Set 4:

Active Galaxies

Phenomenology

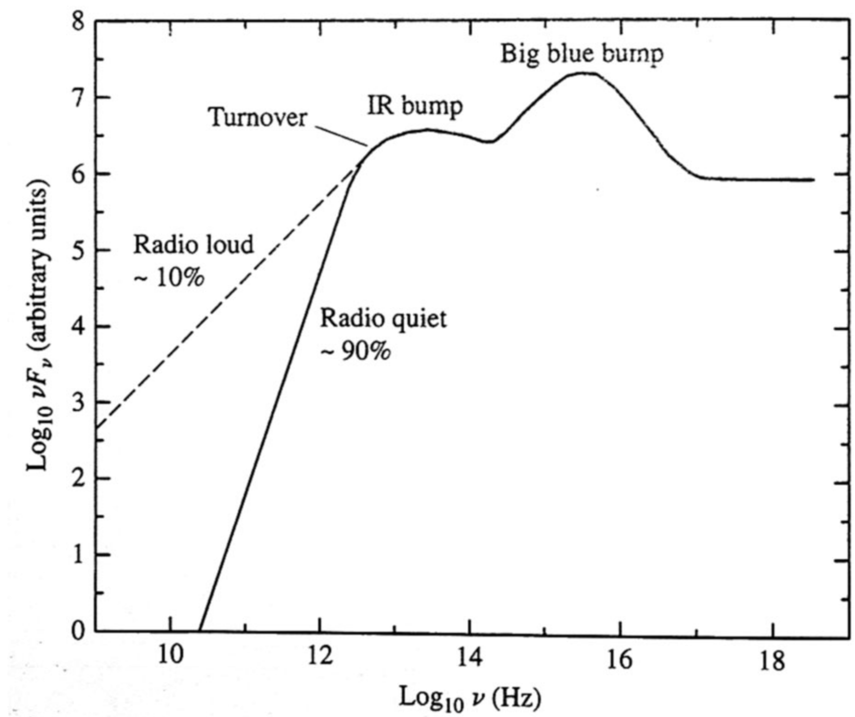
- History: Seyfert in the 1920's reported that a small fraction (few tenths of a percent) of galaxies have bright nuclei with broad emission lines. 90% are in spiral galaxies
- Seyfert galaxies categorized as 1 if emission lines of HI, HeI and HeII are very broad - Doppler broadening of 1000-5000 km/s and narrower forbidden lines of ~ 500km/s. Variable. Seyfert 2 if all lines are ~ 500km/s. Not variable.
- Both show a featureless continuum, for Seyfert 1 often more luminous than the whole galaxy
- Seyferts are part of a class of galaxies with active galactic nuclei (AGN)
- Radio galaxies mainly found in ellipticals - also broad and narrow line - extremely bright in the radio - often with extended lobes connected to center by jets of ~ 50kpc in extent

Phenomenology

- Quasars discovered in 1960 by Matthews and Sandage are extremely distant, quasi-starlike, with broad emission lines. Faint fuzzy halo reveals the parent galaxy of extremely luminous object - visible luminosity $L \sim 10^{38-41}$W or $\sim 10^{11-14} L_\odot$
- Quasars can be both radio loud (QSR) and quiet (QSO)
- Blazars (BL Lac) highly variable AGN with high degree of polarization, mostly in ellipticals
- ULIRGs - ultra luminous infrared galaxies - possibly dust enshrouded AGN (alternately may be starburst)
- LINERS - similar to Seyfert 2 but low ionization nuclear emission line region - low luminosity AGN with strong emission lines of low ionization species

Spectrum

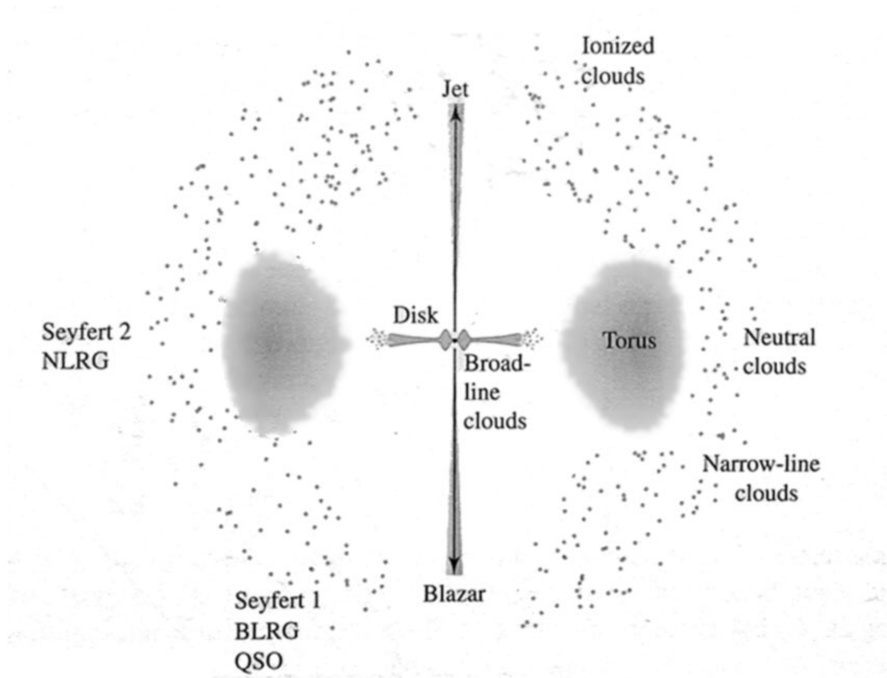
- AGN
  share a basic general form
  for their continuum emission
- Flat broken power
  law continuum - specific
  flux $F_\nu \propto \nu^{-\alpha}$. Usual to
  plot νF_ν which gives the flux
  per log interval in frequency



$$F = \int F_\nu d\nu = \int \nu F_\nu \frac{d\nu}{\nu} = \int \nu F_\nu d\ln\nu$$

Spectrum Interpretation

- High frequency end has $\alpha \sim 1$ or equal amount of energy out to X-ray frequencies
- Low frequency power law turns over to $\alpha \sim -2$
- On top of power law: two bumps - big blue bump in the visible, IR bump
- High frequency power law is synchrotron emission - accounts for polarization

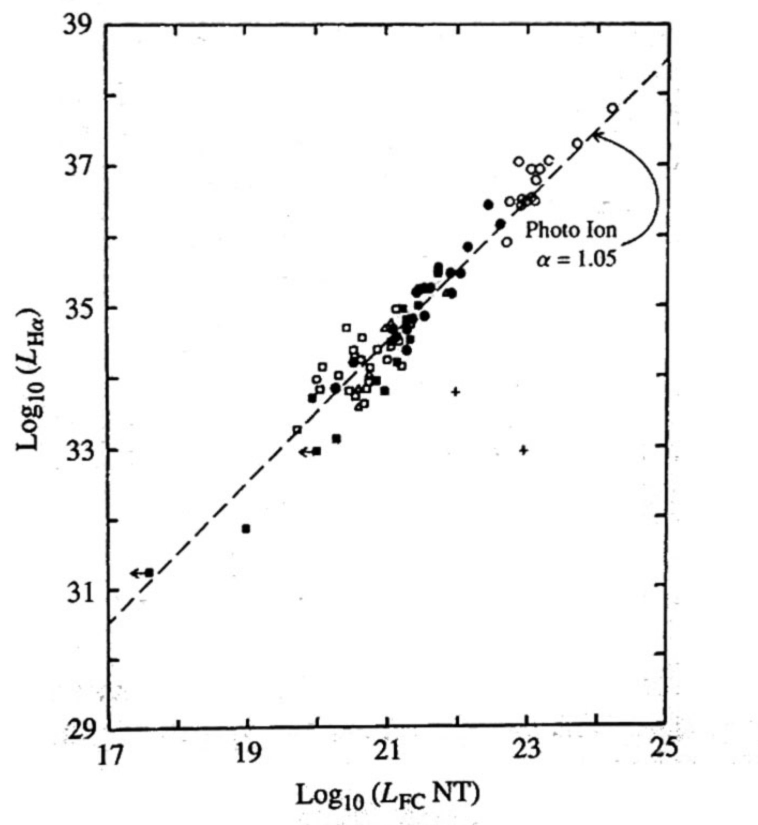


Unified Model

- Bumps are thermal component with the IR component from re-radiation by warm dust
- Low frequency is Rayleigh Jeans tail of thermal emission and turn over of synchrotron into the self-absorption regime
- All AGNs are powered by accretion of material onto central SMBH
- Observational differences such as broad emission lines, radio and X ray strength are mainly dependent on viewing angle and different accretion rates and masses

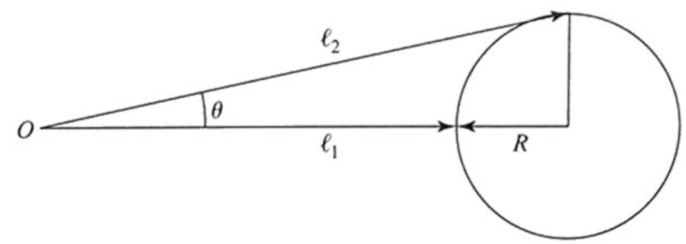
Unified Model

- Evidence:
  $H\alpha$ emission from ionization of gas by continuum radiation so the correlation between the two should be the same across AGN
- Seyfert 2s are Seyfert 1s that are hidden from direct view by optically thick material, reflection from ISM shows a diminished Seyfert 1 spectrum with reflection polarization



Central Engine

- Rapid variability on the hour time scale indicates a compact source
- Light travel time between the edge and center of a source of radius R will blur out intrinsic variability



$$l_2 = \frac{l_1 + R}{\cos\theta} \approx l_1 + R$$

$$\Delta t = \frac{l_2 - l_1}{c} \approx R/c$$

Central Engine

- Plugging in 1 hr gives $R \sim c\Delta t \sim 1.1 \times 10^{12}\mathrm{m} = 7.2\mathrm{AU}$ More generally with a relativistic velocity of source:

$$R \sim c\Delta t/\gamma$$

- Mass is not an observable but a rough lower limit comes from comparing the observed luminosity to the Eddington luminosity. Eddington luminosity (§10.6) is the limit at which radiation pressure exceeds the gravitational force
- Momentum of photons $p = E/c$
- Change in momentum related to luminosity

$$\frac{dp}{dt} = \frac{1}{c}\frac{dE}{dt} = \frac{L}{c}$$

Eddington Luminosity

- Pressure is force per unit area

$$P = \frac{L}{4\pi r^2 c}$$

- Given an interaction between and the photon (e.g. Thomson scattering) with cross section σ the outward force (per electron-proton pair)

$$F_{\mathrm{rad}} = \sigma \frac{L}{4\pi r^2 c}$$

- Balance gravitational force on proton

$$F_{\mathrm{grav}} = -\frac{GMm_p}{r^2}$$

Eddington Luminosity

- Solve for L yields Eddington luminosity

$$L_{\rm Ed} = 4\pi Gc\frac{m_p}{\sigma}M \sim 1.5\times 10^{31}W\left(\frac{M}{M_\odot}\right)$$

For $L = 5\times 10^{39}$W

$$M > 3.3\times 10^{8}M_\odot$$

- Lower limit since gravitational force can exceed radiation pressure - not vice versa otherwise source of luminosity will be blown out in an outflow
- Like galactic center, mass in small radius can only be black hole.

Radiative Efficiency

- Deep gravitational potential provides a source of energy. Dropping matter directly into a black hole does not release the energy - must strike something - matter in the accretion disk
- Rough estimate of efficiency says that it depends mainly on how far the matter falls before radiating its energy and the mass accretion rate
- Define the efficiency η and relate it to the gravitational potential energy of the infalling material

$$L_{\rm disk} = \eta \dot{M} c^2 \sim \frac{d}{dt}\frac{GMm}{r} = \frac{GM\dot{M}}{r}$$

Radiative Efficiency

- Take infall radius in units of Schwarzschild radius $R_S = 2GM/c^2$

$$\eta \dot{M} c^2 \sim \frac{1}{2}\frac{R_S}{r}\dot{M}c^2$$

$$\eta \sim \frac{1}{2}\frac{R_S}{r}$$

  which is a relatively high efficiency (c.f. stars $\eta = 0.007$) if the material gets to near the Schwarzschild radius. A better modelling of the accretion disk corrects this estimate downwards by ~ 2

- Last stable orbit of a non-rotating black hole is $r = 3R_S$ (where the Schwartschild radius is on order 2 AU for $10^8 M_\odot$)
- Radiative efficiency is $\eta \sim 0.057$
- Maximally rotating black hole has $r = 0.5R_S$ and can release 0.423 of rest mass energy

Accretion Disk

- Somewhat more detailed description: available energy heats the accretion disk which then radiates the luminosity as a quasi-black body
- As mass m falls in the potential M, its total energy gets increasingly negative and the energy difference goes into radiation. From Virial theorem or Keplerian orbits:

$$E = -G\frac{Mm}{2r}$$

- The energy difference of mass falling through a ring of disk dr is radiated

$$dE = \frac{dE}{dr}dr = G\frac{Mm}{2r^2}dr$$

Accretion Disk

- The amount of mass falling within a time dt can be reexpressed through the accretion rate $m = \dot{M}dt$

$$dE = \frac{GM\dot{M}}{2r^2}drdt$$

- Luminosity from ring $dL = dE/dt$

$$dL = \frac{GM\dot{M}}{2r^2}dr$$

- Associate with a temperature given Stefan-Boltzmann law $L = A\sigma_B T^4$ with area A of both sides of the disk

Accretion Disk

- With $A = 2(2\pi r dr) = 4\pi r dr$ eliminate in favor of temperature

$$dL = 4\pi r dr \sigma_B T^4 = \frac{GM\dot{M}}{2r^2} dr$$
$$T^4 = \frac{GM\dot{M}}{8\pi\sigma_B r^3}$$

- With an inner radius $r \propto R_S \propto M$ and $\dot{M} \propto M$ (assuming near Eddington limited), expect a scaling of

$$T \propto M^{-1/4}$$

for $M \sim 10^8 M_\odot$ and Eddington limited accretion $3kT$ peak photons correspond to UV to soft-Xray with a peak frequency that declines slowly with mass

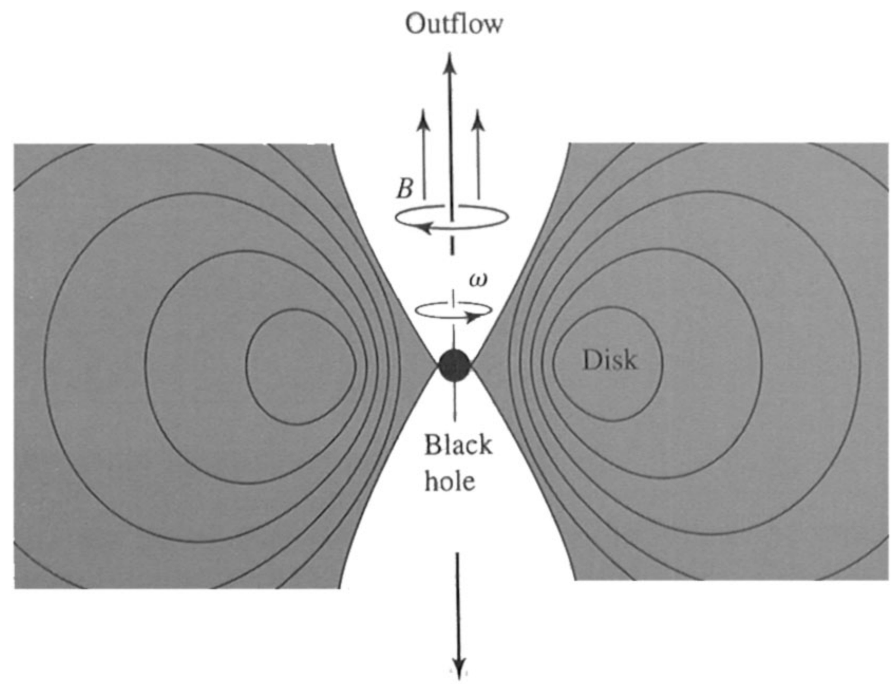
Accretion Disk

- Structure: in the interior $1000R_S$ radiation pressure exceeds gas pressure resulting in thick hot disk or torus - responsible for thermal emission - big blue bump
- From 10^{4-5} R_S gas pressure dominates and a thin disk is supported by gas pressure
- Beyond 10^5R_S the disk breaks up into small clouds
- Continuum radiation from synchrotron radiation - accretion disk is highly conducting so orbiting material generates magnetic field - varying magnetic field generates electric fields that accelerate charged particles away from disk - spiralling in magnetic field
- X-rays can come from an additional boost of synchrotron photons by inverse Compton scattering

Broad/Narrow Line Regions

- Broad-line region - responds to variability of the central source on order a month - indicates clumpy clouds distributed in a region of 10^{15}m around the central source
- In Seyfert 2s, the thick torus obscures the broad line clouds
- Narrow line clouds further out, unobscured at a temperature $\sim 10^4$K in a roughly spherical distribution

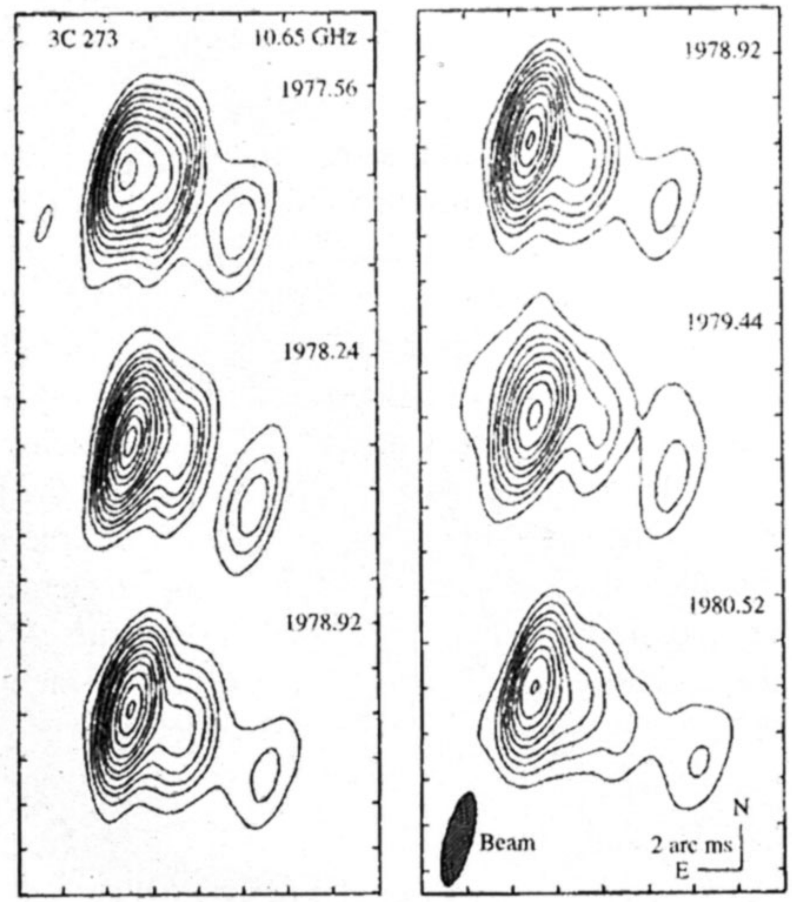
Jets



- Outflows and energy
  can also come from rotation
  - Blandford Znajak process
- Outflows columnated
  into a jet by the thick
  disk along the axis of disk
  - if line of sight intersects this
  axis AGN appears as blazar
- Jet propagates outwards and
  hits ISM forming a shock front
  and radio lobes. Shocks can also accelerate particles through the
  Fermi mechanism

“Superluminal” Motion

- Apparent
  proper motion of knots in jets
  indicate relativistic motion.
- Radio
  interferometry measurements
  measure angular
  velocity of knot across the sky.
- Given a distance
  infer transverse velocity



“Superluminal” Motion

- Example quasar 3C 273 has angular velocity $\mu = 0.0008''$/yr and a distance of $d = 440h^{-1}$ Mpc (from the cosmological redshift)

$$v_{\rm app} = d\mu = 5.57h^{-1}c$$

  where $h \sim 0.72$ is the reduced Hubble constant which parameterizes the distance redshift relation

- Apparent superluminal motion
- Superluminal motion is an optical illusion from projection. Consider a knot moving at some true velocity v at some angle ϕ from the line of sight

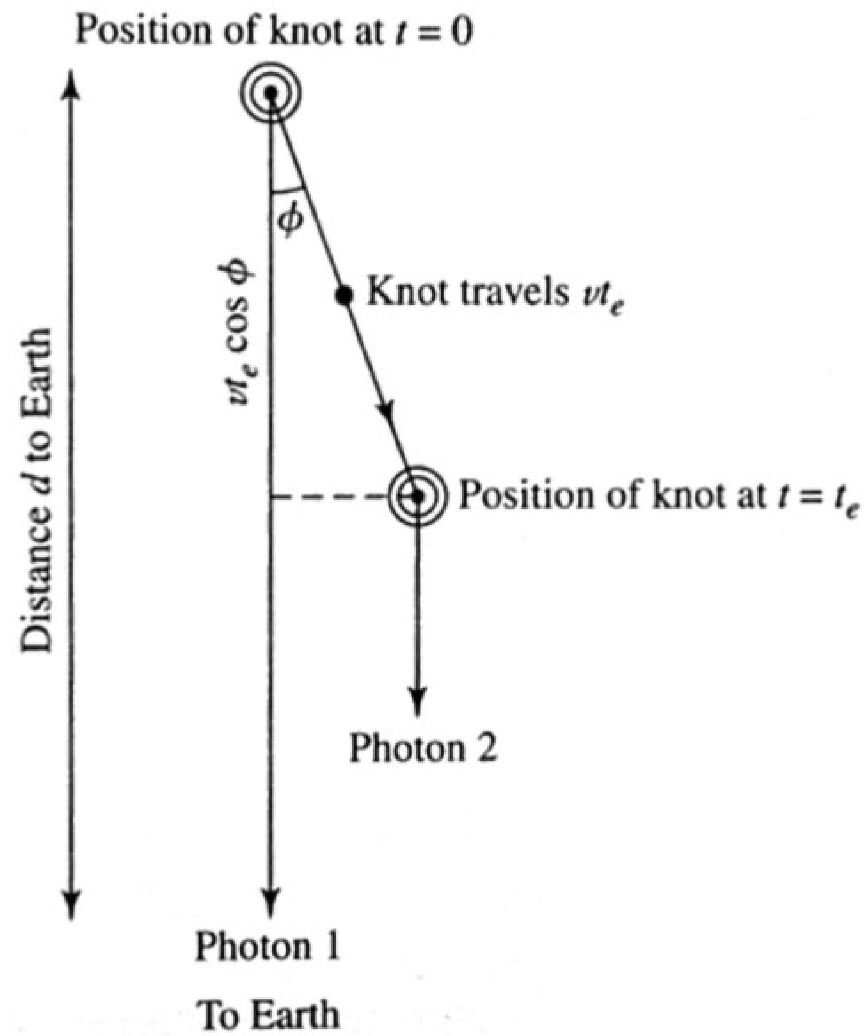
"Superluminal" Motion

- Photon emitted from the knot at $t = 0$ arrives at the observer a distance d away after

$$t_1 = \frac{d}{c}$$

- Photons emitted some time later at t_e come from a distance that is closer by $vt_e \cos\phi$ and hence take a shorter time to arrive

$$t_2 = t_e + \frac{d - vt_e \cos\phi}{c}$$



“Superluminal” Motion

- If the velocity is close to the speed of light and motion nearly along line of sight the blob will be almost caught up with the first photon and so the time delay between the two will be small

$$\Delta t = t_2 - t_1 = t_e \left(1 - \frac{v}{c} \cos\phi\right)$$

- Apparent velocity is the transverse distance over the delay

$$v_{\rm app} = \frac{v t_e \sin\phi}{\Delta t} = \frac{v \sin\phi}{1 - (v/c)\cos\phi}$$

- If $v \longrightarrow c$ and $\phi \longrightarrow 0$ then

$$v_{\rm app}/c \longrightarrow \frac{\sin\phi}{1 - \cos\phi} = \frac{2}{\phi}$$

which can be $\gg 1$

Gravitational Lensing of Quasars

- If a galaxy lies in the the line of sight to a quasar, it can be gravitationally lensed and produce multiple images
- In general relativity, masses curve space and bend the trajectory of photons
- Can be modelled as an optics problem - coordinate speed of light slows in the presence of mass due to the warping of spacetime which is quantified by the gravitational potential

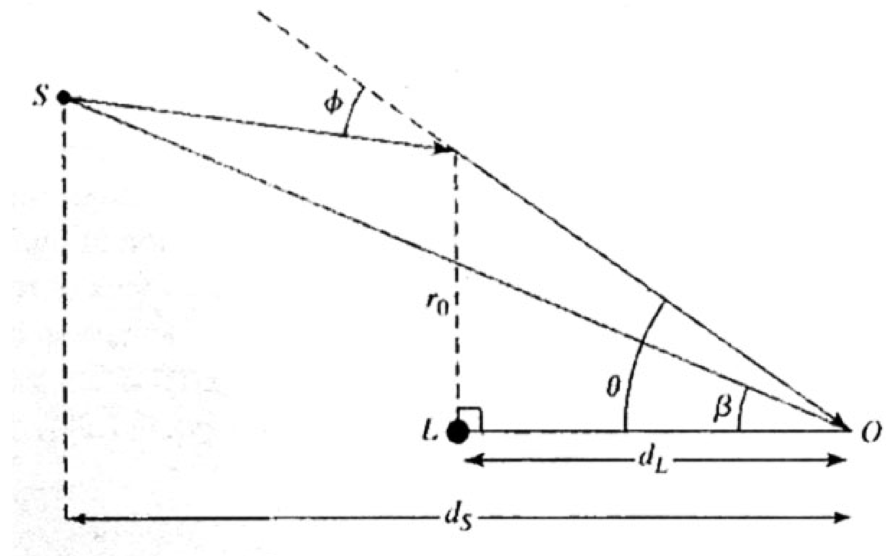
$$v = c\left(1 - \frac{2GM}{rc^2}\right)$$

which defines an effective index of refraction

$$n = \frac{c}{v} = \left(1 - \frac{2GM}{rc^2}\right)^{-1} \approx 1 + \frac{2GM}{rc^2}$$

Gravitational Lensing of Quasars

- As light passes by the object, the change in the index of refraction or delay of the propagation of wavefronts bends the trajectory



$$\nabla n = -\frac{2GM}{r^2 c^2}\hat{\mathbf{r}}$$

- Deflection is small so integrate the transverse deflection on the unperturbed trajectory

$$\phi = -\int_{-\infty}^{\infty} dx \nabla_\perp n = \int_{-\infty}^{\infty} dx \frac{2GMr_0}{\left(r_0^2 + x^2\right)^{3/2} c^2} = \frac{4GM}{r_0 c^2}$$

Lens Equation

- Given the thin lens deflection formula, the lens equation follows from simple geometry
- Solve for the image position θ with respect to line of sight. Small angle approximation

$$(d_S - d_L)\sin\phi = d_S \sin(\theta - \beta)$$

$$(d_S - d_L)\phi \approx d_S(\theta - \beta)$$

- Substitute in deflection angle

$$(d_S - d_L)\frac{4GM}{r_0 c^2} \approx d_S(\theta - \beta)$$

- Eliminate $r_0 = d_L \sin\theta \approx d_L\theta$

Lens Equation

- Solve for θ to obtain the lens equation

$$\theta^2 - \beta\theta - \frac{4GM}{c^2}\left(\frac{d_S - d_L}{d_S d_L}\right) = 0$$

- A quadratic equation with two solutions for the image position - two images

$$\theta_\pm = \frac{\beta}{2} \pm \frac{1}{2}\sqrt{\beta^2 + 16\frac{GM}{c^2}\left(\frac{d_S - d_L}{d_S d_L}\right)}$$

- Sum of angles - second image has negative angle - opposite side of lens

$$\theta_+ + \theta_- = \beta$$

Lens Equation

- Measure both images and measure the mass:

$$\theta_+\theta_- = \frac{\beta^2}{4} - \frac{1}{4}\left(\beta^2 + 16\frac{GM}{c^2}\left(\frac{d_S - d_L}{d_S d_L}\right)\right)$$

$$\theta_+\theta_- = -4\frac{GM}{c^2}\left(\frac{d_S - d_L}{d_S d_L}\right)$$

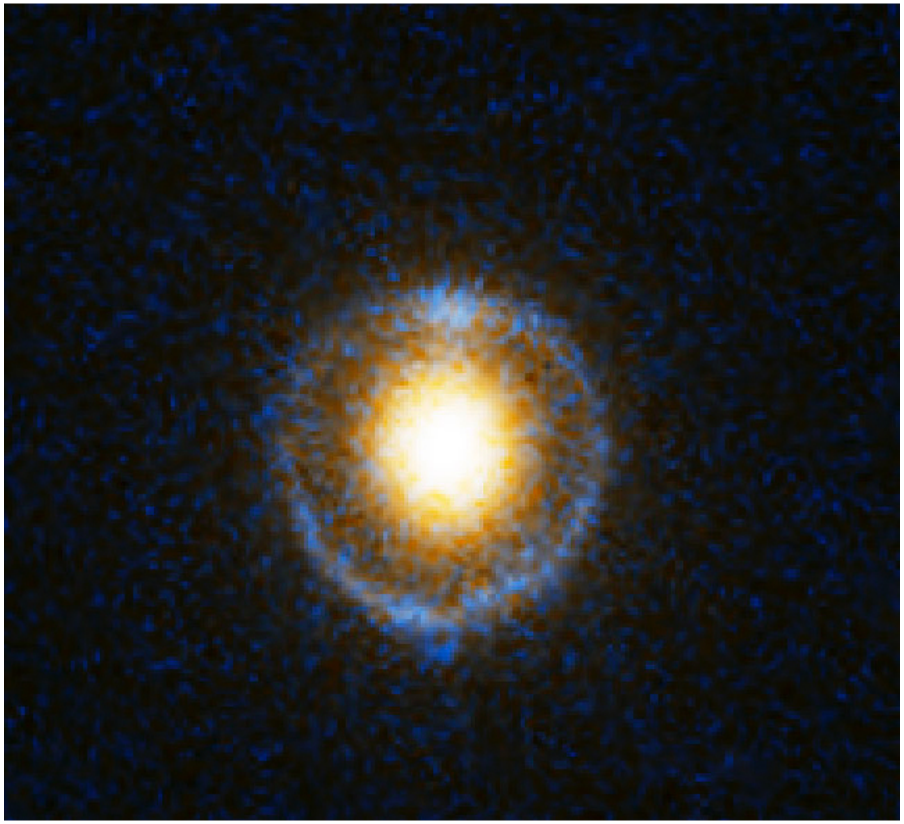
$$M = -\frac{\theta_1\theta_2 c^2}{4G}\left(\frac{d_S d_L}{d_S - d_L}\right)$$

Einstein Ring

- If source is aligned right behind the lens $\beta = 0$ and the two images merge into a ring - Einstein ring - at an angular separation

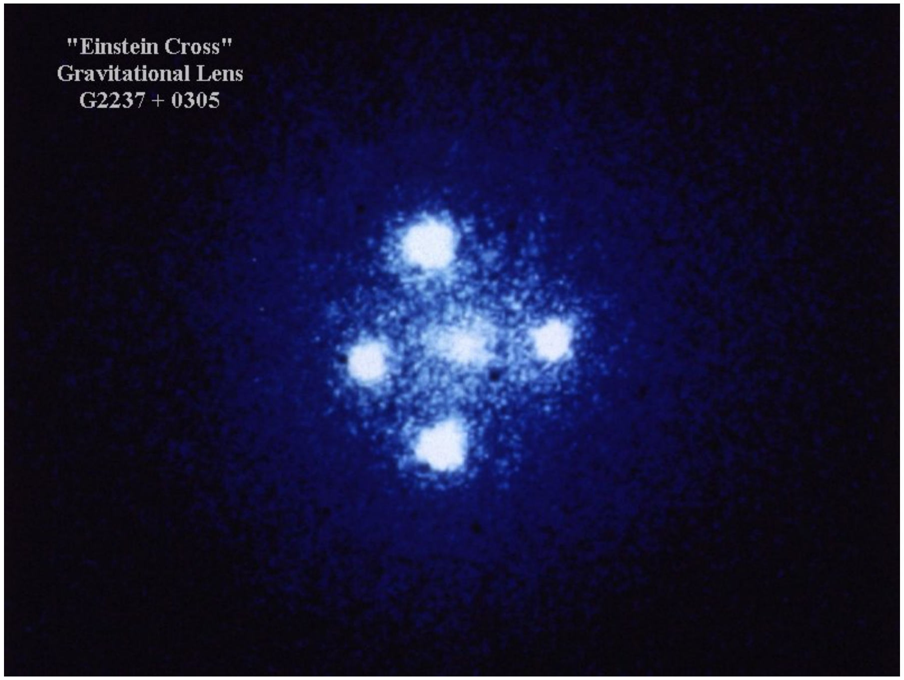
$$\theta_E = \sqrt{\frac{4GM}{c^2}\left(\frac{d_S - d_L}{d_S d_L}\right)}$$

- More generally, quasar is lensed by the extended mass of a galaxy that is not perfectly axially symmetric



Einstein Cross

- With non symmetric extended potential - e.g. an ellipsoidal potential, multiple images form - mathematically an odd number of images but with an even number of bright detectable images
- 4 image system is an Einstein cross



Time Variability

- That the images are of the same object can be verified since quasars are time variable
- Light curve of each image repeats pattern with a time delay associated with geometric delay in propagation and general relativistic time delay
- A way of measuring distances

Magnification

- Lens equation in terms of Einstein radius

$$\theta^2 - \beta\theta - \theta_E^2 = 0$$

- Given an extended source that covers an angular distance $d\beta$ will have an image cover an angular distance $d\theta_\pm$ related by the derivative $d\theta_\pm/d\beta$
- The displacement in the image is purely radial so that the annulus $d\phi$ remains unchanged.
- The surface area of the source $\beta d\beta d\phi$ thus becomes is then given by $\theta_\pm d\theta_\pm d\phi$.

Magnification

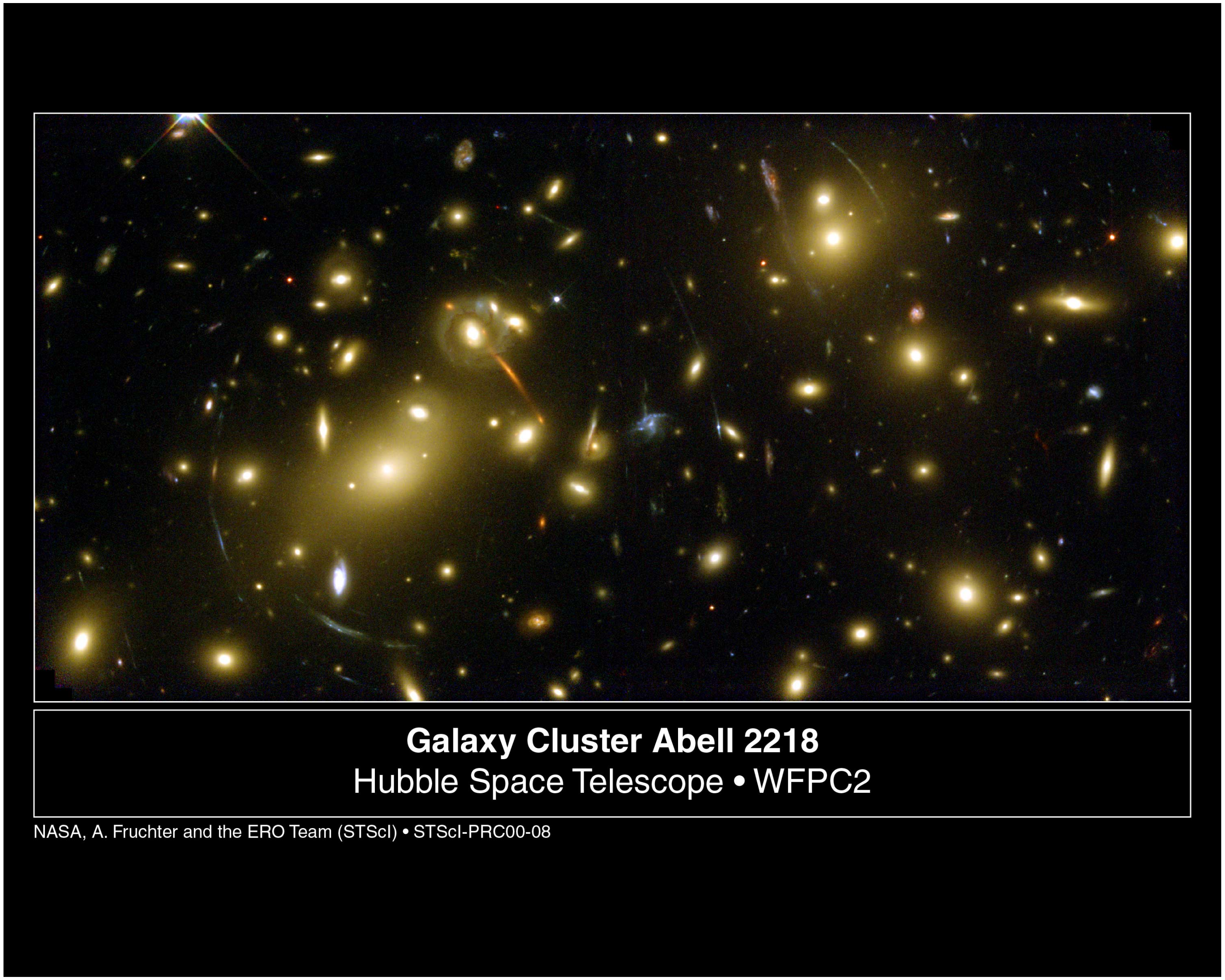
- Summing the two images yields

$$\frac{A_{\rm images}}{A_{\rm source}} = \sum_{\pm} \left| \frac{\theta_\pm}{\beta} \frac{d\theta_\pm}{d\beta} \right| = \frac{(\beta/\theta_E)^2 + 2}{(\beta/\theta_E)\sqrt{(\beta/\theta_E)^2 + 4}}$$

- Surface brightness is conserved so the area ratio gives the magnification
- If two images are not resolved this gives the microlensing magnification formula used in Chap 24 with a moving lens and $u(t) = \beta(t)/\theta_E$
- Magnification and conservation of $d\phi$ implies that image is distorted - stretched out into the tangential direction or "sheared"

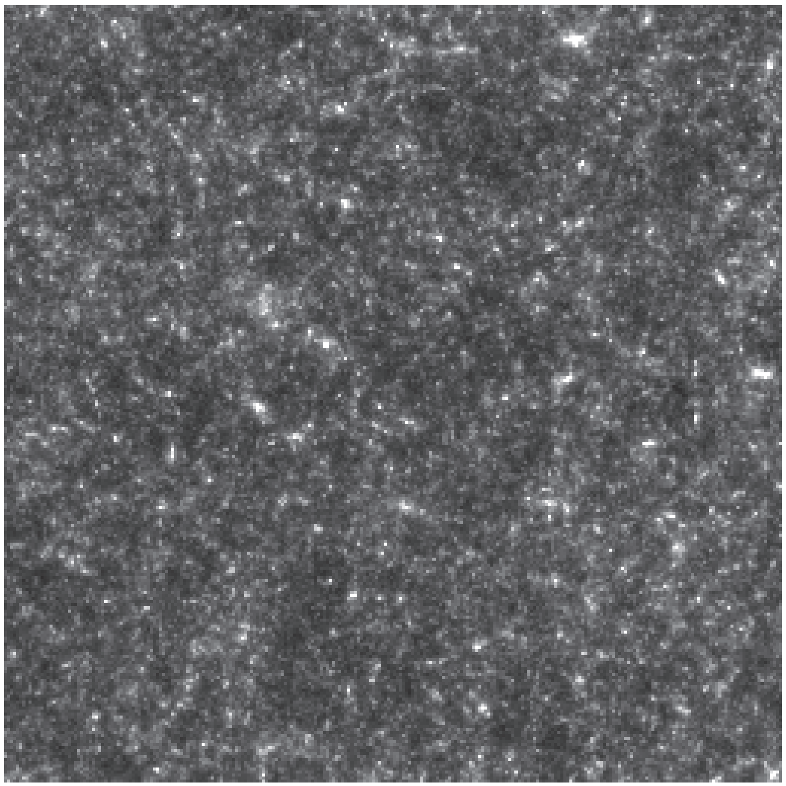
Giant Arcs

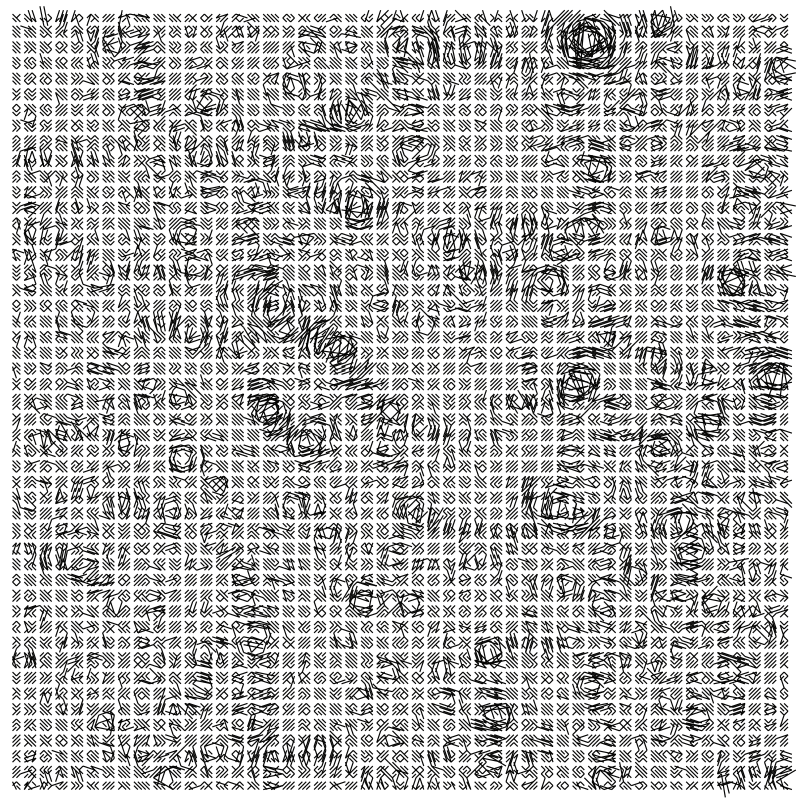
- Giant arcs in galaxy clusters: galaxies, source; cluster, lens



Cosmic Shear

- On even larger scales, the large-scale structure weakly shears background images: weak lensing

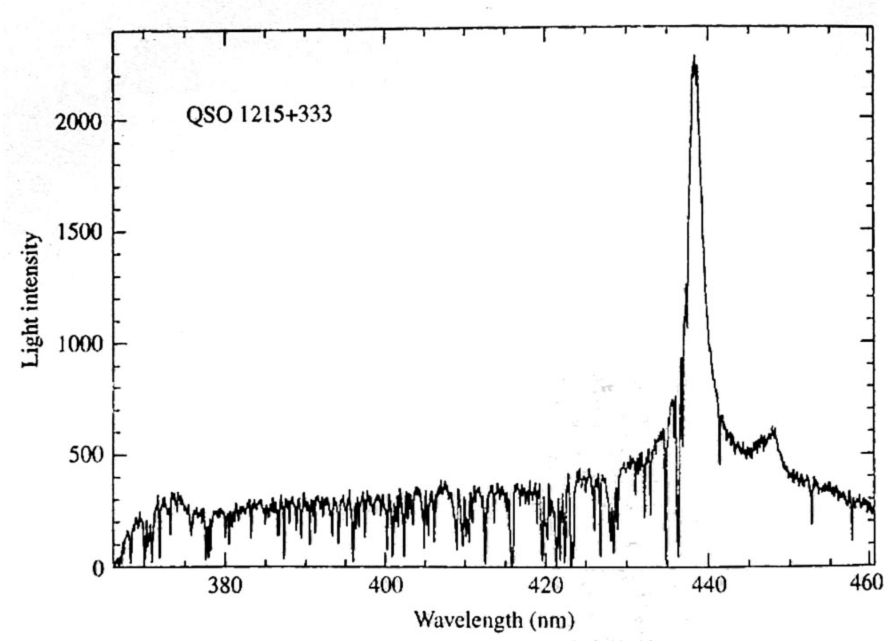




Gunn-Peterson Effect

- Quasars also act as a back light to gas in the universe
- If there is neutral hydrogen along the line of sight, quasar light will be absorbed by the Lyman-α $n = 2 \to 1$ transition
- Gunn-Peterson effect: large cross section implies that seeing *any* flux indicates the intergalactic medium is nearly fully ionized
- Fully ionized out to $z = 6$ with indications from the highest redshift quasars from SDSS that beyond that redshift there is a detectable neutral fraction

Lyα Forest



- Since recombination is more efficient in a dense medium, density fluctuations in the large scale structure of the universe produce a forest of lines called the Lyα forest
- Observed flux in the forest gives a map of large scale structure that can be used to infer cosmological information such as the power spectrum of density fluctuations