Let's explore how black holes warp the space around them, causing light to bend and creating some very interesting images. You've each been given an oddly shaped 'gravitational lens' that can very closely mimic how light behaves near a black hole.

Section A: How warped?

Using your lens and the provided space images, consider the following questions:

1. What happens when you…
   - Slide the black hole up, down, left, and right?
   - Move the black hole towards or away from you?
2. Can you…
   - Make an Einstein ring? Shrink or magnify the Einstein Ring?
   - Create multiple images?
3. How can you increase/decrease the angle at which light bends (also known as the **deflection angle**) as it passes through the lens? (You may find the laser pointer helpful here. Make sure it is always directed below eye level!)
4. What other effects can you see with your lens? Be creative and take pictures!

Section B: How Massive?

Now that your group has had some time to experiment with the black hole, you are ready for today's mission:

Use gravitational lensing to

measure the mass of your black hole.

You will need to refer to your **Diagrams and Equations** sheet for this section.

You should also have a **Black Hole Measurement Kit** which includes different types of grid paper, a ruler and a protractor.

Devise and Carry Out a Plan

1) Choosing one of the model diagrams, list the quantities you would need to measure in order to calculate the mass. Make sure to specify which method you will use.

2) Using the materials provided, design a simple experiment that will allow you to measure the quantities you listed in Question 1. Think about how you will get reliable and precise measurements. Sketch and label your setup, and write down the measured quantities in the space below. *Hint: When measuring any distance to the lens, measure to the curved side of the lens. (Why?)*

3) Carry out your experiment and calculate the mass of the black hole using the equations provided. Show your work.

Record and Analyze Your Results

1) What is the mass of the black hole in **kilograms**? ____________________

2) Calculate the ratio of the black hole mass to the following masses.

	M_{BH}/M
You (1 lb = 0.45 kg)	
Earth (6×10^{24} kg)	
Common black hole (2×10^{31} kg)	
Supermassive black hole (8×10^{36} kg)	

<u>Section C: How small?</u>

The boundary of a black hole is called the **Schwarzschild radius** or **event horizon.** Anything that crosses this spherical surface can never exit the black hole**.**

This radius can be calculated with

$$r_s = \frac{2GM}{c^2}$$

where *G* is the gravitational constant, *M* is the mass of the black hole, and *c* is the speed of light.

1) What is the Schwarzschild radius of each of the following? Find the ratio between the Schwarzschild radius of the object and the radius of the Sun. (r_{Sun} = 7 x 10^8 m).

	$\boldsymbol{r_s}$	$\boldsymbol{r_s/r_{Sun}}$
Your black hole		
Common black hole		

2) The Schwarzschild radius is also the size you'd have to compress an object to turn it into a black hole. How small would **you** have to be compressed to turn yourself into a black hole? How does this compare to the size of an atom?

Challenge: Given that the mass of the Sun is 2 x 10^{30} kg, what would the size of the Sun be as a black hole? To form into a black hole it would need to shrink down to its Schwarzschild radius while its mass stays the same. How would that change the Earth's orbit?

Section D: How'd You Do It?

As official black hole scientists, you will present your results to your peers in the scientific community. As a group, consider your answers to the following questions. You may want to take notes.

1) What did you consider while designing your experiment?

2) What problems came up during your measurements? How did you fix them?

3) What are the possible sources of error in your mass measurement? If you were to repeat this experiment, how could your measurement be improved?

4) What are the limitations of using your lens to model a black hole?