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Review Article

Astronomical Signatures of Dark Matter

Paul Gorenstein and Wallace Tucker

Harvard-Smithsonian Center for Astrophysics, 60 Gardens Street, MS-4, Cambridge, MA 02138, USA

Correspondence should be addressed to Paul Gorenstein; pgorenstein@cfa.harvard.edu

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Several independent astronomical observations in different wavelength bands reveal the existence of much larger quantities of matter than what we would deduce from assuming a solar mass to light ratio. They are very high velocities of individual galaxies within clusters of galaxies, higher than expected rotation rates of stars in the outer regions of galaxies, 21 cm line studies indicative of increasing mass to light ratios with radius in the halos of spiral galaxies, hot gaseous X-ray emitting halos around many elliptical galaxies, and clusters of galaxies requiring a much larger component of unseen mass for the hot gas to be bound. The level of gravitational attraction needed for the spatial distribution of galaxies to evolve from the small perturbations implied by the very slightly anisotropic cosmic microwave background radiation to its current web-like configuration requires much more mass than is observed across the entire electromagnetic spectrum. Distorted shapes of galaxies and other features created by gravitational lensing in the images of many astronomical objects require an amount of dark matter consistent with other estimates. The unambiguous detection of dark matter and more recently evidence for dark energy has positioned astronomy at the frontier of fundamental physics as it was in the 17th century.

1. Introduction

Astronomy and physics have had a mutually beneficial partnership. The late 16th century astronomical observations of planetary positions as a function of time by the Danish astronomer Tycho Brahe were analyzed and interpreted by Johannes Kepler. Three laws relating planetary motion and distance from the Sun were abstracted from Kepler's analysis. Galileo's telescopic observations of the Sun and planets in the early 17th century established the connection between Kepler's analysis and the validity of the Copernican view of the solar system. With that knowledge in late 17th century Isaac Newton founded modern theoretical physics by explaining Kepler's findings in the context of Galileo's physical picture with his three laws of classical mechanics and the law of universal gravitational attraction.

Aside from the synergy between solar/stellar and laboratory atomic spectroscopy, from that time until the turn of the 20th century, astronomy and fundamental physics did not forge any more connections with such significance. Classifying and cataloging stars, noting their positions, color, and spectra, observing the occurrence of eclipses and the comings and goings of comets, all in accordance with Newton's laws, were the preoccupations of astronomers. In fact, Simon Newcomb the most distinguished American astronomer of his era, founding member and first president of the American Astronomical Society said in 1888, *"We are probably nearing the limit of all we can know about astronomy."* This proved to be as accurate as the belief of many physicists—buoyed by the great success of Maxwell's equations at the turn of the 20th century, prior to the discovery of X-rays and radioactivity, that the only things left to do in fundamental physics was design better measuring devices and build faster computational aids to facilitate applications of Newton's laws and Maxwell's equations [1, 2].

Beginning with the 20th century, profound changes in both astronomy and laboratory physics, plus the development of Einstein's special and general theories of relativity, would bring the two disciplines together again at the frontiers of fundamental physics. Astronomy underwent a great expansion in scope thanks to the construction of new tools such as very large optical telescopes, solid state image sensors, large radio telescopes, and with access to space above the absorption of the atmosphere, far infrared, ultraviolet, X-ray and gamma-ray telescopes. This capability led to the discovery of neutron stars and black holes, objects whose existence could be explained by theoretical physicists following their discovery. Astronomers have also discovered evidence for dark matter, which seems to be primarily nonbaryonic and an even more enigmatic entity known as dark energy. At the current time the total mass-energy content of the known universes described by the so-called Lamda-Cold Dark Matter model is believed to be 5% ordinary matter, 23% dark nonbaryonic matter, and 72% "dark energy."

Dark matter has been discussed by many authors. Trimble reviews our understanding of dark matter from an elegant historical perspective describing events up to 1987. She includes early indications of the existence of dark matter whose significance was not widely recognized at the time [3]. The cosmological connection is described by, for example, Bergstrom [4].

2. Evidence for the Existence of Dark Matter

A variety of independent lines of evidence indicate that galaxies and clusters of galaxies contain much more gravitating matter than the total amount that has been detected across the entire electromagnetic spectrum. The excess is called dark matter (DM). The evidence includes galactic rotation curves, large oxygen-rich halos of star-forming galaxies, the velocity dispersions of stars in elliptical galaxies and of galaxies in clusters of galaxies, gravitational lensing, the confinement of hot gas in galaxy clusters, the pattern of acoustic oscillations in the power spectrum of the cosmic microwave background (CMB), and the imprint of these oscillations on the relative strength, and shape of the galaxy-distribution power spectrum at large wave numbers. The collective evidence suggests that dark matter comprises some twenty-three percent of the energy density of the universe today, ($\Omega_{\mathrm{dm}} = 0.23$) with a precision of a few percent.

2.1. Baryonic Dark Matter.

Some baryons are tied up in dark forms, such as extremely low mass stars or black holes. The Hubble Space Telescope detected large (150 kiloparsec) halos of ionized oxygen surrounding star-forming galaxies. They contain a substantial amount of heavy elements and gas, perhaps exceeding the reservoirs of gas within the galaxies [5]. However, only a small fraction of DM can be baryonic. The ratio of the acoustic peaks in the CMB radiation spectrum, as well as calculations of the nuclear synthesis processes that took place following the Big Bang (prior to any star formation), when compared to the observed ratios of D/H, He/H and Li/H, indicate that the normalized mass-energy density of baryonic matter is $\Omega_b = 0.0456 \pm 0.0016$ [6]. At high redshifts ($z > 2$), most of the baryonic matter in the universe resides outside of galaxies in diffuse filamentary photoionized intergalactic clouds. Their presence has been revealed through the detection of hydrogen absorption lines in the spectra of distant quasars. Each individual cloud, which in general has a different redshift, leaves its Lyman-alpha fingerprint as an absorption feature at a different wavelength in the observed optical spectrum of a distant quasar. Collectively the Lyman-alpha clouds impose a complex of absorption lines known as the "Lyman-alpha forest" on the visible light spectrum of the distant quasar [7]. With time, gravity causes a fraction of gas in the intergalactic clouds to condense and form galaxies.

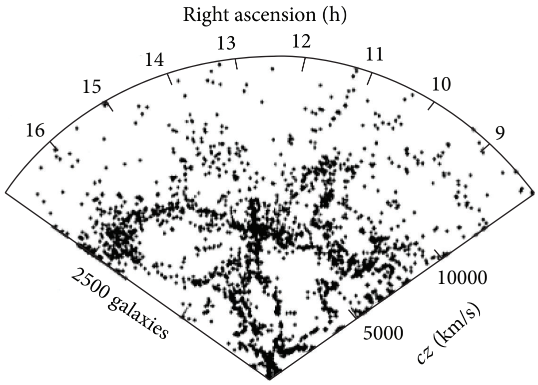


Figure 1: The web-like spatial distribution of galaxies reported by Geller and Huchra [8].

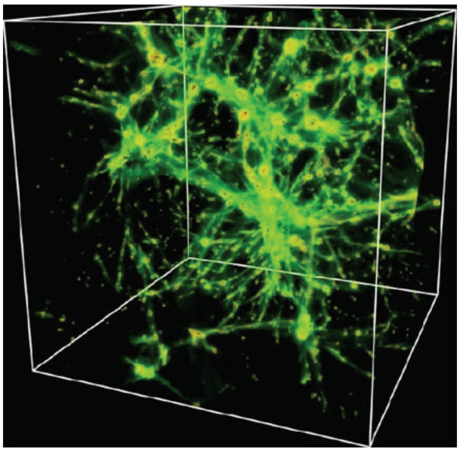


Figure 2: The spatial distribution of hot baryons in the model of Cen and Ostriker [9] and Davé et al. [10].

On a large scale, the spatial distribution of relatively nearby galaxies (Figure 1) [8] exhibits a web-like structure with regions of high and low density concentrations of galaxies. Hydrodynamic simulations of the evolution of structure of the intergalactic medium under the influence of gravity can reproduce the Lyman-alpha forest and the observed web-like structure of galaxies (see Figure 2). The models show that, by the present day, approximately half of all baryons should have become incorporated into galaxies, and a hot intracluster medium in galaxy clusters. The remaining ~50% is predicted to be in a warm-hot intergalactic medium (WHIM) [10] that was shock-heated by gravitational collapse to temperatures in the range $0.1\,\mathrm{MK} < T < 10\,\mathrm{MK}$.

The simulations show that the temperature of the baryonic portion of the clouds increases with time. This implies that clouds closer to the observer and further from a distant background quasar are warmer. The higher temperature hydrogen in nearby clouds is ionized and not capable of causing Lyman-alpha absorption. The clouds also contain heavier elements, for example, carbon and oxygen with abundance $\sim 10^{-3}$ hydrogen. Warm oxygen in a cloud along the line of sight absorbs ~0.6 keV (2 nm wavelength) X-rays in the spectrum of a quasar or other type active galaxy. Because we do not know the distance and temperature of the X-ray absorbing cloud and the degree of ionization of the oxygen atoms, the exact wavelengths of the absorption lines are not known a priori.

The most promising method for detecting the hot part of the WHIM is through absorption of far-ultraviolet (FUV) and X-radiation from a background source. Over the last few years, detections have been reported by a number of authors, but these have been biased toward the strongest systems, or trace extreme galaxy overdensity regions, and therefore may not be representative. Chandra grating spectromers, combined with earlier XMM-Newton and Chandra observations, gave a 4σ detection of the OVII Kα absorption line in the spectrum of a background blazer (a bright nonthermal source thought to be powered by accretion onto a supermassive black hole) at redshift $z = 0.165$ behind the SculpterWall, a large superstructure of galaxies at $z = 0.03$ [11]. Because the redshift of the SculpterWall is known, absorption signatures can be regarded as significant even if they are less prominent than those found in a random search. For a metallicity $Z =$ 10% of the solar value the implied overdensity is consistent with cosmological simulations. A dedicated X-ray mission with much larger area and much better spectral resolution is needed to trace the bulk of the WHIM. The current status of intergalactic soft X-ray absorption line spectroscopy is described in a special section of the journal Science [12].

2.2. The Velocity Dispersion of Galaxies in Large Clusters of Galaxies. Papers by Zwicky in the 1930s [13, 14] were early indications of the existence of dark matter. Zwicky noted that the radial velocities of the galaxies in the Coma Cluster of galaxies (Figure 3) were much larger than what would be expected by assuming that the galaxies have the same ratio of mass to light, M/L, as the Sun. The Coma Cluster of galaxies is one of largest structures in the universe and therefore an excellent sample of its constituents. The virial theorem states that $\langle W\rangle = -\langle U\rangle/2$, where $\langle W\rangle$ is the time average of the total kinetic energy and $\langle U\rangle$ is the time average of the total potential energy. It applies to a stable system consisting of particles, bound by potential forces, with the total potential energy U. Because it is nota young object, it is reasonable to assume that the galaxies in the Coma Cluster are in equilibrium within a stable system.

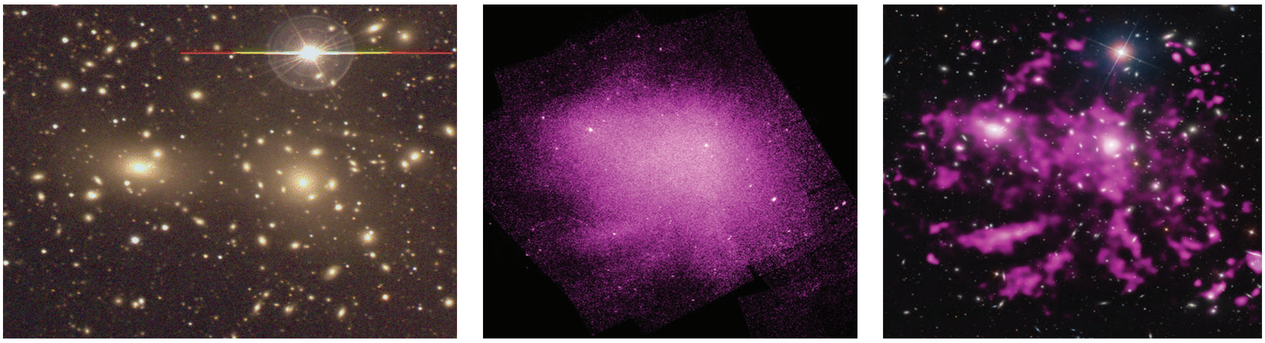
Applying the virial theorem to the observed kinetic energy indicates that the potential energy and consequently the mass of the Coma Cluster is much larger than the mass obtained by assuming a solar-like mass to light ratio. The popular term for this disparity became known as the "missing mass." Although there were other indications of a discrepancy between the solar mass to light ratio and the mass of some other objects, it took thirty years for other types of measurements to confirm the existence of dark matter as convincingly as had Zwicky's measurements of the Coma Cluster.

Zwicky and his contemporaries did not know that the Coma Cluster contains a halo of hot, $\sim 10^8$ K gas whose mass is ~5 times larger than the mass of the stars in the galaxies. That became known some forty years later after X-ray telescopes were launched into space. Although the baryonic mass becomes much larger after taking the hot gas into account, it is still a factor ~6 too small to explain the high velocities of the galaxies. Also the existence and presumably the stability of the hot gas halo is also an indication that a larger quantity of mass is present. Determining the mass of an object by measuring the parameters of a hot gas halo is discussed in more detail in Section 2.4. There are modern investigations of dark matter using Zwicky's methods [15].

A 1959 theoretical paper by Kahn and Woltjer showed that the Local Group of galaxies can be dynamically stable only if contains an appreciable amount of intergalactic matter that is not seen [16]. At the time visible light images were thought to define the limits of the galaxy so their extended dark halos could satisfy the need for dark matter. They did not address the issue of whether and not the intergalactic dark matter was baryonic. Measurements with the Hubble Space Telescope of the velocity vector of neighbor galaxy M31 towards the Milky Way confirm that the Local Group of galaxies has a much larger mass to light ratio than the Sun [17], confirming the theoretical work of Kahn and Woltjer. The RAVE survey of high velocity stars constrains the local galactic escape speed to within a range that demonstrates the presence of the Galaxy's dark halo [18].

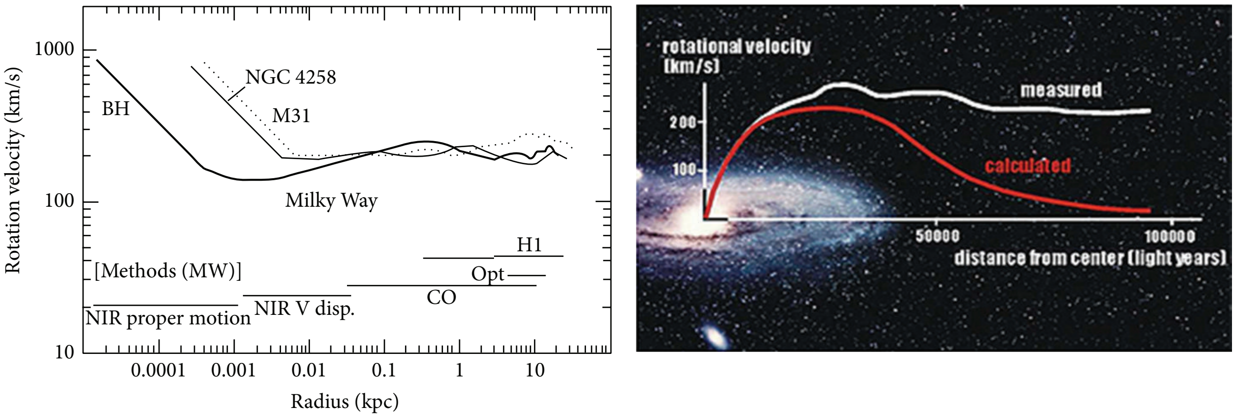
2.3. The Flatness of the Rotation Curve of Galaxies. As was first discovered a hundred years ago, the stars and clouds of a spiral galaxy are generally rotating about the galaxy's center. A measurement of the orbital velocities of stars as a function of distance from the center of rotation in spiral galaxies yields the mass interior to the stars' positions. Rubin and her colleagues studied the rotation of several spiral galaxies including the Milky Way and the Andromeda galaxy, M31 [19, 20]. The orbital, or circular velocities of stars and clouds. V_c were measured in visible light and by others in radio. According to simple Newtonian mechanics $V_c^2 = GM/r$, the rotation curve $V_c(r)$ should first rise (because more mass is being included with increasing radius) and then decrease inversely with distance beyond the radius where the mass ends. But the rotation curves of the observed galaxies, after first rising and then falling, almost invariably flatten out. This behavior continues well beyond the edge of the disk as traced by the 21 cm line of atomic hydrogen with even more confidence [21]. The failure of galactic rotation curves to fall off as theoretically expected is perhaps the strongest evidence for the widespread belief that disk galaxies are all embedded in massive DM halos. This is shown in Figure 4(a), as actually measured and, in Figure 4(b), pictorially.

These optical and radio observers did not claim that the dark matter was nonbaryonic. However there were others



(a) (b) (c)

Figure 3: The Coma Cluster of galaxies. An optical image (a) shows two giant galaxies near the center plus a number of smaller galaxies. The raw X-ray image (b) was taken by the Chandra X-Ray Observatory. The size of the optical and X-ray fields shown is about 600 kpc (2 million light years). (c) is an overlay of the optical image with a high contrast X-ray image that displays the regions with high X-ray surface brightness around two giant elliptical galaxies that dominate the cluster.



(a) (b)

Figure 4: (a) shows the rotational velocity of stars as a function of distance from the center for three galaxies, the Milky Way, M31, and NGC 4258. (b) is a pictorial representation [20, 22].

who claimed that indeed the halo mass contained a nonbaryonic component [23].

The same general analysis applied to elliptical galaxies, with the dispersion of the stellar velocities replacing the circular velocities, also provides evidence for the existence of dark matter. Dwarf spheroidals (dSphs) are small galaxies, with Mtot ~10^7 solar masses, and relatively large dispersion velocities. In some extreme cases the deduced amount of dark matter is an order of magnitude or higher than that deduced for spiral galaxies, implying that dark matter constitutes more than 95% of the matter in these galaxies [24]. One possible explanation for the extreme dark matter content of dwarf spheroidal galaxies is that heating, by supernovae or some other process, has driven most of the baryonic matter out of these galaxies.

A modification of Newtonian dynamics (MOND), according to which the acceleration term in Newton's second law become nonlinear for very small accelerations, corresponding to large distances, has been offered as an alternative explanation for the flattening of the rotation curves of galaxies [25]. A general-relativistic version was described later [26]. When it was introduced MOND was as good an explanation for the high rotation rates as assuming that the galaxy had a dark matter corona. However, it is not clear that it is possible to find a single version of MOND that can explain all the phenomena that have been associated with dark matter.

2.4. The Hot Gas Coronas of Large Elliptical Galaxies. M87 is a giant elliptical galaxy with an extended corona of X-ray emitting hot gas and two opposing jets projecting out from a giant black hole at the center. The mass of M87's giant central black hole is 3×10^9 solar, where the solar mass is 2×10^{33} grams [27]. It is small compared to the visible mass and much smaller than the DM in M87. A Chandra X-Ray Observatory image of M87 is shown in Figure 5. The hot gaseous corona is likely to be in hydrostatic equilibrium.

From the equation of hydrostatic equilibrium shown below, the total mass, $M(< r)$ can be determined almost

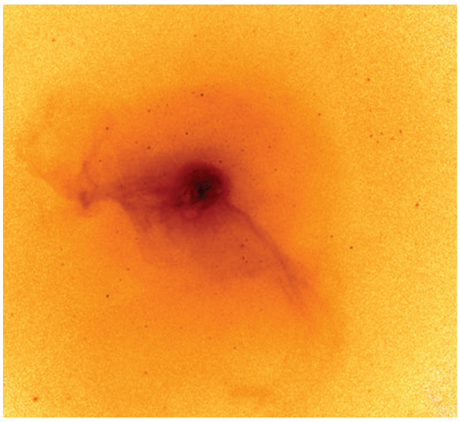


FIGURE 5: A Chandra X-Ray Observatory image of the giant elliptical galaxy M87 in the constellation Virgo. (provided by W. Forman of CfA). There is a large X-ray halo as well as features created by episodic outbursts emanating from a giant black hole at the center [28]. The field is about 10 arc minutes. The distance to M87 is about 16.4 Mpc (53 million light years).

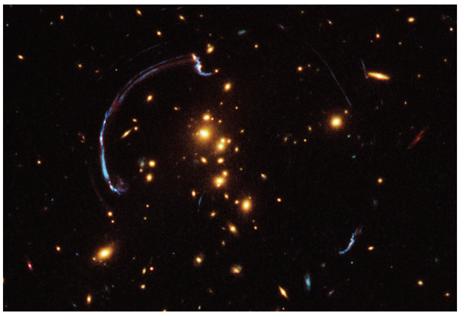


FIGURE 6: Gravitational arc from a distant galaxy behind a foreground galaxy cluster [36]. Credit: NASA, ESA, and A. Gonzalez (University of Florida, Gainesville), A. Stanford (University of California, Davis and Lawrence Livermore National Laboratory), and M. Brodwin (University of Missouri-Kansas City and Harvard-Smithsonian Center for Astrophysics) The giant arc, an incomplete Einstein Ring shown is an example of strong gravitational lensing. The more typical effect is weak gravitational lensing [37]. The process is described in more detail by Massey et al. [38].

independent of the model by measuring the density and temperature gradients as a function of radius, assuming spherical symmetry, and taking in account that we are observing M87 projected onto a plane:

$$M(<r) = \frac{-kT_{\text{gas}}}{G_{\mu}M_H}\left(\frac{d\log\rho_{\text{gas}}}{d\log r} + \frac{d\log T_{\text{gas}}}{d\log r}\right) r. \qquad (1)$$

Within a radius of 87 kpc, or 275 million light years, (20 arc minutes) the optical luminosity is 6.6×10^{10} solar (solar luminosity = 2×10^{33} ergs/sec), the mass of the gas $M_{\text{gas}} = 2.1 \times 10^{11}$ solar (solar mass = 2×10^{33} g), and the total mass including DM is $M_{\text{tot}} = 1.3 \times 10^{13}$ solar, with a model dependent uncertainty of a factor of 2 due to errors in chemical abundances and assumptions made in deprojecting the X-ray image [29]. At larger radii the visible light does not increase much more and the ratio of mass of DM to the gas is larger. M87 is in the Virgo cluster of galaxies so there is a limit to how much further from the center can be studied without encountering another galaxy.

These results are confirmed, within the uncertainties, by observing the velocities of 161 globular clusters orbiting M87 [30]. A globular cluster is a gravitationally bound aggregate of up to a million stars usually in the halo of a galaxy. They act as test particles, whose positions and velocities can be measured. Planetary nebular are another set of test particles. They are observed in M87's halo up to a radial distance of 150 kpc [31].

The X-ray measuring technique has been widely applied, especially to data from the Chandra X-Ray Observatory, to measure the baryonic and dark matter content of many hydrodynamically relaxed galaxy clusters, with the general result that the mass of dark matter in galaxy clusters is ~5 to 10 times that of the baryonic matter [32, 33]. If, as seems reasonable, large galaxy clusters are representative of the universe as a whole, this can be taken to be the cosmic value of the ratio of dark to baryonic matter [34].

2.5. Gravitational Lensing. Gravitational lensing is a technique that uses the distorted images of distant galaxies as a tracer of dark matter in a foreground object. The patterns of the distortions reflect the density of matter along the line of sight. The process is essentially the same as that which Arthur Eddington used for measuring the change in positions of stars when their positions are close to the solar disk, as observed during a solar eclipse. After applying some corrections, Eddington reported that the changes in stellar positions were in agreement with the predictions of General Relativity. On a cosmic scale the same process can be used to map the distribution of matter in a foreground object by observing the distorted and often multiple images of a distant point source. The geometry is far more complex because unlike the Sun the foreground lens is not a simple sphere but a cluster of galaxies. Figure 6 is one of the Hubble Space Telescope images that show the effect [35].

One of the most significant examples of utilizing gravitational lensing to trace the location of mass is shown in Figure 7. Two clusters of galaxies collided ~100 Myr ago and appear to be passing through each other to create the "Bullet Cluster" [39]. The clusters are believed to be moving in the plane of the figure. The gaseous halos are lagging behind. Analysis of weak gravitational lensing effects in the image shows that the mass, which is mostly DM, is associated with the galaxies and not with the hot gas [40].

Since the discovery of the Bullet Cluster, a half dozen or so other examples have been found, establishing cluster mergers as important cosmic laboratories for the study of the constraints on the cross-sectionfor dark matter self-interactions. At present the best constraints are still from the Bullet Cluster.

2.6. The Cosmic Microwave Background and the Evolution of Structure. The 2.73 K thermal CMB is the strongest evidence that our universe was indeed created in a Big Bang. The

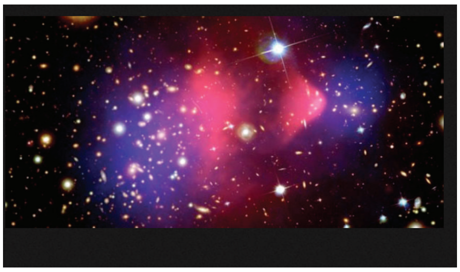


Figure 7: A composite X-ray/optical image of the galaxy cluster 1E 0657-56, also known as the "Bullet Cluster." This cluster was formed following the collision of two large clusters of galaxies. The X-ray image, pink, is from the Chandra X-Ray Observatory. The optical image is from the Magellan telescope and the Hubble Space Telescope; the galaxies are orange and white. The distribution of mass as determined by gravitational lens analysis is blue.

general picture is that quantum fluctuations caused the newborn post-Big Bang ionized matter to be slightly nonuniform. These fluctuations were frozen-in by a sudden inflation or expansion in volume, which has been described as a change in state [41]. About four hundred thousand years after the Big Bang ($z \sim 1000$) the universe had cooled enough for the electrons and protons to combine into neutral atoms that decoupled from the radiation. Following recombination the small nonuniformities ($\delta T/T \sim 10^{-5}$) in the background radiation did not change as it cooled from the infrared to the microwave band, while the universe was expanding.

The current structure of the microwave background radiation represents the structure of the universe as it was 4×10^5 years after the Big Bang. The amount of mass needed to provide the level of gravitational attraction required for the structure of the universe as it was 4×10^5 years ago to evolve into the web-like structure of the galaxies, clusters of galaxies, and the voids we observe today is much larger than what we can detect over the entire electromagnetic spectrum, and it is consistent with other measurements of the amount of dark matter. Although this conclusion is based entirely upon theoretical considerations it is one of the strongest pieces of evidence for the existence of dark matter. However, it provides no direct indication of whether the matter is baryonic or nonbaryonic. Light element abundances and models of Big Bang nuclear synthesis point to the latter (Section 2.1).

Three spacecraft with increasing resolution and sensitivity were launched to map the cosmic microwave background. The first was NASA's Cosmic Background Explorer (COBE) launched in 1989 It was followed by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) in 2001 and ESA's Planck in 2009. A collection of papers on the results of Planck are available online [42]. Figure 8 is the Plank map and a chart of the power in its multipole components.

Analysis of the Planck data is ongoing following a new release in May, 2013. Methods of accounting for terrestrial, solar system, or galactic foreground radiation are being refined, but these corrections are unlikely to change the basic conclusions on the amount of dark matter in the Universe [43].

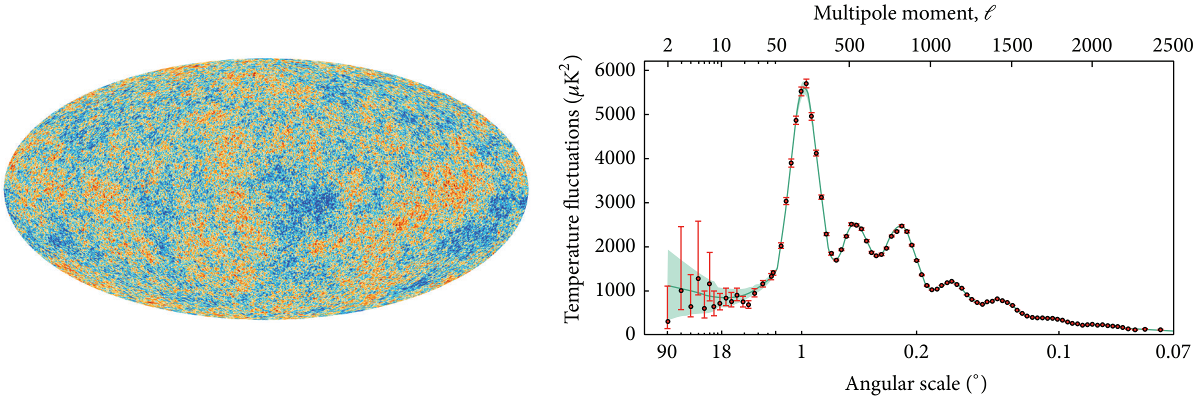
Simulation by computation of complex hydrodynamic and magnetodynamic processes that cannot be studied in the laboratory or observed in the cosmos with any type of telescope has become an important tool in astrophysics, indeed virtually a separate branch of astrophysics on a par with theory and observation. It is being applied to studying the evolution of structure in the universe under the influence of gravity. For example, starting with the structure of the microwave background, which represents the universe as it was 4×10^5 years after the Big Bang determining what is required for it to evolve to the web-like structure it has today with the correct number of spiral and elliptical galaxies and the observed quantities of dark matter and baryonic matter. This effort has been occurring over a period of two decades at various institutions. The most recent and the most detailed simulation so far is the work of the *Illustris* collaboration reported in Nature [44]. This work demonstrates that the Lamda-Cold Dark Matter can correctly describe the evolution of the universe to the web-lie structure it has today with the correct number of spiral and elliptical galaxies, as well as a variety of observational data on small and large scales.

2.7. The Cosmic High Energy Positron and Gamma-Ray Spectra. Some models of the decay of DM predict that high energy positrons will be produced [45]. Indeed, several observations—the positron fraction as measured by the Alpha Magnetic Spectrometer [46] aboard the Space Station and the PAMELA magnetic spectrometer (aboard the Russian Resurs DK-1 spacecraft) [47] plus an excess of gamma-rays, presumably from positron annihilation, seen by the Fermi Gamma-ray Space Telescope [48]—indicate a positron fraction considerably higher than expected from ordinary cosmic ray production. However, there are possible astrophysical sources such as pulsars and the acceleration region of supernova remnants, whose rates of positron production have not been quantified. The positron fraction has been measured up to 300 GeV and is still rising from a minimum at ~7 GeV. While the rising positron flux with energy is not necessarily a positive indication of DM because of other possible cosmic production modes, the results can be interpreted as upper limits upon the rates of decay of a DM particle into positrons.

Another investigator team presents evidence of a 110–140 GeV gamma-ray emission feature from the inner galaxy where dark matter is expected to be enhanced, in the Fermi data [49]. This is expected in some models of the decay of a dark matter particle. However, the statistics are poor and there is the possibility that the emission is from known astrophysical processes. The HESS array of ground based very high energy (>TeV) gamma-ray telescopes in Namibia also searched the galactic center region, without success so far [50].

3. Identity of Dark Matter

3.1. Introduction. We consider the possible identities of dark matter only in general terms. If an element of dark matter is a particle we do not provide a specific description of its



(a)

(b)

Figure 8: Planck all-sky map of the intensity of the cosmic microwave background radiation is shown in (a). (b) is an analysis of its angular structure and multipole components.

properties or attempt to find a place for it within the Standard Model of subatomic particles. It would not be one of those already detected in the laboratory. Other articles in this issue are likely to address this, as has a recent paper by Bergstrom [51] and references in the following paragraphs.

As discussed in Section 2.1, the dark matter is primarily nonbaryonic. That excludes as candidates such very low luminosity stars whose emission is below the detection threshold and isolated planetary objects, also known as "Massive Compact Halo Objects" or MACHOs, although they could account for a small fraction of DM. When a compact object in the halo of our galaxy passes in front of a source star in a nearby dwarf galaxy, the image of a source star experiences a temporary magnification due to gravitational microlensing [52]. MACHOs have been eliminated as accounting for all the dark matter by an unsuccessful search for long-duration microlensing events toward the Large Magellanic Cloud. The observations of the MACHO and EROS collaboration showed that objects whose mass is less than 30 solar masses contribute less than 40% of the dark matter [53]. However the teams did detect a microlensing effect near the center of the galaxy [54]. That effect could be attributed to a region containing many stars plus Sgr A∗, the black hole at the center of the Milky Way.

It has been long thought that dark matter could be explained by an as yet undiscovered massive, weakly interacting elementary particle (WIMP),that is, a thermal relic of the Big Bang. Initially the early Universe was dense and hot, and all particles were in thermal equilibrium. The Universe then cooled to temperatures below the pair creation of dark matter particle's with mass m_{DM} and the number of dark matter particles would have dropped exponentially once $kT \ll m_{\mathrm{DM}}c^2$. In addition to cooling, the Universe was also expanding. Eventually, the Universe would have become so large and the gas of dark matter particles would have become so dilute that they cannot have found each other to annihilate. The dark matter particles then have "frozen out," with their number asymptotically approaching their thermal relic density. These considerations imply that a weakly interacting particle that makes up all of dark matter is predicted to have mass in the range ~100 GeV to 1 TeV [55]. However, if the annihilation cross-section is much less than the weak interaction cross-section, this mass constraint can be relaxed, and dark matter candidates which satisfy the relic density and Big Bang nucleosynthesis constraints successfully can have masses in the keV to TeV range [56].

Observations of large-scale cosmological structures imply that dark matter must be stable, or at least metastable, on Gyr time scales. This rules out all unstable Standard Model particles. Furthermore, the observation that galaxies formed at redshifts $z \sim 10$–20 implies that dark matter cannot be "hot," that is, have a large thermal velocity, at the redshift at which it decouples from matter in the cooling early Universe. For thermal relics, this criterion selects the mass of the dark candidate as well, so that colder particles are heavier. However, alternative nonthermal production scenarios can exist and very light particles can also act as cold dark matter, as in the case of the axion.

Another line of investigation into the nature of dark matter is to look for its effects in the X-ray spectra of cosmic sources. One class of dark matter candidates is called axion-like particles (ALPs). The presence of a magnetic field is predicted to induce conversions of photons into ALPs. The absence of anomalous irregularities in the Chandra X-ray spectrum of the Hydra A cluster produces the most stringent constraint to date in the range of very low mass ALPs, with mass $<10^{-11}$ eV [57]. The archive of 70 Chandra observations of the central region of M31 were used to effectively rule out canonical oscillation-based sterile neutrinos as a viable dark matter candidate in the 2.5–10 keV range, although other mechanisms for producing sterile neutrinos are still possible. Phase-space constraints derived from optical observations of dwarf galaxies in the Local Group have closed the window at lower energies [58].

3.2. MOND, No Dark Matter.

One possibility is that there is no such thing as dark matter. The effects described in

Section 2 would then be entirely due to deviations from Newton's law. The model is Modification of Newtonian Dynamics (MOND). MOND was proposed as an alternative to DM to explain the rotation rates of stars far from the center of the galaxy as described in Section 3.3. The same version of MOND can perhaps also explain the existence of massive hot gaseous halos around M87 and other giant elliptical galaxies, but it is not clear that the same version of MOND can also explain the effects attributed to gravitational lensing by DM in complex geometries like the Bullet Cluster [59]. While a single version of MOND may be able to explain several effects attributed to dark matter, it may not be able to offer an explanation for the growth of structure. Perhaps this could be accomplished by a modified version of MOND that weakens the effects of gravity on the scale of a galaxy to explain the large rotation rates of stars in the gaseous coronas of certain galaxies and modifies the Newtonian dynamics again at the largest distances to explain gravitational lenses and the growth of structure [60]. However, MOND still has a significant number of proponents and its originator has recently offered more evidence in its support [61].

3.3. Primordial Black Holes. The limits on the baryonic mass-energy density rule out black holes created through the process of star formation and evolution. However, it is possible that primordial black holes were created in the very early universe and thereby evades Big Bang nucleosynthesis and CMB constraints. Primordial black holes with masses much less than $\sim 10^{15}$ g ($= 2 \times 10^{-18}$ solar mass) will have evaporated into gamma-rays [62] but more massive black holes could survive until the present epoch [63]. The negative results of the MACHO/EROS collaborative search for microlensing events concluded that objects within the mass range from 3×10^{-8} to 30 solar masses cannot account for more than 40% of dark matter. The lower limit was reduced to 10^{-9} solar masses (2×10^{24} g) by an analysis of Kepler microlensing data [64]. Constraints from the Fermi Observatory of the lack of observed femto-lensing in gamma-ray bursts rule out the range 5×10^{17}–10^{20} g [65]. That left a narrow window of masses in the range 10^{20}–10^{24} g for primordial black holes as viable dark matter candidates. However, an analysis of the capture rate of primordial black holes by neutron stars by Pani & Loeb suggests that primordial black holes with masses between 10^{15} and 10^{24} grams cannot exist in sufficient numbers to explain dark matter [66]. Otherwise tidal capture of primordial black holes by neutron stars followed by rapid accretion into the black hole would have led to the disruption of all the neutron stars in the Galaxy and the Large Magellanic Cloud. If confirmed, this result would severely narrow the window on the possibility that primordial black holes can explain a significant amount of the observed dark matter.

4. Conclusions

As in the 16th and 17th centuries, the interests of astronomers, now more appropriately called astrophysicists, and laboratory physicists are converging upon the same issue at the frontier of fundamental physics, identifying the source and nature of the elusive dark matter. Astronomers are developing a new generation of tools including ground optical based telescopes with 28 to 40 m segmented apertures provided with adaptive optics to correct for atmospheric jitter. Large area optics will be stationed in both the northern and southern hemispheres. The Large Synoptic Survey Telescope (LSST) is likely to find numerous examples of gravitational lenses that will shed light upon dark matter. There will be a second generation space telescope, the James Webb Space telescope (JWST), with extended infrared sensitivity to view objects at very large redshift, which are closer in time to the first generation of star formation and perhaps unveiling the condition of dark matter at that epoch. Radio telescopes can reach even further back in time to study structure at earlier times by mapping the redshifted ubiquitous 21 cm hydrogen line. Radio astronomers are constructing the low frequency array (LOFAR), an international partnership led by The Netherlands. LOFAR will be able to map redshifted 21 cm lines that reveal structure at earlier epochs. Radio astronomers are also planning the Square Kilometer Array. The European Space Agency has approved "Athena," an X-ray telescope system that will have a much larger aperture and much better spectroscopic resolution than the currently orbiting Chandra X-Ray Observatory and XMM-Newton. It will be capable of detecting and measuring the mass of the WHIM by observing oxygen and other elemental absorption lines by foreground clouds in the spectra of quasars with orders of magnitude more sensitivity and better resolution than Chandra and XMM-Newton.

These astronomical facilities will no doubt improve our knowledge about the behavior of dark matter, but a definitive resolution of what the dark matter particles actually are and where they fit in the Standard Model of fundamental particles, if they do indeed fit within, or upset the Standard Model, will ultimately require a positive detection of individual particles either in a debris of particles created by the Large Hadron Collider or by a ground, subterranean or deep oceanic based large area detector array.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] M. Planck, "When I began my physical studies [in Munich in 1874] and sought advice from my venerable teacher Philipp von Jolly...he portrayed to me physics as a highly developed, almost fully matured science...Possibly in one or another nook there would perhaps be a dust particle or a small bubble to be examined and classified, but the system as a whole stood there fairly secured, and theoretical physics approached visibly that degree of perfection which, for example, geometry has had already for centuries," 1924, http://www.goodreads.com/quotes/tag/johann-philipp-gustav-von-jolly.

[2] J. Al-Khalli, "Where science is going," *International New York Times*, vol. 15, 2013.

[3] V. Trimble, "Existence and nature of dark matter in the universe," *Annual Review of Astronomy and Astrophysics*, vol. 25, pp. 425–472, 1987.

[4] L. Bergström, "Cosmology and the dark matter frontier," *Physica Scripta*, vol. 2013, Article ID 014014, 2013.

[5] J. Tumlinson, C. Thom, J. K. Werk et al., "The large, oxygen-rich halos of star-forming galaxies are a major reservoir of galactic metals," *Science*, vol. 334, no. 6058, pp. 948–952, 2011.

[6] G. Steigman, "Primordial nucleosynthesis in the precision cosmology era," *Annual Review of Nuclear and Particle Science*, vol. 57, pp. 463–491, 2007.

[7] July 2013, http://www.astr.ua.edu/keel/agn/forest.html.

[8] M. J. Geller and J. P. Huchra, "Mapping the universe," *Science*, vol. 246, no. 4932, pp. 897–903, 1989.

[9] R. Cen and J. P. Ostriker, "Where are the baryons?" *The Astrophysical Journal*, vol. 514, no. 1, pp. 1–6, 1999.

[10] R. Davé, R. Cen, J. P. Ostriker et al., "Baryons in the warm-hot intergalactic medium," *The Astrophysical Journal*, vol. 552, no. 2, pp. 473–483, 2001.

[11] T. Fang, D. A. Buote, P. J. Humphrey et al., "Confirmation of X-ray absorption by warm-hot intergalactic medium in the sculptor wall," *The Astrophysical Journal*, vol. 714, no. 2, pp. 1715–1724, 2010.

[12] F. Nicastro, S. Mathur, and M. Elvis, "Perspective: missing baryons and the warm-hot intergalactic medium," *Science*, vol. 319, no. 5859, pp. 55–57, 2008.

[13] F. Zwicky, "Die Rotverschiebung von extragalasktischen Nebeln," *Helvetica Physica Acta*, vol. 6, pp. 110–127, 1933.

[14] F. Zwicky, "On the masses of nebulae and of clusters of nebulae," *The Astrophysical Journal*, vol. 86, pp. 217–246, 1937.

[15] A. B. Newman, T. Treu, R. S. Ellis, and D. J. Sand, "The density profiles of massive, relaxed galaxy clusters. II. Separating luminous and dark matter in cluster cores," *The Astrophysical Journal*, vol. 765, no. 1, article 25, 12 pages, 2013.

[16] F. D. Kahn and L. Woltjer, "Intergalactic matter and the Galaxy," *The Astrophysical Journal*, vol. 130, pp. 705–717, 1959.

[17] R. P. van der Marel, M. Fardal, G. Besla et al., "The M31 velocity vector. II. Radial orbit toward the milky way and implied local group mass," *The Astrophysical Journal*, vol. 753, no. 1, article 8, 14 pages, 2012.

[18] M. C. Smith, G. R. Ruchti, A. Helmi et al., "The RAVE survey: constraining the local Galactic escape speed," *Monthly Notices of the Royal Astronomical Society*, vol. 379, no. 2, pp. 755–772, 2007.

[19] V. C. Rubin, D. Burstein, W. K. Ford Jr., and N. Thonnard, "Rotational velocities of 16 Sa galaxies and a comparison of Sa, Sb, and Sc rotation properties," *The Astrophysical Journal*, vol. 289, pp. 81–104, 1985.

[20] Y. Sofue and V. Rubin, "Rotation curves of spiral galaxies," *Annual Review of Astronomy and Astrophysics*, vol. 39, no. 1, pp. 137–174, 2001.

[21] A. Bosma, "21-cm line studies of spiral galaxies. II. The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types," *Astronomical Journal*, vol. 86, pp. 1845–1846, 1981.

[22] November 2013, http://cdn.physorg.com/newman/gfx/news/hires/2011/coulddarkmat.jpg.

[23] D. J. Hegyi and K. A. Olive, "A case against baryons in galactic halos," *The Astrophysical Journal*, vol. 303, pp. 56–65, 1986.

[24] R. R. Muñoz, J. L. Carlin, P. M. Frinchaboy, D. L. Nidever, S. R. Majewski, and R. J. Patterson, "Exploring halo substructure with giant stars: the dynamics and metallicity of the dwarf spheroidal in Boötes," *The Astrophysical Journal Letters*, vol. 650, no. 1, pp. L51–L54, 2006.

[25] M. Milgrom, "A modification of the newtonian dynamics as a possible alternative to the hidden mass hypothesis," *The Astrophysical Journal*, vol. 270, pp. 365–370, 1983.

[26] J. D. Bekenstein, "The modified Newtonian dynamics—MOND and its implications for new physics," *Contemporary Physics*, vol. 47, no. 6, pp. 387–403, 2006.

[27] T. di Matted, S. W. Allen, A. C. Fabian, A. S. Wilson, and A. J. Young, "Accretion onto the supermassive black hole in M87," *The Astrophysical Journal*, vol. 582, no. 1, pp. 133–140, 2003.

[28] W. Forman, C. Jones, E. Churazov et al., "Filaments, bubbles, and weak shocks in the gaseous atmosphere of M87," *The Astrophysical Journal*, vol. 665, no. 2, pp. 1057–1066, 2007.

[29] D. Fabricant and P. Gorenstein, "Further evidence for M87's massive dark halo," *The Astrophysical Journal*, vol. 267, pp. 535–546, 1983.

[30] X. Wu and S. Tremaine, "Deriving the mass distribution of M87 from globular clusters," *The Astrophysical Journal*, vol. 643, no. 1, pp. 210–221, 2006.

[31] A. Longobardi, M. Arnaboldi, O. Gerhard, L. Coccato, S. Okamura, and K. C. Freeman, "The planetary nebula population in the halo of M87," *Astronomy & Astrophysics*, vol. 558, p. A42, 2013.

[32] A. Vikhlinin, A. Kravtsov, W. Forman et al., "Chandra sample of nearby relaxed galaxy clusters: mass, gas fraction, and mass-temperature relation," *The Astrophysical Journal*, vol. 640, no. 2, pp. 691–709, 2006.

[33] L. P. David, C. Jones, and W. Forman, "The universal gas mass fraction in clusters of galaxies," *The Astrophysical Journal*, vol. 748, no. 2, article 120, 8 pages, 2012.

[34] R. W. Schmidt and S. W. Allen, "The dark matter haloes of massive, relaxed galaxy clusters observed with Chandra," *Monthly Notices of the Royal Astronomical Society*, vol. 379, no. 1, pp. 209–221, 2007.

[35] November 2013, http://hubblesite.org/newscenter/archive/releases/exotic/gravitational%20lens/2012/08/image/a/format/large_web/.

[36] http://hubblesite.org/newscenter/archive/releases/2012/19/full/.

[37] D. M. Wittman, J. A. Tyson, D. Kirkman, I. Dell'Antonio, and G. Bernstein, "Detection of weak gravitational lensing distortions of distant galaxies by cosmic dark matter at large scales," *Nature*, vol. 405, no. 6783, pp. 143–148, 2000.

[38] R. Massey, T. Kitching, and J. Richard, "The dark matter of gravitational lensing," *Reports on Progress in Physics*, vol. 73, Article ID 086901, 26 pages, 2010.

[39] M. Markevitch, A. H. Gonzalez, L. David et al., "A textbook example of a bow shock in the merging galaxy cluster 1E 0657-56," *The Astrophysical Journal Letters*, vol. 567, no. 1, pp. L27–L31, 2002.

[40] D. Clowe, A. Gonzalez, and M. Markevitch, "Weak-lensing mass reconstruction of the interacting cluster 1E 0657-558: direct evidence for the existence of dark matter," *The Astrophysical Journal*, vol. 604, no. 2, pp. 596–603, 2004.

[41] A. H. Guth and S.-Y. Pi, "Fluctuations in the new inflationary universe," *Physical Review Letters*, vol. 49, no. 15, pp. 1110–1113, 1982.

[42] December 2013, http://planck.caltech.edu/publications2013Results.html.

[43] D. Spergel, R. Flauger, and R. Hlozek, “Planck data reconsidered,” http://arxiv.org/abs/1312.3313.

[44] M. Vogelsberger, S. Genel, V. Springel et al., “Properties of galaxies reproduced by a hydrodynamic simulation,” *Nature*, vol. 509, pp. 177–182, 2014.

[45] M. S. Turner and F. Wilczek, “Positron line radiation as a signature of particle dark matter in the halo,” *Physical Review D*, vol. 42, no. 4, pp. 1001–1007, 1990.

[46] L. Bergstrom, T. Bringmann, I. Cholis, and D. Hooper, “New limits on dark matter annihilation from alpha magnetic spectrometer cosmic ray positron data,” *Physical Review Letters*, vol. 111, Article ID 171101, 5 pages, 2013.

[47] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya et al., “The cosmic-ray positron energy spectrum measured by PAMELA,” *Physical Review Letters*, vol. 111, Article ID 081102, 2013.

[48] D. Hooper and L. Goodenough, “Dark matter annihilation in the Galactic Center as seen by the Fermi Gamma Ray Space Telescope,” *Physics Letters B*, vol. 697, no. 5, pp. 412–428, 2011.

[49] M. Su and D. P. Finkbeiner, “Strong evidence for gamma-ray line emission from the inner galaxy,” http://arxiv.org/abs/1206.1616.

[50] A. Abramowski, F. Acero, F. Aharonian et al., “Search for photon-linelike signatures from dark matter annihilatioins with H.E.S.S.,” *Physical Review Letters*, vol. 110, no. 4, Article ID 041301, 2013.

[51] L. Bergstrom, “Cosmology and the dark matter frontier,” *Physica Scripta*, vol. 2013, no. T158, Article ID 014014, 2013.

[52] B. Paczynski, “Gravitational microlensing by the galactic halo,” *The Astrophysical Journal*, vol. 304, pp. 1–5, 1986.

[53] C. Alcock, R. A. Allsman, D. R. Alves et al., “Macho project limits on black hole dark matter in the 1–30 $M_\odot$ range,” *The Astrophysical Journal Letters*, vol. 550, no. 2, pp. L169–L172, 2001.

[54] C. Alcock, R. A. Allsman, D. R. Alves et al., “Direct detection of a microlens in the Milky Way,” *Nature*, vol. 414, no. 6864, pp. 617–619, 2001.

[55] 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.

[56] S. Gardner and G. M. Fuller, “Dark matter studies entrain nuclear physics,” *Progress in Particle and Nuclear Physics*, vol. 71, pp. 167–184, 2013.

[57] D. Wouters and P. Brun, “Constraints on axion-like particles from X-ray observations of the hydra galaxy cluster,” *The Astrophysical Journal*, vol. 772, no. 1, article 44, 2013.

[58] S. Horiuchi, P. J. Humphrey, J. Oñorbe, K. N. Abazajian, M. Kaplinghat, and S. Garrison-Kimmel, “Sterile neutrino dark matter bounds from galaxies of the Local Group,” *Physical Review D*, vol. 89, Article ID 025017, 2013.

[59] G. W. Angus, B. Famaey, and H. S. Zhao, “Can MOND take a bullet? Analytical comparisons of three versions of MOND beyond spherical symmetry,” *Monthly Notices of the Royal Astronomical Society*, vol. 371, no. 1, pp. 138–146, 2006.

[60] S. Dodelson and M. Liguori, “Can cosmic structure form without dark matter?” *Physical Review Letters*, vol. 97, no. 23, Article ID 231301, 2006.

[61] M. Milgrom, “Testing MOND over a wide acceleration range in X-ray ellipticals,” *Physical Review Letters*, vol. 109, no. 13, Article ID 131101, 2012.

[62] D. N. Page and S. W. Hawking, “Gamma-rays from primordial black holes,” *The Astrophysical Journal*, vol. 206, pp. 1–7, 1976.

[63] B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, “New cosmological constraints on primordial black holes,” *Physical Review D*, vol. 81, no. 10, Article ID 104019, 33 pages, 2010.

[64] K. Griest, A. M. Cieplak, and M. J. Lehner, “New limits on primordial black hole dark matter from an analysis of Kepler source microlensing data,” *Physical Review Letters*, vol. 111, Article ID 181302, 15 pages, 2013.

[65] A. Barnacka, J.-F. Glicenstein, and R. Moderski, “New constraints on primordial black holes abundance from femtolensing of gamma-ray bursts,” *Physical Review D*, vol. 86, no. 4, Article ID 043001, 6 pages, 2012.

[66] P. Pani and A. Loeb, “Exclusion of the remaining mass window for primordial black holes as the dominant constituent of dark matter,” http://arxiv.org/abs/1401.3025.