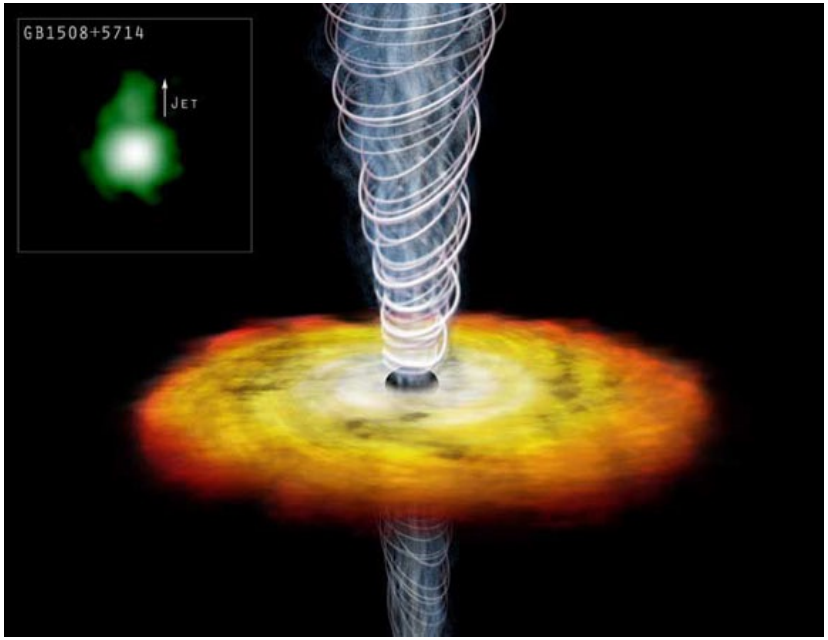
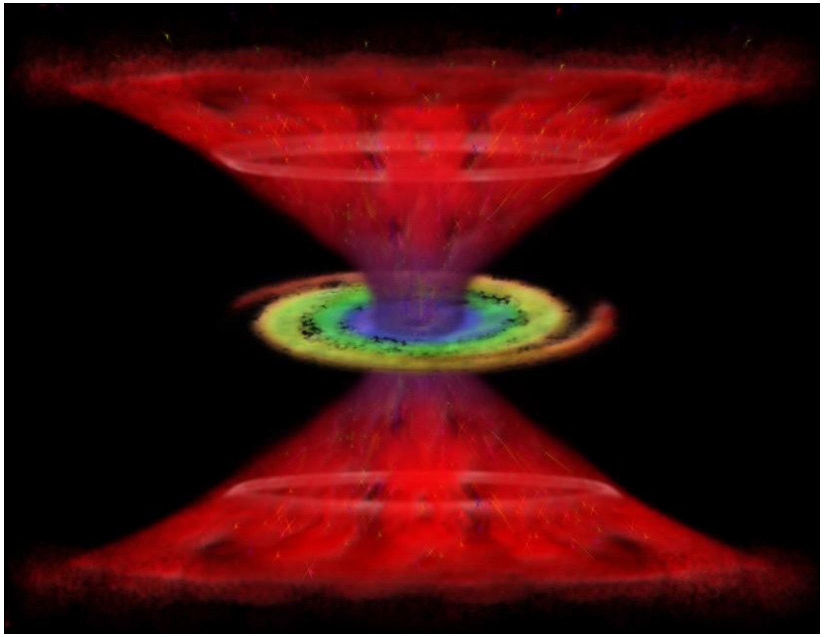
Active Galactic Nuclei



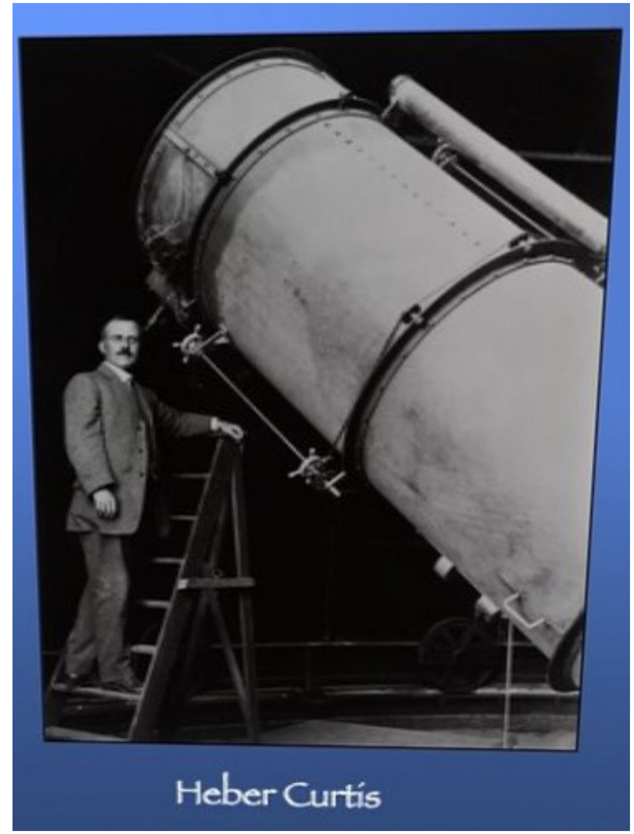


The Discovery of Active Galactic Nuclei

Very soon after the existence of galaxies was established by Edwin Hubble's astronomers began to realize that something strange was going on in galactic nuclei.

The light emanating from the centers of many galaxies appeared to be very different from that observed in stars.

In 1917 Heber Curtis observed a jet-like feature emanating from the nucleus of the galaxy M87.

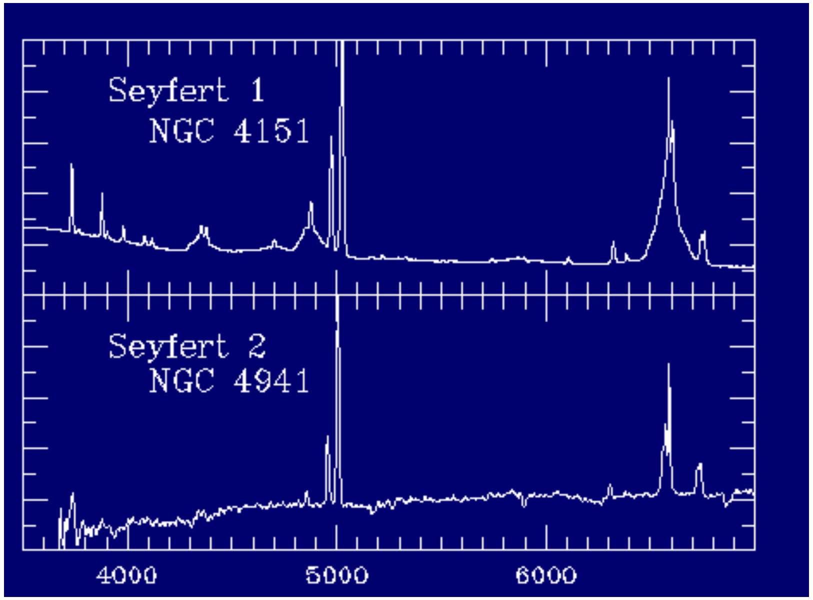


The Discovery of Active Galactic Nuclei

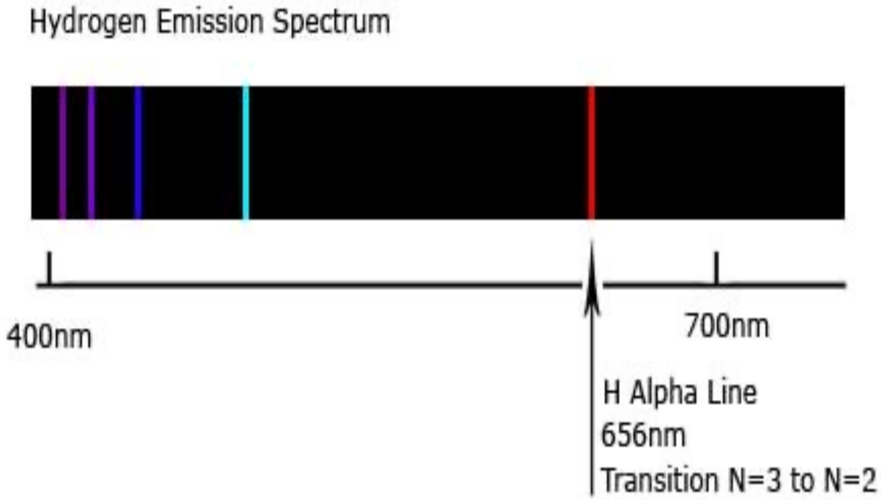
Carl Seyfert at the Mount Wilson observatory in California first observed that a few percent of spiral galaxies contain intense blue nuclei. Such spiral galaxies are now called **Seyfert galaxies.**

The spectra of Seyfert galaxies show strong emission lines of the type typically produced by ionized gas.

The Discovery of Active Galactic Nuclei



Wavelength



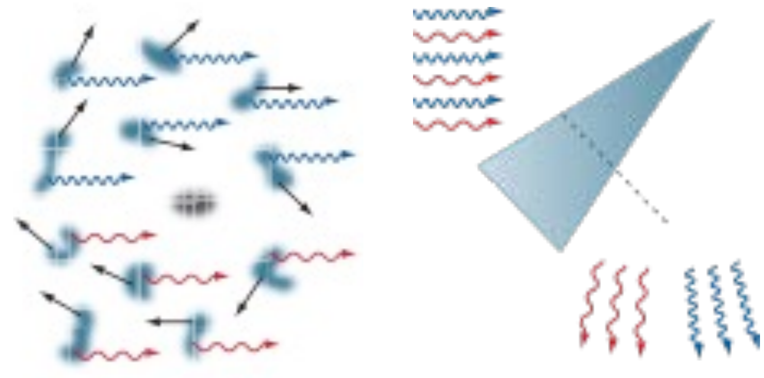
Seyfert galaxies are observationally grouped into ones that show broad and narrow emission lines (**Type I Seyferts**) and ones that show only narrow emission lines (**Type II Seyferts**)

The **narrow lines** are thought to be produced by low density ionized gas with $n_e \sim 10^3$ - $10^6 cm^{-3}$ producing forbidden narrow lines with widths of ~100 km/s

The **broad lines** are thought to come from higher density ionized gas with $n_e > 10^9$ cm^{-3} producing permitted lines with widths of up to 10^4 km/s

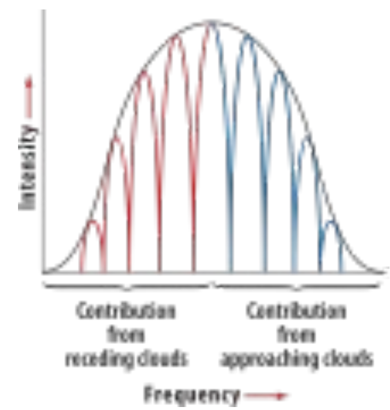
The Broad Emission Lines in Seyfert 1's

The broad lines in type I Seyfert galaxies are thought to be produced in part by Doppler effects in a turbulent gas.



If an array of randomly moving gas clouds emits light in a spectral line, the receding clouds will appear reddened relative to the approaching clouds.

The light from the whole system when spread into a spectrum, yields a line that is much broader than that from an individual cloud.

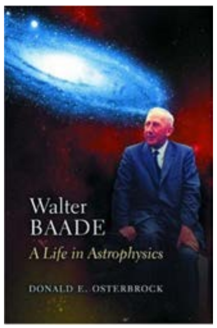


The **overall line width** is determined by the spread in cloud velocities.

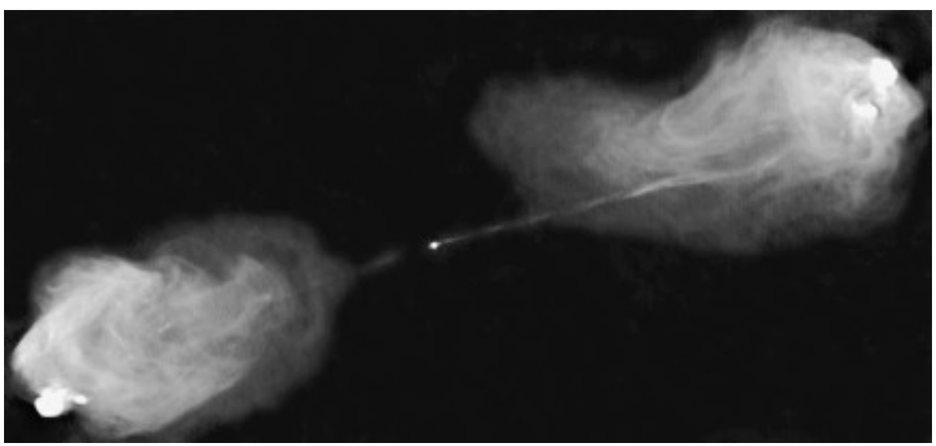
In general, the velocity field might be a superposition of different components, such as Doppler motions, turbulence, shock components, in/outflow components, and rotation.

The Discovery of Active Galactic Nuclei

The Armenian astronomer Markarian discovered that some elliptical galaxies also harbor bright blue nuclei.



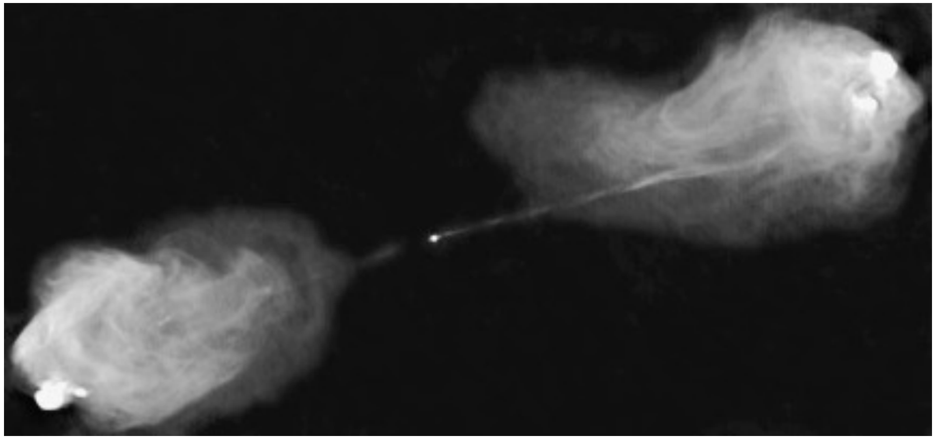
In 1954 Walter Baade of the Mount Wilson and Palomar Observatories was able to identify that a faint galaxy at a redshift of 0.05 was associated with the bright radio source Cygnus A.



Soon after Baade's discovery radio observations showed that the radio emission was emanating from two distinct patches placed symmetrically about the galaxy at ¼ million light-years on each-side.

The Discovery of Active Galactic Nuclei

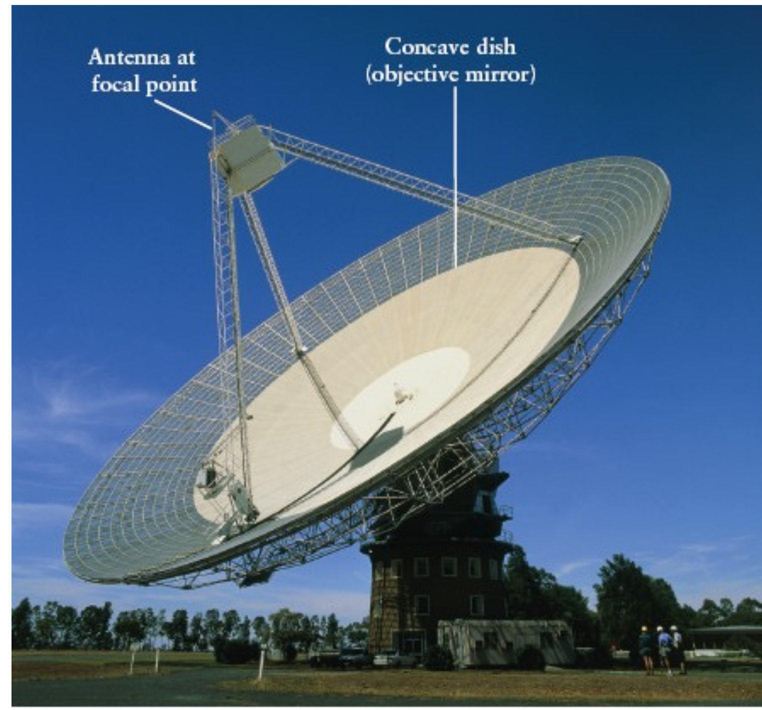
The American astronomer Geoffrey Burbidge showed that the amount of energy needed to power the radio lobes of Cygnus A was equivalent to $10^6\ M_{\odot}c^2$. This indicated that AGN can release energy that is considerably larger than that released in a supernova explosion.



The Discovery of Quasars

In 1963 Hazard and his colleagues using the Parkes Radio telescope in Australia obtained the position of the radio source 3C 273 to an accuracy of a few arcsec. This was made possible by observing 3C 273 during its occultation by the moon.

Single dish radio telescopes have relatively poor resolution due to **diffraction**.

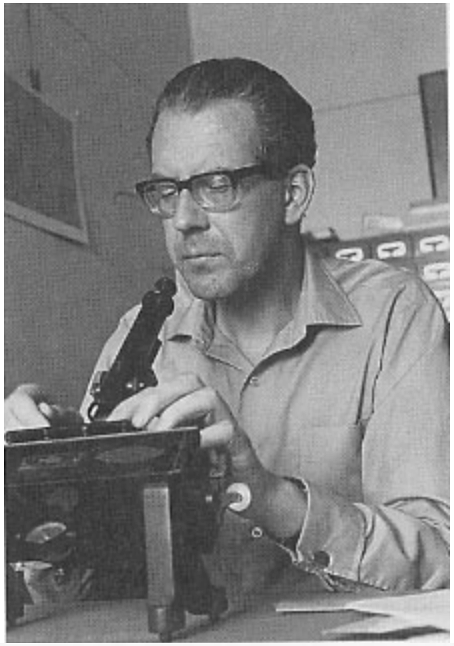


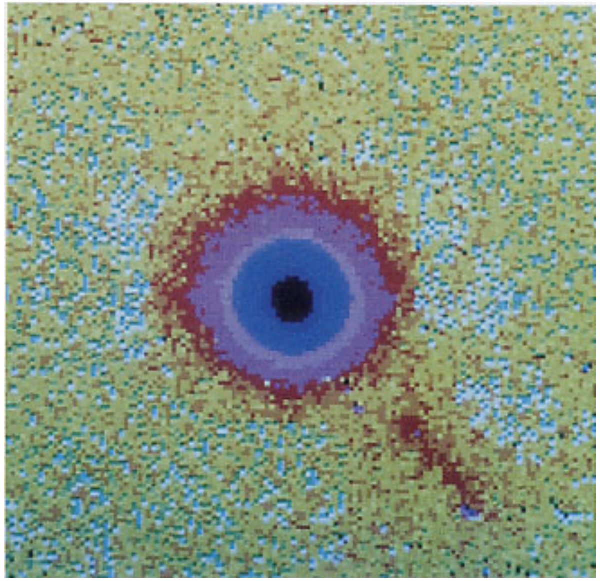
PARKES, NSW, Australia
(64 m diameter)

The Discovery of Quasars

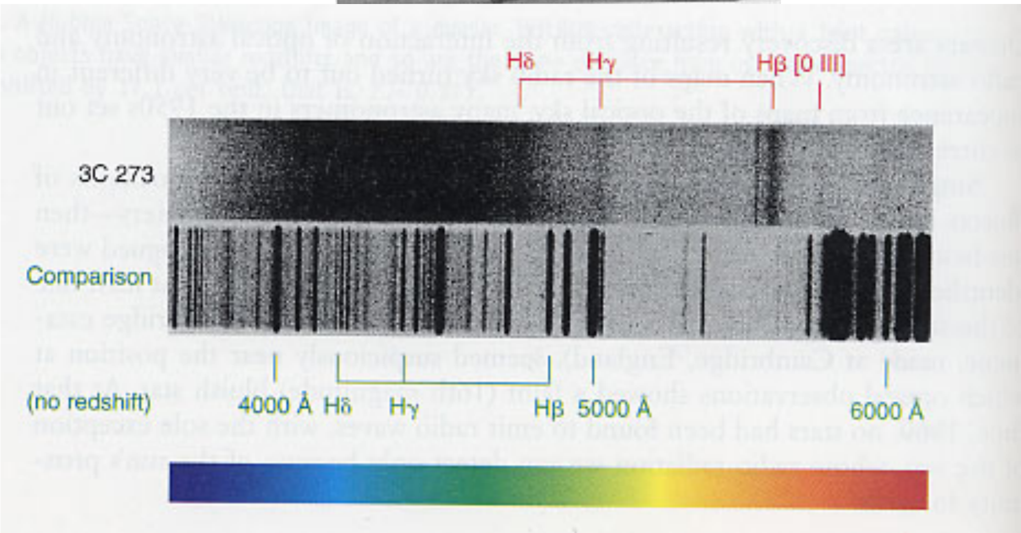
The accurate position of 3C 273 allowed Maarten Schmidt to locate the optical counterpart of 3C 273 and obtain its optical spectrum.

The first breakthrough that lead to the understanding of quasars was the realization by Maarten Schmidt that the emission lines detected in 3C273 were the Balmer-series lines and MgII l2798 lines at a large redshift of $z = 0.158$.





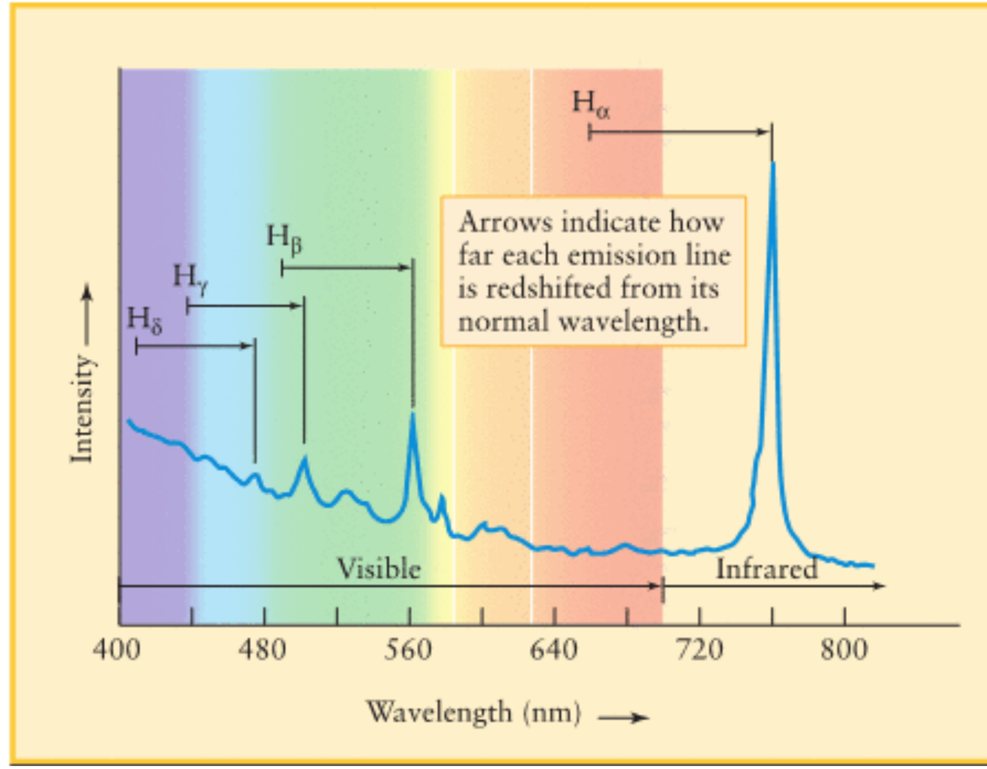
3C 273



The Discovery of Quasars

The large distances of quasars was revealed by their redshifts.

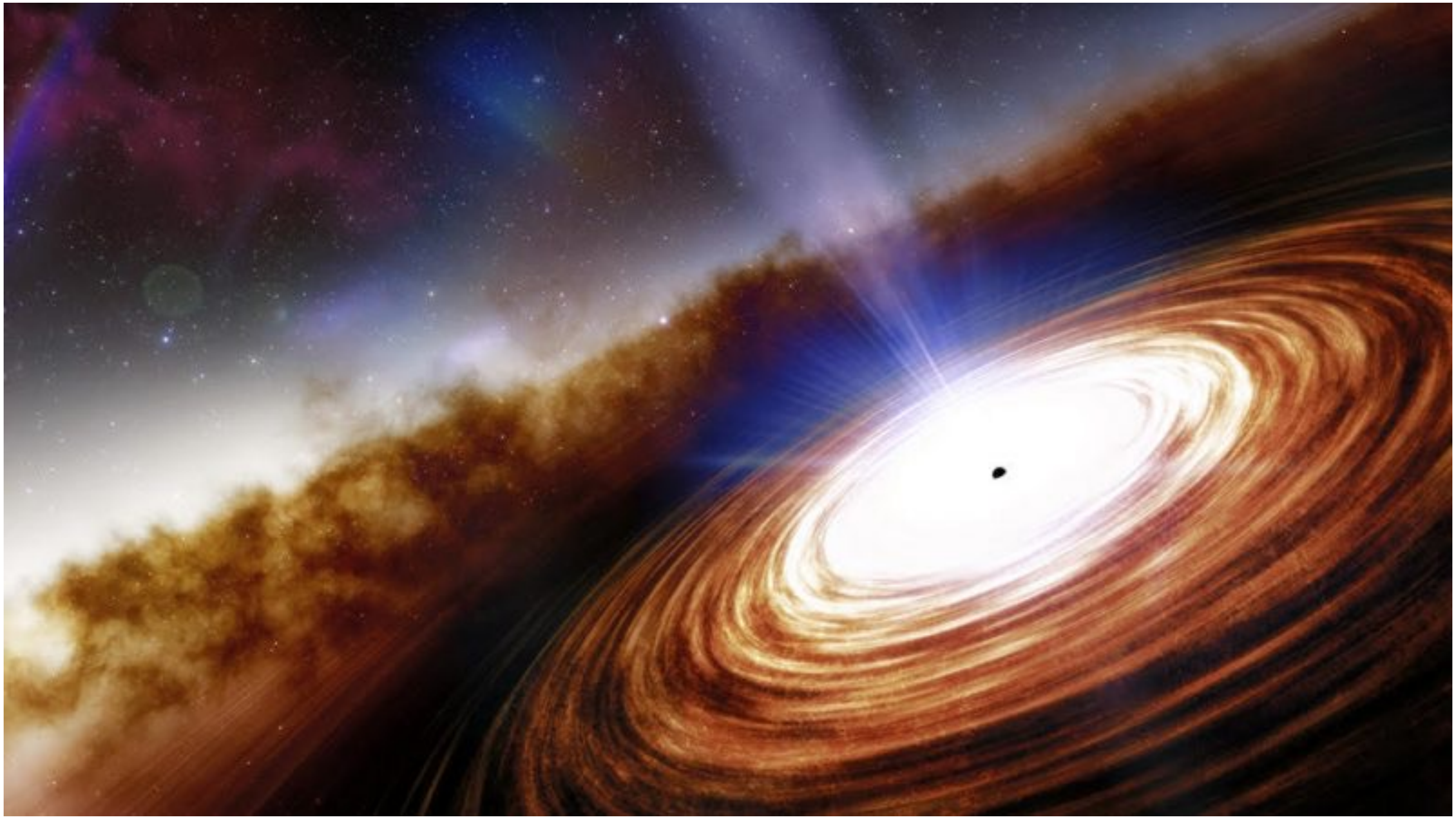
Caution: When a photon travels from a distant object to us the Universe is expanding during its travel so the distance between the object and us has increased by the time the photon gets to us.
The relationship between redshift and distance depends on the cosmological model assumed for the expansion of the Universe!



Maarten Schmidt from Caltech first realized that the emissions lines in 3C 273 were significantly redshifted Balmer lines.

Schmidt determined that 3C 273 has a redshift of $z = 0.158$ which corresponds to a comoving distance of $\sim 2 \times 10^9$ ly.

J0313-1806: The Most Distant Quasar (as of Jan 2021)



The light-travel time to this quasar is 13 billion years (z = 7.64)

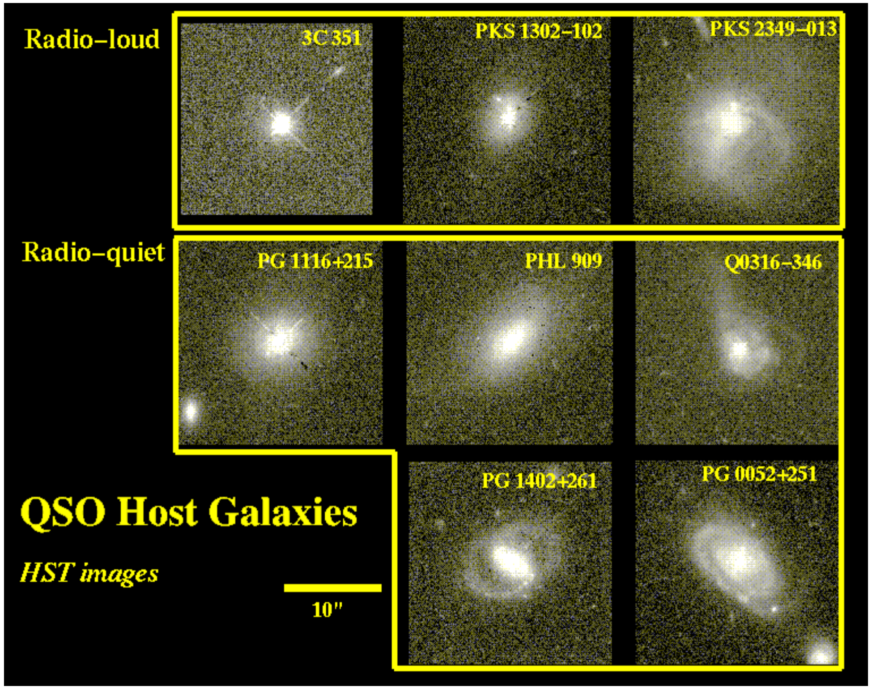
The Discovery of Quasars

Quasars are more luminous versions of Seyfert galaxies. HST observations found that quasars reside in galaxies.

About 10% of quasars are **radio loud** and ~90% **radio quiet at z~2** (but the fractions depend on redshift**)**.

Quasar luminosities are calculated from distances inferred from redshifts, the apparent brightnesses and using the inverse square law.

The average luminosity of 3C 273 is about 10^{40} watts ($L_{\odot} \sim 3.9 \times 10^{26}$ watts and $L_{\text{Milky Way}} \sim 10^{37}$ watts)



Most **radio-loud quasars** reside in the centers of **elliptical galaxies**. Nearby ($z < 0.2$) radio-quiet quasars reside mostly in spiral galaxies and distant ($z > 0.2$) radio-quiet quasars reside in either spiral or elliptical galaxies.

Luminosity from Flux Density

$$L_\nu = 4\pi D_L^2 F_\nu (1 + z)$$

where L_ν is the luminosity density (erg/s/A)
F_ν is the flux density (erg/cm^2/s/A)
D_L is the luminosity distance in cm

Properties of AGN

1. Enormous energy output that can surpass the output from an entire galaxy by a factor of 10^2-10^4 in a tiny volume (<< $1pc^3$). AGN are extremely compact based on their variability.

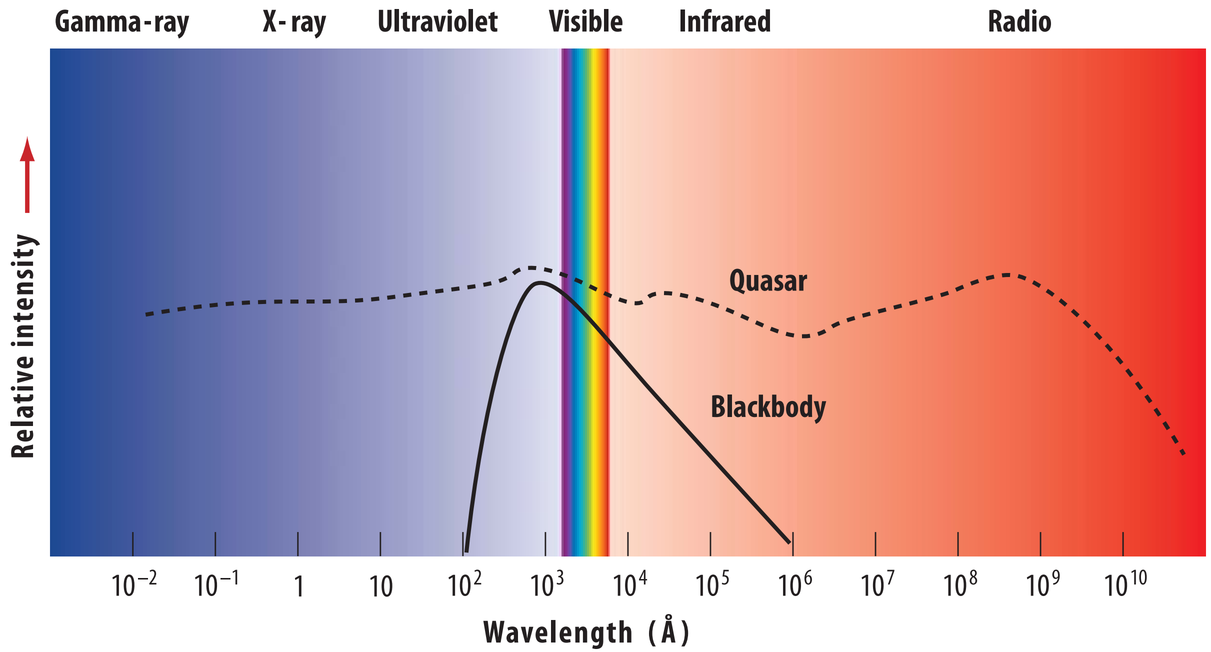
2. The AGN emission can emerge over a wide range of frequencies.

1. Many AGN show strong emission lines in the optical and UV with widths up to 10^4 km/s.

2. AGN show strong cosmological evolution. The more luminous AGN at $z \sim 2.5$ were > 1000 times more numerous then than they are now.

3. Most observations indicate indirectly that AGNs are powered by accretion onto supermassive black holes.

Properties of AGN



The surface of stars emit approximately blackbody radiation whose spectrum has a characteristic shape and peaks at shorter wavelengths for hotter bodies.

A spectrum of a quasar, however, shows that energy is distributed over a much broader range of wavelengths. This is because several regions of different temperature contribute to the total spectrum and also because some of the emission comes from processes (such as synchrotron radiation) that do not have a well defined temperature.

Spectra of AGN

In restricted energy bands the spectra of AGN are approximated with power-laws of the form:

$$F_\nu \propto \nu^{-\alpha}$$

where F_ν *is the flux per unit frequency and* α *is the spectral index*

If we integrate the flux density between 2 frequencies:

$$F(\nu_1, \nu_2) = \int_{\nu_1}^{\nu_2} \nu F_\nu \frac{d\nu}{\nu} = \int_{\nu_1}^{\nu_2} \nu F_\nu \, d\ln\nu = \ln 10 \int_{\nu_1}^{\nu_2} \nu F_\nu \, d\log\nu$$

Used: $\frac{d\ln\nu}{d\nu} = \frac{1}{\nu} \Longrightarrow \frac{d\nu}{\nu} = d\ln\nu$ *and* $\ln\nu = \ln 10 \log\nu$

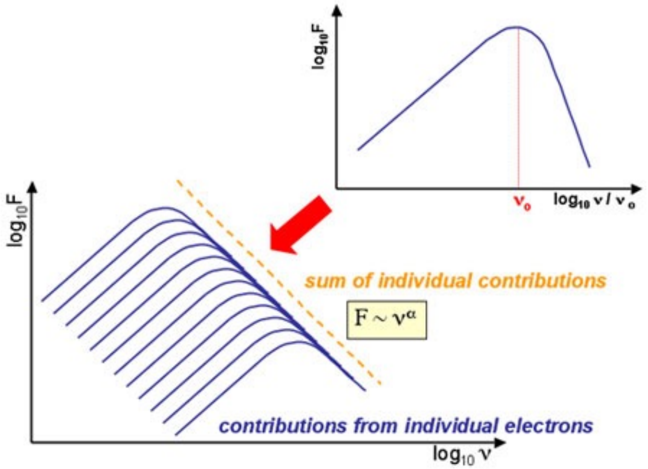
In a plot of νF_ν versus $\log\nu$ the area under the curve between frequencies ν_1 and ν_2 represents energy emitted per unit time and unit area.

Spectra of AGN

Big Blue Bump: Optical/UV emission originating mostly from the accretion disk. The "sum" of blackbody spectra over a range of temperatures.

Infrared Bump: Emission from warm dust grains (T < 2000K)

(Top right) **Synchrotron emission** produced by a single electron performing a circular motion in a B field. The cutoff arises because above some frequency the radiation cannot penetrate the plasma of electrons. This is called synchrotron self absorption.



(Bottom left) If the distribution of electrons obeys a power law the spectrum from all the electrons is also a power law.

Thermal, Non-Thermal and Polarized Radiation.

Thermal radiation is caused by the random thermal motion of the atoms and molecules that make up the emitting object. Any body with some temperature emits thermal radiation.

The spectra of stars resemble that of a blackbody spectrum. Superimposed on this are usually absorption lines. The spectrum of a normal galaxy is just the sum of the spectra of the stars in the galaxy smeared by the Doppler effect.

Non thermal radiation is radiation other than that emitted by a heated body One type of non thermal radiation is called **synchrotron** and is produced by **relativistic** electric charges accelerating in a strong magnetic field.

Polarized radiation is radiation where the direction of the electric field vector is oriented in a specific direction. **Synchrotron radiation is** usually **partially polarized** whereas thermal radiation is usually not.

Estimate the Radio Luminosity of Cygnus A

The distance to Cygnus A: $d = 170$ Mpc ($z = 0.05607$)
The flux density at 1400 MHz: $F(1400\ \mathrm{MHz}) = 1.255\ 10^{-23}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$
Assume a spectral index of $\alpha = 0.8$
Estimate the luminosity between $\nu_1 = 10^7$ Hz and $\nu_2 = 3 \times 10^9$ Hz:

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Assume a spectral index of $\alpha = 0.8$
The luminosity between frequencies of $\nu_1 = 10^7$ Hz and $\nu_2 = 3 \times 10^9$ Hz is:

$$L = 4\pi d^2 F(\nu_1, \nu_2) = 4\pi d^2 \int_{\nu_1}^{\nu_2} F_\nu d\nu$$

$$\frac{F_\nu}{F(1400\text{ MHz})} = \frac{\nu^{-\alpha}}{(1400MHz)^{-\alpha}} \Longrightarrow F_\nu = F(1400MHz)\left(\frac{\nu}{1400MHz}\right)^{-\alpha}$$

$$L = 4\pi d^2\ F(1400MHz) \int_{\nu_1}^{\nu_2} \left(\frac{\nu}{1400MHz}\right)^{-\alpha} d\nu = 2.4 \times 10^{37} W$$

(note: to include the cosmological correction we multiply this by 1+z)

This is several million times more than what is produced by a normal galaxy like M31.

Black Hole Paradigm

Black Hole Paradigm

The reasoning that led to the black hole paradigm (ie that black holes reside in the centers of AGN) is the following:

Scientists estimated the compactness M/R of AGN and compared it to the maximum *observable* compactness predicted for a spinning black hole:

$$\left(\frac{M}{R}\right)_{max} = \left(\frac{c^2}{G}\right)$$

where M is the mass of the black hole and R is the inner most stable orbit

The size R of an AGN can be estimated from its variability. **R < cΔt**, where Δt is the shortest variability timescale observed in the AGN.

Black Hole Paradigm

The mass of an AGN can be inferred from a variety of methods.

Method 1:
From the width Δv of the broad emission line H_β and the distance R of the broad line clouds from the BH.

$$M_{BH} \approx \frac{R \Delta v^2}{G}$$

Method 2:
For the AGN in our galaxy we estimate the size of the central object from measuring the orbits of the stars near the central object and using Newtonian mechanics.

Black Hole Paradigm

Observed compactness M/R of the z = 3.91 quasar APM 08279+5255:

Based on the observed X-ray variability of this source of $\Delta t \sim 16.2$ days
$R \sim c\Delta t/(1+z) = 7.4 \times 10^{15}$cm

The mass of the "compact object" is estimated to be $M \sim 10^{10}\ M_\odot$

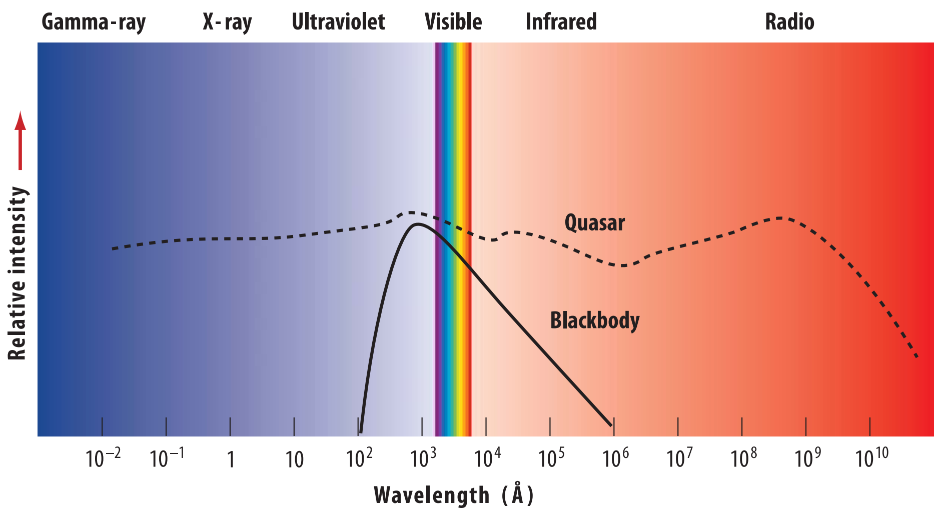
$M/R \sim 0.1\ c^2/G$ which is close to the upper limit of c^2/G predicted by General Relativity!

AGN Spectra

An AGN spectrum is made up of:

- Thermal emission radiated from the accretion disk at UV and optical wavelengths.

- The infrared emission from dust that has been heated to a temperature of about 1000 K by absorbing UV radiation from the disk.



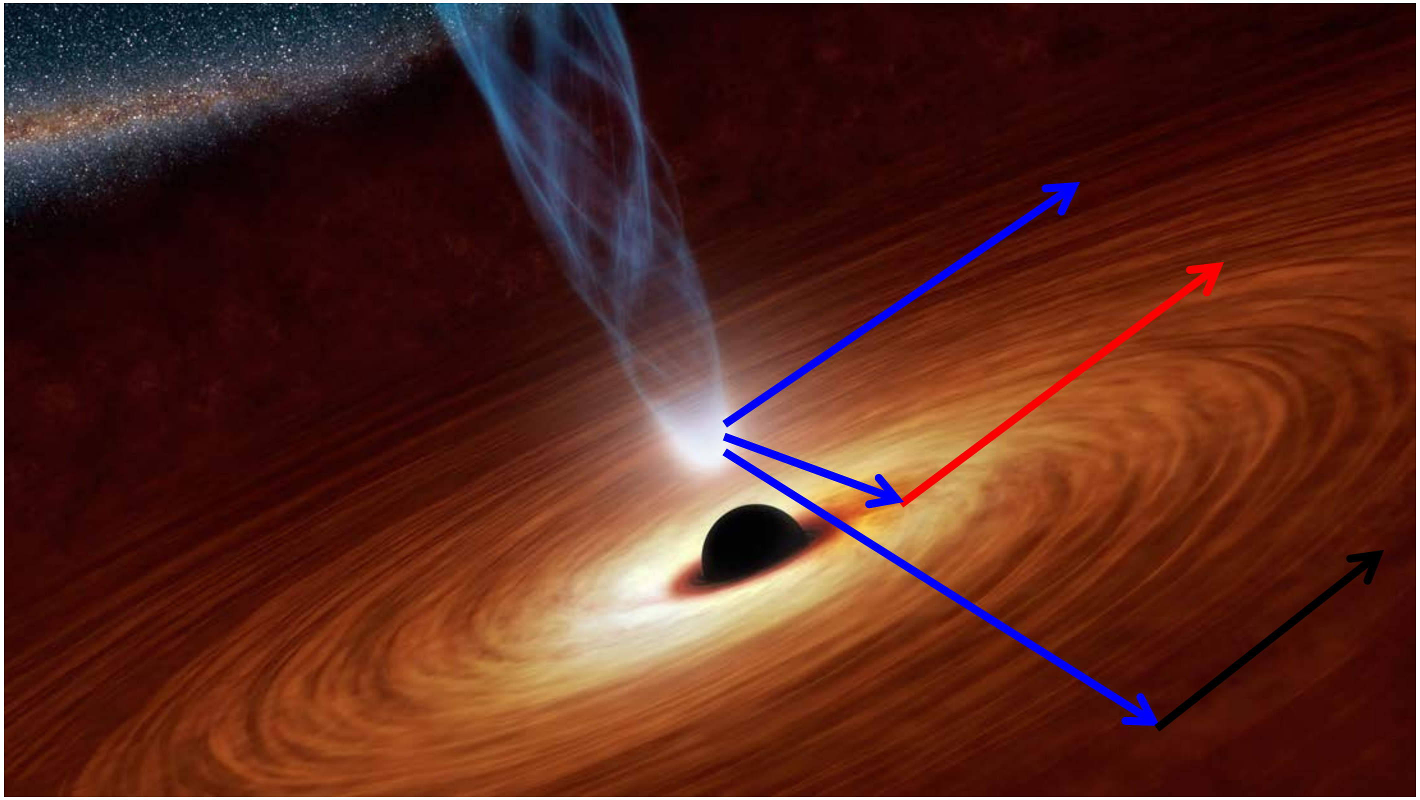
- X-ray emission from a hot corona made up of energetic electrons.

- X-rays *reprocessed* in the accretion disk.

- Radio and gamma ray emission from jets.

- X-ray, optical and UV emission lines from ionized gas clouds and winds.

Fiducial Model

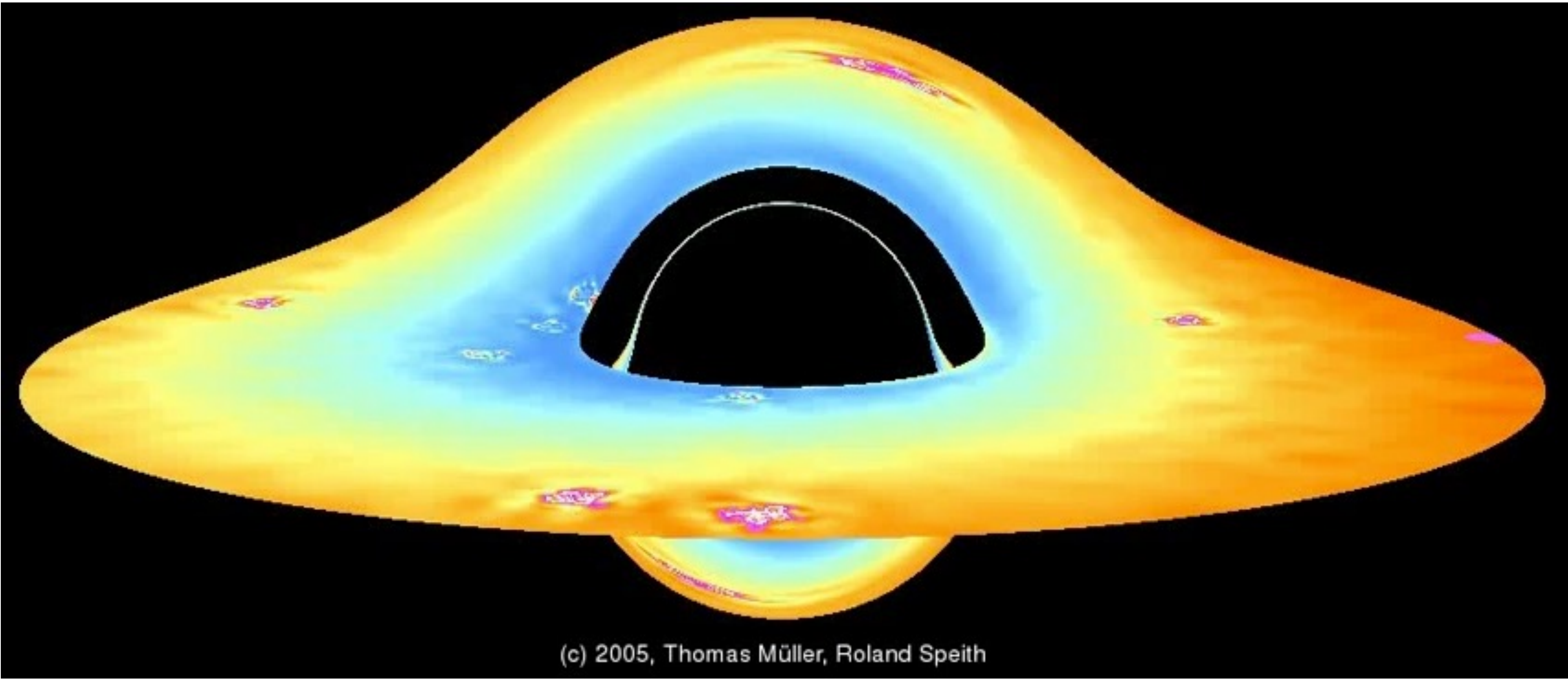


X-ray Power-Law
from compact corona

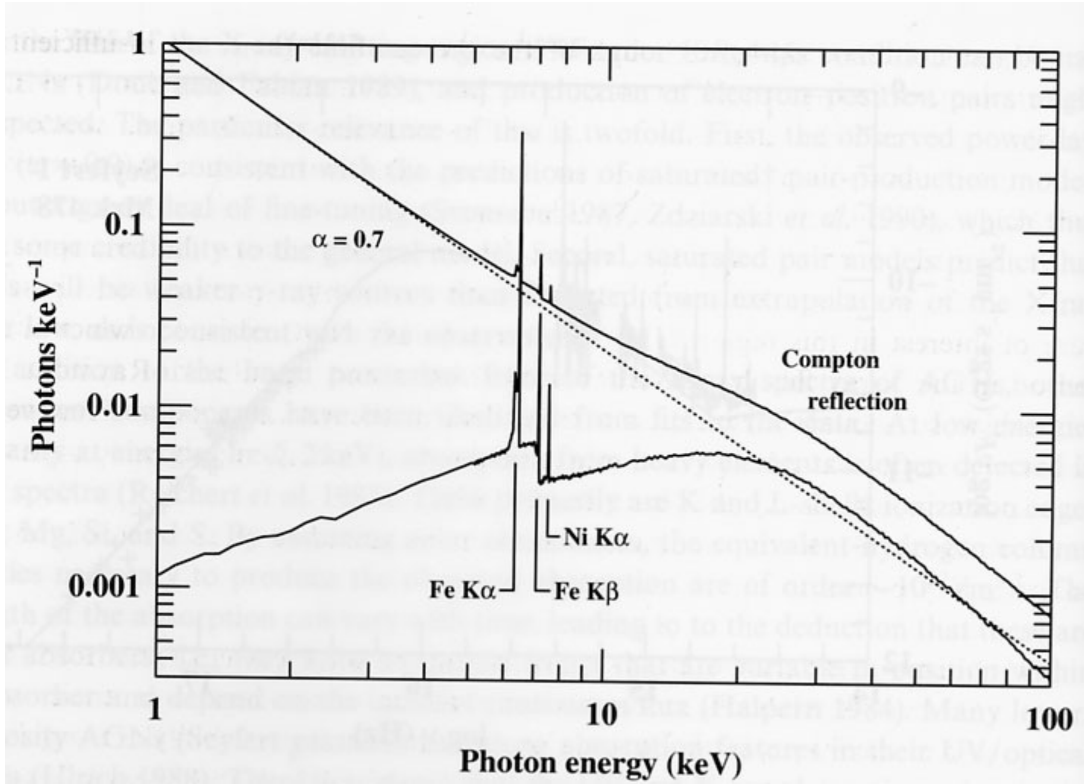
Relativistically
Blurred Reflection
(line + continuum)

(line + continuum)

Geometrically thin, optically thick accretion disk emitting primarily in UV/Optical


(c) 2005, Thomas Müller, Roland Speith

AGN X-ray Spectra



The main components of an AGNs X-ray spectrum are:

a) a power-law produced by X-ray emission from a hot corona made up of energetic electrons (UV disk photons are *up-scattered* in the hot corona to become X-ray photons)

b) a reflection component produced from X-rays being reprocessed in the accretion disk.

AGN Structure

The main structural elements of an AGN are thought to be;

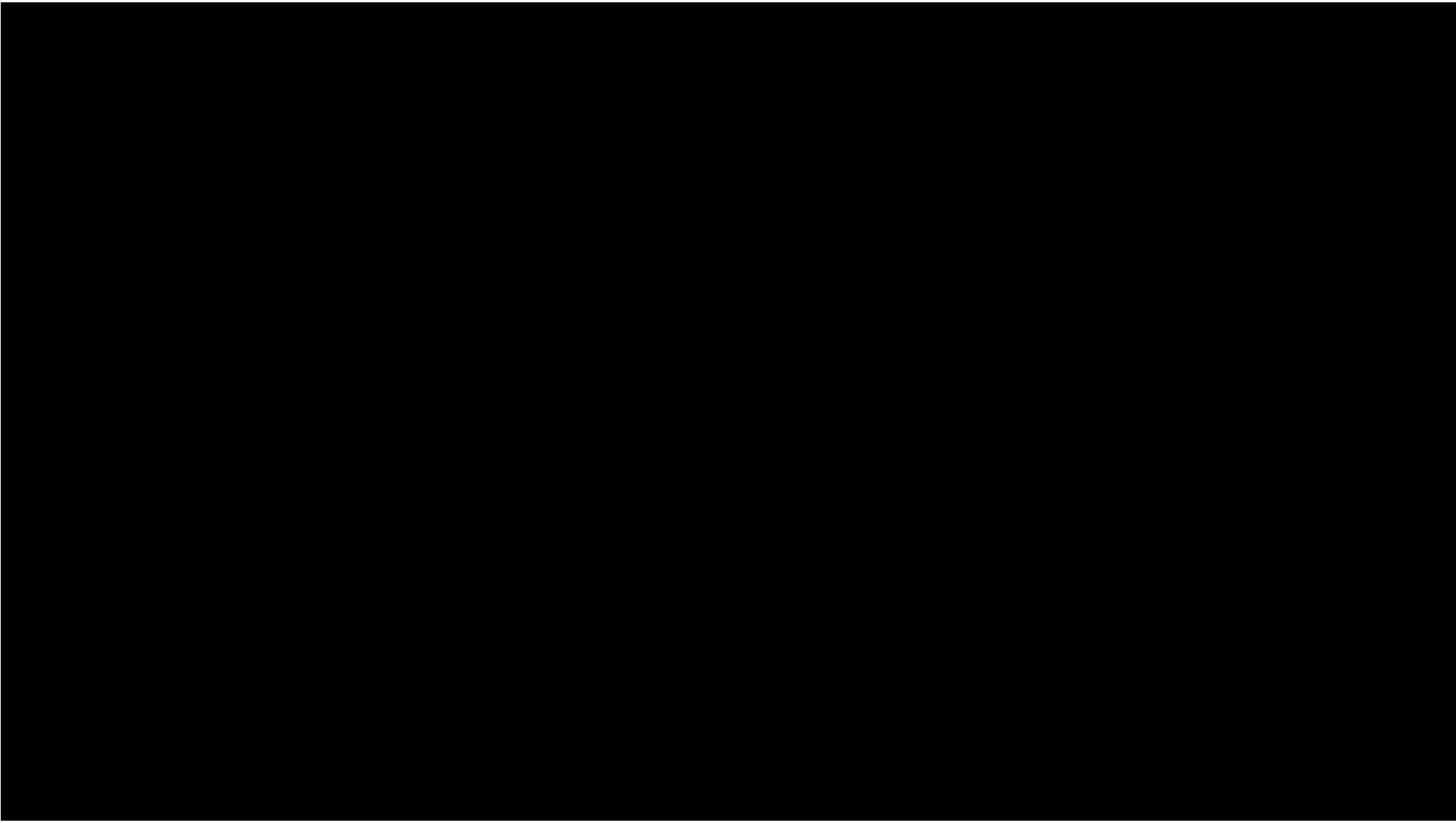
- An **accretion disk** surrounding a supermassive black hole

- In many cases, an **optically thick torus** of dust and gas surrounds the accretion disk. The torus absorbs optical and UV from the disk and re-radiates it in the infrared.

- In some cases, **jets of energetic particles** are ejected from near the center of the black hole in a direction perpendicular to the disk.

- Clouds or streamers of low and high density gas surround the AGN. These clouds are thought to produce the observed optical and UV **emission lines** of AGN.

AGN Clouds



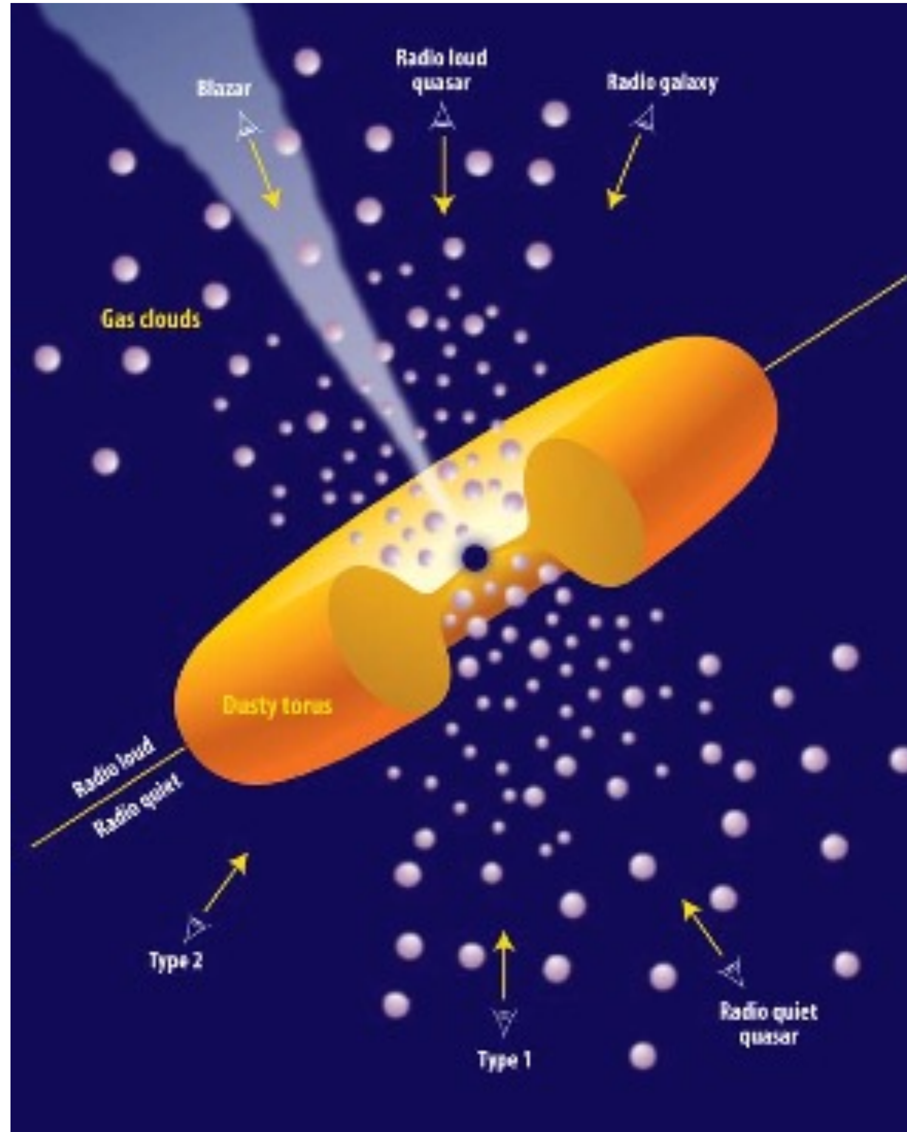
Unification of AGN

AGN with identical intrinsic properties may appear to be different due to the viewing angle.

Unification of radio quiet AGN

Seyfert 1s are AGN viewed along lines of site that have an unobstructed view of the black hole.

Seyfert 2s are AGN viewed along lines of site that are obstructed by the torus. In Seyfert 2s the observer cannot see the clouds near the black hole that emit the broad emission lines.



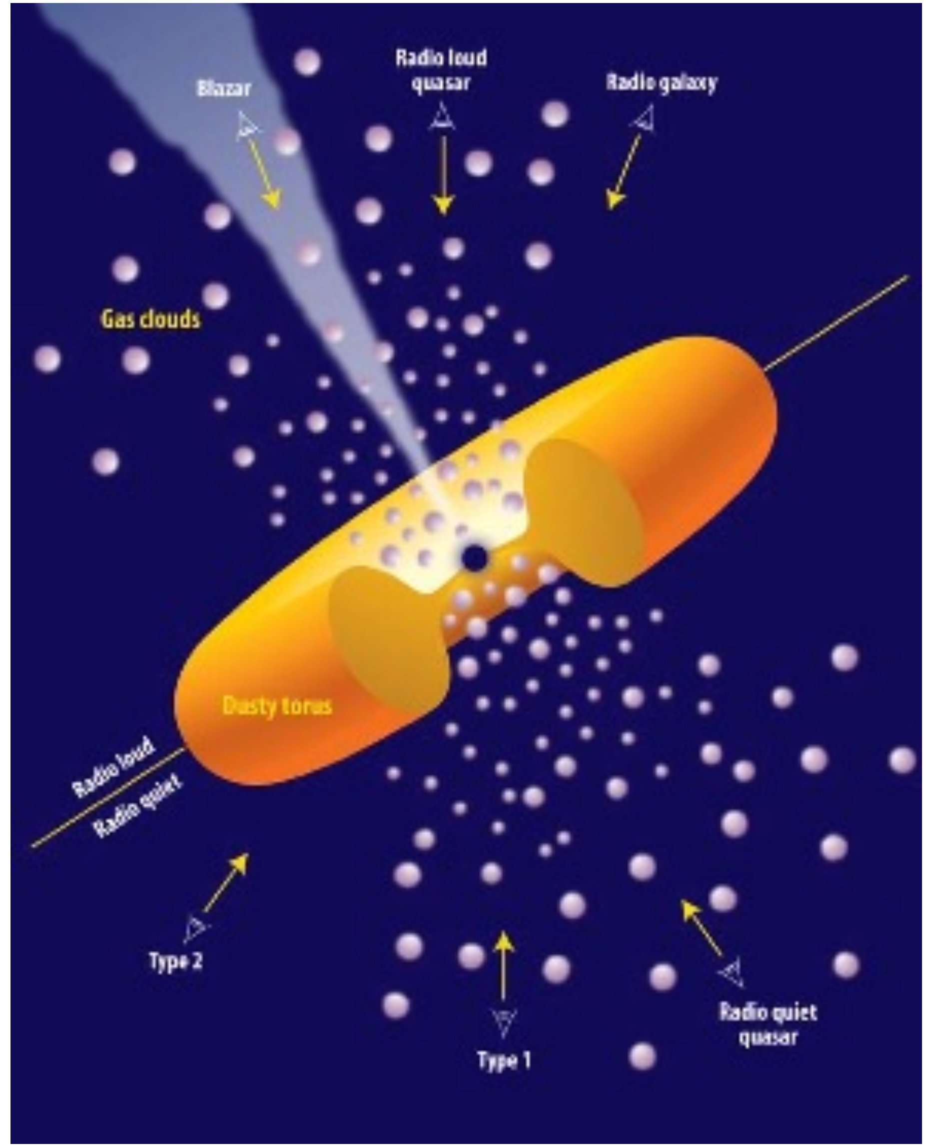
Unification of AGN

AGN with identical intrinsic properties may appear to be different due to the viewing angle.

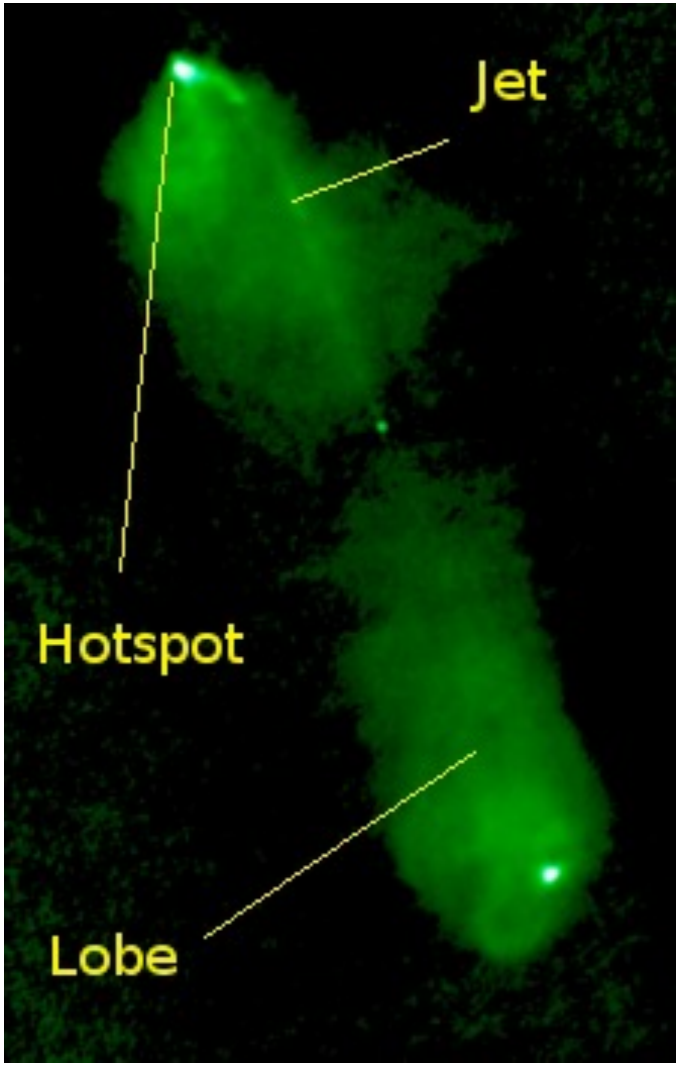
Unification of radio loud AGN

Blazars are AGN viewed along the jet. The radio emission is beamed along this direction and therefore appears much brighter than when viewed along other directions.

Radio loud quasars or radio galaxies are AGN viewed along lines of site away from the jet.



Jets



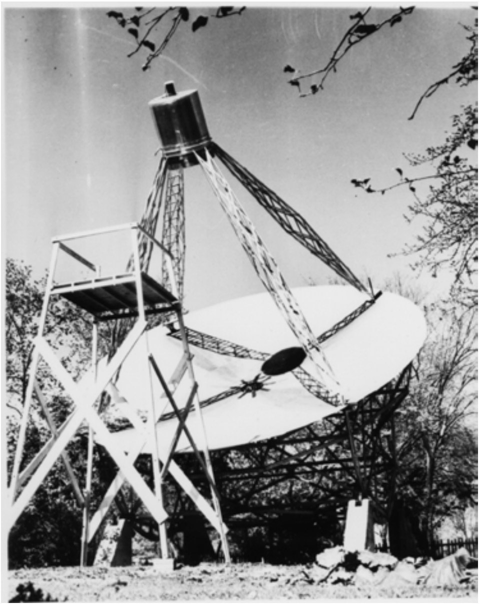
Radio Astronomy

The first radio waves of an astronomical origin were discovered by **Karl Jansky** in the early 1930s.

Jansky was trying to figure out what was causing interference at 20 MHz with a trans-atlantic radio link. He built a steerable **radio antenna** to search for the source of the noise.

He concluded that an astronomical object in the direction of the constellation Sagittarius must be causing the radio interference.

In 1936 **Grote Reber** built the first parabolic "dish" radio telescope and conducted the first sky survey in the radio frequencies.



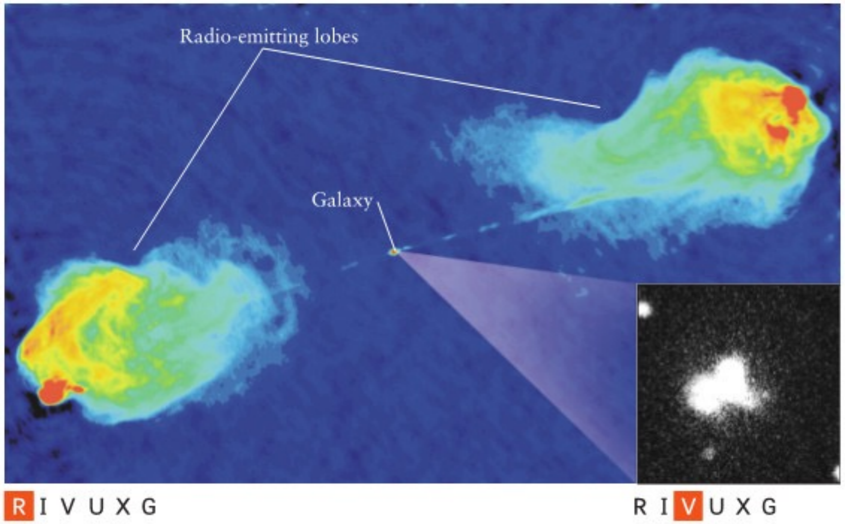
Reber's radio telescope

VLA in New Mexico

Quasars and Active Galaxies

Grote Reber was the first to build a true radio telescope and map the radio sky. Some of the radio sources Grote Reber discovered included **Cassiopeia A** (a supernova remnant) , **Sagittarius A** (the center of our Galaxy) and **Cygnus A**.

Optical follow up of Cygnus A showed a point like source unresolved in the optical. Its optical spectrum contained strong emission lines.



(a) Radio image of Cygnus A

(b) Visible-light close-up of the central galaxy

The VLA radio image of Cygnus A shows two bright radio lobes and jets on opposite sides of the central galaxy. Like all radio galaxies, Cygnus A contains an **active galactic nucleus (AGN)**.

Radio Telescopes: Dealing with Diffraction

The diffraction limited angular resolution of a 10 m radio dish at λ = 21-cm is $\theta \sim 2.5 \times 10^5$ (21 cm /10 m) = 5250 arcsec

To improve the angular resolution of radio telescopes astronomers use the interferometry technique.

The **Very Large Array** (VLA) consists of 27 parabolic dishes, each 25 m in diameter. By pointing all 27 telescopes at the same object and combining the 27 radio signals, the VLA can produce radio views of the sky with an angular resolution as small as 0.05 arcsec.

CONTACT

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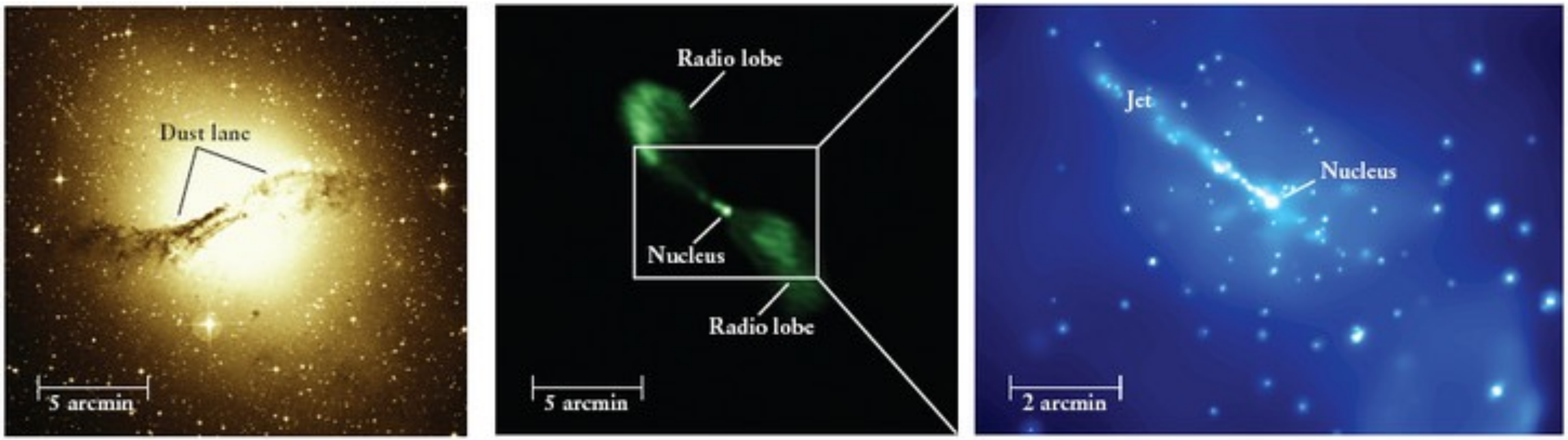
Jets and Radio Lobes



(a) Centaurus A: light from stars
R I V U X G

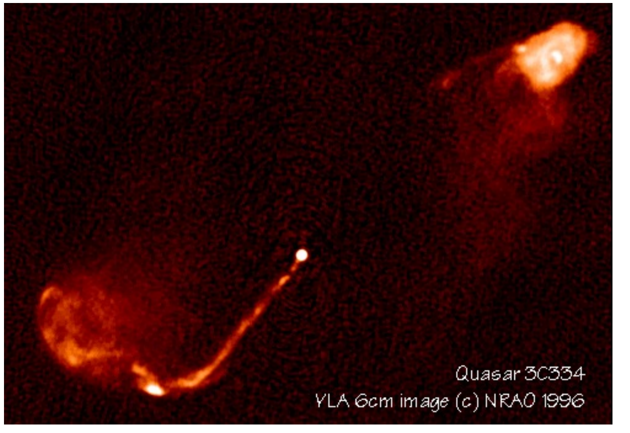
(b) Centaurus A: radio lobes
R I V U X G

(c) An X-ray-emitting jet emanates from the nucleus
R I V U X G

Images of Centaurus A.
The **emission from the jets and lobes is partially polarized** supporting the model of relativistic charged particles being accelerated in these jets. The distance between the lobes can be >10 times larger than the size of the galaxy.

Streams of Flowing Gas

Once the **VLA** went online many images of radio galaxies showed narrow beams extending up to millions of light years from the centers of the galaxies.



Questions:

- Are jets streams of flowing gas?

- Why are some jets one-sided?

- How can jets be stable, narrow and straight over distances as long as ~ 10^6 light years?

- Why do blobs in the jets sometimes appear to be moving faster than the speed of light?

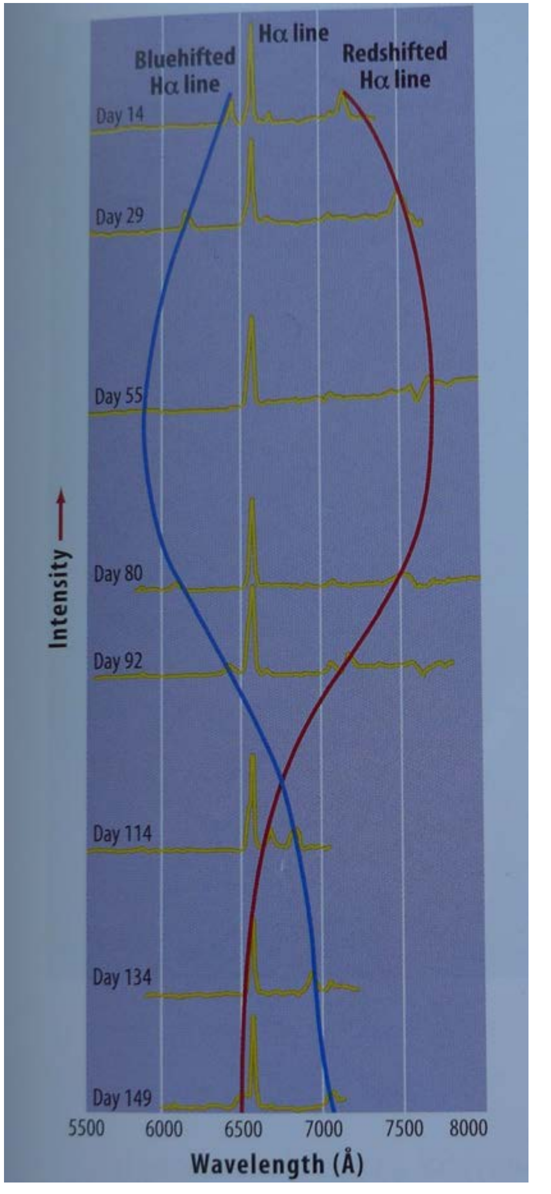
- How do jets form and where do they get their energy from?

Jets are Streams of Fast Flowing Gas

The breakthrough to addressing the question of whether jets are streams of fast-moving gas came with observations of SS433 (An eclipsing X-ray binary in our galaxy where the compact object is most likely a black hole).

Spectroscopy of the jets of SS433 showed:
-They were made primarily of hydrogen gas moving at a speed of ~0.25c

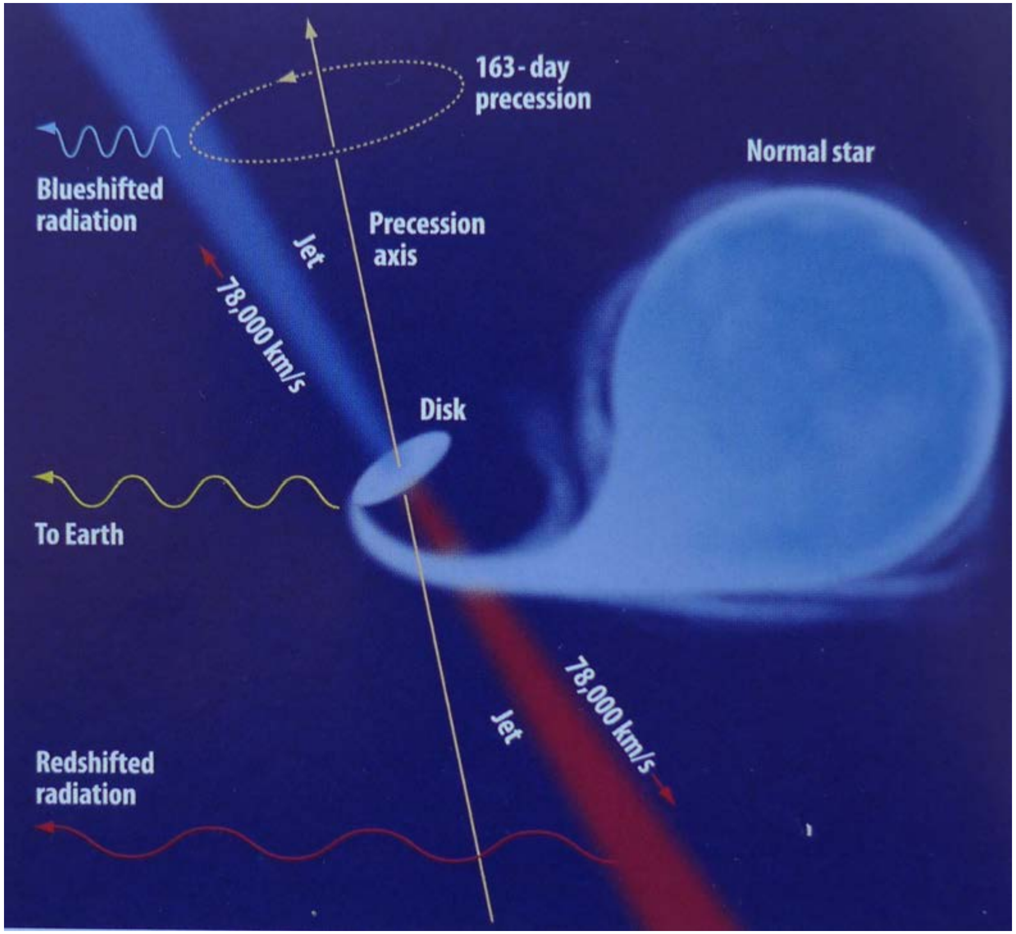
- The spectrum showed three sets of H_α lines. A mostly redshift H_α component, a mostly blueshifted H_α one and a stationary H_α one.



Microquasar SS 433

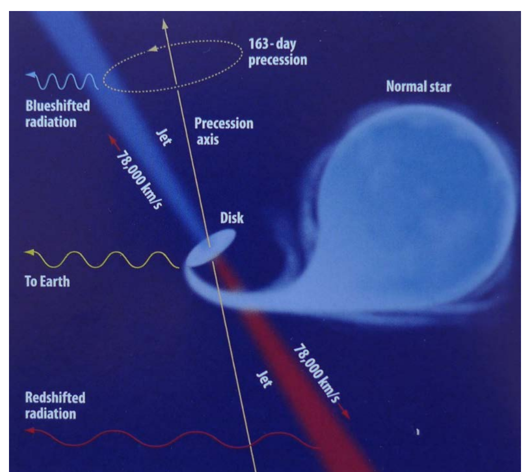
George Abell and Bruce Morgan first interpreted the spectrum of SS433 as resulting from the precession of a pair of jets ($v_j \sim 0.25c$) around a fixed axis every 163days.

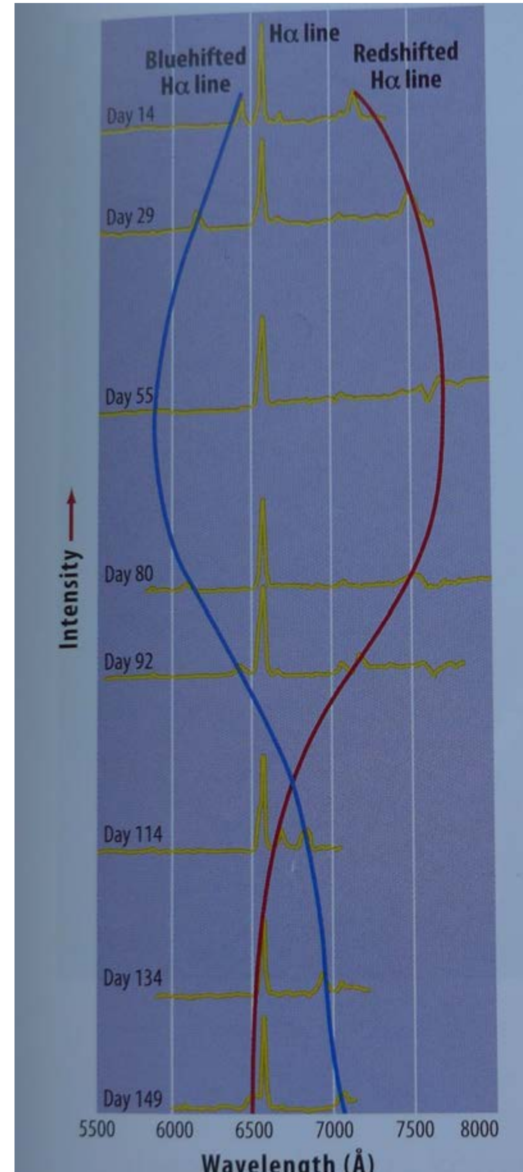
As the jets swing steadily around the component of velocity directed along our line of sight varies. Because of the Doppler shift, the observed wavelengths trace out patterns that repeats every precession period.



Microquasar SS 433

Question: Why do both shifted Hα lines show the same redshift at one point in the orbit?
Use this shift to calculate the velocity of the hydrogen gas.
Hint: $\frac{1}{\lambda_{obs}} = \frac{1}{\lambda_{rest}}\frac{1}{\gamma}$ Transverse Doppler effect.





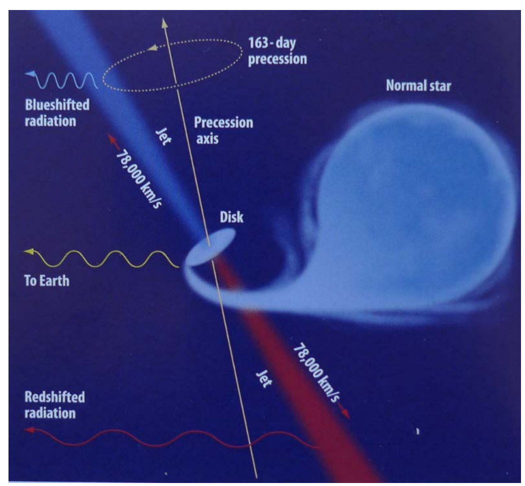
Microquasar SS 433

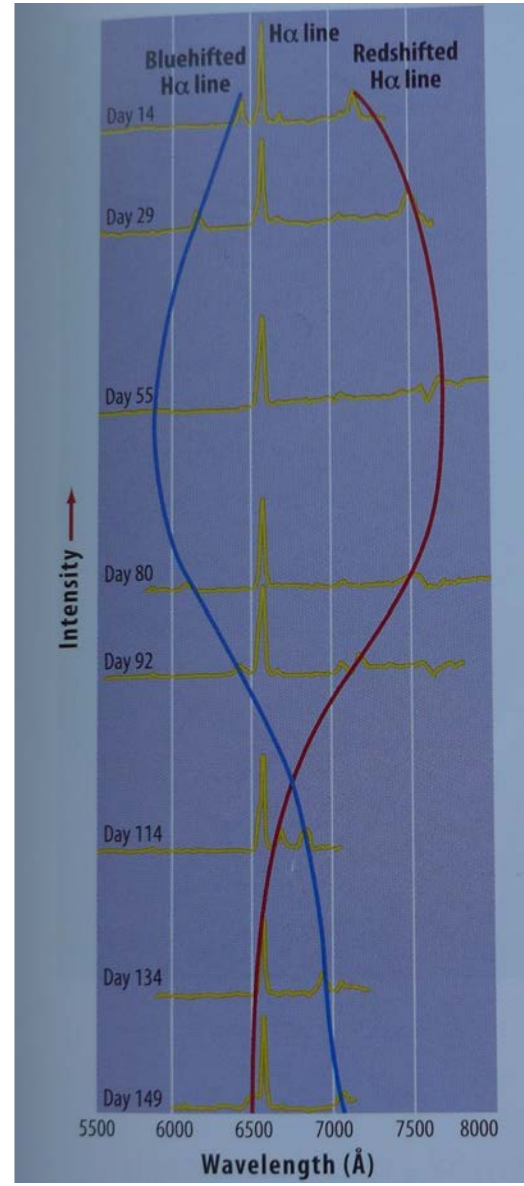
Question: Why do both shifted Hα lines show the same redshift at one point in the orbit?
Use this shift to calculate the velocity of the hydrogen gas.

The transverse Doppler effect:

$$\frac{1}{\lambda_{obs}} = \frac{1}{\lambda_{rest}}\frac{1}{\gamma} \rightarrow 6563 = 6770\sqrt{1-\left(\frac{v}{c}\right)^2} \rightarrow$$

$$\left(\frac{6563}{6770}\right)^2 = 1-\left(\frac{v}{c}\right)^2 \Rightarrow \left(\frac{v}{c}\right) \sim 0.25c$$





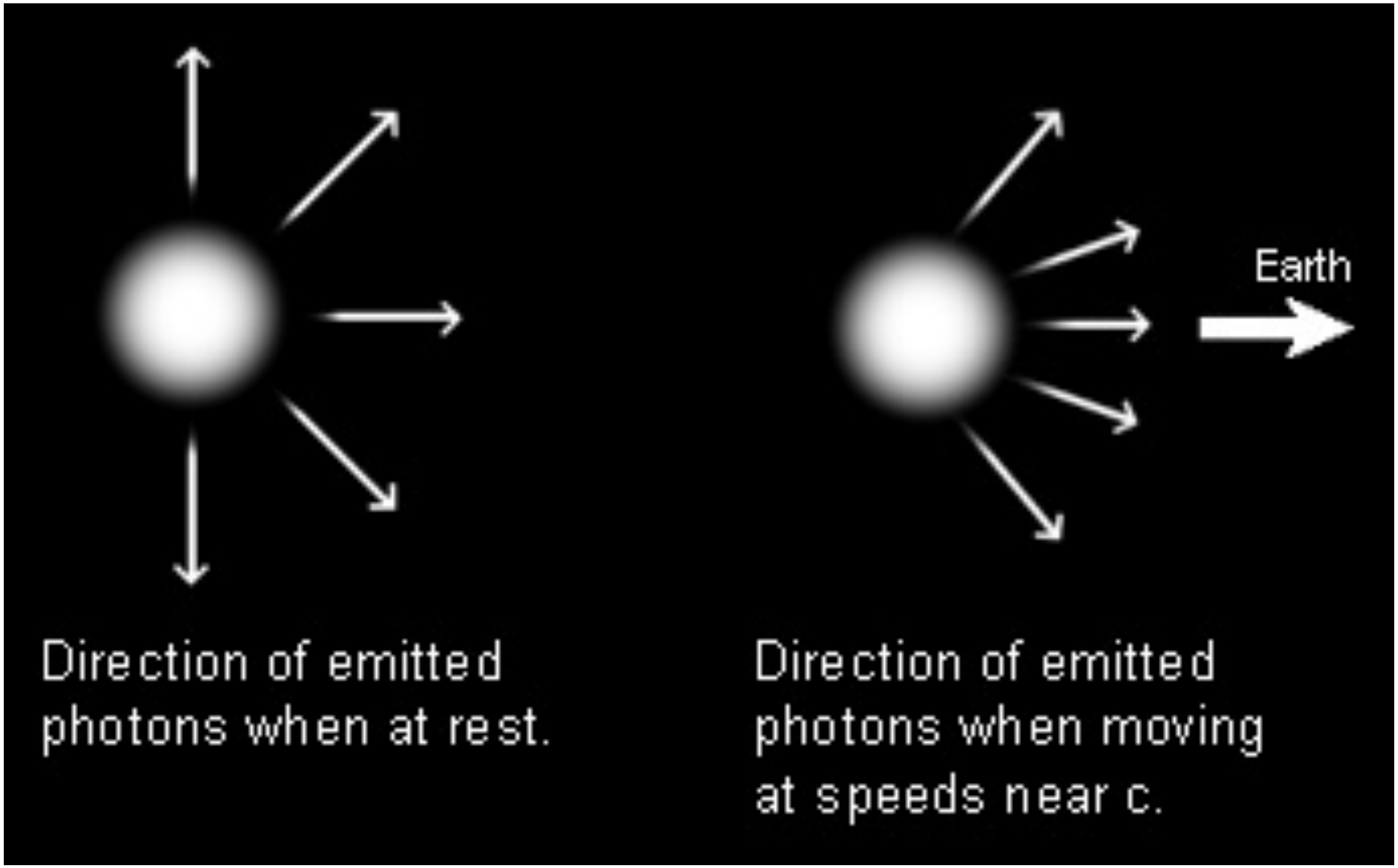
Explaining single-sided jets

The main reason for single-sided jets in now thought to be the result of **beaming**.

Assume a blob that radiates photons equally in all directions when at rest.

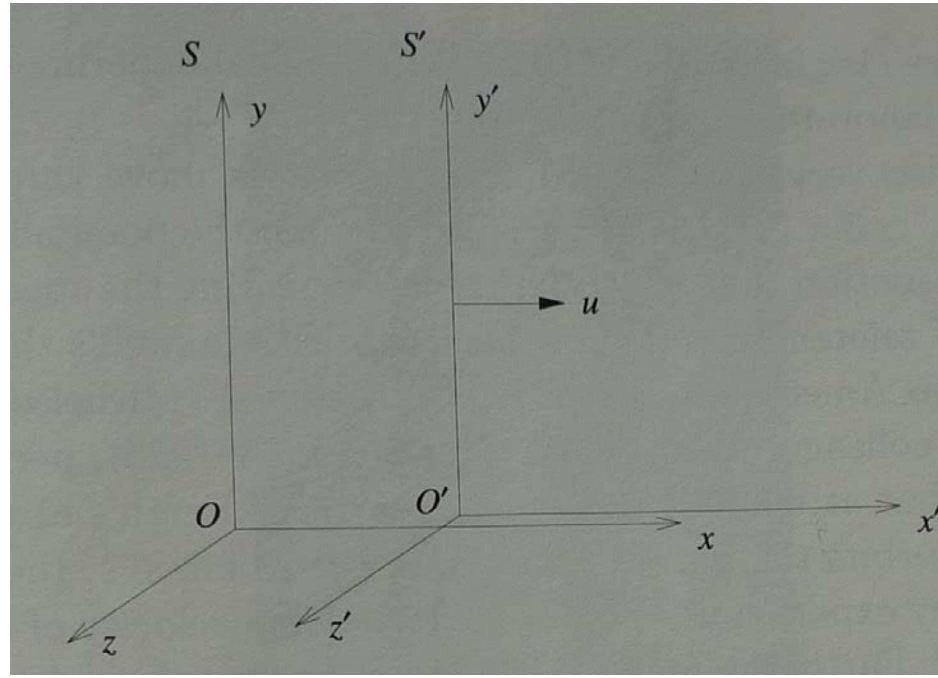
The same blob when moving will appear to shine within a beam along the direction of motion.

Beaming


Earth
Direction of emitted photons when at rest.
Direction of emitted photons when moving at speeds near c.

Lorentz Transformations

$$t' = \frac{t - \frac{ux}{c^2}}{\sqrt{1 - \frac{u^2}{c^2}}} = \gamma\left(t - \frac{ux}{c^2}\right)$$



$$x' = \frac{x - ut}{\sqrt{1 - \frac{u^2}{c^2}}} = \gamma(x - ut)$$

$$y' = y$$

$$z' = z$$

The factor $\gamma = \frac{1}{\sqrt{1 - \frac{u^2}{c^2}}}$ is called the Lorentz factor.

Note the intertwining roles of space and time. Events are identified by their **spacetime** coordinates (x, y, z, t).

Relativistic Velocity Transformations

Write the Lorentz transformations as differentials and divide the *dx'*, *dy'*, and *dz'* equations by the *dt'* equation.

$$v_x' = \frac{v_x - u}{1 - \frac{u v_x}{c^2}}$$

$$v_y' = \frac{v_y}{\gamma\left(1 - \frac{u v_x}{c^2}\right)}$$

$$v_z' = \frac{v_z}{\gamma\left(1 - \frac{u v_x}{c^2}\right)}$$

You can infer the inverse transformations by substituting u➔-u

Now assume frame *S'* is moving with respect to frame *S* along the *x* axis with a velocity *u* and a photon is moving in frame *S'* along the *y'* axis.

$v_x' = 0$, $v_y' = c$, $v_z' = 0$

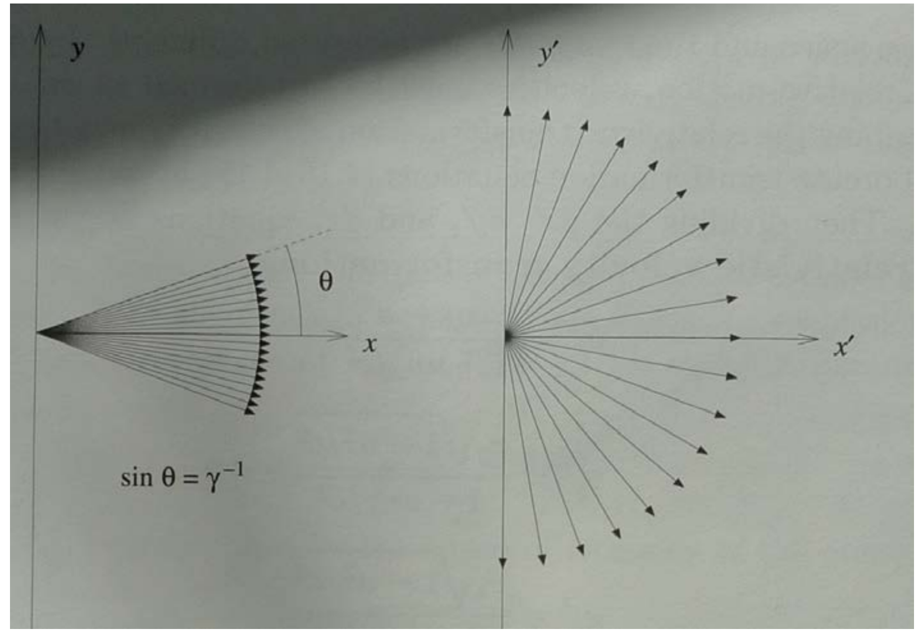
Use the inverse velocity transformations to infer v_x, v_y, v_z

Relativistic Beaming

$v_x = u,\ v_y = c/\gamma,\ v_z = 0$

For u/c~1

$\sin\theta = v_y/v = \gamma^{-1}$



The **beaming angle** θ is half of the opening angle and the inverse of the Lorentz factor.

Examples: relativistic electrons spiraling around magnetic field lines emit synchrotron radiation collimated in beams pointed in their direction of motion.

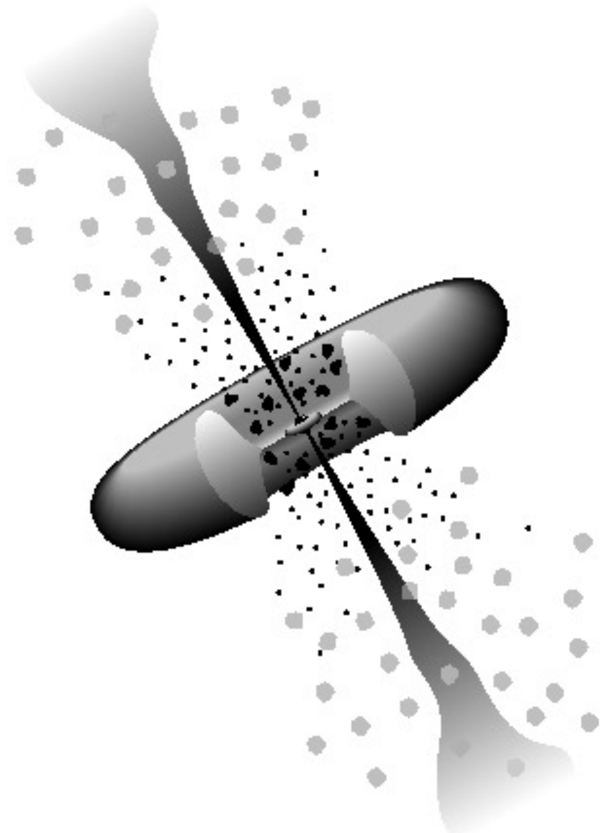
Blazars

Blazars are AGN with a relativistic jet that is pointing in the general direction of the Earth. We observe "down" the jet, or nearly so, and this accounts for the rapid variability and compact features of blazars.

Blazars, like all AGN, are thought to be ultimately powered by material falling onto a supermassive black hole at the center of the host galaxy.

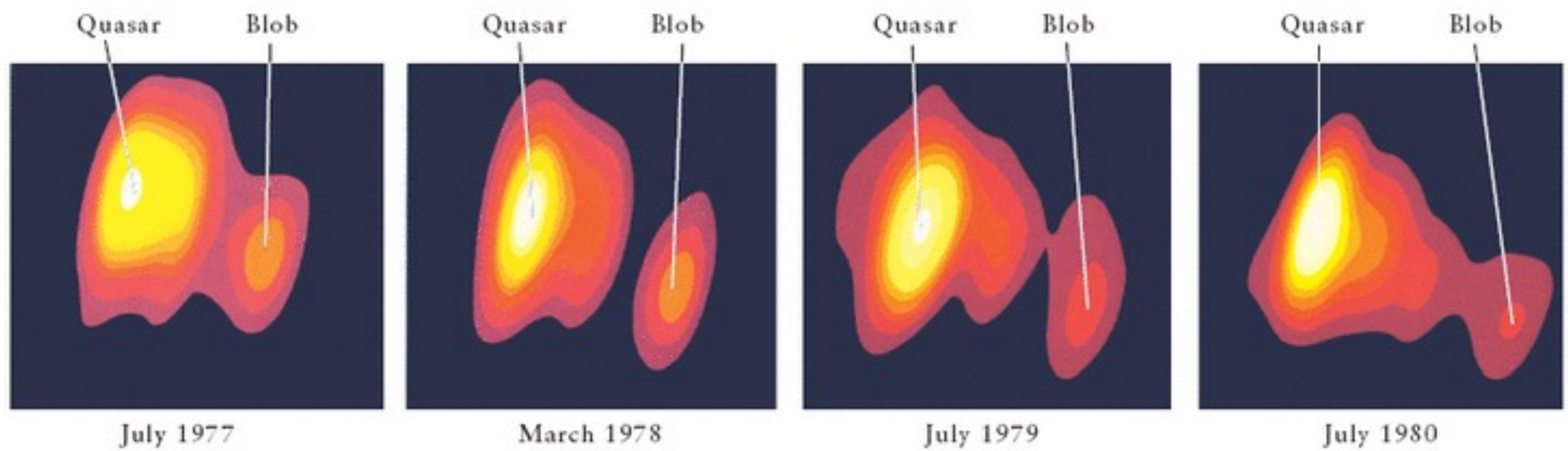
Blazars are subdivided into **BL Lac objects** and optically violent variable **OVV quasars**.

BL Lac objects are intrinsically weak radio galaxies while OVV quasars are intrinsically powerful radio galaxies.



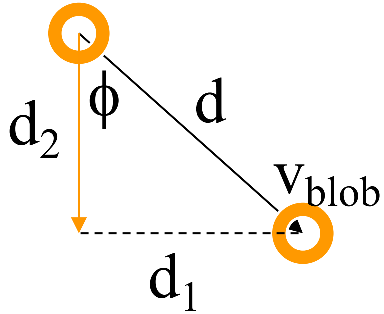
The bulk speed of the plasma in the jet can be in the range of 95% – 99% the speed of light.

Superluminal Motion in Blazars



Superluminal Motion is motion that appears to involve speeds greater than the speed of light. In the observations of 3C 273 shown above the blob in 3 years covered a projected distance of 0.003 arcsec. The apparent velocity of the blob is ~ 10 times the speed of light. It turns out **the blob does not travel faster than the speed of light** and the apparent superluminal motion is just the result of projection effects combined with the relativistic motion of the blobs.

Superluminal Motion in Blazars



$$v_{obs} = \frac{d_1}{t_2 - t_1} \quad (1)$$

$$t_2 - t_1 = \frac{d}{v_{blob}} - \frac{d_2}{c} \quad (2)$$

$$(1)\ (2) \Longrightarrow v_{obs} = \frac{d_1}{\frac{d}{v_{blob}} - \frac{d_2}{c}} = \frac{v_{blob}\, c\, d_1}{c\, d - d_2\, v_{blob}} = \frac{v_{blob}\, c\, d\, sin\varphi}{c\, d - d\, cos\varphi\, v_{blob}} \Longrightarrow$$

$$v_{obs} = \frac{v_{blob} sin\varphi}{1 - \frac{v_{blob}}{c} cos\varphi}$$

Example: for $v_{blob} = (5/6)c$ and φ=45 degrees $\Longrightarrow v_{obs} \sim 1.4$c

Making a Relativistic Jet

A simple viewpoint to describe electromagnetic properties of an ionized gas was introduced by Hannes Alfven.

Think of the magnetic field lines as being attached to the fluid.

The magnetic field lines give the **fluid resiliency**. For example, if the field lines are slightly curved they will try to spring back but once bent into a loop they will try to contract.

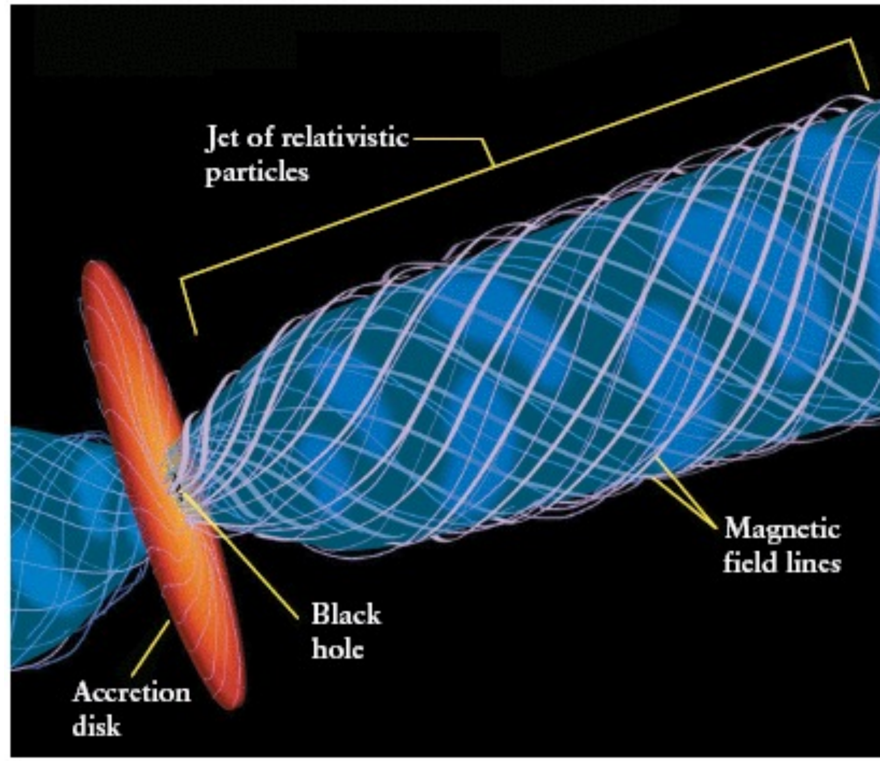
Because of the **differential rotation of the accretion disk,** field lines will follow the motion of the disk. Ionized particles below and above the disk will then follow the motion of the magnetic field lines. The centrifugal force then flings particles outward along magnetic field lines.

Inflows and Outflows from Active Galaxies

Magnetic forces play a crucial role in collimating fast-moving particles from the accretion disk into narrow beams.

The Keplerian rotation of the plasma in the disk creates a strong magnetic field that is twisted in helical shapes on either side of the plane of the disk.

Particles from the accretion disk follow these twisted magnetic field lines and are focused into two jets.



Jets from a Supermassive Black Hole

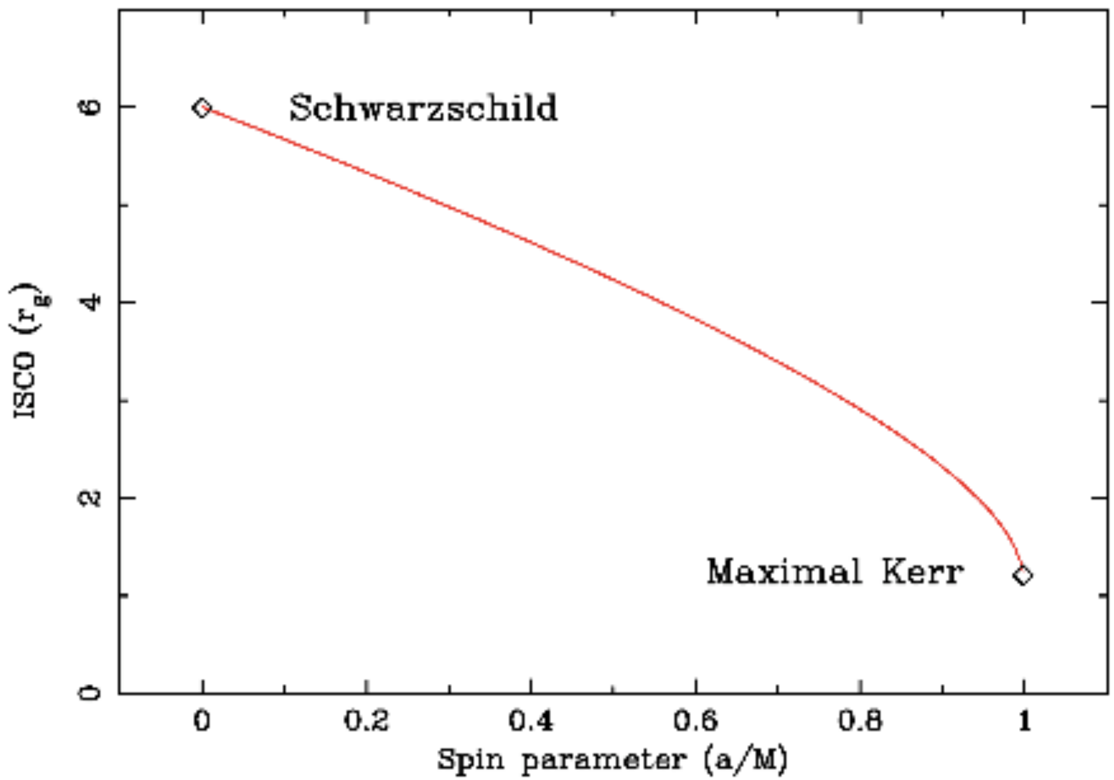
Where does the energy needed to accelerate jets come from?

possibly: The energy may come from the conversion of gravitational energy released by infalling material.

possibly: The energy may come from the spinning black hole. This mechanism was first proposed by Roger Penrose.

But wait, I thought you could not extract anything from a black hole. It turns out that the law governing the growth of black holes states that the surface area of a black hole's event horizon cannot decrease. This is not violated when the spin of a black hole is reduced.

Where does the energy needed to accelerate jets come from?



The surface area of a black hole's event horizon increases as the spin slows down.

How are Black Holes spun up?

- Accretion of material over millions of years.

- Black holes may be formed with considerable spin during core collapse of a massive star.

- Merging of black holes. Some of the angular momentum ends up in the spin of the black hole.

Extracting Energy from Spinning Black Holes

Remaining Puzzles:

-Why do most AGN with jets **(radio-loud AGN) reside in elliptical galaxies** and radio-quiet AGN typically reside in spiral galaxies.

- We think of whether or not a jet is formed is decided on scales not much larger than the event horizon of the black hole, whereas, somehow the host galaxy properties seem to depend on the radio loudness of the nucleus.

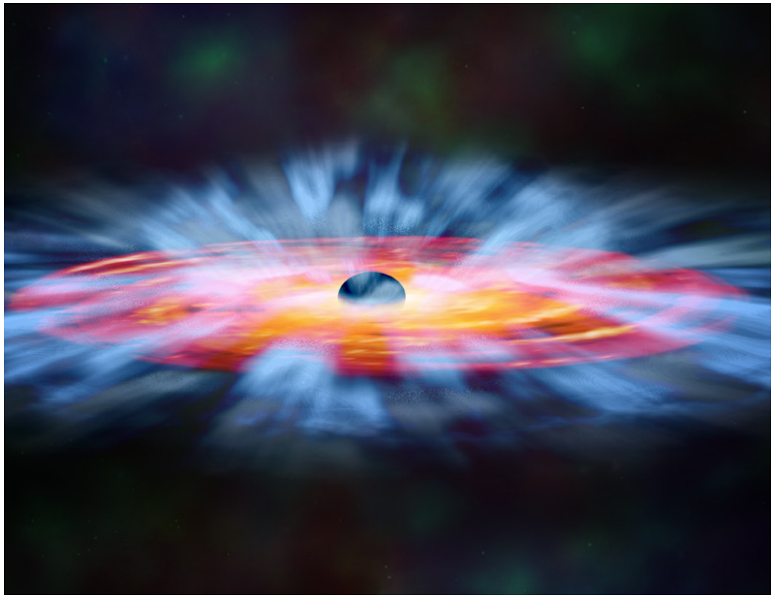
- Preliminary estimates of the spins of black holes of Seyfert's (radio-quiet AGN) point to large values of the spin parameter. This seems to contradict models that posit that energy to power jets is extracted from the spin of a black hole.

- AGN with large accretion rates ($L/L_{Edd} \sim 1$) in general do not have radio jets.

Accretion onto a Black Hole

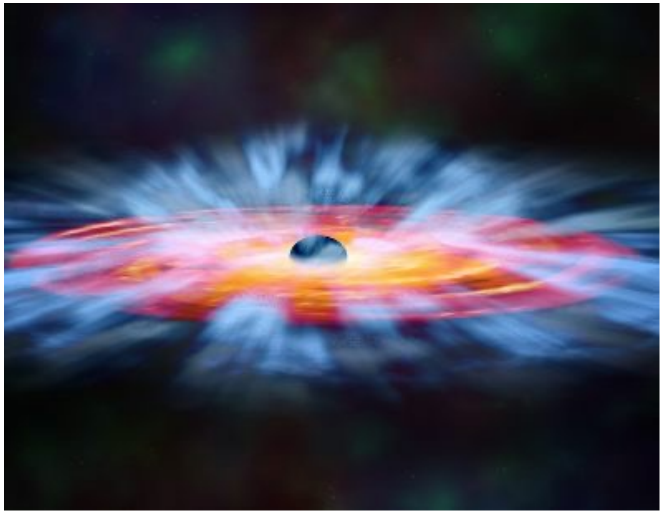
Energy released from accretion of mass onto a black hole goes into:

1. Heating the accretion disk
2. Electromagnetic radiation emitted
3. Outflowing winds in some cases
4. Powerful jets in some cases
5. The remaining mass and energy is sucked in by the black hole



Accretion Disks

Gas captured by a neutron star or a black hole in general does not fall radially inward; because of its angular momentum, the gas forms a swirling disk or vortex. Because the gas is relatively compressible it often gets flattened into an **accretion disk**.



Some properties of accretion disks:

Differential rotation: inner parts rotate faster than outer ones

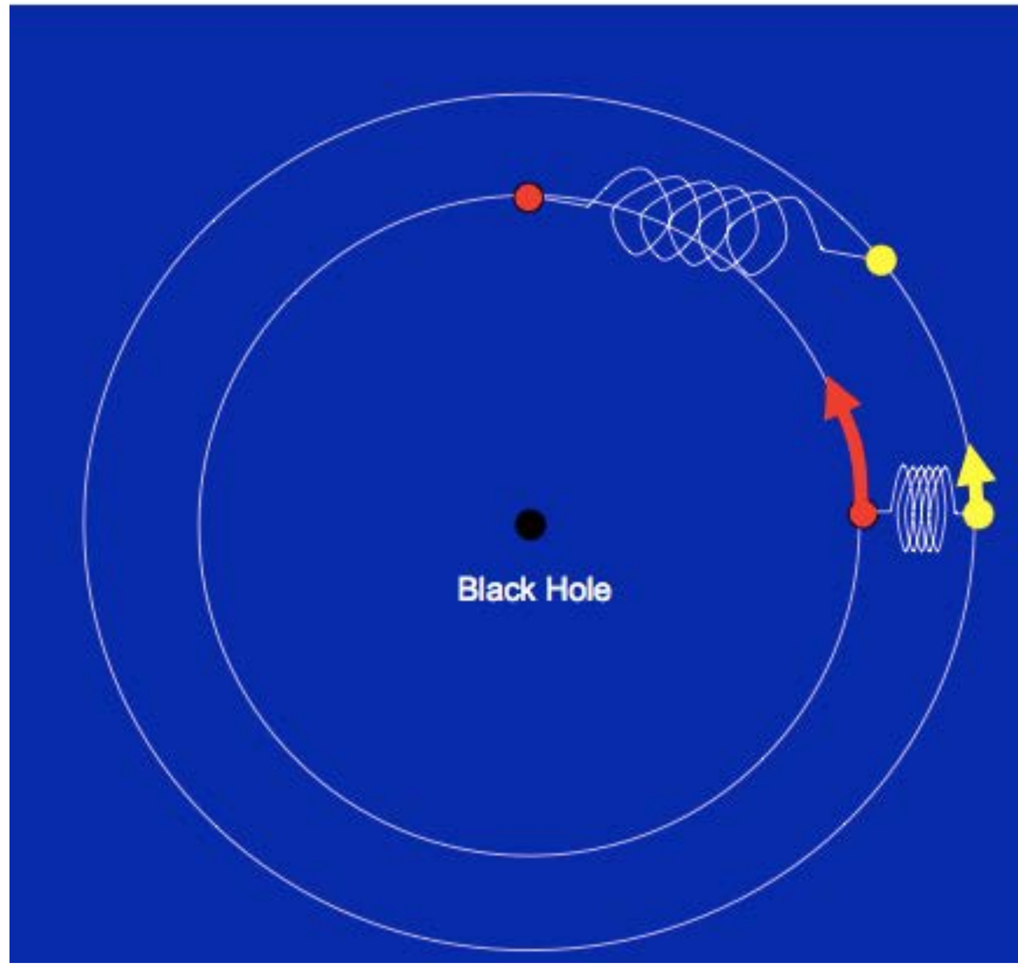
Temperature gradient: inner parts are hotter than outer ones

Viscosity: friction produced by magnetic reconnection allows the material to inflow inwards

The Magneto-Rotational Instability (MRI) model for Accretion onto a Black Hole

In a Keplerian disk the inner particle orbits faster than the outer one.

Magnetic fields act as springs between particles. The spring action removes angular momentum from the inner particle making it enter a lower orbit whereas the outer particle gains momentum and enters a larger orbit.



AGN Accretion

Accretion is the extraction of gravitational potential energy from material which falls into a gravitating body and is the principle power supply for AGN's.

The **energy released** from bringing a mass from infinity to the surface of a body of mass M and radius R is:

$$\Delta E_{accretion} = \frac{GMm}{R} = \frac{GM}{Rc^2} mc^2 = \eta mc^2$$

For a neutron star $\eta \sim 0.1$
For a black hole $\eta \sim 0.06\text{-}0.42$
For a white dwarf $\eta \sim 0.001$

The efficiency of nuclear reactions is about 0.01-0.001

AGN Accretion

The **luminosity of an AGN** depends on the rate at which material is accreting.

At high luminosities, however, accretion may be impeded by photon pressure from Thomson scattering of photons off electrons of the accreting material.

$$L_{accretion} = \frac{GM\dot{M}}{R} = \eta \dot{M} c^2$$

To power a typical AGN requires an accretion rate of:

$$\dot{M} = \frac{L_{accretion}}{\eta c^2} \sim 1.8 \times 10^{-3} \left(\frac{L_{44}}{\eta}\right) M_{\odot} yr^{-1}$$

Where L_{44} is the central source luminosity in units of 10^{44} erg s^{-1}

Eddington Luminosity of an AGN

We assume steady, spherically symmetrical accretion, with the accreting material being mainly hydrogen and fully ionized.

The **radiation force** from the compact object exerts a force on the free electron through Thomson Scattering.

Force = $\frac{\Delta P}{\Delta t} = N_{col}\frac{\Delta p}{\Delta t}$, N_{col}= (number flux of photons)× (cross section) × (Δt)

Radiation force on electrons: (number flux per cm^2)x(cross section)x(momentum of each photon) =

$$\frac{\left(\frac{L_{Edd}}{h\nu}\right)}{4\pi R^2}\sigma_T\left(\frac{h\nu}{c}\right) = \frac{L_{Edd}\sigma_T}{4\pi R^2 c}$$

We balance this force with gravity:

$$\frac{L_{Edd}\sigma_T}{4\pi R^2 c} = \frac{GMm_p}{R^2} \Rightarrow L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} \Rightarrow L_{Edd} = 1.3\times10^{38}\left(\frac{M}{M_\odot}\right)\text{ erg s}^{-1}$$

Notice that the photons scatter off the electrons but we take the proton mass in the above equation since the protons and electrons are attracted through the electrostatic force.

AGN have luminosities close to L_{EDD} ie. $L/L_{EDD} \sim 0.1 - 1$

Temperature Profile of Accretion Disk

A simple temperature profile for the accretion disk of a black hole can be estimated if we assume that the observed luminosity is mainly produced by accretion, the medium is optically thick, and energy is dissipated locally. Under these conditions the local spectrum is approximately that of a blackbody.

The total energy of an accreting mass m in a Keplerian orbit at a radius r is:

$$E_{tot} = -\frac{GMm}{2r}$$

We assume the mass transfer rate is: $\dot{m} = \frac{dm}{dt}$

The energy change in a ring due to the transfer of mass m is:

$$dE = \frac{dE}{dr}dr = \frac{d}{dr}\left(-\frac{GMm}{2r}\right)dr = \frac{GMm}{2r^2}dr$$

$\left(\frac{dE}{dt}\right)_{disk} = \frac{GM\dot{m}}{2r^2}dr$ this is the rate of energy deposited into the disk from accretion

Temperature Profile of Accretion Disk

Assume that the energy deposited in the ring *dr* during accretion is radiated as blackbody radiation.

$$\left(\frac{dE}{dt}\right)_{BB} = 4\pi r dr \sigma T^4$$

$$\left(\frac{dE}{dt}\right)_{disk} = \left(\frac{dE}{dt}\right)_{BB} \Rightarrow \frac{GM\dot{m}}{2r^2}\, dr = 4\pi r dr \sigma T^4 \Rightarrow T^4 = \frac{GM\dot{m}}{8\pi r^3 \sigma}$$

A more thorough analysis that takes into account viscosity results in:

$$T_{disk}(r) = \left(\frac{3GM\dot{m}}{8\pi R^3 \sigma}\right)^{1/4} \left(\frac{R}{r}\right)^{3/4} \left(1 - \sqrt{\frac{R}{r}}\right)^{1/4}$$

Where R is the radius of the compact object.

Temperature Profile of Accretion Disk

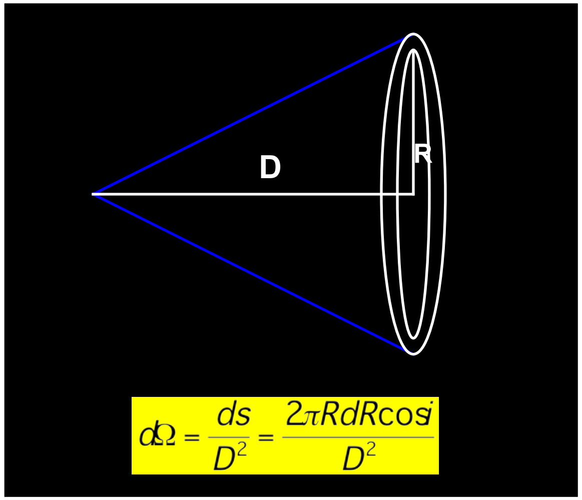
The emitted spectrum at a radius R is the Planck function :

$$B_\nu[T(r)] = \frac{2h\nu^3}{c^2\left(e^{\frac{h\nu}{kT(r)}} - 1\right)} \text{ (erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}\text{ sr}^{-1}\text{)}$$

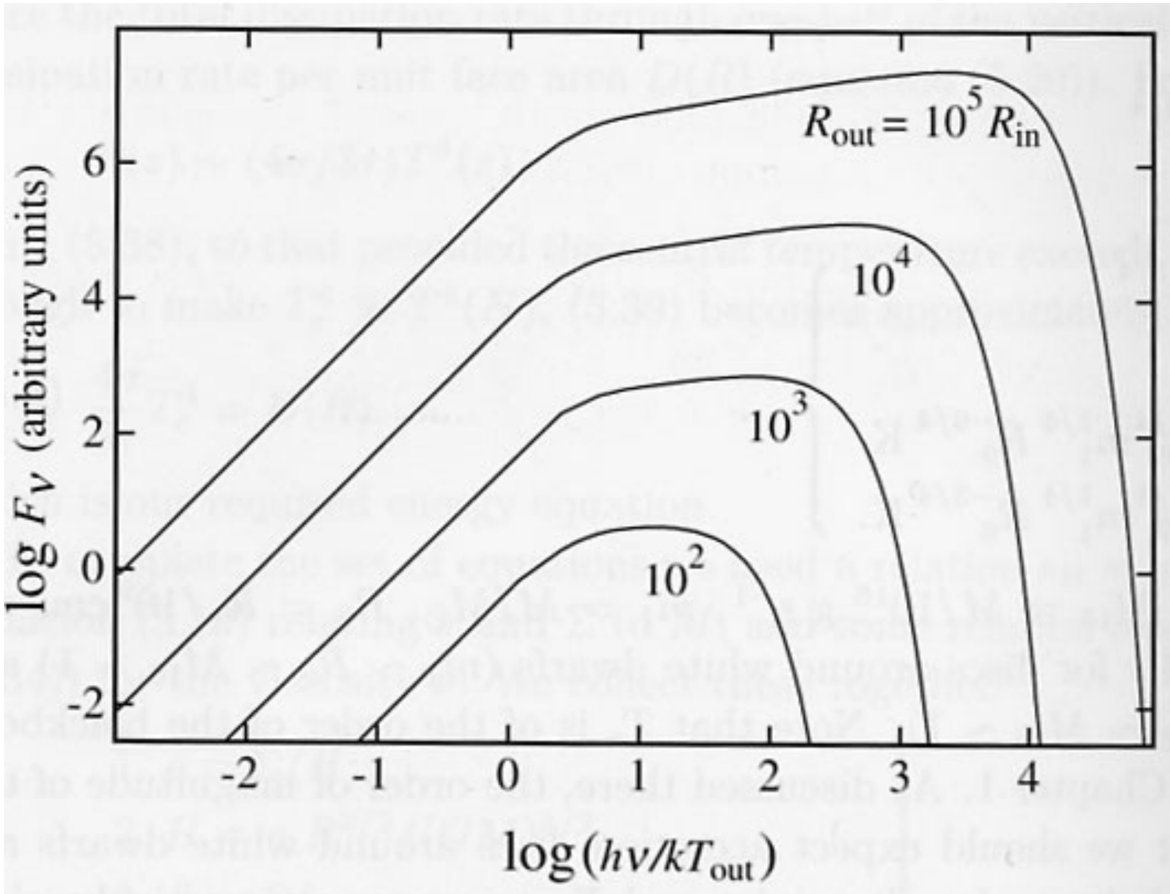
Integrating over the solid angle we obtain the flux

at a frequency ν:

$$F_\nu = \frac{2\pi \cos i}{D^2} \int_{r_{in}}^{r_{out}} \frac{2h\nu^3}{c^2\left(e^{\frac{h\nu}{kT(r)}} - 1\right)} r dr$$



Temperature Profile of Accretion Disk

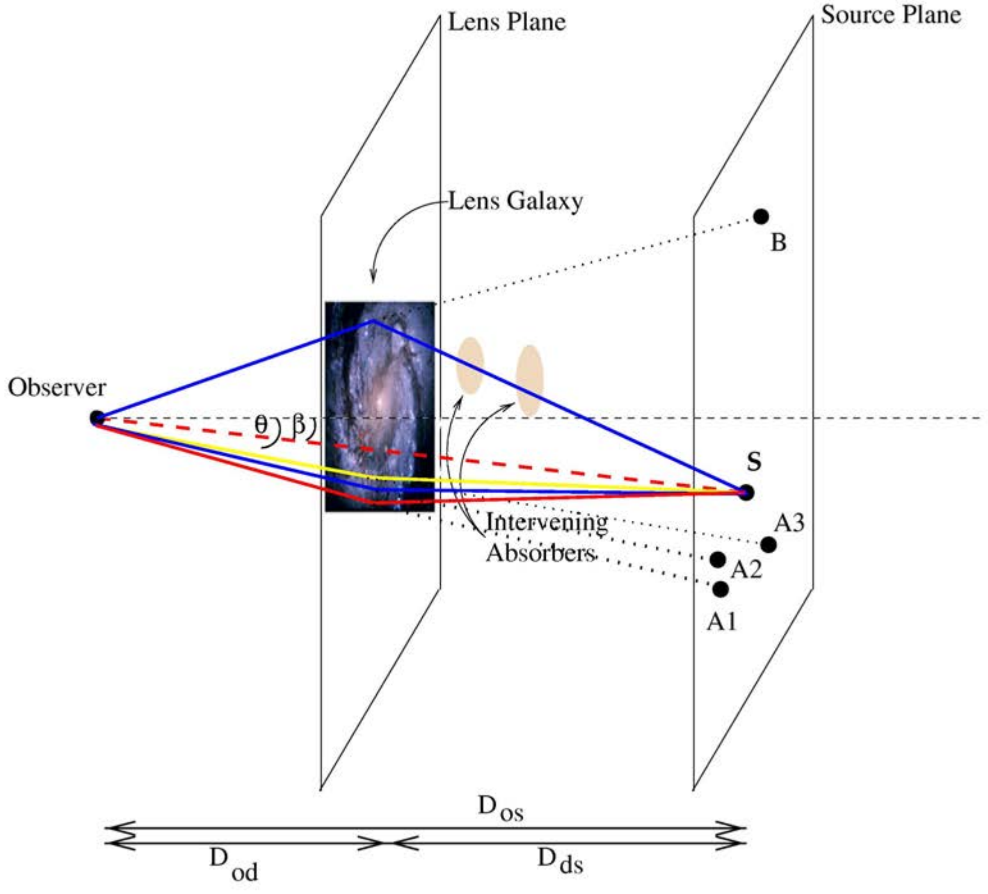


For $\nu \ll KT/h$, $F_\nu \sim \nu^2$,

For $\nu \gg KT/h$, $F_\nu \sim e^{-h\nu/KT}$

For intermediate frequencies $F_\nu \sim \nu^{1/3}$

Determining Lens Mass from Gravitational Lensing



Conceptual diagram of the gravitational deflection of light in a quad GL system.

Gravitational Lensing; Basics

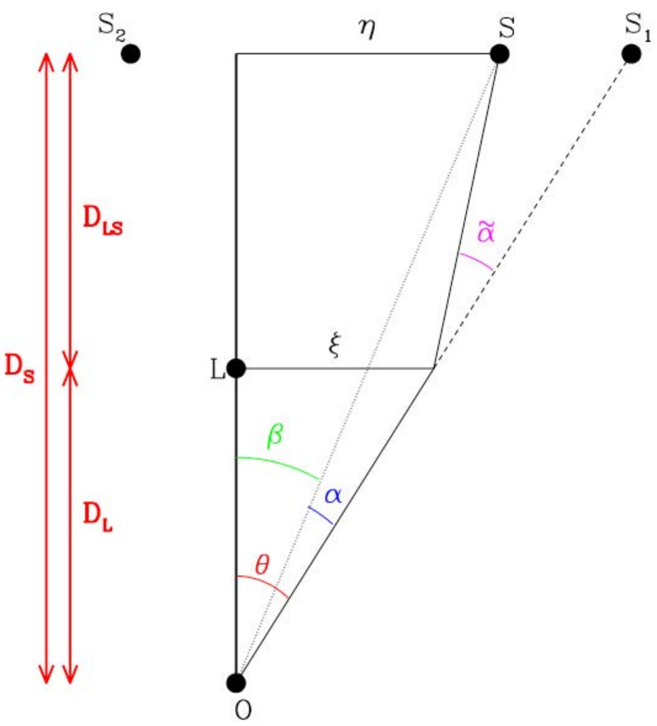
The two-dimensional lens equation is: $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

The reduced deflection angle is: $\vec{\alpha} = \frac{D_{LS}}{D_S}\tilde{\alpha}$

The position vector in the lens plane is: $\vec{\xi} = D_L\,\vec{\theta}$

The deflection angle at position ξ is the sum of the deflections due to all the mass elements in the lens plane:

$$\tilde{\alpha}(\vec{\xi}) = \frac{4G}{c^2}\int \frac{(\vec{\xi}-\vec{\xi'})\Sigma(\vec{\xi'})}{[\vec{\xi}-\vec{\xi'}]^2}\, d^2\xi'$$



Gravitational Lensing; Basics

The deflection angle of a photon passing a distance ξ from a mass M is a = $4GM/\xi c^2$ (in units of radians).

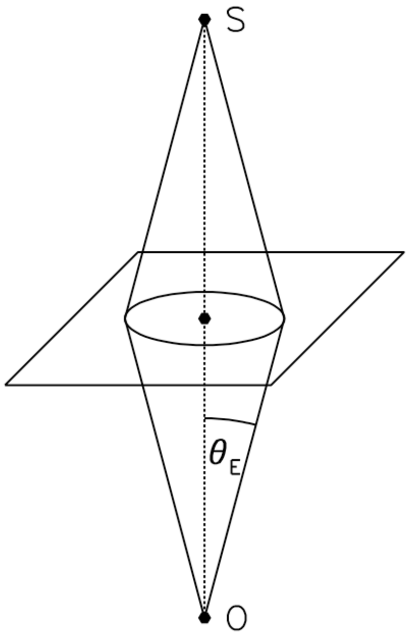
The lens equation from a point mass then becomes:

$$\theta^2 - \theta\beta - \frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S} = 0$$

Solution:

$$\beta = \theta_1 + \theta_2 \text{ and } M = -\frac{\theta_1\theta_2 c^2}{4G}\left(\frac{D_L D_S}{D_{LS}}\right)$$

Gravitational Lensing; Basics



Several commonly used quantities in lensing are the critical surface-mass density, Σ_{crit} , and the the Einstein Radius, R_E.

Multiple images are produced when the surface mass density of the lens exceeds the critical value:

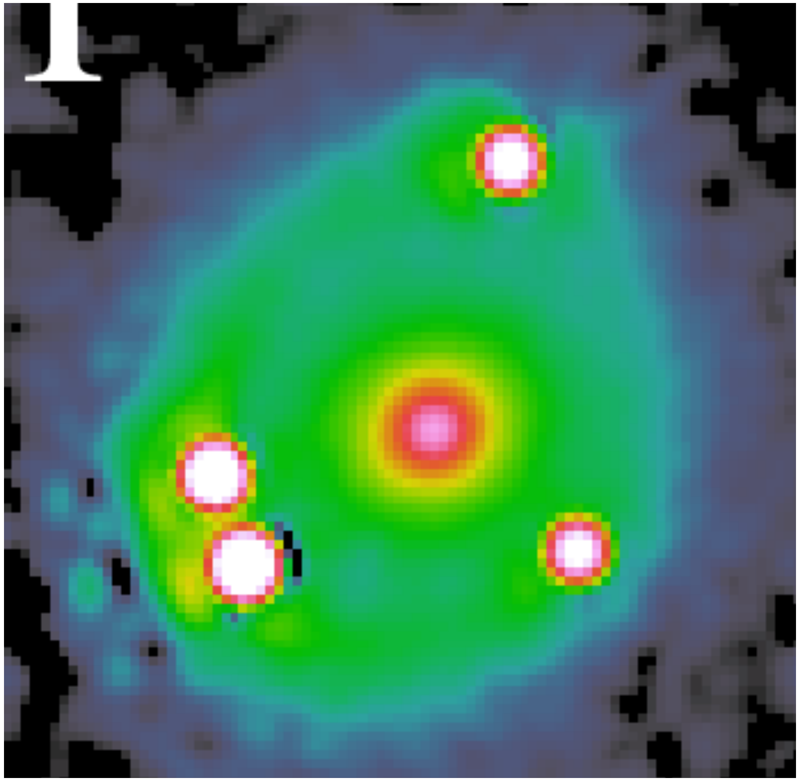
$$\Sigma_{crit} = \frac{c^2}{4\pi G}\frac{D_{LS}}{D_L D_S}$$

$\Sigma_{crit} \sim 0.8$ g cm^{-2} for lens and source redshifts of 0.5 and 2.0, respectively.

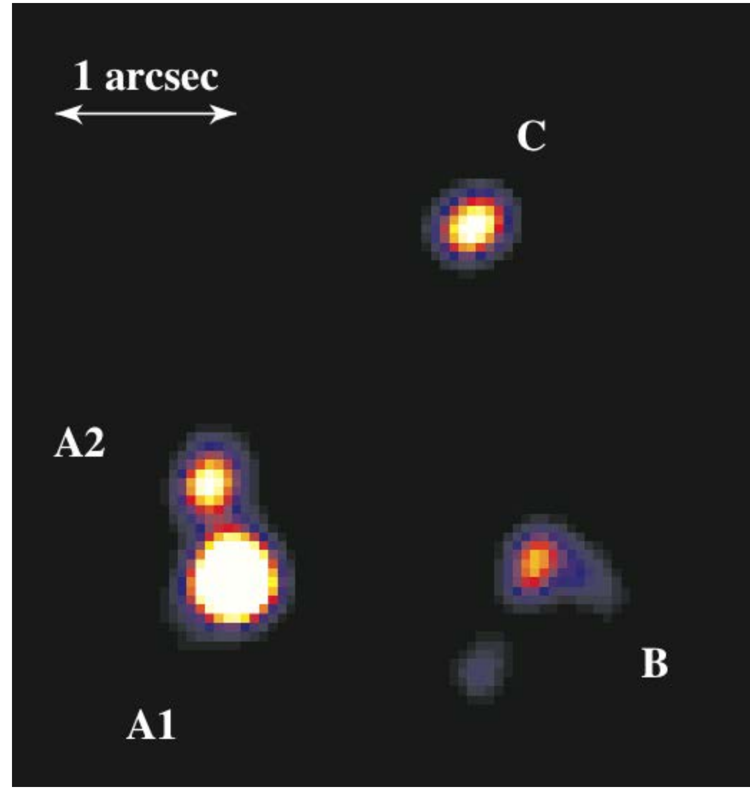
For the special case in which the source lies exactly behind the lens ($\beta = 0$) a ring-like image is produced with a radius (commonly referred to as the Einstein Radius) θ_E:

$$\theta_E = \sqrt{\frac{4\pi G}{c^2}\frac{D_{LS}}{D_L D_S}} = (0.9 arcsec)\left(\frac{M}{10^{11} M_\odot}\right)^{1/2}\left(\frac{D_L D_{LS}/D_S}{Gpc}\right)^{-1/2}$$

Gravitational Lensing; Basics

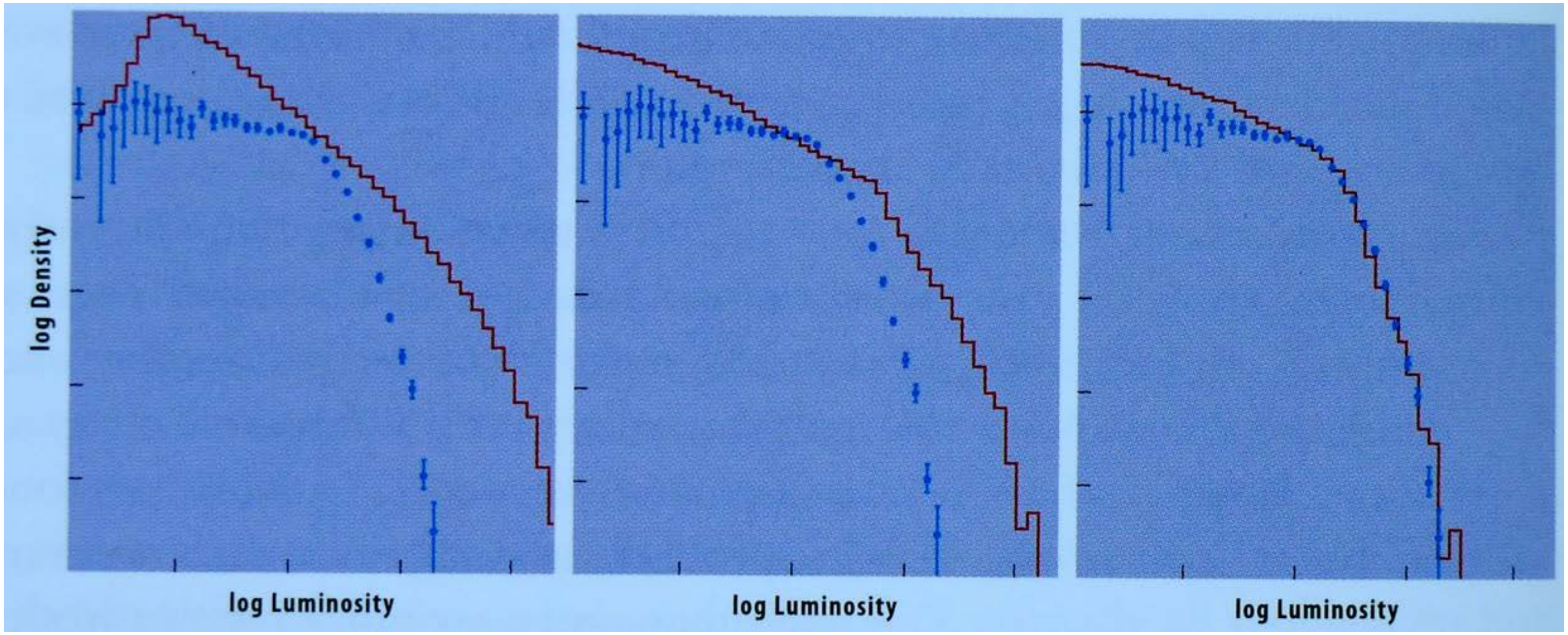


Hubble Space Telescope Image
of PG 1115+080 (H band)



Chandra X-ray Observatory Image
of PG 1115+080 (deconvolved)

Cosmic Feedback



The effects of feedback on the predicted distribution of galaxy masses compared to the observed distribution (blue).

(left) Without feedback galaxy formation theory predicts too many large galaxies and small galaxies.
(middle) Including feedback from supernova the theory suppresses the formation of small galaxies but has little effect at large masses.
(right) Including feedback from the SMBH one can fit the observed numbers of massive galaxies as well.

Feedback

A problem with hierarchical theory of galaxy formation is that **galaxies should have many small satellites** but this does not seem to be the case. For example our own galaxy has very few small satellites.

The observations are therefore telling us that there appears to be some missing **distractive agent** from the theory of galaxy formation.

A process (often referred to as **feedback**) is thought to release energy into the intergalactic medium and somehow inhibit the collection of too much gas in the halo.

According to Cold Dark Matter theory each galaxy-sized dark matter halo should contain large numbers of subhalos (dwarf-galaxies). However, observations do not find any subhalos that might be associated with luminous structures. A possible solution is that these dwarf galaxies may have very few stars.

Feedback

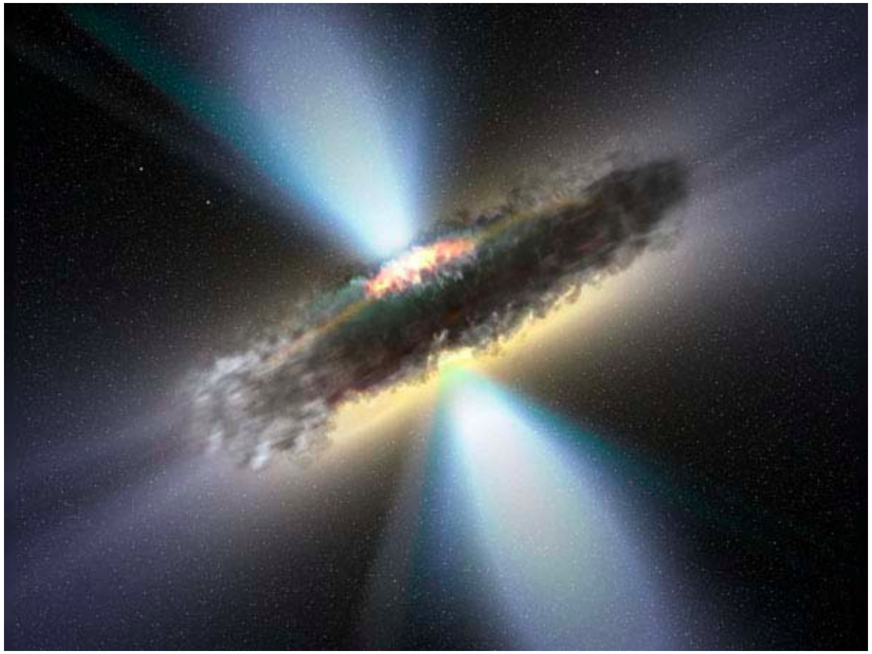
Many scientists now think that the SMBH is the distractive agent that inhibits the growth of its host galaxy.

In many cases the energy released by SMBHs seems to be adequate. For example $0.1M_{BH}c^2$ would be more than enough energy to eject all the gas from the galaxy.

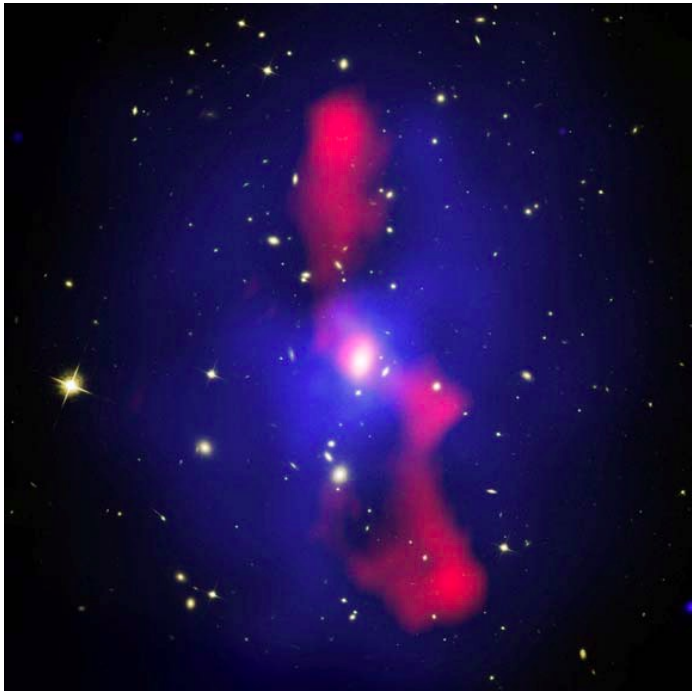
The problem is how does the energy released by a SMBH spread over large distances and how does it interact with the gas in the galaxy.

AGN put out energy in the forms of radiation, jets and winds.

Modes of interaction of AGN with their environments



AGN Wind and Radiation Mode



MS0735.6+7421 (McNamara & Nulsen 2007)

Radio Jet Mode

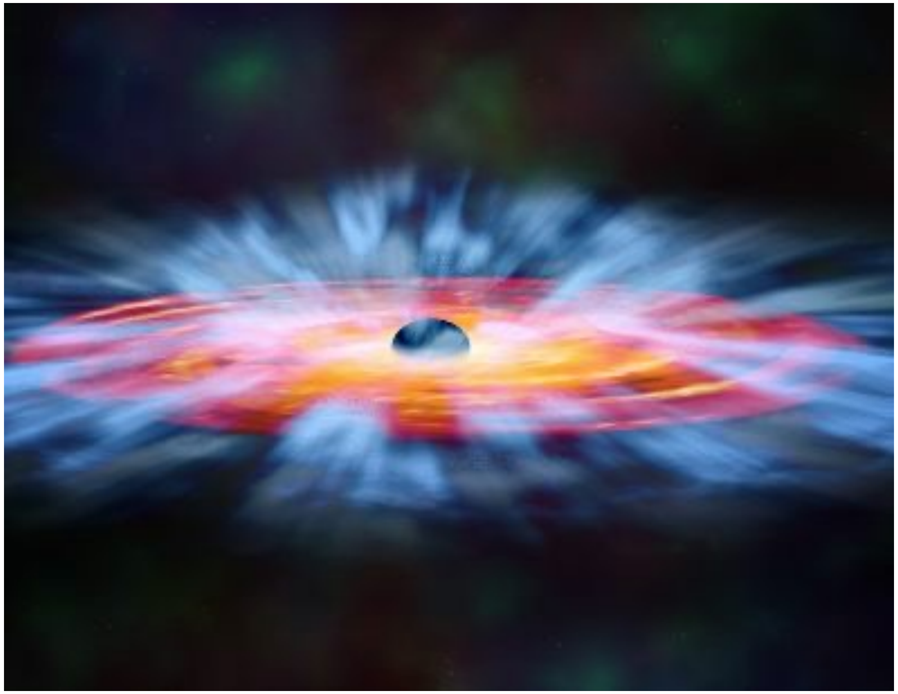
Quasar Winds

Density evolution of a disk wind driven by radiation pressure on spectral lines. Proga Stone & Kallman (2000)

Quasar Winds

Proposed mechanisms for quasar wind acceleration include:

- radiative driving
- magnetic driving
- thermal driving



Radiatively Driven Outflows

The radial equation of motion for material under the influence of radiation pressure and gravity at a distance R from the black hole:

$$mv\frac{\partial v}{\partial r} = \frac{L}{4\pi r^2}\frac{\sigma_T}{c} - \frac{GM_{bh}m}{r^2} \Rightarrow v_{wind} = \left[2GM_{bh}\left(M_f\frac{L_{UV}}{L_{Edd}} - 1\right)\left(\frac{1}{R_{in}} - \frac{1}{R}\right)\right]^{1/2}$$

where σ_T is the Thomson cross section, L_{Edd} is the Eddington luminosity and M_f is the force multiplier.

Radiation pressure force on the gas via :

(a) Electron scattering

(b) Scattering by dust grains

(c) Scattering in atomic resonance lines

Magnetically Driven Quasar Outflows

Two classes of magnetic wind models exist:
(a) Models where the magnetic tension term of $J \times B$ dominates
(b) Models where the magnetic pressure term of $J \times B$ dominates.

Where $J = I/A = \rho v$ is the current density, and $\rho = dq/dV$ is the charge density

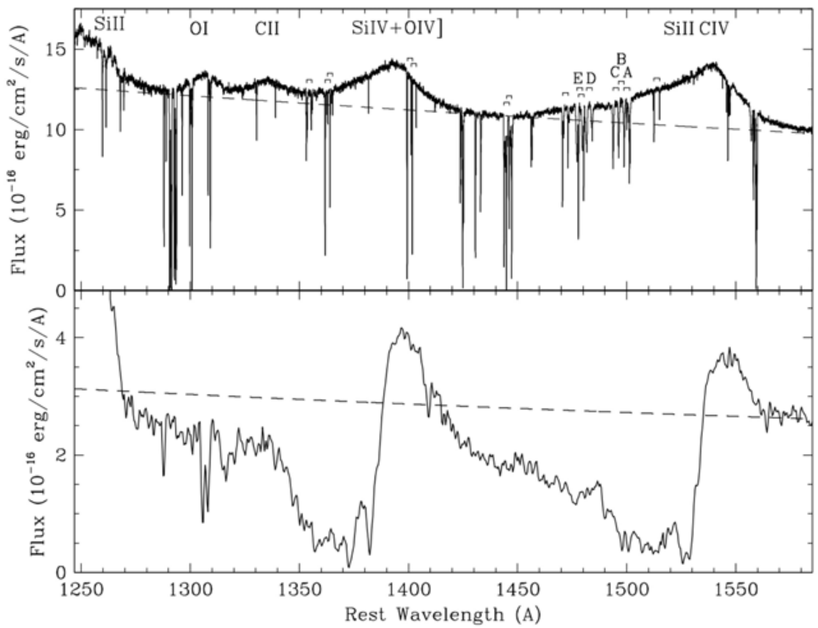
Magnetic wind models can explain the observed high velocity winds of highly ionized X-ray absorbing material.

Winds driven by magnetocentrifugal forces co-rotate with the disk near the launch radius whereas winds driven by radiation alone do not co-rotate.

Quasar Winds Observed in the UV Band

NAL Quasar
J2123-0050

BAL Quasar
Q1331-0108



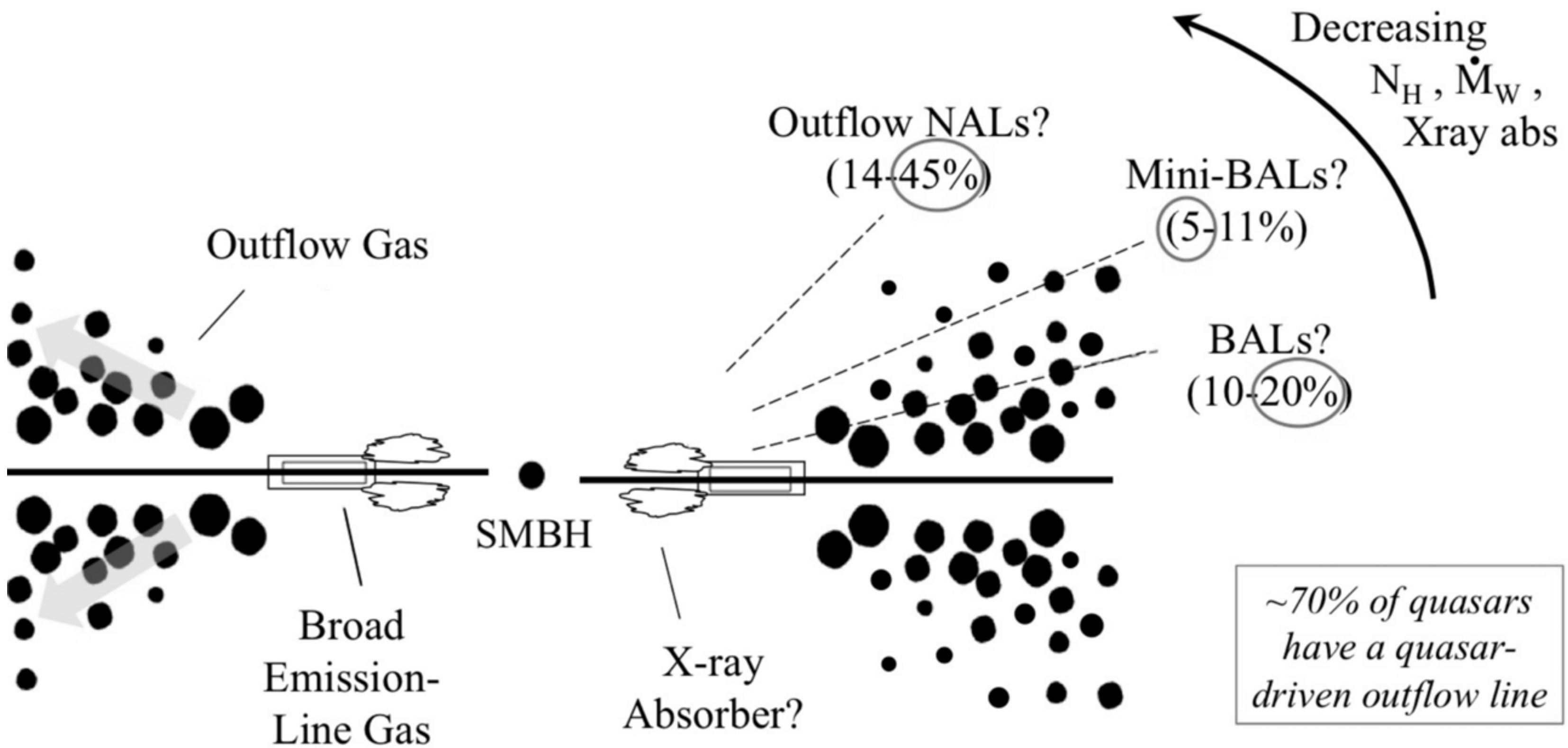
Top panel: Spectrum of the quasar J2123−0050 with numerous CIV NAL doublets labeled by open brackets. Bottom panel: Spectrum of the BAL quasar 1331-0108. (Hamann et al.2011)

NALs: FWHM < 500 km/s

BALs: FWHM > 2000 km/s

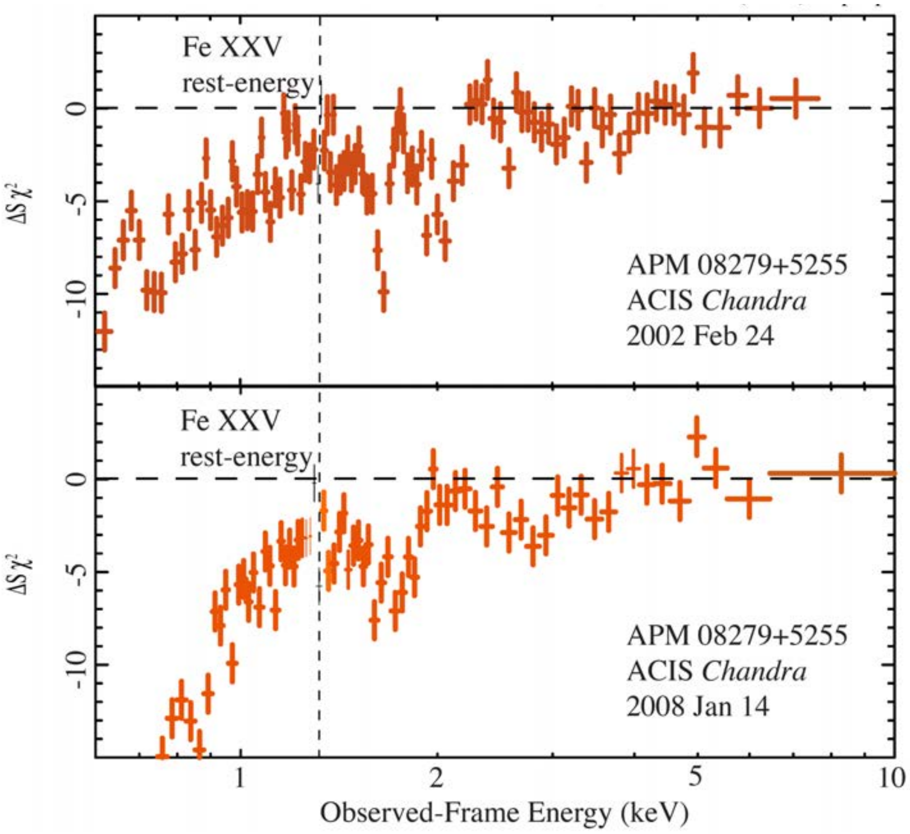
Mini-BALs : 500 km/s < FWHM < 2000 km/s

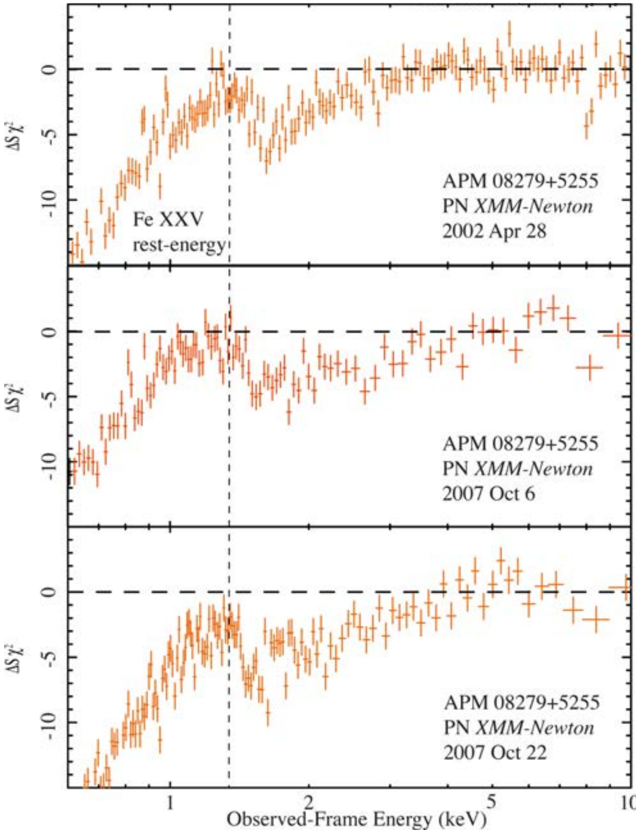
Possible Wind Geometry



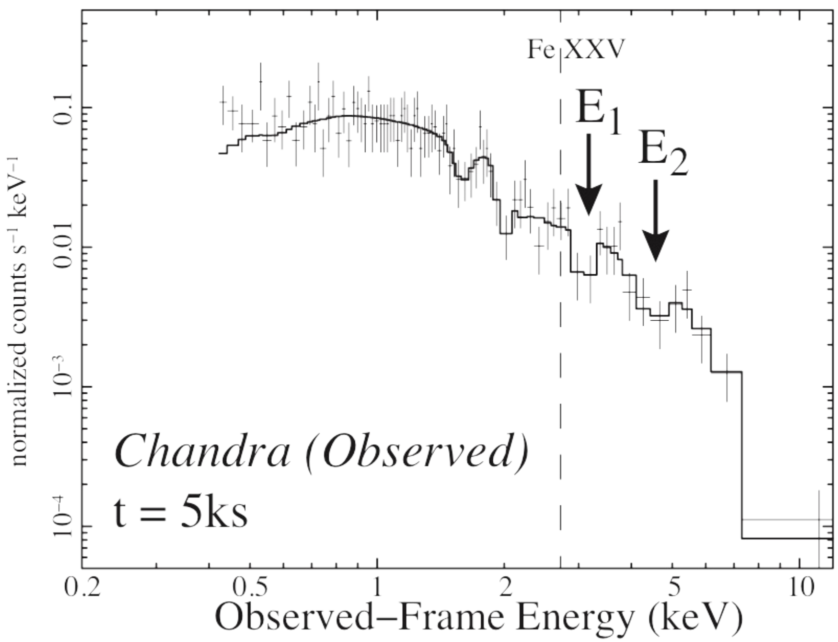
(Hamann et al. 2012)

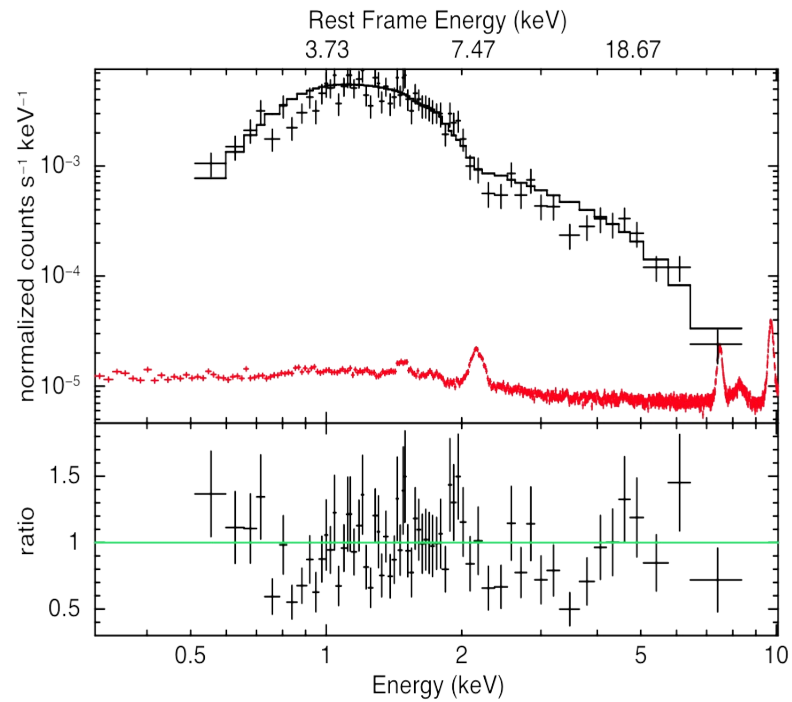
X-ray Observations of Winds in a BAL Quasar





X-ray Observations of Winds in NAL Quasars

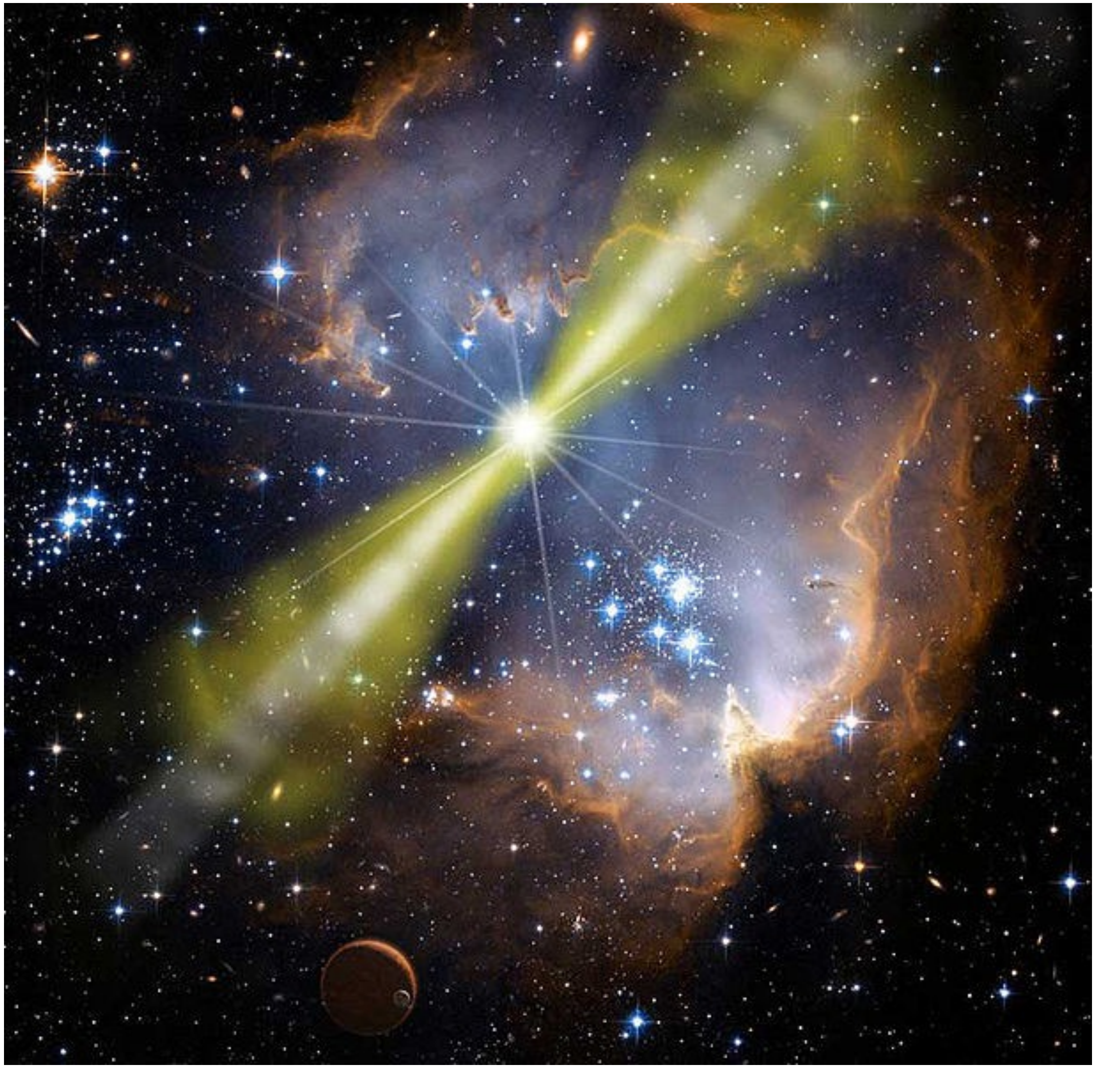




NAL quasar HS 0810+2554
$z = 1.5$
$M_{BH} \sim 5 \times 10^8 M_{\odot}$
v_X-ray = $0.14 - 0.46c$
v_UV = $0.06c$

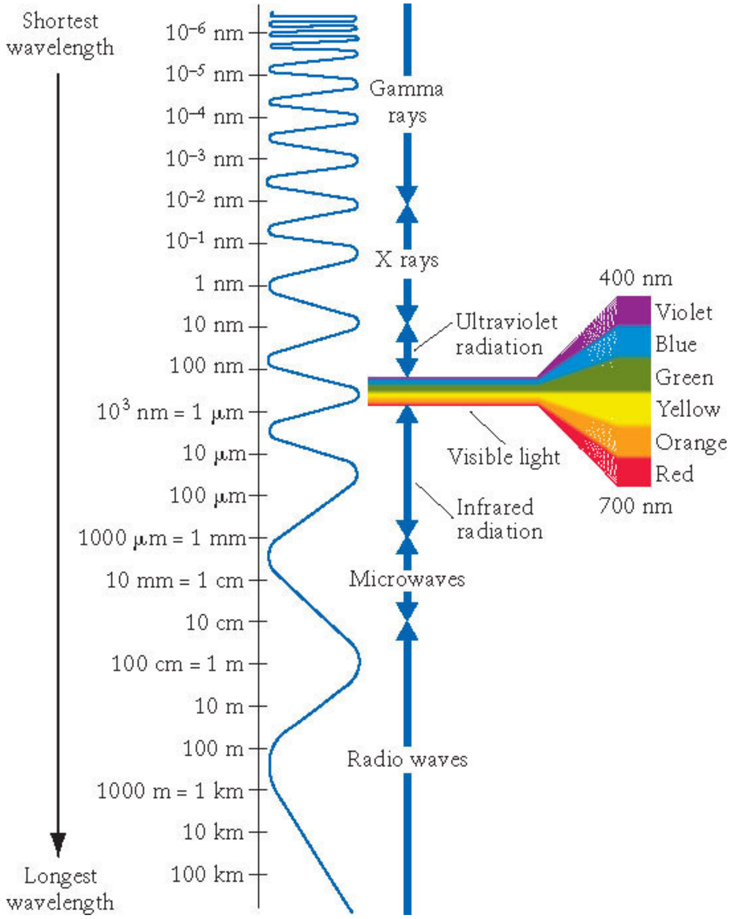
NAL quasar HS 1700+6414
$z = 2.74$
$M_{BH} \sim 2 \times 10^{10} M_{\odot}$
v_X-ray = $0.12 - 0.59c$
v_UV = $0.08c$

Gamma-Ray Bursts



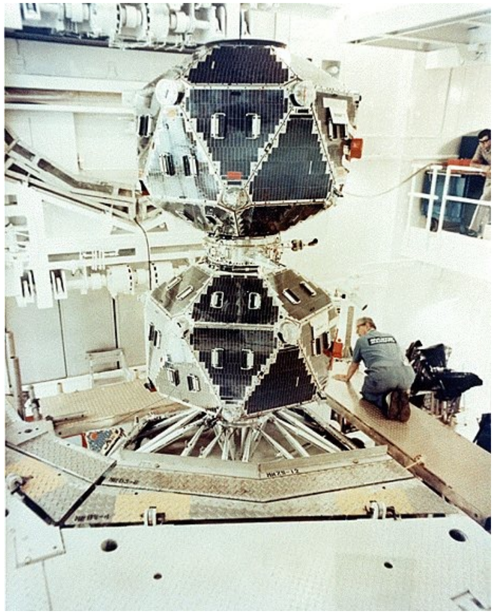
Gamma-Ray Astronomy

Gamma rays are photons with energies > 100 keV and are produced by sub-atomic particle interactions. They are absorbed by our atmosphere making observations from satellites necessary.



Gamma-Ray Bursts

Unexpected Discoveries of the Cold War Era
Gamma-ray bursts were first observed in the late 1960s by the U.S. Vela satellites, which were built to detect gamma radiation pulses emitted by nuclear weapons tested in space.


VELA 5A, 5B

A team at Los Alamos was able to determine rough estimates for the sky positions of several bursts and definitively rule out a terrestrial or solar origin.

The discovery was declassified and published in 1973 as an Astrophysical Journal article entitled "*Observations of Gamma-Ray Bursts of Cosmic Origin*"

Gamma-Ray Bursts

The location of Gamma-Ray Bursts
For more than 20 years after their discovery it was debated whether Gamma-ray bursts were produced in our galaxy or originated in other distant galaxies.

The poor positional accuracy of the early detections and their short duration made it difficult to follow up GRBs.

Gamma-Ray Astronomy

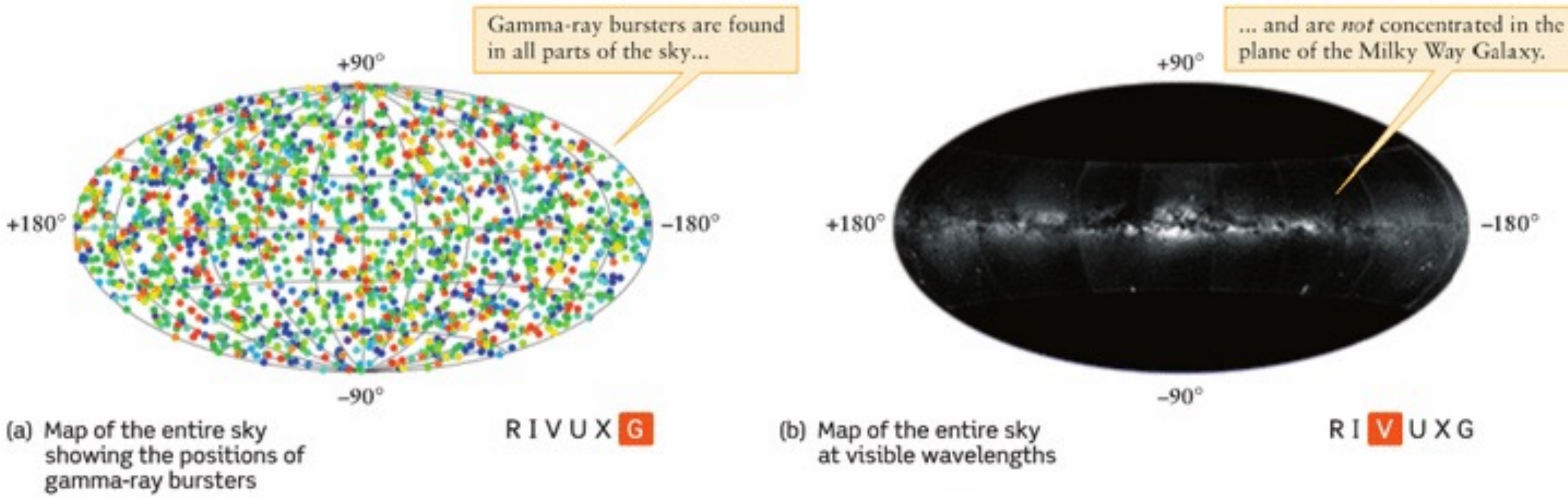
One of the most important gamma-ray telescopes placed in orbit in 1991 was **the Compton Gamma ray Observatory (CGRO)**.

The **EGRET** instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources.

The Burst and Transient Source Experiment **(BATSE)** instrument (20-600keV) made about 2700 GRB detections.

Instruments on CGRO were **EGRET, BATSE, OSSE, and COMPTEL.**
Energy range (20 keV - 30 GeV).

GRB Distribution

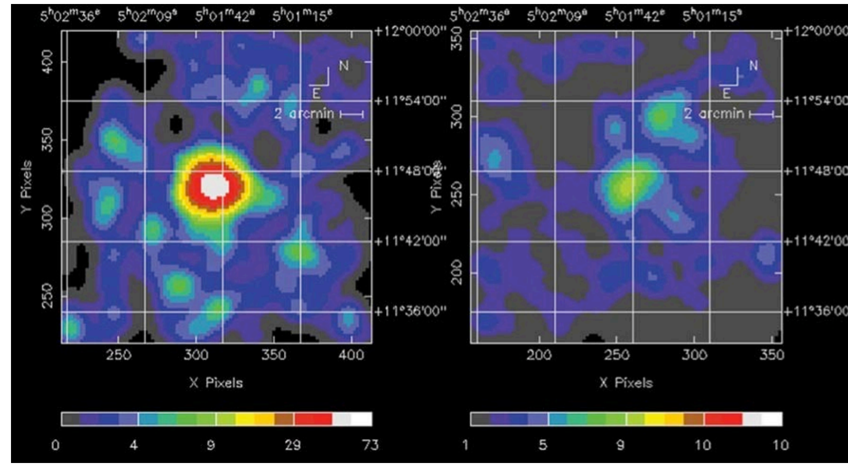


Positions of the 2704 GRBs recorded by the BATSE on the **Compton Gamma-Ray Observatory** are plotted on the sky.

Directions appear to be completely random. This favors the hypothesis that GRBs originate from outside our galaxy and likely from distant galaxies. If GRBs originated from our Galaxy one would have expected an accumulation along the galactic plane or towards the galactic center.

Gamma-Ray Bursts

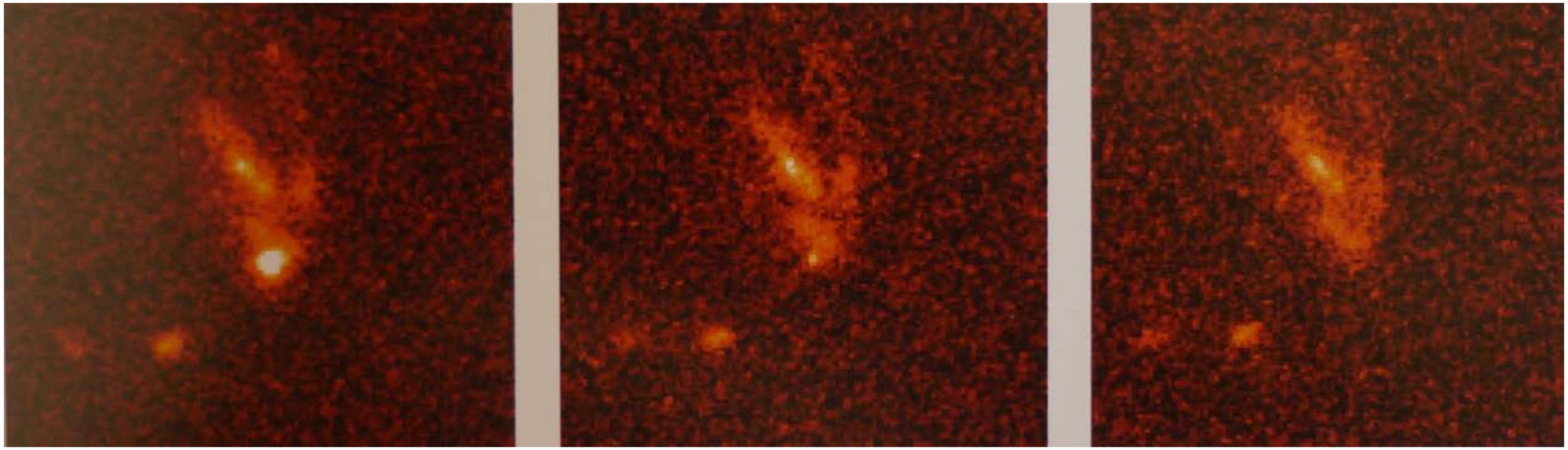
A breakthrough came after the launch of the Gamma-ray and X-ray telescope satellite named **Beppo-SAX**. It combined arcmin resolution and a rapid response.



Beppo-SAX discovered the first GRB afterglow. X-ray images of the afterglow 8 hours (left) and 3 days (right) after the burst.

Astronomers were able to follow up GRBs by taking optical spectra with large optical telescopes such as the 10m Keck in Hawaii. The strong redshifted absorption features confirmed their cosmological origin.

Gamma-Ray Bursts



(a) + 16 days **(b) + 59 days** **(c) + 380 days**

Deep optical observations in the locations where GRBs went off showed that they originate in galaxies.

The ultraluminous GRB 990123 was located on the outskirts of a star-forming galaxy with a redshift of 1.6. The Hubble Space Telescope images show the afterglow at (a)16, (b) 59 and (c)380 days after the burst.

Models of Gamma-Ray Bursts

Questions:
How are Gamma-Ray bursts produced?

Early measurements indicated that the total energy released during a gamma-ray burst was far more than a supernova's output. Could GRB's arise from some rare type of stellar explosion ("hypernova")?

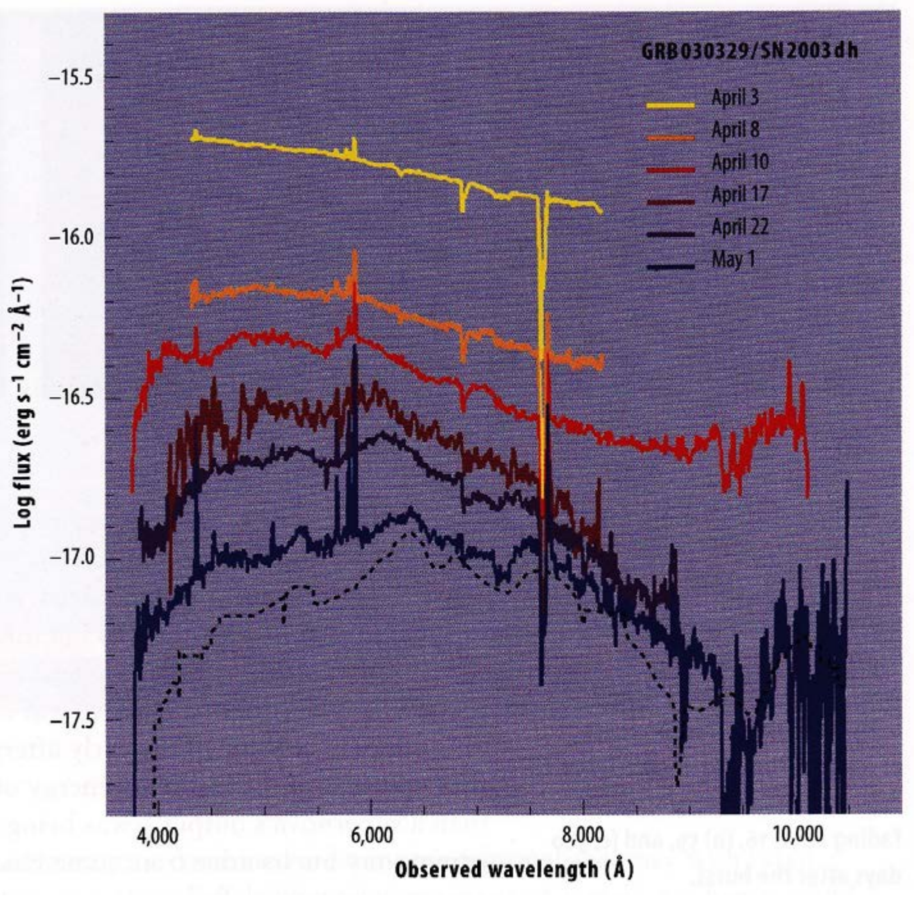
If so how could the energy escape from the stellar envelope of the star within seconds. In regular supernova explosions the stellar envelope slows the release of radiation.

Could the collision of two neutron stars explain the short time-scale of the burst?

Models of Gamma-Ray Bursts

Follow up of several GRBs with optical spectral observations showed spectra that resembled those of supernovae.

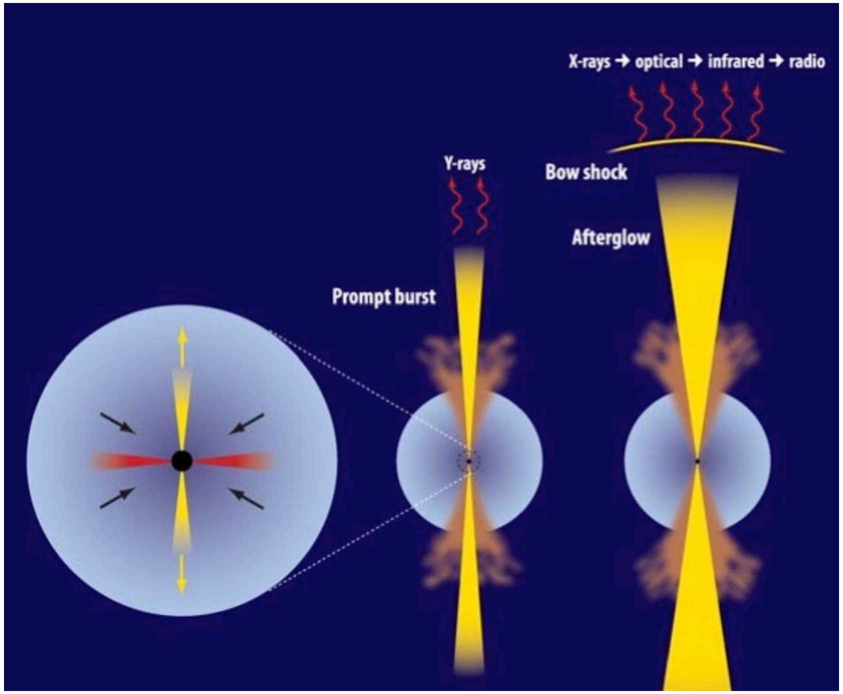
As the optical afterglow of GRB 030329 faded, the spectrum of the underlying supernova, SN 2003dh, became visible. After 34 days its spectrum resembled that of the supernova SN 1998bw of a similar age (dashed line).



Collapsar Model of Gamma-Ray Bursts

This schematic illustrates the **collapsar model** of GRBs. The left image shows a pair of jets being launched from and accretion disk fed by matter falling in.

In the central image the jets have broken through the stellar surface and emit the prompt burst of gamma-rays. Later, the jets slow down and spread out as they plow into surrounding matter, producing the afterglow.



Collapsar Model of Gamma Ray Bursts

The **collapsar model** proposes that a **long gamma ray burst** occurs during a core collapse supernova (Type Ic) of a ~ 30 $M_{\odot}$ star that is spinning rapidly.

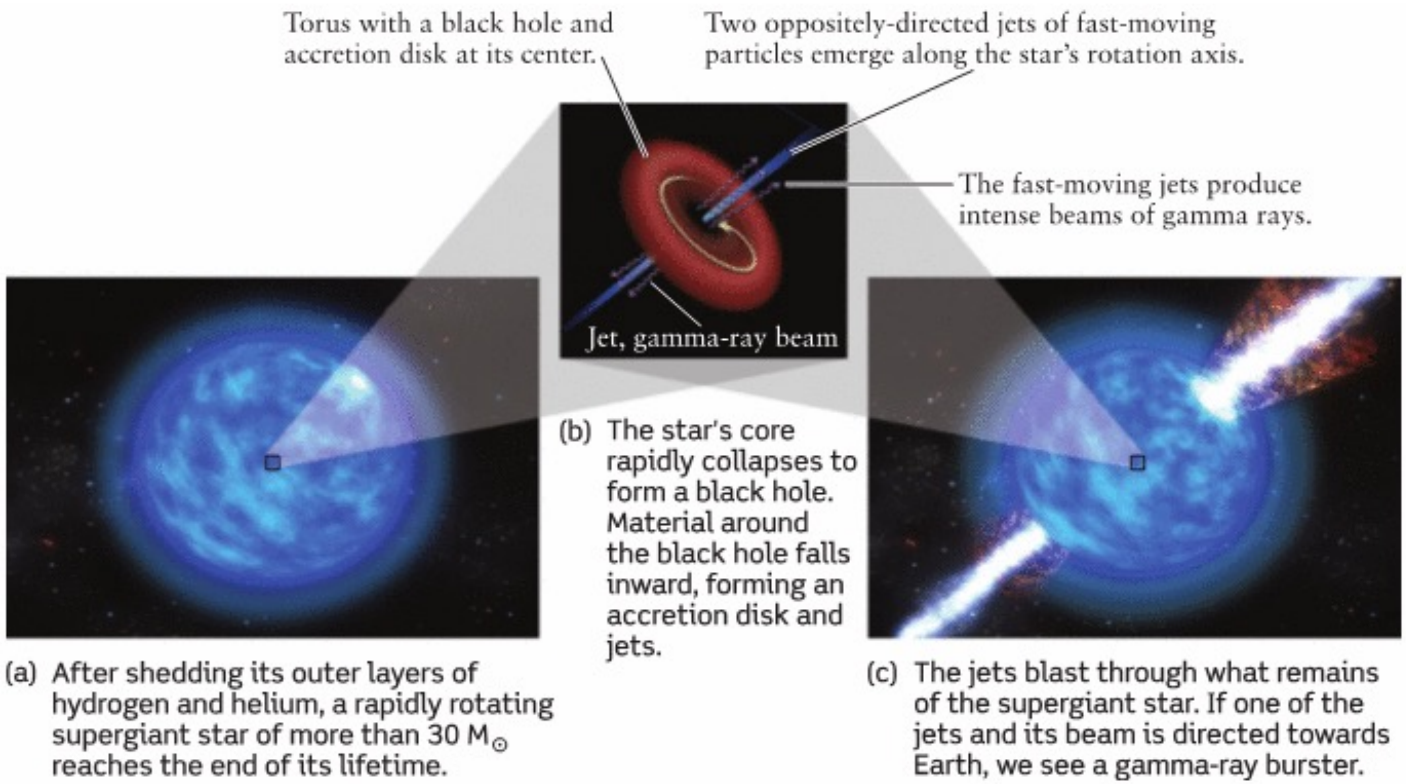
In this model **the core of the star collapses** to form a BH. The material just around the BH forms an accretion disk that is drawn into the BH. The magnetic field of this accretion disk forms jets of charged particles that break through the outer layers of the star.

(Key point: in a Type Ic supernova the outer **H and He layers have been blown away** so its easier for the jets to break through the star)

The energetic particles in the jet produce gamma-rays. If a jet is pointed towards the Earth we see a gamma ray burst.

The accretion disk is sucked into the BH within a few seconds and the gamma-rays burst ends.

Collapsar Model



Beamed radiation: A typical Type Ic supernova releases 10^{46} Joules of energy (0.03% goes into light and the rest mostly into neutrinos)

If we were to assume that all the energy released in a gamma ray burst was distributed uniformly the total energy would be ~ 3×10^{47} Joules but if the energy is beamed then the total energy is less and close to a normal Type Ic.

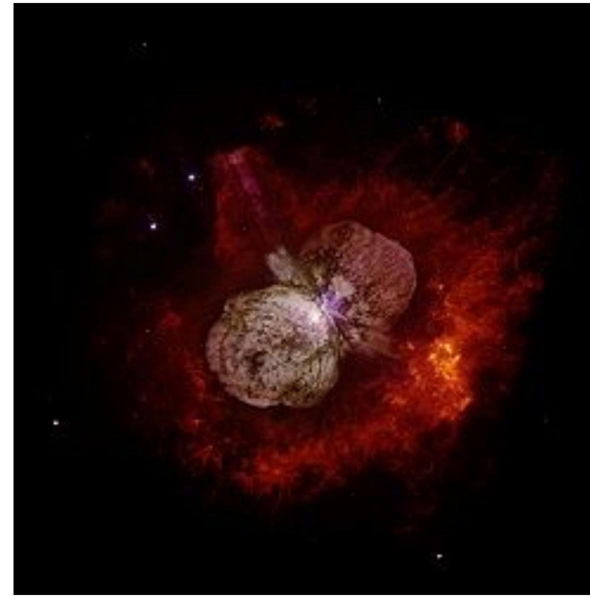
Collapsar Model

Three special conditions are required for a star to evolve all the way to a GRB under the Collapsar Model:

1) the star must be **very massive** (~40 $M_\odot$ on the main sequence) to form a central black hole in the first place,

2) the star must be **rapidly rotating** to develop an accretion disk capable of launching jets, and

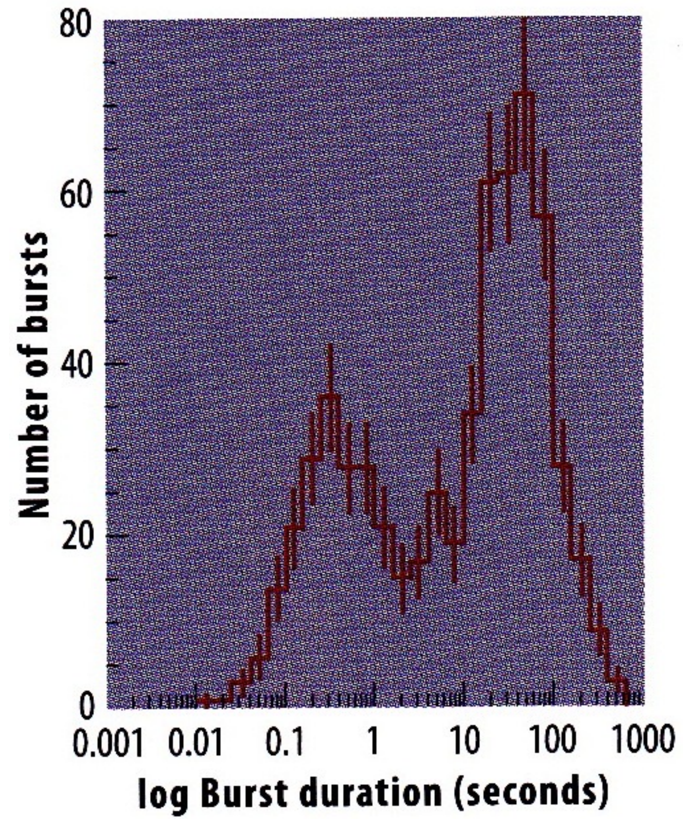
3) the star must have **low metallicity** in order to strip off its hydrogen envelope so the jets can reach the surface. As a result, gamma-ray bursts are far rarer than ordinary core-collapse supernovae, which only require that the star be massive enough to fuse all the way to iron.



Eta Carinae, in the constellation of Carina, one of the nearer candidates for a hypernova!

Long and Short GRBs

Gamma-ray bursts fall into two types. **Long bursts** ~ 2 - 1000 sec duration and **short bursts** ~ 0.01 sec - 2 sec duration (contain lower energy photons than long bursts)



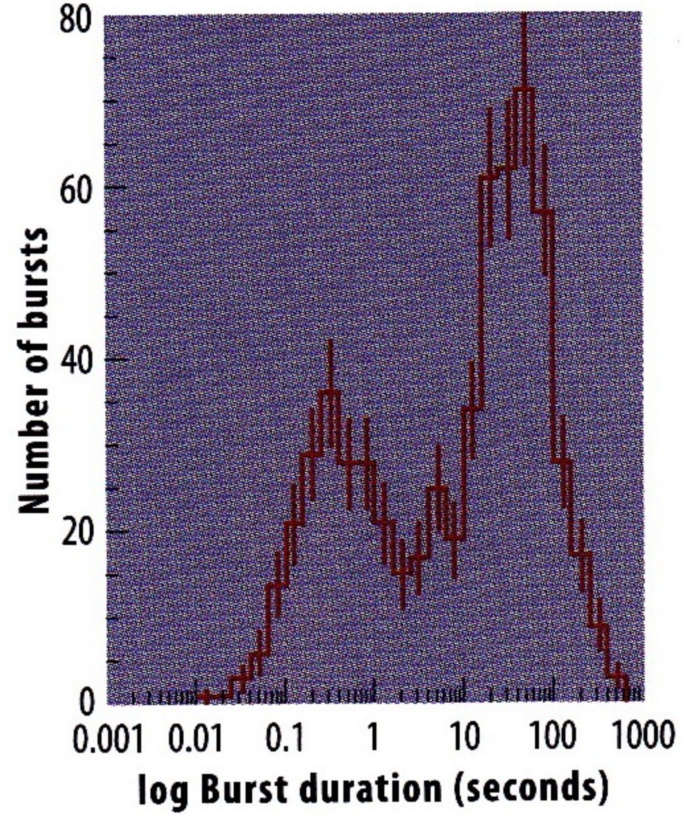
Their cosmic origin was confirmed with the measurement of their redshift. The spectrum of the **afterglow** in long bursts is consistent with a Type Ic supernova spectrum.

Progenitors of Long GRBs

Long GRBs are found in systems with abundant recent star formation (ie. contain massive stars) , such as in irregular galaxies and **in the arms of spiral galaxies**.

Why are star formation regions likely to contain massive stars?

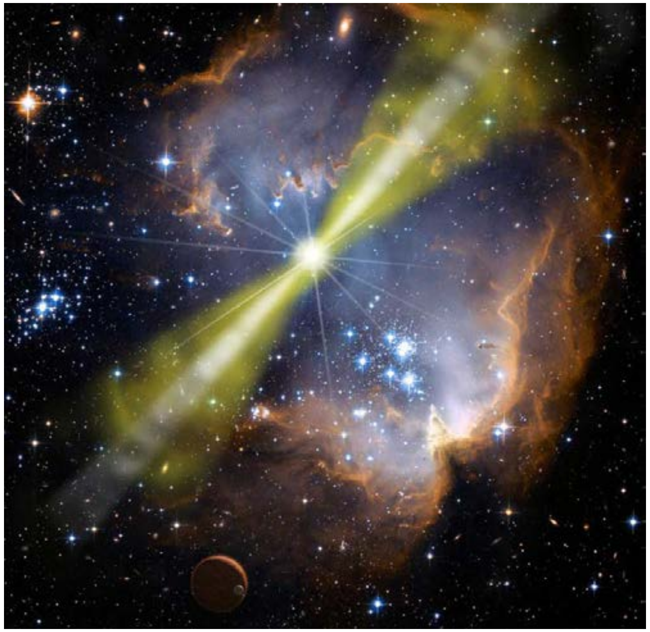
Follow up observations of several long GRBs have detected emission from type Ib/c supernova at the same location.



Progenitors of Long GRBs

Long GRBs are thought to be highly focused explosions, with most of the explosion energy collimated into a narrow jet traveling at speeds exceeding 0.99995c.

Observations suggest significant variation in the jet angle from between 2 and 20 degrees



Emission Mechanism

Gamma Rays in GRBs: One model posits that gamma rays are produced in GRBs by inverse Compton scattering. Specifically, pre-existing low-energy photons are scattered by relativistic electrons within the explosion, increasing their energy into gamma-rays.

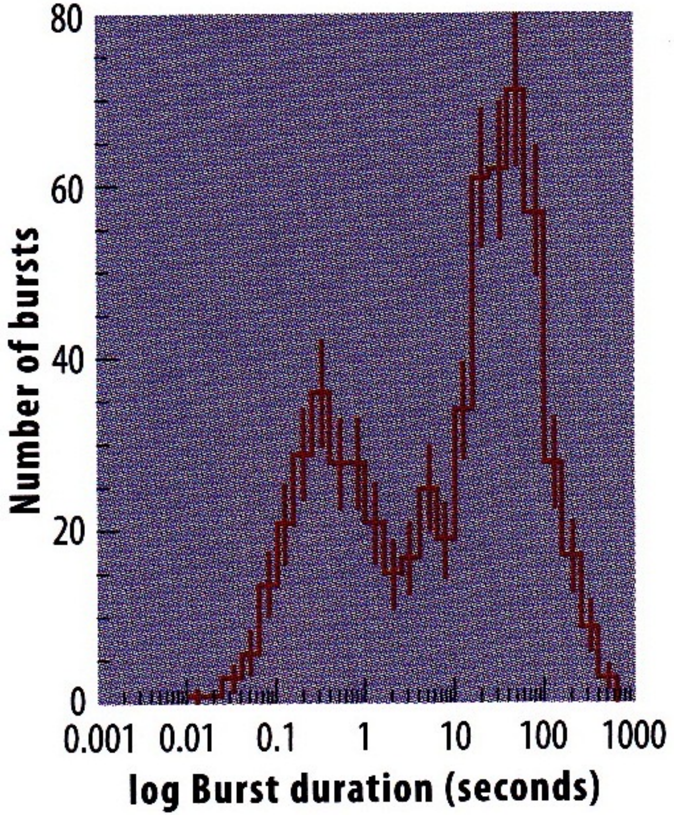
Afterglow Emission: As matter form the explosion collides with the surrounding gas, it creates a relativistic shock wave that then propagates forward into interstellar space. A second shock wave, the reverse shock, may propagate back into the ejected matter. Energetic electrons within the shock wave are accelerated by strong magnetic fields and radiate as synchrotron emission across most of the electromagnetic spectrum.

Progenitors of Short GRBs

Several **short GRBs have been associated with** the outer regions and even the outer halo of large **elliptical galaxies** in which star formation has nearly ceased.

All the hosts identified so far have also been at low redshift.

No supernova has been associated with any short GRB.



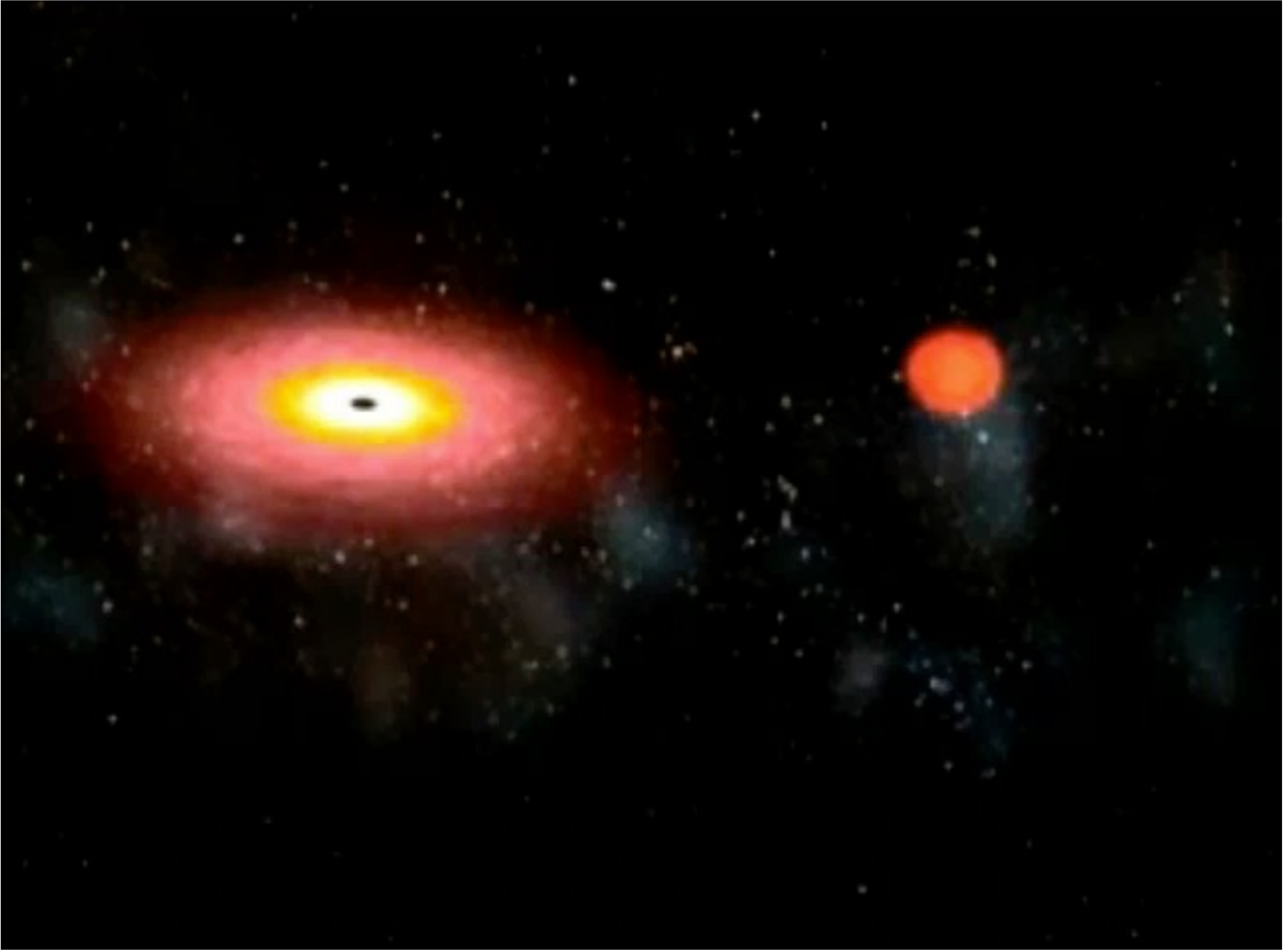
Models of Short GRBs

One model posits that short GRBs are the result of the merger of two compact objects : two neutron stars, or a black hole and a neutron star.

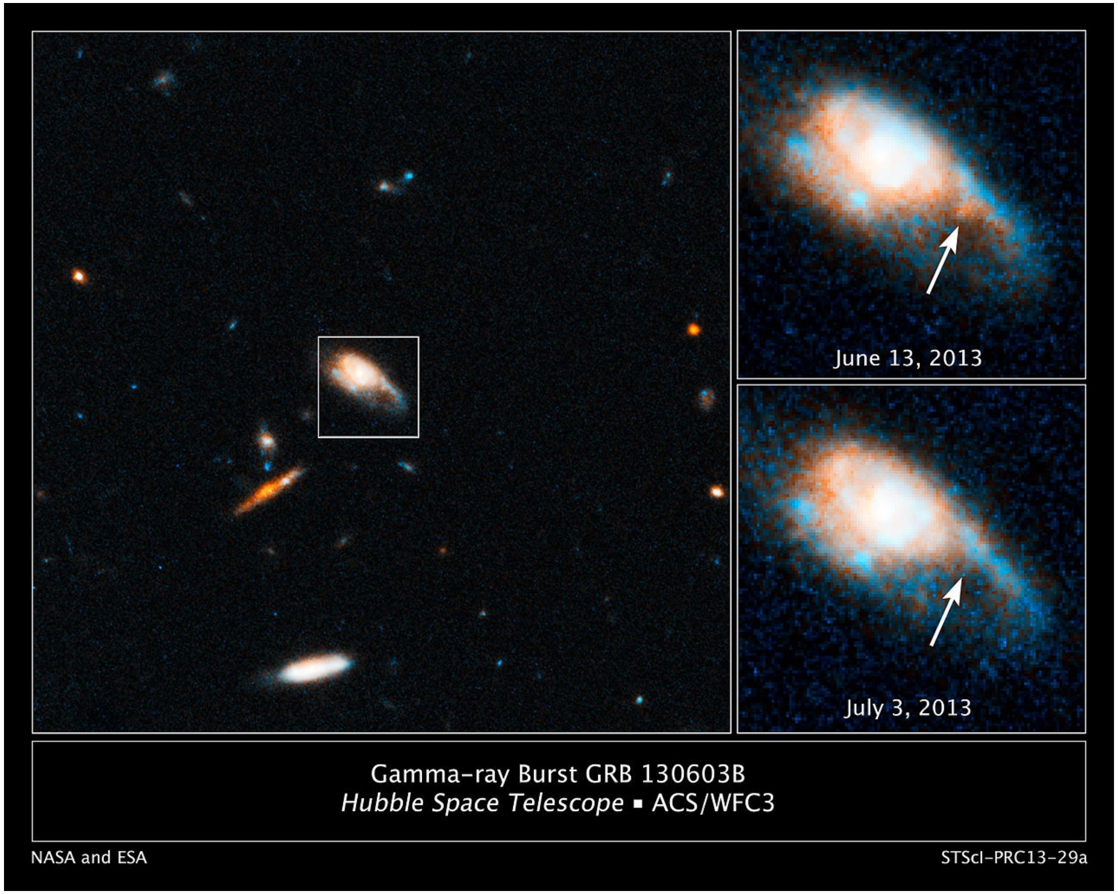
During the merger immense amount of energy is liberated before the matter plunges into a single black hole.

Strong electromagnetic radiation is emitted due to the decay of heavy **ions** that are produced and ejected fairly isotropically during the merger process.

The whole process is believed to occur extremely quickly and be completely over within a few seconds, accounting for the short nature of these bursts.



Kilonovae progenitors of Short GRBs



The first clear detection of a kilonova was in association with the short-duration gamma-ray burst GRB 130603B. This gamma-ray burst was in a relatively nearby galaxy, enabling the faint infra-red emission from the kilonova to be detected using the Hubble Space Telescope.

Mass Extinction Event?

It has been hypothesized that a gamma-ray burst in the Milky Way, pointing directly towards the Earth, could cause a mass extinction event (astro-ph/0309415.pdf).

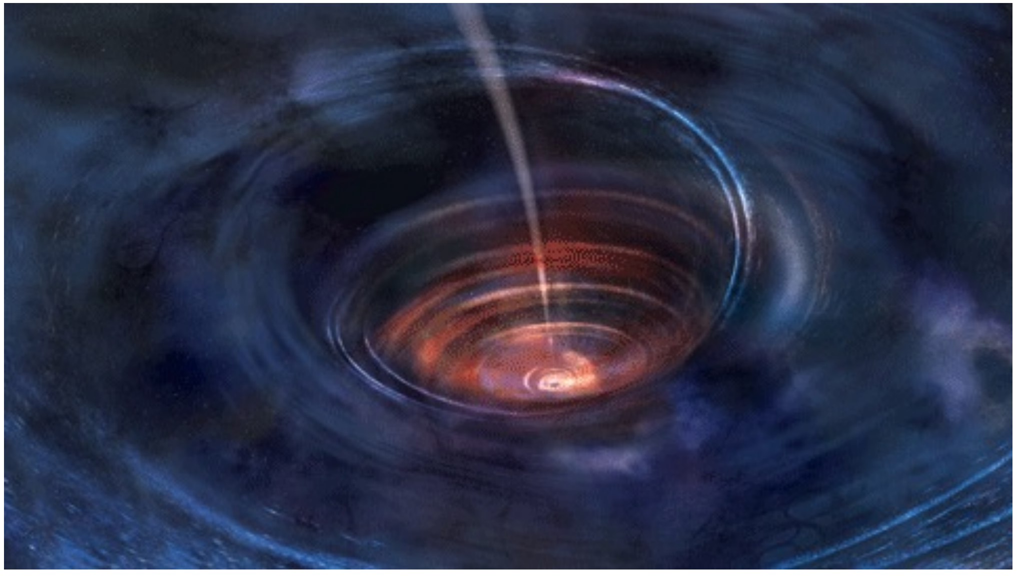
A GRB within our galaxy could damage the Earth's biosphere

GRB Rate in Galaxy: 1-2 every billion years

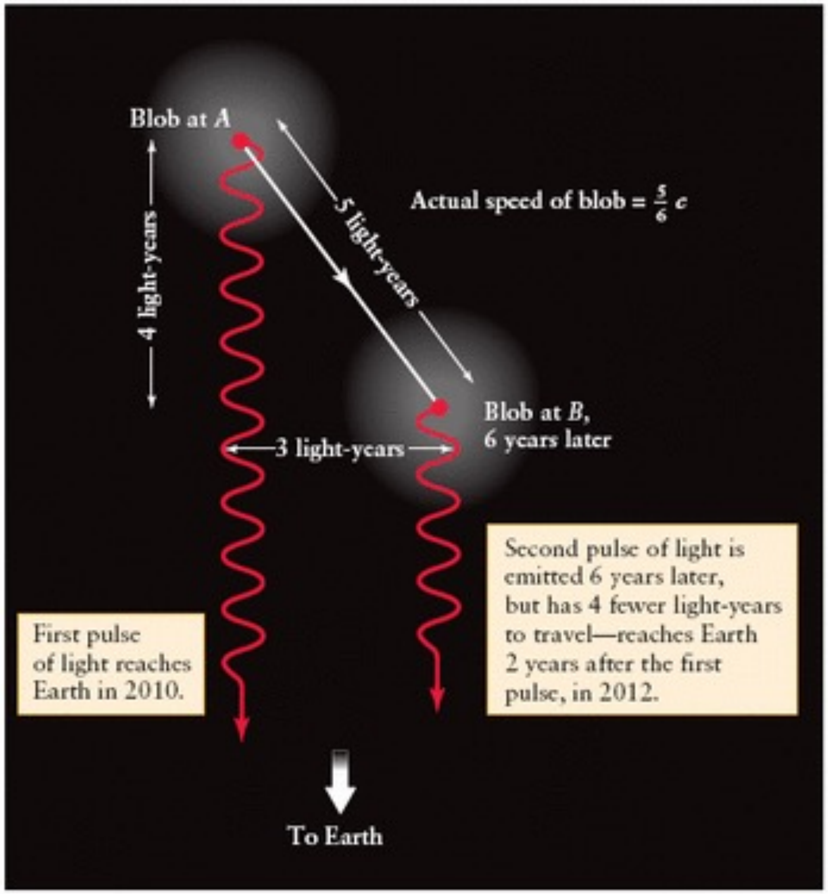
Depletion of ozone layer may lead to elevated levels of UV

Tidal Disruption Events Produce GRBs

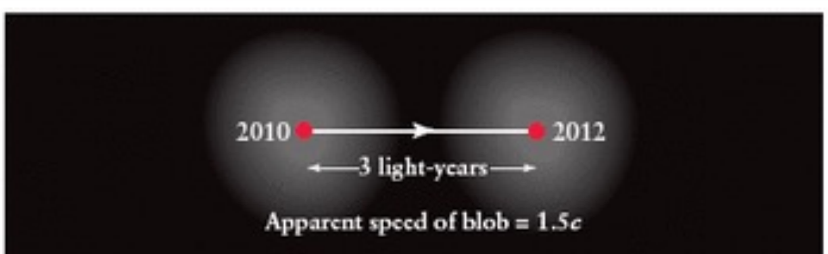
A tidal disruption event may occur when a MS star (or white dwarf) interacts with a supermassive black hole shredding the star, and in some cases creating a relativistic jet which produces bright emission of gamma ray radiation



An Explanation of Superluminal Motion



(a) View from above



(b) View from Earth

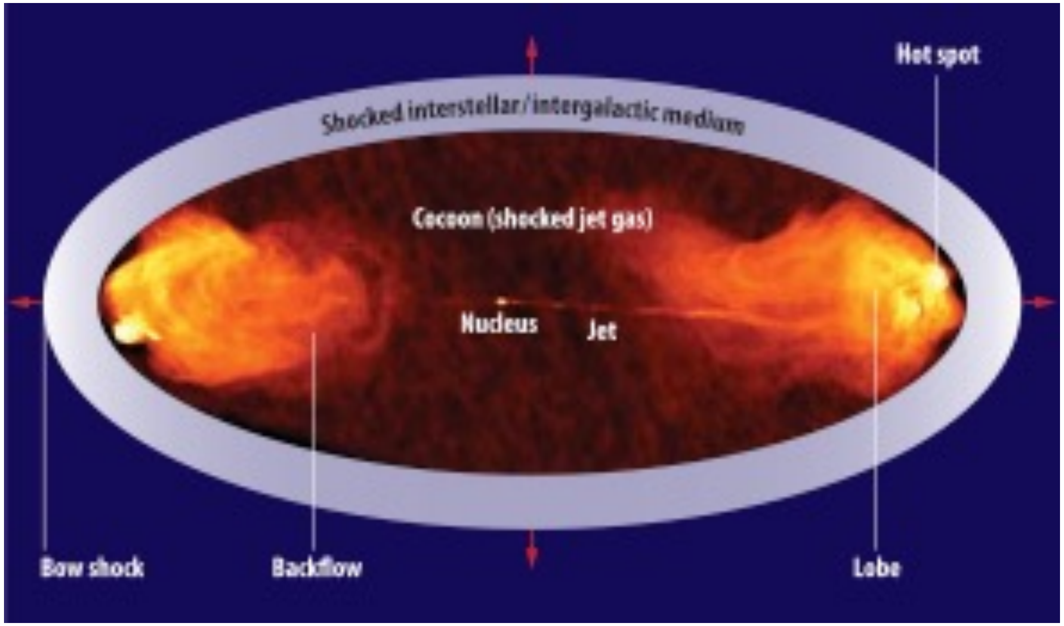
(a) If a blob of material ejected from a quasar moves at five-sixths of the speed of light, it covers the 5 ly from point A to point B in 6 years. In the case shown here, it moves 4 ly toward Earth and 3 ly in a transverse direction. The light emitted by the blob at A reaches us in 2010. The light emitted by the blob at B reaches us in 2012. The light left the blob at B 6 years later than the light from A but had 4 fewer light-years to travel to reach us.

(b) From Earth we can see only the blob's transverse motion across the sky. It appears that the blob has traveled 3 ly in just 2 years, so its apparent speed is 3/2 of the speed of light, or 1.5c.

What powers the lobes and hot spots?

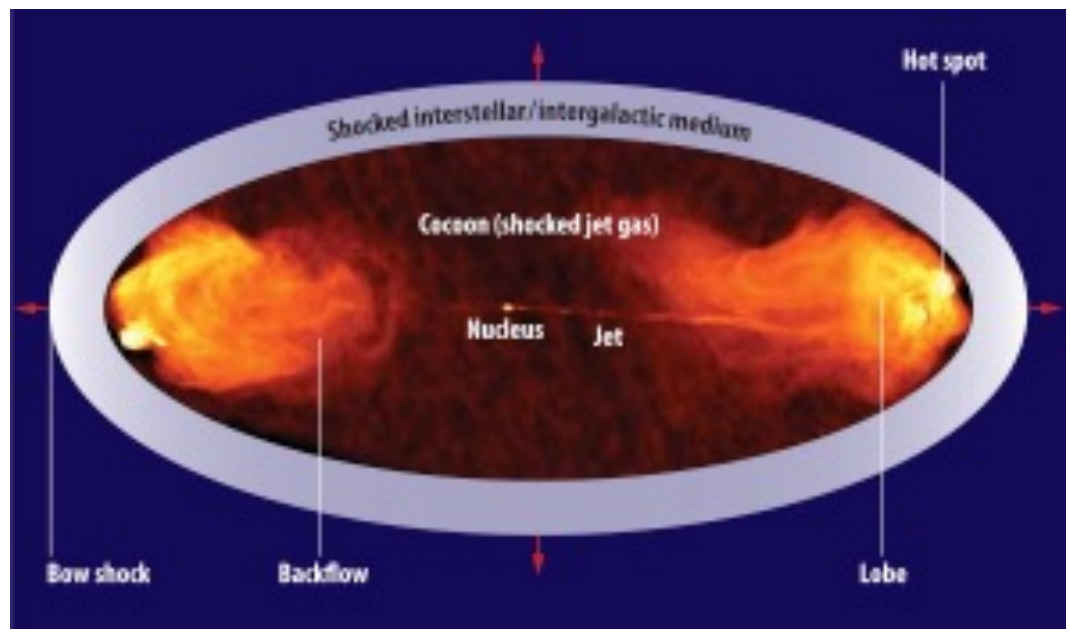
Researchers from Cambridge University first proposed that lobes were powered by twin streams of fast-moving gas, created in the nucleus of the galaxy.

Jet Model: As the gas in the jet moves through the IGM it pushes the medium out of the way; hence the end of the jet moves slower than the gas flowing inside the jet. As a result, **energy accumulates at the end of the jet** forming the hot spots.



What powers the lobes and hot spots?

The speed of the gas in the jet is faster than the speed of sound in the gas. The flow is thus referred to as **supersonic**. As the fast-moving gas approaches the almost stationary hot spot the gas suddenly decelerates forming a **shock wave across the jet**.



Beaming

The luminosity of a jet is increased due to various relativistic effects including beaming and the Doppler shift (the energy of each photon appears to have increased).

Beaming Angle:
Half of the opening angle is $\theta = 1/\gamma$,

$$\gamma = \frac{1}{\sqrt{1-\frac{u^2}{c^2}}}$$

The luminosity of a jet is increased due to various relativistic effects including beaming and the Doppler shift (the energy of each photon appears to have increased).

Beaming Angle:
Half of the opening angle is $\Theta = 1/\gamma$,

$$\gamma = \frac{1}{\sqrt{1-\frac{u^2}{c^2}}}$$

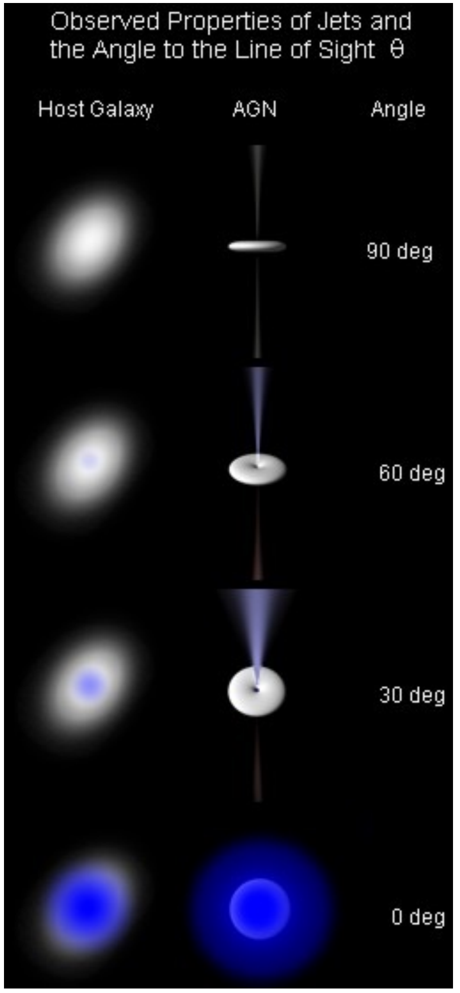
A sphere at rest emits photons in all directions (not all are shown). If the sphere is moving at relativistic speeds then we would observe these same photons to be emitted from a cone centered around the direction of motion.

Unification of Radio Loud AGN

Unified models for radio galaxies:
Radiation sources that emit in an anisotropic way will appear different depending on how they are oriented with respect to our line of sight.

Examples: If we a looking close the one of the jet directions we only see the projected length of one beamed jet. The radio lobes will radiate isotropically but will not be resolved so only a **compact radio source** is observed.

If we are looking almost perpendicular to the jet direction we **see a radio galaxy with two resolved lobes**. Emission from the jets is faint especially if they are relativistic.



Unification. From bottom to top:
Down the jet – Blazar
90° from jet – Radio Galaxy + 2 lobes