Unveiling the Invisible: The Interplay Between Dark Matter and Dark Energy in Cosmic Evolution

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Abstract: In astrophysics, a lot of astrophysical phenomena seem to act differently than what is predicted by typical understandings of regular physics. For example, in reference to the expansion of the universe, the expansion rate should be slowing down due to the force of gravity, yet it does not, and through measurements of Standard candles, the universe is observed to be expanding at an increasingly fast rate. This implies the existence of another force or energy counteracting and overpowering the force of predicted gravity. Dark matter and dark energy play the crucial roles in the formation of all cosmic structures. The former study reveals that there are some things that cannot be directly observed that have significant impact on cosmic evolution: dark matter and dark energy. In this paper, the author will demonstrate the interplay between dark matter and dark energy, which will eventually play important role on the cosmic evolution.

1 INTRODUCTION

In the universe, everything seemed to make sense in accordance to Newtonian physics, yet when looking at astronomical objects, certain obejcts behave differently, and eventually patterns emerge. Following the Big Bang, the universe had expanded at a rapid rate, and contrary to prediction of the force of gravity slowing down said expansion, an unknown energy or force was driving the expansion to speed up. Once observing certain astronomical objects, it can be noted that certain objects seemed to be moving on its own, which does not make sense, implying an unseen gravitational influence on these objects, which is considered as dark matter. Due to its obvious significance in cosmic evolution and expansion, scientists have come up with a vast number of theories and models to predict the behvaiors and properties of dark matter and dark energy. Dark matter and dark energy's properties make it hard to work with, and as a result it is a theoretical form of matter and energy.

2 THEORETICAL FRAMEWORK

Matter is described as anything that has mass and occupies space. However, there are 2 kinds of matters, normal matter, something people are more accustomed to, since light of different wavelengths can typically reflect off it, and dark matter. Dark matter is a theoretical type of matter that is "invisible", meaning it does not emit, reflect, or absorb any kind of electromagnetic radiation (e.g. X-rays, radio waves) or light, and moves slowly relative to the speed of light. Based on the ΛCDM model, 95% of the universe is dark matter and dark energy, and 5% of the universe consists of atomic matter (NASA).

Dark energy, on the other hand, is predicted to be a hypothetical type of energy that is primarily thought to contribute to the universe's expansion (NASA). It produces a negative pressure which drives the acceleration of the universe, disproving the belief that gravity will eventually slow down the expansion. Despite having a very low density, its widespread presence across the universe makes it dominant in the mass-energy content.

Free streaming length is an important distance in astrophysics in regard to dark matter, since it

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describes the maximum distance dark matter can travel before being slowed down by gravitational interactions (Einasto, 2009). Dark matter can then be divided into three categories, which, contrary to the name of the three categories has nothing to do with the temperature and more so to do with the velocity: CDM (Baudis & Promufo, 2021), WDM, and HDM, cold, warm, and hot. In simple terms, CDM would result in structural formation that follows galaxies forming before galaxy clusters, while HDM will result in large-scale matter congregations, followed by a separation into galaxies (Primack & Gross, 2000).

2.1 WIMPS

There are several theories about dark matter and dark energy, one of which are weakly interacting massive particles, or WIMPs. WIMPs are defined as heavy, electromagnetically neutral subatomic particles. It is theorized to be a major constituent of dark matter. It is seen as an elementary particle, not necessarily from the Standard Model, that interacts with gravity and the weak nuclear force, and is predicted by supersymmetry, universal extra dimension models, and the little Higgs model. Other traits are its greater mass relative to typical standard particles. It doesn't absorb or emit any sort of electromagnetic radiation (Caltech, 2002). All evidence on WIMPs has been indirect.

2.2 MACHOS

Another theory of dark matter is abbreviated as MACHOs, or massive compact halo object. Little is known about MACHOs due to their lack of luminosity (Caltech, 2002). However, there are several MACHOs candidates, black holes, neutron stars, brown dwarfs, and potentially planets that drift through space without a proper planetary system all can be categorized as candidates.

2.3 NEUTRINOS

A neutrino is a fermion that only interacts with the weak nuclear force and gravity. There are a few distinctive traits of neutrinos. Neutrinos are electromagnetically neutral, and thus do not interact with electromagnetic forces, adding on to its already elusive nature. The neutrino also has an extremely small mass. While unknown, it is predicted to be significantly smaller than electrons. It has ½ unit of spin. There are three leptonic flavors of neutrinos: the electron neutrino, muon neutrino, and the tau neutrino. Neutrinos are created because of radioactive decay, examples such as beta decay, nuclear reactions within a star, supernovae, and more. The three leptonic flavors are potential candidates for dark matter, specifically hot dark matter, meaning it moves at nearly the speed of light at redshift $z \sim 10^6$

2.4 Leading Theories of Dark Energy

2.4.1 Cosmological Constant

The cosmological constant, a fundamental constant in Einstein's general relativity is associated with dark energy. In Einstein's equation $E = mc^2$, mass and energy are relative to one another, indicating this energy has a gravitational effect. The cosmic microwave background does not rule neutrinos as a candidate for dark energy, but sterile neutrinos, those that exclusively interact with gravity and no fundamental forces, could potentially make up hot dark matter.

2.4.2 Quintessence

Quintessence is a hypothetical candidate for dark energy, an attempt to explain the constant expansion of the universe, a form of vacuum energy. Its variation in space and time differs it from the cosmological constant (Caldwell, 2019). Quintessence is predicted to be a scalar field. It is spatially inhomogeneous, thus varies in different locations. It is predicted to have a negative pressure, which can be associated with the accelerating expansion of the universe.

3 OBSERVATIONAL EVIDENCE

3.1 Dark Matter Evidence

3.1.1 Galactic Rotation Curve

In galaxies, the arms rotate around the center, and this rotation is solid evidence of the existence of dark matter. Rotation curves are calculated via rotational velocity of stars along the length of the galaxy. When studying galactic rotation curves, it can be found that stellar rotational velocity remains constant, even when the stars are further away from the center of the galaxy. Based on Newton's law of universal gravitation, rotational velocity should theoretically decrease as the distance from the center increases, yet it remains constant. In the solar system, planets that are further away rotate around the sun at a slower rate.

Based on Kepler's laws, this is clearly different for galaxies, indicating that there is a halo of abundant dark matter surrounding galaxies. Through studying gas clouds near the edge of galaxies, one can conclude that there is no concentrated mass distribution in galaxies.

3.1.2 Gravitational Lensing

Gravitational lensing is a phenomenon where massive objects bend light between said object and an observer. Since it is known that although direct observation of dark matter is impossible, dark matter does still distort light. When light passes through dense amounts of dark matter, these distortions can be observed on galaxies. There are three types of gravitational lensing, strong gravitational lensing, weak gravitational lensing and microlensing. Strong gravitational lensing involves a large mass acting as the lens, with favourable geometry, and a large deflection, usually capable of producing multiple copies of images. Weak gravitational lensing involves a large mass with less favourable geometry, with distorted imagery. Microlensing involves smaller masses, such as stars, and despite favourable geometry, it is difficult to fix distortions in images. Microlensing can be used to indirectly observe MACHOs, using the duration of certain events to predict lens mass, which in turn can be used to predict the halo model. This permits measurement of cluster mass without needing velocity.

Two galaxy clusters collided onto one another, and specifically the smaller cluster traveling away from the collision was designated 1E 0657-56, better known as the Bullet cluster. It is strong evidence for the existence of dark matter. Dark matter was detected indirectly by using gravitational lensing. In accordance with MOND, the gravitational lensing should follow baryonic matter, yet it doesn't, and is instead separated into 2 parts. And with the knowledge that dark matter interacts with gravity exclusively, it can be predicted that the 2 areas with the strongest gravitational concentration is dark matter. Other modified theories cannot otherwise explain this displacement in its center of mass.

3.1.3 Velocity Dispersion

Stellar velocity dispersion is shown to be related to dark matter halos. In accordance with the Virial theorem, it is possible to measure distribution of mass within a system, such as a galaxy cluster. Scattering in radial velocity of galaxies can help with mass estimation (Yang et al., 2011). Velocity dispersion is different from observed mass distribution, which can only be explained by dark matter.

3.1.4 Linear Structure Formation

Dark matter is important for linear structure formation, since it permits the formation of compact structures without the influence of radiation pressure due its property of only interacting with gravity. Dark matter halos form through gravitational collapse, creating the familiar astronomical web (Frenk & White, 2012), which reveals all kinds of structures like galaxies, galaxy clusters and more (Nadler, 2022).

3.1.5 Non-Linear Structure Formation

Dark matter is also proposed to be crucial in non-linear structure formation. Dark matter overdensities help with structure formation, as baryonic fluctuations are smaller (Mina et al., 2022). This results in dark matter being the dominant force of structure formation.

3.1.6 Lyα Forest

The Lyα forest is an absorption feature in astronomical spectroscopy, specifically from distant quasars' spectra. It is caused by photons' interactions with neutral hydrogen in the intergalactic medium. There are thousands of absorption systems from these high-redshift quasars. The Lyα forest can be used to constrain cosmological models that are related to dark matter and constrain its properties.

3.2 Dark Energy Evidence

3.2.1 Type Ia Supernovae Observation

A method of observing dark energy involves comparing distance measurements with predicted redshift, which helped conclude that the universe had expanded more in later stages, indicating an acceleration. Type Ia supernovae are good cosmic landmarks for observing things, called Standard Candles. Observations of Type Ia Supernovae at redshifts where $z > 0.5$ demonstrates the acceleration of the universe, which disagrees with the common belief that the universe's expansion rate is decelerating.

3.2.2 Baryon Acoustic Oscillations

Similarly to how Type Ia supernovae are crucial as standard candles, BAO can be used as standard rulers to provide a length scale (Harvard). The lengths of these hypothetical rulers is the distance between the peaks of galaxy distribution. It is given that dark energy is the reason for the universe's accelerating expansion. Understanding dark energy means understanding and successfully measuring the rate of acceleration, which BAO can help with, since it provides information about the current sound horizon to that of different time periods. BAO can help measure the distance-redshift relations, in particular the expansion history of the universe, something commonly associated with dark energy. Having BAO data can make different test models for dark energy possible.

3.2.3 Large-Scale Structures

Large-scale structures contribute to the formation of all kinds of astronomical objects, and observations point to the matter of such structures is up to 30% of the universe's density, which is constant with the idea that 71.3% of the universe if dark matter while 27.4% of it is dark matter and baryonic matter (NASA).

3.2.4 Cosmic Microwave Background

According to CMB anisotropies, the universe is generally flat, which means mass-energy density has to be equal to critical density, which gives scientists the measurement of the ratio of matter to energy, needing dark energy to fill the void that is the 70% remaining (Harvard).

3.3 Combined Observation

Gravitational lensing is one of the most universally useful methods for both dark matter and dark energy observation. Gravitational lensing provides evidence of objects' existence that can't be detected normally. This combined with measurements from the CMB and large-scale structure formation are consistent with the λCDM model of the universe (Harvard).

4 METHODOLOGY

4.1 Data Methods

There are many methods for detecting dark matter and dark energy. Starting with dark matter, there are numerous ways of direct and indirect detection. Direct means of detection are very challenging, but there are attempts, such as using SuperCDMS (Cryogenic Dark Matter Search) SNOLAB, which uses germanium and silicon detectors to find low-mass dark matter particles, or WIMPs, or the LUX-ZEPLIN, which utilizes liquid xenon to detect interactions between dark and normal atomic matter.

As a result, scientists typically directly detect dark matter and dark energy by observing changes in movement in other objects, such dark matter decay. Gamma-ray telescopes look for extra gamma-ray emissions from high-density regions, such as the center of a galaxy. Other methods involve the use of particle accelerators in an attempt to create dark matter via particle collisions. The most reliable way is simply to observe things.

4.2 Analytical Techniques

A model was developed and then improved upon to demonstrate the accretion of dark matter subhalos. The function has many purposes, allowing the prediction of un-evolved subhalo mass functions, the mass function of subhalo accretions, accretion distributions after being given a starting mass, and frequency of mergers. Testing this with N-body simulations reveals that the predictions of this analytical model match up well with the simulations (Yang et al., 2011).

5 RESULTS

5.1 Effects of Dark Matter on Cosmic Structures

Dark matter plays a crucial role in the formation of all cosmic structures. Its properties state it is exclusively affected by gravity, and thus the effects of radiation do nothing to it. Normal matter collapses later and accelerates structure formation. From a technical "bird's eye view" of the universe, it can be seen that all large-scale cosmic structures, galaxies, galaxy clusters all seem to be arranged in a web-like structure as a result of dark matter's gravitational influence, whether it be observed with linear and non-linear dark matter structures.

5.2 Effects of Dark Energy on Cosmic Expansion

Dark energy can be held accountable for the unexpected accelerating rate of expansion of the universe. Dark energy is proposed to exert a negative pressure. Originally, the universe was predicted to have stopped expanding and should slowly collapse, as gravity brings cosmological objects together, which is no longer the case. It can be thought of as a cosmological tug-of-war, where gravity originally slower the expansion, only to be overpowered by dark energy. Dark energy is also thought of as the force that pushes galaxies and other large scale astronomical objects apart. In most models of the universe, the universe is "flat". Dark energy's existence explains this as well.

6 CONCLUSIONS

Dark matter and dark energy are both unable to be directly observed but extremely critical for cosmic evolution, impacting numerous things, such as galaxies, galaxy clusters, the distribution of astronomical objects across the universe, formation of large-scale linear and nonlinear structures, as well as playing a role in the expansion of the universe itself. Despite having similar names and overlapping areas where it's influence comes together, there are no direct interactions between dark matter and dark energy. The biggest problem with dark matter is that it has not been directly reproduced or directly observed, since it is known to not interact with electromagnetic radiation. It only interacts with gravity. Numerous other attempts at explaining cosmological phenomena have been tried, usually without inventing a completely different form of matter, the best known being MOND, Modified Newtonian Dynamics. Other problems with dark matter is there is no understanding of its mass ranges, which makes testing these theories impossible. One of the most accepted models of dark matter, WIMPs, have inconsistencies between its predicted abundance in comparison to the dark matter density in the universe. Current theories also struggle to give truly accurate predictions of galactic rotation curves.

Similarly, dark energy faces several limitations regarding its proposed theories. For example, there are no set properties of dark energy, which prevents good development of models. There are no real constraints for dark energy modelling.

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