**Dark matter**

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(<https://en.wikipedia.org/wiki/Dark_matter>)

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**Abstract:** Dark matteris a form of [matter](https://en.wikipedia.org/wiki/Matter) composed for approximately 85% of the matter in the [universe](https://en.wikipedia.org/wiki/Universe) and about a quarter of its total [mass - energy density](https://en.wikipedia.org/wiki/Energy_density). Primary evidence for dark matter comes from calculations showing that many [galaxies](https://en.wikipedia.org/wiki/Galaxy) would fly apart, or that they would not have formed or would not move as they do, if they did not contain a large amount of unseen matter. Other lines of evidence include observations in [gravitational lensing](https://en.wikipedia.org/wiki/Gravitational_lensing) and in the [cosmic microwave background](https://en.wikipedia.org/wiki/Cosmic_microwave_background), along with astronomical observations of the [observable universe](https://en.wikipedia.org/wiki/Observable_universe)'s current structure, the [formation and evolution of galaxies](https://en.wikipedia.org/wiki/Galaxy_formation_and_evolution), mass location during [galactic collisions](https://en.wikipedia.org/wiki/Galactic_collision), and the motion of galaxies within [galaxy clusters](https://en.wikipedia.org/wiki/Galaxy_cluster). In the standard [Lambda-CDM](https://en.wikipedia.org/wiki/Lambda-CDM) model of cosmology, the total [mass–energy](https://en.wikipedia.org/wiki/Mass%E2%80%93energy_equivalence) of the universe contains 5% [ordinary matter](https://en.wikipedia.org/wiki/Baryon#Baryonic_matter) and [energy](https://en.wikipedia.org/wiki/Energy), 27% dark matter and 68% of a form of energy known as [dark energy](https://en.wikipedia.org/wiki/Dark_energy).

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**Keywords**: dark matter;[universe](https://en.wikipedia.org/wiki/Universe); [energy](https://en.wikipedia.org/wiki/Energy_density); [galaxy](https://en.wikipedia.org/wiki/Galaxy); [gravity](https://en.wikipedia.org/wiki/Gravitational_lensing); [cosmic microwave background](https://en.wikipedia.org/wiki/Cosmic_microwave_background), cosmology

**Dark matter** is a form of [matter](https://en.wikipedia.org/wiki/Matter) composed for approximately 85% of the matter in the [universe](https://en.wikipedia.org/wiki/Universe) and about a quarter of its total [mass - energy density](https://en.wikipedia.org/wiki/Energy_density) (about 2.241×10−27 kg/m3). Its presence is implied in a variety of [astrophysical](https://en.wikipedia.org/wiki/Astrophysical) observations, including [gravitational](https://en.wikipedia.org/wiki/Gravitation) effects that cannot be explained by accepted theories of [gravity](https://en.wikipedia.org/wiki/Gravity) unless more matter is present than can be seen. For this reason, most experts think that dark matter is abundant in the universe and that it has had a strong influence on its structure and evolution. Dark matter is called dark because it does not appear to interact with the [electromagnetic field](https://en.wikipedia.org/wiki/Electromagnetic_field), which means it doesn't absorb, reflect or emit [electromagnetic radiation](https://en.wikipedia.org/wiki/Electromagnetic_radiation), and is therefore difficult to detect.[[1]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-CERN_Dark_Matter-1)

Primary evidence for dark matter comes from calculations showing that many [galaxies](https://en.wikipedia.org/wiki/Galaxy) would fly apart, or that they would not have formed or would not move as they do, if they did not contain a large amount of unseen matter.[[2]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Siegfried-2) Other lines of evidence include observations in [gravitational lensing](https://en.wikipedia.org/wiki/Gravitational_lensing)[[3]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Trimble_1987-3) and in the [cosmic microwave background](https://en.wikipedia.org/wiki/Cosmic_microwave_background), along with astronomical observations of the [observable universe](https://en.wikipedia.org/wiki/Observable_universe)'s current structure, the [formation and evolution of galaxies](https://en.wikipedia.org/wiki/Galaxy_formation_and_evolution), mass location during [galactic collisions](https://en.wikipedia.org/wiki/Galactic_collision),[[4]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-4) and the motion of galaxies within [galaxy clusters](https://en.wikipedia.org/wiki/Galaxy_cluster). In the standard [Lambda-CDM](https://en.wikipedia.org/wiki/Lambda-CDM) model of cosmology, the total [mass–energy](https://en.wikipedia.org/wiki/Mass%E2%80%93energy_equivalence) of the universe contains 5% [ordinary matter](https://en.wikipedia.org/wiki/Baryon#Baryonic_matter) and [energy](https://en.wikipedia.org/wiki/Energy), 27% dark matter and 68% of a form of energy known as [dark energy](https://en.wikipedia.org/wiki/Dark_energy).[[5]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NASA_Planck_Mission-5)[[6]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NASA_Science_Dark_Matter-6)[[7]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-planck_overview-7)[[8]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-wmap7parameters(a)-8) Thus, dark matter constitutes 85%[[a]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-9) of total [mass](https://en.wikipedia.org/wiki/Mass), while dark energy plus dark matter constitute 95% of total mass–energy content.[[9]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-planckcam-10)[[10]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-DarkMatter-11)[[11]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-12)[[12]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-wmap7parameters-13)

Because dark matter has not yet been observed directly, if it exists, it must barely interact with ordinary [baryonic](https://en.wikipedia.org/wiki/Baryonic) matter and radiation, except through gravity. Most dark matter is thought to be non-baryonic in nature; it may be composed of some as-yet undiscovered [subatomic particles](https://en.wikipedia.org/wiki/Subatomic_particle).[[b]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-14) The primary candidate for dark matter is some new kind of [elementary particle](https://en.wikipedia.org/wiki/Elementary_particle) that has [not yet been discovered](https://en.wikipedia.org/wiki/Physics_beyond_the_Standard_Model), in particular, [weakly interacting massive particles](https://en.wikipedia.org/wiki/Weakly_interacting_massive_particles) (WIMPs).[[13]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Copi_1995-15) Many experiments to directly detect and study dark matter particles are being actively undertaken, but none have yet succeeded.[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16) Dark matter is classified as cold, warm, or hot according to its [velocity](https://en.wikipedia.org/wiki/Velocity) (more precisely, its [free streaming length](https://en.wikipedia.org/wiki/Free_streaming)). Current models favor a [cold dark matter](https://en.wikipedia.org/wiki/Cold_dark_matter) scenario, in which [structures emerge](https://en.wikipedia.org/wiki/Structure_formation) by gradual accumulation of particles.

Although the existence of dark matter is generally accepted by the scientific community, some astrophysicists, intrigued by certain observations which do not fit some dark matter theories, argue for various modifications of the standard laws of [general relativity](https://en.wikipedia.org/wiki/General_relativity), such as [modified Newtonian dynamics](https://en.wikipedia.org/wiki/Modified_Newtonian_dynamics), [tensor–vector–scalar gravity](https://en.wikipedia.org/wiki/Tensor%E2%80%93vector%E2%80%93scalar_gravity), or [entropic gravity](https://en.wikipedia.org/wiki/Entropic_gravity). These models attempt to account for all observations without invoking supplemental non-baryonic matter.[[15]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Angus-17)

## History

## Early history

The hypothesis of dark matter has an elaborate history.[[16]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-18) In a talk given in 1884,[[17]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-19) [Lord Kelvin](https://en.wikipedia.org/wiki/William_Thomson,_1st_Baron_Kelvin) estimated the number of dark bodies in the [Milky Way](https://en.wikipedia.org/wiki/Milky_Way) from the observed velocity dispersion of the stars orbiting around the center of the galaxy. By using these measurements, he estimated the mass of the galaxy, which he determined is different from the mass of visible stars. Lord Kelvin thus concluded many of our stars, perhaps a great majority of them, may be dark bodies.[[18]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-20)[[19]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-:1-21) In 1906 [Henri Poincaré](https://en.wikipedia.org/wiki/Henri_Poincar%C3%A9) in The Milky Way and Theory of Gases used dark matter.[[20]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-22)[[19]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-:1-21)

The first to suggest the existence of dark matter using stellar velocities was Dutch astronomer [Jacobus Kapteyn](https://en.wikipedia.org/wiki/Jacobus_Kapteyn) in 1922.[[21]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-23)[[22]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Patras2014-24) Fellow Dutchman and radio astronomy pioneer [Jan Oort](https://en.wikipedia.org/wiki/Jan_Oort) also hypothesized the existence of dark matter in 1932.[[22]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Patras2014-24)[[23]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-25)[[24]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-26) Oort was studying stellar motions in the [local galactic neighborhood](https://en.wikipedia.org/wiki/Local_Group) and found the mass in the galactic plane must be greater than what was observed, but this measurement was later determined to be erroneous.[[25]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-27)

In 1933, Swiss astrophysicist [Fritz Zwicky](https://en.wikipedia.org/wiki/Fritz_Zwicky), who studied [galaxy clusters](https://en.wikipedia.org/wiki/Groups_and_clusters_of_galaxies) while working at the California Institute of Technology, made a similar inference.[[26]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-zwicky1933-28)[[27]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-zwicky1937-29) Zwicky applied the [virial theorem](https://en.wikipedia.org/wiki/Virial_theorem) to the [Coma Cluster](https://en.wikipedia.org/wiki/Coma_Cluster) and obtained evidence of unseen mass 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 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 some unseen matter provided the mass and associated gravitation attraction to hold the cluster together.[[28]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-30) Zwicky's estimates were off by more than an order of magnitude, mainly due to an obsolete value of the [Hubble constant](https://en.wikipedia.org/wiki/Hubble_constant);[[29]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-31) the same calculation today shows a smaller fraction, using greater values for luminous mass. Nonetheless, Zwicky did correctly conclude from his calculation that the bulk of the matter was dark.[[19]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-:1-21)

Further indications the [mass-to-light ratio](https://en.wikipedia.org/wiki/Mass-to-light_ratio) was not unity came from measurements of galaxy rotation curves. In 1939, [Horace W. Babcock](https://en.wikipedia.org/wiki/Horace_W._Babcock) reported the rotation curve for the [Andromeda nebula](https://en.wikipedia.org/wiki/Andromeda_Galaxy), which suggested the mass-to-luminosity ratio increases radially.[[30]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-:0-32) He attributed it to either light absorption within the galaxy or modified dynamics in the outer portions of the spiral and not to the missing matter he had uncovered. Following [Babcock's](https://en.wikipedia.org/wiki/Horace_W._Babcock) 1939 report of unexpectedly rapid rotation in the outskirts of the Andromeda galaxy and a mass-to-light ratio of 50; in 1940 [Jan Oort](https://en.wikipedia.org/wiki/Jan_Oort) discovered and wrote about the large non-visible halo of [NGC3115](https://en.wikipedia.org/wiki/NGC_3115).[[31]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-33)

**1970s**

[Vera Rubin](https://en.wikipedia.org/wiki/Vera_Rubin), [Kent Ford](https://en.wikipedia.org/wiki/Kent_Ford_(astronomer)), and [Ken Freeman](https://en.wikipedia.org/wiki/Ken_Freeman_(astronomer))'s work in the 1960s and 1970s[[32]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-34) provided further strong evidence, also using galaxy rotation curves.[[33]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NYT-20161227-35)[[34]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-36)[[35]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Rubin1970-37) Rubin and Ford worked with a new [spectrograph](https://en.wikipedia.org/wiki/Spectrograph) to measure the [velocity curve](https://en.wikipedia.org/wiki/Galaxy_rotation_curve) of edge-on [spiral galaxies](https://en.wikipedia.org/wiki/Spiral_galaxies) with greater accuracy.[[35]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Rubin1970-37) This result was confirmed in 1978.[[36]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-38) An influential paper presented Rubin and Ford's results in 1980.[[37]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Rubin1980-39) They showed most galaxies must contain about six times as much dark as visible mass;[[38]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-FOOTNOTERandall201513%E2%80%9314-40) thus, by around 1980 the apparent need for dark matter was widely recognized as a major unsolved problem in astronomy.[[33]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NYT-20161227-35)

At the same time Rubin and Ford were exploring optical rotation curves, radio astronomers were making use of new radio telescopes to map the 21 cm line of atomic hydrogen in nearby galaxies. The radial distribution of interstellar atomic hydrogen ([H-I](https://en.wikipedia.org/wiki/H_I_region)) often extends to much larger galactic radii than those accessible by optical studies, extending the sampling of rotation curves – and thus of the total mass distribution – to a new dynamical regime. Early mapping of Andromeda with the 300 foot telescope at [Green Bank](https://en.wikipedia.org/wiki/Green_Bank_Observatory)[[39]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Roberts1966-41) and the 250 foot dish at [Jodrell Bank](https://en.wikipedia.org/wiki/Jodrell_Bank_Observatory)[[40]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Gottesman1966-42) already showed the H-I rotation curve did not trace the expected Keplerian decline. As more sensitive receivers became available, Morton Roberts and Robert Whitehurst[[41]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Roberts1975-43) were able to trace the rotational velocity of Andromeda to 30 kpc, much beyond the optical measurements. Illustrating the advantage of tracing the gas disk at large radii, Figure 16 of that paper[[41]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Roberts1975-43) combines the optical data[[35]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Rubin1970-37) with the H-I data between 20–30 kpc, exhibiting the flatness of the outer galaxy rotation curve; the solid curve peaking at the center is the optical surface density, while the other curve shows the cumulative mass, still rising linearly at the outermost measurement. In parallel, the use of interferometric arrays for extragalactic H-I spectroscopy was being developed. In 1972, David Rogstad and [Seth Shostak](https://en.wikipedia.org/wiki/Seth_Shostak)[[42]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Rogstad1972-44) published H-I rotation curves of five spirals mapped with the Owens Valley interferometer; the rotation curves of all five were very flat, suggesting very large values of mass-to-light ratio in the outer parts of their extended H-I disks.

A stream of observations in the 1980s supported the presence of dark matter, including [gravitational lensing](https://en.wikipedia.org/wiki/Gravitational_lensing) of background objects by [galaxy clusters](https://en.wikipedia.org/wiki/Galaxy_cluster),[[43]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-FOOTNOTERandall201514%E2%80%9316-45) the temperature distribution of hot gas in galaxies and clusters, and the pattern of anisotropies in the [cosmic microwave background](https://en.wikipedia.org/wiki/Cosmic_microwave_background). According to consensus among cosmologists, dark matter is composed primarily of a not yet characterized type of [subatomic particle](https://en.wikipedia.org/wiki/Subatomic_particle).[[13]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Copi_1995-15)[[44]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Bergstrom_2000-46) The search for this particle, by a variety of means, is one of the major efforts in [particle physics](https://en.wikipedia.org/wiki/Particle_physics).[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16)

## Technical definition

In standard cosmology, matter is anything whose energy density scales with the inverse cube of the [scale factor](https://en.wikipedia.org/wiki/Scale_factor_(cosmology)), i.e., *ρ*∝*a*−3. This is in contrast to radiation, which scales as the inverse fourth power of the scale factor *ρ*∝*a*−4, and a [cosmological constant](https://en.wikipedia.org/wiki/Cosmological_constant), which is independent of *a*. These scalings can be understood intuitively: For an ordinary particle in a cubical box, doubling the length of the sides of the box decreases the density by a factor of 8 (=23). For radiation, the energy density decreases by a factor of 16 (=24), because any act whose effect increases the scale factor must also cause a proportional [redshift](https://en.wikipedia.org/wiki/Redshift). A cosmological constant, as an intrinsic property of space, has a constant energy density regardless of the volume under consideration.[[45]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-47)

In principle, dark matter means all components of the universe which are not visible but still obey *ρ*∝*a*−3. In practice, the term dark matter is often used to mean only the non-baryonic component of dark matter, i.e., excluding [missing baryons](https://en.wikipedia.org/wiki/Missing_baryon_problem). Context will usually indicate which meaning is intended.

## Observational evidence

This artist's impression shows the expected distribution of dark matter in the [Milky Way](https://en.wikipedia.org/wiki/Milky_Way) galaxy as a blue halo of material surrounding the galaxy.[[46]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-49)

**Galaxy rotation curves**

The arms of [spiral galaxies](https://en.wikipedia.org/wiki/Spiral_galaxies) rotate around the galactic center. The luminous mass density of a spiral galaxy decreases as one goes from the center to the outskirts. If luminous mass were all the matter, then we can model the galaxy as a point mass in the centre and test masses orbiting around it, similar to the [Solar System](https://en.wikipedia.org/wiki/Solar_System).[[d]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-50) From [Kepler's Second Law](https://en.wikipedia.org/wiki/Kepler%27s_Second_Law), it is expected that the rotation velocities will decrease with distance from the center, similar to the Solar System. This is not observed.[[47]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-51) Instead, the galaxy rotation curve remains flat as distance from the center increases.

If Kepler's laws are correct, then the obvious way to resolve this discrepancy is to conclude the mass distribution in spiral galaxies is not similar to that of the Solar System. In particular, there is a lot of non-luminous matter in the outskirts of the galaxy.

**Velocity dispersions**

Stars in bound systems must obey the [virial theorem](https://en.wikipedia.org/wiki/Virial_theorem). The theorem, together with the measured velocity distribution, can be used to measure the mass distribution in a bound system, such as elliptical galaxies or globular clusters. With some exceptions, velocity dispersion estimates of elliptical galaxies[[48]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-52) do not match the predicted velocity dispersion from the observed mass distribution, even assuming complicated distributions of stellar orbits.[[49]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-53)

As with galaxy rotation curves, the obvious way to resolve the discrepancy is to postulate the existence of non-luminous matter.

**Galaxy clusters**

[Galaxy clusters](https://en.wikipedia.org/wiki/Galaxy_clusters) 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](https://en.wikipedia.org/wiki/X-ray) 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.
* [Gravitational lensing](https://en.wikipedia.org/wiki/Gravitational_lens) can measure cluster masses without relying on observations of dynamics.

Generally, these three methods are in reasonable agreement that dark matter outweighs visible matter by approximately 5 to 1.[[50]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-54)

**Gravitational lensing**

One of the consequences of [general relativity](https://en.wikipedia.org/wiki/General_relativity) is massive objects lying between a more distant source and an observer should act as a lens to bend the light from this source. The more massive an object, the more lensing is observed.[[51]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-55)

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](https://en.wikipedia.org/wiki/Abell_1689).[[52]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-56) 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.[[53]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-57) Lensing can lead to multiple copies of an image. By analyzing the distribution of multiple image copies, scientists have been able to deduce and map the distribution of dark matter around the [MACS J0416.1-2403](https://en.wikipedia.org/wiki/MACS_J0416.1-2403) galaxy cluster.[[54]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-58)[[55]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-59)

[Weak gravitational lensing](https://en.wikipedia.org/wiki/Weak_gravitational_lensing) investigates minute distortions of galaxies, using statistical analyses from vast [galaxy surveys](https://en.wikipedia.org/wiki/Redshift_survey). By examining the apparent shear deformation of the adjacent background galaxies, the mean distribution of dark matter can be characterized. The mass-to-light ratios correspond to dark matter densities predicted by other large-scale structure measurements.[[56]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-60) Dark matter does not bend light itself; mass bends [spacetime](https://en.wikipedia.org/wiki/Spacetime). Light follows the curvature of spacetime, resulting in the lensing effect.[[57]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-61)[[58]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-62)

**Cosmic microwave background**

Although both dark matter and ordinary matter are matter, they do not behave in the same way. In particular, in the early universe, ordinary matter was ionized and interacted strongly with radiation via [Thomson scattering](https://en.wikipedia.org/wiki/Thomson_scattering). Dark matter does not interact directly with radiation, but it does affect the CMB by its gravitational potential (mainly on large scales), and by its effects on the density and velocity of ordinary matter. Ordinary and dark matter perturbations, therefore, evolve differently with time and leave different imprints on the cosmic microwave background (CMB).

The cosmic microwave background is very close to a perfect blackbody but contains very small temperature anisotropies of a few parts in 100,000. A sky map of anisotropies can be decomposed into an angular power spectrum, which is observed to contain a series of acoustic peaks at near-equal spacing but different heights. The series of peaks can be predicted for any assumed set of cosmological parameters by modern computer codes such as [CMBFAST](https://en.wikipedia.org/wiki/CMBFAST) and [CAMB](https://en.wikipedia.org/w/index.php?title=CAMB&action=edit&redlink=1), and matching theory to data, therefore, constrains cosmological parameters.[[59]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Wayne_Hu-63)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.[[59]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Wayne_Hu-63)

The CMB anisotropy was first discovered by [COBE](https://en.wikipedia.org/wiki/Cosmic_Background_Explorer) in 1992, though this had too coarse resolution to detect the acoustic peaks. After the discovery of the first acoustic peak by the balloon-borne [BOOMERanG](https://en.wikipedia.org/wiki/BOOMERanG) experiment in 2000, the power spectrum was precisely observed by [WMAP](https://en.wikipedia.org/wiki/WMAP) in 2003–2012, and even more precisely by the [Planck spacecraft](https://en.wikipedia.org/wiki/Planck_spacecraft) in 2013–2015. The results support the Lambda-CDM model.[[60]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Hinshaw2009-64)[[61]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Planck15-65)

The observed CMB angular power spectrum provides powerful evidence in support of dark matter, as its precise structure is well fitted by the [Lambda-CDM model](https://en.wikipedia.org/wiki/Lambda-CDM_model),[[61]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Planck15-65) but difficult to reproduce with any competing model such as [modified Newtonian dynamics](https://en.wikipedia.org/wiki/Modified_Newtonian_dynamics) (MOND).[[61]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Planck15-65)[[62]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-66)

**Structure formation**

Structure formation refers to the period after the Big Bang when density perturbations collapsed to form stars, galaxies, and clusters. Prior to structure formation, the [Friedmann solutions](https://en.wikipedia.org/wiki/FRW_metric) to general relativity describe a homogeneous universe. Later, small anisotropies gradually grew and condensed the homogeneous universe into stars, galaxies and larger structures. Ordinary matter is affected by radiation, which is the dominant element of the universe at very early times. As a result, its density perturbations are washed out and unable to condense into structure.[[64]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Jaffe-68) If there were only ordinary matter in the universe, there would not have been enough time for density perturbations to grow into the galaxies and clusters currently seen.[[63]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-67)

Dark matter provides a solution to this problem because it is unaffected by radiation. Therefore, its density perturbations can grow first. The resulting gravitational potential acts as an attractive [potential well](https://en.wikipedia.org/wiki/Potential_well) for ordinary matter collapsing later, speeding up the structure formation process.[[64]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Jaffe-68)[[65]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-69)

**Bullet Cluster**

If dark matter does not exist, then the next most likely explanation must be general relativity – the prevailing theory of gravity – is incorrect and should be modified. The Bullet Cluster, the result of a recent collision of two galaxy clusters, provides a challenge for modified gravity theories because its apparent center of mass is far displaced from the baryonic center of mass.[[66]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-70) Standard dark matter models can easily explain this observation, but modified gravity has a much harder time,[[67]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-71)[[68]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-72) especially since the observational evidence is model-independent.[[69]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-73)

**Type Ia supernova distance measurements**

Type Ia [supernovae](https://en.wikipedia.org/wiki/Supernovae) can be used as [standard candles](https://en.wikipedia.org/wiki/Standard_candles) to measure extragalactic distances, which can in turn be used to measure how fast the universe has expanded in the past.[[70]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-74) Data indicates the universe is expanding at an accelerating rate, the cause of which is usually ascribed to [dark energy](https://en.wikipedia.org/wiki/Dark_energy).[[71]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-75) Since observations indicate the universe is almost flat,[[72]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NASA_Shape-76)[[73]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Fermi_Flat-77)[[74]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-78) it is expected the total energy density of everything in the universe should sum to 1 (Ωtot ≈ 1). The measured dark energy density is ΩΛ ≈ 0.690; the observed ordinary (baryonic) matter energy density is Ωb ≈ 0.0482 and the energy density of radiation is negligible. This leaves a missing Ωdm ≈ 0.258 which nonetheless behaves like matter – dark matter.[[75]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-planckesa2015-79)

**Sky surveys and baryon acoustic oscillations**

Baryon acoustic oscillations (BAO) are fluctuations in the density of the visible [baryonic](https://en.wikipedia.org/wiki/Baryonic) matter of the universe on large scales. These are predicted to arise in the Lambda-CDM model due to acoustic oscillations in the photon–baryon fluid of the early universe, and can be observed in the cosmic microwave background angular power spectrum. BAOs set up a preferred length scale for baryons. 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%) preference for pairs of galaxies to be separated by 147 Mpc, compared to those separated by 130–160 Mpc. This feature was predicted theoretically in the 1990s and then discovered in 2005, in two large galaxy redshift surveys, the [Sloan Digital Sky Survey](https://en.wikipedia.org/wiki/Sloan_Digital_Sky_Survey) and the [2dF Galaxy Redshift Survey](https://en.wikipedia.org/wiki/2dF_Galaxy_Redshift_Survey).[[76]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-80)Combining the CMB observations with BAO measurements from galaxy [redshift surveys](https://en.wikipedia.org/wiki/Redshift_survey) provides a precise estimate of the [Hubble constant](https://en.wikipedia.org/wiki/Hubble%27s_law) and the average matter density in the Universe.[[77]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Komatsu2009-81)The results support the Lambda-CDM model.

**Redshift-space distortions**

Large galaxy [redshift surveys](https://en.wikipedia.org/wiki/Redshift_survey) 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](https://en.wikipedia.org/wiki/Redshift); 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 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. Their angular positions are unaffected. This effect is not detectable for any one structure since the true shape is not known, but can be measured by averaging over many structures. It was predicted quantitatively by Nick Kaiser in 1987, and first decisively measured in 2001 by the [2dF Galaxy Redshift Survey](https://en.wikipedia.org/wiki/2dF_Galaxy_Redshift_Survey).[[78]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-82) Results are in agreement with the [Lambda-CDM model](https://en.wikipedia.org/wiki/Lambda-CDM_model).

**Lyman-alpha forest**

In [astronomical spectroscopy](https://en.wikipedia.org/wiki/Astronomical_spectroscopy), the Lyman-alpha forest is the sum of the [absorption lines](https://en.wikipedia.org/wiki/Spectral_line) arising from the [Lyman-alpha](https://en.wikipedia.org/wiki/Lyman_series) transition of [neutral hydrogen](https://en.wikipedia.org/wiki/Hydrogen_line) in the spectra of distant [galaxies](https://en.wikipedia.org/wiki/Galaxy) and [quasars](https://en.wikipedia.org/wiki/Quasar). Lyman-alpha forest observations can also constrain cosmological models.[[79]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-83) These constraints agree with those obtained from WMAP data.

## Theoretical classifications

## Composition

Dark matter can refer to any substance which interacts predominantly via gravity with visible matter. Hence in principle it need not be composed of a new type of fundamental particle but could, at least in part, be made up of standard baryonic matter, such as protons or neutrons.[[e]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-BaryonicFootnote01-91) However, for the reasons outlined below, most scientists think the dark matter is dominated by a non-baryonic component, which is likely composed of a currently unknown fundamental particle.

**Baryonic matter**

[Baryons](https://en.wikipedia.org/wiki/Baryon) ([protons](https://en.wikipedia.org/wiki/Proton) and [neutrons](https://en.wikipedia.org/wiki/Neutron)) make up ordinary stars and planets. However, baryonic matter also encompasses less common non-primordial [black holes](https://en.wikipedia.org/wiki/Black_hole), [neutron stars](https://en.wikipedia.org/wiki/Neutron_star), faint old [white dwarfs](https://en.wikipedia.org/wiki/White_dwarf) and [brown dwarfs](https://en.wikipedia.org/wiki/Brown_dwarf), collectively known as [massive compact halo objects](https://en.wikipedia.org/wiki/Massive_compact_halo_object) (MACHOs), which can be hard to detect.[[87]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-FOOTNOTERandall2015286-92)

However, 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](https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis) predicts the observed [abundance of the chemical elements](https://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements). If there are more baryons, then there should also be more helium, lithium and heavier elements synthesized during the Big Bang.[[88]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-93)[[89]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-94) Agreement with observed abundances requires that baryonic matter makes up between 4–5% of the universe's [critical density](https://en.wikipedia.org/wiki/Friedmann_equations#Density_parameter). In contrast, [large-scale structure](https://en.wikipedia.org/wiki/Large-scale_structure_of_the_universe) and other observations indicate that the total matter density is about 30% of the critical density.[[75]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-planckesa2015-79)
* Astronomical searches for [gravitational microlensing](https://en.wikipedia.org/wiki/Gravitational_microlensing) in the [Milky Way](https://en.wikipedia.org/wiki/Milky_Way) found at most only a small fraction of the dark matter may be in dark, compact, conventional objects; 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.[[90]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-95)[[91]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-96)[[92]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-97)[[93]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-98)[[94]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-99)[[95]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-100)
* Detailed analysis of the small irregularities in the [cosmic microwave background](https://en.wikipedia.org/wiki/Cosmic_microwave_background).[[96]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-101) Observations by [WMAP](https://en.wikipedia.org/wiki/WMAP) and [Planck](https://en.wikipedia.org/wiki/Planck_(spacecraft)) indicate that around five-sixths of the total matter is in a form that interacts significantly with ordinary matter or [photons](https://en.wikipedia.org/wiki/Photon) only through gravitational effects.

**Non-baryonic matter**

Candidates for non-baryonic dark matter are hypothetical particles such as [axions](https://en.wikipedia.org/wiki/Axion), [sterile neutrinos](https://en.wikipedia.org/wiki/Sterile_neutrino), [weakly interacting massive particles](https://en.wikipedia.org/wiki/Weakly_interacting_massive_particles) (WIMPs), [gravitationally-interacting massive particles](https://en.wikipedia.org/wiki/Gravitationally-interacting_massive_particles) (GIMPs), [supersymmetric](https://en.wikipedia.org/wiki/Supersymmetric) particles, or [primordial black holes](https://en.wikipedia.org/wiki/Primordial_black_holes).[[97]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-102) 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 too tiny, they can only supply a small fraction of dark matter, due to limits derived from [large-scale structure](https://en.wikipedia.org/wiki/Observable_universe) and high-[redshift](https://en.wikipedia.org/wiki/Redshift" \o "Redshift) galaxies.[[98]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_merritt-103)

Unlike baryonic matter, nonbaryonic matter did not contribute to the formation of the [elements](https://en.wikipedia.org/wiki/Chemical_element) in the early universe [[13]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Copi_1995-15) and so its presence is revealed only via its gravitational effects, or [weak lensing](https://en.wikipedia.org/wiki/Weak_lensing). In addition, if the particles of which it is composed are supersymmetric, they can undergo [annihilation](https://en.wikipedia.org/wiki/Annihilation) interactions with themselves, possibly resulting in observable by-products such as [gamma rays](https://en.wikipedia.org/wiki/Gamma_rays) and neutrinos.[[98]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_merritt-103)

**Dark matter aggregation and dense dark matter objects**

If dark matter is composed of weakly-interacting particles, an obvious question is whether it can form objects equivalent to [planets](https://en.wikipedia.org/wiki/Planet), [stars](https://en.wikipedia.org/wiki/Star), or [black holes](https://en.wikipedia.org/wiki/Black_hole). Historically, the answer has been it cannot,[[99]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-curio-104)[[100]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-siegel-105) because of two factors:

**It lacks an efficient means to lose energy**[[99]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-curio-104)

Ordinary matter forms dense objects because it has numerous ways to lose energy. Losing energy would be essential for object formation, because a particle that gains energy during compaction or falling inward under gravity, and cannot lose it any other way, will heat up and increase [velocity](https://en.wikipedia.org/wiki/Velocity) and [momentum](https://en.wikipedia.org/wiki/Momentum). Dark matter appears to lack means to lose energy, simply because it is not capable of interacting strongly in other ways except through gravity. The [virial theorem](https://en.wikipedia.org/wiki/Virial_theorem) suggests that such a particle would not stay bound to the gradually forming object – as the object began to form and compact, the dark matter particles within it would speed up and tend to escape.

**It lacks a range of interactions needed to form structures**[[100]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-siegel-105)

Ordinary matter interacts in many different ways. This allows the matter to form more complex structures. For example, stars form through gravity, but the particles within them interact and can emit energy in the form of [neutrinos](https://en.wikipedia.org/wiki/Neutrino) and [electromagnetic radiation](https://en.wikipedia.org/wiki/Electromagnetic_radiation) through [fusion](https://en.wikipedia.org/wiki/Nuclear_fusion) when they become energetic enough. [Protons](https://en.wikipedia.org/wiki/Proton) and [neutrons](https://en.wikipedia.org/wiki/Neutron) can bind via the [strong interaction](https://en.wikipedia.org/wiki/Strong_interaction) and then form [atoms](https://en.wikipedia.org/wiki/Atom) with [electrons](https://en.wikipedia.org/wiki/Electron) largely through [electromagnetic interaction](https://en.wikipedia.org/wiki/Electromagnetic_interaction). But there is no evidence that dark matter is capable of such a wide variety of interactions, since it seems to only interact through gravity.

In 2015–2017 the idea dense dark matter was composed of [primordial black holes](https://en.wikipedia.org/wiki/Primordial_black_hole), made a comeback[[101]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-106) following results of [gravitational wave](https://en.wikipedia.org/wiki/Gravitational_wave) measurements which detected the merger of intermediate mass black holes. Black holes with about 30 solar masses are not predicted to form by either stellar collapse (typically less than 15 solar masses) or by the merger of black holes in galactic centers (millions or billions of solar masses). It was proposed the intermediate mass black holes causing the detected merger formed in the hot dense early phase of the universe due to denser regions collapsing. A later survey of about a thousand supernovae detected no gravitational lensing events, when about eight would be expected if intermediate mass primordial black holes above a certain mass range accounted for the majority of dark matter.[[102]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-107)

The possibility atom-sized primordial black holes account for a significant fraction of dark matter was ruled out by measurements of positron and electron fluxes outside the Sun's heliosphere by the Voyager 1 spacecraft. Tiny black holes are theorized to emit [Hawking radiation](https://en.wikipedia.org/wiki/Hawking_radiation). However the detected fluxes were too low and did not have the expected energy spectrum suggesting tiny primordial black holes are not widespread enough to account for dark matter.[[103]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-108) Nonetheless, research and theories proposing dense dark matter accounts for dark matter continue as of 2018, including approaches to dark matter cooling,[[104]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-109)[[105]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-110) and the question remains unsettled. In 2019, the lack of microlensing effects in the observation of Andromeda suggests tiny black holes do not exist.[[106]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-111)

However, there still exists a largely unconstrained mass range smaller than that can be limited by optical microlensing observations, where primordial black holes may account for all dark matter.[[107]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-112)[[108]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-113)

**Free streaming length**

Dark matter can be divided into *cold*, *warm*, and *hot* categories.[[109]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-114) 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*](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Protogalaxy): Dark matter particles are classified as cold, warm, or hot according to their FSL; much smaller (cold), similar to (warm), or much larger (hot) than a protogalaxy.[[110]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-115)[[111]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-116) Mixtures of the above are also possible: a theory of [mixed dark matter](https://en.wikipedia.org/wiki/Mixed_dark_matter) was popular in the mid-1990s, but was rejected following the discovery of [dark energy](https://en.wikipedia.org/wiki/Dark_energy).

Cold dark matter leads to a bottom-up formation of structure with galaxies forming first and galaxy clusters at a latter stage, while hot dark matter would result in a top-down formation scenario with large matter aggregations forming early, later fragmenting into separate galaxies, the latter is excluded by high-redshift galaxy observations.[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16)**Fluctuation spectrum effects**

These categories also correspond to [fluctuation spectrum](https://en.wikipedia.org/wiki/Fluctuation_spectrum) effects and the interval following the Big Bang at which each type became non-relativistic. Davis *et al.* wrote in 1985:[[112]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-117)

Candidate particles can be grouped into three categories on the basis of their effect on the [fluctuation spectrum](https://en.wikipedia.org/wiki/Mixed_dark_matter) (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](https://en.wikipedia.org/wiki/Gravitino) and [photinos](https://en.wikipedia.org/wiki/Photino) 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.

**Alternative definitions**

Another approximate dividing line is 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](https://en.wikipedia.org/wiki/Radiation-dominated_era), with a photon temperature 2.7 million Kelvins. Standard physical cosmology gives the [particle horizon](https://en.wikipedia.org/wiki/Particle_horizon) size as 2 *ct* (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 approximately 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 mega[parsecs](https://en.wikipedia.org/wiki/Parsec), today, around the size containing an average large galaxy.

The 2.7 million [K](https://en.wikipedia.org/wiki/Kelvin_(unit)) photon temperature gives a typical photon energy of 250 electronvolts, thereby setting a typical mass scale for warm dark matter: particles much more massive than this, such as GeV–TeV mass [WIMPs](https://en.wikipedia.org/wiki/Weakly_interacting_massive_particles), would become non-relativistic much earlier than one 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](https://en.wikipedia.org/wiki/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 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[[113]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Hawkins-118) and [Preon stars](https://en.wikipedia.org/wiki/Preon_star)[[114]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Phys.Lett.B616,1(2005-119)) or [RAMBOs](https://en.wikipedia.org/wiki/Robust_associations_of_massive_baryonic_objects), to new particles such as [WIMPs](https://en.wikipedia.org/wiki/Weakly_interacting_massive_particles) and [axions](https://en.wikipedia.org/wiki/Axion).

Studies of [Big Bang nucleosynthesis](https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis) and gravitational lensing convinced most cosmologists[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16)[[115]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Carr-120)[[116]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Peter-121)[[117]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Garrett-122)[[118]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Bertone-123)[[119]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Olive-124) that MACHOs[[115]](https://en.wikipedia.org/wiki/Dark_matter" \l "cite_note-Carr-120)[[117]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Garrett-122) cannot make up more than a small fraction of dark matter.[[13]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Copi_1995-15)[[115]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Carr-120)[[116]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Peter-121)

The 1997 [DAMA/NaI](https://en.wikipedia.org/wiki/DAMA/NaI) experiment and its successor [DAMA/LIBRA](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Supersymmetry) models offer dark matter candidates in the form of the WIMPy [Lightest Supersymmetric Particle](https://en.wikipedia.org/wiki/Lightest_Supersymmetric_Particle) (LSP).[[120]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-125) Separately, heavy sterile neutrinos exist in non-supersymmetric extensions to the [standard model](https://en.wikipedia.org/wiki/Standard_Model) which explain the small [neutrino](https://en.wikipedia.org/wiki/Neutrino) mass through the [seesaw mechanism](https://en.wikipedia.org/wiki/Seesaw_mechanism).

**Warm dark matter**

[Warm dark matter](https://en.wikipedia.org/wiki/Warm_dark_matter) comprises 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 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](https://en.wikipedia.org/wiki/Sterile_neutrino): A heavier, slower form of neutrino that does not interact through the [weak force](https://en.wikipedia.org/wiki/Weak_interaction), unlike other neutrinos. Some modified gravity theories, such as [scalar–tensor–vector gravity](https://en.wikipedia.org/wiki/Scalar%E2%80%93tensor%E2%80%93vector_gravity), require warm dark matter to make their equations work.

**Hot dark matter**

[Hot dark matter](https://en.wikipedia.org/wiki/Hot_dark_matter) consists of particles whose FSL is much larger than the size of a protogalaxy. The [neutrino](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Cowan%E2%80%93Reines_neutrino_experiment). Neutrinos' [mass](https://en.wikipedia.org/wiki/Neutrino_mass) is less than 10−6 that of an [electron](https://en.wikipedia.org/wiki/Electron). Neutrinos interact with normal matter only via gravity and the [weak force](https://en.wikipedia.org/wiki/Weak_interaction), making them difficult to detect. This makes them weakly interacting light particles (WILPs), as opposed to WIMPs.

The three known [flavours](https://en.wikipedia.org/wiki/Flavour_(particle_physics)) 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](https://en.wikipedia.org/wiki/Upper_and_lower_bounds) on the collective average mass of the three neutrinos. For example, if the average neutrino mass were over 50 [eV](https://en.wikipedia.org/wiki/Electronvolt)/c2, the universe would collapse. CMB data and other methods indicate that their average mass probably does not exceed 0.3 eV/c2. Thus, observed neutrinos cannot explain dark matter.[[121]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-126)

Because galaxy-size density fluctuations get washed out by free-streaming, hot dark matter implies the first objects that can form are huge [supercluster](https://en.wikipedia.org/wiki/Supercluster)-size pancakes, which then fragment into galaxies. [Deep-field observations](https://en.wikipedia.org/wiki/List_of_deep_fields) show instead that galaxies formed first, followed by clusters and superclusters as galaxies clump together.

## Detection of dark matter particles

If dark matter is made up of sub-atomic particles, then millions, possibly billions, of such particles must pass through every square centimeter of the Earth each second.[[122]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Gaitskell_2004-127)[[123]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Number_per_second-128) Many experiments aim to test this hypothesis. Although [WIMPs](https://en.wikipedia.org/wiki/Weakly_interacting_massive_particles) are popular search candidates,[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16) the [Axion Dark Matter Experiment](https://en.wikipedia.org/wiki/Axion_Dark_Matter_Experiment) (ADMX) searches for [axions](https://en.wikipedia.org/wiki/Axion). Another candidate is heavy [hidden sector](https://en.wikipedia.org/wiki/Hidden_sector) particles which 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 dark matter particle annihilations or decays.[[98]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_merritt-103)

**Direct detection**

Direct detection experiments aim to observe low-energy recoils of nuclei induced by interactions with particles of dark matter, which are passing through the Earth. After such a recoil the nucleus will emit energy in the form of [scintillation](https://en.wikipedia.org/wiki/Scintillation_(physics)) light or [phonons](https://en.wikipedia.org/wiki/Phonon), as they pass through sensitive detection apparatus. To do this effectively, it is crucial to maintain a low background, and so such experiments operate deep underground to reduce the interference from [cosmic rays](https://en.wikipedia.org/wiki/Cosmic_ray). Examples of underground laboratories with direct detection experiments include the [Stawell mine](https://en.wikipedia.org/wiki/Stawell_Underground_Physics_Laboratory), the [Soudan mine](https://en.wikipedia.org/wiki/Soudan_mine), the [SNOLAB](https://en.wikipedia.org/wiki/SNOLAB) underground laboratory at [Sudbury](https://en.wikipedia.org/wiki/Greater_Sudbury), the [Gran Sasso National Laboratory](https://en.wikipedia.org/wiki/Gran_Sasso_National_Laboratory), the [Canfranc Underground Laboratory](https://en.wikipedia.org/wiki/Canfranc_Underground_Laboratory), the [Boulby Underground Laboratory](https://en.wikipedia.org/wiki/Boulby_Underground_Laboratory), the [Deep Underground Science and Engineering Laboratory](https://en.wikipedia.org/wiki/Deep_Underground_Science_and_Engineering_Laboratory) and the [China Jinping Underground Laboratory](https://en.wikipedia.org/wiki/China_Jinping_Underground_Laboratory).

These experiments mostly use either cryogenic or noble liquid detector technologies. Cryogenic detectors operating at temperatures below 100 mK, detect the heat produced when a particle hits an atom in a crystal absorber such as [germanium](https://en.wikipedia.org/wiki/Germanium). [Noble liquid](https://en.wikipedia.org/wiki/Noble_gas) detectors detect [scintillation](https://en.wikipedia.org/wiki/Scintillation_(physics)) produced by a particle collision in liquid [xenon](https://en.wikipedia.org/wiki/Xenon) or [argon](https://en.wikipedia.org/wiki/Argon). Cryogenic detector experiments include: [CDMS](https://en.wikipedia.org/wiki/Cryogenic_Dark_Matter_Search), [CRESST](https://en.wikipedia.org/wiki/Cryogenic_Rare_Event_Search_with_Superconducting_Thermometers), [EDELWEISS](https://en.wikipedia.org/wiki/EDELWEISS), [EURECA](https://en.wikipedia.org/wiki/European_Underground_Rare_Event_Calorimeter_Array). Noble liquid experiments include ZEPLIN, [XENON](https://en.wikipedia.org/wiki/XENON), [DEAP](https://en.wikipedia.org/wiki/DEAP), [ArDM](https://en.wikipedia.org/wiki/ArDM), [WARP](https://en.wikipedia.org/wiki/WIMP_Argon_Programme), [DarkSide](https://en.wikipedia.org/wiki/DarkSide), [PandaX](https://en.wikipedia.org/wiki/PandaX), and LUX, the [Large Underground Xenon experiment](https://en.wikipedia.org/wiki/Large_Underground_Xenon_experiment). Both of these techniques focus strongly on their ability to distinguish background particles from dark matter particles. Other experiments include [SIMPLE](https://en.wikipedia.org/wiki/SIMPLE_(dark_matter)) and [PICASSO](https://en.wikipedia.org/wiki/PICASSO_(dark_matter)).

Currently there has been no well-established claim of dark matter detection from a direct detection experiment, leading instead to strong upper limits on the mass and interaction cross section with nucleons of such dark matter particles.[[124]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-129) The [DAMA/NaI](https://en.wikipedia.org/wiki/DAMA/NaI) and more recent [DAMA/LIBRA](https://en.wikipedia.org/wiki/DAMA/LIBRA) experimental collaborations have detected an annual modulation in the rate of events in their detectors,[[125]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-130)[[126]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-131) which they claim is due to dark matter. This results from the expectation that as the Earth orbits the Sun, the velocity of the detector relative to the [dark matter halo](https://en.wikipedia.org/wiki/Dark_matter_halo) will vary by a small amount. This claim is so far unconfirmed and in contradiction with negative results from other experiments such as LUX, SuperCDMS[[127]](https://en.wikipedia.org/wiki/Dark_matter" \l "cite_note-132) and XENON100.[[128]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-133)

A special case of direct detection experiments covers those with directional sensitivity. This is a search strategy based on the motion of the Solar System around the [Galactic Center](https://en.wikipedia.org/wiki/Galactic_Center).[[129]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-apssyn-134)[[130]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-samlee-135)[[131]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-dmgsheff-136)[[132]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Kavli-137) A low-pressure [time projection chamber](https://en.wikipedia.org/wiki/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 travels may then be separated from background, which should be isotropic. Directional dark matter experiments include [DMTPC](https://en.wikipedia.org/wiki/Dark_Matter_Time_Projection_Chamber), [DRIFT](https://en.wikipedia.org/wiki/Directional_Recoil_Identification_From_Tracks), Newage and MIMAC.

**Indirect detection**

Indirect detection experiments search for the products of the self-annihilation or decay of dark matter particles in outer space. For example, in regions of high dark matter density two dark matter particles could [annihilate](https://en.wikipedia.org/wiki/Annihilation) to produce [gamma rays](https://en.wikipedia.org/wiki/Gamma_ray) or Standard Model particle–antiparticle pairs.[[134]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Bertone2010-139) Alternatively, if the dark matter particle is unstable, it could decay into Standard Model particles. These processes could be detected indirectly through an excess of gamma rays, [antiprotons](https://en.wikipedia.org/wiki/Antiproton) or [positrons](https://en.wikipedia.org/wiki/Positron) emanating from high density regions in our galaxy or others.[[135]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-140) A major difficulty inherent in such searches is that various astrophysical sources can mimic the signal expected from dark matter, and so multiple signals are likely required for a conclusive discovery.[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16)[[98]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_merritt-103)

A few of the dark matter particles passing through the Sun or Earth may scatter off atoms and lose energy. Thus dark matter 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](https://en.wikipedia.org/wiki/Neutrino).[[136]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-141) Such a signal would be strong indirect proof of WIMP dark matter.[[14]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-bertone_hooper_silk-16) High-energy neutrino telescopes such as [AMANDA](https://en.wikipedia.org/wiki/Antarctic_Muon_And_Neutrino_Detector_Array), [IceCube](https://en.wikipedia.org/wiki/IceCube) and [ANTARES](https://en.wikipedia.org/wiki/ANTARES_(telescope)) are searching for this signal.[[137]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-FOOTNOTERandall2015298-142) The detection by [LIGO](https://en.wikipedia.org/wiki/LIGO) in [September 2015](https://en.wikipedia.org/wiki/GW150914) of gravitational waves, opens the possibility of observing dark matter in a new way, particularly if it is in the form of [primordial black holes](https://en.wikipedia.org/wiki/Primordial_black_holes).[[138]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-143)[[139]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-144)[[140]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-145)

Many experimental searches have been undertaken to look for such emission from dark matter annihilation or decay, examples of which follow. The [Energetic Gamma Ray Experiment Telescope](https://en.wikipedia.org/wiki/Energetic_Gamma_Ray_Experiment_Telescope) observed more gamma rays in 2008 than expected from the [Milky Way](https://en.wikipedia.org/wiki/Milky_Way), but scientists concluded this was most likely due to incorrect estimation of the telescope's sensitivity.[[141]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-146)

The [Fermi Gamma-ray Space Telescope](https://en.wikipedia.org/wiki/Fermi_Gamma-ray_Space_Telescope) is searching for similar gamma rays.[[142]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-147) In April 2012, an analysis of previously available data from its [Large Area Telescope](https://en.wikipedia.org/wiki/Fermi_LAT) instrument produced statistical evidence of a 130 GeV signal in the gamma radiation coming from the center of the Milky Way.[[143]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-148) WIMP annihilation was seen as the most probable explanation.[[144]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-149)

At higher energies, [ground-based gamma-ray telescopes](https://en.wikipedia.org/wiki/IACT) have set limits on the annihilation of dark matter in [dwarf spheroidal galaxies](https://en.wikipedia.org/wiki/Dwarf_spheroidal_galaxies)[[145]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-150) and in clusters of galaxies.[[146]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-151)

The [PAMELA](https://en.wikipedia.org/wiki/Payload_for_Antimatter_Matter_Exploration_and_Light-nuclei_Astrophysics) experiment detected excess [positrons](https://en.wikipedia.org/wiki/Positron). They could be from dark matter annihilation or from [pulsars](https://en.wikipedia.org/wiki/Pulsar). No excess [antiprotons](https://en.wikipedia.org/wiki/Antiproton) were observed.[[147]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-152)

In 2013 results from the [Alpha Magnetic Spectrometer](https://en.wikipedia.org/wiki/Alpha_Magnetic_Spectrometer) on the [International Space Station](https://en.wikipedia.org/wiki/International_Space_Station) indicated excess high-energy [cosmic rays](https://en.wikipedia.org/wiki/Cosmic_ray) which could be due to dark matter annihilation.[[148]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-APS-20130403-153)[[149]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-AMS-20130403-154)[[150]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-AP-20130403-155)[[151]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-BBC-20130403-156)[[152]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NASA-20130403-157)[[153]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-NYT-20130403-158)

**Collider searches for dark matter**

An alternative approach to the detection of dark matter particles in nature is to produce them in a laboratory. Experiments with the [Large Hadron Collider](https://en.wikipedia.org/wiki/Large_Hadron_Collider) (LHC) may be able to detect dark matter particles produced in collisions of the LHC [proton](https://en.wikipedia.org/wiki/Proton) beams. Because a dark matter particle should have negligible interactions with normal visible matter, it may be detected indirectly as missing energy and momentum that escape the detectors, provided other collision products are detected.[[154]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-kane_watson-159) Constraints on dark matter also exist from the [LEP](https://en.wikipedia.org/wiki/Large_Electron%E2%80%93Positron_Collider) experiment using a similar principle, but probing the interaction of dark matter particles with electrons rather than quarks.[[155]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-160) Any discovery from collider searches must be corroborated by discoveries in the indirect or direct detection sectors to prove that the particle discovered is, in fact, dark matter.

## Alternative hypotheses

Because dark matter has not yet been conclusively identified, many other hypotheses have emerged aiming to explain the observational phenomena that dark matter was conceived to explain. The most common method is to modify general relativity. General relativity is well-tested on solar system scales, but its validity on galactic or cosmological scales has not been well proven. A suitable modification to general relativity can conceivably eliminate the need for dark matter. The best-known theories of this class are [MOND](https://en.wikipedia.org/wiki/MOND) and its relativistic generalization [tensor-vector-scalar gravity](https://en.wikipedia.org/wiki/Tensor-vector-scalar_gravity) (TeVeS),[[156]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-161) [f (R) gravity](https://en.wikipedia.org/wiki/F(R)_gravity),[[157]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-162) [negative mass](https://en.wikipedia.org/wiki/Negative_mass), [dark fluid](https://en.wikipedia.org/wiki/Dark_fluid),[[158]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-163)[[159]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-164)[[160]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-Farnes-165) and [entropic gravity](https://en.wikipedia.org/wiki/Entropic_gravity).[[161]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-physorgnewtheory-166) [Alternative theories](https://en.wikipedia.org/wiki/Alternatives_to_general_relativity) abound.[[162]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-167)[[163]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-168)

A problem with alternative hypotheses is observational evidence for dark matter comes from so many independent approaches. Explaining any individual observation is possible but explaining all of them is very difficult. Nonetheless, there have been some scattered successes for alternative hypotheses, such as a 2016 test of gravitational lensing in entropic gravity.[[164]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-169)[[165]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-170)[[166]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-171)

The prevailing opinion among most astrophysicists is while modifications to general relativity can conceivably explain part of the observational evidence, there is probably enough data to conclude there must be some form of dark matter.[[167]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-172)

## 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.[[86]](https://en.wikipedia.org/wiki/Dark_matter#cite_note-BaryonicSource01-90)

## References

* 1. ^ "Dark Matter". CERN Physics. 20 January 2012.
  2. ^ Siegfried, T. (5 July 1999). "Hidden space dimensions may permit parallel universes, explain cosmic mysteries". The Dallas Morning News.
  3. ^ Trimble, V. (1987). "Existence and nature of dark matter in the universe" (PDF). Annual Review of Astronomy and Astrophysics. 25: 425–472. Bibcode:1987ARA & A..25..425T. doi:10.1146/annurev.aa.25.090187.002233.
  4. ^ "A history of dark matter". 2017.
  5. ^ "Planck Mission Brings Universe into Sharp Focus". NASA Mission Pages. 21 March 2013.
  6. ^ "Dark Energy, Dark Matter". NASA Science: Astrophysics. 5 June 2015.
  7. ^ Ade, P.A.R.; Aghanim, N.; Armitage-Caplan, C.; et al. (Planck Collaboration) (22 March 2013). "Planck 2013 results. I. Overview of products and scientific results – Table 9". Astronomy and Astrophysics. 1303: 5062. arXiv:1303.5062. Bibcode:2014A & A...571A...1P. doi:10.1051/0004-6361/201321529. S2CID 218716838.
  8. ^ Francis, Matthew (22 March 2013). "First Planck results: the Universe is still weird and interesting". Ars Technica.
  9. ^ "Planck captures portrait of the young Universe, revealing earliest light". University of Cambridge. 21 March 2013. Retrieved 21 March 2013.
  10. ^ Carroll, Sean (2007). Dark Matter, Dark Energy: The dark side of the universe. The Teaching Company. Guidebook Part 2 p. 46.... dark matter: An invisible, essentially collisionless component of matter that makes up about 25 percent of the energy density of the universe... it's a different kind of particle... something not yet observed in the laboratory...
  11. ^ Ferris, Timothy (January 2015). "Dark matter". Hidden cosmos. National Geographic Magazine. Retrieved 10 June 2015.
  12. ^ Jarosik, N.; et al. (2011). "Seven-year Wilson microwave anisotropy probe (WMAP) observations: Sky maps, systematic errors, and basic results". Astrophysical Journal Supplement. 192(2): 14. arXiv:1001.4744. Bibcode:2011ApJS..192...14J. doi:10.1088/0067-0049/192/2/14. S2CID 46171526.
  13. ^ Jump up to:a b c d Copi, C.J.; Schramm, D.N.; Turner, M.S. (1995). "Big-Bang Nucleosynthesis and the Baryon Density of the Universe". Science. 267 (5195): 192–199. arXiv:astro-ph/9407006. Bibcode:1995Sci...267..192C. doi:10.1126/science.7809624. PMID 7809624. S2CID 15613185.
  14. ^ Jump up to:a b c d e f g Bertone, G.; Hooper, D.; Silk, J. (2005). "Particle dark matter: Evidence, candidates and constraints". Physics Reports. 405(5–6): 279–390. arXiv:hep-ph/0404175. Bibcode:2005PhR...405..279B. doi:10.1016/j.physrep.2004.08.031. S2CID 118979310.
  15. ^ Angus, G. (2013). "Cosmological simulations in MOND: The cluster scale halo mass function with light sterile neutrinos". Monthly Notices of the Royal Astronomical Society. 436 (1): 202–211. arXiv:1309.6094. Bibcode:2013MNRAS.436..202A. doi:10.1093/mnras/stt1564. S2CID 119276329.
  16. ^ de Swart, J.G.; Bertone, G.; van Dongen, J. (2017). "How dark matter came to matter". Nature Astronomy. 1 (59): 0059. arXiv:1703.00013. Bibcode:2017NatAs...1E..59D. doi:10.1038/s41550-017-0059. S2CID 119092226.
  17. ^ "A History of Dark Matter".
  18. ^ Kelvin, Lord (1904). Baltimore Lectures on Molecular Dynamics and the Wave Theory of Light. London, England: C.J. Clay and Sons. p. 274. From p. 274: "Many of our supposed thousand million stars, perhaps a great majority of them, may be dark bodies;… "
  19. ^ Jump up to:a b c "A history of dark matter". Ars Technica. Retrieved 8 February 2017.
  20. ^ Poincaré, H. (1906). "La Voie lactée et la théorie des gaz" [The Milky Way and the theory of gases]. Bulletin de la Société astronomique de France (in French). 20: 153–165.
  21. ^ Kapteyn, Jacobus Cornelius (1922). "First attempt at a theory of the arrangement and motion of the sidereal system". Astrophysical Journal. 55: 302–327. Bibcode:1922ApJ....55..302K. doi:10.1086/142670. It is incidentally suggested when the theory is perfected it may be possible to determine the amount of dark matter from its gravitational effect. (emphasis in original)
  22. ^ Jump up to:a b Rosenberg, Leslie J (30 June 2014). Status of the Axion Dark-Matter Experiment (ADMX) (PDF). 10th PATRAS Workshop on Axions, WIMPs and WISPs. p. 2.
  23. ^ Oort, J.H. (1932). "The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems". Bulletin of the Astronomical Institutes of the Netherlands. 6: 249–287. Bibcode:1932BAN.....6..249O.
  24. ^ "The hidden lives of galaxies: Hidden mass". Imagine the Universe!. NASA/GSFC.
  25. ^ Kuijken, K.; Gilmore, G. (July 1989). "The Mass Distribution in the Galactic Disc – Part III – the Local Volume Mass Density" (PDF). Monthly Notices of the Royal Astronomical Society. 239 (2): 651–664. Bibcode:1989MNRAS.239..651K. doi:10.1093/mnras/239.2.651.
  26. ^ Zwicky, F. (1933). "Die Rotverschiebung von extragalaktischen Nebeln" [The red shift of extragalactic nebulae]. Helvetica Physica Acta. 6: 110–127. Bibcode:1933AcHPh...6..110Z.
  27. ^ Zwicky, F. (1937). "On the Masses of Nebulae and of Clusters of Nebulae". The Astrophysical Journal. 86: 217–246. Bibcode:1937ApJ....86..217Z. doi:10.1086/143864.
  28. ^ Some details of Zwicky's calculation and of more modern values are given in Richmond, M., Using the virial theorem: the mass of a cluster of galaxies, retrieved 10 July 2007.
  29. ^ Freese, Katherine (2014). The cosmic cocktail: Three parts dark matter. Princeton University Press. ISBN 978-1-4008-5007-5.
  30. ^ Babcock, Horace W. (1939). "The rotation of the Andromeda Nebula". Lick Observatory Bulletin. 19: 41–51. Bibcode:1939LicOB..19...41B. doi:10.5479/ADS/bib/1939LicOB.19.41B.
  31. ^ Oort, J.H. (April 1940). "Some problems concerning the structure and dynamics of the galactic system and the elliptical nebulae NGC 3115 and 4494" (PDF). The Astrophysical Journal. 91 (3): 273–306. Bibcode:1940ApJ....91..273O. doi:10.1086/144167. hdl:1887/8533.
  32. ^ Freeman, K.C. (June 1970). "On the Disks of Spiral and S0 Galaxies". The Astrophysical Journal. 160: 811–830. Bibcode:1970ApJ...160..811F. doi:10.1086/150474.
  33. ^ Jump up to:a b Overbye, Dennis (27 December 2016). "Vera Rubin, 88, Dies; Opened Doors in Astronomy, and for Women". The New York Times. Retrieved 27 December 2016.
  34. ^ "First observational evidence of dark matter". Darkmatterphysics.com. Archived from the original on 25 June 2013. Retrieved 6 August 2013.
  35. ^ Jump up to:a b c Rubin, Vera C.; Ford, W. Kent, Jr. (February 1970). "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions". The Astrophysical Journal. 159: 379–403. Bibcode:1970ApJ...159..379R. doi:10.1086/150317.
  36. ^ Bosma, A. (1978). The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types (PhD Thesis). Rijksuniversiteit Groningen.
  37. ^ Rubin, V.; Thonnard, W.K. Jr.; Ford, N. (1980). "Rotational Properties of 21 Sc Galaxies with a Large Range of Luminosities and Radii from NGC 4605 (R = 4kpc) to UGC 2885 (R = 122kpc)". The Astrophysical Journal. 238: 471. Bibcode:1980ApJ...238..471R. doi:10.1086/158003.
  38. ^ Randall 2015, pp. 13–14.
  39. ^ Roberts, Morton S. (May 1966). "A High-Resolution 21 cm hydrogen-line survey of the Andromeda nebula". The Astrophysical Journal. 159: 639–656. Bibcode:1966ApJ...144..639R. doi:10.1086/148645.
  40. ^ Gottesman, S.T.; Davies, R.D.; Reddish, V.C. (1966). "A neutral hydrogen survey of the southern regions of the Andromeda nebula". Monthly Notices of the Royal Astronomical Society. 133(4): 359–387. Bibcode:1966MNRAS.133..359G. doi:10.1093/mnras/133.4.359.
  41. ^ Jump up to:a b Roberts, Morton S.; Whitehurst, Robert N. (October 1975). "The rotation curve and geometry of M 31 at large galactocentric distances". The Astrophysical Journal. 201: 327–346. Bibcode:1975ApJ...201..327R. doi:10.1086/153889.
  42. ^ Rogstad, D.H.; Shostak, G. Seth (September 1972). "Gross properties of five Scd galaxies as determined from 21 centimeter observations". The Astrophysical Journal. 176: 315–321. Bibcode:1972ApJ...176..315R. doi:10.1086/151636.
  43. ^ Randall 2015, pp. 14–16.
  44. ^ Bergstrom, L. (2000). "Non-baryonic dark matter: Observational evidence and detection methods". Reports on Progress in Physics. 63 (5): 793–841. arXiv:hep-ph/0002126. Bibcode:2000RPPh...63..793B. doi:10.1088/0034-4885/63/5/2r3. S2CID 119349858.
  45. ^ Baumann, Daniel. "Cosmology: Part III" (PDF). Mathematical Tripos. Cambridge University. pp. 21–22. Archived from the original (PDF) on 2 February 2017. Retrieved 24 January 2017.
  46. ^ "Serious Blow to Dark Matter Theories?" (Press release). European Southern Observatory. 18 April 2012.
  47. ^ Corbelli, E.; Salucci, P. (2000). "The extended rotation curve and the dark matter halo of M33". Monthly Notices of the Royal Astronomical Society. 311 (2): 441–447. arXiv:astro-ph/9909252. Bibcode:2000MNRAS.311..441C. doi:10.1046/j.1365-8711.2000.03075.x. S2CID 10888599.
  48. ^ Faber, S.M.; Jackson, R.E. (1976). "Velocity dispersions and mass-to-light ratios for elliptical galaxies". The Astrophysical Journal. 204: 668–683. Bibcode:1976ApJ...204..668F. doi:10.1086/154215.
  49. ^ Binny, James; Merrifield, Michael (1998). Galactic Astronomy. Princeton University Press. pp. 712–713.
  50. ^ Allen, Steven W.; Evrard, August E.; Mantz, Adam B. (2011). "Cosmological Parameters from Clusters of Galaxies". Annual Review of Astronomy and Astrophysics. 49 (1): 409–470. arXiv:1103.4829. Bibcode:2011ARA & A..49..409A. doi:10.1146/annurev-astro-081710-102514. S2CID 54922695.
  51. ^ "Dark matter may be smoother than expected – Careful study of large area of sky imaged by VST reveals intriguing result". www.eso.org. Retrieved 8 December 2016.
  52. ^ Taylor, A.N.; et al. (1998). "Gravitational lens magnification and the mass of Abell 1689". The Astrophysical Journal. 501 (2): 539–553. arXiv:astro-ph/9801158. Bibcode:1998ApJ...501..539T. doi:10.1086/305827. S2CID 14446661.
  53. ^ Wu, X.; Chiueh, T.; Fang, L.; Xue, Y. (1998). "A comparison of different cluster mass estimates: consistency or discrepancy?". Monthly Notices of the Royal Astronomical Society. 301 (3): 861–871. arXiv:astro-ph/9808179. Bibcode:1998MNRAS.301..861W. CiteSeerX 10.1.1.256.8523. doi:10.1046/j.1365-8711.1998.02055.x. S2CID 1291475.
  54. ^ Cho, Adrian (2017). "Scientists unveil the most detailed map of dark matter to date". Science. doi:10.1126/science.aal0847.
  55. ^ Natarajan, Priyamvada; Chadayammuri, Urmila; Jauzac, Mathilde; Richard, Johan; Kneib, Jean-Paul; Ebeling, Harald; et al. (2017). "Mapping substructure in the HST Frontier Fields cluster lenses and in cosmological simulations" (PDF). Monthly Notices of the Royal Astronomical Society. 468 (2): 1962. arXiv:1702.04348. Bibcode:2017MNRAS.468.1962N. doi:10.1093/mnras/stw3385. S2CID 113404396.
  56. ^ Refregier, A. (2003). "Weak gravitational lensing by large-scale structure". Annual Review of Astronomy and Astrophysics. 41 (1): 645–668. arXiv:astro-ph/0307212. Bibcode:2003ARA & A..41..645R. doi:10.1146/annurev.astro.41.111302.102207. S2CID 34450722.
  57. ^ "Quasars, lensing, and dark matter". Physics for the 21st Century. Annenberg Foundation. 2017.
  58. ^ Myslewski, Rik (14 October 2011). "Hubble snaps dark matter warping spacetime". The Register. UK.
  59. ^ Jump up to:a b The details are technical. For an intermediate-level introduction, see Hu, Wayne (2001). "Intermediate Guide to the Acoustic Peaks and Polarization".
  60. ^ Hinshaw, G.; et al. (2009). "Five-year Wilkinson microwave anisotropy probe (WMAP) observations: Data processing, sky maps, and basic results". The Astrophysical Journal Supplement. 180 (2): 225–245. arXiv:0803.0732. Bibcode:2009ApJS..180..225H. doi:10.1088/0067-0049/180/2/225. S2CID 3629998.
  61. ^ Jump up to:a b c Ade, P.A.R.; et al. (2016). "Planck 2015 results. XIII. Cosmological parameters". Astron. Astrophys. 594 (13): A13. arXiv:1502.01589. Bibcode:2016A & A...594A..13P. doi:10.1051/0004-6361/201525830. S2CID 119262962.
  62. ^ Skordis, C.; et al. (2006). "Large scale structure in Bekenstein's theory of relativistic modified Newtonian dynamics". Phys. Rev. Lett. 96 (1): 011301. arXiv:astro-ph/0505519. Bibcode:2006PhRvL..96a1301S. doi:10.1103/PhysRevLett.96.011301. PMID 16486433. S2CID 46508316.
  63. ^ "Hubble Maps the Cosmic Web of "Clumpy" Dark Matter in 3-D"(Press release). NASA. 7 January 2007.
  64. ^ Jump up to:a b Jaffe, A.H. "Cosmology 2012: Lecture Notes" (PDF).
  65. ^ Low, L.F. (12 October 2016). "Constraints on the composite photon theory". Modern Physics Letters A. 31 (36): 1675002. Bibcode:2016MPLA...3175002L. doi:10.1142/S021773231675002X.
  66. ^ Clowe, Douglas; et al. (2006). "A Direct Empirical Proof of the Existence of Dark Matter". The Astrophysical Journal Letters. 648(2): L109–L113. arXiv:astro-ph/0608407. Bibcode:2006ApJ...648L.109C. doi:10.1086/508162. S2CID 2897407.
  67. ^ Lee, Chris (21 September 2017). "Science-in-progress: Did the Bullet Cluster withstand scrutiny?". Ars Technica.
  68. ^ Siegel, Ethan (9 November 2017). "The Bullet Cluster proves dark matter exists, but not for the reason most physicists think". Forbes.
  69. ^ Markevitch, M.; Randall, S.; Clowe, D.; Gonzalez, A. & Bradac, M. (16–23 July 2006). Dark matter and the Bullet Cluster (PDF). 36th COSPAR Scientific Assembly. Beijing, China. Abstract only
  70. ^ Planck Collaboration; Aghanim, N.; Akrami, Y.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Ballardini, M.; Banday, A. J.; Barreiro, R. B.; Bartolo, N.; Basak, S. (2020). "Planck 2018 results. VI. Cosmological parameters". Astronomy & Astrophysics. 641: A6. arXiv:1807.06209. Bibcode:2020A & A...641A...6P. doi:10.1051/0004-6361/201833910. S2CID 119335614.
  71. ^ Kowalski, M.; et al. (2008). "Improved Cosmological Constraints from New, Old, and Combined Supernova Data Sets". The Astrophysical Journal. 686 (2): 749–778. arXiv:0804.4142. Bibcode:2008ApJ...686..749K. doi:10.1086/589937. S2CID 119197696.
  72. ^ "Will the Universe expand forever?". NASA. 24 January 2014. Retrieved 16 March 2015.
  73. ^ "Our universe is Flat". FermiLab/SLAC. 7 April 2015.
  74. ^ Yoo, Marcus Y. (2011). "Unexpected connections". Engineering & Science. 74 (1): 30.
  75. ^ Jump up to:a b "Planck Publications: Planck 2015 Results". European Space Agency. February 2015. Retrieved 9 February 2015.
  76. ^ Percival, W.J.; et al. (2007). "Measuring the Baryon Acoustic Oscillation scale using the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey". Monthly Notices of the Royal Astronomical Society. 381 (3): 1053–1066. arXiv:0705.3323. Bibcode:2007MNRAS.381.1053P. doi:10.1111/j.1365-2966.2007.12268.x.
  77. ^ Komatsu, E.; et al. (2009). "Five-Year Wilkinson Microwave Anisotropy Probe Observations: Cosmological Interpretation". The Astrophysical Journal Supplement. 180 (2): 330–376. arXiv:0803.0547. Bibcode:2009ApJS..180..330K. doi:10.1088/0067-0049/180/2/330. S2CID 119290314.
  78. ^ Peacock, J.; et al. (2001). "A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey". Nature. 410 (6825): 169–173. arXiv:astro-ph/0103143. Bibcode:2001Natur.410..169P. doi:10.1038/35065528. PMID 11242069. S2CID 1546652.
  79. ^ Viel, M.; Bolton, J.S.; Haehnelt, M.G. (2009). "Cosmological and astrophysical constraints from the Lyman α forest flux probability distribution function". Monthly Notices of the Royal Astronomical Society. 399 (1): L39–L43. arXiv:0907.2927. Bibcode:2009MNRAS.399L..39V. doi:10.1111/j.1745-3933.2009.00720.x. S2CID 12470622.
  80. ^ University of Amsterdam. "A new era in the quest for dark matter". Phys.org.
  81. ^ Espinosa, J. R.; Racco, D.; Riotto, A. (23 March 2018). "A Cosmological Signature of the Standard Model Higgs Vacuum Instability: Primordial Black Holes as Dark Matter". Physical Review Letters. 120 (12): 121301. arXiv:1710.11196. Bibcode:2018PhRvL.120l1301E. doi:10.1103/PhysRevLett.120.121301. PMID 29694085. S2CID 206309027.
  82. ^ Clesse, Sebastien; García-Bellido, Juan (2018). "Seven Hints for Primordial Black Hole Dark Matter". Physics of the Dark Universe. 22: 137–146. arXiv:1711.10458. Bibcode:2018PDU....22..137C. doi:10.1016/j.dark.2018.08.004. S2CID 54594536.
  83. ^ Lacki, Brian C.; Beacom, John F. (12 August 2010). "Primordial Black Holes as Dark Matter: Almost All or Almost Nothing". The Astrophysical Journal. 720 (1): L67–L71. arXiv:1003.3466. Bibcode:2010ApJ...720L..67L. doi:10.1088/2041-8205/720/1/L67. ISSN 2041-8205. S2CID 118418220.
  84. ^ Kashlinsky, A. (23 May 2016). "LIGO gravitational wave detection, primordial black holes and the near-IR cosmic infrared background anisotropies". The Astrophysical Journal. 823 (2): L25. arXiv:1605.04023. Bibcode:2016ApJ...823L..25K. doi:10.3847/2041-8205/823/2/L25. ISSN 2041-8213. S2CID 118491150.
  85. ^ Frampton, Paul H.; Kawasaki, Masahiro; Takahashi, Fuminobu; Yanagida, Tsutomu T. (22 April 2010). "Primordial Black Holes as All Dark Matter". Journal of Cosmology and Astroparticle Physics. 2010(4): 023. arXiv:1001.2308. Bibcode:2010JCAP...04..023F. doi:10.1088/1475-7516/2010/04/023. ISSN 1475-7516. S2CID 119256778.
  86. ^ "Baryonic Matter". COSMOS – The SAO Encyclopedia of Astronomy. Swinburne University of Technology. Retrieved 9 April2018.
  87. ^ Randall 2015, p. 286.
  88. ^ Weiss, Achim (2006). Big bang nucleosynthesis: Cooking up the first light elements. Einstein Online. 2. p. 1017. Archived from the original on 6 February 2013.
  89. ^ Raine, D.; Thomas, T. (2001). An Introduction to the Science of Cosmology. IOP Publishing. p. 30. ISBN 978-0-7503-0405-4. OCLC 864166846.
  90. ^ Tisserand, P.; Le Guillou, L.; Afonso, C.; Albert, J.N.; Andersen, J.; Ansari, R.; et al. (2007). "Limits on the Macho content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds". Astronomy and Astrophysics. 469 (2): 387–404. arXiv:astro-ph/0607207. Bibcode:2007A & A...469..387T. doi:10.1051/0004-6361:20066017. S2CID 15389106.
  91. ^ Graff, D.S.; Freese, K. (1996). "Analysis of a Hubble Space Telescope Search for Red Dwarfs: Limits on Baryonic Matter in the Galactic Halo". The Astrophysical Journal. 456 (1996): L49. arXiv:astro-ph/9507097. Bibcode:1996ApJ...456L..49G. doi:10.1086/309850. S2CID 119417172.
  92. ^ Najita, J.R.; Tiede, G.P.; Carr, J.S. (2000). "From Stars to Superplanets: The Low‐Mass Initial Mass Function in the Young Cluster IC 348". The Astrophysical Journal. 541 (2): 977–1003. arXiv:astro-ph/0005290. Bibcode:2000ApJ...541..977N. doi:10.1086/309477. S2CID 55757804.
  93. ^ Wyrzykowski, L.; Skowron, J.; Kozlowski, S.; Udalski, A.; Szymanski, M.K.; Kubiak, M.; et al. (2011). "The OGLE View of Microlensing towards the Magellanic Clouds. IV. OGLE-III SMC Data and Final Conclusions on MACHOs". Monthly Notices of the Royal Astronomical Society. 416 (4): 2949–2961. arXiv:1106.2925. Bibcode:2011MNRAS.416.2949W. doi:10.1111/j.1365-2966.2011.19243.x. S2CID 118660865.
  94. ^ Freese, Katherine; Fields, Brian; Graff, David (2000). "Death of stellar baryonic dark matter candidates". arXiv:astro-ph/0007444.
  95. ^ Freese, Katherine; Fields, Brian; Graff, David (1999). "Death of Stellar Baryonic Dark Matter". The First Stars. The First Stars. ESO Astrophysics Symposia. pp. 4–6. arXiv:astro-ph/0002058. Bibcode:2000fist.conf...18F. CiteSeerX 10.1.1.256.6883. doi:10.1007/10719504\_3. ISBN 978-3-540-67222-7. S2CID 119326375.
  96. ^ Canetti, L.; Drewes, M.; Shaposhnikov, M. (2012). "Matter and Antimatter in the Universe". New J. Phys. 14 (9): 095012. arXiv:1204.4186. Bibcode:2012NJPh...14i5012C. doi:10.1088/1367-2630/14/9/095012. S2CID 119233888.
  97. ^ Overduin, J. M.; Wesson, P. S. (November 2004). "Dark Matter and Background Light". Physics Reports. 402 (5–6): 267–406. arXiv:astro-ph/0407207. Bibcode:2004PhR...402..267O. doi:10.1016/j.physrep.2004.07.006. S2CID 1634052.
  98. ^ Jump up to:a b c d Bertone, G.; Merritt, D. (2005). "Dark Matter Dynamics and Indirect Detection". Modern Physics Letters A. 20 (14): 1021–1036. arXiv:astro-ph/0504422. Bibcode:2005MPLA...20.1021B. doi:10.1142/S0217732305017391. S2CID 119405319.
  99. ^ Jump up to:a b Buckley, Matthew R.; Difranzo, Anthony (1 February 2018). "Synopsis: A Way to Cool Dark Matter". Physical Review Letters. 120 (5): 051102. arXiv:1707.03829. Bibcode:2018PhRvL.120e1102B. doi:10.1103/PhysRevLett.120.051102. PMID 29481169. S2CID 3757868. One widely held belief about dark matter is it cannot cool off by radiating energy. If it could, then it might bunch together and create compact objects in the same way baryonic matter forms planets, stars, and galaxies. Observations so far suggest dark matter doesn't do that – it resides only in diffuse halos... As a result, it is extremely unlikely there are very dense objects like stars made out of entirely (or even mostly) dark matter.
  100. ^ Jump up to:a b Siegel, Ethan (28 October 2016). "Why doesn't dark matter form black holes?". Forbes.
  101. ^ Cho, Adrian (9 February 2017). "Is dark matter made of black holes?". Science. doi:10.1126/science.aal0721.
  102. ^ "Black holes can't explain dark matter". astronomy.com. 18 October 2018. Retrieved 7 January 2019.
  103. ^ "Aging Voyager 1 spacecraft undermines idea that dark matter is tiny black holes". sciencemag.org. 9 January 2019. Retrieved 10 January 2019.
  104. ^ "There could be entire stars and planets made out of dark matter".
  105. ^ Buckley, Matthew R.; Difranzo, Anthony (2018). "Collapsed Dark Matter Structures". Physical Review Letters. 120 (5): 051102. arXiv:1707.03829. Bibcode:2018PhRvL.120e1102B. doi:10.1103/PhysRevLett.120.051102. PMID 29481169. S2CID 3757868.
  106. ^ Niikura, Hiroko (1 April 2019). "Microlensing constraints on primordial black holes with Subaru/HSC Andromeda observations". Nature Astronomy. 3 (6): 524–534. arXiv:1701.02151. Bibcode:2019NatAs...3..524N. doi:10.1038/s41550-019-0723-1. S2CID 118986293.
  107. ^ Katz, Andrey; Kopp, Joachim; Sibiryakov, Sergey; Xue, Wei (5 December 2018). "Femtolensing by dark matter revisited". Journal of Cosmology and Astroparticle Physics. 2018 (12): 005. arXiv:1807.11495. Bibcode:2018JCAP...12..005K. doi:10.1088/1475-7516/2018/12/005. ISSN 1475-7516. S2CID 119215426.
  108. ^ Montero-Camacho, Paulo; Fang, Xiao; Vasquez, Gabriel; Silva, Makana; Hirata, Christopher M. (23 August 2019). "Revisiting constraints on asteroid-mass primordial black holes as dark matter candidates". Journal of Cosmology and Astroparticle Physics. 2019(8): 031. arXiv:1906.05950. Bibcode:2019JCAP...08..031M. doi:10.1088/1475-7516/2019/08/031. ISSN 1475-7516. S2CID 189897766.
  109. ^ Silk, Joseph (2000). "IX". The Big Bang: Third Edition. Henry Holt and Company. ISBN 978-0-8050-7256-3.
  110. ^ Vittorio, N.; J. Silk (1984). "Fine-scale anisotropy of the cosmic microwave background in a universe dominated by cold dark matter". Astrophysical Journal Letters. 285: L39–L43. Bibcode:1984ApJ...285L..39V. doi:10.1086/184361.
  111. ^ Umemura, Masayuki; Satoru Ikeuchi (1985). "Formation of Subgalactic Objects within Two-Component Dark Matter". Astrophysical Journal. 299: 583–592. Bibcode:1985ApJ...299..583U. doi:10.1086/163726.
  112. ^ Davis, M.; Efstathiou, G.; Frenk, C.S.; White, S.D.M. (15 May 1985). "The evolution of large-scale structure in a universe dominated by cold dark matter". Astrophysical Journal. 292: 371–394. Bibcode:1985ApJ...292..371D. doi:10.1086/163168.
  113. ^ Hawkins, M.R.S. (2011). "The case for primordial black holes as dark matter". Monthly Notices of the Royal Astronomical Society. 415 (3): 2744–2757. arXiv:1106.3875. Bibcode:2011MNRAS.415.2744H. doi:10.1111/j.1365-2966.2011.18890.x. S2CID 119261917.
  114. ^ Hansson, J.; Sandin, F. (2005). "Preon stars: a new class of cosmic compact objects". Physics Letters B. 616 (1–2): 1–7. arXiv:astro-ph/0410417. Bibcode:2005PhLB..616....1H. doi:10.1016/j.physletb.2005.04.034. S2CID 119063004.
  115. ^ Jump up to:a b c Carr, B.J.; et al. (2010). "New cosmological constraints on primordial black holes". Physical Review D. 81 (10): 104019. arXiv:0912.5297. Bibcode:2010PhRvD..81j4019C. doi:10.1103/PhysRevD.81.104019. S2CID 118946242.
  116. ^ Jump up to:a b Peter, A.H.G. (2012). "Dark matter: A brief review". arXiv:1201.3942 [astro-ph.CO].
  117. ^ Jump up to:a b Garrett, Katherine; Dūda, Gintaras (2011). "Dark Matter: A Primer". Advances in Astronomy. 2011 (968283): 1–22. arXiv:1006.2483. Bibcode:2011AdAst2011E...8G. doi:10.1155/2011/968283. S2CID 119180701. MACHOs can only account for a very small percentage of the nonluminous mass in our galaxy, revealing that most dark matter cannot be strongly concentrated or exist in the form of baryonic astrophysical objects. Although microlensing surveys rule out baryonic objects like brown dwarfs, black holes, and neutron stars in our galactic halo, can other forms of baryonic matter make up the bulk of dark matter? The answer, surprisingly, is 'no'...
  118. ^ Bertone, G. (2010). "The moment of truth for WIMP dark matter". Nature. 468 (7322): 389–393. arXiv:1011.3532. Bibcode:2010Natur.468..389B. doi:10.1038/nature09509. PMID 21085174. S2CID 4415912.
  119. ^ Olive, Keith A (2003). "TASI Lectures on Dark Matter". p. 21. arXiv:astro-ph/0301505.
  120. ^ Jungman, Gerard; Kamionkowski, Marc; Griest, Kim (1 March 1996). "Supersymmetric dark matter". Physics Reports. 267 (5–6): 195–373. arXiv:hep-ph/9506380. Bibcode:1996PhR...267..195J. doi:10.1016/0370-1573(95)00058-5. S2CID 119067698.
  121. ^ "Neutrinos as dark matter". Astro.ucla.edu. 21 September 1998. Retrieved 6 January 2011.
  122. ^ Gaitskell, Richard J. (2004). "Direct Detection of Dark Matter". Annual Review of Nuclear and Particle Science. 54: 315–359. Bibcode:2004ARNPS..54..315G. doi:10.1146/annurev.nucl.54.070103.181244. S2CID 11316578.
  123. ^ "Neutralino Dark Matter". Retrieved 26 December 2011. Griest, Kim. "WIMPs and MACHOs" (PDF). Retrieved 26 December2011.
  124. ^ Drees, M.; Gerbier, G. (2015). "Dark Matter" (PDF). Chin. Phys. C. 38: 090001.
  125. ^ Bernabei, R.; Belli, P.; Cappella, F.; Cerulli, R.; Dai, C.J.; d’Angelo, A.; et al. (2008). "First results from DAMA/LIBRA and the combined results with DAMA/NaI". Eur. Phys. J. C. 56 (3): 333–355. arXiv:0804.2741. Bibcode:2008EPJC...56..333B. doi:10.1140/epjc/s10052-008-0662-y. S2CID 14354488.
  126. ^ Drukier, A.; Freese, K.; Spergel, D. (1986). "Detecting Cold Dark Matter Candidates". Physical Review D. 33 (12): 3495–3508. Bibcode:1986PhRvD..33.3495D. doi:10.1103/PhysRevD.33.3495. PMID 9956575.
  127. ^ Davis, Jonathan H. (2015). "The past and future of light dark matter direct detection". Int. J. Mod. Phys. A. 30 (15): 1530038. arXiv:1506.03924. Bibcode:2015IJMPA..3030038D. doi:10.1142/S0217751X15300380. S2CID 119269304.
  128. ^ Aprile, E. (2017). "Search for electronic recoil event rate modulation with 4 years of XENON100 data". Phys. Rev. Lett. 118(10): 101101. arXiv:1701.00769. Bibcode:2017PhRvL.118j1101A. doi:10.1103/PhysRevLett.118.101101. PMID 28339273. S2CID 206287497.
  129. ^ Stonebraker, Alan (3 January 2014). "Synopsis: Dark-Matter Wind Sways through the Seasons". Physics – Synopses. American Physical Society. doi:10.1103/PhysRevLett.112.011301.
  130. ^ Lee, Samuel K.; Lisanti, Mariangela; Peter, Annika H.G.; Safdi, Benjamin R. (3 January 2014). "Effect of Gravitational Focusing on Annual Modulation in Dark-Matter Direct-Detection Experiments". Phys. Rev. Lett. 112 (1): 011301 [5 pages]. arXiv:1308.1953. Bibcode:2014PhRvL.112a1301L. doi:10.1103/PhysRevLett.112.011301. PMID 24483881. S2CID 34109648.
  131. ^ The Dark Matter Group. "An Introduction to Dark Matter". Dark Matter Research. Sheffield: University of Sheffield. Retrieved 7 January 2014.
  132. ^ "Blowing in the Wind". Kavli News. Sheffield: Kavli Foundation. Retrieved 7 January 2014. Scientists at Kavli MIT are working on... a tool to track the movement of dark matter.
  133. ^ "Dark matter even darker than once thought". Space Telescope Science Institute. Retrieved 16 June 2015.
  134. ^ Bertone, Gianfranco (2010). "Dark Matter at the Centers of Galaxies". Particle Dark Matter: Observations, Models and Searches. Cambridge University Press. pp. 83–104. arXiv:1001.3706. Bibcode:2010arXiv1001.3706M. ISBN 978-0-521-76368-4.
  135. ^ Ellis, J.; Flores, R.A.; Freese, K.; Ritz, S.; Seckel, D.; Silk, J. (1988). "Cosmic ray constraints on the annihilations of relic particles in the galactic halo" (PDF). Physics Letters B. 214 (3): 403–412. Bibcode:1988PhLB..214..403E. doi:10.1016/0370-2693(88)91385-8.
  136. ^ Freese, K. (1986). "Can Scalar Neutrinos or Massive Dirac Neutrinos be the Missing Mass?". Physics Letters B. 167 (3): 295–300. Bibcode:1986PhLB..167..295F. doi:10.1016/0370-2693(86)90349-7.
  137. ^ Randall 2015, p. 298.
  138. ^ Sokol, Joshua; et al. (20 February 2016). "Surfing gravity's waves". New Scientist. No. 3061.
  139. ^ "Did gravitational wave detector find dark matter?". Johns Hopkins University. 15 June 2016. Retrieved 20 June 2015. While their existence has not been established with certainty, primordial black holes have in the past been suggested as a possible solution to the dark matter mystery. Because there is so little evidence of them, though, the primordial black hole–dark matter hypothesis has not gained a large following among scientists. The LIGO findings, however, raise the prospect anew, especially as the objects detected in that experiment conform to the mass predicted for dark matter. Predictions made by scientists in the past held conditions at the birth of the universe would produce many of these primordial black holes distributed approximately evenly in the universe, clustering in halos around galaxies. All this would make them good candidates for dark matter.
  140. ^ Bird, Simeon; Cholis, Illian (2016). "Did LIGO detect dark matter?". Physical Review Letters. 116 (20): 201301. arXiv:1603.00464. Bibcode:2016PhRvL.116t1301B. doi:10.1103/PhysRevLett.116.201301. PMID 27258861. S2CID 23710177.
  141. ^ Stecker, F.W.; Hunter, S.; Kniffen, D. (2008). "The likely cause of the EGRET GeV anomaly and its implications". Astroparticle Physics. 29 (1): 25–29. arXiv:0705.4311. Bibcode:2008APh....29...25S. doi:10.1016/j.astropartphys.2007.11.002. S2CID 15107441.
  142. ^ Atwood, W.B.; Abdo, A.A.; Ackermann, M.; Althouse, W.; Anderson, B.; Axelsson, M.; et al. (2009). "The large area telescope on the Fermi Gamma-ray Space Telescope Mission". Astrophysical Journal. 697 (2): 1071–1102. arXiv:0902.1089. Bibcode:2009ApJ...697.1071A. doi:10.1088/0004-637X/697/2/1071. S2CID 26361978.
  143. ^ Weniger, Christoph (2012). "A tentative gamma-ray line from dark matter annihilation at the Fermi Large Area Telescope". Journal of Cosmology and Astroparticle Physics. 2012 (8): 7. arXiv:1204.2797. Bibcode:2012JCAP...08..007W. doi:10.1088/1475-7516/2012/08/007. S2CID 119229841.
  144. ^ Cartlidge, Edwin (24 April 2012). "Gamma rays hint at dark matter". Institute of Physics. Retrieved 23 April 2013.
  145. ^ Albert, J.; Aliu, E.; Anderhub, H.; Antoranz, P.; Backes, M.; Baixeras, C.; et al. (2008). "Upper Limit for γ‐Ray Emission above 140 GeV from the Dwarf Spheroidal Galaxy Draco". The Astrophysical Journal. 679 (1): 428–431. arXiv:0711.2574. Bibcode:2008ApJ...679..428A. doi:10.1086/529135. S2CID 15324383.
  146. ^ Aleksić, J.; Antonelli, L.A.; Antoranz, P.; Backes, M.; Baixeras, C.; Balestra, S.; et al. (2010). "Magic Gamma-Ray Telescope observation of the Perseus Cluster of galaxies: Implications for cosmic rays, dark matter, and NGC 1275". The Astrophysical Journal. 710 (1): 634–647. arXiv:0909.3267. Bibcode:2010ApJ...710..634A. doi:10.1088/0004-637X/710/1/634. S2CID 53120203.
  147. ^ Adriani, O.; Barbarino, G.C.; Bazilevskaya, G.A.; Bellotti, R.; Boezio, M.; Bogomolov, E.A.; et al. (2009). "An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV". Nature. 458(7238): 607–609. arXiv:0810.4995. Bibcode:2009Natur.458..607A. doi:10.1038/nature07942. PMID 19340076. S2CID 11675154.
  148. ^ Aguilar, M.; et al. (AMS Collaboration) (3 April 2013). "First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV". Physical Review Letters. 110 (14): 141102. Bibcode:2013PhRvL.110n1102A. doi:10.1103/PhysRevLett.110.141102. PMID 25166975.
  149. ^ AMS Collaboration (3 April 2013). "First Result from the Alpha Magnetic Spectrometer Experiment". Archived from the originalon 8 April 2013. Retrieved 3 April 2013.
  150. ^ Heilprin, John; Borenstein, Seth (3 April 2013). "Scientists find hint of dark matter from cosmos". Associated Press. Retrieved 3 April2013.
  151. ^ Amos, Jonathan (3 April 2013). "Alpha Magnetic Spectrometer zeroes in on dark matter". BBC. Retrieved 3 April 2013.
  152. ^ Perrotto, Trent J.; Byerly, Josh (2 April 2013). "NASA TV Briefing Discusses Alpha Magnetic Spectrometer Results". NASA. Retrieved 3 April 2013.
  153. ^ Overbye, Dennis (3 April 2013). "New Clues to the Mystery of Dark Matter". The New York Times. Retrieved 3 April 2013.
  154. ^ Kane, G.; Watson, S. (2008). "Dark Matter and LHC:. what is the Connection?". Modern Physics Letters A. 23 (26): 2103–2123. arXiv:0807.2244. Bibcode:2008MPLA...23.2103K. doi:10.1142/S0217732308028314. S2CID 119286980.
  155. ^ Fox, P.J.; Harnik, R.; Kopp, J.; Tsai, Y. (2011). "LEP Shines Light on Dark Matter". Phys. Rev. D. 84 (1): 014028. arXiv:1103.0240. Bibcode:2011PhRvD..84a4028F. doi:10.1103/PhysRevD.84.014028. S2CID 119226535.
  156. ^ For a review, see: Kroupa, Pavel; et al. (December 2012). "The failures of the Standard Model of Cosmology require a new paradigm". International Journal of Modern Physics D. 21 (4): 1230003. arXiv:1301.3907. Bibcode:2012IJMPD..2130003K. doi:10.1142/S0218271812300030. S2CID 118461811.
  157. ^ For a review, see: Salvatore Capozziello; Mariafelicia De Laurentis (October 2012). "The dark matter problem from f (R) gravity viewpoint". Annalen der Physik. 524 (9–10): 545. Bibcode:2012AnP...524..545C. doi:10.1002/andp.201200109.
  158. ^ "Bringing balance to the Universe". University of Oxford.
  159. ^ "Bringing balance to the universe: New theory could explain missing 95 percent of the cosmos". Phys.Org.
  160. ^ Farnes, J.S. (2018). "A Unifying Theory of Dark Energy and Dark Matter: Negative Masses and Matter Creation within a Modified ΛCDM Framework". Astronomy & Astrophysics. 620: A92. arXiv:1712.07962. Bibcode:2018A & A...620A..92F. doi:10.1051/0004-6361/201832898. S2CID 53600834.
  161. ^ "New theory of gravity might explain dark matter". phys.org. November 2016.
  162. ^ Mannheim, Phillip D. (April 2006). "Alternatives to dark matter and dark energy". Progress in Particle and Nuclear Physics. 56 (2): 340–445. arXiv:astro-ph/0505266. Bibcode:2006PrPNP..56..340M. doi:10.1016/j.ppnp.2005.08.001. S2CID 14024934.
  163. ^ Joyce, Austin; et al. (March 2015). "Beyond the Cosmological Standard Model". Physics Reports. 568: 1–98. arXiv:1407.0059. Bibcode:2015PhR...568....1J. doi:10.1016/j.physrep.2014.12.002. S2CID 119187526.
  164. ^ "Verlinde's new theory of gravity passes first test". 16 December 2016.
  165. ^ Brouwer, Margot M.; et al. (11 December 2016). "First test of Verlinde's theory of Emergent Gravity using Weak Gravitational Lensing measurements". Monthly Notices of the Royal Astronomical Society. 466 (to appear): 2547–2559. arXiv:1612.03034. Bibcode:2017MNRAS.466.2547B. doi:10.1093/mnras/stw3192. S2CID 18916375.
  166. ^ "First test of rival to Einstein's gravity kills off dark matter". 15 December 2016. Retrieved 20 February 2017.
  167. ^ Sean Carroll (9 May 2012). "Dark matter vs. modified gravity: A trialogue". Retrieved 14 February 2017.
  168. https://en.wikipedia.org/wiki/Dark\_matter.

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