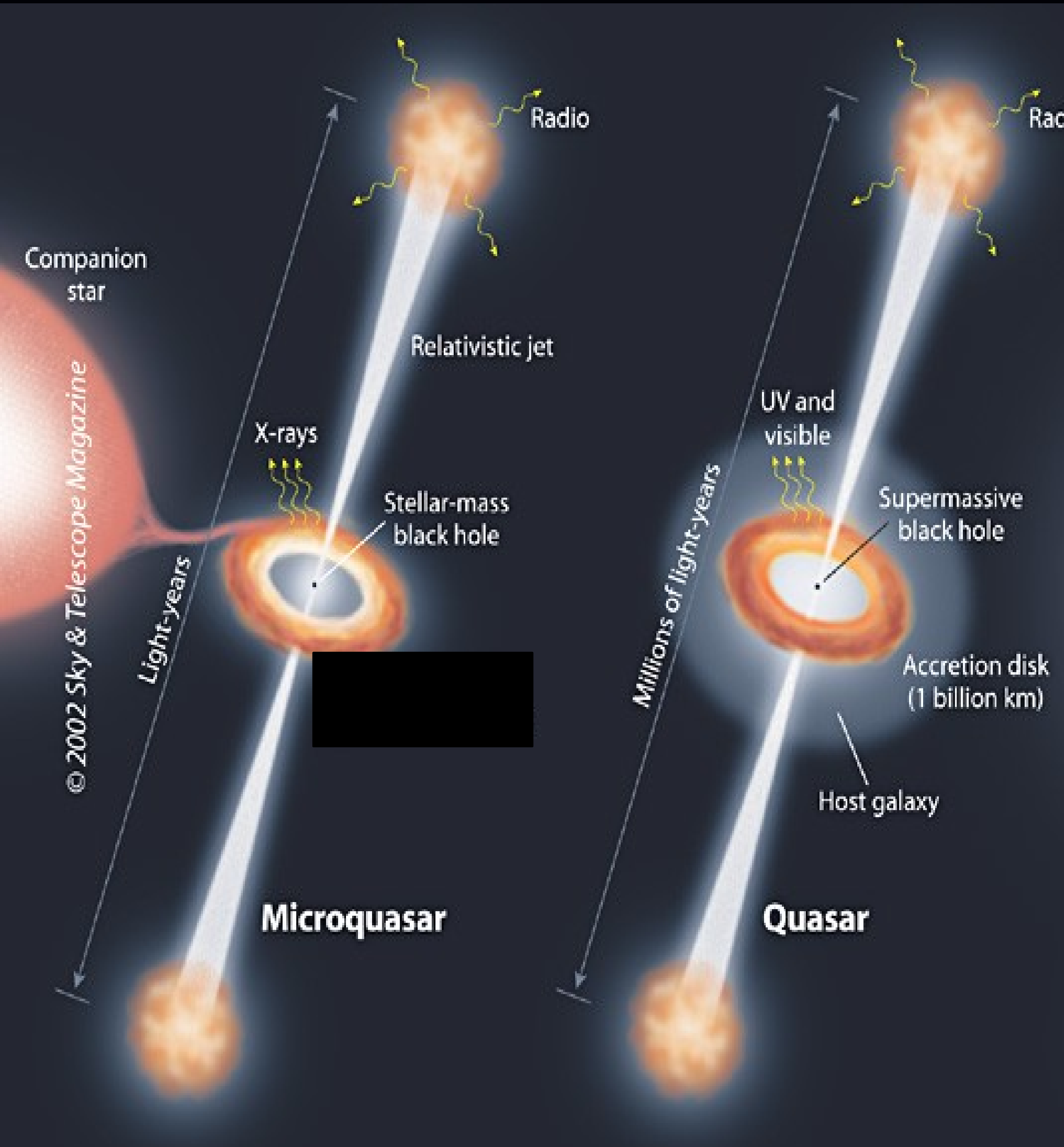
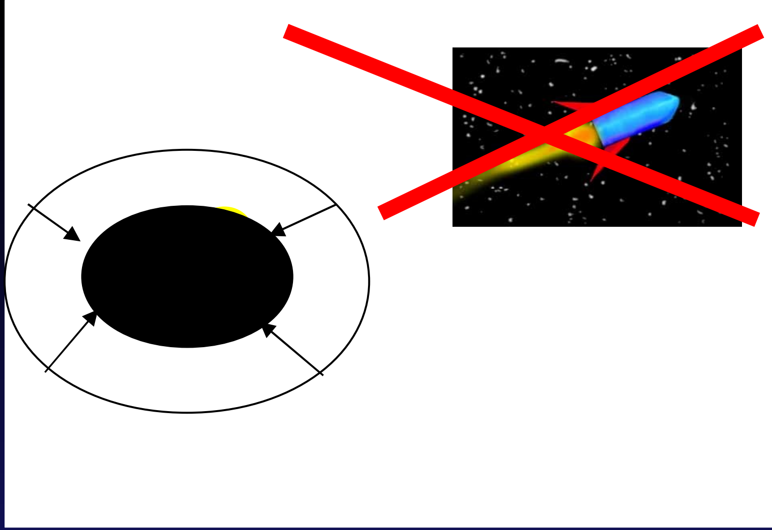


Radio
Companion
star
Relativistic jet
X-rays
Stellar-mass
black hole
Light-years
[redacted]
Microquasar
© 2002 Sky & Telescope Magazine
UV and
visible
Supermassive
black hole
Millions of light-years
Accretion disk
(1 billion km)
Host galaxy
Quasar

Schwarzchild Radius



The radius where

escape speed = the speed of light.

$$R_s = 2\ GM/c^2$$

R_s = 3 x M (R$_s$ in km; M in solar masses)

<u>A sphere of radius R_s around the black hole is called the **event horizon**.</u>

Object	Mass (solar)	Black Hole Event Horizon
Star	10	30 km
Star	3	9 km

General Relativity: Orbits around BHs

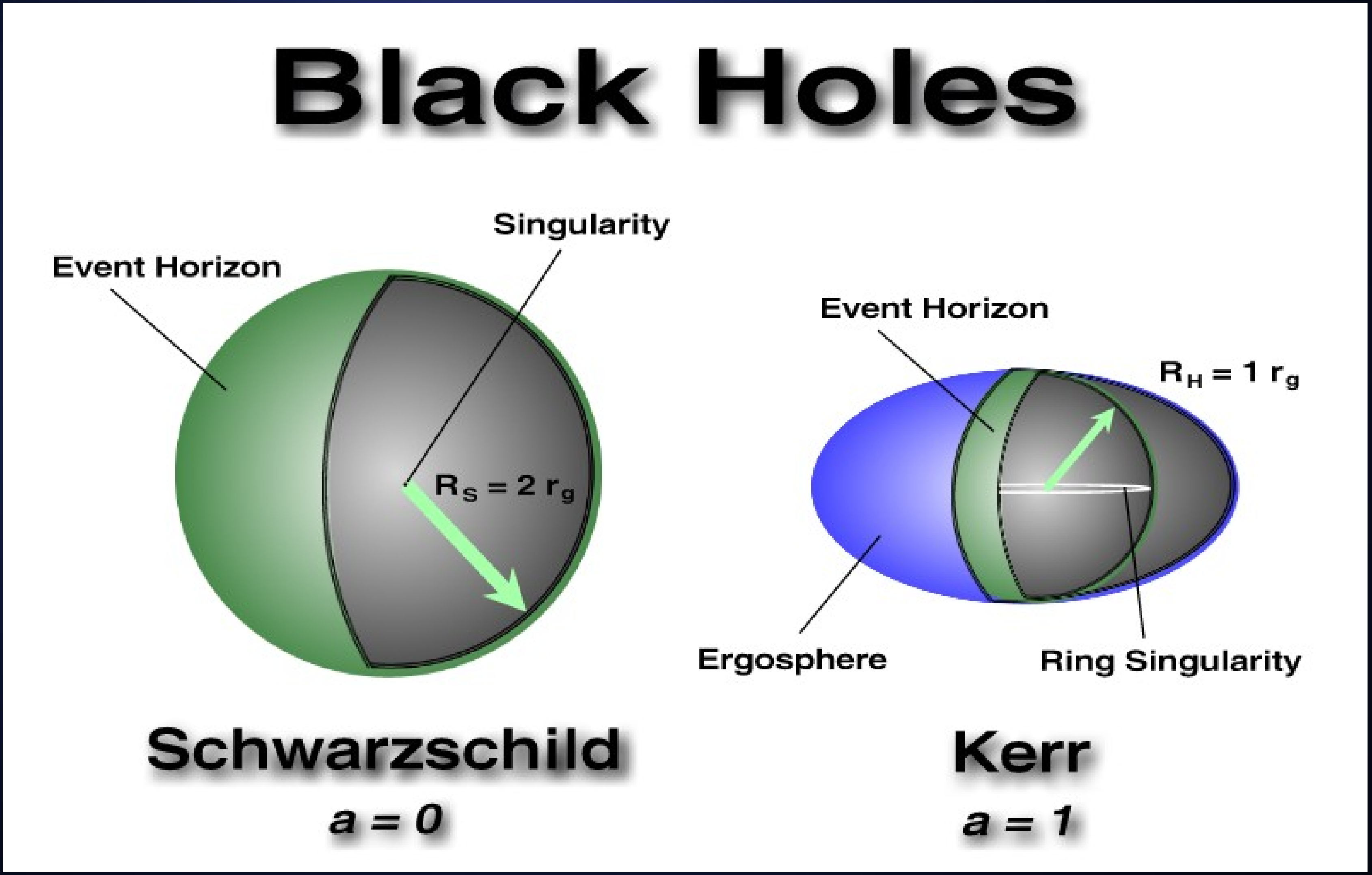
Schwarzchild BH: an innermost stable orbit at $\boldsymbol{R_{ms}}=3R_s$

KERR BH: 1) presence of a static limit, inside of which one must co-rotate with the BH

2) The horizon moves further inward the faster the BH spins. This implies ***Rms*** also move inward.

Efficiency: The amount of binding energy that is extracted from infalling matter goes up from <0.06 to ~0.42 m(c^2)

black holes – schwarzschild vs. kerr



$$\boxed{F_{rad} < F_{grav}}$$

$$\boxed{\sigma_T \frac{L}{4\pi\ r^2 c} < \frac{GM_{\bullet} m_p}{r^2}}$$

$$\boxed{L < L_{edd} = \frac{4\pi c G M_{\bullet} m_p}{\sigma_T} \approx 1.3 \times 10^{38} \left(\frac{M_{\bullet}}{M_{sol}} \right) erg / s}$$

If the disc radiates like a Blackbody

$$L_E = T^4 4\pi\ r^2\ \sigma_{Stefan\text{-}Boltzmann}$$

We assume as „r“ the last stable orbit around the black hole

$$T = 2 \times 10^7\ M^{-1/4}\ K$$

	M (solar masses)	T (K)	λ (Angstrom)	
Microquasar	3	1.5 10^7	2	X-ray
AGN	10^9	10^5	300	uv

3.1 The Nature of the Compact Object

The most reliable method to determine the nature of the compact object is the study of the Doppler shift of absorption lines in the spectrum of its companion. The study of the changing radial velocity during the orbital motion is a technique that has been applied for more than one hundred years to measure the masses of stars in binary-systems. The same method is applied for systems like X-ray binaries, where one component is "invisible". In this case the variations of the radial velocity of the normal companion during its orbit are studied.

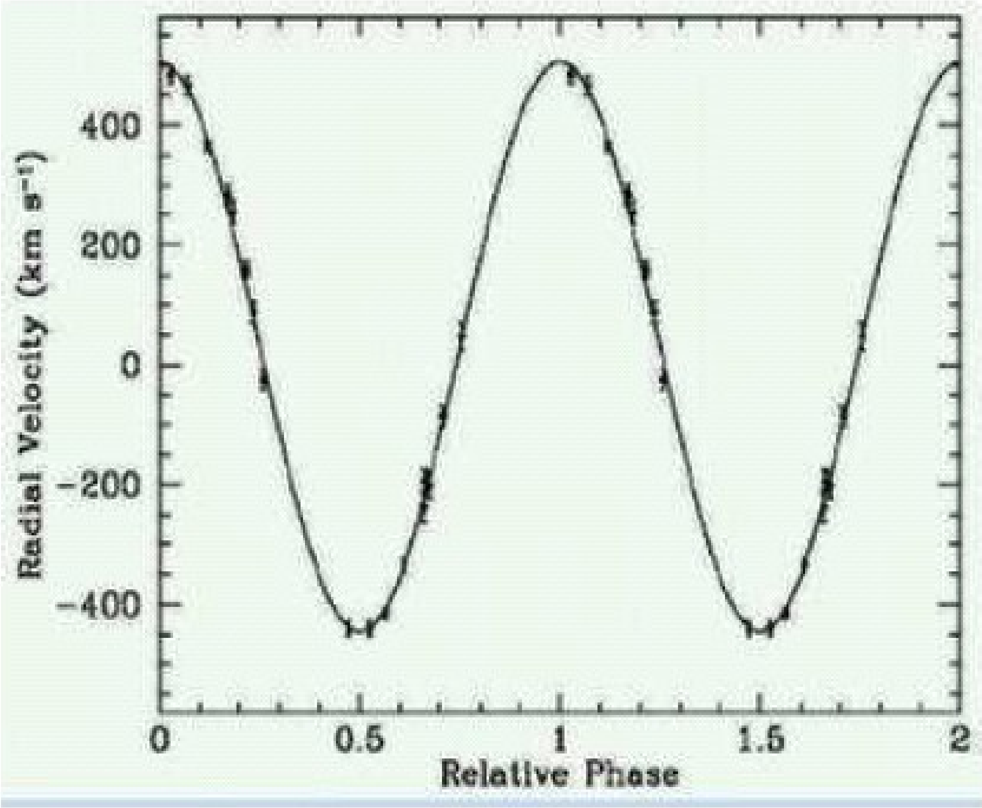
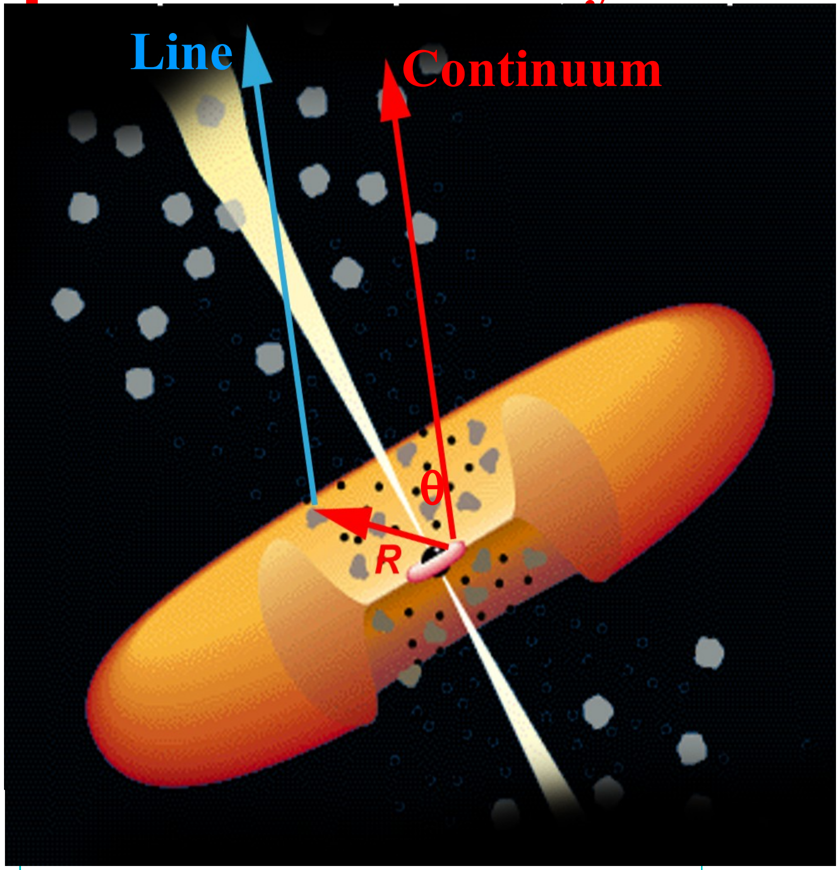


Figure 6: : **Amplitude of the radial velocity variations versus orbital** phase(Filippenko et.al. 1999; GRS 1009-45). Using the Doppler shift of spectral

Reverberation mapping from optical variability

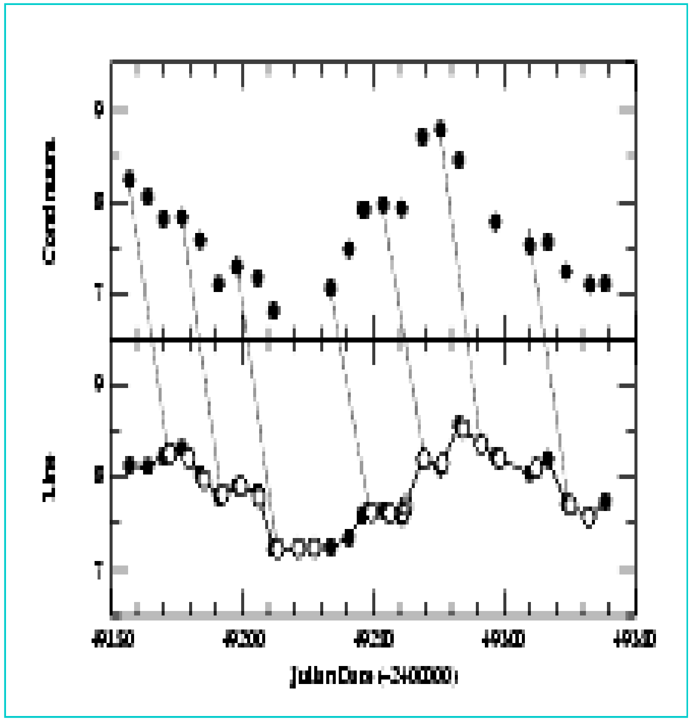
- **Broad emission line region: 0.01 - 1pc; Illuminated by the AGN's photoionizing continuum radiation and reprocess it into emission lines**
- **R_{BLR} estimated by the time delay that corresponds to the light travel time between the continuum source and the line-emitting gas: $R_{BLR} = c\,\Delta t$**



Reverberation mapping from optical variability

- **Broad emission line region: 0.01 - 1pc; Illuminated by the AGN's photoionizing continuum radiation and reprocess it into emission lines**
- **R_{BLR} estimated by the time delay that corresponds to the light travel time between the continuum source and the line-emitting gas:** $R_{BLR} = c\,\Delta t$
- ***V* estimated by the FWHM of broad emission line**

Peterson (1997)



$$V = f\ \mathrm{FWHM(H\beta)},\quad f = \sqrt{3}/2 \text{ for random distribution of BLR clouds}$$

$$\longrightarrow M_*$$

Central AGN Mass

Using R_{BLR} the central mass is:

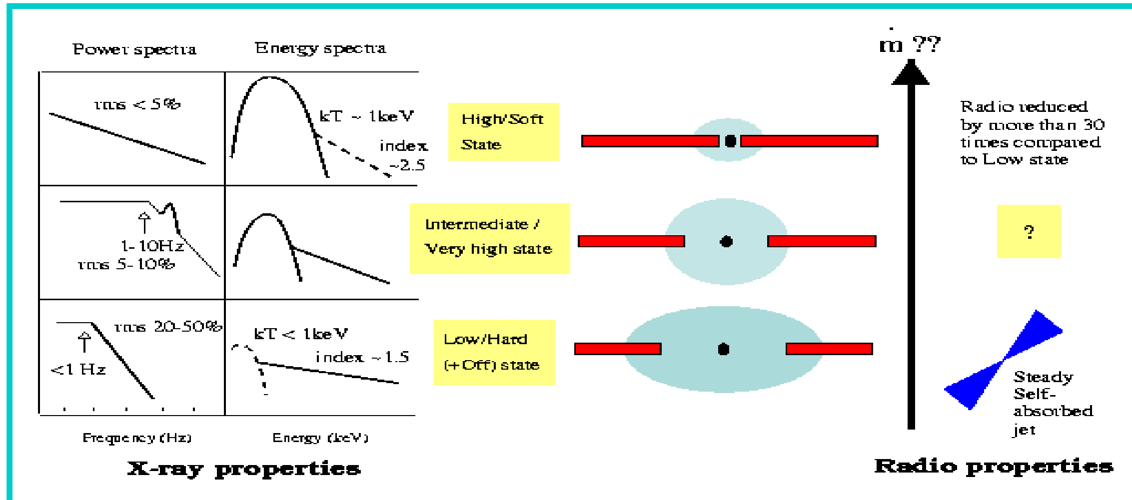
$$M = \frac{fR_{BLR}V^2}{G}$$

V is the BLR clouds velocity (either from FWHM or σ_{LINE})

f is a dimensionless factor that depends on the geometry and kinematics of the BLR.

Quiescent State:

- \- Large transient radius;
- \- very low luminosity, L_x~$10^{30.5}$-$10^{33.5}$ erg/s ;
- \- power law spectrum photon index Γ=1.5~2.1;
- \- Jet is thought to be exist



Hard State:

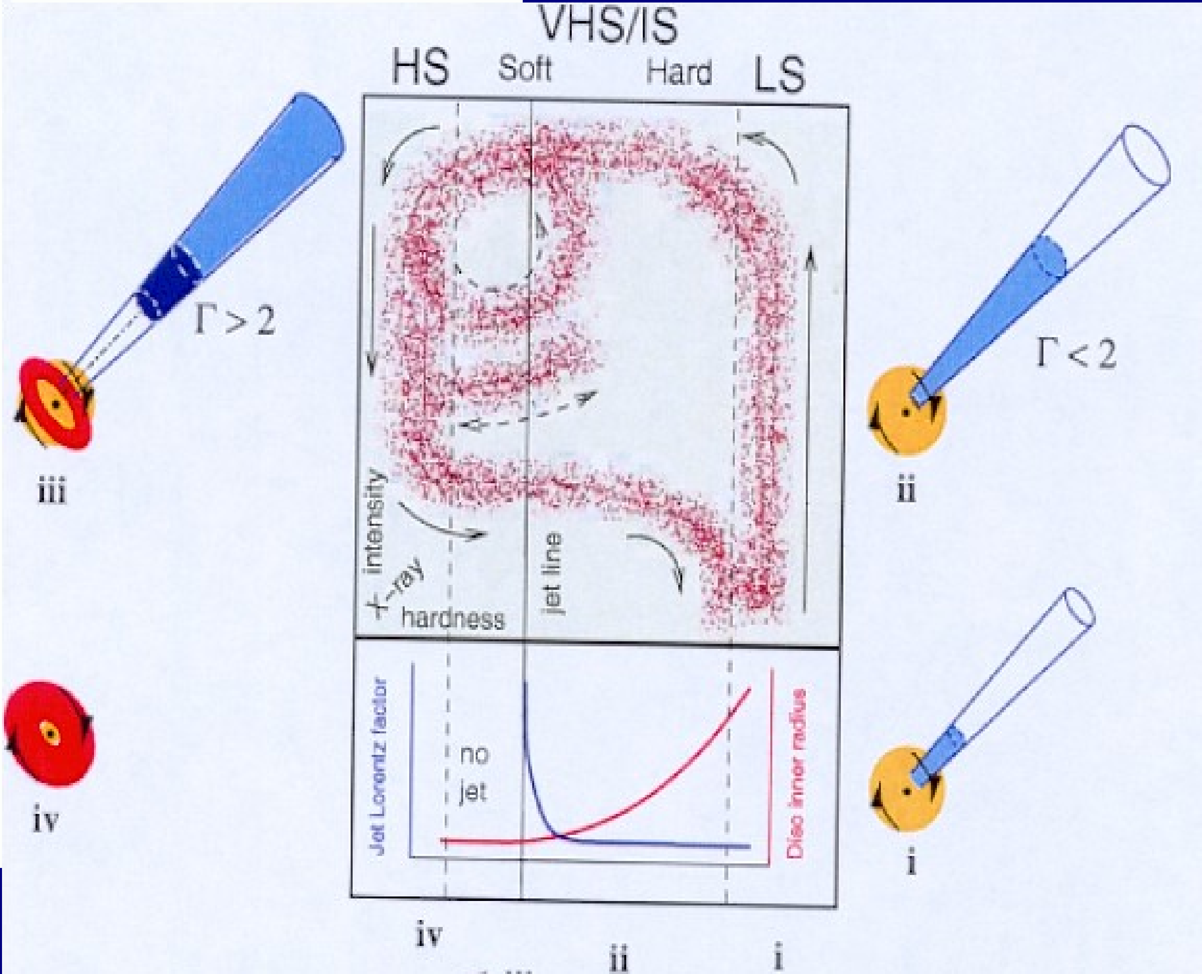
- \- power law spectrum >80% (2-20keV)
- \- power law spectrum photon index Γ=1.4~2.1
- \- strong varibility (QPO)
- \- strong radio emission (Jet exist)

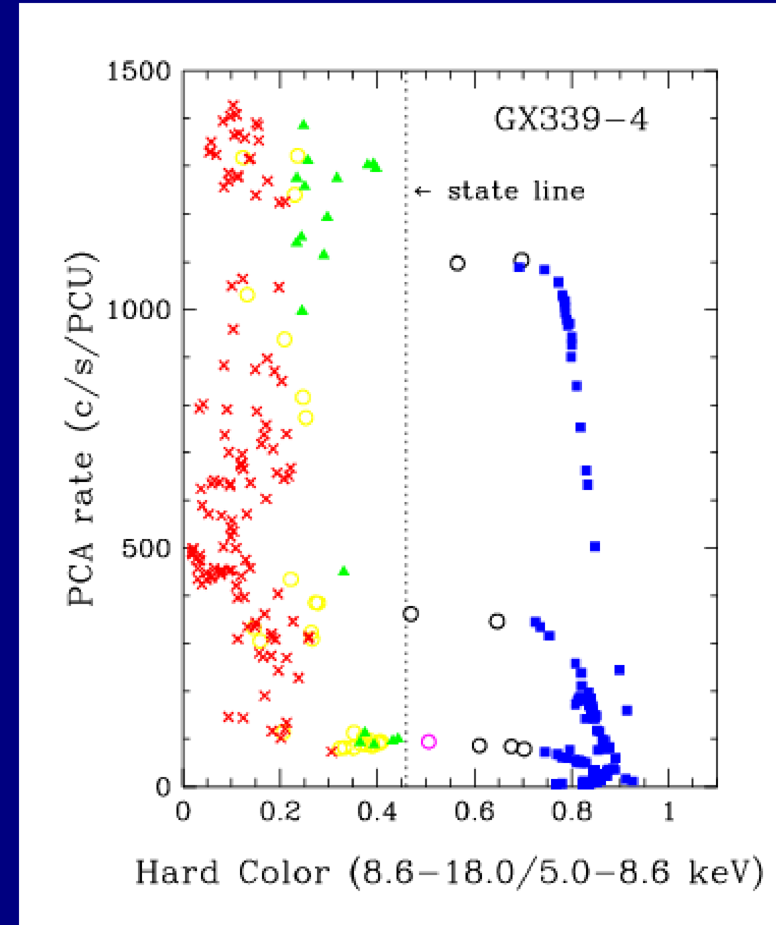
SPL/Very High State/Intermediate State :

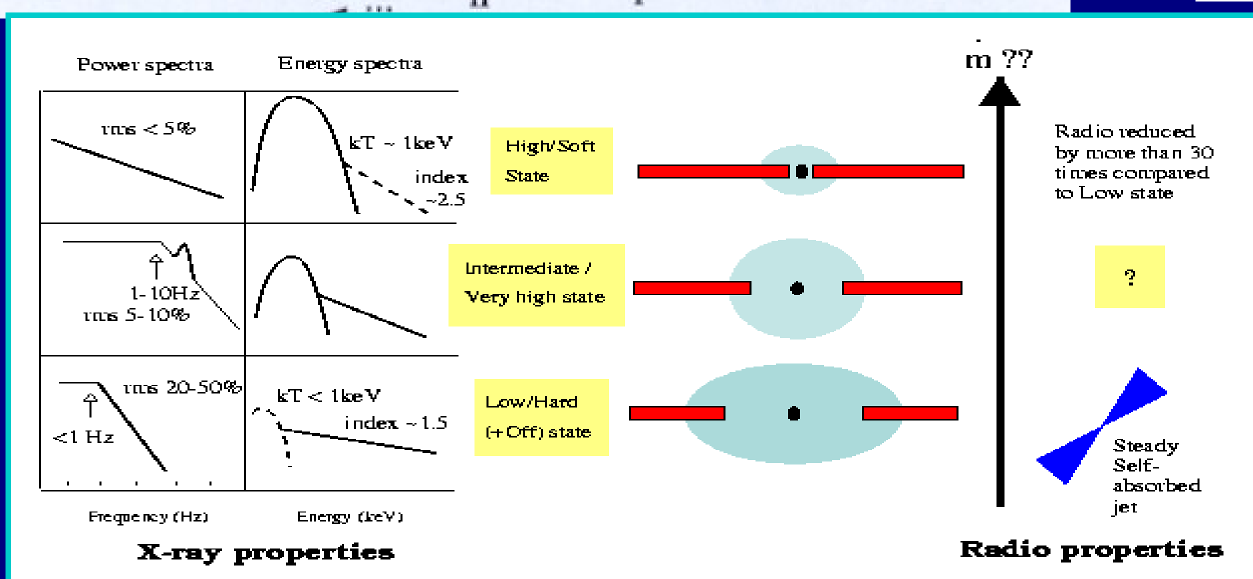
- \- power law spectrum photon index Γ>2.4
- \- power law component>20% (2-20keV)and QPO
- \- power law component>50% (2-20keV) and no QPO
- \- radio flare at HS–>VHS

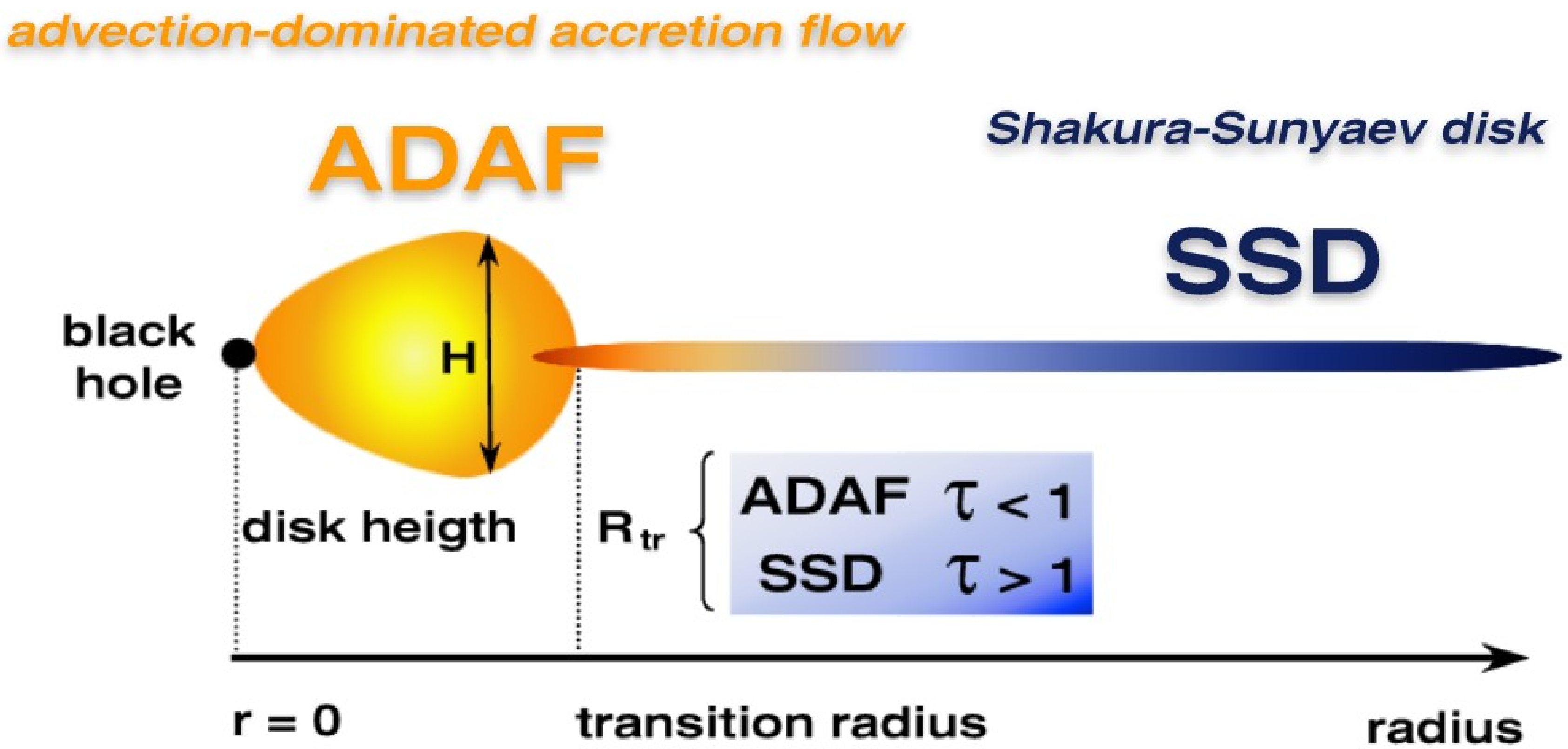
High Soft State (Thermal Dominant State):

- \- disk component>75%(2-20keV)
- \- no QPO or QPO is toot weak to be detected
- \- very weak radio emission and no Jet exist
- \- power law spectrum photon index Γ=2.1~4.8


VHS/IS
HS
Soft
Hard
LS
Γ > 2
Γ < 2
iii
ii
i
iv
X-ray intensity
hardness
jet line
no jet
Jet Lorentz factor
Disc inner radius
iv
ii
i


GX339−4
← state line
PCA rate (c/s/PCU)
Hard Color (8.6−18.0/5.0−8.6 keV)
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1


Power spectra
Energy spectra
rms < 5%
kT ~ 1keV
index ~2.5
High/Soft State
1-10Hz
rms 5-10%
Intermediate / Very high state
rms 20-50%
<1 Hz
kT < 1keV
index ~1.5
Low/Hard (+Off) state
Frequency (Hz)
Energy (keV)
X-ray properties
ṁ ??
Radio reduced by more than 30 times compared to Low state
?
Steady Self-absorbed jet
Radio properties



gracia et al., mnras 344, 468, 2003

Atoll and Z Sources -- CCD

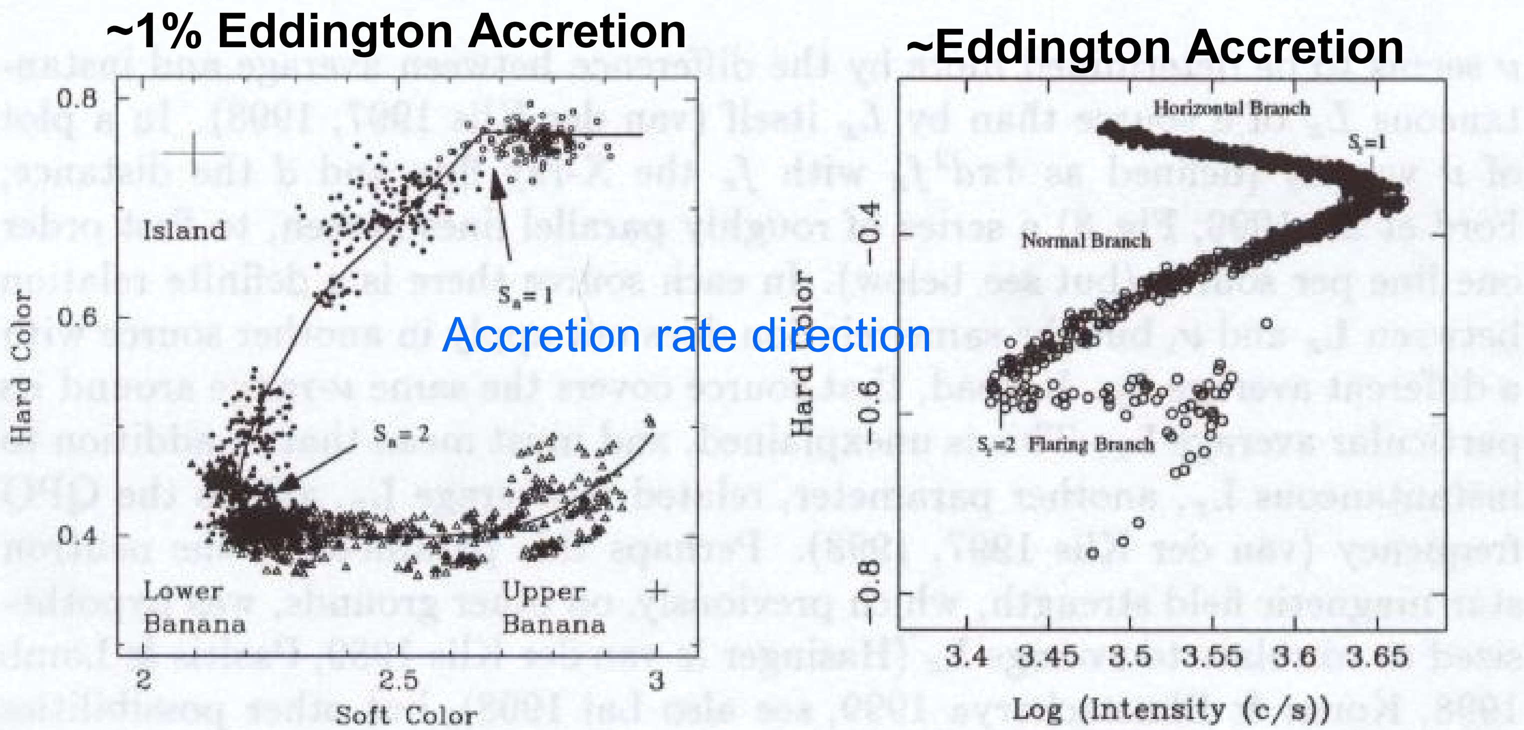


Figure 7: Left: X-ray color-color diagram of the atoll source 4U 1608−52. (Méndez et al. 1999) Right: X-ray hardness vs. intensity diagram of the Z source GX 340+0. (after Jonker et al. 1999c) Values of curve-length parameters S_z and S_a and conventional branch names are indicated. Mass accretion rate is inferred to increase in the sense of increasing S_a and S_z. X-ray color is the log of a count rate ratio (3.5–6.4/2.0–3.5 and 9.7–16.0/6.4–9.7 keV for soft and hard color respectively); intensity is in the 2–16 keV band. kHz QPO detections are indicated with filled symbols.

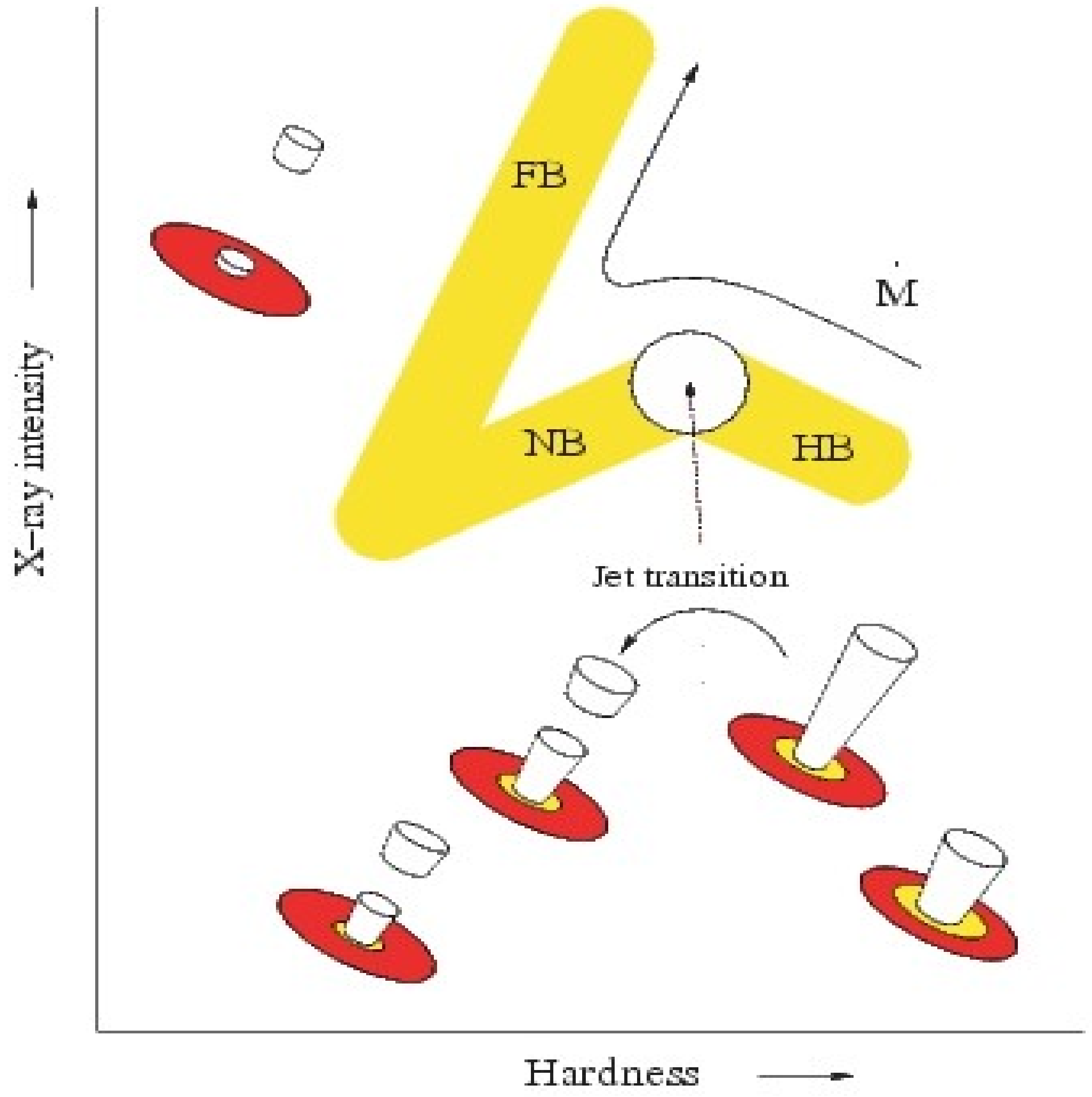
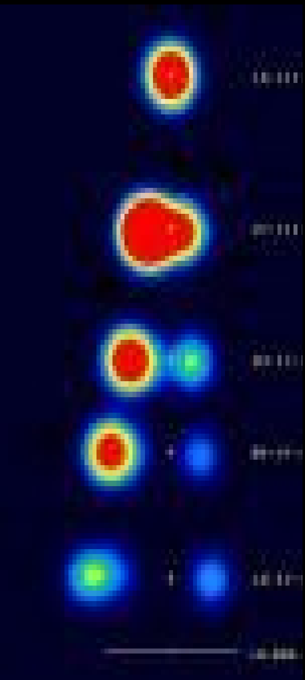


Figure 6. Sketch of the disc–jet coupling in Z-type sources, which we believe to be the NS equivalents of the BH GRS 1915+105, constantly accreting at approximately Eddington rates and producing powerful jets associated with rapid state transitions. See Section 4.5 for a discussion.



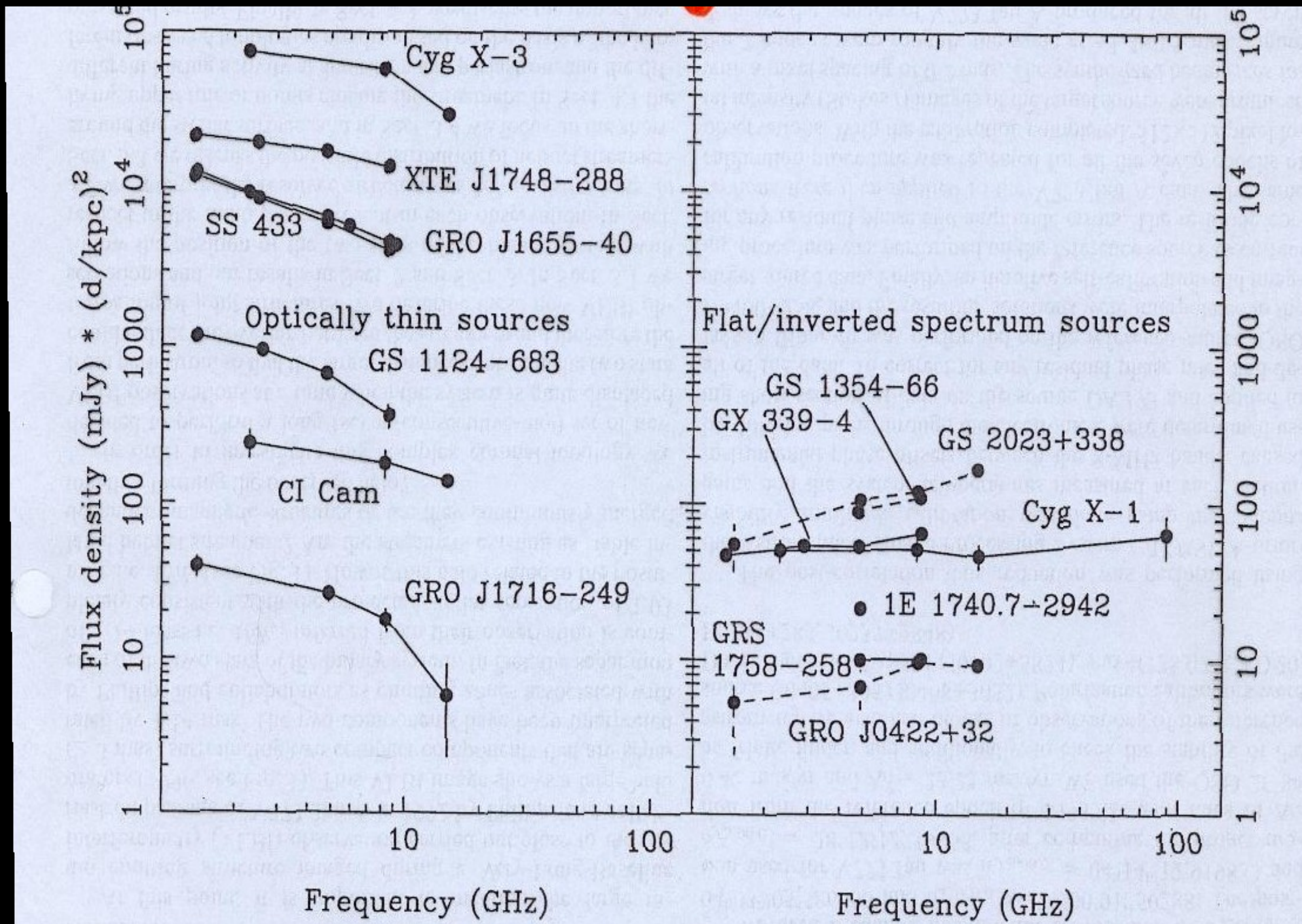
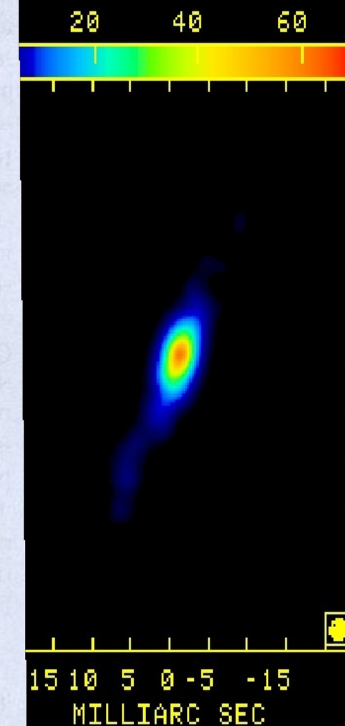


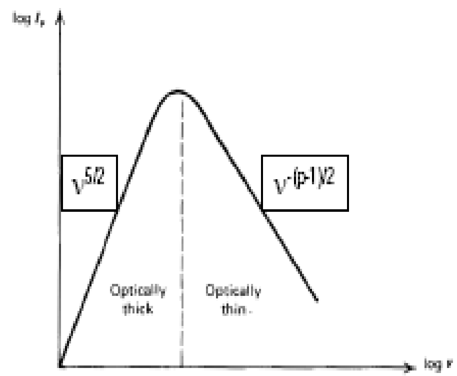
Figure 4. Optically thin (i.e. spectral index $\alpha < 0$) radio spectra from several radio-bright X-ray binaries which were *not* in the Low/Hard X-ray state at the time of the observations, compared with the flat/inverted spectra of the seven sources in Figs 1 & 4 (for the transients, the later, ie. most inverted, spectra are plotted). As well as the different spectral indices (the optically thin sources all have $-1 \leq \alpha \leq -0.2$, the source in the Low/Hard state all have $0.0 \leq \alpha \leq 0.6$), note also the much wider range of fluxes observed from optically thin emission.



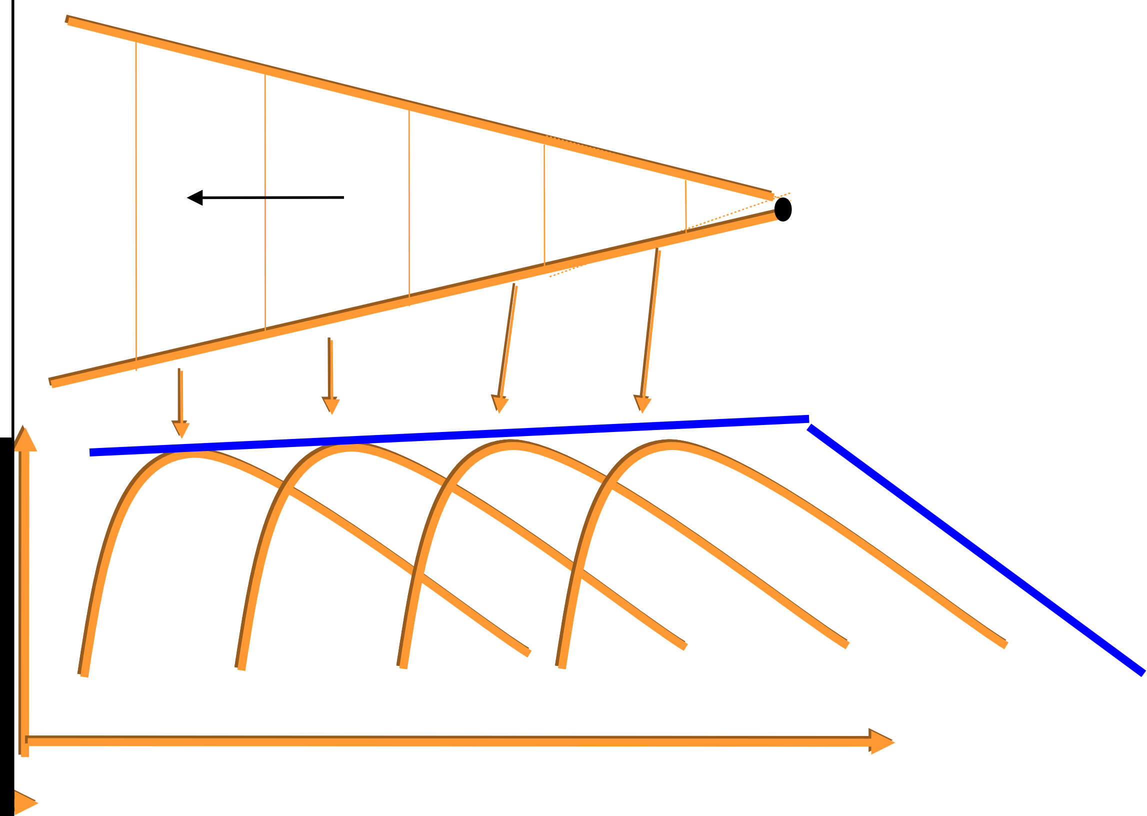
Synchrotron spectra

- Importantly, then, the medium becomes optically thick. It can be shown that, regardless of the energy spectrum of the electrons, the specific intensity in the optically thick region $\propto \nu^{5/2}$. We thus observe a steep, rising spectrum at low ν.

- Since the emission is from a non-thermal population, this optically thick component of the spectrum differs from the ν^2 behaviour of the Rayleigh-Jeans law.



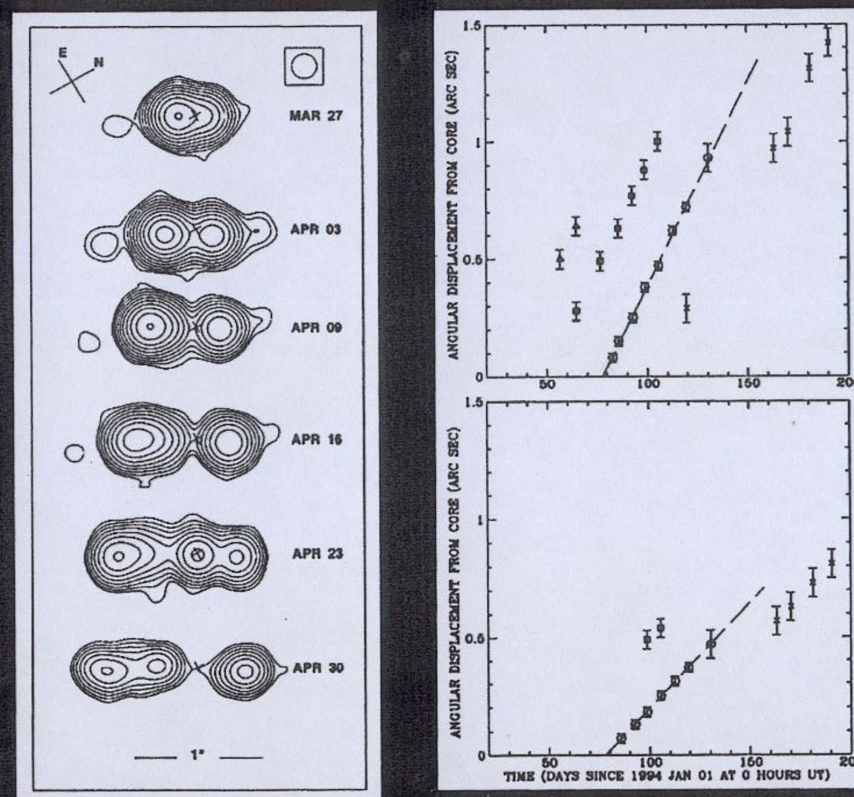
The production of synchrotron radiation is indicative of the presence of violent particle acceleration + B fields. It is seen within the Galaxy, and also in supernova remnants, pulsars, external AGN, radio sources, gammaray bursters etc.



Relativistic Jets

Relativistic jets known for many years in AGN

Spectacular examples seen recently in XRBs: Microquasars

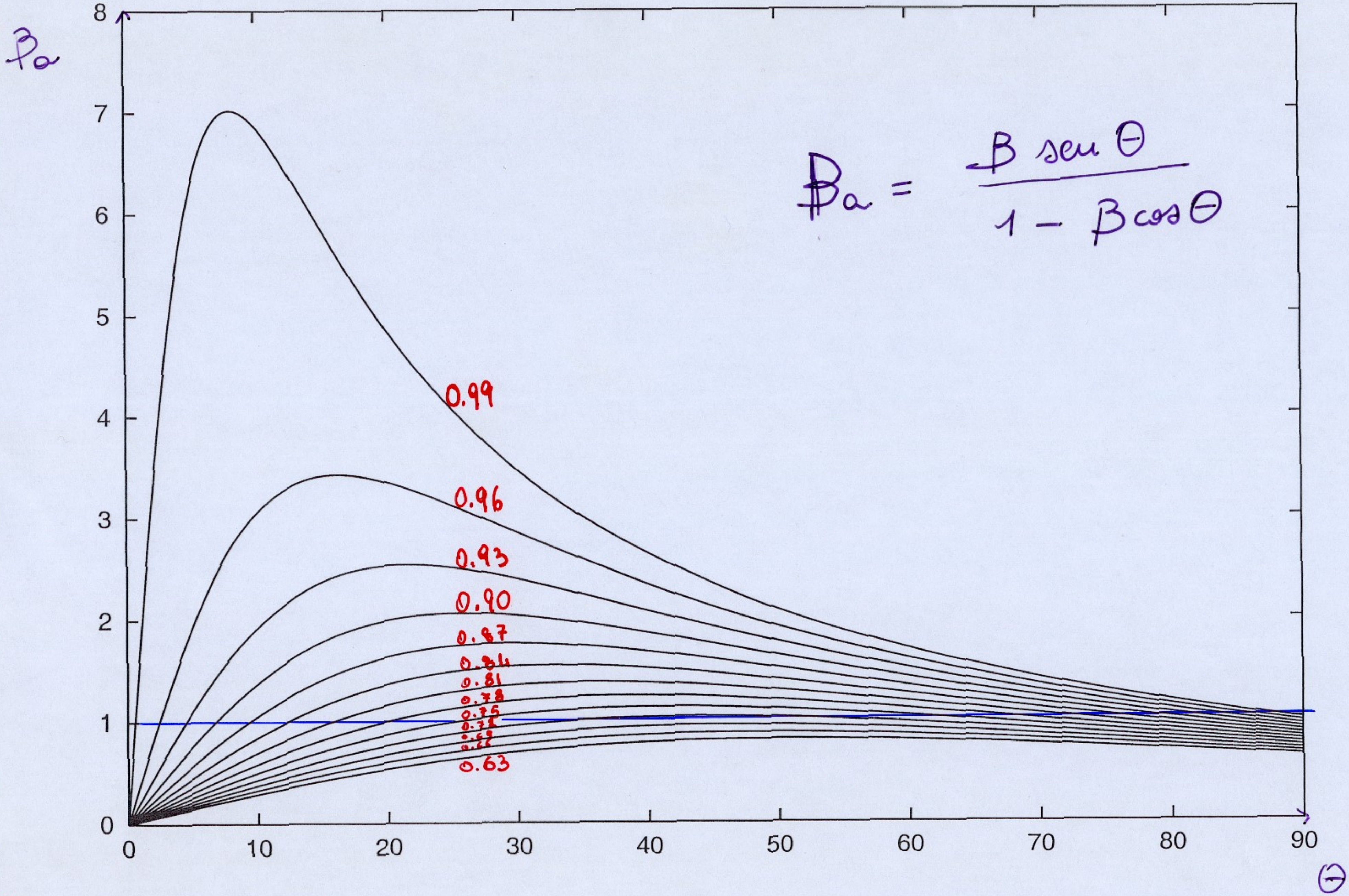


GRS 1915+105: Mirabel & Rodriguez (1995)

$\beta_a = \mu_a \frac{D}{c}$

$\beta_r = \mu_r \frac{D}{c}$

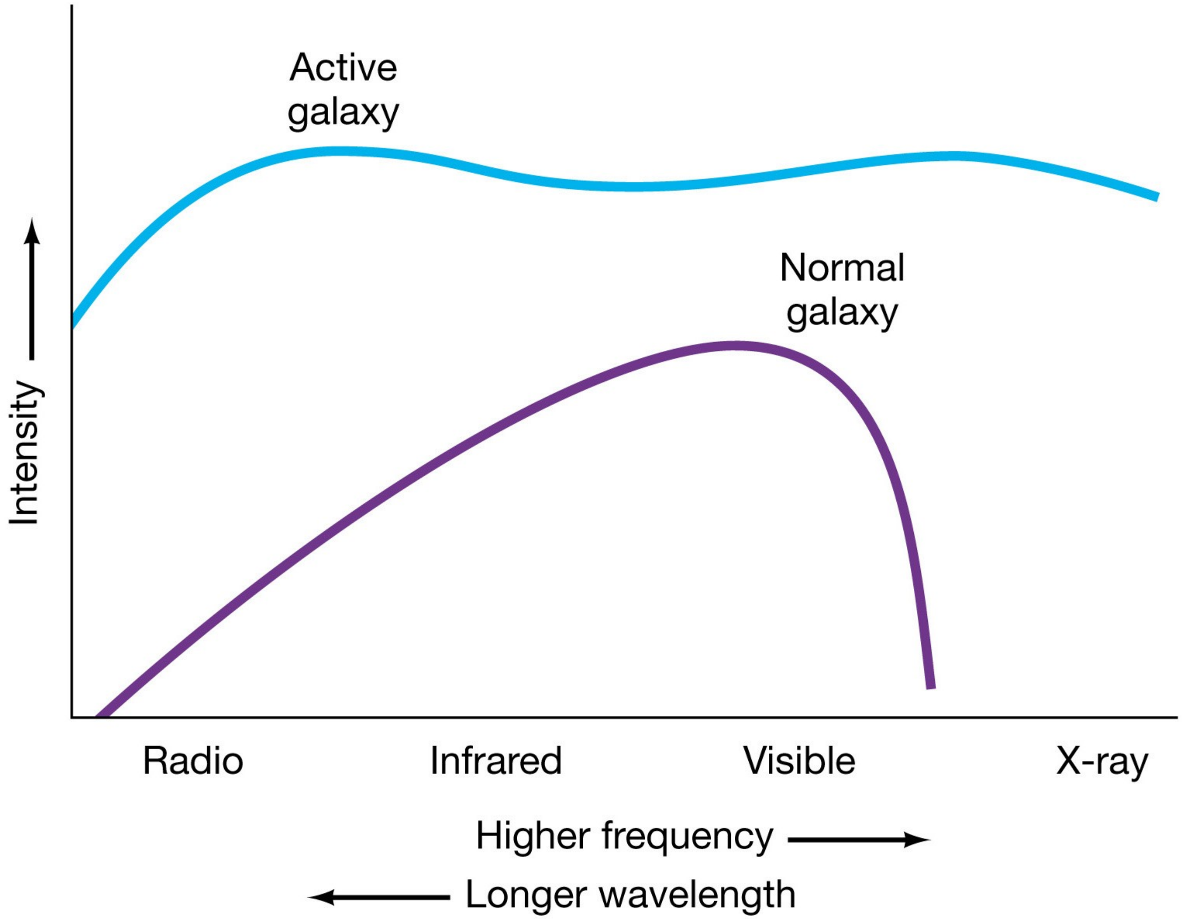
$\beta_a > 1$!



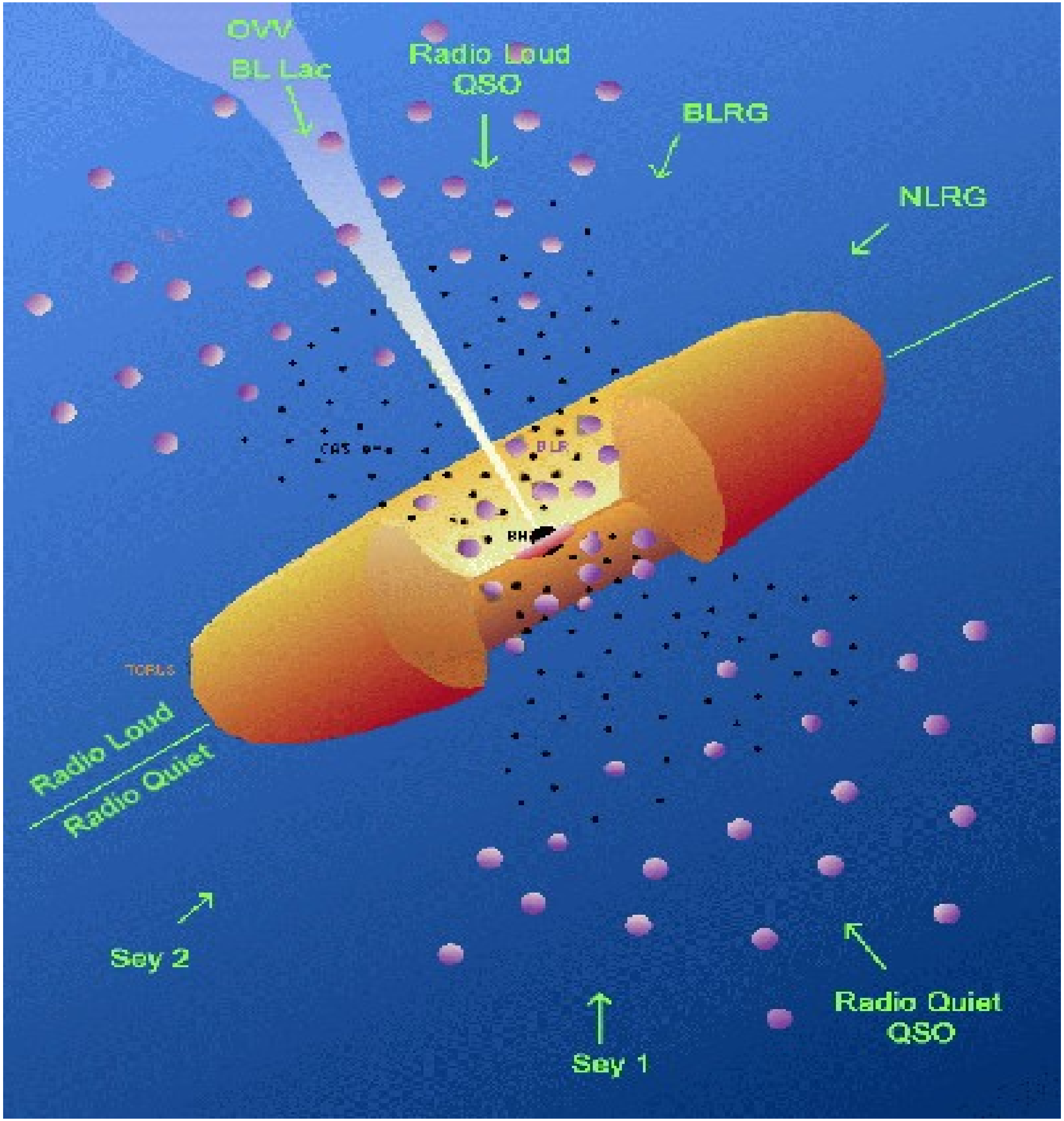
β_a
$\beta_a = \dfrac{\beta \operatorname{sen} \theta}{1 - \beta \cos \theta}$
0.99
0.96
0.93
0.90
0.87
0.84
0.81
0.78
0.75
0.63
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
θ

Active Galaxies

But a small fraction of galaxies are different; they are much brighter and produce more long- and short-wavelength emission. They are called active galaxies.



- Blazars
  - BL Lacs
  - OVV
- Quasars
  - Radio Loud
  - Radio Quiet
- Radio
  - Narrow Line
  - Broad Line
- Seyfert
  - Type 1
  - Type 2



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

table 27-2 Properties of Active Galactic Nuclei (AGNs)

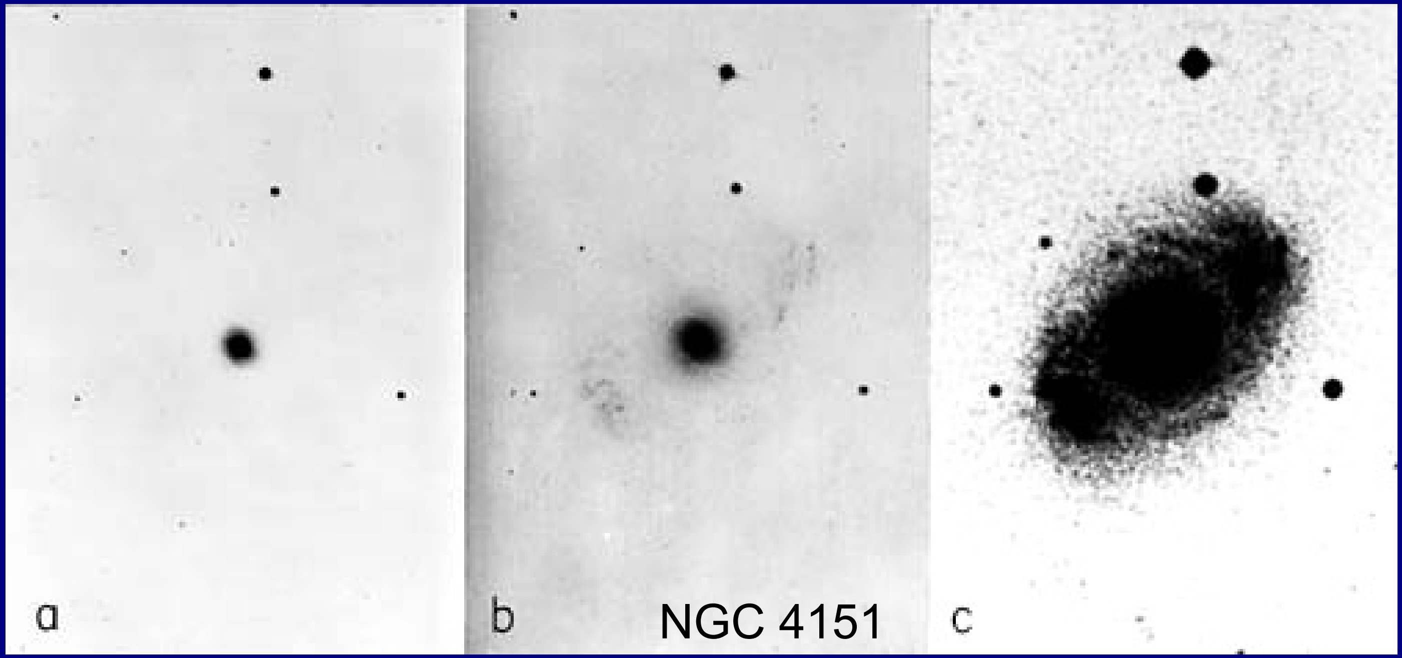
Object	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	Luminosity (watts)	Luminosity (Milky Way Galaxy = 1)
Blazar	Elliptical	Strong	Weak (compared to synchrotron emission)	10^{38} to 10^{42}	10 to 10^5
Radio-loud quasar	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^5
Radio galaxy	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^5
Seyfert 1	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Seyfert 2	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

Seyfert galaxies were first identified by Carl Seyfert in 1943.

He defined this class based on observational characteristics:

Almost all the luminosity comes from a **small (unresolved) region** at the center of the galaxy – the galactic nucleus.

Nuclei have $M_B > -23$ (arbitrary dividing line between quasars/seyferts)



short exposure

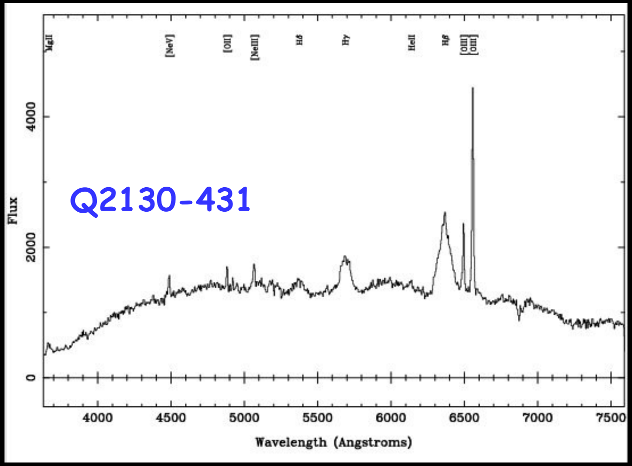
long exposure

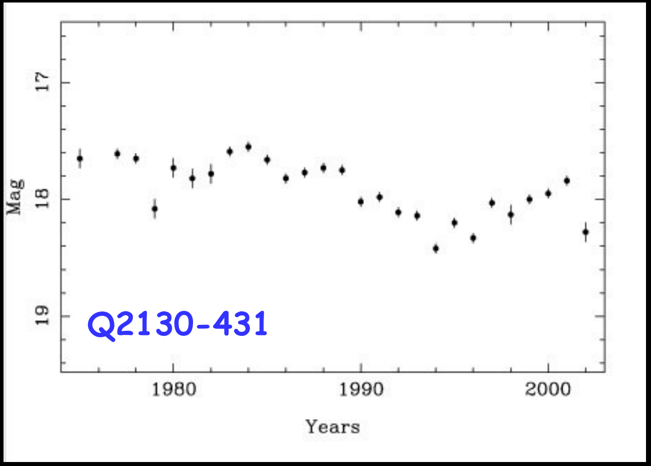
10000 times brighter than our galactic nucleus!

Note: Quasar 3C 273 , located in the Virgo constellation,.
Is one of the closest with a redshift, z, of 0.158.[2] = 2.44 Giga light years . It is also one of the most luminous quasars known, with an absolute magnitude of **-26.7**

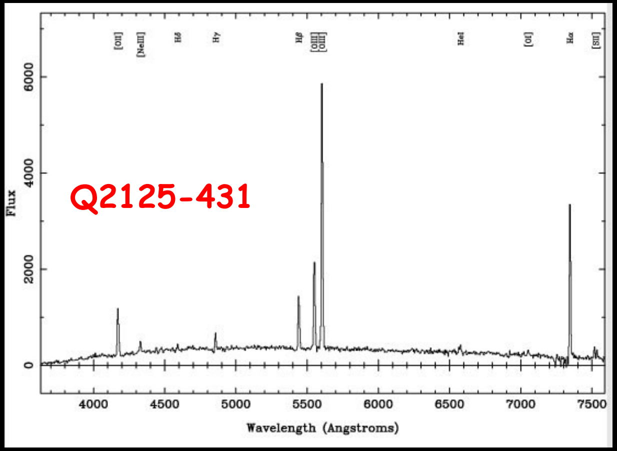
Optical View:

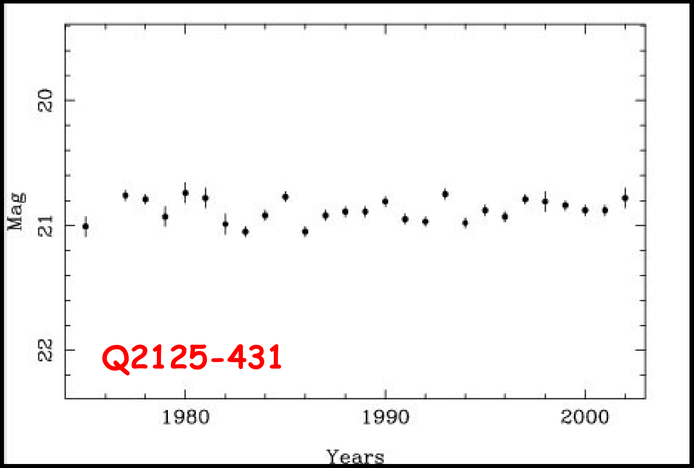
Type I AGN:





Type II AGN:

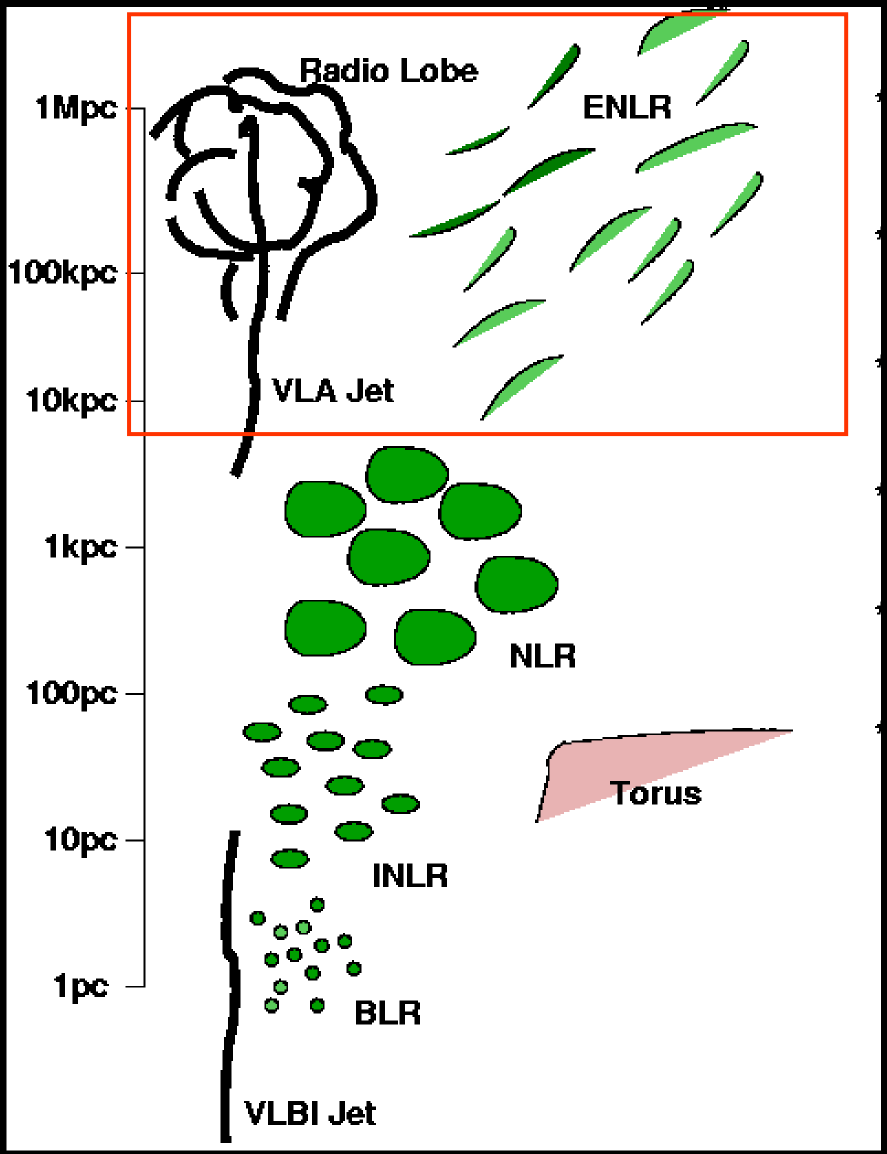




[Fig. from Hawkins 2004]

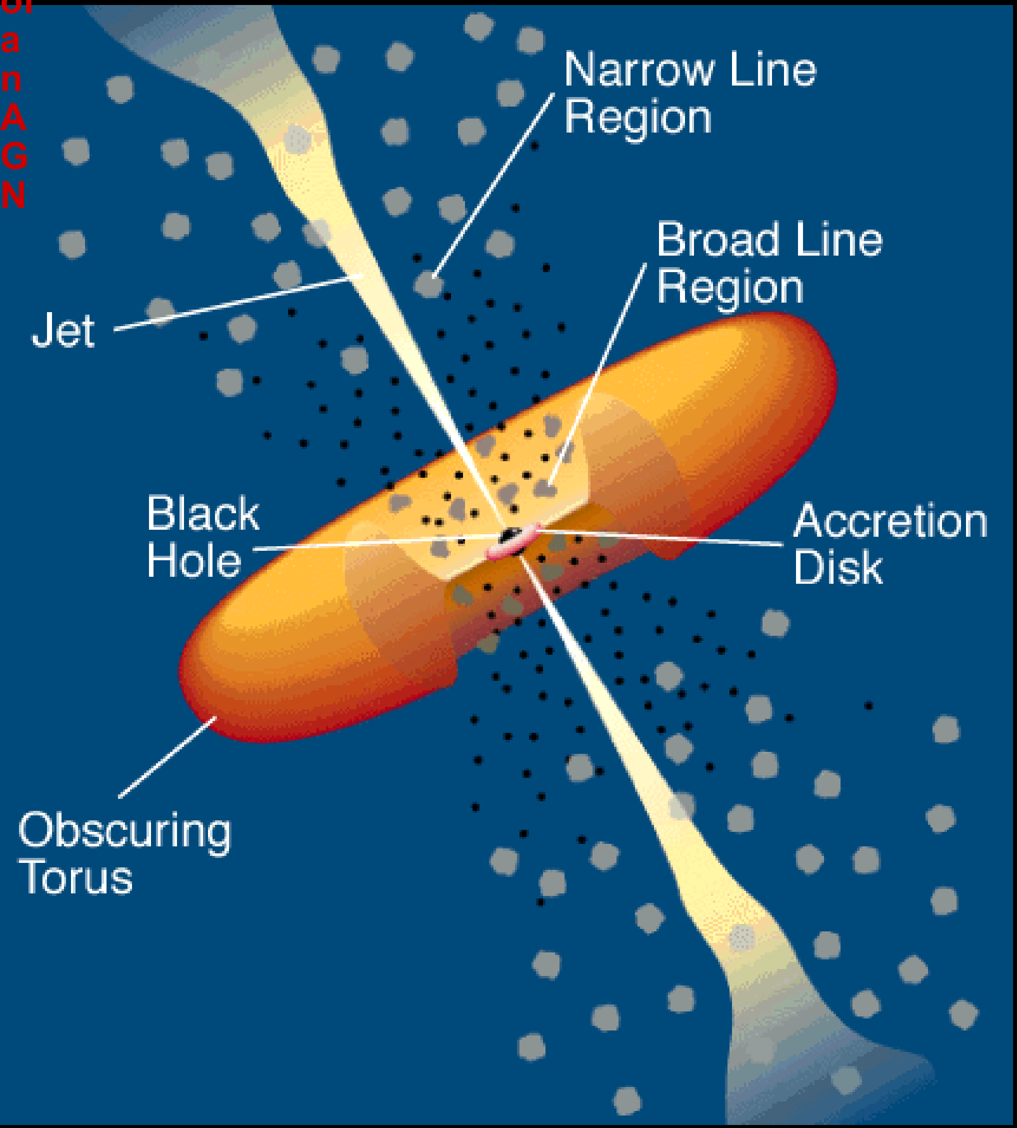
Type 1 Seyfert galaxies have both narrow and broadened optical spectral emission lines. The broad lines imply gas velocities of 1000 - 5000 km/s very close to the nucleus.

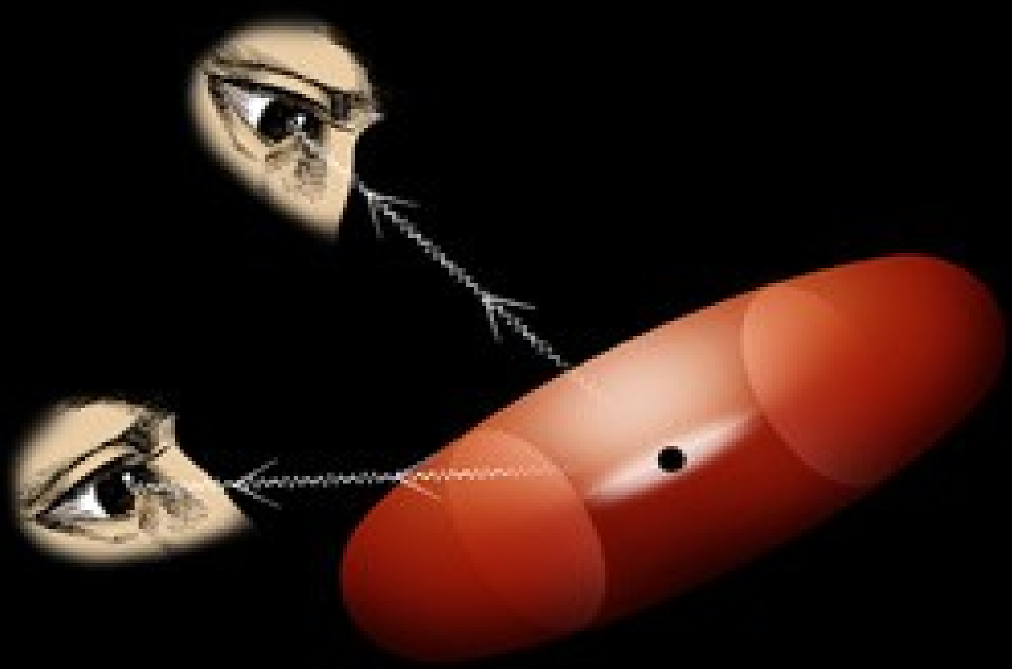
Seyfert type 2 galaxies have narrow emission lines only (but still wider than emission lines in normal galaxies) implying gas velocities of ~ 500-1000 km/s. These narrow lines are due to low density gas clouds at larger distances (than the broad line clouds) from the nucleus.



Radio Lobe
ENLR
1Mpc
100kpc
10kpc
VLA Jet
1kpc
NLR
100pc
Torus
10pc
INLR
1pc
BLR
VLBI Jet

Model of an AGN





Active Galactic Nuclei (AGN)

In some Type 2 Seyfert galaxies, the broad component can be observed in polarized light

Seyfert galaxies were subdivided into types 1 and 2 20 years ago (Khachikian & Weedman 1974), a classification scheme that has served astronomers well in attempting to determine the nature of these galaxies. The original classification into two types was based almost entirely on the relative widths of the strong emission lines. In the Seyfert 1 galaxies, the permitted lines have strong components with widths on the order of 10,000 km s^{-1}; they also may have weaker components with widths on the order of 500 km s^{-1}, as do the forbidden emission lines (such as [O III]). Both permitted and forbidden lines have similar widths of 500 km s^{-1} in Seyfert 2 galaxies. Intermediate Seyfert classifications ranging from 1.2 to 1.9 have been proposed over the years based on the relative strengths of the broad and narrow components of the permitted lines (e.g., Osterbrock & Koski 1976; Osterbrock 1981; Cohen 1983). Some Seyfert galaxies have changed their classifications on time scales of weeks to months, usually within the various intermediate Seyfert classifications (e.g., Cohen *et al.* 1986).

It was long believed that the nuclei of Seyfert 2 galaxies have radio sources that are systematically more powerful and larger than those in Seyfert 1 galaxies, with Seyfert 1.2 through 1.9 galaxies being intermediate in radio properties (de Bruyn & Wilson 1978; Meurs 1982; Meurs & Wilson 1984; Ulvestad & Wilson 1984a, b; Ulvestad 1986). Edelson

...rt 1 and ...-limited sample, although he had insufficient resolution to separate nuclear and disk radio emission. Ulvestad & Wilson (1989) showed that the apparently higher nuclear radio luminosity and size of the Seyfert 2 galaxies might be accounted for by selection effects; when the weaker Seyferts (mostly Seyfert 2 galaxies) found in surveys of nearby galaxies are included and radio-source sizes are compared at equivalent dynamic ranges, the differences in radio powers and sizes are no longer statistically significant. A contemporaneous study by Giuricin *et al.* (1990), based on a sample of bright, spectroscopically selected Seyferts, also concluded that the radio sources in the different Seyfert types are not significantly different. A recent summary of the radio properties of Seyfert galaxies can be found in Wilson (1991).

Antonucci (1983) noted that the Seyfert 1 galaxies tend to have optical continuum polarization parallel to their radio major axes, while Seyfert 2 galaxies have perpendicular polarization. This has been interpreted as a difference between thin and thick scattering disks (Antonucci 1984). However, the remarkable result that NGC 1068, the archetypal Seyfert 2 galaxy, shows very broad permitted line emission in polarized light (Antonucci & Miller 1985) indicates that at least some of the difference between Seyfert 1 and Seyfert 2 galaxies might be merely an orientation effect; a similar suggestion, based on x-ray properties of the galaxies, was made by

 0004-6256/95/109(1)/81/6/$0.90

Radio Galaxies

- Emit most of their energy at radio wavelengths
- Emission lines from many ionization states
- Nucleus does not dominate galaxy's emission
- Host galaxies are Elliptical/S0

Radio morphology first classified by Fanaroff & Riley (1974)

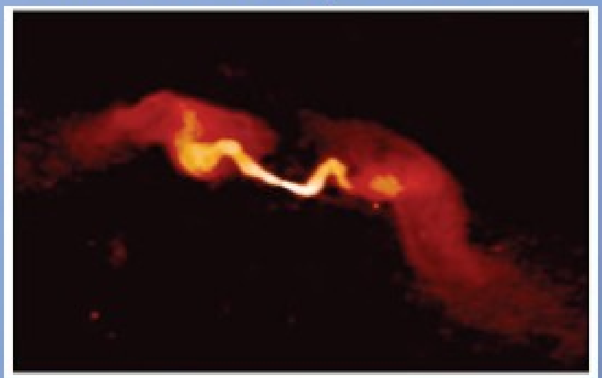
- FR I: less luminous, 2-sided jets brightest closest to core and dominate over radio lobes
- FR II: more luminous, edge-brightened radio lobes dominate over 1-sided jet (due to Doppler boosting of approaching jet and deboosting of receding jet)

Spectroscopic classification of radio galaxies

- NLRGs (Narrow line …): like Seyfert 2s; FR I or II
- BLRGs (Broad line …): like Seyfert 1s; FR II only

FRI/FRII Radio Morphology Classification

Fanaroff-Riley ClassI

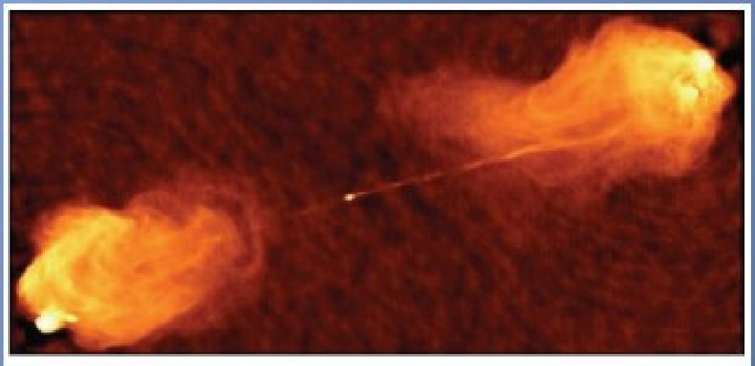


Edge-darkened

$P_{178Mhz} < 5 \times 10^{25}\ W\ Hz^{-1}$

All FRIs classified as WLRG

Fanaroff-Riley ClassII



Edge-brightened

$P_{178Mhz} > 5 \times 10^{25}\ W\ Hz^{-1}$

FRIIs mainly classified as NLRG/BLRG/RLQ

Faranoff-Riley Typ I (FR I)

$L_\nu(1.4\text{GHz}) < 10^{32}$ erg/s/Hz

Faranoff-Riley Typ II (FR II)

$L_\nu(1.4\text{GHz}) > 10^{32}$ erg/s/Hz

On *small scales* (< 15 kpc): 3 types of sources

Compact, Flat Spectrum (CFS)

usually < 1”, physically small < 10 pc

$f_\nu \sim \nu^{-\alpha}$, $\alpha \sim 0 - 0.3$

variable, polarized, superluminal on VLBI scales

Compact, steep spectrum (CSS)

alpha = 0.7 – 1.2

sizes 1-20 kpc (within host galaxy)

peak at < 500 MHz

(limited by Ionospheric cutoff is at 10 MHz)

30% of cm-selected radio sources

GigaHertz Peaked Spectrum (GPS)

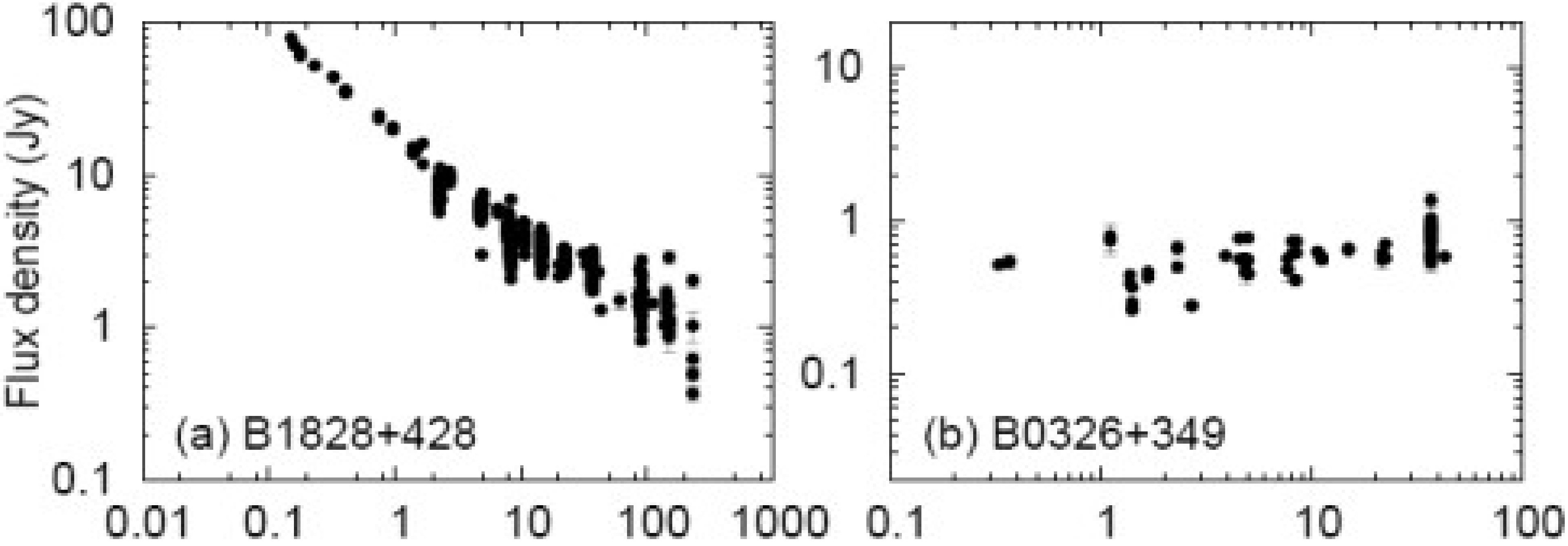
radio spectrum peaks at 500 MHz to 10 GHz

sizes < 1 kpc (within NLR)

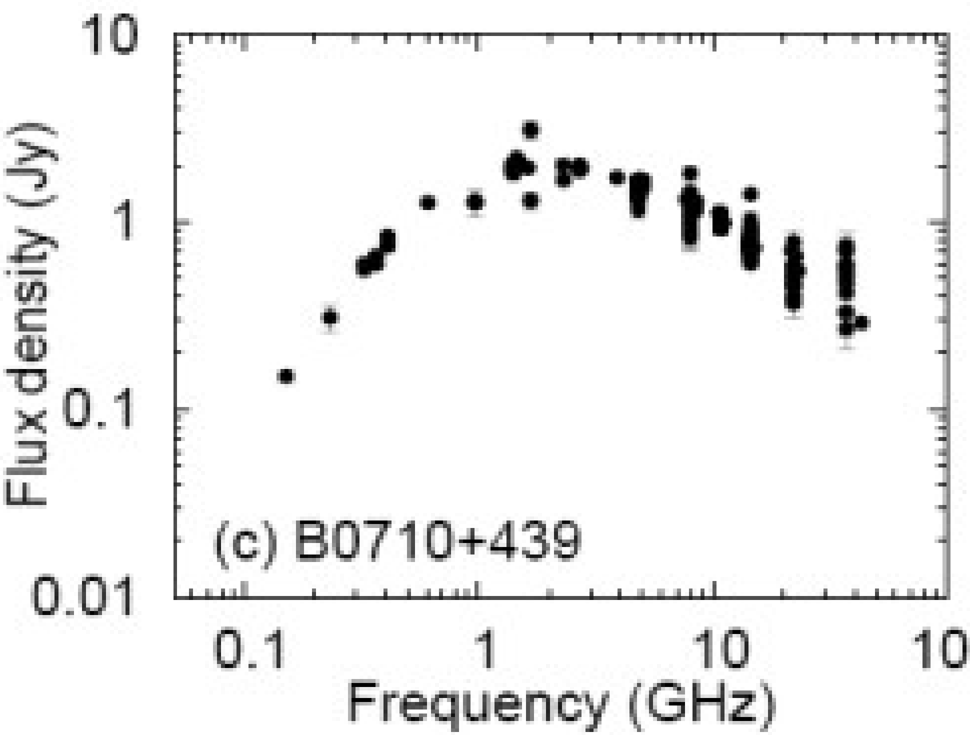
not very polarized

alpha ~0.77 for E>E(peak)

10% of cm-selected radio sources



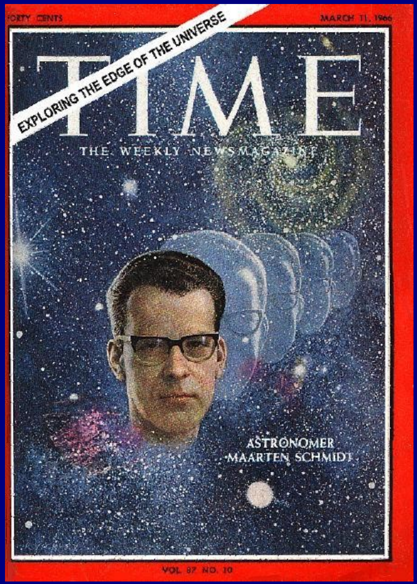
Flux density (Jy)
(a) B1828+428
(b) B0326+349
100
10
1
0.1
0.01
1000



Flux density (Jy)
(c) B0710+439
Frequency (GHz)
10
1
0.1
0.01

Quasars

• First discovered in the 1960s.
• Detected radio sources with optical counterparts appearing as unresolved point sources.
• *Unfamiliar* optical emission lines.
• Maartin Schmidt was the first to recognize that these lines were normal Hydrogen lines seen at *much* higher redshifts than any previously observed galaxies.



D = 660 Mpc (2.2 billion light years) for 3C273

1340 Mpc (4.4 billion light years) for 3C 48

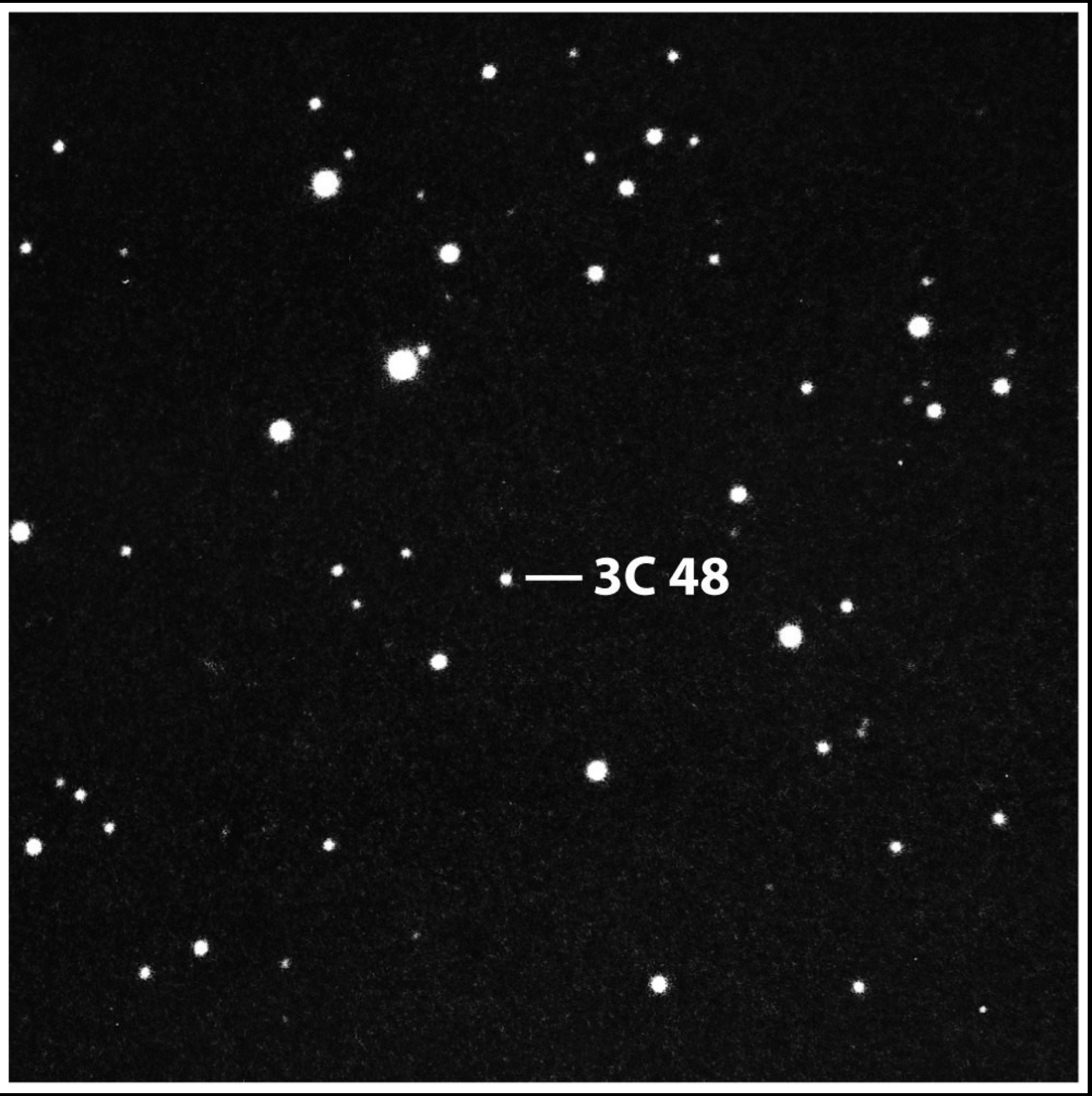
$L = 2 \times 10^{13}\ L_{sun}$ for 3C273.

• Within ~2 years, quasars were discovered with:
$z > 2$ and $L \approx 10^{14}\ L_{sun}$

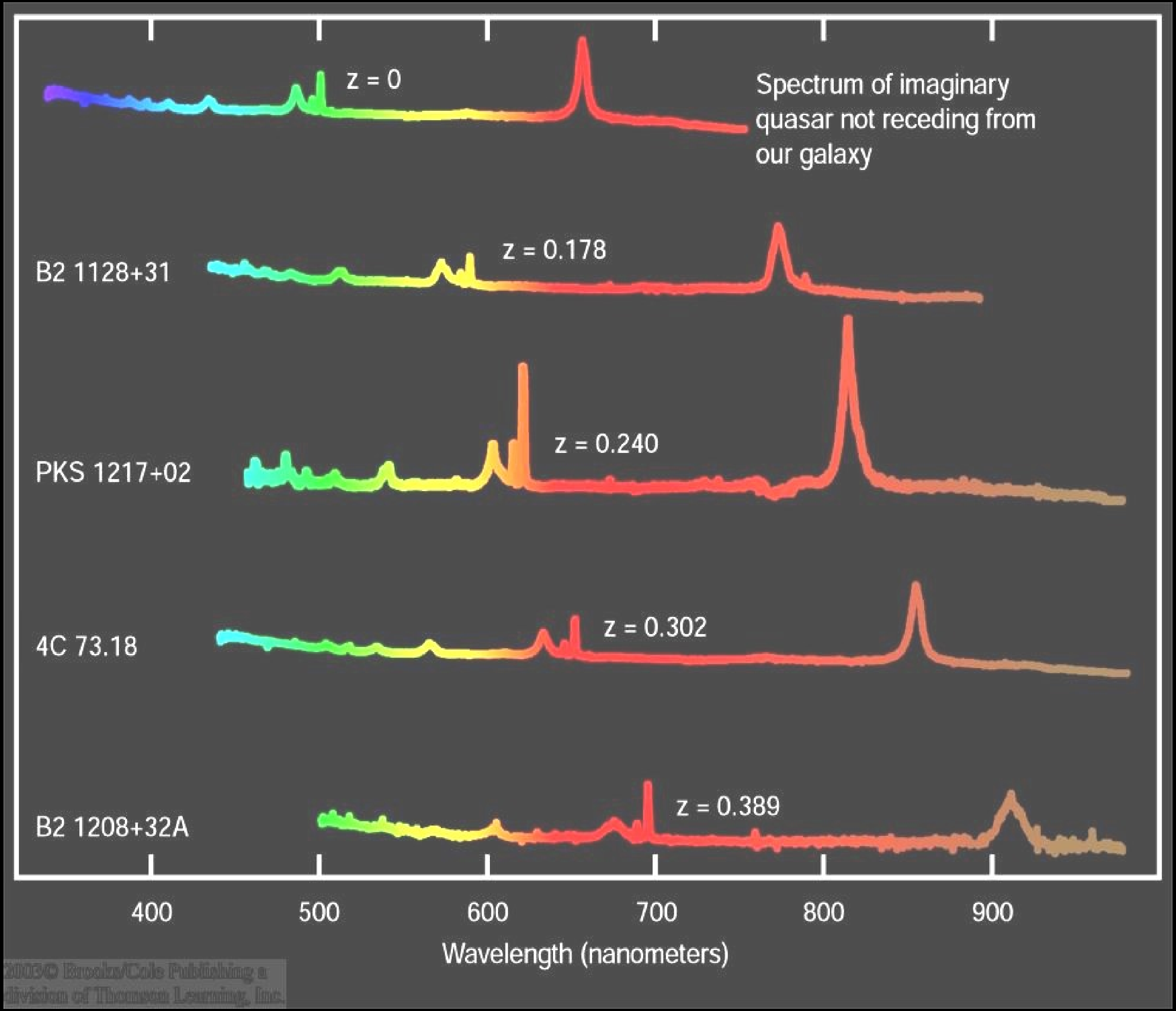
• *Most distant QSO discovered today - z = 6.42*

About 10% of all quasars are strong sources of radio emission and are therefore called “radio-loud”; the remaining 90% are “radio-quiet”

To be seen at such large distances, quasars must be very luminous, typically about 1000 times brighter than an ordinary galaxy



Quasar Red Shifts



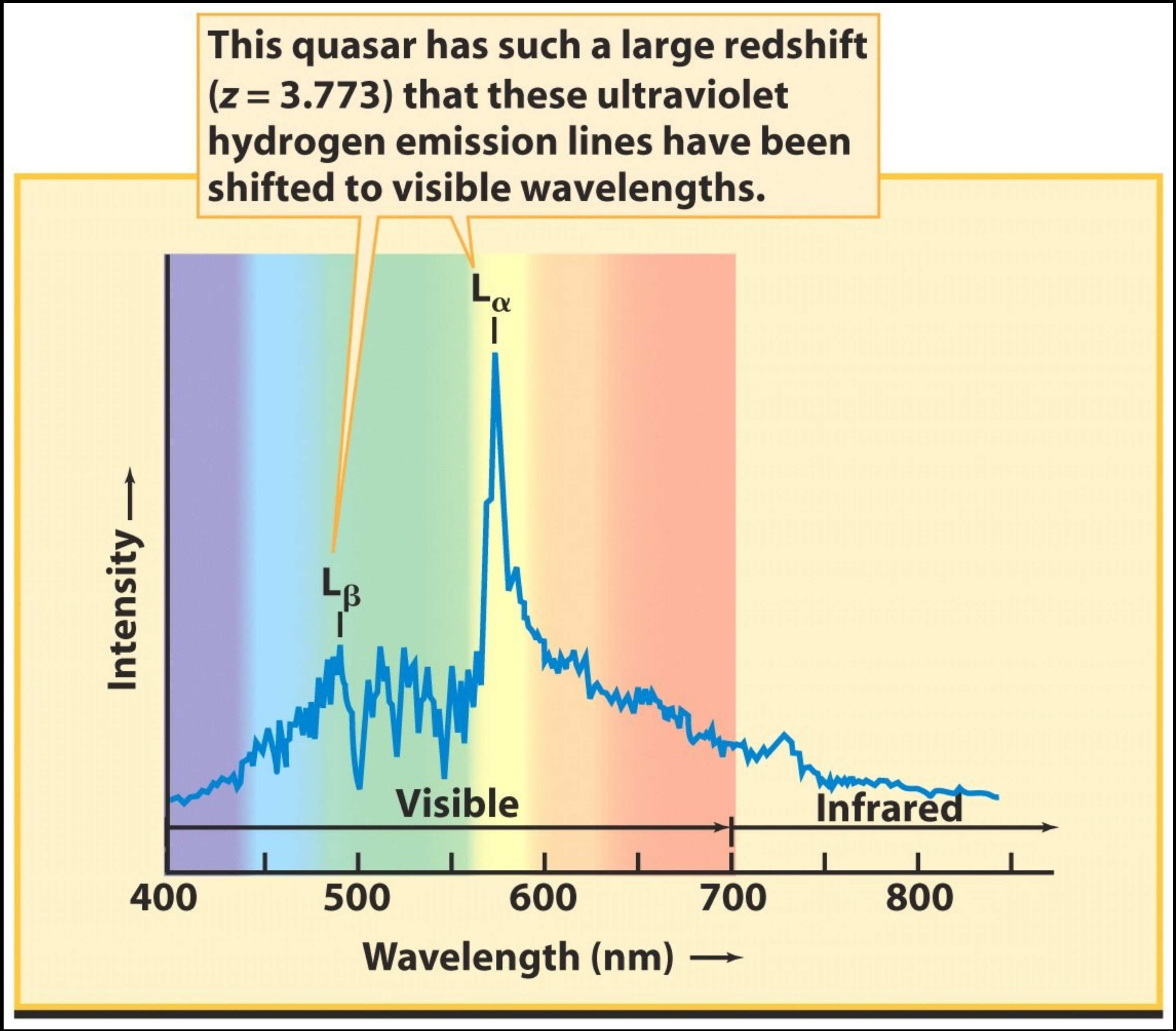
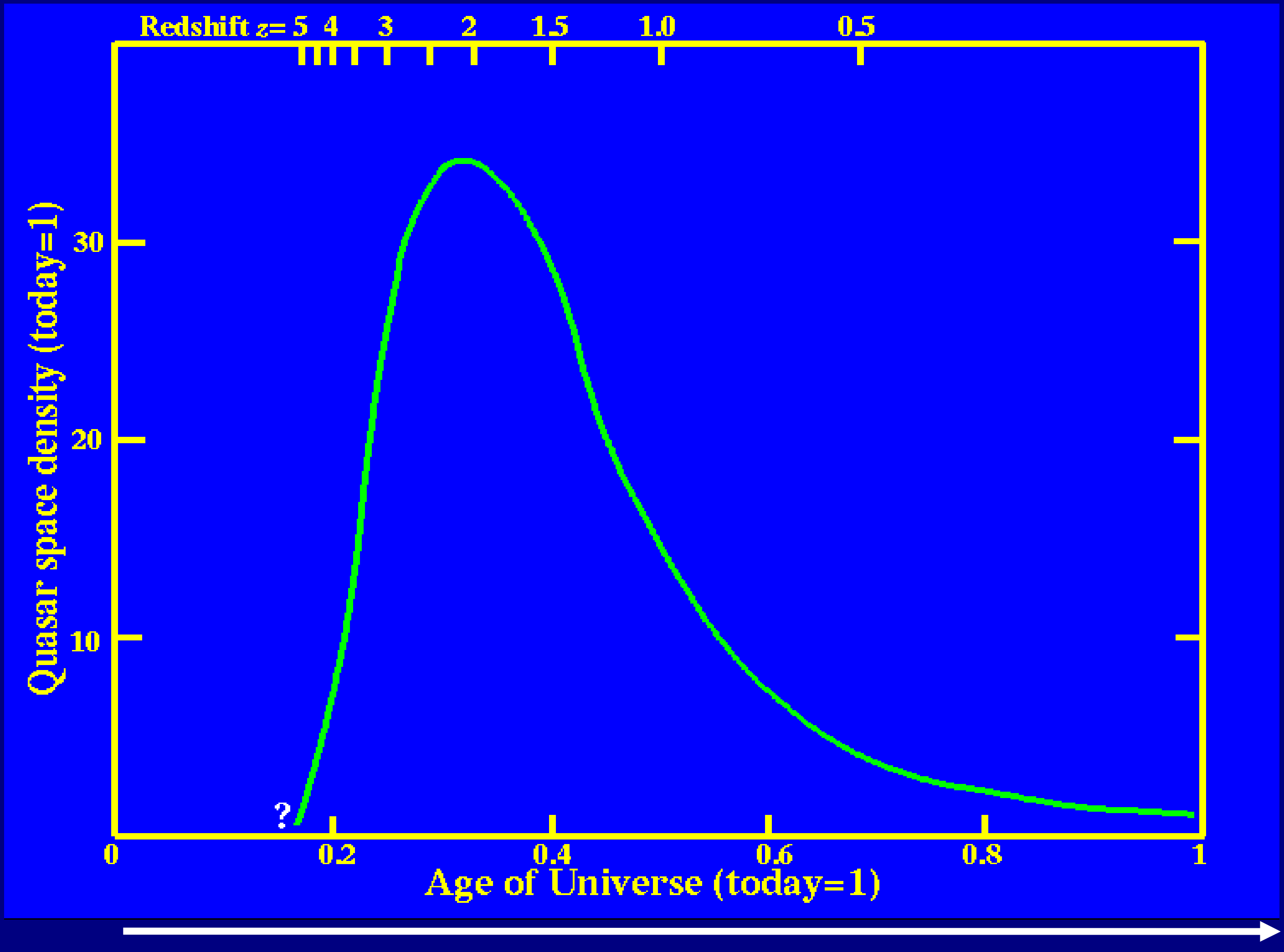

This quasar has such a large redshift ($z = 3.773$) that these ultraviolet hydrogen emission lines have been shifted to visible wavelengths.
L_α
L_β
Intensity
Visible
Infrared
400
500
600
700
800
Wavelength (nm)

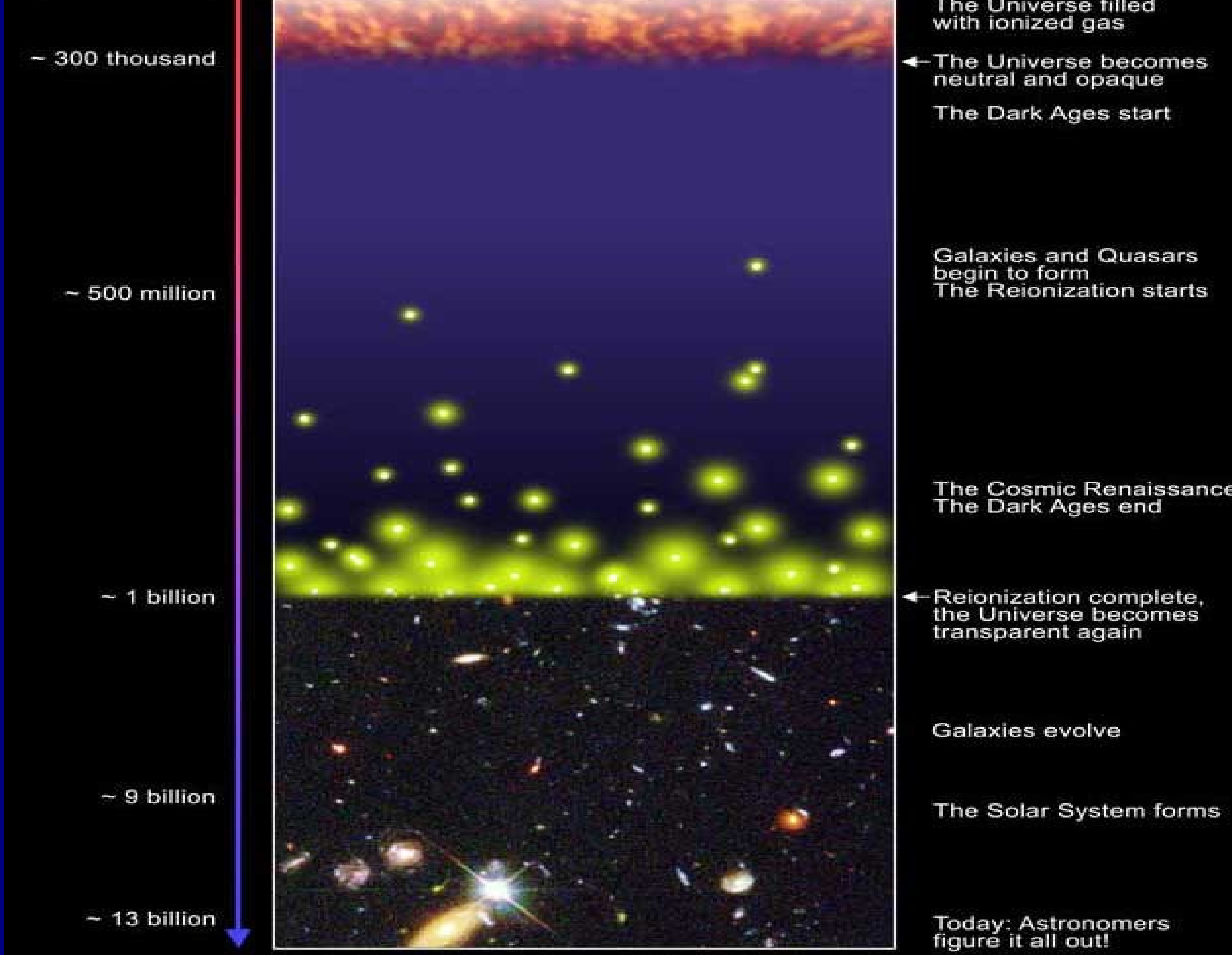
table 27-1 Redshift and Distance

Redshift z	Recessional velocity v/c	Distance (Mpc)	Distance (10^9 ly)
0	0	0	0
0.1	0.095	394	1.29
0.2	0.180	739	2.41
0.3	0.257	1040	3.39
0.4	0.324	1310	4.26
0.5	0.385	1540	5.02
0.75	0.508	2010	6.57
1	0.600	2370	7.73
1.5	0.724	2860	9.32
2	0.800	3170	10.3
3	0.882	3520	11.5
4	0.923	3710	12.1
5	0.946	3830	12.5
10	0.984	4040	13.2
Infinite	1	4190	13.7

This table assumes a Hubble constant $H_0 = 71$ km/s/Mpc, a matter density parameter $\Omega_m = 0.27$, and a dark energy density parameter $\Omega_\Lambda = 0.73$ (see Chapter 28). The distance in light-years is equal to the light travel time in years.



Quasar density peaks at z~2
~3 billion after the Big bang


The Universe filled with ionized gas
~ 300 thousand
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
~ 500 million
The Cosmic Renaissance
The Dark Ages end
~ 1 billion
Reionization complete, the Universe becomes transparent again
Galaxies evolve
~ 9 billion
The Solar System forms
~ 13 billion
Today: Astronomers figure it all out!

Type		Radio Galaxy	Seyfert Galaxy	Quasar	Blazar
Examples		M87, Cygnus A	NGC4151	3C273	BL Lac, 3C279
Galaxy Type		Elliptical, irregular	Spiral	Irregular	Elliptical?
Luminosity (Solar units)		10^{6} - 10^{8}	10^{8} - 10^{11}	10^{11} - 10^{14}	10^{11} - 10^{14}

- RG 10^{39} - 10^{41} erg/s

Quasars 10^{44} - 10^{47} erg/s

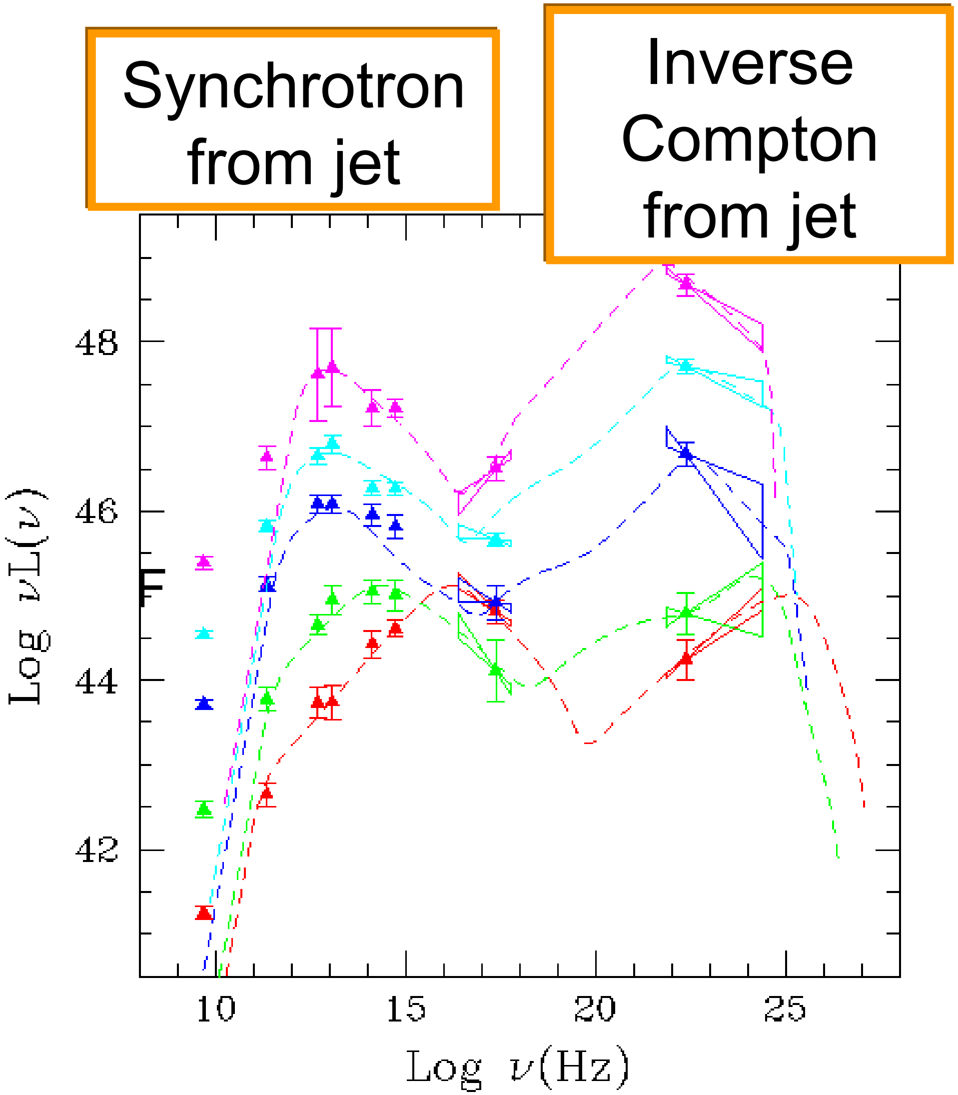
* 'Blazars' (BL Lac objects and OVV quasars). These classes are distinguished by **rapidly variable**, polarized optical, radio and X-ray emission. BL Lac objects show no optical emission lines, broad or narrow, so that their redshifts can only be determined from features in the spectra of their host galaxies.

OVV quasars **behave more like standard radio-loud quasars** with the addition of a rapidly variable component.

In both classes of source, the variable emission is believed to originate in a relativistic jet oriented close to the line of sight. Relativistic effects amplify both the luminosity of the jet and the amplitude of variability.

www.astro.isas.ac.jp/conference/bh2003/program/ppt/20031029am/KyotoBH2003_Falcke.ppt

BL Lacs – A Pure Jet Spectrum



- BL Lacs are thought to be beamed FRI radio galaxies (low power!)
- In BL Lacs the emission is dominated by the jet due to relativistic beaming.
- But there is also no evidence for any disk spectrum.
- <u>The jet spectrum resembles a „camel's back".</u>
- Radio – optical – X-rays: synchrotron from jet
- X-ray – TeV: inverse Compton from inner jet