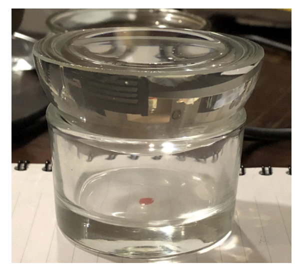
SAGE Astrophysics Lab Worksheet
Gravitational Lensing

We can create a pseudo-gravitational lens at home using stemmed glassware in order to mimic and study its effects.

Note: If you finish this lab quickly and have time left over during the lab period, start working on the spectroscopy worksheet. We can estimate the temperature of the sun just by observing some information about the wavelengths of light it emits!

Materials

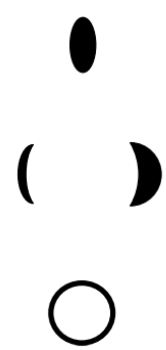
- Stemmed glassware (two different kinds)
- Magnifying dome
- Candle holder
- Graph paper (3 sheets)
- Black marker
- High-res astronomical photos



Section 1: During the Lesson

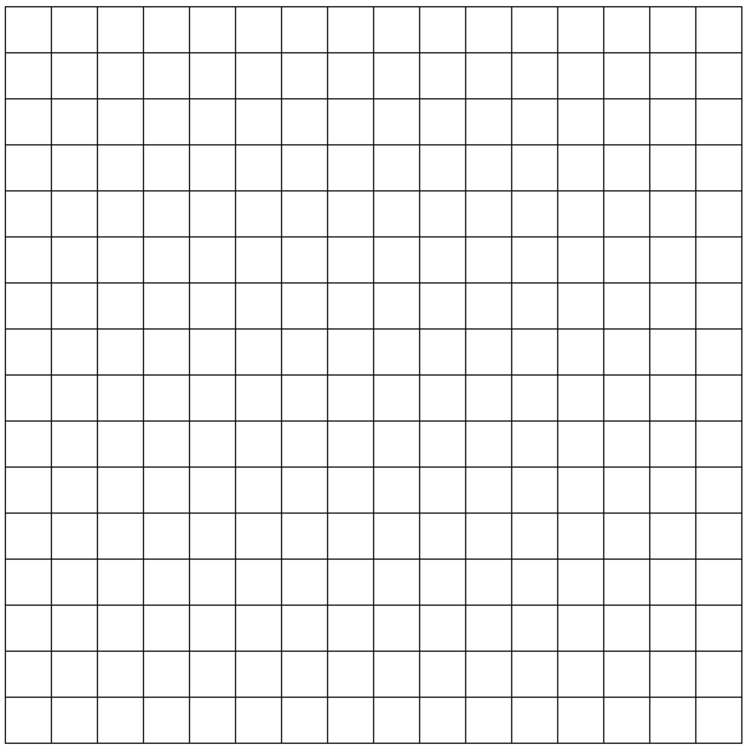
Follow along during the lesson for this first part of the lab worksheet.

1. Draw a black circle below (you may want to try a few different sizes, from a millimeter in diameter up to the size of a pinky nail).
2. Set the glass down on the paper and slowly move it across the dot, observing as you go (look through the base, not the upper bell/rounded part of the glass).
3. Where does the glass need to be to get an elliptical shape? This is called "shear distortion".
4. Do the same thing with the other stemmed glass, and then with the candle holder, placing the magnifying dome on top of the candle holder as seen in the image above. How do the three lenses differ?
5. How many multiple images can you make? Is it possible with all three lenses? Can you get two dots of the same size? When one dot is bigger than the other, is it closer or further away?
6. Can you make an Einstein ring? How do you make it thicker or thinner? What happens when you lift the glass off the paper?



Section 2: Graph Paper (~15-20 minutes)

By using our gravitational lens to look at a regular grid (graph paper), we can start to understand how the shapes are changed.



1. Take the graph paper and move the lens over the grid lines. How do the lines warp? (Inward? **Outward? Circular?** Square? **Symmetrically?**) Sketch the result, and note whether it's the same or different for the two stemmed glasses.
    a. The grid lines represent flat space. What could be causing the observed distortion?

        The distortion is caused by light passing through the glass and refracting, like an optical lens. Also, the glass is a different thickness in different parts, making the refraction non-uniform so the lines are transformed to curves.

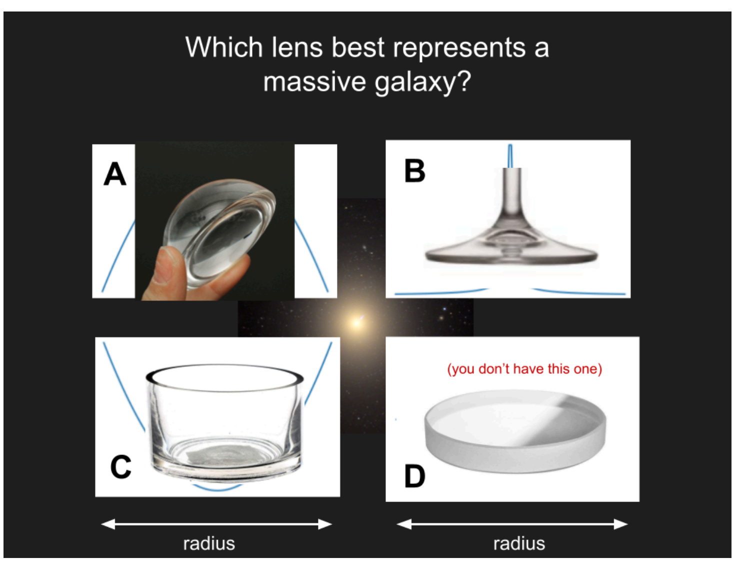
2. Draw a triangle, an oval, and a circle on the graph paper (use your separate sheets). How does the lens distort each of these shapes? Sketch some of the results.

    This is mostly to get the students to start thinking about how the un-distorted image relates to the distorted image. There are lots of different potential shapes that can arise with different geometries of lensing.

3. When do you think the glassware stem/base should mimic the effect of an astrophysical gravitational lens? When (i.e. looking through which part) does it become a poor model of gravitational lensing?

    This connects back to the exploration the students did during the lesson of which lens best represents a massive galaxy. The bottom of the wineglass is the most suitable because the glass is much thicker in the middle and then thinner as you get further towards the edge. This represents a galaxy having much more mass in the center compared to the edges, which is what we observe in space.

    If instead of the bottom you look through the bell of the glass (top), it's not very representative anymore because there's too much mass in the outer part of the radius compared to the middle. Same goes for the other lens shapes. We really need the extra-thick glass in the center to represent the concentration of mass in the center of a galaxy.



4. Draw a solid oval (galaxy) about half the size of a fingernail on an intersection of grid lines. As you move the lens about the galaxy, you will notice four configurations: an undistorted galaxy, a single distorted galaxy, two strongly distorted galaxies, and an Einstein ring.

    a. As you move the lens, how does the galaxy stretch with the space-time lines?
    it stretches around the stem tangentially, gets pushed into a circular shape as you pass over, (forming a ring when directly behind) and then ends up distorted on the other side of the lens

    b. In your own words, describe the galaxy's location (in relation to the lens' center) when it appears undistorted yet still under the lens. This is weak lensing.
    the galaxy looks the most undisturbed when only the thin most radially extreme part of the base is over the galaxy (thin glass, less distortion, small gradient)

    c. In your own words, describe the galaxy's location when it is distorted, but you only see one image of it. This is strong lensing.
    right on the edge of the thickening stem region we get one image, but very stretched and elongated shapes along the tangential line

    d. In your own words, describe the galaxy's location when you see two images of it. Briefly explain how this is possible. Hint: it will be helpful to imagine how the light travels from the galaxy to you. Astronomers regularly observe this phenomena, for example, as double quasars. This is another example of strong lensing.
    when the glass stem is offset slightly to one side but still between the galaxy and the viewer, we see two images heavily distorted about the stem

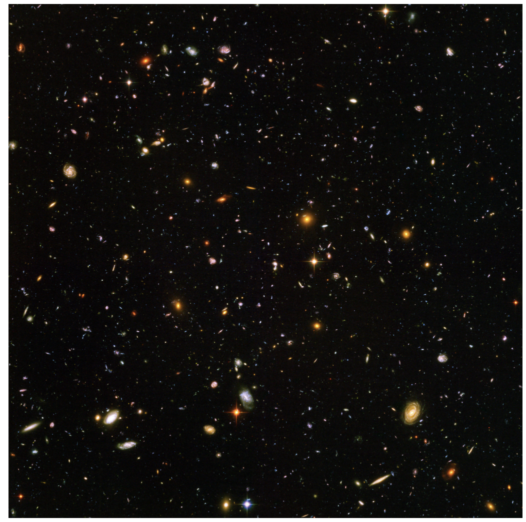
    e. In your own words, describe the galaxy's location when it appears to spread into a ring? This feature, called an Einstein ring, is also characteristic of strong lensing.
    when the stem is directly over the background galaxy we get a ring

5. Draw four galaxies of varying radii. How does the Einstein ring depend on the galaxy's radius? What happens for galaxies of “zero” radius?

   The einstein ring gets much thicker the larger the background galaxy radius, at zero radius (a dot) we struggle to get a ring at all

Section 3: Hubble Deep Field (~10-15 minutes)

The Hubble Deep Field is a set of images taken by the Hubble Space Telescope in 1995 of a tiny portion of the sky with very few stars in it. By allowing the telescope's camera to capture the images over several days, the field shows some of the most distant (and youngest) galaxies that scientists know of. Since then, the field has generated a plethora of research results and is one of the most well-known images of modern astronomy. It also represents a galaxy field with very little gravitational lensing, which makes it perfect for this next activity.



1. Place the bottom of the stemmed glassware on top of the printout of the Hubble Deep Field and move the lens around on the picture, then do the same with the other stemmed glass. How are the shapes/appearances of the differently-shaped galaxies changed?

   Galaxies get 'spaghettified' or stretched out as the stem of the glass passes over them, since galaxies get warped tangential to the circular stem, the angles and magnitude of distortion will change with a different size stem (the alternate wineglass)

2. Compare the original image with the image after you place the lens in front of it. Can you tell the difference between when the lens is in front of the image and when it is not? Why or why not?

   The lensing effects are visible through the lens, distorting the galaxies, so they should be able to tell when the lens is in front of the image and when it is not based on whether there are distortions or not.

3. Keep the lens above a particular galaxy and move the lens towards you (i.e. pick the glass up off of the paper). How does the distortion change when the lens is closer to you compared to when it is sitting directly on the image?

   More of an observational question. When the distance between the observer and the lens is roughly the same, you'll see the largest magnitude effect on shape distortion. When the lens is very close to the observer, we don't see a huge effect, and when it's directly in front of the object we see a diluted effect as well. Lensing is most dramatic when the lens sits directly (halfway) between the observer and the source.

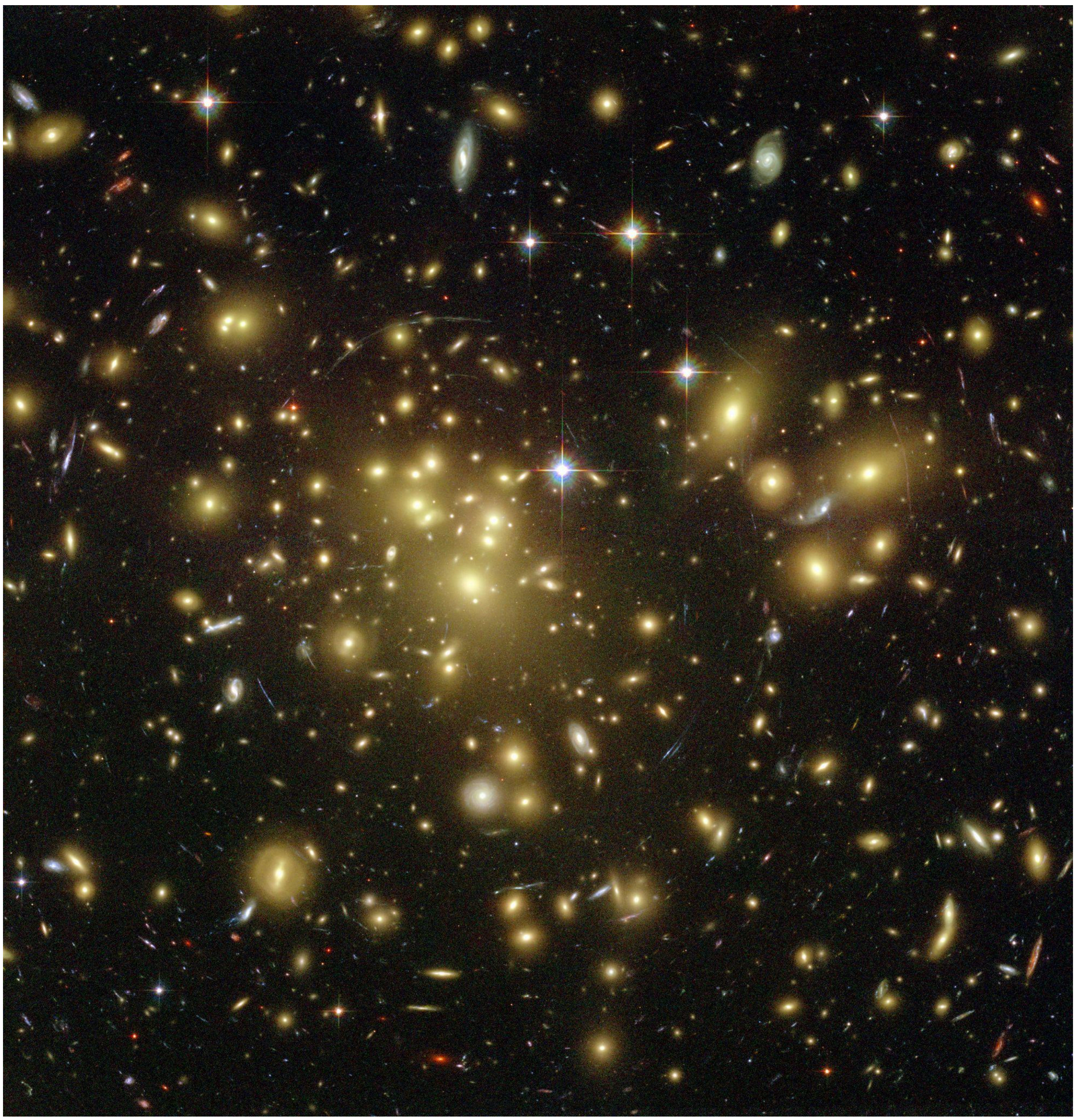
4. Place the lens back on the image. Compare the distortion of galaxies near the center to those near the edge. Is it easier to tell that the lens is there by looking at the objects near the middle of the lens or the objects near the edge? Why?

   Recall that very little distortion (almost like weak lensing) is visible in the flat part of the wine glass base. The lensing is most dramatic right around the thickening part of the stem, where all the light that enters behind the center of the stem gets 'pushed' off to, and where objects get the most elongated and/or duplicated. So it's easiest to identify the 'arcs' or einstein rings which are located directly behind the lens, but end up sitting just outside the stem of the glass when you view them through the lens.

This last example should give you an idea of why, in general, strong lensing (distorted objects nearer the center of the lens) is easier to observe and quantify than weak lensing (distorted objects nearer the edge of the lens).

Section 4: Abell 1689 (~10-15 minutes)

Abell 1689 is one of the largest galaxy clusters known. It is so large that its mass significantly distorts the light of stars behind it. Hence, it is of great use to astronomers studying dark matter.



1. Compare the shapes of the distorted galaxies behind Abell 1689 with that of the distorted galaxies you made with our pseudo-gravitational lens.

    a. How are they similar? How are they different?

    When you place your lens in front of the Hubble Deep Field, there are no foreground galaxies (the orange-ish fuzzy shapes in Abell 1689 that identify where the lens is), both have the stretched out arcs of strong lensing around where the foreground matter is distributed.

    b. Does the mass distribution have an obvious center like for the base of the glass, or are there multiple centers? How many centers do you see?

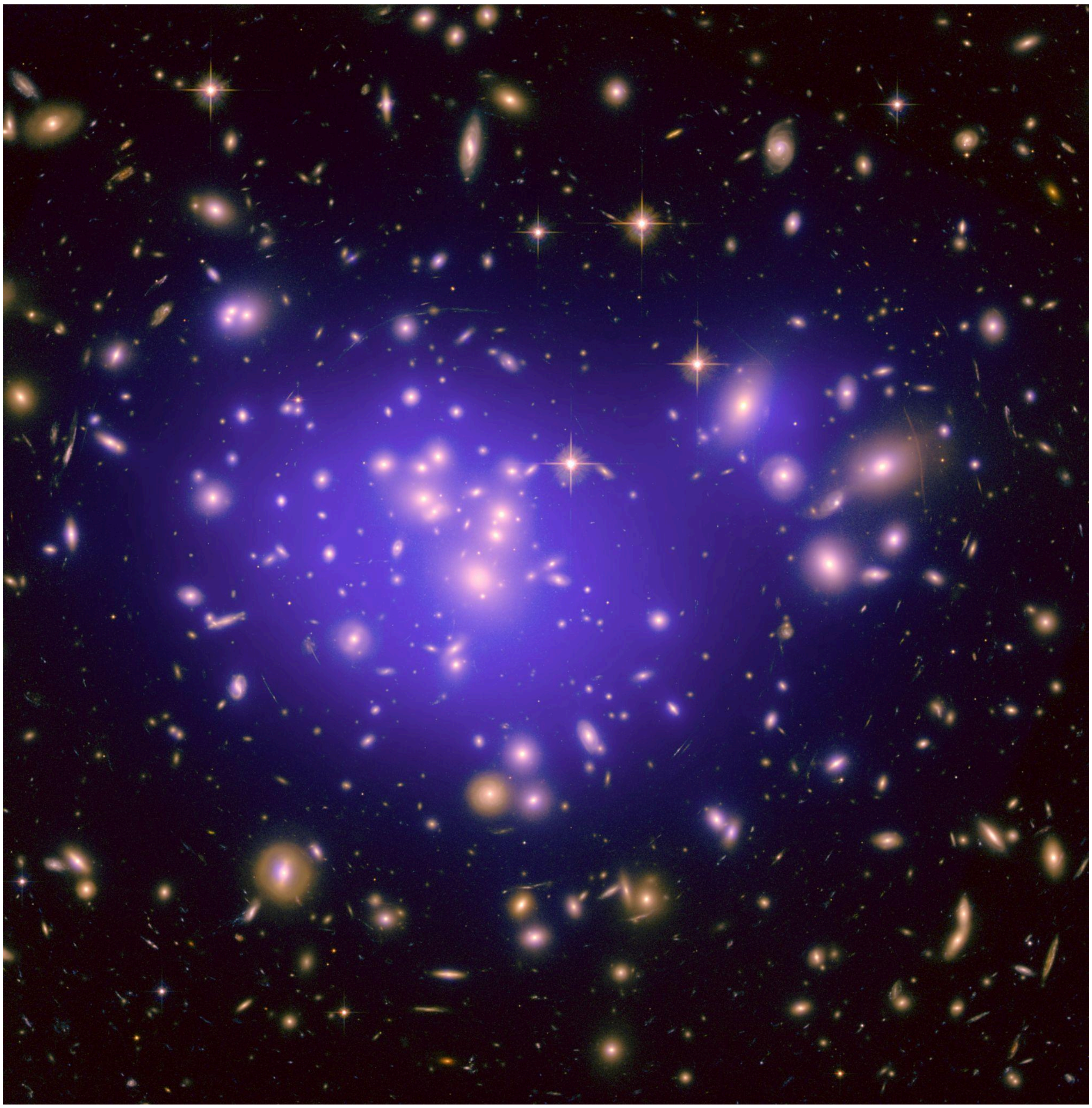
    There are two clear centers in Abell 1689, which we can find by looking at how the arcing, distorted galaxies are angled. If we were to draw lines through the angles of these stretched galaxies and followed them around the image, we'd see two major clumps that are populated by these foreground galaxies.

2. Try to find the center of the main mass distribution in the middle. Is it close to the large galaxies in the middle, or is it actually slightly off-center?

    It's pretty close to the center, but not quite exactly on the center galaxy, we can use the same method of following tangential lens arcs around the center to circle the central mass

3. Now compare the visible image to the image below that includes the dark matter layout calculated by astronomers, shown as purple clouds/dust. How does it compare to your answers in the previous questions? How does it differ?

Ought to be similar, but some students might not see the second center to the right.



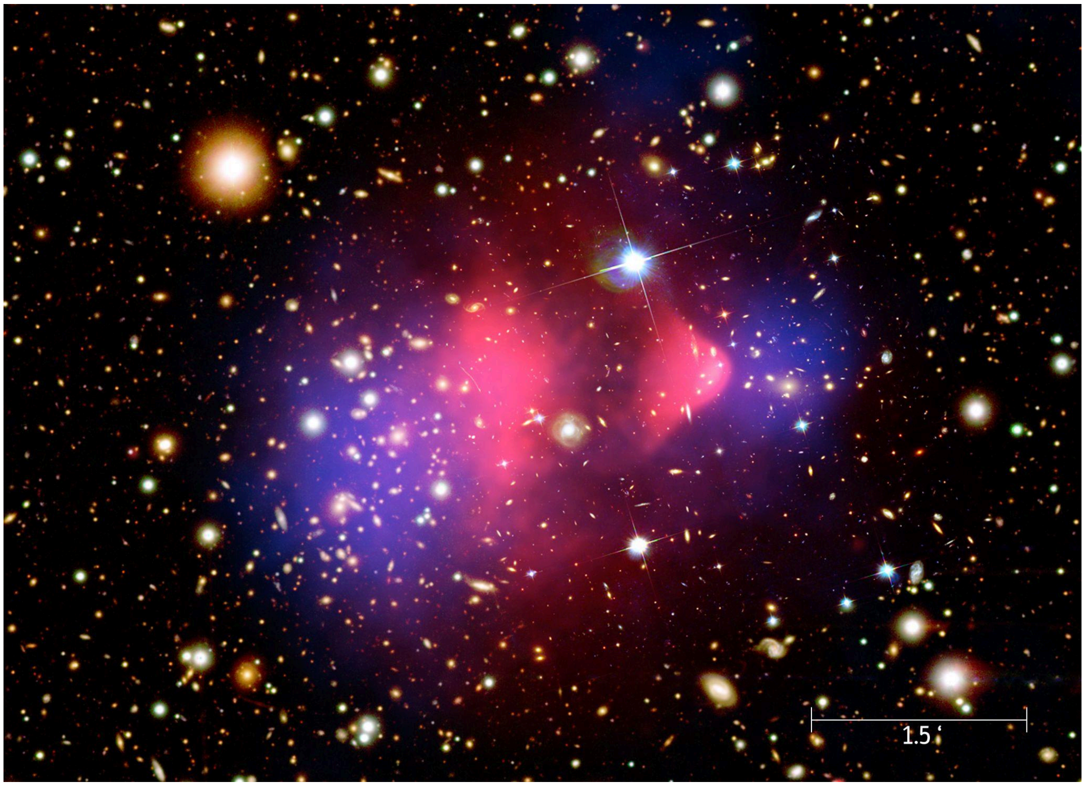
4. What does the distribution of dark matter relative to the location of the large galaxies tell you about dark matter? In other words, does the dark matter necessarily line up with the visible matter in the Universe?

   For one, we see dark matter in the gaps of this galaxy cluster where there *is no visible matter*, so it doesn't necessarily line up. However, we see that visible matter tends to live in these massive dark matter halos! That is galaxies are *tracers* of dark matter structure. Since DM is much much more prevalent than regular matter (outweighing it 7:1), it makes sense that regular matter will be dramatically affected by the distribution of dark matter in our universe.

   In fact, almost all galaxies live in DM halos that span many times the radius of their visible light.

The answer to the last question in the previous part is one of the key elements for helping understand dark matter. Although dark matter is still one of science's greatest mysteries, bit by bit astronomers and physicists are getting closer to learning its true nature.

Bonus: Bullet Cluster



The above image of the Bullet Cluster is a composite image of optical data, X-ray data, and a reconstructed mass map. The image shows two galaxy clusters that have recently collided. During this collision, the individual galaxies and stars present within the clusters passed right through one another. Space is mostly empty, and the odds of a collision are exceedingly low. However, the intergalactic gas within each cluster, highlighted in pink and **Dark Matter in blue** in the image, collided and heated up, emitting X-rays that we can see today. But when scientists used their knowledge of general relativity and gravitational lensing to analytically calculate where that same mass must be, it doesn't match the observed location. Hence, there must be some other mass exerting a gravitational effect in that location: dark matter.

We don't have any questions for you about this, just wanted to share a cool photo! :)
This shows that hot gas (visible matter) collides, and Dark Matter tends not to, an important piece of information to understand the nature of dark matter (that is it doesn't strongly interact with itself by means of friction)