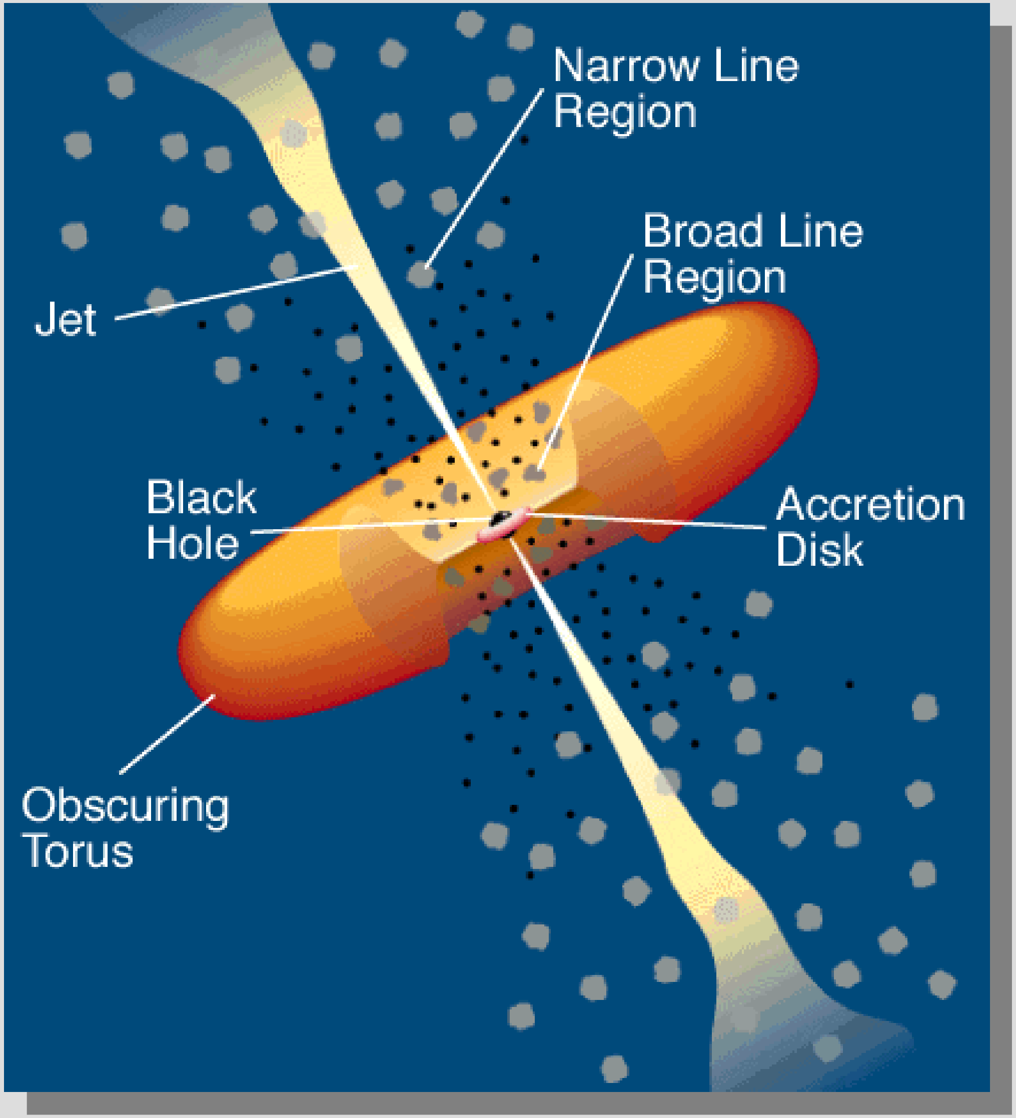
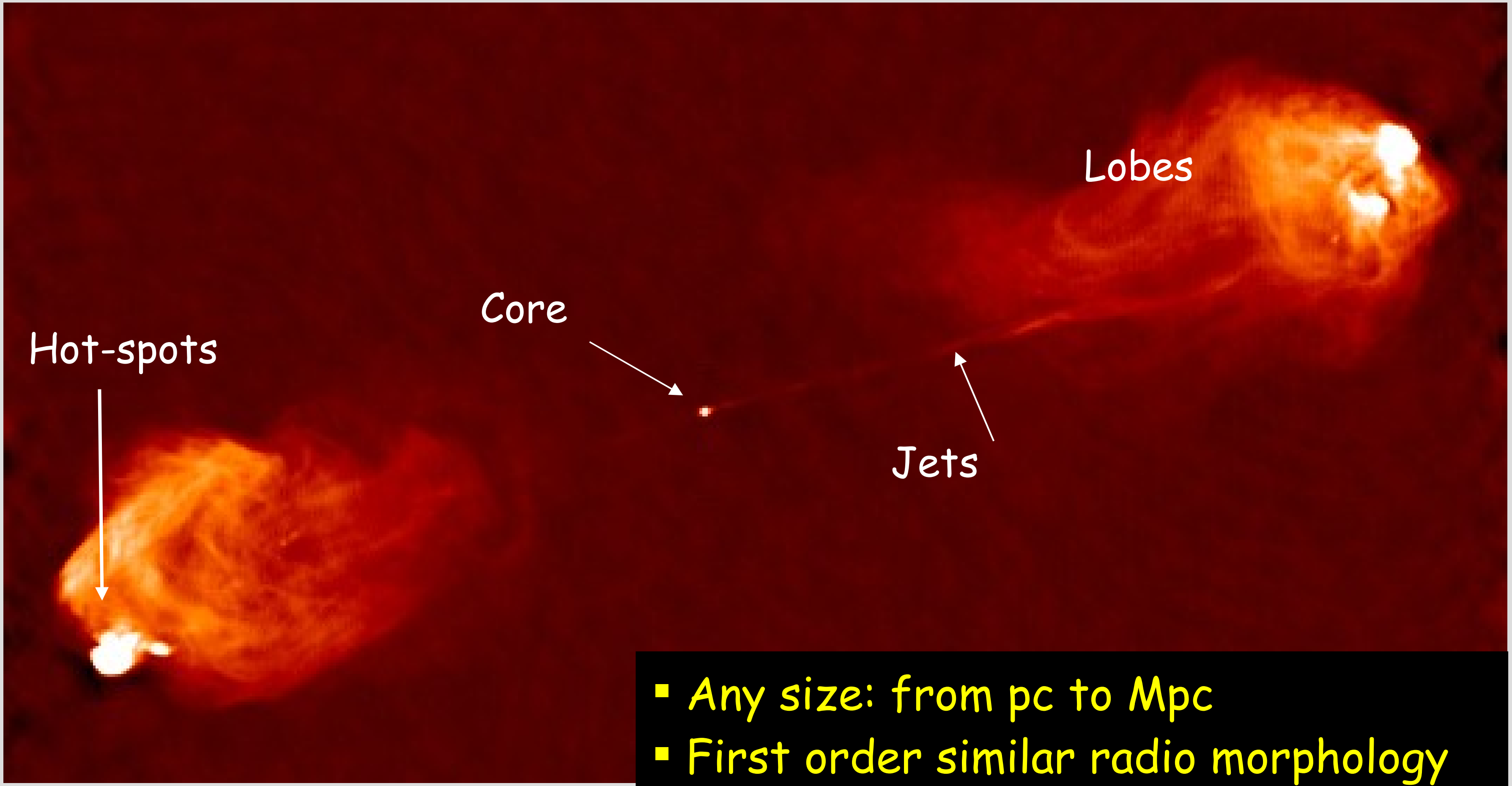
Introduction Active Galactic Nuclei

Lecture -8- Radio Galaxies



A prototypical radio galaxy



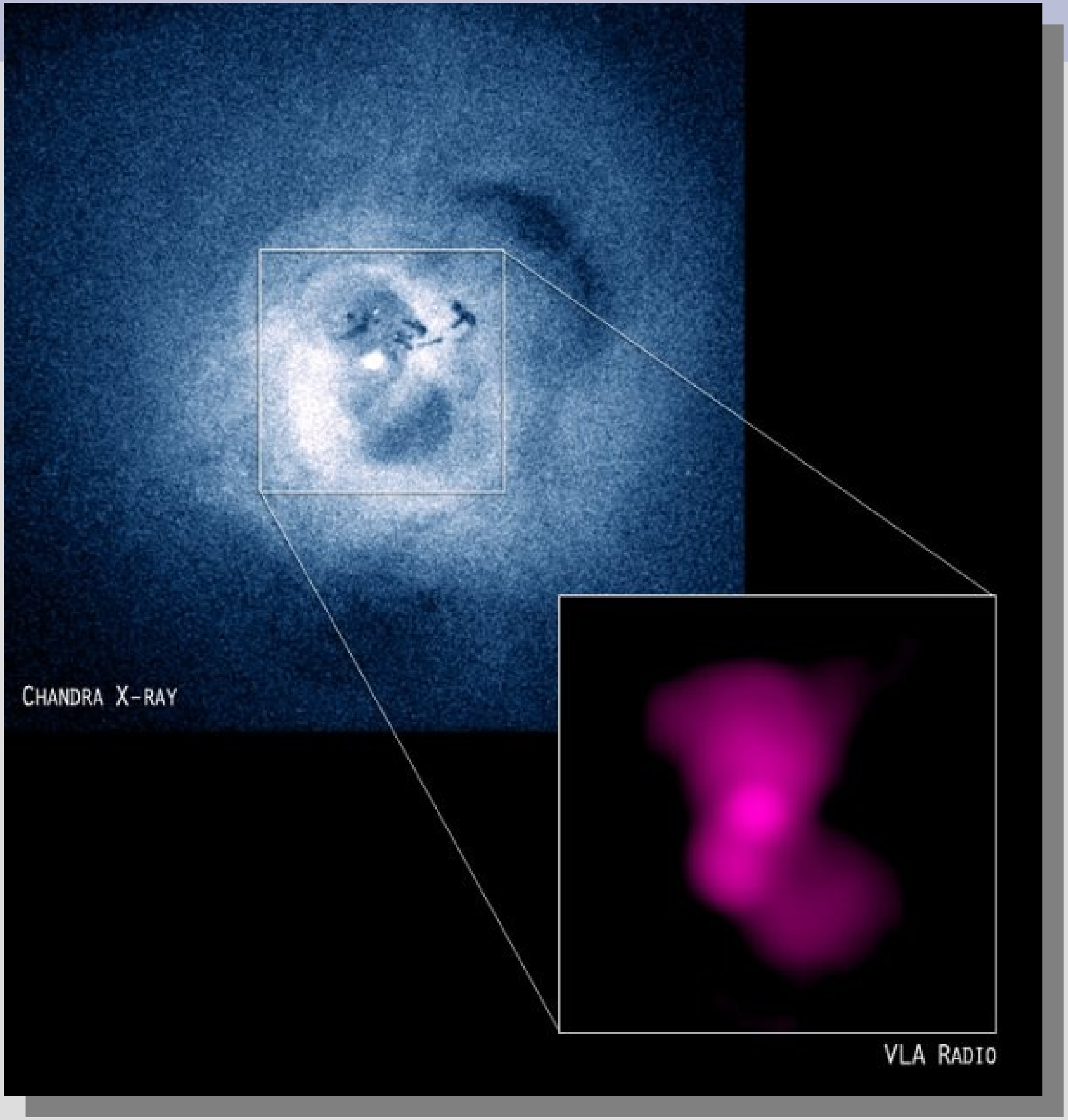
- Any size: from pc to Mpc
- First order similar radio morphology

  (but differences depending on radio power, optical luminosity & orientation)
- Typical radio power 10^{23} to 10^{28} W/Hz

Why study radio-loud AGN?

- Comparison of radio-loud AGN and optical AGN samples => investigate origin of radio-loudness
- Some radio and soft X-ray selected AGN show little or no line emission => include AGN missed by emission-line selection in such sureys
- Radio-loud activity provides an efficient means of feeding AGN energy directly back into environment (cf. sound waves in Perseus cluster, from Fabian et al) => role of AGN feedback

Why study radio-loud AGN?



Feedback of radio-loud AGN into the surrounding IGM (seen through X-ray here).

Fabian et al.

Why study radio-loud AGN?

Radio galaxies & radio-loud quasars: the most powerful radio sources

(Usually) extended (or very extended!) radio emission
with common characteristics (core-jets-lobes)
Typically hosted by an elliptical (early-type) galaxy

Amazing discovery when they were identified with
extragalactic, i.e. far away, objects

⇩

Unexpectedly high amount of energy involved!

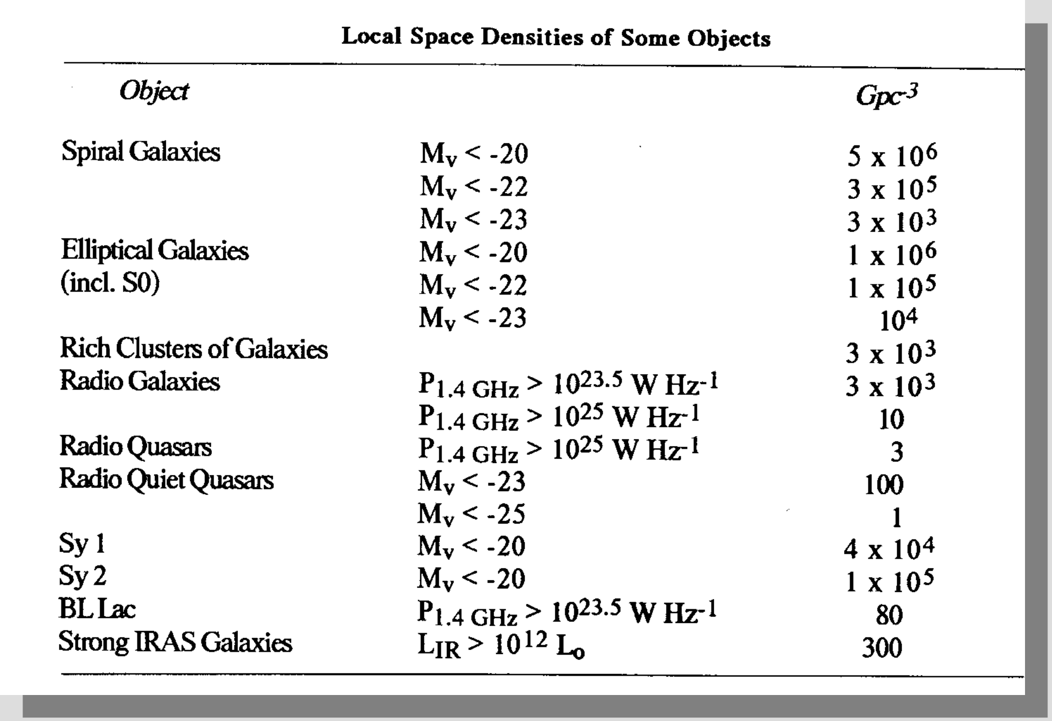
Nevertheless, the radio contribute only to a minor
fraction of the energy actually released by these AGNs.
(ratio between radio and optical luminosity ~10^{-4})

Why study radio-loud AGN?

They show most of the phenomena typical of AGNs
(e.g. optical lines, X-ray emission etc.)
→ very interesting objects in (almost) all wavebands

In addition they have
<u>spectacular radio morphologies</u>

But they are quite rare!



Local Space Densities of Some Objects

Object		*Gpc^{-3}*
Spiral Galaxies	$M_V < -20$	5×10^6
	$M_V < -22$	3×10^5
	$M_V < -23$	3×10^3
Elliptical Galaxies (incl. S0)	$M_V < -20$	1×10^6
	$M_V < -22$	1×10^5
	$M_V < -23$	10^4
Rich Clusters of Galaxies		3×10^3
Radio Galaxies	$P_{1.4\ GHz} > 10^{23.5}$ W Hz^{-1}	3×10^3
	$P_{1.4\ GHz} > 10^{25}$ W Hz^{-1}	10
Radio Quasars	$P_{1.4\ GHz} > 10^{25}$ W Hz^{-1}	3
Radio Quiet Quasars	$M_V < -23$	100
	$M_V < -25$	1
Sy 1	$M_V < -20$	4×10^4
Sy 2	$M_V < -20$	1×10^5
BL Lac	$P_{1.4\ GHz} > 10^{23.5}$ W Hz^{-1}	80
Strong IRAS Galaxies	$L_{IR} > 10^{12}$ L_o	300

How to find RGs?

Because of the variety of AGNs, there is also a variety of techniques to find them
(e.g. blue colours, strong emission lines etc.).

↓

Here we focus on the way radio galaxies have been found: radio surveys

Some Radio surveys

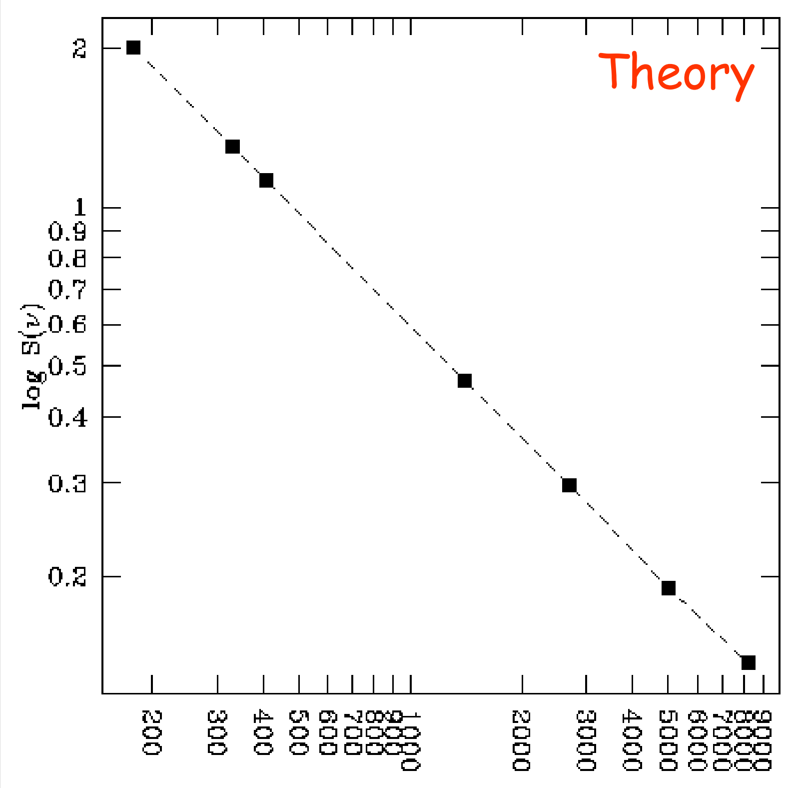
Start: 3CR (Cambridge Telescope) → 328 sources with $\delta > -5^{o}$
flux above 9 Jy @ 178 MHz
(1 Jy= 10^{-26} W m^{-2} Hz^{-1})

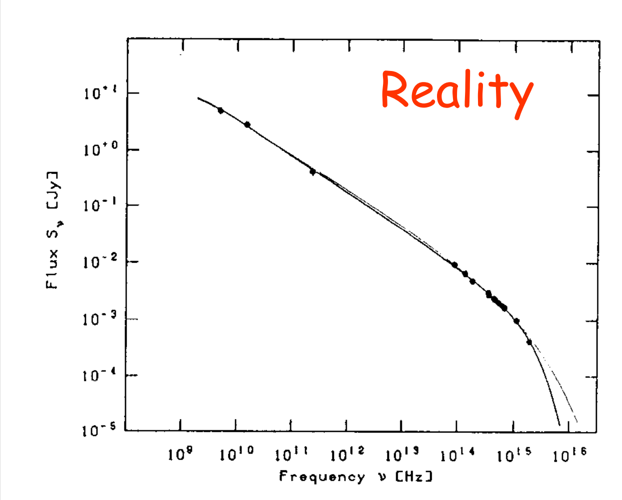
4C	**2Jy**	**178 MHz**	**Cambridge (+5,6,7C)**
PKS	**~3Jy**	**408 MHz**	**Parkes**
			Molonglo
B2	**0.25**	**408 MHz**	**Bologna (+B3)**
NRAO	**0.8Jy**	**1.4-5GHz**	**NRAO**
PKS	**0.7Jy**	**2.7 GHz**	**Parkes**
NVSS	**2.5 mJy (45” res.)**	**1.4 GHz**	**NRAO VLA Sky Survey**
FIRST	**1mJy (~5” res)**	**1.4 GHz**	**Faint Images Radio Sky at Twenty centimeters**
WENSS		**300 MHz**	WSRT

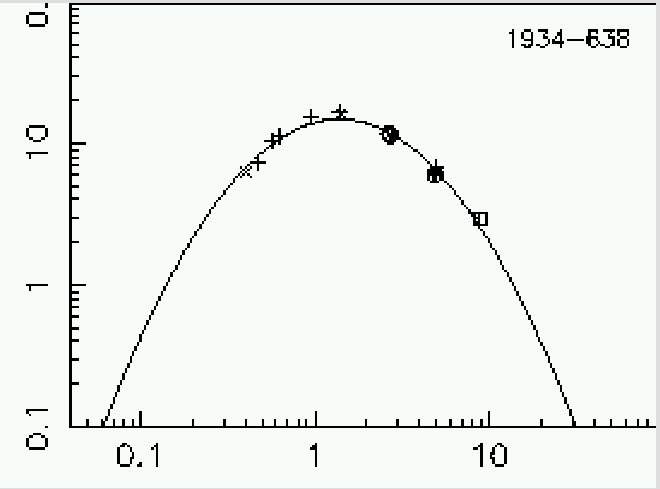
Spectral Index/Power-law Energy Distribution

Deviations from a constant spectral index

1. Energy loss
2. Self-absorption in the relativistic electrons gas
3. Absorption from ionized gas between us and the source (free-free absorption) -> torus!







Energy loss

The relativistic electrons can loose energy because of a number of process (adiabatic expansion of the source, synchrotron emission, inverse-Compton etc.).

→ the characteristics of the radio source and in particular the energy distribution *N(E)* (and therefore the spectrum of the emitted radiation) tend to modify with time.

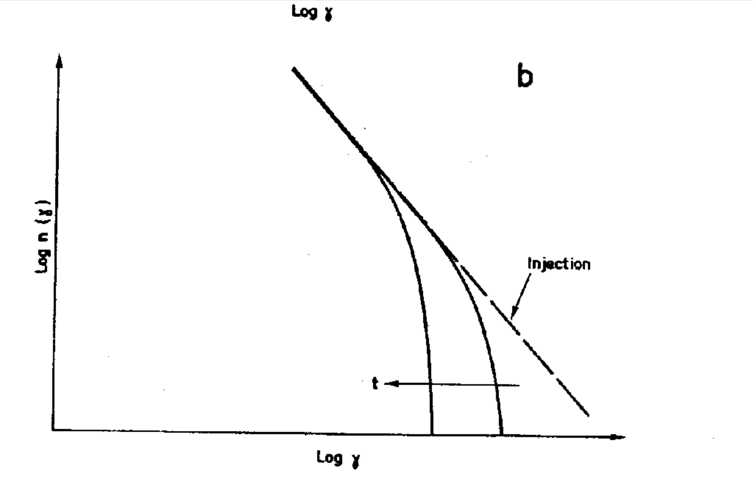
Adiabatic expansion: strong decrease in luminosity but the spectrum is unchanged

Energy loss through radiation:
characteristic electron half-life time
(time for energy to half)

$$E_b = \frac{1.7\cdot 10^8}{B^2 t_b}$$

(Special case assuming *p=2*)

After a time t_b only the particle with $E_0<E^*$ still survive while those with $E_0>E^*$ have lost their energy.

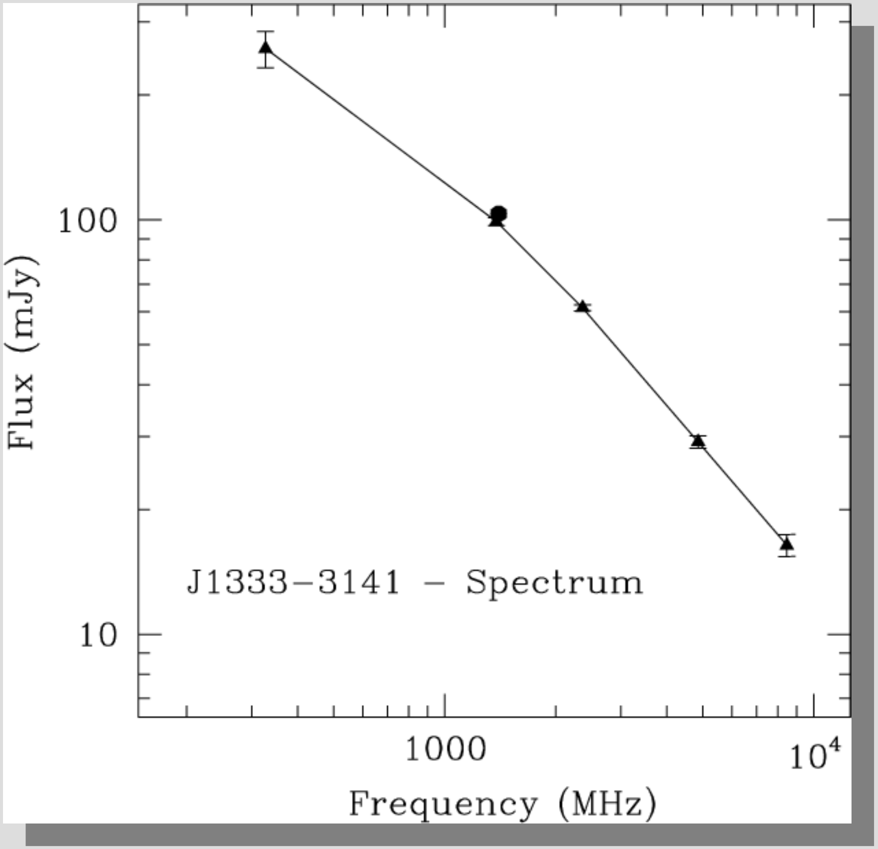


For $\nu < \nu_{break}$ the spectral index remains constant ($\alpha = \alpha_0$)

For $\nu > \nu_{break}$ → $\nu_{break} \sim B^{-3}\, t_{yr}^{-2}$
→ $\alpha = (\alpha_0 - 1/2)$

Single burst
Continuous injection

Energy loss



- These energy lost affect mainly the large scale structures (e.g. lobes).
- Typical spectral index of the lobes → α = 0.7

$$t_b(Myr) = 1.6 \cdot 10^3 (B/\mu G)^{-3/2} (\nu_b/GHz)^{-1/2}$$

Typically 20-50 Myr for B=10μG, freq 8-1 GHz

Unless there is re-acceleration in some regions of the radio source!

Self-absorption in the relativistic electron gas

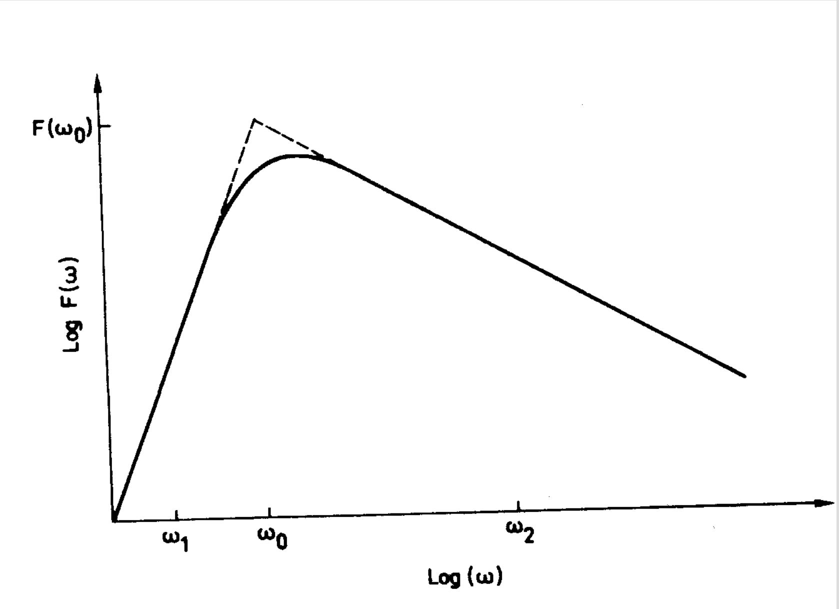
Optically thick case: the internal absorption from the electrons needs to be considered ⇨ the brightness temperature of the source is close to the kinetics temperature of the electrons.

The opacity is larger at lower frequency -> plasma opaque at low frequencies and transparent at high

$$\tau \gg 1 \qquad S(\nu) \propto \nu^{-5/2} B^{-1/2} d\Omega$$

Frequency corresponding to $\tau = 1$

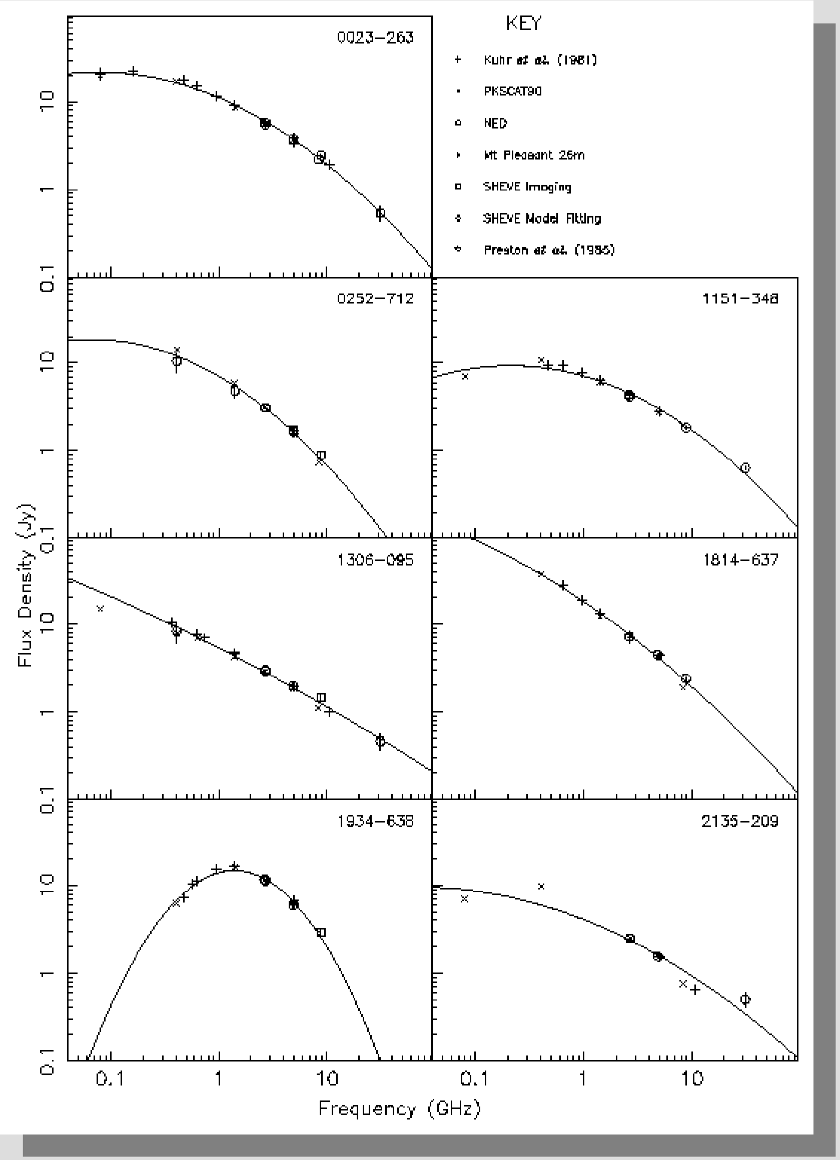
$$\nu_{max} \approx f(p) B^{1/5} S_m \theta^{-4/5} (1+z)^{1/5} GHz$$



Self-absorption in the relativistic electron gas

Affects mainly the central compact region or very small radio sources

Higher “turnover” frequency
⇒ smaller size of the emitting region.



Polarization

Characteristic of the synchrotron emission: the radiation is highly polarized.

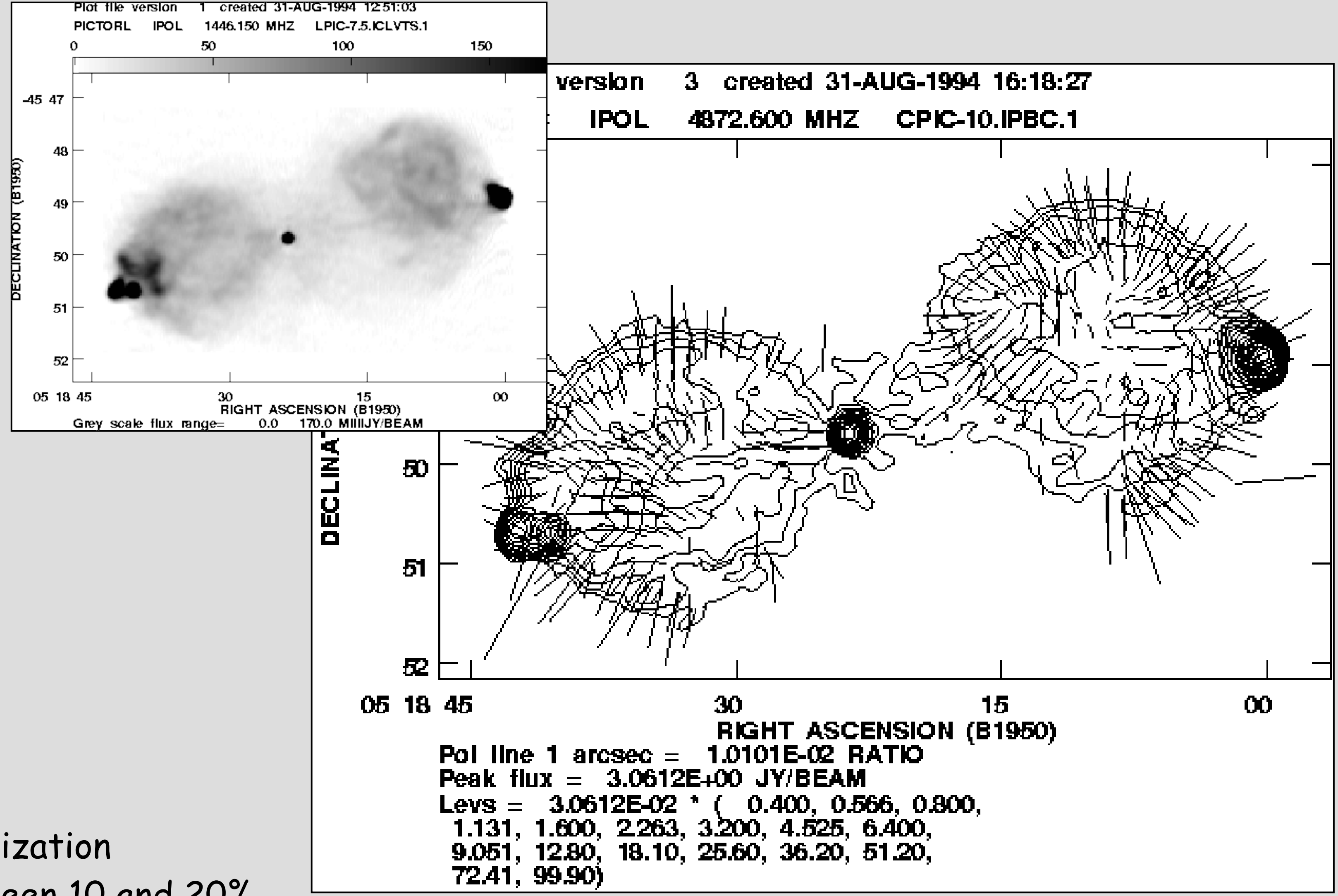
For an uniform magnetic field, the polarization of an ensemble of electrons is linear, perpendicular to the magnetic field and the fractional polarization is given by:

$$p=\frac{3p+3}{3p+7}\ percent$$ ➡ 0.7- 0.8 for 2<p<4

never!

Typical polarization from few to ~20% ➡ Tangled magnetic field

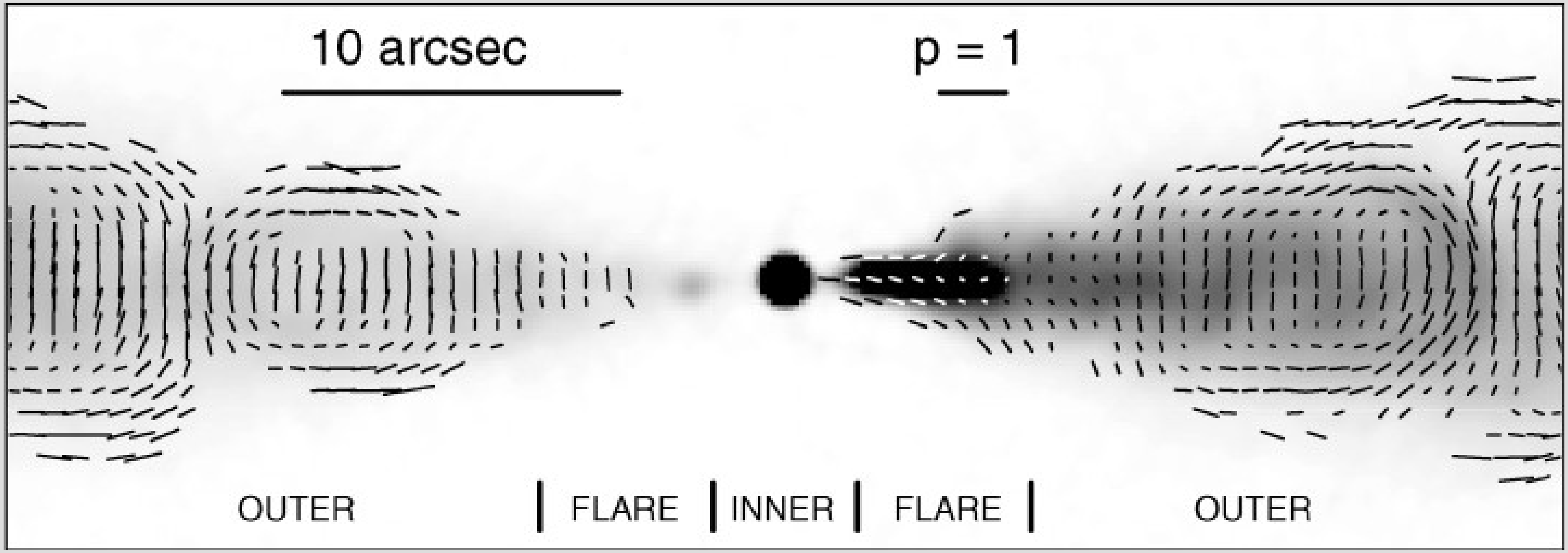
Polarization



Polarization
between 10 and 20%
(some peaks at ~40% around the edge of the lobes)

Polarization

Example of polarization in radio jets.



Faraday rotation

Travel through a *plasma+magnetic field* (that can be internal or external to the source) changes the polarization angle

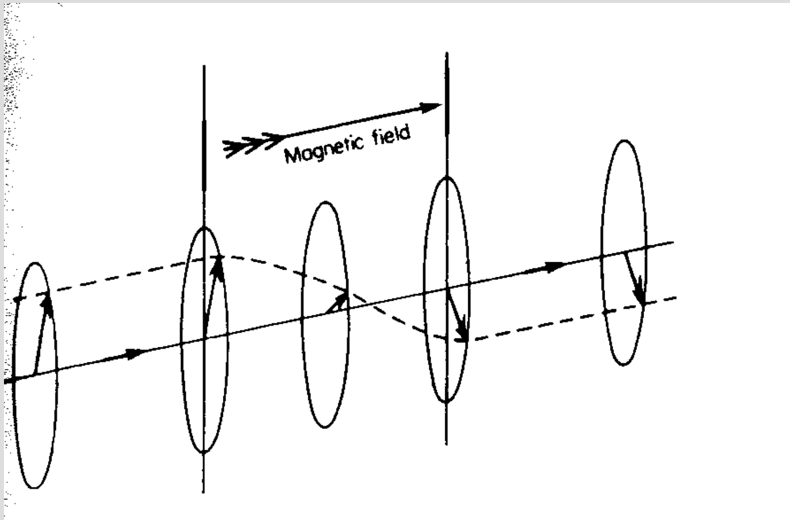
$$\Delta\theta = 2.6\cdot 10^{-17}\lambda^2 \boxed{\int n_e B\, dl}$$

N_e = electron density of the plasma
dl = depth
B = component of the magnetic field parallel to line of sight

Rotation measure (RM)

RM can be derived via observations at different wavelengths

- If the medium is in front of the radio source: no change in the fractional polarization
- If the medium is mix in the radio source: depolarization dependence on wavelength (if due to Faraday rotation)

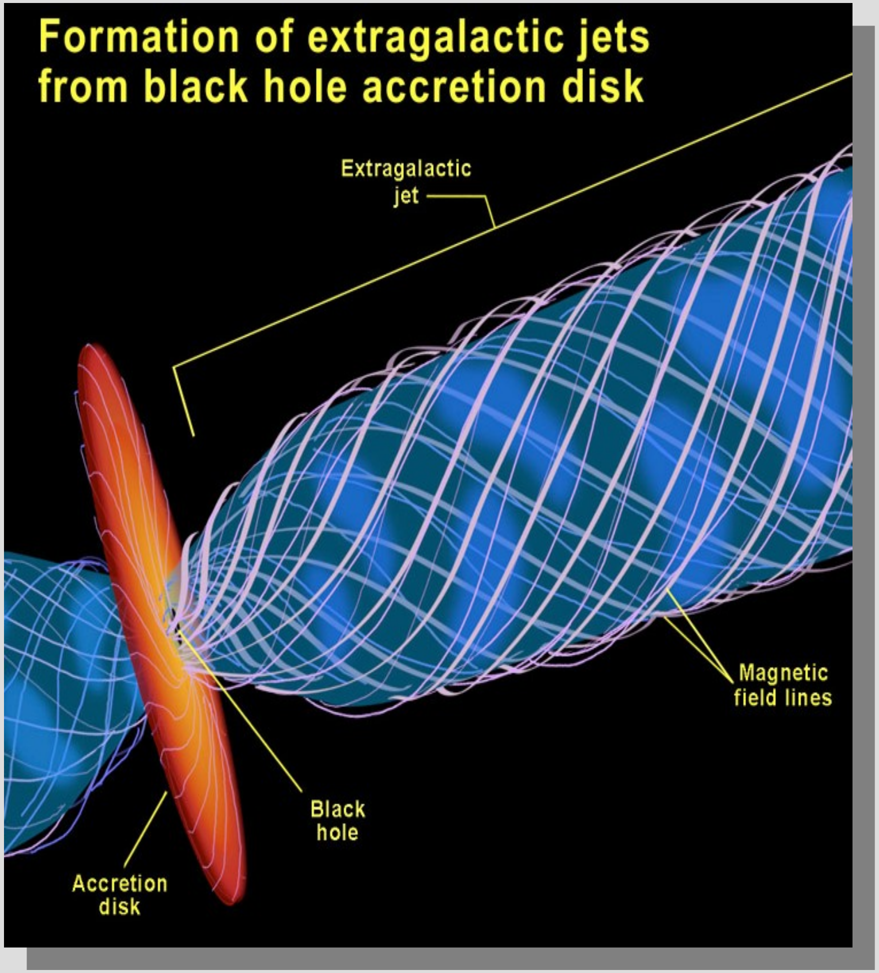


thermal electrons with density ~ 10^{-5} cm^{-3}

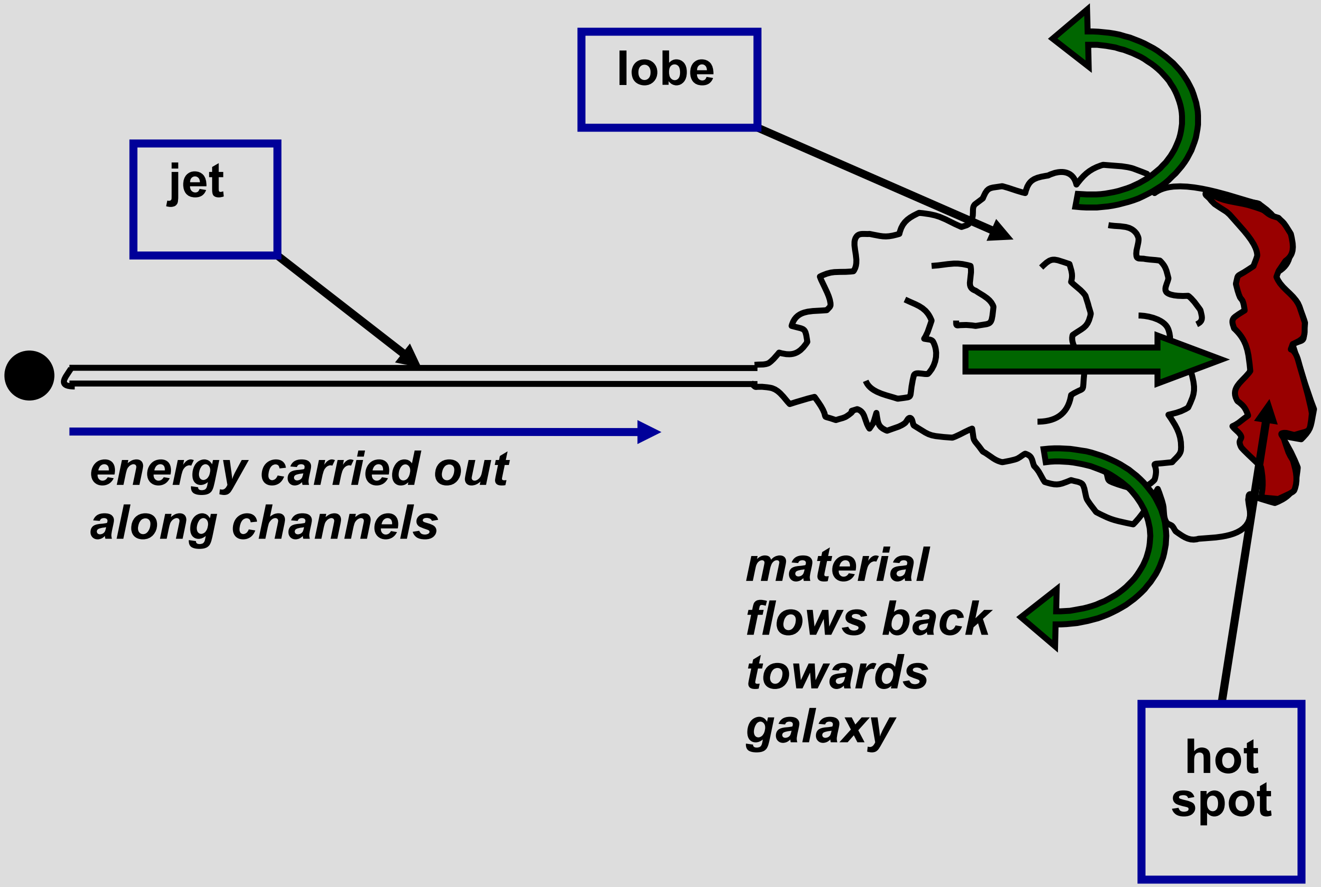
Depolarization happens also if the magnetic field is tangled on the scale of the beam of the observations

Jets

- Not well understood
- Emitted from axis of rotation
- Clues from Polarized light
- Acceleration of charged particles from strong magnetic fields and radiation pressure
- Synchrotron Radiation
  - Produces radiation at all wavelengths especially at Radio wavelengths
- Possible source of Ultra high energy cosmic rays and neutrinos



Jets: Focussed Streams of Ionized Gas



Shock waves in jets

Lifetimes short compared to extent of jets

=> additional acceleration required.

Most jet energy is ordered kinetic energy.

Gas flow in jet is supersonic; near hot spot gas decelerates suddenly

=> shock wave forms. Energy now in relativistic

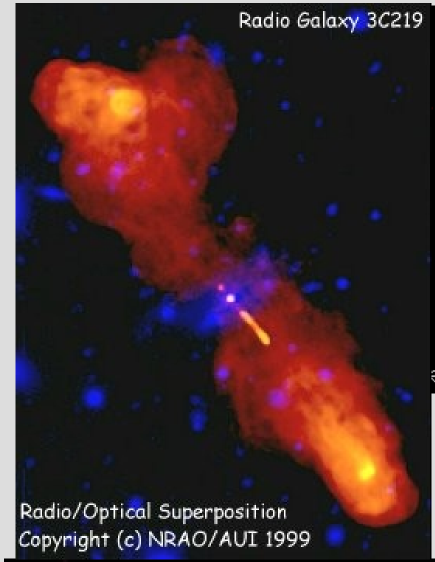
e- and mag field.

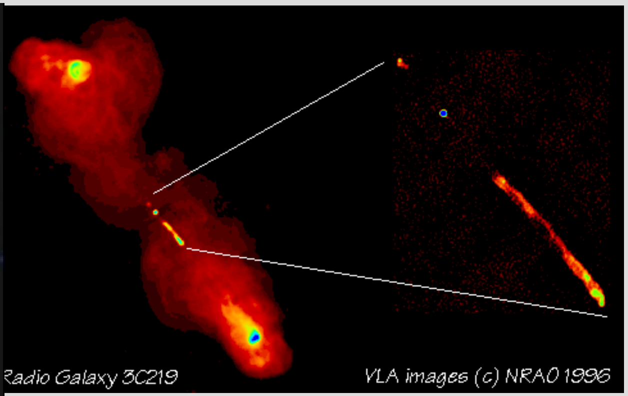
Different types of radio galaxies

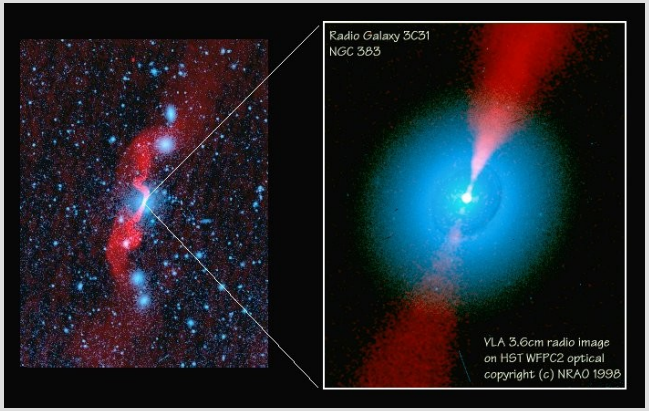
The morphology of a radio galaxy may depend on different parameters:

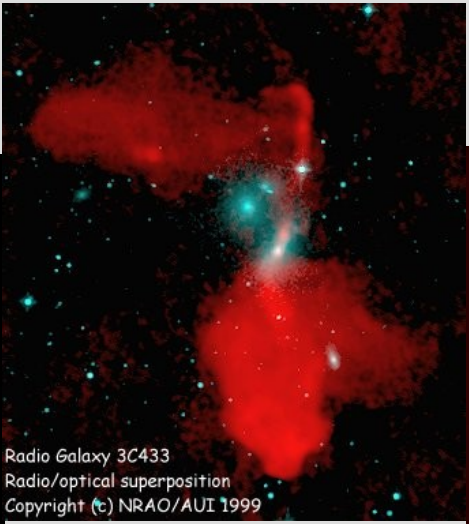
- radio power (related to the power of the AGN?)
- orientation of the radio emission
- intrinsic differences in the (nuclear regions of) host galaxy
- environment

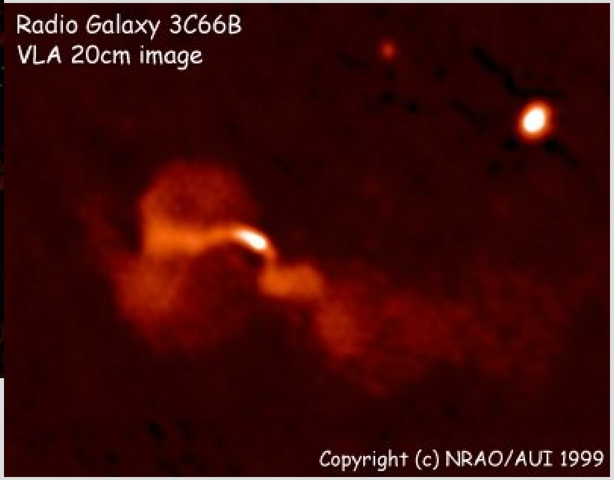
Different types of radio galaxies

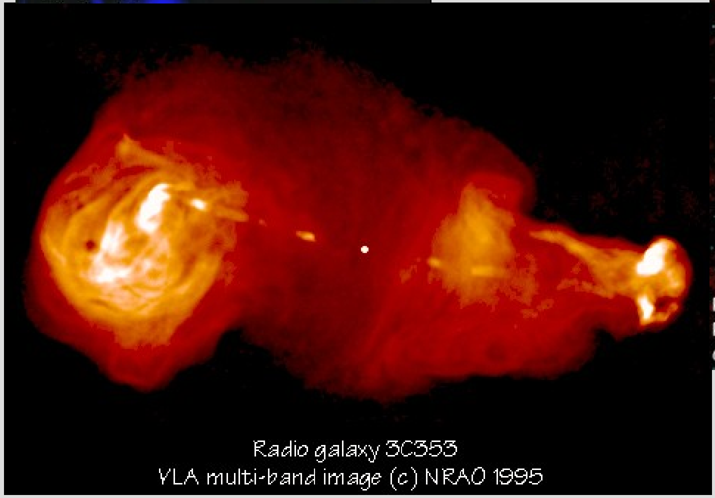




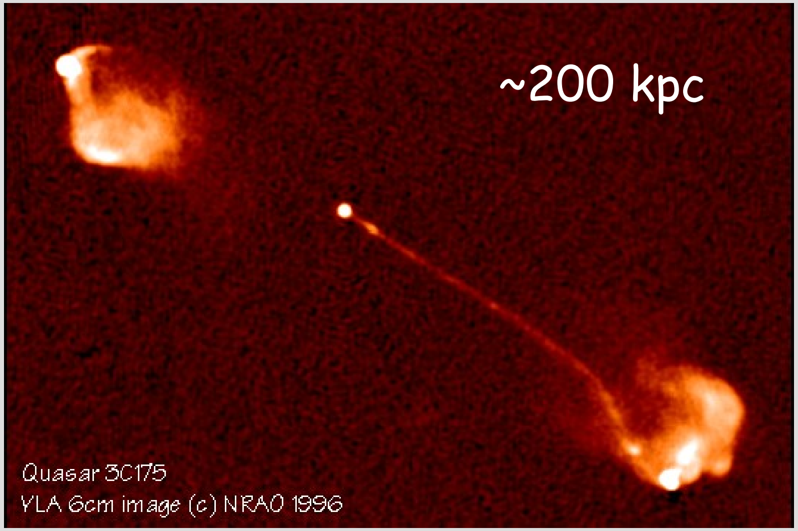




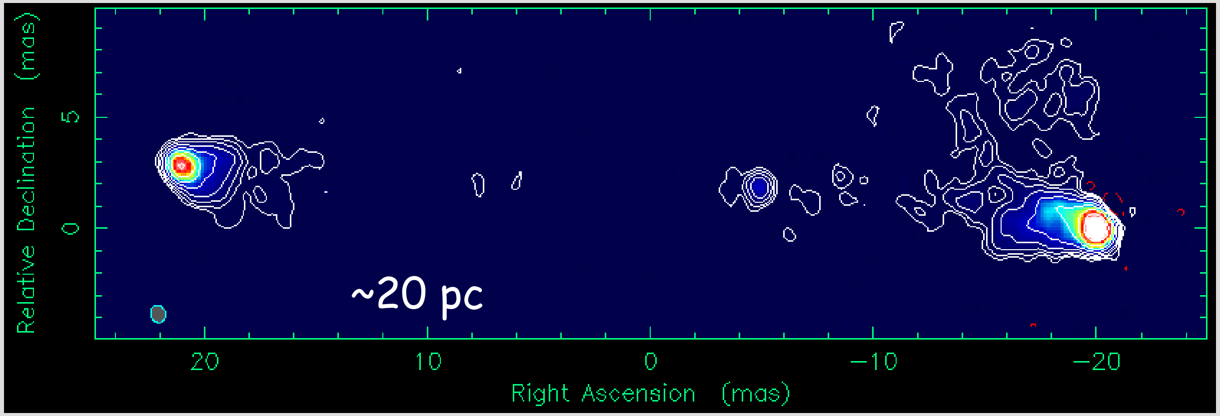




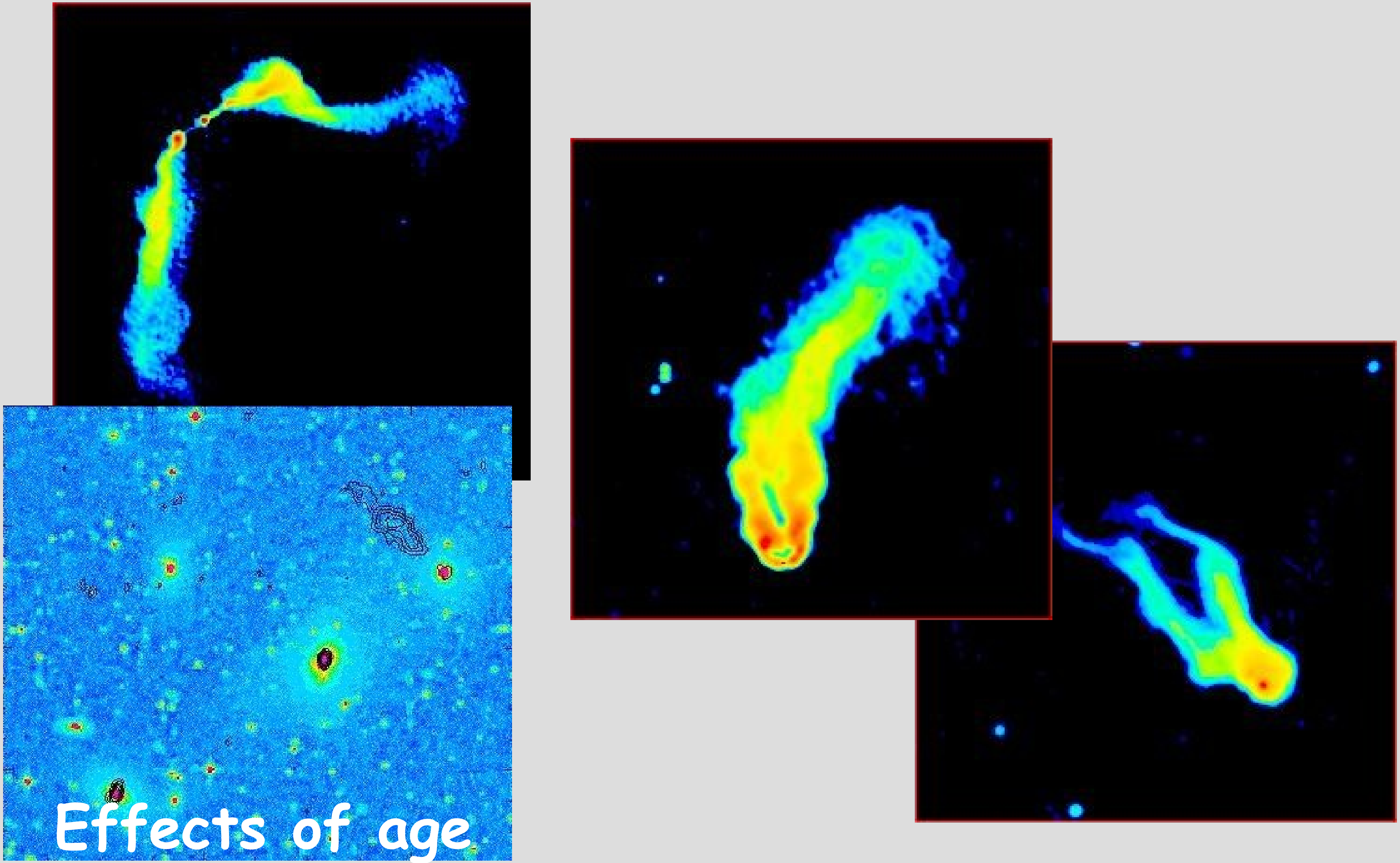
Different types of radio galaxies



The morphology does not depend on size!

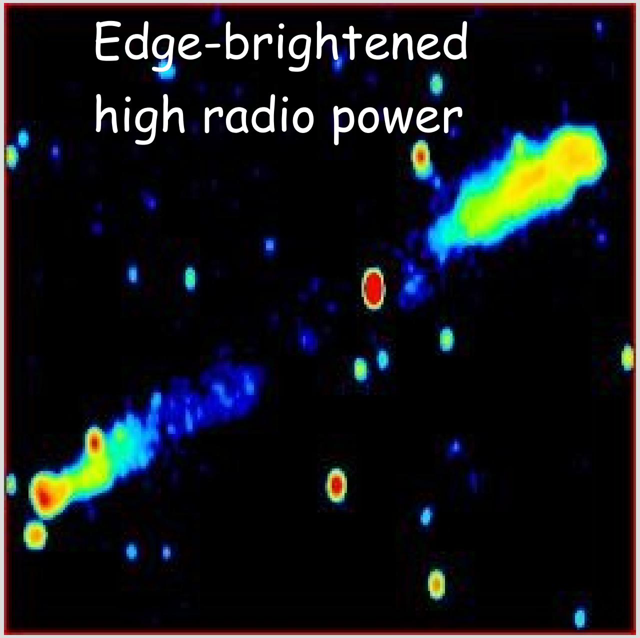


Effects of the interaction with the environment

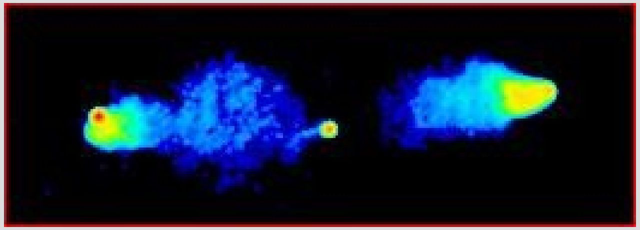


Effects of age

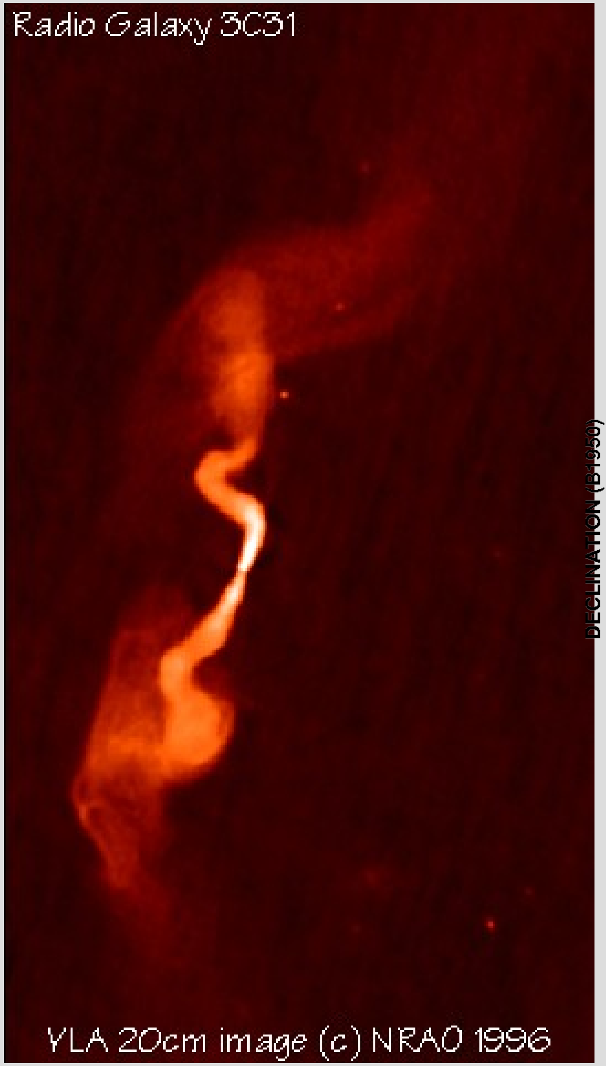
Two main types of RGs

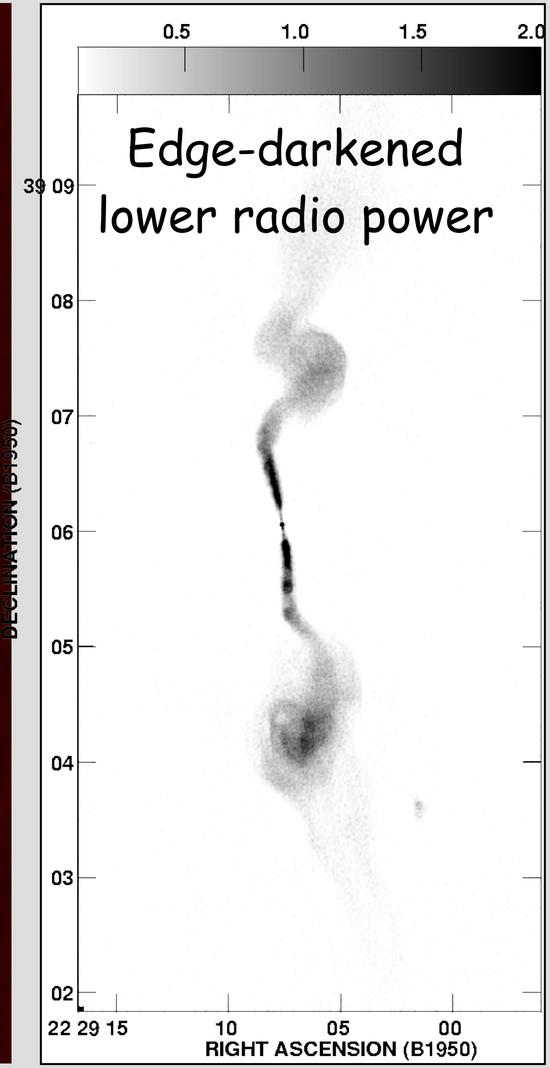


Edge-brightened
high radio power



Fanaroff-Riley type I and II





Edge-darkened
lower radio power

Two main types of RGs

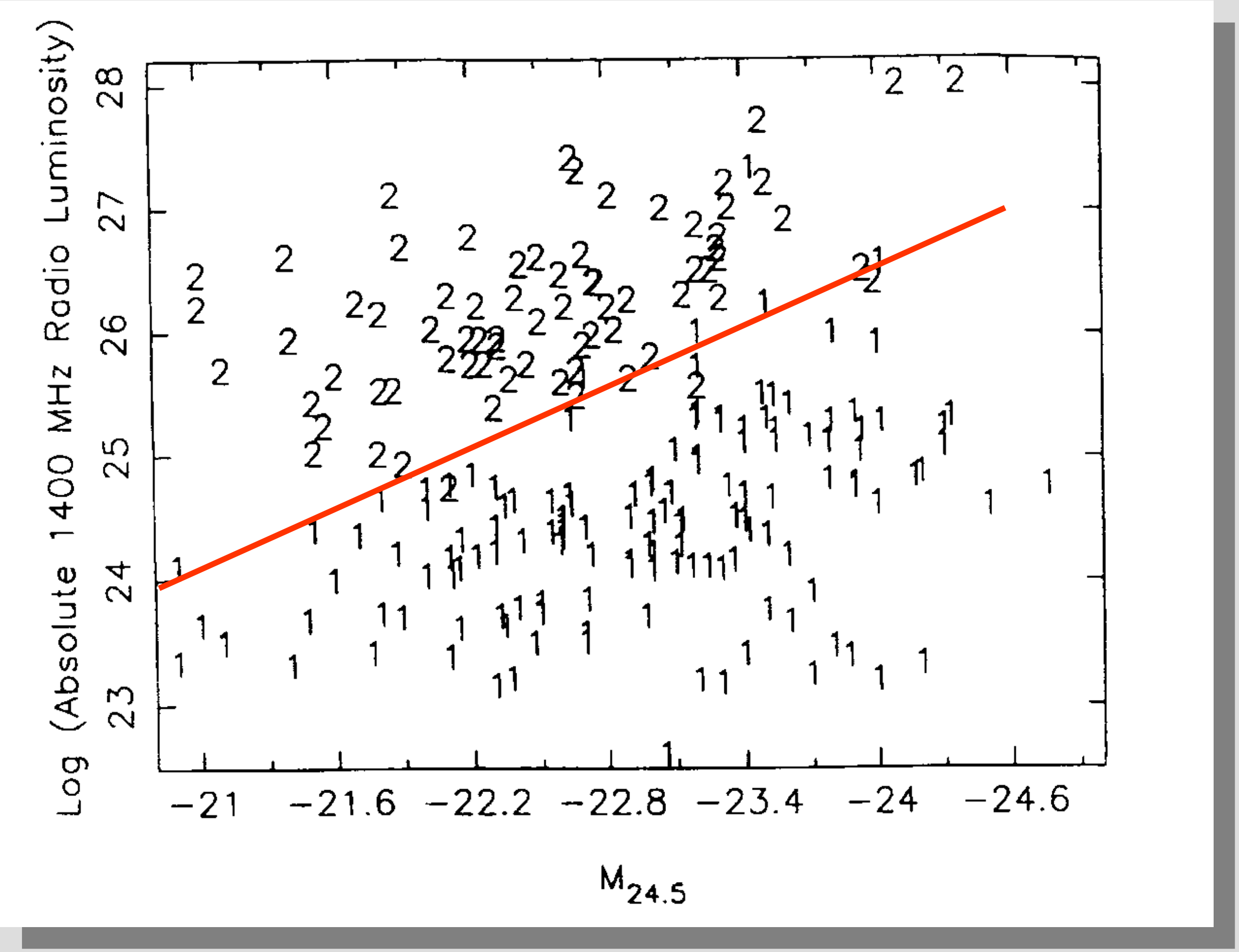
	FRI	**FRII**
Jets	Large opening angle low Mach number	Very collimated high Mach number
Magnetic Field	Perpendicular to the jet	Parallel to the jet
Hot-spot	--	Yes
Lobes	Plume-like	Backflow
Spectral index in the Lobes	Steeper away from the nucleus	Steeper toward the nucleus (from hot-spots)

- The reason(s) for these differences is not completely clear; likely related to the nuclear regions (BH?).
- Differences are seen also in other wavebands.
- Possibly also environment: lower-power radio galaxies tend to be in clusters

Two main types of RGs: Optical/Radio

Strong separation in M_B-F_{1400} space.

FR-II are much brighter in the radio for a given optical luminosity.



What makes the difference?

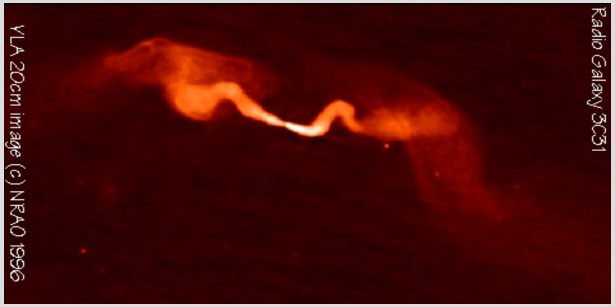
Well known <u>dichotomy</u>:
low *vs* high power radio galaxies

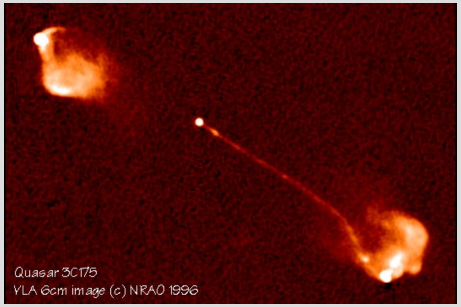
Differences not only in the radio

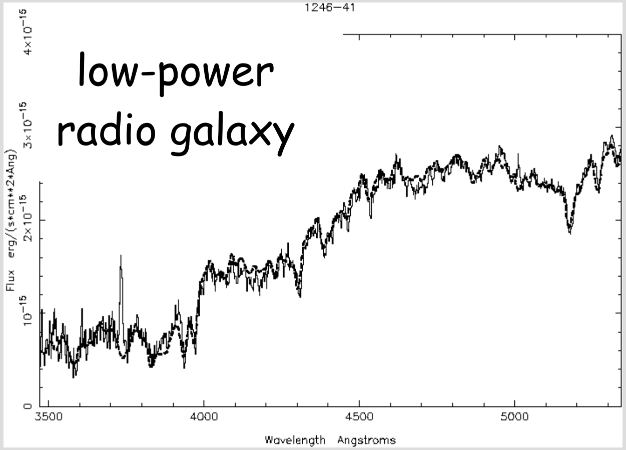
WHY?

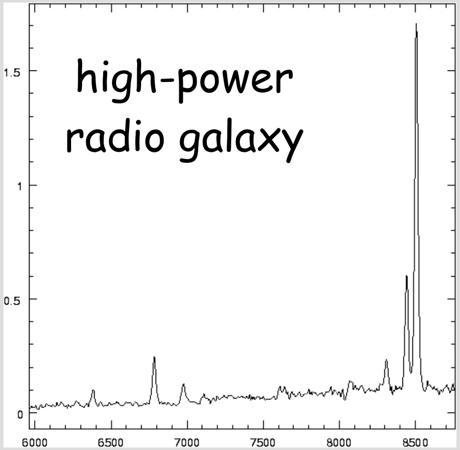
Intrinsic differences in the nuclear regions?

Accretion occurring at low rate and/or radiative efficiency?
No thick tori?






low-power radio galaxy


high-power radio galaxy

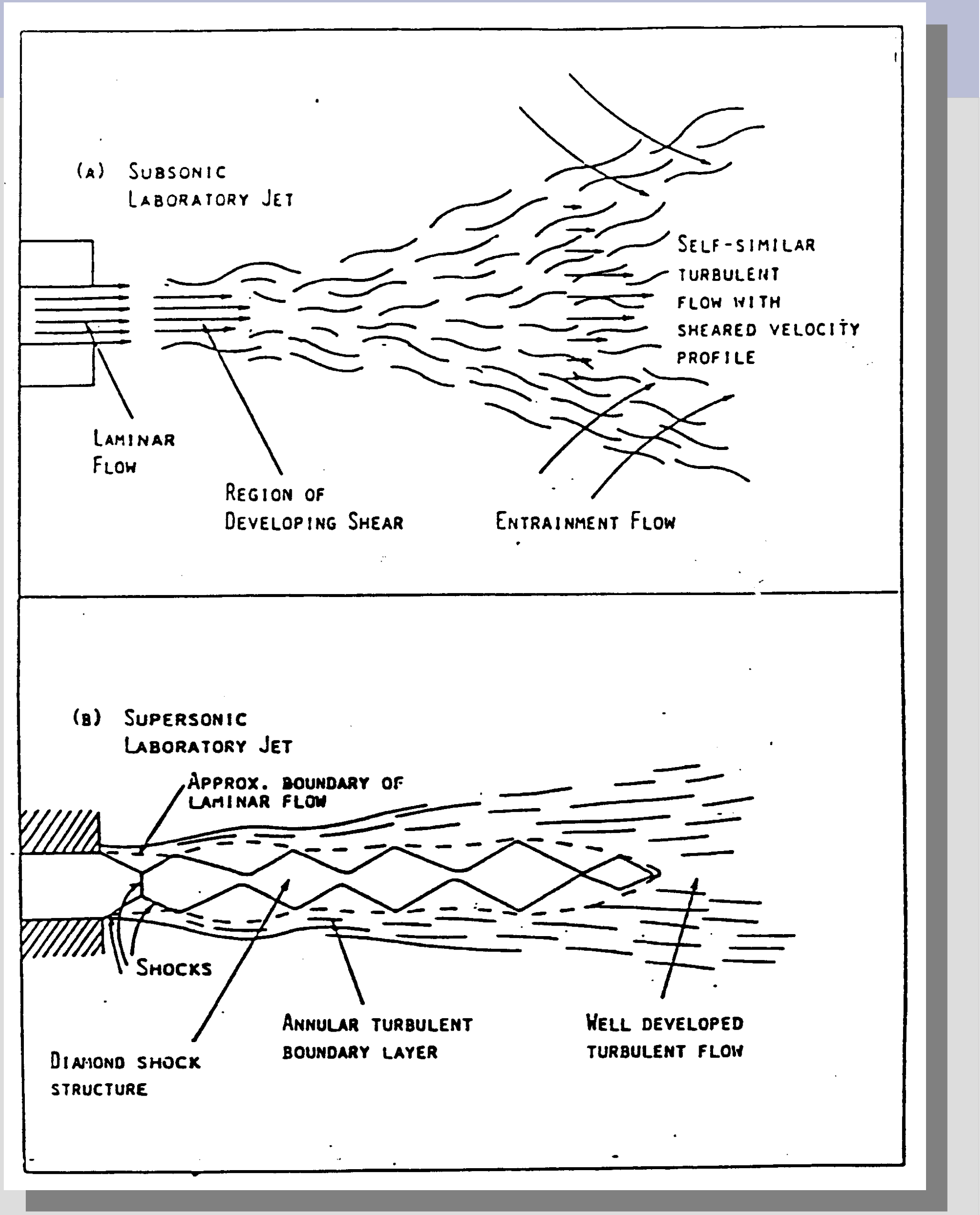
Two main types of RGs: Jets

Two flavors also for the jets:

- supersonic and highly collimated
- subsonic with entrainment

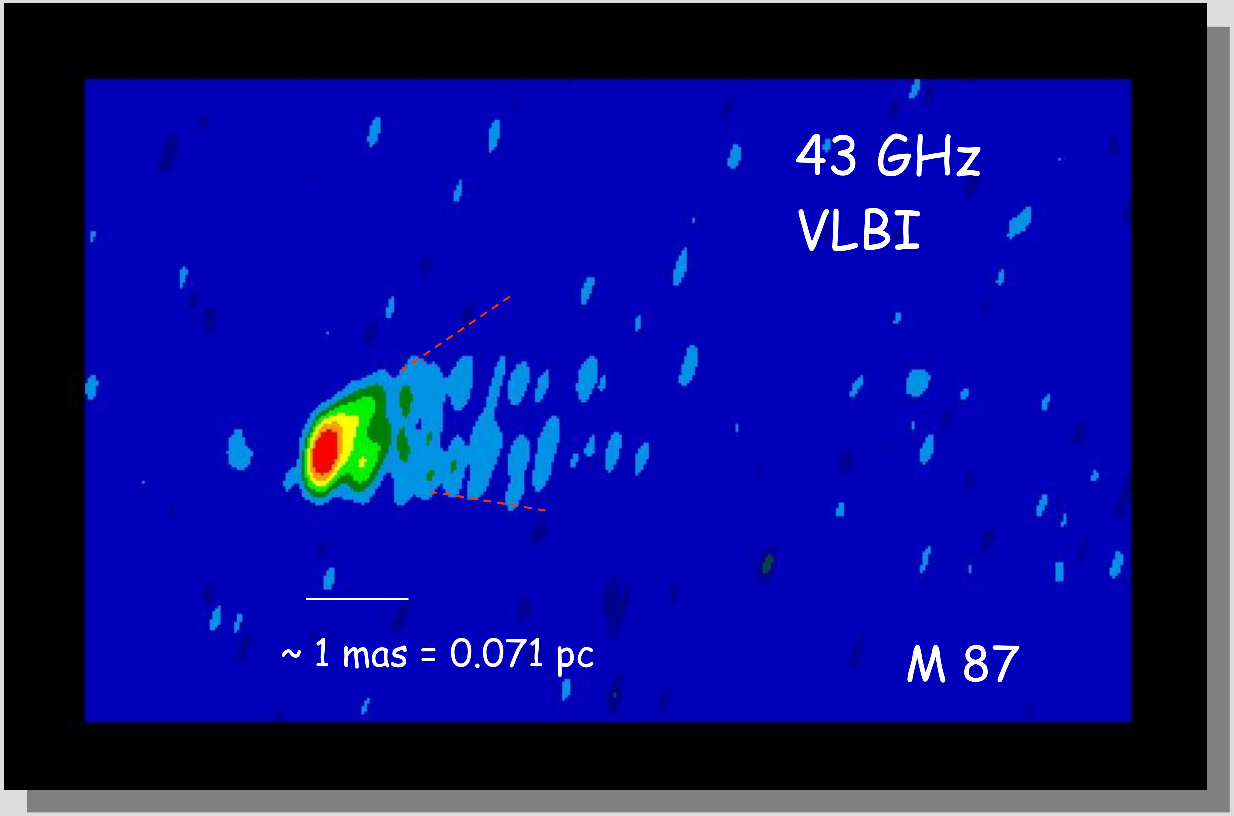
↓

This can explain the presence of hot-spots and the collimation of the jets.



Jets Collimation

Going very close to the BH to see how the collimation of the jet works.



rapid broadening of the jet opening angle as the core is approached on scale below 1 mas (0.1 pc).

The jet does not seem to reach a complete collimation until a distance of many tens of Schwarzschild radii (escape velocity = *c*)

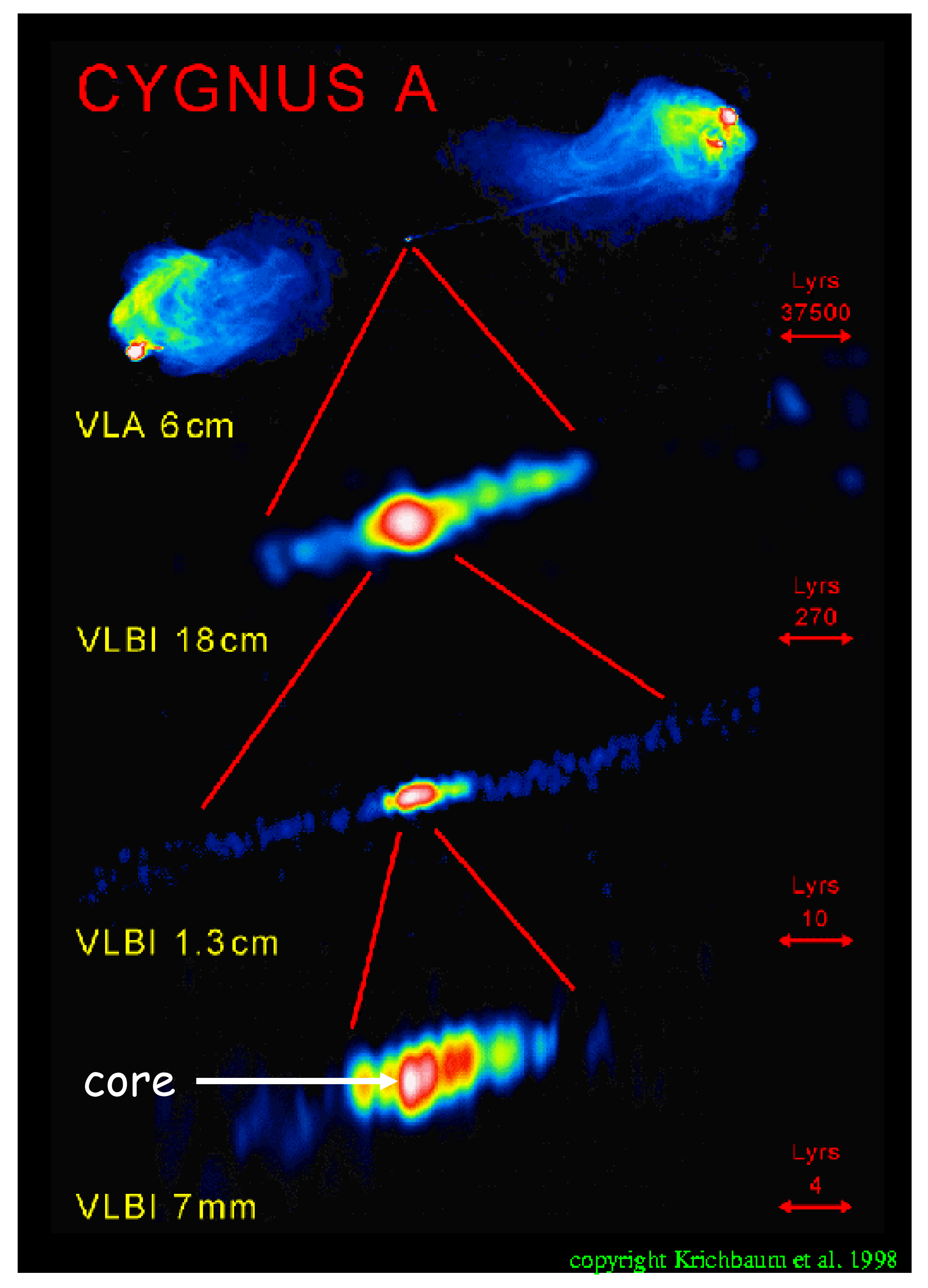
Jet emanating from the accretion disk, not yet collimated

Jets

Often the radio emission is more symmetric on the large scale and <u>asymmetric on the small scale</u>

The core is defined based on the spectral index: flat ($\alpha \sim 0$)

[to find which component is the radio core is not always easy: free-free absorption can complicate the story!]



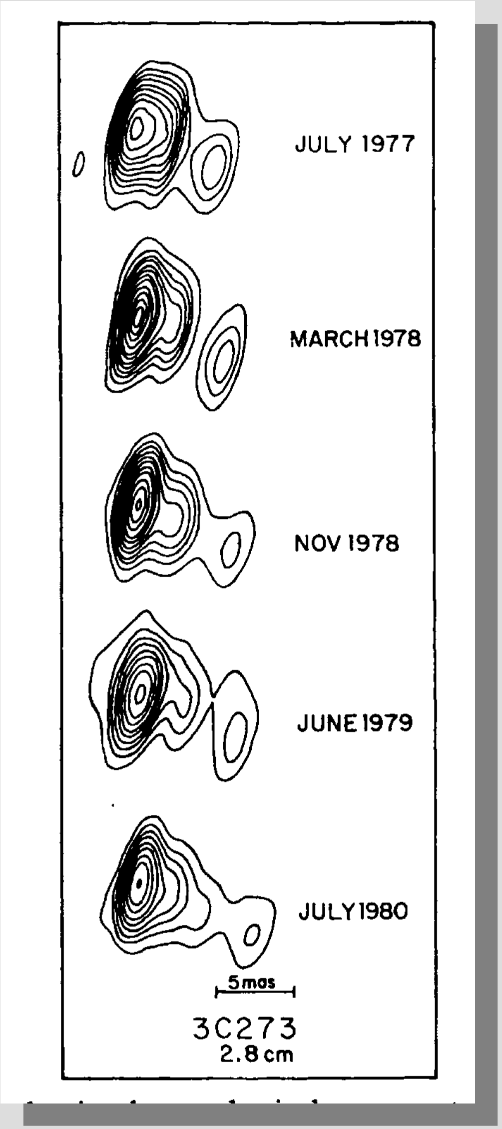
copyright Krichbaum et al. 1998

Superluminal motions

Discovered (around 1970-80) in powerful radio galaxies and quasars:

- apparent change (on the VLBI scale) in the structure of some sources during a period of few months.
- the velocities appear superluminal
- the components of the velocities and direction remain constant
- there are no observed “contractions”
- a flux outburst seems to be associated with the appearance of new components

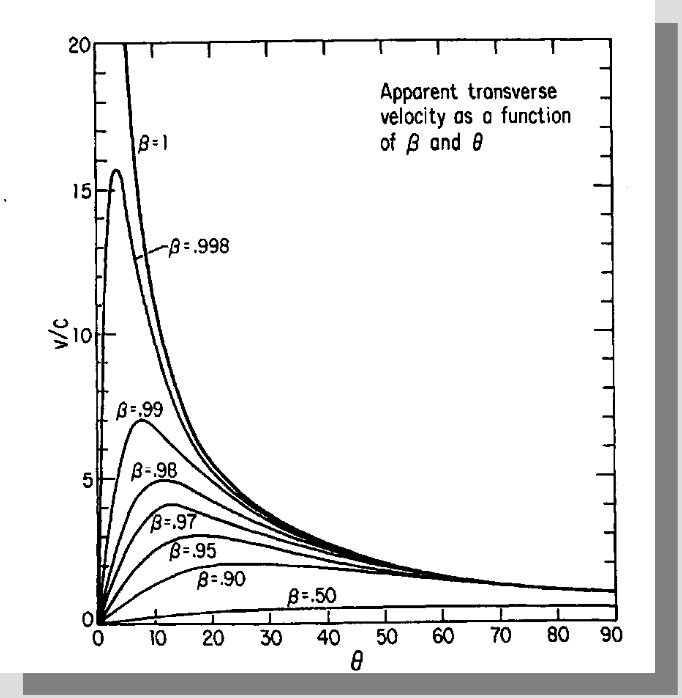
Case of 3C273 (quasar)
apparent velocity ~10c

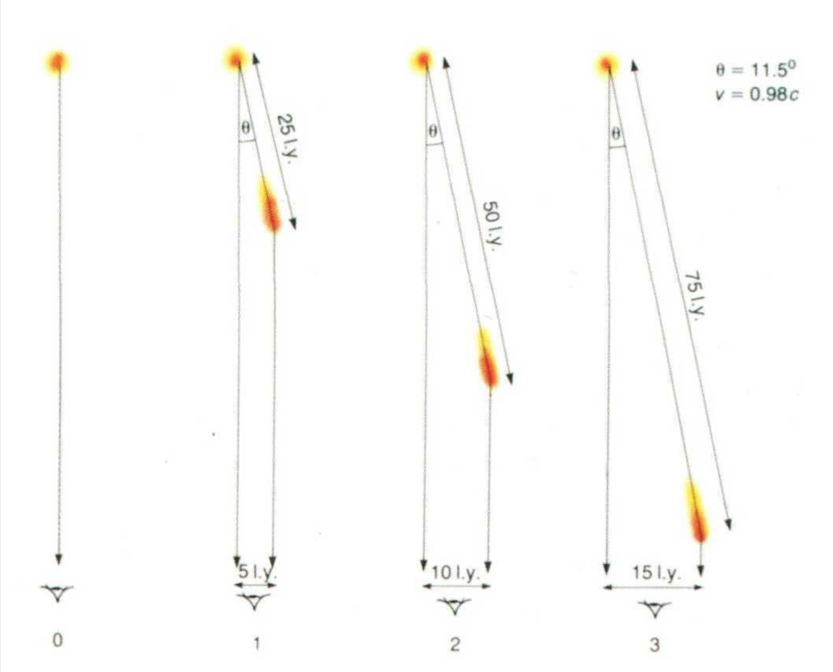


Superluminal motions

Next Lecture

Superluminal motions





These projection effects explain:

- the apparent superluminal motion
- the asymmetry between the two jets, also the flux of the approaching and receding components are affected by projection (Doppler Boosting)

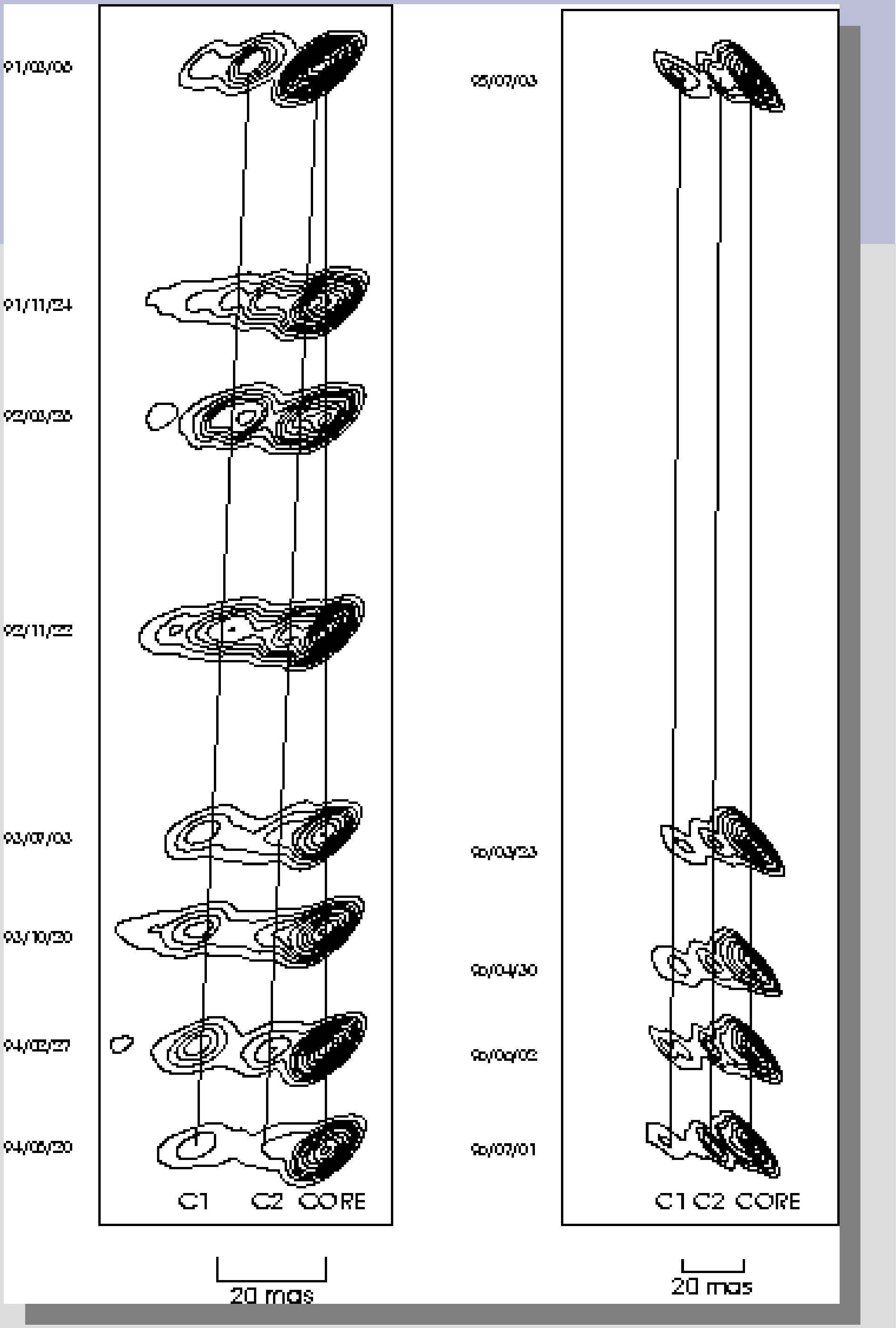
These are among the methods used to find out the orientation of a source

Sub-luminal motions

VLBI observations of Centaurus A (between 1991 and 1996)

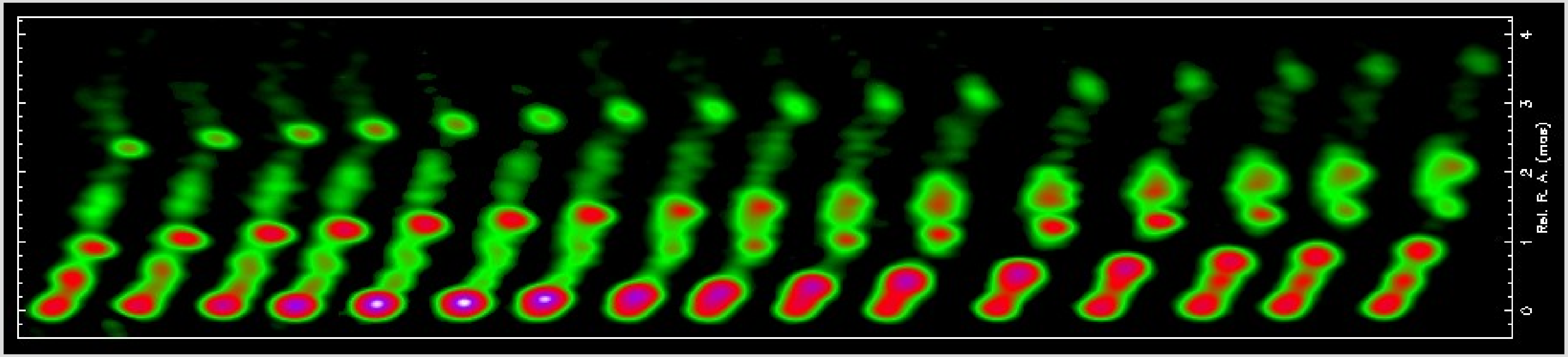
Apparent motion subluminal speed ~ 0.1c

However this does not seem to be characteristics common to all lower power (Fanaroff-Riley I) radio galaxies



3C120: FR-I

Apparent motion
of the components
between 4 and 6 *c*
but very complex.



Summary

- RGs come in two main type: FR-I & FR-II
  Difference might be caused by the nature of the
  jet (sub-sonic/super-sonic) and/or nature of nuclear source

- Energy loss, Polarisation, Faraday rotation play important roles in the appearence/energetics and study of radio galaxies.
  (Environment might also shape jet/lobe structure)

- Superluminal motion is detected in many jets (projection effect of relativisic jet pointed to an observer) -> More next lecture.