

Dark matter

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Dark matter is an unidentified type of matter distinct from dark energy, baryonic matter (ordinary matter), and neutrinos. It comprises approximately 27% of the mass and energy in the observable universe.^{[1][2]} The name refers to the fact that it does not emit or interact with electromagnetic radiation, such as light, and is thus invisible to the entire electromagnetic spectrum.^[3] Although dark matter has not been directly observed, its existence and properties are inferred from its gravitational effects such as the motions of visible matter, gravitational lensing, its influence on the universe's large-scale structure, and its effects in the cosmic microwave background. Dark matter is transparent to electromagnetic radiation and/or is so dense and small that it fails to absorb or emit enough radiation to be detectable with current imaging technology.

Estimates of masses for galaxies and larger structures via dynamical and general relativistic means are much greater than those based on the mass of the visible "luminous" matter.^[4]

The standard model of cosmology indicates that the total mass–energy of the universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.^{[5][6]} Thus, dark matter constitutes 84.5%^[note 1] of total mass, while dark energy plus dark matter constitute 95.1% of total mass–energy content.^{[7][8][9][10]} The great majority of ordinary matter in the universe is also unseen, since visible stars and gas inside galaxies and clusters account for less than 10% of the ordinary matter contribution to the mass–energy density of the universe.^[11]

The dark matter hypothesis plays a central role in current modeling of cosmic structure formation and galaxy formation and evolution and on explanations of the anisotropies observed in the cosmic microwave background (CMB). All these lines of evidence suggest that galaxies, galaxy clusters, and the universe as a whole contain far more matter than that which is observable via electromagnetic signals.^[12]

The most widely accepted hypothesis on the form for dark matter is that it is composed of weakly interacting massive particles (WIMPs) that interact only through gravity and the weak force.^[13]

Although the existence of dark matter is generally accepted by most of the astronomical community, a minority of astronomers^[14] argue for various modifications of the standard laws of general relativity, such as MOND, TeVeS, and conformal gravity^[15] that attempt to account for the observations without invoking additional matter.^[16]

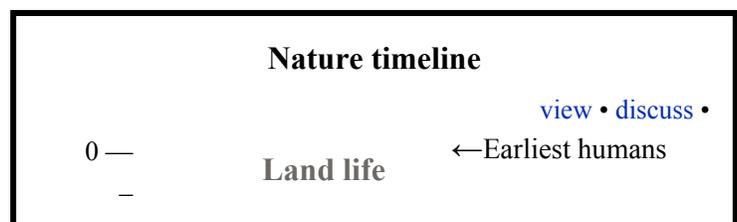
Many experiments to detect proposed dark matter particles through non-gravitational means are under way.^[17] On 25 August 2016, astronomers reported that Dragonfly 44, an ultra diffuse galaxy (UDG) with the mass of the Milky Way galaxy, but with nearly no discernable stars or galactic structure, may be made almost entirely of dark matter.^{[18][19][20]}

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History

The first to suggest the existence of dark matter (using stellar velocities) was Dutch astronomer Jacobus Kapteyn in 1922.^{[21][22]} Fellow Dutchman and radio astronomy pioneer Jan Oort also hypothesized the



existence of dark matter in 1932.^{[22][23][24]}

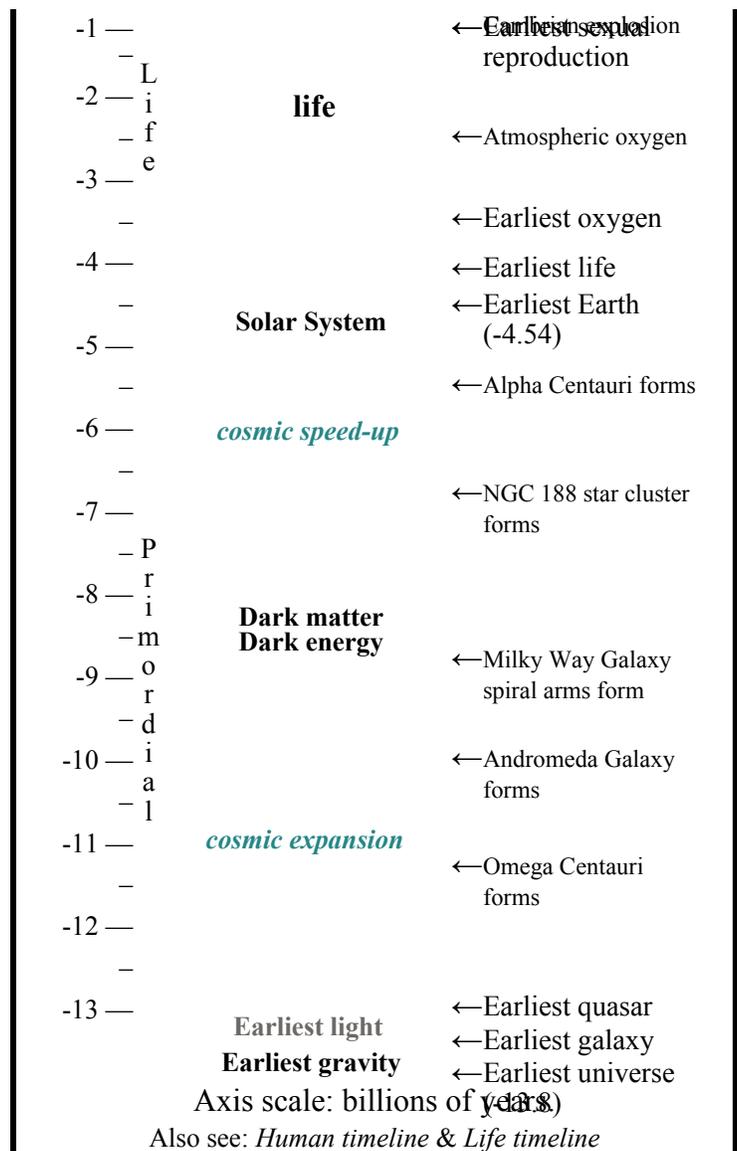
Oort was studying stellar motions in the local galactic neighborhood and found that the mass in the galactic plane must be greater than what was observed, but this measurement was later determined to be erroneous.^[25]

In 1933, Swiss astrophysicist Fritz Zwicky, who studied galactic clusters while working at the California Institute of Technology, made a similar inference.^{[26][27][28]} Zwicky applied the virial theorem to the Coma galaxy cluster and obtained evidence of unseen mass that he called *dunkle Materie* 'dark matter'. Zwicky estimated its mass based on the motions of galaxies near its edge and compared that to an estimate based on its brightness and number of galaxies. He estimated that the cluster had about 400 times more mass than was visually observable. The gravity effect of the visible galaxies was far too small for such fast orbits, thus mass must be hidden from view. Based on these conclusions, Zwicky inferred that some unseen matter provided the mass and associated gravitation attraction to hold the cluster together. This was the first formal inference about the existence of dark matter.^[29]

Zwicky's estimates were off by more than an order of magnitude, mainly due to an obsolete value of the Hubble constant,^[30] the same calculation today shows a smaller fraction, using greater values for luminous mass. However, Zwicky did correctly infer that the bulk of the matter was dark.^[29]

The first robust indications that the mass to light ratio was anything other than unity came from measurements of galaxy rotation curves. In 1939, Horace W. Babcock reported the rotation curve for the Andromeda nebula, which suggested that the mass-to-luminosity ratio increases radially.^[31] He attributed it to either light absorption within the galaxy or modified dynamics in the outer portions of the spiral and not to missing matter.

Vera Rubin and Kent Ford in the 1960s–1970s provided further strong evidence, also using galaxy rotation curves.^{[32][33][34]} Rubin worked with a new spectrograph to measure the velocity curve of edge-on spiral galaxies with greater accuracy.^[34] This result was independently confirmed in 1978.^[35] An



influential paper presented Rubin's results in 1980.^[36] Rubin found that most galaxies must contain about six times as much dark as visible mass,^[37] thus, by around 1980 the apparent need for dark matter was widely recognized as a major unsolved problem in astronomy.^[32]

A stream of independent observations in the 1980s indicated its presence, including gravitational lensing of background objects by galaxy clusters,^[38] the temperature distribution of hot gas in galaxies and clusters, and the pattern of anisotropies in the cosmic microwave background. According to consensus among cosmologists, dark matter is composed primarily of a not yet characterized type of subatomic particle.^{[13][39]} The search for this particle, by a variety of means, is one of the major efforts in particle physics.^[17]

Cosmic microwave background radiation (CMB)

In cosmology, the CMB is explained as relic radiation which has travelled freely since the era of recombination, around 375,000 years after the Big Bang. The CMB's anisotropies are explained as the result of small primordial density fluctuations, and subsequent acoustic oscillations in the photon-baryon plasma whose restoring force is gravity.^[40]

The Cosmic Background Explorer (COBE) satellite found the CMB spectrum to be a very precise blackbody spectrum with a temperature of 2.726 K. In 1992, COBE detected CMB fluctuations (anisotropies) at a level of about one part in 10^5 .^[41]

In the following decade, CMB anisotropies were investigated by ground-based and balloon experiments. Their primary goal was to measure the angular scale of the first acoustic peak of the anisotropies' power spectrum, for which COBE had insufficient resolution. During the 1990s, the first peak was measured with increasing sensitivity, and in 2000 the BOOMERanG experiment^[42] reported that the highest power fluctuations occur at scales of approximately one degree, showing that the Universe is close to flat. These measurements were able to rule out cosmic strings as the leading theory of cosmic structure formation, and suggested cosmic inflation was the correct theory.

Ground-based interferometers provided fluctuation measurements with higher accuracy, including the Very Small Array, the Degree Angular Scale Interferometer (DASI) and the Cosmic Background Imager (CBI). DASI first detected the CMB polarization,^{[43][44]} and CBI provided the first E-mode polarization spectrum with compelling evidence that it is out of phase with the T-mode spectrum.^[45] COBE's successor, the Wilkinson Microwave Anisotropy Probe (WMAP) provided the most detailed measurements of (large-scale) anisotropies in the CMB in 2003–2010.^[46] ESA's Planck spacecraft returned more detailed results in 2013-2015.

WMAP's measurements played the key role in establishing the Standard Model of Cosmology, namely the Lambda-CDM model, which posits a dark energy-dominated flat universe, supplemented by dark matter and atoms with density fluctuations seeded by a Gaussian, adiabatic, nearly scale invariant process. Its basic properties are determined by six adjustable parameters: dark matter density, baryon (atom) density, the universe's age (or equivalently, the Hubble constant), the initial fluctuation amplitude and their scale dependence.

Observational evidence

Much of the evidence comes from the motions of galaxies.^[48] Many of these appear to be fairly uniform, so by the virial theorem, the total kinetic energy should be half the galaxies' total gravitational binding energy. Observationally, the total kinetic energy is much greater. In particular, assuming the gravitational mass is due to only visible matter, stars far from the center of galaxies have much higher velocities than predicted by the virial theorem. Galactic rotation curves, which illustrate the velocity of rotation versus the distance from the galactic center, show the "excess" velocity. Dark matter is the most straightforward way of accounting for this discrepancy.^[49]

The distribution of dark matter in galaxies required to explain the motion of the observed matter suggests the presence of a roughly spherically symmetric, centrally concentrated halo of dark matter with the visible matter concentrated in a central disc.^[50]

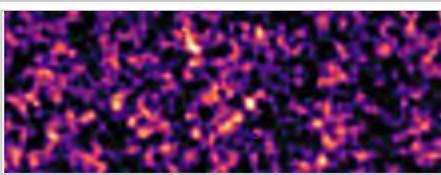
Low surface brightness dwarf galaxies are important sources of information for studying dark matter. They have an uncommonly low ratio of visible to dark matter, and have few bright stars at the center that would otherwise impair observations of the rotation curve of outlying stars.



This artist's impression shows the expected distribution of dark matter in the Milky Way galaxy as a blue halo of material surrounding the galaxy.^[47]

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Gravitational lensing observations of galaxy clusters allow direct estimates of the gravitational mass based on its effect on light coming from background galaxies, since large collections of matter (dark or otherwise) gravitationally deflect light. In clusters such as Abell 1689, lensing observations confirm the presence of considerably more mass than is indicated by the clusters' light. In the Bullet Cluster, lensing observations show that much of the lensing mass is separated from the X-ray-emitting baryonic mass. In July 2012, lensing observations were



Dark matter map of KiDS survey region (region G12).^[51]

used to identify a "filament" of dark matter between two clusters of galaxies, as cosmological simulations predicted.^[52]

In August 2016, astronomers reported that Dragonfly 44, an ultra diffuse galaxy (UDG) with the mass of the Milky Way galaxy, but with nearly no discernable stars or galactic structure, may be made almost entirely of dark matter.^{[18][19][20]}

Galaxy rotation curves

A galaxy rotation curve is a plot of the orbital velocities (i.e., the speeds) of visible stars or gas in that galaxy versus their radial distance from that galaxy's center. The rotational/orbital speed of galaxies/stars does not decline with distance, unlike other orbital systems such as stars/planets and planets/moons that also have most of their mass at the centre. In the latter cases, this reflects the mass distributions within

those systems. The mass observations for galaxies based on the light that they emit are far too low to explain the velocity observations. The dark matter hypothesis accounts for the missing mass, explaining the anomaly.^[31]

A universal rotation curve can be expressed as the sum of an exponential distribution of visible matter that tapers to zero with distance from the center, and a spherical dark matter halo with a flat core of radius r_0 and density $\rho_0 = 4.5 \times 10^{-2}(r_0/\text{kpc})^{-2/3} M_{\odot}\text{pc}^{-3}$.^[53]

Low-surface-brightness (LSB) galaxies have a much larger visible mass deficit than others. This property simplifies the disentanglement of the dark and visible matter contributions to the rotation curves.^[17]

Rotation curves for some elliptical galaxies do display low velocities for outlying stars (tracked for example by the motion of embedded planetary nebulae). A dark-matter compliant hypothesis proposes that some stars may have been torn by tidal forces from disk-galaxy mergers from their original galaxies during the first close passage and put on outgoing trajectories, explaining the low velocities of the remaining stars even in the presence of a halo.^{[17][54]}

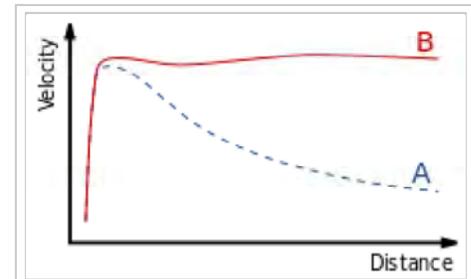
Velocity dispersions of galaxies

Velocity dispersion estimates of elliptical galaxies,^[55] with some exceptions, generally indicate a relatively high dark matter content.

Diffuse interstellar gas measurements of galactic edges indicate missing ordinary matter beyond the visible boundary, but those galaxies are virialized (i.e., gravitationally bound and orbiting each other with velocities that correspond to predicted orbital velocities of general relativity) up to ten times their visible radii.^[56] This has the effect of pushing up the dark matter as a fraction of the total matter from 50% as measured by Rubin to the now accepted value of nearly 95%.

Dark matter seems to be a small component or absent in some places. Globular clusters show little evidence of dark matter.^[57] Star velocity profiles seemed to indicate a concentration of dark matter in the disk of the Milky Way. It now appears, however, that the high concentration of baryonic matter in the disk (especially in the interstellar medium) can account for this motion. Galaxy mass and light profiles appear to not match. The typical model for dark matter galaxies is a smooth, spherical distribution in virialized halos. This avoids small-scale (stellar) dynamical effects. A 2006 study explained the warp in the Milky Way's disk by the interaction of the Large and Small Magellanic Clouds and the 20-fold increase in predicted mass from dark matter.^[58]

In 2005, astronomers claimed to have discovered a galaxy made almost entirely of dark matter, 50 million light years away in the Virgo Cluster, which was named VIRGOHI21.^[59] Unusually, VIRGOHI21 does not appear to contain visible stars: it was discovered with radio frequency



Rotation curve of a typical spiral galaxy: predicted (A) and observed (B). Dark matter can explain the 'flat' appearance of the velocity curve out to a large radius

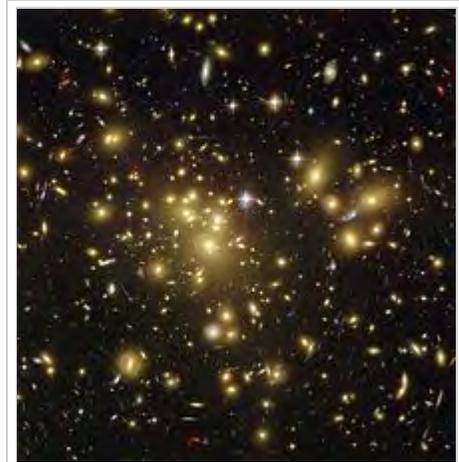
observations of hydrogen. Based on rotation profiles, scientists estimate that this object contains approximately 1000 times more dark matter than hydrogen and has a mass of about 1/10 that of the Milky Way. The Milky Way is estimated to have roughly 10 times as much dark matter as ordinary matter. Models of the Big Bang and structure formation suggested that such dark galaxies should be very common, but VIRGOHI21 was the first to be detected.

The velocity profiles of some galaxies such as NGC 3379 indicate an absence of dark matter.^[60]

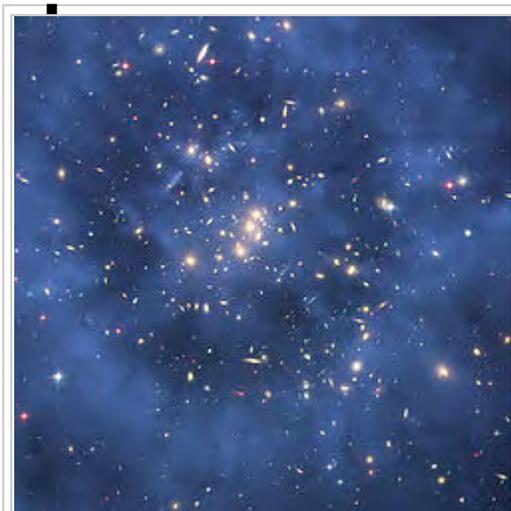
Galaxy clusters and gravitational lensing

Clusters of galaxies are particularly important for dark matter studies since their masses can be estimated in three independent ways:

- From the scatter in radial velocities of the galaxies within clusters
- From X-rays emitted by hot gas in the clusters. From the X-ray energy spectrum and flux, the gas temperature and density can be estimated, hence giving the pressure: assuming pressure and gravity balance determines the cluster's mass profile. Many Chandra X-ray Observatory experiments use this technique to independently determine cluster masses. These observations generally indicate that baryonic mass is approximately 12–15 percent, in reasonable agreement with the Planck spacecraft cosmic average of 15.5–16 percent.^[61]



Strong gravitational lensing as observed by the Hubble Space Telescope in Abell 1689 indicates the presence of dark matter—enlarge the image to see the lensing arcs.



Dark matter is invisible. Based on the effect of gravitational lensing, a ring of dark matter has been inferred in this image of a galaxy cluster (CL0024+17) and has been represented in blue.^[62]

Gravitational lensing (usually of more distant galaxies) can measure cluster masses without relying on observations of dynamics (e.g., velocity). There are two types of lensing: strong lensing produces multiple images or giant arcs near the cluster core, while weak lensing is observed as small shape distortions around the outer regions. Multiple Hubble space telescope projects have used this method to measure cluster masses.

Generally, these three methods are in reasonable agreement that dark matter outweighs visible matter by approximately 5 to 1.

Gravity acts as a lens to bend the light from a more distant source (such as a quasar) around a massive object (such as a cluster of galaxies) lying between the source and the observer in accordance with general relativity.

Strong lensing is the observed distortion of background galaxies into arcs when their light passes through such a gravitational lens. It has been observed around many distant clusters including Abell 1689.^[63] By measuring the distortion geometry, the mass of the intervening cluster can be obtained. In the dozens of cases where this has been done, the mass-to-light ratios obtained correspond to the dynamical dark matter measurements of clusters.^[64]

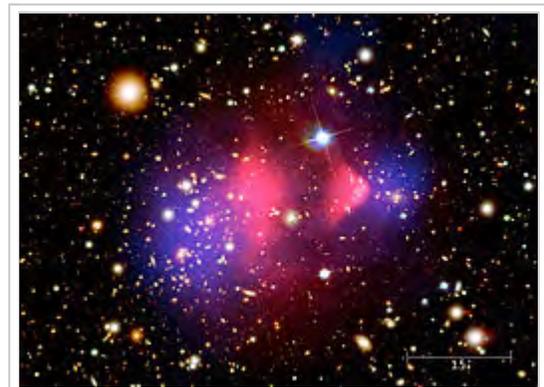
Weak gravitational lensing investigates minute distortions of galaxies, using statistical analyses from vast galaxy surveys. By examining the apparent shear deformation of the adjacent background galaxies, astrophysicists can characterize the mean distribution of dark matter. The mass-to-light ratios correspond to dark matter densities predicted by other large-scale structure measurements.^[65]

Galaxy cluster Abell 2029 comprises thousands of galaxies enveloped in a cloud of hot gas and dark matter equivalent to more than $10^{14} M_{\odot}$. At the center of this cluster is an enormous elliptical galaxy likely formed from many smaller galaxies.^[66]

The most direct observational evidence comes from the Bullet Cluster. In most regions dark and visible matter are found together,^[67] due to their gravitational attraction. In the Bullet Cluster however, the two matter types split apart, due to a past collision between two smaller clusters. Electromagnetic interactions between gas particles has caused the gas to slow and concentrate near the point of impact. The galaxies, stars and dark matter continued through with negligible collisions. Lensing observations show two dark matter peaks near the galaxy peaks, as expected in dark matter theory. Since the gas peaks contain more ordinary matter than the stars, modified-gravity theories should show the lensing peaks near the gas peaks, contrary to the observations.

X-ray observations show that much of the luminous matter (in the form of 10^7 – 10^8 Kelvin^[68] gas or plasma) is concentrated in the cluster's center. Weak gravitational lensing observations show that much dark matter resides outside the central region. Unlike galactic rotation curves, this evidence is independent of the details of Newtonian gravity, directly supporting dark matter.^[68] Dark matter's observed behavior constrains whether and how much it scatters off other dark matter particles, quantified as its self-interaction cross section. If dark matter has no pressure, it can be described as a perfect fluid that has no damping.^[69] The distribution of mass in galaxy clusters has been used to argue both for^{[70][71]} and against^[72] the significance of self-interaction.

An ongoing survey using the Subaru Telescope uses weak lensing to analyze background light, bent by dark matter, to determine the statistical distribution of dark matter in the foreground. The survey studies galaxies more than a billion light-years distant, across an area greater than a thousand square degrees (about one fortieth of the entire sky).^{[73][74]}

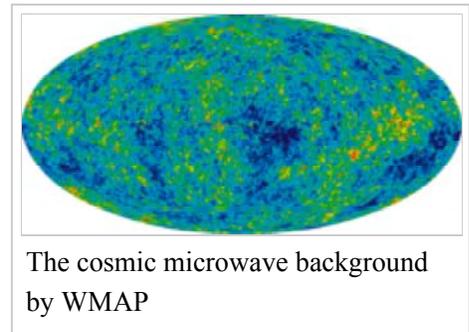


The Bullet Cluster: HST image with overlays. The total projected mass distribution reconstructed from strong and weak gravitational lensing is shown in blue, while the X-ray emitting hot gas observed with Chandra is shown in red.

Cosmic microwave background

Angular CMB fluctuations provide evidence for dark matter. The typical angular scales of CMB oscillations, measured as the power spectrum of the CMB anisotropies, reveal the different effects of baryonic and dark matter. Ordinary matter interacts strongly via radiation whereas dark matter particles (WIMPs) do not; both affect the oscillations by way of their gravity, so the two forms of matter have different effects.

The spectrum shows a large first peak and smaller successive peaks.^[46] The first peak mostly shows the density of baryonic matter, while the third peak relates mostly to the density of dark matter, measuring the density of matter and the density of atoms.



Sky surveys and baryon acoustic oscillations

The early universe's acoustic oscillations in the photon-baryon fluid are observed as the prominent acoustic peaks in the CMB spectrum. This set up a preferred length scale for baryons in the early universe which is determined as 147 megaparsec (comoving) by the Planck spacecraft. As the dark matter and baryons clumped together after recombination, the effect is much weaker in the galaxy distribution in the nearby universe, but is detectable as a subtle (~ 1 percent) preference for pairs of galaxies to be separated by 147 Mpc, rather than 130 or 160 Mpc, called the BAO feature. This feature was predicted theoretically in the 1990s and then discovered in 2005, in two large galaxy redshift surveys, the Sloan Digital Sky Survey and the 2dF Galaxy Redshift Survey.^[75] Combining the CMB observations with BAO measurements from galaxy redshift surveys provides a precise estimate of the Hubble constant and the average matter density in the Universe.^[40]

Redshift-space distortions

Large galaxy redshift surveys may be used to make a three-dimensional map of the galaxy distribution. These maps are slightly distorted because distances are estimated from observed redshifts; the redshift contains a contribution from the galaxy's so-called peculiar velocity in addition to the dominant Hubble expansion term. On average, superclusters are expanding but more slowly than the cosmic mean due to their gravity, while voids are expanding faster than average. In a redshift map, galaxies in front of a supercluster have excess radial velocities towards it and have redshifts slightly higher than their distance would imply, while galaxies behind the supercluster have redshifts slightly low for their distance. This effect causes superclusters to appear "squashed" in the radial direction, and likewise voids are "stretched"; angular positions are unaffected. The effect is not detectable for any one structure since the true shape is not known, but can be measured by averaging over many structures assuming we are not at a special location in the Universe.

The effect was predicted quantitatively by Nick Kaiser in 1987, and first decisively measured in 2001 by the 2dF Galaxy Redshift Survey.^[76] Results are in agreement with the Lambda-CDM model.

Type Ia supernova distance measurements

Type Ia supernovae can be used as "standard candles" to measure extragalactic distances. Extensive data sets of these supernovae can be used to constrain cosmological models.^[77] They constrain the dark energy density $\Omega_\Lambda = \sim 0.713$ for a flat, Lambda CDM universe and the parameter w for a quintessence model. The results are roughly consistent with those derived from the WMAP observations and further constrain the Lambda CDM model and (indirectly) dark matter.^[40]

Lyman-alpha forest

In astronomical spectroscopy, the Lyman-alpha forest is the sum of the absorption lines arising from the Lyman-alpha transition of neutral hydrogen in the spectra of distant galaxies and quasars. Lyman-alpha forest observations can also constrain cosmological models.^[78] These constraints agree with those obtained from WMAP data.

Structure formation

Structure formation refers to the serial transformations of the universe following the Big Bang. Prior to structure formation, e.g., Friedmann cosmology solutions to general relativity describe a homogeneous universe. Later, small anisotropies gradually grew and condensed the homogeneous universe into stars, galaxies and larger structures.

Observations suggest that structure formation proceeds hierarchically, with the smallest structures collapsing first, followed by galaxies and then galaxy clusters. As the structures collapse in the evolving universe, they begin to "light up" as baryonic matter heats up through gravitational contraction and approaches hydrostatic pressure balance.

CMB anisotropy measurements fix models in which most matter is dark. Dark matter also closes gaps in models of large-scale structure. The dark matter hypothesis corresponds with statistical surveys of the visible structure and precisely to CMB predictions.

Initially, baryonic matter's post-Big Bang temperature and pressure were too high to collapse and form smaller structures, such as stars, via the Jeans instability. The gravity from dark matter increases the compaction force, allowing the formation of these structures.

Computer simulations of billions of dark matter particles^[80] seem to confirm that the "cold" dark matter model of structure formation is consistent with the structures observed through galaxy surveys, such as the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey, as well as observations of the Lyman-alpha forest.



3D map of the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing with the Hubble Space Telescope.^[79]

Tensions separate observations and simulations. Observations have turned up 90-99% fewer small galaxies than permitted by dark matter-based predictions.^{[81][82]} In addition, simulations predict dark matter distributions with a dense cusp near galactic centers, but the observed halos are smoother than predicted.

Composition

The composition of dark matter remains uncertain. Possibilities include dense baryonic (interacts with electromagnetic force) matter and non-baryonic matter (interacts with its surroundings only through gravity).

Baryonic vs. nonbaryonic matter

Baryonic matter

Baryonic matter is made of baryons (protons and neutrons) that make up stars and planets. It also encompasses less common black holes, neutron stars, faint old white dwarfs and brown dwarfs, collectively known as massive compact halo objects (MACHOs).^[83]

Multiple lines of evidence suggest the majority of dark matter is not made of baryons:

- Sufficient diffuse, baryonic gas or dust would be visible when backlit by stars.
- The theory of Big Bang nucleosynthesis predicts the observed abundance of the chemical elements;^{[84][85]} agreement with observed abundances requires that baryonic matter makes up between 4–5% of the universe's critical density. In contrast, large-scale structure and other observations indicate that the total matter density is about 30% of the critical density (with dark energy providing the remaining 70%).
- Astronomical searches for gravitational microlensing in the Milky Way found that at most a small fraction of the dark matter may be in dark, compact, conventional objects (MACHOs, etc.); the excluded range of object masses is from half the Earth's mass up to 30 solar masses, which covers nearly all the plausible candidates.^{[86][87][88][89][90][91]}
- Detailed analysis of the small irregularities (anisotropies) in the cosmic microwave background observed by WMAP and Planck shows that around five-sixths of the total matter is in a form that interacts significantly with ordinary matter or photons only through gravitational effects.

Non-baryonic matter

Unsolved problem in physics:

? *What is dark matter?
How is it generated? Is it related to supersymmetry?*
(more unsolved problems in physics)



Fermi-LAT observations of dwarf galaxies provide new insights on dark matter.

Candidates for nonbaryonic dark matter are hypothetical particles such as axions or supersymmetric particles. The three neutrino types already observed are indeed abundant, and “dark”, and matter, but because their individual masses – however uncertain they may be – are almost certainly tiny, they can only supply a small fraction of dark matter, due to limits derived from large-scale structure and high-redshift galaxies.^[92]

Unlike baryonic matter, nonbaryonic matter did not contribute to the formation of the elements in the early universe ("Big Bang nucleosynthesis")^[13] and so its presence is revealed only via its gravitational effects. In addition, if the particles of which it is composed are supersymmetric, they can undergo annihilation interactions with themselves, possibly resulting in observable by-products such as gamma rays and neutrinos ("indirect detection").^[92]

Classification: cold/warm/hot

Dark matter can be divided into *cold*, *warm* and *hot* categories.^[93] These categories refer to velocity rather than an actual temperature, indicating how far corresponding objects moved due to random motions in the early universe, before they slowed due to cosmic expansion – this is an important distance called the "free streaming length" (FSL). Primordial density fluctuations smaller than this length get washed out as particles spread from overdense to underdense regions, while larger fluctuations are unaffected; therefore this length sets a minimum scale for later structure formation. The categories are set with respect to the size of a protogalaxy (an object that later evolves into a dwarf galaxy): dark matter particles are classified as cold, warm, or hot according as their FSL; much smaller (cold), similar (warm), or much larger (hot) than a protogalaxy.^{[94][95]}

Mixtures of the above are also possible: a theory of mixed dark matter was popular in the mid-1990s, but was rejected following the discovery of dark energy.

Cold dark matter leads to a "bottom-up" formation of structure while hot dark matter would result in a "top-down" formation scenario; the latter is excluded by high-redshift galaxy observations.^[17]

Alternative definitions

These categories also correspond to fluctuation spectrum effects and the interval following the Big Bang at which each type became non-relativistic. Davis *et al.* wrote in 1985:

Candidate particles can be grouped into three categories on the basis of their effect on the fluctuation spectrum (Bond *et al.* 1983). If the dark matter is composed of abundant light particles which remain relativistic until shortly before recombination, then it may be termed "hot". The best candidate for hot dark matter is a neutrino ... A second possibility is for the dark matter particles to interact more weakly than neutrinos, to be less abundant, and to have a mass of order 1 keV. Such particles are termed "warm dark matter", because they have lower thermal velocities than massive neutrinos ... there are at present few candidate particles which fit this description. Gravitinos and photinos have been suggested (Pagels and Primack 1982; Bond, Szalay and Turner 1982) ... Any particles which became

nonrelativistic very early, and so were able to diffuse a negligible distance, are termed "cold" dark matter (CDM). There are many candidates for CDM including supersymmetric particles.^[96]

Another approximate dividing line is that "warm" dark matter became non-relativistic when the universe was approximately 1 year old and 1 millionth of its present size and in the radiation-dominated era (photons and neutrinos), with a photon temperature 2.7 million K. Standard physical cosmology gives the particle horizon size as $2ct$ (speed of light multiplied by time) in the radiation-dominated era, thus 2 light-years. A region of this size would expand to 2 million light years today (absent structure formation). The actual FSL is roughly 5 times the above length, since it continues to grow slowly as particle velocities decrease inversely with the scale factor after they become non-relativistic. In this example the FSL would correspond to 10 million light-years or 3 Mpc today, around the size containing an average large galaxy.

The 2.7 million K photon temperature gives a typical photon energy of 250 electron-volts, thereby setting a typical mass scale for "warm" dark matter: particles much more massive than this, such as GeV – TeV mass WIMPs, would become non-relativistic much earlier than 1 year after the Big Bang and thus have FSLs much smaller than a protogalaxy, making them "cold". Conversely, much lighter particles, such as neutrinos with masses of only a few eV, have FSLs much larger than a protogalaxy, thus qualifying them as "hot".

Cold dark matter

"Cold" dark matter offers the simplest explanation for most cosmological observations. It is dark matter composed of constituents with an FSL much smaller than a protogalaxy. This is the focus for dark matter research, as hot dark matter does not seem to be capable of supporting galaxy or galaxy cluster formation, and most particle candidates slowed early.

The constituents of "cold" dark matter are unknown. Possibilities range from large objects like MACHOs (such as black holes^[97]) or RAMBOs (such as clusters of brown dwarfs), to new particles such as WIMPs and axions.

Studies of Big Bang nucleosynthesis and gravitational lensing convinced most cosmologists^{[17][98][99][100][101][102]} that MACHOs^{[98][100]} cannot make up more than a small fraction of dark matter.

^{[13][98]} According to A. Peter: "... the only *really plausible* dark-matter candidates are new particles."^[99]

The 1997 DAMA/NaI experiment and its successor DAMA/LIBRA in 2013, claimed to directly detect dark matter particles passing through the Earth, but many researchers remain skeptical, as negative results from similar experiments seem incompatible with the DAMA results.

Many supersymmetric models offer dark matter candidates in the form of the WIMPy Lightest Supersymmetric Particle (LSP).^[103] Separately, heavy sterile neutrinos exist in non-supersymmetric extensions to the standard model that explain the small neutrino mass through the seesaw mechanism.

Warm dark matter

"Warm" dark matter refers to particles with an FSL comparable to the size of a protogalaxy. Predictions based on warm dark matter are similar to those for cold dark matter on large scales, but with less small-scale density perturbations. This reduces the predicted abundance of dwarf galaxies and may lead to lower density of dark matter in the central parts of large galaxies; some researchers consider this to be a better fit to observations. A challenge for this model is the lack of particle candidates with the required mass ~ 300 eV to 3000 eV.

No known particles can be categorized as "warm" dark matter. A postulated candidate is the sterile neutrino: a heavier, slower form of neutrino that does not interact through the weak force, unlike other neutrinos. Some modified gravity theories, such as scalar-tensor-vector gravity, require "warm" dark matter to make their equations work.

Hot dark matter

"Hot" dark matter consists of particles whose FSL is much larger than the size of a protogalaxy. The neutrino qualifies as such particle. They were discovered independently, long before the hunt for dark matter: they were postulated in 1930, and detected in 1956. Neutrinos' mass is less than 10^{-6} that of an electron. Neutrinos interact with normal matter only via gravity and the weak force, making them difficult to detect (the weak force only works over a small distance, thus a neutrino triggers a weak force event only if it hits a nucleus head-on). This makes them 'weakly interacting light particles' (WILPs), as opposed to WIMPs.

The three known flavours of neutrinos are the *electron*, *muon*, and *tau*. Their masses are slightly different. Neutrinos oscillate among the flavours as they move. It is hard to determine an exact upper bound on the collective average mass of the three neutrinos (or for any of the three individually). For example, if the average neutrino mass were over 50 eV/ c^2 (less than 10^{-5} of the mass of an electron), the universe would collapse. CMB data and other methods indicate that their average mass probably does not exceed 0.3 eV/ c^2 . Thus, observed neutrinos cannot explain dark matter.^[104]

Because galaxy-size density fluctuations get washed out by free-streaming, "hot" dark matter implies that the first objects that can form are huge supercluster-size pancakes, which then fragment into galaxies. Deep-field observations show instead that galaxies formed first, followed by clusters and superclusters as galaxies clump together.

Detection (of WIMPS or Axions)

If dark matter is made up of WIMPs, then millions, possibly billions, of WIMPs must pass through every square centimeter of the Earth each second.^{[105][106]} Many experiments aim to test this hypothesis. Although WIMPs are popular search candidates,^[17] the Axion Dark Matter eXperiment (ADMX) searches for axions. Another candidate is heavy hidden sector particles that only interact with ordinary matter via gravity.

These experiments can be divided into two classes: direct detection experiments, which search for the scattering of dark matter particles off atomic nuclei within a detector; and indirect detection, which look for the products of WIMP annihilations.^[92]

Direct detection

Direct detection experiments operate deep underground to reduce the interference from cosmic rays. Detectors include the Stawell mine, the Soudan mine, the SNOLAB underground laboratory at Sudbury, the Gran Sasso National Laboratory, the Canfranc Underground Laboratory, the Boulby Underground Laboratory, the Deep Underground Science and Engineering Laboratory and the Particle and Astrophysical Xenon Detector.

These experiments mostly use either cryogenic or noble liquid detector technologies. Cryogenic detectors operating at temperatures below 100mK, detect the heat produced when a particle hits an atom in a crystal absorber such as germanium. Noble liquid detectors detect scintillation produced by a particle collision in liquid xenon or argon. Cryogenic detector experiments include: CDMS, CRESST, EDELWEISS, EURECA. Noble liquid experiments include ZEPLIN, XENON, DEAP, ArDM, WARP, DarkSide, PandaX, and LUX, the Large Underground Xenon experiment. Both of these techniques distinguish background particles (that scatter off electrons) from dark matter particles (that scatter off nuclei). Other experiments include SIMPLE and PICASSO.

The DAMA/NaI, DAMA/LIBRA experiments detected an annual modulation in the event rate^[107] that they claim is due to dark matter. (As the Earth orbits the Sun, the velocity of the detector relative to the dark matter halo will vary by a small amount). This claim is so far unconfirmed and unreconciled with negative results of other experiments.^[108]

Directional detection is a search strategy based on the motion of the Solar System around the Galactic Center.^{[109][110][111][112]}

A low pressure time projection chamber makes it possible to access information on recoiling tracks and constrain WIMP-nucleus kinematics. WIMPs coming from the direction in which the Sun is travelling (roughly towards Cygnus) may then be separated from background, which should be isotropic. Directional dark matter experiments include DMTPC, DRIFT, Newage and MIMAC.

Results

In 2009, CDMS researchers reported two possible WIMP candidate events. They estimate that the probability that these events are due to background (neutrons or misidentified beta or gamma events) is 23%, and conclude "this analysis cannot be interpreted as significant evidence for WIMP interactions, but we cannot reject either event as signal."^[113]

In 2011, researchers using the CRESST detectors presented evidence of 67 collisions occurring in detector crystals from subatomic particles.^[114] They calculated the probability that all were caused by known sources of interference/contamination was 1 in 10⁵.

Indirect detection

Indirect detection experiments search for the products of WIMP annihilation/decay. If WIMPs are Majorana particles (their own antiparticle) then two WIMPs could annihilate to produce gamma rays or Standard Model particle-antiparticle pairs. If the WIMP is unstable, WIMPs could decay into standard

model (or other) particles. These processes could be detected indirectly through an excess of gamma rays, antiprotons or positrons emanating from high density regions. The detection of such a signal is not conclusive evidence, as the sources of gamma ray production are not fully understood.^{[17][92]}

A few of the WIMPs passing through the Sun or Earth may scatter off atoms and lose energy. Thus WIMPs may accumulate at the center of these bodies, increasing the chance of collision/annihilation. This could produce a distinctive signal in the form of high-energy neutrinos.^[116] Such a signal would be strong indirect proof of WIMP dark matter.^[17] High-energy neutrino telescopes such as AMANDA, IceCube and ANTARES are searching for this signal.^[117]

WIMP annihilation from the Milky Way galaxy as a whole may also be detected in the form of various annihilation products.^[118] The Galactic Center is a particularly good place to look because the density of dark matter may be higher there.^[119]

The detection by LIGO in September 2015 of gravitational waves, opens the possibility of observing dark matter in a new way. Dark matter seems to have no effects except gravitational, and so the actual observation of gravitational waves provides scientists with a new way of observing the phenomenon.

^{[120][121][122]}

Results

The EGRET gamma ray telescope observed more gamma rays in 2008 than expected from the Milky Way, but scientists concluded that this was most likely due to incorrect estimation of the telescope's sensitivity.^[123]

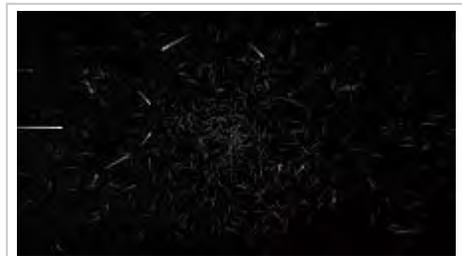
The Fermi Gamma-ray Space Telescope is searching for similar gamma rays.^[124] In April 2012, an analysis of previously available data from its Large Area Telescope instrument produced statistical evidence of a 130 GeV signal in the gamma radiation coming from the center of the Milky Way.^[125] WIMP annihilation was seen as the most probable explanation.^[126]

At higher energies, ground-based gamma-ray telescopes have set limits on the annihilation of dark matter in dwarf spheroidal galaxies^[127] and in clusters of galaxies.^[128]

The PAMELA experiment (launched 2006) detected excess positrons. They could be from dark matter annihilation or from pulsars. No excess antiprotons were observed.^[129]



Collage of six cluster collisions with dark matter maps. The clusters were observed in a study of how dark matter in clusters of galaxies behaves when the clusters collide.^[115]



Video about the potential gamma-ray detection of dark matter annihilation around supermassive black holes. *(Duration 3:13, also see file description.)*

In 2013 results from the Alpha Magnetic Spectrometer on the International Space Station indicated excess high-energy cosmic rays that could be due to dark matter annihilation.^{[130][131][132][133][134][135]}

Synthesis

An alternative approach to the detection of WIMPs in nature is to produce them in a laboratory. Experiments with the Large Hadron Collider (LHC) may be able to detect WIMPs produced in collisions of the LHC proton beams. Because a WIMP has negligible interaction with matter, it may be detected indirectly as (large amounts of) missing energy and momentum that escape the detectors, provided other (non-negligible) collision products are detected.^[136] These experiments could show that WIMPs can be formed, but a direct detection experiment must still show that they exist in sufficient numbers to account for dark matter.

Alternative theories

Mass in extra dimensions

In some multidimensional theories, the force of gravity is the only force with effect across all dimensions.^[137] This explains the relative weakness of gravity compared to the other forces of nature that cannot cross into extra dimensions. In that case, dark matter could exist in a "Hidden Valley" in other dimensions that only interact with the matter in our dimensions through gravity. That dark matter could potentially aggregate in the same way as ordinary matter, forming other-dimensional galaxies.^{[12][138]}

Topological defects

Dark matter could consist of primordial defects ("birth defects") in the topology of quantum fields, which would contain energy and therefore gravitate. This hypothesis may be investigated by the use of an orbital network of atomic clocks that would register the passage of topological defects by changes to clock synchronization. The Global Positioning System may be able to operate as such a network.^[139]

Modified gravity

Some theories modify the laws of gravity. The earliest was Mordehai Milgrom's Modified Newtonian Dynamics (MOND) in 1983, which adjusts Newton's laws to increase gravitational field strength where gravitational acceleration becomes tiny (such as near the rim of a galaxy). It had some success explaining the rotational velocity curves of elliptical and dwarf elliptical galaxies that it was designed to match, but fails on galaxy cluster gravitational lensing. MOND was not relativistic: it was an adjustment of the Newtonian account. Attempts were made to bring MOND into conformity with general relativity; this spawned competing MOND-based hypotheses—including TeVeS, MOG or STV gravity, and the phenomenological covariant approach.^[140]

In 2007, John Moffat proposed a modified gravity hypothesis based on nonsymmetric gravitational theory (NGT) that claims to account for the behavior of colliding galaxies.^[141] This model requires the presence of non-relativistic neutrinos or other cold dark matter, to work.

Another proposal uses a gravitational backreaction from a theory that explains gravitational force between objects as an action, a reaction and then a back-reaction. Thus, an object A affects an object B, and the object B then re-affects object A, and so on, creating a feedback loop that strengthens gravity.^[142]

In 2008, a group proposed "dark fluid", a modification of large-scale gravity. It hypothesized that attractive gravitational effects are instead a side-effect of dark energy. Dark fluid combines dark matter and dark energy in a single energy field that produces different effects at different scales. This treatment is a simplification of a previous fluid-like model called the generalized Chaplygin gas model in which the whole of spacetime is a compressible gas.^[143] Dark fluid can be compared to an atmospheric system. Atmospheric pressure causes air to expand and air regions can collapse to form clouds. In the same way, the dark fluid might generally disperse, while collecting around galaxies.^[143]

Spacetime fractality

Applying relativity to fractal, non-differentiable spacetime, Nottale suggests that potential energy may arise due to the fractality of spacetime, which would account for the missing mass-energy observed at cosmological scales.^{[144][145]}

In popular culture

Mention of dark matter is made in works of fiction. In such cases, it is usually attributed extraordinary physical or magical properties. Such descriptions are often inconsistent with the hypothesized properties of dark matter in physics and cosmology.

See also

- Chameleon particle
- Conformal gravity
- Dark electromagnetism
- DEAP, a dark matter experiment
- DAMPE, a space mission
- General Antiparticle Spectrometer
- Illustris project, astrophysical simulations
- Light dark matter
- Mirror matter
- Multidark, a research program
- Scalar field dark matter
- Self-interacting dark matter
- SIMP, hypothetical particles of dark matter
- Unparticle physics

Notes

1. Since dark energy, by convention, does not count as "matter", this is $26.8/(4.9 + 26.8)=0.845$

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