Dark matter matters

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If there's one thing that physicists are consistently bad at, it is naming things. Dark Matter does not refer to material that carries the dark side of the force throughout the galaxy, and it isn't dark so much as invisible. It is, however, metaphorically dark in that its identity is a complete mystery despite the immense amount of evidence suggesting it exists. This essay is not an explanation of a scientific principle, but an explanation of why a new scientific principle is needed.

During the 20th century, several different astronomical observations were found to strongly disagree with predictions from some theories that we know and love; those of Newton and Einstein. Rather than revolting against the vast swathes of evidence that $F = ma$ and that General Relativity holds, explanations for these observations were sought through the addition of some new kind of matter populating the universe. This so-called dark matter needs to have mass and experience gravity in order to affect the structure and behaviour of the universe in such a way as to explain the observed disagreements. It also needs to be largely invisible to ordinary matter in order to explain why it has not been seen by direct methods such as observation through a telescope.

To account for the observed disagreements fully, dark matter also needs to be incredibly abundant. Considering the total mass and energy within the universe in the standard model of cosmology, dark matter should make up about 27%. By comparison, ordinary matter from which everything from stars to essay writers is made, makes up only 5%. The remaining 68% comprises an equally puzzling mystery form of energy. This is, highly imaginatively, called dark energy. It is not expected that dark energy and dark matter are particularly related to each other, apart from both being fascinating mysteries facing scientists today. Thus, we shall not discuss dark energy further.

1 The evidence for dark matter

There are many different observations of the universe's structure which strongly disagree with predictions from our current theory of gravity. These span different scales from the galactic to the cosmic, as well as representing a wealth of different kinds of impressive astronomical measurement.

The first suggestion of a problem in the universe's structure came from the Coma Cluster, beautifully imaged by the Sloan Digital Sky Survey and the Spitzer Space Telescope in Figure 1. The Coma Cluster is a group of over one thousand galaxies which are gravitationally bound to each other, situated over three hundred million light years away from earth. When Fritz Zwicky studied this cluster in 1933 [1], he concluded that there must be some 'missing mass' in the cluster. The galaxies and dust made from ordinary matter only provided 1% of the mass required for the Cluster's gravitational field to be strong enough to hold itself together. The ordinary matter is all observable through telescopes which measure the electromagnetic radiation it emits, such as visible light, radio-waves or infared heat. Since this 'missing mass' wasn't observed, it must not interact with electromagnetic radiation like ordinary matter. A proposed explanation for this 'missing mass' also remained missing until more unexpected observations were made in the 1970s.

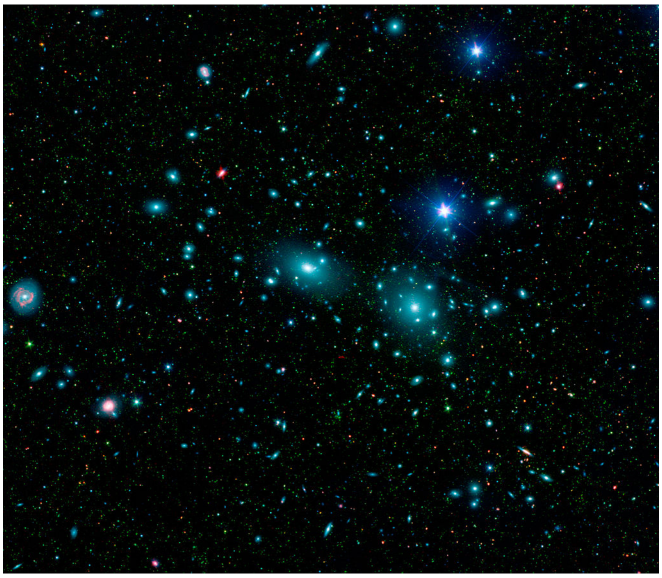

Figure 1: Infared (green and red) and visible light image of the Coma Cluster from the Sloan Digital Sky Survey. [2].

When crowds of stars and dust become held together in galaxies they rotate about their centre. As you move further away from the galactic centre, the gravitational force becomes weaker. If energy is conserved (it is) and Newton and Kepler know what they're talking about (they do), then at greater distances from the galactic centre objects move more slowly in their galactic orbits. However, in the 1970s Vera Rubin observed that in fact the stars further away from the galactic centres of spiral galaxies do not move more slowly [3]. In the equation governing the rotation speed of the 'stuff' at a given radius, the only variable we can change is the mass of the stuff.

The simplest explanation for the lack of change of speed is that there is more mass at the outer rims of galaxies than can be observed through any ordinary means, and thus that there is more 'stuff'. After this phenomenon was measured with a high precision in many galaxies, and more galactic clusters were observed to have an apparent lack of mass, dark matter was widely concluded to be a major problem in physics.

On a larger scale, one example of evidence for dark matter can be found in the Cosmic Microwave Background (CMB). This electromagnetic radiation is a remnant from just after the big bang, and to this day permeates space. Its properties contain plentiful information about the structure of the early universe. The CMB was measured with incredible precision by the Planck cosmology probe in 2013 [4]. Whilst it is largely a uniform black-body spectrum, the CMB contains small perturbations and irregularities caused by the interaction of the radiation with early universe structures. These irregularities can be predicted given a specific model of early universe structure. As you may have guessed, these irregularities do not agree with what is expected considering structure formed solely from ordinary matter. Furthermore, the resulting universe structure one would see today from a given model itself also disagrees. Once again, it is favourable to have an extra source of mass affecting the gravitational pull of objects right back to the big bang.

A final piece of evidence for dark matter is the bullet cluster. Casting your eyes to Figure 2, you can see a beautiful image of two galactic clusters which have collided. In pink, the distribution of ordinary matter in the form of stars, galaxies and dust is shown through the X-ray spectrum obtained by the Chandra X-ray observatory in 2004 [6]. In blue, we instead see the predicted locations of mass. This is calculated using gravitational lensing data, where huge gravitational fields caused by large amounts of mass can remarkably bend light from more distant stars as it travels towards us. This is a phenomenon predicted by General Relativity, and by quantifying the amount of bending of light, the position and amount of mass causing it can be calculated.

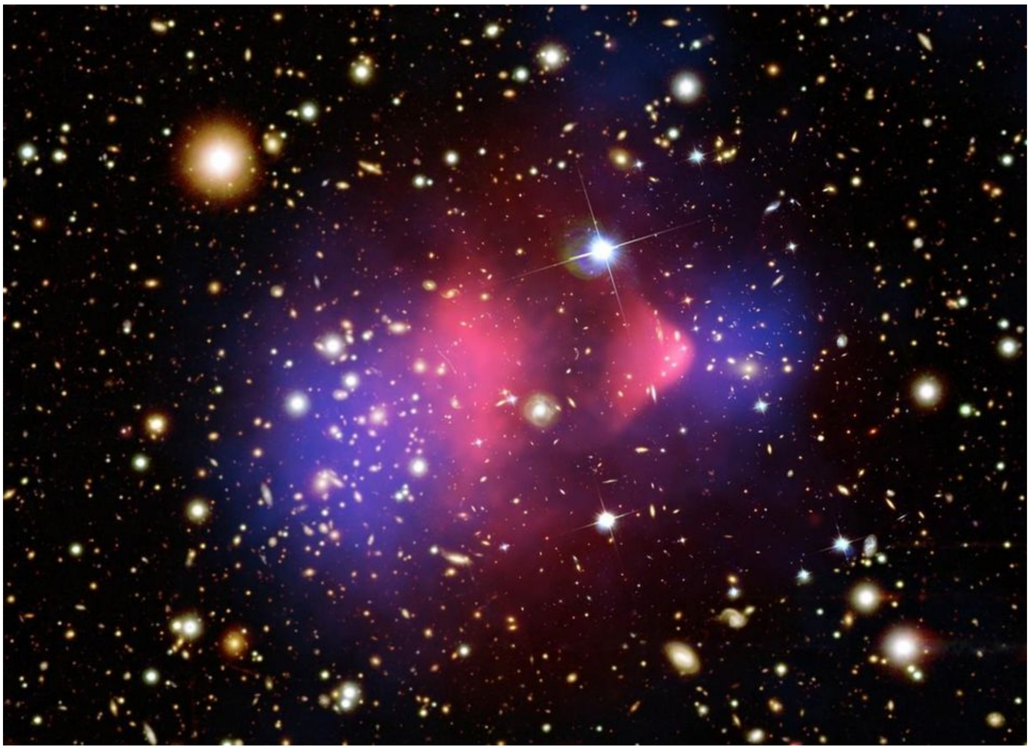

Figure 2: Image of the bullet cluster overlaying X-ray and gravitational wave data, obtained by the Chandra X-ray observatory. [5].

The distributions of mass and ordinary matter observed in the Bullet Cluster match predictions from dark matter models quite easily. On the other hand, the main alternative hypothesis to dark matter has yet to provide a model which predicts the observations. This alternative is called 'Modified Gravity' where we suppose that instead of there being invisible, heavy matter causing the change in gravitational fields, gravity itself obeys slightly different laws on a large enough scale.

Leaving astronomy, there are many experiments currently running which are trying to measure and identify dark matter. There are three different and complementary ways of doing this: firstly we can try to create dark matter. At the Large Hadron Collider, dark matter could, and hopefully will, be produced in incredibly high energy proton-proton collisions.

Secondly, we can try to directly detect dark matter interacting with ordinary matter as the earth passes through the dark matter present in the Milky Way. This interaction frequency would have an annual modulation as we orbit the sun and have a changing velocity relative to the dark matter orbiting the outer region of the Milky Way.

Finally, dark matter could be indirectly detected as it interacts with itself and annihilates to produce some ordinary detectable particle.

Since dark matter should not interact very strongly with anything we can build a detector with, all three of these tasks are incredibly challenging. Unfortunately we are yet to discover anything we can identify as dark matter, but as we search for it, we learn more about what dark matter isn't. This is very important in working out what dark matter is more likely to be, and thus how we can best look for it in the future.

2 Candidates for dark matter

There are a ridiculously large number of models suggesting what dark matter could be. The first possibility to consider is that dark matter is made of some kind of ordinary matter we already know about. The selection of candidates is the Standard Model of particle physics, which consists of all of the basic ingredients of the universe we have discovered — called particles. This includes things like electrons, photons (which are the particle equivalent of electromagnetism), and quarks (which make up protons and neutrons). But it also contains one kind particle called a neutrino, which is produced in radioactive decays in stars, and critically doesn't interact with electromagnetism, or much else, so passes our first test. Hundreds of billions of neutrinos are produced in the sun every second and fly off, passing right through us all the time. Clearly, they pass the second test of being invisible.

On the other hand, neutrino masses are also vanishingly small. This means they prefer to zoom about close to the speed of light, rather than sitting still in, for example, the blue coloured patches in the bullet cluster. It also means that they wouldn't produce enough of a gravitational field to account for the observed discrepancies.

Scientists have moved on to the second possibility, that the Standard Model of particle physics is incomplete, and dark matter is made of something entirely new. The most popular kind of dark matter candidate since the 1970s is the WIMP, or weakly-interacting massive particle. This once again imaginative name entirely sums up what WIMPs are. There are many different 'Beyond the Standard Model' theories which include a viable WIMP dark matter candidate, and many different experiments are looking to discover them. A key example is supersymmetry, a mathematically elegant class of model with the capacity to solve several other problems within particle physics too. Supersymmetry predicts many new particles, and one of these is a WIMP: the neutralino. The neutralino is a strong focus for new-physics searches at the Large Hadron Collider [7], though there are many other example as discussed in Reference [8].

An alternative model for dark matter that is growing in popularity as we continue to not discover a WIMP is called the Axion [9]. Like supersymmetry, models including axions arose from a desire to solve other problems with the Standard Model, and serendipitously happened to deliver a viable dark matter candidate. Axions are about a billions times lighter than WIMPS, but they behave differently. Self-interactions between axions allow them to group together with a much higher density, forming a state called a 'Bose-Einstein Condensate'. This overall results in a strong enough gravitational field to account for our discrepancies.

3 Conclusion

In summary, an astonishing number of observations from all corners of astronomy converge to tell us we are missing something. Some unidentified, heavy, and invisible kind of matter exists. It contributes over 5 times more to the mass-energy of the universe than the kind of matter we experience on a daily basis, and for most of the history of civilisation thought solely existed.

There are several popular models that can predict a viable dark matter candidate explaining our discrepancies, and many different experiments looking to test these models in different ways. It is an exciting challenge for particle physics at the moment, and one which is critical to solve to propely understand our universe.

Hopefully, in the near future, this essay competition will include an entry which really provides an explanation for dark matter.

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