Strong Field Gravitational Tests

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When the density of the body becomes large enough, general relativity predicts the formation of a black hole. The neutron stars of about 1.4 solar masses and the black holes are the final stage for the evolution of the massive stars. [1] Usually a black hole in a galaxy has played an important role in its formation and related cosmic structures. Such bodies provide an efficient mechanism for the emission of electromagnetic radiation[2] and the formation of microquasars. [3] Accretion can lead to relativistic jets. General relativity allows the modeling of these phenomena, [4] confirmed by observations.

Black holes are the areas where gravitational waves are searched, sometimes formed by combining binary stars with black holes, detected on Earth; the pre-fusion phase ("chirp") can be used as a "standard illumination" to deduce the distance to the fusion events, serving as a proof of cosmic expansion over long distances. [5] When a black hole joins another supermassive black hole, it can provide direct information about the geometry of the supermassive black hole. [6]

In February 2016 and later in June 2016, June 2017 and August 2017, Advanced LIGO announced that it had directly detected gravitational waves from a black hole stellar fusion. [7] Gravitational waves can be detected directly, and many aspects of the Universe can be found in their study. The astronomy of gravitational waves is concerned with the testing of general relativity and of alternative theories, verifying the predicted shape of the waves and their conformity with solutions of the field equations of the theories. [8]

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[1] Cole Miller, "Stellar Structure and Evolution (Lecture Notes for Astronomy 606)," 2002, http://www.astro.umd.edu/~miller/teaching/astr606/.

[2] R. D. Blandford, "Astrophysical Black Holes.," in *Three Hundred Years of Gravitation*, 1987, 277–329, http://adsabs.harvard.edu/abs/1987thyg.book..277B.

[3] Annalisa Celotti, John C. Miller, and Dennis W. Sciama, "Astrophysical Evidence for the Existence of Black Holes," *Classical and Quantum Gravity* 16, no. 12A (December 1, 1999): A3–A21, https://doi.org/10.1088/0264-9381/16/12A/301.

[4] José A. Font, "Numerical Hydrodynamics in General Relativity," *Living Reviews in Relativity* 6, no. 1 (August 19, 2003): 2, https://doi.org/10.12942/lrr-2003-4.

[5] Neal Dalal et al., "Short GRB and Binary Black Hole Standard Sirens as a Probe of Dark Energy," *Physical Review D* 74, no. 6 (September 18, 2006): 063006, https://doi.org/10.1103/PhysRevD.74.063006.

[6] Leor Barack and Curt Cutler, "LISA Capture Sources: Approximate Waveforms, Signal-to-Noise Ratios, and Parameter Estimation Accuracy," *Physical Review D* 69, no. 8 (April 30, 2004): 082005, https://doi.org/10.1103/PhysRevD.69.082005.

[7] Charles Q. Choi, "Gravitational Waves Detected from Neutron-Star Crashes: The Discovery Explained," Space.com, 2017, https://www.space.com/38471-gravitational-waves-neutron-star-crashes-discovery-explained.html.

[8] B. P. Abbott et al., "Tests of General Relativity with GW150914," *Physical Review Letters* 116, no. 22 (May 31, 2016): 221101, https://doi.org/10.1103/PhysRevLett.116.221101.

Other tests for strong gravity allow the gravitational redshift of the light from the star S2 orbiting the supermassive black hole Sagittarius A* in the center of the Milky Way, with the help of the Very Large Telescope using GRAVITY, NACO and SIFONI. [9]

The strong equivalence principle of general relativity for bodies with strong self-gravity was tested using a triple star system called PSR J0337+1715, consisting of a neutron star with a white dwarf star located approximately 4,200 light-years from Earth. which orbit along with another distant white dwarf star. The observations, with high accuracy, compare the way in which the gravitational pull of the outer white dwarf affects the pulsar which has a strong autogravity and the inner white dwarf. The results confirmed the general theory of relativity. [10]

[9] R. Abuter et al., "Detection of the Gravitational Redshift in the Orbit of the Star S2 near the Galactic Centre Massive Black Hole," *Astronomy & Astrophysics* 615 (July 1, 2018): L15, https://doi.org/10.1051/0004-6361/201833718.

[10] Anne M. Archibald et al., "Universality of Free Fall from the Orbital Motion of a Pulsar in a Stellar Triple System," *Nature* 559, no. 7712 (July 2018): 73–76, https://doi.org/10.1038/s41586-018-0265-1.

Gravitational lenses

When a massive astronomical body lies between the observer and a distant body with an appropriate mass and distance, several distorted images of the distant body can be seen, forming the effect known as gravitational lenses, [11] two or more images are the shape of a light ring. known as the Einstein ring or partial rings (arches). [12] The first such observation was in 1979. [13] The effect can be measured according to the brightness of the distant body. Gravitational lenses allow the presence and distribution of dark matter to be detected, being a kind of "natural telescope" for observing distant galaxies and obtaining an independent estimate of the Hubble constant. Their statistical assessments provide information about the structural evolution of galaxies. [14] The observation of gravitational lenses is expected to complement observations in the electromagnetic spectrum, [15] to provide information on black holes, neutron stars and white dwarfs, and on processes in supernovae and the very early universe, and to check the alternative theories including string theory in quantum gravitation. [16]

Gravitational lenses also form at the level of the solar system, with the Sun interposed between the observer and the light source, but the convergence point of such lenses would be approximately 542 AU from the Sun. However, this distance exceeds the capabilities of the probe equipment and goes far beyond the solar system.

Sources for gravitational lenses are radio sources far away, especially some quasars. For detection are used long-distance radio telescopes combined with very long basic interferometry technique. For accuracy, we consider the systematic effects on the Earth level, where the telescopes are located. The observations confirmed the value of the deformation predicted by the general relativity. [17]

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[11] Joachim Wambsganss, "Gravitational Lensing in Astronomy," *Living Reviews in Relativity* 1, no. 1 (November 2, 1998): 12, https://doi.org/10.12942/lrr-1998-12.

[12] Bernard Schutz, "Gravity from the Ground Up by Bernard Schutz," Cambridge Core, December 2003, https://doi.org/10.1017/CBO9780511807800.

[13] D. Walsh, R. F. Carswell, and R. J. Weymann, "0957 + 561 A, B: Twin Quasistellar Objects or Gravitational Lens?," *Nature* 279, no. 5712 (May 1979): 381–384, https://doi.org/10.1038/279381a0.

[14] Ramesh Narayan and Matthias Bartelmann, "Lectures on Gravitational Lensing," *ArXiv:Astro-Ph/9606001*, June 3, 1996, sec. 3.7, http://arxiv.org/abs/astro-ph/9606001.

[15] Kip S. Thorne, "Gravitational Waves," *ArXiv:Gr-Qc/9506086*, June 30, 1995, 160, http://arxiv.org/abs/gr-qc/9506086.

[16] Curt Cutler and Kip S. Thorne, "An Overview of Gravitational-Wave Sources," *ArXiv:Gr-Qc/0204090*, April 30, 2002, 4090, http://arxiv.org/abs/gr-qc/0204090.

[17] E. Fomalont et al., "Progress in Measurements of the Gravitational Bending of Radio Waves Using the VLBA," *The Astrophysical Journal* 699, no. 2 (July 10, 2009): 1395–1402, https://doi.org/10.1088/0004-637X/699/2/1395.

With the help of the astronomical satellite Hipparcos of the European Space Agency it was found that the whole sky is slightly distorted due to the gravitational deviation of the light caused by the Sun (except the direction opposite to the Sun). This requires some minor corrections for virtually all stars.

Gravitational waves

Gravitational waves were predicted in 1916 by Albert Einstein. [18] They are disturbances in the curved spacetime geometry, generated by the accelerated masses and propagating with the speed of light. They were confirmed on February 11, 2016 by the Advanced LIGO team. [19] For the weak fields a linear approximation can be made for these waves. Data analysis methods are based on the Fourier decomposition of these waves. [20] Exact solutions can be obtained without approximation, but for gravitational waves produced by the fusion of two black holes, numerical methods are the only way to build suitable models. [21]

Gravitational waves were initially suggested by Henri Poincaré in 1905, and then predicted in 1916 by Albert Einstein based on the general theory of relativity. The laws of classical mechanics do not guarantee their existence, this being one of the classical limitations. Binary neutron star systems are a powerful source of gravitational waves during fusion. Gravitational waves were detected by the LIGO and VIRGO observatories. They allow the observation of the fusion of black holes and the study of the distant universe, opaque to electromagnetic radiation.

Einstein and Rosen published the first correct version of gravitational waves in 1937. [22] Gravitational waves are created by accelerating mass in space, but if the acceleration is spherically symmetrical, no gravitational waves are radiated. Binary systems always radiate gravitational waves, because their acceleration is asymmetrical.

The first indirect detection of gravitational waves was in 1974 by Hulse and Taylor, from a binary pulsar PSR 1913+16, using delayed radio wave detection. [23] They found that the gravitational time

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[18] Albert Einstein, "Näherungsweise Integration Der Feldgleichungen Der Gravitation," *Sitzungsberichte Der Königlich Preußischen Akademie Der Wissenschaften (Berlin), Seite 688-696.*, 1916, 1: 688–696, http://adsabs.harvard.edu/abs/1916SPAW.......688E.

[19] B. P. Abbott, The LIGO Scientific Collaboration, and the Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger," *Physical Review Letters* 116, no. 6 (February 11, 2016): 116(6): 061102, https://doi.org/10.1103/PhysRevLett.116.061102.

[20] Piotr Jaranowski and Andrzej Królak, "Gravitational-Wave Data Analysis. Formalism and Sample Applications: The Gaussian Case," *Living Reviews in Relativity* 8, no. 1 (March 21, 2005): 8 (1): 3, https://doi.org/10.12942/lrr-2005-3.

[21] Edward Seidel, "Numerical Relativity: Towards Simulations of 3D Black Hole Coalescence," *ArXiv:Gr-Qc/9806088*, June 23, 1998, 6088, http://arxiv.org/abs/gr-qc/9806088.

[22] A. Einstein and N. Rosen, "On Gravitational Waves," *Journal of The Franklin Institute* 223 (January 1, 1937): 43–54, https://doi.org/10.1016/S0016-0032(37)90583-0.

[23] R. A. Hulse and J. H. Taylor, "Discovery of a Pulsar in a Binary System," *The Astrophysical Journal Letters* 195 (January 1, 1975): L51–L53, https://doi.org/10.1086/181708.

dilation was in line with the GR prediction and contradicted most alternative theories. [24] The first direct detection of gravitational waves occurred in 2015, with two Advanced LIGO detectors, from source GW150914, a binary black hole. [25] These observations confirmed the spacetime curvature as described by GR.

Joseph Weber designed and built the first gravitational wave detectors, in 1969 reporting that he detected the first gravitational waves, then reporting signals regularly from the Galactic Center. But the frequency of detection raised doubts about the validity of his observations. [26]

Some scientists disagree with the fact that experimental results are accepted on the basis of epistemological arguments. Based on gravitational wave detection experiments, Harry Collins developed an argument he calls the "experimenters' regress":[27] a correct result is obtained with a good experimental apparatus, respectively one that gives correct results. Collins argues that there are no formal criteria for checking the device, not even by calibrating a device by using a "surrogate" signal. [28] The problem is finally solved by negotiation within the scientific community, depending on factors such as the career, social and cognitive interests of the scientists, and the perceived usefulness for future work, but without using epistemological criteria or rational judgment. Thus, Collins asserts that there is serious doubt about experimental evidence and their use in evaluating scientific hypotheses and theories. The example given by Collins is early experiments to detect gravitational radiation or gravitational waves. [29]

The physical community was forced to compare Weber's assumptions with reports of six other experiments that did not detect gravitational waves. Collins argues that the decision between these contradictory experimental results could not be made on epistemological or methodological grounds - the six negative experiments could not legitimately be considered as replications, and thus were considered less important. In his experiments Weber used a new type of device to detect

[24] Clifford M. Will, "The Confrontation between General Relativity and Experiment," *Living Reviews in Relativity* 17, no. 1 (December 2014): 17, https://doi.org/10.12942/lrr-2014-4.

[25] Abbott, The LIGO Scientific Collaboration, and the Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger," 116(061102).

[26] Jorge L. Cervantes-Cota, Salvador Galindo-Uribarri, and George F. Smoot, "A Brief History of Gravitational Waves," *Universe* 2, no. 3 (September 2016): 2 (3): 22, https://doi.org/10.3390/universe2030022.

[27] Harry M. Collins, *Changing Order: Replication and Induction in Scientific Practice*, Reprint edition (Chicago: University of Chicago Press, 1992), 4:79-111.

[28] Allan Franklin and Slobodan Perovic, "Experiment in Physics," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2016 (Metaphysics Research Lab, Stanford University, 2016), https://plato.stanford.edu/archives/win2016/entries/physics-experiment/.

[29] Allan Franklin, "Calibration," in *Can That Be Right? Essays on Experiment, Evidence, and Science*, ed. Allan Franklin, Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 1999), 5: 31–80, https://doi.org/10.1007/978-94-011-5334-8_9.

a hitherto unobserved phenomenon, which could not be subjected to standard calibration techniques. [30]

The results of other scientists who contradicted Weber's were more numerous, and have been carefully verified, and have been confirmed by other groups of researchers. They investigated whether their analysis procedure, a linear algorithm, could explain the failure in observing Weber's results. They changed the procedure to the one used by Weber, a nonlinear algorithm, to analyze their own data, but again found no trace of gravitational waves. They recalibrated their experimental devices by introducing known acoustic energy impulses and thus detecting a signal. [31]

There were other doubts about Weber's analysis procedures. An admitted programming error generated false coincidences between the two detectors that could be interpreted during the experiments as real.

The results of the critics were much more credible from the point of view of the procedures that had to be followed: they verified the results by independent confirmation that included the sharing of data and analysis programs, eliminated a plausible source of error, and they calibrated the devices by injecting known energy pulses and observing the output. Allan Franklin and Slobodan Perovic believe that the scientific community made a motivated judgment by initially rejecting Weber's results by accepting those of his critics. Although no strict formal rules were applied, the procedure was reasonable. [32]

Another way of detecting gravitational waves is through the interaction of the waves with the walls of a microwave cavity, with a formalism developed by Caves, for measuring inertial frame dragging[33] and detecting high frequency gravitational waves. [34]

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[30] Franklin and Perovic, "Experiment in Physics."

[31] Franklin and Perovic.

[32] Franklin and Perovic.

[33] C. M. Will, "The Theoretical Tools of Experimental Gravitation," 1974, 1, http://adsabs.harvard.edu/abs/1974exgr.conf....1W.

[34] Carlton Morris Caves, "Theoretical Investigations of Experimental Gravitation" (phd, California Institute of Technology, 1979), http://resolver.caltech.edu/CaltechTHESIS:03152016-161054898.

Synchronization binary pulsars

Pulsars are rotating neutron stars that emit radio waves in pulses as they rotate, thus functioning as watches that allow a very precise measurement of their orbital movements. Their observations showed that their precessions that cannot be explained by classical mechanics can be explained by general relativity. [35]

Measurements on binary pulsars can test the combined relativistic effects, including the Shapiro delay. [36] And, since the gravitational field near the pulsars is strong, the weak equivalence principle can also be tested due to the invariant position of the objects with strong self-gravity properties. [37]

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[35] Joel M. Weisberg, David J. Nice, and Joseph H. Taylor, "Timing Measurements of the Relativistic Binary Pulsar PSR B1913+16," *The Astrophysical Journal* 722, no. 2 (October 20, 2010): 722 (2): 1030–1034, https://doi.org/10.1088/0004-637X/722/2/1030.

[36] Lijing Shao and Norbert Wex, "Tests of Gravitational Symmetries with Radio Pulsars," *Science China Physics, Mechanics & Astronomy* 59, no. 9 (September 2016): 59(699501), https://doi.org/10.1007/s11433-016-0087-6.

[37] Clifford M. Will, *Theory and Experiment in Gravitational Physics, Revised Edition*, Revised edition (Cambridge England ; New York, NY, USA: Cambridge University Press, 1993).

Extreme environments

Extreme gravity environments are close to very massive compact bodies, where the curvature of spacetime is very pronounced and the general relativistic effects are profound. These are usually neutron stars and black holes (especially supermassive ones), the active galactic nucleus and quasars. Deviations from the GR are most likely to occur here, under strong gravity regime. Such a test, for 16 years, was performed by Gillessen et al., [38] for Sagitarius A* [Sgr A*], a light radio source in the center of the Milky Way where there is a supermassive black hole. The observations made by Hambaryan et al. [39] were in full agreement with the GR, an essential confirmation for this theory.

[38] S. Gillessen et al., "Monitoring Stellar Orbits around the Massive Black Hole in the Galactic Center," *The Astrophysical Journal* 692, no. 2 (February 20, 2009): 692(2), pp.1075–1109, https://doi.org/10.1088/0004-637X/692/2/1075.

[39] V. Hambaryan et al., "On the Compactness of the Isolated Neutron Star RX J0720.4-3125," *Astronomy & Astrophysics* 601 (May 2017): A108, https://doi.org/10.1051/0004-6361/201630368.

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