



THE MISSING MASS PROBLEM: A REVIEW OF DARK MATTER EVIDENCE AND MODELS

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Abstract

Dark matter remains one of the most compelling and unresolved problems in modern physics and cosmology. Although it does not emit, absorb, or reflect electromagnetic radiation, its presence is inferred through a wide range of astrophysical observations. This review examines the historical development, observational evidence, and current experimental efforts aimed at understanding the nature of dark matter. The earliest indication of missing mass was reported by Fritz Zwicky in studies of galaxy clusters, where the visible matter could not account for the observed gravitational effects. Later, precise measurements of galactic rotation curves by Vera Rubin provided strong evidence that galaxies contain significantly more mass than what is visible. Additional confirmation arises from gravitational lensing phenomena and detailed measurements of the cosmic microwave background radiation by missions such as the Planck Collaboration, which indicate that dark matter constitutes approximately 27% of the total energy density of the universe.

This paper reviews leading dark matter candidates, including Weakly Interacting Massive Particles (WIMPs), axions, and Massive Compact Halo Objects (MACHOs), discussing their theoretical motivations and physical properties. It further surveys major detection strategies, such as direct detection experiments using ultra-sensitive underground detectors, indirect searches for annihilation products, and high-energy collider investigations at facilities like CERN. Despite decades of intensive research, no conclusive detection has yet been achieved, prompting ongoing refinement of experimental techniques and theoretical models.

By synthesizing current evidence and research approaches, this review highlights both the robustness of the dark matter hypothesis and the significant challenges that remain in identifying its fundamental nature. Dark matter continues to represent a critical frontier in understanding the composition and evolution of the universe.

Introduction

What is Dark Matter

Dark matter is a hypothetical form of matter that does not emit, absorb, or reflect any electromagnetic radiation (like visible light, X-rays, or radio waves), making it completely invisible to our telescopes. Its presence is only known through its gravitational effects on ordinary, visible matter.



Think of it as an invisible cosmic glue or scaffolding. It makes up about 27% of the universe's total mass and energy, while the ordinary matter that makes up stars, planets, and us accounts for only about 5%. The rest is an even more mysterious force called dark energy.

Why visible matter is insufficient?

The postulation of dark matter arose directly from the insurmountable discrepancies between the observed dynamics of celestial objects and the dynamics predicted by Newtonian gravity based solely on the mass of visible, baryonic matter. The insufficiency of visible matter is empirically demonstrated by two foundational lines of evidence.

- **Galactic Rotation Curves**

The most compelling evidence comes from the measurement of galactic rotation curves. In a gravitationally-bound system like a spiral galaxy, the orbital velocity of stars and gas around the galactic centre is determined by the mass enclosed within their orbit. According to Keplerian dynamics, if the mass of the galaxy were concentrated in the visible, luminous disk (stars and gas), one would expect a **Keplerian decline** in orbital velocity at large radii. Specifically, beyond the central bulge, where the visible mass drops off, the velocity should decrease proportionally to the inverse square root of the radius $v \propto 1/\sqrt{r}$.

However, pioneering work by Rubin and Ford (1970) demonstrated that the rotation curves of spiral galaxies are **flat**; that is, the orbital velocity remains constant out to the farthest measurable distances, far beyond where most of the visible matter resides. This phenomenon indicates that the total mass of the galaxy continues to increase linearly with radius. The gravitational mass required to produce these flat curves is substantially greater than the luminous mass. Consequently, the visible matter accounts for only a fraction of the total mass, necessitating the existence of an extended, non-luminous halo surrounding the galaxy.

- **Mass Discrepancy in Galaxy Clusters**

Prior to galactic rotation curves, Zwicky (1933) identified a mass discrepancy in the Coma Cluster. By applying the virial theorem, which relates the average kinetic energy of the cluster's galaxies to the gravitational potential holding them together,

Zwicky calculated the total dynamical mass required for cluster stability. He observed that the velocity dispersion of the galaxies was far too high; the cluster should have dispersed were it held together only by the gravity of its visible components.

The dynamical mass he derived was approximately 400 times greater than the mass inferred from the luminosity of the galaxies. This significant disparity between the dynamical mass and the luminous mass confirmed that visible matter alone is



insufficient to provide the gravitational binding force necessary to maintain the structural integrity of galaxy clusters.

Importance in Cosmology

The significance of dark matter in cosmology is fundamental, as it governs the structural evolution of the universe rather than representing a peripheral anomaly. Its importance is primarily understood through structure formation and observations of the Cosmic Microwave Background (CMB).

In the standard cosmological model, the universe began in a hot, dense, nearly uniform state. Quantum fluctuations generated during inflation produced small density variations that later served as the seeds of cosmic structure. However, baryonic matter alone cannot explain the rapid formation of galaxies and large-scale structures. In the early universe, baryons were tightly coupled to photons through radiation pressure, preventing gravitational collapse until recombination, when neutral hydrogen formed and photons decoupled.

If only baryonic matter existed, gravitational growth would have been too slow to produce the structures observed today. Dark matter, which does not interact with radiation, began collapsing earlier under gravity. These early dark matter clumps formed gravitational potential wells into which baryonic gas later fell, cooled, and condensed, enabling efficient galaxy formation. Dark matter therefore acted as the gravitational scaffolding for hierarchical structure formation.

Independent evidence arises from the CMB, which contains tiny temperature anisotropies encoded in a power spectrum of acoustic peaks produced by baryon acoustic oscillations in the early photon–baryon plasma. The positions and amplitudes of these peaks depend sensitively on the universe’s composition. While the first peak indicates overall spatial flatness, the relative heights of later peaks require a substantial component of non-baryonic, pressure-less matter. Dark matter modifies gravitational potentials and suppresses higher-order acoustic peaks in a way that matches observations only when it constitutes roughly 26% of the universe’s energy density, compared to about 5% for baryonic matter. Models without dark matter fail to reproduce the observed spectrum.

Historical Context

The concept of invisible mass predates modern cosmology, emerging in the early 20th century when astronomers applied dynamical methods to estimate unseen matter. Jacobus Kapteyn (1922) and Jan Oort (1932) analysed stellar motions near the Sun and suggested the presence of unseen mass. However, the first clear cosmological argument for “dark matter” (Dunkle Materie) was made by Swiss astrophysicist Fritz Zwicky.



In 1933, studying the Coma galaxy cluster, Zwicky applied the virial theorem to galaxy velocities and found that the cluster required roughly 400 times more mass than could be explained by visible light alone. He concluded that large amounts of non-luminous matter were necessary to gravitationally bind the system. Despite its significance, this result was largely overlooked for several decades.

Dark matter remained a marginal idea until mid-20th-century technological advances enabled systematic observations. A major breakthrough came from Vera Rubin and Kent Ford at the Carnegie Institution. In the 1960s, Ford developed the image tube spectrograph, allowing measurements of faint galactic regions. Using this instrument, Rubin and Ford measured rotation curves of the Andromeda Galaxy and many other spiral galaxies. Their results showed that stellar rotational velocities remained nearly constant at large radii rather than declining as predicted by visible mass distributions. These flat rotation curves implied massive, extended halos of unseen matter surrounding galaxies. The consistency of these observations provided the first widely accepted galactic-scale evidence for dark matter.

By the 1980s, multiple lines of evidence—including Zwicky's cluster dynamics, Rubin's rotation curves, gravitational lensing observations, and numerical simulations of structure formation—produced a paradigm shift. Astronomers concluded that dark matter is a dominant, non-baryonic component of the universe that governs large-scale structure formation. This view became formalized in the Λ CDM (Lambda Cold Dark Matter) cosmological model, establishing dark matter as a fundamental constituent of the cosmos.

Observational Evidence

- **Galactic Rotation Curves**

The first robust, systematic evidence for dark matter on galactic scales emerged from the study of spiral galaxy rotation curves. In a gravitationally-bound system such as a spiral galaxy, the orbital velocity of stars and gas around the galactic centre is determined by the mass enclosed within their orbit. If the majority of a galaxy's mass were concentrated in the visible, luminous disk (stars and gas), one would expect a **Keplerian decline** in orbital velocity at large radii. Specifically, beyond the central bulge, where the visible mass density drops off, the velocity should decrease proportionally to the inverse square root of the radius ($v \propto 1/\sqrt{r}$).

Pioneering work by astronomers **Vera Rubin and Kent Ford** in the 1970s fundamentally challenged this prediction. Utilizing advanced spectroscopic techniques, they observed the Andromeda Galaxy (M31) and subsequently dozens of other spiral galaxies. Their observations consistently revealed that the rotational velocities of stars and gas in the outer regions did not decrease with distance from the galactic centre.



Instead, they remained **flat**, meaning the orbital velocity is roughly constant out to the farthest measurable distances. This phenomenon indicates that the total mass of the galaxy continues to increase linearly with radius. The gravitational mass required to produce these flat curves is substantially greater than the luminous mass, necessitating the existence of an extended, non-luminous **dark matter halo** surrounding each galaxy. This evidence has been further refined and tested in the modern era. Observations from the European Space Agency's **Gaia satellite** have provided unprecedented precision in mapping the rotation curve of our own galaxy, the Milky Way. A 2025 study led by Alain Blanchard at the Institut de Recherche en Astrophysique et Planétologie used Gaia data to demonstrate that the Milky Way's rotation curve shows a gradual decrease at large distances. Crucially, this specific declining shape is perfectly reproduced by models that include a dark matter halo but is incompatible with Modified Newtonian Dynamics (MOND), a leading alternative theory to dark matter. This finding strongly reinforces the dark matter hypothesis as the most robust explanation for galactic dynamics.

- **Gravitational Lensing**

Gravitational lensing, a phenomenon predicted by Einstein's theory of general relativity, provides a powerful and purely gravitational probe of dark matter, independent of the dynamical assumptions used in rotation curve analyses. The effect occurs when a massive foreground object (the "lens") warps the fabric of spacetime, causing the path of light from a distant background source to bend as it travels toward the observer. The amount of distortion is directly proportional to the total mass—both luminous and dark—of the foreground object.

This method is particularly potent because it does not rely on the lensing object emitting any detectable light. As noted by researchers preparing for NASA's Nancy Grace Roman Space Telescope, dark matter possesses mass, and like anything else with mass, it causes gravitational lensing. "We won't see dark matter in the images — it's invisible — but we can measure its effects". By meticulously analysing the distorted shapes of background galaxies, astronomers can map the total mass distribution of the foreground lens, including its dark matter component.

A landmark example of this technique's power is the detection of a low-mass dark object at a cosmological distance, reported in 2025 by a team using a global Very Long Baseline Interferometry (VLBI) array. By employing a novel methodology called **gravitational imaging** on the lens system JVAS B1938+666, the team detected an object with a mass of just 1.13 million solar masses that has no detectable optical emission. The probability of finding such an object is consistent with predictions from the **cold dark matter (CDM) model**, and it represents the lowest mass dark object ever found at such a distance, over two orders of magnitude smaller than previous detections. This discovery showcases the unparalleled sensitivity of gravitational lensing for probing the small-scale structure of dark matter. Upcoming missions like the Nancy



Grace Roman Space Telescope are expected to discover hundreds of thousands of gravitational lenses, enabling precise statistical studies of dark matter's distribution and its particle nature.

- **The Cosmic Microwave Background (CMB)**

The Cosmic Microwave Background (CMB), the remnant afterglow of the Big Bang, offers a unique window into the universe's composition when it was just 380,000 years old. The CMB is not perfectly uniform; it contains minuscule temperature anisotropies. The statistical properties of these anisotropies, often represented as a power spectrum, are exquisitely sensitive to the cosmological parameters, including the densities of ordinary (baryonic) matter and dark matter.

The specific pattern of peaks in the CMB power spectrum is a direct consequence of **baryon acoustic oscillations (BAOs)**—sound waves propagating through the coupled baryon-photon fluid in the early universe. The relative heights and positions of these peaks provide a precise measurement of the universe's constituents. The presence of a significant amount of non-baryonic, pressure-less dark matter alters the gravitational potential driving these oscillations, which in turn suppresses the amplitude of the third and subsequent acoustic peaks. Observations from missions like the Planck satellite match theoretical models precisely only when a substantial fraction (approximately 85% of all matter) of the universe's energy density is composed of cold dark matter, with ordinary baryons comprising the remainder. Without dark matter, the predicted peak ratios would be inconsistent with the measured data.

Furthermore, the CMB continues to provide potential clues about the nature of dark matter. Recent analyses of CMB polarization data from experiments like the Atacama Cosmology Telescope (ACT) have found evidence for a phenomenon called **cosmic birefringence**—a slight rotation of the polarization plane of CMB light. This effect, if confirmed to be cosmological in origin, is predicted by some dark matter models involving particles like axions. A 2026 study from the Max Planck Institute for Astrophysics found a cosmic birefringence angle of $\beta = 0.215^\circ \pm 0.074^\circ$ with a 99.6% confidence level in ACT data, an independent confirmation of hints previously seen in WMAP and Planck data. This suggests that CMB studies are not only confirming dark matter's existence but may also be starting to unveil its fundamental physical properties.

Dark Matter Candidates and Detection

The quest to understand the nature of dark matter is defined by two parallel efforts: the theoretical proposal of candidate particles and the experimental endeavour to detect them. The viable candidates span an enormous range of masses, and consequently, the detection strategies are equally diverse.



The leading class of candidates is the **Weakly Interacting Massive Particle (WIMP)**. WIMPs are hypothetical particles predicted by extensions of the Standard Model, most notably supersymmetry. They are massive (typically in the GeV to TeV range) and interact via the weak nuclear force and gravity. This combination naturally yields the correct relic abundance from the early universe; a scenario termed the "WIMP miracle." The search for WIMPs is pursued through three complementary strategies: direct detection, indirect detection, and production at colliders.

A second well-motivated candidate is the **axion**. Axions were originally postulated to solve a fundamental problem in quantum chromodynamics (the Strong CP Problem), but they serendipitously also serve as a viable dark matter candidate. In stark contrast to WIMPs, axions are predicted to be extraordinarily light, with masses potentially billions of times smaller than an electron. They would behave less like discrete particles and more like a coherent wave-like field. Axions could be detected through their predicted conversion into photons in the presence of a strong magnetic field. Experiments such as ADMX utilize resonant cavities within powerful magnetic fields to catalyse and detect this conversion.

A historically significant but now largely excluded class of candidates is **MACHOs (Massive Compact Halo Objects)**. This hypothesis proposed that dark matter could be composed of ordinary baryonic matter in the form of faint astronomical objects such as brown dwarfs or black holes. The primary method to detect them was gravitational microlensing. In the 1990s and 2000s, collaborations like EROS and MACHO surveyed millions of stars and found far fewer microlensing events than predicted, conclusively demonstrating that MACHOs cannot constitute a significant fraction of the dark matter halo.

Direct detection experiments aim to observe the rare interaction between a dark matter particle and an ordinary atomic nucleus. Detectors must be placed deep underground to shield them from cosmic rays and other background radiation. The most sensitive experiments to date employ dual-phase **xenon** time projection chambers, such as **XENONnT** in Italy and **LUX-ZEPLIN (LZ)** in the United States. These detectors contain several tons of liquid xenon. When a particle interacts with a xenon nucleus, it produces a prompt flash of light and ionization electrons. The pattern of these signals allows researchers to reconstruct the interaction and distinguish a potential dark matter signal from background events. These experiments have placed the most stringent limits on the WIMP-nucleon interaction cross-section to date.

The third prong of the search is **creation at colliders**, most notably at **CERN's Large Hadron Collider (LHC)**. This approach attempts to produce dark matter particles by colliding protons at enormous energies. If created, dark matter particles would not interact with the detector and would simply escape, leaving a signature of **missing transverse energy** and momentum. The LHC experiments, particularly ATLAS and CMS, have conducted extensive searches for such signatures. While the LHC has also



not yet discovered dark matter, its results provide powerful complementary constraints, probing different regions of dark matter parameter space than direct detection experiments

Current Challenges and Future Outlook

The field of dark matter research, while progressing rapidly, confronts several significant challenges that complicate the path to discovery. Simultaneously, the future outlook is defined by an expanding portfolio of innovative experiments and refined theoretical frameworks poised to explore vast new parameter space.

One of the primary challenges is the **persistent non-detection** of the most theoretically favoured candidate, the WIMP. After decades of increasingly sensitive searches, experiments like XENONnT and LZ have placed stringent upper limits on the WIMP-nucleon interaction cross-section without observing a definitive signal, pushing the simplest WIMP models into regions of parameter space that are becoming increasingly difficult to reconcile with naturalness arguments. Compounding this is the onset of the **"neutrino fog."** As direct detection experiments approach the required sensitivity, they will inevitably begin to detect coherent elastic neutrino-nucleus scattering (CEvNS) from astrophysical neutrinos. This irreducible background will obscure potential dark matter signals, requiring the development of directional detectors to distinguish a true Galactic dark matter signal from solar neutrinos.

Further complicating direct detection efforts are **significant astrophysical uncertainties**. The precise velocity distribution and local density of dark matter in the Galactic halo are not known with high certainty. As recent work utilizing information theory has demonstrated, deviations from the assumed Maxwell-Boltzmann distribution can introduce uncertainties in predicted scattering rates ranging from less than an order of magnitude to as much as three orders of magnitude for certain interaction operators. This makes it difficult to interpret null results and to compare the sensitivity of different experiments and target materials.

Cosmological and astrophysical observations are also imposing increasingly tight constraints. Measurements from the Cosmic Microwave Background (CMB) strongly limit the annihilation cross-section of dark matter in the early universe, disfavours many simple models where dark matter annihilates via s-wave processes into visible Standard Model particles. These constraints force theorists to consider more complex scenarios, such as p-wave annihilation or annihilation primarily into neutrinos. Additionally, persistent tensions in large-scale structure data, such as the σ_8 tension, suggest that our understanding of dark matter's properties may be incomplete, potentially pointing towards complex dark sector interactions rather than a simple cold, collisionless fluid.



Looking toward the future, the field is diversifying its approach. Theoretically, the assumption that dark matter must be "cold" from its birth is being challenged. New research demonstrates that dark matter could have been produced "ultrarelativistic" or "hot" during the post-inflationary reheating era and subsequently cooled sufficiently to behave as cold dark matter by the time galaxies formed. This opens up a much broader range of viable particle models and production mechanisms, including "freeze-in" scenarios where dark matter never attained equilibrium with the Standard Model bath. The experimental landscape is expanding to probe this wider theoretical terrain. **Next-generation direct detection experiments** are pushing to lower thresholds to access sub-GeV dark matter masses, utilizing novel targets such as semiconductors and even exploring unconventional materials like sucrose crystals, as demonstrated by the CRESST collaboration's "SWEET" project. The **intensity frontier** will play a crucial role, with beam-dump experiments like Ship, DUNE, and DarkQuest offering powerful probes of the freeze-in parameter space and light mediator scenarios that are inaccessible to direct detection. On the astrophysical front, new observational strategies are being developed, including the search for subtle "color" fingerprints imprinted on light by dark matter interactions via chains of virtual particles. The future of dark matter research thus lies in this multi-pronged, synergistic effort, combining direct detection, collider searches, and astrophysical observations to ultimately reveal the nature of this dominant component of our universe.

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