Anomalies of General Relativity

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Over time, the general theory of relativity has accumulated several anomalies and discrepancies, indicating the need for a better theory about gravity or other approaches:

- Stars in galaxies have a distribution of increasing speeds from the center to the periphery, with a greater variation than predicted. The same is true of galaxies in galaxy clusters. The hypothesis of dark matter, which would interact by gravity but not electromagnetically, could explain the discrepancy. There are also various changes in Newtonian dynamics that can explain this anomaly, such as the MOND theory.
- Spacecrafts experienced greater acceleration than predicted during gravitational maneuvers.
- The metric expansion of space seems to be accelerating. Dark energy was introduced as a hypothesis to explain this. A recent explanation is that space geometry is not homogeneous due to galaxy clusters, but this hypothesis is challenged.[1]
- Recent measurements show that planetary orbits grow faster than predicted by the loss of the Sun's mass by radiative energy.
- Photons from cosmic radiation should gain energy and then lose it on the way, but in reality, they gain twice as much energy as predicted by theory. One hypothesis would be that gravity decreases faster than the inverse square at certain distances.
- Extra massive hydrogen clouds: Lyman-alpha spectral lines suggest that hydrogen clouds are more crowded at certain scales than expected and, like dark flux, may indicate that gravity is slower than inverse squares at certain distances.[2]

The ad-hoc hypotheses introduced in general relativity to explain gravitational singularities based on energy conditions are not very efficient. More detailed assumptions on the content of the subject are needed.[3] Many scientists and philosophers have come to the conclusion that singularities must be associated with reaching the limits of the physical validity of general relativity, and a new theory of quantum gravity needs to be developed.

A singularity that can causally influence certain parts of the space is called *naked singularity*. Penrose proposed the elimination of naked singularities using the cosmic censorship hypothesis.[4] Demonstrating the cosmic censorship hypothesis is one of the central mathematical problems of general relativity.

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[1] Anil Ananthaswamy, “Swiss-Cheese Model of the Cosmos Is Full of Holes,” New Scientist, 2008, https://www.newscientist.com/article/mg20026783-800-swiss-cheese-model-of-the-cosmos-is-full-of-holes/.

[2] Marcus Chown, “Gravity May Venture Where Matter Fears to Tread,” New Scientist, accessed May 3, 2019, https://www.newscientist.com/article/mg20126990-400-gravity-may-venture-where-matter-fears-to-tread/.

[3] Alan D. Rendall, “The Nature of Spacetime Singularities,” *ArXiv:Gr-Qc/0503112*, November 2005, 76–92, https://doi.org/10.1142/9789812700988_0003.

[4] R. Penrose, “Singularities and Time-Asymmetry.,” 1979, 581–638, http://adsabs.harvard.edu/abs/1979grec.conf..581P.

According to some scientists, general relativity contains the germs of its own destruction, since the theory is incapable of predicting physics on the Planck scale, and problems such as non-renormalizability and singularities are "known unknown." [5]

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[5] David Tong, *String Theory* (University of Cambridge, 2009), http://www.damtp.cam.ac.uk/user/tong/string/string.pdf.

The saturation point of general relativity

According to the methodology of Lakatos research programs, general relativity can be divided into several periods: the initial period, the stagnation period, the maturity period, and the saturation point. The initial period ("Genesis", 1887-1919) includes the two great experiments of relativistic physics, the Michelson-Morley experiment and the Eotvos experiment, and the two confirmations, the deformation of light and the perihelion advance of Mercury. There followed a period of stagnation ("Hibernation", 1920-1960) during which the theory took it before technological and experimental possibilities, the theory being even removed from the textbooks of physics and astronomy.

The maturity of the theory begins in 1960, when the astronomical discoveries and new experiments drew attention to the GR. This period (1960 - 1980) was named by Will as a "Golden Era",[6] in which observable predictions of GR were systematized, compared to other alternative theories, and new experiments were proposed for testing. The first experiment of this period was developed to confirm the change in gravitational frequency of light (1960) and ended with the confirmation of the GR prediction of the energy loss of gravitational waves (1979) by observing the Hulse-Taylor binary pulsar.

From 1980 the saturation zone of the GR began, called by Will as "Quest for Strong Gravity". Some of the new predictions of the theory are now insignificant and difficult to verify, in some cases requiring still undeveloped technologies. The theory began to be attacked by new experimental theories or techniques, such as using laser-cooled ion atoms and traps to perform ultra-precise tests, proposing a "fifth" force, or additional dimensions to test the inverse square law of gravity. Increased attention has begun to be paid to the effects of strong gravitational fields, near the horizon of the event of a non-rotating black hole, in neutron stars or, for the extended universe, associated gravitational fields on the Planck scale.

In Einstein's equations of classical general relativity, there remains a fundamental asymmetry between gravitational and non-gravitational fields: on the left, a geometrical object ($g_{\mu\nu}$, the Einstein tensor), representing the curvature of spacetime, is identical with the phenomenological but non - geometrical representation of tensor of the matter on the right side.

$$(1)\ G_{\mu\nu} = kT_{\mu\nu}, \text{ where } G_{\mu\nu} \equiv R_{\mu\nu} - (1/2)g_{\mu\nu}R$$

Thus, in his lecture for the Nobel Prize in July 1923, Einstein stated:

> "The mind striving after unification of the theory cannot be satisfied that two fields should exist which, by their nature, are quite independent. A mathematically unified field theory is sought in which the gravitational field and the electromagnetic field are interpreted as only different components or manifestations of the same uniform field, … The gravitational theory, considered

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

> in terms of mathematical formalism, i.e., Riemannian geometry, should be generalized so that it includes the laws of the electromagnetic field." [7]

There is theoretical evidence that disregards Einstein equivalence principle (EEP) in certain cases, through quantum gravitational effects, effects derived from string theory, or through other undetected interactions so far. In string theory there are such fields that violate EEP, but the theory is not yet mature enough to materialize such a refutation. Clifford M. Will states that observing effects that appear to violate the EEP is, to some extent, semantic. The fields involved in string theory can be long distances and can mimic gravitational fields, but no way has been found to do so. [8] The idea of using EEP tests in this way appeared in the 1980s, in search of a "fifth" force[9] as a force of about a percentage of gravity but with a range of several hundred meters, implying a deviation from the inverse-square law of Newtonian gravity. The idea came about when using gravity profile measurements from deep mines in Australia and from new ideas in particle physics, suggesting the possible presence of very small gravity particles. Numerous experiments have sought evidence of this force by measuring acceleration differences by composition, but the results have not been conclusive, the consensus being that there is no credible experimental evidence for a fifth force. [10]

The possibility that the inverse square law would be violated at very short intervals in laboratory tests[11] provided that some of the extra spatial dimensions in string theory could extend beyond macroscopic scales. On a small scale, gravity deviates from the known law. Many methods of high precision and low noise have been developed, adapted for laboratory tests. No deviations from the inverse square law were found. [12]

Gravitational singularities are considered to be a spacetime limit. General relativity allows for the existence of singularities, but it cannot say anything about what is happening inside them, and scientists have not yet agreed on a definition of them, also considering that without a geometry in accordance with the laws of physics cannot exist a spacetime location. In conclusion, they say, one cannot speak of singularities, but rather of singular spacetimes, although in principle these terms

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[7] Albert Einstein, *Fundamental Ideas and Problems of the Theory of Relativity: Lecture Delivered to the Nordic Assembly of Naturalists at Göteborg on July 11, 1923* (Nobel Museum, 2009), 489.

[8] Will, "The Confrontation between General Relativity and Experiment."

[9] E. Fischbach et al., "Reanalysis of the Eotvos Experiment," *Physical Review Letters* 56 (January 1, 1986): 56, 3–6, https://doi.org/10.1103/PhysRevLett.56.3.

[10] C. M. Will, "Twilight Time for the Fifth Force?," 1990, 80, 472–479, http://connection.ebscohost.com/c/articles/9011192203/twilight-time-fifth-force.

[11] Lisa Randall and Raman Sundrum, "An Alternative to Compactification," *Physical Review Letters* 83, no. 23 (December 6, 1999): 83, 4690–4693, https://doi.org/10.1103/PhysRevLett.83.4690.

[12] Joshua C. Long et al., "Upper Limits to Submillimetre-Range Forces from Extra Space-Time Dimensions," *Nature* 421, no. 6926 (February 2003): 421, 922–925, https://doi.org/10.1038/nature01432.

are equivalent.[13] Clarke[14] and Earman,[15] as well as Geroch, Can-bin and Wald[16] and Curiel,[17] argue that a precise, rigorous and univocal definition of singularity is needed for a better approach to them and for a more accurate modeling of spacetime aspects.[18] It is common assertion that general relativity, considering spacetime as singular, predicts its own inability to limit the singularities of black holes and the Big Bang, negating their reality. It is hoped that a more fundamental theory, possibly quantum gravity, will solve this problem.[19]

The black holes appear, according to general relativity, when the cosmic body collapsed under the so-called Schwarzschild ray, proportional to the body mass. The "event horizon" of a black hole is the point where there is no turning back, within which the gravitational attraction is greater than any attempt to exit this area, including for light.[20] (1) For a standard black hole (uncharged, non-rotating), the horizon of the event is within the Schwarzschild radius. From the point of view of a person outside the event horizon, the time near a black hole is delayed due to the strong gravity, until the time intervals reach infinitely large within the horizons of events. From the perspective of the person entering the horizon of events, nothing unusual happens. Time is running the same way and he does not realize that he has entered the horizon of events.

Relativistic black holes are purely gravitational entities. They are solutions to the "vacuum" of Einstein's field equations. In the context of general relativity, Erik Curiel states that gravity is given up and a curved geometry of spacetime is postulated that produces all the effects of gravity, the black hole being no more a "thing" in space, but a feature of spacetime itself.[21] The matter of the collapsing star disappears in the singularity of the black hole, leaving only the geometrical properties

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[13] Erik Curiel, "Singularities and Black Holes," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2019 (Metaphysics Research Lab, Stanford University, 2019), https://plato.stanford.edu/archives/spr2019/entries/spacetime-singularities/.

[14] C. J. S. Clarke, "The Analysis of Space-Time Singularities by C. J. S. Clarke," Cambridge Core, May 1994, https://doi.org/10.1017/CBO9780511608155.

[15] John Earman, "Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes," *British Journal for the Philosophy of Science* 49, no. 2 (1998): 338–347.

[16] Robert Geroch, Liang Can-bin, and Robert M. Wald, "Singular Boundaries of Space–Times," *Journal of Mathematical Physics* 23, no. 3 (March 1, 1982): 23(3): 432–435, https://doi.org/10.1063/1.525365.

[17] Erik Curiel, "The Analysis of Singular Spacetimes," *Philosophy of Science* 66, no. 3 (1999): 66(S1): S119–S145.

[18] Nicolae Sfetcu, *Singularitățile ca limite ontologice ale relativității generale* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.17470.18242.

[19] Abhay Ashtekar and Martin Bojowald, "Quantum Geometry and the Schwarzschild Singularity," *Classical and Quantum Gravity* 23, no. 2 (January 21, 2006): 23(2): 391–411, https://doi.org/10.1088/0264-9381/23/2/008.

[20] A more accurate description distinguishes other types of horizon, such as apparent horizons, cf. HawkingStephen W. Hawking et al., *The Large Scale Structure of Space-Time*, New Ed edition (Cambridge: Cambridge University Press, 1975), 312–20.

[21] Curiel, "Singularities and Black Holes."

of the black hole (mass, charge and angular momentum), according to theorems called "no-hair", regardless of the previous physical properties of objects that collapse into a black hole.

A "naked" singularity does not have a horizon of events. This implies a fundamental break in the structure of spacetime.[22] [23] A version of a naked singularity is the "white hole", a black hole reversed in time, from which matter and objects from nothing could appear. Since the equations of the field of general relativity do not select a preferred direction of time, and the formation of a black hole is allowed, then white holes will be allowed by these laws.[24] Roger Penrose asserts that naked singularities will never be formed, introducing an ad-hoc hypothesis called the "cosmic censorship hypothesis": a singularity will always be in a black hole that is surrounded by the horizon of events. The former was abandoned in time. Several alternative hypotheses have been proposed to eliminate the possibility of naked singularities that violate the principle of causality,[25] [26] but none is considered satisfactory to date.

Black holes provide an essential testing ground for the conceptual problems underlying quantum gravity and general relativity, regarding the violation of energy conservation and micro-causality, and the paradox of information loss. Quantum gravity seems to be the best candidate for modeling these phenomena.

In 1971, Hawking introduced the conjecture that the total surface of event horizons in any group of black holes does not decrease, even if they unite (the second law of black hole mechanics, by similarity to entropy in thermodynamics).[27] To prevent the black holes from having zero entropy, Bekenstein proposed that a black hole would have an entropy proportional to the area of its horizon.[28] Hawking discovered that quantum field theory predicts that a black hole behaves like a black body radiating at a constant temperature, thus violating the second law of black hole mechanics due to energy loss and hence shrinkage. But radiation removes also entropy, and so the amount of entropy of matter is increasing. This allows the formulation of the first law of black hole mechanics similar to the first law of thermodynamics, with the mass acting as energy, the gravity

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[22] Sfetcu, *Singularitățile ca limite ontologice ale relativității generale*.

[23] Earman, "Bangs, Crunches, Whimpers and Shrieks," 65–66.

[24] Curiel, "Singularities and Black Holes."

[25] Pankaj S. Joshi, "Cosmic Censorship: A Current Perspective," *ArXiv:Gr-Qc/0206087*, June 28, 2002, 17(15): 1067–1079, http://arxiv.org/abs/gr-qc/0206087.

[26] Earman, "Bangs, Crunches, Whimpers and Shrieks," chap. 3.

[27] S. W. Hawking, "Gravitational Radiation from Colliding Black Holes," *Physical Review Letters* 26, no. 21 (May 24, 1971): 26 (21): 1344–1346, https://doi.org/10.1103/PhysRevLett.26.1344.

[28] Robert M. Wald, "The Thermodynamics of Black Holes," *Living Reviews in Relativity* 4, no. 1 (July 9, 2001): 4 (1): 6, https://doi.org/10.12942/lrr-2001-6.

of the surface as temperature, and the area as entropy.[29] In this interpretation of the black hole, general relativity is unsatisfactory, and a better theory of quantum gravity is needed.[30]

A black hole only holds information about the total mass, charge and angular momentum. The theory of stable black holes states that this loss is not a problem, because the information can be considered as being present in the black hole, inaccessible from the outside but represented on the horizon of the event in accordance with the holographic principle. But in the theory that black holes slowly evaporate through Hawking radiation, information about the matter that formed the black hole is irretrievably lost. In quantum mechanics, the loss of information corresponds to the violation of unity, related to the conservation of probability, resulting in the violation of energy conservation.[31] The latest studies show that information and unity are nevertheless preserved in a quantum treatment of the problem.[32]

In the case of a body falling into a black hole, the theory of the quantum field in curved space involves quantities of Hawking radiation, including only a finite amount of information encoded in Hawking radiation. But the inseparability of the particle at the exit of all the Hawking radiation that the black hole has previously emitted creates a paradox called "the monogamy of inseparability."[33] To solve the paradox, one of the three theories tested over time should be discarded: the principle of Einstein's equivalence, unitarity, or the existing theory of the quantum field. The renunciation of the principle of equivalence implies a "firewall" that destroys the particles that enter in the horizon of the event.[34] The 2016 LIGO data shows possible echo signals due to a fuzzy horizon of events, possible in fuzzball theories, but impossible in general classical relativity.[35]

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[29] Wald, 4 (1): 6.

[30] S. Carlip, "Black Hole Thermodynamics and Statistical Mechanics," in *Physics of Black Holes: A Guided Tour*, ed. Eleftherios Papantonopoulos, Lecture Notes in Physics (Berlin, Heidelberg: Springer Berlin Heidelberg, 2009), 769: 89–123, https://doi.org/10.1007/978-3-540-88460-6_3.

[31] Steven B. Giddings, "The Black Hole Information Paradox," *ArXiv:Hep-Th/9508151*, August 28, 1995, http://arxiv.org/abs/hep-th/9508151.

[32] Samir D. Mathur, "The Information Paradox: Conflicts and Resolutions," *Pramana* 79, no. 5 (November 1, 2012): 1059–73, https://doi.org/10.1007/s12043-012-0417-z.

[33] Zeeya Merali, "Astrophysics: Fire in the Hole!," *Nature News* 496, no. 7443 (April 4, 2013): 20–23, https://doi.org/10.1038/496020a.

[34] Jennifer Ouellette, "Black Hole Firewalls Confound Theoretical Physicists," Scientific American, 2012, https://www.scientificamerican.com/article/black-hole-firewalls-confound-theoretical-physicists/.

[35] Zeeya Merali, "LIGO Black Hole Echoes Hint at General-Relativity Breakdown," *Nature News*, 2016, 540, https://doi.org/10.1038/nature.2016.21135.

The need for consistency between quantum theory and general relativity,[36] and the existence of singularities, require the emergence of a complete theory of quantum gravity.[37] So far, such a complete and consistent theory has failed to develop, although there are several candidates.[38]

The generalization of quantum field theory from the elementary particle physics to include gravity has failed.[39] At low energies the theory is acceptable, but at very high energies, the results are very divergent and lead to models without predictive power.[40]

An attempt to eliminate these limitations is string theory, a quantum theory. The theory promises a unification of gravity with the other forces, supplementing the three spatial dimensions with another six.[41] A newer version of the theory, the superstring theory, is trying to unify general relativity and supersymmetry, under the name of supergravity,[42] and a hypothetical unifying model with eleven dimensions known as M-theory.[43]

Another approach uses the canonical quantization of quantum theory in which, starting from general relativity, one reaches the Wheeler-deWitt equation, an analogue of the Schrödinger

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[36] S. Carlip, "Quantum Gravity: A Progress Report," *Reports on Progress in Physics* 64, no. 8 (August 1, 2001): sec. 2, https://doi.org/10.1088/0034-4885/64/8/301.

[37] Bernard Schutz, "Gravity from the Ground Up by Bernard Schutz," Cambridge Core, December 2003, 407, https://doi.org/10.1017/CBO9780511807800.

[38] Herbert W. Hamber, *Quantum Gravitation: The Feynman Path Integral Approach* (Berlin Heidelberg: Springer-Verlag, 2009), https://www.springer.com/gp/book/9783540852926.

[39] G. 't Hooft and M. Veltman, "One-Loop Divergencies in the Theory of Gravitation," *Annales de L'Institut Henri Poincare Section (A) Physique Theorique* 20 (1974): 20 (1): 69, http://adsabs.harvard.edu/abs/1974AIHPA..20...69T.

[40] Steven Weinberg, *The Quantum Theory of Fields, Volume 2: Modern Applications*, 1 edition (Cambridge: Cambridge University Press, 2005).

[41] M. B. Green, J. H. Schwarz, and E. Witten, "Superstring Theory. Vol. 1: Introduction," *ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift Für Angewandte Mathematik Und Mechanik* 68, no. 6 (1988): 258–258, https://doi.org/10.1002/zamm.19880680630.

[42] Steven Weinberg, *The Quantum Theory of Fields, Volume 3: Supersymmetry*, 1st Edition edition (Cambridge: Cambridge University Press, 2005).

[43] P. K. Townsend, "Four Lectures on M-Theory," *ArXiv:Hep-Th/9612121*, December 11, 1996, 13: 385, http://arxiv.org/abs/hep-th/9612121.

equation, but which has been wrongly defined.[44] By introducing Ashtekar *ad-hoc* (variable) hypotheses, it was developed the theory of loop quantum gravity.[45]

There are numerous other attempts to arrive at a viable theory of quantum gravity, based on the Feynman approach and the Regge calculation, dynamic triangulations, causality sets, twistor models[46] or the models based on integrals of paths of the quantum cosmology.[47] All candidate theories still have major formal and conceptual problems that are difficult to overcome so far, including the impossibility of verifying predictions through experimental tests.[48]

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[44] Karel Kuchař, "Canonical Quantization of Gravity," *Relativity, Astrophysics and Cosmology*, 1973, 237–288, https://doi.org/10.1007/978-94-010-2639-0_5.

[45] Abhay Ashtekar and Jerzy Lewandowski, "Background Independent Quantum Gravity: A Status Report," *Classical and Quantum Gravity* 21, no. 15 (August 7, 2004): 21 (15): R53–R152, https://doi.org/10.1088/0264-9381/21/15/R01.

[46] Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, Reprint edition (New York: Vintage, 2007).

[47] S. W. Hawking and W. Israel, *Quantum Cosmology, in Three Hundred Years of Gravitation* (Cambridge University Press, 1989), 631–651.

[48] John H. Schwarz, "String Theory: Progress and Problems," *Progress of Theoretical Physics Supplement* 170 (May 1, 2007): 170: 214–226, https://doi.org/10.1143/PTPS.170.214.

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