An introduction to Radio-Loud AGN

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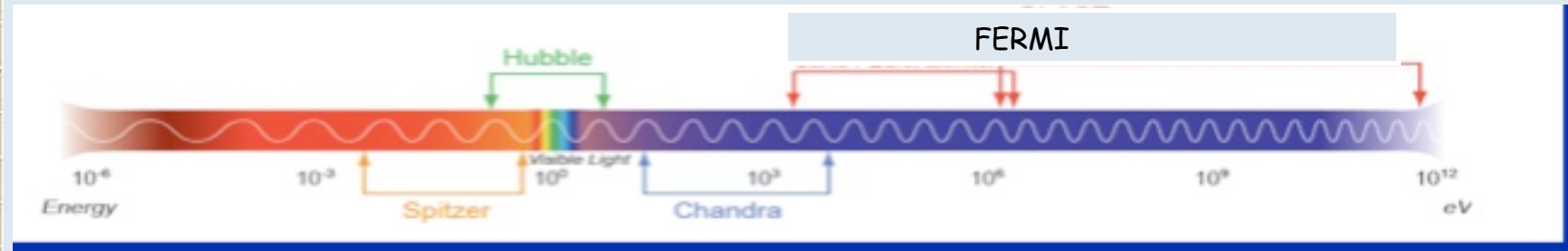
Laboratorio alte energie
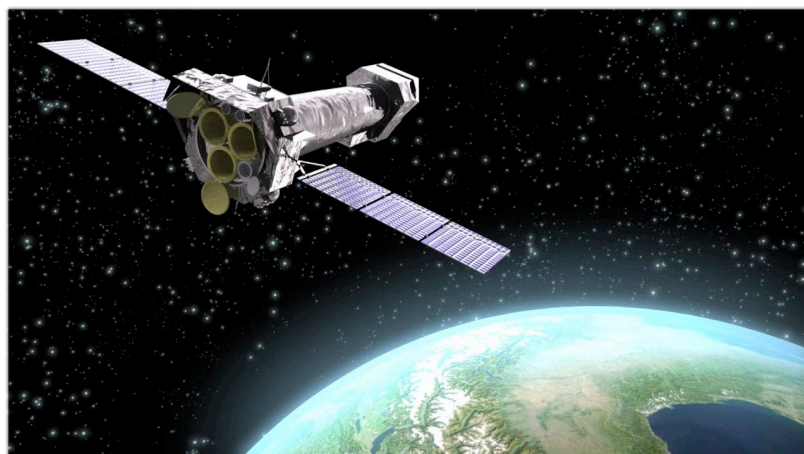**12.11.2019**

High and very high energy observations

Spectrum of Electromagnetic Radiation			
Region	Wavelength (Angstroms)	Wavelength (centimeters)	Frequency (Hz)
Radio	$> 10^9$	> 10	$< 3 \times 10^9$
Microwave	$10^9 - 10^6$	$10 - 0.01$	$3 \times 10^9 - 3 \times 10^{12}$
Infrared	$10^6 - 7000$	$0.01 - 7 \times 10^{-5}$	$3 \times 10^{12} - 4.3 \times 10^{14}$
Visible	$7000 - 4000$	$7 \times 10^{-5} - 4 \times 10^{-5}$	$4.3 \times 10^{14} - 7.5 \times 10^{14}$
Ultraviolet	$4000 - 10$	$4 \times 10^{-5} - 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{17}$
X-Rays	$10 - 0.1$	$10^{-7} - 10^{-9}$	$3 \times 10^{17} - 3 \times 10^{19}$
Gamma Rays	< 0.1	$< 10^{-9}$	$> 3 \times 10^{19}$

FERMI

Hubble

Spitzer   Chandra

Energy 10^{-6} 10^{-3} 10^0 10^3 10^6 10^9 10^{12} eV

Chandra ~0.5- 7 keV

Magic ~ 30 GeV- 100 TeV

FERMI -LAT ~ 100 MeV - 2 TeV

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Non-thermal emission
Synchrotron
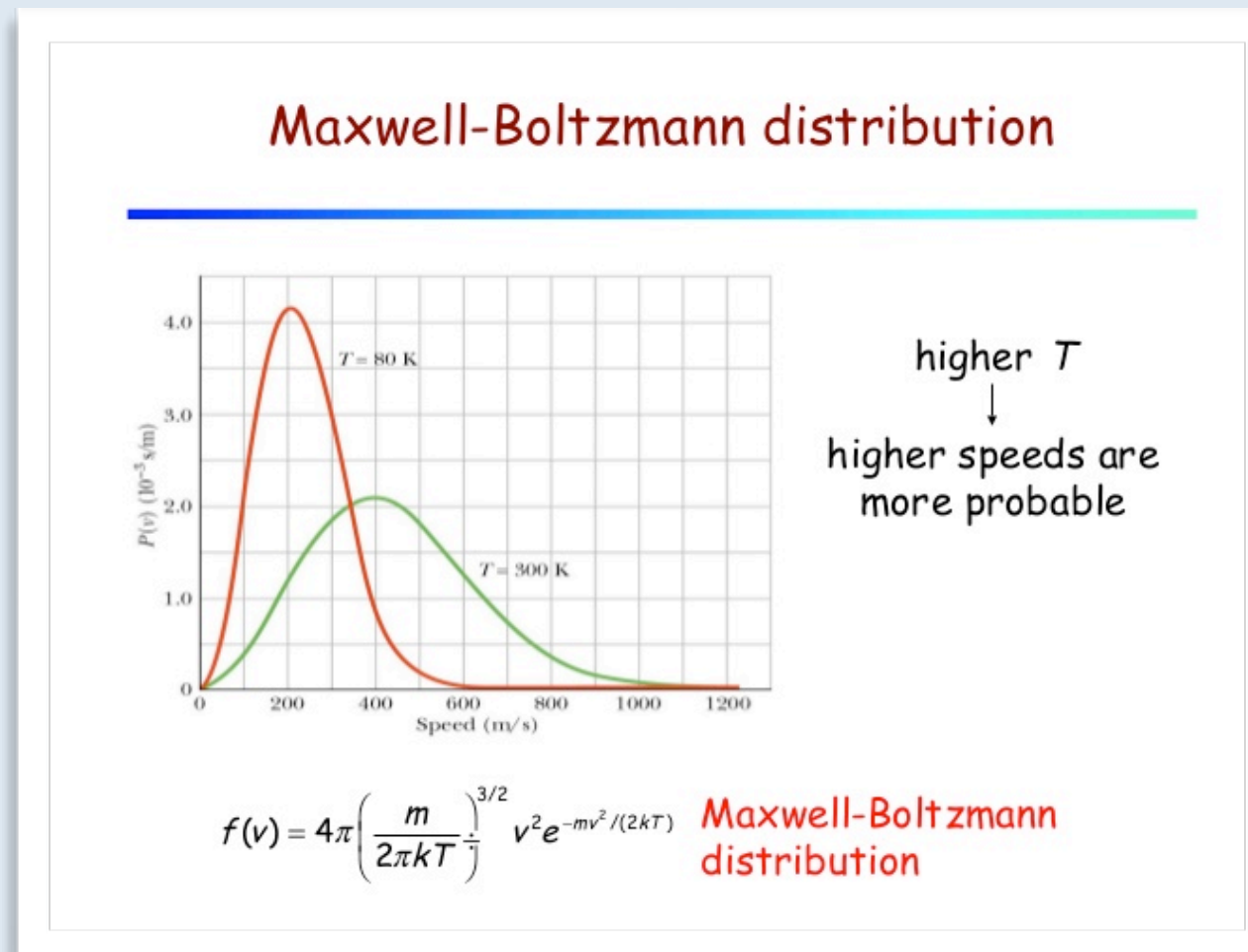**Inverse Compton**

Thermal emission
Accretion flow
Thermal Comptonization
Reprocessed features

Radiative processes

Thermal means that the radiation is dependent solely on the temperature of the emitter.

Maxwell-Boltzmann distribution

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

Maxwell-Boltzmann distribution

higher T
$\downarrow$
higher speeds are more probable

(graph: $P(v)$ (10^{-3} s/m) vs Speed (m/s), showing curves for $T = 80$ K and $T = 300$ K)
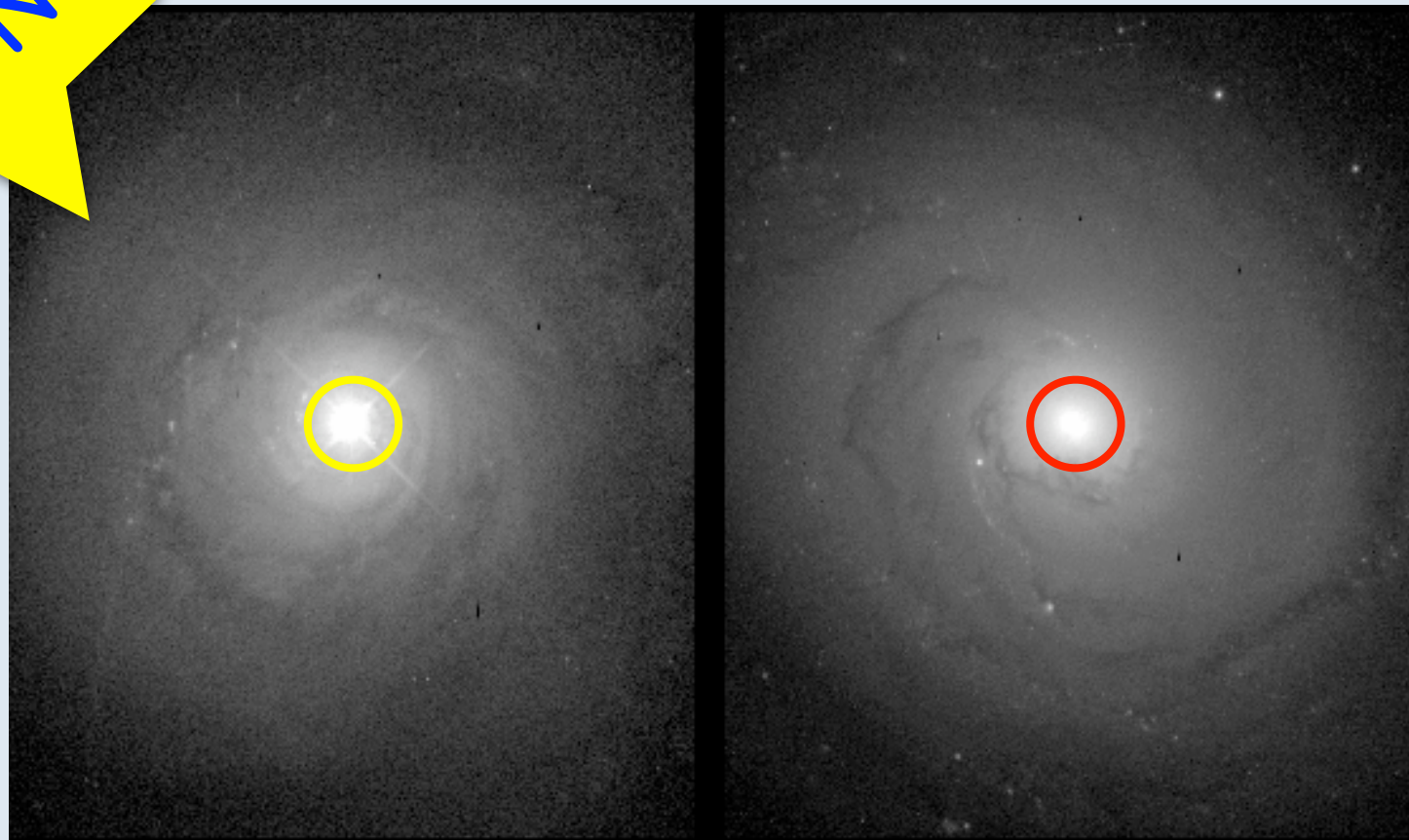
Non-thermal radiation involves other processes and generally requires accelerators

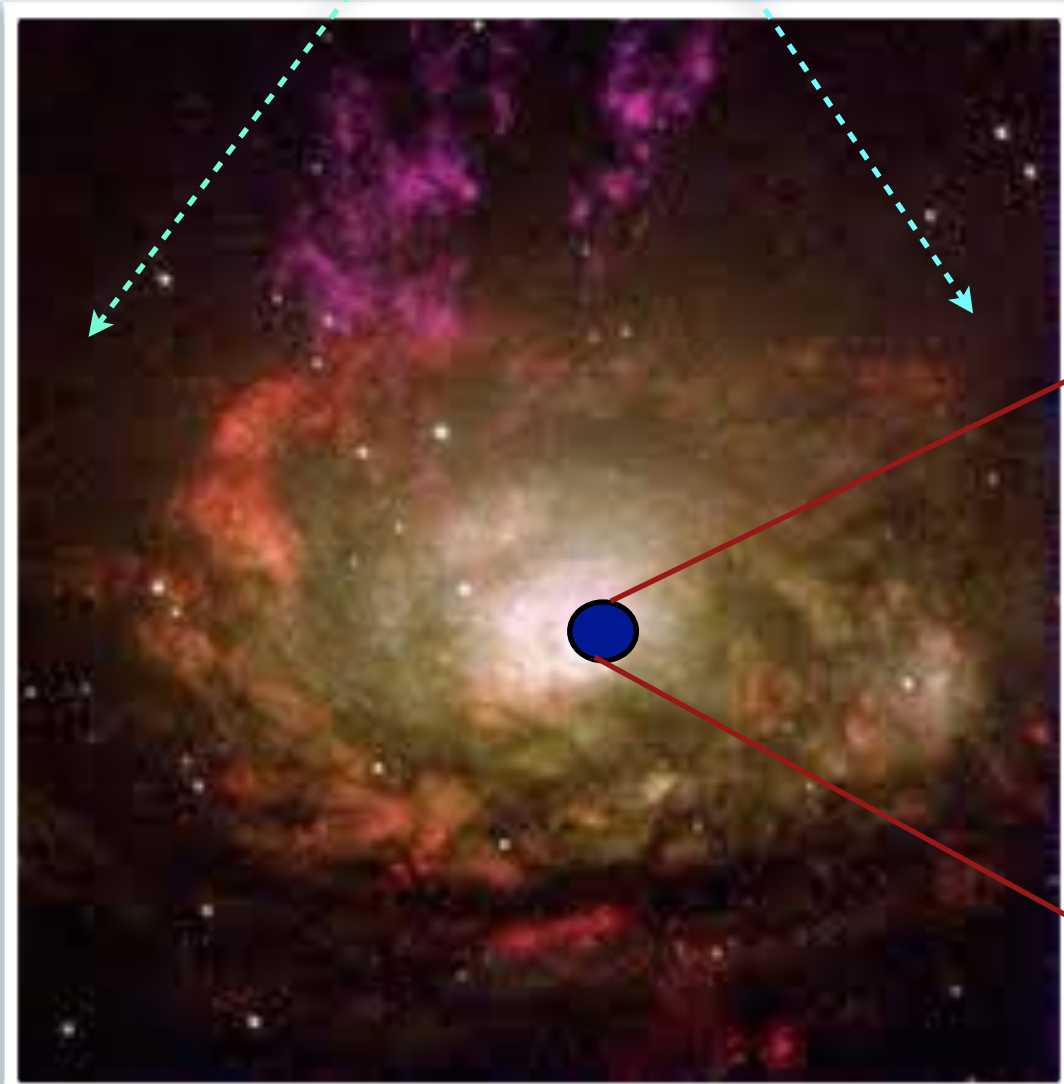# Almost every galaxy hosts a black hole from millions to billions of solar masses
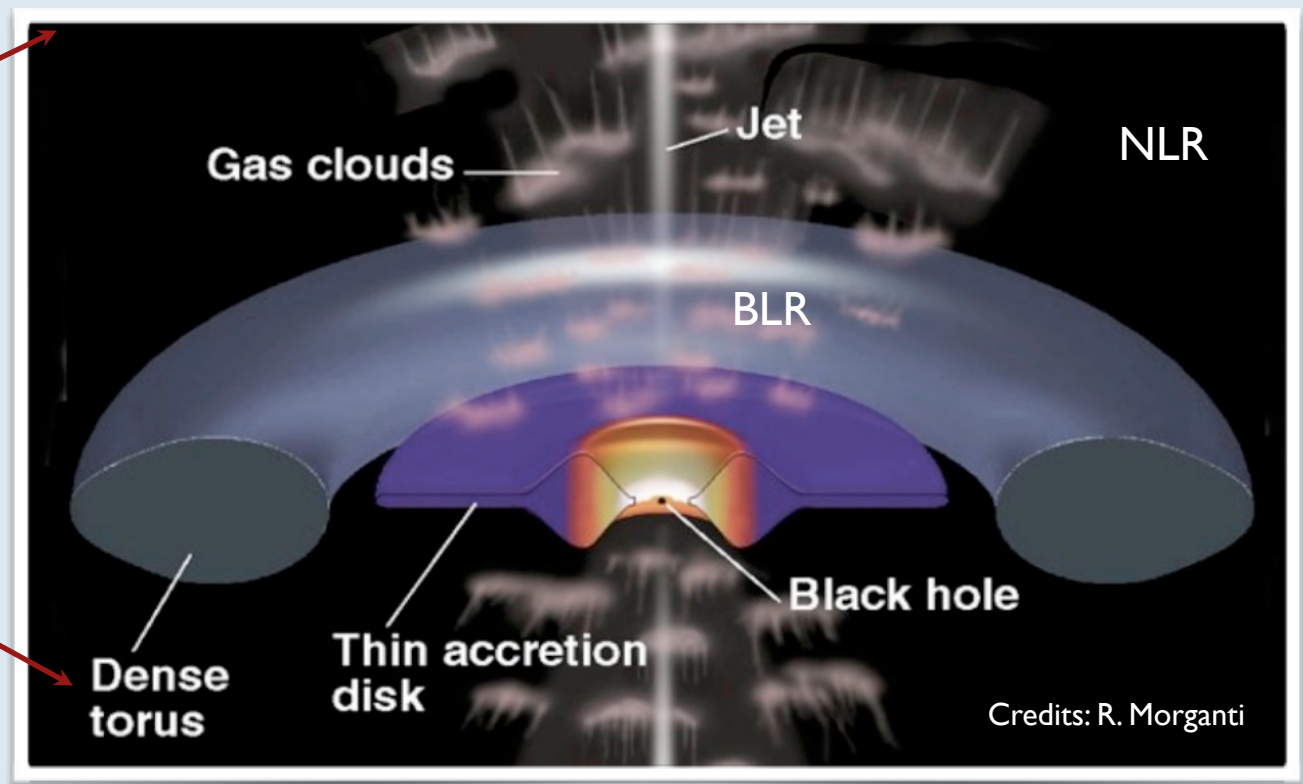
but...

1% active   99% silent

AGN

NGC 4151

Flux (10^{-13} erg cm^{-2} s^{-1} Å^{-1})

OII   OVI   HeII   Lyα   NV   SiIV+OIV]   NIV]   CIV   L2+L2'   HeII   OII   HeI

OI

ArI   OVI   CII*   SIV   SiIII   SiII   SiII

PII   PV   CIII*   NV   CII   SIV   CIV

SVI   CIII   NIII

HI

Wavelength (Å)

Intensity

Normal Galaxy spectra

4000   5000   6000

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

30 kpc

2–3 pc

Gas clouds

Jet

NLR

BLR

Black hole

Dense torus

Thin accretion disk

Credits: R. Morganti

The extraordinary amount of energy is produced through accretion of gas close to a SMBH

About 10% of AGNs are Radio-Loud,
i.e. these systems are able to launch relativistic jets
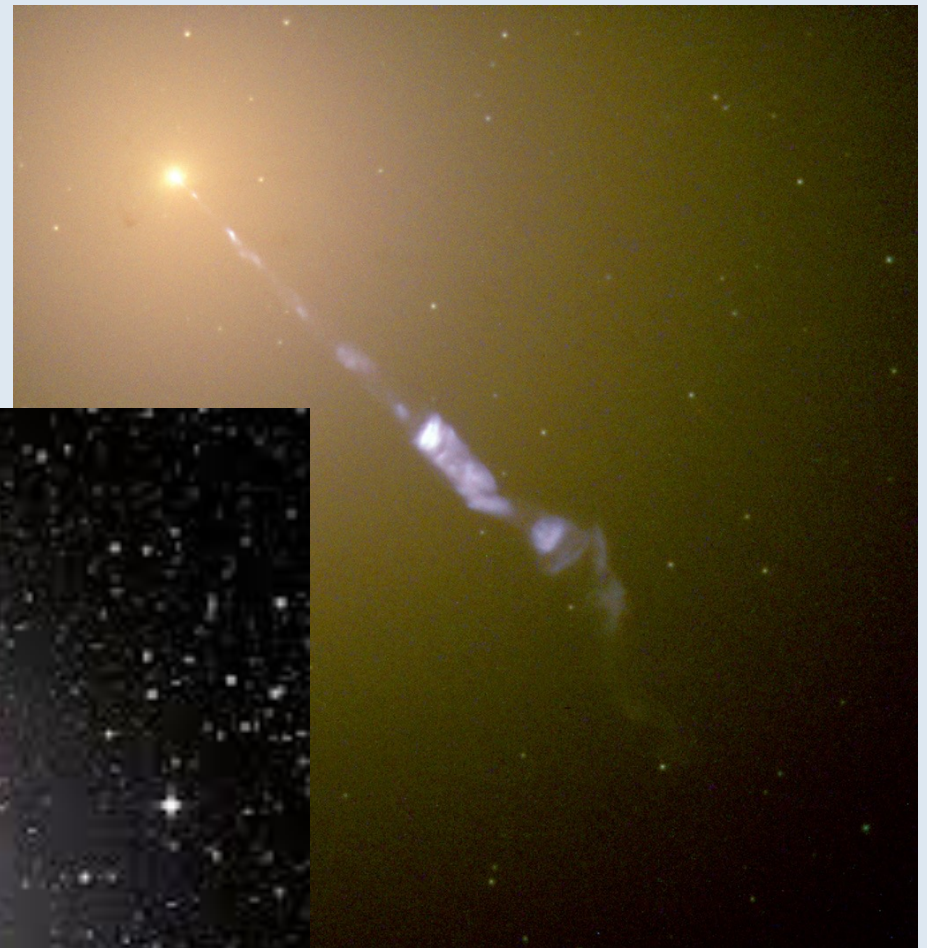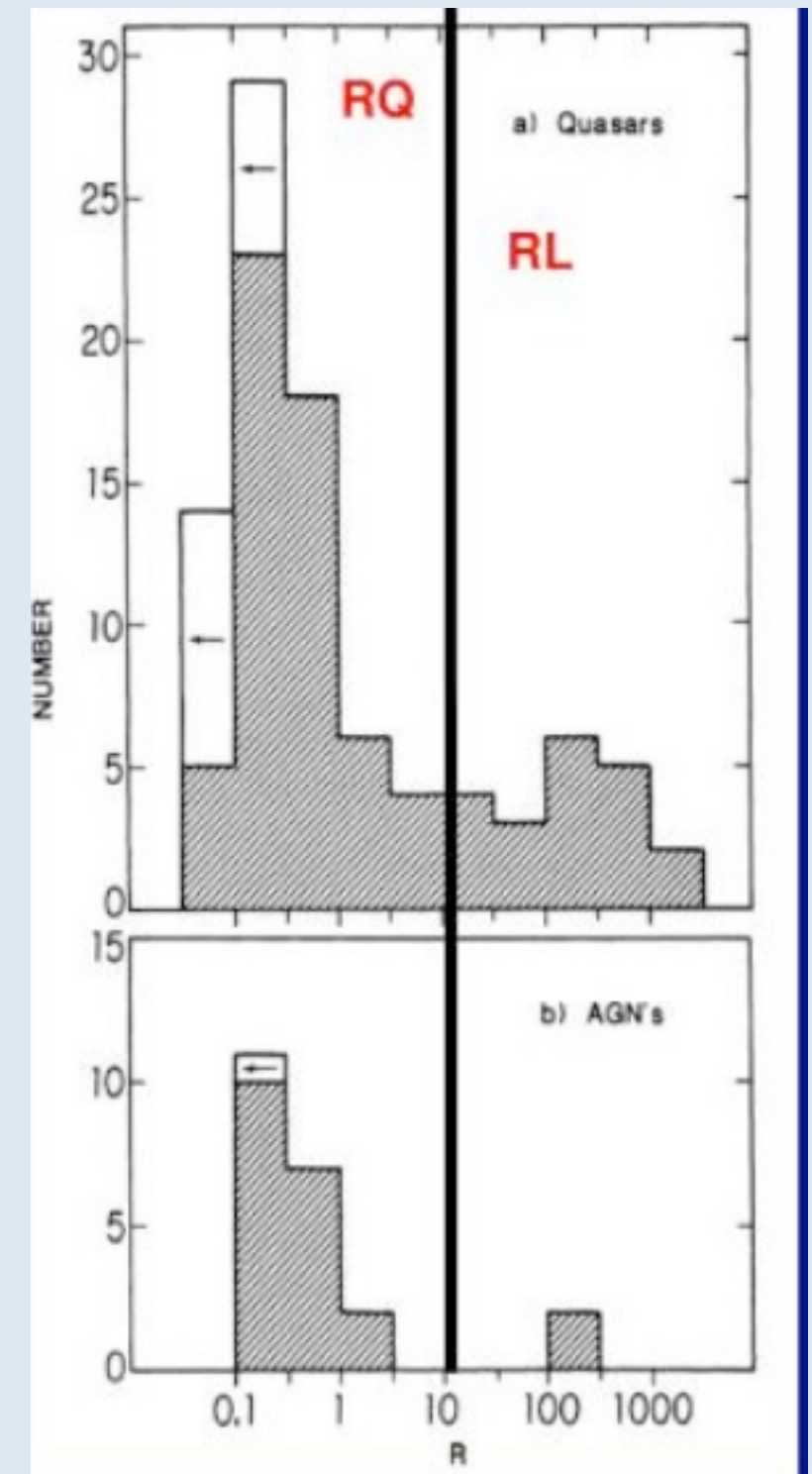
RL AGN lie in ellipticals
RQ AGN lie in spirals and ellipticals

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RADIO LOUDNESS PARAMETER (R)

$$R = \frac{F_{GHz}}{F_B} \geq 10.$$

This definition is based on a study of 114 objects from the Palomar Bright Quasar Survey with VLA (Kellermann 1989)

Quasars have blue magnitude $M_B<-23$, while AGN have $M_b>-23$

Current Space Densities of Selected Objects

Type of objects	Space Density (Gpc^{-3})
Radio Quiet	
Seyfert 2	$8 \times 10^5\ h_0^3$
Seyfert 1	$3 \times 10^5\ h_0^3$
QSO	$800\ h_0^3$
Radio Loud	
FRI	$2 \times 10^4\ h_0^3$
FRII	$80\ h_0^3$

Jets end at kpc/Mpc distances forming lobes

Narrow Line Region

Broad Line Region

Jet

Black Hole

Accretion Disk

Obscuring Torus

logarithmic scale!

Antonucci 1993 + Urry, Padovani 1995
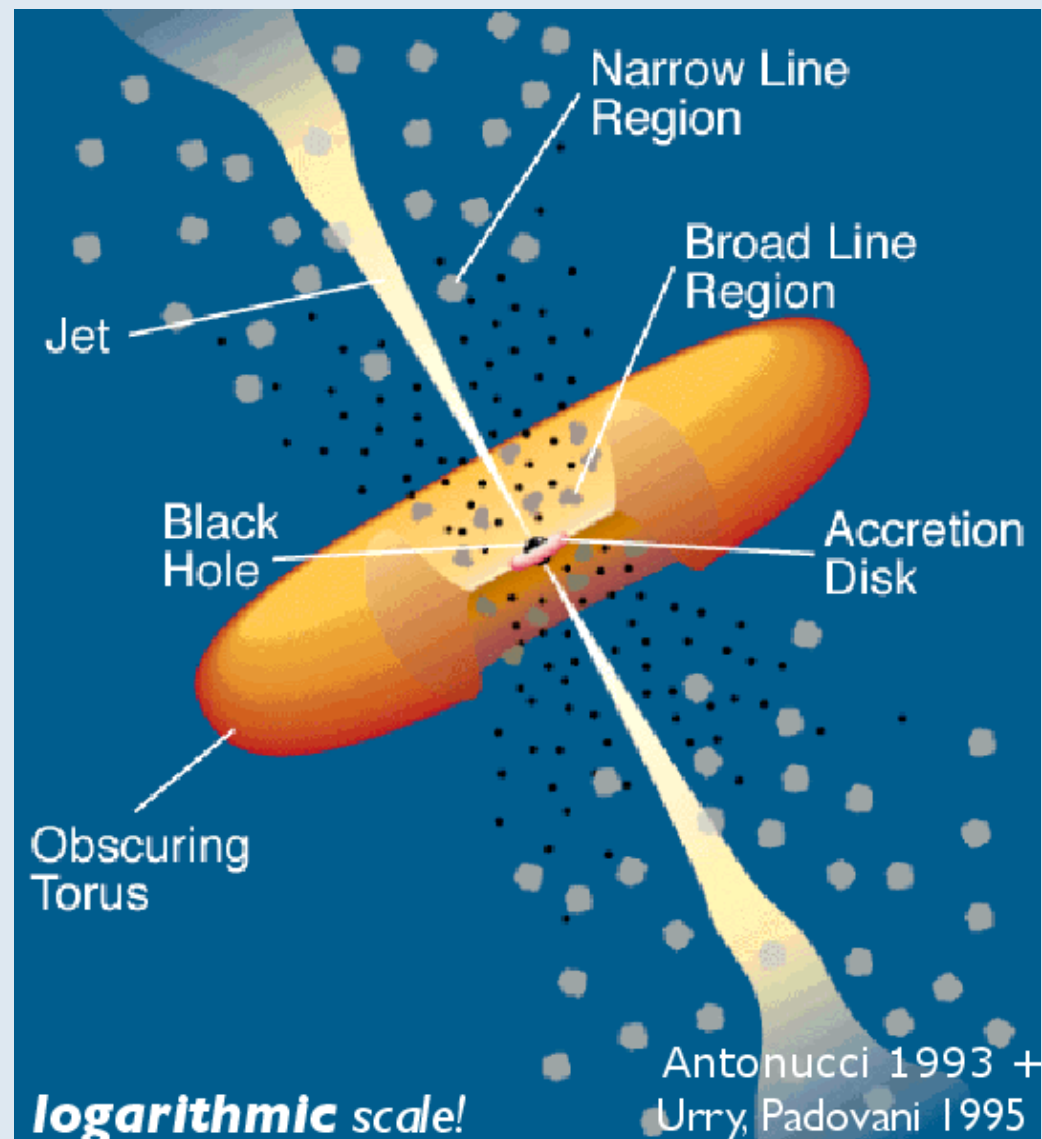
Fig. 1—A schematic diagram of the current paradigm for radio-loud AGN (not to scale). Surrounding the central black hole is a luminous accretion disk. Broad emission lines are produced in clouds orbiting above the disk and perhaps by the disk itself. A thick dusty torus (or warped disk) obscures the broad-line region from transverse lines of sight; some continuum and broad-line emission can be scattered into those lines of sight by hot electrons that pervade the region. A hot corona above the accretion disk may also play a role in producing the hard X-ray continuum. Narrow lines are produced in clouds much farther from the central source. Radio jets, shown here as the diffuse jets characteristic of low-luminosity, or FR I-type, radio sources, emanate from the region near the black hole, initially at relativistic speeds. For a $10^8 M_\odot$ black hole, the black hole radius is $\sim 3 \times 10^{13}$ cm, the accretion disk emits mostly from $\sim 1 - 30 \times 10^{14}$ cm, the broad-line clouds are located within $\sim 2 - 20 \times 10^{16}$ cm of the black hole, and the inner radius of the dusty torus is perhaps $\sim 10^{17}$ cm. The narrow-line region extends approximately from $10^{18} - 10^{20}$ cm, and radio jets have been detected on scales from 10^{17} to several times 10^{24} cm, a factor of ten larger than the largest galaxies.
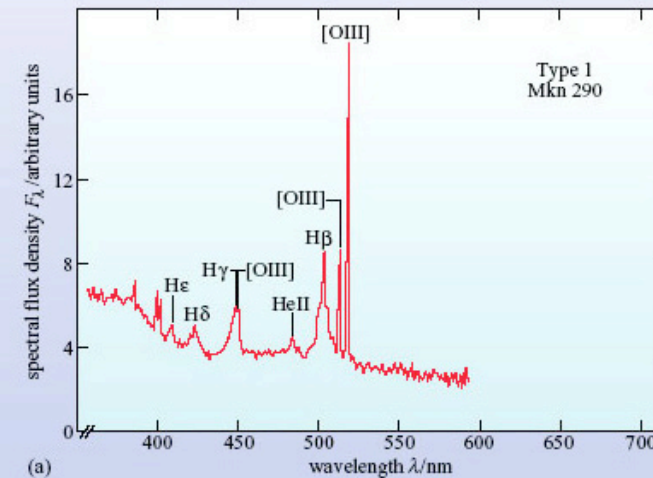
Urry & Padovani 1995
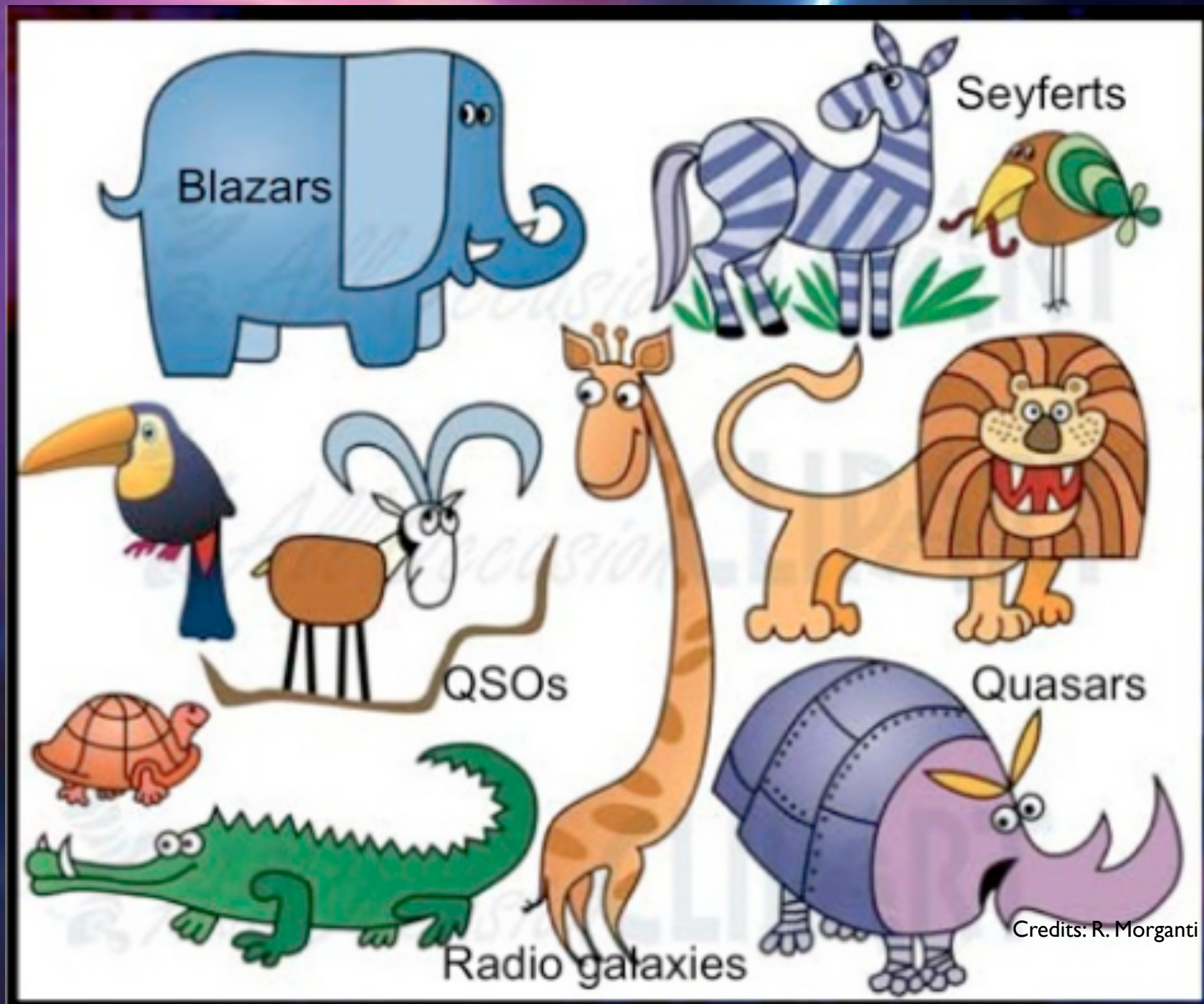
http://articles.adsabs.harvard.edu/full/1995PASP..107..803U

AGN classification

Credits: R. Morganti

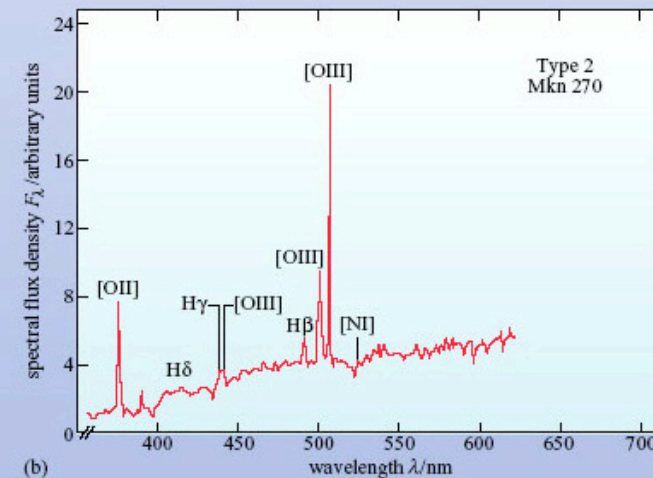# Optical Classification

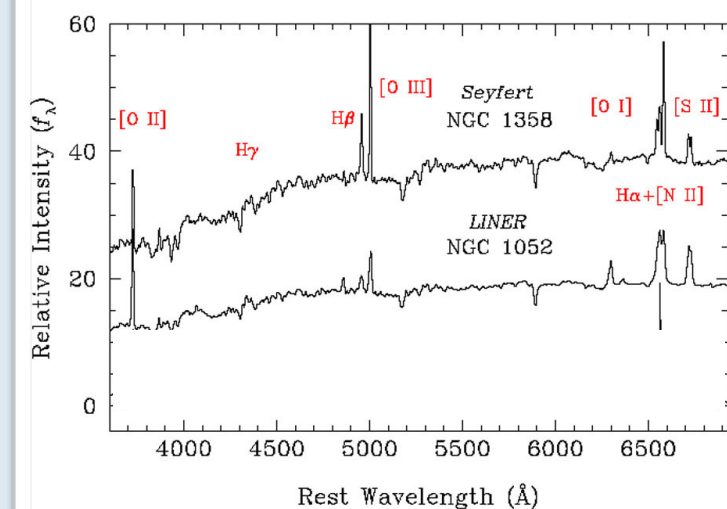|		
Type I	**bright continuum and BROAD emission lines from hot high velocity gas (FWHM~10^{3-4} km s^{-1})**	
Type II	**weak continuum and only NARROW emission lines (FWHM~10^2 km s^{-1})**	
Liner	**Low luminosity. Similar to Seyfert 2 galaxies, except that the low-ionization lines, e.g., [O I] 6300 and [N II] 6548, 6583, are relatively strong**	

RL AGN borrowed their optical classification from RQ AGN (old approach)

Brod Line Radio Galaxy (BLRG) Quasars (large z)	bright continuum and broad emission lines from hot high velocity gas	TYPE I
Narrow line Radio Galaxy	weak continuum and only narrow emission lines	TYPE II
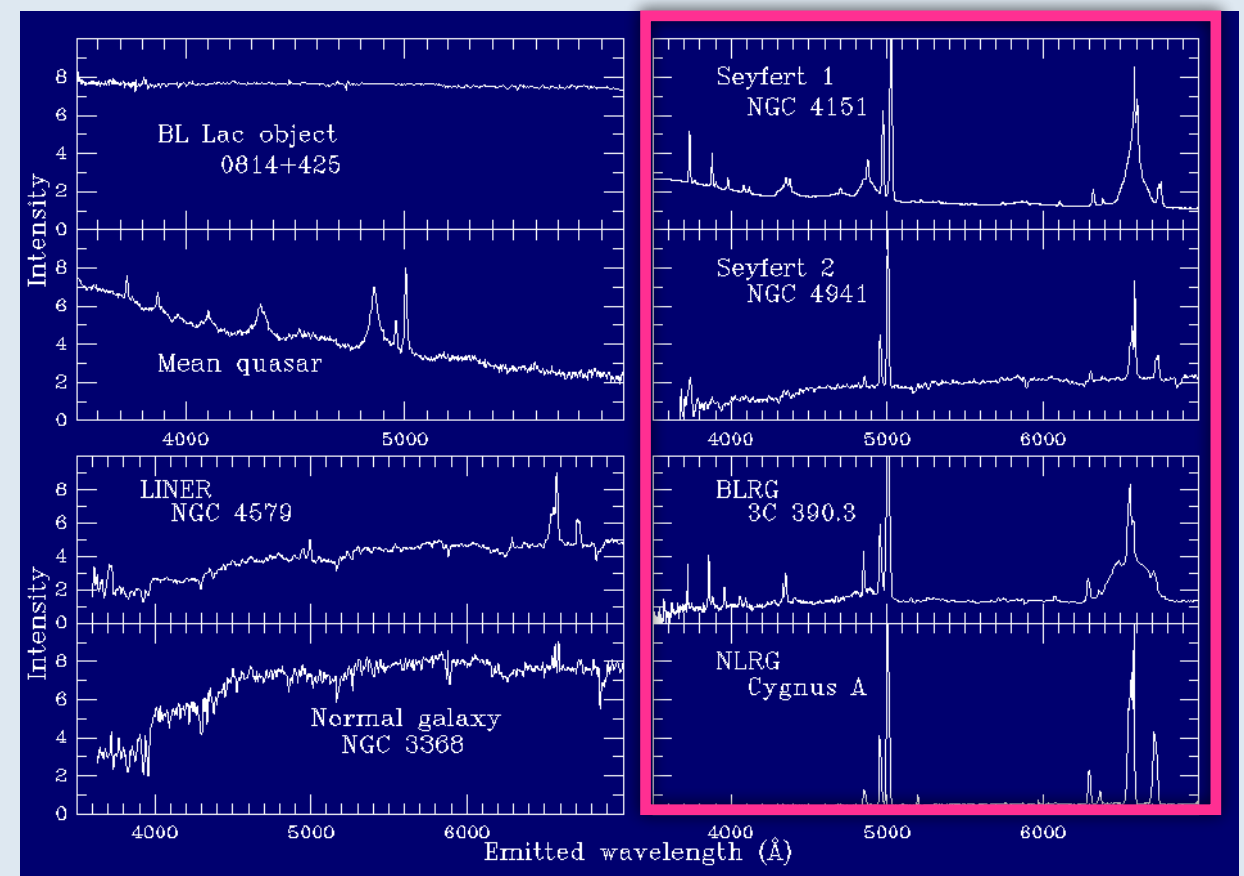
New optical classification
High-excitation (HERG) low-excitation (LERG) Radio Galaxy

This classification is related to the <u>excitation modes of the gas in the Narrow Line Regions</u>: different excitation modes correspond to different accretion rates
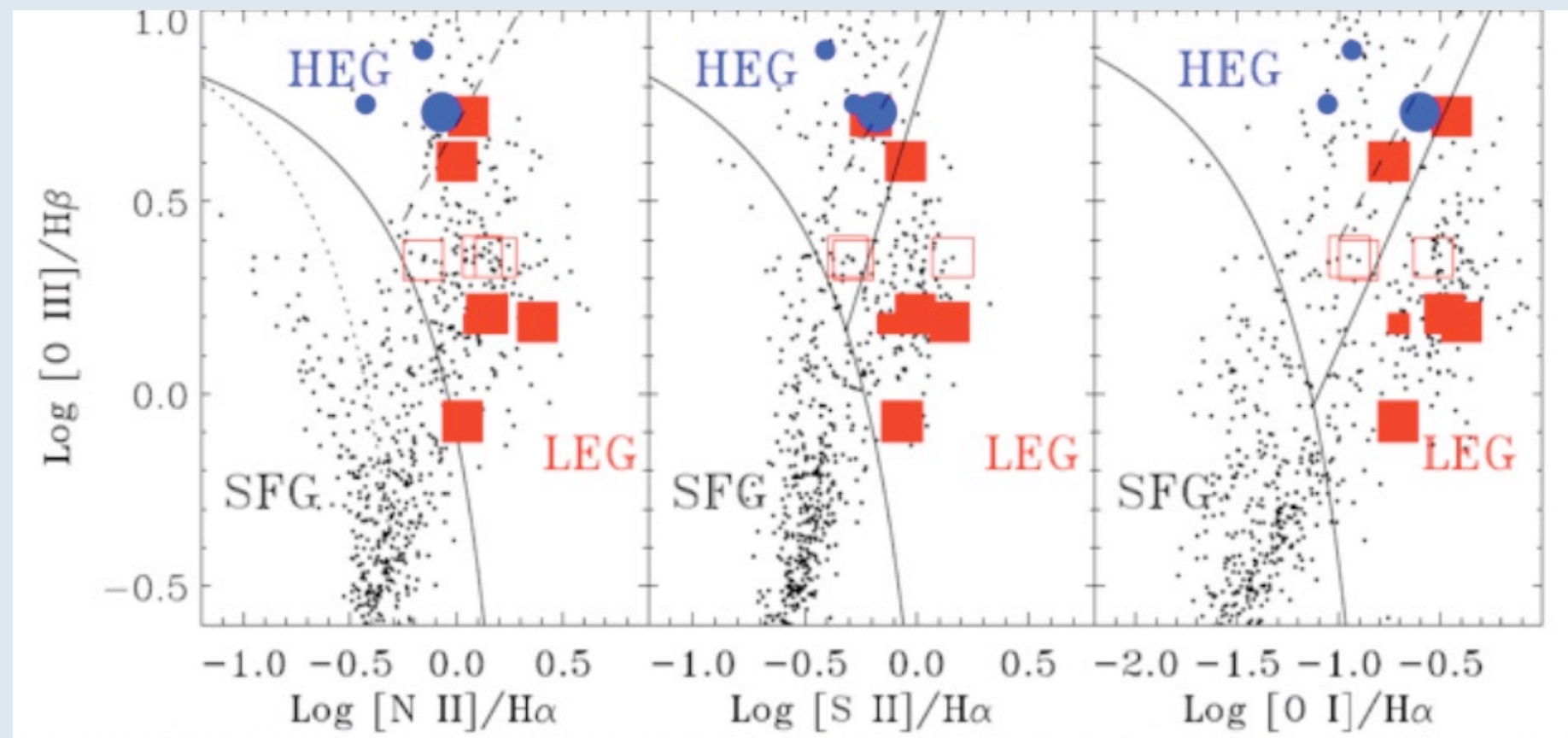
Best & Heckmann

Buttiglione et al.

New optical Radio Loud classification

High-Excitation Radio Galaxy (HERG)

Efficient engine

Low-Excitation Radio Galaxy (LERG)

Inefficient engine

in converting gravitational power into radiation

FRI/FRII classification (Fanaroff & Riley 1974)
RADIO MORPHOLOGY

FRI - $L_{178MHz} < 2 \times 10^{25}$ W Hz^{-1} sr^{-1}

FRII - $L_{178MHz} > 2 \times 10^{25}$ W Hz^{-1} sr^{-1}
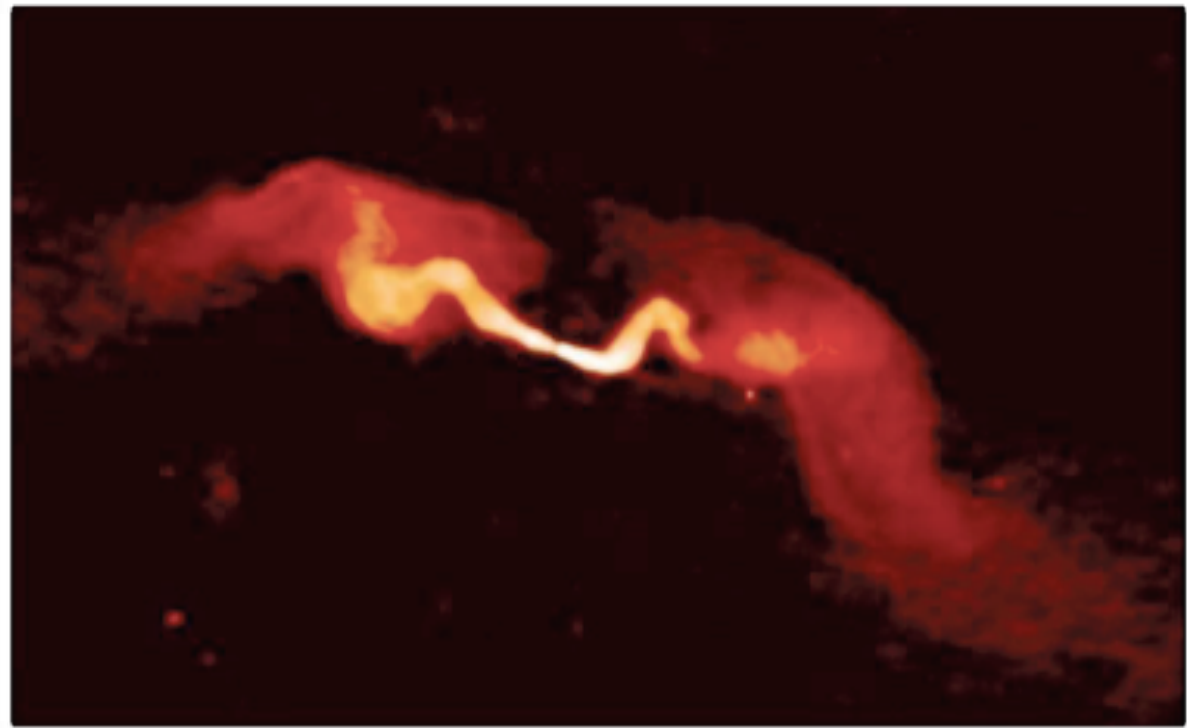
FRI/jet dominated

In FRI the jets are thought to decelerate and become sub-relativistic on scales of hundred of pc to kpc.

The nuclei of FRI are powered by inefficient engine

Edge-darkened

FRII/lobe dominated

The jets in FRII are at least moderately relativistic and supersonic from the core to the hot spots.

Most FRII are **thought** to have an efficient engine
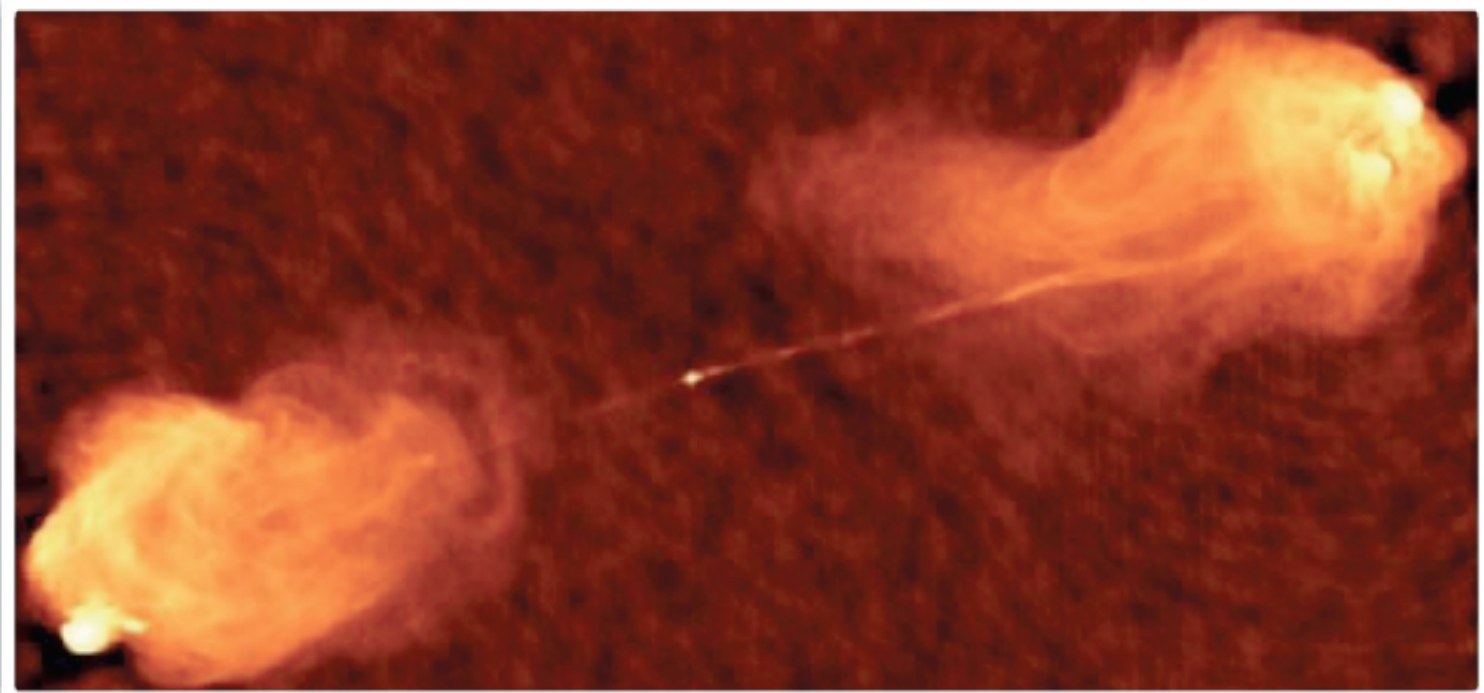
Edge-brightened
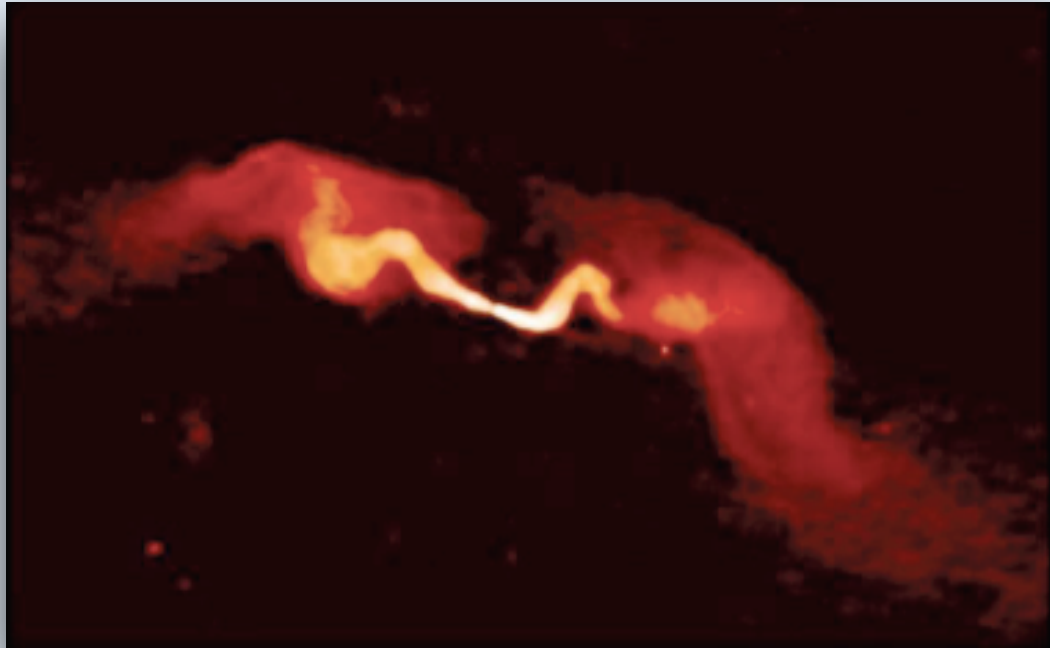
FRI/jet dominated

FRI -> LERG
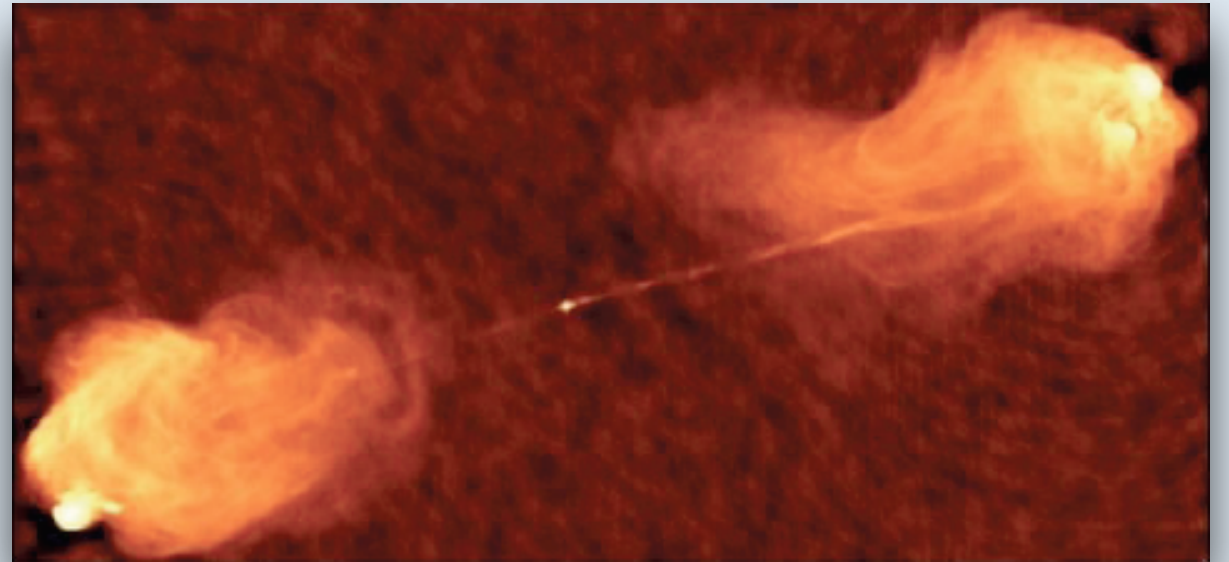
FRII/lobe dominated

FRII -> HERG

Different Engine

The inner AGN engine
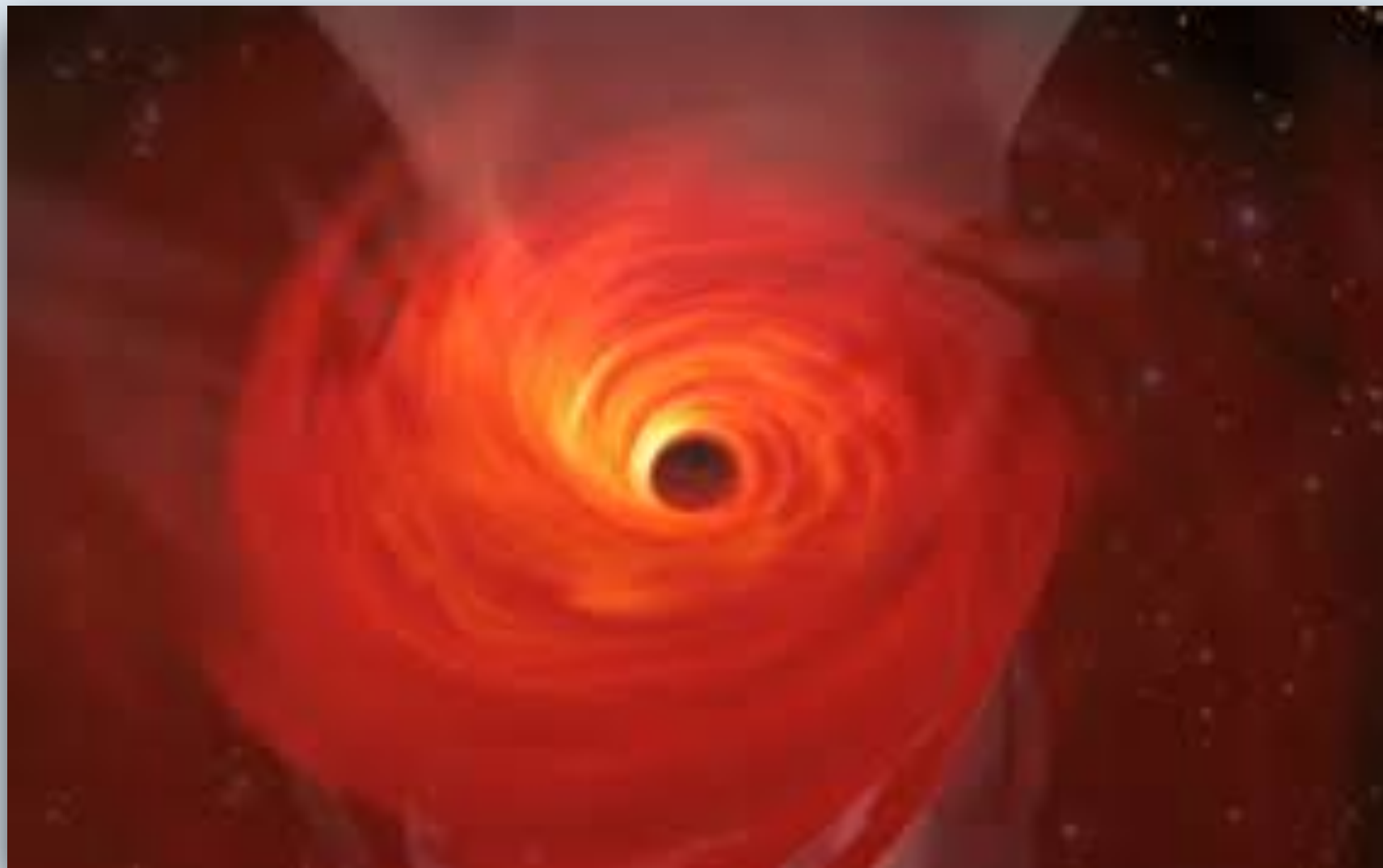
Accretion process is very efficient in producing energy

Assuming $M \sim M_{sun}$ and R=10 Km

$$\Delta E_{acc} = \frac{GMm}{R} \quad \sim \ 10^{20} \ \text{erg/g}$$

NOTE that in case of nuclear energy generation, the greatest release of nuclear binding energy is:

$$\Delta E_{nuc} = 7 \times 10^{-2} mc^2 \sim 6 \times 10^{18} erg/g$$

If the rate at which mass is accreted onto M is $\dot{M}$ the luminosity of the source is

$$L_{acc} = GM\dot{M}/R$$

<u>Note</u>: M/R is the compactness of the accretion. The more compact, the more energy can be released.

Eddington Luminosity L_E is a sort of "unit of measurement". It is the luminosity at which the outward force of the radiation pressure is balanced by the inward gravitational force, i.e. it is the maximum luminosity a spherically symmetric source of mass M can emit in a steady state

$$L_{Edd} = \frac{4\pi GMm_pc}{\sigma_T} \sim 1.3 \times 10^{38} \frac{M}{M_\odot} erg/s \ ($$

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$$L_{acc} = GM\dot{M}/R$$

Introducing the Schwarzschild radius

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

L_{acc} can be written as:

$$L_{acc} = 2\eta GM\dot{M}/R = \eta\dot{M}c^2$$
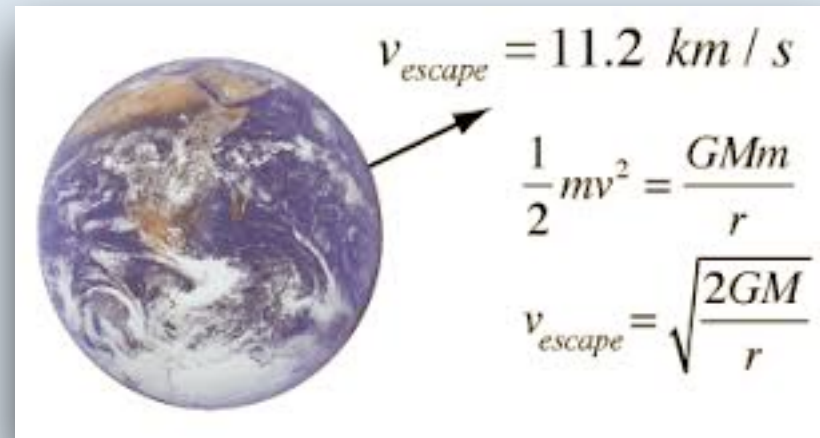
Longair, Malcolm
pag. 445

Black hole radius can be derived by the escape velocity of the light

$$v_{escape} = c = \left(\frac{2GM}{R_S}\right)^{\frac{1}{2}}$$

Schwarzschild radius $\quad R_S = \frac{2GM}{c^2}$

Accretion processes around black holes involve rotating gas flow. Therefore the accretion flow structure is determined by solving simultaneously four conservation equations:

conservation of vertical momentum
conservation of mass
conservation of energy
conservation of angular momentum

Four solutions are currently known. In these solutions 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.

The most famous solutions are:

i) Shakura & Sunyaev thin optically thick disk model (standard model)
ii) Optically thick Advection-Dominated Accretion Flow (ADAF)

Efficient Engine

R M_{BH}

Thin H/R<< 1

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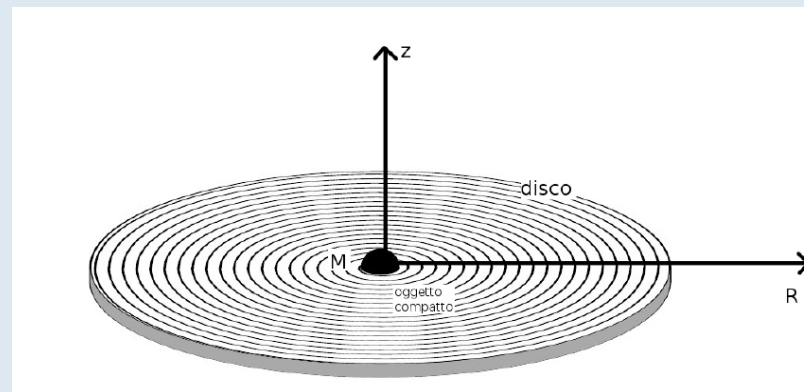
Thick, in the sense that each element of the disk radiates as a black body

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

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

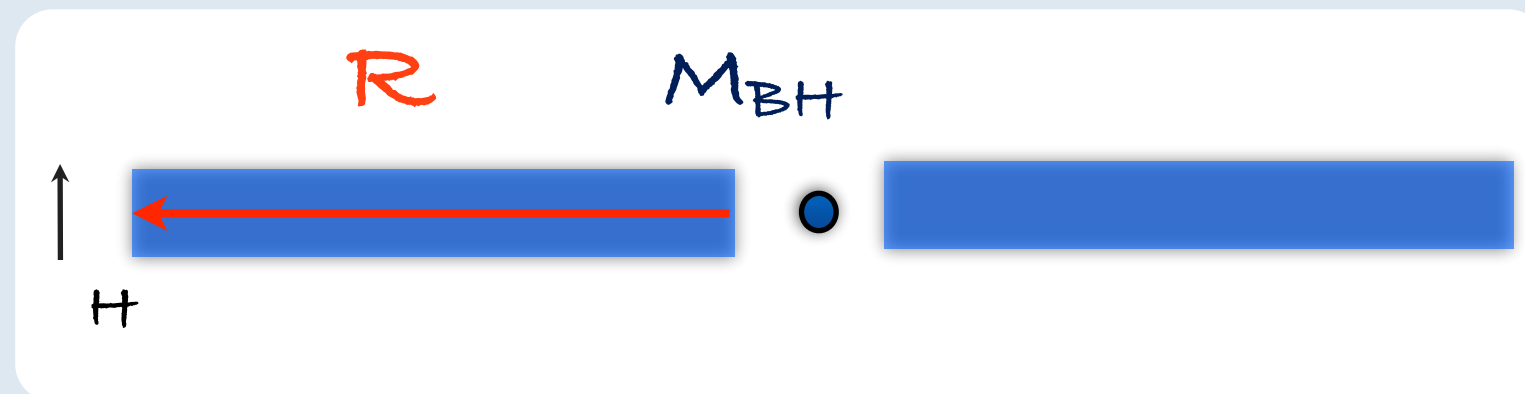For AGN with $\quad M_{BH} = 10_8 = 10^8 M_\odot \qquad \dot{M} \sim \dot{M}_E = \frac{L_E}{\eta c^2}$
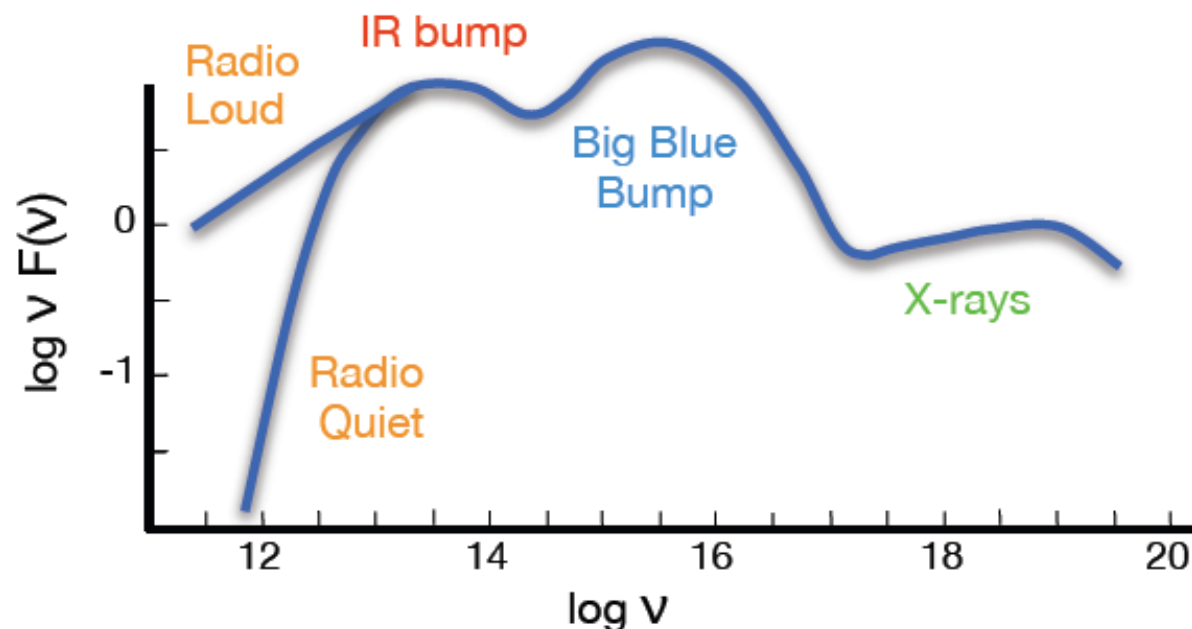
the peak occurs at UV-soft-X-ray region

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

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

Longair, Malcolm
pag. 451
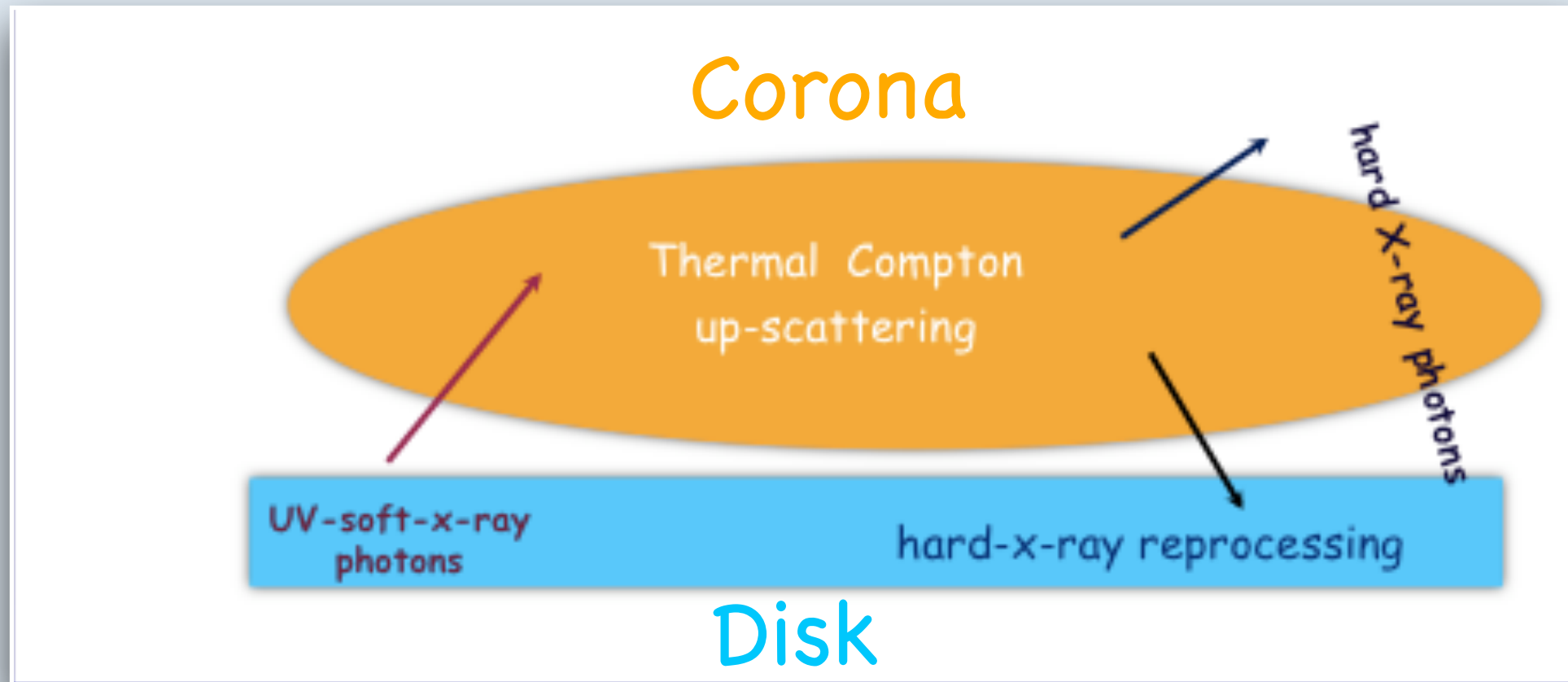
Thermal Comptonization

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
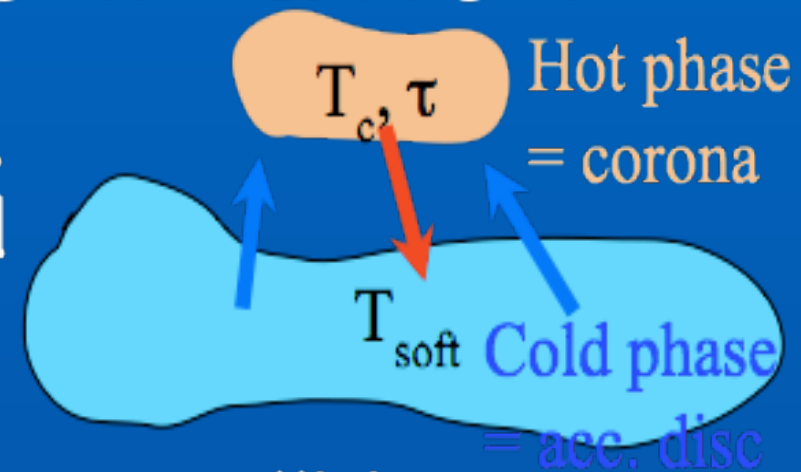
T_c, τ **Hot phase** = corona

T_{soft} **Cold phase** = acc. disc

✓ mean relative energy gain per collision

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

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

✓ mean number of scatterings

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

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

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

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


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

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.

Spectral Energy Distribution (SED)
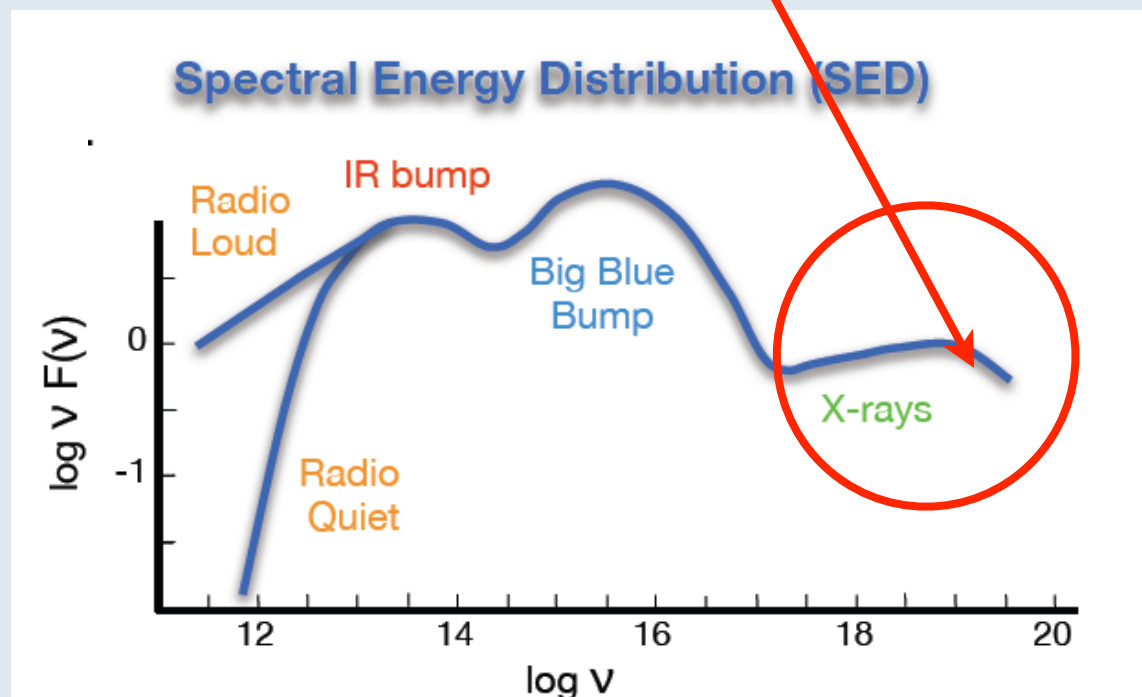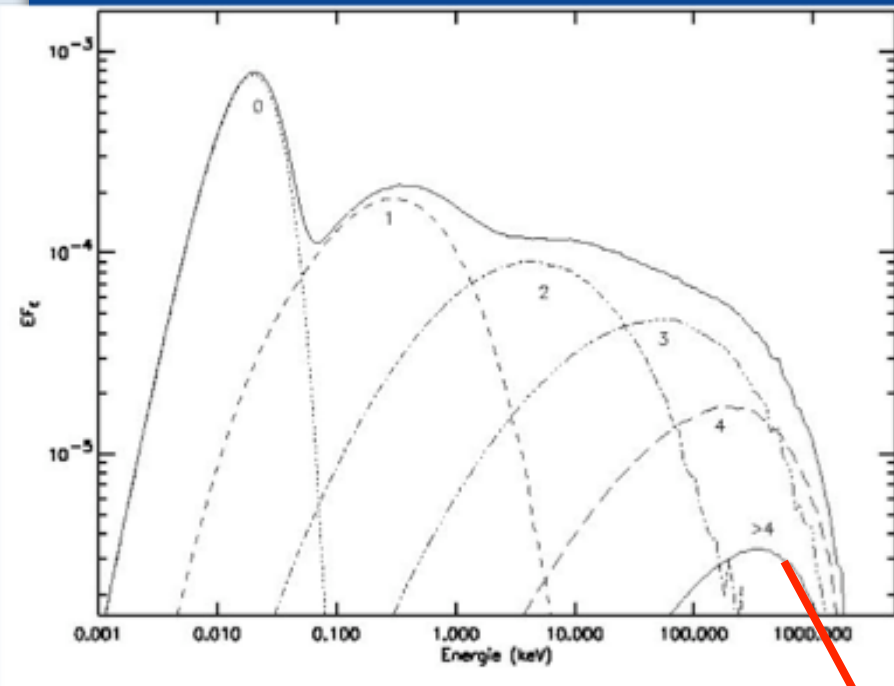
Haardt & Maraschi 1991

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Reprocessed features
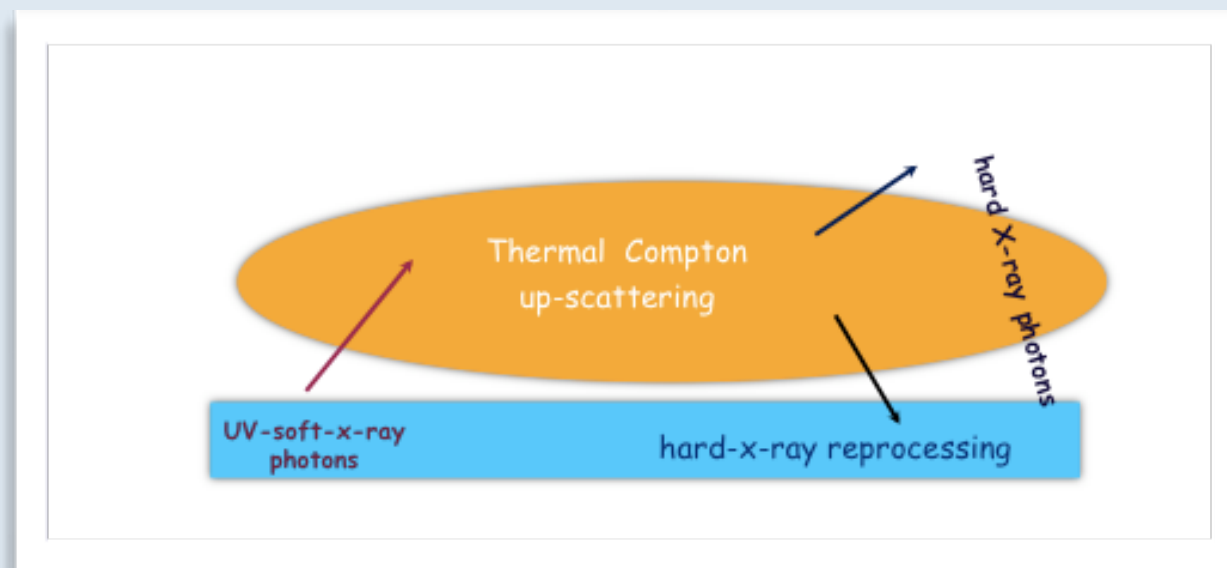
- **Thermal Comptonization**

- **Hard X-ray reprocessing**

Iron line

Compton hump

George & Fabian <u>1991</u>

Lightman & White <u>1988</u>
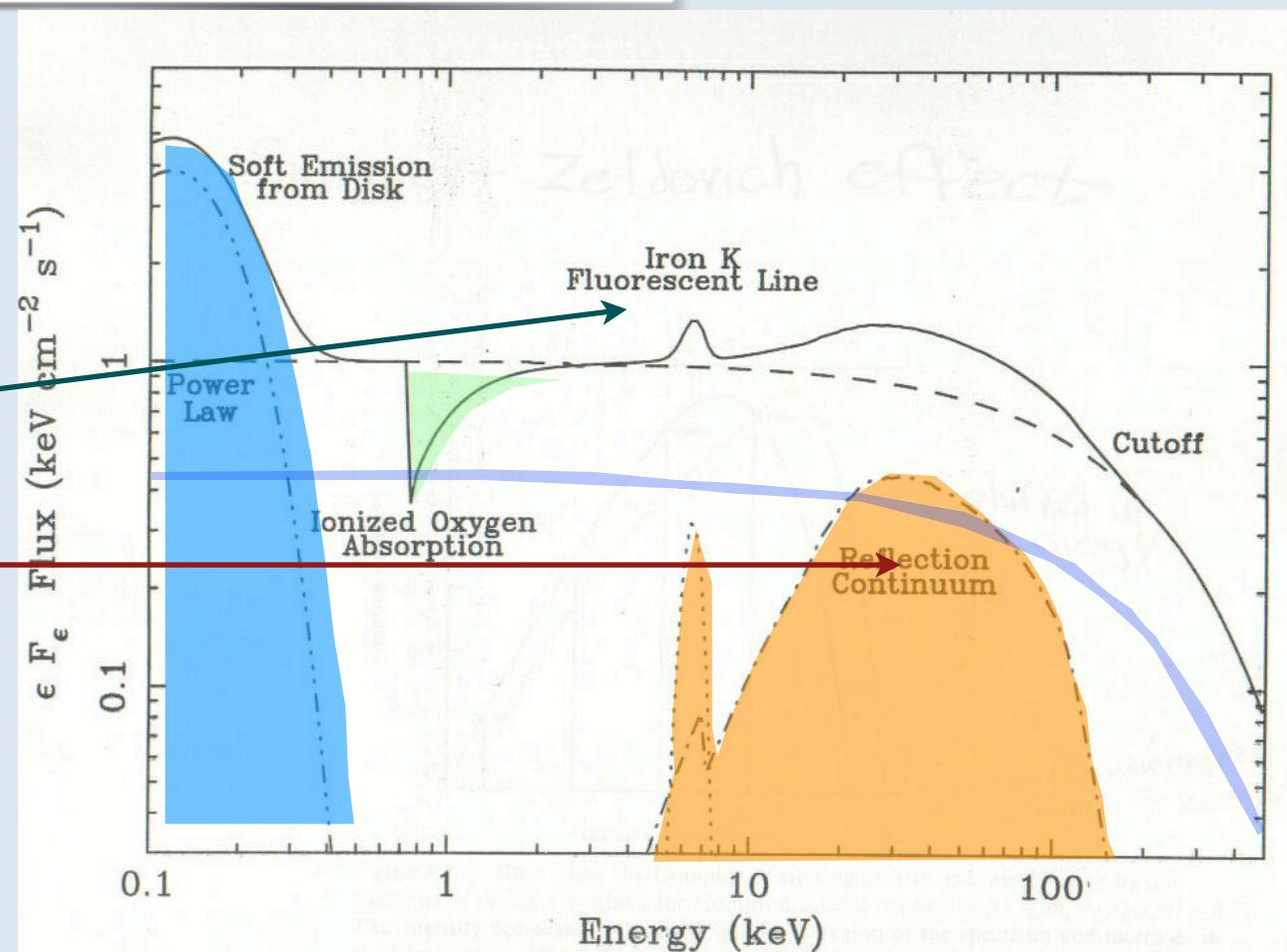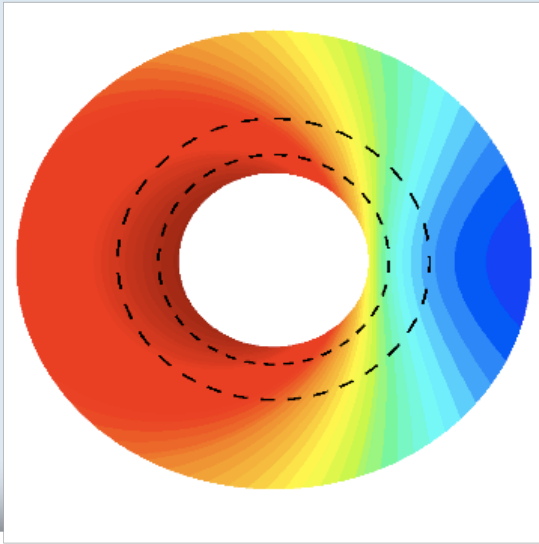
Newtonian

Special relativity — Transverse Doppler shift / Beaming
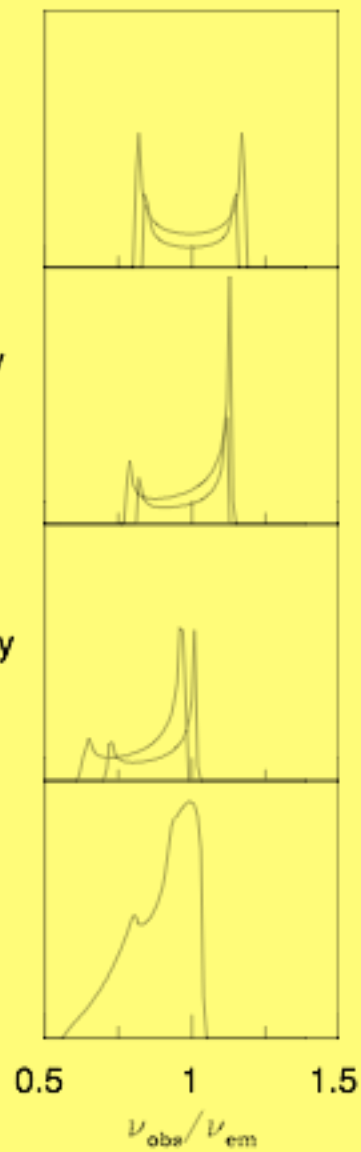
General relativity — Gravitational redshift

Line profile

ν_{obs}/ν_{em}

Schwarzschild

Kerr

Kerr disk

8m–30m

Photons/cm^2 s keV

Energy

33
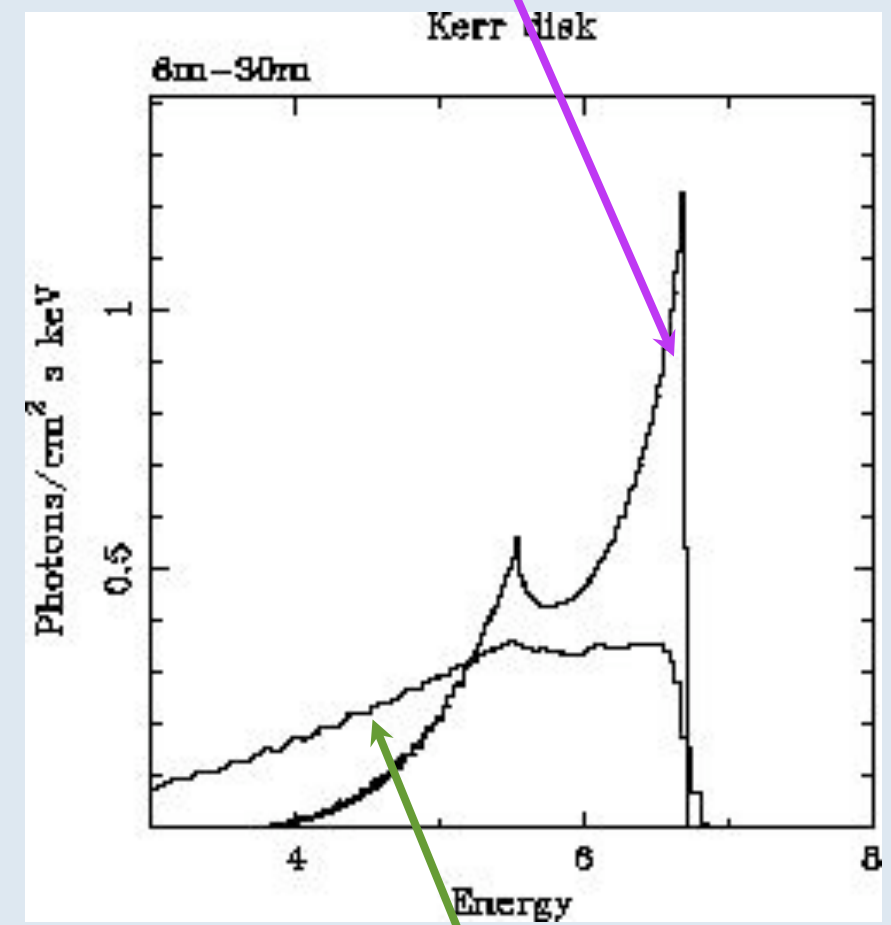
Reflection

At low energies <10 keV the high-Z ions absorb 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.

Inefficient Engine

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

Thin Accretion Disk
(Shakura & Sunyaev 1973; Novikov & Thorne 1973;...)

Most of the viscous heat energy is radiated

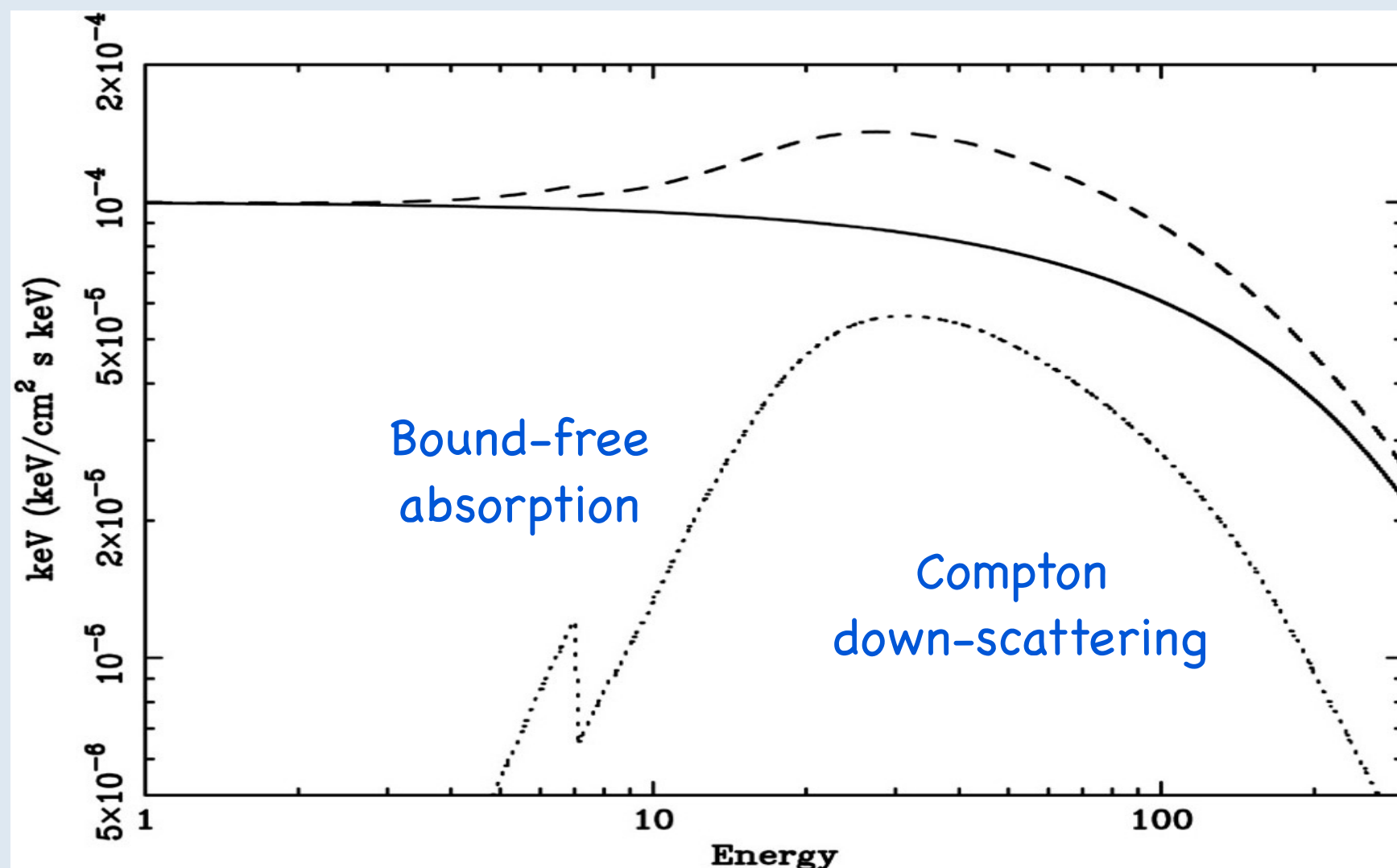$$q^- \approx q^+ \gg q^{adv}$$

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

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

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

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

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

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

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: $T_i \sim 10^{12}$K (R_S/R), $T_e \sim 10^{9-11}$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)

Narayan et al paper
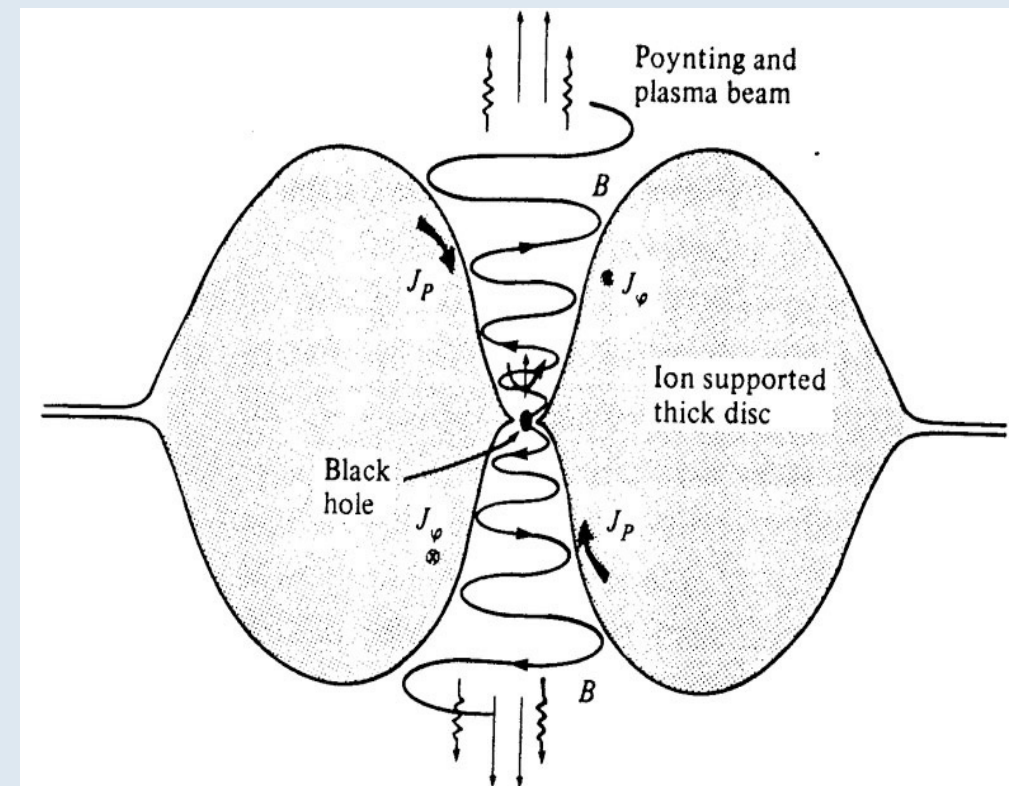
Typical luminosities: L <(0.01-0.1) L~Edd~
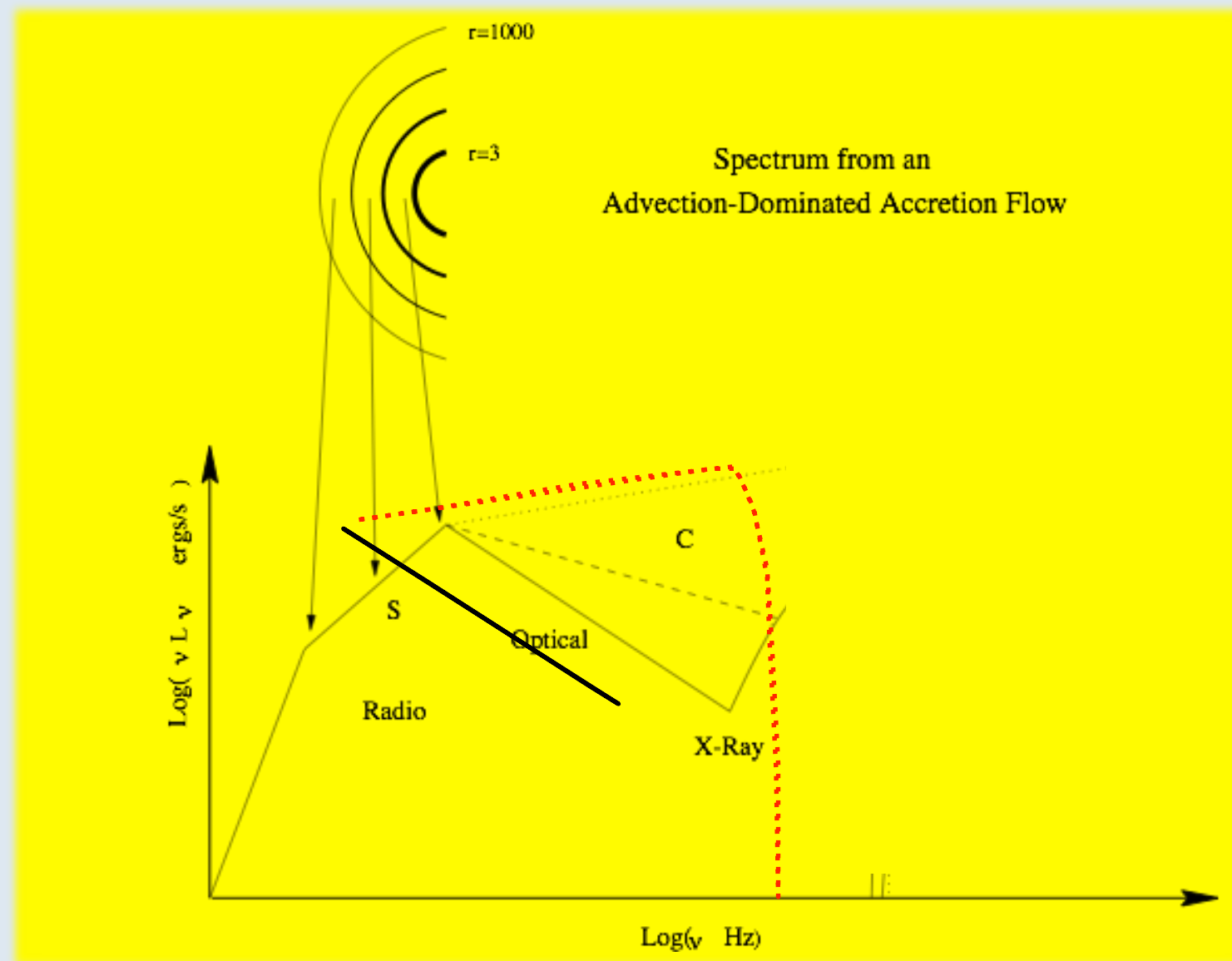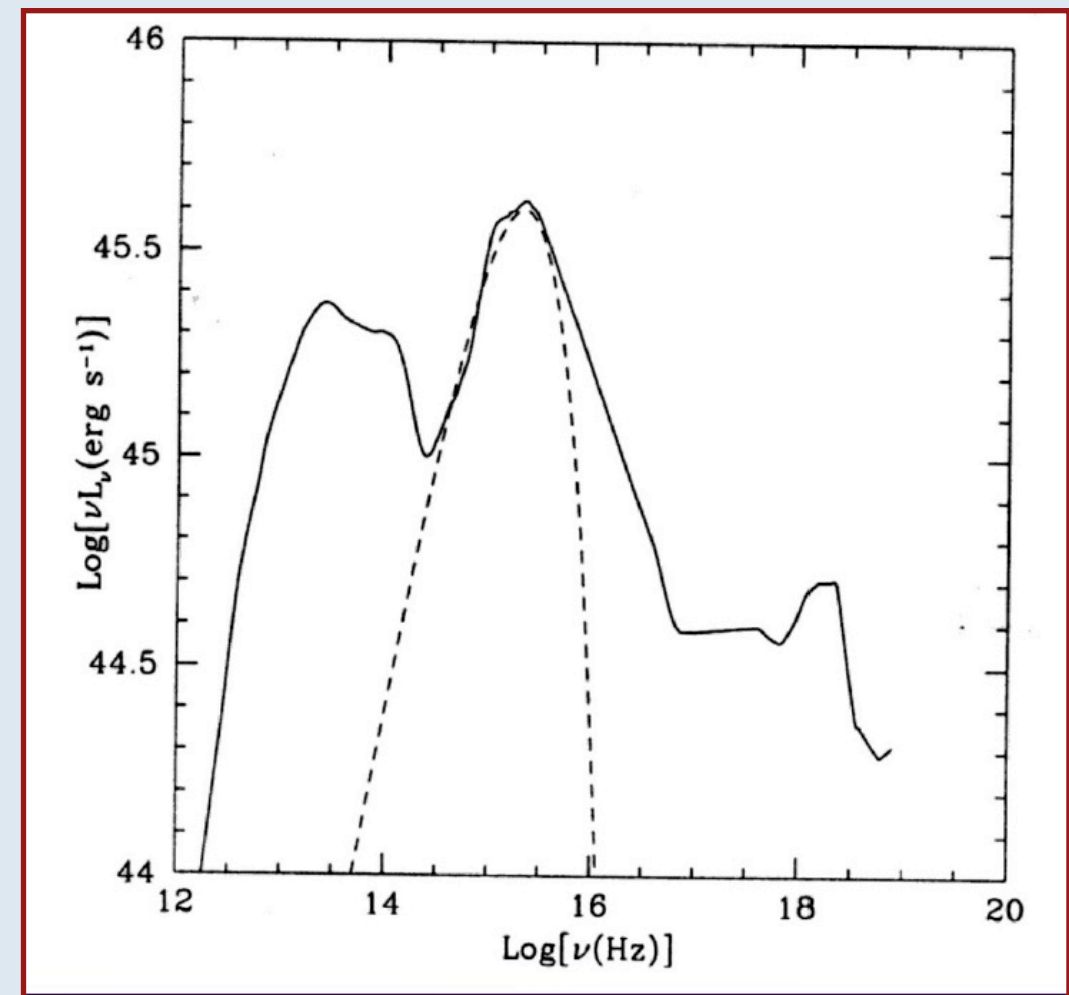

Schematic spectrum of an ADAF around a black hole. S, C, and B refer to electron emission by synchrotron radiation, inverse Compton scattering, and bremsstrahlung, respectively. The solid line corresponds to a low accretion, the dashed line to an intermediate accretion , and the dotted line to the highest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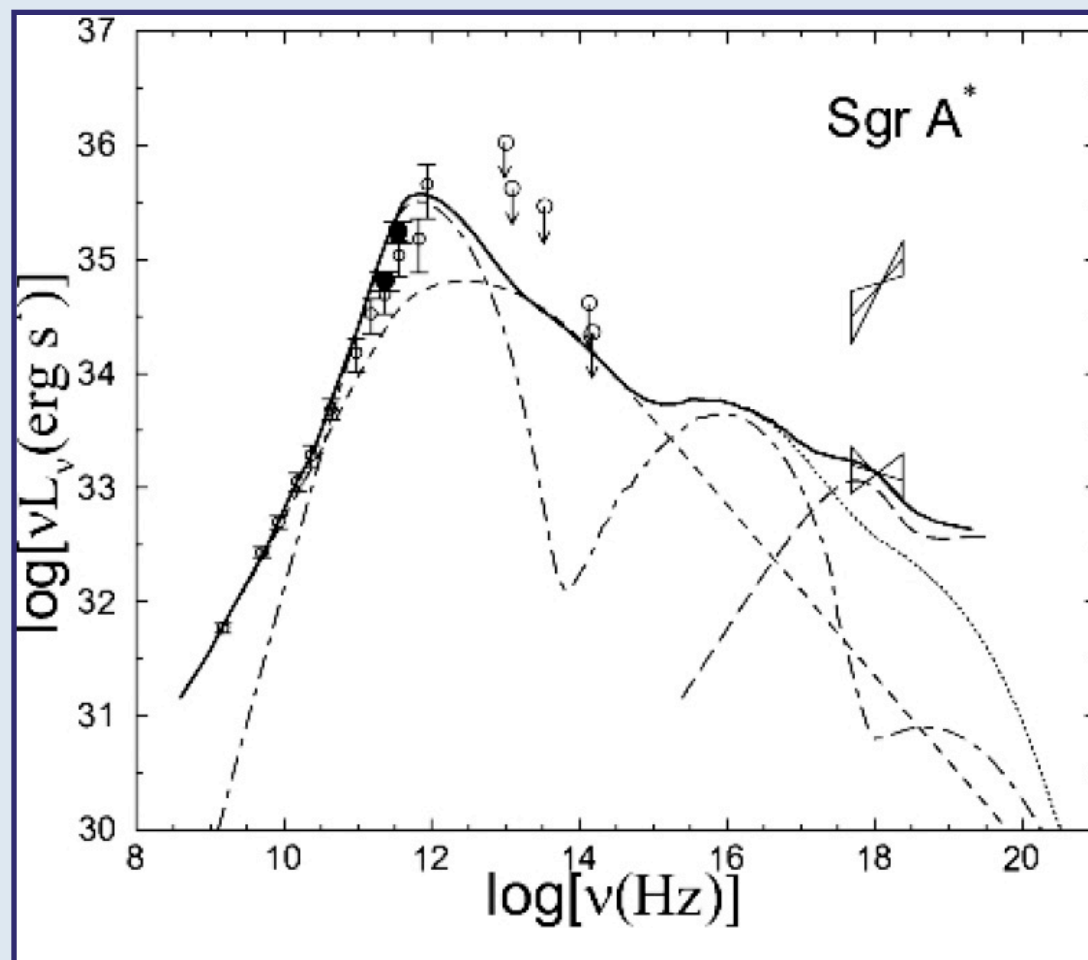
ADAF

Accretion disk
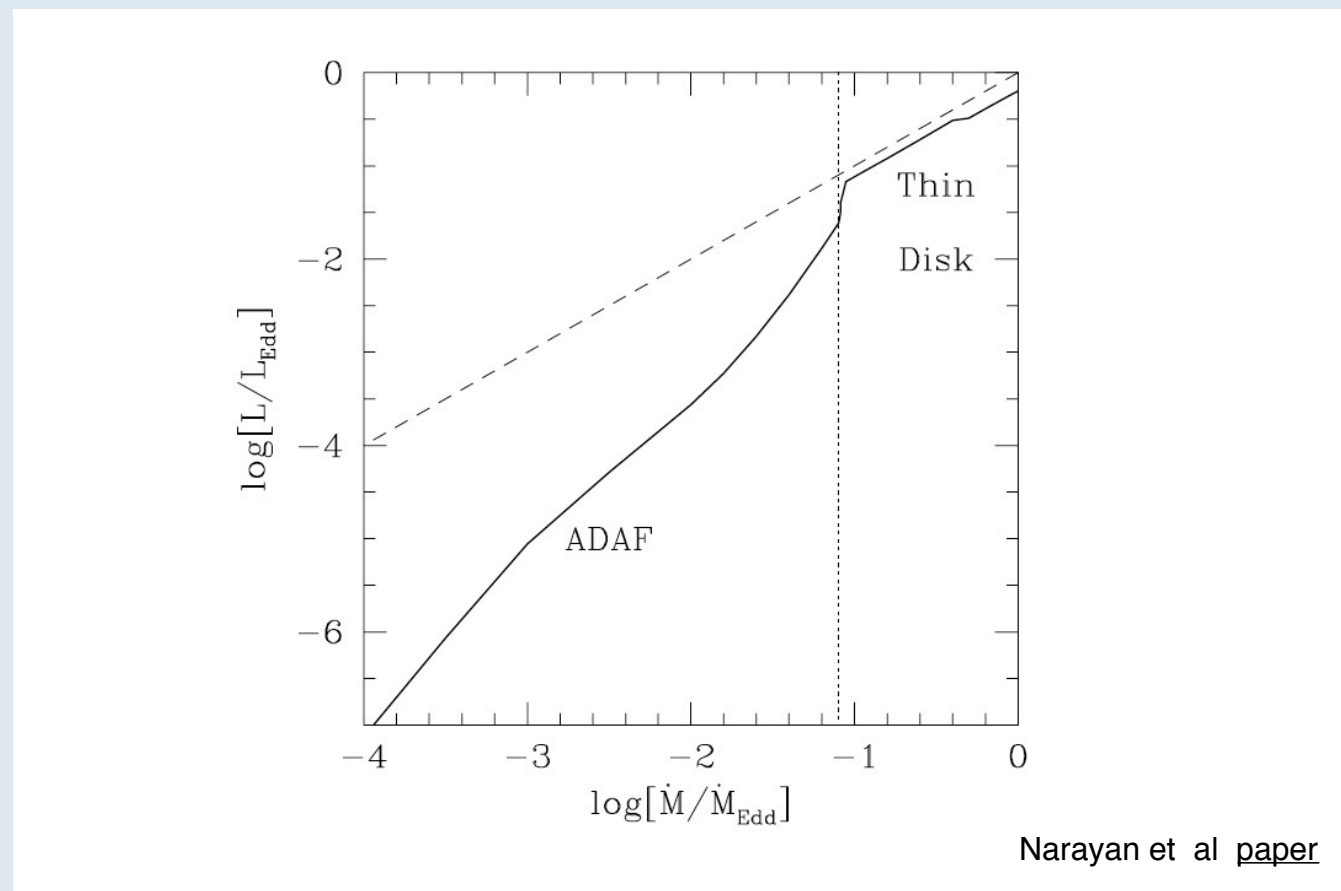
Narayan et al paper

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AGN radio loud are more complex than RQ:
They have another source of anisotropy: the jet

Jet Scale
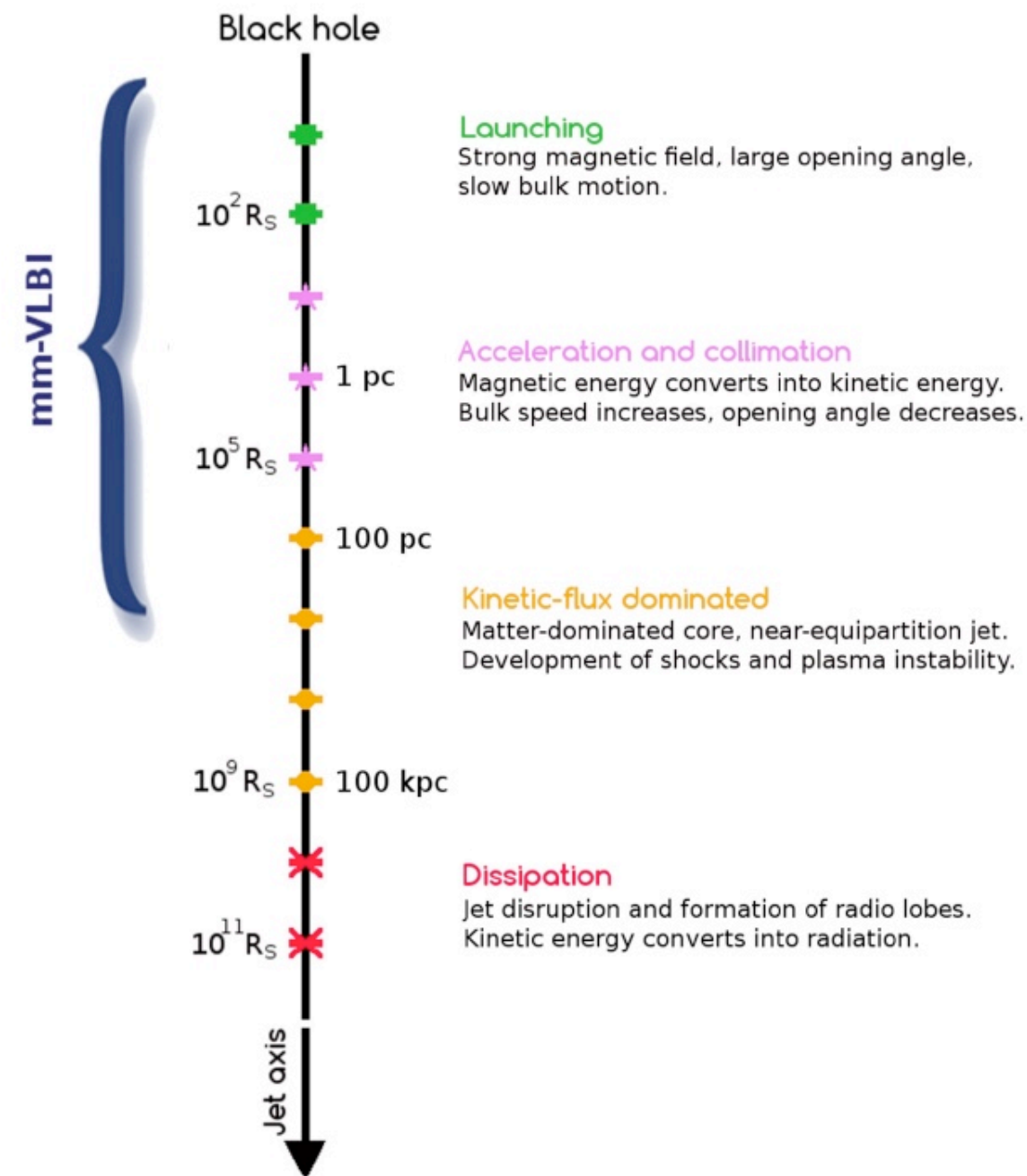
Fig. 5 Schematic view of the main regions of a relativistic jet, according to the current paradigm for magnetically-driven flows. The radial separation from the black hole is represented in a logarithmic scale, in units of Schwarzschild radii R_S. We also report the corresponding distance in units of parsecs (pc) for a black hole mass of $10^9 M_\odot$. The extension of each region is approximate, and may vary in different jets. VLBI observations at millimeter wavelengths are suited for probing the magnetically dominated jet base and the transition to the kinetic-flux dominated region.

Paper Boccardi
et al. 2017

The jet emission is strongly Doppler boosted

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

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

$=\sqrt{(1 - \beta^2)}$

Lorentz factor

$=v/c$
bulk velocity

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: $F'(\nu') = K (\nu')^{-\alpha}$
the **observed** flux density is

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

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

Blazar   Radio Galaxy/SSRQ

$\gamma = 15$
$\gamma = 10$
$\gamma = 5$
$\gamma = 2$

Doppler factor, δ

Viewing angle, θ

Details can be found in Appendix A of   <u>Urry & Padovani 1995</u>
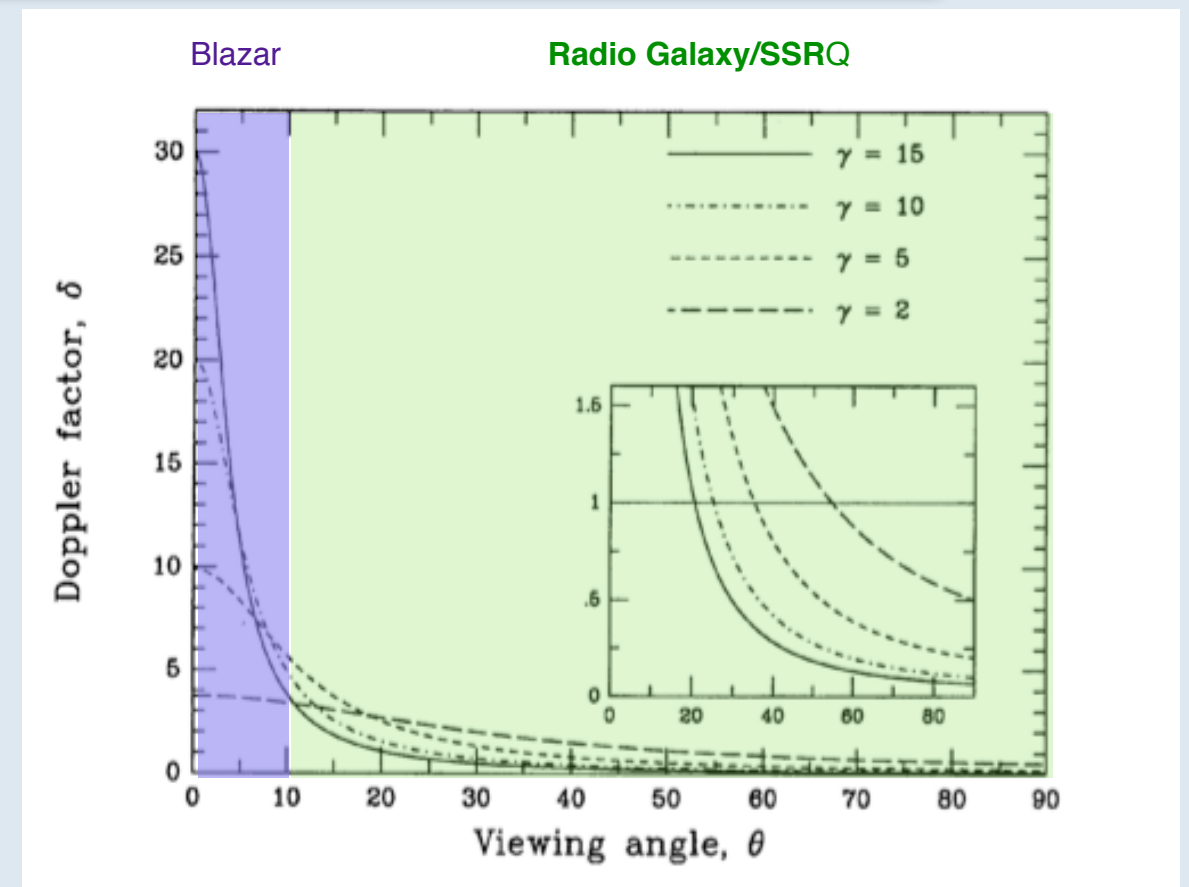
Blazars are divided into two classes:
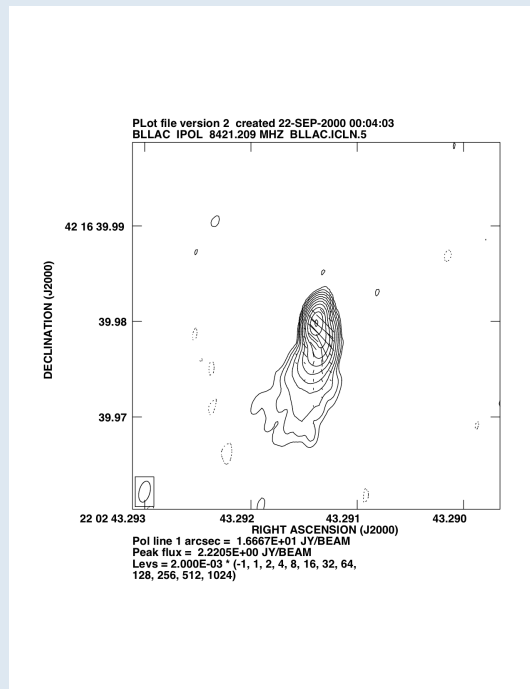## BL Lacs (BL) and Flat Spectrum Radio Quasar (FSRQ)

Extremely variable

Both are compact in radio maps and extremely variable at all frequencies

BL are almost featureless in the optical band (FSRQ can show emission lines overimposed on a strong continuum)
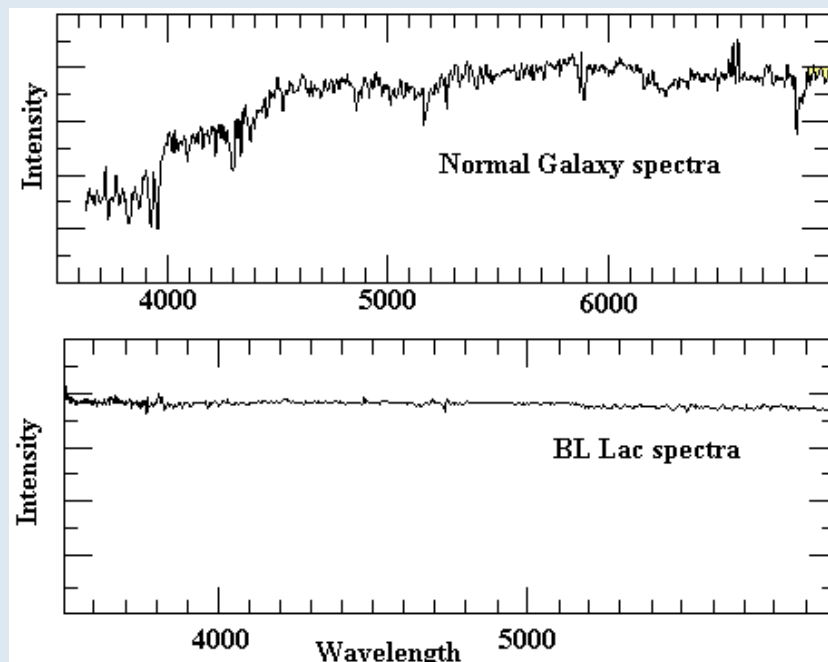
OJ 287 light curves from radio to gamma Agudo et al. 2011ApJL 726, L13

Revised AGN Unified Model

Efficient Accretion
DISK

Inefficient flow
ADAF

Observed Properties of Jets and
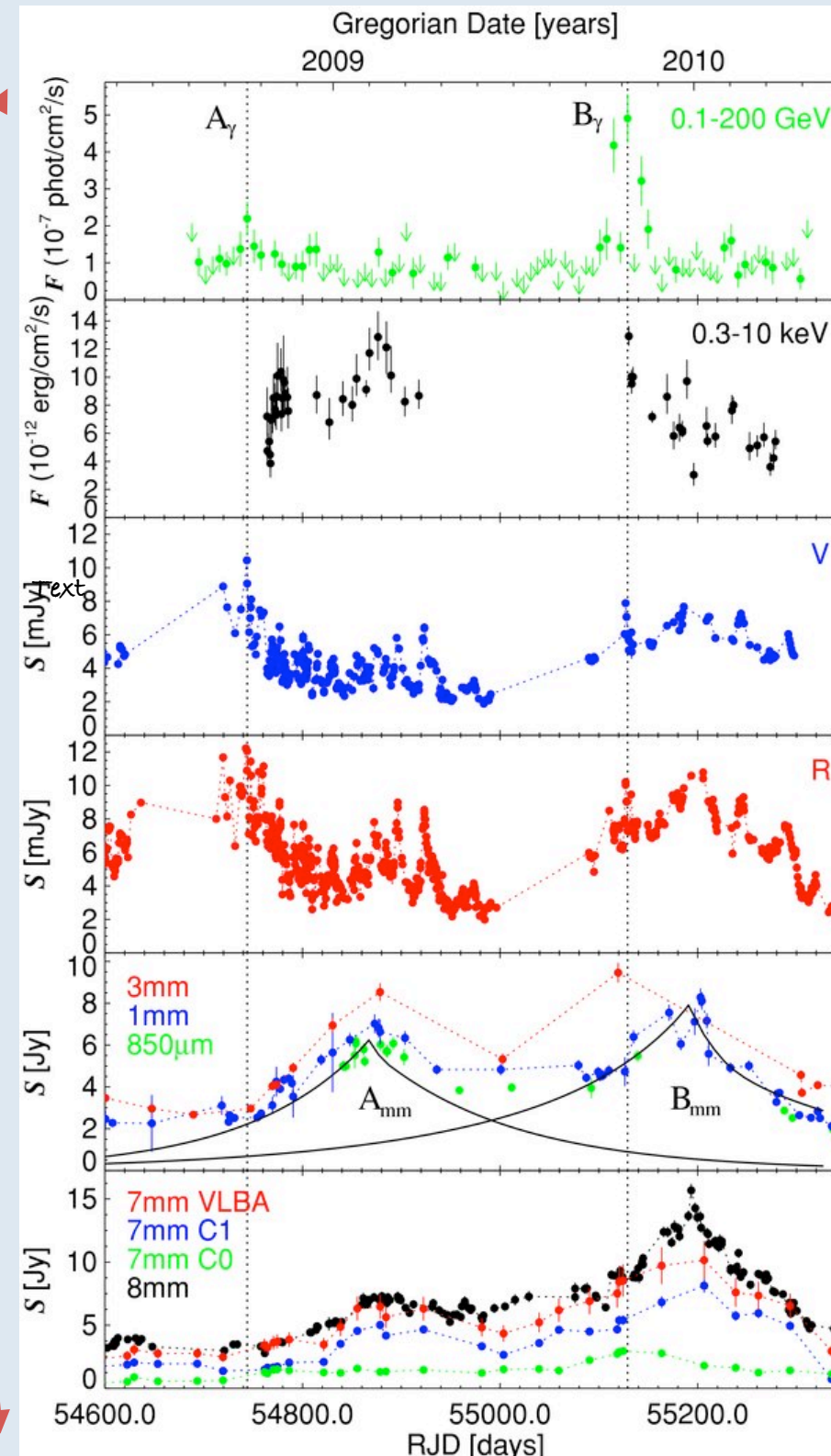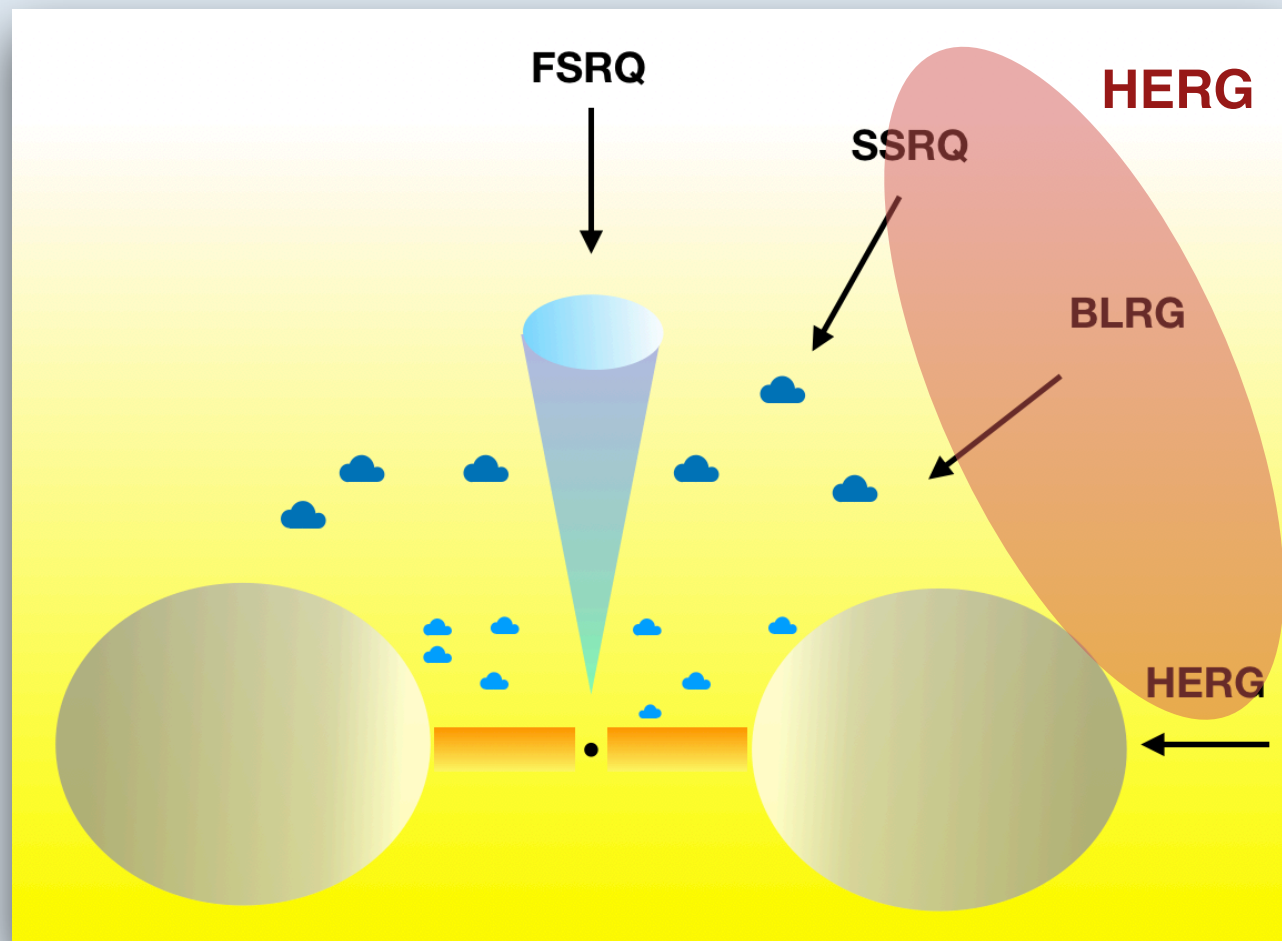the Angle to the Line of Sight θ

Host Galaxy   AGN   Angle

90 deg

60 deg

30 deg

0 deg
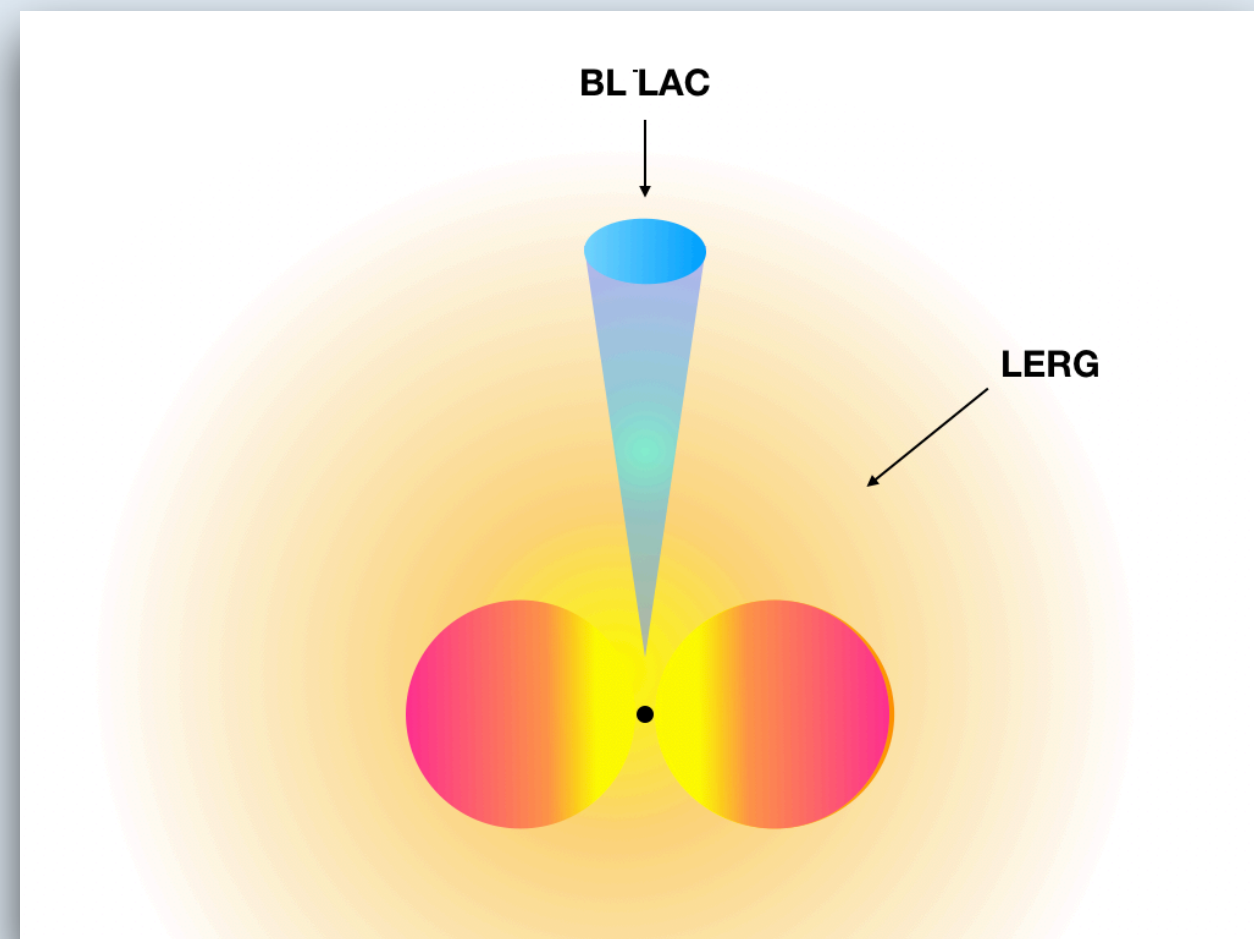
Radio Galaxies HERG

Blazar
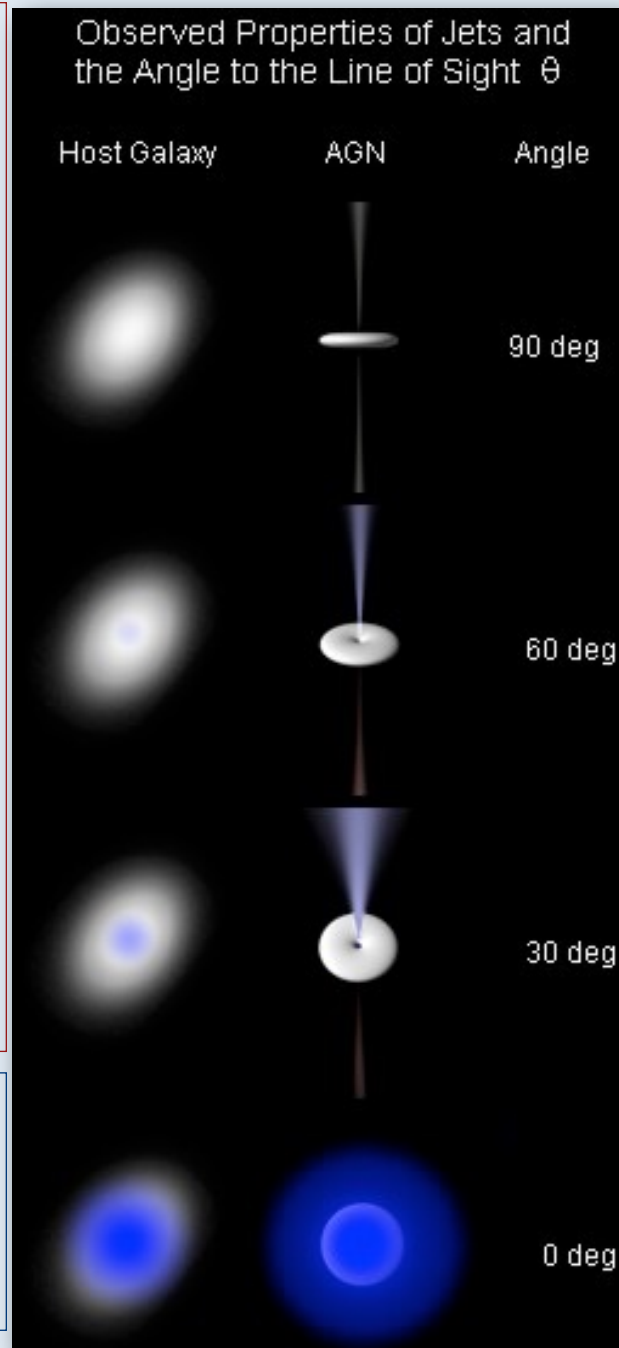
HERG: Thermal radiation dominates the spectrum in the IR-optical-UV-X-ray band

HERG (BLRG): Thermal and non thermal radiation are in competition

Blazar: Non-Thermal radiation dominates all the spectrum

LERG: Non-Thermal radiation dominates the spectrum having an efficient accretion flow

Core Emission

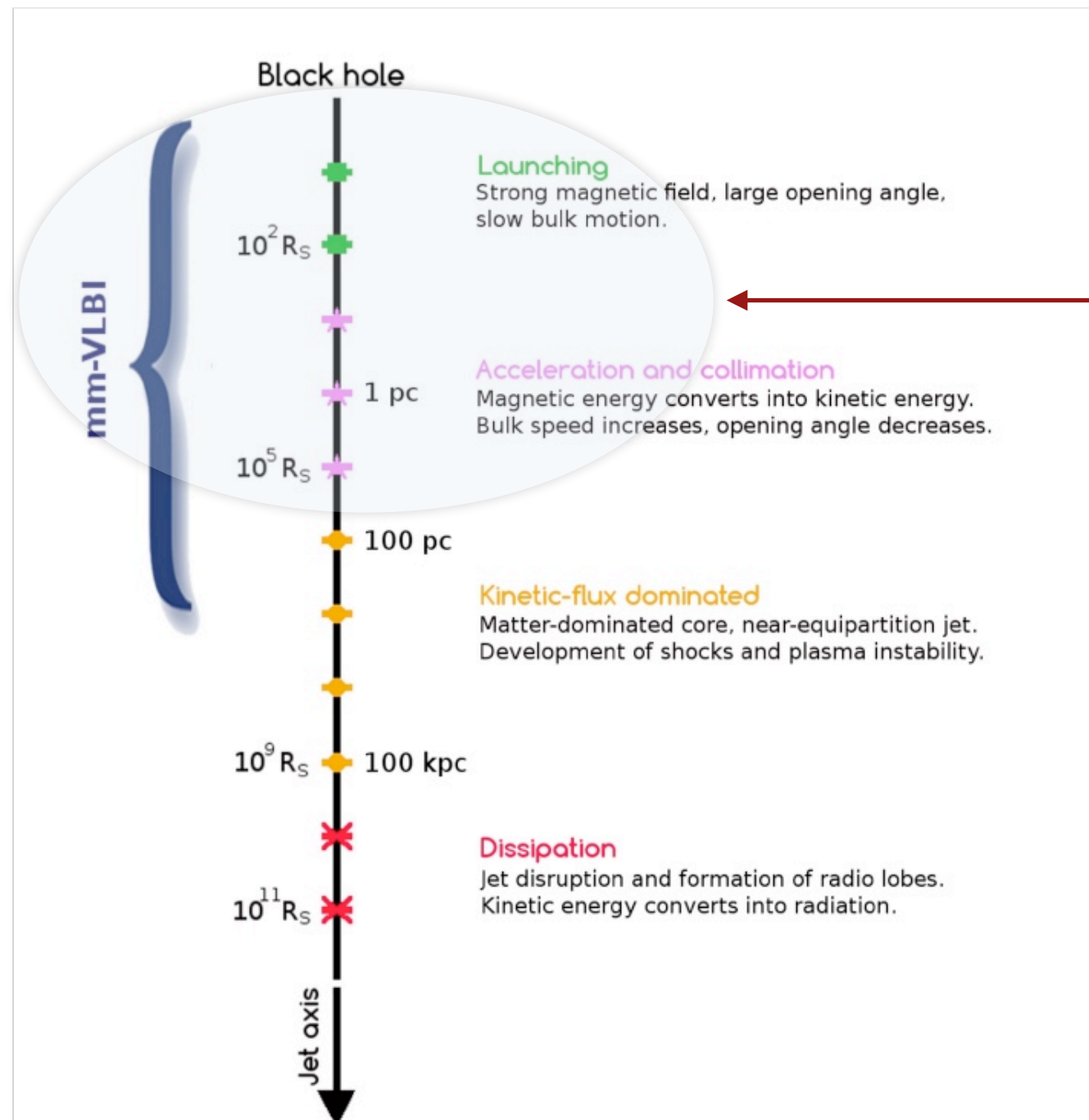Fig. 5 Schematic view of the main regions of a relativistic jet, according to the current paradigm for magnetically-driven flows. The radial separation from the black hole is represented in a logarithmic scale, in units of Schwarzschild radii R_S. We also report the corresponding distance in units of parsecs (pc) for a black hole mass of $10^9 M_\odot$. The extension of each region is approximate, and may vary in different jets. VLBI observations at millimeter wavelengths are suited for probing the magnetically dominated jet base and the transition to the kinetic-flux dominated region.

Non-thermal radiation coming from the core region dominates the SED if the jet intercepts the line of sight of the observer (BLAZAR) and/or the accretion is inefficient (LERG). The Observed Spectral Energy Distribution consists of two peaks of emission

Double peaked Spectral Energy Distribution
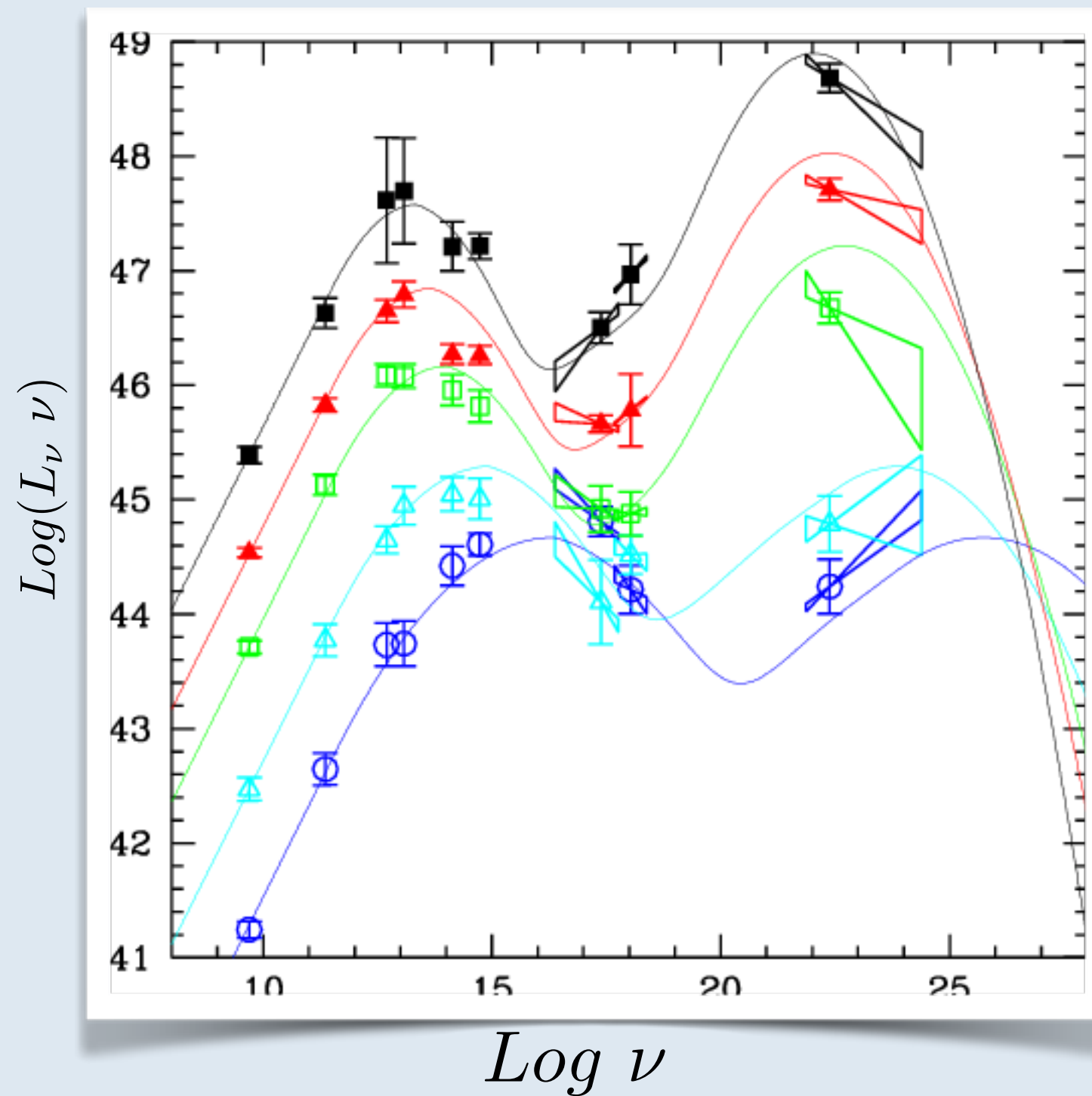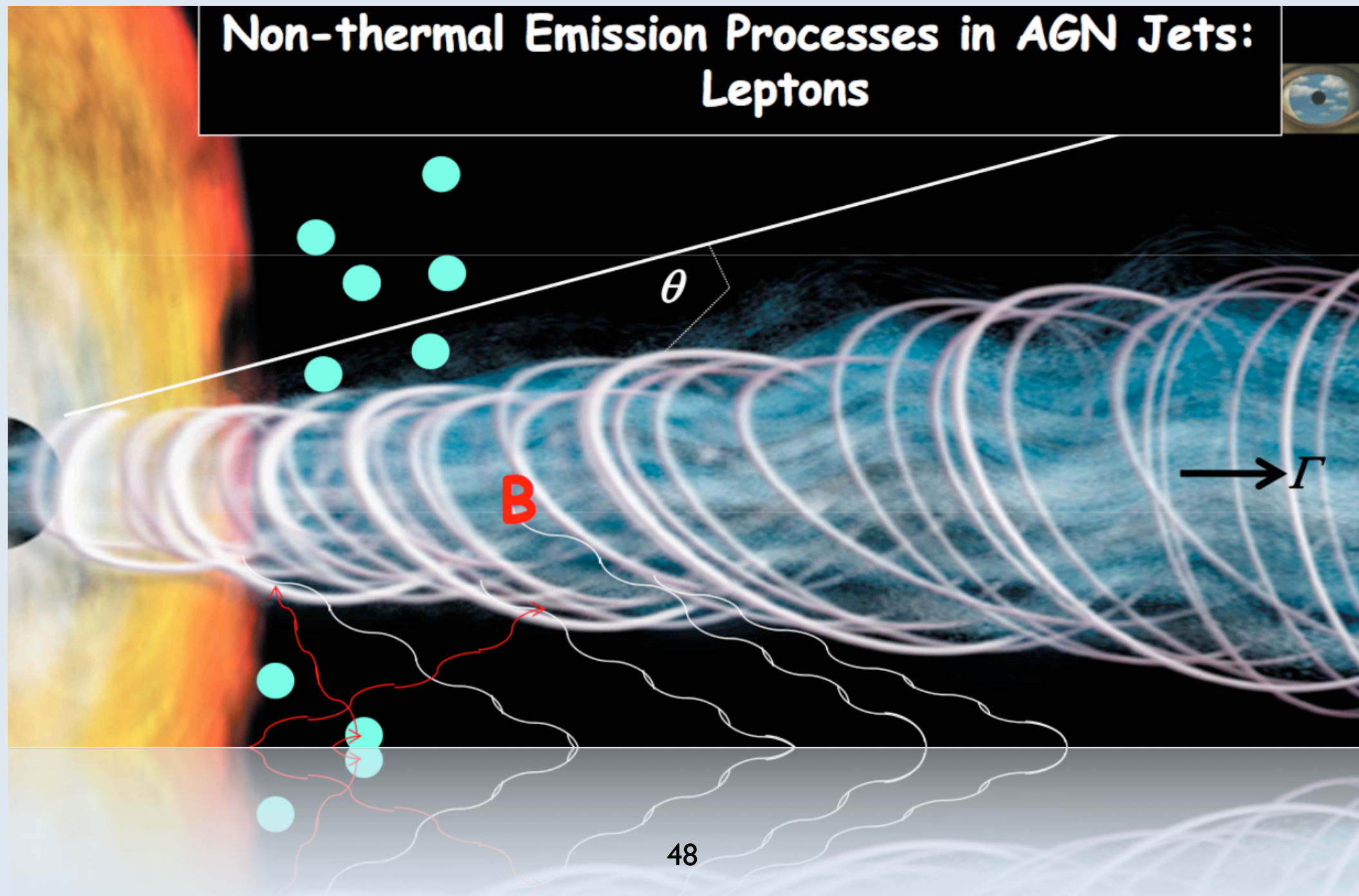

Fossati 's sequence --->paper

Non thermal emission:

Synchrotron: Magnetic Field + Leptons
Inverse Compton: Photons   + Leptons

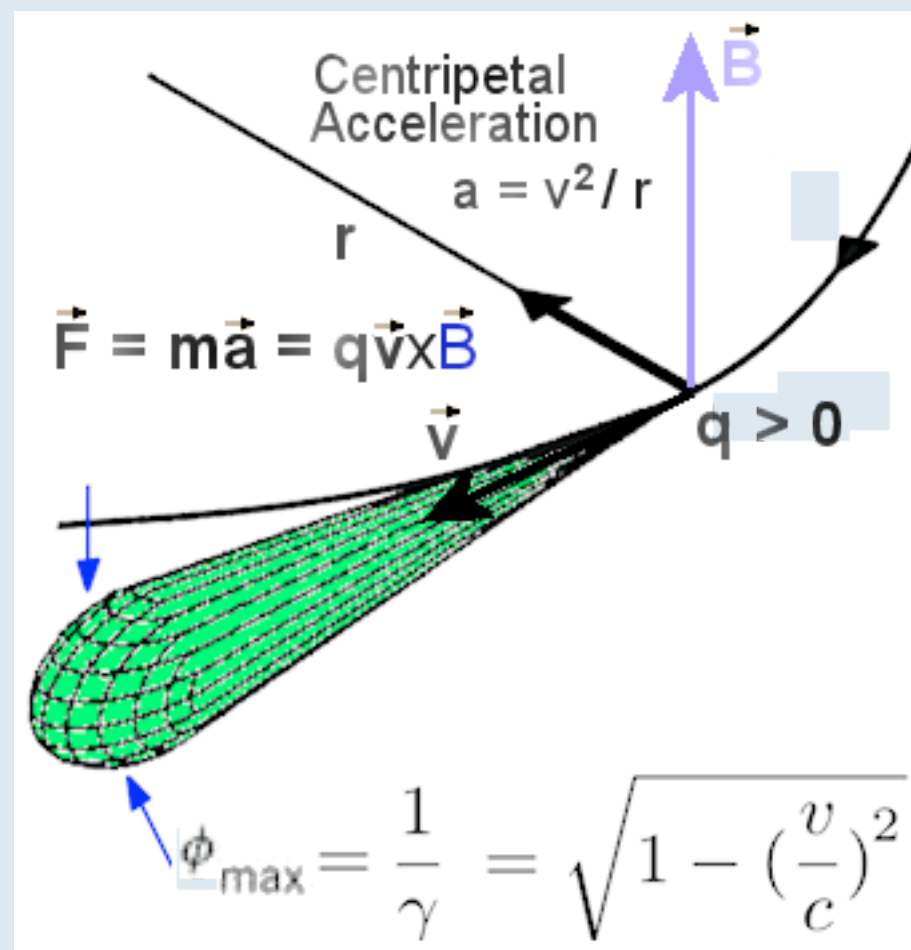Non-thermal Emission Processes in AGN Jets: Leptons

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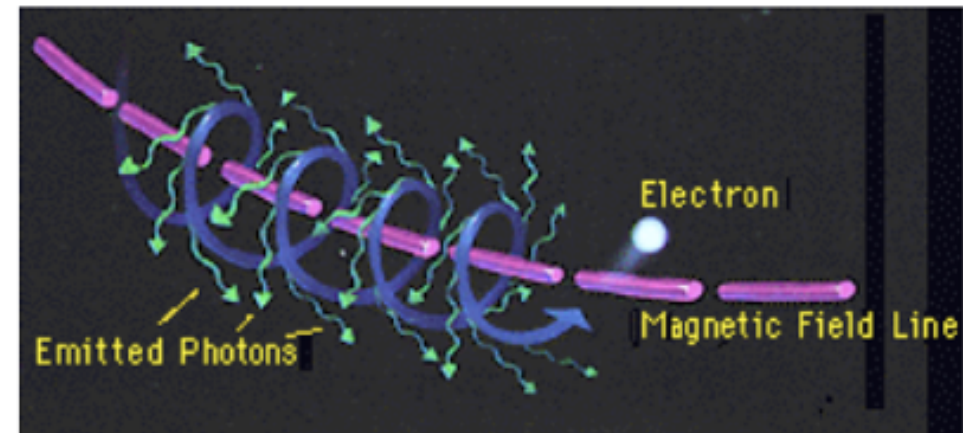
Synchrotron radiation is highly polarized and is seen at all wavelengths. At relativistic speeds, the radiation can also be beamed. It is very common in radio spectrum, but can be seen in x-rays. It is usually fit as a power law. For full details, see the review by Ginzburg & Syrovatskii (1969)

Centripetal
Acceleration
$a = v^2 / r$

$\vec{F} = m\vec{a} = q\vec{v}x\vec{B}$

$q > 0$

$\vec{B}$

$\vec{v}$

$\phi_{max} = \dfrac{1}{\gamma} = \sqrt{1 - \left(\dfrac{v}{c}\right)^2}$

A moving charged particle in a magnetic field would be reflected by the Lorentz force **F** = q (**v**x**B**), where q is the charge, **v** is the velocity, and **B** is the magnetic field.

In a region with uniform magnetic field, the curvilinear path of the charged particle becomes a circle and if the velocity has a component in the direction of the magnetic filed then the trajectory will be a helix

The synchrotron radiation of a power law distribution of electron energies

Synchrotron

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

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

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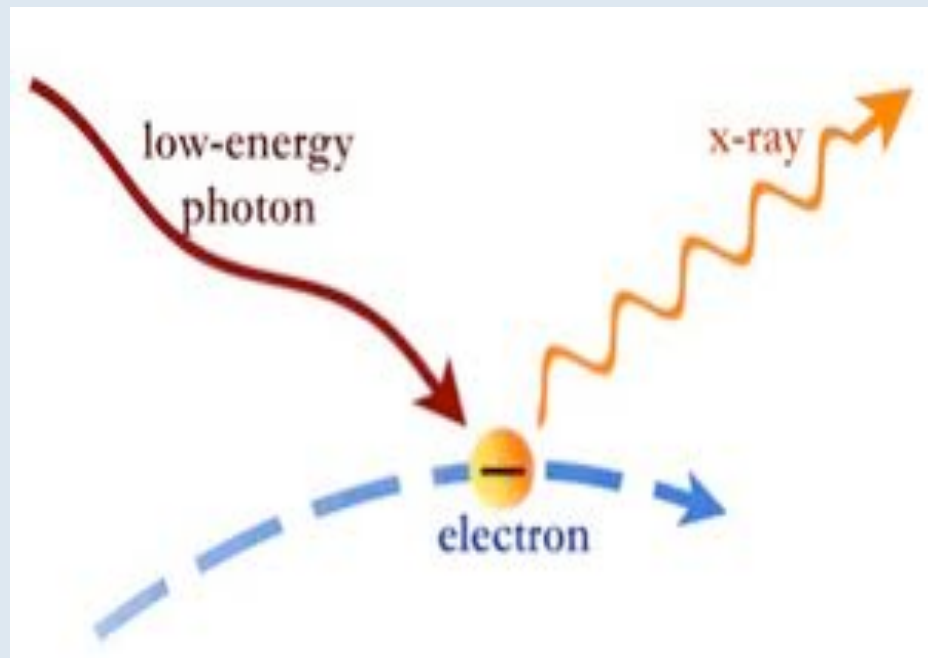
$$< \nu >= \frac{4}{3}\gamma^2\nu$$

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}	$3 \times 10^{18} =$ X-rays
Optical	4×10^{14}	$4 \times 10^{21} \equiv 1.6\text{MeV} = \gamma\text{-rays}$

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

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

U_r is the radiation energy density

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

- Synchrotron photons in the jet
- Environment photons from Accretion Flow, BLR, NLR, Torus
- Cosmic Microwave Background (CMB) photons

Synchrotron Self–Compton works in BL LAC

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.

External Compton works in FSRQ

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.

In the Self Synchrotron Model, U(r) is due to synchrotron photons in the jet.

Spectral energy distribution (SED) of the Blazar Markarian 421

Abdo et al 2011, ApJ 736, 131
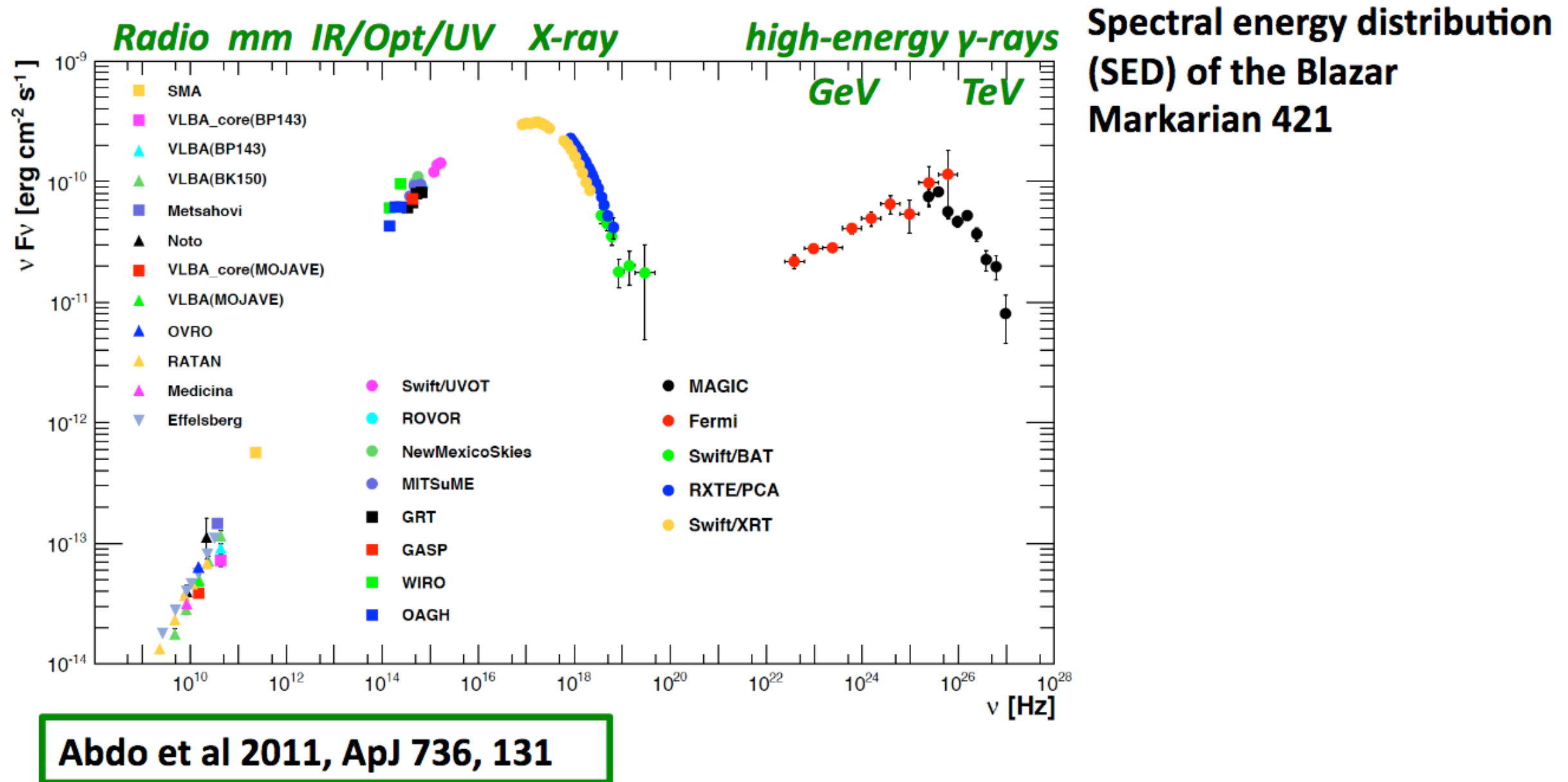
External Compton
U(r) is due to environment photons
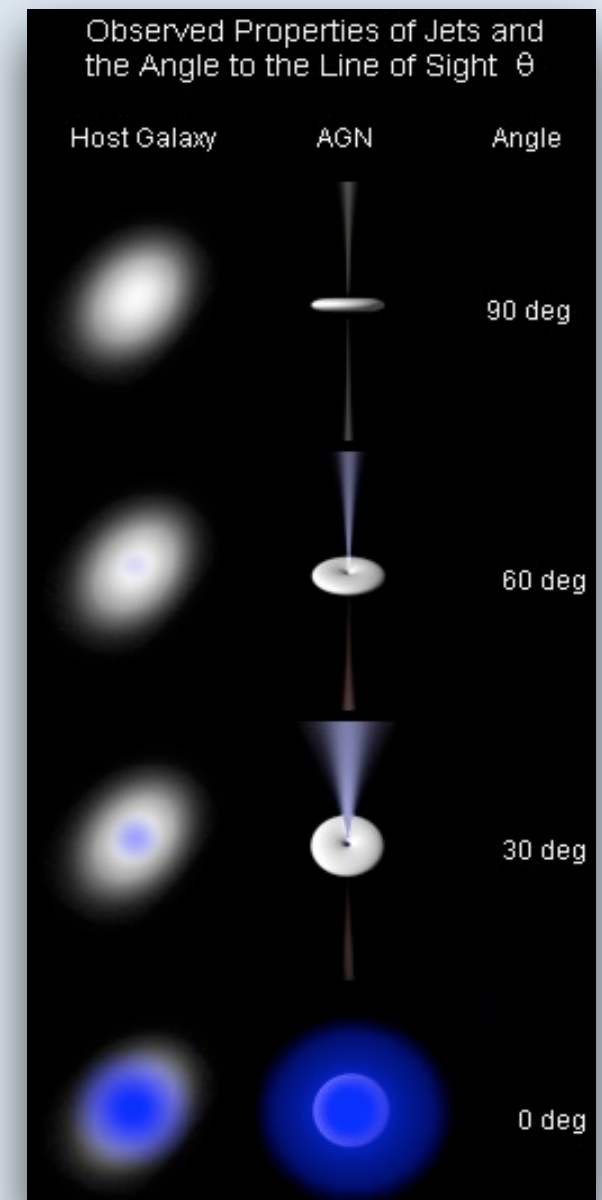## from Accretion Flow, BLR, NLR, Torus
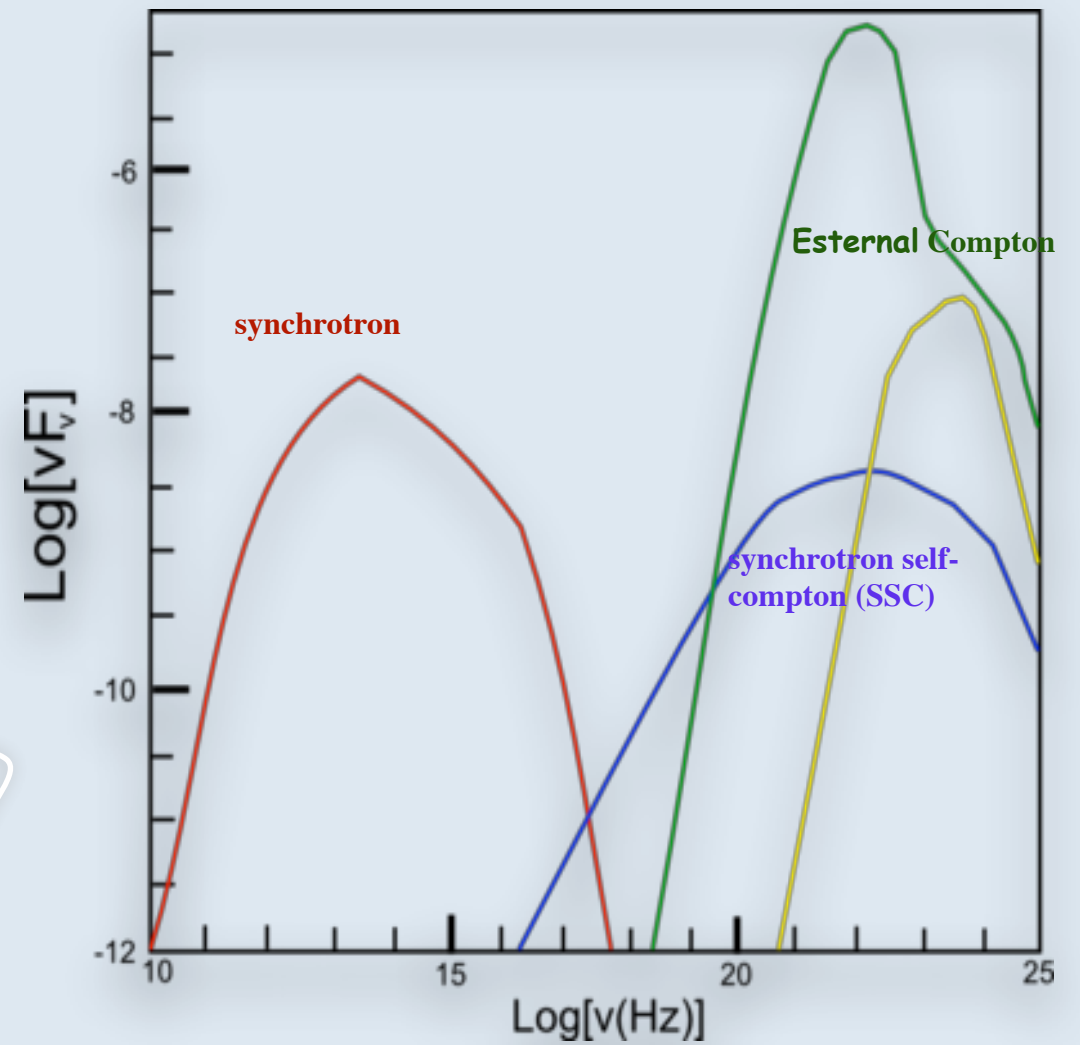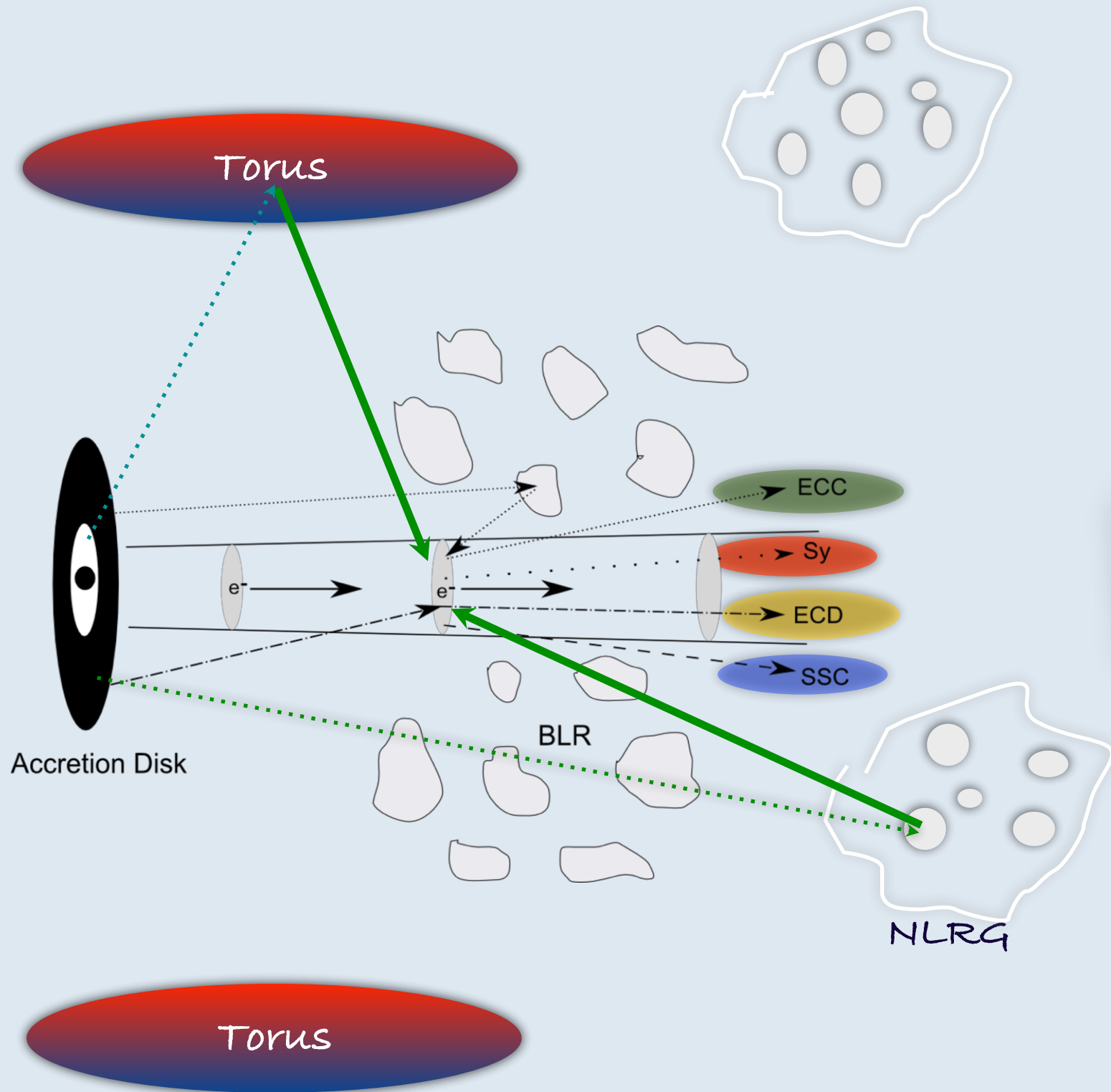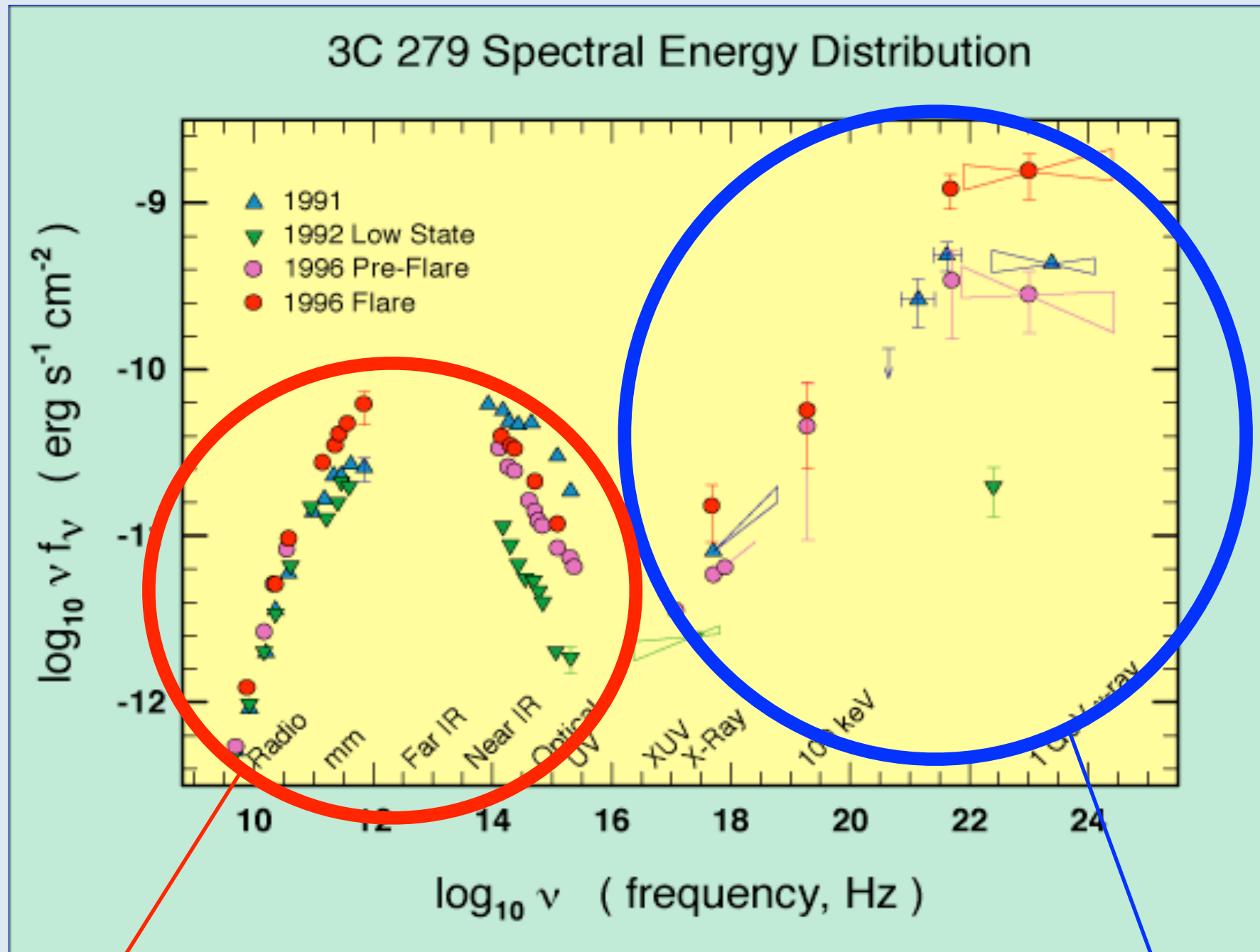
3C 279 Spectral Energy Distribution

While in LERG jet is always the dominant component, in HERG jet and disk emission are in competition

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

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

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

Observed Properties of Jets and the Angle to the Line of Sight θ

Host Galaxy   AGN   Angle

90 deg

60 deg

30 deg

0 deg

An example: the case of 3C273. In this FSRQ at small inclination angle, the spectrum is generally a jet dominated continuum.
However, when the jet is less bright, the accretion disk spectrum and the iron line can emerge from the continuum.
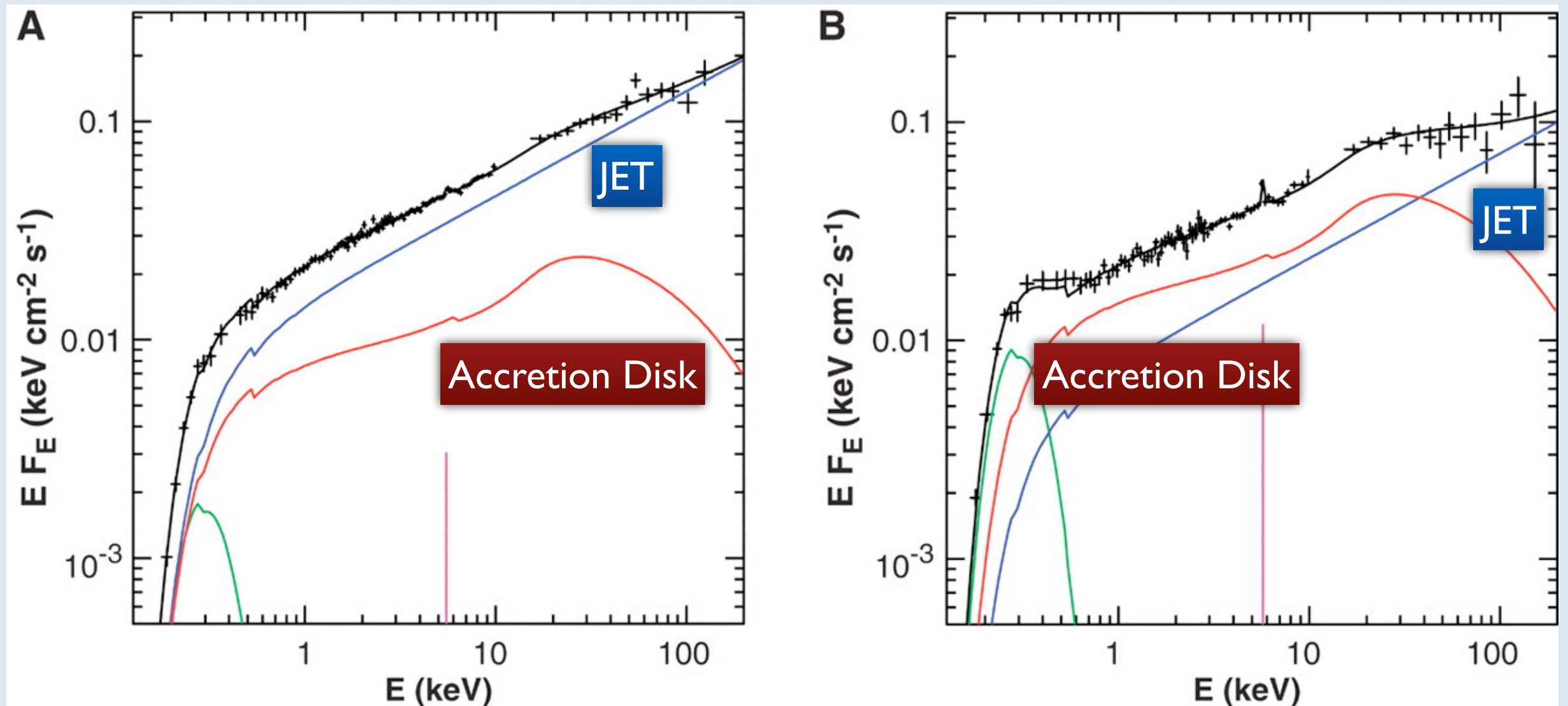
The observer is near the jet axis

# In HERG the thermal components can be observed more easily

For example in the Broad Line Radio Galaxy 3C120, torus and blue bump are evident in the SED and the Fe iron line is detected in the X-ray spectrum.
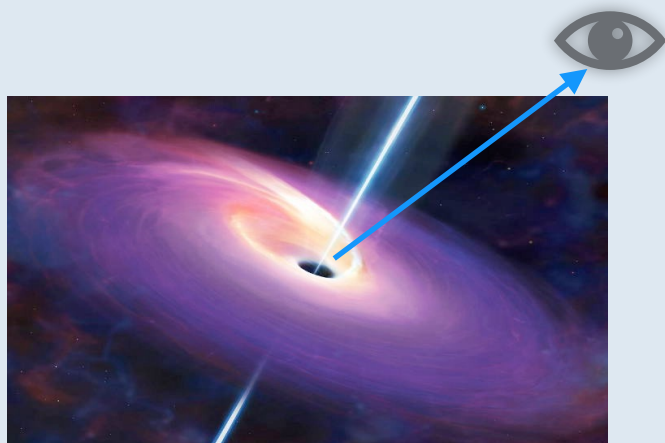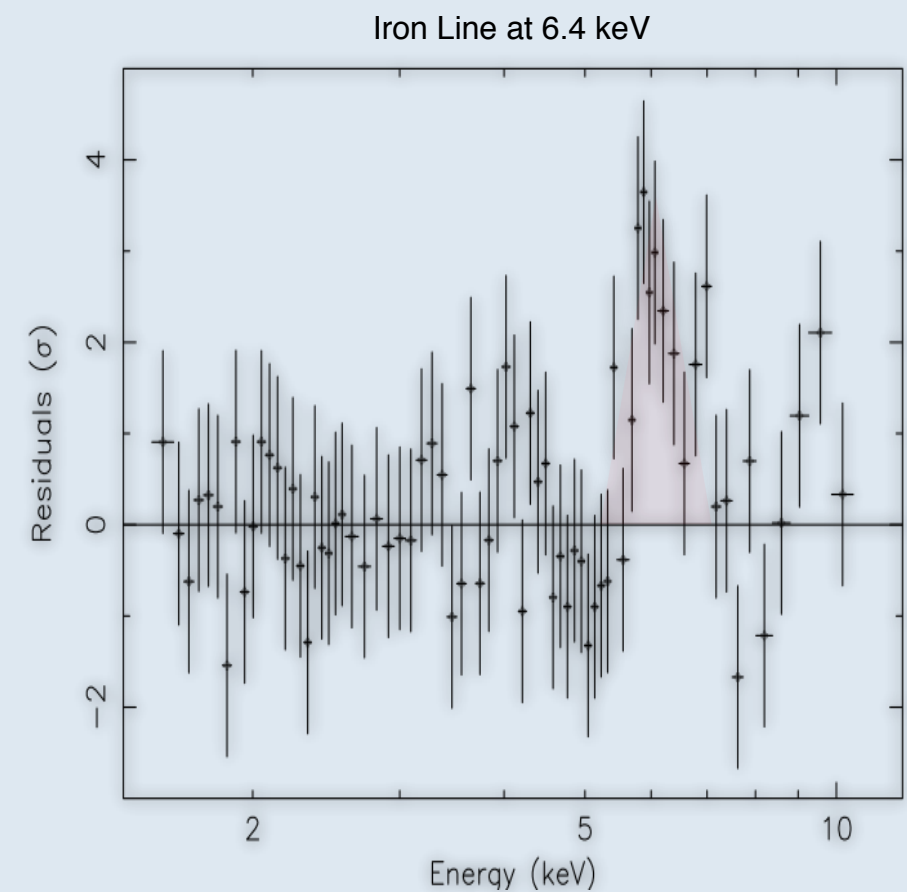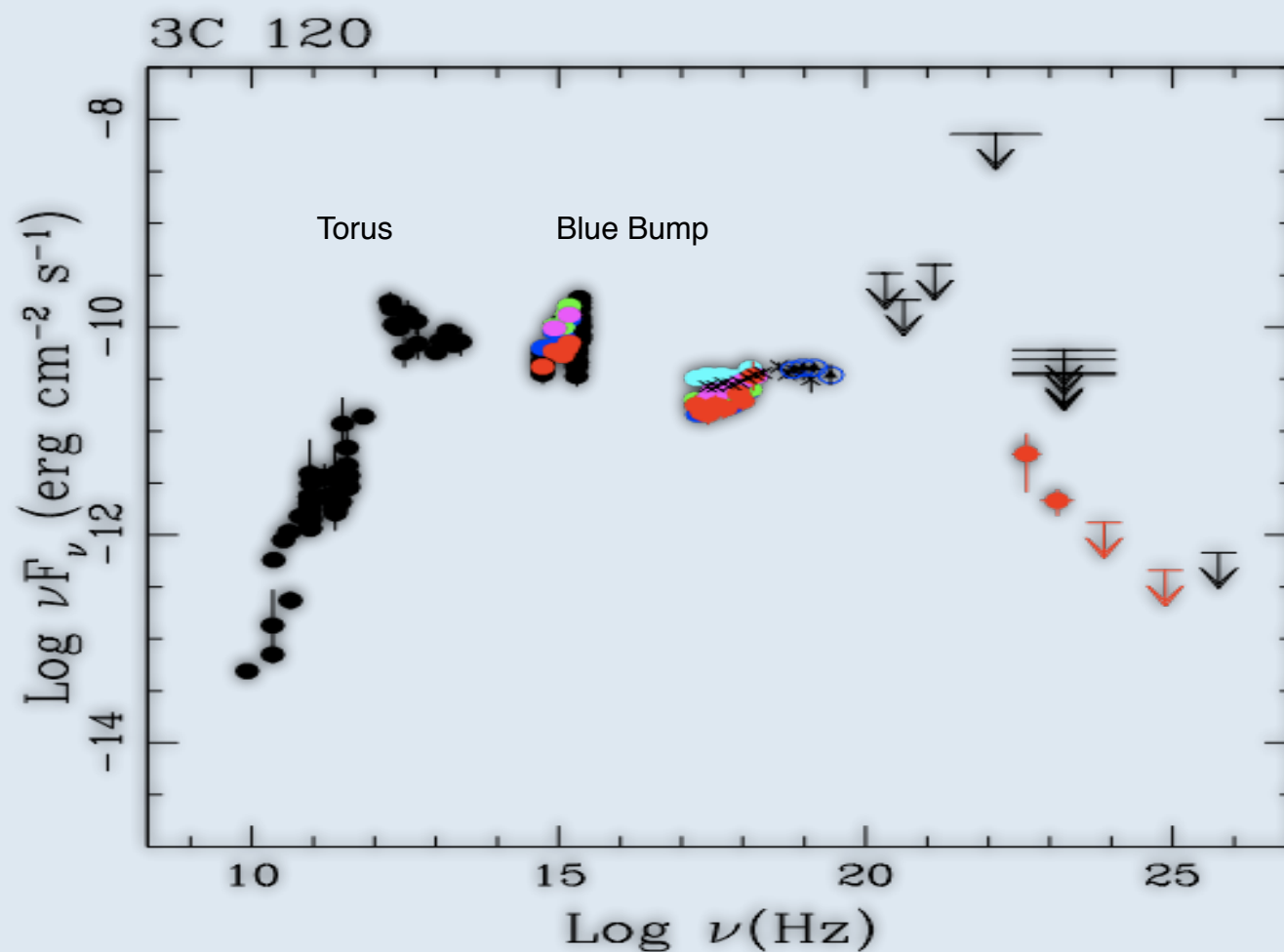
In radio galaxies the jet pointed away from the observer favouring the observation of extended structures.
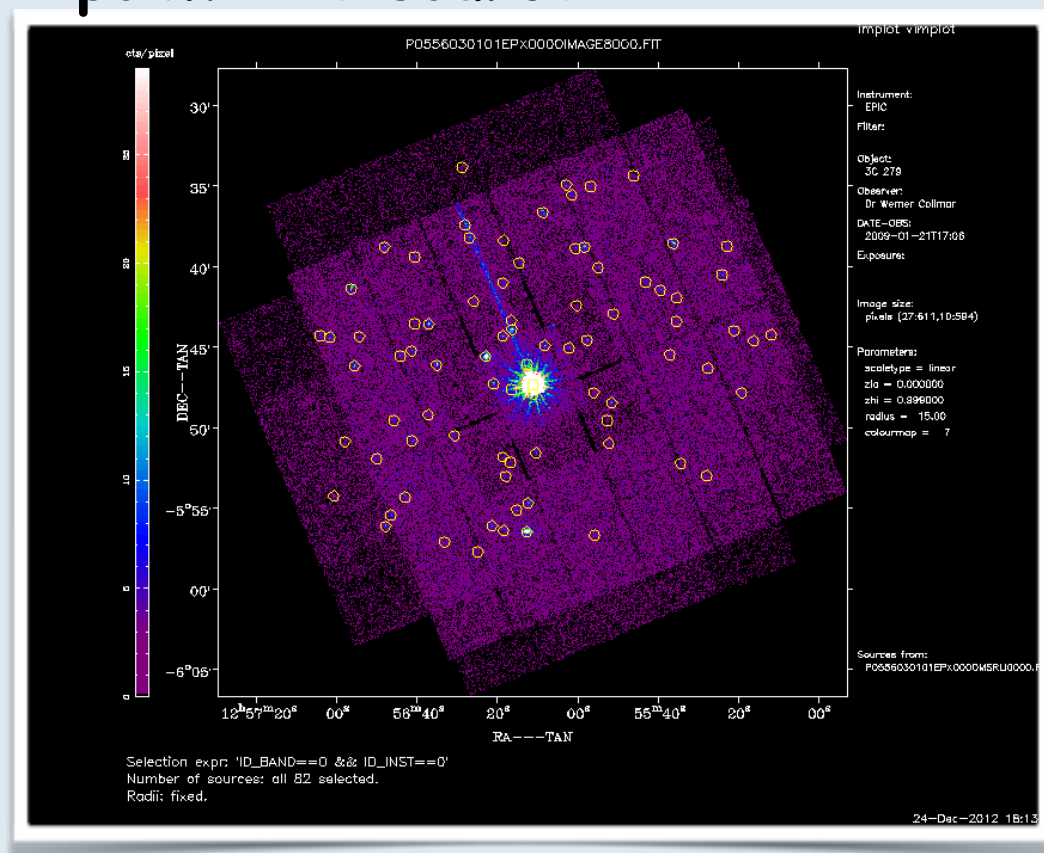**In blazars they are hidden by the jet luminosity amplification.**

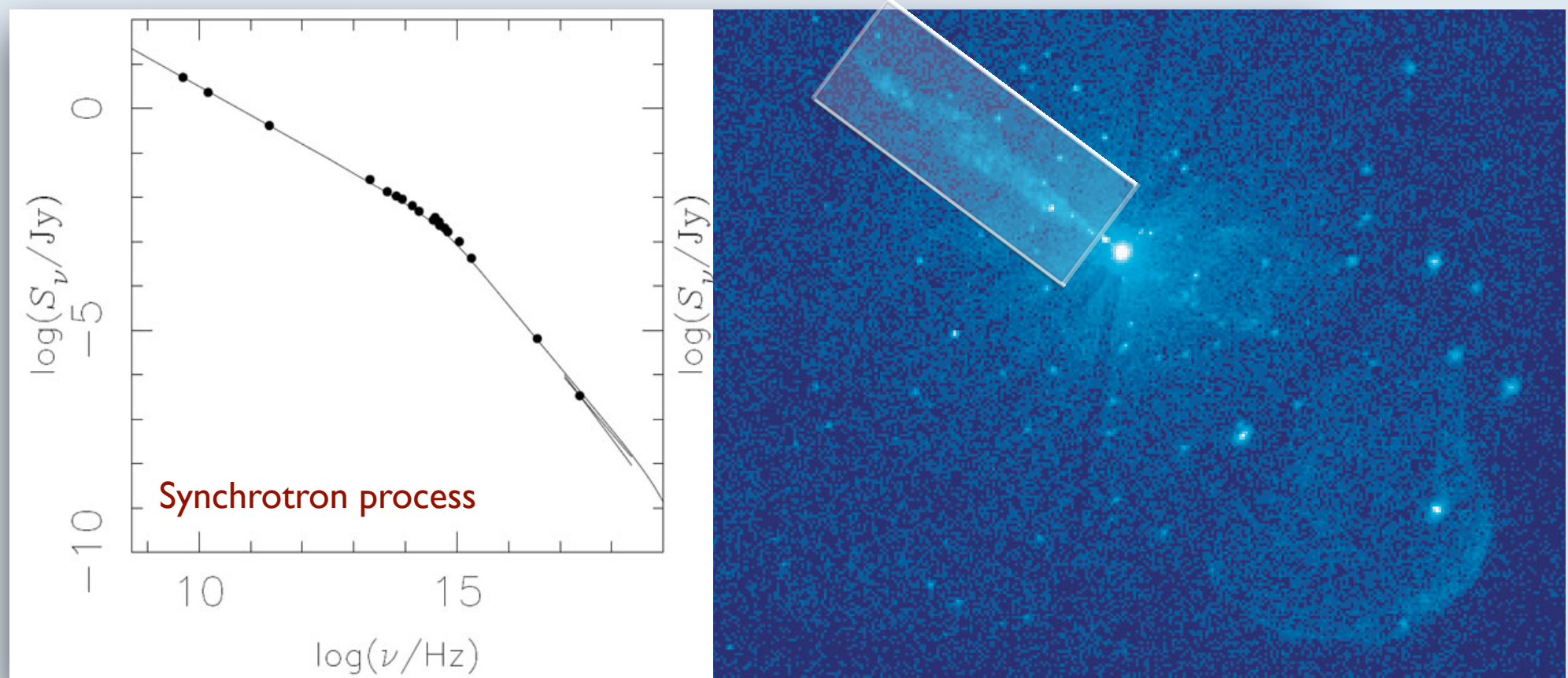Extended structures can be studied
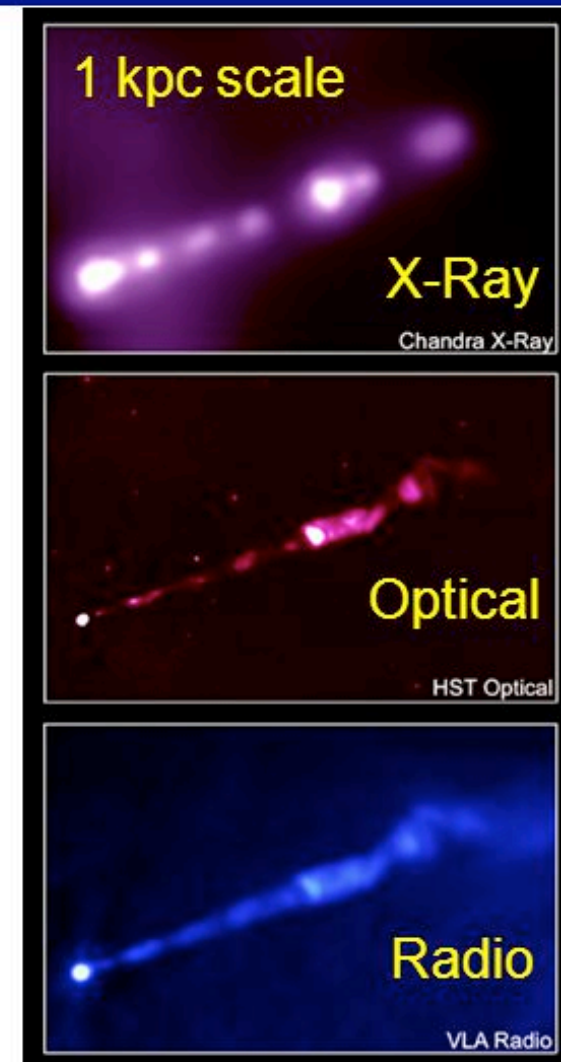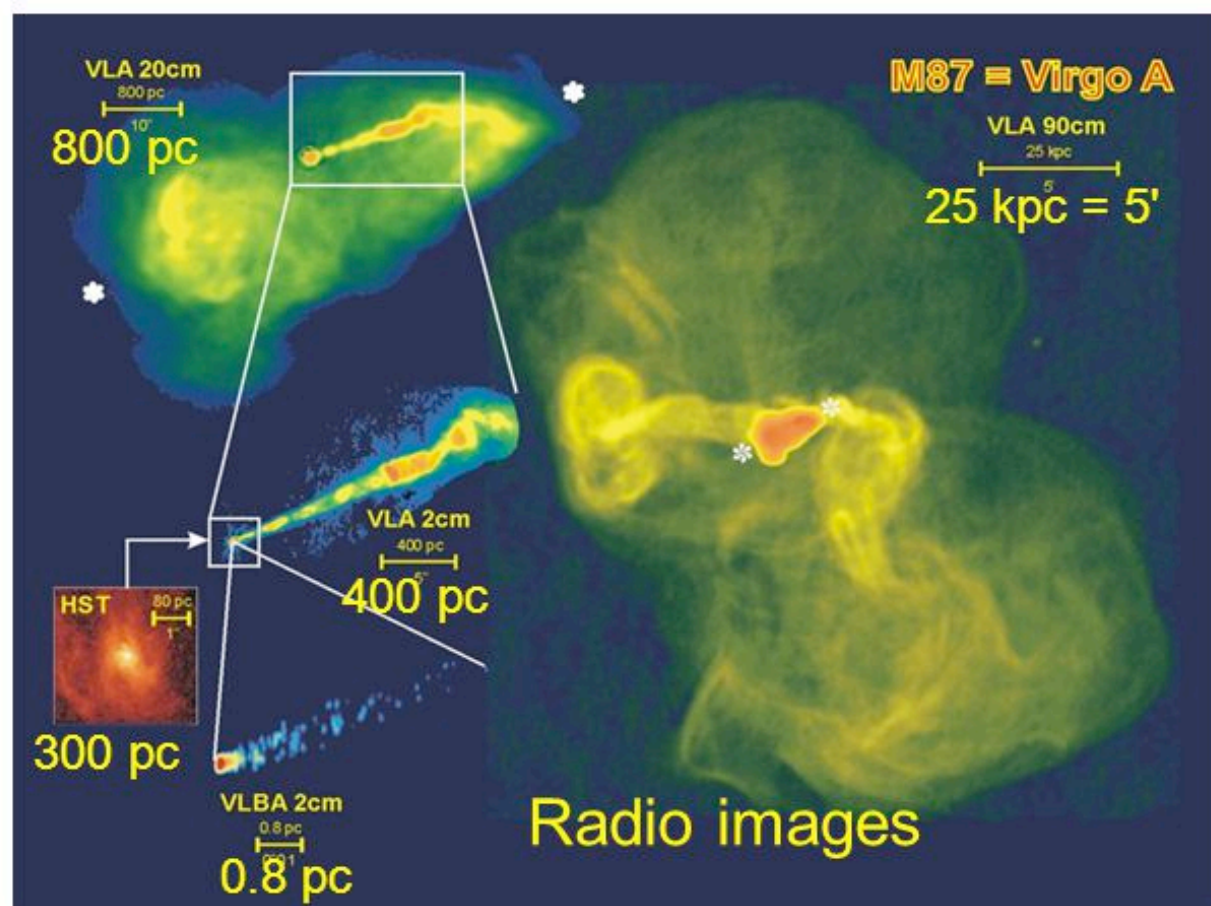
In the X-ray band

BLAZAR X-RAY IMAGE:
point like source

Radio Galaxy X-RAY IMAGE
resolves core, jet and lobe

kpc-scale Jet
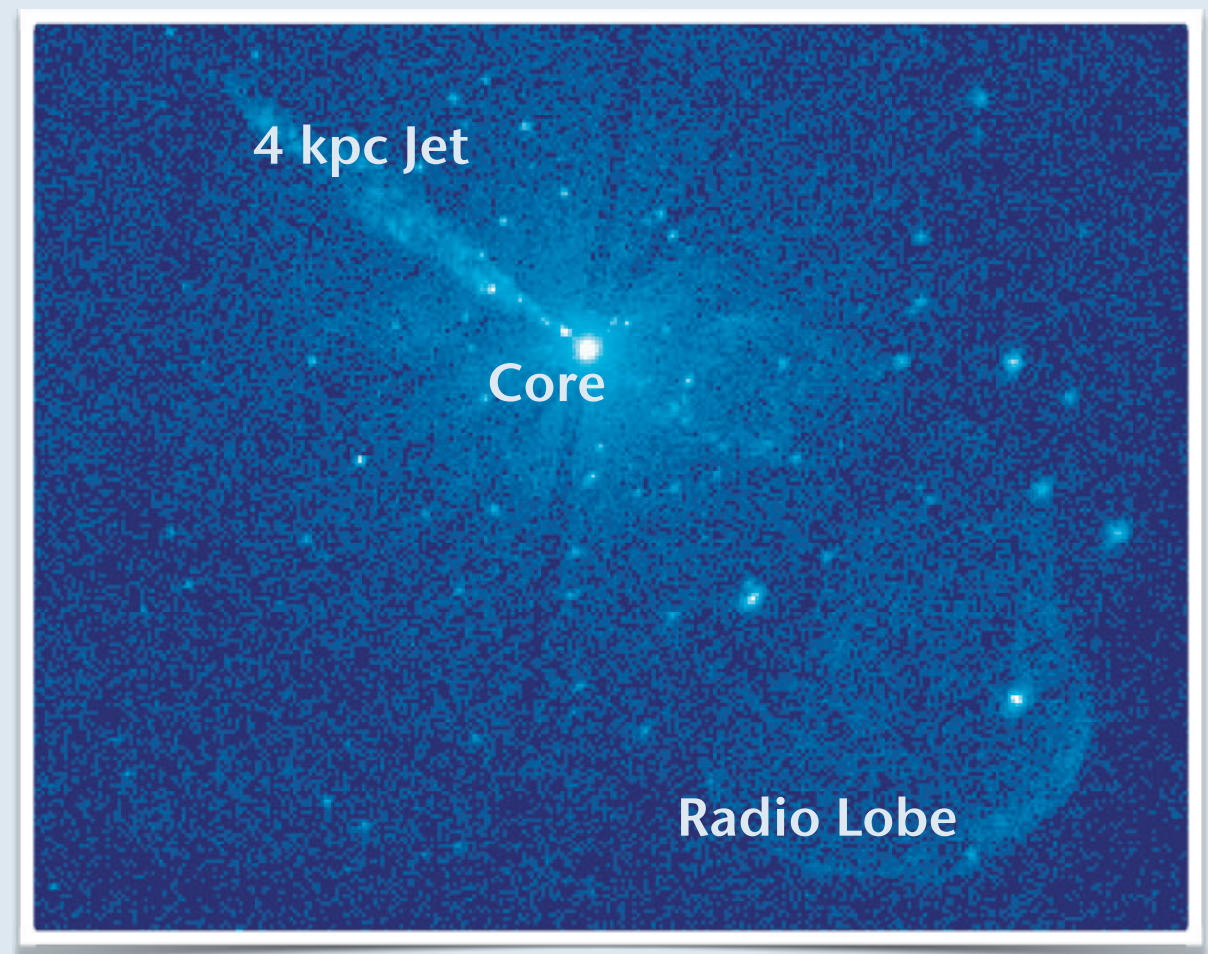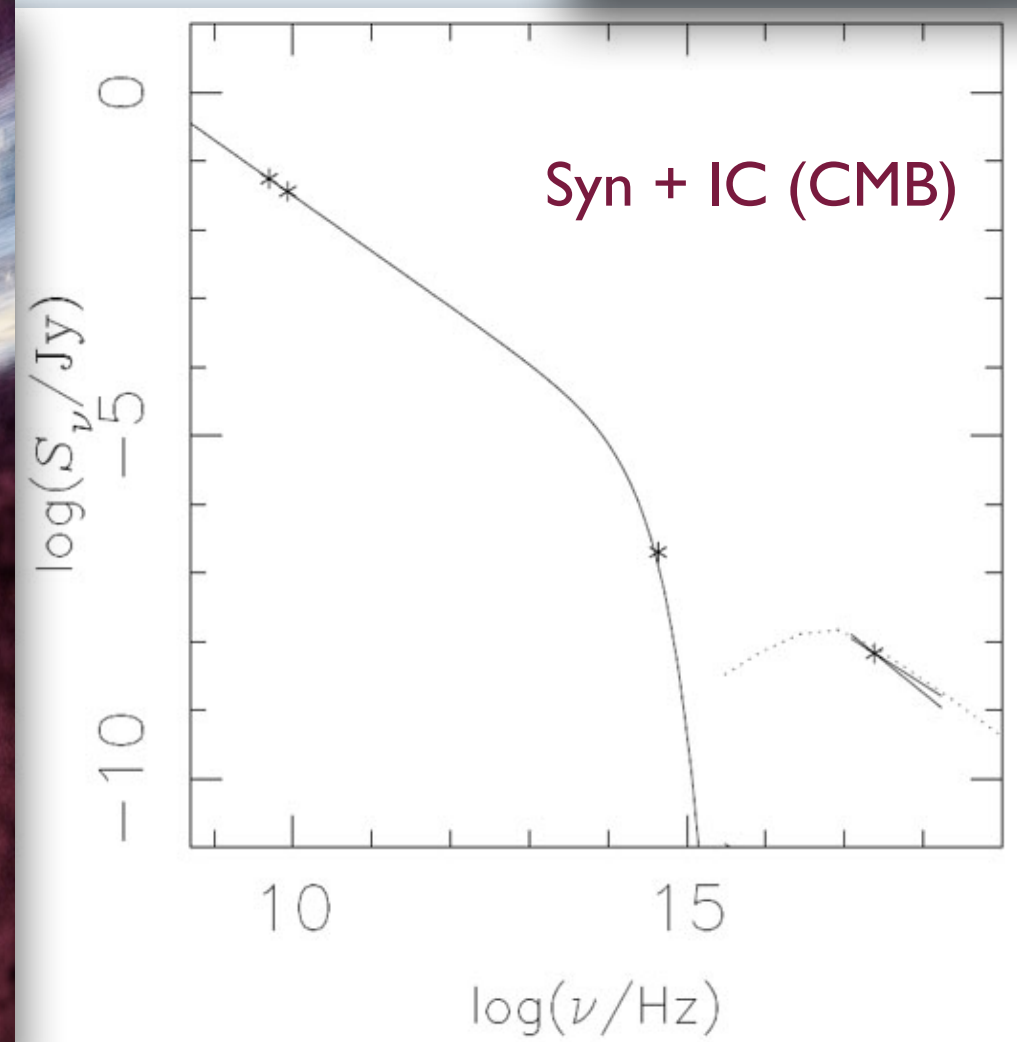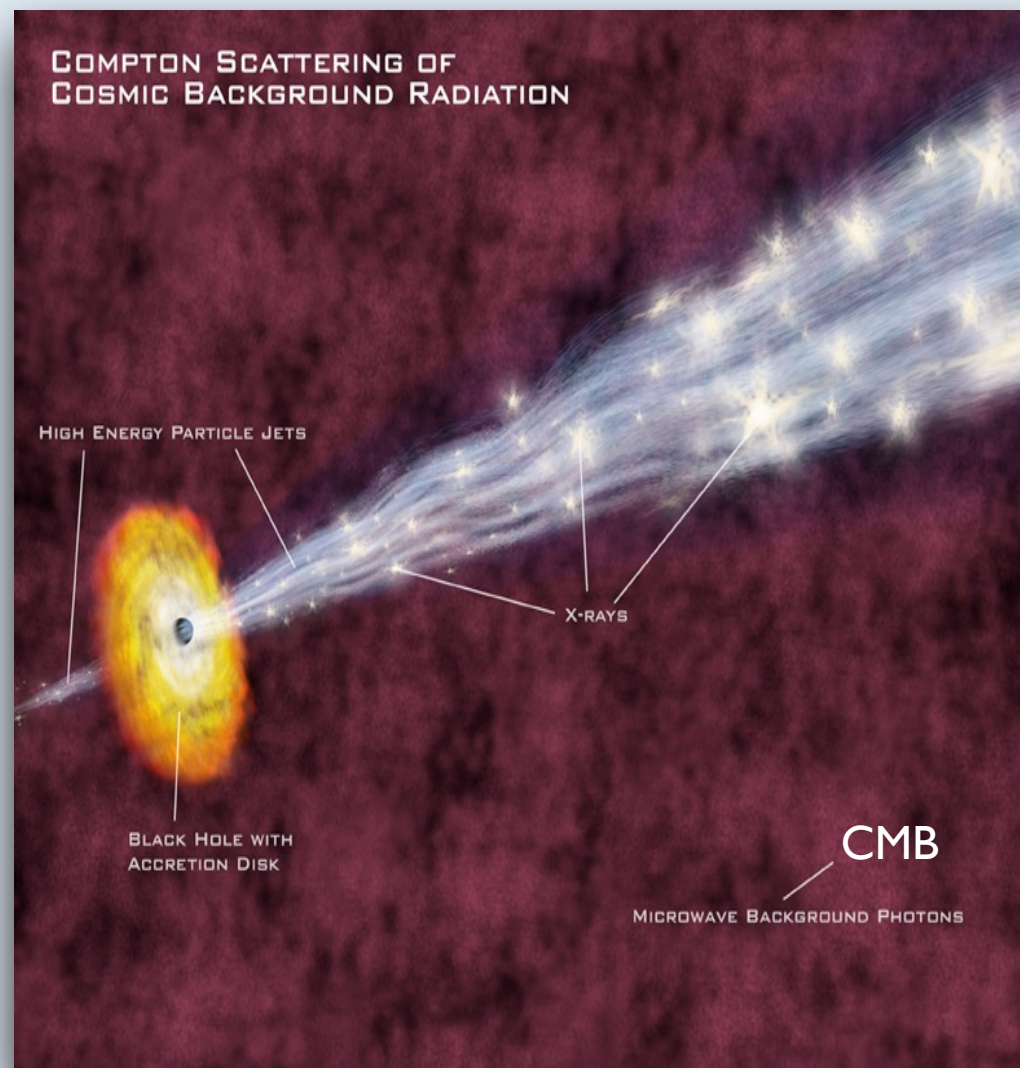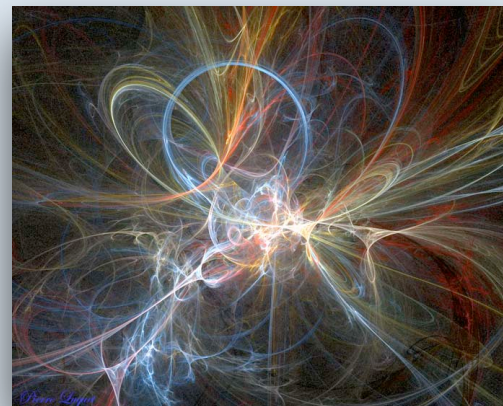

Synchrotron process

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
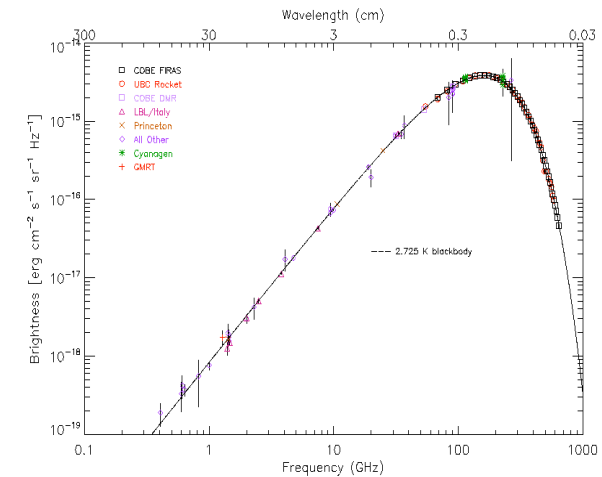
FRII sources require multi-zone synchrotron models, or synchrotron and IC models (seed photons: CMB).
The most popular model postulates very fast jets with high bulk Lorentz factors Γ.

FRII-PKS0637-75

Lobes

relativistic electrons

+

CMB

synchrotron
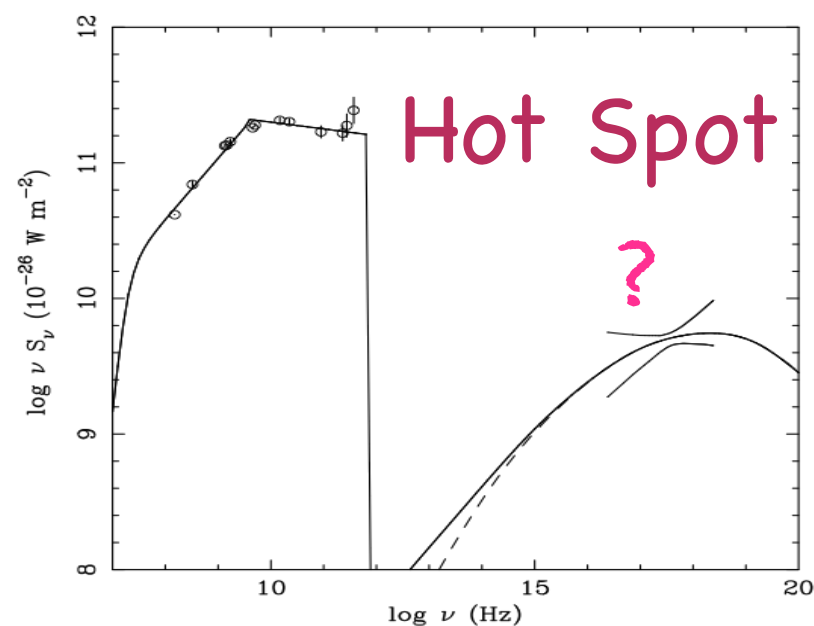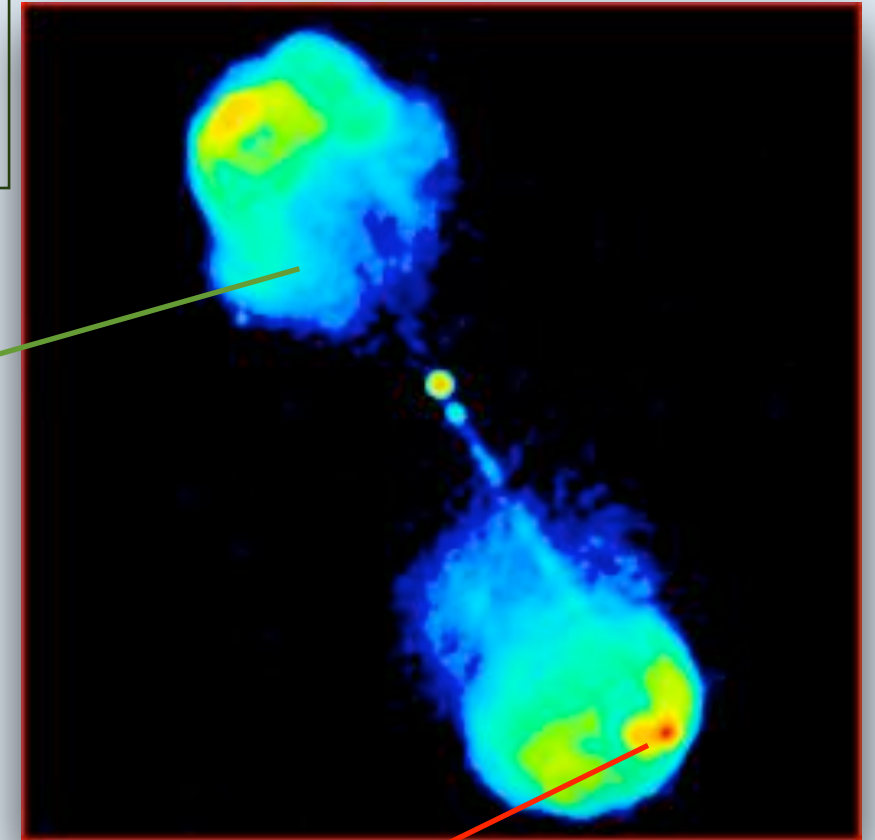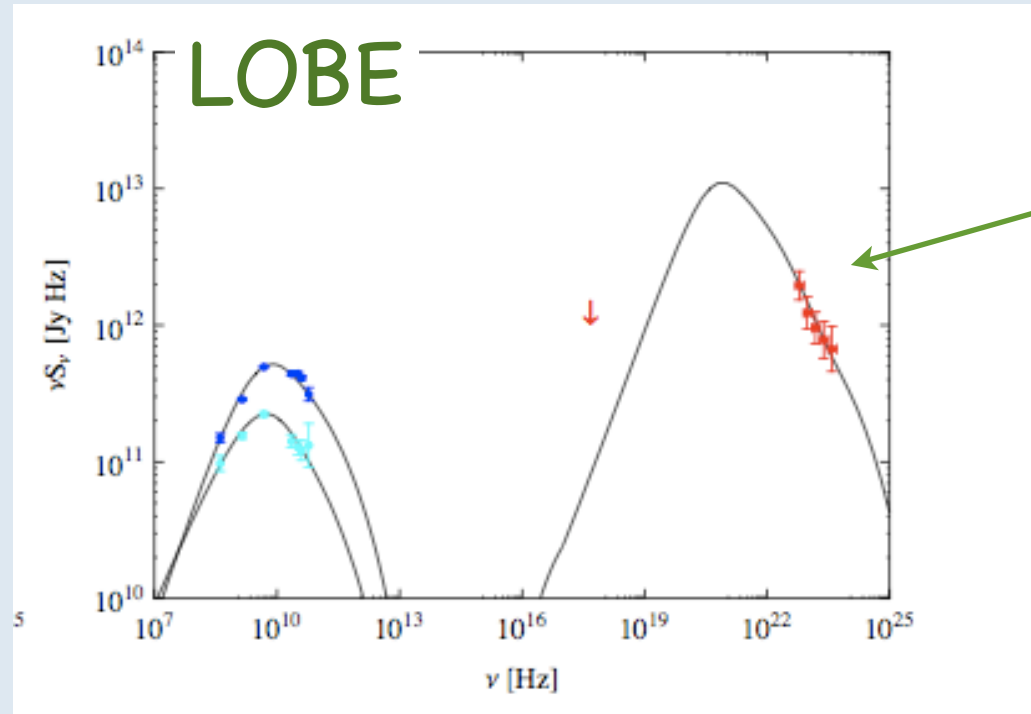
EC/CMB
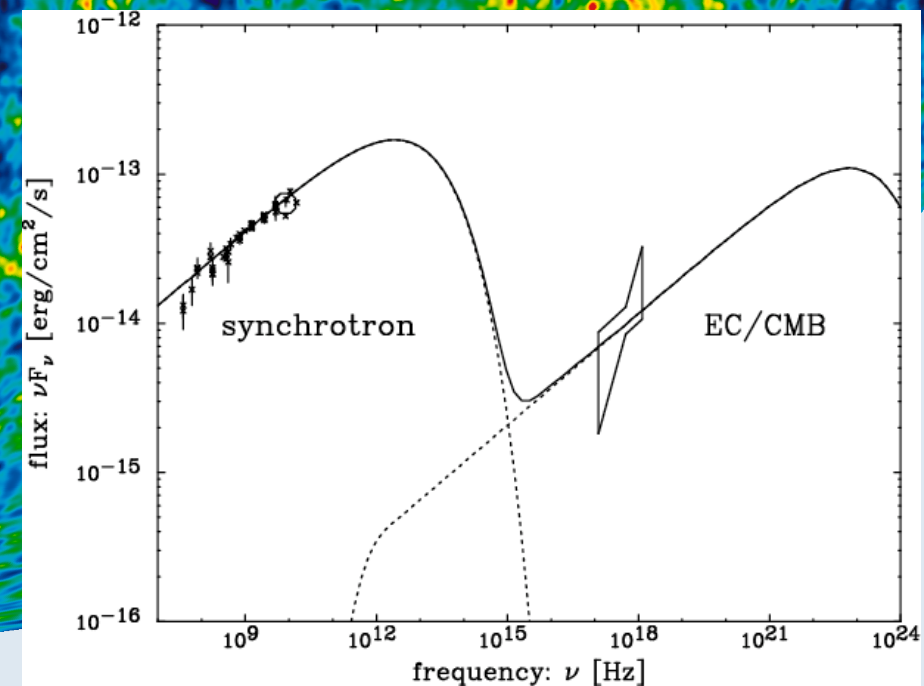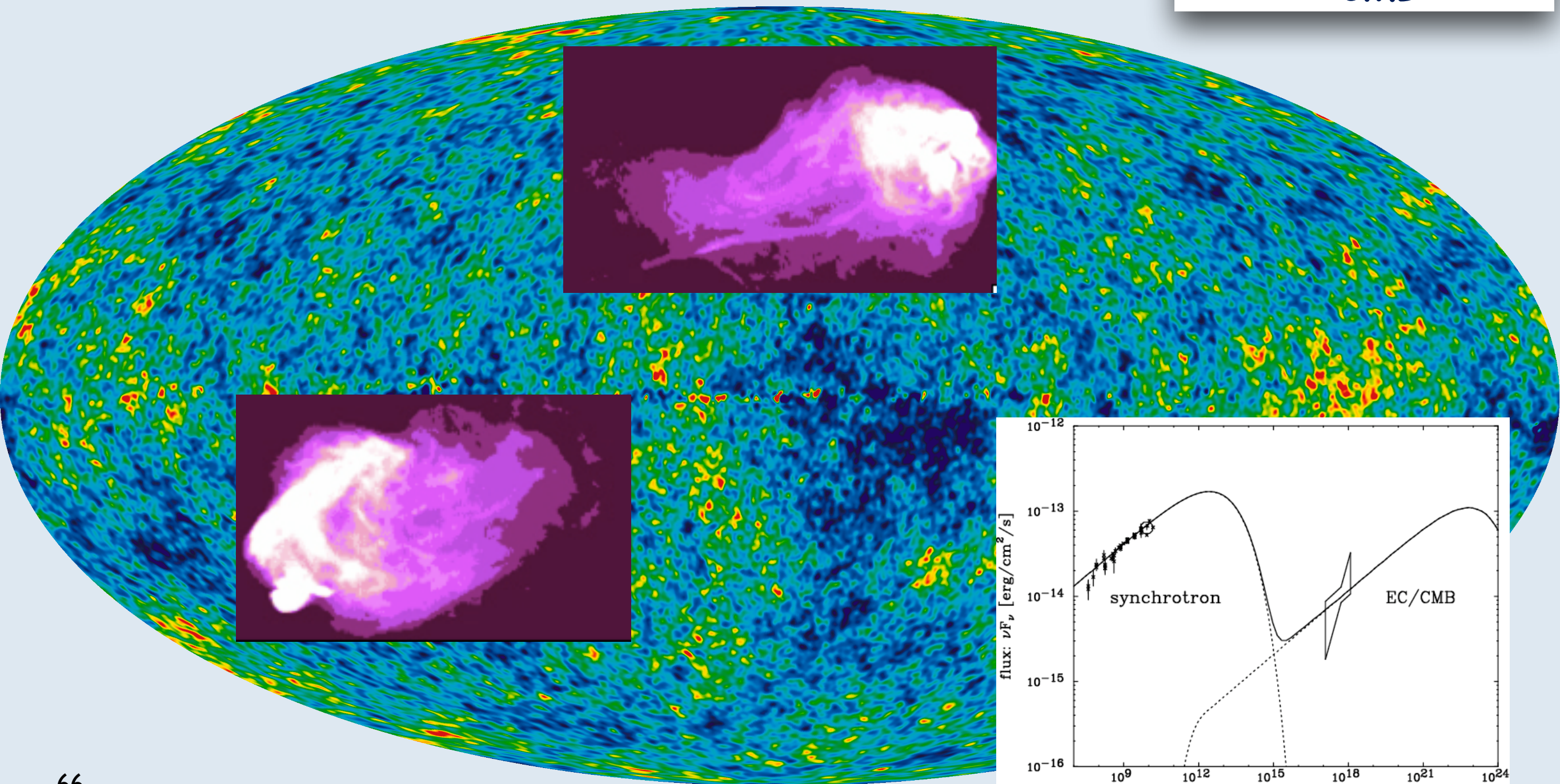
Radio Galaxies:
hundreds of kpcs away from the core

LOBE

Hot Spot

?

We use new and archival Chandra data to investigate the X-ray emission from a large sample of compact hot spots of FR II radio galaxies and quasars from the 3C catalog. We find that only the most luminous hot spots tend to be in good agreement with the predictions of a synchrotron self-Compton model with equipartition magnetic fields. At low hot spot luminosities inverse Compton predictions are routinely exceeded by several orders of magnitude, but this is never seen in more luminous hot spots. We argue that an additional synchrotron component of the X-ray emission is present in low-luminosity hot spots