

# HubVis: Software for Gravitational Lens Estimation and Visualization from Hubble Data

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**Abstract**—The Hubble Ultra-Deep Field (HUDF) image spans less than one millionth of the sky, but it contains as many as 10,000 galaxies at distances on the order of 13 billion light years. However, Hubble images are difficult to process and require merging of multiple images from different optical wavelengths. In addition, the interpretation of such images can be complicated by intervening distortion caused by gravitational lensing. To address these issues, a NetBeans visualization tool called HubVis is being developed that includes the capability to: 1) simulate simple gravitational lensing and 2) search for gravitational lenses in Hubble data. The search method utilizes a novel algorithm to estimate gravitational lenses in Hubble data. Results are presented illustrating the current capabilities of the tool.

**Keywords**—visualization; graphics; Hubble; astronomy; gravitational lensing

## I. INTRODUCTION

The Hubble Ultra-Deep Field (HUDF) is an image of less than one millionth of the sky, but it contains as many as 10,000 galaxies at distances on the order of 13 billion light years [1], [2]. Such images offer great potential for understanding the universe, but can present significant challenges in processing such large datasets with multiple images covering different optical wavelengths. These challenges are further exacerbated when combined with intervening unknown distortion of images, such as may be caused by unknown distributions of gravitational lensing or other dispersive processes, as illustrated in Fig. 1. Therefore, a visualization and analysis tool is being developed to: 1) simulate simple gravitational lensing and 2) search for gravitational lenses in Hubble data. Furthermore, the search method utilizes a novel algorithm to estimate gravitational lenses in Hubble data.

This article provides background information on Hubble images and the basic underlying physics of gravitational lenses. It then details to methods for simulating and estimating gravitational lenses.

## II. BACKGROUND

### A. Hubble Images

Hubble images commonly seen in the literature are usually significantly altered versions of the raw Hubble telescope image data. In fact, most raw Hubble images mainly consist of faint objects with the exception of a few bright objects which tend to obscure faint image phenomenon such as gravitational



Fig. 1. Image of Abell 2218 galaxy cluster with gravitational lensing causing distortion of galaxies lying behind the cluster into clearly visible arcs [7].

lenses. In addition, Hubble images are typically formed by merging multiple images taken through many filters at different optical wavelengths. Thus, researchers must work from heavily preprocessed images such as Fig. 1.

### B. Gravitational Lensing

As illustrated in Fig. 2, deep space objects can be distorted by gravitational lensing [3]. In this figure, the light from some true star field of distant objects passes through some intervening distortion field created by large gravitational fields, causing the observed star field to become a distorted version of the original star field. As shown in Fig. 1, distant galaxies can be distorted into arcs or rings known as Einstein rings.

Gravitational lensing by a point mass is governed by:

$$\alpha = \frac{4GM}{c^2} \frac{1}{r}, \quad (1)$$

where  $G$  is the gravitational constant,  $c$  is the speed of light in a vacuum, and  $\alpha$  is the angle of a light ray passing at a distance  $r$  from an object of mass  $M$ .

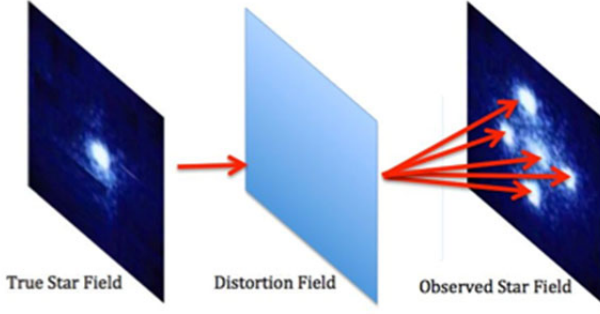


Fig. 2. Illustration of proposed approach: the original observed Hubble star field on the right is to be decomposed into a “true star field” on the left and an intervening “distortion field” (i.e., gravitation lens field) capable of producing the observed star field.

Fig. 3 illustrates the geometry of gravitational lensing for a point source located at  $S$  in the presence of a point mass,  $M$ , at location  $L$ . The original source location  $S$  at angle  $\beta$  appears to the observer,  $O$ , to be at angle  $\theta$  corresponding to position  $S_1$ . The angle  $\beta$  and  $\theta$  are given by the relations shown below:

$$\beta = \tan^{-1} \frac{\eta}{D_S} \quad (2)$$

$$\theta = \frac{\beta \pm \sqrt{\beta^2 + \frac{16GMD_LS}{c^2 D_S D_L}}}{2} \quad (3)$$

where  $D_S$  is the distance from the observer to the source,  $D_L$  is the distance from the observer to the mass, and  $D_{LS}$  is the distance from the mass to the source.

### III. GRAVITATIONAL LENS SIMULATOR

#### A. Simulator Software Interface

The HubVis simulation interface is shown in Fig. 4. It includes a tab for performing a simulation of the lensing scenario of Fig. 3. Interface components allow the user to set the mass of the object,  $M$ , along with its specified  $(x, y)$  location of the source  $S$ , the radius of the source  $S$ , through the use of sliders or by clicking in the lower right image. The parameters of the lens can also be set through sliders that set the source-observer distance,  $D_L$ , and the lens-observer distance,  $D_L$ . A save button also allows the user to save the simulated results.

#### B. Simulator Results

The simulator draws the source image as a green circle in the  $(x, y)$  location specified by the user. The Einstein ring is drawn in red, and its size is determined by the geometry of Fig. 3 [5]. The blue images represent the image of the

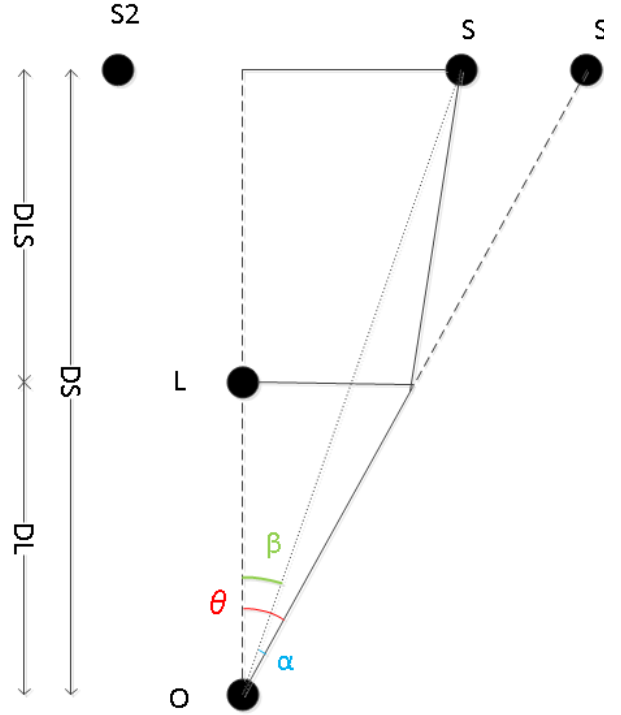


Fig. 3. The angles and distances in the gravitational lensing of a source object to the observer.  $S$  represents the location of the source, the object undergoing the lensing, and  $S_1$  and  $S_2$  are the observed lensed images of  $S$ .  $S_1$  and  $S_2$ 's locations come from the roots of the equation (3). [5]

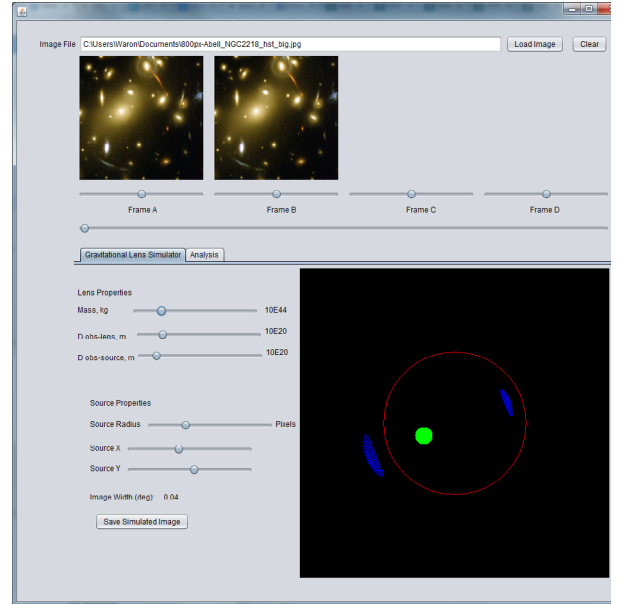


Fig. 4. A screenshot of HubVis gravitational lens simulator. The large image on the lower right of the window displays the simulated image of the lensed object with parameters specified by the interfaces on the lower left.[7]

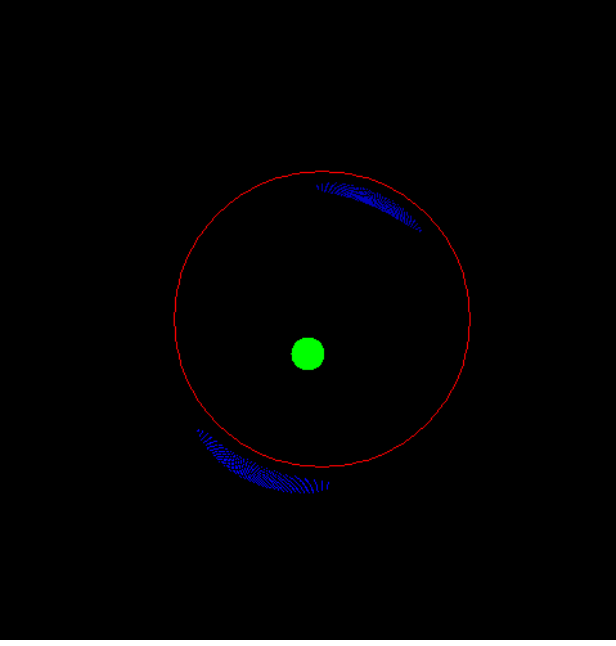


Fig. 5. A simulation of gravitational lensing generated by the HubVis. A point mass is located in the center of the Einstein ring (red circle), the green circle is the true source starfield, the two blue arcs are the observed starfield corresponding to the gravitationally distorted source.

gravitationally lensed source when viewed from the location of the observer. Fig. 5 shows a simulation result with the source in green, Einstein ring in red, and the gravitationally distorted source in blue. These two blue arcs are similar to the arcs seen in the Hubble image from Fig. 1.

#### IV. AUTOMATIC LENS EXTRACTION TOOL

HubVis includes a tool for automatic extraction of the center of gravitational lenses. This is accomplished by having the user select a point in the image hypothesized to belong to a gravitationally distorted arc. An automated algorithm estimates the center of the gravitational lens. The algorithm accomplishes this task through 3 steps: 1) estimate the pixels belonging to the complete arc from the selected  $(x,y)$  location, 2) subdivide these pixels into 3 groups that span the extent of the arc, 3) random samples are extracted from each group to create a triplet and the circles computed from these triplets are statistically integrated into a single estimate of the unknown gravitational lens center and radius for the arc. A final refinement step is applied to find the arc minimizing the Euclidean distance to all of the arc pixel data.

##### A. Finding Radius and Center

Using the pixel coordinate of the arc selected by the user within the image, a region growing algorithm is used to find all the pixels that make up the image of the arc. The region grower takes the selected pixel, records its value, and compares it to its

8 neighboring pixels. If the neighboring pixel contains values within a certain threshold of the pixel it is being compared to, it is declared a neighbor and added to that region. When there are no more pixel neighbors, the region is complete, and the  $x, y$  locations of the pixels are used to fit a circle to the arc, whose center will represent the estimation of the source location.

##### 1) Selecting ArcPixels

Regions are estimated by classifying the image pixels into arc-candidate pixels and background pixels. This is accomplished by choosing thresholds for the red, green, and blue components of the image and subsequently applying dilation and erosion morphological operations to remove small and noisy regions. The arc of interest is taken as the region that includes the user-selected  $(x,y)$  location [6].

##### 2) Region subdivision

The  $(x,y)$  points are then divided into 3 groups based on their approximate position along the arc of the circle. The principal components of the region  $(x,y)$  data are used to estimate the tangent line to the arc that passes through the center of the region [8]. The points are divided into 3 groups according to their positions along this tangent line. Quantiles of the position data are used to divide these points into groups varying of sizes which is controlled through the HubVis interface where the default setting makes all three groups equal in size.

##### 3) Compute Initial Arc Estimate

Random samples are selected from each group to generate plausible arc-triplets. For each triplet, a circle is computed and an estimate of the initial unknown gravitational lens  $(x,y)$  center and radius is taken as the average of the randomly computed circles.

##### 4) Refinement of the Arc Estimate

Using the initial arc estimate as a starting point gradient descent is applied to minimize the sum of squared Euclidean distances between the arc region  $(x,y)$  data and the unknown circular arc.

#### B. Lens Extraction Interface

The HubVis lens extraction interface is shown in Fig. 6. A typical lens extraction process is accomplished as follows: 1) the user loads a Hubble image which is displayed in the lower right, 2) the user clicks on an  $(x,y)$  location in the image suspected to be a pixel from a gravitationally distorted arc, 3) the arc region is extracted from the image and the refined estimate of the unknown gravitational lens is computed automatically. A visual representation of the estimated arc is shown.

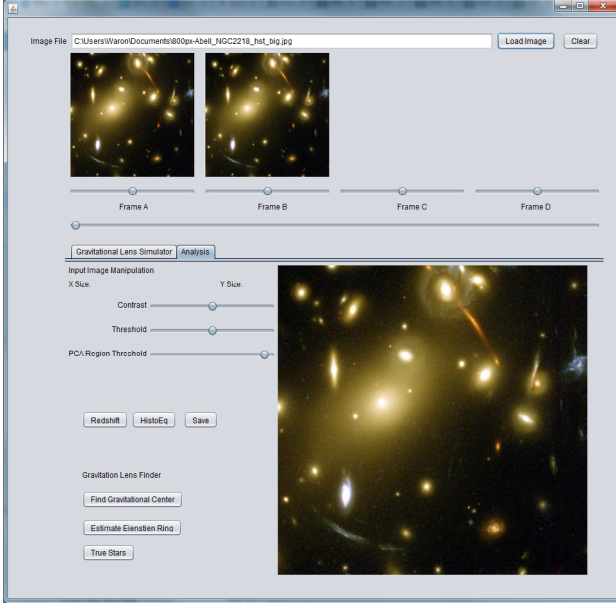


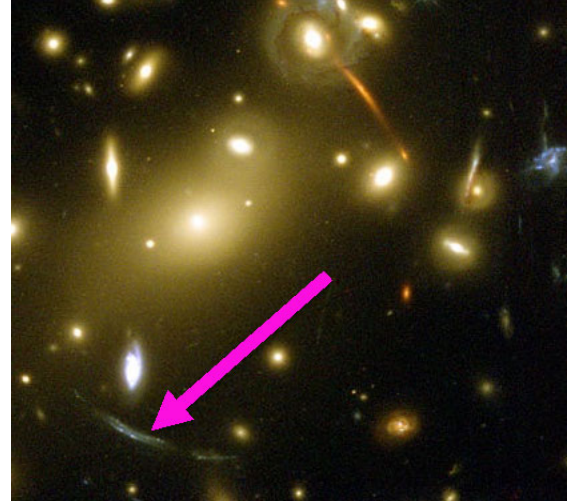
Fig. 6. A screenshot of HubVis lens extraction tool. The large image on the lower right of the window displays a user-selected image that includes suspected gravitationally distorted arcs. Interface controls on the lower left allow the user to control the extraction process. [7]

### C. Lens Extraction Results

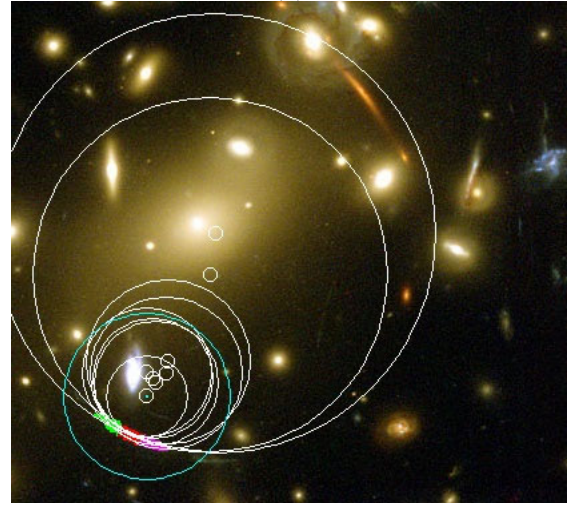
Fig. 7 illustrates the steps to lens extraction for an excerpt from a Hubble image of Abell 2218 [7].[4]. In Fig. 7(a) the red arrow points to a suspected gravitationally distorted arc. Fig. 7(b) shows the three groups of pixel data for the extracted arc region as green, red, and magenta pixel clusters. Also shown in Fig. 7(b) are the randomly fit circles (in white) and the mean circle (in cyan). Fig. 7(c) shows the refinement process as a sequence of magenta circles and associated center points which converge to the global minimum estimate shown in cyan. Fig. 8 illustrates the steps to lens extraction for an excerpt from a Hubble image of Abell 370, with similarly effective results [9]. Finally, Fig. 9 gives the final results for lens extraction using a simulated gravitational lensing scenario generated by HubVis. In this image the red filled circle in the center corresponds to the estimated location of the gravitational source. The estimated location of the gravitational source (filled red circle) corresponds well with the true location of the simulation gravitational source at the center of the yellow crosshair.

## V. CONCLUSION

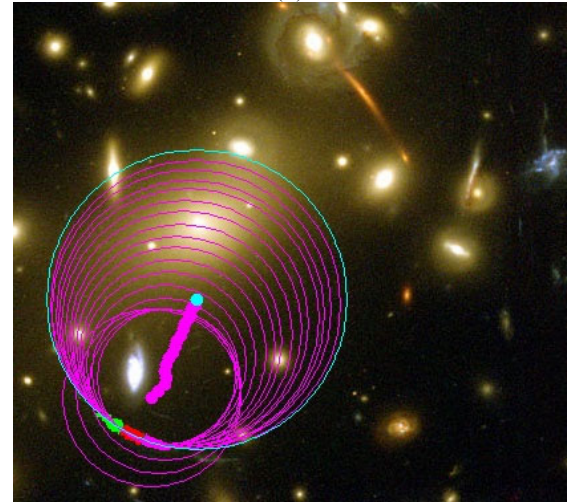
This article describes a new software tool, HubVis, intended to facilitate the simulation and estimation of gravitational lens effects on recorded imagery. The simulation tool allows users to postulate a lensing scenario and compute the observed images of a gravitationally lensed source object. The extraction tool allows users to extract estimates of gravitational lens attributes directly from astronomical images. These two tools in concert enable users to research gravitational lensing effects using either a generative approach, i.e., simulation, or an inverse-problem estimation approach, i.e., the lens extraction tool.



(A)



(B)



(C)

Fig. 7. shows results from the proposed lens extraction method. (A) shows the original excerpt of Abell NGC2218 [7]. (B) shows the 3 groups of arc data in green, red, and magenta and a collection of circles fit to random triplets from these groups in white. The initial estimate for the gravitationally distorted arc is shown as a cyan circle. (C) shows the refinement process for the gravitationally distorted arc as a sequence of magenta circles with the cyan circle and center being the best-fit estimate.

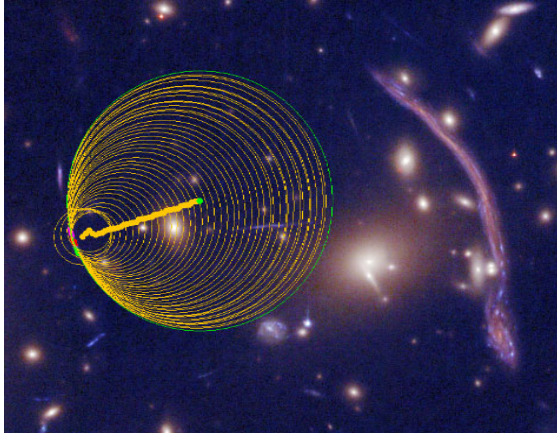


Fig. 8. A screenshot of the lens extraction tool on a modified excerpt from Abell 370. In this image the progression of the circle fitting algorithm is expressed by the yellow circles and the final result by the green circle.[9]

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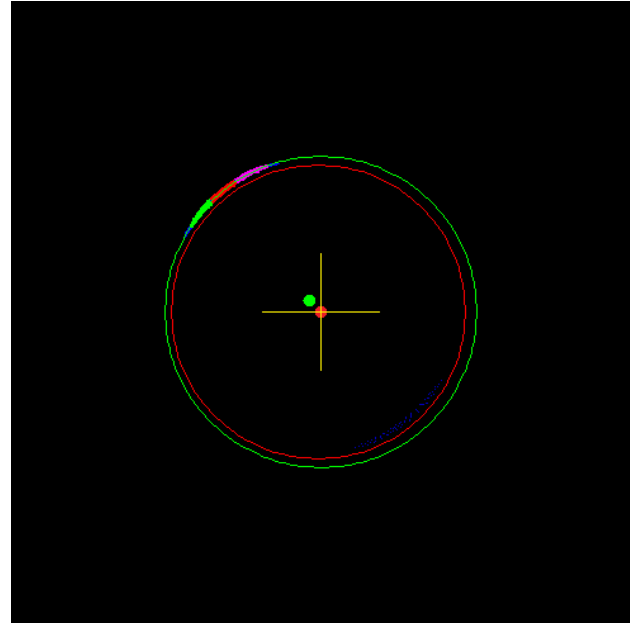


Fig. 9. A screenshot of the lens extraction tool results using a simulated gravitational lensing scenario generated by HubVis. A point mass is located in the center (yellow crosshair "+") of the red Einstein ring, the filled green circle is the true source starfield, and the upper left green, red, and magenta arc is the gravitationally distorted starfield. In this image, the circle fitting algorithm results in the outer green circle and results in the red filled circle in the center that corresponds to the estimated location of the gravitational source. The estimated location of the gravitational source (filled red circle) corresponds well with the true location of the simulation gravitational source at the center of the yellow crosshair.