Journeying toward the centre of Gravity

Clive Speake

Inaugural Lecture 28th May 2009.

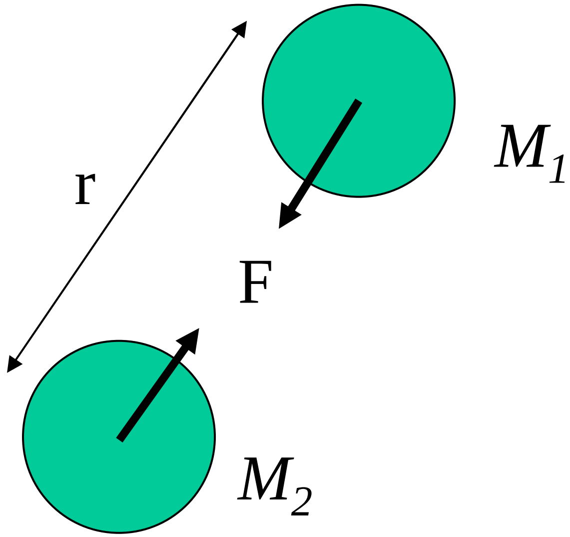
What to expect on the journey!

- Gravitation and the other forces:
  – Quantum mechanics vs geometry.
- Experimental Gravity Workshop:
  – The battle of Signal against Noise.
- Experiments and Technologies:
  – A tale of two paradigms.

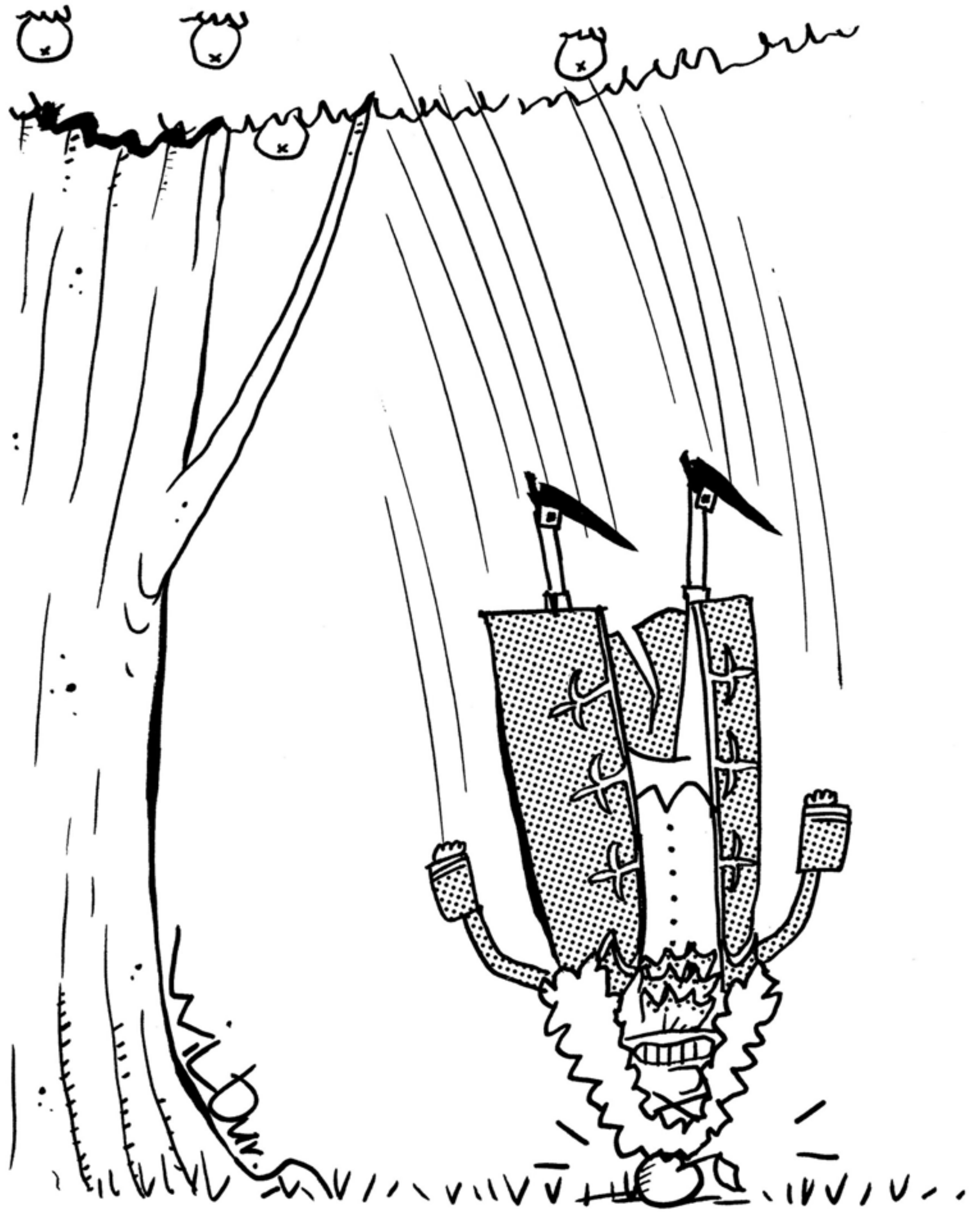
Gravitation: a classical theory.

- Newton's law describes the weakest known force:

$$F = G\frac{M_1 M_2}{r^2}$$



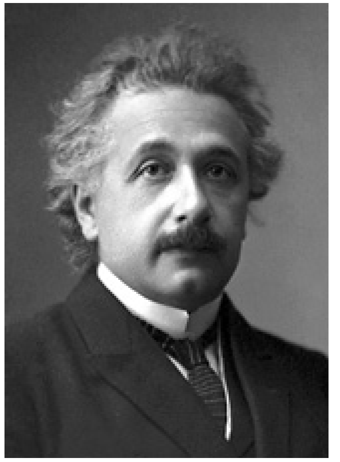
Sir Isaac Newton 1643-1727



NEWTON'S CLUMSIER BROTHER DISCOVERS GRAVITY

Gravitation: still a classical theory

- Einstein went further than Newton and showed that Gravity was caused by the distortion of the **geometry** of space and the uneven flow of time generated by the presence of mass/energy.



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- **General Relativity has passed all experimental tests on laboratory and astrophysical scales.**
- **But singularities in Black Holes suggest incompleteness of theory.**

The Other forces

- The Standard Model of Particle Physics successfully describes:

  - Electromagnetism which holds the electrons to the nuclei of atoms;
  - the two nuclear forces that are responsible for holding the protons and neutrons together in the nuclei of atoms but also for enabling them to disintegrate.

- **The Standard Model is based on quantum physics and says nothing about gravity. It is not a self contained theory and requires at least 19 arbitrary constants to be put in 'by hand'.**

Quantum Physics

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- The world of atoms is defined by Planck's constant, h.
- Particles of energy, E, can spontaneously appear from the vacuum and travel distances, l, given by

$$l \approx \frac{hc}{E}$$

- As we probe space at shorter length scales so we can expect to see more massive virtual particles.

What is the smallest physical scale?

- Our best guess at the highest physically meaningful energy is the regime where gravity is as strong as the other forces.
  - **The gravitational attraction between 2 protons is about 36 powers of 10 weaker than the electrostatic repulsion they experience.**
- If we make the protons put on mass by giving them energy, we can make the two forces equal in magnitude if we could increase the mass of each proton by **18 powers of 10**.

This is the Planck scale of 1.6 x 10^{-35} m:

0.000000000000000000000000000000000016
meters

BUT if this is the case…

- **According to quantum theory the Standard Model describing all the other forces should not work!**

- **According to quantum theory the Universe would be so dense (10^{102} kg/m^3) that General Relativity dictates that it would have blown itself apart 10^{-43} s after its birth.**

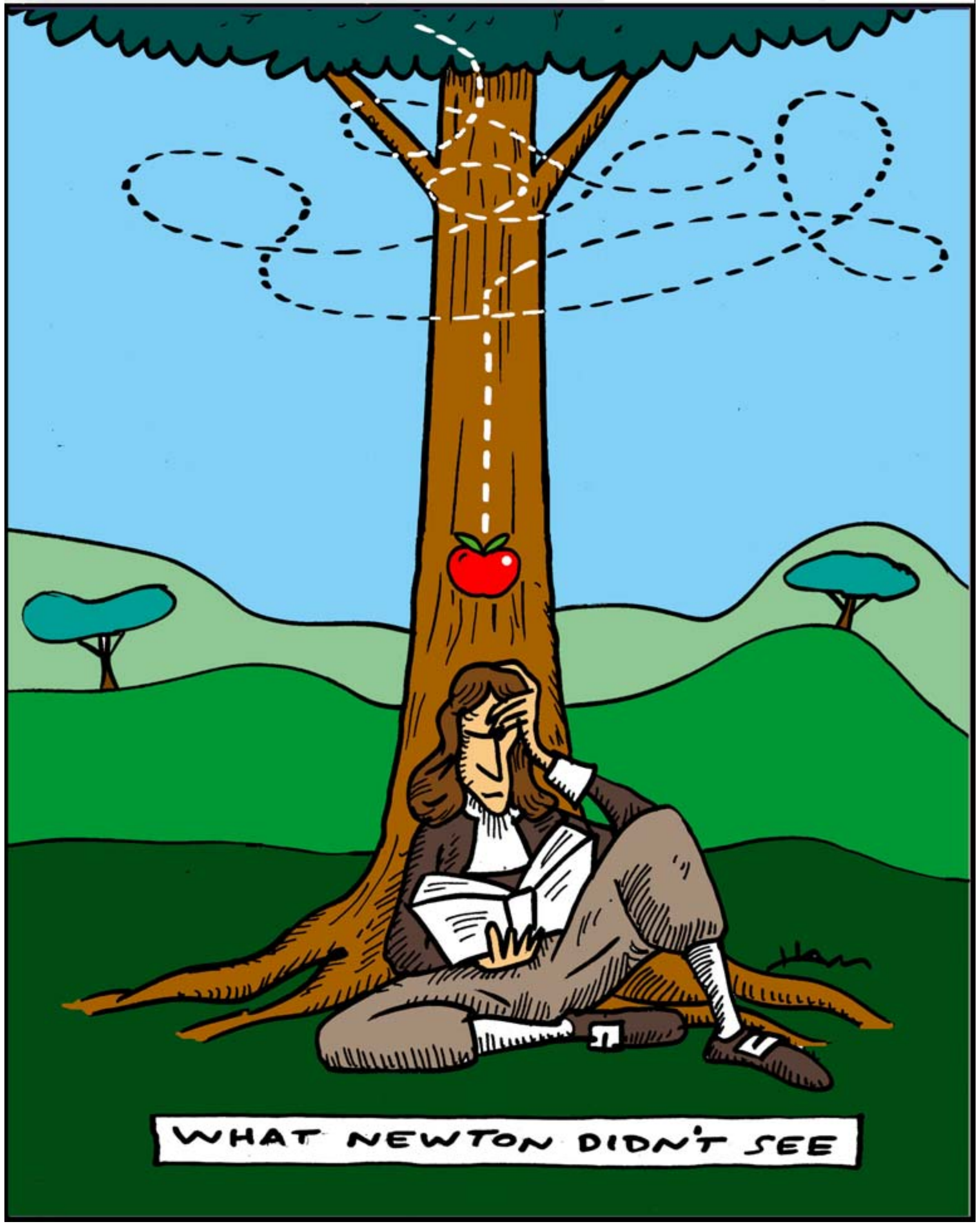
Something must be wrong!

- **Either there are forces of strength intermediate between the quantum forces and gravity that can somehow bridge the gap;**

- **Or the natural distance scale of gravity is actually larger than we now suppose and, hence, the highest plausible energy is not actually as high as it appears.**

- **Both approaches lead to predictions of new weak interactions of short or infinite range.**

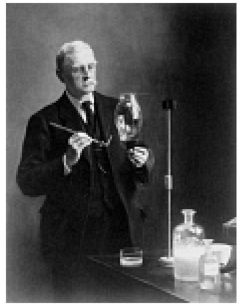
LIFE ON EARTH by Ham



Experimental Gravity Workshop

- The weakness of gravity makes it also difficult for experimentalists!
  - The Newtonian acceleration between two gold spherical masses weighing 1 kg would produce a tiny acceleration (0.1 μms^{-2}). It would take about 9 days to cover the marathon distance with this acceleration!
- Some hints from history…

Boys’measurement of Newton’s gravitational constant, G.



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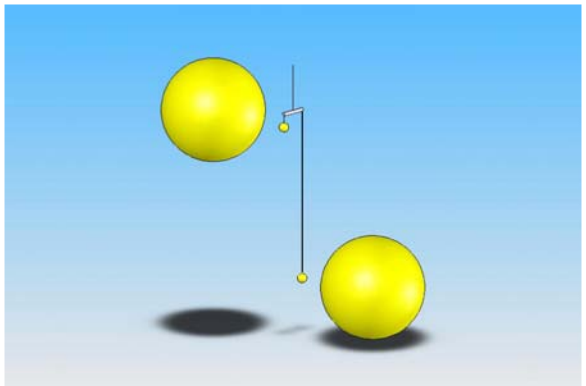
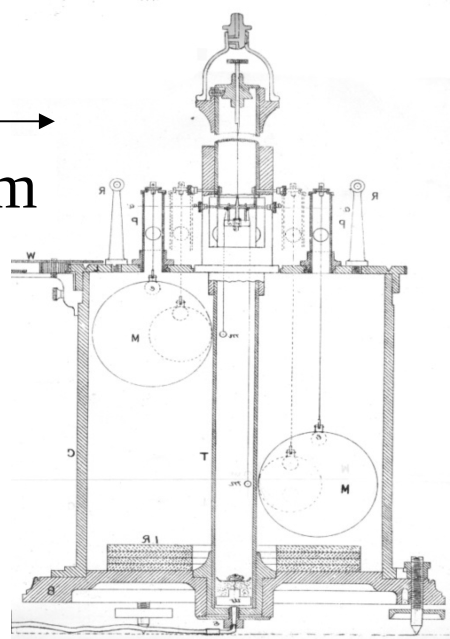
- Circa 1890 Boys developed methods of making extremely fine quartz fibres. He used these fibres to make exquisitely sensitive torsion balances.
- Torque measured was 6×10^{-12} Nm.

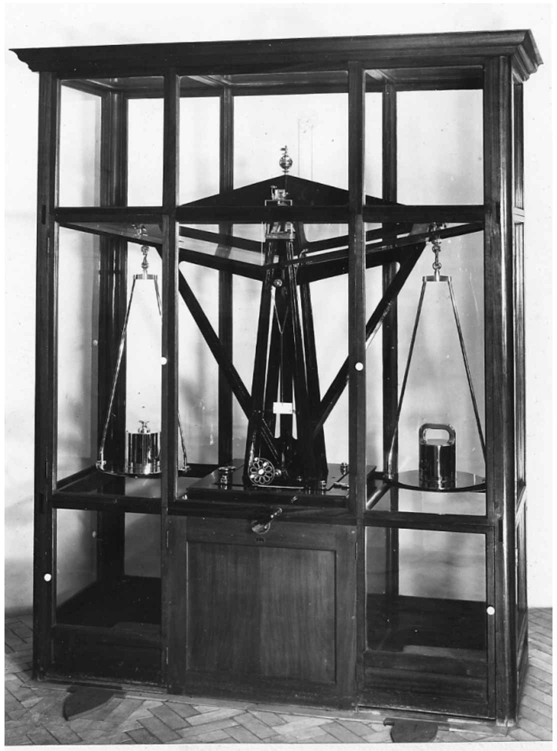


15 cm

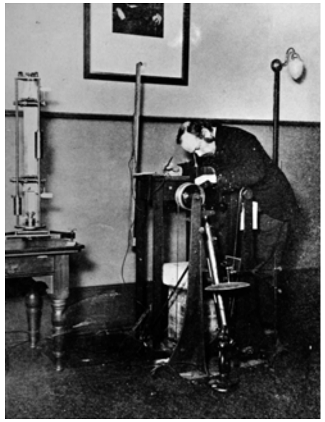


Courtesy Science Museum

Poynting's determination of G.



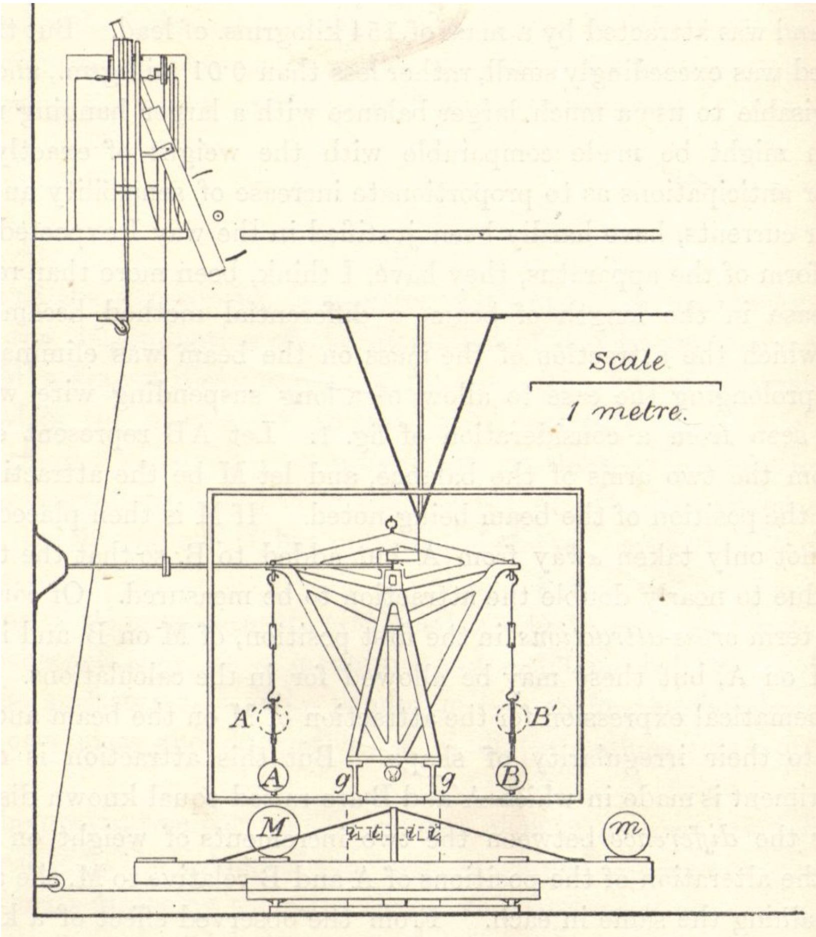
Courtesy Science Museum

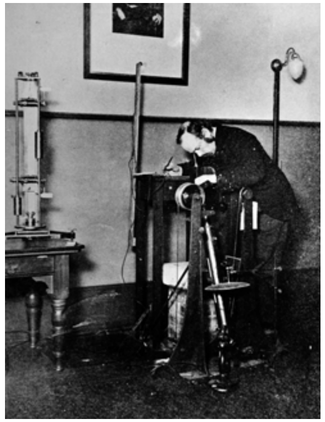


Courtesy Special Collections

- Poynting, 1876-91, employed a common balance with a source mass of 153 kg and test masses of 21 kg.
- Torque 3×10^{-6} Nm.

Poynting’s determination of G.

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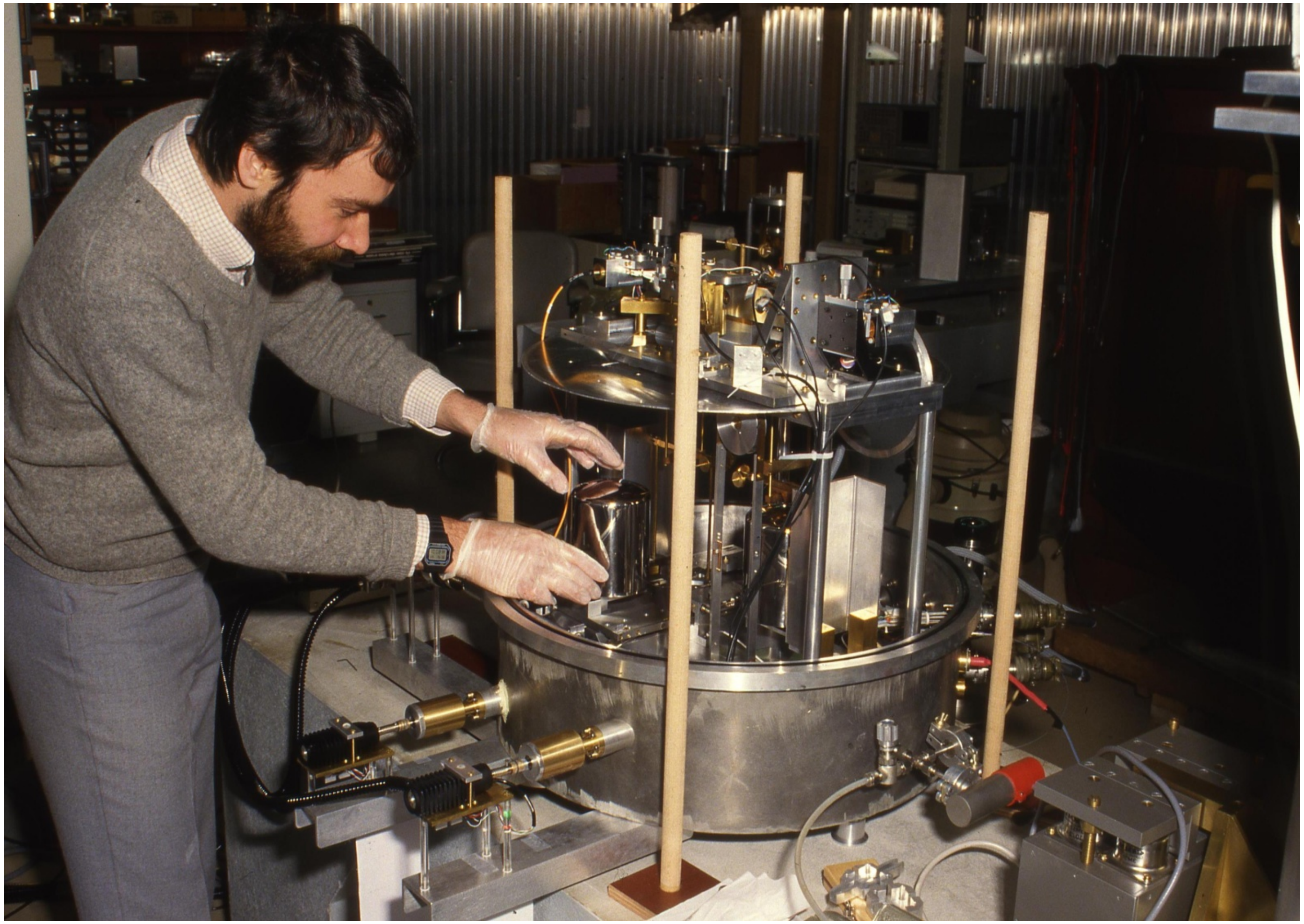
Poynting's achievement

- 'Imagine a balance large enough to contain on one pan the whole population of the British Islands, and that all the population were placed there but one medium-sized boy. The increase in the weight which had to be measured was equivalent to measuring the increase due to putting that boy on with the rest. The accuracy of measurement was equivalent to observing from the increase in weight whether or no he had taken off one of his boots before stepping onto the pan.'

- This accuracy corresponded to 3 parts in 10 billion change in the weight of the test masses.

Some more history…



International Bureau of Weights and Measures (BIPM) circa 1987: The flexure strip balance and the test of the 'fifth force'

Tests of the inverse square law at the Erie Tower, Colorado.

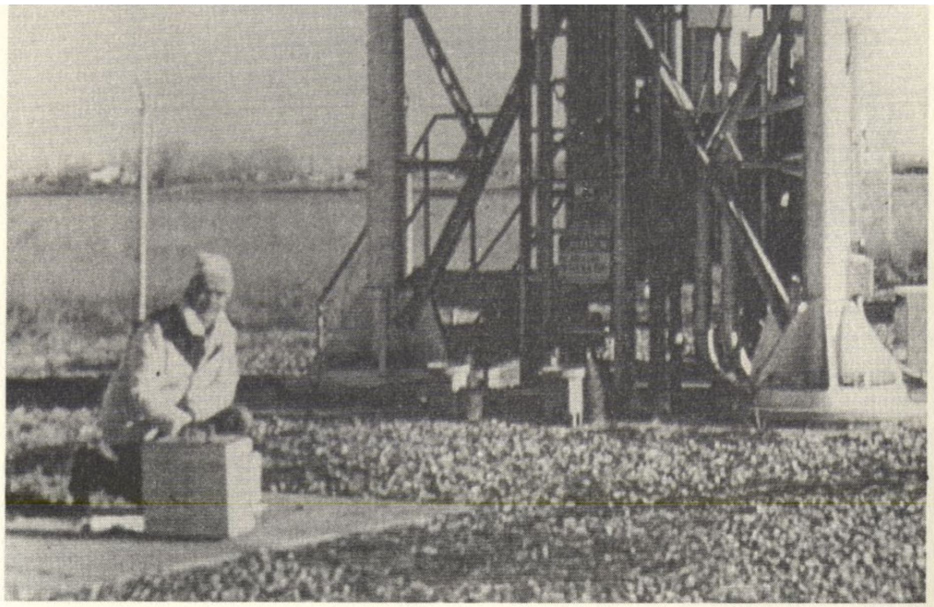


FIGURE 42. Clive Speake and a LaCoste-Romberg gravimeter at the base of the Erie tower. Courtesy of Jim Faller.

From: The rise and fall of the Fifth Force by Allan Franklin.

Experimental gravity workshop

- **Signal:**
  - proportional to the product of values of the test mass and source mass. This leads to macroscopic-sized mechanical experiments.

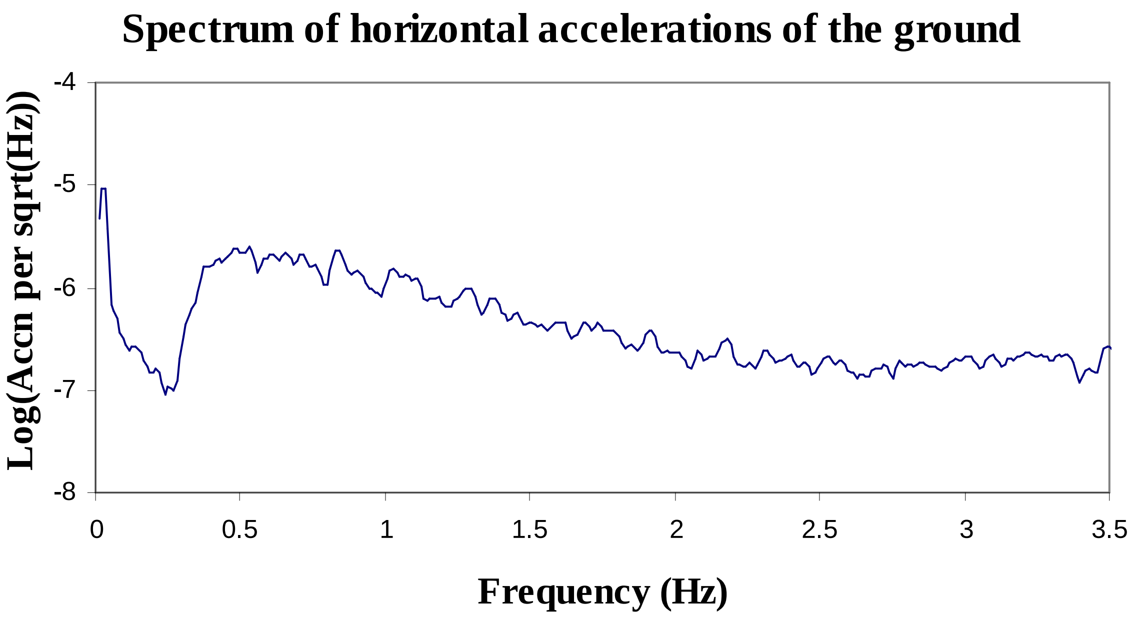
Readout noise

- The suspension has to be flexible enough for us to ‘sense’, with some device, its deflection due to the applied force.
- This means the suspension should have a long natural period of oscillation.
- **Experiments in gravity take a long time.**

Thermal noise

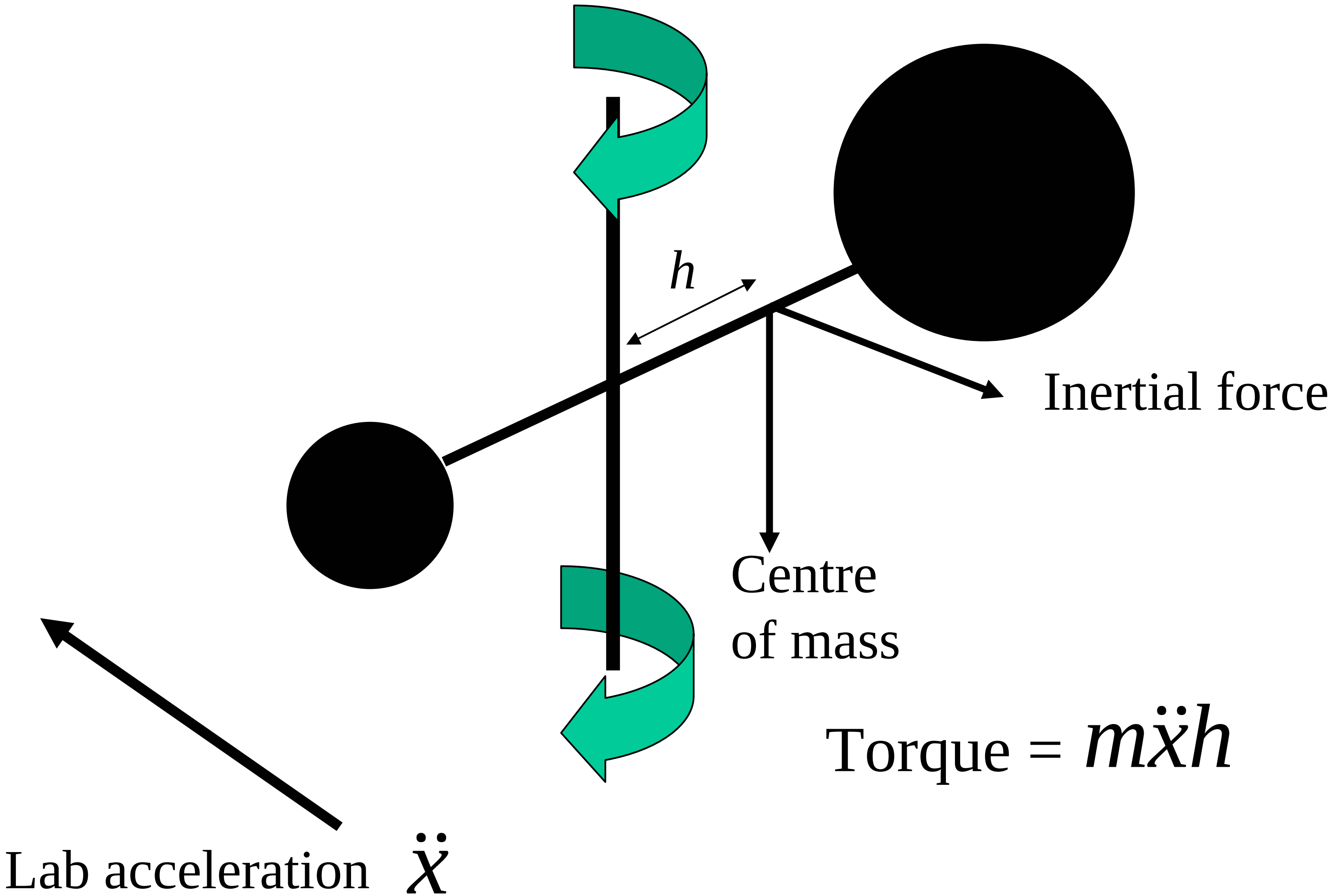
- Noise due to the thermal motion of atoms/molecules in the suspension and increases with temperature.
- The noise increases with energy dissipation.
- The dissipation increases with the stiffness of the suspension. A stiff suspension is also difficult to decouple from the losses in its point of attachment.
- **We need a suspension with low elastic stiffness to make sure that thermal noise is minimised.**
- 1/f noise is a problem.

Ground vibrations



- Microseismic and cultural ground vibrations shake the balance and introduce noise in the readout and spurious torques.

Coupling of ground vibrations.



Two Paradigms?

- We can exploit the gene pool of experimental techniques to optimise tests of different theoretical predictions.

- The torsion balance, as used by Boys, has a good performance but it is limited by thermal noise. It is also sensitive to ground vibrations.

- Poynting's balance was less sensitive to ground vibrations but knife edges are not high quality suspensions.

Two types of experiment:

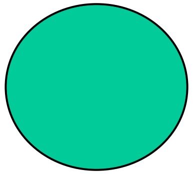
- In searches for new long-range forces the simple pendulum motion of a torsion balance need not be too problematic.

- In searches for short-range forces we need to maintain the distance between the source and test masses to within, perhaps, one micrometer. We need the dynamics of Poynting's beam balance.

Improvements to the torsion balance.

- The torsion strip balance:
  - We can increase the cross-sectional area of a ‘strip’ **without** a proportional increase in its elastic stiffness. Signal to noise ratio improves as

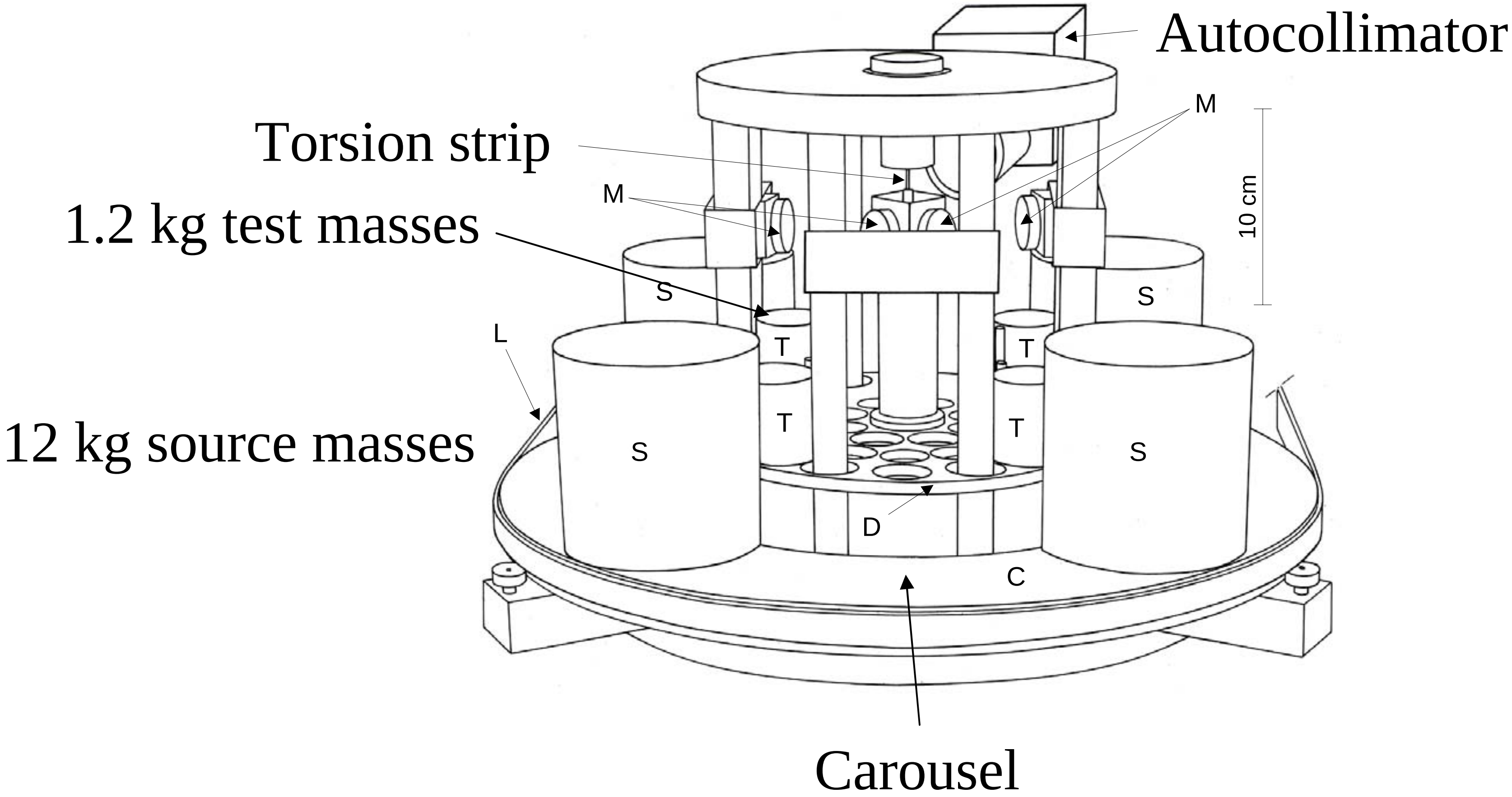
$$\sqrt{\frac{3}{2\pi}\frac{width}{thickness}}$$



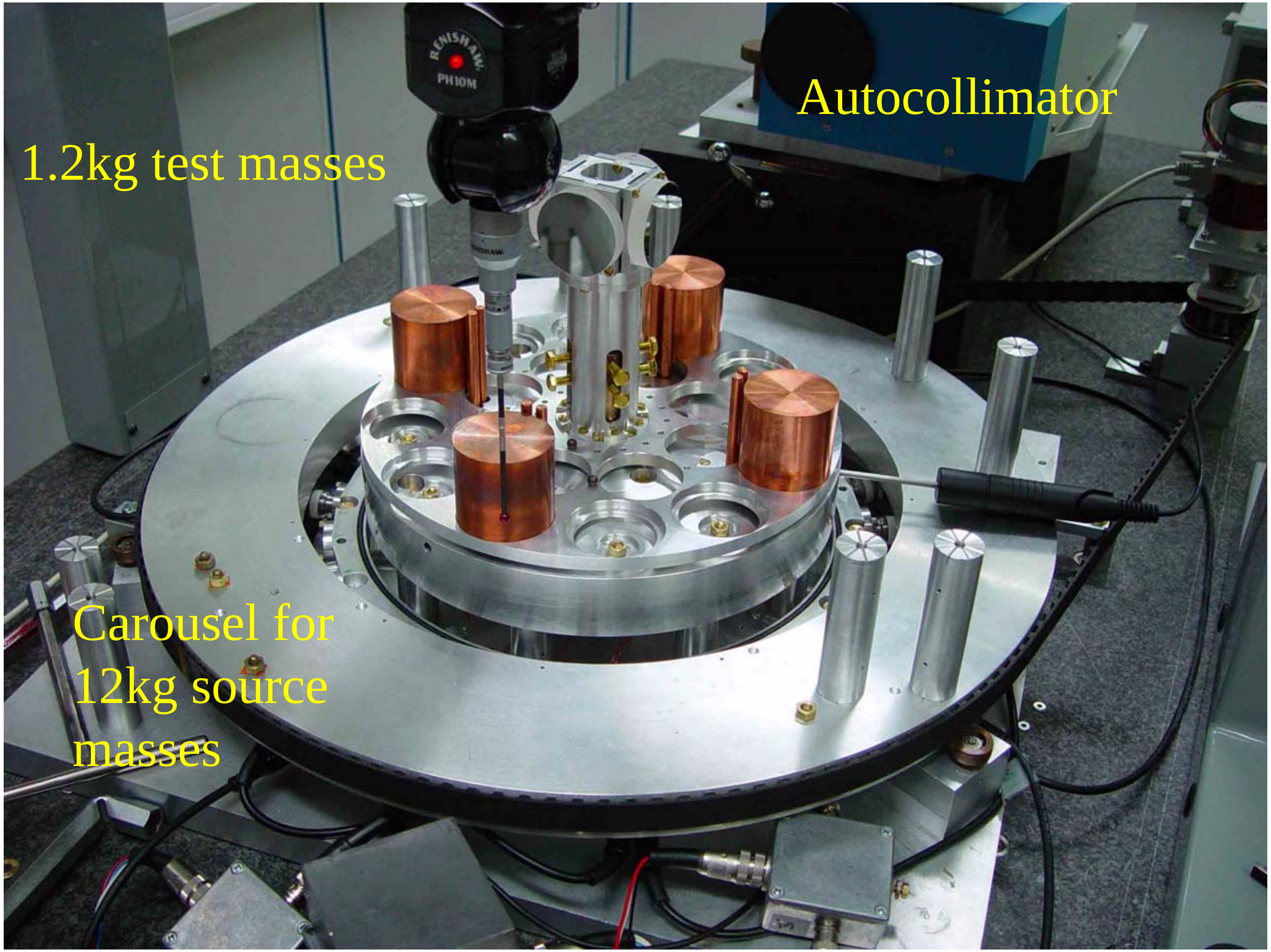
  - But we need a high sensitivity detector to overcome gravitational stiffness.

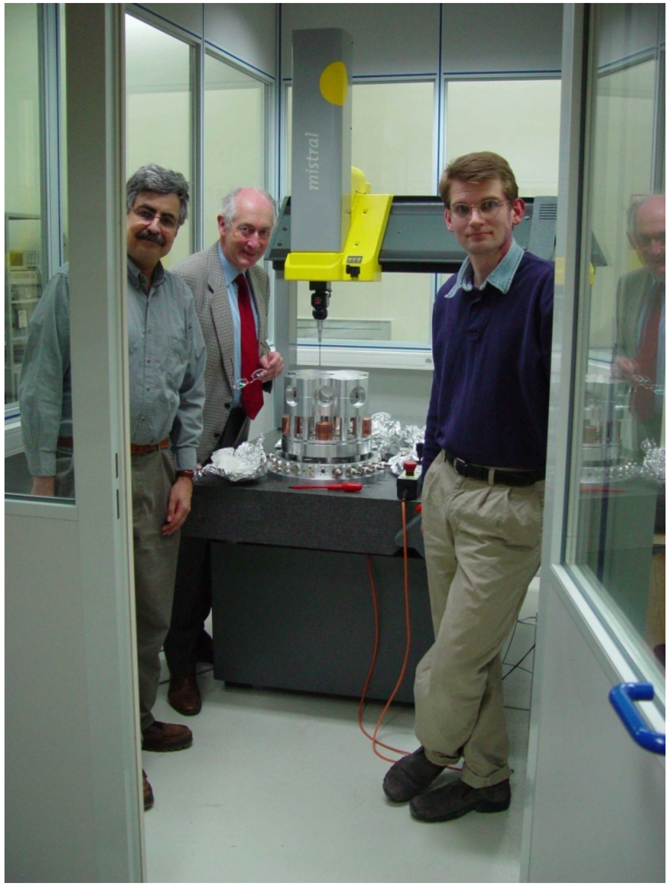
- **Precision measurement of the Newtonian constant of gravitation.**
- **Search for variations in G.**

Outline of G machine



‘G-machine’


Autocollimator
1.2kg test masses
Carousel for
12kg source
masses
RENISHAW
PH10M



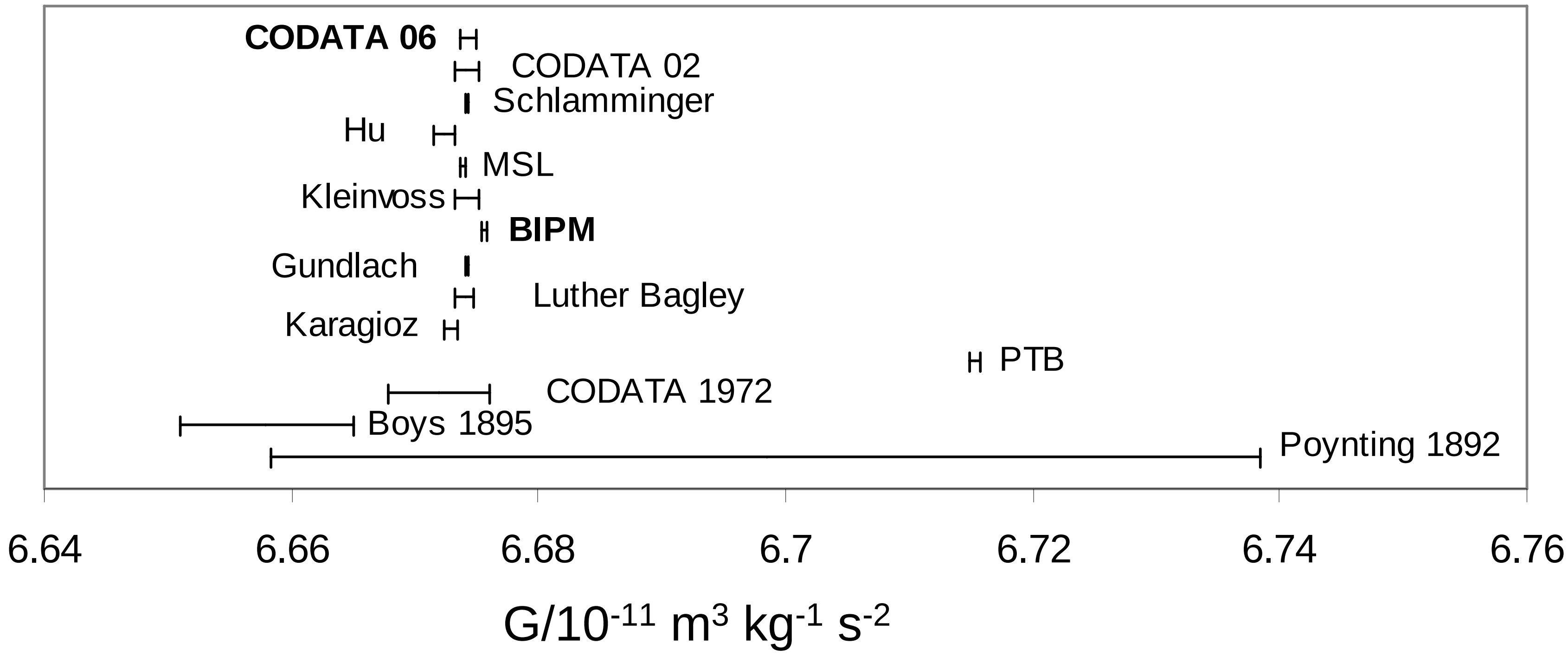
The G team at BIPM 2003
Torque $=1.7\mathrm{x}10^{-8}$ Nm

Preferred Frames lab in
the basement 2008.

- Measure G with 2 different methods to eliminate systematic uncertainties.

- Establish isotropy of G within 1.5 parts per million.

Determinations of Newton's G



Current CODATA value for G

$(6.67428 +/- 0.00067) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

Reduction in the readout noise.

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- Interferometers make very sensitive measurements of displacement but normally cannot cope with tilt.
- The EUCLID detector is a unique interferometer because its performance does not deteriorate due to the tilt or rotation of the target mirror over a useful working range.
- This is ideal for torsion balances!

The Spherical Superconducting torsion balance.

- A hybrid of Poynting's beam balance and Boys torsion balance?
- Eliminate the long torsion fibre and replace with magnetic suspension. The centre of gravity is about 2 mm below the centre of motion. This improves the dynamics so that forces between objects that are separated by micrometers can be measured with high sensitivity.
- Operation at 4 K lowers thermal noise.

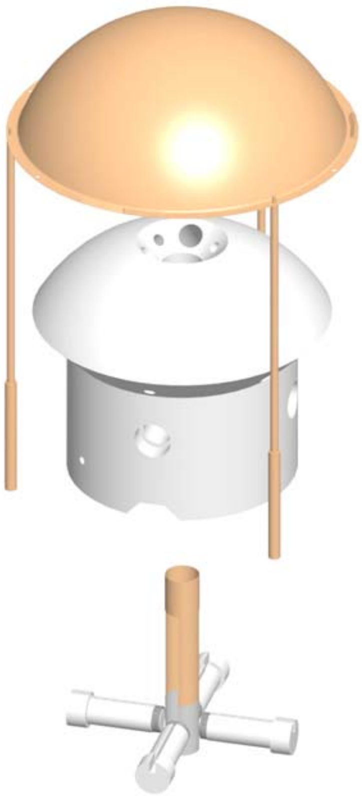
- Search for **short range** couplings between mass and intrinsic spin.

Spherical Superconducting Torsion balance

Float

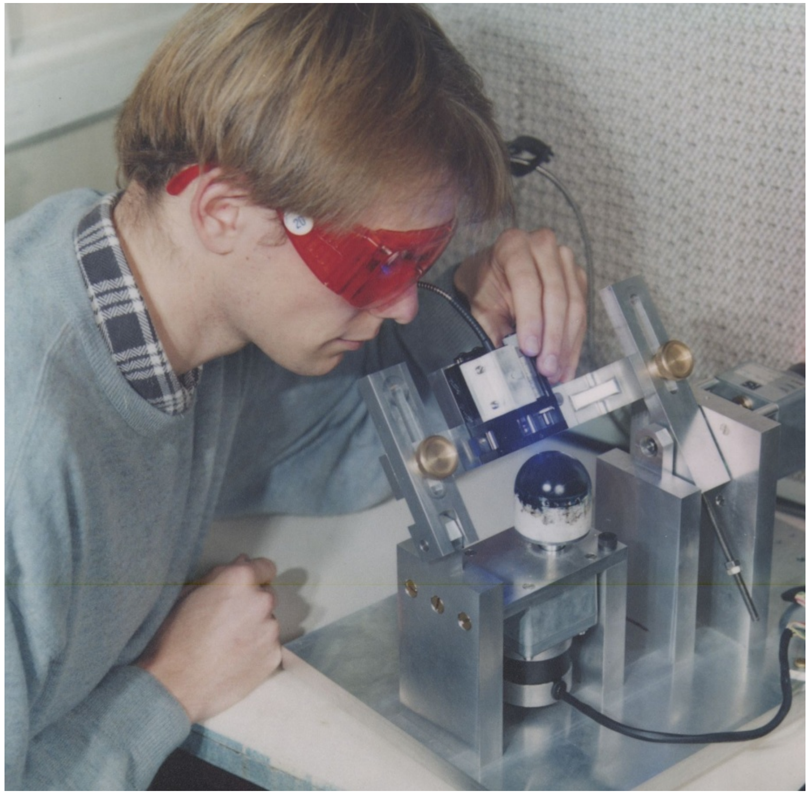
Levitation bearing

Rotation Detector uses SQUID

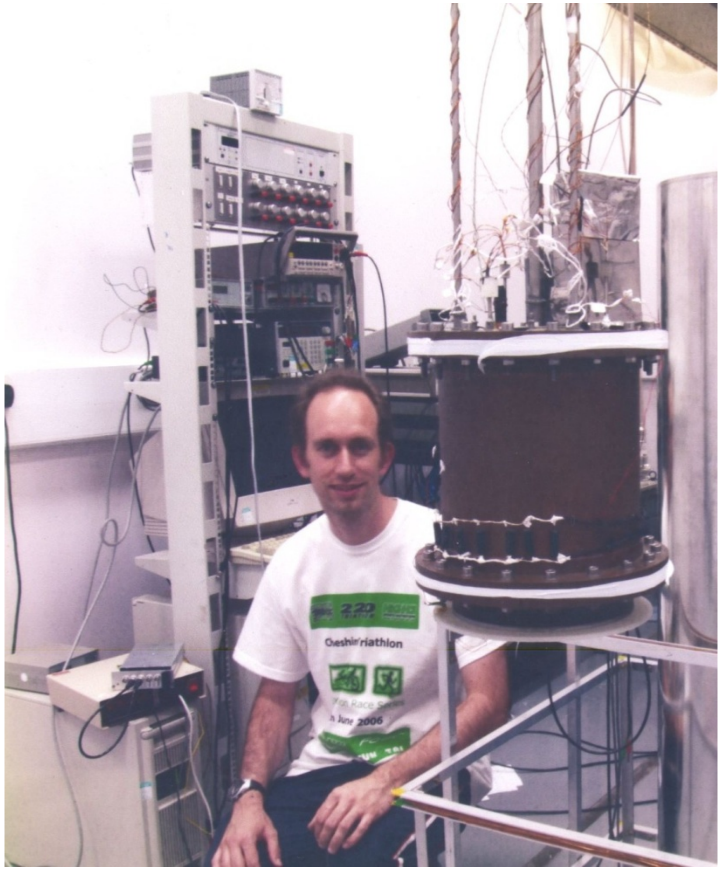


Final sensitivity~$2x10^{-15}$ Nm
$2x10^{-13}$ Nm/$Hz^{1/2}$.

Lead coil on spherical bearing.



Superconducting levitation coil etched into Lead on a spherical substrate.



And finally the experiment!

Next generation superconducting torsion balance

• We need a sensitivity of about 10^{-14} Nm/Hz$^{1/2}$ to test the Newtonian gravitational attraction at a range of 10 μm in about 3 months of averaging.

• We can choose a period of oscillation to be about 10s to minimise sensitivity to ground vibrations.

• We need to ensure that the centre of gravity is within 10 μm of the centre of buoyancy.

• With a moment of inertia of 10^{-5} m^3 kg, we need a sensor noise of better than about 1 nrad/Hz$^{1/2}$.

• We need a ring-down time of a few 100 s to ensure that the thermal noise is sufficiently small.

• We have to eliminate spurious forces to the appropriate level!

To recap:

- Testing gravitation is a vital part of our continuing understanding of the Universe.
- New technologies are necessary for this challenge.
- We have barely started our journey!

Some acknowledgments

- **Steve Brookes and U of B Main workshop**
- **Past students of the group.**
- **Ludo, Tendai, Barry, Mark, Dave.**
- **Jose Sanjaime BIPM workshop**

Gravitational Physics All-Stars 2009