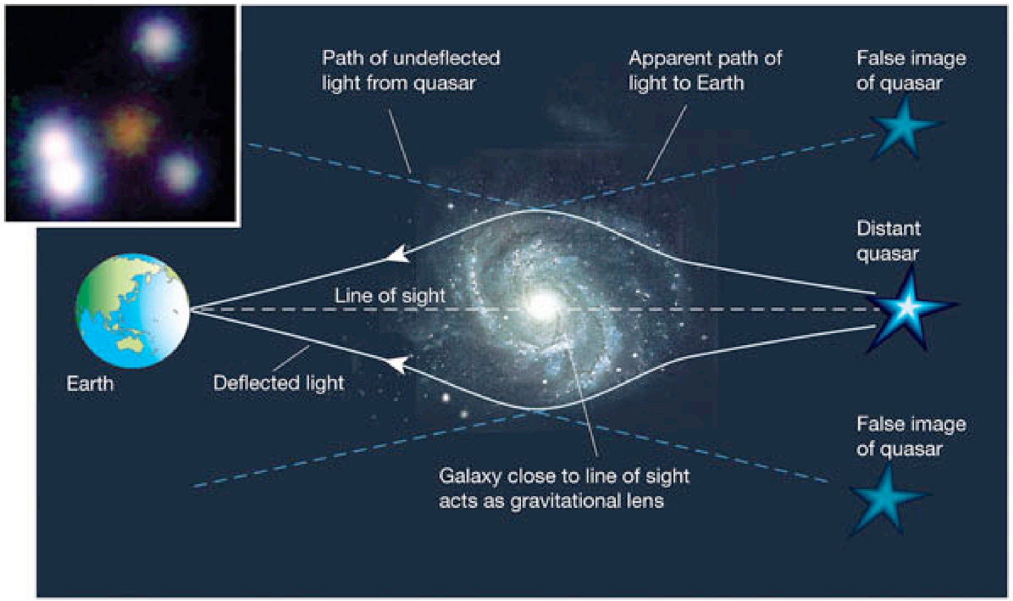
Nature's telescopes



Outline

- Introduction to gravitational lensing
- Strong lensing
- Microlensing
- Weak lensing

Outline

- Introduction to gravitational lensing
- Strong lensing
- Microlensing
- Weak lensing

Gravitational lensing

- Georgia O'Keeffe greatly magnified tiny flowers "to startle busy New Yorkers into noticing them".
- Her large-format flowers are even brighter and more colorful than their tiny models.
- She magnified both the size and the brightness.

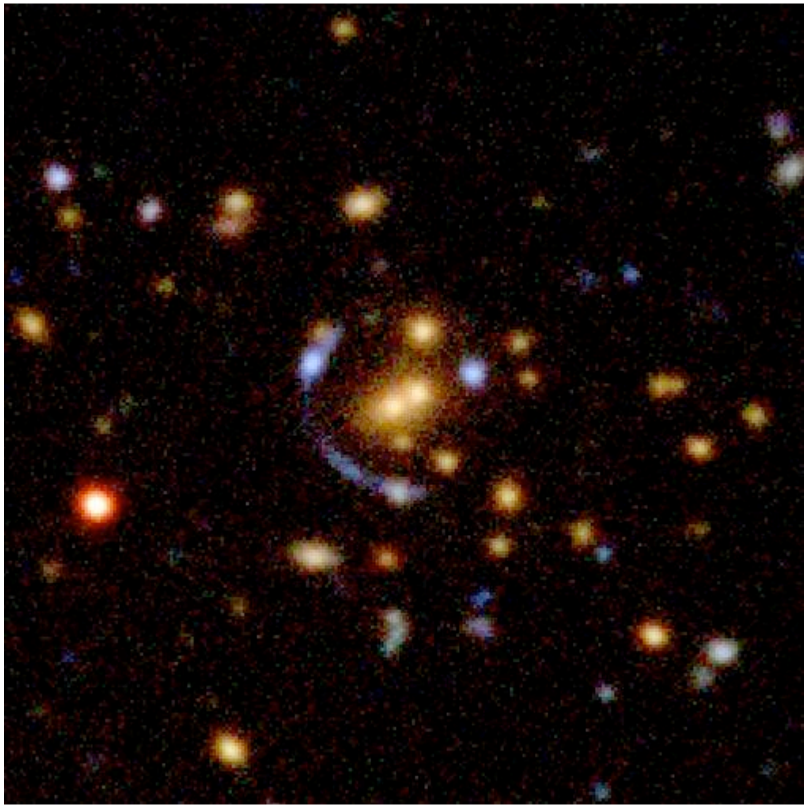
White Rose with Larkspur, No. 2 by Georgia O'Keeffe 1927
(101.6 cm x 76.2 cm)

Contrast optical magnification

- In the case of magnification by optical lenses, magnified objects are dimmer.

Gravitational lensing

- Similarly, gravitational lenses magnify distant galaxies that might otherwise remain undetected.
- Also, as Georgia O'Keeffe's flowers are brighter and more colorful than tiny, real flowers, gravitational lensing amplifies the luminosity of the source, enabling observation of objects too distant or intrinsically too faint to be observed without lensing.
- Both the size and the luminosity of distant objects are magnified by gravitational lensing.



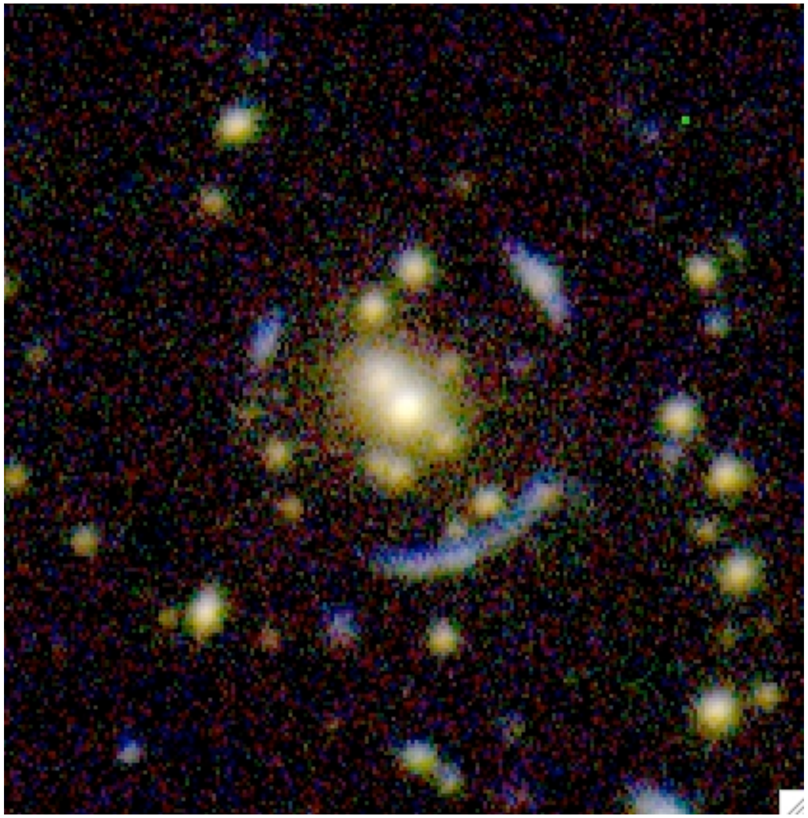
Contrast optical magnification

- In the case of optical lenses, magnified objects are dimmer.
- As magnification increases, the field of view shrinks, and the image gets dimmer.
- Dimming does *not* accompany magnification when the magnification is due gravitational lensing.

Orion Nebula
Magnified by an optical lens
50x, 80x, and 120x.

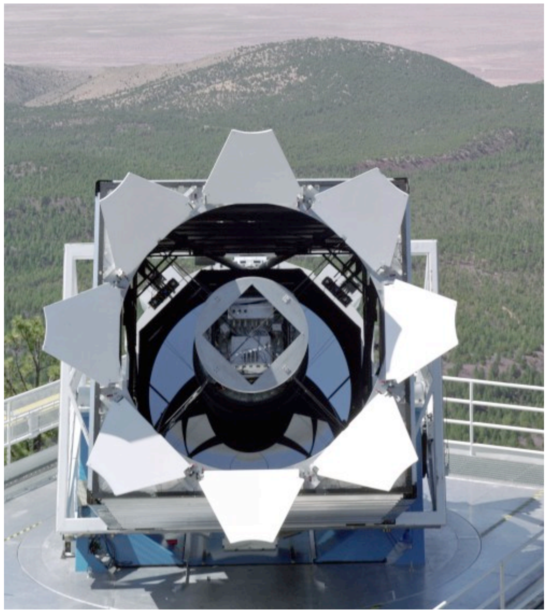
Gravitational lensing

- The total flux received is amplified in proportion to the ratio of the solid angles of the image and source.
- Consider a galaxy that subtends one square arcsecond on the sky.
- If this galaxy, when magnified by a gravitational lens, results in an image that subtends ten square arcseconds, the observed luminosity will be ten times the luminosity of the source in the absence of lensing.

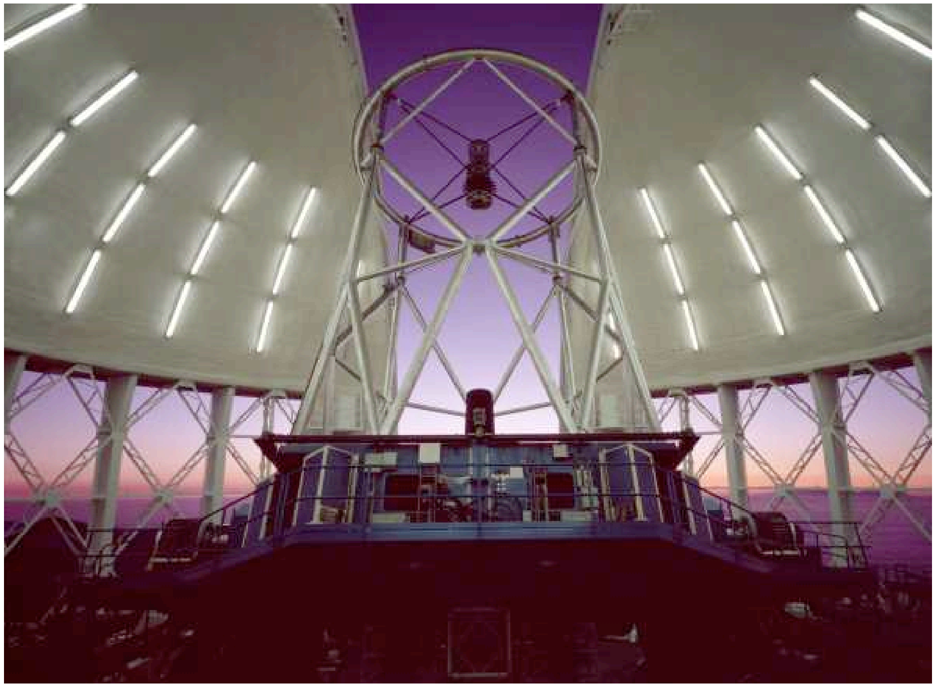


Contrast optical magnification

- This is equivalent to using a telescope with 10 times the collecting area.

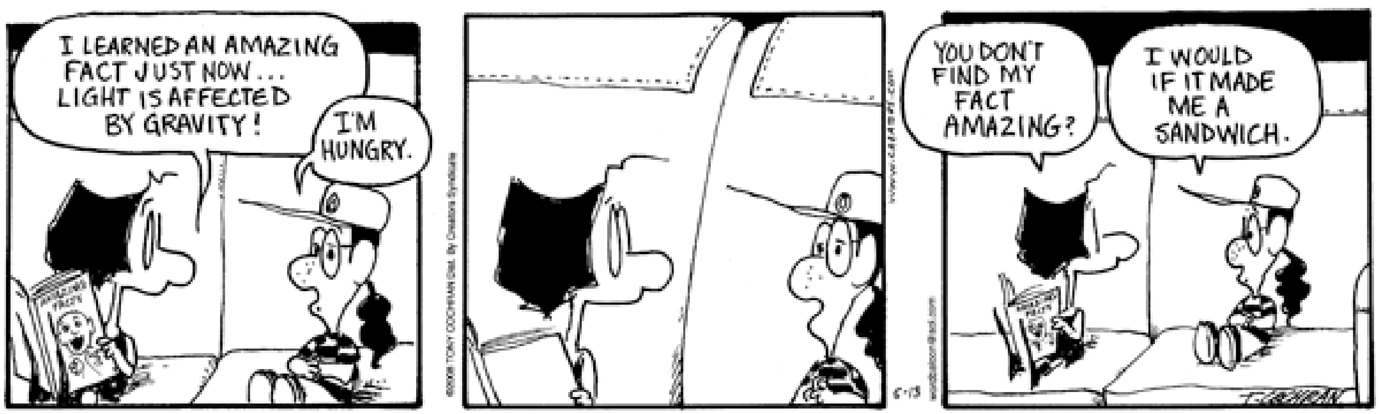


SDSS 2.5 meter telescope, Apache Point, NM



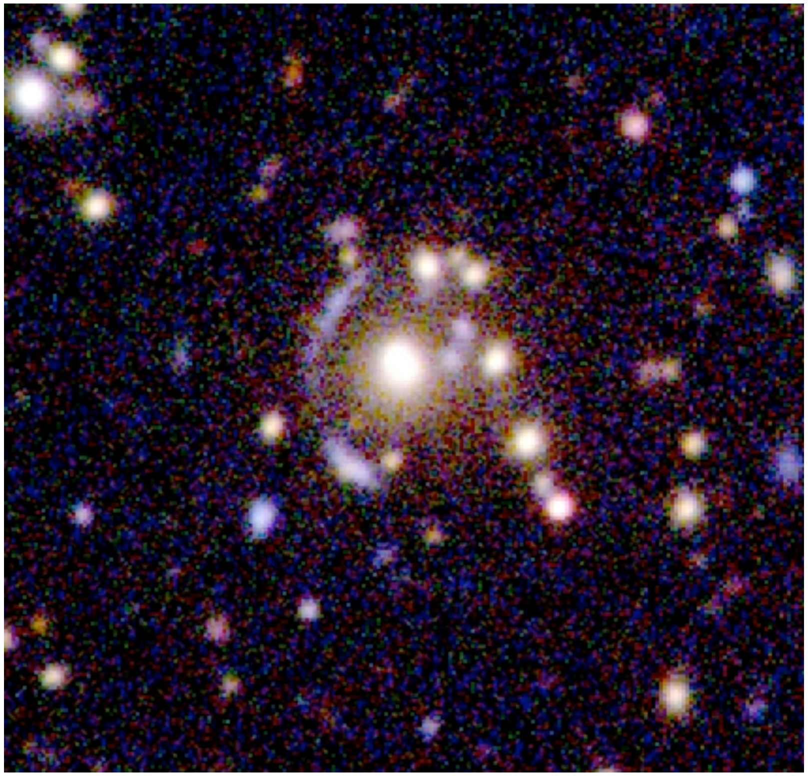
Gemini North 8 meter telescope, Mauna Kea,

What is gravitational lensing good for?



What we can learn from gravitational lensing: The lensed source galaxies

- The strongly-lensed source galaxies are useful for studies of galaxy evolution.
- The magnified galaxies are often better-resolved, permitting more-detailed study of their structure and dynamics than would be possible without lensing.

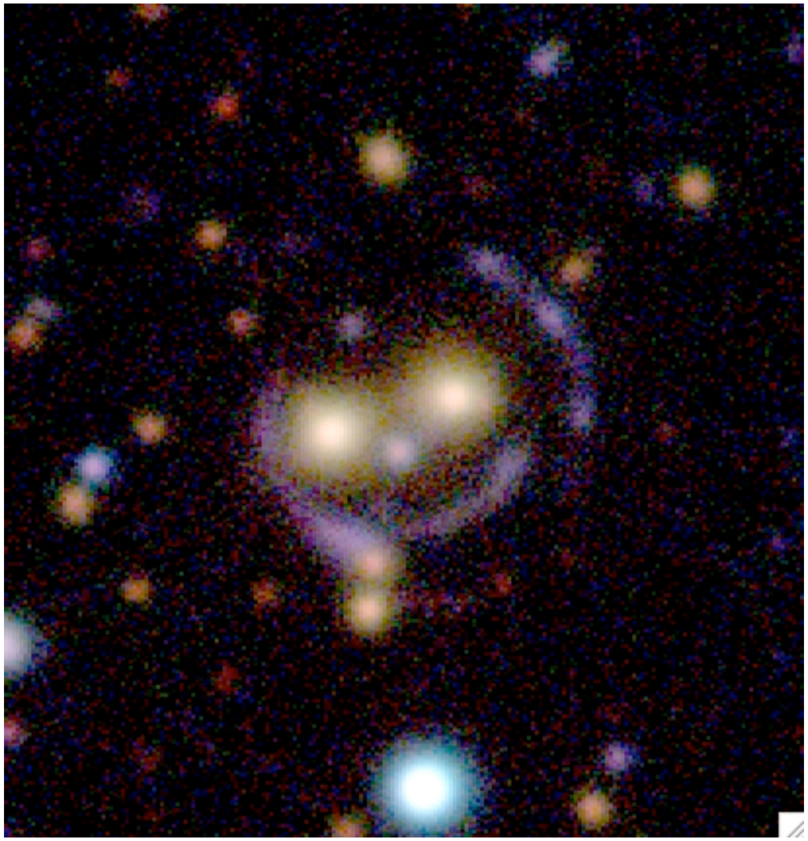


What we can learn from gravitational lensing: The lens galaxies

- On the flip side, we learned something about the artist who magnified flowers; that she wanted to make even busy New Yorkers take time to notice a flower.

- Similarly, we can infer characteristics of the lens that magnified background galaxies, such as its mass.

- Since the light paths of the lensed galaxies respond to *mass*, analysis yields the total mass of the lens, providing a probe of dark matter.

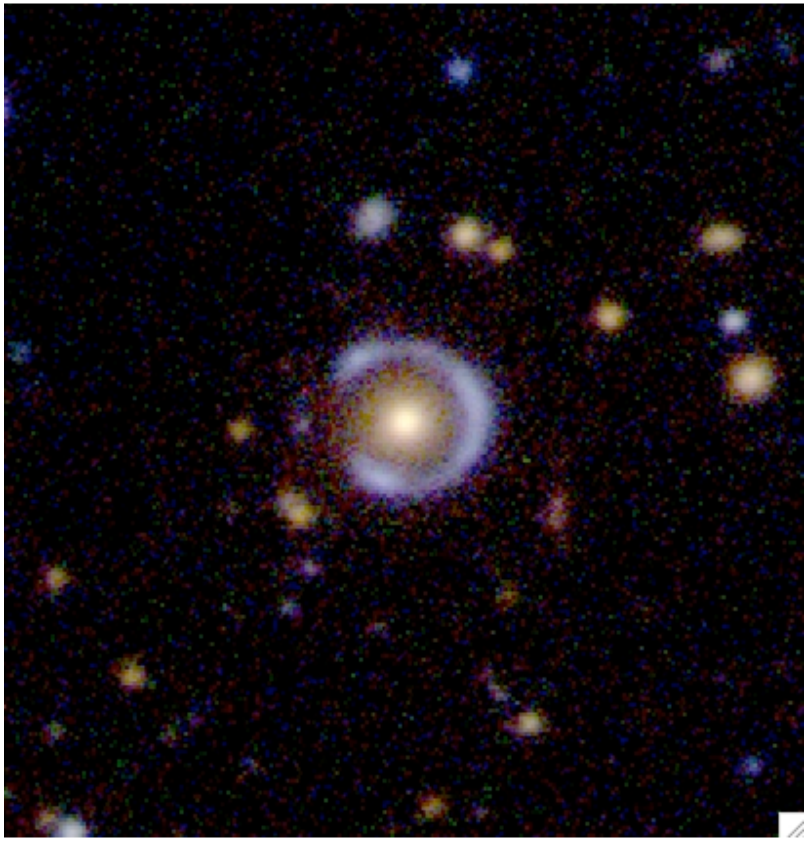


What we can learn from gravitational lensing: Cosmology

- “Cosmic shear” (basically lensing by the general distribution of matter in the universe) has been used to constrain cosmological parameters like the matter density of the universe

- Calibration of the masses of galaxy clusters via lensing is very useful for cosmology studies using clusters

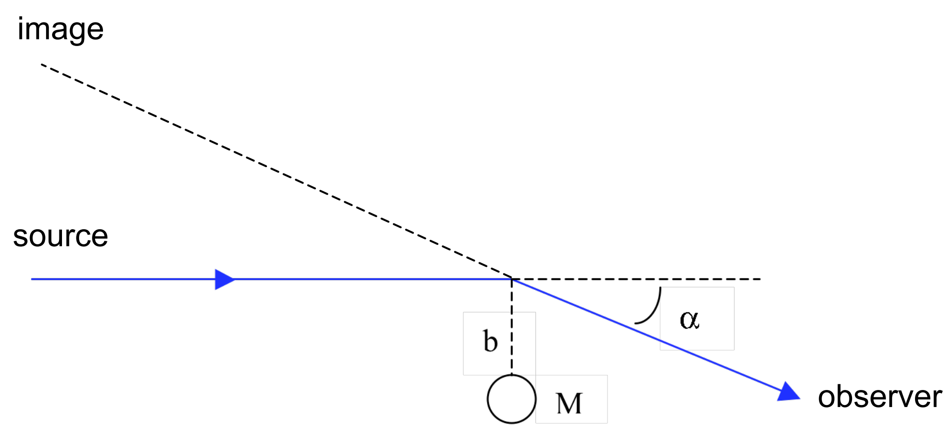
- Statistics of gravitational lensing systems have provided additional evidence for dark energy, independent of supernova data



Gravitational lensing is a direct consequence of general relativity

- A photon passing near a massive object will be deflected by an angle:

$$\alpha = \frac{4GM}{c^2 b}$$



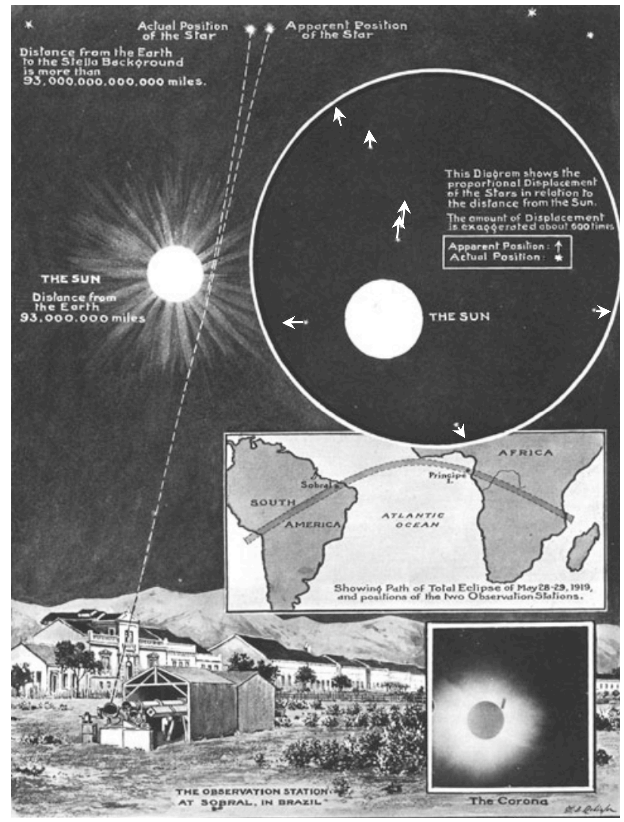
  - M is the mass
  - b is the impact parameter
  - G is Newton's gravitational constant
  - c is the speed of light

Experimental support to the theory of general relativity

- Light from a distant star that just grazes the Sun's surface will be deflected by an angle:

$$\alpha = \frac{4GM_{\odot}}{c^2 R_{\odot}}$$

  - $M_{\odot}$ is the mass of the Sun
  - $R_{\odot}$ is the radius of the Sun
  - G is Newton's gravitational constant
  - c is the speed of light



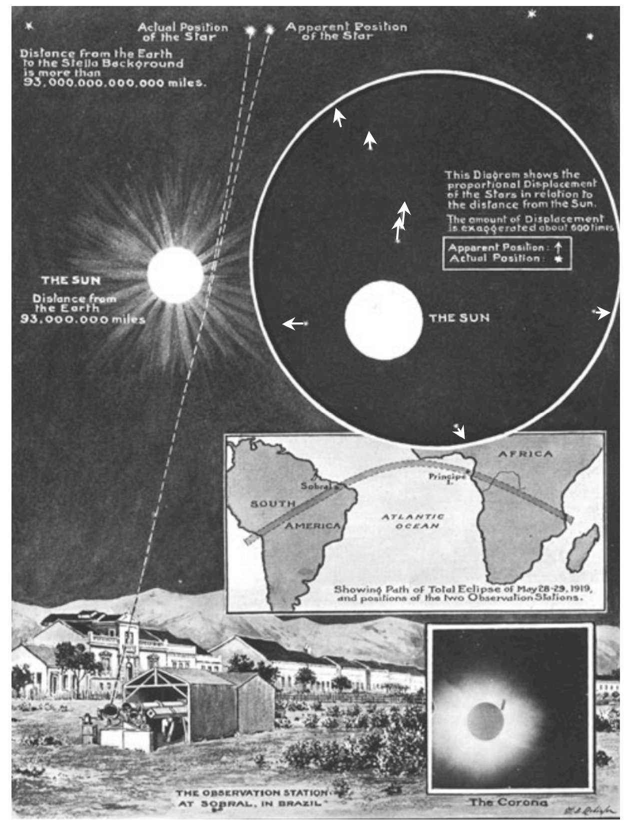
Graphical explanation of Eddington's experiment as it appeared in *Illustrated London News* of November 22, 1919. (Fernie 2005)

Experimental support to the theory of general relativity

- The stars with the smallest impact parameter were deflected the most.

$$\alpha = \frac{4GM_{\odot}}{c^2 b} \qquad \downarrow b \ \uparrow \alpha$$

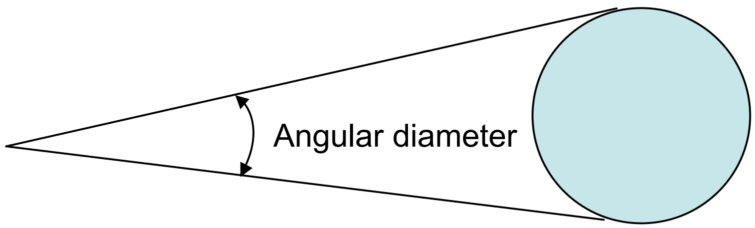
- The deflections were on the order of ~0.25 to ~1.0 arcseconds.



Graphical explanation of Eddington's experiment as it appeared in *Illustrated London News* of November 22, 1919. (Fernie 2005)

A few words about angular diameter

Object	Angular diameter
Moon	29.3’ - 34.1’ (~1800”)
Jupiter	30” - 49”
Venus	10” - 66”
Spica	0.0059”



Why we see arcs

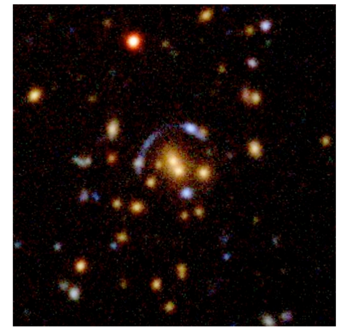
- This relation also explains why we see arcs

$$\alpha = \frac{4GM_{\odot}}{c^2 b} \qquad \downarrow b \ \uparrow \alpha$$

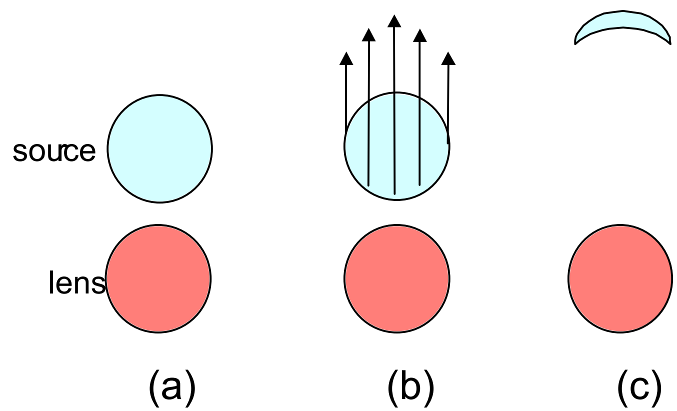
(a) The source (blue) galaxy is more distant than the lensing (red) galaxy. Light rays from the source are deflected as they pass near the lens.

(b) Rays traveling closest to the lens get deflected the most.

(c) The resulting image is an arc.



$\downarrow b \ \uparrow \alpha$



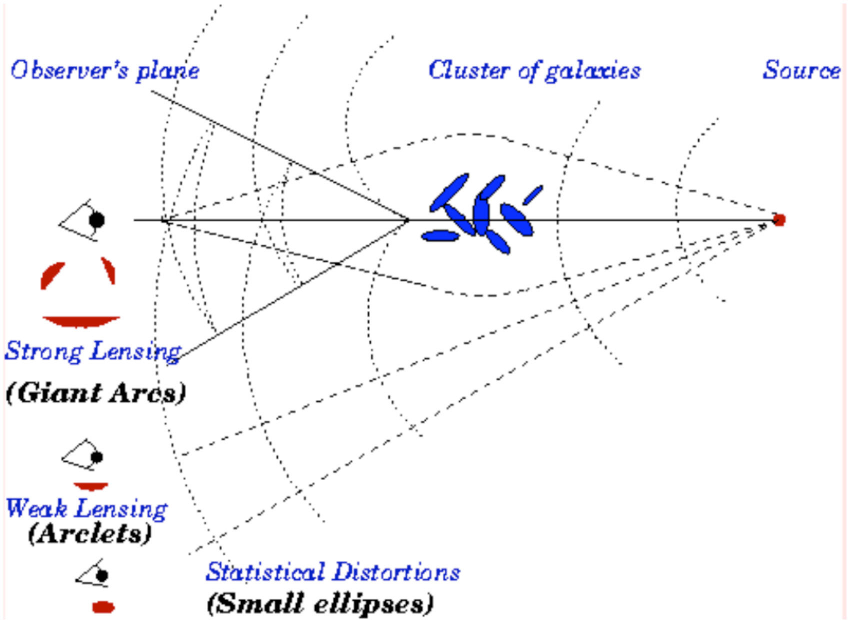
Gravitational lensing

- In this image, we see many different types of lensed images
  - Giant arcs
  - Arclets
  - Small ellipses

Abell 1689

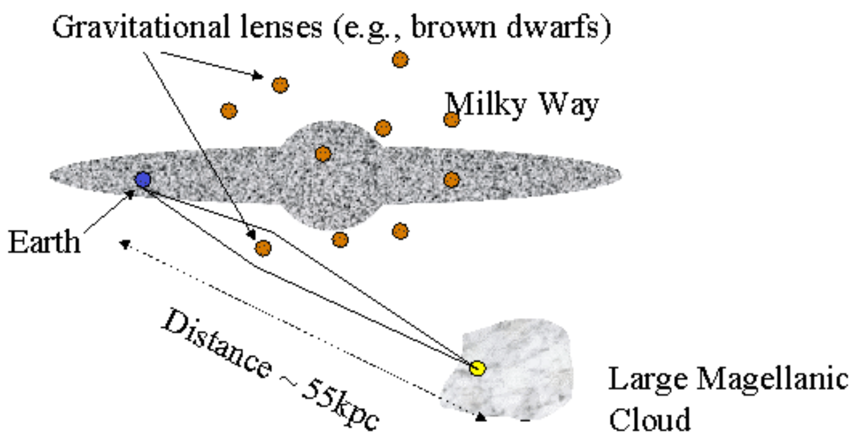
Strong lensing, weak lensing, microlensing

- The distinction between these regimes depends on the relative positions of the source, lens, and observer and the mass distribution of the lens.
- Strong lensing can produce multiple giant arcs.
- Weak lensing can lead to small distortions at the level of a few percent in the shapes of distant galaxies.



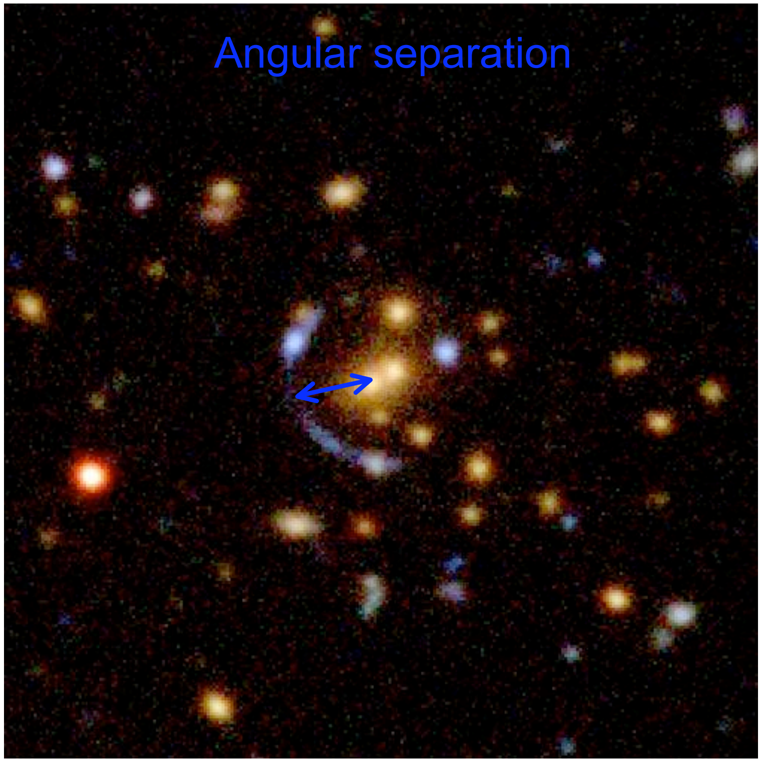
Strong lensing, weak lensing, microlensing

- Microlensing occurs when a massive foreground object, such as a brown dwarf, passes between us and background star or quasar.
- Unlike strong and weak lensing, no single observation can establish that microlensing is occurring.
- Instead, the rise and fall of the source brightness must be monitored over time using photometry.



Typical angular separation between the lens and the lensed image

Mass	Typical angular separation
$\sim 1 M_{\odot}$	~0.001 arcsecond
$\sim 10^{12} - 10^{13} M_{\odot}$	≤ 10 arcseconds
$\sim 10^{15} M_{\odot}$	10's of arcseconds



History of lensing

TIME

- 2007 More than 200 strong lensing systems known
- 2002 1000th microlensing events observed
- 1993 First microlensing event observed; QSO 2237+0305
- 1990 First application of weak lensing to study mass distribution in clusters (Tyson, et al.)
- 1979 First observation strong lensing; multiple imaging of QSO 00957+561

?

- 1937 Zwicky shows the possibility of galaxy-galaxy lensing noting it could provide information about the mass of the lensing galaxy and make possible the observation distant objects due to magnification
- 1936 Einstein published expression of magnification of images
- 1924 Chwolson predicts ring-like images of source
- 1920 Eddington notes possibility of double images

Why did it take so long to actually observe lensing when it was predicted decades before?

- The reasons for microlensing, strong lensing, and weak lensing are due to different, but slightly overlapping, developments….

Why did it take so long to observe strong lensing?

- Lensing systems are rare!
- A large search area betters one's chances of discovering new arcs.
- Huge sky surveys provide a wonderful search areas, for example:

CLASS (Cosmic Lens All-Sky Survey)
CASTLES (CfA-Arizona Space Telescope LEns Survey)
SLACS (Sloan Lens ACS Survey)
SDSS Quasar Lens Survey
S2LS (CFHT Strong Lensing Legacy Survey)
Sand et al. (2005) HST archive cluster arc search
SDSS cluster arc search Hennawi et al. (2008)
And our SDSS search, which Huan will discuss!

Why did it take so long to observe weak lensing?

- The flourishing of weak lensing in the past 10 years was mainly due to 3 developments.*
  - The potential of weak lensing was realized and theoretical methods were worked out for using weak lensing measurements in many applications.
    - This realization increased the telescope time allocated to weak lensing observations.
  - Large fields of view are required for many weak lensing applications.
    - The development of large, wide-field cameras installed at very good astronomical sites has allowed progress to be made in weak lensing.
  - Quantitative methods for the correction of observational effects, as blurring of images by the atmosphere and telescope optics, have been developed.

* *Weak Gravitational Lensing*, Schneider, P. astro-ph/0509252

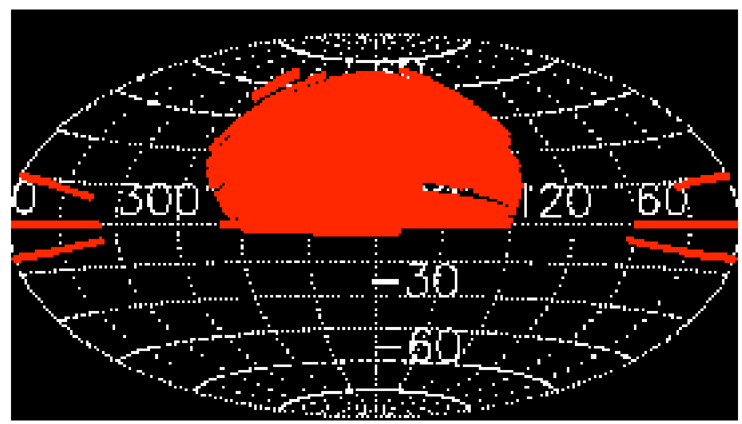
Why did it take so long to observe microlensing?

- The main reason why microlensing searches in the Local Group gained significance in recent years was the realization that, with the advent of CCDs, monitoring the light curves of several million stars in the LMC for a few years is now feasible.

The Sloan Digital Sky Survey

- The Sloan Digital Sky Survey (SDSS) provides a large area required to find strong lensing systems.
- Imaging data cover about 8000 square degrees and includes information on ~215 million objects.
- But, how can we search 215 million images?

SDSS telescope, Apache Point, NM



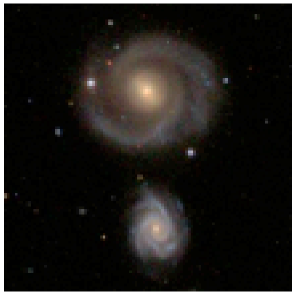
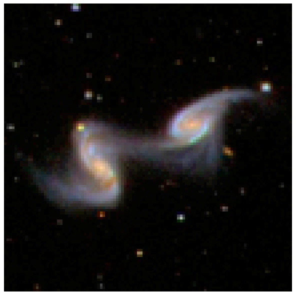
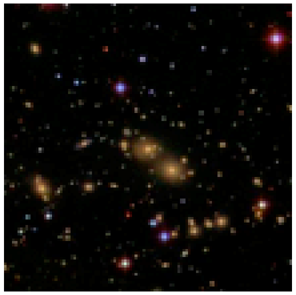
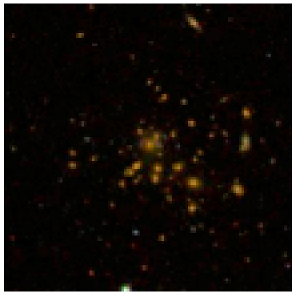
SDSS Imaging sky coverage

Sdss

Advanced Search
Preferences
Language Tools

Google Search | I'm Feeling Lucky

Advertising Programs - Business Solutions - About Google

Outline

- Introduction to gravitational lensing
- Strong lensing
- Microlensing
- Weak lensing

The Gravitational Lens Equation

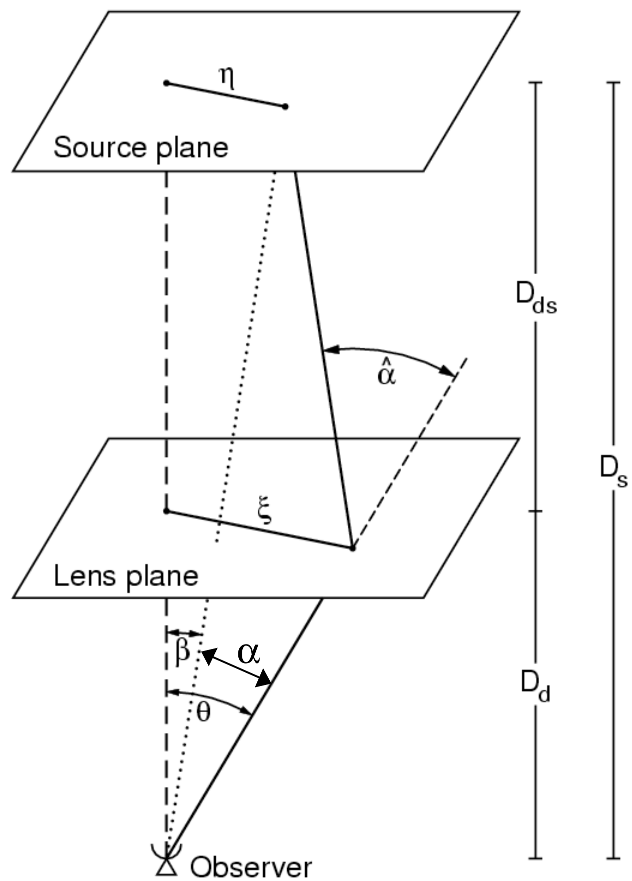
- The angular positions of the lensed images (θ) and the original unlensed source (β) are related through the ***gravitational lens equation***

$$\theta = \beta + \alpha$$

- The lens equation is derived from the geometry of the lensing configuration (see figure)

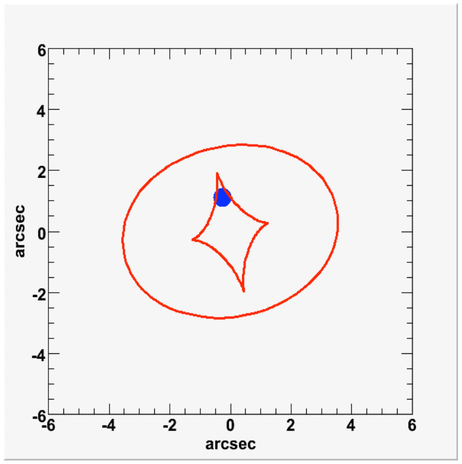
- ***Cosmology*** enters through the various distances between source, lens, and observer

- The lensing ***mass distribution*** enters through the (reduced) deflection angle α, which determines how much the light from the source is bent at different (projected) radii from the lens



Strong Lensing Nomenclature

- Strong lensing is characterized by ***multiple images*** of the same source object
- Detailed solutions of the lens equation determine the number, positions, magnifications, and distortions of the lensed images
- In general there are curves called ***caustics*** (or cuts) in the ***source plane***
  - The number of lensed images changes as the source position crosses a caustic
  - The lensed images are highly magnified and distorted when the source is located on or near a caustic
- The caustics map onto ***critical curves*** in the ***image plane***
  - Highly magnified and distorted lensed images are located near critical curves



Source plane showing source position and caustic curves

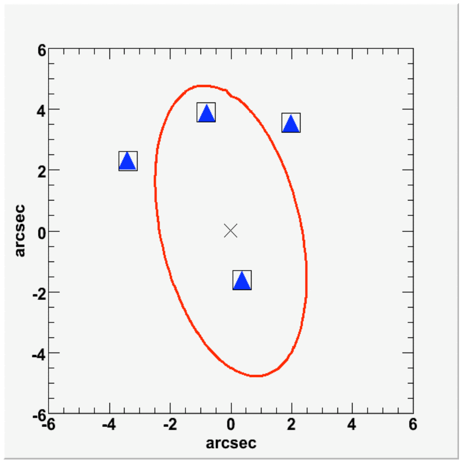
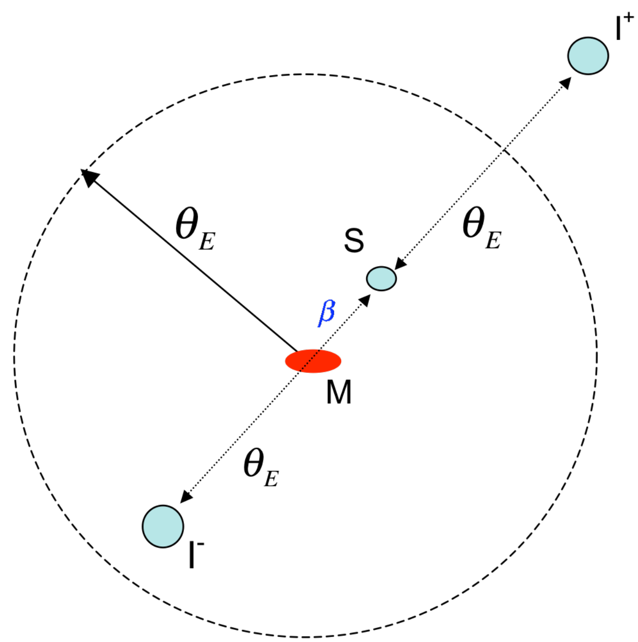


Image plane showing positions of 4 lensed images and a critical curve

Circular Lenses

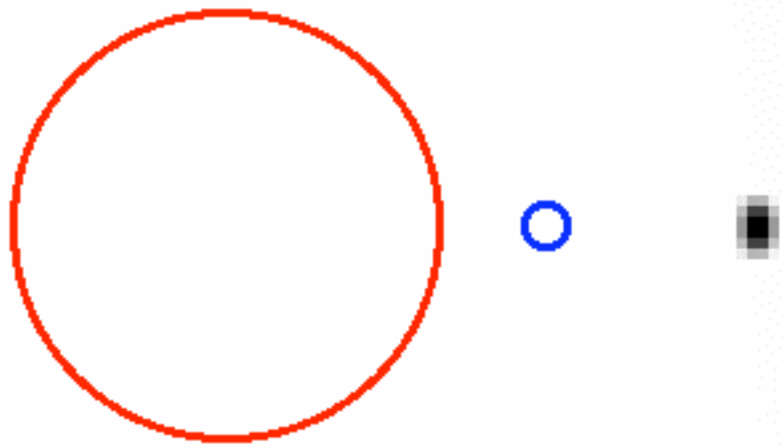
- For a lens with a circularly symmetric (projected) mass distribution, we can get the following typical image configurations
- For perfect alignment of the source and lens, we get an ***Einstein ring***
  - The size of the Einstein ring gives a measurement of the *total enclosed mass, including dark matter* as well as stars
- For misaligned source and lens, we can get two strongly lensed images (a “double”)
- See movie



Example circular lens (singular isothermal sphere)

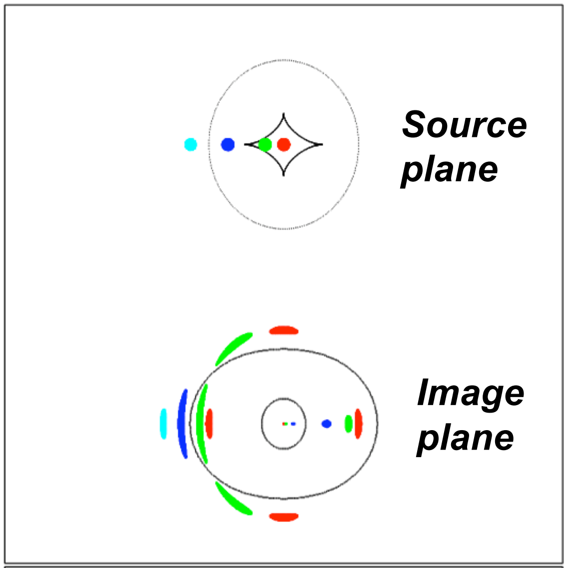
Red circle = Einstein ring centered on lens

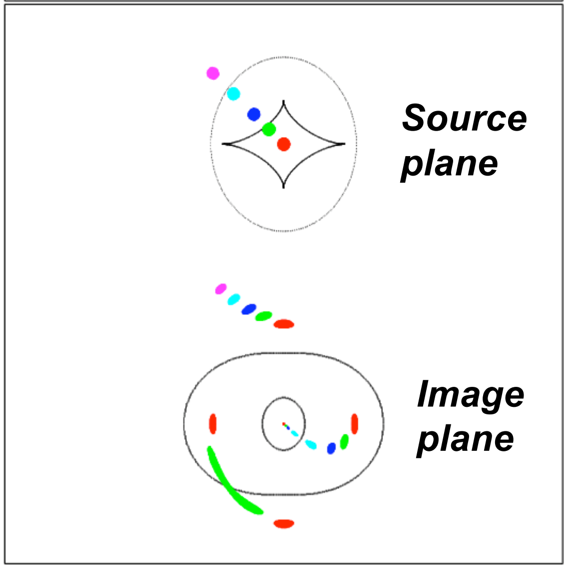
Blue circle = source position



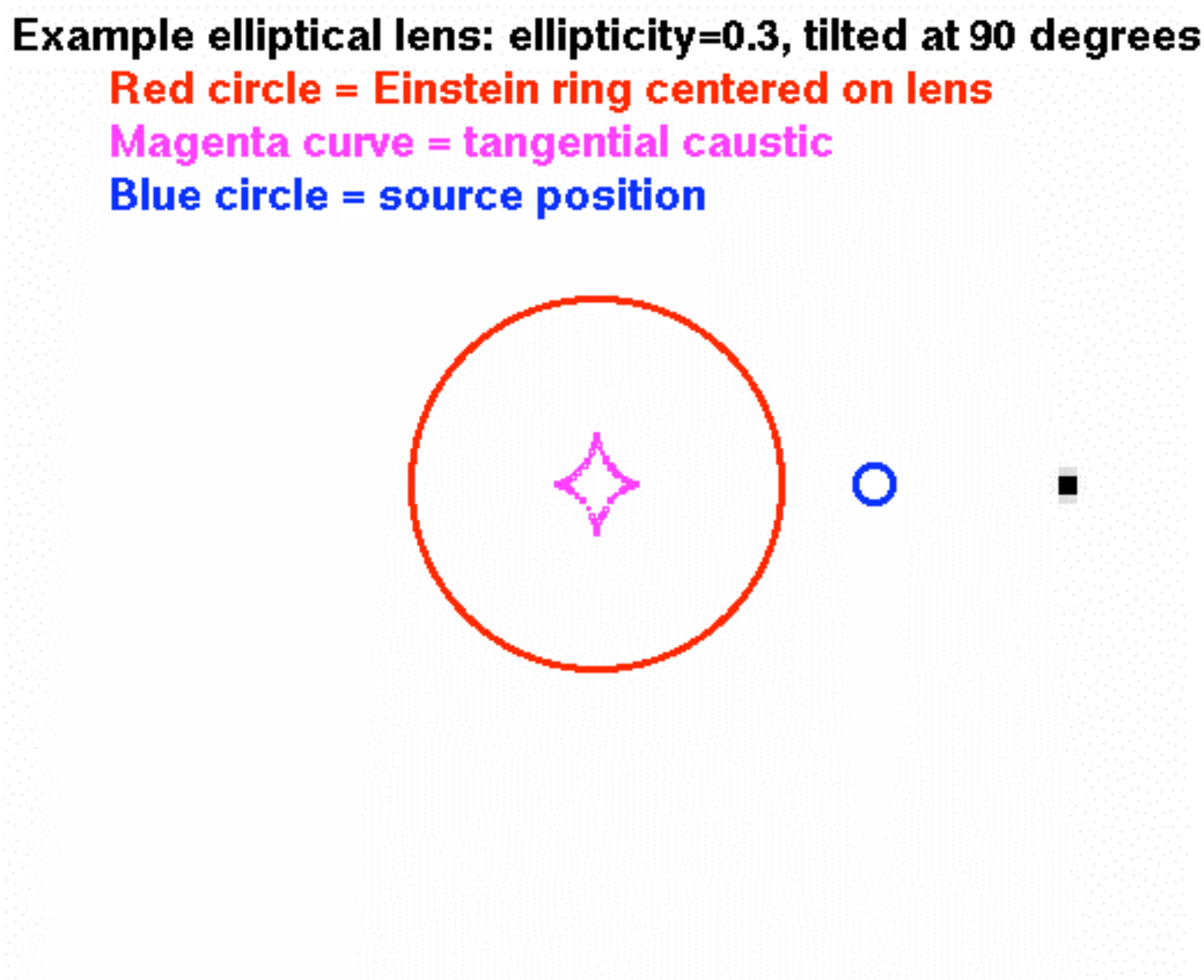
Elliptical Lenses

- The mass distribution of lenses is generally elliptical rather than perfectly circular
- For perfect alignment of the source and lens, we get 4 images in an ***Einstein cross*** configuration
- For misaligned source and lens, but source inside the inner caustic, we still get 4 images, called a ***quad***
- For a source between the inner and outer caustics, we get 2 images, called a ***double***
- See movies

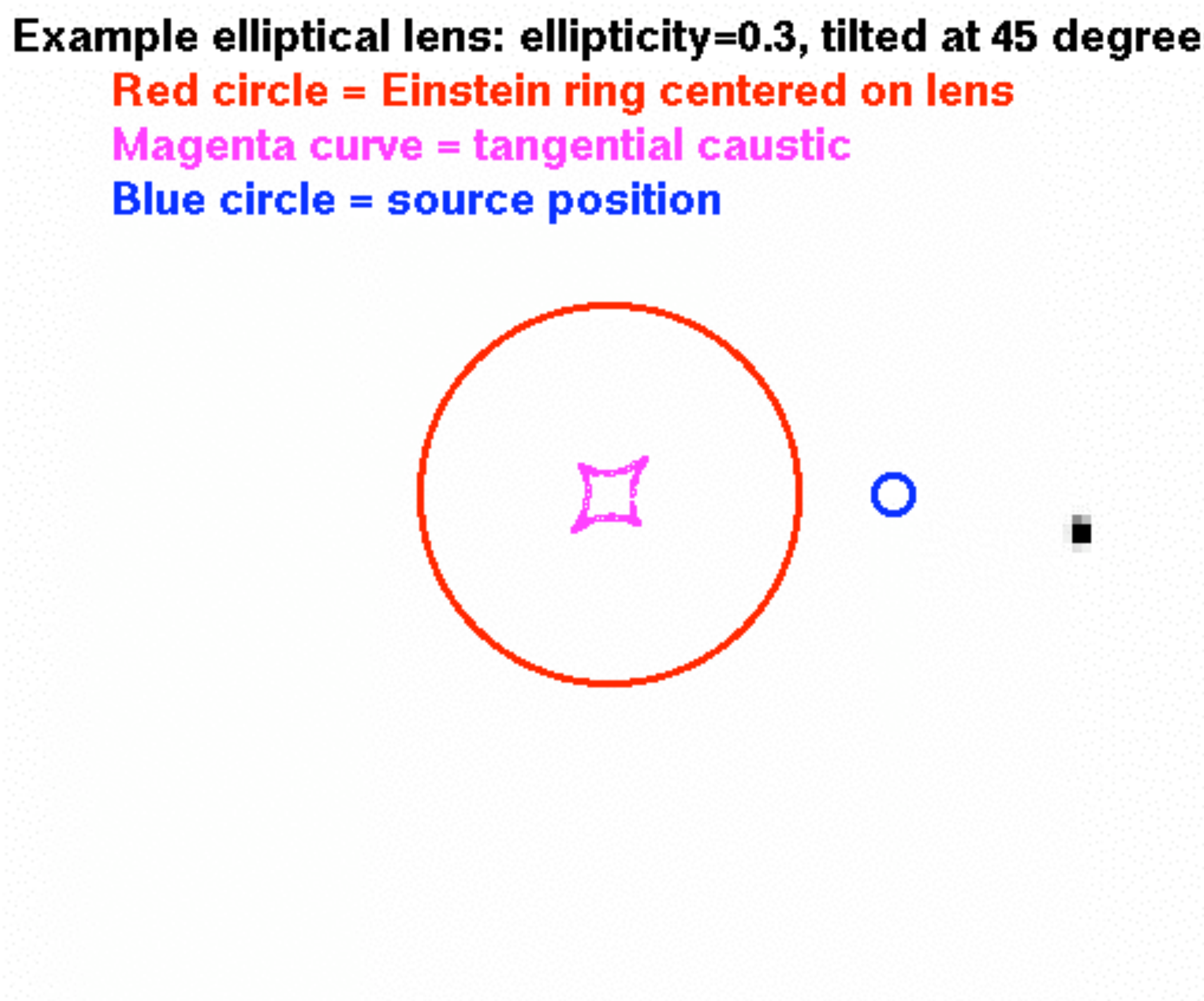




“Cusp Arc” Animation

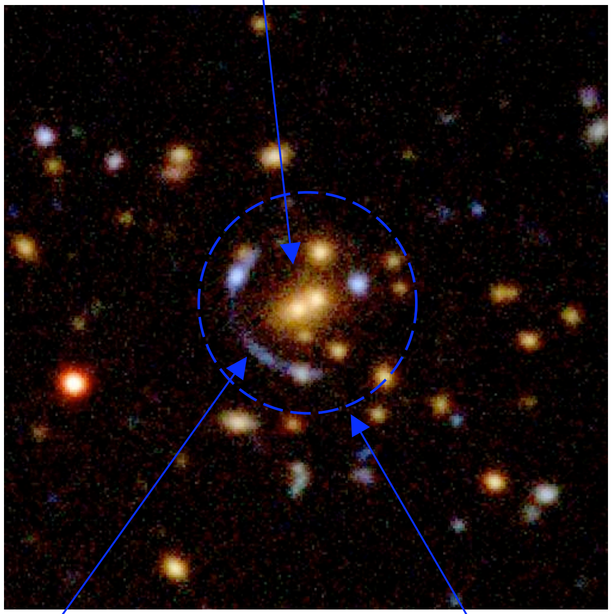


“Fold Arc” Animation

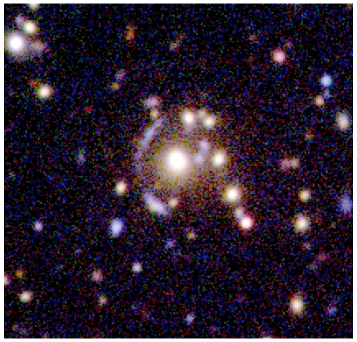


Example Lens Search: Bright Arcs in SDSS

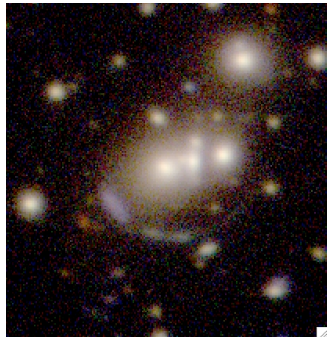
- Database query search: Look for potential blue, high-redshift galaxies lensed by red, luminous, massive galaxies in the SDSS (Donna Kubik's thesis)
- Also look for candidate lensing systems in Sahar Allam's sample of merging/interacting galaxies
- Visually inspect candidates and trim down to best candidates for follow-up (remote) observations on 3.5m telescope at Apache Point Observatory in New Mexico
- Lensing systems are confirmed by spectroscopic redshift measurements of lensed images



Lensing Examples: Bright SDSS Arcs found by Fermilab group

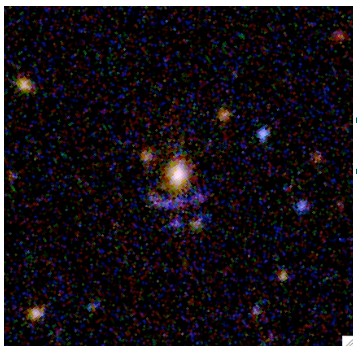


lrg-3-817
$z_l = 0.35$
$z_s = 2.26$

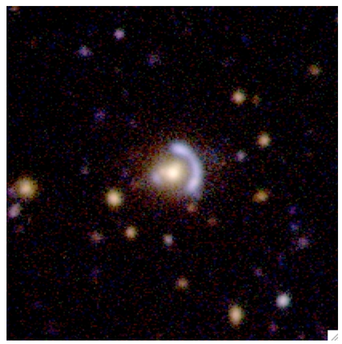


SSA_1113
$z_l = 0.35$
$z_s = 0.77$

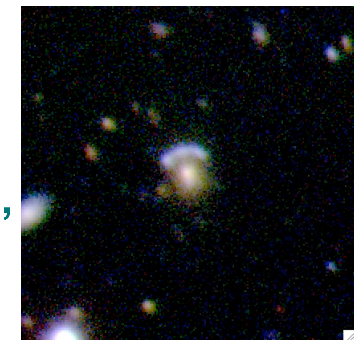
lrg-4-606
$z_l=0.49$
$z_s = 2.03$



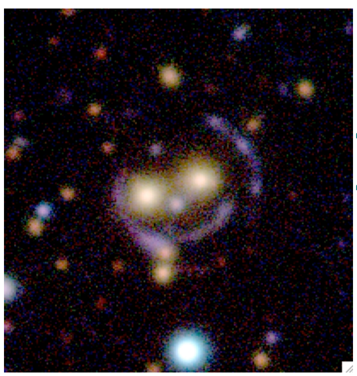
lrg-3-227
$z_l = 0.45$
$z_s = 0.98$



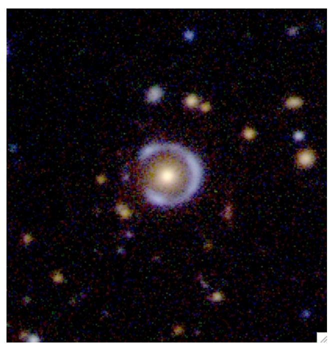
lrg-2-2811
$z_l = 0.42$
$z_s = 2.0$
"The Clone"



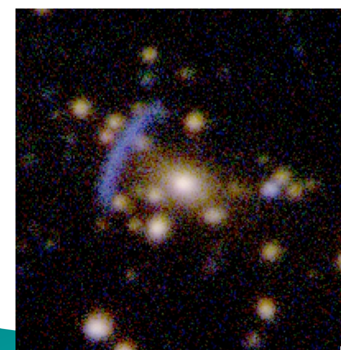
8 o'clock arc
$z_l = 0.38$
$z_s = 2.73$



lrg-4-581
$z_l = 0.43$
$z_s = 0.97$
"Cosmic Snowman"



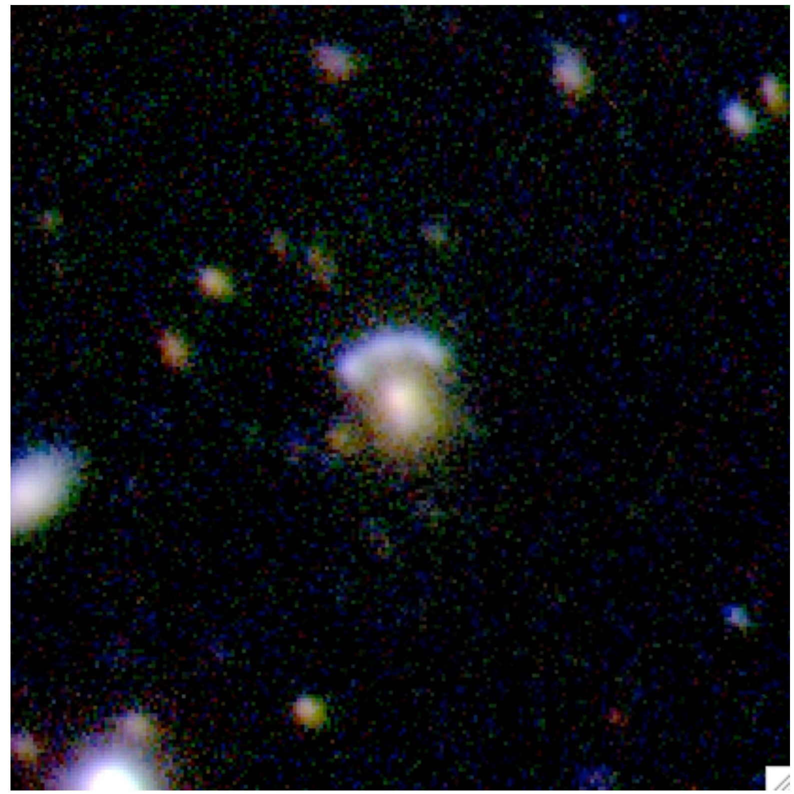
lrg-3-757
$z_l = 0.44$
$z_s = 2.38$
"Cosmic Horseshoe"



SSA_1343
$z_l = 0.42$
$z_s = 2.1$

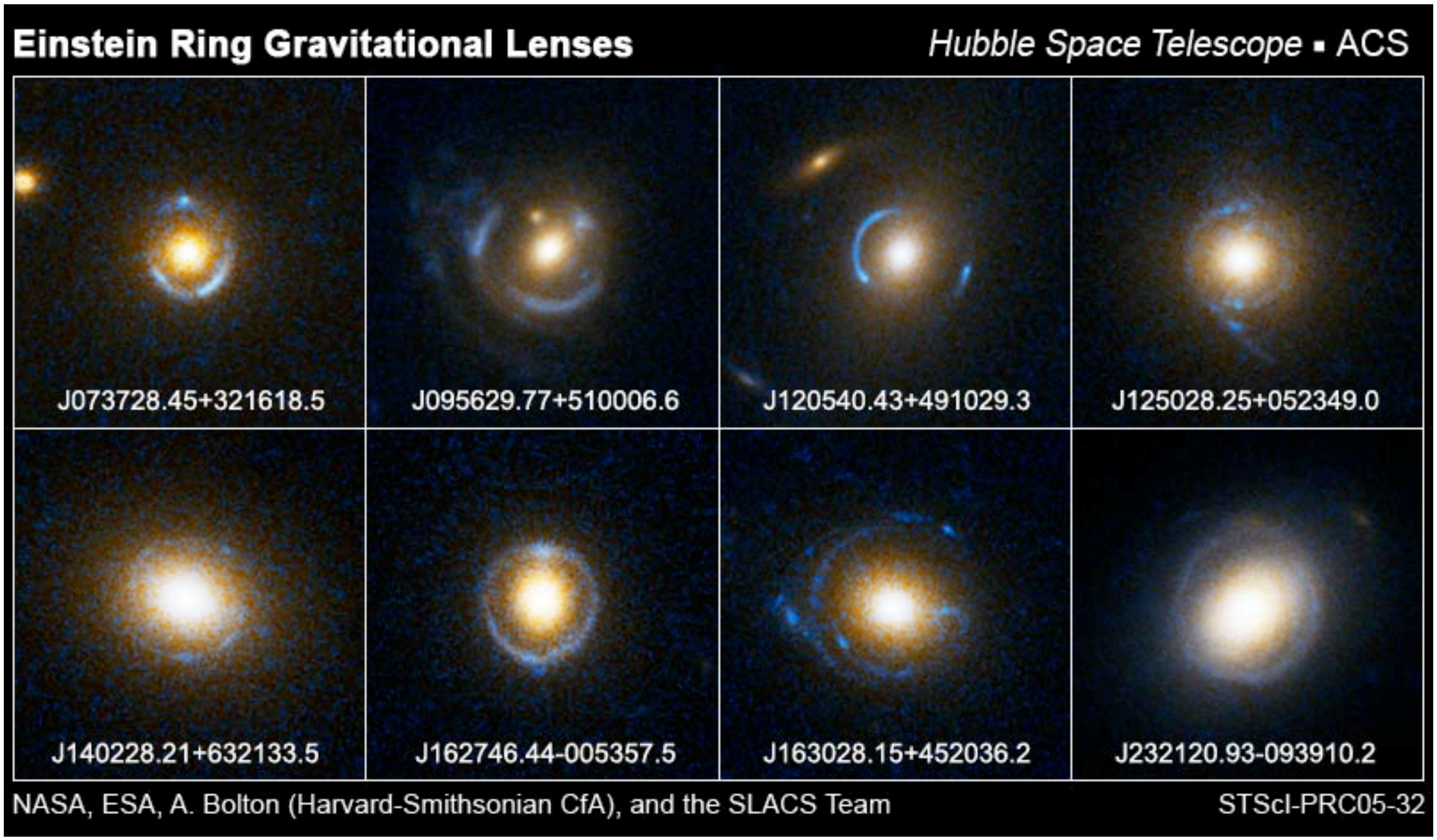
Lensing Example: The "8 O'Clock Arc": The brightest known lensed high-redshift galaxy

- Discovered serendipitously in the SDSS (Allam et al. 2007)
- High-redshift z = 2.73 blue star-forming galaxy lensed by a luminous red elliptical galaxy at z = 0.38
- Brightest known high-redshift lensed galaxy: total magnitude r ~ 19, with each of the 3 lensed knots at r ~ 20.5
- Arc is about 3.5" from the lens galaxy
- Within reach of a large amateur telescope with a CCD?

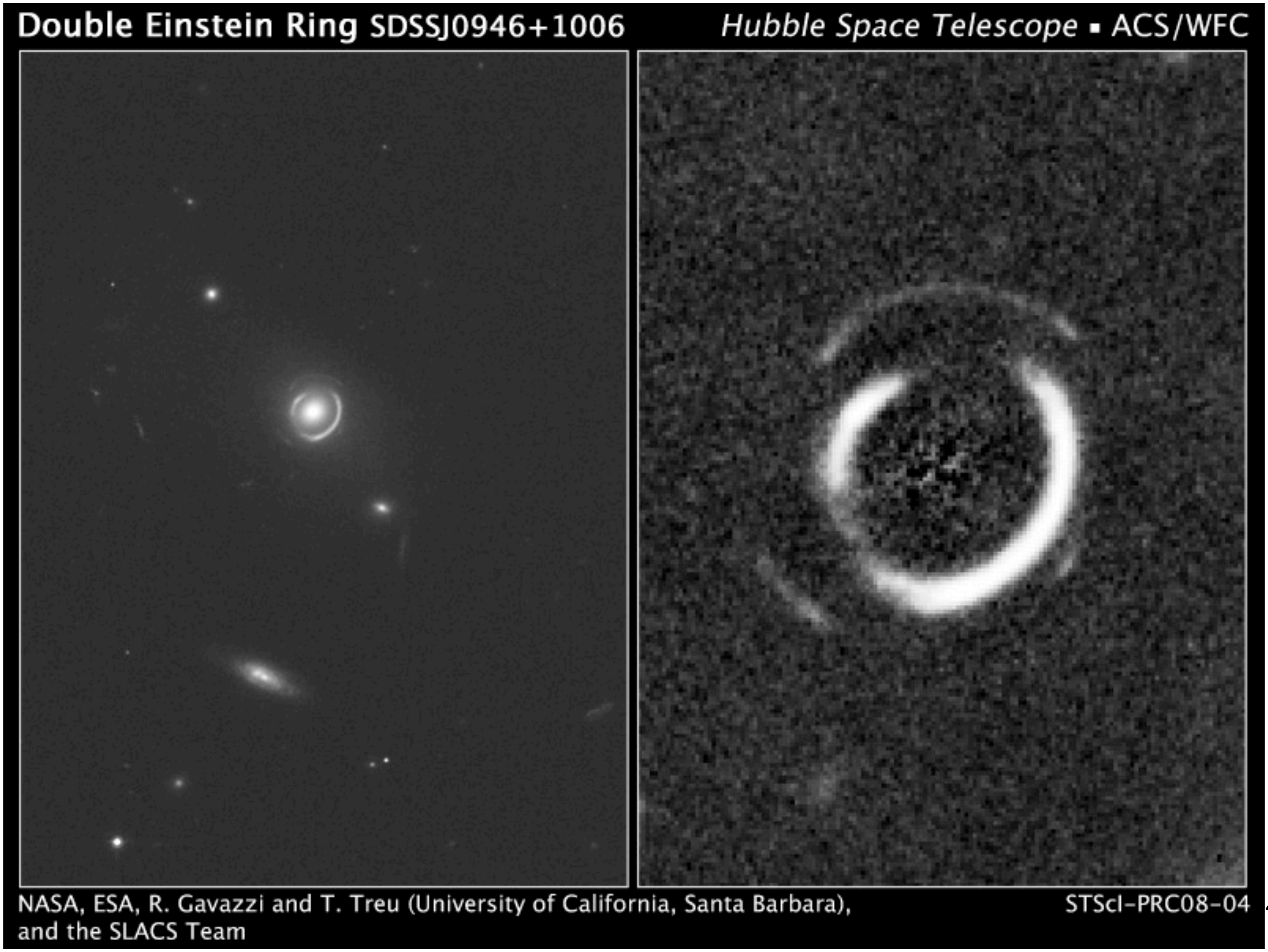


Color composite image made from g, r, i images, each a 15-minute exposure taken with the SPIcam CCD camera on the APO 3.5m telescope

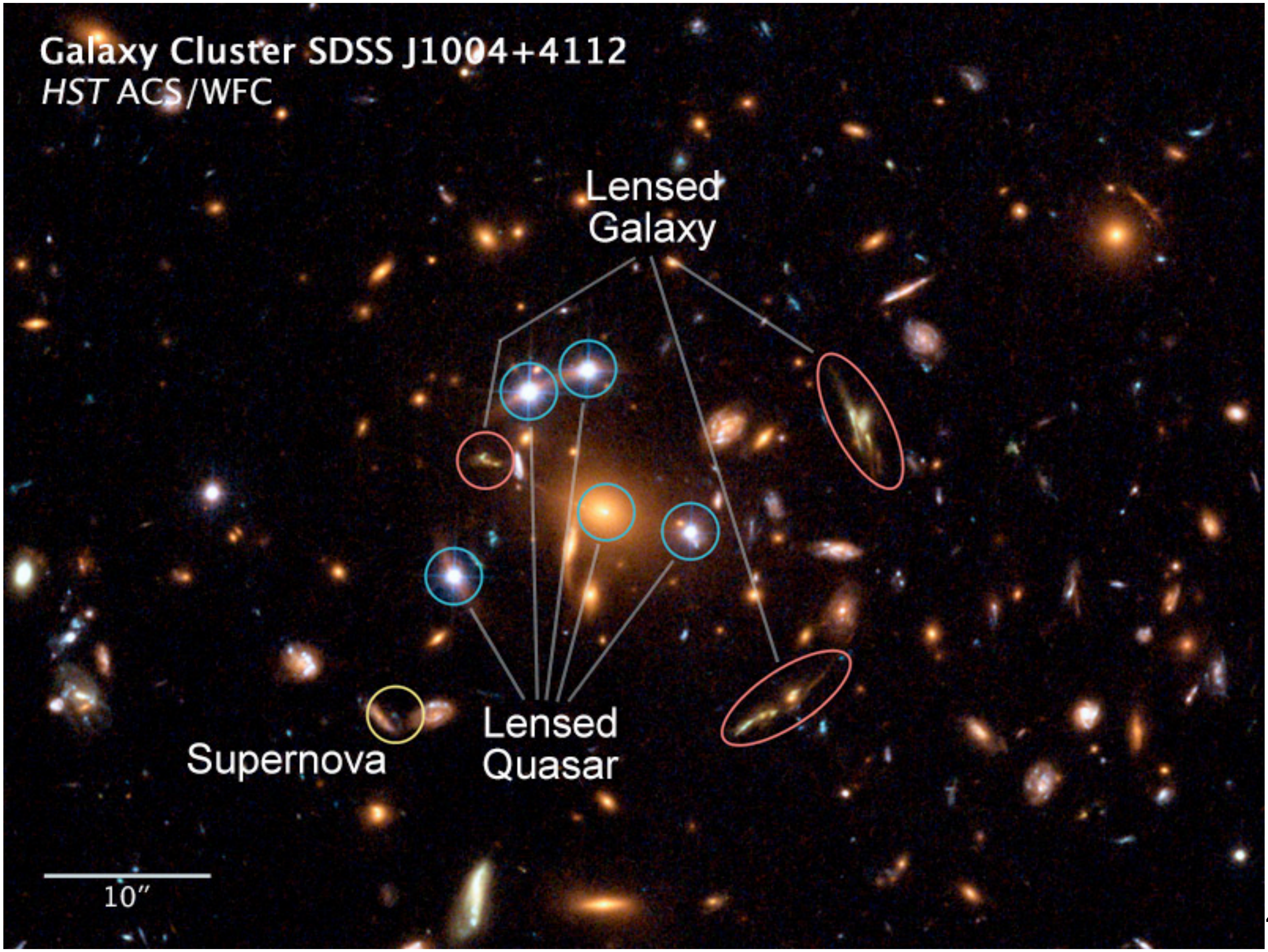
Lensing Examples: (Nearly) Einstein Rings



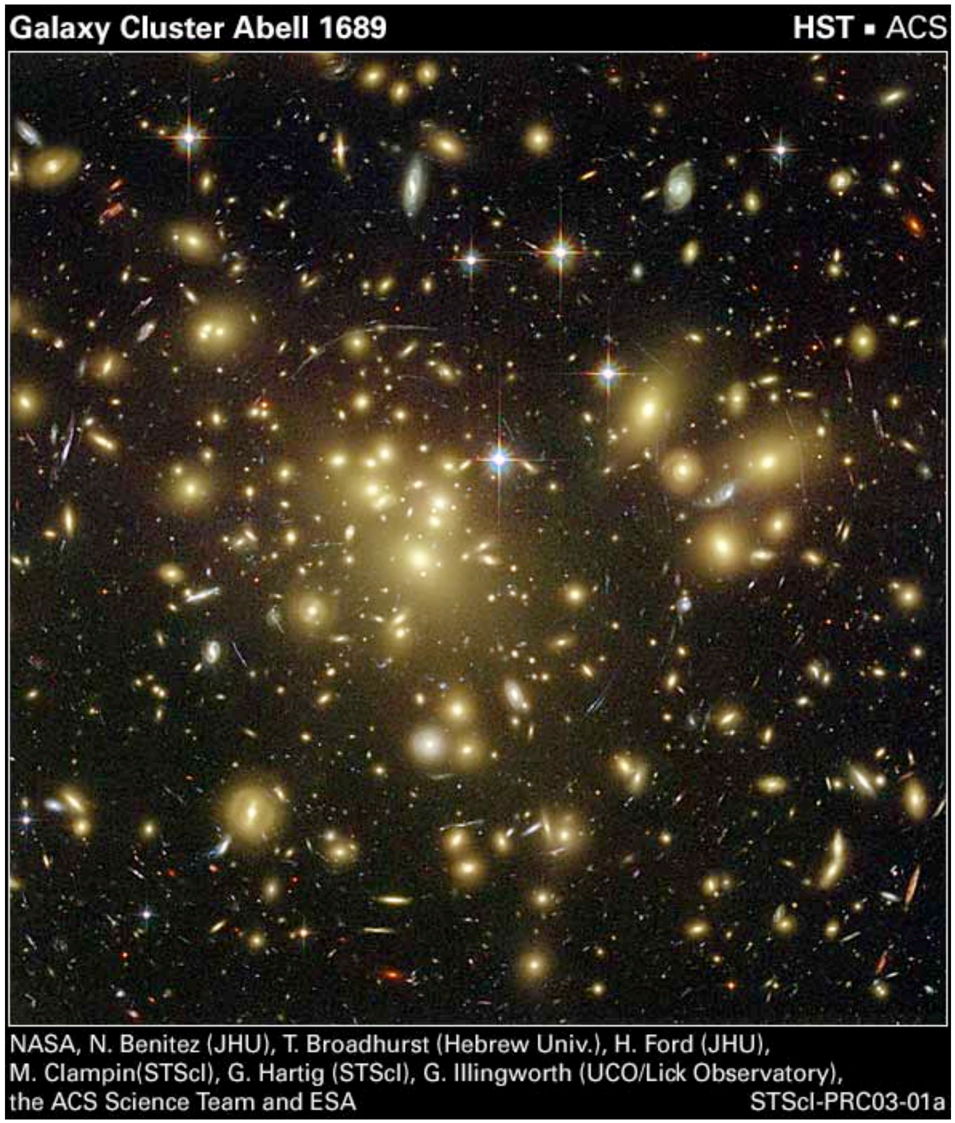
Lensing Example: Rare Double Einstein Ring



Lensing Example: Quintuple Lensed Quasar



Lensing Example: Giant Arcs in Rich Galaxy Cluster Abell 1689



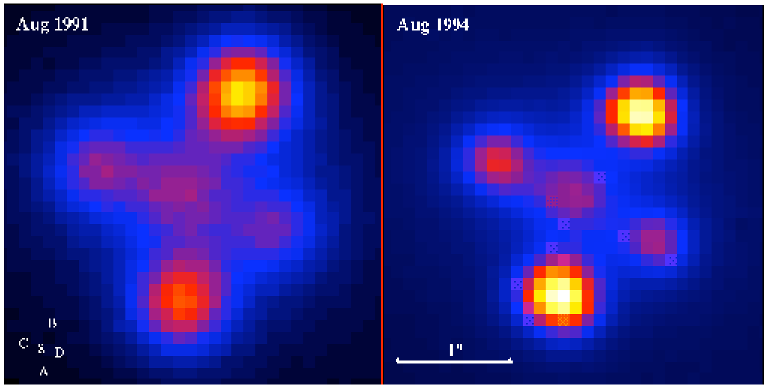
Outline

- Introduction to gravitational lensing
- Strong lensing
- Microlensing
- Weak lensing

QSO 2237+0305
Einstein Cross

- In the formation of the Einstein Cross, the gravitational field of the visible foreground galaxy breaks light from a distant quasar into four distinct images.
- The effect is strong lensing and this specific case is known as the Einstein Cross.
- Additionally, the images of the Einstein Cross vary in relative brightness, due to the additional microlensing effect of stars in the foreground galaxy.

QSO 2237+0305 Einstein Cross



Microlensing of QSO 2237+0305
Einstein Cross

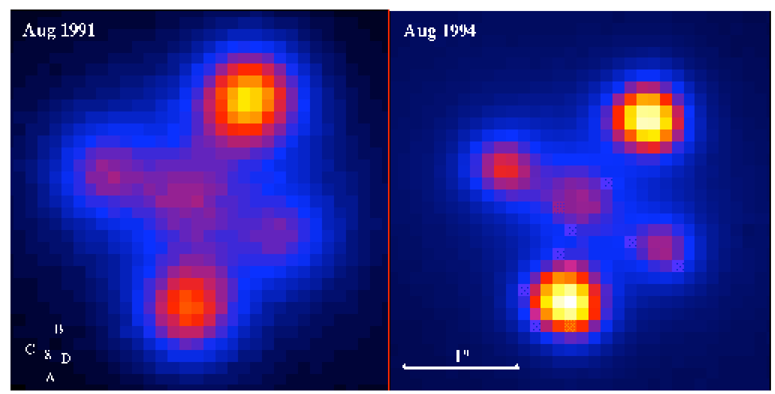
Microlensing

- Microlensing produces separations too small to resolve.

- The origin of the name arose because the first observational search for this effect was in the context of the lensing of one of the images of QSO 2237+0305 by the individual stars in the lensing galaxy.

- The typical separation between the two images produced turns out to be of order microarcseconds, too small to resolve with present day telescopes.

QSO 2237+0305 Einstein Cross

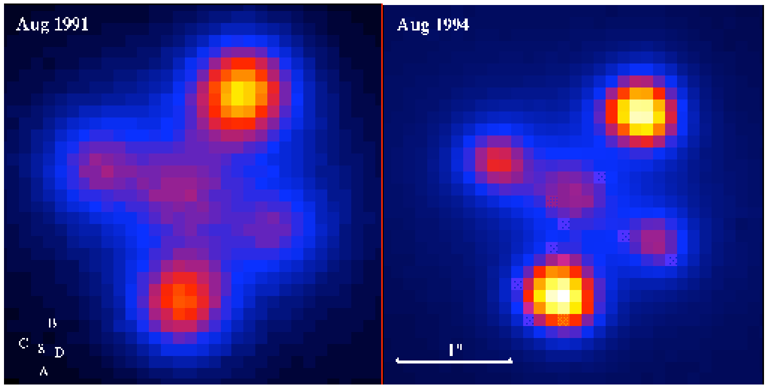


Microlensing of QSO 2237+0305
Einstein Cross

Microlensing

- But gravitational lenses don't just magnify the size, they also magnify the brightness.
- Even if the morphological change is too small to discern, we may see an increase in an object's brightness as it is lensed.

QSO 2237+0305 Einstein Cross

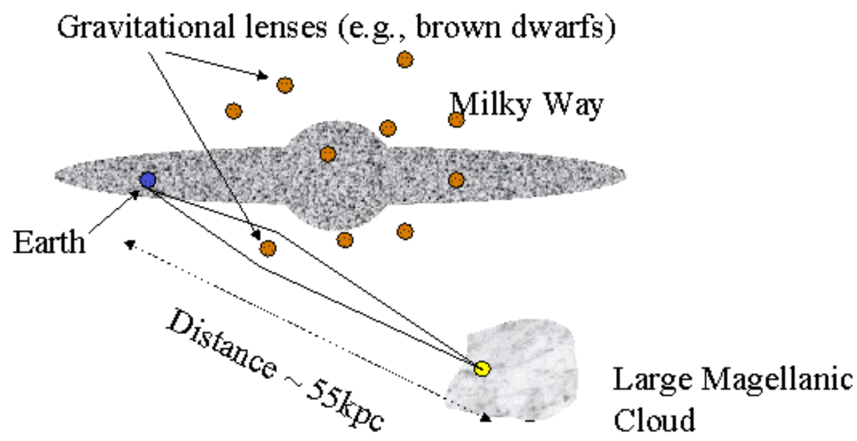


Microlensing of QSO 2237+0305 Einstein Cross

Microlensing

- The most active microlensing searches today are those involving stars from our galaxy or from galaxies in the Local Group (in particular the Magellanic Clouds and the Andromeda galaxy) which are lensed by intervening stellar-size dark objects.

- The images are unresolvable with most present day telescopes, although the typical angular separation is a bit larger, on the order milliarcseconds, not microarcseconds as was the case for quasar microlensing.



Angular resolution of present day optical/IR interferometers

- However, optical interferometry can provide milliarsecond resolution.
- The Very Large Telescope Interferometer (VLTI) consists of the four VLT Unit Telescopes and of four moveable 1.8m Auxiliary Telescopes.
- The VLTI provides both a high sensitivity as well as milliarcsecond angular resolution provided by baselines of up to 200m length.

VLTI

Cerro Paranal, Chile

Angular resolution of present day optical/IR interferometers

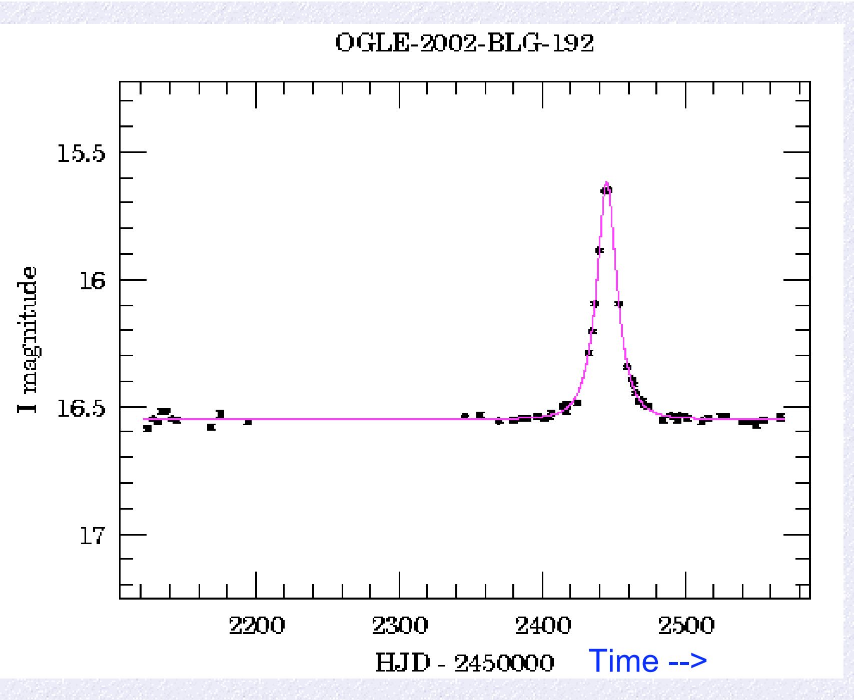
- Center for High Angular Resolution Astronomy (CHARA) is an optical/IR interferometer comprised of six telescopes located on Mount Wilson, California.
- CHARA's longest baseline is 330 meters, providing an angular resolution of 0.38 milliarcseconds at IR wavelengths.
- This will improve by a factor of 3 when they begin observations at optical wavelengths later this year.

$$\theta_{resolution} = \frac{\lambda_{wavelength}}{D_{baseline}} \quad \downarrow \lambda \ \uparrow \theta$$

CHARA, Mount Wilson

Microlensing light curves

- The crucial fact which allows microlensing phenomena to be observed is that, due to the relative motion of the lens and the source, the amplification of the unresolved images is time dependent.



Typical microlensing light curve

Microlensing light curves

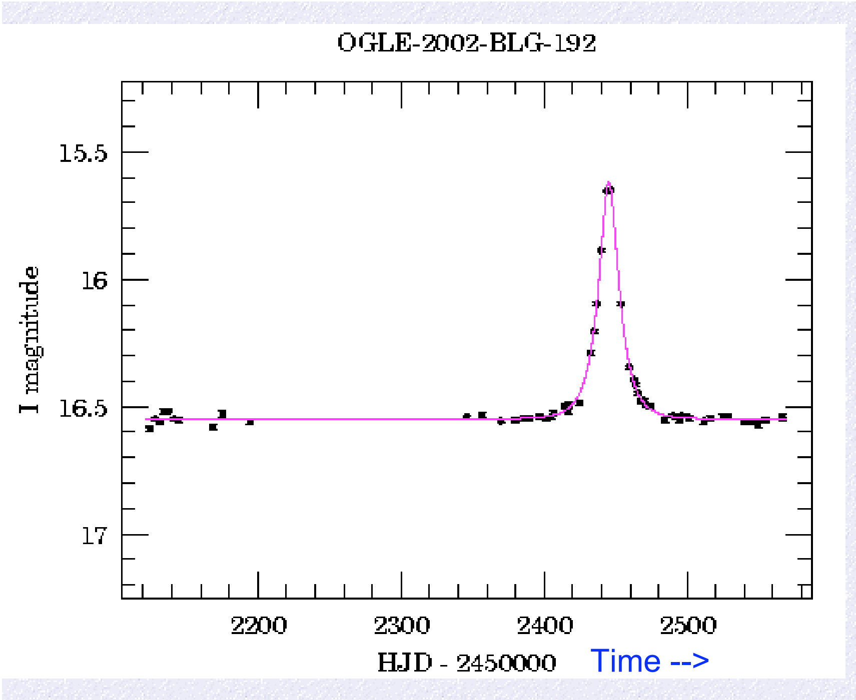
- In order to distinguish a microlensing event from other variations in stellar brightness, astronomers rely on several criteria:

  1. The shape of the light curve should be symmetrical.

  2. The light curve should not repeat.

  3. The light curve should be achromatic.

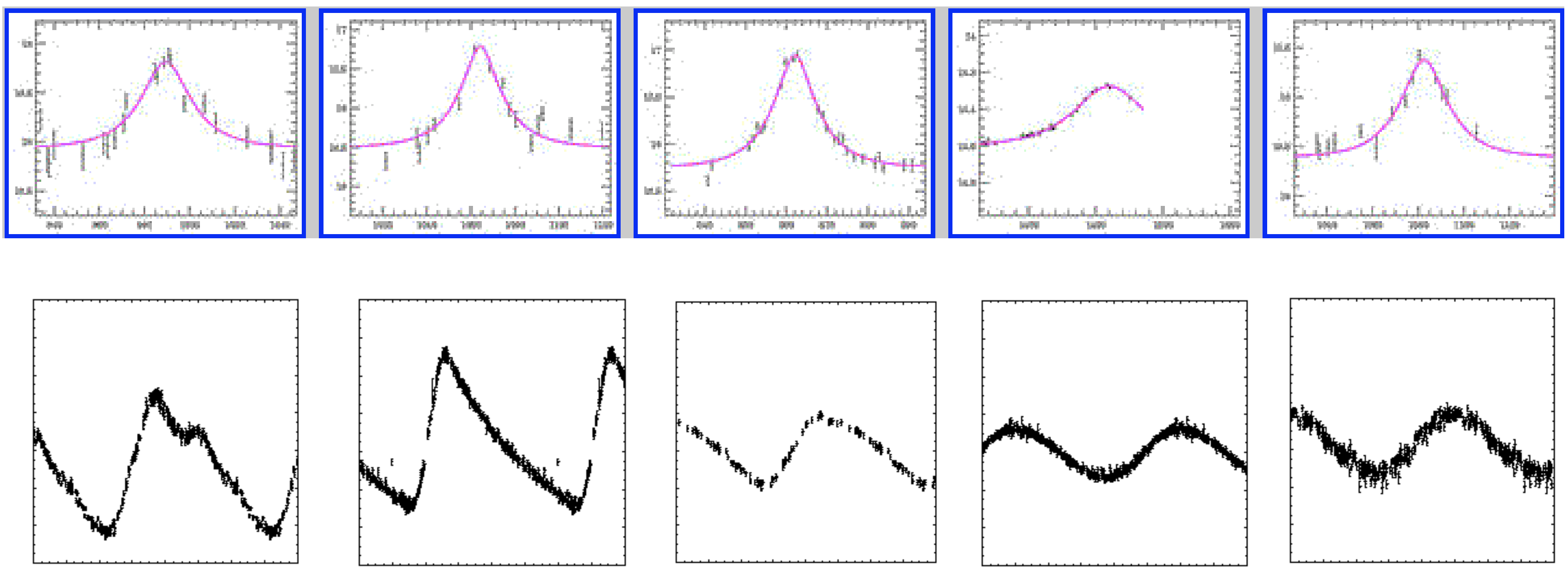
- Examples of each are shown on the following 3 slides



Typical microlensing light curve

Microlensing light curves

1. The shape of the light curve must be symmetrical, and the curve must follow the theoretical shape closely.

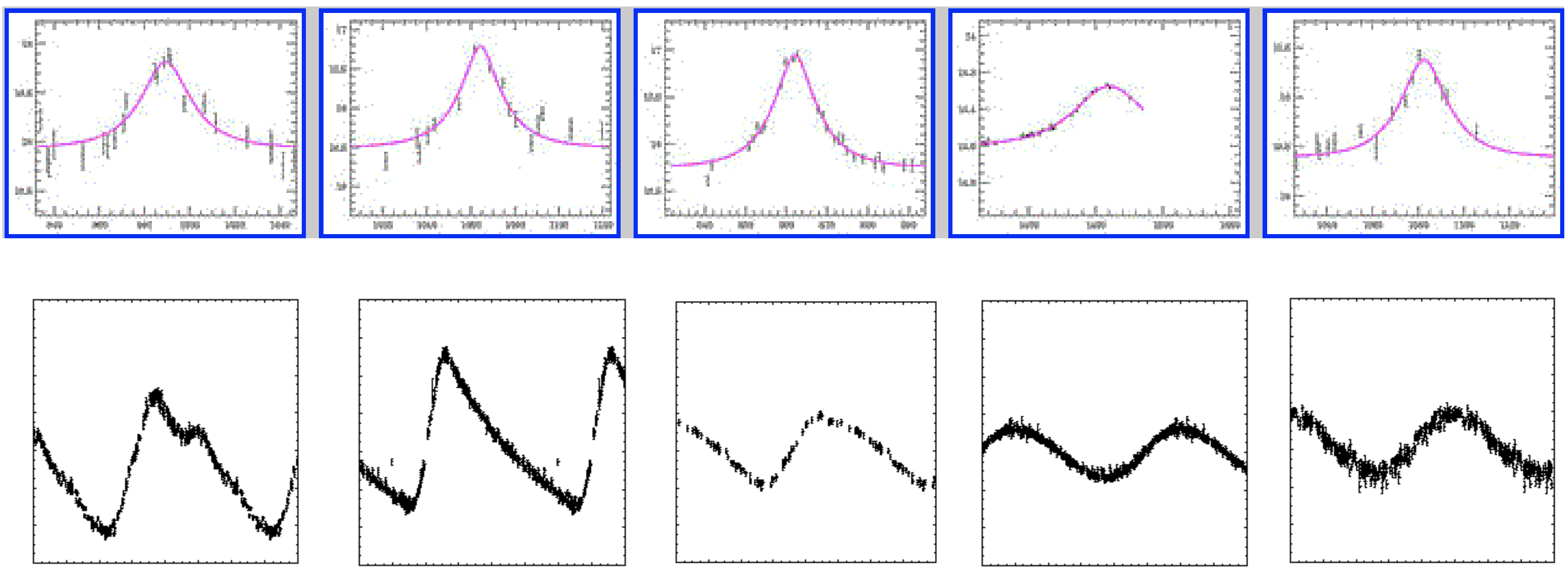


Microlensed light curves (top) vs. variable star light curve (bottom)

Microlensing light curves

2. Due to the small probability of microlensing, the pattern should never repeat for the same star.

   - This criterion rejects almost all other variable stars, because they usually repeat changes in brightness periodically.

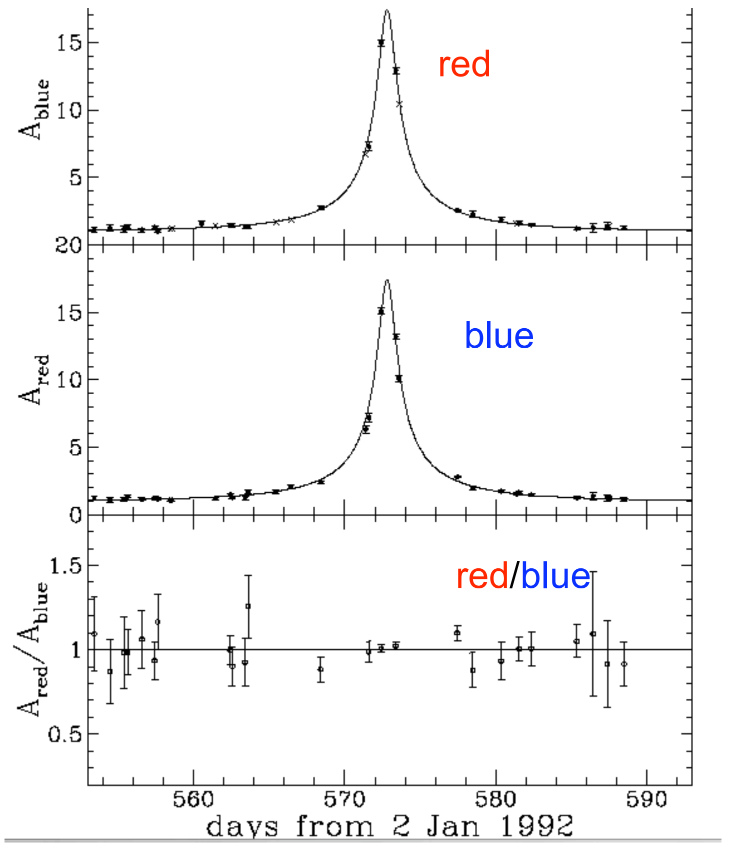


Microlensed light curves (top) vs. variable star light curve (bottom)

Microlensing light curves

3. Due to its gravitational origin, the effect should be achromatic: it should look the same at different wavelengths.

   We know of no stellar phenomenon other than microlensing, which would produce such behavior.

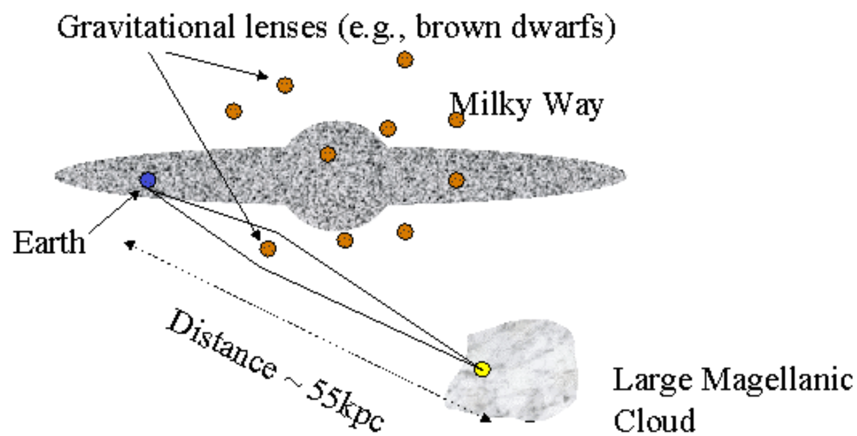


Microlensing light curve from MACHO team

Microlensing searches

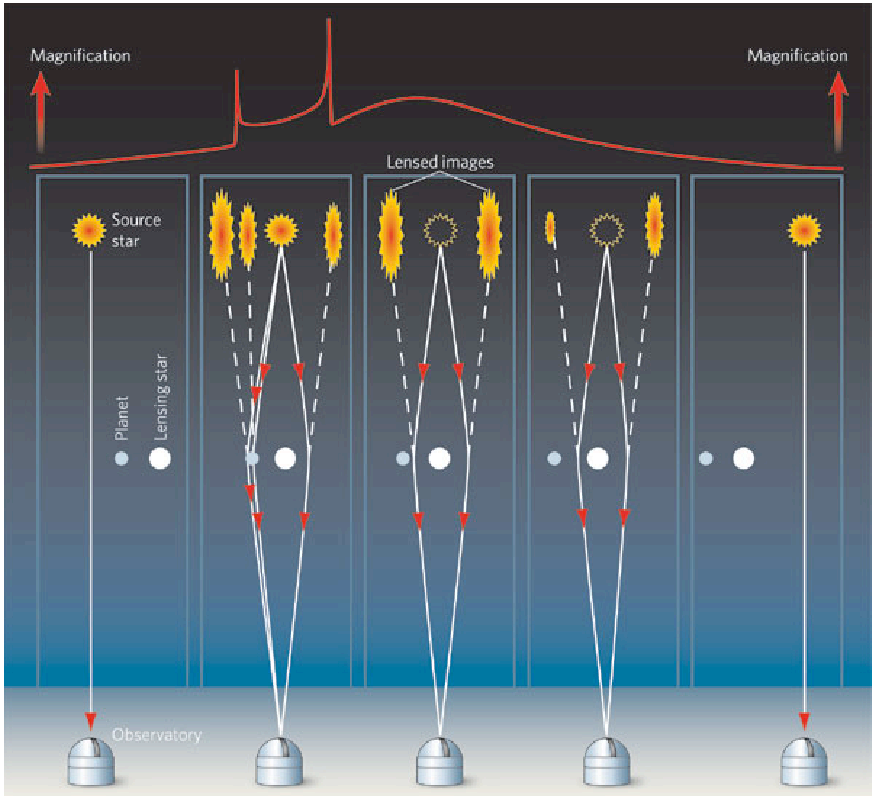
- The main reason why microlensing searches in the Local Group gained significance in recent years was the realization that, with the advent of CCDs, monitoring the light curves of several million stars in the LMC for a few years is now feasible.

- It would be possible to establish whether the dark halo of our Galaxy consists of compact dark objects such as dead stars, black holes, brown dwarfs, or planets called MACHOs (MAssive Compact Halo Objects).

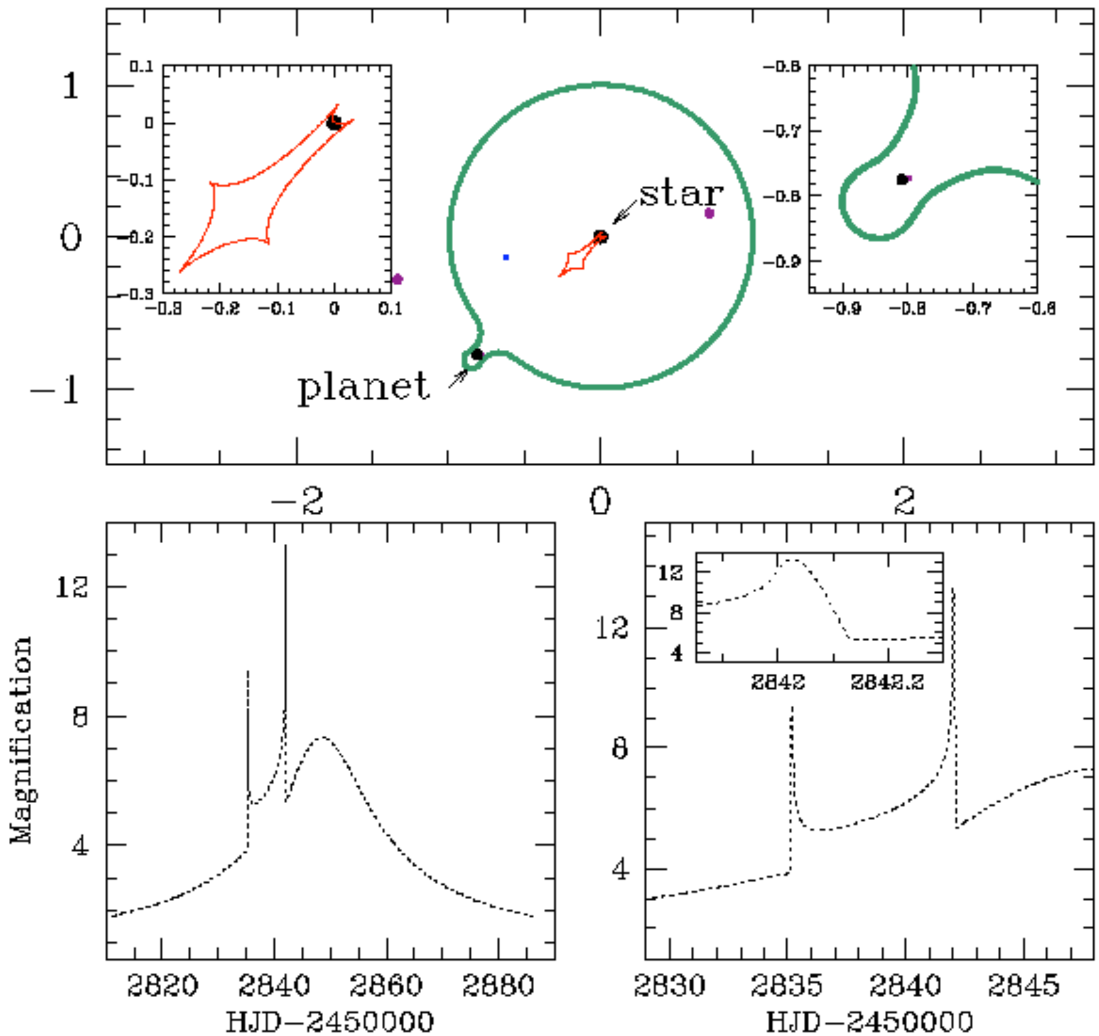


Extra-solar planet microlensing searches

- If the lensing object is a star with a planet orbiting it, then the planet can be detected by its influence on the microlensing event.
- This is seen as a deviation from the light curve that would occur if the star alone were acting as a lens.
- The red plot on the right shows the total light produced by microlensing as a function of time.
- Note that the lensed images (shown in yellow) are not resolvable, so the telescope only sees the sum of the light from the images.



Planet microlensing animation



Animation by
B. Scott Gaudi

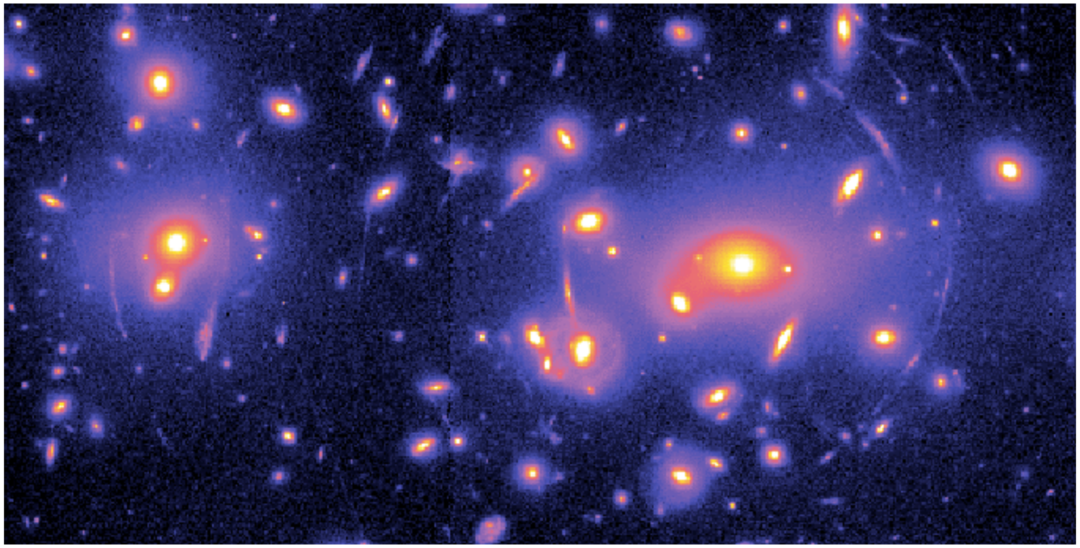
Outline

- Introduction to gravitational lensing
- Strong lensing
- Microlensing
- Weak lensing

Weak lensing

- The farther the background galaxy is from the axis of symmetry, the smaller the arcs produced by strong lensing.

- Galaxies farther away from the mass concentration of Abell 2218 than those we see as arcs are still stretched by the foreground cluster's mass.



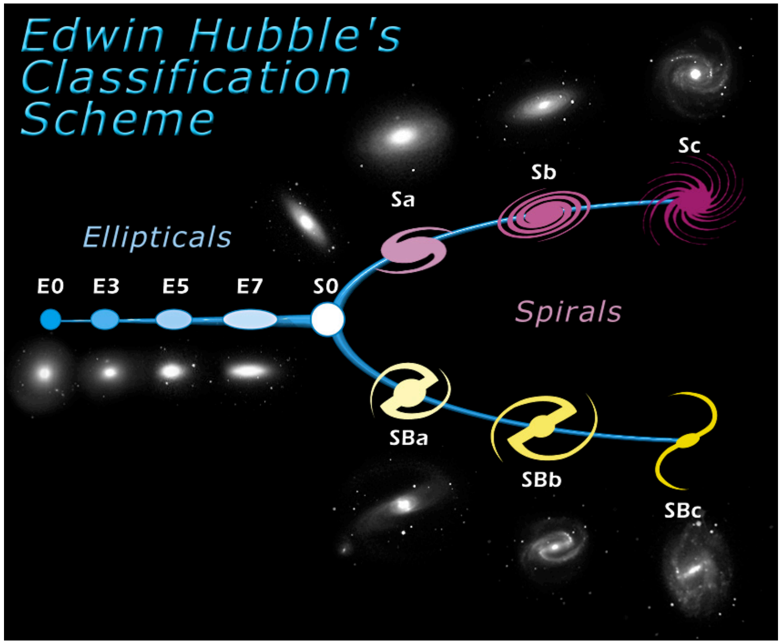
Abell 2218

Weak lensing

- However, the lengths of the would-be arcs are very small, producing only a single arc-shaped (or elliptical) image.
- Definition: *Shear* distorts the shape of the source.

Weak lensing

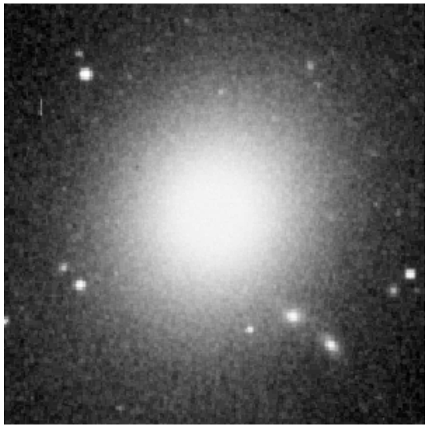
- The distortions are smaller than the *intrinsic* ellipticity of the galaxies, which means you cannot tell on a case-by-case basis which direction the galaxies are stretched.



Some galaxies are intrinsically elliptically shaped

Weak lensing

- Is the galaxy on the right intrinsically more elliptical?

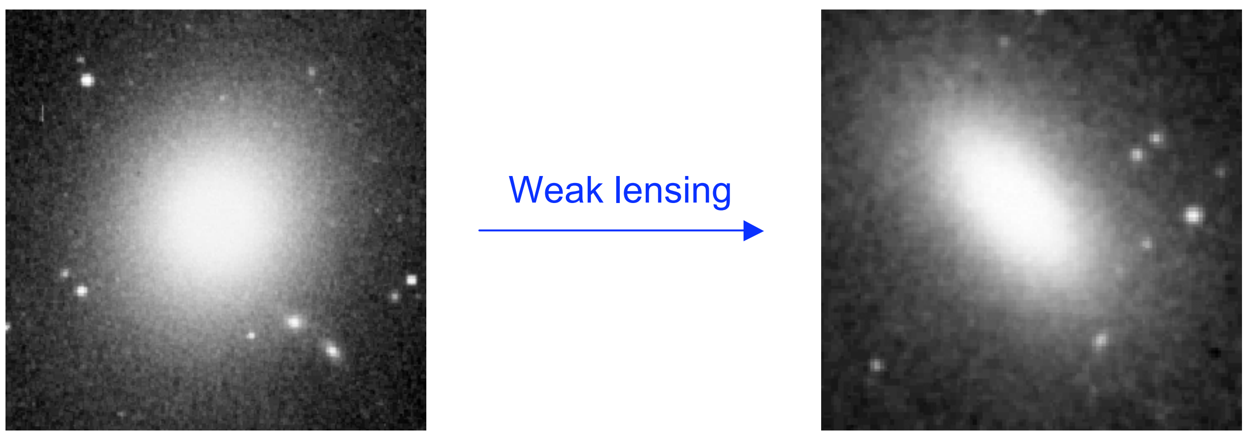


E0

E6

Weak lensing

- Or is the galaxy intrinsically circular, and it appears elliptical to us due to weak lensing?



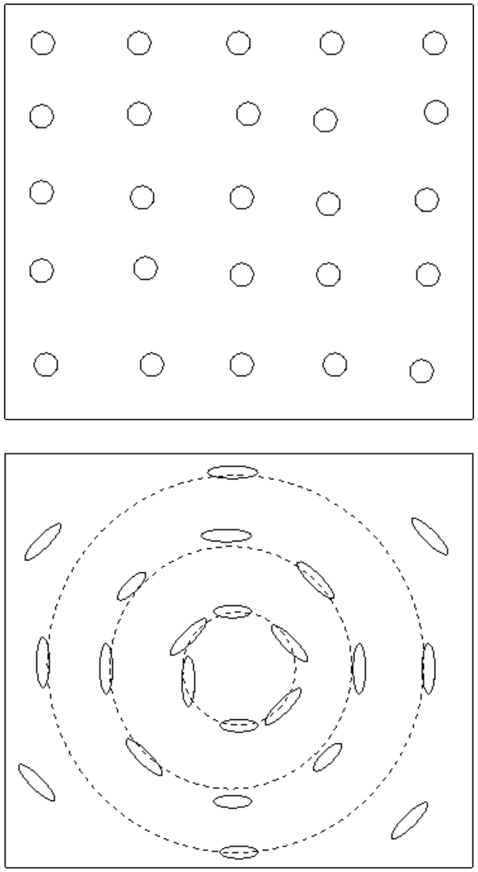
Source galaxy

Weakly-lensed source galaxy

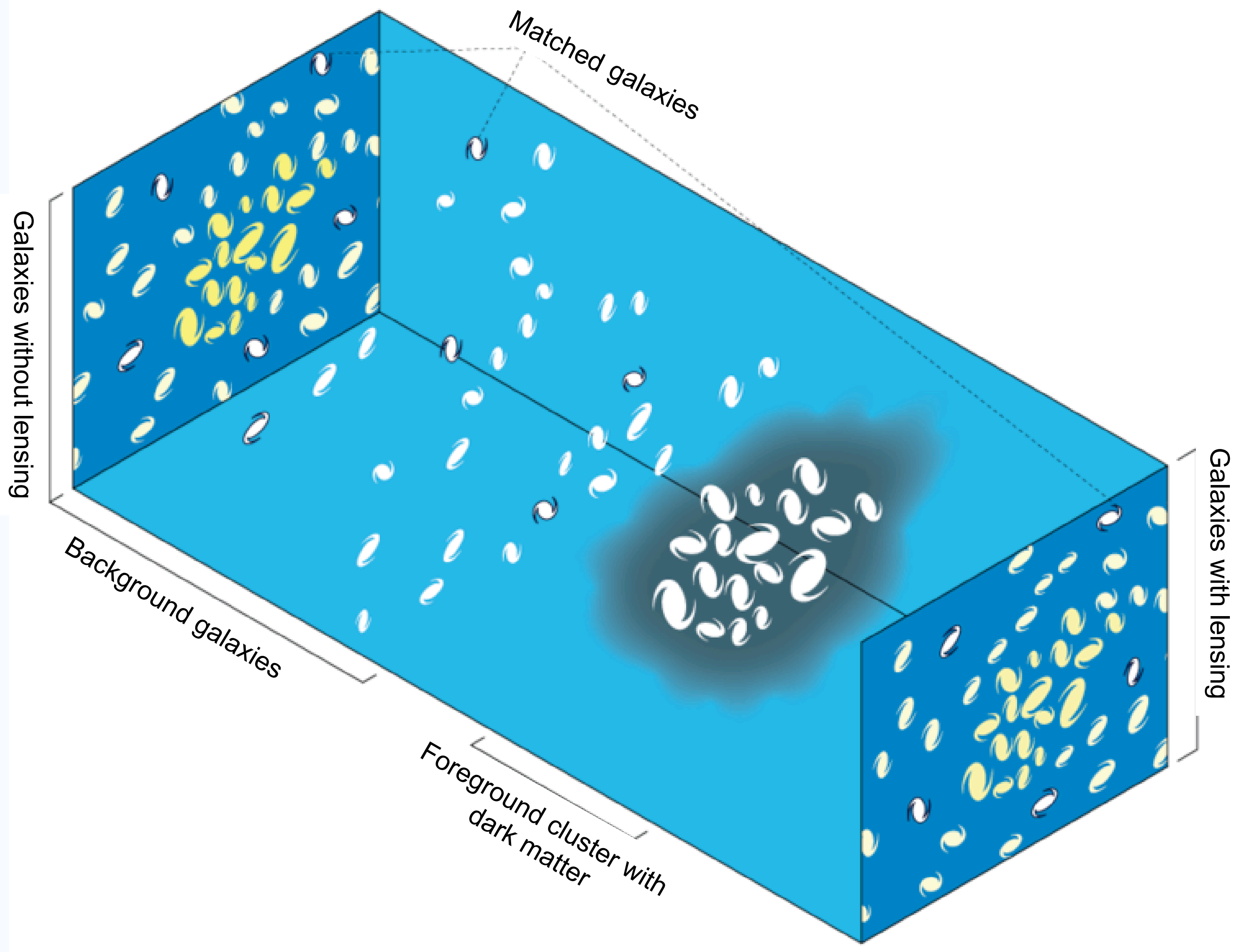
Weak lensing

- Only by looking at many galaxies on average can one tell that there is a preference for the ellipticities to be oriented tangentially to the center of the cluster.

- This study is known as weak gravitational lensing.



Weak lensing



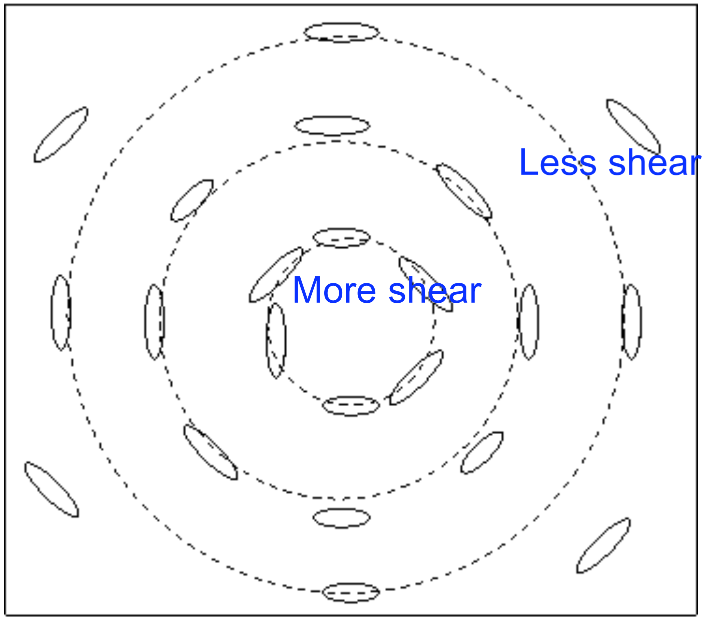
Shear vs. radius

- The average shear is measured in concentric annuli about the center of the lens

- Remembering that the deflection is a function of the impact parameter,

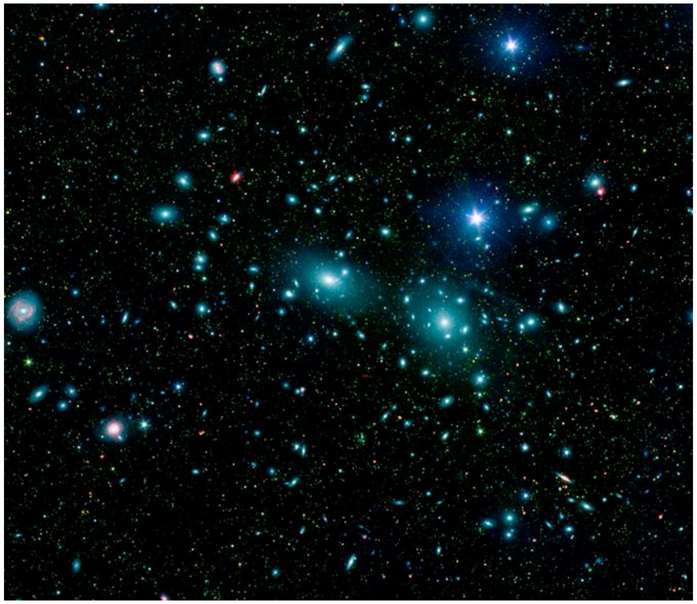
$$\alpha = \frac{4GM_{\odot}}{c^2 b} \qquad \downarrow b \uparrow \alpha$$

(recall above formula for the Sun) one would also expect the shear to decrease with distance from the lens center.



Shear vs. radius

- This was shown by Kubo, et al. in the measurement of shear in the Coma Cluster.*



Coma cluster

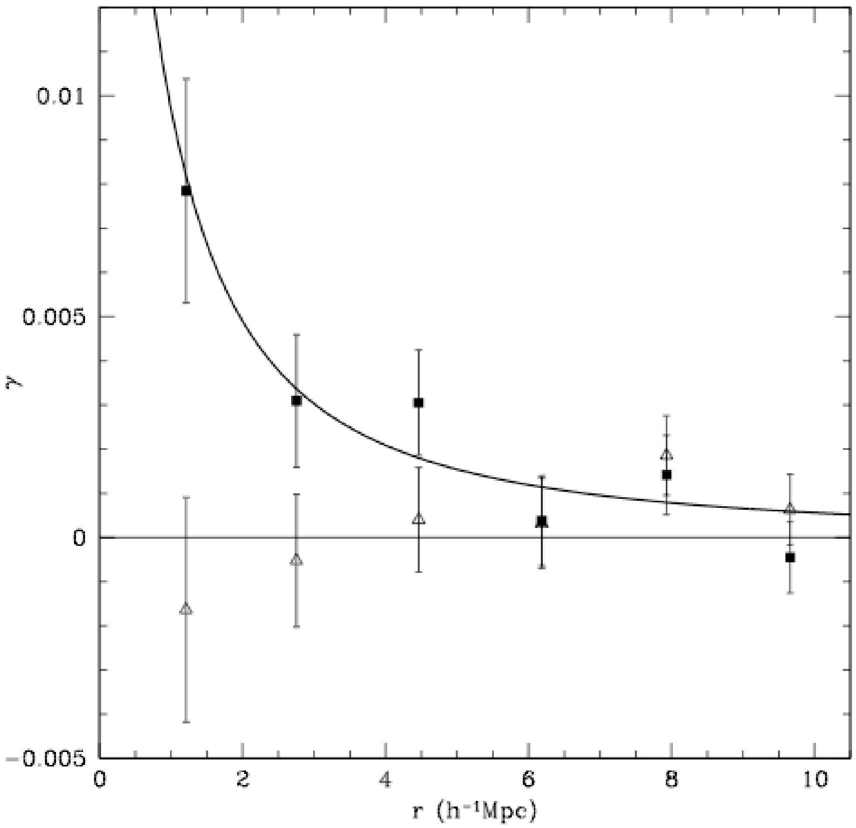
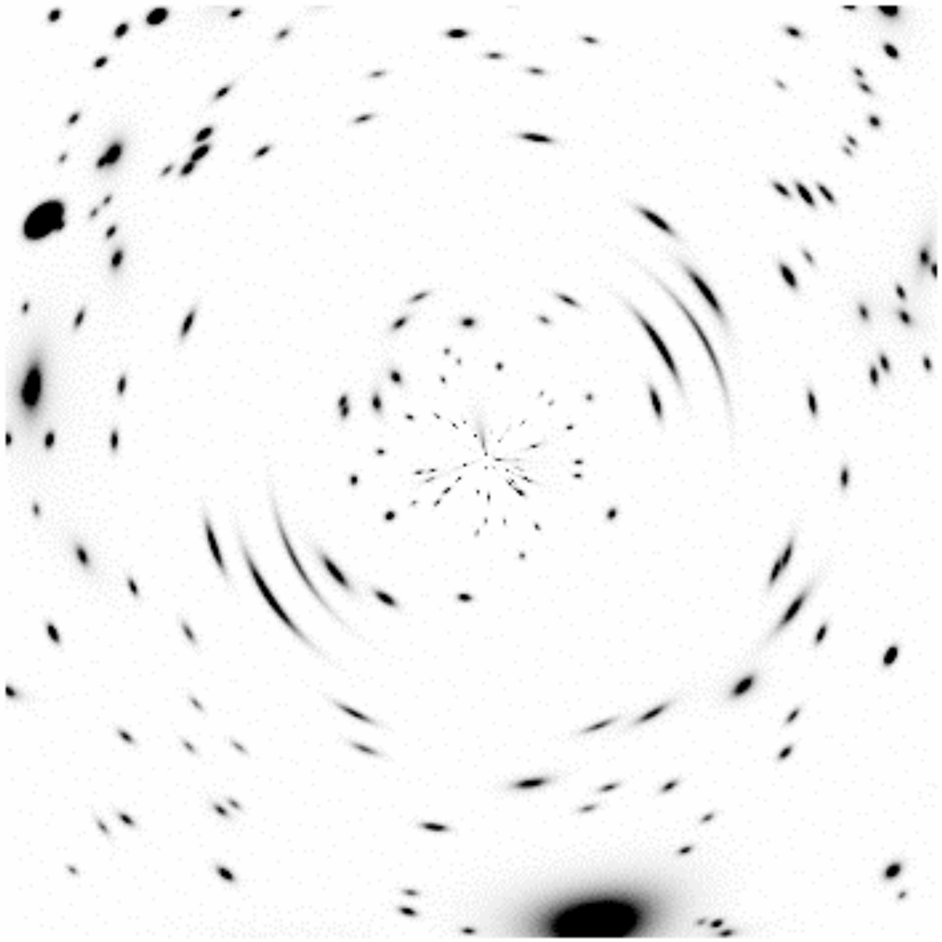


Fig. 2.— Tangential shear centered on the Coma Cluster in the SDSS. The measured shear is shown as *solid squares* along with 1σ error bars. The 45° component is shown as *open triangles* and is consistent with zero. The *solid line* represents our best fit NFW model.

*Kubo, et al., 2007 astro-ph/0709.0506

Cluster Lensing Animation

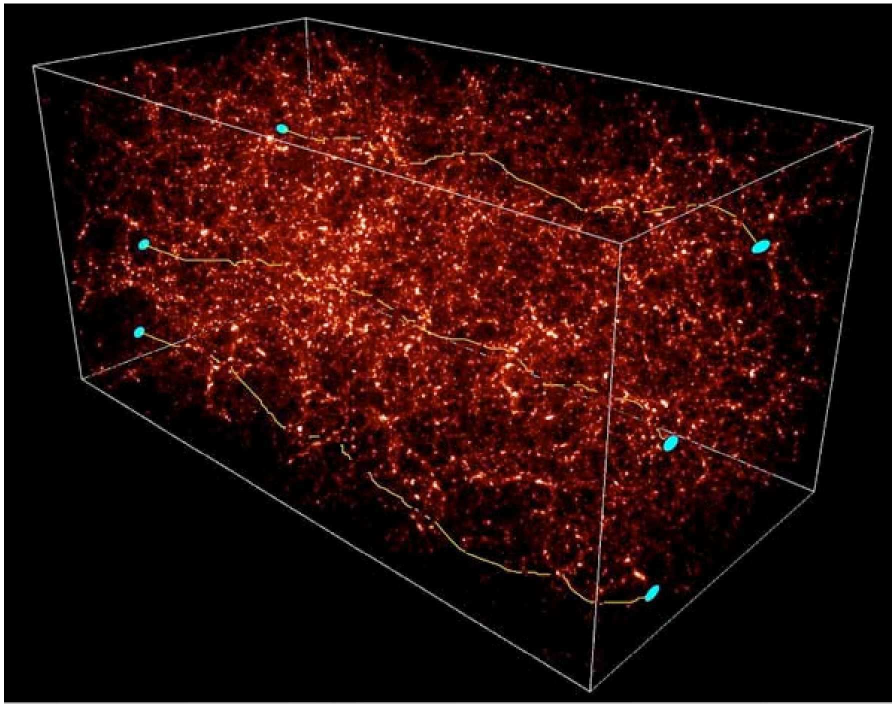


Weak lensing

- Galaxy clusters were the first objects studied with weak lensing.
- It has since been applied to study the average properties of galaxies, the relation of galaxies and dark matter, galaxy clusters, and the ambient large-scale structure in the universe (via “cosmic shear”).

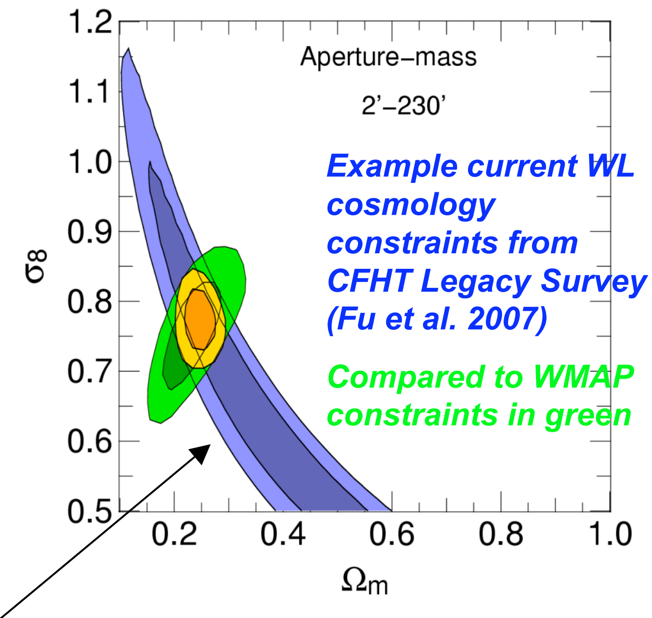
Cosmic Shear

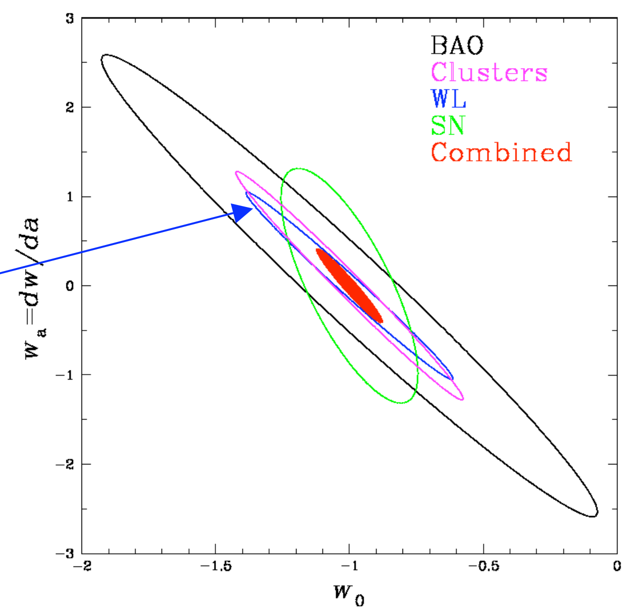
- Depending on the amount and distribution of dark matter, light has been deflected by some typical amount once it reaches Earth.
- The measurement of this weak lensing signal is difficult, but not impossible, as has been demonstrated in the last few years.
- This "cosmic shear" has been used to constrain cosmological parameters, and to study the relation between galaxies and dark matter.



Cosmology Constraints from Weak Lensing (WL)

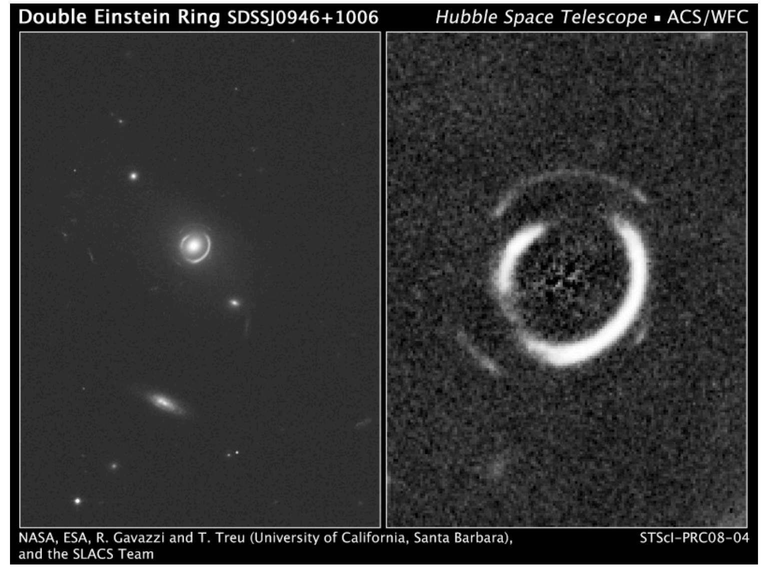
- Weak lensing can constrain cosmology using cosmic shear measurements, i.e., correlations in the ellipticities of pairs of galaxies
- How the cosmic shear signal varies with galaxy separation and with redshift is determined by the distribution of matter in the universe, and hence by cosmological parameters like the matter density Ω_M and the dark energy parameter w
- Need large galaxy imaging surveys with excellent image quality ("seeing")
- Current samples cover sky areas of hundreds of deg^2 and provide cosmology constraints consistent with those from the cosmic microwave background
- Forecast constraints on dark energy parameters from weak lensing (*blue*) for Dark Energy Survey and similar future surveys covering thousands of deg^2 are very competitive with constraints from other methods

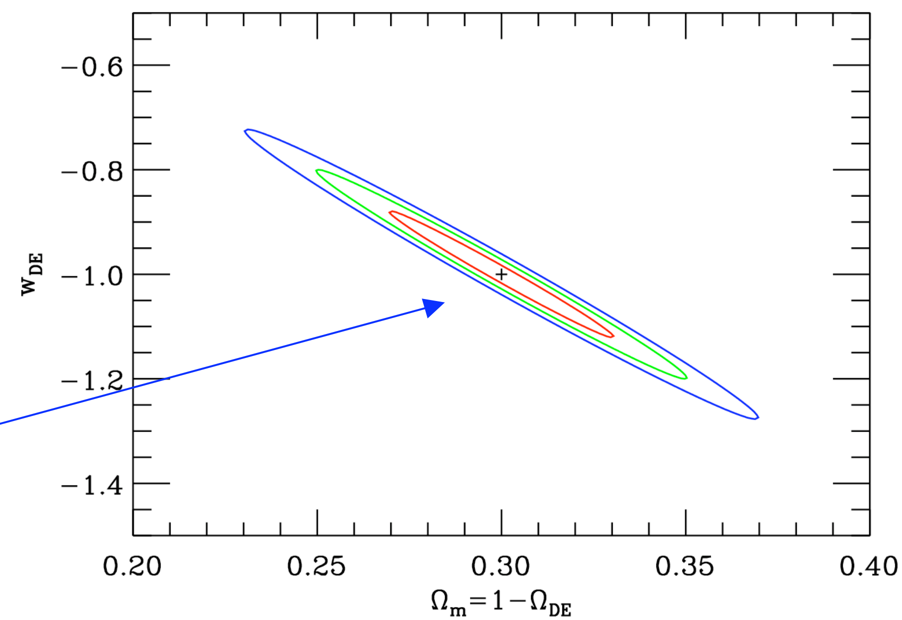




Cosmology from Strong Lensing: Double Einstein Ring Example

- Traditional strong lensing cosmology constraints rely on predicting, say, the distribution of image-lens separations, and provide independent evidence for dark energy (e.g., Mitchell et al. 2005), consistent with supernova results
- Strong lensing cosmology constraints are however hampered by uncertainties in the detailed mass distributions of the lenses
- A novel approach takes advantage of double Einstein ring systems with sources at different redshifts
- The ratio of the sizes of the Einstein rings depends on the ratio of the distances involved in the system and hence on cosmology (it's a *geometric* constraint)
- A sample of 50 double Einstein ring systems from a future space-based survey like JDEM can yield constraints on matter density Ω_M and dark energy parameter w comparable to those from Type Ia supernovae (Gavazzi et al. 2008)





- "The laws of gravity are very, very strict.
  And you're just bending them for your own benefit"

-*"She's got a new spell"* by Billy Bragg

http://uk.youtube.com/watch?v=pguvMxwzm14