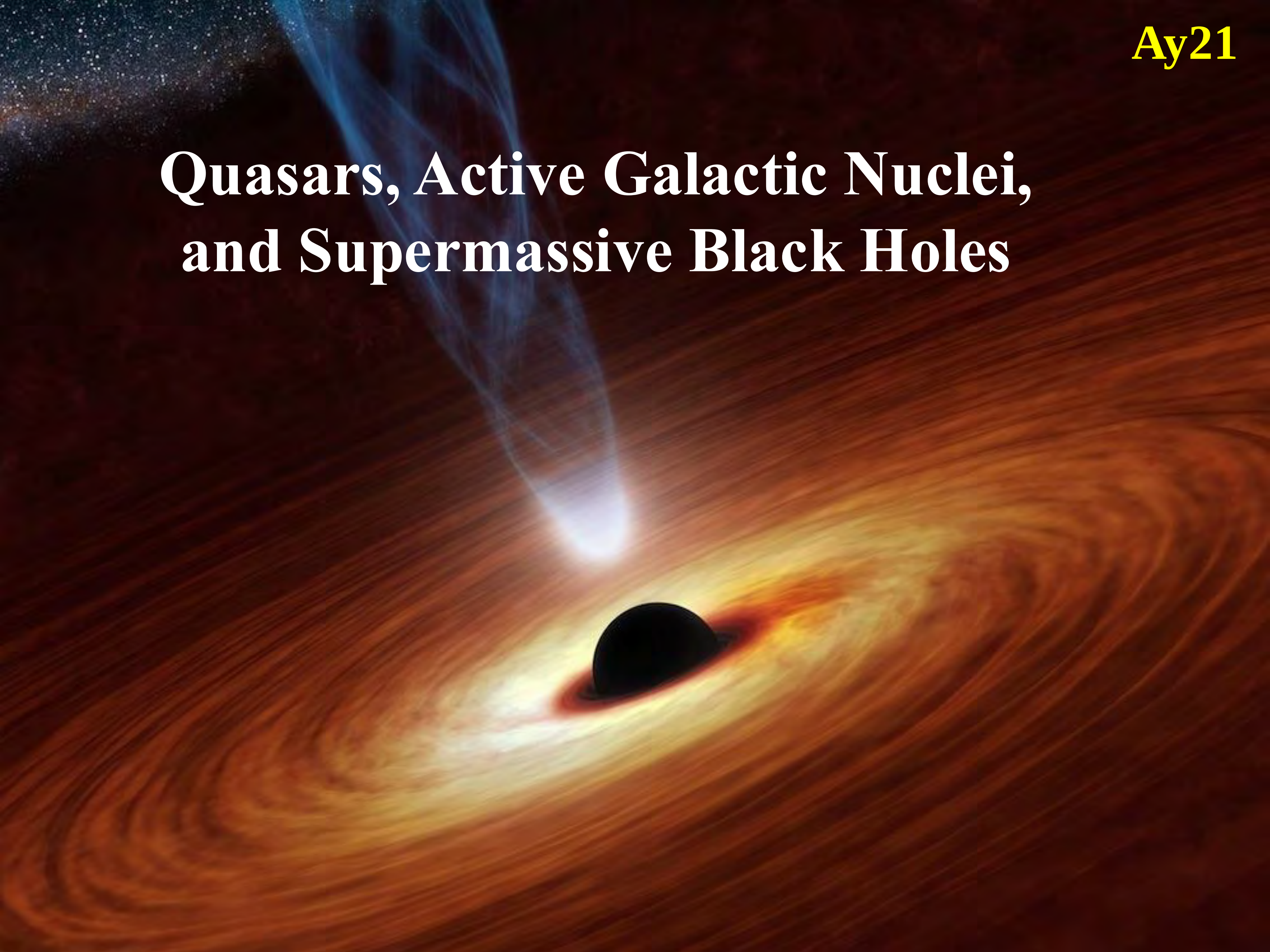
Ay21

Quasars, Active Galactic Nuclei, and Supermassive Black Holes



Quasars and AGN

- They are highly energetic manifestations in the nuclei of galaxies, believed to be powered by accretion onto massive black holes
- Empirical classification schemes and various types have been developed, based of their spectra; but recently, various unification schemes have been developed to explain AGN as different appearances of the same underlying phenomenon
- Quasars/AGN are observed to evolve strongly in time, with the comoving densities of luminous ones increasing by $\sim 10^3$ from $z \sim 0$ to $z \sim 2$
- At $z \sim 0$, at least 30% of all galaxies show some sign of a nuclear activity (mostly at a low level); ~ 1% can be classified as Seyferts (moderately luminous), and $\sim 10^{-6}$ contain luminous quasars
- However, we think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase

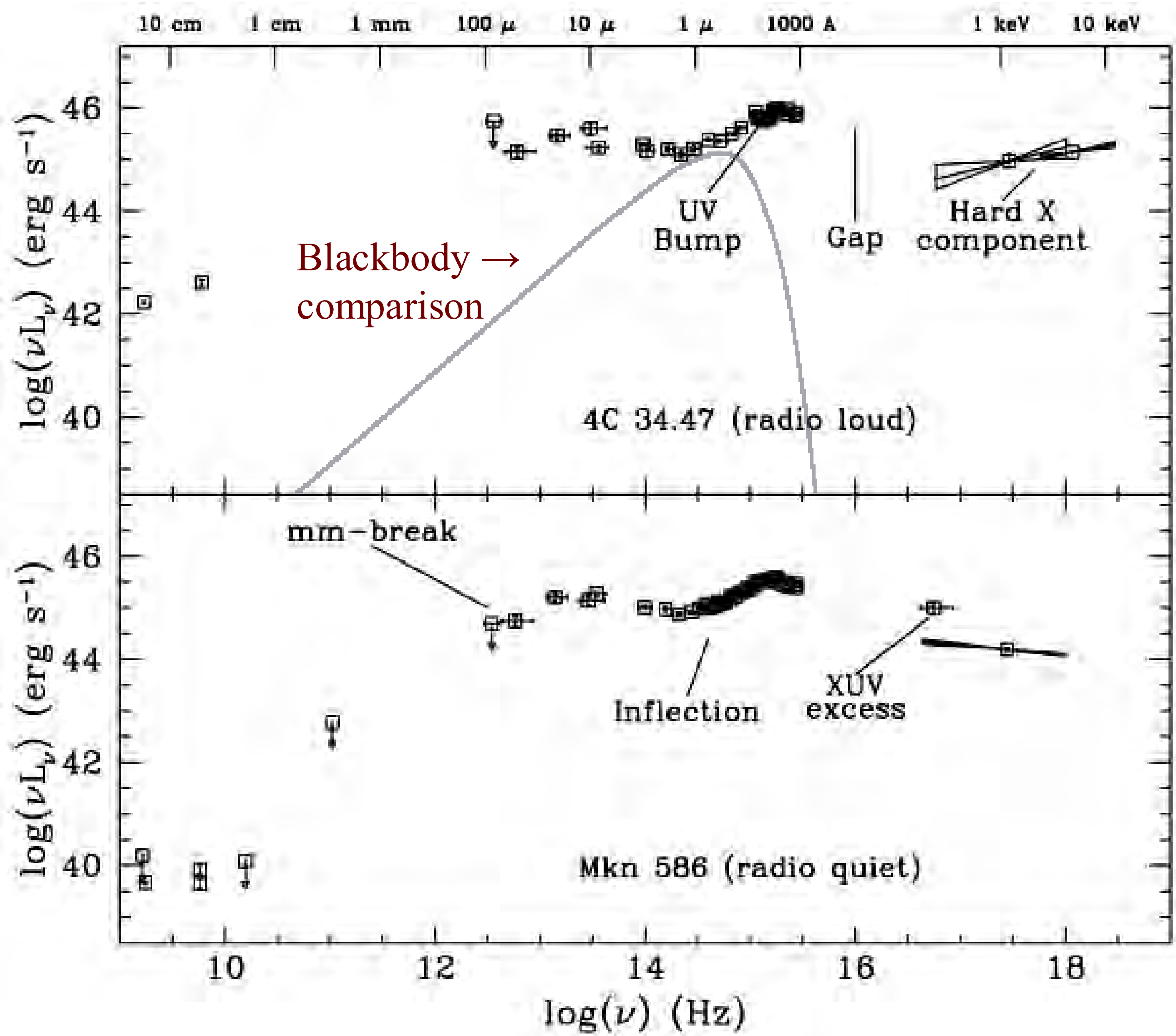
Supermassive Black Holes

Observable Properties of AGN

- Energy emission over a broad range of frequencies, from radio to gamma rays
  - Nonthermal radio or X-ray emission is a good way to find AGN
  - Generally bluer spectra than stars: "UV excess"
  - Colors unlike those of stars, especially when modified by the intergalactic absorption
- Presence of strong, usually broad emission lines in their spectra
- Can reach large luminosities, up to $\sim 10^{15}\ L_\odot$
- Strong variability at all time scales
  - Implies small physical size of the emission region
- Central engines unresolved
- Zero proper motions due to a large distances

All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects

Broad-Band Spectra of Quasars

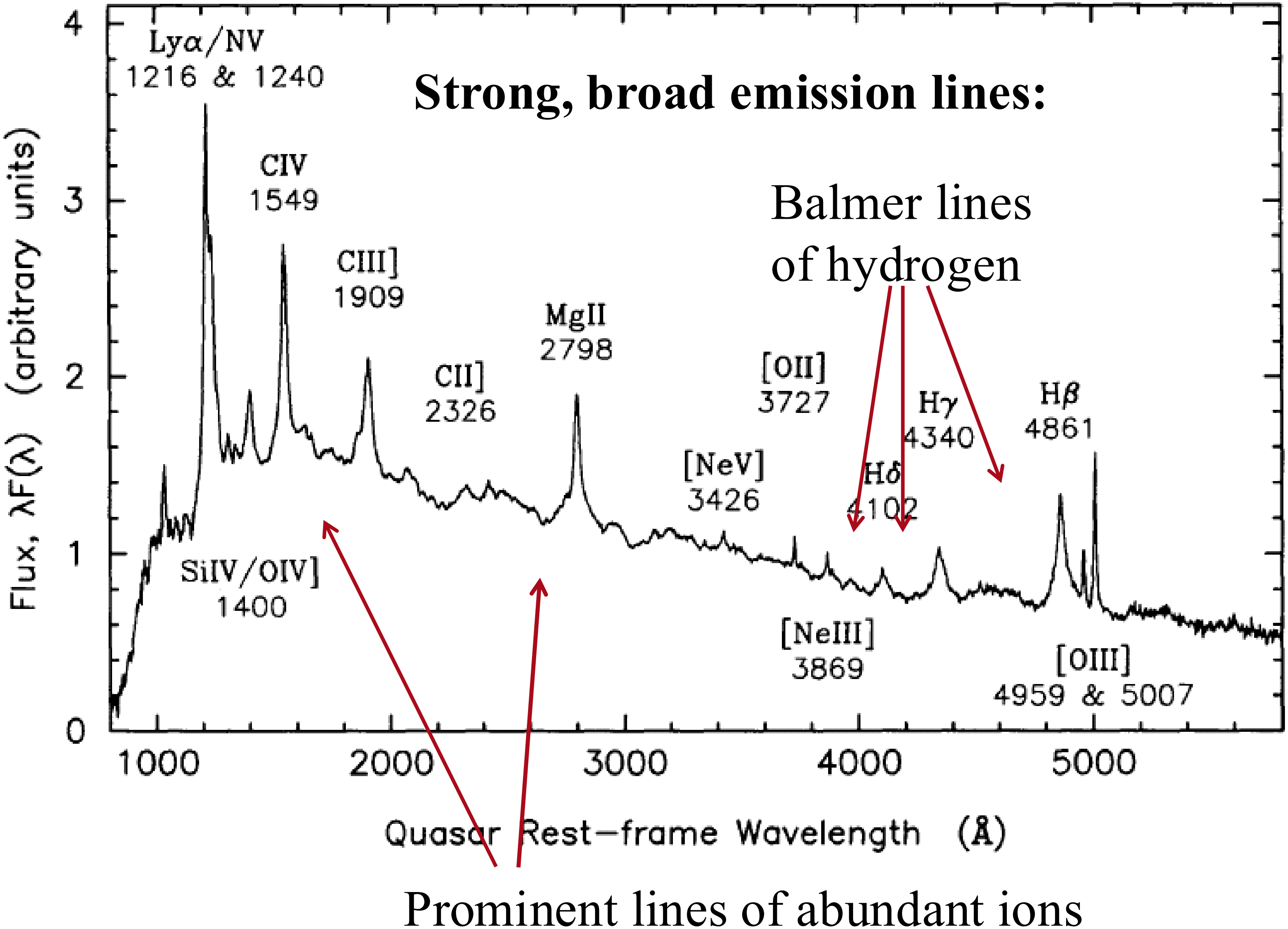


Radio Loud

Much broader than a single blackbody spectrum

Radio Quiet

UV-Optical Spectra of Quasars

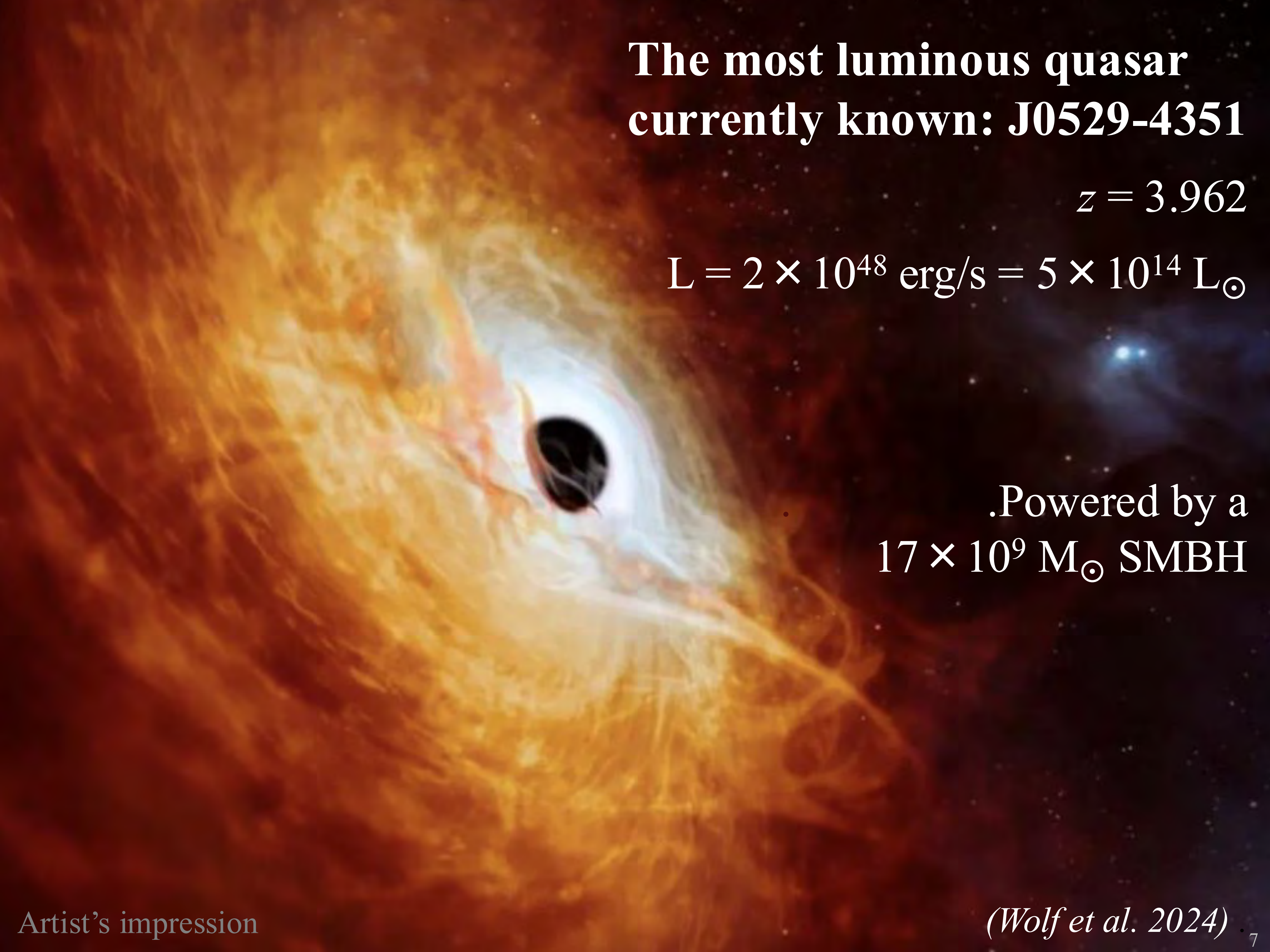


The most luminous quasar currently known: J0529-4351

$z = 3.962$

$L = 2 \times 10^{48}$ erg/s $= 5 \times 10^{14}\ L_\odot$

.Powered by a $17 \times 10^9\ M_\odot$ SMBH



Artist's impression

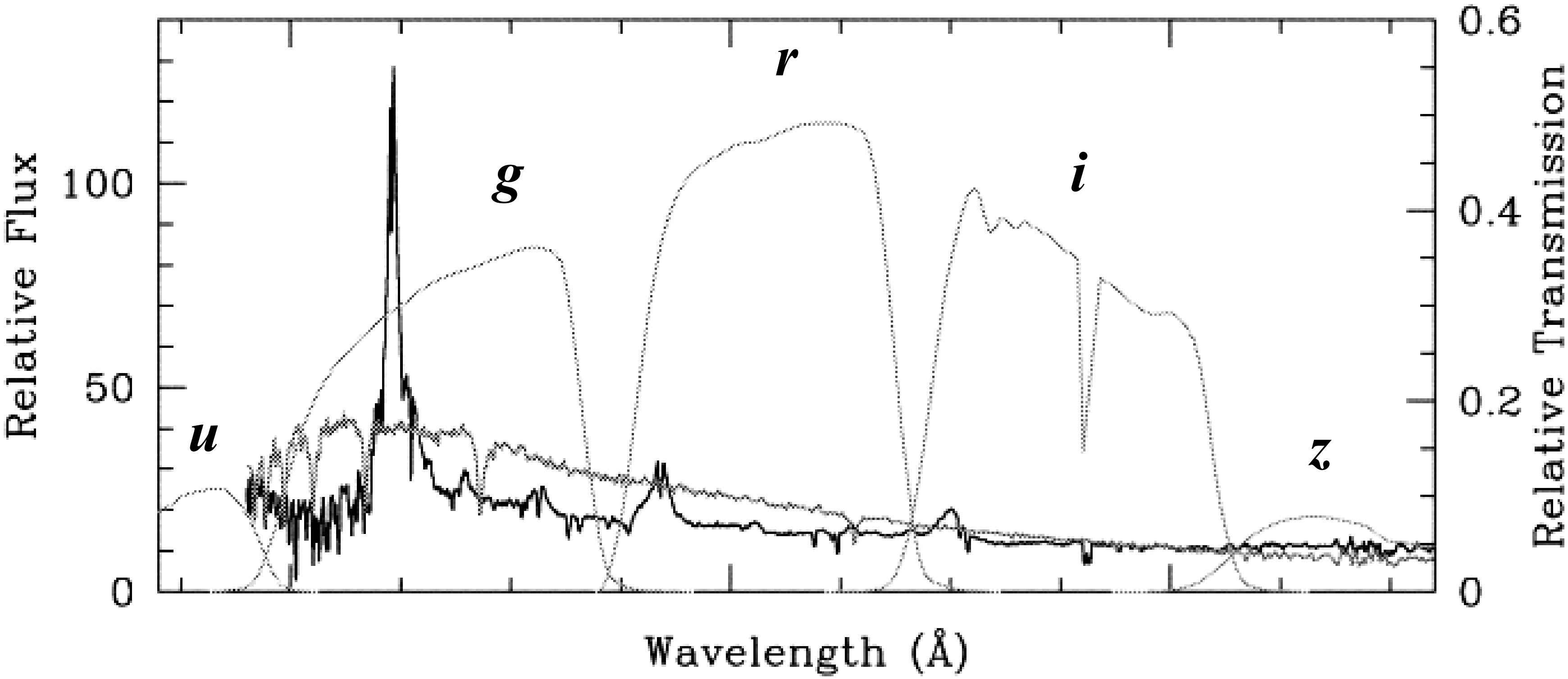
(Wolf et al. 2024)

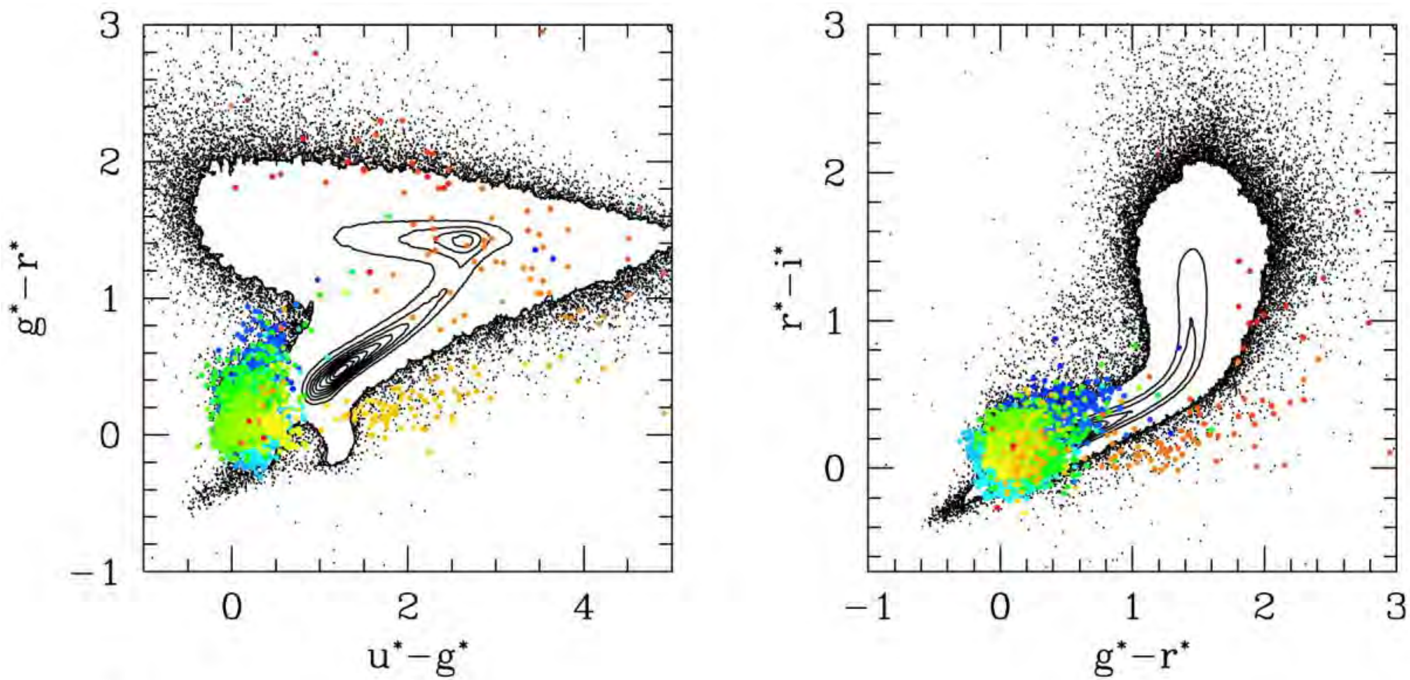
Quasar Surveys

- In order to study QSOs (and other AGN), we first have to find them, in large numbers, and hopefully in a systematic fashion
  - This is especially important for studies of their evolution
- Recall that ***each discovery method has its own biases***
- Nowadays the most popular technique is to use colors to separate QSOs from normal stars
  - In optical, one can also use slitless spectroscopy, variability, and zero proper motions
- Soft X-ray (up to a few keV) and optical selection find the same types of relatively unobscured objects; hard X-ray selection and FIR/sub-mm detect more obscured populations; radio finds both
- As of ~ early 2024, there are > 1million spectroscopically confirmed QSOs, and ~ 4 million of additional, color and/or variability selected QSO candidates

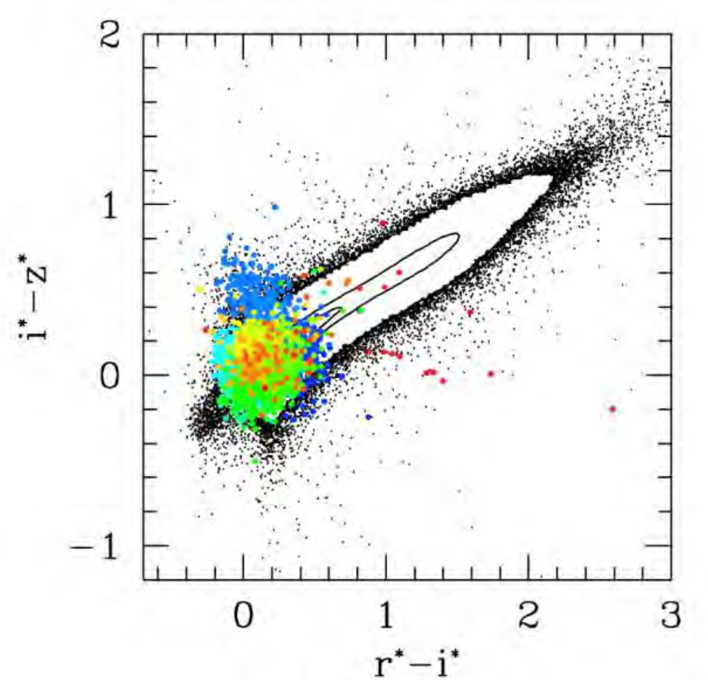
SDSS Quasar Survey

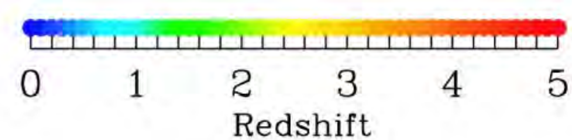
Ratios of fluxes in different survey filters (=colors) are in general different for QSOs and for stars - even though both look "stellar" on the images. The colors will change with redshift as different features (emission lines, continuum breaks) shift from one filter to another. For each redshift range, a different filter combination would be the optimal one for QSO selection





Black dots: stars and galaxies





Where the QSOs (colored dots) are as a function of redshift in each color space

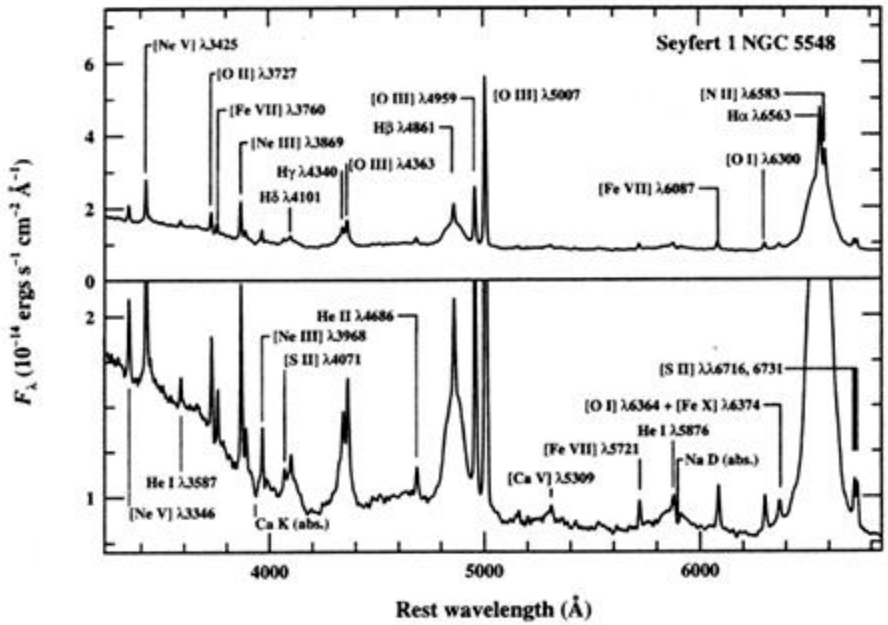
AGN Classification

- According to the radio emission:
  - Radio loud: radio galaxies (RGs) and quasars; F-R types I and II
  - Radio quiet (but perhaps not entirely radio silent)
- According to the optical spectrum:
  - Narrow-line RGs, Seyfert 2's; Liners
  - Broad line RGs, Seyfert 1's, quasars
- According to the optical luminosity:
  - Seyfert to quasar sequence, range of radio powers, etc.
- Special types:
  - Blazars (aka BL Lac's) and optically violently variable (OVV) objects
- These classifications are largely parallel
- Some distinctions may reflect real, internal physical differences, and some may be simply orientation effects
  - This is the central thesis of the AGN unification models

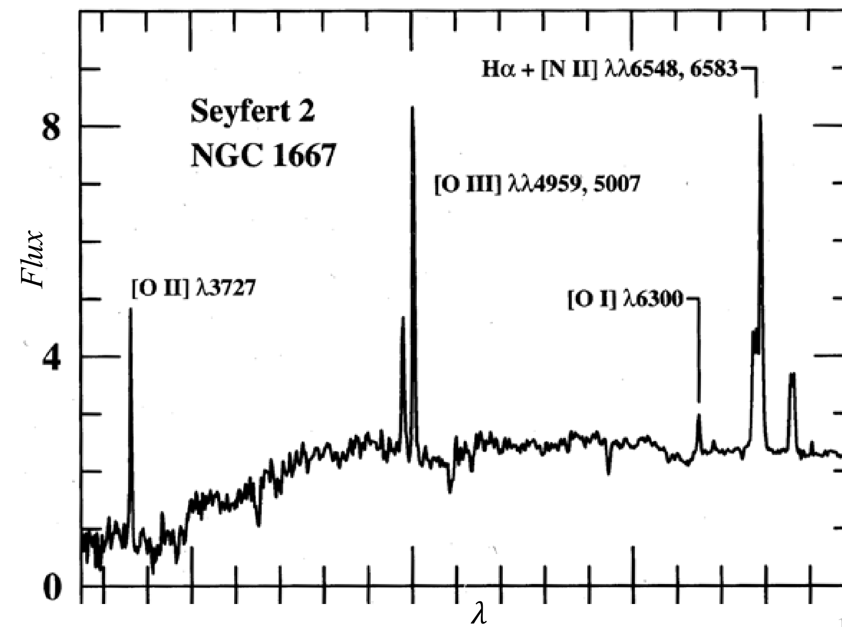
Types of Seyfert Galaxies

Type 1 Seyfert galaxies have:

- **Narrow emission lines**, with a width of several hundred km/s
- **Broad emission lines**, with widths up to 10^4 km/s
- Blue continuum emission atop of the normal galaxy spectrum



Type 2 Seyfert galaxies have only the narrow line component:

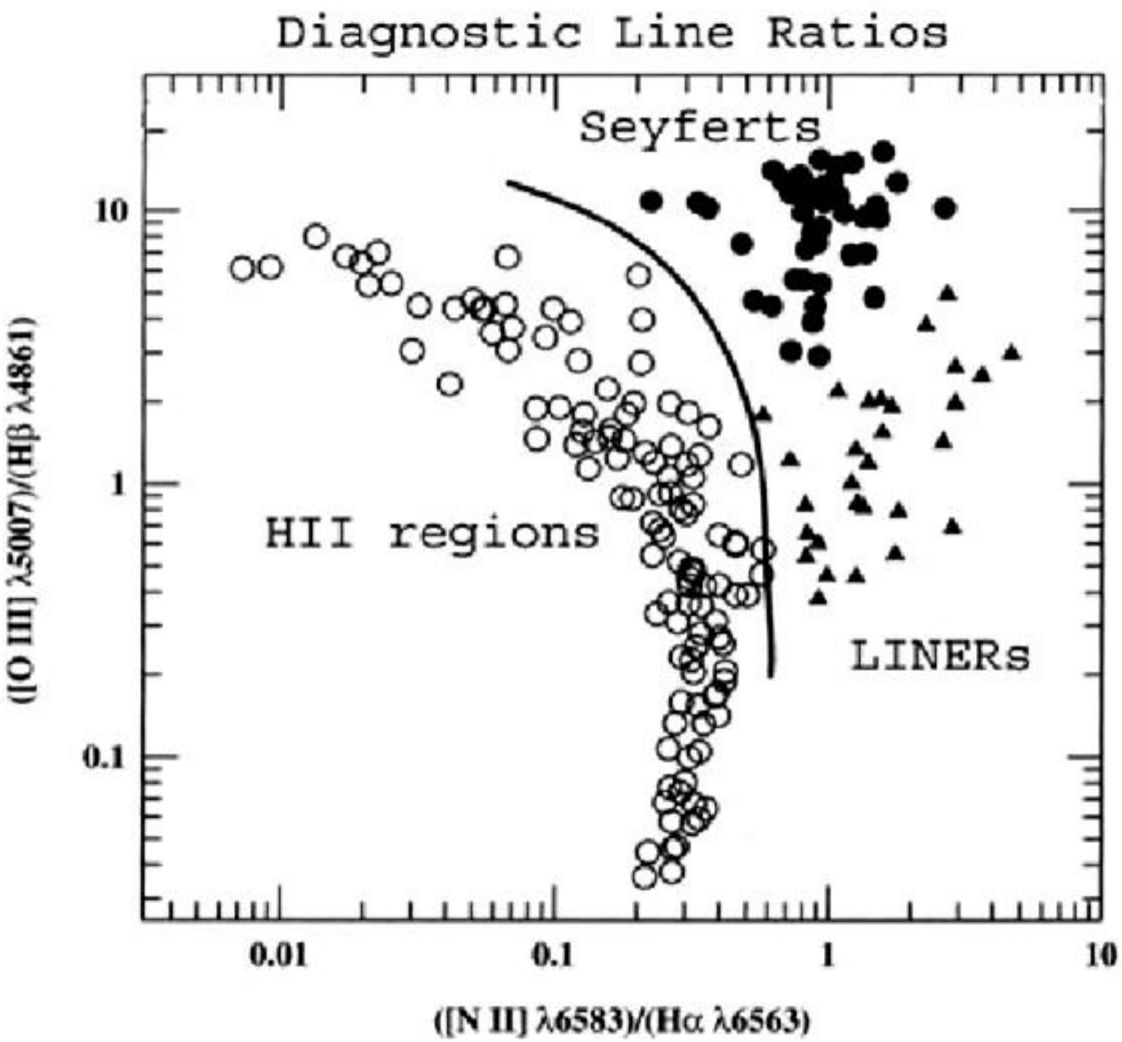


This generalizes to Type 1 and Type 2 quasars

Both types have high ionization, forbidden lines (= transitions not easily observed in the lab)

Spectroscopic Diagnostics

Intensity ratios of various emission lines depend on the spectrum of the ionizing continuum radiation: to get lines from high energy levels

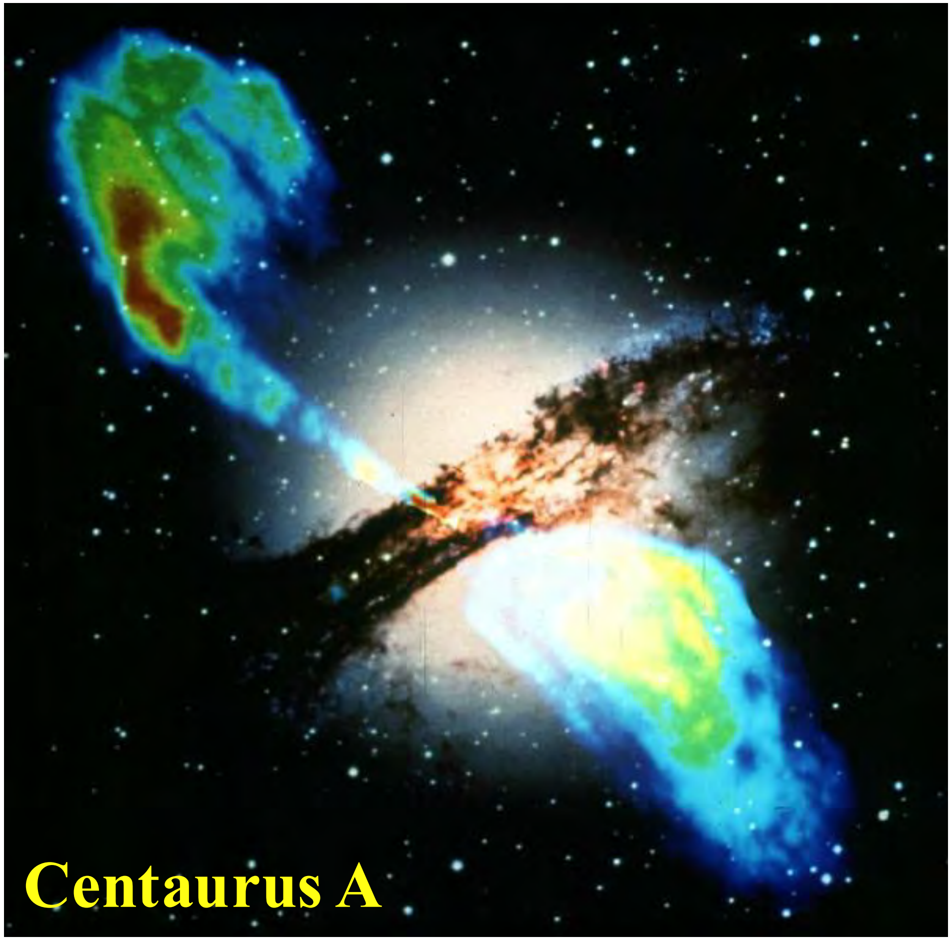


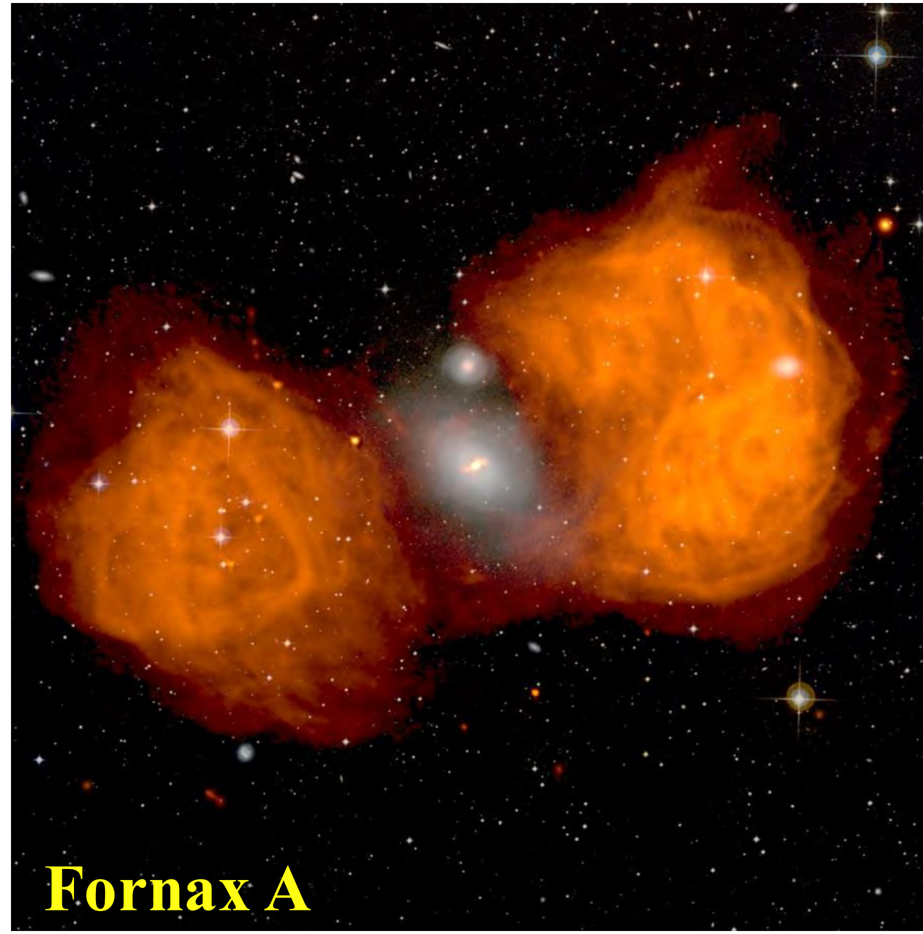
(e.g., ionizing potentials of tens of eV), one needs "hard" spectra with lots of high energy (UV / soft X-ray) photons.

Accretion disks can provide those in AGN, while objects powered by star formation have much "softer" spectra

Radio Galaxies: Typical Examples

Radio overlayed on optical images

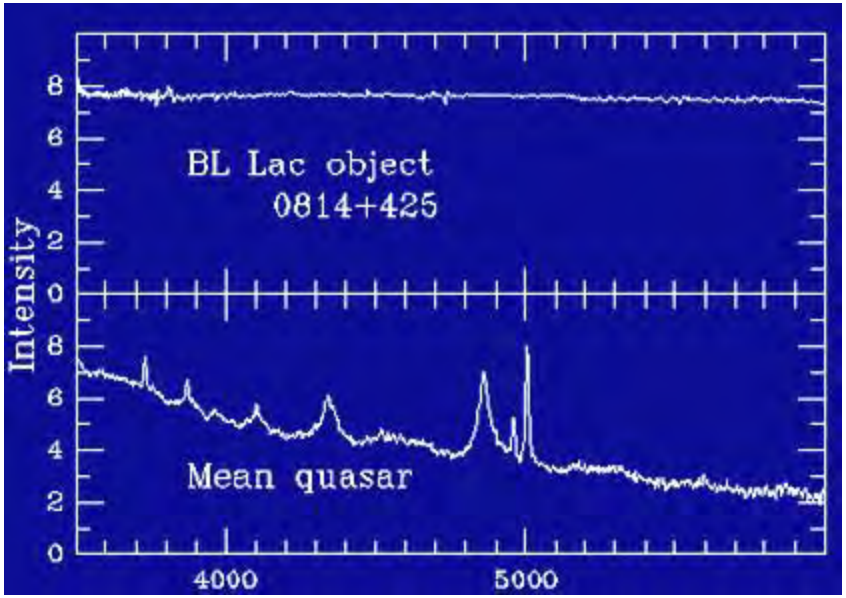




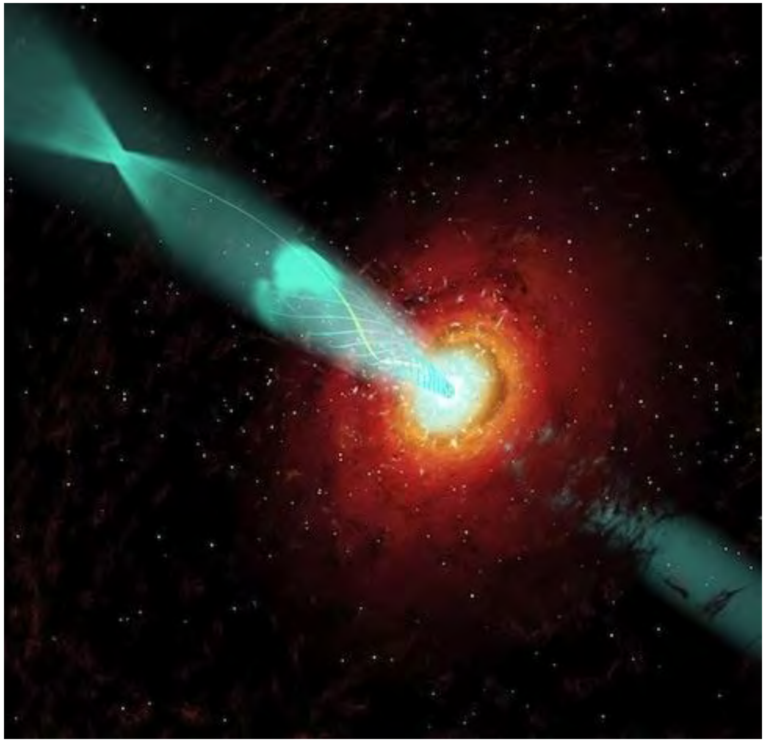
Energy stored in radio lobes can reach ~ 10^{60} - 10^{61} erg. If jet lifetime is ~ 10^{8} yrs, the implied *mechanical luminosities* are ~ 10^{12} - 10^{13} $L_{\odot}$

BL Lacs (Blazars)

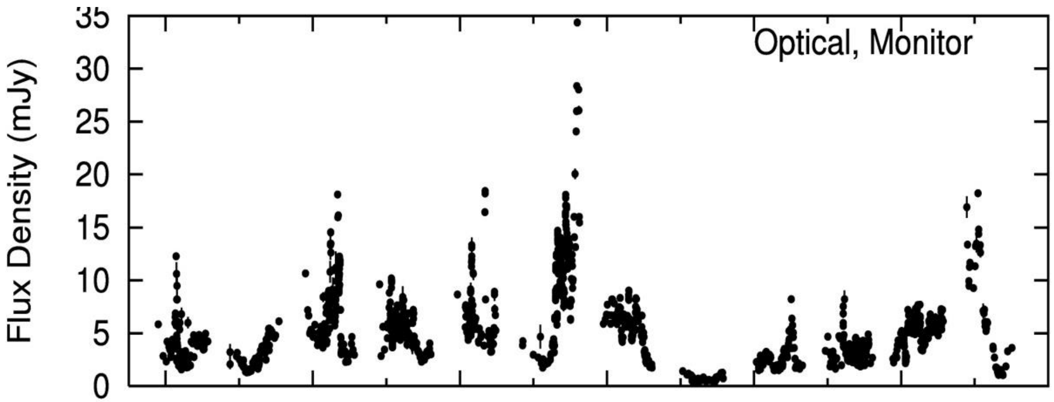
Named after the prototype BL Lacertae. They have strong, blue, variable continua, and lack strong emission *or* absorption lines



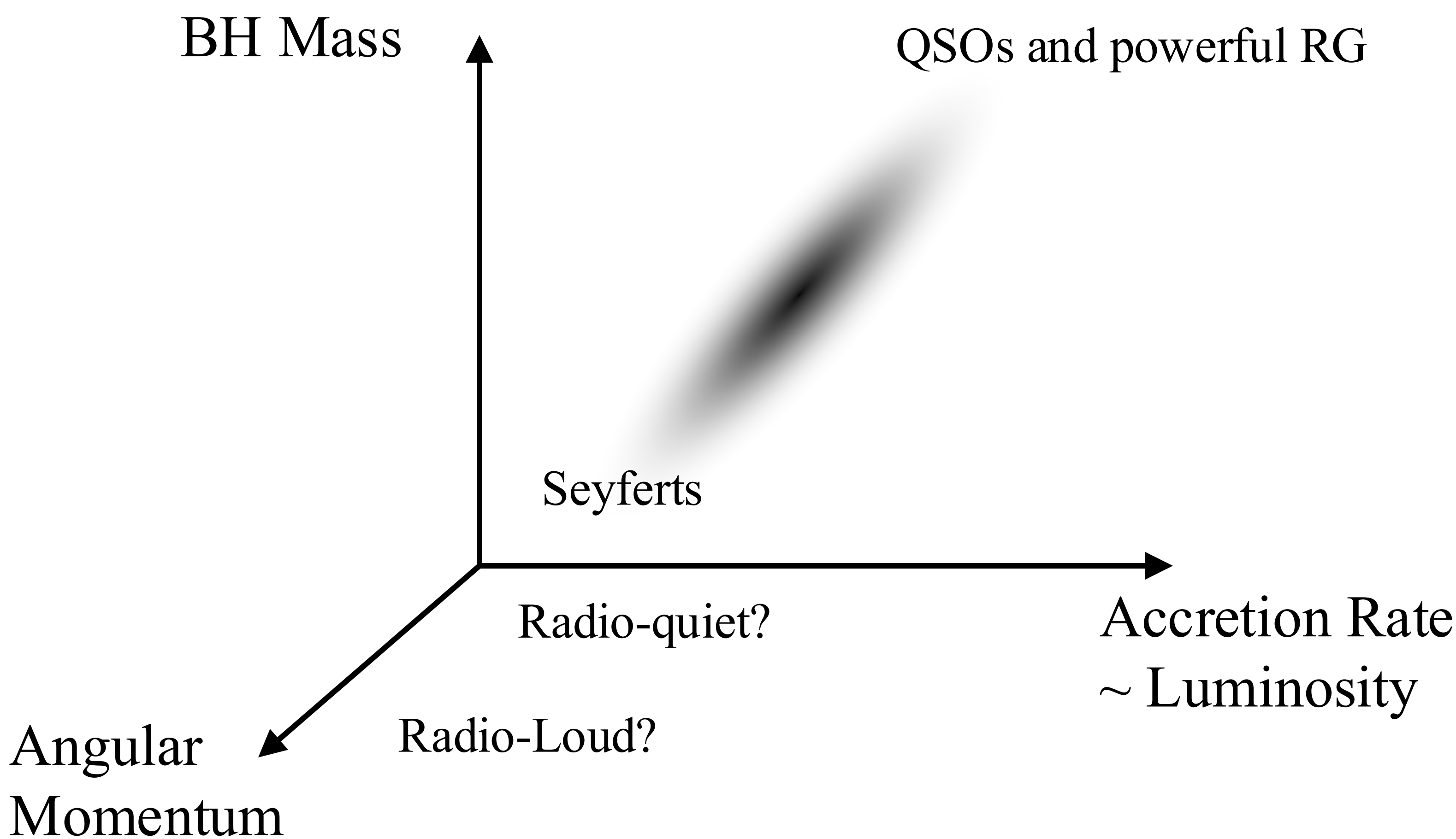
They are radio-loud quasars, viewed along the relativistic jet



They are highly variable. Relativistic beaming amplifies variations in intensity



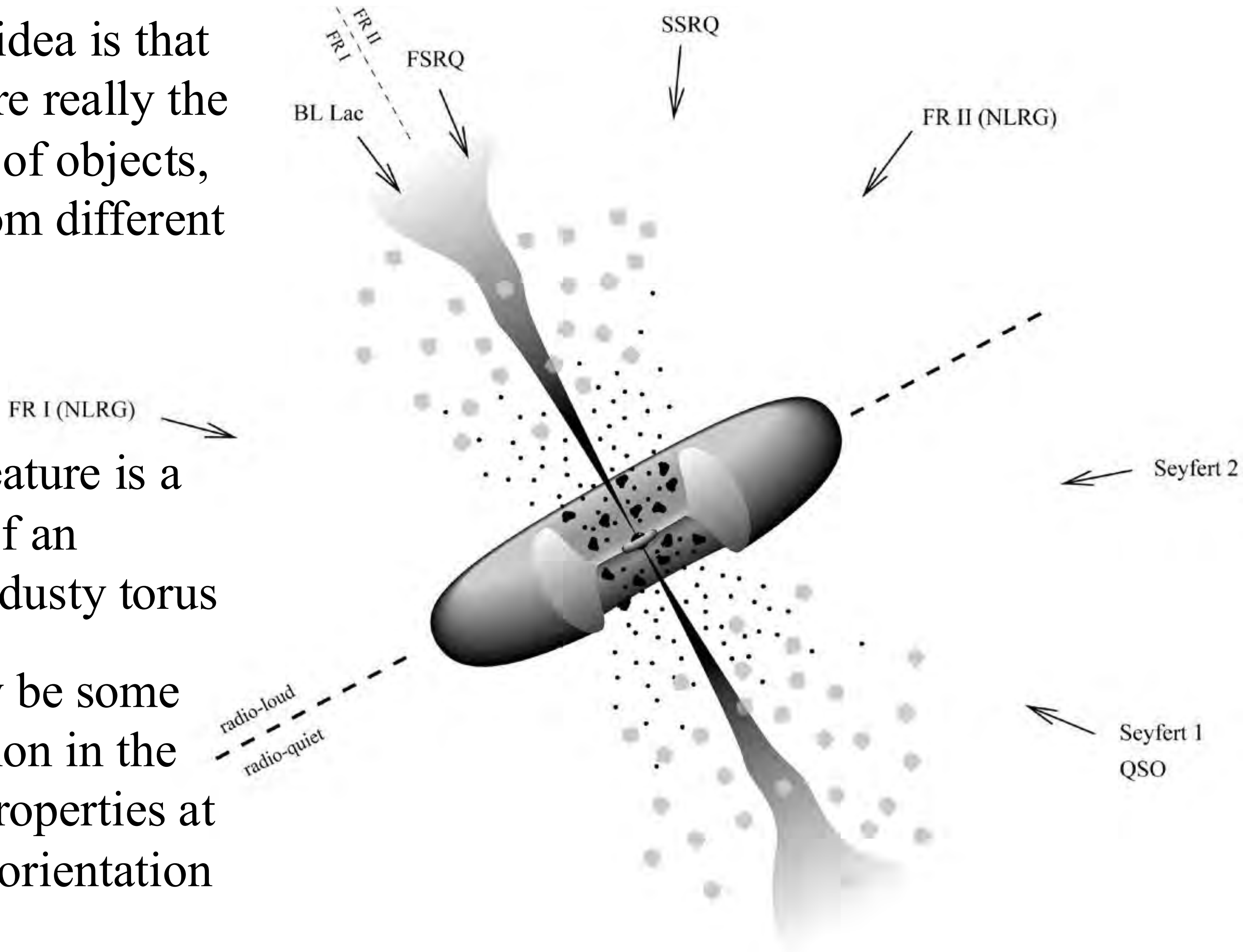
AGN: A Physical Classification



… but in addition, there will be some dependence on the viewing orientation

Unification Models for AGN

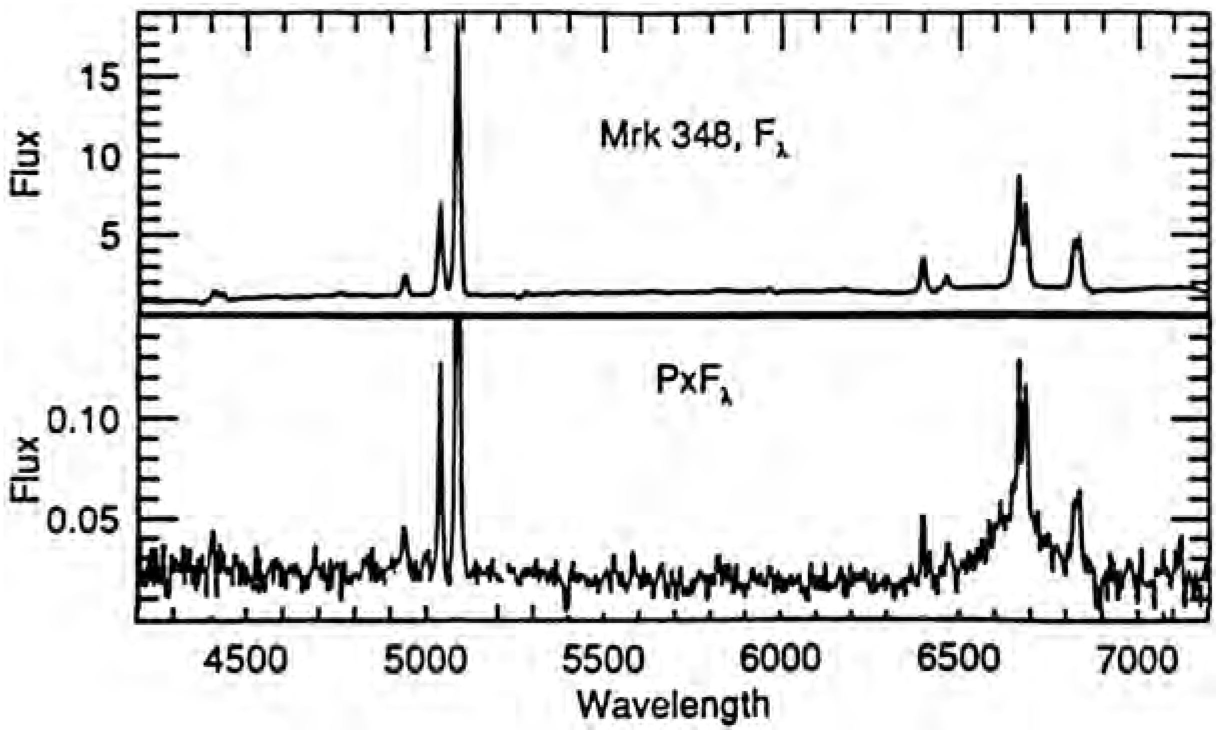
The basic idea is that all AGN are really the same type of objects, viewed from different angles



The key feature is a presence of an obscuring dusty torus

There may be some real variation in the physical properties at any given orientation

Support for this picture: in some Seyfert 2 galaxies the ***polarized emission*** (e.g., reflected from dust grains) shows broad lines:



This is consistent with the unification, since scattering produces polarization. Conclude:

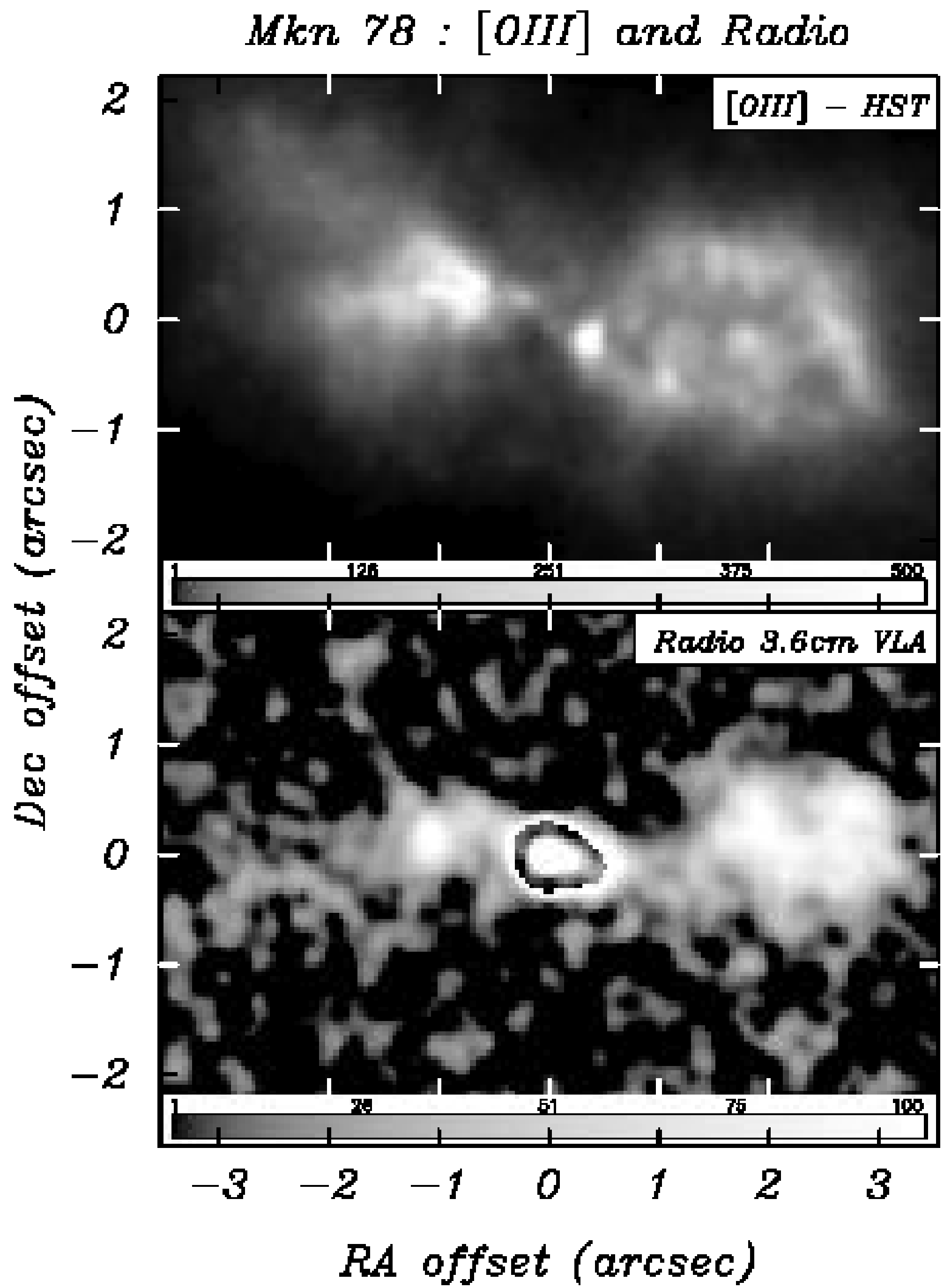
- At least some Seyfert 2's are intrinsically similar to Seyfert 1's
- If this applies to all Seyferts, statistics mean that the torus must block about 3/4 of the sky as seen from the nucleus

Ionization Cones

In addition to the spectro-polarimetry, evidence for anisotropy in AGN comes from images of resolved narrow-line emission region:

The gas seems ionized in cones bracketing the nucleus, which are also aligned with the radio jets (if present)

This is as expected if the rest of the gas does not see the nucleus, due to a toroidal obscuration



AGN Unification

It is now easonably secure to also fit quasars and blazars, and the radio loud equivalents, into this unified scheme:

Obscured	**Seyfert 2**	**Type 2 QSO or radio galaxy**
Unobscured	**Seyfert 1**	**Type 1 QSO or radio quasar**
Viewed directly down the jet	**Blazars**	

Accretion rate

Type 2 or highly obscured luminous AGN are also needed to make up the hard X-ray background. Populations of such objects have been found recently both in the optical and X-ray surveys

But there are some low-*L*, unobscured AGN, with no broad lines…

The Black Hole Paradigm for AGN

Black holes are completely specified by their mass M, angular momentum J, and charge Q (likely ~ 0): the *no-hair theorem*

Schwarzschild black hole: $Q = 0, J = 0$

Spherically symmetric. The solution has two important radii:

- An **event horizon** at Schwarzschild radius: $$R_s = \frac{2GM}{c^2}$$
- The *last stable circular orbit* radius: $$R_{ms} = \frac{6GM}{c^2}$$ Outside R_{ms} test particles can orbit indefinitely in stable circular orbits, inside R_{ms} they spiral rapidly past the event horizon into the BH. This defines the inner edge of the gas disk in AGN and sets a minimum orbital period, ~ hours for the $M_\bullet \sim 10^7$ -10^8 $M_\odot$

Radio Loud vs. Radio Quiet

More ambitious unification schemes aim to explain why some AGN are radio loud, others radio quiet. *Possible* physical difference is the spin of the SMBH:

Radio loud	**Radio quiet**
High spin holes with $\boldsymbol{a} \sim 1$	Low spin holes, $\boldsymbol{a} \ll 1$
Produce jets, which are the origin of radio emission (note: blazars are radio loud)	No jets
Jets powered by spin energy extracted from black hole	Spectrum produced by the accretion disk (blackbody + nonthermal em.)
Also have accretion disks	a is the spin parameter: $a = \dfrac{cJ}{GM^2}$

Spinning Black Holes

Kerr black hole: $Q = 0$, J and M arbitrary

Axisymmetric solution - hole has a preferred rotation axis.
Define the amount of angular momentum via a dimensionless **spin parameter**:

$$a = \frac{cJ}{GM^2}$$

Maximum angular momentum of a Kerr BH corresponds $\boldsymbol{a} = 1$
Gas can spiral deeper into the potential well before reaching R_{ms} around a Kerr black hole: **more energy can be extracted**

A Kerr black hole has an **irreducible mass**, given by:

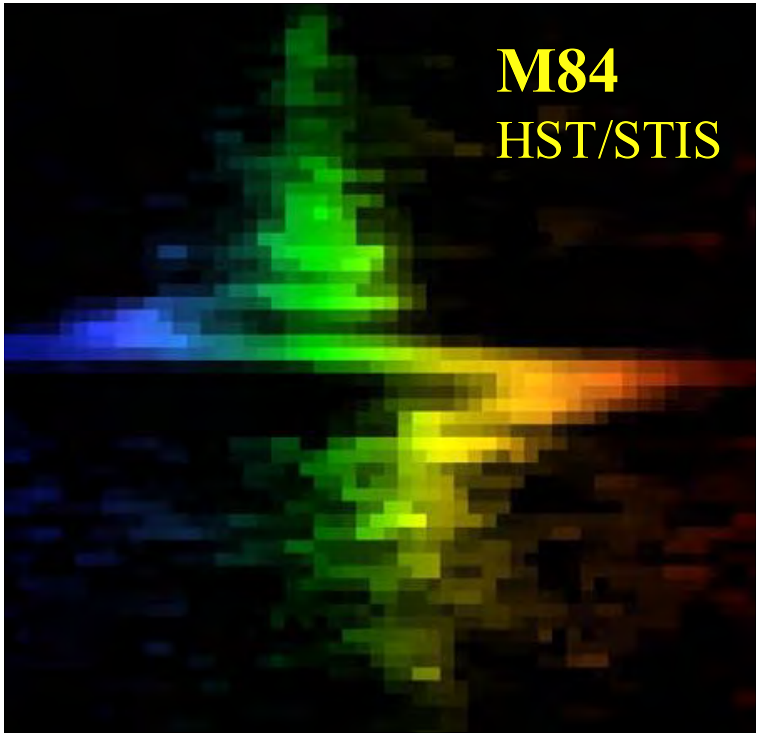
$$M_{ir} = \frac{M}{2}\left[\left(1+\sqrt{1-a^2}\right)^2 + a^2\right]^{1/2}$$

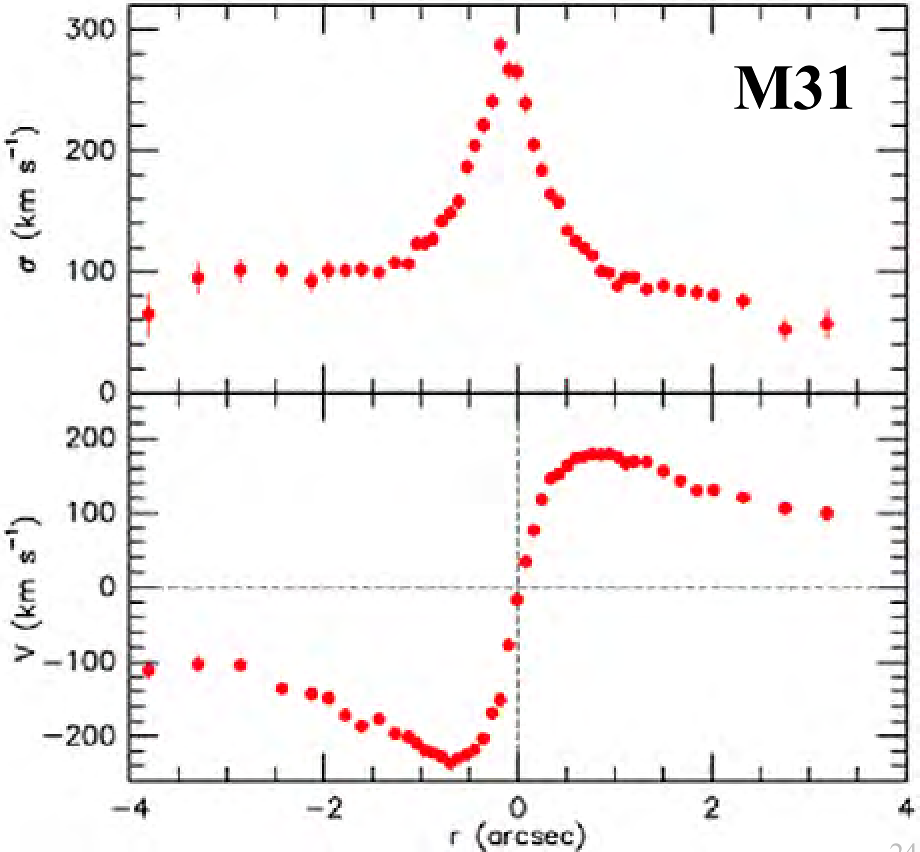
For $a = 1$, $M_{ir} = 0.707\,M$

(M-M_{ir}) represents *rotational energy of the BH* which can in principle be extracted, possibly by threading the hole with a large scale magnetic field (the Blandford-Znajek process)

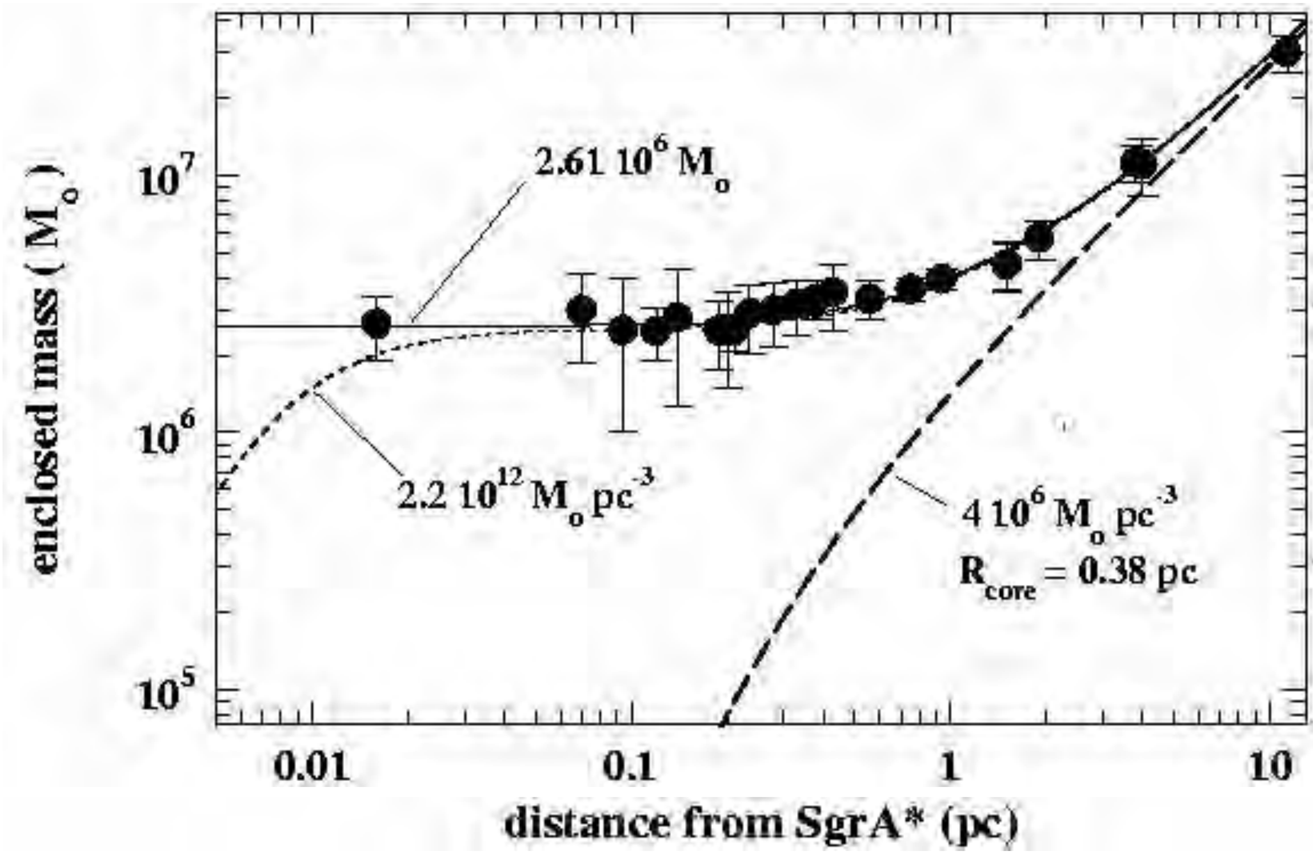
Massive Black Holes in Galactic Nuclei

- They are ***ubiquitous***, even though only a small fraction are active today; but these SMBHs are just ***dormant quasars***, which were once active - this is where their mass comes from!
- They are detected through central velocity dispersion or rotation cusps near the center, or kinematics of emission line gas





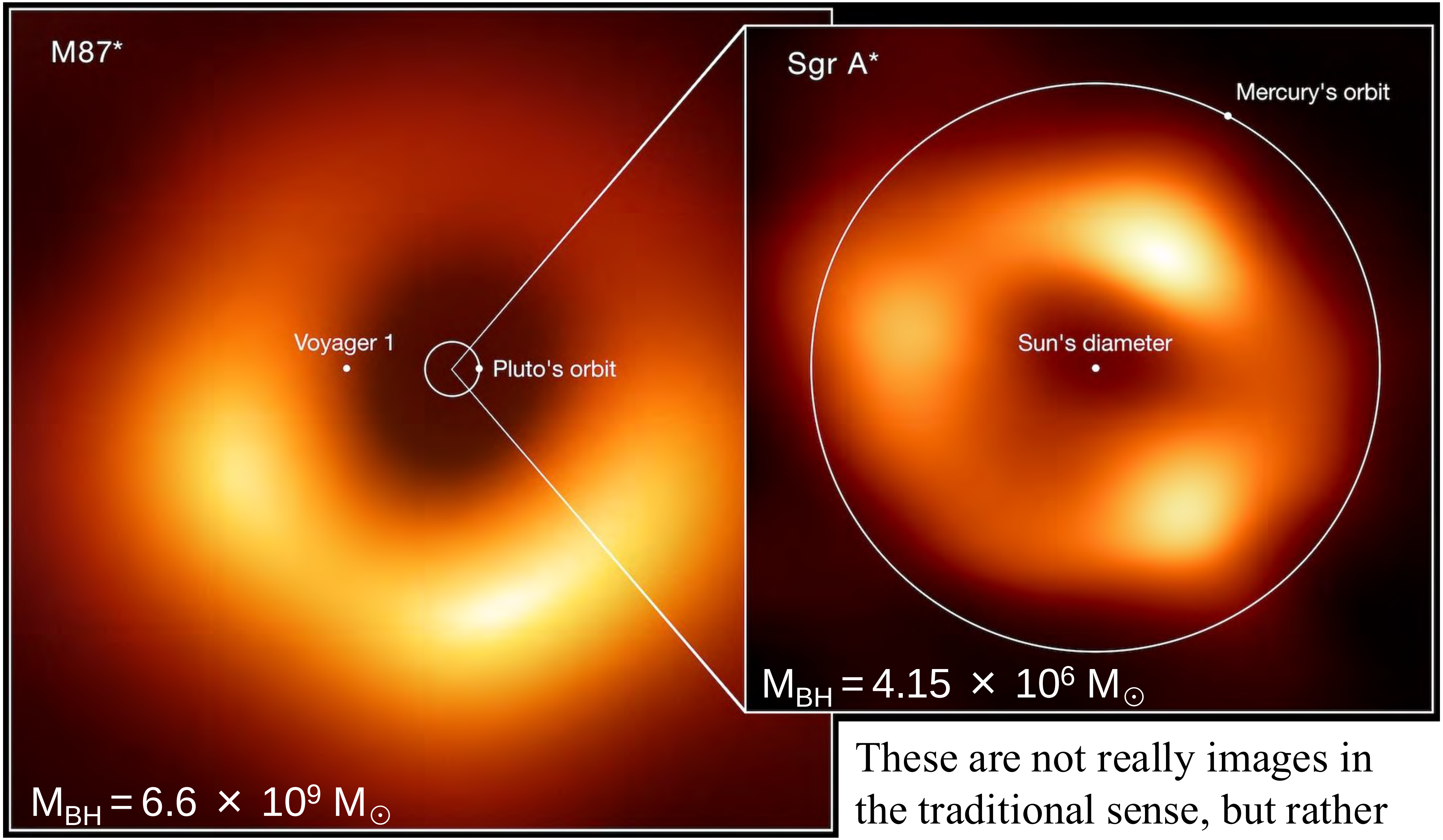
Dynamical Evidence for a Supermassive Black Hole at the Galactic Center



(Genzel et al., Ghez et al.)

An improved measurement gives the mass of $M_\bullet = 4.1.5 \times 10^6\ M_\odot$
Corresponding to a Schwarzschild radius $R_S = 1.25 \times 10^{12}$ cm
Angular size ~ 10^{-5} arcsec at ~ 8 kpc ~ resolution of the EHT

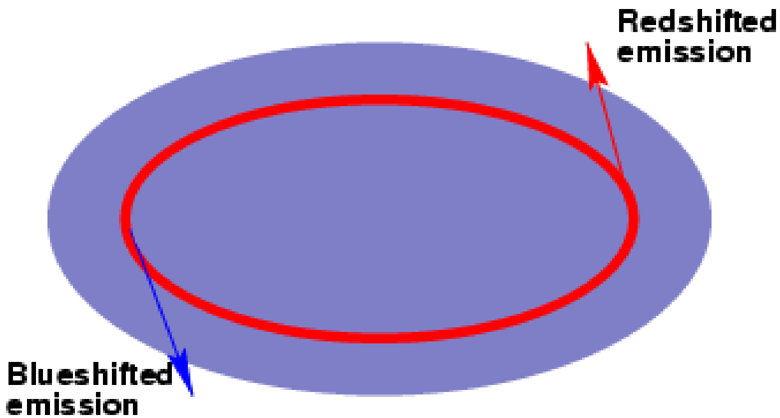
Direct (Kind of) Imaging of SMBHs by the Event Horizon Telescope



These are not really images in the traditional sense, but rather statistical models that fit the data

Evidence for SMBHs From X-Ray Spectroscopy

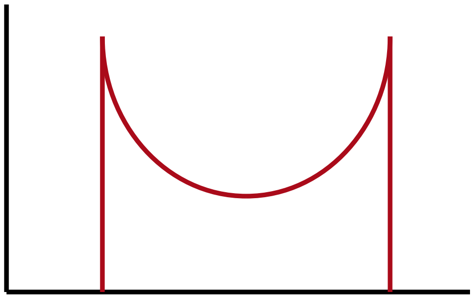
Measuring of the spectral line profiles in the inner parts of the accretion disk, close to the SMBH, offers another test for the presence of SMBHs in AGN



Fe lines in the X-rays come from the innermost parts of the disk, and are used for this test

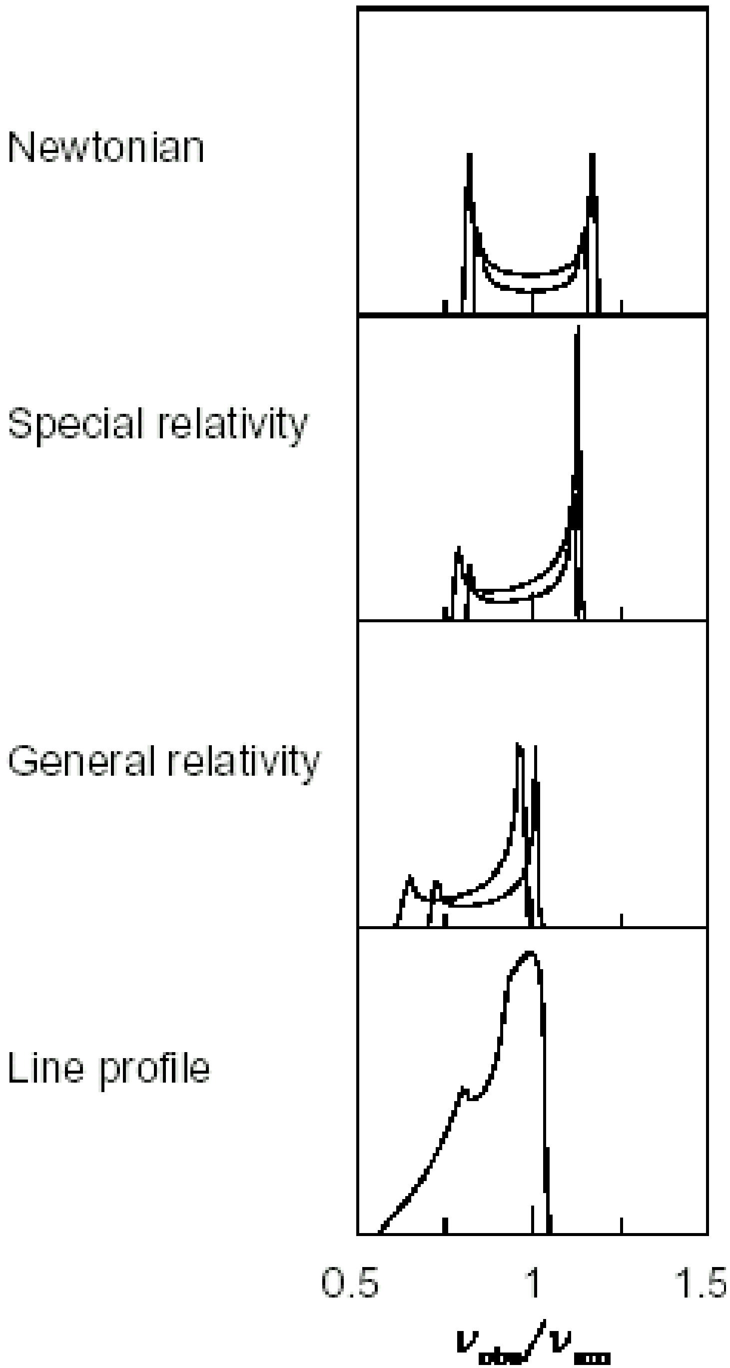
Newtonian case:

$$\frac{\Delta \nu}{\nu} = \frac{v_{obs}}{c}$$



Characteristic "double-horned" profile from a Doppler shift will only work for a Newtonian disk

But in a relativistic case, several new effects appear …



Relativistic disk: several new effects

Newtonian profile from single annulus

Transverse doppler effect: "moving clocks appear to run slow". Observed frequency is reduced compared to rest frame value by factor $(1 - v^2 / c^2)^{-1/2}$

Beaming: Boosts blue wing of the line, attenuates red wing

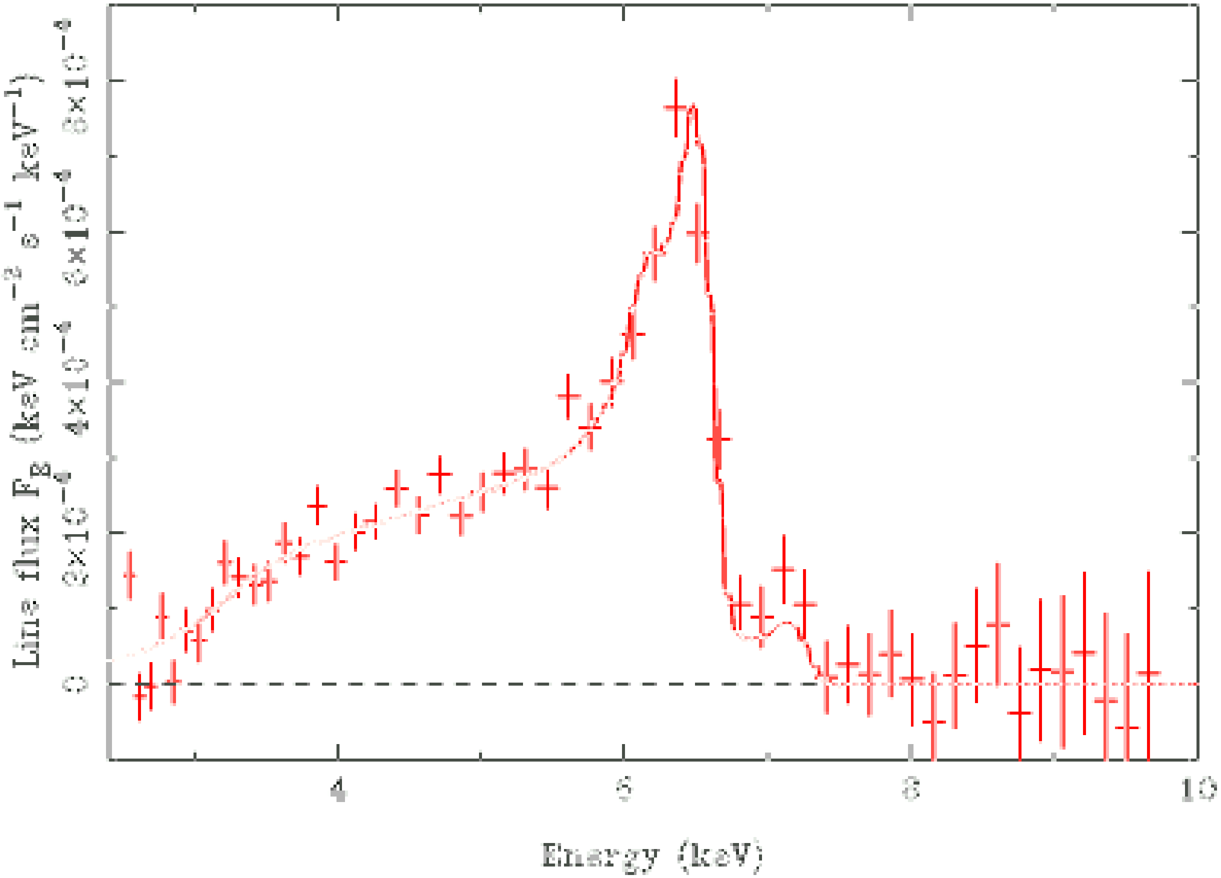
Gravitational redshift

Further shifts profile to lower energies

Integrate over all disk radii and predict:

Broad, asymmetric line profile with a sharp cutoff at high E

… And the Observations Show:



Fe line profile for the Seyfert galaxy MCG-6-30-15

(Observation with XMM-Newton)

Fe line profile is found to be often extremely broad, and the detailed modeling of the line shape favors a rapidly spinning BH

Possibly the best proof to date of presence of BHs in AGN

Where Does the Energy Come From?

- Accretion onto the central supermassive black holes provides the only known viable answer
- The fuel comes from ~ kpc scales (or larger) and ends near the ***Schwarzschild radius***, $R_s = \frac{2GM}{c^2}$ (actually, the relevant radius is the smallest stable orbit, at a few R_s). For a $M_\bullet \sim 10^8 M_\odot$, $R_s \sim 3 \times 10^8$ km ~ 10^{-5} pc
- The binding energy for a mass element m is: $E_b(R) = G\, m\, M_\bullet / R$
- In order for it to be accreted over many orders of magnitude in radius, it has to release the amount of energy comparable to E_b namely $G\, m\, M_\bullet / R_{min} = m\, c^2 / 2$, where $R_{min} \sim$ a few R_s

□ ***Accretion to black holes can result in the energy release comparable to the rest mass energy!*** Usually a ~ 10% net efficiency is assumed, still much larger than the 0.1% energy conversion efficiency of thermonuclear reactions.

Eddington Limit

For an AGN with an observed bolometric luminosity *L*, we can estimate the *minimum* mass of the black hole involved:

Suppose the gas around the BH is spherically symmetric, and fully ionized hydrogen.

At distance *r*, energy flux is: $$F = \frac{L}{4\pi r^2}$$

The corresponding momentum flux, which would produce the radiation pressure, is: $$P_{rad} = \frac{L}{4\pi r^2 c}$$

Force exerted on the gas depends upon the opacity, but the *minimum* force is due to the absorption by free electrons, given by the Thomson cross-section:

$$\sigma_e = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65\times 10^{-25}\ \mathrm{cm}^2$$

The resulting *outward* radiation pressure force on a single electron is: $$F_{rad} = \frac{L\sigma_e}{4\pi r^2 c}$$

Eddington Limit, cont.

This has to be balanced by the inward force due to gravity of a central point mass M:

$$F_{grav} = \frac{GM(m_p + m_e)}{r^2} \approx \frac{GMm_p}{r^2}$$

We include the proton mass since electrons and protons are coupled electrostatically

Setting $F_{rad} = F_{grav}$, and solving for L:

$$L = \frac{4\pi Gcm_p}{\sigma_e} M$$

The Eddington Luminosity

This is the *maximum luminosity* which an isotropically emitting source with a mass M could have

$$= 1.26 \times 10^{38} \left(\frac{M}{M_{sun}} \right) \text{erg s}^{-1}$$

Invert the formula:

$$M_E = 8 \times 10^5 \left(\frac{L}{10^{44} \text{ erg s}^{-1}} \right) M_{sun}$$

Fuelling of Active Galactic Nuclei

Given the Eddington limit, in order to produce the observed AGN luminosities of $L \sim 10^{44}$ - 10^{46} erg s^{-1}, we need BHs with masses of *at least* $M_\bullet \sim 10^6$ - 10^8 $M_\odot$. But how fast must gas be accreted?

Define the efficiency of the accretion process $\boldsymbol{\eta}$: $L = \eta \dot{M} c^2$

A mass δm of gas at $r = \infty$ has $E_{pot} = 0$. Energy available if the gas spirals in to radius r is:

$$dE = \frac{GM_{BH}\,dm}{r} \longrightarrow L \approx \frac{GM_{BH}\dot{M}}{r}$$

This is really an upper limit - not all the potential energy will be radiated as the gas falls in…

Note that since $L \sim M$ (Eddington) and also $L \sim dM/dt$, the accretion process and the BH growth is *exponential*

Fuelling of Active Galactic Nuclei

Assume that the gas falls into the last stable orbit at 6 GM / c^2 before being swallowed by the BH.

Estimate of the efficiency is:

$$\eta = \frac{GM_{BH}\dot{M}}{6GM_{BH}/c^2} \times \frac{1}{\dot{M}c^2} \approx 0.17$$

A Newtonian calculation, but it gives right order of magnitude

Actual efficiency of disk accretion onto a BH is estimated to be:

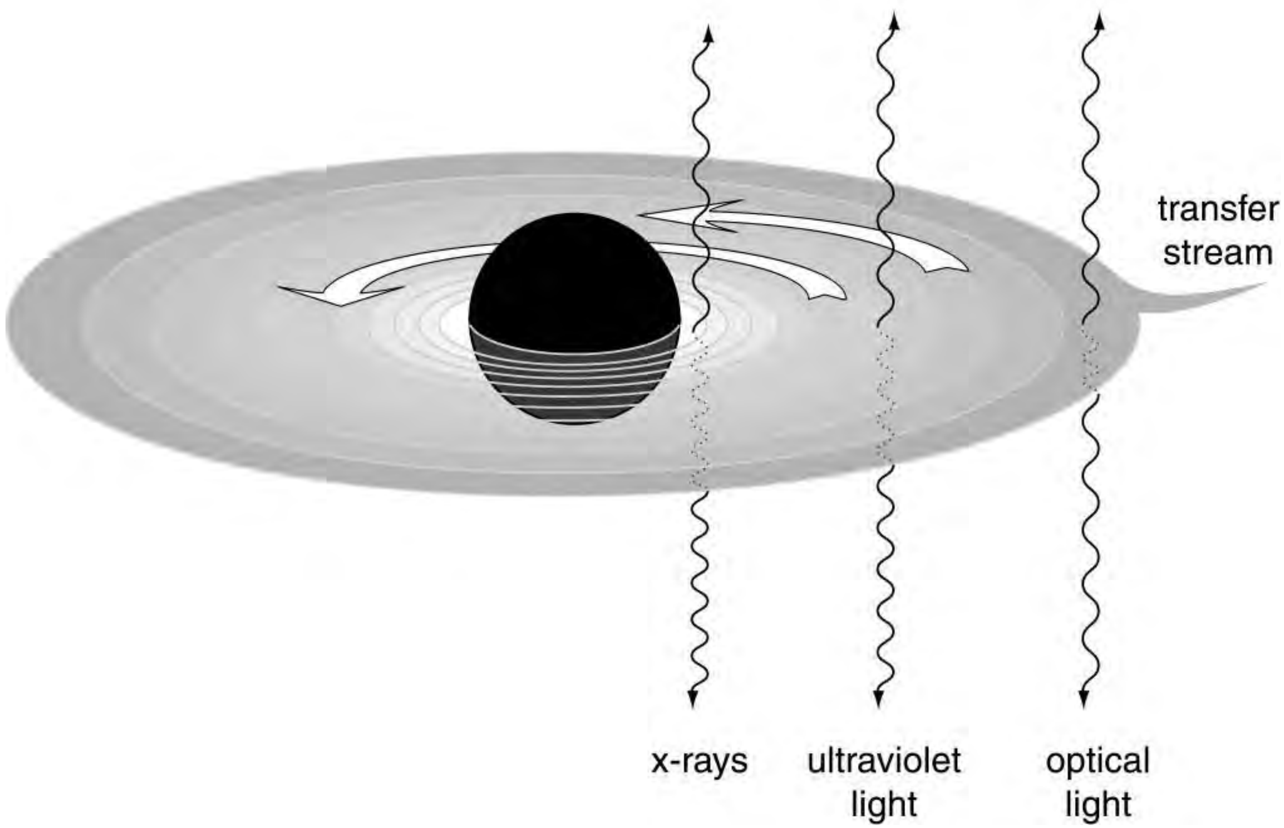
- Schwarzschild BH: $\boldsymbol{\eta} = 0.06$
- Kerr BH (corotating disk): $\boldsymbol{\eta} = 0.42$

Standard estimate is $\boldsymbol{\eta} \sim 0.1$. Using this, mass flow needed to sustain a quasar is:

$$\dot{M} \approx \frac{10^{46}\ \text{erg s}^{-1}}{0.1 \times c^2} \approx 10^{26}\ \text{g s}^{-1} \approx 2\ \text{Solar masses yr}^{-1}$$

Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself



Thermal Emission From Accretion Disks

For a SMBH, the effective disk temperature as a function of radius is:

$$T(R) \approx 6.3 \times 10^5 \left(\frac{\dot{M}}{\dot{M}_E} \right)^{1/4} \left(\frac{M}{10^8 M_{sun}} \right)^{-1/4} \left(\frac{R}{R_s} \right)^{-3/4} \text{ K}$$

Accretion rate at the Eddington luminosity for $\eta = 0.1$

A thermal spectrum at temperature T peaks at $h\nu_{\max} \approx 2.8kT$

An inner disk temperature of ~10^5 K corresponds to peak emission at ~50 nm. Thus, we expect the disk emission in AGN accreting at close to the Eddington limit to be strong in the UV; this is the origin of the broad UV peak in quasar SEDs

Since the emission comes from a range of radii / temperatures, the emergent spectrum is broader than the simple blackbody

Synchrotron Emission

Electron moving perpendicular to a magnetic field feels a Lorentz force.

Acceleration of the electron Radiation (Larmor's formula)

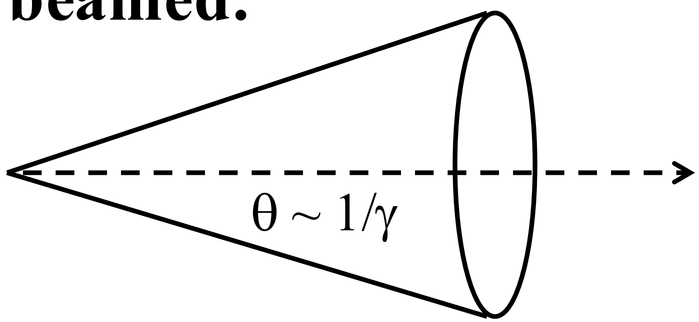
Define the Lorentz factor: $$\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}}$$

For non-relativistic electrons: $\gamma \sim 1 \Rightarrow$ **cyclotron radiation**
For relativistic electrons: $\gamma >> 1 \Rightarrow$ **synchrotron radiation**
Same physical origin but very different spectra …

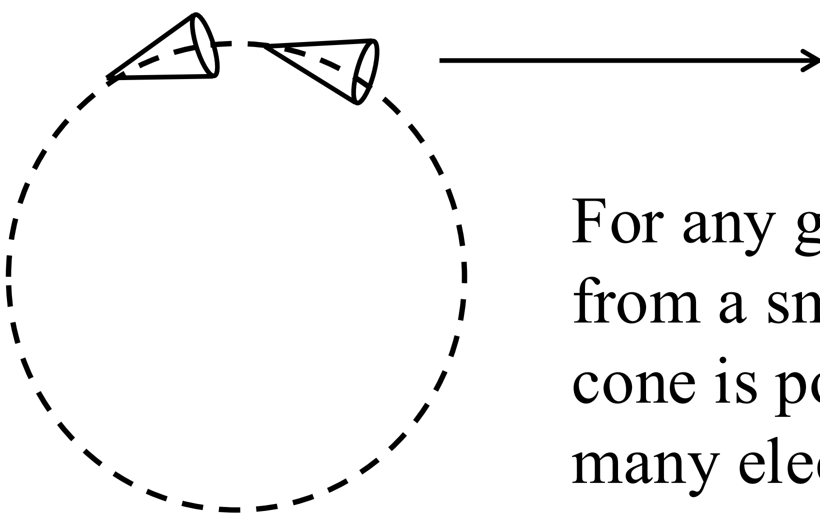
Syncrotron radiation is responsible for all of the observed radio and high energy emission from AGN (and GRBs)

Synchrotron Radiation

If the electrons are moving at close to the speed of light, radiation is **beamed:**



Particle moving with Lorentz factor γ toward observer emits radiation into cone of opening angle $\theta \approx \gamma^{-1}$



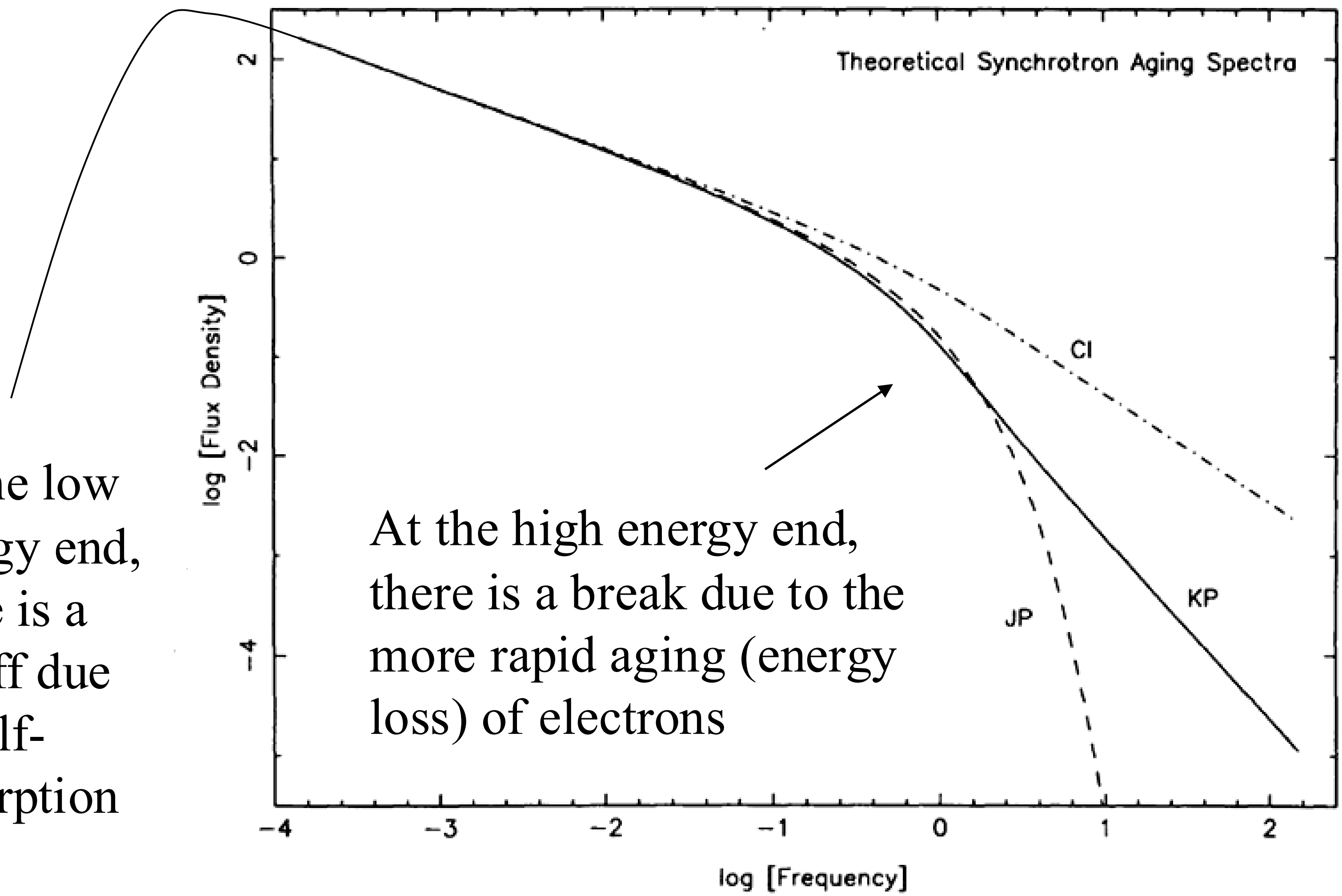
To observer

For any given electron, we only see radiation from a small portion of the orbit when the cone is pointed toward us - but there are many electrons…

The net emergent spectrum depends on the distribution of energies

Synchrotron Radiation

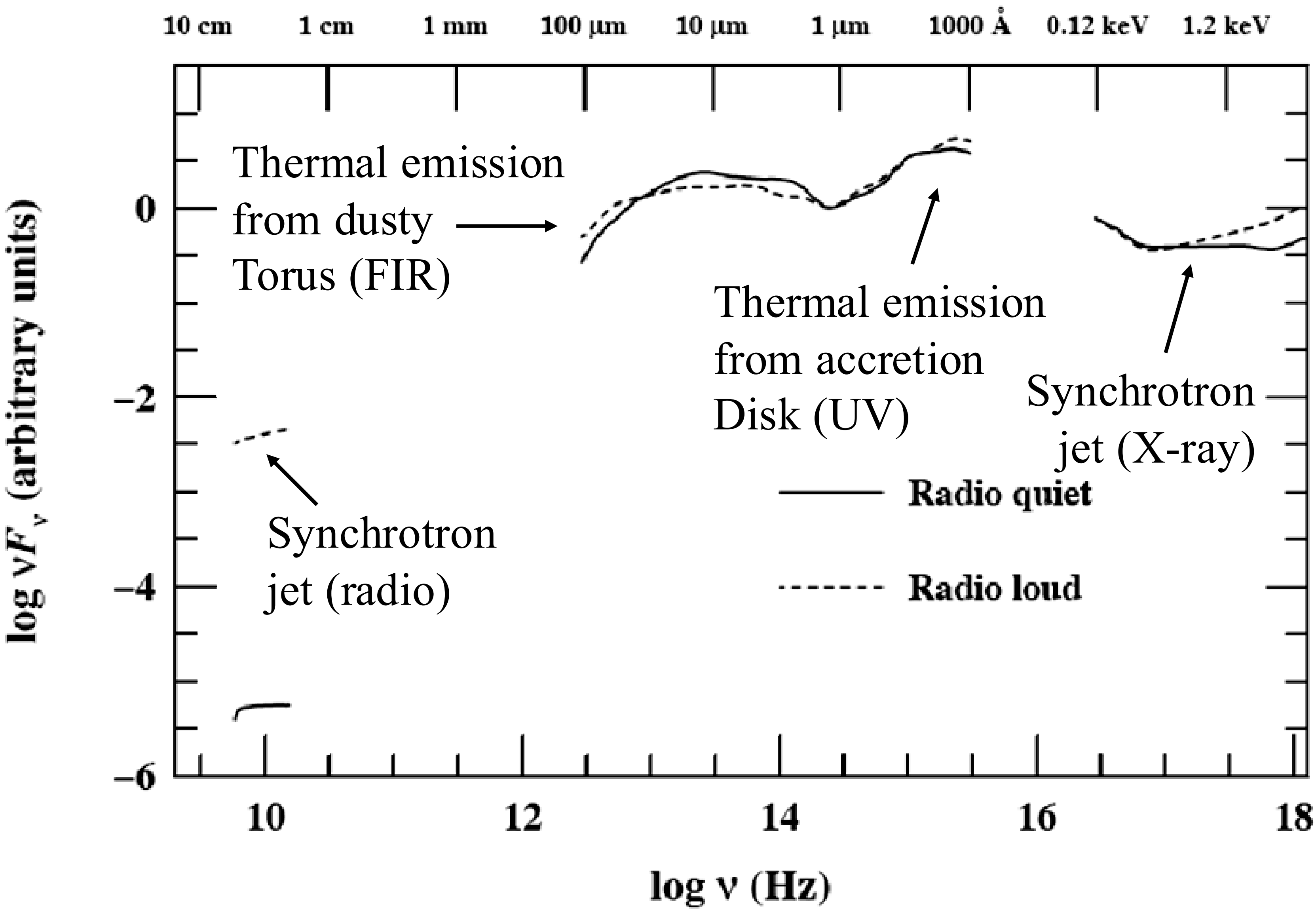
If the distribution of electron energies is a power-law (a common case), so will be the emergent spectrum, $P(\nu) \sim \nu^{\alpha}$, but with cutoffs



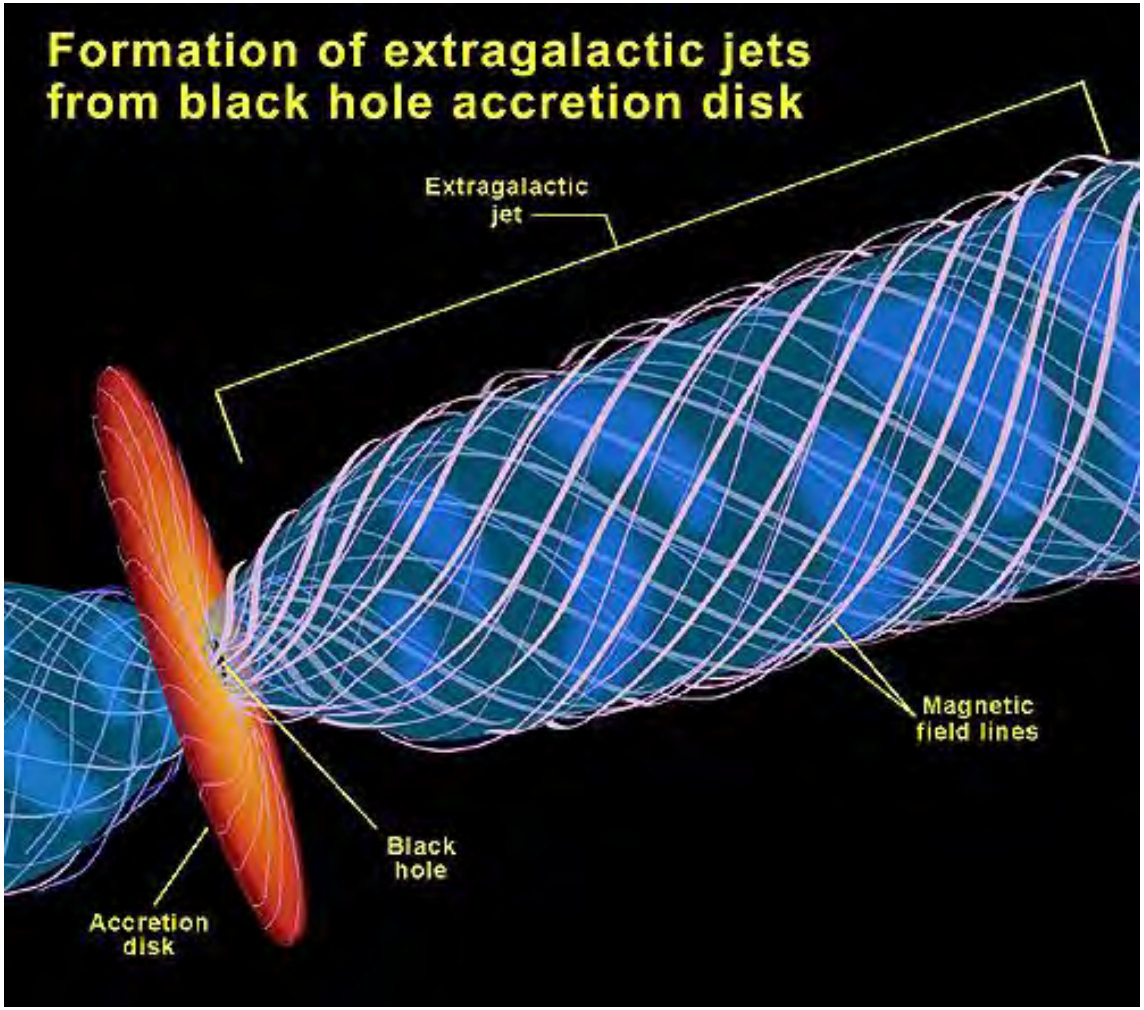
At the low energy end, there is a cutoff due to self-absorption

At the high energy end, there is a break due to the more rapid aging (energy loss) of electrons

Explaining the Broad-Band Spectral Energy Distribution in AGN



The Origin of AGN Jets



Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

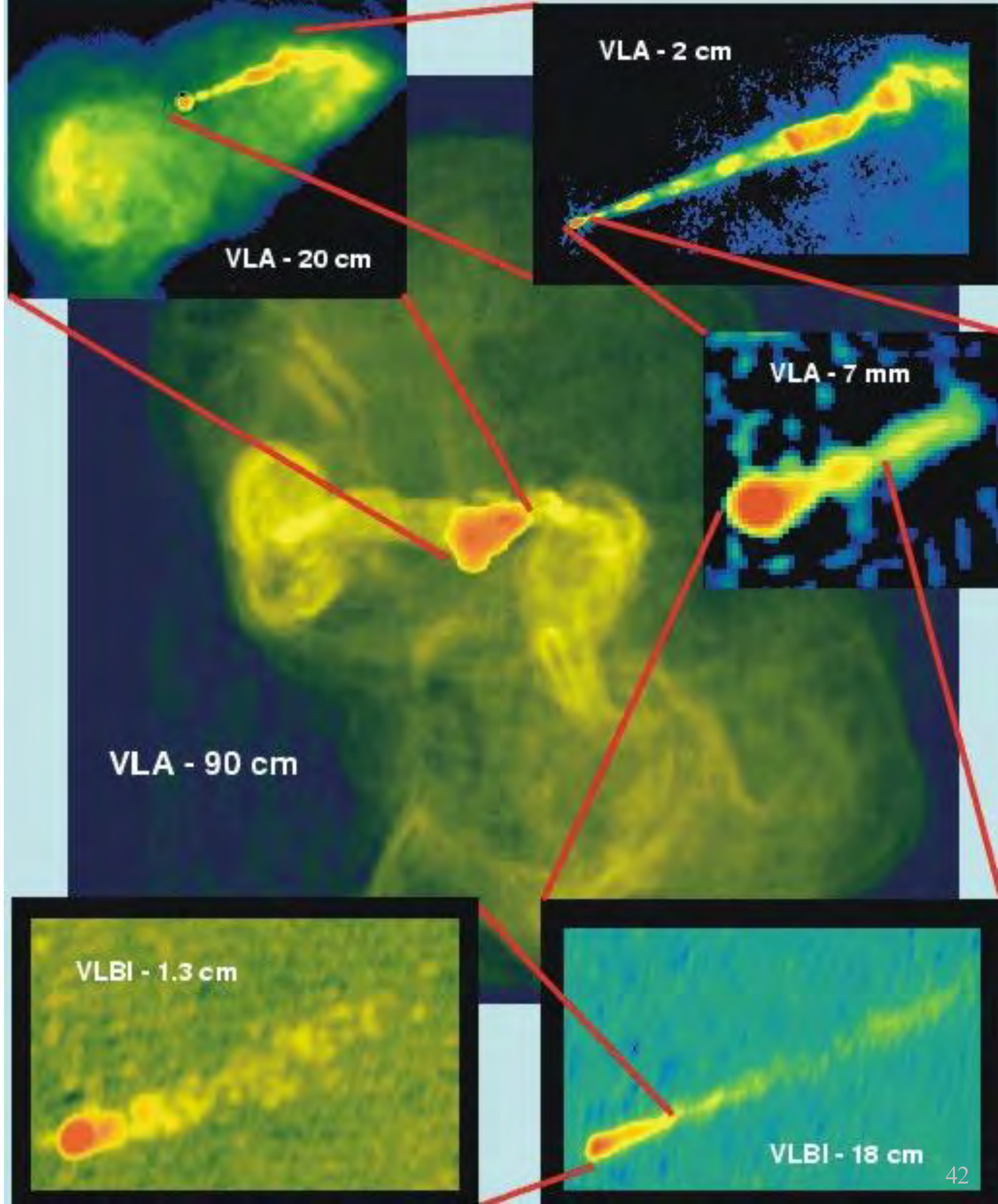
This saps the rotational energy of the disk and/or the BH itself; aside from radiation, mechanical energy is carried by the jets to lobes

Collimated Radio Emission (Jets)

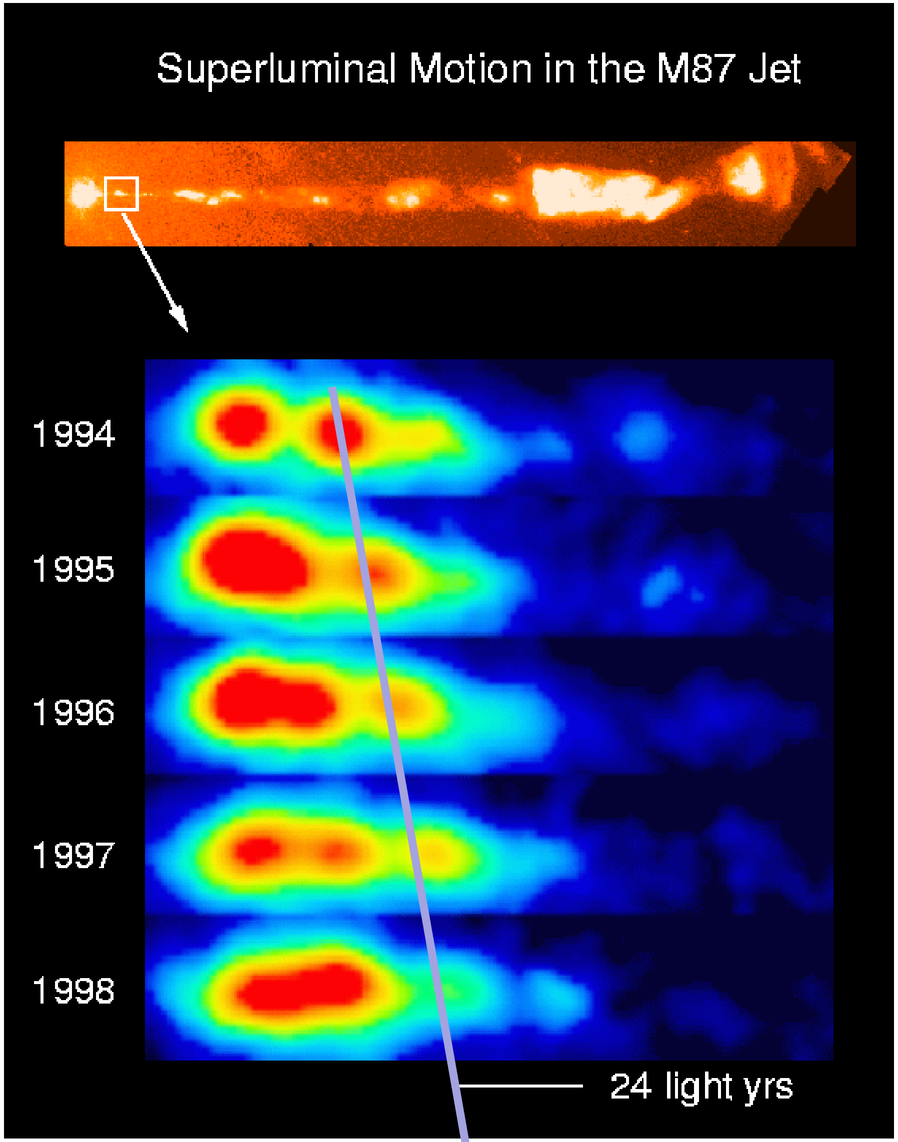
An example of M87 = Virgo A

Generally present in most non-thermal radio sources

Persists over many orders of magnitude in linear scale



Apparent Superluminal Motions



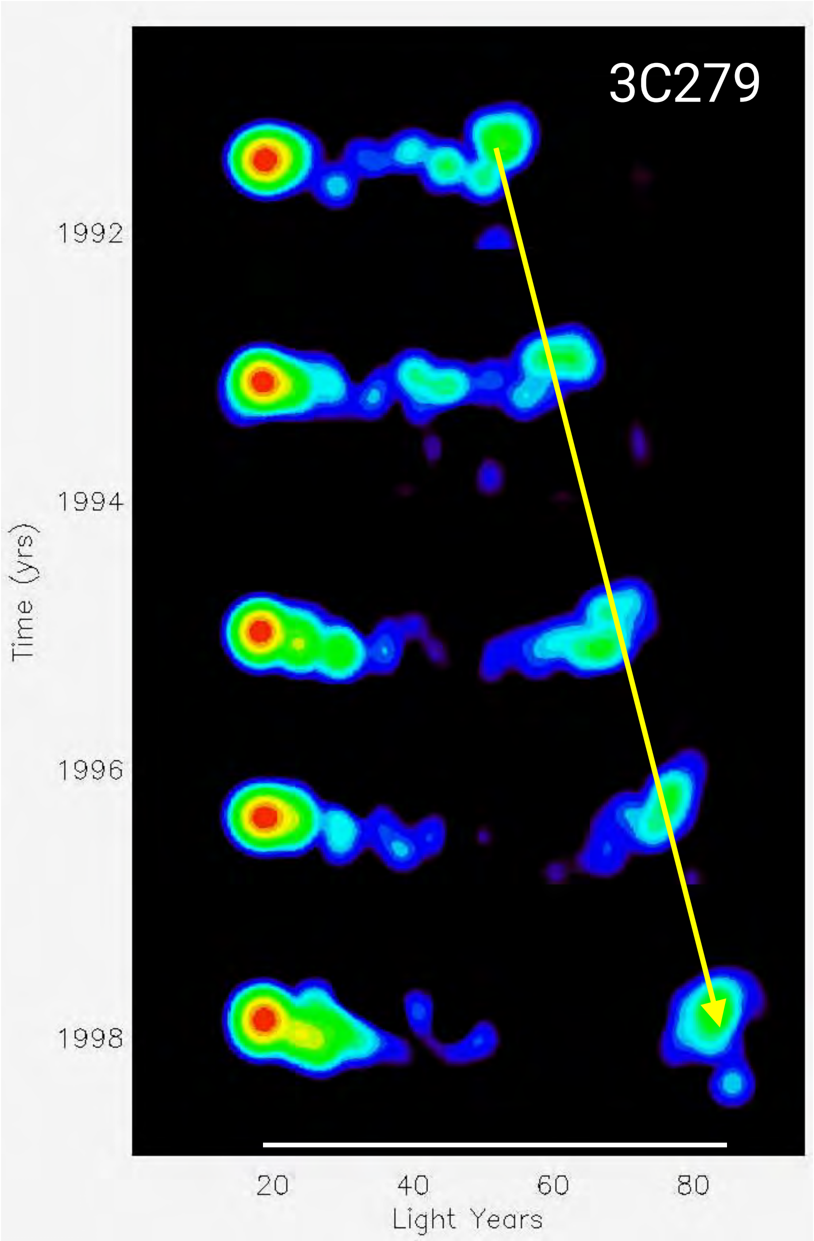
On small scales, jets near the nucleus often show hotspots or knots which can be seen to move with time, e.g., in M87, with apparent speeds exceeding the speed of light!

At first, it was not clear if this reflects a physical speed of the jet, or just motion of the illumination patterns

It is *an optical illusion caused by the relativistic effects*

Apparent transverse speed ~ 6 *c*!

Apparent Superluminal Motions



Apparent motion ~ 35 ly
Elapsed time ~ 6.5 yrs
Apparent speed ~ 5.4 c

AGN jets are moving at speeds close to the speed of light. When these jets are directed *nearly towards the observer*, the light from the jet appears to come from a point closer than it actually is, *creating the illusion of superluminal motion*. The faster the jet moves towards the observer, the more pronounced the superluminal effect becomes.

Summary of the Key Points

- Quasars/AGN are highly energetic manifestations in the nuclei of galaxies, powered by an accretion onto supermassive black holes
- The evidence for the existence of these SMBHs comes from the dynamics of gas and stars in the galactic centers, and now also interferometric imaging by the EHT
- AGN unification implies that many observed properties depend on the angle from which we observe them
- Their luminosities come from the release of binding energy by the accreted mass via the accretion disks; on average, ~ 10% of the rest mass is radiated away
- The emerging spectra are highly non-thermal, with multiple components; synchrotron radiation is one key mechanism
- Collimated magnetic fields produce the relativistic jets in AGN