Tests of the Equivalence Principle

Stephan Schlamminger
with Todd Wagner, Ki-Young Choi, Jens Gundlach and Eric Adelberger

Friday 1/5/2007
AAPT-Visit

Outline

- What is the Equivalence Principle?
- Why do we want to test it?
- How has it been tested?
- The principle of our Apparatus
- What will you see in the lab tour?
- Results

The Equivalence Principle

Our Current theory of gravity, **General Relativity,**

is based on the **Equivalence Principle:**

All bodies fall in a gravitational field with the same acceleration regardless of their mass or internal structure.

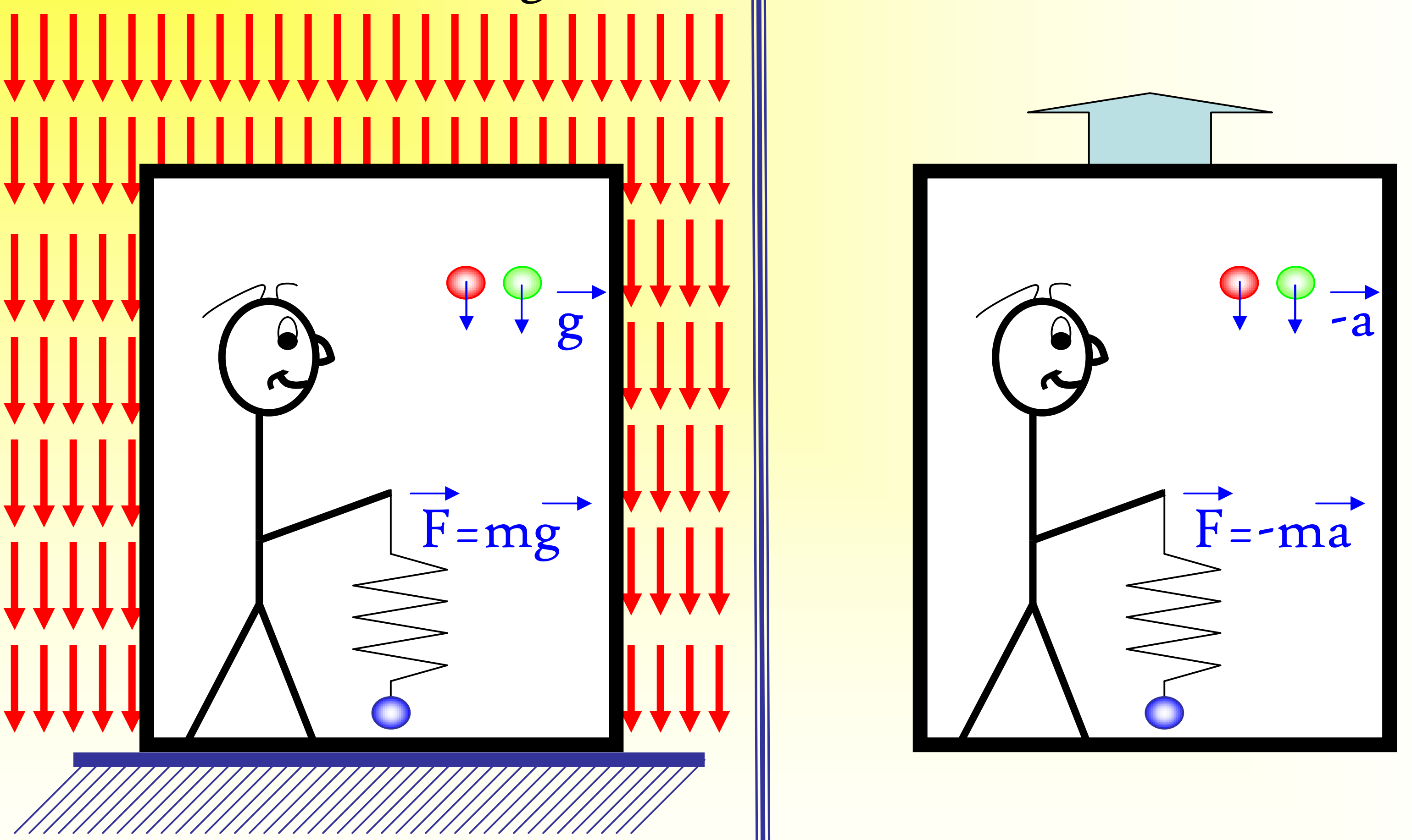
Einstein realized, that:

A uniform gravitational field is the same as an accelerated reference frame.

The Equivalence Principle

Gravitational field g

Acceleration a



Inertial mass = gravitational mass, $m_I = m_G$ for all bodies

General Relativity and the EP

Three classical tests:

- Perihelion shift of Mercury
- Deflection of light by the Sun
- Gravitational red shift of light

The last two can be explained and calculated with the EP alone!

Motivation

GR is one of the most essential pillars of modern physics.

- We should continue to test it.

GR should be combined with quantum mechanics for a full description of Nature.

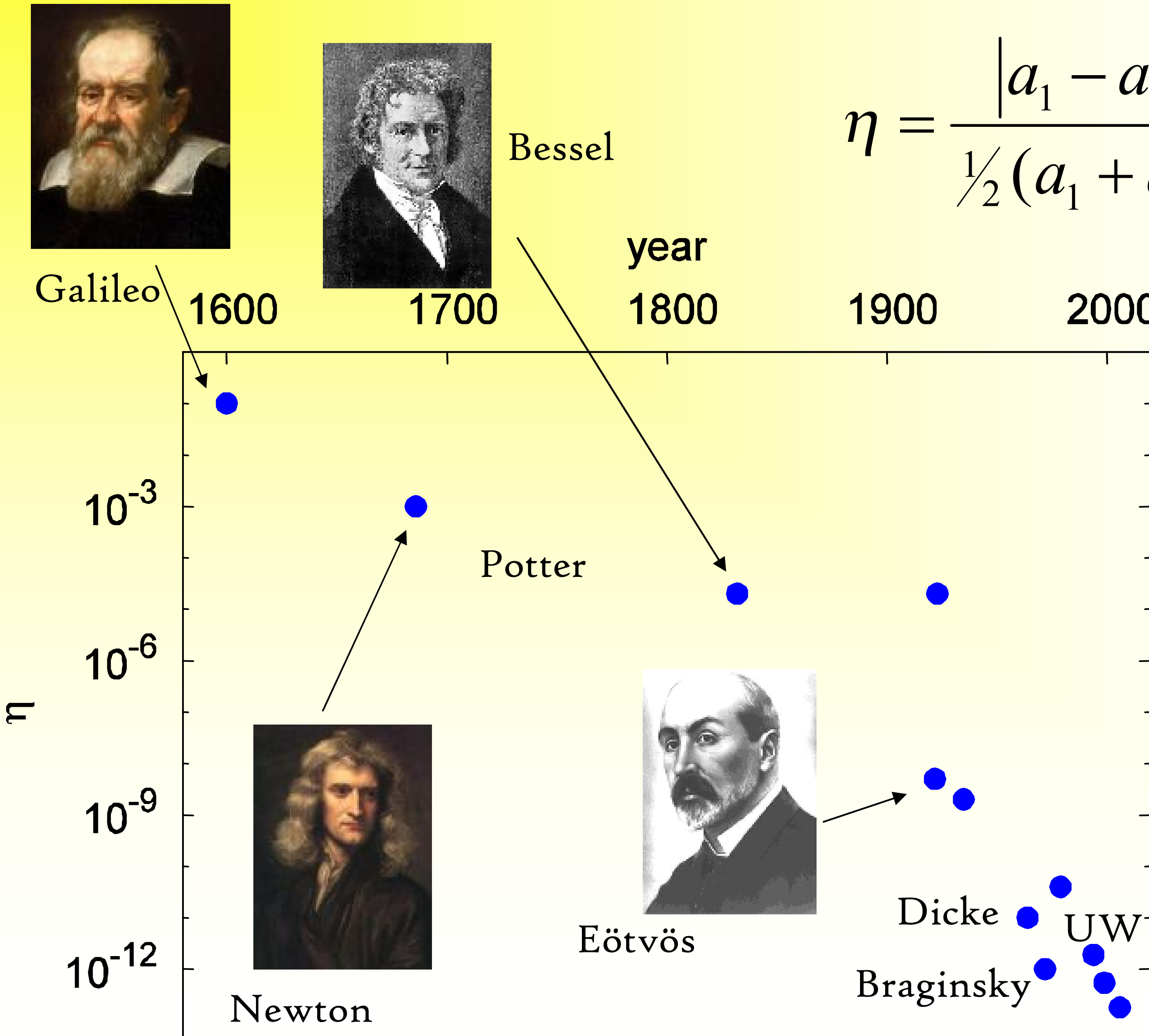
- New theories like string theory, quantum gravity, etc., most of which violate the equivalence principle at small level

Tests like this can be used to find new interactions ("fifth force")

Tests of the equivalence principle are the most sensitive probes of fundamental physics.

Historical overview

$$\eta = \frac{|a_1 - a_2|}{\frac{1}{2}(a_1 + a_2)}$$



Type of experiment

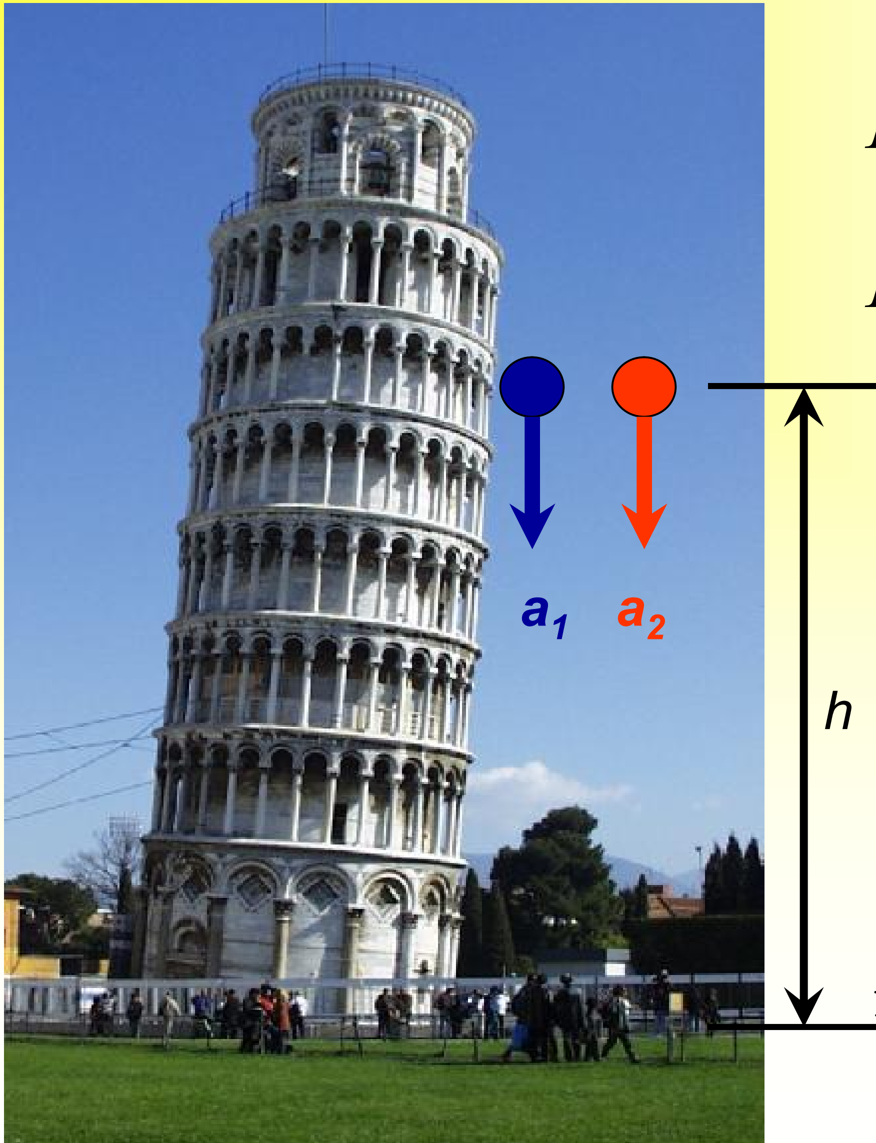
drop

pendula

torsion balance

modulated torsion balance

1st Tests of the Equivalence Principle



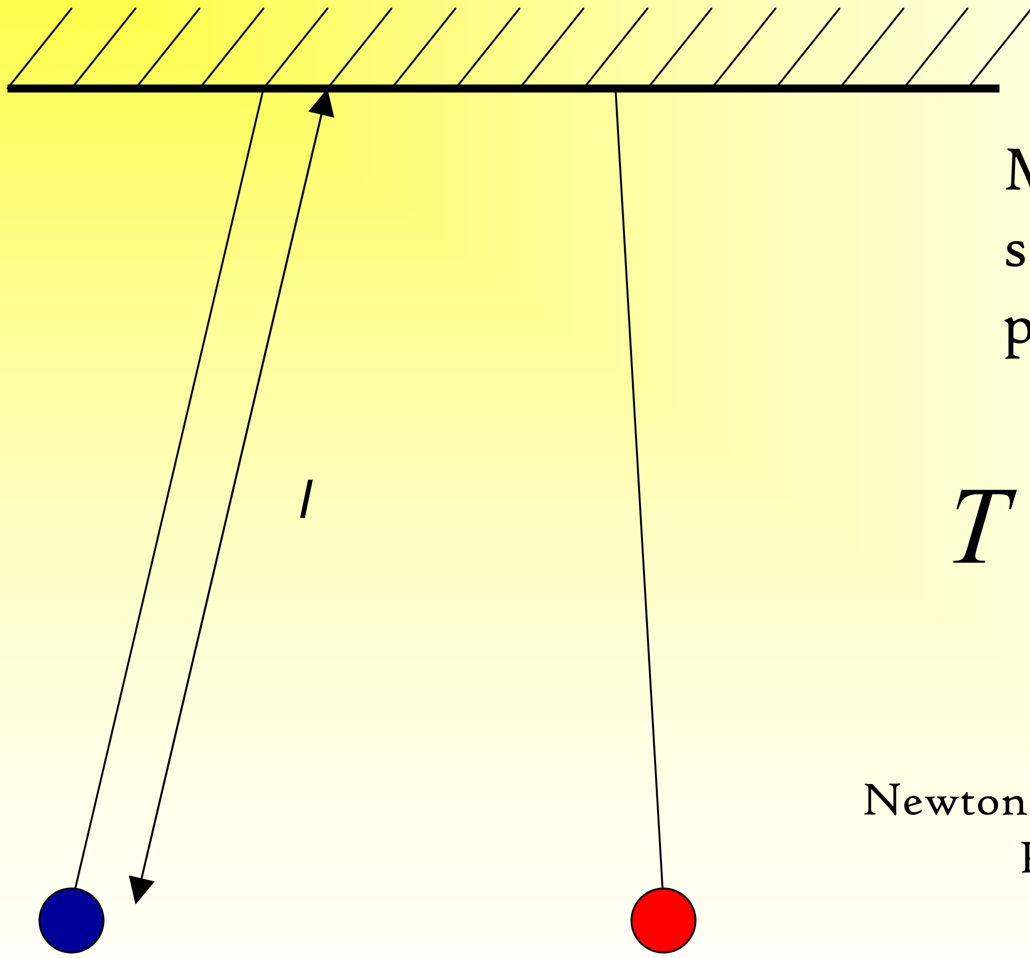
$$\left.\begin{aligned} F &= m_G g \\ F &= m_I a \end{aligned}\right\} a = \frac{m_G}{m_I} g$$

Time t to fall from h:

$$t = \sqrt{\frac{2h}{{}^{m_G}\!/_{m_I}\, g}}$$

1600 Galileo: $\eta = \dfrac{a_1 - a_2}{\frac{1}{2}(a_1 + a_2)} \approx 0.1$

2^{nd} Generation Tests



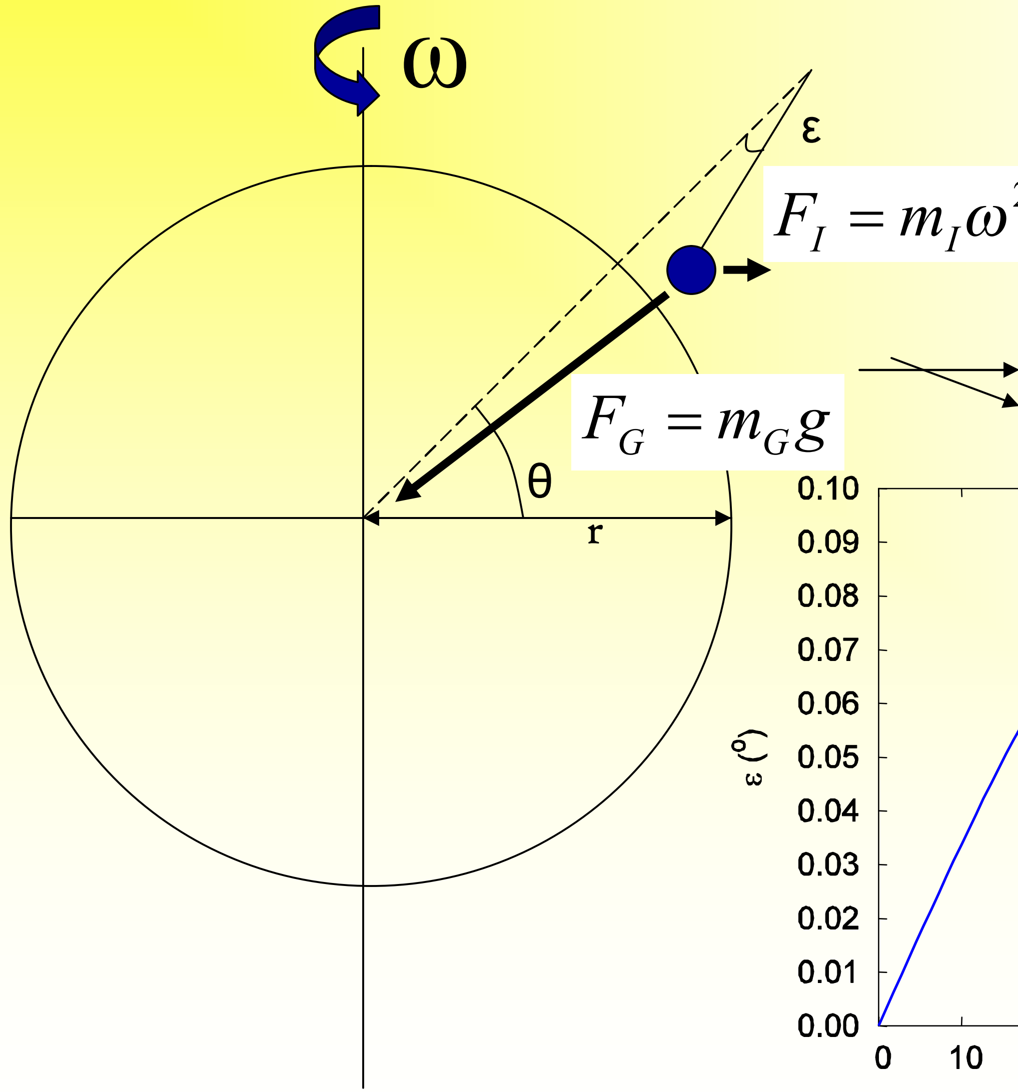
Measurement of the swing periods of pendula:

$$T = 2\pi\sqrt{\frac{L}{g}\frac{m_I}{m_G}}$$

Newton (1686), Bessel (183), Porter (1923)

$$\eta \approx 2x10^{-5}$$

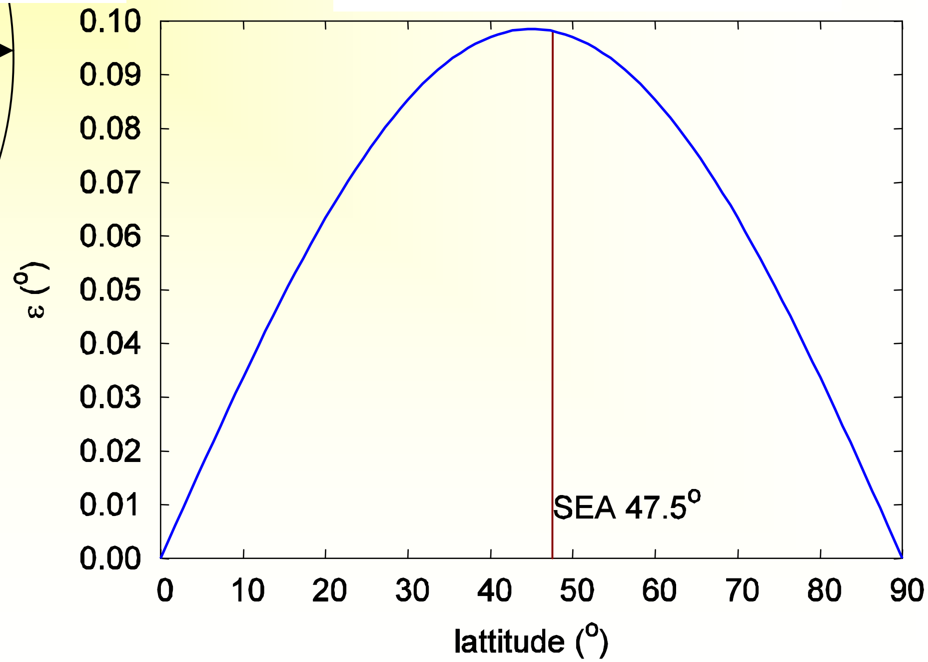
Eötvös Experiments



$$F_I = m_I \omega^2 r \cos\theta$$

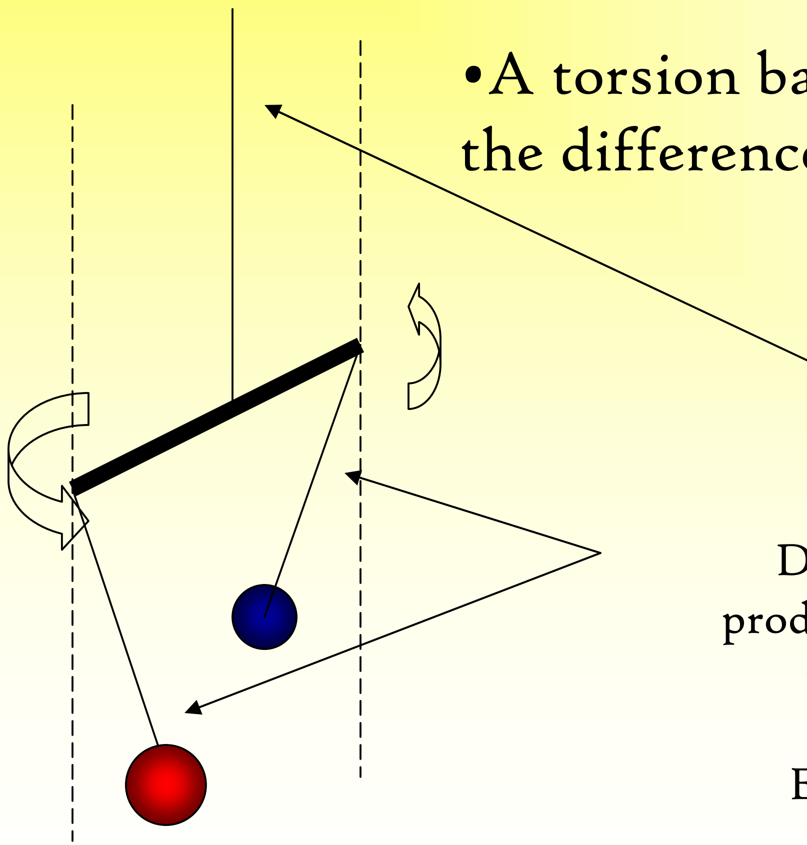
$$F_G = m_G g$$

$$\varepsilon = \frac{m_I}{m_G}\frac{\omega^2 r}{2g}\sin(2\theta)$$



Why a torsion balance?

- A violation of the EP would yield to different plumb-line for different materials.
- A torsion balance can be used to measure the difference in plumb-lines:

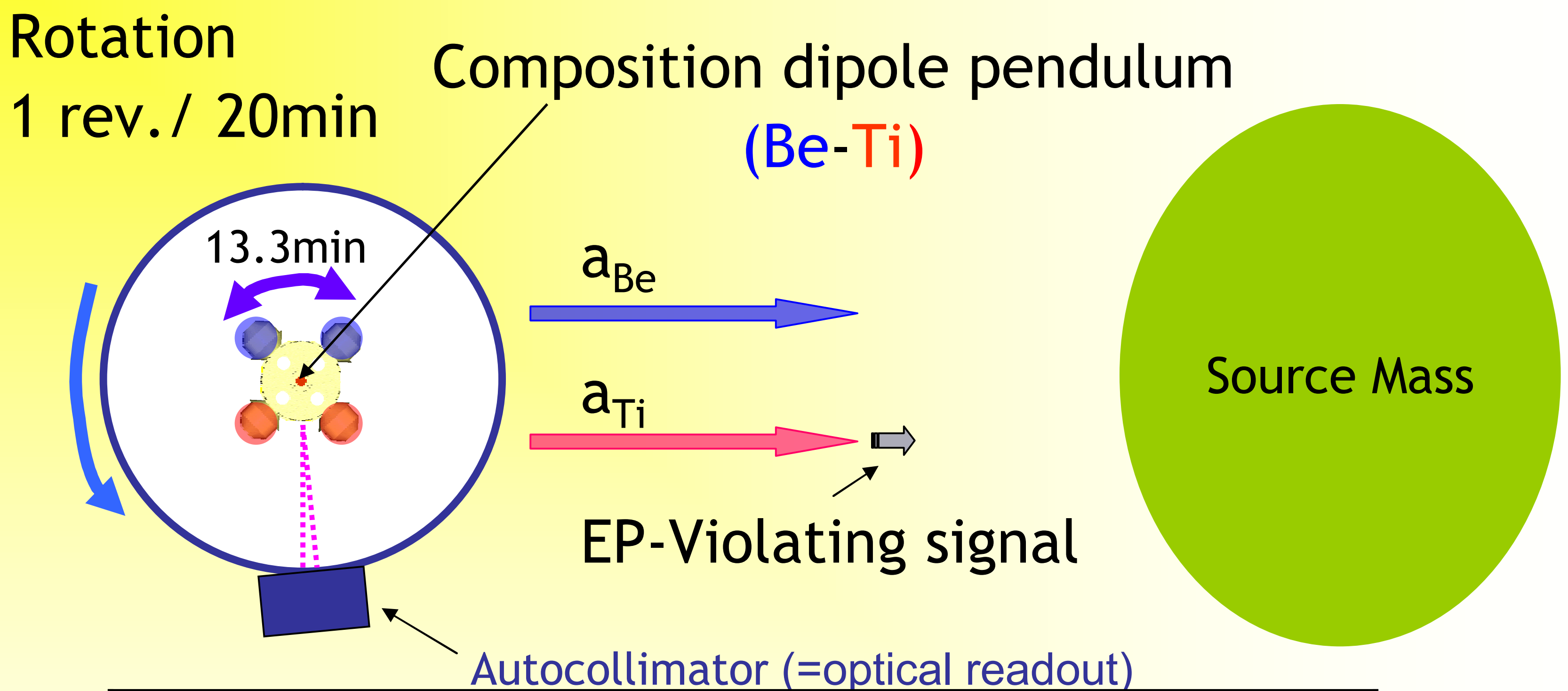


Torsion fiber hangs like the average plumb line.

Difference in plumb lines produces a torque on the beam.

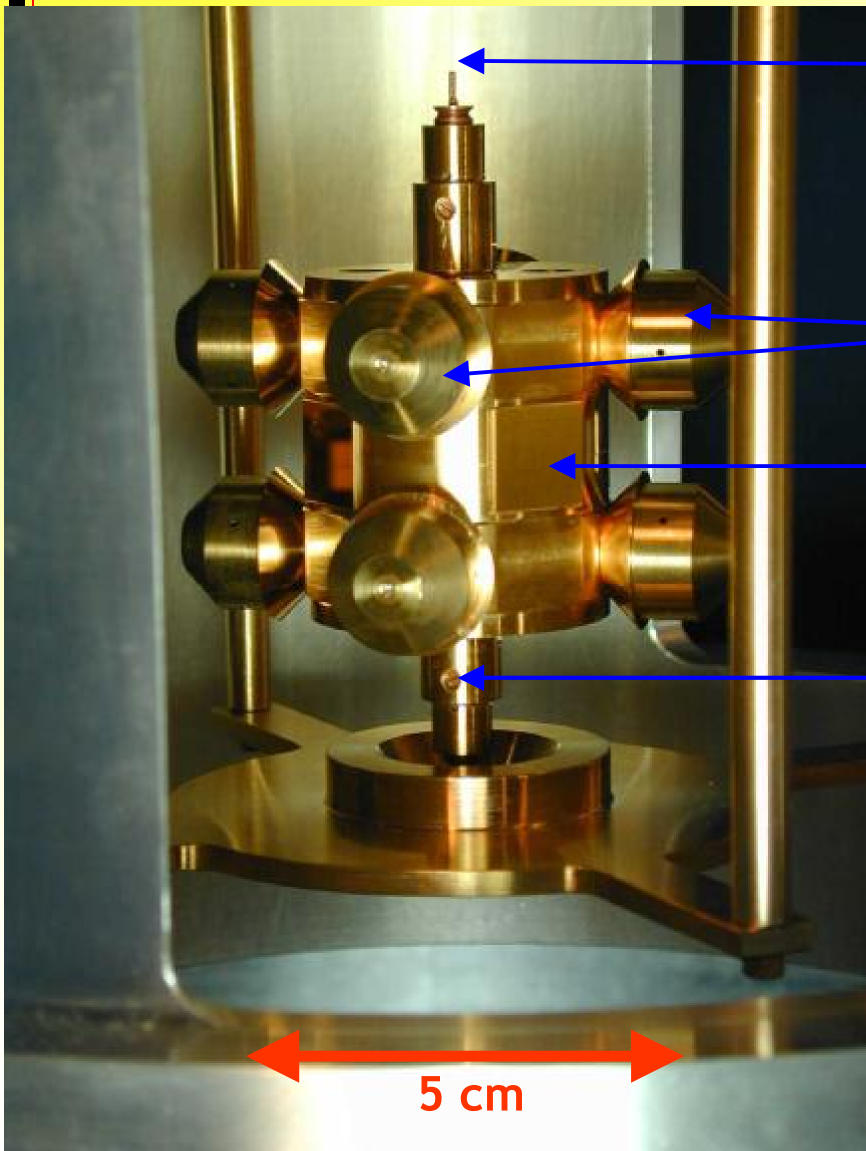
Eötvös (1922) $\eta \approx 5x10^{-9}$

Principle of our Experiment



source mass	λ (m)
local masses (hill)	$1 - 10^4$
entire earth	$10^6 - 10^7$
Sun	$10^{11} - \infty$
Milky Way (incl. DM)	$10^{20} - \infty$

EP Torsion Pendulum



20 μm diameter tungsten fiber
(length: 108 cm)

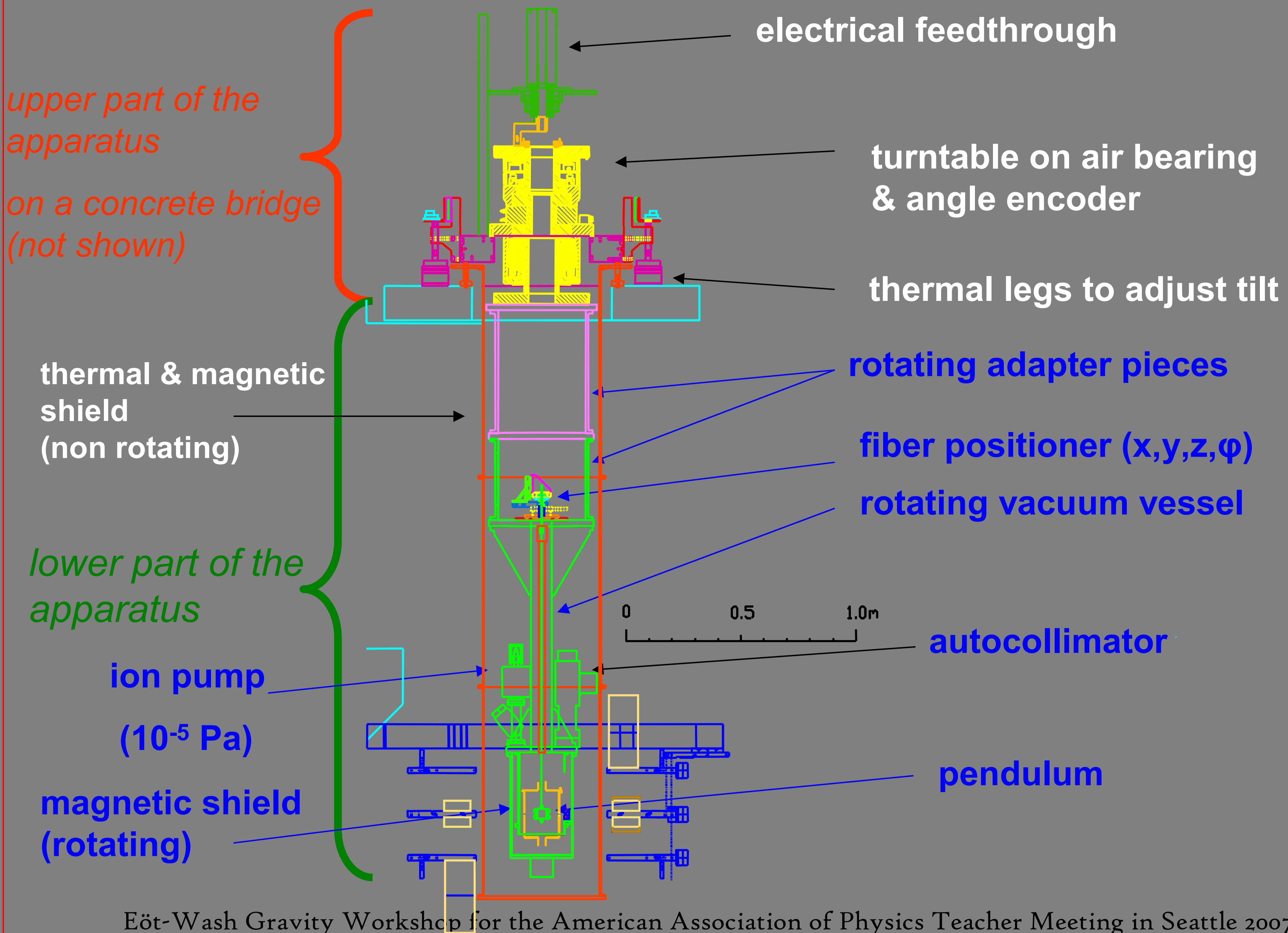
8 test masses (4 Be & 4 Ti)
4.84 g each (within 0.1 mg)

4 mirrors

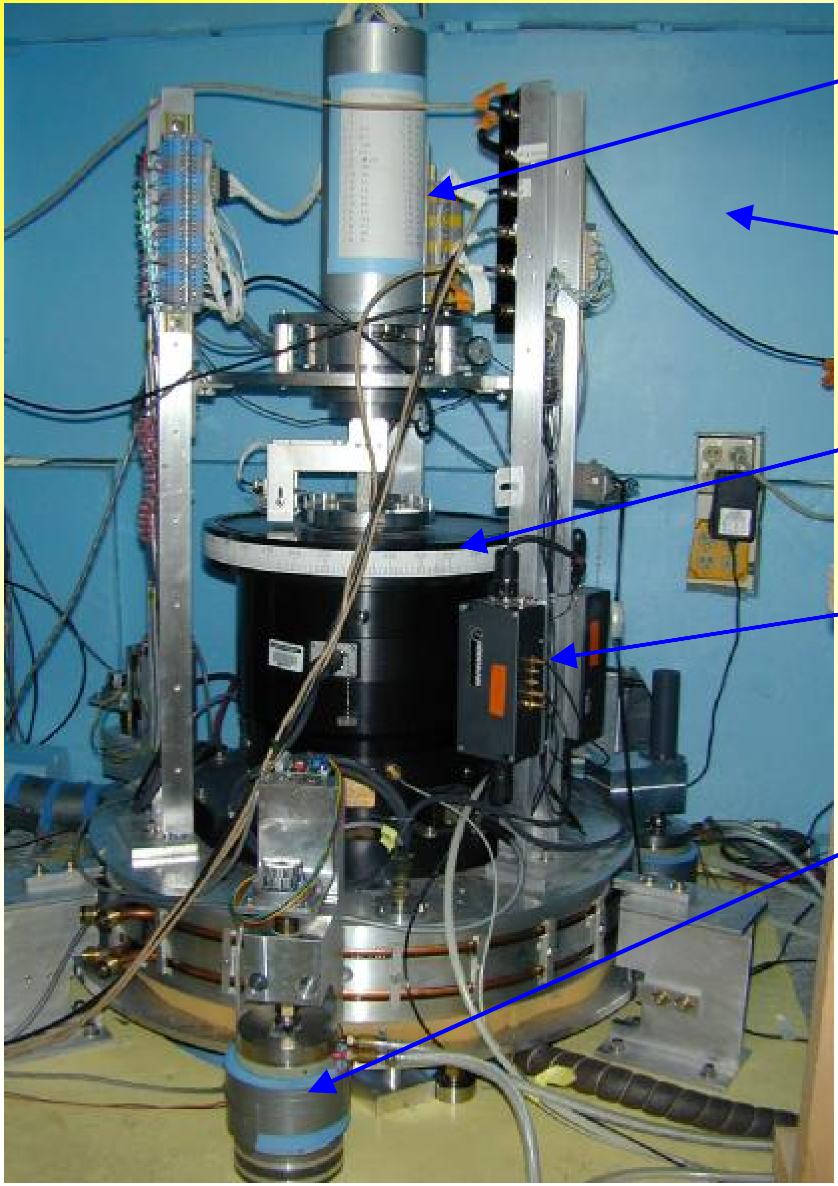
tuning screws for adjusting
tiny asymmetries

frequency:	1.261 mHz
quality factor:	4000
decay time:	11d 6.5 hrs
machining tolerance:	5 μm
total mass :	70 g

The Apparatus



The Upper Part of the Apparatus



feedthrough for
electric signals

thermal insulation

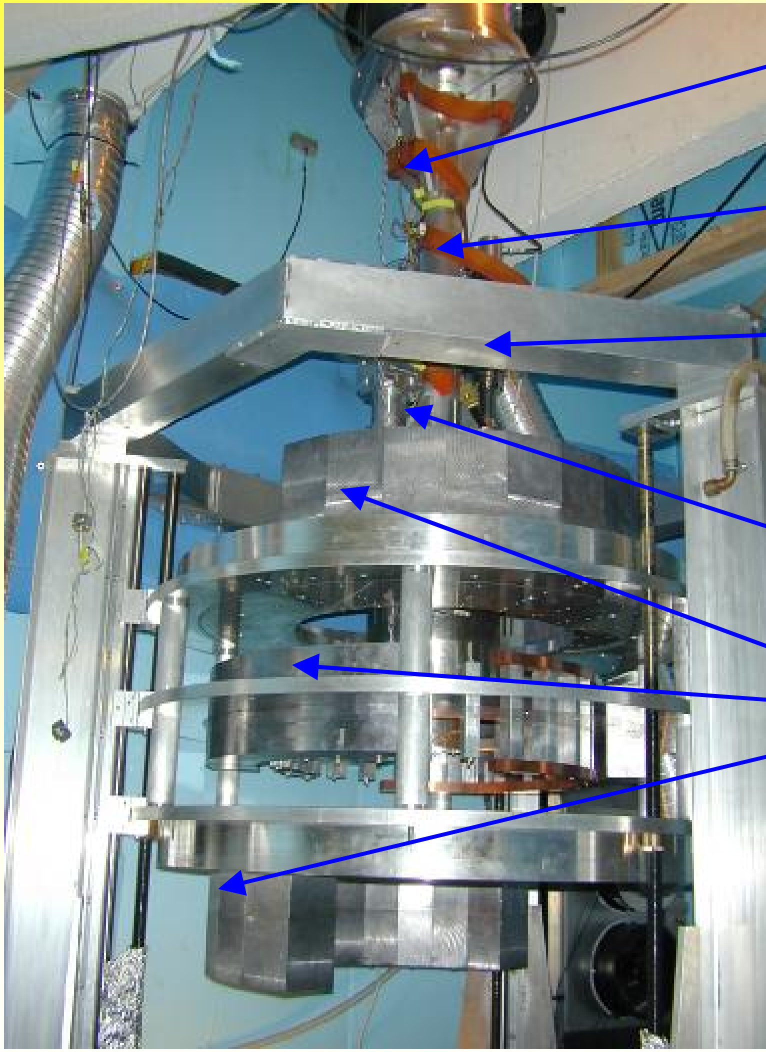
air bearing turntable

electronics of angle encoder

thermal expansion feet

to level turntable

The Lower Part of the Apparatus



vacuum chamber

ion pump

support structure for gravity gradient compensators

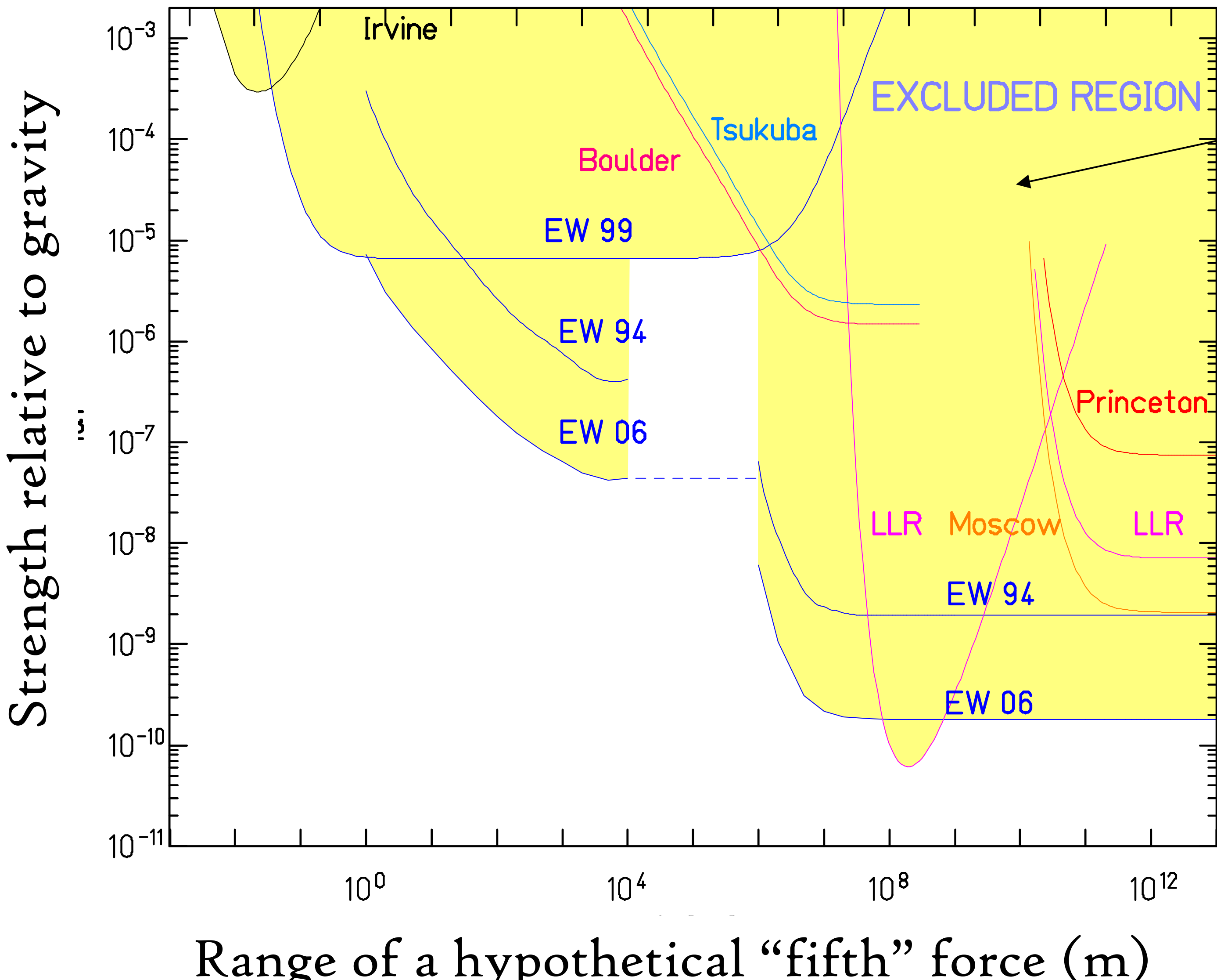
autocollimator

gravity gradient compensators

Systematic Effects

	(cm/s²)
Gravitational Coupling	0.9×10^{-13}
Magnetic	0.3×10^{-13}
Temperature	1.7×10^{-13}
Tilt	0.3×10^{-13}
Turntable Rate	0.6×10^{-13}
Total Systematic	$\mathbf{2.2 \times 10^{-13}}$
Statistical Uncertainty	$\mathbf{3.6 \times 10^{-13}}$

Results



Excluded with 95 % confidence

THE END