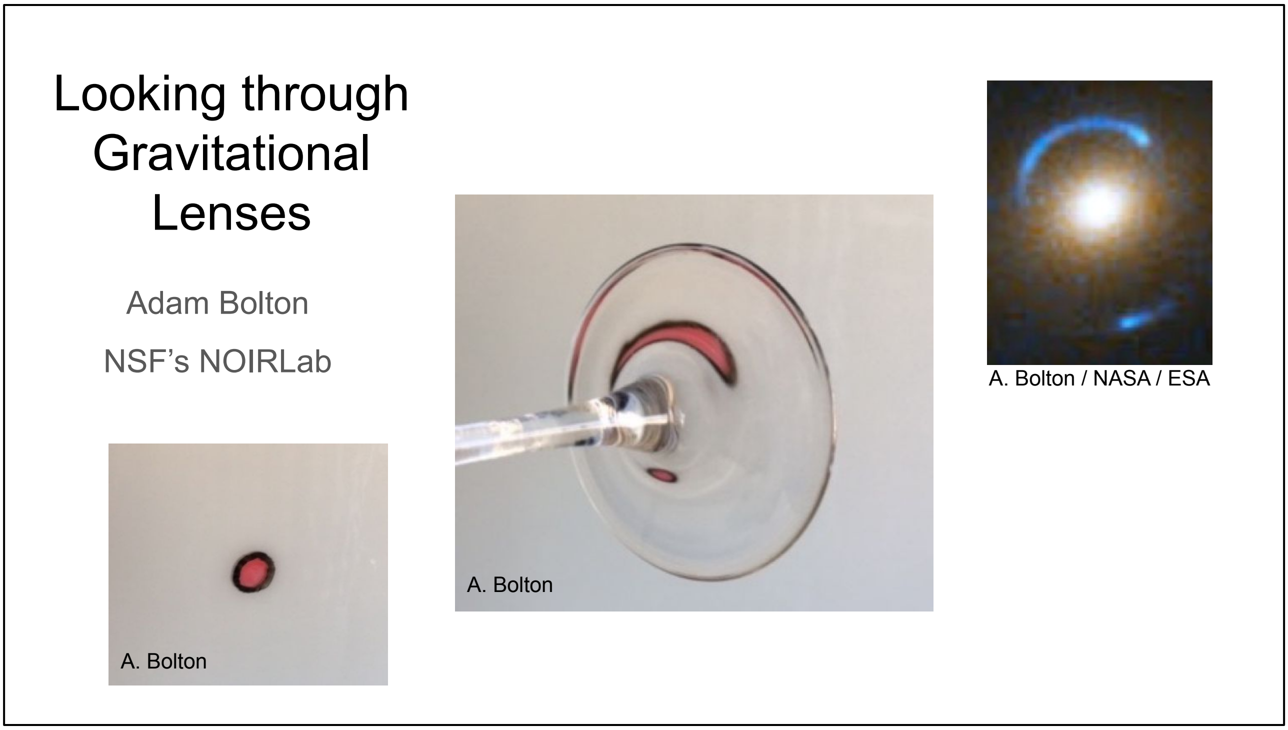
Welcome to the Teen Astronomy Café

Hosted by NSF's NOIRLab

Image credit: James Lowenthal



Looking through Gravitational Lenses

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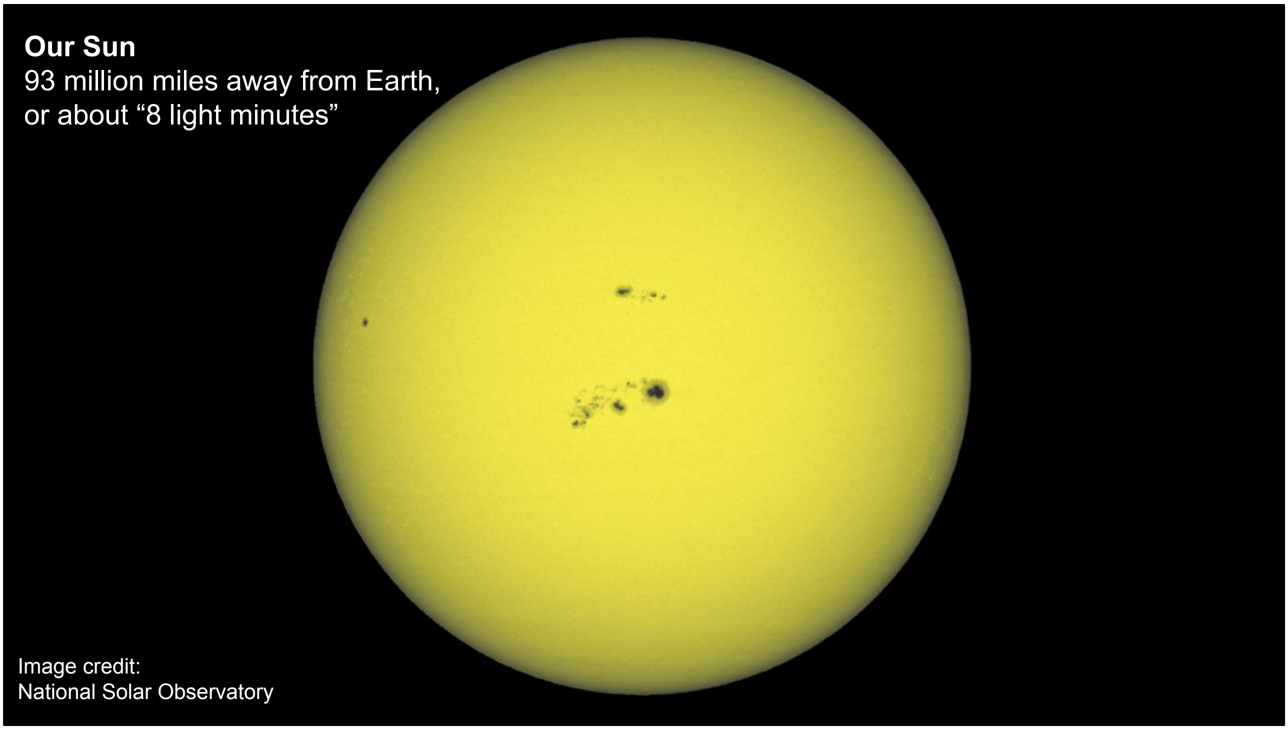
A. Bolton / NASA / ESA

Today we will explore the phenomenon of gravitational lensing.

What is shown on this slide is (i) a spot drawn on a whiteboard, (ii) that same spot as viewed through the base of a wine glass held at the right distance and angle, and (iii) an image of a pair of distant galaxies – a "gravitational lens" – that shows a very similar kind of image.

Explore the phenomena: Ask students to develop questions based on their observations of this phenomenon. Potential student questions: "How does the wine glass distort the image of the spot?" "What causes the image of the galaxies to be distorted like the wine glass?" "How are there only two galaxies in the third image? I see three "parts" to that image." Questions should be displayed (ex. Jamboard) for everyone to see with the goal to answer as many questions as possible throughout this Café.

We will explore this phenomenon in detail today, and also learn how gravitational lensing provides us with a method to make direct measurements of the masses of galaxies.



Our Sun
93 million miles away from Earth,
or about “8 light minutes”

Image credit:
National Solar Observatory

We will start out relatively close to home, to establish our sense of scale.

This is a photo of our Sun, taken by the facilities of the National Solar Observatory.

Those black spots are “sunspots” related to magnetic fields breaking out of the surface of the Sun.

On average, our Sun is about 93 million miles away from Earth.

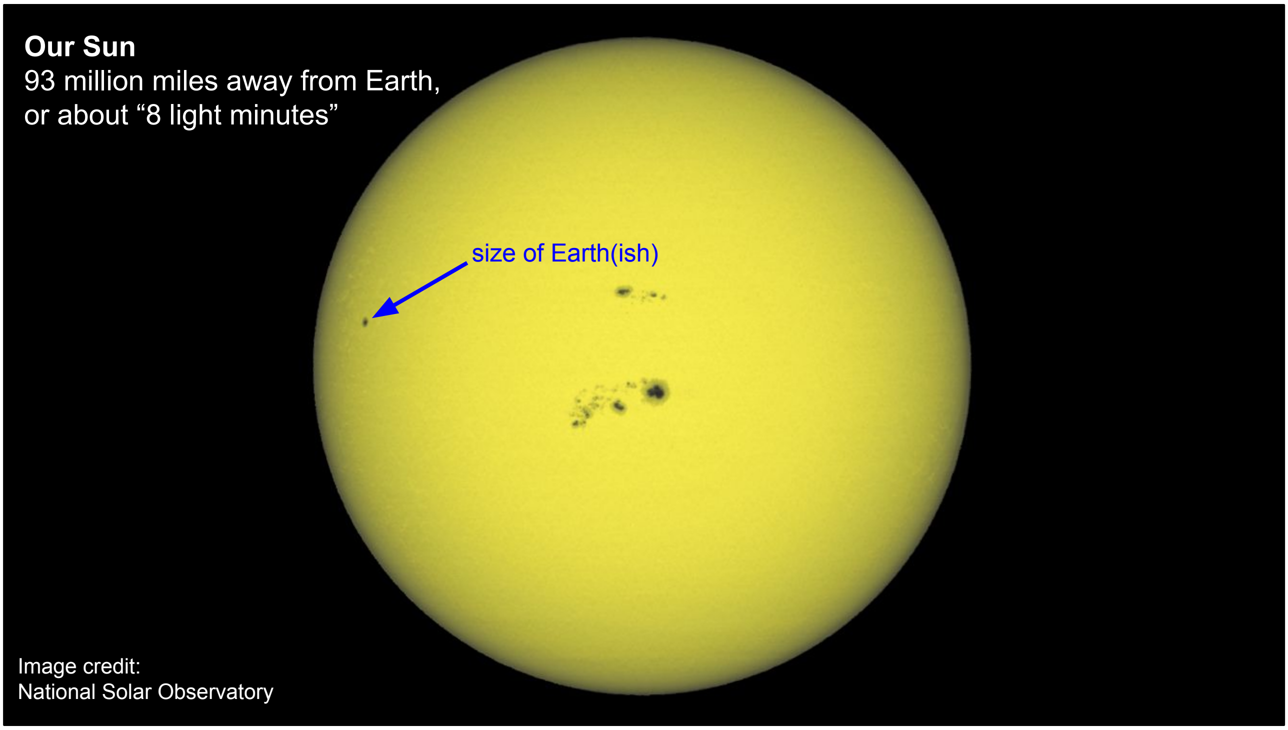
Now, the speed of light is about 670 million miles per hour.

So, doing the math, we can conclude that the light from the Sun takes about 8 minutes to get to Earth.

Alternatively, we can say that the Earth is about “8 light-minutes” away from the Sun.

This means that current light we see from the Sun, in this very moment, is 8 minutes old.

How big would the Earth be if it were on the same scale?



Our Sun

93 million miles away from Earth,
or about “8 light minutes”

size of Earth(ish)

Image credit:
National Solar Observatory

How big would the Earth be if it were on the same scale?

It would be about the size of one of the smaller of the sunspots that you see.

Other stars

Separated by light years from one another

This cluster of stars is about 1,600 light years from Earth

Image credit: N. A. Sharp, M. Hanna, NOIRLab/NSF/AURA

Our Sun is a star—and in some sense an unremarkable star!—and when we look up at the sky at night we can see many others.

Here, for example, is an image taken in 1995 using the Burrell Schmidt telescope on Kitt Peak of a cluster of stars known as the Butterfly Cluster (or Messier 6).

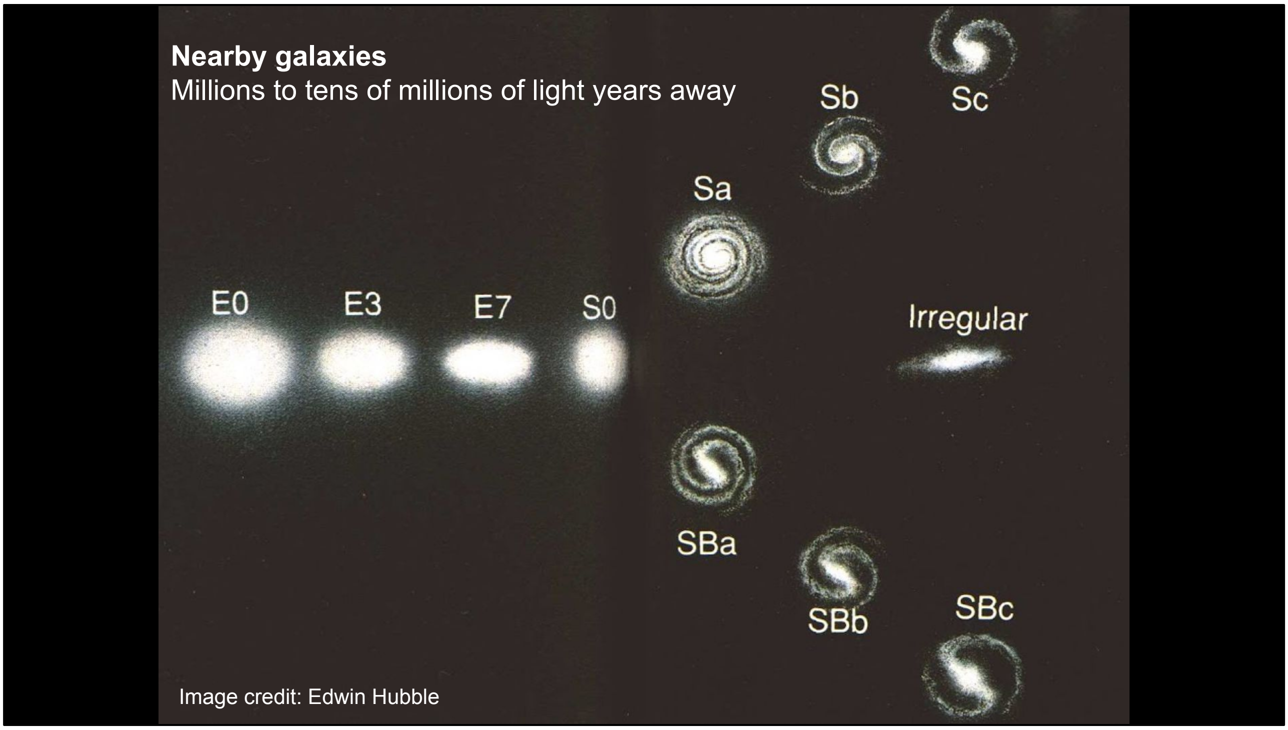
The stars in this cluster are separated by characteristic distances measured in light *years*, which is also the typical distance from our Sun to the nearest stars in our neighborhood.

The cluster itself is about 1,600 light years from Earth.

Our "Milky Way" Galaxy
tens of thousands of light years in size

Image credit: Markus Oblander/imageBROKER/Shutterstock

At a dark location, you can see a band of light running across the sky at night.
Tucson is one of the best cities in the US for this, due to the widespread understanding of the importance of minimizing light pollution here.
This band is the collective light of billions of stars that make up our Milky Way Galaxy.
Every star that you can see with your unaided eye is within the Milky Way.
The Milky Way as a whole is measured in tens of thousands of light years.



Nearby galaxies

Millions to tens of millions of light years away

Image credit: Edwin Hubble

We also know, as of the 20th Century, that our Milky Way is just one of many galaxies in the Universe.

This slide shows the original classification scheme for other galaxies that was devised by Edwin Hubble in the 1920s.

Originally these were called “spiral nebulae” before it was established that they are galaxies like our own.

Hubble is credited with the first observational (or experimental) proof that these “spiral nebulae” were outside the Milky Way, not inside it.

The distance to “nearby” galaxies is measured in millions or tens of millions of light years.

Has anybody heard the term “nebula” before? What does it mean?

In the past it referred to any cloudy, fuzzy, or indistinct object in the night sky, including other galaxies.

In modern times, astronomers use “nebula” to refer specifically to a cloud of gas and/or dust in outer space, but not to other galaxies.

It comes from the Latin term for “mist”. Anybody know the Spanish word for “cloud”? (“nube”). Also related to the English word “nebulous”.

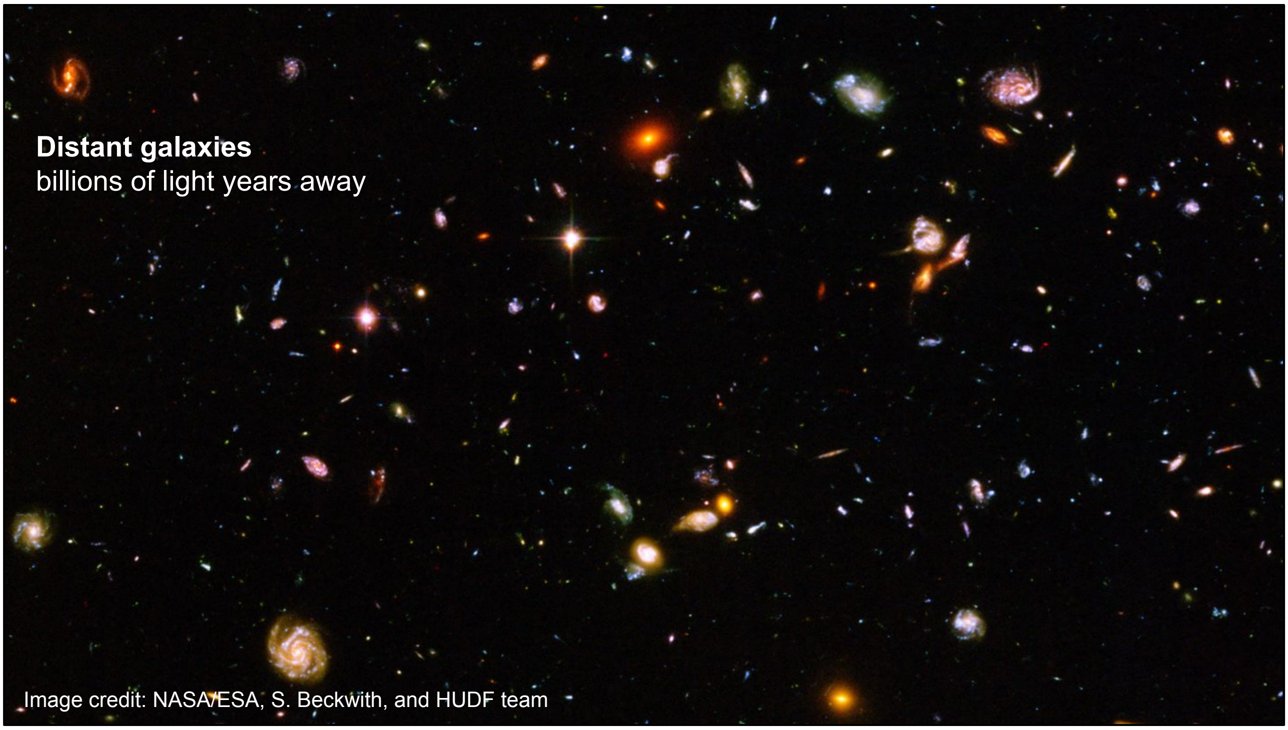

Distant galaxies
billions of light years away

Image credit: NASA/ESA, S. Beckwith, and HUDF team

In more recent years, we've learned that if you use a telescope to stare deeply into any seemingly blank patch of sky, you see that the Universe is filled with galaxies. The distances to the galaxies seen in this image are measured in billions of light years. Does anyone know what telescope this image was taken with?

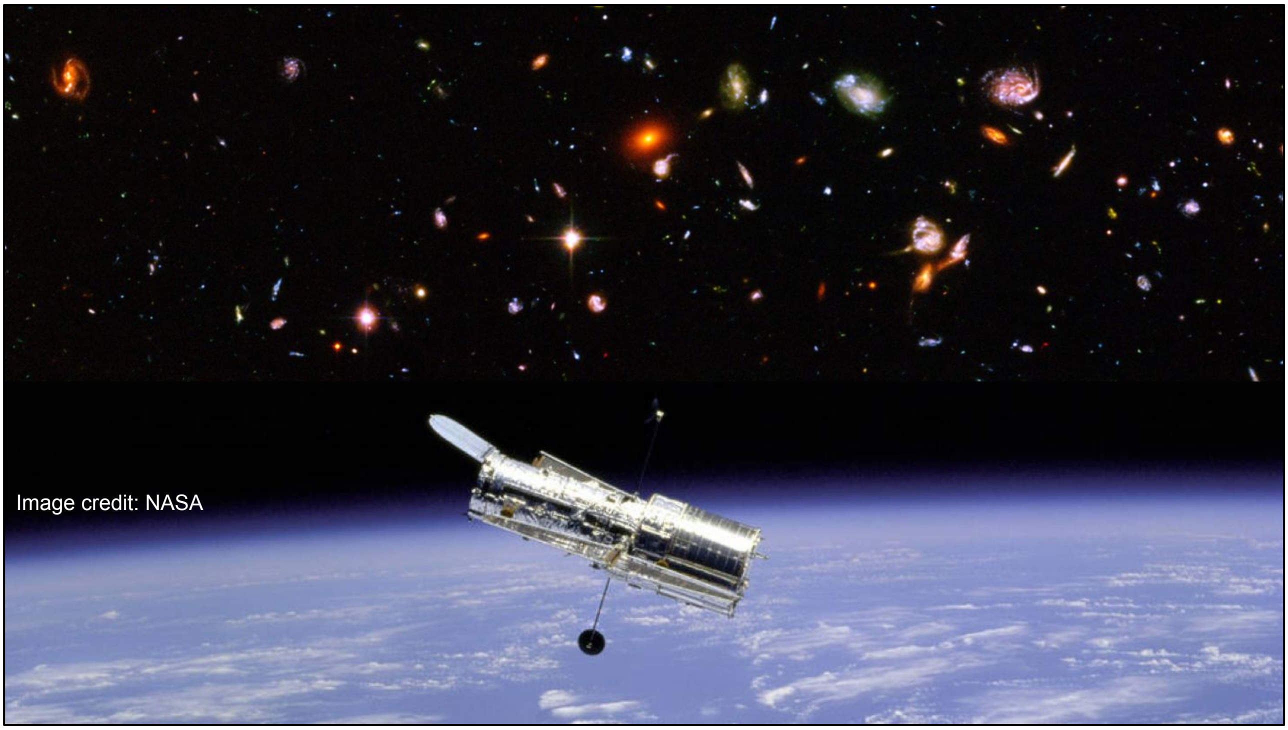


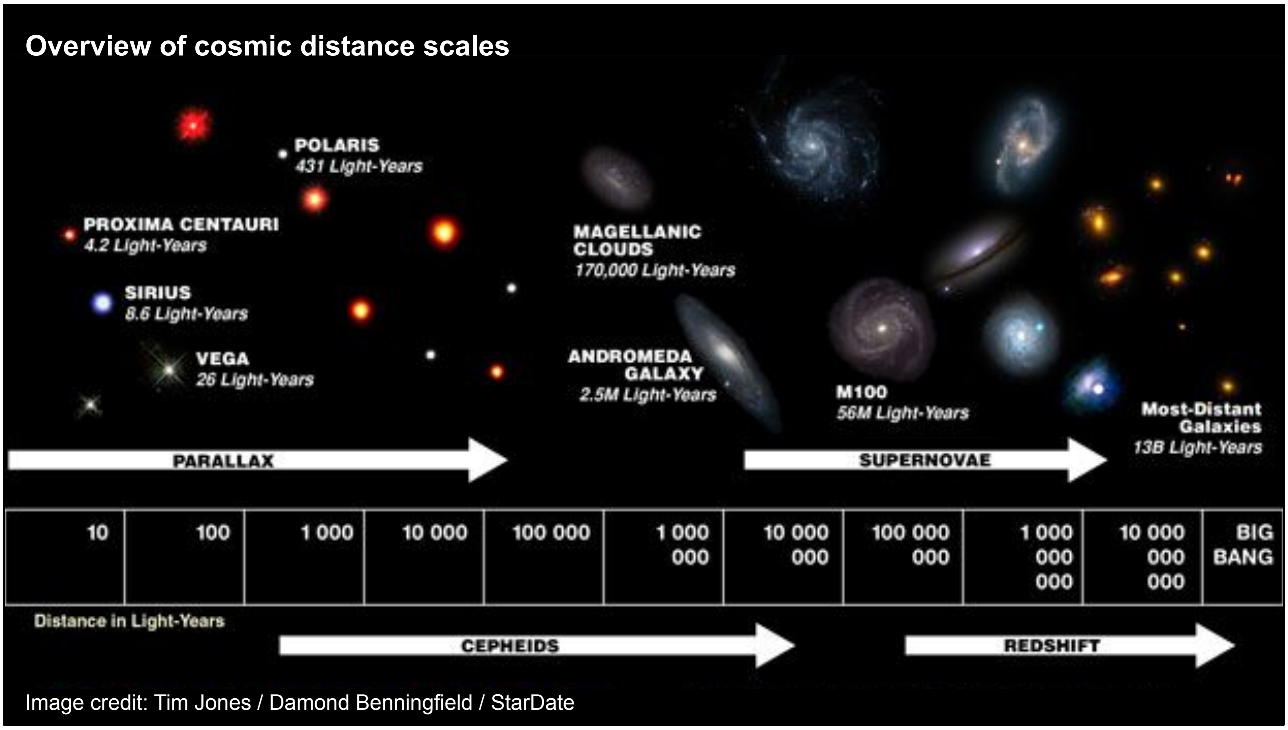
Image credit: NASA

In case you haven't already guessed, this image was taken by the Hubble Space Telescope, named of course for the same Edwin Hubble who originally determined the nature of other galaxies.

The Hubble Telescope is able to take these incredibly sharp and detailed images because it operates above the Earth's atmosphere, and is not affected by the blurring effects that the atmosphere imposes on ground-based telescopes.

This image is a part of a larger image called the "Hubble Ultra Deep Field".

("Deep" is astronomer jargon for an image that uses a lot of telescope time to achieve the greatest possible sensitivity for detecting faint objects.)



Overview of cosmic distance scales

Image credit: Tim Jones / Damond Benningfield / StarDate

Slide 10:
This slide summarizes the many distance scales we’ve covered.
Each box is an increase by a factor of 10 (which is called a “logarithmic scale”)
This doesn’t show the 8 light minutes from the Earth to the Sun.
You can work out where that distance would be from the fact that there are about a half-million minutes in a year (and therefore a half-million light minutes to a light year.)

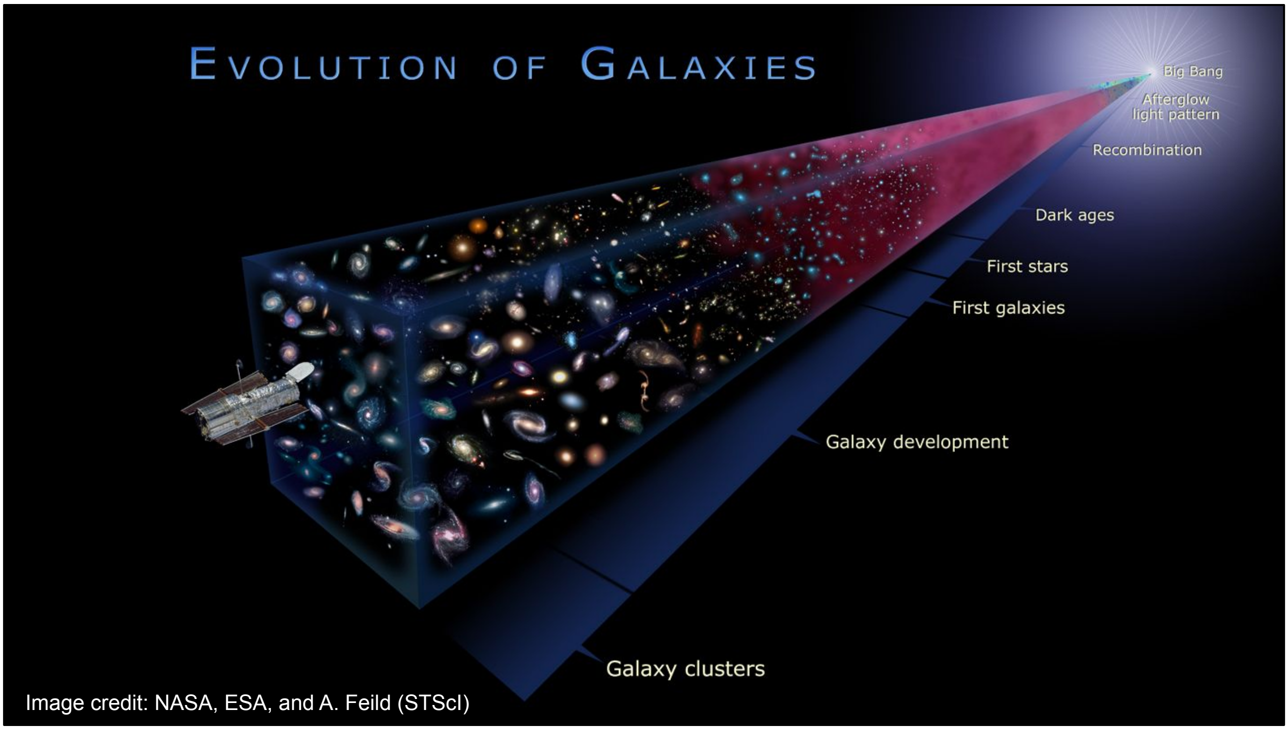


Image credit: NASA, ESA, and A. Feild (STScI)

One of the most significant things that we've learned from studying distant galaxies is that they don't look like galaxies in the nearby universe.

If we think back to the idea that light takes time to get from these galaxies to us, we realize that when we look at a galaxy that is billions of light years away, we are seeing that galaxy as it was billions of years ago.

This shows us that galaxies themselves evolve as the Universe evolves.

All of this was set in motion by a "big bang" about 14 billion years ago.

In addition to the evidence from galaxy evolution, we believe in the Big Bang because we can measure the resulting expansion of the Universe, we can see the relic afterglow radiation from the Big Bang, and we can see based on our understanding of nuclear physics that the relative abundances of elements in the Universe can only be explained if the Universe was born in a hot Big Bang.

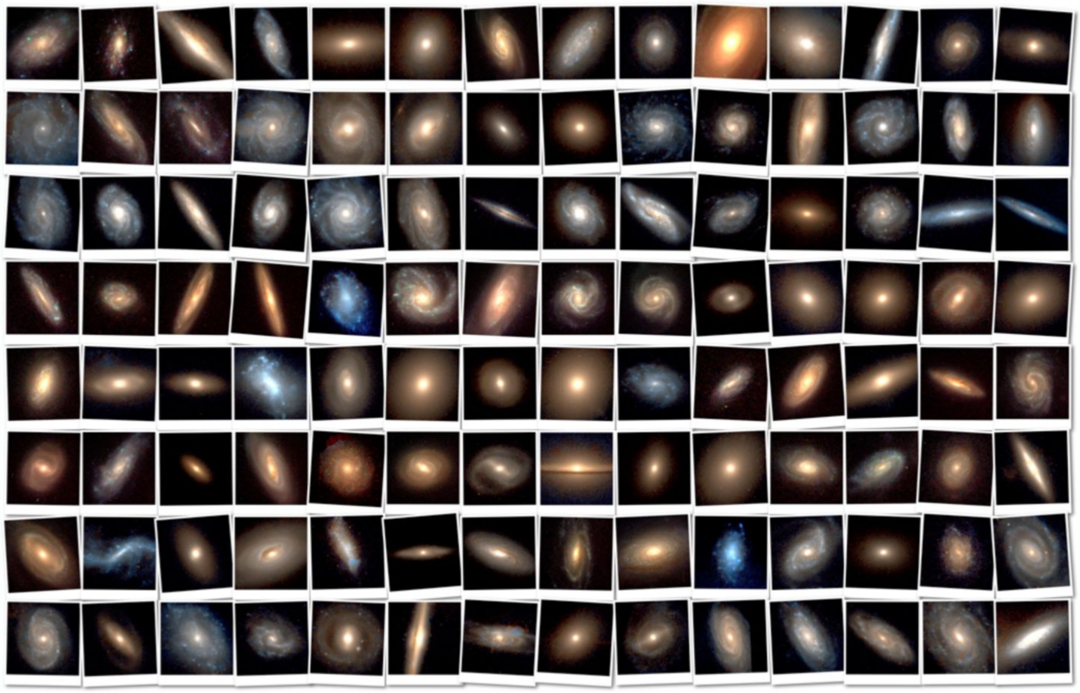


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Image credit:
Z. Frei,
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So, the Universe is filled with galaxies.
And almost everything that we know about these galaxies comes from studying the light that they emit.
This light comes from the stars and gas within each galaxy.

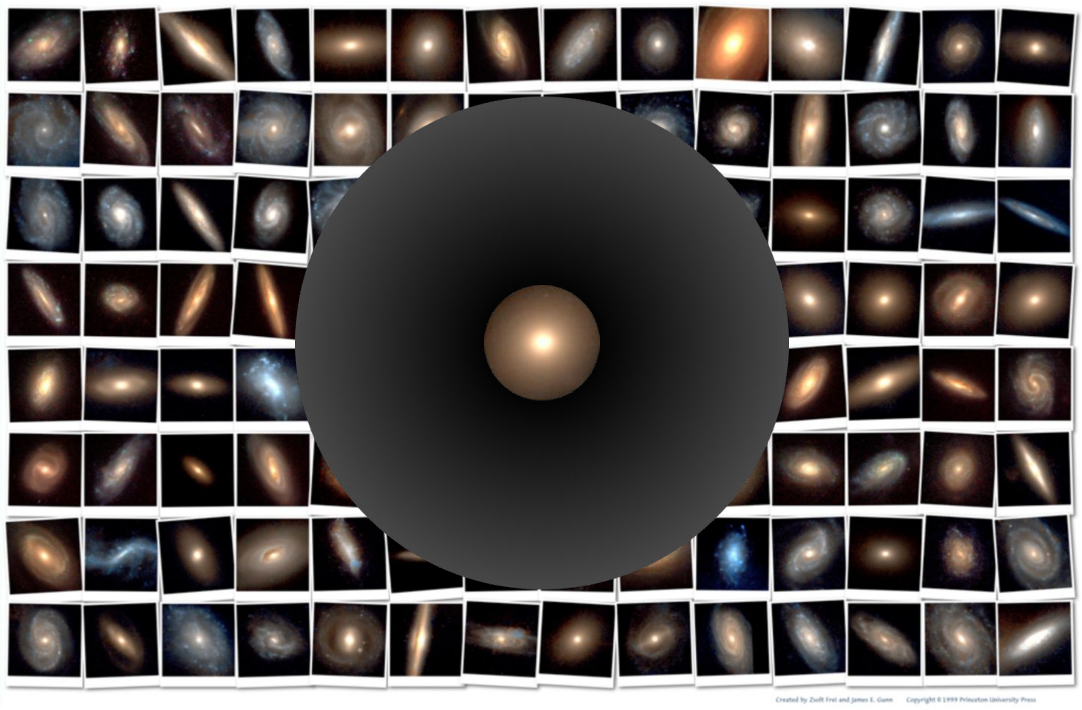

Image credit:
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But we also learned in the 20th Century that much of the mass of galaxies does not come from stars or gas, but rather from a mysterious substance that we refer to as “dark matter”.

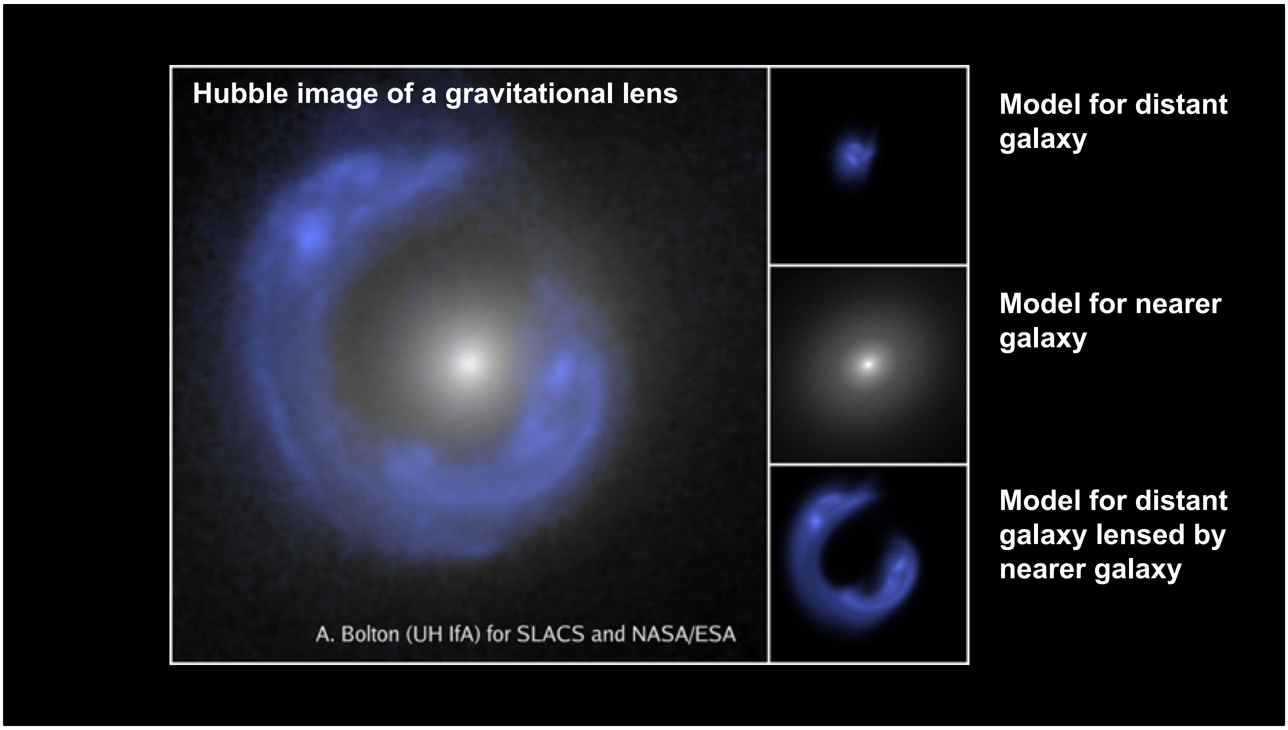
Has anyone heard of dark matter? If so, what have you heard about it?

The main thing we know about dark matter is that there is more dark matter in the universe than regular matter, and that we can only infer its existence through its gravitational effects.

We know from these effects that the dark matter is found all throughout galaxies, and it also surrounds galaxies in a more extended way in what we call “dark matter halos”.

The relationship between galaxies and dark matter is essential to how galaxies form and evolve, and it is also one of the primary ways that we can understand the mystery of dark matter itself.

But dark matter is very hard to observe and measure directly.



Hubble image of a gravitational lens

A. Bolton (UH IfA) for SLACS and NASA/ESA

Model for distant galaxy

Model for nearer galaxy

Model for distant galaxy lensed by nearer galaxy

This now brings us to the main subject of today’s café: gravitational lensing.

If by chance alignment, two galaxies in the Universe—one more distant than the other—happen to fall along the same line of sight from Earth, we observe a fascinating phenomenon that we call “gravitational lensing”.

In gravitational lensing, the image of the more distant galaxy is distorted by the gravitational field of the more nearby galaxy, and the nature of this distortion is directly related to the total mass—dark matter plus regular matter—in the more nearby galaxy.

So, gravitational lensing gives us a way to directly measure the total mass of distant galaxies.

In this image (which has enhanced colors), we see a gravitational lens observed by the Hubble Space Telescope in the large panel.

The three smaller panels illustrate the elements that we use to build a mathematical model of this effect. We use this model to make our measurement of the nearer galaxy’s mass.

The top small panel shows what the more distant galaxy would look like in the absence of the nearby galaxy.

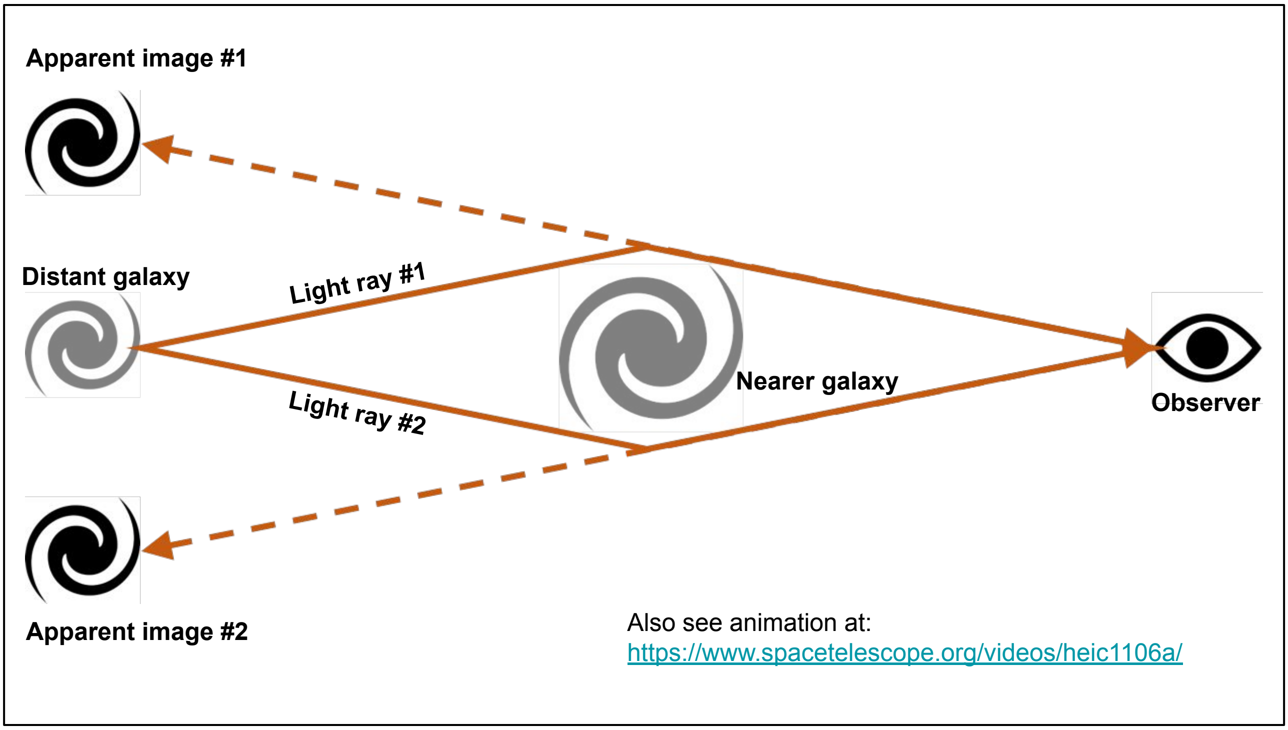
The middle small panel shows the model for the light of the nearer galaxy.

The bottom small panel shows the “lensing effect” of the nearer galaxy’s gravity on the image of the more distant galaxy, producing the features shown in the observed image.

You will explore a computer implementation of this mathematical modeling process in today’s interactive

The bottom small panel shows the “lensing effect” of the nearer galaxy’s gravity on the image of the more distant galaxy, producing the features shown in the observed image.

You will explore a computer implementation of this mathematical modeling process in today’s interactive exercise.



Also see animation at:
https://www.spacetelescope.org/videos/heic1106a/

In the simplest terms, you can think of gravitational lensing as seeing more than one image of the same distant galaxy.

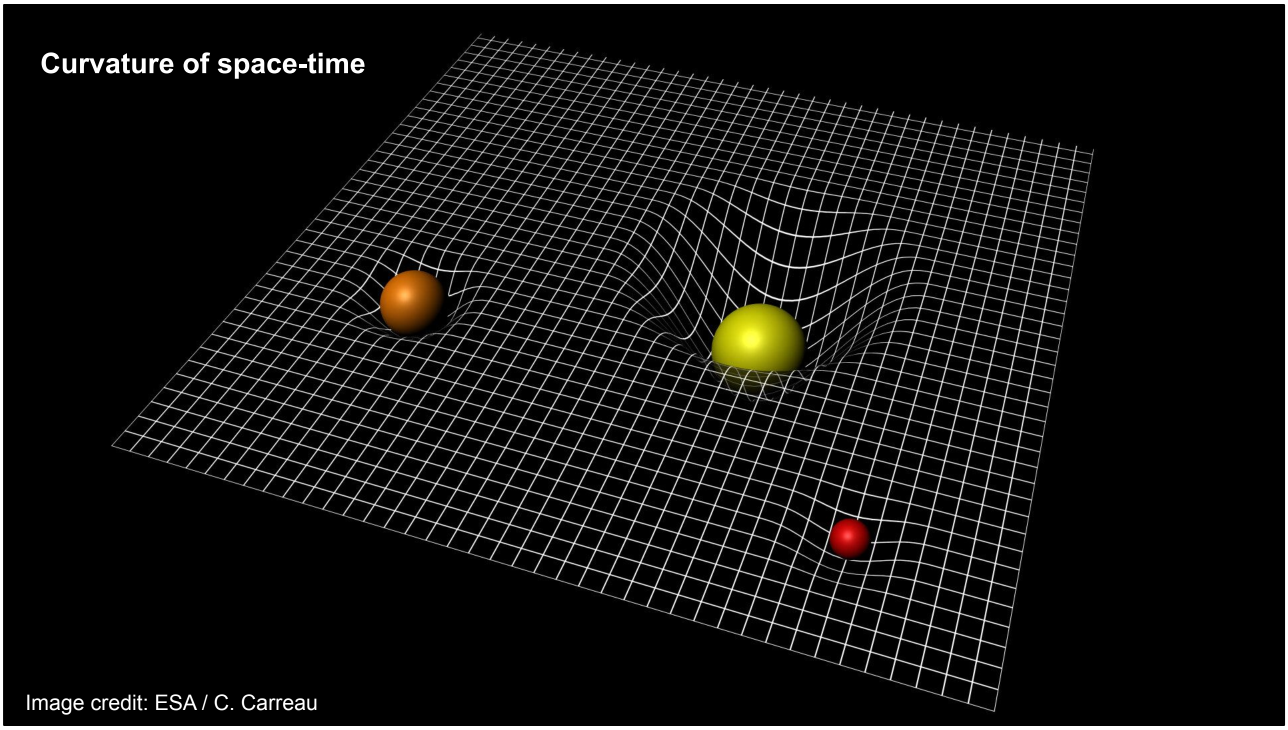
This is because rays of light that diverge away from the more distant galaxy are bent by the nearer galaxy back into converging paths. To an observer on earth, this looks like there are multiple images of the distant galaxy.

That effect is illustrated schematically in a “sideways view” in this diagram.

We are able to measure the nearer galaxy’s mass because more mass makes the light rays bend through larger angles, and that shows up in the lensed images being more separated from each other.

If the alignment is perfect, we can see a complete “ring” rather than multiple separate images.

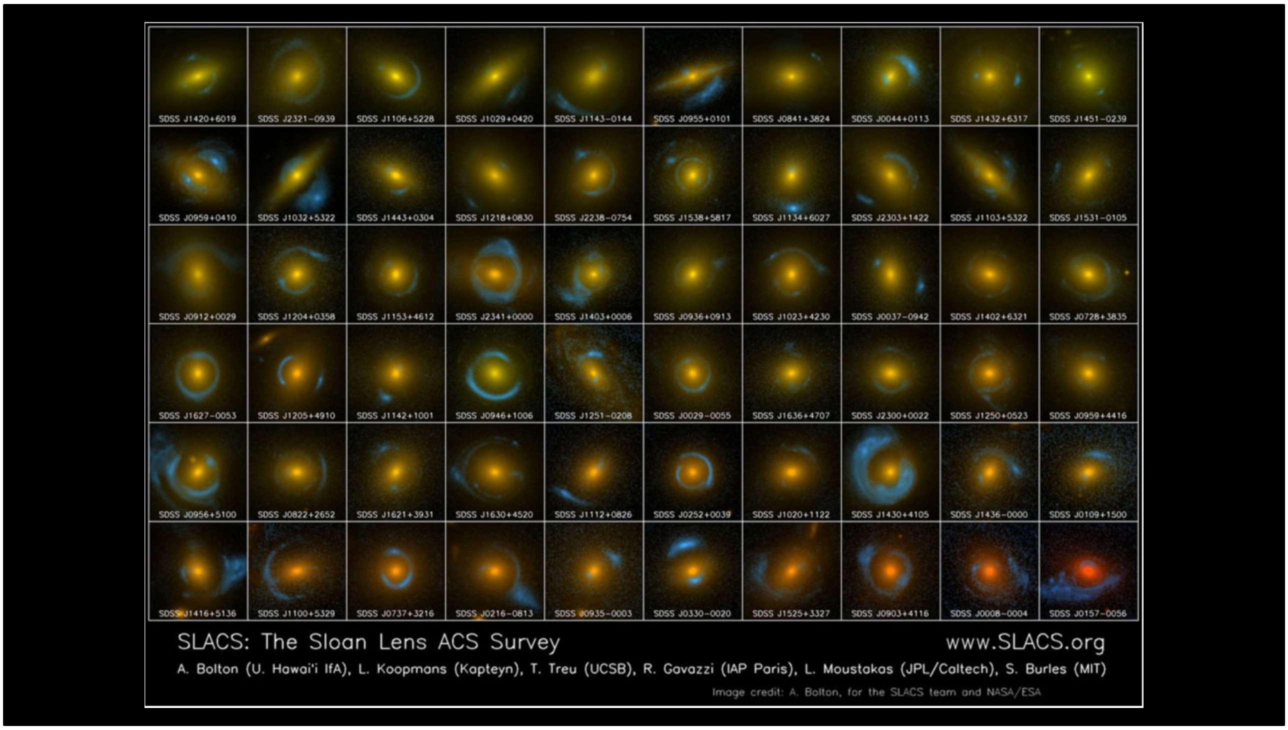
We call that ring an “Einstein ring”, because the proper mathematical treatment of gravitational lensing makes use of Einstein’s theory of gravity, which is called “General Relativity”.



Curvature of space-time

Image credit: ESA / C. Carreau

Einstein’s theory describes gravity in terms of curvature of space and time.
More massive objects impart a greater amount of curvature.
When light passes by a massive object, its path is determined by the curvature of space-time, and in the presence of massive objects, it can take the multiple paths that we see in the gravitational lensing phenomenon.



SLACS: The Sloan Lens ACS Survey www.SLACS.org

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Image credit: A. Bolton, for the SLACS team and NASA/ESA

Gravitational lenses used to be rare, but today we know of hundreds (or maybe thousands!) of examples.

Shown here is a gallery of Hubble Space Telescope images of gravitational lenses from one particular project.

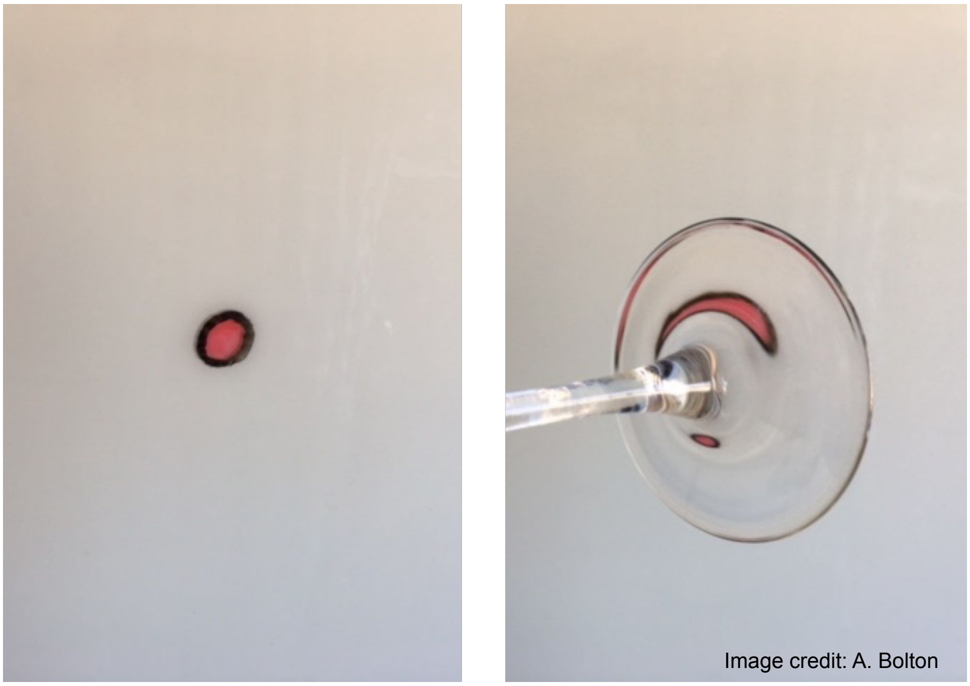

Image credit: A. Bolton

Revisiting the phenomena: Let’s look back at the wine glass phenomena. Can we answer your original question(s)? What remaining questions do you still have?

In summary, gravity can act as a lens in the Universe just like glass can act as a lens in our everyday experience.

One particularly fun way to explore this, as shown at the start of this presentation, is to use the base of wine glasses or other stemware to create images that look surprisingly similar to what we see out in the Universe. Light travels at a different speed through the wine glass than air, causing the glass to act as a lens and bend the image of the spot.

Another way to explore the gravitational lensing phenomenon is to work with computer implementations of the kind of mathematical modeling that we use to describe it in our research work.

This will be the focus of our interactive exercise.