WHIOCE PUBLISHING PTE. LTD.
PROVIDING FIRST-CLASS SCIENTIFIC INFORMATION FOR TOP SCHOLARS

2025 Volume 3, Issue 8
Lecture Notes in Education, Arts, Management and Social Science
ISSN(Online): 2705-053X

Challenges to Classical Empiricism by Modern Cosmology and Astronomy

Yushen Du*
UWC Atlantic, St Donat's Castle, Llantwit Major, CF61 1WF, Wales, United Kingdom

***Corresponding author:** *Yushen Du, duyushen07@gmail.com*

Abstract: This paper explores the clashes between classical empiricism and modern cosmology, focusing on the epistemological challenges posed by the study of dark matter. Classical empiricism states that the production of knowledge relies on direct sensory experiences, including observations and experiments. It features testability, repeatability, and falsifiability, as argued by Locke, Hume, and later by Popper. However, contemporary astronomy and cosmology are increasingly dependent on indirect observations and mathematical modelling and simulations. Dark matter and dark energy, constituting around 95% of the total mass-energy of the universe, epitomizes the tension between classical empiricism and progressing cosmology. Dark matter's existence could be inferred from its gravitational effects on the surroundings and anomaly in galactic rotational curves, despite its invisibility. This paper argues that such evidence by essence satisfies the empiricist view of scientific inquiry. The synthetic analysis concludes that modern cosmology reveals the refinement of traditional empiricism in real-life practices, transcending sensory experiences through technological advancement and logical inference. Hence, the boundaries of empirical evidence have been extended in the philosophy of science.

Keywords: Philosophy of science; Cosmology and astronomy; Dark matter; Empiricism; Contemporary science

Online publication: September 26, 2025

1. Introduction

Empiricism, as a philosophical concept in epistemology, basically states that the production of knowledge should be based on observation and experience. According to the writings of philosophers like David Hume, John Locke, and Francis Bacon, empiricism focuses on the idea that scientific assertions are measurable, testable, and based on sensory perception [1,2]. These scientific theories are validated by the correspondence of the theories to observable phenomena, to the extent that the repeated results of experiments will verify the truthfulness of the predictions by these theories. In natural science, empiricism has historically been used to define what is considered a truly scientific investigation and the difference between scientific knowledge and speculation or metaphysical conjecture.

Modern astronomy and cosmology, which attempt to unravel the mystery of the universe, its origin, and structure, stem from the combination of empirical observations and theoretical modelling. For example, N-body simulation can be exceedingly useful in modelling dark matter particles which researchers couldn't observe directly [3,4]. Dark matter, an intriguing topic in modern cosmology, occupies 80% of the matter in the universe, but cannot be observed directly [5].

Unlike the studies of stars and galaxies, where we could probe into their luminosities and motions, those of dark matter particles are rather mysteriously indirect, through the gravitational lensing effect and rotational curves [6,7]. The quest into dark matter casts a profound doubt regarding the nature of science, especially the criteria outlined by the empirical views in the philosophy of science, whether pure inference and mathematical modelling would be reliable enough for science.

This paper discusses how modern astronomy and cosmology have been connected to empiricism. In particular, it will address the question whether the study of dark matter meets the empirical criteria of scientific knowledge or it questions the traditional limits of empirical science. The paper will examine the extent to which the field of cosmology can be called scientific in the empiricist use of the term by exploring the role of observation, inference and theoretical modelling in this field. This inquiry will not only point out the strengths and weaknesses of the current cosmology but it will also give a bigger picture of the changing nature of the scientific inquiry.

2. Empiricism in science

Empiricism states that the production of knowledge mainly derives from sensory experiences. According to this perspective, humans acquire knowledge via direct interaction and observations of the world around them through their senses. Empiricists, such as John Locke, George Berkeley, and David Hume, who are foundational to the development of empiricism, would argue that all meaningful knowledge must feature perceivable, observable, or measurable in any means [8,9]. Sensory experiences mainly include all types of raw input from the external world to the human brains. Empiricism as a philosophical view has been the core underlying the development of modern science. Loads of experiments and observations that consolidate theoretical assumptions are essential to the progression of modern science in terms of the affirmation of hypotheses and the inductive nature of scientific research.

We here examine the core philosophers who laid the cornerstone of empiricism in the philosophy of science. In John Locke's infamous work, "An Essay Concerning Human Understanding," empiricism finds its cornerstone established by the great philosopher. Locke asserted that knowledge is not innate due to its nature. He also argues that the human mind is a "tabula rasa" (blank slate) innately, so that sensory experiences could produce knowledge upon the blank slate. This implies that the entirety of human knowledge depends on personal experiences that input external sensory data into our brain, and without such input, no knowledge would be produced. The idea places sensory experiences as the very centrality of the acquisition of knowledge, inquired by interpretation of observable phenomena [9]. At the same time, another important empiricist philosopher, David Hume, further developed empiricism in his work "A Treatise of Human Nature," by skeptically examining this philosophical ideology. He mainly casts doubt on the validity of inductive reasoning. Induction refers to the method of reasoning that moves from particular instances to general principles, the foundation of scientific methods. Hume instead questions that scientific knowledge is not produced directly from experience, but inferred based on habitual patterns of observations. This skepticism, discussing the limitations of empirical knowledge, laid the cornerstone for future philosophical conversations regarding the nature of scientific theories and knowledge [10].

Empiricism in philosophy of science is characterized by three main principles: testability, repeatability, and falsifiability. For a knowledge claim to be qualified as scientific, there must be direct observation or experiment that could test the theory. At the same time, scientific knowledge should be repeatable across spacetime, meaning that under different contexts, scientists are able to deduce the exact same results using the same methods. Karl Popper emphasized that a scientific theory is only falsifiable rather than provable due to the inductive nature of scientific methods [2]. Falsifiability lies in the very core of all scientific theories. Within the scientific method determines the way in which science produces knowledge, as it presupposes the process from hypotheses, controlled experiments, to the analysis of data that makes a conclusion. This methodology is proved to be remarkably effective in various natural sciences, like physics and chemistry, in terms of discovering patterns and principles in nature. For instance, Newtonian mechanics is based on the correlations between measurable parameters, including velocity, mass and forces, etc. These quantities can be experimented and measured physically in the real world, hence counted as solid pieces of empirical evidence. In empiricist ideology, science can be only considered correct and solid, when based on observable phenomena and able to be tested through repeatable experiments or experiences across spacetime. This method enables the testability, repeatability, and falsifiability of the scientific knowledge that is derived from sensory experiences.

Criticism about empiricism will be discussed, despite its eminent status in the philosophy of science. Karl Popper was one of the greatest philosophers of science in the 20th century who revolutionized people's understanding of empiricism. He stated that the validation of scientific theories through observable experiences by no means correlate to the correctness of the theories, but rather, the falsifiability more directly relates to the solidity of the proposed ideas. Only if the theory is falsifiable could it be considered correct and solid through scientific experiments or observations. This has shifted the stress on the nature of scientific research from the testification to the falsification of the existing theories [2].

As Popper stated, one of the weaknesses of traditional empiricism is that not all scientific theories can be tested through direct sensory experiences or experiments. For instance, quantum entanglement and dark matter, two of the most significant phenomena in modern cosmology and quantum mechanics, could not be observed or detected directly in the usual senses of observations or experiments. This has challenged the empiricist view of science since it indicates that the customary definition of observations and testing does not apply to all aspects of scientific knowledge which is by no means invalid in modern physics. Another criticism stemmed from the problems with scientific theoretical models. In modern physics and cosmology, the construction of abstract mathematical models, which generate predictions unmeasurable and untestable in conventional means, including the behaviors of subatomic particles and structures of dark matter particles. Although these theories are based on empirical evidence, they cannot be empirically verified. Hence, it casts doubt on empiricism which asserts that the production of knowledge should be constructed on observable phenomena. The emphasis on sensory experiences and observations in empiricism is undoubtedly the core of modern science. But on the other hand, in modern physics, especially in quantum physics and cosmology, where observations are limited to instruments, we have to question the confines of our empirical sciences. These domains normally describe unobservable phenomena via abstract models, simulations, and mathematical equations, which are intangible. To illustrate, in dark matter studies, scientists use the N-body simulations without direct detection as a gravity-only simulation to simulate and predict the motion of dark matter particles, which presumably only interact with each other via gravity [3]. This is an indirect form of scientific inquiry and collection of evidence. It poses a question to all of us whether these phenomena should be deemed scientific under the traditional criteria of empiricism.

In conclusion, despite that empiricism is the cornerstone of scientific inquiry, the modern application in fields such as cosmology and quantum physics forces us to reexamine the definition of scientific knowledge and empirical evidence. As modern science progresses, we might need to extend the definitions of these terminologies in philosophy of science to reflect on those complex theories and phenomena that could not be detected through direct sensory observations [2].

3. Modern astrophysics

Modern astrophysics and cosmology can trace back to ancient astrology and sciences of the heavens, but these disciplines did not become empirical until the scientific evolution in the 16th and 17th centuries. From the geocentric to the heliocentric, the model of the universe has transformed dramatically, a historic event in astronomy, while Copernicus and Galileo pushed the development of modern astrophysics. Furthermore, Issac Newton developed universal gravitation in the 17th century. In the 20th century, the introduction of the Big Bang theory marked that modern astrophysics stepped into a new era, probing into the evolution of the universe through dark matter and dark energy [11,12,15].

3.1. Historical overviews

In ancient times, astronomers observed stars and planets using their naked eyes and proposed models that explained their motions. The Greek suggested the geocentric model, in which the Earth is at the center of the universe. It became the most prevalent theory during the millennium. However, in the 16th century, Copernicus proposed the hypothesis that the Earth and other planets orbit around the Sun, which challenged the original model. Galileo later demonstrated the heliocentric model and provided empirical evidence using his telescope, disapproving of the geocentric model. Copernicus further refined Kepler's theory, which supplemented the laws of planetary motions. These laws explained the elliptical orbits of planets around the Sun with mathematical approaches. These discoveries constitute the concrete basis on which Isaac Newton then developed the Newtonian laws of motion and universal gravitation. These laws mathematically describe the interaction between celestial bodies. At the end of the 17th century, Newton illustrated that the laws that govern the motion on Earth also govern the motion in space, which connected the terrestrial and celestial mechanics. In the 20th century, general relativity by Einstein attributed gravity to the curvature of space and time, revolutionizing cosmology. Edwin Hubble's theory of the expansion of the universe combined with relativity, eventually formed the Big Bang theory [11]. Big Bang theory states that the universe was initially a singularity, expanding in acceleration afterwards. Although these theories were based on empirical observations, they brought new ideas for theoretical physics, extending the boundaries of traditional empiricism. Modern astronomy heavily relies on observations, but as technology progresses, means of observations are transformed. With more advanced telescopes, astronomers are able to observe distant galaxies, nebulae and other phenomena at the edge of the universe. Technological tools like the Hubble Space Telescope are utilized to acquire images of galaxies billions of lightyears away from us, for us to understand the structure and evolution of the universe. The introduction of radio telescopes, infrared, and X-ray observatories has increased our capabilities to see the universe at the electromagnetic spectrum and observe phenomena that are invisible to the naked eye. The most significant discovery in the 20th century in cosmology is the Cosmological Microwave Background radiation (CMB). CMB is the faint remains of the Big Bang, which provides solid evidential support for the Big Bang theory. With tools like the Planck satellite, astronomers mapped out CMB in detail, forming an image for the early universe. These observations form some of the most obvious pieces of empirical evidence of the origins of the universe, but they are indirect [12,15].

Although cosmology is mainly observational science, it also relies on theoretical models. One of the theories is the Big Bang. It was established from the mathematical equations combining general relativity and observational evidence, including the redshifts of distant galaxies. Scientists utilize these models to predict the behaviors of the universe, such as the CMB, galaxy distribution, and the accelerating expansion of the universe [11].

In the past decades, dark matter and dark energy have been lying in the core of cosmology. Nonetheless, the properties of this invisible matter and energy are inferred from their gravitational impacts on visible matter. For example, dark matter, approximately occupying 27% of the total mass-energy, neither glows nor absorbs or reflects light [5]. Its existence was confirmed by the flattened rotation curves of galaxies and the gravitational lensing effect of massive celestial bodies [6,7,13,14]. Similarly, dark energy is believed to explain the acceleration in the expansion of the universe. It is an imagined form of energy in the universe that has not been measured directly. Despite their invisibility, they play a central role in the modern cosmological knowledge system. Theories confirmed their existence, and the search for empirical evidence is in progress. Empirical experiments and observations (e.g. those done by the Large Hadron Colliders and Space Stations) still continuously push our knowledge boundaries, seeking dark matter particles and more precisely measuring their effects [15–17].

Currently, most research in cosmology is grounded in advanced mathematical models and computer simulations. Through these simulations, scientists can study the dynamics of the large-scale structures in the universe, including clusters and supernovae. They are also used to verify the predictions of cosmological models. These simulations, constructed on verified physical laws and existing empirical evidence, cope with phenomena that could not be detected directly. The formation and evolution of the galaxies would be the perfect example. Scientists use supercomputers to model galaxy formation and evolution, considering the effect of gravity, dark matter, and gas components. These simulations provide us with the general situation of the universe, but they are indirect and dependent on the correctness of the assumptions.

3.2. Dark matter

Dark matter, as our case study, is one of the most interesting and mysterious concepts. Although it cannot be detected electromagnetically, its existence can be deduced by its gravitational effect on visible matter. In estimation, dark matter is approximately 27% of the mass-energy of the entire universe, far outweighing that of visible matter, which is around 5%. Due to its difficulty to detect, it provides us with a perfect example to examine whether modern astronomy and cosmology satisfy the requirements of empiricism according to the empiricist view in the philosophy of science, which emphasizes observable and testable sensory experiences.

The initial strong evidence of dark matter originated from the observation of flattening rotational curves of the galaxies. In the 1970s, Vera Rubin and Kent Ford analyzed the rotational velocities of stars in spiral galaxies and discovered astonishing disparities [7,14]. According to Newtonian mechanics, stars located at the edge of the galaxy should rotate far more slowly than those at the core of the galaxy, as rotational velocity is indirectly proportional to the radius of rotation. However, Rubin's measurements showcased that the rotational velocities of outer stars have comparable values with those of inner stars at the center of the galaxy. This further implies the extended clusters of unseen masses must be placed at the outskirts of the galaxy which results in the phenomenon. The observations provide the first empirical evidence that a large portion of the mass content in the universe is invisible and undetectable.

The gravitational lensing effect is another evidence of great importance, predicted by general relativity. When the light from a distant object travels near a massive body, which bends spacetime, the direction of light would be curved, so that the image we receive from that distant object would be distorted in shape and position. The studies of giant clusters, including the Bullet Cluster, showcased the inconsistency between gravitational lensing with visible matter distribution. The discrepancy strongly suggests the existence of a massive, invisible cluster of matter—dark matter, which controls the gravitational potential wells of galaxies. Gravitational lensing effect provides indirect but powerful evidence for dark matter existence to its obvious impact on the motion of light and matter on the large scale.

Other evidence stems from the detection of Cosmic Microwave Background (CMB) radiation, the relic radiation from the Big Bang. According to measurements by missions like WMAP and the Planck satellites, the early universe mainly consists of dark matter. This matter plays an indispensable role in the formation of galaxies and large-scale structures. The fluctuation in CMB attributed to nothing but dark matter in the Standard Model, which further confirms its existence.

Although much indirect evidence has been presented, dark matter particles have never been observed directly. There are many models proposed to explain its properties. One of the candidates is Weakly Interacting Massive Particles (WIMPs). WIMPs are considered to interact via weak forces and gravitation rather than electromagnetic forces, which accounts for their invisibility. Other hypotheses include axions, ultralight particles, and sterile neutrinos, which only interact with each other gravitationally, through weak forces in rare cases. These models enable predictions in particle physics experiments, including those done with the Large Hadron Colliders and deep underground detectors which aim to detect rare interactions between particles with the least disturbance and noises. However, none of the definitive detections have been done so far, which shows how hard it is to prove the existence of the dark matter empirically.

4. Challenge to empiricism

The fact that dark matter cannot be observed directly poses a challenge to empiricism. Empiricism emphasizes knowledge based on sensory experiences, measurable phenomena, and repeatable experiments. But dark matter can be only confirmed by its gravitational effects rather than direct observations. Despite that gravity is measurable, the cause of these phenomena is invisible. Hence, dark matter challenges the boundary of empiricist criteria of production of scientific knowledge: When something cannot be perceived directly, but its impact can be measured, whether it is acceptable scientifically?

This becomes complex for the use of theories and computational models. Cosmologists use advanced simulative technology to simulate the formation and evolution of galaxies, considering the impact of dark matter. These simulations are guided by observations, including rotation curves of galaxies and cosmic microwave background radiation, but the conclusions are entirely based on the assumption of dark matter properties. Although these predictions made by theories align with the empirical observations, they rely on the validity of the theoretical framework implemented.

The other challenge is grounded in the possibilities of other explanations. For example, an alternative theory for dark matter, Modified Newtonian Dynamics (MOND), believes that the anomaly in galactic rotational curves is caused by a variation in Newtonian gravity rather than invisible clusters of mass. Although MOND could explain rotation patterns in galaxies without dark matter, it encounters difficulty in the gravitational lensing effect and large-scale structures of the universe. The existence of multiple but reasonable alternatives to the existence of dark matter highlights the ambiguity in classifying dark matter as a completely empirically proven physical quantity. That being said, the importance of dark matter in cosmological studies still firmly holds, because the assumption has been consistent across different independent observations. Rotation data, gravitational lensing, and CMB support the existence of dark matter convergently, even without direct sensory data verification. From empiricist point of view, the usage of indirect evidence makes it hard to classify it as science, since traditional empiricism emphasizes phenomena that can be directly perceived and experimented with. However, the consistency shown across different measuring systems with repeatable results could be very solid and powerful, despite pushing the limits of traditional empiricism in science [5,6,13,18].

The study of dark matter evokes a significant philosophical problem regarding the essence of scientific evidence and the scope of empirical studies. It questions the opinion that science is confined to phenomena observable by human perceptions or measurable by instruments. Conversely, it proposes that science can expand its evidential criteria to cover those invisible phenomena whose impact could be measured. This approach can be seen in many fields of modern physics, such as quantum mechanics and cosmology, in which indirect measurements, simulations, and mathematical models are important in the testing of theories.

Challenges to empiricism regarding dark matter reveal a shift in scientific procedure. Though empiricism is the foundation, contemporary science increasingly depends on inferential and model-driven methods. These approaches correspond to a wider scope of what should be considered as evidence. In this regard, dark matter epitomizes the clash between classical empiricism and modern scientific practices, because it demonstrates the need for flexibility in philosophical explanations when distinguishing what could be considered as scientific knowledge. Besides, the utilization of statistics and big data is not a flaw in the cosmological empirical basis. Instead, it is the complex expression attempting to describe the phenomenon. Due to the tremendous scale of time and space on cosmology, direct experiments are not feasible, while observations play a central role. The empirical basis does not stem from direct sensory interactions, but rather from a systematic compilation and explanation of quantifiable information in multiple independent areas [5,19].

The empirical study of the universe makes philosophers of science reexamine the definition of "empiricism." Classical empiricism regards observations as equivalent to sensory experiences, but modern science uses technology as a medium to extend scope of observation. According to cosmological opinion, equipment is the epistemic magnifier which allows humans to see objects further than naked eyes. Admittedly, in this progressing empiricism, we can observe without directly contacting the phenomena but inferring from indirect evidence, like the Doppler shifts of galaxies or even the weak microwave background, which communicates actual information about things that are not visible to the naked eye [5,11,12].

Therefore, contemporary astronomy and cosmology can be regarded as sciences that transcend empirical methods, these fields push the empirical approach to its classical limits while not forgetting the underlying principles. They also adhere to empirical verification, reproducibility, and predictive accuracy, although the objects of study themselves may not be directly accessible. This reform of empiricism has brought science into closer contact with the facts in modern research, where mathematical modelling, statistical inference, and indirect detection are key factors. After all, the flexibility of the scientific method has been demonstrated in modern astronomy and cosmology. They show that science is not dogmatic but a dynamic exploration that continuously expands its epistemological boundaries with the advancement of technology and theory. Although strict positivists might say that concepts such as dark matter or dark energy, which are unobservable, might challenge the empirical basis of science, when the positivist perspective is interpreted in a broader way, including indirect observation and inference methods as well as successful predictions, cosmology can still meet the basic requirements of scientific inquiry.

Cosmological theories are not just guesses: they are limited by observations, strengthened by successful predictions, and constantly subject to new tests. Although this theory cannot be directly observed, the ability to propose coherent, testable, and unified explanations makes it still significant in the scientific field. Therefore, although contemporary cosmology does not conform to the orthodox positivist ideology of science, it is an example of a dynamic and progressive positivism, this positivism is aware of the limitations of human perception, but does not lose the positivist spirit of exploration.

5. Conclusion

The question of whether modern astronomy and cosmology, especially the study of dark matter, conform to the requirements of the empiricist scientific view indicates a profound conflict between traditional philosophy and modern scientific practice. The classical empiricism advocated by philosophers such as Locke and Hume holds that knowledge should be based on direct sensory experiences and repeatable observations. However, the success of modern cosmology is built on theoretical construction and evidence far beyond the scope of human senses. This does not mean that cosmology has abandoned empiricism; rather, it merely indicates that the ideal of empiricism has evolved to adapt to the scale and abstraction of contemporary science.

The study of dark matter is an intuitive manifestation of this change. Although dark matter has not been directly observed, its gravitational influence on visible matter, as well as its ability to produce gravitational lensing effects and cosmic microwave background radiation, provide solid and multifaceted empirical support. The situation presented by these indirect pieces of evidence combined together is a typical example of the operation mode of modern science: it is not achieved through immediate sensory confirmation but through the systemization of reasoning based on measurable phenomena. In this sense, cosmology is empirically real in spirit, although its operational procedures may exceed the scope envisioned by early empiricists. Furthermore, with the advancement of technology, the concept of scientific inquiry is also constantly strengthening. Radio telescopes, particle detectors, and gravitational wave observatories are just one of the extensions of human perception, helping scientists collect evidence related to phenomena that were previously inaccessible. These technologies do not violate empiricism but redefine it, indicating that observation can be conducted through an indirect and instrumental experience rather than relying solely on direct perception. Modern astronomy and cosmology can be regarded as science in a philosophical sense because they meet the basic requirements of empirical inquiry, namely observation, prediction, and falsifiability, but do not ignore the limitations of direct observation. They can be regarded as an example of what can be called “empiricism beyond experience”: this is a scientific methodology that integrates an internalized and self-correcting system.

In conclusion, through the exploration of phenomena such as dark matter, empiricism in cosmology reveals a deeper fact about science, that it is not stagnant but a process of continuous advancement. The universe enables science to adapt to it, thereby expanding the scope of what is considered empirical. Therefore, modern astronomy and cosmology not only confirm the validity of its science but also demonstrate the long-term flexibility of the empiricist tradition.

Disclosure statement

The author declares no conflict of interest.

References

[1] Hume D, Millican P, 2007, An Enquiry Concerning Human Understanding. Oxford University Press, Oxford.

[2] Popper K, 2008, The Logic of Scientific Discovery. Routledge, London.

[3] Bagla JS, 2004, Cosmological N-Body Simulation: Techniques, Scope and Status. arXiv, 1–14

[4] Springel V, White S, Jenkins A, et al., 2005, Simulations of the Formation, Evolution and Clustering of Galaxies and Quasars. Nature, 435: 629–636.

[5] Planck Collaboration, Aghanim N, Akrami Y, et al., 2020, Planck 2018 Results. VI. Cosmological Parameters. Astronomy & Astrophysics, 641: A6.

[6] Clowe D, Bradac M, Gonzalez A, et al., 2006, A Direct Empirical Proof of the Existence of Dark Matter. The Astrophysical Journal, 648(2): L109–L113.

[7] Rubin V, Ford W, 1970, Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions. The Astrophysical Journal, 159: 379.

[8] Berkeley G, 1710, A Treatise Concerning the Principles of Human Knowledge. Publisher Unknown, London.

[9] Locke J, 1690, An Essay Concerning Human Understanding, visited on June 30, 2025, http://archive.org/details/in.ernet.dli.2015.236542

[10] Hume D, 1739, A Treatise of Human Nature. David Hume, London.

[11] Hubble E, 1929, A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae. Proceedings of the National Academy of Sciences, 15(3): 168–173.

[12] Penzias A, Wilson R, 1965, A Measurement of Excess Antenna Temperature at 4080 Mc/s. The Astrophysical Journal, 142: 419–421.

[13] Bartelmann M, Schneider P, 2001, Weak Gravitational Lensing. Physics Reports, 340(4–5): 291–472.

[14] Rubin V, Thonnard N, Ford W, 1980, Rotational Properties of 21 SC Galaxies with a Large Range of Luminosities and Radii, from NGC 4605 (R = 4 kpc) to UGC 2885 (R = 122 kpc). The Astrophysical Journal, 238: 471.

[15] Akerib D, Alsum S, Araújo H, et al., 2017, Results from a Search for Dark Matter in the Complete LUX Exposure. Physical Review Letters, 118(2): 021303.

[16] Aprile E, Aalbers J, Agostini F, et al., 2018, Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T. Physical Review Letters, 121(11): 111302.

[17] Cui X, Abdukerim A, Chen W, et al., 2017, Dark Matter Results from 54-Ton-Day Exposure of PandaX-II Experiment. Physical Review Letters, 119(18): 181302.

[18] Famaey B, McGaugh S, 2012, Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions. Living Reviews in Relativity, 15(1): 10.

[19] Bertone G, Hooper D, 2018, A History of Dark Matter. Reviews of Modern Physics, 90(4): 045002.