What is a Gravitational Lens?

- A **gravitational lens** is formed when the light from a distant, bright source is "bent" around a massive object (such as a massive galaxy or cluster of galaxies) between the source object and the observer.
- The process is known as **gravitational lensing**, and is one of the predictions of Einstein's theory of general relativity (predicted by Einstein in 1936).
The lens phenomenon exists because gravity bends the paths of light rays.

In general relativity, gravity acts by producing curvature in space-time.

The paths of all objects, whether or not they have mass, are curved if they pass near a massive body.

Prediction of bending confirmed for starlight passing near the Sun in the 1919 solar eclipse.
Discovering Gravitational Lenses

Mysterious arcs discovered in 1986
(a) Cluster Abell 370 (left)
- cluster redshift $z=0.37$
- arc redshift $z=0.735$
(b) Cluster C12244 (right)
- cluster redshift $z=0.31$
- arc redshift of 2.24

Bright knots on the arcs show the structure of the intrinsic distribution of brightness of the galaxies, whose images are strongly distorted.

The influence of individual cluster galaxies on the detailed morphology of the arc in A370, which coils around these galaxies, can also be recognized.
Three Classes of Gravitational Lenses

- **Strong lensing** - easily visible distortions
  - Einstein rings, arcs, and multiple images

- **Weak lensing** - distortions are much smaller
  - Detected by analyzing large numbers of objects to find distortions of only a few percent.
  - The lensing shows up statistically as a preferred stretching of the background objects perpendicular to the direction to the center of the lens

- **Microlensing** - no distortion in shape can be seen but the amount of light received from a background object changes with time
  - Microlensing occurs with stars and extrasolar planets

The Double Quasar – the first gravitational lens

Lensing Galaxy

Galaxy Core

The Einstein Cross
Unlike optical lenses, gravitational lenses produce multiple images.

- In an optical lens, maximum bending occurs furthest from the central axis.
- In a gravitational lens, maximum bending occurs closest to the central axis.
- A gravitational lens has no single focal point.
- If the source, the lens, and the observer lie in a straight line, the source will appear as a ring around the lens.
- If the lens is off-center, multiple images will appear. The lensed image will always be distorted.
Simulating Gravitational Lenses

- HST MDS WFPC2 HST Gravitational Lens Simulation (mds.phys.cmu.edu/ego.cgi.html)

A galaxy having a mass of over 100 billion solar masses will produce multiple images separated by only a few arcseconds.

- Galaxy clusters can produce separations of several arcminutes.
Arcs in the Galaxy Cluster Abell 2218 (z=0.175)

- Several arcs surround the cluster center
  - Arc A0 has a redshift of 2.515;
  - Near A2 is another image of the same galaxy
- Several arcs also surround a second concentration of mass to the right above the middle of the picture
- Multiple images of the lensed galaxy can be identified by comparing the light distribution and by the spectra of the arcs as well as by the spectral properties of their light (i.e. of the colors)
- A detailed model of the mass of the lensing cluster can be made with so many lensed galaxies
The reddish objects are galaxies in the lensing cluster at $z=0.39$.

The bluish objects are multiple images of a distant galaxy at $z=1.63$ lensed by the cluster.

The distant galaxy has been reconstructed from models of the individual pieces of the arc.
Galaxy Cluster Cl1358+62

- The reddish arc is a lensed image of a background galaxy with $z=4.92$
- upper right - an enlarged version of the lensed galaxy
- lower right - a reconstruction of the unlensed source
Abell 2390

- A thick arc with $z=0.913$
- Two more arc systems are also seen (indicated by the letters A and B)
  - system A has redshift $z=4.04$
  - system B has redshift $z=4.05$
The Bottom Line...

- The visible matter does not provide enough gravity to produce the gravitational lenses we see from galaxies and galaxy clusters.
- Dark matter must be present to account for what we observe.
Mapping the Dark Universe

The distribution of dark matter in the lens can be mapped by modeling the distortions of the lensed galaxies.
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1E 0657-56 – The Bullet Cluster

Direct Observation of Dark Matter
Proof that Dark Matter Exists

- 1E 0657-56 – A collision of galaxy clusters
- A cluster of galaxies consists of three components

1. Galaxies
2. Hot Gas
3. Dark Matter
What’s going on with 1E 0657-56?

- TWO clusters of galaxies collide
The gas interacts, the dark matter and galaxies don’t

- The galaxies and dark matter pass through unimpeded, but the hot gas is separated from the clusters

- Animation of 1E: 0657-56
  [http://chandra.harvard.edu/photo/2006/1e0657/bullett_anim_lg.mpg](http://chandra.harvard.edu/photo/2006/1e0657/bullett_anim_lg.mpg)
A collision between two massive galaxy clusters 1-2 billion years ago and 5 billion light years away formed a ring of dark matter.

Our view of the collision is “head-on”.

The ring measures 2.6 million light-years across.

The distribution of the dark matter is inferred from how its gravity bends the light of more distant background galaxies.

As the two clusters collided, the dark matter fell to the center of the combined cluster and then sloshed back out. As the dark matter moved outward, it slowed down under the pull of gravity and piled up, forming a ring.
**Cluster**

- The Bullet Cluster
- Collision seen from the side
- Dark matter and gas are separated

**Collisions**

- ZwCl0024+1652
- Collision seen head-on
- Dark matter forms a ring

**Two views of interacting galaxy clusters**

- Side view of cluster collision
  - 0.5 billion years before collision
  - 0.25 billion years before collision
  - Collision
  - 1 billion years after collision
  - 2 billion years after collision
- Cluster collision as seen from Earth
  - Dark-matter "ring" detected by Hubble
Lensing Review

- Lensing is more evidence for dark matter
- Lensing tells us about the distribution and properties of dark matter

- Gravitational lenses act on all kinds of electromagnetic radiation, not just visible light
  - Strong lenses have been observed in radio and x-ray images
- Lensing provides a “telescope” to view the distant universe
In a galaxy far, far away...

- The Lynx Arc
- Biggest, brightest, hottest star forming region ever seen
- 12 billion light years away
- Stars as hot as 140,000 K
- >1,000,000 hot, massive, blue-white stars (Orion has only 4!)
- Seen through a gravitational lens