Supplementary Information

Bowl-Tape Demo

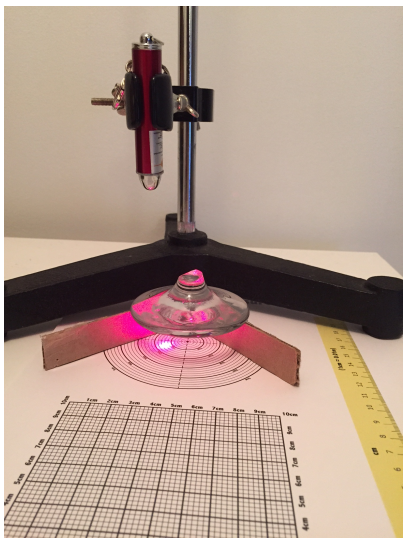
- Place a lightly curved bowl or plate upside-down on a tabletop.
- Unroll masking tape along the table towards the bowl. This represents a light ray.
- The path of the tape(light) is 'deflected' as it passes over the edge of the bowl due to its curved geometry.
- A student that stands where the tape ends (after it has been bent) can look back along the line of sight to see where an image would appear.

Suggested Experimental Designs

Although students are free to design their own experimental set up to measure the mass of their black hole lens, we have found two simple designs that can be used as references. Groups that appear to be struggling can be led towards these set ups by the facilitator.

1) **Simple deflection:** measure the deflection angle of a single ray using a laser

Directions:



- Mount a laser pointer so that the ray is directed vertically downward onto the polar grid and measure where the beam intersects the grid (this is the impact parameter)
- Cut out a strip of cardboard of uniform width and bend it into a 'V' shape
- Mount the lens on the cardboard strip so that the center of the lens is directly above the origin on the grid paper
- Measure the shifted position of the laser beam on the grid paper
- Measure the height from the grid paper to the point where the beam first hits the lens

- The deflection angle can be found with a scale diagram and a protractor if students are uncomfortable with trigonometry

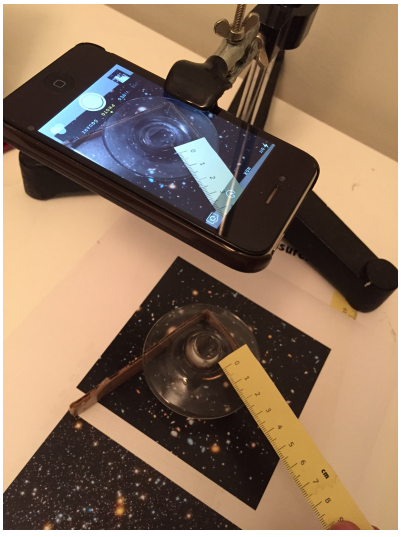
Notes:

- This will work well when the cardboard strip is about 2.0cm and the beam is directed directly between the edge and center of the lens.
- This can easily be done on a much larger scale. This will make angle measurements more accurate but distortions caused by irregularities in the lens will be magnified.
- For their safety, ensure that learners do not walk through the path of the laser beam!

2) **Einstein Ring:** measure the radius of an Einstein ring

Directions:

- Mount the lens on a uniform width strip of cardboard above one of the space images
- Slide the lens so that the center is directly above a bright but circular source so that a ring appears to an observer that is directly above the center of the ring (a mounted phone camera can be used)
- Measure the distance from the source (the photograph) to the observer (either a student's eye or the camera lens)
- Measure the distance from the center or edge of the lens to the ring



Notes:

- As with 1), a cardboard mount of width 2.0cm will work well
- A lens to observer distance of 20-50cm is suggested.
- The lens must be within about 20cm of the source for a clear, undistorted ring to appear.
- If using a camera phone, centering the image on the screen will ensure that the camera lens is directly

above the center of the gravitational lens.
- Measure the relevant distances appearing in the Einstein ring equation and solve for the mass

General notes:

- A wide variety of experimental designs are possible. Students may wish to use the incandescent bulb of the laser pointer as a source instead of one of the space images. However, this may require more careful supervision as is it easy to mistakenly switch to the laser beam while it is directed at a learner's eyes.