2) Structure of radio AGN and their life cycle

Raffaella Morganti

Netherlands Institute for Radio Astronomy (ASTRON)
and
Kapteyn Institute Groningen





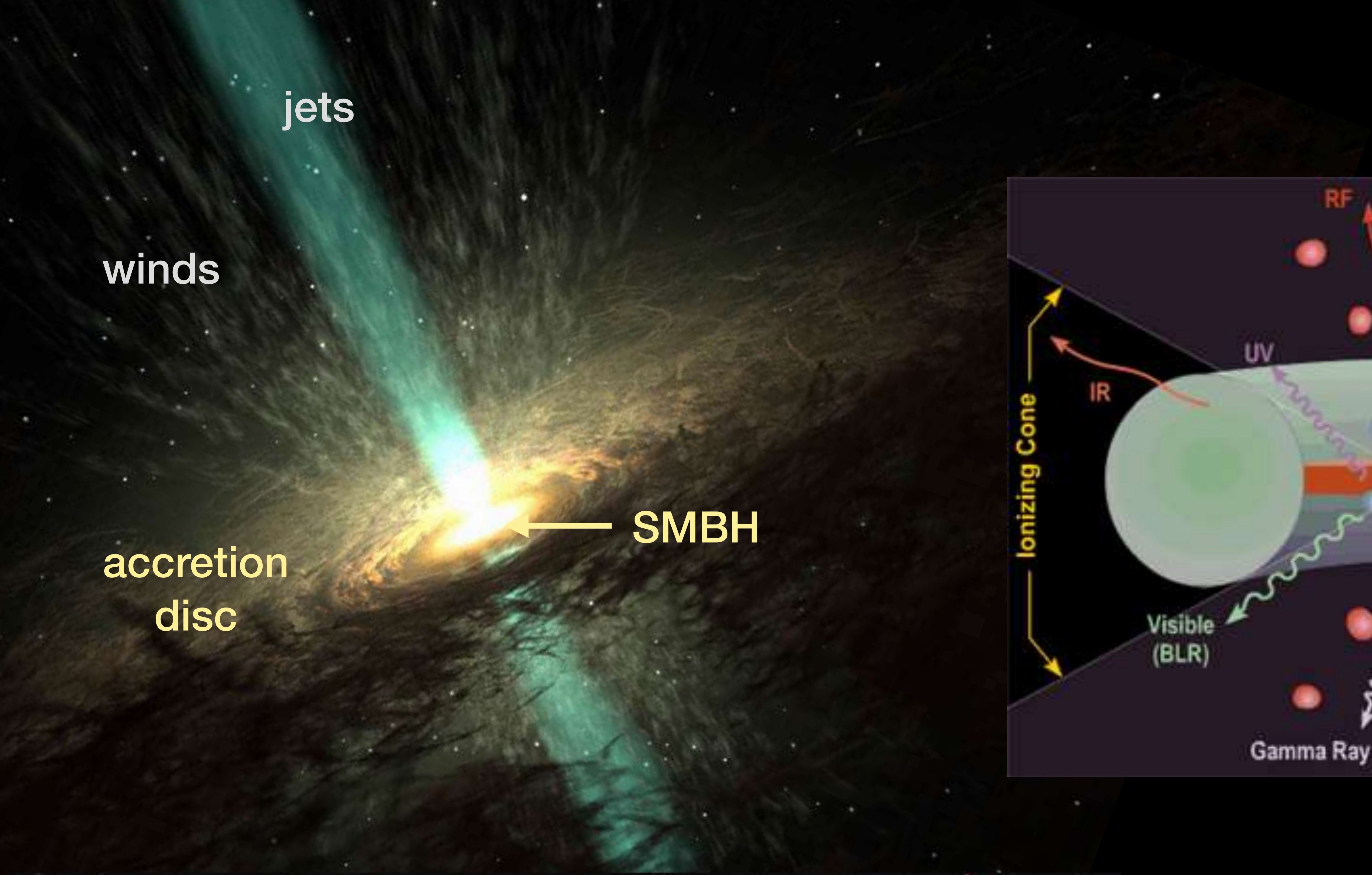


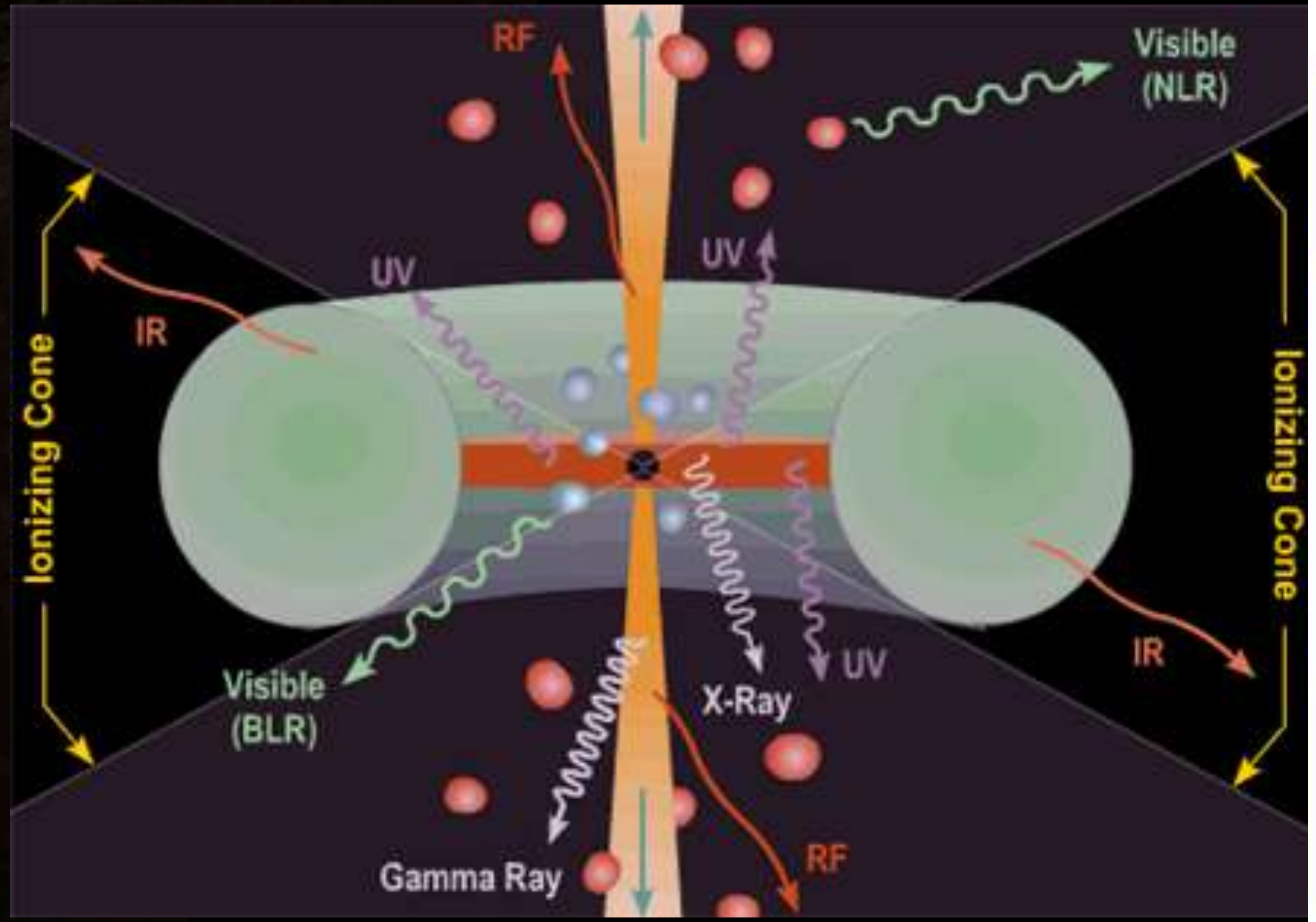
Active galactic nuclei at radio wavelengths: properties, life and impact

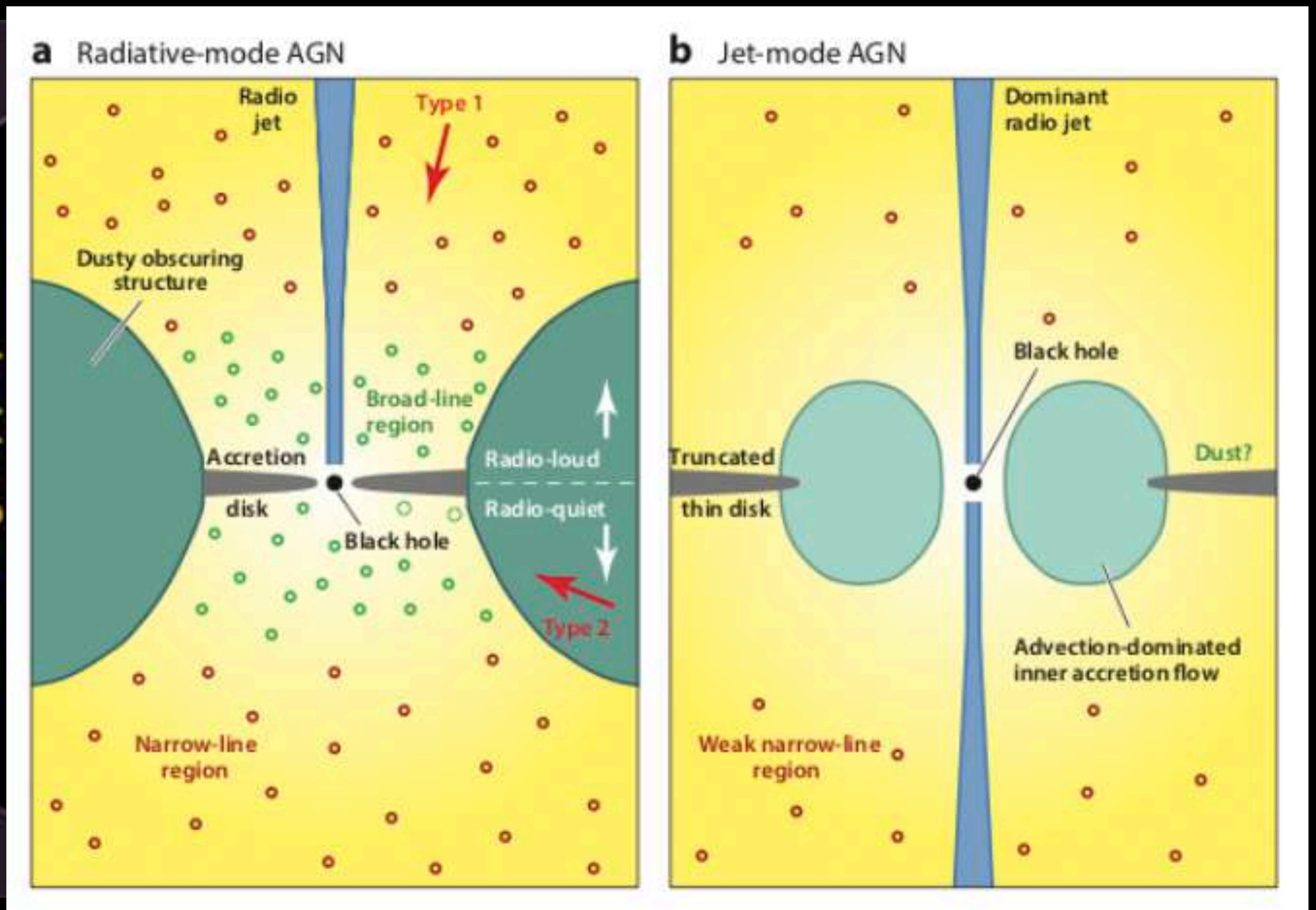
Themes of the lectures

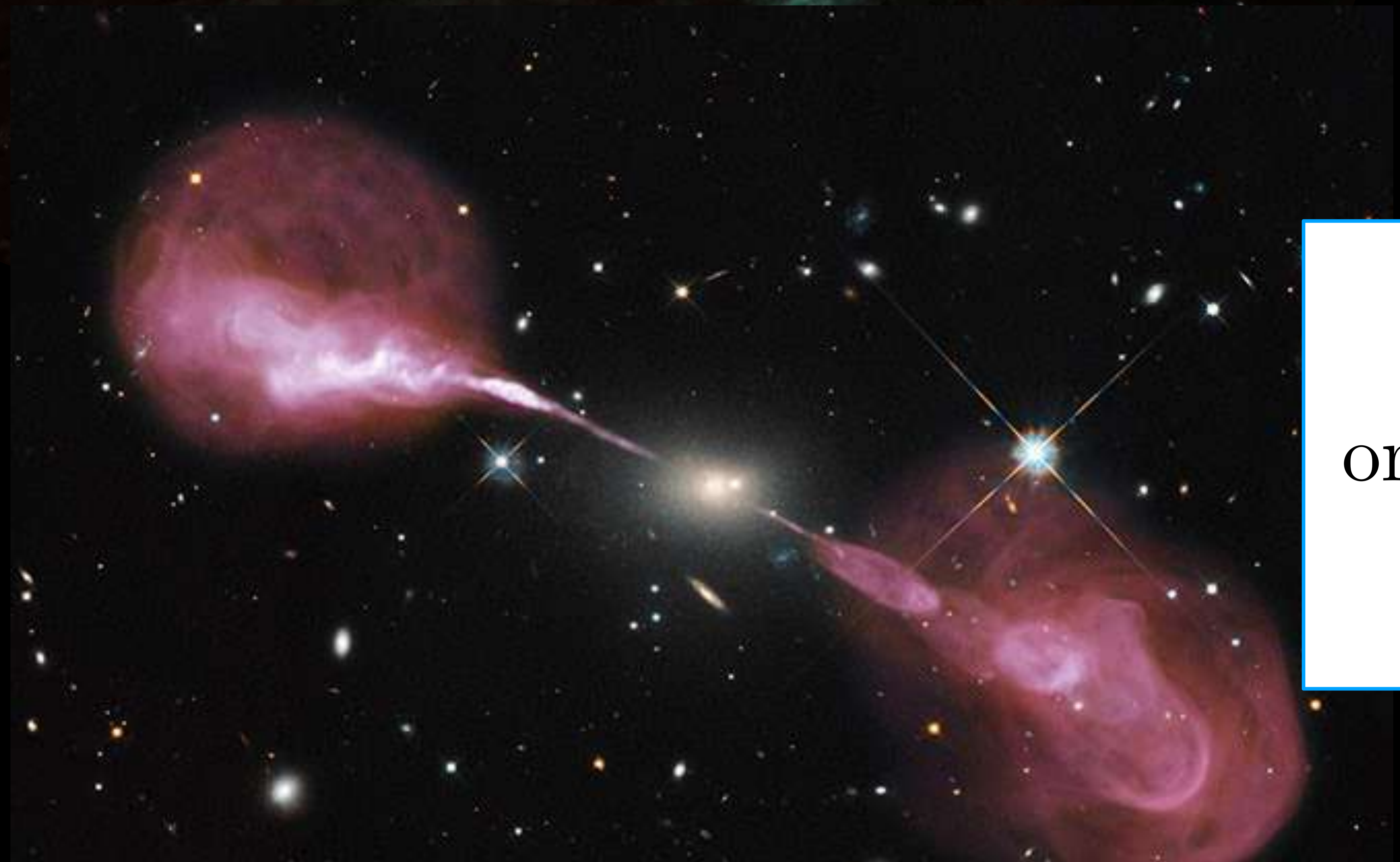
- ➡ Active galactic nuclei (AGN): introduction of their properties
- ➡ Structure of radio AGN and their life cycle
- ➡ Radio jets and their impact in galaxy evolution

From Les 1





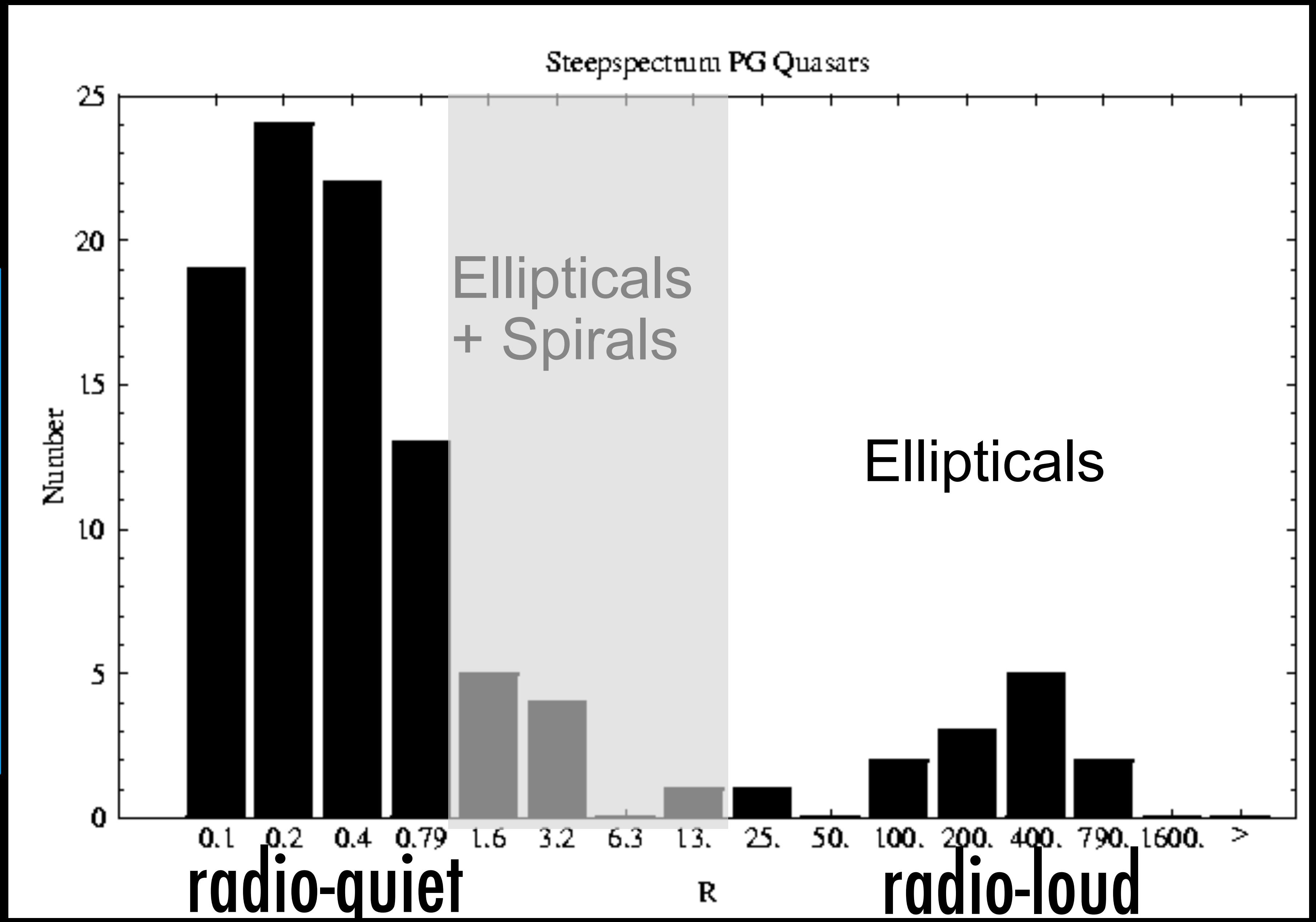




$$R = F_{\nu_r}/F_{\nu}(4400\mathring{A})$$

or in term of luminosity

$$R = L_{5GHz}/L_B$$



2) Structure of radio AGN and their life cycle

Plan of this lesson

a) Overall structure of radio AGN
b) From small to large scale: the launching of the jet; the large scale (relativistic) jets and the radio lobes
c) Synchrotron emission and spectral properties
d) The cycle of life of radio AGN: young, adult, dying and restarted. How to identify these phases and relevance (Les 3)
e) Radio quiet AGN

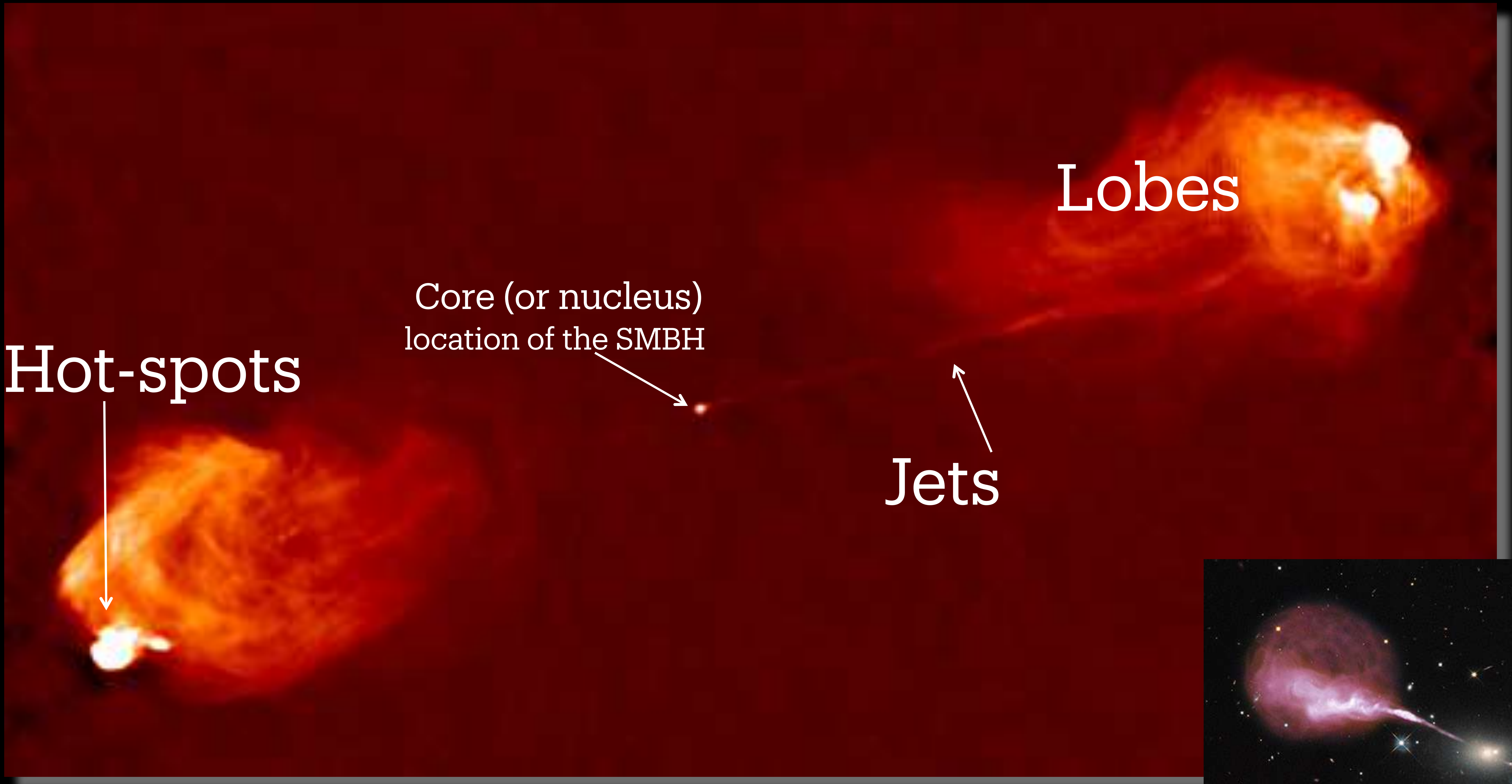
a) Overall structure of radio AGN

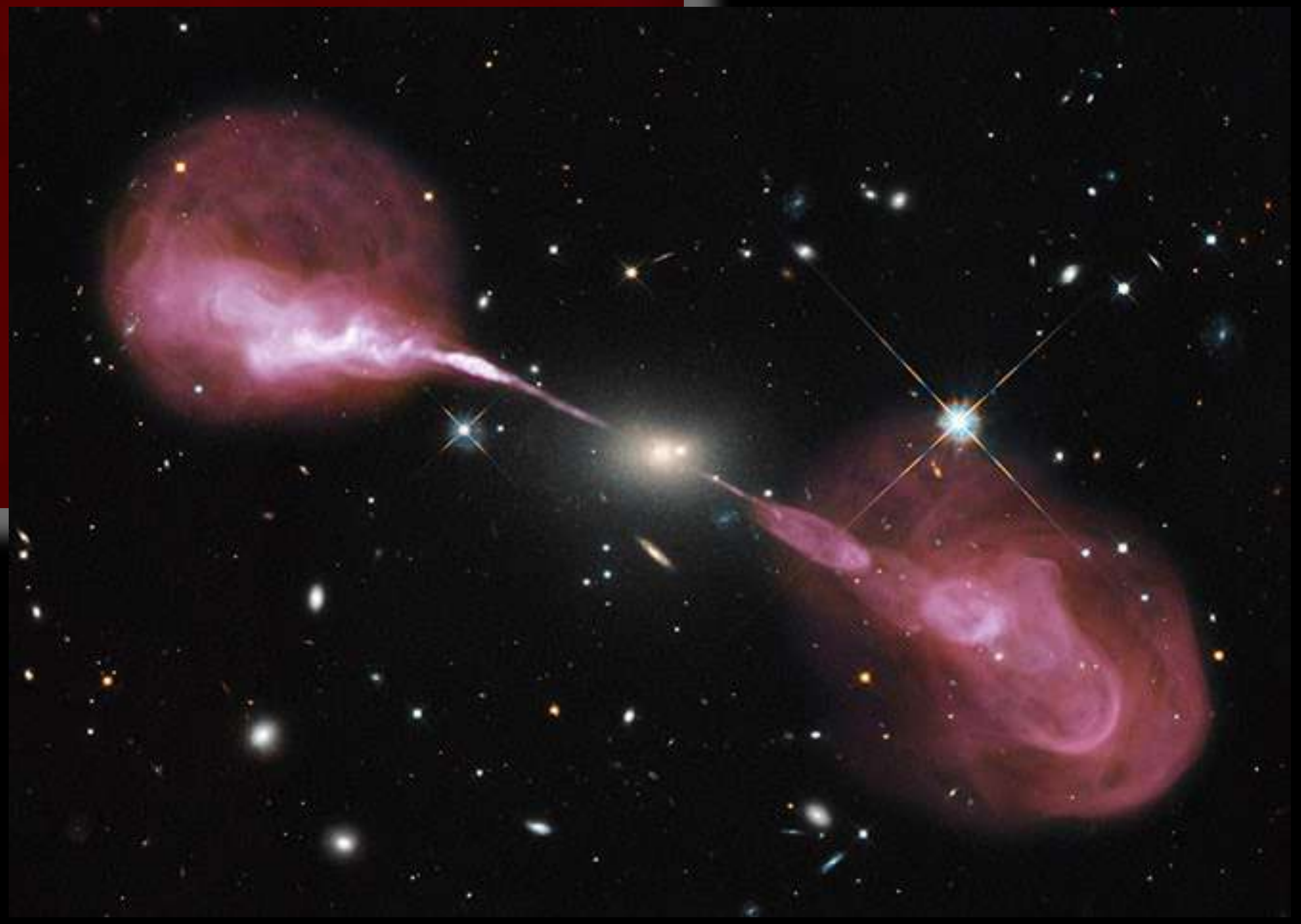
(and connection to optical)

Main focus on radio-loud
(back to “radio quiet” at the end of the les)

A prototypical (powerful) radio galaxy

Cygnus A

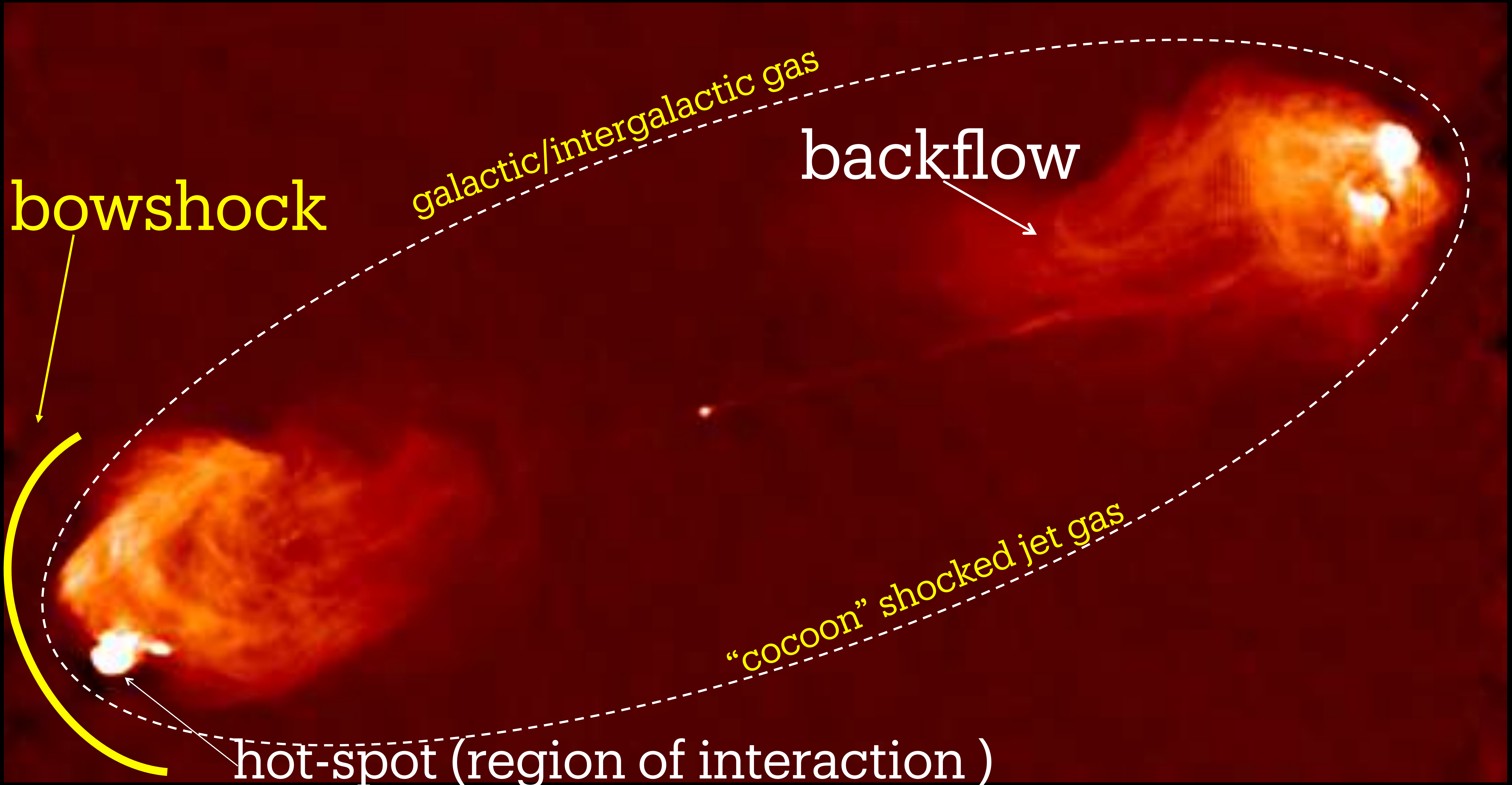




These structures can be of any size: from pc to Mpc
First order similarity of the radio morphology in all radio galaxies
but differences depending on radio power, optical luminosity & orientation)
Typical monochromatic radio luminosity (@ 1.4 GHz) 10^{23} to 10^{28} W/Hz

A prototypical (powerful) radio galaxy

Cygnus A

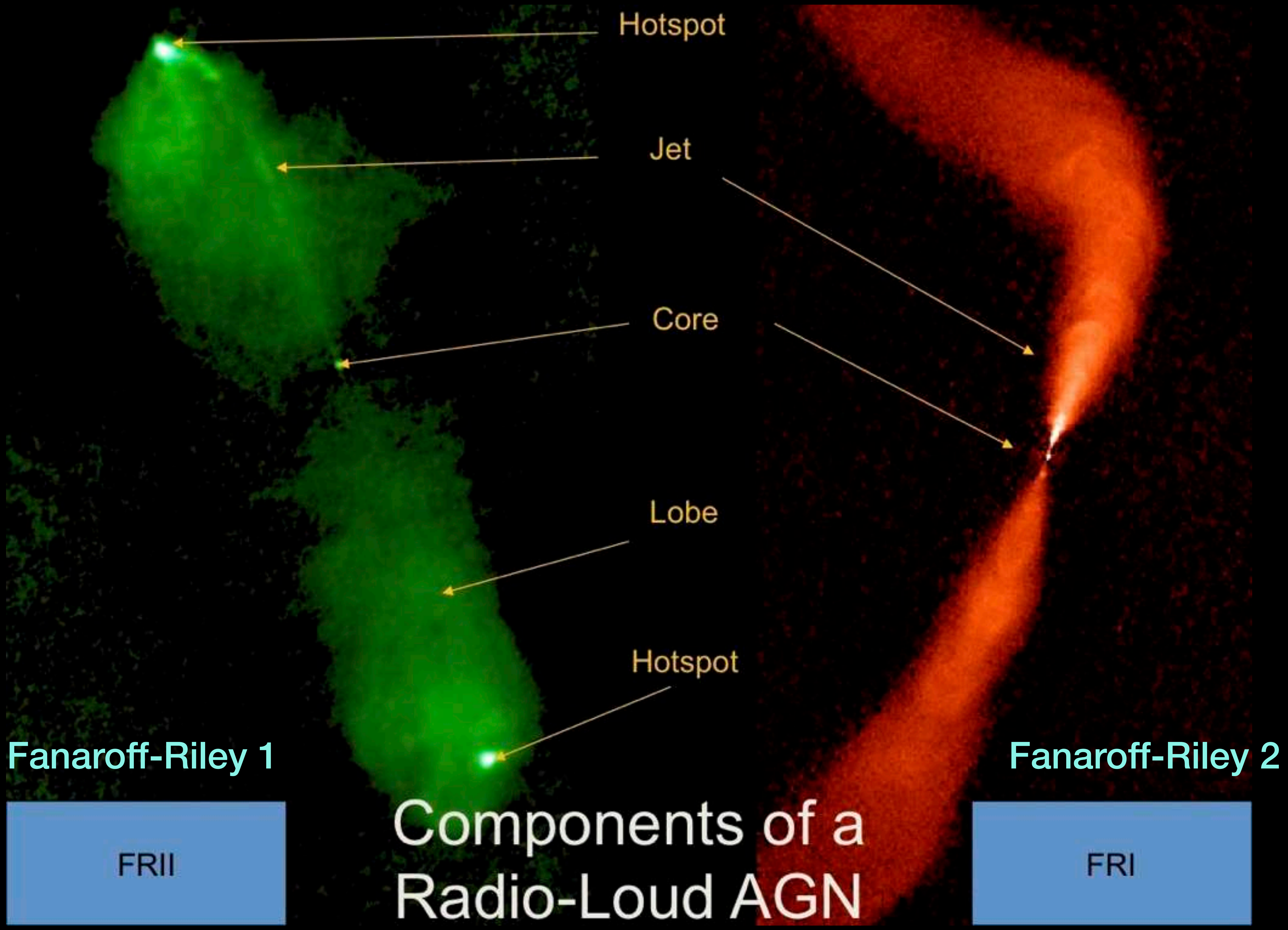


Structure of radio (loud) AGN

Classification proposed by Fanaroff & Riley (1974) based on the location of the region of that the relative positions of regions of high and low surface brightness in the lobes of extragalactic radio

- To first order, two type of structures: useful for classification and understanding of the physical processes…in reality a large variety of properties are observed.

- The type of structure tells us about the properties of the jet (high/low Mach number), environment (dense/cluster or field) efficiency of the central AGN and power of the radio source.



Hot spots at the end of the jets
overpressure wrt medium
no strong entrainment,

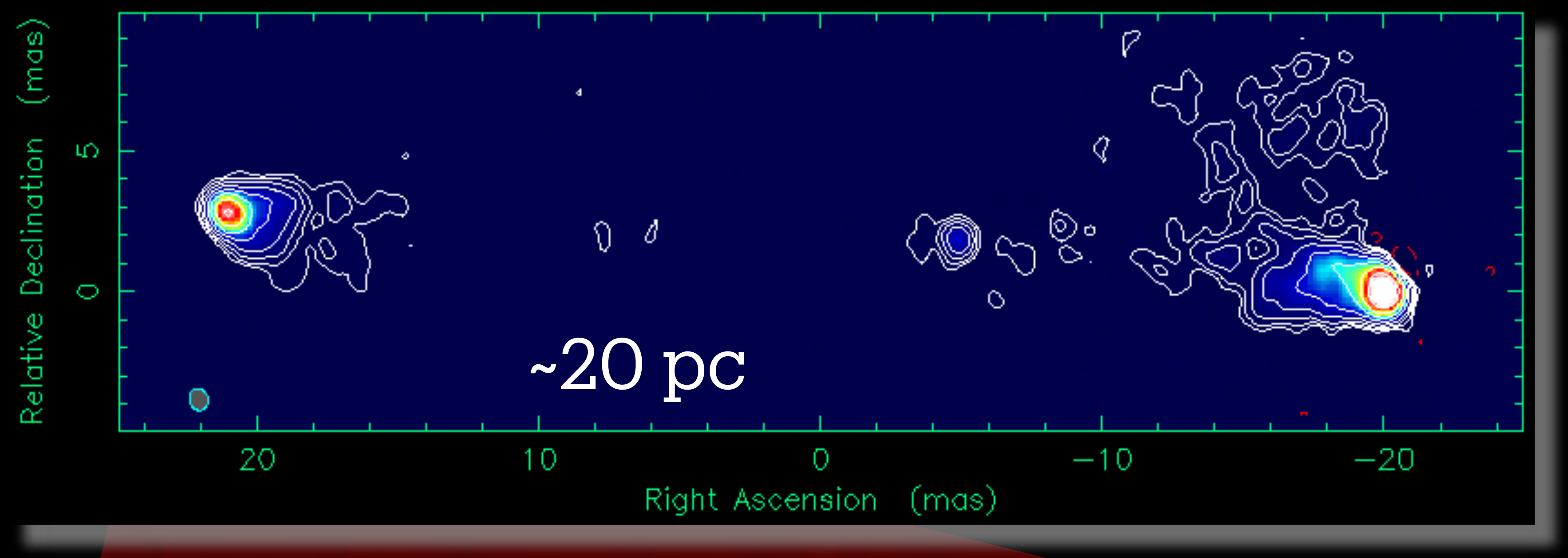
Croston et al. 2018
Mingo et al. 2019

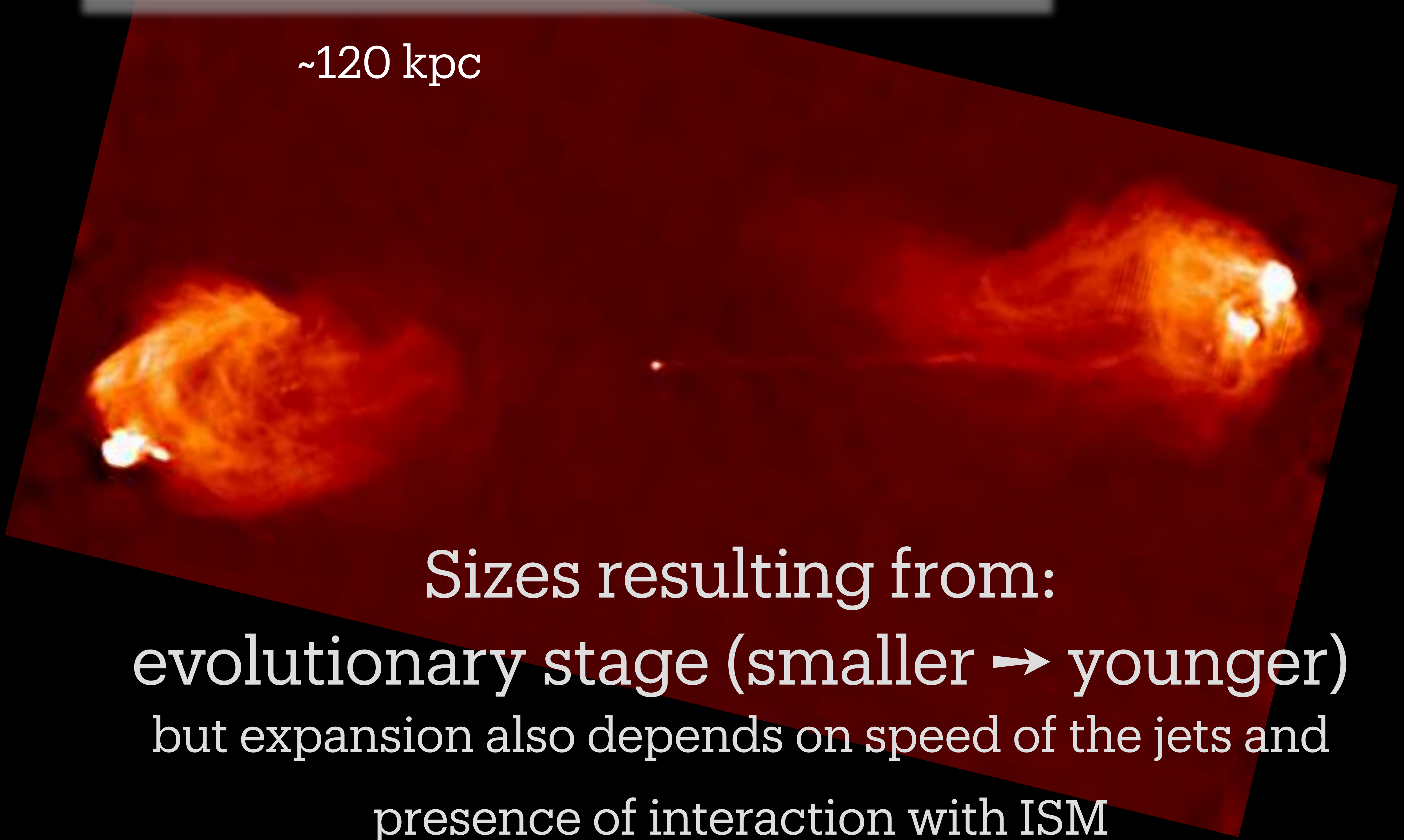
Widen rapidly, jet decelerate from relativistic to sub-relativistic speeds on scales of 1-10 kpc and recollimate. FRI strong entrainment otherwise underpressure - strong deceleration

Laing & Bridle 2002, Laing 2015

Radio structures from pc to Mpc

- Radio AGN structures can be of any size - from pc to Mpc





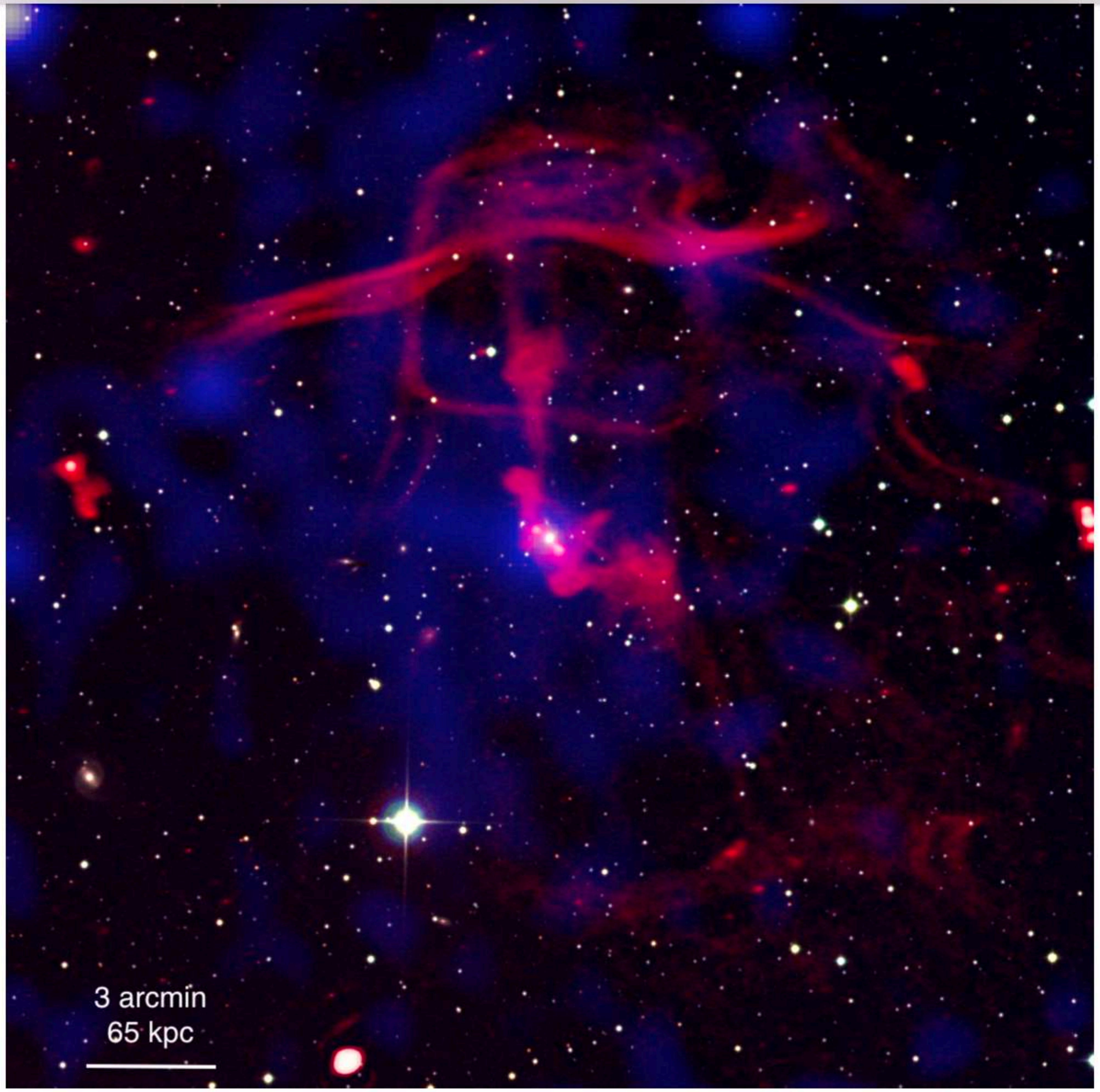
Similar morphologies on small and large scales

Sizes resulting from:
evolutionary stage (smaller → younger)
but expansion also depends on speed of the jets and presence of interaction with ISM
or
orientation effects

→

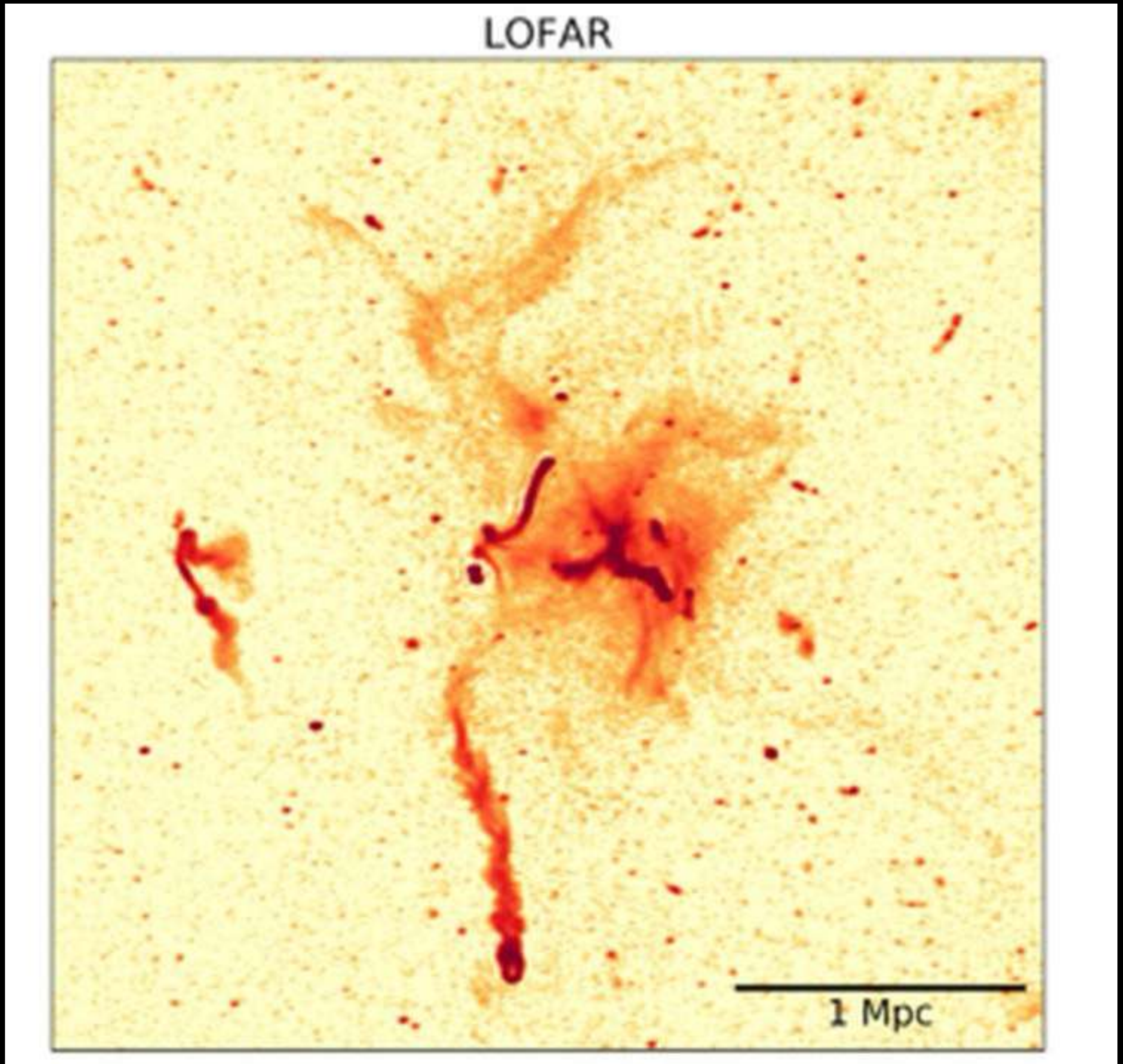
selfsimilar expansion but can be modified by the interaction with medium or moving inside a cluster

Extreme cases: radio AGN in galaxy groups and clusters



Supplementary Figure 1: Composite image of the galaxy group Nest200047. Radio data are shown in red (LOFAR image at 144 MHz with a resolution of 4.3 arcsec × 8 arcsec), X-ray data are shown in blue (SRG/eROSITA image at 0.5-2.3 keV) and optical data are shown in background (r-band, g-band and i-band Pan-STARRS images). A reference scale is shown in the bottom-left corner.

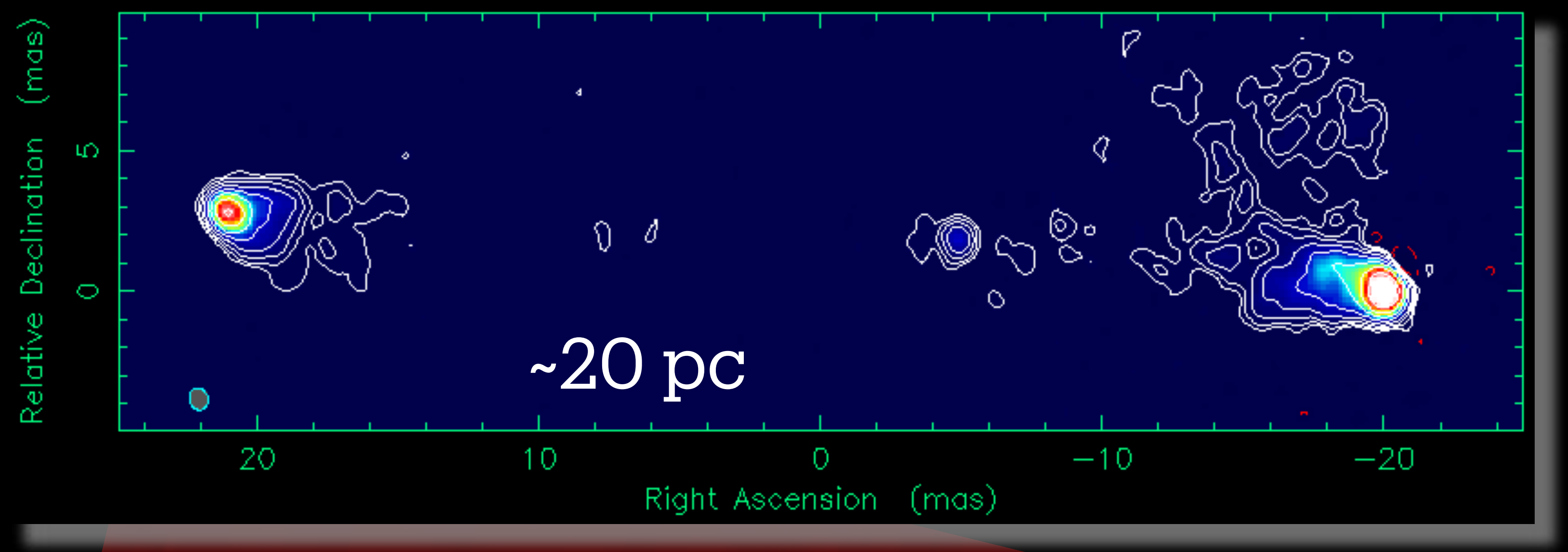
Brienza et al. 2021 Nature Astronomy

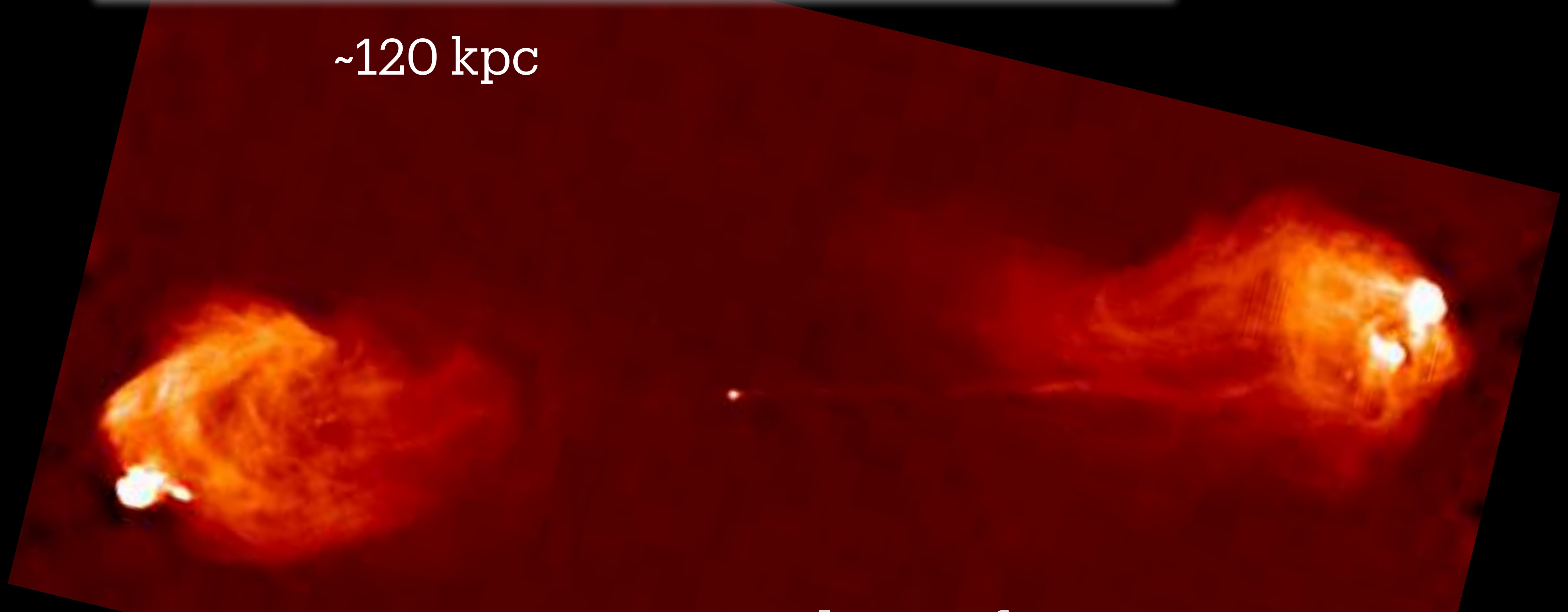


Abell 2255 - Botteon et al. 2020

Radio structures from pc to Mpc

- Radio AGN structures can be of any size - from pc to Mpc





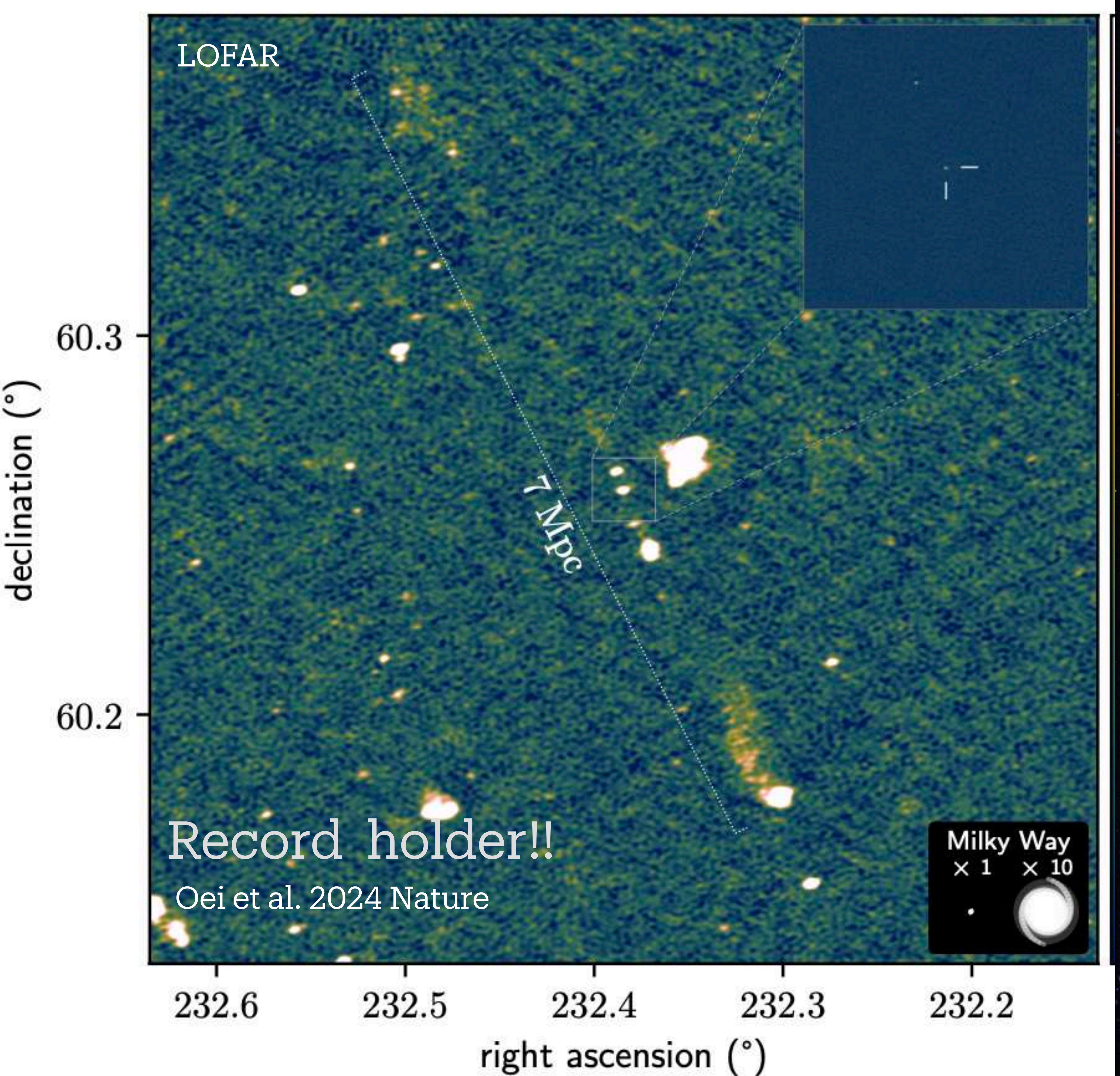
Sizes resulting from:
evolutionary stage (smaller → younger)
but expansion also depends on speed of the jets and
presence of interaction with ISM
or
orientation effects

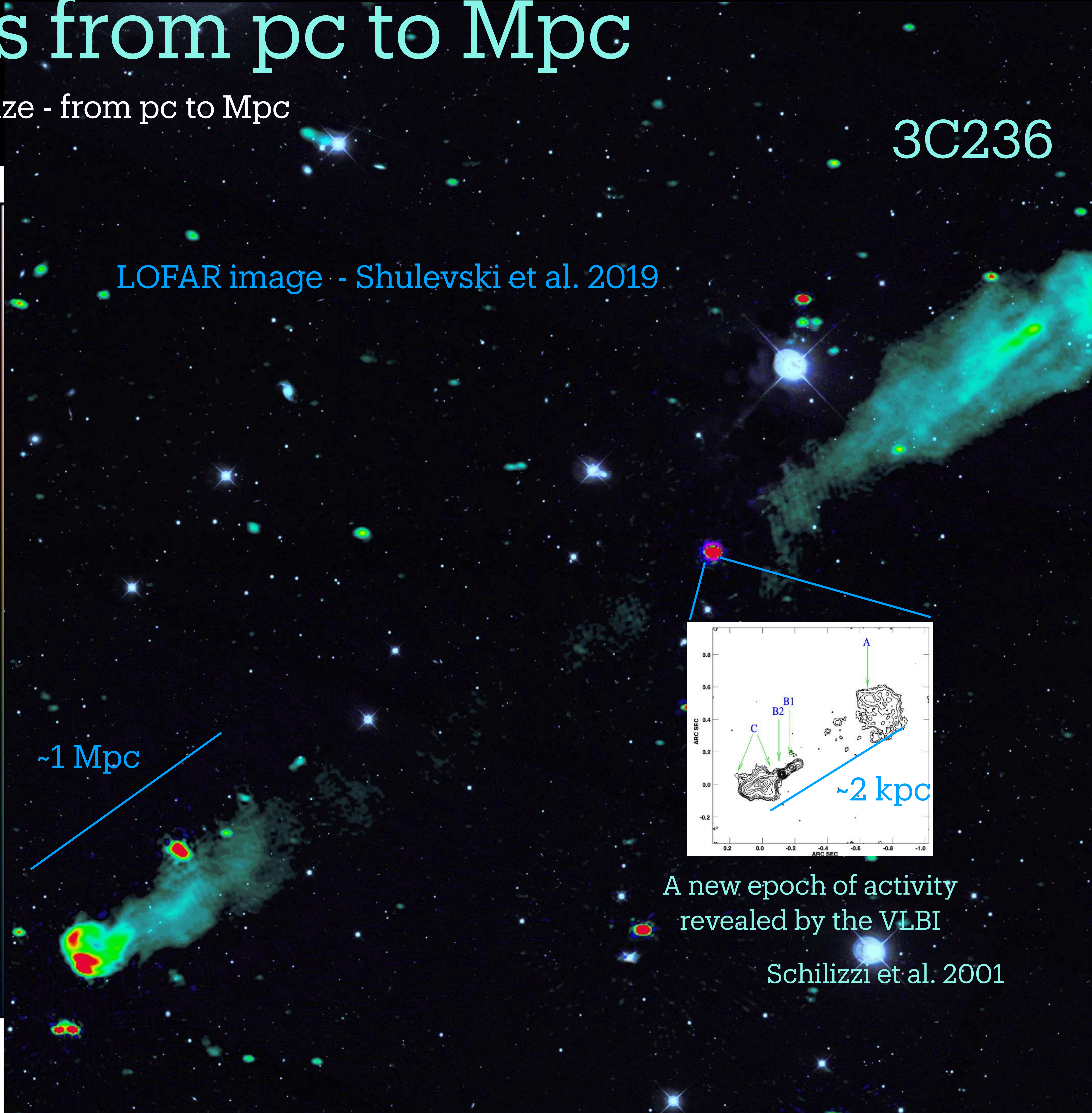
Similar morphologies on small and large scales
selfsimilar expansion but can be modified by the interaction with medium or moving inside a cluster

radio observations covering a range
of angular resolution are needed to get a complete view

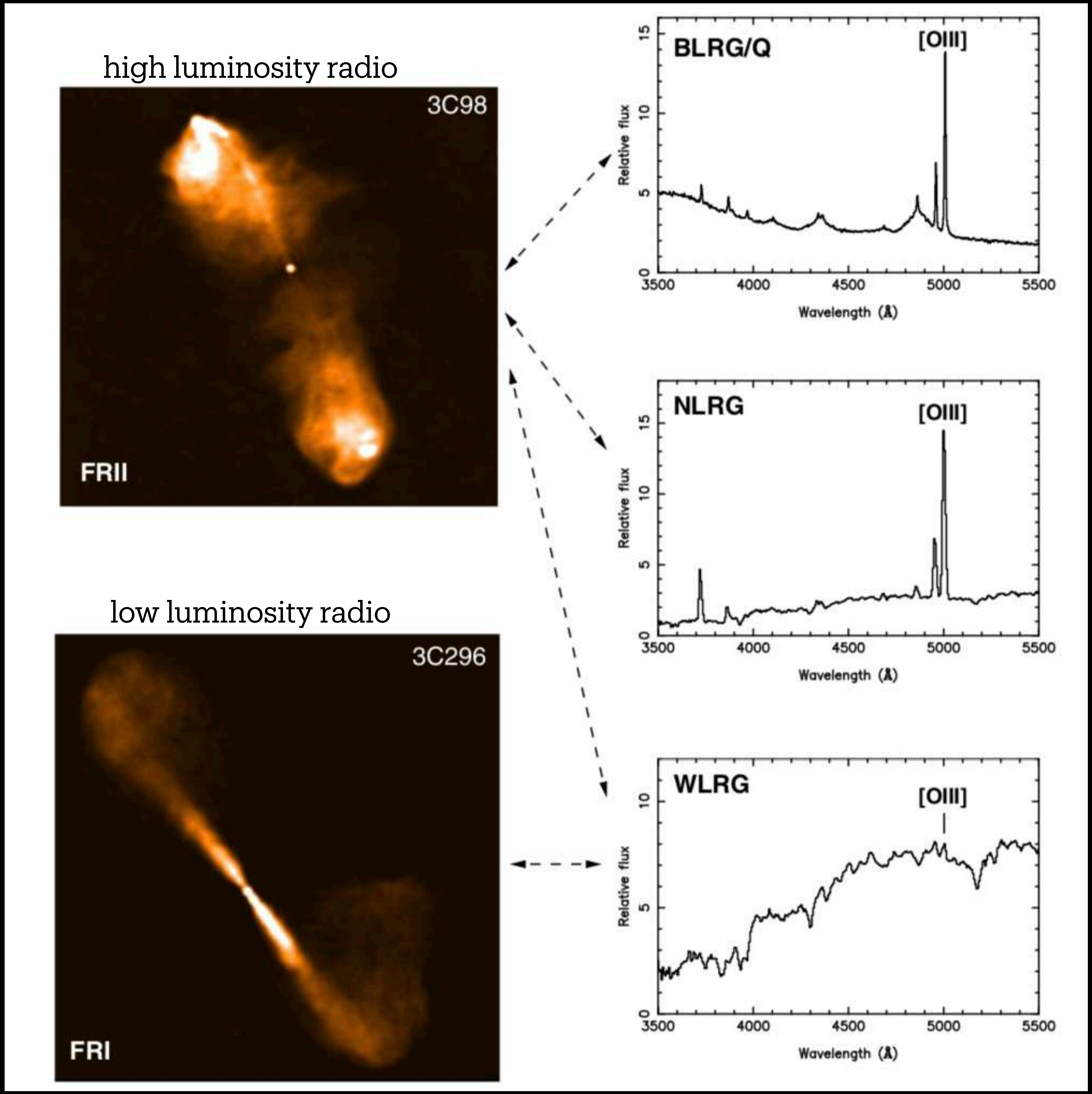
Radio structures from pc to Mpc

- Radio AGN structures can be of any size - from pc to Mpc





Radio and optical properties …



From Tadhunter 2016

comparison radio and presence of ionised gas in the host galaxy

high excitation, broad line radio galaxies

radiatively efficient

high excitation RG

low excitation RG

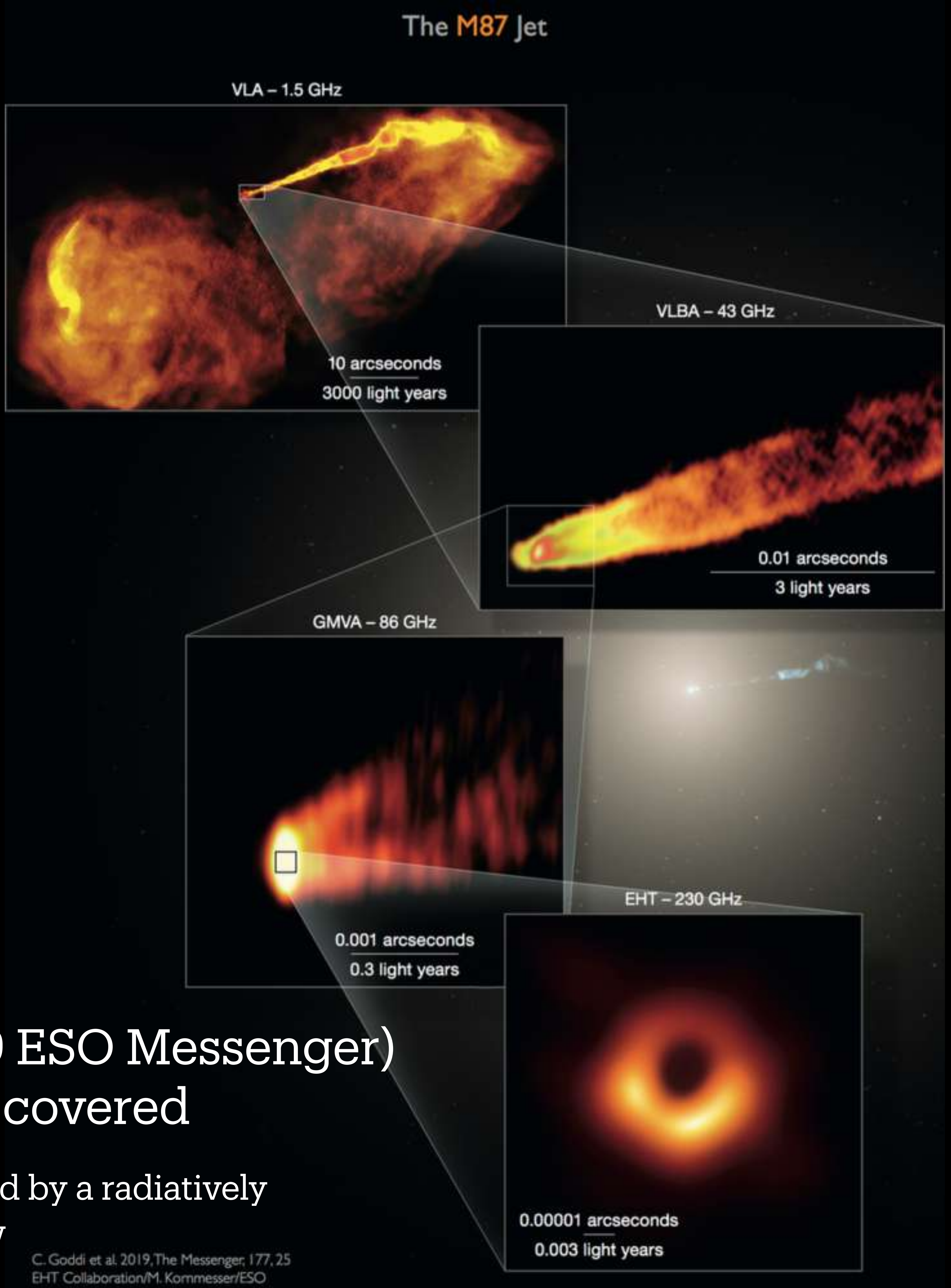
radiatively inefficient

hardly any emission line detected
often hard to put them in the "Baldwin, Phillips & Terlevich" (BPT) diagnostic diagrams!
Clearly AGN but only in the radio…

b) From small to large scale:

The nuclear regions, the launching of the jet, the large scale (relativistic) jets and the radio lobes

Structures on many scales: observations with different radio telescopes are needed to trace them



Case of M87 (Goddi et al. 2019 ESO Messenger)
huge range of scales covered

→ M87: low-Eddington regime, described by a radiatively inefficient accretion flow

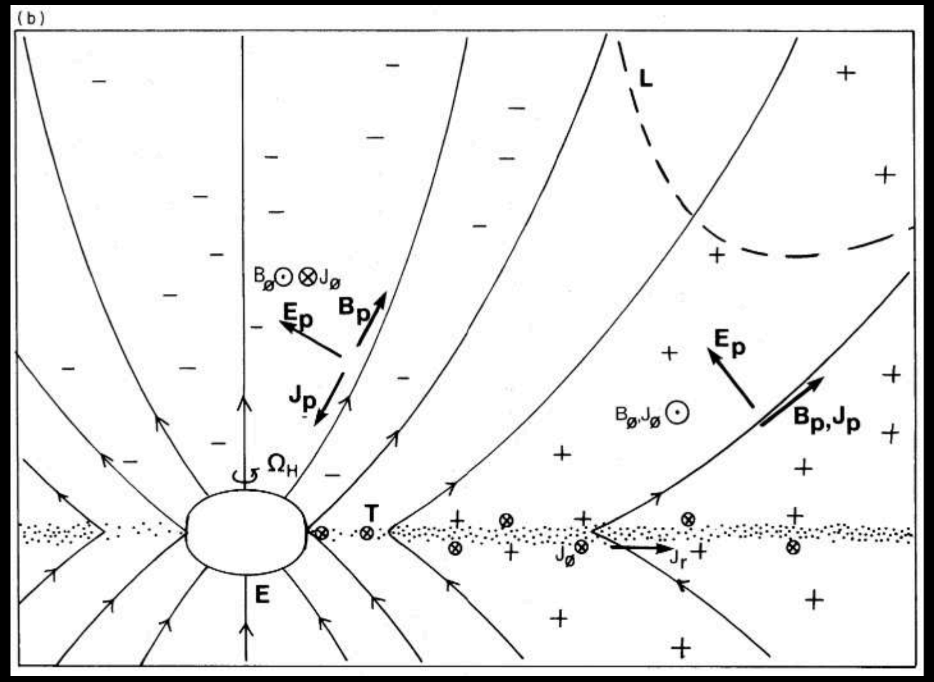
Jet production and collimation

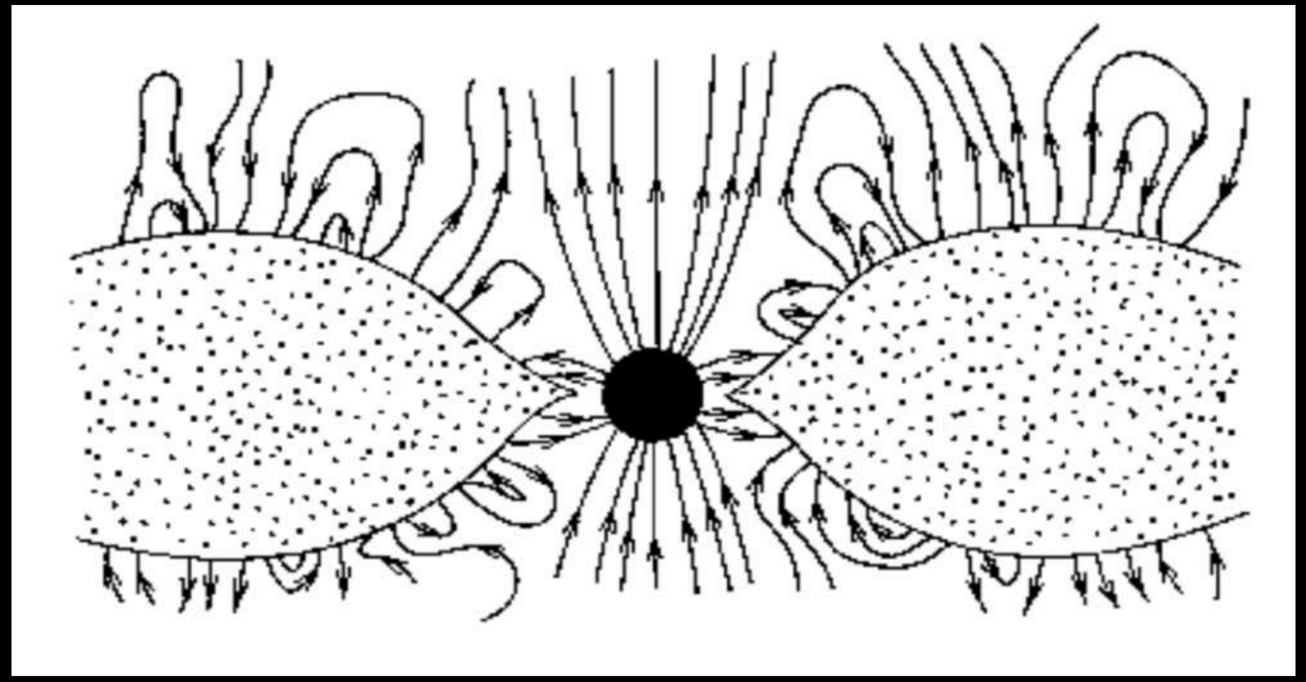
Proposed by Blandford & Znajek 1977: *Electromagnetic extraction of energy from Kerr BH*

First numerical simulations: Uchida & Shibata (1985)

This theory explains the extraction of energy from magnetic fields around an accretion disk, magnetic lines are dragged and twisted by the spin of the black hole. Relativistic material is then launched by the tightening of the field lines.

Blandford & Znajek 1977

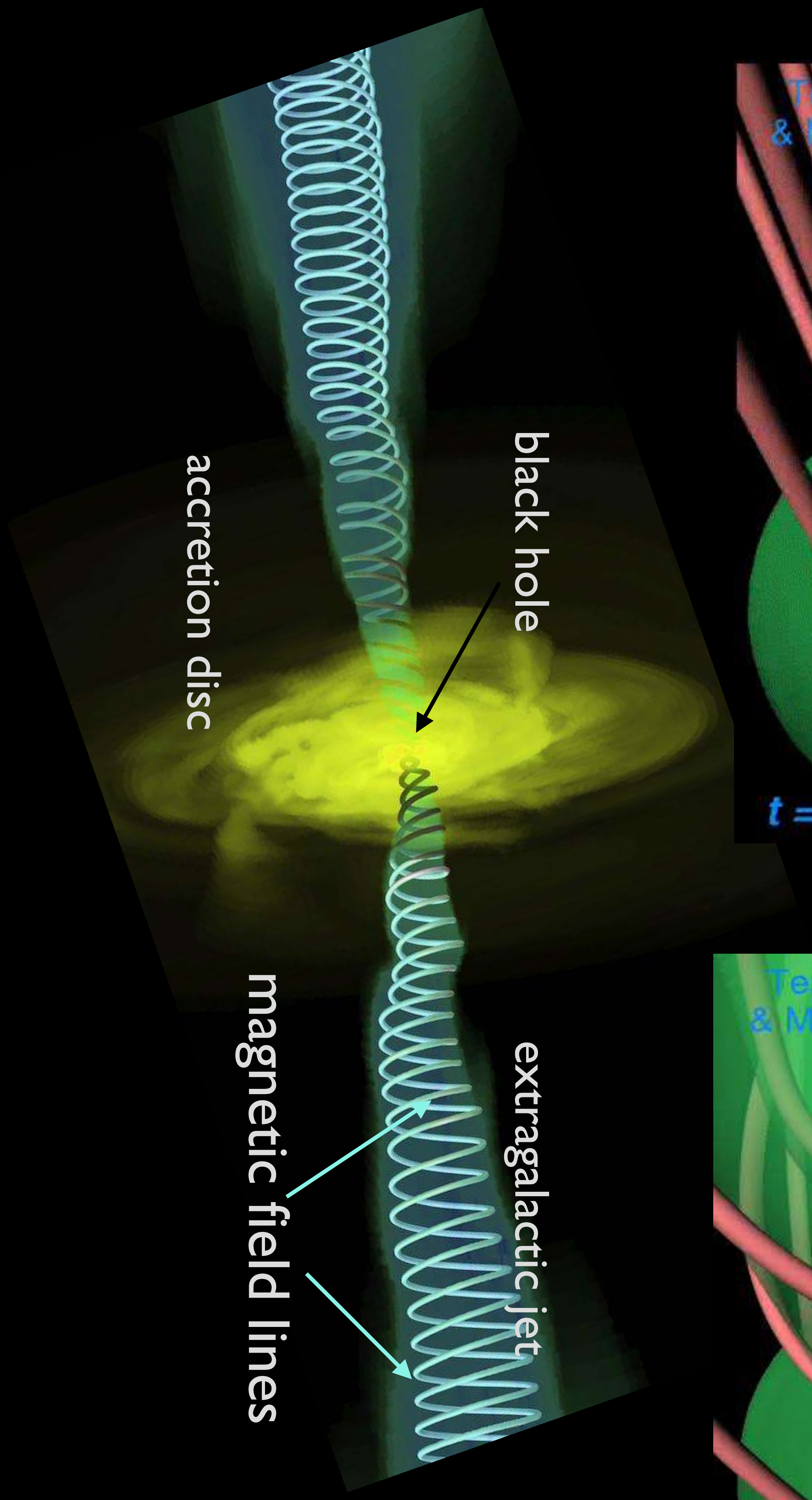




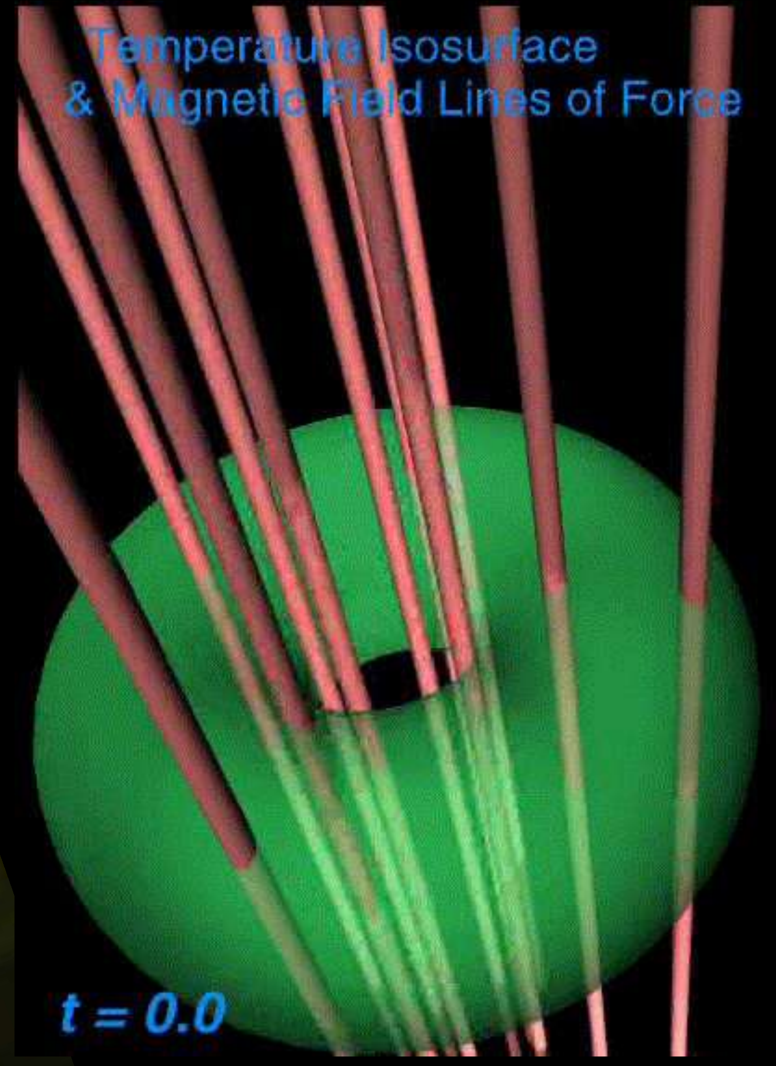
- Differential rotation (different angular velocity at different distance) twists up the field lines into toroidal component, slowing rotation
- Disk accretes inward, further enhancing differential rotation and B_φ
- Greatest field enhancement is at torus inner edge

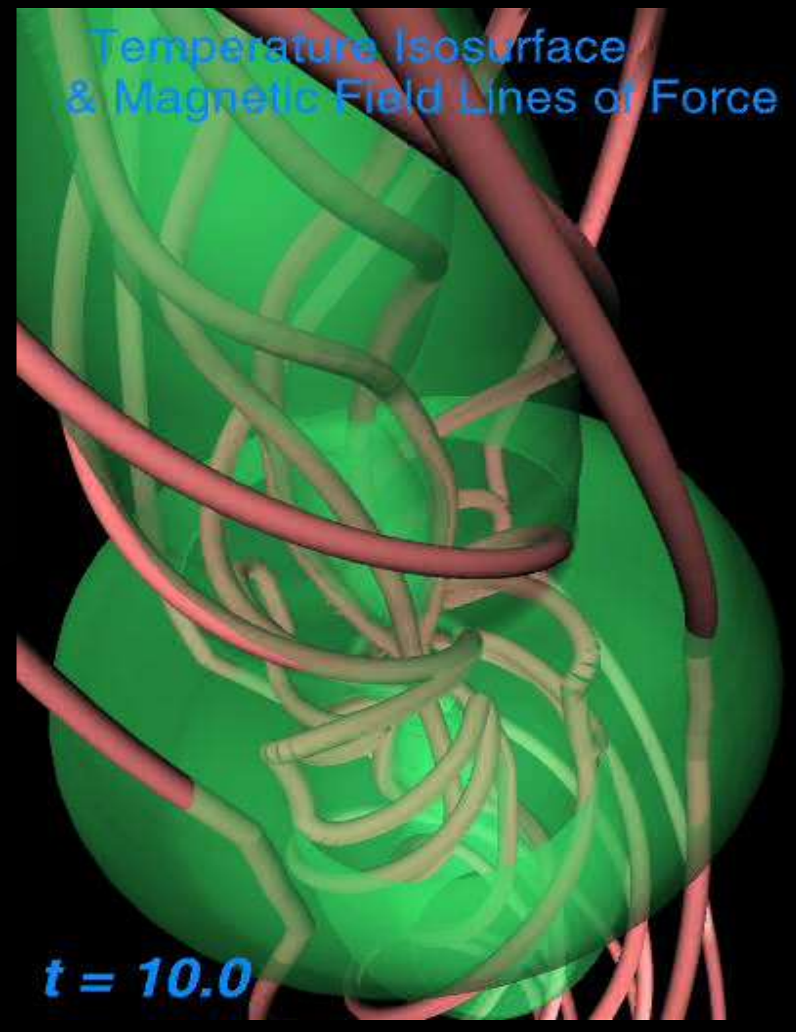
  - Jet direction is along the rotation axis

Way to extract angular momentum and the energy when accretion disc is inefficient (lack of radiative losses)



Some reviews: Meier et al. 2001 and Blandford, Meier, D., Readhead, A. 2019

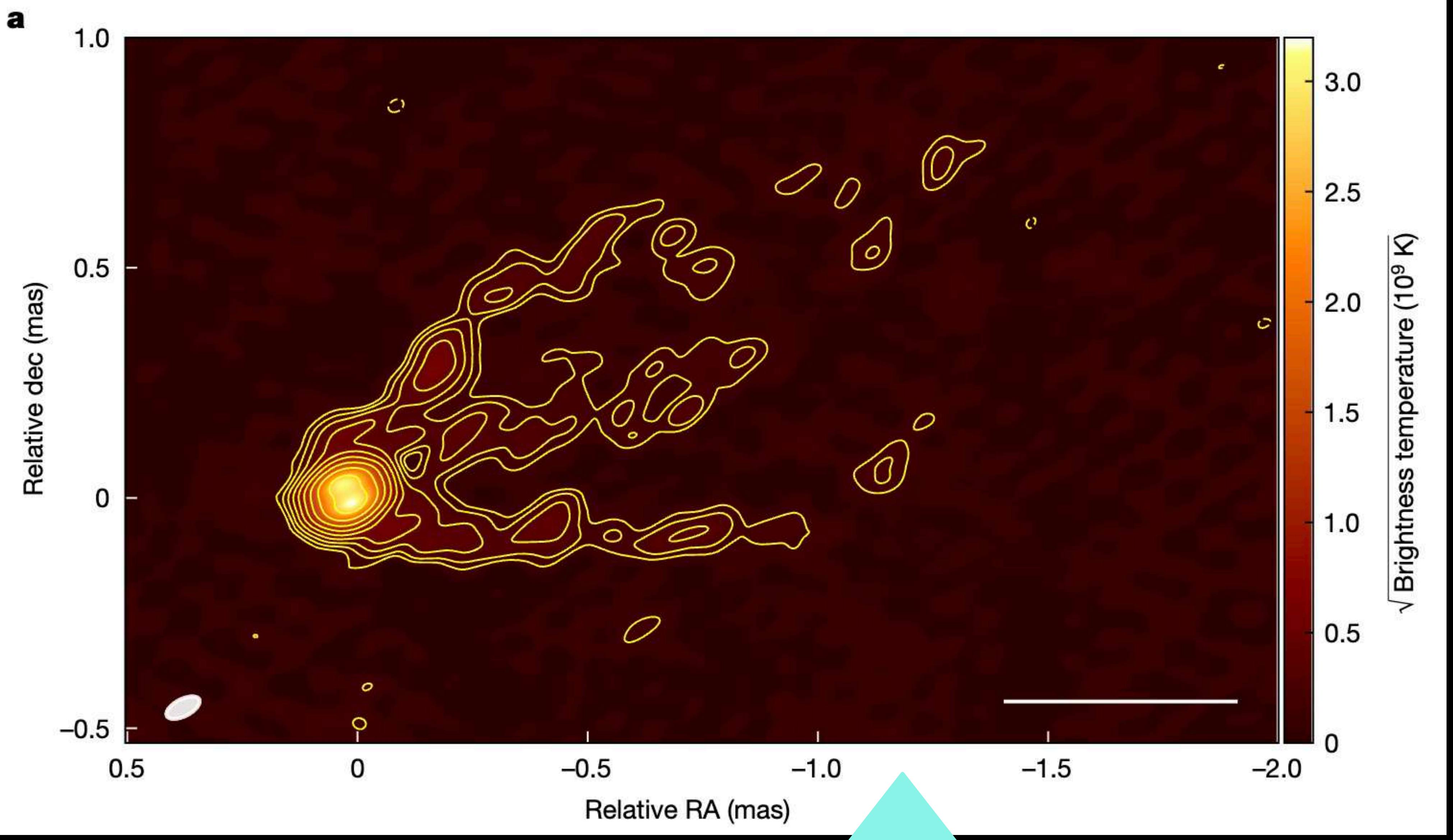


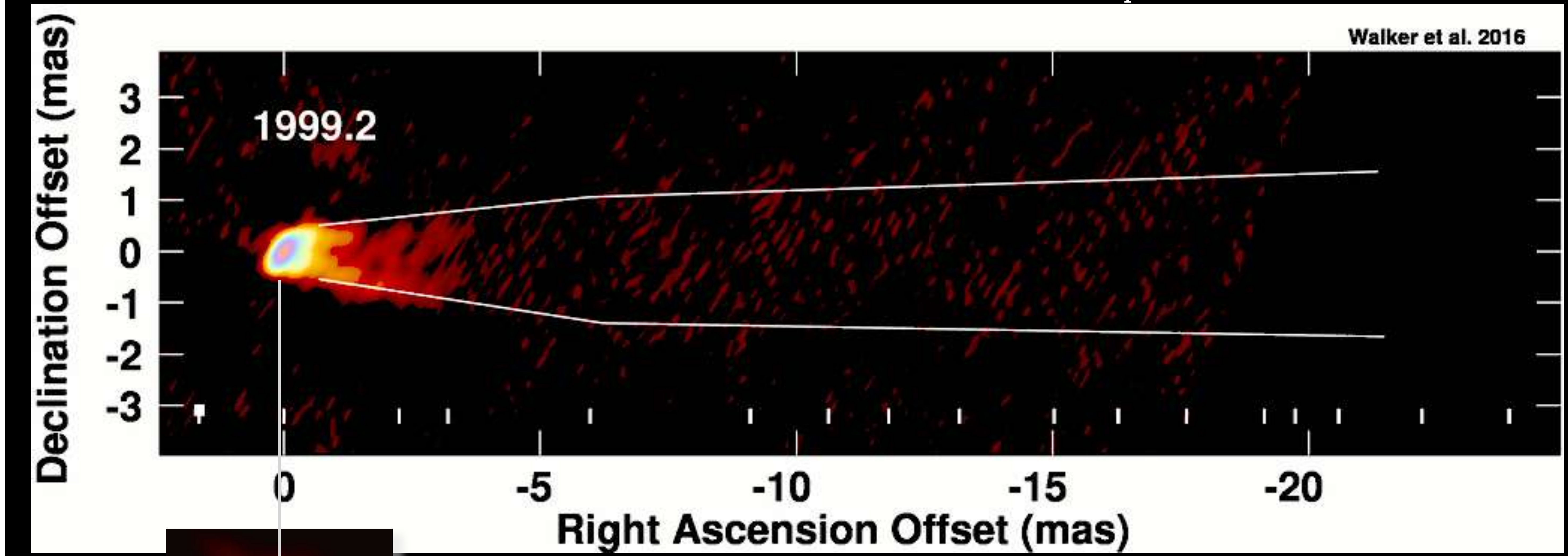


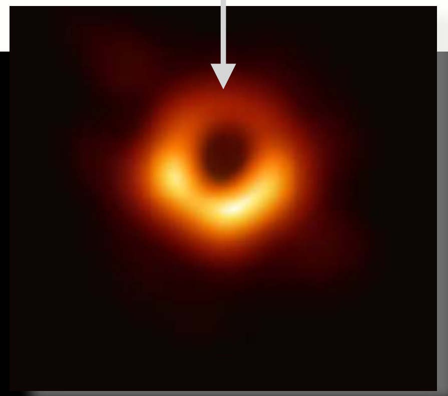
Uchida et al. 1999
Meier et al. 2001

Jet collimation: case of M87

From Craig Walker
Schwarzschild radius of the M87 black hole ($2GM/c^2$) is 7.3 microarcseconds.
acceleration from apparent speeds of < 0.5c to > 2c in the inner ~2 milliarcsec (mas) and suggest a helical flow.
linear conversion scale of 1 mas ~0.08 pc



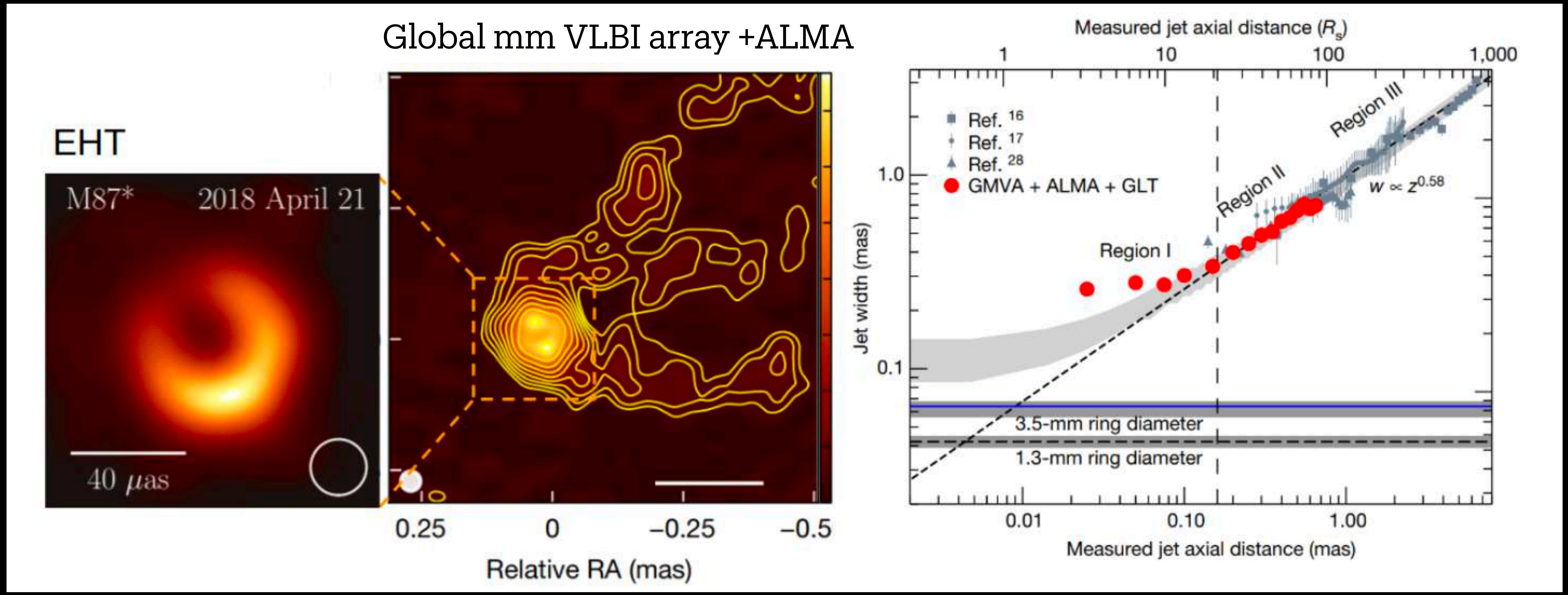




M87 jet movie - radio observations at different epochs - Walker et al. 2018 (see also Mertens et al. 2016)

1.3mm

3.5mm Lu et al. 2023



The images show that the edge-brightened jet connects to the accretion flow of the black hole.
The observed parabolic shape is consistent with a black-hole-driven jet through the Blandford–Znajek process
BUT close to the black hole, the emission profile of the jet-launching region is wider than the expected profile of a black-hole-driven jet, suggesting the possible presence of a wind associated with the accretion flow.

Lu et al. 2023 Nature

Jet collimation: case of 3C84

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

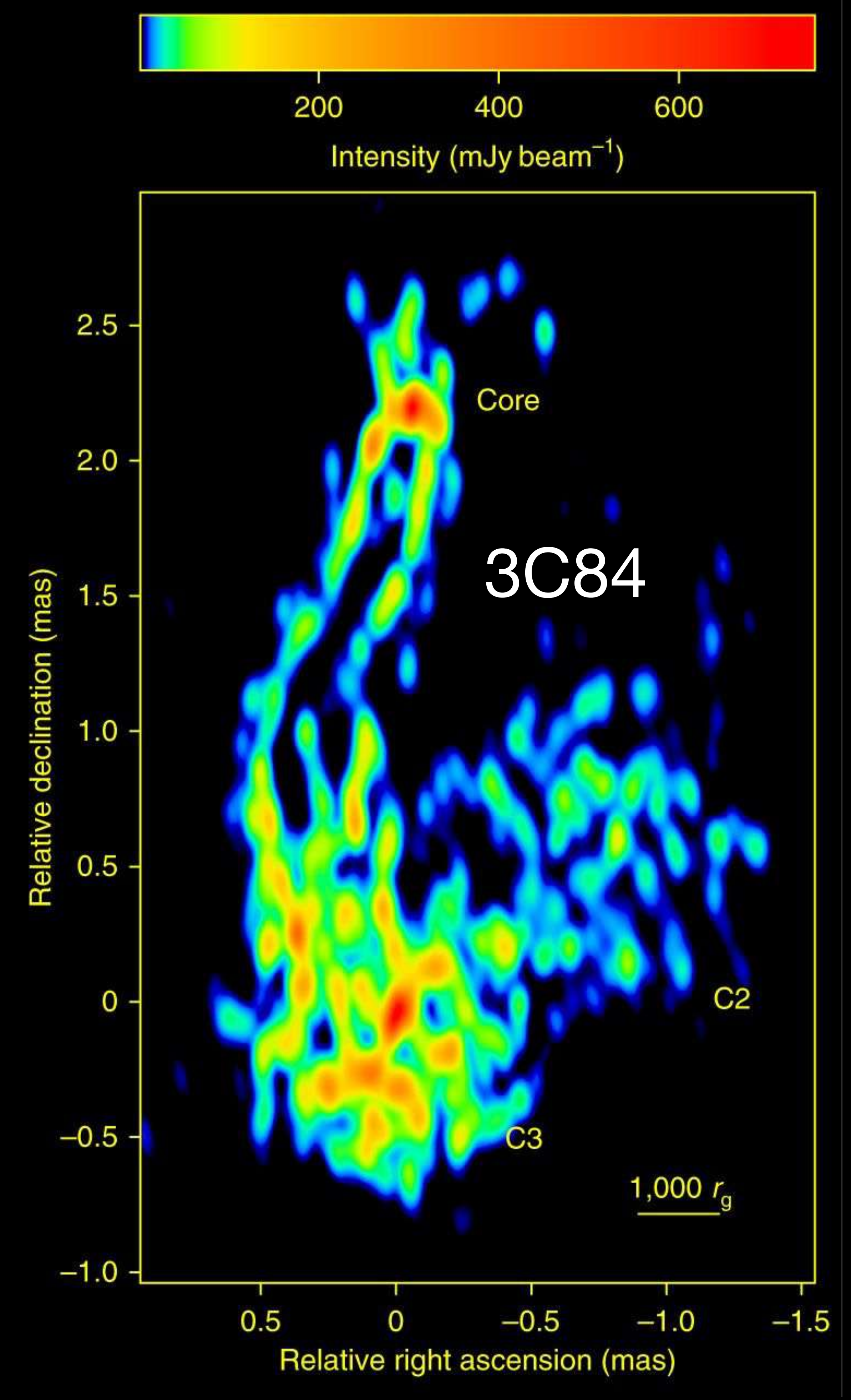
rapid broadening of the jet opening angle as the core is approached on scale below 0.1 mas

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

The jet can also originate from an accretion disk, known as the Blandford-Payne (BP) mechanism

“spine-sheath” structure

More cases (jets of different radio power) needed where the jet collimation is traced



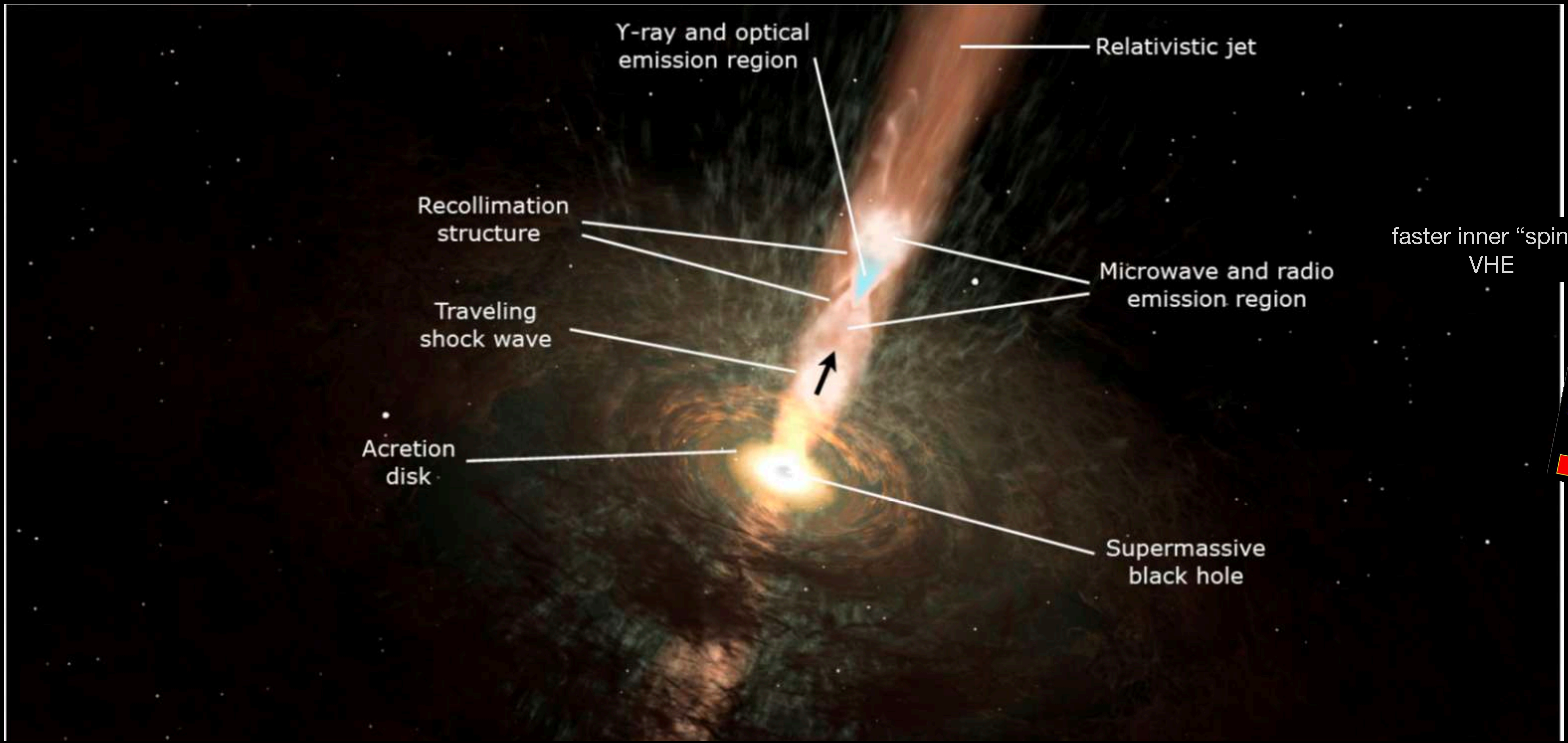
3C84

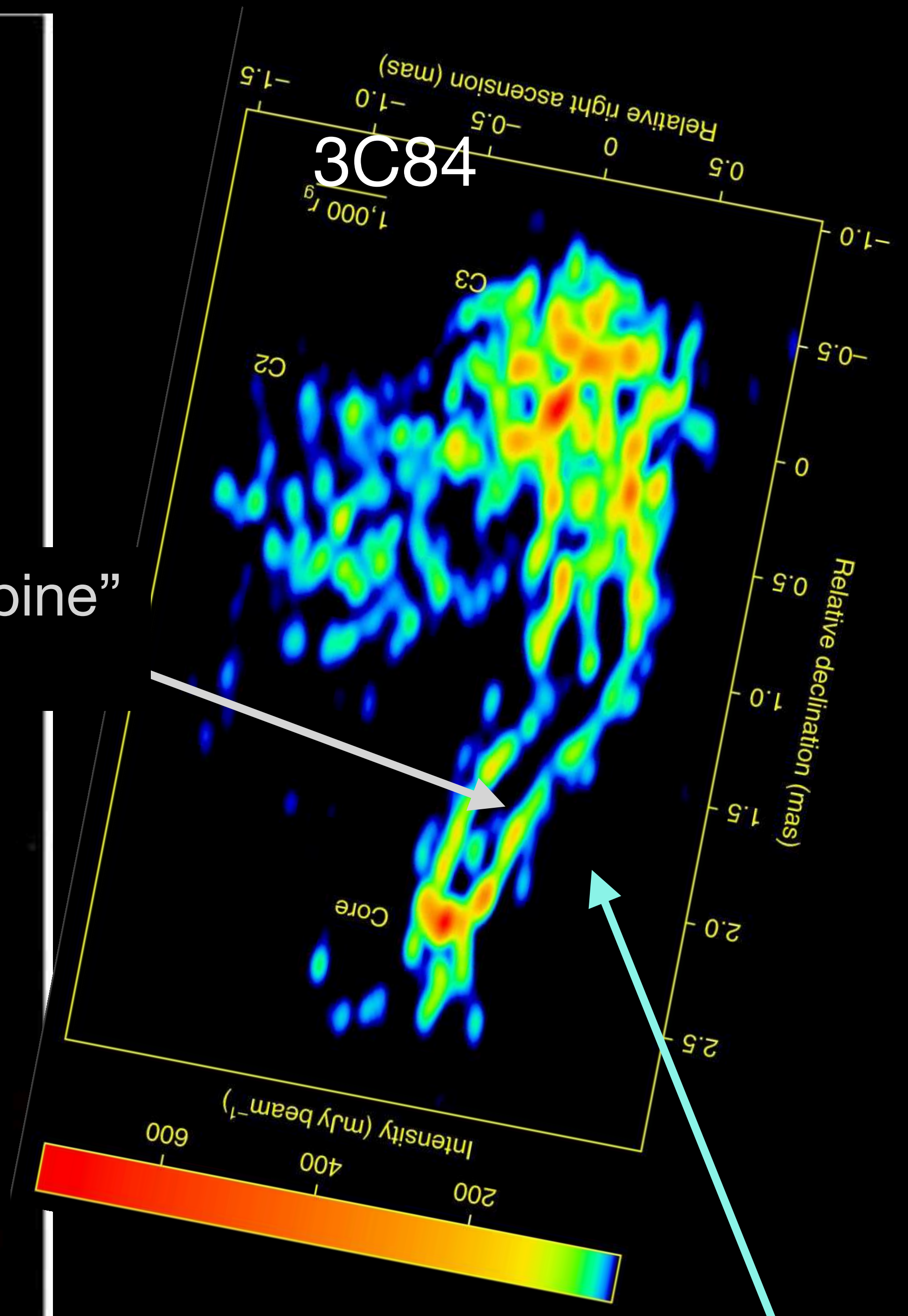
Giovannini et al. 2017

1 mas ≈ 0.344 pc ~3.58 × $10^3\ r_g$

using interferometry with RadioAstron satellite

Composition of the jets and particle accelerations





➙ this is evidence for a “spine-sheath” structure (Sol et al 1989; Laing 1996) in which the outer layers of the relativistic jet, which form the “sheath” have slower bulk velocity along the jet axis than do the inner layers, which form the “spine”. Such a structure could also explain the relative fractions of AGN that are γ–ray bright and radio bright, if the spine is predominantly γ–ray-emitting and the sheath is predominantly radio-emitting.

Dominated by relativistic electrons (leptonic component) or also protons (hadronic component) and other particles?

Initial part of the jet important place for the emission of very-high-energy radiation: it requires that the radiating particles, electrons or cosmic nuclei, are accelerated to even higher energies. A favoured acceleration process is Fermi (diffusive) shock acceleration: charged particles gain energy by the frequent and repeated crossing of a shock

Processes all happening in the very inner region of the jet

Collimation processes relevant for the properties of the jet on large scales: e.g. velocity, morphology and composition (light vs heavy jets)

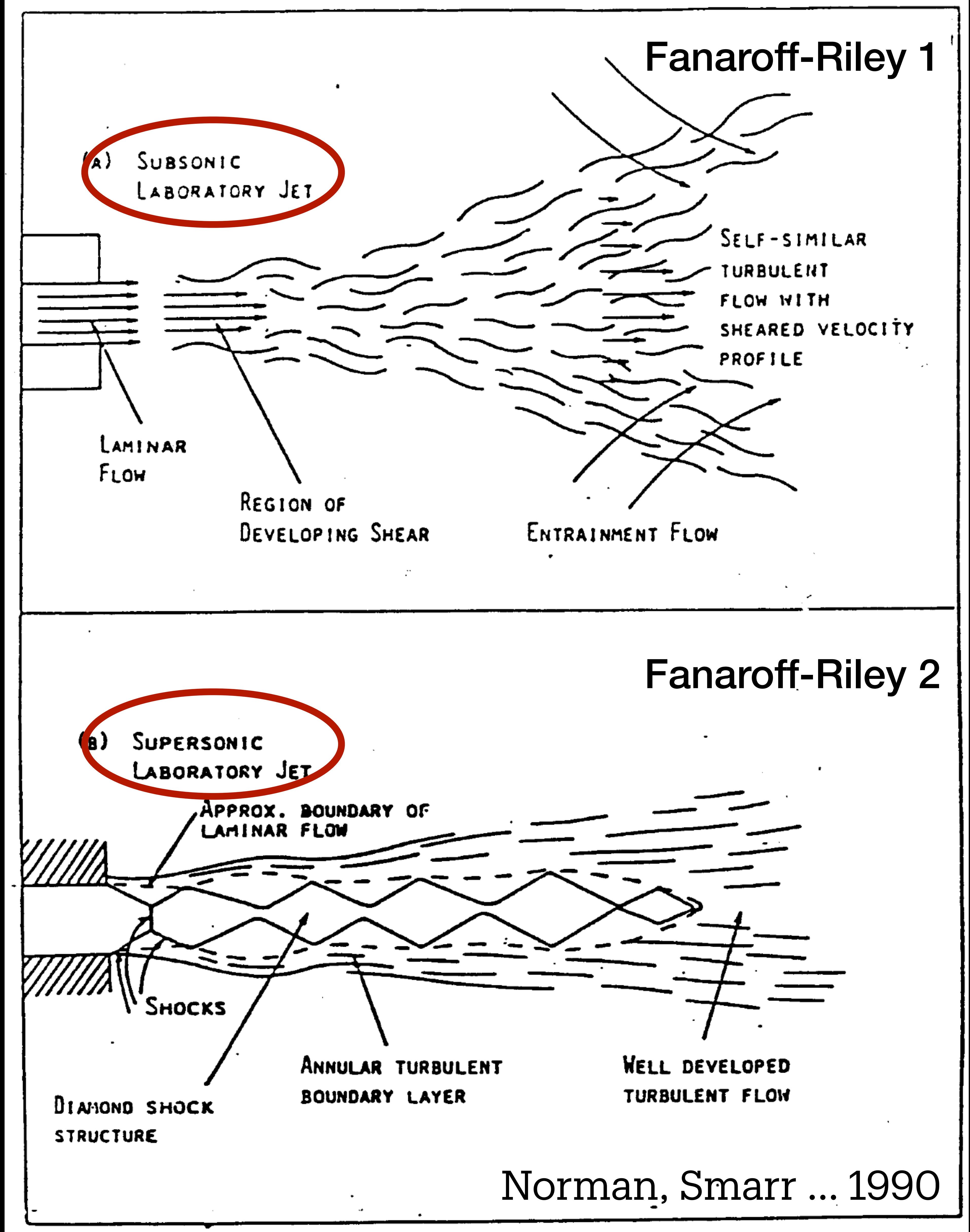
Two flavours for the large-scale jets:
supersonic and highly collimated
subsonic with entrainment

Mach number M = flow velocity/local sound speed
density ratio jet/external medium

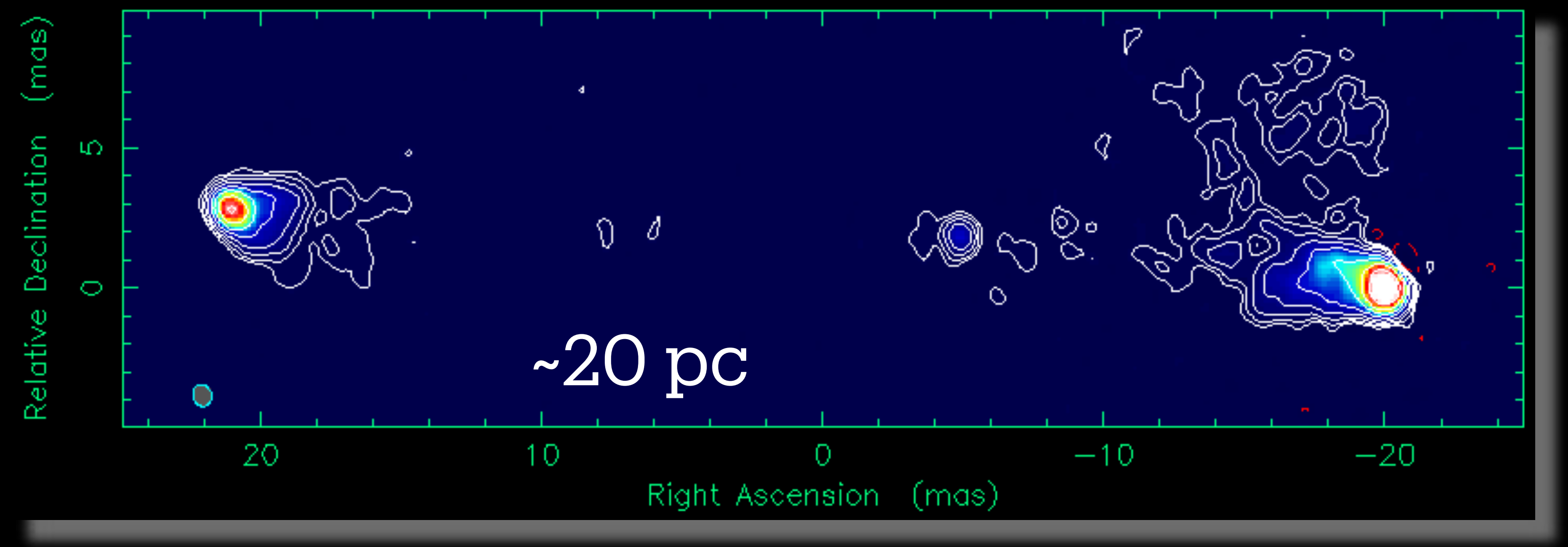
This can explain the presence of hot-spots and the collimation of the jets.

strong shock with the interstellar/galactic medium

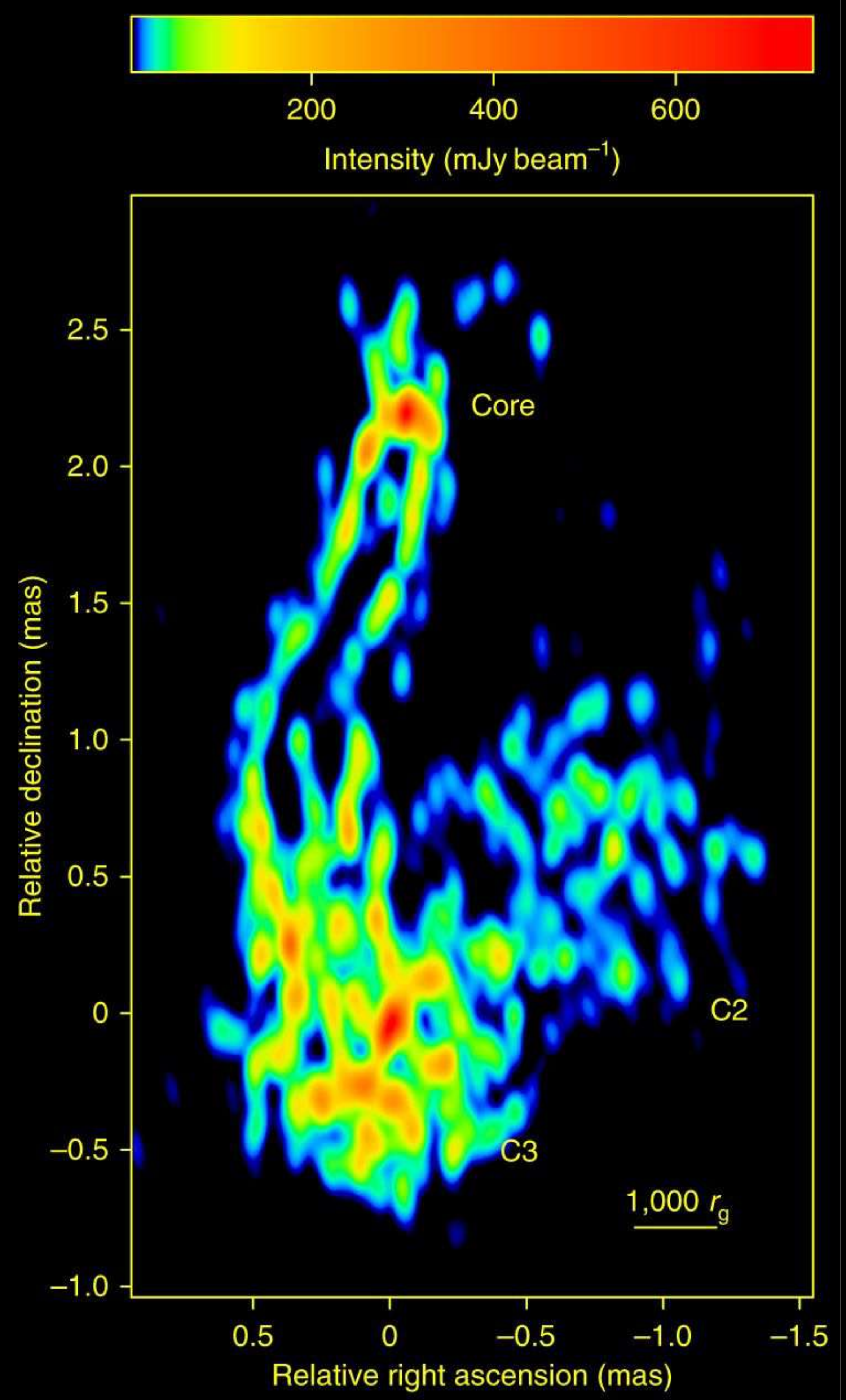
Dominated by relativistic electrons (leptonic component) or also protons (hadronic component) and other particles?



Norman, Smarr ... 1990



Are you still with me?



Radio AGN: emission from expanding jets originating from the nucleus (SMBH) and expanding creating radio lobes

Synchrotron emission from relativistic electrons in a magnetic field

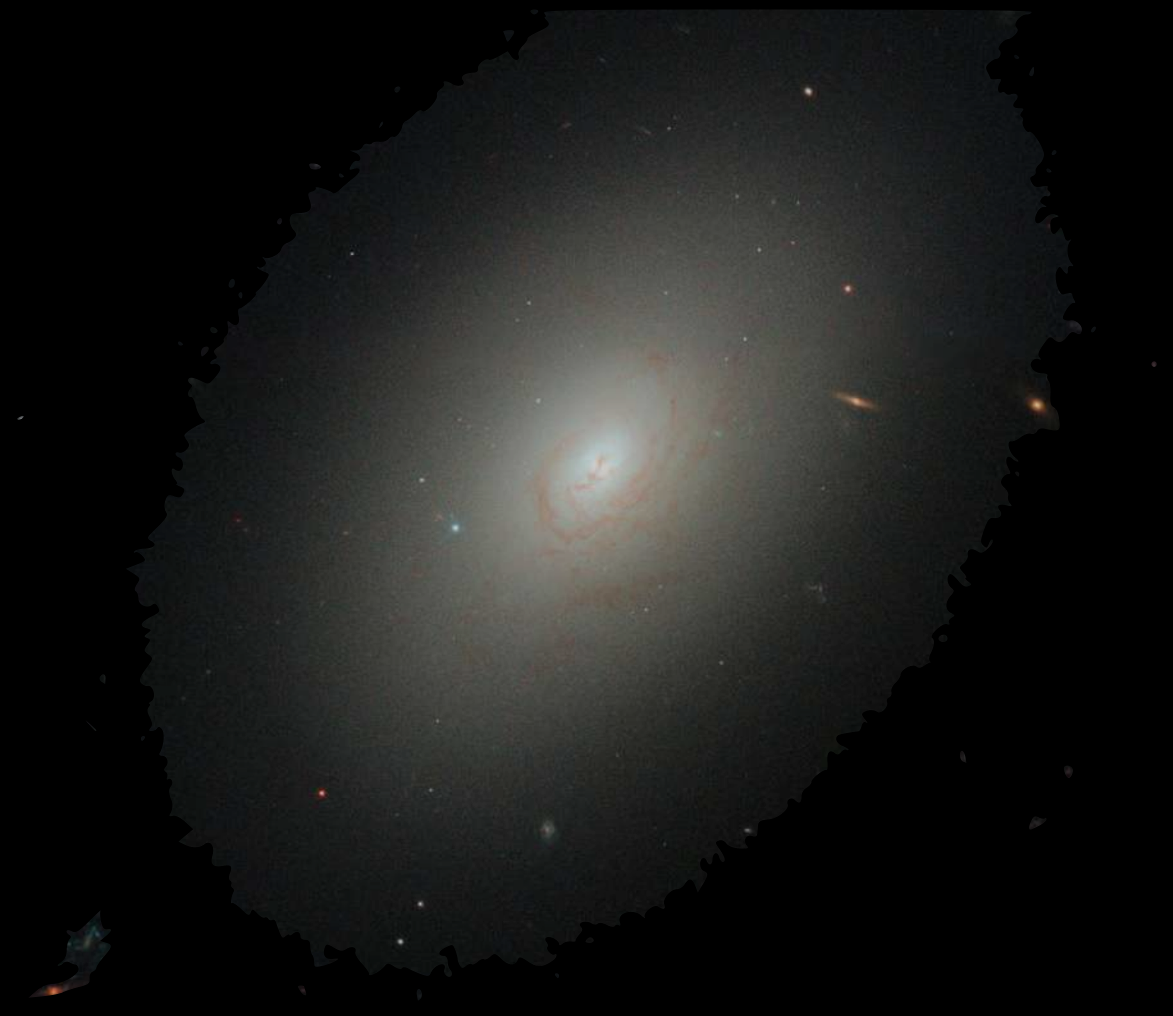
Different morphologies can tell about properties of the jet and environment

Collimation of the jets can impact the large scale evolution (velocity, entrainment etc.)

c) Synchrotron emission and spectral properties

the most common way of timing the radio AGN phase

Jets and lobes: evolution of a radio galaxy



Heinz et al. 2006

- Continuous injection of relativistic electrons: power law spectrum with steepening due to energy losses

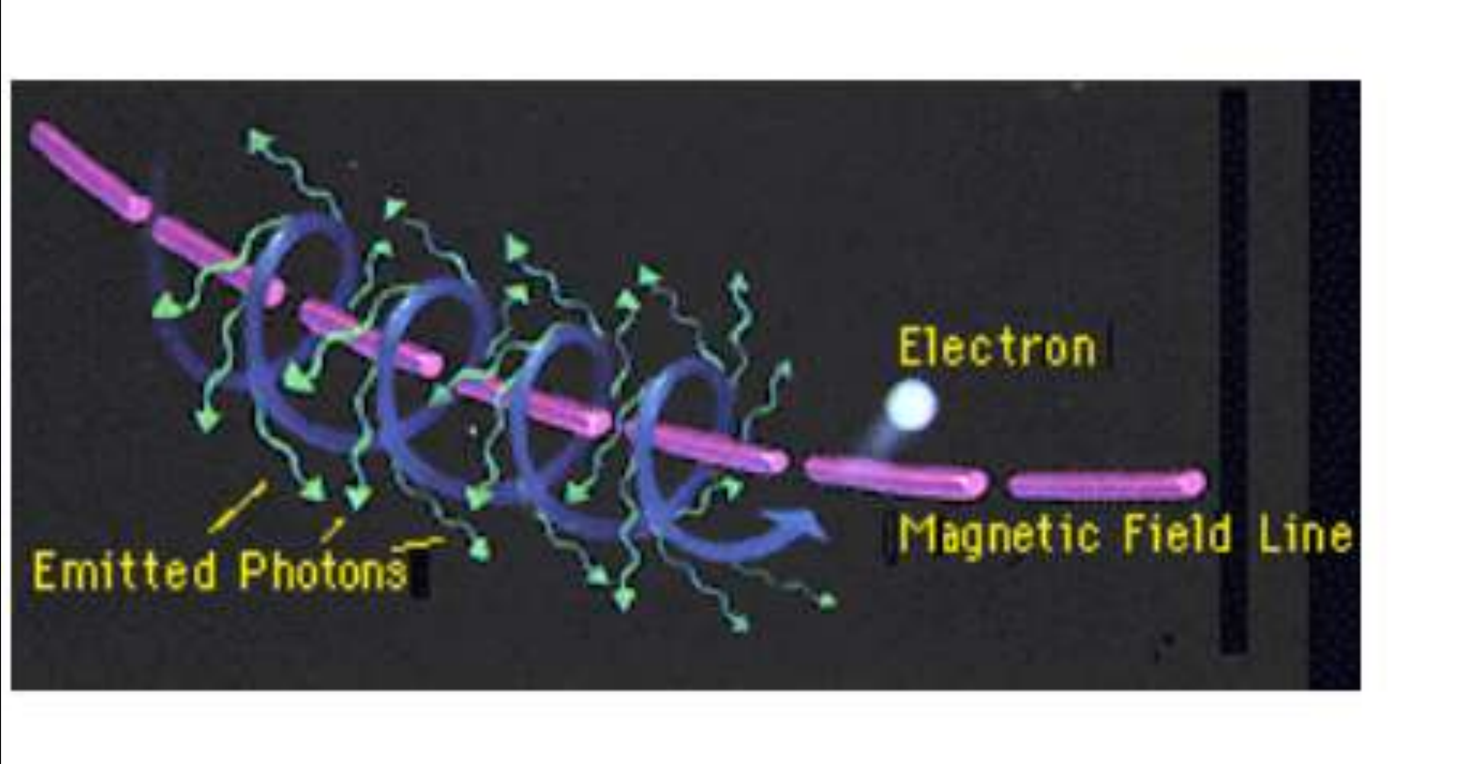
- Central energy supply stops: typical age a few 10^8 yr (but can be as short as 10^6 yr) and can restart

radio phase much shorter than the life of the host galaxy but radio AGN phase can repeat: on which time scales?
Important for defining the role of radio AGN for feedback

Continuum Radio emission mechanisms: "active" galaxies

Dominant mechanism: Synchrotron radiation

Particle accelerated by a magnetic field will radiate.
Emission but also synchrotron self-absorption: in compact structure ➙ density of relativistic electrons so high that the source is opaque at its own radiation
Beamed and polarised radiation



Energy of the electrons

$$E = \gamma m_e c^2$$

Lorentz factor

$$\gamma = \frac{1}{\sqrt{(1-(v/c)^2}}$$

Frequency of emission $\nu_c = \frac{3\gamma^2 eB}{4\pi m_e c} \sim 4.2 \times 10^6 \gamma^2 (\frac{B}{1G}) Hz$ magnetic field

Emission at e.g. 10GHz in a field 10^{-4} G ➜ $\gamma \sim 10^5$
➜ relativistic electrons ➜ cosmic ray origin

$$N(E)dE \propto E^{-s} dE$$

spectral index

$$\alpha = (s-1)/2$$

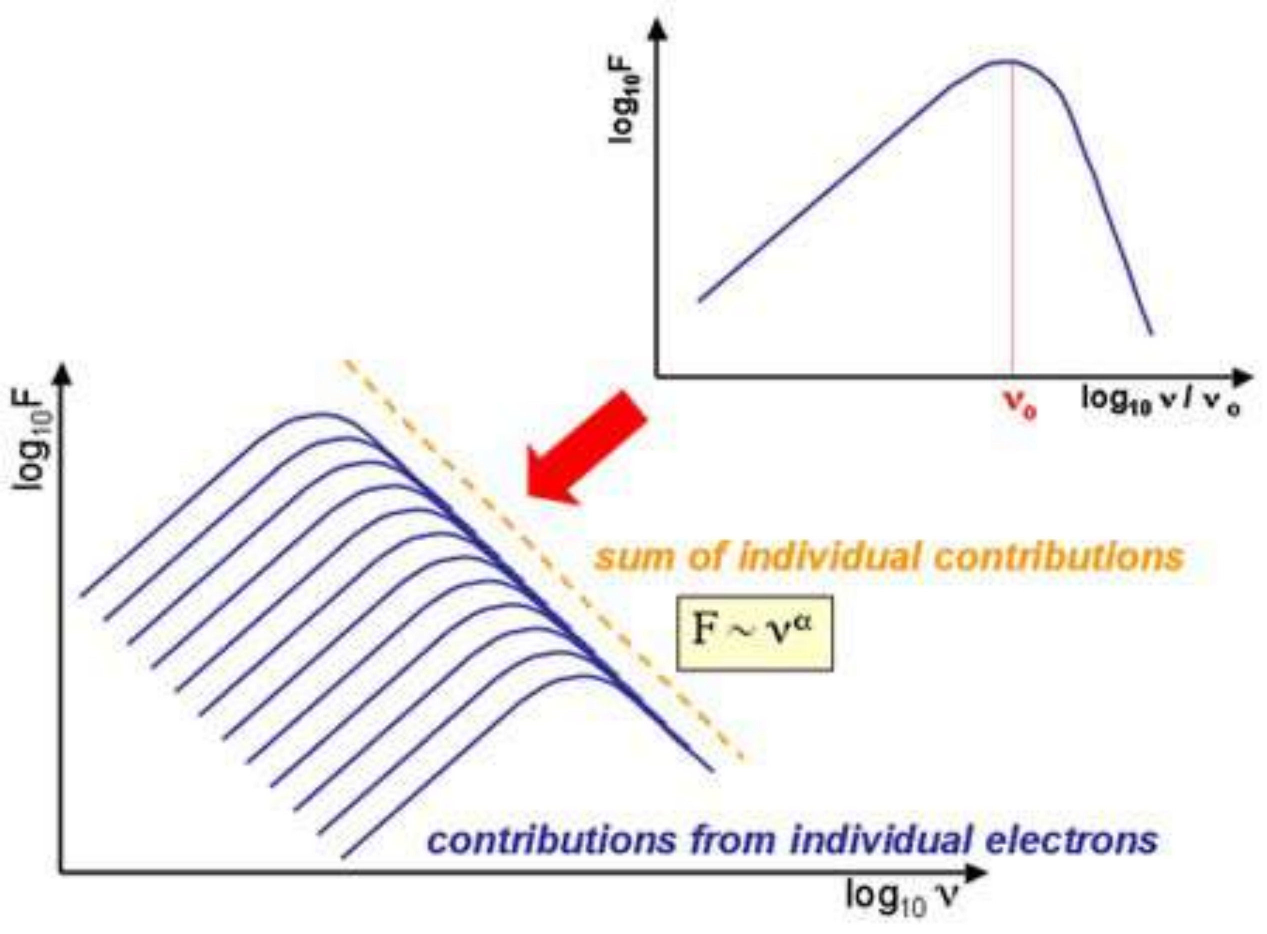
emitted flux

$$F \propto \nu^{\alpha}$$

spectral index

observed α~0.7 ➙ s~2.4
consistent with measured spectrum of cosmic rays

also indicated as
$F \propto \nu^{-\alpha}$
(check always the definition in papers)

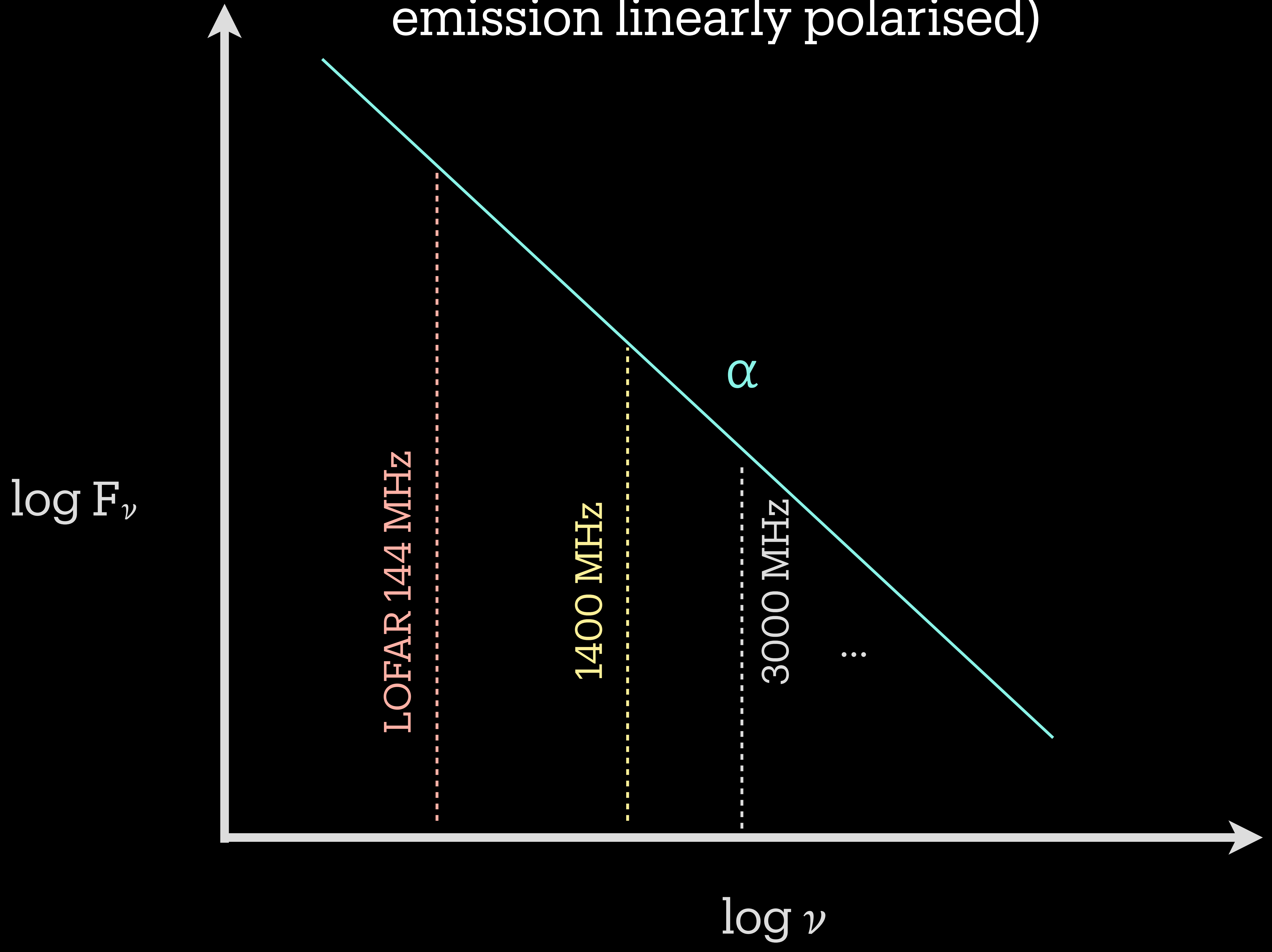


ensemble of relativistic electrons
➙ power law spectrum
in absence of absorption mechanisms...

An important tool: the radio spectrum

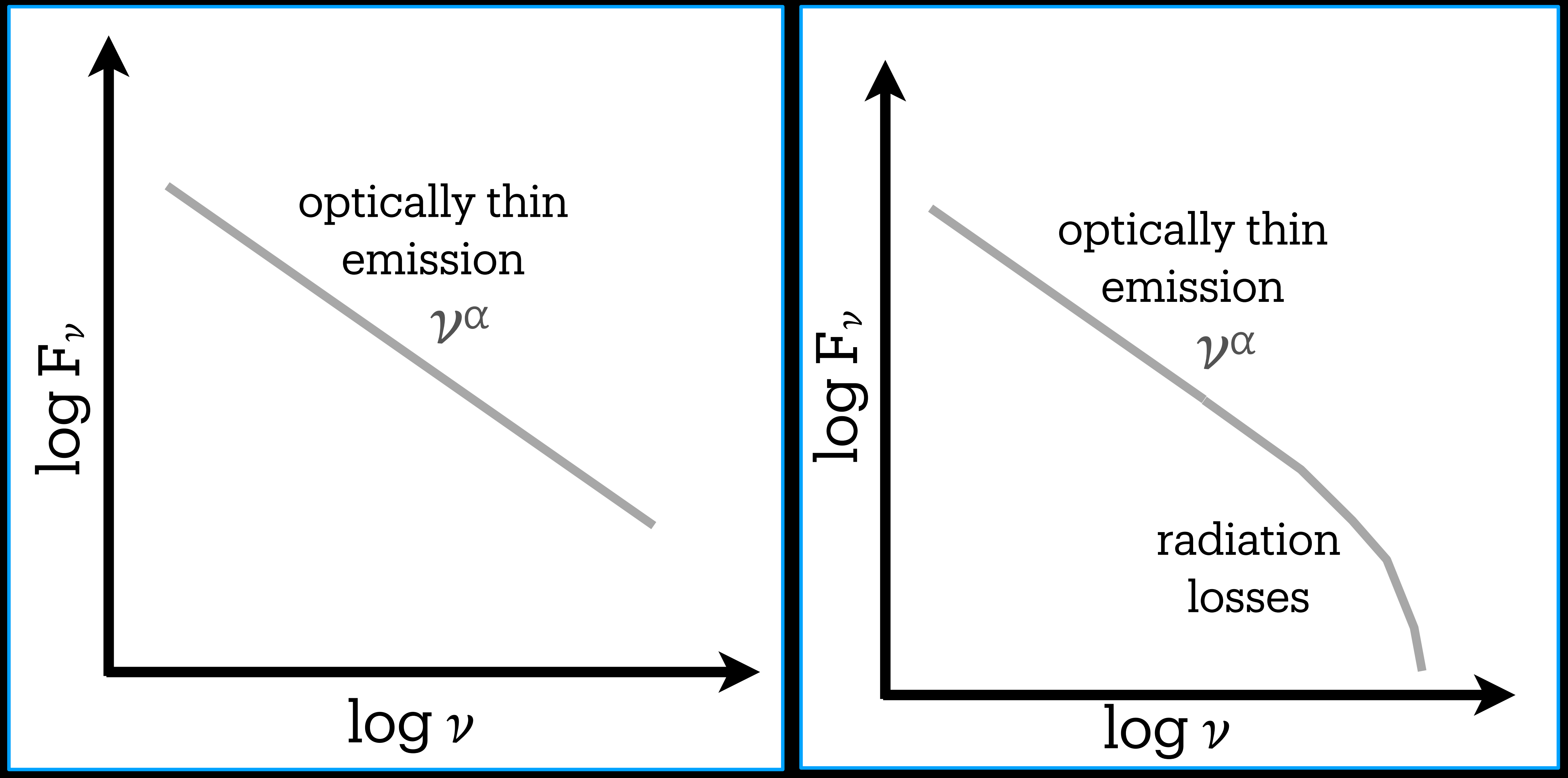
Synchrotron spectrum $F \propto \nu^{\alpha}$

(magnetic field and relativistic electrons emission linearly polarised)



typical spectral index for active radio AGN

α around -0.7 to -0.8



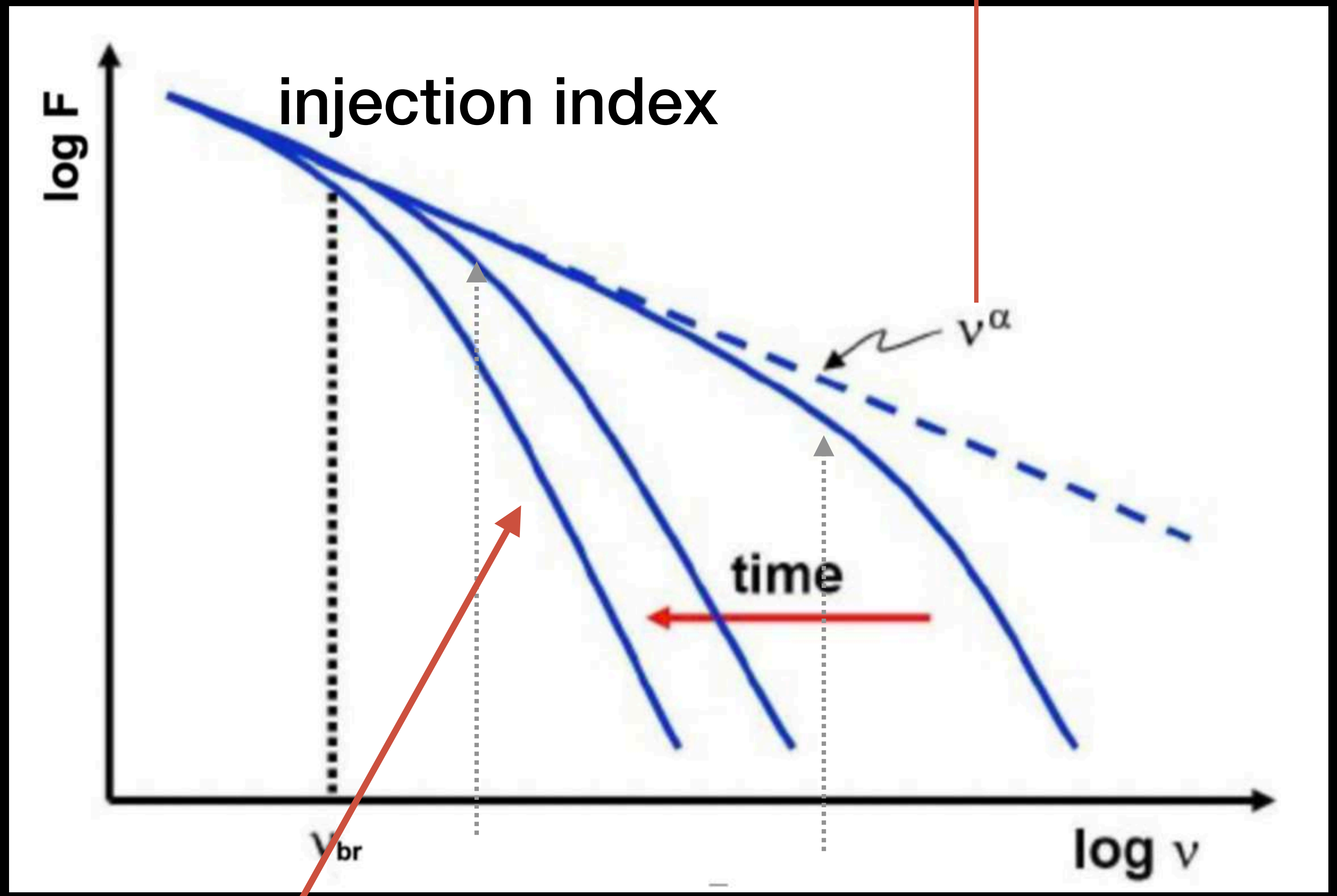
with multiple frequencies we can trace the history of the radio emission

Importance of the spectral indices: tracing the energy losses

The relativistic electrons lose energy because of a number of process:
synchrotron emission, adiabatic expansion of the source, inverse-Compton etc.

➡ the energy distribution (and therefore the spectrum of the emitted radiation) tend to modify with time ➝ ageing

Typical synchrotron spectral index -0.7



Rate of loss of energy by the electron to synchrotron emission

Characteristic electron half-life time (time for energy to half) time for an electron to lose half of its initial energy E_0

$$\frac{dE}{dt} = const \times B^2 E \sim const \times B^2 \gamma$$

$$t_{1/2} = (const \times B^2 E_0)^{-1} yr$$

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

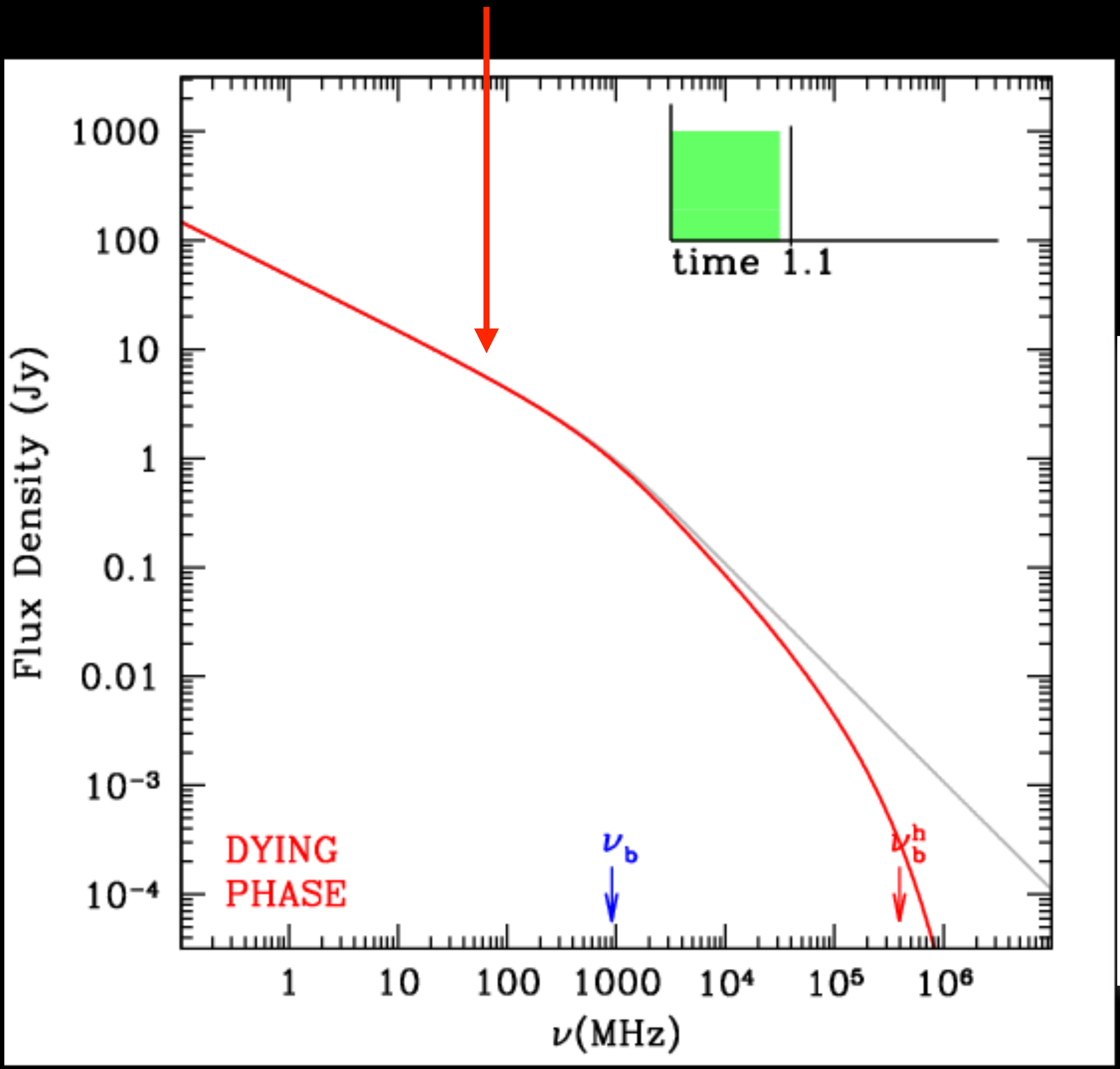
For $\nu < \nu_{break}$ the spectral index remains unchanged ➔ injection index

Higher B magnetic field and higher γ ➔ higher frequency of the emission, higher emitted radiation, shorter life time

$$\nu_{break} \sim B^{-3}\, t_{yr}^{-2} \quad GHz$$

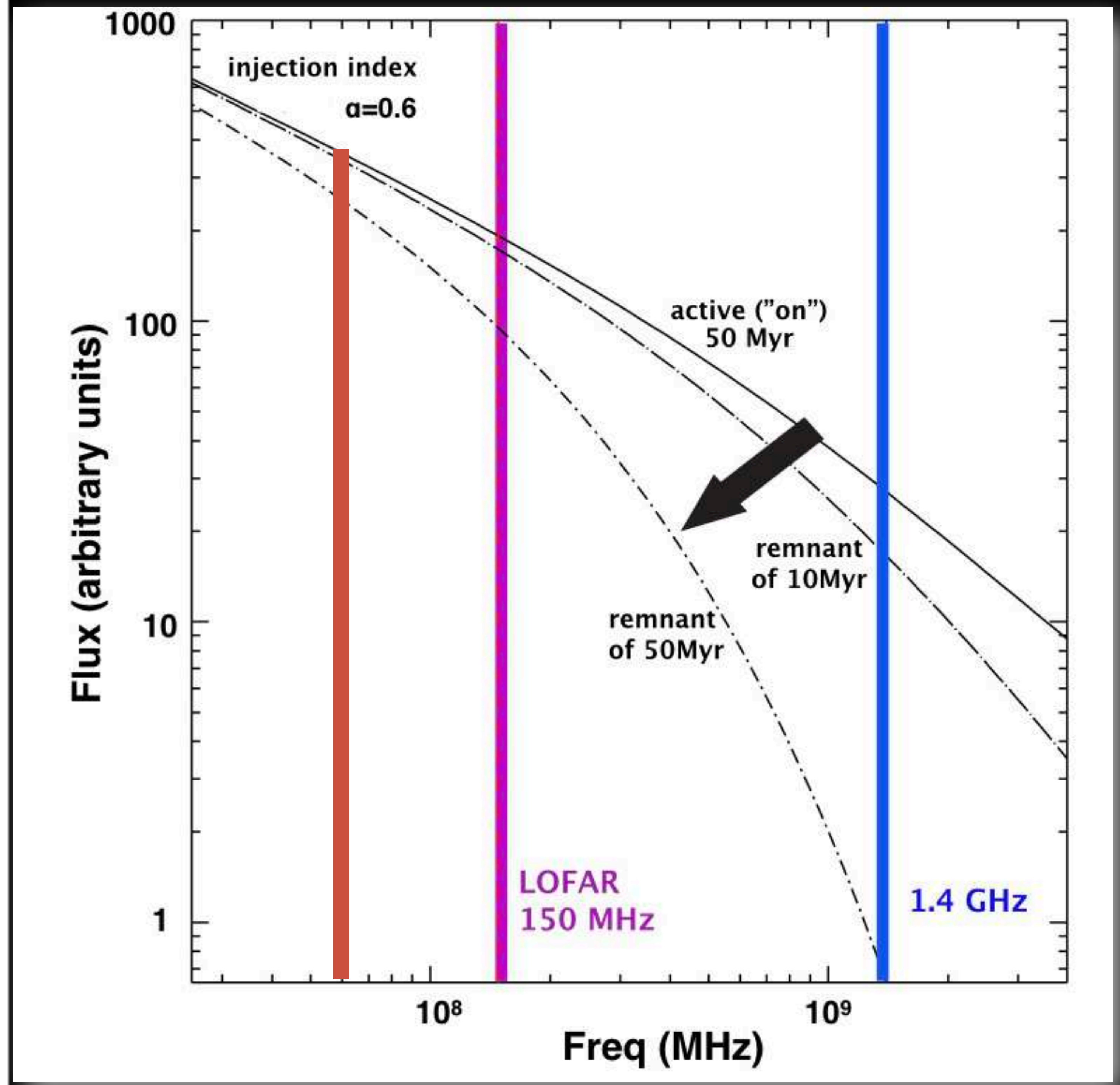
when the nuclear activity stops (dying sources) the spectrum shows an extra steepening (steeper than -1.2)

Adding the spectral information
Low frequencies last affected by ageing....



Sampling many frequencies is the only way to trace the ageing and evolution process

Key to have the low frequencies



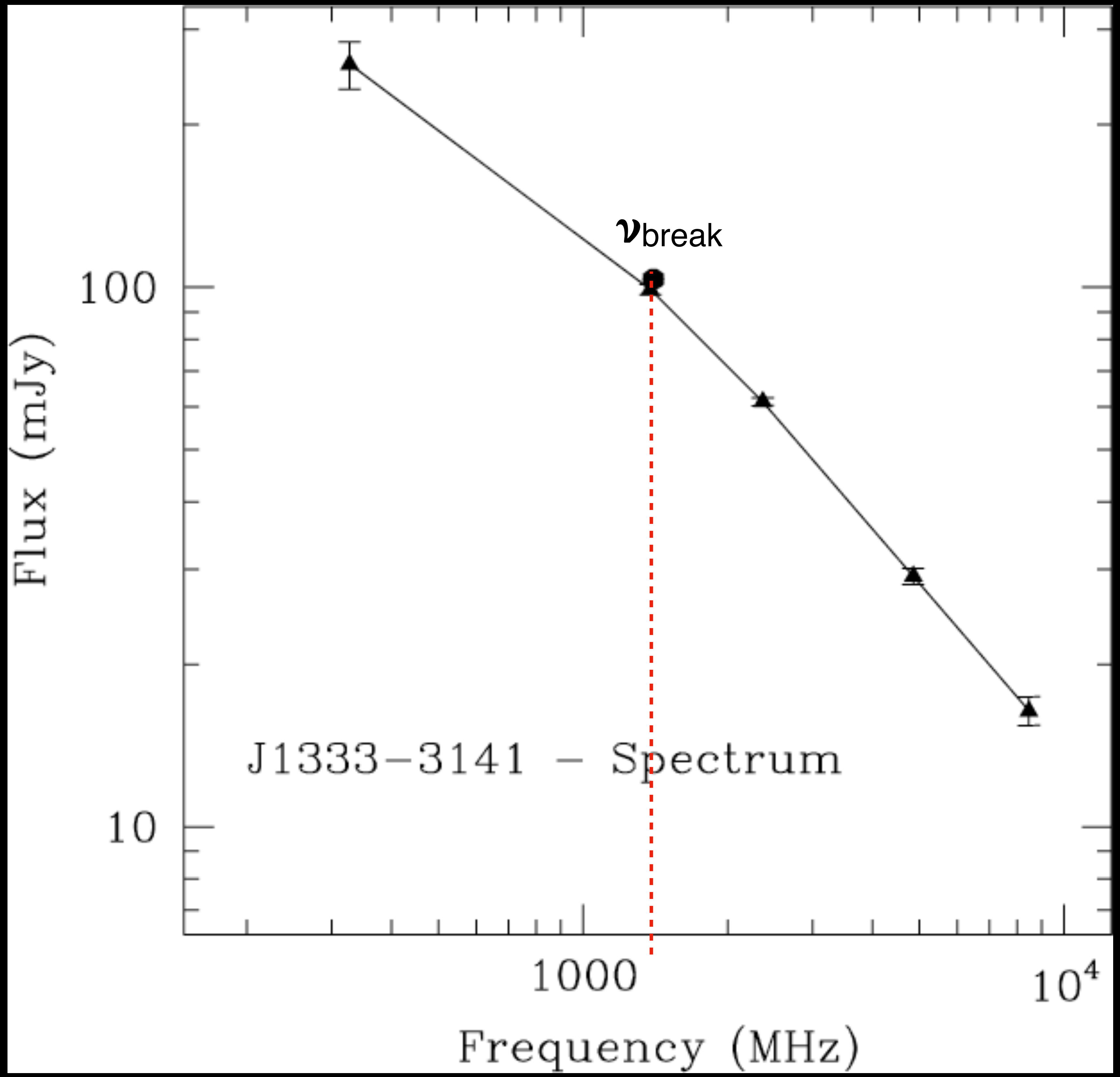
Morganti 2017

Courtesy of M. Murgia

An example...

...as we have seen earlier:

$$\upsilon_{break} \sim B^{-3} t_{yr}^{-2} \quad GHz$$



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

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

Typically 50 - 20 Myr for B=10μG
for ν_{break} between 1 and 8 GHz

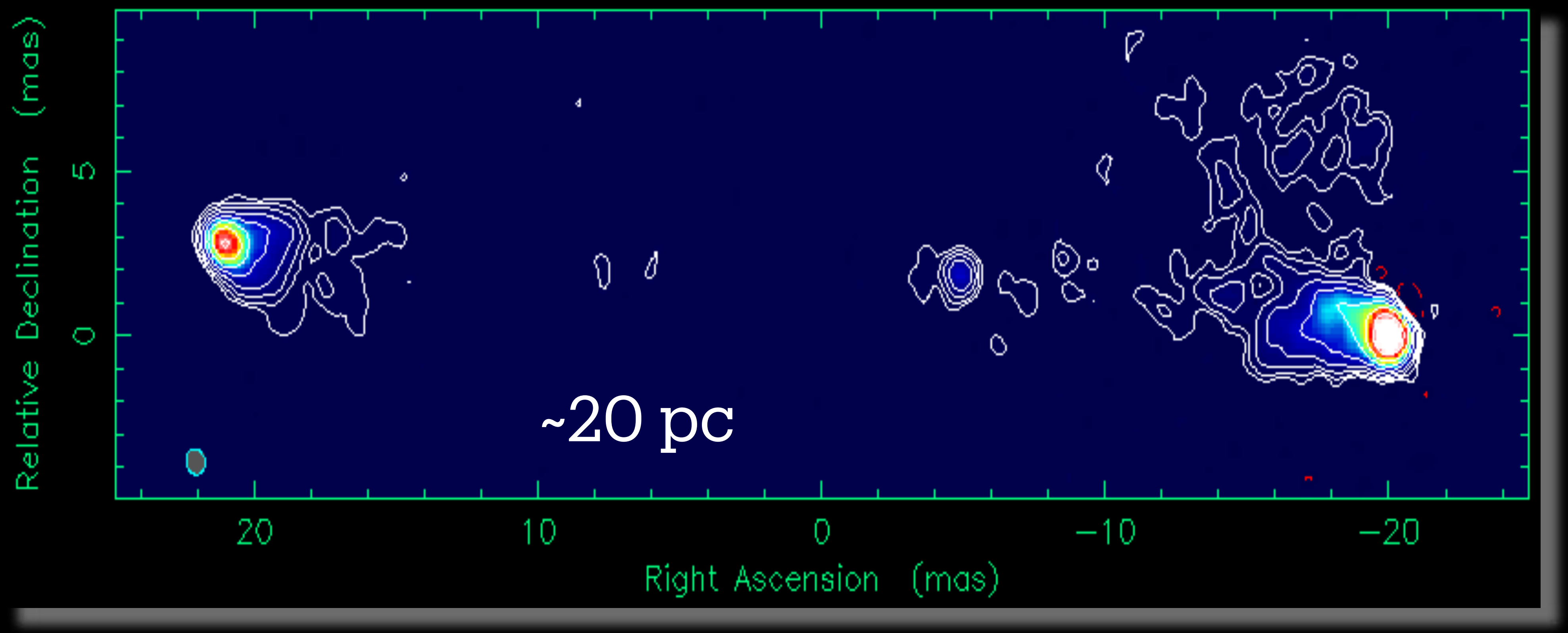
typical ages of the active phase around few x 10^7 to few 10^8 yr

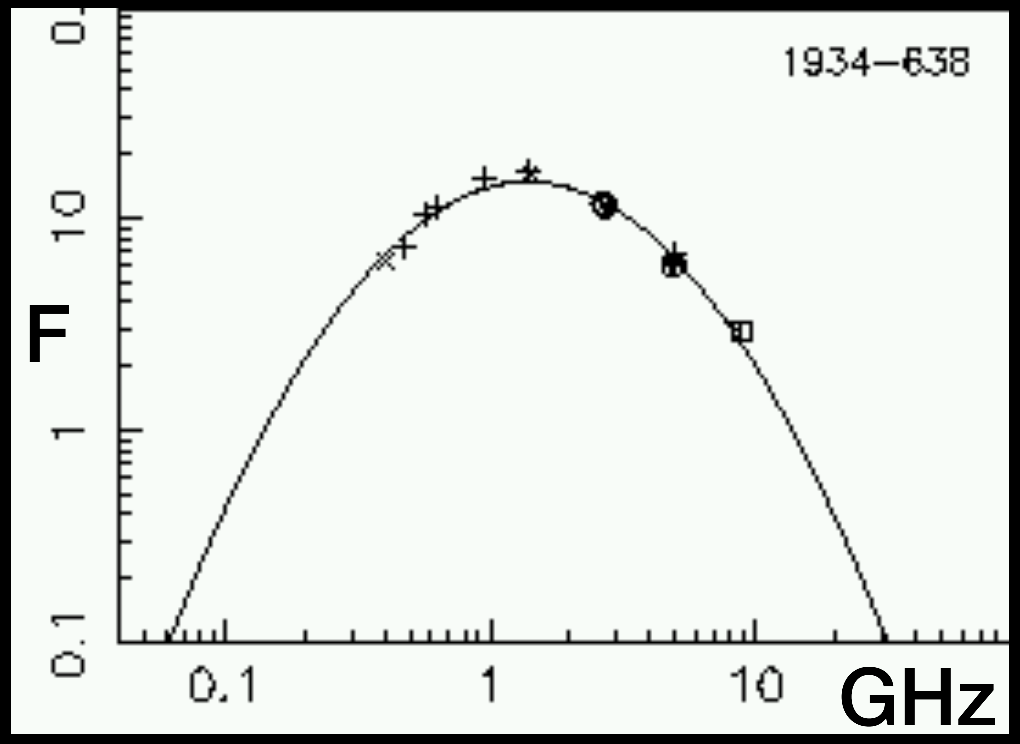
Unless there is re-acceleration in some regions of the radio source!

Not always a power law: young radio AGN when the absorption is present in the spectrum

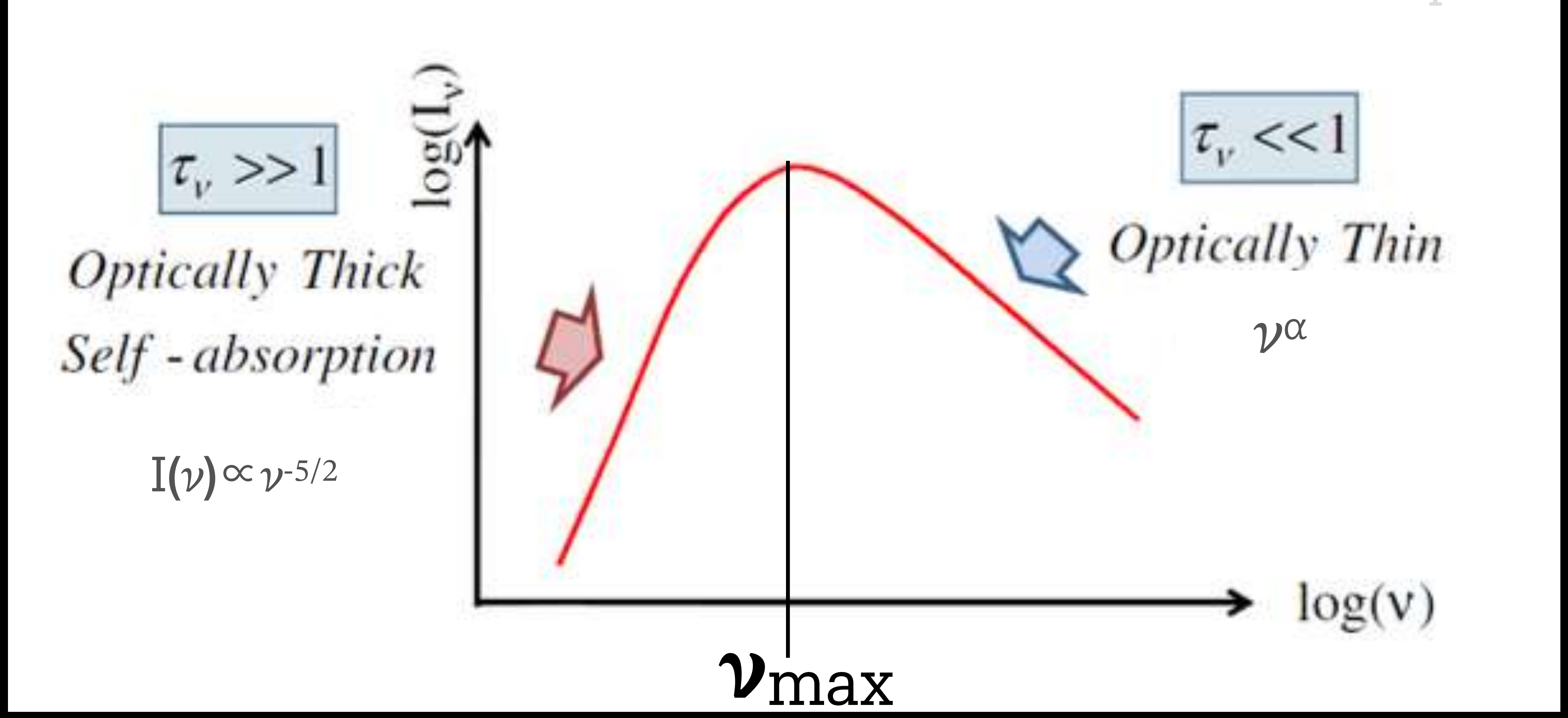
compact peaked sources

see review O'Dea & Saikia 2022



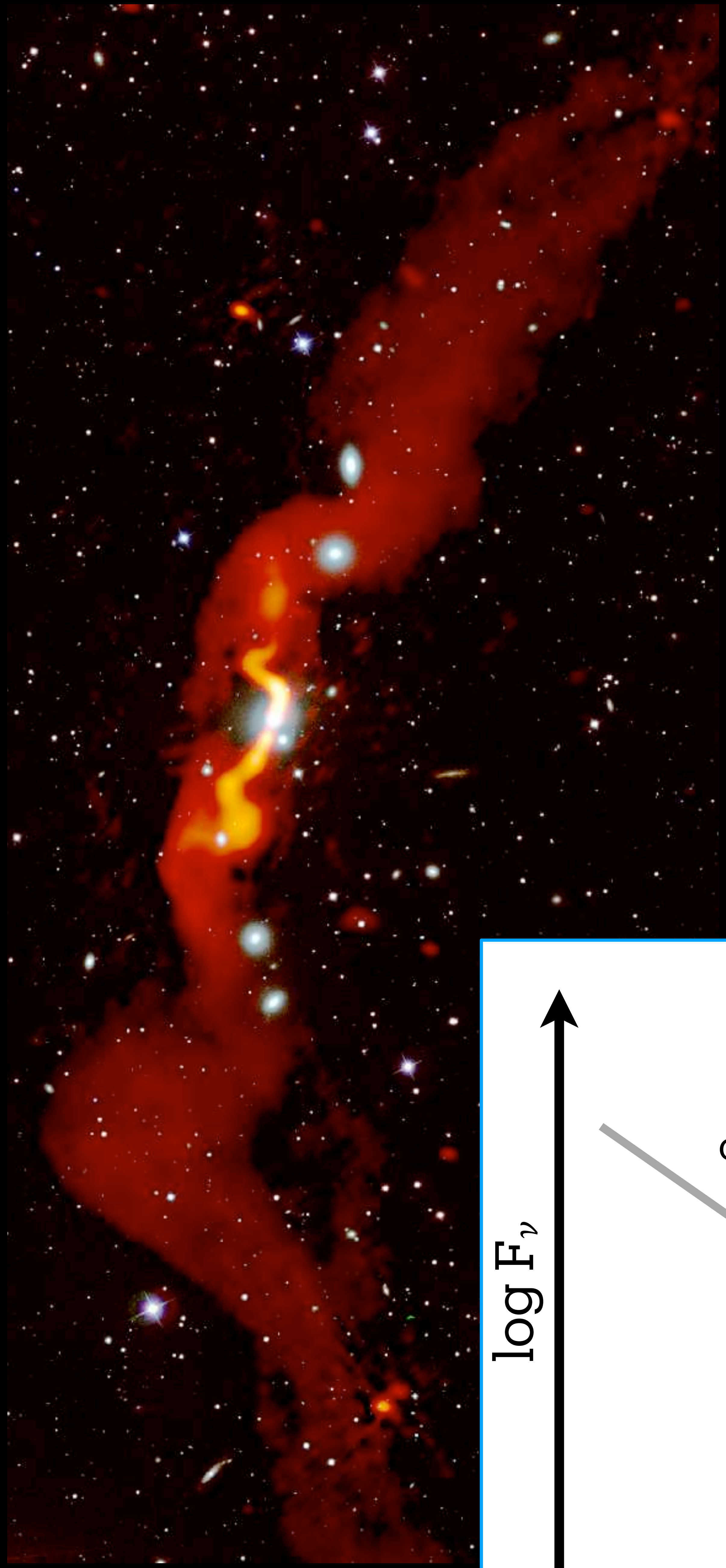


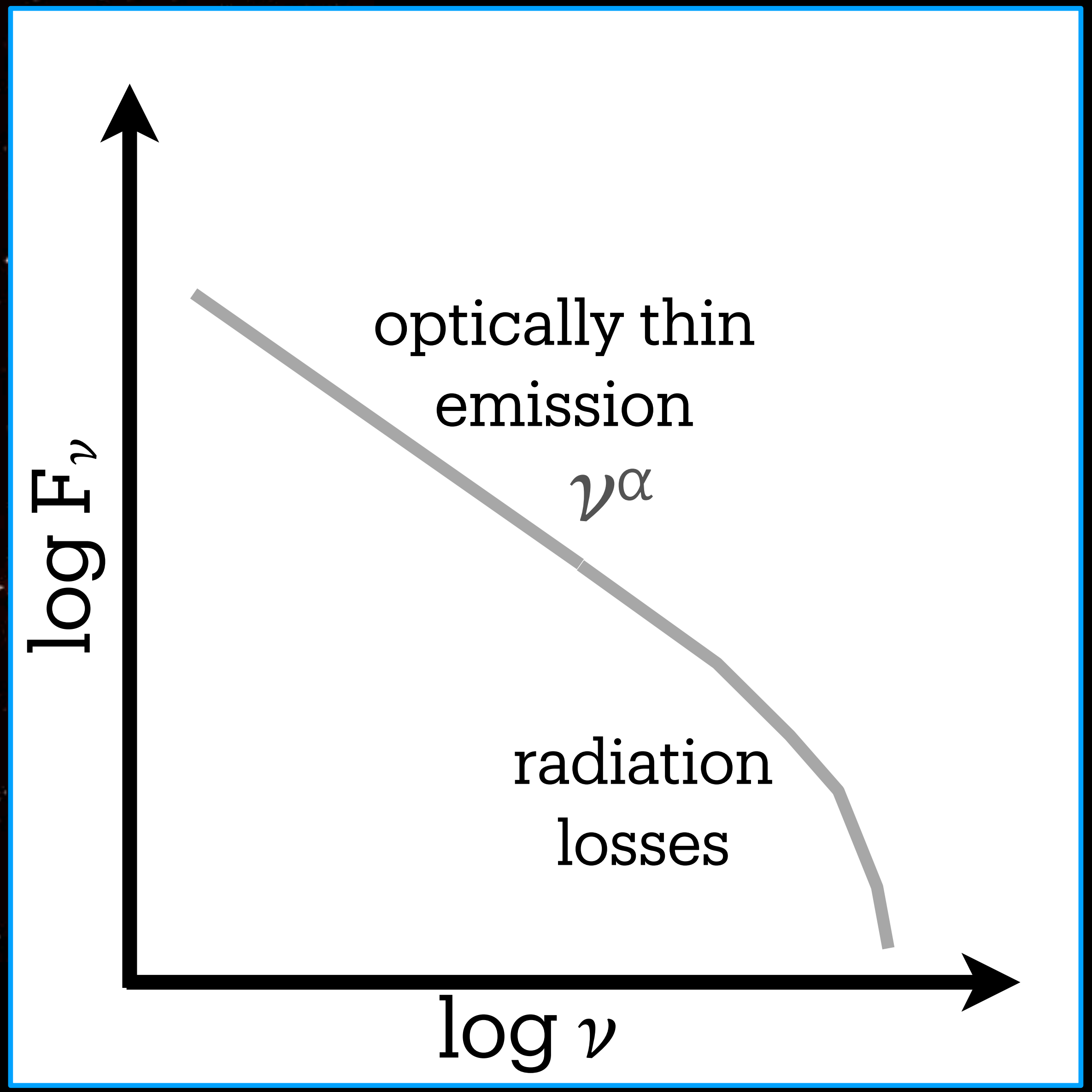
Optically thick case: the internal absorption from the electrons needs to be considered synchrotron self absorption or free-free absorption



ν_{max} moving to low frequency as the source expands and the emission becomes optically thin: we use this to derive the age of the radio source in this first stage (typically $<<10^6$ yr)

Are you still with me?





Spectral shape very useful diagnostic

Power law spectrum which tend to modify with time:

compact peaked spectrum ➙ can identify young sources ($<10^6$ yr)

steepening with the ageing of the electrons due to e.g. radiative losses

Ultra steep spectrum for dying sources (where the activity has stopped)

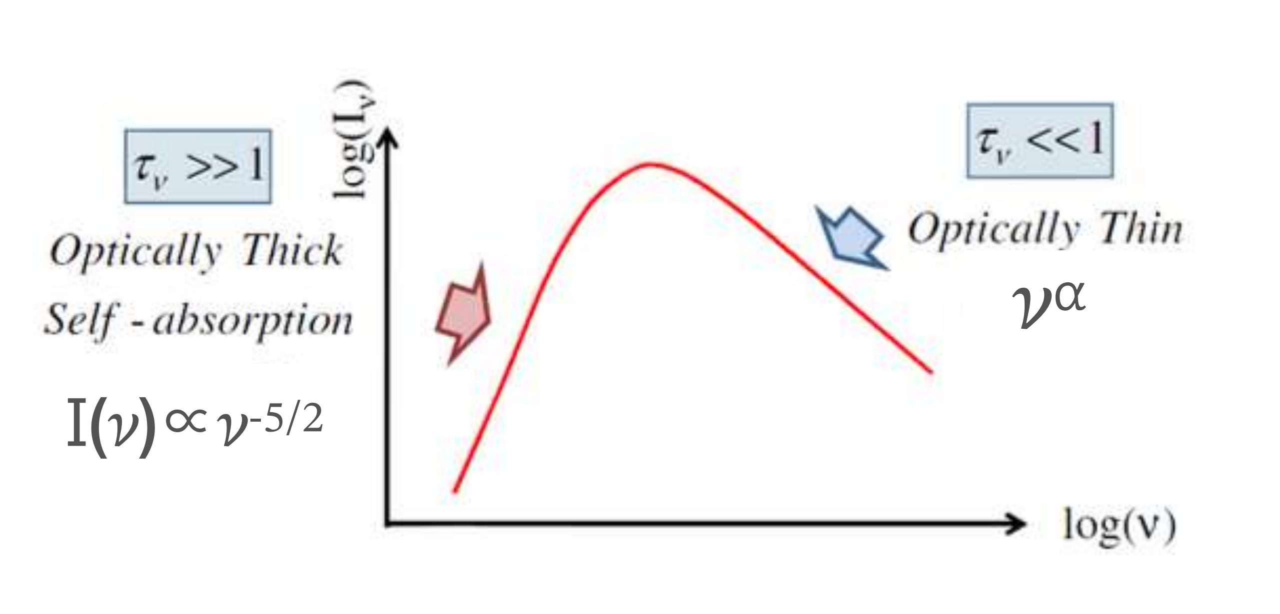
Unique possibility to time (to first order) the activity ...

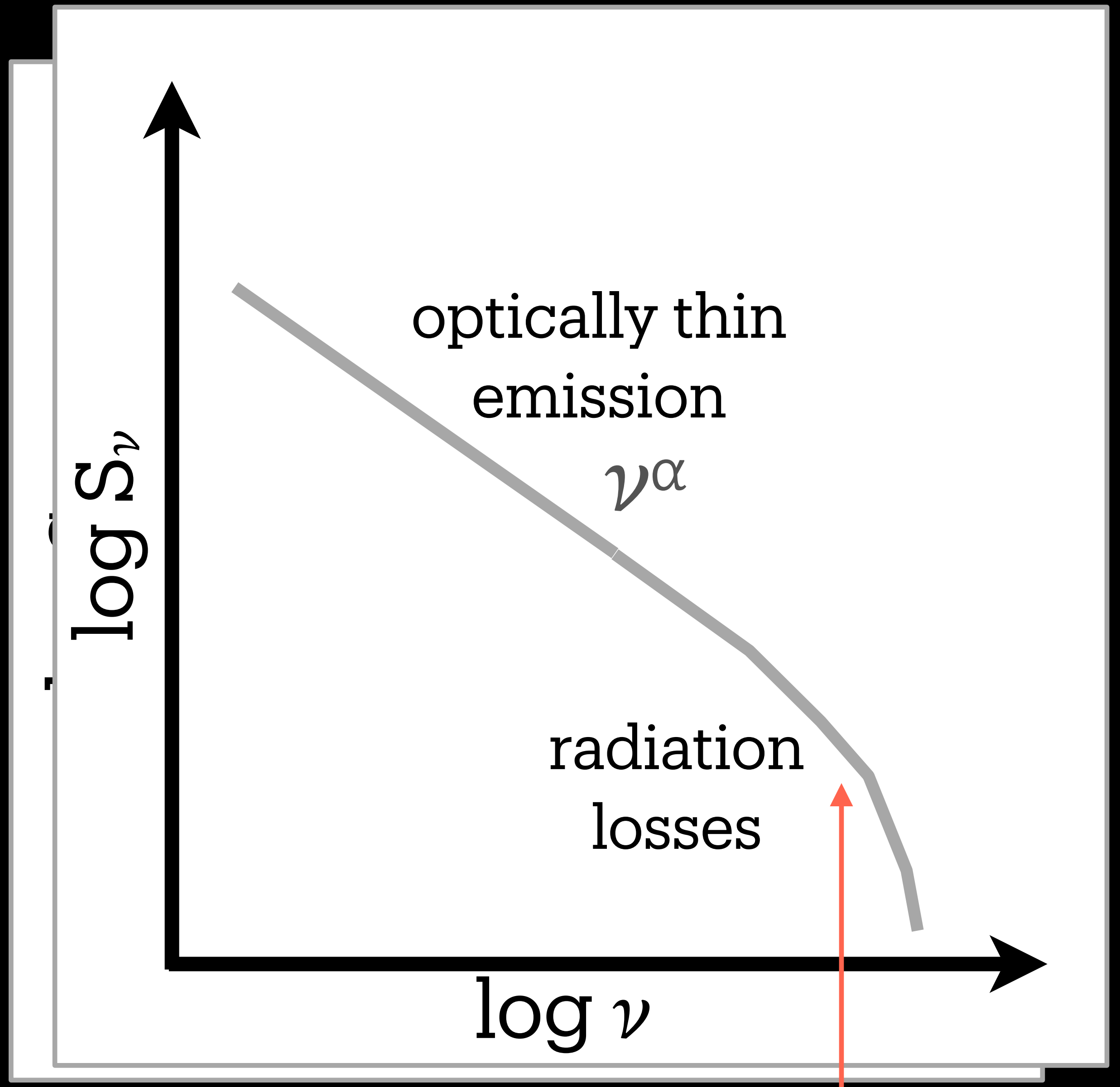
d) The cycle of life of radio AGN

Young, adult, dying and restarted.
How to identify these phases and how long do they last
(i.e. fraction of radio AGN in the different phases)

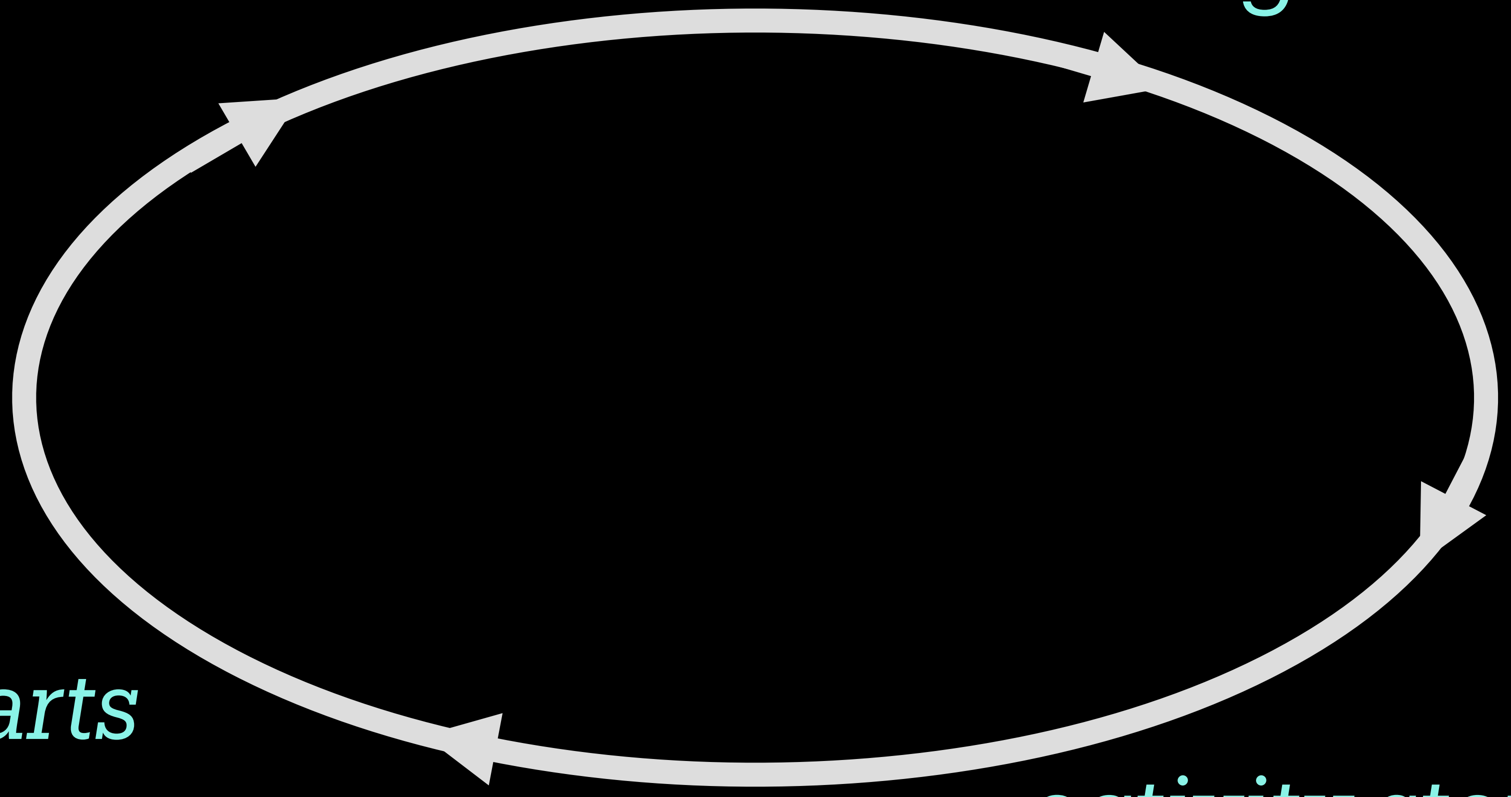
(connect to AGN feedback ➝ Les 3)

Radio AGN evolution imprinted in the radio spectrum





proportional to age



new born jet

10^5-10^6 yr

growing to adult source and ageing

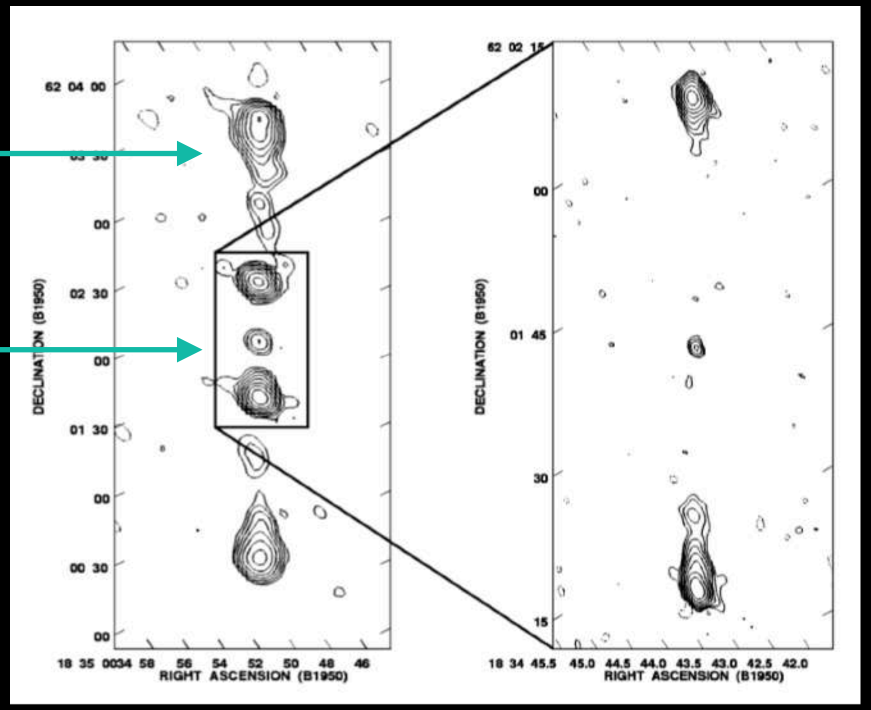
10^7-10^8 yr

activity stops - remnant/dying

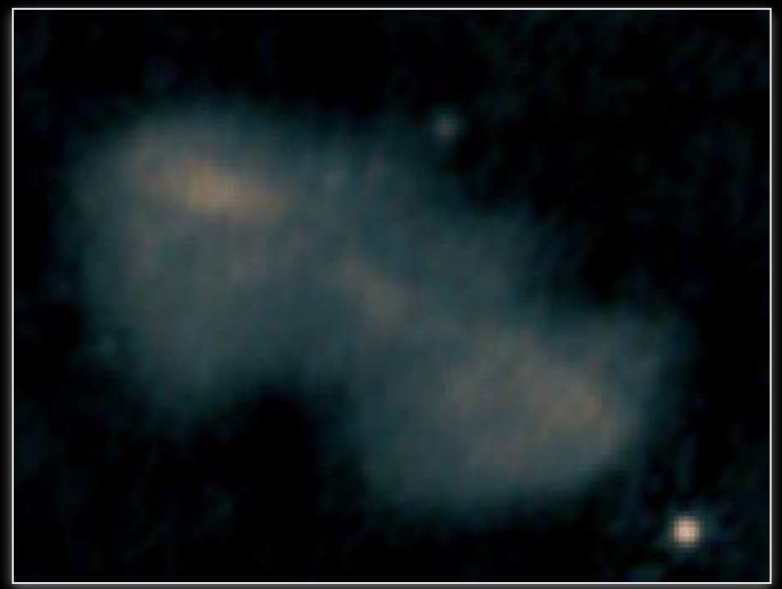
activity restarts

old phase

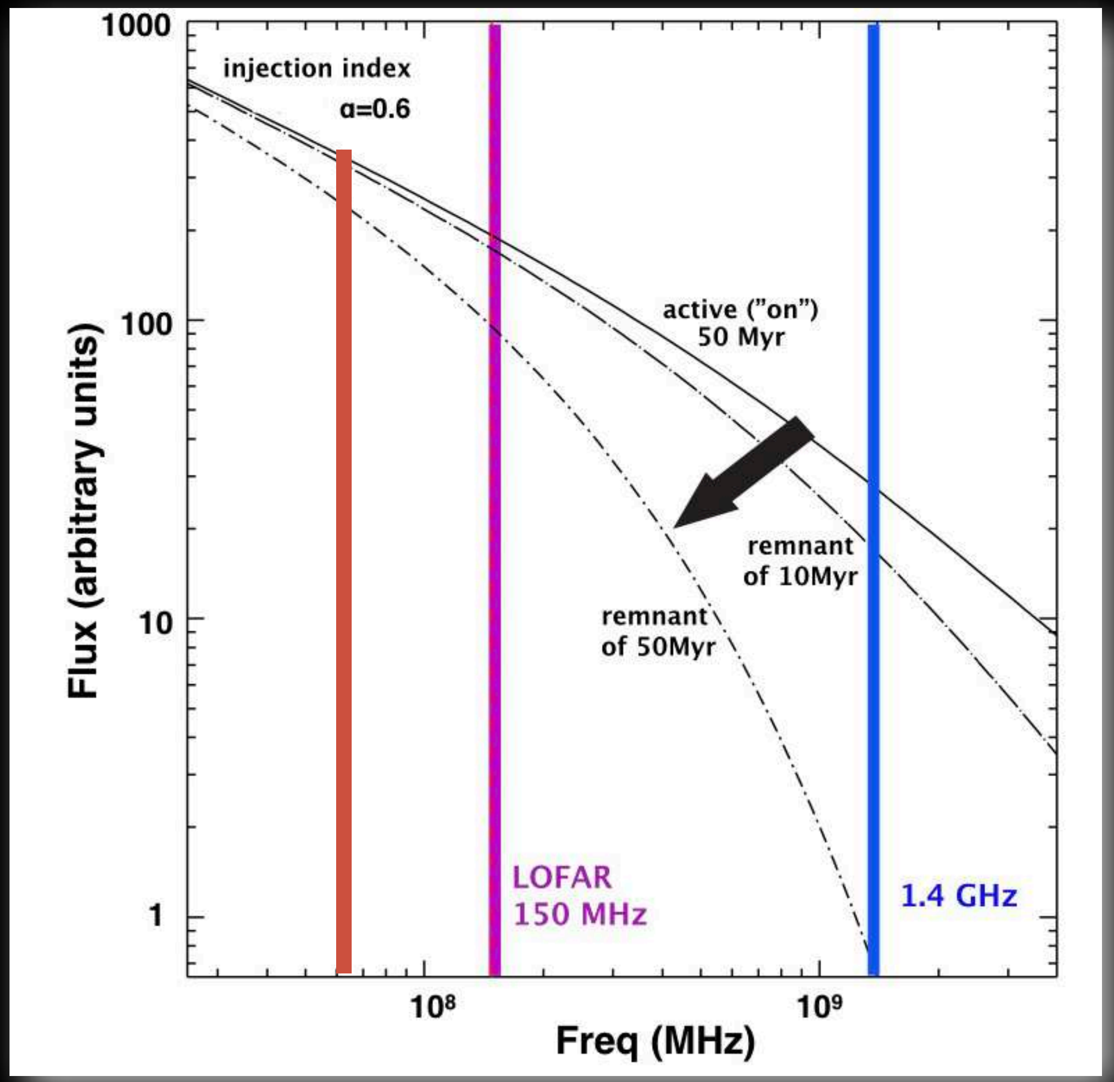
new born jet



Schoenmakers et al. 1999



B2 0924 Shulevski et al.



life-cycle: a key requirement for feedback

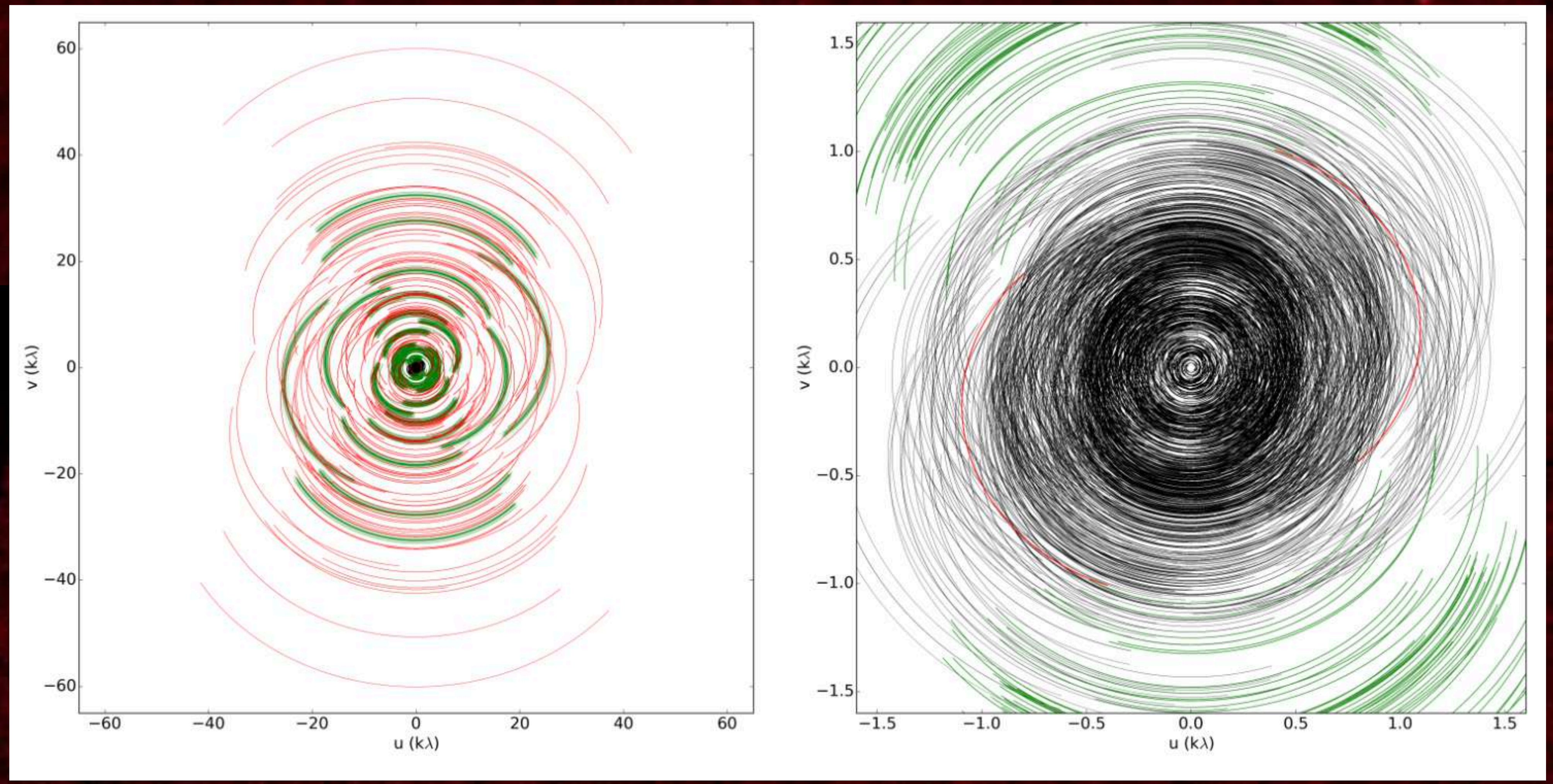
Importance of good low frequency images: LOFAR

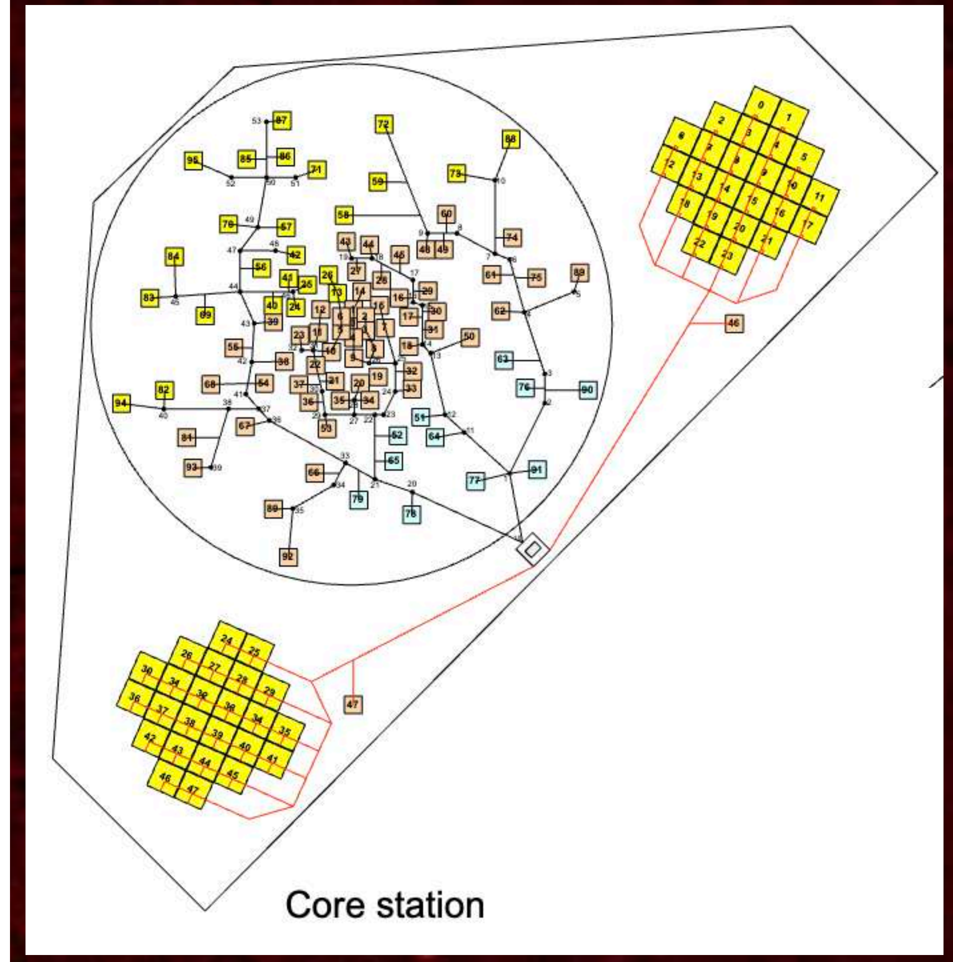
LOFAR image @ 150 MHz

Importance of good low frequency images: LOFAR

LOFAR surveys in the northern sky: https://lofar-surveys.org/
6 arcsec resolution at 150MHz

LOFAR (NL) central core "superterp"
HBA=150 MHz(2 m) and LBA=50 MHz





uv coverage of LOFAR Dutch stations @ 150 MHz

van Haarlem et al. 2017

Importance of good low frequency images: LOFAR

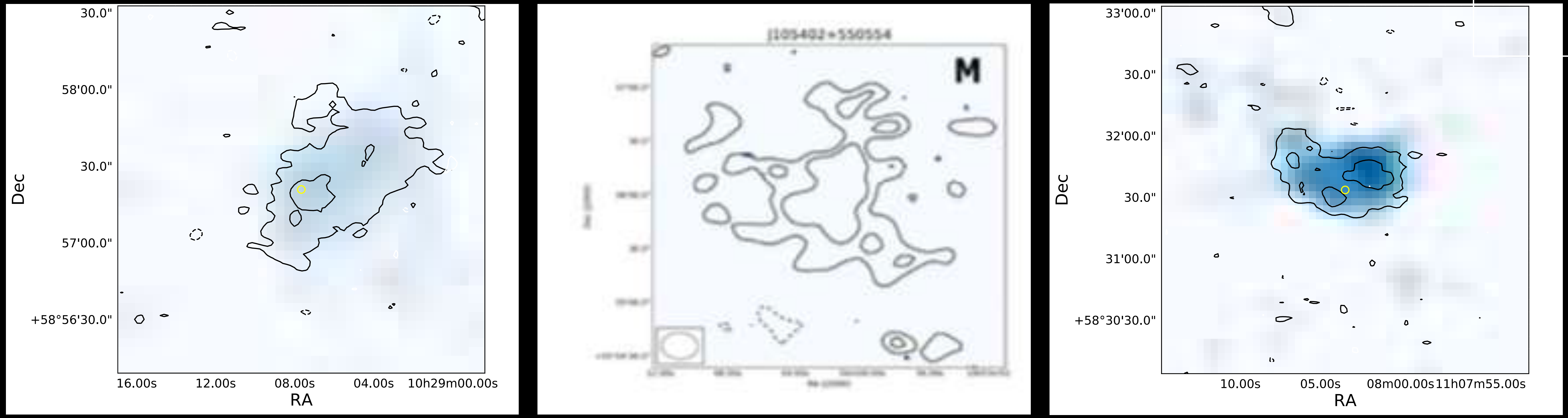
LOFAR image @ 150 MHz

Looking for remnant/dying sources with LOFAR

Selection based on
morphology (>60”)
Amorphous, low surface brightness
(10 - 30 mJy arcmin^{-2} @150MHz)
low core prominence
and ultra-steep spectrum emission

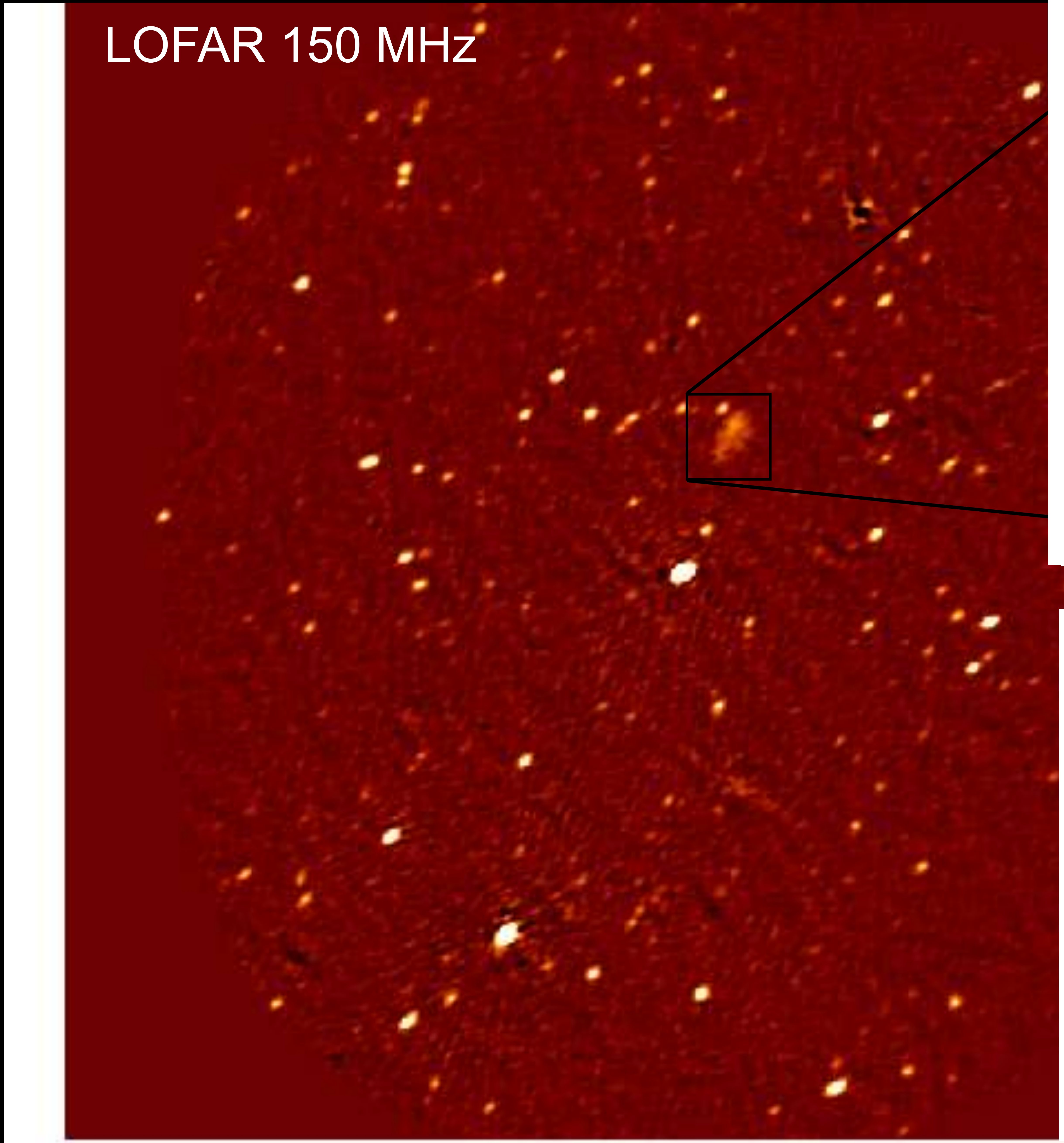
Using all criteria, up to 10% radio sources are remnants (dying radio sources)

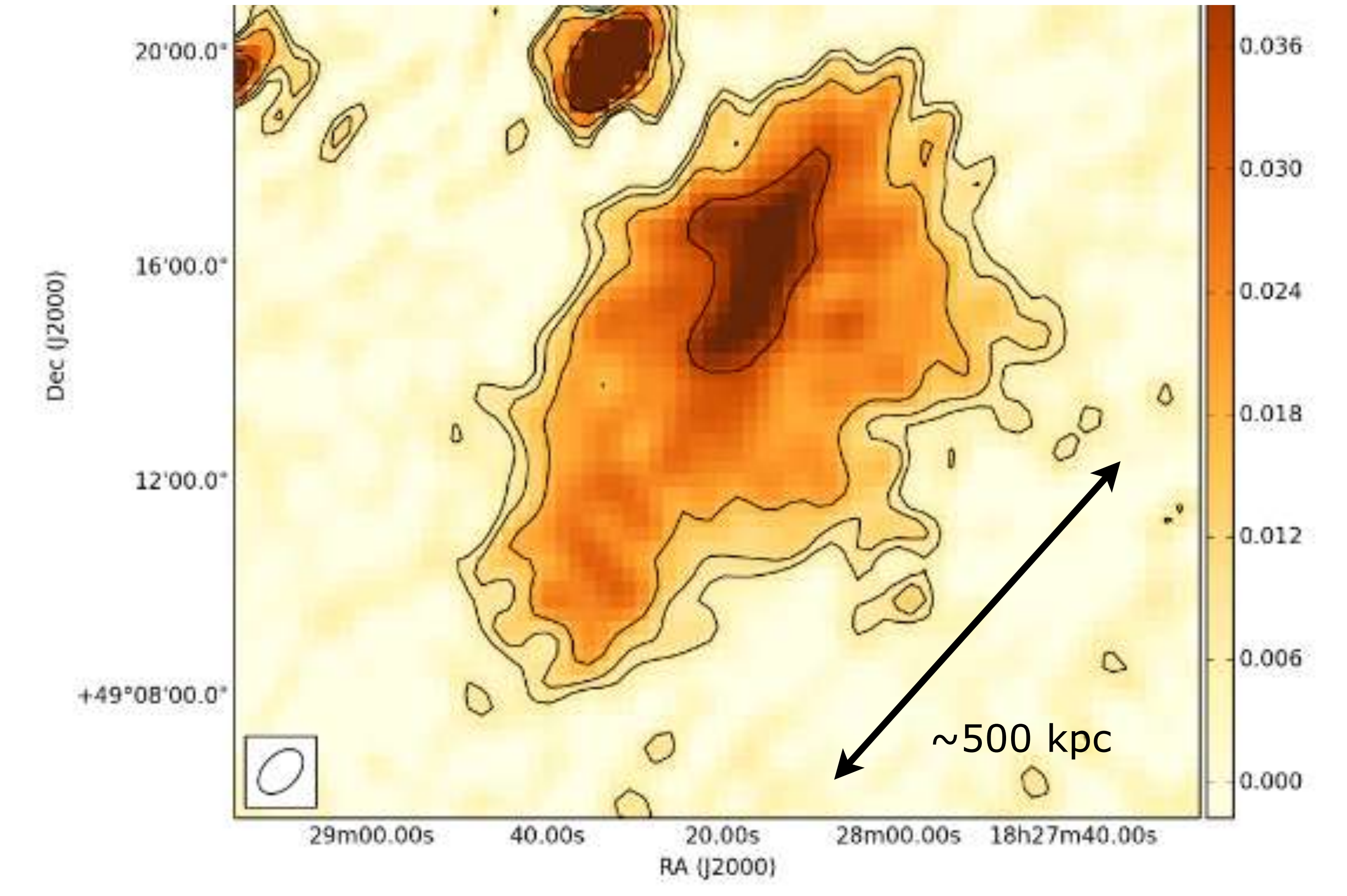
LOFAR 150 MHz - 18 arcsec and 6 arcsec

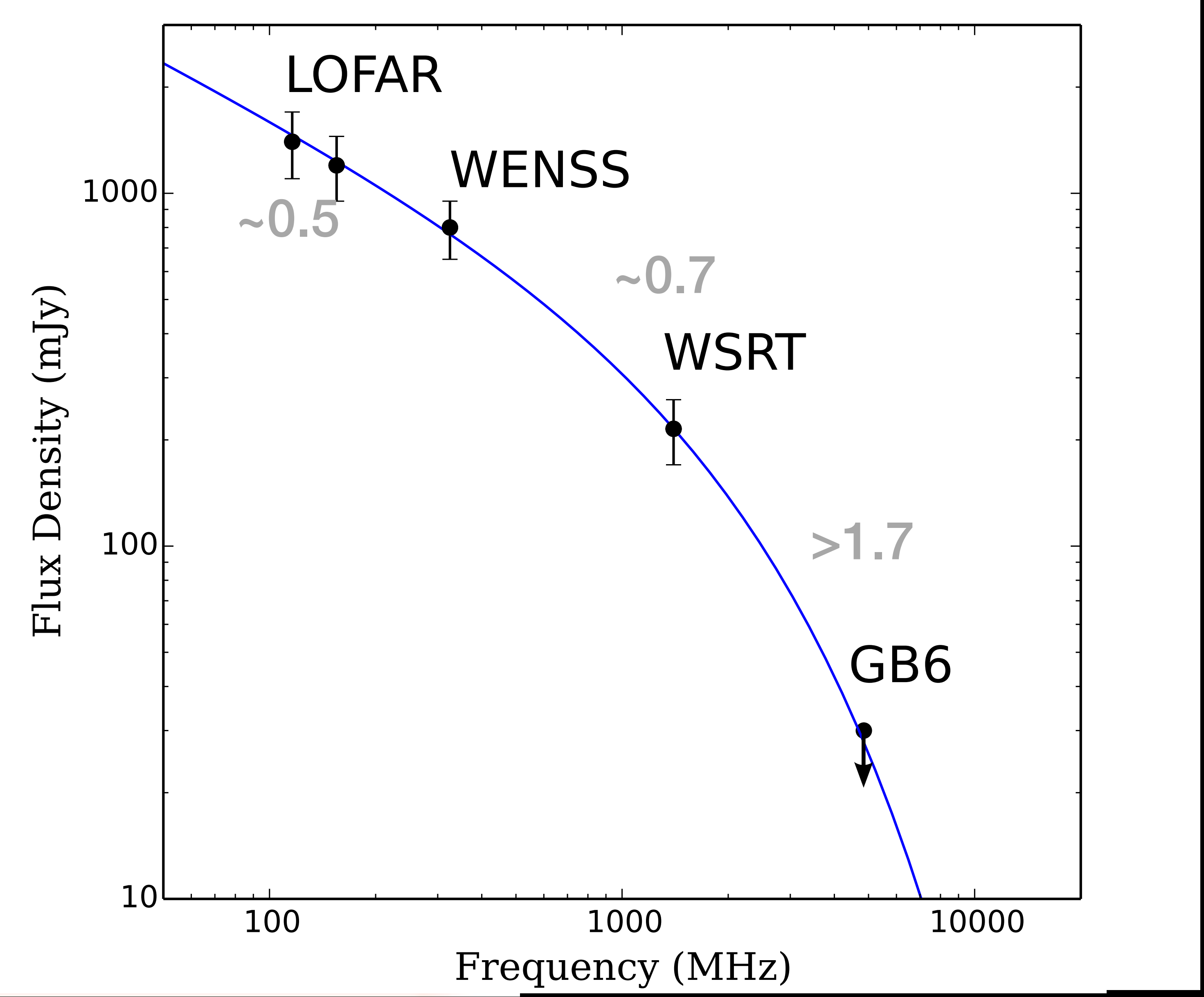


Brienza et al. 2017
Jurlin et al. 2021

Example of remnant discovered with LOFAR but not because ultra-steep-spectrum but for the morphology







diffuse, low surface brightness emission

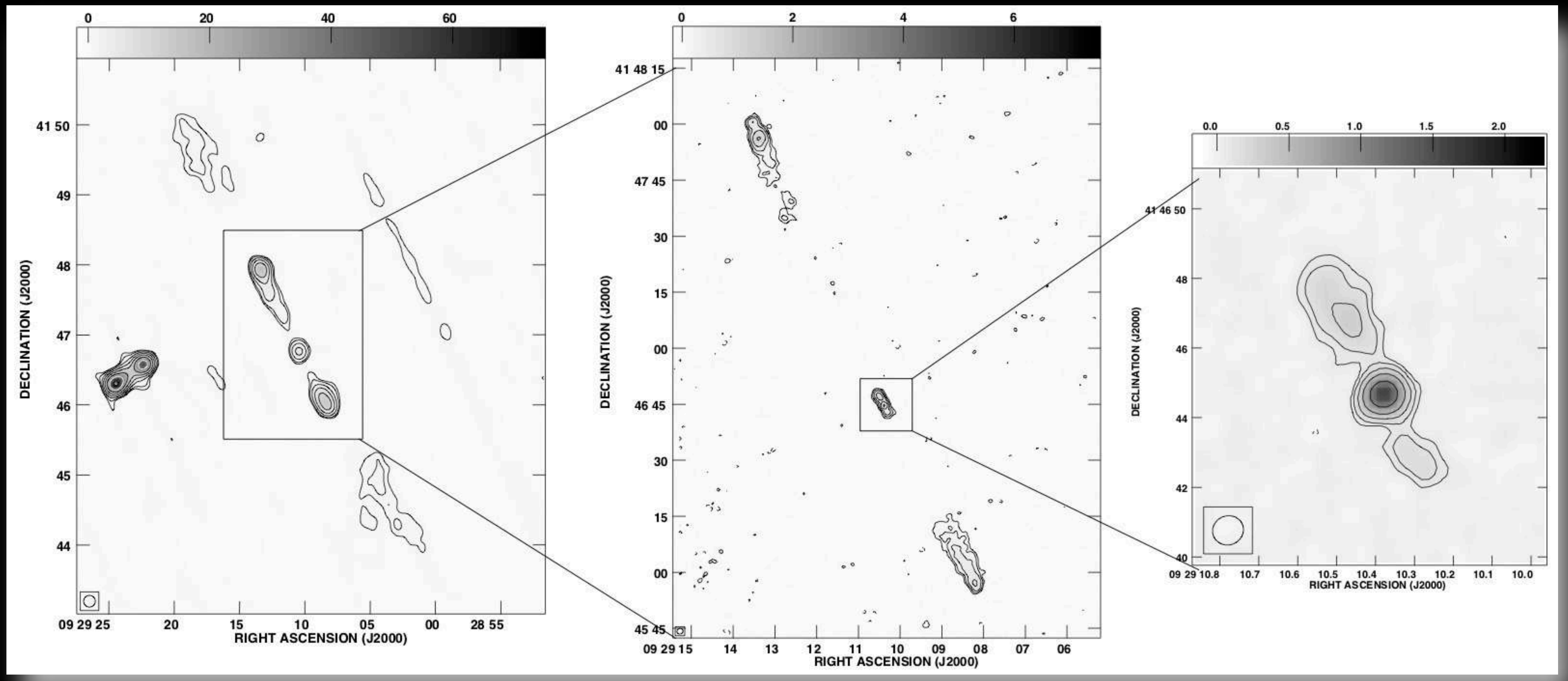
t_{on} = 15 Myr
t_{off} = 60Myr
t_{on}/t_{tot} = 20%

Brienza et al. 2015

important the availability of both low and high radio frequencies (from 150MHz to 1.4GHz and beyond)

The radio AGN can restart

Brocksopp et al. 2007

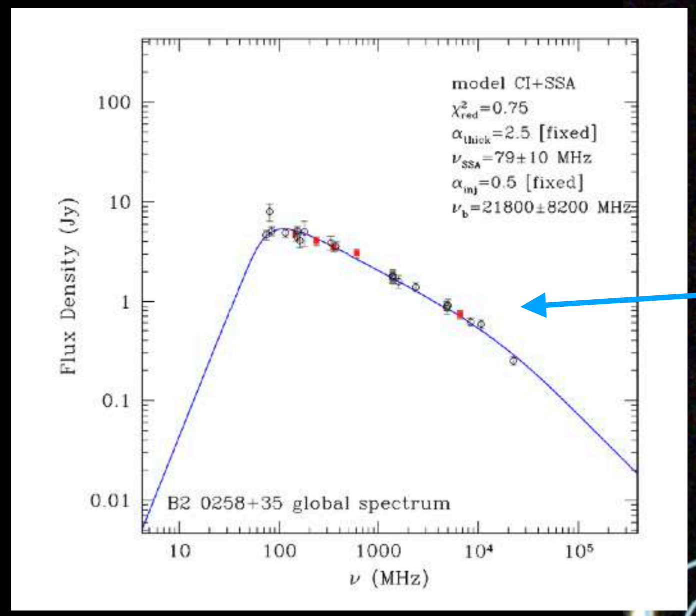


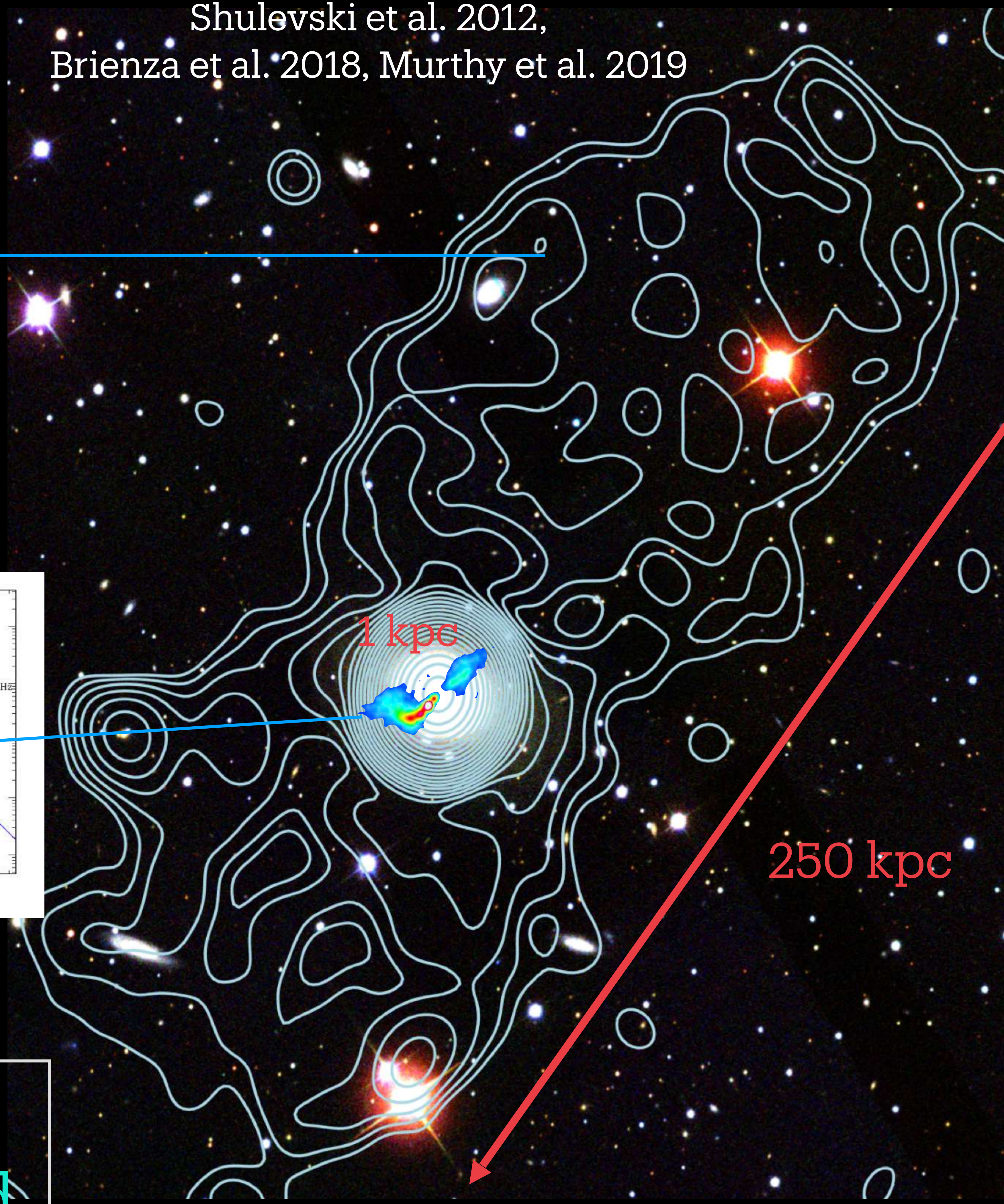
Radio galaxy B0925+420, showing three phases of activity. The images, obtained using the Very Large Array, show three pairs of lobes. The age of the outer lobes was derived to be 25–270 Myr, while that of the inner lobes is 0.4–2 Myr. The supply of energy for the outer lobes ceased 4–70 Myr ago, while the inner lobe is still supplied by fresh electrons.

Shulevski et al. 2012, Brienza et al. 2018, Murthy et al. 2019

total age 110 Myr

restarted source 0.4Myr age

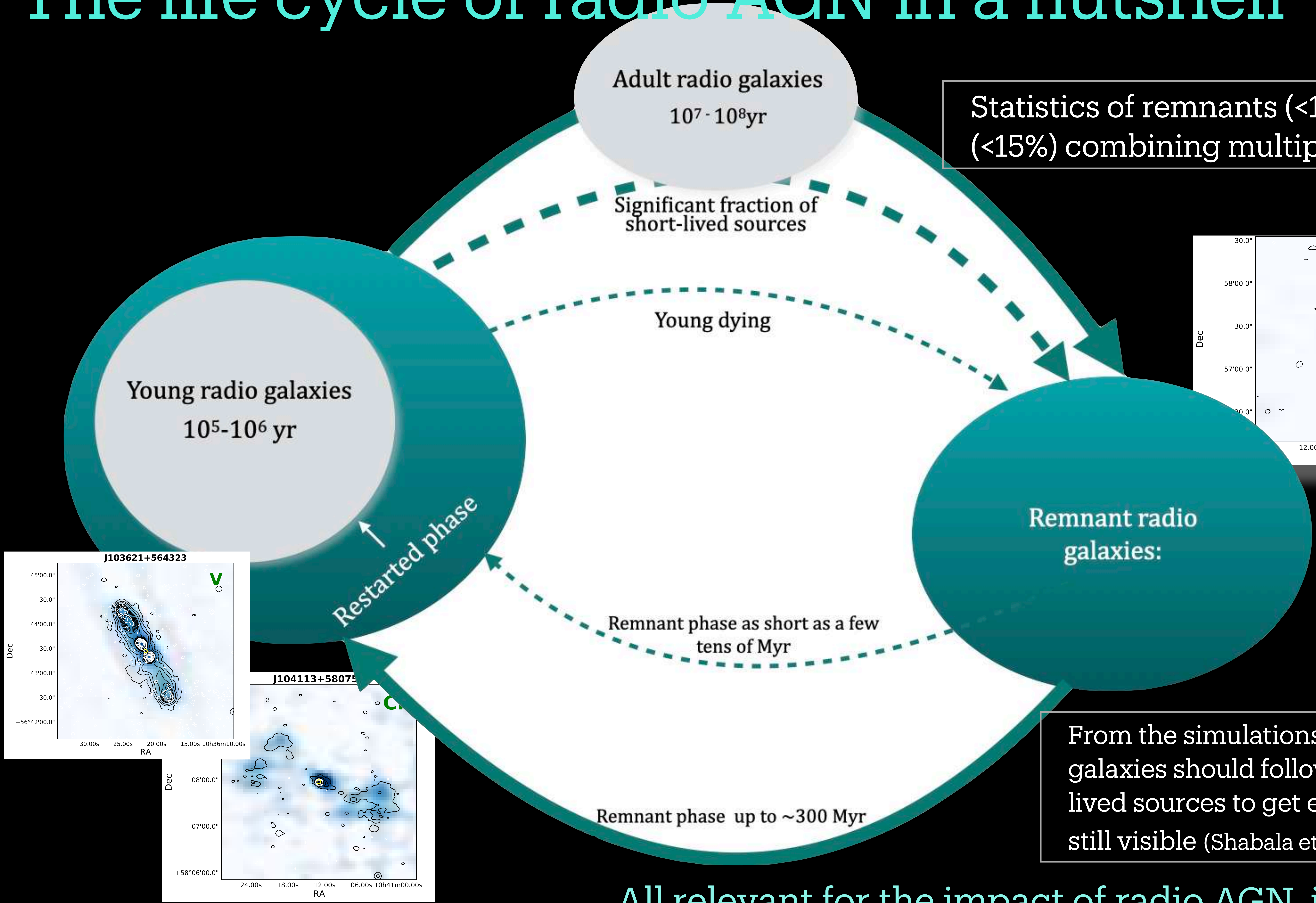


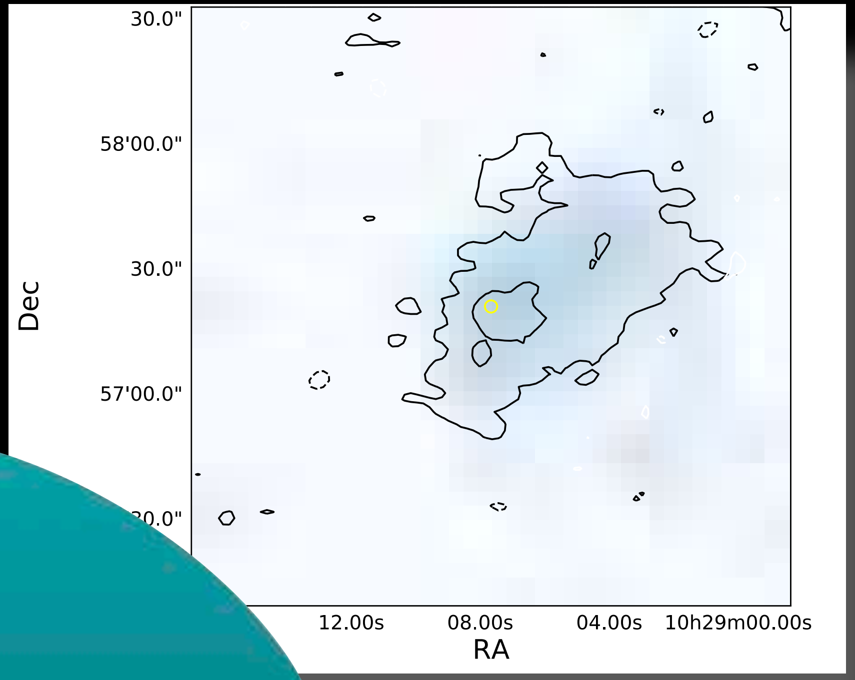


Up to 15% are candidate restarted radio galaxies!

The life cycle of radio AGN in a nutshell

Statistics of remnants (<10%) and restarted (<15%) combining multiple selection criteria

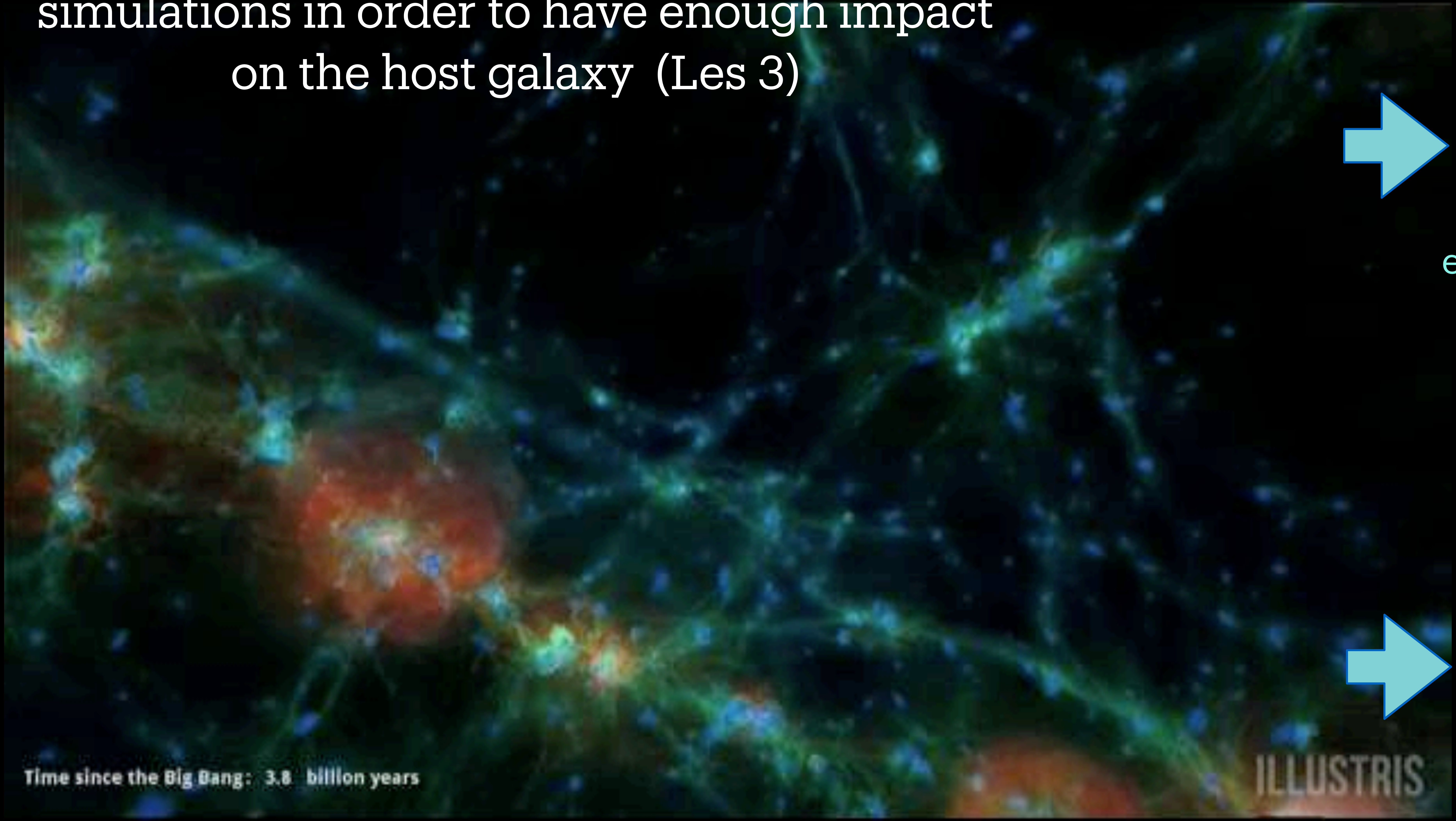


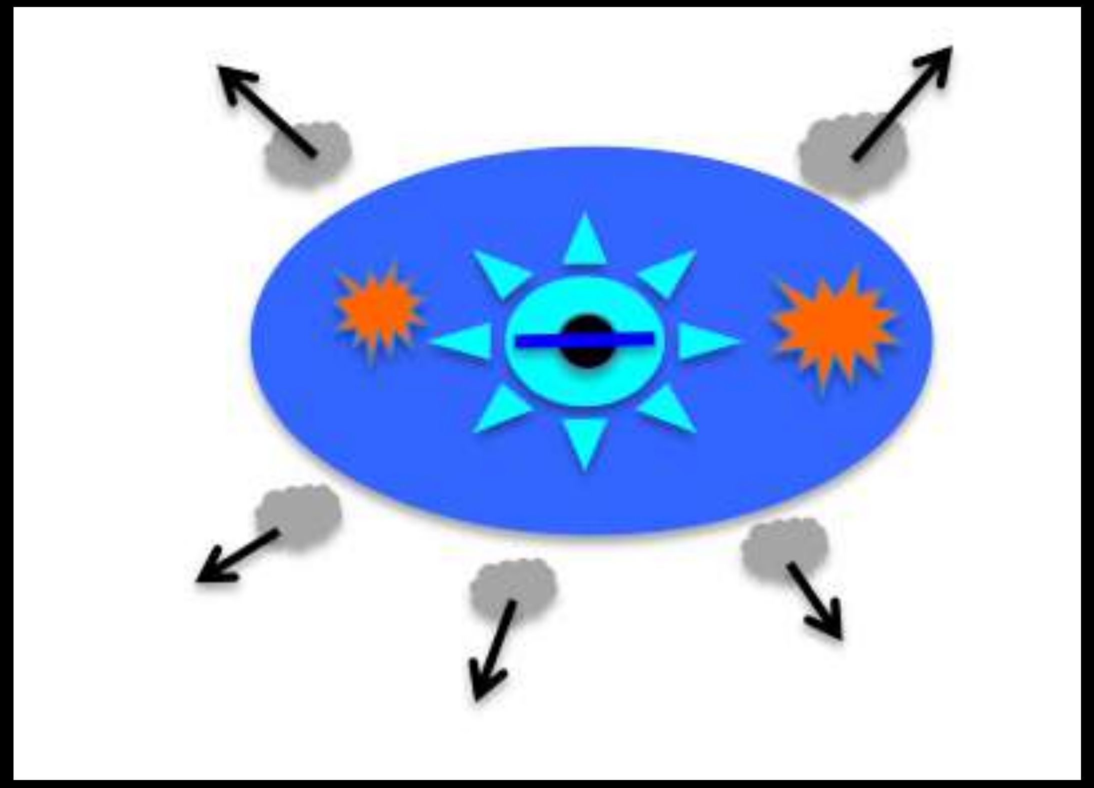


From the simulations: the age distribution of radio galaxies should follow a power law: we need short lived sources to get enough remnant lobes which are still visible (Shabala et al. 2020), see also Orienti et al. 2023

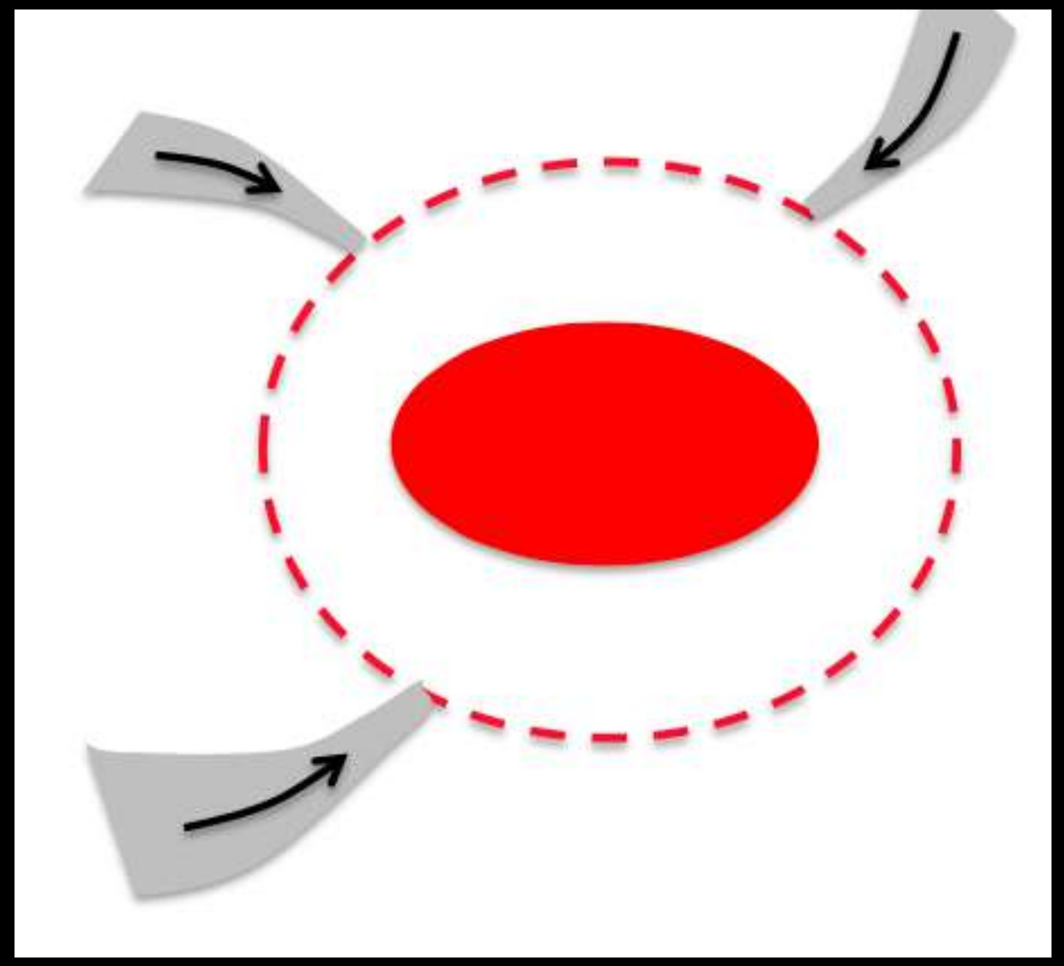
All relevant for the impact of radio AGN in galaxy evolution

The observations show that radio AGN are recurrent as required by cosmological simulations in order to have enough impact on the host galaxy (Les 3)





ejecting mode (gas outflows)

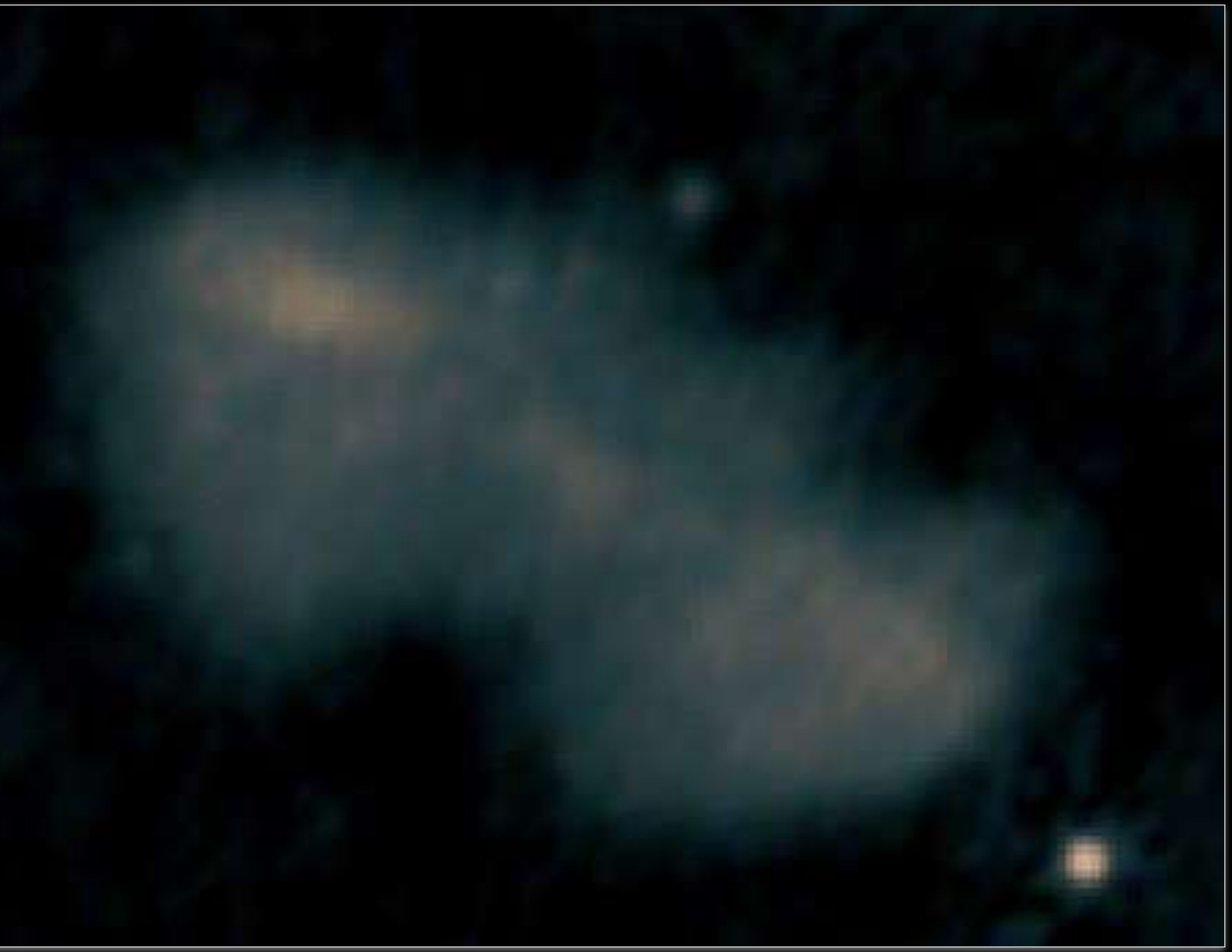


“maintenance” mode

preventing gas from cooling/halt gas supply

from R. Maiolino lectures

Are you still with me?



Possibility of identify active radio AGN but also dying and restarted

using morphology - thanks to the new low-frequency surveys of LOFAR
(sensitive to diffuse emission)
→ dying sources

and the spectral properties: synchrotron self-absorbed indicating young sources, ultra steep spectrum indicating dying sources

using the life cycle when study AGN feedback in Les 3...

e) Back to "radio-quiet" or better low-luminosity radio AGN

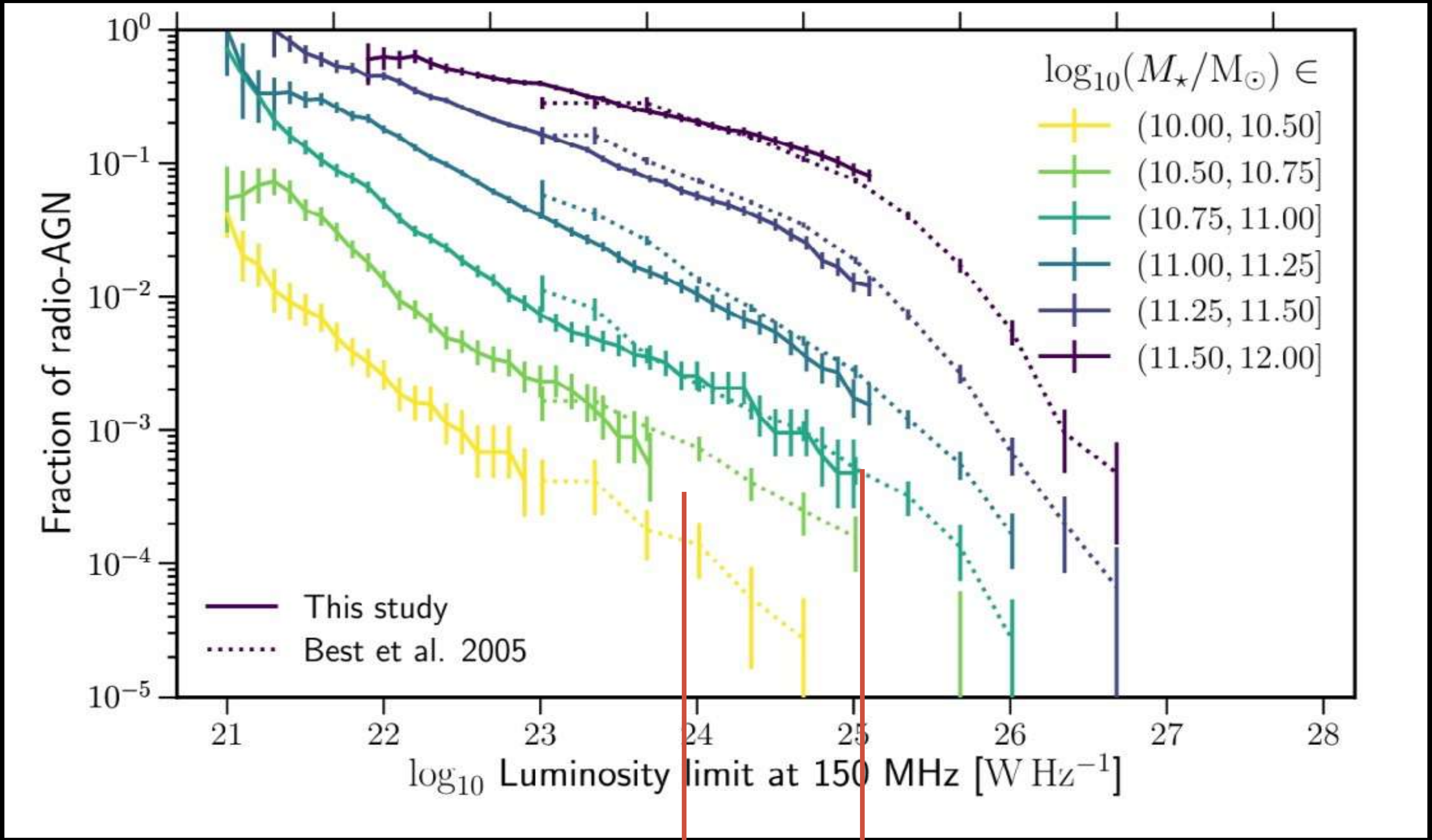
LINER

Seyfert (spiral galaxies)

why important? they are the majority!

“Radio-quiet” the dominant population of radio AGN

Best et al. 2005 and Sabater et al. 2019 using the LOFAR survey LoTSS (144 MHz)



(low luminosity) radio AGN
in almost all massive galaxies

roughly
NGC1068

powerful radio galaxies

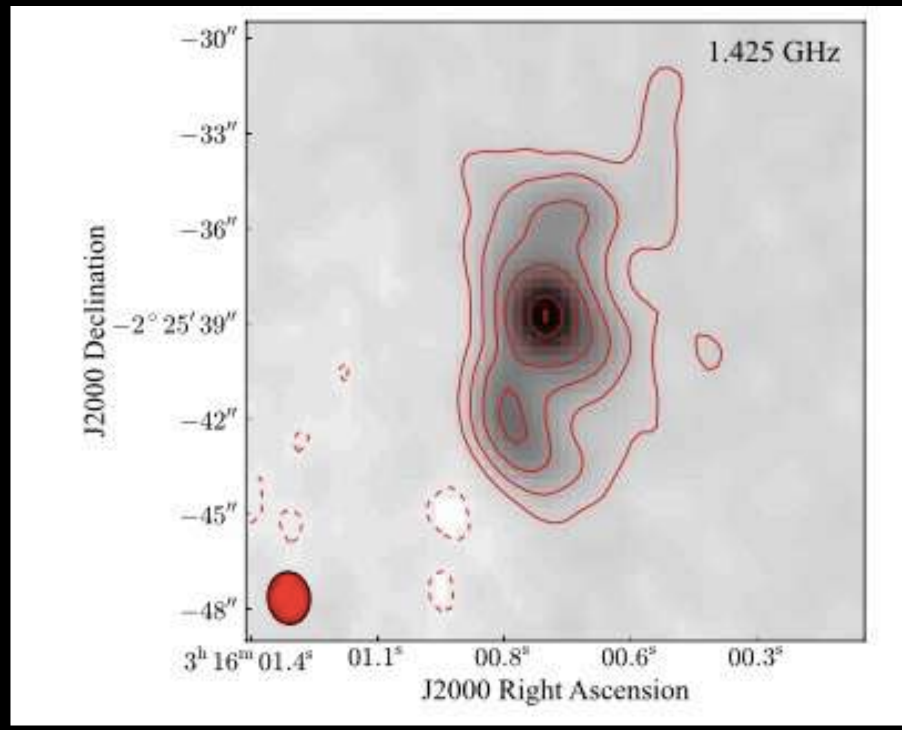
a variety of criteria used to classify AGN - see later

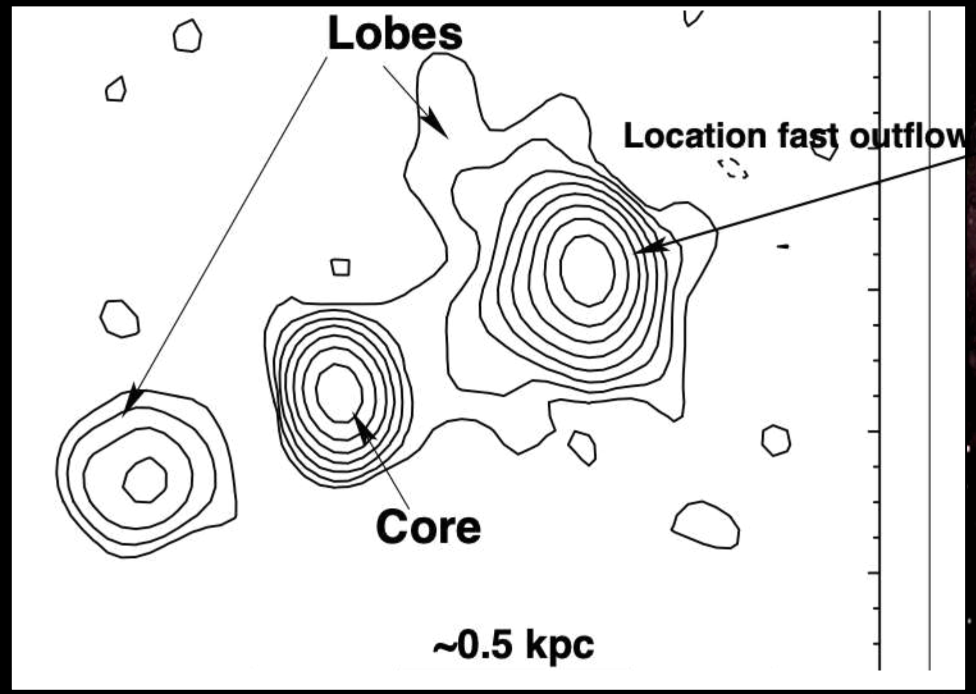
“radio-quiet”

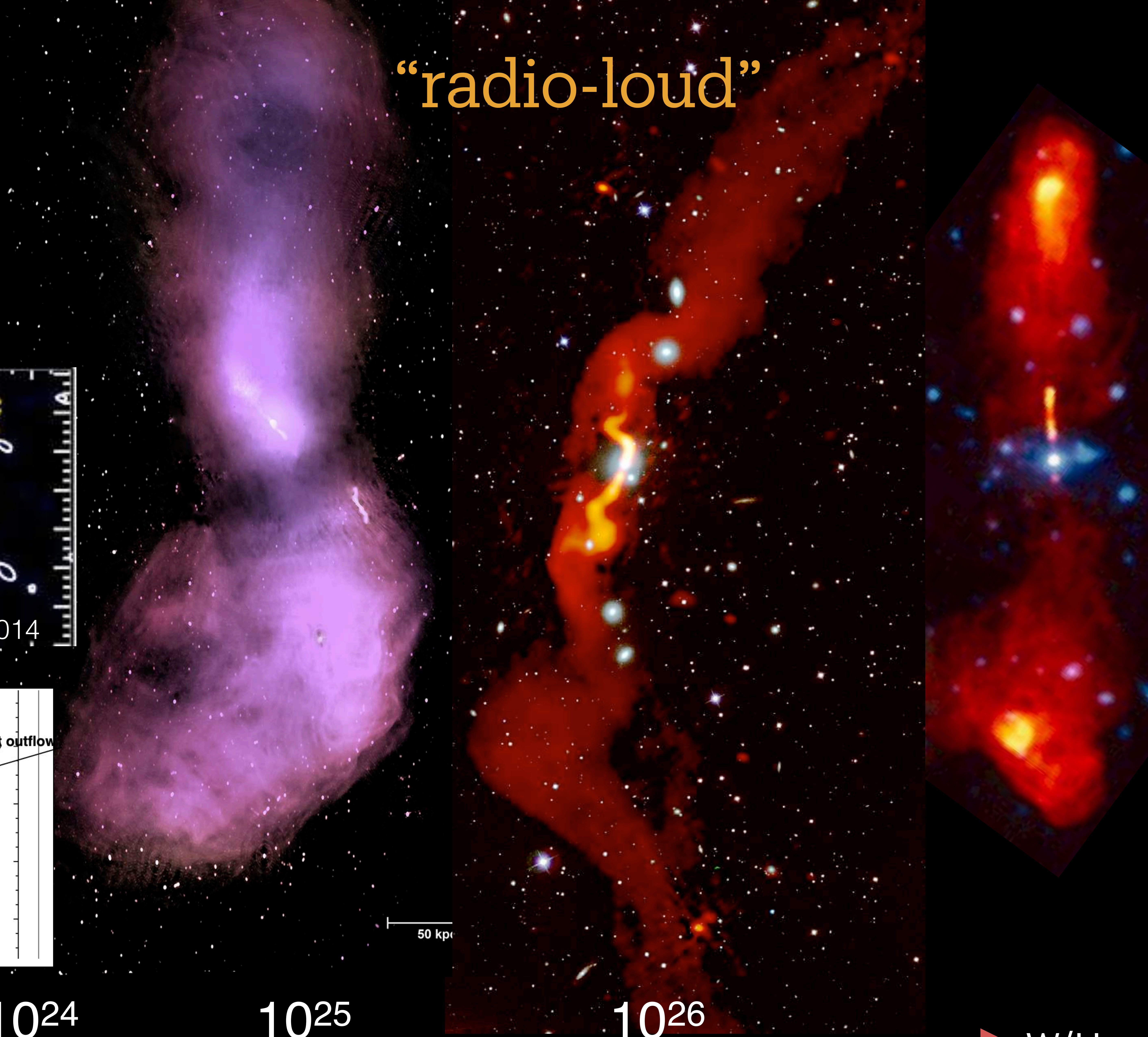
R = L_{5GHz}/L_B <10 (Kellermann et al. 1989)

“radio-loud”

Alatalo et al. 2012







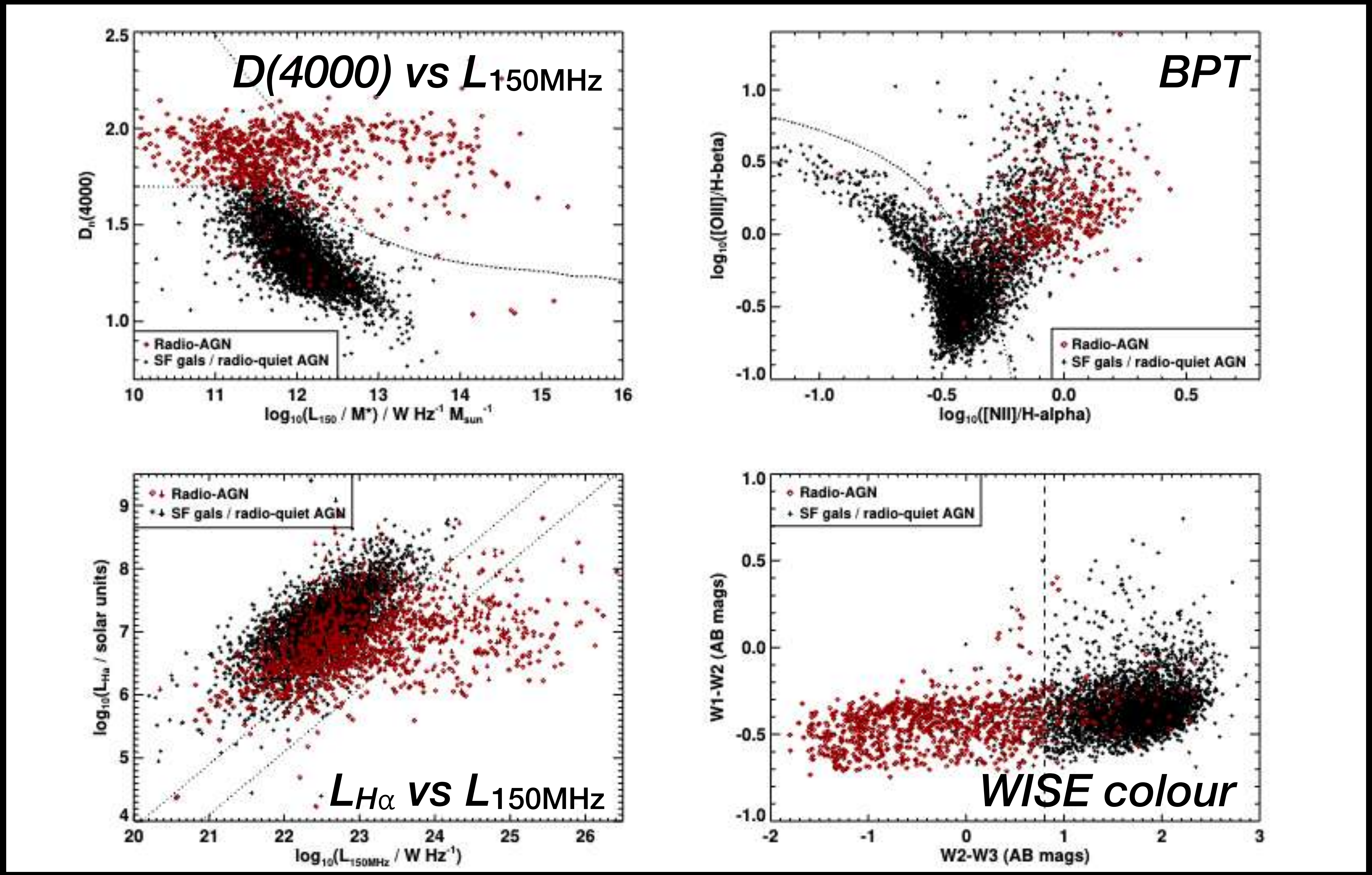
10^{21} 10^{23} 10^{24} 10^{25} 10^{26} W/Hz

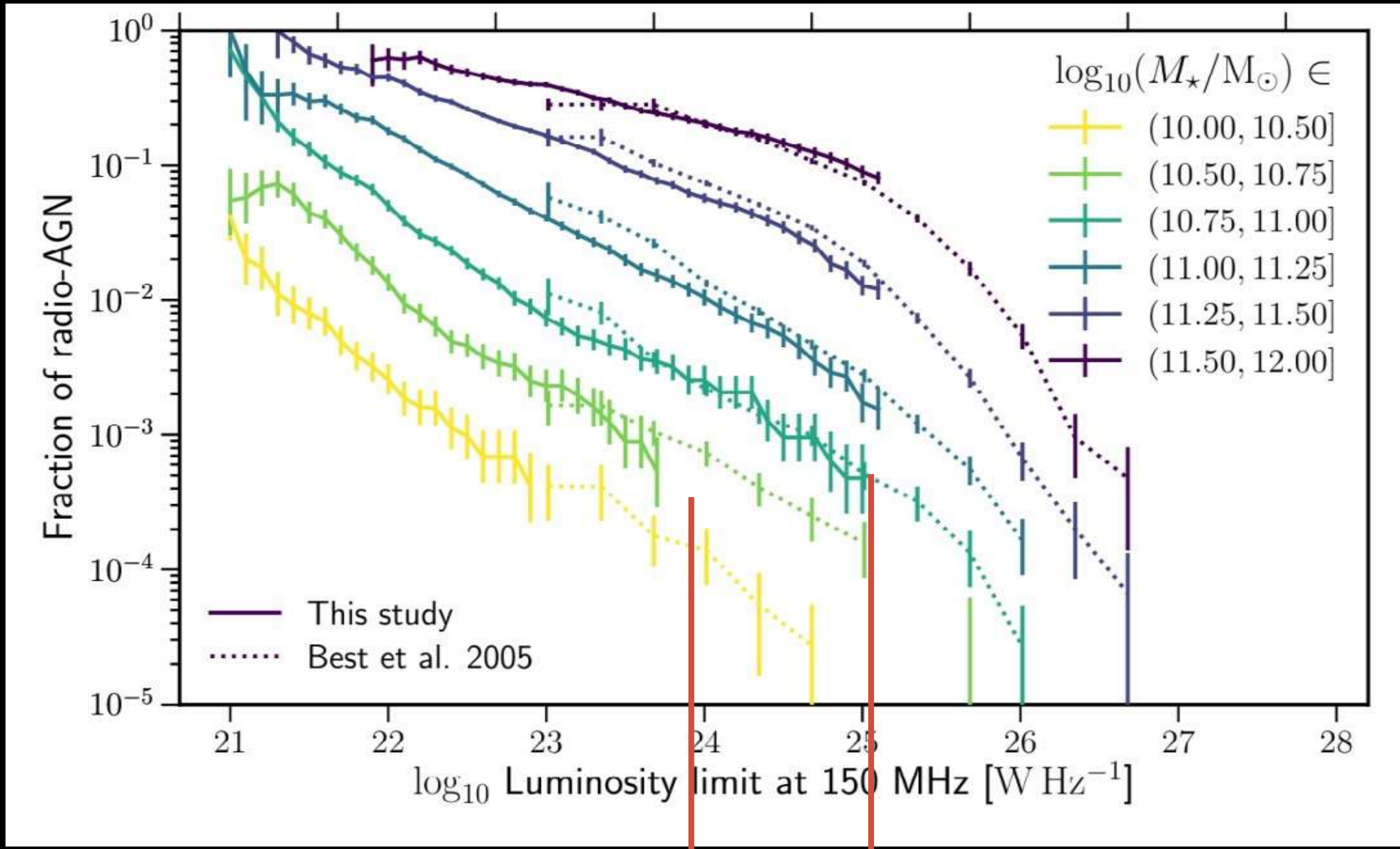
radio luminosity

“Radio-quiet” the dominant population of radio AGN

criteria to identify radio AGN (i.e. radio originating from the active BH and non-thermal synchrotron emission) even among faint radio source.

Best et al. 2005 and Sabater et al. 2019 using the LOFAR survey LoTSS (144 MHz)





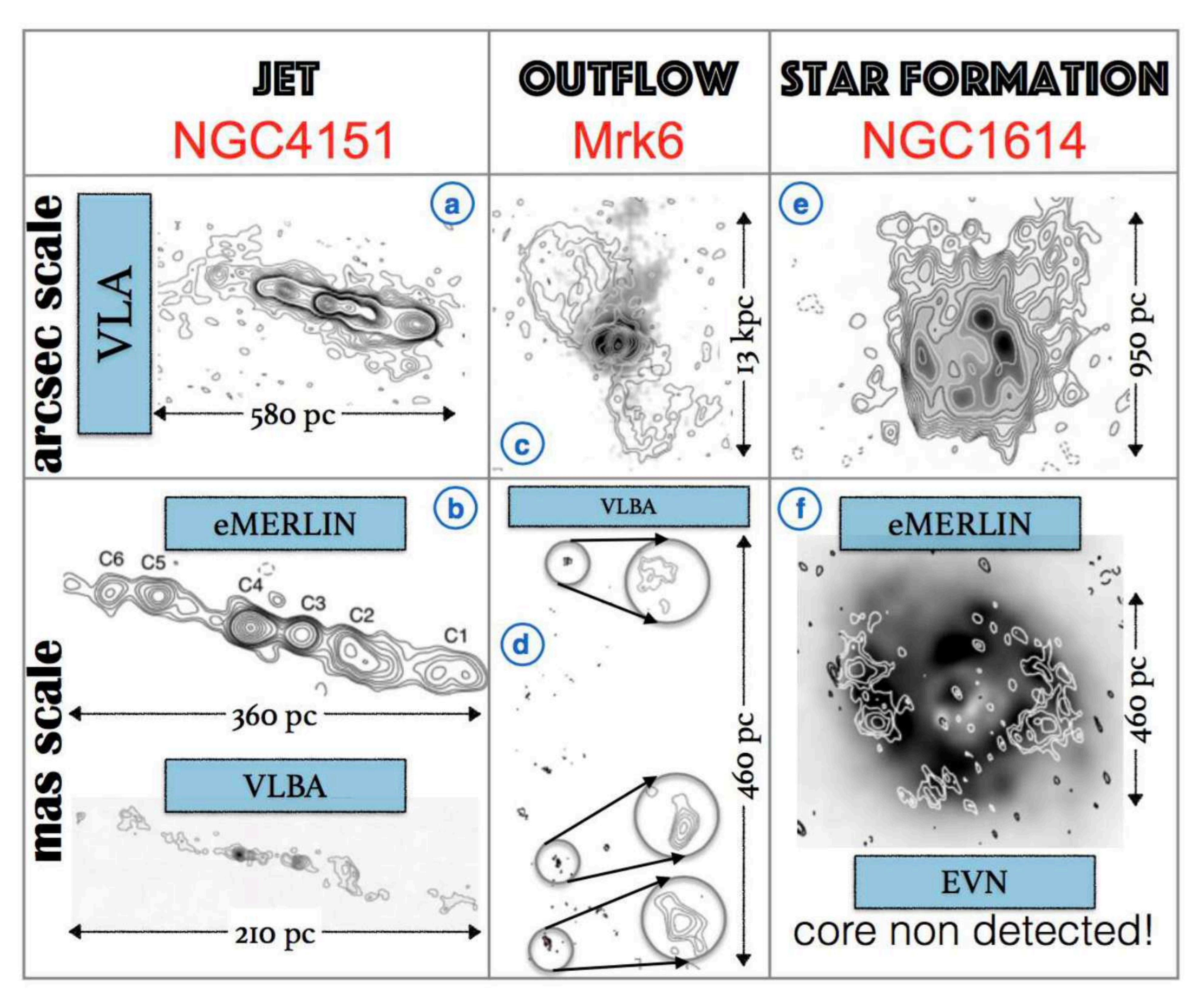
(low luminosity) radio AGN in almost all massive galaxies

roughly NGC1068

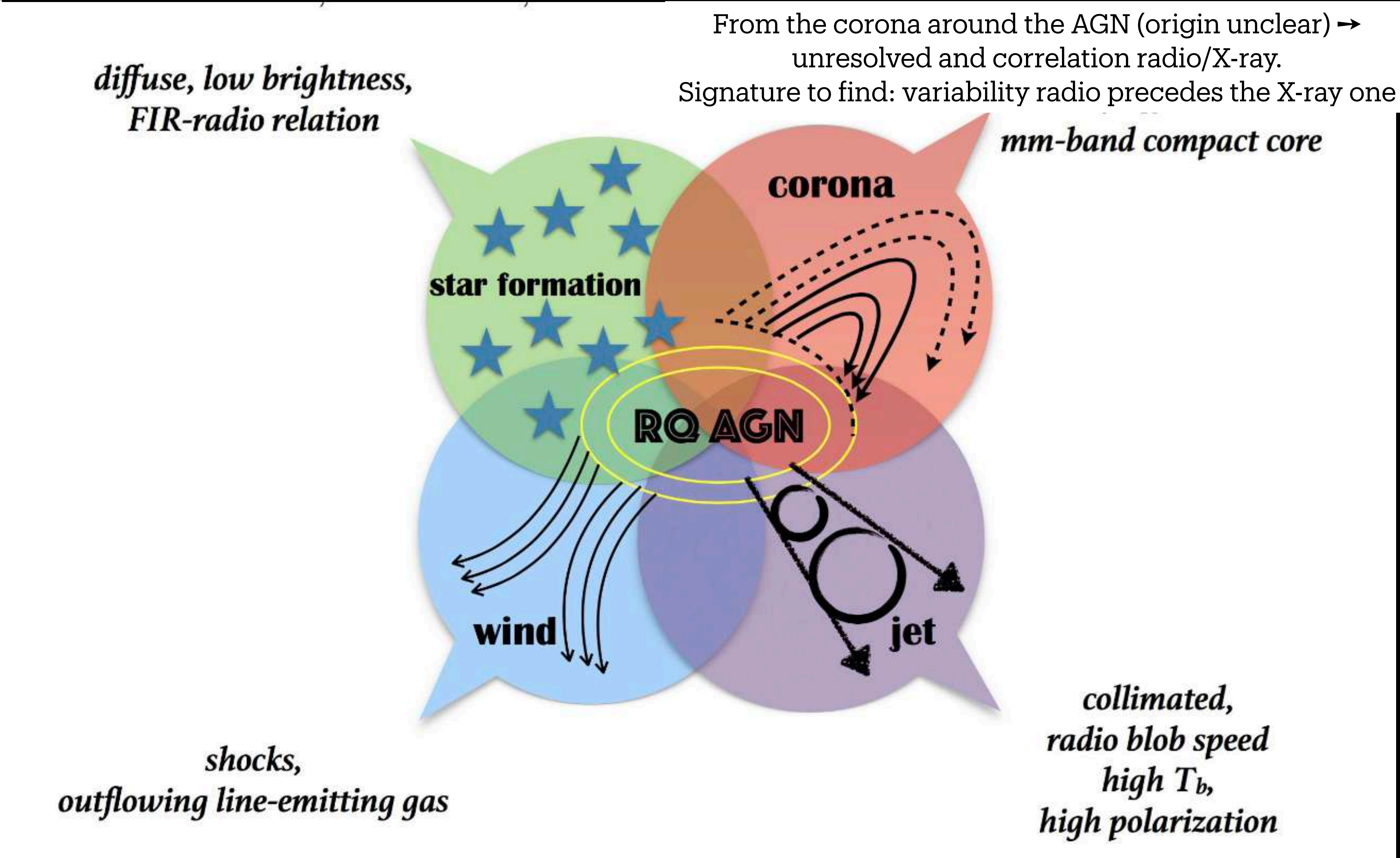
powerful radio galaxies

... it is clear that not all the “radio quiet” are originate from star-formation, but also not all from jets, alternatives have been proposed

Radio emission: typically small sizes - more complex morphologies
Dominated by entrainment - large fraction of thermal component (not only electrons)....



From the corona around the AGN (origin unclear) ➙ unresolved and correlation radio/X-ray.
Signature to find: variability radio precedes the X-ray one

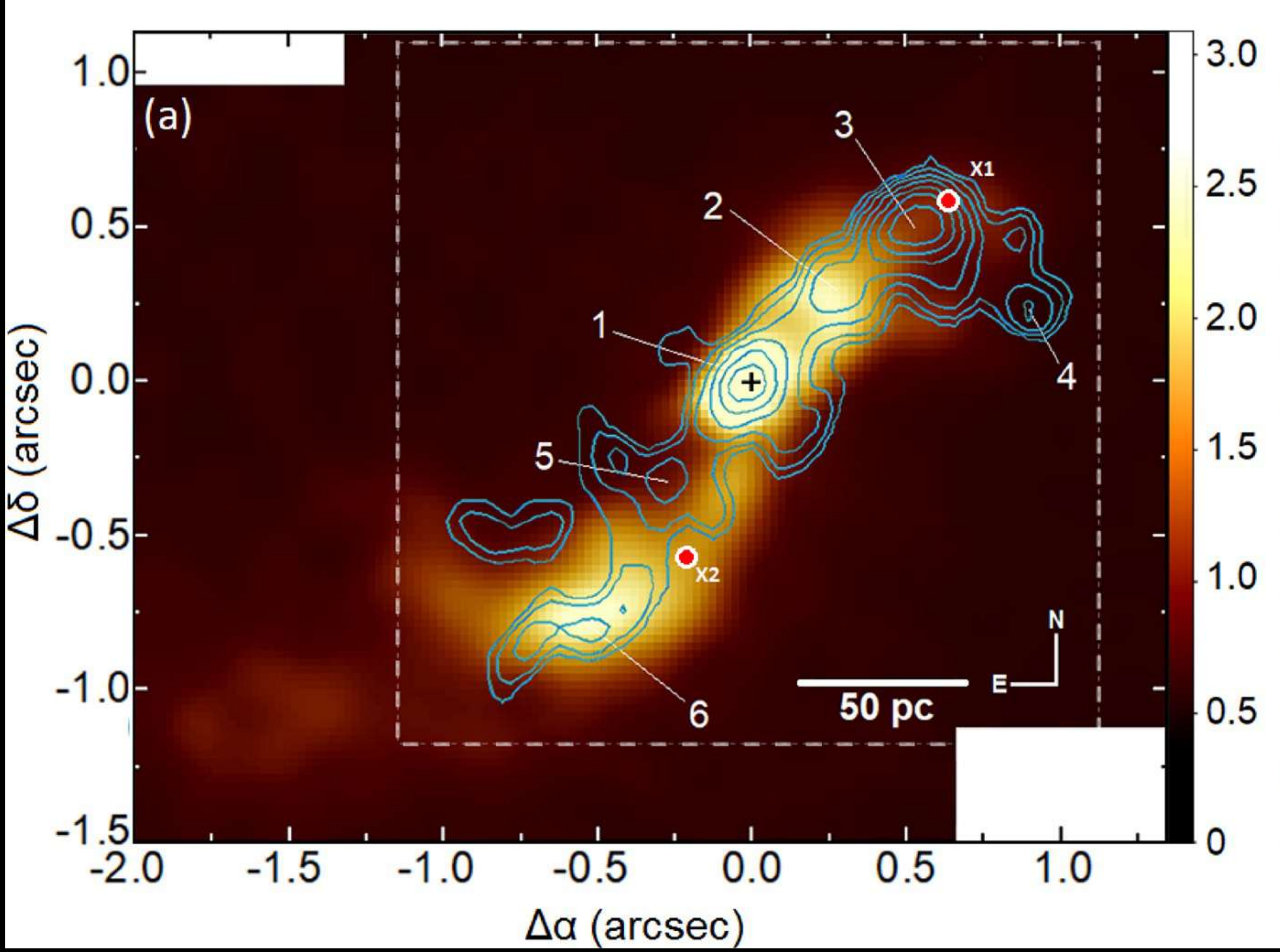


shocks accelerate relativistic electrons producing synchrotron radio emission on scales > 100 pc, with powers at the level of those observed in RQ AGN, $\nu L_\nu \sim 10^{-5}$ LAGN (Nims et al. 2015).

review Panessa et al. 2019

Hot topic: spatial coincidence radio - ionised gas in low luminosity AGN signature of the radio affecting the surrounding gas?

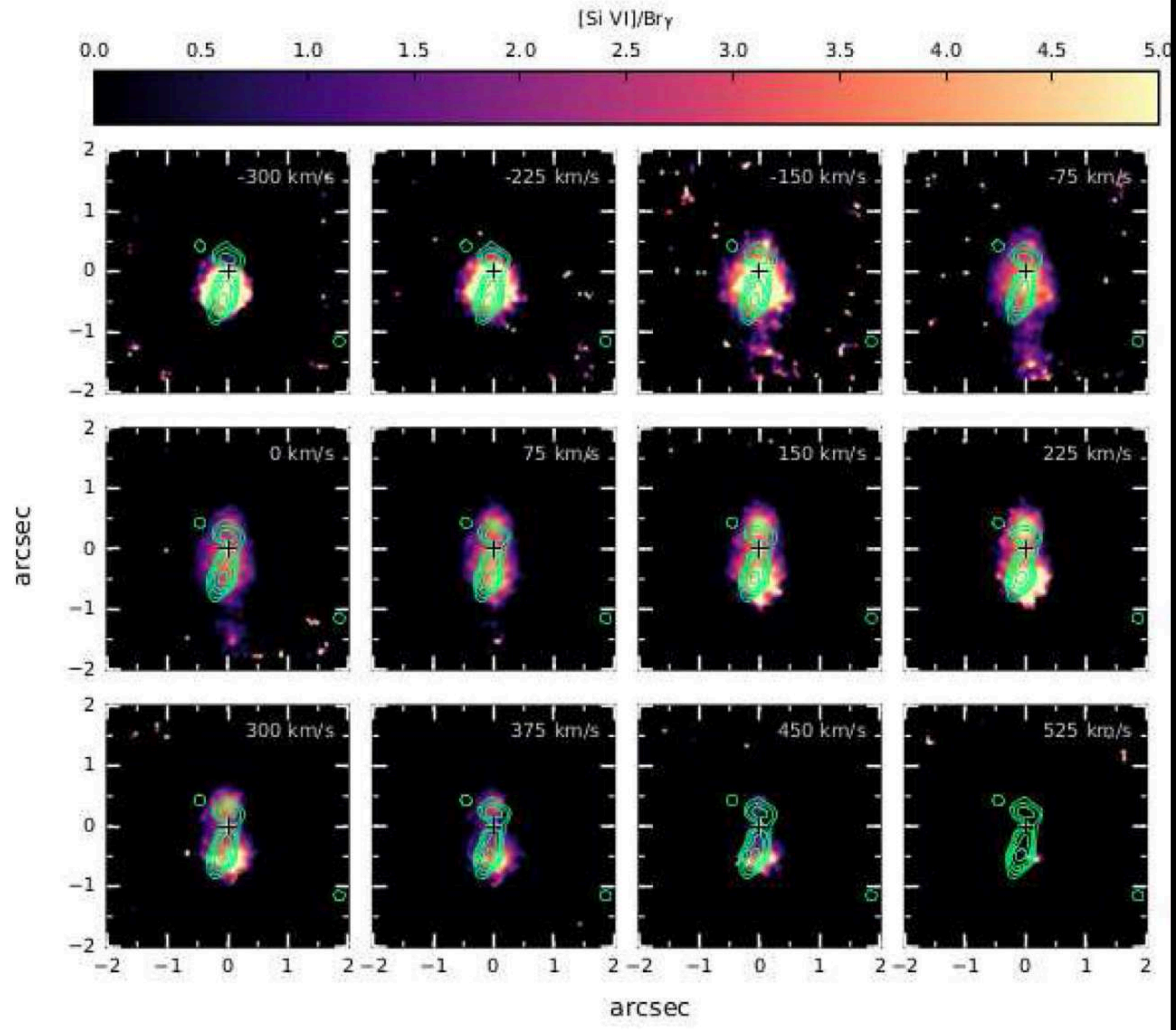
see the work of Alberto Rodríguez-Ardila



May, Rodríguez-Ardila et al. 2018

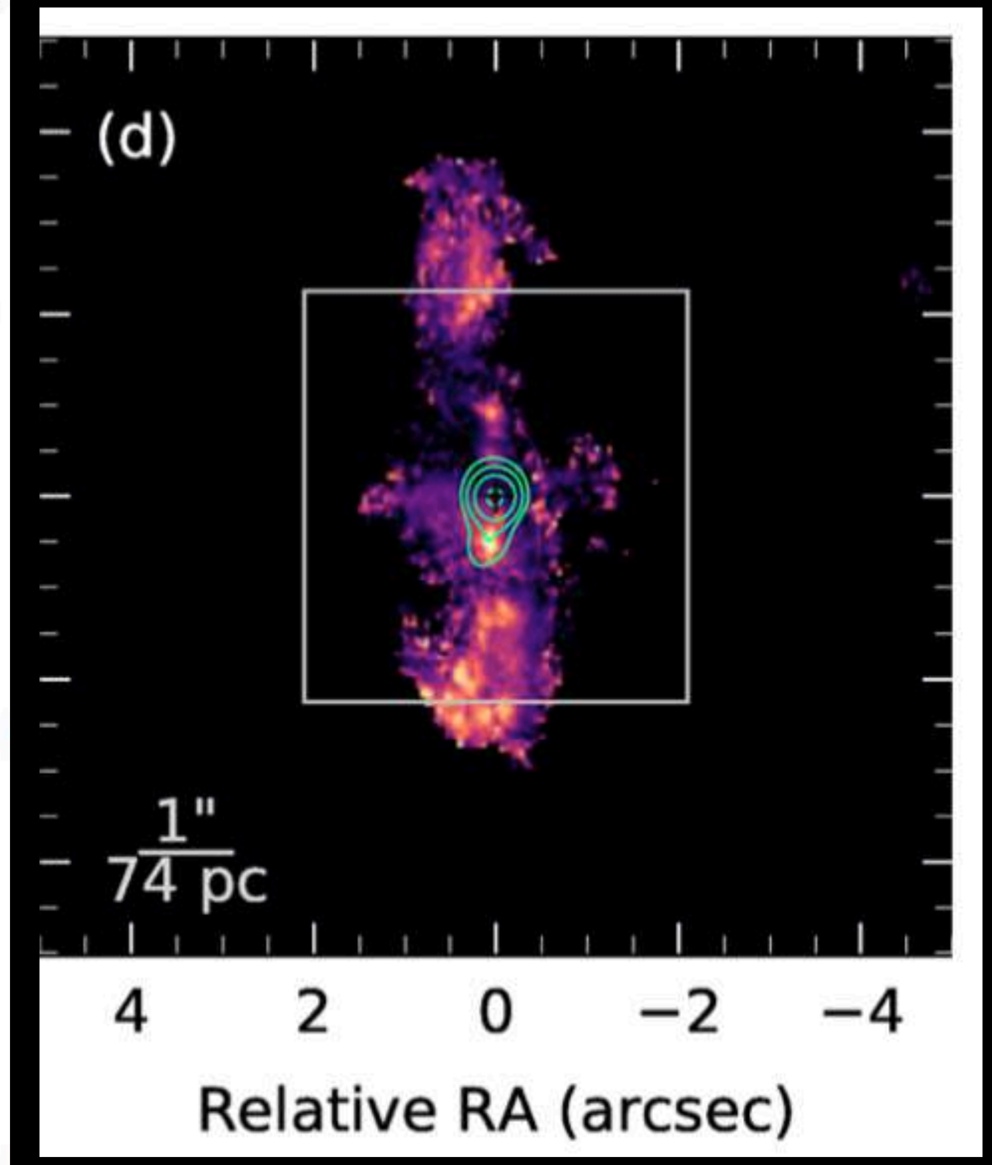
ESO 428-G14 [Sivi] λ19641 Å emission line overlaid with the VLA 2 cm radio emission (blue contours)

LLAGN with high ionisation coronal lines



Channel maps derived for the excitation ratio [Si VI]/Br γ in steps of 75 km/s. Green contours correspond to the 8.4 GHz radio data after subtraction of the nuclear unresolved source.

Excitation map [O III]/(H α+[N II])



NGC1386 Rodríguez-Ardila et al. 2017

Growing number of “radio-quiet” and low luminosity AGN (LLAGN, i.e. weak radiation) where a low power jet could be responsible for driving a cocoon of disturbed/ionised gas

Growing number of “radio-quiet” and low luminosity AGN (LLAGN) where a low power jet could be responsible for driving a cocoon of disturbed/ionised gas

This is a way to produce gas outflows: we will get back to this in Les 3

In summary...

- Radio AGN collimated radio jet of relativistic electrons and magnetic field (synchrotron emission). Collimated by the BH spinning and/or corona and expanding in the ISM and outside - up to Mpc scales ➙ the inner regions relevant also for defining the large scale morphology

- Radio-loud sources (radio galaxies): two main morphological classes identified (Fanaroff-Riley type) to first order connected to the ionised gas and jet power

- Radio emission from synchrotron radiation: radio spectra give the possibility of identify the evolutionary stage of the radio AGN ➙ relevant role in AGN feedback

- The definition of radio "quiet" can be misleading: they have radio emission which can come from jets and impact the surrounding gas ➙ relevant role in AGN feedback?

- At lower radio luminosity, it can be difficult to separate radio from star formation to the radio emission from an AGN: many diagnostics needed