

Tests of gravitation in the laboratory

Clive Speake

Giles Hammond, Tony Matthews,
Emanuele Rocco, Fabian Pena-Arellano.
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:

$$V_3 = -\left(\frac{G}{\hbar c}\right) \cdot m_1 m_2 \frac{\hbar c}{r}$$

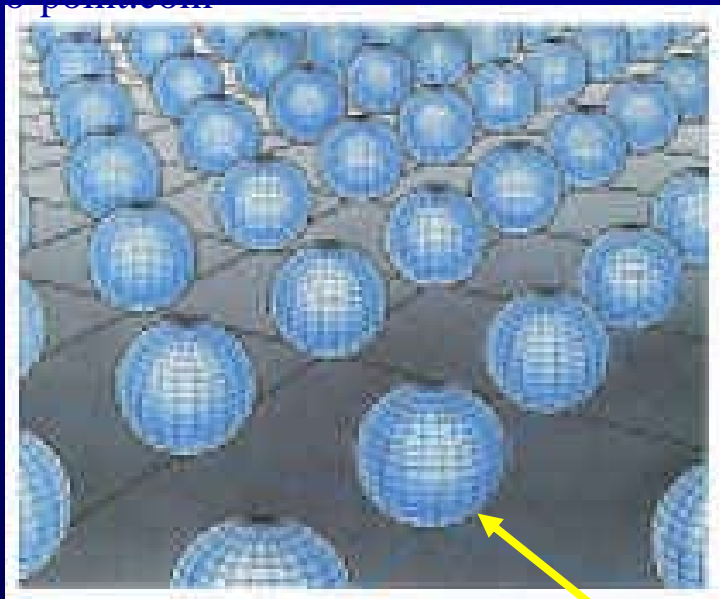
$$V_3 = -\frac{1}{M_p^2} \cdot m_1 m_2 \frac{\hbar c}{r}$$

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

- Electro-weak unification scale is around 0.1 TeV.
- LED hypothesis within String Theory proposes a new energy scale M_* .

The LED hypothesis

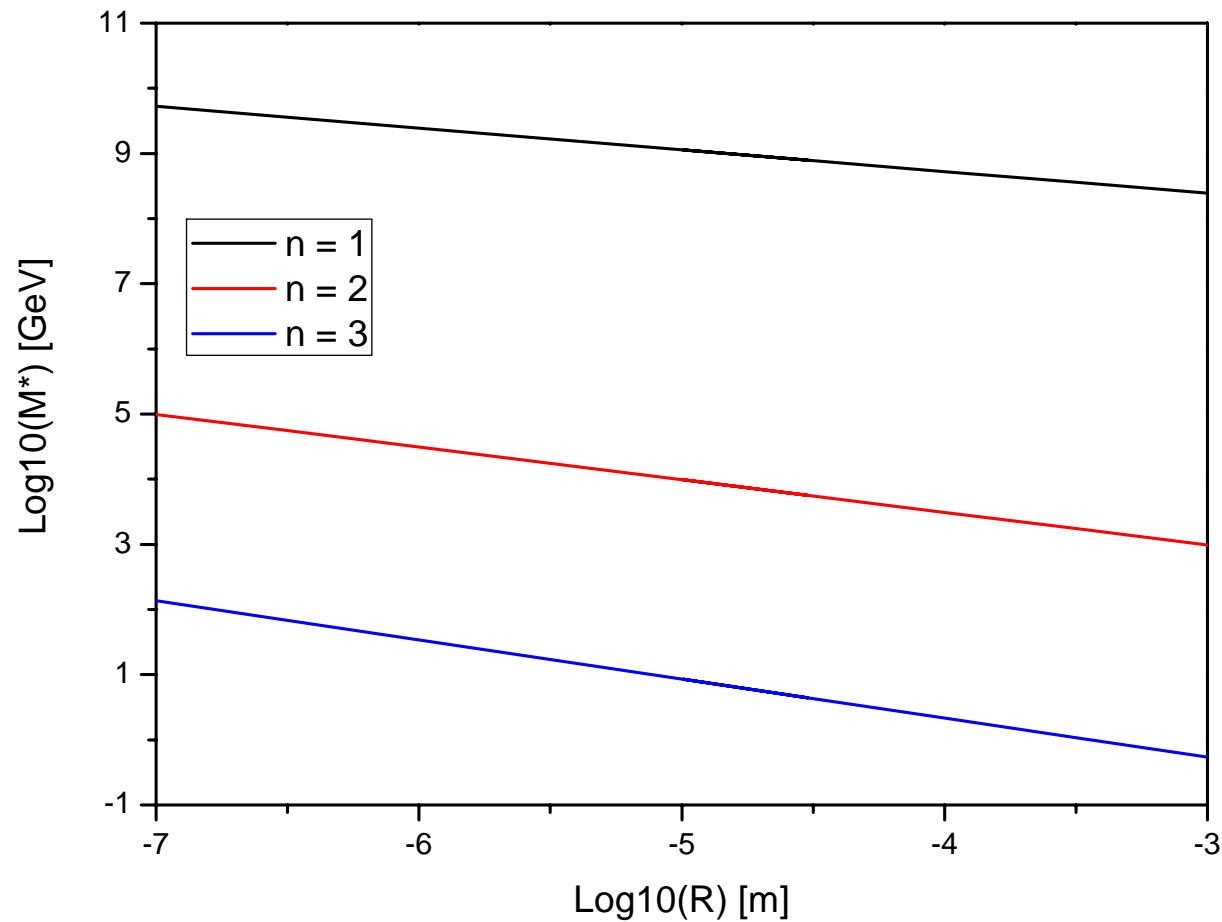
Imagine a 2-d space with **1** extra compactified dimension of radius R :



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

Imagine these to be circles!

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 $\lambda = a/2\pi = 14 \mu\text{m}$.
- The SLED hypothesis.

Motivation

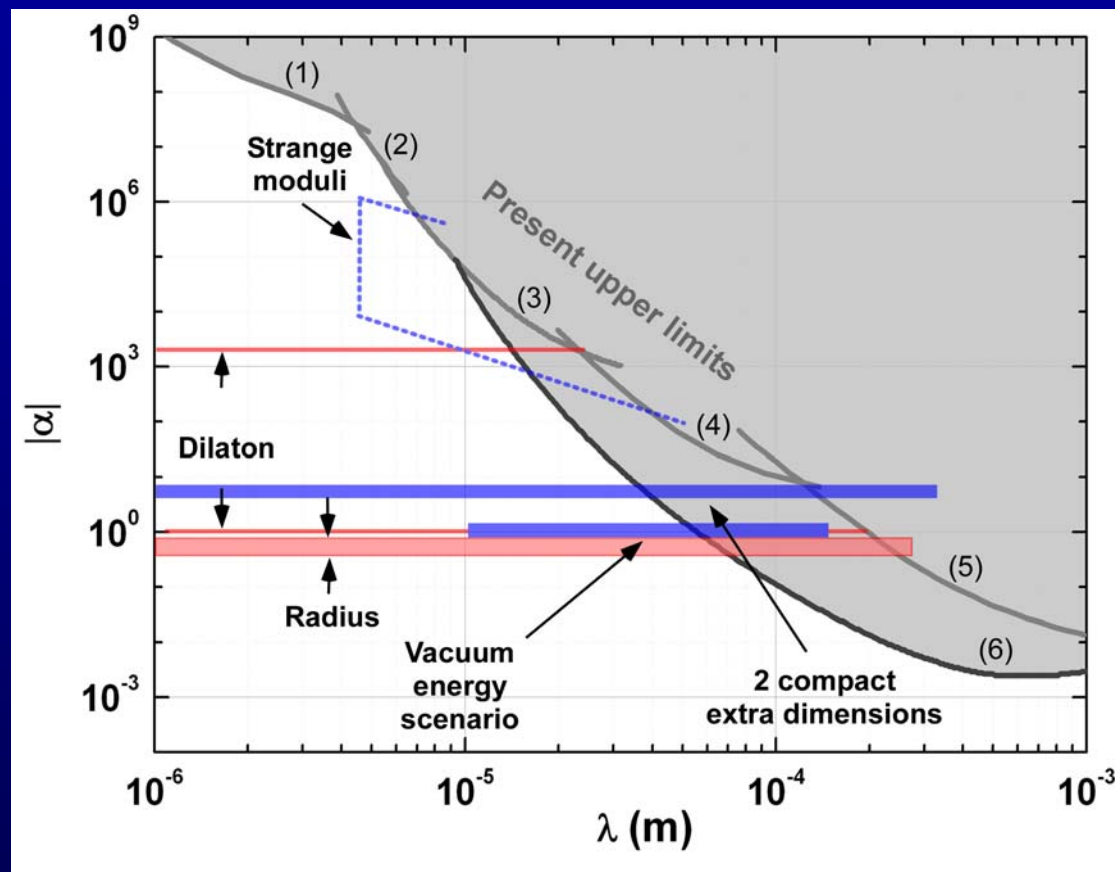
- The signature for the breakdown of ISL can be parametrised as:

$$r \geq R_i$$

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

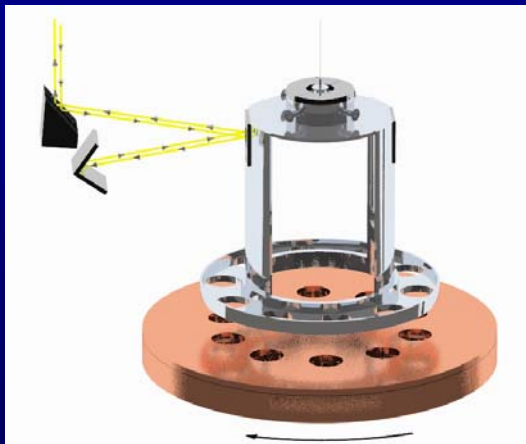
- Many other theoretical predictions to be tested:
 - Chameleons
 - Moduli, dilatons, axions...

Current constraints to violations of the ISL



Searches for a violation of the ISL

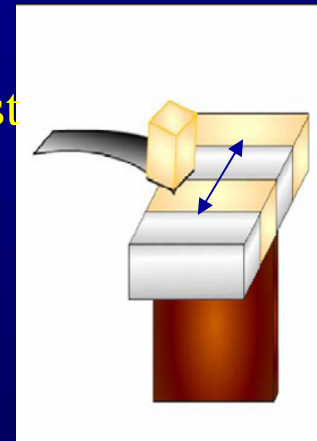
Adelberger and colleagues,
the Eot-wash collaboration.



Mass separation $56\text{ }\mu\text{m}$ with
 $10\text{ }\mu\text{m}$ shield.

Kapitulnik and colleagues

Gold Test
Mass



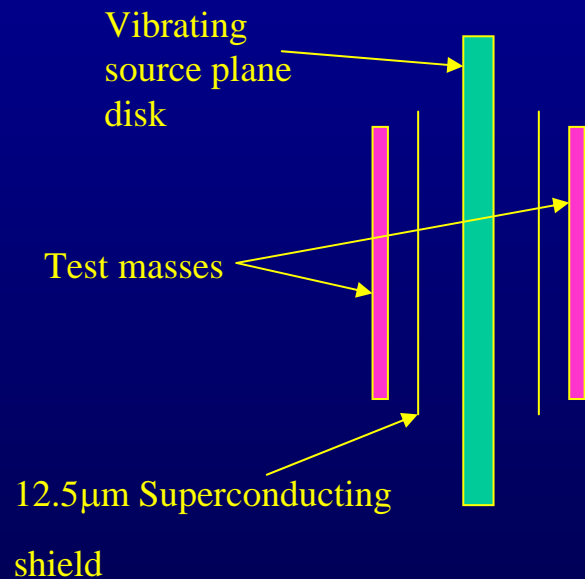
Au/Si
Drive Mass

Mass separation $25\text{ }\mu\text{m}$
with $3\text{ }\mu\text{m}$ shield.

Searches for a violation of the ISL

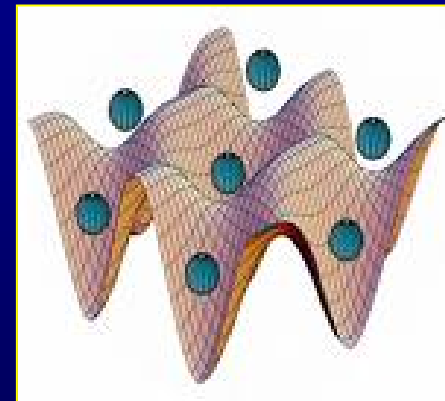
University of Maryland

H-J Park University of Maryland



Cryogenic expt, source
mass motion of $\pm 50\mu\text{m}$

**Cold Atom methods eg Ferrari
et al PRL 2006**



Bloch Oscillations

$$v = mg\Lambda/2\hbar$$

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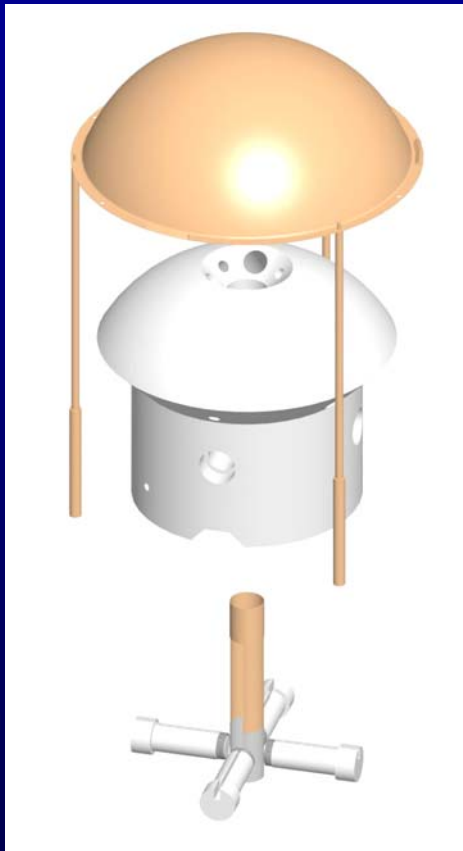
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Spherical Superconducting Torsion Balance (Mk1 SSTB)

Float

Levitation
bearing

Rotation
detector



Key Features

- Meissner Effect Suspension
 - Spherical Symmetry
 - Programmable Stiffness
($\tau=200\text{s}-20\text{s}$)
- SQUID Angular Readout
 - $7 \times 10^{-14} \text{ Nm}/\sqrt{\text{Hz}}$
- 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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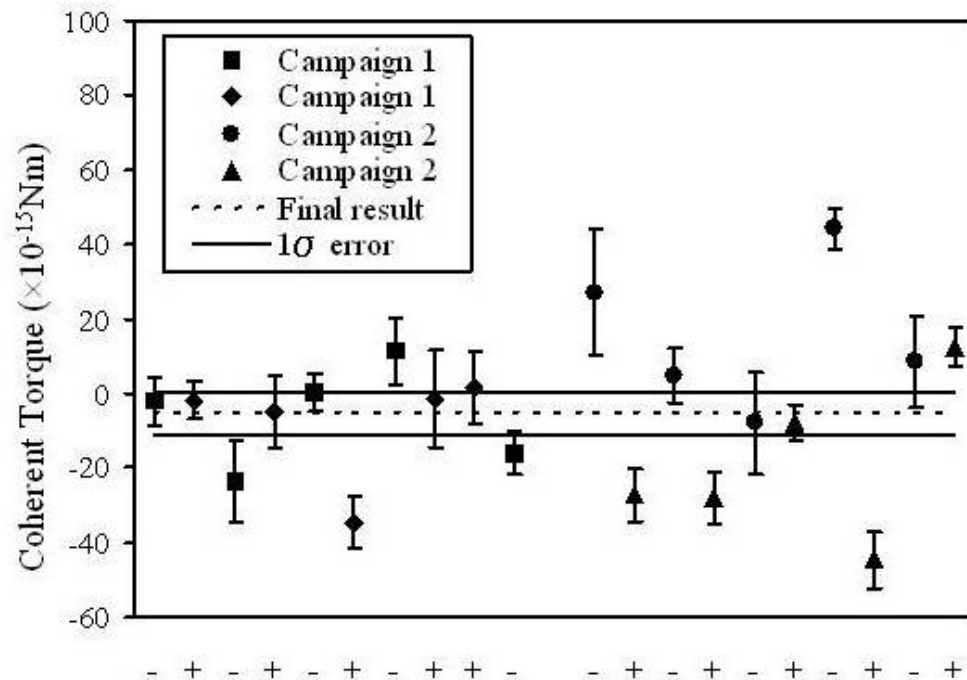
The SSTB and Search for forces coupling mass to intrinsic spin

- 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 ($20 \mu\text{m} < \lambda < 20 \text{ cm}$ or $1 \mu\text{eV} < E < 10 \text{ meV}$) and violate the ISL.



Search for new forces coupling mass to intrinsic spin.

$$= (-5.4 \pm (3.8)_{\text{stat}} \pm (4.2)_{\text{sys}}) \times 10^{-15} \text{Nm}$$

$$= (-5.4 \pm 5.7) \times 10^{-15} \text{Nm}$$

Measurement Polarity

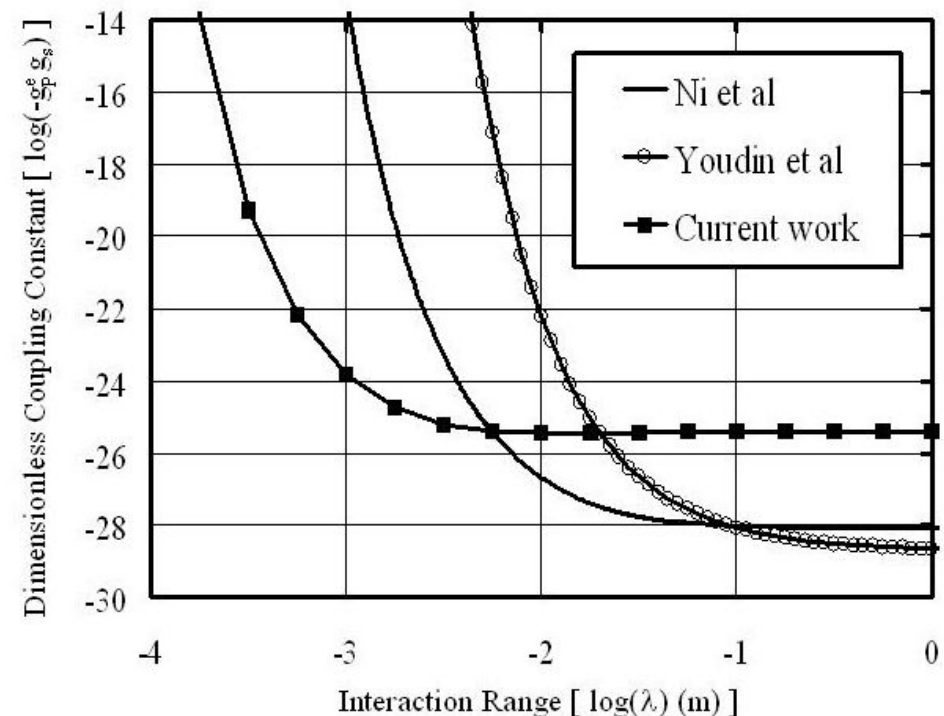
$$g_p g_s = (-1.9 \pm (1.3)_{\text{stat}} \pm (1.5)_{\text{sys}}) \times 10^{-26} \text{Nm}$$

$$= (-1.9 \pm 2.0) \times 10^{-26} \text{ for } \lambda > 10 \text{mm}$$

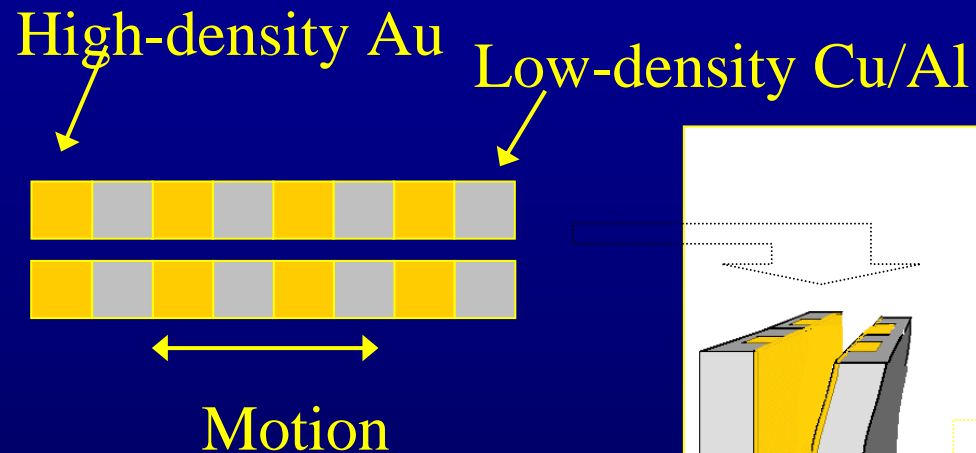
Most conservative limit assumes $g_p g_s$ is -3.9×10^{-26} for $\lambda > 10 \text{mm}$

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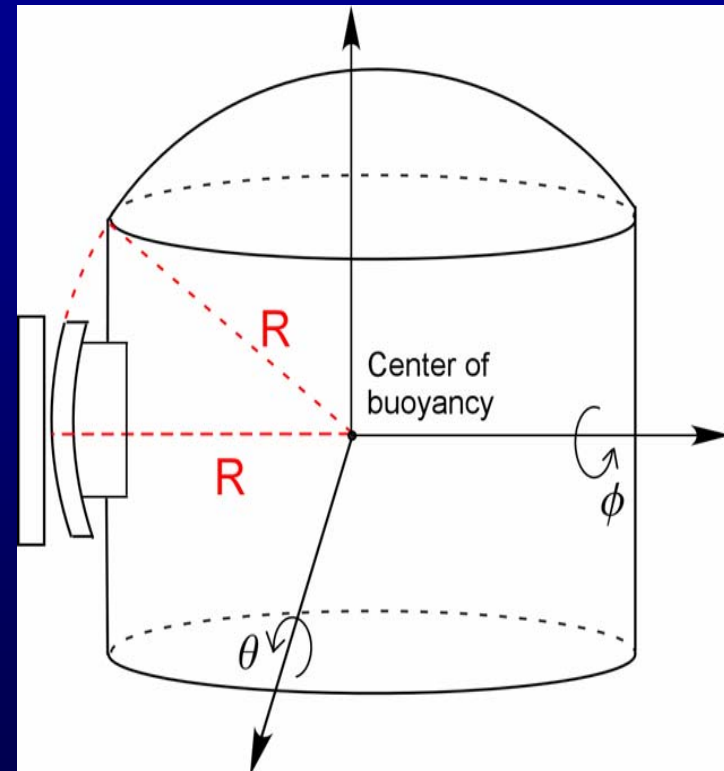
Physical Review Letters, **98**, 081101, 2007



ISL test at Birmingham: concept design



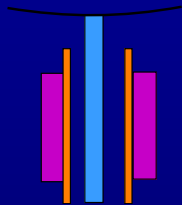
Test masses
manufactured at
RAL



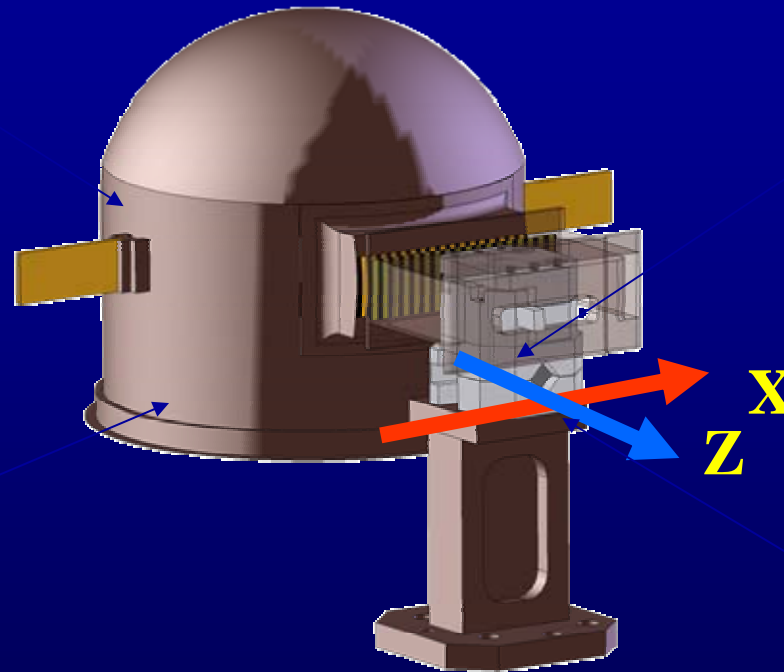
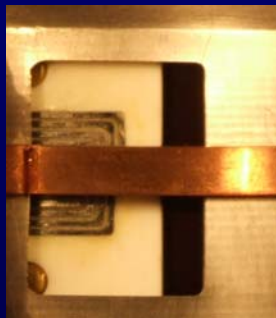
Mk2 float design

ISL test: experimental setup

Capacitive readout



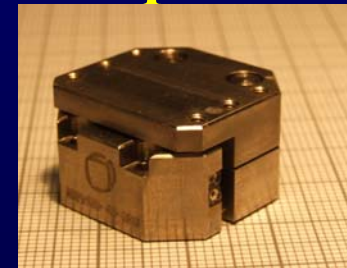
Magnetic actuation



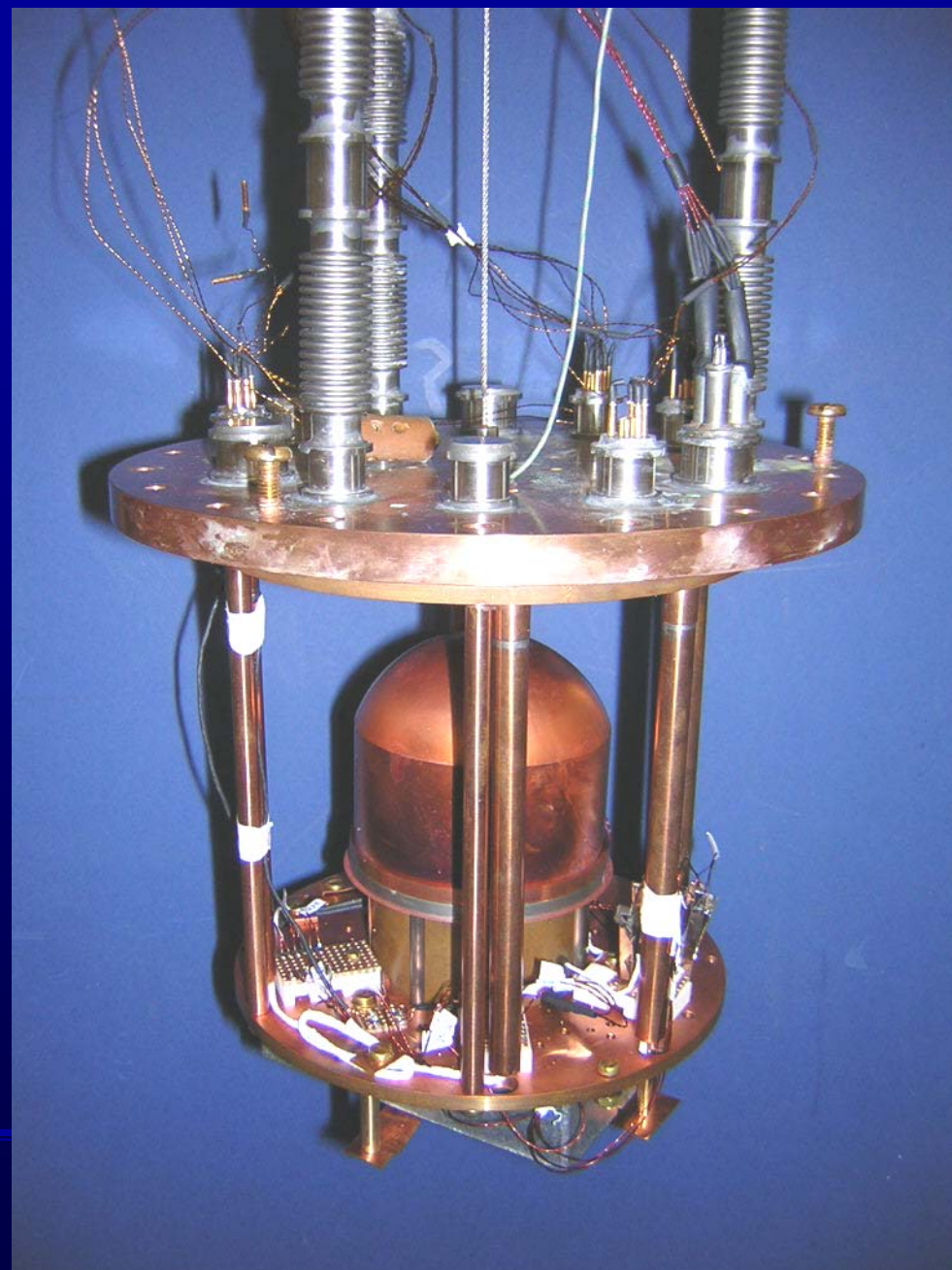
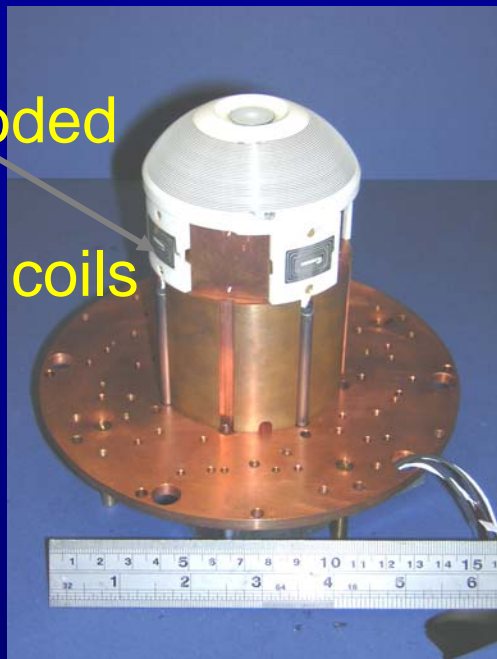
Test masses



Attocube manipulators

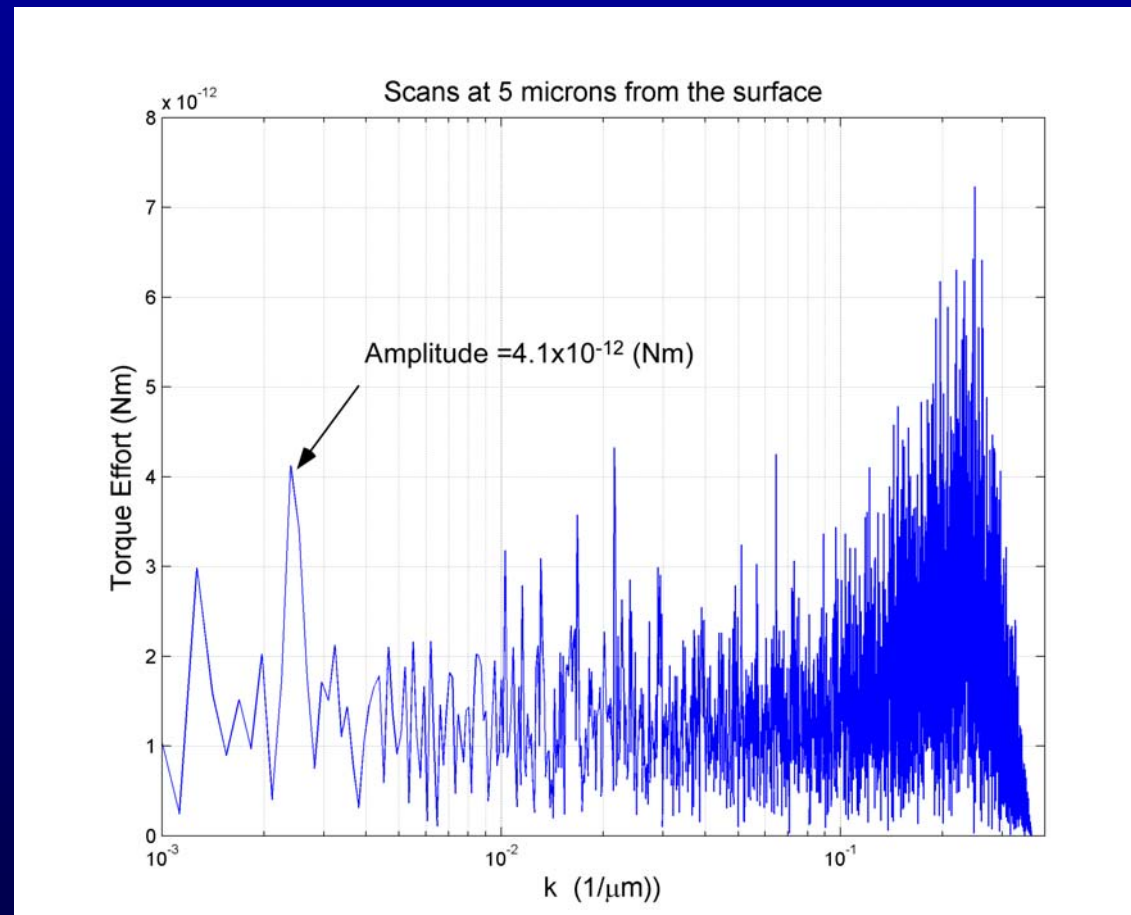


Spark eroded
Nb foil
feedback coils

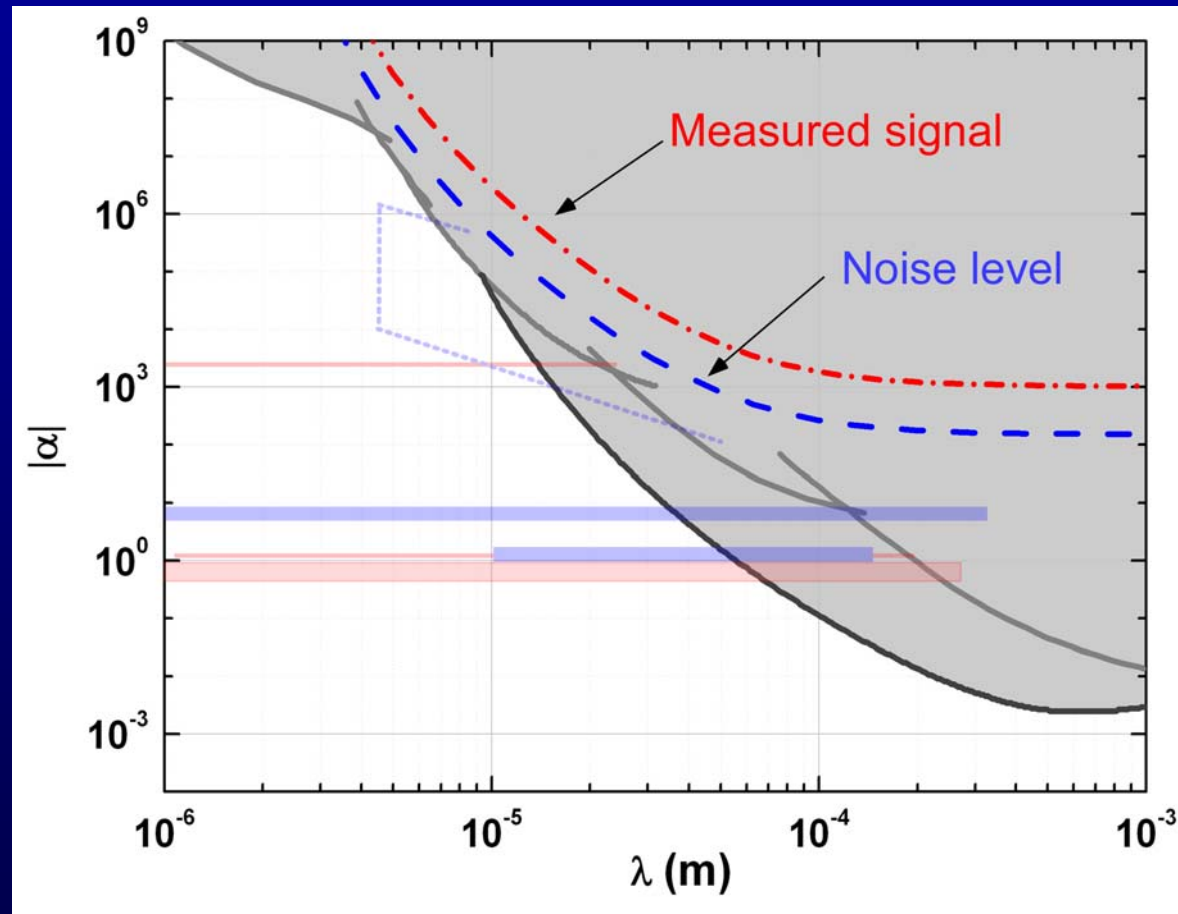


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Tests of the inverse square law at short ranges.



Tests of the inverse square law at short ranges.

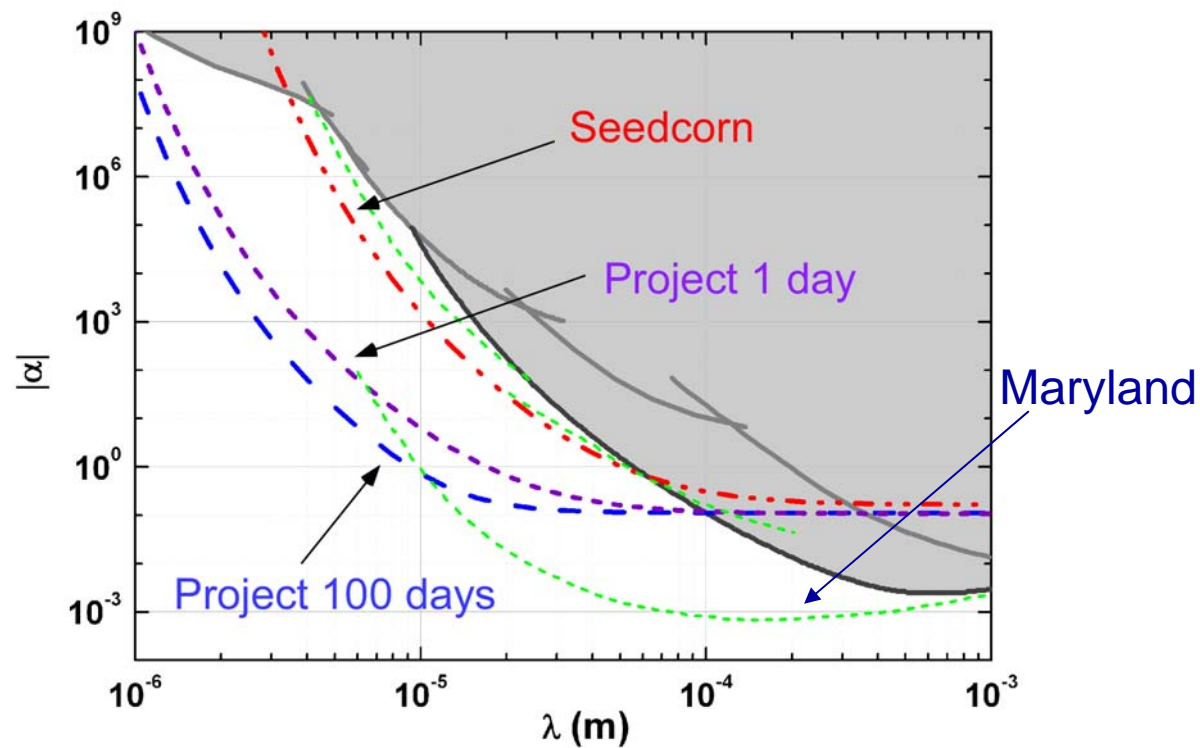


Error Budget

<u>Systematics</u>	<u>notes</u>	<u>Torque compared with nominal target of $6 \times 10^{-19} \text{Nm}$</u>
Casimir/ plasma wavelength	Au/Cu	1.7×10^{-22}
Casimir/corrugation*	Corrugation amp=100 nm, surface separation $8 \mu\text{m}/1 \mu\text{m}$ 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 $2 \mu\text{V}$	3.3×10^{-19}
diamagnetism	Au/Cu with background $4 \mu\text{T}$	4×10^{-20}
Newtonian force*	Calculated to 10%	7×10^{-19}
<u>RMS</u>		<u>$8.2 \times 10^{-19} \text{Nm}$</u>
<u>Statistical uncertainty</u>		<u>Torque noise compared with nominal level of $2 \times 10^{-15} \text{Nm/Hz}^{1/2}$</u>
Float metrology	Fractional ellipticity= 10^{-3} Horizontal vibration spectrum $10^{-5} \text{ms}^{-2}/\text{Hz}^{1/2}$. 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}
<u>RMS torque with 6 months integration time</u>		<u>$1.5 \times 10^{-15} \text{Nm/Hz}^{1/2}$ $= 2.7 \times 10^{-19} \text{Nm}$</u>
<u>TOTAL uncertainty</u>		<u>$8.6 \times 10^{-19} \text{Nm}$</u>



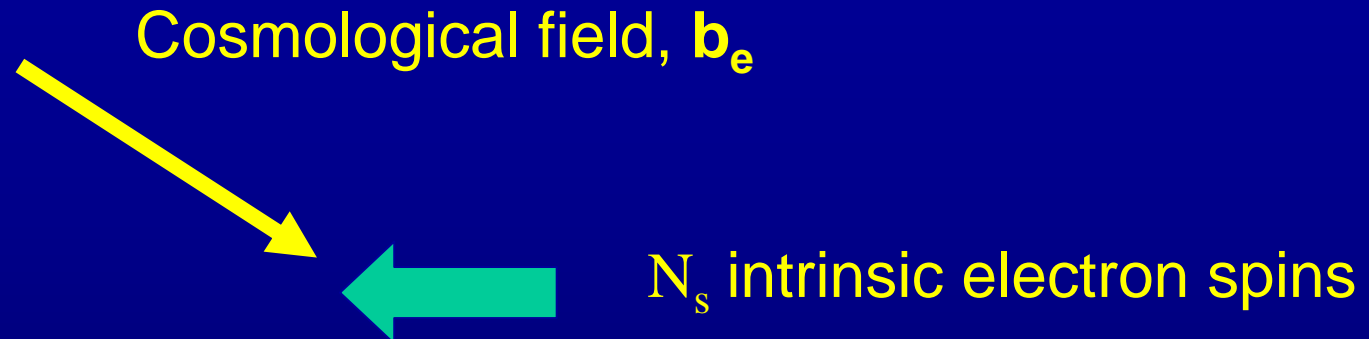
STFC proposal.



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

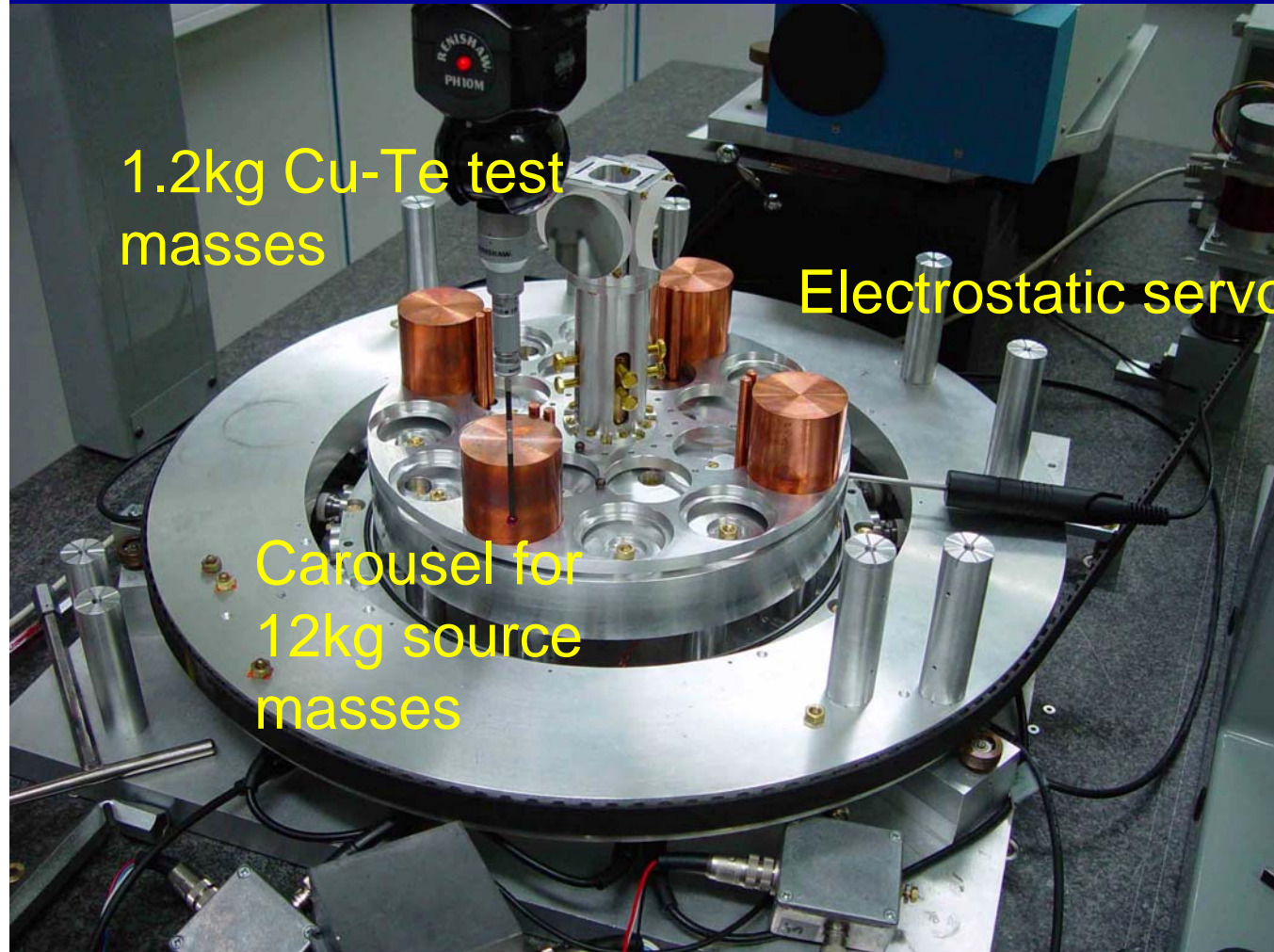


Induced torque: $\vec{\Gamma} = N_s \hat{\sigma} \times \vec{b}_e$

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



1.2kg Cu-Te test masses

Electrostatic servo

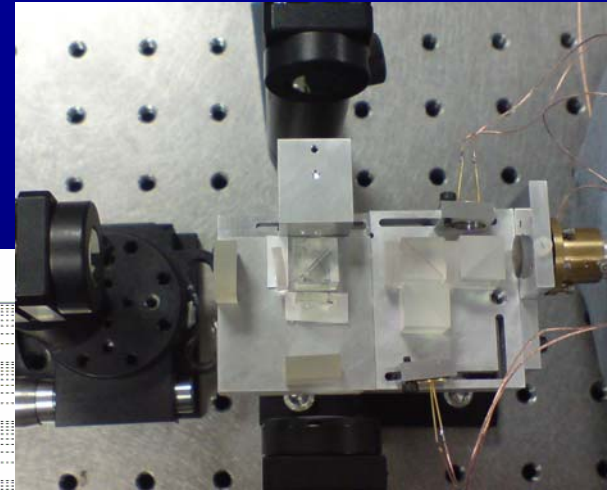
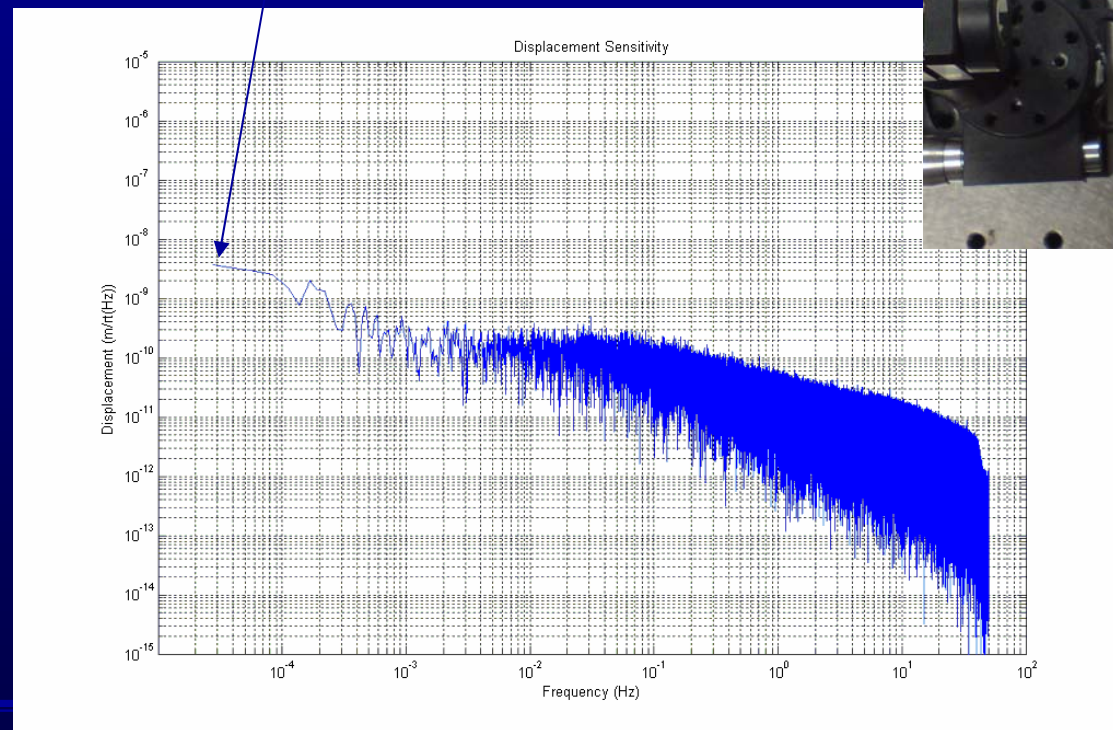
Carousel for 12kg source masses

Torsion strip balance:

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

Polarising homodyne with novel optics to measure angular displacement

4nm/Hz^{1/2} at 30μHz



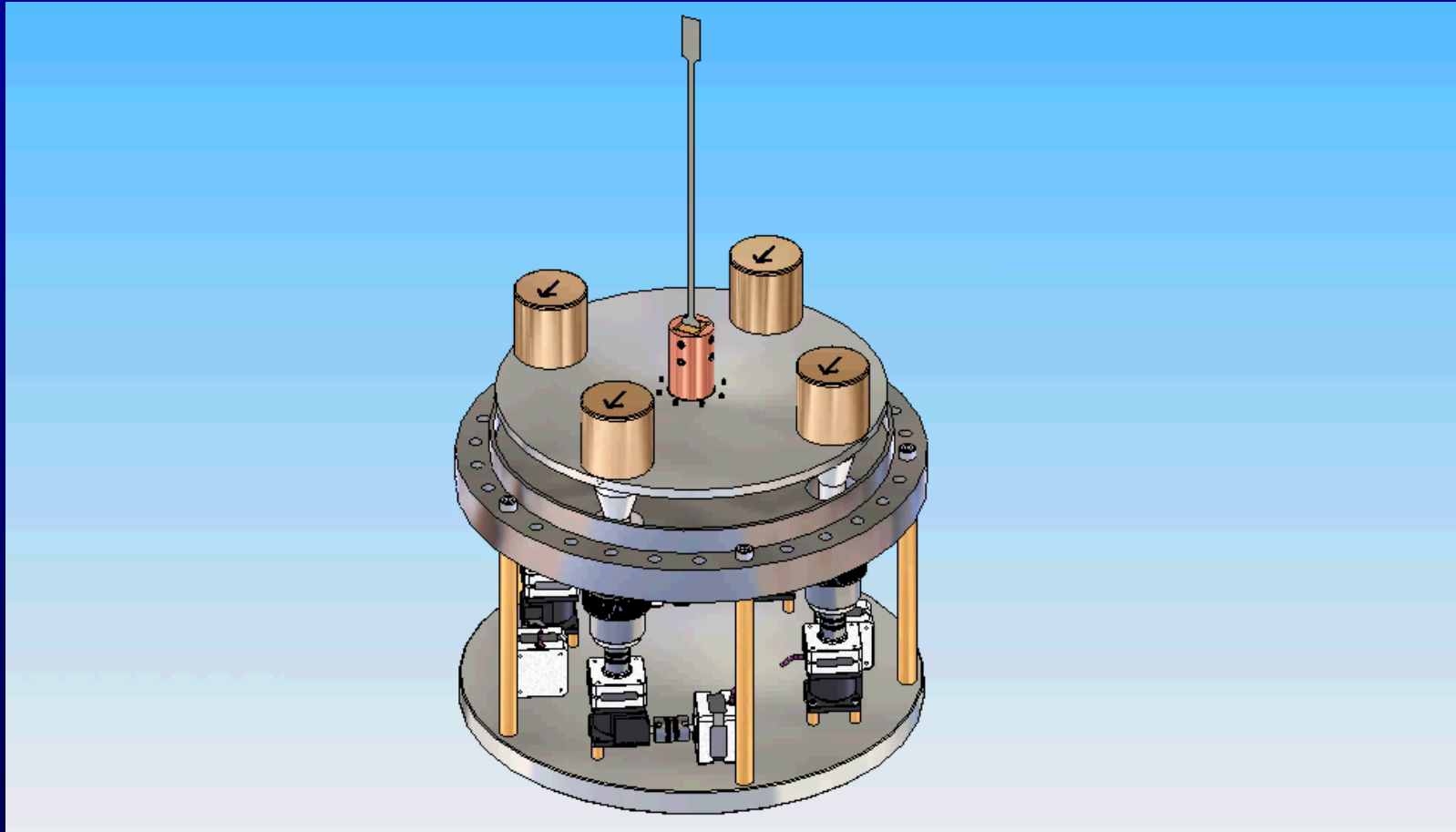
EUCLID
Developed for
drag-free control
and for the SSTB.

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Spin-modulation scheme



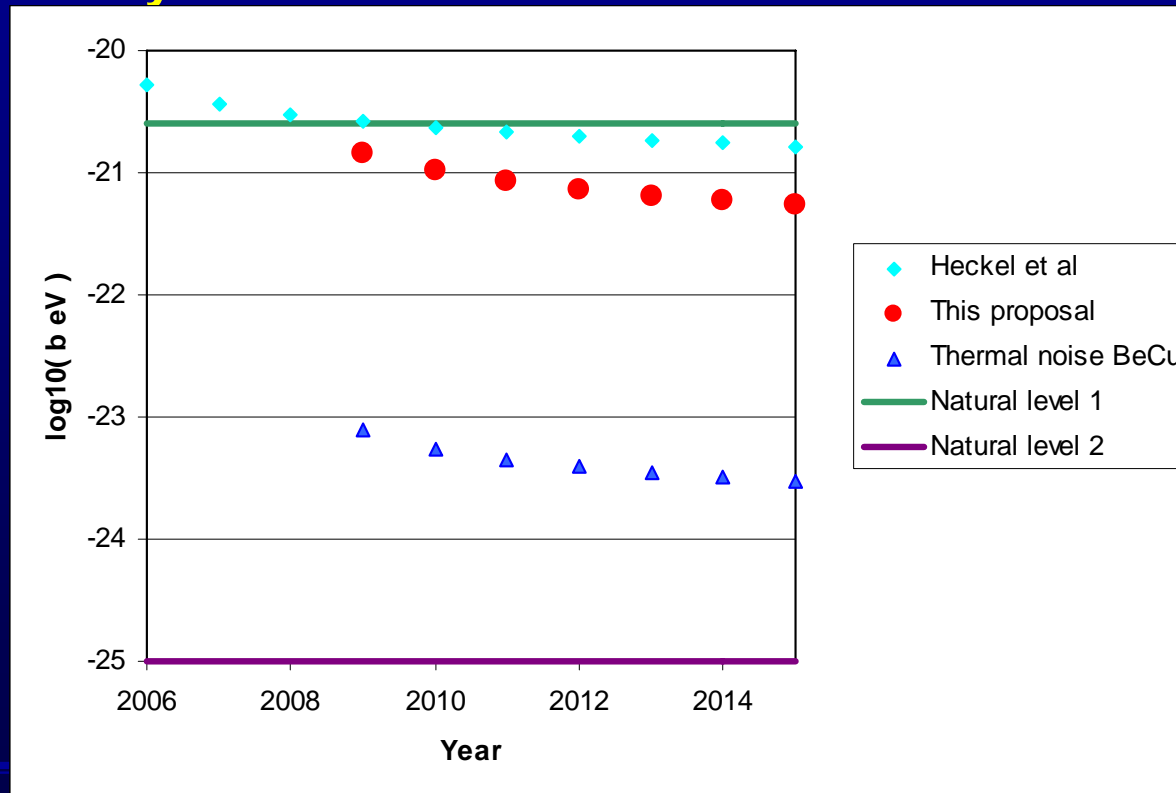
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Test for violation of Lorentz symmetry

- 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

$$r \ll R$$

$$V = -\frac{G_{3+n} m_1 m_2}{r^{1+n}}$$

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

$$\Lambda = \frac{\hbar}{M_* c}$$

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

$$r \gg R$$

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

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 $r \ll R$.