New Constraints on Short Range Forces Coupling Mass to Intrinsic Spin

Clive Speake,
Giles Hammond, Christian Trenkel
and Antonio Pulido-Paton

Centre for Gravity and Space Research

UNIVERSITY OF BIRMINGHAM

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Outline

- **Motivation**
- **Description of the Experiment**
  - **The Spherical Superconducting Torsion Balance**
  - **The Spin Source**
- **Systematic Effects**
  - **Thermal**
  - **Magnetic**
- **Results**
- **Conclusions**

Motivation

- **Violation of CP is required in order to produce a net number of particles from the primordial soup. CPT conservation implies that CP violation requires T to be violated. Any processes that violate T are therefore of interest.**

- **Axions are possible dark matter candidates (20 μm <λ< 20 cm or 1 μeV<E<10 meV) and are well motivated candidates as exchange particles for such an interaction. They provide an elegant solution to the strong CP-problem. This provides motivation for concentrating on short range interactions.**

- **Attempts to unify Gravitation with the gauge interactions usually involve extensions to the Standard Model. These extensions generally involve new symmetries and therefore new possible interactions mediated by new exchange particles.eg u-bosons,schizons,arions...**

- **Moody and Wilczek (1984) proposed new interactions coupling mass and spin**

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

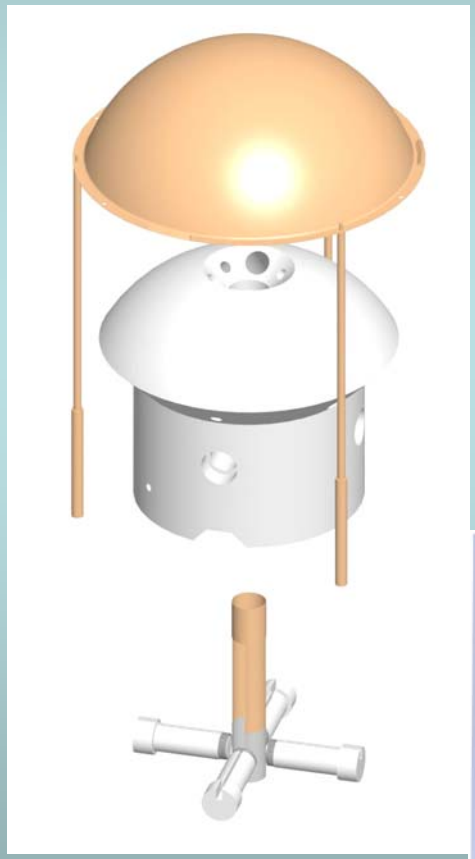
- **Violation of P and T on a macroscopic scale!**

Spherical Superconducting Torsion Balance (Mk1 SSTB)

Float

Levitation bearing

Rotation detector

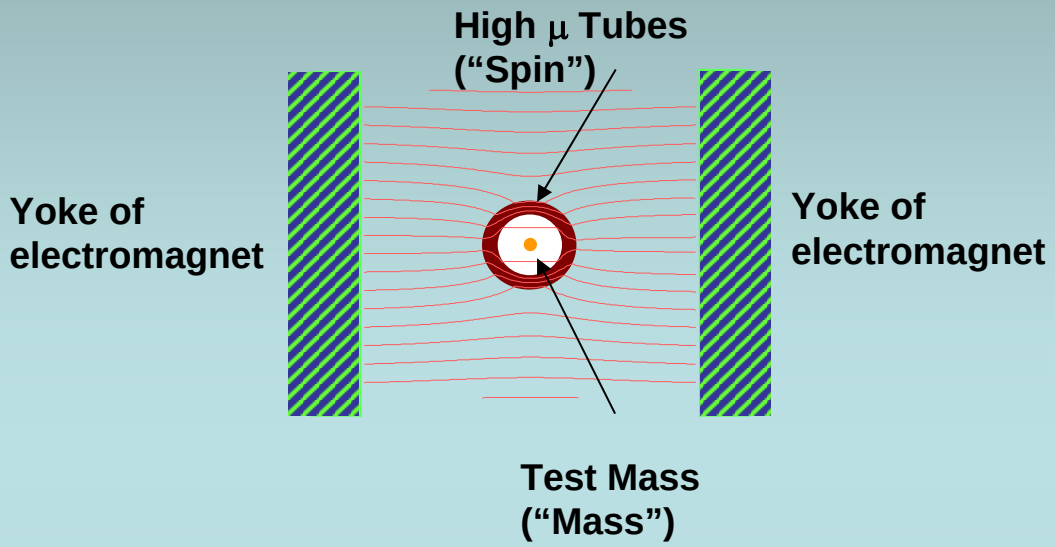


Key Features

- Meissner Effect Suspension
- Spherical Symmetry
- Programmable Stiffness (τ=200s-20s)
- SQUID Angular Readout (2×10^{-13}Nm/$\sqrt{Hz}$)
- Optimised for Short Ranges
- Based on Lead

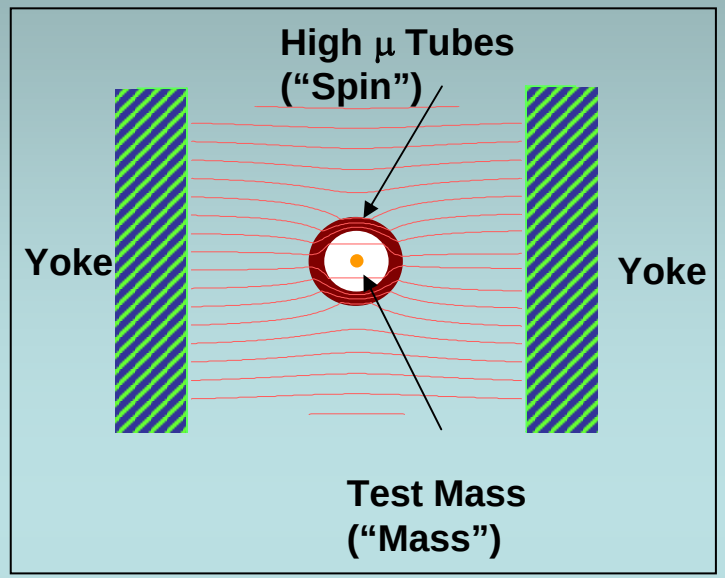
Review of Scientific Instruments, **75**, pp 955-961, 2004.
Precision Engineering, **24**, pp 139-145, 2000.
Measurement Science and Technology, **10**, pp508-513, 1999.

Spin Source



- **The magnetic field associated with the polarised spins (in the tube) *cancels* the external field that is used to polarise them (from the yoke).**
- **We can modulate spins by reversing current flow in the magnet and look for coherent signal at that frequency (1ω).**
- **Electromagnet and tubes manufactured at Imperial College (Geoff Rochester, Diana Shaul, Tim Sumner). Details to be published.**

Spin Source



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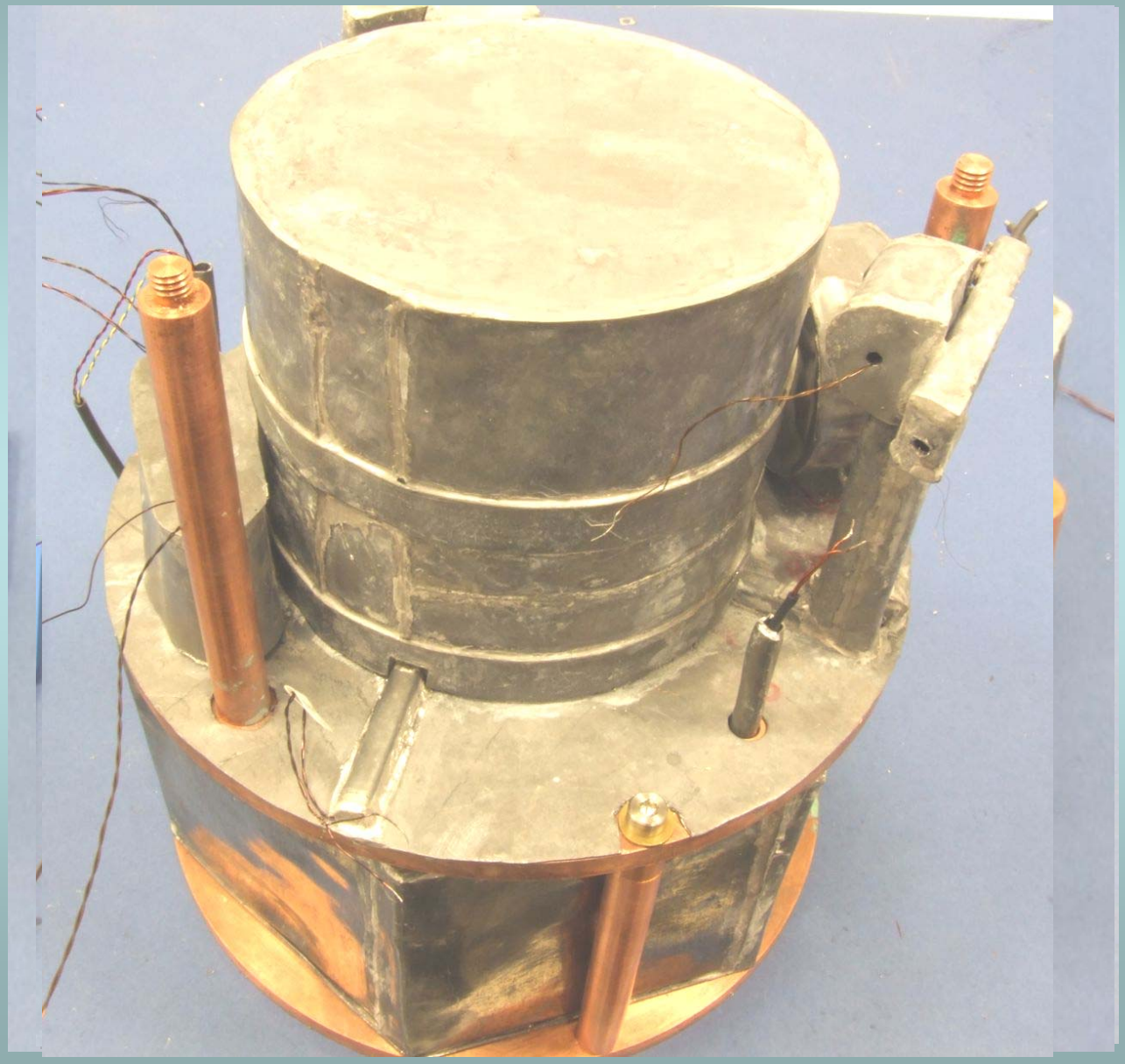
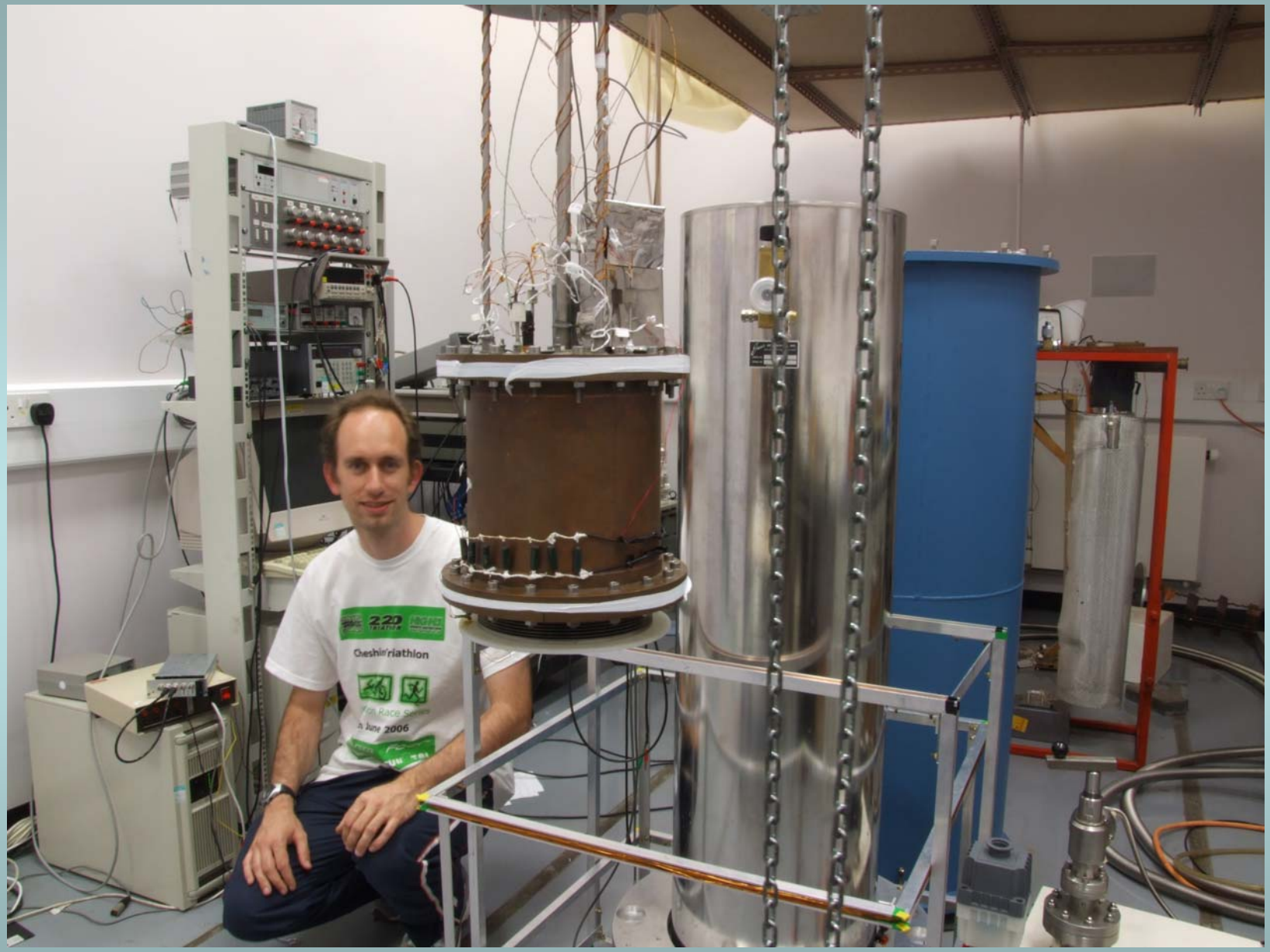
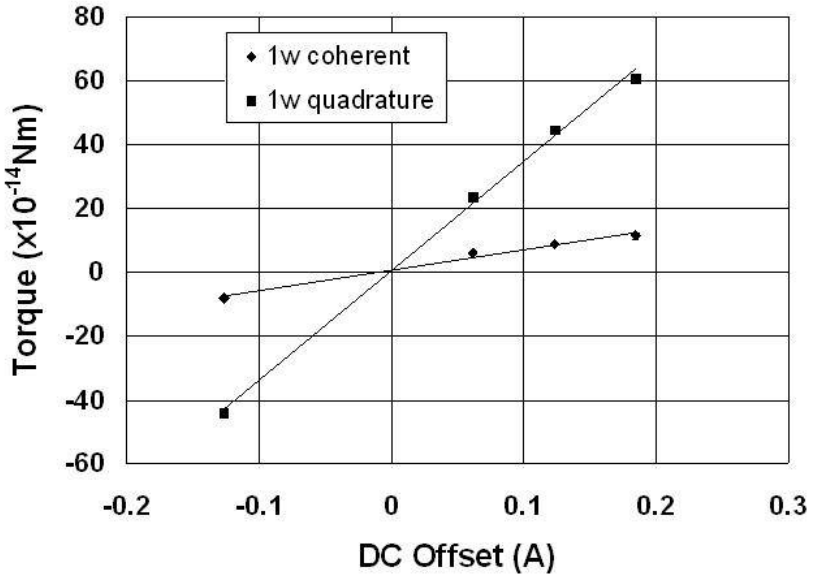
Experimental Setup

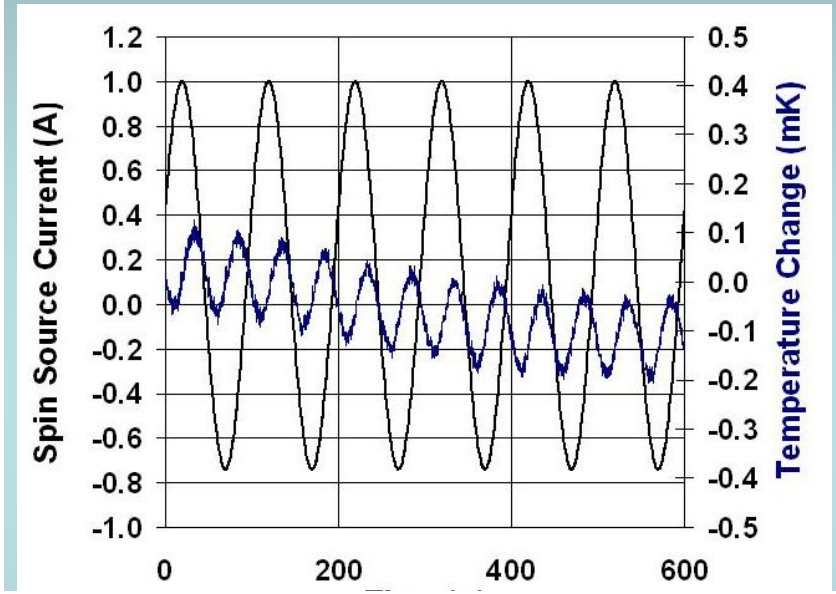



Cheshir'riathlon

Systematic Effects (Thermal)

- **Heating from hysteresis gives rise to signals at both the drive frequency (1ω) and first harmonic (2ω) of the current modulation through the spin source windings. Eddy currents dominant source of heating.**





- **• DC offsets in the spin source current give rise to heating effects and torques at 1ω (can tune these effects out to <10^{-16}Nm for I_{offset}<2mA)**

  • A possible mechanism is that the heating changes the configuration of the trapped flux in the superconducting films/modifies penetration depth of films

Systematic Effects (Magnetic)

- **Reversal of all the angular momenta/spins in the experiment is a 'pseudo-time reversal' and a powerful method for eliminating magnetic systematic effects.**

- **Pseudo-time reversal is *not* perfect because we cannot reverse all the spins (impurities and stored magnetic moments on the float). We also do not reverse the bias current in the SQUID.**

- **Magnetic systematic effects comprise terms due to a possible magnetic moment $\vec{m}(\phi)$ and susceptibility χ interacting with the modulated field $\vec{B}_{\mathrm{mod}}$ and a possible static field $\vec{B}_0$.**

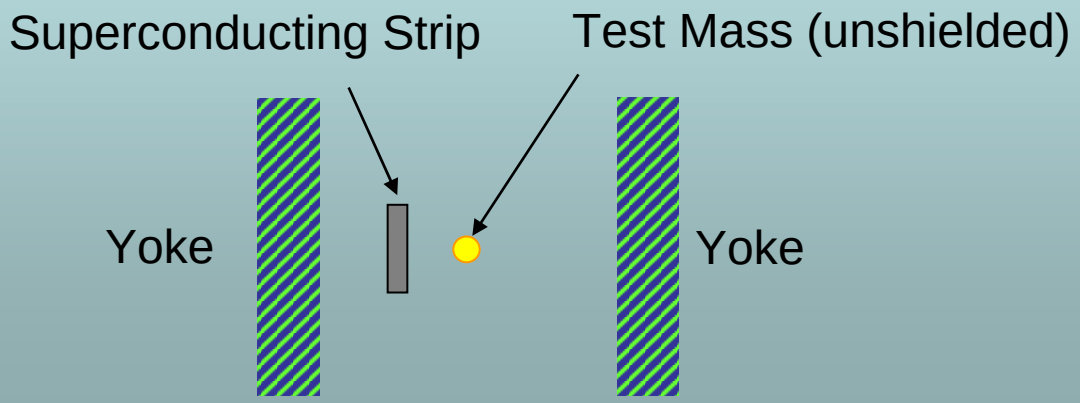
$$U_{mag} = -\left\{\vec{m}(\phi) - \frac{\chi}{\mu_0} V(\vec{B}_0 + \vec{B}_{mod})\right\} \cdot (\vec{B}_0 + \vec{B}_{mod})$$

$$= -\vec{m}(\phi) \cdot \left(\vec{B}_0 + \vec{B}_{mod}\right) + \frac{\chi}{\mu_0} V\vec{B}_0 \cdot \vec{B}_0 + \frac{2\chi}{\mu_0} V\vec{B}_0 \cdot \vec{B}_{mod} + \frac{\chi}{\mu_0} V\vec{B}_{mod} \cdot \vec{B}_{mod}$$

1ω signal 1ω signal 2ω signal

Permanent Moments/Impurities in test masses

- **Temporarily remove the high permeability tubes in order to generate a known magnetic field/ field gradient. Measure residual force on the test mass.**
- **We found that $m_{test\text{-}mass} \leq 8\times10^{-10}$ Am^2 which corresponds to 1% net polarization of iron impurities for 2ppm concentration.**
- **Total residual torque (quadrature sum) < 10^{-18}Nm.**

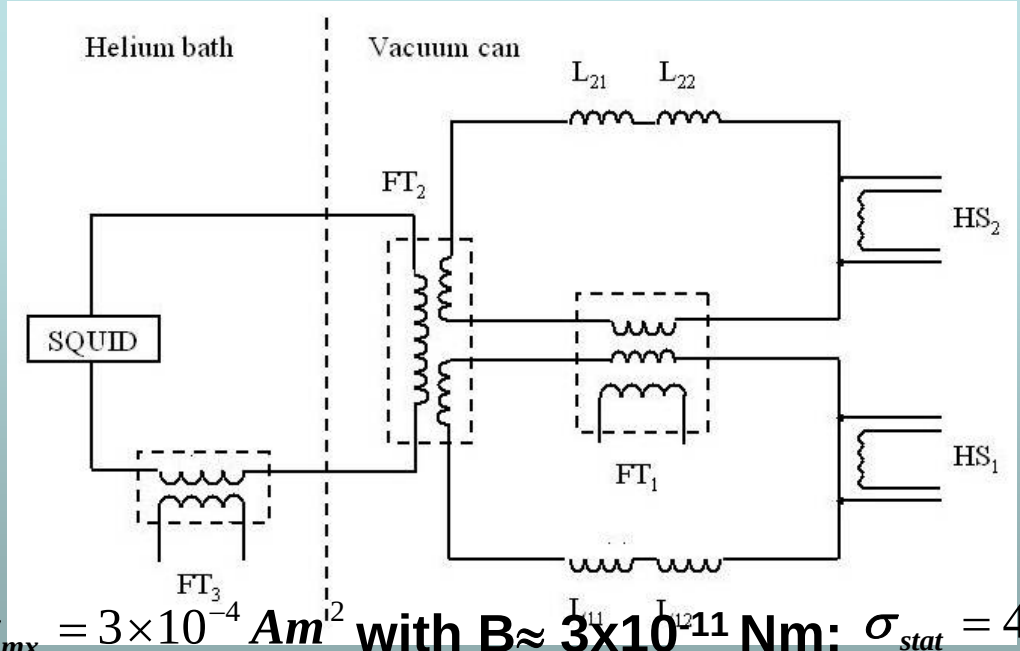


Induced Moments in float during levitation

- **The levitation process can potentially trap flux in superconducting films which can then interact with any leakage field from spin source.**

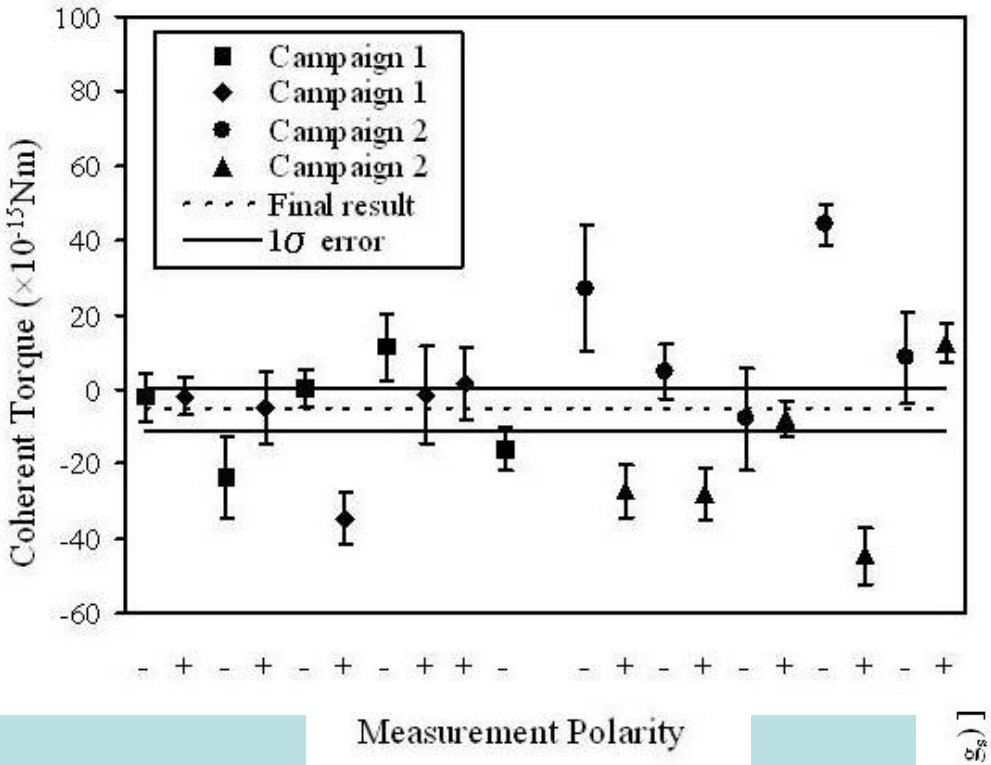
- **We thermally anneal the experiment between data runs of alternate polarity to remove its magnetic memory (not guaranteed to remove the systematic effect, torque= mxB).**

- **We determined an uncertainty in one component of m by coupling flux into the detector circuit and measuring the dynamics of the torsion balance.**



- **We found** $\sigma_{mx} = 3\times10^{-4}\,Am^2$ **with B≈ 3x10^{-11} Nm:** $\sigma_{stat} = 4.2\times10^{-15}\,Nm$

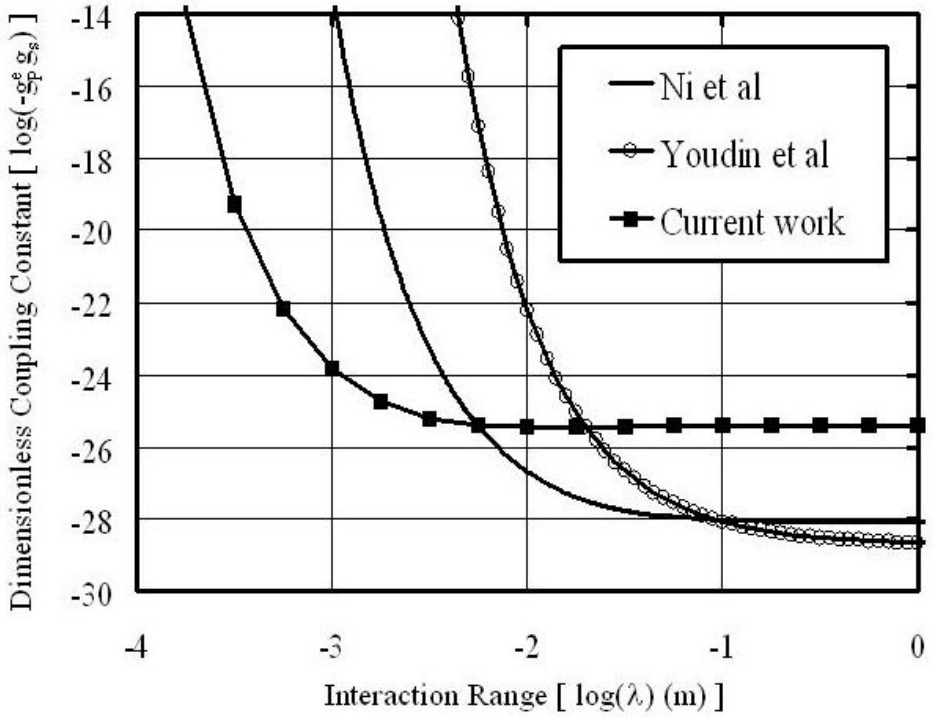
Results



$\Gamma=(-5.4\pm(3.8)_{stat}\pm(4.2)_{sys})\times10^{-15}$Nm
$=(-5.4\pm5.7)\times10^{-15}$Nm

$g_p g_s=(-1.9\pm(1.3)_{stat}\pm(1.5)_{sys})\times10^{-26}$Nm
$=(-1.9\pm2.0)\times10^{-26}$ for $\lambda>10$mm

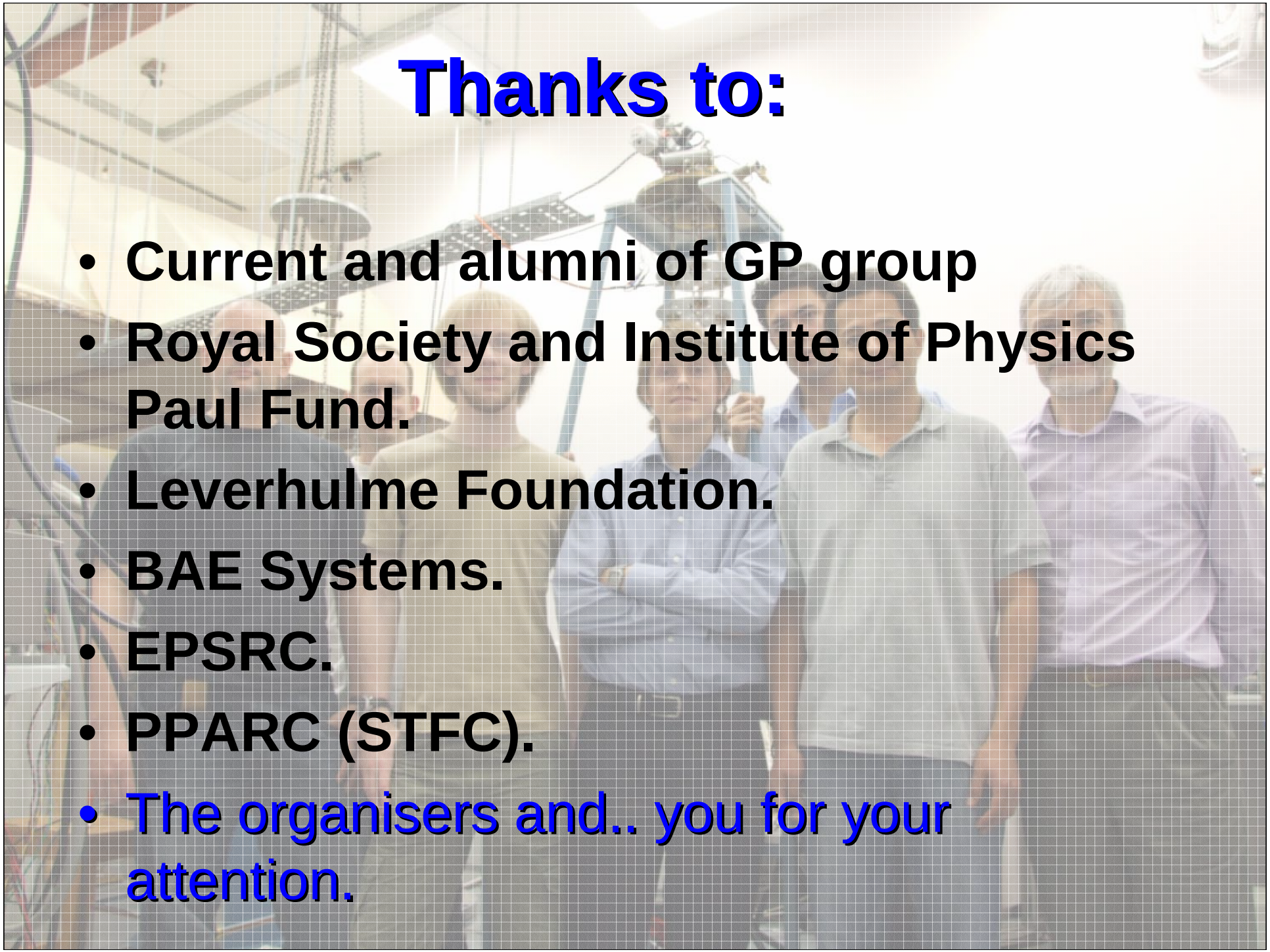
Most conservative limit assumes $g_p g_s$ is -3.9×10^{-26} for $\lambda>10$mm



Physical Review Letters, **98**, 081101, 2007

Conclusions

- **We have new limits on possible forces coupling mass to intrinsic spin.**
- **These improve limits on previous refereed work by 10 orders of magnitude at 1mm. (~2 orders improvement over Jen at al 1992, preliminary result.)**
- **We have recently completed Mk2 SSTB and are using it to test $1/r^2$ at short ranges and to determine the Casimir force.**



Thanks to:

- Current and alumni of GP group
- Royal Society and Institute of Physics Paul Fund.
- Leverhulme Foundation.
- BAE Systems.
- EPSRC.
- PPARC (STFC).
- The organisers and.. you for your attention.

Induced Moments in float during levitation

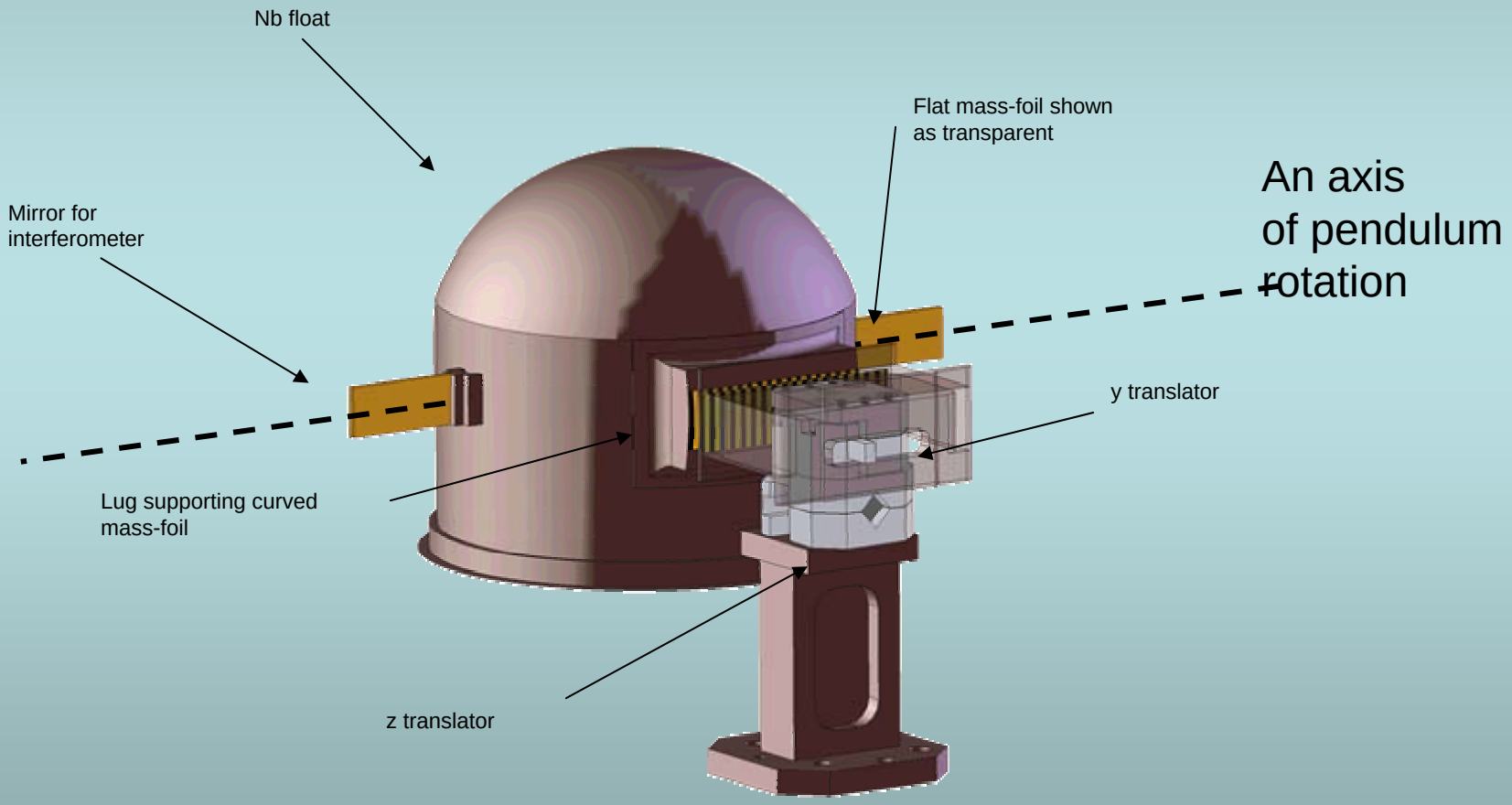
Simple example of systematics using Pseudo time reversal:

	Polarity +	Polarity -
Float magnetic moment	+	-
Leakage field	+	-
Torque **m x B**	+	+
Float rotation	+	+
SQUID output	+	-

If polarity of **m x B** does **not** flip then we get systematic shift in mean of data. This is the signature of T-violation.

Tests of the inverse square law at short ranges in the Lab.

Mk 2 SSTB



Torques measured at spacing of 5 μm

Hammond et al Rev Sci Inst in preparation.

Spin Source 1

•Manufactured at Imperial College (Tim Sumner, Diana Shaul, Geoff Rochester)

•Although flux containment is desirable, a closed magnetic loop comprising a single magnetic material produces zero spin coupling force!!!

•The potential, Φ, between a single fermion and the spin source can be written

$$\Phi = \int \vec{\rho}_s \cdot \vec{\nabla}\phi \, d^3r = -\int \phi(\vec{\nabla} \cdot \vec{\rho}_s) \, d^3r + \int \vec{\nabla} \cdot (\vec{\rho}_s \phi) \, d^3r$$

where

$$\phi(r) = -g_p g_s \frac{\hbar^2}{8\pi m_e} \left(\frac{e^{-r/\lambda}}{r} \right)$$

•The 1st term on the right hand side is zero

•The 2nd term on the right hand side can be written as a surface integral

$$\Phi = \int \phi \vec{\rho}_s \cdot d\vec{S}$$

•Thus a spin source without leakage field (with all spins tangential to its surface) does not produce a mass-spin coupling interaction potential.

Other things happening in Birmingham:

- Using the Mk 2 SSTB:
  - Test of the inverse square law at short ranges.
  - Precision measurement of Casimir force at 4K.

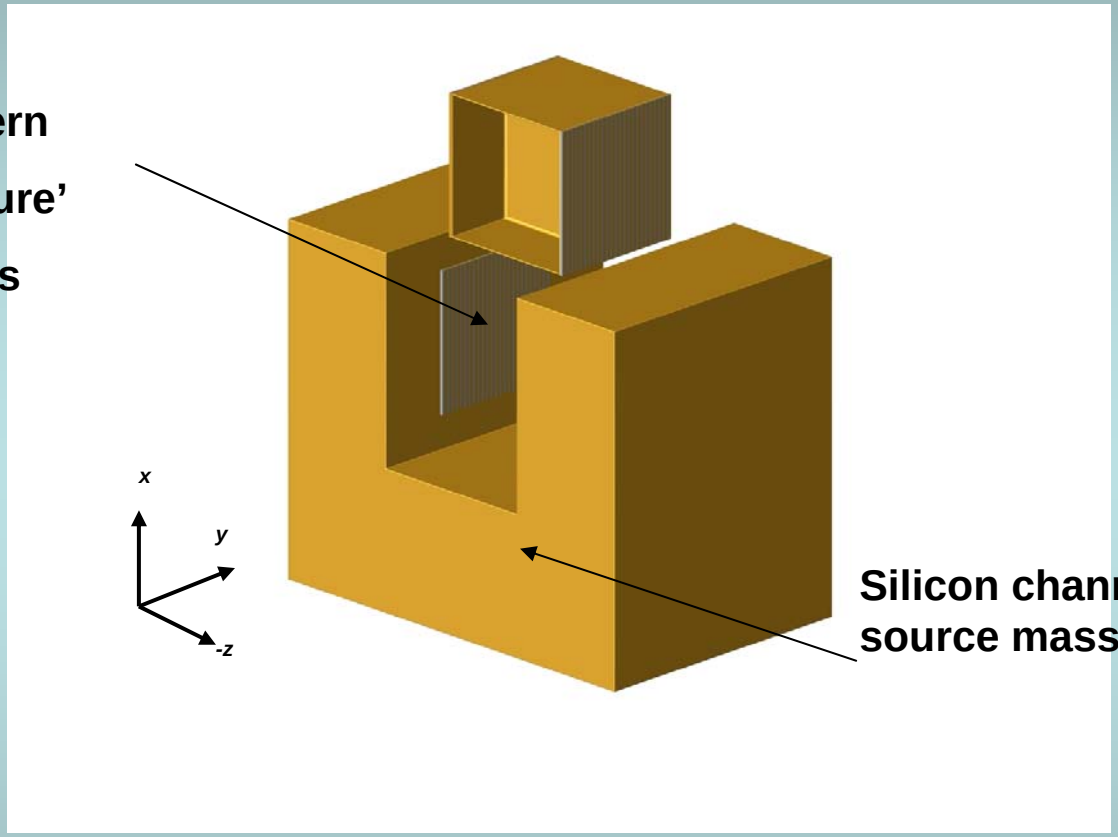
  Tony Matthews, Emanuele Rocco, Fabian Pena-Arellano.
- Development of homodyne interferometer for inertial control, possibly for LISA, and as a rotation sensor for the SSTB. Stuart Aston
- Search for cosmic spin field produced by spontaneous CPT and Lorentz violation using torsion-strip balance and angle interferometer.

Space test of inverse square law at 1 micrometer

Stripe pattern

in ‘quadrature’

to test mass pattern

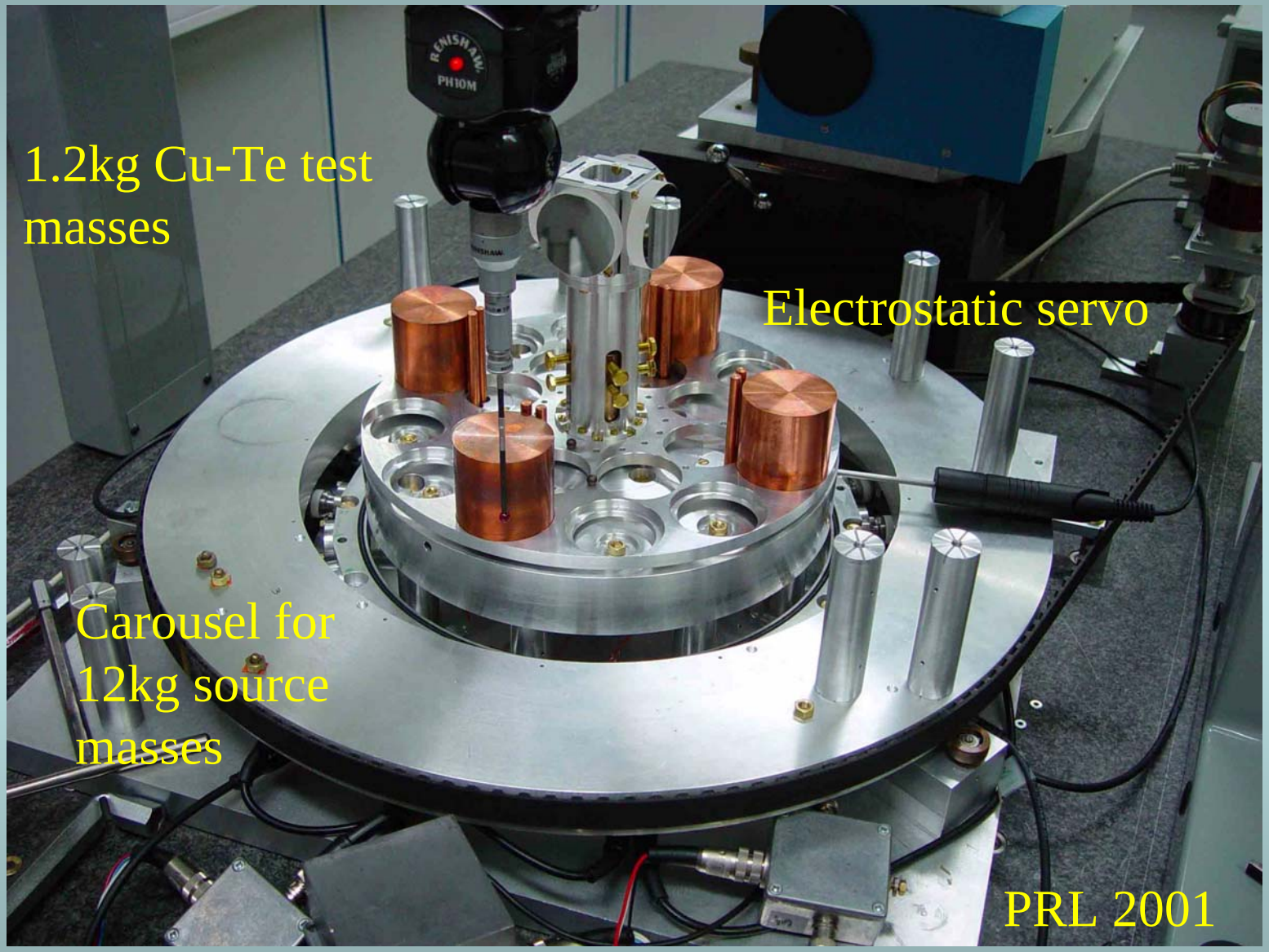


Silicon channel to support source mass stripes.

- **Motion of source mass channel in y direction by 10 pitches of pattern, nΛ, generates torque about x-axis at characteristic spatial/temporal frequency.**
- **Separation, *a*, of surfaces 1.3μm**

C.C.Speake, C.Trenkel and G.D.Hammond
General Relativity and Gravitation, 36, pp503-521 (2004)

Torsion strip balance: the ‘BIPM G-machine’.



Homodyne interferometer for inertial control