Simulating the Deep Lens Survey

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Abstract

The Deep Lens Survey (DLS) is a detailed galaxy survey in the optical spectrum. The primary purpose of the DLS is to build topographic maps of dark matter in the local universe using weak gravitational lensing. I built upon already existing software to create a realistic computer simulation of the DLS. This simulation is important because it can help asses systematic error in the DLS.

1 Background

Cosmology is the study of the physical universe at its largest scales. As in every field of science, cosmological theories must rely on careful experiment. Experiment tends to involve large telescopes and detailed images of stars and distant galaxies. The DLS is no different. In particular, the DLS covers seven four square degree fields of the sky. These observations were taken from two separate four meter telescopes. Images were captured in four color bands: B (450nm), V (520nm), R (600nm), and z (860nm). The entire survey took five years to complete[1].

1.1 Gravitational Lensing

Astrophysicists have found that most of the mass in the universe does not emit any light[2]. The DLS was conceived to construct large unbiased maps of this dark matter. This might seem difficult because dark matter is invisible. The trick to doing this relies on the fact that, even though dark matter does not absorb or emit light (or interact through any known force except gravity), it interacts gravitationally with it. General relativity shows that light is bent by matter. When large chunks of dark matter lie in front of distant galaxies, dark matter will distort the image of the background, causing a cosmic mirage. Figure 1 shows an example of this. Here, light from two different paths is bent and meets at the earth. From earth, we would see the same image in the sky at several different locations. This distortion is called gravitational lensing. A very unrealistic simulation of figure 1 can be seen in figure 2. Even when the distortion is not powerful enough to cause multiple images, the distortion will tent to shear, or squash, the galaxies tangentially around the center of the mass.

Physicists quantify this by analyzing images to build detailed topographical maps of dark matter. By doing so, we can learn about dark matter. We can see how it is dis-

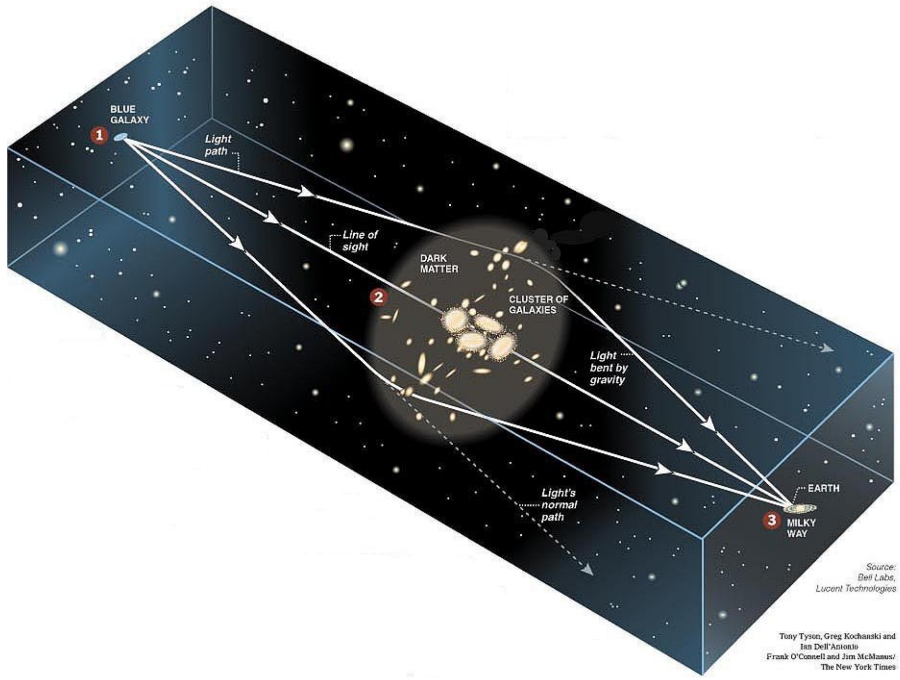

Figure 1: The classic diagram of gravitational lensing. Here, light from a background galaxy is bent around dark matter and arrives at the earth from two different paths. Humans would see a double image.[2]

tributed, how it clusters, and therefore how it behaves. We hope that this will teach us about what this mysterious dark matter really is. Furthermore, we will also be able to learn about dark energy, which has been recently (cosmologically speaking) accelerating structures apart.

To perform dark matter calculations, one actually measures the correlation between the ellipticities of galaxies. To do so, you look at how each galaxy's shape is related to the shape of its neighbors. One would assumed that without the presence of dark matter, there would be no statistical correlation between the shape of galaxies. Our simulation in figure 2 shows this. On the left, where no dark matter is present, there is no correlation between the shapes of any galaxies. On the other hand, when a large amount of dark matter is present, galaxy shapes are strongly correlated tangentially around the mass.

This correlation can be mathematically measured with two statistics. The first statistic is called the E-mode. The E-mode measures the correlation which can be caused by gravitational lensing. This is the tangential alignment. An example of this correlation can be seen in figure 3. If a large E-mode is present in your data, you know that you are looking through a lot of dark matter. The second statistic is called the B-mode. An example of it can be seen in figure 3. The B-mode cannot be caused by gravitational lensing. In fact, there is no physically real situation whereby a B-mode could be produced. The B-mode is an important sanity check. If you find much of a B-modes in your data, you know that something has gone terribly wrong in your

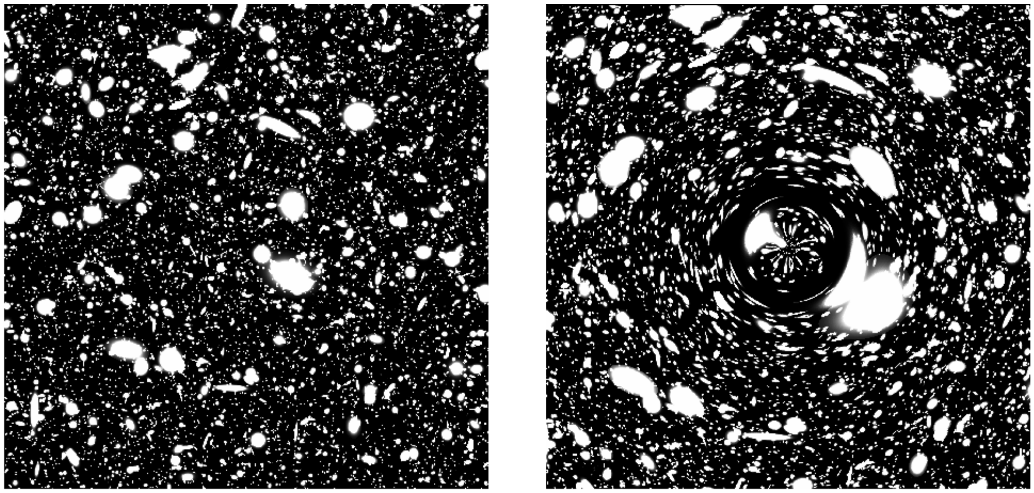

Figure 2: A simulation of gravitational lensing. The left is a random distribution of galaxies. The right is the same distribution gravitationally lensed by a large amount of dark matter. The dark matter is at the center of the image.

analysis. You cannot rule out the possibility that whatever error is causing your B-mode could also cause your E-mode. Therefore, you could not believe that what you were measuring was actually dark matter. Instead, the signal would likely be caused by errors introduced somewhere in the experiment. Unfortunately, the B-mode does not tell you what has gone wrong and there is no way to correct for it.[1]

Figure 4 shows the correlation function calculated for the images in figure 2. As you can see, when no gravitational lensing is present, there is little E-mode and little B-mode. The B-mode here is likely caused by the unrealistic simulation. When lensing is present, there is a big E-mode and only a small B-mode. The E-mode and B-mode intuitively measure the dark matter signal and the error.

1.2 Errors

Astrophysicists are interested in looking for E-modes in their data and making sure that B-modes are not present. This involves careful measurement of small correlation between the shape of lots of galaxies. Experimental errors can make this measurement difficult. The atmosphere can be particularly problematic. It will blur any image that comes through it. The atmosphere can cause circular objects to look elliptical and elliptical objects to look circular or more elliptical. And the atmospheric distortion can be anisotropic and spatially varying. This means that the amount and shape of the distortion will vary across the image. It will also vary from exposure to exposure. The atmosphere can cause a false lensing signal and introduce a B-mode.

The DLS deals with these errors in several ways. The first is a process called dithering. For each patch in the sky,

[1]The actually definition and calculation of E-modes and B-modes is quite involved. And their meaning is much more complicated that has been presented. For a more in depth discussion, see [3].

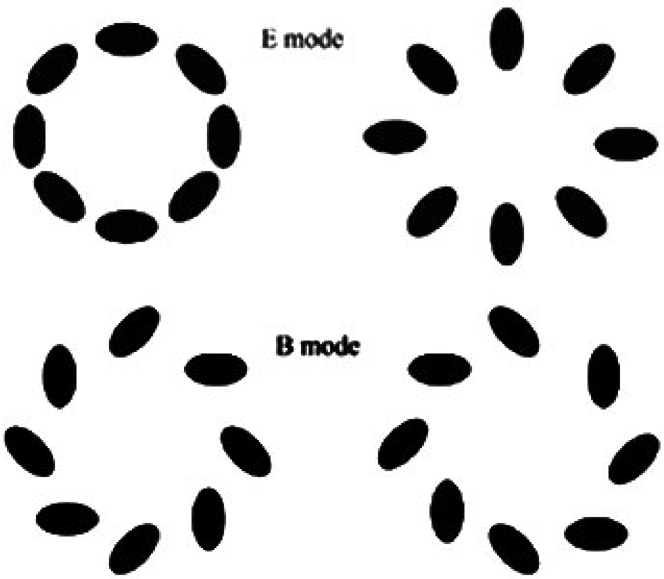

Figure 3: Example galaxy correlations which would lead to E-modes and B-modes.[4].

twenty separate and slightly offset images are taken. The twenty images are then coadded together. This technique helps to ensure that systematic defects in the camera do not bias the exposures. Furthermore, by adding together several pictures of the same object, each with a different atmospheric distortion, the total anisotropic distortion and spatially varying nature of it will be reduced. This process will not correct for the isotropic blurring. Physicists invented another process to correct for the anisotropy of the atmospheric distortion. If there was no atmosphere and a perfectly focussed camera, stars would look almost like point sources. It is blurring that causes stars to look elliptical. Since the stars and galaxies are effected identically by the atmospheric distortion and camera errors, measuring the shapes of the stars allows analysts to correct the shapes of the galaxies. A process called circularizing is applied to every image. By transforming the image to make all the stars circular, you can minimize the anisotropic effect of the atmosphere and telescope.

The DLS has been able to generate accurate data, but there is still a small lingering B-mode. The only way to get a sense of what is causing the B-modes is to do very accurate simulations of the data. By properly simulating the experiment and the data analysis, the same error should present itself and one should be able to learn how to correct for it.

2 The Simulation

My summer project involved working on a simulation of the DLS. The goal was to make the simulation as accurate as possible. A smaller simulation of the DLS had already been built. It is from this old simulation that my simulation was born. The main program is written in Python. Python proved particularly nice because it interfaced well with other astronomy tools. My simulation runs as follows:

1. Generate a random list of stars and

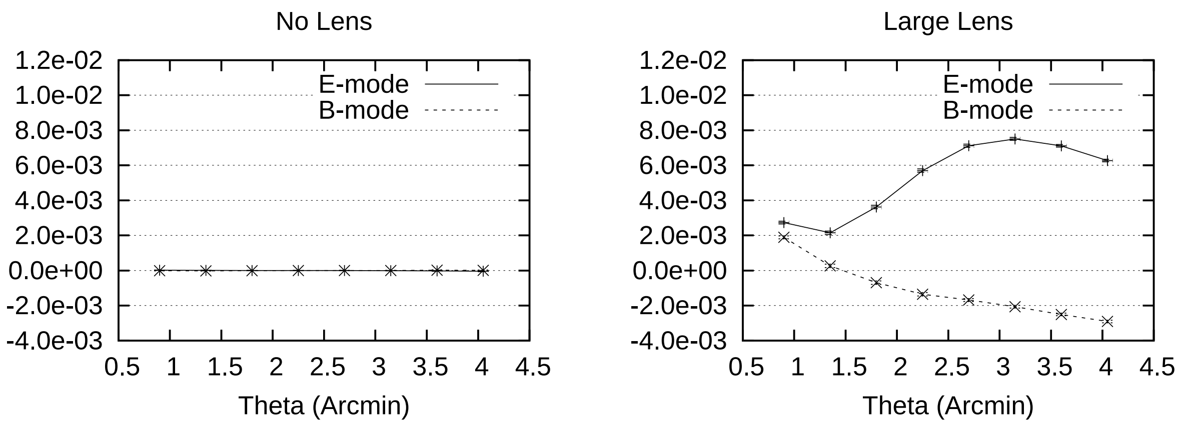

Figure 4: The correlation function for figure 2.

a random list of galaxies in statistical agreement with observation.

2. Create each of the twenty dithered images:
   (a) Divide the image into 8 CCDs[2], which are simulated separately.
   (b) Add galaxies to the CCD.
   (c) Have the galaxies gravitationally lensed by a mass of dark matter.
   (d) Add stars to the CCD.
   (e) Add a realistic atmospheric blur to the image.
   (f) Add atmospheric noise to the image.
   (g) Circularize the image[3]
   (h) Combine the 8 CCDs into one image.
3. Coadd the 20 individual dithers into one image.

This program posed a computational challenge. Each of the 20 dithered images was 300MB. The total simulation generates over 10GB of data and take days to run. To speed up the simulation, the program was modified to run on a 32-node cluster. This sped up the simulation so that it would run in a reasonable amount of time. The final images that were produced were 8192 pixels by 8192 pixels. This simulates a 0.7 degree by 0.7 degree patches of the sky, the same size as the DLS images.

3 Results and Discussion

I ran the full simulation and generated large simulated images. Some real data from the DLS can be seen in Appendix A. A similar sized patch of the simulated data can be seen in Appendix B. Notice that the simulated data with and without gravitational lensing looks very similar. This shows that the effect of gravitational lensing is small. E-mode and B-mode graphs for the data can be seen in figure 5. Unfortunately, not much can yet be learned from these graphs because image circularization has not been applied yet.

[2]Each telescope image is actually built up out of 8 smaller images taken from separate CCDs. These are combined into one larger image after the exposure.

[3]This step is described further in section 4.

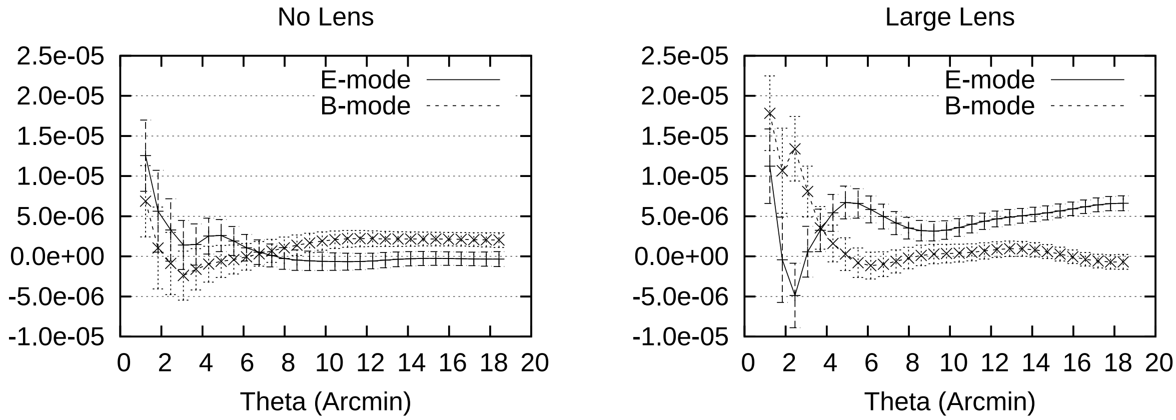

Figure 5: The correlation function for images from the full simulation.

4 Future Work

I put a lot of work into building the simulation, but there is still a lot of work to be done. I never had a chance to get the simulation to circularize the images before they are stacked. Since this is a major step in the DLS analysis pipeline, my results cannot yet be properly interpreted. Furthermore, there is much to be learned by doing the circularizing step several different ways. One way would be to to change the atmospheric blur so that the blur itself is circular. The second would be to circularize the image with an a priori knowledge of what the atmospheric distortion was (i.e. do a perfect circularization). Finally, one could circularize the image more realistically using star out of roundness calculations taken from the simulated data.

This would be nice because each method would be more realistic, and we could see which of the steps of realism are problematic. The first method would let us see if error was introduced even with a perfectly circular atmospheric distortion (which should only lose signal and not introduce false correlation). The second method would test if the error was introduced by the circularizing process done perfectly. Finally, the third method would tell if the problem lay in our ability to detect stars.

The program could be improved in other way. The galaxy and star distribution and lens file could be set more realistically to mirror DLS data. It could also be modified so that not all of the galaxies in the simulation came from the same distance. It would be nice to try redoing the simulation with perfectly circular galaxies. This would reduce to zero the shape noise and allow for more accurate shear correlations to be performed. Finally, the algorithm used for stacking the images is not the same algorithm used by the DLS. It would be nice to use the better DLS algorithm.

5 Acknowledgements

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References

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[2] LSST: Large Synoptic Survey Telescope. Website, 2006. www.lsst.org.

[3] P. Schneider, L. van Waerbeke, and Y. Mellier. B-modes in cosmic shear from source redshift clustering. *ASTRON.ASTROPHYS.*, 389:729, 2002. astro-ph/0112441.

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Appendices

A Real Data

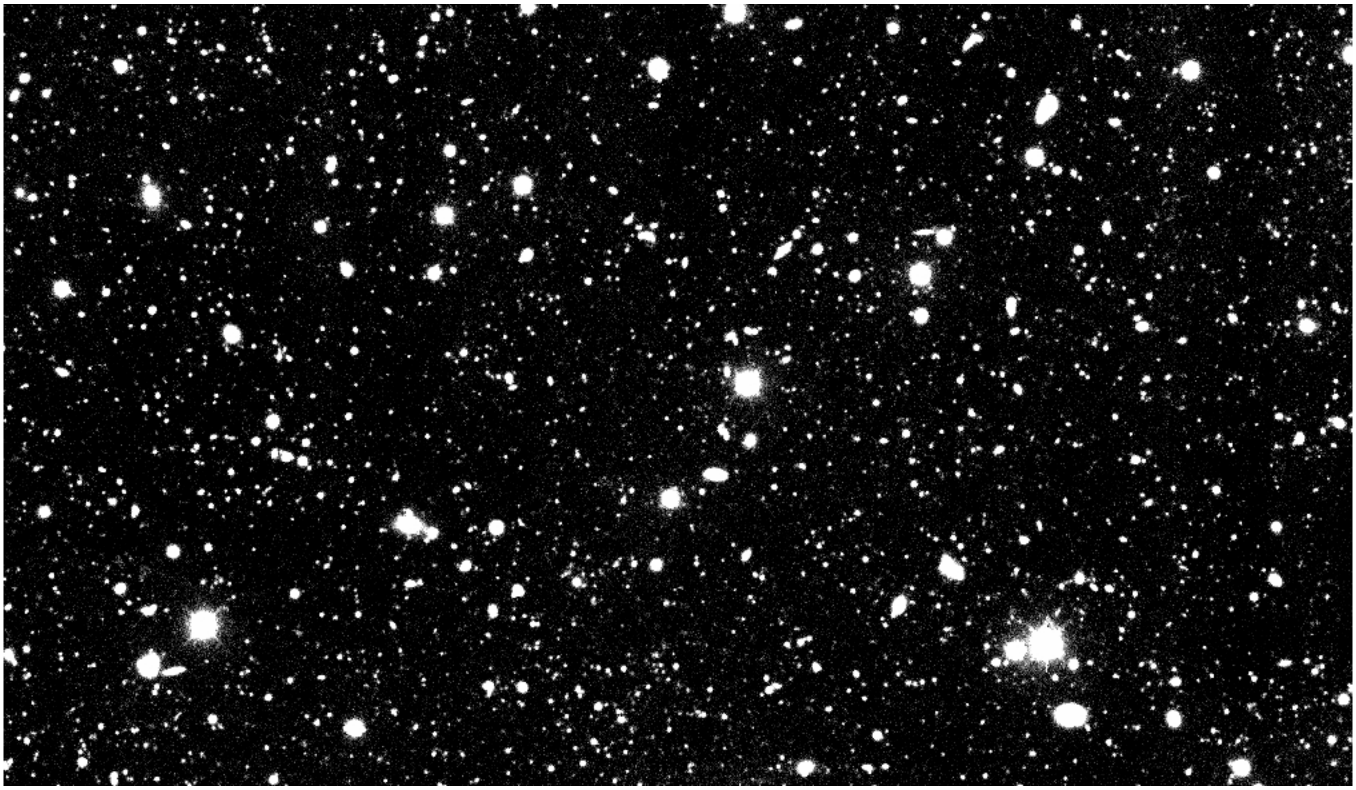

Figure 6: Some real data from the DLS.

B Simulated Data

Figure 7: Some simulated data without gravitational lensing.

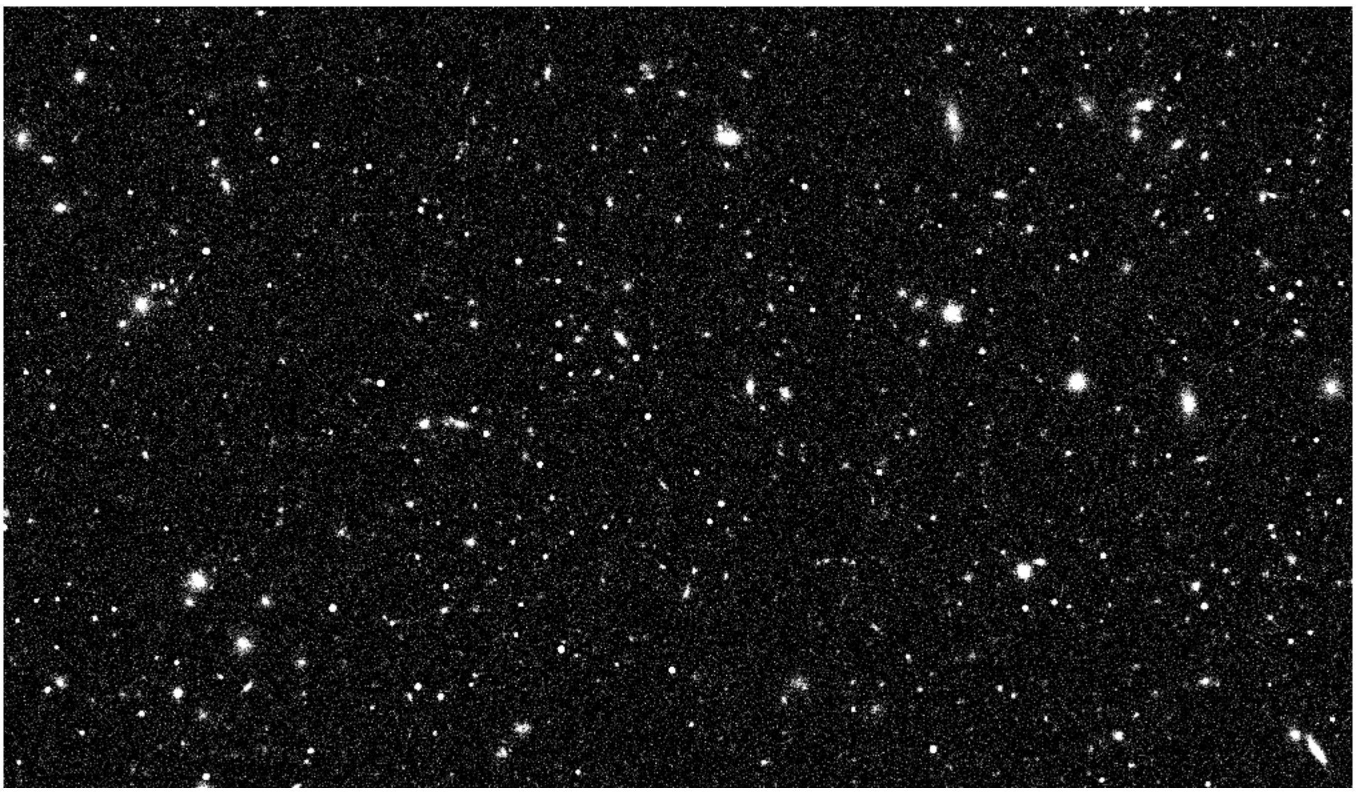

Figure 8: Some simulated data with gravitational lensing.