Why is it so difficult to measure the gravitational constant?

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Most people learned the law of universal gravitation in high school. Written down by Isaac Newton in the 17th century, although in a different form, this law describes the gravitational force between two masses. The attractive force is given by

$$F = G\,\frac{m_1 m_2}{r^2},$$

where $m_1$and m_2 are the masses of two bodies at a distance r. The constant G denotes the strength of gravitation and is a fundamental constant of nature. Since this law is so old, one might think that everything that can be known about it is known and the scientists can focus their attention elsewhere. Unfortunately, this is not the case. And the state of affairs is quite embarrassing.

It is notoriously difficult to measure the strength of gravity. Since the first measurement by Maskelyne, ca. 1774, and the famous first laboratory measurement (1793-1798) by Cavendish, more than 300 measurements have been made. Yet today, the most precise measurements still don't agree. Figure 1 shows fourteen measurements that have been carried out at renowned laboratories worldwide. While the smallest relative uncertainties achieved in these experiments are of order 20 parts in 1 000 000, the relative difference between the smallest and largest result is larger than 500 parts in 1 000 000. Clearly, this dataset is statistically inconsistent. Explaining this inconsistency is difficult and attempts to do so can be sorted into three categories. (1) Some or all experiments underestimate the true uncertainty in the experiment. Statisticians have named the missing part of the uncertainty budget the dark uncertainty. The reported value is correct but the reported uncertainty too small. (2) Some or all experiments suffer a measurement bias that was not detected and taken into account by the experimenters. The reported uncertainty is correct, but the reported value is wrong. (3) There is new unknown physics that can explain the scatter in the experiments. While the third possibility is the least likely, it is also the most exciting one. This possibility should not be discarded lightly.

Attempts to understand these results and to find ways to improve the current understanding of the true value of *G* have several merits. Short of the exciting possibility of finding new physics, a real impact can be made in measurement science. After all, measuring *G* means determining a weak force with absolute accuracy in the presence of a large non-shieldable background. Being able to measure a force absolutely will become especially important after 2018, when, according to the current plan, the international system of units will be redefined. This redefinition will free the definition of the unit of mass from an artifact currently kept in a vault near Paris. After 2018, the unit of mass will be realized by apparatuses that can generate an absolute force and balance it against the weight of a mass. It seems obvious that G experiments and the experiments to realize the unit of mass at small mass scales have a lot in common and the lessons learned in one can be applied to the other.

There are several factors that make it hard to measure G. (1) The forces are small. Typically, the gravitational forces produced by the mass arrangement is well below 1 µN. (2) The gravitational background fields generated by the earth, structures and objects in the laboratory, and humans cannot be shielded. (3) The density profile of the test masses used in the experiment must be well known. This can be challenging at the level of 10 parts in 1 000 000. (4) The exact mass distribution of the experiment must be known and a numerical mass integration must be conducted to convert the measured force or torque into a value for *G*.

A coordinated effort is needed to understand the puzzle surrounding *G*. Individual experimenters have measured this constant for more than 300 years and the situation is dismal. The primary purpose of the International Union of Pure an Applied Physics (IUPAP) Working Group on the Newtonian Constant of Gravitation *G* is to coordinate experimental efforts to measure G. To achieve this goal, the working group will provide a group of experts that can advise experimenters on technical issues, convene regular meetings on the subject of G measurements, serve as a forum to discuss future experiments, proposals and new ideas, and attempt to understand the discrepancies between results.

One first step into understanding the discrepancy was recently undertaken. The experimental apparatus used by Quinn and coworkers to measure *G* at the Bureau International des Poids et Mesures (BIPM) was shipped to the National Institute of Standards and Technology (NIST). There, a group of independent researchers will undertake another measurement campaign. This is the first time in history that a specific *G* experiment is being repeated at a second laboratory halfway around the world with independent researchers. This is, in fact, how the scientific method should work. Different researchers should be able to reproduce the results that have been originally published. It will be exciting and interesting to see what results the researchers at NIST, who intend to perform the experiment blind, will obtain. This will give us for the first time a measure of how truly reproducible one experiment is. Stay tuned.

Other interesting things are also happening. The National Science Foundation (NSF) in the US is planning on holding an ideas lab. (This is being done outside the Working Group). The aim of the ideas lab is to get researchers from outside the field interested in this measurement problem. Experts in other areas should be able to apply their knowledge to help tackle *G*. The NSF is looking for high risk and new ideas to solve this problem.

The current state of high precision results on *G* is unsatisfying. The data points are statistically inconsistent with each other. An expansion factor of 6.3 would need to be applied to each experiment to make the data set statistically consistent. This is an unacceptable situation for the experimenters, who work hard to obtain the smallest reasonable uncertainty. However, there is a silver lining. The IUPAP working group on *G* is helping to solve the inconsistency problem. As a first step, one *G* experiment has been shipped across the Atlantic for a second measurement campaign. The NSF is encouraging new researchers to get into the field. And completely different methods, like atom interferometry, are recently coming online for G measurements. In addition, the International Committee for Weights and Measures has established a framework for National Metrology Institutes to provide traceability to the SI at the highest level for laboratories engaged upon determinations of G.

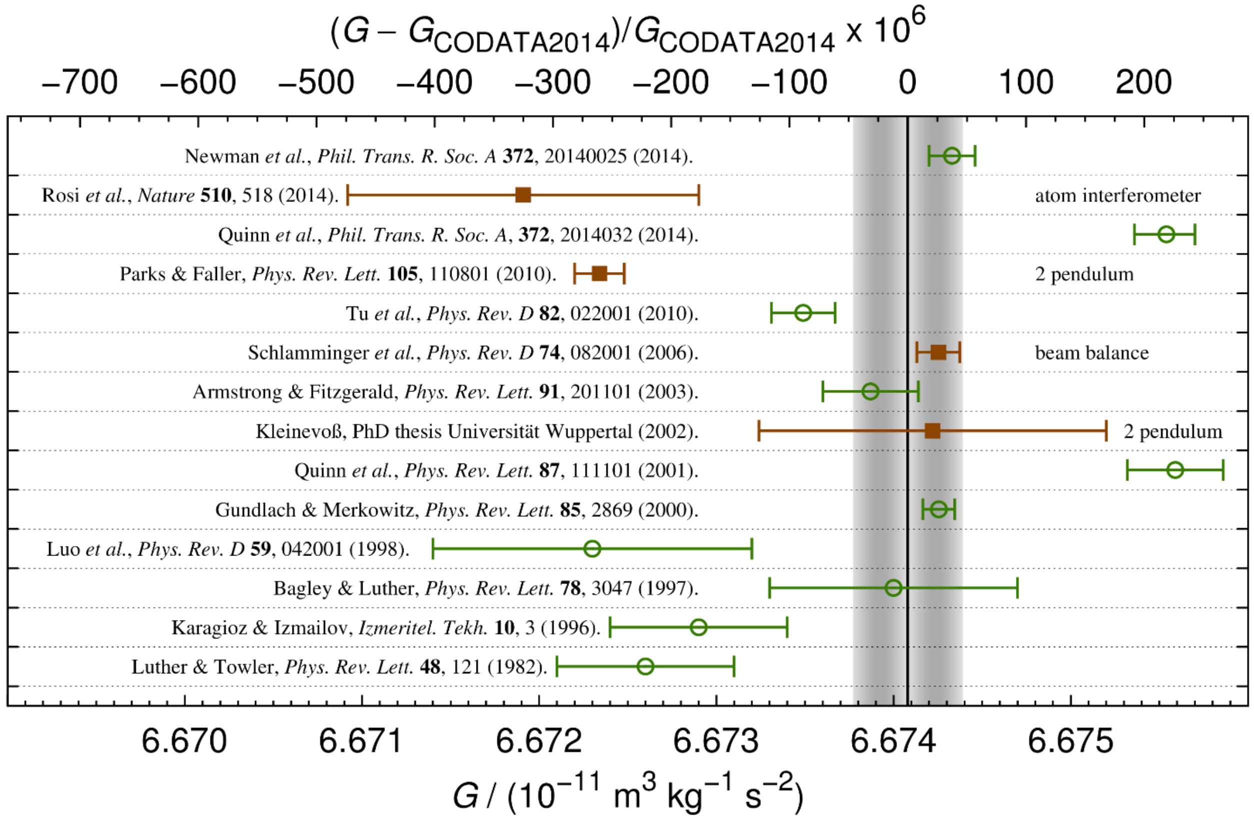

Figure 1 Measurements of the gravitational constant published in the last 34 years. The points denoted with open circles were measured using a torsion balance, the solid points by other means. The error bars denote the 1-sigma standard uncertainty. The black vertical line indicates the recommended value by the task group on fundamental constants of the Committee on Data for Science and Technology (CODATA). The grey area surrounding the black line denotes the 1-sigma uncertainty interval of the recommended value.

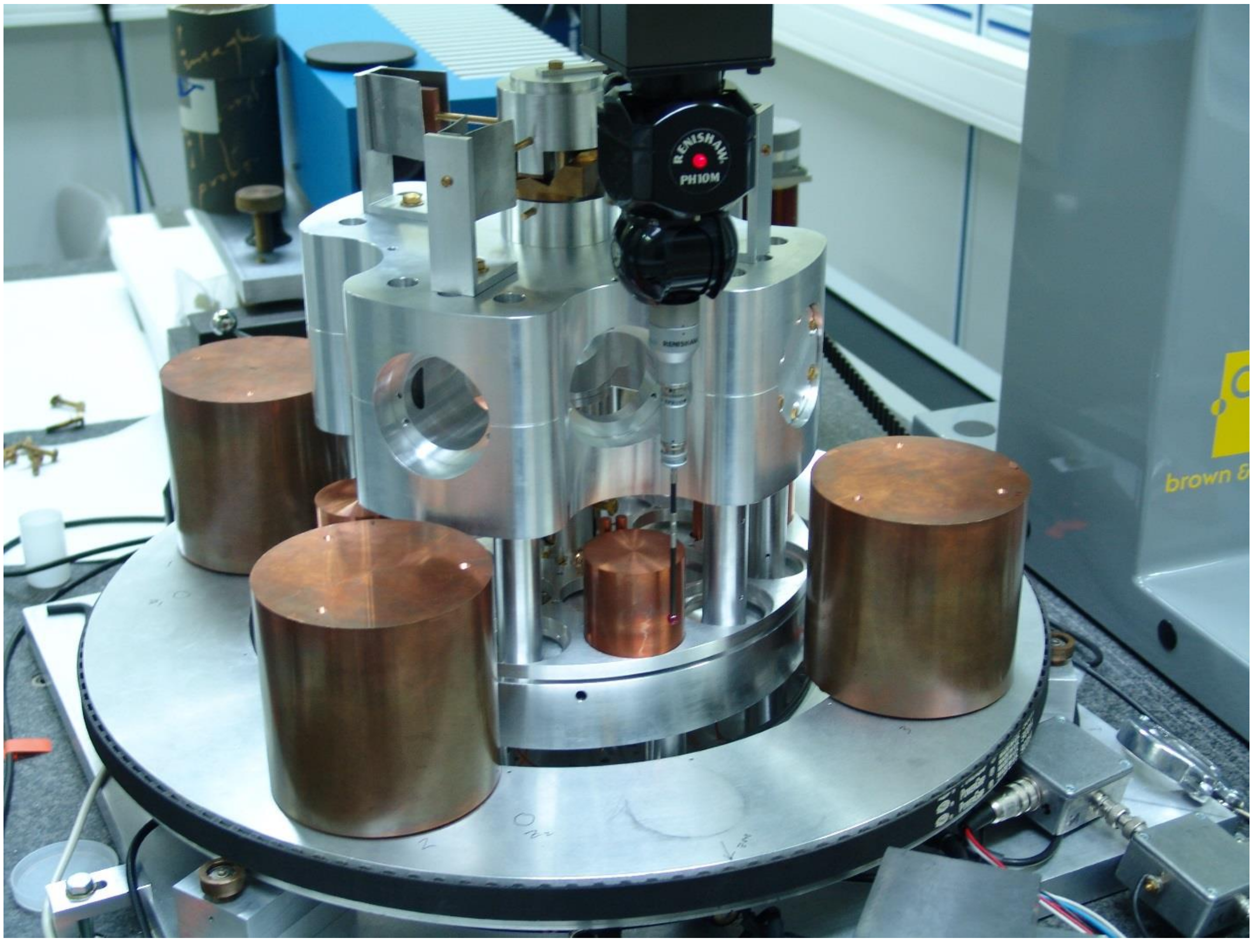

Figure 2 The G experiment carried out at the Bureau International des Poids et Mesures (BIPM) by Quinn and others. At the beginning of May 2016, this experiment was shipped to the National Institute of Standards and Technology (NIST). There the experimental apparatus will be used in another measurement campaign. Photo: T. J. Quinn (BIPM)