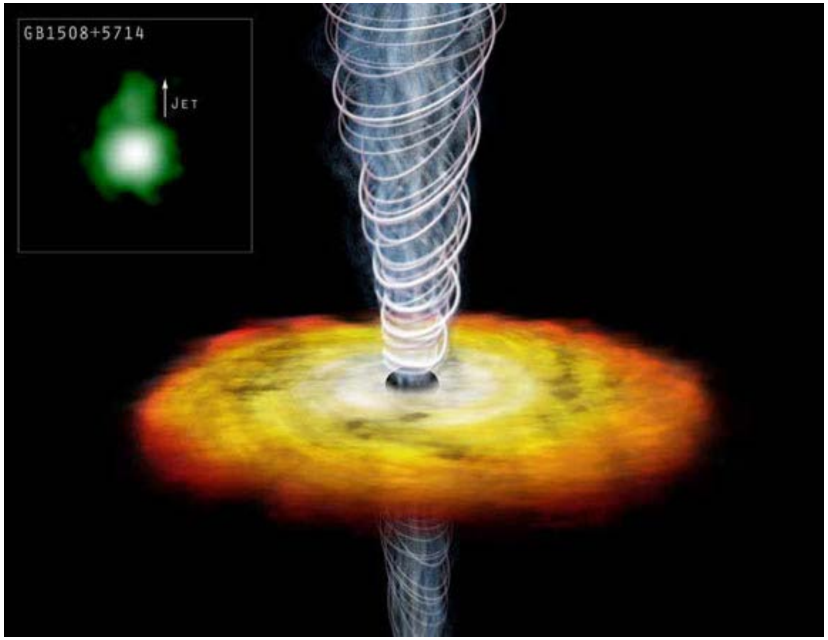
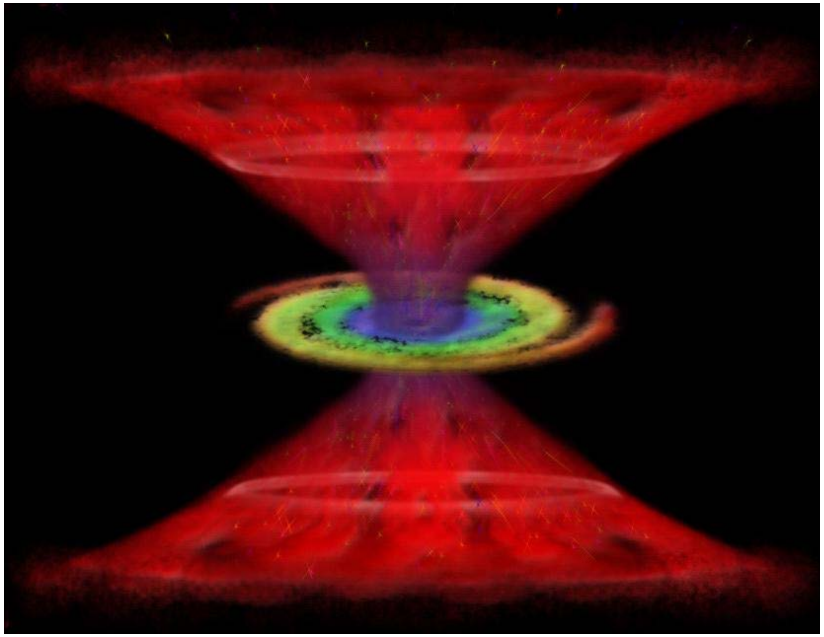
Quasars and Kin



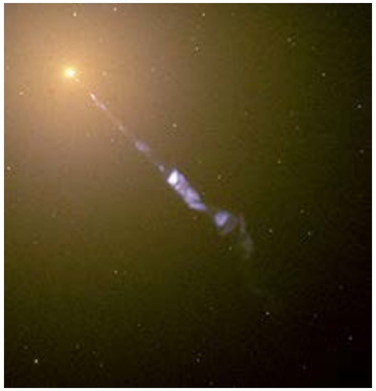


The Discovery of Active Galactic Nuclei

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.



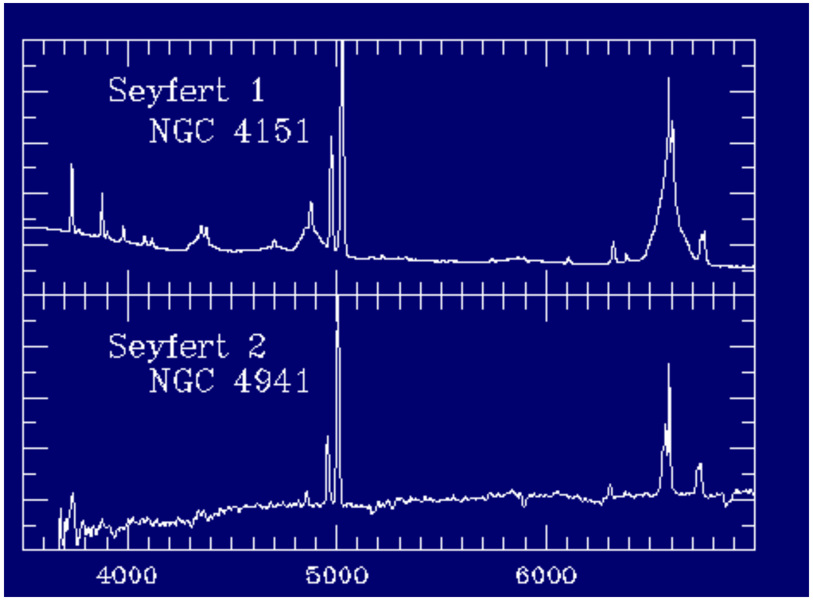
Heber Curtis

The Discovery of Active Galactic Nuclei

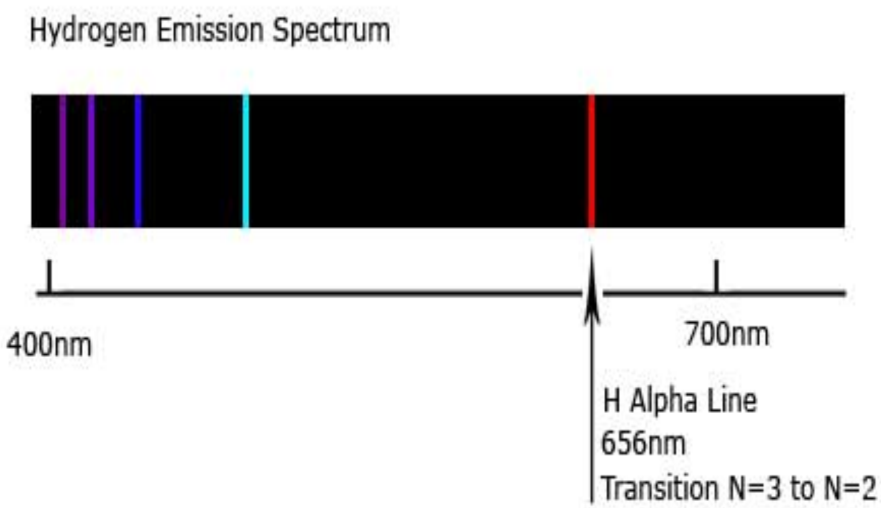
Carl Seyfert at the Mount Wilson observatory in California first observed that a few percent of spiral galaxies contain intense blue nuclei. Such spiral galaxies are now called **Seyfert galaxies.**

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

The Discovery of Active Galactic Nuclei



Wavelength



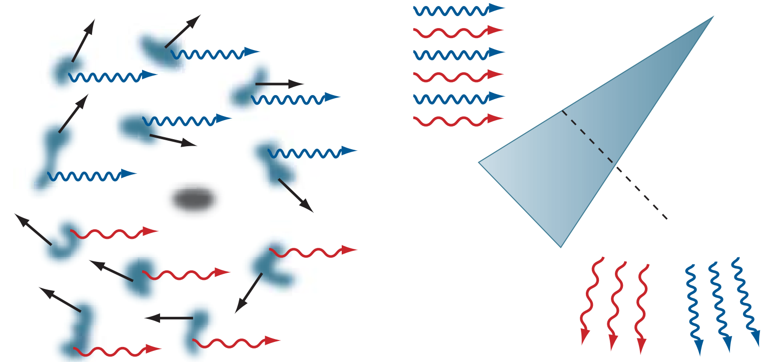
Seyfert galaxies are observationally grouped into ones that show broad and narrow emission lines (**Type I Seyferts**) and ones that show only narrow emission lines (**Type II Seyferts**)

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

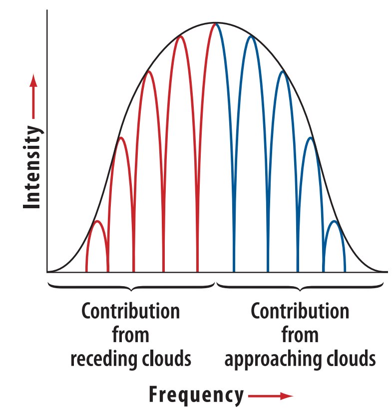
The **broad lines** are thought to come from higher density ionized gas with $n_e > 10^9$ cm^{-3} producing emission lines with widths of up to 10^4 km/s

The Broad Emission Lines in Seyfert 1's

The broad lines in type I Seyfert galaxies are thought to be produced by the Doppler effect and indicates that the gas emitting the lines is extremely turbulent.



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.

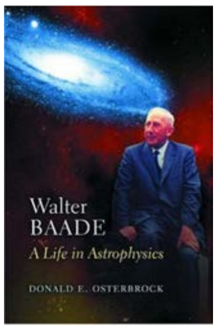


The light from the whole system when spread into a spectrum, yields a line that is much broader than that from an individual cloud.

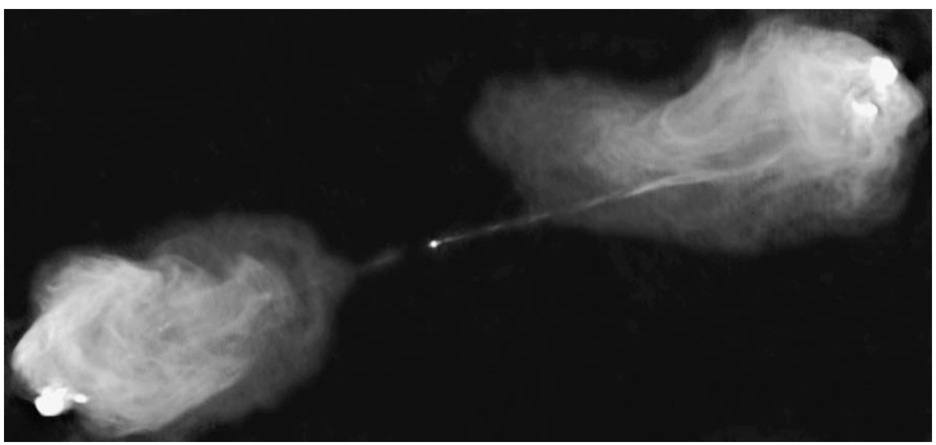
The **overall line width** is determined by the spread in cloud velocities.

The Discovery of Active Galactic Nuclei

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



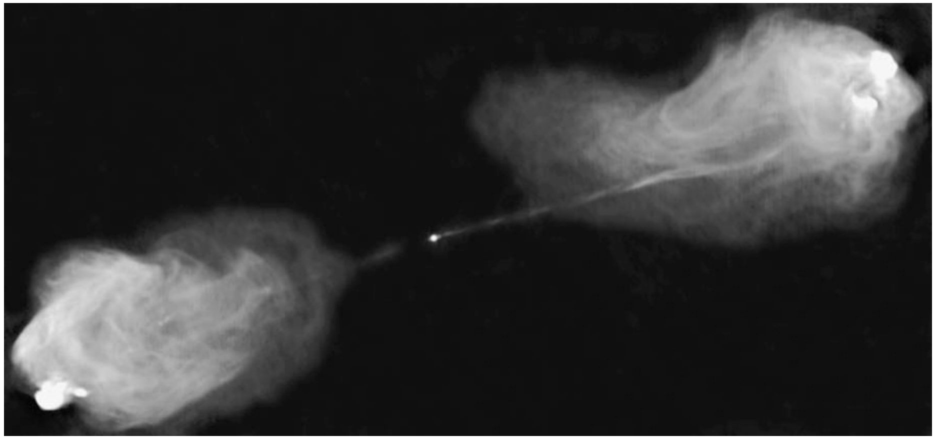
In 1954 Walter Baade of the Mount Wilson and Palomar Observatories was able to identify that a faint galaxy at a redshift of 0.05 was associated with the bright radio source Cygnus A.



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

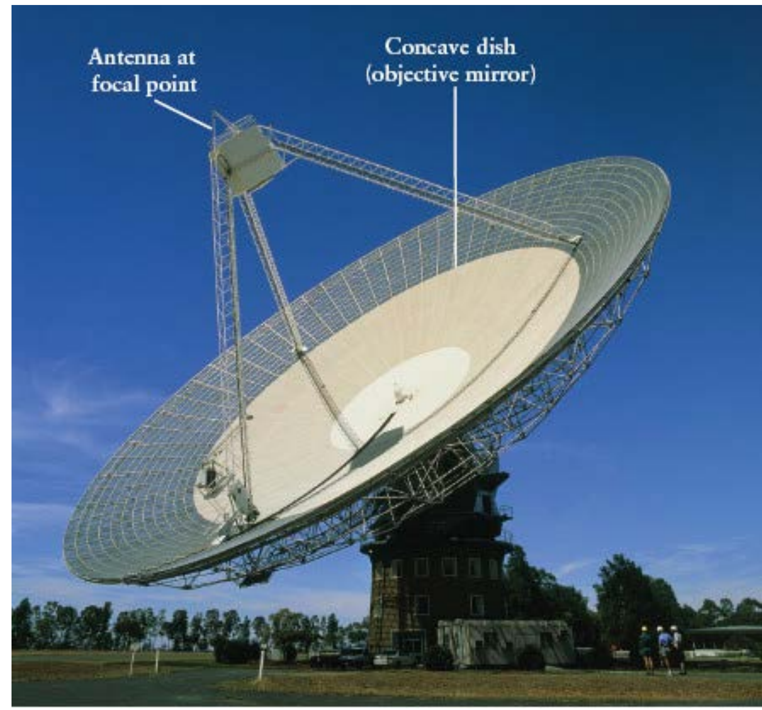
The American astronomer Geoffrey Burbidge showed that the amount of energy needed to power the radio lobes of Cygnus A was equivalent to $10^6\ M_{\odot}c^2$. This indicated that AGN can release energy that is considerably larger than that released in a supernova explosion.



The Discovery of Active Galactic Nuclei

In 1963 Cyril 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.

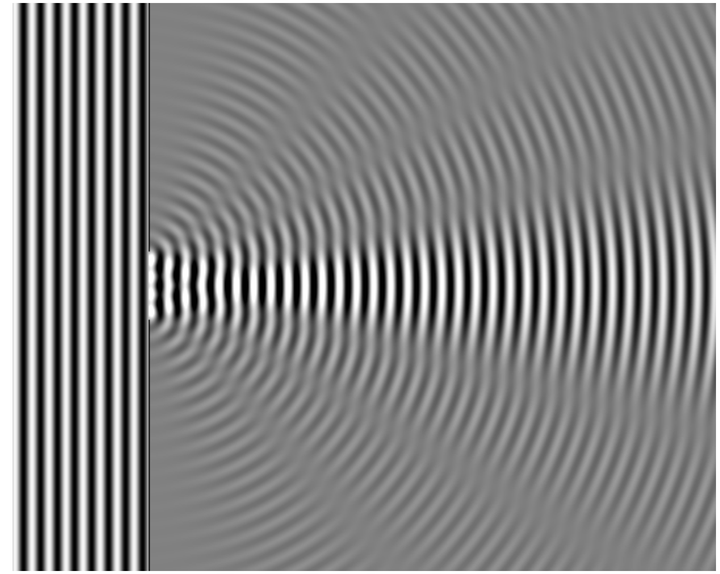
Single dish radio telescopes have relatively poor resolution due to **diffraction**.

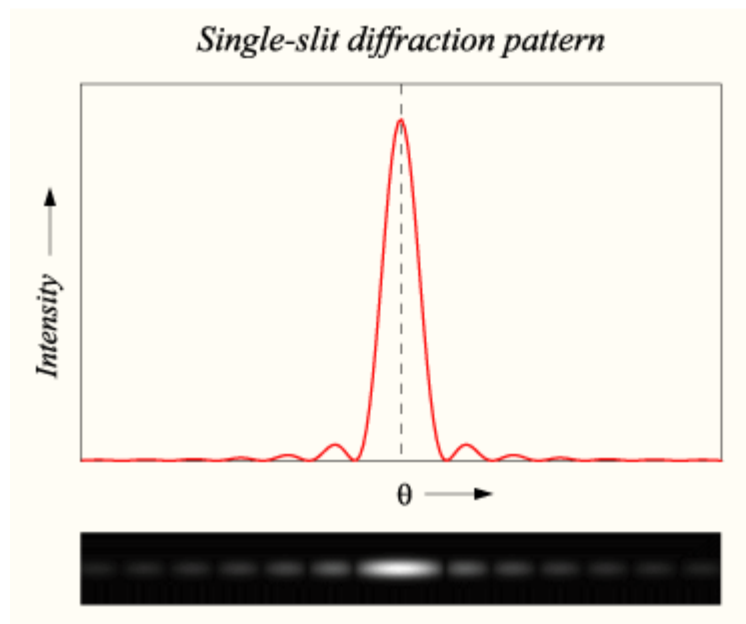


PARKES, NSW, Australia
(64 m diameter)

Diffraction

Diffraction is the apparent bending of waves around small obstacles and the spreading out of waves past small openings.





Diffraction

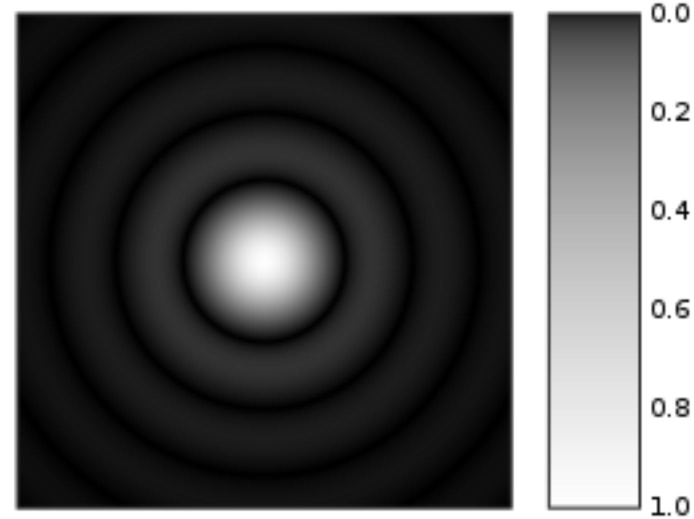
The light collected by a telescope at the focal point is not focused to a point but forms a **diffraction pattern** having a central peak with a angular size between the peak and the first null:

$$\theta = 2.5 \times 10^5 \frac{\lambda}{D}$$

θ = diffraction - limited angular resolution of a telescope, in arcseconds

λ = wavelength of light, in meters

D = diameter of telescopes objective, in meters



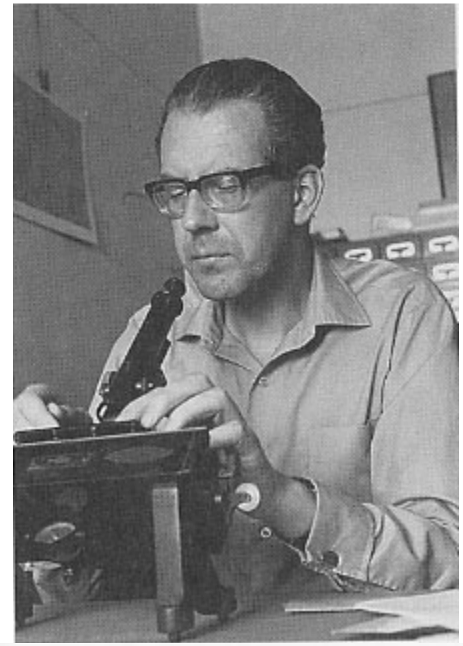
Diffraction by a **circular aperture.** Notice the variation of intensity with angle.

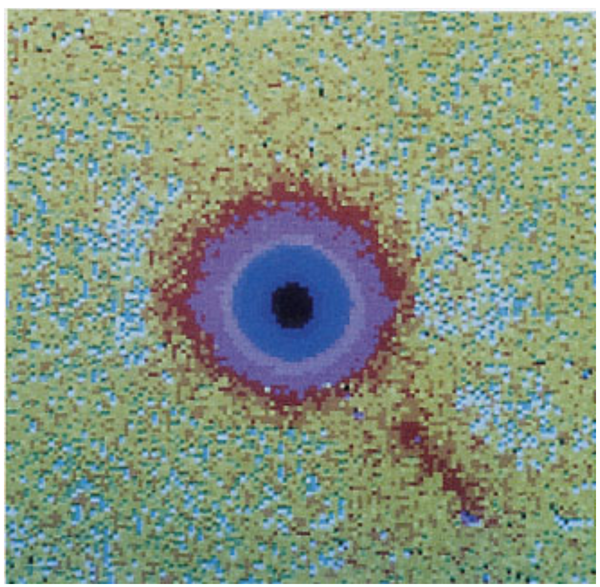
The diffraction limited angular resolution of a 64m radio dish at λ= 21cm is :
$\theta \sim 2.5 \times 10^5$(21cm /64m) = 820 arcsec

The Discovery of Quasars

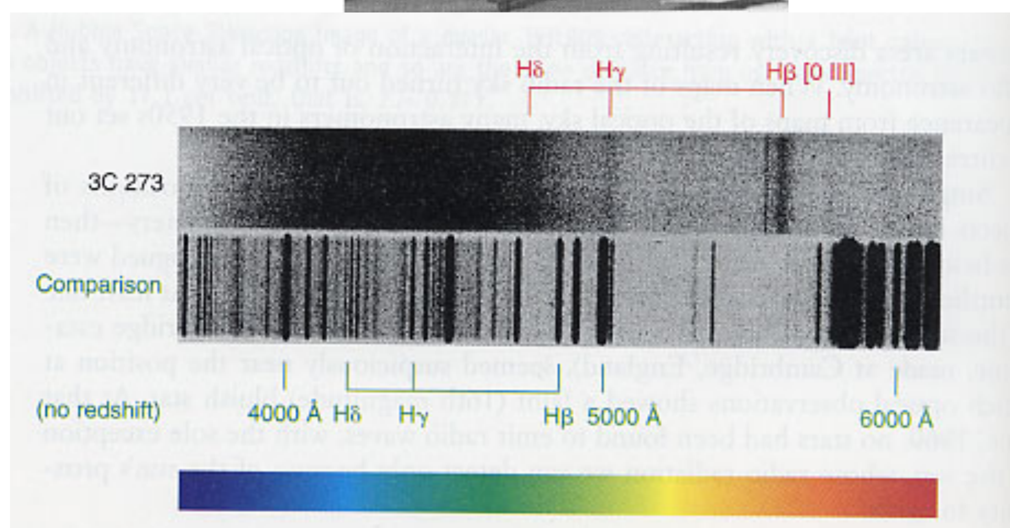
The accurate position of 3C 273 allowed Maarten Schmidt to locate the optical counterpart of 3C 273 and obtain its optical spectrum.

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 $z = 0.158$.

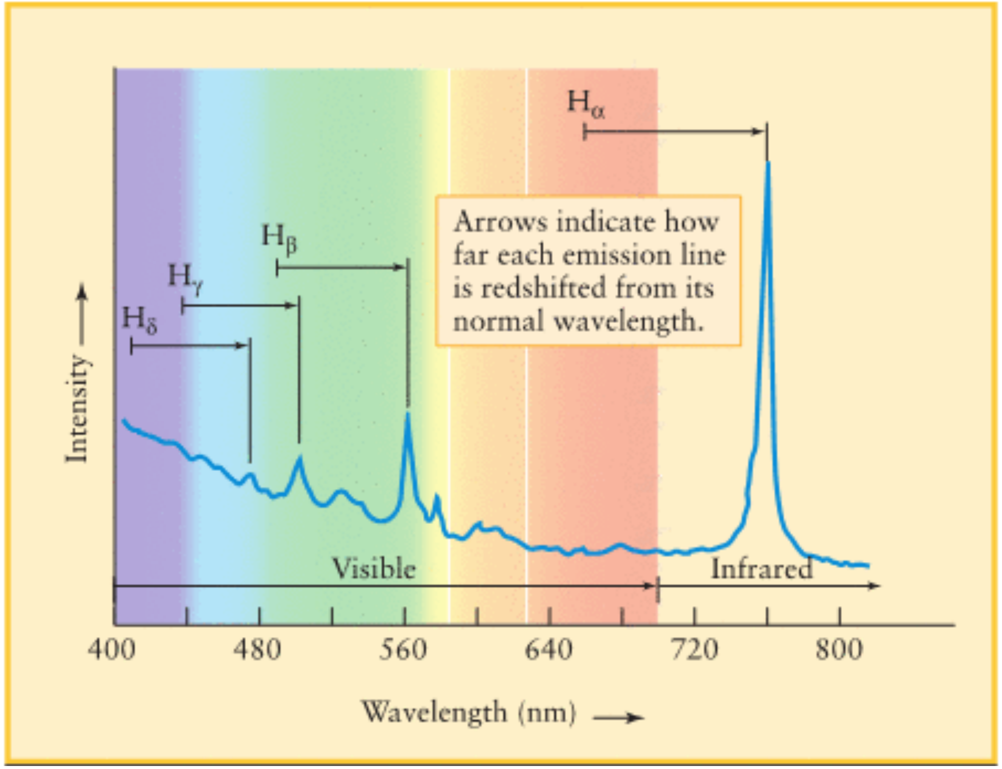




3C 273



The Discovery of Quasars

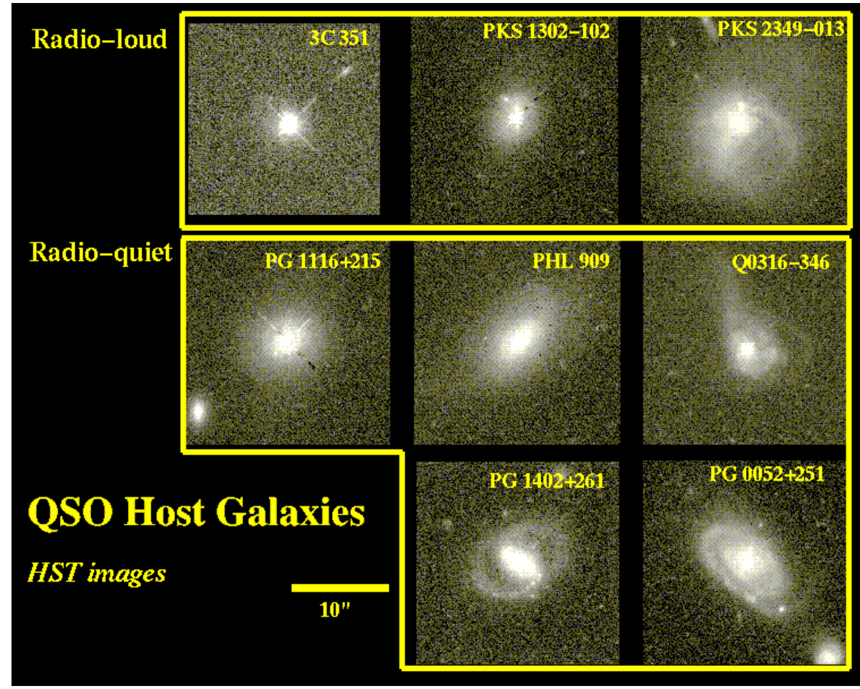


Maarten Schmidt from Caltech first realized that the emissions lines in 3C 273 were significantly redshifted Balmer lines.

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.

The Discovery of Quasars

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



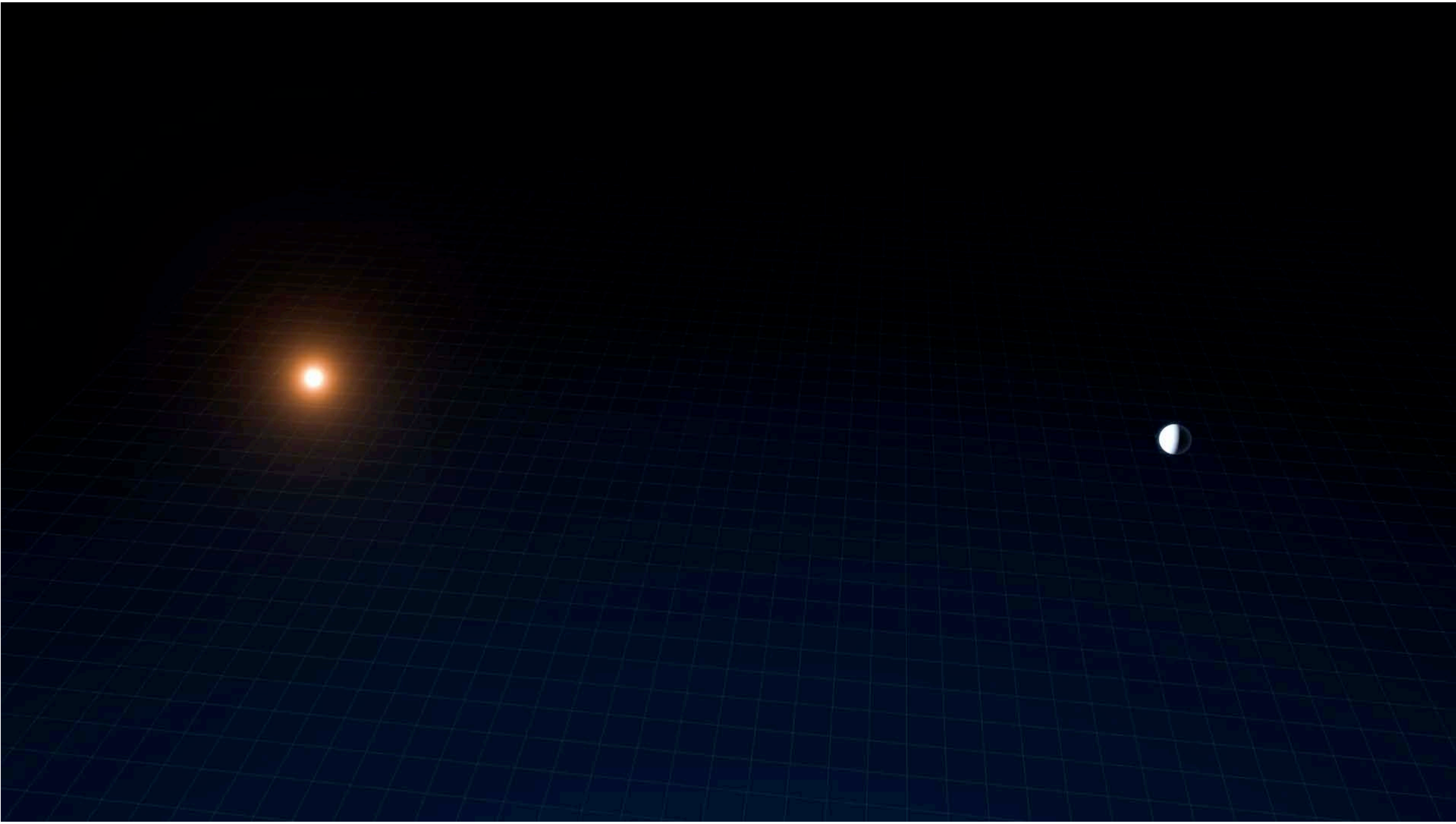
About 10% of quasars are **radio loud** and ~90% **radio quiet**.

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.

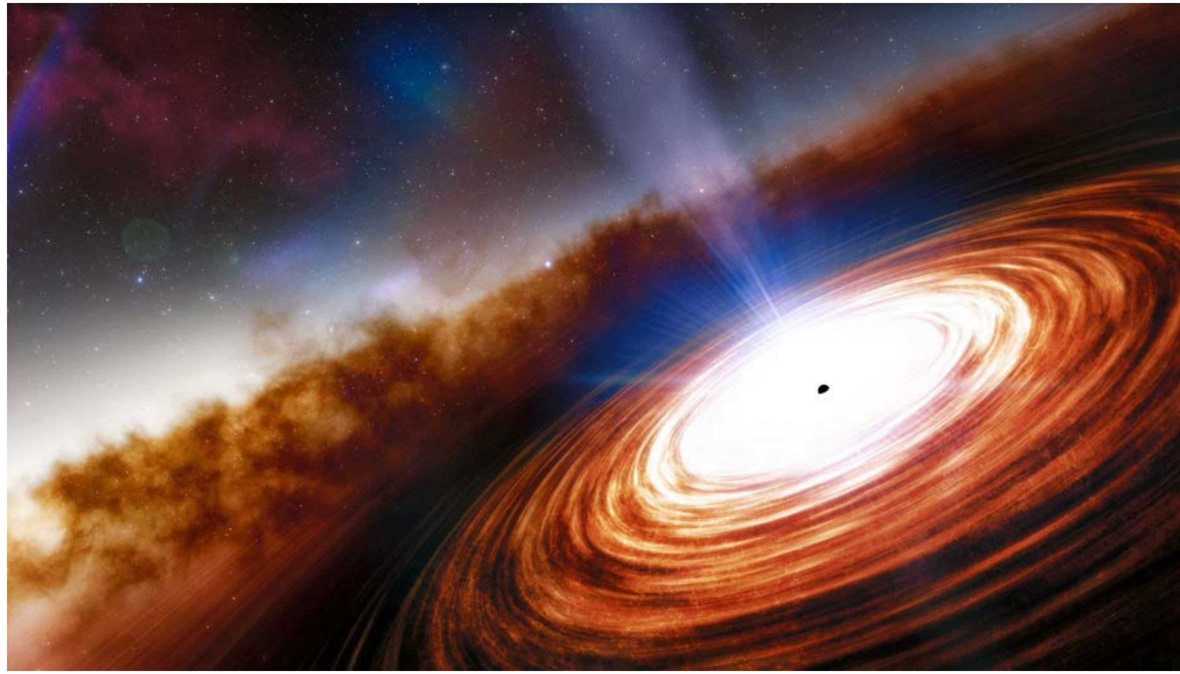
UHS J043947.08+163415.7: The Brightest Quasar



The light-travel time to this gravitationally lensed quasar is 12.8 billion years ($z = 6.51$).The luminosity of this quasar is about 2.3×10^{41} Watts (~600 trillion times brighter than the sun).

J0313-1806: The most distant Quasar

Astronomers Feige Wang and Jinyi Yang, both of Steward Observatory at the University of Arizona, helped measure the distance for quasar J0313-1806,



Most distant supermassive black hole with a mass of $1.6 \pm 0.4 \times 10^9$ solar masses.(z = 7.64)

Properties of Active Galactic Nuclei (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 ($\ll 1 pc^3$)

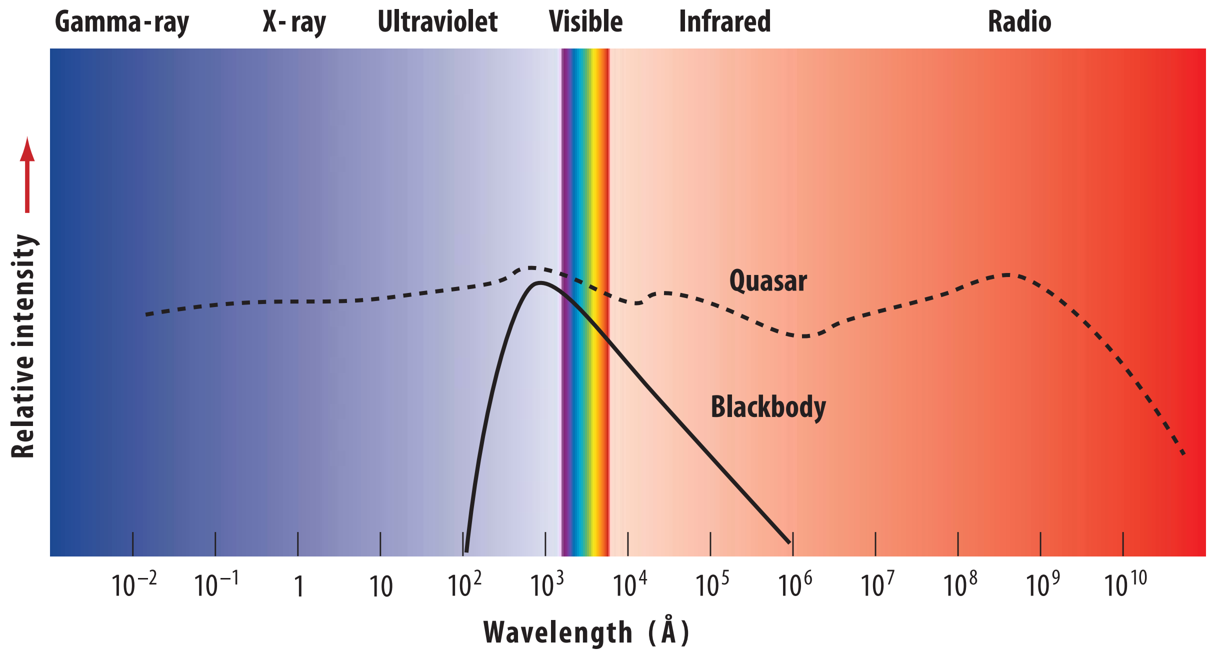
2. The AGN emission can emerge over a wide range of frequencies.

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

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

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

Properties of AGN



The surfaces 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.

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 wavelength of the peak of the spectrum decreases with increasing temperature.**

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.

Relativistic means anything traveling close to the speed of light.

Black Hole Paradigm

Black Hole Paradigm

The reasoning that led to the black hole paradigm (i.e., 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 :

$$\left(\frac{M}{R}\right)_{\max} = \frac{c^2}{G}, \text{ compactness of a spinning black hole}$$

where M is the mass of the AGN and R represents the innermost stabel circular 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:
A lower limit of the mass can be inferred from the observed luminosity L.
The luminosity of an AGN is less than the Eddington luminosity.

$L < L_{Edd} = 1.3 \times 10^{38}\ M/M_\odot$ ergs/s => $M > M_\odot(L/1.3 \times 10^{38}$ ergs/s)

Method 2:
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 3:
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

Method 4:

From the total energy released over the lifetime of a quasar.

$$E_{tot} = t_{life} L_{ave}$$

where E_{tot} is the total energy released over an AGNs average lifetime t_{life}, assuming its average luminosity $\mathrm{L_{ave}}$ is the currently observed.

$$\mathrm{t_{life}} \approx \frac{10 \text{ billion years}}{100}$$, since approximately 1% of galaxies have active nuclei

The total mass accreted onto the AGN over its lifetime is then:

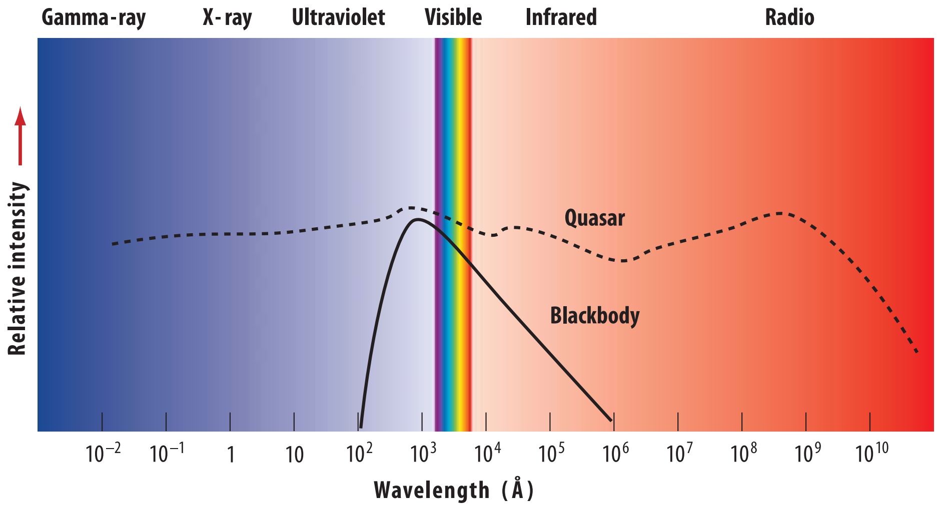
$$\mathrm{m_{acc}} = \frac{E_{tot}}{\eta \mathrm{c}^2} = \frac{\mathrm{t_{life} L_{ave}}}{\eta \mathrm{c}^2}$$ and at least half of that adds to the mass of the black hole.

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.



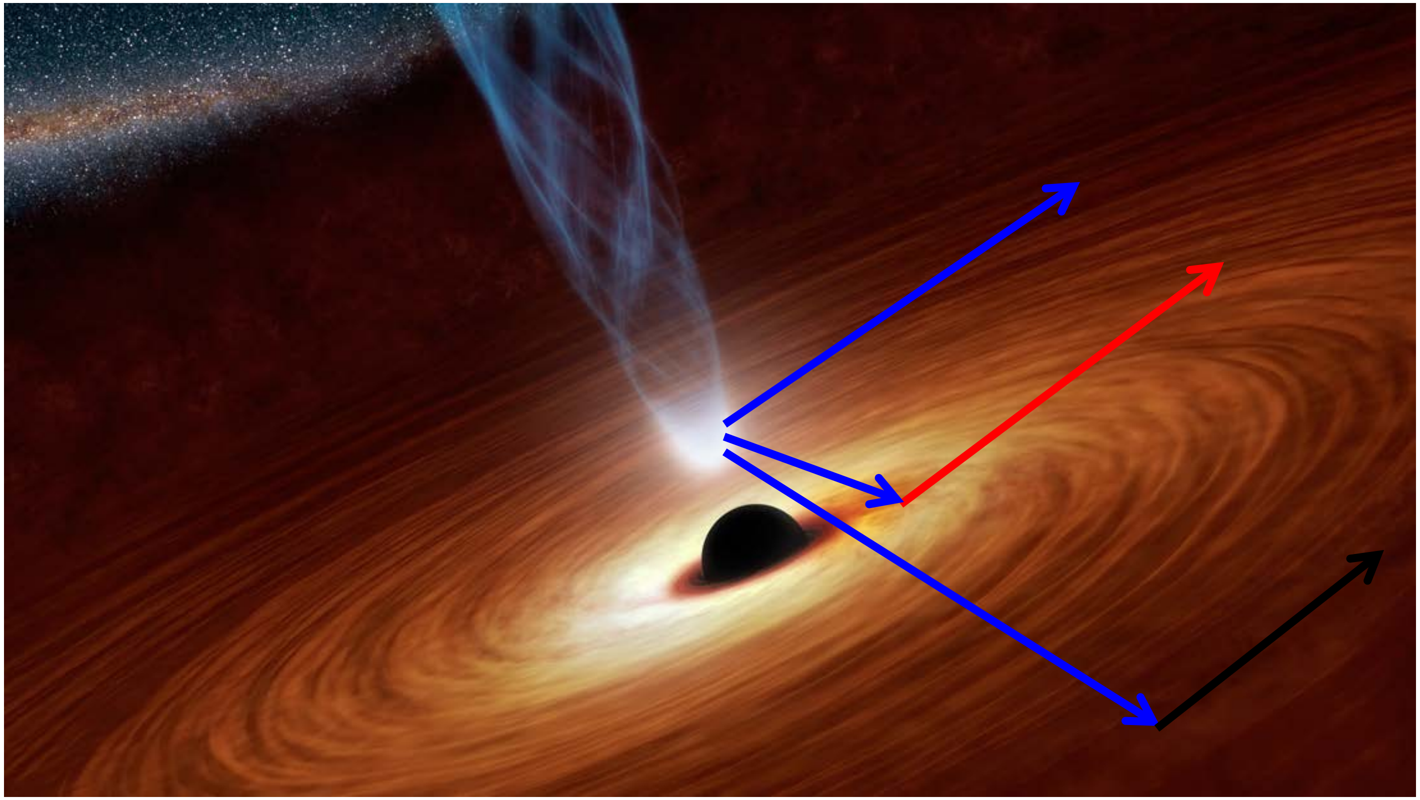
- X-ray emission from a hot corona made up of energetic electrons.

- 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

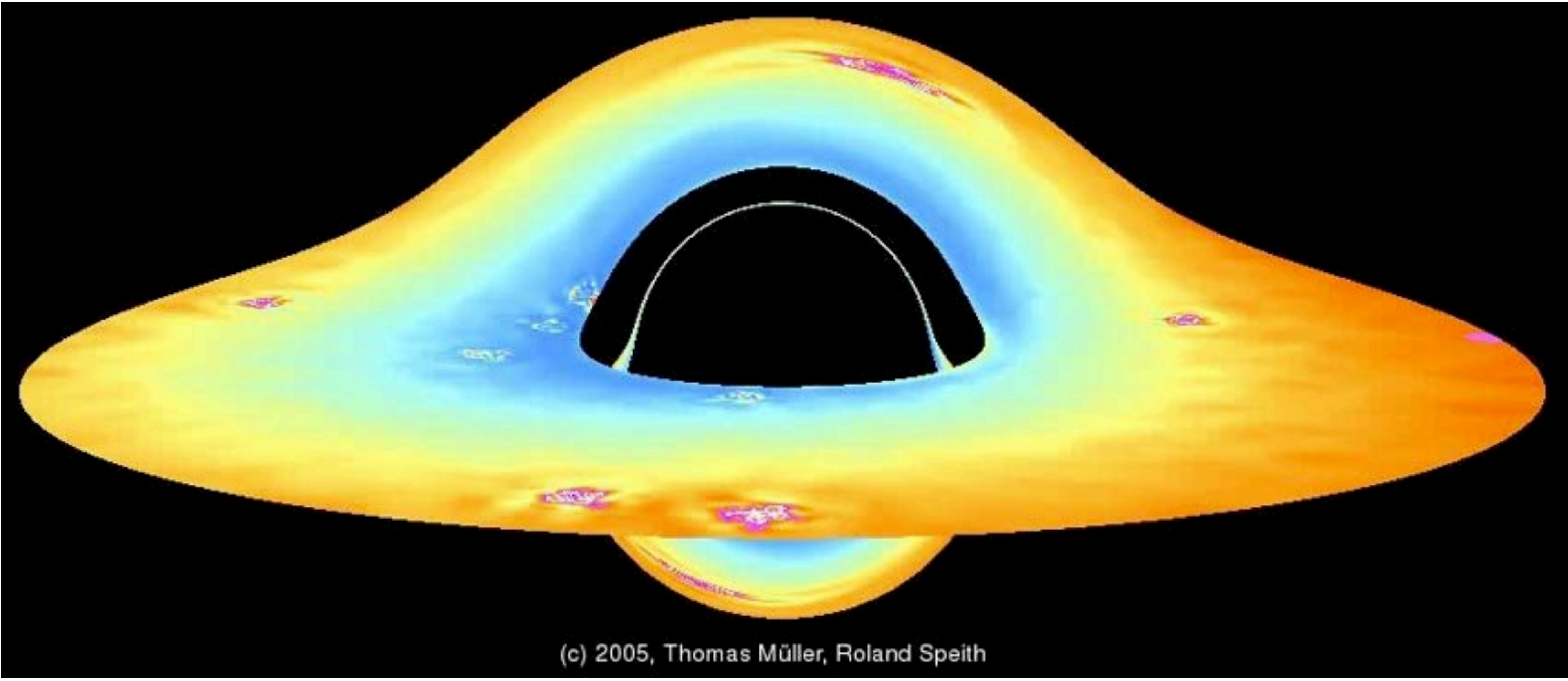


X-ray Power-Law
from compact corona

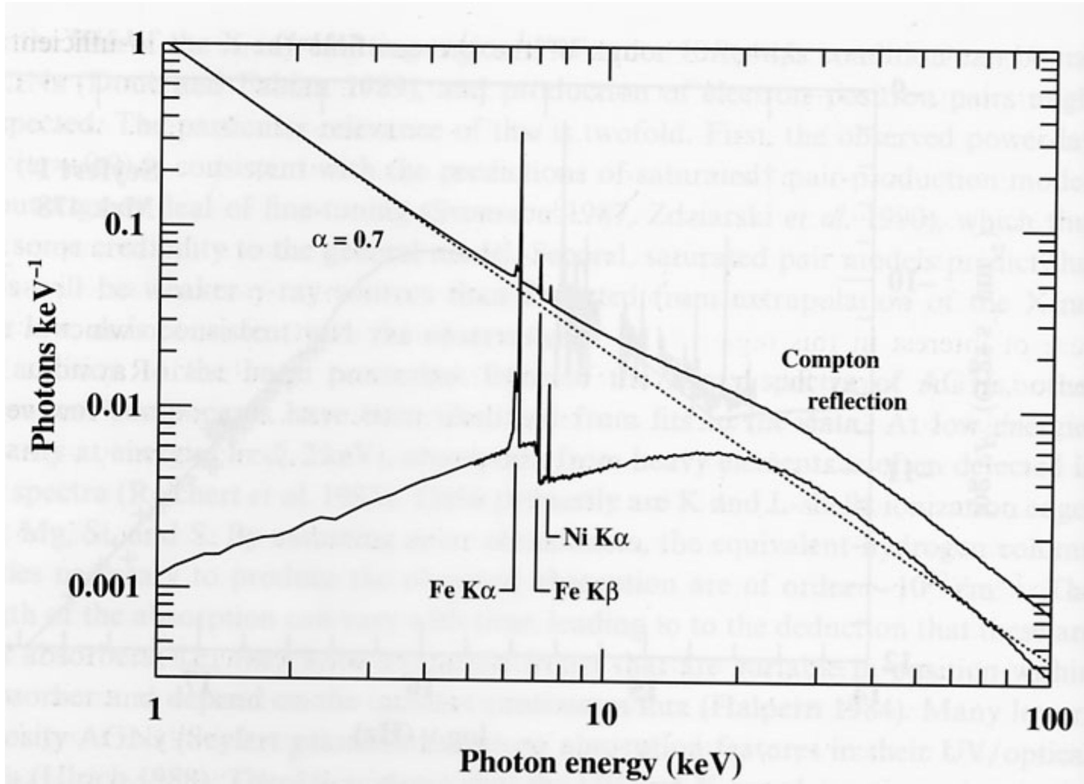
Relativistically
Blurred Reflection
(line + continuum)

(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:

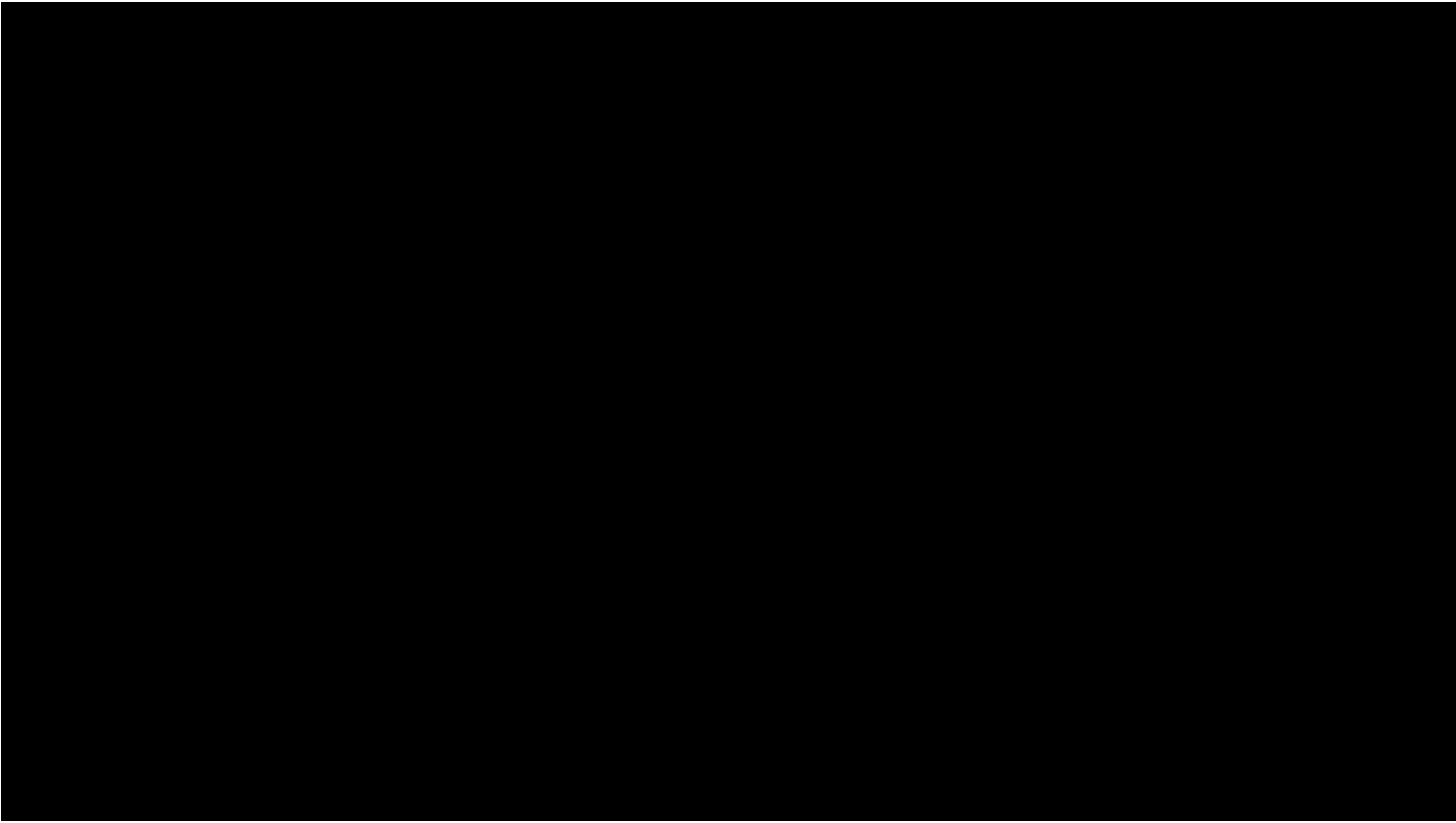
- An **accretion disk** surrounding a supermassive black hole

- 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



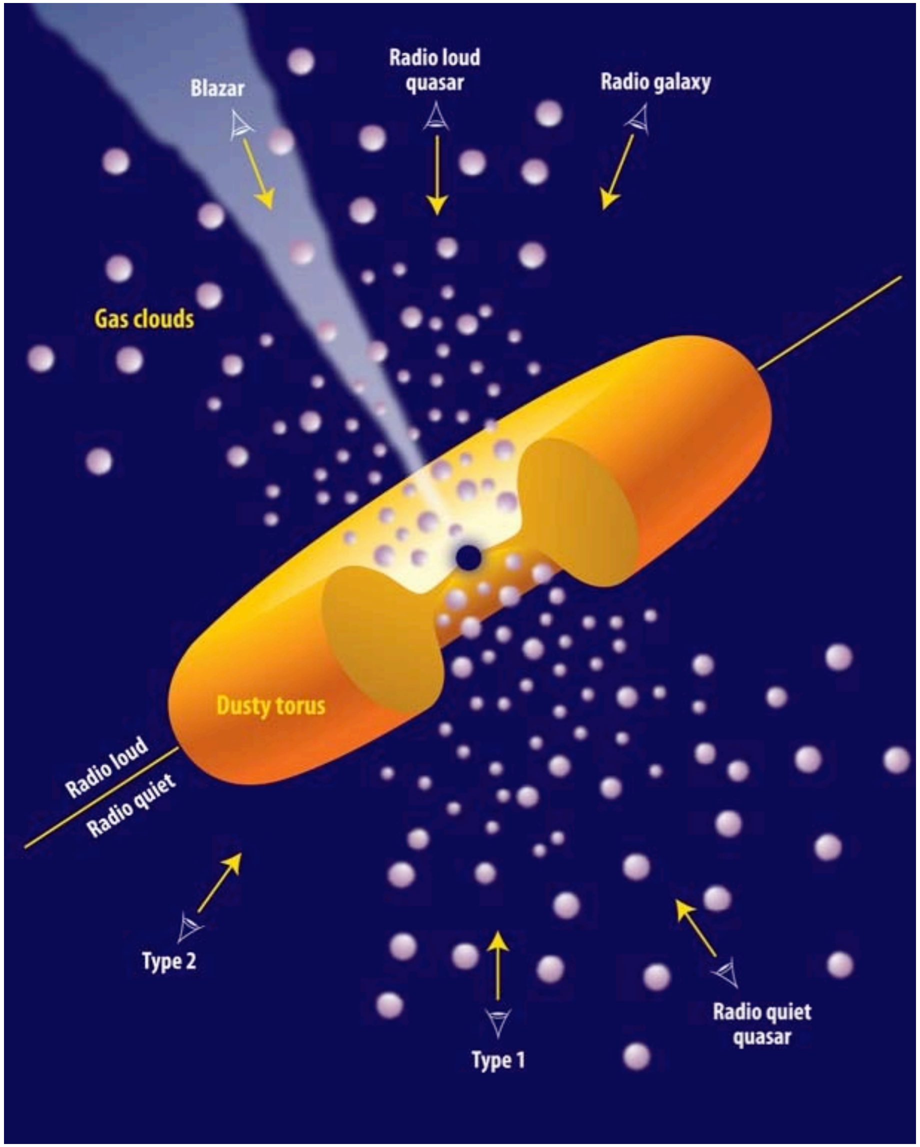
Unification of AGN

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.