ISSN 2959-6157

Searching for Dark Matter Based on Gravitational Lensing

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Abstract:

Gravitational lensing is a powerful astronomical tool in which scholars can accurately predict the distribution of dark matter in massive objects by observing the bending effects of light in the gravitational fields of huge objects (e.g., galaxies or galaxy clusters). Since dark matter does not emit directly, or is strongly interacts with ordinary matter, gravitational lensing gives us a unique view of observing and measuring dark matter. This study introduces some principles of gravitational lensing effect to provide favorable evidence in the study of dark matter and other celestial bodies (including an engineering study in the focal region of solar gravitational lensing (SGL) and other experiments). This research will see how the properties of the clear and focused gravitational lens are applied to celestial observations, and how they are captured by the detector. Strong gravitational lensing can better show distant galaxies (including high redshift) around the dark matter distribution, and through the several basic quantities in gravitational lens analytical and numerical calculation and analysis, to simulate the center of the supermassive black hole, and gravitational lensing image and model of dark matter mass can be detected and dark matter has the key evidences of the interaction. It reveals the intrinsic and distribution of dark matter, thus driving the understanding of the universe's evolution and its fundamental components. Therefore, gravitational lensing has an irreplaceable value and a far-reaching influence in exploring the unsolved mystery of dark matter.

Keywords: Gravitational lens; dark matter; gravitational field; galaxy

1. Introduction

Gravitational lensing is a special optical effect in a strong gravitational field extended by general relativity [1]. The effect can be used to study invisible substance in this universe, especially dark matter. Before searching for dark matter, it is crucial to learn about its first. Establishing a generalization in the conceptual construction of dark matter is the first step in understanding the application principle of gravitational lensing to dark matter. Back in the 1930s, Zwiki studied the star clusters and noticed that individual galaxies moved surprisingly fast, much more than the gravitational force of stars observed in the chart. In fact, with their huge obsession, they should escape the cluster completely [2]. Another explanation for the presence of a large new component of the comet cluster could be an obvious answer. This must be the motivation to pull the galaxies and accelerate them. The matter that existed came to be called dark matter. The concept of this matter which is detected fom galaxy clusters thus leads to astronomy. Some observational evidence of dark matter has been used to clarify the matter. The rotation curves demonstrate for the first time the presence of a tremendous circular dark matter halo in galaxies. This rotation curve indicates that dark matter is a stable, isotropic energy meteor galaxy [3]. Many new and promising theories and techniques can be discovered. Such as abnormal interaction force and class axion dark matter theory model, reviewed in recent years researchers use atomic magnetoometer and common magnetic force for dark matter search technology for dark matter measurement can also take a lot of indirect means [4], e.g., PAMELA for cosmic ray antiproton measurements, ATIC and Fermi satellite for positive and negative electron total energy spectrum measurement results. Another important result comes from the Fermi and ground experiments, which impose strong restrictions on dark matter properties [5]. In fact, the evidence of dark matter is very strong. Without exception, however, the evidence comes entirely from gravity measurements, such as the rotation curve of galaxies, cluster dynamics, gravitational lensing, large-scale structure, and microwave background anisotropy [6]. Among them, the relationship between gravitational lensing and dark matter is an important field of modern astronomy research. In galaxy clusters, the distribution of dark matter affects visible matter's motion , and is closely related to gravitational lensing phenomena. Based on this situation, it is sufficient to prove the value of gravitational lens for the understanding and study of dark matter. This study will introduce and explain the principle of gravitational lens (Sec. 2) and the role of the effect in dark matter detection (Sec. 3 and Sec. 4), to show the current limitations of the observation method and possible improvements in the future (Sec. 5).

2. Descriptions of Gravitational Lensing

The effect is an astronomical phenomena in which massive objects (e.g., galaxies) bend the light that passes around them, causing distant background objects (such as other galaxies or stars) to deform, enlarge or have multiple images in the eyes of observers. As Einstein predicted, galaxy strong gravitational lensing has changed into one of the significant facilities for the study of cosmology [7], galaxy structure and evolution [8]. Simply put, the space around massive objects (such as black holes, galaxies, galaxy clusters) is distorted, causing the light from the underlying bodies (such as galaxies) to bend near the massive object, and then converge into the eyes of the observer. So the observer sees one or more images of the distortion that has occurred. If there is a spercific case of faultless alignment, the illuminant won't be obstructed by the lens. However, it is conspicuous as a luminous ring which is also called the Einstein ring. It has another intereasting condition, an axisymmetric lens, the ring's the angular radius, namely the Einstein radius, is as follows [9]:

$$\theta_E = \sqrt{\frac{4GM_l}{c^2}\frac{D_{ls}}{D_l D_s}} \qquad (1)$$

In 1979, Walsh et al. found that the „biquasar“ Q0957 + 561, and the gravitational lens became the vital notion in the field of astronomy. Figure 1 shows a stunning image of the system [10]. The elliptical galaxies close the quasar image below as well as the rest galaxies in this region are part of the Z=0.36 cluster, which together form the gravitational lensing. The field of view shown is 30-30, north on top, east at left [10].

Fig. 1. The prototype of a strong gravitational lens: Q0957 + 561. Two brilliant blue substances (diffraction spikes) are lensed pictures of quasars (redshift Z=1.41) [10].

In the years following 1979, what has become of the discovery of over a thousand multiple-imaging gravitational lens systems, akin to Q0957 + 561. These systems, often referred to as „strong lens“ systems, beg the question: how do they differ from their counterparts, the weak lenses. From a mathematical standpoint, it is understood that a surface mass density exceeding 1 demarcates the realm of strong gravitational lensing, while densities below this threshold are indicative of weak gravitational lensing. There are optical deflection and image distortion, but there are no multiple images on weak lensing in the solar system.[10] After years of extensive observation and research, it has been confirmed that early-type galaxies act as lenses in most of the detected strong gravitational lensing systems. Although the details of their formation and evolution remain poorly understood [11]. In addition, the micro gravitational lens is also the „family" characteristic branch, under the smooth matter distribution model, the critical curve is strong gravitational lensing system like a plane of a magnification for infinite line, and considering a small amount of discrete mass micro lensing, the source plane distribution will appear complex structure, for dark matter composition detection provides an effective way [12]. Micro-gravitational lensing method indirectly predicts the existence of exoplanets by searching for anomalous „peaks" on the curve of light change. Microgravitational lensing planetary detectors are detectors used to detect gravitational lensing phenomena. Such detectors are specifically designed to detect planets through micro-gravitational lensing, an indirect detection method of distant exoplanets. Microgravitational lensing is an astronomical phenomenon in which a star in a distant galaxy is located between two objects creates gravitational lensing on the star, causing the light to be observed on Earth. This effect can be used to detect and measure planets in distant galaxies by briefly enhancing its luminosity as the planet passes between the star and Earth and is captured by the detector.

3. Principle for Detection

Strong gravitational lensing: a unique key, an exclusive entry, a profound lens into the realm of minute dark matter halos. It acts as cosmic magnifier, depicter, revealer; peering deeper, exploring further, understanding more within these mysterious celestial structures. A beacon of discovery, which guides to the heart of dark matter's domain [13]. Dark matter, an enigmatic presence shrouded in the galaxy's ethereal "halo," exists in a realm beyond the reach of the telescopes. The tale of its evolution is etched into the cosmic fabric, a narrative that whispers through the stars, yet remains veiled by the impenetrable darkness of uncharted space. Its mysterious progression is a cornerstone in the grand epic of the universe, bearing significance that defies human comprehension.But there are still ways to measure the imprint that dark matter leaves in the temperature fluctuations of the cosmic microwave background (CMB) through gravitational lensing. Using measurements of this lens, Hironao Miyatake and colleagues of Nagoya University, Japan, to map the dark matter distribution of stars around distant galaxies with information on the distribution of distant ones at a redshift of about 4.

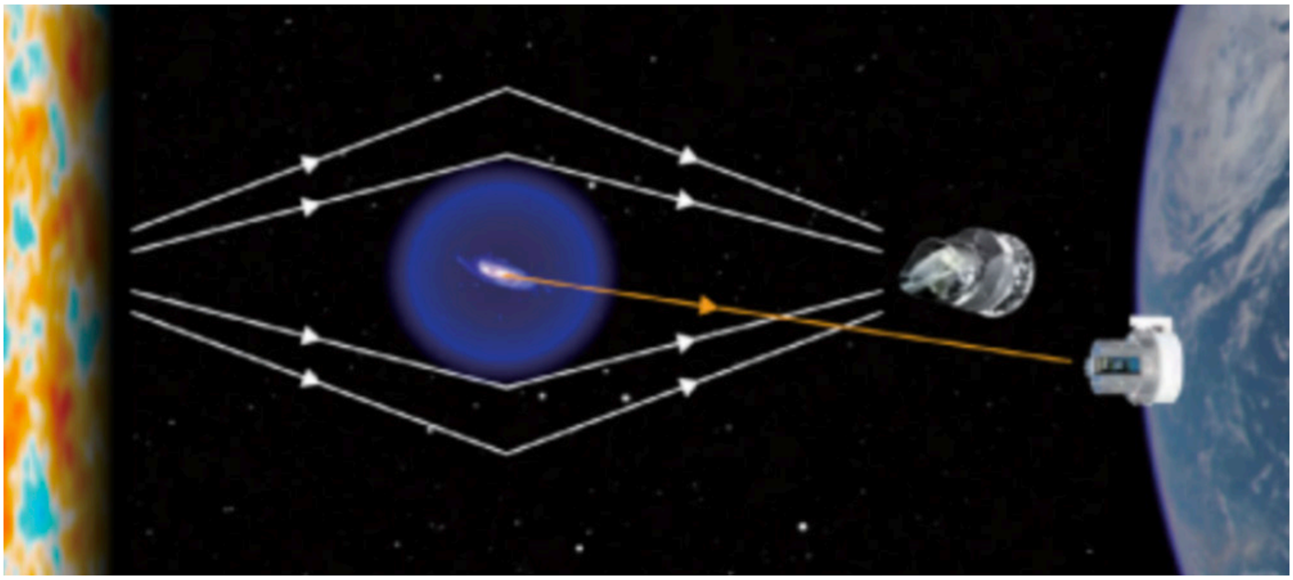

Fig. 2 Far-away galaxies and their surrounding dark matter haloes (blue) can bend CMB light through gravitational lenses (white arrows). Miyatake and colleagues used the Planck satellite's measurements of such lenses, and the Subaru telescope on the ground's optical band of light (orange arrows) from distant galaxies to detect the distribution of dark matter around the galaxies from this area [15].

Using Planck satellite data to study the imprint of high-redshift galaxies on the CMB lens map, Miyatake et al. The team found about 1.5 million clear lens signals generated from high-redshift galaxies called the Lyman Break galaxy (LBG). The researchers juxtaposed the lensing signals with an ethereal model depicting the shrouded embrace of dark matter around galaxies.[14] Using the characteristics of gravitational lensing and dark matter, also conducive to the observation of deep space of other difficult to be found and understand objects, such as black holes, in order to effectively simulate in a simple way galaxy center (surrounded by dark matter halo) supermassive black hole, one studies the perfect fluid dark matter halo Schwarzschild black hole and charged Reissner-Nordstrom black hole, use to the gravitational lens in several basic quantity (gravitational deflection of light, photon ball, black hole shadow radius, gravitational lensing equation and Einstein ring) analytical and numerical calculation and analysis. A meticulously crafted second-order analytical expansion of the gravitational deflection angle is assiduously obtained within the circumscribed boundaries of the weak deflection limit, precisely delineating the gentle curvature of light's path as it succumbs to the subtle gravitational pull in this regime. Assuming M λ DMQ, the results show that dark matter can greatly influence the gravitational lensing of the central black hole [15]. A sketch for detection is shown in Fig. 2.

4. Facilities and Searching Results

Gravitational lensing itself is widely used in the field of astronomy involves the higher requirements of observation equipment, in order to study and measure gravitational lensing, astronomers and researchers use a variety of measuring devices and technology, to the application of the telescope including optical telescope (used to observe the visible band of gravitational lensing phenomenon), radio telescope (can study radio band gravitational lensing, especially when see distant galaxy), space telescope-such as Hubble space telescope (can avoid the influence of the earth‘s atmosphere, provide clearer observation). A CCD (charge-coupled device) camera on the telescope can allow high sensitivity observation and imaging, which is especially suitable to slowly scan the sky for candidate gravitational lensing galaxies. If one wants to have a deeper understanding of gravitational lens how to use equipment in practical applications, one might as well look at a specific project: about the solar gravitational lens (SGL) focus area of the preliminary results of the project, the mission goal is in the sun center distance range for exoplanet imaging operation 548900 astronomical units (AU). The exoplanets, nestled at a distant 547.6 astronomical units from the sun, are bathed in the golden light that is significantly magnified by the Sun Gravitational Lens (SGL). This luminosity, harnessed and channeled with precision, serves as the illuminating beacon for multipixel imaging of far-flung exoplanets, positioned a whopping 100 light-years away from the solar system.Leveraging a meter-scale telescope, one can capture the necessary data to produce images of exoplanets with a surface resolution measured in tens of kilometers, potentially identifying signs of habitability. As the imaging spacecraft traverses within the view, it gathers data pixel by pixel. Given the protracted mission duration and the decades required to reach 900 astronomical units, one proposes an architectural framework designed to minimize transportation time while also reducing mission risk and overall costs. This mission architecture is realized through the spatial integration of solar navigation technology with modular functional units, thereby fostering a mission-capable spacecraft [16]. Through this effect, scientists have obtained some important conclusions about dark matter, including but not limited to direct evidence for the existence of dark matter, and studied the distribution of dark matter halo by observing different galaxies and clusters. There are even clues about the nature of dark matter: one uses simulated observations to demonstrate the feasibility of a forward modeling approach, which extracts information about low-mass dark halos located on the line of sight of strong galaxy-galaxy lenses. This can be used to constrain the mass of the hot relic dark matter particle, the mDM [17]. Previous scholars conduct a rigorous exploration of strong lensing images produced by eight unique clusters, with the objective of quantifying the enigmatic density distribution of their dark matter. the analysis delves into radial regions spanning from 10 kpc to 150 kpc, aiming to unveil the self-interaction cross section of dark matter (DM) particles that has hitherto remained obscured from direct observation. One can deduce the mass configuration of the dark matter subhalos surrounding the central dark matter halos, along with the prominent central galaxies and key member galaxies across all eight galaxy clusters, utilizing the qlens code. This deduced surface density of the dark matter halo is then integrated into the self-interacting dark matter model, thereby enabling us to define the self-interacting cross section on the mass ratio σ / m.The above is a discussion of the dark matter mass and self-interaction [18]. Gravitational lensing results also help astronomers understand the large-scale structure and universe's evolution. The mysterious matter plays a key role in the formation of galaxies and clusters, and gravitational lensing data are able to provide important information about the formation process of these structures.

5. Limitations and Prospects

From the research so far, the study of gravitational lens still has many limitations in the model. In this paper to introduce the principle of gravitational lens, the problem of „simplifying assumption“ is exposed-most models assume that the lens is a mass concentration or a spherically symmetric distribution (such as the glass lens model). This simplification cannot accurately describe complex mass distributions, especially in galaxy groups or large-scale structures. Gravity lensing models are usually based on the assumptions of geometric optics, ignoring possible subtle effects during light propagation, such as the fluctuating properties of light and multipath effects, so, the accuracy of light path propagation also needs to be improved. In terms of dark matter models, the analysis of gravitational lensing often relies on assumptions about the distribution of dark matter within the lens. For example, many models use NFW (Navarro-Frenk-White) or other simple models to describe the density distribution of dark matter, but the parameters of these models are often uncertain. Besides, the neglect of dynamic evolution- -many models assume that the lens mass distribution is static, while, in fact, galaxies and their components may change over time, affecting the accuracy of gravitational lensing. Many gravitational lensing models adopt Gaussian distribution assumptions, but in fact the mass distributions may present more complex non-Gaussian features, which may be overlooked in modeling, so non-Gaussiity will also become a limitation of gravitational lensing. In some cases, there may be multiple lens sources that have an effect on the same background light source, which is considered to be multiple lensing effects, which makes the model and make it difficult to accurately distinguish the contributions of each lens. The common thing is the influence of measurement error and noise. In the observation of gravitational lens, the brightness, shape, redshift and other data of the background source are often affected by measurement error and cosmic noise, which causes difficulties in model fitting and parameter estimation. Nevertheless, in recent years, model corrections and equipment improvements, as well as advances in other fields such as machine learning and data analysis, have made the gravitational lens more promising to uncover more important clues to the mysteries of the universe. For example, a combination of gravitational waves and gravitational lensing could provide a more comprehensive view of events such as black hole mergers. With the use of high-resolution telescopes (e.g., the James Webb Space Telescope), astronomers will be able to observe gravitational lensing phenomena more clearly, obtain higher-quality data, and thus more accurately analyze lensing effects. The discovery of new lensing systems, current and future observations may reveal more complex gravitational lensing systems, such as multiple lensing features or time-varying lensing phenomena, which will provide more clues to the physical mechanisms of gravitational lensing. Interestingly, the application of improving machine learning and data analysis technology also has the use of gravitational lens reality applications, because with the increase of data volume, the application of advanced technologies such as machine learning will enable us to be able to extract gravitational lens signals more effectively, and automatically identify and analyze lens effects, and improve research efficiency.

6. Conclusion

To sum up, the light is bent by dark matter based on gravitational lens based on the analysis. After analyzing the principle of how to use gravitational lensing, one finds that this phenomenon can directly reflect the gravitational field of massive objects, and thus can indirectly detect the presence of dark matter. Many dark matter detection methods, such as the analysis of the cosmic microwave background radiation or observations of stellar motion, have their limitations. Gravitational lensing provides a complementary method to obtain different observation angles and information, and it can even be combined with other observation methods or matter (such as CMB) to provide a clearer picture of the distribution of dark matter. In addition, it has a high sensitivity to amplify distant objects. From its multiple practical significance and concrete research results, gravitational lensing observation provides important empirical support for the study of dark matter, enabling us to explore the distribution and properties of the gravitational effect on light when it cannot be detected directly explored. In the future, the gravitational lens will continue to develop in some aspects, such as verifying and comparing different dark matter models (e.g., cold dark matter, hot dark matter), and measuring the time delay on the gravitational field to better understand the properties of dark matter. As an important astrophysical research clue, one will also use its properties to explore its larger role.

References

[1] Su Y. Gravitational lensing and dark matter detection. Nature, 2010, 32(04): 236-238+250-251.

[2] Xu L, Xu C, Zhang X, et al. The enlightenment of the galaxy rotation curve on the dark matter problem (one of the two dark problems in the universe). Journal of Inner Mongolia University of Science and Technology, 2015, 34(3): 4.

[3] Xu L, Xu F, Zhang X, et al. Guess on “dark matter” (exploration of the two dark problems of the universe ii). Journal of Inner Mongolia University of Science and Technology, 2016, 35(1): 1-7.

[4] Zhao Y, Liu X, Yu D, et al. Application of atomic magnetoometer in anomalous force and axion-like dark matter detection. Measuring technique, 2023, 43(4): 1-14.

[5] Bi X. Status of indirect dark matter detection. Chinese

Science: Physics, mechanics, Astronomy, 2011, 41(12): 4.

[6] Yuan Q. Doctoral dissertation-Dark Matter indirect detection study. The Center for Particle Astrophysics, 2010.

[7] Cao S, Biesiada M, Gavazzi R, et al. Cosmology with strong-lensing systems. The Astrophysical Journal, 2015, 806(2): 185.

[8] Cao S, Biesiada M, Yao M, et al. Limits on the power-law mass and luminosity density profiles of elliptical galaxies from gravitational lensing systems. Monthly Notices of the Royal Astronomical Society, 2016, 461(2): 2192-2199.

[9] Biesiada M, Harikumar S. Gravitational lensing of continuous gravitational waves. Universe, 2021, 7(12): 502.

[10] Saha P, Sluse D, Wagner J, et al. Essentials of strong gravitational lensing. Space Science Reviews, 2024, 220(1): 12.

[11] Treu T, Koopmans L V, Bolton A S, et al. The sloan lens acs survey. ii. stellar populations and internal structure of early-type lens galaxies. The Astrophysical Journal, 2006, 640(2): 662.

[12] Yang X L, Chen Xuechun, Zheng Wenwen, the microgravitational lensing simulation near the isocritical curve. Astronomical News, 2023,64 (2): 17.

[13] Wagner-Carena S, Aalbers J, Birrer S, et al. From images to dark matter: End-to-end inference of substructure from hundreds of strong gravitational lenses. The Astrophysical Journal, 2023, 942(2): 75.

[14] Measurement of the distribution of dark matter around distant galaxies. Physics, 2022, 51(11): 785-786.

[15] Qiao C, Zhou M. The gravitational lensing of Schwarzschild black holes and charged black holes in the perfect fluid dark matter halo. Journal of Cosmology and Astroparticle Physics, 2023, 2023(12): 005.

[16] Helvajian H, Rosenthal A, Poklemba J, et al. Mission Architecture to Reach and Operate at the Focal Region of the Solar Gravitational Lens. Journal of Spacecraft and Rockets, 2023, 60(3): 829-847.

[17] He Q, Robertson A, Nightingale J, et al. A forward modeling approach to infer the mass of dark matter particles from strong gravitational lensing. Monthly Journal of the Royal Astronomical Society, 2022, 511(2): 3046-3062.

[18] Andrade K E, Fuson J, Gad-Nasr S, et al. Strict upper limit on the self-interaction cross section for dark matter by cluster strong lensing. Monthly Journal of the Royal Astronomical Society, 2022, 510(1): 54-81.