Inferring Dark Matter Content through Gravitational Lensing Arc Measurements with JWST Data

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Abell 2744, also known as Pandora's cluster, is a giant galaxy cluster located in the Sculptor constellation. Located 4 billion light years away from earth and having a diameter of 4 million light years, the cluster has previously been imaged by the James Webb Space Telescope and the Chandra X-Ray Observatory. The strong gravitational lensing present in recent images from JWST (taken in February 2023) allows us to infer dark matter content in the cluster.

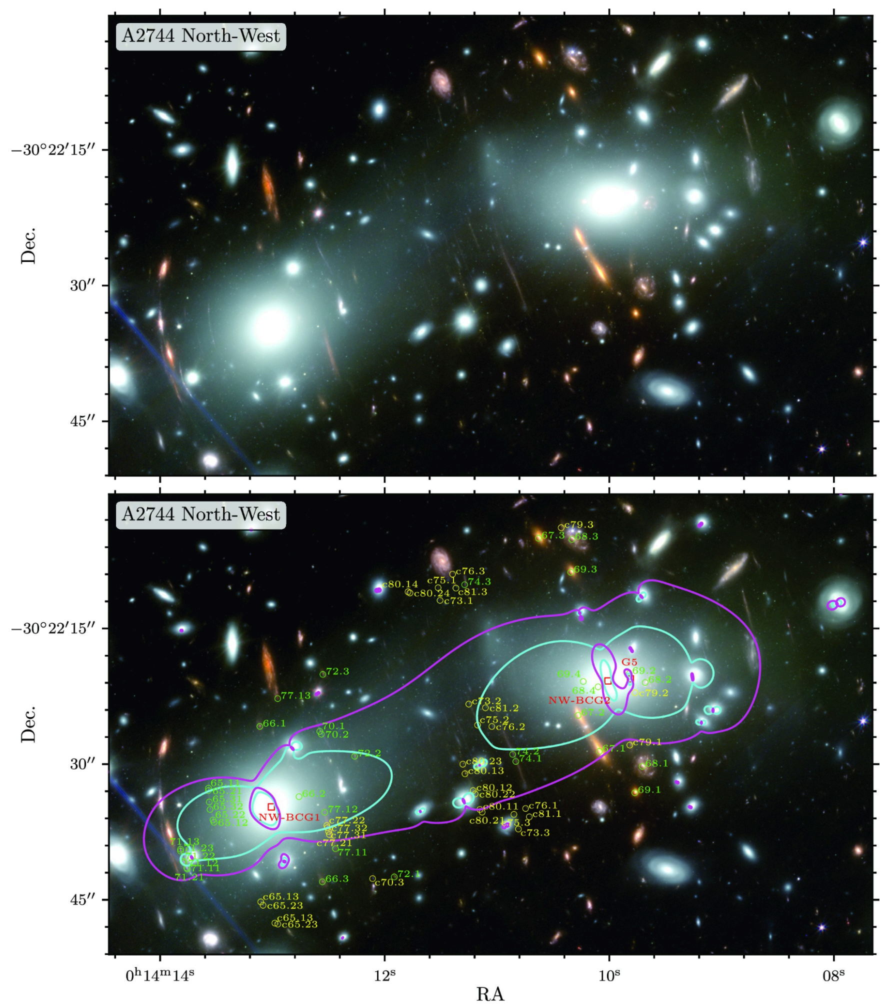


Figure 1. Showing some major points where gravitational lensing can be seen

Gravitational lensing is a phenomenon predicted by Einstein's general theory of relativity, which explains that mass can curve the fabric of spacetime. When a massive object is positioned between a distant light source and an observer, the gravitational field of the object can act as a lens that can bend and focus the light from the source. This effect can produce various observable phenomena, such as the magnification and distortion of the background source, the formation of multiple images, and even the creation of ring-like structures known as Einstein rings. Abell 2744 is an example of such a lens, as we can see the bending of the light of galaxies around some point in Figure 1, and it is seen that some of these galaxies curve elliptically. Since galaxy clusters like Abell 2744 contain large amounts of dark matter that contribute to the lensing, the amount of lensing lets us determine the dark matter content in the region.

The Einstein radius θ_E is a critical concept in gravitational lensing. It defines the angular radius of an Einstein ring formed when the source, lens, and observer are perfectly aligned. The Einstein radius depends on the mass distribution (we will attempt two different distribution within in this short study) within the lens, as well as the relative distances between the observer, the lens, and the source:

$$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{\mathrm{LS}}}{D_{\mathrm{L}} D_{\mathrm{S}}} \right)^{1/2}$$

Here, G is the gravitational constant, C is the speed of light, M is the mass of the lens, which is the cluster, D_{LS} is the angular diameter distance between the lens and the source, D_L is the angular diameter distance from the observer to the lens, and D_s is the angular diameter distance from the observer to the source.

The Einstein mass M_E can be inferred from the Einstein radius. It represents the mass along the line of sight with a radius equal to the Einstein radius. The mass calculation involves the critical surface mass density Σ_{crit} and is given by:

$$M_E = \pi\, \theta_E^2\, D_l^2\; \Sigma_{crit}$$

where Σ_{crit} is defined as:

$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}$$

<u>Procedure</u>

Analyzing the Einstein radius and inferring the Einstein mass provides a method to probe the distribution of both visible and dark matter in the universe without relying on its luminosity, offering crucial insights into the mass distribution of galaxy clusters and the large-scale structure of the universe.

The code first accesses observational data from the James Webb Space Telescope using the `Observations` module from `astroquery.mast`. It retrieves and downloads files for Abell 2744 at different wavelengths, which we then use to create an rgb image in DS9. We use the 356 nm filter as red, the 200 nm filter as green, and the 90 nm filter as blue.

After creating the initial image of Abell 2744, it is necessary to crop the image to only include the relevant part of the image. We can do this using information found in the header of the FITS file.

$$NAXIS1 = 24397 : \text{ number of pixels in the RA axis}$$
$$CD1\_1 = -8.6299 * 10^{-6} : \text{ Linear projection matrix in the RA axis}$$
$$FOV = NAXIS1 * |CD1| * 3600$$
$$\implies FOV = 757 \text{ arcseconds}$$
$$d_{\text{Abell 2744}} = 3.982 * 10^9 \text{ ly}$$

Source: NASA/IPAC Extragalactic Database.

$$\theta_{\text{arcseconds}} = 206265 \frac{D}{d}$$
$$\implies D_{\text{image}} = 1.46 * 10^7 \text{ ly}$$

Expected diameter of cluster:

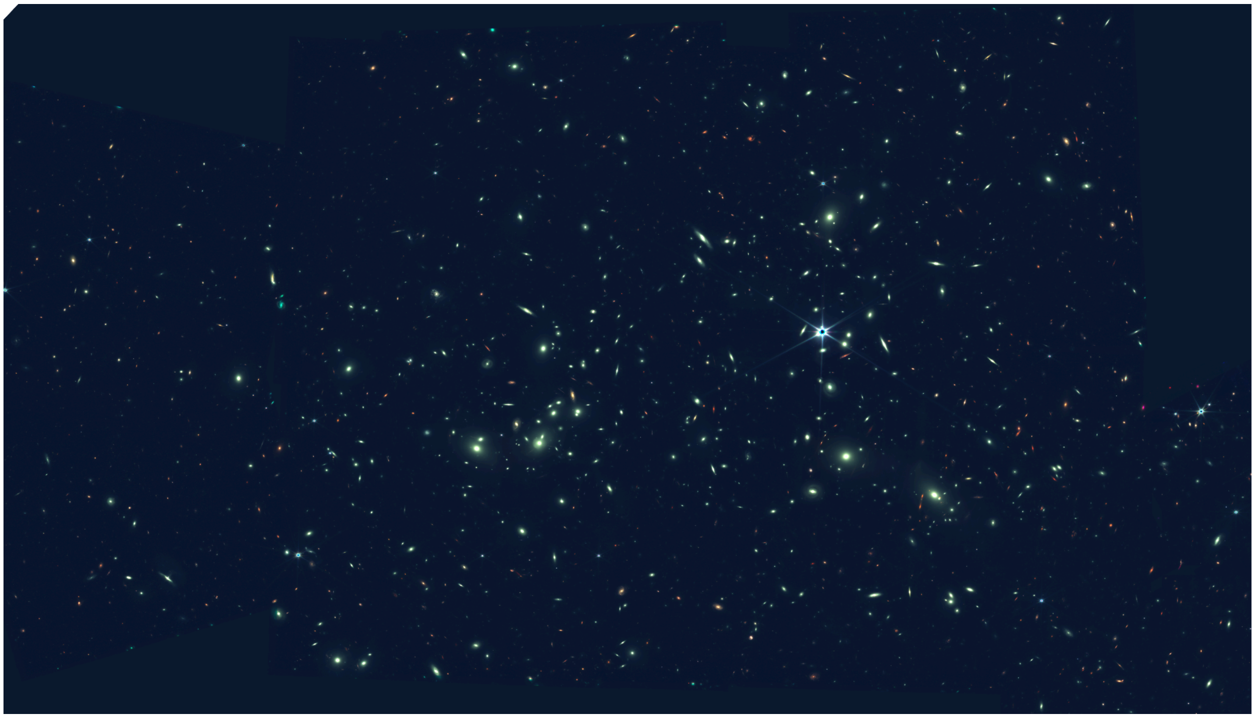
$$D_{\text{Abell 2744}} = 4 * 10^6 \text{ ly}$$

Source: NASA Hubblesite

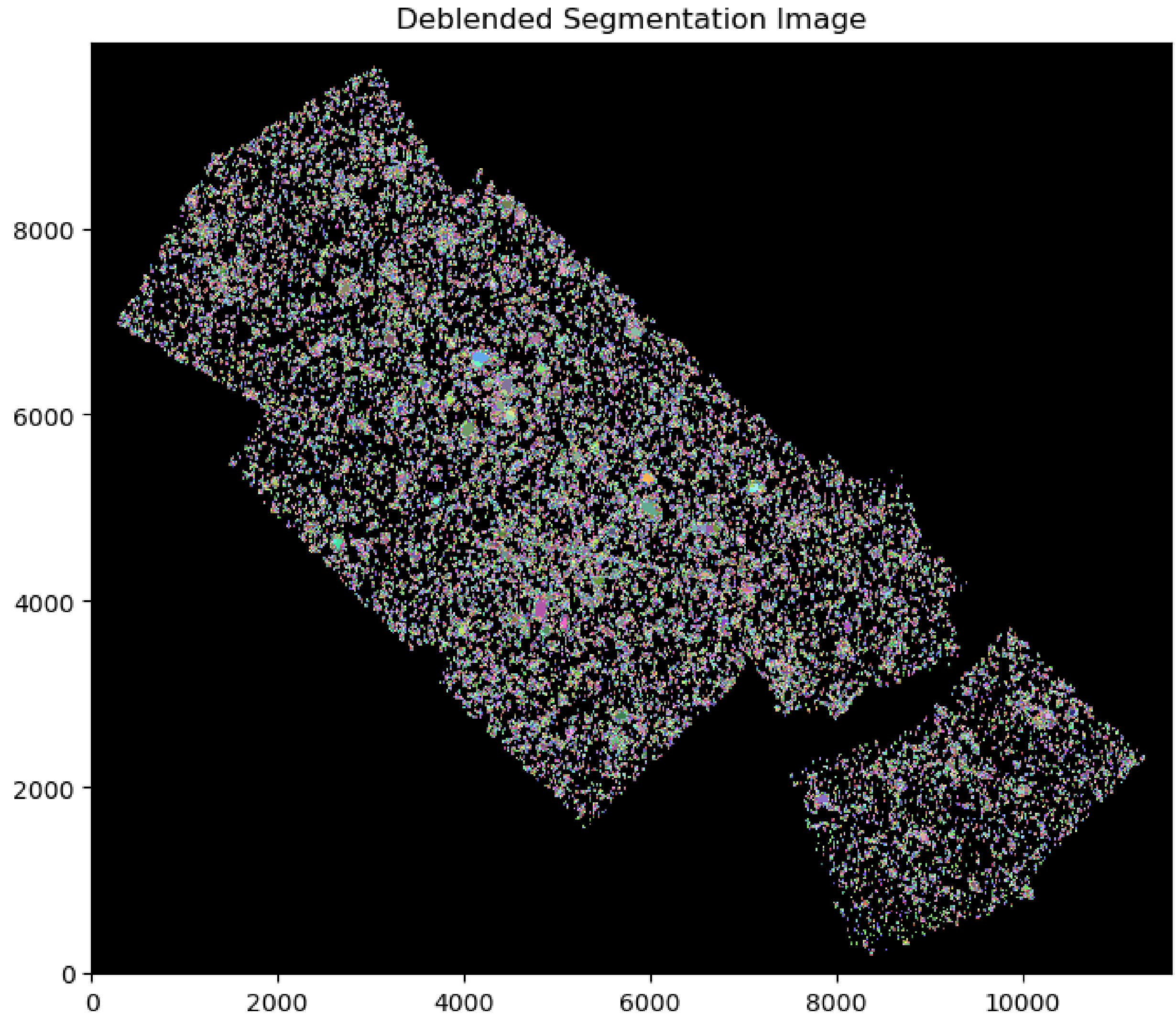
Crop the image:

$$\theta' = 206265 * \frac{4 * 10^6}{3.982 * 10^9}$$
$$\implies \theta' = 207.3 \text{ arcseconds} \rightarrow \boxed{6663 \text{ pixels}}$$

By looking at the header file for the FITS file, we can see the (CD1) degree that each pixel of the image represents. By multiplying the total amount of the pixels by the degree/pixel we can find the angular view of the fits in degrees, which can be converted to arcseconds. Knowing the distance to the cluster is 3.98 billion light years away, we can use a small angle approximation to estimate that the field of view of the cluster fits as 14.6 million light years across. Since Nasa's hubble site states that Pandora's cluster is ~4 million light years across, we crop the image, by using another calculation that goes from the FOV to arcseconds given distance, and from there converts to pixels using the CD1 constant. Using this image, allows us to better capture just Abell 2744 in our fits image. Then an RGB image is exported from DS9 after being cropped, before being processed by the code.



The code converts the rgb into grayscale for analysis, simplifying the data handling. Using functions from the photoutils library, it uses a Gaussian kernel to estimate and subtract the background noise from the image data, helping isolate significant sources from the background fluctuations. To detect instances of gravitational lensing in the image using a detection threshold and a minimum number of pixels to identify actual possible galaxies while avoiding spurious detections.



Then we use the deblend function to avoid overlapping instances. From there we can measure and catalog properties of the detected sources, such as centroids and ellipticities, which we will use in our calculations. We then define cosmological parameters and calculate relevant distances using the redshift information and a chosen cosmological model – we first use the Flat Lambda-CDM model and then the Navarro-Frenk-White (NFW) profile – to model the dark matter distribution within the cluster, using parameters derived from previously published statistical analysis of the Chandra X-ray data of the cluster. Calculating the mass enclosed within a given radius based on the NFW profile parameters and the Einstein radius for each source, is inferred from its ellipticity. The code loops over all the instances, and calculates Einstein mass for objects that meet an ellipticity criterion. This procedure allows the analysis of deep space images, detect gravitational lensing effects, and infer the underlying dark matter content of the galaxy cluster Abell 2744 based on the ratio of the Einstein mass and the total known mass of the cluster.

Navarro-Frenk-White Profile

Density of dark matter

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Mass within a radius R

$$M(R) = 4\pi\rho_0 R_s^3 \left[\ln\left(\frac{R_s + R}{R_s}\right) - \frac{R}{R_s + R}\right]$$

Using the parameters

$$\rho_0 = 1.05 * 10^{-23} kg/m^3$$
$$R_s = 4.26 * 10^{22} m$$

Source: Babyk et al. (2012)

<u>Results</u>

	Einstein Mass (Kg)	Total Mass (Kg)	Ratio of Dark Matter
Flat Lambda Model	6.29e41 kg	7.956e42 Kg	~8%
NFW model	1.36e35 kg	7.956e42 Kg	1.71e-6 %

<u>Discussion</u>

Several assumptions and limitations inherent to our methodology merit discussion, notably concerning the treatment of redshift, the selection of the NFW profile in addition to the **λ**CDM model for dark matter calculations, and the simplifications regarding the lensing phenomena observed.

A critical simplification in our analysis was the uniform application of the galaxy cluster's redshift $z = 0.308$ across all lensing calculations, without considering the individual redshifts of lensed galaxies. This approach, while practical for a broad analysis, overlooks the significant impact that accurate redshift measurements for each lensed object have on the precision of the Einstein radius and, consequently, the mass estimates derived from gravitational lensing. The redshift of each lensed galaxy influences the angular diameter distances in the lens equation, which are pivotal for calculating the lensing mass. Ignoring the variation in redshift can lead to over- or underestimation of these distances, affecting the accuracy of mass estimations and the understanding of the mass distribution within the cluster.

The choice of the NFW profile for dark matter calculation stems from its robust representation of the density profiles of dark matter halos observed in numerical simulations of structure formation in the universe. This profile provides a more nuanced understanding of the dark matter distribution within galaxy clusters, offering advantages over the simplified mass distribution models that might be derived from a flat Lambda CDM cosmology alone (J Schwinn 2017). The NFW profile, with its characteristic density ρ_0 and scale radius r_s, allows for a detailed modeling of the cluster's mass density as a function of radius, which is critical for interpreting the gravitational lensing signals. The values for the characteristic density and scale radius parameters utilized in this study are derived from published research (Babyk et al 2012), which itself may be based on extensive X-ray observations of Abell 2744 by facilities like Chandra. This reliance is primarily due to the complex nature of directly calculating these parameters, which would require a detailed analysis of the cluster's X-ray emissions to map its mass distribution—a process beyond the scope of this study. Adopting these values from existing literature, therefore, represents a necessary compromise to facilitate our gravitational lensing analysis.

From the results the flat lambda model showed that the cluster was made of 8% dark matter, while the NFW profile provided unexpected results and showed a very low ratio of dark matter in the cluster. This difference can be for the different way dark matter distribution over the cluster is accounted for, combined with the lack of accounting for redshift in applying the NFW profile. Furthermore, our focus on identifying galaxies with significant elliptical distortions as evidence of strong lensing phenomena inherently limits our study's scope. This approach neglects the subtle but widespread effects of weak lensing, which manifest as slight distortions in the shapes of background galaxies (optical shearing), as well as other forms of lensing that manifest as magnification, distortion, duplication, and the creation of mirrored images. Weak lensing provides a complementary view of the mass distribution on larger scales and across the entire field of view of the galaxy cluster. By not incorporating weak lensing signals or other forms of lensing, our analysis may overlook significant portions of the mass distribution (Furtak 2023).

While this study has provided valuable insights into the dark matter content of Abell 2744, the aforementioned limitations underscore the need for a more nuanced approach. Future studies should strive to incorporate individual redshifts for lensed galaxies, leverage both strong and weak lensing phenomena, and, if possible, directly calculate the parameters for dark matter distribution profiles. Such comprehensive analyses will enhance our understanding of the complex interplay between dark matter, galaxy clusters, and the broader cosmic web, offering a more complete picture of the universe's mass structure.

Works Cited

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