# IDENTIKIT OF A RADIO GALAXY

Reference paper:

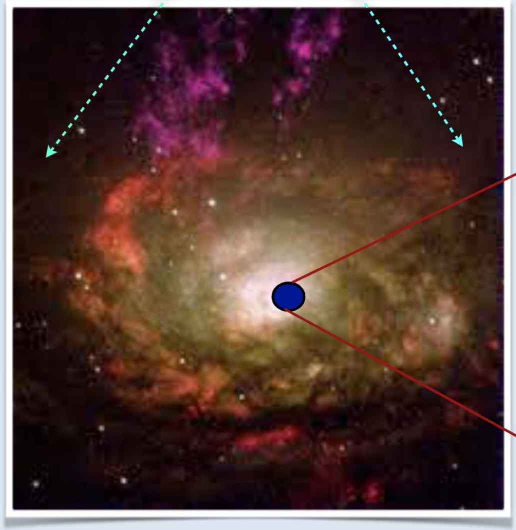
[1] https://arxiv.org/pdf/astro-ph/0511784
[2] https://arxiv.org/pdf/astro-ph/0512600

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

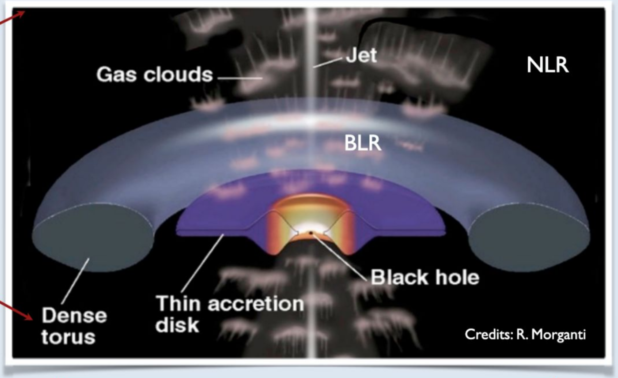
# The central engine of a AGN

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

30 kpc



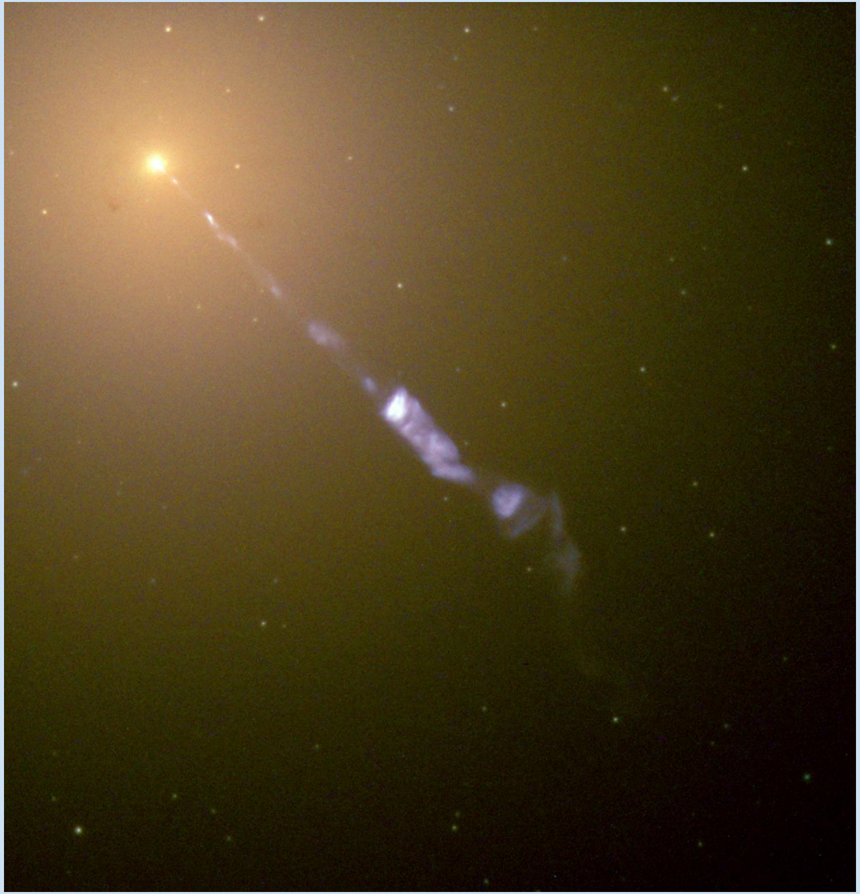
2-3 pc

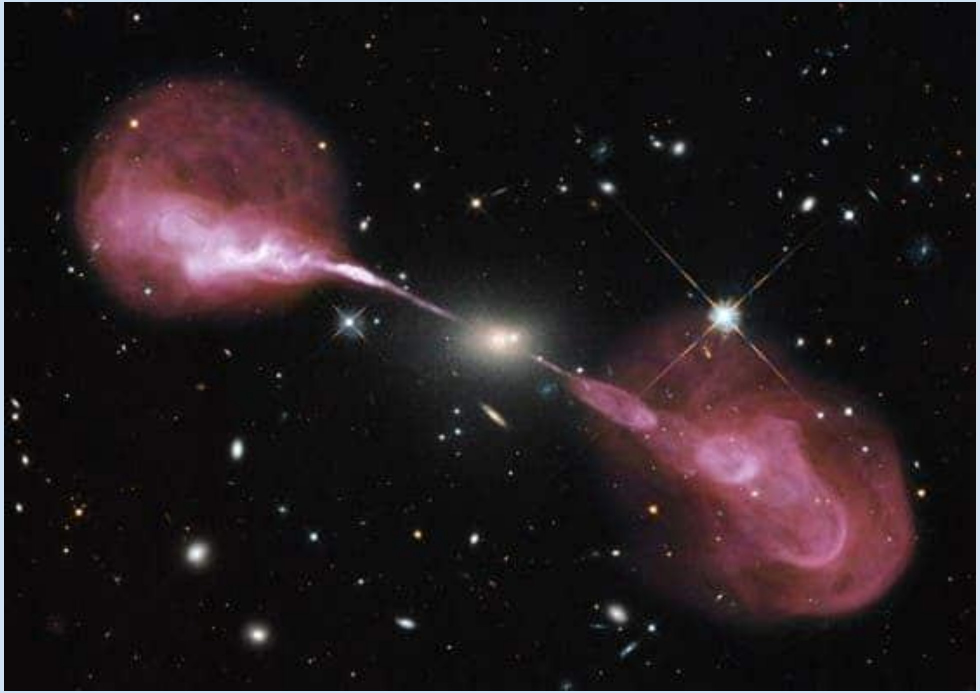



The extraordinary amount of energy is produced through accretion of gas close to a SMBH

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

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

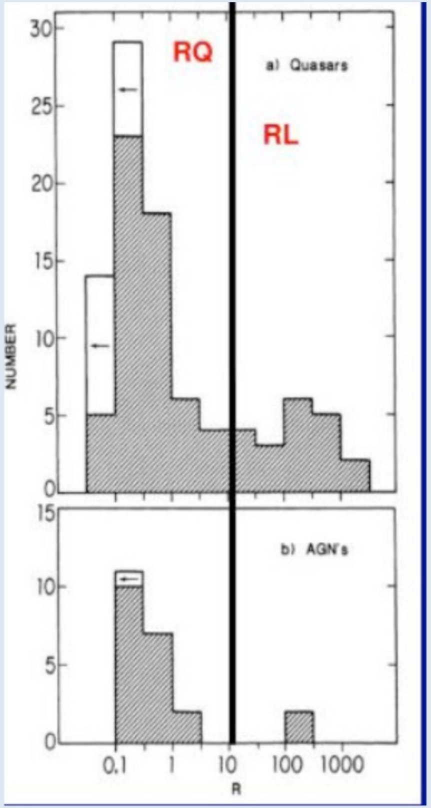




RL AGN represent ~10% of all AGN

# RADIO LOUDNESS PARAMETER (R)

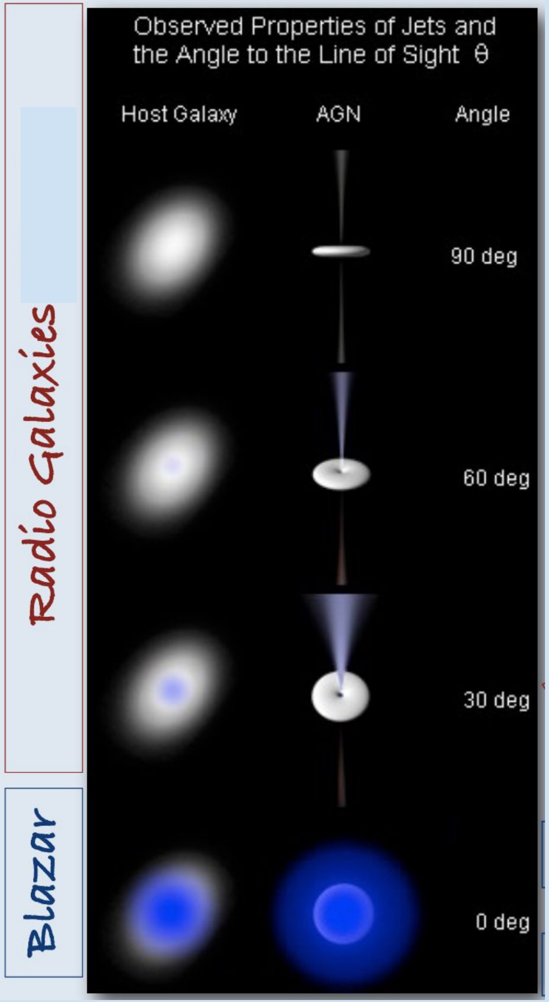
$$R = \frac{F_{GHz}}{F_B} \geq 10.$$



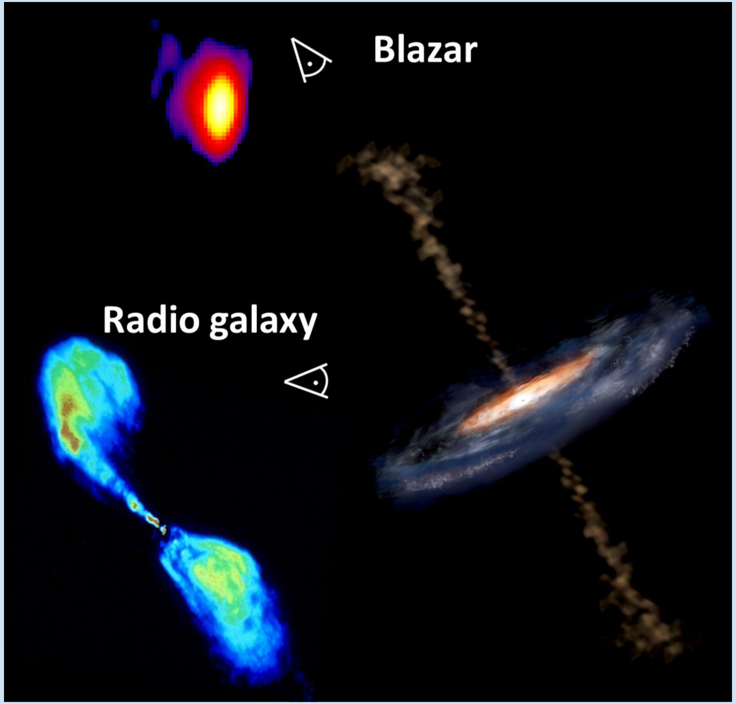

This definition is based on a study of 114 objects from the Palomar Bright Quasar Survey with VLA (Kellermann 1989)

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

http://articles.adsabs.harvard.edu/full/1989AJ.....98.1195K

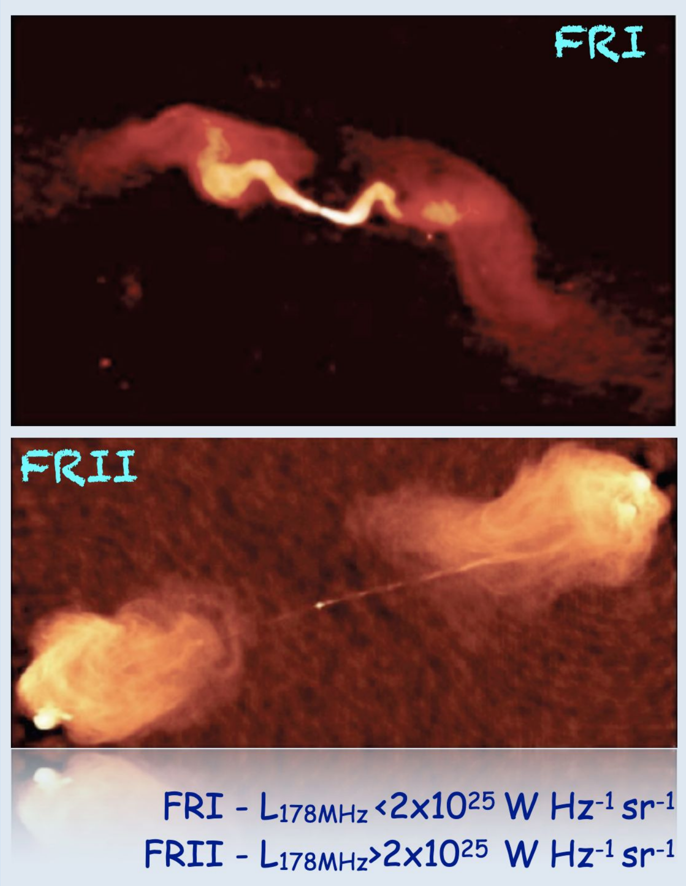



Radio-loud AGN are divided into **Blazars** and **Radio Galaxies**, depending on the inclination angle of the relativistic jet w.r.t. the observer.



# Radio classification

(Fanaroff & Riley 1974)




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**).

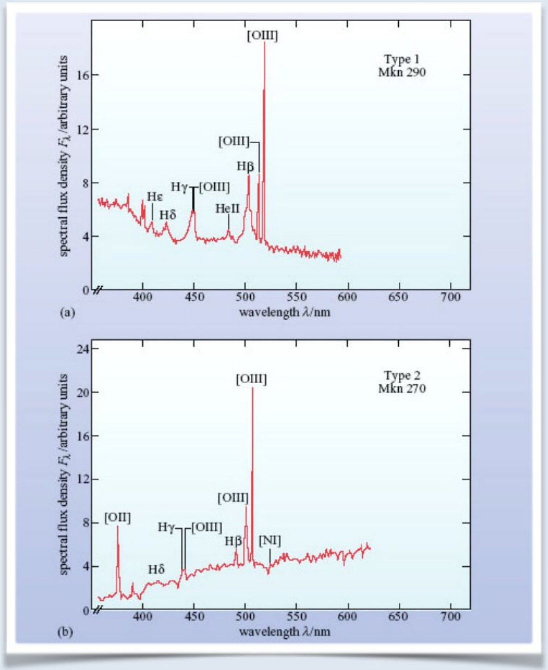
> More powerful and well-defined structures.

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

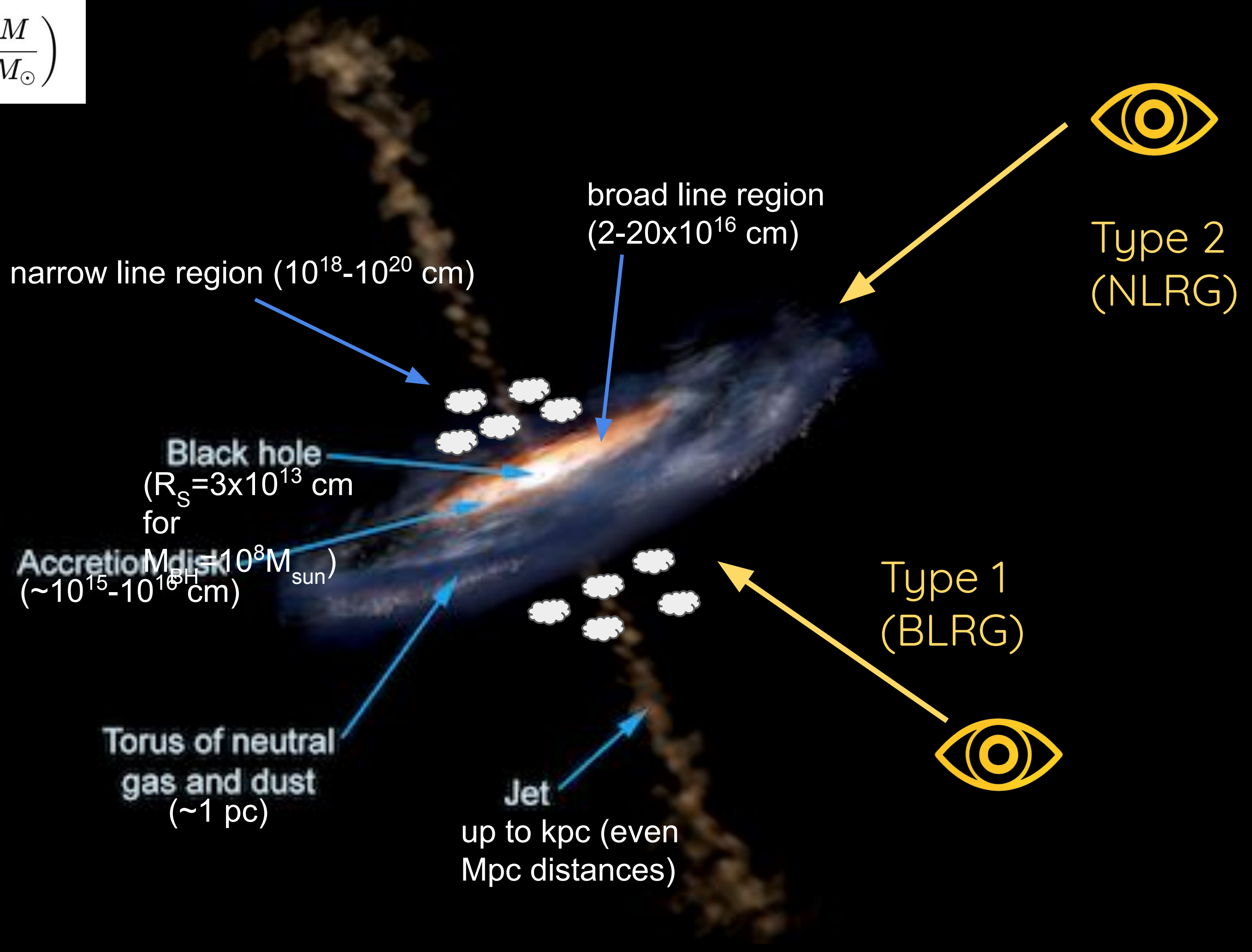
# Optical classification

## i) Orientation

| | | |
|---|---|---|
| **Type I**<br>face-on | **bright continuum and BROAD emission lines from hot high velocity gas (FWHM~$10^{3-4}$ km $s^{-1}$)** | **Broad Line Radio Galaxies (BLRG)**<br><br>Quasars (large z) |
| **Type II**<br>edge-on | **weak continuum and only NARROW emission lines (FWHM~$10^{2}$ 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 parsec = 3.0857 × $10^{18}$ cm

# Optical classification

## ii) accretion efficiency in the central engine

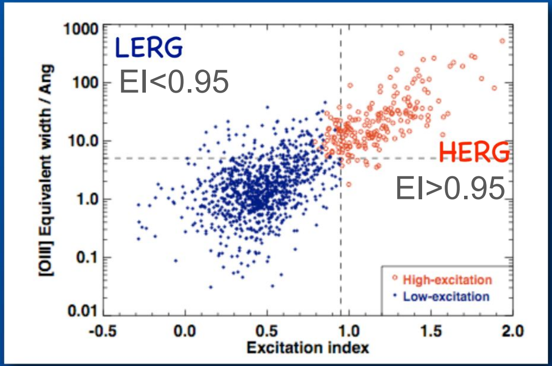
Optical

### 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 Å
[OIII]/Ha > 0.2

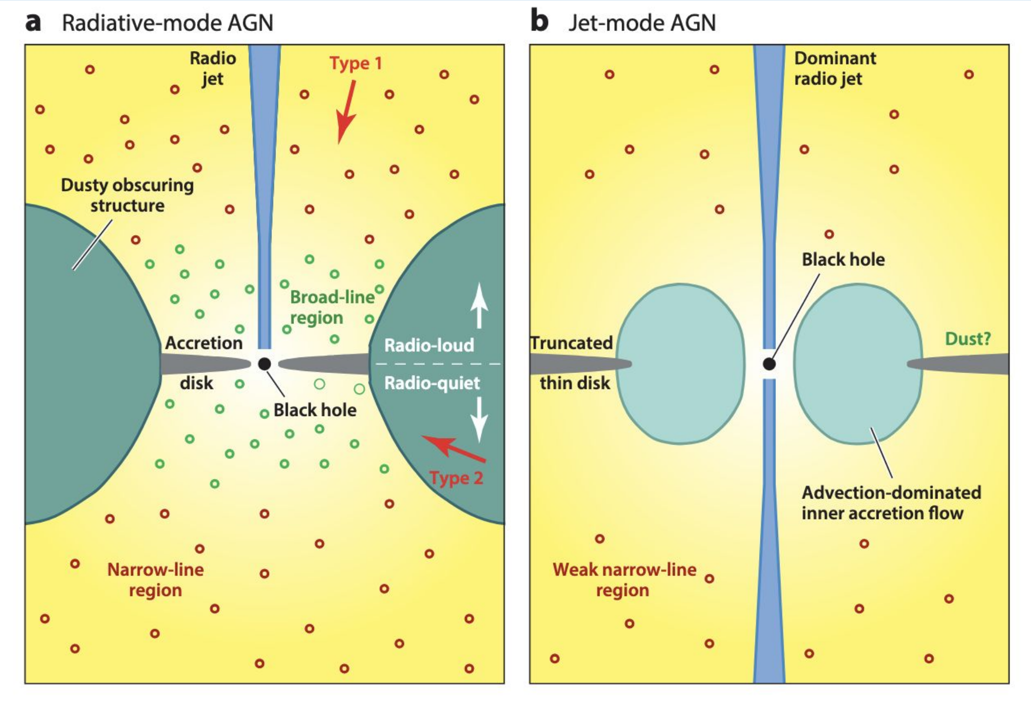
Excitation Index
(Buttiglione et al. 2010)
EI=log([OIII]/Hb)-1/3[log([NII])/Ha)
+log([SII]/Ha)+log([OI]/Ha)]




HERG: almost FRII
LERG: both FRI and FRII

Best & Heckman 2012

Efficient accretion




Inefficient accretion

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

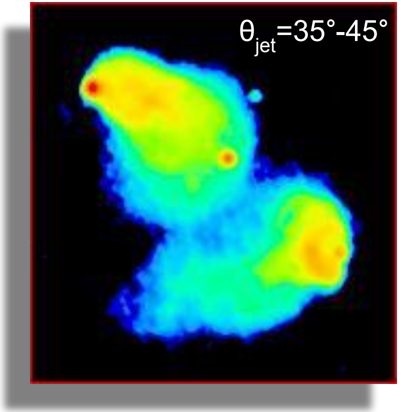
**LERG**
($L/L_{Edd} \lesssim 0.01$)

**L**=bolometric luminosity;

$\mathbf{L_{Edd}}$=Eddington luminosity= $(4\pi G m_p c/\boldsymbol{\sigma}_T)M_{BH} = 3.3 \times 10^4 M_{BH}$ (Heckman & Best 2014)

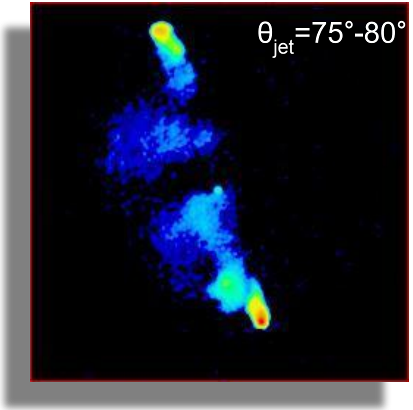
# The sources

## 3C 382




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

## 3C 33




- $z=0.061$
- FR II
- Narrow Line Radio Galaxy
- HERG
- $M_{BH}=5.3 \times 10^8 M_{sun}$ (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

Enter your search term



## TUTORIALS

Chandra tutorial (C. Vignali)

XMM-Newton tutorial (E. Torresi)

Commands for XMM data reduction

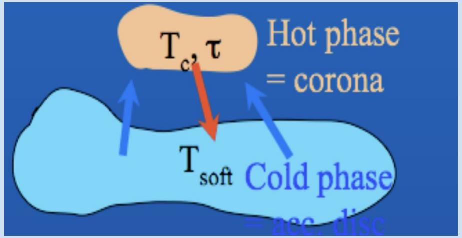
XSPEC TUTORIAL (C. Vignali)

# Thermal Comptonization Spectrum: the Continuum

cut-off power law

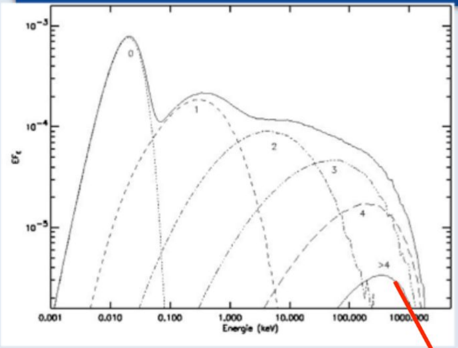
$$F_E \propto E^{-\Gamma(kT,\tau)} \exp\left(-\frac{E}{E_c(kT,\tau)}\right)$$

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



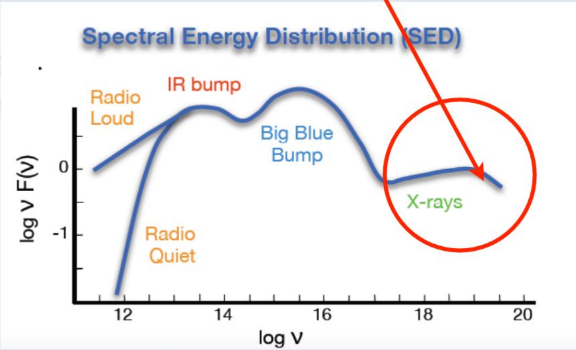

$$\Gamma(\tau, kT)$$

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



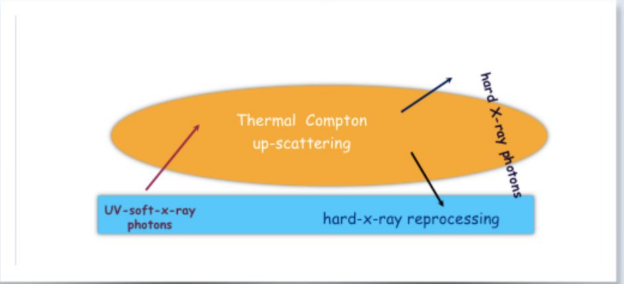

$$E_c \simeq kT$$

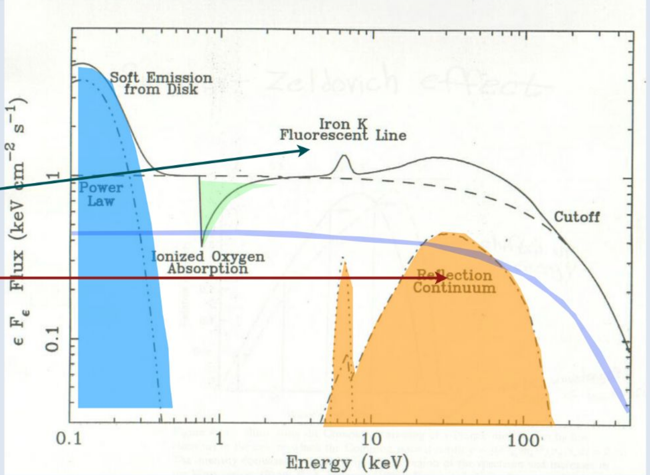
As photons approach the electron thermal energy, they no longer gain energy from scattering, and a sharp rollover is expected in the spectrum.
The observed high energy spectral cutoff yields information about the temperature of the underlying electron distribution.




Haardt & Maraschi 1991

# Reprocessed features




- Thermal Comptonization
- Hard X-ray reprocessing

Iron line

Compton hump

George & Fabian 1991

Lightman & White 1988

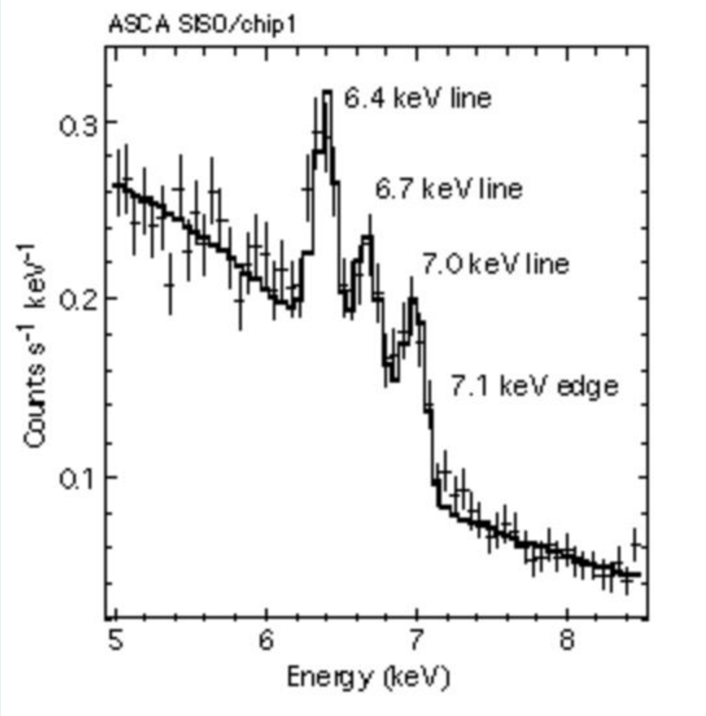
# Iron line & Reflection

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

- **6.4 keV** → neutral or weakly ionized **FeKα**
- **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 keV** → narrow line from distant material (it can be fixed also =0)
    - **$\sigma \gtrsim$ 0.1–0.3 keV** → broader line (higher velocities)

**3. Norm – Line normalization**

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

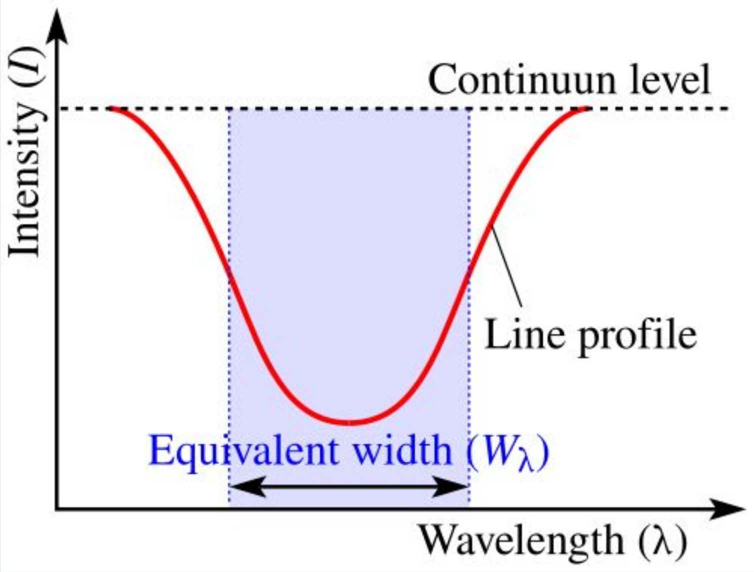
# Equivalent width

**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 FeKα Line

## 1. From line width to velocity

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

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

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:

$$v^2 \simeq GM_{BH}/R$$

So the emission radius is:

$$R \simeq GM_{BH}/v^2 \quad [\mathrm{cm}]$$

see also [Eracleous et al. (1996)]

# 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:

  $N_H$ [$cm^{-2}$]

- 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, $H_2$, 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

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

Mass accretion rate in Eddington units

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

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

$$\dot{m} \propto \frac{L_X}{L_{\rm Edd}}.$$


ENJOY!