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Report: The search for Dark Matter—an overview.

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This report was written at the demand of His Majesty the Shah W. B. Ahabjian of Tajaboustan, who is devoting his life to scientific learning, but desires to acquire more knowledge of dark matter problem, with the possible prospect of funding research.

It assumes good general scientific knowledge but not necessarily relevant to the field.

Abstract

This report will consider major aspects of the problem commonly described as "missing mass" or "dark matter" and the range of solutions that have been brought to it.

Attempt will be made to present an overview of the matter as broad as possible, rather than a detailed description of a particular solution to the dark matter problem: we will first look at the experimental evidence for existence of dark matter, and then the different solutions and how they perform in relation to each other.

It is found that the search for MACHOs and Neutrino mass will not solve the problem, and that solutions in the form of WIMPs are needed to complete the mass count.

1 Introduction

In the 1920s, Edwin Hubble discovered that we lived in a galaxy, and that galaxies got further from each other as they were further away, as predicted by the newly founded theory of General Relativity. It was soon realised that galaxies clustered together into spatial structure (and were not randomly dispersed in space). It was soon possible to measure their relative velocities (using Redshift and spectral lines) and in the 1930s the Swiss Astrophysicist Firtz Zwicky[1] realised that the galaxies kinetic agitation was much greater than their observed masses would allow: there was an enormous invisible mass, 10 to 100 times larger than the one we could see.

Seventy years onwards, the mystery still hasn't been solved: 90 to 99% of the mass of the universe is unknown to us, and we are searching for it.

The 1930s observation was later confirmed at different length scales, from galactic rotation curves to superclustering—the largest cosmic scale. There are now at least 10 completely independent ways in which we can clearly see that a large proportion of mass in the universe is invisible; how much mass and what this mass is made of is at the heart of arguably the largest controversy of physics and astrophysics.

Possible "Cold Dark Matter" (CDM i.e. slow-moving and heavy) candidates range from large sub-stellar objects (MACHOs, cf. section 3.1) to new, heavy undiscovered particles (WIMPs, section 3.2). "Hot Dark Matter" (very light very fast particles) is another option that has been considered, with neutrinos as the chief possibility.

In the mean time some recent discoveries about supernovae[2] and direct gravitational microlensing[3] are shedding new light on the matter, arguing that some of the effects attributed to dark matter could be due to the energy of vacuum, estimating the amount of missing mass to 10 times the visible mass.

In fact as shall be shown in the conclusion, each set of experimental data restricts the value of the missing mass to a certain range, and, amazingly, at the intersections of all these an agreement is emerging between theorists and experimentalists[4].

The question of the amount of missing mass seems to be resolving quite fast, but some others remain open—the first of these being the nature of the mass in question…

2 Evidence for Dark matter

Evidence for dark matter is found from a range of sources and experiments. We will first expose the primary source of evidence qualitatively, and then compare the quantitative restrictions they put on dark matter abundance and nature in section 3.5 (Quintessence and the Cosmological constant.) It turns out that dark matter cannot be considered on its own without thinking about the different parameters that contribute to shape cosmology.

2.1. Gravitational and Direct evidence

The two broad categories below illustrate ways in which the existence of dark matter was detected. They mainly involve classical physics, and in general concentrate on detecting dark matter though its gravitational or thermodynamic impact.

2.1.1. Galactic Rotation Curves

Perhaps the most compelling piece of evidence for dark matter is the rotation curves of spiral galaxies. If one looks at the radial velocity of objects relative to the centre of the galaxy, one realises that their orbital velocities do not decrease with distance as predicted by their visible mass. Newtonian Dynamics predicts that objects further from the centre, where mass is lighter, should rotate much slower than in the bulge[5].

The rotation velocities are measured by looking at Doppler shifts of absorption and emission lines and so they are a direct measurement since we know accurately the values of the elements' spectra. The quantity of visible matter is itself measured simply by looking how much light is emitted, and this is also a measurement since we know the mass/light ratio of stars quite accurately at least accurately enough not to be off by a factor of 10!

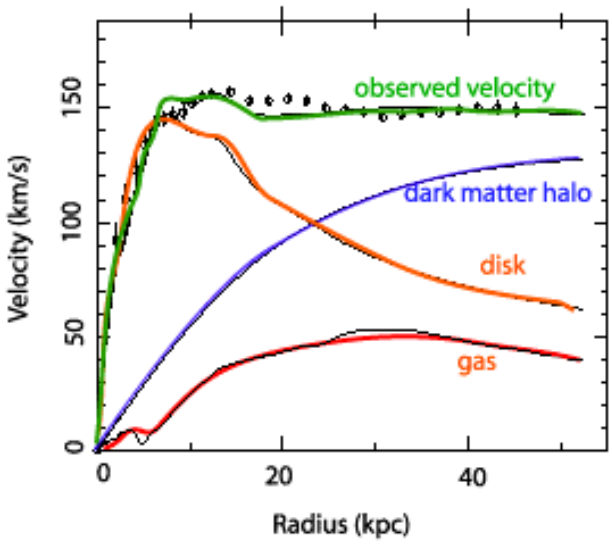


Image showing the observed rotational velocity of the galaxy NGC3198, and the components of the galaxy with their respective velocities, including a dark matter halo (in blue). (adapted from http://nedwww.ipac.caltech.edu/level5/Bosma/Figures/figure1a.gif)

Galactic rotation curves also give us a clue as to what makes up the dark matter by looking at how the different parts of the galaxy rotate. The key concept here is transfer of angular momentum from the disk to the halo, and some simulations[6] show that the halo of a galaxy has to have some "lumps" or discontinuities to spin faster, which favours a cold dark matter (CDM) hypothesis. However this is still an unsolved issue.

This is the first and most direct evidence for dark matter, i.e. in the halo of spiral galaxies. It is measured at "close" distances on the astronomical scale, so we know we are dealing with a case not too different from that of our galaxy—the physics we know has to apply there.

2.1.2. Evidence from clusters

Going further away from galaxies, we look at galactic clusters, and Superclusters (which are effectively clusters of clusters.)

Clusters are one of the largest sources of information about dark matter, and were indeed the reason why its existence was first conjectured from observation of the Coma and Virgo clusters in the 1930s.

They are one scale up from galaxies, and allow us to verify the existence of dark matter on a scale larger than that of galaxies[7].

It is interesting to note that from the early 1990s and until recently, the amount of missing mass in clusters was believed to be 10 times that of matter missing in galactic haloes, because of the newly-retrieved large-scale maps of the universe[8]. However, the recent supernovae and light paths measurements are bringing the values down to 90% dark matter, agreeing with galactic DM.

The arguments below are borrowed form N. A. Bahcall (2000 cf. reference 4.), and echoes in ref. 7.

"Cluster masses can be directly and reliably determined using three independent methods: i.) the motion (velocity dispersion) of galaxies within clusters reflect the dynamical cluster mass [...] ii.) the temperature of the hot intracluster gas, like the galaxy motion, traces the cluster mass iii.) gravitational lensing distortions of the background galaxies can be used to directly measure the intervening cluster masses [...].

All three independent methods yield consistent cluster masses [...][9]."

Note that argument ii.) above assumes thermodynamic equilibrium, for which we can balance the energy input to a gas (radiation, gravitational potential energy) with the energy output.

Additionally, it is found that the mass is very well correlated with the light from galaxies, within clusters, i.e. there does not seem to be dark matter where there is no visible (or baryonic) matter. Of course, this is a difficult statement to test since the nature of dark matter is such that it cannot be detected…

But if this is true this means that we can estimate the amount of dark matter solely from the cluster dynamics, and other phenomena, and that dark matter is bound to baryonic matter gravitationally. This is an important statement because it was thought that the amount of dark matter increases with distance from visible matter.

2.2. "Cosmological" evidence

The experiments below have detected evidence for dark matter through its relativistic effects (light-bending, space-deformation.) They are both quite recent, and there is still possibility that their results are affected by systematic errors. However, since they are in remarkable agreement with each other and earlier evidence, their contribution to the field is very precious.

2.2.1. High-Redshift Type 1a Supernovae

Type 1a Supernovae are believed to be "standard candles". That is, their explosion is believed to always generate the same amount of light and power, to within 15%. But they also are some of the brightest identifiable events: for a few days, the light of a supernova is as bright as all the other stars in its galaxy.

The shape of a light curve of a supernova can therefore tell us precious information about its distance and the space between the supernova and us.

Two independent studies of high-redshift supernovae[10] have shown that the apparent luminosities of supernovae in the past (i.e. at high redshift) is on average ~20% lower than expected in a critical density universe (more on this in section 3.4.) This implies that a universe with 99% dark matter is ruled out at 7σ confidence level—the most probable is a universe with 90% dark matter (as in galactic haloes.)

However, one has to stress again that these results are too recent to be guaranteed free of systematic error, and that it relies on the assumption that supernovae were the same in the past as they are now.

Another study of supernova bursts is also attempting to show that the shape of the light curve, as it arrives to us, can tell us whether the light has passed though dark matter in the form of sub-stellar objects or massive particles[11] (i.e. in microscopic or macroscopic form). The light curve having passed though macroscopic matter will be more concentrated towards its peak brightness, whereas that coming through particles will be broadened to a wider range of brightness. The models are still unfinished and need more observed supernovae, but this line of thought can be expected to yield fruits with the advent of the large optical telescopes in the next few years.

2.2.2. Weak Gravitational Lensing distortions

This experiment uses the fact that light paths are distorted by gravity[12]. By measuring the ellipticity of a few hundred thousand distant galaxies and their variation from the average, the group has deduced the distorting mass between the viewer and the galaxies (using general relativity). This was done along three different lines of sight and at multiple wavelengths, using sophisticated software analysis to eliminate errors due to observing particularities.

The result found does not give directly the amount of visible vs. total mass, but give the total mass instead. Form that it is possible to infer the visible/invisible ratio from observation and the findings are consistent with a ~1:10 ratio, as above.

3 Possible solutions to the problem

3.1. Modified Newtonian Dynamics (no dark matter)

The *MOND* theory[13] postulates that there is no dark matter, but that Newtonian gravity is wrong. The laws of gravity are modified beyond a certain distance, which would mean that gravitational interactions between very distant objects are not ruled by the same laws, whence we could not conclude for a missing mass. But the theory does not seem to hold for the scales at which the effects of dark matter are felt, nor does it explain the gravitational lensing phenomena.

3.2. Hot Dark Matter (Neutrinos)

There has been great hope that the all-pervading neutrinos would come as a solution to the dark matter problem. Neutrinos are emitted in many nuclear reactions, and were believed for a long time not to have a mass. Their interaction with matter is minimal and their speeds are very close to the speed of light—the big bang should have produced an enormous quantity of them, which makes them omnipresent in the universe.

3.2.1. Determination of Neutrino Mass

In the late 1990s, several large experiments were ready to measure the neutrino mass: at last a mass upper-limit was found, and first confirmed by the Super-Kamiokande experiment. The task was further complicated by the fact that neutrinos have mass by oscillating between the three different "flavours" that they can take.

But neutrino mass turns out to be very small, whatever its complications: it could definitely not fill up the conservative 90% missing mass estimate.

3.2.2. Consequences of Light Neutrino Mass

The picture gets more confusing as some rule out the possibility of neutrinos affecting cosmology in a significant way[14] while others[15] still have arguments in favour of simulations of universe involving Hot Dark Matter (neutrinos), which fits some observations better. However, it seems unlikely that neutrinos can become the major constituent of dark matter, as most simulations show that too much hot dark matter would not allow for the small-scale clumping that we observe in the universe (such as galaxies etc.) because HDM moves too fast, and has too small a mass.

If neutrinos have to play a role, it will be marginal and only one of improving an already-existing cold dark matter model (CDM, see 3.5 below.)

3.3. The Search for MAssive Compact Halo Objects (MACHOs)

Dark matter might be "simply" caused by planet-like objects that do not emit light, located in the halo of galaxies.

The MACHO and EROS experiments were set up to detect such objects[16,17] through the gravitational lensing that they provoke: a dark object passing in front of a background light (star) will make the star look brighter, because it bends the space between the observer and the star—the relativistic effect known as gravitational lensing.

Over ten years, the results of both groups together, after having monitored about 30 million stars, amount to no more than twenty occurrences of microlensing. The largest difficulty was to separate the occurrences from intrinsically variable stars, which are 1000 times more frequent than microlensing occurrences.

The duration of a microlensing event is proportional to root of the mass of the lensing object, and since no lensing occurrence of less than 15 days was observed, it can be concluded that no more than 10% of the galactic halo can be made up of brown dwarfs, and no more than 20% can be made out of objects in the range of 10^{-7}-0.02 M_M (M_M is the solar mass.)

Instead, it was noted that the average duration of events was 40 days, which gives objects a 0.5 M_M average mass. But a brown dwarf has maximum mass 0.09 M_M, and the only objects in this mass range are white dwarfs, which are stellar remnants. It is observed that if white dwarfs were to be present in the halo in

large quantities, we should be able to see more of them in galaxies at high redshift, and there should be a substantial enrichment in heavier elements resulting from their nuclear burning phase in the interstellar gas[18].

The nature of these objects is not completely settled, and the results of the MACHO search projects are sure to have some very interesting consequences but it is sure that they cannot make up more than a small portion of the observed missing mass.

3.4. The Search for Weakly Interacting Massive Particles (WIMPs)

Since a few years the most favoured candidates to account for the missing mass are undoubtedly the elusive WIMPs. None has been detected as yet, and they do not really hold a place in all declinations of the standard particle physics model, but the slow and weakly interacting particles fit best the profile that is wanted of dark matter. Cosmological simulations have shown for a few years now that the structure of the universe (clustering etc.) has to have been formed by some cold dark matter as well as hot dark matter.

3.4.1. Which heavy particle?

The range of exotic particles investigated is enormous, from Wimpzillas to Neutralinos and Q-balls, but there are some clear favourites in the race: some particles are predicted by Supersymmetry[19], an addition to the standard model where all the forces (particles) of nature are symmetric, and have a "sparticle" with an extra ½ spin —photons would be coupled to "photinos", gluons to "gluinos" and neutrinos to…neutralinos. The neutralinos would be as elusive as the neutrinos but extremely massive (forty to one thousand times the weight of a proton) and would therefore constitute an ideal dark matter particle.

Axions are a completely different type of particle, which also acts as cold matter. The axions were invented in particle theory to prevent violation of the symmetry of charge parity in the strong interaction. Their mass is not known, but pilot experiments have produced limits of 30 times their predicted density. Axions should be present in large numbers in the galactic halo, as they would have been produced in large numbers in the early universe.

3.4.2. WIMP detection experiments

There are three large experiments underway to detect WIMPs directly (DAMA, CDMS, EDELWEISS), and a controversy is already underway. If they exist, neutralinos should have the same velocity spread as stars in the galaxy, with a mean Maxwell velocity of ~250km/s in the direction of the solar system's around the galaxy's core. This implies that as the earth moves around the sun, we should observe a difference in detection between summer, when earth moves with the sun, and winter, when the earth moves in the opposite direction.

In all these experiments detectors are buried underground and extremely carefully shielded from radiation and electrostatics, so as to detect only the neutralinos. The Dama collaboration has detected a modulation in 1997, and confirmed it in 2000 after having collected ~100,000 events in its Sodium-Iodide detector. In the same time, the Stanford CMDS group has not detected any such modulation, and argues that it would have done so with its geranium-detector setup. The French EDELWEISS group started later and should be getting its first results by the end of this year, while the other two groups improve their setup and check their calculations.

The search for WIMPs seems to be only starting, but is already leading to some interesting discoveries. The models could solve a broad range of problems, from particles physics to cosmology, but their incidence on dark matter is of the first importance.

3.5. Quintessence and the Cosmological constant

Many experiments are now designed to test several cosmological parameters at a time: their results give us areas in parameter-space that are ruled out or more probable. This is because one way of looking at dark matter is only as a parameter to wider cosmological puzzle, such as why all the values of Ω seem to be close to 1.

Note that Ω is defined as the ratio of the density of the universe to the critical density.

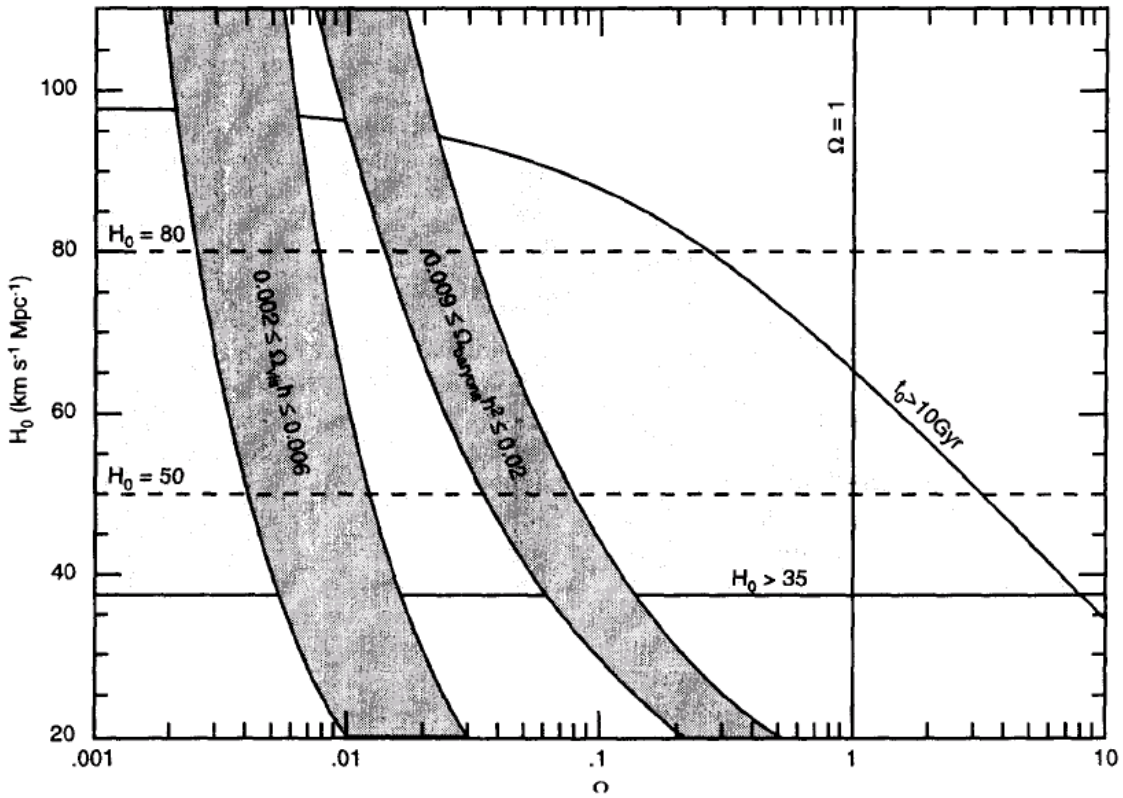
The critical density is that at which the universe is flat, and expands forever at ever-slowing rate. If Ω is larger than 1, then the universe will experience a big crunch at the end of time, whereas if it is smaller than 1,

it will go on expanding forever. The case where Ω=1 is that of a universe which expands forever, slowing down forever.

The Supernovae experiments, analysis of cluster density and the microlensing experiments all point to a flat, open-ended universe, with $\Omega_{total} = \Omega_{matter} + \Omega_{vacuum}$.

Ω_{vacuum} is introduced because Ω_{matter} is believed to be ~0.25, but we can see from geometry and the COBE and BOOMERANG results, as well as from inflation and big bang theory that Ω_{total} =1, or very close to 1. This energy of vacuum (Λ) is newly re-introduced (after Einstein included it in his equations, and later rejected it) and unexplained by physics, and thus its introduction seems arbitrary—but it seems to fit very well with gravitational N-body simulations, and gives rise to the so-called ΛCDM model.

The direct relevance of this to dark matter is that it reduces the amount of dark matter in clusters from 99% to 90%, and so there is considerable agreement between the different experiments.



The above figure summarises the "allowed ranges" for visible and baryonic matter, from cosmology, inflation and big-bang theory.

The accepted value from Hubble's constant H_0 is 65 km s^{-1} Mpc^{-1}, and t_0 is the age of the universe, with a lower limit of 10 billion years, which is the age of the oldest known objects.

From the diagram it can be seen that, $\Omega_{baryons}$ lies in the range 0.009 to 0.02, and knowing a value of Ω_{matter} = ~0.25, we then get ~90% missing mass.

4 Conclusions

We have seen that from galactic rotation curves, cluster dynamics, weak gravitational lensing and distant supernovae surveys, a value for the ratio of baryonic and visible matter to dark matter is ~1:10.

The mystery of the missing 9/10 of the matter is still unknown, but it is surely not baryonic, as big-bang nucleosynthesis and the MACHO search has ruled the possibility out. Baryonic objects can account to at most another 10% of halo dark matter.

The search for neutrino mass has yielded interesting but irrelevant results, as the masses found were too small even for comparison.

The chief remaining possibility is to find some heavy, slow and weakly interacting particles, which would solve other particle physics problems—the best hopes at the moment lie in finding neutralinos (which

can be thought of as very heavy neutrinos) and axions (hypothetical light scalar-field particles.) Three major international experiments are expected to yield results in 2002.

Many new methods now rely on cosmological approaches, where the total mass of matter is estimated, and then the baryonic fraction, from big bang theory and primordial nucleosynthesis. These may seem somewhat elaborate and less direct than traditional ones, but with such a huge problem to solve one can only expect that a large embrace of the field can shed light, when the simpler ones have failed.

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