THROWING LIGHT ON DARK MATTER

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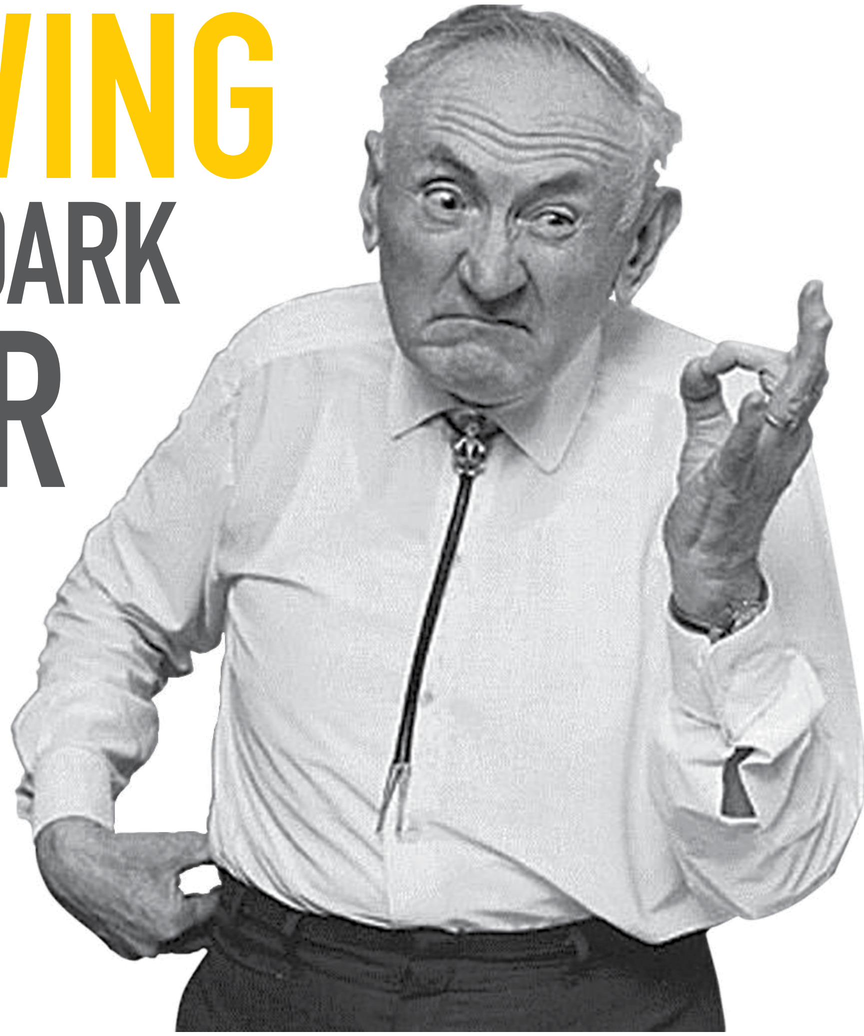

What is dark matter? How do we know it exists? Where is it found? This article explores such questions, showing how the study of the largest structures in the Universe tells us something about the smallest constituents of matter.

If we look at the universe as a whole, we see many objects that emit light. Obvious examples are stars, such as our Sun. In addition, there are enormous glowing clouds of gas and other mysterious objects, such as quasars. Collectively, these are referred to as luminous or bright matter.

However, not everything in the universe emits light. Examples include our own Earth, and indeed all the planets in the solar system. Such objects are collectively called Dark Matter. The solar system has very little dark matter – all the planets, asteroids, comets etc., put together make up only about 0.14% of its mass. Why then should we worry about dark matter, and why should it be a subject of study? The reason is that the solar system is very small when seen on the scale of the universe as a whole; there is a lot of dark matter of other kinds 'out there'.

Detecting dark matter

Before we widen our discussion, let's take a look at how dark matter can be detected. While planets as distant as Saturn are visible to the naked eye by the sunlight that they reflect, this method is unlikely to work for more distant objects.

One way to find more dark matter is illustrated by the discovery of Neptune in the 19th century. Irregularities in the orbit of Uranus indicated an unexplained gravitational pull on the planet – perhaps by another, as yet undiscovered, planet. Neptune was discovered, telescopically in 1846, close to this predicted position. In other words, even when an object emits no light, its presence can be inferred from its gravitational effects. Since gravitation is universal, other kinds of dark matter, on different distance scales, are

Fig. 1. A recent image of the Andromeda Galaxy.
Source: Adam Evans, Wikimedia Commons. License: CC-BY. URL: https://en.wikipedia.org/wiki/File:Andromeda_Galaxy_(with_h-alpha).jpg.

also likely to make their presence felt through their gravitational effects.

Another piece of evidence for the existence of dark matter comes from spiral galaxies. Our Milky Way is an example of a spiral galaxy. So is the Andromeda galaxy, also known as M31, whose spiral arms are beautifully visible in Figure 1. As we can see, the galaxy appears to be flat, with the stars distributed close to the central plane, forming a bulge in the centre. This is how most spiral galaxies look.

Now comes the interesting part. The stars in a galaxy exert gravitational forces on one another, while they rotate about the centre of the galaxy. Newton's law of gravitation allows us to calculate how the rotation speed of a star depends on its distance from the centre. A simple calculation shows that the rotation speed should decrease with the distance from the centre (think of our solar system: the innermost planet Mercury whizzes around the Sun at 47.87 km a second while Neptune moves at a sedate 5.43 km/s). Thus, we can actually measure how fast the stars are rotating in nearby galaxies, such as M31. In M31, and hundreds of other similar galaxies, however, something quite different is observed. As we move out towards the edge of the galaxy, the speed of the stars remains constant rather than decreasing.

There are two main ways to account for this discrepancy. The first is to say that Newton's Law of Gravitation does not hold at galactic scales. While some scientists believe that the solution to the problem lies in this direction, we will not be discussing this any further in this article. The second way is to assume that Newton's Law holds, but that the mass in a galaxy is distributed in a much more uniform manner than it seems to be. Moreover, the mass of the galaxy appears to be much more than the total mass of the stars in it. In other words, the galaxy is full of dark matter. A picturesque way to put it is to say that, apart from the visible disk, the galaxy has a halo, which, unlike the disk, is not flat but more or less spherical.

You may wonder if this holds for non-spiral galaxies. Measurements of the speeds of stars in the other important type of galaxies – elliptical galaxies – leads to the same conclusion: most galaxies are full of dark matter.

Box 1. What is a black hole?
A black hole is a place in space where the pull of gravity is so strong that even light cannot get out. This pull of gravity is because matter has been squeezed into a tiny space. This can happen when a star is dying. And it is because no light can get out that people can't see black holes – they are invisible!

Estimates for our own galaxy, the Milky Way, indicate that over 80% – perhaps even as much as 95% – of its total mass is in the form of a dark matter halo.

Dark matter in galactic halos

What is the precise nature of the dark matter in galactic halos? This is still an open question. One possibility is that the halo is made of planet-like objects, or stars that are still in the process of formation. Black holes are another possibility.

Such massive astrophysical compact halo objects or MACHOs (scientists like to make up such acronyms) have one common feature: they are made up of 'ordinary' matter. As we know, ordinary

Box 2. Supersymmetry: In the 1970s, some theorists suggested that Nature may possess a new symmetry, called supersymmetry, which connects existing elementary particles to other, as yet undiscovered, ones. For example, the electron, which has spin half, would have a superpartner with spin zero. All the superpartners would have to be very heavy, since they haven't shown up in particle collisions so far. If we extend the standard model to include supersymmetry, we get models with many undiscovered massive particles, including WIMPs.

matter consists basically of protons, neutrons and electrons, with the last being much lighter than the others. Protons and neutrons belong to a type of elementary particles called baryons (from Greek *barys*, meaning heavy), so ordinary matter is called baryonic matter. Now if the proposed MACHOs are planet-like objects made of baryonic matter, they will reflect the starlight falling on them. Since our galaxy is presumably full of MACHOs, they should show up in our telescopes. Searches specifically designed to look for them have failed to find any. There are other arguments too, which together, lead to the conclusion that MACHOs, if they exist at all, contribute only a small amount of mass to our galaxy.

We are led to the inescapable conclusion that galactic dark matter, unlike the dark matter in our solar system, is composed of something exotic. A favoured category of candidates is weakly interacting massive particles, or WIMPs (acronym-coining again!). Many times heavier than protons and neutrons, WIMPs interact through weak nuclear forces and gravitation. The Standard Model of particle physics, which has enjoyed great success starting with the discovery of W bosons in 1983 to that of the Higgs boson in 2012, simply does not have place for such particles. Thus, if galactic halos are largely made up WIMPs, particle physics has to go beyond the standard model. What makes this field of study so exciting is the interplay between the very large and the very small: galactic halos that are typically hundreds of thousands of light years in size suggesting that we need to rethink laws of physics at scales smaller than the radius of a proton! Interestingly, theorists have, for completely different reasons, also been suggesting that we need to go beyond the standard model. A popular idea, in this context, has been that of supersymmetry, and supersymmetric models indeed naturally lead to WIMPs.

Dark matter in galaxy clusters

While galaxies are very big, they are not the largest structures in the universe. Most galaxies lie in clusters consisting of 100–1000 galaxies, held together by their mutual gravitational attraction. The distance scales are mind-boggling: a typical cluster size is 10–20 million light years. Figure 2 shows the Coma Cluster, whose centre is about 320 million light years away. Note that each star-like object in the picture is actually a galaxy, typically consisting of a billion stars or more.

Now when a system of objects interacting through gravitation has been around for a long time, we expect the average energy of motion of its members to be roughly the same as the energy of interaction. In fact, it can be shown that the average kinetic energy is one-half of the magnitude of the average potential energy. But we see something quite different: the galaxies in most clusters appear to be moving much faster than expected. By now you must have guessed the explanation: there are invisible sources of gravitational attraction distributed through the cluster – in short, dark matter. In fact, the term Dark Matter was first used by the Swiss astronomer Fritz Zwicky, way back in 1933, in connection with his studies of the Coma cluster, whose modern image we saw in Figure 2. Zwicky concluded that the mass of this cluster was 400 times

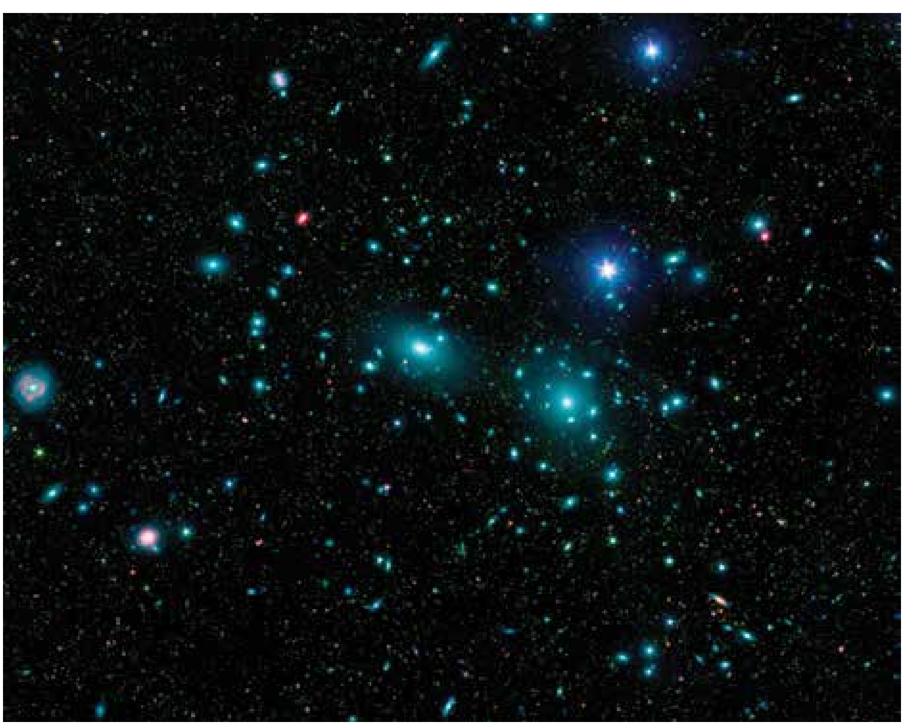

Fig. 2. A composite image of the Coma Cluster.

Source: NASA / JPL-Caltech / L. Jenkins (GSFC), Wikimedia Commons. License: Public Domain. URL: https://commons.wikimedia.org/wiki/File:Ssc2007-10a1.jpg.

the sum of the masses of its galaxies, indicating that the cluster was made mostly of dark matter. The modern estimate is somewhat lower, but 90% of the total mass of clusters such as these is typically believed to be contributed by dark matter.

To conclude

Clearly, since dark matter is spread out over such immense scales in the universe, it seems likely that it plays an important role in our understanding of the universe as a whole – its structure as well as its evolution. And it does – with a majority of cosmologists now believing that dark matter has played a crucial role in the origin of complex structures in the universe. The microwave background radiation that permeates the whole universe shows tiny wiggles. These, as well as the formation and evolution of galaxies and their clusters, is consistent with the model that dark matter makes up about 85% by mass of the total matter in the universe.

According to the latest data available from the Planck satellite, whose mission was to study the wiggles in the microwave background radiation, the energy content of the universe is as follows: baryonic matter 4.9%, dark matter 26.8%, and dark energy 68.3%. The last quantity may come as a surprise, since we have not spoken about it so far. However, since media reports often talk of dark matter and dark energy, it is important to note that the two are quite distinct.

In summary, dark matter of various kinds is found at various distance scales in the universe. Our Earth, and we ourselves, are part of the dark matter story. However, planets etc. are composed of baryonic matter, while most of the dark matter 'out there' is non-baryonic. Its precise nature is a subject of current study, and connects our understanding of the very large – cosmology – to that of the very small – particle physics. This is something no one would have imagined a hundred years ago. We are lucky to be living in exciting times!

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