Analyzing the Components of the Universe and Types of Dark Matter to Better Understand the Universe Evolution

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Abstract: Dark matter, which makes up over 20% of the universe, has been a mysterious substance to humans. Nowadays, scientists and astronomers are researching and experimenting using advanced technology to find out what dark matter is. This paper gives a thorough background to the components of the universe's substances, explains important theories regarding expansion of the universe and their relationship to dark matter, analyzes different models of dark matter and their rationales, presents some of the most popular candidates for what dark matter is, and discusses important current researches done by experts in the field. The overall purpose of this Abstractis to analyze the most significant aspects of dark matter in order to prompt future research to uncover more about dark matter.

1. Introduction

The Study of Dark Matter and Why is it Important

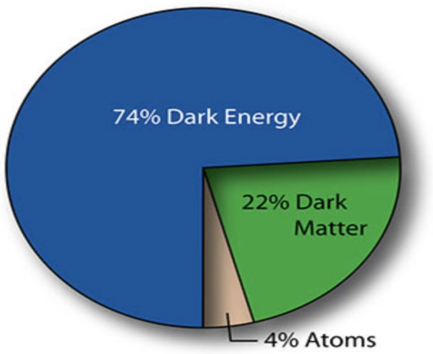

Fig.1 Credit: Nasa, Components of the Universe

The universe is composed of three substances: normal matter, dark energy, and dark matter, the percentages of which are shown in figure 1 respectively. Normal matter (atoms), also called ordinary matter, only makes up about 4% of the universe[1]. It is everything we can see, including ourselves. Basically, normal matter forms the observable part of the universe. Normal matter can be in several states: solid, liquid, and gas, depending on temperature and other factors[2]. Scientists such as Issac Newton and Einstein have had great impact on the basic ideas about matter and its measurement, mass. While Newton's equation F=ma explained the casual relationship between mass, acceleration, and force, Einstein's equation of $E=mc^2$ explains how mass and energy are the same physical entity and can be interchangeable[3]. $E=mc^2$ is an equation of the special relativity, which is an explanation of how speed affects mass, time, and space[4]. Einstein explains an object with mass m at rest has the rest energy of E, which is different from the physics theories before special relativity[3]. While scientists have been formulating more advanced models explaining how normal matter and energy behave, dark matter and dark energy, which in total makes up 95% of the universe, have been largely mysterious and remained so for a long time.

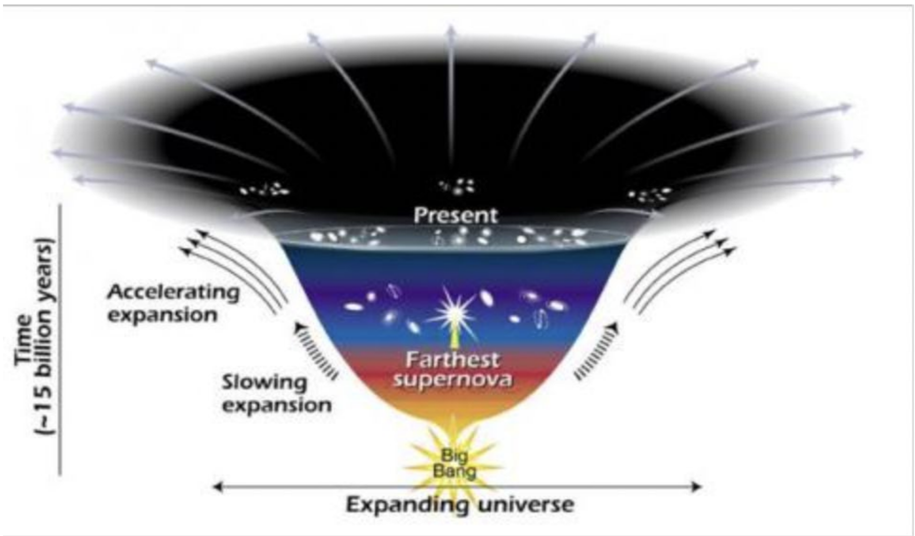

Fig.2 Credit, Nasa/Stsci/ Ann Field, Universe is Expanding At Accelerating Speed

As figure 2 shows, the universe has been expanding since it first formed after the Big Bang[1]. The universe's rate of expansion is increasing, due to an unkown force that is hypothized to be dark energy. The properties that are needed to explain the observation regarding dark energy include extremely low density, even spread out across all space, strong negative pressure emittion, and effective push of everything to the sourroundings[5]. Einstein's own study of general relativity has already shown that the universe is dynamic and there has to be a negative pressure that is pushing outward, countering the gravity's pull[5]. As later found by Edwin Hubble and other astrophysics the further away things are from us, the faster they recede, it is evident that the accelerating pace of the universe is ascending due to this unknown energy, but it is still unsure what exactly dark energy is[5]. One popular candidate for dark energy is cosmological constant[6]. Einstein first introduced this concept as a repulsive force required to hold the universe in static equilibrium– which means it is non-expanding. The existence of cosmological constant is also predicted by quantum physics as a form of vacuum energy, which exists in the form of perfect fluid. The perfect fluid model well defines dark energy's properties of energy density, temperature, and entropy, thus explaining why cosmological constant could be dark energy[25]. The equation of energy-momentum tensor of a perfect fluid if shown in figure 3 below[6].

$$T_{\mu\nu} = (\rho + p)U_\mu U_\nu + p g_{\mu\nu}.$$

Fig.3 Equation: the Energy-Momentum Tensor of a Perfect Fluid

Other models suggest the dark energy to be non-contact energy or gravity is carried by graviton, which is a particle that has mass and could change how general relativity works by causing accelerated expansion[5]. While these different models including perfect fluid, non-contact energy, and graviton exist, none of the theories right now could completely explain universe expansion; despite this, scientists have predicted that if the universe keep expanding as accelerating rate, the galaxies will eventually all be separated far away from each other and disappear from view. Ultimately, a number of black holes will form as the death of supernovae or stars occur, and everything will be pushed until the last star is engulfed by the black holes, and the last black holes disappear into nothing. This is known as the Big Freeze, in which the universe will end up in a cold and lonely death[7].

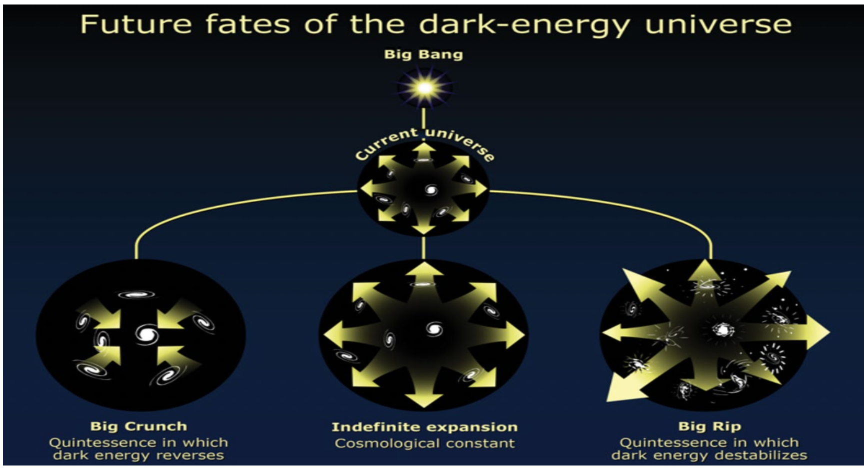

Fig.4 Credit: Nasa/ a. Field/ Space Telescope Science Institute

In another model, as shown by figure 3, the universe might end up in the Big Rip when the dark energy keeps expanding and destabilizes, which will result in the rip apart of spacetime[8]. In either of the models, dark energy plays a significant role, so it is important for scientists to study dark energy to better understand the evolution of the universe through the behavior of dark energy.

Just like dark energy, dark matter is also a mysterious yet intriguing topic to humans. Dark matter, which makes up about 20% of the universe and over 80% of all matter substances, is a substance that is invisible. Though dark matter is completely transparent because all kinds of light seem to be able to pass through, it has mass and thus can be seen by its gravitational influence[9].

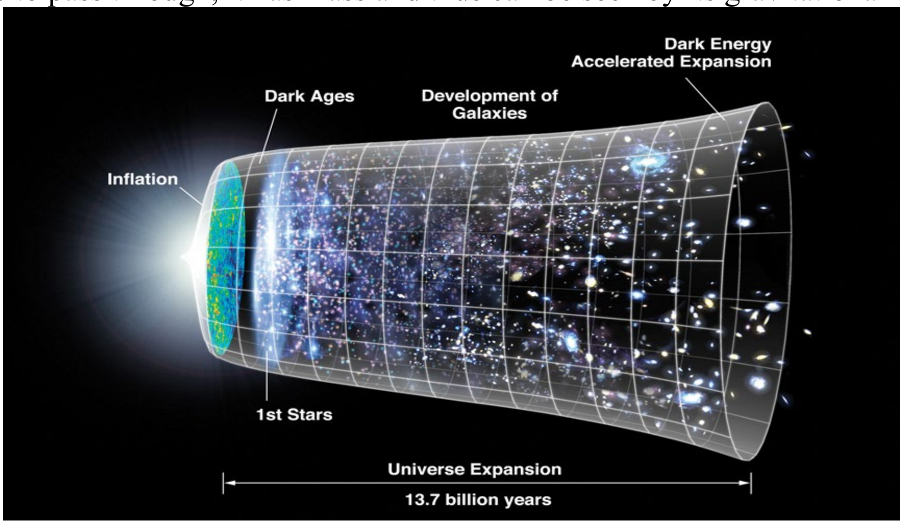

Fig.5 Credit: Nasa/Wmap Science Team

As this figure from NASA shows, the development of the universe is closely tied to dark matter: dark matter is in charge of organizing the cosmos, forming galaxies and galaxy clusters[10]. The large-scale organization of the galaxies are attributed to dark matter[9].

2. How is Dark Matter Measured

Galactic dark matter surrounds the galaxy's normal matter in a "halo," according to the velocity of what we can see. Dwarf galaxies, which are darker and consequently more difficult to observe yet have a higher percentage of dark matter than their larger counterparts, are another subject of study for astronomers[9]. Gravitational lensing is an effect in which cluster dark matter gravity affects light, which can be used to determine the amount of cluster dark matter[9][10]. Scientists measure the amount of dark matter in a certain galaxy according to how it causes light coming from a background source to bend[10].

Fig.6 Credit: Nasa, Esa, and J.Lotz and the Hfff Team

Fig.7 Credit: Esa/Hubble & Nasa

Figure 6 shows hundreds of galaxies, which are pulled together by the force of gravity, with arcs of blue light among them. The arcs of blue light are actually remote galaxies behind the clusters, those of which would be too faint to be seen on themselves. Basically, the lensing effect is like a giant magnifying glass, allowing researchers to study the details of galaxies that were formed very long ago[14]. Gravitational lensing is used for studying objects in the cosmos that are usually faint and vague to see with the current technology[13]. There are three types of gravitational lensing, and they are used for different purposes. Strong lensing helps the search for the earliest galaxies, which are too far away to be directly detected. Weak gravitational lensing helps to map the galaxy distribution on the most vast scale of the cosmos. Lastly, microlensing is used for the purpose of exoplanet detection[13]. The ring in Figure 7 is created by gravitational lensing from the red galaxy in the middle of the ring. The magnification from lensing allows astronomers to detect and see the blue galaxy ring which would be too vague to be seen on its own.

The lensed images suggest that most of the matter within a galaxy cluster is invisible but not gas, and they do not emit light; therefore, such matter became known as dark matter to us[14]. For example, in figure 8, the image on the right is the same image on the left but overlaps with the cluster's mass distribution. The right image has a ring-like structure, which is one of the strongest pieces of evidence that dark matter exists.

There are many types of dark matter models proposed by scientists. In this paper, I will discuss five types of most popular candidates for dark matter and their specific classification and how they could be more closely classified in the future. Better researching and experimenting methods could potentially help scientists to one day really see what dark matter is.

Fig.8 Credit: Nasa, Esa, m.J. Jee and h. Ford (Johns Hopkins University)

3. Classification of Dark Matter Candidates

Fig.9 Credit: Gianfranco Bertone, a New Era in the Search for Dark Matter

As figure 9 shows, there are many inspections regarding what makes up dark matter. The candidates range from light bosons, neutrinos, weak scale, macroscopic, modified gravity, to other particles[11]. We will discuss a few well-known types of dark matter in detail.

4. Cold Vs. Fuzzy Dark Matter Models

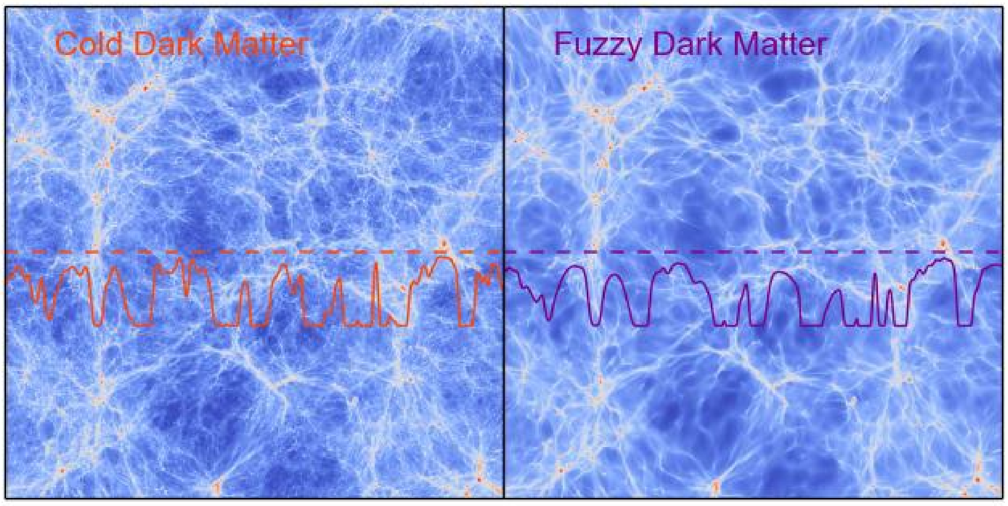

Fig.10 Credit: University of Washington

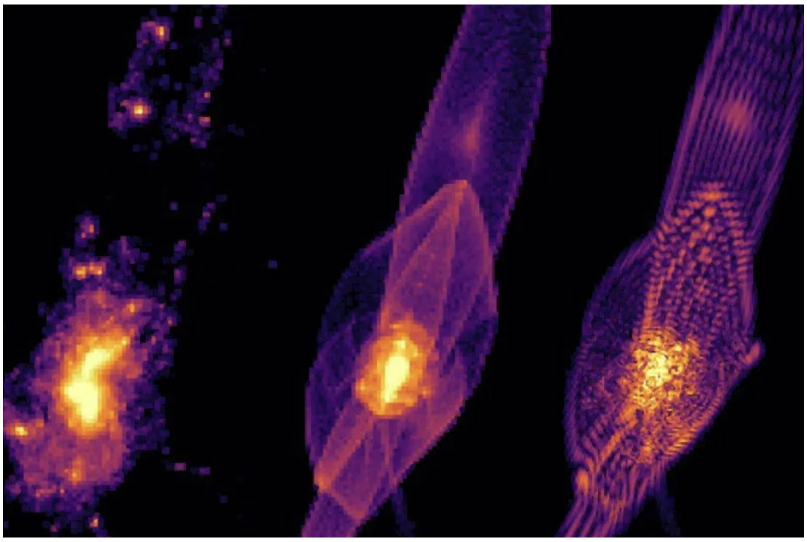

Fig.11 Credit: Universities of Princeton, Sussex, Cambridge

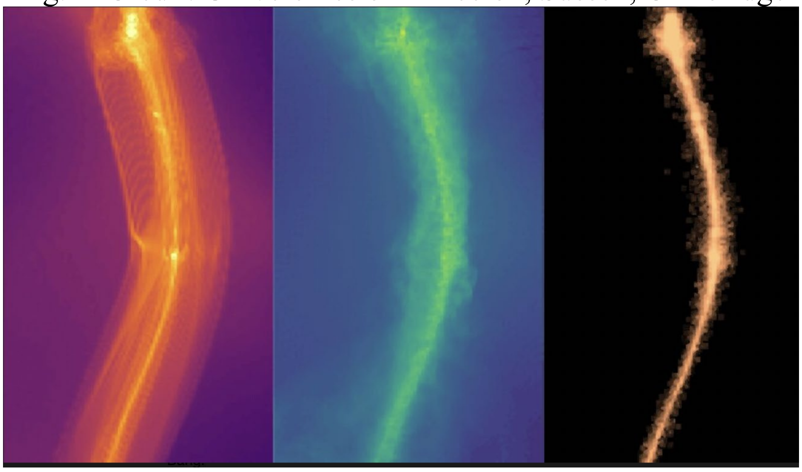

Fig.12 Credit: Universities of Princeton, Sussex, Cambridge

Currently, there are discussions on whether the dark matter is cold or fuzzy. Figure 10 shows simulations of a cold dark matter model and a fuzzy dark matter model by the University of Washington. Figure 11 shows simulations of how galaxies form in cold, warm, and fuzzy (left to right) dark matter models and figure 12 shows filament (tail) of galaxies formed in the aforementioned models[15].

The most popular model assumes that dark matter is a particle more massive than a proton that is “cold”, meaning that it is a particle that moves slowly relatively to the speed of light[17]. Axions and neutralinos are examples of cold dark matter: axions are extremely light but very cold, as in Bose-Einstein condensate, and neutralinos are very heavy and move super slow[16]. Cold dark matter model has been successful at explaining the structure of the universe on very large scales, much bigger than galaxies, but it has problems with explaining how matter is distributed on the smaller scales of galaxies.

For instance, according to the cold dark matter concept, galaxies' centers have a far larger density of dark matter than their nearby surroundings. Normal matter should have a strong peak in density in the core of galaxies because it is drawn to the dark matter. However, astronomers have found that the density of both dark and normal matter is considerably more uniformly distributed near the core of galaxies. Another issue with the cold dark matter model is that it predicts a much higher number of small galaxies orbiting around galaxies like the Milky Way than astronomers actually see.

An alternative model, the “fuzzy dark matter” model, a relatively new concept, was proposed to address the problems that are associated with the cold dark matter model[15]. The fuzzy dark model takes the advantage of the principle in quantum mechanics that each subatomic particle has a wave associated with it. If the dark matter particle has an extremely small mass, about ten thousand trillion trillion times smaller than an electron's mass, its corresponding wavelength will be about 3,000 light years[12]. Because fuzzy dark matter particles are such light, they act in quantum, wave-like fashion, which would produce a completely different galaxy as from the earlier models predicted for cold matter[15]. This distance from one peak of the wave to another is about one eighth of the distance between the Earth and the center of the Milky Way. By contrast, the longest wavelength of light, a radio wave, is only a few miles long. Waves from different particles would overlap and interfere with each other on large scales just like waves on a pond (or surface waves). These waves “act[ing] like a quantum system on galactic rather than atomic scales”, Harvard research says[12].

“The first galaxies in the early universe may illuminate what type of dark matter we have today,” says Mark Vogelsberger from MIT. With the development of new technologies and telescopes, scientists are able to see further back what the early cosmos looked like and the galaxy formation pattern, and this may be the key for humans to understand the nature of dark matter[15].

5. Weakly Interacting Massive Particles (Wimp)

Weakly Interacting Massive Particles, or WIMPs, has been the current best explanation for the dark matter[10]. WIMP are heavy, electromagnetically neutral subatomic particle that is theorized to make up the majority portion of dark matter; they are believed to be slow in speed and heavy because if the dark matter particles were light and fast moving, they would not have clumped together and caused density fluctuations.They are hypothesized to be electromagnetically neutral because the absence of light and they are believed to be “non baryonic” (baryons are massive particles such as protons and neutrons)[19]. Currently, scientists are still studying WIMP’s properties and hope one day they can be actually seen.

6. Axion Dark Matter and Bose-Einstein Condensate Dark Matter

Axion, a hypothetical subatomic particle postulated to account for the rarity of processes that break charge-parity symmetry. It is very light, lighter and more weakly coupled than WIMP, electrically neutral, and pseudoscalar. Though in the past, more research was conducted on WIMP than action, the axion has emerged in recent years as a leading particle candidate to provide the mysterious dark matter in the cosmos, and many researchers believe that axion could be detected in laboratories in the near future. It is believed that the discovery of axions could shed light on the super high-energy events in the most distant past of the universe[20]. Another possibility is that dark matter could exist in the form of a self-interacting Bose-Einstein Condensate (BEC). The fundamental properties of the dark matter in this model are determined by two parameters only, the mass and the scattering length of the particle[21].

7. Current Studies

There are many different specific research areas done by scientists and astronomers around the world. They collectively add up to a better understanding of dark matter and the Universe.

For example, at the Center for Astrophysics of Harvard & Smithsonian, researchers measure the influence of dark matter on the structural organization and evolution of galaxies, detect dwarf galaxies using new instruments, and study why dark matter models estimate that there are more dwarf galaxies than humans can currently observe. They also use observed data to create models that can theoretically monitor dark matter behavior since there is not a method to directly measure dark matter behaviors yet[9].

Also, researchers at Princeton University, including Wayne Hu, Rennan Barkana, and Andrei Gruzinov, have been studying the wave properties of ultra light dark matter (cold dark matter) and have been using their findings to try to explain the accelerated expansion of the universe[18].

At Massachusetts Institution of Technology, the MIT Kavli Institute is conducting laboratory experiments to detect WIMPs[22]. MIT’s laboratory for nuclear physics is also studying dark matter physics, notably, neutrinos[23]. Professor Mark Vogelsberger, a theoretical astrophysicist at MIT, creates computational models for universes, which is helpful to better understanding of the universe formation and evolution. His research is especially useful in understanding dark matter distribution across the cosmos[24].

8. Discussion

My research is focused on explaining the main components of the universe, describing how dark matter is measured, presenting current classification of dark matter, analyzing some of the most important dark matter candidates, and organizing significant research done in the field. The overarching purpose of my research is to give readers an overview of the important concepts about dark matter and related theories. The paper does give a thorough background regarding the most necessary aspects of current research on dark matter.

This paper will help someone who is interested in the field of physics, more specifically, astrophysics, to understand more about normal matter, dark energy, and dark matter, and have a deeper comprehension about dark matter especially. As dark matter becomes an increasingly studied subject in atronomy and astrophysics, more astronomers and scientists are specialized in this field of study and have been working on developing ways to unveil the true form of this substance. The researches conducted by researchers at different institutions which I mentioned in the section 7(i.e. Current Studies) have important implications to the field of astrophysics as they have been contributing noteworthy findings to humans' understanding of dark matter.

Though the paper has thorough discussion on many details about dark matter and its subtopics, this paper did not dive deep into more complex findings which would require expertise to understand. In the future, I will be conducting more research on dark matter. For example, I would concentrate on how specifically each of the branches of dark matter classification were determined. I believe better understanding of dark matter classification could help readers to notice the similarities and differences between the different dark matter models, which can result in better understanding of the bigger picture. I would also research more on current technologies and innovative methods used for studying and potentially detecting dark matter. Advancement in technologies is a key factor for learning more about dark matter, as the observation of galaxies and stars within them requires superior space telescopes and detection of dark matter-normal matter interactions requires complicated devices.

Dark matter is indeed a sophisticated subject, and modern researchers are working hard and producing progressive results. It is highly possible to see ground-breaking and revolutionary studies within the next few decades.

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