



IDENTIKIT OF A RADIO GALAXY



Reference paper:

[1] <https://arxiv.org/pdf/astro-ph/0511784>

[2] <https://arxiv.org/pdf/astro-ph/0512600>

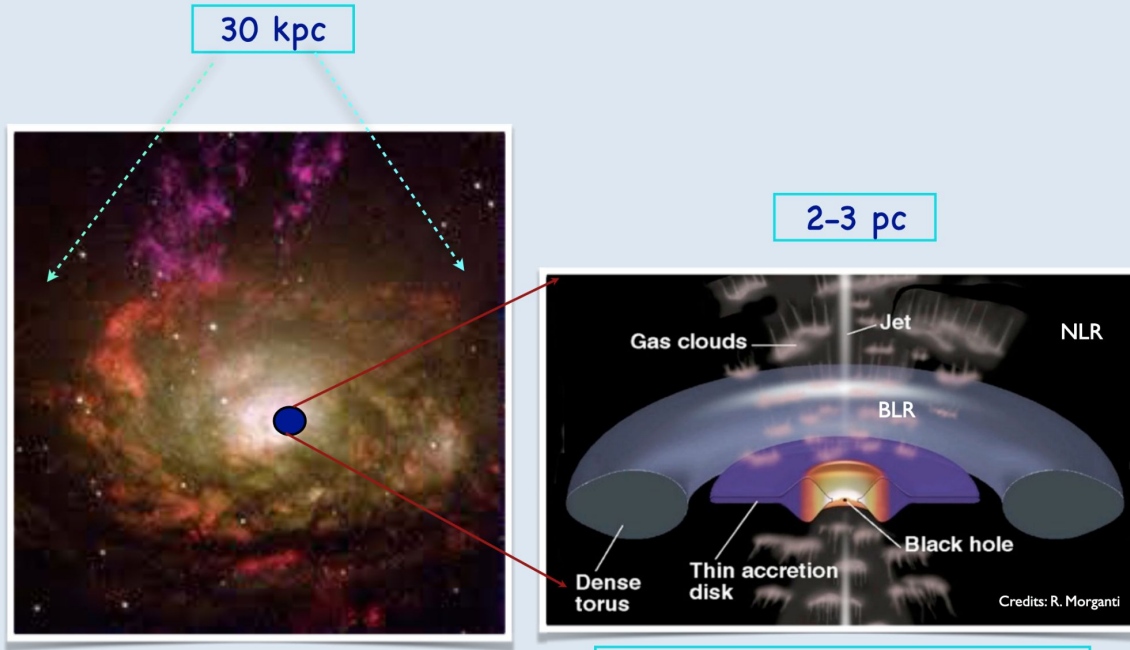
For further insight into radio-loud AGN:

http://labx.iasfbo.inaf.it/2018/resources/pgrandi_RLAGN_2018.pdf

Aim: To build the “*identity card*” of a radio galaxy by reducing and analyzing data provided by the XMM-Newton satellite.

The central engine of a AGN

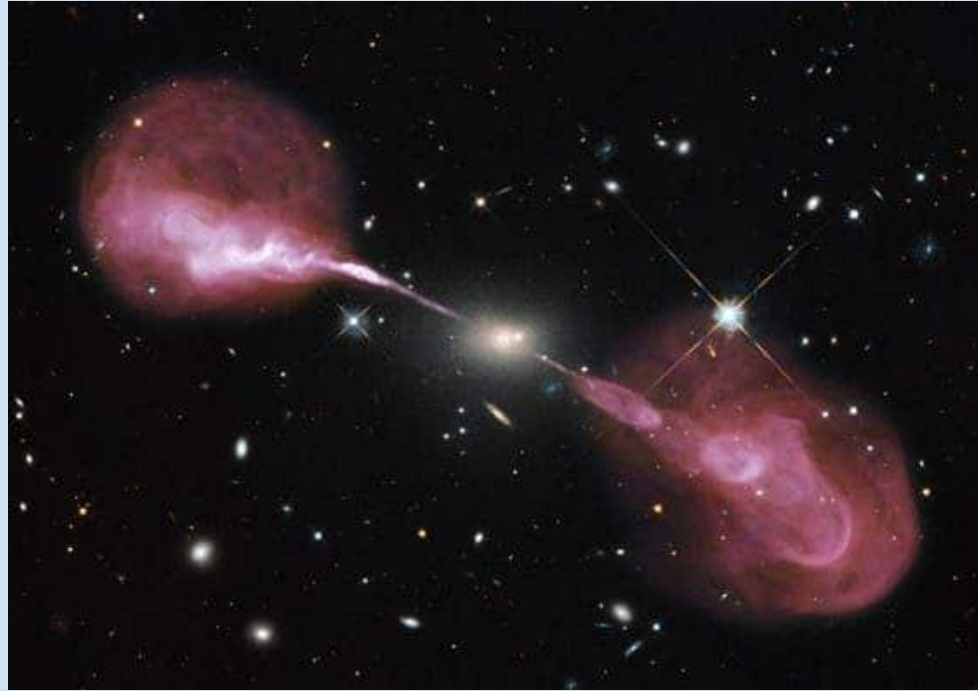
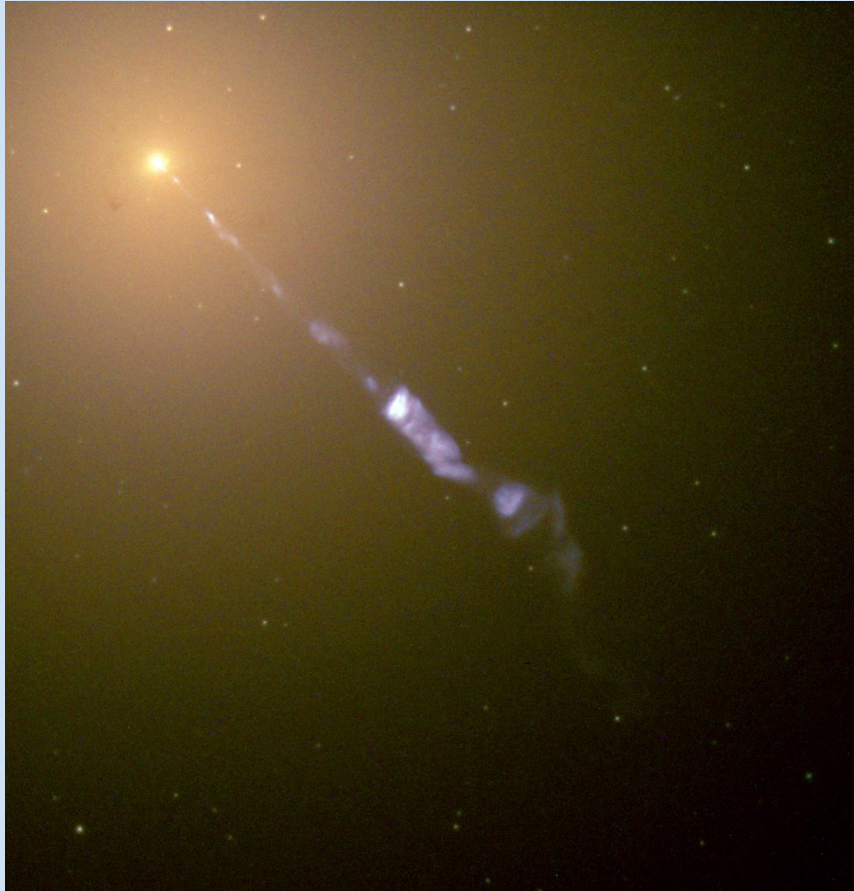
The engine occupies a tiny region in the center of the galaxy



This is the same for both
Radio-Quiet and Radio-Loud AGN

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

Radio-Loud (RL) AGN are able to launch **RELATIVISTIC JETS**



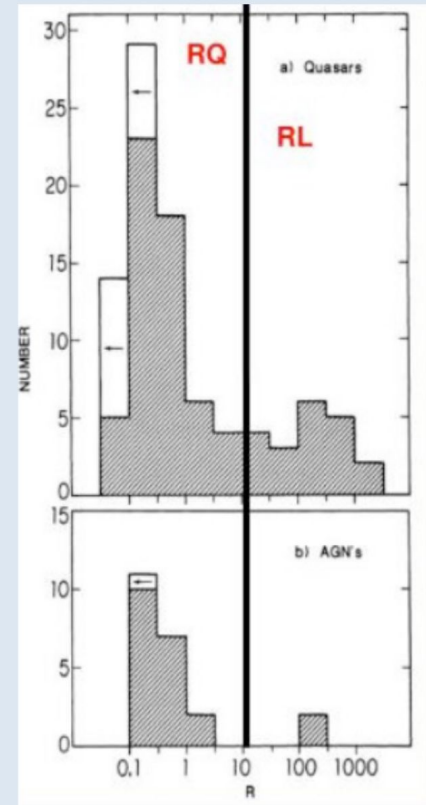
RL AGN represent ~10% of all AGN

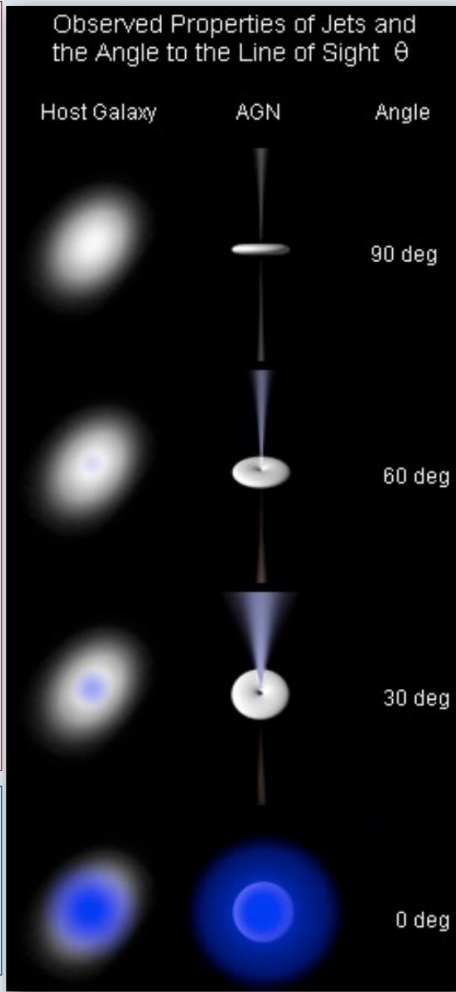
RADIO LOUDNESS PARAMETER (R)

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

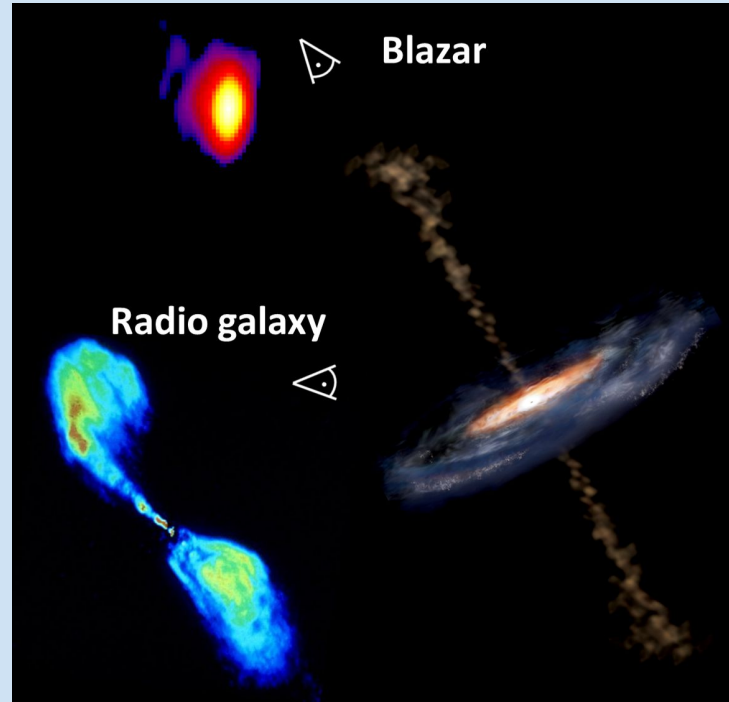
This definition is based on a study of 114 objects from the Palomar Bright Quasar Survey with VLA (Kellermann 1989)

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



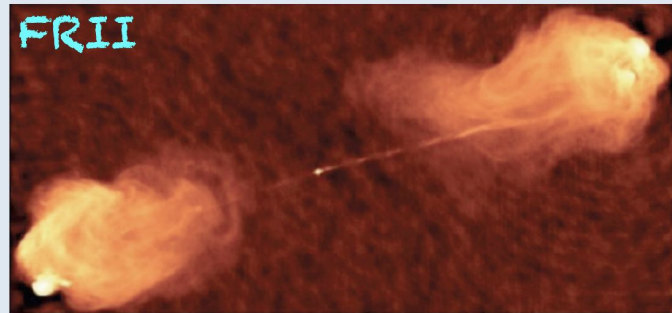
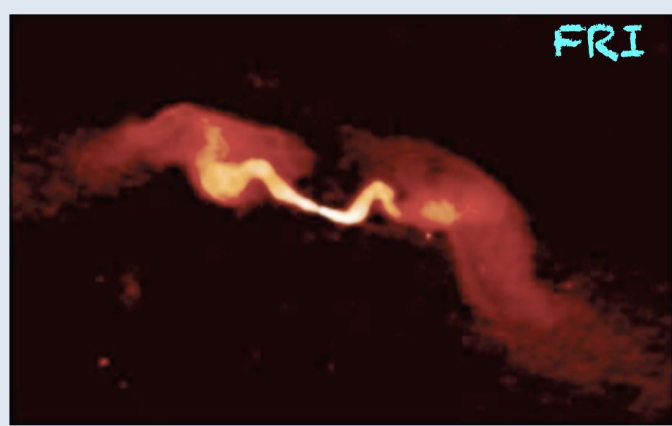


Radio-loud AGN are divided into **Blazars** and **Radio Galaxies**, depending on the inclination angle of the relativistic jet w.r.t. the observer.



Radio classification

([Fanaroff & Riley 1974](#))



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

Historically, the classification was based on **radio morphology**, which in practice translated into a distinction by radio luminosity at 178 MHz.

FR I:

- > The regions of maximum brightness are **close to the center**.
- > Jets are bright near the core and then *fade* outward (**edge-darkened**).
- > More diffuse and less collimated large-scale structure.



FR I: edge-dimmed –
brightest near core – low radio power

FR II:

- > The brightest regions lie **at the outer edges** of the lobes (hotspots).
- > Jets remain collimated and terminate in bright hotspots (**edge-brightened**).
- > More powerful and well-defined structures.



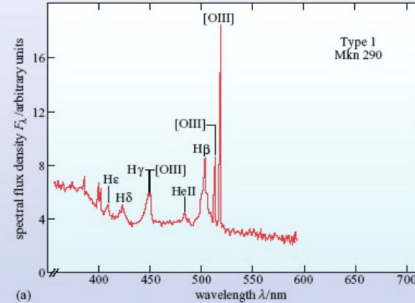
FR II: edge-brightened – hotspots at the ends – high radio power

Optical classification

i) Orientation

Type I
face-on

bright continuum and BROAD
emission lines from hot high
velocity gas ($\text{FWHM} \sim 10^3\text{-}4 \text{ km s}^{-1}$)

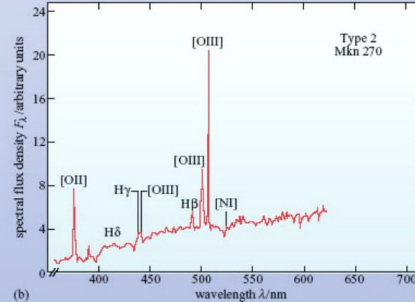


Broad Line
Radio Galaxies
(BLRG)

Quasars (large
 z)

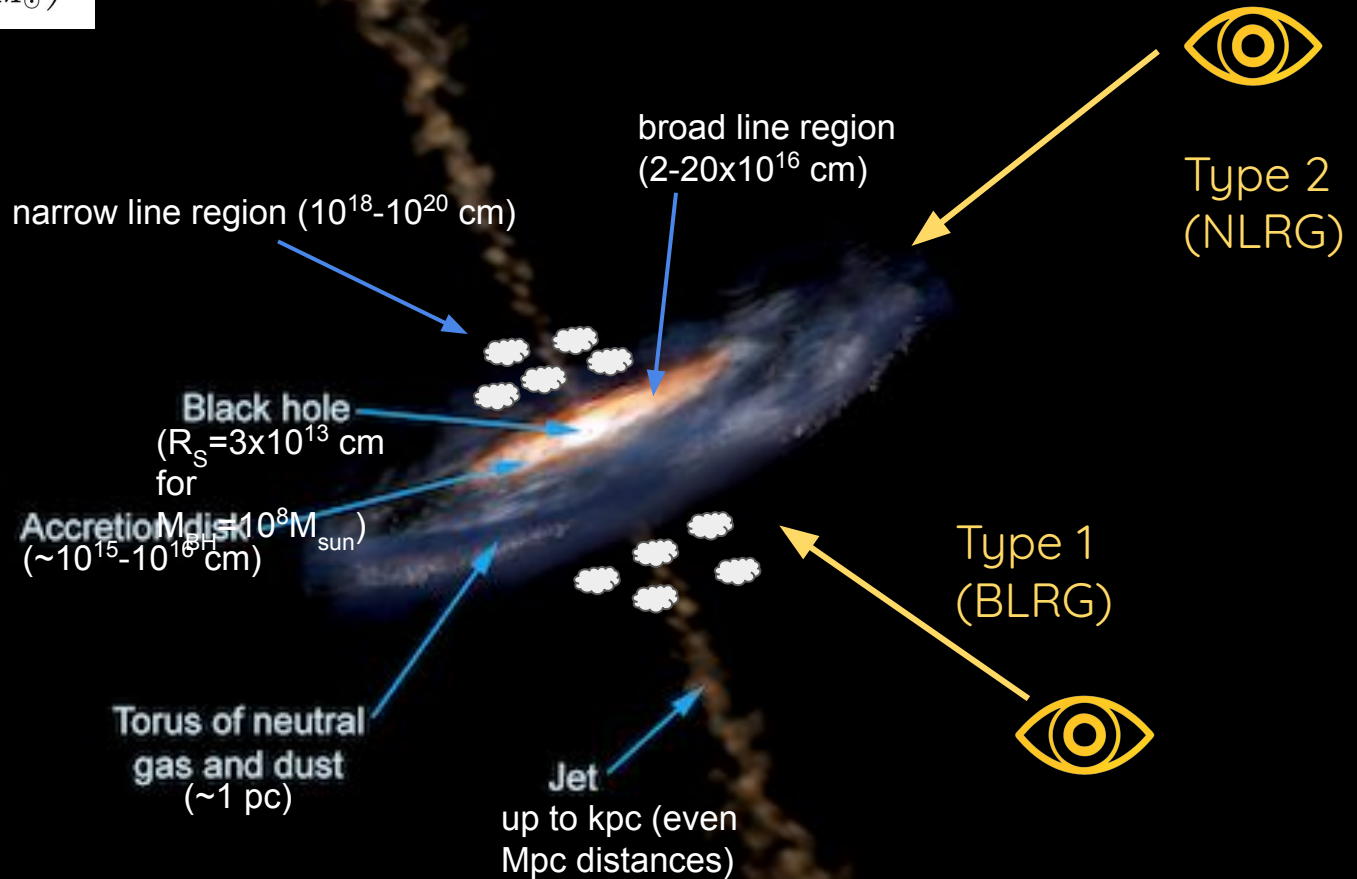
Type II
edge-on

weak continuum and only
NARROW emission lines
($\text{FWHM} \sim 10^2 \text{ km s}^{-1}$)



Narrow Line
Radio Galaxies
(NLRG)

$$R_s = \frac{2GM}{c^2} \approx 3 \times 10^5 \text{ cm} \times \left(\frac{M}{M_\odot} \right)$$



$$1 \text{ parsec} = 3.0857 \times 10^{18} \text{ cm}$$

Optical classification

ii) accretion efficiency in the central engine

Optical

High-excitation (HERG) and low-excitation (LERG) RG ACCRETION MODE

This classification is related to the excitation modes of the gas in the Narrow Line Regions:
different excitation modes correspond to different accretion rates

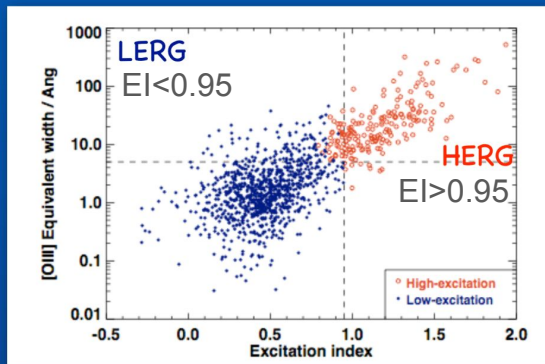
Laing et al. (1994)

HERG: $EW_{[OIII]} > 3 \text{ \AA}$
 $[OIII]/H\alpha > 0.2$

Excitation Index

(Buttiglione et al. 2010)

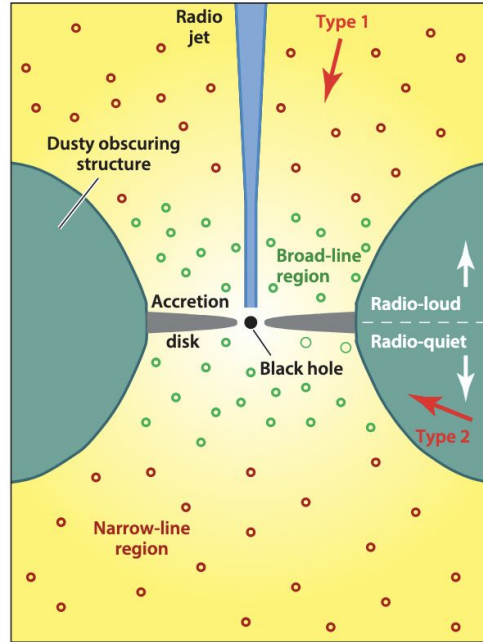
$EI = \log([OIII]/H\beta) - 1/3[\log([NII])/H\alpha) + \log([SII]/H\alpha) + \log([OI]/H\alpha)]$



HERG: almost FRII
LERG: both FRI and FRII

Efficient
accretion

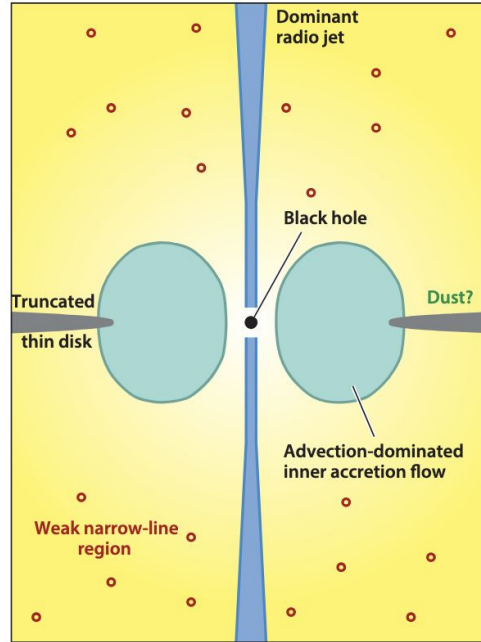
a Radiative-mode AGN



HERG

$$(L/L_{\text{Edd}} \gtrsim 0.01)$$

b Jet-mode AGN



LERG

$$(L/L_{\text{Edd}} \lesssim 0.01)$$

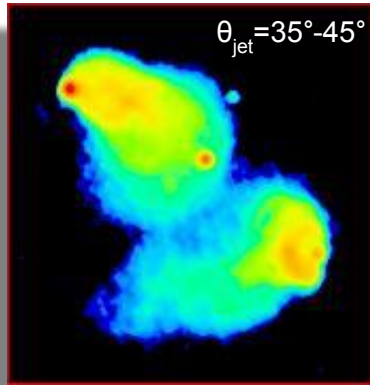
Inefficient
accretion

L = bolometric luminosity;

L_{Edd} = Eddington luminosity = $(4\pi G m_p c / \sigma_T) M_{\text{BH}} = 3.3 \times 10^4 M_{\text{BH}}$ ([Heckman & Best 2014](#))

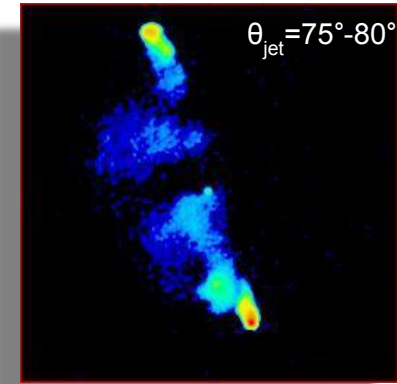
The sources

3C 382



- $z=0.055$
- FR II
- Broad Line Radio Galaxy
- HERG
- $M_{\text{BH}} = 1.1 \times 10^9 M_{\text{sun}}$ (Ferrarese et al. 2004)

3C 33



- $z=0.061$
- FR II
- Narrow Line Radio Galaxy
- HERG
- $M_{\text{BH}} = 5.3 \times 10^8 M_{\text{sun}}$ (Buttiglione et al. 2010)

1. Choose one of the two sources:

❑ DATA REDUCTION

- creation of the background light curve above 10 keV (soft protons!)
- selection of the good time intervals (GTI)
- overlay of the radio contours and selection of the source and background spectral extraction regions (in particular for 3C 33)
- spectrum extraction

❑ EXTRACTION OF THE (BACKGROUND-CORRECTED) LIGHT CURVE OF THE SOURCE

❑ SPECTRAL ANALYSIS→XSPEC

- find the **best-fit model** and describe the resulting spectral parameters in their physical context (e.g. photon index Γ , N_H , iron line)
- estimate of the (intrinsic or observed) **flux** and/or **luminosity** with relative uncertainties
- estimate of the **accretion rate** of the source

2. Repeat the exercise for the other radio galaxy, then compare the two sources (optional)

X-ray Laboratory 2025

17 November 2025 to 12 December 2025
Europe/Rome timezone

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Overview

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BIBLIOGRAPHY

TUTORIALS



[Chandra tutorial](#) (C. Vignali)

[XMM-Newton tutorial](#) (E. Torresi)

[Commands for XMM data reduction](#)

[XSPEC TUTORIAL](#) (C. Vignali)

Thermal Comptonization Spectrum: the Continuum

cut-off power law

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

$$F_E \propto E^{-\Gamma}$$

power law

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

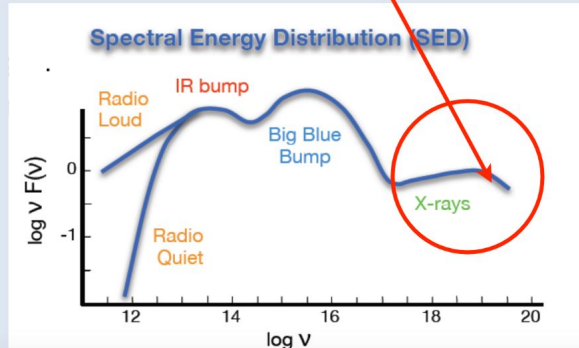
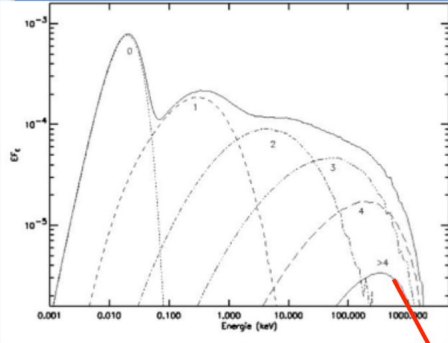
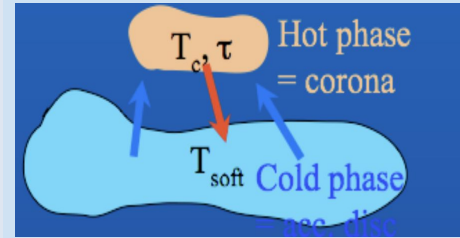
The exact relation between spectral index and optical depth depends on the geometry of the scattering region.

$$E_c \simeq kT$$

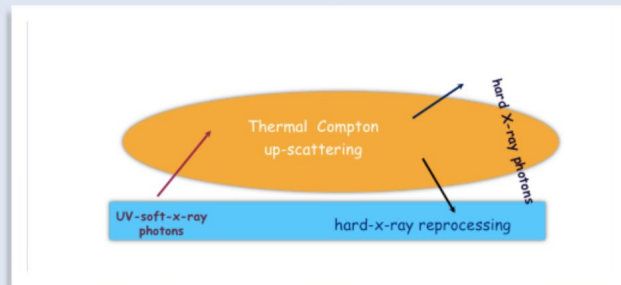
As photons approach the electron thermal energy, they no longer gain energy from scattering, and a sharp rollover is expected in the spectrum.

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

Haardt & Maraschi 1991



Reprocessed features

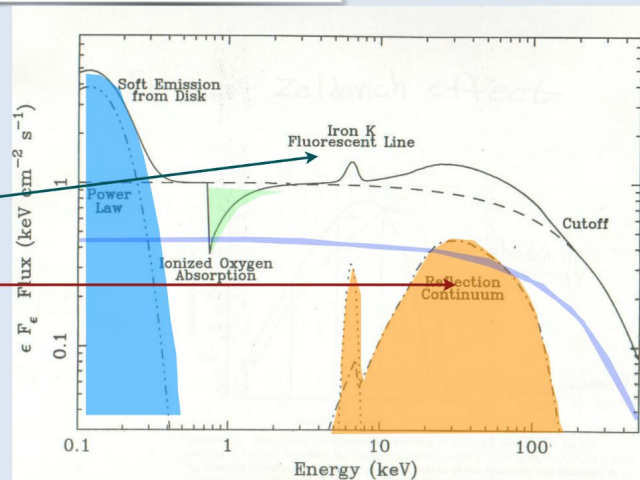


- Thermal Comptonization

- Hard X-ray reprocessing

Iron line

Compton hump



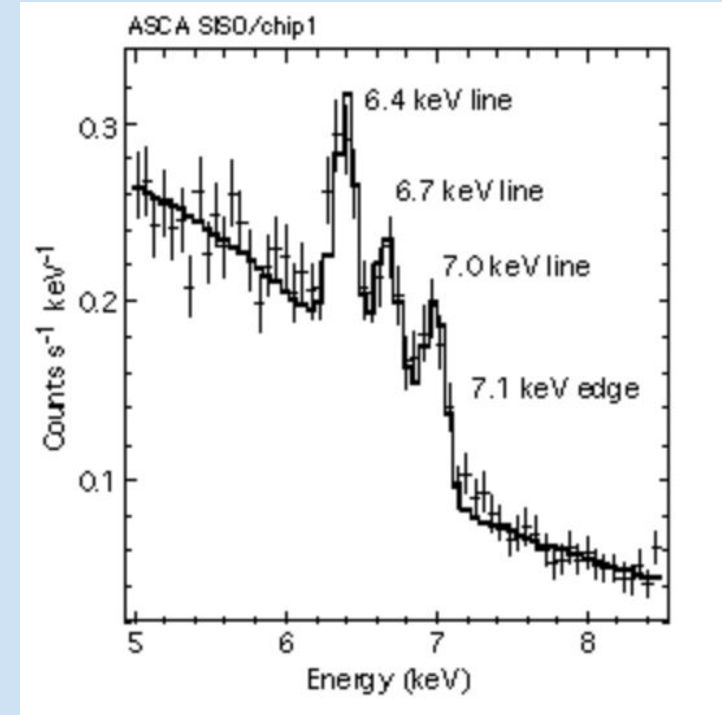
Iron line & Reflection

A prominent spectral feature produced by **fluorescent emission of iron** after X-ray illumination:

- **6.4 keV** → neutral or weakly ionized **FeK α**
- **6.7 keV** → He-like Fe XXV
- **6.97 keV** → H-like Fe XXVI

It is a key diagnostic of the **accretion environment**, revealing information about:

- ionization state of the gas
- relativistic effects near the black hole (broadening of the line)
- reflection from the torus or accretion disk



In XPEC the simplest way to represent the line is a gaussian model (**gauss**, **zgauss**)

Parameters of the Gaussian Line Model

1. LineE (keV) – Line energy

- Rest-frame energy of the Fe line.

2. Sigma (keV) – Line width

- Standard deviation of the Gaussian profile.
- Controls how broad the line appears.
- Physically related to gas velocity via Doppler broadening.
- Typical regimes:
 - $\sigma \lesssim 0.05 \text{ keV}$ → narrow line from distant material (it can be fixed also =0)
 - $\sigma \gtrsim 0.1\text{--}0.3 \text{ keV}$ → broader line (higher velocities)

3. Norm – Line normalization

- Total flux of the emission line ($\text{photons cm}^{-2} \text{ s}^{-1}$).
- Measures the *strength* of the line.
- Used to compute the **equivalent width (EW)**.

Equivalent width

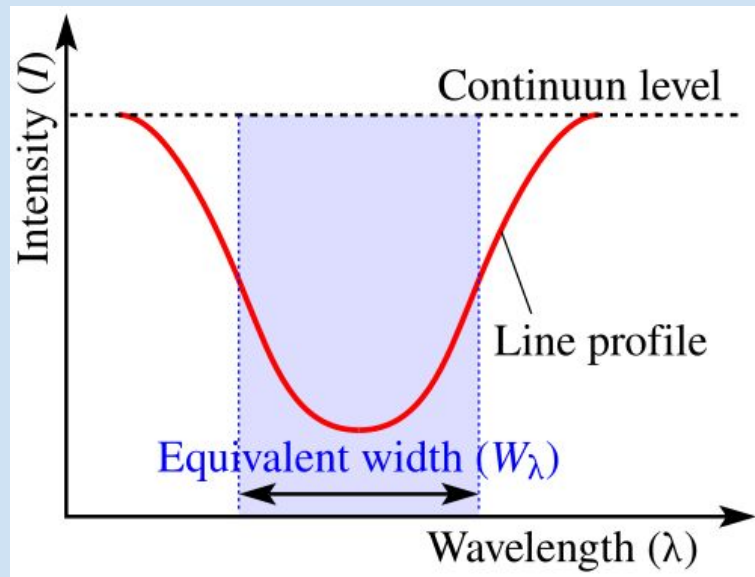
The Equivalent Width (EW) is a measure of the strength of an emission or absorption line relative to the underlying continuum.

It represents the width of a hypothetical rectangle, at the level of the continuum, that contains the same total flux as the spectral line.

$$EW = \int \frac{F_{\text{line}}(E)}{F_{\text{cont}}(E)} dE$$

xspec

eqwidth <component_number>



Estimating the Emission Radius of the FeK α Line

1. From line width to velocity

A narrow Fe K α line is usually broadened by **Doppler motion** of gas orbiting the black hole.
From the observed Gaussian width:

$$\Delta v = (8 \ln 2)^{1/2} \sigma_{\text{obs}} c / E_{\text{obs}}$$

This gives an estimate of the **orbital velocity** of the emitting gas ($\Delta v \sim v$).

2. Virial assumption

If the gas is **gravitationally bound** and moves in Keplerian orbits, we can relate velocity and radius:

$$v^2 \approx GM_{\text{BH}} / R$$

So the emission radius is:

$$R \approx GM_{\text{BH}} / v^2 \quad [\text{cm}]$$

The N_H parameter

What is the column density N_H ?

- N_H is the total number of hydrogen atoms per unit area along the line of sight:
$$N_H \text{ [cm}^{-2}\text{]}$$
- It quantifies **how much gas absorbs X-ray photons** before they reach the observer.
- Low-energy photons are absorbed more efficiently → producing the *photoelectric cutoff* in the spectrum.

Types of N_H in a X-ray spectrum

1. Galactic N_H

- Absorption due to the interstellar medium of the Milky Way (HI, H₂, dust).
- It is fixed for a given sky direction.
- Typical values: 10^{20} – 10^{21} cm⁻²
- In XSPEC it is usually modeled with **tbabs** / **phabs** / **wabs**, with N_H **frozen** to literature values (HI4PI, Kalberla et al. 2005, Willingale et al. 2013).

2. Intrinsic N_H

- Absorption produced by gas **within the source**, e.g. circumnuclear material in an AGN (generally associated with a torus)
- It is **free to vary** during the fit, providing physical insight.
- Compton-**thin**: $N_H < 10^{24}$ cm⁻²
- Compton-**thick**: $N_H > 10^{24}$ cm⁻²
- In XSPEC it is typically modeled with **ztbabs** (or **zphabs**) at the redshift of the source.

Estimate of the accretion rate

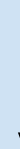
Mass accretion rate

$$\dot{M} = \frac{L_{\text{bol}}}{\epsilon c^2}$$

Mass accretion rate in Eddington units

$$\dot{m} = \frac{L_{\text{bol}}}{L_{\text{Edd}}}$$

$L_{\text{bol}} = L_X \times 30$
([Elvis et al. 1994](#))



This ratio can also be used as a
proxy for the accretion rate

$$\dot{m} \propto \frac{L_X}{L_{\text{Edd}}}$$

For a comparison of L_X/L_{Edd} with other radio galaxies see [Macconi et al. \(2020\)](#)

Enjoy!

