Strong evidence for composition-dependent gravity from Cavendish experiments [21.06.2022 (three digits agreement for lead); 26.06.2022 (distinguishing G_{Fe} and G_{Steel}); 07.07.2022 (refined values for G_{Fe} and G_{H}); 09.07.2022 (above 99.91% match for all elements); 16.07.2022 (Heyl's measurements of G_{Pt}, G_{Au} and G_{glass}); 29.07.2022 (standard deviations: all except silver and glass agree within margins of error); 02.08.2022 (Pontikis' initial results); 23.08.2022 (Brush & Crémieu); 25.09.2022 (Poynting-method is always unreliable); 05.06.2023 (the Eötvös experiment is not a valid test of the equivalence principle); 14.10.2023 (corrected method for the G-values of molecules: sums of inertial and gravitational masses respectively); 09.12.2023 (correct method for mixed materials: using atomic ratios, not mass ratios); 18.12.2023 (average-based graph); 20.12.2023 (separating tool steel from stainless steel); 21.12.2023 (graphs based on median and mode); 26.01.2024 (corrected value for glass); 07.02.2024 (one value per person or team); 11.02.2024 (abolishing the acceptable range and excluding pre-1971 values instead); 15.02.2024 (using minimal value for water and most frequent value for most of Heyl's measurements); 23.02.2024 (all of Heyl's different materials were test masses); 26.02.2024 (accounting for test mass composition of all measurements); 20.01.2025 (corrected odds)]

Author: Sky Darmos (Germany & Greece).

Sponsored by: Yi-song Lin (林宜松) (PR China); Janine Hofmann (Swiss); Gẳm-shịng Zhău (周錦盛) (SAR Hong Kong); OSS Capital (US).

Note: All G-values are given in $10^{-11}\ \mathrm{m}^2\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$. The order of magnitude and the units will be omitted throughout this chapter.

Many measurements of the gravitational constant have been conducted over the last 200 years. If we know which materials were used for the source and the test masses in those measurements, then we can compare the results of these measurements to the predictions of SPD-chromogravity.

The measurements we are going to look at in this chapters are mostly taken from two papers, namely "The attracting masses in measurements of G: an overview of physical characteristics and performance" by G. T. Gillies (2014) and "Determining the Newtonian gravitational constant G" by Ulf Kleinevoß (2002). Those are followed by a number of other values from various other lists and some were found without being listed.

The meta-analysis in this chapter was originally using a fixed range of acceptable values, which was going from 6.661 until 6.6745, based on the G-values of water and steel. Values outside this range were treated as outliers and were not included into the averages. It later turned out that all values that are in this range also happened to all be from 1971 and later. The only exceptions were measurements by Heyl (1930 & 1942).

Originally the analysis in this chapter was solely focused on source mass composition, because it was assumed that the mass of the beam carrying the test masses always dwarfs the test masses. In reality this is only sometimes the case. I realized the importance of test mass composition when it became clear that the different materials used by Heyl (Heyl; 1930) were really what he used for the test masses and not for the source masses.

In all the data of this chapter, the only experiment where test mass composition did not seem to matter was Schlamminger's measurement of the gravity of a mercury tank (Schlamminger; 2002), where switching the copper test masses by tantalum test masses did not impact the result significantly. In this case however it is a bit suspicious that the results with tantalum were tossed out and disregarded as inaccurate in his later publication (Schlamminger; 2006). He stated that inaccuracies were greatly increased with tantalum.

Values that are pre-1971 are marked gray, except of those from Heyl. Values that have standard deviations of $\pm\,0.01$ and more are marked orange. They too are excluded from the averages of different materials. Following Fischbach's 1986-claim of a fifth force, a lot of intermediate range gravity experiments were performed. Those all yield unusually high values for big-G and are also marked orange. Values from experiments that are not standard Cavendish experiments, such as for example freefall perturbation experiments (Schwarz; 1999), where the attraction between a freefalling mass and a stationary mass is measured, are also excluded. Most of those very exotic methods have been used only one time. Values that are excluded for such reasons are generally outside of the range $6.661 - 6.6745$.

When only source mass composition was taken into account, the observed values for most materials were averages sourced from many measurements. Now that test mass composition is accounted for, there is only one measurement for each combination of source and test mass composition in most cases.

Gillies' list already contained the source mass compositions, but no information on the composition of test masses. Kleinevoß' list contained both source and test mass composition. For the rest the test mass composition had to be searched for in the respective papers. In four cases it was not possible to find out the composition of the test masses. Those are Dousse (1987), Speake (1983), Liu (1987) and Oelfke (1984). For the latter three this does not matter much, as they were mainly testing the inverse square law and got only very low precision measurements of big-G. For Dousse (1987) it is very important to find out the test mass composition. For now, it is assumed that he was using the same material for both source and test masses.

Overall, we find that the measured values or averages of all elements are below the measured values or averages of copper and steel, which, according to space particle dualism theory, have the highest amount of gravity per kilogram.

Before we look at all measurements, we shall first discuss a few particular cases.

Heyl's fleeting doubts about the equivalence principle

Form 1925 - 1930, Heyl tried to measure the gravitational constant and found large discrepancies between different elements (Heyl; 1930). Here are the values that Heyl published in 1930, together with his value for steel-platinum from 1942:

SM	TM	Year	Measured G-value	Kind of value	SPD prediction	Agreement in percent	Agreement within

							margins of error
Steel	Platinum	1926	6.667 ± 0.012	Highest number of same-day measurements (4).	6.6712015 ± 0.000022	99.94%	Yes
Steel	Platinum	1942	6.672 ± 0.004	Average.	6.6712015 ± 0.000022	99.99%	Yes
Steel	Glass	1928	6.671 ± 0.003	Lowest, second-latest and highest number of same-day measurements (4).	6.671986 ± 0.000022	99.99%	Yes
Steel	Gold	1925	6.672 ± 0.004	Lowest, latest and highest number of same-day measurements (6).	6.671152 ± 0.000022	99.99%	Yes

Note: Heyl (1942) gave a value of 6.673 ± 0.003, which is a weighted mean. I instead take the unweighted mean to be more accurate. Taylor (1973) also lists Heyl (1942) as 6.6720 ± 0.0049, saying it is the unweighted mean.

Now, platinum and gold are neighboring elements in the periodic table and when paired with steel, the resulting value should be 6.671 for both. For the pair steel-glass it should be 6.672. However, what Heyl measured was the opposite, namely 6.672 for steel-platinum and steel-gold and 6.671 for steel-glass.

It should be noted that with the exception of his 1942-value for steel-platinum, the values listed here are not averages, but instead lowest values. All his measurements began with very high values that then gradually became smaller as the balance came closer to its equilibrium state. As we saw in chapter 6.10, insufficient air-sealing always leads to too high values of big-G, never to too low values. Heyl did not realize this and instead just used the averages of all measurements. This of course led to the differences between elements being exaggerated.

While Heyl's results agree well with SPD in their value, they do not show the expected hierarchy between the materials, and so in and out of themselves they don't represent a strong case against the equivalence principle. However, because Heyl's 1926-measurements based on steel source masses and platinum test masses were very imprecise and yielded very low values, this prompted him to briefly question the equivalence principle. In his 1942-paper he stated:

> "The results with each material were reasonably concordant among themselves, but there appeared to be considerable difference with the nature of the material. For instance, the mean values of the platinum and glass sets differed by an amount five times as great as the average departure from the mean in either set."

In order to rule out a violation of the equivalence principle, he repeat the famous Eötvös experiment from 1922, which was used by Einstein to justify his equivalence principle. As already mentioned before, composition-dependence in the Eötvös experiment is only residual, because a balance is not supposed to measure weight but mass, and the only reason differences between materials have been measured is because the test masses on one side were suspended using strings, creating an inequality between the two sides. As we will see in chapter 6.24, this residual composition dependence is so small that it is below the detection threshold and was only measured because it was linearly amplified by background fluctuations. Only when conducting these experiments for as long as Eötvös did, can the residual effect crystalize out of the background noise. Of course, his test, for which he used platinum and glass, came back negative. For reasons unknown, Heyl trusted the Eötvös balance more than the Cavendish balance, and so he used his quick repetition of the Eötvös experiment to quell his doubts of the equivalence principle.

About this, Taylor (1973) notes:

"Since the three measurements are not consistent, at least one of them contains an unidentified systematic error."

Similar differences emerged when Heyl compared annealed and hard drawn filaments. As others found out more than half a century later, they have to do with violations of Hook's law which are referred to as the 'anelastic effect' (Kuroda; 1995).

Heyl (1930) is usually cited with the value 6.6721 ± 0.0073, based on the average of the three tested materials. This agrees with the predicted average, which is 6.67145 ± 0.00047, to 99.99% and within margins of error.

Pontikis' two-year long battle with the equivalence principle

In Gillies' 2014-list, Pontikis (1972) is listed with a G-value of 6.6714, which is the average of the values he got for silver, copper, bronze, and lead. However, the materials Gillies lists for this are silver, copper, lead and mercury, which are the materials from Pontikis' original 1971-publication. The values that Pontikis obtained and which can be found in his original publication fit the predictions of space particle dualism extremely well:

Source mass composition	Test mass composition	Measured G-value	SPD prediction	Agreement in percent	Agreement within margins of error
Lead	Lead or brass	6.668 ± 0.003	6.667878 ± 0.000022	100%	Yes
Brass	Brass	6.674 ± 0.002	6.673973 ± 0.000022	100%	Yes
Copper	Copper	6.674 ± 0.002	6.673995 ± 0.000022	100%	Yes
Mercury	Mercury or brass	6.666 ± 0.01	6.668090 ± 0.000022	99.97%	Yes
Silver	Silver	6.671 ± 0.001	6.672615 ± 0.000022	99.97%	Yes
Silver	Brass	6.671 ± 0.002	6.673294 ± 0.000022	99.97%	Yes

The reader may wonder why in two cases there are two possible test masses listed. The reason is that Pontikis paired equal composition materials in the case of brass, copper and silver, and it would be strange to not do the same for lead and mercury. We notice that lead agrees with the predictions of SPD to 100% if lead was also used for the test masses, but Pontikis lists brass for the test mass. Brass test masses would allow him to obtain higher values for big-G, but it seems he did not have enough time to do that, and so the majority of measurements could have been based on lead for both source and test masses. Lead and mercury both are predicted to have G-values of 6.668 when rounded to three digits after the decimal point, and well enough, the lowest two values that Pontikis obtained are for lead and mercury. As we will see in our detailed analysis, there is only a 0.25% chance for him to really have matched up lead and mercury with brass, considering the odds of the phenomenal agreement with the predictions for lead-lead and mercury-mercury.

In the above list we see that the accuracy of Pontikis' 1971-measurements was quite high, being 99.985% on average, which is close to the average of all post-1971 measurements of big-G, namely 99.988%.

Unfortunately, he did not know that, and so one year later, in 1972, he applied computerized data homogenization to his values, under the backdrop assumption that the equivalence principle must be correct. The data homogenization achieved the goal of minimizing the differences between different materials.

The minimizing of the differences between different elements was achieved not only by the use of data homogenization, but also by only using brass as the source mass and only varying the material of the test masses. Methods to minimize differences between elements include:

1. Data homogenization.
2. Pairing low-G materials with high-G materials.
3. Only varying the test masses and not the source masses. If the beam is heavy, then it can dwarf the mass of the test masses.
4. Using a swing damper. They are usually made of steel with an aluminum disk in the middle. Swing dampers easily dwarf the test masses and thereby make their composition less significant.

From these methods, Pontikis employed (1) to (3). In "Gravitational Measurements, Fundamental Metrology and Constants" (Sabbata; 1987), we find the altered values by Pontikis, and they are:

Source mass composition	Test mass composition	Homogenized G-value	SPD prediction	Agreement in percent	Agreement within margins of error
Brass	Bronze	6.67122 $\pm$ 0.00061	6.673886 $\pm$ 0.000022	99.96%	No
Brass	Lead	6.67126 $\pm$ 0.00066	6.670926 $\pm$ 0.000022	99.99%	Yes
Brass	Silver	6.67162 $\pm$ 0.00051	6.673294 $\pm$ 0.000022	99.97%	No

Brass	Mercury	6.67157 ± 0.00051	6.6710315 ± 0.000022	99.99%	No

That is an average of tempered values of 6.67142 ± 0.00021, consistent with his published value of 6.6714 ± 0.0006. The average of the predicted values here is 6.6723 ± 0.00022. That is an agreement of 99.99%, and if Pontikis had not pretended that using data homogenization suddenly increases his measurement precision by a factor of 10, then we would also have an agreement within margins of error.

If we use the average of the standard deviations given in his 1971-paper, which is ± 0.003, then the values agree. Since there is no reason why precision should have improved, it is reasonable to go with the original standard deviations.

The fact that researchers would resort to data manipulation to save the equivalence principle shows the unquestionable faith that the physics community has in the equivalence principle. Instead of shaking up the scientific community, Pontikis chose to hide his big discovery.

At least Pontikis published his initial (nearly) undoctored results in 1971. That way the community had the choice to either deal with the results or look the other way. With Pontikis himself not trying to drawing any attention at all to his 1971-results, they went pretty much unnoticed.

Data tampering normally does not happen when different experimenters get very different results. In that case it is always possible to assume that the other experimenters made systematic errors. One is only responsible for one's own results, and thus vastly deviating results only become a problem when they show up in the same experiment, conducted by the same person or team. Due to how strong the belief in the equivalence principle is, vastly deviating results for different materials will always be seen as a sign of poor measurement quality.

About Pontikis' result Taylor (1973) points out:

> "The uncertainties are the statistical standard deviations of the means of each series of ten measurements … unfortunately, insufficient information is given in Pontikis' result to properly evaluate his systematic error. Indeed, he obtained a significantly different result from measurements taken in September, 1971."

This shows that Pontikis suddenly changing all his results from one year to the other did not go completely unnoticed. In this present work, only material-specific values from his 1971-publication will enter the analysis. From his 1972-publication we only take the average of different materials. Pointikis' sudden alteration of his data demonstrates personal bias, and should therefore be dismissed. Of course, if in the future access to the unadjusted 1972-data can be gained, then we can include that in the present analysis.

De Boer (1981) reinforces this view on Pontikis (1972):

> "Unfortunately, the documentation of the results is obscure and incomplete; it is not clear, for example, which material combinations were selected for the large and small masses to obtain the results published in 1972. The authors announced a final, detailed report which, however, to my

knowledge was not published."

His description of the computation method sounds complicated and convoluted, which makes it seem highly likely that some type of data homogenization process was employed. De Boer writes:

> "The measurements are evaluated using a computer, the respective geometric data and the oscillation values actually measured being used in the theoretical differential equation of oscillation from which the G-value best suited for the measurements is calculated."

Homogenizing the data is making the use of different materials pointless. Similar methods lead to the corruption of data in climate science. When we homogenize data from a rural area with a city, then the unreliable data from the city corrupts the rural data. In science we have to be careful to not let our personal bias influence the way we analyze data.

Purely statistical standard deviations

In both the case of Heyl (1930) and Pontikis (1971), Taylor (1973) dismisses their result pointing out that their standard deviations are purely statistical. He does the same with Luther (1975), who reported a final result of 6.6699 ± 0.0014 for measurements using tungsten source and test masses. The value predicted by SPD is 6.6688. The statistical standard deviations here are very small, which made the near disagreement with the up to then most trusted value of 6.673 ± 0.003 by Heyl (1940) ever more serious.

However, if having no systematic standard deviations listed was an excuse for dismissing results of careful measurements, then the famous Eötvös experiment (Eötvös; 1922) would have to be dismissed as well, yet it is treated as a textbook demonstration of the equivalence principle.

Karagioz' claim of temporal variations

Another interesting case is that of Karagioz. From 1975 until 1998, he was always using stainless steel of the type 'ShKhl5', and when he was trying to measure a singular value of the gravitational constant, then he would have values ranging from 6.672 to 6.675, but when he was looking at possible temporal variations of the gravitational constant, then he was getting vastly diverging values, ranging anywhere between 6.0 and 6.8. In a 1993 paper by Izmailov and Karagioz, the value 6.678 is listed 28 times, and values starting with 6.7 are listed 37 times. The used material is again stainless steel of the type 'ShKhl5'. Since his measurements peak at values that are all outliers, and since only 7% arrive at the value that would be expected, we have to consider his experiments as so inaccurate, that they cannot enter our analysis.

Despite all this, Izmailov and Karagioz list an overall value of '6.6771 ± 0.0004' for their 1993 paper, which implies a tiny standard deviation. This is a case where a systematic standard deviation is listed that is smaller than the statistical standard deviation. This is not meaningful. Of course, they could claim that the vastly diverging values are due to this hypothesized temporal variation, however, if G would really vary between 6.0 and 6.8, then this would be reflected in the values found by other experimenters. It also contradicts the fact that such a time variability is not reflected in Karagioz's other works. His other works mostly show that he was trying to arrive at the G-values that were popular at the time.

Having other results from exactly the same experiment, simply because one is exploring another hypothesis is not acceptable. It is a clear sign of scientific fraud.

Ultimately it was his measurement method that was unsuitable for precision measurements of G. In fact, he had planned to test different materials, but found that he could get somewhat reliable results only when using steel. De Boer (1981) writes about this:

"Only with a mass of steel did it prove possible to carry out measurements with a small deviation of the measured values."

It is very likely that Karagioz initially used low-G materials such as lead and mercury, and was perplexed by the unusually low values he obtained. Indeed, we find that the first two values he published are extremely low, namely 6.668 ± 0.002 in 1975 and 6.6364 ± 0.0015 in 1981. All other values appear to be the result of trying to match the value of Luther & Towler (1982), despite the difference in material.

It is interesting to note that after trying many different materials, he decided to focus on brass and then steel, both of which are high-G materials.

For the above reasons, Karagioz's measurements will be excluded from the statistical analysis in this chapter.

Gundlach and his Eöt-Wash Group

No experiment that was aiming at measuring Big-G with high precision has simultaneously explicitly aimed at testing the equivalence principle. The so called "Eöt-Wash Group", which was led by Gundlach claims to have tested the equivalence principle, and that their tests confirmed it, yet the only official value that was published by Gundlach was using stainless steel as the source mass and pure silica glass as the test mass (Gundlach; 2000) (note: *due to the presence of a swing damper, the effective test mass composition was also steel*). On their website we see that they did four tests, three of which were Eötvös-type pendulum experiments, and the fourth was a Cavendish-type experiment that was looking at test mass composition only. That means all four experiments were only looking at test mass composition.

Theoretically, test mass composition is just as important as source mass composition, but the mass of the test mass or test masses can easily be dwarfed by a too heavy beam or by a too heavy swing damper. The use of swing dampers has become more prevalent in recent decades. Luther (1975) did not use a swing damper, which is why his value of 6.6699 is fairly close to the value one would expect for a tungsten-aluminum combination for the source and test masses. This changed in Luther (1982) and Luther (1996), where swing dampers were used that dwarfed the very small test masses.

In Gundlach's precision measurement of big-G, the test mass is a single very thin Pyrex glass plate, which is dwarfed by the mass of the swing damper. Anything moving together with the test masses obviously has to be counted as part of the test masses and has to therefore contribute to the effective G-value.

In his test of the equivalence principle, Gundlach used uranium for the source masses, and switched between lead and copper for the test masses. Uranium has a very low gravitational constant, which is probably way Gundlach only reported that he did not find any difference between lead test masses and copper test masses and did not also report what G-value he found, as that could in itself be viewed as a violation of the equivalence principle.

In principle, the vast disagreements between the measured G-values of different researchers should already be enough to disprove the equivalence principle. Unfortunately, one can always make excuses to not draw any conclusions from meta-analyses, based on the fact that they use different methods and have varying levels of precision.

Why the Eötvös experiment is not a valid test of the equivalence principle

Fischbach's 1986-claim of a medium-range composition-dependent fifth force inspired a lot of experimenters to conduct tests of the inverse square law. Very few focused on the composition dependence itself, and those who did always just repeated the Eötvös experiment. The reason why most ignored the composition dependence aspect is that the effect claimed by Fischbach was so small that it was far beyond anything one could reliably measure.

Trying to measure the material dependence of gravity with an Eötvös-type experiment is rather naïve. It is like trying to measure weight on a balance, well knowing that balances measure mass and not weight. Just like with a classical balance where one side cannot move down unless the other side moves up, one side of an Eötvös balance cannot turn left unless the other side turns right. That means that at any given moment in time, the gravitational acceleration experienced by any moving part of the balance depends on the composition of all moving parts.

If an Eötvös-balance could reveal the composition-dependence of gravity, then we could no longer trust balances to accurately measure mass, and then Cavendish experiments could not reveal the composition dependence of gravity, because source masses in those experiments must have been measured using balances.

With this being said, if one side is suspended, then the effective g-value on that side will depend more strongly on the composition of the suspended side than on the composition of the rest of the beam, because that side experiences a higher gravitational potential due to being closer to Earth.

Intermediate and long-range gravity experiments

In the 90s many tests of the inverse square law have been conducted. Some of those experiments did not measure the gravitational constant, but many list those experiments with a G-value of 6.6726. This value is from Luther & Towler (1982), and it was the mainstream value throughout the 80s, 90s and early 2000s. Listing this value for an inverse square law test simply means that the inverse square law was not violated. Examples for this are Yu (1979), Zumberge (1990), Yang (1991).

Long range gravity experiments tend to lead to unusually large G-values and poor measurement accuracy. That is because laboratory-level conditions are impossible to achieve at large scales. A torsion balance needs to be operated in an air-sealed environment. Poynting-type experiments, which measure gravity using a spring scale instead of a torsion balance, should be less sensitive to outside influences, but the Poynting method is not suitable for high precision measurements. We can see this from his own lab-based G-values: 6.7 in 1881 and 6.6984 in 1891. These are extreme outliers. Since torsion balances are limited in size, large scale experiments typically employ plumb bobs or spring scales. The largest ever measured G-value was using a plumb bob to measure the gravity of the Schiehallion mountain (Maskelyne; 1774), which yielded a value of 7.8.

Similar as with the case of poor air-isolation in Cavendish experiments (see chapter 6.10), poor measurement quality in Poynting-type experiments always manifests itself in unusually high G-values, as we can see from this list:

Source mass	G-value	Reference
ocean water	6.688 ± 0.011	Baldi (2001)
ocean water	6.712 ± 0.037 6.730 ± 0.025	Stacey (1987)
Rock	6.795 ± 0.021	Whetton (1957)
Rock	6.7390 ± 0.0025 6.724 ± 0.014 6.726 ± 0.012 6.747 ± 0.013	McCulloh (1965)
Rock	6.81 ± 0.07	Hinze (1978)
Rock	6.705 ± 0.060	Hussain (1981)

All measurements of the gravity of water have been intermediate-range gravity measurements. Only two out of ten were usable, the rest were either outliers or low accuracy. This again shows how unreliable the methods are that are used to measure gravity in the intermediate range. The only classical Cavendish experiments conducted with water seem to be my own experiments from 2020 (see chapter 6.10).

Brush's Cavendish experiments

Charles F. Brush (1849 – 1929) had an ether-based theory of gravity, which predicted differences in gravity between different elements. He conducted both freefall experiments and Cavendish experiments. His freefall experiments were purely comparative, not measuring the actual freefall time, and so we shall omit them here. About his Cavendish-type experiments, Roberto de Andrade Martins wrote the following (Martins; 2022):

> "Brush compared the gravitational attractions of zinc and bismuth, using a Cavendish balance. According to his report (Brush; 1921-1922), the attraction produced by bismuth was only 72% of the attraction produced by an equivalent weight of zinc. He also made pendulum experiments and measured a difference of about $1/50{,}000$ between the ratio of inertial and gravitational mass for those substances."

SPD predicts:

$$G_{\mathrm{Zn}} = 6.673932 \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$$

$$G_{\mathrm{Bi}} = 6.667715 \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$$

We see that bismuth has 99.91% the gravity of zinc. Brush's figure of 72% is wrong, but he was right that zinc has more gravity per kilogram than bismuth.

His pendulum experiment on the other hand reported too little of a difference. $1/50{,}000$ is 0.00002, while SPD-chromogravity predicts 0.0009.

Crémieu's oil drop experiment

In the early 20th century, there was a series of investigations into the possibility of gravitational shielding and similar non-Newtonian effects that were inspired by the same kinetic gravity theory that Brush was investigating. Some of these experiments were looking at a possible medium-dependence of gravity. In 1905, one experimenter named Crémieu wanted to see how the gravity between oil drops disappears when the density of the surrounding medium equals that of the oil drops. Roberto de Andrade Martins (Martins; 2022) describes the experiment as follows:

> "Crémieu (1905) described a strange effect. He suspended small olive oil drops in a solution of water and alcohol. The density of the solution was equal to the density of the drops and they remained in equilibrium in this solution. However, after some time, the drops began to approach to one another. There was no classical explanation for this phenomenon: the approach could not be ascribed to gravitation, capillary or hydrodynamic effects."

This is quite confusing when one assumes that all materials exert the same amount of gravity per kilogram. In that case gravity should disappear if the density is equal everywhere. In SPD-chromogravity that is different, because there every material has its own specific gravitational constant.

The gravitational constant of water is 6.661723, while that of olive oil is 6.65157. The oil drops had less gravity than the surrounding water, and so different compartments of the body of water were able to attract each other and thereby push the oil drops together.

It would be computationally quite challenging to use this oil drop experiment for measurements of G, but as a qualitative demonstration of chromogravity it is quite intriguing.

Comparing all measurements of the gravitational constant with the predictions of SPD-quantum gravity

We shall now compare the measurements with different source and test masses with the values predicted by space particle dualism theory.

We recall from previous chapters that the mass-gravity constant of any material X is given by its chemical composition, according to:

$$G_{\mathrm{X}} = G_{\mathrm{H}} \times \frac{n_{\mathrm{p}_\mu} m_{\mathrm{p}} + n_{\mathrm{n}_\mu} m_{\mathrm{n}}}{m_{\mathrm{X}_\mu}}$$

With G_{H} being the mass-gravity constant of hydrogen, given by:

$$G_{\mathrm{H}} = 6.613431 \times 10^{-11} \mathrm{~m^3~kg^{-1}~s^{-2}}$$

As an example, we shall calculate the mass-gravity constant of lead:

Lead:
Inertial mass:

$$(203.9730436 \times 0.014) +$$
$$(205.9744653 \times 0.241) +$$
$$(206.9758969 \times 0.221) +$$
$$(207.9766521 \times 0.524) = 207.216907663$$

Gravitational mass:

$$(((82 \times 1.00727647) + (122 \times 1.008665)) \times 0.014) +$$
$$(((82 \times 1.00727647) + (124 \times 1.008665)) \times 0.241) +$$
$$(((82 \times 1.00727647) + (125 \times 1.008665)) \times 0.221) +$$
$$(((82 \times 1.00727647) + (126 \times 1.008665)) \times 0.524) = 208.922883805$$

$$G_{\mathrm{Pb}} = G_{\mathrm{H}} \times \frac{208.922883805}{207.216907663} = 6.667878 \times 10^{-11} \mathrm{~m^3~kg^{-1}~s^{-2}}$$

When the source and test mass compositions are different, then we use the geometric mean of the respective G-values:

$$G_{\mathrm{AB}} = \sqrt{G_{\mathrm{A}} \times G_{\mathrm{B}}}$$

Now let us look at the measured values for each material combination and compare them with the values predicted by space particle dualism theory:

Water

All the experiments measuring the gravity of water were using lakes or very large water tanks as source masses. For such large-scale experiments proper environmental isolation is impossible. Lack of proper isolation always leads to too large values, especially when the Poynting method is used, and so in this case the smallest value is the most accurate one, and that is Hubler (1995) for stainless steel test masses, and Oldham (1993) for copper test masses. Hubler published two values, 6.669 ± 0.005 for his 112-meter experiment, and 6.678 ± 0.007 for his 88-meter experiment. The combined value given was 6.6700 ± 0.0054. However, the value from the 112-meter experiment has smaller standard deviations and is therefore preferred.

Reference	Test mass composition	G-value
Hubler (1995)	Stainless steel	6.669 ± 0.005
Oldham (1993)	Copper	6.671 ± 0.015

Nolting (1999)	Copper	6.6754 ± 0.0015
Zumberge (1991)	LaCoste-Romberg gravity meter (tungsten carbide)	6.677 ± 0.013
Baldi (2001)	Superconductive gravimeter (niobium)	6.688 ± 0.011
Müller (1990)	LaCoste-Romberg gravimeter (tungsten carbide)	6.689 ± 0.027
Moore & Stacey (1988)	Stainless steel	6.689 ± 0.00057
Stacey (1984)	Stainless steel	6.712 ± 0.037 6.730 ± 0.025

Hubler (1995)
SM: Water (6.661723).
TM: Stainless steel (6.674200).
SPD-prediction: $\mathbf{6.6679615} \pm \mathbf{0.000022}$.
Measured value-1 (112 meter): $\mathbf{6.669} \pm \mathbf{0.005}$.
Measured value-2 (88 meter): 6.678 ± 0.007.
SPD-Agreement: **Yes**.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.98}\%$.
GR-accuracy: 99.93%.

Oldham (1993)
SM: Water (6.661723).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.667859} \pm \mathbf{0.000022}$.
Measured value: $\mathbf{6.671} \pm \mathbf{0.015}$.
SPD-Agreement: **Yes**.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.953}\%$.
GR-accuracy: 99.951%.

Uranium

Reference	Test mass composition	G-value
Saulnier (1989)	Lead	6.65 ± 0.09

Saulnier (1989)

SM: Uranium (6.665765).
TM: Lead (6.667878).
SPD-prediction: $\mathbf{6.6668215 \pm 0.000022}$.
Measured value: $\mathbf{6.65 \pm 0.09}$.
SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.75}$%.
GR-accuracy: 99.64%.

Lead

Two values are post-1971 and with small standard deviations. Dousse (1987) has four measured values from four student teams, and the one with the smallest standard deviations was chosen. He did not clarify the material of his test masses. Typically, most experiments use copper test masses, for maximizing density and minimizing magnetism. Lead does that too, but it deforms easily. Choosing lead for the source mass was likely in order to minimize costs.

There is some doubt about Pontikis having paired up lead with brass. If he had, he should have gotten a value of 6.671. The value of 6.668 that he obtained agrees with to 100% with both source and test masses being made of lead. His range of values was $6.666 - 6.674$, and the chance for the result being exactly 6.668 by accident is only $1/8$. The same is the case with mercury, for which the chance is $1/5$. The combined chance for this is 2.5%.

Page (1981) was mainly testing quantum superpositioning, while Schurr (1992) and Fixler (2003) were testing the inverse square law. Their main focus not being the gravitational constant explains their outlier values. The value listed for Schurr (1992) is the initial value obtained. Gillies cites a subsequent value of 6.6613 ± 0.0011, but that is nowhere to be found.

Reference	Test mass composition	G-value
Page & Geilker (1981)	Lead	6.1 ± 0.4
P. v. Jolly (1878)	Mercury	6.447 ± 0.11
J. Wilsing (1889)	Copper and lead-antimony alloy	6.594 ± 0.15
F. Bailey (1843)	Platinum, Lead, Zinc, Glass, Brass, Ivory	6.63 ± 0.07
G. Burgess (1902)	Lead	6.64 ± 0.04
Fr. Reich (1838)	Lead, zinc, bismuth, iron	6.64 ± 0.06
R. Eötvös (1896)	Lead (?)	6.657 ± 0.013
C. v. Boys (1895)	Gold	6.658 ± 0.007
J. Zahradníček (1930)	Lead	6.66 ± 0.04
J. Schurr (1992)	Fabry–Pérot resonators (silica)	6.66 ± 0.06

Wang (2009)	Silica	6.6665 ± 0.0554

Pontikis (1971)	Lead	6.668 ± 0.003
Dousse team-1 (1987)	Copper (?)	6.6704 ± 0.0048

F. Richarz (1888; 1898)	Lead	6.684 ± 0.011
Fixler (2003)	Cesium	6.693 ± 0.027
Poynting (1881; 1891)	Lead-antimony alloy	6.70 ± 0.04 6.6984 ± 0.004
H. Cavendish (1798)	Lead	6.754 ± 0.041

Other values by Dousse (1987):

Dousse team-2	6.6735 ± 0.0068
Dousse team-3	6.6740 ± 0.0053
Dousse team-4	6.6722 ± 0.0051

Wang (2009)

SM: Lead (6.667878).
TM: Silica (6.669853).
SPD-prediction: $\mathbf{6.6688655 \pm 0.000022.}$
Measured value: $\mathbf{6.6665 \pm 0.0554}$.
Note: the many digits suggest a measurement with greater accuracy than the standard deviations. The measured value is only 0.0024 *away from the predicted value.*
SPD-Agreement: **Yes**.
GR-Agreement: Yes, but only due to overestimated SD.
SPD-accuracy: 99.96%.
GR-accuracy: 99.88%.

Pontikis (1971)

SM & TM: Lead.
SPD-prediction: $\mathbf{6.667878 \pm 0.000022}$.
Measured value: $\mathbf{6.668 \pm 0.003}$.
SPD-Agreement: **Yes**.
GR-Agreement: No.
SPD-accuracy: **100**%.
GR-accuracy: 99.91%.

Dousse (1987)

SM: Lead (6.667878).
TM: Copper (6.673995) (?).
SPD-prediction: $\mathbf{6.6709365 \pm 0.000022}$.
Measured value: $\mathbf{6.6704 \pm 0.0048}$.
SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: **99.992**%.
GR-accuracy: 99.94%.

Mercury

The standard deviations given for Pontikis (1971) here are based on his other measurements from the same year. His own estimate of his accuracy for mercury was ± 0.01, but it is likely that this was based on the G-value of mercury being the furthest away from the values for the other materials he tested.

Nolting (1999) included a G-value for water and a preliminary result for mercury, the final result of which is published under Schlamminger (2002 & 2006). Nolting belonged to the same team as Schlamminger, measuring the gravity of water and mercury at the university of Washington.

The final result for Schlamminger (2002) has smaller standard deviations and is thus preferred over Nolting (1999). Schlamminger (2006) is simply a re-interpretation of the data from Schlamminger (2002), applying what he calls ‘zero-point corrections’. I see it as an attempt to get closer to the value of Gundlach (2000).

Schlamminger (2002) is normally cited with a value of 6.67407 ± 0.00022, but that is a mix of trails with both copper and tantalum test masses.

There is some doubt about Pontikis having paired up mercury with brass. If he had, he should have gotten 6.671, but he got 6.666, which is closest to 6.668 (the mercury-mercury value), and the chance for that to be a coincidence is $1/5$. There is only a 2.5% chance that he did not use lead-lead pairs and mercury-mercury pairs (or pairs of pairs).

We also notice that he only switched to using different material source and test masses when he obtained lower values. His application of data homogenization one year later suggests that it is likely he tried to already hide the violation of the equivalence principle a little bit in 1971, by making it look more like measurement error.

Reference	Test mass composition	G-value
Cornu & Baille (1873)	Copper	6.64 ± 0.017
K. Braun (1895 & 1897)	Brass	6.654 ± 0.002
Pontikis (1971)	Mercury	6.666 ± 0.01
Renner (1973)	Copper	6.670 ± 0.008
Schlamminger (2002)	Copper	6.67404 ± 0.00021
Schlamminger (2002)	Tantalum	6.67409 ± 0.00021

Pontikis (1971)
SM & TM: Mercury.
SPD-prediction: $\mathbf{6.668090 \pm 0.000022}$.
Measured value: $\mathbf{6.666 \pm 0.01}$.
SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.97}\%$.
GR-accuracy: 99.88%.

Renner (1973)
SM: Mercury (6.668090).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.671043 \pm 0.000022}$.
Measured value: $\mathbf{6.670 \pm 0.008}$.
SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.98}$%.
GR-accuracy: 99.94%.

Schlamminger (2002)
SM: Mercury (6.668090).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.6710425 \pm 0.000022}$.
Measured value: $\mathbf{6.67404 \pm 0.00021}$.
SPD-Agreement: **No**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.96}$%.
GR-accuracy: 99.996%.

Schlamminger (2002)
SM: Mercury (6.668090).
TM: Tantalum (6.668949).
Note: the tantalum test masses were probably dwarfed by the mass of the beam, which would likely be made of steel.
SPD-prediction: $\mathbf{6.6685195 \pm 0.000022}$.
Measured value: $\mathbf{6.67404 \pm 0.00021}$.
SPD-Agreement: **No**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.91}$%.
GR-accuracy: 99.996%.

Steel-gold

Heyl's 1925-measurements clearly started out with insufficient environmental isolation. He obtained a very high value of 6.683 in March. Then that dropped to 6.676 in April, and then to 6.672 in May. This suggests that the average he gave for gold, namely 6.6782(16), has to be disregarded in favor of the minimal value. The minimal value is also the final value that was measured on the last day.

Number of swings and date	G-value
Heyl (6 × 27.05.1925)	$\mathbf{6.672}$
Heyl (5 × 15.05.1925)	6.679
Heyl (4 × 01.05.1925)	6.679

Heyl (6 × 15.04.1925)	6.676
Heyl (2 × 08.04.1925)	6.681
Heyl (1 × 25.03.1925)	6.683

Heyl (1925)
SM: Tool steel (6.674119).
TM: Gold (6.668185).
SPD-prediction: $\mathbf{6.671152 \pm 0.000022}$.
Measured value: $\mathbf{6.672 \pm 0.004}$.
SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.99}$%.
GR-accuracy: 99.97%.

Steel-platinum

Heyl (1930) was using tool steel source masses and gold, platinum and glass as test masses. His later work from 1942 was only using platinum test masses. The statistical spread in his 1930-data was very large, and so here we shall only use his high accuracy measurements from 1942. The official value given by Heyl in 1942 was 6.673 ± 0.003, but the true average of his measurements was 6.672 ± 0.004. Heyl used a weighted average where his results with the hard-drawn filament would count more than his results with the annealed filament.

Reference	G-value
Heyl (1942)	6.672 ± 0.004
Heyl (1926-most frequent-most swings)	6.667 ± 0.012
Heyl (1926-weighted average)	6.6640 ± 0.0013

Breakdown of the 1926-data:

Number of swings and date	G-value
1 × 14.06.1926	6.6605
2 × 10.08.1926	6.6605
3 × 25.08.1926	6.667
4 × 25.08.1926	6.667
5 × 05.11.1926	6.6375

Heyl (1942)
SM: Tool steel (6.674119).
TM: Platinum (6.668284).
SPD-prediction: $\mathbf{6.6712015 \pm 0.000022}$.
Measured value: $\mathbf{6.672 \pm 0.004}$.

SPD-Agreement: **Yes**.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.99}$%.
GR-accuracy: 99.97%.

Tungsten

Rose (1969), Luther (1975), Luther & Towler (1982) and Bagley & Luther (1996) all were using the same pair of tungsten spheres and all involved the same group of people using a new method proposed by Beams (1964). Luther wasn't involved in the first value by Rose (1969), but Rose (1969) and Luther (1975) had Beams as a common team member. Luther (1982) became a CODATA-G-value, and Luther himself later worked for CODATA. The desire to reconcile the different values of big-G would have easily introduced a bias into the data that would skew it towards higher values. The later values published by Luther do not agree with his 1975-value within margins of error, and shall thus be considered as inaccurate.

In Rose (1969) the test mass is an aluminum drumbell. In Luther (1975) the material of the test mass is not specified, but since Luther (1975) is generally considered to be the final result of the experiments started by Rose, and since the design and the source masses didn't change, it stands to reason that the material of the test masses did not change. Both Kleinevoß (2002) and Gillies (2014) describe the two as one continuous series of measurements, and both omit Rose's very imprecise 1969-result, treating it as a preliminary value.

Schwarz (1999) was based on freefall perturbation, which is a classical version of a freefall interferometer experiment. Such experiments are not reliable. Michaelis (1996) obtained his outlier value by measuring big-G in a liquid.

Reference	Test mass composition	G-value
Lamporesi (2008)	Tungsten	6.667 ± 0.003
De Boer (1987)	Tungsten	6.667 ± 0.005
Luther (1975)	Aluminum	6.6699 ± 0.0014
Prevedelli (2014)	Rubidium	6.67191 ± 0.00099
Parks (2010)	Copper	6.67234 ± 0.00014
Luther & Towler (1982)	7 g Tungsten dumbbell & 1 kg (?) magnetic damper (aluminum disk with 4 thick steel clamps attached)	6.6726 ± 0.0005

Rose (1969) [Preliminary result of Luther (1975)]	Aluminum	6.674 ± 0.012
J. P. Schwarz (1999)	Corner cube retroreflector (fused silica)	6.6873 ± 0.0094
J. P. Schwarz (1999)	Corner cube	6.6873 ± 0.0094

	retroreflector (fused silica)	
W. Michaelis (1996)	Zerodur glass ceramic	6.71540 ± 0.00056

Excluded values from the same people or teams:

Reference	Test mass composition	G-value	Same as
Bagley & Luther (1996)	Mainly steel	6.6740 ± 0.0007 Note: This is the average from two other values 6.6739 ± 0.0011 and 6.6741 ± 0.0008.	Luther (1982)

De Boer & Lamporesi (1987 & 2008)
SM & TM: Tungsten.
SPD-prediction: $\mathbf{6.668815 \pm 0.000022}$.
Measured average: $\mathbf{6.667 \pm 0.003}$.
SPD-Agreement: **Yes**.
GR-Agreement: No.
SPD-accuracy: **99.99**%.
GR-accuracy: 99.91%.

Parks (2010)
SM: Tungsten (6.668815).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.671405 \pm 0.000022}$.
Measured value: $\mathbf{6.67234 \pm 0.00027}$.
SPD-Agreement: No.
GR-Agreement: No.
SPD-accuracy: **99.99**%.
GR-accuracy: 99.97%.

Rose & Luther (1969 & 1975)
SM: Tungsten (6.668815).
TM: Aluminum (6.670876).
SPD-prediction: $\mathbf{6.6698455 \pm 0.000022}$.
Measured value: $\mathbf{6.6699 \pm 0.0014}$.
SPD-Agreement: Yes.
GR-Agreement: No.
SPD-accuracy: **99.999**%.
GR-accuracy: 99.93%.

Prevedelli (2014)
SM: Tungsten (6.668815).
TM: Rubidium (6.673702).
SPD-prediction: $\mathbf{6.6712585 \pm 0.000022.}$

Measured value: $\mathbf{6.67191 \pm 0.00099}$.
SPD-Agreement: Yes.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.99}\%$.
GR-accuracy: 99.96%.

Glass

The only example of an experiment where the source mass was glass is Michaelis (1996). Unfortunately, it was using an unreliable method, namely suspension inside a liquid. Michaelis also used tungsten source masses, as already mentioned above. For glass as the test mass, we have Heyl (1930).

Reference	Test mass composition	G-value
Michaelis (1996)	Zerodur glass	6.7174 ± 0.0020

Steel-glass

Heyl's 1928 measurements clearly started out with insufficient environmental isolation. He obtained a very high value of 6.678 in March. Then that dropped to 6.675 in early April, and then to 6.671 at the end of April. Although the value jumped back up to 6.675 on the last day of measurement, it is safe to say that his vacuum was far from perfect, and in such conditions, it is always the right choice to use the minimal value, which in this case is 6.671. Heyl himself used the average, which is 6.674 ± 0.003. He gave SD of only ± 0.0012 for this, but it is unclear why.

He described the glass he used as optical glass, which is more or less pure silica glass, also known as quartz.

Date with number of swings	G-value
3 × 08.05.1928	6.675
4 × 20.04.1928	6.671
3 × 10.04.1928	6.675
2 × 01.04.1928	6.671
3 × 14.03.1928	6.678

Heyl (1928)
SM: Tool steel (6.674119).
TM: Pure silica glass (6.669853).
SPD-prediction: $\mathbf{6.671986 \pm 0.000022}$.
Measured value: $\mathbf{6.673 \pm 0.003}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.985}\%$.
GR-accuracy: 99.981%.

DyFe

The only measured value for Dy_6Fe_{23} is from a freefall interferometer experiment, and those always have large standard deviations. Despite the large standard deviations, the measured value is remarkably close to the predicted value. The same value was published twice, once as Goldblum (1987) and once as Ritter (1990), differing only in the standard deviations. Goldblum was a co-author in Ritter's publication. The aim of their measurement was testing theories of spin-dependent gravity, which is why they used spin-polarized dysprosium iron powder.

Reference	Test mass composition	G-value
Goldblum (1987)	Dy_6Fe_{23}	6.67 ± 0.07
Ritter (1990)	Dy_6Fe_{23}	6.67 ± 0.09

Goldblum (1987)
SM & TM: Dy_6Fe_{23}.
SPD-prediction: $\mathbf{6.672372 \pm 0.000022}$.
Measured value: $\mathbf{6.67 \pm 0.07}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.96}$%.
GR-accuracy: 99.94%.

Silver

For silver, Pontikis officially listed two types of test masses, silver and brass. In this case it is normal to get the same value when measuring three digits after the decimal point (6.671 was measured and 6.673 is predicted).

Reference	Test mass composition	G-value
Pontikis (1971)	Silver	6.671 ± 0.001
Pontikis (1971)	Brass	6.671 ± 0.002

Pontikis (1971)
SM & TM: Silver.
SPD-prediction: $\mathbf{6.672615 \pm 0.000022}$.
Measured value: $\mathbf{6.671 \pm 0.001}$.
SPD-Agreement: No.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.98}$%.
GR-accuracy: 99.95%.

Pontikis (1971)
SM: Silver (6.672615).
TM: Brass (6.673973).
SPD-prediction: $\mathbf{6.673294 \pm 0.000022}$.
Measured value: $\mathbf{6.671 \pm 0.002}$.

SPD-Agreement: No.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.97}$%.
GR-accuracy: 99.95%.

Bronze

Bronze is made of 88% copper and about 12% percent tin. The predicted G-value for it is 6.673798 ± 0.000022, but unfortunately there are no precise measurements for this material. Pontikis (1972) used bronze as the test mass, but he applied data homogenization for his 1972-results for different materials, and so only his average from that year is usable.

Reference	Test mass composition	G-value
Koldewyn (1976)	?	6.575 ± 0.026

Brass

Speake (1983), Liu (1987) and Oelfke (1984) are low precision measurements by own admission. The reason for the poor quality of these measurements is that their main aim was not to get a most precise value for big-G, but to test the inverse square law.

Note that Kleinevoß published two values, one in 1999 and one in 2002. The latter had smaller standard deviations and was therefore chosen to enter the average.

Reference	Test mass composition	G-value
Speake (1983)	?	6.65 ± 0.23
Liu (1987)	?	6.660 ± 0.026
Walesch (1995)	Fabry–Pérot resonators (silica)	6.6719 ± 0.0008
Pontikis (1971)	Brass	6.674 ± 0.002
Kleinevoß (2002)	Copper	6.67422 ± 0.00098
Oelfke (1984)	?	6.7 ± 0.2

Walesch (1995)
SM: brass (6.673973).
TM: Silica (6.669853).
SPD-prediction: $\mathbf{6.671913 \pm 0.000022}$.
Measured value: $\mathbf{6.6719 \pm 0.0008}$.
SPD-Agreement: Yes.
GR-Agreement: No.
SPD-accuracy: $\mathbf{99.9998}$%.
GR-accuracy: 99.96%.

Pontikis (1971)

SM & TM: brass.
SPD-prediction: $\mathbf{6.673973 \pm 0.000022}$.
Measured value: $\mathbf{6.674 \pm 0.002}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.9999996}$%.
GR-accuracy: 99.996%.

Kleinevoß (2002)
SM: brass with 90% copper (6.673988).
TM: Oxygen-free copper (6.673995).
SPD-prediction: $\mathbf{6.6739915 \pm 0.000022}$.
Measured value: $\mathbf{6.67422 \pm 0.00098}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.997}$%.
GR-accuracy: 99.999%.

Copper

Newman (2014) is using the same apparatus and method as Cross (2009), namely a 'Cryogenic Torsion Pendulum'. Cross was also among the authors of Newman (2014). Since Newman's value has smaller standard deviations, it shall be the one entering the average. Richman (1999) and Quinn (2001 & 2013) are based on a new method called 'electrostatic servo control'. This method has never been used before nor after, and his measurement result has to therefore be considered inaccurate. Their results also disagree with Newman who claims higher precision.

Both Armstrong (2003) and Newman (2014) gives us three values for copper respectively, based on different fibers. The median and the highest of Armstrong (2003) agree with the lowest and the median of Newman (2014). That leaves two choices for Armstrong, and the one with smaller SD shall be chosen.

Reference	Test mass composition	G-value
Armstrong (2003)	Copper	6.67399 ± 0.00045
Pontikis (1971)	**Copper**	$\mathbf{6.674 \pm 0.002}$
Newman (2014)	Fused silica & Neodymium magnets	6.67408 ± 0.00015

Unreliable method (electrostatic servo control):

Reference	Test mass composition	G-value
Quinn (2001)	Copper	6.67559 ± 0.00027 (Cavendish: 6.67565 ± 0.00045; Servo: 6.67553 ± 0.00040)
Quinn (2013)	Copper	6.67554 ± 0.00016 *Pre-revision value:* 6.67545 ± 0.00018

Richman (1999)	Copper	6.683 ± 0.011

Other values by Armstrong (2003) based on different fibers are 6.67359 ± 0.00044 and 6.67398 ± 0.00046. The published average based on both his three copper and his steel trail is 6.67387 ± 0.00027.

Other values by Newman (2014) based on different fibers are 6.67435 ± 0.00010 and 6.67455 ± 0.00013. The published average was 6.67433 ± 0.00013.

Values by the same person or team:

Reference	Test mass composition	G-value	Associated with
William D. Cross (2009)	Fused silica & swing damper	$6.67464\,^{+0.00017}_{-0.00028}$ *Symmetric:* 6.674585 ± 0.000225	Newman (2014)

Armstrong (2003)
SM & TM: Copper.
SPD-prediction: $\mathbf{6.673995 \pm 0.000022}$.
Measured value: $\mathbf{6.67398 \pm 0.00045}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.999925}$%.
GR-accuracy: 99.995%.

Pontikis (1971)
SM & TM: Copper.
SPD-prediction: $\mathbf{6.673995 \pm 0.000022}$.
Measured value: $\mathbf{6.67398 \pm 0.00045}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.999925}$%.
GR-accuracy: 99.995%.

Newman (2014)
SM: Copper (6.673995).
TM: Fused silica plate (6.669853), neodymium magnets (6.673248), aluminum insulation (6.670876).
Note: the test mass composition is dominated by the neodymium magnets that are part of the magnetic swing mode damping.
SPD-prediction: $\mathbf{6.6736215 \pm 0.000022}$.
Measured value: $\mathbf{6.67398 \pm 0.00045}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.994}$%.

GR-accuracy: 99.995%.

Stainless steel

HUST-05 (based on Luo (1999)), Tu (2010) and HUST-18 are all publications by the same team known as HUST, under the supervision of Jun Luo (羅俊), and based in Wuhan. In order to avoid skewing the data, only one value per person or team should enter the average. The most precise measurement is HUST-18, and so only this can be part of the average. In fact, the HUST-team published two different values in 2018, based on two different methods, the usual time-of-swing method, and the 'Angular Acceleration Feedback' method. The result from the first agrees with Gundlach and is therefore preferred.

Baldi (2005) was using a superconducting gravimeter instead of a torsion balance, which explains the outlier result; his value shall therefore not enter the average. Fitzgerald conducted two measurements of the gravitational constant of stainless steel, one in 1995 and one in 1999. The latter had a higher claimed precision, and is therefore preferred.

Fitzgerald (1999) and Armstrong (2003) are based on the same two authors and the same materials. Armstrong (2003) is a newer value with smaller standard deviations and therefore to be preferred.

Normally only standard deviations at or above $\pm$ 0.01 are considered large, but in the case of copper the standards are higher, and so Sagitov (1879) can be considered a low precision measurement.

Reference	Test mass composition	G-value
HUST-05 (2014)	Copper	6.67228 ± 0.00087
Armstrong (2003)	Copper	6.67392 ± 0.00049
HUST-09 (2009)	Magnetic damper (112 g Fe & Cu), reflecting mirror (0.158 g SO2), ferrule (0.774 g Al), clamp (3.470 g Al) and fused silica plate (63 g SO2).	6.67349 ± 0.00018
Fitzgerald (1999)	Copper	6.6742 ± 0.0007
Gundlach (2000)	Magnetic damper (Fe), Pyrex glass plate (SO2).	6.674215 ± 0.000092
Sagitov (1979)	Copper	6.6745 ± 0.003
Baldi (2005)	Superconducting gravimeter (niobium)	6.675 ± 0.007

Excluded values from the same people or the same team:

Reference	Test mass composition	G-value	Same as
Luo (1999)	Copper	6.6699 ± 0.0007	HUST-05 (2014)

HUST-05-A (2005)	Copper	6.67222 ± 0.00087	HUST-05 (2014)
HUST-05-B (2005)	Copper	6.67228 ± 0.00087	HUST-05 (2014)
HUST-18 (2018)	Same as HUST-09	6.674184 ± 0.000078	HUST-09 (2009)

HUST-05 (1999; 2014)
SM: stainless steel (6.674200).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.6740975 \pm 0.000022}$.
Measured value: 6.67228 ± 0.00087.
SPD-agreement: No.
GR-agreement: No.
SPD-accuracy: $\mathbf{99.973}$%.
GR-accuracy: 99.970%.

Armstrong (2003)
SM: Stainless steel (6.674200).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.6740975 \pm 0.000022}$.
Measured value: $\mathbf{6.67392 \pm 0.00049}$.
SPD-agreement: Yes.
GR-agreement: Yes.
SPD-accuracy: $\mathbf{99.997}$%.
GR-accuracy: 99.994%.

HUST-09 (2009)
SM: Stainless steel (6.674200).
TM: 64% steel & copper (6.6740975), 36% silica (6.669853).
Note: it should be pretty safe to assume that the magnetic damper, made of copper and steel, and which rotated together with the test mass, dwarfed the test mass, which was a light silica plate.
SPD-prediction: $\mathbf{6.673385 \pm 0.000022}$.
Measured value: $\mathbf{6.674184 \pm 0.000078}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.9998}$%.
GR-accuracy: 99.998%.

Fitzgerald (1999)
SM: Stainless steel (6.674200).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.6740975 \pm 0.000022}$.
Measured value: $\mathbf{6.6742 \pm 0.0007}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.

SPD-accuracy: $\mathbf{99.99846}$%.
GR-accuracy: 99.99850%.

Gundlach (2000)
SM & TM: Stainless steel.
Note: same as in the case of HUST-18, a magnetic damper was used, and the test mass was silica based and therefore easily dwarfed by the mass of the damper.
SPD-prediction: $\mathbf{6.674200 \pm 0.000022}$.
Measured value: $\mathbf{6.674215 \pm 0.000092}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.9998}$%.
GR-accuracy: 99.9987%.

Sagitov (1979)
SM: Stainless steel (6.674200).
TM: Copper (6.673995).
SPD-prediction: $\mathbf{6.6740975 \pm 0.000022}$.
Measured value: $\mathbf{6.6742 \pm 0.0007}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.99846}$%.
GR-accuracy: 99.99850%.

Baldi (2005)
SM: Stainless steel (6.674200).
TM: Niobium (6.673406).
SPD-prediction: $\mathbf{6.673803 \pm 0.000022}$.
Measured value: $\mathbf{6.6745 \pm 0.0007}$.
SPD-Agreement: Yes.
GR-Agreement: Yes.
SPD-accuracy: $\mathbf{99.990}$%.
GR-accuracy: 99.997%.

Confidence level of the observed correlation

The following graph visualizes just how well all of the measurements of the mass gravity constant of different materials align with the predictions of SPD:

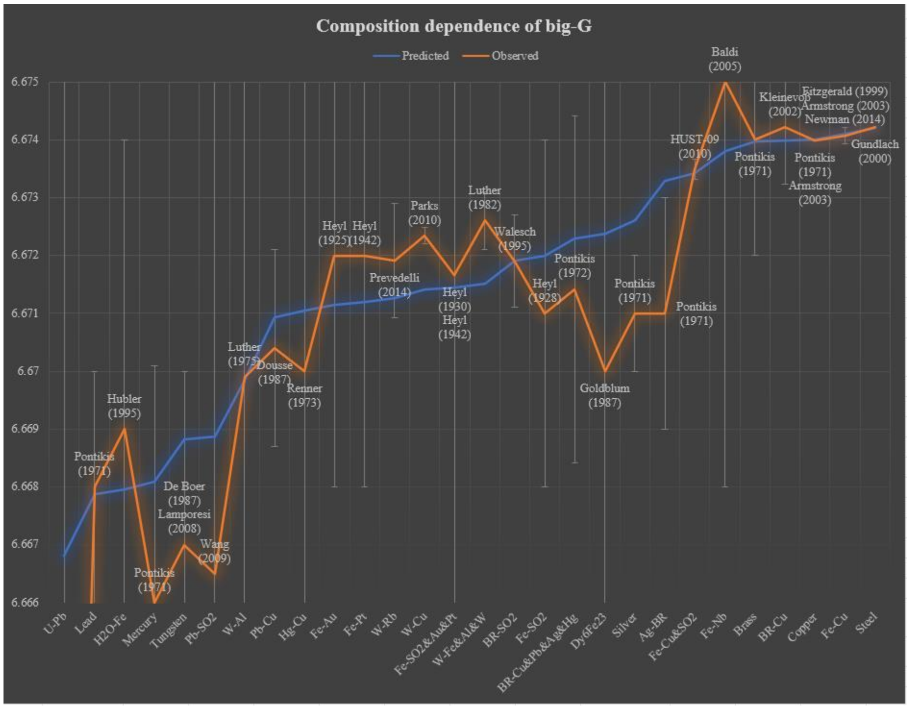

Fig. 126. The outcomes of measurements of big-G can be predicted very reliably based on the chemical composition of the source mass and the test mass. Schlamminger is excluded, because his value was based on large tanks as source masses. The only value included for such experiments is Hubler. Data points with more than one name attached are averages.

We can evaluate the chance for our observed correlation with the predictions of SPD to be a statistical fluke by looking at the hierarchical relationships between the different materials. If composition-dependent gravity was not real, then the chance for each material to be measured below and above any other material would be 50%. In a random heads and tails game, the chance for hit and miss is:

$$q = \frac{0.5^h}{0.5^m}$$

In the case of silver, we have:

$$q = \frac{0.5^{10}}{0.5^9} = 0.5$$

Here one of the elements that was supposed to have a G-value that is lower than that of silver had an identical G-value. This also counts as a miss.

However, this method only works if we are only interested in a single element and if our only categories are higher and lower. The obtained probabilities evaluated relative to different elements can also not be multiplied, because they are not independent probabilities. The correct formula for calculating the probability of a specific hierarchical order is derived in chapter 6.26.

As laid out in chapter 6.26, the p-value of a hierarchy is given by:

$$p = \left(n - \sum_{i=1}^{k=n} \frac{0.5^{n-k}}{0.5^{m_n}}\right)! \Big/ n!$$

Here n is the number of elements, and m is the degree of order for a single element, which is defined as the number of elements that are in the correct hierarchical order relative to it minus the number of elements that are in the incorrect hierarchical order relative to it. Note that because the value of m is different for each term of this summation, there is no shortcut to this calculation, which means every term of the summation has to be calculated independently.

The resulting p-value is:

$$p = \frac{(28 - 9.8487598896)!}{28!} = 3.3 \times 10^{-14}$$

That means there is a 1 in 3×10^{13} (thirty trillion) chance of the composition dependence being a statistical fluke. In percent that is 0.000000000003%.

We can also look at source mass and test mass composition independently. In that case we get fig. 2 & 3:

Fig. 2 & 3: the correlation is still quite strong when looking at source mass and test mass independently.

For the source mass correlation, we get odds of:

$$p = \frac{\left(9 - \frac{0.5^1}{0.5} + \frac{0.5^2}{0.25} + \frac{0.5^3}{0.5} + \frac{0.5^4}{0.25} + \frac{0.5^5}{0.125} + \frac{0.5^6}{0.015625} + \frac{0.5^7}{0.03125} + \frac{0.5^8}{0.00390625}\right)!}{9!}$$

$$p = 6.61376 \times 10^{-5}$$

Which is a 1 in 15,120 chance (0.0066%).

For the test mass correlation, we get:

$$p = \frac{\left(10 - \frac{0.5^1}{0.5} + \frac{0.5^2}{1} + \frac{0.5^3}{2} + \frac{0.5^4}{1} + \frac{0.5^5}{0.5} + \frac{0.5^6}{0.25} + \frac{0.5^7}{0.125} + \frac{0.5^8}{0.00390625} + \frac{0.5^8}{0.0078125}\right)!}{10!}$$

$$p = 0.002031466$$

Which is a 1 in 492 chance (0.2%).

The somewhat weaker correlation for test mass composition can be explained with the weakening effect of the test masses being suspended on a beam balance. All the parts that move together with the test masses weaken the effect of their chemical composition.

The calculation of G-values for molecules and mixed materials

The calculations for the G-values of pure chemical elements can be found in the document "G-values of all chemical elements" (Sky Darmos; 2023). The calculations of the G-values of molecules, alloys and mixed materials that have been mentioned above shall be shown here. Note that the inertial and gravitational masses of pure elements used in the following calculations are taken from said document:

Water:

Inertial mass of hydrogen atom:

$$(1.007825031898 \times 0.999855) + (2.014101777844 \times 0.000145) = 1.00797094202616217$$

Gravitational mass of hydrogen:

$$(((1 \times 1.00727647) + (0 \times 1.008665)) \times 0.999855) + (((1 \times 1.00727647) + (1 \times 1.008665)) \times 0.000145) = 1.007422726425$$

Inertial mass of water:

$$15.999400923892921698 + (2 \times 1.00797094202616217) = 18.015342807945246038$$

Gravitational mass of water:

$$16.13204654454 + (2 \times 1.007422726425) = 18.14689199739$$

$$G_{H_2O} = \frac{18.14689199739}{18.015342807945246038} \times 6.613431$$

$$G_{H_2O} = 6.661723$$

Pure silica glass (SiO_2):

Inertial mass:
$$28.0858083887861 + (2 \times 15.999400923892921698) = 60.084610236571943396$$

Gravitational mass:
$$28.333125065 + (2 \times 16.13204654454) = 60.59721815408$$

$$G_{\mathrm{SiO_2}} = \frac{60.59721815408}{60.084610236571943396} \times 6.613431$$

$$G_{\mathrm{SiO_2}} = 6.669853$$

Dy_6Fe_{23}:
Inertial mass:
$$(6 \times 162.499465697163) + (23 \times 55.845144405992) = 2259.435115520794$$

Gravitational mass:
$$(6 \times 163.88856932745) + (23 \times 56.35828776345) = 2279.57203452405$$

$$G_{\mathrm{Dy_6Fe_{23}}} = 6.672372$$

Brass (66% copper and 34% zinc):
Atomic distribution:
$$660 \div 63.546039732 = 10.386170448756424165$$
$$340 \div 65.37778242711 = 5.2005434778866599537$$

$$10.386170448756424165 \div 15.586713926643084119 = 0.66634766620069078 46$$
$$5.2005434778866599537 \div 15.586713926643084119 = 0.33365233379930921538$$

Inertial mass:
$$(0.6663476662006907846 \times 63.546039732) + (0.33365233379930921538 \times 65.37778242711) = 64.157204957143288007$$

Gravitational mass:
$$(0.6663476662006907846 \times 64.127973935) + (0.33365233379930921538 \times 65.975871816) = 64.744529375618448177$$

$$G_{\mathrm{Brass}} = 6.673973$$

Tool steel (99% iron and 1% carbon):
Atomic distribution:
$$990 \div 55.845144405992 = 17.727593160163379608$$
$$10 \div 12.0116389160898976 = 0.83252585844923661401$$

$$17.727593160163379608 \div 18.560119018612616222 = 0.95514436854557042655$$

$$0.83252585844923661401 \div 18.560119018612616222 = 0.04485563145442957345$$

Inertial mass:

$$(0.95514436854557042655 \times 55.845144405992) + (0.04485563145442957345 \times 12.0116389160898976) = 53.878964838381235866$$

Gravitational mass:

$$(0.95514436854557042655 \times 56.35828776345) + (0.04485563145442957345 \times 12.107349334) = 54.373383977745936192$$

$$G_{\text{Tool steel}} = 6.674119$$

Measuring inertial mass

Some researchers cannot appreciate that balances, unlike scales, are truly independent from both the local g-acceleration as well as from the material-specific g-acceleration. The Chinese physicist Hong Du for example has a theory that also predicts baryon-dependent gravity, but he does not look at Cavendish experiments, because he does not trust that balances accurately measure inertial mass (Hong Du; personal correspondence; 2023).

A material that experiences less acceleration will weigh less on a scale, and if we were to use the resulting mass reading for a Cavendish experiment, then any composition-dependent effect would cancel out. While scales measure weight, balances measure inertial mass. A scale will show a different weight at different locations on the Earth, because the freefall acceleration is different in different locations and altitudes. A balance cancels this altitude and location dependence by using a counterweight. When a weight is measured by comparing it to a counterweight, then any increase in Earth acceleration applies to both the weight and the counterweight equally, cancelling out any change in total acceleration, and so what is actually measured by a balance is the true and unchanging inertial mass, and not the weight.

Hong Du argues that while it is true that a balance is independent of elevation dependent differences in gravity, the gravitational acceleration on the two sides would still be different, because the compositions are different.

This is why he only focuses on pendulum experiments and freefall experiments. Pendulum experiments are similar to freefall experiments and in those the mass of the test object only matters in terms of air friction, and does thus not need to be as precisely measured as in Cavendish experiments. Furthermore, we can ignore the mass entirely when conducting the same experiments in a vacuum.

Giacomo De Toma, from Italy, has voiced the same kind of concerns, despite having himself tried to back up his own version of a composition-dependent gravity by looking at 20 measurements of G (Giacomo De Toma; personal correspondence; 2023).

The key to understanding why balances still measure mass accurately even in theories with composition-dependent gravity is understanding that the two weights are part of a single system, which is the balance: when a mass with a specific g-value wants to fall, it is met with the resistance of the counter-weight of the balance. The two form a single system and so their g-value is a mix. Since the effective g-value depends on both sides, both sides are affected equally, leading to no net change.

It is also possible to measure inertial mass using catapults or mass measurement devices (MMD) that measure mass by shaking, but unfortunately such devices have a measurement resolution of only 0.1 gram, which is not precise enough for Cavendish experiments.

References:

Armstrong (2003)	"New Measurements of G Using the Measurement Standards Laboratory Torsion Balance". T. R. Armstrong and M. P. Fitzgerald. Phys. Rev. Lett. 91, 201101 – Published 13 November 2003.
Bailey (1843)	F. Bailey; Mem. Astron. Soc. 14, 1 (1843).
Bagley (1996)	Bagley C H 1996 A determination of the Newtonian constant of gravitation using the method of Heyl PhD Dissertation University of Colorado, Boulder.
Bagley (1996)	C. H. Bagley et. al.; Phys. Rev. Lett.; Vol 78 (16), 3047–3050, (1997).
Baldi (2001)	P. Baldi et al., 2001, Phys. Rev. D64, 082001.
Baldi (2005)	Baldi P, Campari EG, Casula G, Focardi S, Levi G, Palmonari F. 2005. "Gravitational constant G measured with a superconducting gravimeter". Phys. Rev. D71, 022002. (doi:10.1103/PhysRevD.71.022002)
Barus (1922)	Barus, C.: "Experiments with the vacuum gravitational needle". Proc. Nat. Acad. Sci. USA 8,13- 15 (1922).
Boer (1987)	Boer, H. de, Haars, H., & Michaelis, W. (1987). A New Experiment for the Determination of the Newtonian Gravitational Constant. Metrologia, 24(4), 171–174. doi:10.1088/0026-1394/24/4/003.
Boys (1895)	Boys CV. 1895. "On the Newtonian constant of gravitation". Phil. Trans. R. Soc. Lond. A186, 1–72. (doi:10.1098/rsta.1895.0001)
Braun (1897)	Braun C. 1897. "Die Gravitations-Konstante, die Masse und mittlere Dichte der Erde nach einer neuen experimentellen Bestimmung". Denkschr. Akad. Wiss. (Wien), Math. Naturwiss. Kl.64, 187–258. (http://www.landesmuseum.at/pdf_frei_remote/DAKW_64_0187-0258.pdf)
Burgess (1899)	Burgess GK. 1899. "Méthode pour déterminer la constant newtonienne". C. R. Hebd. Seances Acad.Sci.129, 407–409.
Cavendish (1798)	Cavendish H. 1798. "Experiments to determine the density of the Earth". Phil. Trans. R. Soc. Lond.88, 469–526. (doi:10.1098/rstl.1798.0021)
Cornu (1873)	A. Cornu u. J. Baille; C. R. Hebd. Seances Acad. Sci 76, 954 (1873).

Cross (2009)	"Systematic Error Sources in a Measurement of G using a Cryogenic Torsion Pendulum". William Daniel Cross. Dissertation. University of California, Irvine. 2009. Dissertation Committee: Riley Newman, Jonas Schultz, Peter Taborek.
Dousse (1987)	Dousse J-C, Rhême C. 1987. "A student experiment for accurate measurements of the Newtonian gravitational constant". Am. J. Phys.55, 706–711. (doi:10.1119/1.15061)
Eötvös (1896)	Eötvös R. 1896. "Untersuchungen über Gravitation und Erdmagnetismus". Ann. Phys. Chem.(Leipzig)295, 354–400. (doi:10.1002/andp.18962951013)
Fitzgerald (1995)	M. P. Fitzgerald et. al.; Newton's Gravitational Constant with Uncertainty Less Than 100 ppm; IEEE Trans. Instr. Measurem. 44, Issue 2, (1995).
Fitzgerald (1999)	M. P. Fitzgerald et. al.; "The measurement of G using the MSL torsion balance"; Meas. Sci. Technol. 10 (6), 439–444 (1999).
Fixler (2007)	Fixler JB, Foster GT, McGuirk JM, Kasevich MA. 2007. "Atom interferometer measurement of the Newtonian constant of gravity". Science315, 74–77. (doi:10.1126/science.1135459)
Gillies (1997)	George T Gillies (1997). "The Newtonian gravitational constant: recent measurements and related studies". Rep. Prog. Phys. 60 (1997) 151–225. Printed in the UK PII: S0034-4885(97)61085-4.
Gillies (2014)	Gillies GT, Unnikrishnan CS. 2014. "The attracting masses in measurements of G: an overview of physical characteristics and performance". Phil. Trans. R. Soc.A372:20140022. (http://dx.doi.org/10.1098/rsta.2014.0022)
Goldblum (1987)	Goldblum C E 1987. "A measurement of the Newtonian gravitational constant G". M.Sc. Thesis (Charlottesville: University of Virginia).
Gundlach (2000)	Gundlach JH, Merkowitz SM. 2000. "Measurement of Newton's constant using a torsion balance with angular acceleration feedback". physics Rev. Lett.85, 2869-2872. (doi:10.1103/PhysRevLett.85.2869)
Heyl (1930)	P. R. Heyl; J. Res. Natl. Bur. Stand. 5, 1243 (1930).
Heyl (1942)	Heyl PR, Chrzanowski P. 1942. "A new redetermination of the constant of gravitation". J. Res. Nat. Bur. Stand.29, 1–31. (doi:10.6028/jres.029.001)
Hubler (1995)	B. Hubler et. al.; "Determination of the gravitational constant with a lake experiment: New constraints for non-Newtonian gravity"; Rhys. Rev. D 51, 8 (1995).
HUST-99 (1999)	J. Luo et. al.; Phys. Rev. D 59, No. 4,6 pp. (1999).
HUST-05-a (2005)	Hu Z-K, Guo J-Q, Luo J. 2005. "Correction of source mass effects in the HUST-99 measurement of G". Phys. Rev. D71, 127505. (doi:10.1103/PhysRevD.71.127505)
HUST-05-b (2005)	Z. K. Hu, J. Q. Guo, J. Luo, Phys. Rev. D 2005, 71, 127505.

HUST-09 (2010)	Tu L-C, Li Q, Wang Q-L, Shao C-G, Yang S-Q, Liu L-X, Liu Q, Luo J. 2010. "New determination of the gravitational constant G with time-of-swing method". Phys. Rev. D82, 022001. (doi:10.1103/PhysRevD.82.022001)
HUST-18-a (2018)	J. P. Liu, J. F. Wu, Q. Li, C. Xue, D. K. Mao, S. Q. Yang, C. G. Shao, L. C. Tu, Z. K. Hu, J. Luo, Acta Phys. Sin. 2018, 67, 160603.
HUST-18-b (2018)	Q. Li, C. Xue, J. P. Liu, J. F. Wu, S. Q. Yang, C. G. Shao, L. D. Quan, W. H. Tan, L. C. Tu, Q. Liu, H. Xu, L. X. Liu, Q. L. Wang, Z. K. Hu, Z. B. Zhou, P. S. Luo, S. C. Wu, V. Milyukov, J. Luo, Nature 2018, 560, 582.
Jolly (1878)	Von Jolly P. 1878. "Die Anwendung der Waage auf Probleme der Gravitation". Ann. Phys. (Leipzig) 5, 112–134. (doi:10.1002/andp.18782410906)
Koldewyn (1976)	Koldewyn WA. 1976. "A new method for measuring the Newtonian gravitational constant G". PhD thesis, Wesleyan University, Middletown, CT, USA.
Karagioz (1993)	Izmailov, V. P., Karagioz, O. V., Kuznetsov, V. A., Mel'nikov, V. N., & Roslyakov, A. E. (1993). Temporal and spatial variations of measured values of the gravitational constant. Measurement Techniques, 36(10), 1065–1069. doi:10.1007/bf00979446.
Karagioz (1998)	Karagioz OV, Izmaylov VP, Gillies GT. 1998. "Gravitational constant measurement using a four-position procedure". Gravit. Cosmol.4, 239–245.
Kleinevoß (1999)	U. Kleinevoß et. al.; Absolute measurement of the Newtonian Force and a determination of G, Meas. Sci. Techn. 10, 492-494, (1999).
Kleinevoß (2002)	Kleinevoß U. 2002. "Bestimming der Newtonschen Gravitationskonstanten G". PhD thesis, Universität Wuppertal. (http://elpub.bib.uni-wuppertal.de/servlets/DerivateServlet/Derivate-429/d080201.pdf)
Kuroda (1995)	"Does the Time-of-Swing Method Give a Correct Value of the Newtonian Gravitational Constant?". Kazuaki Kuroda. Phys. Rev. Lett. 75, 2796 – Published 9 October 1995.
Lamporesi (2008)	Lamporesi G, Bertoldi A, Cacciapuoti L, Prevedelli M, Tino GM. 2008. "Determination of the Newtonian gravitational constant using atom interferometry". Phys. Rev. Lett.100, 050801. (doi:10.1103/PhysRevLett.100.050801)
Liu (1987)	Liu B-L, Zhang J-L, Ren H-Z, Pao P-L, Wei T-D, Wen B, Zhu J-A, Song D-J. 1987. "An electrometric method of determining the gravitational constant G". J. Phys. E.: Sci. Instrum.20, 1321–1325. (doi:10.1088/0022-3735/20/11/003)
Luther (1975)	Luther GG, Towler WR, DesLattes RD, Lowry R, Beams JW. 1975. "Initial results from a new measurement of the Newtonian gravitational constant". In Atomic masses and fundamental constants 5 (eds JH Sanders, AH Wapstra), pp. 592–598. New York, NY: Plenum.
Luther (1982)	Luther GG, Towler WR. 1982. "Redetermination of the Newtonian gravitational constant G". physics Rev. Lett.48, 121-123. (doi:10.1103/PhysRevLett.48.121)
Luther (1996)	Bagley C H and Luther G G 1996 Phys. Rev. Lett. submitted.

Martins (2021)	“Experimental studies on mass and gravitation in the early twentieth century: The search for non-Newtonian effects”. Studies in History and Philosophy of Science I (Scientiarum Historia et Theoria Studia). Roberto de Andrade Martins. 2021.
Maskelyne (1775)	N. Maskelyne; Phil. Trans. R. Soc., 65, 500–42, (1775).
Michaelis (1996)	Michaelis W, Haars H, Augustin R. 1995/1996. “A new precise determination of Newton’s gravitational constant”. Meterologia 32, 267–276. (doi:10.1088/0026-1394/32/4/4)
Moore (1988)	G. I. Moore, F. D. Stacey, G. J. Tuck, B. D. Goodwin, N. P. Linthorne, M. A. Barton, D. M. Reid, and G. D. Agnew; Determination of the gravitational constant at an effective mass separation of 22 m (1988); Physics Department, University of Queensland, Brisbane Q4067, Australia.
Müller (1990)	Müller G, Zürn W, Lindner K and Rösch N 1990 Geophys. J. Int. 101 329–44.
Newman (2014)	Newman, R., Bantel, M., Berg, E., & Cross, W. (2014). A measurement of G with a cryogenic torsion pendulum. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2026), 20140025–20140025. doi:10.1098/rsta.2014.0025.
Nolting (1999)	Nolting F, Schurr J, Schlamminger S, Kündig W. 1999. “A value for G from beam-balance experiments”. Meas.Sci.Technol.10, 487–491. (doi:10.1088/0957-0233/10/6/312)
Oldham (1993)	Oldham M, Lowes F J and Edge R J 1993 Geophys. J. Int. 113 83–94.
Page (1981)	Page D N and Geilker C D 1981 Phys. Rev. Lett. 47 979–82.
Parks (2010)	Parks HV, Faller JE. 2010. “Simple pendulum determination of the gravitational constant”. Phys.Rev. Lett.105, 110801. (doi:10.1103/PhysRevLett.105.110801)
Pontikis (1971)	“Détermination de la constante de gravitation par la méthode de résonance.”. Facy, L.; Pontikis, C. Publication: Comptes Rendus de l'Academie des Sciences Paris, Sér. B, Tome 272, p. 1397 - 1398. Pub Date: 1971.
Pontikis (1972)	Pontikis C. 1972. “Détermination de la constant de gravitation par la méthode de resonance”. C.R. Hebd. Seances Acad. Sci. Ser. B274, 437–440.
Poynting (1879)	J. H. Poynting; Proc. R. Soc. London; A 29, (1879).
Poynting (1891)	Poynting JH. 1891. “On a determination of the mean density of the Earth and the gravitation constant by means of the common balance”. Phil. Trans. R. Soc. Lond. A182, 565–656. (doi:10.1098/rsta.1891.0014)
Prevedelli (2010)	“Sensitive gravity-gradiometry with atom interferometry: progress towards an improved determination of the gravitational constant”. F Sorrentino, Y-H Lien, G Rosi, L Cacciapuoti, M Prevedelli and G M Tino. 24th September 2010. IOP Publishing Ltd. New Journal of Physics, Volume 12, September 2010. Focus on Atom Optics and its Applications. Citation F Sorrentino et al 2010 New J.

Phys. 12 095009. DOI 10.1088/1367-2630/12/9/095009.

Prevedelli (2014) Prevedelli M, Cacciapuoti L, Rosi G, Sorrentino F, Tino GM. Measuring the Newtonian constant of gravitation G with an atomic interferometer. Philos Trans A Math Phys Eng Sci. 2014 Oct 13;372(2026):20140030. doi: 10.1098/rsta.2014.0030. Epub 2014 Sep 8. PMID: 25202001; PMCID: PMC4173270.

Quinn (2001) Quinn TJ, Speake CC, Richman SJ, Davis RS, Picard A. 2001. "A new determination of G using two methods". physics Rev. Lett.87, 111101. (doi:10.1103/PhysRevLett.87.111101)

Quinn (2013) Quinn T, Parks H, Speake C, Davis R. 2013. "Improved determination of G using two methods". Phys. Rev. Lett.111, 101102. (doi:10.1103/PhysRevLett.111.101102)

Reich (1838) Reich F. 1838. "Versuche über die mittlere Dichtigkeit der Erde mittels der Drehwaage." Freiberg, Deutschland: J. G. Englehardt.

Renner (1970) Renner Y. 1970. "On experimental studies for new determination of the constant of gravitation". Commun. Sternberg Astron. Inst.167, 3–8.

Renner (1973) J. Renner; Determination of the gravitational constant in Budapest in Determination of Gravity Constants and measurements of Certain Fine Gravity Effects, Ed. by Y. D. Boulanger and M. U. Sagitov, Nauka Press, Moskau (1973)

Richarz (1898) Richarz F, Krigar-Menzel O. "Gravitationsconstante und mittlere Dichtigkeit der Erde, bestimmt durch Wägungen". 1898 Ann. Phys.(Leipzig) 302, 177–193. (doi:10.1002/andp.18983021002)

Richman (1999) S. J. Richman et. al.; Meas. Sci. Technol.10, (6), 460–466 (1999).

Ritter (1990) Ritter RC, Goldblum CE, Ni W-T, Speake CC, Gillies GT. 1990. "Experimental test of equivalence principle with polarized masses". Phys. Rev. D42, 977–991. (doi:10.1103/PhysRevD.42.977)

Rose (1969-a) R. D. Rose et.al.; Phys. Rev. Lett. 23, 655 (1969).

Rose (1969-b) Rose RD, Parker HM, Lowry RA, Kuhlthau AR, Beams JW. 1969. "Determination of the gravitational constant G". Phys. Rev. Lett. 23, 655–658. (doi:10.1103/PhysRevLett.23.655)

Sabbata (1988) "Gravitational Measurements, Fundamental Metrology and Constants". Venzo Sabbata, V. N. Melnikov. 1988.

Sagitov (1979) Sagitov MU, Milyukov VK, Monakhov EA, Nazarenko VS, Tadzhidinov KG. 1979. "A new determination of the Cavendish gravitational constant". Doc. Akad. Nauk SSSR Fiz. Zemli 245, 567-569.

Saulnier 1989) Saulnier MS, Frisch D. 1989. "Measurement of the gravitational constant without torsion". Am. J. Phys.57, 417–420. (doi:10.1119/1.16013)

Schlamminger (2002) "Determination of the Gravitational Constant with a Beam Balance". St. Schlamminger, E. Holzschuh, and W. Kündig. Physik-Institut, Universitat Zürich, CH-8057 Zürich, Switzerland. (Received 26 July 2002; published 30 September 2002). DOI:10.1103/PhysRevLett.89.161102.

Schlamminger Schlamminger S, Hozschuh E, Kündig W, Nolting F, Pixley RE, Schurr J,

(2006)	Straumann U.2006. “Measurement of Newton’s gravitational constant”. Phys. Rev. D74, 082001. (doi:10.1103/PhysRevD.74.082001)
Schurr (1991)	Schurr, J., Klein, N., Meyer, H., Piel, H., & Walesch, H. (1991). A New Method for Testing Newton’s Gravitational Law. Metrologia, 28(5), 397–404. doi:10.1088/0026-1394/28/5/004.
Schurr (1992)	J. Schurr; Eine neue Methode zum Test des Newtonschen Gravitationsgesetzes - erste Ergebnisse von zwei Laborexperimenten, Bergische Universität Gesamthochschule Wuppertal, WUB 92–8 (1992).
Schwarz (1999)	Schwarz JP, Robertson DS, Niebauer TM, Faller JE. 1999. “A new determination of the Newtonian constant of gravity using the free fall method”. Meas. Sci. Technol.10, 478–486. (doi:10.1088/0957-0233/10/6/311)
Speake (1983)	Speake CC. 1983. “A beam balance method for determining the Newtonian gravitational constant”. PhD thesis, University of Cambridge, Cambridge, UK.
Stacey (1984)	Stacey, F.D., and G.J. Tuck, Non-Newtonian Gravity: Geophysical Evidence, Precision Measurement and Fundamental Constants II, p.597-600, B.N. Taylor and W.D. Phillips (editors), National Bureau of Standards (U.S.) Special Publication 617, 1984.
Taylor (1973)	Cohen, E. R., & Taylor, B. N. (1973). “The 1973 Least-Squares Adjustment of the Fundamental Constants”. Journal of Physical and Chemical Reference Data, 2(4), 663–734. doi:10.1063/1.3253130.
Taylor (1981)	“Precision Measurement and Fundamental Constants II”. Proceedings of the Second International Conference held at the National Bureau of Standards. Gaithersburg, MD, June 8-12, 1981. Edited by: B.N. Taylor and W.D. Phillips Center for Basic Standards National Measurement Laboratory National Bureau of Standards Gaithersburg, MD 20899. Page 566.
Walesch (1994)	H. Walesch, H. Meyer, H. Pial and J. Schurr, “The gravitational force at mass separation from 0.6 m to 2.1 m and the precise measurement of G”, Proceedings of Conference on Precision Electromagnetic Measurements Digest, 1994, pp. 17-18, doi: 10.1109/CPEM.1994.333309.
Walesch (1995-a)	H. Walesch; “Test des Newtonschen Gravitationsgesetzes und die präzise Bestimmung von G”, Dissertation, Bergische Universität Gesamthochschule Wuppertal, WUB 95–4 (1995).
Walesch (1995-b)	H. Walesch, H. Meyer, H. Piel and J. Schurr, “The gravitational force at mass separations from 0.6 m to 2.1 m and the precise measurement of G,” in IEEE Transactions on Instrumentation and Measurement, vol. 44, no. 2, pp. 491-493, April 1995, doi: 10.1109/19.377889.
Wang (2009)	Wang, Y., Ke, X., Zhang, W. et al. Measurement of the Newtonian gravitational constant based on the principle of free fall. Chin. Sci. Bull. 54, 1019–1025 (2009). https://doi.org/10.1007/s11434-009-0091-9.
Wilsing (1889)	Wilsing J. 1889. “Bestimmung der mittleren Dichtigkeit der Erde mit Hilfe eines Pendelapparates (Zweite Abhandlung)”. Publicationen des Astrophyikalischen Observatoriums zu Potsdam 6, 133–193.43.

Yang (1991)	Yang X-S, Liu W-M, Zhao H-L, Li J-T. 1991. "Testing the intermediate-range force at separations around 50 meters". Chinese Phys. Lett.8, 329-332. (doi:10.1088/0256-307X/8/7/001)
Yu (1979)	Yu H-T, Ni W-T, Hu C-C, Liu F-H, Yang C-H and Liu W-N 1978 Chin. J. Phys. 16 201–13—1979 Phys. Rev. D 20 1813–15.
Zahradníček (1933)	Zahradníček J. 1933. "Resonanzmethode für die Messung der Gravitationskonstante mittels der Drehwaage". Physik. Zeitschr.34, 126–133.
Zumberge (1990)	M. A. Zumberge et al., 1990, J. Geophys. Res. 95, 15483.
Zumberge (1991)	M. Zumberge et al.; "Submarine measurement of the Newtonian gravitational constant"; Phys. Rev. Lett., Vol. 67, Nr. 22, (1991).