Gravitational Interaction of Vibrating Systems

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Theory and Measurement of Gravity

Nowadays, gravity is most accurately described by Einstein's general theory of relativity. However, in the laboratory, gravity is well approximated by **Newton's law of universal gravitation** from 1687, stating that every point mass m_1 attracts every other point mass m_2 by a force

$$F_g = G \cdot \frac{m_1 m_2}{r^2}$$

acting along the line connecting the two points, where r is the distance between the point masses and G is the **Newtonian constant of gravitation [5]**

$$G = 6.67430(15)10^{-11}\ \frac{\mathrm{m}^3}{\mathrm{kg}\cdot\mathrm{s}^2}$$

In order to determine G, Henry Cavendish established in 1798 the measuring principle of a static **torsion balance** [2], which is still used today in improved versions. Since then, only few other principles have been used, such as free fall or **dynamic experiments** (vibrating or rotating rods). Due to the relatively **large uncertainties** in the measurements and/or theory, the natural constant G is the **least known** of all the basic constants of physics, cf. Fig. 2

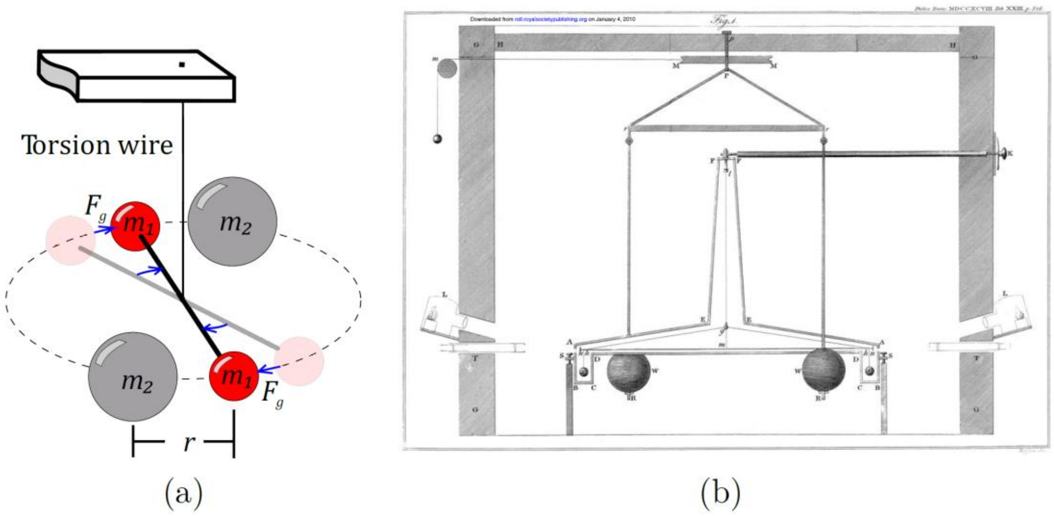

Figure 1: Torsion balance to measure the attraction of two masses due to gravitation. (a) Measurement scheme; (b) Drawing of the first setup by Cavendish in 1798. Extract from [2]

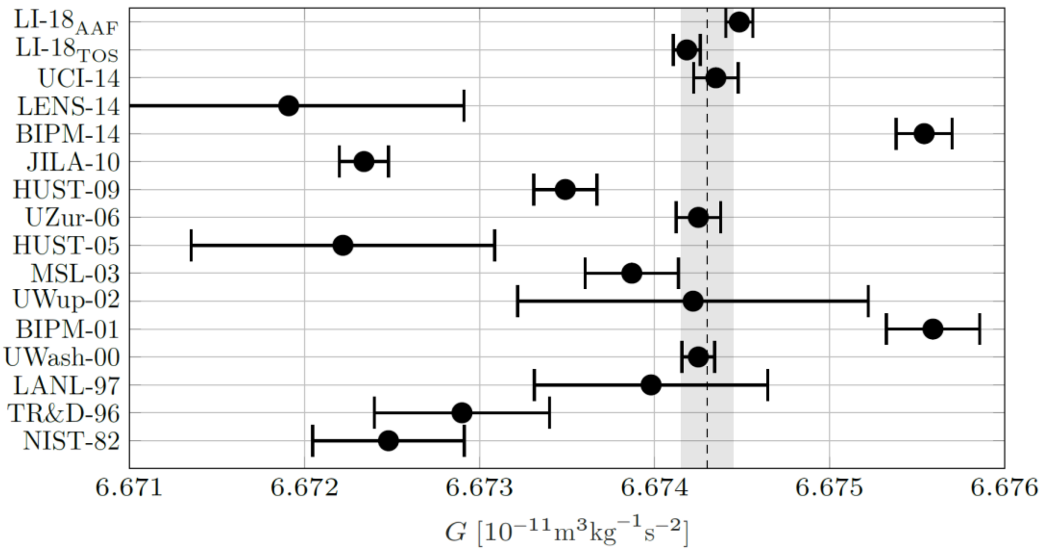

Figure 2: Measurements of G taken over the past 40 years. The dashed line denotes the 2018 CODATA recommended value. The uncertainties are indicated by error bars and the shaded area. Data from [3] and [4].

In contrast to Newton, Einstein predicts the existence of **gravitational waves** propagating from their source at the speed of light. Such waves could be first detected in 2015 by the LIGO (Laser Interferometer Gravitational-Wave Observatory) [1].

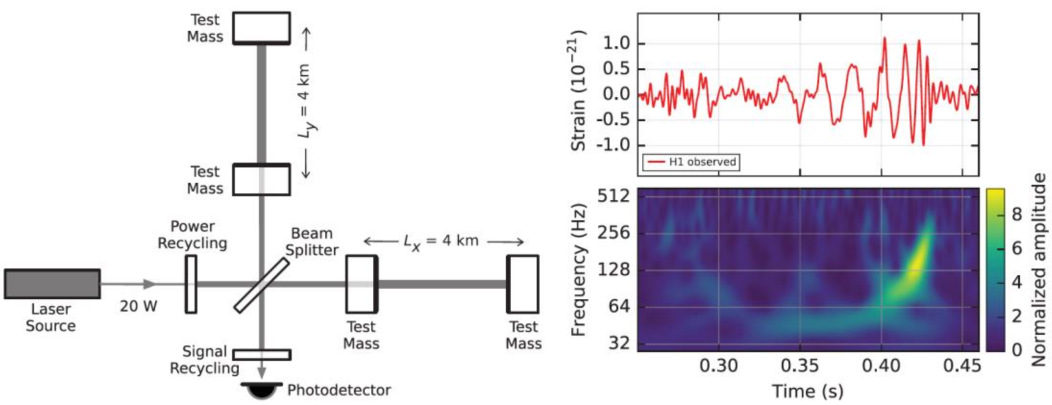

Figure 3: Simplified diagram of an Advanced LIGO detector (not to scale) and measured signal of the gravitational event GW150914 observed by the LIGO Hanford, Washington. Figures from [1].

Goal and Measurement Method

Goal

Establish a new high precision experiment to investigate various aspects of gravity, such as

- the value of the gravitational constant G
- the inverse square law $F_g \sim r^2$
- gravitational shielding

Measurement Methods

The experiment is dynamic, thereby eliminating gravitational influences from the environment. It consists of a **detector beam** and a mechanically decoupled **transmitter**.
The transmitter is excited externally in order to produce a vibration of large amplitude, with a frequency as close to the first bending resonance frequency of the detector beam as possible (ca. 42 Hz). With proper decoupling, the detector beam will experience **gravitational forces** only. Due to the dynamic movement of the transmitter and hence a dynamic gravitational force, a first mode bending vibration of the detector beam is excited.
Due to resonance and the resulting amplification (Q ~ 15000), **measurable vibrations** develop. The detector deflection is measured using multiple **laser vibrometers** and high precision **lock-in amplifiers**. The amplitudes are then linked to the excitation force using **models from continuum mechanics**.

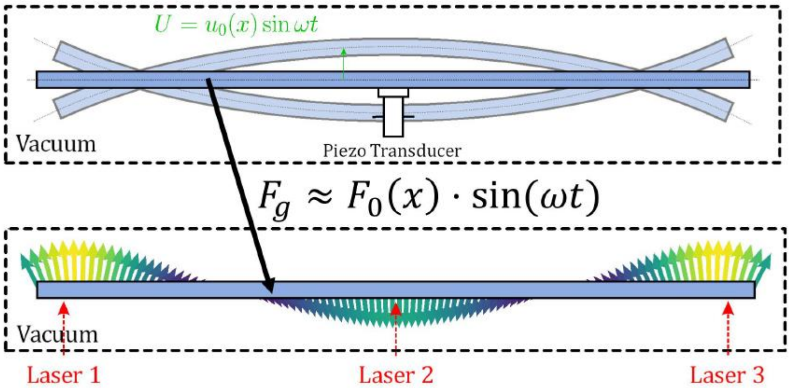

Figure 4: Measurement principle: while the transmitter is excited externally, the detector beam performs gravitation induced vibrations that can be detected optically.

Challenges

- eliminate **parasitic coupling** (mechanic, acoustic, electromagnetic, etc.)
- measurement of **extremely small movements** (10^{-11} m/s; 10^{-13} m)
- ensure stable **environmental conditions** ($\Delta T \sim 10^{-3}$ °C/h, pressure, etc.)