# Needles in a Cosmic Haystack

## Strong Gravitational Lensing as a Pioneer of 21st-Century Astronomy

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Image courtesy of ESA/Hubble.

### Introduction

Strong gravitational lensing occurs when a massive object warps the fabric of spacetime, causing light from behind it to bend while it passes by (Treu, 2010). The resulting magnification makes strong gravitational lenses a long-coveted tool for studying everything from black holes to the birth of the universe. Though predicted by Einstein's Theory of Relativity as early as 1912, these "imperfect natural telescopes" have remained elusive, with astronomers discovering only a few dozen lenses by the turn of the 21st century (Treu, 2010). Yet the recent advent of astronomy's Big Data era, powered by telescopes like the Sloan Digital Sky Survey (2000) and the Vera Rubin Telescope (2025), has ushered in a profound change in the field (Barone et al., 2025). These survey-style telescopes have created a new epoch of data availability, and will soon be able to image millions of objects per night, covering ever-wider areas of the sky in myriad wavelengths.

However, the field of strong gravitational lensing now faces new challenges. The biggest hurdle is no longer detecting *enough* lenses (there are now over one thousand confirmed lenses), but rather efficiently identifying lenses within piles of data and building accurate simulations (Shajib et al., 2025). This article will explain the physical processes behind strong gravitational lensing, investigate the new issues faced by the field in its Big Data era, and introduce how researchers are turning to neural networks to break through these bottlenecks.

### Strong Gravitational Lensing

Objects massive enough to warp spacetime (e.g., black holes, large galaxies, galaxy clusters; Treu, 2010) to the extent that causes strong gravitational lensing are called "deflectors." This curvature of spacetime refocuses and redirects light passing by it, and causes an observer on the other side to see magnified, multiplied, and distorted images of the light's source (Figs. 1 and 2). Thus, it is the precise alignment required between an observer, the deflector, and the source(s) that make strong gravitational lenses so rare.

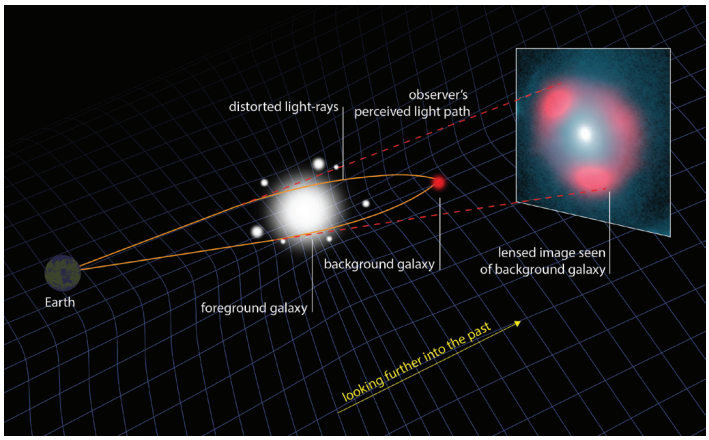



**Figure 1.** Light from a background galaxy bends as it travels through the warped spacetime around the foreground galaxy. (Image courtesy of Iris Sung; adapted from image courtesy of ESO/NRAO/NAOJ.)

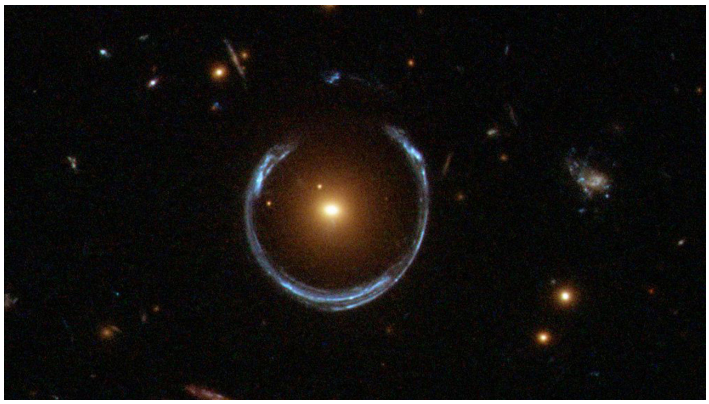


**Figure 2.** The most recognizable feature of a strong lens is its "Einstein Ring." These thin arcs come from the light of background galaxies being distorted by the orange deflector in the foreground. (Image courtesy of ESA/Hubble.)

Two properties make strong gravitational lenses a powerful tool to probe the universe's composition and evolution. First, recording how sharply light curves when passing by a deflector allows astronomers to measure the deflector's mass (Treu, 2010). This is crucial for astronomers to develop better understandings of otherwise "invisible" objects like black holes and dark matter. Second, the natural magnification of light from lensed sources allows astronomers to see faint and distant objects in greater detail than current telescopes can achieve (Zheng et al., 2012). Since light takes a finite amount of time to travel, seeing distant objects also means seeing further back in time. Thus, analyzing the source, deflector, and surroundings of strong gravitational

lenses can help astronomers glean information about a variety of objects and processes. For example, astronomers at the Harvard and Smithsonian Center for Astrophysics are using images of strong lenses with distant galaxy deflectors to model their mass distribution and weigh the massive black holes at their centers. By comparing these metrics of galaxies with different distances, which they are therefore viewing at different points in the past, astronomers can deduce how black holes evolve with respect to their host galaxies. (Bowden et al., 2025; Sahu et al., 2024).

## Information and Computational Bottlenecks

Although studying any physical phenomenon in the 21st century requires collecting and analyzing many data points, astronomers who study gravitational lensing face uniquely high computational and information barriers to scientific progress.

Firstly, the unprecedented influx of data coming from powerful new telescope surveys has made the traditional way of discovering lenses too time- and resource-intensive. Since strong gravitational lenses are exceedingly rare, searching for them amidst the Big Data era is akin to trying to find a needle in an ever-growing haystack. Traditionally, astronomers identify lenses through a two-step observation and analysis process: They begin by manually looking through telescope images for lens-like objects. Then they differentiate real lenses from lookalikes by conducting targeted follow-up observations with a spectrograph, which spreads light out into a range of wavelengths and allows astronomers to tell whether the central source and surrounding arcs are truly separate objects (Fig. 3; Barone et al., 2025).

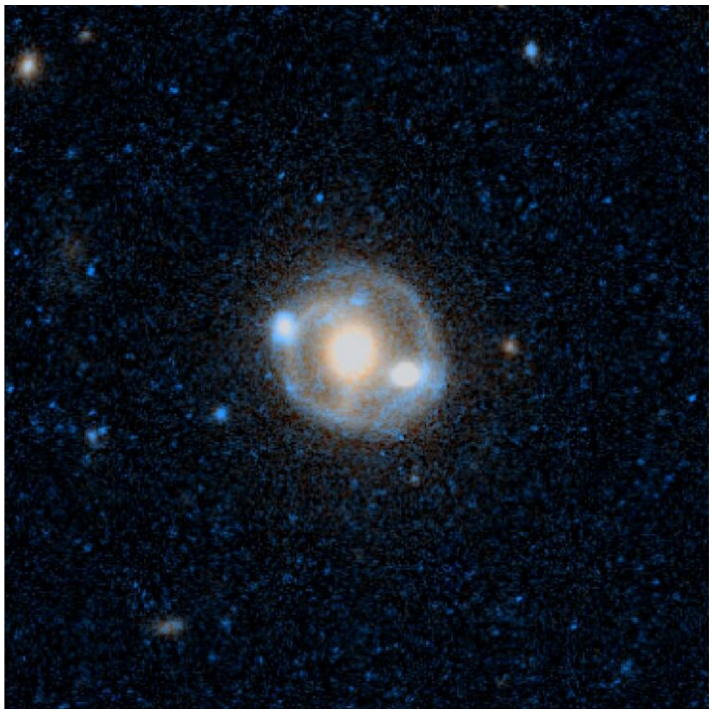


**Figure 3.** A ring galaxy with arms that look deceptively similar to the Einstein Ring produced through gravitational lensing. This object was confirmed to be an imposter after spectrographic imaging (Barone et al., 2025).

Critically, the arrival of survey-style telescopes means that it is no longer possible for researchers to identify lenses by parsing through each image. If astronomers cannot meaningfully process most of the data, the huge leaps made by telescope instrumentalists will only translate into a tiny step forward in humanity's understanding of strong lenses. Researchers will not be able to find and take advantage of the hundreds of thousands of lenses hiding within the images of new surveys—and the lenses that they do identify and confirm with their limited follow-up time may not be the most scientifically valuable if they cannot see the broader picture in the cumulative set of lenses (Weiner et al., 2020).

Second, the complex environments that govern how gravitational lenses appear mean that immense computing power is required to work backwards from collected observations to the physical properties of the source and deflector. Many different source-deflector configurations can produce the same image for an observer on Earth. For example, two configurations with different deflector mass distributions and relative source positions can yield the same observed image. The absence of a one-to-one relationship that connects observations to a specific configuration of sources and deflectors means that astronomers must go through an iterative modeling process.

Traditionally, astronomers start by providing a model with an educated guess about the system's physical properties, such as the suspected mass, size, and matter distribution of the lens and source. The software then tweaks these parameters slightly, each time generating a new image of what a telescope would observe until it closely matches the actual observations. Therefore, generating a correct lens model requires first generating tens of thousands of incorrect models (Park et al., 2021). This inefficiency essentially wastes computational resources, something which astronomers can no longer afford as the amount of lenses grows faster than the amount of available computational power for any given lab (Park et al., 2021; Shajib et al., 2025). Since all applications of lenses must contain modeling at some step, efficient modeling poses the most critical bottleneck for better understanding of the universe.

## Neural Networks Emerge as a Solution

Convolutional neural networks (CNNs) are a special type of neural network built for image classification and object recognition (IBM, n.d.). Their rapid and self-augmenting pattern recognition capability makes CNNs the perfect tool to push past strong gravitational lensing's most pressing computational bottlenecks. Excitingly, the promising results of groups currently developing CNNs suggest that neural networks will revolutionize the field of gravitational lensing.

One research group pushing the frontier of CNN-led lens identification is the ASTRO 3D Galaxy Evolution with Lenses (AGEL) Survey, headquartered at the Harvard-Smithsonian Center for Astrophysics. In 2022, AGEL trained a CNN to achieve a lens identification success rate of 88%, and published a survey of the 68 lenses which the neural network found (Tran et al., 2022). The role of neural networks as a turning point in lens identification is evident from the fact that, within four years, AGEL had confirmed the second-highest number of lenses of any survey, surpassed only by a group with 15 years of publications (SLACS, n.d.). A second round of data in 2025 saw a success rate of 96% (Barone et al., 2025). Critically, AGEL's progress will continue to accelerate: lenses

identified by current CNNs expand the datasets which train the next generation—making models more efficient and accurate.

On the modeling side, a team at the University of Chicago has created a fully-automated modeling system through training a CNN on a dataset of images and associated models. Given a new image of a strong gravitational lens, the CNN can propose a new model which a traditional modeling software only needs to iterate over a couple times before reaching a physical reconstruction that matches the image (Shajib et al., 2025). Whereas conventional modeling could take months under personal supervision, such CNNs will soon allow astronomers to create thousands of lens models on just one Graphics Processing Unit, with each iteration of an image generated in less than a second (Gentile et al., 2023; Park et al., 2021).

As more groups work on expanding the types of lenses that CNNs can model, astronomers will finally be able to tap into the full potential of lenses as cosmological probes. From studying how black holes evolve, to probing dark matter and quantifying the universe's accelerating expansion, neural networks are turning the 21st-century data deluge into a better understanding of the fundamental nature of the universe.

## Looking Forward

Although strong gravitational lensing's unique computational barriers compelled the subfield's early adoption of neural networks, lensing is not the only subfield which neural networks will benefit. As lensing experts develop more neural networks, they will inspire, inform, and learn from other subfields of astronomy—especially ones that study rare phenomena or require intensive data analysis. For example, exoplanet astronomers are working on training networks to identify Earth-like planets amidst thousands of light curves (Wang, 2025). While the accelerating use of AI in science may be challenging for some to accept, the overarching benefit of neural network adoption in astronomy is clear: Ultimately, when astronomers are able to spend less time and resources on cranking computations, they'll be able to turn their attention to developing new questions to explore.

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