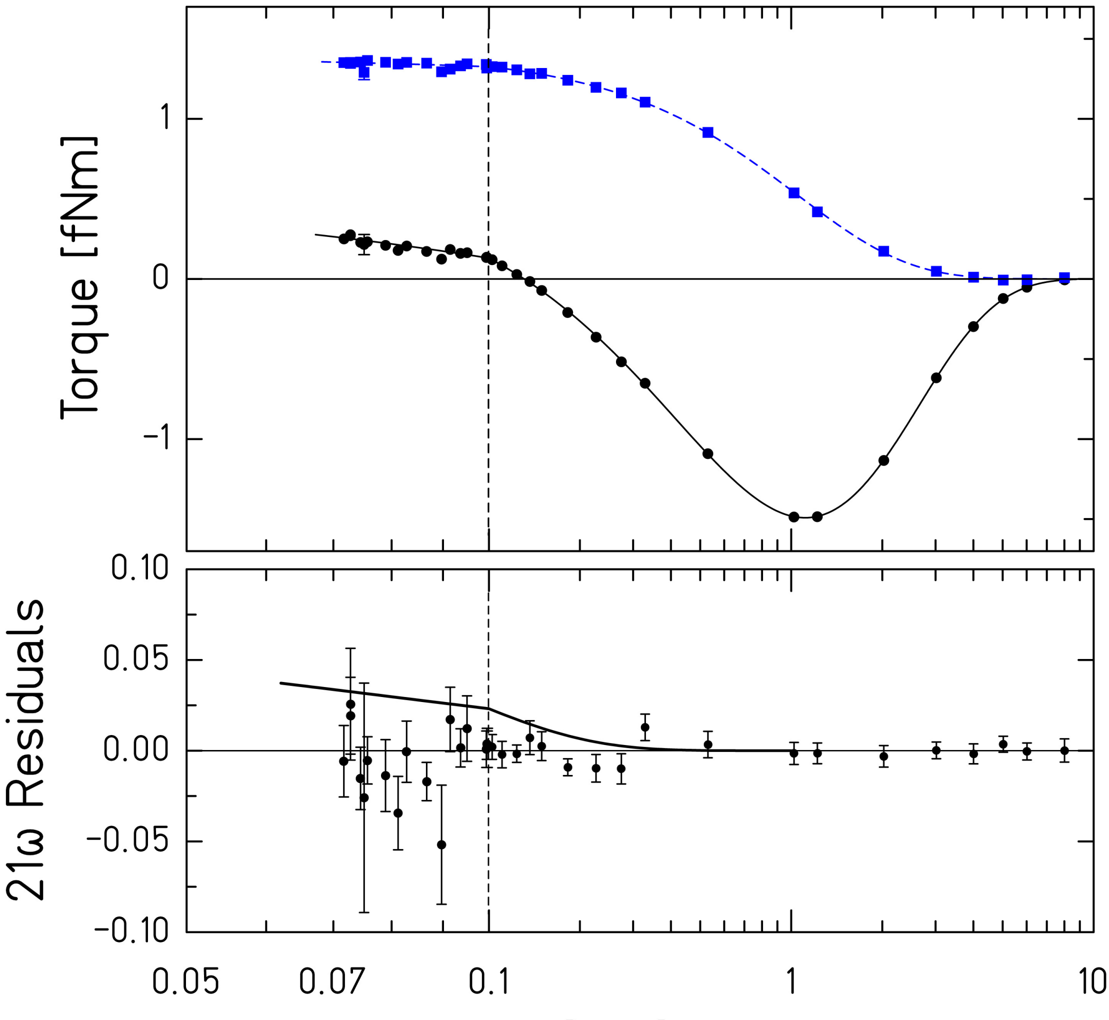

Torque [fNm]
2
1
0
−1
−2
× 1/20
21ω Residuals
0.2
0.1
0.0
−0.1
−0.2
0.05
0.07
0.1
1
10
s [mm]

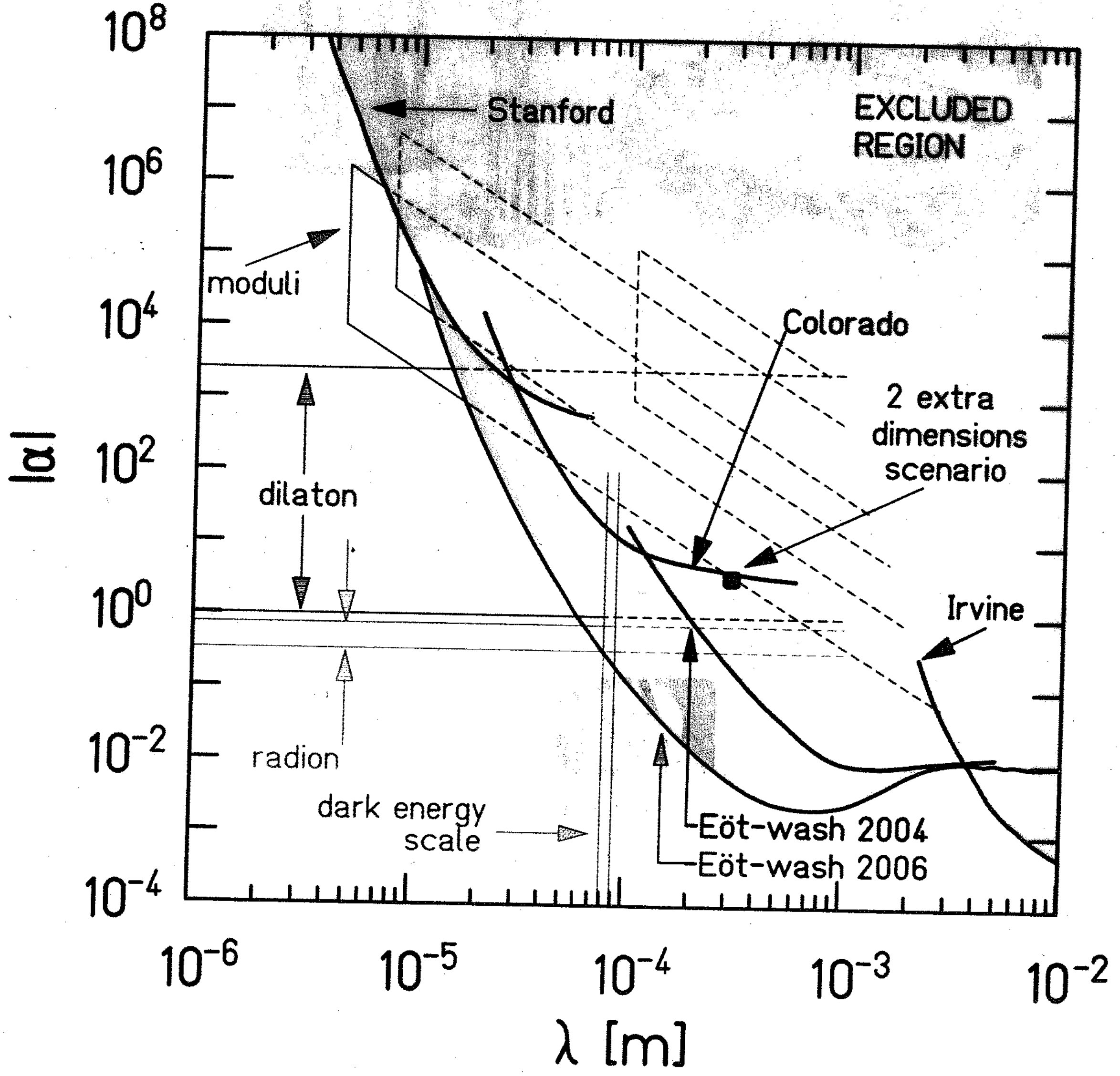

Torque [fNm]
1
0
−1
21ω Residuals
0.1
0.0
−0.1
0.05
0.07
0.1
1
10
s [mm]


Torque [fNm]
1
0
−1
× 1/20
0.15
0.10
0.05
0.00
−0.05
21ω Residuals
α = 1, λ = 80μm
0.05
0.07
0.1
1
10
s [mm]

after replacing Au coatings on
detector ring + electrostatic shield




Torque [fNm]
1
0
−1
21ω Residuals
0.10
0.05
0.00
−0.05
−0.10
0.05
0.07
0.1
1
10
s [mm]



10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
$|\alpha|$
Stanford
EXCLUDED REGION
moduli
Colorado
2 extra dimensions scenario
dilaton
Irvine
radion
dark energy scale
Eöt-wash 2004
Eöt-wash 2006
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
λ [m]