Through the Cosmic Lens: The Science, Challenges, and Future of Gravitational Lensing

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ABSTRACT

Gravitational lensing, a consequence of Einstein's general theory of relativity, is one of the most powerful tools in modern astrophysics. This phenomenon occurs when massive celestial objects bend and magnify light from distant sources, enabling astronomers to study otherwise hidden regions of the universe. This article explores the impact of gravitational lensing in detecting distant galaxies, quasars, and exoplanets, as well as its crucial role in mapping dark matter. Despite its advantages, gravitational lensing presents challenges such as image distortion, dependence on unknown mass distributions, and the unpredictability of microlensing events. However, advancements in telescope technology, artificial intelligence, and automated de-lensing techniques rapidly enhance our ability to interpret and utilize gravitational lensing data. As AI-driven analysis and next-generation telescopes, including the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope, come into operation, gravitational lensing is poised to revolutionize our understanding of the cosmos, from uncovering the secrets of dark matter to discovering Earth-like exoplanets.

Keywords: Gravitational lensing, Dark matter mapping, Microlensing exoplanet detection, AI-driven analysis, Next-generation telescopes

Introduction: What Is Gravitational Lensing?

Contrary to popular belief, light does not always travel in a straight line. Its path can be curved as it passes near massive objects like galaxies or black holes, a phenomenon known as gravitational lensing.

But how does gravitational lensing work? The greater the mass of a celestial body, the stronger its gravitational attraction. The gravitational force of an asteroid is minimal, whereas that of the Sun is sufficiently strong to maintain planetary orbits. In the presence of substantial cosmic entities such as galaxies and black holes, gravity distorts spacetime to such an extent that light, which typically travels in a linear trajectory, adheres to curved pathways around these phenomena. This indicates that the light from a star or galaxy can bend around an object to reach our telescopes on Earth, rendering gravitational lensing more than merely a natural occurrence. It serves as an instrument enabling astronomers to observe concealed regions of the universe (Figure 1).

Einstein first proposed gravitational lensing in 1915 as part of his general theory of relativity.[2] According to this theory, gravitational lenses can bend light and magnify celestial objects and structures. In 1919, scientists first observed this phenomenon during a solar eclipse when stars near the Sun appeared slightly displaced from their known positions.[3] This change in their apparent position resulted from the Sun's "lensing effect" on their starlight (Figure 2).

This groundbreaking discovery was confirmed by Einstein's theory and marked the beginning of gravitational lensing as a powerful tool in astrophysics. Since then, scientists have used the phenomenon to discover distant stars and galaxies and learn more about dark matter.

But gravitational lensing, like many scientific endeavors, has certain challenges. While it identifies and magnifies distant objects, it can also distort or fragment them, complicating observations. The present study delves into the remarkable discoveries facilitated by gravitational lensing, the intriguing challenges it presents, and the innovative strategies scientists are beginning to use to overcome these challenges.

Discoveries: Gravitational Lensing as a Window into the Distant Universe

Detecting Galaxies, Quasars, and Stars

The Hubble Space Telescope captured its first gravitationally lensed object 5 months after its launch in April 1990. This object, known as Einstein's Cross, was a quasar whose light was split into four images by the gravitational field of a nearby galaxy (Figure 3).[5]

Since then, Hubble has captured images of some of the most distant gravitationally lensed objects, including MACS0416, a pair of colliding galaxy clusters located 4.3 billion light-years away.[7] One of its most remarkable discoveries came in 2022 when it captured the image of Earendel, the most distant star ever

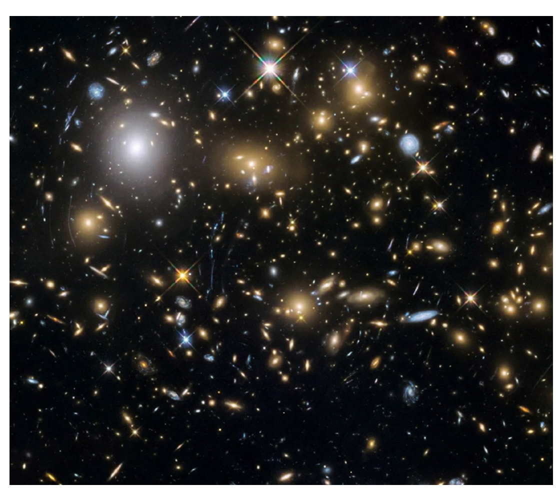

Fig 1 | The image taken by the Hubble telescope reveals some of the faintest and earliest known galaxies. These galaxies can be viewed thanks to gravitational lensing.[1] Credit: ESA/NASA

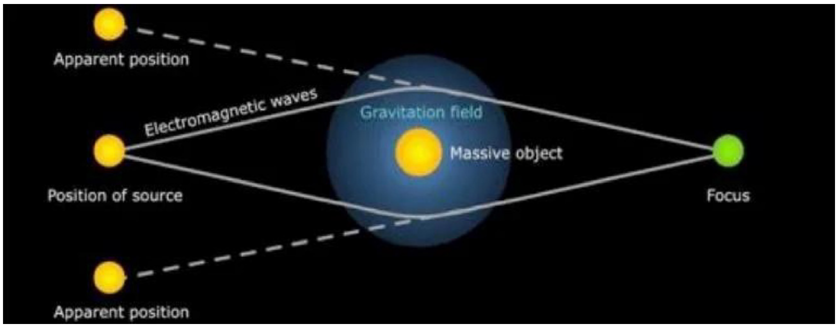

Fig 2 | For the 1919 solar eclipse experiment, scientists looked for stars behind the Sun. If Einstein's General Theory were right, their starlight would be bent by the Sun's gravity, making them appear on either side of the Sun.[4] Credits: NASA

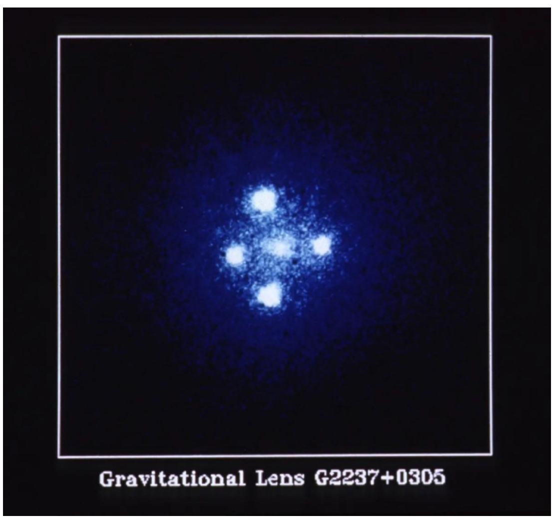

Fig 3 | The image shows an Einstein Cross.[6] Credits: NASA

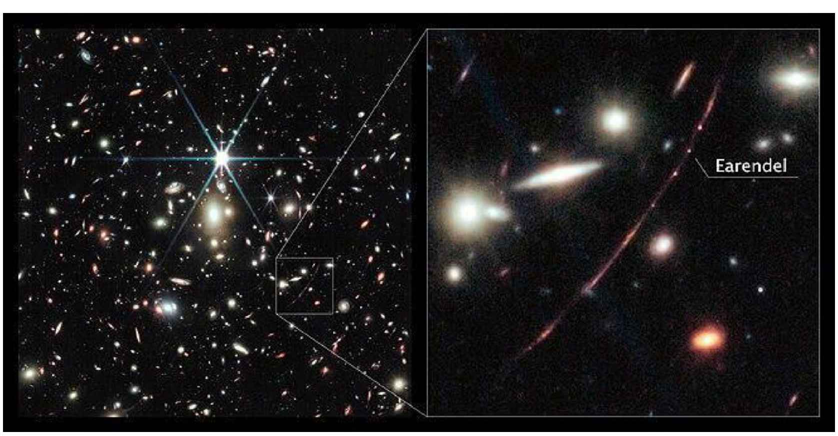

Fig 4 | The image shows galaxy cluster WHL0137-08 and Earendel. Earendel's galaxy is so warped that it only appears as a red streak.[9] Credit: Wikipedia

observed. Its light travelled 12.9 billion years to reach Earth, indicating that Hubble observed it as it appeared when the universe was merely 7% of its current age. Earendel would have been impossible to view if its light had not been magnified thousands of times by the galaxy WHL0137-08 (Figure 4).[8]

Another significant discovery is SPT0418-47, an extremely distant galaxy, resembling the Milky Way, observed as it appeared over 12 billion years ago.[10] Astronomers could examine its structure and acquire new insights into the formation of galaxies in the early universe.

Revealing Dark Matter

Dark matter constitutes 26% of the universe, but it remains a mystery to astronomers. This is because it does not emit, absorb, or reflect light, making it invisible to telescopes. Astronomers investigate this invisible matter through its gravitational effects on visible matter, cosmic structures, and light traversing space.

Various methods have been used for this purpose over the years. One of these methods involves analyzing the rotation curves of galaxies.[11] Newtonian physics states that objects farther from the center of a galaxy experience weaker gravitational forces, leading to reduced orbital speeds. However, this does not apply to spiral galaxies. Observations indicated that these outer regions spin much faster than predicted by Newton's law. This suggests that visible matter cannot be the only source of gravitational force. Astronomers can ascertain the distribution and quantity of dark matter within galaxies by comparing the observed rotation speeds with their theoretical predictions.[11]

Even though rotation curves provide strong evidence for dark matter in spiral galaxies, they do not help study other cosmic structures, such as elliptical galaxies or clusters. Conversely, gravitational lensing offers a more general method that can be applied across a broader range of systems. Gravitational lensing is a consequence of mass bending spacetime. The greater the mass, the stronger the lensing effect. When astronomers studied this distortion in galaxies, they found that visible matter alone cannot fully account for the observed gravitational lensing. By measuring this discrepancy, they could calculate the presence of dark matter and study its distribution in different galaxies in the universe.[12]

Significant lensing-based evidence for dark matter is derived from colliding galaxy clusters, such as the Bullet Cluster. Astronomers compare the distribution of hot gas, which traces visible matter, with the distribution of mass predicted by gravitational lensing. Research indicated that upon impact, visible matter decelerated, whereas dark matter components passed through without being impeded.[13] This provides compelling evidence that dark matter is a separate component of the universe and interacts primarily through gravity.

Finding Exoplanets

Exoplanets are planets that orbit stars outside our solar system. Scientists find and study these exoplanets to understand the evolution of solar systems and search for the possibility of extraterrestrial life.[14] Astrophysicists have used various methods to search for exoplanets over the years. These techniques include the transit method, which measures the dip in a star's brightness when an exoplanet passes in front of it, direct imaging, and the radial velocity method, which detects the tiny wobble of a star caused by an orbiting planet's gravitational pull.[15]

Microlensing is another powerful technique for detecting exoplanets. It relies on gravitational lensing to observe planets that are otherwise too distant or dark to be observed by other methods. When a massive object, such as an exoplanet, passes before its parent star, its gravitational field bends and magnifies its light. This creates a temporary brightening that astronomers can analyse to detect exoplanets.[15]

So far, the microlensing method has detected 235 exoplanets.[15] This includes OGLE-2003-BLG-235Lb, a Jupiter-like planet located 17,000 light-years away in the Milky Way's bulge, and OGLE-2016-BLG-1195Lb, an Earth-like planet orbiting around a faint star approximately 13,000 light years away.[16,17] The latter discovery indicates terrestrial planets may be more common in the Milky Way than previously believed.[17] In this method, the most significant achievement lies in discovering rogue exoplanets, which are free-floating planets that drift through space without a host star, which no other detection method can easily achieve.[18]

Fig 5 | Image shows an Einstein ring in galaxy LRG 3-757.[21] Credits: NASA

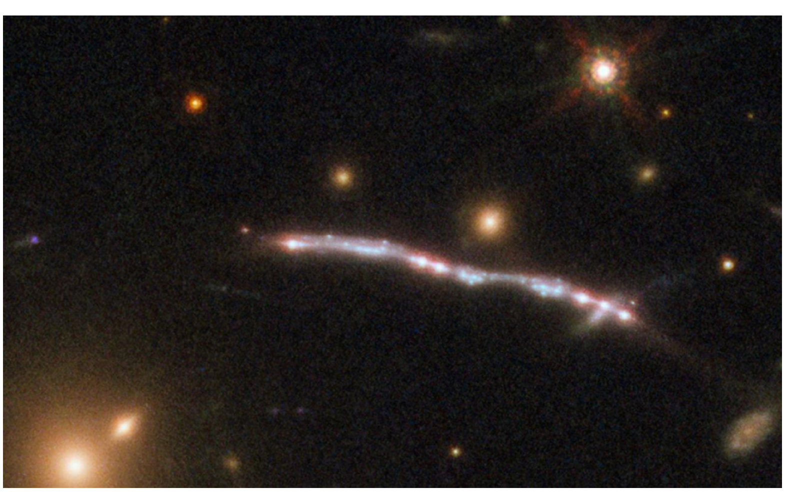

Fig 6 | The image shows one of four arcs formed from the light coming from the Sunburst Arc galaxy. This bright arc consists of at least six copies of the image of a single galaxy.[23] Credit: ESA/Hubble, NASA, Rivera-Thorsen et al.

Challenges and Current Solutions

While Einstein theoretically predicted gravitational lensing in large cosmic structures like galaxies, he believed its effects would be nearly impossible to observe.[19] Although astrophysics and technology have made significant advancements since then, gravitational lensing still presents many challenges today.

Correcting Image Distortions: Measurement and De-lensing Challenges

Gravitational lensing reveals and magnifies images, but it distorts images of celestial bodies. These distortions depend on the alignment between the hidden celestial object, the body acting as the lens, and Earth. When the alignment is perfect, the lens can stretch the light from the source, creating a perfect ring around itself. This phenomenon is known as an Einstein ring (Figure 5).[20]

If the alignment is slightly imperfect, the light from the source can form elongated arcs around the lens. Moreover, if the lens is not spherical, an imperfect alignment can create multiple images of the source. This mirage-like effect, as previously mentioned, is called Einstein's Cross (Figure 6).[22]

Astronomers require high-precision measurements before rectifying these distortions and producing an accurate representation of the source. Combining observations from multiple wavelengths obtained through space- and ground-based telescopes is a method to refine these measurements. This multi-wavelength approach can help reveal details that a single wavelength could not show independently.[24] However, combining data from different telescopes introduces new challenges. Each telescope has a different sensitivity and resolution. These variations can lead to discrepancies that require additional calibration and modelling. Moreover, coordinating observations across multiple facilities, sometimes spanning different continents or space, is expensive and time-consuming.

Using mathematical simulations to reverse the effects of lensing further complicates situations. These methods, known as de-lensing techniques, exhibit high sensitivity and require ultra-deep observations that can be expensive.[25] Moreover, even minor calculation errors can lead to inaccurate estimates of an object's mass and distance, vastly affecting our understanding of dark matter and the universe.

Dependence on Unknown Mass Distributions

The strength of a lens depends on its mass, and a significant portion of this mass can come from dark matter. Unfortunately, despite everything astronomers have learnt about dark matter over recent years, it remains one of the biggest mysteries of the known universe. Thus, the present estimates of a galaxy or cluster's total mass and its exact influence on passing light can be uncertain.[26] Since gravitational lensing is one of our best tools for studying dark matter, these uncertainties create a paradox. We need accurate mass estimates to study dark matter to determine mass precisely, limiting our understanding of the fundamental laws of the universe.

Temporary and Unpredictable Lensing Events

Microlensing events are unpredictable, rare, and temporary. They need near-perfect alignment with the Earth to be visible and can last anywhere from a few days to months. Astronomers often struggle to catch them in time since they happen randomly and do not repeat. While dedicated surveys, like OGLE (Optical Gravitational Lensing Experiment) and MOA (Microlensing Observations in Astrophysics), do continuously monitor large sections of the sky to increase the odds of observing such events, astronomers still cannot observe them long-term.[27] Hence, even if they discover an exoplanet through this phenomenon, they cannot re-observe it to confirm key details about its atmosphere, orbit, or composition.[27]

The Future of Gravitational Lensing

As discussed in the previous section, gravitational lensing has complicated limitations. Yet, it is still one of the most powerful tools for uncovering the universe's hidden structures. This section explores the role of different ongoing and future advancements in telescope technology and data analysis in enhancing the accuracy of lensing studies.

Next-Generation Telescopes and Observatories Equipped with AI-Powered Detection and Analysis

Modern telescopes on Earth and in space record a staggering amount of information daily. This data is far more than what humans alone can process. To keep pace, scientists are now using AI to analyze data and identify patterns and anomalies.

The European Space Agency's Gaia mission, which was launched in 2013, has already demonstrated AI's potential in lens detection. Gaia's extensive dataset, intended for mapping the Milky Way, provided an unexpected opportunity to search for gravitational lenses. AI algorithms analyzed 4.8 million sources, filtered candidates based on light distortions, and identified 381 strong gravitational lens candidates.[28]

Building on Gaia's success, several upcoming telescopes will use AI to uncover thousands of new gravitational lenses. This includes the Vera C. Rubin Observatory, currently under construction in Chile. This observatory will conduct a 10-year sky survey to capture billions of galaxies in high resolution.[29] AI will then sift through this immense dataset to detect subtle lensing effects and identify tens of thousands of strong gravitational lenses.[30]

Another example is the Euclid Mission. Launched in 2023 as a space telescope by ESA. This mission will use weak gravitational lensing to investigate the nature of dark energy and dark matter.[31] Using Euclid's data, AI will identify lensing distortions in millions of galaxies and offer deeper insights into the universe's expansion.[32]

However, future telescopes will not be the only ones to find gravitational lenses in the sky. While the James Webb Space Telescope, or JWST for short, is not a survey telescope, its high-resolution capabilities allow for detailed follow-ups on strong gravitational lensing systems.[33] AI-driven analysis can help prioritize promising targets, which will help astronomers focus and manage their time and energies more efficiently.

Automated De-lensing and Pattern Recognition

The role of AI does not stop with the identification of these lenses. Machine learning (ML) techniques are a subset of AI that enables systems to learn patterns from data and make decisions without being explicitly programmed; they are already being used to automate de-lensing and detect faint lensing patterns with unprecedented accuracy.

Convolutional Neural Networks (CNNs) are a type of deep learning model that can be used to identify image patterns. Deep learning is a branch of ML that uses neural networks to automatically extract and learn complex features from large datasets. These neural networks comprise layers of interconnected nodes, or "neurons", that process information in stages. After training on simulated gravitational lensing images, these networks can "de-lens" images, restoring them to their original form more efficiently than traditional methods.[34]

While CNNs can focus on spatial features, RNNs, or Recurrent Neural Networks, can process lensed images of the same object recorded using different telescopes across different wavelengths.[33] Astronomers can use these networks to find and track lens changes since this data will have been recorded at different times. This is particularly helpful in observing microlensing events, where the brightness of a lensed object fluctuates over time.[34]

However, the distortions created by gravitational lensing are not always obvious. While strong gravitational lensing is evident due to the rings, arcs, and crosses it produces, weak gravitational lensing can produce subtle distortions that are difficult to detect using traditional methods and sometimes even go undetected. Convolutional Autoencoders (CAEs) are a simple type of unsupervised ML that can identify these faint gravitational signals without requiring any previous training.[35] CAEs compress these images by keeping only important information like rings or arcs. This removes unnecessary background clutter. It then reconstructs the image from this compressed version. If it can do this easily, the information of the compressed image can be completed. However, if it struggles to rebuild some parts, those features are unusual, which may signify distortion caused by weak gravitational lensing.[35] Thus, CAEs can learn directly from data and discover and highlight unexpected lensing features. This makes them especially valuable for weak lensing analysis and anomaly detection while reducing the chance of human error and false positives.[35]

Conclusion

Gravitational lensing is a highly effective instrument for modern astrophysics. It enables us to observe the remote universe, map the invisible distribution of dark matter, and reveal concealed exoplanets. Since the initial confirmation of Einstein's theory in 1919, gravitational lensing has persistently transformed our comprehension of the universe, particularly through the revolutionary findings of telescopes such as Hubble and JWST. Despite the challenges posed by image distortions, unpredictable lensing phenomena, and the intricacies of de-lensing, progress in artificial intelligence, state-of-the-art telescopes, and computational modeling facilitates increasingly accurate and extensive discoveries. Yet, beyond its scientific applications, gravitational lensing is also a testament to human curiosity, ingenuity, and the relentless pursuit of knowledge. The utilization of the gravitational pull of entire galaxies as cosmic magnifying glasses exemplifies the pinnacle of human accomplishment in astronomy and physics. It demonstrates our capacity to perceive the universe and devise novel methodologies that uncover previously unseen phenomena. As technology progresses and our comprehension expands, gravitational lensing will persist in revealing the cosmos, demonstrating no bounds to what humanity can discover when motivated by the urge to explore.

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