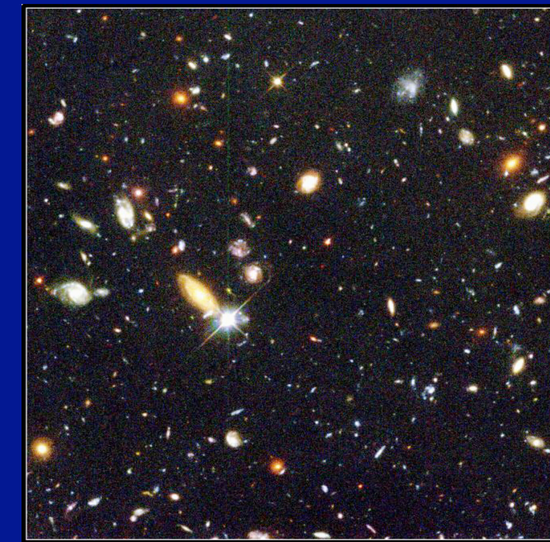
Radio Loud AGN

Paola Grandi
IASF-BO

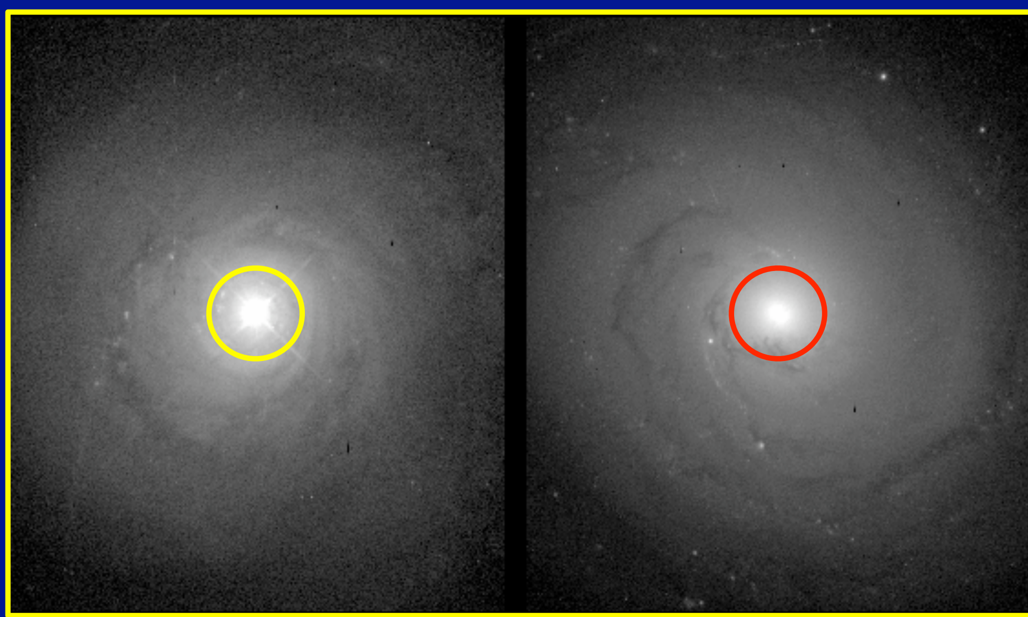
X-ray LAB
2 ottobre 2013

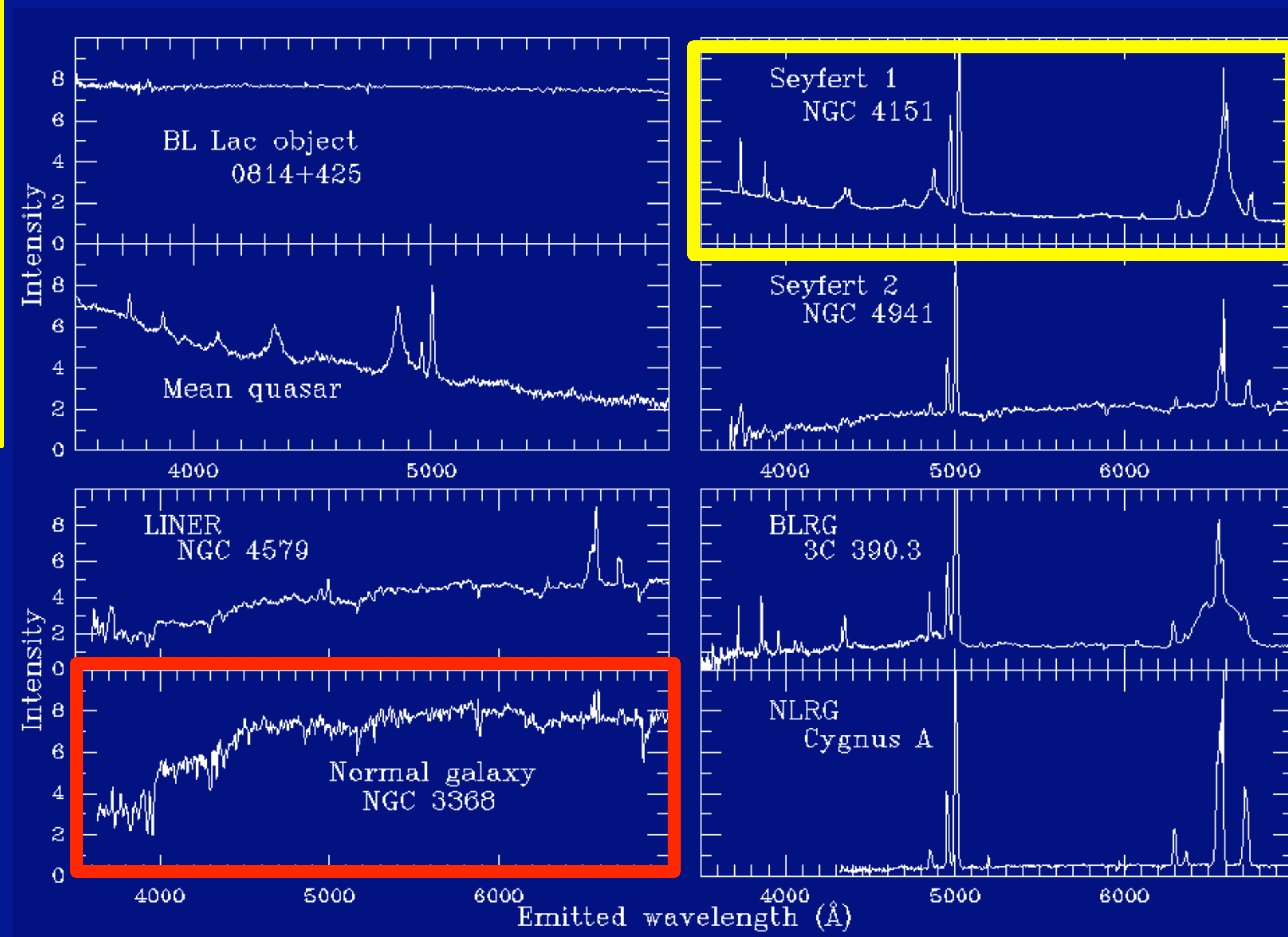
AGN in general

Almost every galaxy hosts a BH



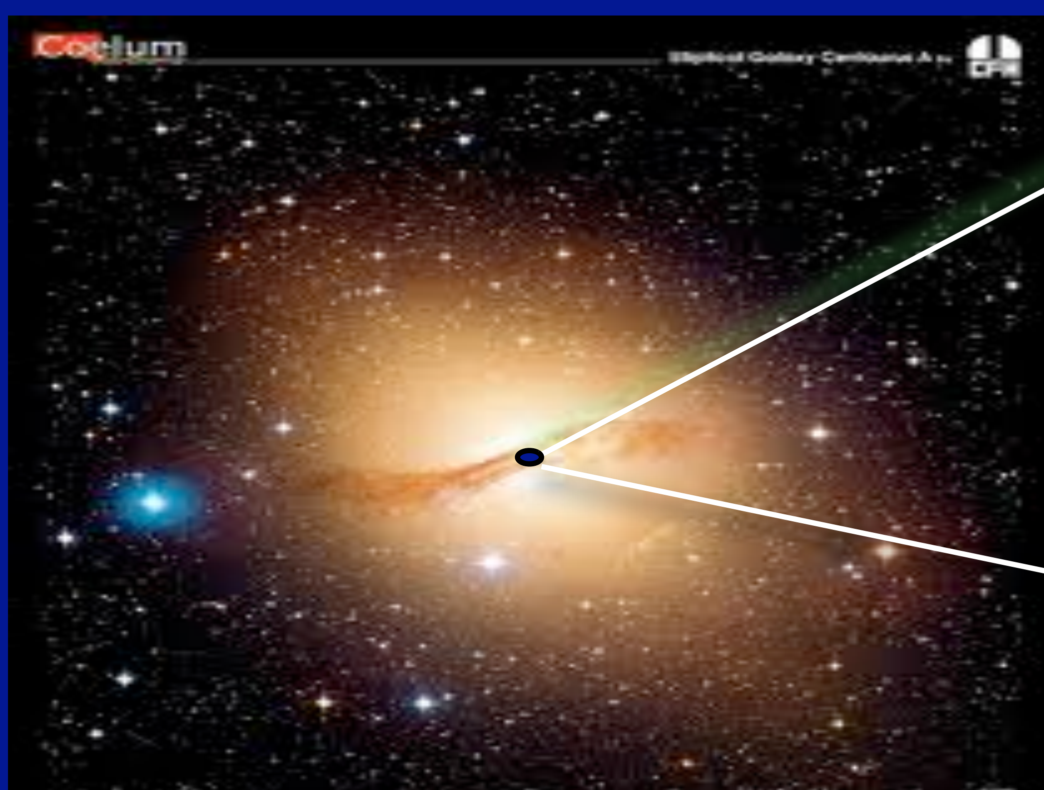
1% are active   99% are silent

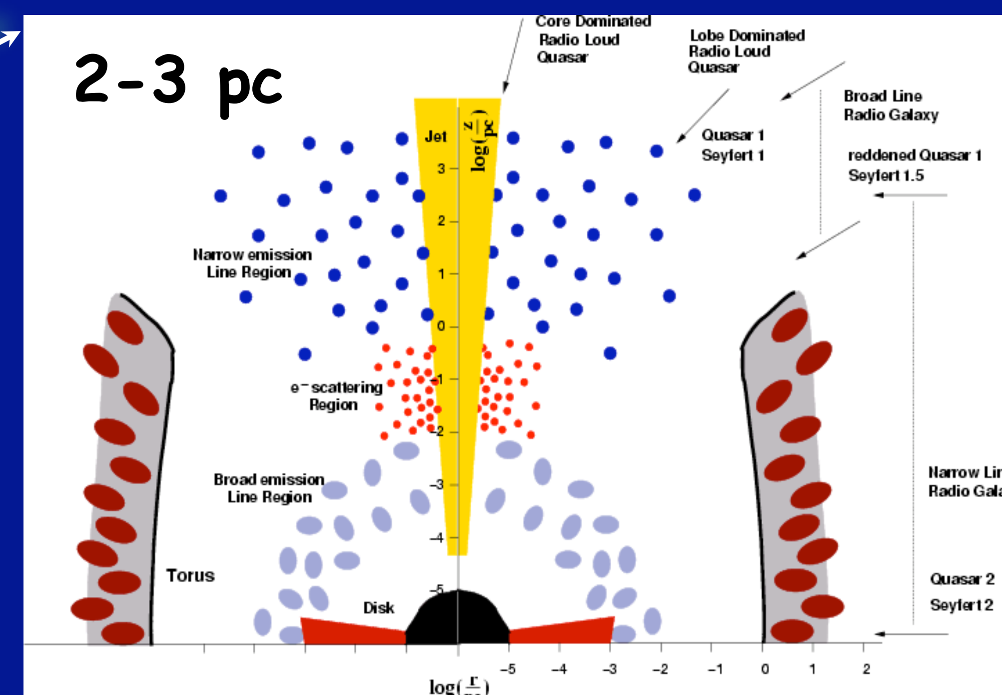




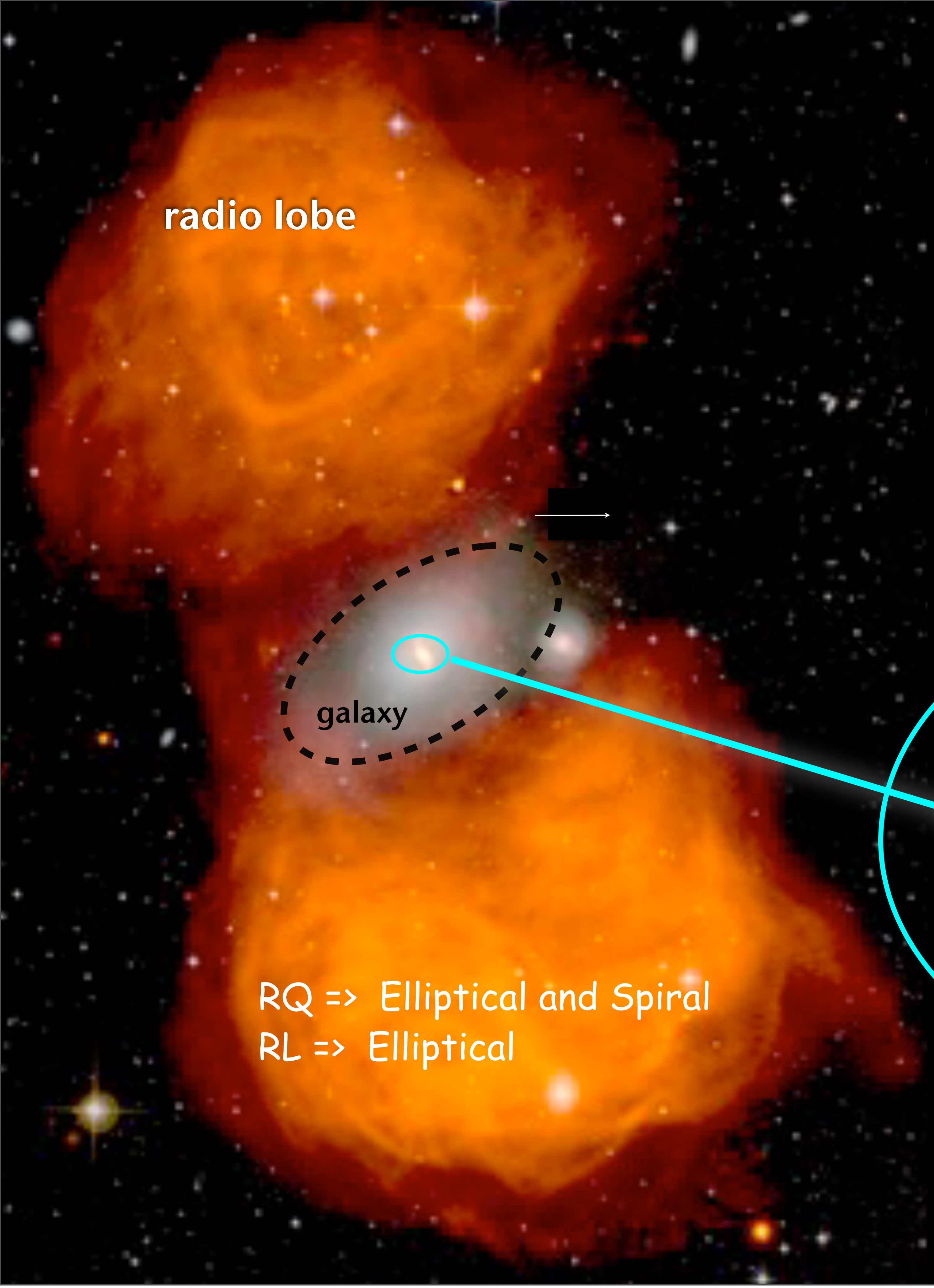
30 kpc

The engine occupies a tiny region in the center of the galaxy





RQ => Elliptical and Spiral
RL => Elliptical

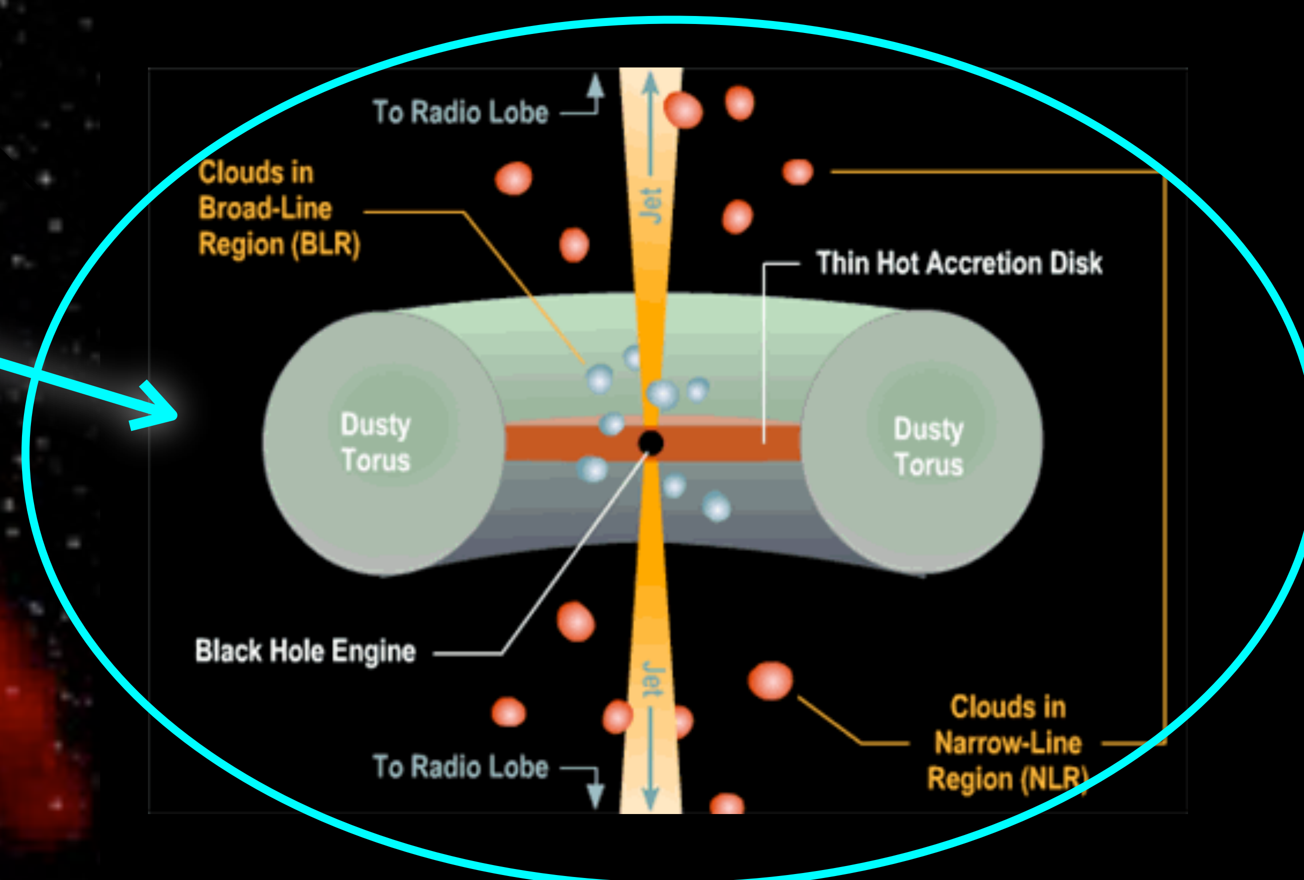


RADIO LOUD AGN

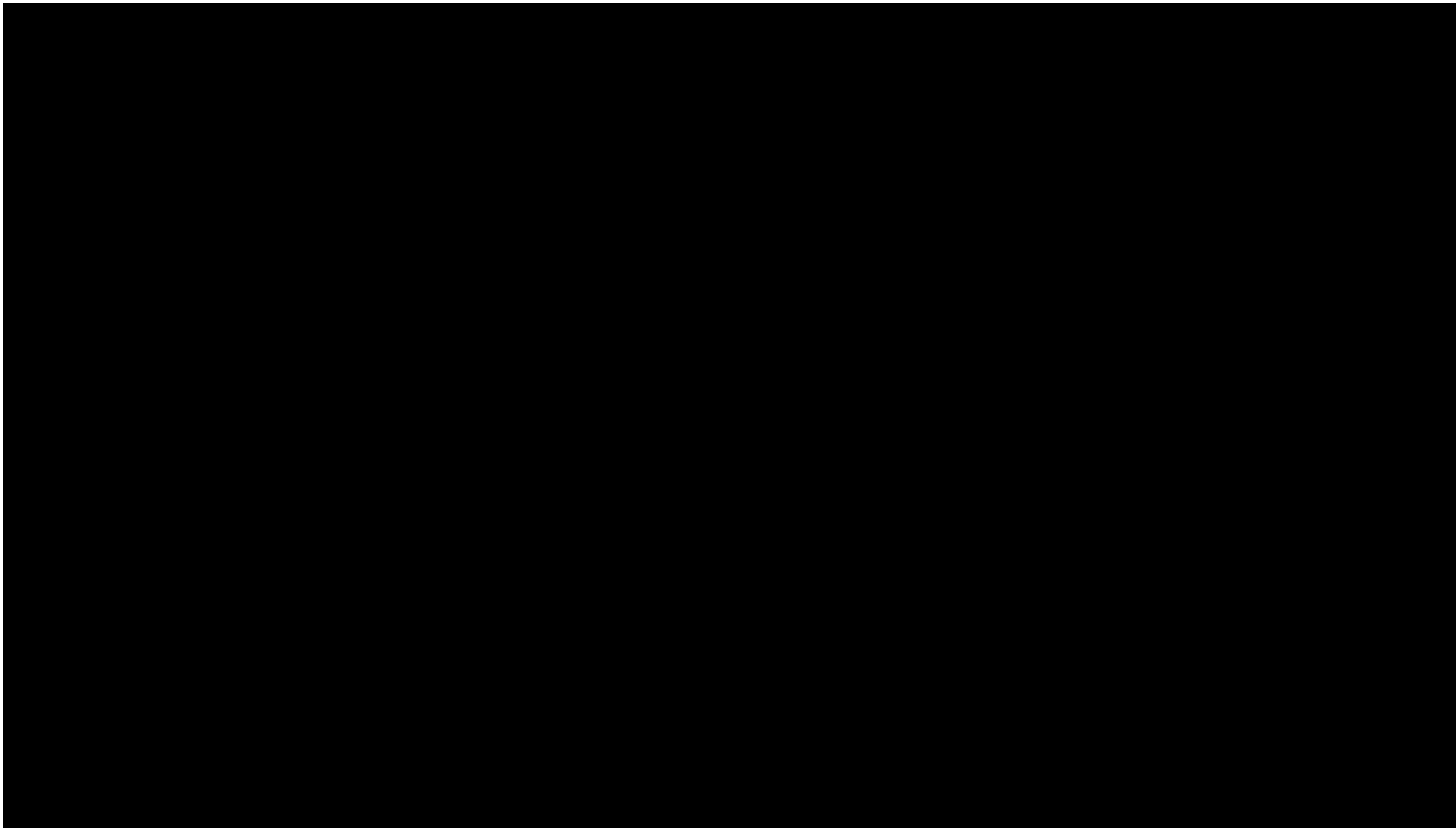
A small fraction 15-20% of AGN are Radio Loud (RL) .

An AGN is Radio Loud when
$F_{5GHz}/F_B > 10$
(controversial classification)

otherwise is Radio Quiet (RQ)



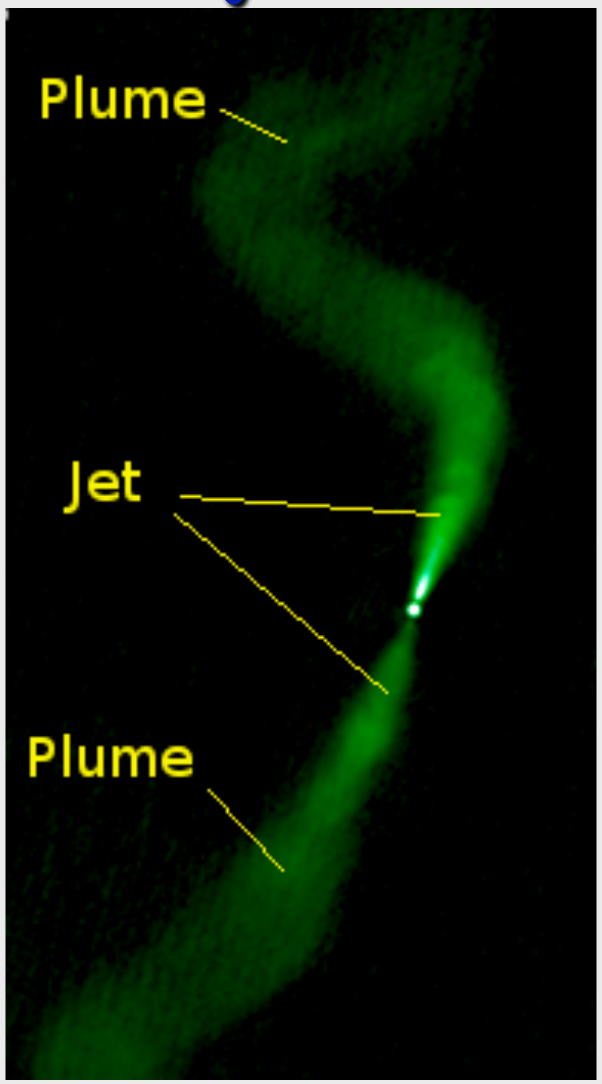
The central engine



Simulaiton of a jet intermittente (duty cicle 13 milioni di anni)
durata 192 milioni di anni (ciclo di 13 milioni di anni)

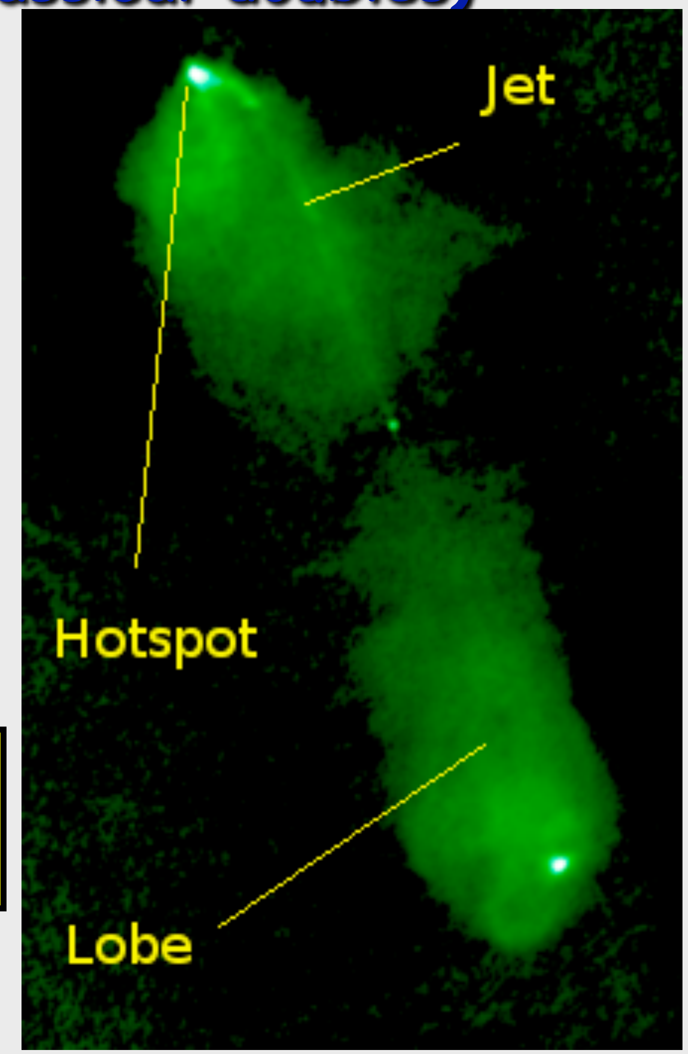
Observed morphologies:
The Fanaroff-Riley classification

FR I or jet dominated



3C 31
VLA

FR II or lobe dominated (classical doubles)

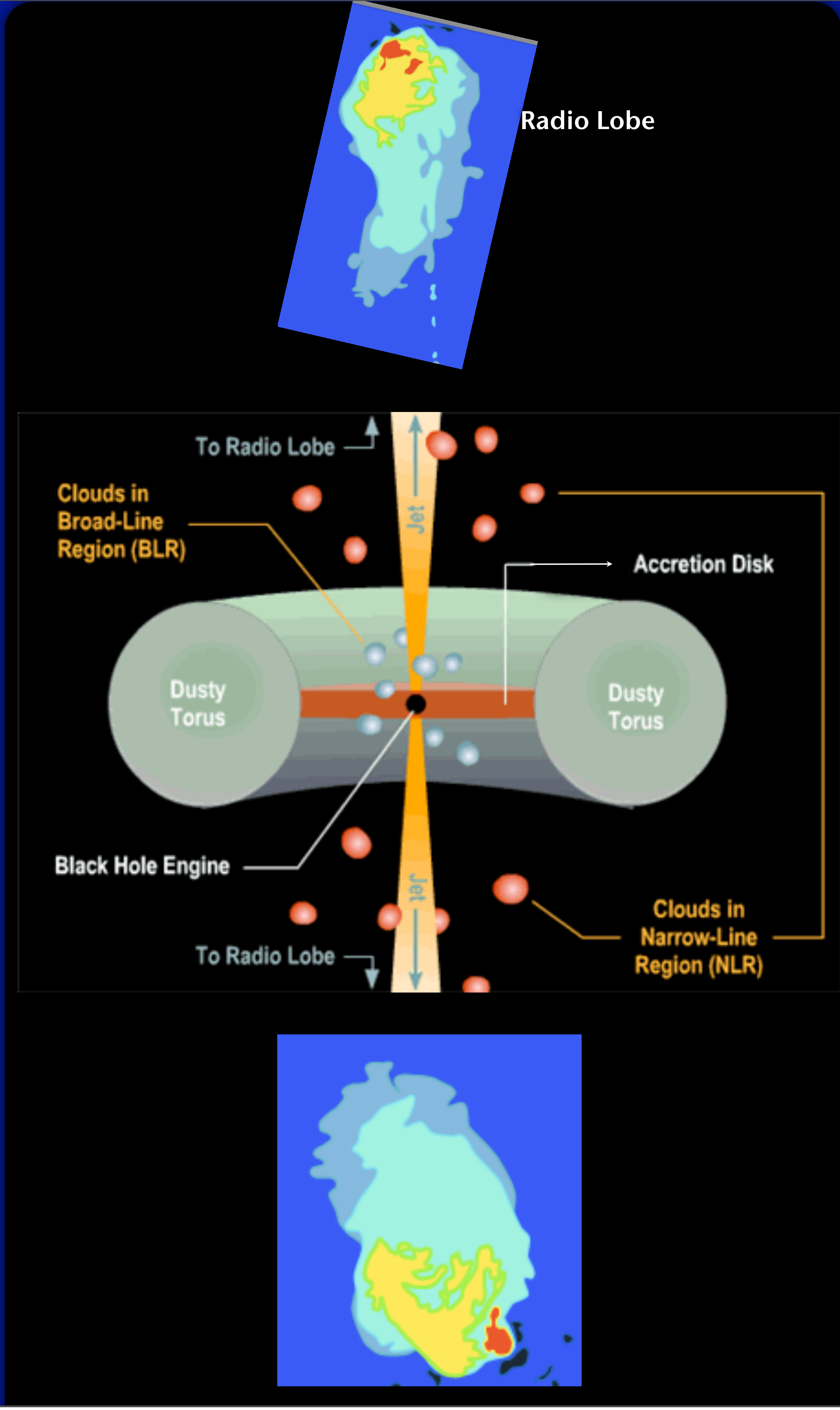


3C 98
VLA

FR II only have Hot-spots!

FR I The separation between the points of peak intensity in the two lobes is smaller than half the largest size of the source. (R<0.5) . $P_{178\ MHz} < 10^{25}$ Watt Hz^{-1} sr^{-1}

FR II: The separation between the points of peak intensity in the two lobes is greater than half the largest size of the source (R>0.5). $P_{178\ MHz} > 10^{25}$ Watt Hz^{-1} sr^{-1}



Some numbers for a typical AGN

BH Mass $\sim 10^8 M\odot$

Luminosity $\sim 10^{44}\ erg\ s^{-1}$

BH radius $\sim 3 \times 10^{13}\ cm$

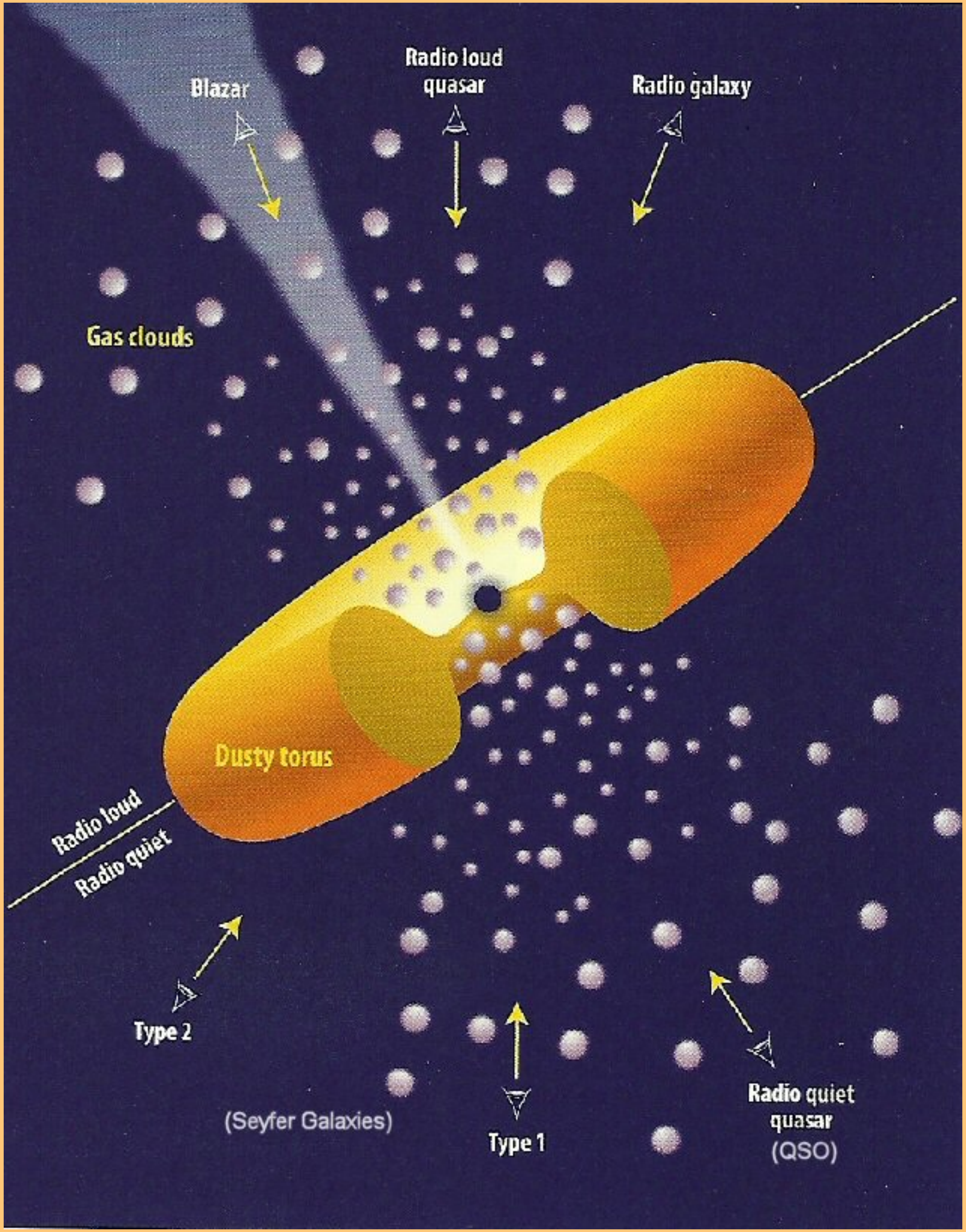
BLR radius $\sim 2 - 20 \times 10^{16}\ cm$

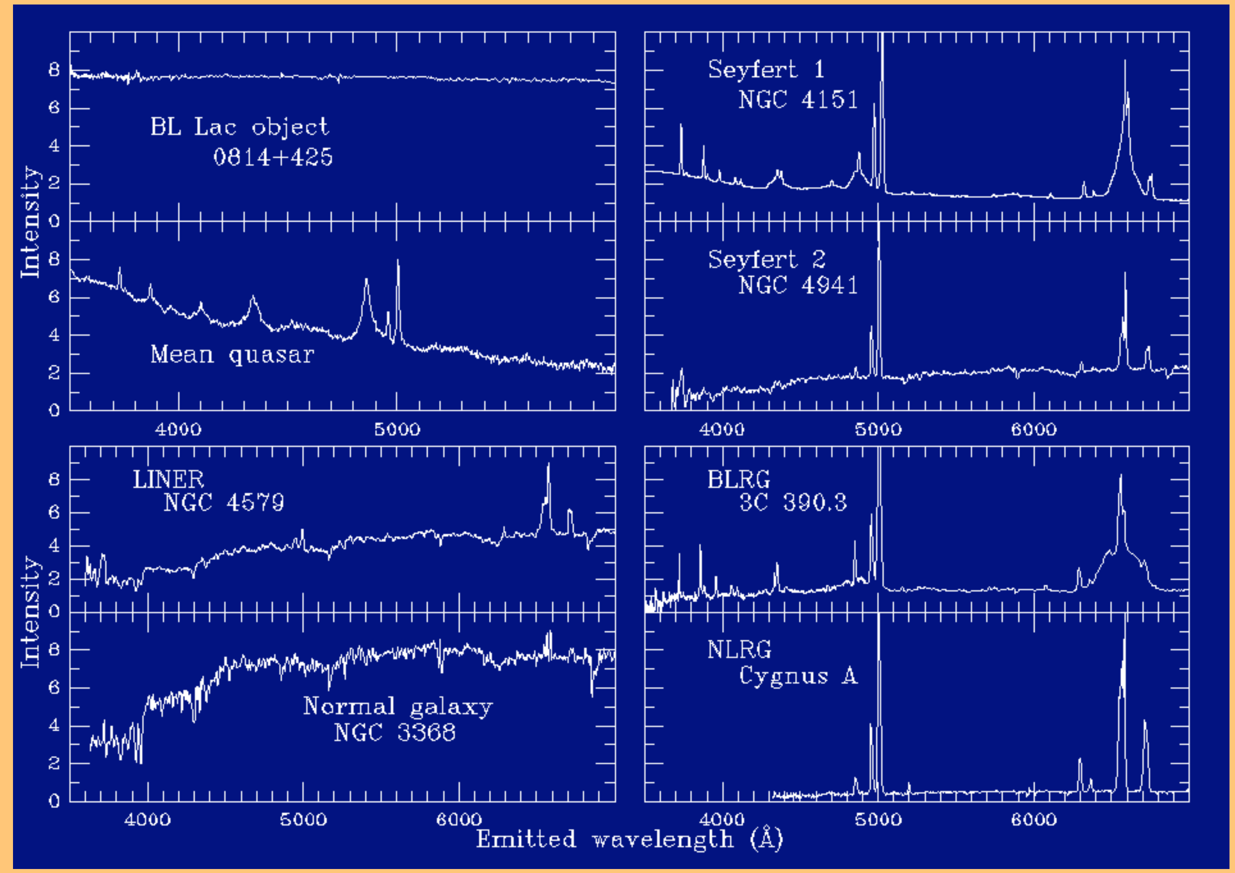
NLRG radius $\sim 10^{18} - 10^{20}\ cm$

In RL AGNs

Jet can be observed at $\sim 10^{17}\ cm$

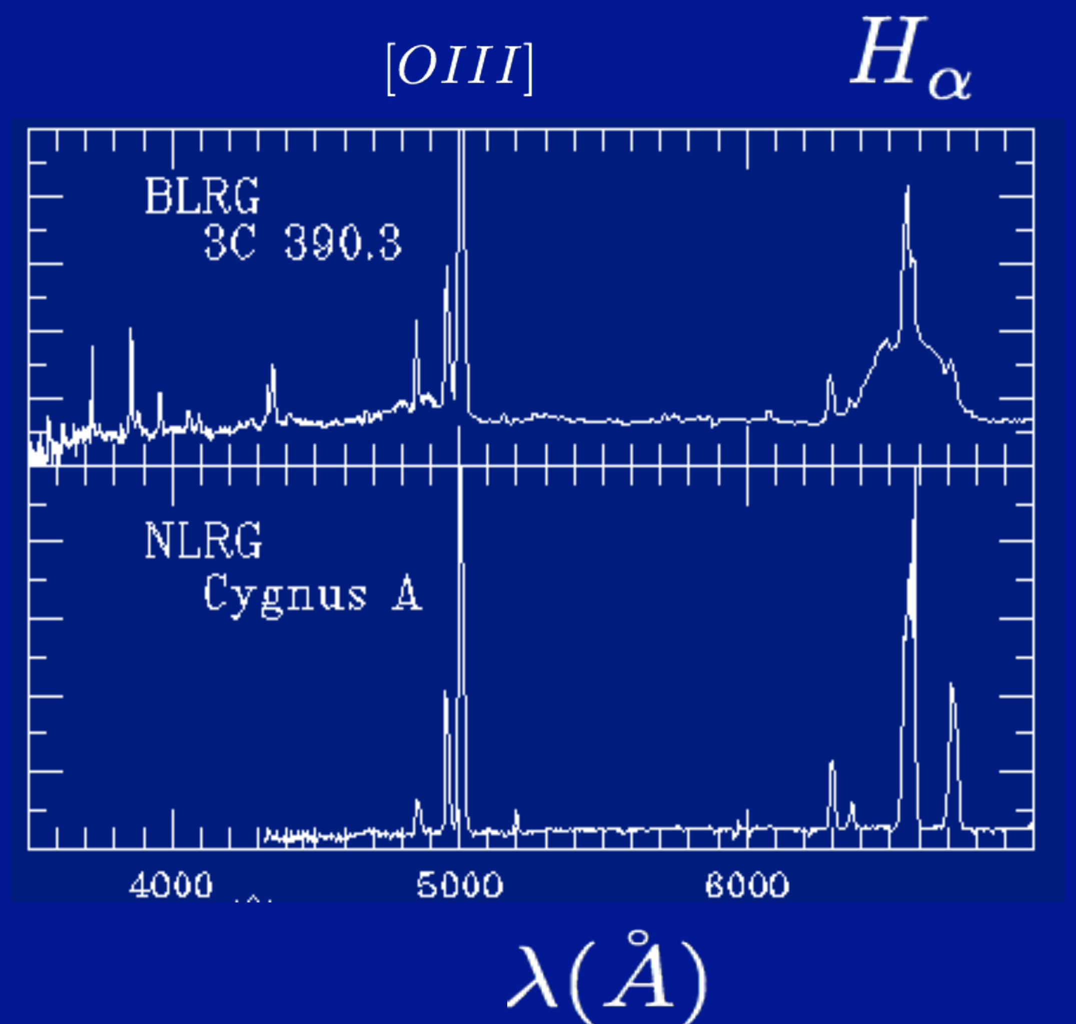
Jet ends at Kpc distances forming radio lobes


Blazar
Radio loud
quasar
Radio galaxy
Gas clouds
Dusty torus
Radio loud
Radio quiet
Type 2
(Seyfer Galaxies)
Type 1
Radio quiet
quasar
(QSO)


BL Lac object
0814+425
Seyfert 1
NGC 4151
Mean quasar
Seyfert 2
NGC 4941
LINER
NGC 4579
BLRG
3C 390.3
Normal galaxy
NGC 3368
NLRG
Cygnus A
Intensity
Emitted wavelength (Å)

Optical classifications:

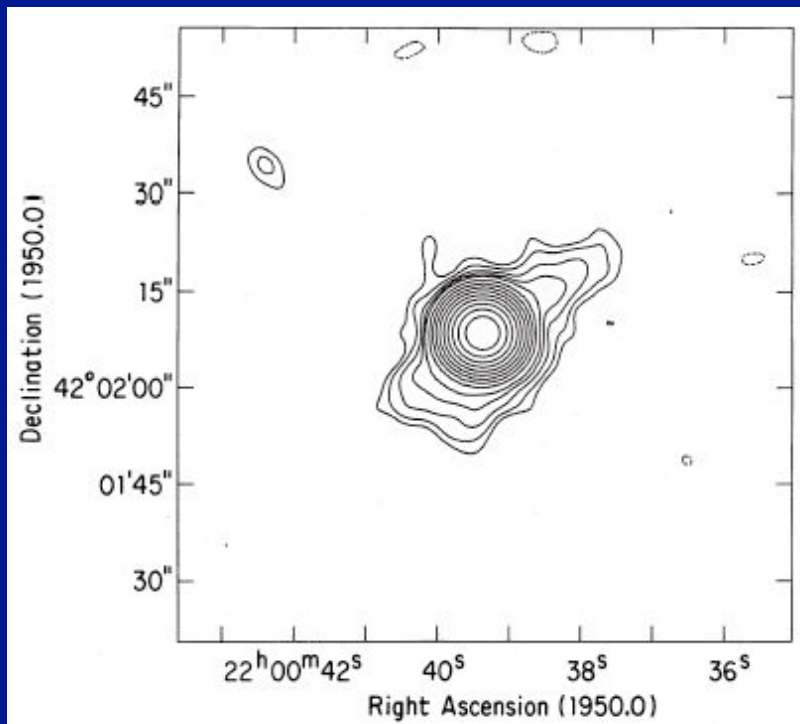
Brod Line Radio Galaxy (BLRG) Quasars (large z)	bright continuum and broad emission lines from hot high velocity gas	FRII
Narrow line Radio Galaxy (NLRG) HEG, LEG	weak continuum and only narrow emission lines	FRII FRI



NLRG/LEG:
narrow emission lines:
$EW_{[OIII]} < 10$ A and /or
O[II]/[OIII] > 1

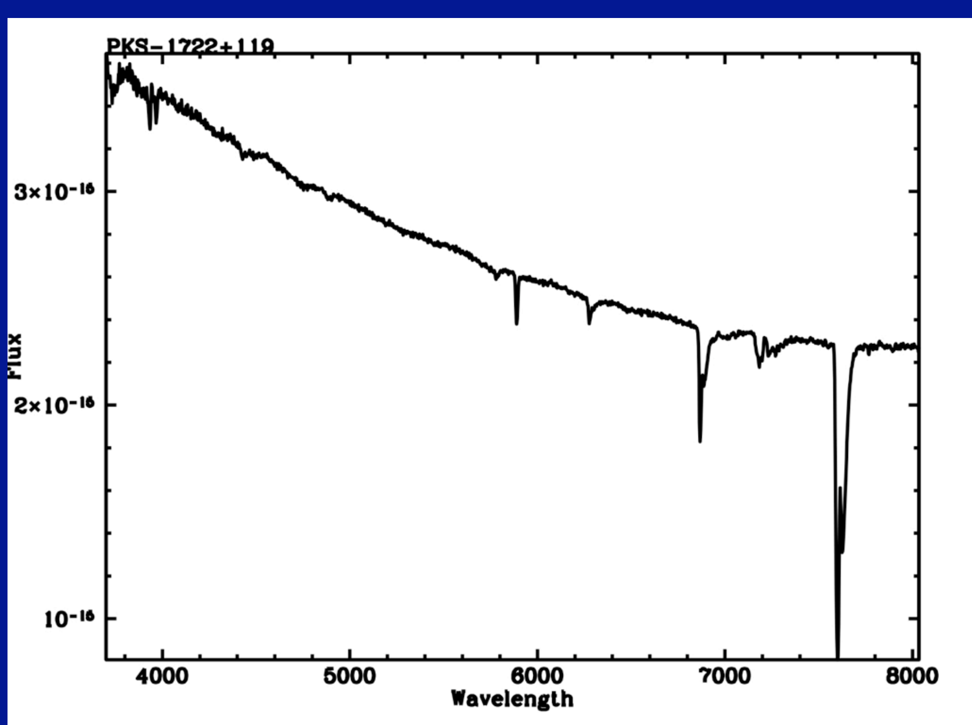
Blazars: BL Lacs (BL) and Flat Spectrum Radio Quasar (FSRQ)

Compact in radio

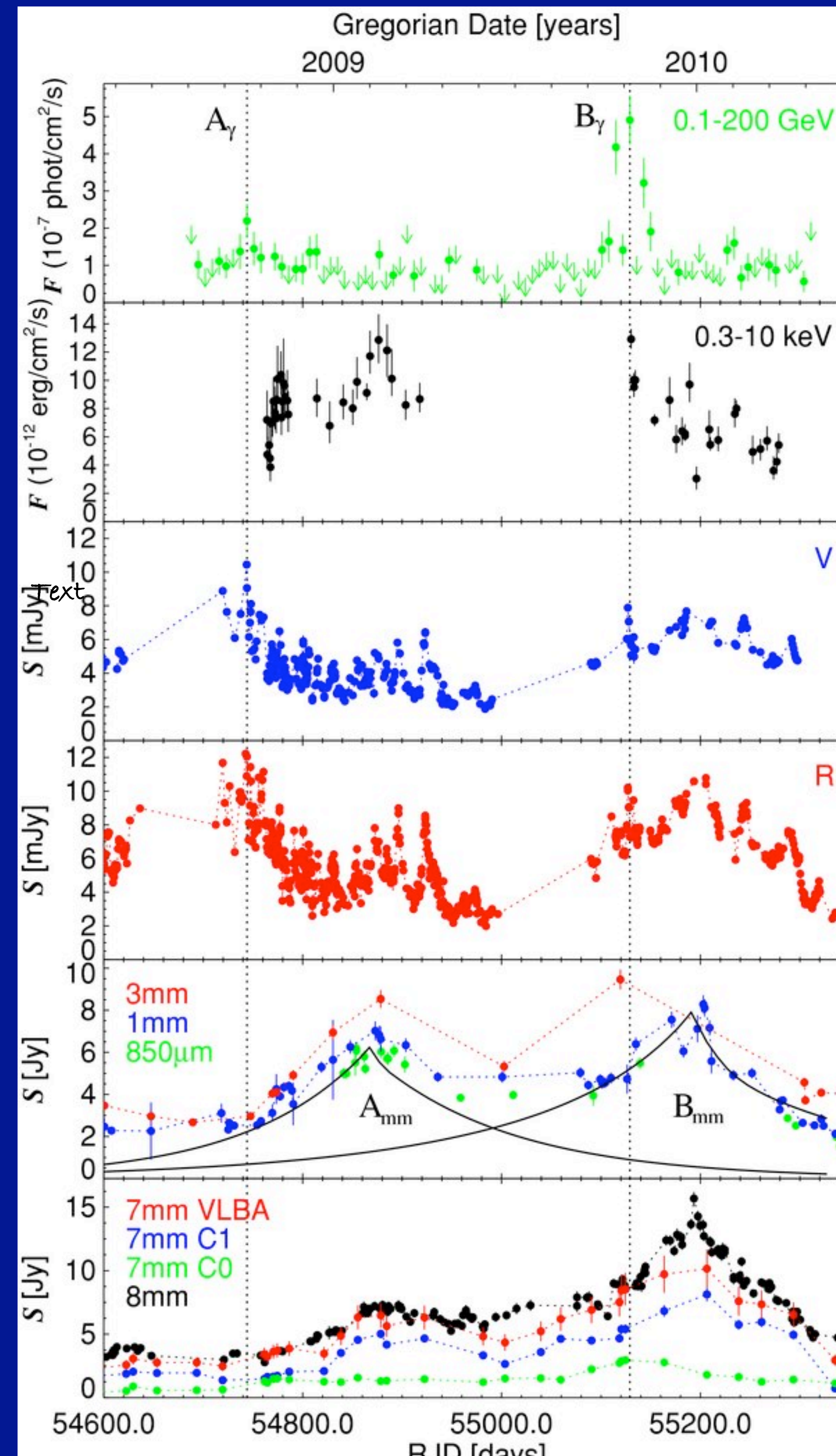


20 cm VLA image of BL Lacertae (Antonucci 1986, ApJ 304, 634)

Almost featureless in the optical band

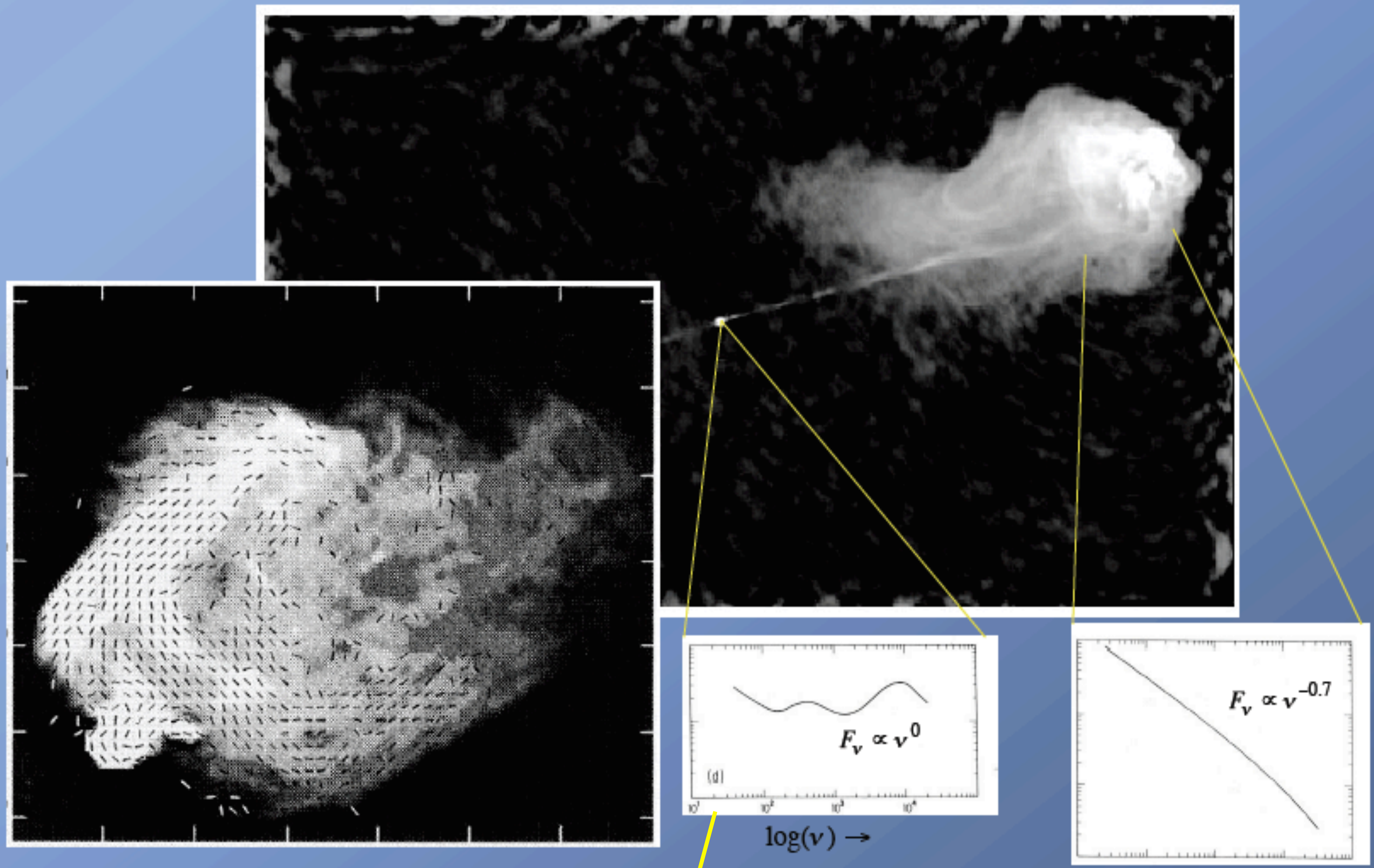


Extremely variable



OJ 287 light curves
from radio to gamma
Agudo et al. 2011ApJL
726, L13

Radio properties



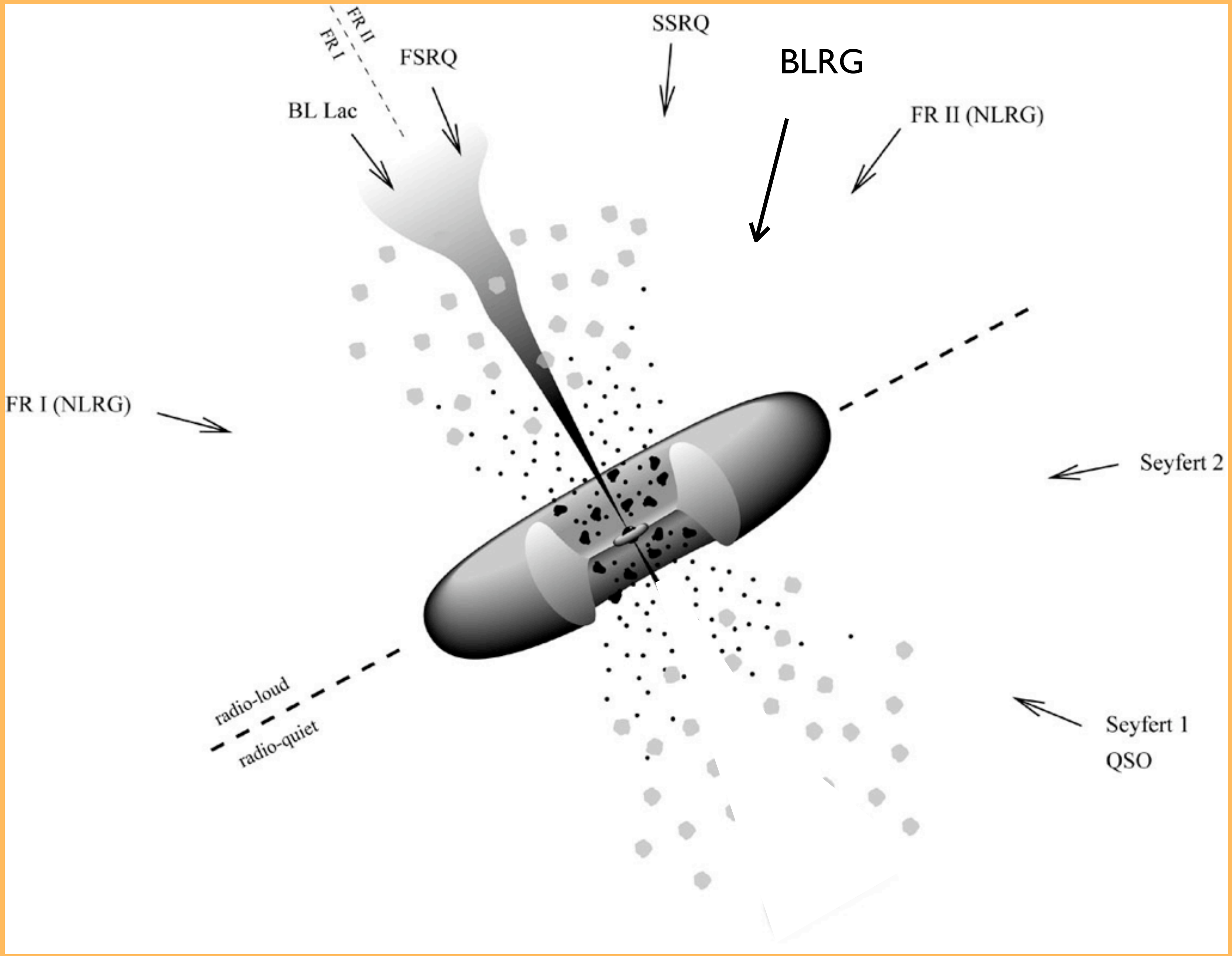
High polarization

Flat spectrum cores

Steep spectrum lobes

Flat Spectrum Radio Quasar FSRQ

Steep Spectrum Radio Quasars SSRQ


FR II
FR I
FSRQ
SSRQ
BLRG
BL Lac
FR II (NLRG)
FR I (NLRG)
Seyfert 2
radio-loud
radio-quiet
Seyfert 1
QSO

The Doppler Factor $\delta(\beta, \theta)$ is the key parameter

$$\delta = [\gamma(1 - \beta cos\theta)]^{-1}$$

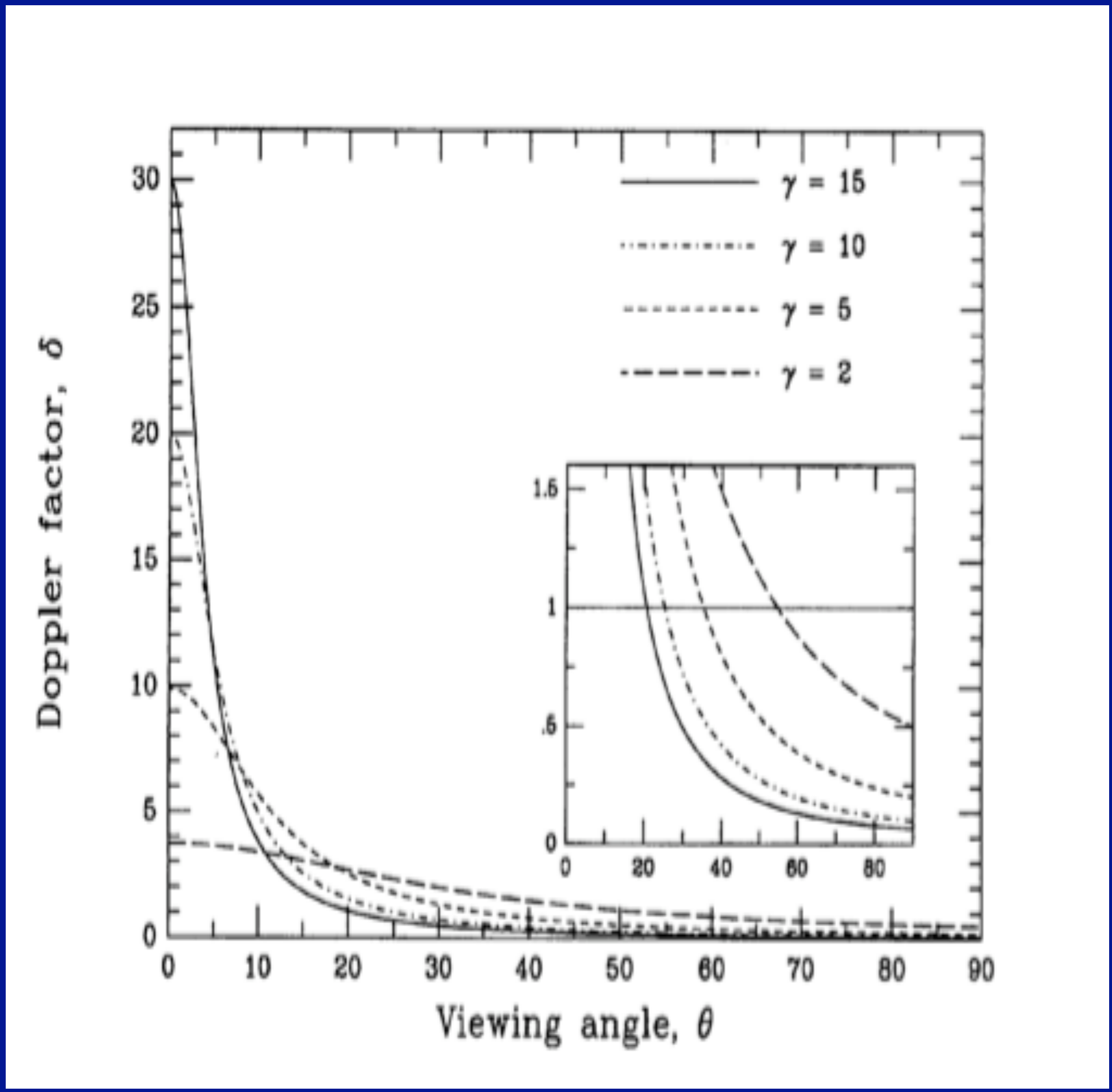
- $\beta = v/c$ is the bulk velocity
- $\gamma = \sqrt{(1-\beta^2)}$ is the Lorentz factor
- θ is the angle between the jet axis and the line of sight

The Doppler factor relates intrinsic and observed flux for a moving source at relativistic speed v=β c.

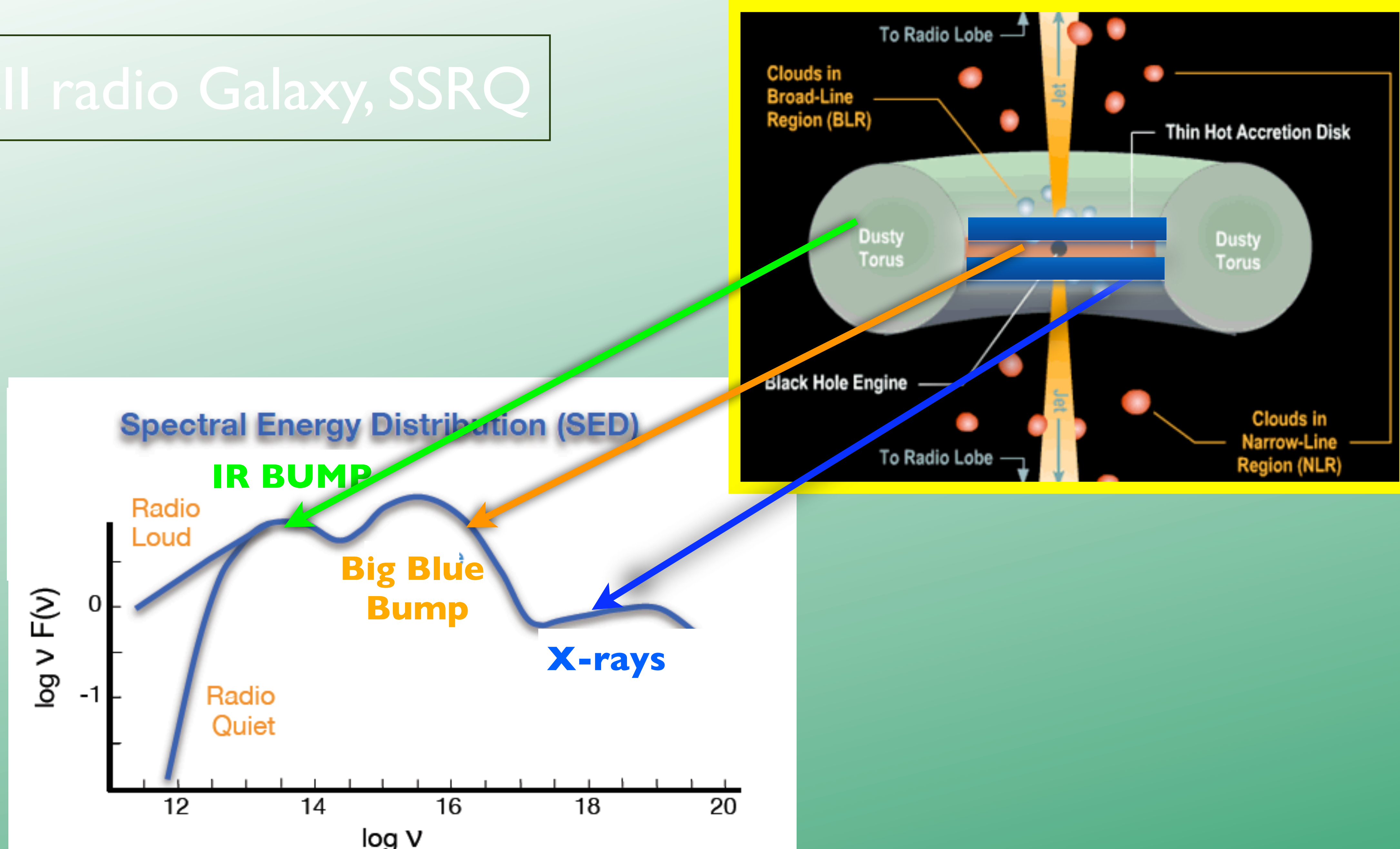
For an **intrinsic** power law spectrum: $F'(\nu') = K (\nu')^{-a}$ the **observed** flux density is

$$F_\nu(\nu) = \delta^{3+\alpha} F'_{\nu'}(\nu)$$

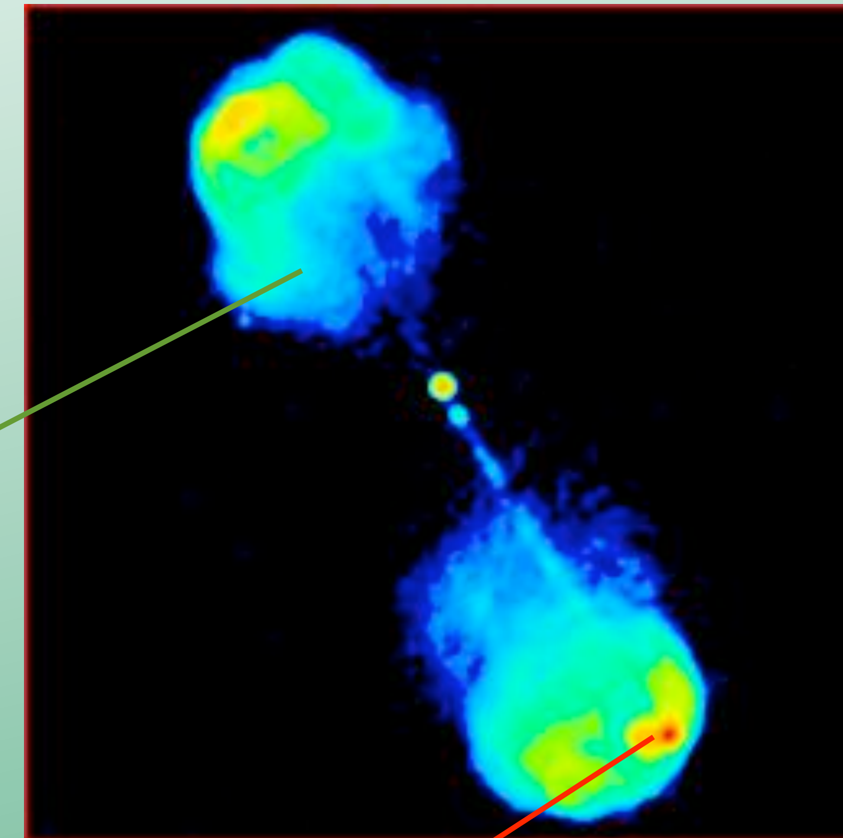
$$\Delta t = \Delta t'/\delta$$

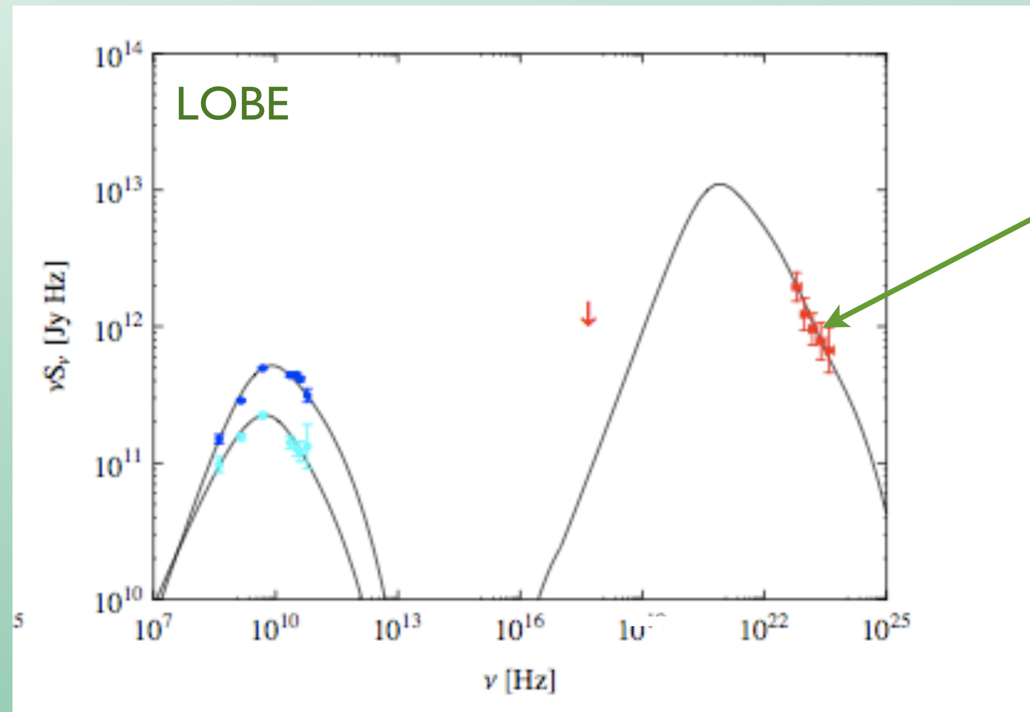


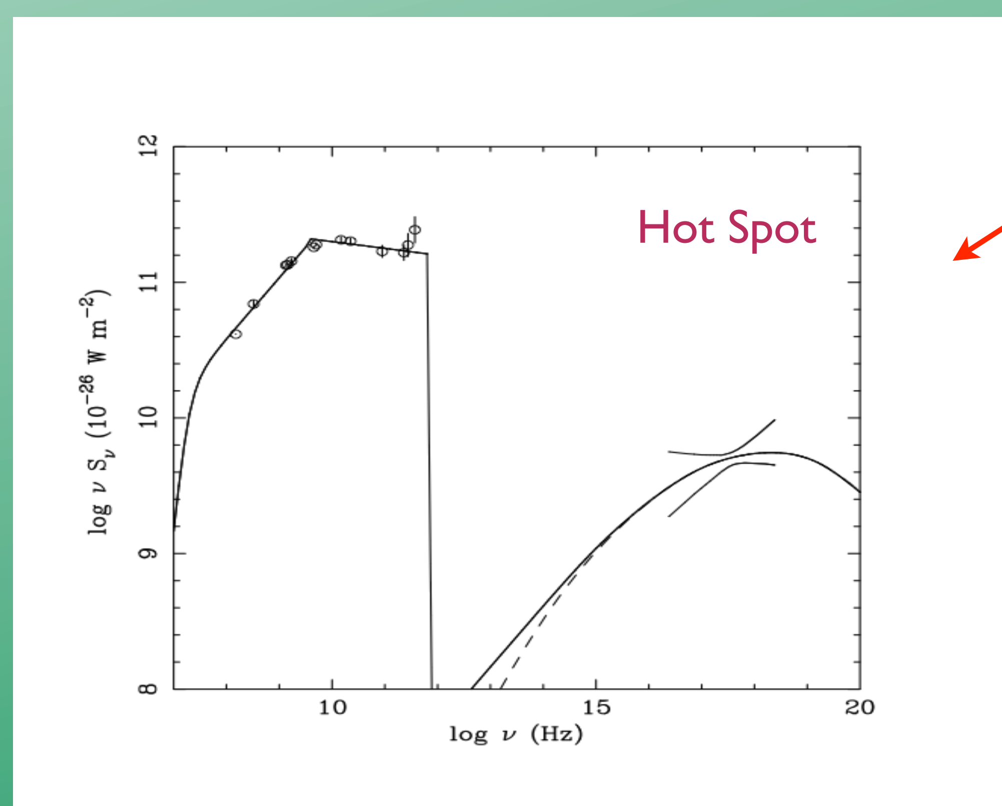
Seyfert, FRII radio Galaxy, SSRQ

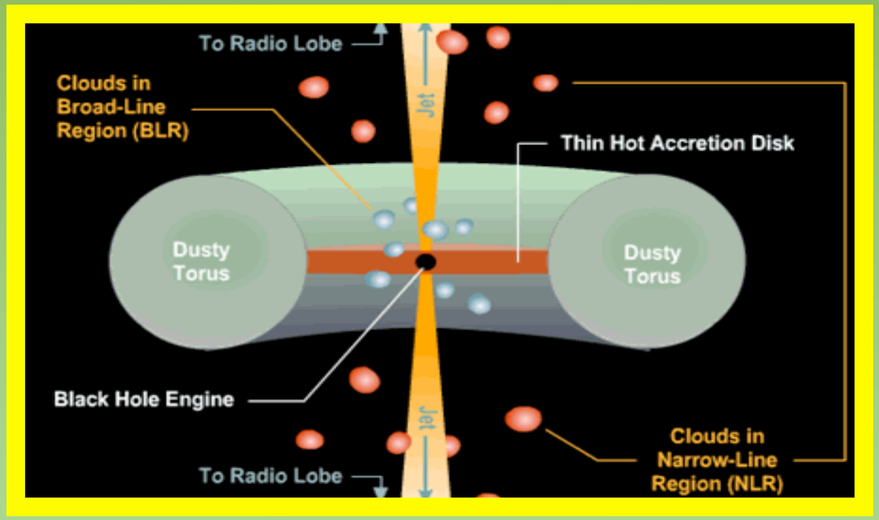


Radio Galaxies: kpc components

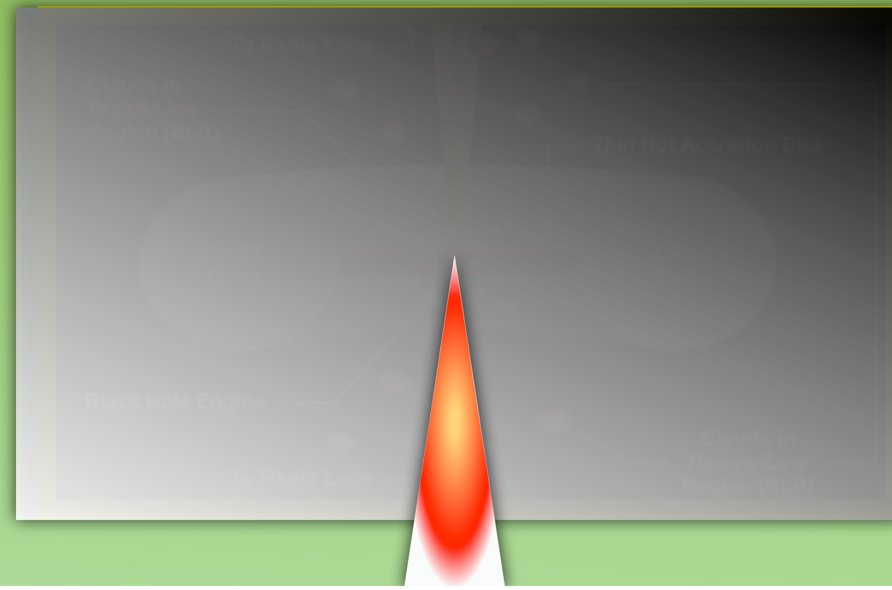


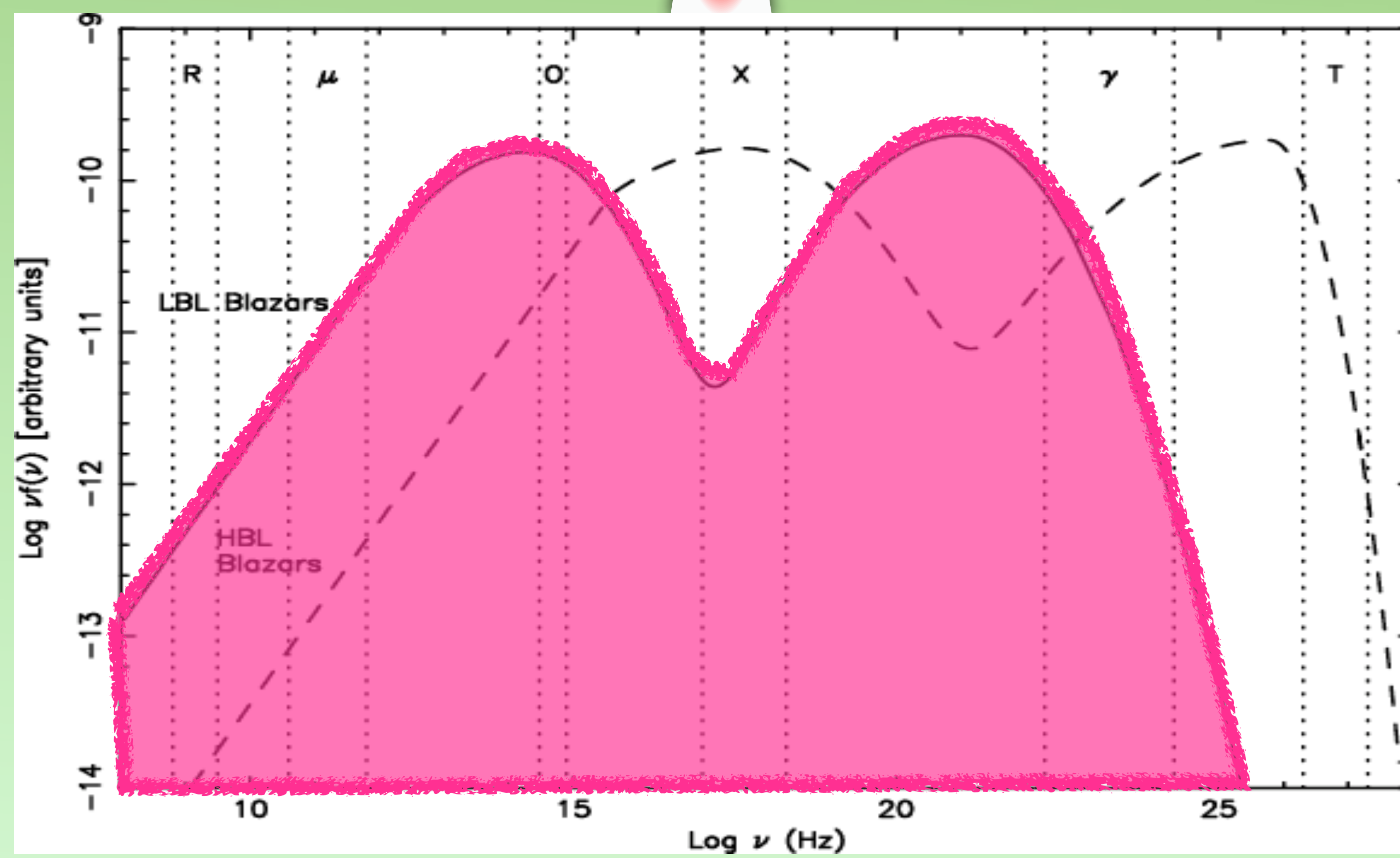




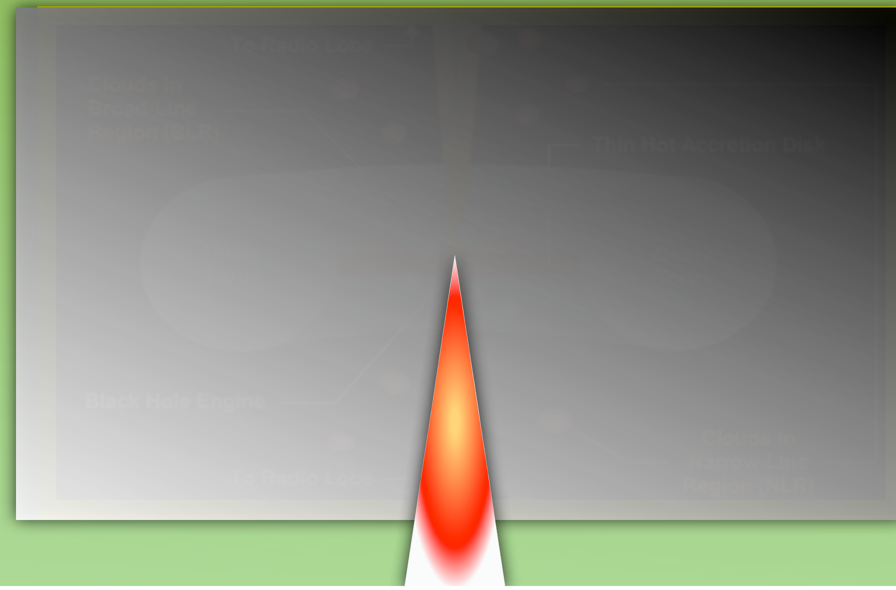

To Radio Lobe
Clouds in
Broad-Line
Region (BLR)
Jet
Thin Hot Accretion Disk
Dusty
Torus
Dusty
Torus
Black Hole Engine
Jet
Clouds in
Narrow-Line
Region (NLR)
To Radio Lobe

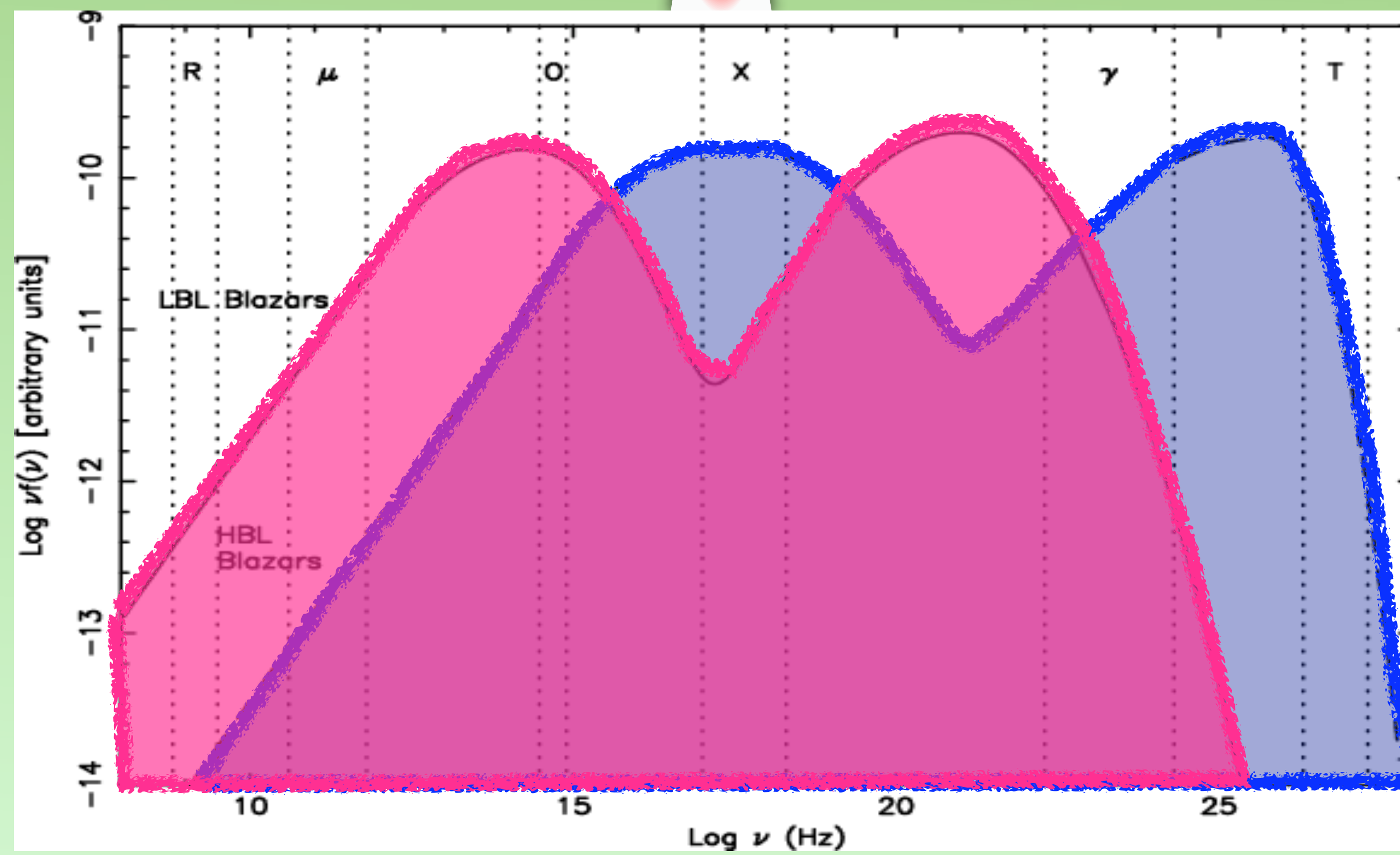
BLAZARS




R
μ
O
X
γ
T
LBL Blazars
HBL
Blazars
Log νf(ν) [arbitrary units]
Log ν (Hz)
−9
−10
−11
−12
−13
−14
10
15
20
25

BLAZARS




R
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Log νf(ν) [arbitrary units]
Log ν (Hz)
−9
−10
−11
−12
−13
−14
10
15
20
25

Brief summary of the physical processes responsible for the observed radiation in the X-ray band

Radiative Processes

Thermal emission

- Disk/accretion flow
- Corona

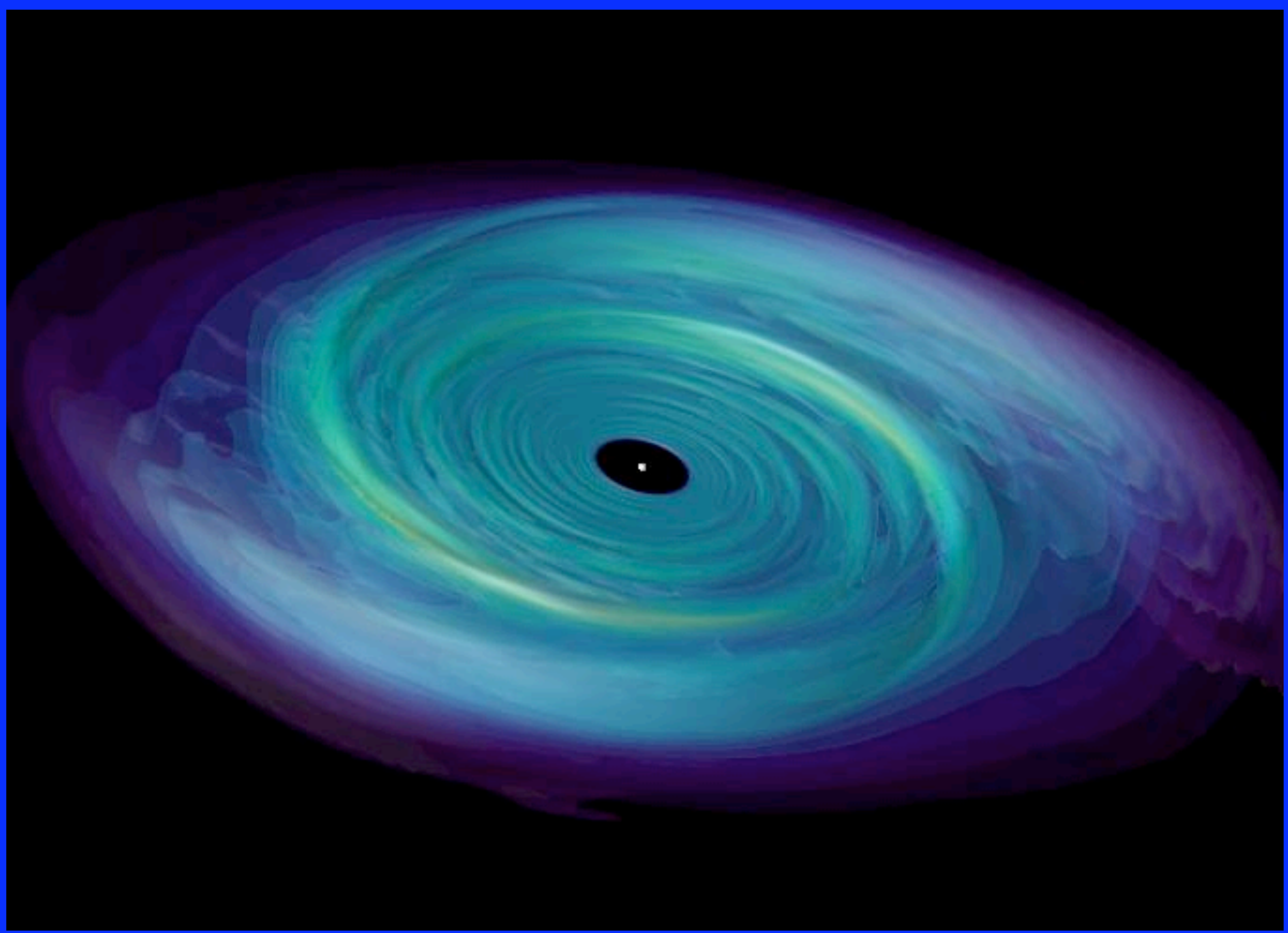
Non-thermal emission

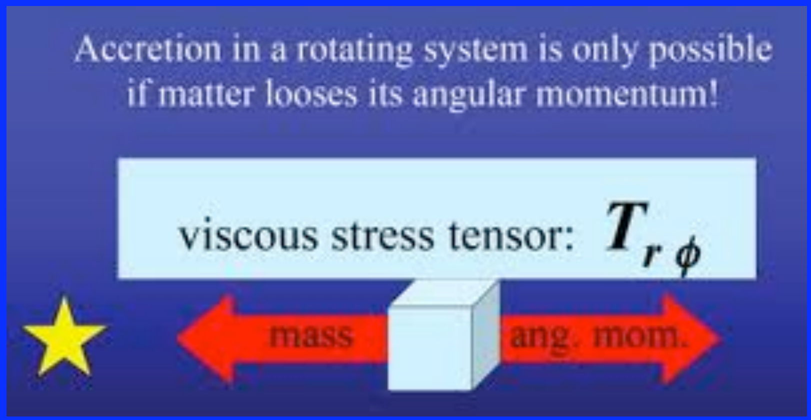
* Jet
* Radio Lobes
* Hot Spot

Accretion

Thermal process

Disks usually rotate such that each fuid element is moving almost in a circular orbit. As the angular velocity is a function of radius, there is a shearing fow. This means that coupling between adjacent radii exerts a force. Given that the outer parts rotate more slowly, inner tries to speed up outer, giving it a higher velocity. This increases the angular momentum of the outer, decreases the angular momentum of the inner, so net result is that angular momentum is transferred outwards and mass flows inwards





Viscosity transports angular momentum outward, allowing the accretion gas to spiral in toward the BH. Viscosity acts a source of heat that is radiated away.

Accretion is the physical process by which black hole aggregates matter from their surroundings. The gravitational energies that such matter must release for accretion to occur is a powerful source of luminosity L.

$$L_{rad} = \eta \dot{M} c^2$$

The efficency of the process is:

with $\eta \propto M/R$ (compactness of the system)

and $\dot{M}$ accretion rate in $M_{\odot} yr^{-1}$

In case of a black hole the size is defined in term of the Schwarzschild radius

$$R_s = \frac{GM}{c^2} \sim 3 \times 10^{13}\ M_8\ \ cm$$

Eddington Luminosity L_E is the luminosity at which the outward force of the radiation pressure is balanced by the inward gravitational force

$$L_E = \frac{4\pi G m_p c}{\sigma_e} M \sim 1.3 \times 10^{38}\ (M/M_{\odot})\ (erg\ s^{-1})$$

$$L = \eta \dot{M} c^2 \quad \text{with} \quad \eta \propto \frac{M}{r}$$

The potential energy of a mass m a distance r from the central mass M is

$$U = \frac{GMm}{r}$$

Il rate at which the energy potential can be converted in radiation is given

$$L \sim \frac{dU}{dt} = \frac{GM}{r}\frac{dm}{dt} = \frac{GM\dot{M}}{r}$$

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Il rate at which the energy potential can be converted in radiation is given

$$L \sim \frac{dU}{dt} = \frac{GM}{r}\frac{dm}{dt} = \frac{GM\dot{M}}{r}$$

This efficency is maximized in the case of a black hole the size of which can be defined

as

$$R_s = \frac{2GM}{c^2}$$

that can be derived by the escape velocity of the line

$$V_{escape} = \sqrt{\frac{2GM}{R}}$$

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

accretion on to a black hole must power the most luminous phenomena in the universe

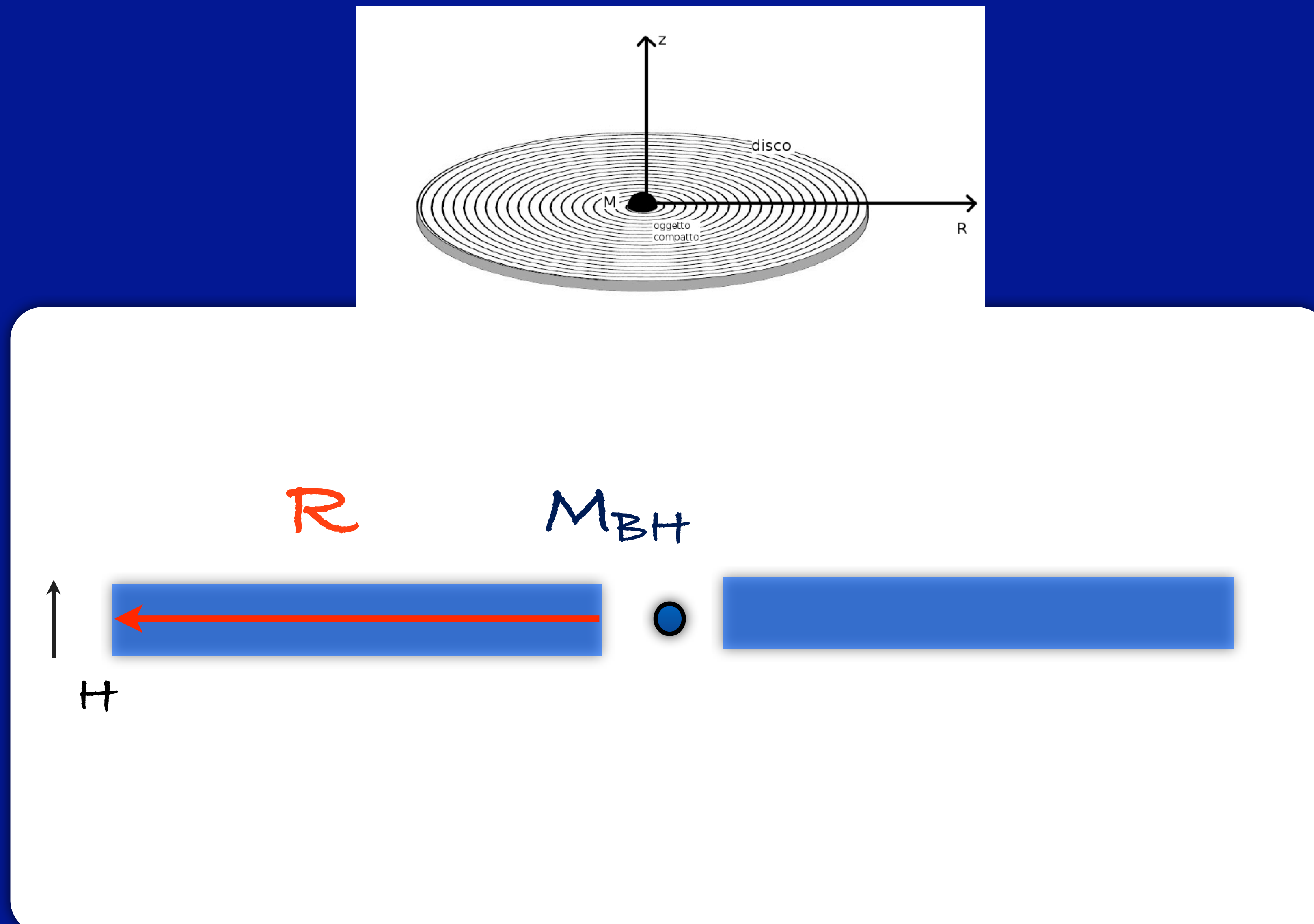
$$L_{acc} = \frac{GM}{R} \dot{M} = \eta c^2 \dot{M}$$

Quasars: $L \approx 10^{46} \, erg/s$ requires $\dot{M} = 1 M_{sun}/yr$

X—ray binaries: $L \approx 10^{39} \, erg/s$ $10^{-7} M_{sun}/yr$

Gamma—ray bursters: $L \approx 10^{52} \, erg/s$ $0.1 M_{sun}/\sec$

Shakura & Sunyaev thin optically thick disk model (standard model)



Thin H/R<< 1

Thick , in the sense that each element of the disk radiates as a black body

If the disk is optically thick will radiate ad a blackbody. Hence via Stephan' Law

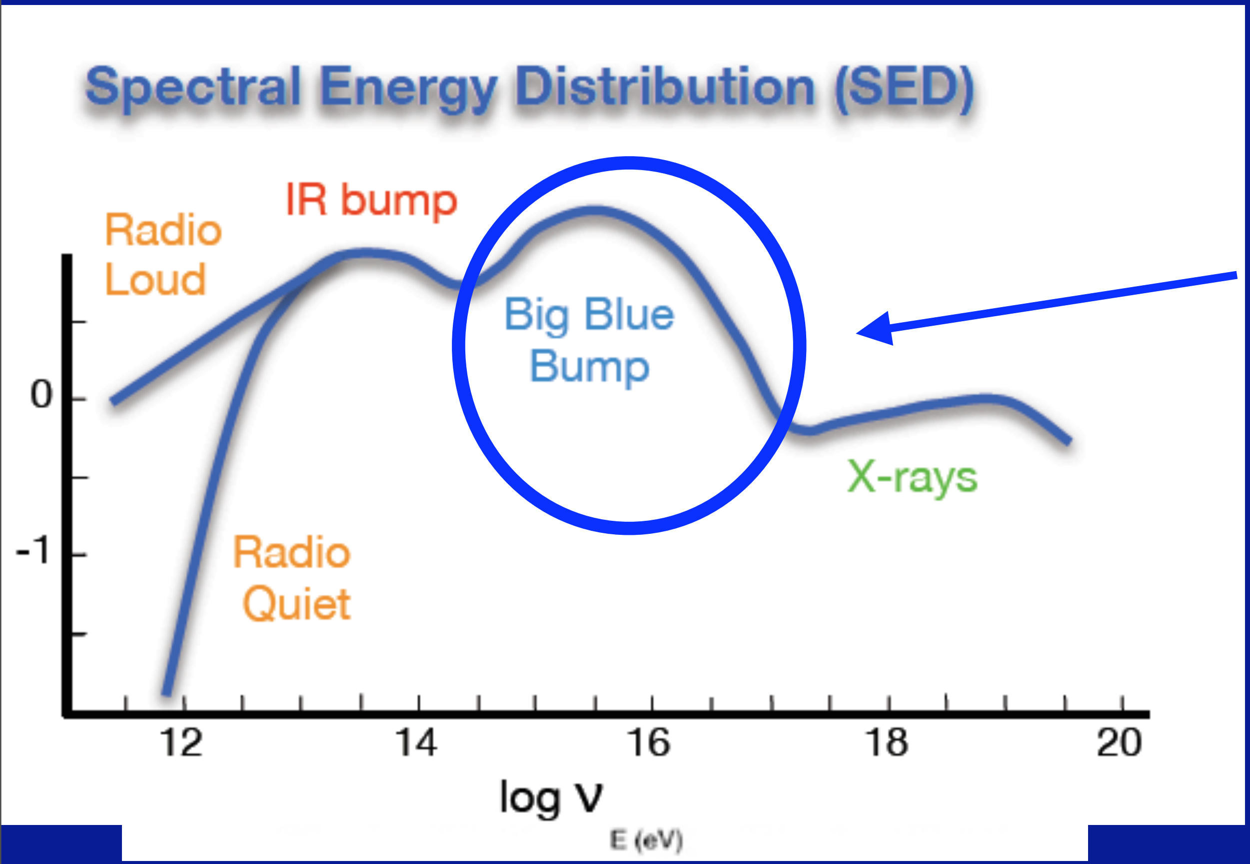
$$L = \frac{GM\dot{M}}{2r} = 2\pi r^2 \sigma T^4$$

$$T = \left(\frac{GM\dot{M}}{4\pi\sigma r^3}\right)^{1/4}$$

If the the disk is optically thick, we can approximate the local emission as blackbody and the effective temperature of the photosphere

$$T(r) \sim 6.3 \times 10^5 (\frac{\dot{M}}{\dot{M}_E})^{1/4} M_8^{-1/4} (\frac{r}{R_s})^{-3/4} \quad K$$

For AGN with $M_{BH} = 10_8 = 10^8 M_\odot$ $\quad \dot{M} \sim \dot{M}_E = \frac{L_E}{\eta c^2}$

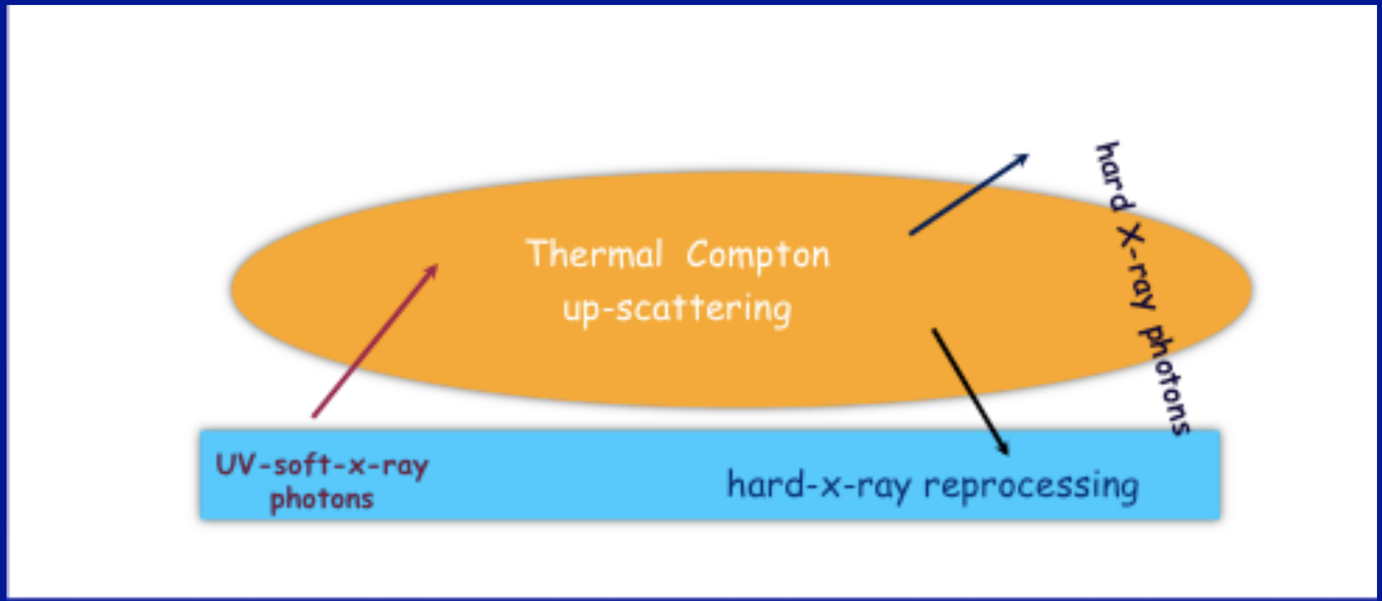


the peak occurs at UV-soft-X-ray region

$$\frac{\partial B}{\partial \nu} = 0 \qquad B(\nu) \propto \nu^3 [e^{\frac{h\nu}{kT}} - 1]^{-1}$$

$$\nu_{max} = 2.8kT/h \sim 10^{16} \quad Hz$$

Corona



Disk

Thermal Comptonization

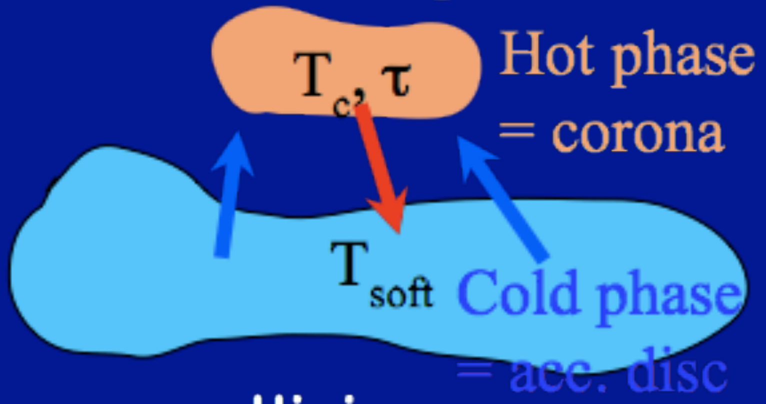
With this term we mean the process of multiple scattering of a photon due to a **thermal (Maxwellian)** distribution of electrons.

There is one fundamental parameter measuring the importance of the Inverse Compton process in general, and of multiple scatterings in particular: the Comptonization parameter, usually denoted with the letter **y**.

y = [average # of scatt.] x[average fractional energy gain for scatt.]

Thermal Comptonization

Comptonization on a thermal plasma of electrons characterized by a temp. T and optical depth τ



✓ mean relative energy gain per collision

$$\frac{\Delta E}{E} \simeq \left(\frac{4kT}{mc^2}\right) + 16\left(\frac{kT}{mc^2}\right)^2 \quad \text{for } E \ll kT$$

$$\leq \quad 0 \quad \text{for } E \gtrsim kT$$

✓ mean number of scatterings

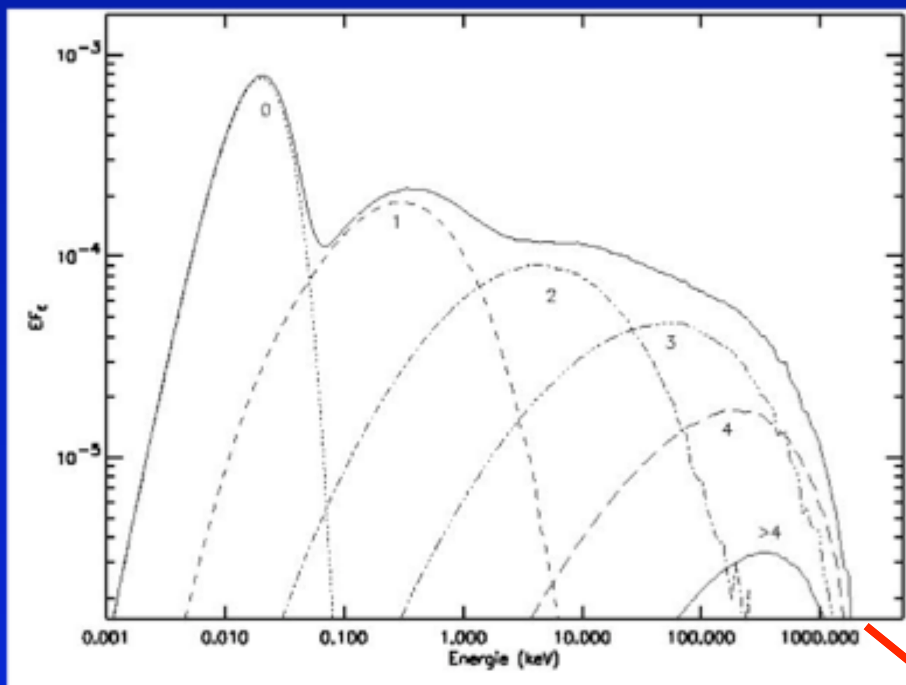
$$N \simeq (\tau + \tau^2)$$

➡ Compton parameter $y = \frac{\Delta E}{E} N$

$$E_f = E_i\, e^y$$

Thermal Comptonization Spectrum: the continuum

$$F_E \propto E^{-\Gamma(kT,\tau)} \exp\left(-\frac{E}{E_c(kT,\tau)}\right)$$



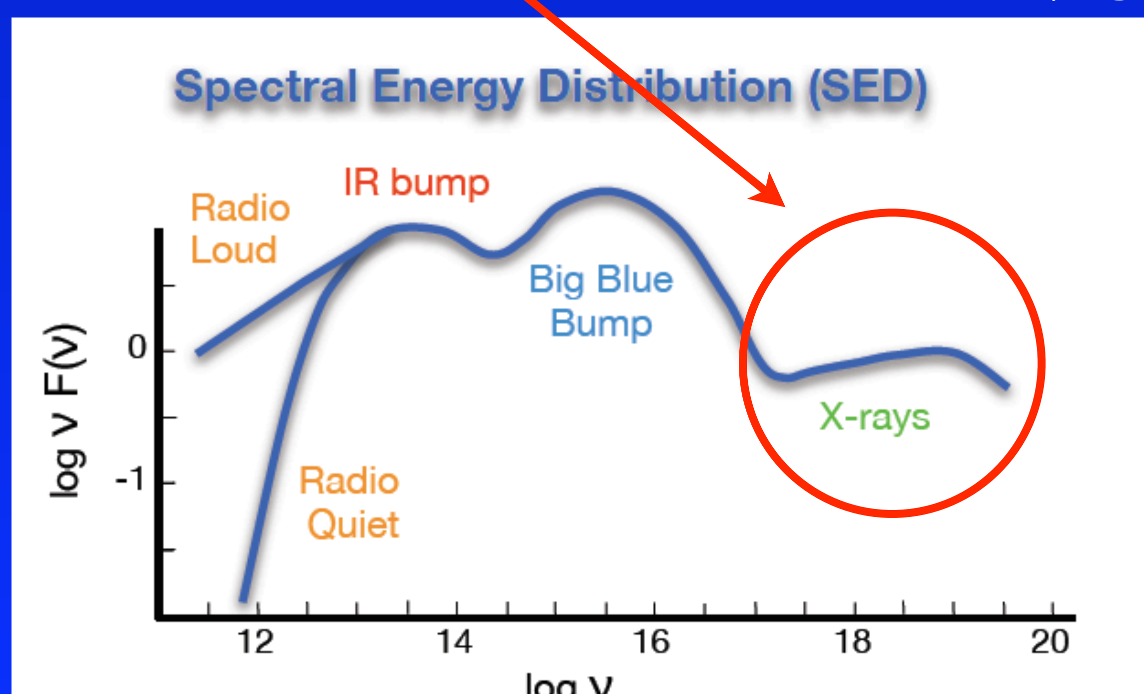
$$\Gamma(\tau, kT)$$

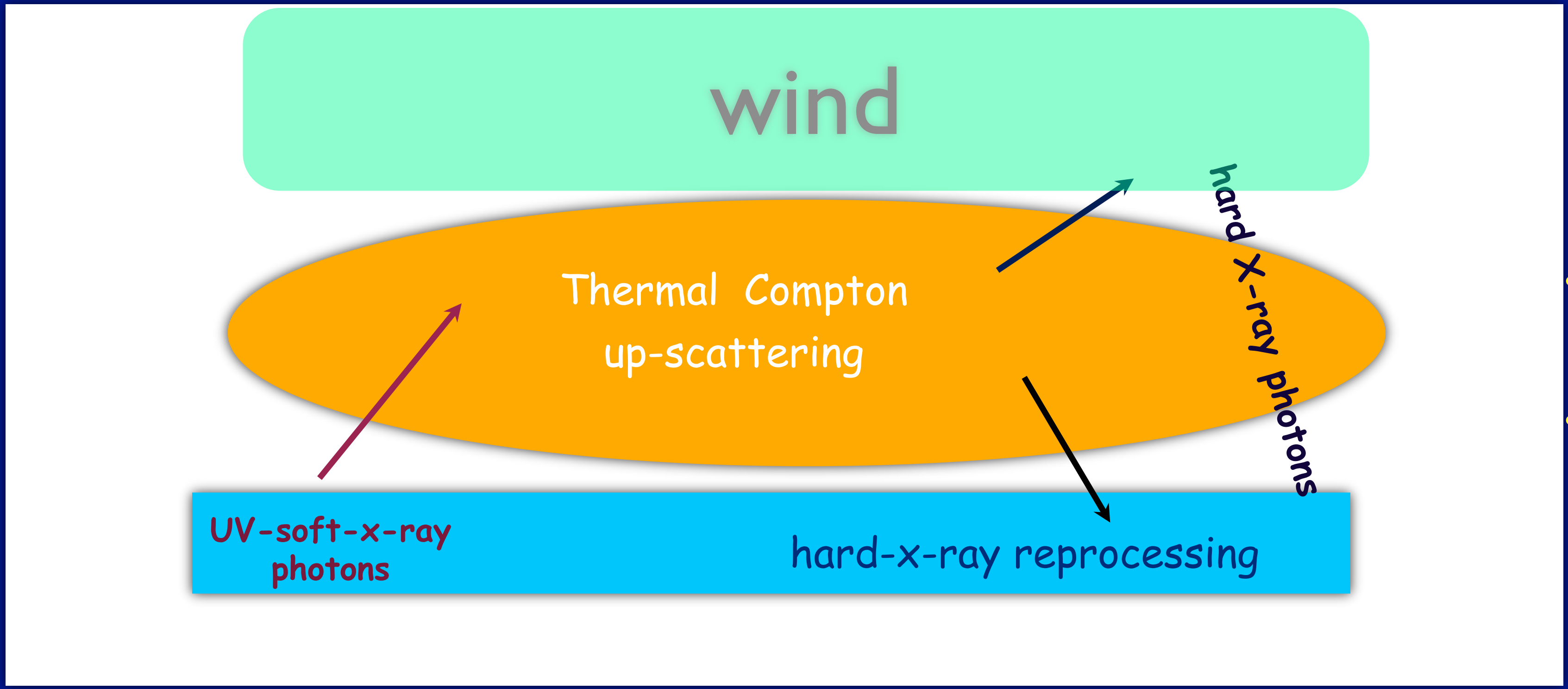
The exact relation between spectral index and optical depth depends on the geometry of the scattering region.

$$E_c \simeq kT$$

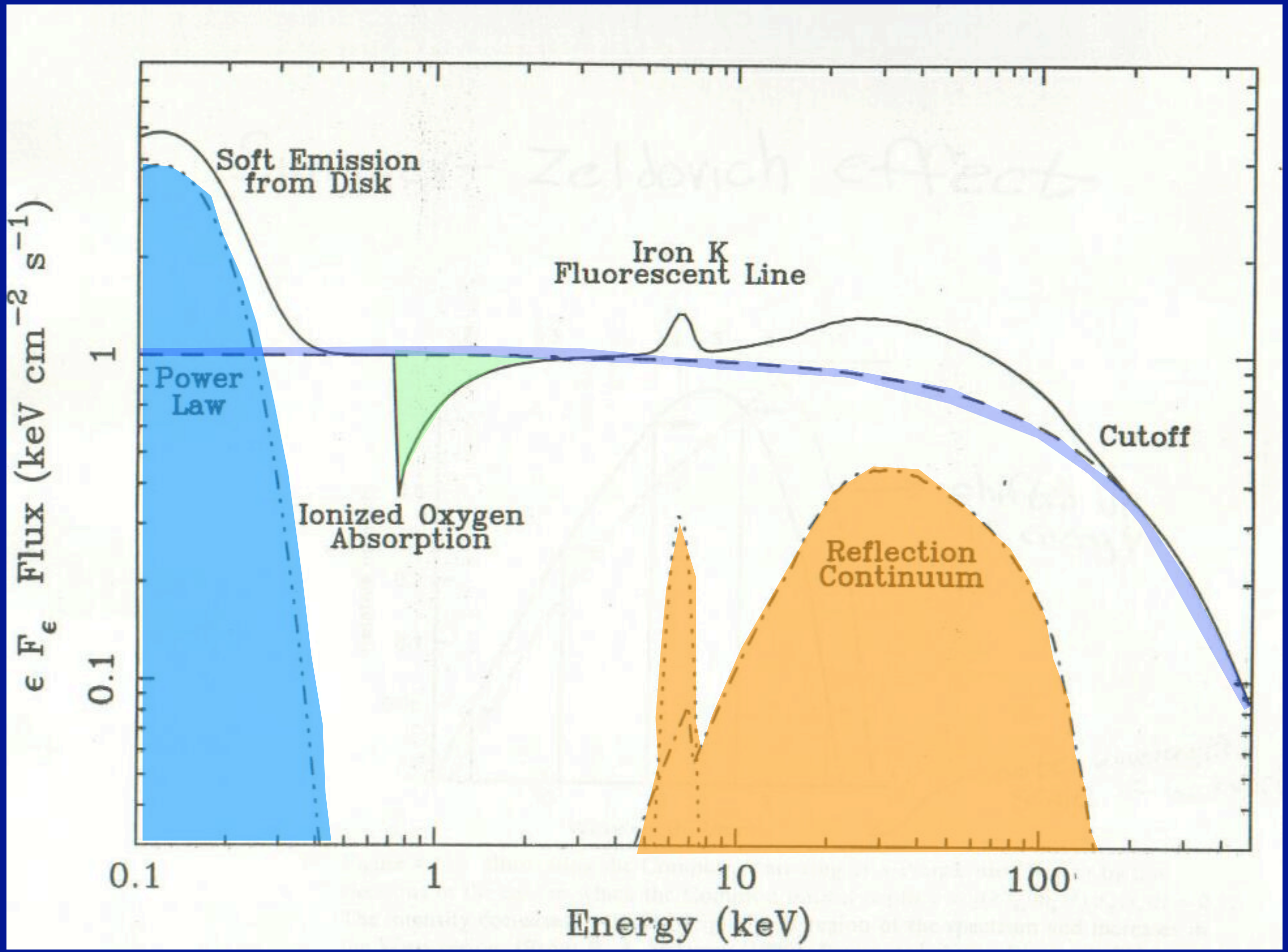
As photons approach the electron thermal energy, they no longer gain energy from scattering, and a sharp rollover is expected in the spectrum.

The observed high energy spectral cutoff yields information about the temperature of the underlying electron distribution.





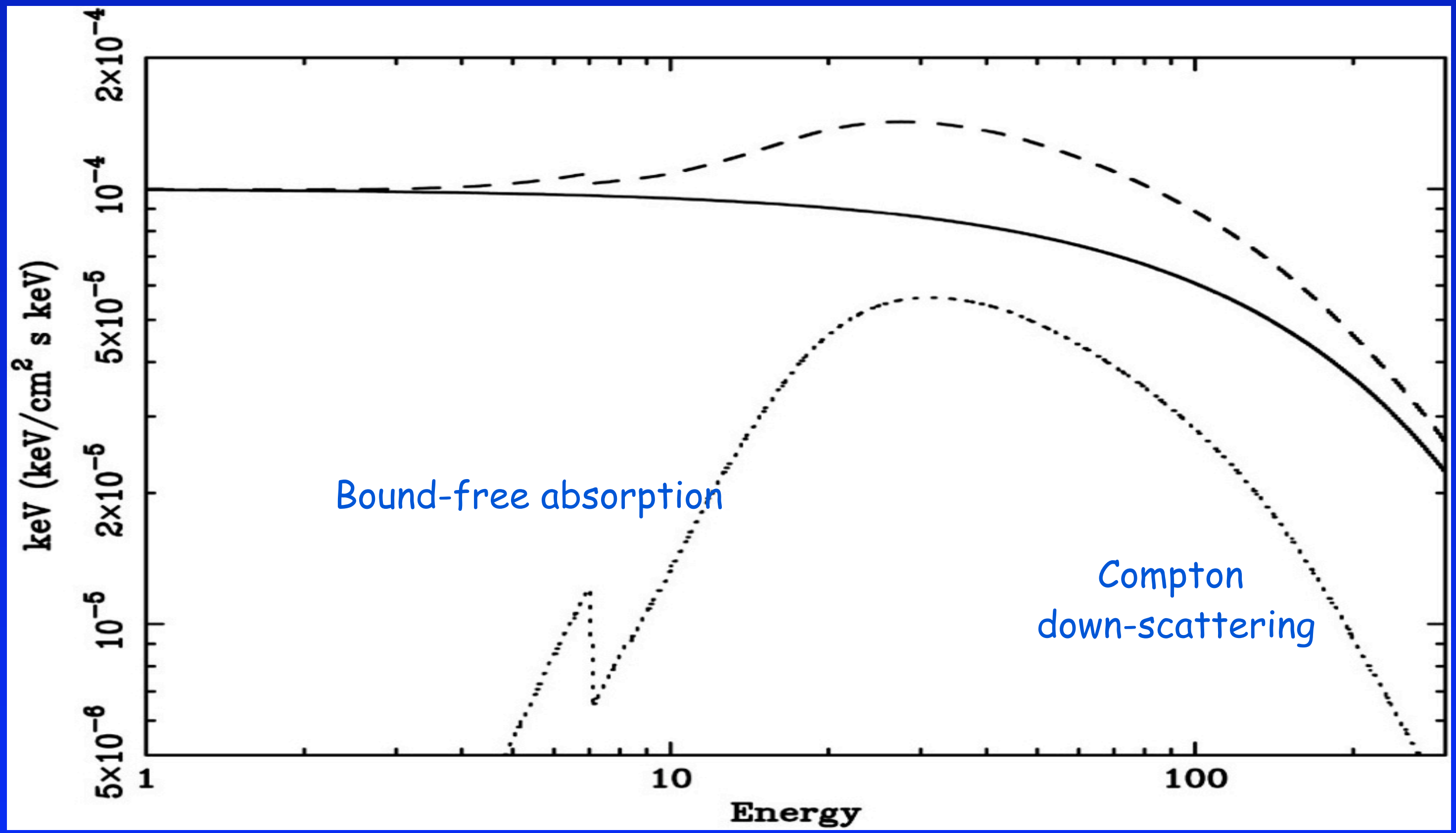
- Thermal Comptonization
- Hard Xray-reprocessing → Iron Line; → Compton hur



Reflection

At low energies <10 keV the high Z ions absorbs the X-rays. A major part of the opacity above 7 keV is due to Fe k-edge opacity .

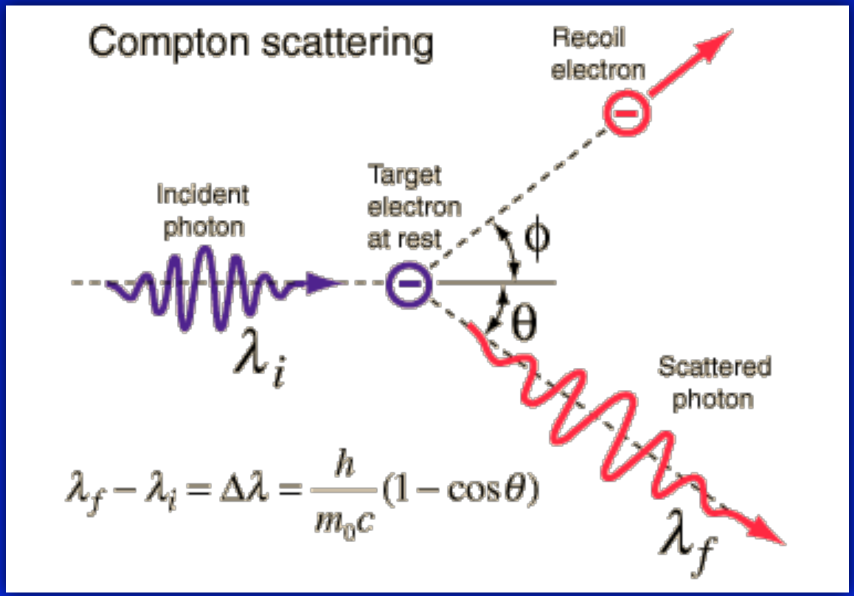
At high energies the Compton shift of the incident photons becomes important $\Delta\nu/\nu \sim -h\nu/m_e c^2$



Photon-electron interaction

Direct Compton Scattering

In this process the photon is absorbed and immediately reradiated by the electron into a different direction but it looses part of its initial energy. It can be thought as an heating mechanism.



$$x_1 = \frac{x_0}{1 + x_0(1 - cos\theta)}$$

$$x = \frac{h\nu}{m_e c^2} = \frac{h}{\lambda m_e c}$$

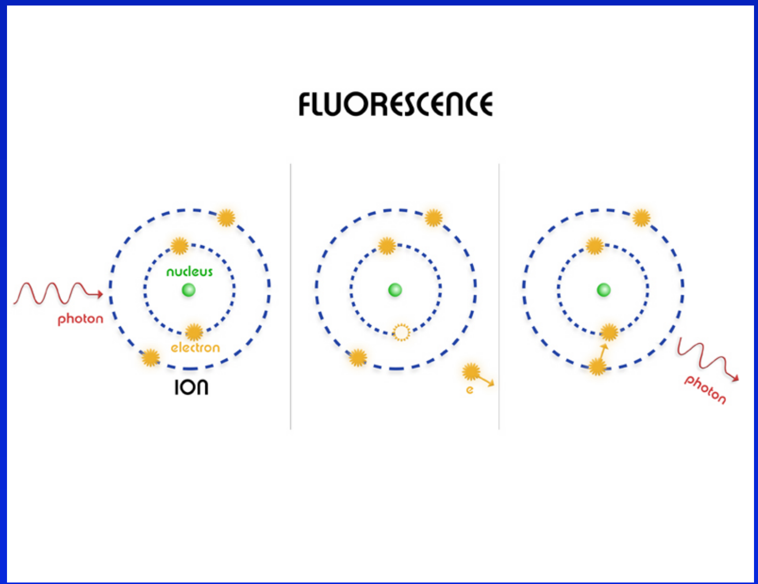
Thompson scattering: $h\nu \ll m_e c^2$

In this process the photon is absorbed and immediately reradiated by the electron into a different direction but it retains all of its initial energy. The cross section for Thompson scattering is

$$\sigma_T = \frac{8\pi}{3} \times (\frac{e^2}{4\pi\epsilon_0 m_e c^2})^2 = 6.7 \times 10^{-29}\ m^2$$

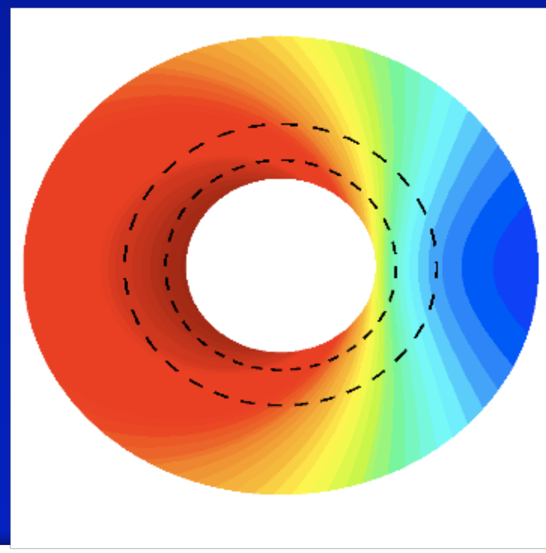
Iron Line

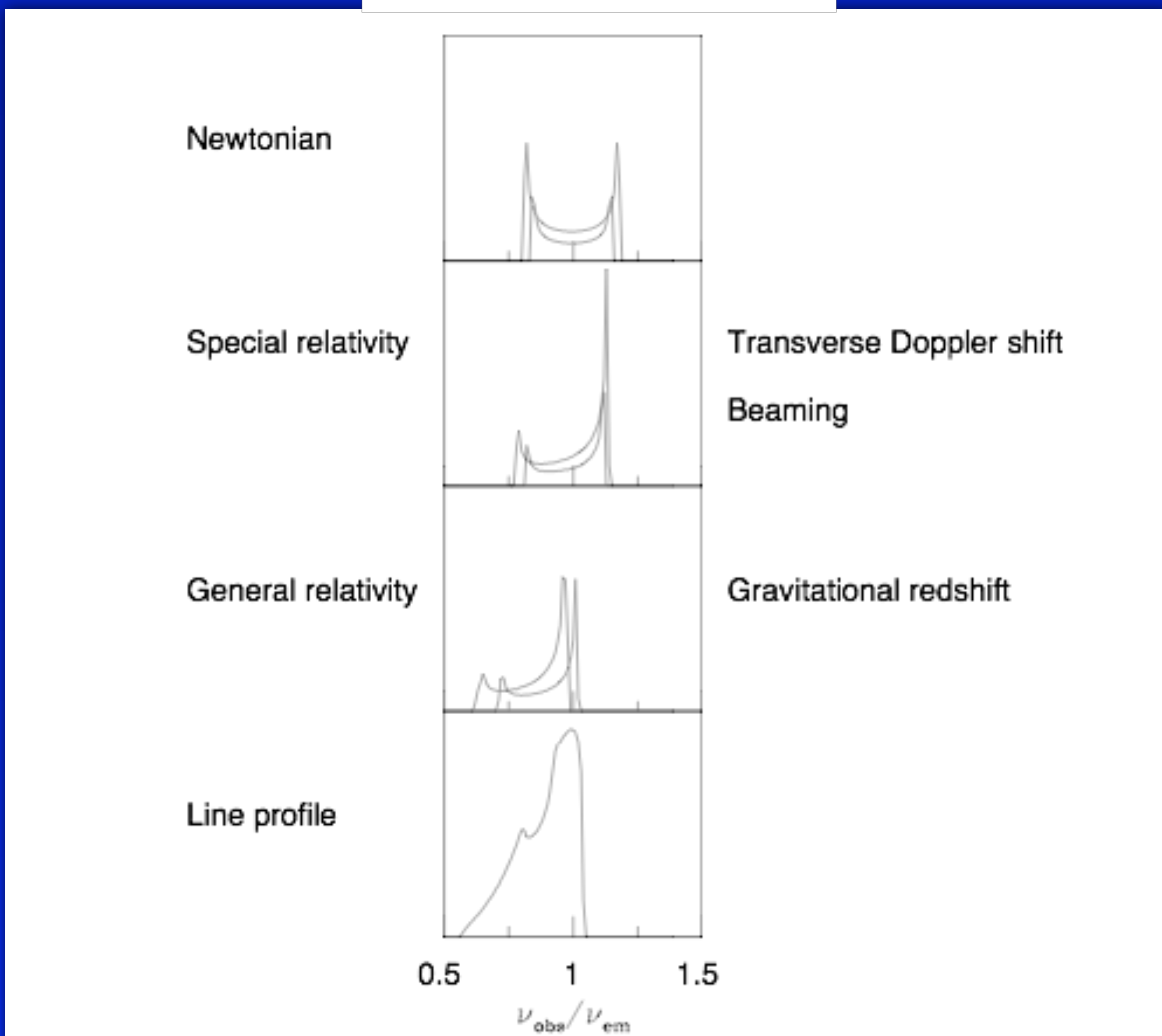
The fluorescent iron line is produced when one of the 2 K-shell (n=1) electrons of an iron atom (or ion) is ejected following photoelectric absorption of an X-ray.
Following the photoelectric event, the resulting excited state can decay in one of two ways. An L-shell (n=2) electron can then drop into the K-shell releasing 6.4~keV of energy either as an emission line photon (34 % probability) or an Auger electron (66 % probability) .

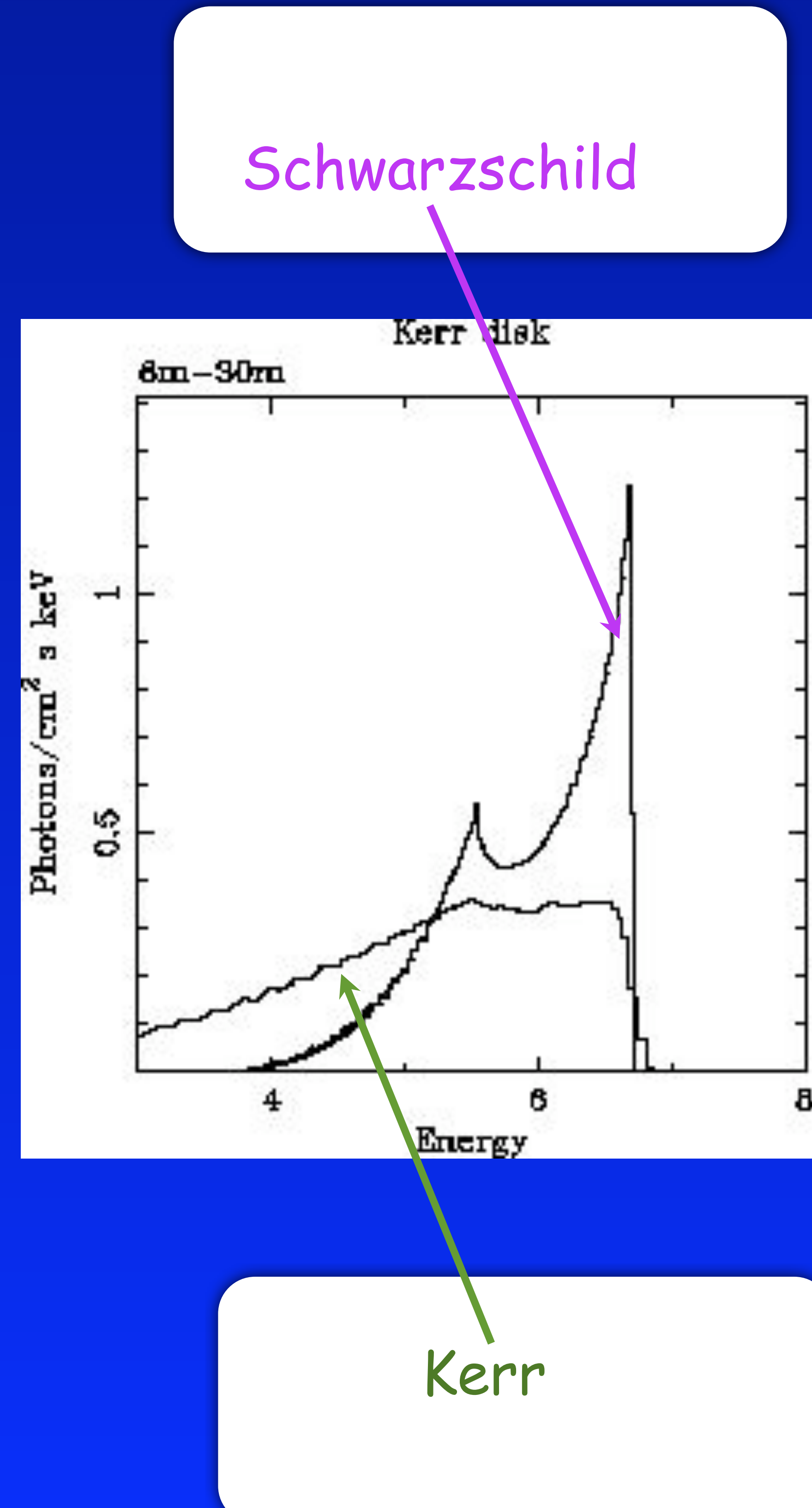


For ionized iron, the outer electrons are less effective at screening the inner K-shell from the nuclear charge and the energy of both the photoelectric threshold and the K line are increased

BROAD LINE




Newtonian
Special relativity
Transverse Doppler shift
Beaming
General relativity
Gravitational redshift
Line profile
0.5
1
1.5
ν_{obs}/ν_{em}


Schwarzschild
Kerr disk
6m–30m
Photons/cm^2 s keV
1
0.5
4
6
8
Energy
Kerr

Energy Equation

$$q^+ = q^- + q^{adv}$$

Thin Accretion Disk

(Shakura & Sunyaev 1973; Novikov & Thorne 1973;...)

Most of the viscous heat energy is radiated

$$q^- \approx q^+ \gg q^{adv}$$

$$L_{\rm rad} : 0.1\,\dot{M}\,c^2$$

Advection-Dominated Accretion Flow (ADAF)

(Ichimaru 1977; Narayan & Yi 1994, 1995; Abramowicz et al. 1995)

Most of the heat energy is retained in the gas

$$q^- \ll q^+ \approx q^{adv}$$

$$L_{\rm rad} \ll 0.1\,\dot{M}\,c^2$$

$$L_{\rm adv} : 0.1\,\dot{M}\,c^2$$

q+ is the energy generated by viscosity per unit volume
q- is the radiative cooling per unit volume
q_{adv} represents the advective transport of energy

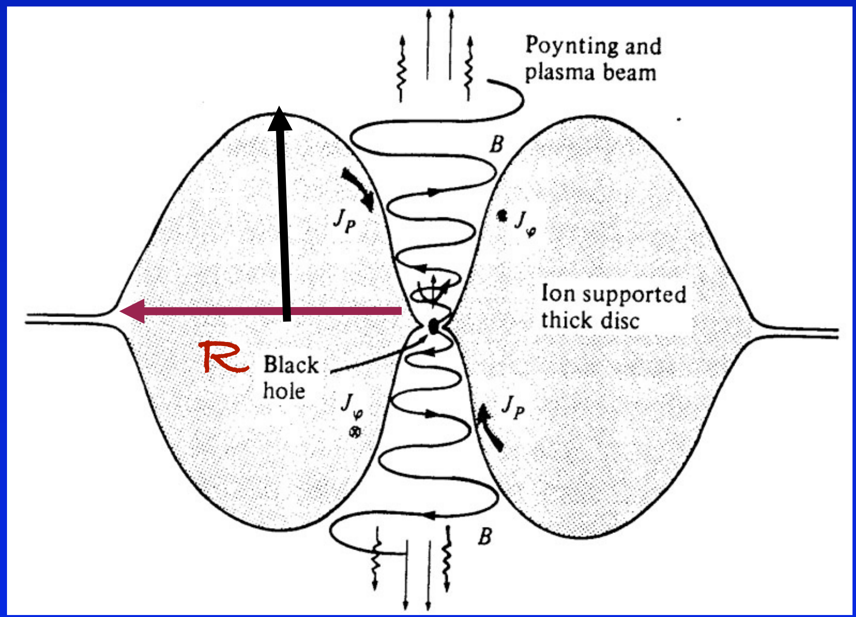
ADAF

In this solution the accreting gas has a very low density and is unable to cool efficiently. The viscous energy is stored in the gas as thermal energy instead of being radiated and is advected onto the BH. Ions and electrons are thermally decoupled.

- Very Hot: Ti~ 10^{12}K (R_S/R), Te~ 10^{9-11}K (since ADAF loses very little heat).

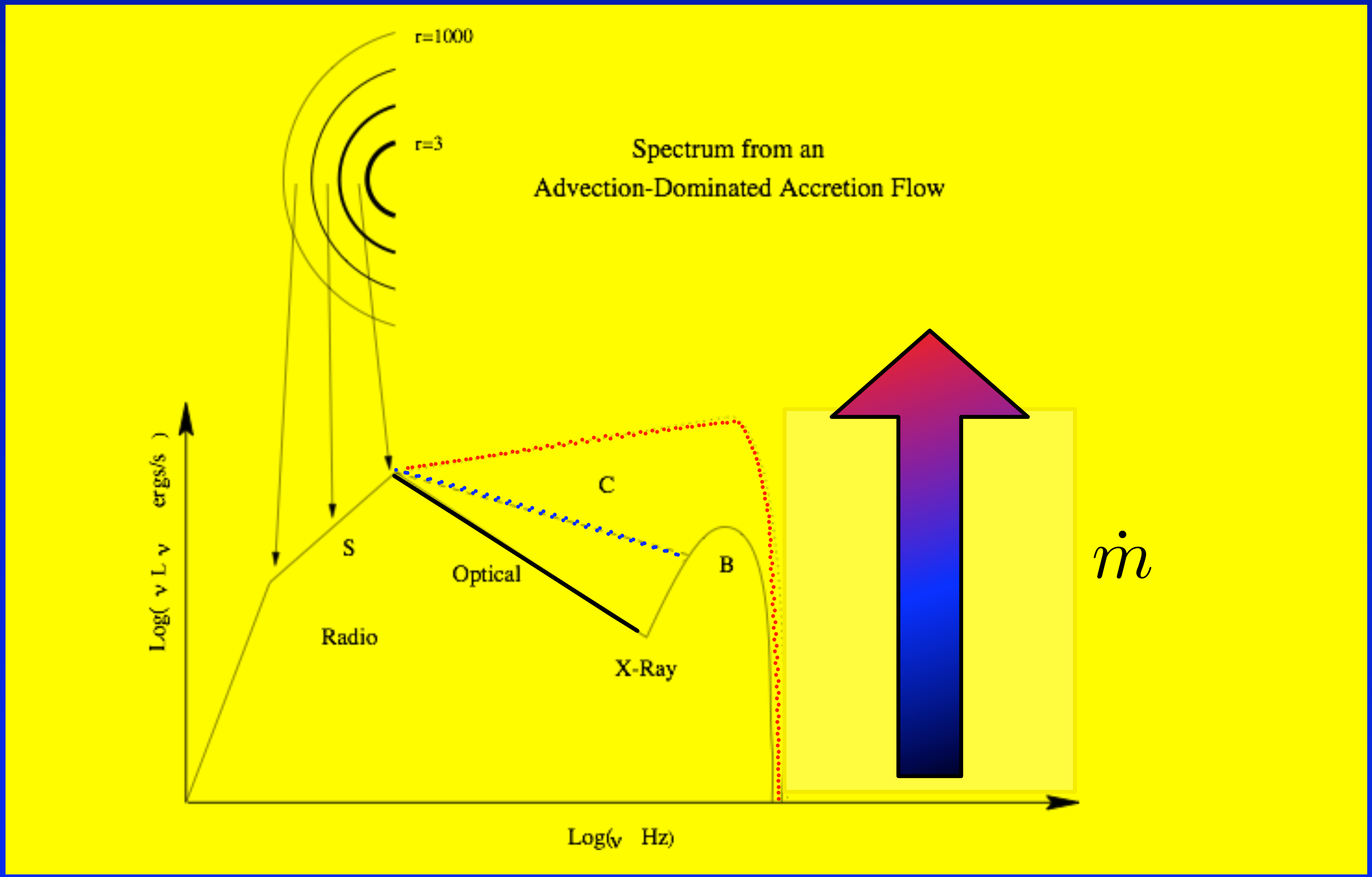
- Geometrically thick: H~R (most of the viscosity generated energy is stored in the gas as internal energy rather than being radiated, the gas puffes up

- Optically thin (because of low density)



ADAF

The ADAF solution exists only for $\frac{\dot{M}}{\dot{M}_E} \leq 0.05 - 0.1$

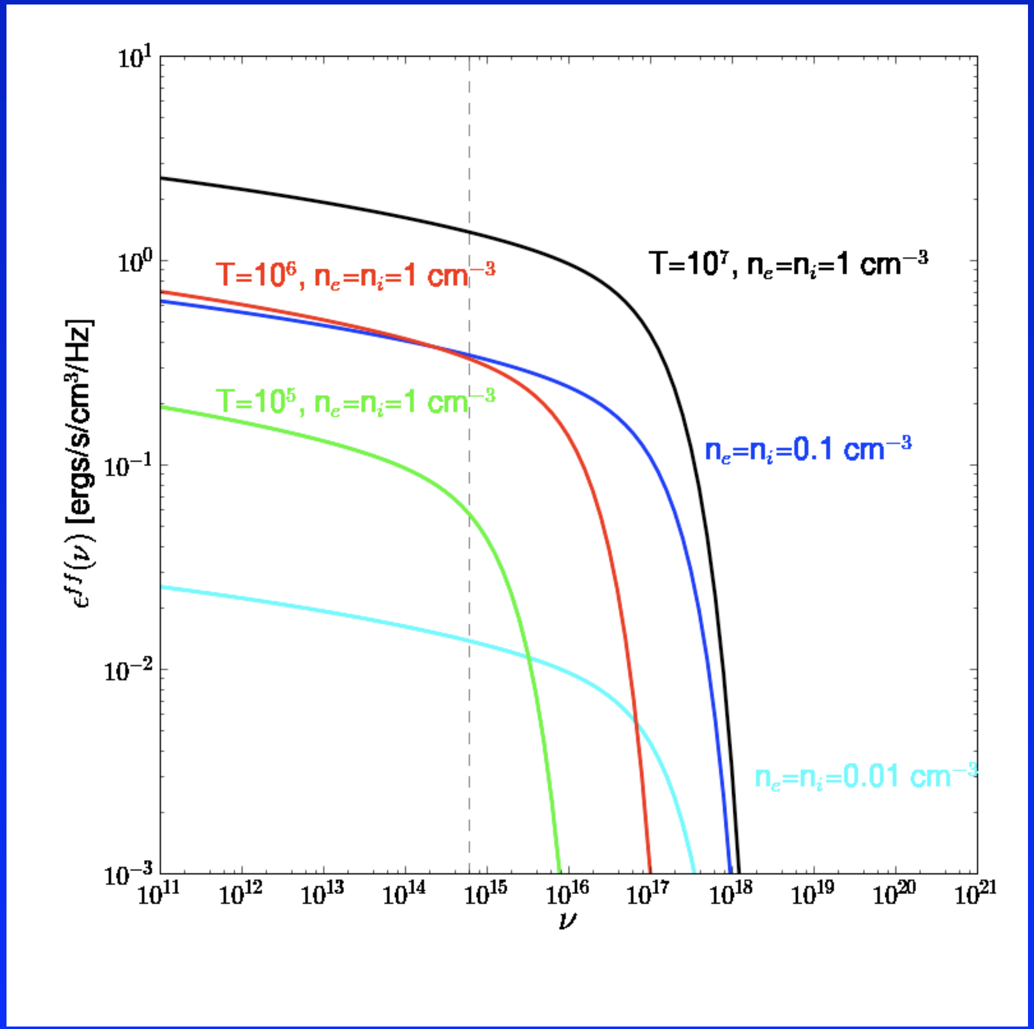


Schematic spectrum of an ADAF around a black hole. S, C, and B refer to electron emission by synchrotron radiation, inverse Compton scattering, and bremsstrahlung, respectively. The solid line corresponds to a low acretion, the dashed line to an intermediate accretion , and the dotted line to the highest (possibile) accretion .

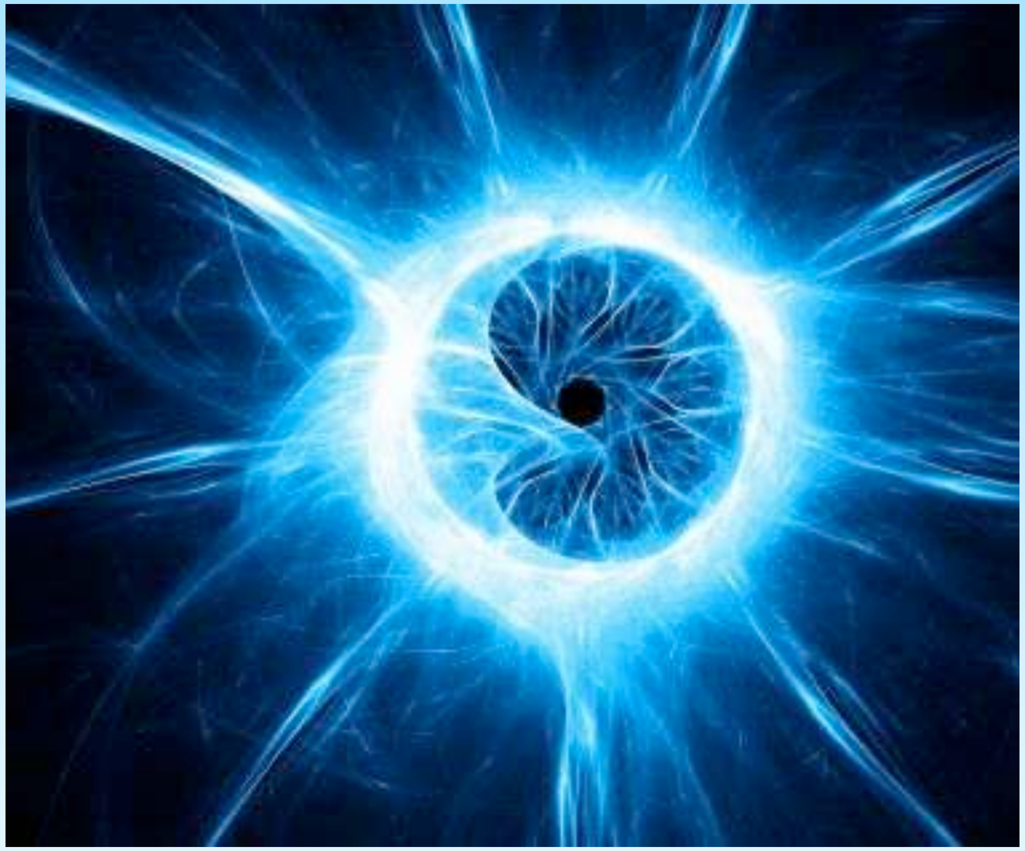
Bremsstrahlung: thermal electrons (i.e distributed according to the Maxwell-Boltzmann distribution with the temperature T).

$$f(v) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 \exp\left[-\frac{mv^2}{kT}\right]$$

$$\epsilon_\nu^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \bar{g}_{ff}$$



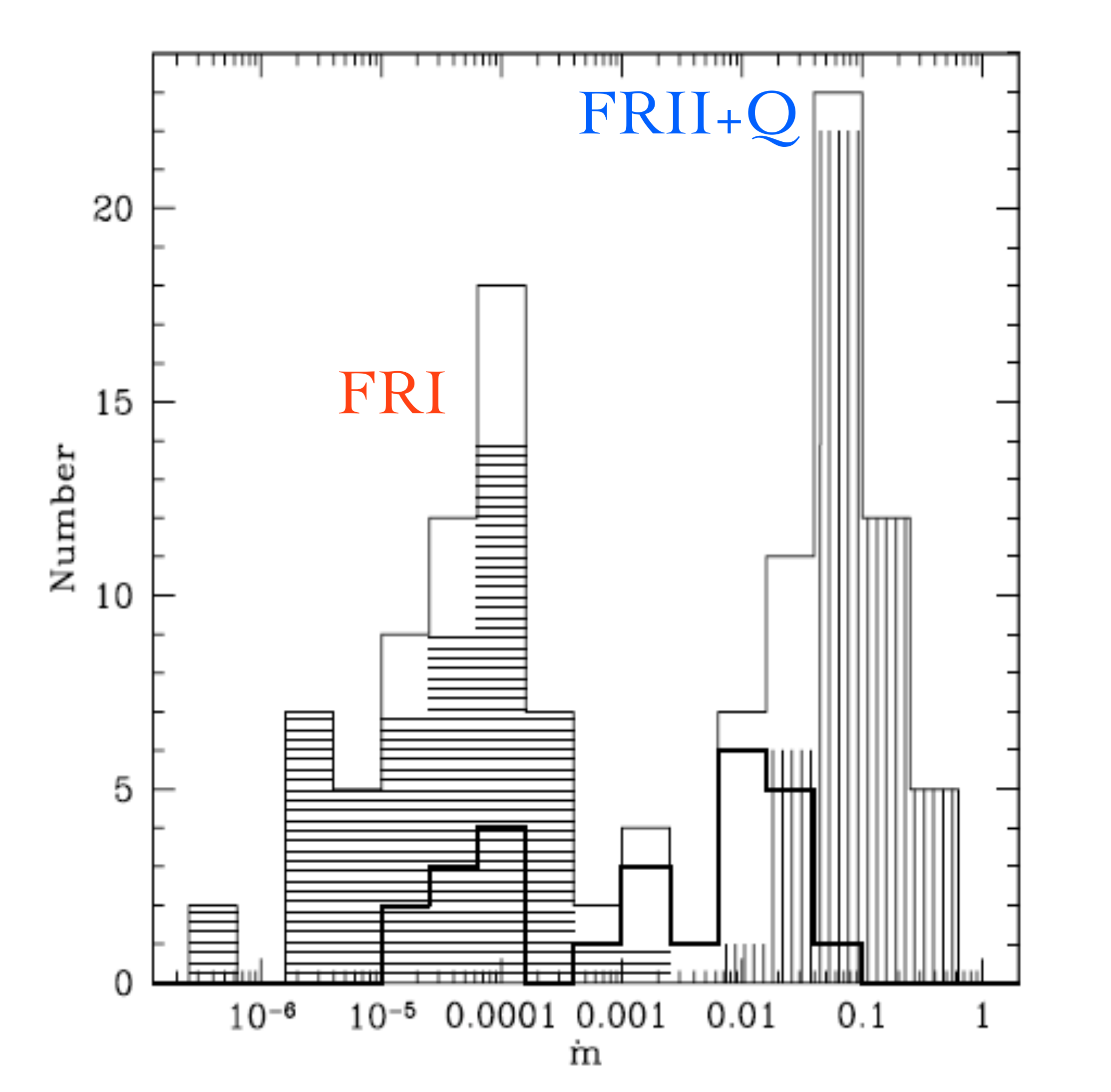
What kind of engine is hidden in the Radio Galaxies?



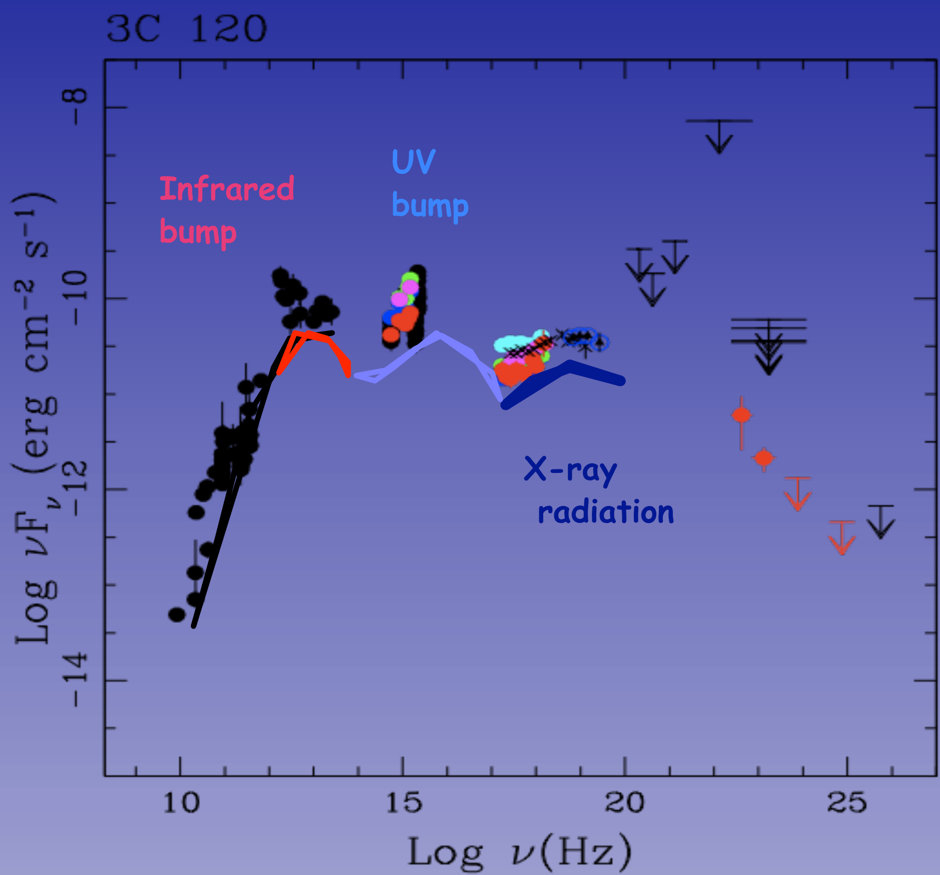
The accretion rate distribution is bimodal:

Low accretion rates => FRI

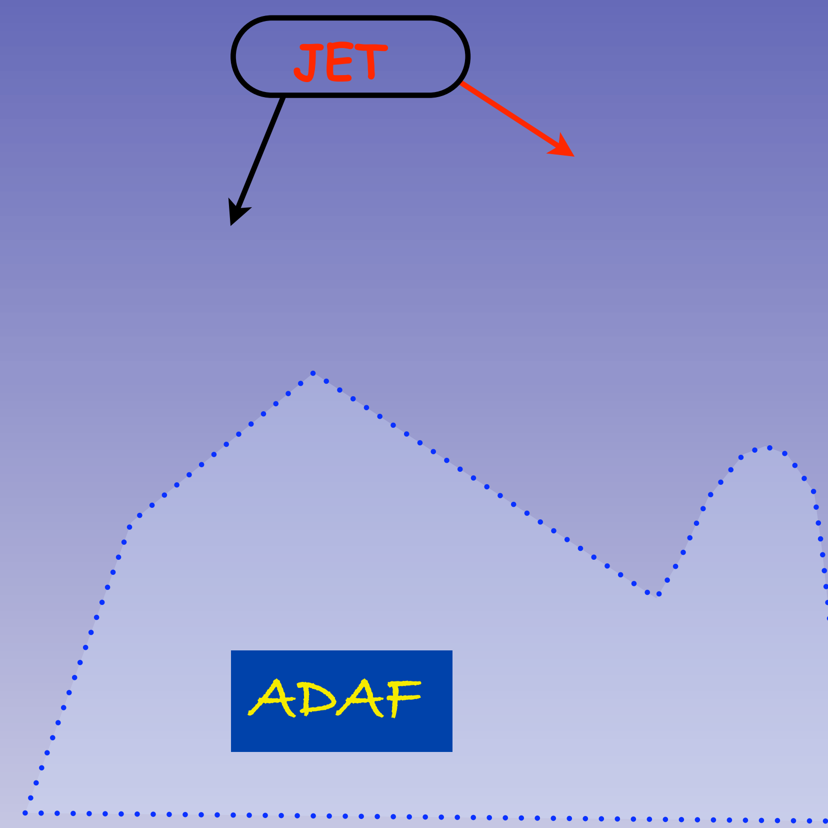
High accretion rate => FRII +Quasar (Q)

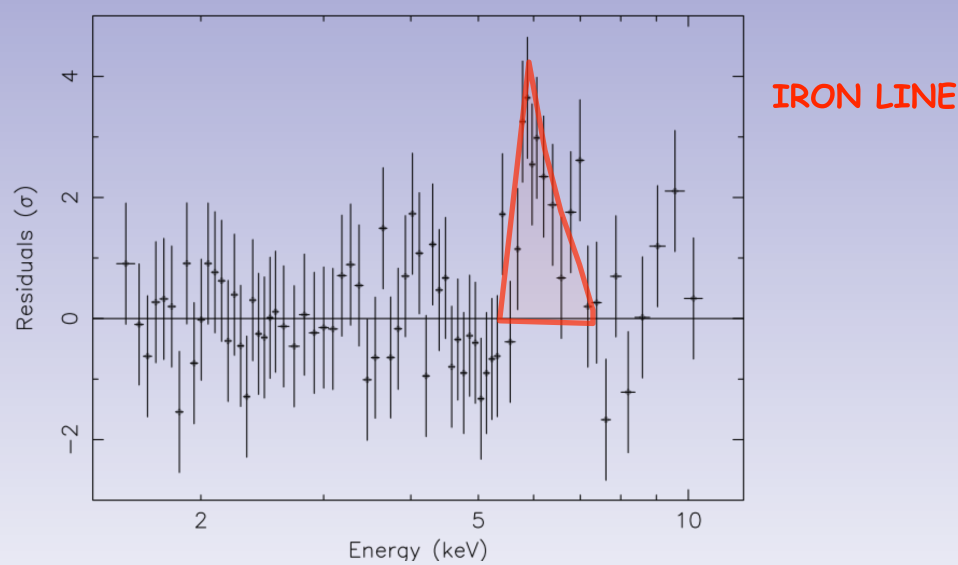


Efficient accretion flow

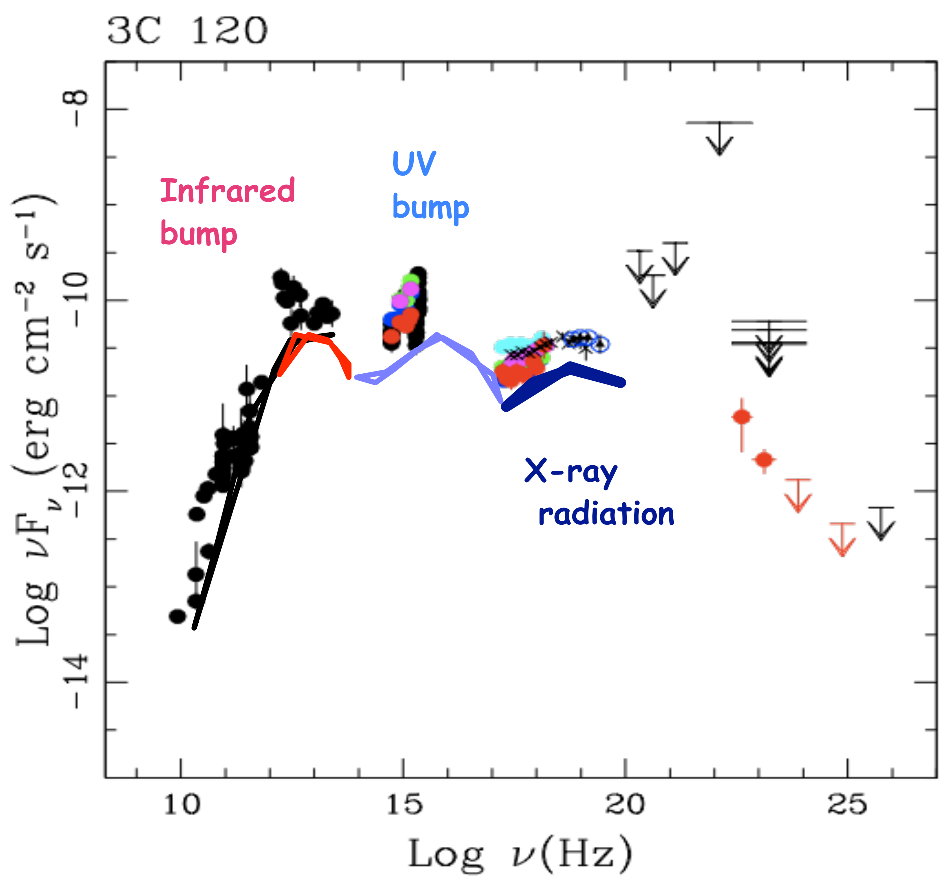


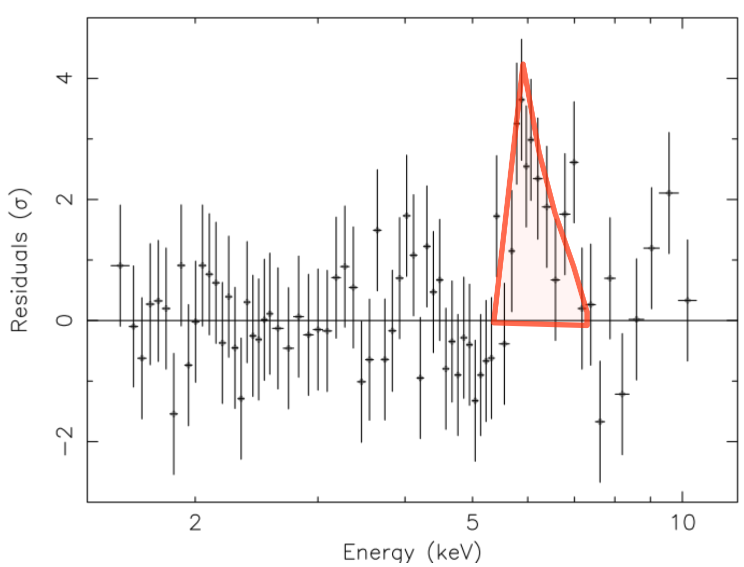
Text





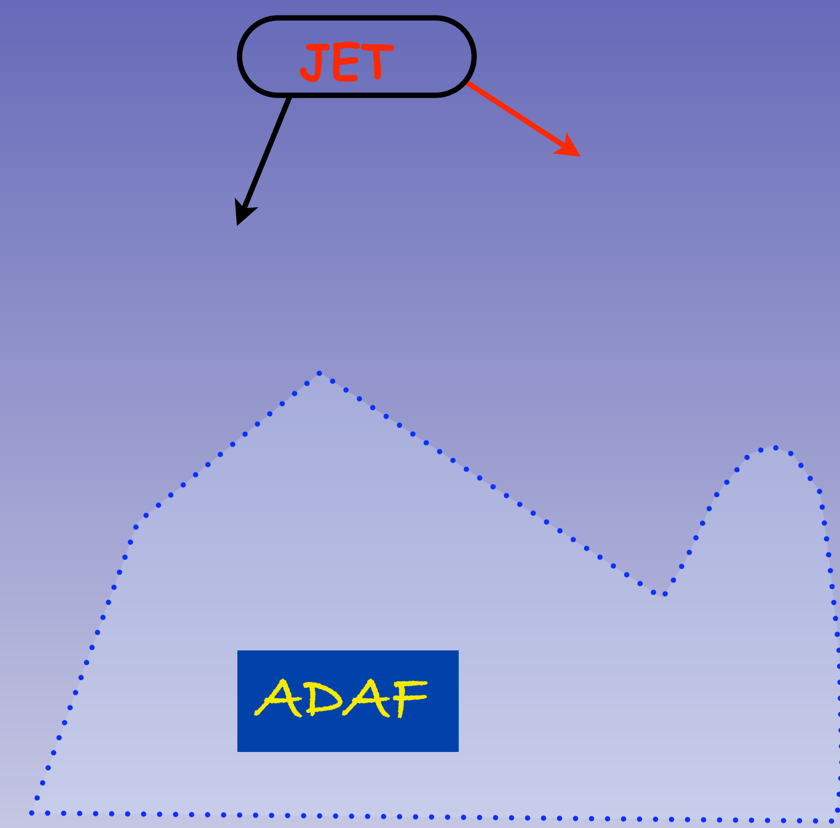
Efficient accretion flow



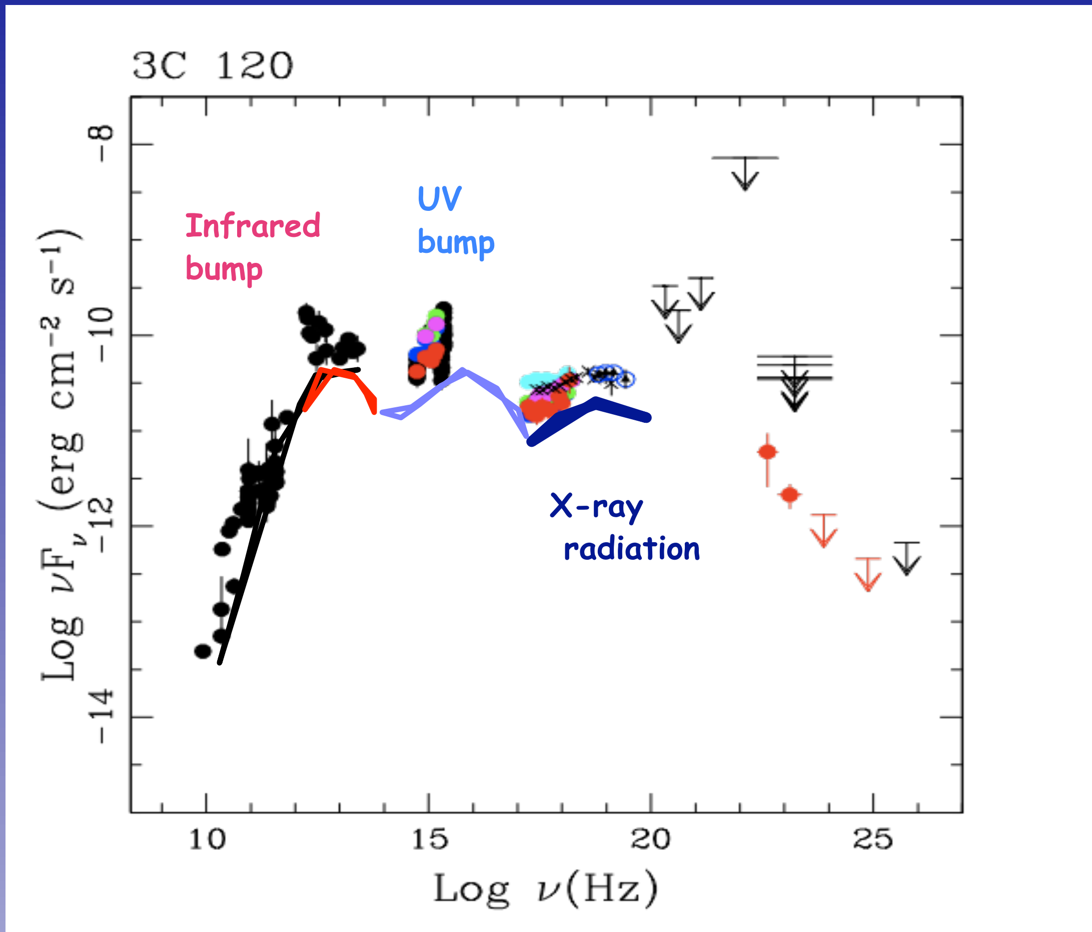


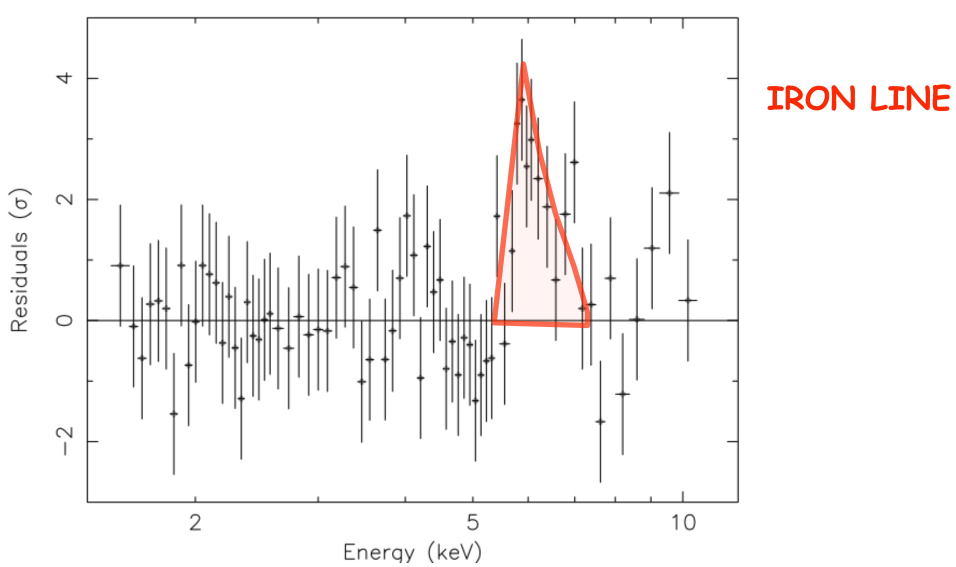
IRON LINE

Text

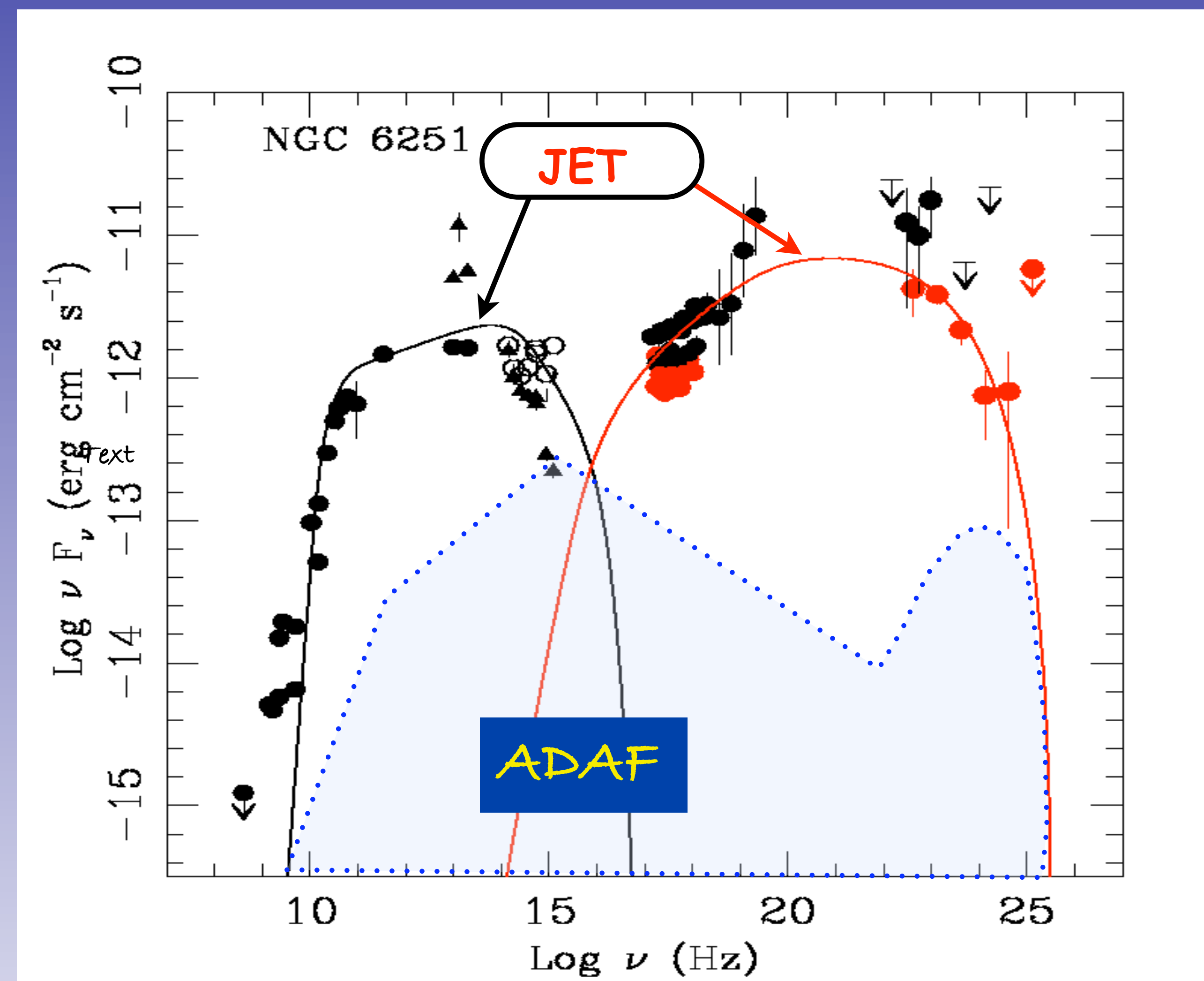


Efficient accretion flow





Inefficient accretion flow

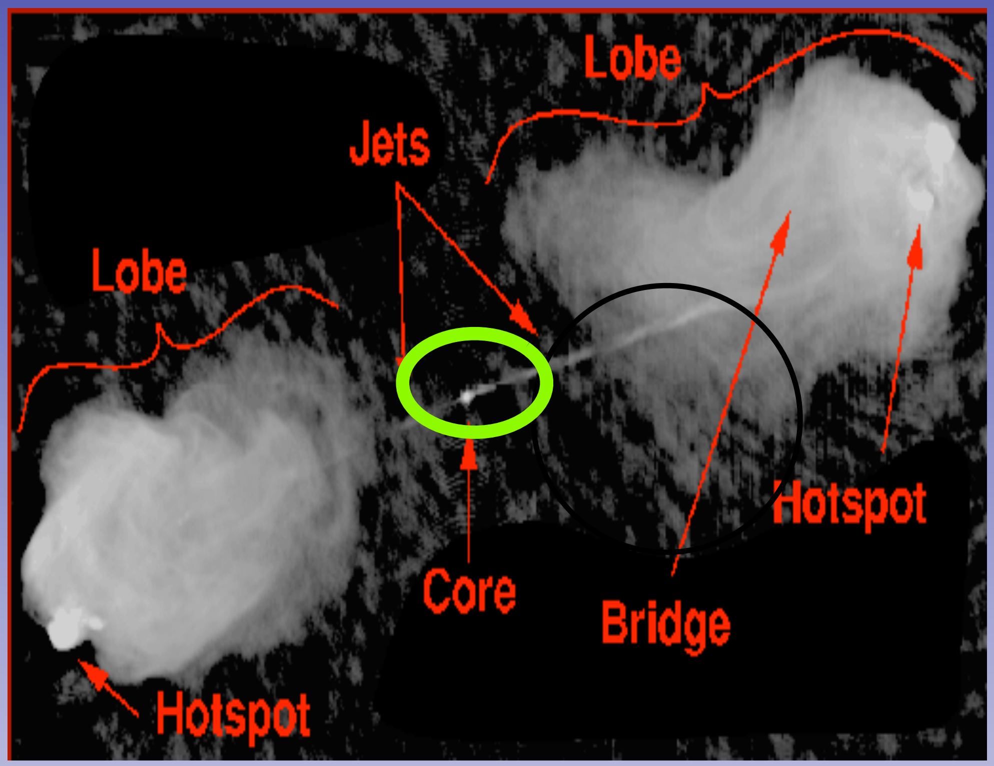


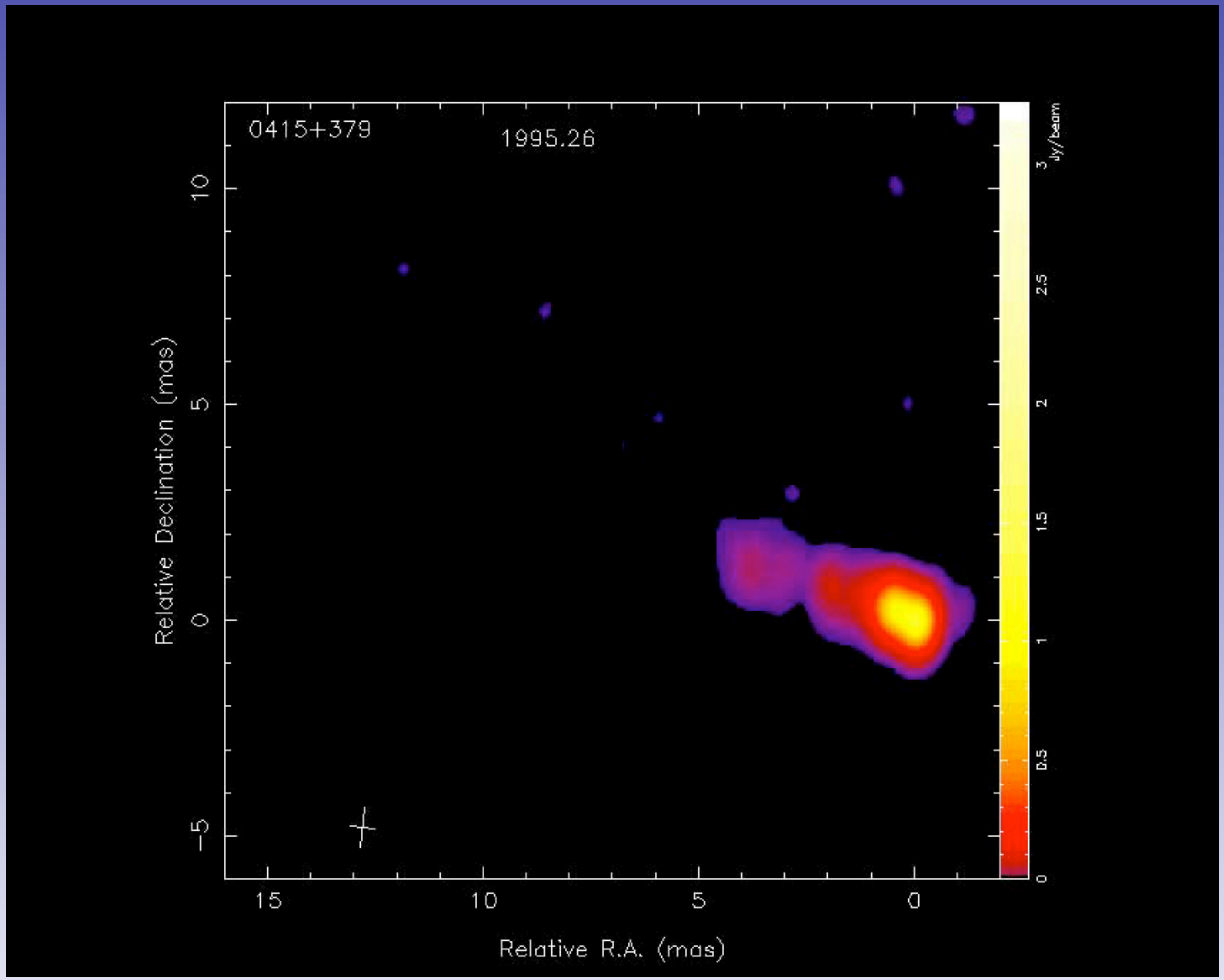
Jets, Hot Spots, Lobes

Non-Thermal processes

Radio Loud AGNs
JET at sub-pc scale (core)

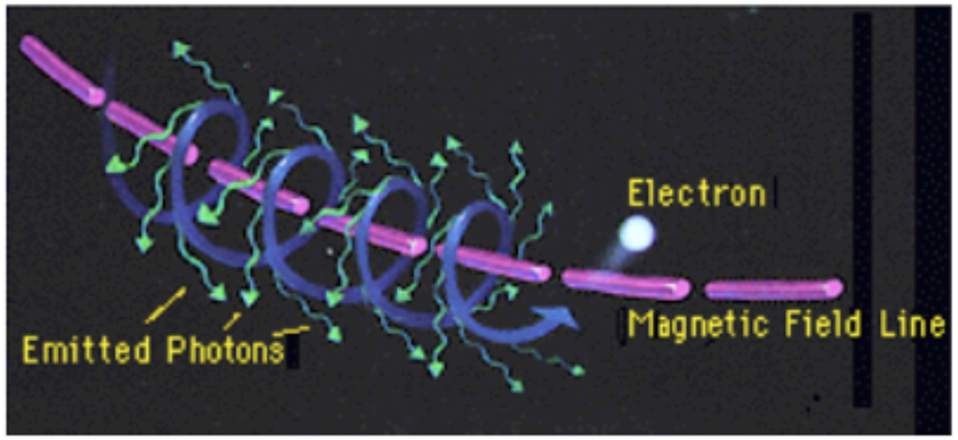
1mas=0.9 pc

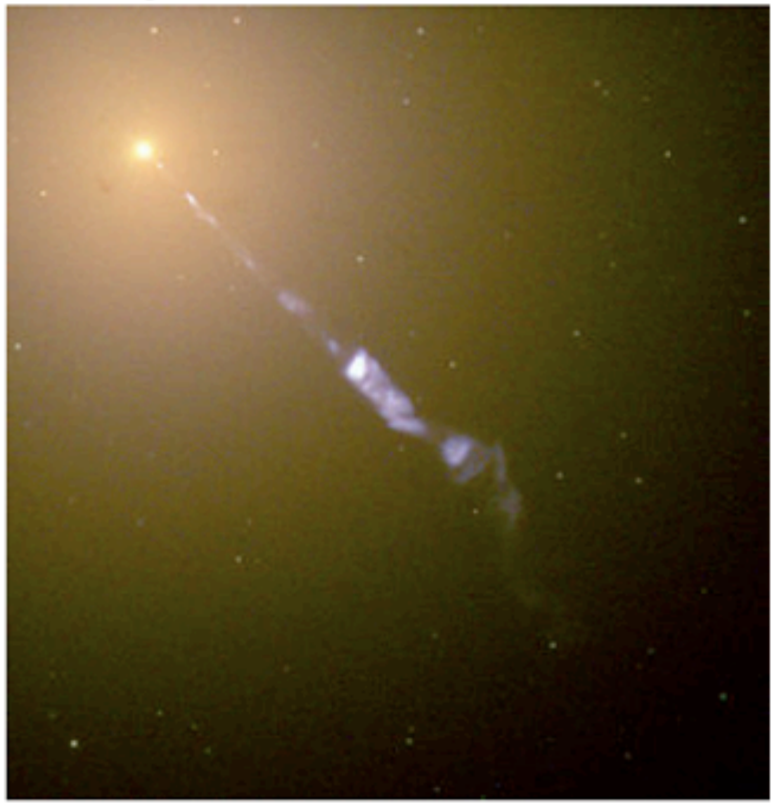




Synchrotron Radiation

Synchrotron radiation is due to the movement of an electron charge in a magnetic field. As a particle gyrates around a magnetic field, it will emit radiation at a frequency proportional to the strength of the magnetic field and its velocity.





Synchrotron radiation is highly polarized and is seen at all wavelengths. At relativistic speeds, the radiation can also be beamed. It is very common in radio spectrum, but can be seen in x-rays. It is usually fit as a power law. For full details, see the review by Ginzburg & Syrovatskii (1969)

A single electron

The frequency of synchrotron radiation is:

$$\omega_B = \frac{qB}{\gamma mc}$$

The total power emitted by each electron is:

$$\frac{dE}{dt} = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_B$$

Where the following definitions have been used:

$$U_B = B^2/8\pi \qquad \beta = (1 - \frac{1}{\gamma^2})^{1/2}$$

$$\sigma_T = \frac{8\pi r_o^2}{3} \qquad \gamma = (1 - \frac{v^2}{c^2})^{-1/2}$$

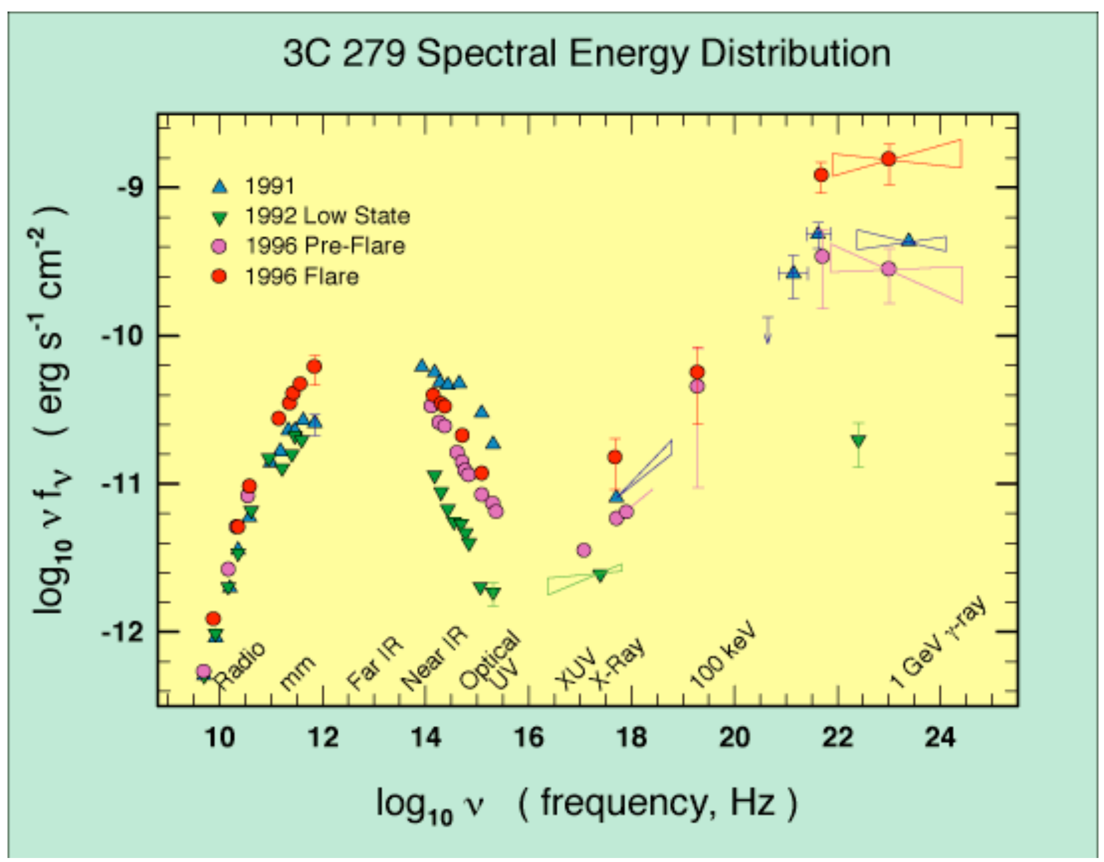
The emission is concentrated into an angle along the direction of motion of order $1/\gamma$

The synchrotron radiation of a power law distribution of electron energies

Synchrotron

$$N(\gamma_e) = K\gamma_e^{-p}, \quad \gamma_{min} < \gamma_e < \gamma_{max}, p = 1 + 2\alpha$$

$$\epsilon_{sin}(\nu) \propto KB^{\alpha+1}\nu^{-\alpha} \quad \text{erg cm}^{-3}\text{ s}^{-1}\text{ sr}^{-1}$$



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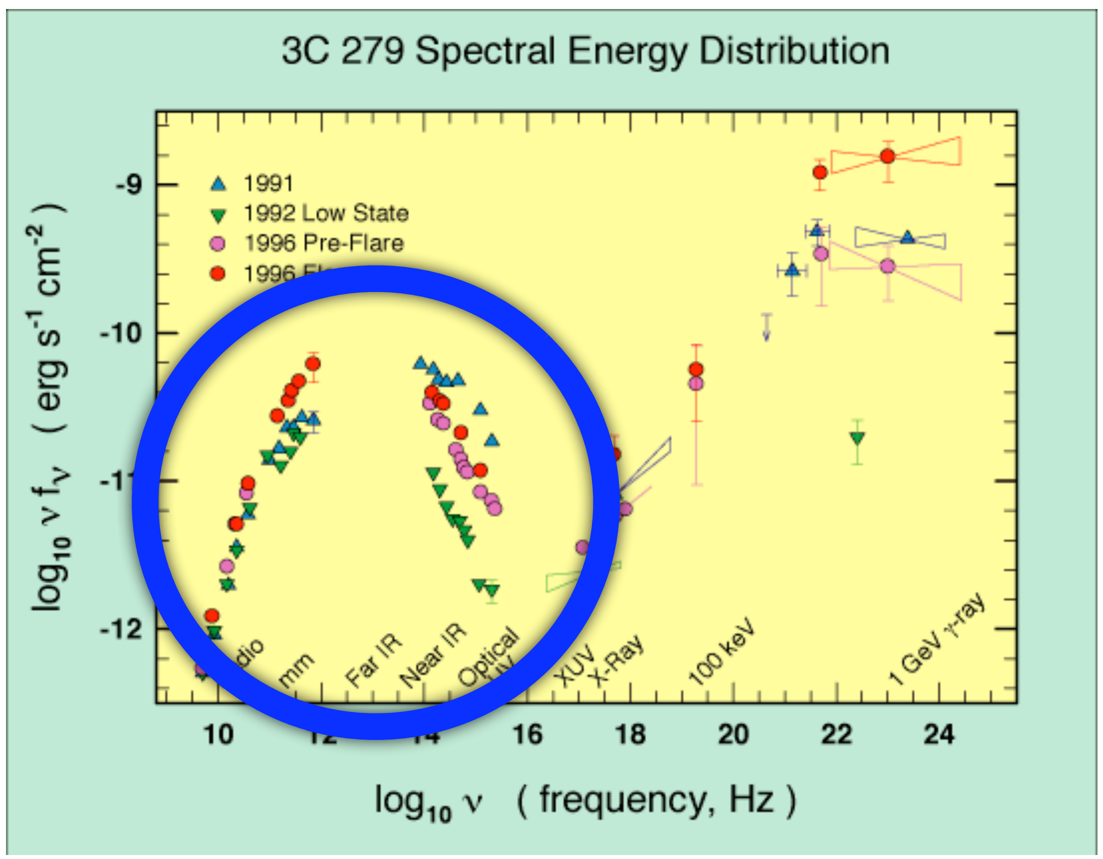
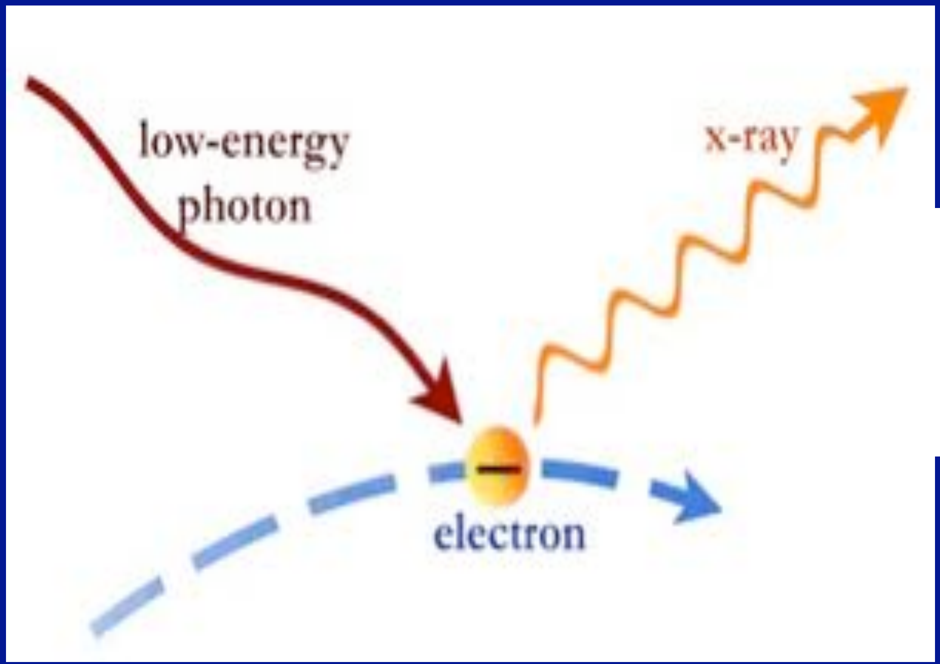


Inverse Compton scattering

When the electron is not at rest, but has an energy greater that the typical photon energy, there can be a transfer of energy from the electron to the photon. This process is called inverse Compton to distinguish it from the direct Compton scattering, in which the electron is at rest, and it is the photon to give part of its energy to the electron.



$$<\nu>=\frac{4}{3}\gamma^2\nu$$

Inverse Compton Radiation

The general result that the frequency of the scattered photons is $\nu \approx \gamma^2 \nu_0$ is of profound importance in high energy astrophysics. We know that there are electrons with Lorentz factors $\gamma \sim 100 - 1000$ in various types of astronomical source and consequently they scatter any low energy photons to very much higher energies. Consider the scattering of radio, infrared and optical photons scattered by electrons with $\gamma = 1000$.

Waveband	*Frequency (Hz)* ν_0	*Scattered Frequency (Hz) and Waveband*
Radio	10^9	10^{15} = UV
Far-infrared	3×10^{12}	3×10^{18} = X-rays
Optical	4×10^{14}	$4 \times 10^{21} \equiv 1.6$MeV = γ-rays

Thus, inverse Compton scattering is a means of creating very high energy photons indeed. It also becomes an inevitable drain of energy for high energy electrons whenever they pass through a region in which there is a large energy density of photons.

Inverse Compton

For a power law distribution of electrons:

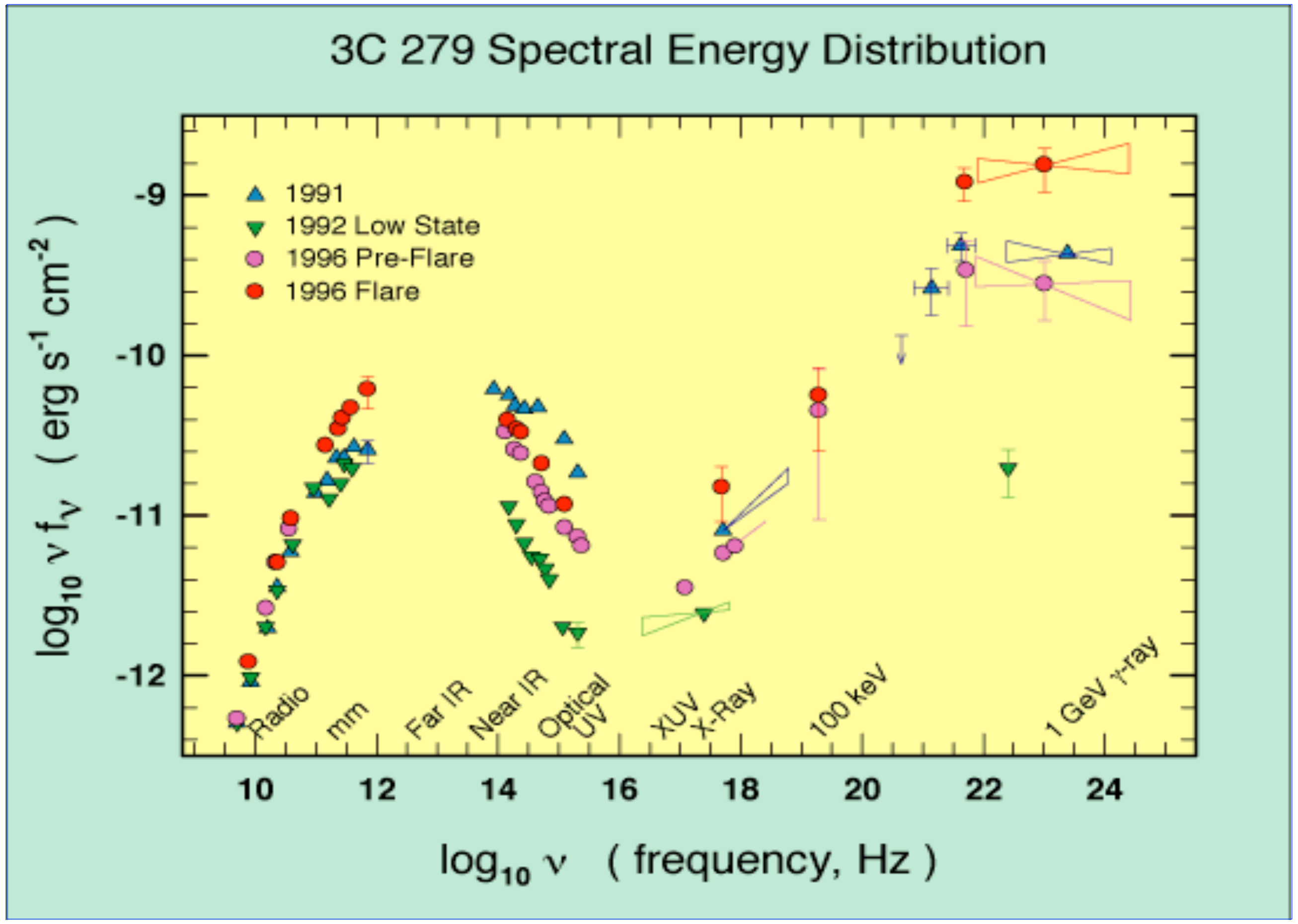
$$N(\gamma_e) = K\gamma_e^{-p}, \quad \gamma_{min} < \gamma_e < \gamma_{max}, p = 1 + 2\alpha$$

Inverse Compton

$$\epsilon_c(\nu_c) \propto K\nu_c^{-\alpha} \int \frac{Ur(\nu)\nu^{\alpha}}{\nu} d\nu$$ erg cm^{-3} s^{-1} sr^{-1}

U_r is the radiation energy density

$$U_r = \int n(\epsilon)\epsilon d\epsilon$$



Inverse Compton

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Inverse Compton

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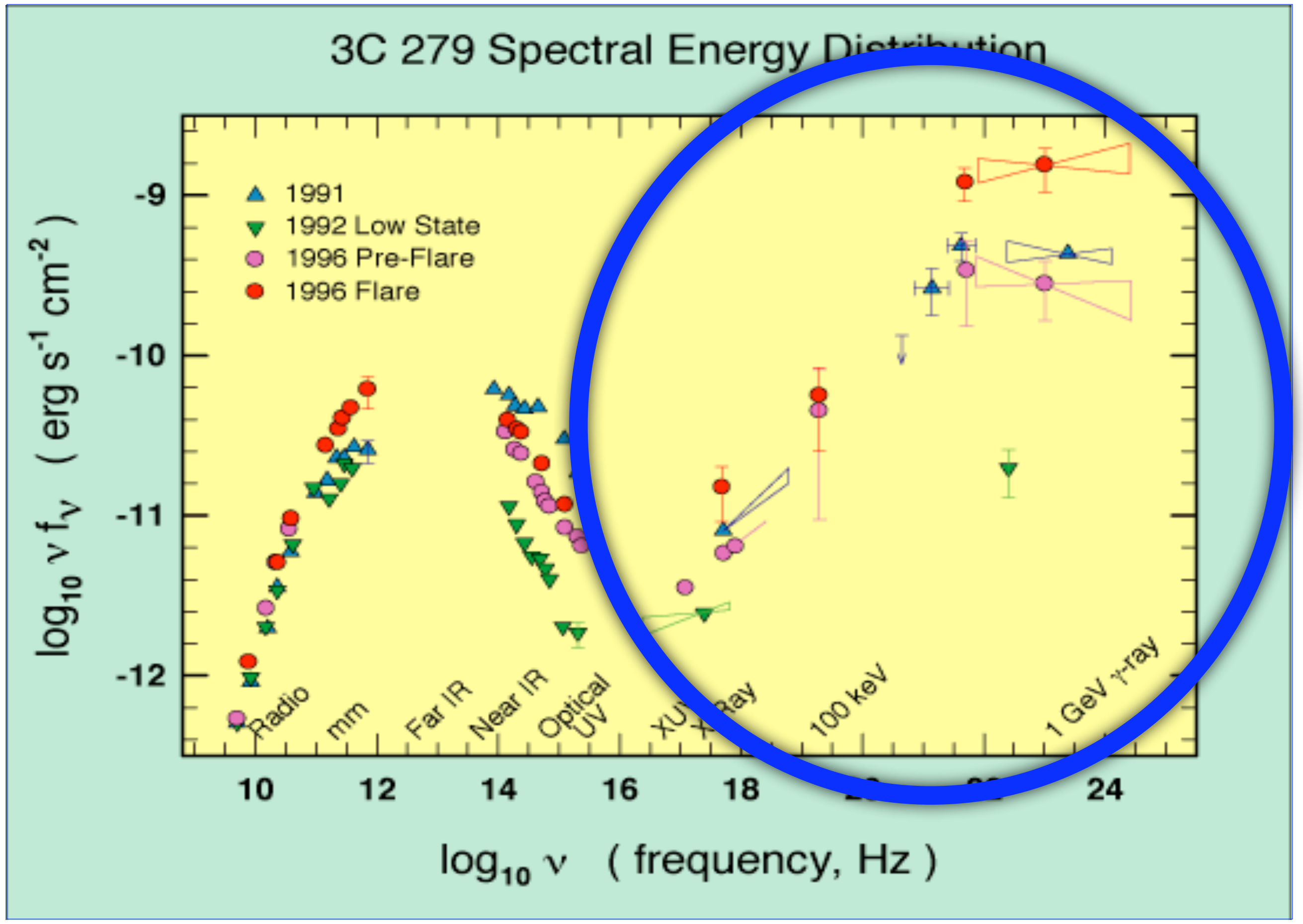


Seed photons up-scattered by relativistic electrons:

- Synchrotron photons in the jet
- Environment photons from Accretion Flow, BLR, NLR, Torus

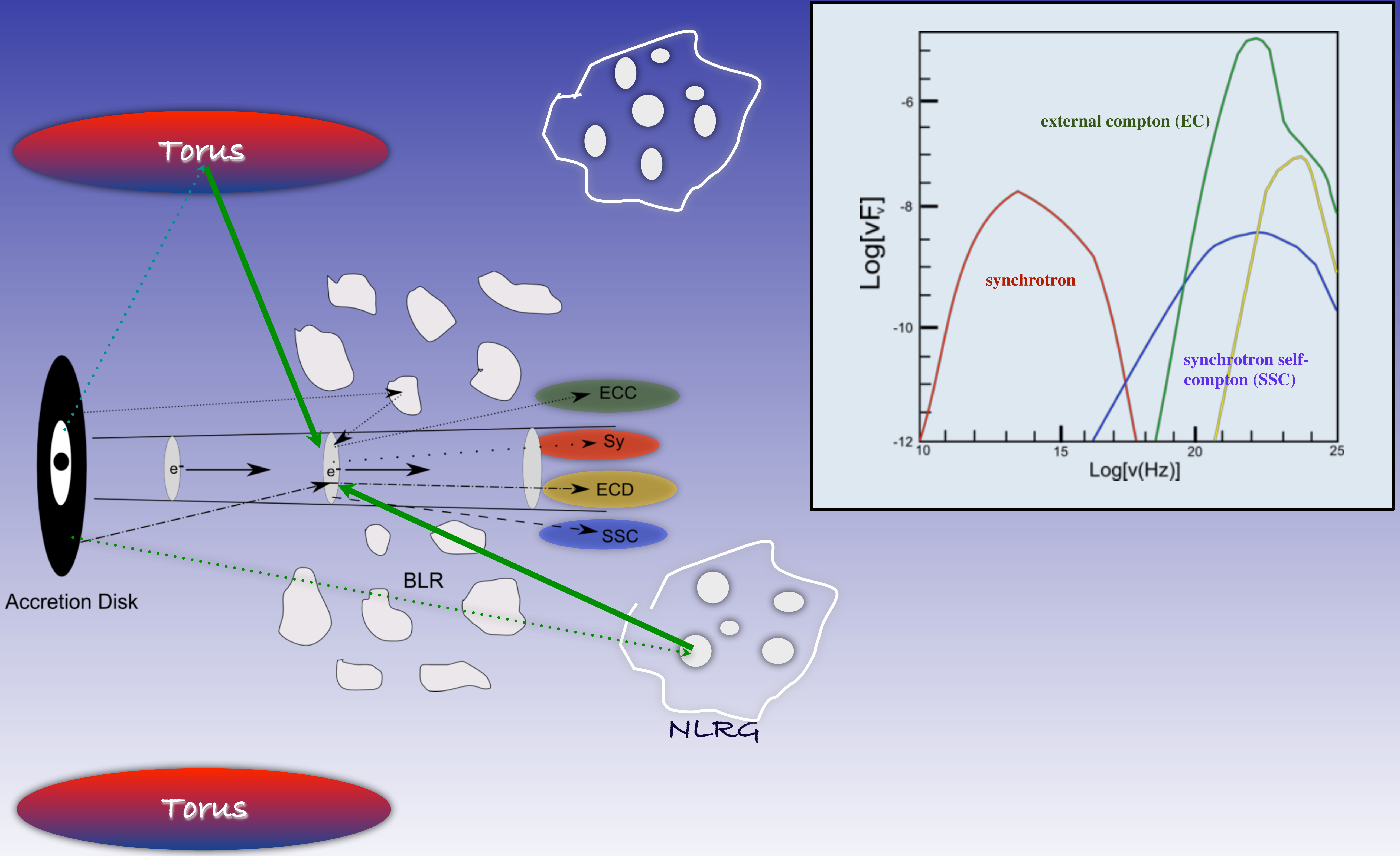
Synchrotron Self–Compton

Consider a population of relativistic electrons in a magnetized region. They will produce synchrotron radiation, and therefore they will fill the region with photons. These synchrotron photons will have some probability to interact again with the electrons, by the Inverse Compton process. Since the electron "work twice" (first making synchrotron radiation, then scattering it at higher energies) this particular kind of process is called synchrotron self-Compton, or SSC for short.

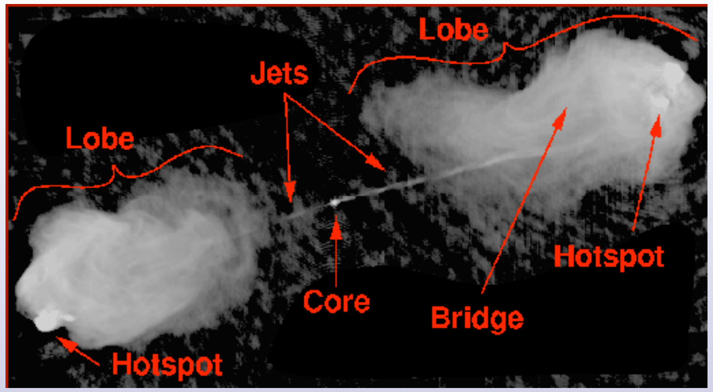
0

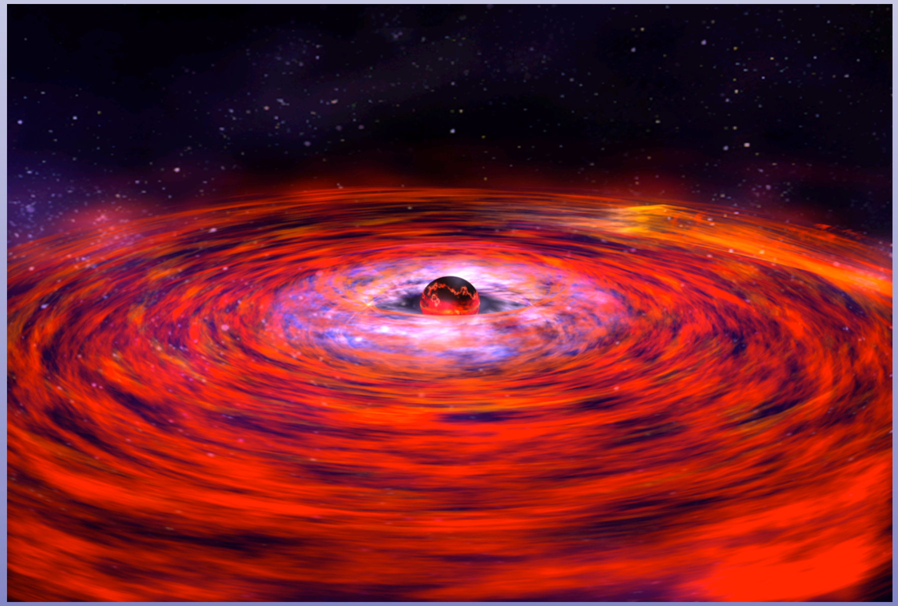
External Compton

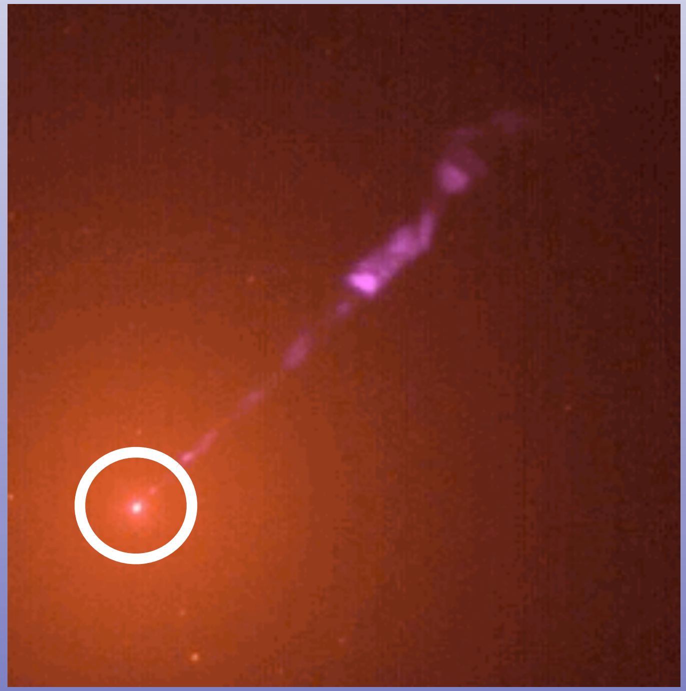
The population of relativistic electrons in a magnetized region can also interact with photons externa to the jet produced in the accretion disk, in the broad/narrow line regions in the torus. This particular kind of process is called External Compton, or EC for short.

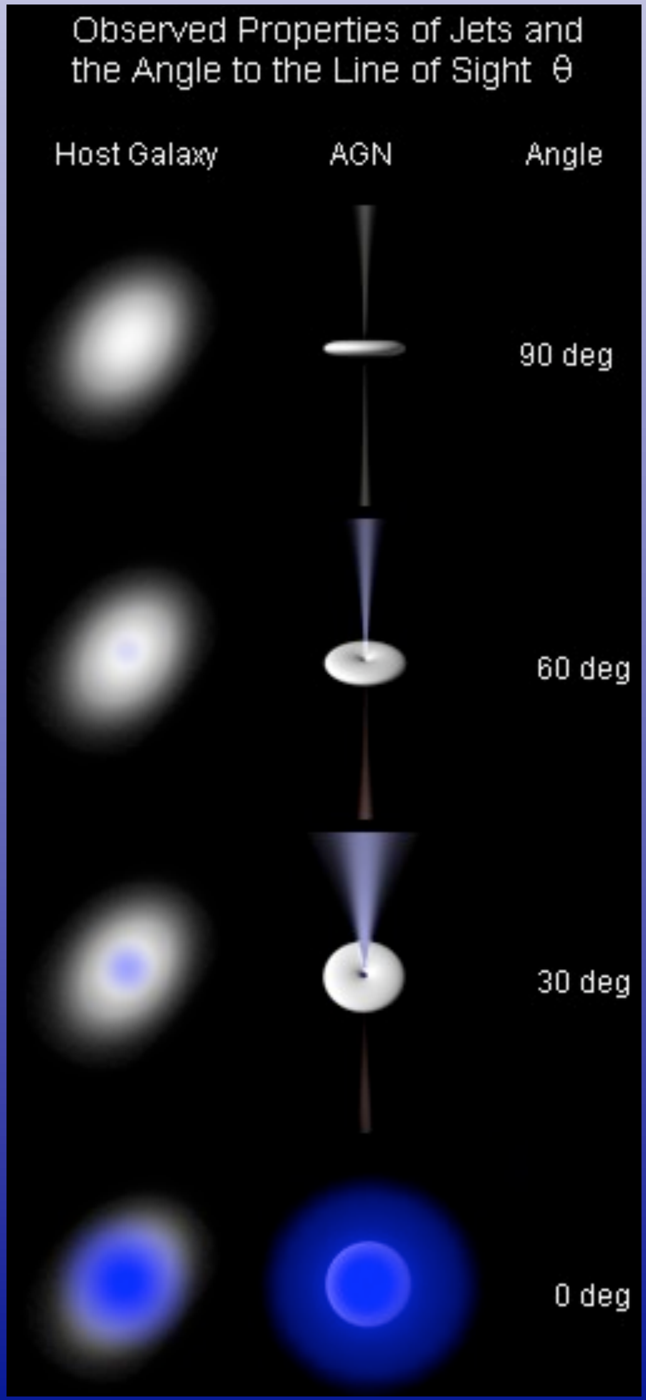

Torus
Torus
Accretion Disk
e-
e-
ECC
Sy
ECD
SSC
BLR
NLRG
Log[νFν]
-6
-8
-10
-12
10
15
20
25
Log[ν(Hz)]
external compton (EC)
synchrotron
synchrotron self-compton (SSC)

Core







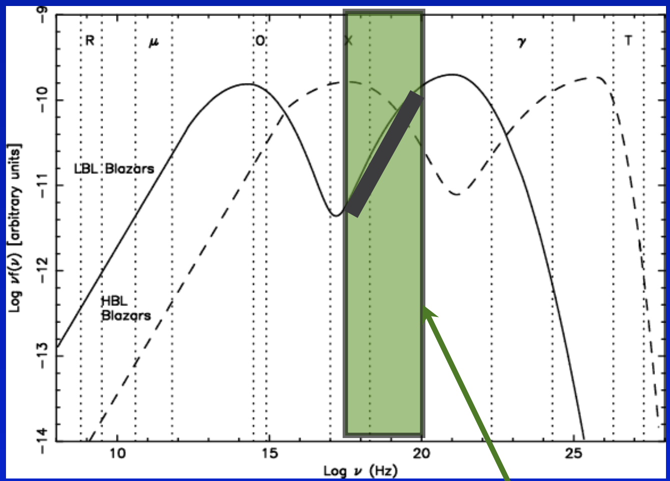


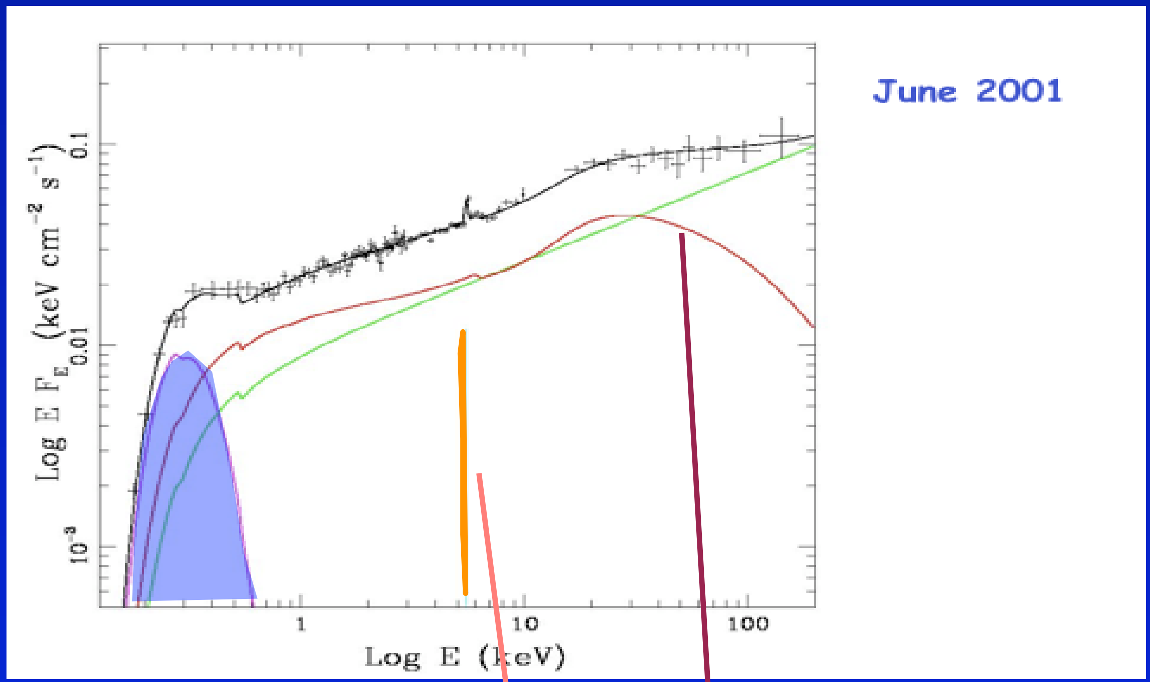
X-ray Spectra:Accretion Disk and pc-scale Jet emission are in competion:

Angle of sight = 0° ==> Jet radiation dominates

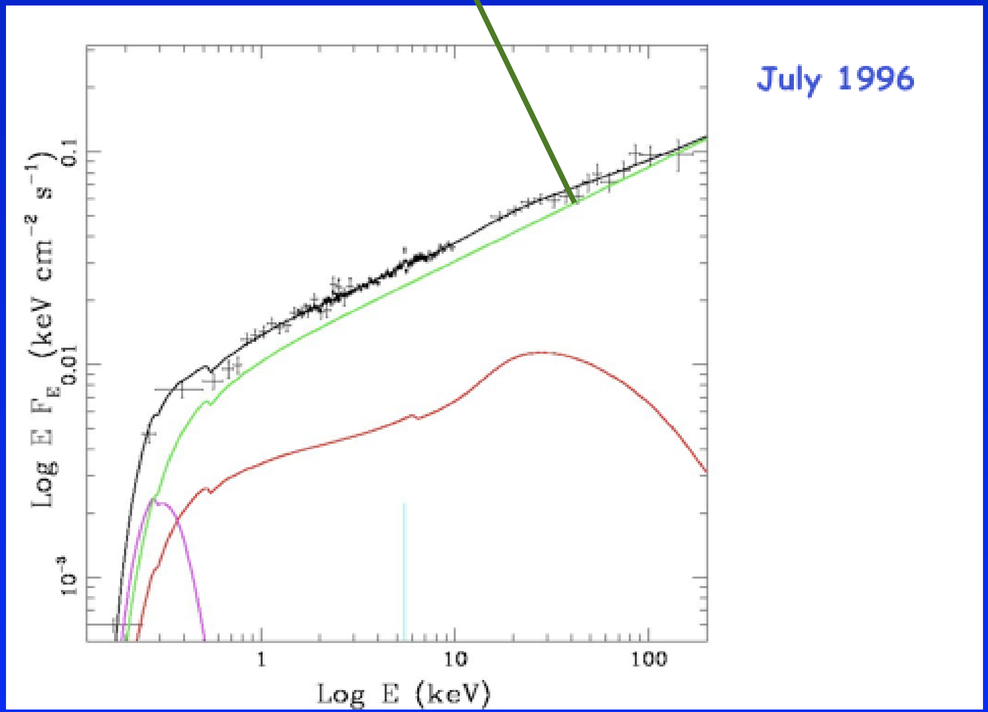
Angle of sight = 90° ==> Accretion disk dominates

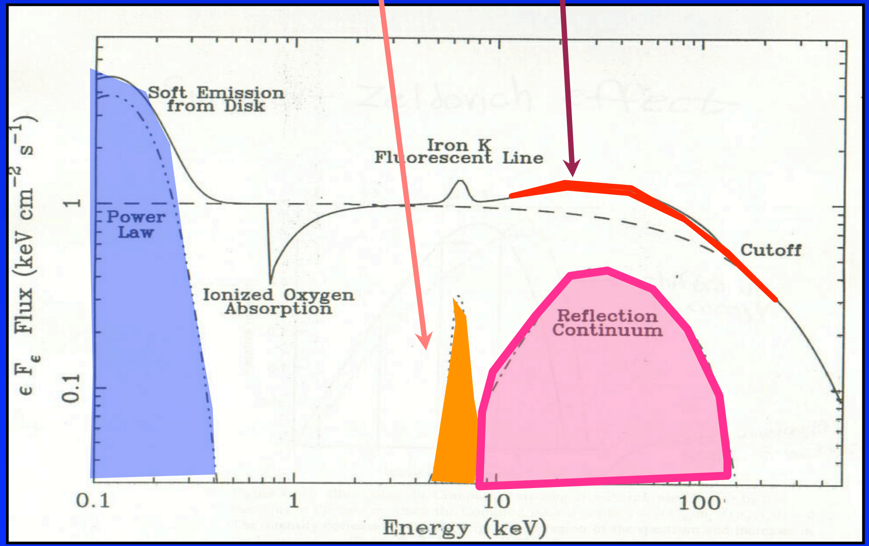
Intermediate case : let us consider the X-ray band
In different occasions, we can observe different spectrum, depending on the flux ratio between the jet and the accretion flow



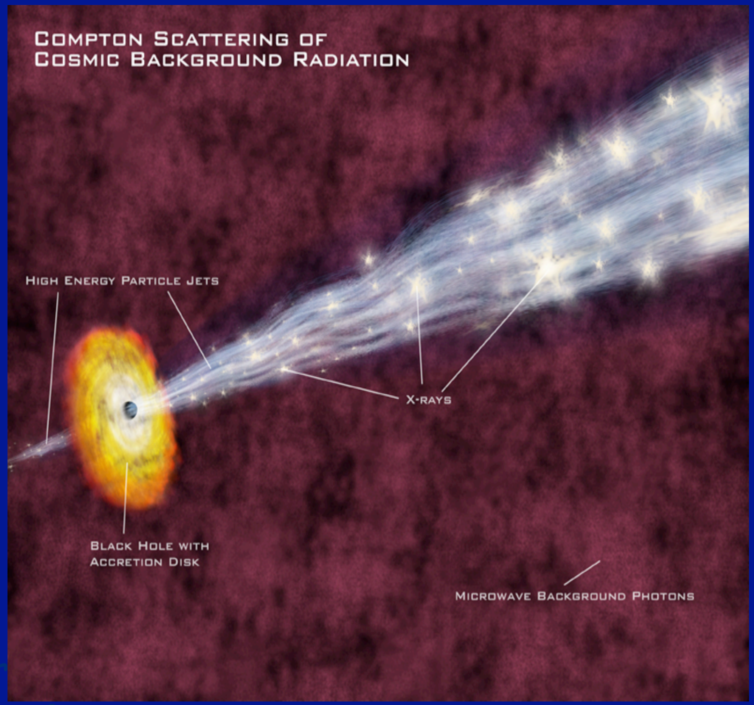


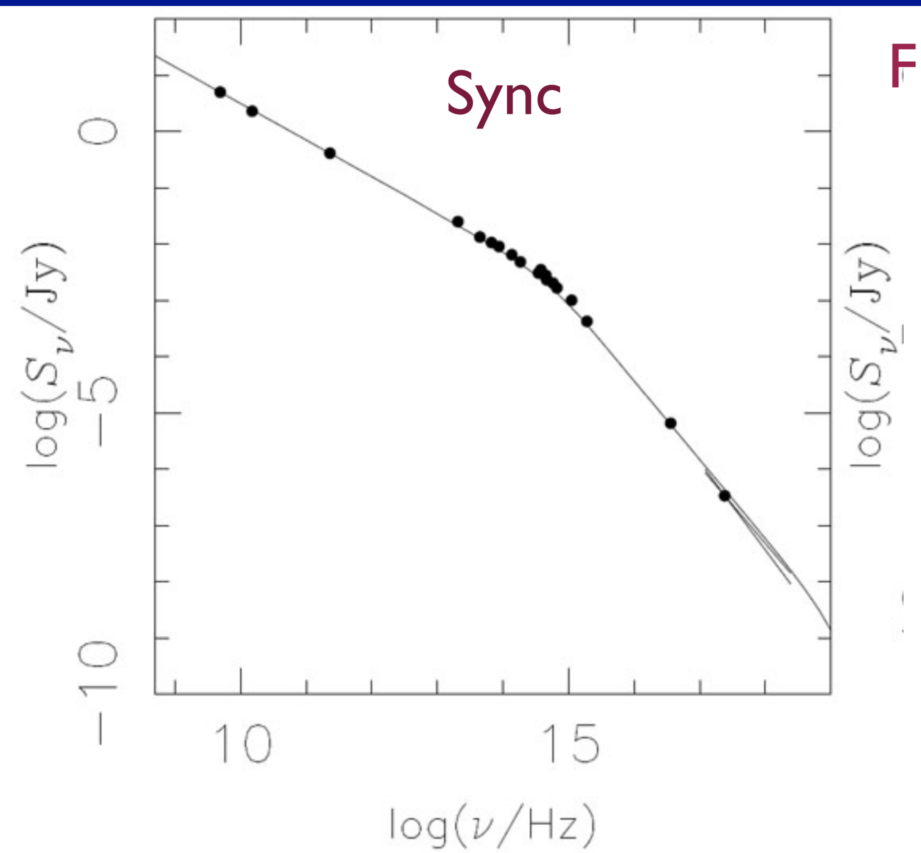
Seyfert-like features





kpc-scale Jet





FRI-M87

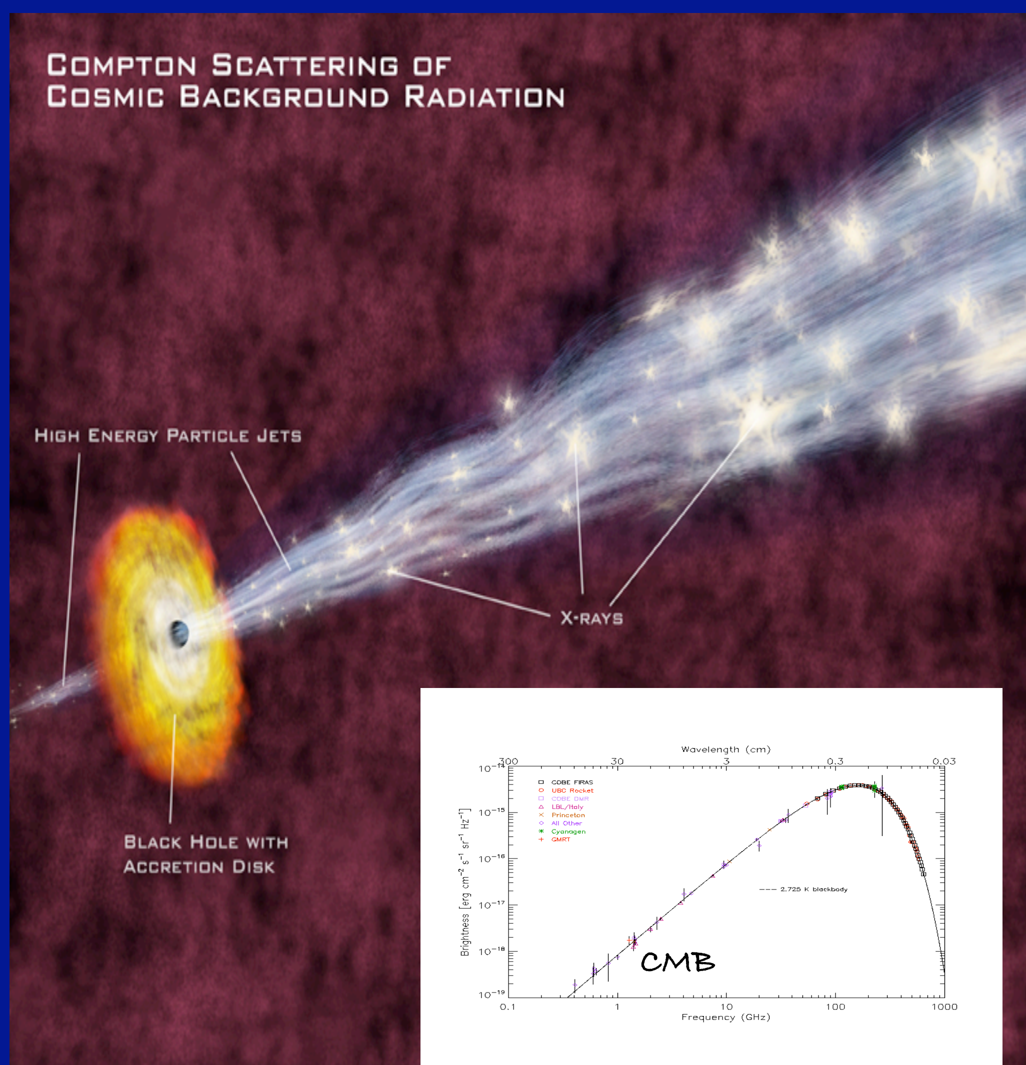
For low-luminosity (FRI) radio sources, there is strong support for the synchrotron process as the dominant emission mechanism for the X-rays, optical, and radio emissions

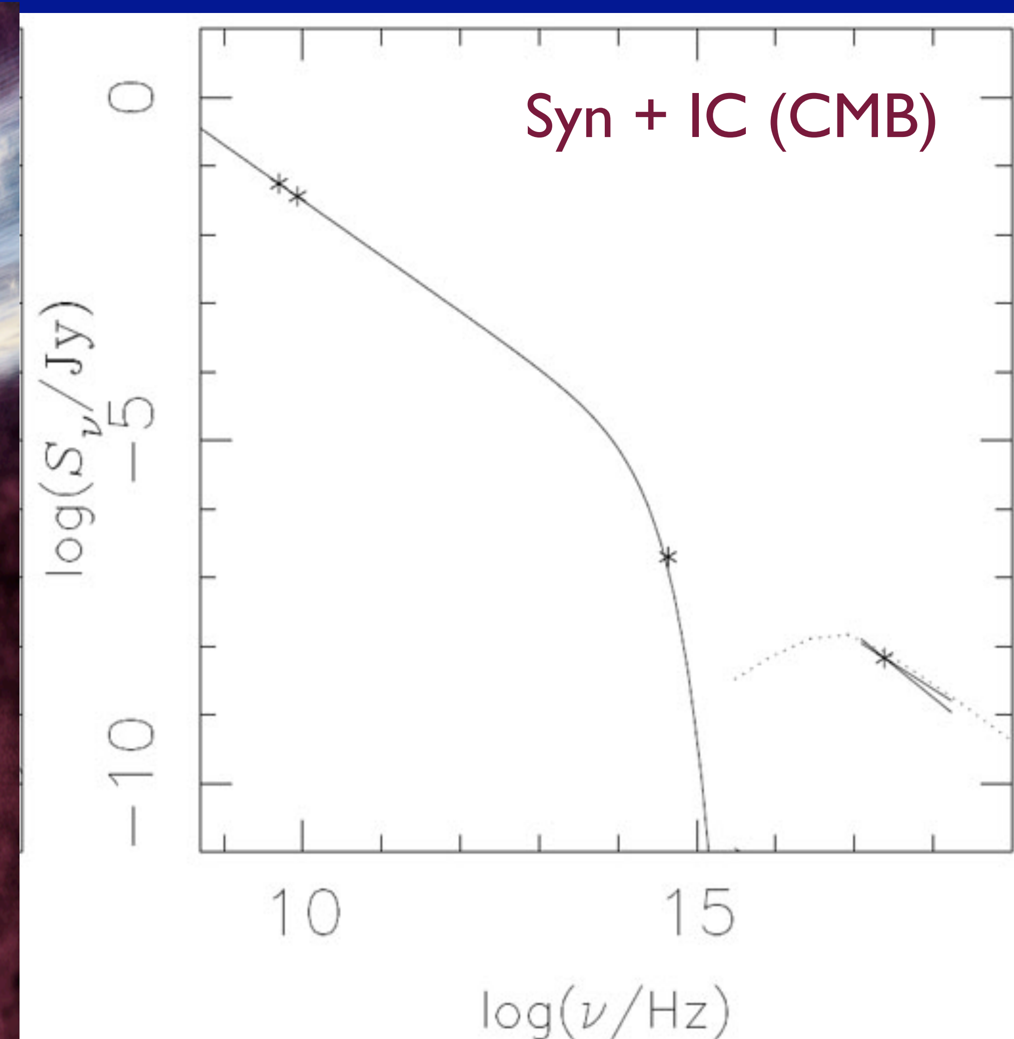
kpc-scale Jet

FRII sources require multi-zone synchrotron models, or synchrotron and IC models (seed photons:CMB).

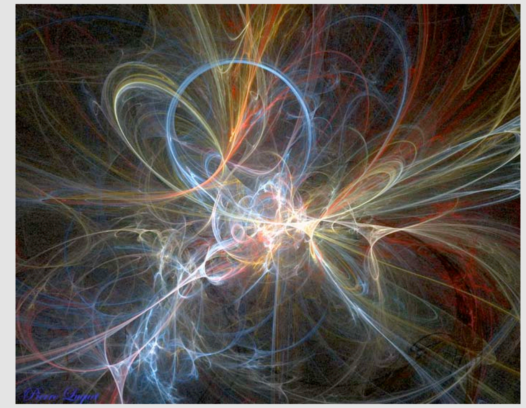
The most popular model postulates very fast jets with high bulk Lorentz factors Γ.

FRII-PKS0637-75



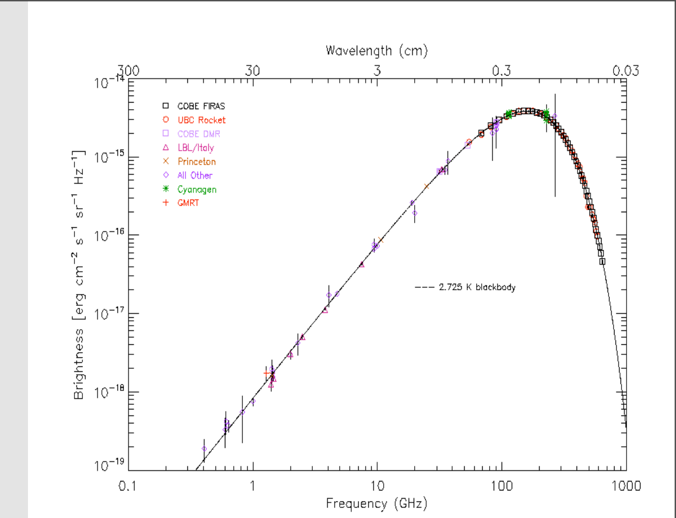


Lobes

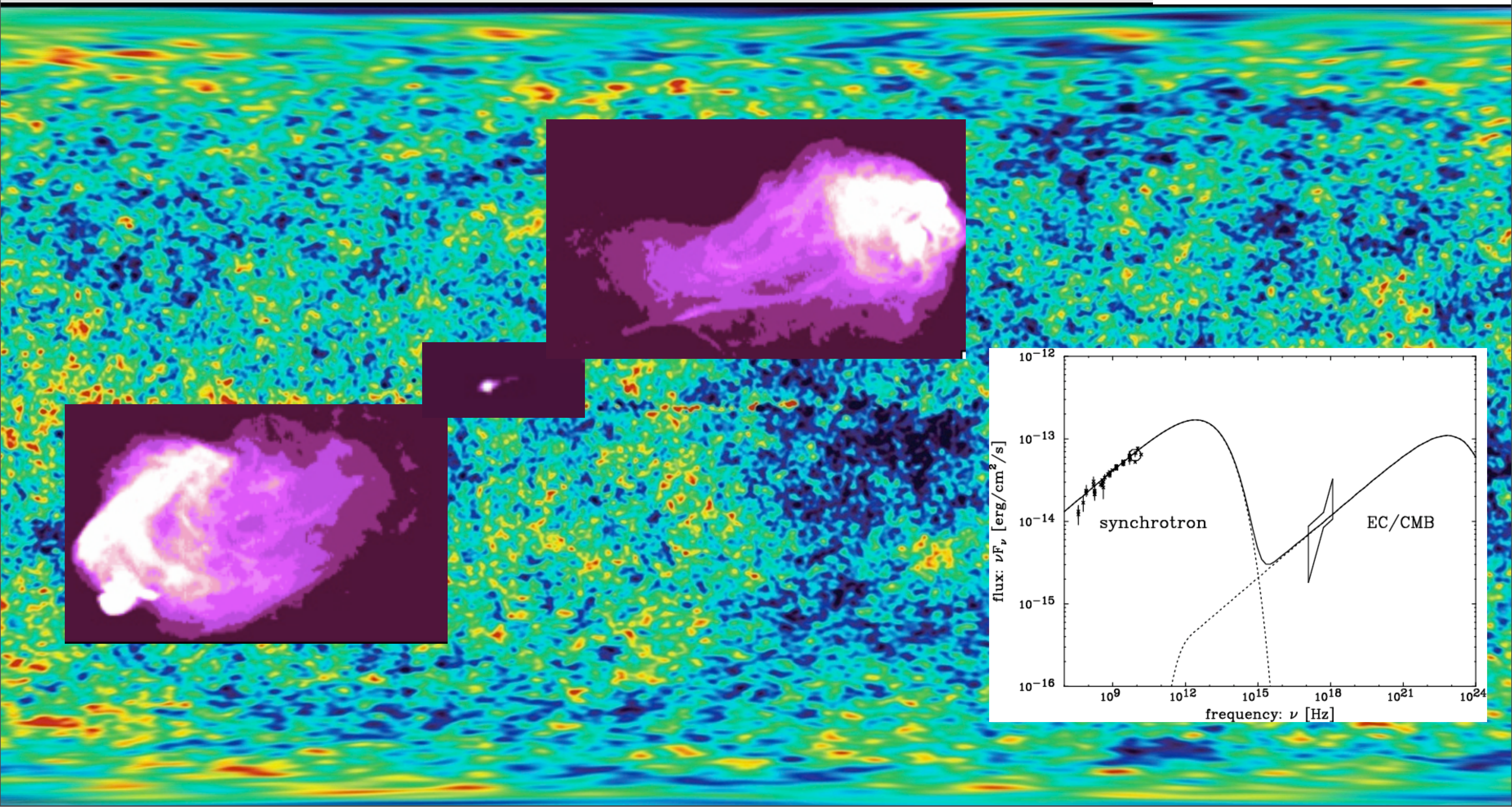


relativistic electrons

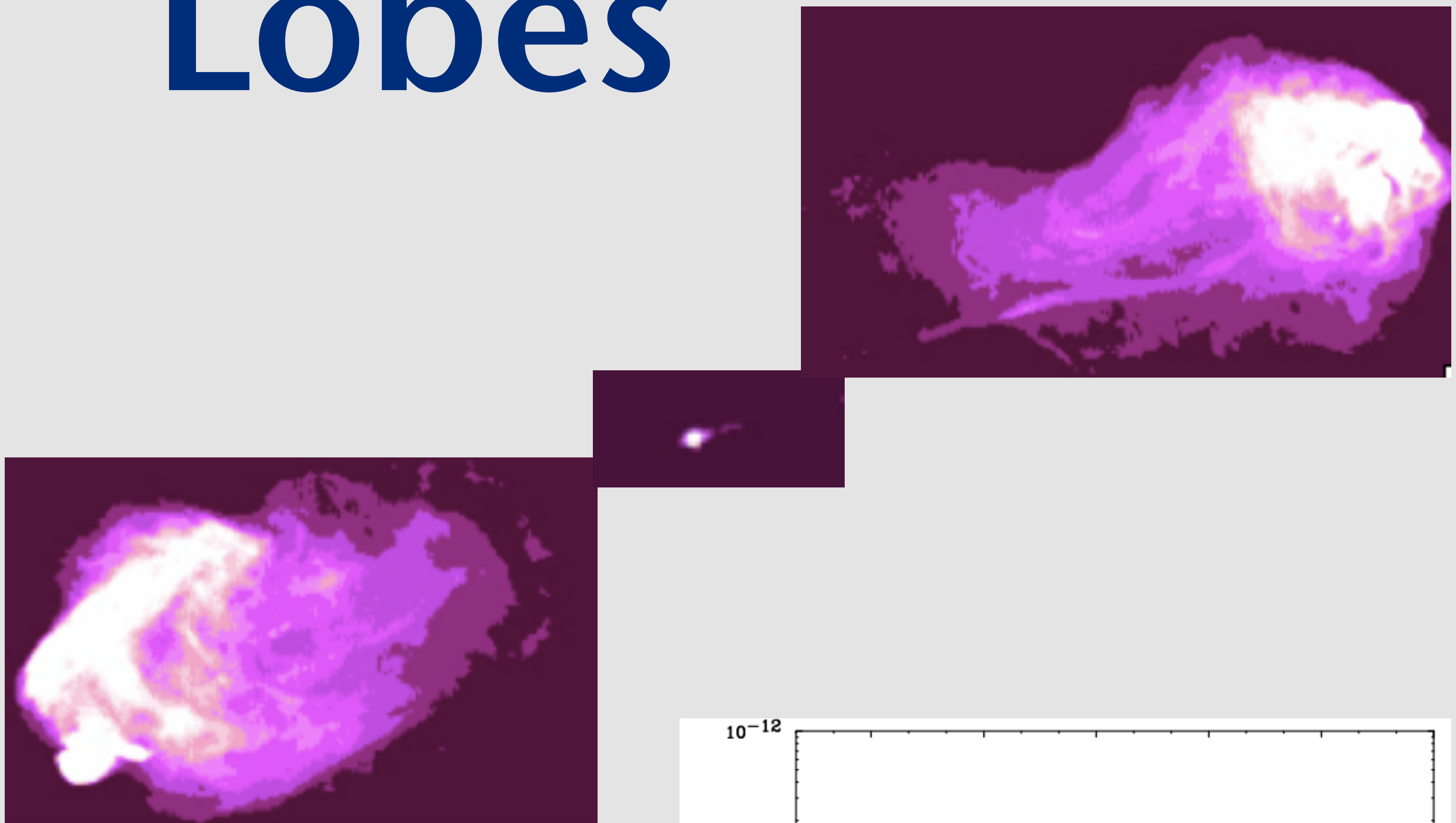
+

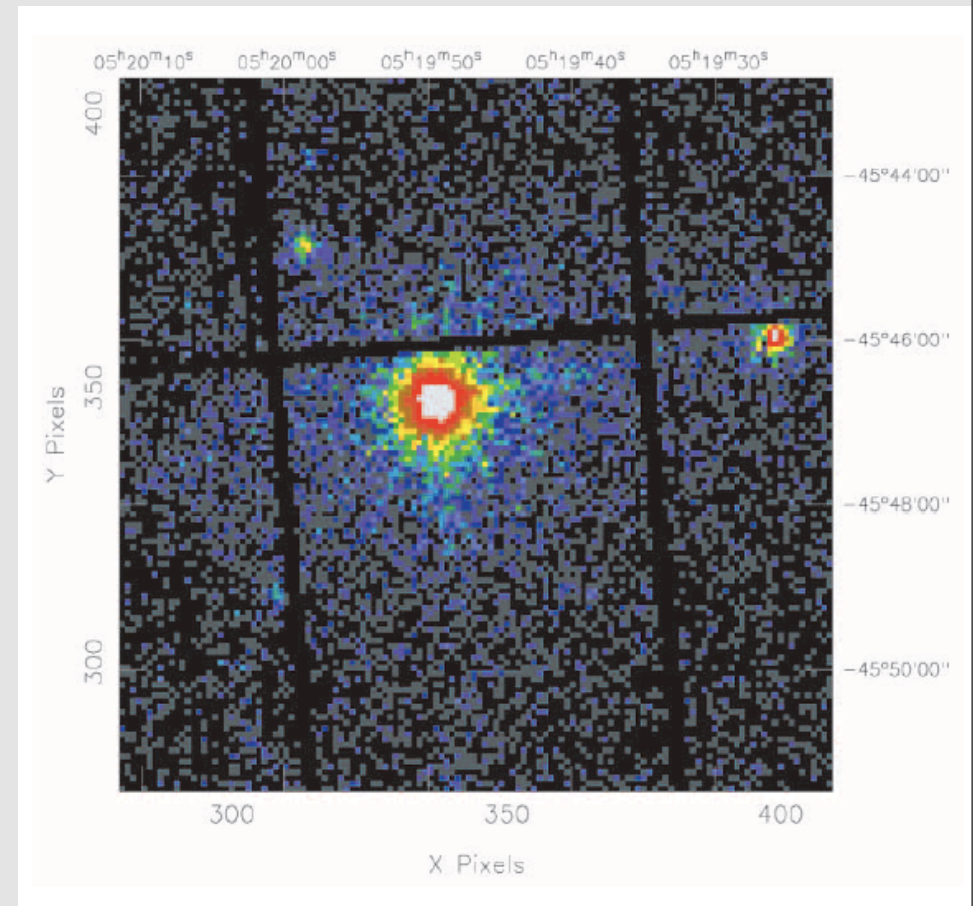


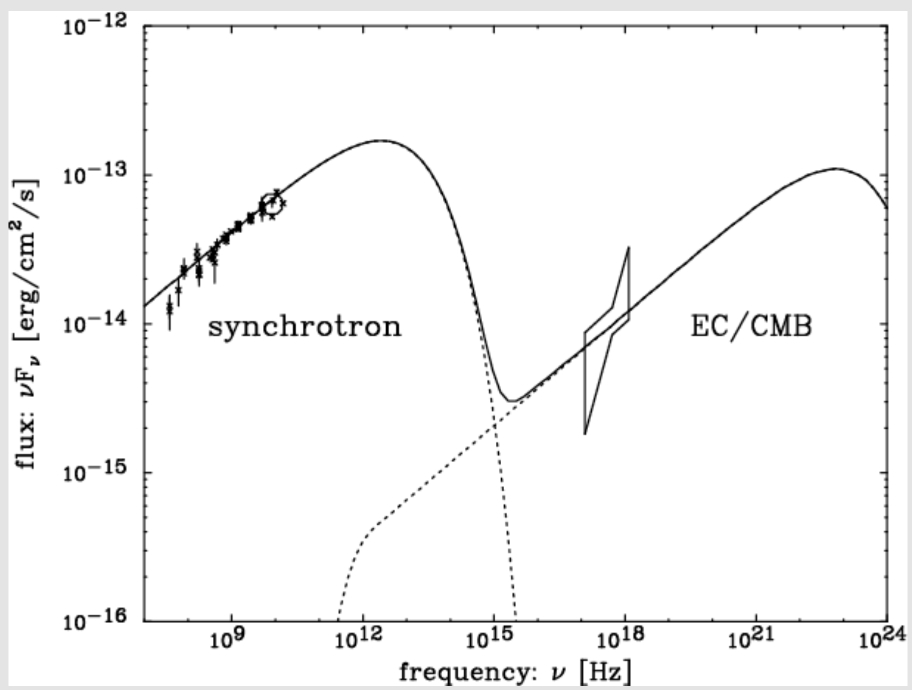
CMB



Lobes




05h20m10s
05h20m00s
05h19m50s
05h19m40s
05h19m30s
−45°44'00"
−45°46'00"
−45°48'00"
−45°50'00"
400
350
300
Y Pixels
300
350
400
X Pixels


10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
flux: νF_ν [erg/cm^2/s]
synchrotron
EC/CMB
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
10^{24}
frequency: ν [Hz]

Hot Spots

Terminal hotspots, like knots, are thought to be localized volumes of high emissivity which are produced by strong shocks or a system of shocks. Hot spot spectra are generally consistent with SSC predictions but a significant number appeared to have a larger X-ray intensity than predicted. This excess could be attributed to a field strength well below equipartition, IC emission from the decelerating jet 'seeing' Doppler boosted hotspot emission or an additional synchrotron component, ecc