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Unraveling the Mysteries of the Cosmos: A Comprehensive Review of Dark Matter and Dark Energy Theories

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Abstract: ***The composition of our universe presents one of the most profound enigmas in modern cosmology. Current evidence suggests that ordinary baryonic matter—the substance of stars, planets, and all visible cosmic structures—constitutes a mere 5% of the universe's total content. The remaining 95% comprises two elusive components: dark matter (~27%) and dark energy (~68%). Despite their dominance in cosmic composition, these "dark" components remain largely mysterious, detectable primarily through their gravitational effects. This comprehensive review synthesizes contemporary understanding of dark matter and dark energy, examining observational evidence, theoretical frameworks, and the intricate relationship between these cosmic components. By analyzing galactic rotation curves, gravitational lensing, cosmic microwave background measurements, and large-scale structure formation, we illuminate the compelling case for dark matter's existence. Similarly, we evaluate evidence for dark energy through type Ia supernovae observations, baryon acoustic oscillations, and cosmic expansion measurements. The review concludes by addressing unresolved questions, ongoing experimental efforts, and future research directions aimed at illuminating these cosmic shadows that shape our universe's past, present, and future evolution.***

Keywords: dark matter, dark energy, cosmology, gravitational lensing, cosmic microwave background, large-scale structure, galactic rotation curves, accelerating universe

1. Introduction

The standard cosmological model describes a universe composed predominantly of components that cannot be observed directly through electromagnetic radiation. This presents a profound contradiction: the cosmos is dominated by entities that remain invisible to our most sophisticated telescopes and detectors. Current measurements indicate that ordinary baryonic matter—the substance of stars, galaxies, and all visible cosmic structures—constitutes merely 5% of the universe's total energy-mass content [1]. The remaining 95% consists of two mysterious components: dark matter (~27%) and dark energy (~68%) [2]. Dark matter, despite its substantial contribution to the universe's mass composition, does not interact with electromagnetic forces, rendering it invisible through conventional observational techniques. Its presence is inferred primarily through gravitational effects on visible matter, particularly in galactic rotation curves and gravitational lensing observations [3]. Meanwhile, dark energy manifests as a pervasive force driving the accelerated expansion of the universe, counteracting the gravitational attraction between cosmic structures [4]. The nature of these cosmic components presents fundamental challenges to our understanding of physics. Dark matter may consist of as-yet-undiscovered particles beyond the Standard Model of particle physics, while dark energy might represent a property of space itself or indicate modifications needed to Einstein's theory of general relativity [5]. These questions have profound implications for fundamental physics, placing dark matter and dark energy at the frontier of contemporary cosmological research. This review paper synthesizes current knowledge regarding dark matter and dark energy, examining their observational evidence, theoretical frameworks, and the ongoing scientific efforts to understand their fundamental nature. We analyze the historical development of these concepts, evaluate competing theoretical models, and discuss future research directions aimed at resolving these cosmic mysteries.

2. Dark Matter: Observational Evidence and Theoretical Models

2.1 Historical Development

The concept of dark matter originated from early astronomical observations that revealed discrepancies between visible mass and gravitational effects. In 1933, Fritz Zwicky studied the Coma Cluster and discovered that the dynamical mass of the cluster, deduced from galaxy motions, exceeded the luminous mass by approximately two orders of magnitude [6]. This observation suggested the presence of "missing mass" or what Zwicky termed "dunkle Materie" (dark matter). For decades, Zwicky's observations remained a curiosity until the 1970s, when Vera Rubin and colleagues conducted pioneering studies of galactic rotation curves. Their observations demonstrated that stars at the outer regions of spiral galaxies orbit at velocities significantly higher than predicted based on visible matter alone [7]. These flat rotation curves provided compelling evidence for an extensive dark matter halo surrounding galaxies—a finding that would fundamentally alter our understanding of cosmic composition.

2.2 Observational Evidence

2.2.1 Galactic Rotation Curves

The motion of stars and gas within galaxies provides one of the most compelling lines of evidence for dark matter. According to Newtonian dynamics, objects farther from the galactic center should exhibit decreased orbital velocities, following a Keplerian decline where velocity decreases with the square root of radius. However, observations consistently reveal that rotation curves remain approximately flat at large radii, indicating that the enclosed mass increases linearly with distance from the galactic center [8]. This phenomenon, initially documented by Rubin and colleagues, has been confirmed across numerous spiral galaxies. The observations suggest the presence of an extensive dark matter halo that extends well beyond the visible disk and dominates the mass at large radii. Additionally, Bosma's studies of neutral hydrogen distribution in galaxies provided complementary evidence through 21-cm line observations, further strengthening the case for dark matter [9].

2.2.2 Gravitational Lensing

Einstein's theory of general relativity predicts that mass curves spacetime, causing light to bend as it passes through this curved geometry. Gravitational lensing—the bending of light by massive objects—provides a powerful tool for mapping mass distributions independent of their luminosity. Strong gravitational lensing occurs when a massive foreground object creates multiple images or arcs of background light sources. Weak lensing manifests as subtle distortions in the shapes of background galaxies. By analyzing these distortions, astronomers can reconstruct the distribution of mass, including dark matter [10]. Gravitational lensing studies consistently reveal that the total mass exceeds the visible mass in galaxies and clusters, providing compelling evidence for dark matter's existence.

2.2.3 The Bullet Cluster

The Bullet Cluster (1E 0657-56) offers what many consider direct empirical proof for dark matter's existence. This system consists of two colliding galaxy clusters, where the hot gas (constituting most of the ordinary matter) interacts during the collision and slows down, emitting X-rays. However, gravitational lensing observations reveal that most of the mass passed through the collision unimpeded, separating from the gas [11]. This spatial separation between the centers of total mass (determined through gravitational lensing) and the centers of baryonic mass (visible in X-ray emissions) strongly supports the dark matter hypothesis. The observations, led by Douglas Clowe and colleagues, have proven particularly challenging to explain through modified gravity theories alone, making the Bullet Cluster a cornerstone in the case for dark matter [12].

2.2.4 Cosmic Microwave Background (CMB)

The cosmic microwave background radiation—the afterglow of the early universe— contains minute temperature fluctuations that encode valuable information about cosmic composition. Precise measurements from missions like Planck have mapped these anisotropies with unprecedented accuracy, allowing cosmologists to determine the relative contributions of different cosmic components [13]. Analysis of the CMB power spectrum—which characterizes the statistical properties of these temperature fluctuations—provides strong constraints on cosmological parameters, including the density of baryonic and dark matter. The observed pattern of acoustic peaks in the power spectrum aligns remarkably well with models incorporating dark matter, further supporting its existence [14].

2.2.5 Large-Scale Structure Formation

Observations of the universe's large-scale structure—the cosmic web of galaxy clusters, filaments, and voids—provide additional evidence for dark matter. Computer simulations demonstrate that without dark matter, the universe would not have developed the observed complex structures within the available time since the Big Bang [15]. Dark matter's gravitational influence accelerated structure formation, allowing density fluctuations to grow sufficiently to form the cosmic web we observe today. The distribution of galaxies and clusters, mapped by surveys like the Sloan Digital Sky Survey (SDSS), closely matches predictions from cosmological models incorporating dark matter [16].

2.3 Theoretical Models and Candidates

2.3.1 Cold Dark Matter (CDM)

The Cold Dark Matter paradigm proposes that dark matter consists of slow-moving, massive particles that interacted minimally with ordinary matter in the early universe. This model successfully explains large-scale structure formation and aligns with CMB observations [17]. Within the CDM framework, several candidate particles have been proposed: **Weakly Interacting Massive Particles (WIMPs):** WIMPs represent hypothetical particles with masses ranging from GeV to TeV scales that interact via the weak nuclear force and gravity. Their appeal lies in the "WIMP miracle"—the observation that particles with weak scale interactions would naturally produce the observed dark matter abundance through thermal production in the early universe [18]. **Axions:** Originally proposed to resolve the strong CP problem in quantum chromodynamics, axions emerged as viable dark matter candidates due to their predicted properties. Unlike WIMPs, axions would be very light particles (μeV to meV range) produced non-thermally in the early universe through mechanisms like vacuum realignment [19].

Sterile Neutrinos: These hypothetical particles would be similar to standard neutrinos but would not participate in weak interactions, interacting primarily through gravity. With masses potentially in the keV range, sterile neutrinos could constitute warm dark matter, exhibiting properties intermediate between hot and cold dark matter [20].

2.3.2 Massive Compact Halo Objects (MACHOs)

An alternative hypothesis suggested that dark matter might consist of ordinary matter in non-luminous forms, such as black holes, neutron stars, brown dwarfs, or unassociated planets—collectively termed Massive Compact Halo Objects (MACHOs). However, extensive microlensing surveys have largely ruled out MACHOs as the primary component of dark matter [21].

2.3.3 Modified Gravity Theories

Some researchers have proposed that apparent dark matter effects might instead indicate modifications needed to our understanding of gravity at galactic and cosmological scales. Theories such as Modified Newtonian Dynamics (MOND) and its relativistic extensions posit that gravitational laws change at low accelerations, potentially explaining phenomena like flat rotation curves without invoking dark matter [22]. However, observations like those of the Bullet

Cluster pose significant challenges to modified gravity theories, as they would need to explain the observed separation between gravitational lensing and X-ray-emitting gas. While not entirely ruled out, modified gravity theories generally struggle to explain the full range of observations that dark matter models address cohesively.

3. Dark Energy: Accelerating the Universe

3.1 Discovery and Historical Context

The concept of dark energy emerged relatively recently compared to dark matter. Although Einstein's equations of general relativity initially included a "cosmological constant" (Λ) to maintain a static universe, he later abandoned this term after Hubble's discovery of cosmic expansion. However, the cosmological constant would experience a remarkable revival in the late 1990s. In 1998, two independent research teams—the Supernova Cosmology Project led by Saul Perlmutter and the High-z Supernova Search Team led by Adam Riess and Brian Schmidt— made the groundbreaking discovery that the universe's expansion is accelerating, not slowing as previously expected [23, 24]. This unexpected finding, which earned the 2011 Nobel Prize in Physics, necessitated the existence of a previously unknown energy component with negative pressure, subsequently termed "dark energy."

3.2 Observational Evidence

3.2.1 Type Ia Supernovae

Type Ia supernovae serve as "standardizable candles" due to their remarkably consistent intrinsic luminosities. By measuring their apparent brightness and redshift, astronomers can construct a cosmic distance ladder and map the universe's expansion history. The original evidence for cosmic acceleration came from observations showing that distant supernovae appear dimmer (and thus farther away) than expected in a universe with only matter and radiation [25]. These observations indicate that the universe's expansion rate has been increasing rather than decreasing over time—a finding directly contrary to expectations in a matter dominated universe where gravity should slow expansion. The supernovae data strongly favor a universe containing a substantial dark energy component [26].

3.2.2 Cosmic Microwave Background (CMB)

The CMB provides crucial evidence not only for dark matter but also for dark energy. Analysis of the CMB power spectrum indicates that the universe's geometry is nearly flat, implying a total energy density close to the critical density. However, measurements of matter density (including dark matter) account for only about 30% of this critical density, suggesting the presence of an additional component—dark energy—making up the remainder [27]. Furthermore, the CMB contains an imprint of baryon acoustic oscillations (BAO)—pressure waves that propagated through the early universe's plasma before recombination. The characteristic scale of these oscillations serves as a "standard ruler" that can be used to measure the universe's expansion history [28].

3.2.3 Baryon Acoustic Oscillations (BAO)

BAO manifest as subtle periodic fluctuations in the distribution of galaxies, representing a preferred separation scale imprinted by acoustic waves in the early universe. This characteristic scale, approximately 500 million light-years in today's universe, serves as a standard ruler for measuring cosmic expansion across different epochs [29]. Large galaxy surveys like the Sloan Digital Sky Survey have detected this BAO signal at various redshifts, allowing precise measurements of the universe's expansion history. These measurements are consistent with the presence of dark energy driving accelerated expansion, providing independent confirmation beyond supernovae observations [30].

3.2.4 Large-Scale Structure and Integrated Sachs-Wolfe Effect

The large-scale distribution of galaxies and the integrated Sachs-Wolfe (ISW) effect provide additional evidence for dark energy. The ISW effect arises from the evolution of gravitational potentials as CMB photons traverse them. In a universe with accelerating expansion, these potentials decay over time, causing subtle temperature shifts in the CMB that correlate with the distribution of large-scale structures [31]. Cross-correlation studies between CMB maps and galaxy surveys have detected this effect, providing independent confirmation of dark energy's influence on cosmic evolution [32].

3.3 Theoretical Models

3.3.1 Cosmological Constant (Λ)

The simplest model for dark energy is Einstein's cosmological constant—a constant energy density uniformly filling space. In this framework, dark energy represents the energy of the vacuum itself, maintaining a constant density as the universe expands. The cosmological constant is characterized by an equation of state parameter $w = -1$, indicating that its pressure is negative and equal in magnitude to its energy density [33]. While conceptually straightforward, the cosmological constant presents significant theoretical challenges. Quantum field theory calculations of vacuum energy density exceed observational constraints by many orders of magnitude—a discrepancy known as the "cosmological constant problem" [34].

3.3.2 Quintessence

Quintessence models propose that dark energy arises from a dynamical scalar field evolving across cosmic time, rather than a constant vacuum energy. These models feature an equation of state parameter that varies with time, potentially resolving some theoretical difficulties associated with the cosmological constant [35]. Unlike the cosmological constant, quintessence can potentially explain the "cosmic coincidence problem"—the puzzling observation that we live in an epoch where the densities of matter and dark energy are comparable, despite their very different evolution with cosmic expansion [36].

3.3.3 Modified Gravity Approaches

As with dark matter, some researchers have explored whether dark energy phenomena might indicate modifications needed to Einstein's theory of general relativity at cosmological scales. Theories such as f(R) gravity and Dvali-Gabadadze-Porrati (DGP) gravity propose alternative explanations for cosmic acceleration without invoking an additional energy component [37]. These approaches face significant observational constraints but remain active areas of research, particularly as they may potentially address both dark energy and dark matter within a unified framework.

4. The Interplay Between Dark Matter and Dark Energy

4.1 Cosmic Structure Formation

Dark matter and dark energy exert opposing influences on cosmic structure formation. Dark matter's gravitational attraction drives the collapse of matter into dense structures, forming the scaffolding of the cosmic web. In contrast, dark energy's repulsive effect inhibits structure growth by accelerating cosmic expansion, which counteracts gravitational collapse [38]. This dynamic tension has evolved throughout cosmic history. In the early universe, matter (including dark matter) dominated, allowing structures to form and grow. As the universe expanded and matter density decreased, dark energy gradually became dominant, leading to accelerated expansion and suppressing further structure growth [39]. Numerical simulations incorporating both components successfully reproduce the observed large-scale structure, showing how these opposing forces shaped cosmic evolution. The timing of dark energy's dominance proves crucial—had it dominated earlier, structures might never have formed; had it emerged later, the universe might have developed even more extensive cosmic structures [40].

4.2 Cosmic Web Evolution

The cosmic web—the interconnected network of filaments, sheets, and voids spanning the universe—emerges from the combined influence of dark matter and dark energy. Dark matter initially forms the gravitational scaffolding, with matter flowing along filaments toward dense nodes that become galaxy clusters. Dark energy subsequently affects this web's evolution by accelerating expansion, stretching the filaments and enlarging the voids [41]. Baryon acoustic oscillations (BAO) provide a powerful probe of this interplay. The characteristic BAO scale, imprinted in the early universe, expands differently depending on the balance between dark matter's attractive force and dark energy's repulsive effect. Precise measurements of this scale across cosmic time constrain both components' properties [42].

4.3 Future Evolution Scenarios

The long-term fate of the universe depends critically on dark energy's properties. If dark energy maintains its current characteristics (consistent with a cosmological constant), the universe will continue expanding at an accelerating rate indefinitely. Eventually, galaxies beyond our local group will recede beyond our observable horizon, leading to an increasingly isolated cosmic environment [43]. More exotic dark energy models suggest alternative scenarios. If dark energy's repulsive effect strengthens over time (phantom energy with $w < -1$), the universe might end in a "Big Rip," where expansion becomes so rapid that it tears apart all bound structures, from galaxy clusters down to atoms [44]. Conversely, if dark energy weakens or changes sign, cosmic expansion could eventually reverse, potentially leading to a "Big Crunch" scenario [45].

5. Current Challenges and Unresolved Questions

5.1 Dark Matter Challenges

5.1.1 Particle Nature

Despite compelling gravitational evidence, direct detection of dark matter particles remains elusive. Multiple experiments utilizing different detection techniques have yielded null results, constraining possible particle candidates. The lack of detection raises questions about whether dark matter particles interact with ordinary matter through any forces besides gravity, potentially requiring new detection approaches [46].

5.1.2 Small-Scale Structure Problems

While the Cold Dark Matter (CDM) paradigm successfully explains large-scale structures, several tensions emerge at galactic and sub-galactic scales:

Missing Satellites Problem: CDM simulations predict substantially more satellite galaxies around Milky Way-sized galaxies than observed. While discoveries of ultra-faint dwarf galaxies have partially alleviated this tension, the discrepancy persists [47].

Core-Cusp Problem: CDM simulations predict dense central concentrations (cusps) in dark matter halos, while observations of dwarf galaxies often reveal constant-density cores. This discrepancy suggests either additional astrophysical processes affecting dark matter distribution or modifications needed to dark matter properties [48].

Too-Big-to-Fail Problem: Simulations predict massive satellite galaxies that should be easily observable but appear absent in observations. Unlike the missing satellites problem, this discrepancy involves massive satellites that should be too substantial to have failed to form stars [49]. These small-scale challenges have inspired alternative dark matter models, including self-interacting dark matter (SIDM) and warm dark matter (WDM), which might better reproduce observed galactic properties while maintaining success at larger scales [50].

5.2 Dark Energy Challenges

5.2.1 Cosmological Constant Problem

If dark energy represents vacuum energy as described by quantum field theory, theoretical calculations suggest a value approximately 10^120 times larger than observed—possibly the most dramatic disagreement between theory and observation in physics history. This discrepancy poses profound questions about our understanding of quantum fields in curved spacetime and potentially indicates missing fundamental physics [51].

5.2.2 Cosmic Coincidence Problem

We live in an epoch where the densities of matter and dark energy are remarkably comparable (within a factor of 2-3), despite these components evolving very differently with cosmic expansion (matter density decreases as the cube of scale factor, while dark energy density remains approximately constant). This coincidence appears implausibly fine-tuned in cosmological constant models but might find natural explanations in dynamical dark energy scenarios [52].

5.2.3 Hubble Tension

Recent observations have revealed a discrepancy in measurements of the universe's expansion rate (Hubble constant). Local measurements using Cepheid variables and Type Ia supernovae yield values approximately 10% higher than those inferred from CMB observations and the standard ΛCDM cosmological model. This "Hubble tension" has persisted despite increasingly precise measurements and might indicate new physics beyond the standard cosmological model, potentially involving dark energy or dark matter properties [53].

6. Future Directions and Ongoing Experiments

6.1 Dark Matter Detection Experiments

6.1.1 Direct Detection

Multiple experiments worldwide aim to detect dark matter particles directly through their interactions with ordinary matter. These include: XENONnT and LZ: These experiments utilize liquid xenon detectors to search for nuclear recoils caused by dark matter particles. Located deep underground to shield from cosmic rays, they represent the current generation of direct detection experiments with unprecedented sensitivity [54]. SuperCDMS: Using cryogenically cooled germanium and silicon detectors, SuperCDMS focuses on detecting low-mass dark matter candidates that might elude other experimental approaches [55].

6.1.2 Indirect Detection

Indirect detection methods search for products of dark matter annihilation or decay: Fermi Gamma-ray Space Telescope: This observatory surveys the sky for gamma rays that might result from dark matter annihilation in regions of high dark matter density, such as the galactic center or dwarf spheroidal galaxies [56]. IceCube Neutrino Observatory: Located at the South Pole, this detector searches for high-energy neutrinos potentially produced through dark matter interactions [57].

6.1.3 Collider Searches

Particle accelerators like the Large Hadron Collider (LHC) search for dark matter production in high-energy collisions. While they cannot directly detect dark matter particles, they can potentially identify energy imbalances indicating the creation of particles that escape detection—a signature consistent with dark matter production [58].

6.2 Dark Energy Surveys and Experiments

6.2.1 Spectroscopic Surveys

Dark Energy Spectroscopic Instrument (DESI): This instrument conducts a five-year survey measuring the redshifts of tens of millions of galaxies and quasars, creating a three-dimensional map of the universe's large-scale structure to constrain dark energy properties through baryon acoustic oscillations and redshift-space distortions [59]. Euclid Mission: This European Space Agency mission combines imaging and spectroscopic surveys to map the distribution of galaxies across cosmic time, providing precise measurements of both dark energy and dark matter properties [60].

6.2.2 Imaging Surveys

Vera C. Rubin Observatory: Formerly the Large Synoptic Survey Telescope (LSST), this facility will conduct a ten-year survey imaging the entire visible sky repeatedly. Its observations will constrain dark energy through multiple methods, including weak lensing, supernovae, and large-scale structure [61].

Nancy Grace Roman Space Telescope: This NASA mission will conduct wide-field imaging and spectroscopic surveys to study dark energy through multiple complementary techniques, including weak lensing, supernovae, and baryon acoustic oscillations [62].

6.3 Theoretical and Computational Advances

Advances in computational cosmology enable increasingly sophisticated simulations incorporating both dark matter and dark energy, allowing researchers to compare theoretical predictions with observations across multiple scales. Projects like IllustrisTNG and EAGLE combine gravity, hydrodynamics, and astrophysical processes to model galaxy formation within the cosmic web [63]. Additionally, machine learning techniques increasingly assist in analyzing the vast datasets from cosmological surveys, potentially revealing subtle patterns and correlations that might provide new insights into the nature of dark matter and dark energy [64].

7. Conclusion

Dark matter and dark energy constitute approximately 95% of our universe's energy-mass content, yet their fundamental nature remains among the most profound mysteries in modern physics. The observational evidence for both components is robust and multi faceted, emerging from independent lines of investigation spanning different cosmic scales and epochs. For dark matter, evidence from galactic rotation curves, gravitational lensing, cosmic microwave background anisotropies, and large-scale structure formation collectively builds a compelling case for its existence. While directly detecting dark matter particles remains an outstanding challenge, ongoing experimental efforts continue to constrain candidate properties and explore novel detection strategies. Similarly, evidence for dark energy from Type Ia supernovae, baryon acoustic oscillations, and cosmic microwave background measurements firmly establishes cosmic acceleration as a fundamental aspect of our universe. Whether dark energy represents the energy of vacuum, a dynamical field, or indicates modifications needed to general relativity remains an open question with profound implications for fundamental physics. The interplay between dark matter and dark energy has shaped cosmic evolution, with dark matter's gravitational attraction driving structure formation while dark energy's repulsive effect accelerates expansion. Understanding this dynamic relationship remains central to cosmology's quest to comprehend the universe's past, present, and future. As we look forward, next-generation observatories and experiments promise unprecedented precision in cosmological measurements, potentially resolving current tensions and shedding new light on these cosmic shadows.

Theoretical advances, computational simulations, and novel analytical techniques will complement these observational efforts, collectively advancing our understanding of the dark universe. The quest to understand dark matter and dark energy transcends cosmology, touching fundamental questions in particle physics, general relativity, and quantum field theory. Resolving these cosmic mysteries may require revolutionary insights that transform our understanding of space, time, matter, and energy—potentially revealing new fundamental principles governing our universe.

References

[1] Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," Astronomy & Astrophysics, vol. 641, p. A6, 2020.

[2] P. J. E. Peebles and B. Ratra, "The cosmological constant and dark energy," Reviews of Modern Physics, vol. 75, no. 2, pp. 559-606, 2003.

[3] G. Bertone and D. Hooper, "History of dark matter," Reviews of Modern Physics, vol. 90, no. 4, p. 045002, 2018.

[4] D. H. Weinberg et al., "Observational probes of cosmic acceleration," Physics Reports, vol. 530, no. 2, pp. 87-255, 2013.

[5] J. L. Feng, "Dark matter candidates from particle physics and methods of detection," Annual Review of Astronomy and Astrophysics, vol. 48, pp. 495-545, 2010.

[6] F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln," Helvetica Physica Acta, vol. 6, pp. 110-127, 1933.

[7] V. C. Rubin, W. K. Ford Jr., and N. Thonnard, "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/," The Astrophysical Journal, vol. 238, pp. 471-487, 1980.

[8] Y. Sofue and V. Rubin, "Rotation curves of spiral galaxies," Annual Review of Astronomy and Astrophysics, vol. 39, pp. 137-174, 2001.

[9] A. Bosma, "21-cm line studies of spiral galaxies. II - The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types," The Astronomical Journal, vol. 86, pp. 1791-1846, 1981.

[10] R. Massey and A. Refregier, "Weak gravitational lensing," Physics Reports, vol. 427, no. 5-6, pp. 143-166, 2005.

[11] D. Clowe et al., "A direct empirical proof of the existence of dark matter," The Astrophysical Journal Letters, vol. 648, no. 2, pp. L109-L113, 2006.

[12] M. Markevitch et al., "Direct constraints on the dark matter self-interaction cross section from the merging galaxy cluster 1E 0657-56," The Astrophysical Journal, vol. 606, no. 2, pp. 819-824, 2004.

[13] Planck Collaboration, "Planck 2015 results. XIII. Cosmological parameters," Astronomy & Astrophysics, vol. 594, p. A13, 2016.

[14] W. Hu and S. Dodelson, "Cosmic microwave background anisotropies," Annual Review of Astronomy and Astrophysics, vol. 40, pp. 171-216, 2002.

[15] V. Springel et al., "Simulations of the formation, evolution and clustering of galaxies and quasars," Nature, vol. 435, no. 7042, pp. 629-636, 2005.

[16] S. Alam et al., "The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample," Monthly Notices of the Royal Astronomical Society, vol. 470, no. 3, pp. 2617-2652, 2017.

[17] B. Moore et al., "Cold dark matter and its challenges," Nature, vol. 370, no. 6491, pp. 629-631, 1994.

[18] G. Jungman, M. Kamionkowski, and K. Griest, "Supersymmetric dark matter," Physics Reports, vol. 267, no. 5-6, pp. 195-373, 1996.

[19] P. Sikivie, "Axion cosmology," Lectures presented at the 2005 RTN Winter School, Schladming, Austria, arXiv:astro-ph/0610440, 2006.

[20] S. Dodelson and L. M. Widrow, "Sterile neutrinos as dark matter," Physical Review Letters, vol. 72, no. 1, pp. 17-20, 1994.

[21] P. Tisserand et al., "Limits on the MACHO content of the Galactic Halo from the EROS 2 Survey of the Magellanic Clouds," Astronomy & Astrophysics, vol. 469, no. 2, pp. 387 404, 2007.

[22] M. Milgrom, "MOND theory," Canadian Journal of Physics, vol. 93, no. 2, pp. 107-118, 2015.

[23] A. G. Riess et al., "Observational evidence from supernovae for an accelerating universe and a cosmological constant," The Astronomical Journal, vol. 116, no. 3, pp. 1009-1038, 1998.

[24] S. Perlmutter et al., "Measurements of Omega and Lambda from 42 high-redshift supernovae," The Astrophysical Journal, vol. 517, no. 2, pp. 565-586, 1999.

[25] A. G. Riess et al., "A 2.4% determination of the local value of the Hubble constant," The Astrophysical Journal, vol. 826, no. 1, p. 56, 2016.

[26] D. M. Scolnic et al., "The complete light-curve sample of spectroscopically confirmed SNe Ia from Pan-STARRS1 and cosmological constraints from the combined Pantheon sample," The Astrophysical Journal, vol. 859, no. 2, p. 101, 2018.

[27] P. A. R. Ade et al., "Planck 2015 results. XIII. Cosmological parameters," Astronomy & Astrophysics, vol. 594, p. A13, 2016.

[28] D. J. Eisenstein et al., "Detection of the baryon acoustic peak in the large-scale correlation function of SDSS luminous red galaxies," The Astrophysical Journal, vol. 633, no. 2, pp. 560-574, 2005.

[29] E. Aubourg et al., "Cosmological implications of baryon acoustic oscillation measurements," Physical Review D, vol. 92, no. 12, p. 123516, 2015.

[30] L. Anderson et al., "The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Data Releases 10 and 11 Galaxy samples," Monthly Notices of the Royal Astronomical Society, vol. 441, no. 1, pp. 24-62, 2014.

[31] R. G. Crittenden and N. Turok, "Looking for a cosmological constant with the Rees Sciama effect," Physical Review Letters, vol. 76, no. 4, pp. 575-578, 1996.

[32] S. Ho et al., "Correlation of CMB with large-scale structure. I. Integrated Sachs-Wolfe tomography and

cosmological implications," Physical Review D, vol. 78, no. 4, p. 043519, 2008.

[33] S. M. Carroll, "The cosmological constant," Living Reviews in Relativity, vol. 4, no. 1, p. 1, 2001.

[34] S. Weinberg, "The cosmological constant problem," Reviews of Modern Physics, vol. 61, no. 1, pp. 1-23, 1989.

[35] R. R. Caldwell, R. Dave, and P. J. Steinhardt, "Cosmological imprint of an energy component with general equation of state," Physical Review Letters, vol. 80, no. 8, pp. 1582-1585, 1998.

[36] I. Zlatev, L. Wang, and P. J. Steinhardt, "Quintessence, cosmic coincidence, and the cosmological constant," Physical Review Letters, vol. 82, no. 5, pp. 896-899, 1999.

[37] A. De Felice and S. Tsujikawa, "f(R) theories," Living Reviews in Relativity, vol. 13, no. 1, p. 3, 2010.

[38] R. A. Battye and A. Moss, "Evidence for massive neutrinos from cosmic microwave background and lensing observations," Physical Review Letters, vol. 112, no. 5, p. 051303, 2014.

[39] V. Springel et al., "The Aquarius Project: the subhaloes of galactic haloes," Monthly Notices of the Royal Astronomical Society, vol. 391, no. 4, pp. 1685-1711, 2008.

[40] M. Vogelsberger et al., "Properties of galaxies reproduced by a hydrodynamic simulation," Nature, vol. 509, no. 7499, pp. 177-182, 2014.

[41] [41] J. R. Bond, L. Kofman, and D. Pogosyan, "How filaments of galaxies are woven into the cosmic web," Nature, vol. 380, no. 6575, pp. 603-606, 1996.

[42] N. G. Busca et al., "Baryon acoustic oscillations in the Lyα forest of BOSS quasars," Astronomy & Astrophysics, vol. 552, p. A96, 2013.

[43] L. M. Krauss and R. J. Scherrer, "The return of a static universe and the end of cosmology," General Relativity and Gravitation, vol. 39, no. 10, pp. 1545-1550, 2007.

[44] R. R. Caldwell, M. Kamionkowski, and N. N. Weinberg, "Phantom energy: dark energy with $w < -1$ causes a cosmic doomsday," Physical Review Letters, vol. 91, no. 7, p. 071301, 2003.

[45] P. J. Steinhardt and N. Turok, "Cosmic evolution in a cyclic universe," Physical Review D, vol. 65, no. 12, p. 126003, 2002.

[46] E. Aprile et al. (XENON Collaboration), "Dark matter search results from a one ton-year exposure of XENON1T," Physical Review Letters, vol. 121, no. 11, p. 111302, 2018.

[47] A. Drlica-Wagner et al., "Eight ultra-faint galaxy candidates discovered in year two of the dark energy survey," The Astrophysical Journal, vol. 813, no. 2, p. 109, 2015.

[48] W. J. G. de Blok, "The core-cusp problem," Advances in Astronomy, vol. 2010, p. 789293, 2010.

[49] M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat, "Too big to fail? The puzzling darkness of massive Milky Way subhaloes," Monthly Notices of the Royal Astronomical Society, vol. 415, no. 1, pp. L40-L44, 2011.

[50] M. Rocha et al., "Cosmological simulations with self-interacting dark matter – I. Constant-density cores and substructure," Monthly Notices of the Royal Astronomical Society, vol. 430, no. 1, pp. 81-104, 2013.

[51] J. Martin, "Everything you always wanted to know about the cosmological constant problem (but were afraid to ask)," Comptes Rendus Physique, vol. 13, no. 6-7, pp. 566-665, 2012.

[52] C. Armendariz-Picon, V. Mukhanov, and P. J. Steinhardt, "Essentials of k-essence," Physical Review D, vol. 63, no. 10, p. 103510, 2001.

[53] A. G. Riess et al., "A comprehensive measurement of the local value of the Hubble constant with 1 km/s/Mpc uncertainty from the Hubble Space Telescope and the SH0ES Team," The Astrophysical Journal Letters, vol. 934, no. 1, p. L7, 2022.

[54] E. Aprile et al. (XENON Collaboration), "Projected WIMP sensitivity of the XENONnT dark matter experiment," Journal of Cosmology and Astroparticle Physics, vol. 2020, no. 11, p. 031, 2020.

[55] R. Agnese et al. (SuperCDMS Collaboration), "Projected sensitivity of the SuperCDMS SNOLAB experiment," Physical Review D, vol. 95, no. 8, p. 082002, 2017.

[56] M. Ackermann et al. (Fermi-LAT Collaboration), "Search for gamma-ray spectral lines with the Fermi Large Area Telescope and dark matter implications," Physical Review D, vol. 88, no. 8, p. 082002, 2013.

[57] M. G. Aartsen et al. (IceCube Collaboration), "Search for neutrinos from dark matter self-annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore," European Physical Journal C, vol. 77, no. 9, p. 627, 2017.

[58] ATLAS Collaboration, "Search for dark matter in events with missing transverse momentum and a Higgs boson decaying to two photons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector," Physical Review D, vol. 96, no. 11, p. 112004, 2017.

[59] DESI Collaboration, "The DESI Experiment Part I: Science, targeting, and survey design," The Astronomical Journal, vol. 157, no. 5, p. 168, 2019.

[60] R. Laureijs et al., "Euclid definition study report," European Space Agency/SRE, vol. 12, p. 2012, 2011.

[61] LSST Science Collaboration, "LSST Science Book, Version 2.0," arXiv:0912.0201, 2009.

[62] D. Spergel et al., "Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report," arXiv:1503.03757, 2015.

[63] V. Springel et al., "First results from the IllustrisTNG simulations: matter and galaxy clustering," Monthly Notices of the Royal Astronomical Society, vol. 475, no. 1, pp. 676 698, 2018.

[64] D. George and E. A. Huerta, "Deep neural networks to enable real-time multimessenger astrophysics," Physical Review D, vol. 97, no. 4, p. 044039, 2018.