

# The Dark Matter Enigma

*Jean-Pierre Luminet*

**T**HE EXISTENCE OF DARK MATTER was first suspected in the early 1930s. While measuring the velocities of galaxies grouped together in clusters, the Swiss astronomer Fritz Zwicky deduced the presence of an invisible mass. His calculations showed that if only the visible mass of the galaxies was taken into account, they should have separated due to their high proper velocities.<sup>1</sup> Yet the galaxies remained grouped together and the clusters were stable. The most plausible explanation was the presence of an invisible mass that gravitationally bound the galaxies but that did not emit electromagnetic radiation. Subsequent measurements have shown that there must be at least ten times more dark matter than luminous matter in galaxy clusters.<sup>2</sup>

Further indirect evidence for the existence of dark matter came from the rotational velocities of spiral galaxies. These systems usually rotate at higher velocities near their centers than at their edges. In the late 1960s, Vera Rubin, W. Kent Ford, and Norbert Thonnard found that the rotational velocity remains more or less constant beyond a certain distance from the center, even in far flung regions containing few stars.<sup>3</sup> This implied that dark matter was present well beyond the limits of the galactic disc, perhaps forming an extended halo.

The notion of dark matter has since become ubiquitous in astronomy and cosmology. Dark matter plays an important role in galaxy formation models, its presence ensuring that the first structures condensed over the short time frames reflected in observations.<sup>4</sup> From studying gravitational mirages, physicists can discern the distribution of visible and invisible matter, and they have concluded that at least ten times more dark matter than luminous matter is needed to account for observations.<sup>5</sup> A significant proportion of dark matter is also needed in the initial composition of the universe to explain the anisotropic spectrum of the cosmic diffuse background.<sup>6</sup>

Recent surveys make possible a precise estimation of the composition of the observable universe.<sup>7</sup> Luminous matter represents only 0.5% of the total; dark energy, a form of nonmaterial and antigravitational energy, 68%. The remaining 32% is attributed to dark matter—a contribution that is almost entirely invisible to telescopes.

The true nature of dark matter is one of the most significant challenges in modern astrophysics, especially since its distribution is far from uniform. Consider the galaxies Dragonfly 44 and NGC1052-DF2. Discovered in 2015, Dragonfly 44 has a mass comparable to the Milky Way, but appears to be almost exclusively dark matter (99.99%).<sup>8</sup> By contrast, NGC1052-DF2, which was discovered in 2018, appears to be devoid of dark matter.<sup>9</sup>

It might seem reasonable to imagine that dark matter is composed from all the celestial bodies too faint to be observed. Interstellar dust would be included, along with clouds of cold molecular hydrogen, and the dark stars in the halos of galaxies known as Massive Compact Halo Objects (MACHOs). This grouping includes black dwarfs, neutron stars, black holes, and brown dwarfs—stars too small to emit a glow from their nuclear reactions. Observations of the Large Magellanic Cloud have found that MACHOs amount to less than 8% of the black mass of the galactic halo.<sup>10</sup>

These celestial bodies are composed of protons and neutrons, collectively known as baryons. Big Bang cosmological models have successfully explained the observed abundance of light chemical elements—deuterium, helium, and lithium—that were produced in a brief primordial nucleosynthesis. The proportions of these elements can be used to determine the density of baryonic matter in the young cosmos. A value for its current density, both visible and black, can be determined by using the Hubble–Lemaître law. These results agree with observations. Primordial nucleosynthesis imposes an upper limit on the current density of baryonic matter: it cannot exceed 5%.<sup>11</sup>

If 32% of the universe is dark matter and baryonic matter is only 5%, that leaves 27% unaccounted. There are two ways to solve this problem. The first is to abandon the very idea of dark matter—astronomers must have made a mistake and Newton’s law of universal attraction requires modification. A second approach originates in particle physics and involves the introduction of nonbaryonic dark matter.

**R**ECENT OBSERVATIONAL EVIDENCE has shown that, aside from gravitational force, dark matter interacts only barely, if at all, with ordinary matter. This

suggests that dark matter is predominantly nonbaryonic in nature, even if it produces gravitational effects similar to those associated with mass.

The theoretical candidates for nonbaryonic dark matter fall into three classes.

Hot dark matter (HDM) does not refer to a specific temperature, but to low-mass particles with velocities close to the speed of light. Obvious candidates are the three types of neutrinos in the Standard Model. Neutrinos have been detected experimentally, even though their limited interactions with the electromagnetic field renders them elusive. On average, there are 400 neutrinos per cubic centimeter of space throughout the universe. Neutrinos would only need a tiny mass to account for all dark matter.<sup>12</sup> Experiments to measure neutrino mass began in 1988 at the Super-Kamiokande detector in Japan and continue today at the Karlsruhe Tritium Neutrino Experiment site in Germany.<sup>13</sup> These studies have yielded a series of gradually decreasing mass values.<sup>14</sup> Neutrino mass is now thought not to exceed  $10^{-34}$  grams—a billionth the mass of a proton. Although negligible, the contribution of neutrinos to the energy density of the universe is on the same order as that of luminous matter (0.5%).

Warm dark matter (WDM) is composed of a hypothetical particle, the sterile neutrino.<sup>15</sup> In contrast to the neutrinos of the Standard Model, sterile neutrinos do not interact with the weak and strong electromagnetic interactions, making them even more difficult to detect. Due to their mass, sterile neutrinos interact via gravity, meaning that, given a sufficient mass, they could account for dark matter.<sup>16</sup> Their existence is due to an anomaly in the helicity of ordinary neutrinos. Particles in the Standard Model have an intrinsic kinetic moment termed spin—as if they were tiny rotors with an axis of rotation parallel to their velocity vector. A particle's helicity is said to be either left- or right-handed depending on the direction of rotation. Although the other particles in the Standard Model—leptons and quarks—can be both left- and right-handed, no right-handed neutrinos have ever been observed.

The minimum Standard Model predicted incorrectly that ordinary neutrinos would have a strictly zero rest mass. In 1998, the discovery of their oscillations forced physicists to assign neutrinos mass, after all. Sterile neutrinos were introduced to account for these masses and oscillations.<sup>17</sup> Models that make use of sterile neutrinos have several advantages. Their presence helps explain, for example, the predominance of matter over antimatter, a process known as baryogenesis. If the mass of sterile neutrinos is found to be greater than  $10^{-29}$  grams, they would be potential dark matter particles. Several experiments have sought to detect sterile neutrinos, but their results are contradictory.<sup>18</sup>

Cold dark matter (CDM) is composed of larger and slower moving particles than HDM or WDM. These exotic particles only appear in high-energy physics theo-

ries beyond the Standard Model. The two main candidates are axions and neutralinos. The former are hypothetical particles assumed to be stable, electrically neutral, and extremely light, with a mass between  $10^{-39}$  and  $10^{-36}$  grams. They were introduced by theorists to help explain charge-parity symmetry in strong interactions.<sup>19</sup> It has been theorized that the Big Bang created sufficient axions to account for the missing dark matter.<sup>20</sup> Experiments in both Europe and the US have been unable to detect axions, which only interact weakly with other matter.<sup>21</sup>

The existence of the neutralino is predicted by the theory of supersymmetry (SUSY),<sup>22</sup> an attempt to unify the three fundamental interactions of the Standard Model. Under SUSY, all known fundamental particles have heavier supersymmetric counterparts, known as superpartners or sparticles. The theory has considerable appeal for researchers because it may offer solutions to several enduring problems, such as the disparity in the calculated mass of the Higgs boson under quantum field theory. SUSY could also account for non-baryonic dark matter using the neutralino,<sup>23</sup> an electrically neutral combination of the photino (superpartner of the photon), the zino ( $Z_0$  boson), and the higgsino (Higgs boson). Neutralinos only form at very high energy levels, such as those found during the Big Bang. As a result of their assumed stability, neutralinos should be abundant, and with a mass a hundred times greater than that of protons ( $10^{-22}$  grams), the neutralino may be the missing dark matter particle.

**N**EUTRALINOS CAN BE DETECTED either directly, from interactions in a detector and collisions in a particle accelerator, or indirectly, by means of the particles created by their disintegration or annihilation—photons, neutrinos, positrons, and antiprotons.

The insensitivity of neutralinos to electromagnetic interaction hampers any attempt at direct detection. Neutralinos belong to a vast family of particles known as weakly interacting massive particles (WIMPs). Despite the extremely low probability of their interaction, it should be possible, with a large enough detector and considerable patience, to observe a WIMP coming in contact with a particle of baryonic matter. A number of experiments are currently underway.<sup>24</sup>

Nothing has been found so far.

Another solution to the problem of detecting WIMPs involves producing them artificially from the collisions of particle beams in accelerators. Attempts to detect WIMPs in this manner are the focus of ongoing research at CERN's Large Hadron Collider (LHC).<sup>25</sup> To date, researchers at the LHC have not found anything either.<sup>26</sup> Despite these disappointing results, SUSY can never really be completely overturned. The theory contains numerous free parameters and can be adjusted so that its predicted particles only appear at energy levels beyond the reach of current

colliders. Such arbitrary adjustments inevitably detract from the elegance of the theory, compromising the attribute that made it attractive in the first place.

**A**NOTHER POTENTIAL INDIRECT means of detecting WIMPs involves antimatter. In theory, each particle has an associated antiparticle with the same mass but the opposite electrical charge: the positron for electrons, antiquark for quarks, antiproton for protons, and so on. Antimatter is composed of these antiparticles. Antihydrogen, for example, has a positron in orbit around an antiproton. When antimatter comes into contact with matter, the two annihilate each other, creating radiative energy. When mass is created from energy, as occurs in particle accelerators, it is equally distributed between particle pairs and antiparticles. Antihydrogen was produced for the first time at CERN in 1996. The Alpha collaboration at CERN has recently managed to confine a thousand antihydrogens for several hours by using a magnetic trap.

Following the Big Bang, the universe was in a hot plasma state, behaving like a vast natural particle accelerator. Although it should have generated just as much matter as antimatter, the composition of the current universe suggests otherwise. On average, there seems to be only one antiparticle for every billion particles.<sup>27</sup> High-energy physics models have been developed to explain this asymmetry. Although none of the models are completely convincing, Gabriel Chardin and, in a different way, Jean-Pierre Petit have nonetheless attributed a negative and repulsive gravitational mass to antimatter.<sup>28</sup> Although it seems unlikely, this hypothesis has the advantage of being easy to test in the laboratory. CERN's Alpha experiment will attempt to find out what happens when artificially produced antiatoms are dropped in a gravitational field.<sup>29</sup> A result that contradicts standard theories would be truly revolutionary, but the chances seem remote. The most likely finding is that antimatter does not contribute to dark matter density.

Despite the lack of results, dark matter researchers are keenly interested in the positron and antiproton fluxes observed in some cosmic rays. Both antiparticles are produced by conventional astrophysical sources such as pulsars, but they might also emerge from the disintegration of exotic dark matter. In 2011, the Alpha Magnetic Spectrometer was installed on the International Space Station. To date, the detector has detected several billion antiparticles, but no anomaly in the flow of antiparticles has revealed their origin.<sup>30</sup>

**T**HREE CATEGORIES OF THEORIES have been developed in an effort to explain non-baryonic dark matter: cold dark matter, hot dark matter, and warm dark matter. In the absence of direct experimental evidence, these theories can still be evaluated by comparing their implications for the formation of galaxies,

clusters, and superclusters of galaxies against astronomical observations.

In the case of HDM, the contribution of ordinary neutrinos to energy density is negligible given their low mass energy. They cannot account for non-baryonic dark matter. There may well be other WIMPs, but their numbers are constrained by the formation of galaxies.<sup>31</sup> High-speed particles slow the formation process and fragment agglomerates of matter. Simulations have shown that if HDM were prevalent, galaxy superclusters would have formed early in the history of the universe, only to break apart into smaller clusters and galaxies.<sup>32</sup> Such a scenario conflicts with observations from both ground and space-based telescopes, which indicate that first stars, then galaxies, must have formed less than a billion years after the Big Bang.<sup>33</sup> HDM will likely be ruled out as a candidate for dark matter.

According to CDM theories, cold WIMPs emerged from the Big Bang at speeds significantly slower than that of light. These particles aggregated into galactic masses faster than hot matter, meaning that galaxies formed before clusters—a scenario supported by observations. Numerical simulations involving CDM also provide a credible account of supergalactic-scale structuring in the early universe. CDM has long seemed the most plausible of the three candidates.

None of these particles has ever been detected.

Both WDM and CDM theories correctly explain the formation of structures on a supergalactic scale. One cannot be chosen over the other on this basis alone.<sup>34</sup> Another approach involves numerical simulations on a subgalactic scale, which can then be compared to observational counts of dwarf galaxies in orbit around large galaxies. These comparisons have also proven inconclusive. Some simulations are indeed compatible with CDM assumptions, but only a portion of WDM models are eliminated. How then to distinguish between CDM and the remaining WDM models? Three scenarios are currently being investigated: the formation of dark halos, or dark matter halos, that envelop galactic discs and extend well beyond the visible limits of galaxies;<sup>35</sup> gravitational shear, the distortion of images of distant galaxies by foreground mass concentrations;<sup>36</sup> and tidal stellar streams, groupings of stars orbiting a galaxy born from an ancient dwarf galaxy predecessor and elongated along its orbit by tidal forces.<sup>37</sup>

Although it is not currently possible to distinguish between CDM and WDM models on scales greater than a few million light-years, the pair offer different predictions on the scale of gravitational microlenses. If it turns out that future results eliminate pure CDM theory, the remaining explanations for nonbaryonic dark matter will be limited. Sterile neutrinos will remain a possible constituent, along with a mixture of different forms of dark matter, provided, of course, that none of the ingredients are mutually exclusive.

FACED WITH SO MANY unresolved questions and problems, researchers have challenged the very notion of dark matter, considering, instead, a change to the laws of gravity. First proposed by Mordehai Milgrom in 1983,<sup>38</sup> modified Newtonian dynamics (MOND) assumes that Newton's second law must be corrected at low accelerations—beneath a threshold several orders of magnitude below earth's gravity. Such a regime would be in effect in the outmost regions of spiral galaxies. Modified gravity may also explain the stellar velocity profile measured by Rubin, Ford, and Thonnard but without recourse to dark matter.

MOND has been modified many times in response to conflicting observations. Although the theory works well for galaxies, it is less effective at larger scales. Under MOND, the dynamics of galaxy clusters cannot be reproduced without incorporating dark matter. This is also true for explanations of the anisotropy spectrum found in the cosmic diffuse background, gravitational lensing, and the formation of large structures.<sup>39</sup>

As observations become ever more refined, MOND is becoming ever more unstable. The absence of dark matter in NGC1052-DF2, for example, contradicts the theory because its gravitational signature should be present in all galaxies. The same is true of super-spiral galaxies much larger than our Milky Way. Astronomers recently measured the rotation speed of 23 super-spirals and found very fast rotations involving the presence of a large quantity of matter.<sup>40</sup>

Despite these issues, MOND has not been discarded. Based on the observation that MOND works best on the scale of galaxies and dark matter on larger scales, various approaches have been proposed to reconcile the two competing models. In 2014, Justin Khoury proposed a new theory of superfluid dark matter.<sup>41</sup> Superfluids are liquids that exhibit zero viscosity when cooled to relatively low temperatures, such as 2 K (−271°C) for helium-4. According to Khoury, dark matter is superfluid at the scale of galaxies, but too hot to maintain these properties at larger scales, whereupon it reverts to conventional dark matter. The idea of a superfluid dark matter had been proposed previously, but Khoury's model was able to reproduce MOND's predictions in galaxies without any need for modified gravity.<sup>42</sup>

Another way to avoid the use of hypothetical dark matter is to view gravity not as a fundamental interaction, but as an emerging phenomenon of fundamental quantum information bits encoded in the intimate structure of space-time. In the recent entropic gravity models of Erik Verlinde, dark matter is considered an illusion arising from the dynamics that link dark energy and ordinary baryonic matter.<sup>43</sup> Although not yet fully developed, this theory has already successfully reproduced the rotation curves of spiral galaxies.<sup>44</sup> The next step is to construct a theory capable of describing the evolution of the primordial universe.

*Translated and adapted from the French by the editors.*

*Jean-Pierre Luminet is Director of Research at the CNRS Astrophysics Laboratory in Marseille and the Paris Observatory.*



1. Fritz Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln (The Redshift of Extragalactic Nebulae)," *Helvetica Physica Acta* 6 (1933): 110–27.
2. Steven Allen, August Evrard, and Adam Mantz, "[Cosmological Parameters from Clusters of Galaxies](#)," *Annual Review of Astronomy and Astrophysics* 49, no. 1 (2011): 409–70, doi:10.1146/annurev-astro-081710-102514.
3. Vera Rubin, W. Kent Ford, and Norbert Thonnard, "[Rotational Properties of 21 Sc Galaxies with a Large Range of Luminosities and Radii from NGC 4605 \(R = 4kpc\) to UGC 2885 \(R = 122kpc\)](#)," *Astrophysical Journal* 238 (1980): 471–87, doi:10.1086/158003.
4. Carlos Frenk and Simon White, "[Dark Matter and Cosmic Structure](#)," *Annalen der Physik* 524, no. 9–10 (2012): 507–34, doi:10.1002/andp.201200212.
5. Alexander Refregier, "[Weak Gravitational Lensing by Large-Scale Structure](#)," *Annual Review of Astronomy and Astrophysics* 41 (2003): 645–68, doi:10.1146/annurev.astro.41.111302.102207.
6. That is, the distribution of temperature irregularities in the first radiation emitted by the universe when it was only 380,000 years old. Charles Bennett et al., "[Nine-Year Wilkinson Microwave Anisotropy Probe \(WMAP\) Observations: Final Maps and Results](#)," *The Astrophysical Journal Supplement Series* 208, no. 2 (2012), doi:10.1088/0067-0049/208/2/20.
7. Peter Ade et al., "[Planck 2015 Results. XIII. Cosmological Parameters](#)," *Astronomy & Astrophysics* 594, no. 13 (2016): A13, doi:10.1051/0004-6361/201525830.
8. Shannon Hall, "[Ghost Galaxy Is 99.99 Per Cent Dark Matter with Almost No Stars](#)," *New Scientist*, August 25, 2016.
9. Pieter van Dokkum et al., "[A Second Galaxy Missing Dark Matter in the NGC 1052 Group](#)," *The Astrophysical Journal Letters* 874, no. 1 (2019), doi:10.3847/2041-8213/ab0d92.
10. The projects involved include EROS (Experiment in Search of Dark Objects) and OGLE (Optical Gravitational Lensing Experiment). Above one-thousandth of a solar mass, MACHOs are massive enough to act as gravitational microlenses. This effect can be used to obtain an upper bound to their presence in the halo of galaxies. See Patrick Tisserand et al., "[Limits on the Macho Content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds](#)," *Astronomy and Astrophysics* 469, no. 2 (2007): 387–404, doi:10.1051/0004-6361:20066017; Lukasz Wyrzykowski et al., "[The OGLE View of Microlensing towards](#)

- [the Magellanic Clouds: IV. OGLE-III SMC Data and Final Conclusions on MACHOs](#),” *Monthly Notices of the Royal Astronomical Society* 416, no. 4 (2011): 2,949–61, doi:10.1111/j.1365-2966.2011.19243.x.
11. Achim Weiss, “[Big Bang Nucleosynthesis: Cooking up the First Light Elements](#),” *Einstein Online* 2 (2006): 1,017.
  12. Ramanath Cowsik and John McClelland, “[An Upper Limit on the Neutrino Rest Mass](#),” *Physical Review Letters* 29, no. 10 (1972), doi:10.1103/PhysRevLett.29.669.
  13. The first cosmology article I published was precisely about the possibility that neutrinos, about which little was known yet, would have sufficient mass to close the universe, i.e., would give it a density higher than the critical density. Jean-Pierre Luminet and J. Schneider, “[Constraints on Leptonic Asymmetry and Cosmological Constant from Neutrino Rest Mass](#),” *Astronomy and Astrophysics* 98, no. 2 (1981): 412–14.
  14. Susanne Mertens, “[Direct Neutrino Mass Experiments](#),” *Journal of Physics: Conference Series* 718, no. 2 (2016), doi:10.1088/1742-6596/718/2/022013.
  15. Mikhail Shaposhnikov, “[Sterile Neutrinos in Cosmology and How to Find Them in the Lab](#),” *Journal of Physics: Conference Series* 136 (2008), doi:10.1088/1742-6596/136/2/022045.
  16. The researcher who provided the first tools to understand them was the Italian physicist Ettore Majorana, one of the great figures in twentieth-century physics. In 1938, Majorana disappeared under mysterious circumstances when he was not yet 32 years old. Like Isaac Newton, he preferred not to make his ideas public and the importance of Majorana’s work was not properly understood for decades. For a brief biography, see Josh Gelernter, “[Lost at Sea](#),” *Inference: International Review of Science* 2, no. 3 (2016).
  17. This work follows from hypotheses previously made by Ettore Majorana. Salvatore Esposito, *The Physics of Ettore Majorana: Theoretical, Mathematical, and Phenomenological* (Cambridge: Cambridge University Press, 2015).
  18. In 2016, researchers at the IceCube Neutrino Observatory in Antarctica found no evidence for the existence of sterile neutrinos. Yet two years later, researchers at the MiniBooNE collaboration found a much larger than expected oscillation for neutrinos, an indication in their favor. See Davide Castelvecchi, “[Icy Telescope Throws Cold Water on Sterile Neutrino Theory](#),” *Nature News* (2016), doi:10.1038/nature.2016.20382; Alexis Aguilar-Arevalo et al. (MiniBooNE Collaboration), “[Significant Excess of Electron-like Events in the MiniBooNE Short-Baseline Neutrino Experiment](#),” *Physical Review Letters* 121, no. 22 (2018): doi:10.1103/PhysRevLett.121.221801.
  19. John Preskill, Mark Wise, and Frank Wilczek, “[Cosmology of the Invisible Axion](#),” *Physics Letters B* 120, no. 1–3 (1983): 127–32, doi:10.1016/0370-2693(83)90637-8. Frank Wilczek adopted the name Axion from a brand of detergent to reflect that the problem plaguing quantum chromodynamics (the theory of strong interaction), namely the violation of charge-parity symmetry, had been resolved.
  20. Alexey Boyarsky et al., “[Sterile Neutrino Dark Matter](#),” *Progress in Particle and Nuclear Physics* 104 (2019): 1–45, doi:10.1016/j.pnpnp.2018.07.004.
  21. The European experiment is the CERN Axion Solar Telescope (CAST). The US experiment is known as the Axion Dark Matter Experiment (ADMX). Nick Du et al. (ADMX Collaboration), “[A Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment](#),” *Physical Review Letters* 120 (2018), doi:10.1103/PhysRevLett.120.151301.
  22. Stephen Martin, “[A Supersymmetry Primer, Perspectives on Supersymmetry](#),” *Advanced Series on Directions in High Energy Physics* 18 (1997): 1–98, doi:10.1142/9789812839657\_0001.
  23. Gerard Jungman, Marc Kamionkowski, and Kim Griest, “[Supersymmetric Dark Matter](#),” *Physics Reports* 267, no. 5–6 (1996):195–373, doi:10.1016/0370-1573(95)00058-5.
  24. These experiments include EDELWEISS in France, XENON in Italy, LUX in the US, and PandaX in China.
  25. Felix Kahlhoefer, “[Review of LHC Dark Matter Searches](#),” *International Journal of Modern Physics A* 32, no. 13 (2017), doi:10.1142/S0217751X1730006X.
  26. In 1994, Kenneth Lane and David Gross made a bet on SUSY during a dinner at the summer school of theoretical physics in Erice, Sicily. At the time, the predicted sparticle had not been detected, but plans for the LHC had been drawn up. Lane proposed that if the new collider proved the theory, he would pay for a meal at Girardet, a restaurant in Lausanne widely considered among the world’s best. If the theory was not proven, Gross would pick up the check. Written on a tablecloth, the terms of the bet stipulated that it would be payable as soon as the LHC produced sufficient high-energy collisions to be certain of the outcome. The minimum number was estimated at 5 quadrillion. A quarter of a century later, Girardet no longer exists. Since 2010, the LHC has collected more than 15 quadrillion pieces of data without finding any trace of a spark, even when the energy range should have allowed for it. Lane claims that the bet is now payable, if not at Girardet’s, then at another restaurant of a similar caliber. But Gross is not about to concede. The data have been gathered, but the analysis is not yet complete. N.b., 1 quadrillion =  $10^{24}$ . The amount of data produced by a particle accelerator is measured in a dark unit known as a reverse femtobarn that corresponds to about 1023 collisions.
  27. As a result, there would be no stars or galaxies made of antimatter. Laurent Canetti, Marco Drewes, and Mikhail Shaposhnikov, “[Matter and Antimatter in the Universe](#),” *New Journal of Physics* 14, no. 9 (2012), doi:10.1088/1367-2630/14/9/095012.
  28. Giovanni Manfredi et al., “[Cosmological Structure Formation with Negative Mass](#),” *Physical Review D* 98 (2018), doi:10.1103/PhysRevD.98.023514; Jean-Pierre Petit and Pierre Midy, “[Geometrization of Matter and Antimatter through Coadjoint Action of a Group on Its Momentum Space](#)” (1998).
  29. Ana Lopes, “[New Antimatter Gravity Experiments Begin at CERN](#),” *CERN*, November 2, 2018.

- 
30. Manuel Aguilar et al. (AMS Collaboration), "[Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station](#)," *Physical Review Letters* 113, no. 12 (2014), doi:10.1103/PhysRevLett.113.121102.
31. Lam Hui et al., "[Ultralight Scalars as Cosmological Dark Matter](#)," *Physical Review D* 95, no. 4 (2017), doi:10.1103/PhysRevD.95.043541.
32. Simon White, Carlos Frenk, and Marc Davis, "[Clustering in a Neutrino-Dominated Universe](#)," *Astrophysical Journal* 274, no. 1 (1983): L1–L5, doi:10.1086/184139.
33. Gianfranco Bertone, Dan Hooper, and Joseph Silk, "[Particle Dark Matter: Evidence, Candidates and Constraints](#)," *Physics Reports* 405, no. 5–6 (2005): 279–390, doi:10.1016/j.physrep.2004.08.031.
34. Robert Smith and Katrina Markovic, "[Testing the Warm Dark Matter Paradigm with Large-Scale Structures](#)," *Physical Review D* 84, no. 6 (2011), doi:10.1103/PhysRevD.84.063507.
35. Risa Wechsler and Jeremy Tinker, "[The Connection between Galaxies and Their Dark Matter Halos](#)," *Annual Review of Astronomy and Astrophysics* 56 (2018): 435–87, doi:10.1146/annurev-astro-081817-051756.
36. Martin Kilbinger, "[Cosmology with Cosmic Shear Observations: A Review](#)," *Reports on Progress in Physics* 78, no. 8 (2015), doi:10.1088/0034-4885/78/8/086901.
37. Nilanjan Banik et al., "[Probing the Nature of Dark Matter Particles with Stellar Streams](#)," *Journal of Cosmology and Astroparticle Physics* (2018), doi:10.1088/1475-7516/2018/07/061.
38. Mordehai Milgrom, "[A Modification of the Newtonian Dynamics as a Possible Alternative to the Hidden Mass Hypothesis](#)," *Astrophysical Journal* 270 (1983): 365–70, doi:10.1086/161130.
39. Constantinos Skordis et al., "[Large Scale Structure in Bekenstein's Theory of Relativistic Modified Newtonian Dynamics](#)," *Physical Review Letters* 96, no. 1 (2006), doi:10.1103/PhysRevLett.96.011301.
40. Patrick Ogle et al., "[A Break in Spiral Galaxy Scaling Relations at the Upper Limit of Galaxy Mass](#)," *The Astrophysical Journal Letters* 884, no. 1 (2019), doi:10.3847/2041-8213/ab459e.
41. Justin Khoury, "[Another Path for the Emergence of Modified Galactic Dynamics from Dark Matter Superfluidity](#)," *Physical Review D* 93, no. 10 (2016), doi:10.1103/PhysRevD.93.103533.
42. At the beginning of the twenty-first century there was much talk of an apparent acceleration anomaly affecting the Pioneer 10 and 11 space probes during their transit through the transneptunian solar system. The anomaly, in this case a very slight deceleration, was measured between 1979 and 2002 and gave rise to numerous studies and speculation. In particular, it was a perfect opportunity for supporters of MOND theory to see it as evidence of the modification of Newton's law in weak gravitational fields. In 2011 the mystery was solved by several teams: the origin of the observed deviation was due to the pressure of infrared radiation emitted by the radioisotope thermoelectric generator (RTG), the small nuclear electric generator embedded on the probes to free itself from solar panels that had become inactive at a long distance from the Sun. The anomaly had nothing to do with modified gravity or dark matter! See Michael Nieto and Slava Turyshev, "[Finding the Origin of the Pioneer Anomaly](#)," *Classical and Quantum Gravity* 21, no. 17 (2004): 4,005–24, doi:10.1088/0264-9381/21/17/001; Slava Turyshev et al., "[Support for the Thermal Origin of the Pioneer Anomaly](#)," *Physical Review Letters* 108, no. 24 (2012), doi:10.1103/PhysRevLett.108.241101.
43. Erik Verlinde, "[Emergent Gravity and the Dark Universe](#)," *SciPost Physics* 2, no. 16 (2017), doi:10.21468/SciPostPhys.2.3.016.
44. Margot Brouwer et al., "[First Test of Verlinde's Theory of Emergent Gravity Using Weak Gravitational Lensing Measurements](#)," *Monthly Notices of the Royal Astronomical Society* 466, no. 3 (2017): 2,547–59, doi:10.1093/mnras/stw3192.
- 

Published on September 28, 2020

<https://inference-review.com/article/the-dark-matter-enigma>