Dark matter and its role in galaxy formation

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Abstract

Dark matter is a core component of the Universe, allowing for the evolution of structure. Although the nature of dark matter is largely unknown because it does not interact with light, a wide range of observational evidence backs up its existence. This includes evidence from galaxy rotational curves, gravitational lensing, the Bullet Cluster, and the Cosmic Microwave Background (CMB). This review examines the role of dark matter in galaxy formation within the scope of the standard model of cosmology. Discussion for the particle candidates of dark matter, like axions, Weakly Interacting Massive Particles (WIMPs), and Massive Astrophysical Compact Halo Objects (MACHOs) are also included. The many proofs of dark matter, growth from primordial heat fluctuations, and the evolution of galaxies are outlined too. Further attention is given to the nature of galaxy evolution by discussing differences between early and late-type galaxies, in respect to metallicity and telescope observations. The paper concludes future prospects of understanding dark matter and its connection to galaxy formation.

1. Introduction

Recent observations across cosmology and astrophysics continue to refine theories and understanding of dark matter and its role in structure formation. Not only does dark matter not absorb or reflect light, it is almost impossible to detect electromagnetically. The Standard Model of Cosmology, specifically the Lambda CDM model, indicates that dark matter makes up 95% of all matter, forming an invisible scaffold for the growth of structure. Evidence exists from galaxy rotation curves, gravitation lensing, the CMB, etc., but astronomers still cannot describe dark matter's quantum nature, i.e., as a particle. Some popular but now debunked or semi-debunked candidates are MACHOs and WIMPs (see Section 2) while current theories indicate that dark matter might be ultra-light instead of massive and be an axion particle or axion-like [1]. This paper provides a comprehensive overview of dark matter and galaxy formation.

In the following, the Lambda CDM is briefly presented in Section 2. Section 3 details the various sources of observational evidence for dark matter through several methods. Section 4, describes the nature of galaxy formation and evolution as well as differences between early and late type galaxies. Finally, Section 5 concludes with future forward thoughts on pinning down dark matter's mystery.

2. Lambda CDM

Cosmology is a subfield of astrophysics that deals with the universe at a very large scale. From the birth of the cosmos to its possible end, cosmology asks some of the most profound questions in science: *What physical forces drove the rapid expansion of the early Universe? What is the nature of dark matter and dark energy? Why do astronomers observe discrepancies, such as the Hubble tension, between measurements in the Hubble constant from* *the early Universe and the present-day Universe?* The current understanding of how the Universe came to be is part of the Standard Model of Cosmology, specifically described to-date Lambda CDM (ΛCDM). Within this model, Lambda is known as a cosmological constant. It stands for dark energy, or the mysterious energy that is responsible for the expansion of the Universe. CDM stands for cold dark matter [2]. “Cold” refers to the matter’s particles moving relatively slower than photons (i.e., non-relativistically), whereas "dark” refers to how this type of matter weakly interacts with baryonic matter, or normal matter [3]. According to Lambda CDM, the universe is composed of 27% dark matter, 68% dark energy, and the rest being ordinary matter [4].

There are several particle candidates for dark matter. Weakly Interacting Massive Particles (WIMPs) are hypothetical particles that are massive and would only interact via gravity or another small force and were a leading candidate; they were hard to detect and other candidates are now gaining traction [2]. MAssive Compact Halo Objects (MACHOs) state that dark matter is mostly baryonic, but the candidate falls short because it is hard to imagine how dark matter forms with this framework. However, axions, a light particle that could be classified as cold matter, is a good candidate for dark matter and explains parts of the Lambda CDM [1].

The Lambda CDM states that the universe formed from a single point. A simplified timeline of the early universe according to the LambdaCDM model begins with the inflationary epoch, around 10^{-36} seconds after its birth [5]. In the first fractions of a second, space expanded exponentially, setting the initial conditions for the cosmos one can observe today. One second later, the universe was an 18 billion degrees Fahrenheit (10 billion degrees Kelvin) primordial soup of light and particles [6]. In the next few minutes, as the temperature dropped to around 1 billion Kelvin (1.8 billion°F), protons and neutrons collided and created early elements like hydrogen and helium, and traces of lithium and beryllium [7], known as Big Bang Nucleosynthesis. After five minutes, most of the Universe's helium supply formed. The Universe expanded and cooled until element formation stopped. However, at this point, the Universe was still too hot for the nuclei of these atoms and elements to catch electrons [7].

The inflationary event is thought to have occurred approximately between 10^{-36} and 10^{-32} seconds after the birth of the Universe, during which the Universe grew by a factor of at least 10^{26} in size [8]. The theory of inflation is widely accepted, but it still requires observational confirmation that such an inflationary event actually occurred, primarily through measurements of the cosmic microwave background (CMB), the oldest observable light in the Universe. Inflationary theories predict that quantum fluctuations in the early Universe were stretched to cosmic scales, eventually seeding the large-scale structure one can observe today. If inflation occurred, evidence for it could appear as a characteristic polarization signal in the CMB.

Theories of inflations state that quantum fluctuation from the singularity in the early universe became exacerbated into the large scale structures (galaxies, galaxy clusters) scientists see today as a result of a rapid exponential expansion. About 380,000 years after the birth of the Universe, it had cooled enough for atomic nuclei to capture free electrons in a process known as recombination, forming neutral hydrogen gas [9]. Since most electrons were now bound to nuclei, photons were no longer frequently scattered and were able to travel freely through space for the first time. This release of radiation revealed what is now known as the observable Universe. The remnant glow from this epoch is still detectable today and is called the Cosmic Microwave Background (CMB) [7].

Much of modern cosmology relies on observations of the CMB to study the physics of the Universe at its earliest moments and highest energies. These measurements allow scientists to trace the distribution of matter—including dark matter—across space and time. Probing the CMB also helps identify tensions within the ΛCDM model and provides insight into the nature of dark matter, dark energy, and perhaps even the quantum nature of gravity. For the purposes of this work, this paper will specifically focus on how the CMB provides insight into dark matter's presence and influence in the early Universe, as well as its impact on the Universe today (see Section 3.4 for more detail).

2.1 Evolution of Structure

After the CMB was released, the universe became *transparent*, allowing photons to travel freely through space. For the next several hundred million years, the universe consisted primarily of hydrogen and helium, with only trace amounts of heavier elements [7]. Although the universe was remarkably uniform overall, small density fluctuations were present, with some regions containing slightly more matter than others.

In regions where the density was higher, gravity caused gas to clump together over time, attracting more matter and growing increasingly dense. As these clumps collapsed under their own gravity, their centers became hot and dense enough to initiate nuclear fusion, leading to the formation of the first stars. The birth and death of these early stars produced heavier elements, which were then dispersed into the surrounding gas. This enrichment enabled the formation of subsequent generations of stars. Over hundreds of millions of years, stars and gas assembled into the first galaxies [10].

3. Observational Evidence for Dark Matter

3.1 Galaxy Rotation Curves

According to Kepler's Third Law, an object farther away from a central mass orbits that mass slower [11]. This phenomenon can be seen in the solar system where planets like Mercury and Venus spin faster around the sun than Saturn and Uranus. However, in galaxies, something strange happens. Scientists derive properties of galaxies by measuring what objects in galaxies are doing. When exploring these properties, scientists observed that objects were going faster than expected, in proportion to their distance [12]. Specifically, when recording light from distant spiral galaxies and plotting the velocity of their stars and their distances from the center of the galaxies, the velocities were greater than expected [13].This implies that there is extra mass unaccounted for (not observed visibly) in the galaxy that would cause stellar objects to travel faster than expected. This extra mass is often thought to be dark matter.

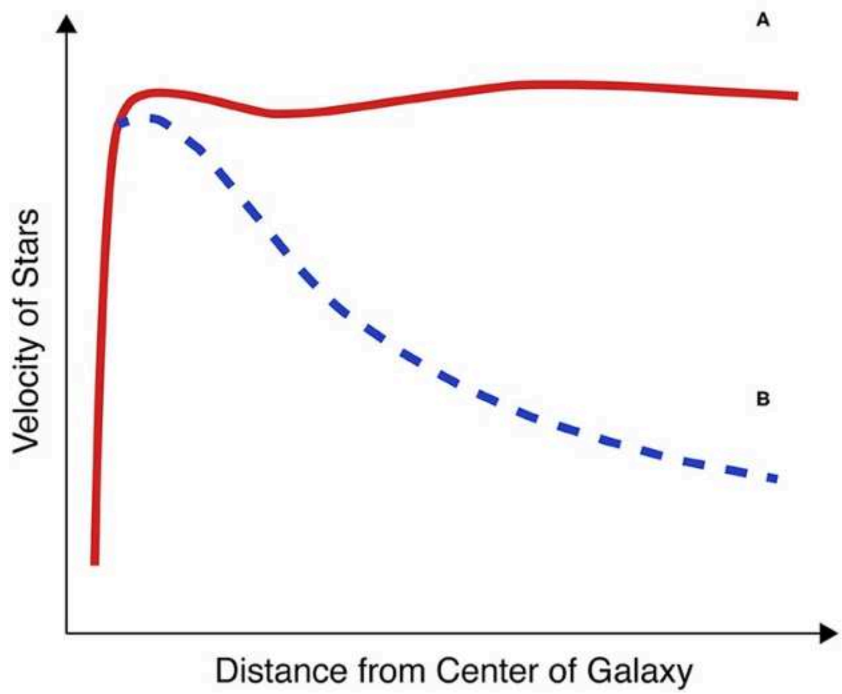

Figure 1. Graph showing the distance from a galaxy center versus the velocity of stars. Curve 'A' represents the velocities that are seen in galaxies through observation. Curve 'B' represents the expected velocities of stars based on visible matter and Kepler's third law (modified from original image by PhilHibbs and licensed under CC BY-SA 3.0 [14]).

3.2 Gravitational Lensing

Gravitational lensing is a consequence of general relativity. It occurs when a massive celestial body, such as a galaxy, bends the path of light from a more distant entity because of its strong gravitational field [15]. The big object between the observer and the light source acts as a lens, meaning that lensing requires mass; the bigger the mass, the larger the lensing. Hence, gravitational lensing can be used to find the mass of large objects, like a galaxy [16]. However, when using lensing, the bending of light is much stronger than accounted for by visible matter alone, suggesting additional unseen matter–or dark matter [13].

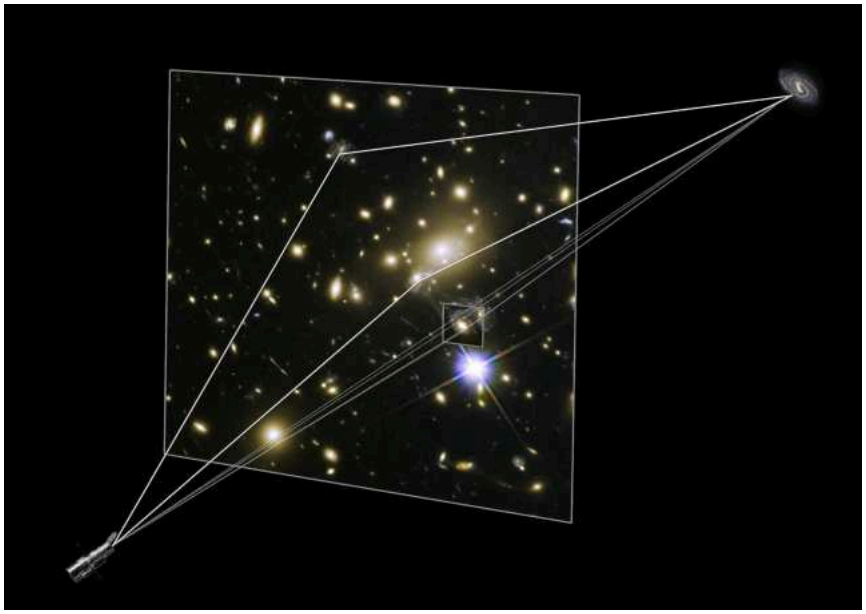

Figure 2. Large galaxy clusters contain both dark and regular matter. The gravity of these clusters is so large that the space around the galaxy bends. The distortion causes light from far away to be magnified, hence the name gravitational lensing. This sketch shows the path of light as it bends from a distant galaxy to a telescope (Image from NASA, ESA [17]).

Dark matter is measured through strong and weak lensing. Strong lensing is when gravitational lensing produces highly distorted images with multiple images or rings [16]. This allows for an accurate way to measure how mass is within a galaxy. However, weak lensing only causes slight distortions and warps. Scientists use this to make 3D maps of the distribution of dark matter by finding the distortions on many background galaxies [18].

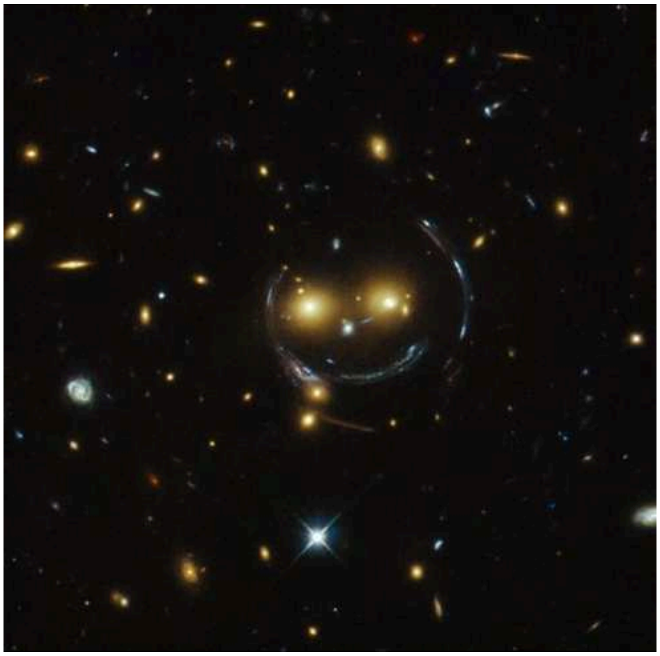

Figure 3. Shows strong gravitational lensing. The image is titled “Hubble Sees A Smiling Face” because of the two large orange eyes and smile. The smile lines are actually arcs distorted by gravitational lensing (Image from NASA, ESA [19]).

3.3 Bullet Cluster

The Bullet Cluster was formed after the collision of two large galaxy clusters and is named after its bullet-like shape. This cluster plays a huge part in proving the existence of dark matter because of its center of mass. If gravitational lensing is used to find the center mass, the center appears in a different location than when observing [20]. This is because during the collision of the two other galaxies, hot gas was slowed by a drag force. However, dark matter was not slowed because it does not interact with gas or itself. Therefore, during the collision, dark matter passed through and caused a separation between the two types of matter [21]. If other theories of gravity were true, hot mass should have been the largest component. However, this effect would not have been seen, indicating the existence of dark matter [22].

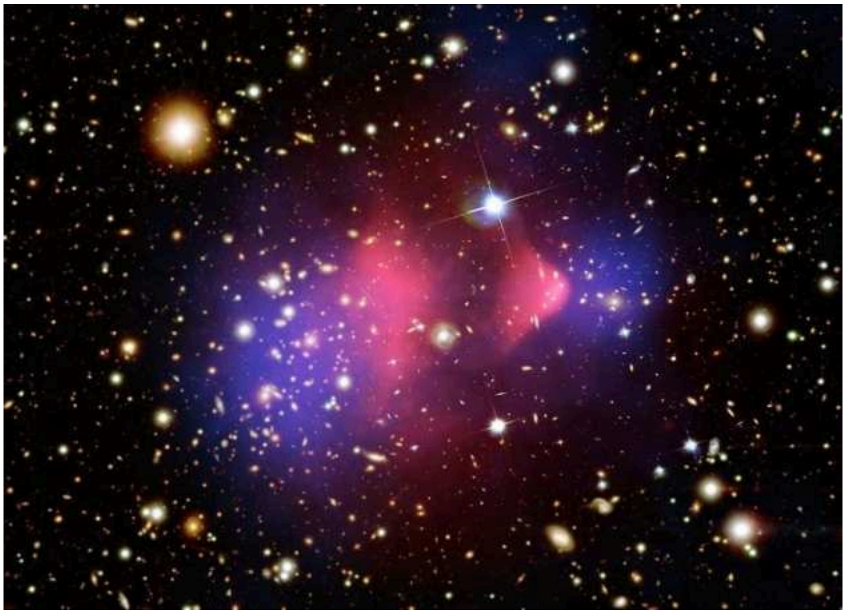

Figure 4. This image shows the galaxy cluster, known as the “bullet cluster.” Formed after the collision of two large galaxies, its bullet-like shape sparked the name. The two large pink clumps are mostly normal matter, while the blue parts show the location of most of the mass in the cluster, through gravitational lensing. Most matter in the clusters is separated from the normal matter, giving evidence that most matter in this cluster is dark matter (Image from Chandra X-ray Observatory ACIS. Credit; X-ray: NASA/CXC/CfA/M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. [20]).

3.4 The Cosmic Microwave Background (CMB)

As mentioned before, the CMB holds information about the early Universe. To see the CMB more clearly and its temperature fluctuations, scientists use a statistical representation called an angular power spectrum. It is measured in angular metric, meaning it measures the separation between points as they appear to us in the sky [23]. In Figure 4, moving along the x-axis corresponds to looking at smaller angular scales in the CMB. As the angular separation decreases, finer details in the temperature fluctuations become visible, meaning the resolution of smaller regions of the CMB increases. Similarly, the y-axis measures the variance of temperature fluctuations or anisotropies. Each peak on the graph tells us something about the Universe [23]. The position of the first peak on the x-axis tells us the geometry of the Universe (flat). The relative heights of the second and third peaks reveal the amounts of normal (baryonic) matter and dark matter, respectively, allowing cosmologists to determine the total matter content of the universe, and the contribution from dark matter [24].

Moreover, when early CMB data began to clearly reveal the second and third peaks, scientists compared these observations to different theoretical scenarios for what the Universe could be made of. Normal (baryonic) matter interacts with radiation, which affects how strongly the peaks appear in the power spectrum. If baryonic matter were the dominant form of matter in the Universe, it would significantly enhance some peaks while suppressing others, leading to a more uneven pattern between the second and third peaks.

However, observations showed that the second and third peaks are very similar in height. This indicates that normal matter alone cannot account for the observed structure of the CMB. Instead, the presence of dark matter— which does not interact with light but still contributes gravitationally—helps explain why higher-order peaks remain strong. This pattern suggests that dark matter makes up most of the matter in the Universe. By comparing the full CMB power spectrum to cosmological models, scientists found that ordinary matter makes up only about 5% of the Universe, with the rest consisting of dark matter and dark energy [4].

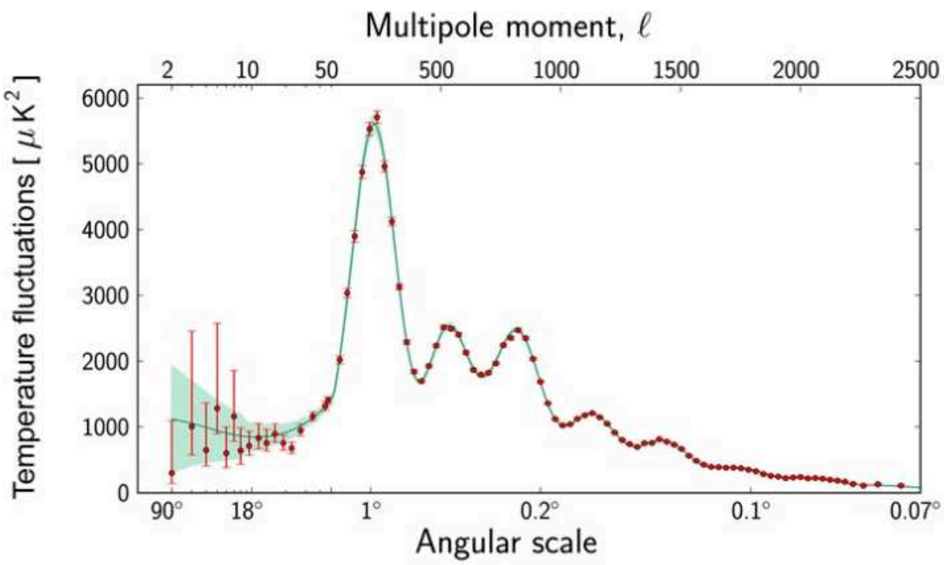

Figure 5. Planck measurements of the CMB temperature power spectrum. It provides some fundamental properties of the universe. The 1st peak tells us about the geometry of the universe while the 2nd and 3rd peaks tell us about dark matter distribution in the universe. Because the 3rd peak is only 5% higher than the 2nd peak, it can be concluded that the universe is made up of 95% dark matter. (Image from ESA and the Planck Collaboration [25]).

3.5 Structure Formation

During the early Universe, everything was extremely hot. Another way to think of the power spectrum is as a collection of pressure waves that compress and rarify. What this means is, photons constantly scattered off free elections and nuclei, creating an outward force (radiation) which resisted gravitational collapse and pushed particles apart [26]. However, a key thing to note is that only ordinary matter is affected by radiation, not dark matter. Since gravity tried to pull matter inward while radiation pressure pushed outward, there was a pattern of compressions and rarefactions of sound waves moving through the hot plasma of photons and baryons [27]. The first peak of these oscillations showcased in the CMB power spectrum represents compression, while the second corresponds to rarefaction, which is always smaller because radiation resists collapse. The third peak, however, reveals the presence of dark matter; unlike ordinary matter, dark matter does not feel radiation pressure [28]. It only responds to gravity, deepening gravitational wells and allowing matter to continue clumping together. Without dark matter, the third peak would be much smaller, and large-scale structures like galaxies and clusters would never have formed.

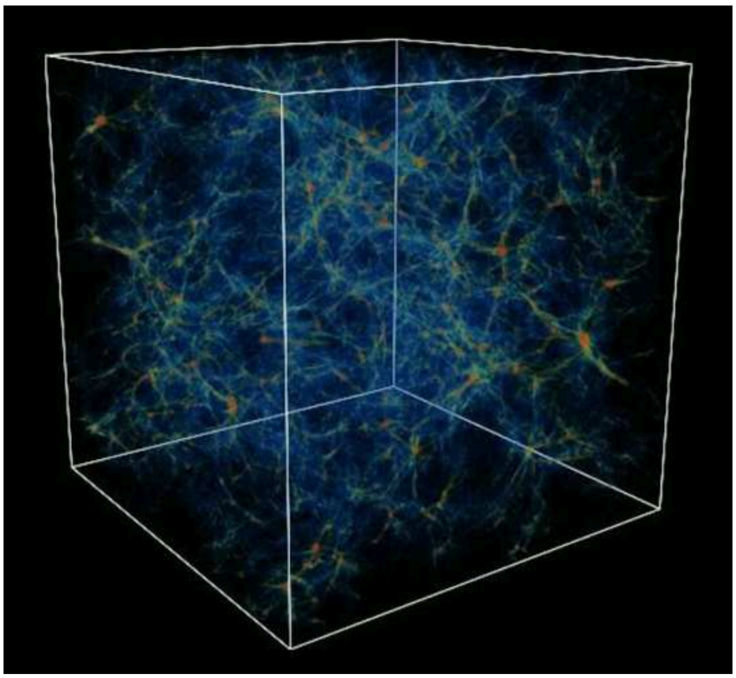

Figure 6. Three-dimensional visualization of the cosmic web through a large-scale simulation. The model shows the network of matter where the blue structures trace the distribution of dark matter. The redder areas indicate gravitational potential wells where baryonic matter accumulates to form galaxies. The presence of these large scale filaments provide evidence for dark matter as the universe could not have grown as rapidly as it did without it. (Image from International Gemini Observatory/NOIRLab/NSF/AURA/G. L. Bryan/M. L. Norman [29]).

4. Galaxy Formation

After clusters formed in the early universe, they were merged together because of gravity. Once these clumps amassed enough matter, they became what are known as galaxies and galaxy clusters today.

4.1 Stellar Formation

Star formation starts from collapsed gas clouds that heat up enough to make the first stars, or protostars. After millions of years, the gravitational pressure in these protostars raised central temperatures above 10^7 K [30] and caused the hydrogen in the star’s nucleus to fuse together and form helium. This act of nuclear fusion released energy for these initial stars and prevented gravity from collapsing them [31]. The balance between this inward gravitational pressure and the external radiation pressure is known as the hydrostatic equilibrium; it keeps a star stable and from exploding [32].

A star's mass determines its position on the Hertzsprung–Russell (HR) diagram (see Figure 7), which plots the star's temperatures against their luminosity [33]. Lower mass stars range from 8-80% of the sun's mass and far outnumber any other type of star by having a large lifespan [34]. Higher mass stars are usually 8 to 20 M ☉ (solar masses) and burn faster, die younger, and usually produce supernovae [35]. To give reference, masses of stars are measured in solar masses; a comparison with the sun (1.9891×10^{30} kg) [36].

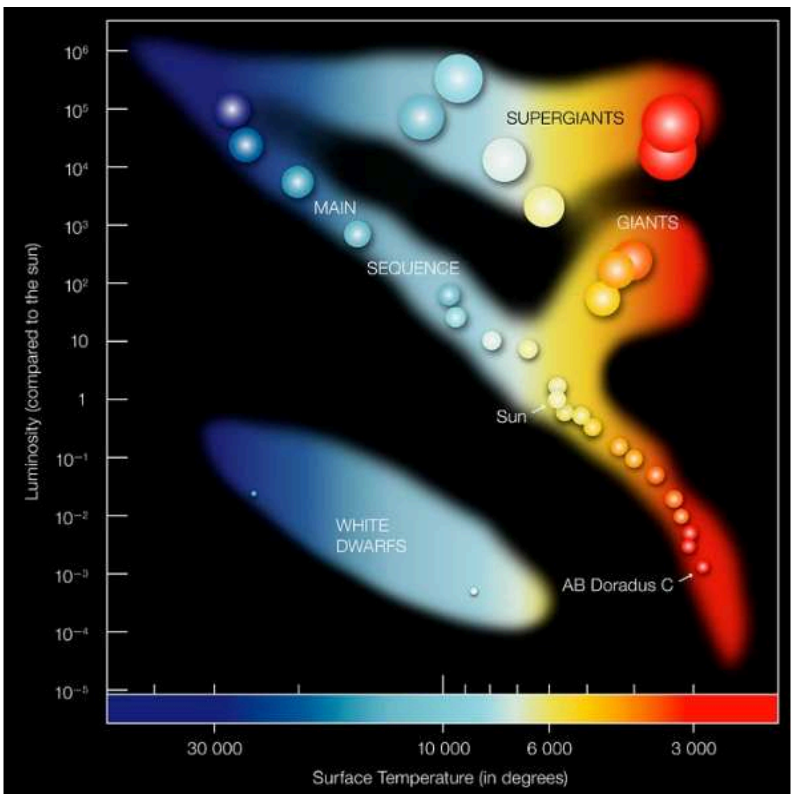

Figure 7. The Hertzsprung–Russell or HR diagram plots the surface tension of stars against their respective luminosities. The star's position on the graph indicates the age and mass of the star. The diagonal band from the top, left corner to the lower, right corner represent stars that fuse hydrogen in their cores. Stars that are hot and bright are at the upper-left corner and are pictured as blue; cooler stars are at the bottom-right corner and are red in color. (Image from ESO [37]).

As nuclear fusion continues, heavier elements and metals like carbon, oxygen, and iron form [38]. These short lived stars enabled future generations of stars to be born through heavier elements like Population II and I stars, enabling more efficient cooling for subsequent generations.

When a star's mass exceeds what is known as the Chandrasekhar limit, which is around 1.44 times the mass of the sun, the degeneracy pressure of an electron can no longer support the star. This means that a star exceeding the limit, once it reaches its end, will become either a neutron star or black hole [39]. A star needs to be greater than 20 solar masses in order to become a black hole [40]. As more stars formed and enriched their surroundings, galaxies took part around supermassive black holes.

4.2 Black Holes

Inside most big galaxies, there is a supermassive black hole [41]. Within the Milky Way, there is a supermassive black hole (Sagittarius A*) that is 4 million times the mass of the sun [42]. These central black holes likely formed during early galaxy formation from either the collapse of large gas clouds or the merging of smaller black holes created by the first stars in the universe, also known as Population III stars [43].

The formation of supermassive black holes is tightly linked to star formation and their host galaxies. As gas collapses toward a galactic center, it feeds both the black hole and triggers intense star formation, creating a feedback cycle that regulates galaxy growth [40]. Moreover, most galaxy bulges are proportional to the masses of their corresponding black holes, establishing the interconnectedness that are seen in most galaxies today [44].

4.3 Early and Late Galaxies

Galaxies have evolved since the formation in the early universe, from smaller irregular galaxies to the wide range of types that are seen today. Observations from the James Webb Telescope and the Hubble Space Telescope have begun to reveal properties of the first galaxies. By analyzing the infrared images of the JWST, scientists can tell that more ovular and tube shaped galaxies might have been common when the Universe was between 600 million and 6 billion years old [45].

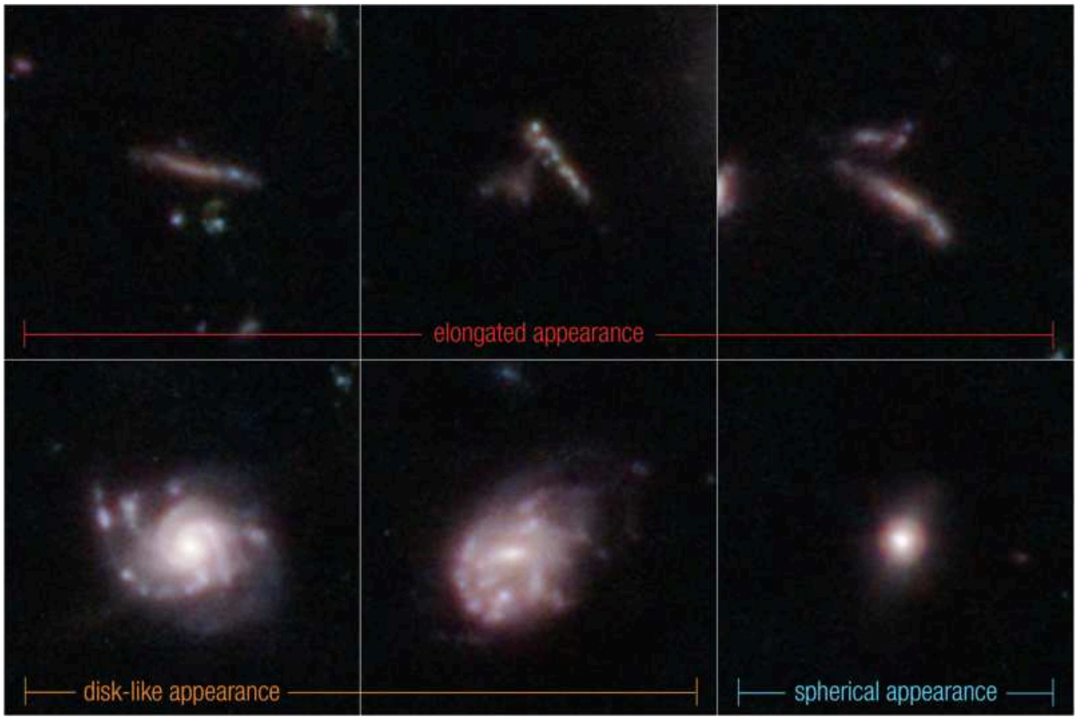

Figure 8. Examples of galaxy morphologies. The top row shows highly elongated galaxies, and the bottom row displays disk-like and spherical systems. These images captured by the James Webb telescope are estimated to have existed when the universe was around 600 million to 6 billion years old. (Image from NASA, ESA, CSA, STScI, Steve Finkelstein (UT Austin), Micaela Bagley (UT Austin), Rebecca Larson (UT Austin) [45]).

In today's galaxies, most are spiral, making up 77% of all galaxies, but others could be elliptical, barred spiral, or irregular [46]. They include three components; a disk (spiral arms), bulge, and a halo. Many galaxies, like the Milky Way, are barred spirals, meaning they include a bar with matter flowing through. Elliptical galaxies are ovular while irregular galaxies have no specific size or shape [47]. Older galaxies tend to be more irregular because of the environment in which they were formed.

It is claimed that early galaxies formed rapidly when the universe was just 2 billion years old. They were populated with elderly, red stars, indicating that they went through quick star formation [48]. They are often located in denser regions of the universe, which allows them to acquire mass more rapidly than typical galaxies [48]. These denser regions are called gravitational wells and are held together by dark matter. In contrast late galaxies tend to be late bloomers, meaning they accumulate gas and merge over millions of years [49]. Overall, differences lie in timing and the environment in which early and late galaxies matured.

There are also several key differences between the metallicity of early and late galaxies. Metallicity refers to the amount of elements heavier than Hydrogen and Helium in a galaxy [50]. Early galaxies, or those housing Population III stars are theorized to be very low in metal content [51]. These galaxies were very massive and extremely hot, with stars weighing around

100 solar masses [10]. Population III stars and galaxies were short lived and their first metals were expelled from resulting supernovae, enriching the Universe. They were built from metal-free primordial gas (Hydrogen gas) and had virtually no metal content [52]. In contrast, late stars and galaxies, such as the sun and Milky Way have higher metallicity. When the first stars burned through hydrogen and became supernovae, their metals flew across the universe through stellar winds. This process allowed for newer stars or Population I to have high metals because they formed from gas that has already been enriched by older stars and galaxies [53].

Within Population I galaxies, on average, older stars and galaxies have higher metallicity. Older stars have higher metallicity because they have more time to burn elements. Moreover, early-type galaxies tend to have lower gas groups compared to late-type galaxies. This difference in gas fractions leads to greater oxygen abundance in early-type galaxies, which is consistent with current observations [54].

5. Conclusion

A wide range of observational evidence demonstrates that dark matter plays a key role in galaxy formation and cosmic structure. From the dynamics of individual galaxies to the anisotropies of the CMB and structure formation, dark matter provides the framework for the growth of the Universe. Without it, galaxies and clusters could not have formed to how they are seen today, given the timeframe.

The Lambda CDM explains how dark matter dictates the environments in which galaxies can form and then evolve. Differences between early and late galaxies reflect changes in growth, merger rates, and differences between baryonic and dark matter.

Despite dark matter's success in explaining many phenomena of the universe, significant challenges remain. The microscopic nature of dark matter is still widely unknown and differences between simulations and observations on small scales continue to create more alternate models of baryonic physics. Future observations from future generation surveys and experiments, promise to refine the understanding of dark matter and its role in galaxy formation.

Ultimately, further progress in this area will require integration of cosmology, astrophysics, and other particle physics. By emphasizing how dark matter helps with the formation of galaxies and other structures, astronomers move closer to understanding both large-scale structure of the Universe and the nature of dark matter. Since dark matter is a particle, understanding would help us understand particle physics. The current field is focused on dark matter being an ultra light or axion. Future CMB experiments and measurements will provide us with higher resolution and detectors, allowing us to pin down the Lambda CDM and understand the properties of dark matter.

7. Acknowledgements

Thank you so much to Sanah Bhimani for giving me guidance, support, and help throughout the course of my writing process for this paper.

8. Conflict of Interest

The author declares no conflicts of interest related to this work.

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