Tests of gravitation in the laboratory

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Cosmo 07, August 21st 2007

UNIVERSITY OF BIRMINGHAM

Talk Outline

- Motivation.
- Tests of the inverse square law (ISL) at short ranges.
- Tests for violation of Lorentz invariance.
- Summary.

Motivation

- The search for evidence for a coherent theory of quantum gravity.
- We would hope that the new theory would solve the hierarchy and the cosmological constant problem!
  - Such a theory may violate Lorentz and CPT symmetries.

Hierarchy Problem

- The problem lies in the difference between the energy scales that describe gravitation and the standard model:

$$V_3 = -\left(\frac{G}{\hbar c}\right)\cdot m_1 m_2 \frac{\hbar c}{r} \qquad V_3 = -\frac{1}{M_p^2}\cdot m_1 m_2 \frac{\hbar c}{r}$$

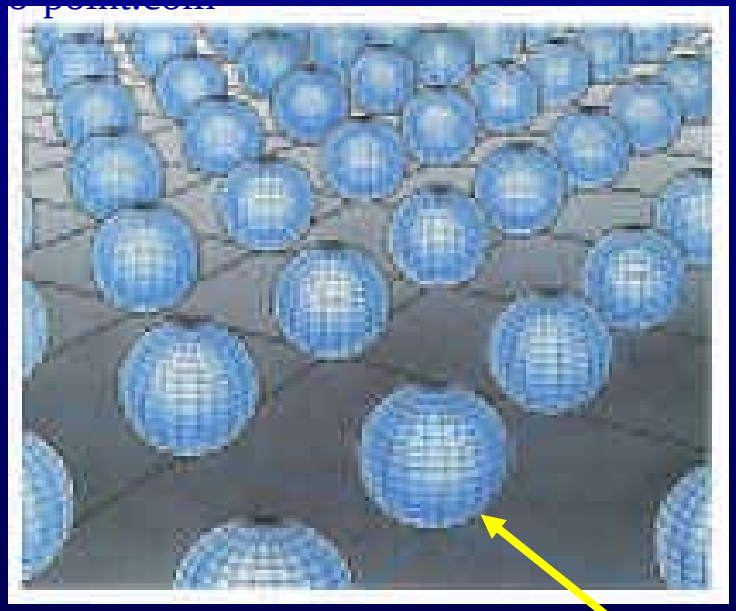
  - With $M_p \sim 10^{16}$ TeV/c^2

- Electro-weak unification scale is around 0.1TeV.

- LED hypthesis within String Theory proposes a new energy scale M_*.

The LED hypothesis

Imagine a 2-d space with ***1*** extra compactified dimension of radius R:

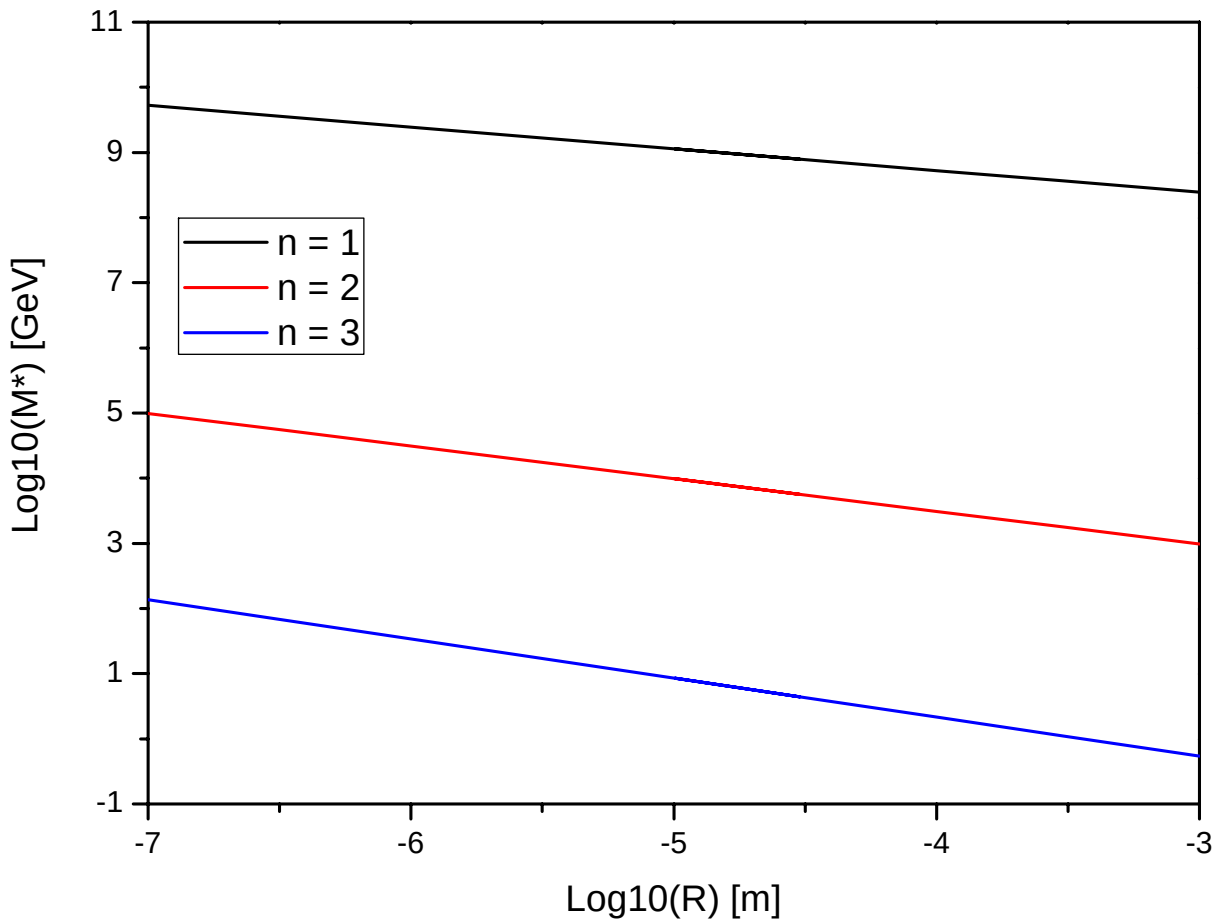


Imagine these to be circles!

- For r<<R, space is essentially 3-d. Get $1/r^2$ force law.
- For r>>R 'image' masses form a 'vertical' line charge. Get 1/r force and space is essentially 2-d.

Arkani-Hamed et al 1998

Relationship between M_* and R



LHC will reach 5 TeV

The Cosmological Constant Problem

- The length scale that characterises the Cosmological Constant problem can be easily calculated from the observed value of Dark Energy density, ρ_{obs} :

$$\rho_{obs} = \frac{\hbar c}{a^4}$$

- This generates deviations from the ISL at ranges $\lambda = a/2\pi = 14\ \mu m$.
- The SLED hypothesis.

Motivation

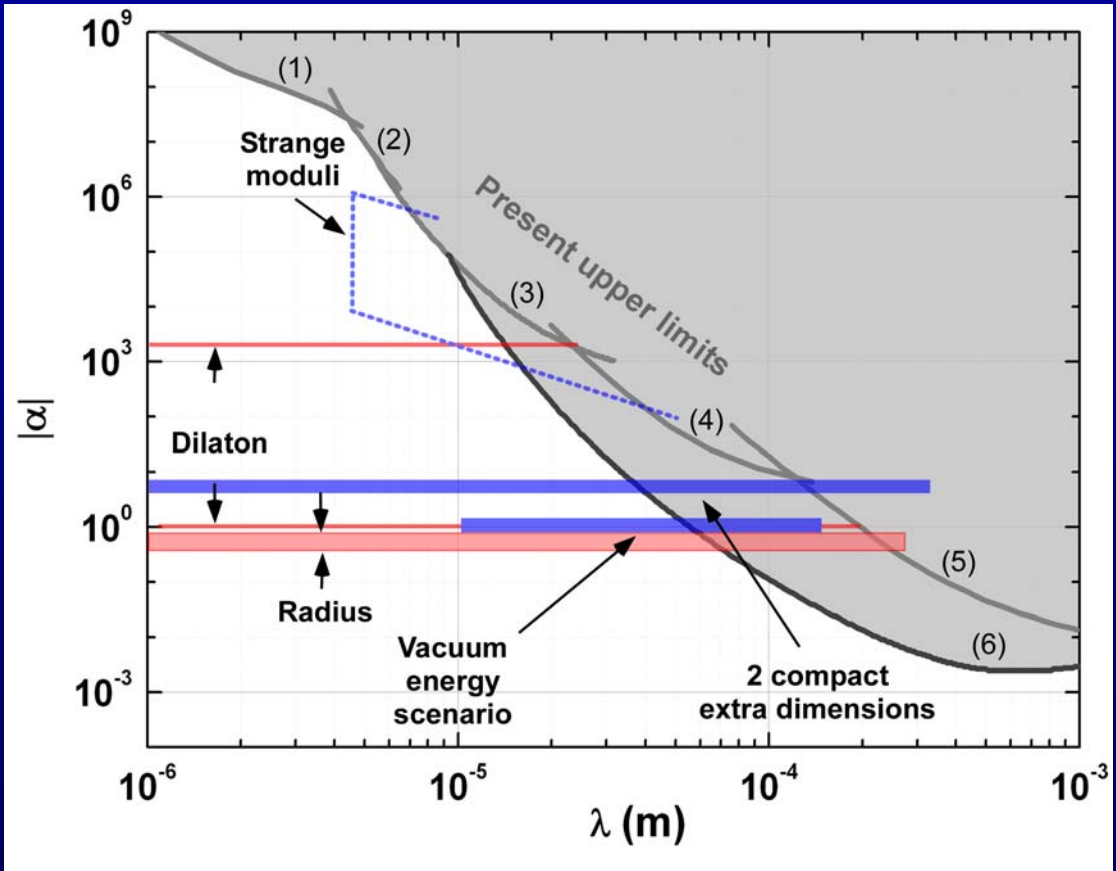
- The signature for the breakdown of ISL can be parametrised as:

$$r \geq R_i$$

$$V = -\frac{G_3 m}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

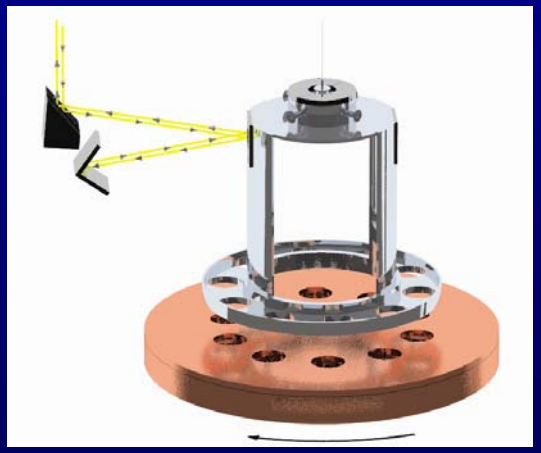
- Many other theoretical predictions to be tested:
  - Chameleons
  - Moduli, dilatons, axions…

Current constraints to violations of the ISL



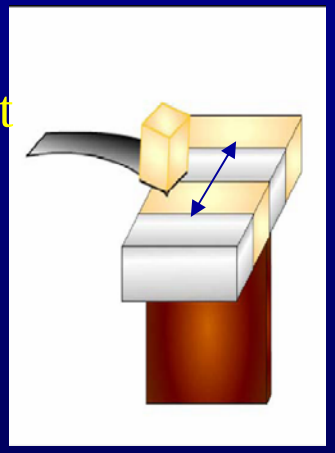
Searches for a violation of the ISL

Adelberger and colleagues, the Eot-wash collaboration.



Mass separation 56 μm with 10 μm shield.

Kapitulnik and colleagues

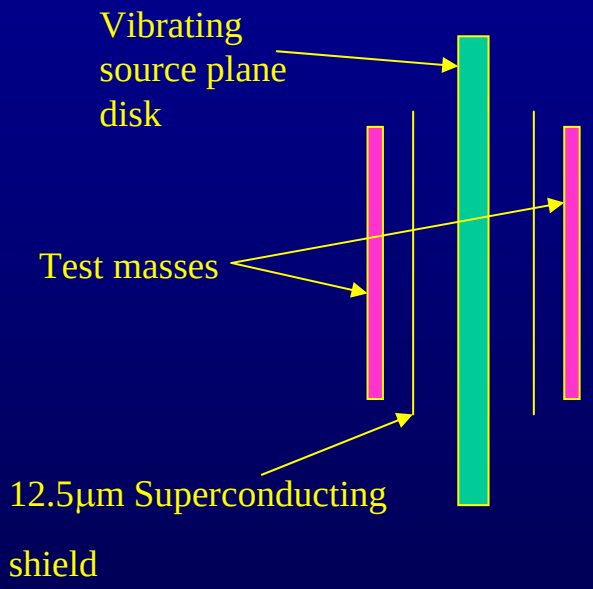


Mass separation 25 μm with 3 μm shield.

Searches for a violation of the ISL

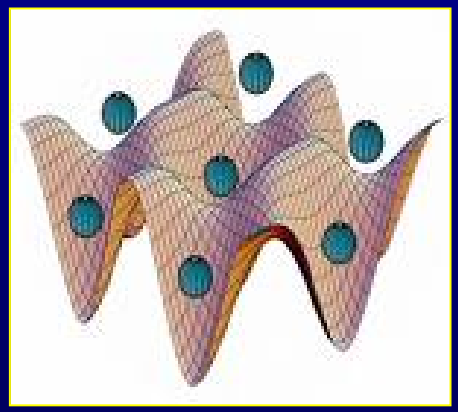
University of Maryland

H-J Paik University of Maryland



Cryogenic expt, source mass motion of +/-50μm

Cold Atom methods eg Ferrari et al PRL 2006



Bloch Oscillations

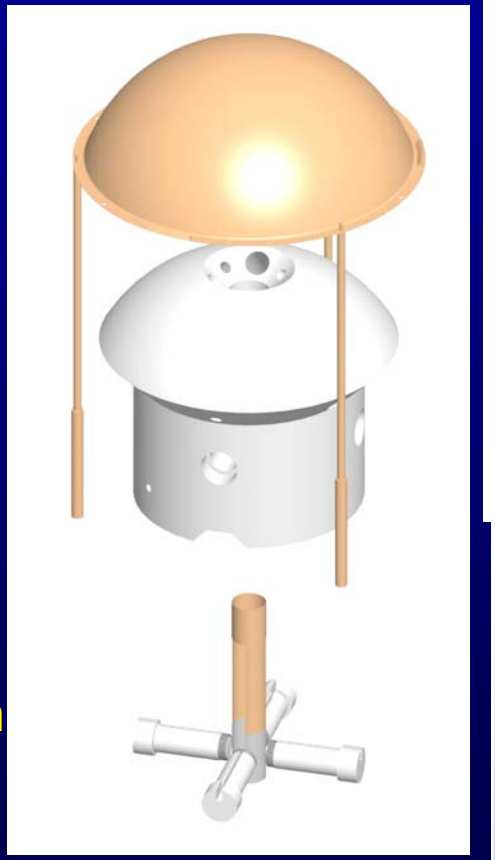
$\nu = mg\Lambda/2h$

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
- 7×10^{-14} Nm/$\sqrt{Hz}$
- Optimised for Short Ranges
- Based on Lead

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

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The SSTB and Search for forces coupling mass to intrinsic spin

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

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

  which can violate P and T on a macroscopic scale

- Axions are well motivated and possible dark matter candidates (20 μm <λ< 20 cm or 1 μeV<E<10 meV) and violate the ISL.

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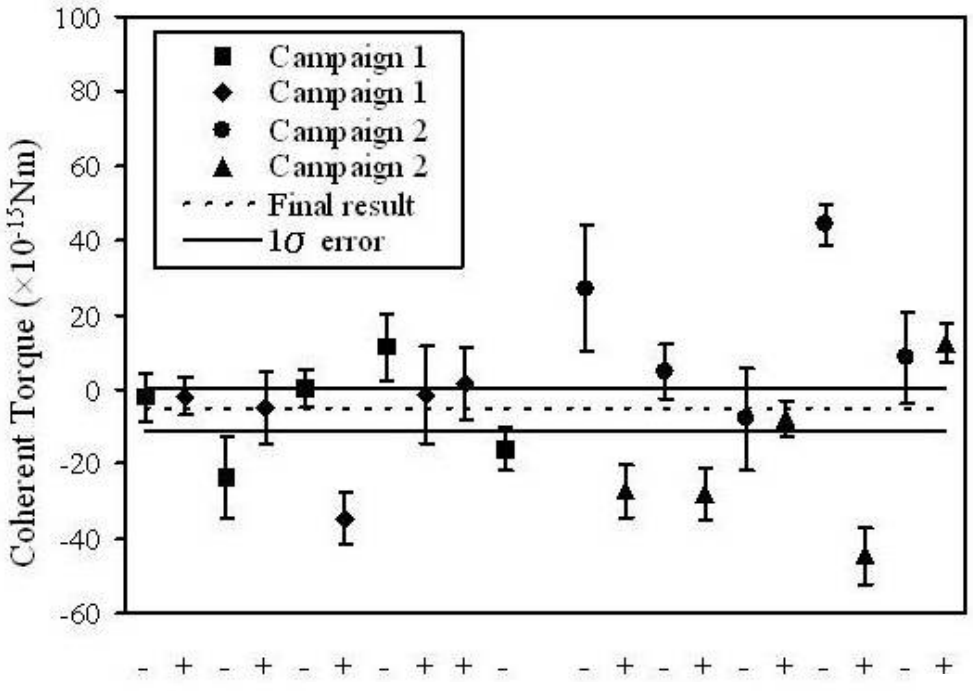
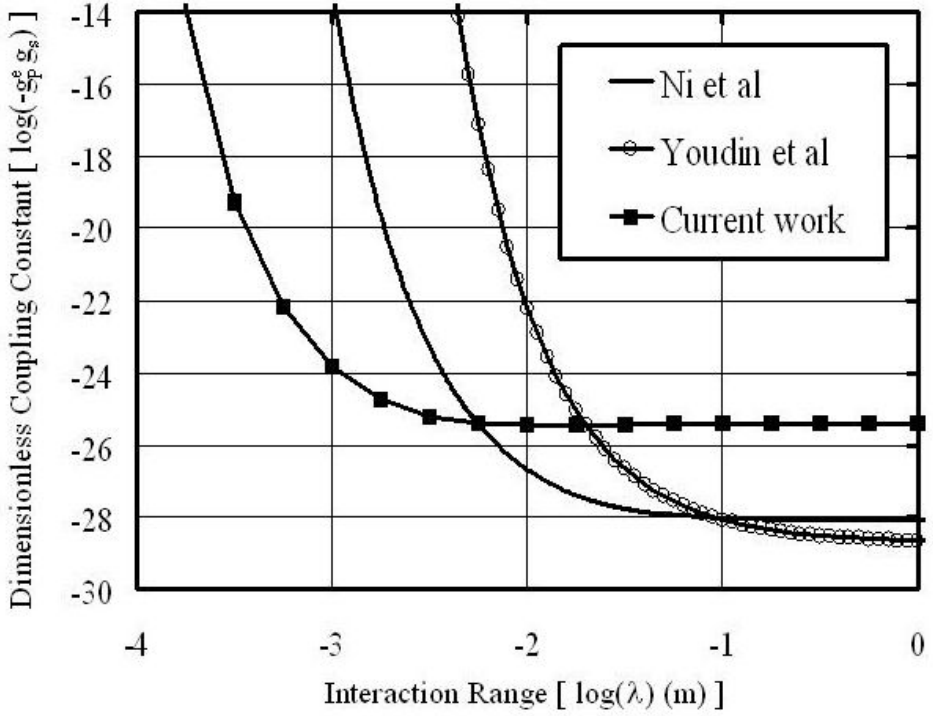


Search for new forces coupling mass to intrinsic spin.

$=(-5.4\pm(3.8)_{stat}\pm(4.2)_{sys})\times10^{-15}$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



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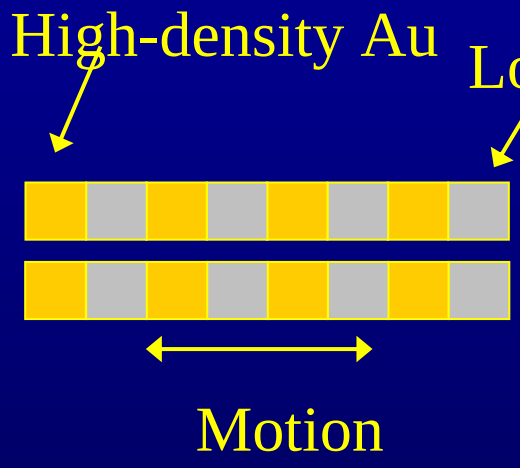
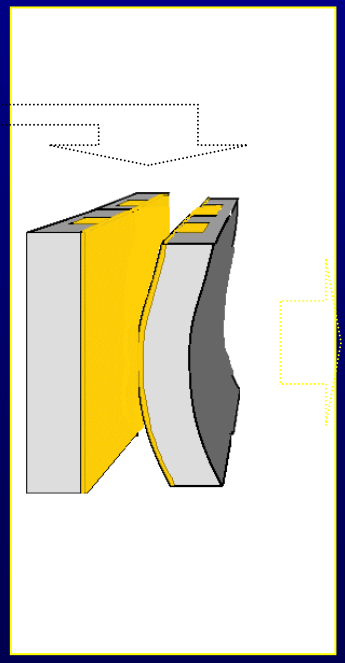
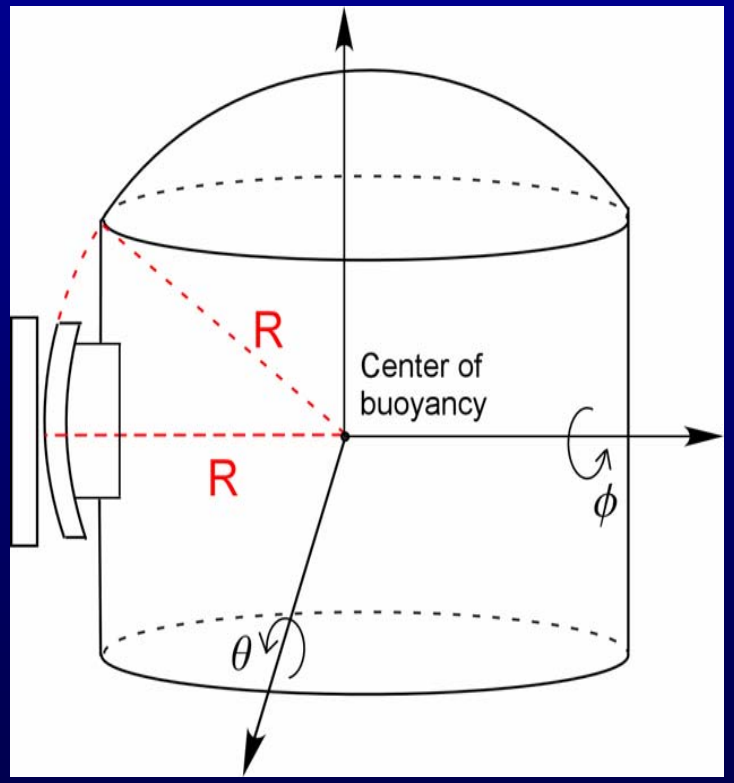
Physical Review Letters, **98**, 081101, 2007

ISL test at Birmingham: concept design





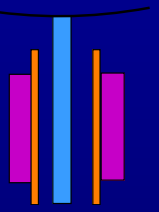
Test masses manufactured at RAL

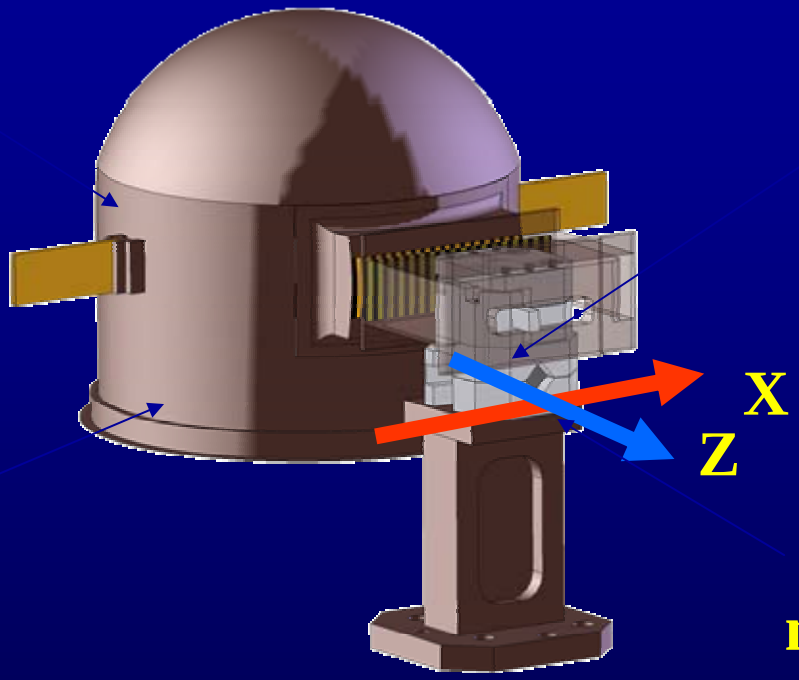


Mk2 float design

ISL test: experimental setup

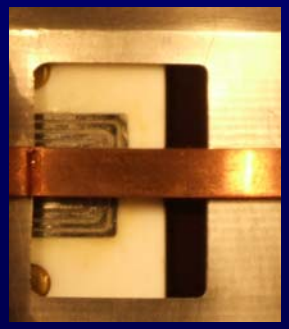
Capacitive readout



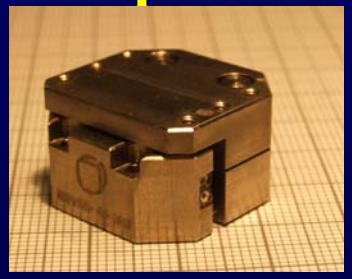


Test masses

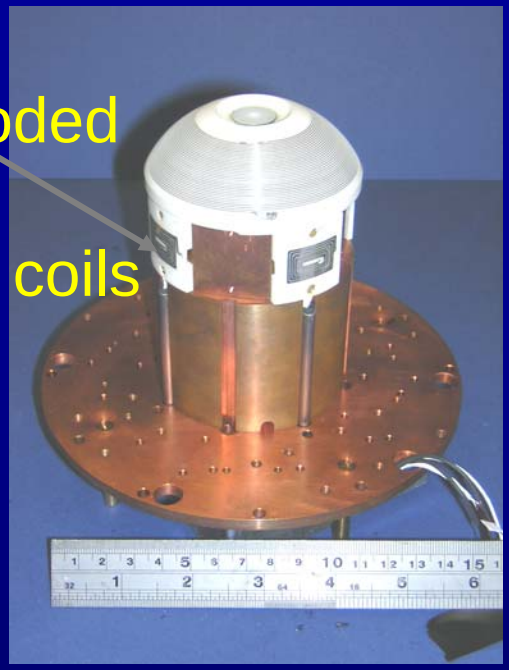
Magnetic actuation

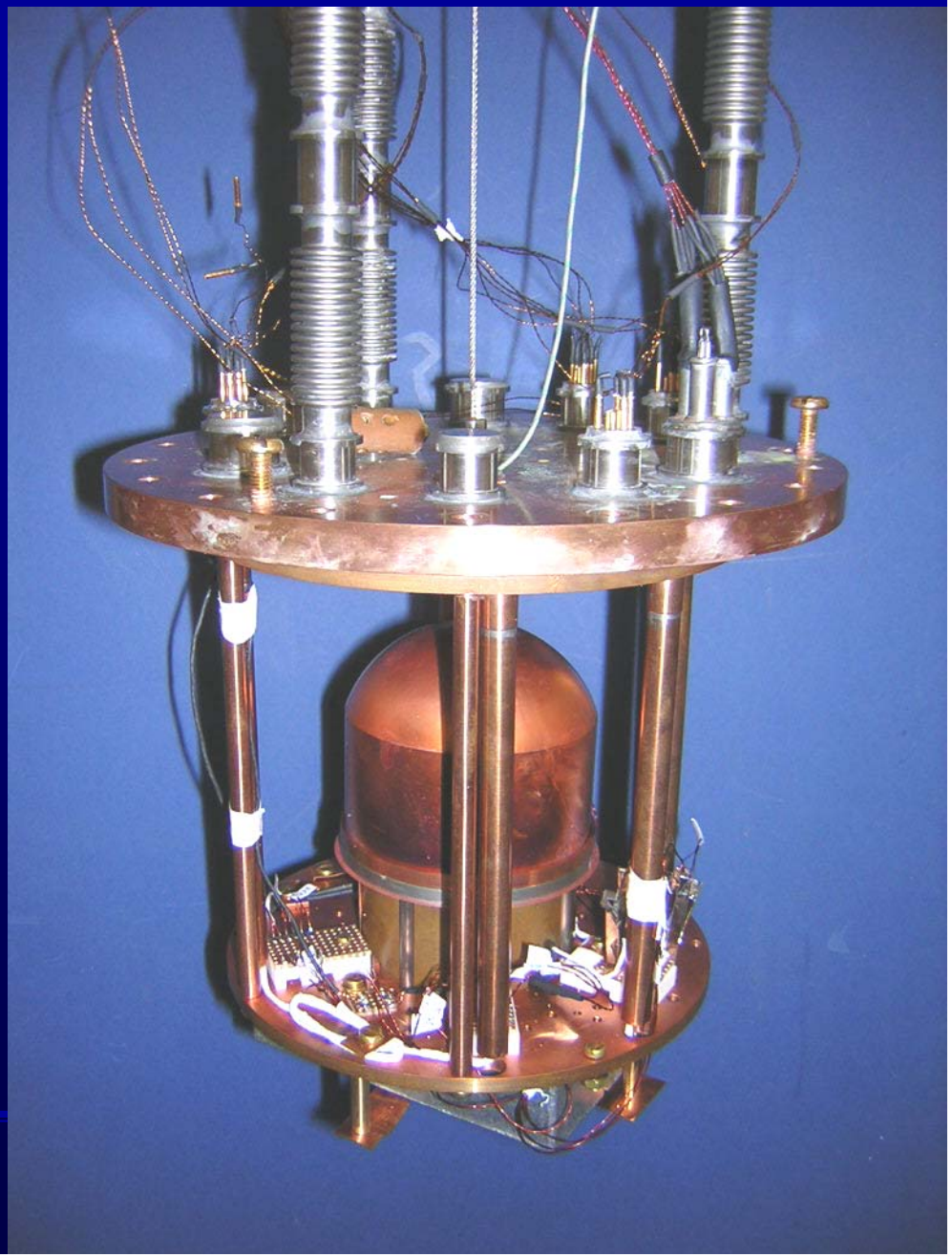


Attocube manipulators

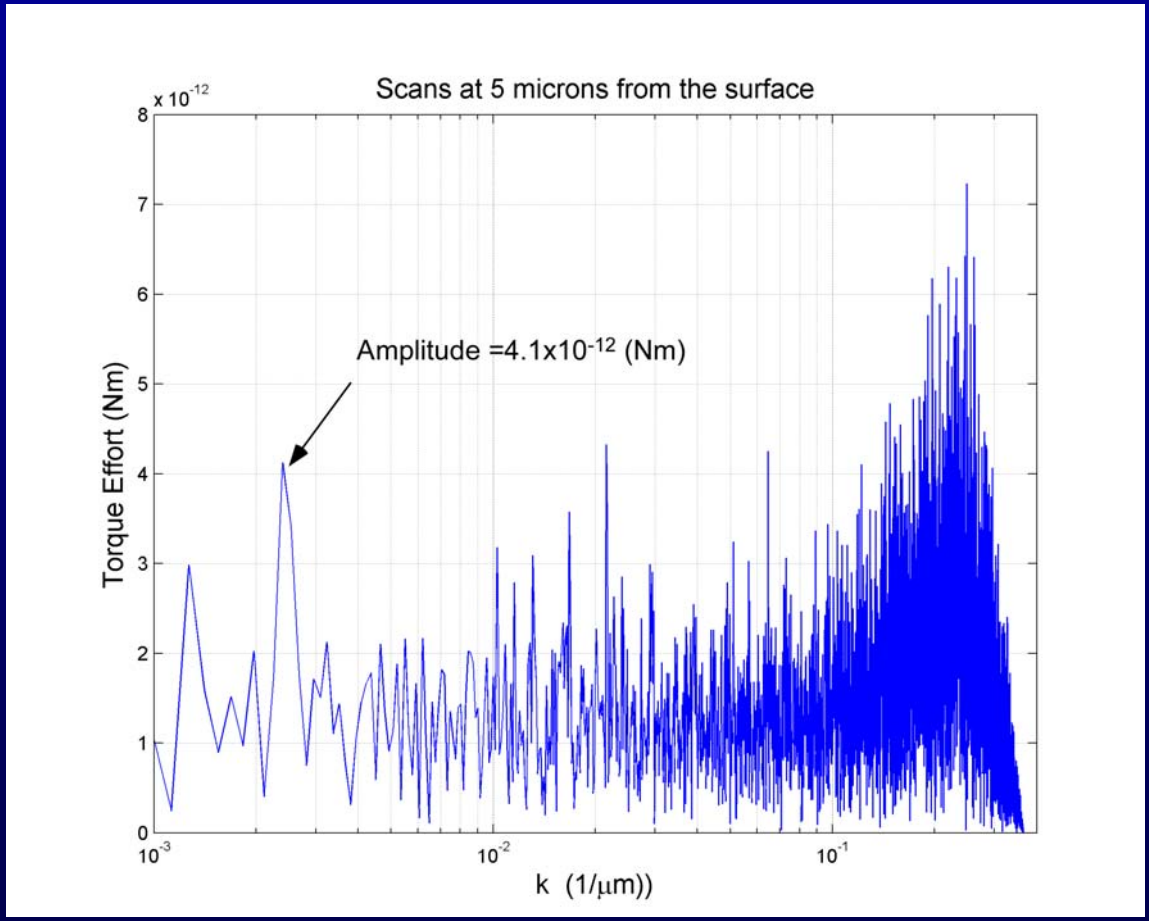


Spark eroded
Nb foil
feedback coils





Tests of the inverse square law at short ranges.



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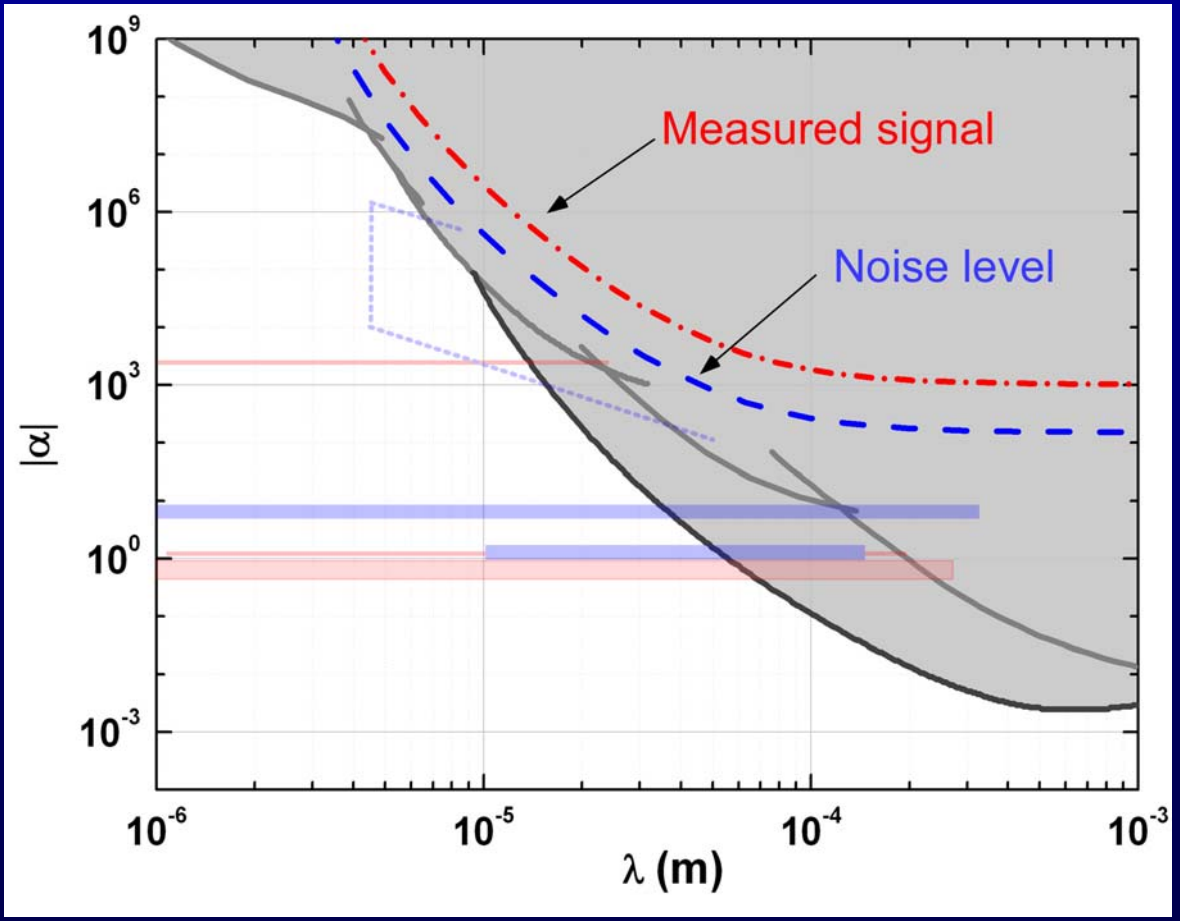
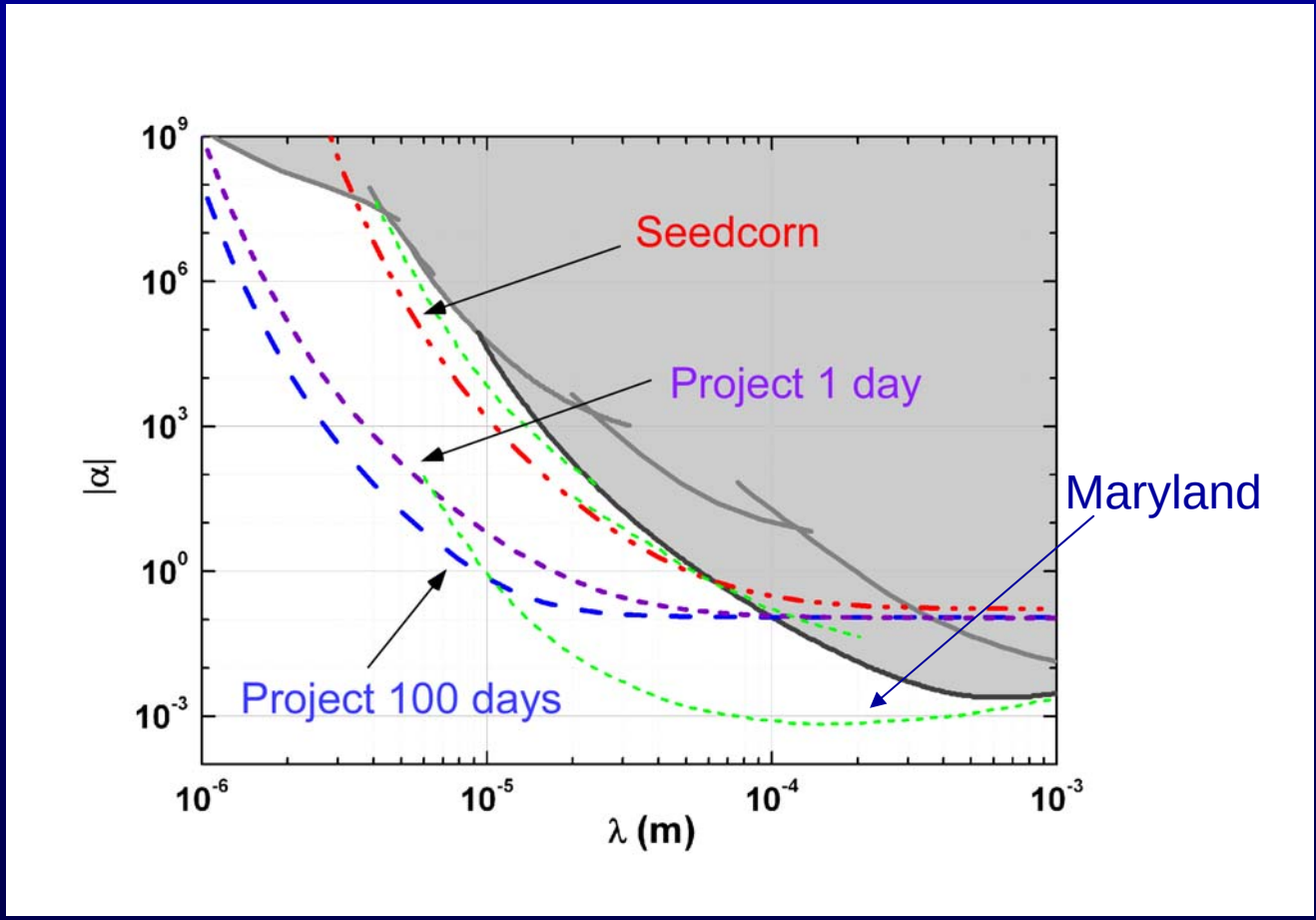


Error Budget

Systematics	**notes**	**Torque compared with nominal target of 6×10^{-19}Nm**
Casimir/ plasma wavelength	Au/Cu	1.7×10^{-22}
Casimir/corrugation*	Corrugation amp=100 nm, surface separation 8 μm/ 1μm Au layer on each surface, force calculated to 10%	2.3×10^{-19}
Electrostatic/corrugation	Voltage difference 0.3 mV	1.6×10^{-19}
Contact potential	Contact potential 2 μV	3.3×10^{-19}
diamagnetism	Au/Cu with background 4 μT	4×10^{-20}
Newtonian force*	Calculated to 10%	7×10^{-19}
RMS		**8.2×10^{-19}Nm**
Statistical uncertainty		**Torque noise compared with nominal level of 2×10^{-15}Nm/Hz$^{1/2}$**
Float metrology	Fractional ellipticity=10^{-3} Horizontal vibration spectrum 10^{-5}ms^{-2}/Hz$^{1/2}$. 50g float.	1×10^{-15}
Trapped flux	100 Gauss trapped field, Nb thin films.	1.3×10^{-20}
Moment of inertia asymmetry	1% asymmetry	1.5×10^{-17}
Read-out noise	Interferometer with 1/f noise reduction of factor 120.	1×10^{-15}
Thermal noise	Q=10^4	5×10^{-16}
RMS torque with 6 months integration time		**1.5×10^{-15}Nm/Hz$^{1/2}$** =2.7×10^{-19}Nm
TOTAL uncertainty		**8.6×10^{-19}Nm**

STFC proposal.

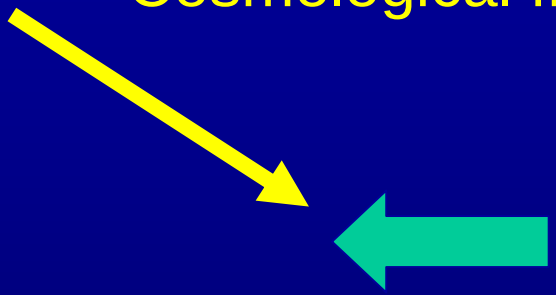


Test for violation of Lorentz symmetry

- String Theory must violate Lorentz invariance as strings have a finite size!

- Kostelecky and colleagues have proposed that violations of Lorentz invariance (and CPT) can be interpreted as relics of an underlying quantum gravity theory (which is valid at the Planck scale).

Experimental concept

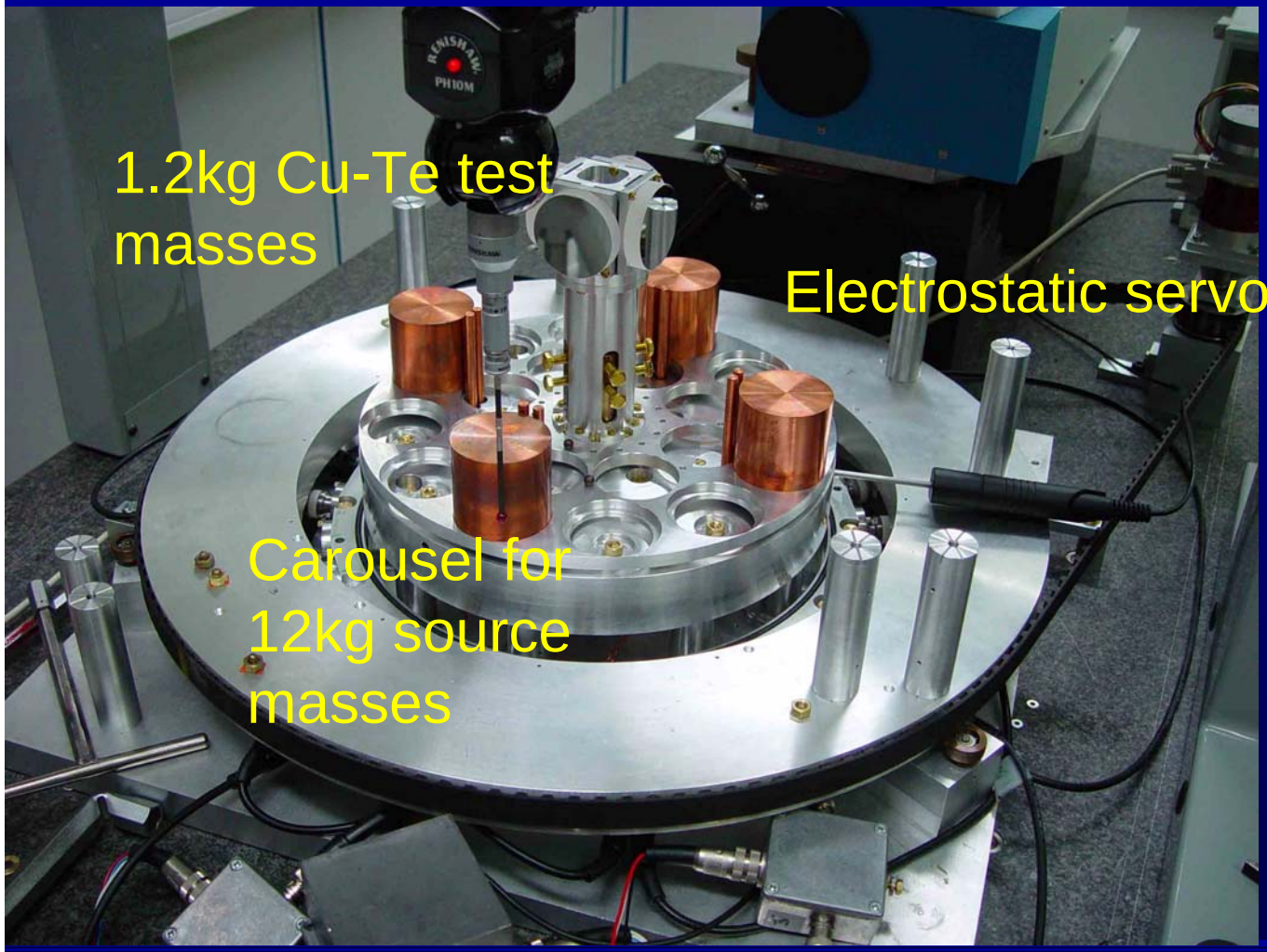


Induced torque: $\vec{\Gamma} = N_s \hat{\sigma} \times \vec{b}_e$

Heckel et al (2006) used a rotating, torsion balance to set the limit: $b_e < 2 \times 10^{-21}$ eV

Predicted levels for violation arise from combinations of ratios of M_{EW}, M_p, m (particle masses). Naturally small.

The G-machine currently at BIPM



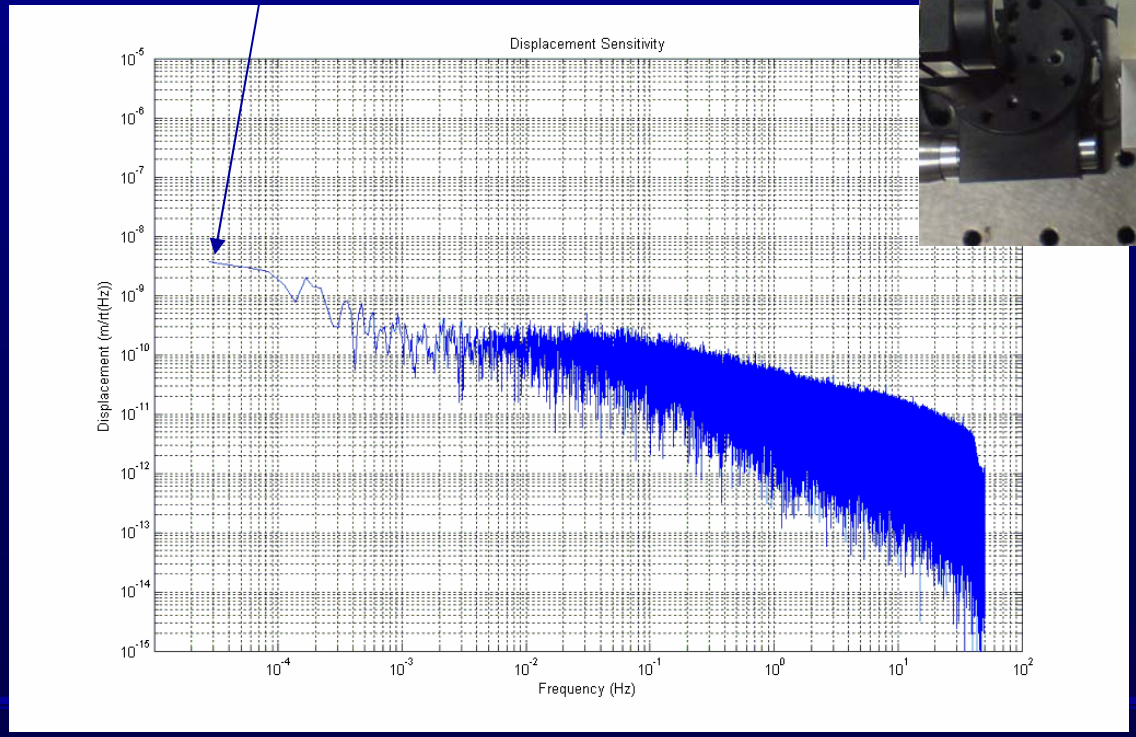
Torsion strip balance:

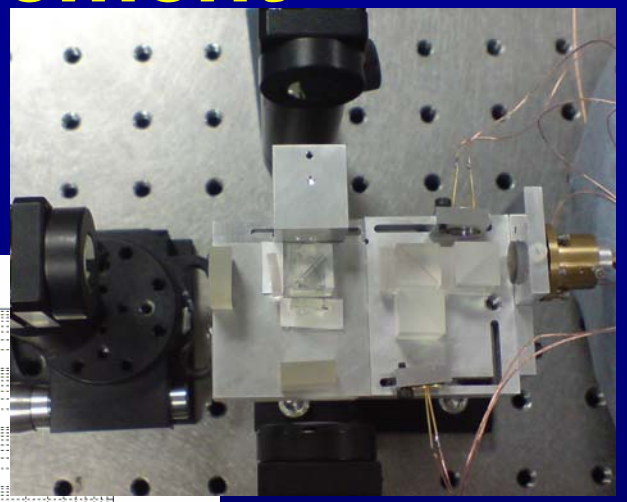
- 96% of restoring torque is gravitational
- Q ~3 x 10^5 with Be Cu strip.
- Period 125s
- better signal to thermal noise than round fibre.

Quinn, CCS et al PRL 2001

Polarising homodyne with novel optics to measure angular displacement

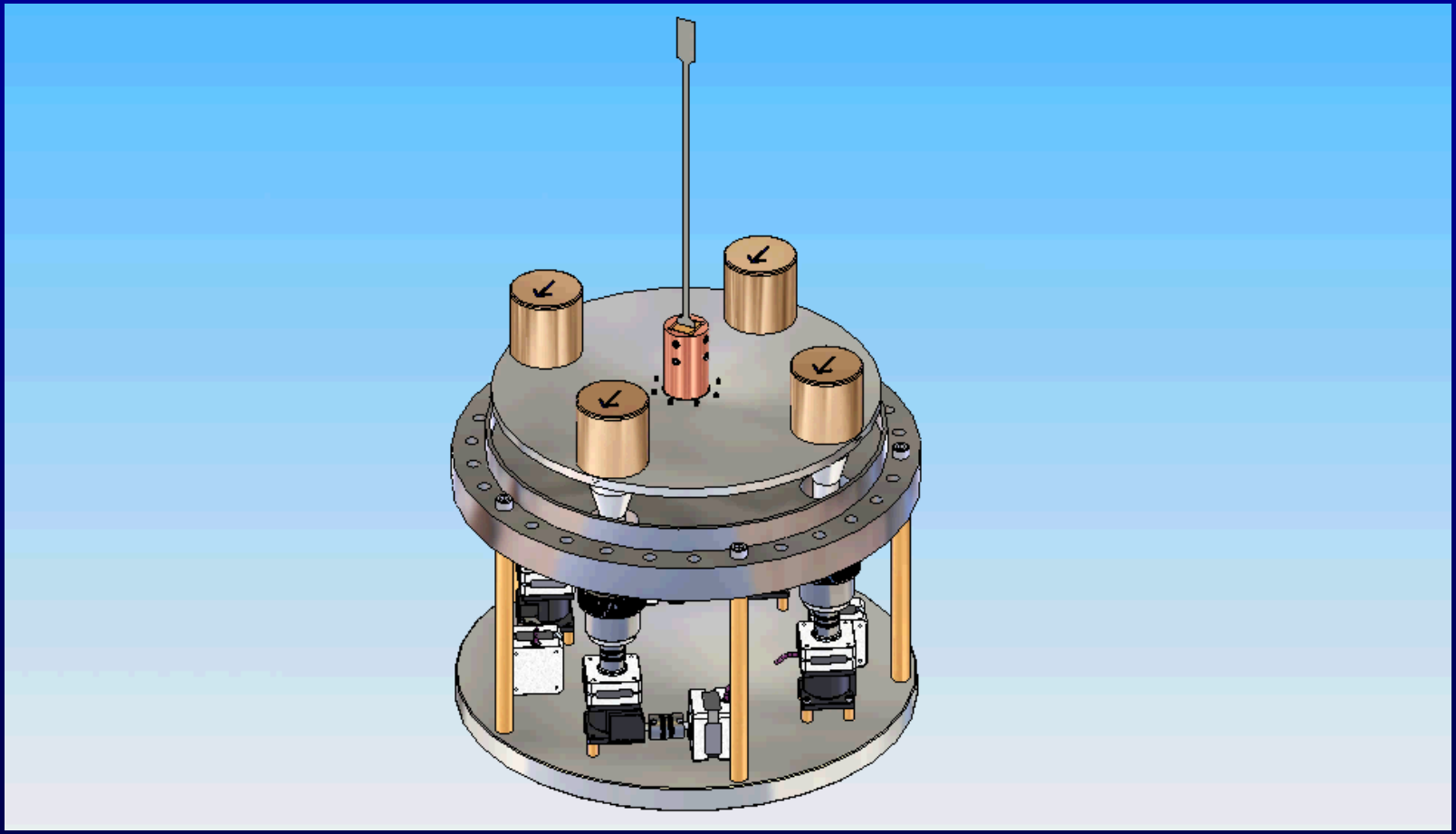
4nm/Hz$^{1/2}$ at 30μHz





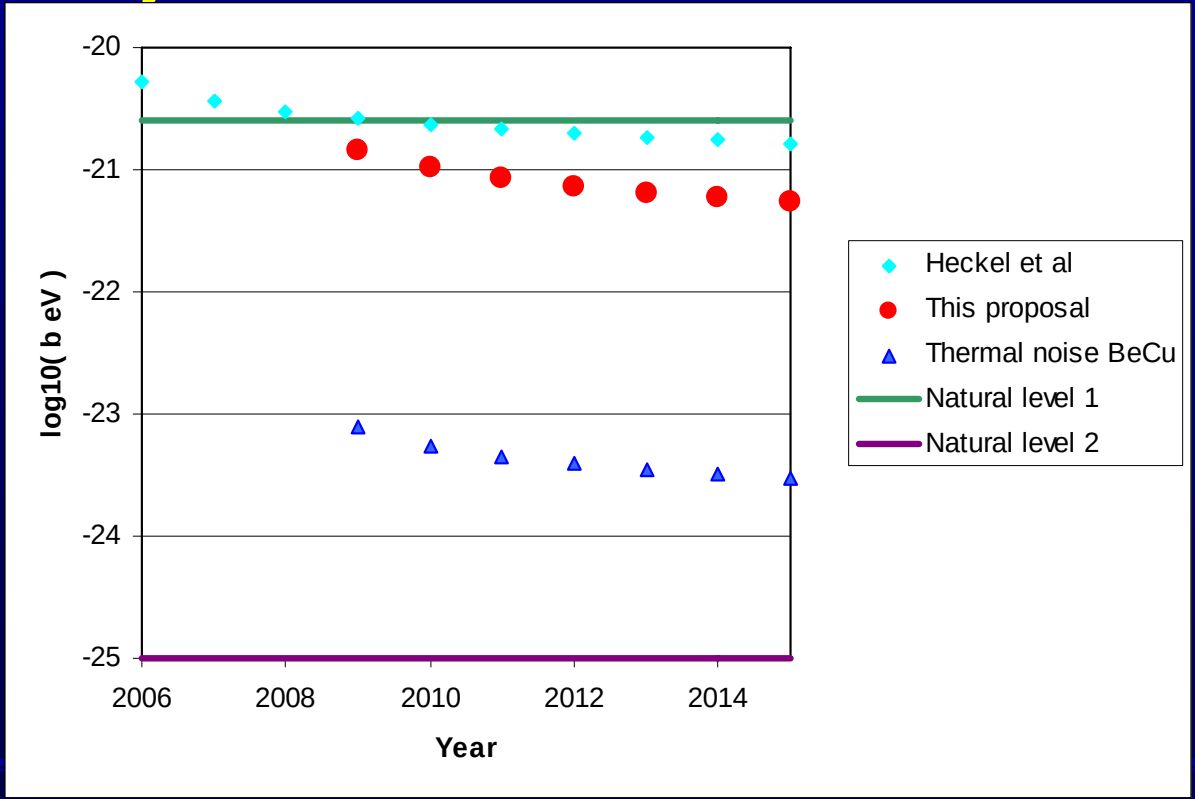
EUCLID
Developed for drag-free control and for the SSTB.

Spin-modulation scheme



Test for violation of Lorentz symmetry

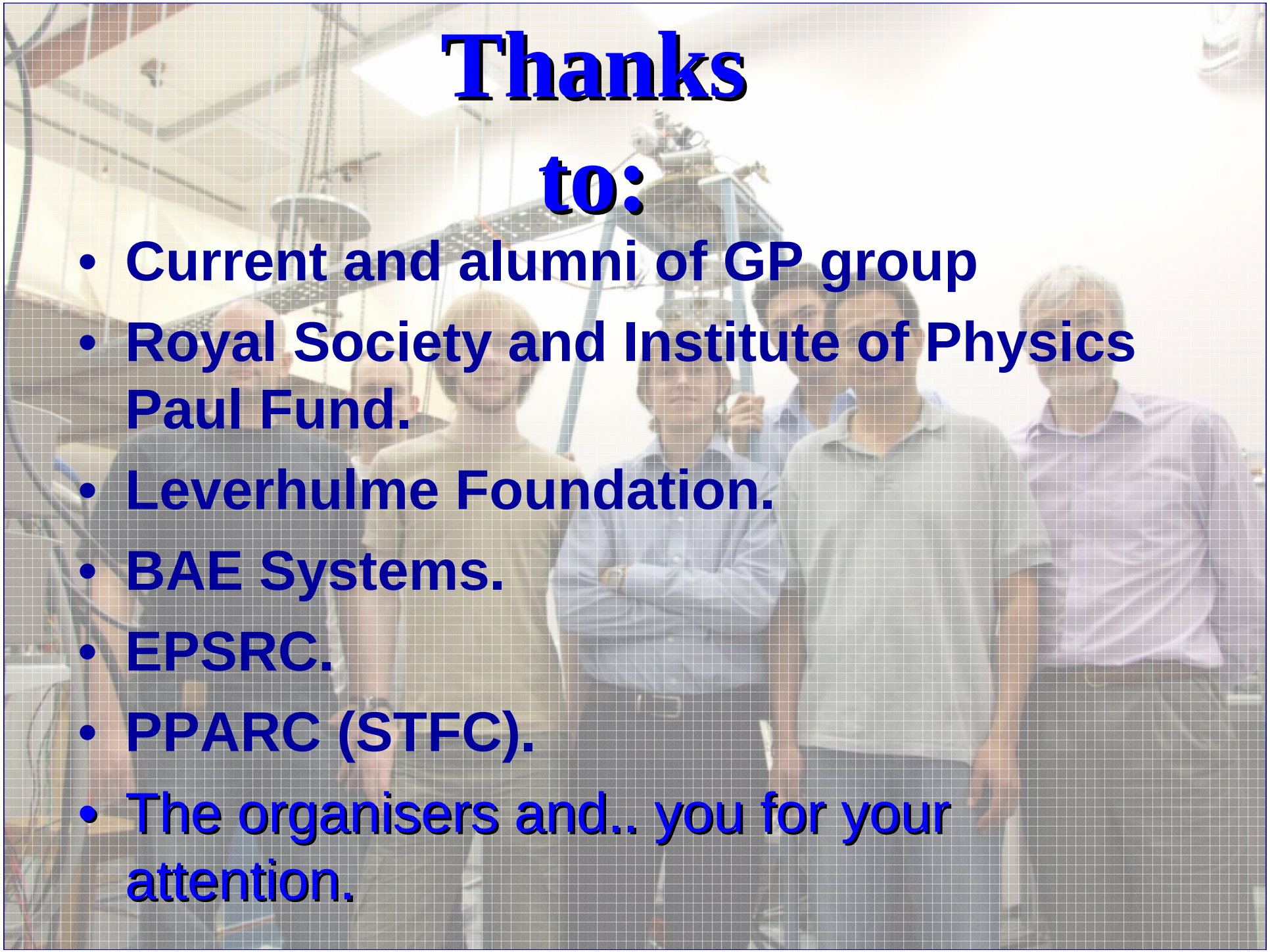
- **Perform search for cosmic spin-field with unprecedented precision. We can improve on Heckel et al. by a factor of 2.5 after 3 years.**



Projected sensitivity assuming $(t)^{-1/2}$ scaling

Summary

- We have set new limits on new interactions coupling mass to intrinsic spin with a new instrument (SSTB).
- Laboratory experiments can search for evidence for proposed theories that unify gravitation and quantum field theories.
- At Birmingham we are developing experimental methods that could shed light on the hierarchy and cosmological constant problems and also could detect residual violations of Lorentz invariance due to an underlying theory of quantum gravity.



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.

The LED hypothesis

$r << R$

$$V = -\frac{G_{3+n} m_1 m_2}{r^{1+n}} = -\frac{G_{3+n}}{\hbar c \Lambda^n} \cdot m_1 m_2 \cdot \frac{\hbar c}{r}\left(\frac{\Lambda}{r}\right)^n$$

$$\Lambda = \frac{\hbar}{M_* c} \qquad G_{3+n} = \frac{\hbar c}{M_*^{\,2}} \Lambda^n$$

$r >> R$

$$V = -\left(\frac{\hbar c}{M_p^2}\right)\frac{m_1 m_2}{r} \approx -\frac{\hbar c}{M_*^{\,2}} \frac{\Lambda^n}{(2\pi R)^n} \frac{m_1 m_2}{r}$$

Motivation

- Arkani-Hamed, Dimopoulos and Dvali boldly suggested that the gauge-hierarchy problem could be solved if up to 3 compactified dimensions were macroscopic! The LED hypothesis lowers the energy scale for gravity, M_*, to the Electro-weak scale.

- The dimensions are curled-up into toroids or spheres of radii R.

- Newton's inverse square law (ISL) would turn into $1/r^{2+n}$ for n LED's for mass spacings r<<R.

Arkani-Hamed et al Phys Lett B 1998