Experimental Search for Spin-Dependent (and Independent) Forces in the Sub-mm range

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Parameterization and Existing Limits

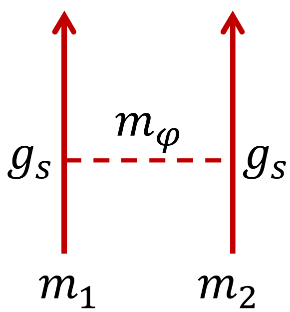
Experimental Approach

Projected Sensitivity

Recent Data and Current Sensitivity (spin-independent)

Spin-Polarized Test Mass R&D

Parameterization



Yukawa

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

$\lambda = \hbar/m_\varphi c$ **= range**

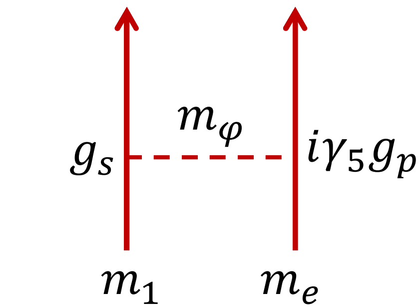
α **= strength relative to gravity**

~ "V_1" [1]

[1] B. Dobrescu and I. Mocioiu, J. High Energy Phys. 0611, 005 (2006)

Spin-Dependent Interactions

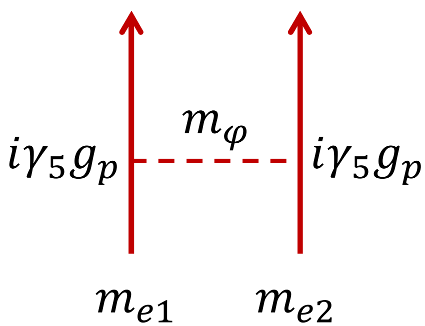
Monopole-dipole [2]



$$V(r) = -g_p g_s \frac{\hbar^2}{8\pi m_e} \hat{\sigma}\cdot\hat{r}\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

~ "$V_9 + V_{10}$" (P, T-odd)

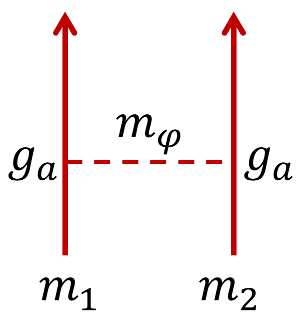
Dipole-dipole



$$V(r) = \frac{g_p g_p \hbar^3}{4\, m_{e1} m_{e2} \boldsymbol{c}}\left[(\sigma_1 \cdot \sigma_2)\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right) - (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right] e^{\frac{-r}{\lambda}}$$

~ "V_3"

V_2

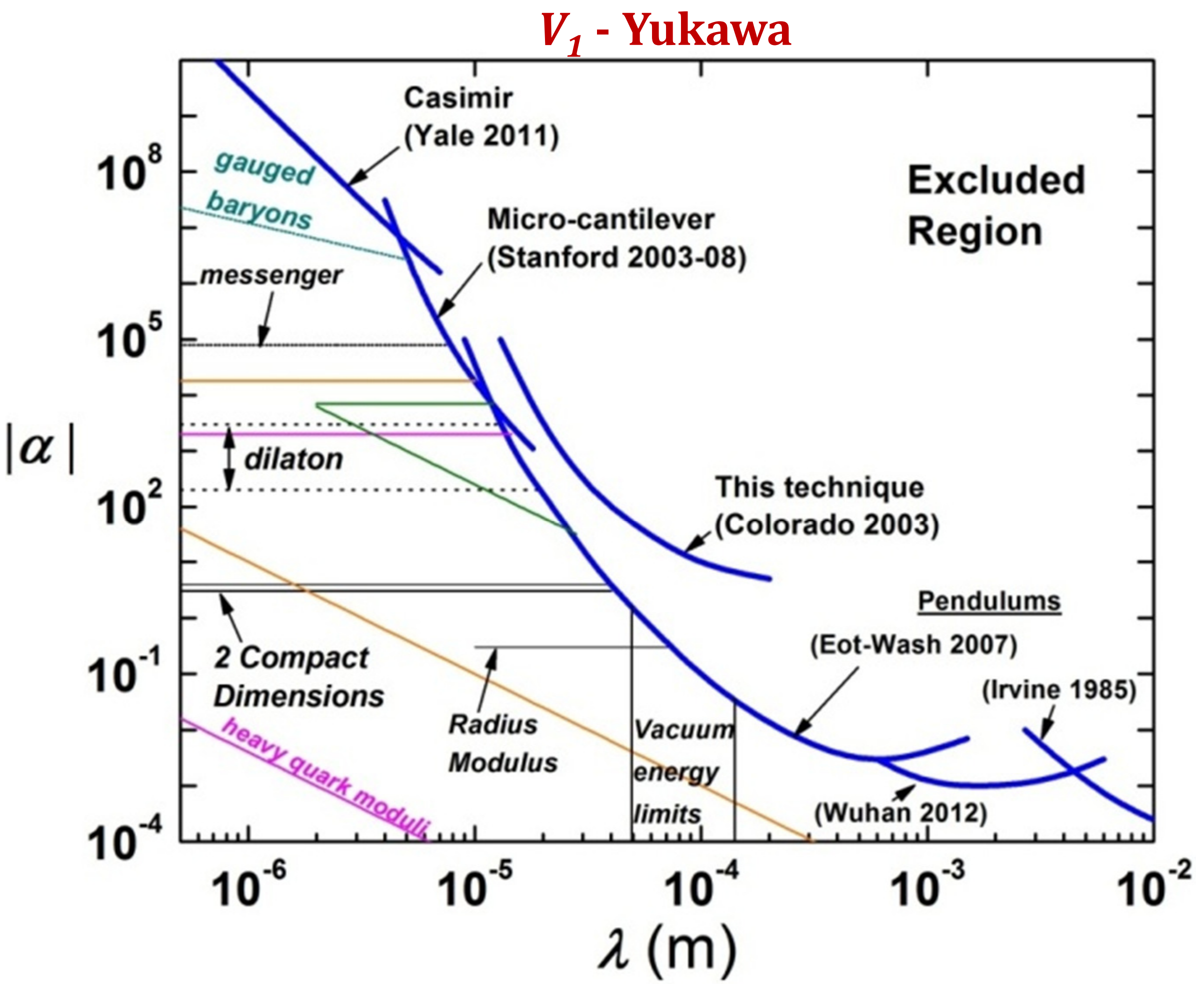


$$\boldsymbol{V}(\boldsymbol{r}) = -\boldsymbol{g_a g_a}\frac{\hbar \boldsymbol{c}}{\boldsymbol{r}}(\sigma_1 \cdot \sigma_2)\boldsymbol{e}^{-\boldsymbol{r}/\boldsymbol{\lambda}}$$

[1] B. Dobrescu and I. Mocioiu, J. High Energy Phys. 0611, 005 (2006)

[2] J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984)

Direct Experimental Limits and Predictions



Irvine: J. Hoskins et al., PRD 32 (1985) 3084

Wuhan: S-Q. Yang et al., PRL 108 (2012) 081101

Eot-Wash: D. Kapner et al., PRL 98 (2007) 021101

Stanford: A. Geraci et al., PRD 78 022002 (2008)

Yale: A. Sushkov et al., PRL 107 (2011) 171101 *[APS: H12 – 1]*

Experimental limits:

Irvine, Wuhan, Eot-Wash, Yale = torsion pendulum experiments

Stanford = AFM-type experiment

Limits still allow forces 1 million times stronger than gravity at 5 microns

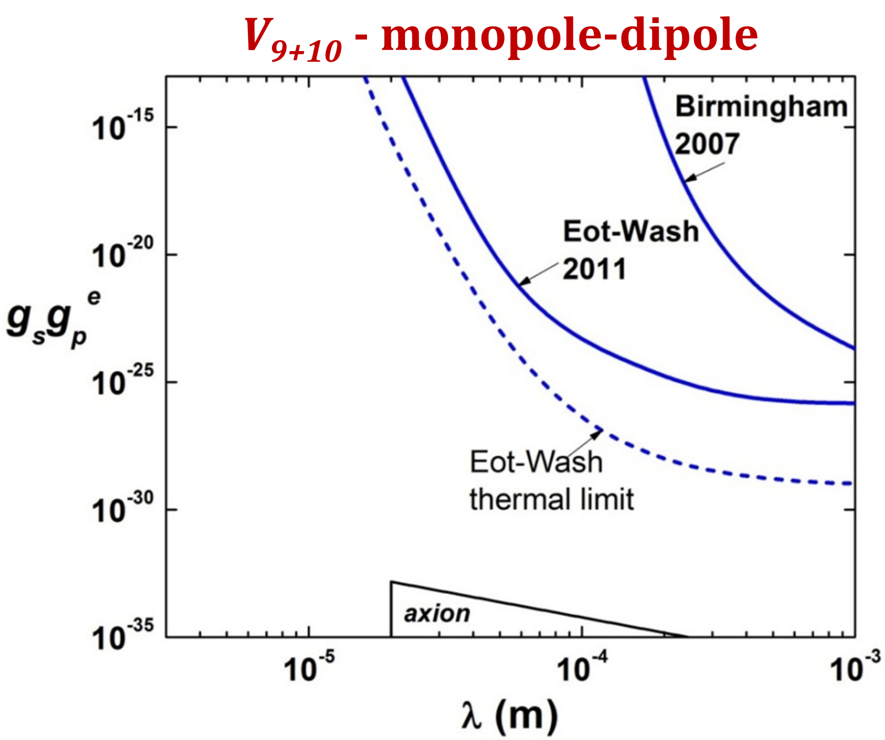
Theoretical predictions:

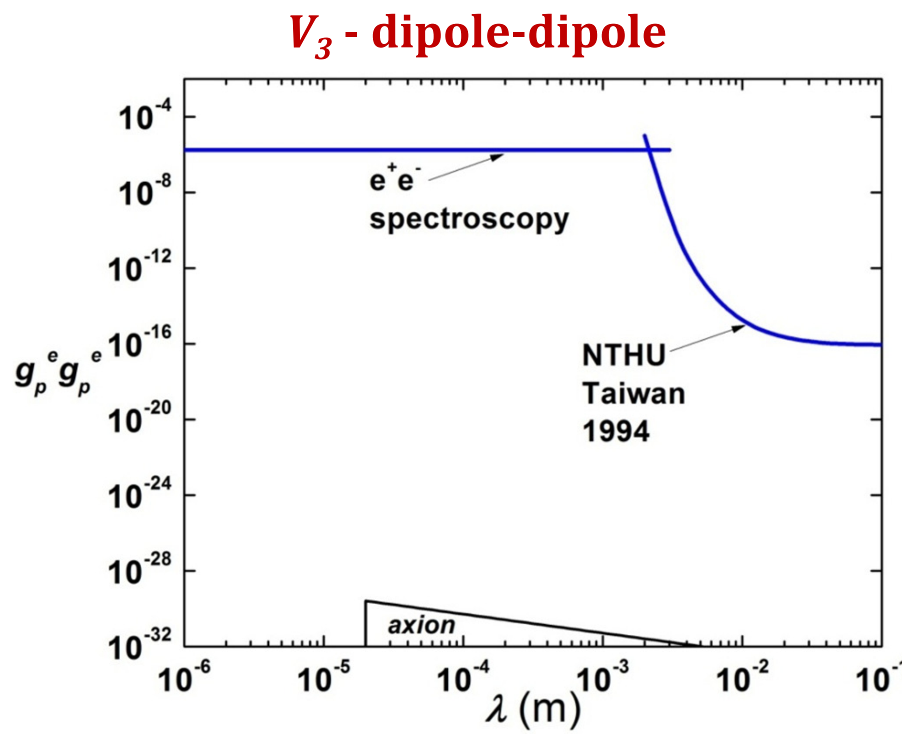
"Large" extra dimensions

Vacuum energy: prediction from new field which also keeps cosmological constant small

Moduli, dilatons: new particles motivated by string models

Direct Experimental Limits and Predictions





Eot-Wash: S. Hoedl et al., PRL 106 (2011) 041801

NTHU: W-T. Ni et al., Physica B 194 (1994) 153

e^+e^-: A. Mills, PRA 27 (1983) 262;
M. Ritter et al., PRA 30 (1984) 1331

Experimental Approach

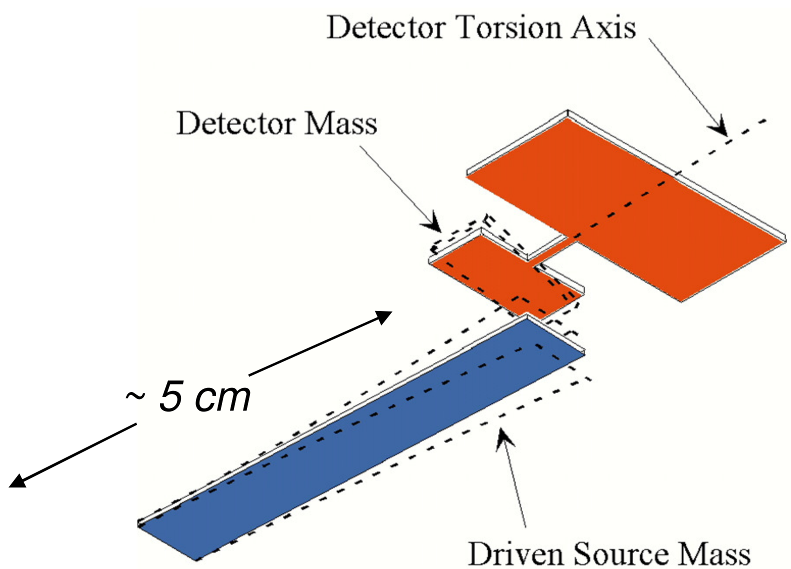
Planar Geometry - null for $1/r^2$

Resonant detector with source mass driven on resonance

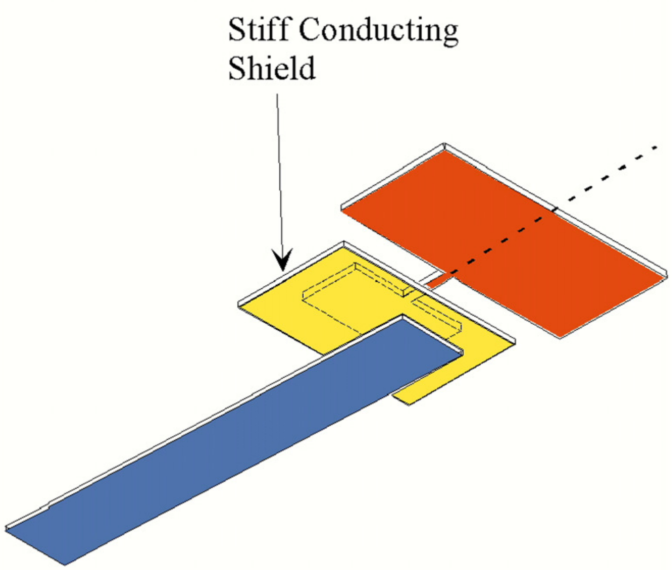
1 kHz operational frequency - simple, stiff vibration isolation

Double-rectangular torsional detector: high Q, low thermal noise

Stiff conducting shield for background suppression



Source and Detector Oscillators



Shield for Background Suppression

Central Apparatus

Vibration isolation stacks: Brass disks connected by fine wires; soft springs which attenuate at $\sim 10^{10}$ at 1 kHz (reason for using 1 kHz)

Readout: capacitive transducer and lock-in amplifier

Vacuum system: 10^{-7} torr

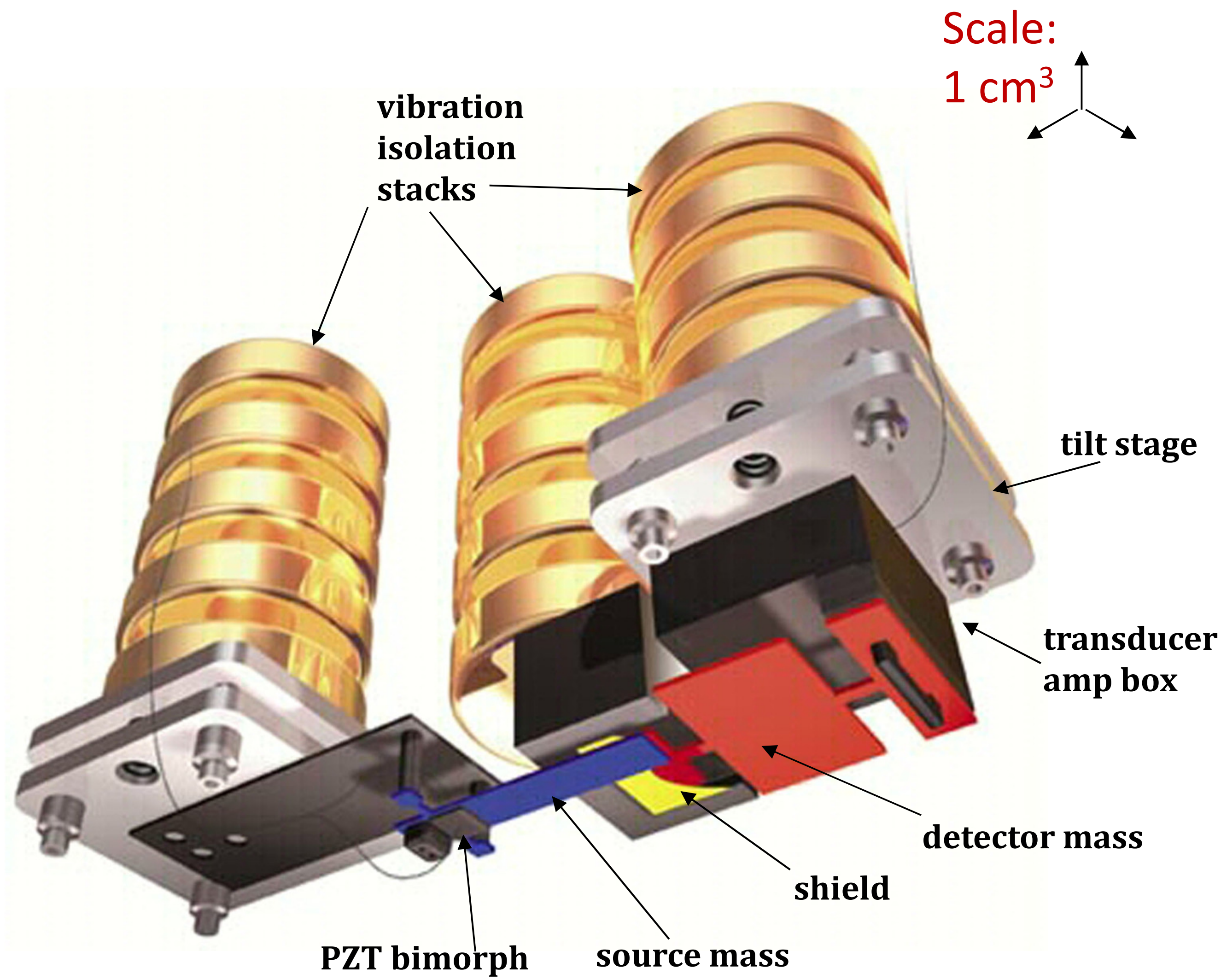
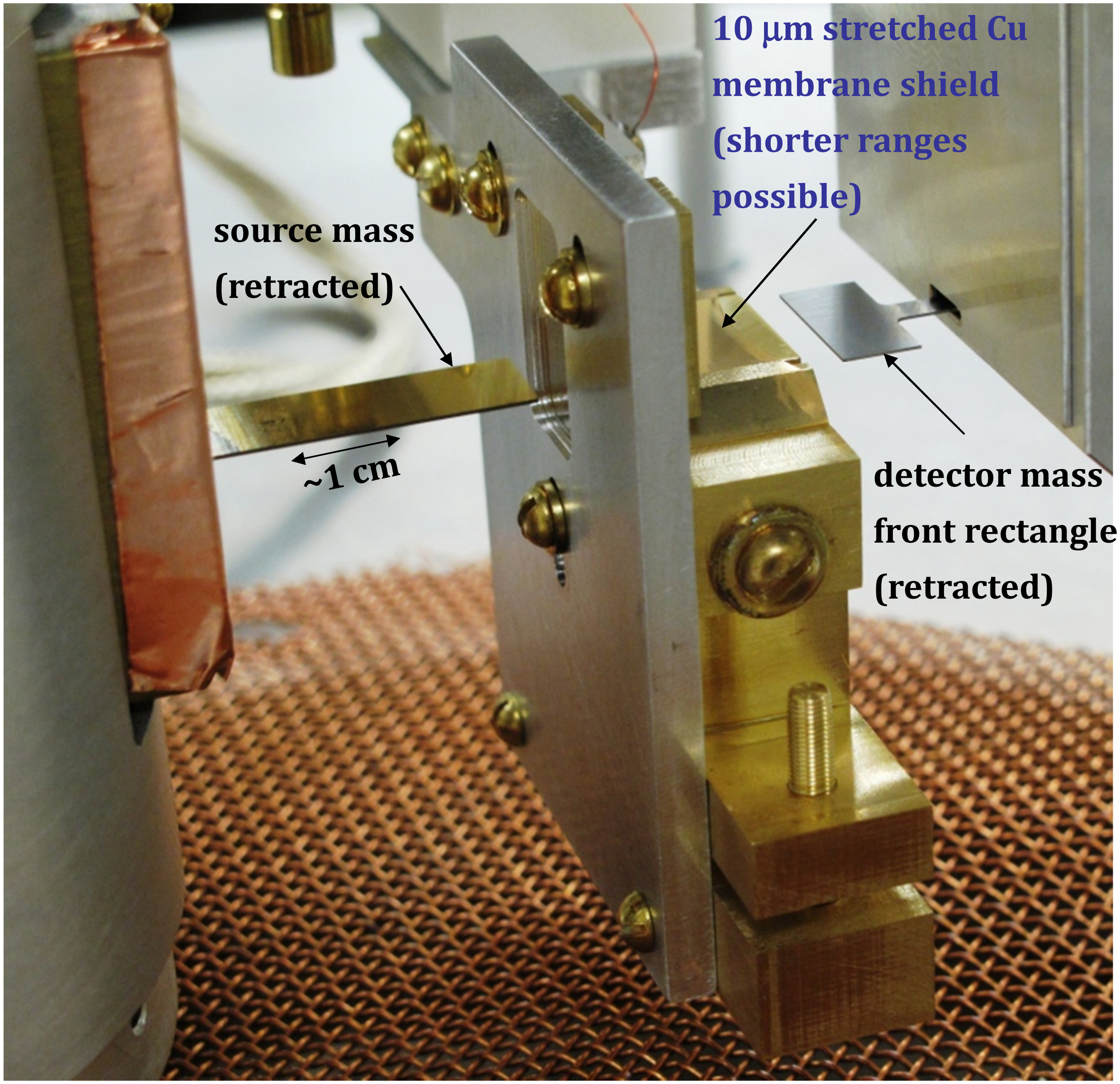


Figure: Bryan Christie (www.bryanchristie.com) for Scientific American (August 2000)

Interaction Region



Thinner shield

60 μm thick sapphire plate replaced by 10 μm stretched copper membrane

Compliance ~5x better than needed to suppress estimated electrostatic force

Minimum gap reduced from 105 μm (2003) to 40 μm.

Sensitivity: increase Q and statistics, decrease T

- **Yukawa signal: Force on detector due to Yukawa interaction with source**

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

$\sim$ 3 x 10^{-15} N (for $\alpha = 1$, $\rho = 20$ g/cc, $\lambda = 50$ μm)

- **Spin-dependent: Integrate V_2, V_3, monopole-dipole numerically with:**

  - $\sim$ cm^2 x 100 μm spin-polarized samples on test masses

  - $n_s = 10^{21}$/cc (10% of world record [1])

- **Thermal Noise**

$$F_T = \sqrt{\frac{4kTD}{\tau}} \qquad D = \frac{\omega m}{Q}$$

$\sim$ 3 x 10^{-15} N rms (300 K, Q = 5 x10^4, 1 day average)

$\sim$ 7 x 10^{-17} N rms (4 K, Q = 5 x10^5, 1 day average)

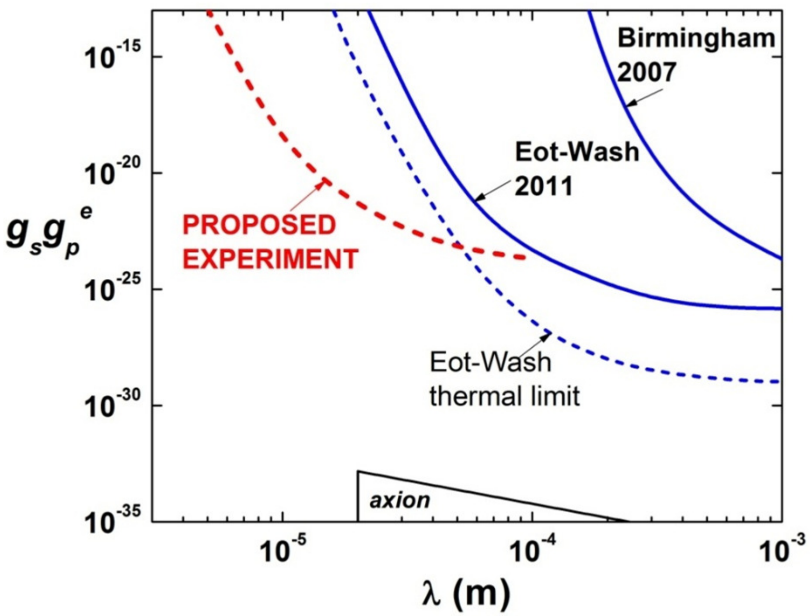
- **Setting SNR = 1 yields**

$$\alpha \sim \frac{1}{\rho^2}\sqrt{\frac{kTm\omega}{Q\tau}} \qquad gg \sim \frac{1}{n^2}\sqrt{\frac{kTm\omega}{Q\tau}}$$

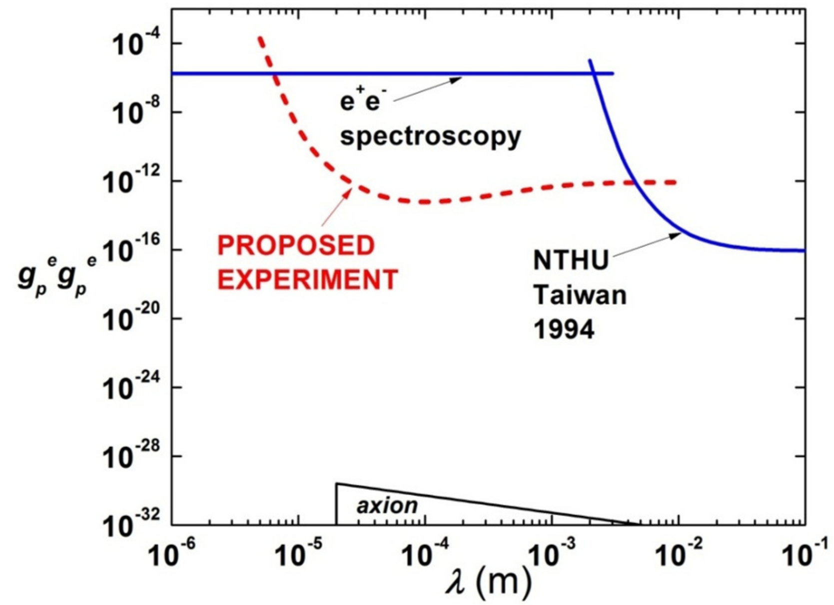
[1] W-T. Ni et al., Physica B 194 (1994) 153

Projected Sensitivity (Ultimate)

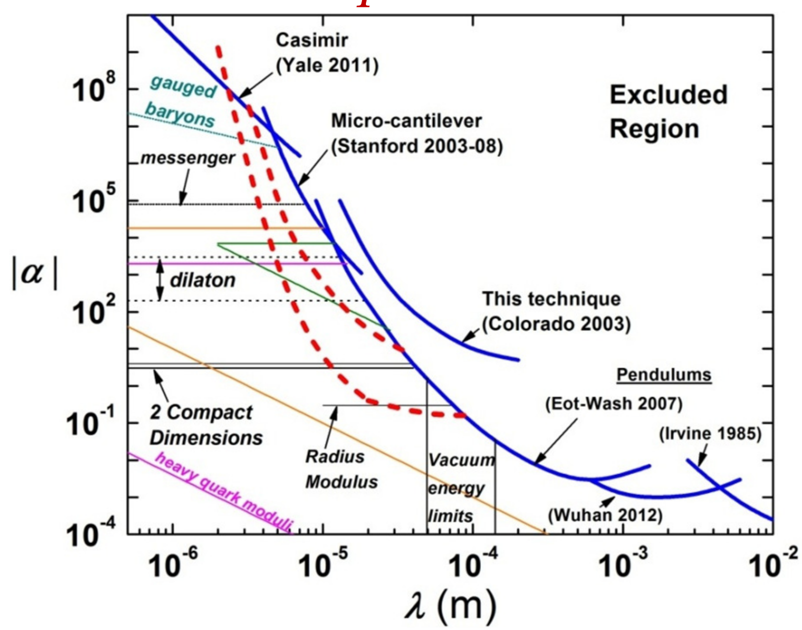
V_{9+10} - monopole-dipole



V_3 - dipole-dipole

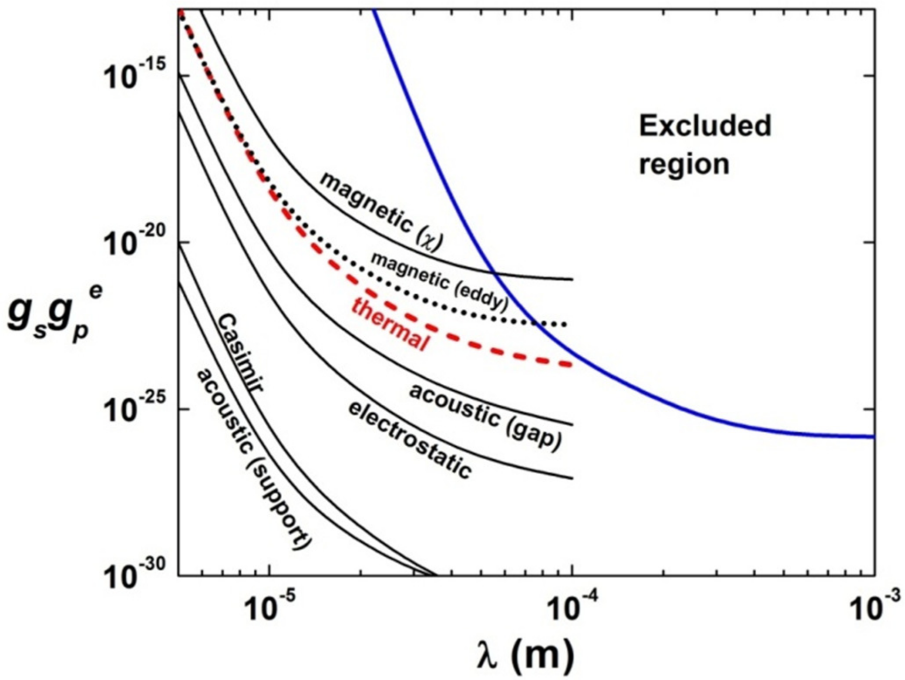


V_1 - Yukawa



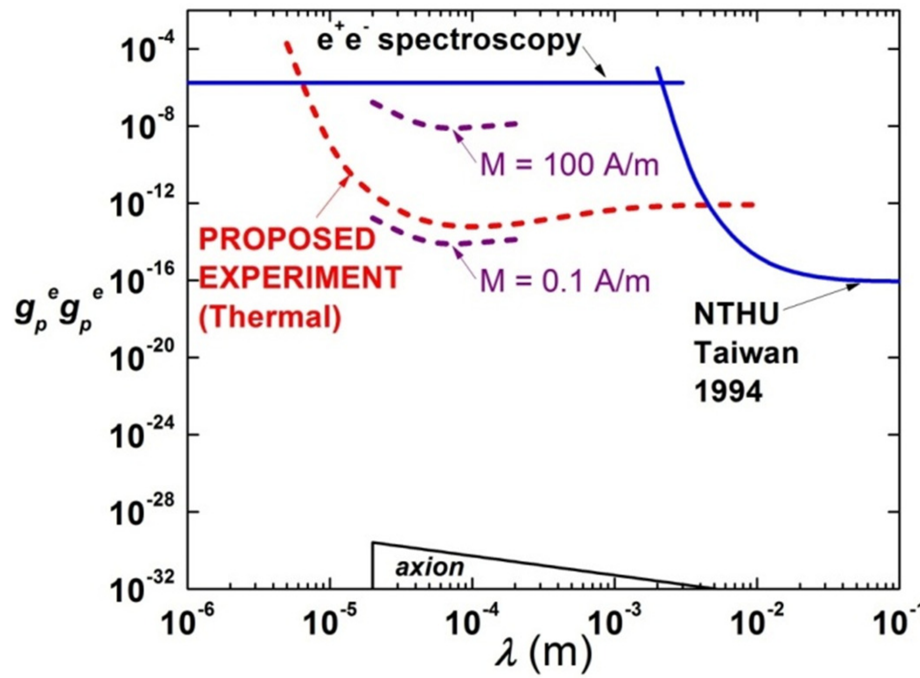
Other Backgrounds

V_{9+10} - monopole-dipole



V_3 - dipole-dipole

(magnetic contaminants)



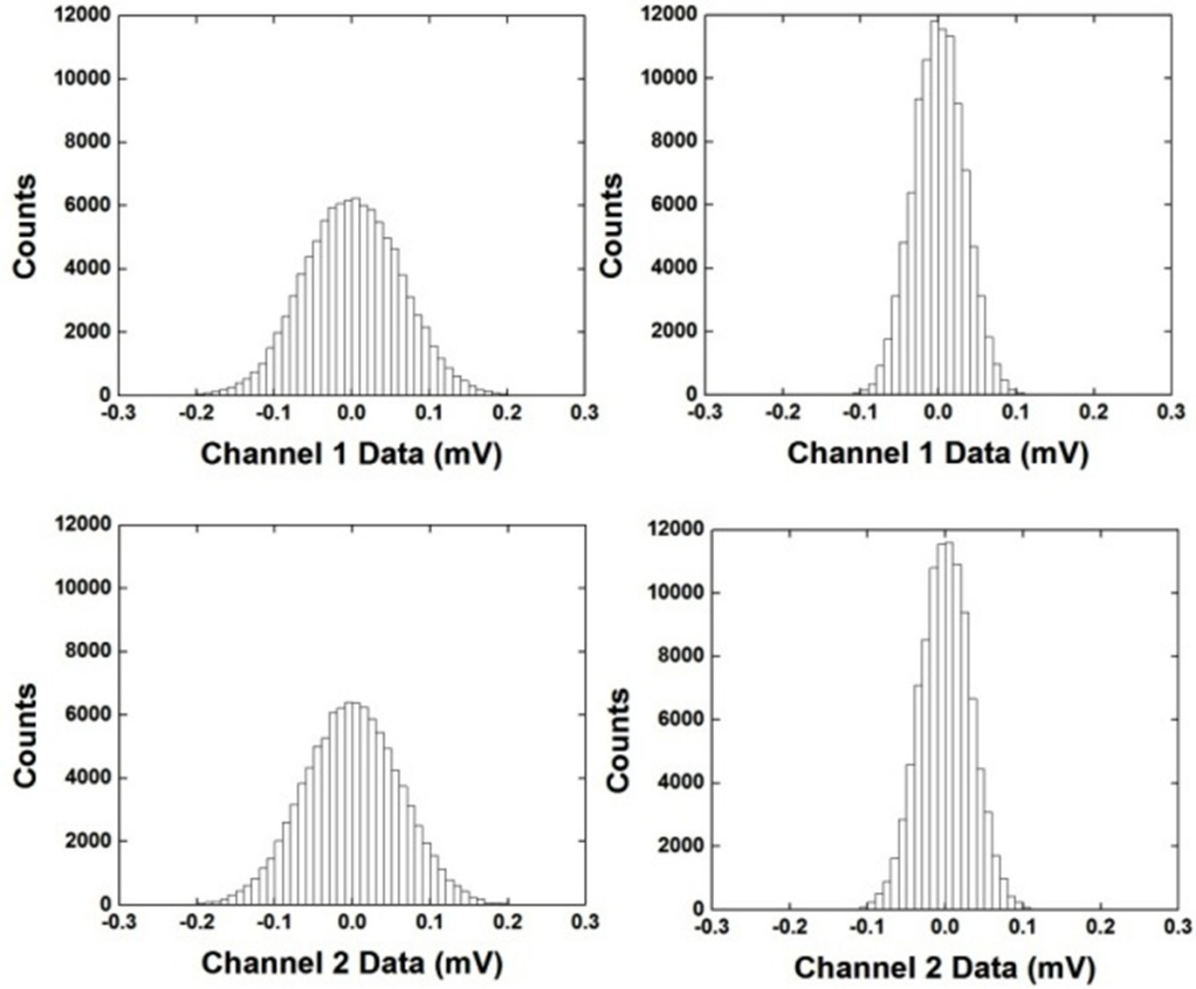
Spin-Independent Force Measurement Data – March 2012

19 hours on-resonance data collected over 3 days with interleaved diagnostic data

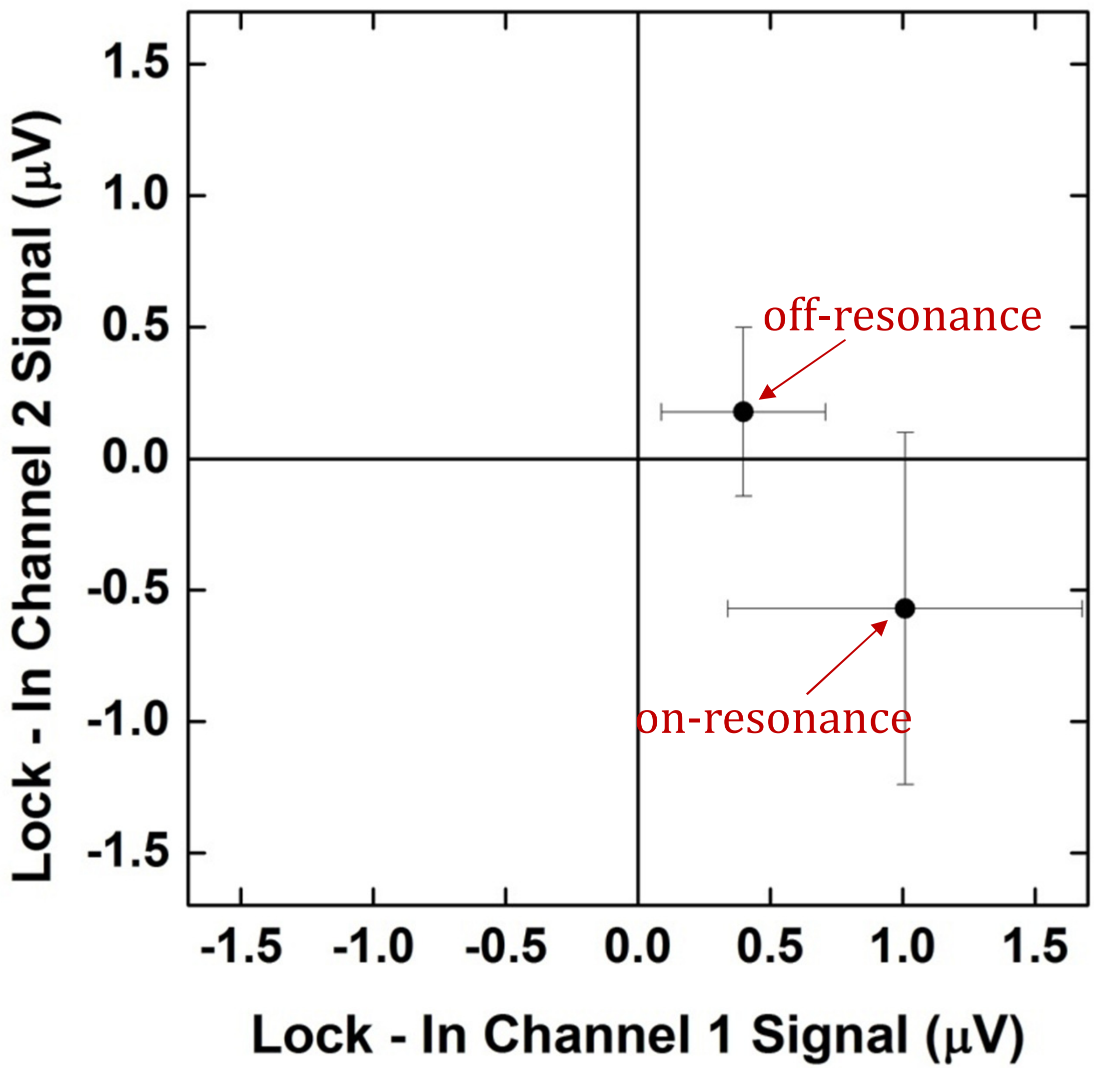
On-resonance: Detector thermal motion and amplifier noise

Off-resonance: amplifier noise

On Resonance | **Off Resonance**



Force Measurement Data - Detail



Net Signal:

$V_{on} - V_{off} = 0.93 \pm 0.74\ \mu V\ (1\sigma)$

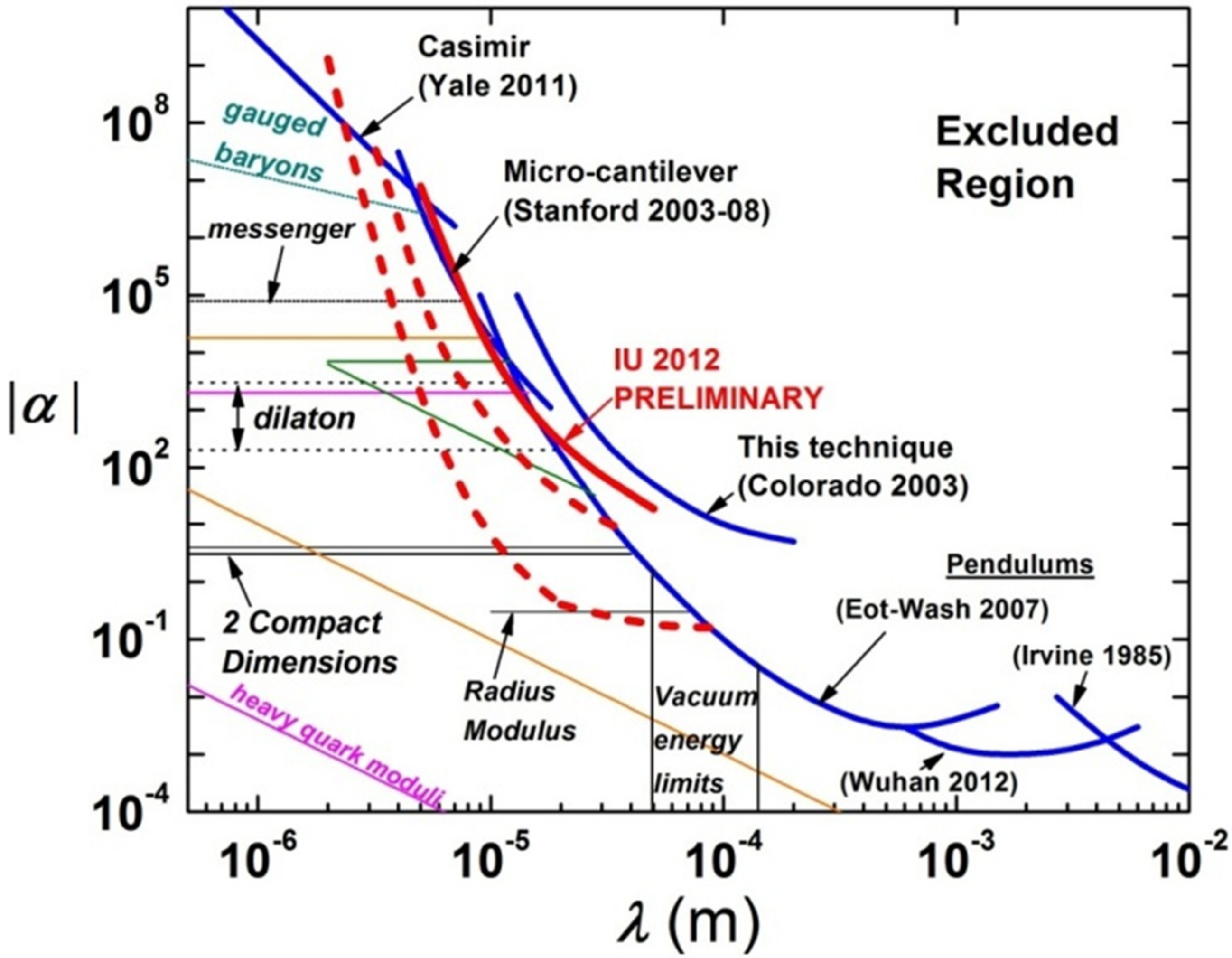
Force:

$F = 4.0 \pm 3.2$ fN

Possible Source:

Detector – *probe* force from ~ nV scale "ground" fluctuations on detector mass

Current Limits (2σ)



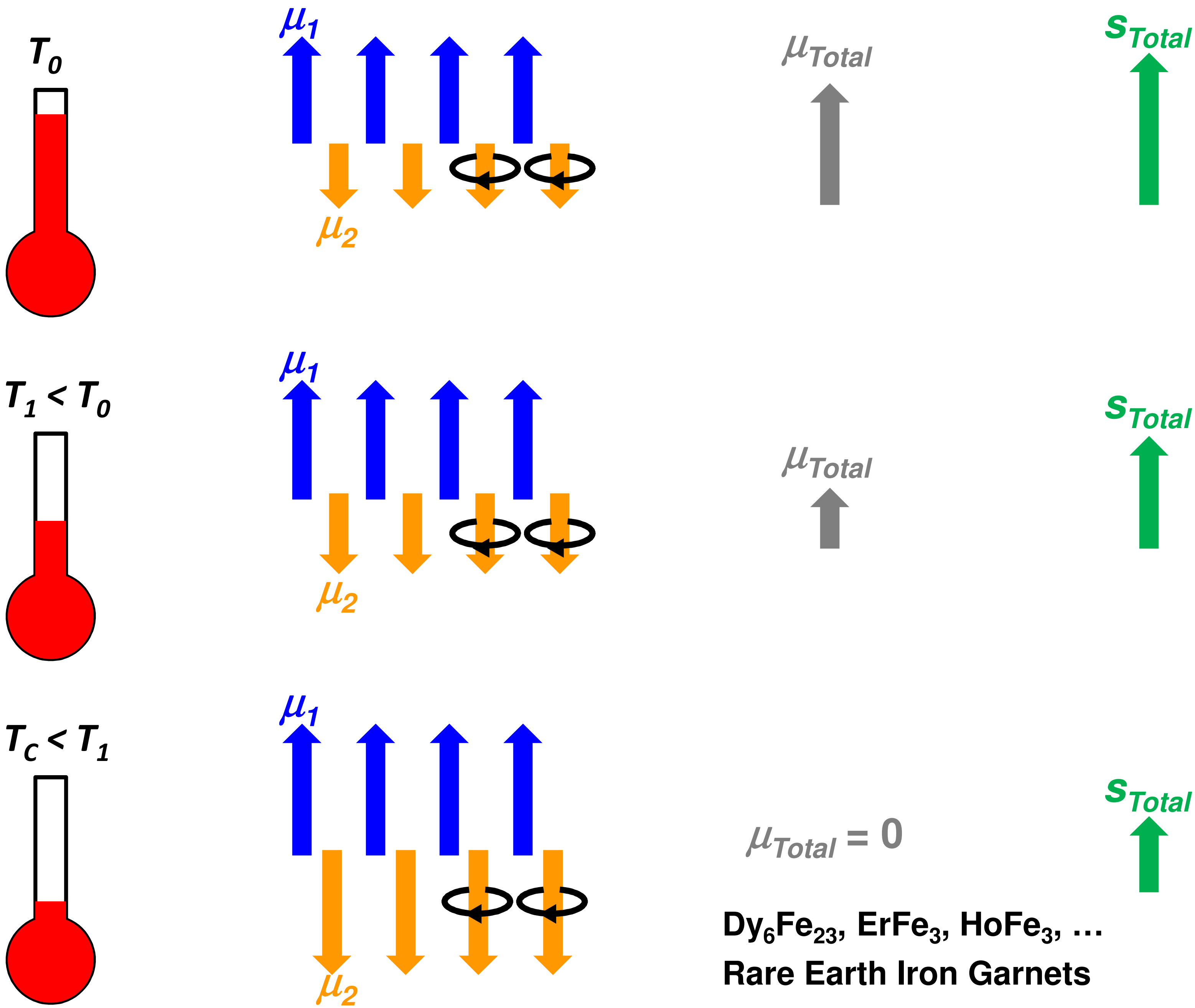
Minimum gap: 55 ± 6 μm

assumes 10 μm shield flat (optimistic)

Assumes phase of Yukawa force in direction of maximum signal

(pessimistic; not yet measured)

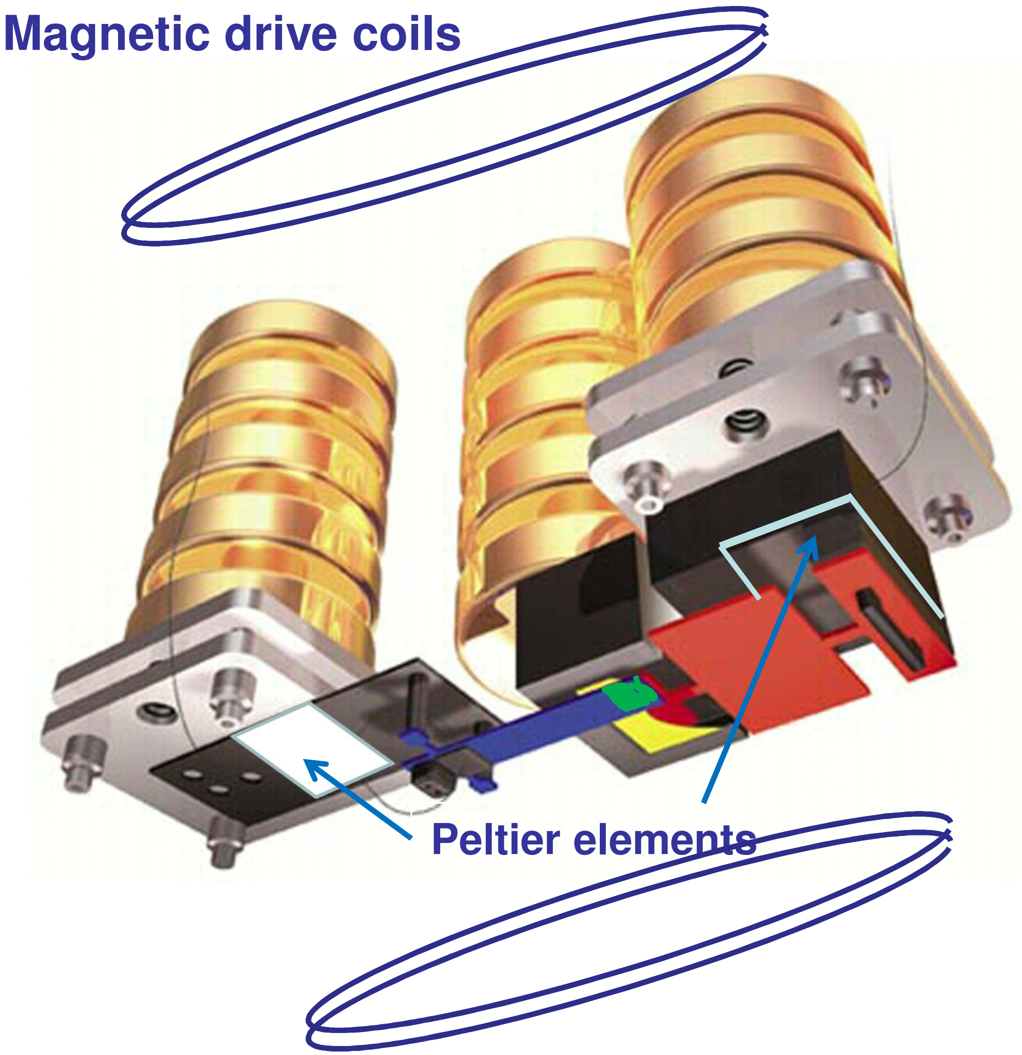
Compensated Ferrimagnet

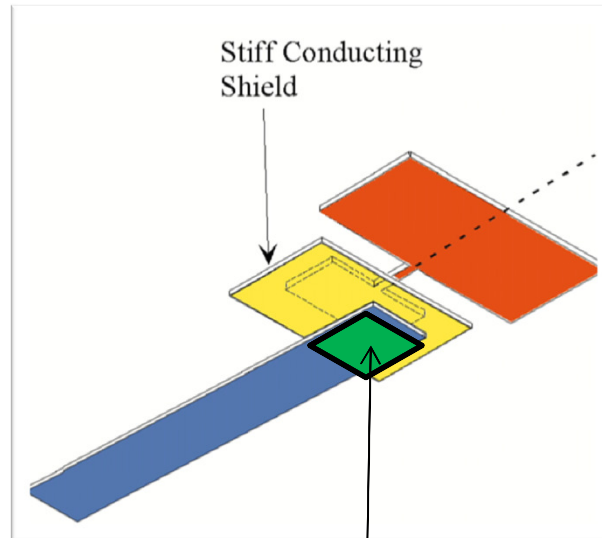


Spin-Dependent Apparatus

Adapt current apparatus

- **Cool to T_{comp} with thermoelectric elements**
- **Drive test masses with AC magnetic field until T_{comp} (no magnetization)**



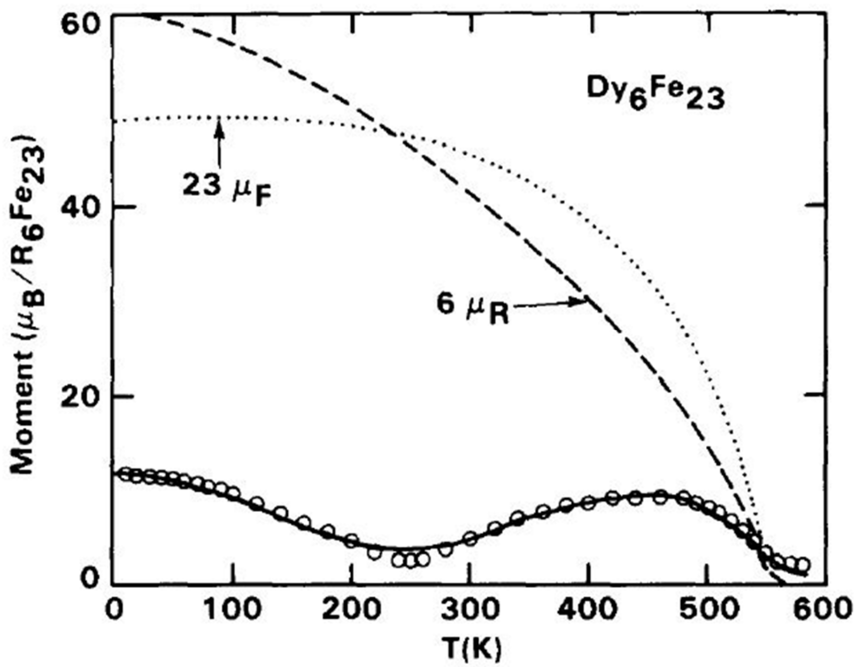


- **Dy_6Fe_{23} test mass 100 μm thick**
- **Magnetic shield 100μm, μ-metal?**

Dy_6Fe_{23} – Magnetization vs T

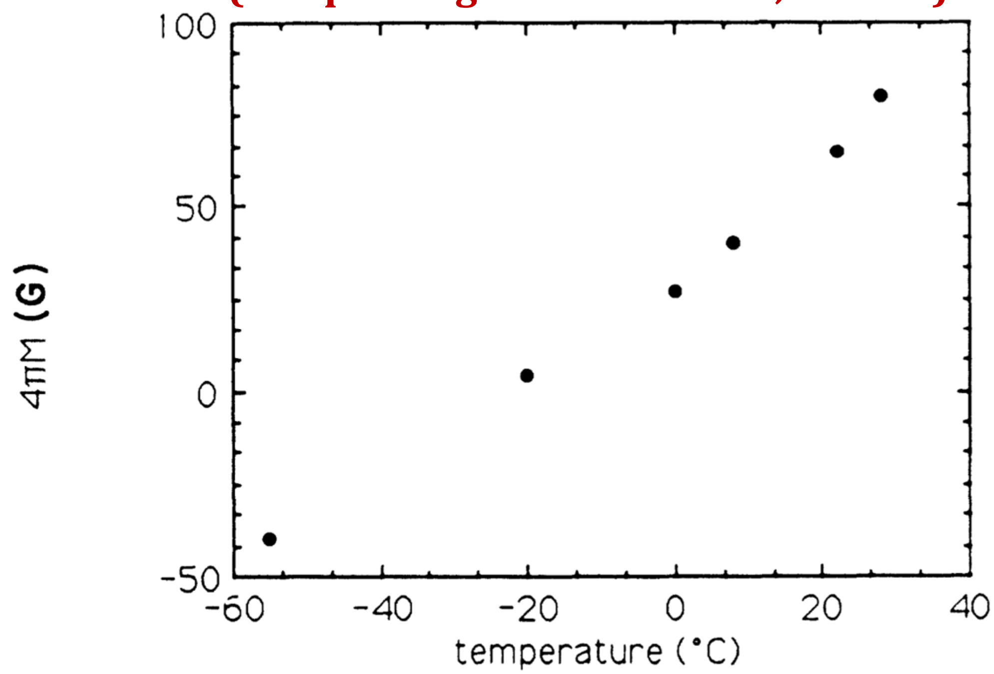
- $T_c \approx 250$ K (Cool with shield, chiller, thermoelectric elements)

Applied field (16 kG) [1]



Dashed: Molecular mean field theory calculation
Solid: sum of individual lattice calculations
Points: measurement

No applied field [2]
(sample magnetized at 25 C, 218 kG)

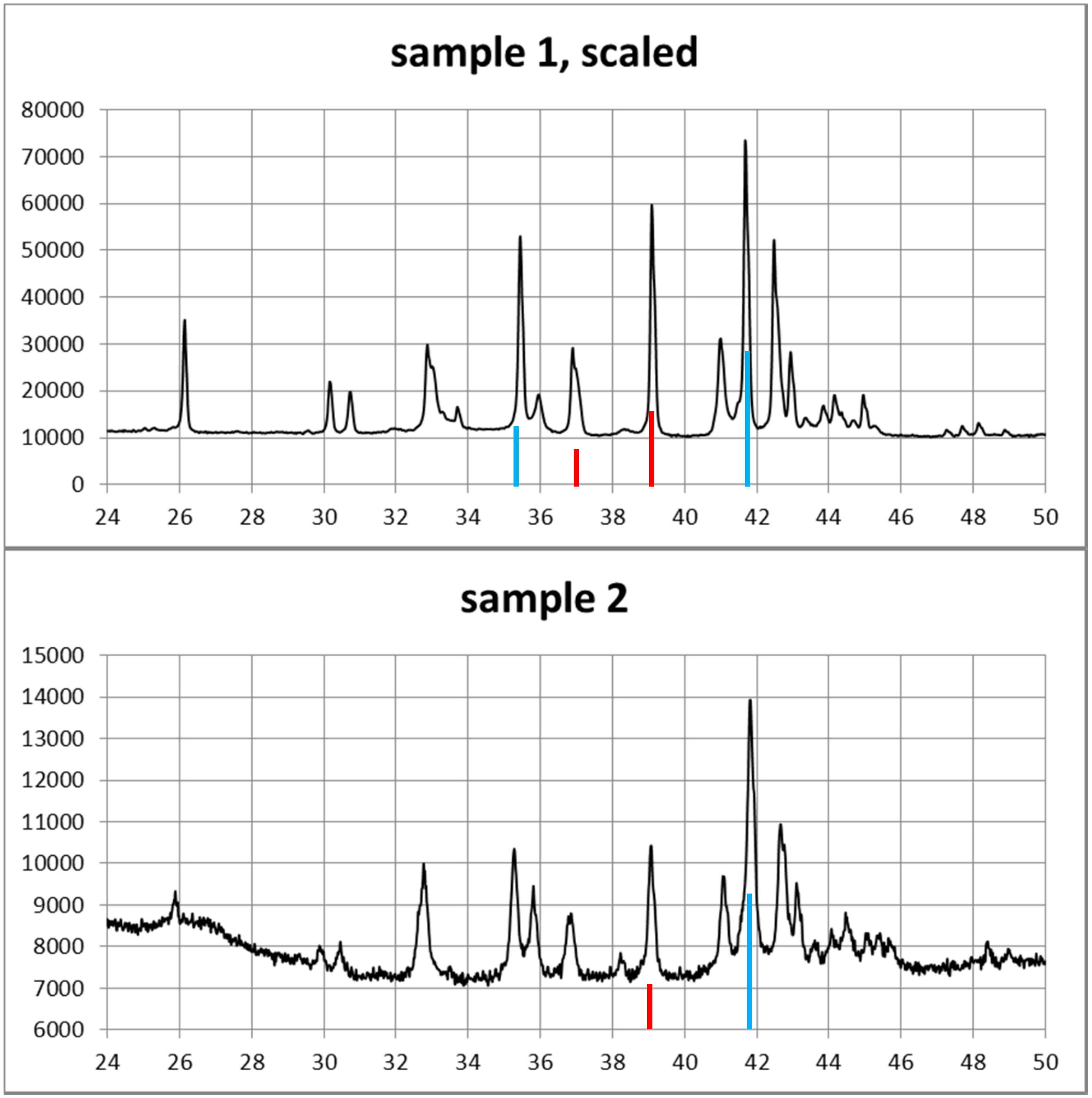


[1] J. Herbst, J. Croat, J. Appl. Phys. 55 (1984) 3023.

[2] R. Ritter, C. Goldblum, W.-T. Ni, G. Gillies, C. Speake, PRD 42 (1990) 977.

Dy_6Fe_{23} Production (Ames National Lab)

- Melt 20.7 / 79.3 wt.% Dy/Fe in furnace
- Anneal several days at 1200°C
- X-Ray diffraction analysis:



Dy_6Fe_{23} peak

Dy_1Fe_3 peak

Relative peak size:
6-23 : 1-3 phase ~ 45%

Second annealing (3 weeks 1200° C):

Ratio 6-23 : 1-3 reduced

- Less 6-23?
- Other phases more abundant?
- Amorphous combination?

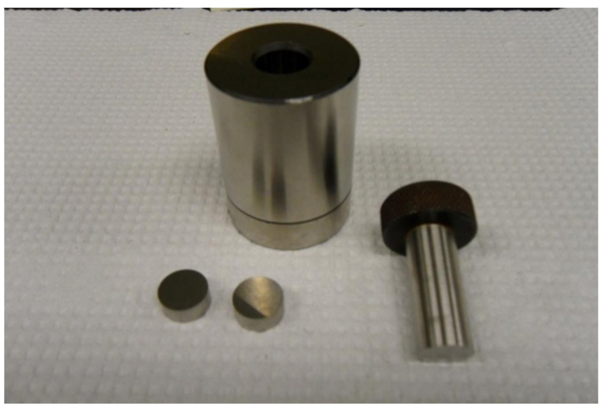
Re-anneal in low pressure O_2 atmosphere?

Other materials…

Dy_6Fe_{23} sample fabrication - Pressing test samples

1. Metallic powder + binder (2g paraffin in heptane, or 10% Cereox powder)
2. Pour mixture into die, press hydraulically at 3000 psi
   - Robust sub-millimeter samples (Fe) routinely attainable
   - Goal: Repeat procedure with ferrimagnet

Die



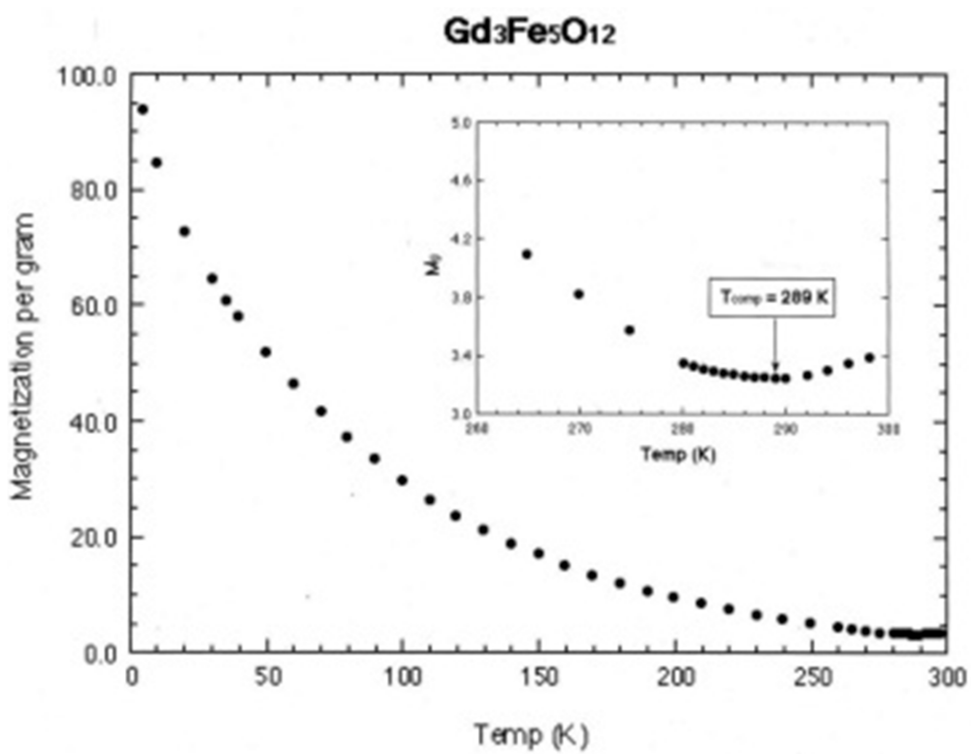
Samples

Press

Next step: Magnetize in strong field, measure magnetization versus temperature

Rare-Earth Iron Garnets

Geselbracht, et al., J. Chem. Edu. 71 (1994) 696



Combine 1 M $Dy(NO_3)_3{\cdot}6H_2O$ with
1 M $FeCl_3{\cdot}6H_2O$

Add NaOH dropwise to precipitate solid

Decant solution, wash & dry solid

Press into pellet

Bake at 900 C in air 18-24 h

Summary and Outlook

High-frequency experiment currently excludes spin-independent forces > 10^5 times gravitational strength above 10 microns

Sensitive to forces 1000 times gravitational strength at 10 microns

- **Reduce metrology uncertainties**
- **Understand, reduce “probe-force” background**
- ***Chameleon Analysis (2003 data)***

Cryogenic experiment with gravitational sensitivity at 20 microns proposed

- **Demonstrate cryogenic transducer and thermal noise below 10 K**

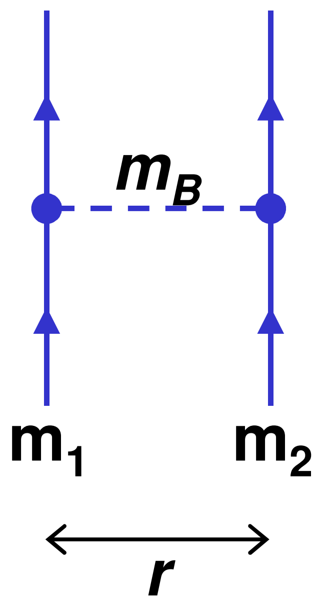
Spin-dependent experiments with same technique potentially ~ 8 orders of magnitude more sensitivity than current experiments (thermal noise limit); 3-5 orders more sensitive with reasonable magnetic backgrounds

- **Find a pure ferrimagnet and demonstrate 200 < Tc < 300 (candidates exist)**
- **Fabricate flat samples, attach to test masses**
- **Assemble cooling system**
- **Demonstrate stimulated magnetic forces at T > Tc**
- **Collect data at Tc**
- **Restore thicker shield (if needed), investigate high permeability layers**

(Supplemental Slides)

Parameterization

Yukawa Interaction



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

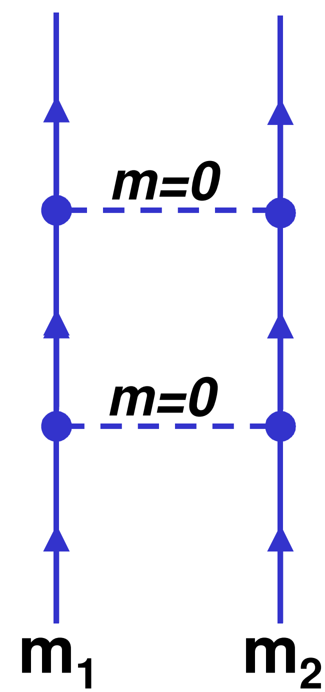
$\lambda = \hbar / m_B c =$ range

α = strength relative to gravity

Power Law

$$V(r) = -G\frac{m_1 m_2}{r}\left[1 + \beta_n \left(\frac{r_0}{r}\right)^{n-1}\right]$$

r_0 = experimental scale



set limits on β_n for n = 2 - 5

Signals in Recent Data

Pre-2010: ~10 x thermal noise (10^3 s), non-resonant

- **electronic pick-up, switched to differential amplifier**

Spring 2010: ~ 5x thermal noise (10^3 s), resonant, position independent

- **Vibration, replaced stacks**

Summer/fall 2010: ~ 2-5 x thermal noise, resonant, weak gap dependence

- **"long-range" capacitive coupling, re-designed shield**

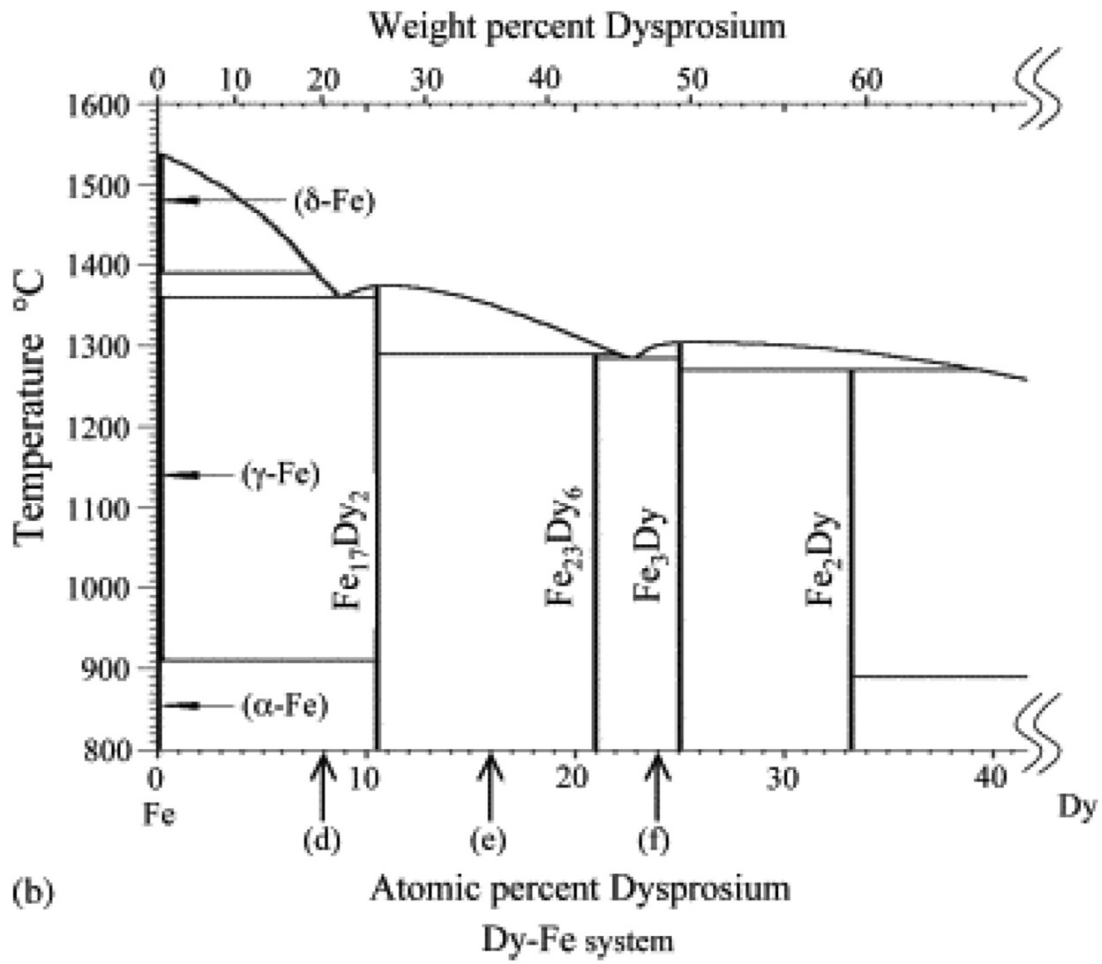
Spring/summer 2011: ~ 2-5 x thermal noise, resonant, smallest gaps

- **Poorly-grounded shield or the problem below (?)**

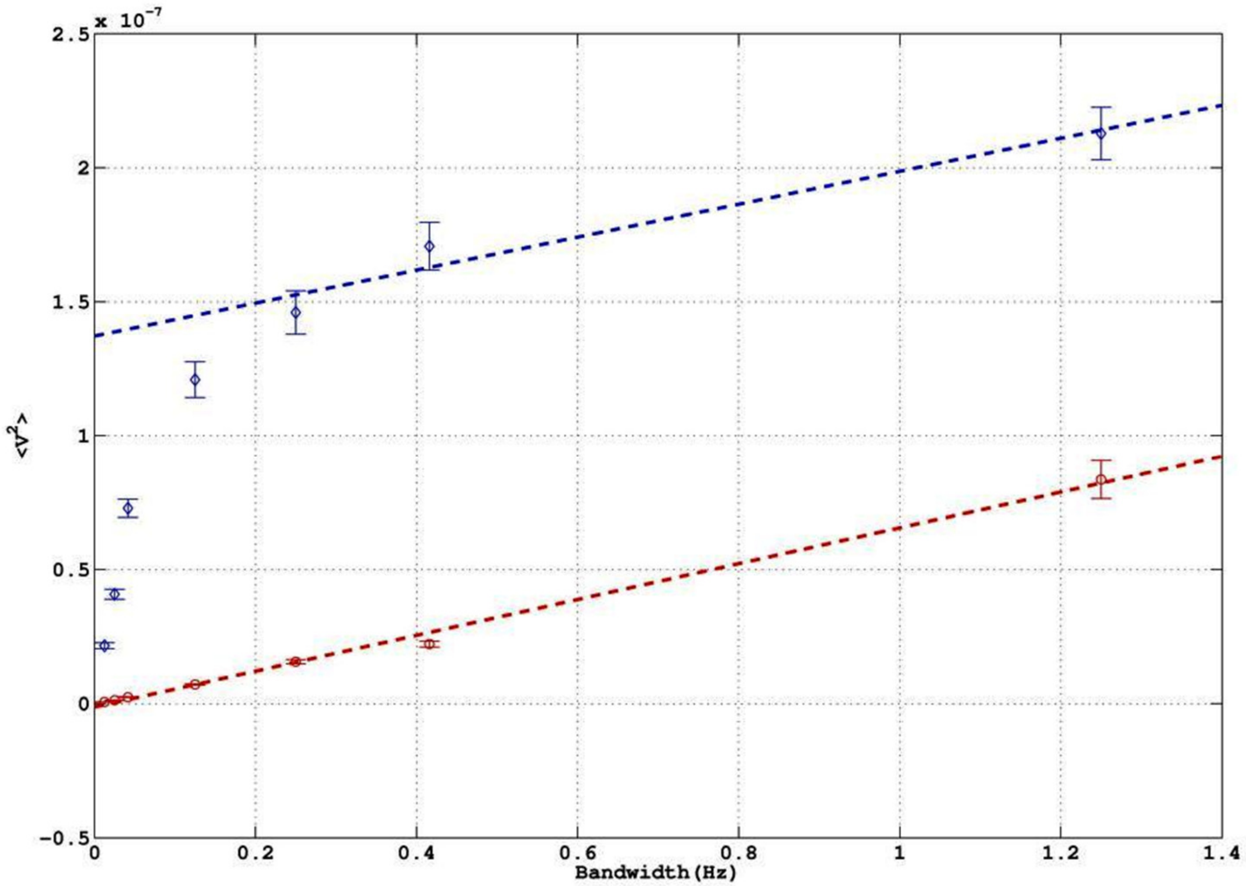
Fall 2011: fluctuating resonant signals *and* noise

- **Faulty (?) differential input on lock-in**

Dy-Fe Phase Diagram



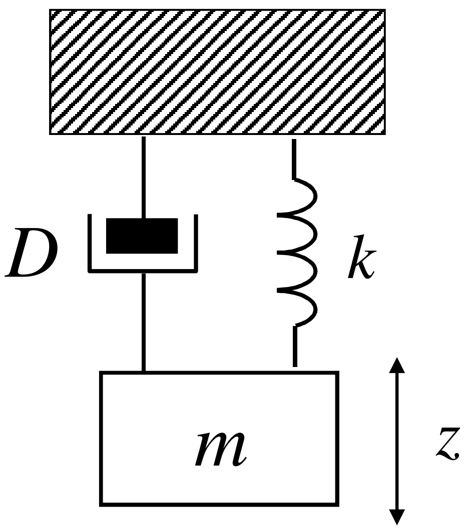
Thermal and Amplifier Noise



G = 20k → amp ~ 10 nV/$\sqrt{\text{Hz}}$

Calibration with Thermal Noise

Detector Model:



Free thermal oscillations:

$$\frac{1}{2}k_B T = \frac{1}{2}m\omega^2 z_{T(rms)}^2$$

Damped, driven oscillations on resonance:

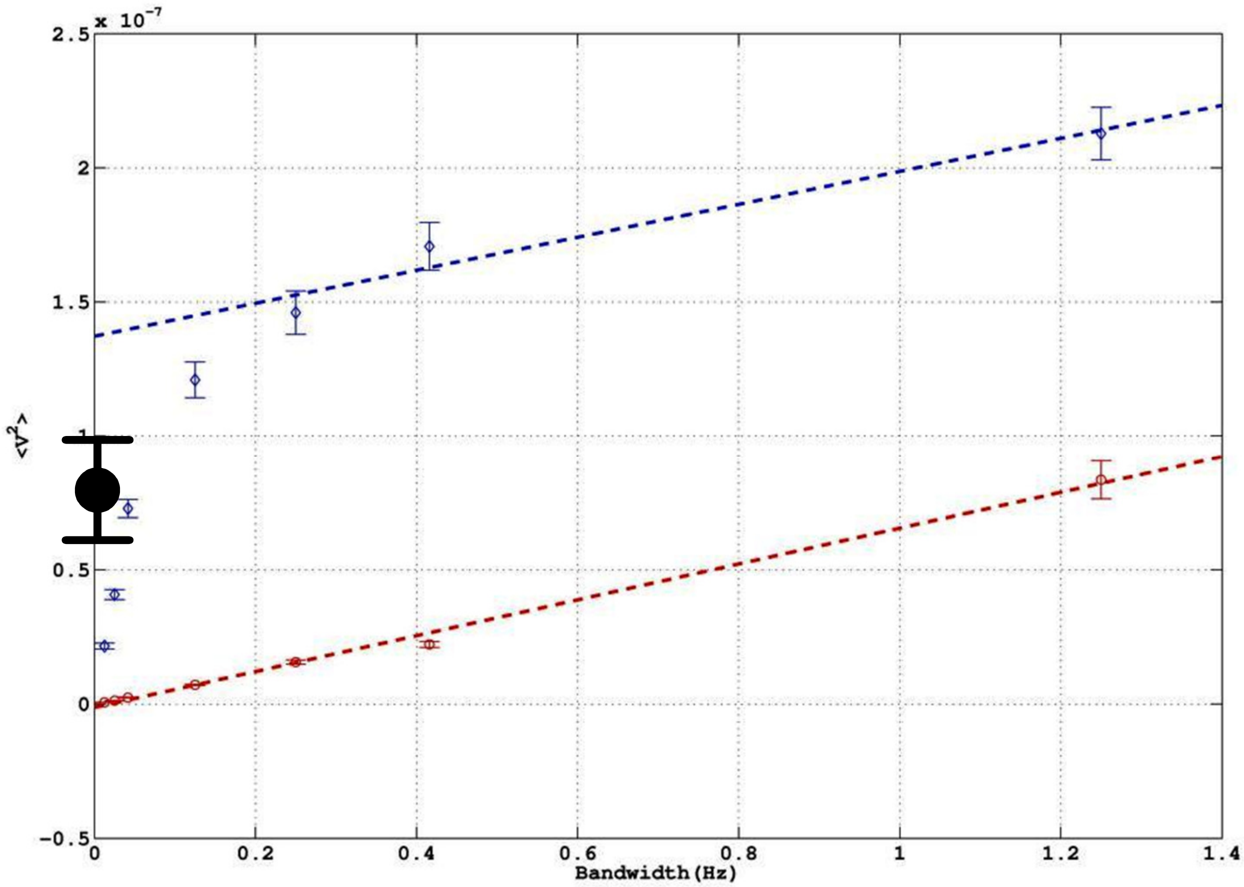
$$F_D = -\frac{m\omega^2}{Q}\overline{z_D} \qquad \textbf{where} \qquad Q = \frac{m\omega}{D}$$

$\Rightarrow$ **Measured force:** $F_D = -\dfrac{\overline{z_D}}{z_{T(rms)}}\dfrac{\omega\sqrt{mk_B T}}{Q}$

z_T, z_D, ω, T, Q **from data,** $\dfrac{\overline{z_D}}{z_{T(rms)}} = \dfrac{\overline{V_D}}{V_{T(rms)}}$

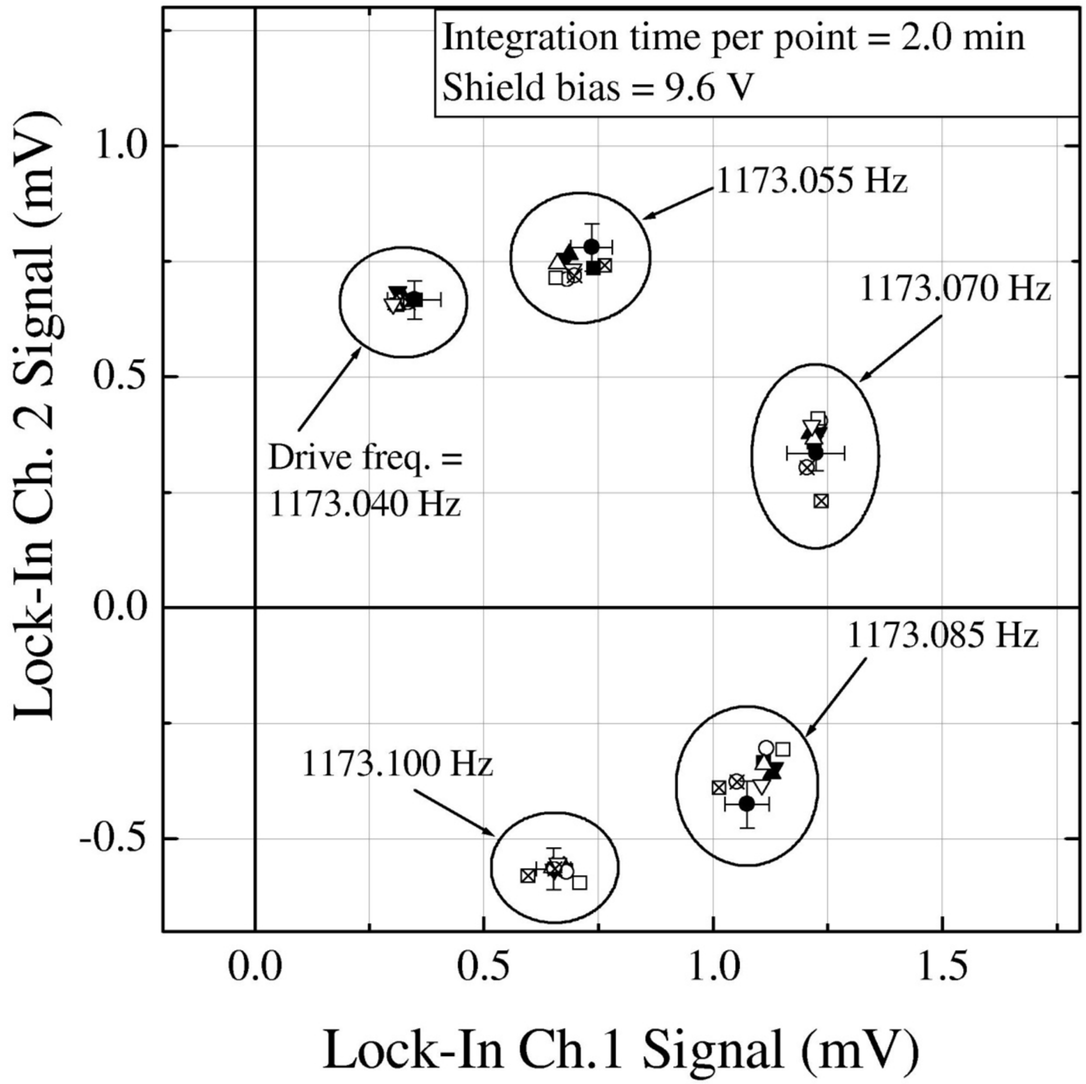
For distributed oscillator sampled at *r*, $m \rightarrow \dfrac{\rho\int |z|^2 dV}{|z(r)|^2}$ $\leftarrow$ mode shape from computer model

Thermal and Amplifier Noise



G = 20k → amp ~ 10 nV/√Hz

Diagnostic Data – Shield Biased



Analysis steps

Likelihood function:

$$L(x\,|\,\alpha,\nu) = \left(\frac{1}{\sigma\sqrt{2\pi e}}\right)^N \exp\left[\frac{-(\bar{x}-\mu(\alpha,\nu))^2}{2(\sigma/\sqrt{N})^2}\right]$$

$\bar{x}$ = average voltage measured, σ = standard deviation, N = number of samples

$\mu(\alpha,\nu)$ = predicted voltage for given α and set of systematics ν

General expression for predicted average voltage:

$$\mu(\alpha,\nu) = \sqrt{|V^T|^2}\,\frac{Q}{\omega_0\sqrt{k_B T \rho_d}}\,\frac{\int d^3\vec{r}\,'\vec{z}^{\,F}(\vec{r}\,')\bullet\vec{f}(\vec{r}\,')}{\sqrt{\int d^3\vec{r}\,'\,|\vec{z}^{\,F}(\vec{r}\,')|^2}}$$

V^T = thermal noise voltage fluctuations

Q = detector mechanical quality factor

ω_0 = detector resonant frequency

ρ_d = detector mass density

$z^F(r')$ = displacement of detector at arbitrary point in detector r'

$f(r')$ = force/unit volume on detector at arbitrary point in detector r'

Analysis steps

Interval [α_{lo}, α_{up}] that contains true α with probability CL:

$$CL = \int_{\alpha_{lo}}^{\alpha_{up}} p(\alpha \mid x)\, d\alpha$$

p(α|x) **= probability density function for α given DATA *x***

(For any λ, find [α_{lo}, α_{up}] so that CL = 0.95)

e.g., for λ = 20 μm, $-6 \times 10^3 < \alpha < 4 \times 10^3$

Bayes' Theorem:

$$p(\alpha \mid x) = \frac{L(x \mid \alpha)\pi(\alpha)}{\int_{-\infty}^{\infty} L(x \mid \alpha')\pi(\alpha')\, d\alpha'}$$

L(α|x) **= likelihood function INTEGRATED OVER SYSTEMATICS ν**

π(α) **= prior pdf for α (assumed uniform between old limits on α)**

Analysis steps

Monte Carlo program calculates:

$$\int d^3\vec{r}'\vec{z}^F(\vec{r}')\bullet\vec{f}(\vec{r}')$$

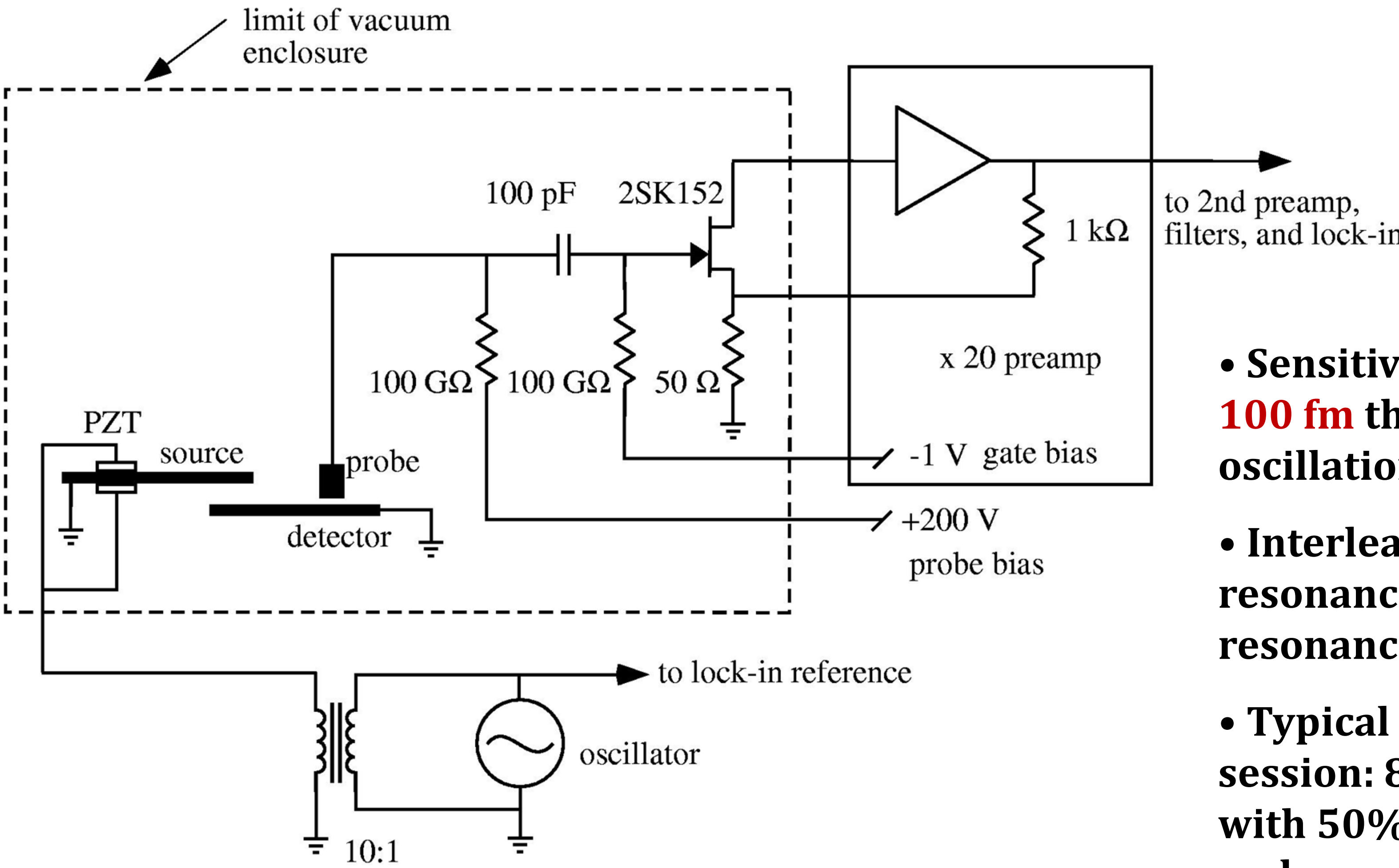
z^F(r') **= displacement of detector at arbitrary point r' in detector**

(given by 2nd order polynomial fit to geometry survey data)

f(r') **= force/unit volume on detector at arbitrary point r' in detector**

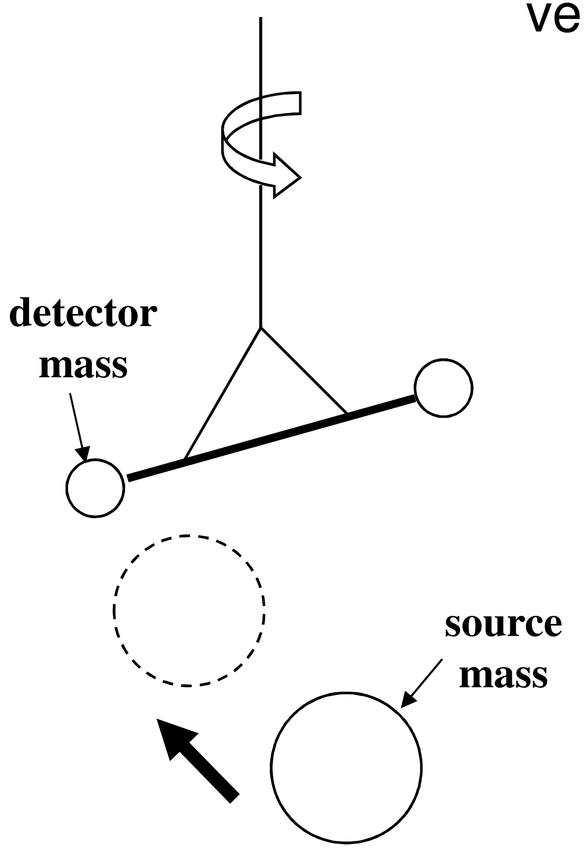
What is *f(r')* due to interaction with source mass for case of LLV force?

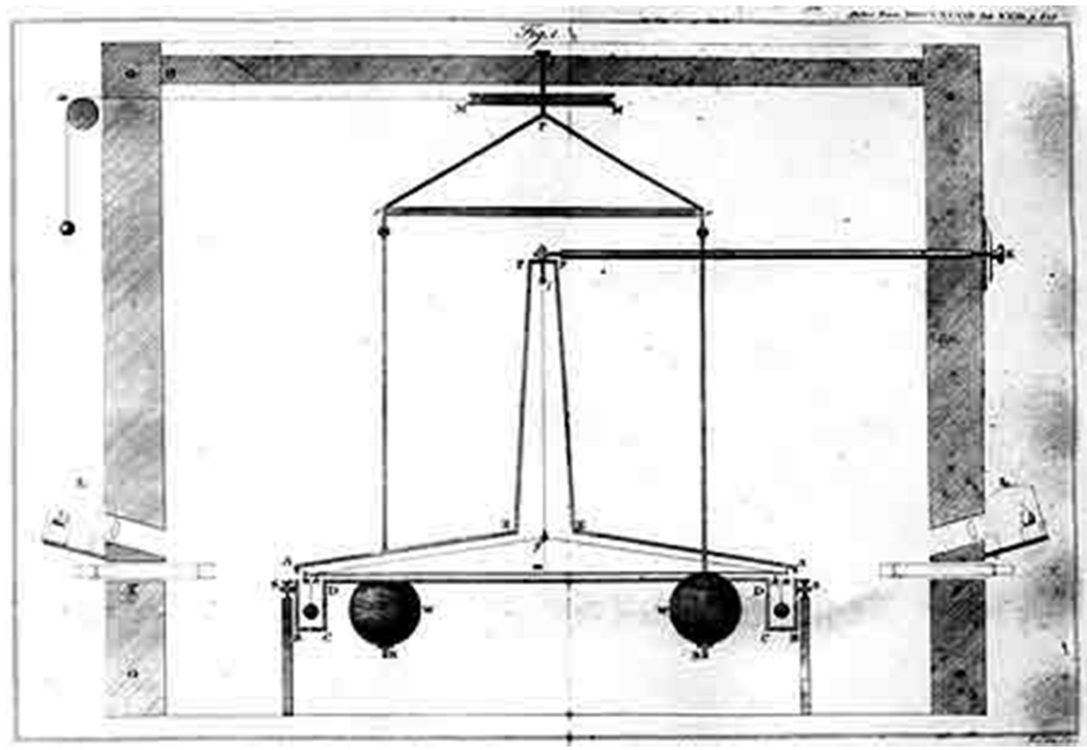
Readout



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

Experiment is short-range (~ 50 μm), high-frequency (1 kHz) version of Cavendish Experiment



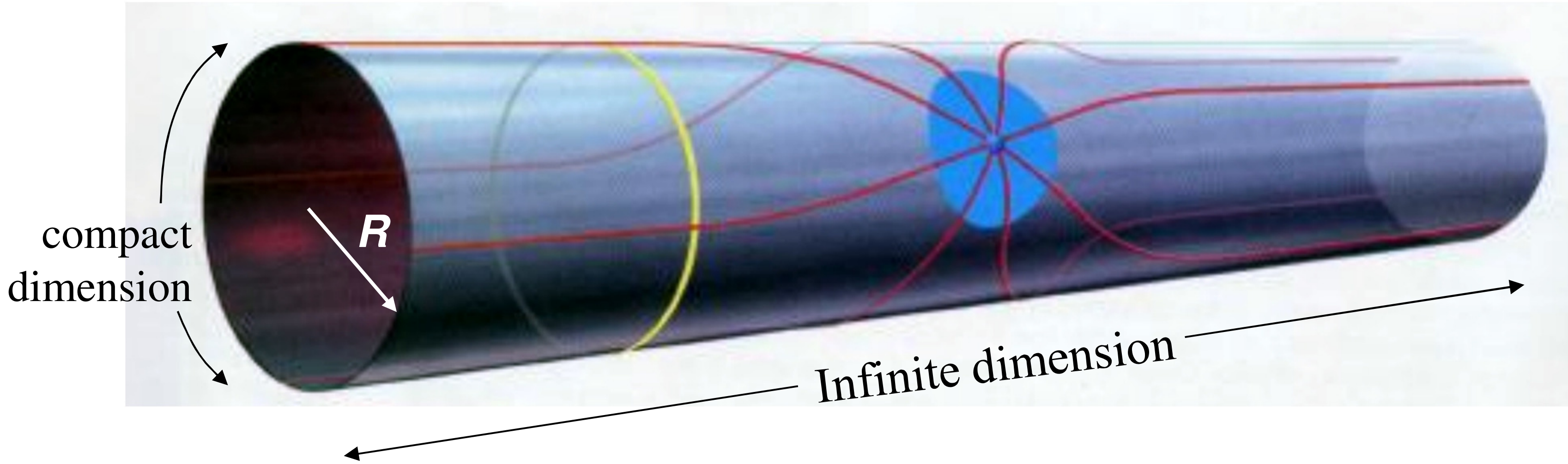


Pb test masses (ρ = 11000 kg/m^3): large = 20 cm diam., small = 5 cm diam

$$\boxed{G = 6.76 \times 10^{-11}\ m^3\, kg^{-1}\, s^{-2}}$$

2006 CODATA: $G = 6.67428(67) \times 10^{-11}\ m^3\, kg^{-1}\, s^{-2}$

"Large" Extra Dimensions



Strong, Weak, EM force confined to 3 dimensions

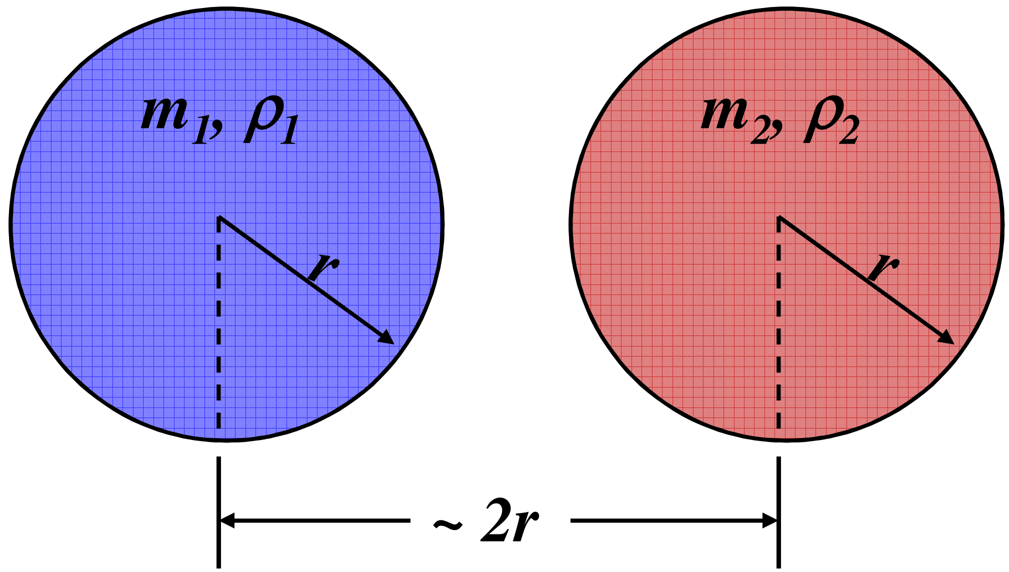
- **Gravity spreads out into *n* extra dimensions of size *R*, appears diluted**

$$R = \left[\frac{M_P}{M^*}\right]^{2/n}\left[\frac{\hbar}{2\pi M^*}\right]$$

- **Gravity unifies with EW force (M* ~ 1 TeV) if $n = 2$, $R \sim 1$ mm**

  $n = 3$, $R \sim 1$ nm

Challenge: Scaling with Size of Apparatus



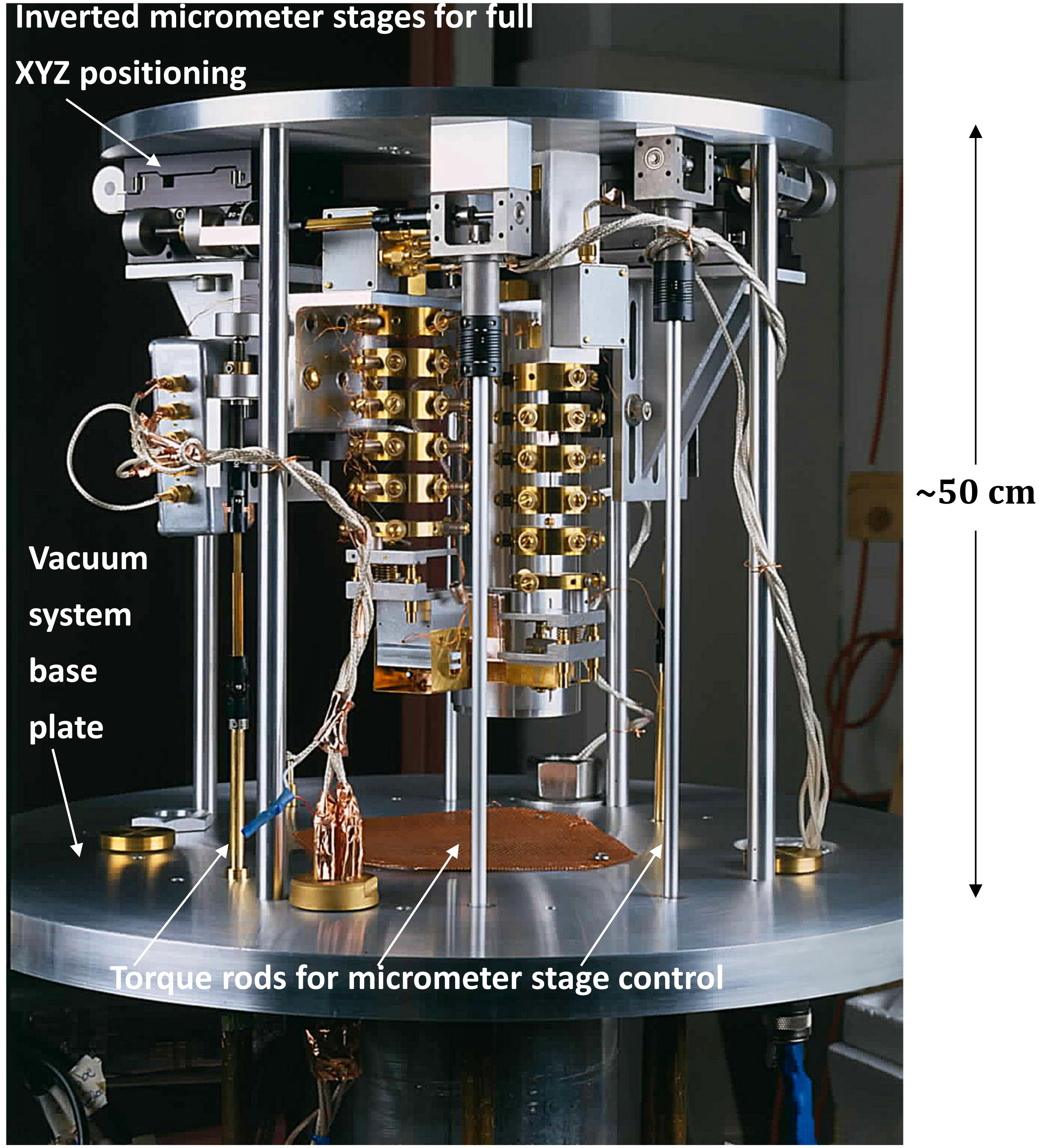
$$F = \frac{Gm_1m_2}{(2r)^2} = \frac{G\rho_1\rho_2(4r^3)^2}{4r^2} \sim G\rho_1\rho_2 r^4$$

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

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

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

Central Apparatus



Installation at IUCEEM

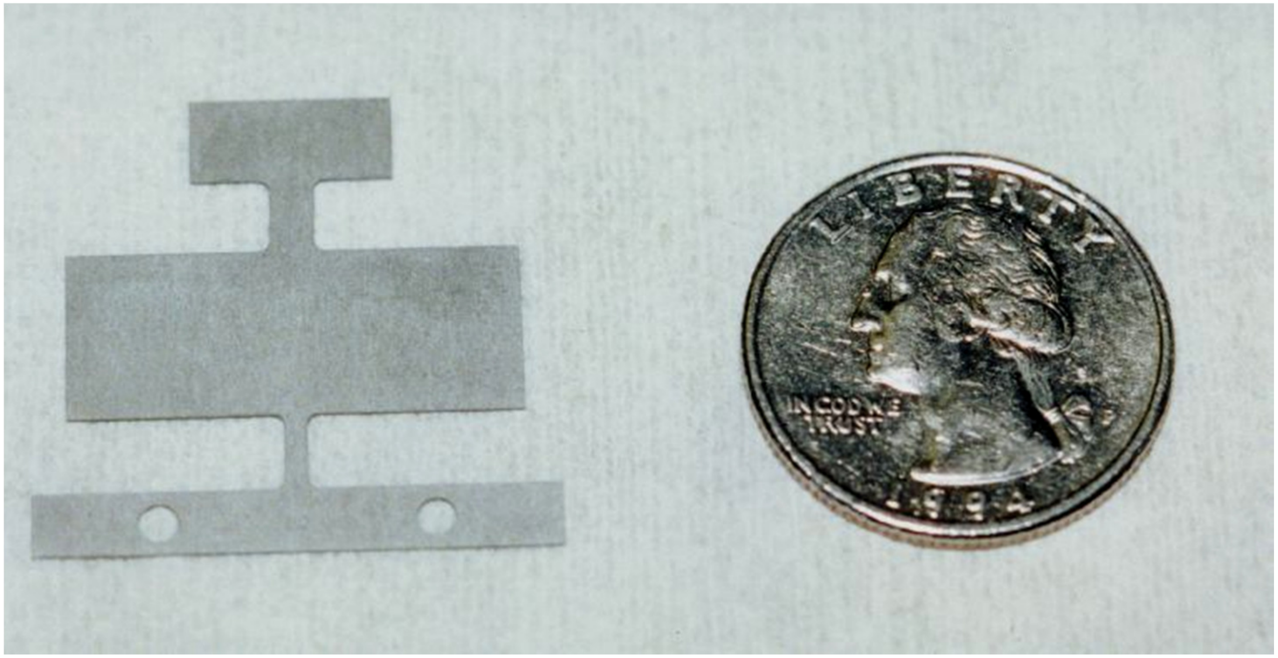
Vacuum System

• Hollow riser for magnetic isolation

• LN_2 - trapped diffusion pump mounts below plate

• P ~ 10^{-7} torr

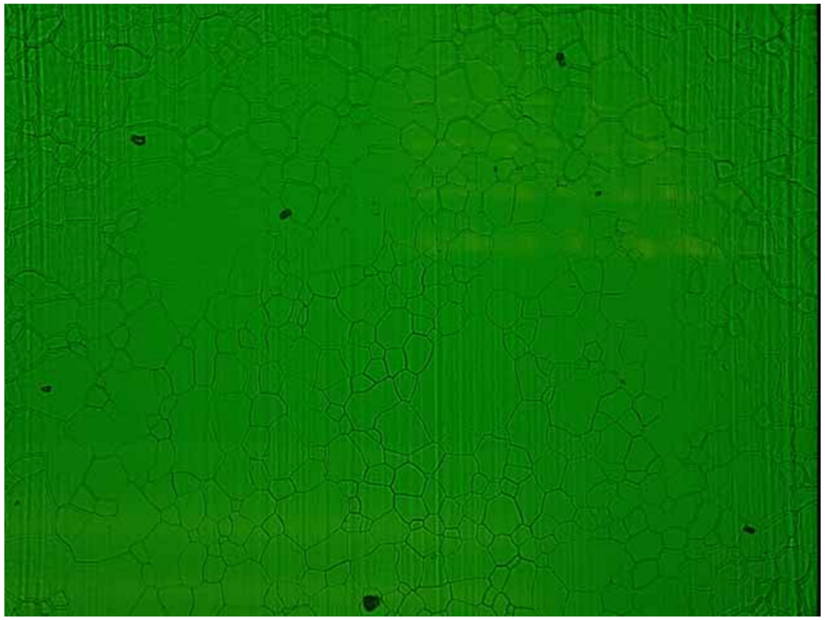
New detector prototypes have been fabricated



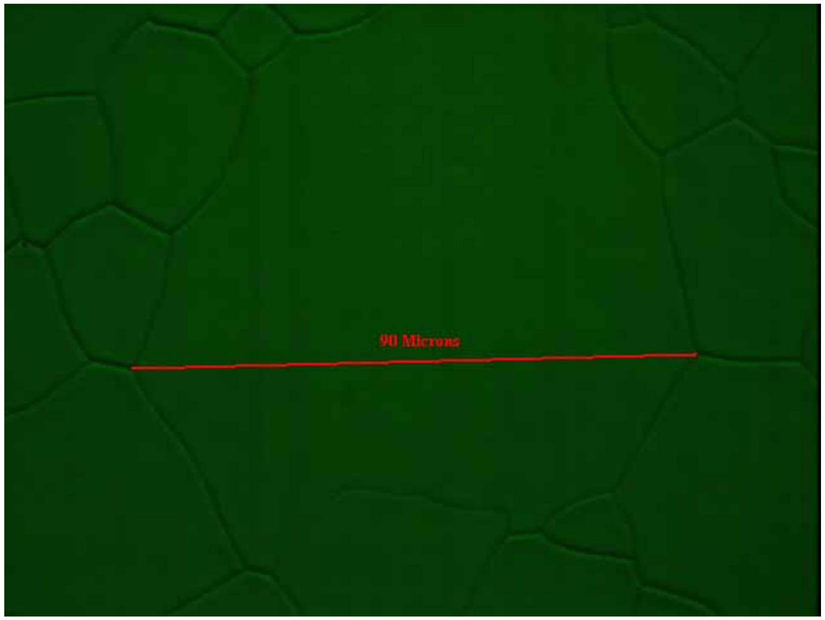
- **200 μm thick tungsten sheet (high density)**
- **Fabricated by wire EDM**
- **First generation: Annealed at 1600 K in helium atmosphere**
- **New oscillators: Annealed at 2700 K; expect larger crystals, higher Q**

2700 K annealing leads to 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 under test…

New detectors and projected sensitivity

Available prototypes

Material	*Q @ 300 K*	*Q @ 77 K*	*Q @ 4 K*
Si	6×10^3	1×10^5	8×10^5
W (as machined)	7×10^3	1×10^3	1.2×10^4
W (1600 K anneal)*	2.5×10^4		
W (2700 K anneal)	2.8×10^4	1.8×10^5	1×10^6 (8K)

**Used for published experiment*

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

J. Appl. Phys. 72 (1992) 5628

Material	*Q @ 300 K*	*Q @ 77 K*	*Q @ 4 K*
W (as machined)	2×10^4	1×10^5	5×10^5
W (2023 K anneal)	2×10^5	1×10^6	1×10^7

$\alpha \backsim \sqrt{T/Q}$ **improves by factor of 50 at 4 K**

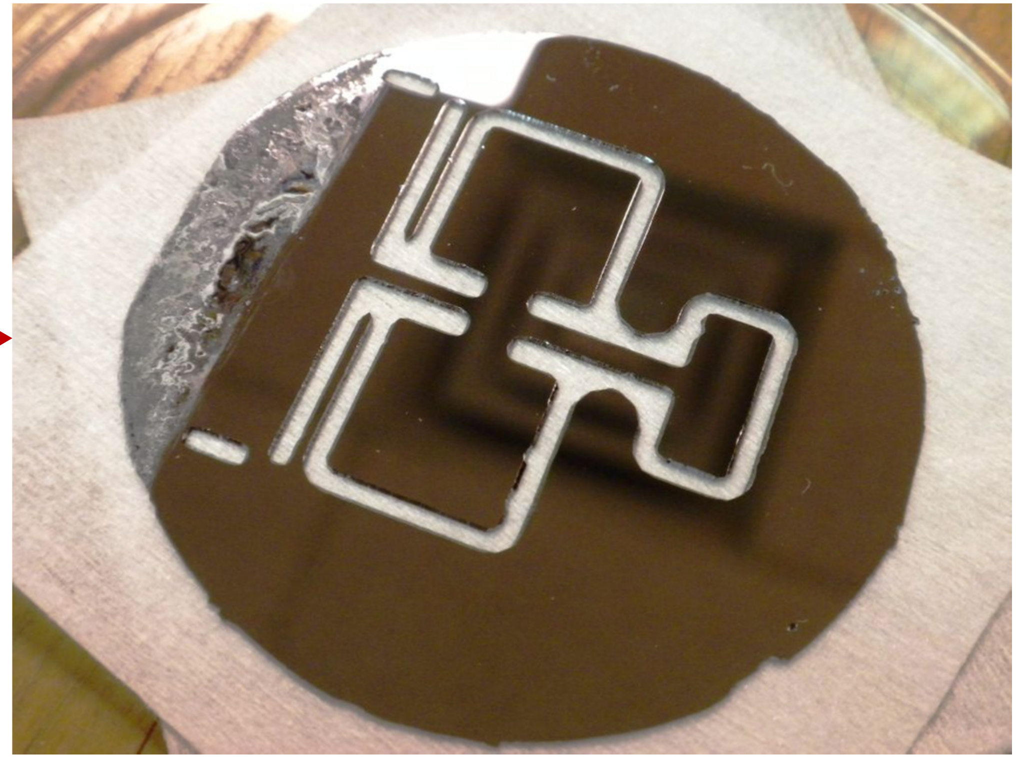
New detectors and projected sensitivity

Thinner test masses

Reduce Newtonian background

Solid, 30 μm W too flimsy

200 μm Si with 30 μm gold plate
S. Jacobson, IU Chemistry

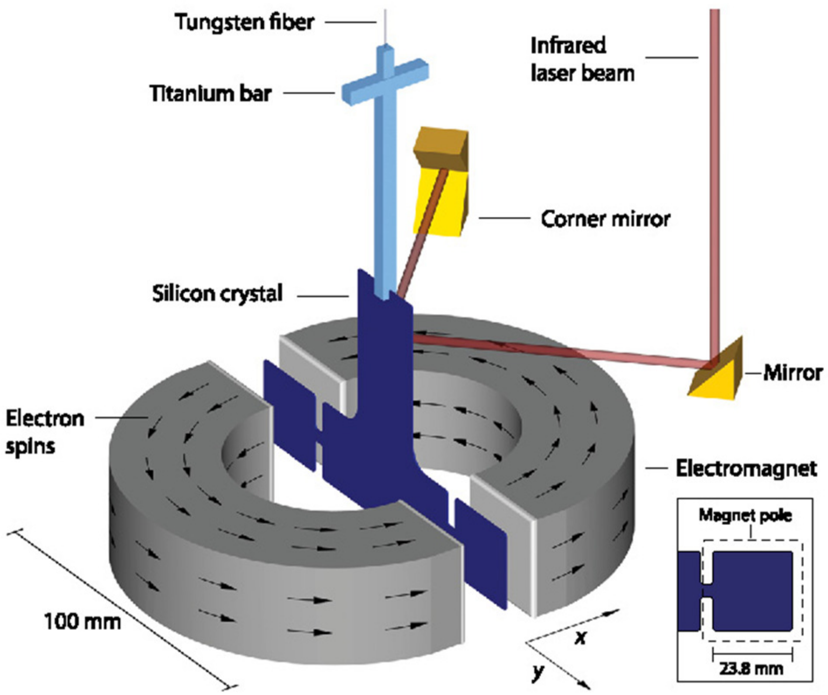


Available prototypes

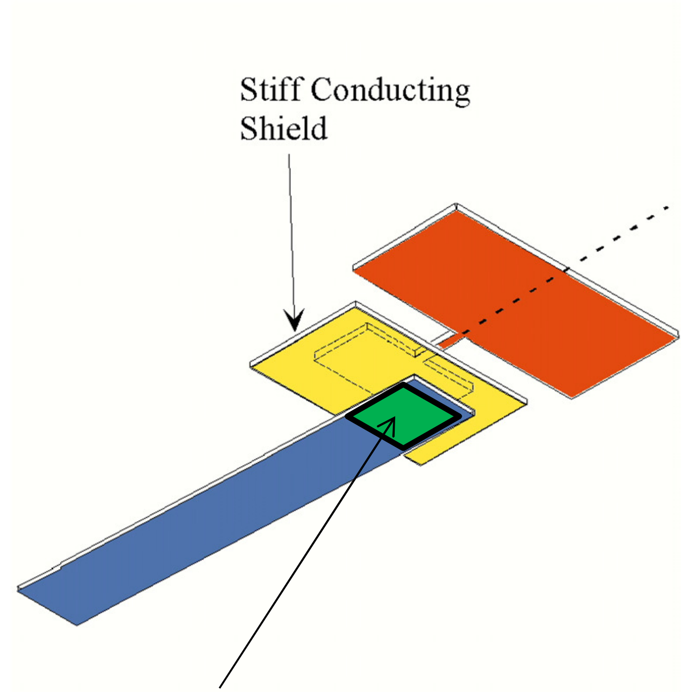
Material	*Q @ 300 K*	*Q @ 77 K*	*Q @ 4 K*
Si	6 x 10^3	1 x 10^5	8 x 10^5
W (2700 K anneal)	2.8 x 10^4	1.8x 10^5	1x10^6 (8K)
Si (new)	1.0 x 10^4	?	?

Spin – Dependent Interactions

Eot-Wash ALP torsion pendulum



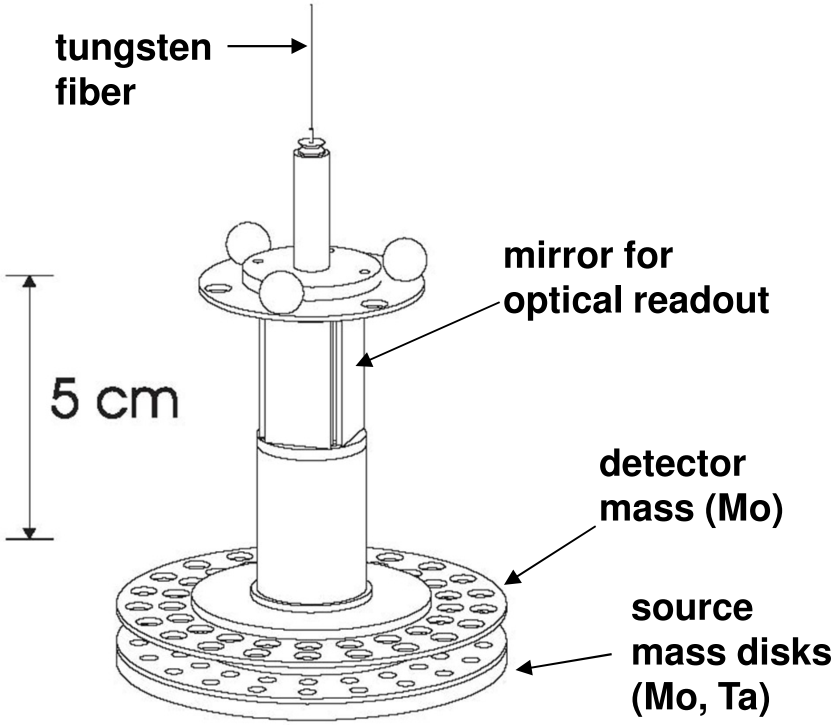
S. Hoedl et al., PRL 106 (2011) 041801



- Compensated test mass (Dy_6Fe_{23})
  - Assume 10% of attained spin densities
  - 1 mm thick
- Magnetic shield
  - μ–metal?
  - ~ 100 μm thick

Eot-Wash Torsion Pendulum Experiment

D. Kapner, E. Adelberger et al., PRL 98 021101 (2007)



- 55 μm minimum gap
- 10 μm BeCu membrane (not shown)

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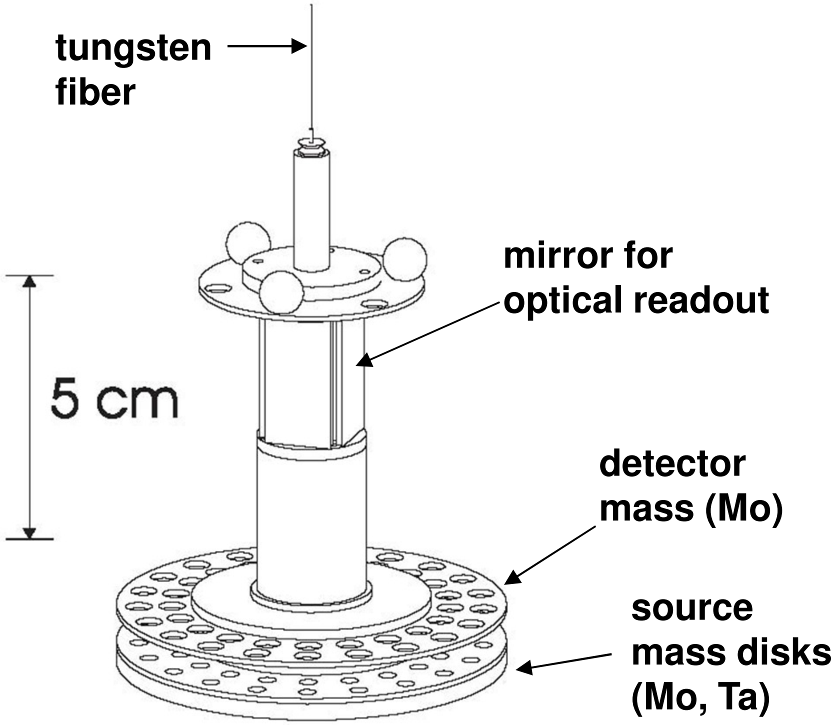
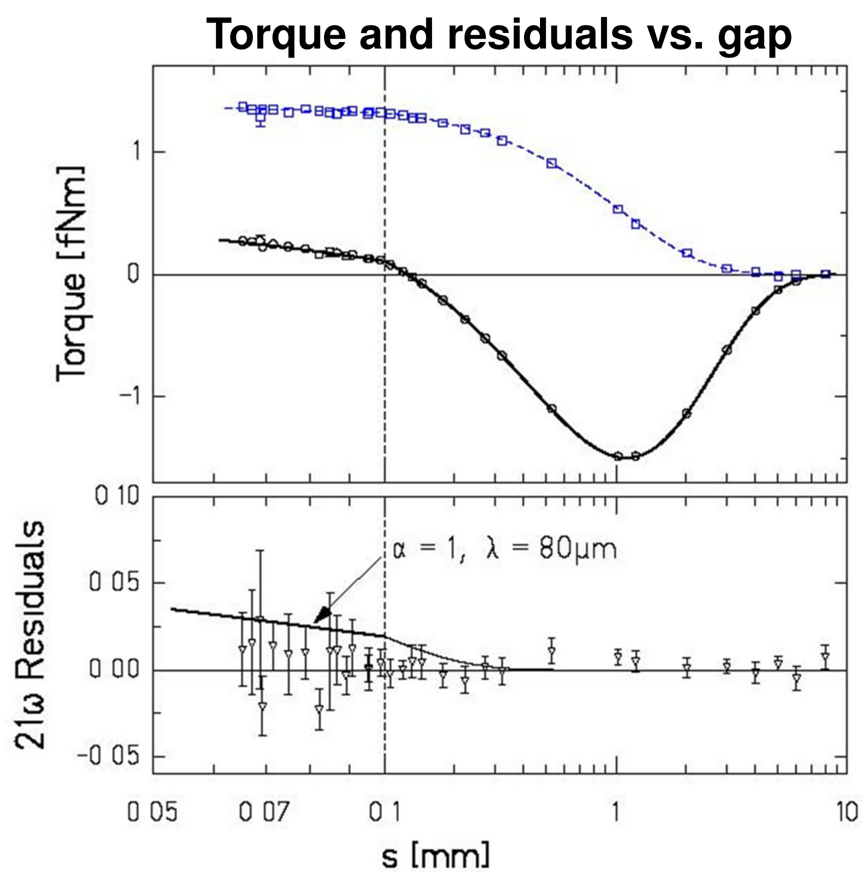
D. Kapner, E. Adelberger et al., PRL 98 021101 (2007)





- 55 μm minimum gap
- 10 μm BeCu membrane (not shown)

Limits: Scenarios with $\alpha \geq 1$ excluded at 95% CL for $\lambda \geq 56$ μm

Largest extra dimension: R < 44 μm

ADD Model (2 equal-sized extra dimensions compactified on a torus): $R < 56$ μm $\Rightarrow M^* \geq 3.2$ TeV

Stretched membrane shield is designed…

- Copper- beryllium alloy stretched over frame
- Ten microns thick
- Hourglass shape for uniform distribution of tension

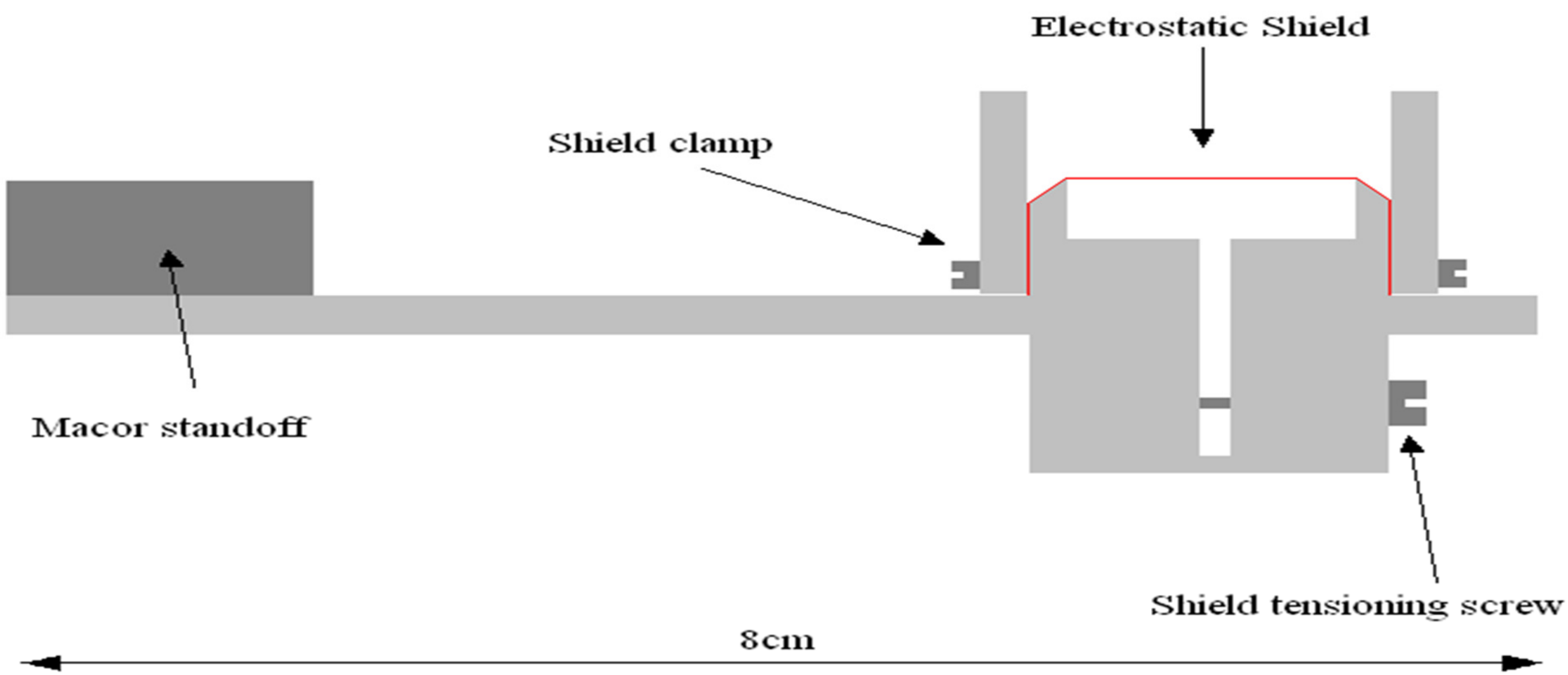
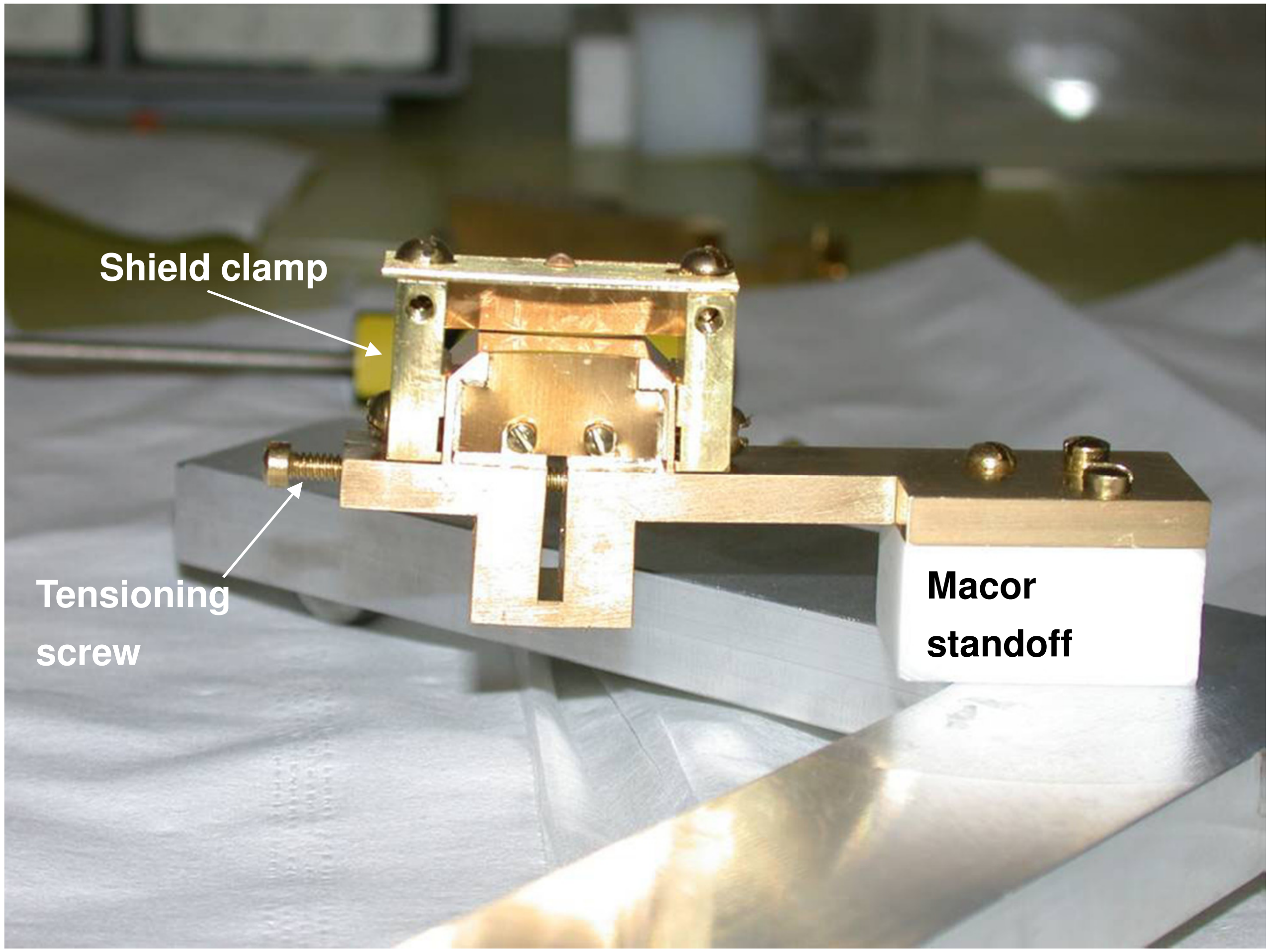


Figure not to scale

D. Thurmer, Undergraduate Thesis, Physics, U. of CO

Shield prototype exists and may be useable



- **Surface variations:**

  5 μm peaks

  0.7 μm rms variations (should be sufficient for ~ 30 μm experiment)

- **Conducting planes surround both test masses on 5 sides (get rid of copper tape)**

- **11/06: minimum gap = 48 microns**

The Reality: Background forces took ~ 2 years to characterize and suppress in 1st experiment; will probably arise again at shorter ranges

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

Systematic Errors

Parameter	Mean	Error	Units
Gravitational constant, G	6.673×10^{-11}	1.0×10^{-13}	$\mathrm{m^3 kg^{-1} s^{-2}}$
Boltzmann constant, k_B	$1.3806503 \times 10^{-23}$	2.4×10^{-29}	$\mathrm{J\ K^{-1}}$
Detector density (tungsten), ρ_d	1.93×10^4	1.9×10^3	$\mathrm{kg\ m^{-3}}$
Source density (tungsten), ρ_s	1.93×10^4	1.9×10^3	$\mathrm{kg\ m^{-3}}$
Thermal noise voltage, $\sqrt{\overline{\lvert V^T \rvert^2}}$	6.09×10^{-5}	2.3×10^{-6}	V
Mechanical quality factor, Q	2.5522×10^4	29	(NA)
Resonant frequency, $\omega_0/2\pi$	1173.085	0.015	Hz
Temperature, T	305.0	0.1	K
Integrated rms free modeshape, $\sqrt{\int d^3\vec{r}' \lvert \vec{z}^F(\vec{r}') \rvert^2}$	5.87×10^{-11}	5.9×10^{-12}	$\mathrm{m^{5/2}}$

Parameter	Mean **(m)**	Error **(m)**
Detector length, l_d	5.0800×10^{-3}	6.4×10^{-6}
Detector width, w_d	1.14550×10^{-2}	6.4×10^{-6}
Detector thickness, t_d	1.950×10^{-4}	6.4×10^{-6}
Source width, w_s	7.0000×10^{-3}	6.4×10^{-6}
Source thickness, t_s	3.048×10^{-4}	6.4×10^{-6}
Touch gap, g_{sd}	1.080×10^{-4}	6.4×10^{-6}
Source amplitude, dz_s	1.87×10^{-5}	3.2×10^{-6}

Consistency checks

Additional runs:

Larger test mass gap

Source over opposite side of detector (and shield)

Reduced overlap

- $F_{pressure} \sim F_{magnetic} \sim r^{-2}$, $F_{electrostatic} \sim r^{-4}$, $F_{vibrational} \sim$ **(constant)**
- **Shield response**

No resonant signal observed

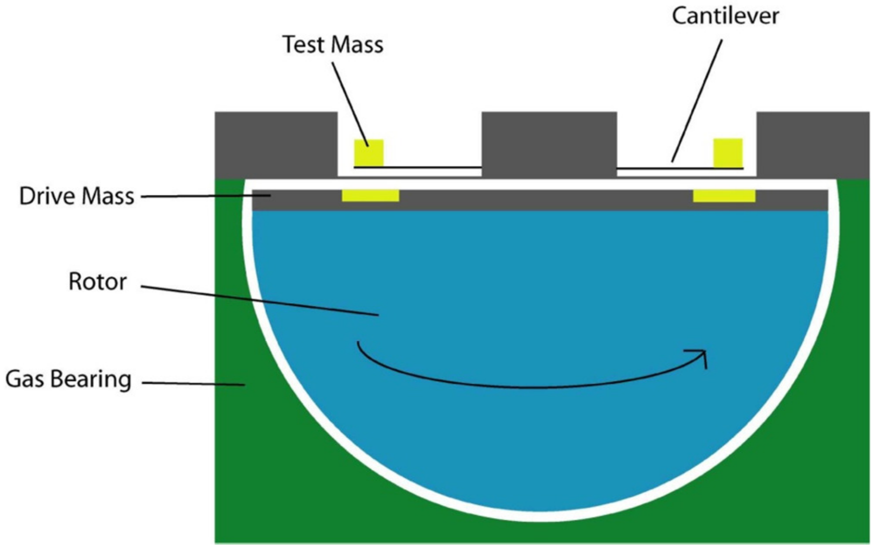
Expected backgrounds from ambient fields:

Magnetic Background = Signal with applied $B \times (B_{ambient} / B_{applied})^2 = 10^{-7}$ **V**

ES Background = Signal with applied V $\times (V_{ambient} / V_{applied})^4 = 10^{-10}$ **V**

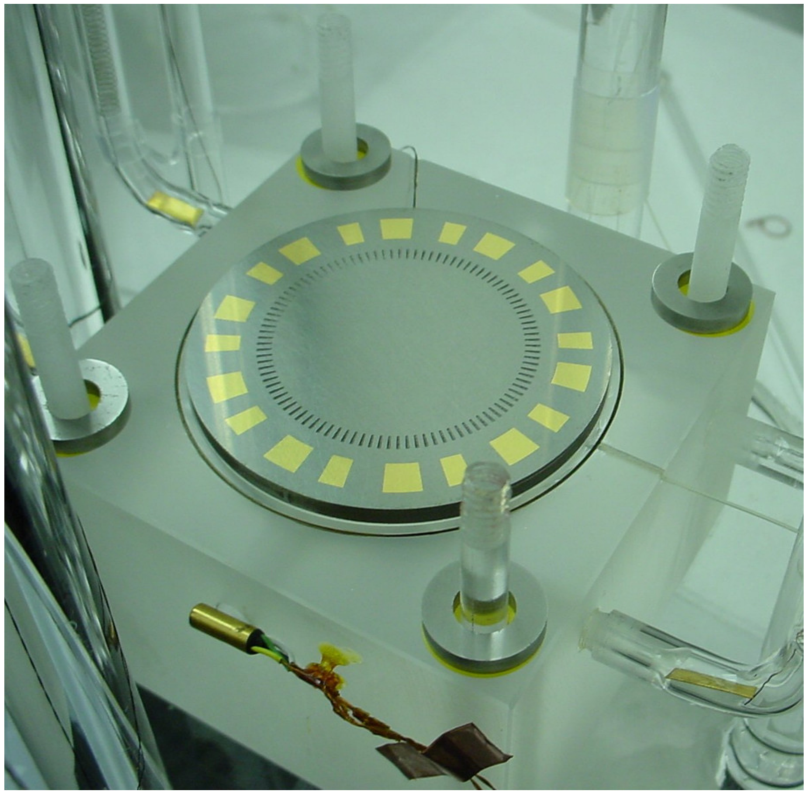
All < thermal noise (10^{-6} V)

Stanford Microcantilever Experiment – Generation II



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

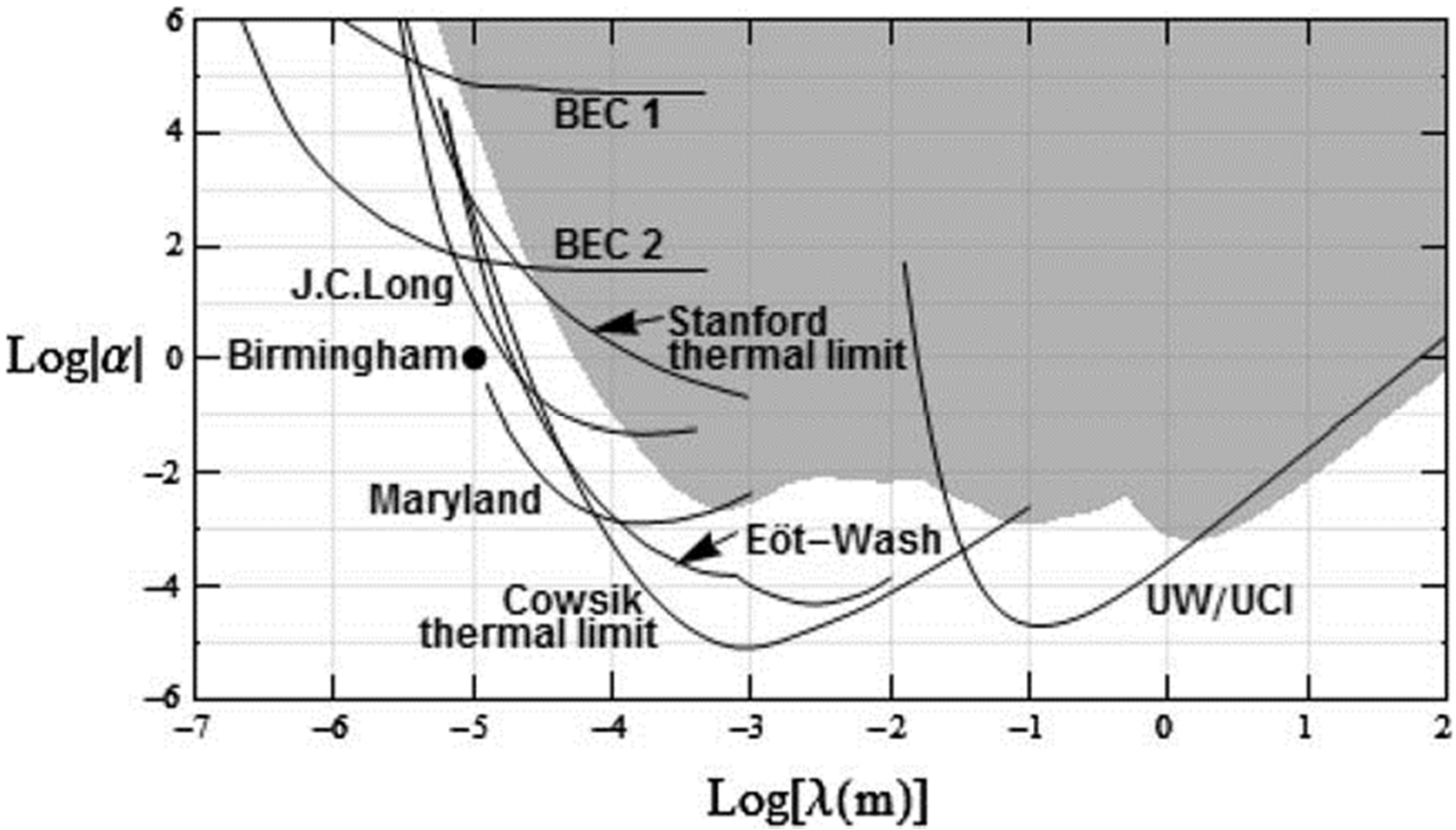
Drive mass mounted in gas bearing



figures courtesy of David M. Weld

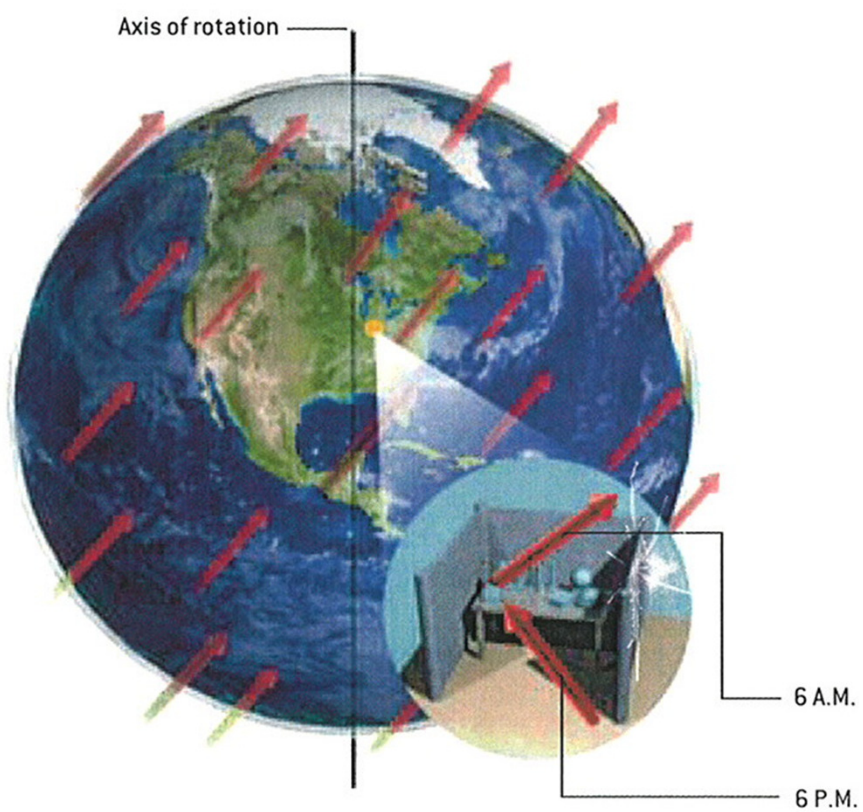
Limits and Projections – 1 µm – 1 m

R. Newman, Space Sci. Rev. 148 (2009) 175



Search for Lorentz Violation

Test for sidereal variation in force signal:



Source: A. Kostelecký, Scientific American, September 2004, 93.

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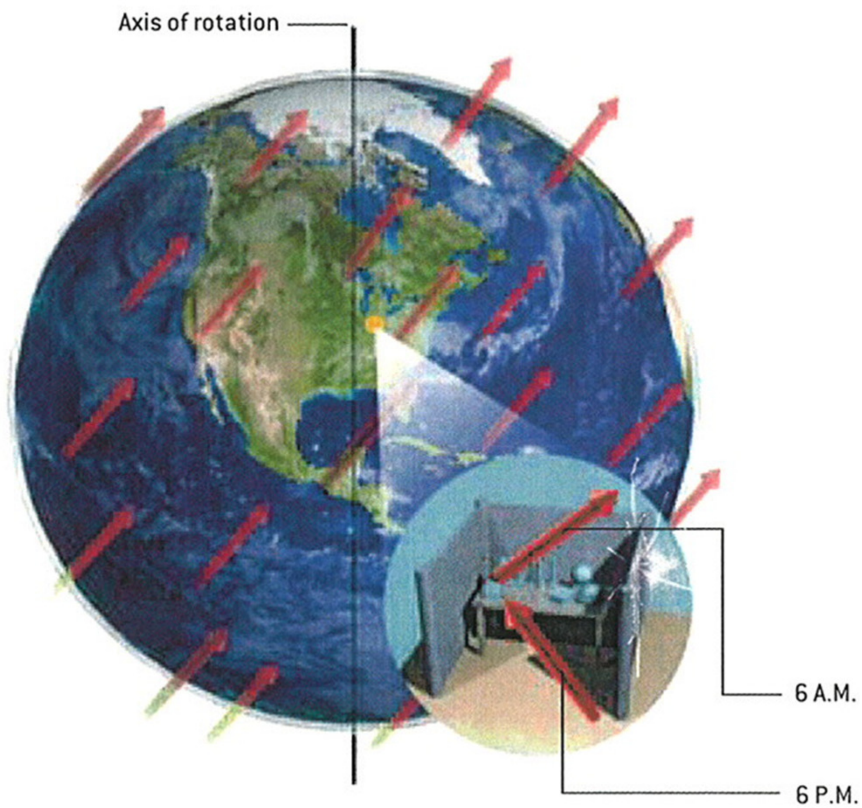

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Standard Model Extension (SME)

Recently expanded to gravitational sector

V. A. Kostelecký, PRD 69 105009 (2004).

Q. G. Bailey and V. A. Kostelecký, PRD 74 045001 (2006).

Action:

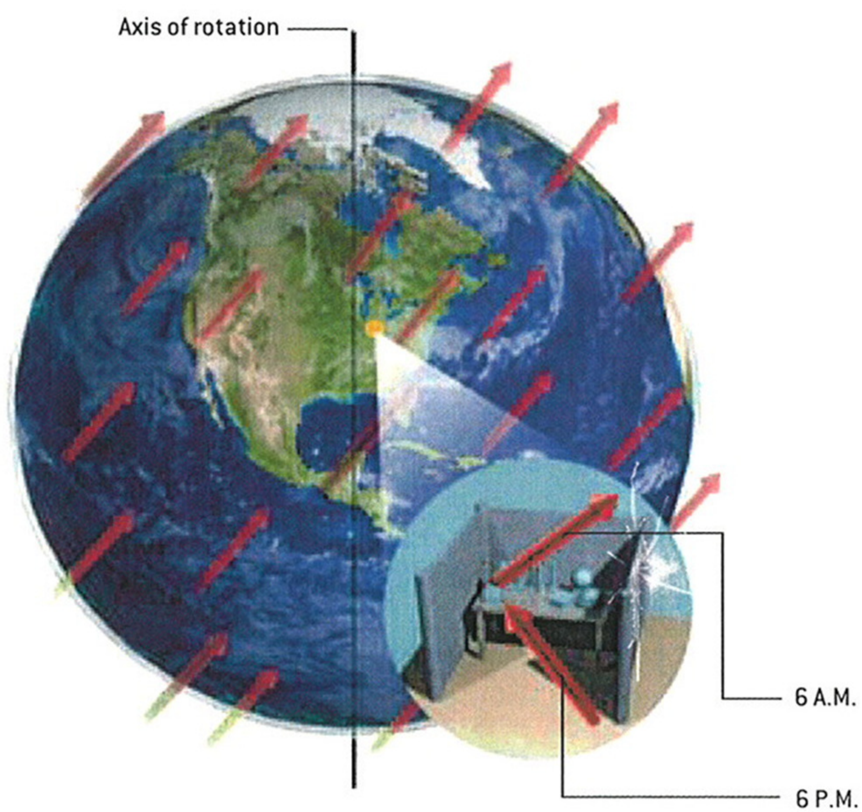
$$S = S_{GR} + S_{LV} + S_{MATTER}$$

$$S_{LV} = f(\underbrace{u, s^{\mu\nu}, t^{\kappa\lambda\mu\nu}}_{\text{20 coefficients controlling L.V.}})$$

Estimated sensitivities: $10^{-15} - 10^{-4}$

New Analysis - Search for Lorentz Violation (2002 Data)

Test for sidereal variation in force signal:



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Estimated sensitivities: $10^{-15} - 10^{-4}$

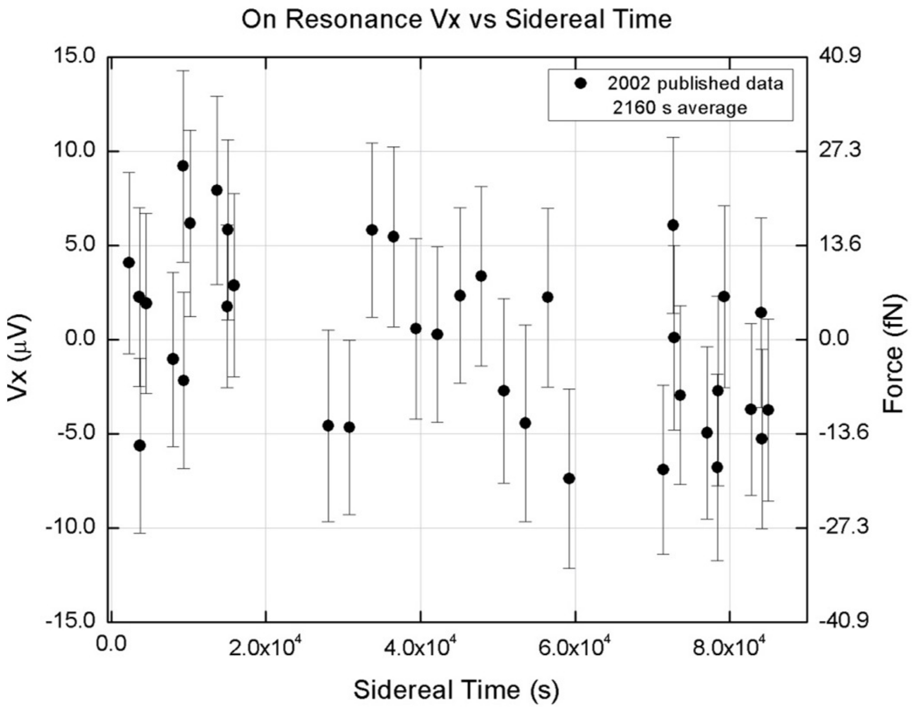
2002 Data as Function of Time

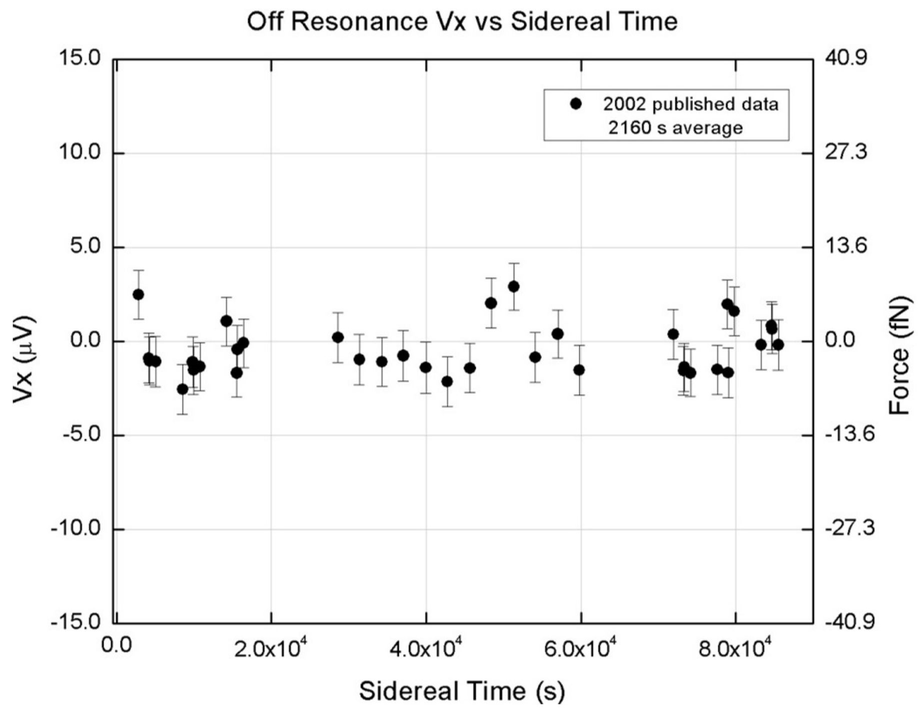
• 22 hrs of data accumulated over 5 days (August 2002)

• On-resonance (signal) data accumulated in 12 minute sets (off-resonance, diagnostic data in between)

• Plots:

Average signal over 3 consecutive sets (best for viewing time distribution) with 1σ error, vs mean time of the sets





Calculation of the Fitting Function

• LV force function [1]:

$$dF^{\hat{j}} = G dm_1 dm_2 \left(-\frac{x^{\hat{j}}}{x^3} - \frac{3}{2}\frac{x^{\hat{j}}}{x^5} x^{\hat{j}} x^{\hat{k}} \bar{s}^{\hat{i}\hat{k}} + \frac{x^{\hat{k}} \bar{s}^{\hat{j}\hat{k}}}{x^3} \right)$$

$\bar{s}^{\hat{j}\hat{k}}$ = coefficients of Lorentz violation in the SME standard lab frame (x_L = South, y_L = East, z_L = vertical)

[1] Q. G. Bailey and V. A. Kostelecký, PRD 74 045001 (2006).

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Force misaligned relative to $\vec{r} = \vec{x}_1 - \vec{x}_2$, but $1/r^2$ behavior preserved

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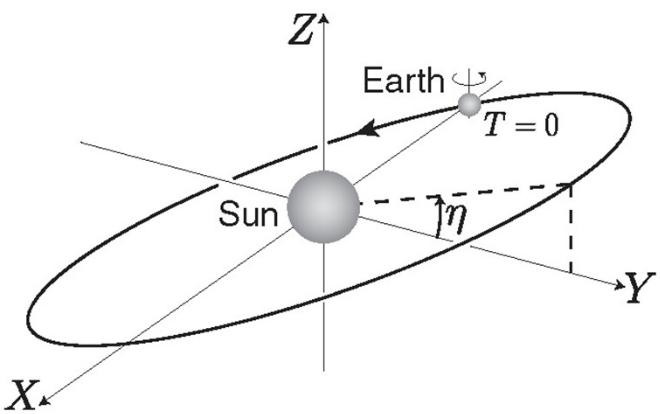
Force misaligned relative to $\vec{r} = \vec{x}_1 - \vec{x}_2$, but $1/r^2$ behavior preserved

- Transform to sun-centered frame [2]:



$$R = \begin{pmatrix} \cos\chi\cos\omega_\oplus T & \cos\chi\sin\omega_\oplus T & -\sin\chi \\ -\sin\omega_\oplus T & \cos\omega_\oplus T & 0 \\ \sin\chi\cos\omega_\oplus T & \sin\chi\sin\omega_\oplus T & \cos\chi \end{pmatrix}$$

$\omega_\oplus$ = sidereal frequency

ignore boost (η); χ = colatitude = 0.87

[1] Q. G. Bailey and V. A. Kostelecký, PRD 74 045001 (2006).

[2] V. A. Kostelecký and M. Mewes, PRD 66 056005 (2002).

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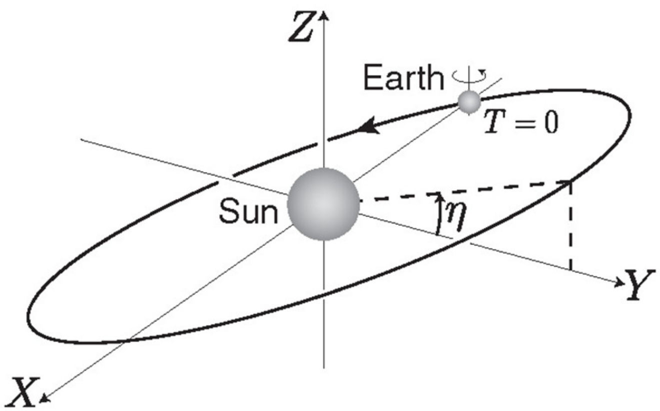

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- Detector has distributed mass:

$$F = \frac{1}{|z\mathrm{max}|} \int_D d^3\vec{x} z^F(\vec{x}) \cdot dF^{\hat{j}}(\vec{x})$$

[1] Q. G. Bailey and V. A. Kostelecký, PRD 74 045001 (2006).

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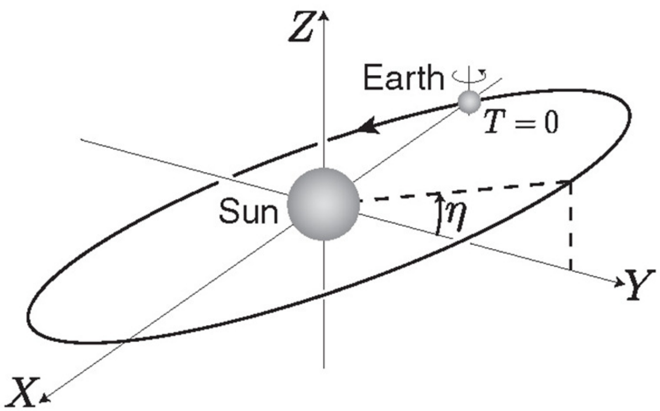

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mode shape from finite element model

[1] Q. G. Bailey and V. A. Kostelecký, PRD 74 045001 (2006).

[2] V. A. Kostelecký and M. Mewes, PRD 66 056005 (2002).

Results

D. Bennett, V. Skavysh, J. Long, Proc. 5th CPT conference

- Force: $$F = C_0 + S_\omega \sin(\omega_\oplus T) + C_\omega \cos(\omega_\oplus T) + S_{2\omega} \sin(2\omega_\oplus T) + C_{2\omega} \cos(2\omega_\oplus T)$$

  C_ω, S_ω functions of detector geometry, s^{JK}

Component	Amplitude ($\times 10^{-16}$ N)
C_0	$1.12\bar{s}^{XX} + 0.00\bar{s}^{XY} - 7.78\bar{s}^{XZ} - 3.48\bar{s}^{YY} + 0.00\bar{s}^{YZ} - 0.21\bar{s}^{ZZ}$
S_ω	$0.07\bar{s}^{XX} + 0.76\bar{s}^{XY} + 0.02\bar{s}^{XZ} + 0.00\bar{s}^{YY} - 0.64\bar{s}^{YZ} - 0.07\bar{s}^{ZZ}$
C_ω	$-0.49\bar{s}^{XX} + 0.11\bar{s}^{XY} - 0.17\bar{s}^{XZ} + 0.00\bar{s}^{YY} - 0.09\bar{s}^{YZ} + 0.49\bar{s}^{ZZ}$
$S_{2\omega}$	$0.06\bar{s}^{XX} - 0.08\bar{s}^{XY} + 0.15\bar{s}^{XZ} - 0.16\bar{s}^{YY} - 0.10\bar{s}^{YZ} - 0.09\bar{s}^{ZZ}$
$C_{2\omega}$	$0.03\bar{s}^{XX} + 0.20\bar{s}^{XY} + 0.06\bar{s}^{XZ} - 0.06\bar{s}^{YY} + 0.24\bar{s}^{YZ} + 0.04\bar{s}^{ZZ}$

- Fit:

Coefficient	Mean and error (2σ)
$\bar{s}^{XX}$	$(-0.04 \pm 4.90) \times 10^4$
$\bar{s}^{XY}$	$(-0.07 \pm 6.12) \times 10^4$
$\bar{s}^{XZ}$	$(-0.01 \pm 2.56) \times 10^3$
$\bar{s}^{YZ}$	$(-0.06 \pm 5.83) \times 10^4$
$\bar{s}^{ZZ}$	$(0.08 \pm 6.68) \times 10^4$

Compare: Chung, Chu, et al., PRD 80 016002: $S^{JK} < 1 \times 10^{-8}$

(atom interferometer sensitive to $\Delta g/g \sim 1 \times 10^{-9}$)