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Cosmological Tests Based on General Relativity for Gravity

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Abstract

In the realm of cosmology, understanding the nature of gravity is crucial for unraveling the mysteries of the universe. The current cosmological models are built based on general relativity. The solutions of the specific equations, Friedmann-Lemaître-Robertson-Walker, allow to model the evolution of the universe starting from the Big Bang. Some of the parameters of the universe have been established by observations. Based on these, and other observational data, the models can be tested. Predictions include the initial abundance of chemical elements formed in a period of nucleosynthesis during the Big Bang period, the subsequent structure of the universe, cosmic background radiation, and so on.
Keywords: cosmological tests, gravity, cosmological models, Friedmann-Lemaître-Robertson-Walker, Big Bang, predictions, general relativity

Teste cosmologice bazate pe relativitatea generală pentru gravitație

Rezumat

În domeniul cosmologiei, înțelegerea naturii gravitației este crucială pentru dezlegarea misterelor universului. Modelele cosmologice actuale sunt construite pe baza relativității generale. Soluțiile ecuațiilor specifice, Friedmann-Lemaître-Robertson-Walker, permit modelarea evoluției universului pornind de la Big Bang. Unii dintre parametrii universului au fost stabiliți prin observații. Pe baza acestor date și a altor date observaționale, modelele pot fi testate. Predicțiile includ abundența inițială a elementelor chimice formate într-o perioadă de nucleosinteză în timpul perioadei Big Bang, structura ulterioară a universului, radiația de fond cosmic și așa mai departe.
Cuvinte cheie: teste cosmologice, gravitație, modele cosmologice, Friedmann-Lemaître-Robertson-Walker, Big Bang, predicții, relativitatea generală

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Introduction

In the realm of cosmology, understanding the nature of gravity is crucial for unraveling the mysteries of the universe. As our understanding of the cosmos deepens, scientists have developed various cosmological tests to scrutinize the behavior of gravity on the largest scales. These tests serve as crucial tools for validating or challenging existing gravitational theories and shedding light on the fundamental principles that govern the cosmos.

The current cosmological models are built based on general relativity. The solutions of the specific equations, Friedmann-Lemaître-Robertson-Walker,[2] allow to model the evolution of the universe starting from the Big Bang.[3] Some of the parameters of the universe have been established by observations. Based on these, and other observational data, the models can be tested.[4] Predictions include the initial abundance of chemical elements formed in a period of nucleosynthesis during the Big Bang period, the subsequent structure of the universe,[5] cosmic background radiation,[6] and so on.

Observations on the expansion velocity of the universe allow estimation of the total amount of matter, some of which theories predict that 90% is dark matter, with mass but without

[2] Sean M. Carroll, "The Cosmological Constant," *Living Reviews in Relativity* 4, no. 1 (February 7, 2001): 4 (1): 1, https://doi.org/10.12942/lrr-2001-1.

[3] At large scales of about one hundred million light-years and more, the universe really looks isotropic and homogeneous, so simplified models are justified.

[4] Sarah L. Bridle et al., "Precision Cosmology? Not Just Yet . . .," *Science* 299, no. 5612 (March 7, 2003): 299 (5612): 1532–1533, https://doi.org/10.1126/science.1082158.

[5] Volker Springel et al., "Simulations of the Formation, Evolution and Clustering of Galaxies and Quasars," *Nature* 435, no. 7042 (June 2005): 435 (7042): 629–636, https://doi.org/10.1038/nature03597.

[6] Uroš Seljak and Matias Zaldarriaga, "Signature of Gravity Waves in the Polarization of the Microwave Background," *Physical Review Letters* 78, no. 11 (March 17, 1997): 78 (11): 2054–2057, https://doi.org/10.1103/PhysRevLett.78.2054.

electromagnetic interactions, and cannot be directly observed. The gravitational redshift of the supernovae and the measurements of the cosmic background radiation show a dependence of the universe evolution on a cosmological constant with an acceleration of the cosmic expansion or, alternatively, a form of energy called "dark energy".[7]

One of the powerful tools for scrutinizing gravity on cosmological scales is the study of the Cosmic Microwave Background (CMB) radiation. The CMB is a relic radiation from the early universe, and its anisotropies – tiny fluctuations in temperature – provide a valuable probe of the gravitational interactions at play during the universe's infancy. Deviations from the predicted patterns in the CMB anisotropy can signal potential modifications or alternatives to General Relativity. From the measurements of the cosmic background radiation,[8] in 1980 the initial existence of an inflationary phase was deduced, followed by a strongly accelerated expansion phase after about 10^{-33} seconds, thus explaining the almost perfect homogeneity of the cosmic background radiation.

The expanding universe

The Big Bang theory is the main cosmological model[9] for the early history of the universe and its subsequent evolution. It provides an explanation for a wide range of phenomena, including the abundance of light elements, the cosmic microwave background, the structure of the universe, and Hubble's law.[10] The physicists did not agree that the universe started from a singularity, or our

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[7]Thomas Buchert, "Dark Energy from Structure: A Status Report," *General Relativity and Gravitation* 40, no. 2 (February 1, 2008): 40 (2–3): 467–527, https://doi.org/10.1007/s10714-007-0554-8.

[8]D. N. Spergel et al., "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology," *The Astrophysical Journal Supplement Series* 170, no. 2 (June 2007): 170 (2): 377–408, https://doi.org/10.1086/513700.

[9]Dennis Overbye, "Cosmos Controversy: The Universe Is Expanding, but How Fast?," *The New York Times*, February 20, 2017, sec. Science, https://www.nytimes.com/2017/02/20/science/hubble-constant-universe-expanding-speed.html.

[10]E. L Wright, "What Is the Evidence for the Big Bang?, In Frequently Asked Questions in Cosmology," 2009, http://www.astro.ucla.edu/~wright/cosmology_faq.html#BBevidence.

present knowledge is insufficient to deduce the initial state. Measures of the expansion rate of the universe show that the universe was born 13.8 billion years ago. After the initial expansion, the universe cooled down into subatomic particles and then atoms. The coagulation of these primordial elements by gravity has led to the formation of stars and current galaxies.

From several alternative theories, the scientific community has preferred the Big Bang theory due to its much greater heuristic power, coupled with a wide range of empirical evidence, such as the redshift analyzed by Edwin Hubble in 1929, and the discovery of cosmic background radiation in 1964.[11] The evolution of the universe is deduced starting from the present situation, towards an initial state of huge density and temperature.

Particle accelerators can replicate conditions after the first moments of the universe, confirming and refining the details of the Big Bang model. The Big Bang theory explains many observed phenomena. The Big Bang model is based on general relativity theory and simplifying assumptions, such as homogeneity and isotropy of space. The model equations were formulated by Alexander Friedmann, and similar solutions were found by Willem de Sitter. The parameterization of the Big Bang model as a standard model, called the Lambda-CDM model, allows current investigations of theoretical cosmology.

The theoretical deductions from the observed phenomena lead us to an initial singularity (at time $t = 0$), with infinite density and temperature.[12] General relativity is not able to describe this regime, nor any other physical laws, nor can these laws be extrapolated beyond the end of the Planck period (10^{-37} seconds from the beginning of the expansion). Expansion measurements by observing supernovae and measuring temperature fluctuations in the cosmic microwave

[11]R. B. Partridge, *3K: The Cosmic Microwave Background Radiation* (Cambridge University Press, 2007), xvii.

[12]Tai L. Chow, *Gravity, Black Holes, and the Very Early Universe: An Introduction to General Relativity and Cosmology* (Springer Science & Business Media, 2007), 211.

environment show that the "age of the universe" is 13.799 ± 0.021 billion years,[13] this result favoring the ΛCDM cosmological model.

Measurements from Wilkinson Microwave Anisotropy Probe (WMAP) show conformity with the Lambda-CDM model where dark matter is assumed to be cold[14] and account for about 23% of the matter / energy of the universe, while baryon matter represents about 4.6%. An "extended model" includes dark hot neutrino matter.

Evidence from supernova observation and cosmic background radiation shows a universe dominated by a form of energy known as dark energy, that permeates all space, accounting for 73% of the total energy density in today's universe. Its composition and mechanism are unknown.[15]

The core of the Big Bang research program includes two major hypotheses: the universality of physical laws and the cosmological principle (according to which the universe is largely homogeneous and isotropic). Currently is testing these hypotheses from the outside of the Big Bang research program. The first hypothesis was tested taking into account the largest possible deviation of the constant fine structure for the age of the universe of the order of 10^{-5}.[16] The cosmological principle was confirmed at a level of 10^{-5} by the observations of the background cosmic radiation.[17]

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[13] P. a. R. Ade et al., "Planck 2015 Results - XIII. Cosmological Parameters," *Astronomy & Astrophysics* 594 (October 1, 2016): 594: A13, https://doi.org/10.1051/0004-6361/201525830.

[14] D. N. Spergel et al., "First-YearWilkinson Microwave Anisotropy Probe(WMAP) Observations: Determination of Cosmological Parameters," *The Astrophysical Journal Supplement Series* 148, no. 1 (September 2003): 148 (1): 175–194, https://doi.org/10.1086/377226.

[15] P. J. E. Peebles and Bharat Ratra, "The Cosmological Constant and Dark Energy," *Reviews of Modern Physics* 75, no. 2 (April 22, 2003): 75 (2): 559–606, https://doi.org/10.1103/RevModPhys.75.559.

[16] A. V. Ivanchik, A. Y. Potekhin, and D. A. Varshalovich, "The Fine-Structure Constant: A New Observational Limit on Its Cosmological Variation and Some Theoretical Consequences," *ArXiv:Astro-Ph/9810166*, October 10, 1998, 343: 459, http://arxiv.org/abs/astro-ph/9810166.

[17] Jeremy Goodman, "Geocentrism Reexamined," *Physical Review D* 52, no. 4 (August 15, 1995): 52 (4): 1821–1827, https://doi.org/10.1103/PhysRevD.52.1821.

The oldest and most direct observational evidence of the Big Bang is the expansion of the universe according to Hubble's law (deduced from the redshift of galaxies), the discovery and measurement of cosmic background radiation, and the relative quantities of light elements produced by Big Bang nucleosynthesis. Recent observations on galaxy formation and the evolution and distribution of cosmic structures on a large scale also confirm this theory.[18]

The current Big Bang models introduce various *ad-hoc* hypotheses for exotic physical phenomena that have not been observed in experiments or incorporated into the standard particle physics model. Of these, the dark matter hypothesis is currently being investigated at the laboratory level.[19] For the dark energy, no direct or indirect detection method has yet been found.[20]

Hubble's law and space expansion are verified by observations of redshifts of galaxies and quasars. The expansion of the universe was predicted from general relativity by Alexander Friedmann in 1922[21] and Georges Lemaître in 1927,[22] confirming the Big Bang theory developed by Friedmann, Lemaître, Robertson and Walker.

Radiation of the cosmic microwave background was discovered in 1964 by Arno Penzias and Robert Wilson, as an omnidirectional signal in the microwave band. This confirmed the Big Bang theory of Alpher, Herman and Gamow in 1950.

In 1989, NASA launched the Cosmic Background Explorer (COBE) satellite which, in 1990, by high-precision spectrum measurements, showed that the cosmic microwave background

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[18]Michael D. Gladders et al., "Cosmological Constraints from the Red-Sequence Cluster Survey," *The Astrophysical Journal* 655, no. 1 (January 2007): 655 (1): 128–134, https://doi.org/10.1086/509909.

[19]Bernard Sadoulet, "The Direct Detection of Dark Matter," ResearchGate, 1998, https://www.researchgate.net/publication/260854303_The_Direct_Detection_of_Dark_Matter.

[20]Partridge, *3K*, xvii.

[21]A. Friedman, "On the Curvature of Space," *General Relativity and Gravitation* 31, no. 12 (December 1, 1999): 10 (1): 377–386, https://doi.org/10.1023/A:1026751225741.

[22]Abbé G. Lemaître, "A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extra-Galactic Nebulæ," *Monthly Notices of the Royal Astronomical Society* 91, no. 5 (March 13, 1931): 47A: 41, https://doi.org/10.1093/mnras/91.5.483.

(CMB) frequency spectrum is an almost perfect black body; then in 1992, others found tiny fluctuations (anisotropies) at cosmic microwave background temperature throughout the sky. In the years 2000-2001, several experiments, such as BOOMERanG, concluded that the shape of the universe is almost a spatial plane, by measuring the typical angular dimension of anisotropies.[23] In 2003, the Wilkinson Microwave Anisotropy Probe (WMAP) results rejected some specific models of cosmic inflation but were in line with inflation theory in general.[24]

The *relative abundances of the elements* depend on the ratio between photons and baryons. The measurements are in agreement with those predicted from a single value of the baryon-photon ratio, fully confirming the deuterium, approximately 4He, and a larger difference for 7Li. But the general identity with the abundances predicted by Big Bang nucleosynthesis confirms this model.[25]

The *evolution and distribution of galaxies and quasars* are in agreement with the Big Bang. Observations and theory suggest that the first quasars and galaxies formed about one billion years after the Big Bang, after which galaxy clusters and superclusters formed. Differences between relatively recently formed galaxies and those formed shortly after the Big Bang confirm this model and disprove the stationary model.[26] The distribution of galaxies on large scales offers another avenue for testing gravitational theories. The way galaxies cluster and form cosmic web structures can be sensitive to the nature of gravity. Sophisticated galaxy surveys, such as the Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey (DES), provide vast datasets that allow scientists to analyze the large-scale structure of the universe and probe the gravitational forces shaping it.

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[23] A. Melchiorri et al., "A Measurement of Omega from the North American Test Flight of BOOMERANG," *The Astrophysical Journal* 536, no. 2 (June 20, 2000): 536(2): L63–L66, https://doi.org/10.1086/312744.

[24] Spergel et al., "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results," 170 (2): 377–408.

[25] Barbara Ryden, *Introduction to Cosmology*, 2003, http://adsabs.harvard.edu/abs/2003itc..book.....R.

[26] Edmund Bertschinger, "Cosmological Perturbation Theory and Structure Formation," *ArXiv:Astro-Ph/0101009*, December 31, 2000, http://arxiv.org/abs/astro-ph/0101009.

The *primordial gas clouds* were confirmed in 2011, by analyzing absorption lines in the spectra of distant quasars. They do not contain heavier elements, just hydrogen and deuterium.[27]

The *age of the universe* estimated from the Hubble expansion and CMB is in agreement with the measurements of the stellar evolution in the globular groups and the radiometric dating of the individual stars.

The prediction that the *CMB temperature* was higher in the past was experimentally proved by the observations of the very low temperature absorption lines in the gas clouds due to the redshift.[28]

Cosmological observations

Stephen Hawking introduced the concept of Hawking radiation according to which black holes have entropy. This concept states that black holes can radiate energy, conserving entropy and solving the problems of incompatibility with the second law of thermodynamics. The loss of energy suggests that black holes "evaporate" over time.

A black hole acts as an ideal black body because it does not reflect light. The theory of the quantum field in curved spacetime predicts that the horizons of the event emit Hawking radiation with the same spectrum as a black body,[29] with a temperature inversely proportional to its mass, the order of billions of kelvins, making them essentially impossible to observe.

The presence of a black hole can be deduced indirectly through its interaction with other materials and electromagnetic radiation. Matter falling on a black hole can form an external

[27]Michele Fumagalli, John M. O'Meara, and J. Xavier Prochaska, "Detection of Pristine Gas Two Billion Years After the Big Bang," *Science* 334, no. 6060 (December 2, 2011): 334 (6060): 1245–9, https://doi.org/10.1126/science.1213581.

[28]A. Avgoustidis et al., "Constraints on the CMB Temperature-Redshift Dependence from SZ and Distance Measurements," *Journal of Cosmology and Astroparticle Physics* 2012, no. 02 (February 2012): 2012 (2): 013, https://doi.org/10.1088/1475-7516/2012/02/013.

[29]P. C. W. Davies, "Thermodynamics of Black Holes," *Reports on Progress in Physics* 41, no. 8 (August 1978): 41 (8): 1313–1355, https://doi.org/10.1088/0034-4885/41/8/004.

accretion disk, one of the brightest objects in the universe. If there are other stars orbiting a black hole, their orbits may be used to determine the mass and location of the black hole, after excluding alternatives such as neutron stars. In this way, it was established that the radio source Sagittarius A*, from the center of the Milky Way galaxy, contains a supermassive black hole of approximately 4.3 million solar masses. On February 11, 2016, LIGO announced the first observation of gravitational waves that are supposed to have been generated by a black hole fusion,[30] and in December 2018, another detection of an event from gravitational waves was announced, resulted from joining a black hole with a neutron star.[31] On April 10, 2019, the first image of a black hole was captured with the help of the Event Horizon Telescope observations in 2017 of the supermassive black holes in the galactic center of Messier 87.[32]

The "no-hair" theorem states that a stable black hole has only three independent physical properties: mass, charge and angular momentum.[33] Any two black holes that have the same values for these properties cannot be distinguished according to classical (non-quantum) mechanics. These properties are visible from outside a black hole and can be measured.

The horizon of events is similar to a dissipative system that is almost analogous to that of an elastic conductive membrane with electric friction and resistance - the membrane paradigm.[34]

[30]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.

[31]LIGO Scientific Collaboration, "Detection of Gravitational Waves," 2019, https://www.ligo.org/detections.php.

[32]K. L. Bouman et al., "Computational Imaging for VLBI Image Reconstruction," in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, 913–922, https://doi.org/10.1109/CVPR.2016.105.

[33]Markus Heusler, Piotr T. Chruściel, and João Lopes Costa, "Stationary Black Holes: Uniqueness and Beyond," *Living Reviews in Relativity* 15, no. 1 (December 2012): 15 (7): 7, https://doi.org/10.12942/lrr-2012-7.

[34]Kip S. Thorne, Richard H. Price, and Douglas A. MacDonald, *Black Holes: The Membrane Paradigm*, 1986, http://adsabs.harvard.edu/abs/1986bhmp.book.....T.

There is no way to avoid losing information about the initial conditions, including quantum parameters.[35] This behavior was called the *paradox of black hole information loss*.[36]

The existence of the black holes is deduced by indirect observations, based on the gravitational interactions with its vicinity.[37]

Observing the *orbits of the stars around Sagittarius A** in the center of the Milky Way, provided strong evidence of the existence of a supermassive black hole.[38] In addition, there is some observational evidence that this cosmic body could have an event horizon, a clear feature of black holes.[39]

By preserving the angular momentum, the gas in the gravitational well of a black hole forms a disk-like structure around the object (*accretion disk*),[40] emitting electromagnetic radiation (mainly X-rays) that can be detected by telescopes. In some cases, the accretion discs may be accompanied by relativistic jets emitted along the poles, by which there is removed much of the energy. Many of the energetic phenomena of the universe are the accumulation of matter by the black holes, especially the active galactic nuclei and the quasars, considered to be the discs of

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[35]The components of a quantum field inside and outside the black hole will generally be separated, but the micro-causality implies that the inseparably degrees of freedom from the black hole cannot recombine coherently with those from the outer universe. Thus, when the black hole has completely evaporated, these separations will disappear, and the entropy of the universe will increase.

[36]Warren G. Anderson, "Black Hole Information Loss," 1996, http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/info_loss.html.

[37]NASA, "Black Holes | Science Mission Directorate," 2019, https://science.nasa.gov/astrophysics/focus-areas/black-holes.

[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): 1075–1109, https://doi.org/10.1088/0004-637X/692/2/1075.

[39]Avery E. Broderick, Abraham Loeb, and Ramesh Narayan, "The Event Horizon of Sagittarius A*," *The Astrophysical Journal* 701, no. 2 (August 20, 2009): 701(2): 1357–1366, https://doi.org/10.1088/0004-637X/701/2/1357.

[40]J. A. Marck, "Shortcut Method of Solution of Geodesic Equations for Schwarzschild Black Hole," *Classical and Quantum Gravity* 13, no. 3 (March 1, 1996): 13 (3): 393–402, https://doi.org/10.1088/0264-9381/13/3/007.

accumulation of supermassive black holes. In November 2011, the first direct observation of an accretion disk for a quasar around a supermassive black hole was reported.[41]

Binary X-ray systems emit a large part of their radiation when one of the stars picks up mass from another star, thus being able to study the existence of a black hole.[42] For this purpose, Cygnus X-1, discovered by Charles Thomas Bolton, Louise Webster and Paul Murdin in 1972, was studied, the results not being certain as the accompanying star is much heavier than the candidate black hole. Subsequently, other better candidates were found. The lack of the accretion disk of such a system is due to an accumulation mass flow dominated by advection which, if confirmed by observation, is a strong evidence for the presence of an event horizon.[43] X-ray emissions from the accretion discs sometimes behave as quasi-periodic oscillations, with frequency dependent on the mass of the compact object. This phenomenon can be used to determine the mass of the black holes.

Astronomers have observed certain galaxies, called "active", with unusual characteristics, such as unusual emission of spectral lines and very strong radio emissions.[44] They can be explained by the presence of supermassive black holes. The observational correlation between the mass of this black hole and the dispersion velocity of the host galaxy, known as the M-sigma relationship, suggests a link between the formation of the black hole and the galaxy itself.[45]

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[41]José A. Muñoz et al., "A Study of Gravitational Lens Chromaticity with the Hubble Space Telescope," *The Astrophysical Journal* 742, no. 2 (December 1, 2011): 742 (2): 67, https://doi.org/10.1088/0004-637X/742/2/67.

[42]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): 16 (12A): A3–A21, https://doi.org/10.1088/0264-9381/16/12A/301.

[43]Ramesh Narayan and Jeffrey E. McClintock, "Advection-Dominated Accretion and the Black Hole Event Horizon," *New Astronomy Reviews*, Jean-Pierre Lasota, X-ray Binaries, Accretion Disks and Compact Stars, 51, no. 10 (May 1, 2008): 51 (10–12): 733–751, https://doi.org/10.1016/j.newar.2008.03.002.

[44]Julian Henry Krolik, *Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment* (Princeton University Press, 1999).

[45]Laura Ferrarese and David Merritt, "A Fundamental Relation Between Supermassive Black Holes and Their Host Galaxies," *The Astrophysical Journal* 539, no. 1 (August 10, 2000): 539 (1): 9–12, https://doi.org/10.1086/312838.

Scientists hope that in the future they will be able to test black holes by observing the effects caused by a strong gravitational field in their vicinity, such as the gravitational lens. There are already observations about weak gravitational lenses, in which the light rays are deflected with only a few seconds, but never directly for a black hole. There are several candidates for this purpose, orbiting around Sagittarius A*.[46]

There are several *ad-hoc* conjectures that have been introduced to better explain the observations of identical astronomical black hole candidates, but with different operating mechanisms: gravastar, black star (semi-classical gravity),[47] dark energy star, etc.[48]

Cosmology, as the study of the physical universe, began as a branch of theoretical physics through the static model of Einstein's 1917 universe, later developed by Lemaître.[49] Since 1960, cosmology has been considered a branch of philosophy. The standard model of cosmology is based on extrapolations of existing theories, especially general relativity. It is based on a set of Friedman-Lemaître-Robertson-Walker (FLRW) solutions with uniform and three-dimensional symmetrical geometry with three possible curves: positive (spherical space), zero (Euclidean space), and negative (hyperbolic space).

The basic characteristics of the models that are based on the FLRW solutions, which can be considered as the hard core for the related cosmological research program, are: the models are dynamic (universe constantly changing), the rate of expansion of the universe varies according to

[46]Valerio Bozza, "Gravitational Lensing by Black Holes," *General Relativity and Gravitation* 42, no. 9 (September 1, 2010): 42 (9): 2269–2300, https://doi.org/10.1007/s10714-010-0988-2.

[47]Charles Q. Choi, "Black Hole Pretenders Could Really Be Bizarre Quantum Stars," Scientific American, 2018, https://www.scientificamerican.com/article/black-hole-pretenders-could-really-be-bizarre-quantum-stars/.

[48]Philip Ball, "Black Holes 'Do Not Exist,'" *Nature*, March 31, 2005, news050328-8, https://doi.org/10.1038/news050328-8.

[49]Lemaître, "A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extra-Galactic Nebulæ."

the different types of dominant material, and FLRW models have a uniqueness in a finite time in the past (Big Bang).

In the case of FKRW models, there are two types of observational tests for their verification: the geometry of the background space and its evolution is studied using the matter and radiation in the universe, or the mode of formation of the model structure that describes the evolution of small disturbances is studied.

The observational study of the geometry of the universe shows that it is isotropic at sufficiently large scales, according to the data resulting from the cosmic radiation of the microwave background (CMB) and from discrete sources (galaxies, etc.). The study of the model's structure formation uses a small number of parameters for observations from different periods, using temperature anisotropies in CMB and the power spectrum of matter by observing galaxies as independent constraints of these parameters, and of the background parameters.[50]

The standard cosmological model includes several periods in the evolution of the universe treated separately in experimental and observational verifications:[51]

- *Quantum gravity*: the beginning period, when quantum effects were essential in describing phenomena
- *Inflation*: a period of exponential expansion of the universe, during which pre-existing substances and radiation are rapidly diluted, and then the universe is repopulated with matter and energy by degrading the field in other areas at the end of inflation ("reheating").
- *Big Bang nucleosynthesis*: the period in which the constituents of the universe include neutrons, protons, electrons, photons and neutrinos, closely coupled in the local thermal equilibrium, and light elements appear.
- *Decoupling*: electrons become bound in stable atoms and photons decouple with matter; as the univers expand, the photons cool adiabically but retain a spectrum of the black body -

[50]Christopher Smeenk and George Ellis, "Philosophy of Cosmology," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2017 (Metaphysics Research Lab, Stanford University, 2017), https://plato.stanford.edu/archives/win2017/entries/cosmology/.

[51]Smeenk and Ellis.

background cosmic radiation that contains much information about the state of the universe at decoupling.[52]

- *Dark period*: after decoupling, the baryon matter formed from neutral hydrogen and helium coagulates into stars; Dark Age ends with the emergence of light from the stars.
- *Structure formation*: the first generation of stars is aggregated into galaxies, and galaxies into clusters; The massive stars end up in supernova explosions and spread in space heavy elements created inside them, forming the second generation of stars surrounded by planets.
- *Dark energy domination*: dark energy (or a non-zero cosmological constant) gets to dominate the expansion of the universe, leading to accelerated expansion; the expansion will continue indefinitely if the dark energy is in fact a cosmological constant.[53]

The standard cosmological model includes several free parameters, such as the abundance density of different types of matter, which can be measured in several ways with distinct theoretical hypotheses and sources of error. At present, there are large differences between the different measurement methods, and the significance and implications of these differences are still unclear.

The standard model of nucleosynthesis is confirmed by several independent evidence to eliminate isolated theoretical errors or sources of systematic errors.

Although it is the most complete, the standard cosmological model encounters three problems that imply the need for a new physics:[54] there is no complete description of the nature or dynamics of dark matter,[55] dark energy[56] and the inflationary field;[57] the formation of galaxies,[58]

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[52]P. a. R. Ade et al., "Planck 2015 Results - XX. Constraints on Inflation," *Astronomy & Astrophysics* 594 (October 1, 2016): 594: A20, https://doi.org/10.1051/0004-6361/201525898.

[53]An alternative explanation, according to string theory, is that the universe has multiple dimensions and gravity is losing gravitons moving from one dimension to another.

[54]Smeenk and Ellis, "Philosophy of Cosmology."

[55]Gianfranco Bertone, Dan Hooper, and Joseph Silk, "Particle Dark Matter: Evidence, Candidates and Constraints," *Physics Reports* 405, no. 5 (January 1, 2005): 405(5–6): 279–390, https://doi.org/10.1016/j.physrep.2004.08.031.

[56]Peebles and Ratra, "The Cosmological Constant and Dark Energy," 75(2): 559–606.

[57]David H. Lyth and Antonio Riotto, "Particle Physics Models of Inflation and the Cosmological Density Perturbation," *Physics Reports* 314, no. 1 (June 1, 1999): 314(1–2): 1–146, https://doi.org/10.1016/S0370-1573(98)00128-8.

[58]Joseph Silk, "Formation of Galaxies," The Philosophy of Cosmology, April 2017, 161–178, https://doi.org/10.1017/9781316535783.009.

and the possible refutation of the model if objects in the universe with an age greater than the determined one of the universe would be discovered, by approx. 13.7 billion years.[59]

There is a view that current cosmological evidence is not sufficient to determine which scientific theory to choose, and each theory according to a certain number of data offers quite different descriptions of the world. Duhem[60] characterized the difficulty of choosing physical theories, and Quine[61] pleaded for sub-determination. The difficulty lies in the characterization of the empirical content of the theories. Van Fraassen (1980) defines a theory as "empirically appropriate" if what is said about observable phenomena is true. In cosmology the basic characteristics of the standard model impose two fundamental limits: the finiteness of the speed of light, and the fact that the theories that can be tested by their implications for cosmology imply too much energy to be tested on Earth. (Ellis (2007))

The observational cosmology research program[62][63] shows to what extent an ideal set of observations can determine the spacetime geometry based on a minimum of cosmological hypotheses. The ideal data set involves astrophysical objects that can be used as standards for determining the properties and evolution of some sources. In practice, observers do not have access to the ideal data set, so they face challenges in understanding the nature of the sources and their evolution.

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[59]G. F. R. Ellis and J. E. Baldwin, "On the Expected Anisotropy of Radio Source Counts," *Monthly Notices of the Royal Astronomical Society* 206, no. 2 (January 1, 1984): 206(2): 377–381, https://doi.org/10.1093/mnras/206.2.377.

[60]Pierre Maurice Marie Duhem, Jules Vuillemin, and Louis de Broglie, *The Aim and Structure of Physical Theory*, trans. Philip P. Wiener, 9932nd edition (Princeton: Princeton University Press, 1991).

[61]W. V. Quine, "On the Reasons for Indeterminacy of Translation," The Journal of Philosophy, January 1, 1970, 67(6): 178–183, https://doi.org/10.2307/2023887.

[62]J. Kristian and R. K. Sachs, "Observations in Cosmology," *The Astrophysical Journal* 143 (February 1, 1966): 143: 379-399, https://doi.org/10.1086/148522.

[63]G. F. R. Ellis et al., "Ideal Observational Cosmology," *Physics Reports* 124, no. 5 (July 1, 1985): 124(5–6): 315–417, https://doi.org/10.1016/0370-1573(85)90030-4.

According to Christopher Smeenk and George Ellis, the problem in cosmology is the discrimination between models of a given theory, rather than a choice between competing theories. They give as an example the global symmetry assumed in the derivation of FLRW models. All the existing evidence is equally compatible with the models where this symmetry is not valid. One possibility would be that it be considered *a priori*, or as a precondition for cosmological theorizing.[64]Recently the justification of the FLRW models has been tried by using another weaker general principle, in conjunction with theorems related to homogeneity and isotropy. The Ehlers-Geren-Sachs theorem[65] shows that if all geodesic observers in a model where expansion is accepted determine the free-propagating background radiation is exactly isotropic, then the FLRW model is confirmed. If the causal past is "typical", the observations along our universe line will constrain what other observers can see (the Copernican principle). This principle can be tested indirectly, by verifying isotropy through the Sunyaev-Zel'dovich effect. Other tests are direct with a sufficiently good set of standards, and an indirect test based on the elapsed time of cosmological redirection. This way of working offers an empirical argument that the observed universe is well approximated by a FLRW model, thus transforming the initial philosophical hypothesis into an observationally tested basis.[66]

Soviet physicist YakovZeldovici called the early universe the "poor man's accelerator", because by observing the early universe phenomena from high energy physics can be studied. For quantum gravity, cosmology offers the only practical way to evaluate competing ideas.

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[64]Claus Beisbart, “Can We Justifiably Assume the Cosmological Principle in Order to Break Model Underdetermination in Cosmology?,” *Journal for General Philosophy of Science* 40, no. 2 (December 1, 2009): 40(2): 175–205, https://doi.org/10.1007/s10838-009-9098-9.

[65]J. Ehlers, P. Geren, and R. K. Sachs, “Isotropic Solutions of the Einstein-Liouville Equations,” *Journal of Mathematical Physics* 9, no. 9 (September 1, 1968): 9(9): 1344–1349, https://doi.org/10.1063/1.1664720.

[66]Smeenk and Ellis, “Philosophy of Cosmology.”

Currently, there are debates about the legitimacy of different research programs in cosmology. One answer is to resort to hypothetical-deductivist (HD) models: a hypothesis becomes more reliable as one of its consequences is verified, and vice versa. But the HD model has several contested aspects (it is often called "naive HD", similar to Popper's naive falsifiability). The naive view does not allow the distinction between the sub-determined rival theories that make the same predictions.[67] Scientists distinguish between theories that simply "fit in with the data," as opposed to those that accurately capture laws and evaluate some successful predictions as more revealing than others.

A more sophisticated methodology can explicitly recognize the criteria that scientists use to evaluate scientific theories,[68] which include explanatory power, and coherence with other theories, in addition to compatibility with evidence. These factors should be clear and discriminatory. Alternatively, some of the desirable characteristics may be considered as part of what constitutes an empirical success.

Monitoring of weak gravitational lenses

The phenomenon of weak gravitational lensing occurs when the light from distant galaxies is subtly distorted by the gravitational influence of foreground mass concentrations. By studying the statistical properties of these distortions, scientists can infer information about the distribution of matter and, consequently, the gravitational forces at play. Weak gravitational lensing surveys, like the Hubble Space Telescope's COSMOS survey, have become pivotal in testing gravity on cosmic scales.

[67] Vincenzo Crupi, “Confirmation,” May 30, 2013, https://plato.stanford.edu/archives/win2016/entries/confirmation/.

[68] George F R Ellis, “Issues in the Philosophy of Cosmology,” in *Philosophy of Physics*, ed. Jeremy Butterfield and John Earman, Handbook of the Philosophy of Science (Amsterdam: North-Holland, 2007), 1183–1286, https://doi.org/10.1016/B978-044451560-5/50014-2.

With the help of the Hubble Space Telescope and the Very Large Telescope, general relativity tests were performed on a galactic scale. The ESO 325-G004 galaxy acts as a strong gravitational lens, distorting light from a farther galaxy and creating an Einstein ring around its center. Comparing ESO 325-G004 mass, by measurements of the motion of the stars inside this galaxy, with the curvature of the space around it, gravity behaved according to general relativity.[69]

Weak gravitational lens studies are in its infancy. The weak lenses produce distortions in the apparent image of the size, shape and fluxes of the astrophysical object used as a cosmic lens. The study of weak gravitational lenses is a good method for GR testing, and a strong proof of the existence of dark energy and dark matter.[70]

Reyes and others measured "gravitational slip" as the difference between two different gravitational potentials that define matter disturbances. In the GR this value is zero or very small, but in other theories it is different from zero and leads to substantial differences in the power of gravitational lenses.[71]

More recently, Blake et al.,[72] performed similar GR tests on cosmological distances, using spectroscopic data and imaging. They found that the results validate the GR.

Conclusion

In addition to testing General Relativity, cosmological observations also allow scientists to explore alternative theories of gravity. Modified gravity theories, such as f(R) gravity or scalar-

[69] Thomas E. Collett et al., "A Precise Extragalactic Test of General Relativity," *Science* 360, no. 6395 (June 22, 2018): 360 (6395): 1342–1346, https://doi.org/10.1126/science.aao2469.

[70] Yong-Seon Song and Olivier Doré, "A Step towards Testing General Relativity Using Weak Gravitational Lensing and Redshift Surveys," *Journal of Cosmology and Astroparticle Physics* 2009, no. 03 (March 23, 2009): 025, https://doi.org/10.1088/1475-7516/2009/03/025.

[71] Reinabelle Reyes et al., "Confirmation of General Relativity on Large Scales from Weak Lensing and Galaxy Velocities," *Nature* 464, no. 7286 (March 2010): 464(7286: 256–258, https://doi.org/10.1038/nature08857.

[72] Chris Blake et al., "RCSLenS: Testing Gravitational Physics through the Cross-Correlation of Weak Lensing and Large-Scale Structure," *Monthly Notices of the Royal Astronomical Society* 456, no. 3 (March 1, 2016): 456(3): 2806–2828, https://doi.org/10.1093/mnras/stv2875.

tensor theories, propose modifications to Einstein's equations on cosmological scales. By comparing the predictions of these theories with observational data, researchers can discern whether these alternative gravitational frameworks better explain the observed large-scale structure and dynamics of the universe.

The phenomena in the area of the black holes question our fundamental concepts about space, time, determinism, irreversibility, information and causality. Normally, we can consider the current state of the Universe as the effect of its past and the cause of its future. Each state of the Universe is determined by a set of initial conditions and the laws of physics. Theorems apply only to mathematical objects, not to reality. The existence of solutions to some equations of physical laws does not imply physical existence, this being independent of our conceptions. The solutions of dynamic equations cannot predict all future events. General relativity implies the existence of all events represented by a manifold, so it is an ontological deterministic theory. But the impossibility of determining the horizons of black holes shows that general relativity is an example of a theory that can be determinist ontologically, but nonetheless epistemologically undetermined.[73]

Cosmological tests of gravity play a crucial role in advancing our understanding of the fundamental forces that govern the universe. Through the scrutiny of cosmic microwave background radiation, large-scale galaxy surveys, weak gravitational lensing, and the exploration of modified gravity theories, scientists are refining our comprehension of gravity on the grandest scales. As technology advances and observational capabilities improve, the cosmological tests of gravity will continue to be at the forefront of our quest to unravel the mysteries of the cosmos.

[73]Gustavo E. Romero, "Philosophical Issues of Black Holes," *ArXiv:1409.3318 [Astro-Ph, Physics:Gr-Qc, Physics:Physics]*, September 10, 2014, http://arxiv.org/abs/1409.3318.

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