How Far Can We Prove The Existence Of Dark Matter Through Direct And Indirect Methods

Devansh Dhabhai

1. Abstract

In this paper we strive to understand the methods by which we can identify dark matter's presence in the universe. This paper will particularly focus on the astrophysical phenomena such as the observed velocities of stars in galaxies other than the Milky Way, as well as gravitational lensing that conflicted with data implied by Einstein's theory of general relativity. Furthermore, we also describe indirect methods particularly dark matter particle annihilation to antimatter and γ rays are reviewed.

2. Introduction

Until around 3 decades ago, astronomers believed that the universe was made essentially out of the baryonic matter[1]. In any case, in the previous decade, there has been proof aggregating that recommends there is something in the universe that we can not see. In spite of the fact that it can not be seen, researchers have a few strong confirmations that over 90% of the total mass of the universe is made out of this undetected mass, called dark matter. The term Dark Matter has been coined because it neither emits or reflects any radiation. Carl Sagan coined it as dark, quintessential, profoundly baffling stuff completely obscure on earth. There is as of now much progressing research by scientists endeavoring to find precisely what dark matter is, how much there is, and what impact it might have on the fate of the universe . We aim to examine the confirmations of the presence of dark matter in the universe.

3.) Direct Detection Of Dark Matter

3.1 Rotational Curves:-

Proof for dark matter started to rapidly arise during the 1900s from astrophysicists. However, while the underlying makeup of dark matter was not definitive, it was obvious that dark matter had mass; consequently, the bulk of support for dark matter came from gravitational properties. Using exclusively Newtonian Mechanics inside a Galactic framework, we can undoubtedly determine the velocity of stars circling the focal point of the Galaxy:

$$\textit{Assuming that the planets are moving in a circular path}$$

[1] Matter that is fundamentally composed of electrons, protons and neutrons

$$\frac{mv^2}{R} = G\frac{Mm}{R^2}$$

$$v^2 = \frac{GM}{R}$$

$$V = \sqrt{\frac{GM}{R}}$$

where R is the orbital radius of the star being referred to, and M is the mass of the baryonic matter enclosed inside the star's orbit. From this straightforward model, it turns out to be certain that as we move further away from the focal point of a galaxy the velocity of the star reduces

In spite of this, what is really seen through plenty of observations is that stars at the border of systems move essentially quicker than what Newtonian mechanics predicts - as R increments, v(r) remains generally constant.

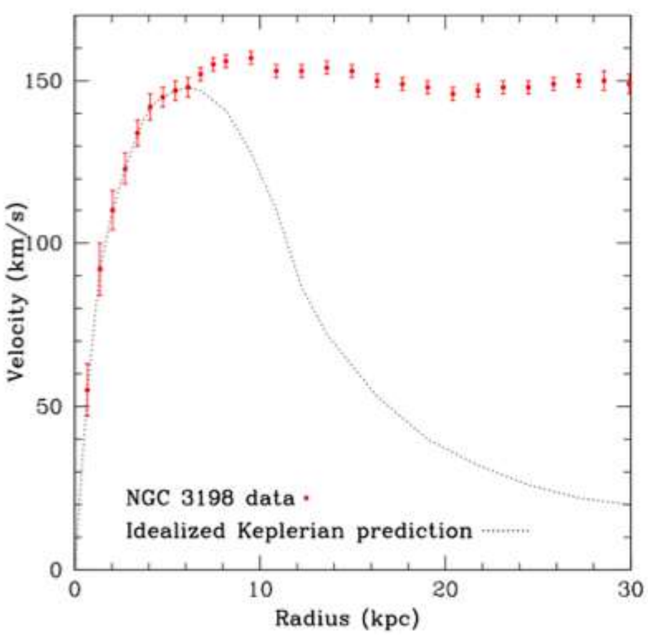

Figure 1: The following graph displays the rotation curves of a star. According to Newtonian mechanics the rotational curve should have shown a decrease in the velocity, however the observed graph(red color) showed that the planets travelled with a constant velocity.

These rotational curves, as demonstrated in Figure 1, give the most grounded proof of extra mass inside galaxies that was invisible and undetectable. The presence of this mass was additionally backed by Lord Kelvin and Henri Poincaré, both of whom discovered an error between the measure of matter directed by observation and that observed on the simple velocities of the bodies. In order to clarify this phenomena, Poincaré coined the expression "dark matter," endeavoring to depict a type of gravity that was not characteristic of luminous matter.

3.2 Gravitational Lensing

Another theory that can be studied in order to prove the existence of dark matter is the Theory of General Relativity. According to Einstein's Theory of General Relativity, space and time were theorized as being conjugated into a single fabric, and gravity began to be interpreted as the curvature of this fabric.

As evidenced by views of eclipses, the curvature of spacetime bends light around areas of relatively high gravitational potential, such as our Sun, large galaxies, or black holes. Often after computing the rotation curves of galaxies as shown above and their corresponding masses, we observe the images of other astronomical objects behind this galaxy is significantly more smeared and lensed than we predict - this once again suggests that there must be some not luminous matter within galaxies that is motivating this extremely large gravitational influence.

Figure-2

The red area depicts the baryonic core of the cluster, while the blue exterior portions denote the postulated dark matter halo that extends beyond the core of the cluster

The distortion caused due to gravitational lensing is condensed in the following equation:

$$\hat{\theta}_i = \hat{\theta}_s - \frac{D_{LS}}{D_{OS}} \quad \hat{\alpha}(D_{OL}\hat{\theta}_i)$$

where θ_S,θ_i indicate the actual and observed positions of the source,D_{LS},D_{OS},D_{OL} indicate respective distances from the gravitational lens, observer, and the source, and $\hat{\alpha}$ is a function that embodies the gravitational potential of the source.

After initial observations which led to the revelation of Dark Matter, the particular ways of light intersection near galaxies and clusters in weak and strong gravitational lensing respectively lend important insights on how dark matter is distributed inside cosmic systems. The accomplishments to be vanquished here are accurately delineating the dark matter even as it is sheared by the gravitational focal point and sifting through any outer gravitational potential or elliptic data that could confound the data.

Overall, lensing will potentially enable physicists to investigate the nature of dark matter within the universe, arguably the most crucial problem in dark matter physics. Inverting the dark matter mass map utilizes both local and global techniques and further dividing up dark matter energies into their rotational and gradient parts. The filtering process consists of methods proposed by Bayesian Methods and Gauss, both attempting to exact signals and reduce interference from other gravitational sources that would cause error.

The Bullet Cluster, as shown in Figure 3, served as a prime location for dark matter evidence in 2006. The light from several of the galaxies behind the Bullet Cluster had been significantly lensed. Because the background images had been so significantly distorted, its discovery seconded the existence of dark matter and proved dark matter extended far beyond the baryonic core of the cluster.

3.3 CMB[2]

While much of the direct data on DM is inconclusive, measurements of the universe's acoustic fluctuations at the time of recombination in the Cosmic Microwave Background Radiation (CMB) are rather compelling, allowing physicists to deduce the presence of DM and estimate its features .

Because of the small quantum density anisotropies in the early universe, matter began to cluster in areas of greater density and higher gravitational potential, creating even larger anisotropies due to gravitational interaction. Until the recombination event at t = 378, 000 years ago, baryonic matter existed in the form of plasma formed by protons, electrons, and photons, and it was characterised by extraordinarily high energy levels. As a result, when such an excited plasma began to fall into gravitational wells, photons began to fall in between protons and electrons and acted as an elastic pressure force - as photons were compressed past their "equilibrium states" within an anisotropy, they began to decompress, eventually counteract the force of gravity. As a result, oscillations in the fabric of space were created by the “back-and-forth” motion of gravitational pressure and photon decompression – oscillations that were similar to those of a harmonic oscillator. We can detect the distinct components of the universe's early wavering motion at different angular frequencies and wavelengths by breaking down density fluctuations as the sum of several simpler wave functions using Fourier Analysis. The oscillations ceased after recombination, when photons escaped from between protons and electrons, and the CMB is the “fingerprint” of the oscillation at t = 378, 000 years. (This is referred to as the "final scattering" because after this period, photons were free to roam and no longer scattered off protons and electrons as frequently.)The CMB's density fluctuations in the fabric of space are what allow galaxies and solar systems to settle down and develop gravitationally.

The following curve is obtained by graphing the above-mentioned fluctuations as a function of angular frequency: The graph's peaks represent the time when a huge volume of matter had gathered inside a well but the decompression force had not yet taken effect, causing a peak in fluctuation.
A trough, on the other hand, indicates when photons have reached their maximum “elasticity” and have stretched as far as possible out of the anisotropy.

[2] Cosmic Background Radiation

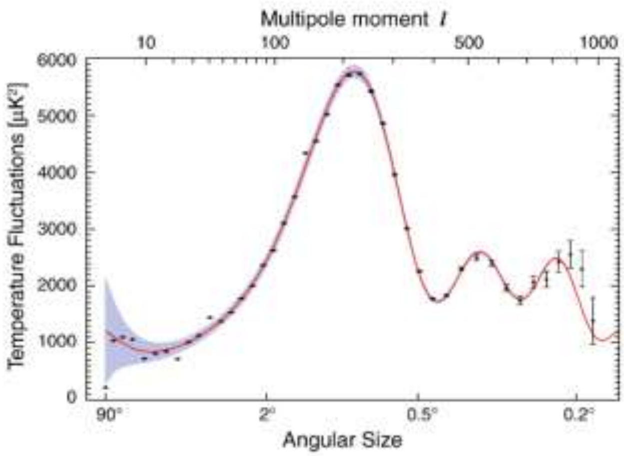

Figure 3:We detect multiple peaks of density corre- sponding to the topography of the cosmos at the time of recombination using decomposed wave functions. At t = 378, 000, these baryonic acoustic oscillations revealed which wave frequencies (and thus density levels) were most abundant.

The relative magnitudes of the initial peak and trough reveal an interesting fact: if the cosmos included solely baryonic matter, the counteracting pressure force would be almost equivalent in strength to the anisotropies' gravity, implying comparable magnitudes within the graph. [nine] However, the peak is clearly larger, implying that the gravitational impact within wells is higher than the photons' counteracting effect. As a result, scientists might deduce that within the anisotropies, there must be a kind of "matter" that interacts primarily through gravity and lacks baryonic flexibility, as seen in the CMB.This not only proves the existence of DM, but also shows its energy density is nearly five times that of baryonic matter.

4.Indirect Detection Of Dark Matter:-

While investigations for dark matter's gravitational effects can provide clues to its identity, definitive identification of DM requires probing its particle nature directly. Evidence for (or against) the veracity of a dark matter hypothesis can be gained by looking at its non-gravitational interactions. These interactions could have astrophysical implications and leave an impression on the properties of luminous stuff. Thermally created WIMPs, for example (as explained in 1.2), are predicted to have ongoing interactions with one another. Standard model particles including gamma rays, neutrinos, and electrons/positrons can be emitted as a result of self-annihilation. The following equation shows the rate of annihilation.

$$R_{annihilation} = \frac{(\sigma v)}{2m^2{}_x} p^2{}_x$$

where ⟨σ*v*⟩ is the thermally-averaged annihilation cross section, m_X is the mass of the dark matter particle, and ρ_X is the density of dark matter. For reference, within the spherical region defined by the radius of the Earth, this would correspond to a single annihilation occurring on average every 110 minutes (assuming ρ_X = 0.3 GeV s$-$1, ⟨σ*v*⟩ = 3×10$-$26 cm3 s$-$1, and m_X = 100 GeV). On larger scales, the slow re- lease of energetic particles can have observable effects – either through production

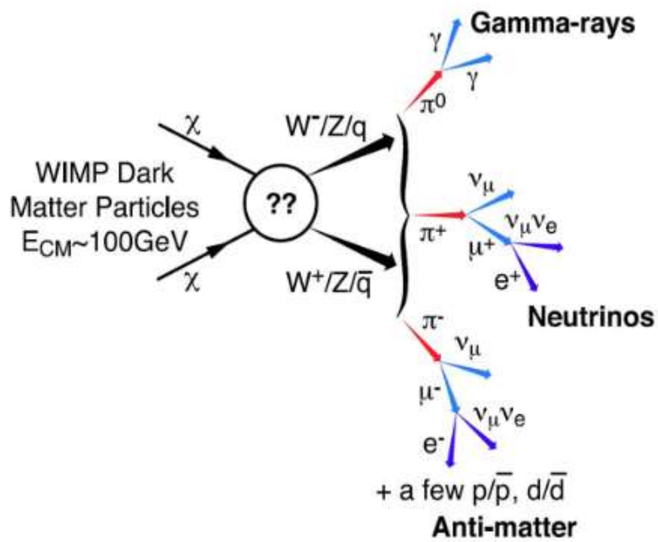

Figure 4: An example of a potential dark matter self- annihilation scheme that results in high energy standard-model annihilation products. Figure from Vitale et al. (2009).

of directly observable radiation (Calore et al., 2015), or by heating the surrounding baryonic matter (Ascasibar, 2007). Dark matter could likewise have a finite decay lifetime. In this case we require a relatively stable particle with a lifetime longer than the age of the Universe, but not so long as to not produce any observable effects. Such a particle would decay at a rate per unit volume given by

$$R_{decay} = \frac{m_x}{t_x \tau_x}$$

where(τ_x) is the dark matter decay lifespan. This decay process could result in the generation of standard model particles, perhaps heating the Universe or emitting a visible signal (Ripamonti et al., 2007).

The purpose of indirect direction in either the annihilating or decaying dark matter scenarios is to eliminate known astrophysical backgrounds in order to seek for dark matter signatures. The remaining unassociated signal's morphological and spectrum features may be examined, allowing us to restrict the particle physics of DM. There are a variety of effects that could potentially increase the signal's power.

For example, if a dark matter particle self-interacts over a larger range before annihilating, the likelihood that the particle would be detected at the annihilation location increases, resulting in a larger effective annihilation cross section — a phenomenon known as Sommerfeld enhancement. In addition to particle impacts, the spatial structure of dark matter, such as increased DM density near the Galaxy's centre or the presence of dark substructure, might produce annihilation enhancement.

Both N-body simulations and observations of galactic rotation curves have yielded an estimated distribution of dark matter within the Galaxy. We can guess where dark matter signals might come from based on this information. The Galactic Centre (GC) is an ideal area to investigate since regions with high dark matter density are inherently the strongest generators of annihi- lation or decay products. It would be expected to be a bright source of these products due to its proximity and density. Similarly, Galactic substructures contain some of the Universe's highest concentrations of dark matter.

Conclusion:-

If the laws of motion and gravity for galaxies hold true, and if galaxy systems are stable, dark matter is required. There is no reason to believe that the laws of motion and gravity in galaxies will fail. Similarly, no evidence of galaxies and clusters of galaxies being unstable has been discovered. Furthermore, gravitational lensing (a modern technique for determining the mass of faraway huge objects), rotational curves, CMB, and dark matter particle annihilation to antimatter and gamma rays all indicate that there must be far more matter in the universe than has been observed thus far.

As a result, even though dark matter is invisible and most of its constituents have yet to be discovered, it is argued that dark matter exists in galaxies, if not elsewhere.

References

Martinez, D., & Sajith, R. (2018). Analyzing Dark Matter and Its Indirect Detection.

Queiroz, F. S. (2016). Dark matter overview: collider, direct and indirect detection searches. arXiv preprint arXiv:1605.08788.

Ringbauer, M. (2014, December 1). Dr Who Meets Professor Heisenberg. Australasian Science, 35(10), 24.

Analyzing Dark Matter and Its Indirect Detection. https://ctlo.caltech.edu/documents/4152/1-summer_paper_6_.pdf