

PART THREE: GRAVITY AND THE MANY LENSES OF KNOWING

Learning Objectives

1. Investigate strong gravitational lensing with real galaxy clusters, and how they can be used as a tool to measure the invisible mass in the universe.
2. Construct 3-color images of galaxy clusters using JS9.
3. Learn about the PISCO instrument, the South Pole Telescope, and some of the astronomers involved in those projects.

NGSS Core Ideas

PS4.B Electromagnetic Radiation (HS-PS4-3)

PS4.A Wave Properties (HS-PS4-2, HS-PS4-5)

PS4.C Information Technologies and Instrumentation (HS-PS4-5)

NGSS Cross-Cutting Concepts

Systems and System Models (HS-PS4-3)

Influence of Science, Engineering, and Technology on Society and the Natural World (HS-PS4-2, HS-PS4-5)

NGSS Science and Engineering Practices

Asking Questions and Defining Problems (HS-PS4-2)

Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena (HS-PS4-3, HS-LS4-1)

Engaging in Argument from Evidence (HS-LS4-5, HS-ESS2-7)

Space required

Classroom with computers for each student, or small groups of students

Materials

For each student

Student worksheets

Pencil

Scissors

Scotch tape or glue stick

Ruler or straight edge

Calculator

Colored pencils

For the class

Internet access to JS9, Foothills College simulations

Computers

PROCEDURE DAY 1

Students will use the online software JS9 to create their own three-color image of a massive cluster of galaxies which hosts a beautiful example of gravitational lensing. The students are also given information about the PISCO instrument, its image processing, the South Pole Telescope, and a scientist spotlight on Dr. Nan Li, who works with PISCO images on gravitational lensing. If there is interest, this is a good time to bring in the extra interview with Rachel Bowens-Rubin.

There are no correct answers to this activity. The students should have a three-color image by the end of the day.

Looking at the Looking Glass

In this section, you will create your own three-color (or “composite”) image of a galaxy cluster using an online tool called JS9. This is based off of (and nearly identical to) DS9, one kind of software that astronomers use to analyze their observational data.

Most three-color images that you see in the news or on social media are - as the name implies - composites of three images taken at three different *wavebands*, or chunks of the electromagnetic (EM) spectrum. Different features become more prominent at different parts of the EM spectrum, so we want to use images that represent as much of the visible spectrum as possible: we typically combine images taken at “red”, “green”, and “blue” wavebands.

Navigate to the JS9 website:

https://waps.cfa.harvard.edu/eduportal/js9/software_PISCO.php

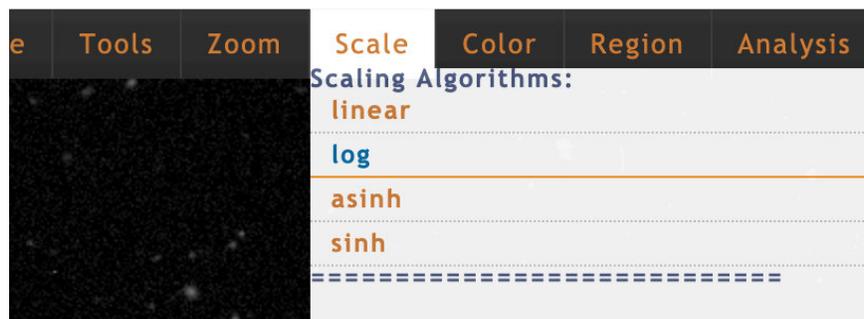
This instance of JS9 comes pre-loaded with three images. You can see them by hovering over the tab that reads “Archived Images.”



You will only be able to work on one image at a time, and you load each image by clicking on the file name in this tab. You can tell which image is in the foreground — that is, the “working” image — by reading the filename below “Image Displayed” in the right-hand panel.

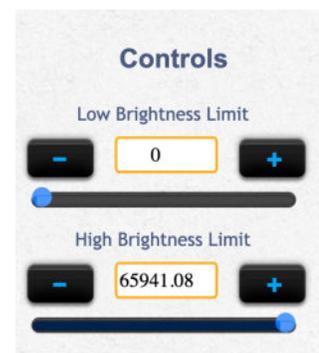
To create your composite image, complete the following steps:

1. Click on the first file, the one named sptclj0106_5355.RED.
2. Looking at the JS9 screen right now, you may notice that this looks like a whole lot of nothing. Maybe a few bright points here and there, but definitely not an interesting astronomical image! That's because we're using a *scale* for the brightness of the image's pixels (short for "picture element," a pixel is the smallest building block of an image) that's not quite right for this image. Move your cursor around the image and pay attention to the "Pixel Value" readout in the far-right panel, under "Image Displayed". In some of the darkest regions on the image, the readout is negative, but in the brightest points it can well over 10,000! That's a huge range!
3. We want to *scale* these values to make it easier to see the variation in brightness from pixel to pixel. Our best option for that is to choose a *logarithmic scale*. Hover over the "Scale" menu, and select "log".



4. At this point, you may be able to tell that there's definitely more to this image than we thought before! To really make the features pop, we need to set the "Low Brightness Limit" and the "High Brightness Limit". You can do this by using the sliders in the right-hand side panel, or by typing in a value into the appropriate box.

The "Low Brightness Limit" sets the value of the background. If while scrolling around the image you notice that much of the darkest areas are about the same value, say 300, then you would change the "Low Brightness Limit" to 300. In our case, it makes the most sense to keep the "Low Brightness Limit" at 0. This means that any pixel with a value less than the "Low Brightness Limit" will be treated as though its value is zero.



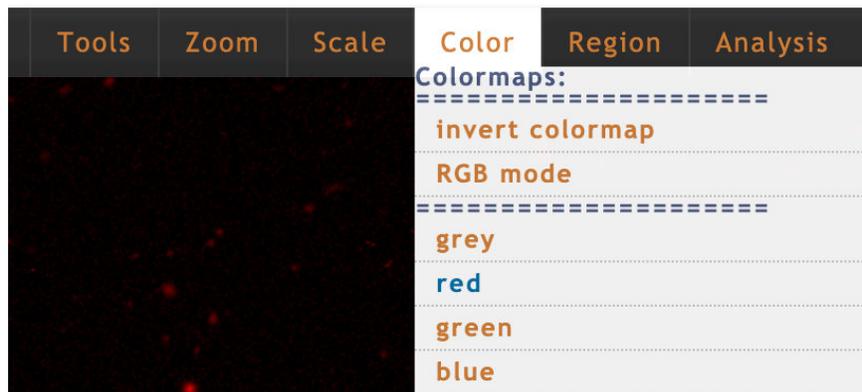
5. Similarly, the "High Brightness Limit" sets the value of the brightest pixel. Just like with the "Low Brightness Limit", setting this parameter will treat all pixel values above your limit as though their value is equal to the "High Brightness Limit". You can explore the image in the same way as you did with the "Low Brightness Limit", by moving the cursor around to look at pixel values — this time, however, focus on some of the brightest regions in the image. If you set this value to be too high, then you lose any details

that might be of a lower brightness. If you set it too low, your image will look like it's oversaturated. For the red and green images, it looks best at 15000, and for the blue image, at around 10000.

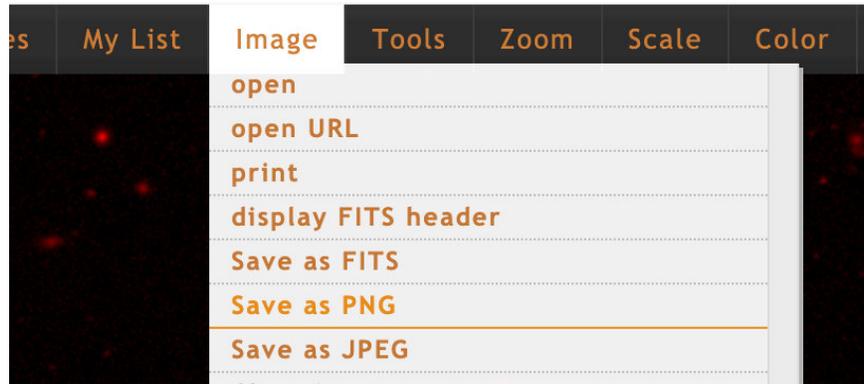
Challenge Question: Based on what you just read, why do you think it's best to set the High Brightness Limit on the blue image just a little lower than the other two?

Many of the details we care about are in the blue, which is why we don't want the high brightness limit to be too high.

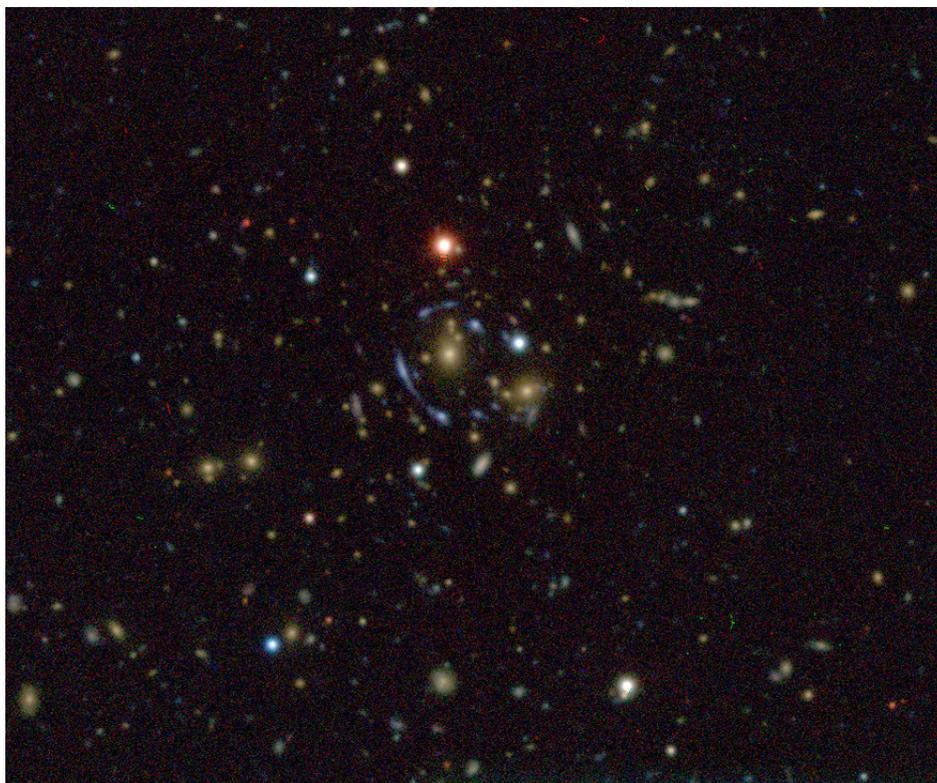
- The last step is to choose the correct colormap for this image. Hover over the "Color" tab and select the colormap that corresponds to the foreground image. Again, you can check this by reading the filename under "Image Displayed". For example, the image that ends in "RED.fits.gz" will use the "red" colormap, and so on.



- Repeat steps 1 through 6 for each of the three cluster images you have in JS9.
- When you have completed these steps for all three images, return to the "Color" tab, and now select "RGB mode." This will automatically combine the three images into one.
- Save your image as a "PNG" file. This file format, and JPEG, will save the colorized information about your image, but will lose the brightness and coordinate information. This will download to your default Downloads folder on your computer. It's good practice to move your file to a more appropriate folder, perhaps one that you use for this class, and to rename the file to something more familiar. For example: "ClusterName_RGB.png".



In the end, your composite cluster image should look something like this:



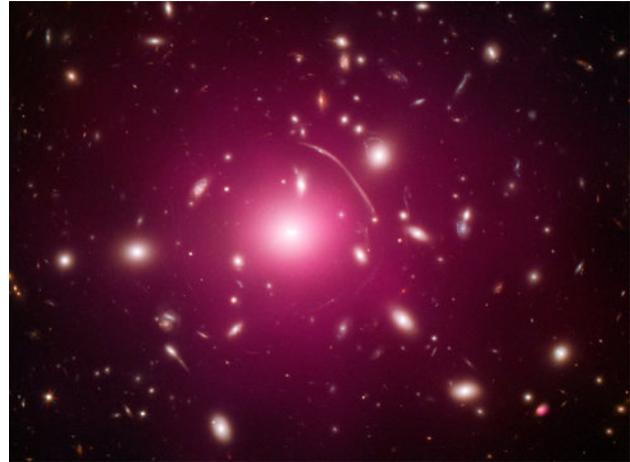
10. Back in JS9, explore the image you've created. Under the "Zoom" tab, you can zoom in and out on the image. Additionally, the "Tools" tab has a Magnifier that may also be useful. What do you notice? What pops out to you about this image?

The students should take note of the bright blue arcs near the center of the cluster. They might also note the color difference between the cluster galaxies and the gravitationally lensed images.

11. Do you think that everything in this image is part of the galaxy cluster? How do you know? Can you tell just from a picture or do you need more information?

We can be fairly certain that the arcs do not belong to the cluster -- these are likely gravitationally lensed images. However, we would need spectroscopic data to tell us the distance to the cluster and the blue arcs in order to be sure (we would expect the blue arcs to be further away than the cluster).

12. At the end of Part 2, when we discussed dark matter, the image here was an example of how the X-ray gas in clusters of galaxies could be used to infer the presence of dark matter. Take another look at the image. Does anything stand out to you? Are there any similarities between the image you created, and the image shown here? List some below, along with any major differences you notice as well.



A composite image of the galaxy cluster Abell 383, shown in both X-ray (red overlay) and optical (tri-color background).

Image Credit: X-ray: NASA/CXC/Cinestav/T.Bernal et al.; Optical: NASA/STScI

Similarities: e.g., This is another example of gravitationally lensed images. You can see one large arc near the center, and many fragments of arcs throughout the image; this is an image of a cluster of galaxies; etc. Differences: e.g., the resolution in this image is much better; we're looking at different wavebands in the two images; etc.

13. Based on what you've learned so far, how might you explain the oddly shaped images in the picture of Abell 383, and the picture you created?

Gravitational lensing.

Technology Spotlight: PISCO and the South Pole Telescope



One of a pair of twin 6.5-meter Magellan Telescopes: this is the Clay Observatory at Las Campanas, Chile. The Parallel Imager for Southern Cosmology Observations (PISCO) can be attached to this telescope at one of the side mounts, where all the collected light comes to a focus.

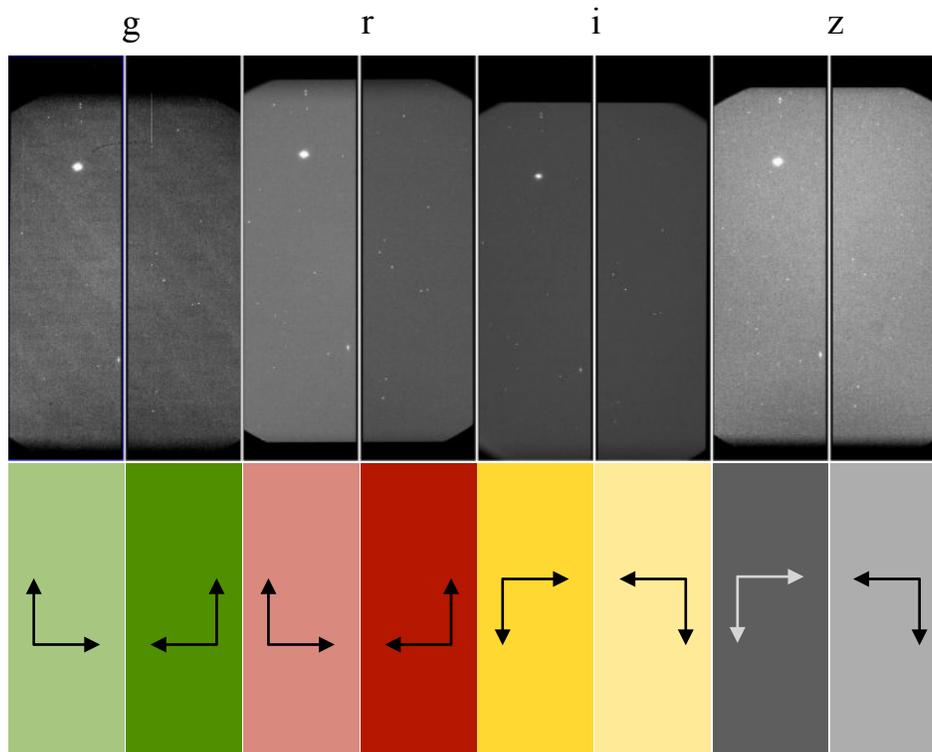
Image credit: Yuri Beletsky and Las Campanas Observatory

The images you have used to investigate gravitational lensing were taken with a very special camera: the Parallel Imager for Southern Cosmology Observations, or PISCO. It can be attached to one of the telescopes at Las Campanas in Chile, pictured to the left. This camera is special because it can take pictures of the sky in four color filters at once (hence “parallel imager”). Because of its design, scientists can observe the night sky about three times faster

than they would using other cameras. That saved time means that astronomers can scan over a larger fraction of the sky in one night without compromising on image quality.

When they are first taken, images from PISCO look very different from the images we used in the previous activity — shown in the figure here. Recall that all four wavebands are observed simultaneously, and so their images are read out at nearly the same time. To make this readout process more efficient, each waveband’s CCD (charge coupled device, the same kind of technology as in your cell phone’s camera) is split into two sections, which get interpreted separately. In fact, some of these sections are inverted or rotated from the original orientation, as shown with the arrows in the figure here. You might also notice that the raw images on the top are not rectangles. This is because the PISCO instrument exhibits *vignetting*, which essentially means that part of the CCD does not get illuminated (or is partially illuminated) due to the internal design of the camera. Astronomers must extract consistently sized rectangles from these images, and stitch them together in the correct orientation, in order to produce the images that we are familiar with. *Challenge question:* How would you have to manipulate the raw PISCO image to generate four separate rectangular images?

The PISCO instrument was built to provide follow-up observations for one science program on the South Pole Telescope (SPT). Using this telescope, scientists discovered several massive clusters of galaxies (including J0106-5355), but needed technology like PISCO to accurately determine redshifts to these clusters. You may recall that the term *redshift* refers to how much a photon’s wavelength is compressed (blueshifted) or stretched (redshifted), depending on its motion toward or away (respectively) from an observer. By applying the same principle to the



Top — A raw image taken by PISCO. Each of the four wavebands (called by astronomers g, r, i, and z; taken simultaneously) produces two images which are read out separately.

Bottom — The image must under go some transformations before it is recognizable as the images we used in the previous activity.

Image credit: Adapted from Anthony J. Taylor, Harvard Undergraduate Thesis

light from clusters of galaxies, we measure how far away that cluster is from us. In fact, all objects outside of our local neighborhood are moving *away* from us, meaning that the light from every galaxy cluster we see in the universe will be shifted toward the red part of the electromagnetic spectrum (that is, it will be *redshifted*). This phenomenon is known as Hubble's Law, which you have already read about in Part 2. Much of observational astronomy is dedicated to measuring accurate distances to objects in the universe. Redshift is only one such way of measuring this value. Other methods include using things like supernovae and variable stars. Each of these (and many more) are best used at particular distance ranges, and as such, scientists refer to these tools as the distance ladder — different methods make up the rungs of the ladder, and as we step up, we can measure farther and farther distances.

Working at the South Pole Telescope is a special privilege. For more information see the Supplemental Interview with Rachel Bowens-Rubin, and her blogpost detailing a day in the life at the South Pole.

Scientist Spotlight: Dr. Nan Li

Dr. Nan Li is an astronomer who has been participating in this research at the South Pole Telescope on gravitational lensing. Below is a short interview with Dr. Li about his work.

1. What is your name and academic position? How long have you been working in gravitational lensing, and/or with the PISCO/SPT groups?

My name is Nan Li, I am a faculty member at National Astronomical Observatories of China, and used to be a postdoc at

University of Chicago/Argonne working with the PISCO/SPT groups. I have been working in gravitational lensing with the group since 2013.



2. Please describe the kind of work that you do. What is your favorite part of this work?

I am focused on generating simulated images of gravitational lensing in galaxies and galaxy clusters. My favorite part of this work is connecting cosmological simulations to gravitational lensing then to the observations. That is, by first using the data of dark matter particles to generate strong lensing images, and then comparing the images to the real observations, one can study whether the theories adopted in the cosmological simulations are reasonable.

3. Where do you see the future of this field going? What excites you about that?

Gravitational lensing signals are sensitive to the dark matter distribution in the lens objects as well as the interaction between dark matter and regular matter, therefore, I look forward to more accurate constraints on dark matter with gravitational lensing with the data from the upcoming large-scale sky surveys. Understanding the properties of dark matter could lead to a revolution in physics, which excites me most.

4. What makes you unique as an astronomer or physicist working in this group (this can be something about your identity, a hobby you have, something about your childhood -- anything, really)?

I think I am an astronomer who can implement the requests from others by programing. Frankly, I am not sharp, but I think I make a good addition to this exciting group because of my work ethic. However, I might be the best soccer player in this group — that I am very proud of.

5. What have you had to struggle with to get where you are (again, this can be loosely interpreted -- maybe something as innocuous as a hard math class)?

I had to struggle with the language when I first joined this group. I am not a native speaker, so I spent a lot of time practicing my English to make conversation with others more smooth. I really appreciate the generous help from my supervisor, Dr Lindsey Bleem.

6. What is your dream job? If you're in your dream job, congratulations! What makes this your dream job?

I have my dream job, curiosity makes this my dream job. I should thank my parents for showing me the stars and telling me stories when I was a little boy. This inspired me a lot.

HOMEWORK #3

Students are given some background information on Dr. Arlie Petters, the mathematician who helped develop the equations to map the gravitational lensing signal to a dark matter distribution. The students are asked to watch a short video about Dr. Petters and respond to some prompts about his path, and how he fits into the broader picture of Einstein's GR.

There are no correct answers to this exercise. It's meant as a STEM identity building activity.

You may have come to the conclusion that the giant arcs in the images above are actually distant galaxies in the early universe whose light has been bent by the massive cluster in the foreground. This is clearly an incredible realization by itself, but how do astronomers take images like these and map out the dark matter?

Dr. Arlie Petters, a Belizean-American and African-American mathematician, determined the mathematical formulae which enable us to do exactly that: translate observations of gravitational lensing into a distribution of dark matter.

Watch the PBS *NOVA scienceNOW* profile on Dr. Arlie O. Petters for more information about his accomplishments, his background, his science, and his educational work:

<https://mlkscholars.mit.edu/apetters/>

Some questions to consider after you've watched this video:

- 1. What parts of Dr. Petters's story can you identify with? What parts are different from your own history?*
- 2. Does anything about his story surprise you? Why?*
- 3. Why do you think it's important that Dr. Petters started the Petters Research Institute in Belize?*
- 4. How do you think Dr. Petters would respond to a statement like the one from Paulino de Britto in Sobral during the 1919 eclipse expedition?*



Dr. Arlie O. Petters is a professor of mathematics, physics and economics at Duke University. He is the first African American to be tenured at the Duke's Department of Mathematics, founded the Petters Research Institute in Belize, and is the mathematical mind behind the way we utilize gravitational lensing in cosmology today.

Image Credit:

Arlie O. Petters, [from his professional website](#)

The images we observe of gravitationally lensed systems are diverse, as the shape, size, magnification, and location of the lensed images (that is, the arcs or distorted images) all depend on a number of parameters. Here, we will investigate how all of these interact with one another.

DAY 2

Students begin with a class-wide discussion of modeling — something which may be redundant (though a good recap) from Part 2. For both DAY 2 and 3, the students will be using the online gravitational lensing modeling software from Foothill College in California. On DAY 2, the students will be taken through a series of exercises to familiarize them with the content in the model.

Models for Gravitational Lensing

In this section, we will build models of gravitational lensing systems using an online tool built by scientists at Foothill College in California. Throughout this series of activities, we have used the word “model” several times now.

Discuss with your classmates some of the examples of models that we’ve seen so far. These could be from the activities themselves, or your daily life. Consider the following questions:

Why do we use models?

What function do they serve?

How do we know what information should go into our models?

How do we know when our models are wrong, or incomplete?

How do we improve our models?

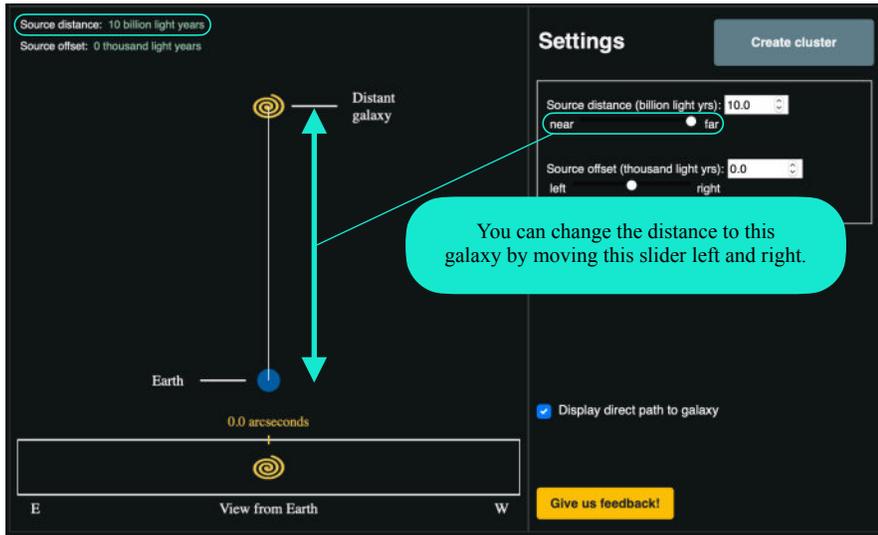
Models are simplified representations of some part of the universe around us. We use models because they allow us to predict the behavior of complex systems by investigating a small part of it we think we understand. Information about how our universe works, how physics works, should be input into our models, but we need not throw everything and the kitchen sink into them — they would become too complicated far too quickly. Only the relevant pieces of physics need to be included. We know when our models are wrong or incomplete when they do not reproduce already well-understood phenomena. For example, if you had a model for gravity that did not reproduce a ball falling back to the ground when you tossed it upward, you would know that there was either something wrong with the ingredients you put in, or there was a piece missing. We can improve our models by including (incrementally!) more complicated physics, or by improving upon the ingredients already included in the model.

To begin, navigate to the following URL:

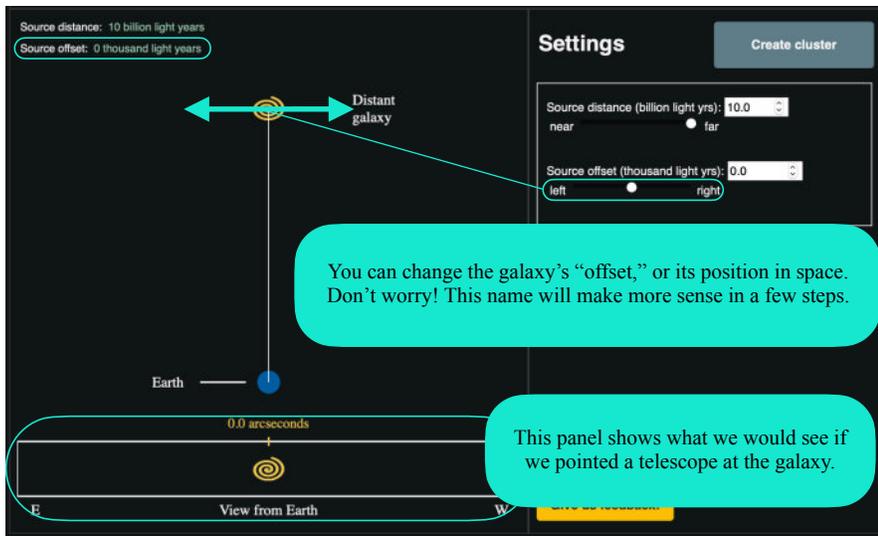
<https://foothillastrosims.github.io/gravitational-lensing/#>

On this screen, you will see a very simple setup: a “distant galaxy,” also called the “source,” automatically placed 10 billion (that’s 10,000,000,000) light-years from Earth. That’s about 4,000 times the distance between the Milky Way and the Andromeda galaxy.

On this screen, you can change two things about this system:
the distance from Earth to the Distant galaxy (also called the *source galaxy*)...



...and the “Source offset,” or the position of the Distant galaxy in space.



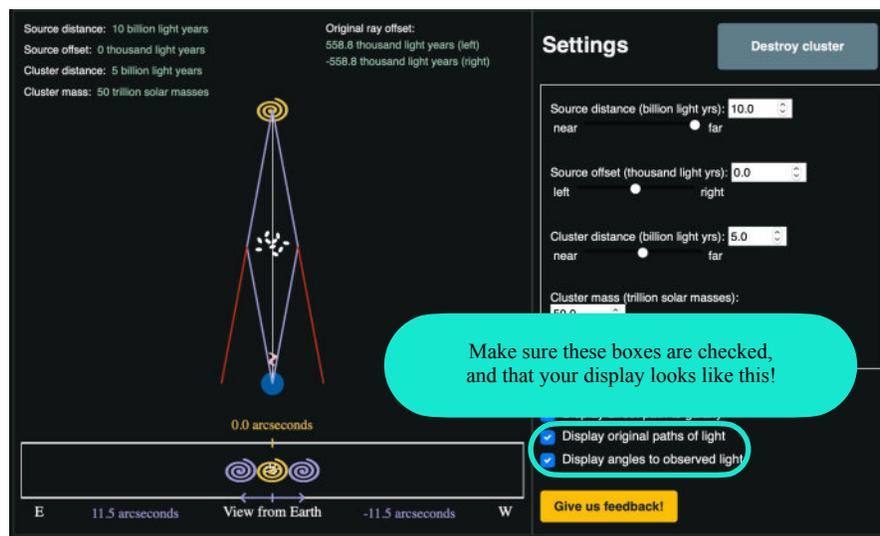
1. Move the Distant galaxy left and right (“Source offset”), closer and farther (“Source distance”): how does the “View from Earth” change?

The “View from Earth” will not change when you move the Distant Galaxy (the yellow swirl) closer or farther, but will move back and further when you change its source offset.

2. What does the number of arcseconds above the “View from Earth” panel refers to?

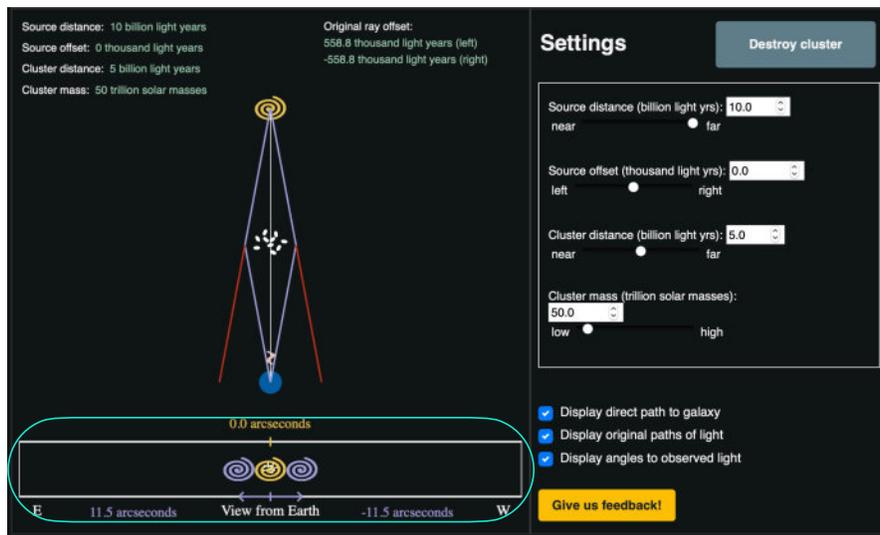
This is the angular distance on the sky the Distant Galaxy is from the center line

Reset your Source distance and offset and click “Create cluster.” You will see something very similar to what you just explored, but now with a cluster of galaxies between the Earth and the distant galaxy.



With the addition of the galaxy cluster (which has parameters Cluster distance and Cluster mass), there are two more ways we can change this system: the mass of the cluster and the distance between the Earth and the cluster. Now, the source “offset” may make more sense. This measures how far from center (the 0.0 arcseconds mark) the source galaxy is, if we were to draw a straight line between the earth and the galaxy cluster.

You may have also noticed that there is much more information in the “View from Earth” panel at the bottom, and in the main display. The purple lines in the main display show the path of the light from source galaxy as it is gravitationally lensed around the cluster. Without the cluster, this light would continue on the paths shown by the red lines, and these light rays would not be visible at Earth (though others would be). However, with the cluster between the Earth and the source galaxy, we can see *images* of the source galaxy — the purple swirls in the “View from Earth” panel.



3. Based on what you know about the yellow arcsecond measurement at the top of the “View from Earth” panel, what do you think the purple arcsecond measurement refers to at the bottom of this panel?

The purple swirls are the images formed by the gravitational lensing event that is being modeled, so the purple arcsecond measurement refers to the images’ distance from the cluster center.

4. In the real universe, what do you think observed images of a source galaxy actually look like? *Hint: Look back at the examples of gravitationally lensed images shown throughout this lesson.*

This depends on the geometry of the lensing system. In some cases, it’s individual points of light repeated around the lensing object (i.e., an Einstein Cross), a full ring around the lensing object (i.e., an Einstein Ring), or distorted arclets distributed around a lensing object.

DAY 3

Now that the students are familiar with how the model works, they will use it to see how changing different parameters alters the resulting lensed image. They are asked to consider four scenarios to investigate how the mass of the cluster, the distance to the cluster, the distance to the source galaxy, and the offset of the source galaxy change the final lensed image.



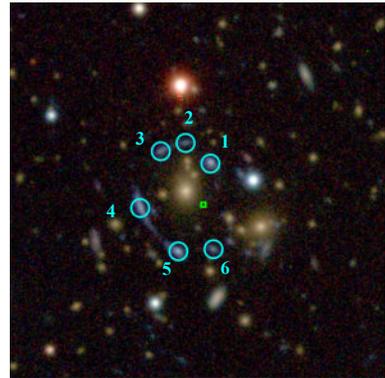
A nearly complete Einstein Ring. Here, the lens is a single galaxy, not a *cluster of galaxies* as in the previous examples.

Image Credit: ESA/NASA

When the Earth, cluster and source galaxy are exactly aligned (that is, the Source offset = 0.0 arcseconds), the observed image of the source galaxy is not two distinct copies, but a distorted and magnified image that forms a full circle. This is known as an Einstein Ring. Small deviations from that exact alignment create arcs that almost form the complete ring, as in the image at the left.

With more complicated distributions of dark matter (as in a cluster of galaxies) acting as a lens, we observe more complicated arc images of the background source galaxies. That's why you're likely to see multiple arcs images of a single source galaxy scattered across a picture of a galaxy cluster.

Consider the three-color image you made of the cluster in an earlier activity, shown here at the right. By eye, we can see that there appear to be several images of the same galaxy. Normally, we would need more information to confirm this suspicion: *spectroscopic data* (see Homework 1 for reference) of each image to confirm that they are all at the same distance. However, for the purposes of this exercise, we can assume that these images are all of the same background source galaxy.



An example three-color image of SPT-CLJ0106-5355. This sequence of letters and numbers indicate what telescope was used to discover the object (SPT = South Pole Telescope), the kind of object it is (CL = cluster), and the location of the object in the night sky (J0106-5355).

Image Credit: Bleem et al. (2019)

1. Set your model to the following parameters:

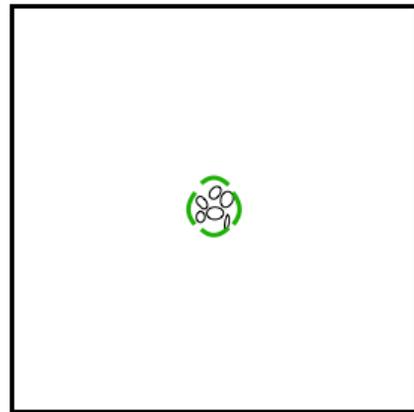
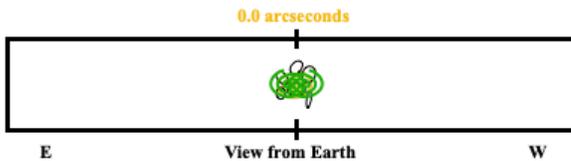
Source distance = 10 billion ly

Source offset = 0.0 arcseconds

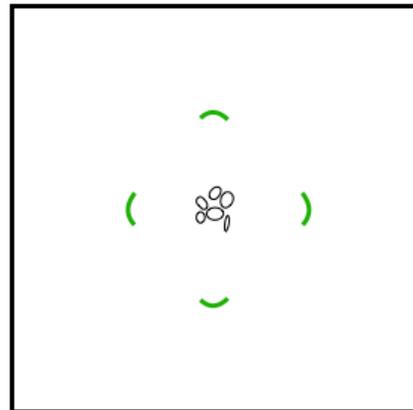
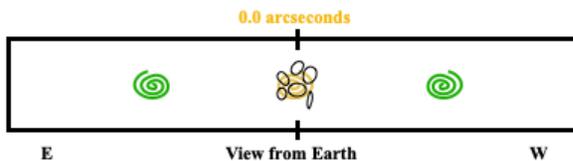
Cluster distance = 5 billion ly

Now, **change the mass of the cluster**. Pick two masses, one near the low-end and another near the high-end. How do the images change? Draw your responses on the panels below, and make a guess as to what the actual image would look like based on the information above.

Cluster #1 mass: 5.0 trillion M_{\odot}



Cluster #2 mass: 1000.0 trillion M_{\odot}



The images would move farther out from the center of the cluster as you increase the mass of the cluster itself. The students don't know enough yet about gravitational lensing to tell if there is more distortion closer or further away from the cluster center. If a student asks, the lensing event in a more

massive cluster is likely to produce smaller, less distorted images due to the geometry.

In this case (and those that follow), the student may know that a direct alignment of the observer, lens, and source produces either an Einstein Cross (shown in the solution above) or an Einstein Ring (this would simply appear as a complete ring around the cluster center). However, this is not expected, and it should also be considered correct if the student just draws the left and right images in the plane of the sky.

2. Set your model to the following parameters:

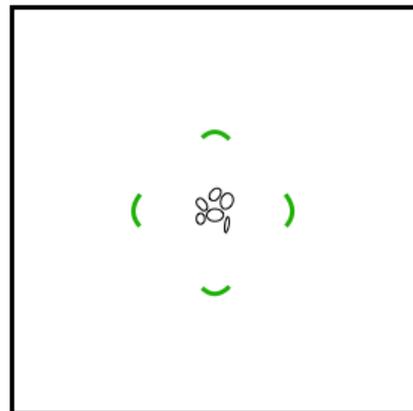
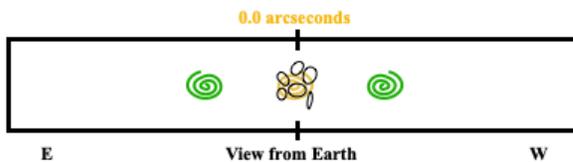
Source distance = 10 billion ly

Source offset = 0.0 arcseconds

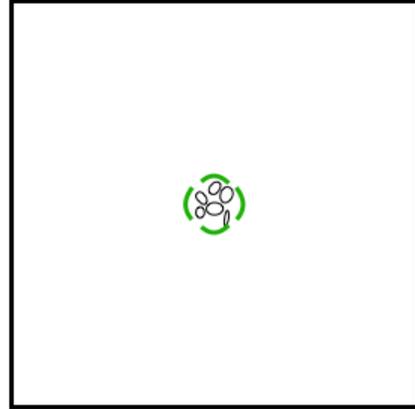
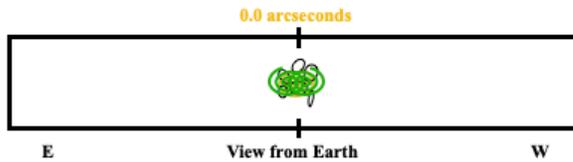
Cluster mass = 50 trillion solar masses

Now, **change the distance to the galaxy cluster**. Pick two distances, one nearby and another far away. How do the images change? Draw your responses on the panels below, and make a guess as to what the actual image would look like based on the information above.

Cluster #1 distance: 1 billion lightyears



Cluster #2 distance: 9 billion lightyears



The images form closer in on the plane of the sky when the cluster is further away.

3. Suppose you wanted to use this model to determine the distance to the source galaxy. In this scenario, you are able to measure the angles of the observed light (purple angles) very precisely, and form a perfect Einstein Ring, but you do *not* know the distance to the cluster nor the mass of the cluster very well. Using the online tool as a guide, explain whether or not you would be able to arrive at a single exact source galaxy distance.

If an Einstein ring is formed, then the source galaxy must be exactly behind the cluster (Source offset = 0.0 arcseconds). If we know the angles precisely, then we can iteratively change the mass of the lens, the distance to the lens, and the distance to the source to find viable solutions. There will be more than one, so you would not be able to arrive at a single answer — you have too many unknowns. You would need to know the cluster mass and distance accurately in order to get a single exact result for the source distance.

4. Set your model to the following parameters:
 Source offset = 0.0 arcseconds
 Cluster distance = 5 billion ly
 Cluster mass = 50 trillion solar masses

Now, **change the distance to the source galaxy**. Pick two distances, one nearby and another far away. How do the images change? Draw your responses on the panels below, and make a guess as to what the actual image would look like based on the information above.

Source #1 distance: 5.1 billion ly

0.0 arcseconds

Source #2 distance: 10 billion ly

0.0 arcseconds

The images form further out from the cluster when the source is further away from the observer.

5. Set your model to the following parameters:

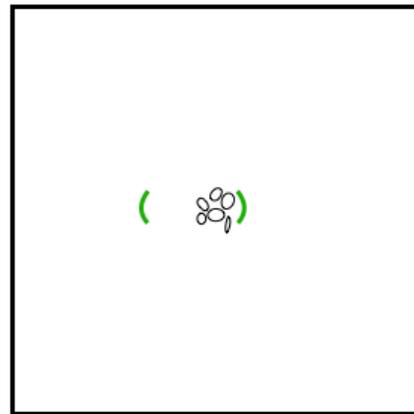
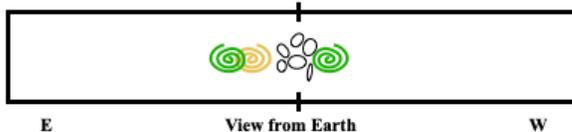
Source distance = 10 billion ly

Cluster distance = 5 billion ly

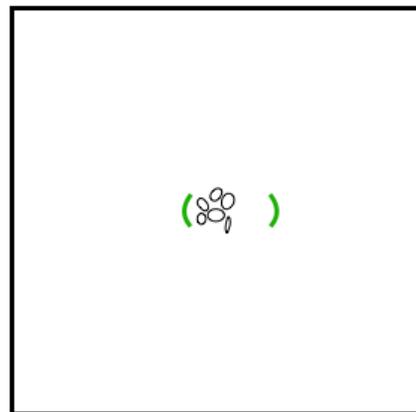
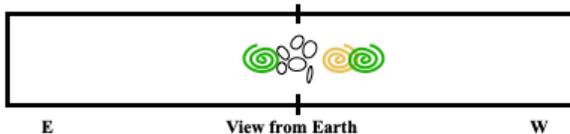
Cluster mass = 50 trillion solar masses

Finally, **change the Source offset**. Pick two offsets, one close to the center and another far away from it. How do the images change? Draw your responses on the panels below, and make a guess as to what the actual image would look like based on the information above.

Source #1 offset: 500 lightyears (left)



Source #2 offset: -500 lightyears (right)



As you move the source galaxy left and right behind the cluster, the position of the source galaxy moves on the plane of the sky and the images move. The images are no longer symmetric around the cluster, but form off-center. Additionally, if your student has been showing the Einstein Cross/Ring up until now, they should omit it here: the geometry of

an offset source galaxy cannot make an Einstein Ring or Cross. The exact distortion of each image formed will depend on the precise offset and mass distribution — something which is far beyond the scope of this exercise.

6. In the last several questions, you have explored many of the variables that can impact the gravitationally lensed image. What do you notice about how the variables change the location of the images? Return to the online model, and try changing more than one variable at a time. What patterns do you notice? Record your observations in the space provided. *Hint: Try to recreate the same image offsets with different combinations of cluster mass, source distance, and cluster distance. If you change one variable, how do you have to adjust the others?*

Many different variables change the images in the same way. The images are closer to the cluster when the source distance is large, cluster distance is large, and the cluster mass is small. Additionally, images form close in when you change the offset — so if you're unable to observe or don't recognize the accompanying image, then you might mistake an offset for any of those other changes in variable. Importantly, you can create the same "View from Earth" with a number of different organizations of the variables above. This is a degenerate system.

DAY 4

Students will apply what they have learned to a real system: SPT-CLJ0106-5355, the cluster they used to make their three-color images. They will measure the distance of the images from the cluster center, and use already measured quantities (the cluster distance and cluster mass) to estimate the distance to the source galaxy and its offset. DAY 8 and Part 3 end with a science spotlight highlighting the final piece of evidence for dark matter: the mass distribution of the Bullet Cluster.

Models for Gravitational Lensing: Applied

Let's apply what we've learned to a real system: SPT-CLJ0106-5355 (catchy name, right?), the cluster you used to make your three-color images. **We will measure the distance of the images from the cluster center, and use already measured quantities (the cluster distance and cluster mass) to estimate the distance to the source galaxy and its offset.**

This cluster is located $4.1064 \pm \begin{matrix} 0.1673 \\ 0.1834 \end{matrix}$ Gly from Earth. You may notice that this isn't just a simple number: there is a range of values that might correspond to the correct distance, but **4.1064 Gly** is the *most probable* one. This is a way to represent the *uncertainty* on a certain quantity. We cannot actually measure anything with 100% confidence. Every measurement we make in science — and in life — has an associated uncertainty, or range of possible values. The mass of the cluster is **266 ± 49 trillion solar masses**. Again, this has an uncertainty associated with it, but in this case the range is symmetric, so the upper and lower limits are the same.

There are many possible sources of uncertainty for these values, depending on how each was measured. More often than not, distance in astronomy is derived from spectroscopic data, which requires careful calibration of the wavelength axis (recall that spectra show intensity as a function of wavelength). The redshift is calculated from the difference in the expected wavelength of an emission line, but if the wavelength calibration is incorrect, then this difference will be, too (in this way, the error is said to *propagate*). The cluster mass is derived from gravitational lensing. This utilizes a series of models, each with their own associated errors, including assumptions about the dark matter distribution, spectral data of the lensed images and cluster galaxies, and images of the cluster in a variety of wavebands.

1. Write down the “knowns” and “unknowns” for our problem. That is, what variables do you know already, and what are you trying to find? *Hint: Reread the bolded statement in the first paragraph.*

known: cluster mass, cluster distance

unknown: source distance, source offset <— these are what we are trying to find

2. Using the information above, complete the following table. This will be a useful reference for the rest of the activity.

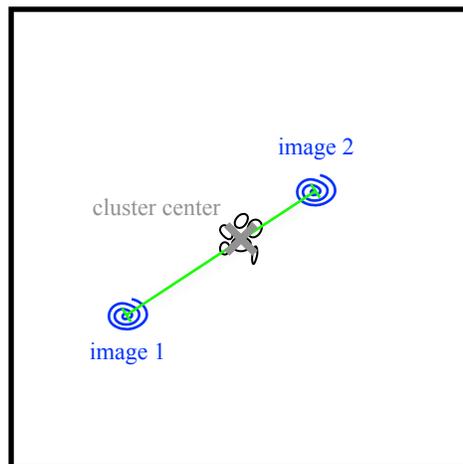
Variable	Value	Units
Cluster mass	266	<i>trillion (10^{12}) solar masses</i>
Cluster distance	4.1064	<i>Gly (billion, or 10^9, lightyears)</i>

Open up JS9 once again by navigating to this website:

https://waps.cfa.harvard.edu/eduportal/js9/software_PISCO.php#

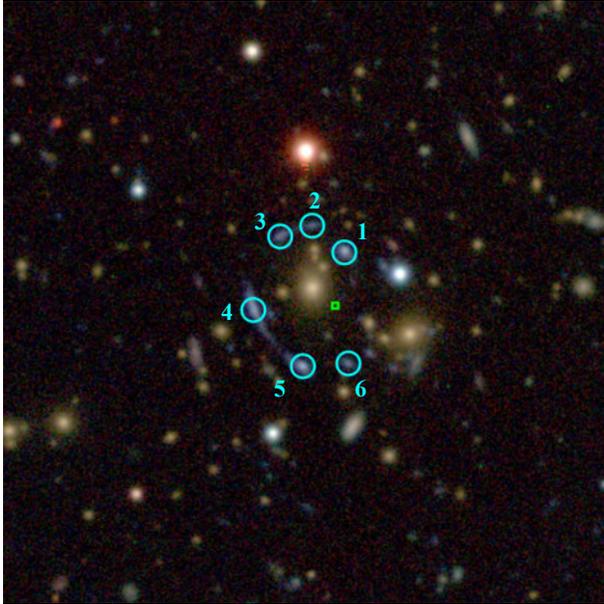
Following the steps from the **Looking at the Looking Glass** activity, quickly recreate your three-color image.

To mimic the layout of the gravitational lensing model from the Foothills College web app that we've been using, we want to use two background source galaxy images that form a (roughly) straight line passing through the center of the cluster. We want something that looks like this:



3. What are some potential sources of uncertainty for measuring the source galaxy distance?

sources of uncertainty: not knowing the precise location of the center of the arc or the cluster; not knowing if these two images are actually from the same source; your model for the dark matter distribution; etc.



The image at the left is, once again, SPT-CLJ0106-5355 with the locations of the lensed images of the background source galaxy indicated by blue numbered circles, and the center of mass of the cluster marked by the green square.

4. What are the components that go into calculating the center of mass of the galaxy cluster?
Hint: What were the different kinds of material we discussed in Andromeda galaxy?

To calculate the center of mass, you need to know the position of each component and the mass of each component. That includes the regular matter (e.g., stars, galaxies, gas) and dark matter.

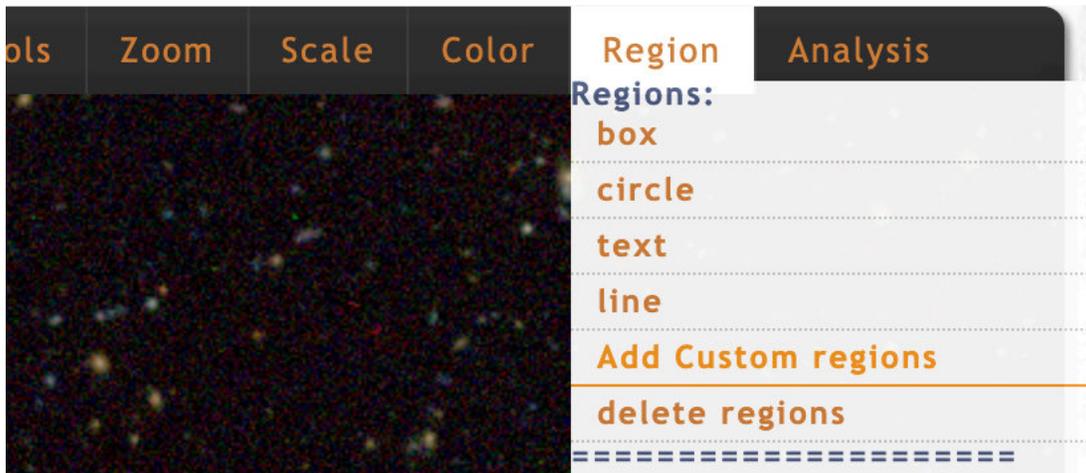
Challenge Question 1: Why doesn't the center of the cluster appear to overlap with its visible light?

There must be some dark matter offsetting the center of mass. This also implies that the dark matter is not necessarily spherically centered around the light matter — there are some inhomogeneities.

Challenge Question 2: Why don't the gravitationally lensed images of the background source galaxy lie on a perfect circle around the center of the cluster?

Gravitationally lensed images only form a perfect ring around the lens when the source is perfectly aligned with the lens and observer.

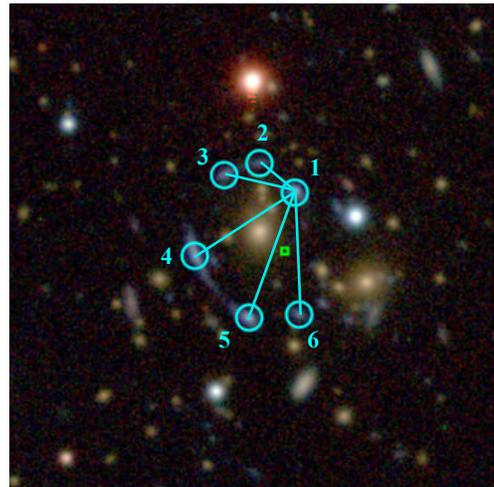
In order to measure the distance between the cluster's center and the galaxy images, we need to first lay down a marker — called a *region* — on the cluster image in JS9. With JS9 and your three-color image open in your browser, hover over the “Region” tab and select “Add Custom regions.”



This will load a preset collection of regions onto your three-color cluster image. They mark the locations of six gravitationally lensed images (blue circles, numbered), and the cluster center (green box). To see the regions better (and what lies beneath them), it may be helpful to zoom in on the image (zoom 2 should work well).

Recall that in the Gravitational Lensing web app, one of the parameters we could observe and measure was the distance of the source galaxy's image to the center of the galaxy cluster. The web app only displays two images at a time, but there may be many, as in our galaxy cluster shown above.

In order to mimic the same kind of measurement we can make on the Gravitational Lensing web app, we must choose two images from the six identified above. We cannot choose just any two images, however. These need to be aligned with one another such that a line that connects the centers of two images passes through the galaxy cluster's center.



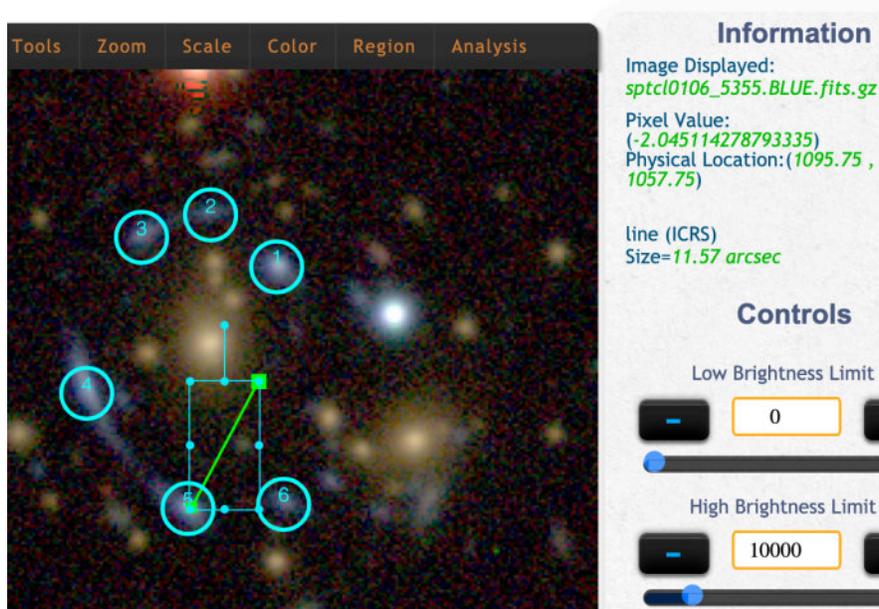
For example, consider Image #1. We can draw lines that connect Image #6 to Image #2-6. While the lines between Image #1 and Images #5 and #6 don't pass exactly through the cluster's center, they pass close enough that either choice is likely to give reasonable results.

This is not the best solution, though! Repeat this for one or two other images and select *one pair* of images to use for the following exercise.

1. Once you have chosen your pair of images, log the image numbers in the first column of the table below.

Image Number	Image Distance [arcseconds]
<i>best pairs to use: 1, 6 ; 1, 5 ; 2, 6 ; 3, 6</i>	<i>responses will vary</i>

- Return to the Regions menu and select “line”. A green line will appear in your screen. Click on this and reposition it such that one of the ends sits at the center of one of the images in your pair. Hover over the other end of the line until a hand appears and move that end of the line to the cluster center. Read out the measurement for the length of the line in the panel to the right, under the heading “line (ICRS) Size=”. Record this in the table above in the column labeled “Image Distance,” and repeat for the other image in your pair.



- Now that we have the image distances to the cluster center, we can use the online model and the given quantities (the cluster distance and cluster mass) to estimate the distance to the source galaxy and its offset.

Navigate to the Foothills College Gravitational Lensing Model:

<https://foothillastrosims.github.io/gravitational-lensing/#>

In the entries for the Cluster distance and the Cluster mass, input the values provided in the text above. *Hint: For reference, see the table in Question #2 under Models for Gravitational Lensing.*

4. Change the Source offset and Source distance until you reproduce the Image Distance you recorded in your table. Try to get your Image Distance and the model values to match as closely as you can, but don't worry if you can't. Why do you think there might be a discrepancy? What other sources of error might you need to consider?

The values could be different because the model is imprecise, the model is flawed or too simplified "under the hood," the alignment of the images is not perfect, the inputs for the cluster mass and distance are not precise (we don't take into account the error on those measurements), etc.

5. Once you have a close match, record the Model Image Distances ("angles to observed light" in the model), Model Source distance and Model Source offset in the table under Try 1.

	Model Image Distances [arcseconds]	Model Source distance [Gly]	Model Source offset [1000 ly]
Try 1	<i>responses will vary</i>		
Try 2			

6. Next, try to recreate the Image Distance again, but using a different combination of the Model Source distance and Model Source offset. Record this in your table under Try 2.
7. How is it possible that the same set of inputs (that is, the same two images) could produce two different solutions? What information would you need to know the exact configuration of this system?

This is a degenerate system, so there is no unique solution. You would need to know one of the two unknowns to uniquely solve for the other.

Science Spotlight: Dark Matter Confirmed



The Bullet Cluster (shown here) is actually two clusters of galaxies in collision. This image shows the visible light image from Hubble, with the superheated X-ray gas in red, and proposed dark matter distribution in blue.

Image Credit: X-ray: NASA/CXC/CfA/ M. Markevitch et al.; Lensing Map: NASA/STScI, ESO WFI, Magellan/U.Arizona/ D.Clowe et al.; Optical: NASA/STScI, Magellan/U.Arizona/ D.Clowe et al.

Believe it or not, even with evidence from gravitational lensing and Vera Rubin's rotation curves, it wasn't until the early 2000s that scientists became convinced of the dark matter theory. Some thought (and many still think) that this evidence is actually a result of some inconsistency in our theory of gravity. They suggested that if we modify our conception of gravity, then the flattened rotation curves of galaxies, high orbital velocities in cluster of galaxies, and gravitational lensing would all occur naturally — no new form of matter needed.

However, in 2004, an international group of astronomers discovered that there was an offset between the hot X-ray gas (shown in red in the image above), which traces the regular matter, and the center of mass of the colliding galaxy cluster known as the Bullet Cluster. These astronomers used gravitational lensing to trace out where the dark matter is distributed in the cluster, shown here in blue. The only way to explain this funny distribution of material is with some kind of dark matter. But the question remains: what *is* dark matter? As we learned in Part 2, this is still a topic of heated debate.