

# Mass Determination of Lens Galaxies using Einstein Rings

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## Abstract

Strong lensing is a gravitational phenomenon in which the light from a distant source is bent and distorted by the gravitational field of an intervening massive object, such as a galaxy or a galaxy cluster, causing the source to be multiply imaged. Among the various types of strong lensing, Einstein rings are particularly intriguing and valuable for studying the characteristics of galaxies. Using Einstein rings to study the mass and environment of a galaxy is uncommon and can present many challenges regarding the obtention of the data, as there are many lensed systems but only a few that qualify as bonafide Einstein rings. The aim of the study is to determine the mass of lens galaxies using such rings. In this research study, we analyze data from the Gravitationally Lensed Quasar database and CASTLES database using Plotly, Matplotlib, Astropy, and pandas. By leveraging the relativistic Doppler shift and the definition of the Einstein radius, we determine the masses of ten lens galaxies. The mass range spans from 27 billion solar masses to 946 billion solar masses. We visually represent these masses through graphs, maps, and histograms. From this we figure the significance of mass in determining the Einstein radius. Furthermore, we observe a distinct pattern in the characteristics of the galaxy environment, where the majority of lens galaxies are red, contain quasars, and exhibit elliptical shapes. Our research is significant as we apply established theories to novel observational data, allowing us to investigate Einstein rings, a rare phenomenon with limited available data. This study demonstrates the importance of utilizing Einstein rings as a powerful tool for studying the features of galaxies. Despite the challenges associated with data acquisition, using Einstein rings is a powerful way to measure characteristics of lensed systems.

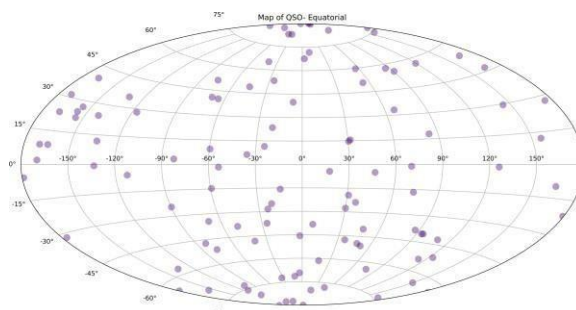
## 1 Introduction and Justification

Einstein rings have solid theoretical models, which allow for the application of observational data. Specifically, they can be used to calculate the mass of lens galaxies and also to study the environment of said galaxies. Among the various types of strong lensing, Einstein rings are particularly intriguing and valuable for studying the characteristics of galaxies. In our study, we were able to figure out the masses of ten subject galaxies using the Einstein ring method and were able to correlate some factors. Our work's significance lies in that our findings on lenses with Einstein rings can be applied to figure out the distribution and structure of dark matter, as well as study the effect that dark matter has on the Einstein radius.

## 2 Materials and Methods

We selected the Gravitationally Lensed Quasars Database (Lemon et al.) for our preliminary analysis, and the CASTLeS Survey (Kochanek et al.) for our main analysis. The Gravitationally Lensed Quasar Database is an open-source base produced by the Astronomy Department at the University of Cambridge

and has data available in the form of a table and FITS files. The CASTLe Survey is produced jointly by the Harvard-Smithsonian Center for Astrophysics and the Astronomy Department at the University of Arizona. This survey in particular is very useful for comparing dark matter and luminous matter concentrations in lensed galaxies. As a part of our preliminary analysis, we made an Aitoff projection of all of the data points from the Gravitationally Lensed Quasars Database (Lemon et al.) for visualization.



**Figure 1: Plot of the GLQD. RA labeled on the side and Dec on the middle. (Kulkarni 2023)**

In order to hone our study though, we selected subject lensed galaxies with a grade rating of "R" or "ER" to determine systems with Einstein rings. From those systems, we then further sorted them based on whether they had a grade rating of "A" or "B," meaning they had a high likelihood of being a gravitationally lensed system. With all of that sorting, we were left with ten subject systems for our study: Q0047- 2808, PMNJ0134-0931, B0218+357, CFRS03.1077, MG0751+2716, HST15433+5352, MG1549+3047, MG1654+1346, PKS1830-211, and B1938+666.

## 2.1 Calculating Masses

Among various methods of calculating a galaxy's mass, we chose to use the Einstein radius and the distance to the lensing galaxy and the source to calculate the masses of our subject galaxies. In order to achieve this, we first had to calculate the recessional velocities and the distances to both the lensing galaxy and the source given the redshift. To do this, we used the Relativistic Doppler Formula and Hubble's Law, shown below as Equation 1 and Equation 2, respectively.

$$v_r = \frac{(1 + z^2) - 1}{(1 + z^2) + 1} * c \tag{1}$$

$$v_r = H_0 d \tag{2}$$

\*Note: the value for the Hubble's constant or  $H_0$  we used was 73 km/s/Mpc.\* Next, we used the distances we obtained for both the lens and the source to find the mass of each galaxy given the Einstein radius (obtained from CASTLeS Survey). In Equation 3 (Courteau et al., 2014),  $\theta_E$  is the Einstein radius (in radians),  $D_L$  is the distance to the lens galaxy, and  $D_S$  is the distance to the source.

$$\theta_E = \frac{r \sqrt{4MD_{LS}}}{D_L D_S} \tag{3}$$

We then obtained the mass of the galaxy in light-years and then proceeded to convert our result to solar masses.

**Table 1: Table showing the Einstein radius and mass of galaxies (Kulkarni and Cho 2023).**

Name	Einstein Radius (rad)	Mass ( $M_{\odot}$ )
Q0047-2808	1.35	581752056711
PMNJ0134-0931	0.365	92907576573
B0218+357	0.17	37050169254
CFRS03.1077	1.05	946027616562
MG0751+2716	0.35	26744383540
HST15433+5352	0.59	127480169485
MG1549+3047	0.85	45136047365
MG1654+1346	1.05	171280502726
PKS1830-211	0.495	205771324930
B1938+666	0.5	229936253905

### 3 Results

We were able to obtain a plethora of useful results such as the mass of each subject galaxy, its environment, and were able to visually and numerically represent these findings.

#### 3.1 Finding the Masses

Using the above method, we were able to obtain the masses of our ten subject galaxies. Below, a table showing the galaxies' Einstein radius and mass is shown. Our results were consistent with the average mass of a galaxy (to the order of  $10^{11}$  solar masses). Moreover, we can also find a correlation between a galaxy's Einstein radius and its mass, which will be further discussed in detail.

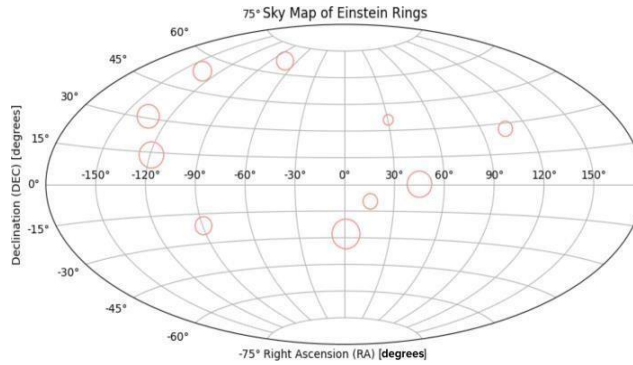
#### 3.2 Environment of the Lens Galaxies

We found that most of our subject galaxies were quasars, which means that they are extremely luminous and are actively accreting matter. Some of our subjects even have relativistic jets, or photons moving at a significant fraction of the speed of light from the magnetic axis. We also discovered that most of the subject galaxies were elliptical, meaning they are very large cloudlike galaxies with no defined structure. Lastly, we observed that most of our galaxies were red, due to redshift and their age.

#### 3.3 Finding Correlations from the Data

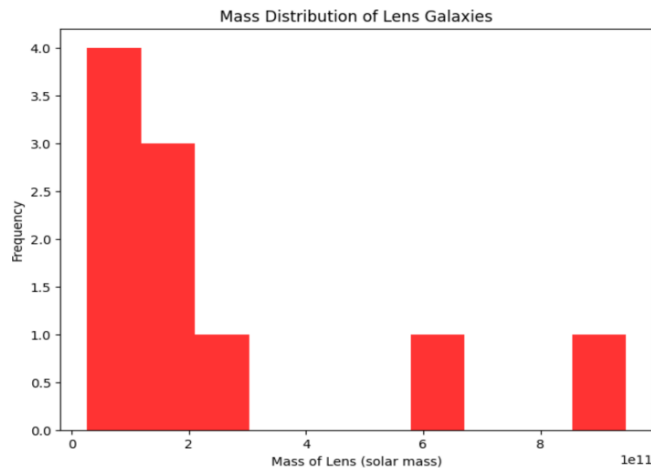
We visually represented our results with the use of a map, a histogram, and a scatter plot.

The first figure we generated is a sky map of Einstein rings. Each ring on the map is representative of a lensed system in our dataset. The radius of the ring is proportional to the Einstein radius of the sample.



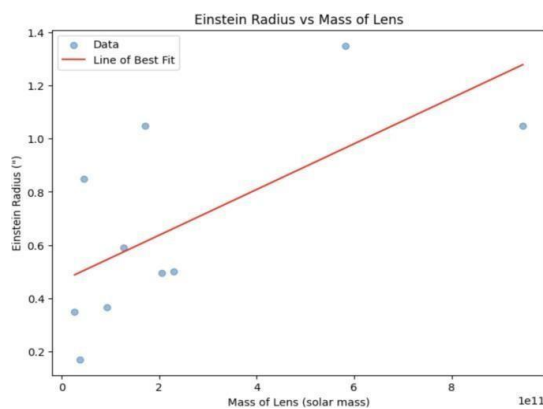
**Figure 2: Aitoff projection of Einstein rings. (Cho 2023)**

Figure 3 is a histogram of the distribution of lens mass. This clarified that most of the lens galaxies had a relatively lower mass.



**Figure 3: Mass distribution of lens galaxies, in  $10^{11}$  solar masses. (Cho 2023)**

Figure 4 is a scatter plot of the Einstein radius against the mass of lens. The line of best fit reveals the positive correlation between the mass of the lens galaxy and the Einstein radius, highlighting the weight of lens mass in determining the size of the Einstein ring. While distances between the lens, source, and observer are factors, the pattern in Figure 4 suggests that the mass of lens is the critical factor.



**Figure 4: Scatter plot of the Einstein radius, in arcseconds, against the mass of lens, in solar masses. (Cho 2023)**

#### 4 Comparison to other Studies

To confirm the robustness of our method and explore various ways the concept of Einstein rings can be applied, we compared our study with 'Photometric mass and mass decomposition in early-type lens galaxies', a 2009 study conducted by Grillo et al.

The objective of our study is to investigate the mass and environment of lens systems with Einstein rings. In contrast, Grillo et al.'s study had the objective of comprehending galaxy structure and evolution by utilizing mass diagnostics. There were some differences between the studies due to this intrinsic distinction.

To achieve our goal, we utilized the CASTLeS survey, from which we examined and selected both class A and class B strongly lensed systems. Grillo et al. relied on the SLACS survey, exclusively incorporating class A strongly lensed systems. Our focus was primarily on analyzing the characteristics and properties of lensed systems with Einstein rings. By employing the definition of the Einstein radius, we determined the mass of the lens galaxy enclosed within this radius. Additionally, we explored the patterns and features of the galaxies' surrounding environment. Meanwhile, Grillo et al.'s research encompassed the investigation of various types of lens effects, the Einstein radius being one. Though they also employed the definition of the Einstein radius to ascertain mass, they specifically identified luminous masses within the Einstein ring through photometry analysis.

#### 5 Reflection and Future Work

With this study, we were able to calculate masses of quasars using the Einstein radius, detect a pattern in the color and structure of lens galaxies, and make a map showing the relative sizes and locations of our subject systems. Since we completed what we set out to do, we can state our study adequately answered our research question. However, this research is only the foundation for more advanced studies. In the near future, we aim to calculate and map the density of the lens galaxies using the mass and radius of lens as denoted by de Vaucouleurs's law (Equation 4).

$$lnI(R) = lnI_e + 7.669[1 - (\frac{R}{R_e})^{1/4}] \quad (4)$$

We also aim to use the masses and density of galaxies to build a dark matter distribution map and eventually compare its structure to that of luminous matter in a galaxy. By correlating the distribution of dark matter with luminous matter in galaxies, we hope to uncover the intricate interplay between these elusive components of the universe. Such a breakthrough would not only deepen our understanding of the mysterious nature of dark matter but also shed light on the fundamental forces shaping the universe.

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#### Data Availability

The two datasets used for this study, the Gravitationally Lensed Quasars (Lemon et al.) and the CASTLeS

survey (Kochanek et al.) can be accessed publically on the Internet. The data is in the form of a table and can be downloaded as an HTML file.

## 6 References

1. Courteau, S., Cappellari, M., de Jong, R. S., et al. 2014, *Reviews of Modern Physics*, 86, 47
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4. Lemon, C. (Cambridge), *Gravitationally Lensed Quasars Database*