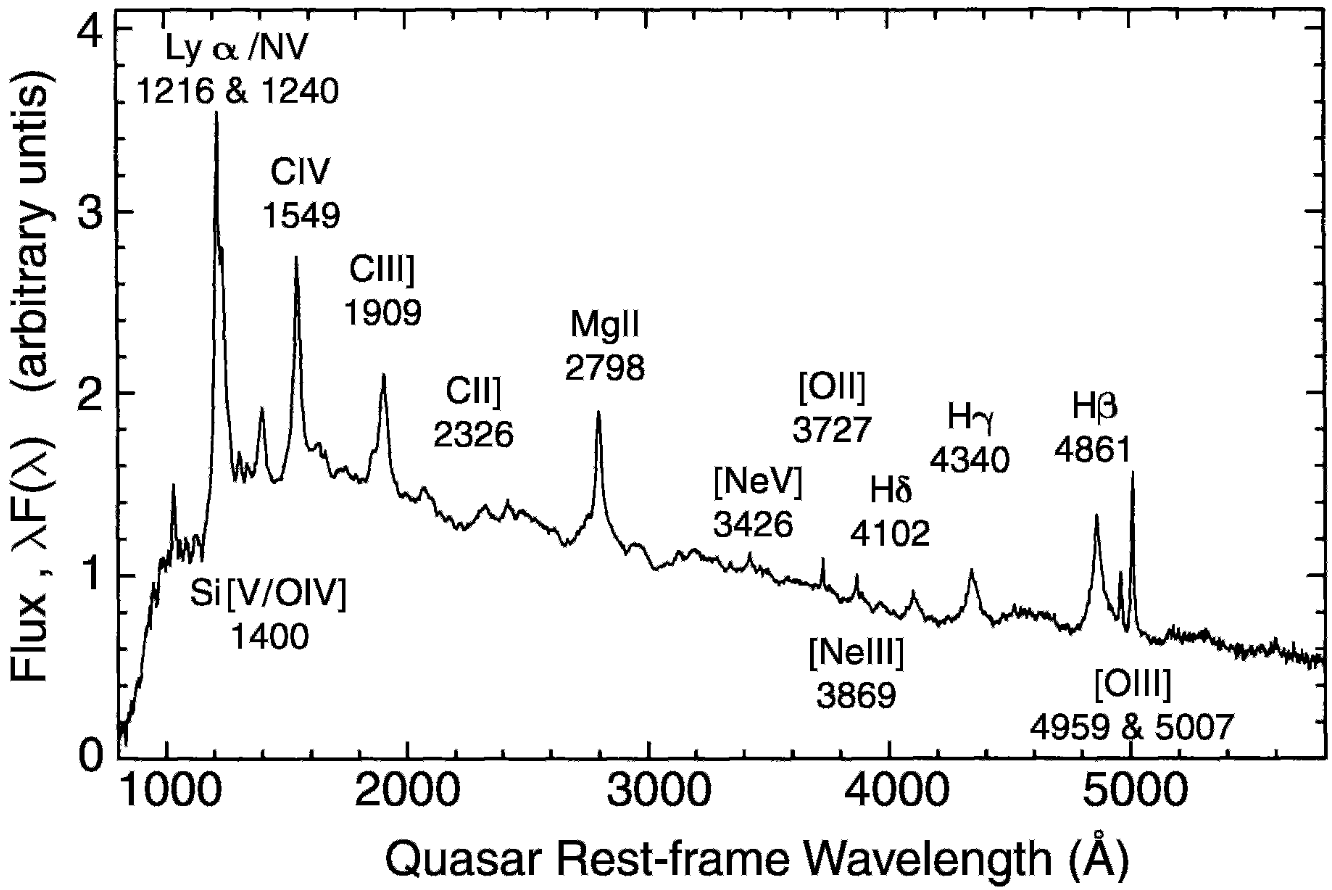
Active Galactic Nuclei

- Optical spectra, distance, line width
- Varieties of AGN and unified scheme
- Variability and lifetime
- Black hole mass and growth
- Geometry: disk, BLR, NLR
- Reverberation mapping
- Jets and blazars
- AGN spectra

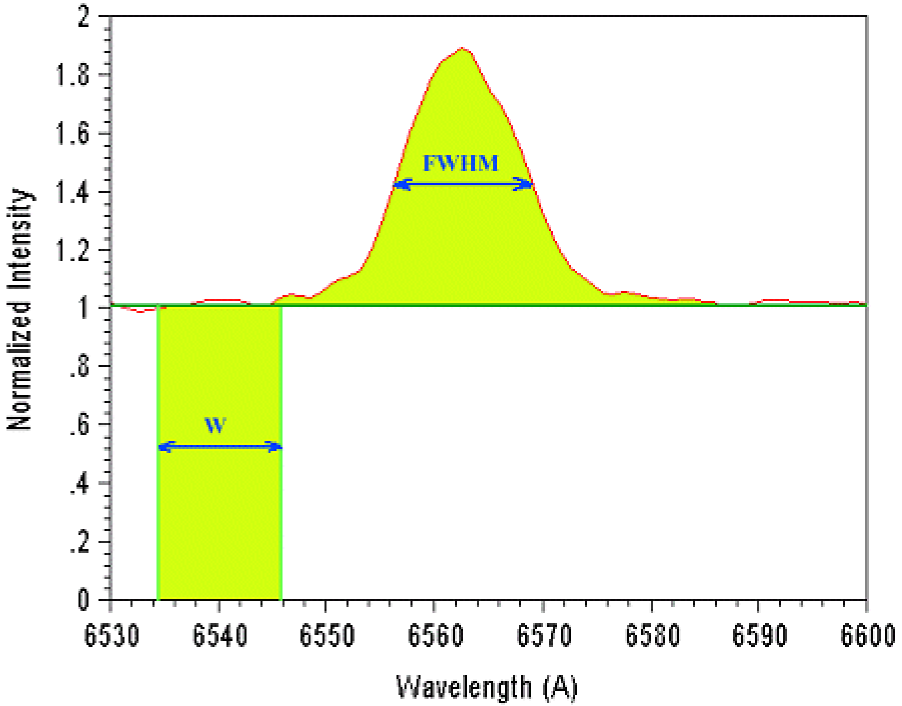
Optical spectrum of an AGN



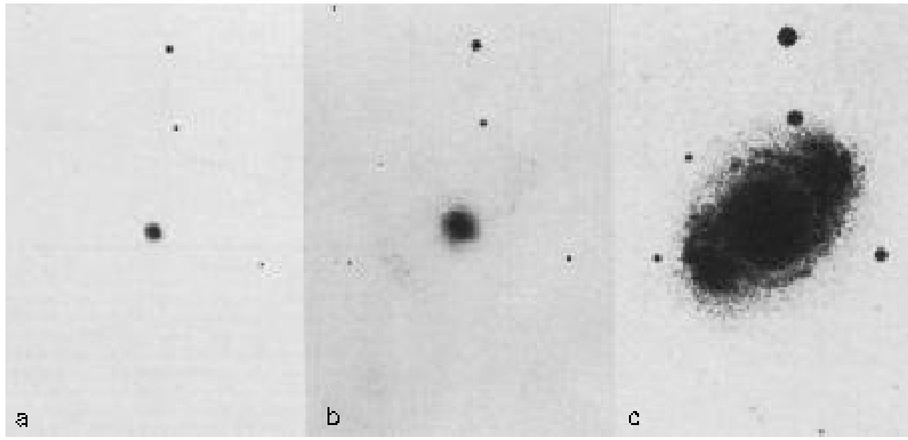
- Variety of different emission lines
- Each line has centroid, area, width
- There is also continuum emission

Emission lines

- Shift of line centroid gives recession velocity $v/c = \Delta\lambda/\lambda$.
- The width is usually characterized by the "Full Width at Half Maximum". For a Gaussian FHWM = 2.35σ.
- The line width is determined by the velocity distribution of the line emitting gas, $\Delta v/c = \sigma/\lambda$.
- Area is proportional to the number of detected line photons or the line flux.
- Usually characterized by "equivalent width" or range in wavelength over which integration of the continuum produces the same flux as the line.



Early observations of AGN



• Very wide emission lines have been known since 1908.

• In 1959, Woltjer noted that if the profiles are due to Doppler motion and the gas is gravitationally bound then $v^2 \sim GM/r$. For $v \sim 2000$ km/s, we have

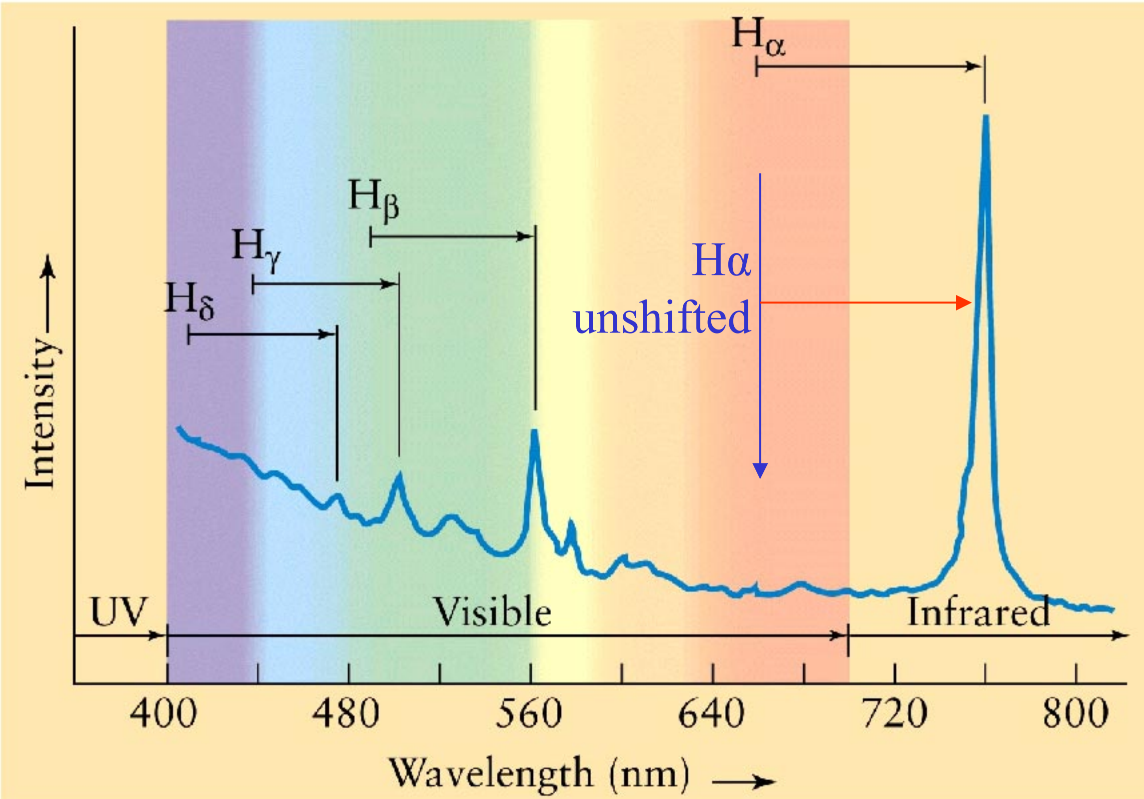
$$M \geq 10^{10} \left(\frac{r}{100 \text{ pc}} \right) M_{\text{Sun}}$$

• So AGN, known at the time as Seyfert galaxies, must either have a very compact and luminous nucleus or be very massive.

Quasars

- Early radio telescopes found radio emission from stars, nebulae, and some galaxies.
- There were also point-like, or star-like, radio sources which varied rapidly these are the \`quasi-stellar' radio sources or quasars.
- In visible light quasars appear as points, like stars.

Quasar optical spectra



Redshift of 3C273 is 0.16.

3C273 is 2.6 billion light years away if redshift is due to Hubble expansion.

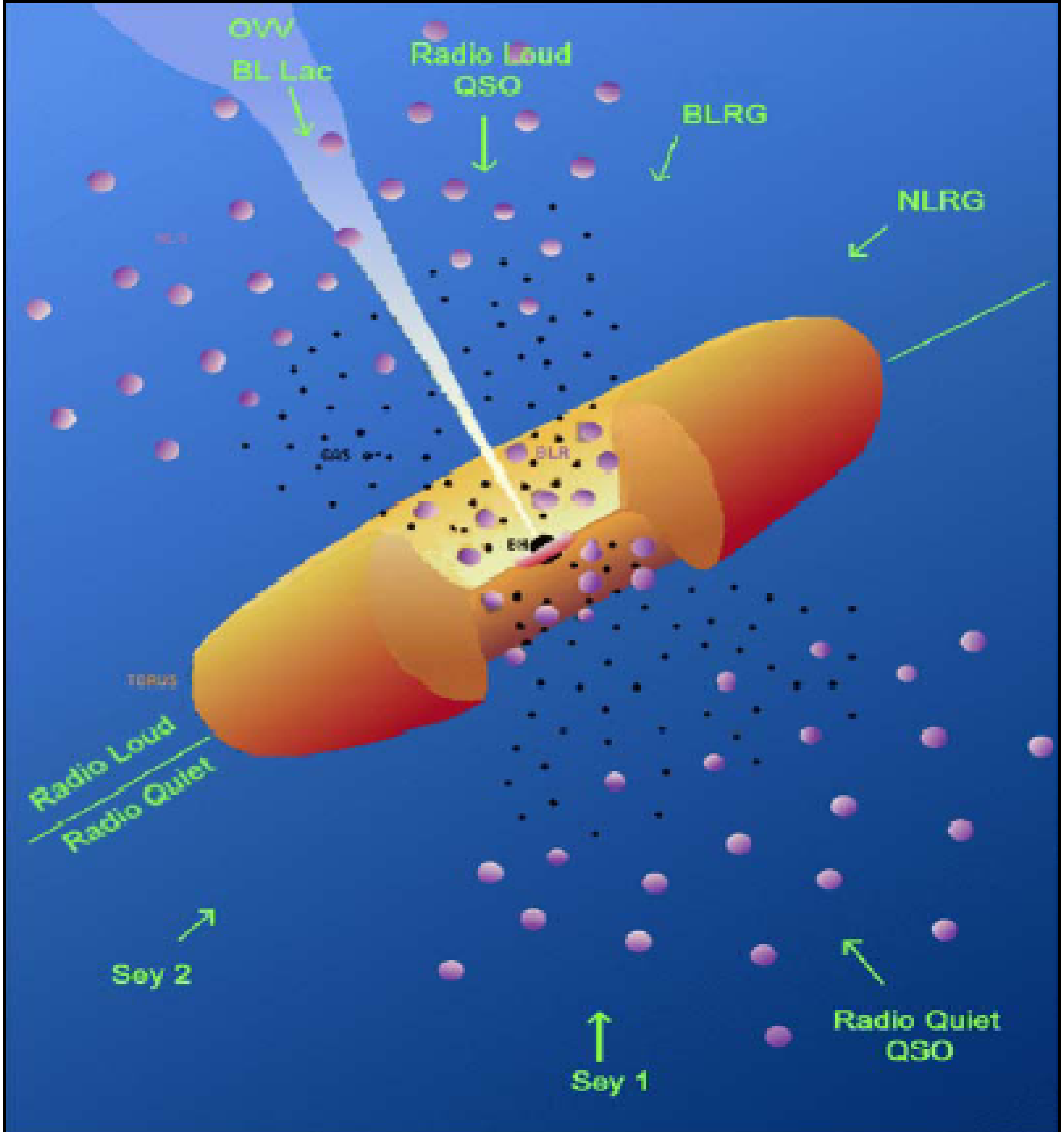
The luminosity of 3C273 is 10^{12} solar luminosities or 100 times the luminosity of the Milky Way.

Active Galactic Nuclei

- Very small angular size: point like
- High luminosity: compared to host galaxies
- Broad-band continuum emission: radio to TeV
- Strong emission lines: unlike stars or galaxies
  - Broad lines ($\Delta\lambda/\lambda \sim 0.05$)
  - Narrow lines ($\Delta\lambda/\lambda \sim 0.002$)
- Variability: some are highly variable
- Polarized emission: very high for some
- Radio emission: radio-loud vs radio-quiet

AGN Classification

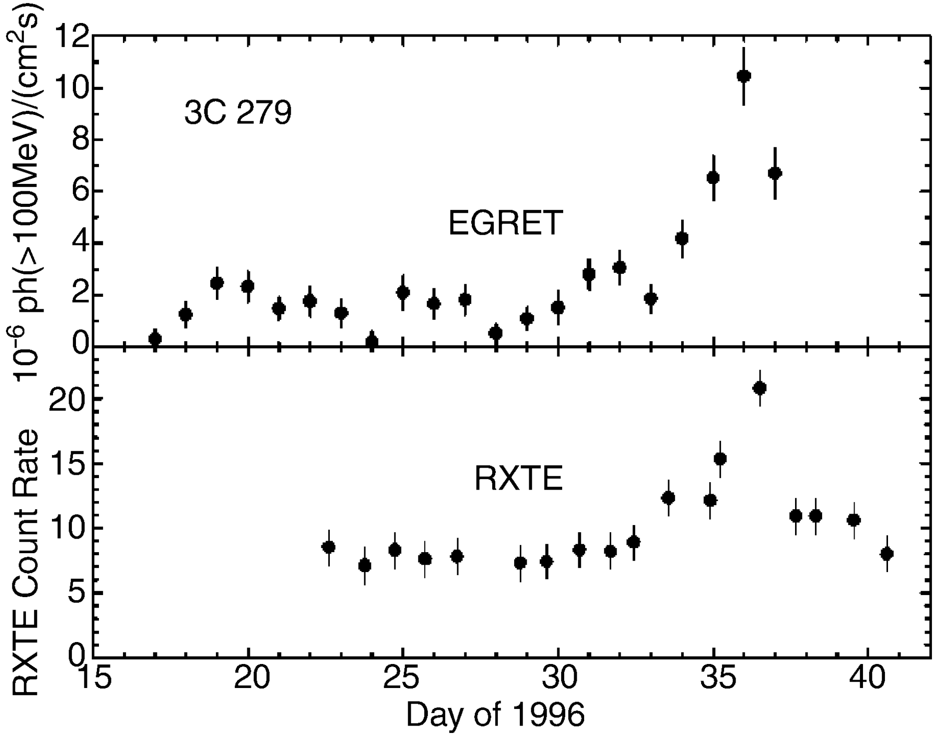
- Radio-Quiet AGN (~90%)
  - Radio-quiet quasars
  - Seyfert galaxies
    - Seyfert 1: both narrow and broad emission lines
    - Seyfert 2: only narrow emission lines
  - LINERs
- Radio-Loud AGN (~10%)
  - Radio-loud quasars: core dominated vs lobe dominated
  - Radio galaxies
    - Faranoff-Riley type 1 (FR 1): only narrow emission lines
    - FR 2: both narrow and broad emission lines
  - BL Lac Objects: very weak emission lines (blazars)
  - Optically Violent Variables (OVV)

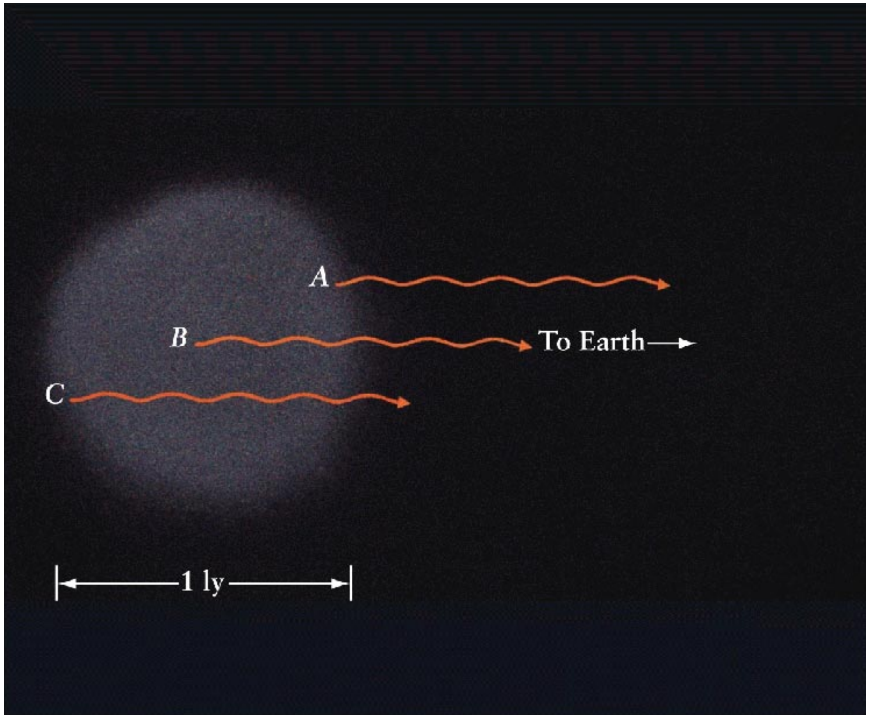

OVV
BL Lac
Radio Loud
QSO
BLRG
NLRG
BLR
BH
Radio Loud
Radio Quiet
Sey 2
Sey 1
Radio Quiet
QSO

AGN Unified Scenario

- Supermassive black hole
- Thin accretion disk – emission peaks in UV, optically thick
- Disk corona – produces X-ray/hard X-ray emission, optically thin
- Dusty torus – essentially outer part of accretion disk, optically thick, produces IR emission
- High-velocity clouds – located near BH, produce broad optical emission lines, electron density above 10^7 cm^{-3} (due to lack of forbidden lines), ionized by disk/corona
- Low-velocity clouds – located near/outside of torus, produce narrow optical emission lines which are collisionally excited, have a range of ionization levels, filling factor is small ~ 10^{-3}, material seems to be mainly outflowing
- Relativistic jets and radio lobes – extend parsecs to 100s kpc, detected up to X-rays, contain highly energetic particles

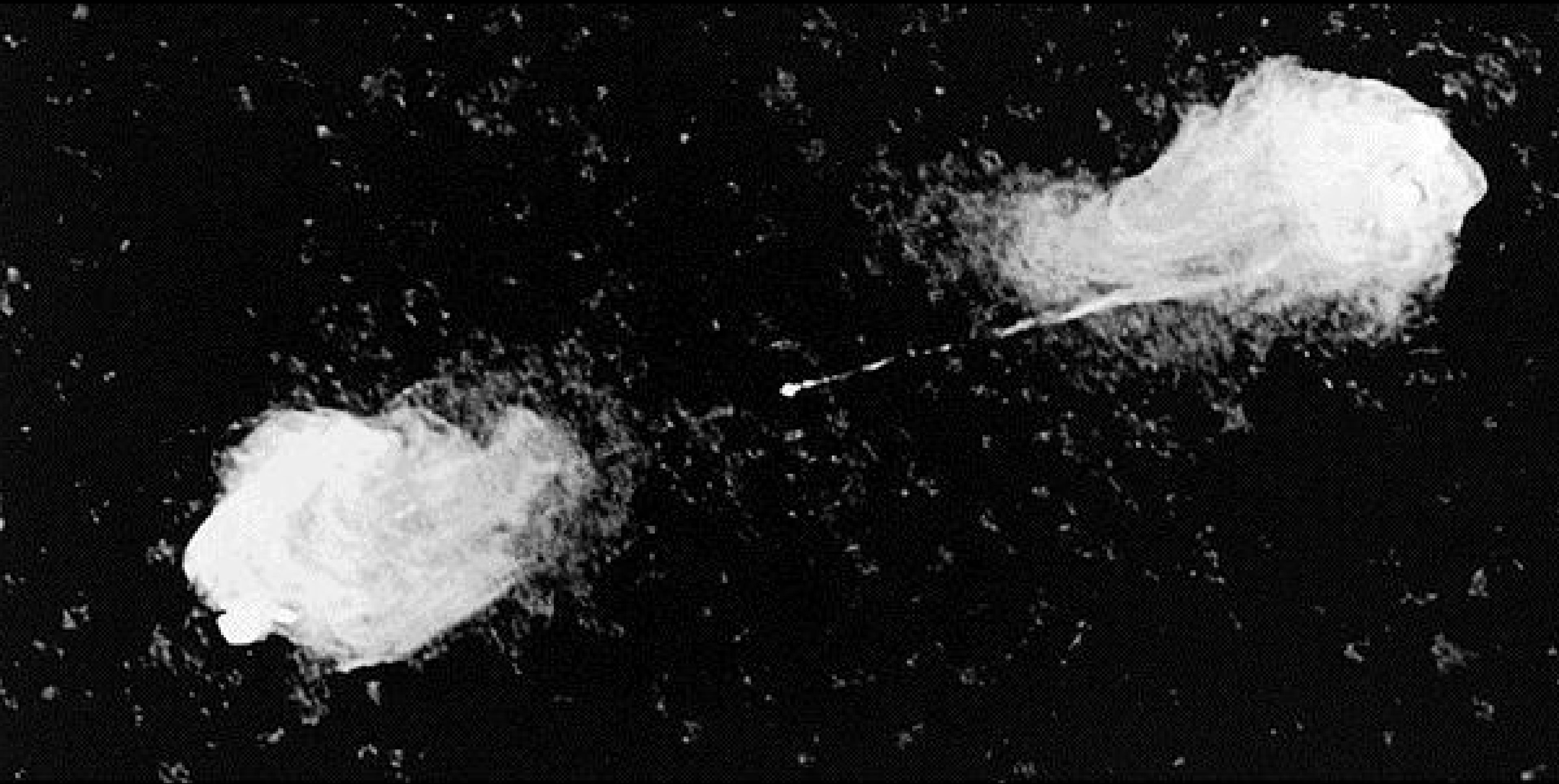
AGN variability and size





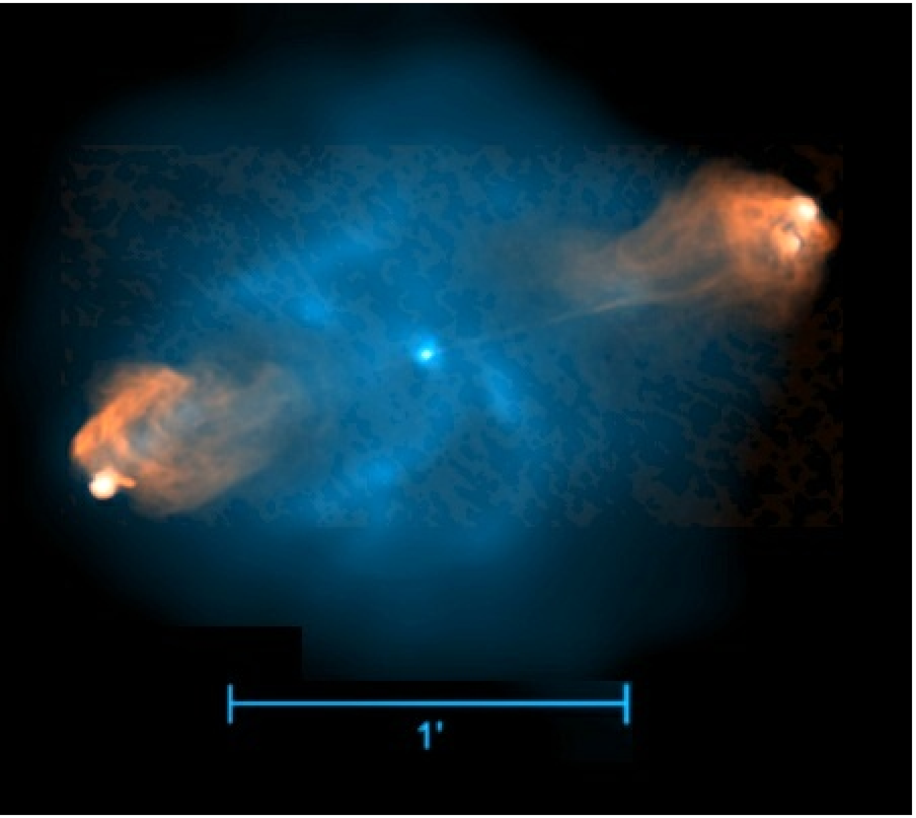
- Size places a limit on how fast an object can change brightness.
- Conversely, rapid variations place a limit on the size of the emitting object, e.g. strong variations on 1 day times scales limit the object size to less than 1 light-day.
- Quasar power source must be smaller than ~ 10^{15} cm.

What is the lifetime of this jet?



| -------------------- | = 150,000 light years

Cyg A radio/x-ray lobes



Lobe separation ~ 100 kpc, speed ~ 1000 km/s

$\Rightarrow$ age $\Delta t \sim 10^8$ years

Alternate way to estimate active lifetime of AGN is

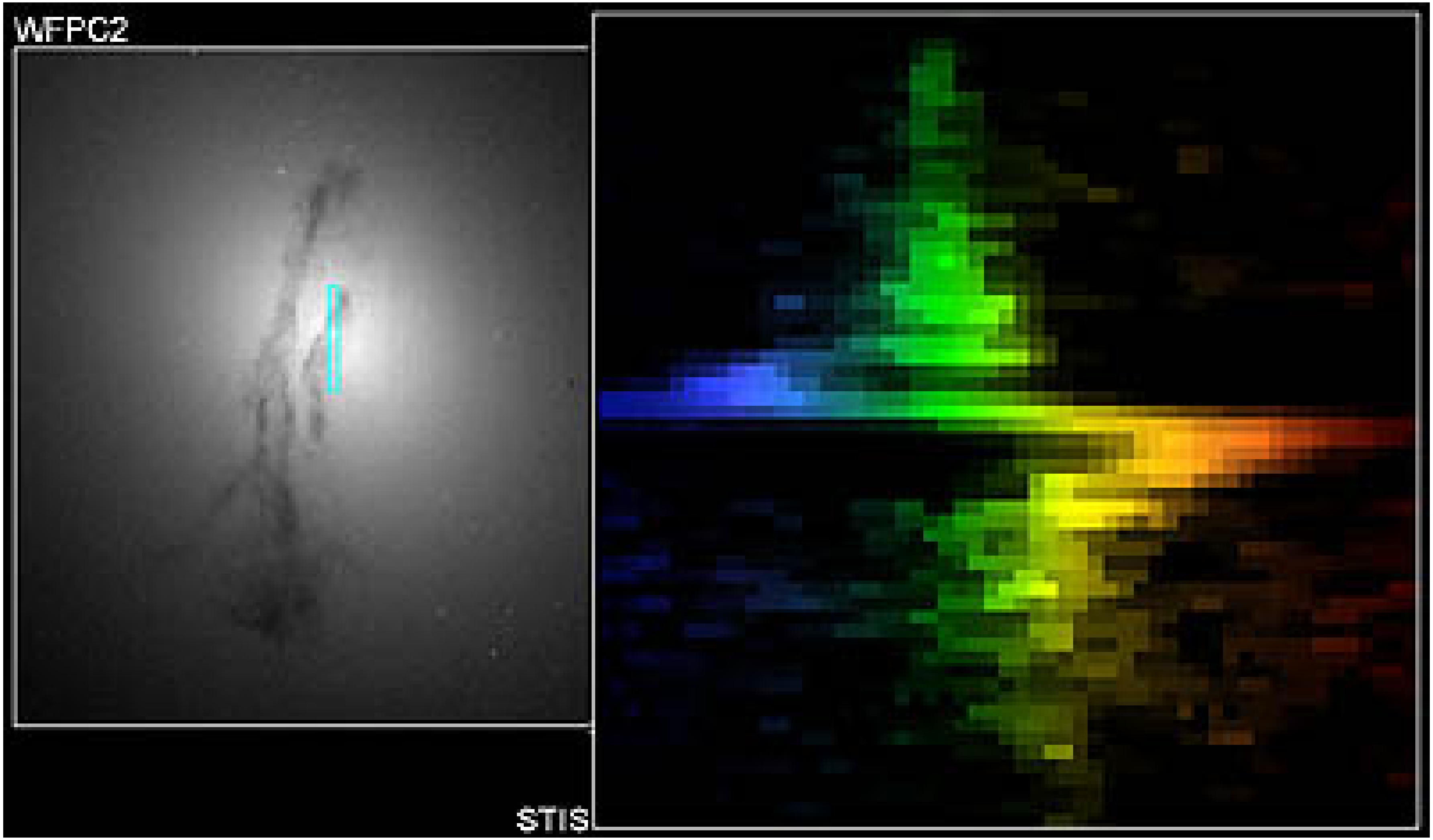
$\Delta t \sim$ (galaxy lifetime)(duty cycle)

$\sim$ (10^{10} years)(1% of galaxies are active) $\sim 10^8$ year

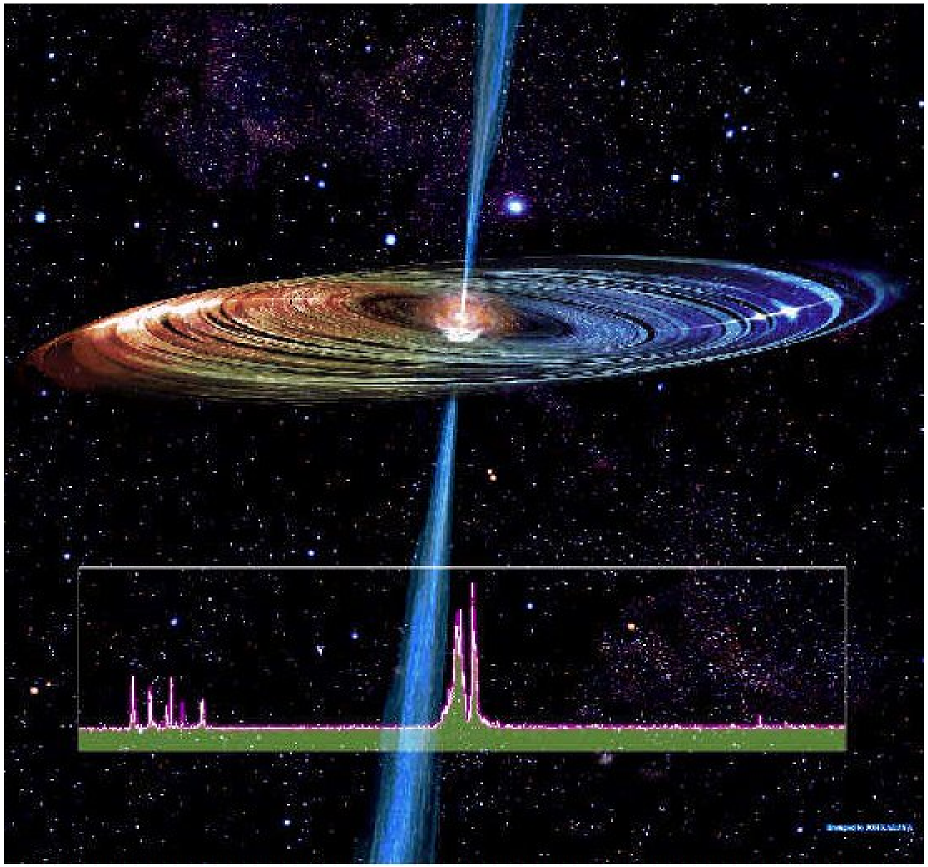
Black Hole Mass

- High luminosity and rapid variability suggest accretion onto black holes
- Estimate mass of black hole:
  - $\eta M c^2 = L \Delta \mathrm{t}$
  - Δt = lifetime – estimate from size and expansion rate of radio lobes ~ 10^8 years
  - $\eta \sim 0.1$, $L \sim 10^{45}$ erg/s
  - Then M ~ 3×10^{40} gm ~ 10^7 $M_\odot$

Mass Determination



Water Maser in NGC 4945



Water maser emission (at 1.3 cm) from radii between 0.14 and 0.29 pc.

Extent is a few milliarcseconds and can be mapped in the radio.

Measured black hole mass is $3.9\times10^{7}\ M_{\odot}$

Masers are also the best direct evidence for accretion disks.

The disks are geometrically thin, but warped.

Temperature of an accreting black hole

- For the spherical object, total luminosity is $L = 4\pi R^2 \sigma T^4$ where T = temperature, R = radius, and σ = Stephan-Boltzman constant = 5.67×10^{-8} W/m^2 ·K^4.

- For a black hole at the Eddington limit $L = 1.3\times10^{38}$ erg/s (M/M_{sun})
- Length scale is set by the Schwarschild radius $r_s = 2GM/c^2$.

- Combining $kM = 4\pi\sigma T^4(2GM/c^2)^2$ thus $T \sim M^{-1/4}$

- For 1 solar mass BH, $T \sim 3\times10^7$ K,
- For 10^6 solar mass BH, $T \sim 1\times10^6$ K.

Growth of an accreting black hole

- The Eddington limit $L = 1.3\times10^{38}$ erg/s (M/M_{sun}) also sets the maximum rate at which matter accretes onto a black hole $(\mathrm{d}M/\mathrm{d}t)_{Edd} = L_{Edd}/c^2$.

- Since $\mathrm{d}M/\mathrm{d}t \sim M$, we have exponential growth. The time scale for the exponential is about 10^8 years.

- Thus, black holes can grow by accretion on cosmologically short time scales.

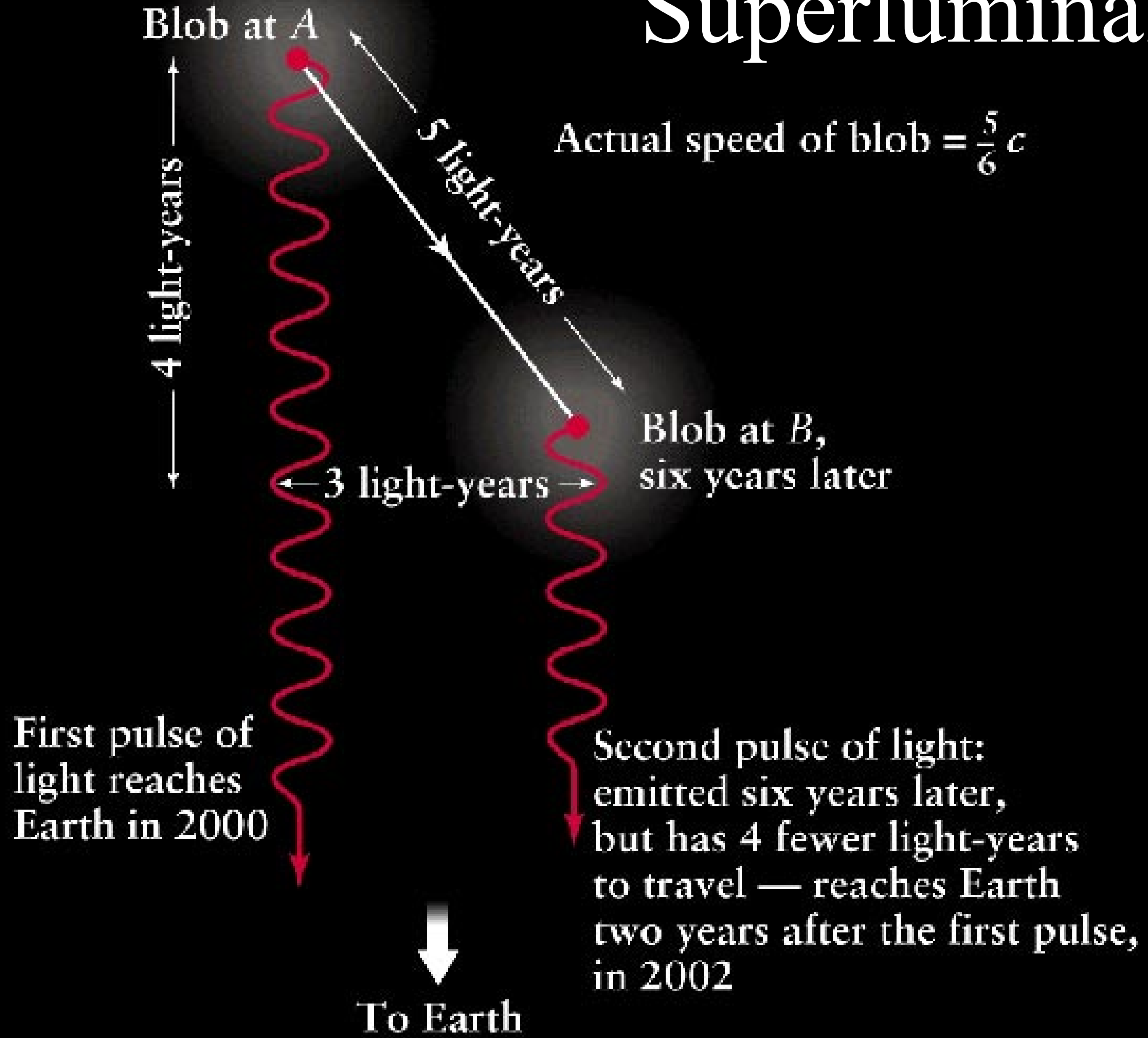
- However, there is a problem with the initial growth if the starting point is a stellar-mass, ~10 solar mass, black hole. Since to go from 10 to 10^6 solar masses requires ~ 10^9 years.

AGN Accrete from the ISM

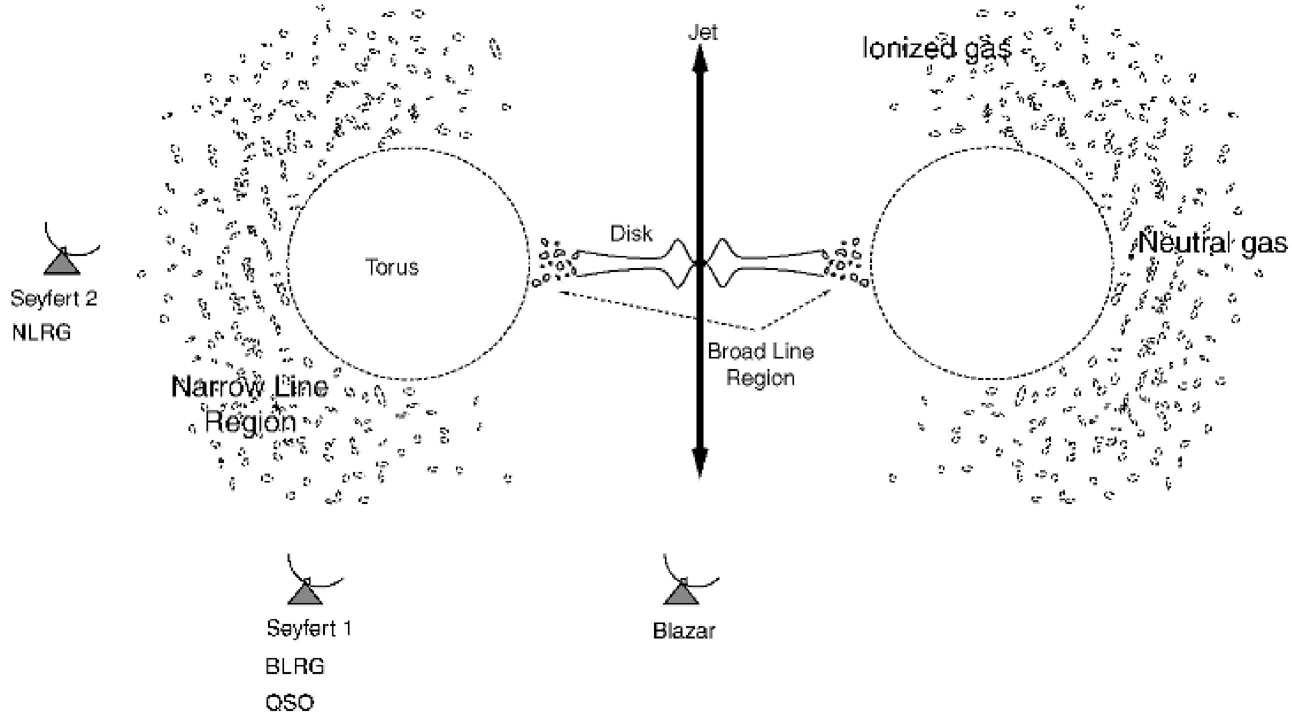
- Via Bondi accretion

$$\dot{M} \simeq \left(1.4\times10^{11}\,\mathrm{g/s}\right)\left(\frac{M}{M_{\Theta}}\right)^{2}\left(\frac{\rho}{10^{-24}\,\mathrm{g/cm^{3}}}\right)\left(\frac{c_{s}}{10\,\mathrm{km/s}}\right)^{-3}$$

Superluminal motion

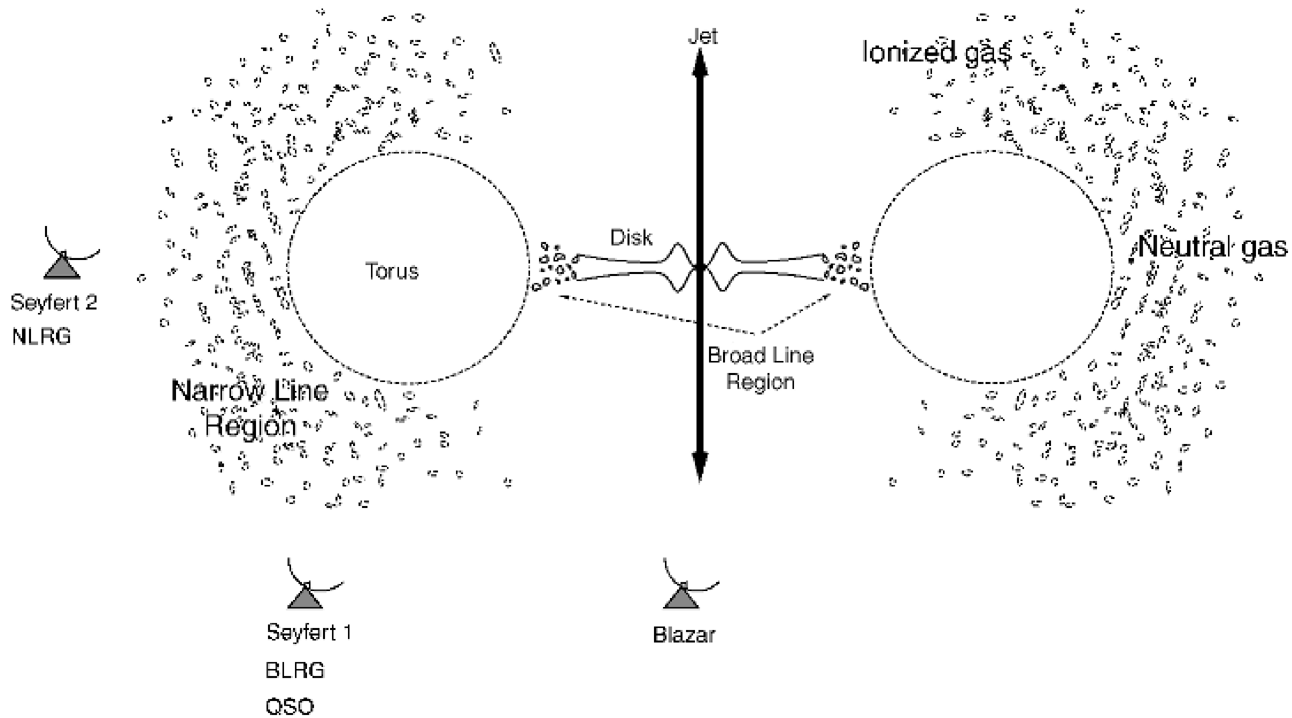


Geometry of an AGN



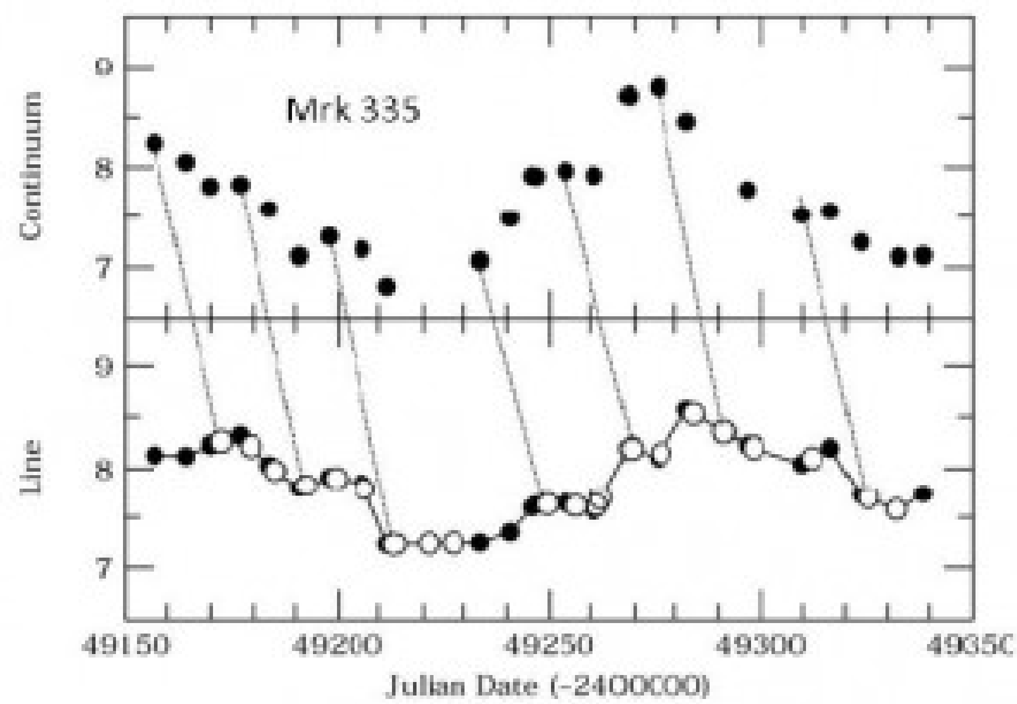
- Black hole at center
- Accretion disk produces thermal emission peaked in the UV - "big blue bump"
  - Big blue bump is not directly detectable due to strong absorption from 13 to 200 eV.
- Accretion also produces X-ray emission with typical spectrum $S_\nu \sim \nu^{-0.7}$.
  - X-rays may arise from a spherical corona above the disk, a thin corona above the disk (either would be powered by magnetic reconnection in the disk) or a separate accretion flow.
- Powerful UV and X-radiation ionized surrounding gas.

Broad line region



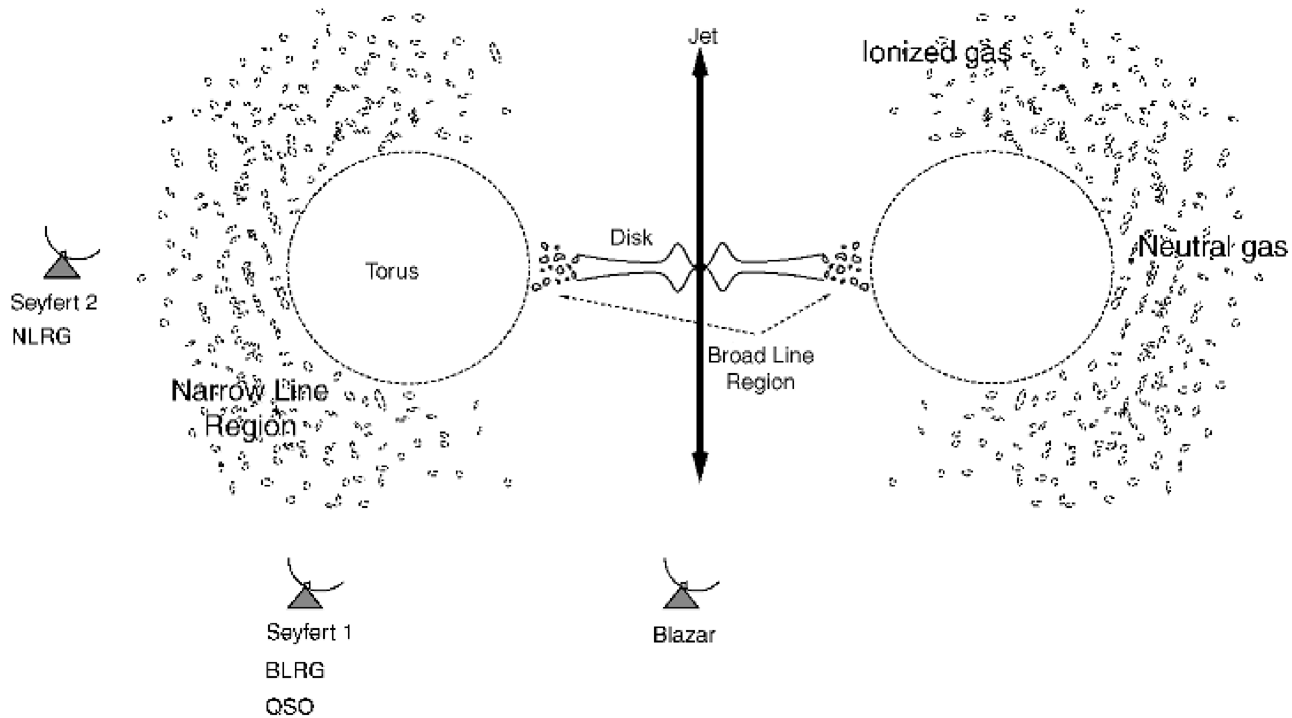
- Emission lines produced when atoms are ionized by X/UV from compact object.
- Ionization parameter $\Xi = L/r^2$, higher closer in, so more highly ionized atoms closer in.
- Line widths indicate speeds up to 10,000 km/s.
- If gravitational, indicated BLR at $r \sim 500\ r_S$.
- From line diagnostics, BLR has $T \sim 20{,}000$ K, density $\sim 10^9$ cm^{-3}, filling factor $\sim 10^{-7}$.

Reverberation mapping



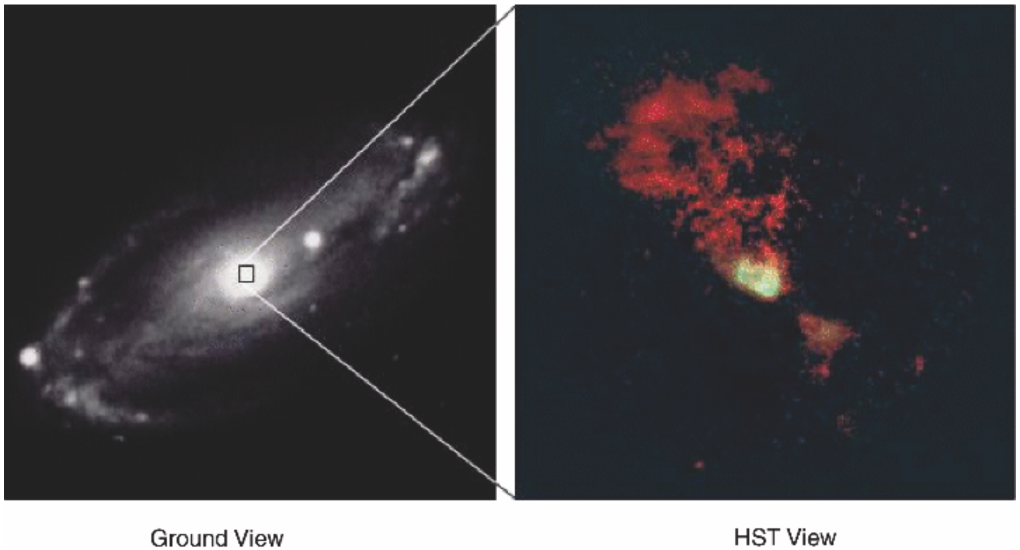
- Variations in X/UV from compact object will produce variations in line strength.
- For line produced at radius *r*, response will be delayed by $\Delta t \sim r/c$.
- By continually monitoring continuum and line strength, then looking for correlated changes, one can measure Δt and then calculate *r*.
- Provides constraints on size of BLR.
- Also provides estimate of BH mass, $M \sim r\sigma^2/G$.

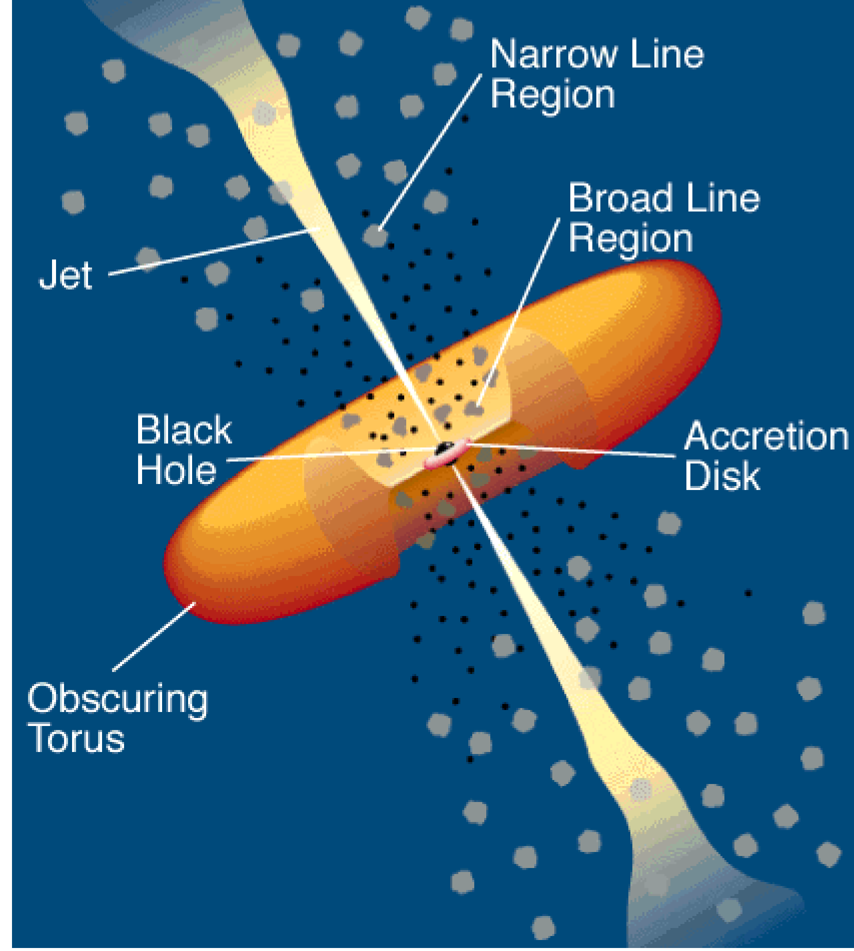
Torus



- To understand the range of AGN, a structure that blocks some lines of sight to the accretion disk is needed.
- The torus contains dust and is geometrically thick.

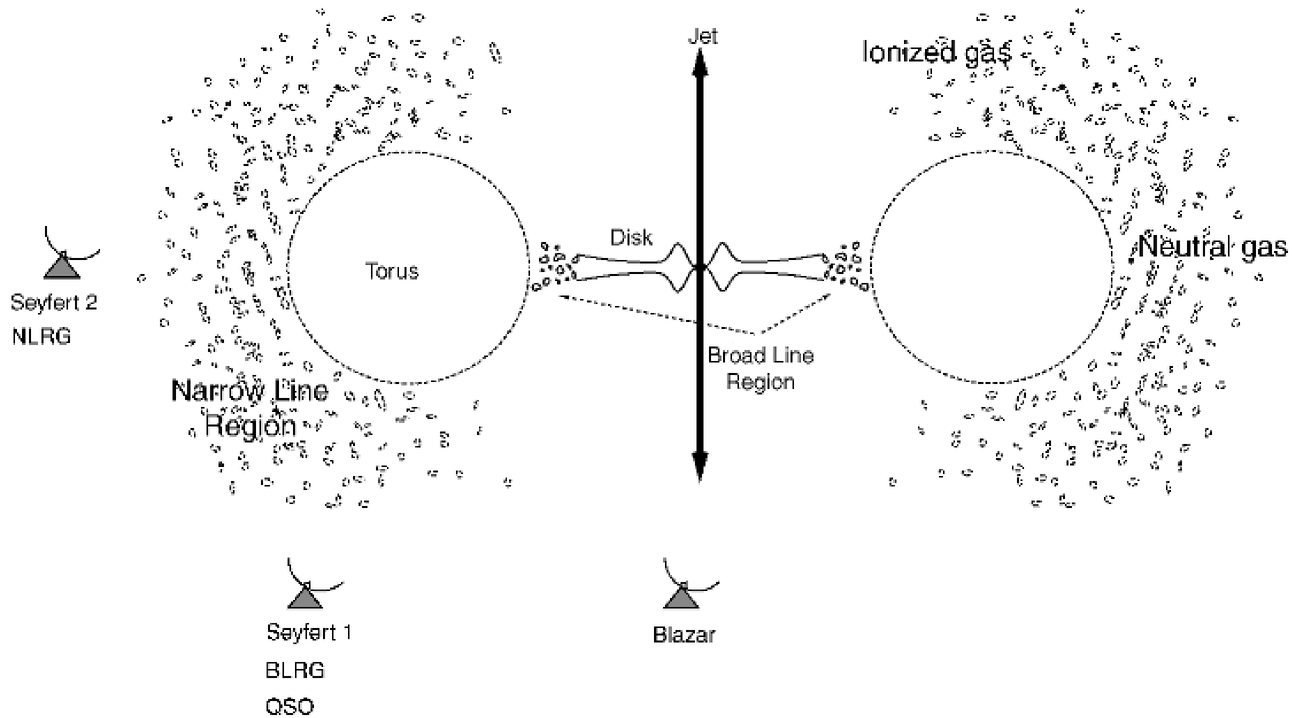
Narrow line region





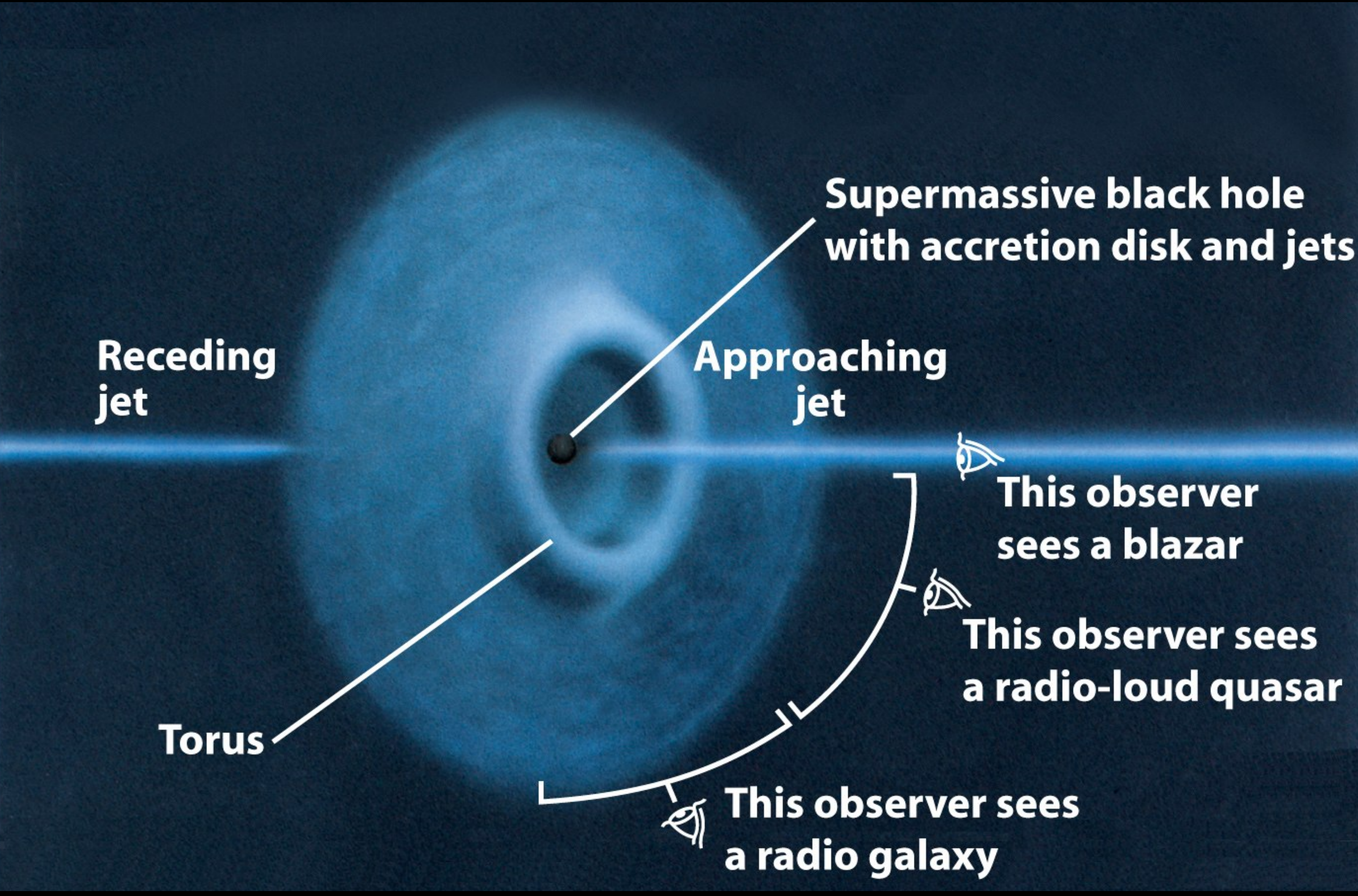
- Narrow line region consists of gas clouds farther away from the BH, thus with lower velocities and lower ionization levels.
- Also ionized by X/UV from accretion disk.
- Distances ~ 100 pc.
- NLR has T ~ 16,000 K, density ~ 10^3 cm^{-3}, and filling factor ~ 0.01.

Unified model

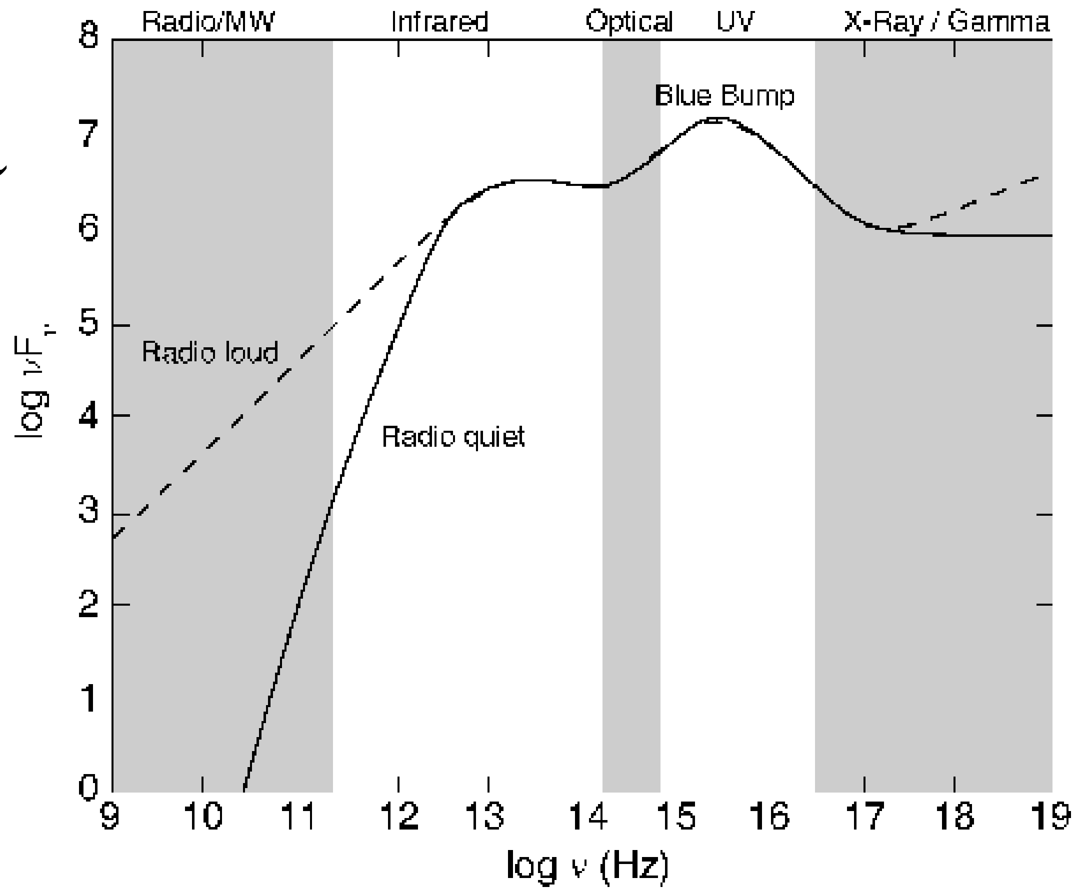


- Differing properties of different types of AGN can be understood as a viewing angle effect.
- For blazars, our line of sight is close to the jet axis and the radiation we see is dominated by the jet.
- For Seyfert 1's, we the disk, BLR, NLR
- For Seyfert 2's, the disk and BLR are blocked by the torus.
- NGC 1068 is a Seyfert 2, but shows BLR in polarized = scattered light

Orientation

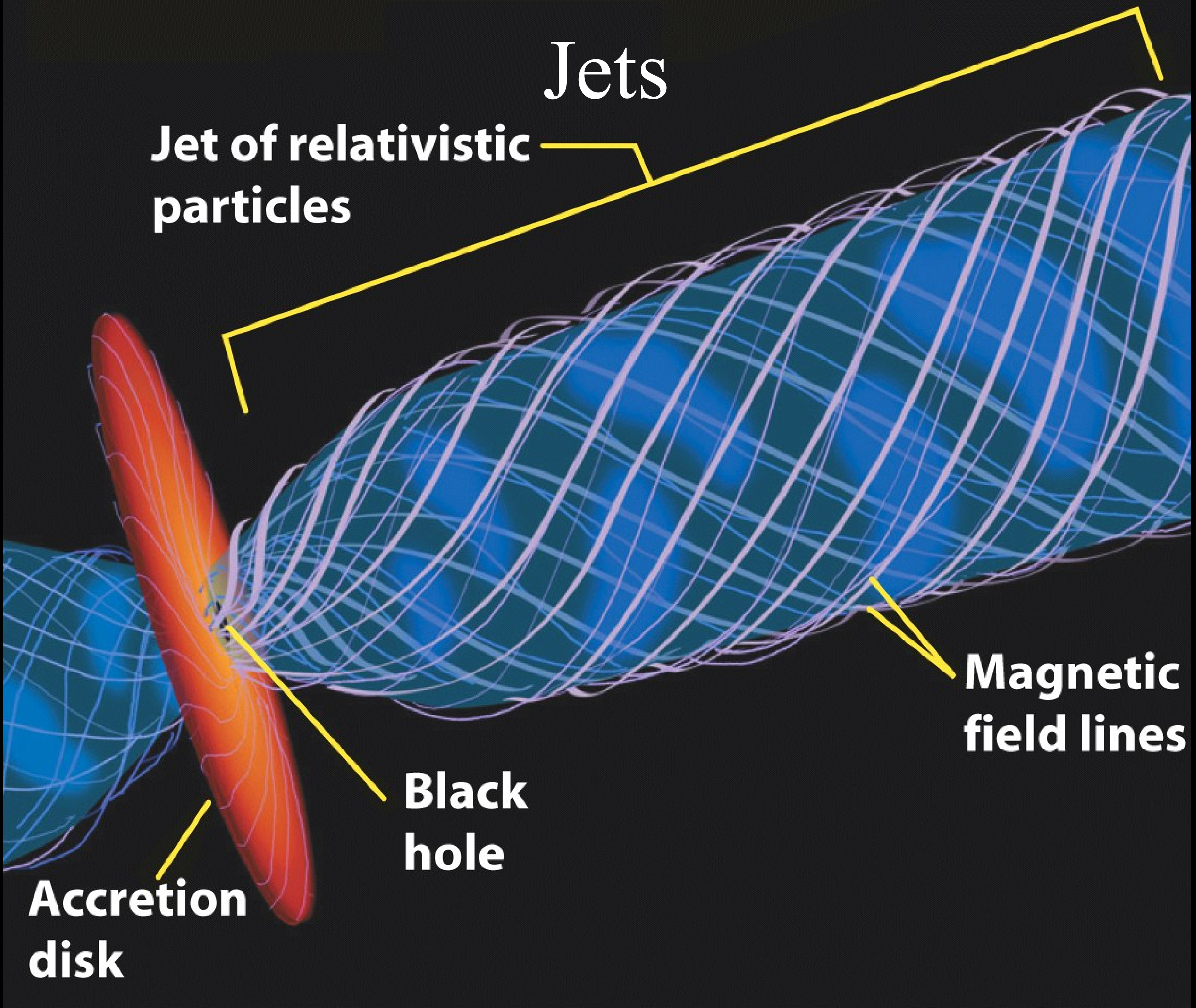


AGN spectra



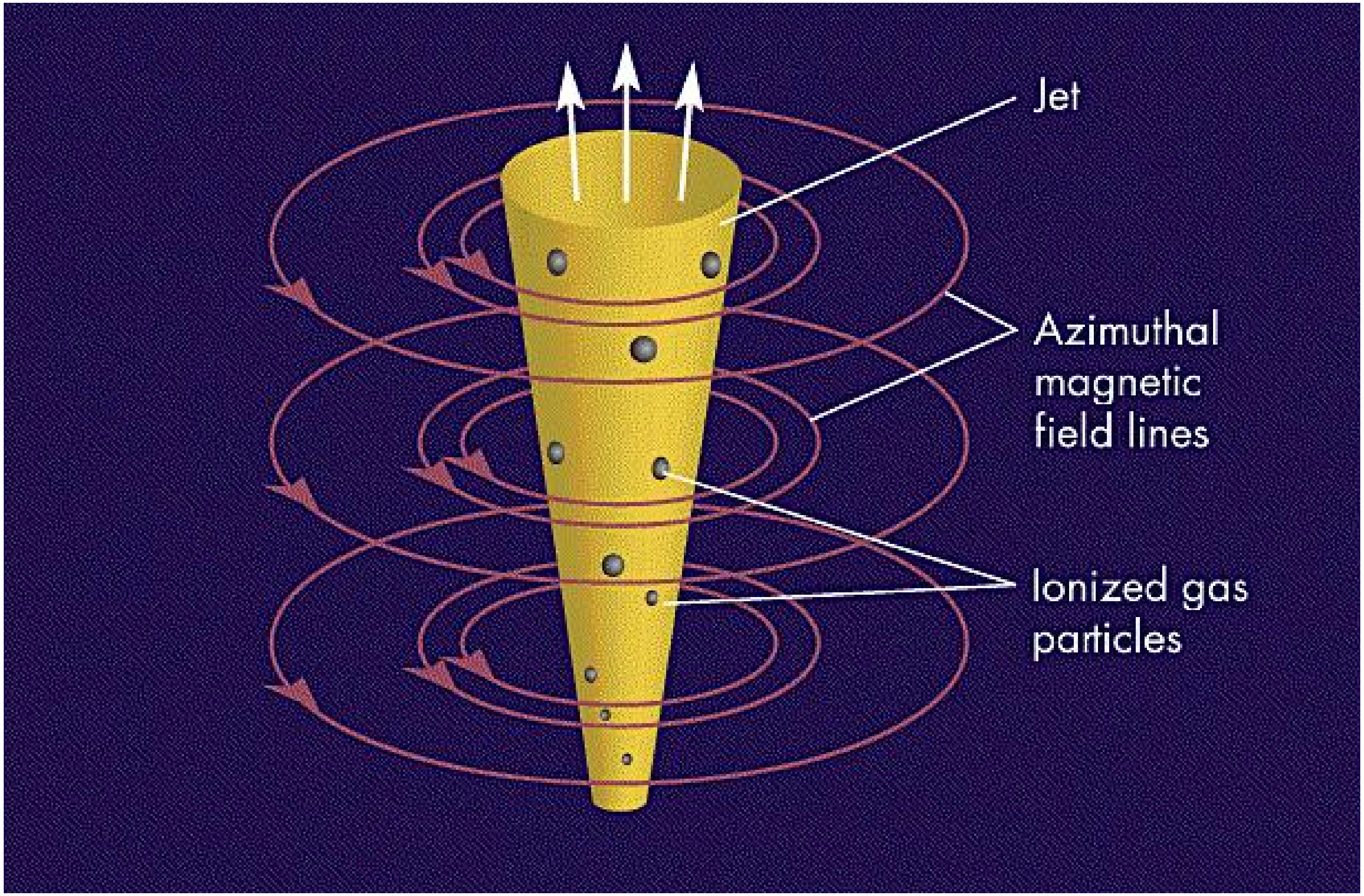
- Low frequency emission is synchrotron emission from relativistic electrons in the jet.
- High frequency emission is inverse-Compton on relativistic electrons in the jet.
- X-rays can come from jet or accretion flow.
- Blue bump is accretion disk emission.
- IR bump is from dust – the torus.

Jets



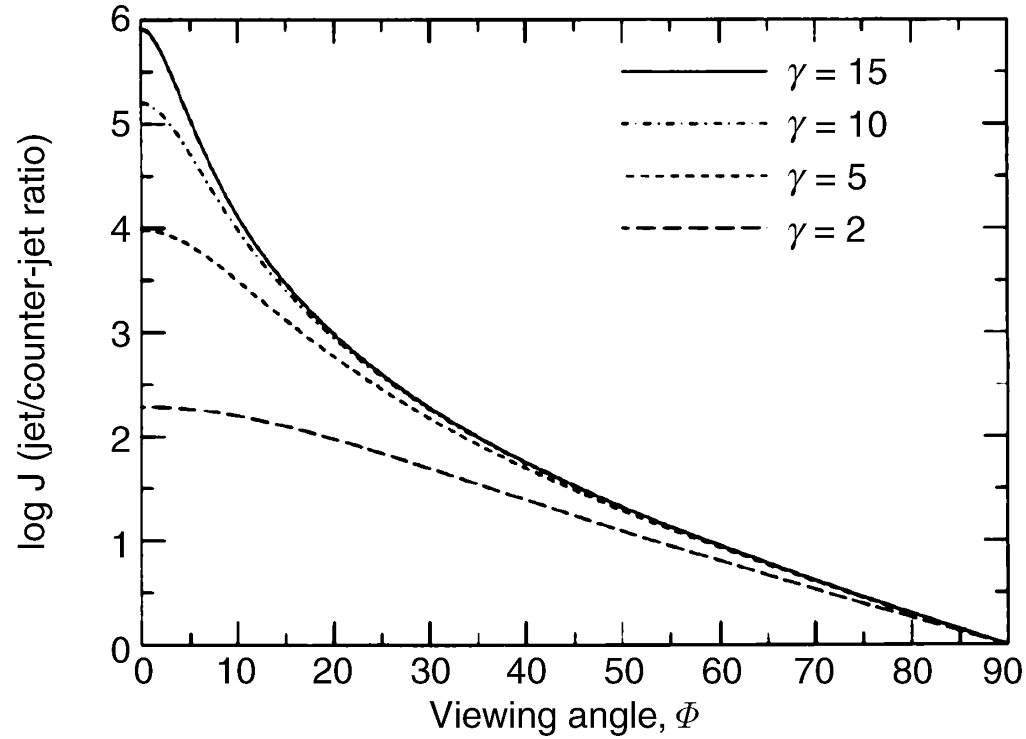
Jet of relativistic particles
Magnetic field lines
Black hole
Accretion disk

Collimation of a jet



Production of jets is not well understood and is a major topic in current research.

Relativistic beaming

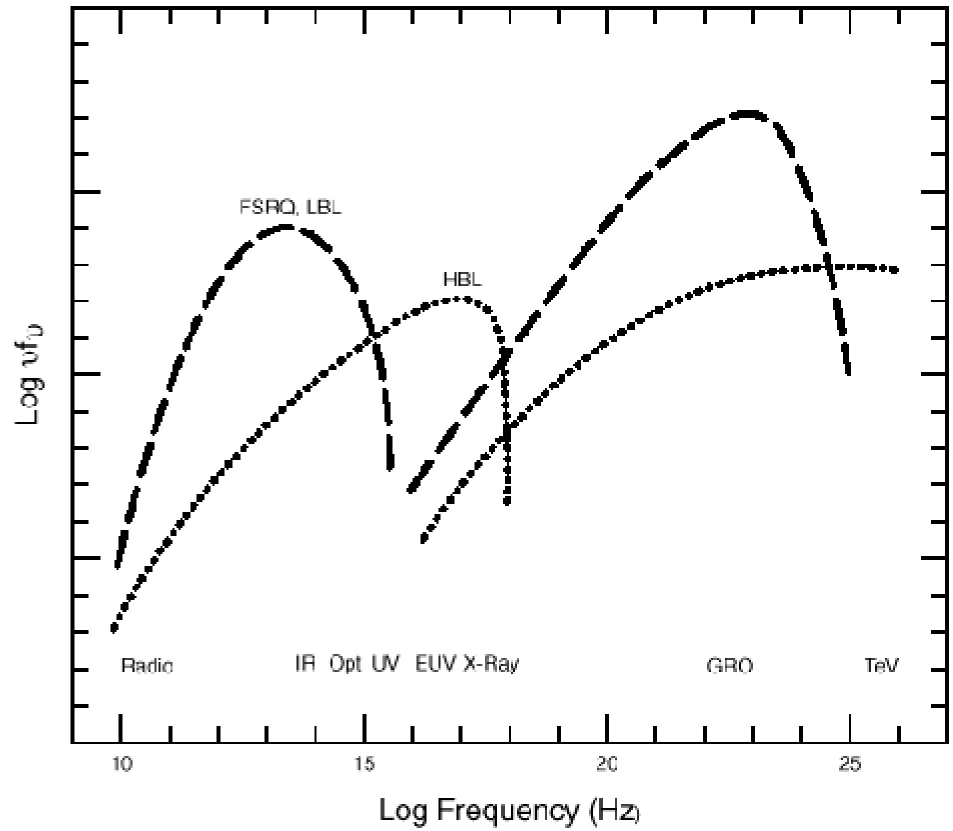


- Doppler boost for approaching jet: $$D_a = \left(\frac{1}{\gamma\left(1-\beta\cos\varphi\right)} \right)^{2+\alpha}$$

- Note that the boost depends on the spectral slope since the observed wavelength is Doppler shifted relative to the emitted wavelength.

- Doppler boosting makes approaching jet (often) much brighter than receding jet.

Blazar spectra

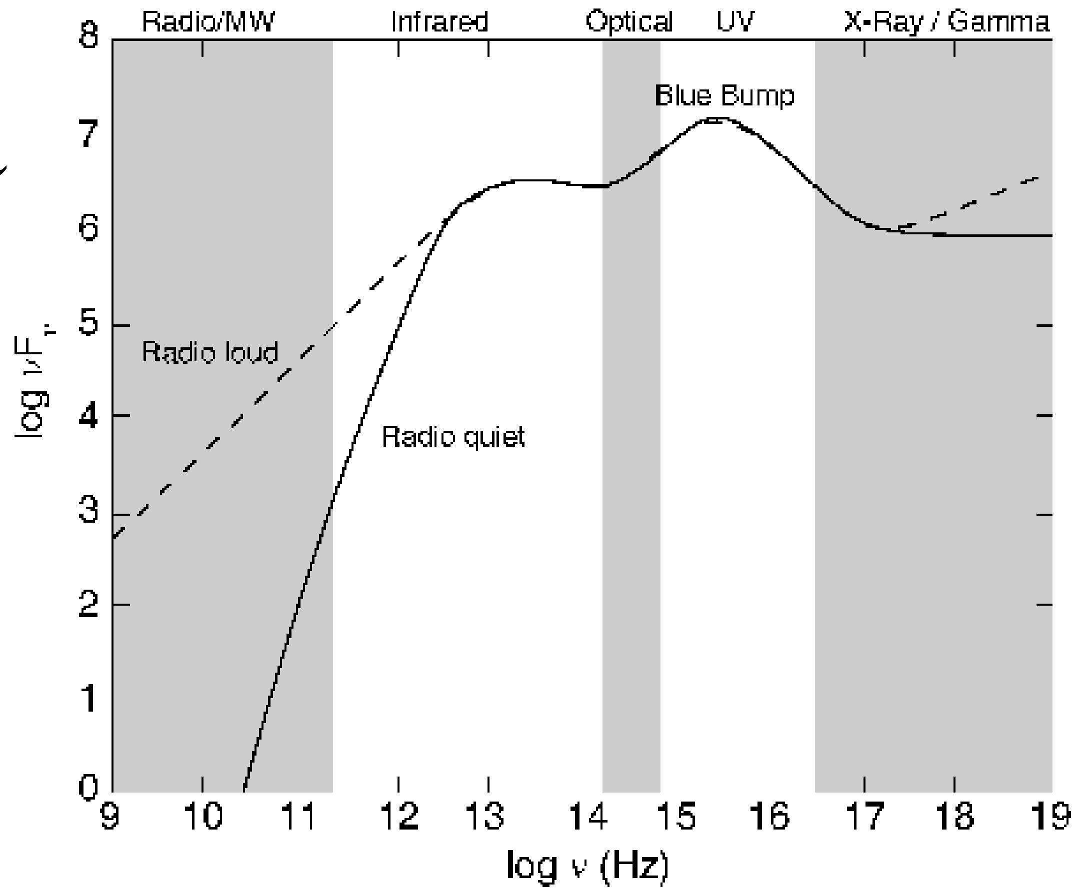


• Low frequency peak is due to synchrotron emission from relativistic electrons.

• High frequency peak is due to inverse-Compton scattering of photons by the same electrons.

• Photons can come from external sources (accretion disk, BLR, torus) thus "external Compton" or from the synchrotron emission "synchrotron self Compton".

AGN spectra



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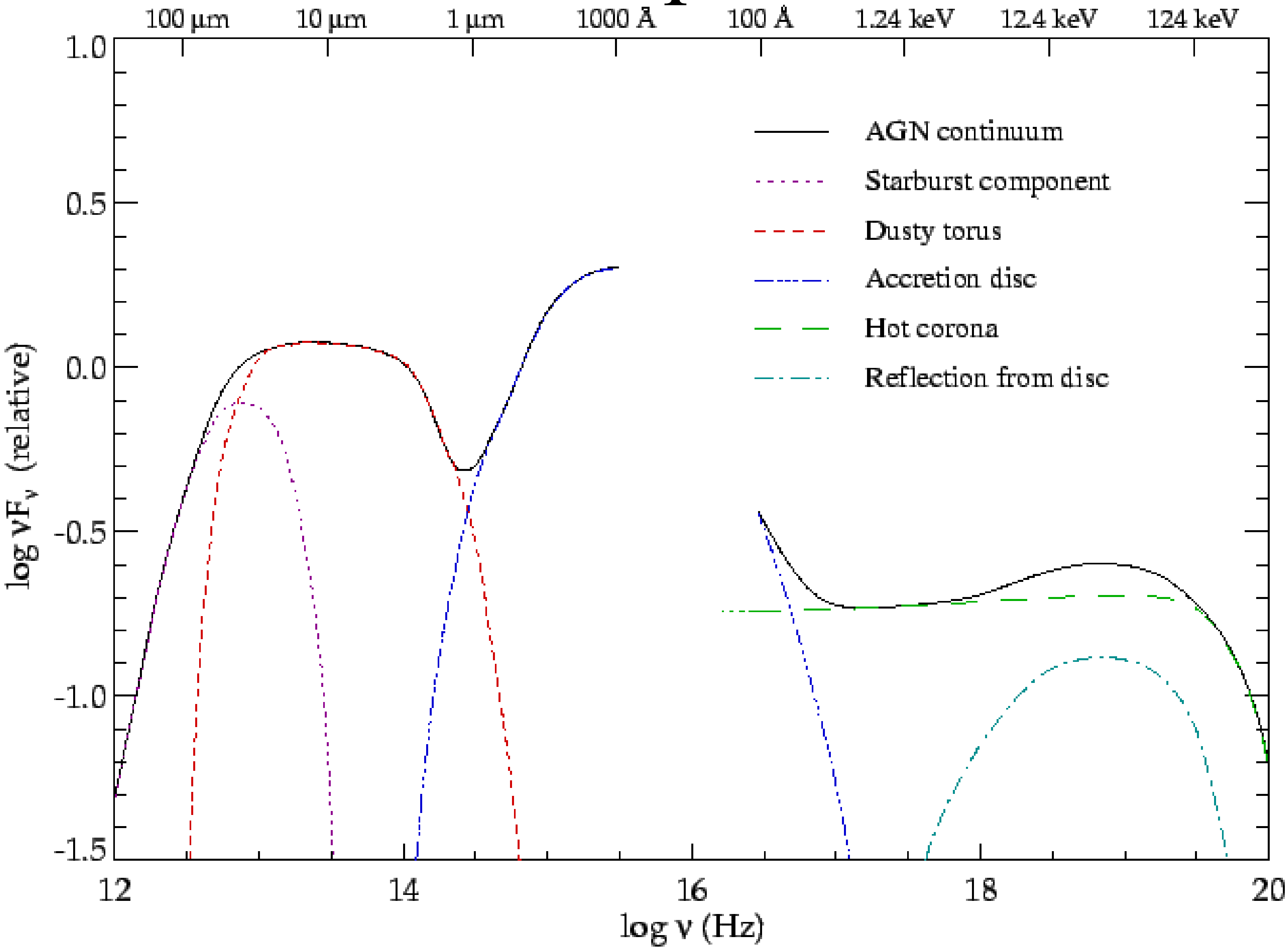
AGN Spectra



100 μm
10 μm
1 μm
1000 Å
100 Å
1.24 keV
12.4 keV
124 keV
1.0
0.5
0.0
-0.5
-1.0
-1.5
log νF$_ν$ (relative)
12
14
16
18
20
log ν (Hz)
AGN continuum
Starburst component
Dusty torus
Accretion disc
Hot corona
Reflection from disc