

Dark Matter Detection through Gravitational Lensing — analyzing how invisible matter bends light

C. Jayavant Kamesh

Abstract - Dark matter, though invisible to electromagnetic observations, reveals its presence through gravitational effects on visible matter and radiation. One of the most powerful methods for detecting and mapping dark matter is gravitational lensing—the bending of light from distant sources by massive foreground structures. This phenomenon, predicted by General Relativity, allows astronomers to infer the distribution and abundance of dark matter independent of its particle properties. Both strong lensing, which produces arcs and multiple images, and weak lensing, which induces subtle distortions in galaxy shapes, provide critical insights into dark matter halos on galactic and cosmological scales. By analyzing lensing signals across large surveys, researchers can reconstruct mass distributions, test cosmological models, and constrain the role of dark matter in structure formation. Gravitational lensing thus serves as a cornerstone technique for probing the nature and behavior of dark matter in the universe.

Keywords - Dark Matter, Gravitational Lensing, Weak Lensing, Strong Lensing, Mass Distribution, General Relativity, Cosmic Structure Formation, Dark Matter Halos.

I. INTRODUCTION

Gravitational lensing serves as a crucial observational tool for probing the elusive nature of dark matter, which constitutes approximately five-sixths of the universe's material content and does not interact electromagnetically, hence neither emitting nor reflecting light .

Dark matter, while elusive, plays a crucial and multifaceted role in the universe's structure and evolution; its absence would profoundly alter the cosmos. The benefits, or rather, the essential contributions of dark matter are primarily understood through its gravitational influence, which is indispensable for the formation and stability of large-scale structures . Without dark matter, the universe as observed would be dramatically different, and the disadvantages of its absence would manifest across various cosmological scales.

One of the primary "benefits" of dark matter is its critical role in structure formation.

Observations from many different directions consistently indicate that dark matter constitutes approximately five-sixths of the material content of the universe, acting as the gravitational scaffold upon which baryonic matter (ordinary matter) collapses to form galaxies and galaxy clusters .

The early universe was nearly homogeneous, but tiny density fluctuations grew over time due to gravity. Baryonic matter alone could not have formed the observed large-scale structures, such as galaxies and galaxy clusters, within the age of the universe . This is because baryons interact strongly with radiation through electromagnetic forces, which would have exerted pressure preventing their efficient collapse. Dark matter, however, does not interact electromagnetically, allowing it to decouple from radiation and begin clumping gravitationally much earlier and more efficiently .

These dark matter halos provided the gravitational potential wells into which baryonic matter subsequently fell, initiating star and galaxy formation . Without dark matter, the gravitational forces would have been insufficient to overcome the early universe's expansion and the pressure from

radiation, preventing the formation of the cosmic web and ultimately, galaxies as we know them.

Secondly, dark matter is essential for the stability and dynamics of galaxies and galaxy clusters. Rotational curves of galaxies, where stars and gas orbit the galactic center at nearly constant velocities even at large distances, provide compelling evidence for extended dark matter halos surrounding visible matter. If only visible matter were present, the orbital velocities of stars far from the galactic center would decrease significantly, consistent with Keplerian dynamics. The observed flat rotation curves imply that there is much more mass—invisible dark matter—distributed beyond the luminous region of galaxies, providing the necessary gravitational pull. Similarly, in galaxy clusters, the velocities of individual galaxies and the hot X-ray gas distribution indicate a total mass far exceeding that of the visible components. Dark matter provides the gravitational binding force that holds these massive structures together, preventing them from flying apart.

The disadvantages or consequences of dark matter's absence would be catastrophic for the cosmic architecture:

- **No Large-Scale Structure Formation:** As previously discussed, the fundamental gravitational instability required for the rapid growth of density perturbations into large-scale structures would be largely absent. Without dark matter, the universe would remain much more uniform, devoid of galaxies, galaxy clusters, and the intricate cosmic web observed today.
- **Unstable Galaxies and Clusters:** Even if some proto-galaxies could form through extremely inefficient processes, they would be gravitationally unstable. The stellar and gas components would quickly disperse due to insufficient gravitational binding, leading to a universe without stable, long-lived galaxies or galaxy clusters.
- **Altered Cosmic Microwave Background (CMB) Anisotropies:** The precise patterns of temperature fluctuations in the CMB, which are remnants of the early universe, are sensitive to

the composition of the universe, including the ratio of dark matter to baryonic matter. The absence of dark matter would lead to significantly different CMB anisotropies, inconsistent with current observations, indicating a universe with a distinct evolutionary history.

- **Inconsistent Cosmological Parameter Estimates:** Current cosmological models, such as the Lambda-CDM model, derive parameters like the dark matter density based on a universe dominated by dark matter. Without dark matter, the values of these parameters would drastically change, leading to a cosmological model that cannot explain current observations, including the expansion rate of the universe and the abundance of light elements.
- **Impact on Gravitational Lensing Phenomena:** Gravitational lensing itself, which is a powerful tool for detecting dark matter, would be profoundly affected. The bending of light observed around galaxies and galaxy clusters, forming arcs, multiple images, and cosmic shear, is largely attributed to the gravitational potential of dark matter [1562]. Without dark matter, these lensing effects would be significantly weaker or entirely absent, making it impossible to observe the strong lensing phenomena used to map mass distributions and test dark matter models. The subtle distortions in the shapes of distant galaxies, used in weak gravitational lensing, would also disappear, removing a crucial probe of the universe's large-scale mass distribution.

Despite its indispensable role, the fundamental nature of dark matter remains one of the greatest mysteries in modern physics. Its "invisible" nature, arising from its lack of interaction with electromagnetic forces, makes direct detection incredibly challenging.

Gravitational lensing, however, provides a unique observational window into its presence and distribution, serving as an indirect detection method. By observing how light is bent by massive structures, scientists can infer the mass distribution of dark matter, probe its properties on various scales,

and differentiate between different dark matter models, such as Cold Dark Matter (CDM) and Warm Dark Matter (WDM).

This technique leverages the bending of light from background sources due to the gravitational fields of massive foreground objects, allowing scientists to infer the presence and distribution of this otherwise invisible matter. The phenomenon is a direct consequence of General Relativity, where mass concentrations modify the space-time metric, deflecting photon paths and altering the apparent flux and shape of astronomical sources.

The application of gravitational lensing to dark matter research spans various scales, from galactic halos to galaxy clusters and cosmic shear. Dark matter halos are fundamental cosmological structures, and their properties such as concentration, ellipticity, and mass centroid encode information about their formation and evolution [9]. Gravitational lensing provides a unique "direct" view of dark matter distribution without needing to speculate on the distribution of ordinary matter within these structures [5].

There are primarily two regimes of gravitational lensing employed in dark matter detection: strong lensing and weak lensing.

Strong Gravitational Lensing Strong gravitational lensing occurs when light from a distant source is significantly deflected by a massive foreground object, such as a galaxy or a galaxy cluster, creating multiple images, arcs, or even Einstein rings of the background source. This phenomenon is particularly effective for probing dark matter on sub-galactic scales.

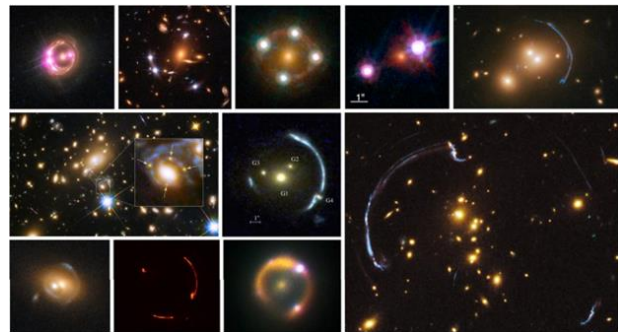
The subtle perturbations observed in lensed images are largely influenced by dark matter substructures within the main lens galaxy and along the line-of-sight.

For instance, strong lensing enables the detection of subhalos with masses as low as approximately 19 Solar Masses. These subhalos, which are smaller clumps of dark matter within larger halos, leave distinct gravitational imprints on the multiple images of lensed sources. Researchers use precision analysis

of galaxy-galaxy strong gravitational lensing images to characterize these small-scale dark matter halos, which can reveal fundamental properties of dark matter constituents, including differentiating between cold dark matter (CDM) and warm dark matter (WDM) models.

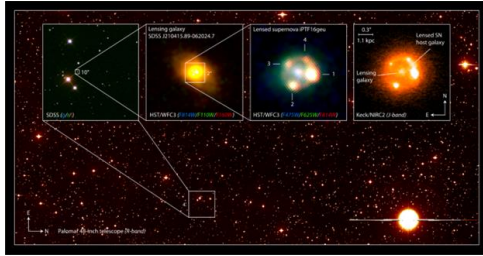
Strong lensing by galaxy clusters also plays a pivotal role in mapping dark matter distribution on a range of scales, revealing the properties of high-redshift background galaxies, and constraining the particle nature of dark matter and global cosmological parameters like the Hubble constant. For example, studies have shown that modeling cluster halos with ellipticity in their gravitational potential can bias the inferred mass and concentration, highlighting the importance of accurate strong lensing data.

The image below illustrates strong lensing phenomena through various astronomical observations, including a prominent curved blue arc indicative of an Einstein ring formed by light from a distant source bent around massive foreground galaxies.



Gravitational Lensing Phenomena

Another example is the multiple imaging of supernovae, like iPTF16geu, caused by strong gravitational lensing, which can be used to measure cosmological distances and constrain cosmological parameters.

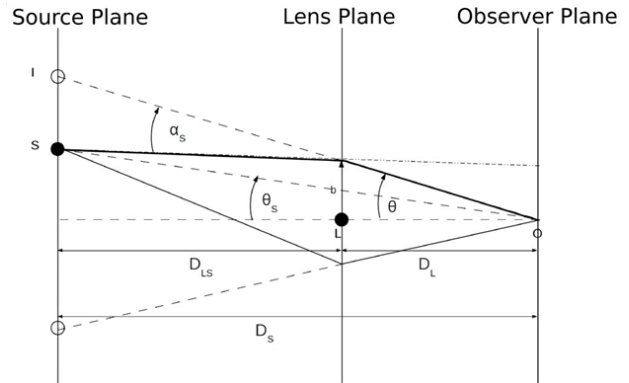


Lensed Supernova iPTF16geu

Weak Gravitational Lensing Weak gravitational lensing, in contrast to strong lensing, involves subtle distortions in the shapes of distant galaxies, which are statistically analyzed to reconstruct mass maps. This technique is sensitive to the total mass distribution, including dark matter, without making assumptions about its physical properties. It is particularly valuable for probing the amount, location, distribution, and power spectrum of dark matter over large cosmic scales, such as cosmic shear, which refers to the coherent distortion of galaxy shapes across vast regions of the sky.

Recent advancements in weak lensing observations have made significant progress in understanding the dark matter component of the universe. Statistical methods have been developed to reconstruct and analyze dark matter mass maps from weak lensing observations, offering insights into the large-scale structure of the universe. Weak lensing can also be used to characterize properties of dark matter halos like concentration and ellipticity, improving mass estimates and testing various dark matter models. However, the distribution of weak lensing cluster shapes might be insensitive to certain dark matter properties, such as self-interacting dark matter, despite significant differences in 3D halo shapes .

The diagram below illustrates the fundamental concept of gravitational lensing, showing the source plane, lens plane, and observer plane, and how light rays are bent by the gravitational field of a massive object (the lens) .

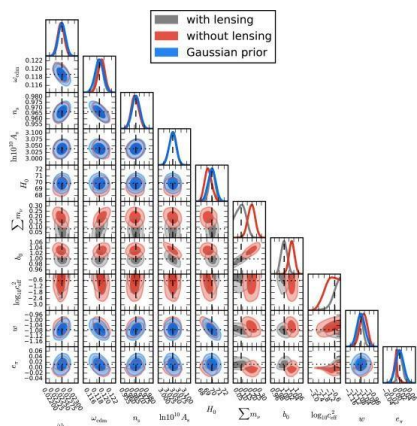


Gravitational Lensing Diagram

Advanced Applications and Future Directions Gravitational lensing is also being explored to study the nature of dark matter microphysics.

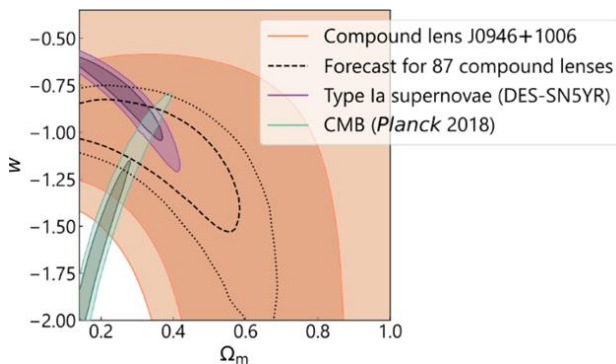
This includes investigating theoretical models such as inelastic dark matter, which attempts to resolve discrepancies in experimental results like those from DAMA/LIBRA . Future experiments like SABRE aim to further test these models . Beyond light, gravitational lensing also affects gravitational waves (GWs). Lensed GW signals from merging massive black hole binaries can be used to probe dark matter halos, including those composed of Fuzzy Dark Matter (FDM). When the GW wavelength is comparable to the characteristic scale of the lens, wave-optics effects manifest as frequency-dependent modulations in the GW waveform, encoding valuable information about the lensing system and potentially the dark matter's viscosity. For instance, future ground-based Einstein Telescope and satellite GW detectors like LISA could potentially discern these effects.

Gravitational lensing observations are critical for cosmological parameter estimation. Studies show that including gravitational lensing effects in analyses often leads to tighter constraints on cosmological parameters such as the cold dark matter density parameter (Ω_{ch2}), baryon density parameter (Ω_{bh2}), and the Hubble constant (H_0) .



Cosmological Parameter Constr...

The various curves in this figure show how different cosmological probes, including gravitational lensing, provide constraints on parameters like matter density (Ω_m) and dark energy equation of state (w). The consistency of these overlapping regions from different probes supports current cosmological models.



Constraints on Ω_m and w

Gravitational lensing also enables the investigation of dark matter halo models that go beyond spherical-collapse approximations, incorporating factors like ellipsoidal-collapse conditions, angular momentum dynamics, and the cosmological constant.

Semianalytical techniques are being used to characterize soliton signatures in self-interacting scalar field dark matter within galaxy clusters through their density profiles, gravitational lensing deflection angles, and surface mass density excess.

This has led to new insights into the distribution of dark matter in the universe and has the potential to revolutionize our understanding of cosmology. But gravitational lensing isn't just about cosmology and astrophysics - it also has practical applications here on Earth. For example, the technology used to detect exoplanets using microlensing can also be used to detect small asteroids and other objects in our own solar system that could potentially collide with Earth. By monitoring the brightness of distant stars over time, scientists can detect the tiny changes caused by the gravitational lensing effect of a passing object and use this information to determine its mass and distance.

One other use of gravitational lensing is to study the structure and evolution of galaxies. By analyzing the distortions in the light of distant galaxies caused by the gravitational lensing effect of foreground objects, astronomers can map out the distribution of matter within the galaxies and study their formation and evolution.

The utility of dark matter for Earth is indirect but profound, primarily stemming from its indispensable role in the formation and stability of the large-scale cosmic structures, including our Milky Way galaxy, which hosts the solar system and Earth. Dark matter, which constitutes approximately five-sixths of the universe's material content, acts as the gravitational scaffolding that enabled the formation of galaxies and galaxy clusters. Without dark matter, the universe as we observe it today, replete with galaxies, stars, and planets, would not exist.

Specifically, the benefits of dark matter that indirectly impact Earth include:

Galaxy Formation and Stability: Dark matter halos provided the gravitational potential wells necessary for baryonic matter (ordinary matter, which makes up stars, planets, and ourselves) to clump together and form galaxies. Baryonic matter alone could not have formed the observed cosmic structures within the age of the universe due to its strong interaction with radiation. The Milky Way galaxy, like others, is embedded within a vast dark matter halo, and this halo's gravitational pull is crucial for the galaxy's

stability. It ensures that stars, gas, and dust (including our solar system) orbit the galactic center at observed velocities, preventing the galaxy from flying apart. If dark matter did not exist, the Milky Way would be gravitationally unstable, and the solar system might not have formed or remained stable within it.

Star and Planet Formation: The existence of stable galaxies is a prerequisite for star formation, as stars coalesce from dense pockets of gas and dust within galactic environments. Planets, including Earth, then form from the remnants of these stellar nurseries. Therefore, dark matter's role in galactic stability indirectly facilitates the conditions necessary for star and planet formation.

Cosmic Evolution and Conditions for Life: The overall structure and evolution of the universe, driven by the gravitational influence of dark matter, have created an environment conducive to the development of complex systems, including life. Without dark matter, the universe would be largely uniform, devoid of the distinct galaxies and clusters that provide localized environments for complex chemical and biological processes to occur.

While dark matter itself does not interact directly with Earth or its inhabitants in any known way—it does not emit or reflect light and only interacts gravitationally—its gravitational omnipresence is a fundamental condition for the existence of the Earth within a stable galaxy. Scientists use indirect methods, such as gravitational lensing, to study dark matter's distribution and properties, which helps us understand the universe's evolution and our place within it. Gravitational lensing allows researchers to map dark matter distribution by observing how the invisible mass bends the light from distant sources, providing crucial evidence for its existence and its role in cosmic structure formation.

The strength of a gravitational lensing effect, which describes the bending of light by massive objects, is primarily dictated by two fundamental factors: the mass of the lensing object and the alignment between the source, the lens, and the observer.

This phenomenon is a direct consequence of Einstein's General Relativity, where mass warps spacetime, causing light to follow curved paths.

The mass of the lens object is paramount. A more massive object produces a stronger gravitational field and, consequently, a greater deflection of light rays passing nearby. This is because the extent to which spacetime is curved is directly proportional to the mass contained within it. For example, galaxy clusters, which are among the most massive structures in the universe, can cause significant lensing effects, including the formation of prominent arcs and multiple images of background galaxies. These distortions are far more pronounced than those caused by individual galaxies, highlighting the direct relationship between lens mass and lensing strength.

The alignment between the source, lens, and observer is equally crucial. The maximal lensing effect, leading to phenomena like Einstein rings, occurs when the source, lens, and observer are almost perfectly aligned along a straight line. As the alignment deviates from perfect, the lensing effects diminish, transitioning from strong lensing (producing multiple images or arcs) to weak lensing (resulting in subtle shape distortions of background galaxies) ³. The closer the light ray from the source passes to the center of the lensing mass, the greater the deflection angle.

The Einstein Radius (θ_{E}) is a key conceptual and quantitative measure directly related to the strength of strong gravitational lensing phenomena, such as Einstein rings. Conceptually, the Einstein Radius represents the angular radius of a perfect ring of light that forms when a background source, a foreground lensing mass, and the observer are in exact alignment. This angular radius is where the light from the background source is maximally deflected to form a circular image around the lens.

For instance, the formation of an Einstein ring, such as the one described by Minwalla (2024), where a star lies directly behind a black hole, illustrates the concept of the Einstein Radius. The angular location of this ring, as observed, is its Einstein Radius.

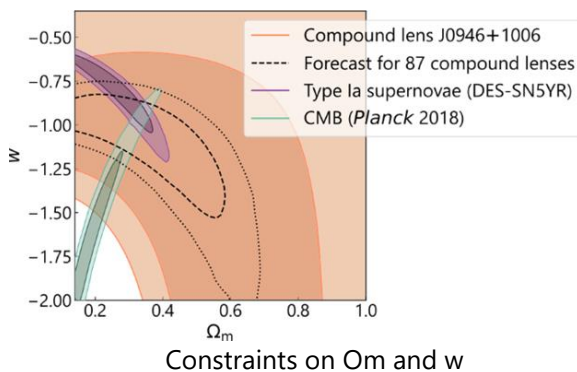
The strong lensing effects characterized by the Einstein Radius are critical for various scientific investigations:

Dark Matter Mapping: The observed configurations of lensed images, particularly the size and shape of Einstein rings and arcs, directly inform the distribution and quantity of dark matter within the lensing galaxy or cluster. By modeling these distortions, scientists can create maps of the dark matter halo, revealing structures that are otherwise invisible.

Probing Substructure: Deviations from a perfectly smooth Einstein ring or multiple arc system can indicate the presence of dark matter substructures (subhalos) within the lensing galaxy.

These substructures leave gravitational imprints that, when analyzed, can help differentiate between various dark matter models, such as Cold Dark Matter (CDM) and Warm Dark Matter (WDM).

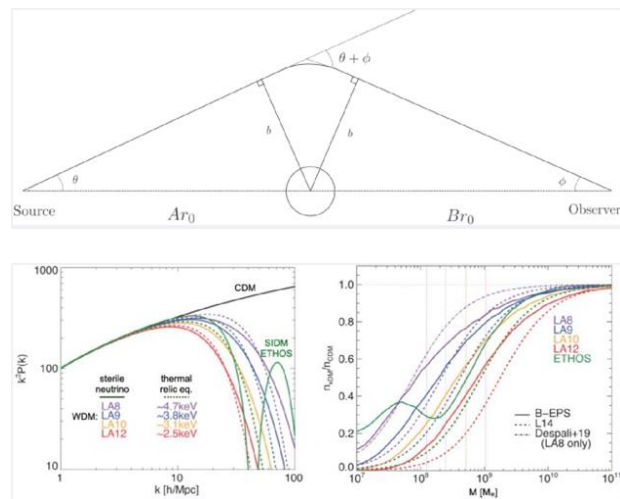
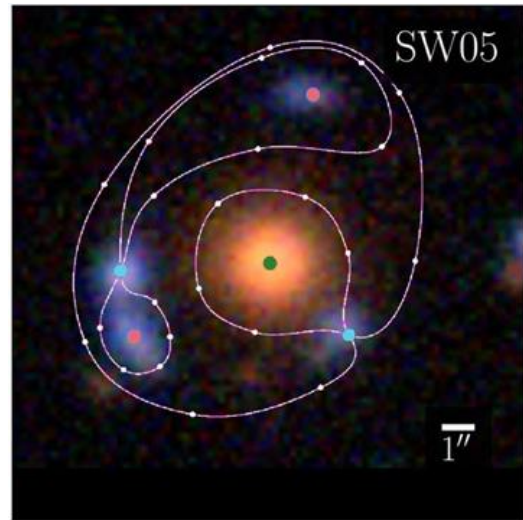
Cosmological Parameter Constraints: The statistics of strong lensing events, including the sizes and numbers of Einstein rings, can be used to constrain cosmological parameters like the Hubble constant and the density parameters for matter and dark energy. The image below illustrates how different cosmological probes, including gravitational lensing, provide constraints on parameters like matter density (Ω_m) and dark energy equation of state (w).



The various curves in this figure show how different cosmological probes, including gravitational lensing, provide constraints on parameters like matter density (Ω_m) and dark energy equation of state (w).

The overlapping regions from different probes underscore the consistency of current cosmological models.

In summary, the strength of gravitational lensing is fundamentally governed by the mass of the lensing object and the precise alignment of the source, lens, and observer. The Einstein Radius serves as a powerful conceptual and quantitative descriptor for the angular scale of strong lensing phenomena, providing invaluable insights into the distribution of dark matter and broader cosmological parameters.



While gravitational lensing is a powerful tool for understanding dark matter and cosmic phenomena, its application is not without inherent difficulties and limitations that complicate the interpretation of observational data. These challenges necessitate

sophisticated analytical techniques and careful consideration during research.

One significant difficulty is the mass-sheet degeneracy . This ambiguity arises because the observed lensing effect is primarily sensitive to the projected mass distribution of the foreground lens along the line of sight, rather than its three-dimensional structure . A uniform sheet of mass added to a lens model, or a rescaling of the mass distribution, can produce a similar lensing effect on the images of background sources, making it challenging to uniquely reconstruct the true mass distribution of the lens.

This degeneracy means that multiple different mass models can equally well explain the same observed lensing configurations, thereby introducing uncertainties in the derived dark matter properties or cosmological parameters. Addressing this requires additional constraints, often from independent measurements or assumptions about the lens's mass profile.

Projection effects further complicate the analysis of dark matter distribution.

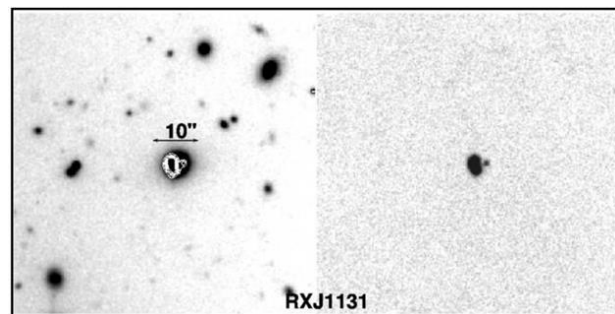
Gravitational lensing inherently measures the projected mass density along the line of sight from the observer to the background source . This means that the lensing signal integrates all the mass present in the foreground, including both the primary lensing object (e.g., a galaxy or cluster) and any other intervening structures or substructures along the path. Consequently, disentangling the contribution of the main lens from foreground or background dark matter halos and substructures along the line of sight becomes complex .

Reconstructing the three-dimensional distribution of dark matter from these two-dimensional projected maps is an ill-posed problem, often requiring tomographic techniques and statistical methods to infer spatial information.

The reliance on source properties also presents a challenge, particularly for weak gravitational lensing. Weak lensing studies require a large number of

distant, background galaxies whose intrinsic shapes are assumed to be statistically random and uncorrelated . Any coherent alignment in the observed shapes of these galaxies is then attributed to the lensing shear caused by intervening dark matter . However, obtaining a sufficiently large sample of faint, distant galaxies with well-measured shapes is observationally intensive and subject to biases, such as those introduced by instrumental point spread functions or intrinsic alignments of galaxies that are not due to lensing. For strong lensing, while it often provides more direct evidence of mass, it still requires high-quality imaging to resolve the multiple images, arcs, or Einstein rings, and to accurately model their distortions. The quality of these images directly impacts the precision with which the lens mass distribution can be constrained.

The example image of RXJ1131, likely an astronomical observation of a celestial object, underscores the need for clear visual data to discern potential lensing features.



RXJ1131

These difficulties highlight that while gravitational lensing is a powerful probe for dark matter, accurate and reliable results depend heavily on sophisticated modeling, advanced observational techniques, and the careful treatment of systematic uncertainties.

II. CONCLUSIONS

Gravitational lensing provides compelling and independent evidence for the existence of dark matter by revealing mass distributions that cannot

be explained by luminous matter alone. Through both strong and weak lensing observations, astronomers are able to map dark matter halos across a wide range of scales, from individual galaxies to large-scale cosmic structures. These observations consistently support the dominant role of dark matter in galaxy formation and evolution, as well as in shaping the large-scale structure of the universe. Moreover, lensing studies offer crucial constraints on cosmological parameters and help test competing models of dark matter and gravity. As observational techniques and survey data continue to improve, gravitational lensing will remain an essential tool for advancing our understanding of the nature, distribution, and fundamental properties of dark matter.

REFERENCES

1. Einstein, A. (1936). Lens-like action of a star by the deviation of light in the gravitational field. *Science*, 84(2188), 506–507.
2. Zwicky, F. (1937). On the masses of nebulae and of clusters of nebulae. *The Astrophysical Journal*, 86, 217–246.
3. Bartelmann, M., & Schneider, P. (2001). Weak gravitational lensing. *Physics Reports*, 340(4–5), 291–472.
4. Clowe, D., et al. (2006). A direct empirical proof of the existence of dark matter. *The Astrophysical Journal Letters*, 648(2), L109–L113.
5. Massey, R., Kitching, T., & Richard, J. (2010). The dark matter of gravitational lensing. *Reports on Progress in Physics*, 73(8), 086901.