

Gravity at the 100 Micron Scale and Below

Joshua Long

Indiana University Cyclotron Facility

Michael Varney, Dominic Thurmer, John Price

(Experiment in Department of Physics, University of Colorado, Boulder)

Parameter space and theoretical motivation

Experiments above $1 \mu\text{m}$

Torsion pendulum

High frequency (Colorado)

Experiments and proposals below $1 \mu\text{m}$

Casimir Force Suppression

Future Prospects



University of Colorado at Boulder

Left to Right:

John Price, Mike Varney, Joshua Long, Elizabeth Lagae

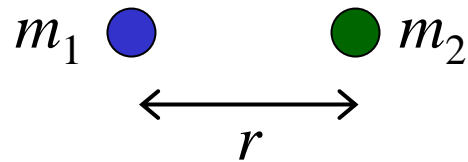
Not Shown:

Dominic Thurmer, Hilton Chan, Allison Churnside, Eric Gulbis

Parameter Space

Deviations from Newtonian gravity are parameterized in terms of an additional Yukawa interaction–

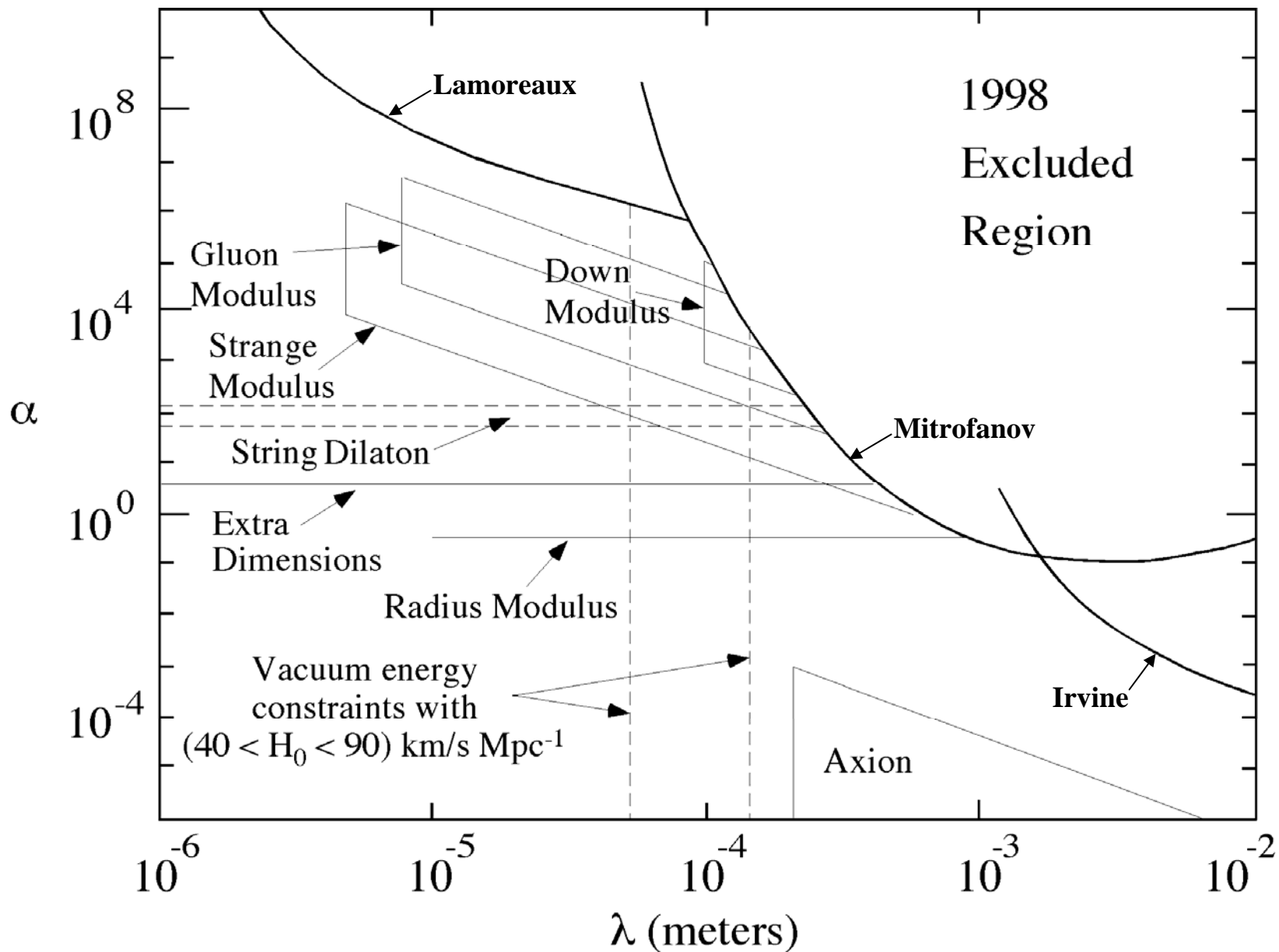
$$V(r) = -G \frac{m_1 m_2}{r} \left[1 + \alpha e^{-r/\lambda} \right]$$



$\alpha \equiv$ strength relative to gravity

$\lambda \equiv$ range

Limits and Predictions - 1998



Theoretical Motivations

Comprehensive Reviews

E. G. Adelberger, B. R. Heckel, A. E. Nelson, Ann. Rev. Nucl. Part. Sci. 53 (2003) 77
J. Hewett, M. Spiropulu, Ann. Rev. Nucl. Part. Sci. 52 (2002) 397

Compact Extra Dimensions

Solution to Hierarchy Problem: Weakness of gravity due to n “large” extra dimensions in which only gravitons propagate. Size R of extra dimensions related to unification scale M^* by:

$$R^n = M_p^2 / M^{*(2+n)} \quad M^* \sim 1 \text{ TeV} \star R \sim 1 \text{ mm for } n = 2$$

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429 (1998) 263

Yukawa corrections with $\alpha \sim 4$ *E.G. Floratos and G. K. Leontaris, Phys. Lett. B 465 (1999) 95; A. Kehagias and K. Sfestos, Phys. Lett. B 472 (2000) 39-44.*

Exotic Boson Exchange Forces

- **Moduli** Gravitationally-coupled light scalars in string theories.

Gauge-mediated model: supersymmetry broken at 10-100 TeV, \Rightarrow Down, Strange, Gluon Moduli with $\lambda \sim 1-100 \mu\text{m}$ [*S. Dimopoulos and G. Giudice, Phys. Lett. B 379, 105 (1996)*]

Compactification model: supersymmetry broken at weak scale ($\sim 1 \text{ TeV}$) \Rightarrow Radius Modulus with $\alpha \sim 1/3$ [*I. Antoniadis, S. Dimopoulos, and G. Dvali, Nuc. Phys. B 516 (1998) 70*]

Theoretical Motivations

Boson Exchange Forces (cont.)

- **Dilaton** Scalar in string models, coupling to nucleons with α up to $\sim 10^4$ or greater [*D. B. Kaplan, M. B. Wise, J. High Energy Phys. 0008 (2000) 037*]
- **Axions** and other **light pseudoscalars**

[*Moody and Wilczek, Phys Rev. D 30 (1984) 130;*

P. Barbieri, A. Romanino, A. Strumina, Phys. Lett. B 387 (1996) 310;

Fischbach and D. Krause, Phys. Rev. Lett. 82 (1999) 4753.]

Cosmological Constant (Λ) problem

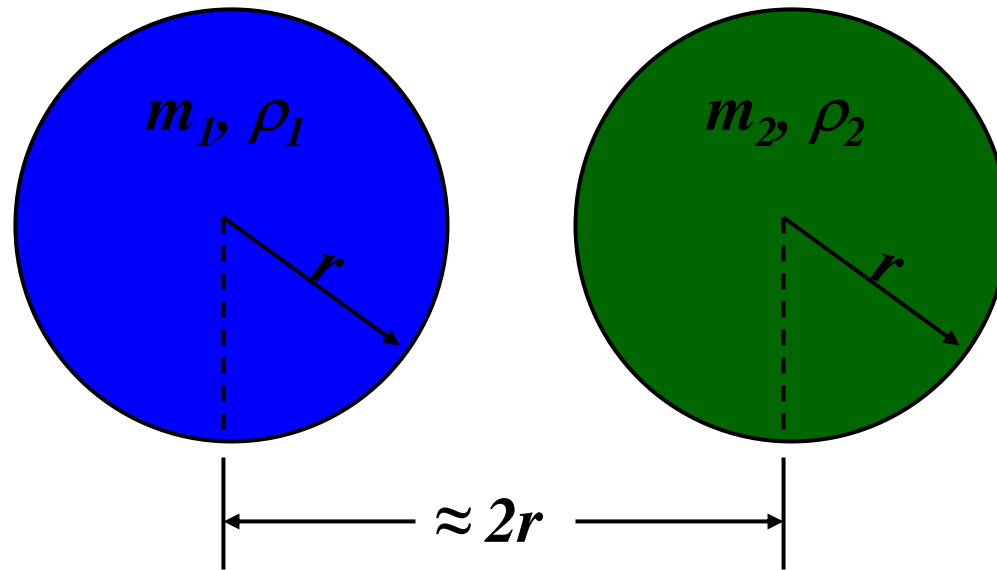
Effective field theories + observed smallness of L implies new quanta

[*S. R. Beane, Gen. Rel. Grav. 29 (1997) 945.*]

New quanta comprised of light gravitational strings

[*R. Sundrum, JHEP 9907 (1999) 001*]

Challenge: Scaling with Size of Apparatus



$$F = \frac{Gm_1m_2}{(2r)^2} = \frac{G\rho_1\rho_2(4r^3)^2}{4r^2} \sim G\rho_1\rho_2r^4$$

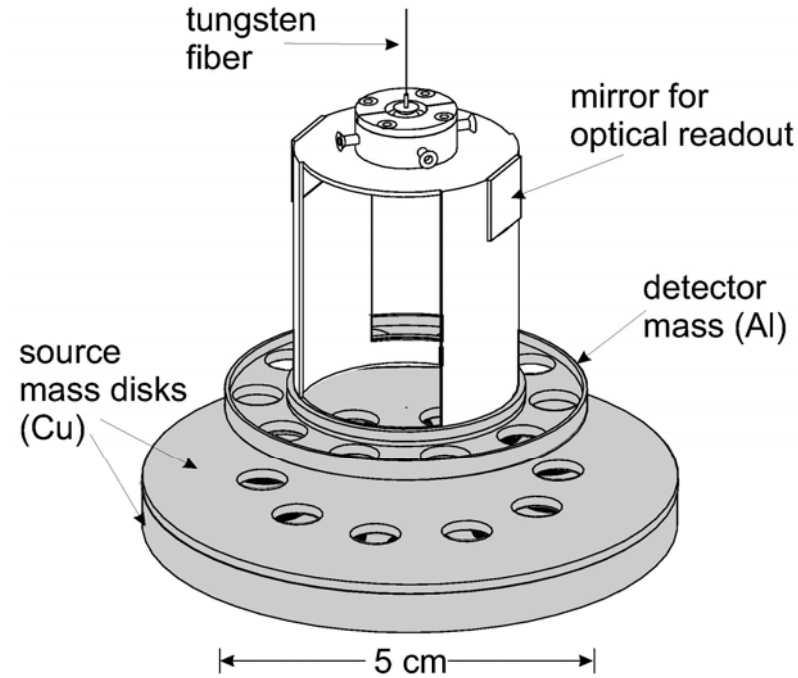
$$\rho_1 = \rho_2 = 20 \text{ g/cm}^3, r = 10 \text{ cm} \Rightarrow F \approx 10^{-5} \text{ N}$$

$$r = 100 \text{ } \mu\text{m} \Rightarrow F \approx 10^{-17} \text{ N}$$

Background Forces: $\sim r^{-2}$ (electrostatics), $\sim r^{-4}$ (magnetic dipoles, Casimir)

Eot-Wash Torsion Pendulum Experiment

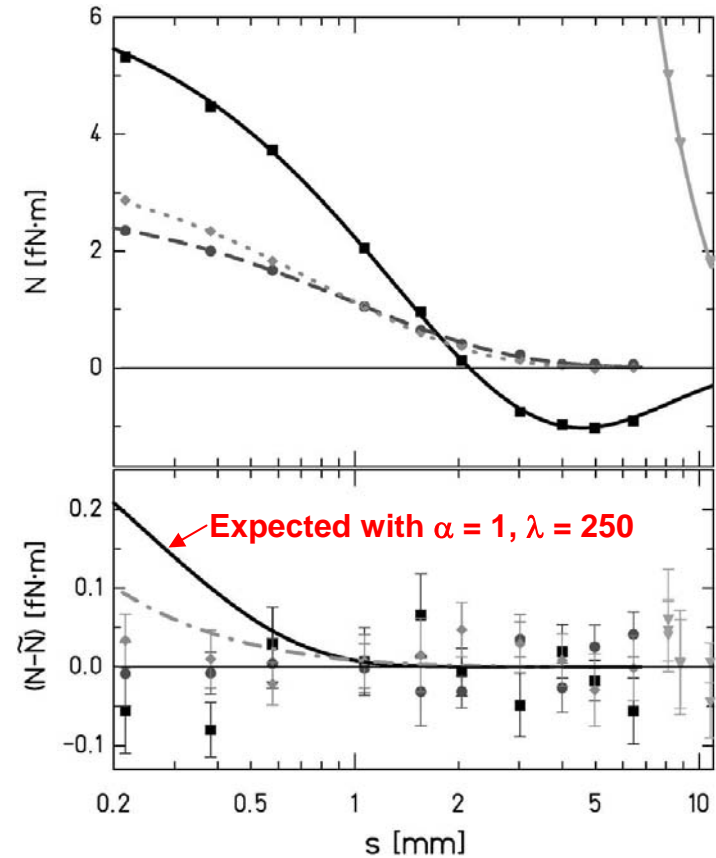
C. D. Hoyle, D. J. Kapner, E. G. Adelberger et al., Phys. Rev. D 70 (2004) 042004



- Version I pictured
- 137 μm minimum gap (version II)
- 20 μm BeCu membrane (not shown)

Limits: Scenarios with $\alpha \geq 1$ excluded at 95% CL for $\lambda \geq 197 \mu\text{m}$
Largest extra dimension: $R \lesssim 160 \mu\text{m}$

Torque and residuals vs. gap



ADD Model (2 equal-sized extra dimensions compactified on a torus):
 $R \lesssim 130 \mu\text{m} \Rightarrow M^* \geq 1.7 \text{ TeV}$

Experiment at University of Colorado

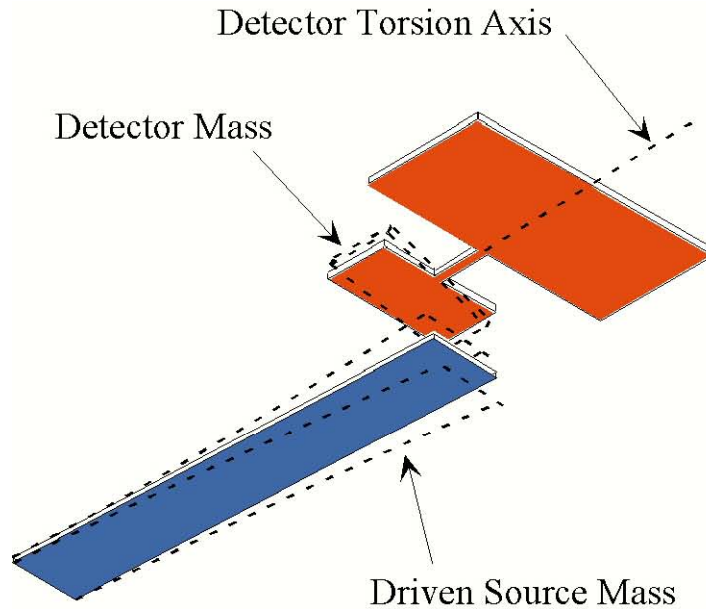
- **Our approach**

- Resonant detector with source mass driven on resonance**
 - High frequency detector (1 kHz) for compact vibration isolation**
 - Planar geometry for largest possible signal**
 - Stiff conducting shield for background suppression**

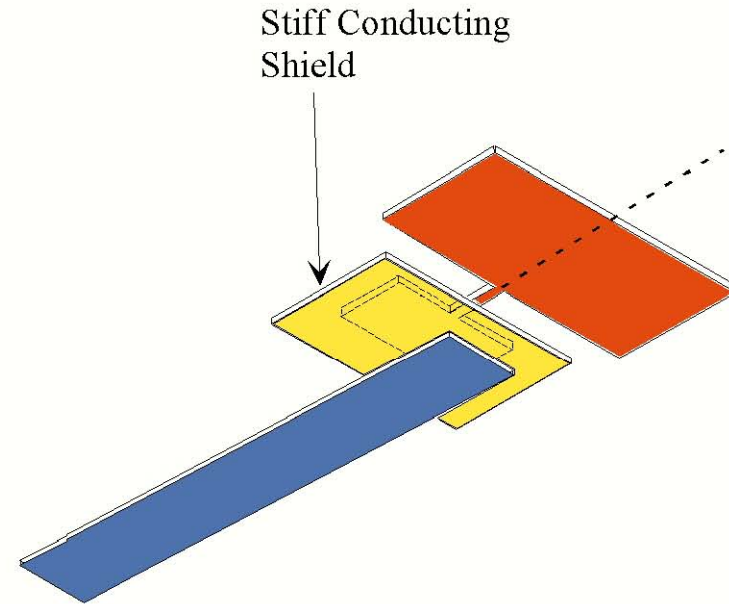
- **Major components**

- Source Mass Oscillator**
 - Detector Oscillator**
 - Transducer and Amplifier**
 - Electrostatic Shield**
 - Vibration Isolation**
 - Vacuum System and Translators**

Planar Geometry



Source and Detector
Oscillators



Shield for Background
Suppression

$$F_{\text{Yukawa}} (\alpha = 1, \lambda = 100 \mu\text{m}) \sim 10^{-14} \text{ N}$$

$$F_{\text{Thermal}} (T = 300 \text{ K}) \sim 10^{-14} \text{ N}$$

$$F_{\text{Newtonian}} \sim 10^{-15} \text{ N}$$

Overview

- 3 independent vibration isolation stacks

- 3 tilt stages

Not shown:

- Transducer

- X-Y-Z translation of source and detector stacks

- Electrostatic shields around source mass stack and transducer

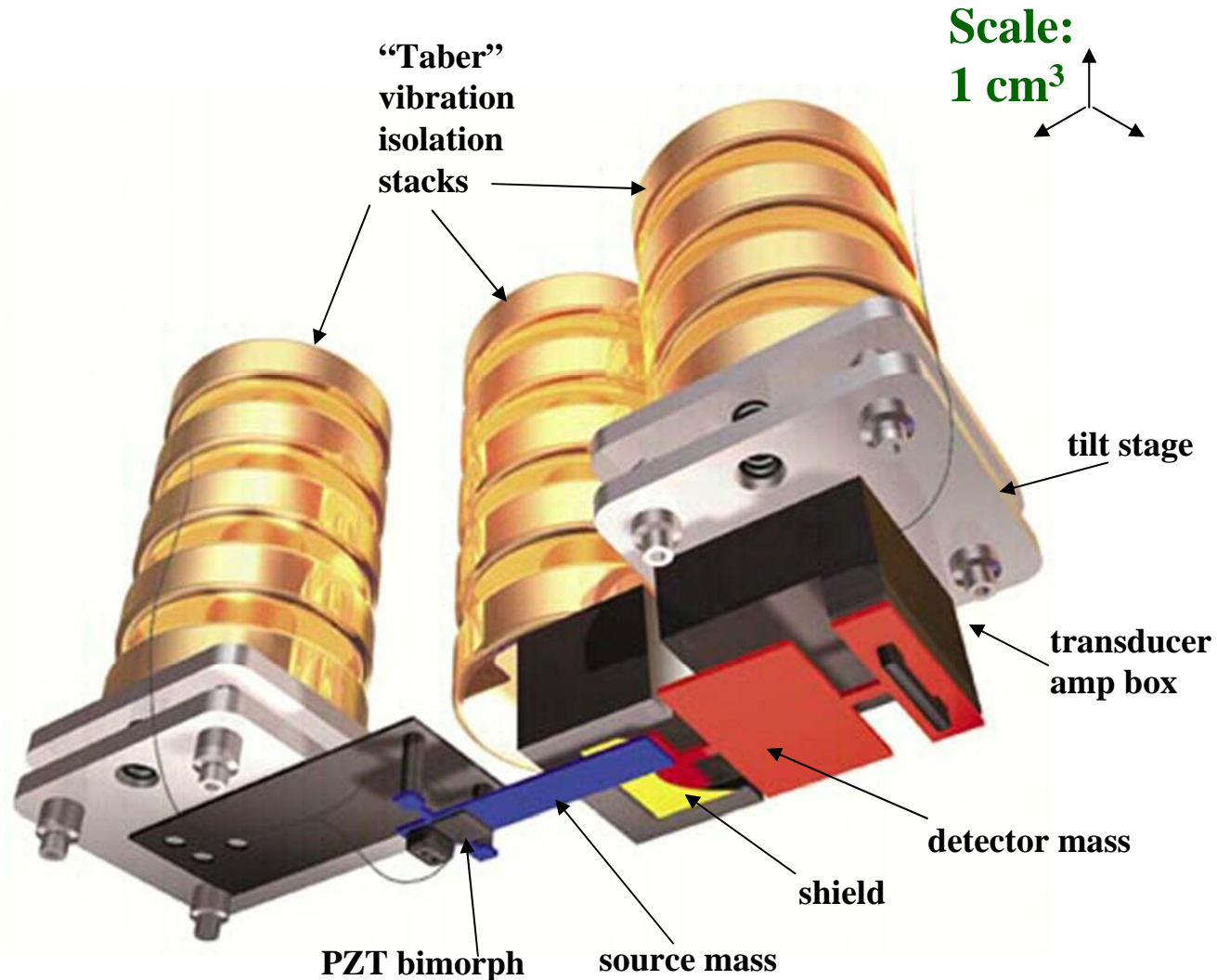


Figure: Bryan Christie (www.bryanchristie.com) for Scientific American (August 2001)

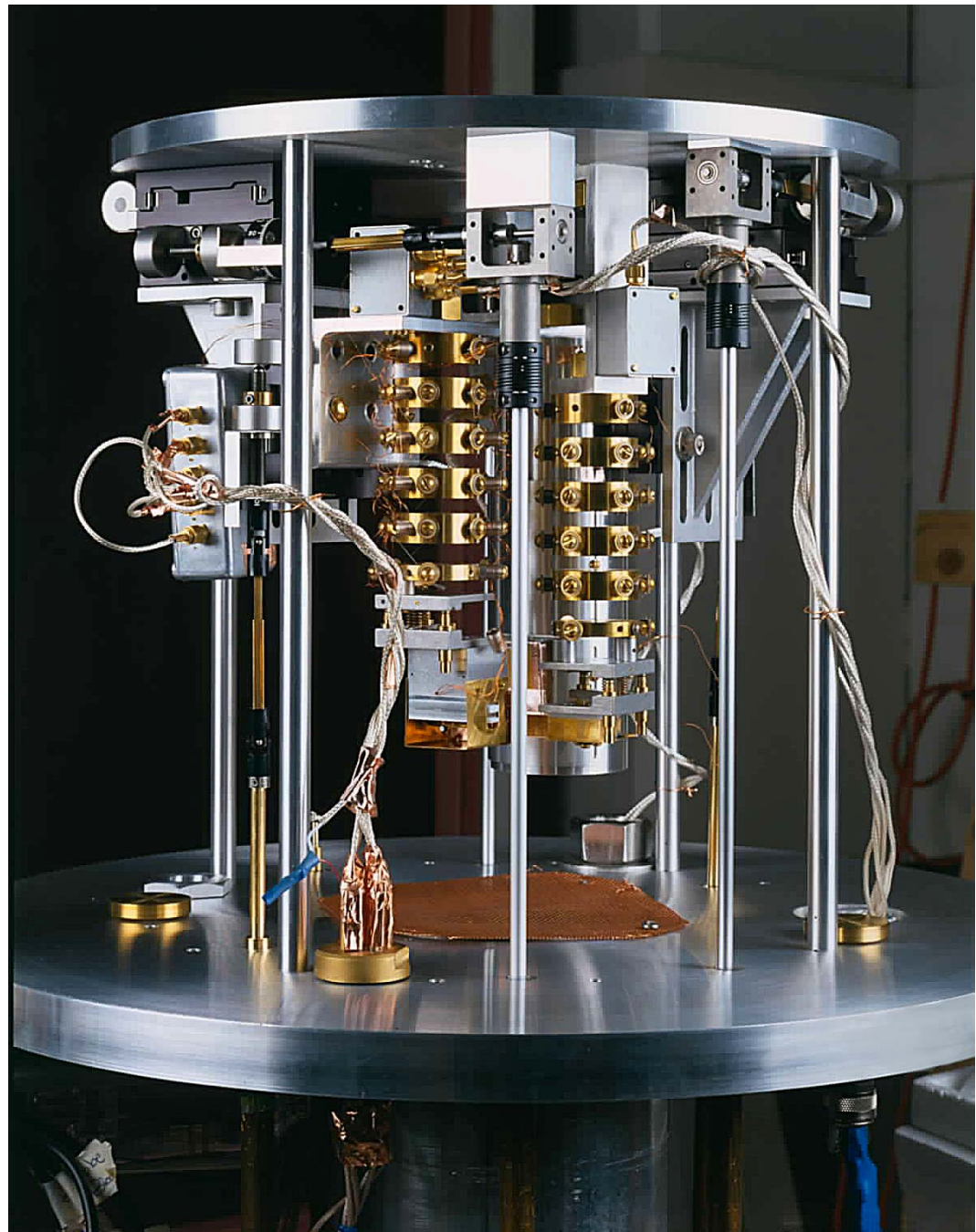
Vibration Isolation Stacks

5-stage Taber isolators

200 dB per stack at 1 kHz

Brass masses and stainless wires

Chan, Long, and Price, RSI 70, 2742 (1999)



~50 cm

Close-up with Detector Retracted

↑
~1 cm
↓



Gold coated 60 μm sapphire shield

Sapphire contact points for leveling and alignment

Sensitivity : increase Q and statistics, decrease T

- Signal

Force on detector due to Yukawa interaction with source:

$$F_Y(t) = \pi\alpha G\rho_s\rho_d A_d \lambda^2 \exp(-d(t)/\lambda)[1 - \exp(-t_s/\lambda)][1 - \exp(-t_d/\lambda)]$$

$$\sim 2 \times 10^{-14} \text{ N} \quad (\text{for } \alpha = 1, \lambda = 100 \text{ mm})$$

- Thermal Noise

$$S_F = 4kT\eta \quad \eta = \frac{\omega m}{Q}$$

$$\sim 4 \times 10^{-14} \text{ N} \quad (300 \text{ K, } 1000 \text{ s average})$$

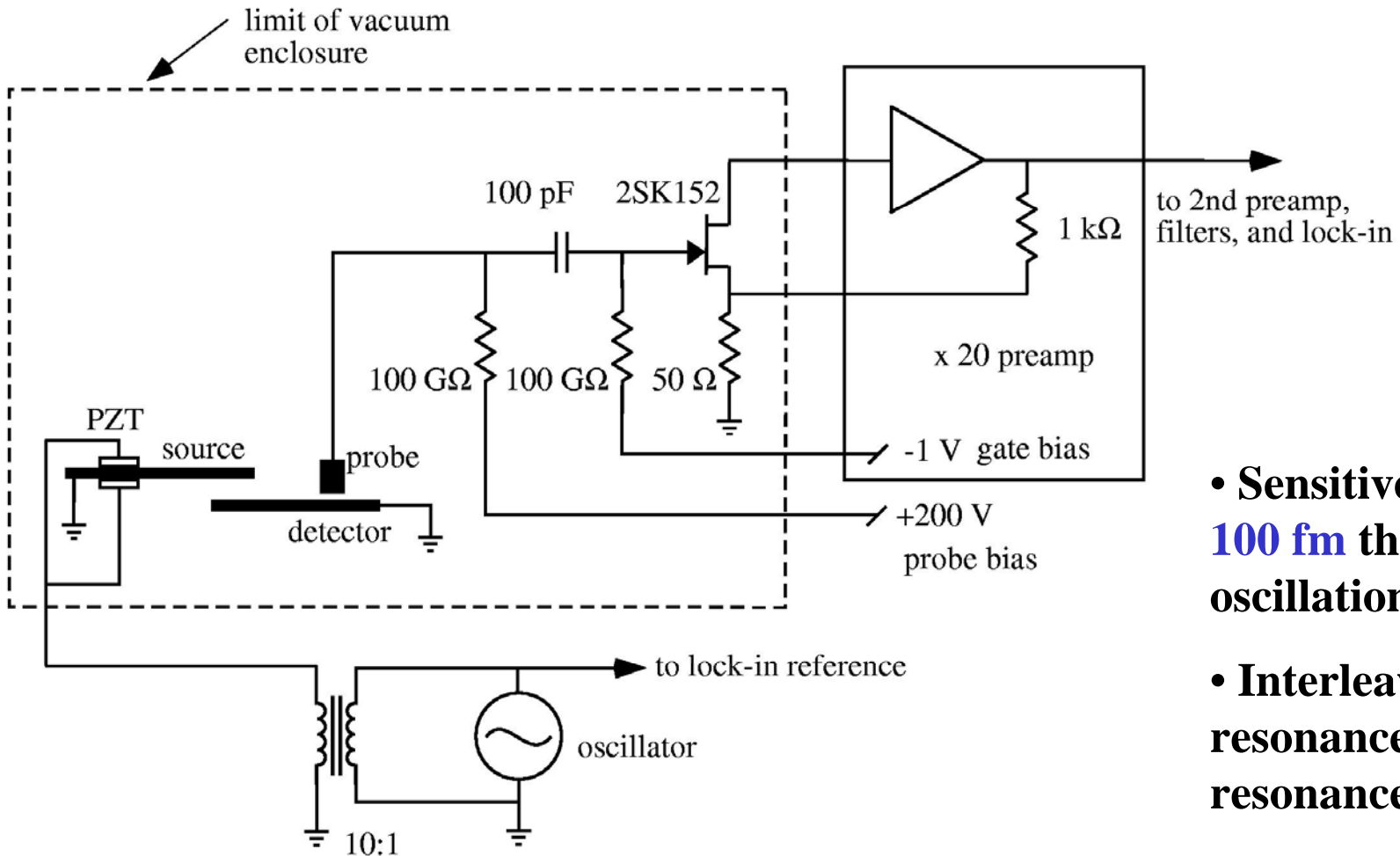
$$\sim 7 \times 10^{-16} \text{ N} \quad (4 \text{ K, } 1000 \text{ s average})$$

- Setting SNR = 1 yields

$$\alpha \sim \frac{1}{G\rho_s\rho_d \lambda^2 A_d} \sqrt{\frac{kTm\omega}{Q\tau}}$$

Similar for all thermal noise limited experiments

Capacitive Transducer and Preamplifier



- Sensitive to \approx **100 fm** thermal oscillations
- Interleave on resonance, off resonance runs
- Typical session: 8hrs with 50% duty cycle

Background Forces

Several months in 2001-2: Observed resonant signal $\approx 10^{-13}$ N

Vibrations

Filter with passive isolation stacks

Check that signals are geometry independent

Residual Gas

Suppress with shield, high vacuum

Study with vacuum control

Magnetic Forces (contaminants, eddy currents)

Use non-magnetic materials

Study with applied gradients, insulating test masses

Electrostatic forces

Suppress with shield

Study with applied potentials, capacitance measurements, geometry

Force Measuring Data – Shield Grounded

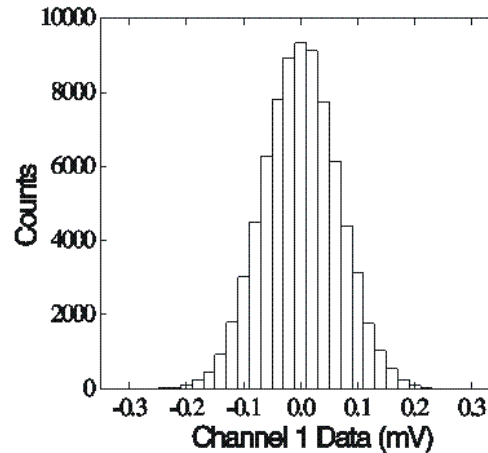
22 hours on-resonance data
collected over 5 days with
interleaved diagnostic data

On-resonance: Detector
thermal motion and amplifier
noise

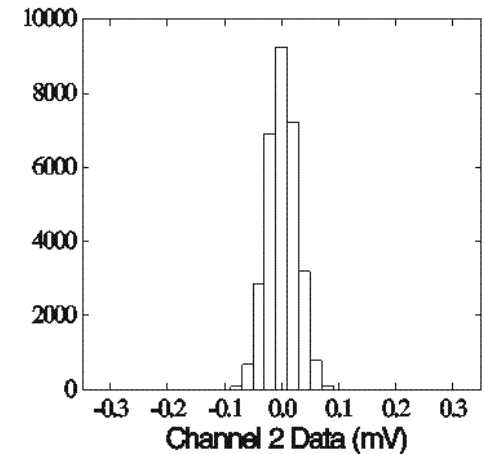
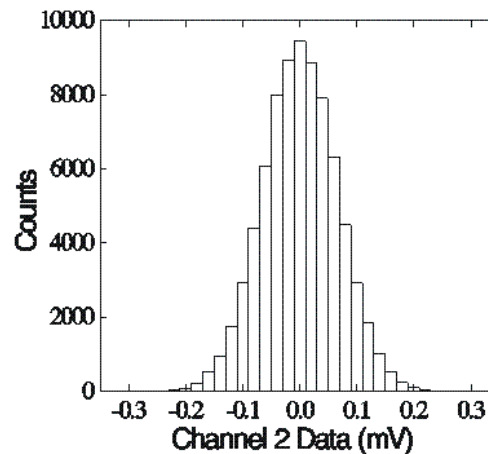
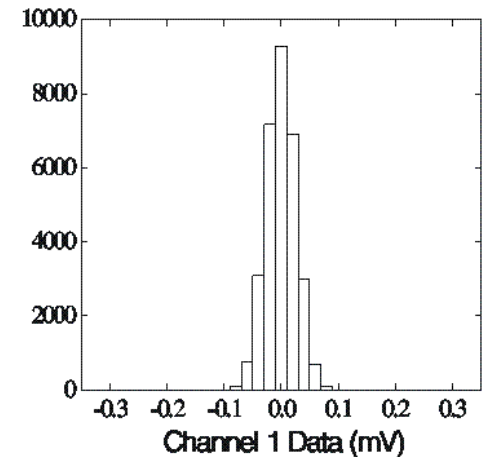
Off-resonance: amplifier
noise

Our latest results:
hep-ph/0210004
Nature 421, 922–925 (2003)

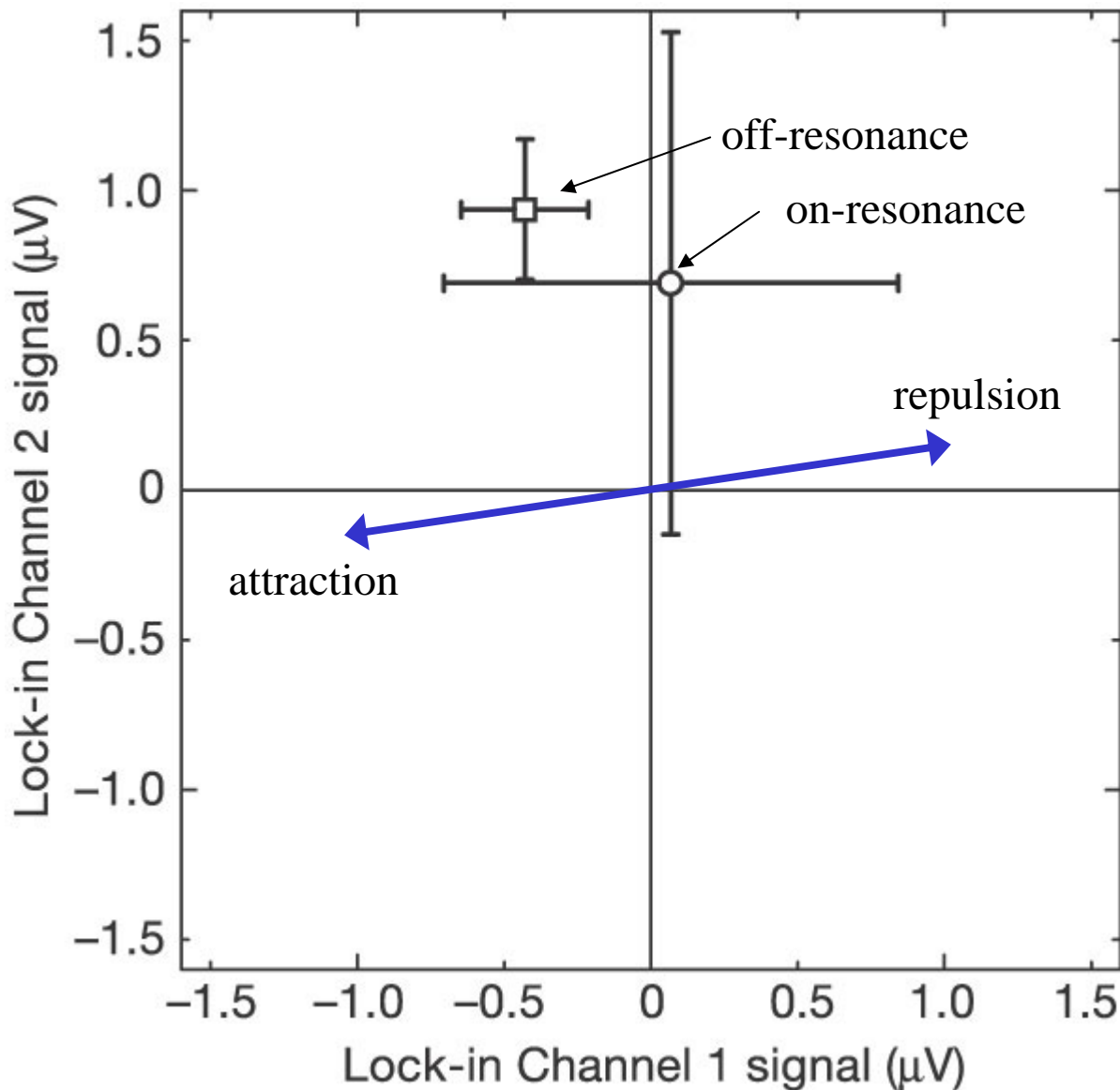
On Resonance



Off Resonance



Means are consistent with zero force



$$V_{\text{on}} - V_{\text{off}} = -0.44 \pm 0.82 \mu\text{V}$$

Corresponds to

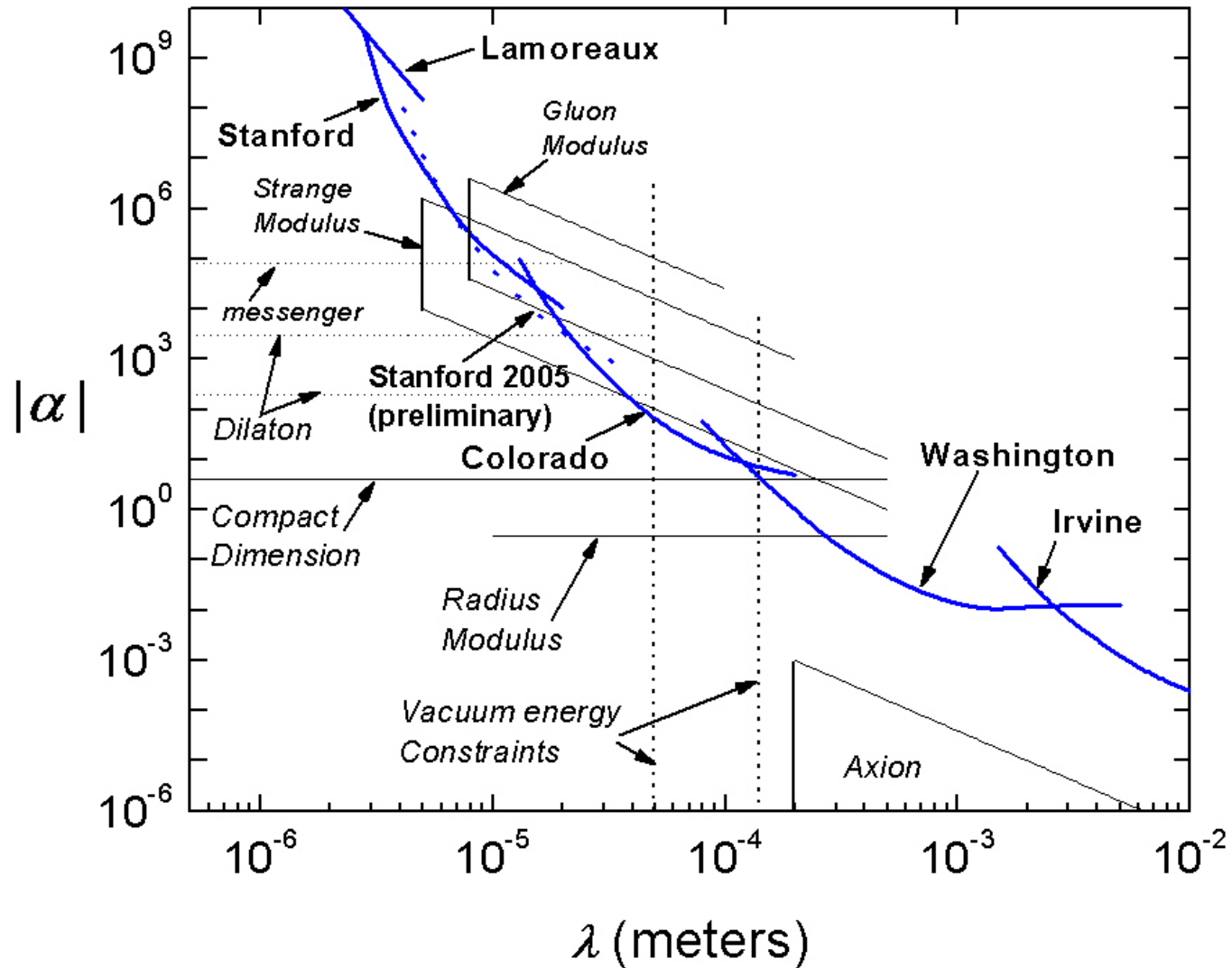
$$F = -1.2 \pm 2.2 \text{ fN}$$

lumped force at outer
radius of detector

**Strongest Yukawa limits
from 20-100 μm
Dilaton mass limit:
 $m = 9 \text{ meV}$**

Limits from 1 μm to 1 cm - 2005

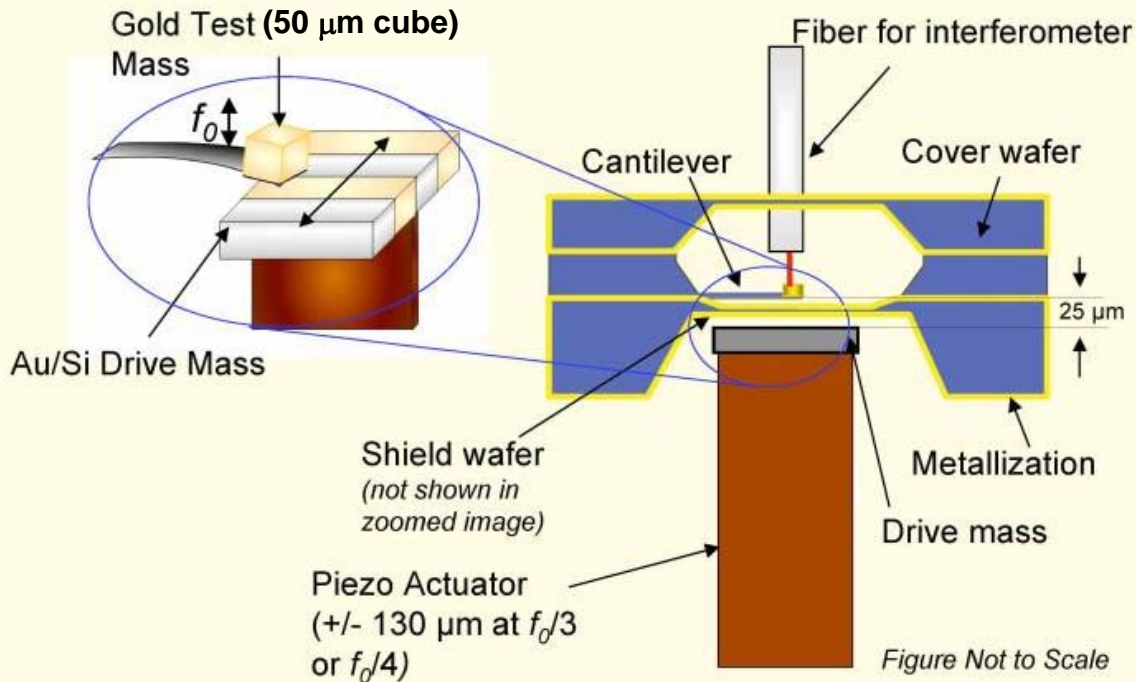
~ 7 square decades since 1998



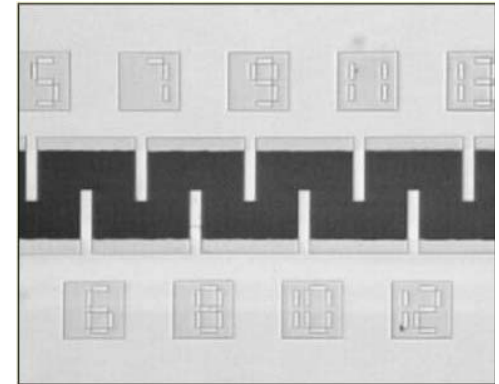
Reviewed in: *J. C. Long, J. C. Price, C. R. Physique 4 (2003) 337*
Stanford 2005: *S. J. Smullin, A. Kapitulnik, private communication*

Stanford Microcantilever Experiment

Schematic of Device

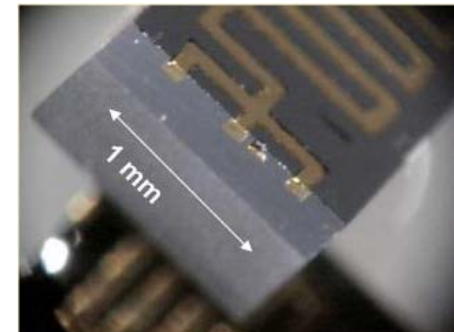


Cantilever prototypes



- 250 x 50 x 0.3 μm
- With mass: $f = 300$ Hz, $Q \sim 4 \times 10^4$
- F_{THERMAL} at 10K, 1 hr ~ 1 aN

Source mass



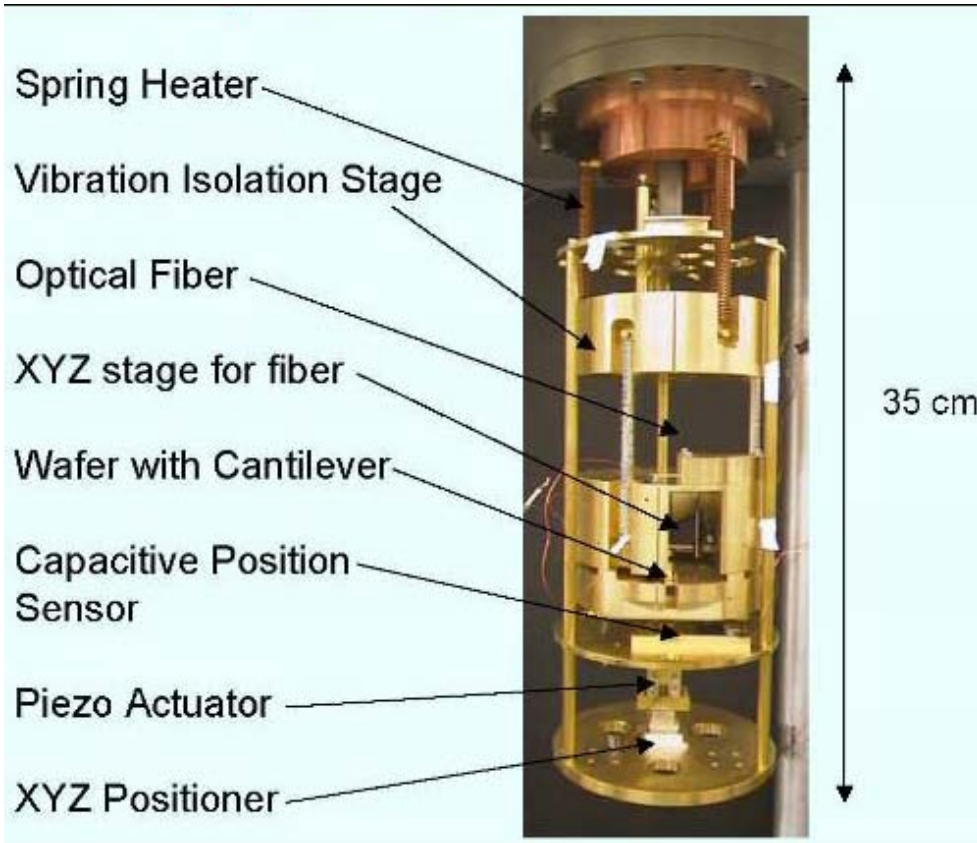
Conducting meander
for magnetic analogue

figures: Sylvia J. Smullin, *Tests of Short Distance Gravity*, SSI 2004

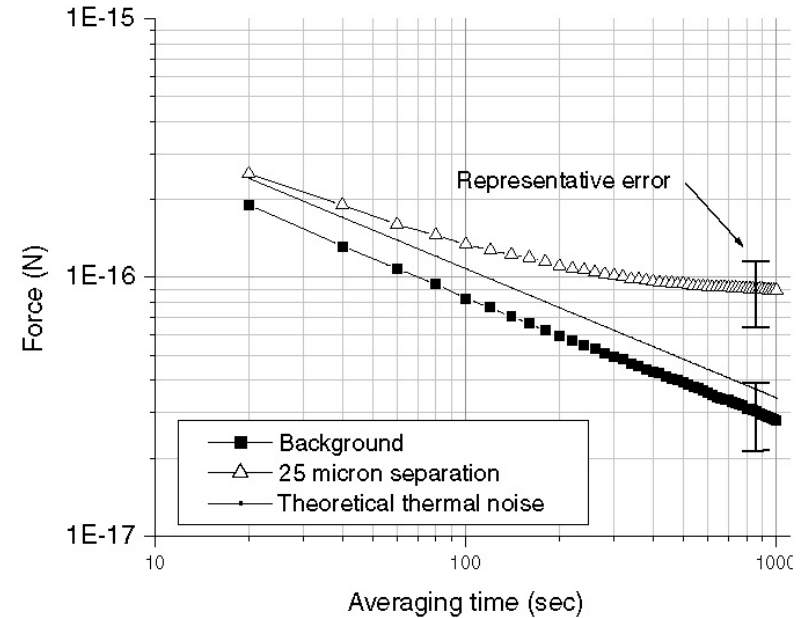
Stanford Microcantilever Experiment

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

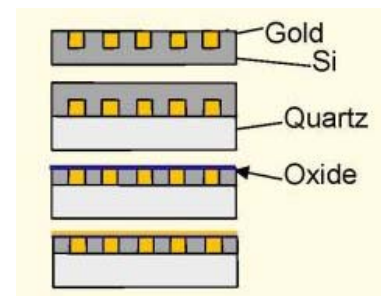
He cryostat insert for operation at ~10 K



S. Smullin

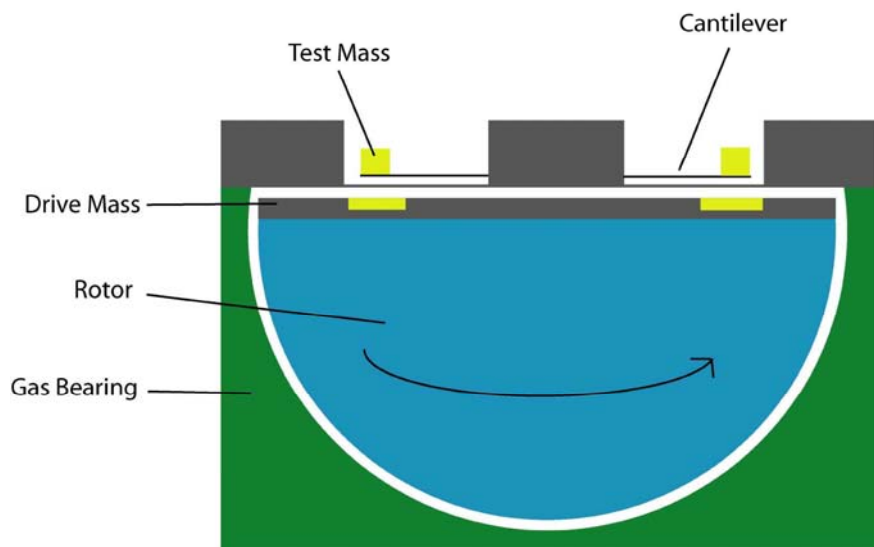


Improvements...



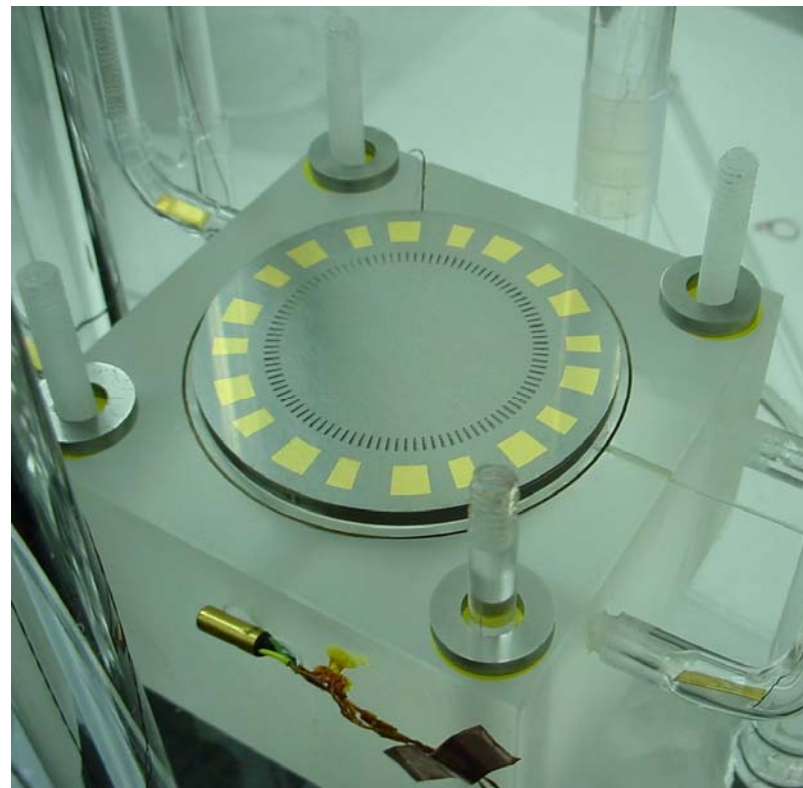
**Buried source masses
reduce surface variation**

Stanford Microcantilever Experiment – Generation II



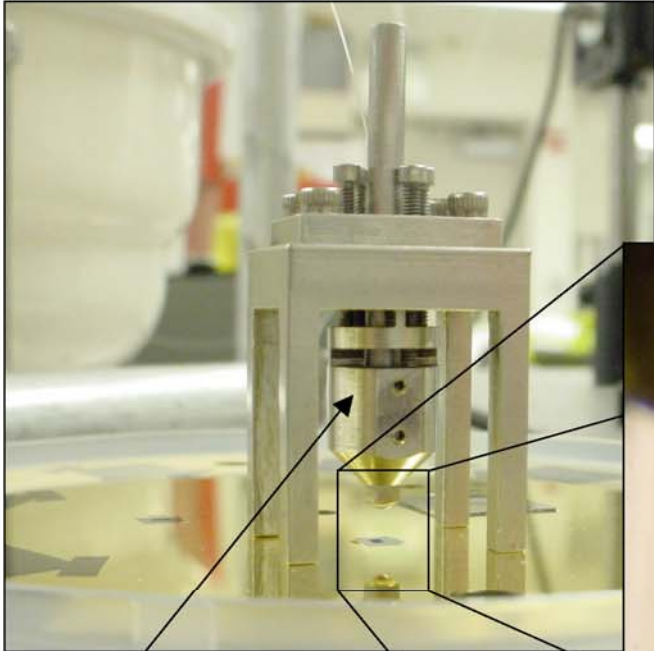
- Masses modulated on spinning rotor
- Larger area drive and test masses for increased sensitivity

Drive mass mounted in gas bearing



figures courtesy of David M. Weld

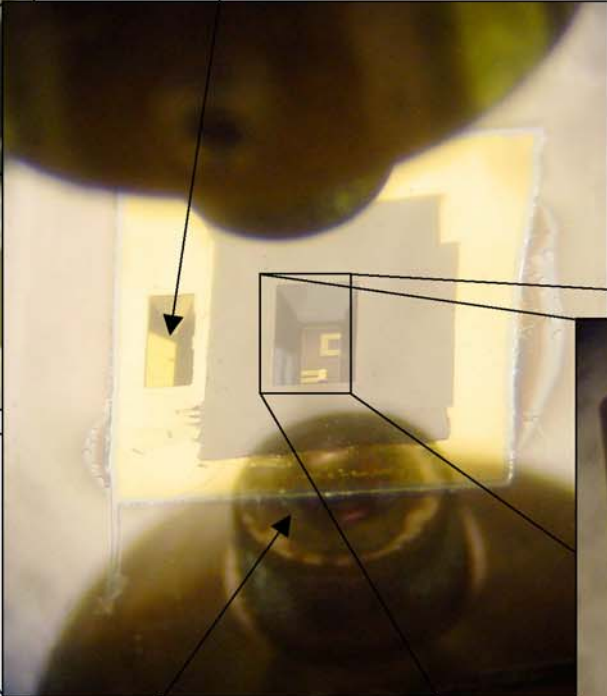
Stanford Microcantilever Experiment – Generation II



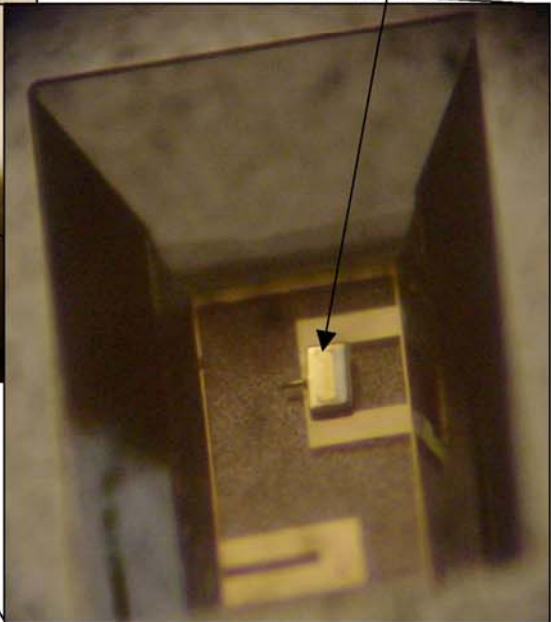
TRENCH FOR INTEGRATED CRYOPUMP

CANTILEVER WITH ATTACHED MASS

STANDOFF FIBER-OPTIC INTERFEROMETER



REFLECTION OF FIBER-FOCUSING LENS



Colorado Experiment at 30 μm ?

$$\mathbf{F_{Yukawa} (\alpha = 1) \sim 10^{-16} \text{ N}}$$

$$\mathbf{F_{thermal} (300 \text{ K}) \sim 10^{-14} \text{ N}}$$

$$\mathbf{F_{pressure} \sim F_{electrostatic} \sim 10^{-10} \text{ N}}$$

Need 10 μm thick shield with compliance $\sim 10^{-4} \text{ m/N}$

Stretched Membrane Shield

- Copper-beryllium alloy stretched over frame
- Ten microns thick
- Hyperbolic shape to distribute tension evenly

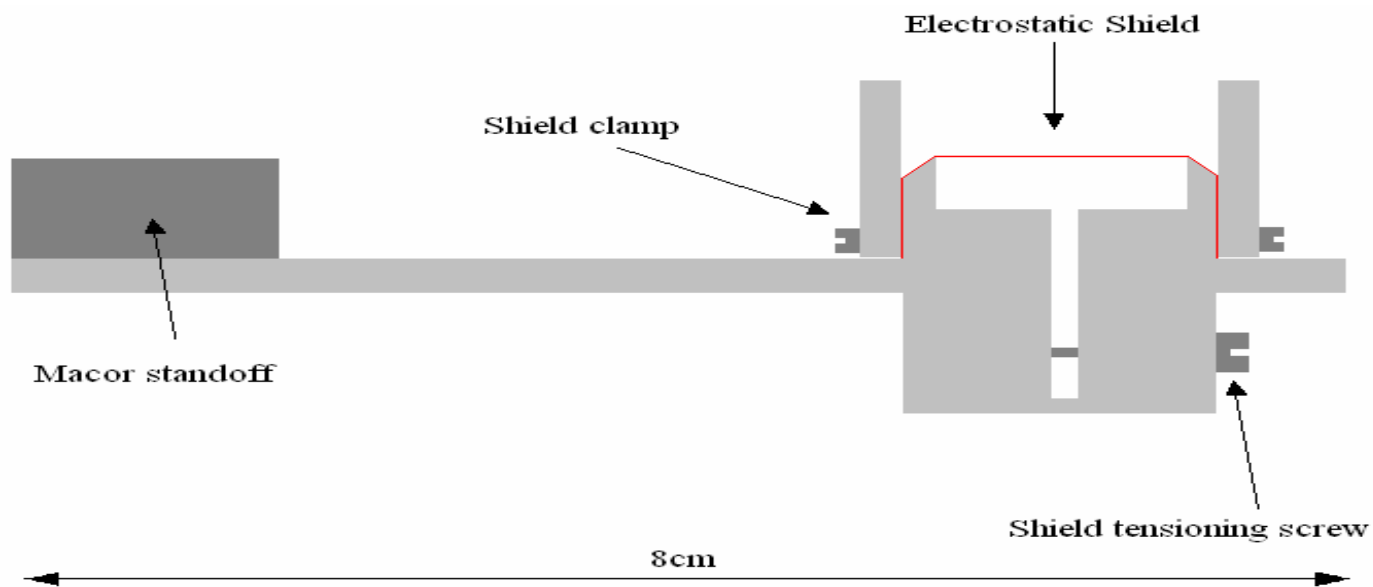
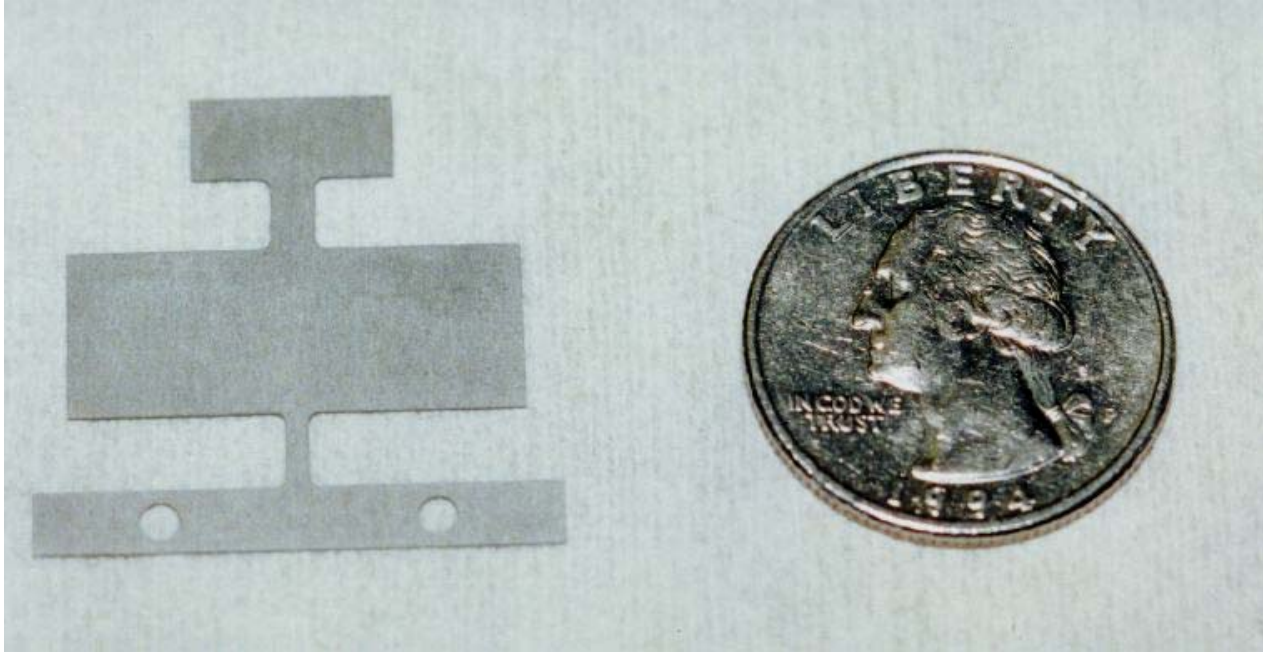


Figure not to scale

- Flatness: $|\Delta z| < 3 \mu\text{m}$
- Compliance at center line: $2.8 \times 10^{-5} \text{ m/N}$

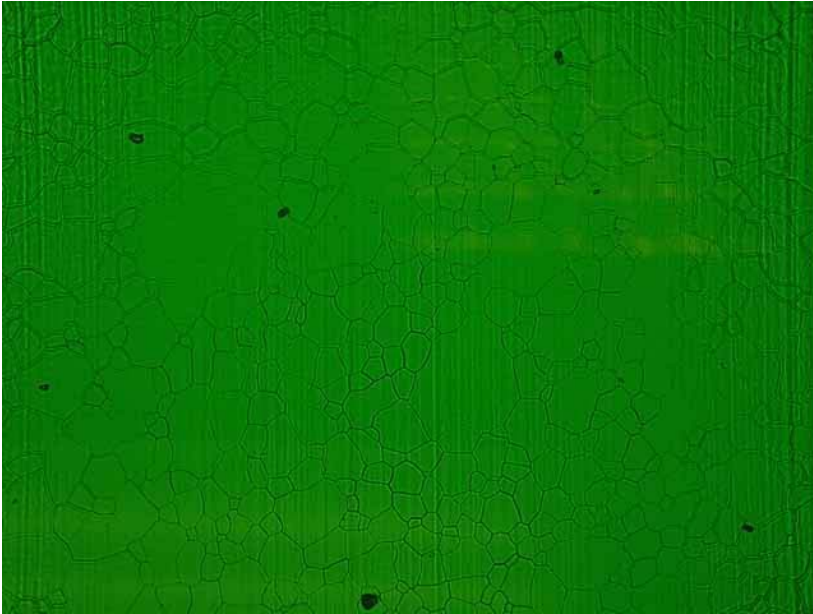
New detector prototypes fabricated



- **200 mm thick tungsten sheet (high density)**
- **Fabricated by wire EDM**
- **First generation: Annealed at 1600 K in helium atmosphere**
- **New oscillators: Annealed at 2700 K; expect larger crystals, higher Q**

2700 K annealing at Los Alamos: Much larger crystals

New detector surface
(200 x magnification)



1000 x showing 90 μm crystal
(previous maximum = 15 μm)



Higher T anneals had expected material effect, but
mechanical properties still unknown...

New detectors and projected sensitivity

Available prototypes

<i>Material</i>	<i>Q @ 300 K</i>	<i>Q @ 77 K</i>	<i>Q @ 4 K</i>
Si	$6 \cdot 10^3$	$1 \cdot 10^5$	$8 \cdot 10^5$
W (as machined)	$5 \cdot 10^3$?	?
W (1600 K anneal)*	$2.5 \cdot 10^4$?	?
W (2700 K anneal)	?	?	?

**Used for published experiment*

Data of W. Duffy (~ 3 cm diameter, 1 kHz cylindrical torsional oscillators):

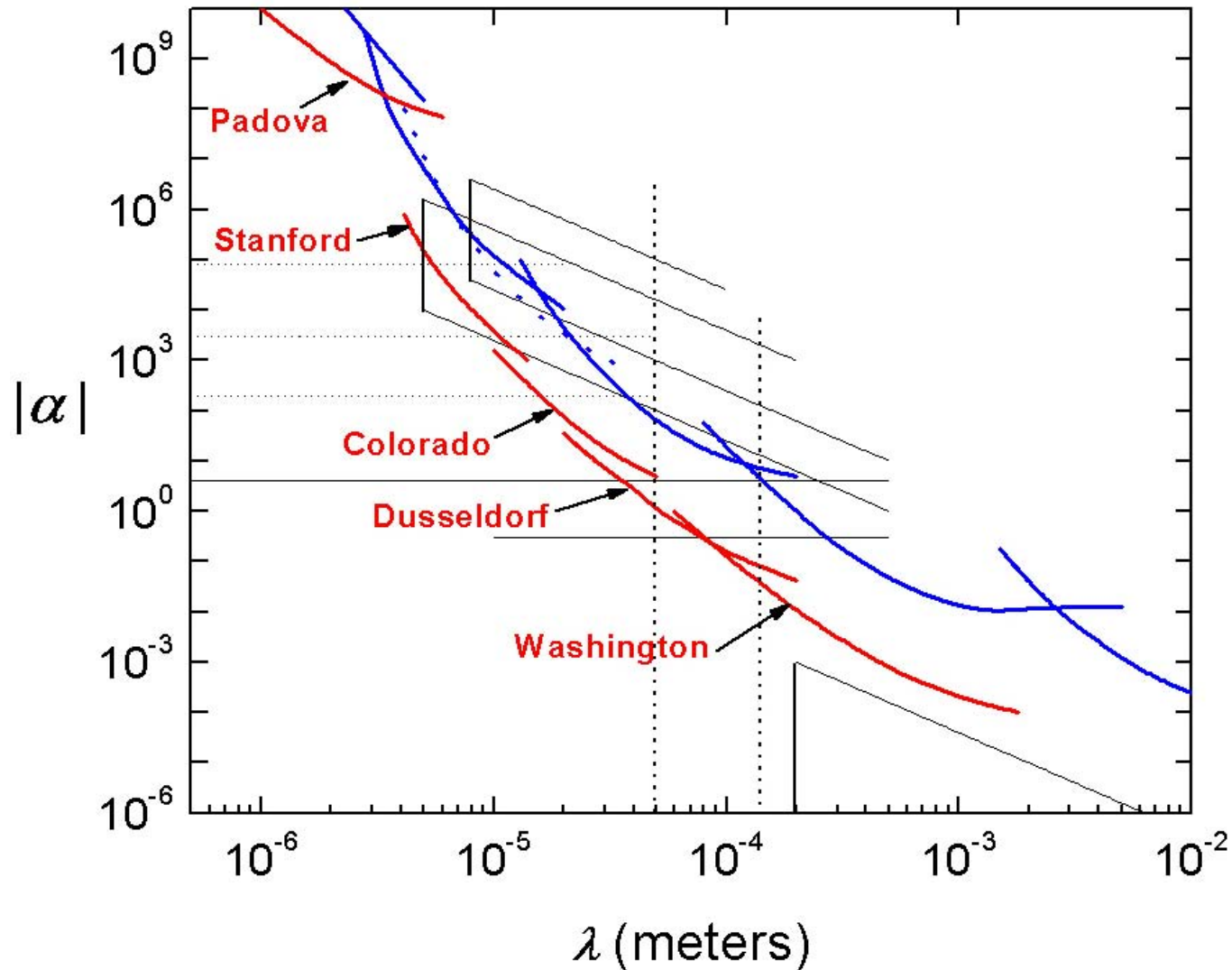
J. Appl. Phys. 72 (1992) 5628

<i>Material</i>	<i>Q @ 300 K</i>	<i>Q @ 77 K</i>	<i>Q @ 4 K</i>
W (as machined)	$2 \cdot 10^4$	$1 \cdot 10^5$	$5 \cdot 10^5$
W (2023 K anneal)	$2 \cdot 10^5$	$1 \cdot 10^6$	$1 \cdot 10^7$

$\alpha \sim (T/Q)^{1/2}$ improves by ~ 2 at 300 K, 20 at 4 K

if no further secondary re-crystallization enhancement...

Projected Sensitivity to 1 μm

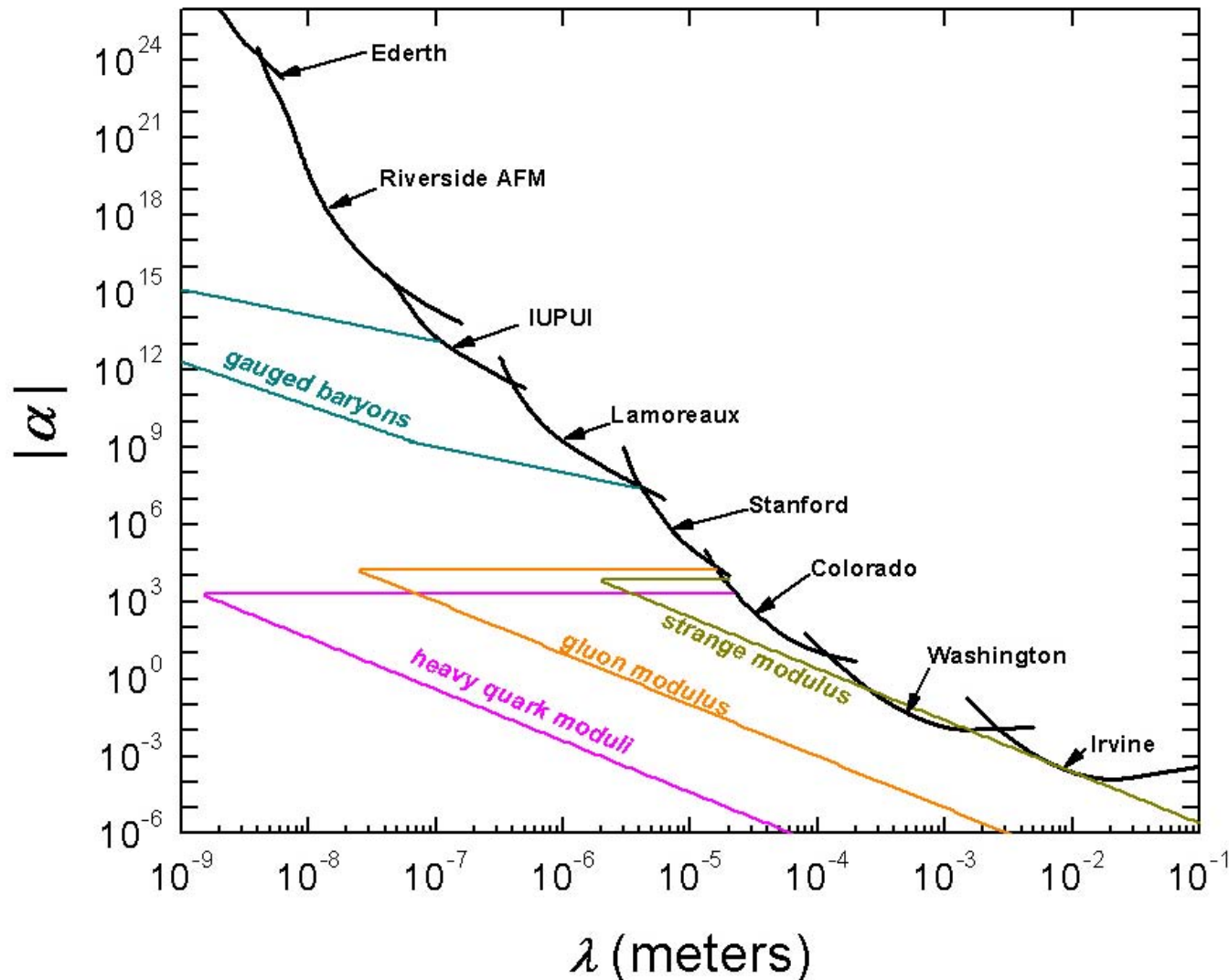


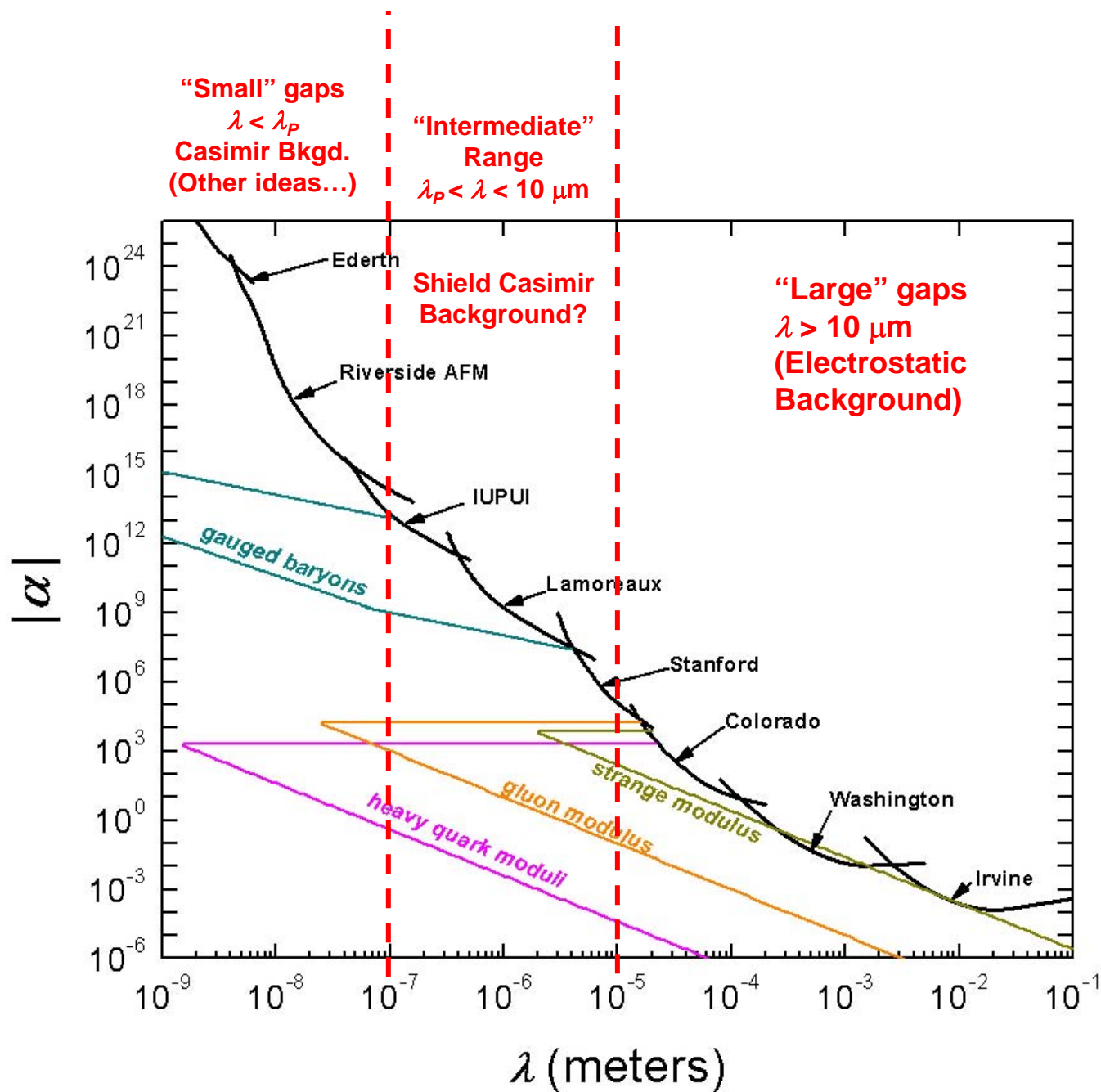
Adapted from: J. C. Long, J. C. Price, C. R. Physique 4 (2003) 337
Stanford: S. J. Smullin, A. Kapitulnik, private communication

Limits to 1 nm and Revised Predictions

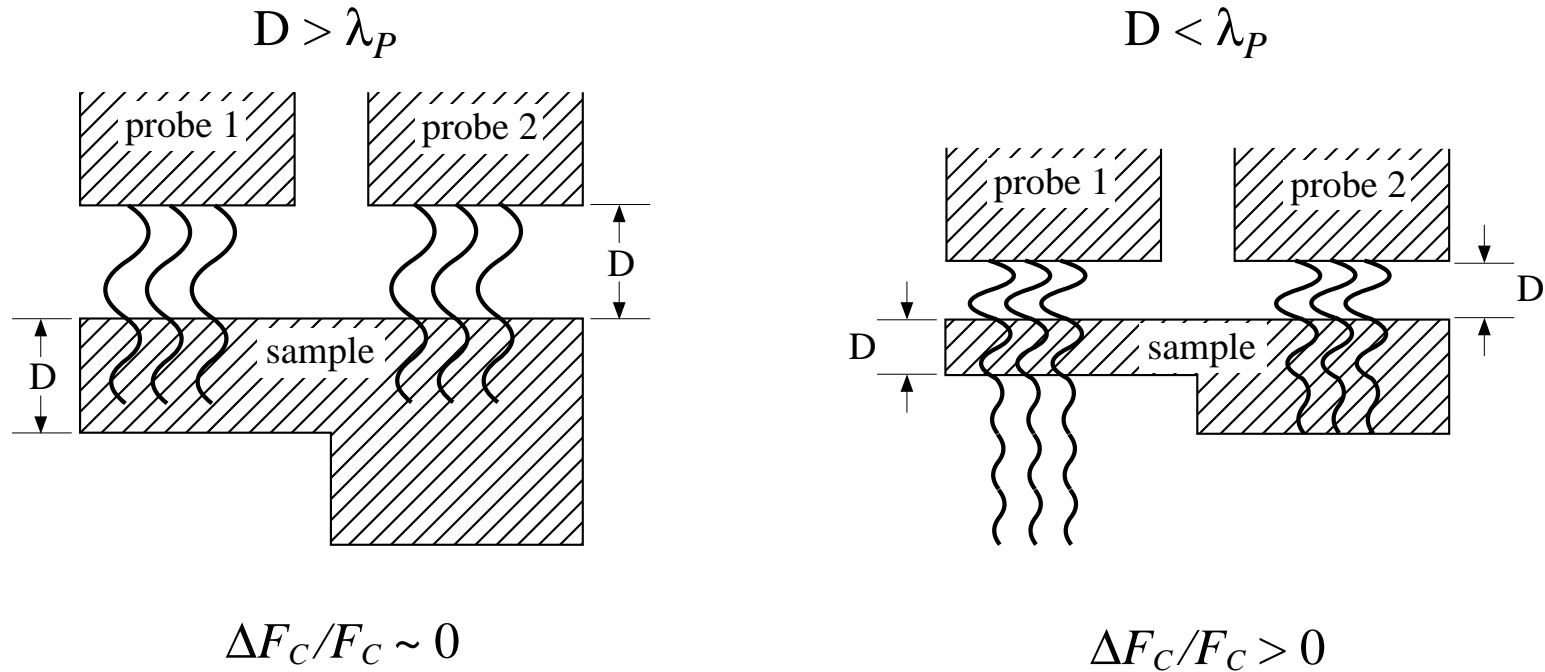
Predictions: S. Dimopoulos, A. A. Geraci *Phys. Rev. D.* 68 (2003) 124021

Limits: E. Fischbach et al., *PRD* 64 (2001) 075010; R. S. Decca et al., *Ann. Phys.* 318 (2005) 37



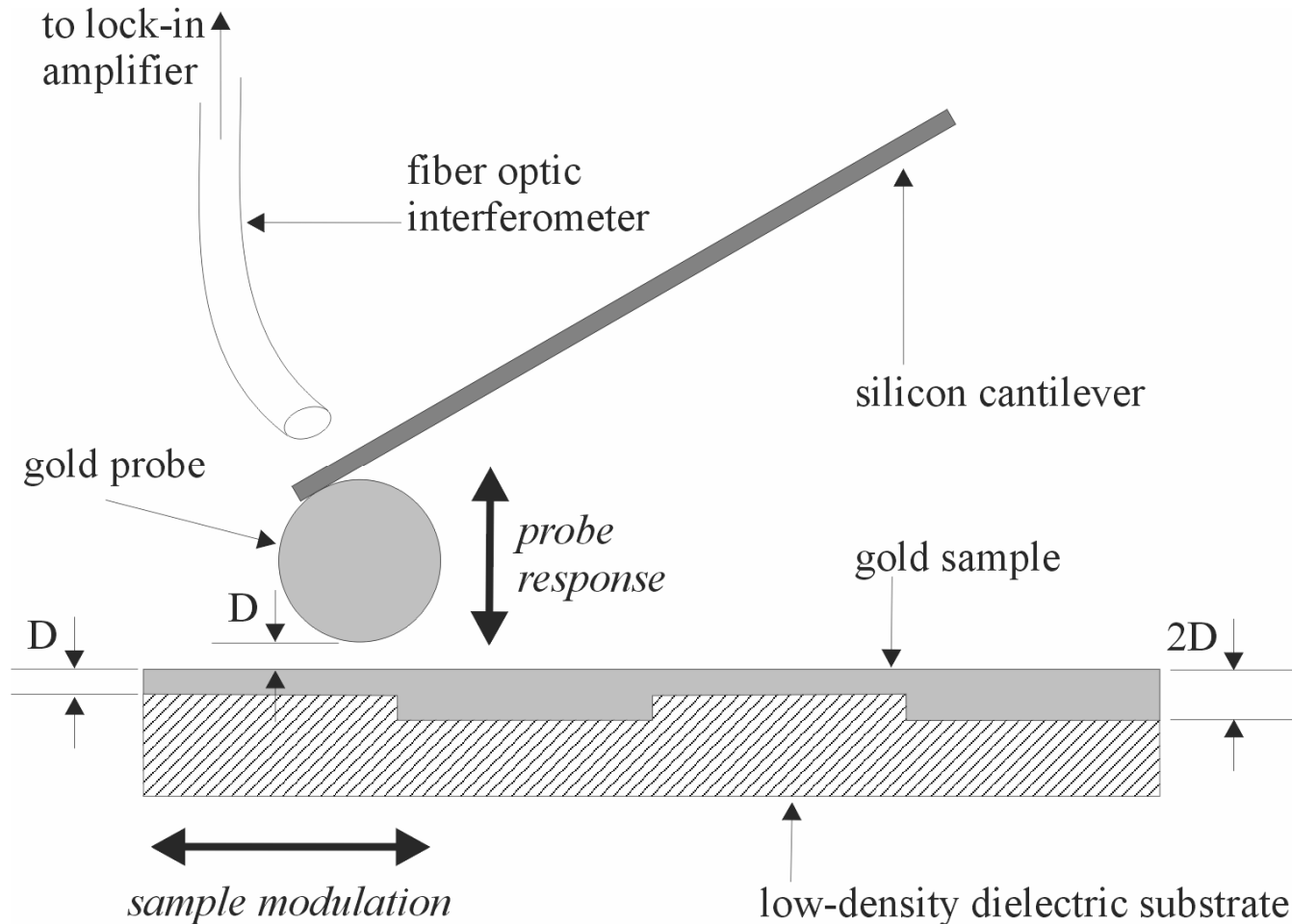


Casimir Background Shielding



- Effect calculated using finite thickness corrections in:
A. Lambrecht and S. Reynaud *Eur. Phys. J. D* 8 (2000) 309
- Compared with Yukawa forces ($\alpha = 1, \lambda = D$) for same geometry

Proposed “Buried Mass” Experiment



*J. C. Long, A. B. Churnside, J. C. Price,
Proceedings of the Ninth Marcel Grossmann Conference C 1825; hep-ph/009062*

Why Bother?

AMERICAN INSTITUTE OF PHYSICS

[advanced search](#)

[home](#)

[contact us](#)

[site map](#)

Physics News Update

The AIP Bulletin of Physics News

[Subscribe to
Physics
News
Update](#)

[Physics
News
Graphics](#)

[Physical
Review
Focus](#)

[Physics
News Links](#)

Archives

[2005](#)

[2004](#)

[2003](#)

Number 734 #2, June 22, 2005 by Phil Schewe and Ben Stein

Gravity is Normal Down to the 100-nm Level

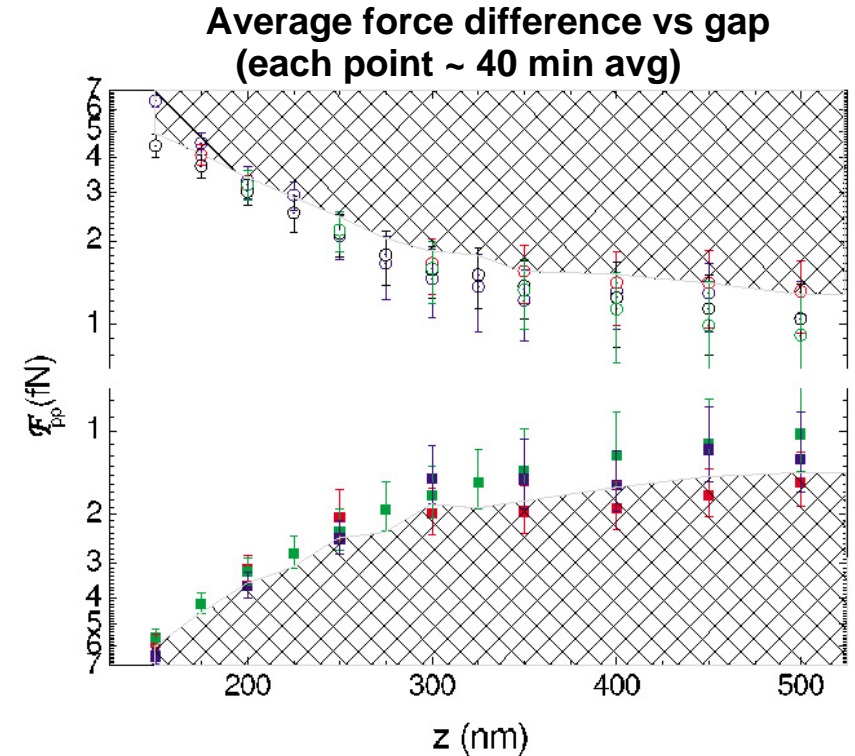
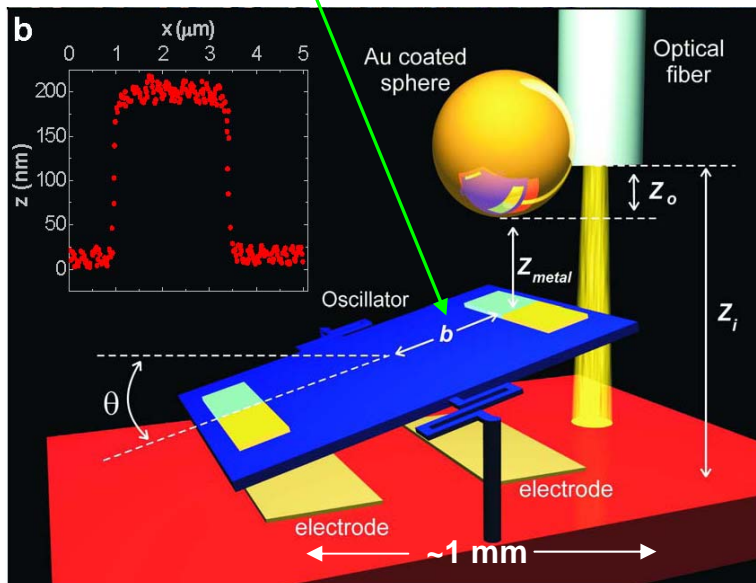
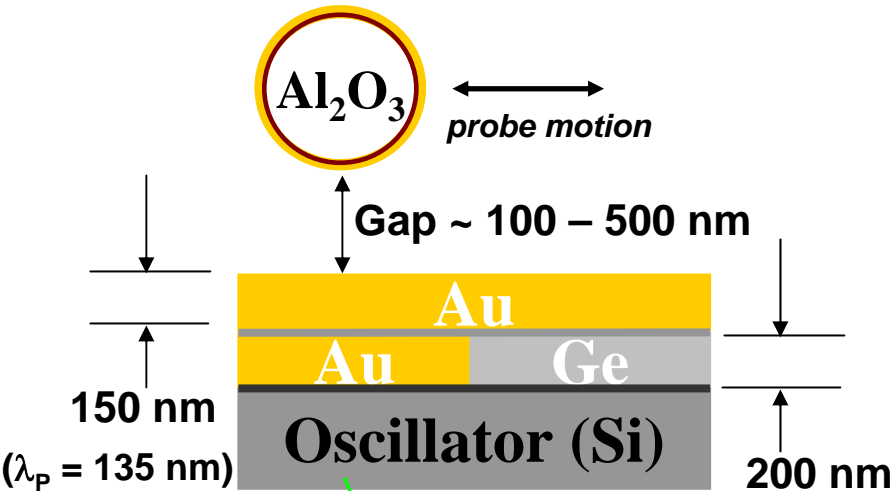
Gravity at the level of planets is well studied, and was known accurately even in Newton's day. This is owing to the fact that the other physical forces, such as the strong and weak nuclear forces, don't operate over such great distances, and electromagnetic forces between immense far-apart, electrically-neutral objects like planets are dilute. Gravity at shorter lengths, by contrast, is harder to measure, partly because all the other forces are in full play.

[...]

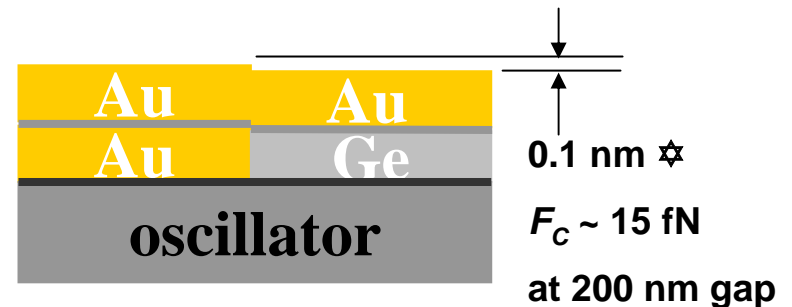
A new experiment, carried out by a Indiana/Purdue/Lucent/Florida/Wabash collaboration examines a shorter distance scale---100 nm---but is **able to rule out only corrections to gravity that are, in fact, a trillion times larger than gravity itself**. Nevertheless, such measurements help to constrain the

Indiana – Purdue “Isoelectronic” Experiment

R. S. Decca, et al., Phys. Rev. Lett. 94 (2005) 240401

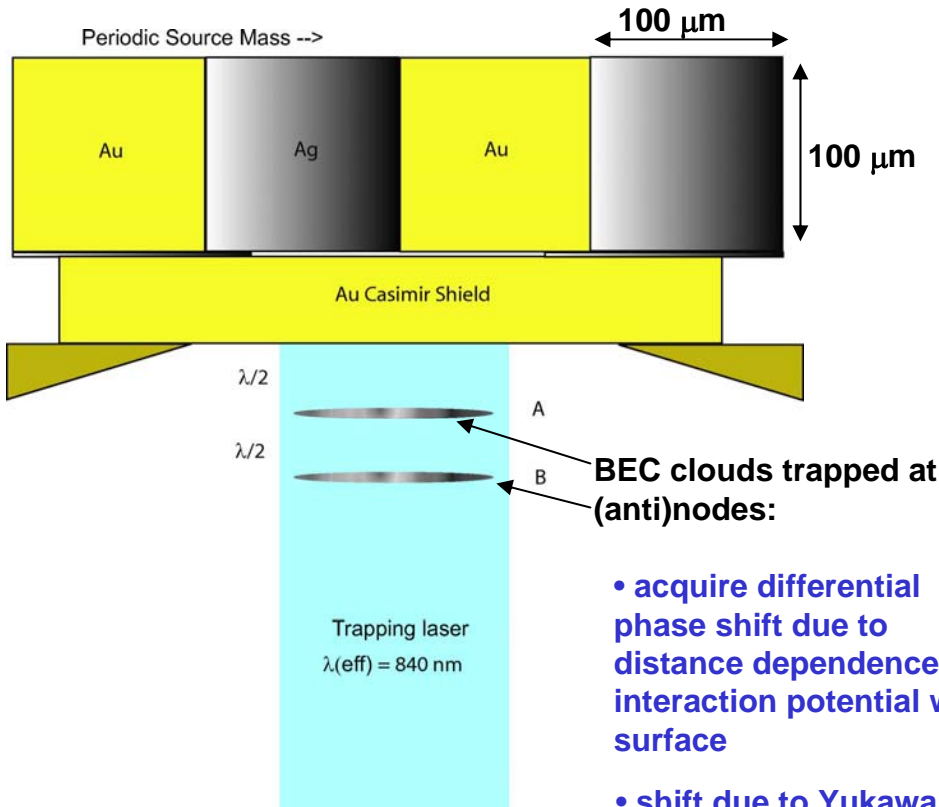


Signal: Casimir force difference from “step:”



Proposed Experiments using BEC Probes

S. Dimopoulos, A. A. Geraci Phys. Rev. D. 68 (2003) 124021



- acquire differential phase shift due to distance dependence of interaction potential with surface

- shift due to Yukawa potential will change with lateral position of source mass

Conducting probe replaced with dielectric

(^{87}Rb BEC with $n \sim 10^{16}/\text{cm}^3$; $\epsilon \sim 1$)

☆ Increased sensitivity (reduction in Casimir background) by $\sim 10^3$ near $1 \mu\text{m}$

JILA BEC Experiment:

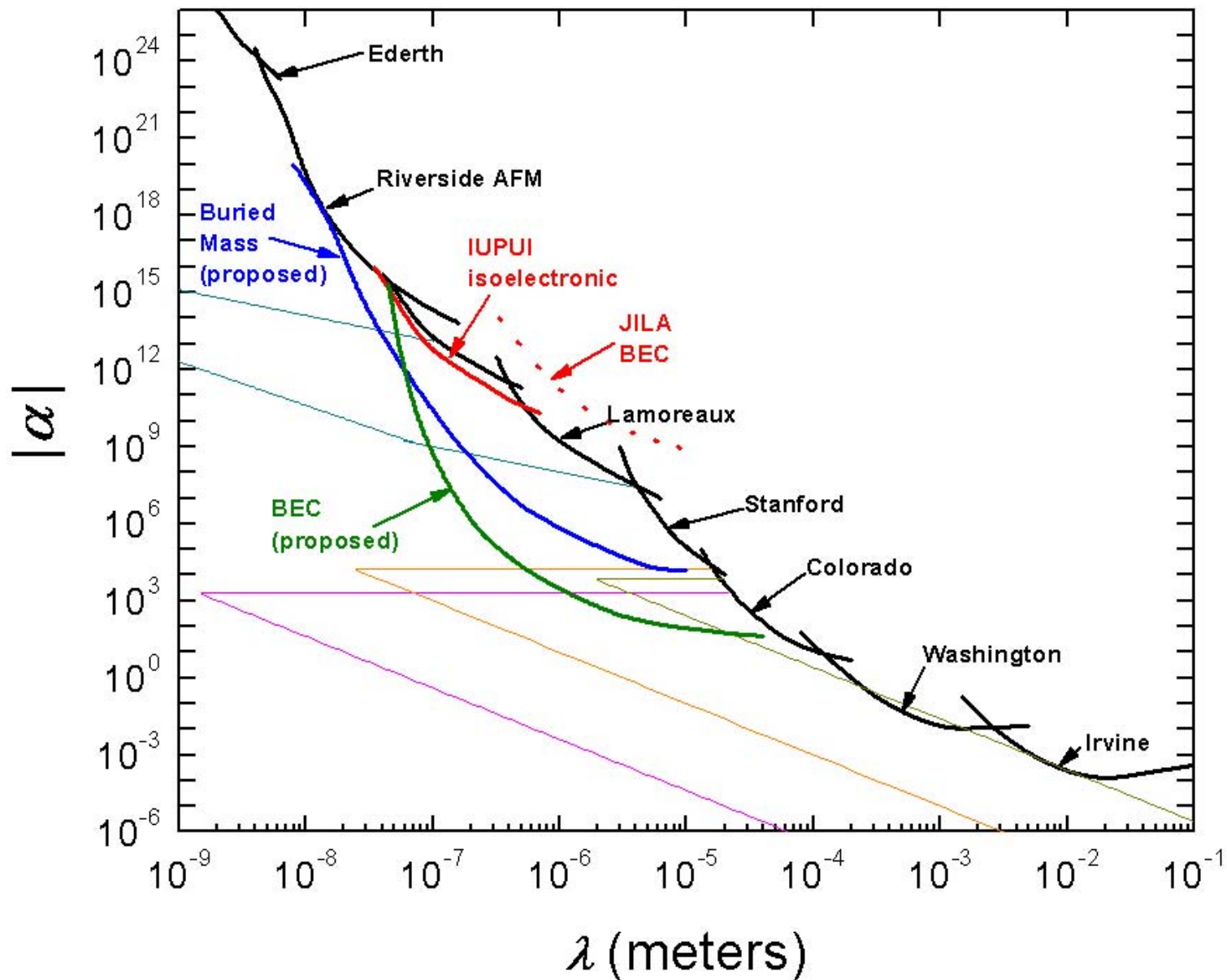
Casimir-Polder effect measured for ^{87}Rb BEC suspended $6\text{-}12\mu\text{m}$ above dielectric surfaces

☆ Yukawa constraints derived

D. M. Harber, E. A. Cornell et al.

cond-mat/0506208

New Limit and Projections



Summary

Experiments have explored 7 new square decades in Yukawa parameter space above 1 μm in past 5-10 years

Several additional decades within reach of active programs in near future

- torsion pendulum above $\sim 50 \mu\text{m}$; high-frequency techniques below
- Regime of cosmological interest ($\alpha = 1$ at $100 \mu\text{m}$) nearly accessible

New and expanding theoretical interest in regimes above and below 1 μm

Dedicated new-force searches have begun to explore range below 1 μm , in addition to precision Casimir Force experiments

~ 10 additional square decades may be accessible below 1 μm if Casimir Force shielding feasible