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The quest for Dark Matter

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Abstract. This paper briefly presents the dark matter problem and the many ongoing attempts to solve it. After a brief introduction to the history of dark matter, the paper reviews the relevance of this mysterious component of the Universe in modern cosmology and it discusses the implications of the absence of evidence for dark matter in all experiments carried out in the past four decades. It then argues that a new era has started in the search for dark matter with much astronomical data about to become available and a new generation of gravitational wave experiments about to start operations. Finally, it stresses that the field of dark matter searches is completely open and that there are exciting opportunities for the next generation of scientists to develop new ideas and to make ground-breaking discoveries.

1. Brief history of the Dark Matter problem

The Dark Matter problem has a long history and the precise meaning of the phrase *Dark Matter* has changed throughout the history of science. In general it is used today to denote a form of matter that we cannot see with our telescopes, but whose existence can be inferred from the gravitational influence it exerts on observable astronomical systems. One of the pioneering scientists in this field, Lord Kelvin presented in 1904 an attempt to apply the kinetic theory of gases to stars in the galaxy. He calculated the velocity dispersion that stars would have in the gravitational field provided by all observable matter and compared it to measured stellar velocities, arguing that many stars in our galaxy could be *"dark"*. This was not conceptually unexpected, as after all many stars could have been too dim to observe and many others might have been already dead. Henri Poincaré, two years later, referred to the work of Lord Kelvin and explicitly used the term *Dark Matter* (first in French, *Matière Noire*, rather than in English). He wrote, *"Since the total number of stars is comparable to that which the telescope gives, then there is no Dark Matter, or at least not so much as there is of shining matter."* (see [1] for further details).

2. The composition of the Universe

Everything we see around us from the very small scale of molecules and atoms to the very large scale of stars, galaxies and larger structures mostly consists of the same fundamental constituents: quarks and electrons. The quarks are locked inside protons and neutrons within the atomic nuclei, while electron clouds surround nuclei. With these two building blocks, we can explain nearly all the forms of matter we see in the Universe.

Is there anything else in the Universe? A wide array of observations from rotation curves of galaxies to velocity dispersion of galaxy clusters and from gravitational lensing to the cosmic microwave background clearly indicate that there must be more matter in the Universe than accounted for by ordinary 'baryonic' matter made of atoms. Ordinary matter contributes approximately 5% of the total mass-energy budget of the Universe, while 26% is in the form of an unknown form of matter called *Dark Matter*. On top of that there is evidence that the expansion rate of the Universe is increasing with time, possibly pushed by a form of energy often referred to as *Dark Energy*. Discovering the fundamental nature of dark matter and dark energy is one of the biggest challenges of fundamental science today.

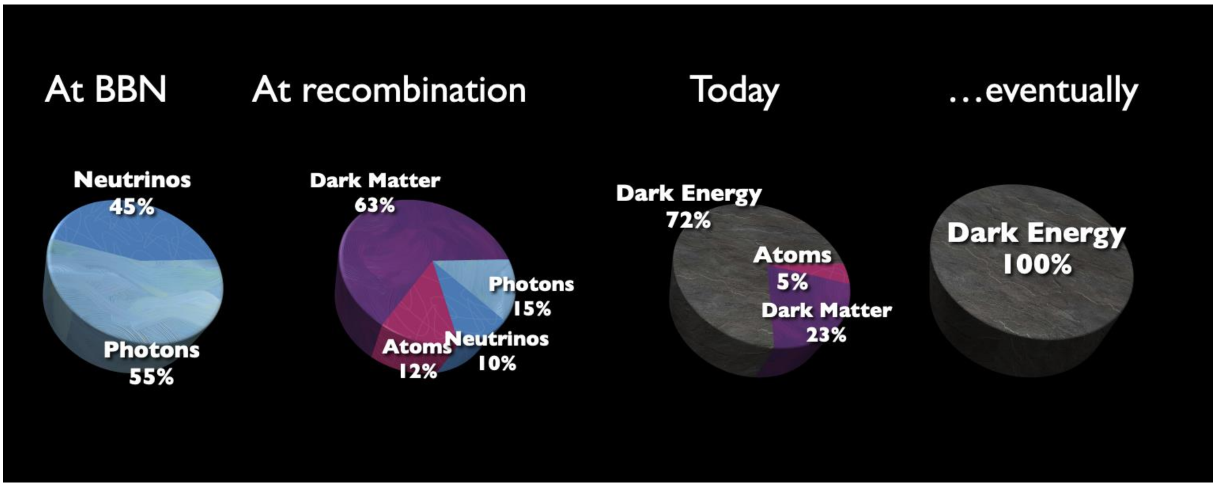

Figure 1. Matter-Energy budget of the Universe in different cosmic epochs: at Big Bang Nucleosynthesis (3 minutes after the Big Bang), at recombination (when the cosmic microwave background radiation was released), today and in a distant future.

But the current composition of the Universe is not a fundamental aspect of nature. Earlier in the history of the Universe the relative contribution of atoms, Dark Matter and Dark Energy was different – in particular the Dark Energy contribution was much less (see figure 1).

If one wants to understand how structures (planets, stars etc.) formed, one must understand the composition of the Universe in a distant past when these formation processes took place. Fortunately, we can still observe some of the light from the Big Bang, the so-called Cosmic Microwave Background and use this to gain insights into how the Universe has evolved. Structures started to form on cosmological scales relatively early, roughly a few hundred thousand years after the Big Bang, and have grown to the size observed today. However, the composition of the Universe when they started to grow was very different; about 12% of matter and energy was in the form of atoms, 15% was photons and 10% was neutrinos. These are well-understood particles in physics. Of more interest is that dark matter comprised more than half of the matter and energy of the early Universe, while dark energy was essentially irrelevant. This indicates that dark matter is a crucial ingredient to form structures in the Universe. Additionally, it can be seen that the proportion of dark matter to observable matter in the Universe has remained approximately constant throughout the evolution of the Universe. About 85% of matter is in the form of dark matter, while 15% is in the form of ordinary matter that can in principle be observed. The key research question is to understand what comprises the 85% of matter and how it can be fundamentally different to ordinary matter.

3. Dark Matter and evolution of the Universe

How do we know that dark matter exists? As mentioned, many observations of the Universe seem to point towards this direction. In fact, regardless what kind of astronomical system is observed beyond the scale of the Solar System or what analysis is performed, the data indicate the existence of an unobserved matter, about five times more abundant than ordinary matter. One very direct argument for dark matter arises from the fact that numerical simulations of structure formation in the early Universe, such as the so-called Illustris Simulation, are able to reproduce the observed large scale structure of the Universe only if dark matter is included in the total matter budget and only if it is included in the precise amount inferred from observations. Simulations start from very small fluctuations in the density of the Universe. As time proceeds a very complex network of dark matter structures form. Stars then form and shine, then inject heavy elements into the Universe as they die and explode. After 13.7 billion years (the current age of the Universe) modern simulations reproduce a virtual universe that looks remarkably similar to the modern Universe. Not only are the properties of the formed galaxies similar to reality, but the precise statistical properties of their distribution appear to match the observed ones. There remain some problems, but the successes of the dark matter theory suggest that modern cosmology is capturing something fundamental about the composition and evolution of the Universe.

4. What is Dark Matter?

An enormous theoretical and experimental effort has been in place since the 1980s to find the answer. Most scientists are convinced that dark matter should consist of particles that have not yet been observed. These particles are a sign of physics beyond the Standard Model. Many different types of particles have been proposed to explain dark matter, the most widely studied being light bosons, axions and sterile neutrinos (see figure 2).

Figure 2. Visualization of possible solutions to the dark matter problem (from [2]).

It is possible that dark matter is not a fundamental particle, but it is made of macroscopic dark matter solution. For example, dark matter may be made of black holes. Now black holes that form at the end of a star's life cannot explain dark matter, but primordial black holes formed in the early Universe in principle can. This idea was first discussed in the 1970s and has gained popularity in the last few years.

Another possibility is that a new form of matter is unnecessary and that the description of gravity must be updated. Perhaps Einstein's equations of general relativity must be modified to understand what dark matter is. This solution appears problematic for a long series of theoretical and observational reasons. But it cannot be discarded unless we manage to identify the nature of dark matter.

A long-time favourite class of candidates is that of Weakly Interacting Massive Particles (WIMPs). The key idea behind WIMPs is quite simple: weak scale interactions might have kept dark matter particles in equilibrium with all the particles of the Standard Model in the early Universe via self-annihilations, turning pairs of WIMPs into Standard Model particles and vice versa. It was realised in the 1970s and 1980s that if the rate of annihilation was at the so-called weak scale in particle physics, then WIMPs would naturally explain the observed abundance of dark matter. This circumstance attracted an enormous interest, as particle physicists were at around the same time investigating many theories around the weak scale for completely different reasons linked to fundamental questions in theoretical particle physics. The connection between the two fields of physics was striking and a large fraction of the astroparticle physics community has since tried and is continuing to try to detect WIMPs.

5. Detecting Dark Matter

There are at least three methods of detecting WIMPs. The first is to search for the particles using colliders such as the Large Hadron Collider at CERN. Another method is indirect detection, which searches for the products of the decay or annihilation of dark matter rather than looking for the dark matter itself. Finally, there is direct detection and this involves experiments that aim to detect the dark matter particles as they travel through the detector.

5.1. Indirect detection

As mentioned earlier, WIMPs should annihilate into particles of the Standard Model. The rate at which these secondary particles are produced is extremely sensitive to the density of dark matter. Therefore, indirect searches focus on regions of very dense dark matter and try to detect the produced Standard Model particles. In particular, photon emissions from dark matter annihilation should predominantly come from the centre of the Milky Way Galaxy and from the centre of dwarf galaxies in the Milky Way halo. The absence of evidence for these dark matter-produced photons in the data of the Fermi Satellite imposes very stringent constraints on the possibility that dark matter is in the form of particles that self-annihilate.

5.2. Direct detection

Direct detection is also based on a relatively simple concept. Dark matter particles, whatever they are, are predicted to travel nearly undisturbed through the Earth: a wind of dark matter particles should go through it as we move together with the rest of the Solar System around the Galaxy. One can then build a detector and wait for the rare events in which dark matter particles hit one of the detector's nuclei. This collision is an extraordinarily rare event, but detectors have become incredibly sensitive. An example of direct detection is the XENONnT: a large tank (a few cubic metres) filled with xenon liquid and a layer of gaseous xenon above the liquid. WIMPs could in principle enter the detector, collide with a xenon atom and ionise some of the atom's electrons, producing a flash of light. Se electrons would then drift to the top of the tank and produce again flashes of light as they travel through the gas, making the passage of the WIMP both detectable and discernible from other particles. Many direct detection experiments are scattered in underground laboratories around the world. Their sensitivity has increased enormously over the past thirty years. However, there is still no trace of dark matter particles from these experiments.

5.3. Detection with colliders

The Large Hadron Collider is a ring of 27 km in circumference at CERN, in which protons are accelerated and collided. A series of pre-accelerators progressively increase the energy of the protons before injecting them into the main ring in 'bunches' travelling in opposite directions. Protons are then made to collide inside large detectors that measure the type, direction and energy of all the particles generated in the collisions. The total energy of the collision can be reconstructed from the fragments measured by the detector and the existence of new particles can be inferred by an imbalance of the reconstructed energy.

6. The future of our search

Despite much effort all dark mark searches have so far come empty-handed. For each dark matter candidate, there is currently a discussion in the scientific community on whether to continue the search, for how long to continue and whether we should move on to something else. The good news is that new theoretical and experimental ideas might help to solve the mystery of dark matter. Astronomical data are becoming extraordinarily precise, especially thanks to the Gaia Satellite launched by the European Space Agency, which is creating a new map of the 1.7 billion stars in our Galaxy. The other technique is that of gravitational waves. In 2016 the sensational discovery was announced of the direct detection of gravitational waves produced by the collision of two black holes. An intriguing possibility is that black holes may have clouds of dark matter *surrounding* them. In this case, dark matter may modify the dynamics of the black holes and thus modify the gravitational waves signal. Hence, one might effectively use these gravitational wave detectors in the future as dark matter detectors.

7. Conclusion

In conclusion this is a time of profound transformation in the search for dark matter. While there is a lack of evidence for many of the popular dark matter candidates, it is important to remember that “absence of evidence” is not “evidence of absence”. The Large Hadron Collider and various astroparticle experiments might still produce some surprises, especially as they increase their sensitivity. At the same time, we must diversify our search, for example, by exploiting precise astronomical measurements and gravitational waves. The most important message is that this field is completely open and there are always opportunities for the next generation to develop new ideas and to make incredible discoveries.

References

[1] Bertone G and Hooper D 2018 *Rev. Mod. Phys.* **90** 45002
[2] Bertone G and Tait T 2018 *Nature* **562** 51–6