Lecture 21
Search for Spin-Mass Interaction and Precision Measurement of *G*

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Search for spin-mass interaction

- The Standard Model predicts a violation of *CP* symmetry in strong interaction, which has not been observed.
  - ⇒ To solve this "strong *CP* puzzle," the axion has been proposed (Peccei and Quinn, 1977; Weinberg, 1978; Wilczek, 1978).
- The axion mediates spin-mass interaction (SMI).
  - ⇒ Potential between an electron and an unpolarized nucleon:

$$V_a = g_s g_p \frac{\hbar^2}{8\pi m_e}(\hat{\sigma}\cdot\hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}, \quad g_s g_p \approx \frac{\theta}{\lambda^2}\times 6\times 10^{-33},$$

where $\theta \leq 3\times 10^{-10}$ and λ is in meters.

- The axion is a strong candidate for cold dark matter.
- Search for SMI complements the cavity search for the axion.
  - ⇒ Unlike the cavity experiment, these experiments do *not* assume any population of the axion.

Two ways to search for SMI

- Modulate σ and search for effect on $\boldsymbol{r}$ using a motion sensor.

  Ritter *et al*. (1993):

  Torsion balance with a modulated spin source

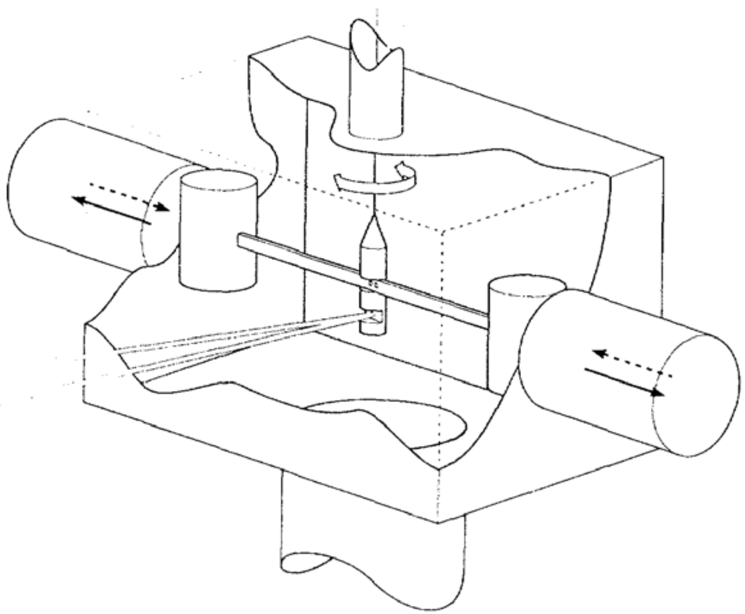
  $\Rightarrow \quad |g_s g_p| \leq 5 \times 10^{-27}$, $\lambda \geq 10$ cm

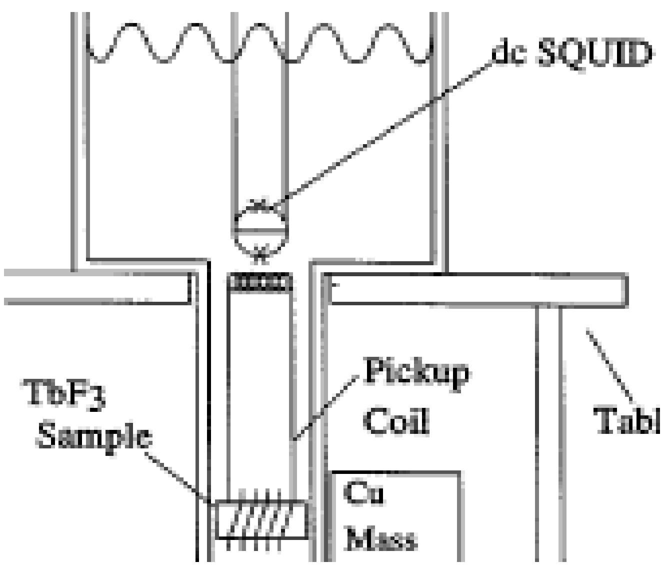
- Modulate $\boldsymbol{r}$ and search for effect on σ using a susceptometer.

  Ni *et al*. (1994, 1999):

  SQUID susceptometer with a moving source mass

  $\Rightarrow \quad |g_s g_p| \leq 7 \times 10^{-29}$, $\lambda \geq 3$ cm.

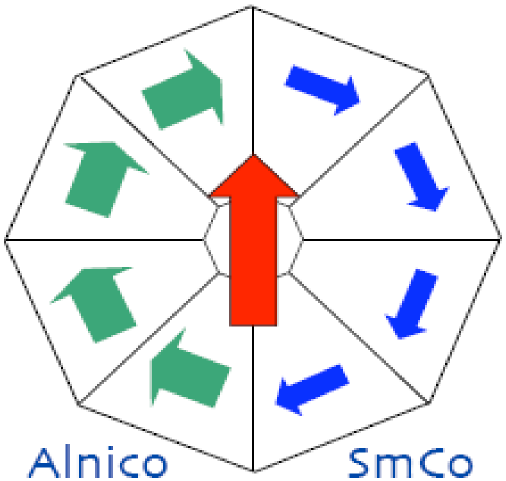


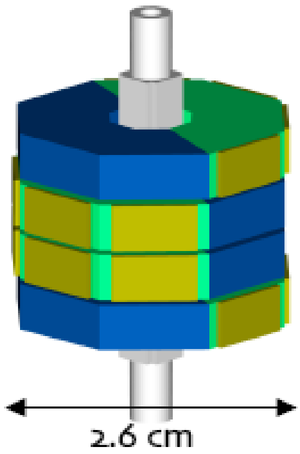


U. Wash. experiment

The spin pendulum

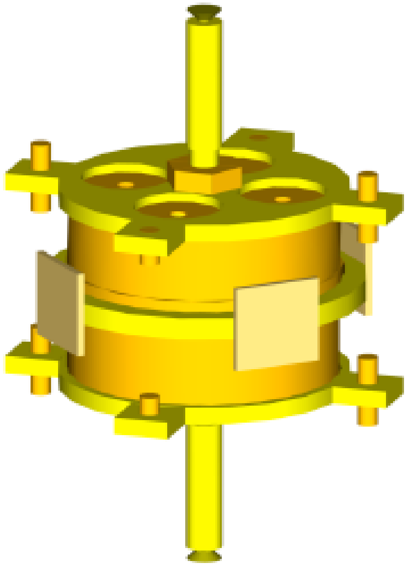
- large net electron spin
- negligible external magnetic field



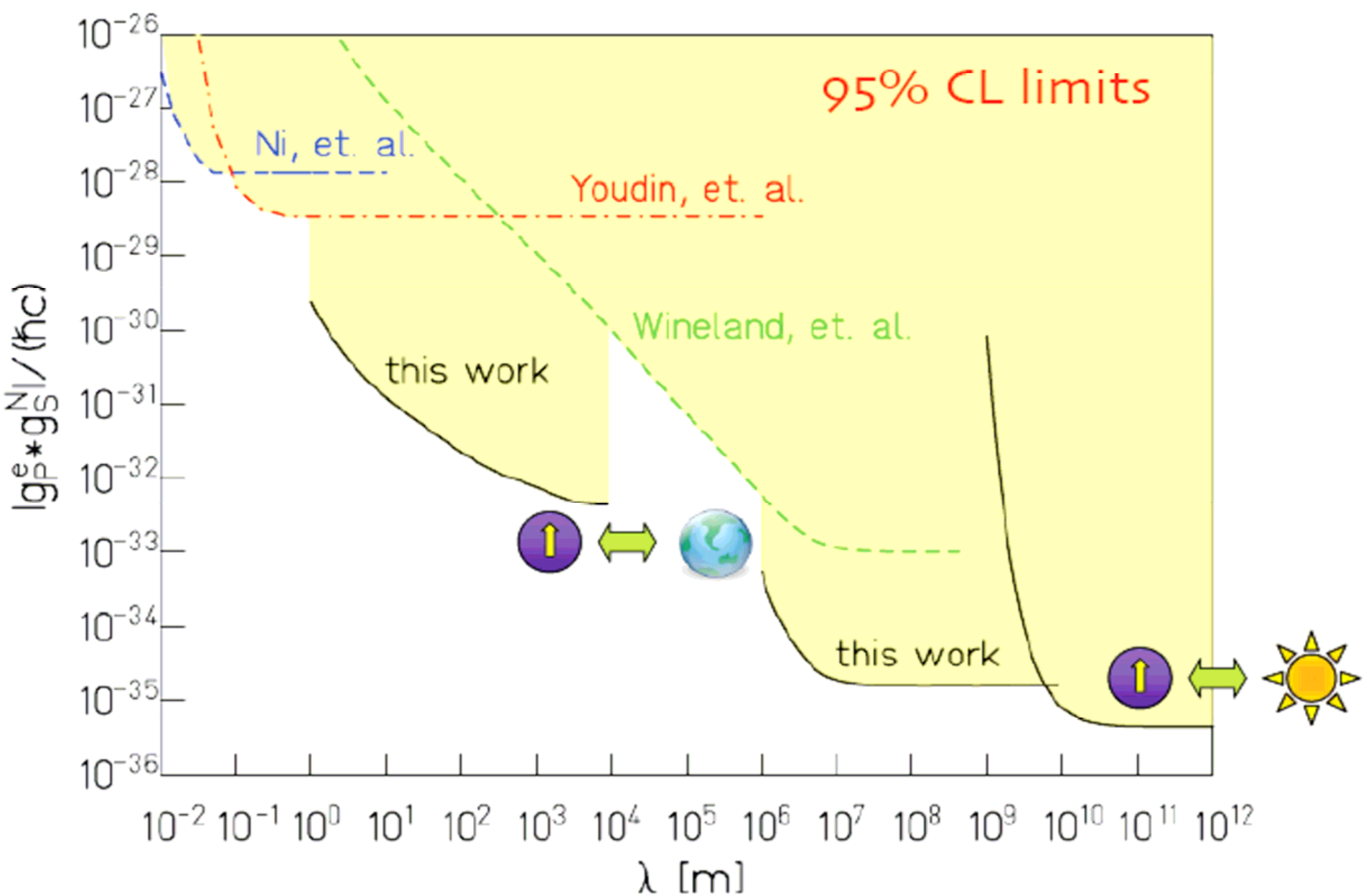


- more spins
- greater symmetry

- gold-plated
- magnetically shielded
- 4 mirrors



Experimental limits on SMI



Heckel *et al*. (2006):

S/C accelerometer experiment

- Torque between a polarized source with an electron spin density ρ_s and a test mass of nucleon density ρ_N:

$$N_a = \frac{\theta}{\lambda^2} \times 7 \times 10^{-71} \rho_s \rho_N \frac{dI}{d\theta} (\mathrm{mks}), \quad I = \frac{1}{8\pi} \int\int (\hat{\sigma} \cdot \hat{r}) \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda} dV_s dV_N .$$

$\Rightarrow$ Problem: *I* = 0 identically for any closed loop of spin.

- Spin source: A toroid with alternating sections of two high-μ materials with spin contrast (e.g., A: Magnifer 7904, B: NdNi).

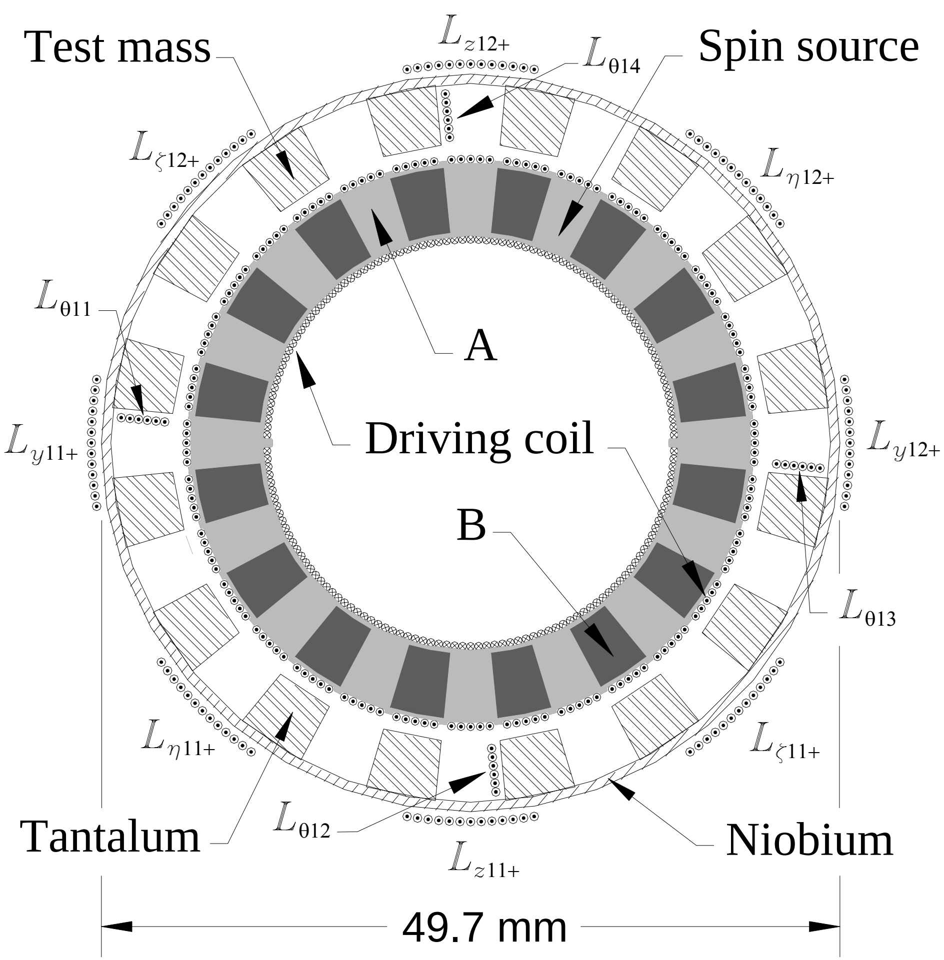
  Due to quenching of ***L***, σ is always parallel to ***J*** in transition metals**.** whereas σ can be anti-parallel to ***J*** in rare-earth magnets.

  $\Rightarrow$ Problem: All rare-earth magnets are hard.

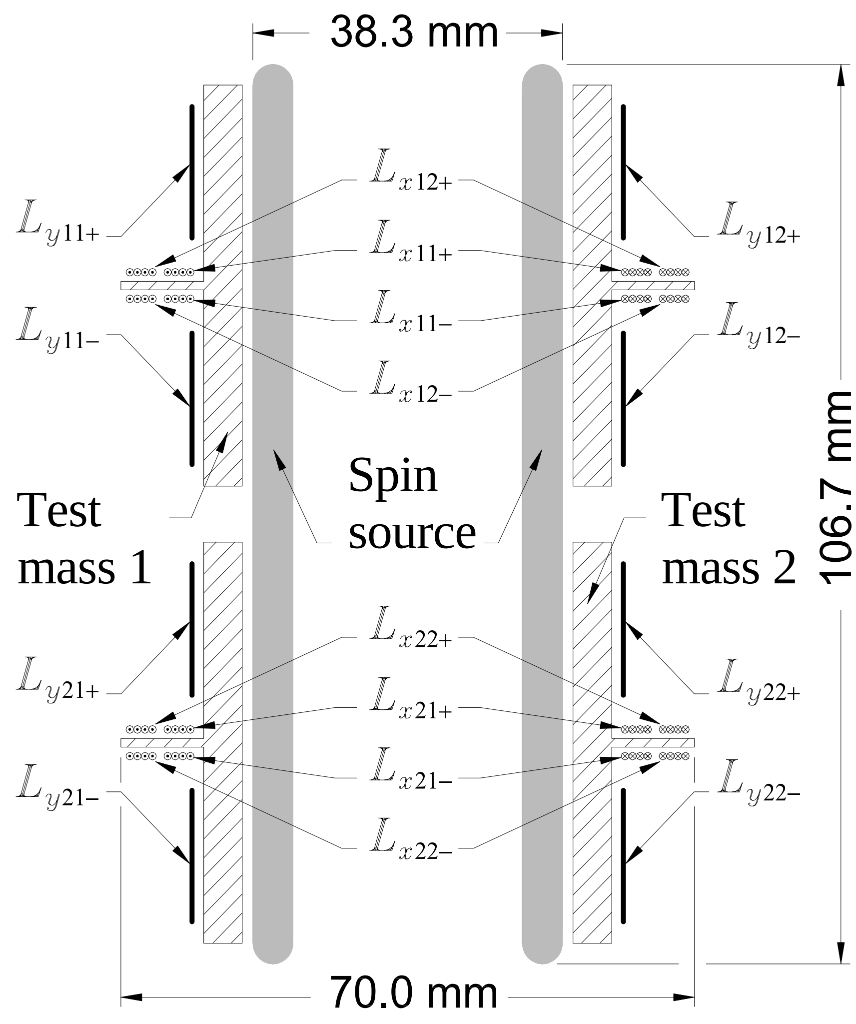
- Force sensor: A superconducting differential angular accelerometer with magnetically levitated test masses.

Experimental design

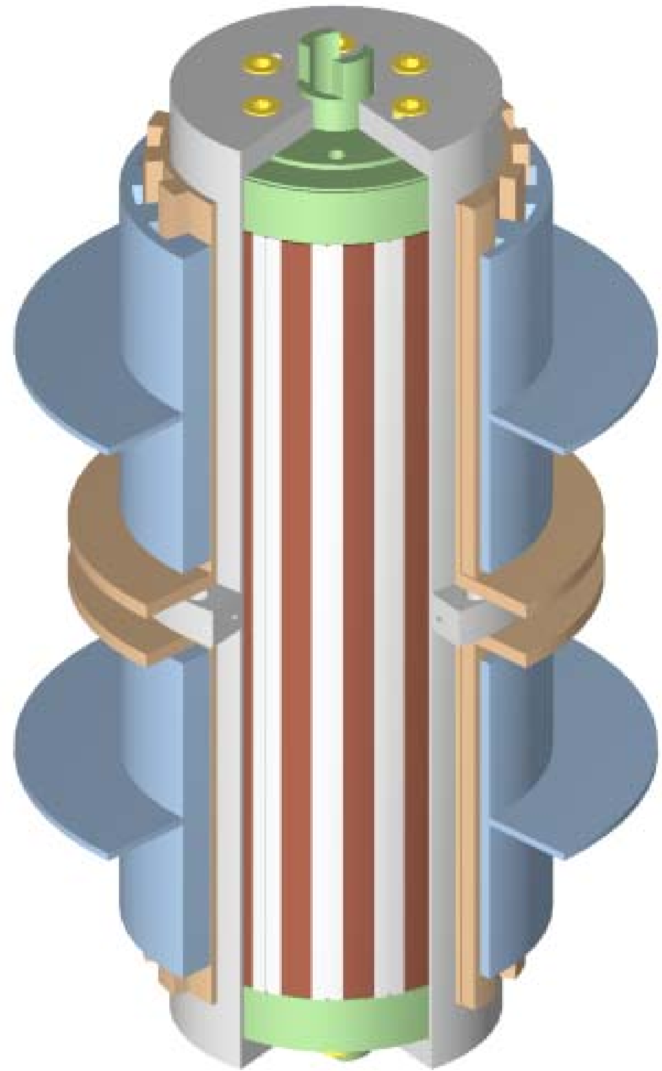
Horizontal cross section



Vertical cross section



Construction of the apparatus



Noise and error reduction

- Intrinsic noise:

  Perform a resonance experiment to suppress the SQUID noise limit:

$$S_\alpha(f) = \frac{8\omega_0}{I}\left[\frac{k_B T}{Q} + \frac{k_B T_N}{Q_{\mathrm{eff}}}\right] \approx \frac{8\omega_0}{I}\frac{k_B T}{Q}, \quad Q_{\mathrm{eff}} = \omega_0 \tau$$

- Common-mode balance and axis alignment:

  By adjusting currents in the sensing and alignment circuits, angular and linear accelerations are rejected to 10^{-5} and 5×10^{-8} m^{-1}.

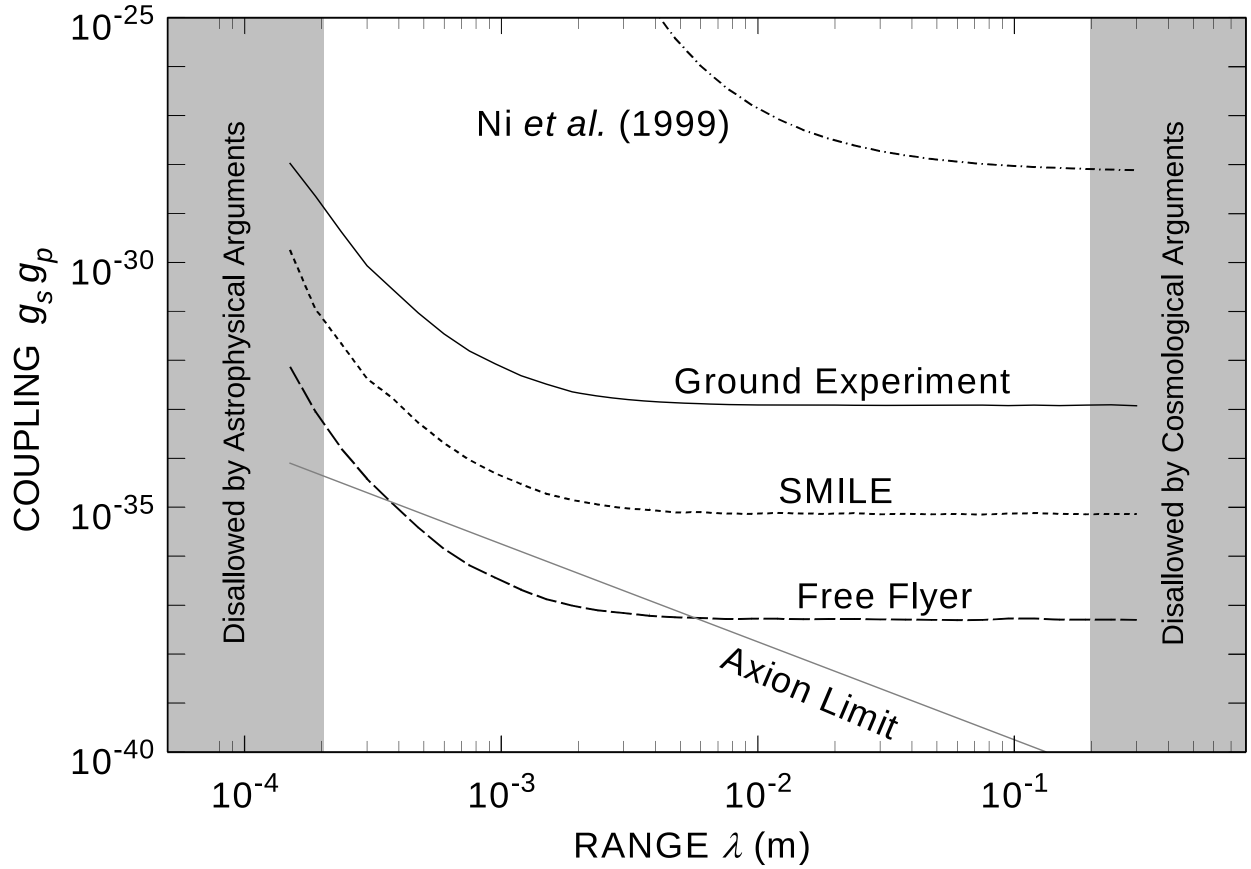
- Dynamic error compensation:

  Angular and linear accelerometer outputs are used to compensate the residual acceleration sensitivity to 10^{-8} and 5×10^{-11} m^{-1}.

- Nonlinearity noise:

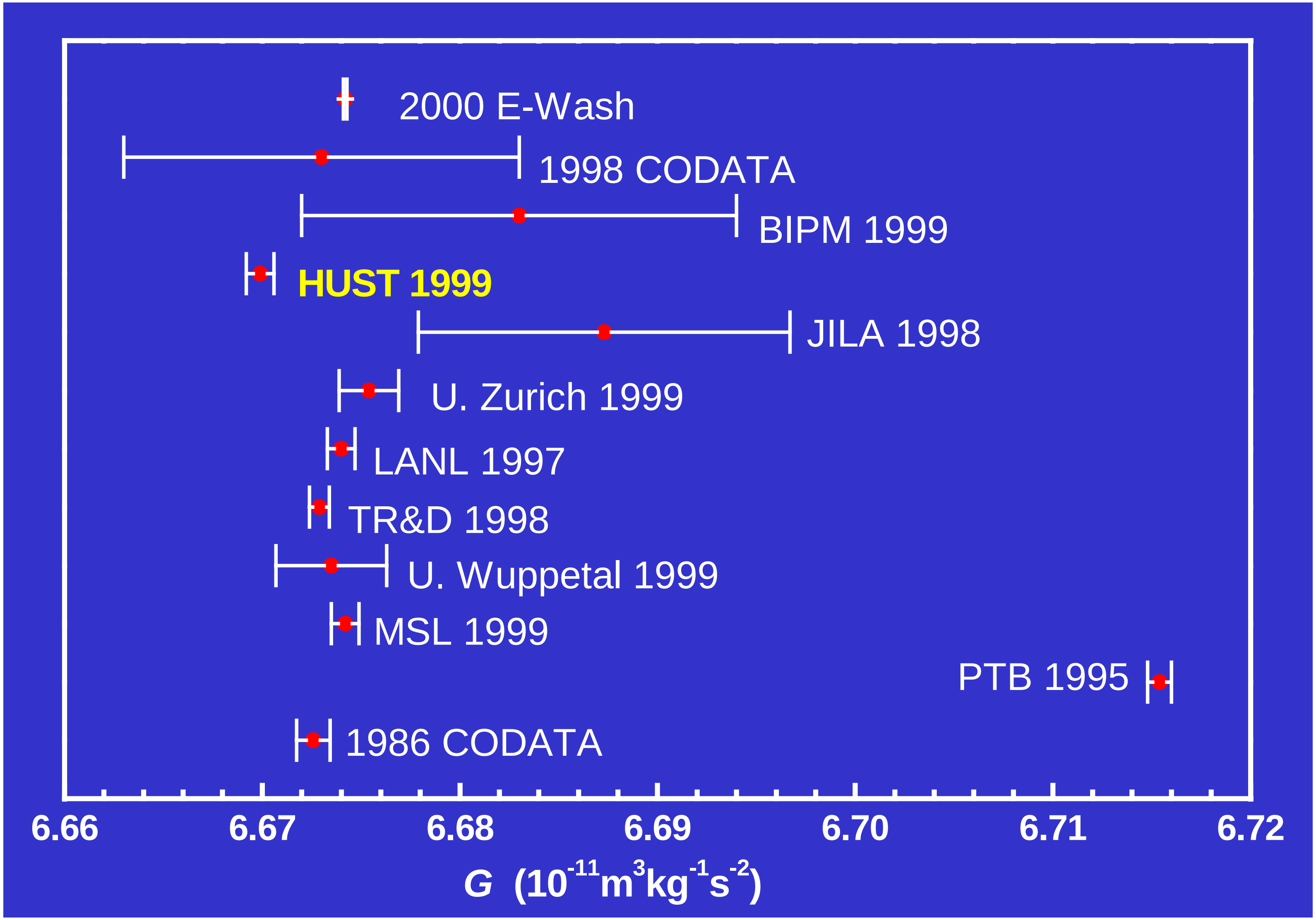
  This noise is reduced to $\leq 10^{-5}$ by stiffening the translational modes by applying feedback to the test masses.

Expected resolution of SMILE



- Soft rare-earth material is assumed.
  - $\Rightarrow$ Without it, a factor of 100 loss in sensitivity.
  - $\Rightarrow$ Experiment shelved in favor of the $1/r^2$ law test.

Status of *G* measurement

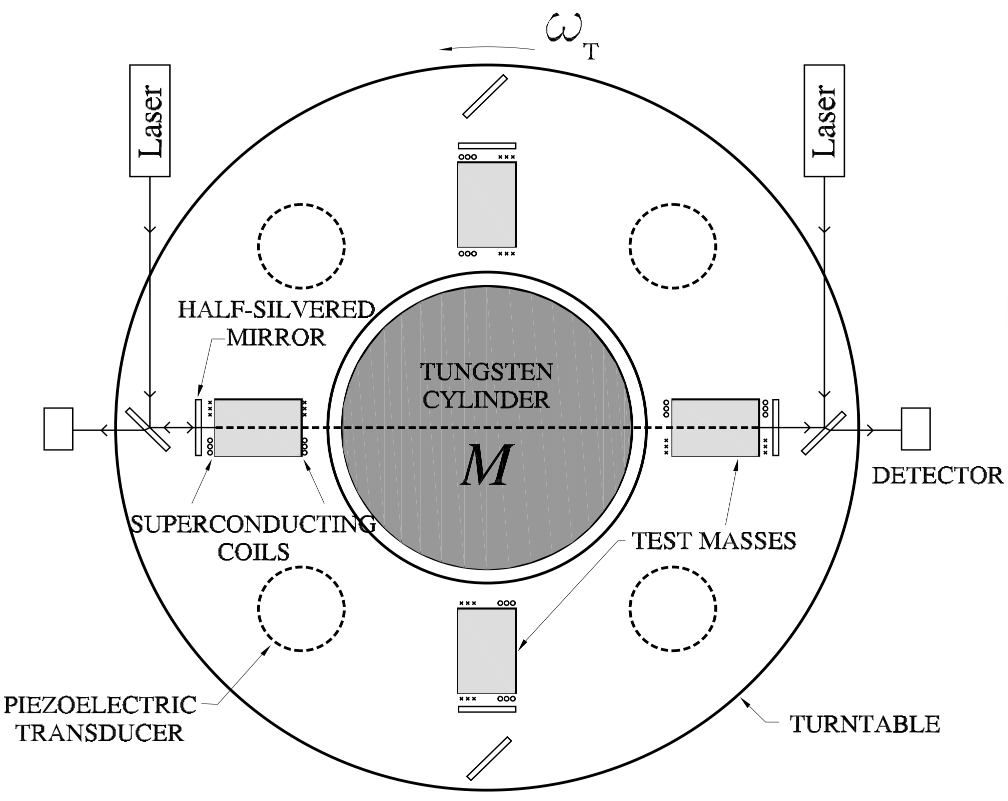


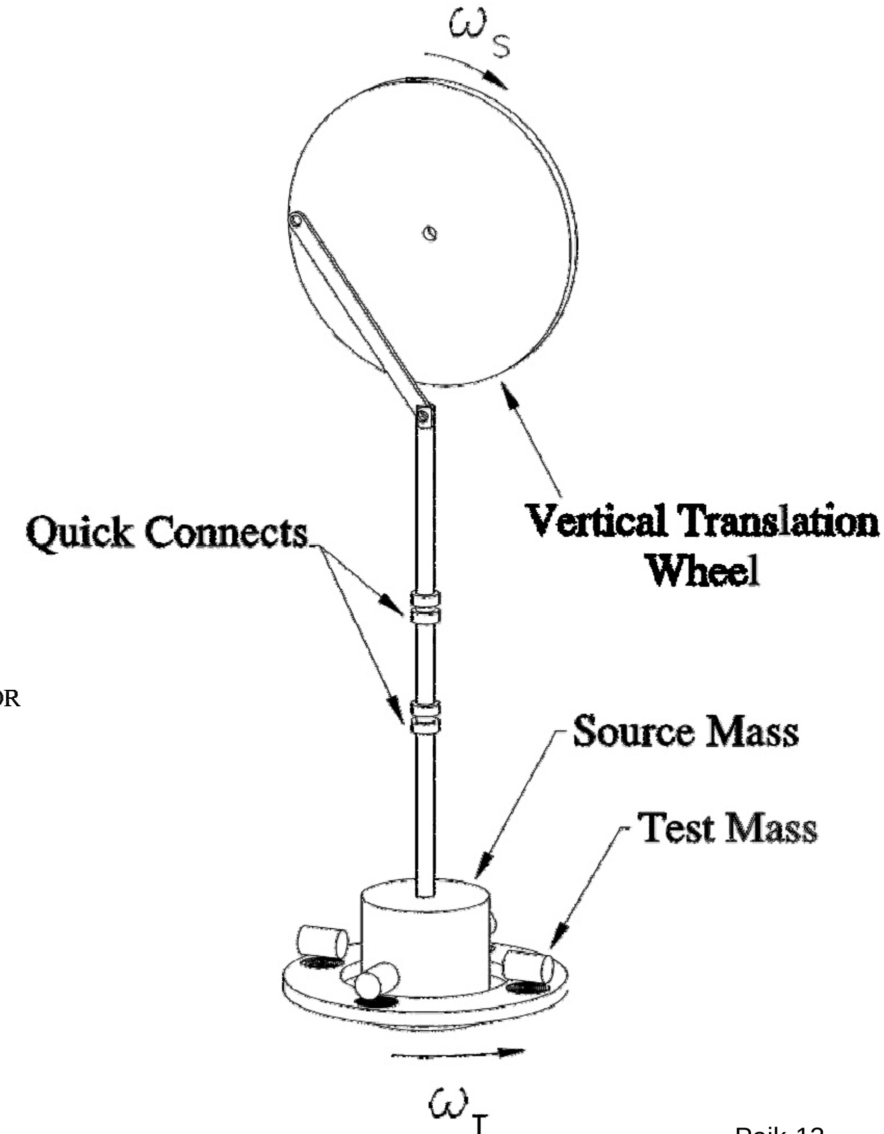
Principle of the experiment

- Planetary system of the source and test masses: $GM/r^3 = \omega^2$.
  - $\Rightarrow$ The differential accelerometer is used as a *null* detector.
  - $\Rightarrow$ Straightforward to measure M and ω to $<10^{-6}$.
- Superconducting levitation of the test masses.
  - $\Rightarrow$ No anelasticity associated with a suspension fiber.
- Superconducting differential accelerometer.
  - $\Rightarrow$ Low thermal (T = 4.2 K) and amplifier (SQUID) noise.
  - $\Rightarrow$ Both linear *and* angular acceleration are rejected to $\geq 10^5$.
- Optical interferometry for distance measurement.
  - $\Rightarrow$ Test mass separation is measured to <100 nm *in situ* at low temperature.

Design of the experiment

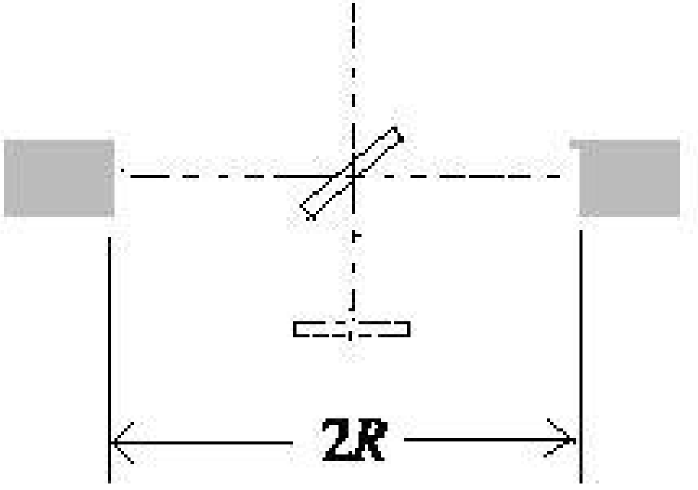
Top view of the experiment





Absolute length measurement

- Multi-frequency interferometry (3~5 frequencies).
  - ⇒ With tunable CW dye laser, ±8.8 nm accuracy demonstrated between up to 1 cm distance.
- Frequency scanning interferometry, developed for alignment of ATLAS tracker.
  - ⇒ ~250 nm accuracy demonstrated for 0.2~1.5 m distances.
- Null detection with frequency scanning interferometry.



$$\Delta d = 4R = n\lambda_1 = (n+1)\lambda_2$$

$$\Rightarrow \quad n = \frac{\lambda_2}{\lambda_1 - \lambda_2}$$

Error budget and expected resolution

Error source	Error (m s^{-2})	$\Delta G/G$
Instrument	2.5×10^{-15}	3.4×10^{-8}
Seismic	1×10^{-14}	1.4×10^{-7}
Source mass metrology	8.5×10^{-15}	1.2×10^{-7}
Source mass position	3.6×10^{-14}	4.9×10^{-7}
Test mass metrology	8.1×10^{-15}	1.1×10^{-7}
Gradiometer baseline	1.5×10^{-14}	2.1×10^{-7}
Mass calibration	1.5×10^{-14}	2.1×10^{-7}
Turntable wobble	$< 10^{-16}$	$< 10^{-9}$
Source driven acceleration	$< 10^{-17}$	$< 10^{-10}$
Angle measurement	$< 10^{-16}$	$< 10^{-7}$
Temperature fluctuations	1×10^{-15}	1.4×10^{-8}
Others	$< 10^{-15}$	$< 10^{-8}$
Total	4.5×10^{-14}	6.2×10^{-7}