Dark Energy and Dark Matter

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Abstract:
Study of space is never ending quest of humanity. An emerging question regards dark energy and dark matter which are the subjects of this contribution. We will consider the difference between the dark energy and dark matter, history of matter and contemporary efforts to find experimental evidence on dark energy and dark matter. We will briefly consider galaxy rotation curves, gravitational lensing and cosmic microwave background.

Keywords: Dark matter, Dark energy, Universe

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1. Introduction

Dark matter theories focus on questions such as how did stellar systems and galaxies evolve throughout time, and how is universe changing with time. Despite its significance, knowledge on cosmology is yet rudimentary and better understanding of dark energy and dark matter presents a challenge.

Dark matter is defined as a substance that pulls galaxies together, while dark energy pushes them apart (causes universe expansion). It was estimated that roughly 27% of the matter in the universe is dark matter and 68% of the energy in the universe is dark energy (NASA, 2024). Normal matter was estimated to form about 5% of the matter in the universe (NASA, 2024).

Normal matter, also known as baryonic matter is composed of particles call baryons, which include protons and neutrons. These baryons make up atoms, which interact with electromagnetic field and can emit, absorb and reflect light. Therefore, normal matter is observable. Dark matter on the other hand is a form of matter that does not interact with electromagnetic field and does not emit, absorb or reflect light. Despite its invisibility dark matter has observable effects on the motion of galaxies (Bertone et al., 2005).

2. History of dark matter

Throughout history, philosophers have been speculating about what are we, what is everything around us made of, and what is the nature of the matter. The ancient Greeks were thinking about these things and they indicated that there might be forms of matter that are imperceptible or not noticeable, simply because it was too far away or invisible and undetectable by our senses. The oldest records on the matter were found from 5th century Before the Christian Era (BCE) (Bertone and Hooper, 2018). Leucippus and Democritus were convinced that all matter was made of the same fundamental and invisible building blocks called atoms and that these atoms were infinite in numbers (Bertone and Hooper, 2018). Sir Isaac Newton contributed significantly to the history of cosmology; in 1687 he published »Philosophia Naturalis Principia Mathematica«. He developed scientific tools leading to discoveries about universe. John Michell and Simon Laplace found that there could exist objects so massive that even light would not be able to escape the gravitational pull (Montgomery et al., 2009). This was considered the first mention of black holes (Bertone and Hooper, 2018). In particular after development of astronomical photography, it was acknowledged that stars were not evenly distributed in the sky. In dense stellar fields, dark regions were observed (Bertone and Hooper, 2018). Two explanations were suggested: either stars were lacking or – an absorbing matter were present along the line of sight (Bertone and Hooper, 2018).The second explanation was considered the more probable one. Lord Kelvin estimated the amount of dark matter in the Milky Way galaxy (Bertone and Hooper, 2018). He claimed that »if stars in Milky Way can be described as a gas of particles, acting under the influence of gravity, then one can establish a relationship between the size of the system and the velocity dispersion of the stars« (Bertone and Hooper, 2018).

The Coma Cluster of galaxies was observed with the telescope (Morrison and Zwicky, 2015, Primack, 2024) and reported on thousands of galaxies. A question was posed what would happen if all these galaxies were stationary? (Morrison and Zwicky, 2015). The answer led to inevitable collapse due to gravity (Morrison and Zwicky, 2015). On the other hand, if the galaxies would be moving above some threshold velocity, they would fly apart (Morrison and Zwicky, 2015). It was concluded that since they are still there after 8000 million years after they were formed, there must exist a fine balance between energy of motion (kinetic energy) and the gravitation attraction (potential energy). If one could measure the kinetic energy, mass of the respective volume of space could be calculated. The result of the calculation indicated that there is about 6 or 7 times more mass in The Coma Cluster than it was observed (Bertone and Hooper, 2018; Morrison and Zwicky, 2015; Primack, 2024).

3. Evidence of dark matter

3.1. *Galaxy rotation curves*

Galaxy rotation curves are rotational velocities of the stars and gas in the galaxy as a function of their distance from the galactic centre. Under some reasonable simplifying assumptions, it is possible to infer the mass distribution of galaxies from their rotation curves.

In 1960s and 1970s, image tube spectrograph was developed (Bertone and Hooper, 2018) to preform spectroscopic observations of the Andromeda Galaxy. The results on the mass in outer parts of some galaxies disagreed with rotation curves predicted from photometry (Bertone and Hooper, 2018). The stars at the edge of galaxies were moving so fast that they should be (according to the theoretical estimations) flung off into space. Instead, the stars stayed in their orbits. This was explained by the gravitational pull exerted by something undetectable (NOVA, 2018).

Newton's law of gravity describes the gravitational force F_g acting on an object with mass m in rotational orbit:

$$F_g = G\, M_{enc}\, m/r^2 \quad , \tag{1}$$

where G is gravitational constant, M_{enc} is the mass enclosed within the orbit and r is the distance from the centre of mass.

The gravitational force acts as the centripetal force F_c needed to keep the object in rotational motion,

$$F_c = mv^2/r \quad , \tag{2}$$

where v is the orbital velocity. When we set these two forces equal to each other and express v, we get

$$v = (G\, M_{enc}/r)^{1/2} \quad . \tag{3}$$

The calculated velocity was however considerably smaller than the measured velocity (**Figure 1**). Agreement however be obtained by assuming the presence of the additional mass, or dark matter, within galaxies. The equations are fundamental to understanding galaxy rotation curves and indicate the existence of dark matter in galaxies.

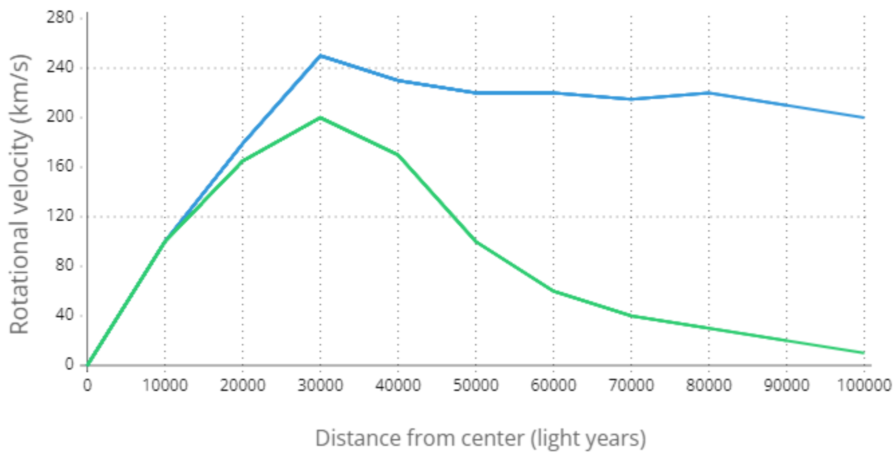

Figure 1: Rotation curves of the Andromeda Galaxy. Measured rotational velocities of the outer stars are the blue line, while velocities that would be expected from the estimated mass of the visible matter in the galaxy are the green line. Adapted from (Nerich, 2011).

3.2 Gravitational lensing

Gravitational lensing is a phenomenon, where the gravitational field of a massive object, such as a galaxy or a cluster of galaxies, bends and distorts the light from distant objects, like background galaxies.

Already Newton considered the possibility that light could be deflected by gravity (Bertone and Hooper, 2018). But within the general relativity theory published by Einstein, this phenomenon was quantitatively predicted (Bertone and Hooper, 2018). The empirical test of gravitational lensing and of the general relativity theory was conducted in 1919 by Arthur Eddington who organized expedition to observe solar eclipse (Bertone and Hooper, 2018). Experiment consisted of measurement of the deflection of light by the gravitational field of the massive object (sun). Bending of light lead to the distortion or magnification of distant objects like background galaxies or quasars. The results of measurement were in favour of Einstein's predictions (Bertone and Hooper, 2018).

After the confirmation, the gravitational lensing became a powerful tool for cosmologists and astrophysicists to study the distribution of matter in universe including dark matter and dark energy. It was used for discovery and study of distant galaxies and for estimation of the expansion rate of the universe (Bertone and Hooper, 2018).

Following Bovy (2023), we describe the deflection of light due to gravity as illustrated in **Figure 2** where a two dimensional representation of the three-dimensional configuration is shown. In the figure, the source is on the left, the lens is in the middle, and the observer is on the right. The extent of the lens are considered much smaller than the distances between the source, lens, and observer so that the lens is taken as very thin in the direction perpendicular to the light ray. The perturbed light path is taken to be a straight line until it reaches the lens at ξ where it changes its direction by the deflection angle $\hat{\alpha}$ and continues its path in a straight line until being observed. The angle β represents the direction of light in the absence of the lens while the angle θ represents the observed direction. All the angles in **Figure 2** are taken to be small and the relation between the angles is (Bovy, 2023)

$$\beta = \theta - \hat{\alpha}(\xi)\, D_{LS}/D_S \qquad (4)$$

where β is the observed angular position of the source, θ is the observed angular position of the image of the source, $\hat{\alpha}$ is the deflection angle, D_{LS} is the distance between the lens and the source and D_S is the distance to the source (**Figure 2**). It follows from the general theory of relativity that in case that point mass is acting as a gravitational lens,

$$\hat{\alpha}(x) = 4GM / (D_L\, \theta\, c^2) \quad , \qquad (5)$$

where G is the gravitational constant, M is the mass of the lensing object and c is the speed of light (Einstein, 1916). Eqs.(4) and (5) relate the apparent position of a distant source θ to its observed position by taking into account the gravitational influence of the mass (M) causing the lensing.

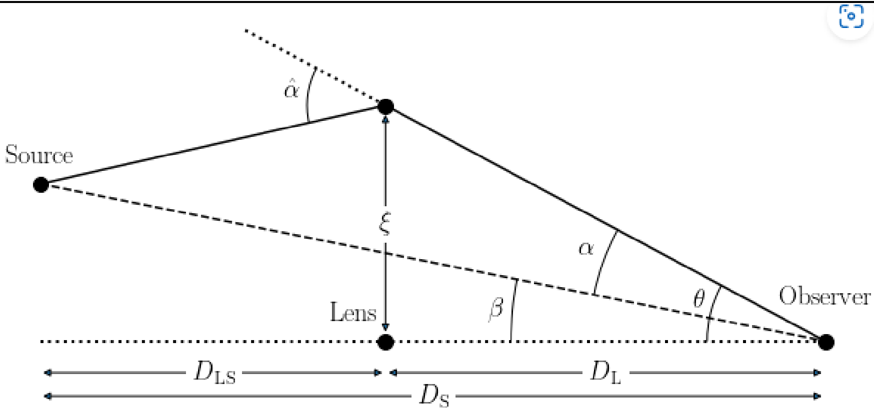

Figure 2: Geometry of lensing system. From (Bovy, 2023).

There are two types of gravitational lensing. Strong lensing: This occurs when the gravitational field is strong enough to produce clearly visible distortions or multiple images of the background object. The lens equation is crucial for understanding and predicting the positions of these multiple images. Weak lensing: In this case, the gravitational distortion is subtle and doesn't produce multiple images but instead causes a slight stretching or shearing of the background object.

3.3 Cosmic microwave background

Cosmic Microwave Background (CMB) is a faint glow of radiation that dates from the very beginning of everything. It's what's left of the early stages of the universe, from the era known as »recombination era«, which occurred 380 000 years after Big Bang (Bertone and Hooper, 2018). At that point the universe cooled down enough for electrons and protons to combine and form different atoms. The first atoms were hydrogen atoms, which made universe transparent for radiation. The light particles (called photons) that were present at that time have been traveling freely through space ever since and we observe them today as cosmic microwave background (Peebles, 1993). CMB supports the Big Bang theory and has provided information about the scale, composition and evolution of the universe, in particular early universe's structure and dynamics.

The radiation spectrum of CMB is given by the Planck's law which law describes the spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature T, when there is no net flow of matter or energy between the body and its environment,

$$I(\nu)= (2h\nu^3)/(c^2(e^{h\nu/kT}-1)) \quad , \qquad (6)$$

where I(ν) is the intensity of radiation, ν is the frequency of the electromagnetic radiation, h is the Planck constant, c is speed of light, k is the Boltzmann constant (Peebles, 1993). The temperature T of CMB is approximately 2.73 K.

To describe CMB, we also need to consider Wien's displacement law that determines at what wavelength λ the intensity of radiation emitted from a blackbody reaches its maximum,

$$\lambda = b/T \qquad (7)$$

where b is the Wien's displacement constant.

3.4 Other evidences

Large scale formation refers to the distribution of matter in the universe on a scale much larger than galaxies such as galaxy clusters and superclusters. By studying these

structures scientists can test the prediction of different cosmological scenarios. The consistency between theoretical models or advanced computer simulations incorporating dark energy and the observed large scale structure may provide evidence for the existence of the dark energy (Blumenthal et al., 1984).
Baryon Acoustic Oscillations (BAO) are unique features imprinted on the distribution of matter in the early universe (Bertone and Hooper, 2018). They originate from acoustical waves in the hot, dense plasma of the early universe, before the formation of atoms. These waves created regions of over-dense and under-dense matter and can be observed in the universe today.

4 Conclusions

The possible realms of dark matter and dark energy continue to captivate and challenge our understanding of the universe. There are evidences and theories that provide explanation of the observations that indicate existence of dark matter and dark energy. This is reflected in accelerated expansion of the universe, gravitational lensing and cosmic microwave background. The pursuit of knowledge regarding dark matter and dark energy, not only expands our scientific comprehension but also pushes us to re-evaluate or re-assess the fundaments of our description by space and time. Technological advances will likely play an important role; we expect a step forward in the field of exploring the universe as in January 2025 Large Synoptic Survey Telescope (LSST) in Chile is expected to start operating (Primack, 2024).

References

1. Bertone G, Hooper D, Silk J. Particle Dark Matter: Evidence, Candidates, and Constraints. Physics Reports. 2005; 405:279-390. DOI: 10.1016/j.physrep.2004.08.031.3
2. Bertone G, Hooper D. Review of modern physics, volume 90: History of dark matter. 2018; 90:2-6. DOI: 10.1103/RevModPhys.90.045002.
3. Blumenthal GR, Faber SM, Primack JR, Rees MJ. Formation of galaxies and large scale structure with cold dark matter. Nature. 1984; 299:37. DOI: 10.1038/311517a0.5
4. Bovy J. Dynamics and Astrophysics of Galaxies. Toronto University; 2023. Chapter 16: Gravitational lensing; E-book Available from: Gravitational lensing (Dynamics and Astrophysics of Galaxies) (galaxiesbook.org)
5. Einstein A. Die Grundlage der allgemeinen Relativitätstheorie. Annalen der Physik. 1916; 354: 769–822.
6. Morisson I, Zwicky F. The Father of Dark Matter. Gresham College. 2015. Available from: https://www.youtube.com/watch?v=TV0c1EFIKy4. Accessed January 16, 2024.
7. Montgomery C, Orchiston W, Whittingham I. Michell, Laplace and the origin of the black hole concept. Journal of Astronomical History and Heritage. 2009; 12: 90 - 96. Available form: https://adsabs.harvard.edu/full/2009JAHH...12...90M
8. NASA. Dark energy, Dark Matter. Available from: https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy/. Accessed: January 16, 2024.
9. Nerich S. Could dark matter not matter? Available from: https://phys.org/news/2011-12-dark.html. Accessed March 8, 2024.
10. NOVA PBS OFFICIAL. How scientists discovered dark matter. 2018. Available from: https://www.youtube.com/watch?v=lNmRHccI4Z8. Accessed January 16, 2024.
11. Peebles PJE. Principles of Physical Cosmology. Princeton University; 1993. Chapter: The thermal cosmic background radiation; p. 131-135.
12. Primack J. A brief history of dark matter. University of California, Santa Cruz. Available from: https://kiss.caltech.edu/workshops/dark_matter/presentations/primack.pdf. Accessed January 16, 2024.
13. Vera Rubin observatory, Monthly updates. Available from: https://www.lsst.org/about/project-status. Accessed March 8, 2024.