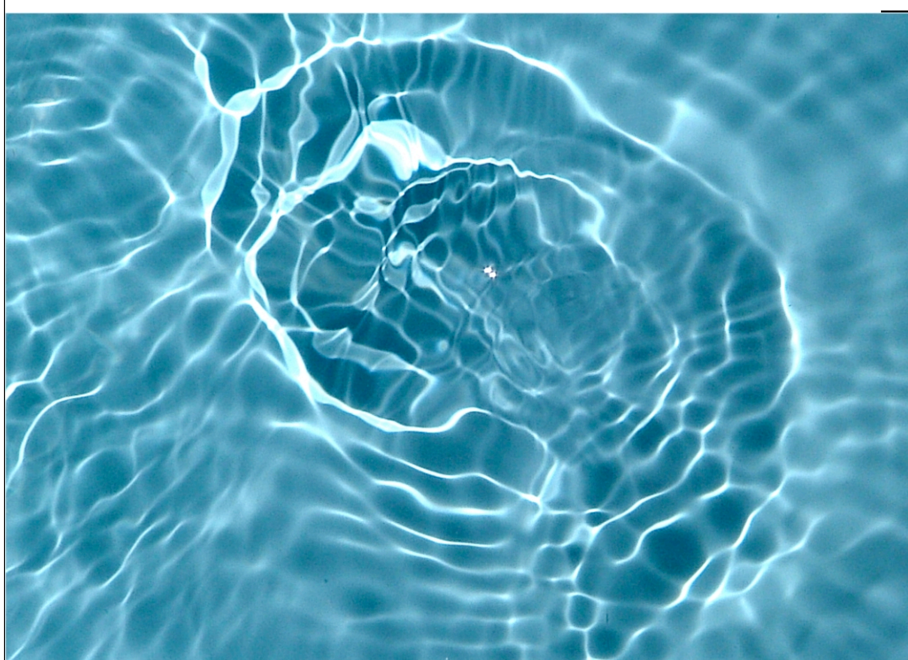
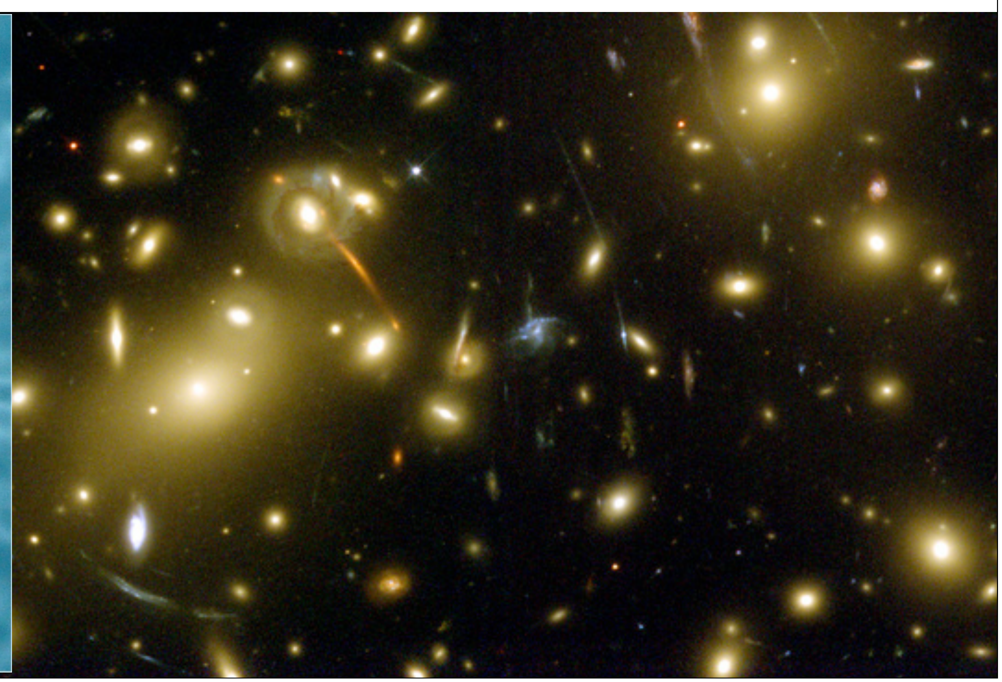
Harvard Astronomy 202 (Extragalactic Astronomy & Cosmology)

Gravitational lensing

Jonathan Pritchard

Lecture 12





References

In preparing this lecture I have shamelessly stolen material from the following sources:

- Narayan & Bartelmann [astro-ph/9606001] - Jerusalem Winter School notes
- Schneider - Extragalactic Astronomy and Cosmology (2006)
- Schneider, Ehlers, & Falco - Gravitational Lenses (1999)
- Carroll - Spacetime and Geometry (2004)

My office is P-243, feel free to stop by if you have questions

Slides will be available from my website by the end of the day
http://www.cfa.harvard.edu/~jpritchard/teaching.htm

Outline

- Brief history
  1. Predictions back in the '30s
  2. Discovery of 0957+561
  3. Rediscovery of cluster arcs
  4. Nearest lens (2237+0305)

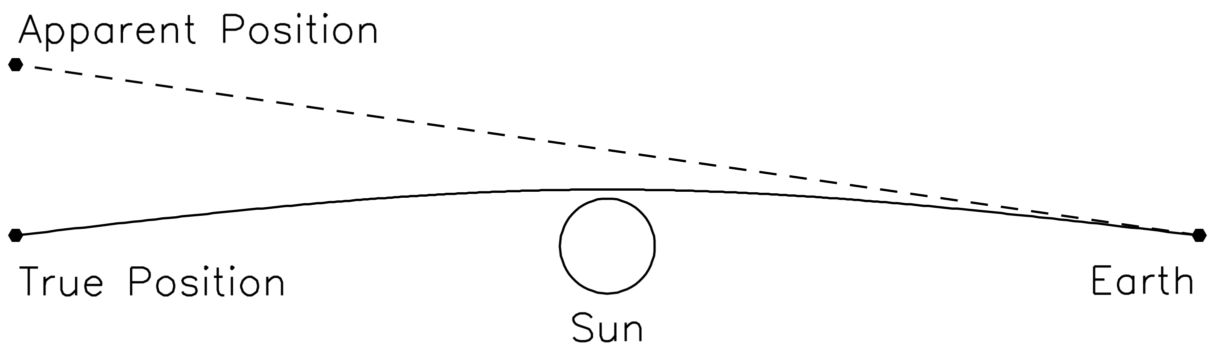
- Simple theory
  1. Deflection Angle
  2. Lens Equation
  3. Magnification

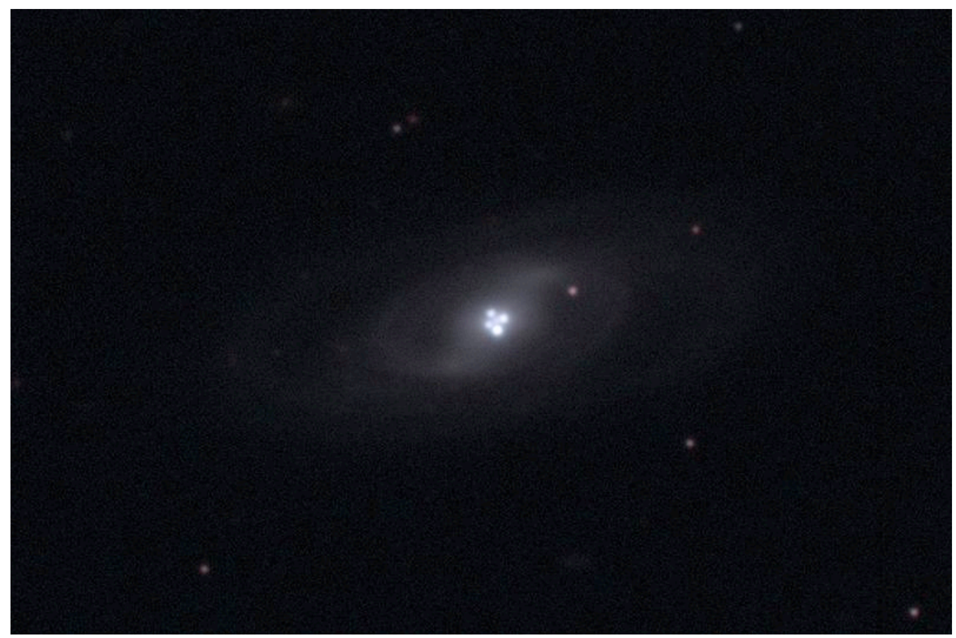
- Microlensing
  1. Probabilities/Timescales
  2. MACHO results

- Galaxy lenses
  1. Point masses
  2. Isothermal spheres
  3. Mass determinations
  4. Distances and H0

- Cluster & LSS lenses
  1. Mass determinations
  2. Weak lensing+cluster searches
  3. Cosmic sheer

History of Lensing





Newtonian and GR predictions

Gravitational lensing first proposed by Soldner (1801) in context of Newtonian theory.
He found a deflection angle

$$\alpha = \frac{2GM}{v^2 r}$$

For sun gives 0.85"

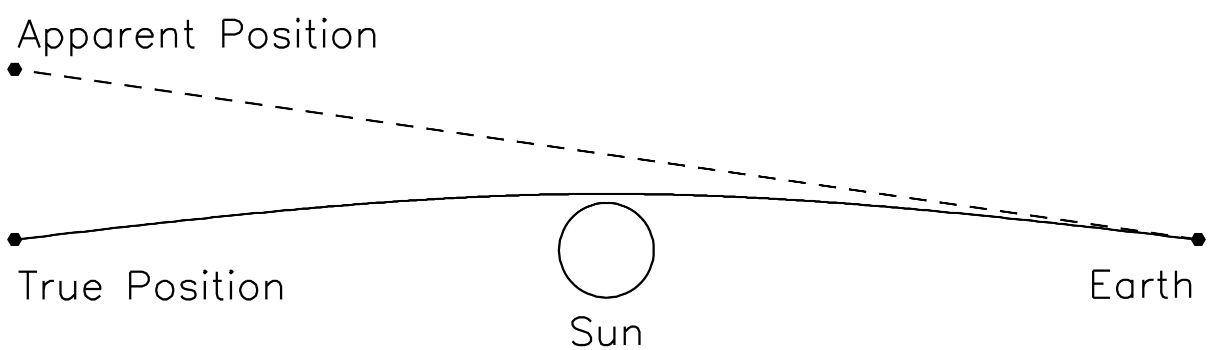
Einstein derived same result in 1911 using Equivalence principle & Euclidean metric

Freundlich's efforts to measure this during an Eclipse in the Crimea were foiled by the outbreak of WWI and his arrest by the Russians...

In 1915 with general relativity, Einstein derived the new result

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

For sun gives 1.7"



Eddington and the Eclipse

Using data taken during a solar eclipse in 1919, Eddington measured a value close to that of the GR prediction

Dyson, Eddington, & Davidson 1920

DETERMINATION OF DEFLECTION OF LIGHT BY THE SUN'S GRAVITATIONAL FIELD. 331

The result from declinations is about twice the weight of that from right ascensions, so that the mean result is

$$1''\cdot 98$$

with a probable error of about $\pm 0''\cdot 12$.

The Principe observations were generally interfered with by cloud. The unfavourable circumstances were perhaps partly compensated by the advantage of the extremely uniform temperature of the island. The deflection obtained was

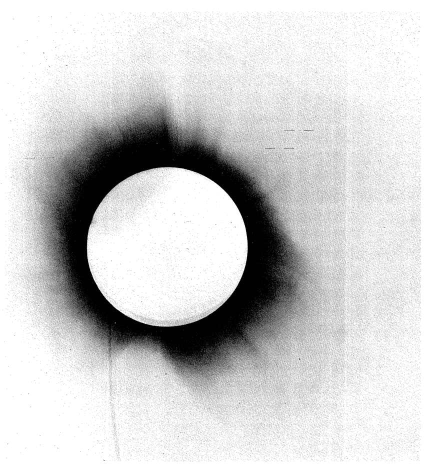
$$1''\cdot 61.$$

The probable error is about $\pm 0''\cdot 30$, so that the result has much less weight than the preceding.

Both of these point to the full deflection $1''\cdot 75$ of EINSTEIN's generalised relativity theory, the Sobral results definitely, and the Principe results perhaps with some uncertainty. There remain the Sobral astrographic plates which gave the deflection

$$0''\cdot 93$$

discordant by an amount much beyond the limits of its accidental error. For the reasons already described at length not much weight is attached to this determination.



332 SIR F. W. DYSON, PROF. A. S. EDDINGTON AND MR. C. DAVIDSON ON A

Thus the results of the expeditions to Sobral and Principe can leave little doubt that a deflection of light takes place in the neighbourhood of the sun and that it is of the amount demanded by EINSTEIN's generalised theory of relativity, as attributable to the sun's gravitational field. But the observation is of such interest that it will

(bizzarely if not for this then Eddington might well have been imprisoned for being a pacifist)

Zwicky’s leap

- Although calculations of lensing by other stars were carried out the small angular separations of the images led to pessimism that they could be seen

- In 1937, Zwicky made the jump of suggesting that extragalactic nebulae (galaxies) would produce well separated images that could be observed
  - by applying the virial theorem to the Coma and Virgo clusters he was
  (correctly) using masses ~400 times larger than was then believed

- He pointed out that gravitational lensing would allow the study of objects at greater distances (via magnification), that many arcs should be visible, and the importance of magnification bias in magnitude limited samples.

Zwicky 1937

Nebulae as Gravitational Lenses

The discovery of images of nebulae which are formed through the gravitational fields of nearby nebulae would be of considerable interest for a number of reasons.

(1) It would furnish an additional test for the general theory of relativity.

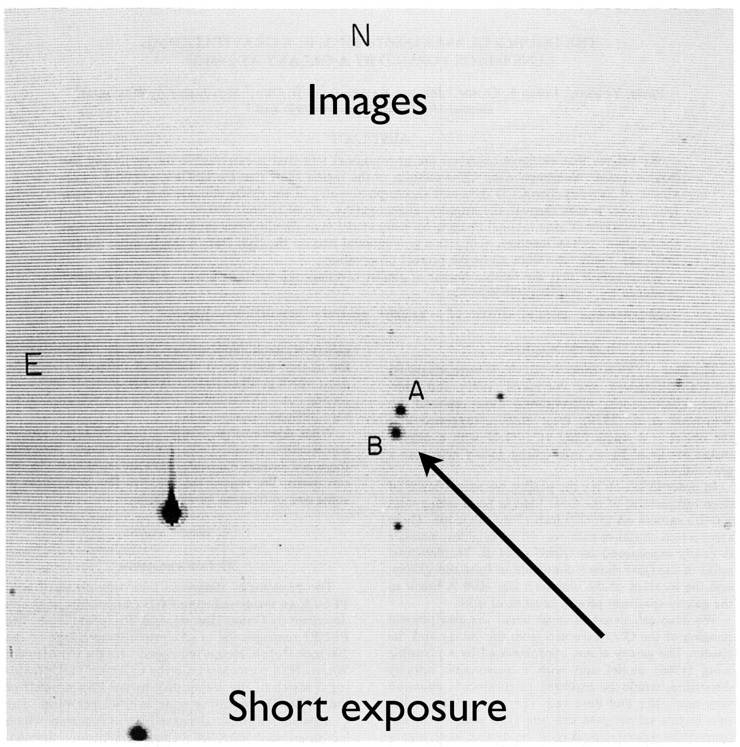
(2) It would enable us to see nebulae at distances greater than those ordinarily reached by even the greatest telescopes. Any such *extension* of the known parts of the universe promises to throw very welcome new light on a number of cosmological problems.

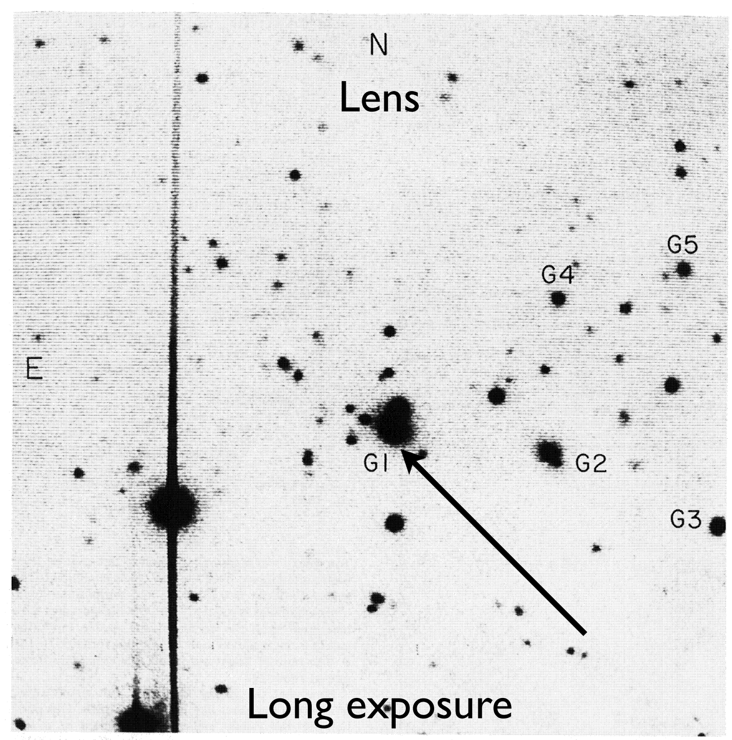
(3) The problem of determining nebular masses at present has arrived at a stalemate. The mass of an average nebula until recently was thought to be of the order of $M_N = 10^9 M_\odot$, where $M_\odot$ is the mass of the sun. This estimate is based on certain deductions drawn from data on the intrinsic brightness of nebulae as well as their spectrographic rotations. Some time ago, however, I showed[2] that a straightforward application of the virial theorem to the great cluster of nebulae in Coma leads to an average nebular mass four hundred times greater than the one mentioned, that is, $M_N' = 4 \times 10^{11} M_\odot$. This result has recently been verified by an investigation of the Virgo cluster.[3] Observations on the deflection of light around nebulae may provide the most direct determination of nebular masses and clear up the above-mentioned discrepancy.

Discovery of 0957+561

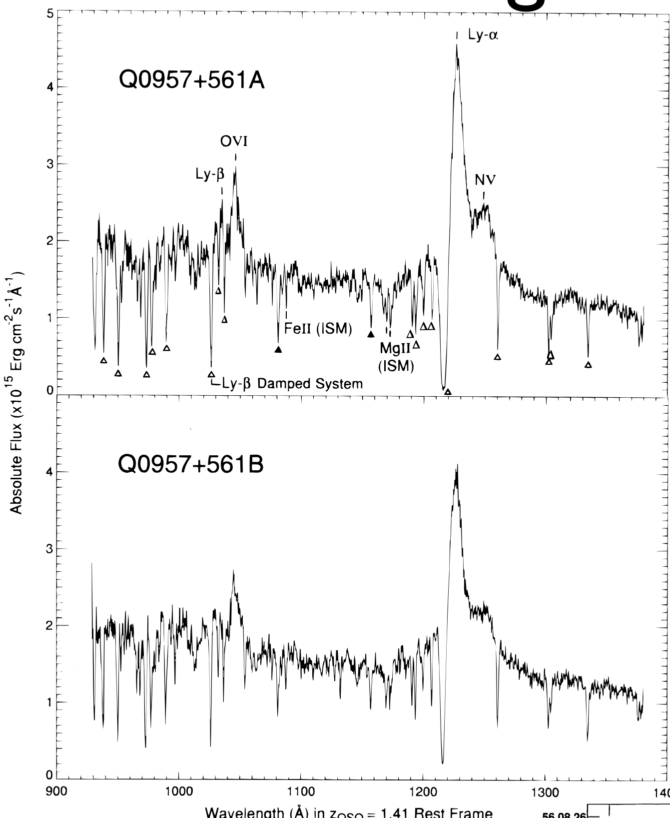
- The first concrete example of a gravitational lens was reported in 1979 in the form of the quasar QSO 957+561 A,B found at z~1.4 (Walsh, Carswell & Weymann 1979). Two seen images separated by 6”.
- Evidence that this is a lens comes from

1. Lensing galaxy detected at z~0.36
2. Similarity of the spectra of the two images
3. Ratio of optical and radio fluxes are consistent between two images
4. VLBI imaging showed detailed correspondence between small scale features





Images of QSO 0957+561



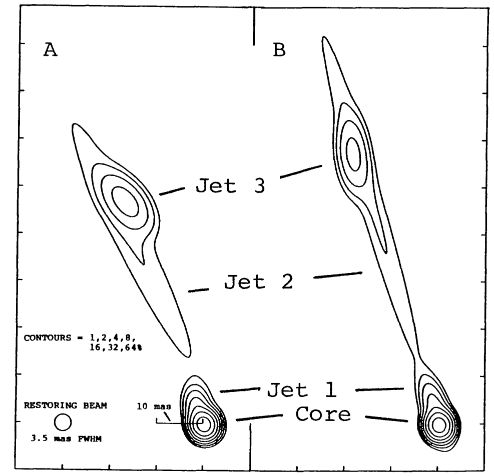
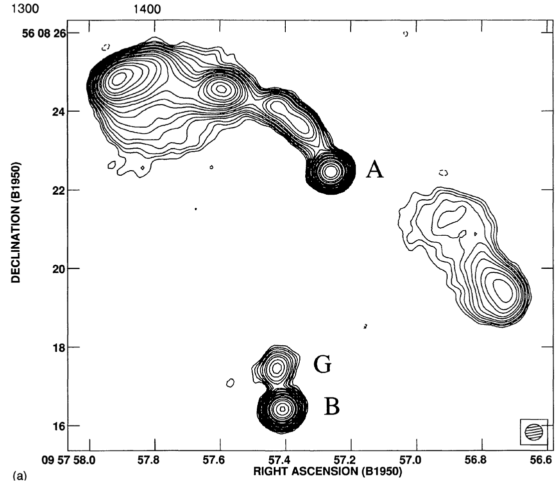
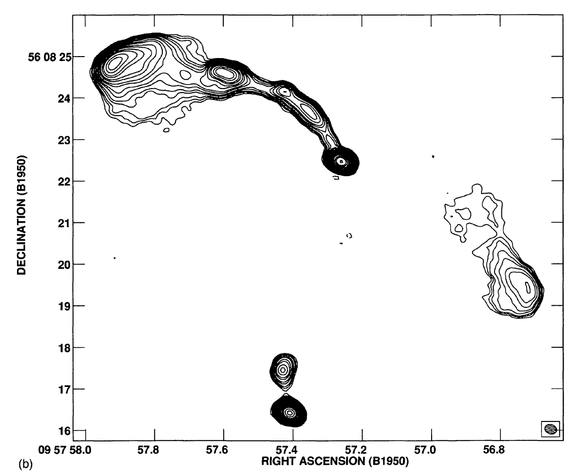


Figure 1 — The brightness distributions of 0957+561A and B. Four elliptical Gaussian components account for the data obtained from the 1981 λ13 cm VLBI observations for A and for B (Model I—see text). The correspondences in the number and in the properties of the components of the respective models, and the evidence for a change in parity from one image to the other, all support the hypothesis that A and B are images of a single object.

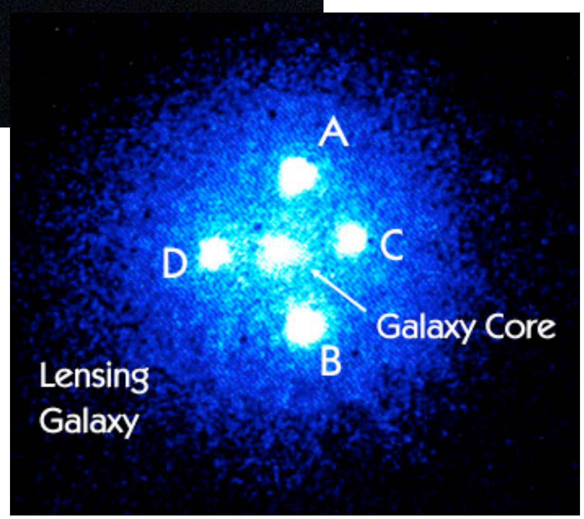


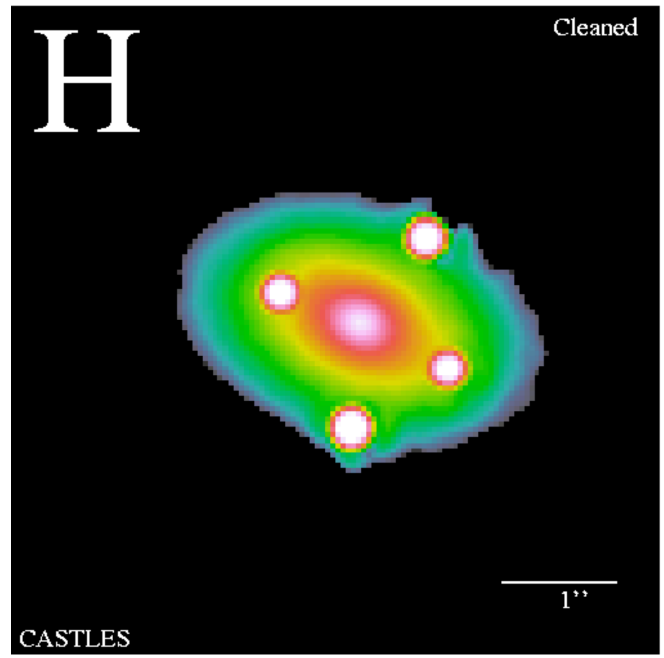


“Huchra’s Lens”

- Quadruply-imaged quasar Q2237+0305 “Einstein Cross” z=1.7 with image separation ~1.8” -> elliptical lens
- Lensing galaxy is ZW2237+030 “Huchra’s Lens” at z=0.04

Huchra+(1985)

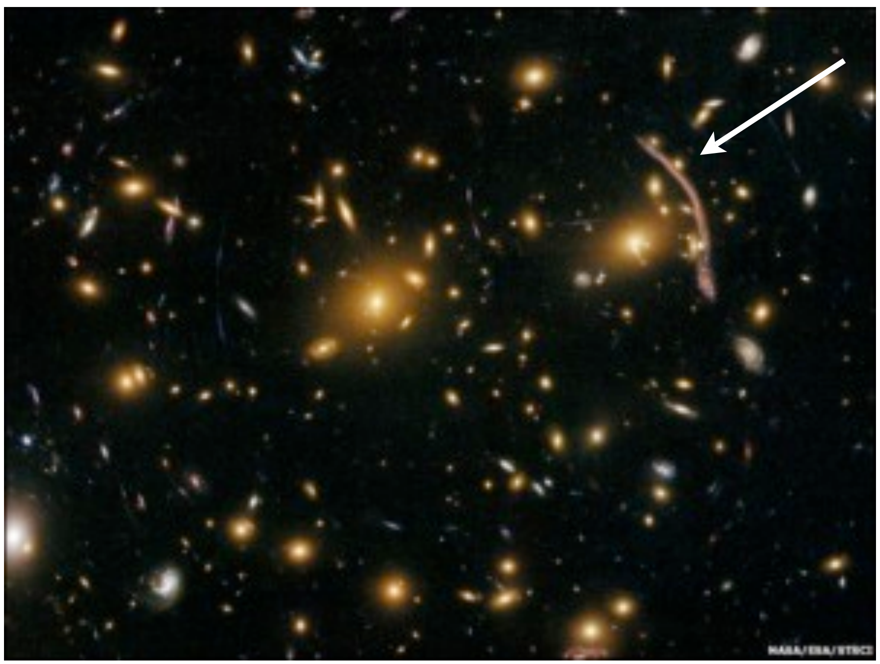




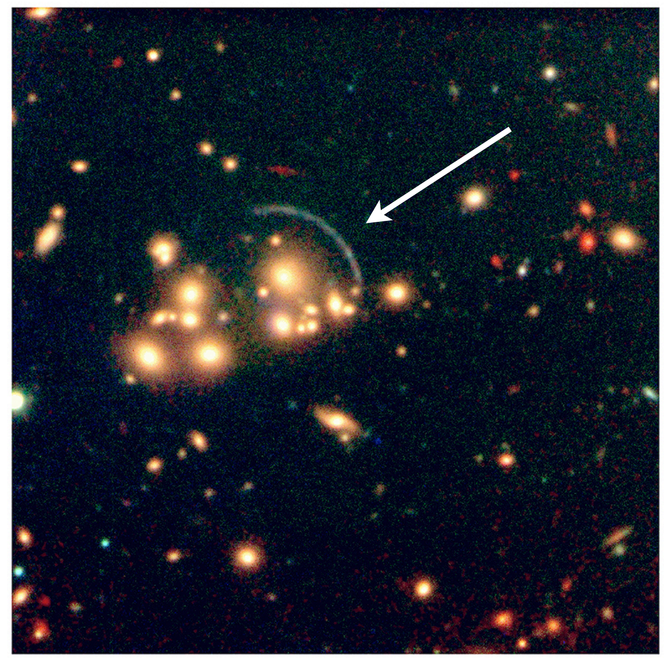
Nearby and isolated
-> key system for testing GR

Cluster Arcs

- In 1986, two groups discovered stretched arcs in clusters of galaxies at high redshift. “giant luminous arcs” - very thin in radial direction (unresolved)
- Light from arc confirmed to be from a much higher redshift source
- Confounded expectations based on pre-ROSAT X-ray observations that the surface mass density of clusters was too low to cause strong lensing
- Suddenly everyone found arcs in their old data...



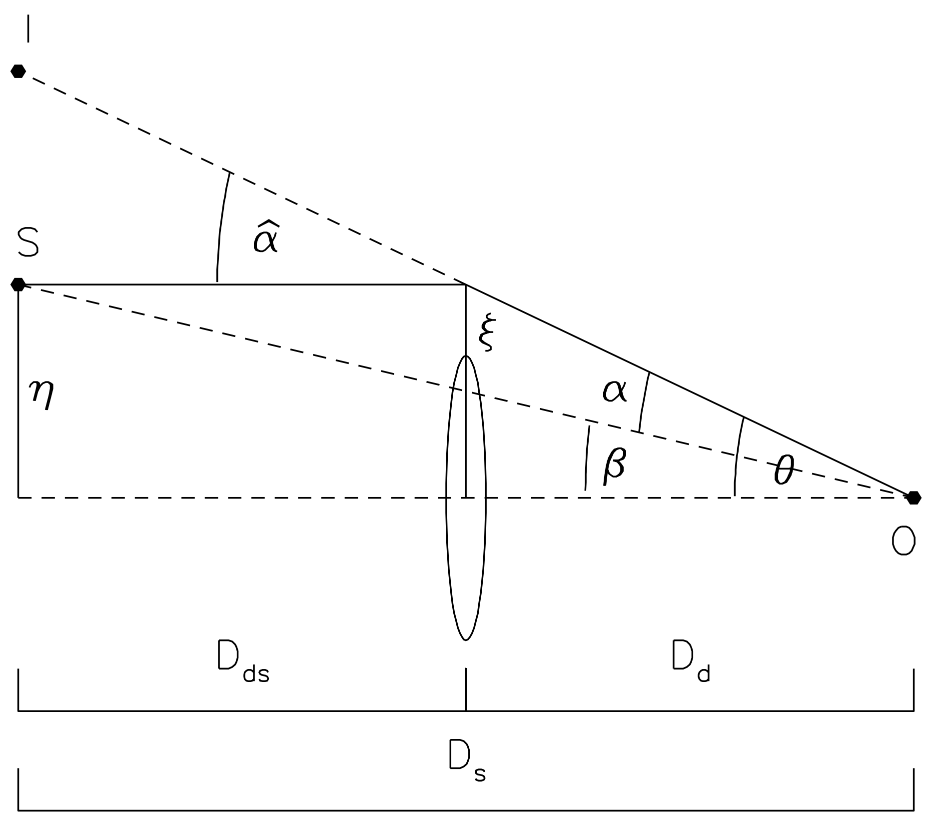
Abel 370 - HST



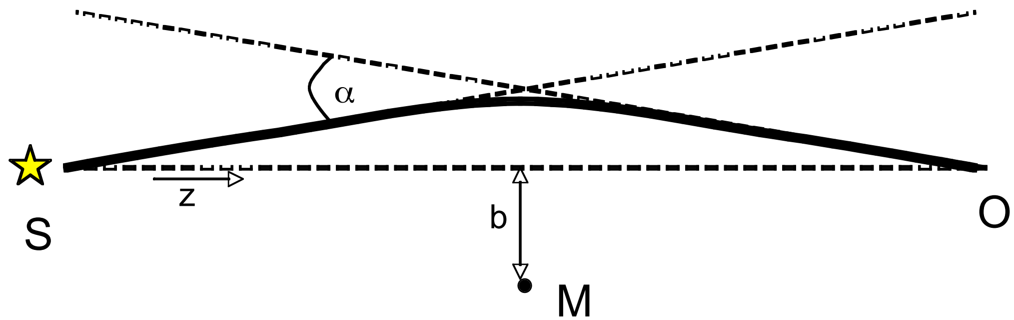
IR Colour Composite of Galaxy Cluster CL2244-02 with Gravitational Arcs
(VLT UT1 + ISAAC)

ESO PR Photo 46d/98 (26 November 1998)

Basic Theory

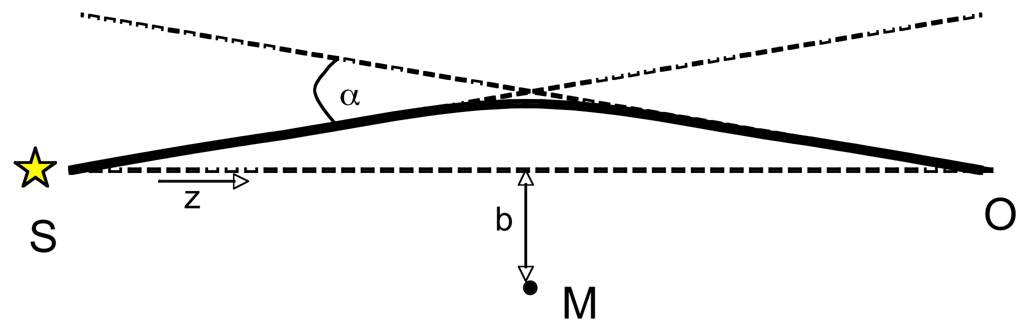


Gravitational Deflection



- Derive gravitational deflection angle α from GR - just sketch elements here see e.g. Carroll for a complete treatment
- Metric: $$ds^2 = -(1+2\Phi)dt^2 + (1-2\Phi)(dx^2+dy^2+dz^2)$$
- Poisson Equation: $$\nabla^2\Phi = 4\pi G\rho$$
- Geodesic equation: $$\frac{\mathrm{d}^2x^\mu}{\mathrm{d}\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{\mathrm{d}x^\rho}{\mathrm{d}\lambda}\frac{\mathrm{d}x^\sigma}{\mathrm{d}\lambda} = 0$$
- Null path condition: $$g_{\mu\nu}\frac{\mathrm{d}x^\mu}{\mathrm{d}\lambda}\frac{\mathrm{d}x^\nu}{\mathrm{d}\lambda} = 0$$
- Solve for photon path assuming that deflection is small so can treat as a small perturbation and integrate along the undeflected path to obtain
- Deflection angle: $$\boxed{\hat{\alpha} = 2\int \nabla_\perp \Phi\, \mathrm{d}s}$$

Example: Point mass



Start here:

$$\hat{\alpha} = 2 \int \nabla_\perp \Phi \, \mathrm{d}s \qquad \nabla^2 \Phi = 4\pi G \rho$$

Poisson eq. gives potential:

$$\Phi(r) = -\frac{GM}{r} = -\frac{GM}{(b^2+z^2)^{1/2}} \qquad \nabla_\perp \Phi(r) = \frac{\partial \Phi}{\partial b} = -\frac{GMb}{(b^2+z^2)^{3/2}}$$

Deflection angle follows:

$$\begin{aligned} \hat{\alpha} &= 2 \int \nabla_\perp \Phi(r) \\ &= 2 \int_{-\infty}^{\infty} \mathrm{d}z \, \frac{GMb}{(b^2+z^2)^{3/2}} \\ &= \frac{2GM}{b} \int_{-\infty}^{\infty} \frac{\mathrm{d}x}{(1+x^2)^{3/2}} \\ &= \frac{4GM}{b} \end{aligned}$$

$$\hat{\alpha} = \frac{4GM}{b}$$