INTRODUCTION TO DARK MATTER

In the early 1990's, the Universe had enough energy density to stop the expansion of itself and prevent itself from re-collapsing, it might have so little energy density that it would never stop expanding, but gravity was certain to slow the expansion as time went on. Granted, the slowing had not been observed, but, theoretically, the Universe had to slow. The Universe is full of matter and the attractive force of gravity pulls all matter together. In 1998, Hubble Space Telescope (HST) made observations that showed that, a long time ago, the Universe was actually expanding more slowly than it is today. So the expansion of the Universe has not been slowing due to gravity, as everyone thought, it has been accelerating. No one expected this, no one knew how to explain it. But something was causing it. And to study the cause, basic terminologies, observational evidences and further on detection as well as studying its history is the main objective.

This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart as a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pulling galaxies apart.

There Were various assumptions made, experiments conducted and eventually theorists came up with three sorts of explanations.

 Maybe it was a result of a version of Einstein's theory of gravity, one that contained what was called a "cosmological constant."

 Maybe there was some strange kind of energy-fluid that filled space.

 Maybe there is something wrong with Einstein's theory of gravity and a new theory could include some kind of field that creates this cosmic acceleration.

 Theorists still don't know what the correct explanation is, but they have given the solution a name. It is called dark energy.

 One explanation for dark energy is that it is a property of space. Albert Einstein was the first person to realize that empty space is not nothing. The first property that Einstein discovered is that it is possible for more space to come into existence. Then one version of Einstein's gravity theory, the version that contains a cosmological constant, makes a second prediction: "empty space" can possess its own energy. Because this energy is a property of space itself, it would not be diluted as space expands. As more space comes into existence, more of this energy-of-space would appear. As a result, this form of energy would cause the Universe to expand faster and faster. Unfortunately, no one understands why the cosmological constant should even be there, much less why it would have exactly the right value to cause the observed acceleration of the Universe.

Another explanation for how space acquires energy comes from the quantum theory of matter. In this theory, "empty space" is actually full of temporary ("virtual") particles that continually form and then disappear. But when physicists tried to calculate how much energy this would give empty space, the answer came out wrong. The number came out 10120 times too big. So the mystery continues.

Another explanation for dark energy is that it is a new kind of dynamical energy fluid, something that fills all of space but something whose effect on the expansion of the Universe is the opposite of that of matter and normal energy. Some theorists have named this "quintessence," after the fifth element of the Greek philosophers. But, if quintessence is the answer, we still don't know what it is like, what it interacts with, or why it exists. So the mystery continues.

A last possibility is that Einstein's theory of gravity is not correct. That would not only affect the expansion of the Universe, but it would also affect the way that normal matter in galaxies and clusters of galaxies behaved. This fact would provide a way to decide if the solution to the dark energy problem is a new gravity theory or not: we could observe how galaxies come together in clusters. But if it does turn out that a new theory of gravity is needed, what kind of theory would it be? How could it correctly describe the motion of the bodies in the Solar System, as Einstein's theory is known to do, and still give us the different prediction for the Universe that we need? There are candidate theories, but none are compelling. So the mystery continues.

The thing that is needed to decide between dark energy possibilities - a property of space, a new dynamic fluid, or a new theory of gravity - is more data, better data.

Dark Matter is a type of matter hypothesized to account for a large part of the total mass in the universe.

1. First, dark meaning not in the form of stars and planets.

2. It is not in the form of dark clouds of normal matter, matter made up of particles called baryons.

3. Dark matter cannot be seen directly with telescopes.

4. It neither emits nor absorbs light or other electromagnetic radiation at any significant level.

 Its existence and properties are inferred from its gravitational effects on visible matter, radiation, and the large-scale structure of the universe.

 DID YOU KNOW?

We know how much dark energy is there because it affects the expansion of the Universe. The total mass-energy of the universe contains

4.9% ordinary matter,

26.8% dark matter and 68.3% dark energy.

Dark matter's existence is inferred from gravitational effects on visible matter and was originally hypothesized to account for discrepancies between calculations of the mass of galaxies, clusters of galaxies and the entire universe made through dynamical (using mechanics) and general relativistic (general theory of relativity) means, and calculations based on the mass of the visible luminous matter these objects contain: stars and the gas and dust.

The most widely accepted explanation for these phenomena is that dark matter exists and that it is most probably composed of weakly interacting massive particles (WIMPs) that interact only through gravity and the weak force.

Many experiments to detect proposed dark matter particles through non-gravitational means are under way.

Dark matter plays a central role in state-of-the-art modelling of cosmic structure formation and Galaxy formation and evolution. All these lines of evidence suggest that galaxies, clusters of galaxies, and the universe as a whole contain far more matter than that which interacts with electromagnetic radiation.

Direct evidence of its existence and a concrete understanding of the nature of dark matter have remained elusive. Though the theory of dark matter remains the most widely accepted theory to explain the anomalies in observed galactic rotation, some alternative theoretical approaches have been developed which broadly fall into the categories of modified gravitational laws and quantum gravitational laws.

BARYONIC AND NONBARYONIC MATTER

There are three separate lines of evidence that the majority of dark matter is not made of baryons, ordinary matter including protons, electrons and atoms:

· The theory of Big Bang nucleosynthesis, which very accurately predicts the observed abundance of the chemical elements, predicts that baryonic matter accounts for around 4–5 percent of critical density of the Universe.

· Large astronomical searches have shown that only a small fraction of the dark matter in the Milky Way can be hiding in dark compact objects.

· Detailed analysis of the small irregularities (anisotropies) shows that around five-sixths of the total matter is in a form which does not interact significantly with ordinary matter or photons.

A small proportion of dark matter may be baryonic dark matter: astronomical bodies, such as massive compact halo objects, that are composed of ordinary matter but which emit little or no electromagnetic radiation. Study of nucleosynthesis in the Big Bang produces an upper bound on the amount of baryonic matter in the universe, which indicates that the vast majority of dark matter in the universe cannot be baryons, and thus does not form atoms. It also cannot interact with ordinary matter via electromagnetic forces; in particular, dark matter particles do not carry any electric charge.

Candidates for nonbaryonic dark matter are hypothetical particles such as axions, or supersymmetric particles; neutrinos can only form a small fraction of the dark matter. Unlike baryonic dark matter, nonbaryonic dark matter does not contribute to the formation of the elements in the early universe ("Big Bang nucleosynthesis") and so its presence is revealed only via its gravitational attraction.

Nonbaryonic dark matter is classified in terms of the mass of the particle(s) that is assumed to make it up, and/or the typical velocity dispersion of those particles (since more massive particles move more slowly). There are three prominent hypotheses on nonbaryonic dark matter, called cold dark matter (CDM), warm dark matter (WDM), and hot dark matter (HDM); some combination of these is also possible. The most widely discussed models for nonbaryonic dark matter are based on the cold dark matter hypothesis, and the corresponding particle is most commonly assumed to be a weakly interacting massive particle (WIMP). Hot dark matter may include (massive) neutrinos, but observations imply that only a small fraction of dark matter can be hot.

DID YOU KNOW?

Black holes absorb dark matter, and over the billions of years since galaxies were first formed, this absorption of dark matter in black holes has very likely altered the population of galaxies from what we can observe today.

OBSERVATIONAL EVIDENCE

In 1932, Jan Oort, a pioneer in radio astronomy, was studying stellar motions in the local galactic neighbourhood and found that the mass in the galactic plane must be more than the material that could be seen, but this measurement was later determined to be essentially erroneous. In 1933 the Swiss astrophysicist Fritz Zwicky, who studied clusters of galaxies while made a similar inference. Zwicky applied the virial theorem to the Coma cluster of galaxies and obtained evidence of unseen mass. Zwicky estimated the cluster's total mass based on the motions of galaxies near its edge and compared that estimate to one based on the number of galaxies and total brightness of the cluster. He found that there was about 400 times more estimated mass than was visually observable. The gravity of the visible galaxies in the cluster would be far too small for such fast orbits, so something extra was required. This is known as the "missing mass problem". Based on these conclusions, Zwicky inferred that there must be some non-visible form of matter which would provide enough of the mass and gravity to hold the cluster together.

Much of the evidence for dark matter comes from the study of the motions of galaxies. Many of these appear to be fairly uniform, so by the virial theorem, the total kinetic energy should be half the total gravitational binding energy of the galaxies. Experimentally, however, the total kinetic energy is found to be much greater: in particular, assuming the gravitational mass is due to only the visible matter of the galaxy, stars far from the center of galaxies have much higher velocities than predicted by the virial theorem. Galactic rotation curves, which illustrate the velocity of rotation versus the distance from the galactic center, cannot be explained by only the visible matter. Assuming that the visible material makes up only a small part of the cluster is the most straightforward way of accounting for this. Galaxies show signs of being composed largely of a roughly spherically symmetric, centrally concentrated halo of dark matter with the visible matter concentrated in a disc at the center. Low surface brightness dwarf galaxies are important sources of information for studying dark matter, as they have an uncommonly low ratio of visible matter to dark matter, and have few bright stars at the center which would otherwise impair observations of the rotation curve of outlying stars.

GALAXY ROTATION CURVES:

After Zwicky's initial observations, the first indication that the mass to light ratio was anything other than unity came from measurements made by Horace W. Babcock. In 1939, Babcock reported measurements of the rotation curve for the Andromeda nebula which suggested that the mass-to-luminosity ratio increases radially. He, however, attributed it to either absorption of light within the galaxy or modified dynamics in the outer portions of the spiral and not to any form of missing matter.

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

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 In the late 1960s and early 1970s, Vera Rubin, worked with a new sensitive spectrograph that could measure the velocity curve of edge-on spiral galaxies to a greater degree of accuracy than had ever before been achieved. Together with fellow staff-member Kent Ford, Rubin announced at a 1975 meeting the discovery that most stars in spiral galaxies orbit at roughly the same speed, which implied that the mass densities of the galaxies were uniform well beyond the regions containing most of the stars. An influential paper presented Rubin's results in 1980. Rubin's observations and calculations showed that most galaxies must contain about six times as much “dark” mass as can be accounted for by the visible stars. Eventually other astronomers began to corroborate her work and it soon became well-established that most galaxies were dominated by "dark matter":

· Low surface Brightness (LSB) galaxies. LSBs are probably everywhere dark matter-dominated, with the observed stellar populations making only a small contribution to rotation curves. Such a property is extremely important because it allows one to avoid the difficulties associated with the deprojection and disentanglement of the dark and visible contributions to the rotation curves.

· Spiral Galaxies. Rotation curves of both low and high surface luminosity galaxies appear to suggest a universal density profile.

· Elliptical galaxies. Some elliptical galaxies show evidence for dark matter via strong gravitational lensing, X-ray evidence reveals the presence of extended atmospheres of hot gas that fill the dark haloes of isolated ellipticals and whose hydrostatic support provides evidence for dark matter. Other ellipticals have low velocities in their outskirts.

Simulated dark matter haloes have significantly steeper density profiles (having central cusps) than are inferred from observations, which is a problem for cosmological models with dark matter at the smallest scale of galaxies. This may only be a problem of resolution: star-forming regions which might alter the dark matter distribution via outflows of gas have been too small to resolve and model simultaneously with larger dark matter clumps. A recent simulation of a dwarf galaxy resolving these star-forming regions reported that strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of a galactic bulge and decreases the dark matter density to less than half of what it would have been in the central kiloparsec. These simulation predictions—bulgeless and with shallow central dark matter profiles—correspond closely to observations of actual dwarf galaxies. There are no such discrepancies at the larger scales of clusters of galaxies and above, or in the outer regions of haloes of galaxies.

Exceptions to this general picture of dark matter haloes for galaxies appear to be galaxies with mass-to-light ratios close to that of stars. Subsequent to this, numerous observations have been made that do indicate the presence of dark matter in various parts of the cosmos, such as observations of the cosmic microwave background, of supernovas used as distance measures, of gravitational lensing at various scales, and many types of sky survey. Together with Rubin's findings for spiral galaxies and Zwicky's work on galaxy clusters, the observational evidence for dark matter has been collecting over the decades to the point that by the 1980s most astrophysicists accepted its existence. As a unifying concept, dark matter is one of the dominant features considered in the analysis of structures on the order of galactic scale and larger.

Velocity dispersions of galaxies:

The velocity dispersion σ, is the range of velocities about the mean velocity for a group of objects, such as a cluster of stars about a galaxy.

 Measurements of velocity curves in spiral galaxies were soon followed up with velocity dispersions of elliptical galaxies. While sometimes appearing with lower mass-to-light ratios, measurements of ellipticals still indicate a relatively high dark matter content. Likewise, measurements of the diffuse interstellar gas found at the edge of galaxies indicate not only dark matter distributions that extend beyond the visible limit of the galaxies, but also that the galaxies are virialized (i.e. gravitationally bound with velocities corresponding to predicted orbital velocities of general relativity) up to ten times their visible radii. This has the effect of pushing up the dark matter as a fraction of the total amount of gravitating matter from 50% measured by Rubin to the now accepted value of nearly 95%.

There are places where dark matter seems to be a small component or totally absent. Globular clusters show little evidence that they contain dark matter, though their orbital interactions with galaxies do show evidence for galactic dark matter. For some time, measurements of the velocity profile of stars seemed to indicate concentration of dark matter in the disk of the Milky Way galaxy. It now appears, however, that the high concentration of baryonic matter in the disk of the galaxy (especially in the interstellar medium) can account for this motion.

In 2005, astronomers claimed to have discovered a galaxy made almost entirely of dark matter, 50 million light years away in the Virgo Cluster, which was named VIRGOHI21. Unusually, VIRGOHI21 does not appear to contain any visible stars: it was seen with radio frequency observations of hydrogen. Based on rotation profiles, the scientists estimate that this object contains approximately 1000 times more dark matter than hydrogen and has a total mass of about 1/10 that of the Milky Way Galaxy we live in.

Galaxy clusters and gravitational lensing:

A gravitational lens is formed when the light from a very distant, bright source (such as a quasar) is "bent" around a massive object (such as a cluster of galaxies) between the source object and the observer. The process is known as gravitational lensing.

Dark matter affects galaxy clusters as well. X-ray measurements of hot intracluster gas correspond closely to Zwicky's observations of mass-to-light ratios for large clusters of nearly 10 to 1.

The galaxy cluster Abell 2029 is composed of thousands of galaxies enveloped in a cloud of hot gas, and an amount of dark matter equivalent to more than 1014 Suns. At the center of this cluster is an enormous, elliptically shaped galaxy that is thought to have been formed from the mergers of many smaller galaxies. The measured orbital velocities of galaxies within galactic clusters have been found to be consistent with dark matter observations.

Another important tool for future dark matter observations is gravitational lensing. Lensing relies on the effects of general relativity to predict masses without relying on dynamics, and so is a completely independent means of measuring the dark matter. Strong lensing, the observed distortion of background galaxies into arcs when the light passes through a gravitational lens, has been observed around a few distant clusters including Abell 1689. By measuring the distortion geometry, the mass of the cluster causing the phenomena 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.

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

Weak gravitational lensing looks at minute distortions of galaxies observed in vast galaxy surveys due to foreground objects through statistical analyses. By examining the apparent shear deformation of the adjacent background galaxies, astrophysicists can characterize the mean distribution of dark matter by statistical means and have found mass-to-light ratios that correspond to dark matter densities predicted by other large-scale structure measurements. The correspondence of the two gravitational lens techniques to other dark matter measurements has convinced almost all astrophysicists that dark matter actually exists as a major component of the universe's composition.

The most direct observational evidence to date for dark matter is in a system known as the Bullet Cluster. In most regions of the universe, dark matter and visible material are found together, as expected because of their mutual gravitational attraction. In the Bullet Cluster, a collision between two galaxy clusters appears to have caused a separation of dark matter and baryonic matter. X-ray observations show that much of the baryonic matter in the system is concentrated in the center of the system. Electromagnetic interactions between passing gas particles caused them to slow down and settle near the point of impact. However, weak gravitational lensing observations of the same system show that much of the mass resides outside of the central region of baryonic gas. Because dark matter does not interact by electromagnetic forces, it would not have been slowed in the same way as the X-ray visible gas, so the dark matter components of the two clusters passed through each other without slowing down substantially. This accounts for the separation. Unlike the galactic rotation curves, this evidence for dark matter is independent of the details of Newtonian gravity, so it is claimed to be direct evidence of the existence of dark matter. Another galaxy cluster, known as the Train Wreck Cluster/Abell 520, appears to have an unusually massive and dark core containing few of the cluster's galaxies, which presents problems for standard dark matter models.

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

The observed behaviour of dark matter in clusters constrains whether and how much dark matter scatters off other dark matter particles, quantified as its self-interaction cross section. More simply, the question is whether the dark matter has pressure, and thus can be described as a perfect fluid. The distribution of mass (and thus dark matter) in galaxy clusters has been used to argue both for and against the existence of significant self-interaction in dark matter. Specifically, the distribution of dark matter in merging clusters such as the Bullet Cluster shows that dark matter scatters off other dark matter particles only very weakly if at all.

Sky surveys and baryon acoustic oscillations:

The acoustic oscillations in the early universe leave their imprint in the visible matter by Baryon Acoustic Oscillation (BAO) clustering, in a way that can be measured with sky surveys such as the Sloan Digital Sky Survey and the 2dF Galaxy Redshift Survey. These measurements are consistent with those of the CMB derived from the WMAP spacecraft and further constrain the Lambda CDM model and dark matter. Note that the CMB data and the BAO data measure the acoustic oscillations at very different distance scales.

Type Ia supernovae distance measurements:

Type Ia supernovae can be used as "standard candles" to measure extragalactic distances, and extensive data sets of these supernovae can be used to constrain cosmological models. They constrain the dark energy density for a flat. Once again, the values obtained are roughly consistent with those derived from the WMAP observations and further constrain the Lambda CDM model and (indirectly) dark matter.

Lyman-alpha forest

In astronomical spectroscopy, the Lyman-alpha forest is the sum of absorption lines arising from the Lyman-alpha transition of the neutral hydrogen in the spectra of distant galaxies and quasars. Observations of the Lyman-alpha forest can also be used to constrain cosmological models. These constraints are again in agreement with those obtained from WMAP data.

Structure formation

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

Dark matter is crucial to the Big Bang model of cosmology as a component which corresponds directly to measurements of the parameters associated with Friedmann cosmology solutions to general relativity. In particular, measurements of the cosmic microwave background anisotropies correspond to a cosmology where much of the matter interacts with photons more weakly than the known forces that couple light interactions to baryonic matter. Likewise, a significant amount of non-baryonic, cold matter is necessary to explain the large-scale structure of the universe.

Observations suggest that structure formation in the universe proceeds hierarchically, with the smallest structures collapsing first and followed by galaxies and then clusters of galaxies. As the structures collapse in the evolving universe, they begin to "light up" as the baryonic matter heats up through gravitational contraction and the object approaches hydrostatic pressure balance. Ordinary baryonic matter had too high a temperature, and too much pressure left over from the Big Bang to collapse and form smaller structures, such as stars, via the Jeans instability. Dark matter acts as a compactor of structure. This model not only corresponds with statistical surveying of the visible structure in the universe but also corresponds precisely to the dark matter predictions of the cosmic microwave background.

This bottom up model of structure formation requires something like cold dark matter to succeed. Large computer simulations of billions of dark matter particles have been used to confirm that the cold dark matter model of structure formation is consistent with the structures observed in the universe through galaxy surveys, such as the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey, as well as observations of the Lyman-alpha forest. These studies have been crucial in constructing the Lambda-CDM model which measures the cosmological parameters, including the fraction of the universe made up of baryons and dark matter.

There are, however, several points of tension between observation and simulations of structure formation driven by dark matter. There is evidence that there are 10 to 100 times fewer small galaxies than permitted by what the dark matter theory of galaxy formation predicts. This is known as the dwarf galaxy problem. In addition, the simulations predict dark matter distributions with a very dense cusp near the centers of galaxies, but the observed halos are smoother than predicted.

HISTORY FOR THE SEARCH OF ITS COMPOSITION

Although dark matter had historically been inferred by many astronomical observations, its composition long remained speculative. Early theories of dark matter concentrated on hidden heavy normal objects, such as black holes, neutron stars, faint old white dwarfs, brown dwarfs, as the possible candidates for dark matter, collectively known as massive compact halo objects or MACHOs. Astronomical surveys for gravitational microlensing, including the MACHO, EROS and OGLE projects, along with Hubble telescope searches for ultra-faint stars, have not found enough of these hidden MACHOs. Some hard-to-detect baryonic matter, such as MACHOs and some forms of gas, were additionally speculated to make a contribution to the overall dark matter content, but evidence indicated such would constitute only a small portion.

Furthermore, data from a number of lines of other evidence, including galaxy rotation curves, gravitational lensing, structure formation, and the fraction of baryons in clusters and the cluster abundance combined with independent evidence for the baryon density, indicated that 85–90% of the mass in the universe does not interact with the electromagnetic force. This "nonbaryonic dark matter" is evident through its gravitational effect. Consequently, the most commonly held view was that dark matter is primarily non-baryonic, made of one or more elementary particles other than the usual electrons, protons, neutrons, and known neutrinos. The most commonly proposed particles then became WIMPs (Weakly Interacting Massive Particles, including neutralinos), oraxions, or sterile neutrinos, though many other possible candidates have been proposed.

The dark matter component has much more mass than the "visible" component of the universe. Only about 4.6% of the mass-energy of the Universe is ordinary matter. About 23% is thought to be composed of dark matter. The remaining 72% is thought to consist of dark energy, an even stranger component, distributed almost uniformly in space and with energy density non-evolving or slowly evolving with time. Determining the nature of this dark matter is one of the most important problems in modern cosmology and particle physics. It has been noted that the names "dark matter" and "dark energy" serve mainly as expressions of human ignorance, much like the marking of early maps with "terra incognita".

Historically, three categories of dark matter candidates had been postulated. The categories cold, warm, and hot refer to how far the particles could move due to random motions in the early universe, before they slowed down due to the expansion of the Universe – this is called the "free streaming length". Primordial density fluctuations smaller than this free-streaming length get washed out as particles move from overdense to underdense regions, while fluctuations larger than the free-streaming length are unaffected; therefore this free-streaming length sets a minimum scale for structure formation.

· Cold dark matter – objects with a free-streaming length much smaller than a protogalaxy.

· Warm dark matter – particles with a free-streaming length similar to a protogalaxy.

· Hot dark matter – particles with a free-streaming length much larger than a protogalaxy.

Though a fourth category had been considered early on, called mixed dark matter, it was quickly eliminated (from the 1990s) since the discovery of dark energy.

As an example, Davis et al. wrote in 1985:

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

The full calculations are quite technical, but an approximate dividing line is that "warm" dark matter particles became non-relativistic when the universe was approximately 1 year old and 1 millionth of its present size; standard hot big bang theory implies the universe was then in the radiation-dominated era (photons and neutrinos), with a photon temperature 2.7 million K. Standard physical cosmology gives the particle horizon size as 2ct in the radiation-dominated era, thus 2 light-years, and a region of this size would expand to 2 million light years today (if there were no structure formation). The actual free-streaming length is roughly 5 times larger than the above length, since the free-streaming length continues to grow slowly as particle velocities decrease inversely with the scale factor after they become non-relativistic; therefore, in this example the free-streaming length would correspond to 10 million light-years or 3 Mpc today, which is around the size containing on average the mass of a large galaxy.

The above temperature 2.7 million K which gives a typical photon energy of 250 electron-volts, so this sets a typical mass scale for "warm" dark matter: particles much more massive than this, such as GeV – TeV mass WIMPs, would become non-relativistic much earlier than 1 year after the Big Bang, thus have a free-streaming length which is much smaller than a proto-galaxy and effectively negligible (thus cold dark matter). Conversely, much lighter particles (e.g. neutrinos of mass ~ few eV) have a free-streaming length much larger than a proto-galaxy (thus hot dark matter).

Cold dark matter:

Today, cold dark matter is the simplest explanation for most cosmological observations. "Cold" dark matter is dark matter composed of constituents with a free-streaming length much smaller than the ancestor of a galaxy-scale perturbation. This is currently the area of greatest interest for dark matter research, as hot dark matter does not seem to be viable for galaxy and galaxy cluster formation, and most particle candidates become non-relativistic at very early times, hence are classified as cold.

The composition of the constituents of cold dark matter is currently unknown. Possibilities range from large objects like MACHOs (such as black holes) or RAMBOs, to new particles like WIMPs and axions. Possibilities involving normal baryonic matter include brown dwarfs or perhaps small, dense chunks of heavy elements.

Studies of big bang nucleosynthesis and gravitational lensing have convinced most scientists that MACHOs of any type cannot be more than a small fraction of the total dark matter. Black holes of nearly any mass are ruled out as a primary dark matter constituent by a variety of searches and constraints.

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

Warm dark matter:

Warm dark matter refers to particles with a free-streaming length comparable to the size of a region which subsequently evolved into a dwarf galaxy. This leads to predictions which are very similar to cold dark matter on large scales, including the CMB, galaxy clustering and large galaxy rotation curves, 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 may be a better fit to observations. A challenge for this model is that there are no very well-motivated particle physics candidates with the required mass ~ 300 eV to 3000 eV.

There have been no particles discovered so far that can be categorized as warm dark matter. There is a postulated candidate for the warm dark matter category, which is the sterile neutrino: a heavier, slower form of neutrino which does not even interact through the Weak force unlike regular neutrinos. Interestingly, some modified gravity theories, such as Scalar-tensor-vector gravity, also require that a warm dark matter exist to make their equations work out.

Hot dark matter:

Hot dark matter are particles that have a free-streaming length much larger than a proto-galaxy size. An example of hot dark matter is already known: the neutrino. Neutrinos were discovered quite separately from the search for dark matter, and long before it seriously began: they were first postulated in 1930, and first detected in 1956. Neutrinos have a very small mass: at least 100,000 times less massive than an electron. Other than gravity, neutrinos only interact with normal matter via the weak force making them very difficult to detect (the weak force only works over a small distance, thus a neutrino will only trigger a weak force event if it hits a nucleus directly head-on). This would classify them as Weakly Interacting Light Particles, or WILPs, as opposed to cold dark matter's theoretical candidates, the WIMPs.

Hot dark matter was popular for a time in the early 1980s, but it suffers from a severe problem: since all galaxy-size density fluctuations get washed out by free-streaming, the first objects which can form are huge supercluster-size pancakes, which then were theorised somehow to fragment into galaxies. Deep-field observations clearly show that galaxies formed at early times, with clusters and superclusters forming later as galaxies clump together, so any model dominated by hot dark matter is seriously in conflict with observations.

 RECENT DISCOVERIES IN THE FIELD OF DARK MATTER

NOVEMBER 30,2012: Douglas Clowe of Ohio University in Athens reported on a new Hubble observations that did not find unusually dense clump of dark matter in the universe. The region of interest lies at the center of a collision among massive galaxy clusters in Abell 520, located 2.4 billion light-years away. Clowe said, “The earlier result presented a mystery. But in our observations we didn’t see anything surprising in the core. Our measurements are in complete agreement with how we would expect dark matter to behave.” Because dark matter is not visible, its presence and distribution is found indirectly through its gravitational effects. The gravity from both dark and luminous matter warps space, bending and distorting light from galaxies and clusters behind it like a giant magnifying glass. Astronomers can use this effect, called gravitational lensing, to infer the presence of dark matter in massive galaxy clusters. Clowe is encouraging other scientists to study the Hubble data and conduct their own analysis on the cluster.

Musket Ball Cluster:

A system of colliding galaxy clusters, nicknamed the “Musket Ball Cluster” has been discovered. Astronomers call it this because it is an older and slower cousin to the famous Bullet Cluster, where normal and dark matter have been torn apart. The image shows the Musket Ball at about 700 million years post-collision, showing it is much older than the Bullet Cluster. Finding this cluster gives scientists insight into a different phase of how galaxy clusters grow an d change after major collisions.

Astronomers have also observed a violent collision between two galaxy clusters in which so-called normal matter has been wrenched apart from the dark matter. The newly discovered system has been nicknamed “Musket Ball Cluster” because the cluster collision is older and slower than Bullet Cluster. This also gives an insight into a different phase of how galaxy clusters-the largest known objects held together by gravity-grow and change after major collisions. The matter distribution determined by telescopes reveal the effects of gravitational lensing, an effect predicted by Einstein where large masses can distort the light from distant objects.

Abel 383:

Teams of astronomers have used data from NASA's Chandra X-ray Observatory and other telescopes to map the distribution of dark matter in a galaxy cluster known as Abell 383, which is located about 2.3 billion light years from Earth. Not only were the researchers able to find where the dark matter lies in the two dimensions across the sky, they were also able to determine how the dark matter is distributed along the line of sight. Galaxy clustrs are the largest gravitationally-bound structures in the universe. The use of clusters as dark matter helps in determining three-dimensional structures and masses of clusters. Dark matter is invisible material that does not emit or absorb any type of light, but is detectable through its gravitational effects. Several lines of evidence indicate that there is about six times as much dark matter as "normal", or baryonic, matter in the Universe. Astronomers have found that the dark matter is stretched out like a gigantic American football, rather than being spherical like a basketball, and that the point of the football is aligned close to the line of sight. The X-ray data (purple) from Chandra in the composite image show the hot gas, which is by far the dominant type of normal matter in the cluster. Galaxies are shown with the optical data from the Hubble Space Telescope (HST), the Very Large Telescope, and the Sloan Digital Sky Survey, colored in blue and white. The X-ray observations of the "normal matter" in the cluster with gravitational lensing information determined from optical data. Gravitational lensing - an effect predicted by Albert Einstein - causes the material in the galaxy cluster, both normal and dark matter, to bend and distort the optical light from background galaxies. The distortion is severe in some parts of the image, producing an arc-like appearance for some of the galaxies. In other parts of the image the distortion is subtle and statistical analysis is used to study the distortion effects and probe the dark matter.

Strong hints of dark matter detected by physicists:

The detector, which weighs nearly seven tonnes, is called the Alpha Magnetic Spectrometer (AMS), and was installed on the space station in May 2011. Since then, physicists have been sifting through its data for hints of dark matter, which has puzzled researchers for decades, and does not interact with light – hence the moniker "dark". For almost a century, physicists have been searching for the mysterious particles, and the latest findings brought them a tantalising step closer. The AMS team tried to deduce them from high energy collisions and the footprint they leave behind. In their observations, the international team of scientists found an unusually high number of positrons, the rare, antimatter counterpart to electrons. The finding fits with the theory that when dark matter particles collide, they destroy each other and create positrons.

Direct detection experiments[edit source | editbeta]Direct detection experiments typically operate in deep underground laboratories to reduce the background from cosmic rays. These include: the Soudan mine; the SNOLAB underground laboratory at Sudbury, Ontario (Canada); the Gran Sasso National Laboratory (Italy); the Canfranc Underground Laboratory (Spain); the Boulby Underground Laboratory (UK); and the Deep Underground Science and Engineering Laboratory, South Dakota (US).

The majority of present experiments use one of two detector technologies: cryogenic detectors, operating at temperatures below 100mK, detect the heat produced when a particle hits an atom in a crystal absorber such as germanium. Noble liquid detectors detect the flash of scintillation light produced by a particle collision in liquid xenon or argon. Cryogenic detector experiments include:CDMS, CRESST, EDELWEISS, EURECA. Noble liquid experiments include ZEPLIN, XENON, DEAP, ArDM, WARP and LUX. Both of these detector techniques are capable of distinguishing background particles which scatter off electrons, from dark matter particles which scatter off nuclei. Other experiments include SIMPLE and PICASSO.

The DAMA/NaI, DAMA/LIBRA experiments have detected an annual modulation in the event rate,[88] which they claim is due to dark matter particles. (As the Earth orbits the Sun, the velocity of the detector relative to the dark matter halo will vary by a small amount depending on the time of year). This claim is so far unconfirmed and difficult to reconcile with the negative results of other experiments assuming that the WIMP scenario is correct.[89]

Directional detection of dark matter is a search strategy based on the motion of the Solar System around the galactic center.[citation needed]

By using a low pressure TPC, it is possible to access information on recoiling tracks (3D reconstruction if possible) and to constrain the WIMP-nucleus kinematics. WIMPs coming from the direction in which the Sun is travelling (roughly in the direction of the Cygnus constellation) may then be separated from background noise, which should be isotropic. Directional dark matter experiments include DMTPC, DRIFT, Newage and MIMAC.

On 17 December 2009 CDMS researchers reported two possible WIMP candidate events. They estimate that the probability that these events are due to a known background (neutrons or misidentified beta or gamma events) is 23%, and conclude "this analysis cannot be interpreted as significant evidence for WIMP interactions, but we cannot reject either event as signal."[90]

More recently, on 4 September 2011, researchers using the CRESST detectors presented evidence[91] of 67 collisions occurring in detector crystals from sub-atomic particles, calculating there is a less than 1 in 10,000 chance that all were caused by known sources of interference or contamination. It is quite possible then that many of these collisions were caused by WIMPs, and/or other unknown particles.

Indirect detection experiments[edit source | editbeta]Indirect detection experiments search for the products of WIMP annihilation or decay. If WIMPs are Majorana particles (WIMPs are their own antiparticle) then two WIMPs could annihilate to produce gamma rays or Standard Model particle-antiparticle pairs. Additionally, if the WIMP is unstable, WIMPs could decay into standard model particles. These processes could be detected indirectly through an excess of gamma rays, antiprotons or positrons emanating from regions of high dark matter density. The detection of such a signal is not conclusive evidence for dark matter, as the production of gamma rays from other sources is not fully understood.[8][13]

The EGRET gamma ray telescope observed more gamma rays than expected from the Milky Way, but scientists concluded that this was most likely due to a mis-estimation of the telescope's sensitivity.[92]

The Fermi Gamma-ray Space Telescope, launched 11 June 2008, is searching for gamma rays from dark matter annihilation and decay.[93] In April 2012, an analysis [94] of previously available data from its Large Area Telescope instrument produced strong statistical evidence of a 130 GeV line in the gamma radiation coming from the center of the Milky Way. At the time, WIMP annihilation was the most probable explanation for that line.[95]

At higher energies, ground-based gamma-ray telescopes have set limits on the annihilation of dark matter in dwarf spheroidal galaxies[96] and in clusters of galaxies.[97]

The PAMELA experiment (launched 2006) has detected a larger number of positrons than expected. These extra positrons could be produced by dark matter annihilation, but may also come frompulsars. No excess of anti-protons has been observed.[98] The Alpha Magnetic Spectrometer on the International Space Station is designed to directly measure the fraction of cosmic rays which are positrons. The first results, published in April 2013, indicate an excess of high-energy cosmic rays which could potentially be due to annihilation of dark matter.[99][100][101][102][103][104]

A few of the WIMPs passing through the Sun or Earth may scatter off atoms and lose energy. This way a large population of WIMPs may accumulate at the center of these bodies, increasing the chance that two will collide and annihilate. This could produce a distinctive signal in the form of high-energy neutrinos originating from the center of the Sun or Earth.[105] It is generally considered that the detection of such a signal would be the strongest indirect proof of WIMP dark matter.[8] High-energy neutrino telescopes such as AMANDA, IceCube and ANTARES are searching for this signal.

WIMP annihilation from the Milky Way Galaxy as a whole may also be detected in the form of various annihilation products.[106] The Galactic center is a particularly good place to look because the density of dark matter may be very high there.[107]

Alternative theories[edit source | editbeta]Although dark matter is the widely accepted explanation for the various astronomical observations of galaxies and galaxy clusters, numerous alternatives have been proposed to explain these observations without the need for a large amount of undetected matter. Most of these modify the laws of gravity established by Newton and Einstein in some way.

Modified gravity laws[edit source | editbeta]The earliest modified gravity model to emerge was Mordehai Milgrom's Modified Newtonian Dynamics (MOND) in 1983, which adjusts Newton's laws to create a stronger gravitational field when gravitational acceleration levels become tiny (such as near the rim of a galaxy). It had some success explaining galactic scale features, such as rotational velocity curves of elliptical galaxies, and dwarf elliptical galaxies, but did not successfully explain galaxy cluster gravitational lensing. However, MOND was not relativistic, since it was just a straight adjustment of the older Newtonian account of gravitation, not of the newer account in Einstein's general relativity. Soon after 1983, attempts were made to bring MOND into conformity with General Relativity; this is an ongoing process, and many competing hypotheses have emerged based around the original MOND model—including TeVeS, MOG or STV gravity, and phenomenological covariant approach,[108] among others.

In 2007, John W. Moffat proposed a modified gravity hypothesis based on the Nonsymmetric Gravitational Theory (NGT) that claims to account for the behavior of colliding galaxies.[109] This model requires the presence of non-relativistic neutrinos, or other candidates for (cold) dark matter, to work.

Another proposal uses a gravitational backreaction in an emerging theoretical field that seeks to explain gravity between objects as an action, a reaction, and then a back-reaction. Simply, an object A affects an object B, and the object B then re-affects object A, and so on: creating a sort of feedback loop that strengthens gravity.[110]

Recently, another group has proposed a modification of large scale gravity in a hypothesis named "dark fluid". In this formulation, the attractive gravitational effects attributed to dark matter are instead a side-effect of dark energy. Dark fluid combines dark matter and dark energy in a single energy field that produces different effects at different scales. This treatment is a simplified approach to a previous fluid-like model called the Generalized Chaplygin gas model where the whole of spacetime is a compressible gas.[111] Dark fluid can be compared to an atmospheric system. Atmospheric pressure causes air to expand, but part of the air can collapse to form clouds. In the same way, the dark fluid might generally expand, but it also could collect around galaxies to help hold them together.[111]

Another set of proposals is based on the possibility of a double metric tensor for space-time.[112] It has been argued that time-reversed solutions in general relativity require such double metric for consistency, and that both Dark Matter and Dark Energy can be understood in terms of time-reversed solutions of general relativity.[113]

Popular culture