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

3) Radio galaxies and their life cycle

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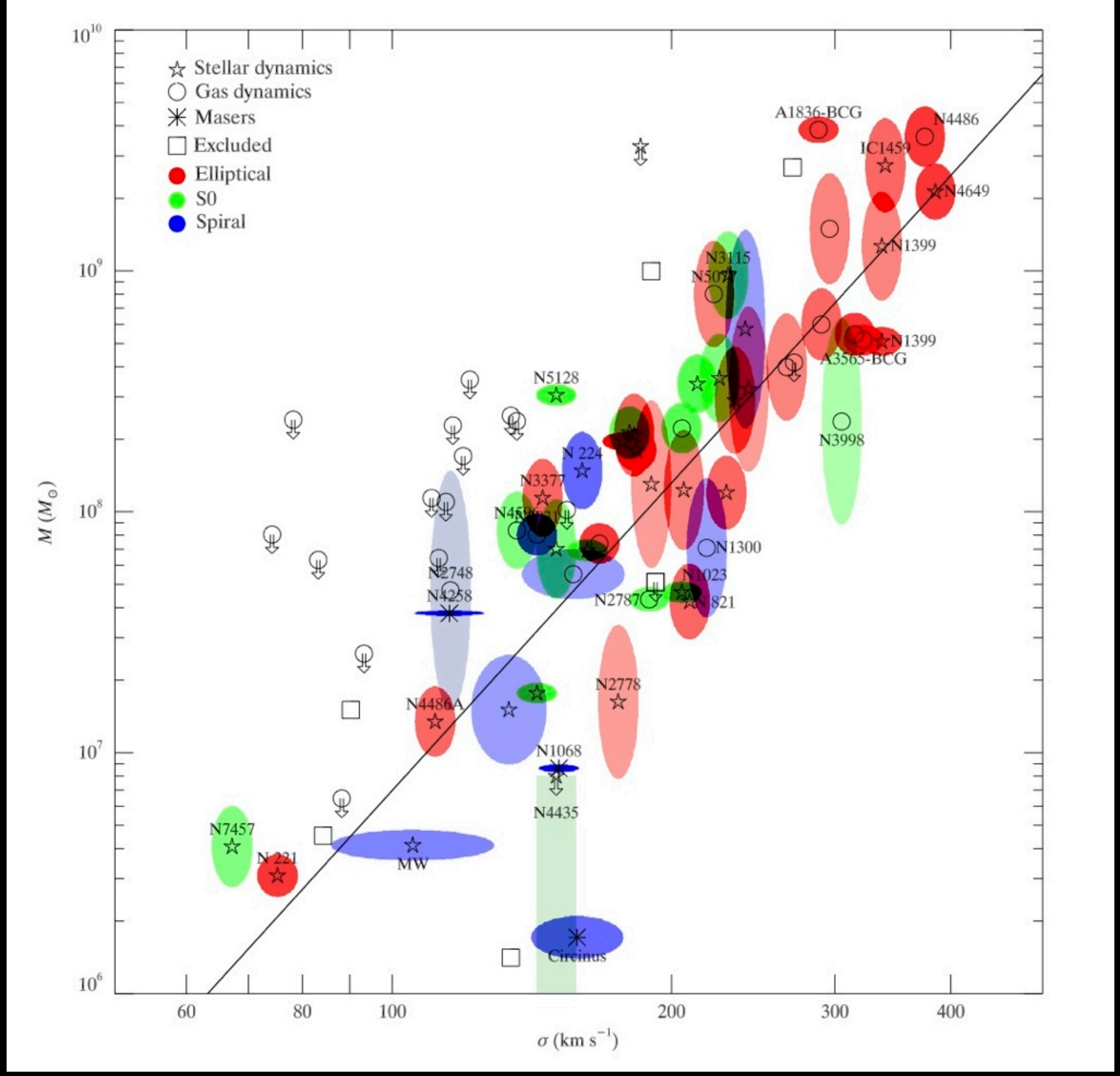
Themes of the lectures

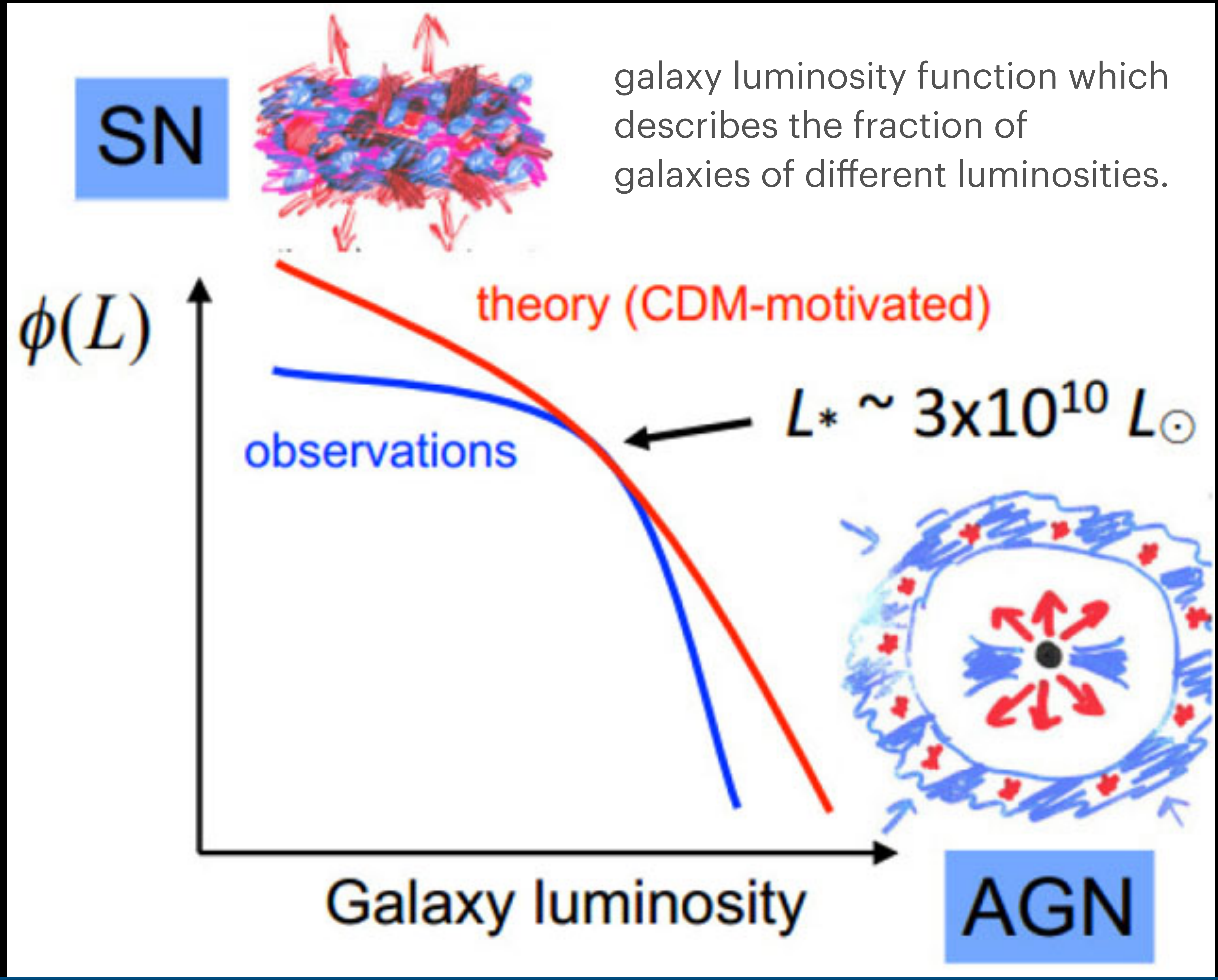
- An introduction to radio-astronomy and radio surveys
- From radio quiet to radio loud AGN: properties and recent results
- **Radio galaxies and their life cycle**
- The impact of radio jets on the interstellar medium and galaxy evolution

Feedback required for reproducing the properties of observed galaxies

- clear relationship between mass of spheroidal component of host galaxy and black-hole mass
- indicates connection between galaxy formation (star formation) and growth/evolution of central black-hole
- simulations require extra ingredients to reproduce galaxy luminosity function and cooling flow problem…



Gebhardt et al. 2000; Ferrarese & Merritt 2000



from Silk et al. 2013

cosmological models derive too many big galaxies and too many dwarf galaxies

Nuclear activity has to repeat in the life of the host galaxy

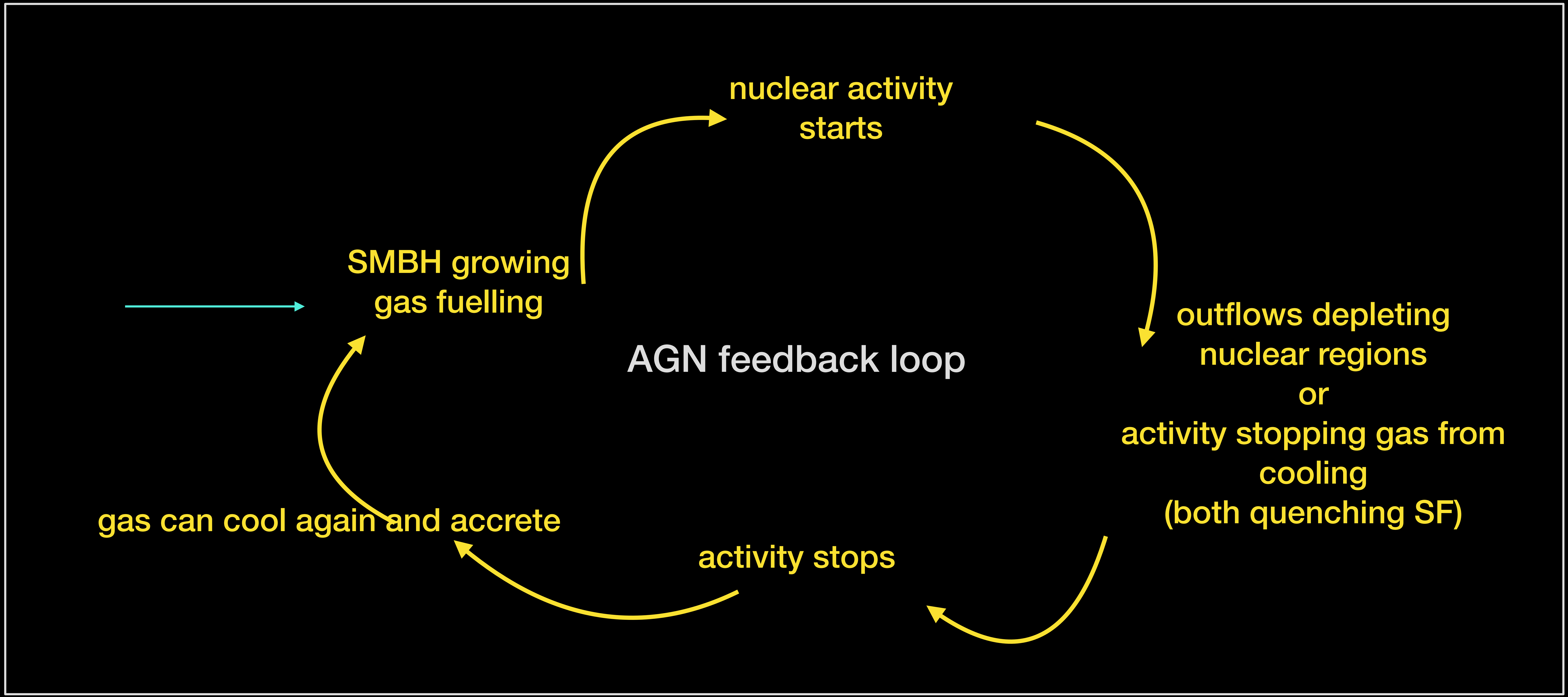
Points to notice:

Enormous release of energy (in this case almost isotropically)
➔ clearing the galaxy from gas
➔ preventing gas cooling

Recurrent "explosions": multiple times in the life of the host galaxy

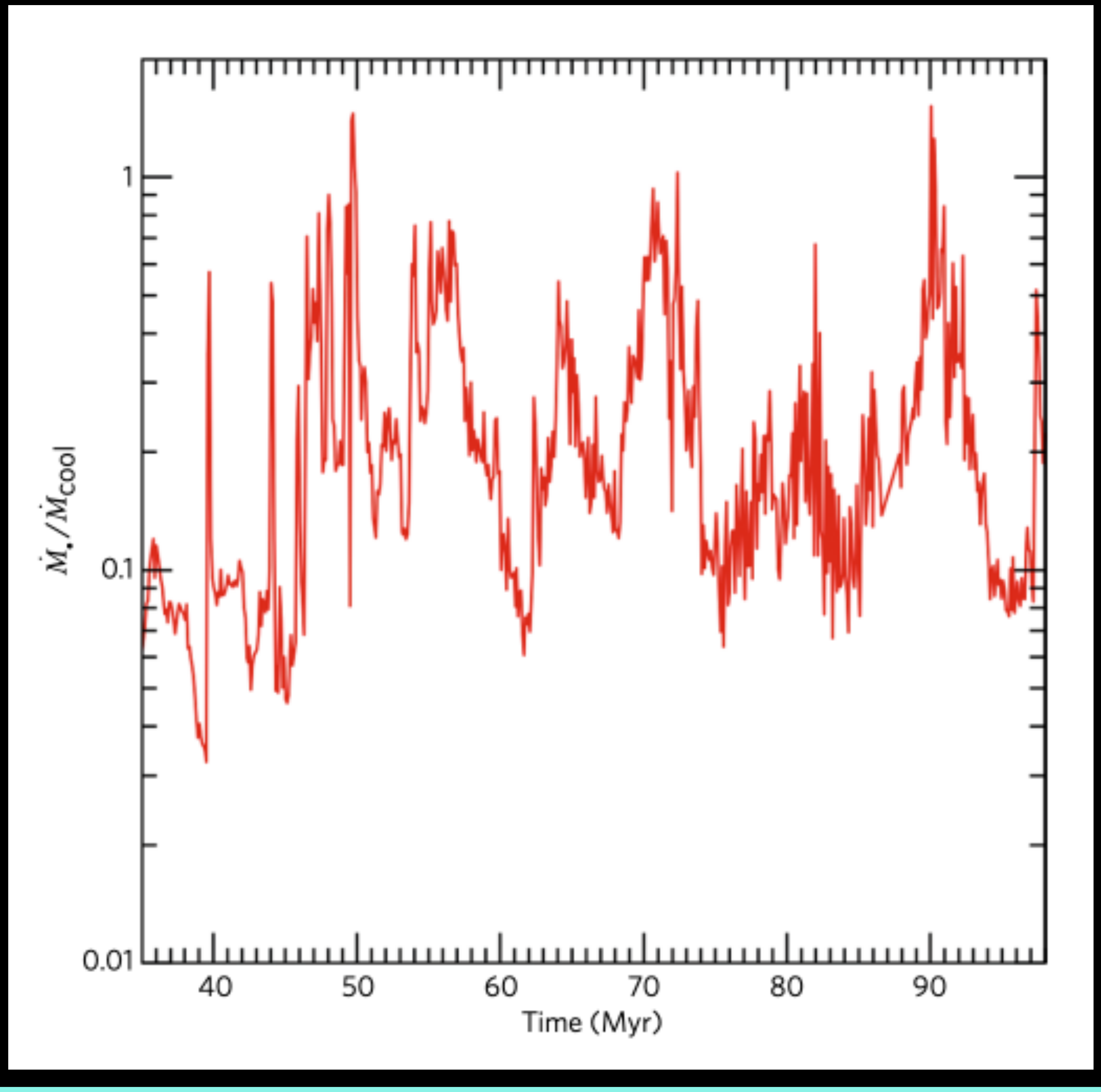
➔ feedback loop
Regulating star formation and the growth of the SMBH

A basic feedback loop...



Complex process: importance of studying high-z objects but looking at objects in the nearby Universe helps to explore the details

Origin of the cycle of activity



The duty cycle of activity and quiescence predicted from simulations of **chaotic cold accretion**. Evolution of the accretion rate (including turbulence, cooling, AGN heating and rotation) as a fraction of the cooling rate. This illustrates the changes in accretion rate (and therefore level of activity) on short timescales.

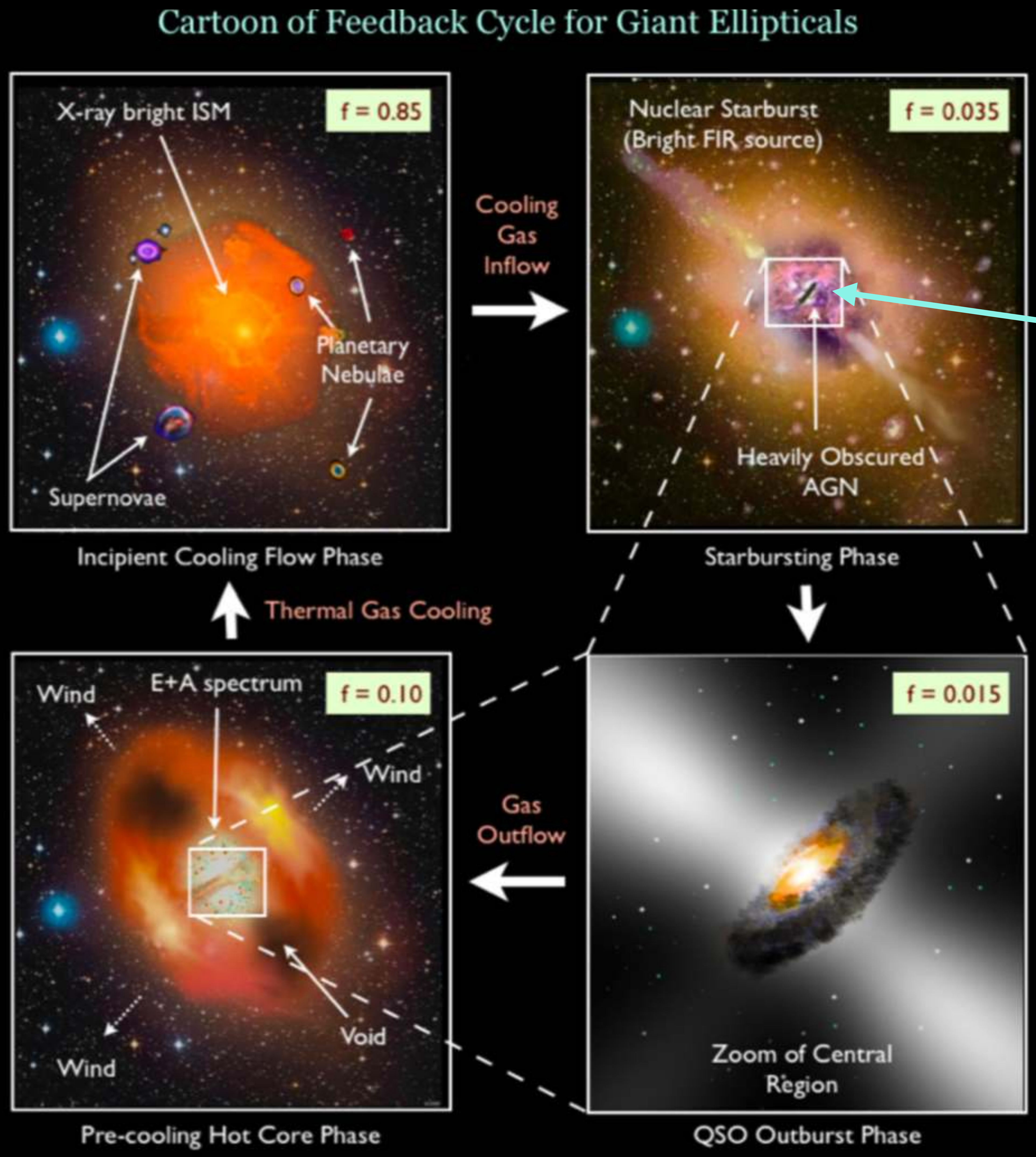
Gaspari et al. 2017

Morganti 2017, Nature Astronomy

Instabilities and other processes in the accretion disc

radiation pressure instabilities and/or magnetic instabilities

Czerny et al. 2009, Lalakos et al. 2023



In this phase the starformation rate increases (using the gas accreted e.g. from the **merger**)

then the AGN starts

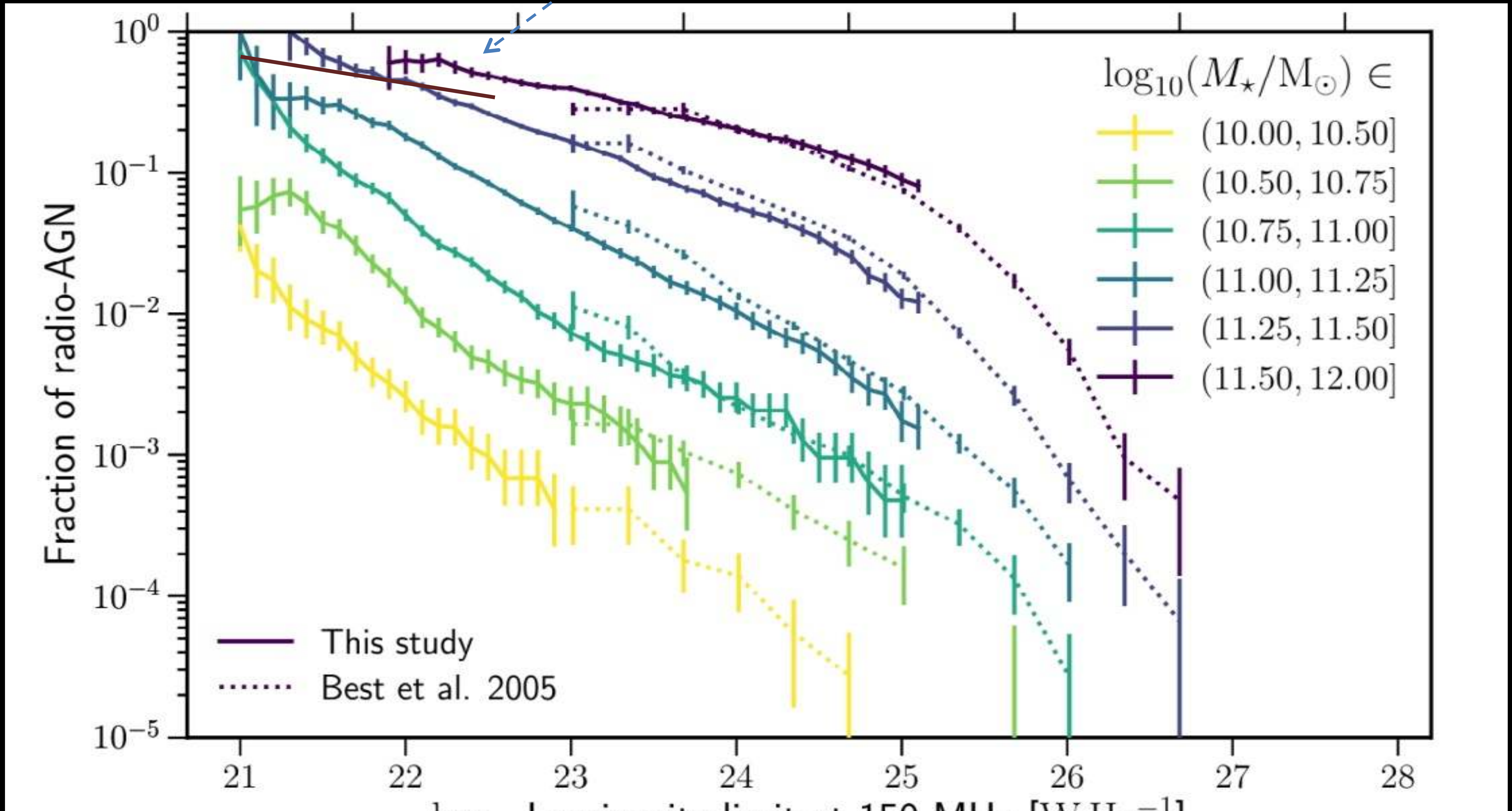
Ciotti et al. 2010

Evidence of this loop in the radio AGN

Statistical argument...

Derived the luminosity function of radio AGN - dependence on stellar mass - fraction changing with radio power.

Best et al. 2005; Sabater et al. 2019

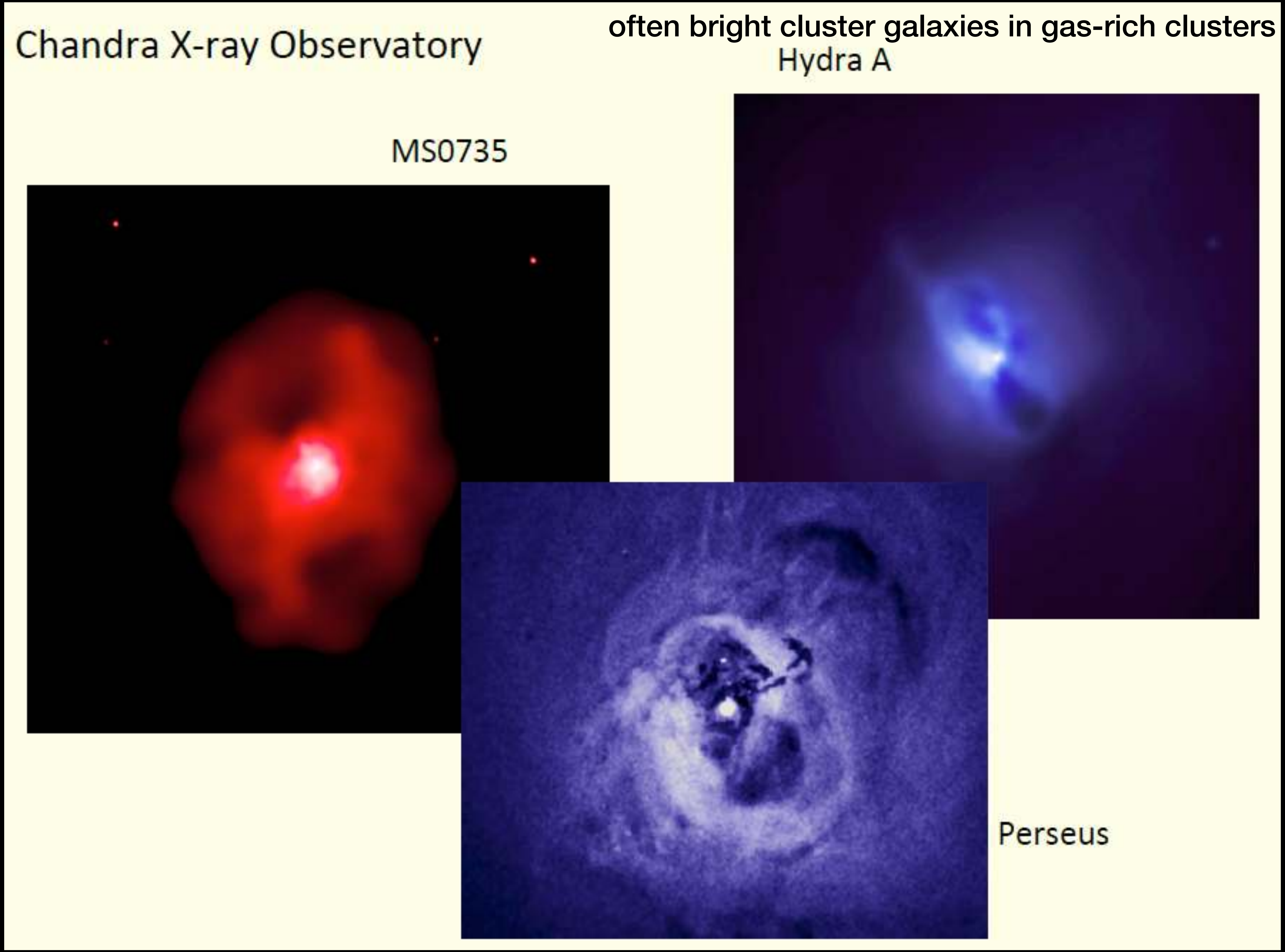


from DR1 - HETDEX area (Shimwell et al. 2019)

the fraction can be used to derive the fraction of time a radio AGN is "on" (active) under the assumption that every massive galaxy becomes a radio source during its life ➙ then the fraction of radio AGN tell us about what fraction of time the soource is "on"

Radio galaxies in cluster: key objects for feedback

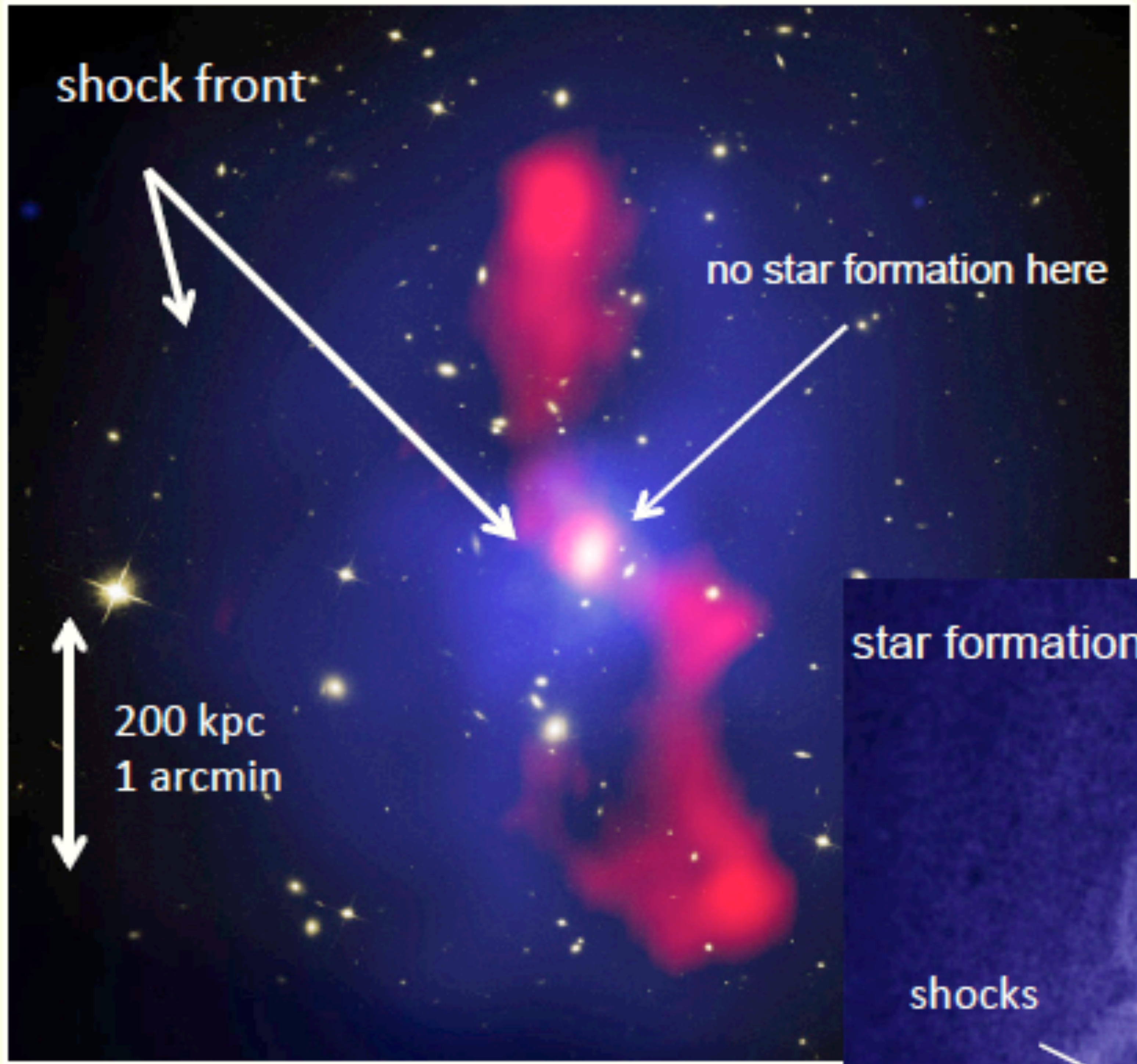
often bright cluster galaxies in gas-rich clusters



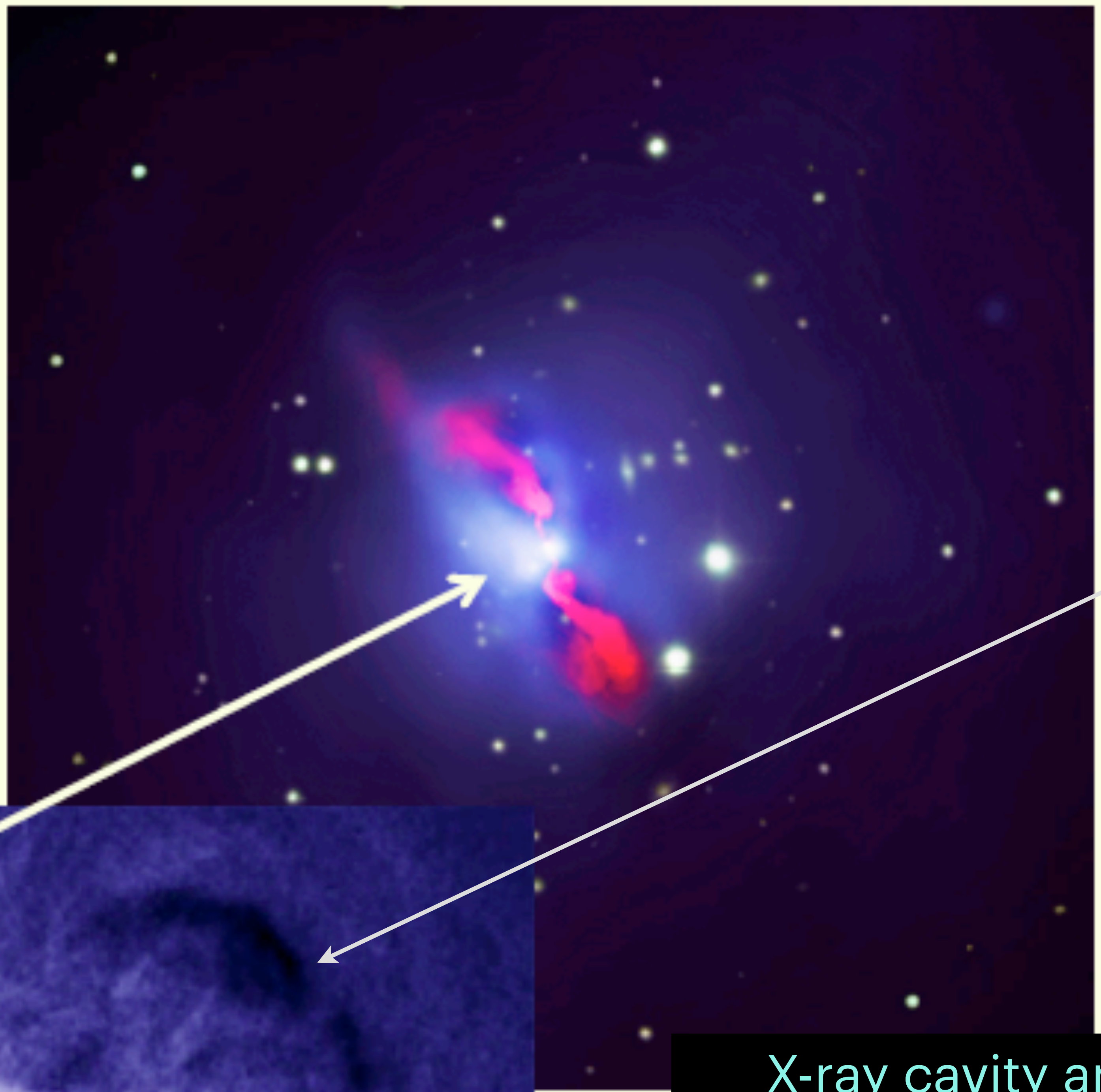
X-ray + radio = mechanical feedback

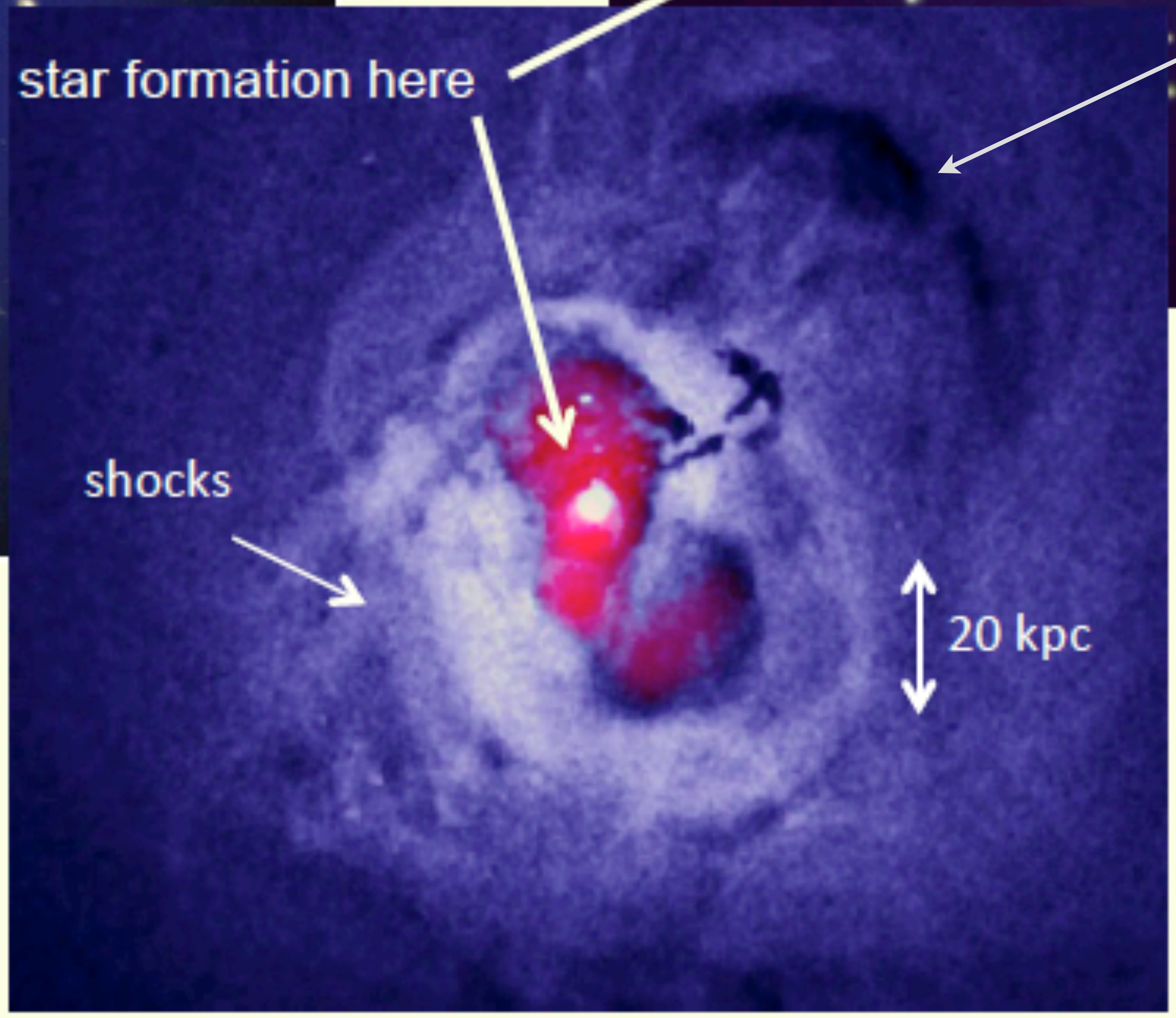
from X-ray cavities derive the time scale of the radio phase...

MS0735 McN + 05,09



Hydra A McN +00, Wise + 07 Kirkpatrick+11





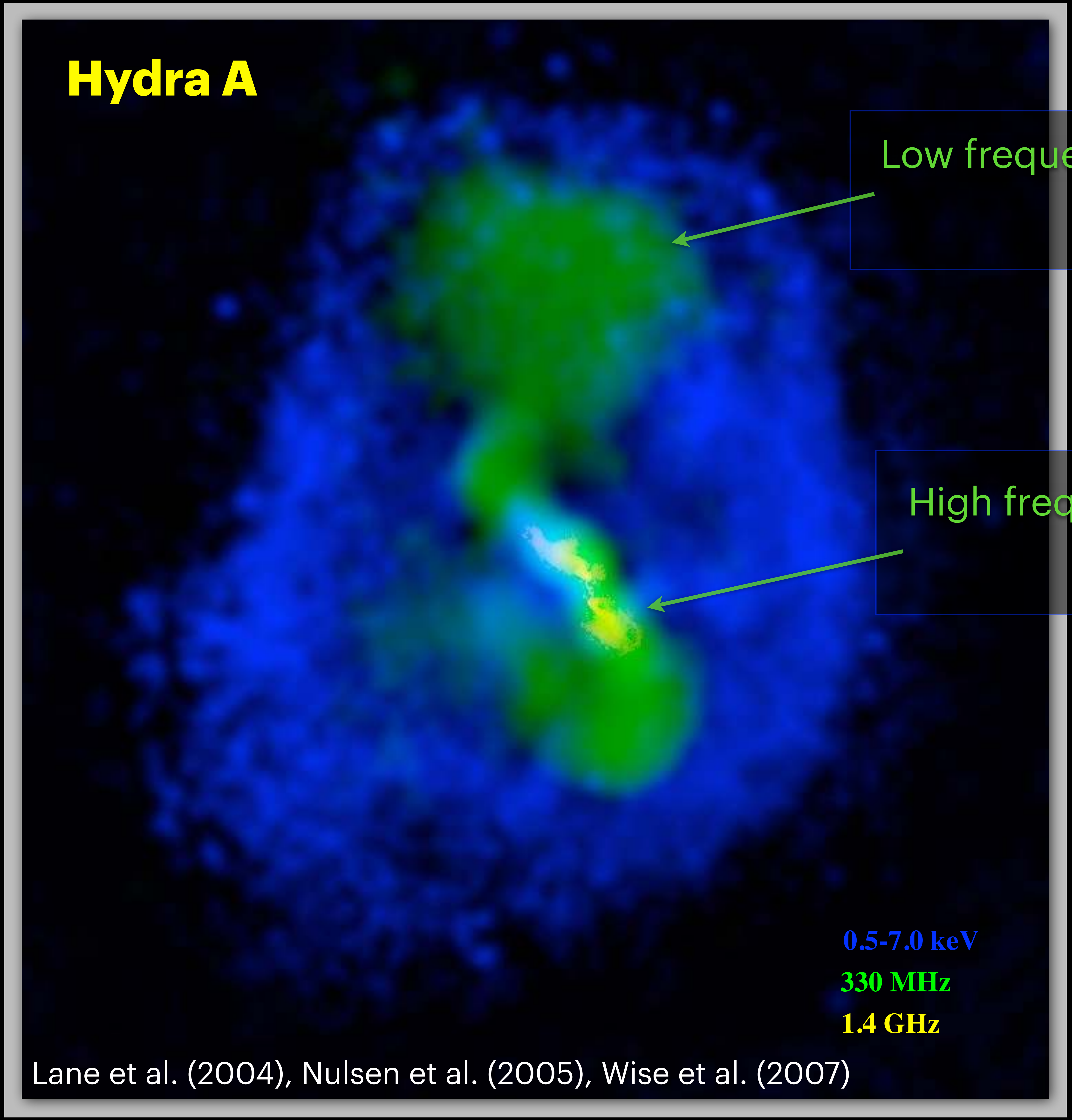
ghost cavities

Credit: H. Russell

Perseus
Fabian et al. 2008

X-ray cavity and their connection with radio plasma have been crucial for two reasons:
calorimeter to measure the energy deposition
and
to trace multiple (past) phases of activity...

Cavity Systems Trace History of (integrated) AGN Output



From radio

Low frequency ⇒ integrated history
t > 200 Myr outer cavities

Diffuse emission
Steep spectrum

High frequency ⇒ recent activity
t ~ 50 Myr inner cavities

From X-ray

Ages of cavities derived with three different methods: 1) as the time required for it to reach its projected location assuming it traveled at the sound speed; 2) as the time for the cavity to rise buoyantly to its present location; 3) the refill time-scale

➝ inner cavities 50-100 Myr

➝ outer cavities 100 - 200 Myr

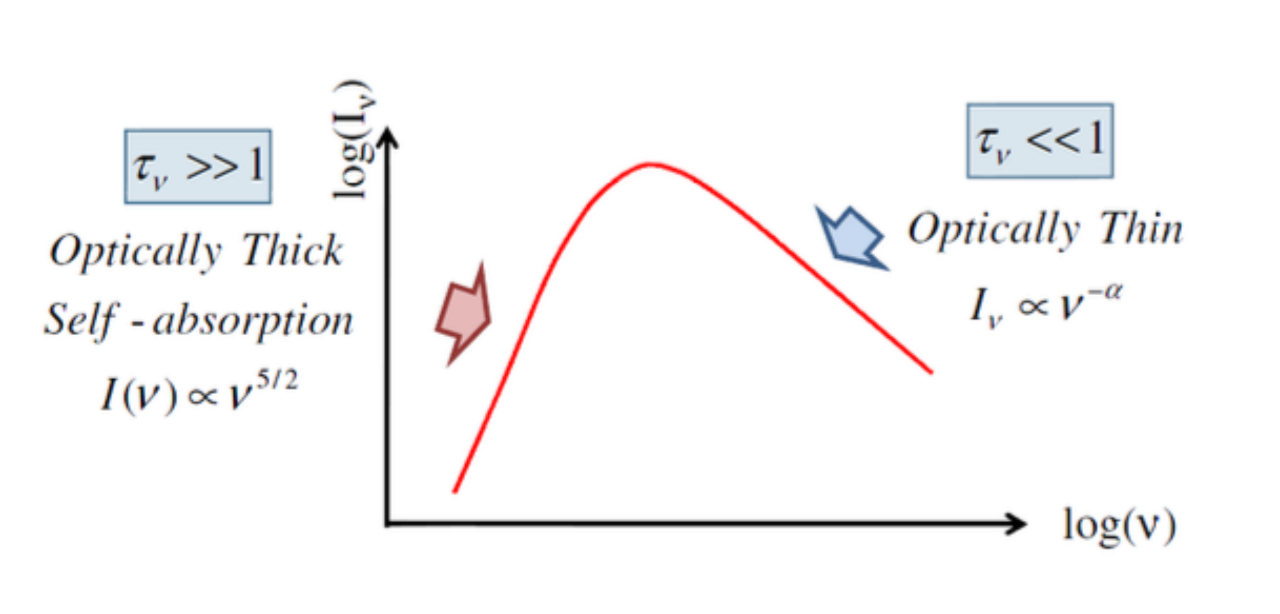
(McNamara et al. 2000; Nulsen et al. 2002, Wise et al. 2007).

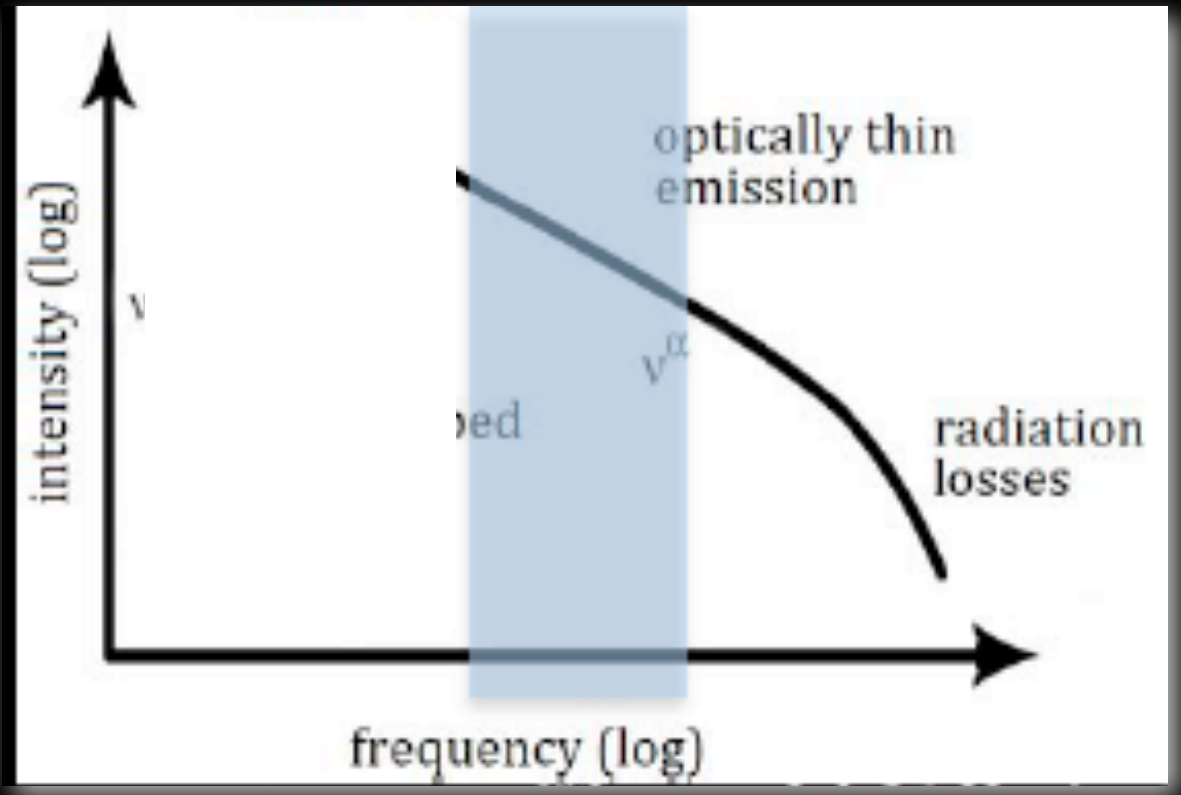
Expand the statistics of the occurrence of this cycle

Using the radio properties to derive the evolutionary stage of a radio source

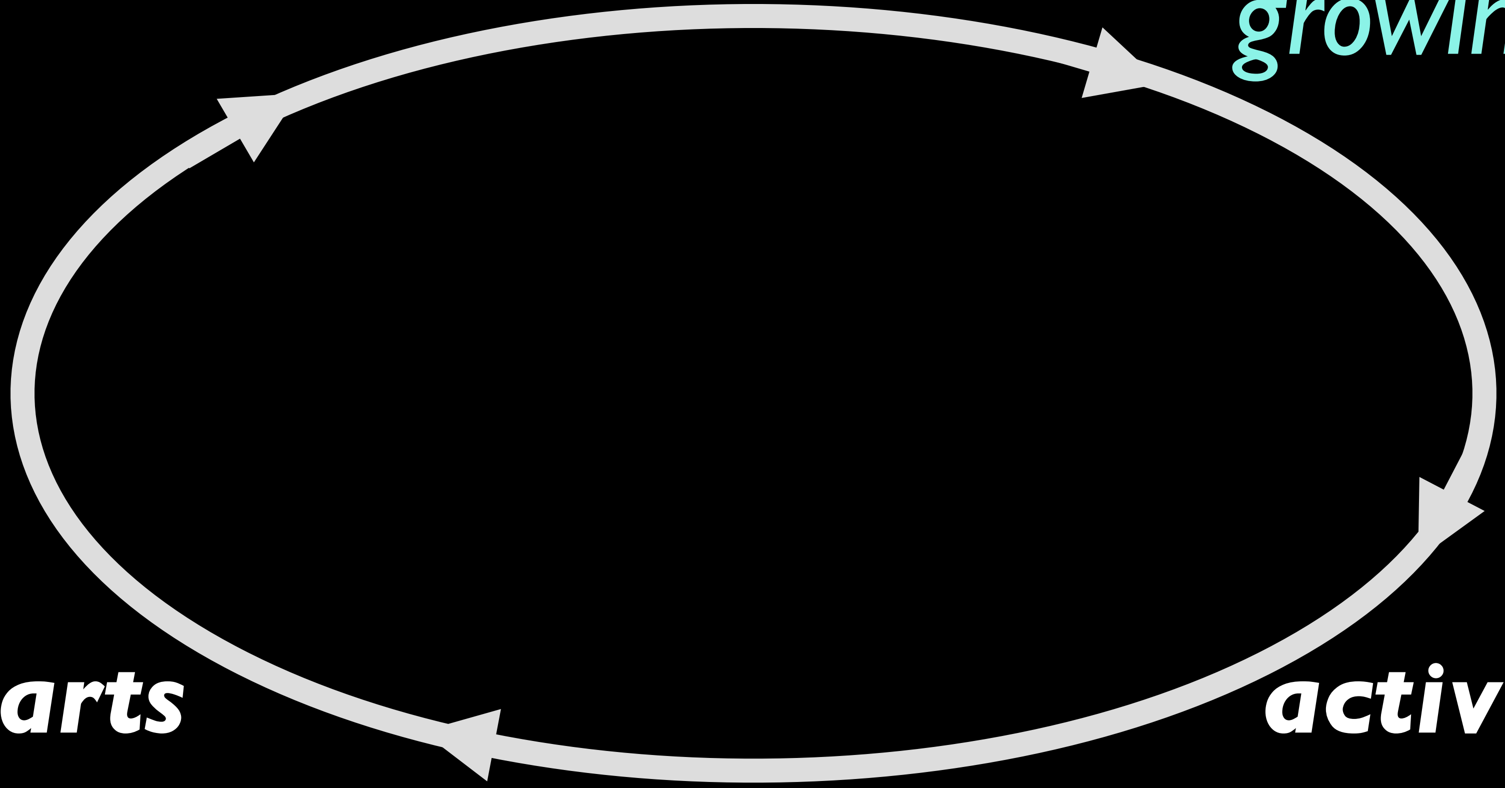
Importance of the radio spectral index

The life of a radio galaxy … seen (mainly) from the spectral index





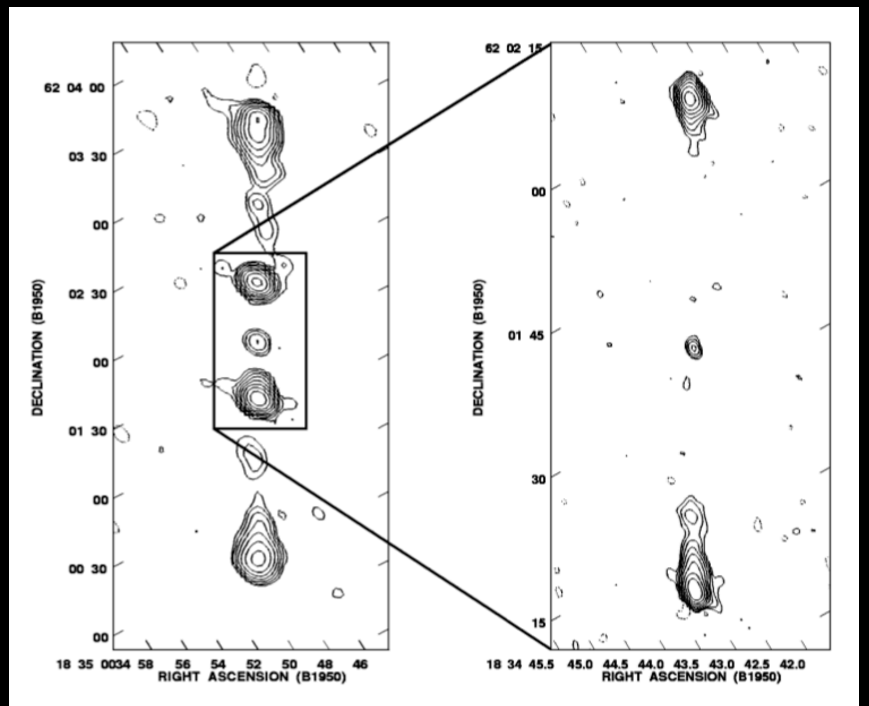
new born jet



growing to adult source

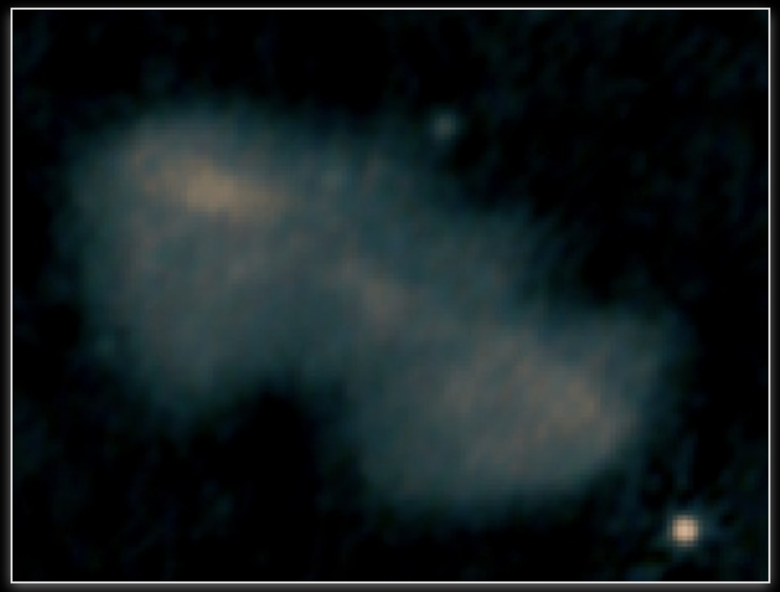
activity restarts

activity stops - remnant

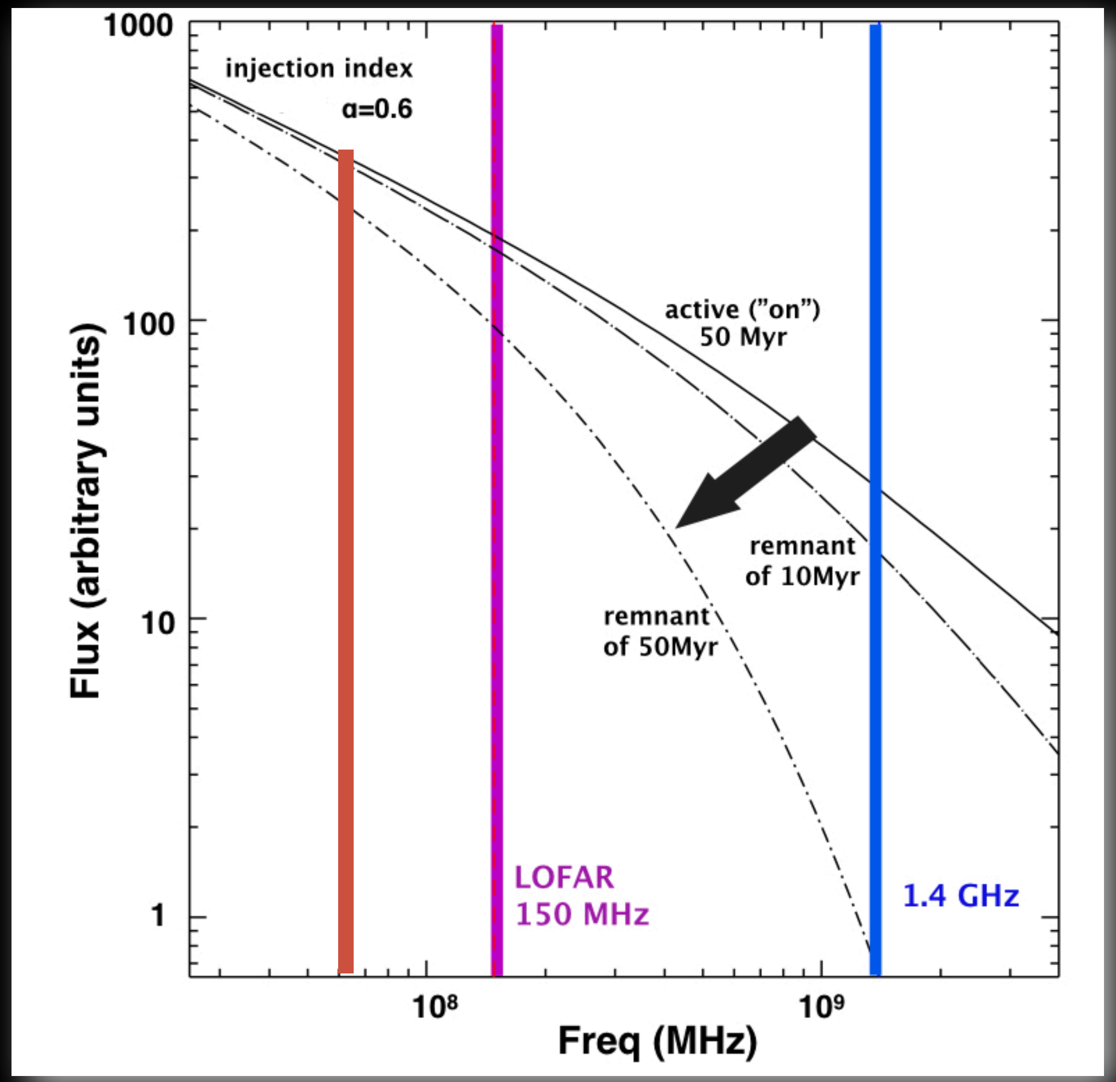


Schoenmakers et al. 1999

You need to find objects in all these phase:
Remnants (dying radio sources) and **restarted radio sources** are the most difficult to identify!

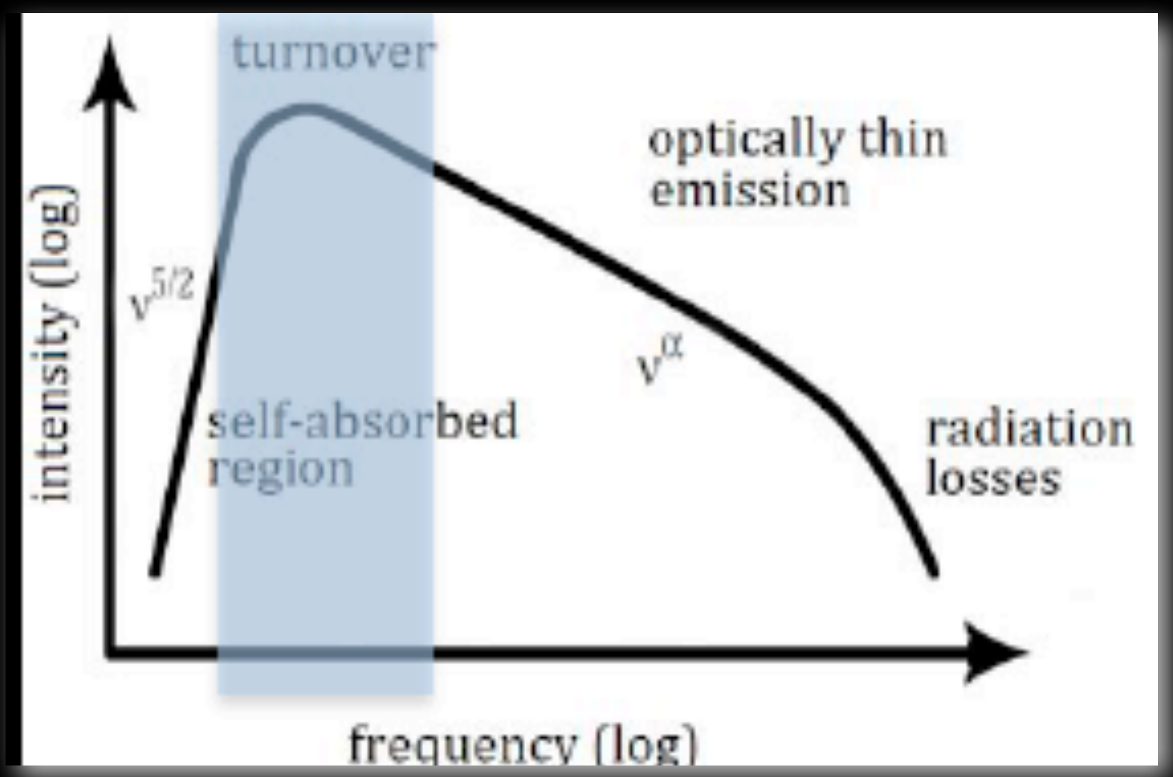


B2 0924 Shulevski et al.

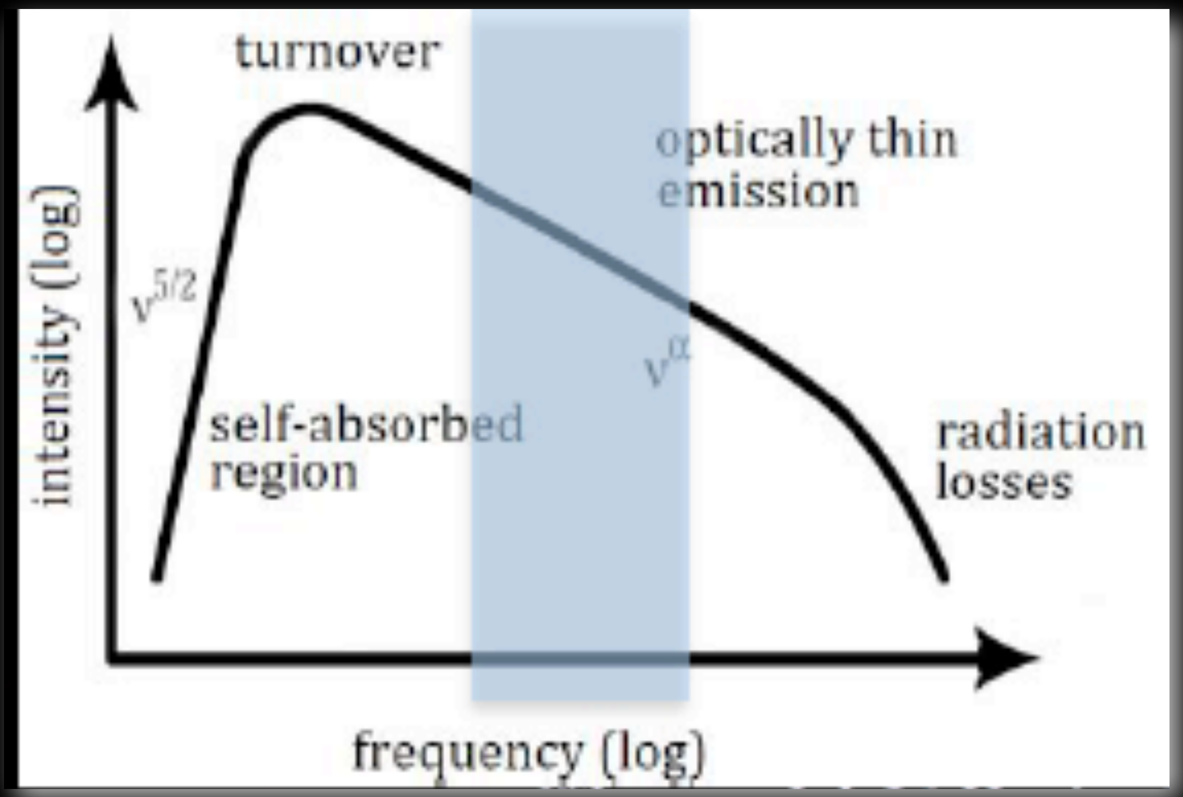


Unique of radio AGN: the evolution can be followed and timed

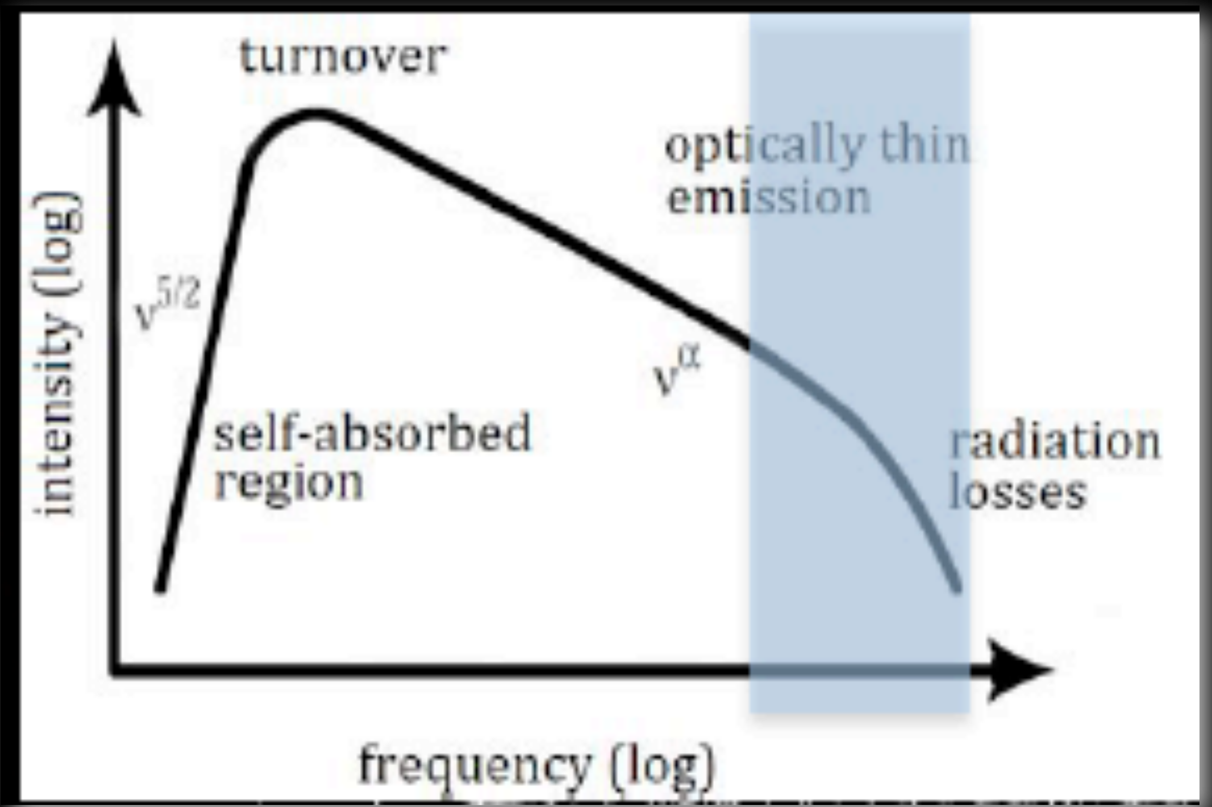
(to first order)



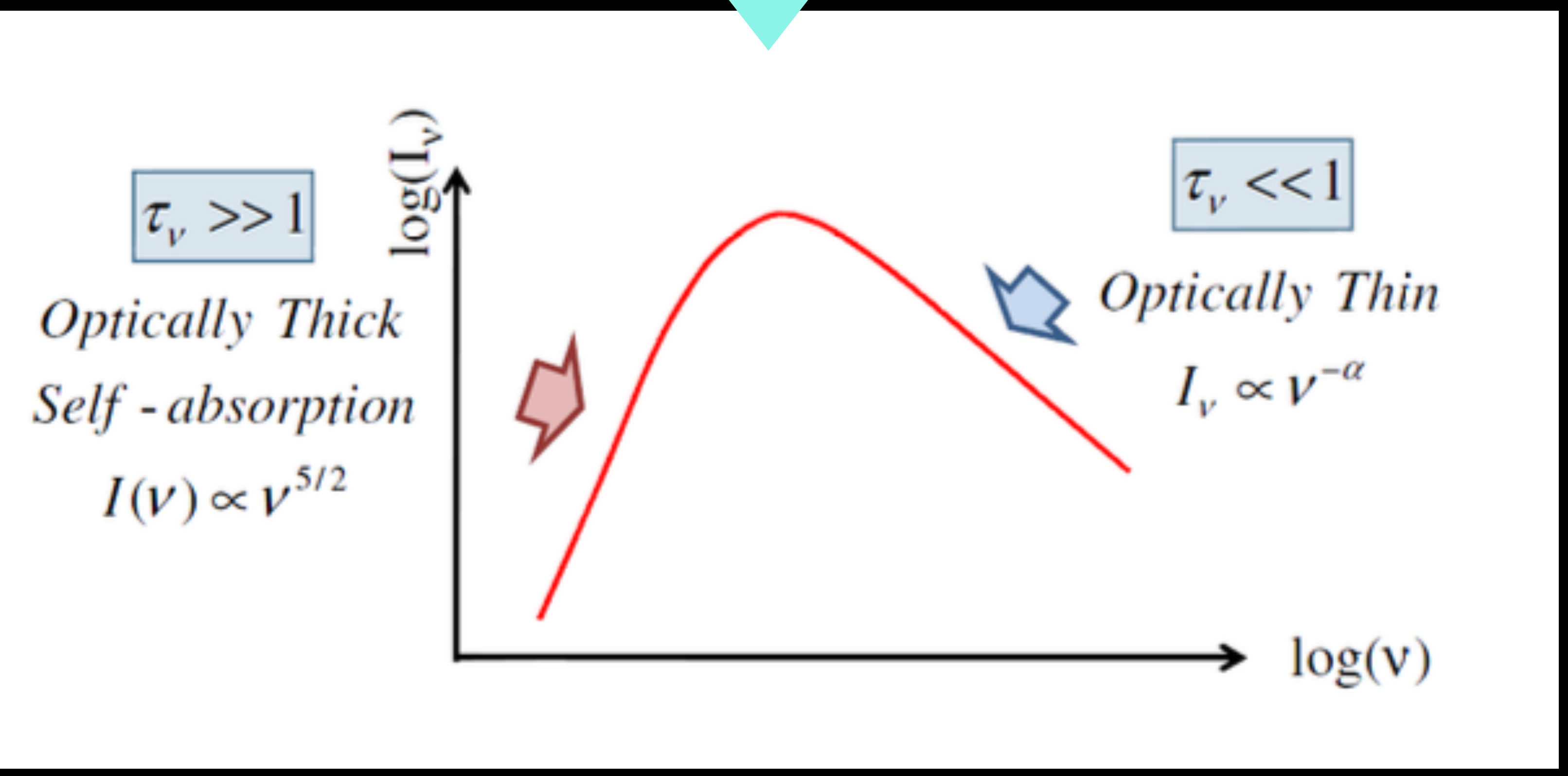
Younger radio galaxies



"adult" radio galaxies



dying - remnant radio galaxies



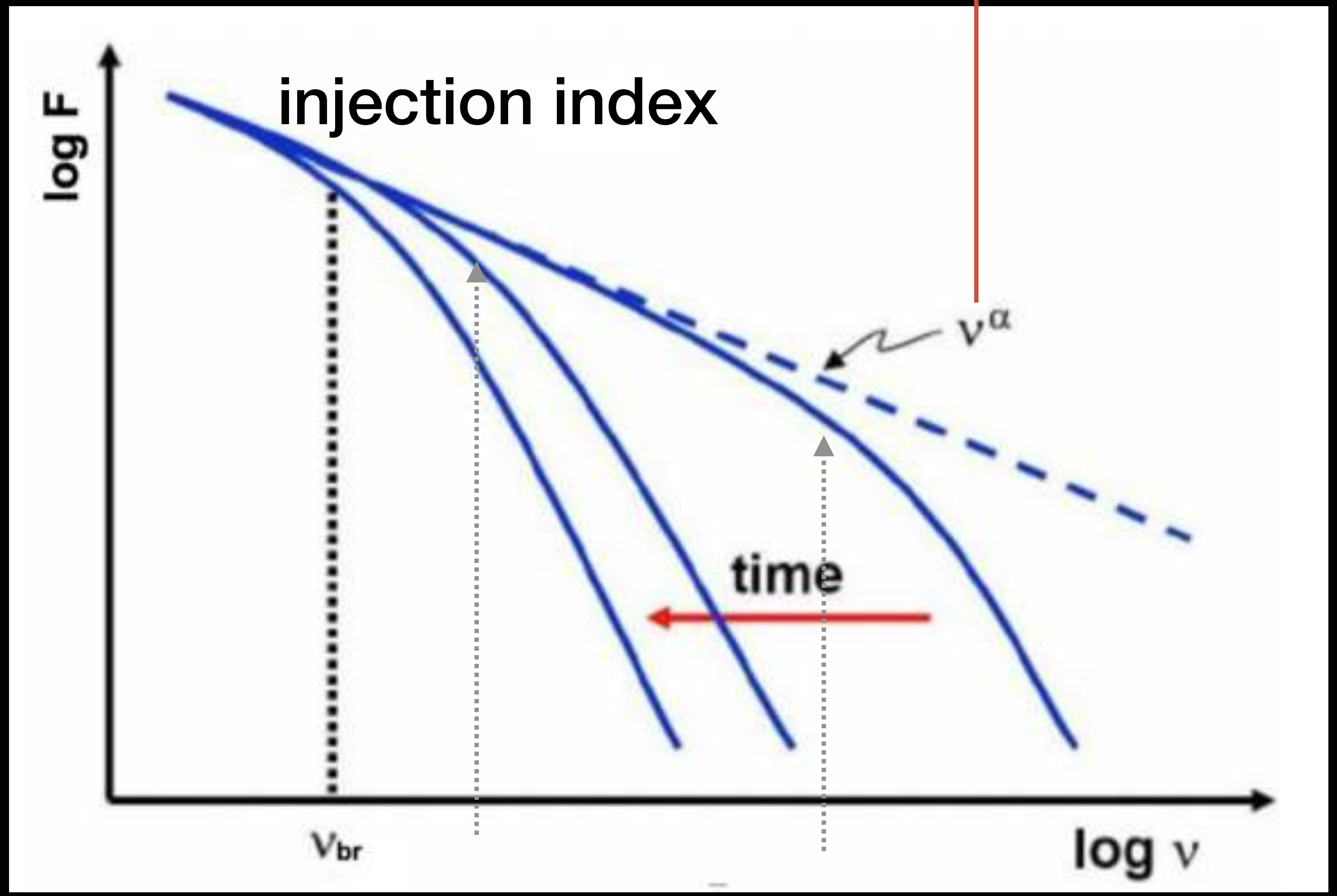
spectral shape provides key information on age/evolutionary stage of the radio AGN

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 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.

Typical synchrotron spectral index -0.7



Power emitted by an electron

$$P = \frac{dE}{dt} = \frac{4e^4}{9m^2c^3} B^2\gamma^2$$

Energy loss through radiation: obtained from $E=\gamma m_e c^2$ and energy losses rate P.
Characteristic electron half-life time (time for energy to half)

$$t_{cool} = \frac{E}{P} = 2.4 \times 10^5 \left(\frac{\gamma}{10^4}\right)^{-1} \left(\frac{B}{10^{-4}G}\right)^{-2} \quad yr$$

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 tcool

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

when nuclear activity stops (dying sources) the spectrum shows an extra steepening

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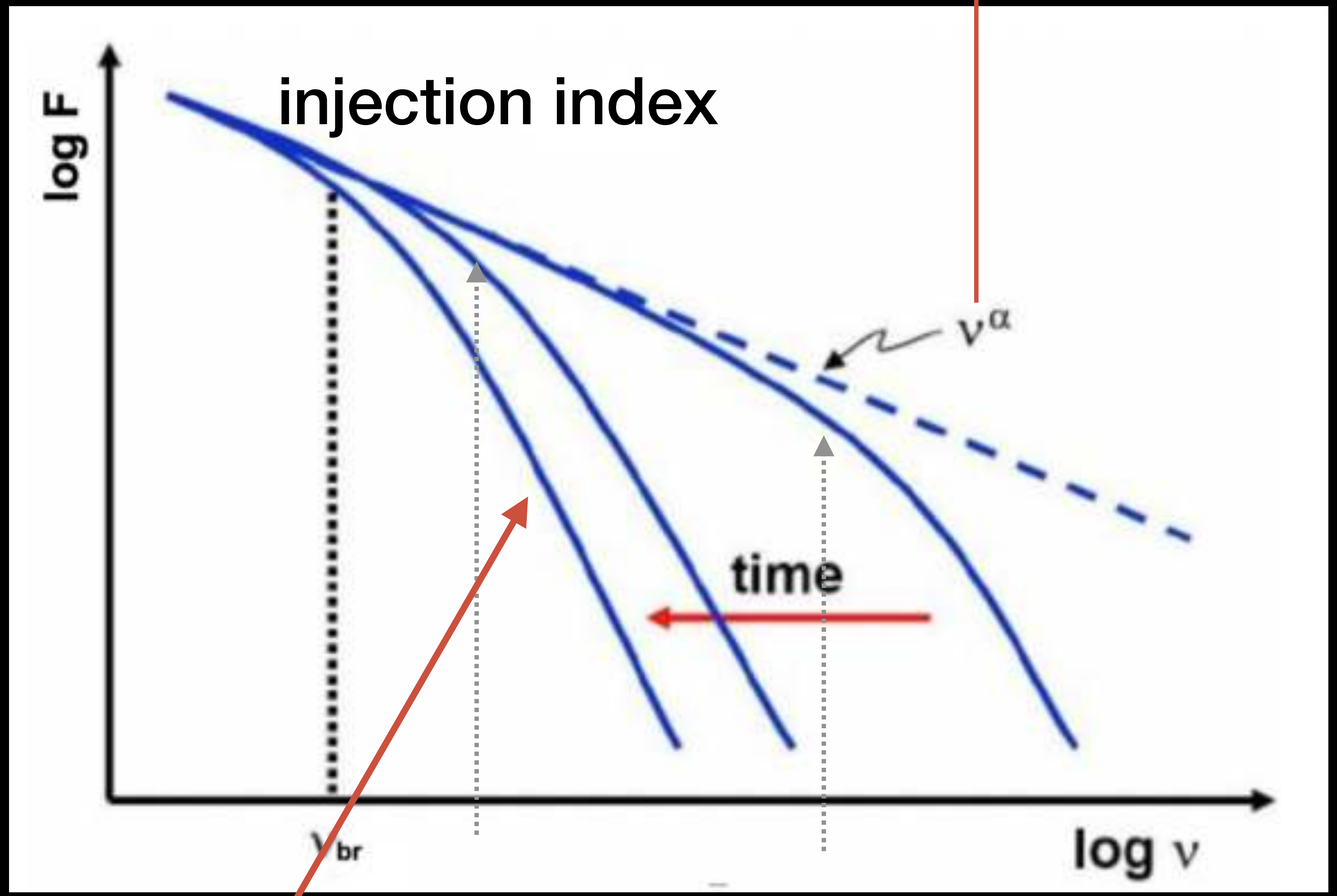

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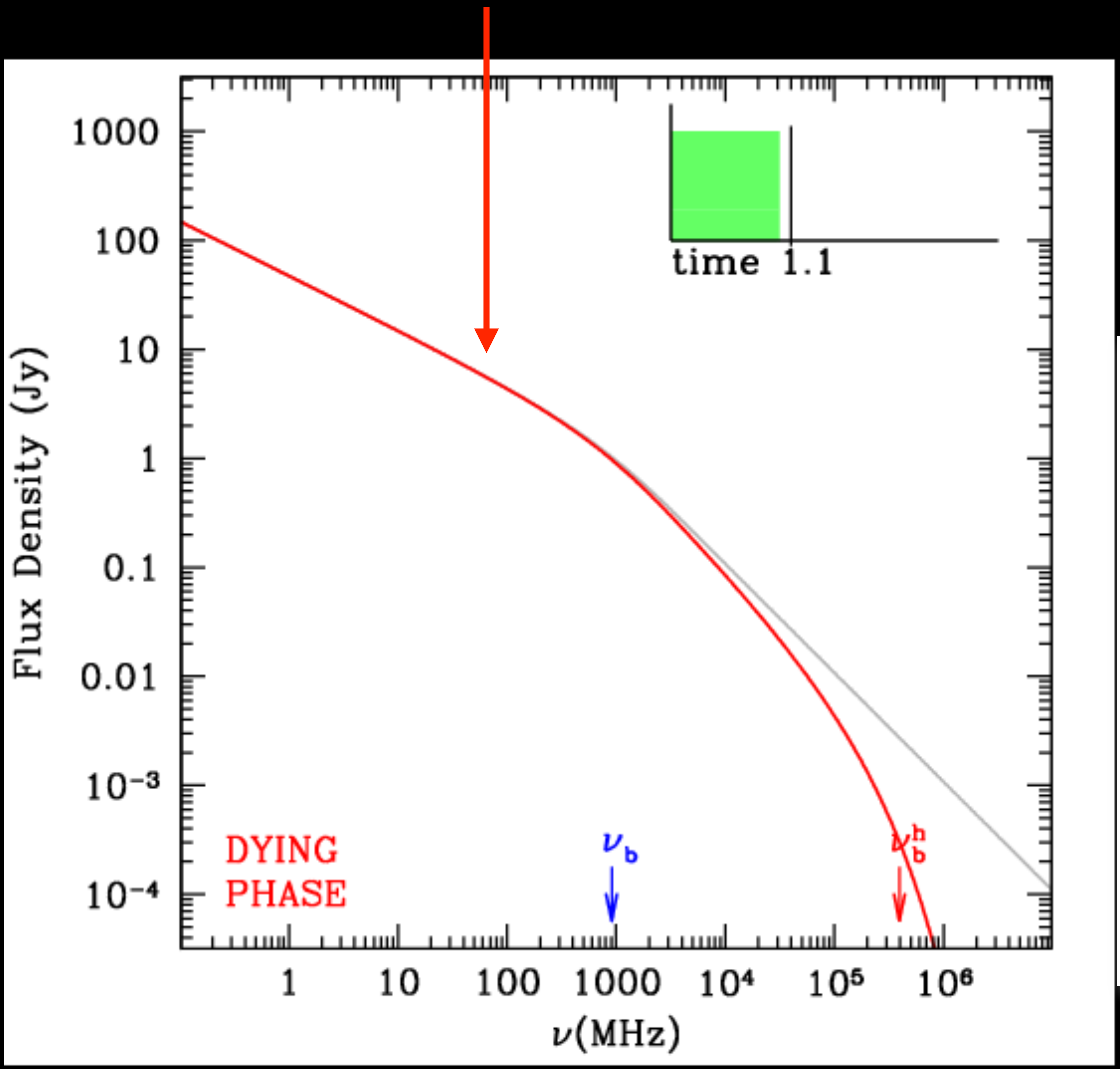
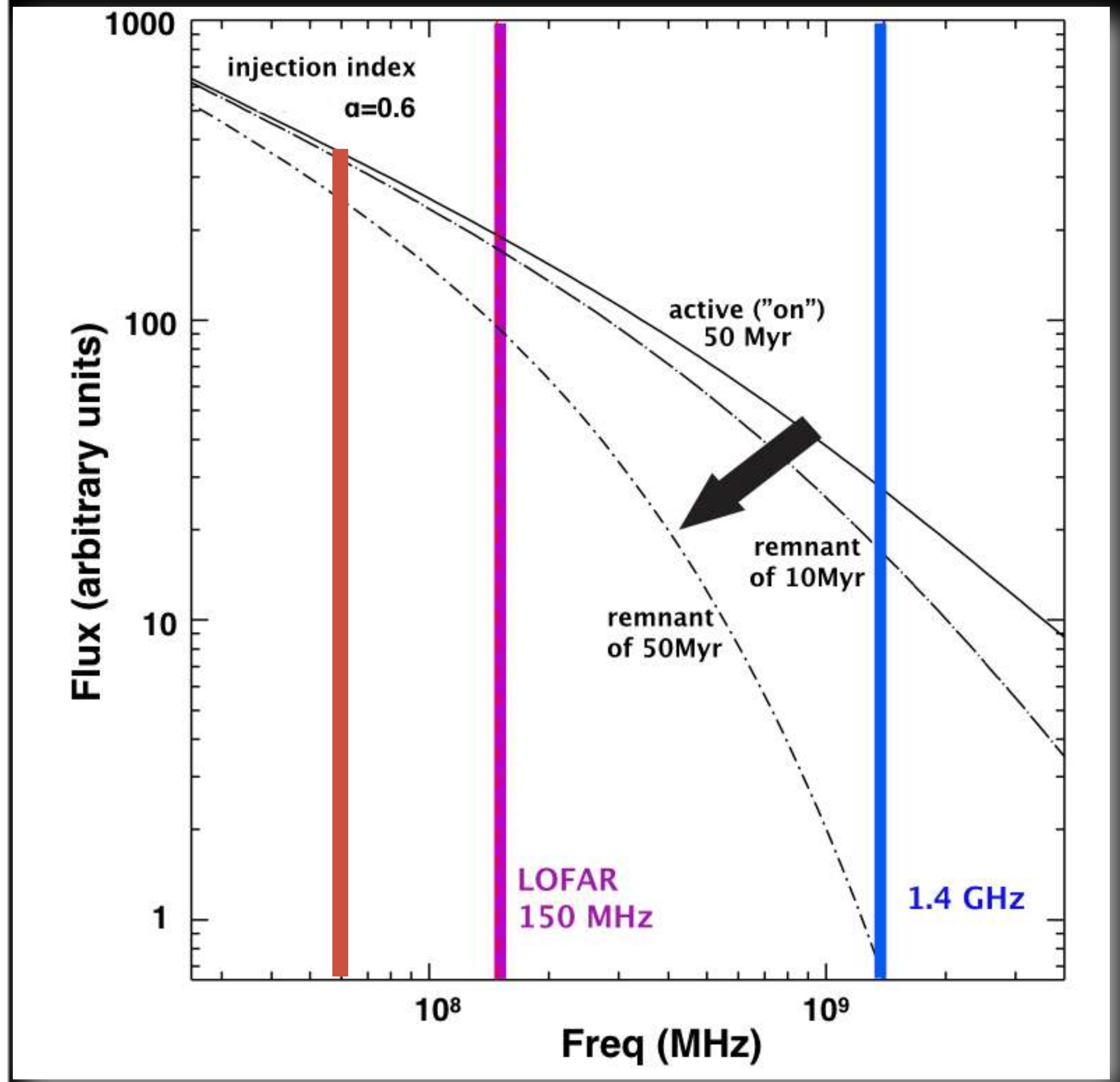
when nuclear activity stops (dying sources) the spectrum shows an extra steepening (steeper than -1.5)

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



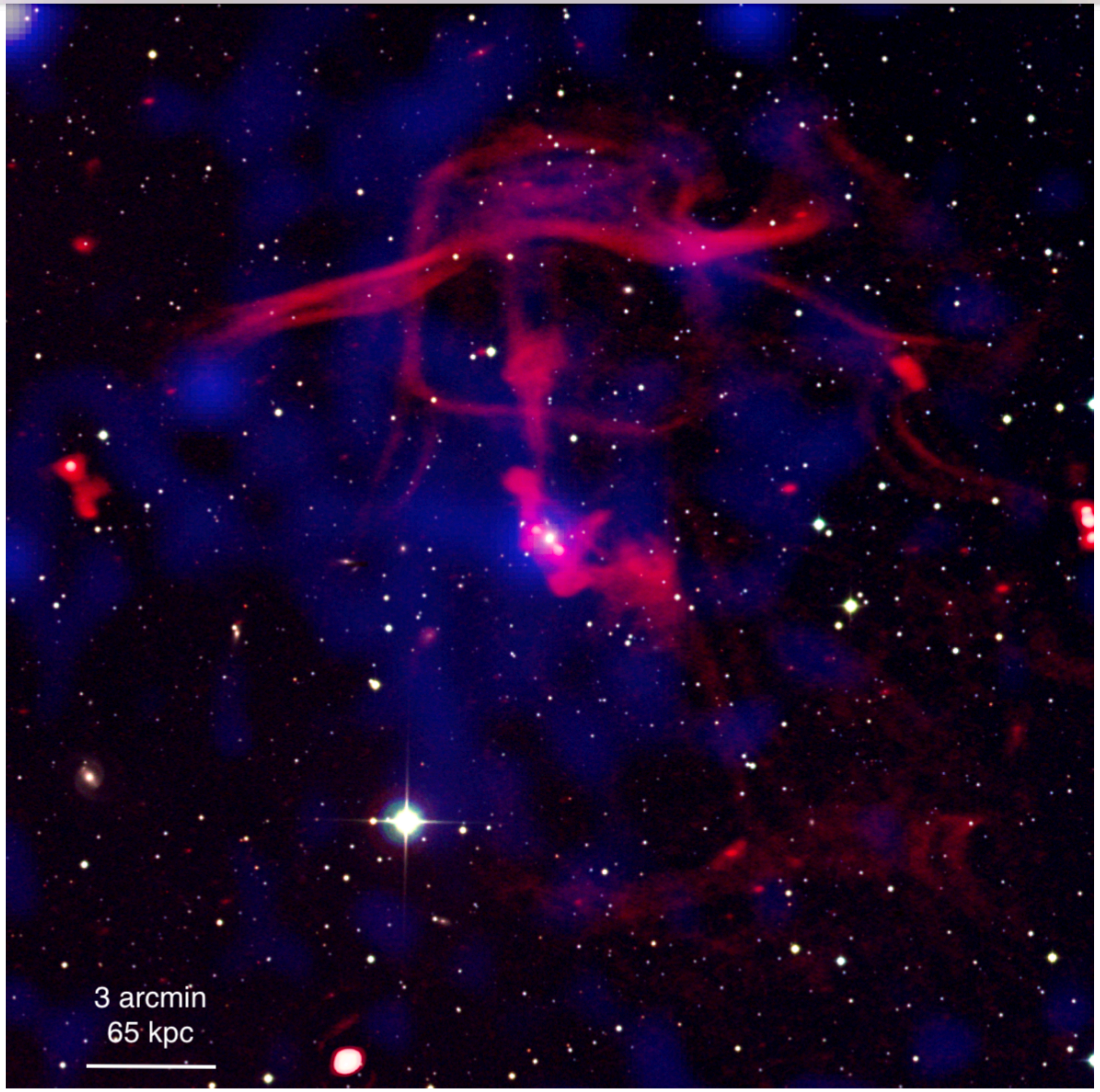
Morganti 2017

Courtesy of M. Murgia

Short intermezzo!

all I have told you about using the spectral indices for ages is ok unless re-accelleration of the electrons is present…

Extreme cases: galaxy groups



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.

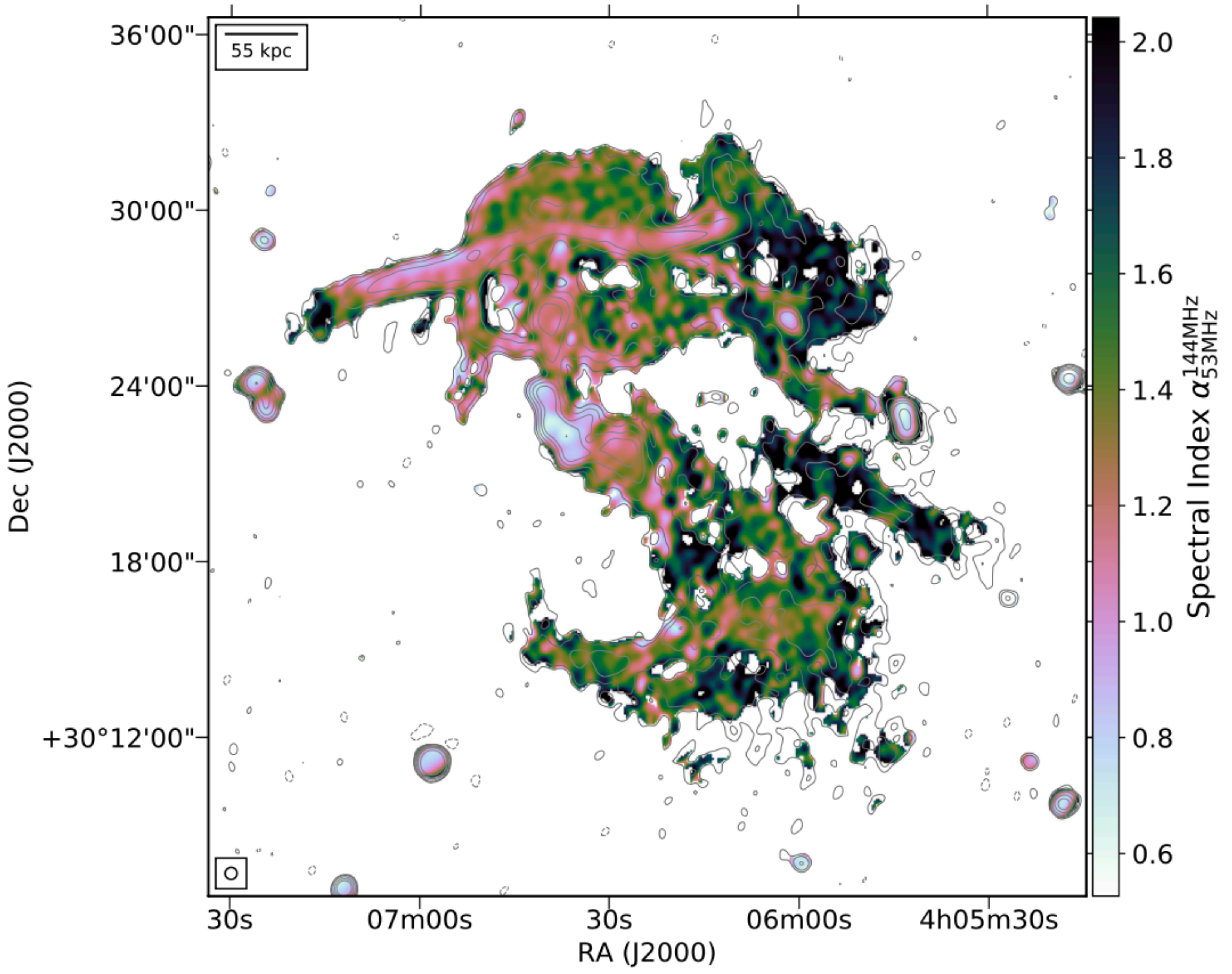
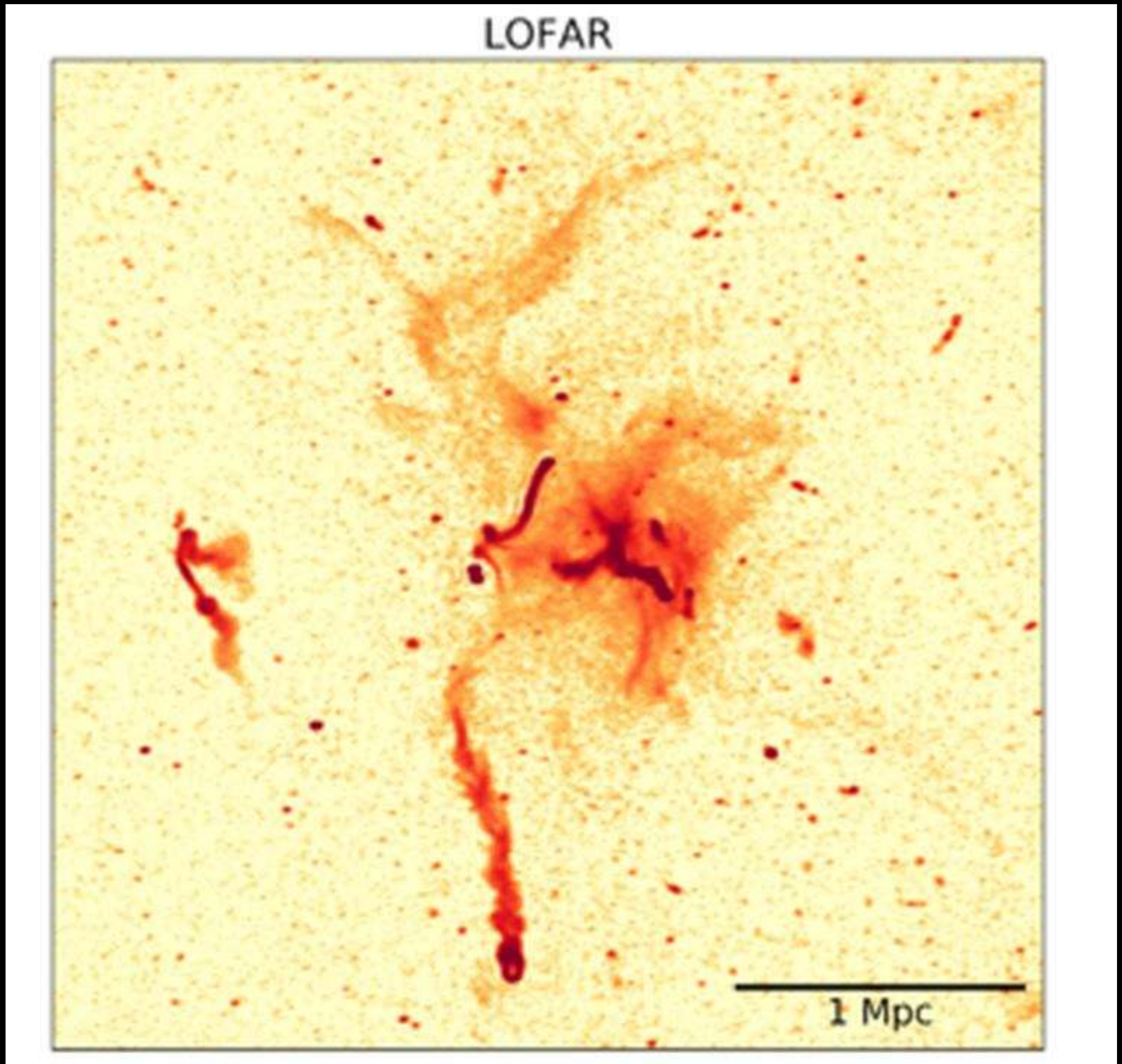


Figure 3: **Spectral index map in the range 53-144 MHz of the galaxy group Nest200047.** The image shows an increasing spectral steepening of the non-thermal plasma towards the system peripheries, implying increasing radiative ages. The map is produced using LOFAR images with uniform weighting scheme, a gaussian uv-taper of 25 arcsec and a restoring beam of 25 arcsec. Only pixels with surface brightness above 3σ in both maps have been used. Contour levels represent the emission at 53 MHz and are drawn at -3, 3, 5, 10, 20, 35, 100 $\times\sigma$ levels, with σ=2.7 mJy beam^{-1}. The beam size is shown in the bottom left corner of the image.

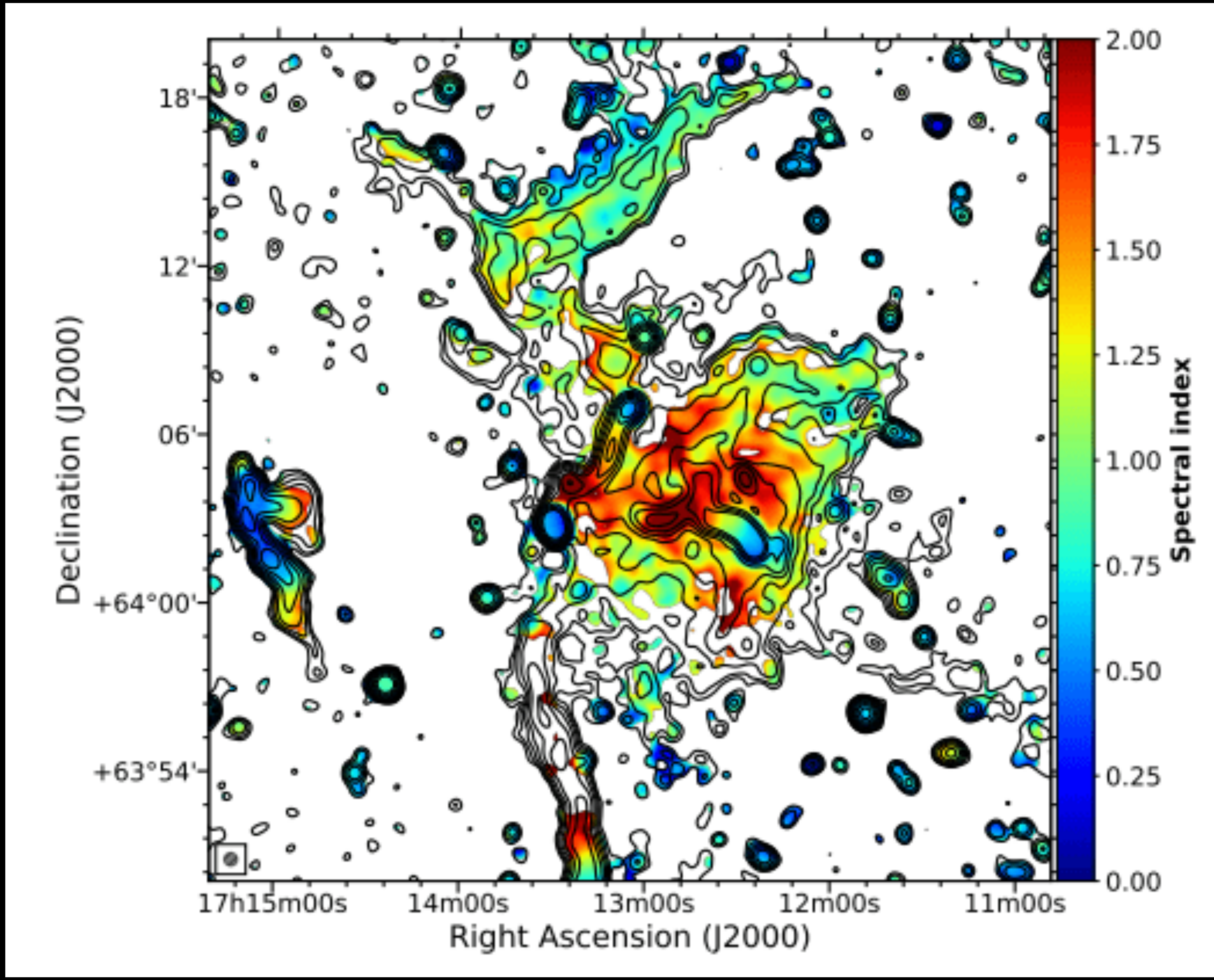
pure particle radiative losses equal to t_{rad} < 400 Myr

Brienza et al. 2021 Nature Astronomy

Extreme cases: galaxy clusters



Abell 2255 - Botteon et al. 2020



Spectral index map between 144 MHz and 1.2 GHz of the central radio emission in A2255 at a resolution of 28″ × 28″

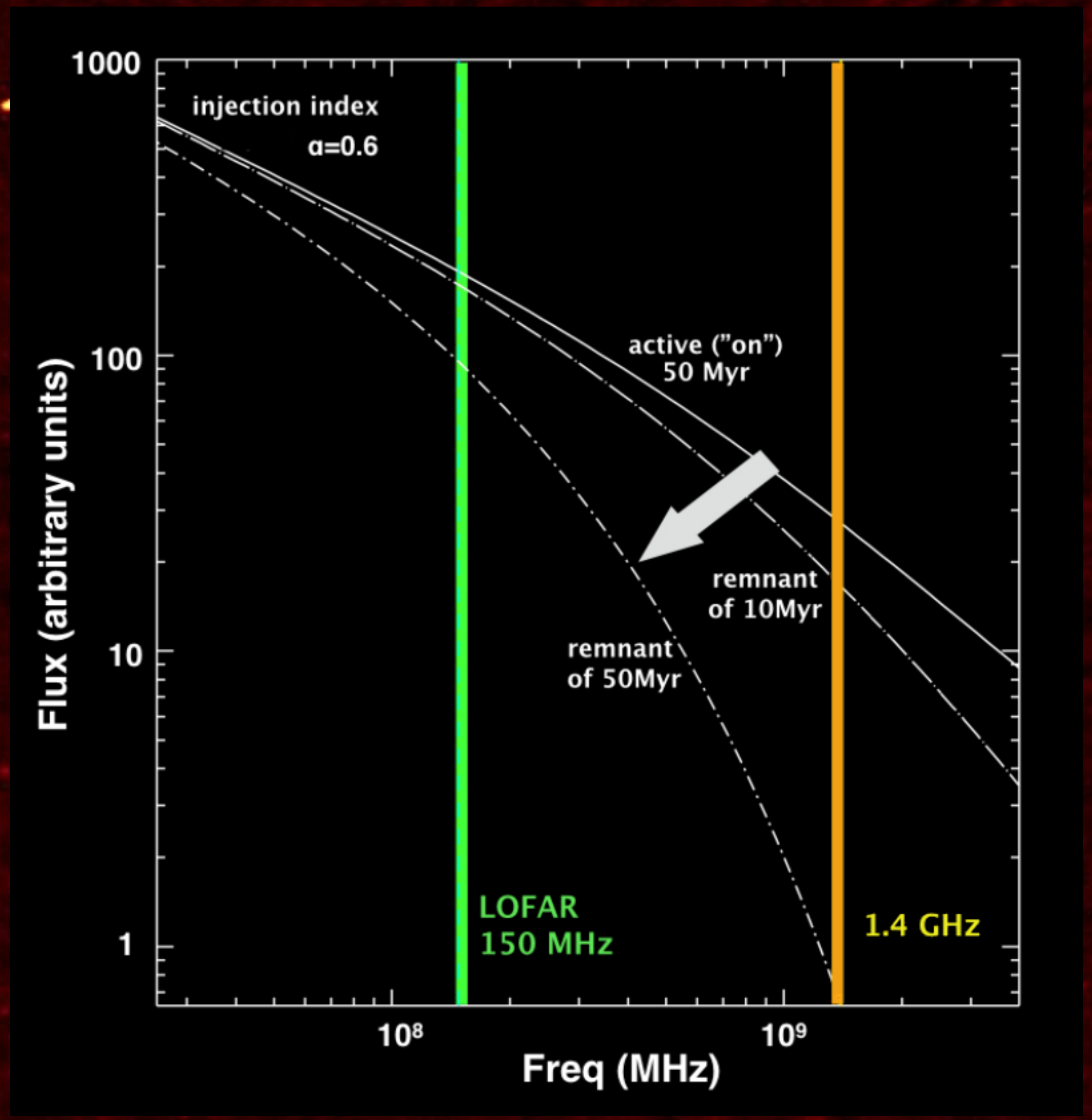
End of the intermezzo!

How do we look for dying and restarted radio galaxies?

How do we look for dying and restarted radio galaxies?

Young and adult radio galaxies are "easy" to find
Dying and restarted radio sources are the most difficult to identify and the rarest

new possibilities offered by the new radio telescopes (Les 1)



Parameters that can be now used (many simultaneously):

✳ Large area that can be covered in one pointing (LOFAR ~ 25 sq deg): remnant and restarted are rare objects

✳ Spectral properties → need multiple frequencies… importance of the surveys (as mentioned in Les 1)

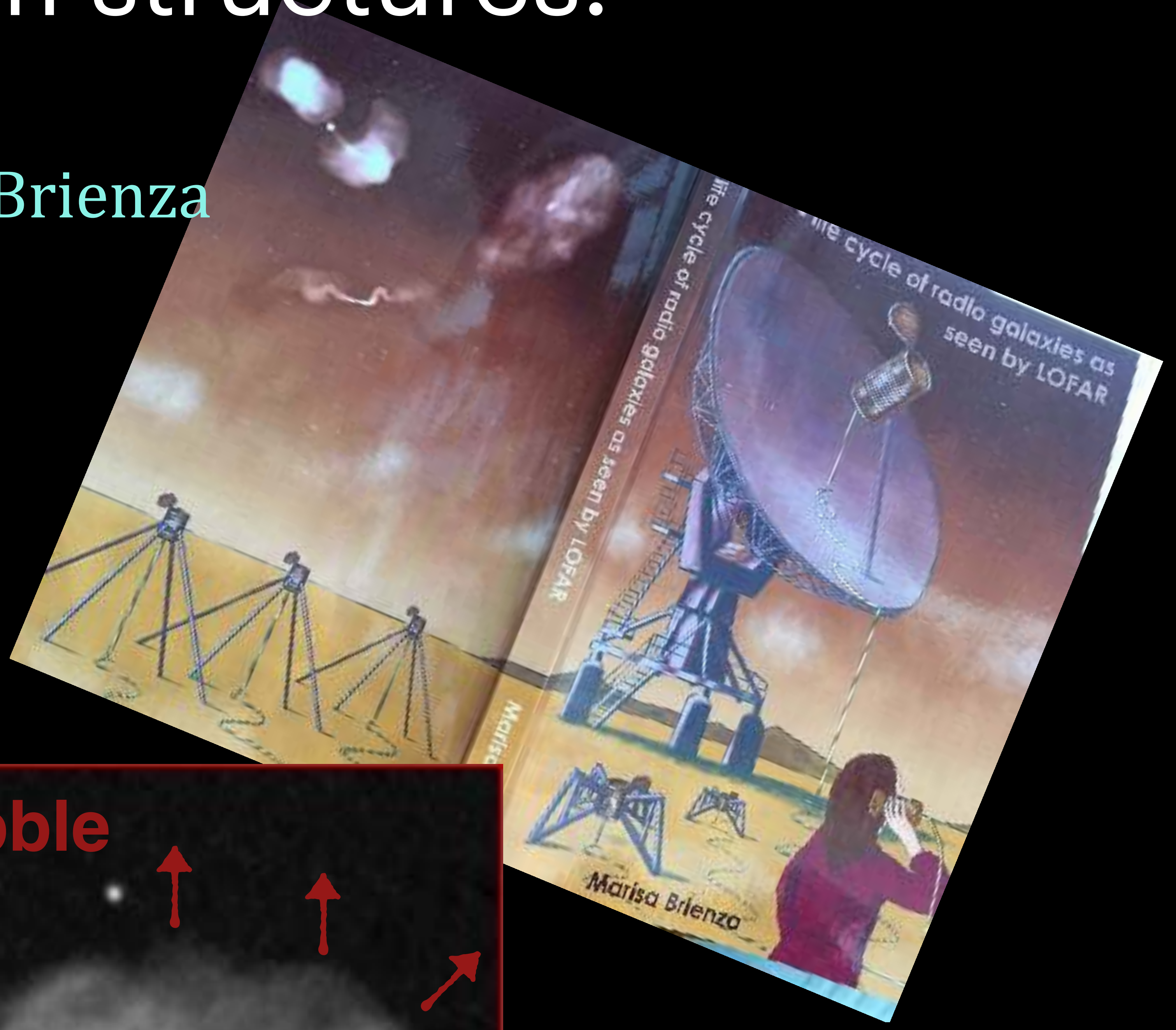
✳ Morphology

Dying (remnant) radio sources: what are their characteristics?

switch off the core, diffuse lobes - adiabatically expanding, no compact structure present, ultra-steep spectrum structures.

Nika Jurlin

Marisa Brienza



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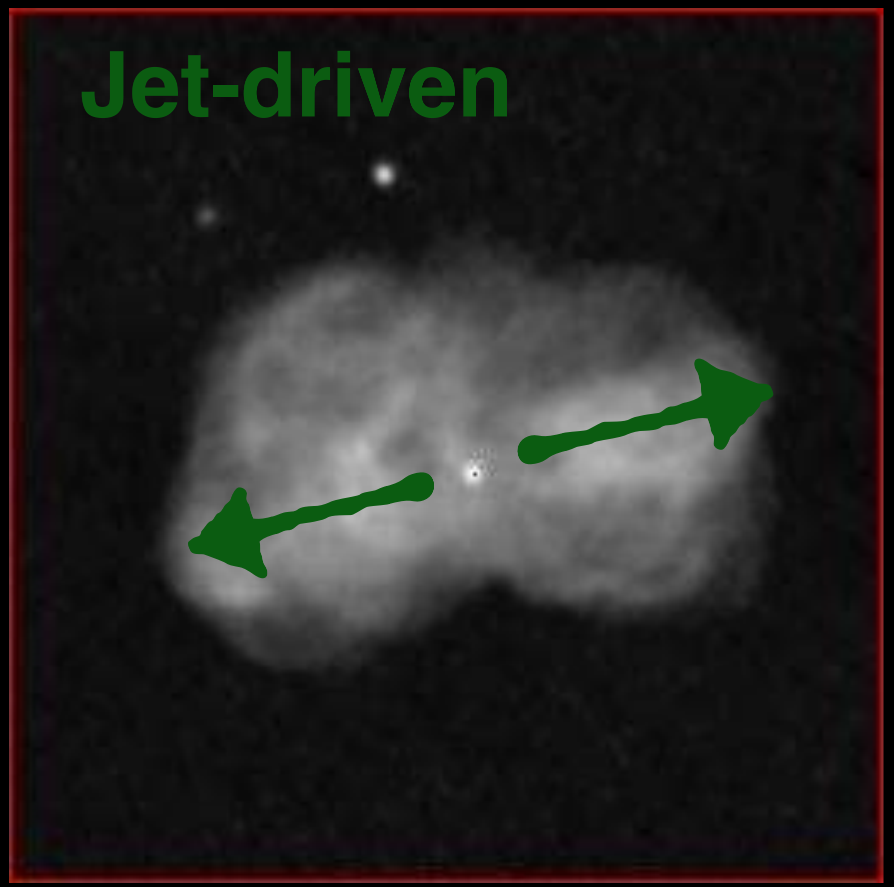

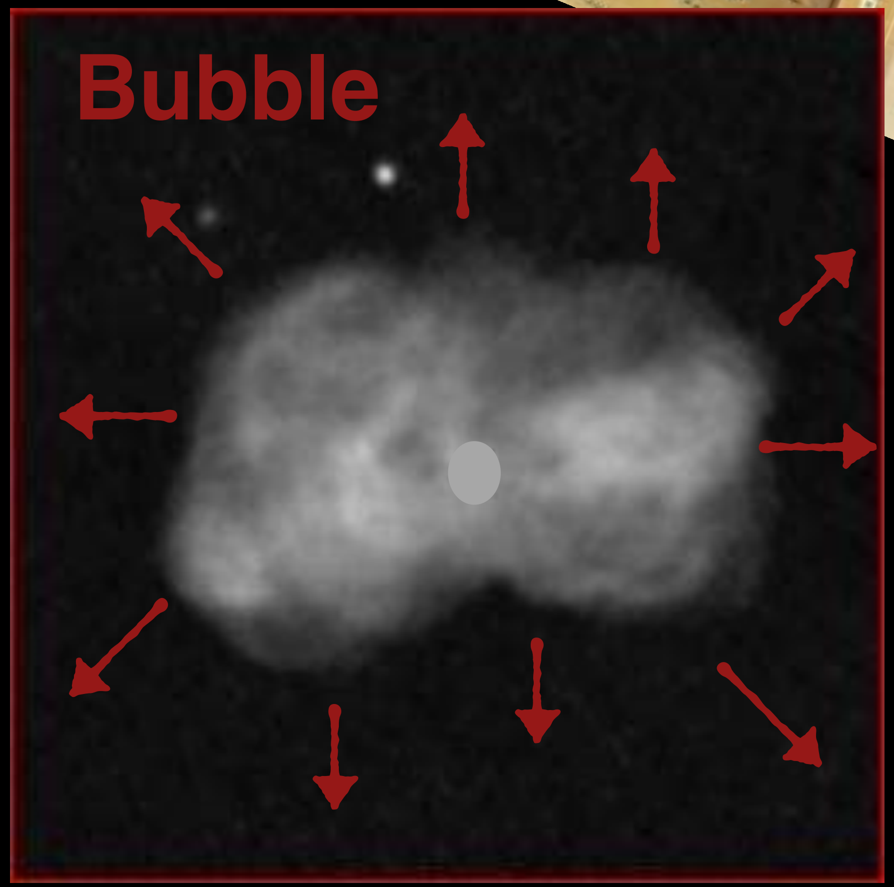

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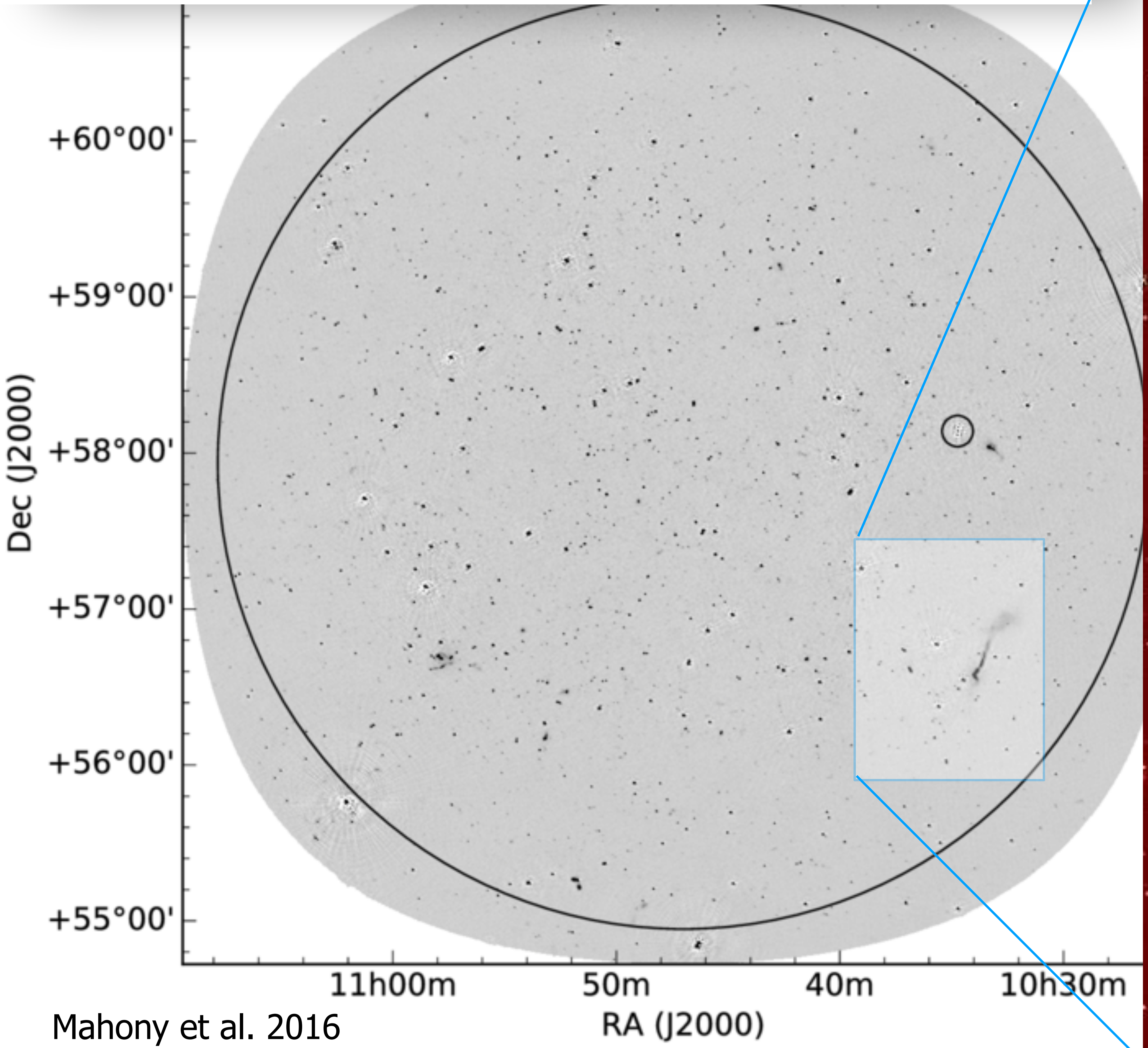
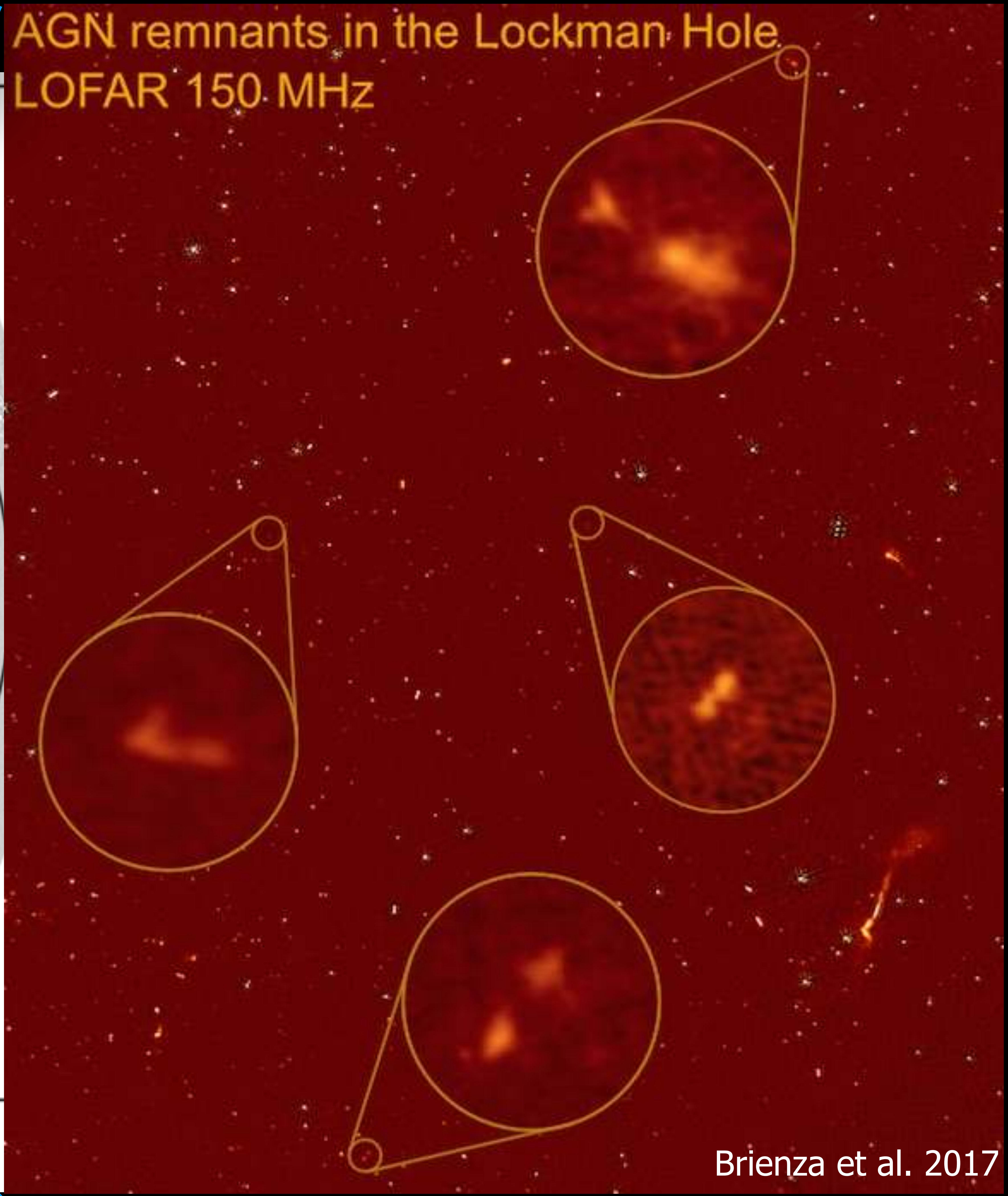
Example: Lockman Hole region: ~ 25 sq deg -
About 5000 radio sources detected
Possibility to select remnants, restarted and comparison sample



Mahony et al. 2016

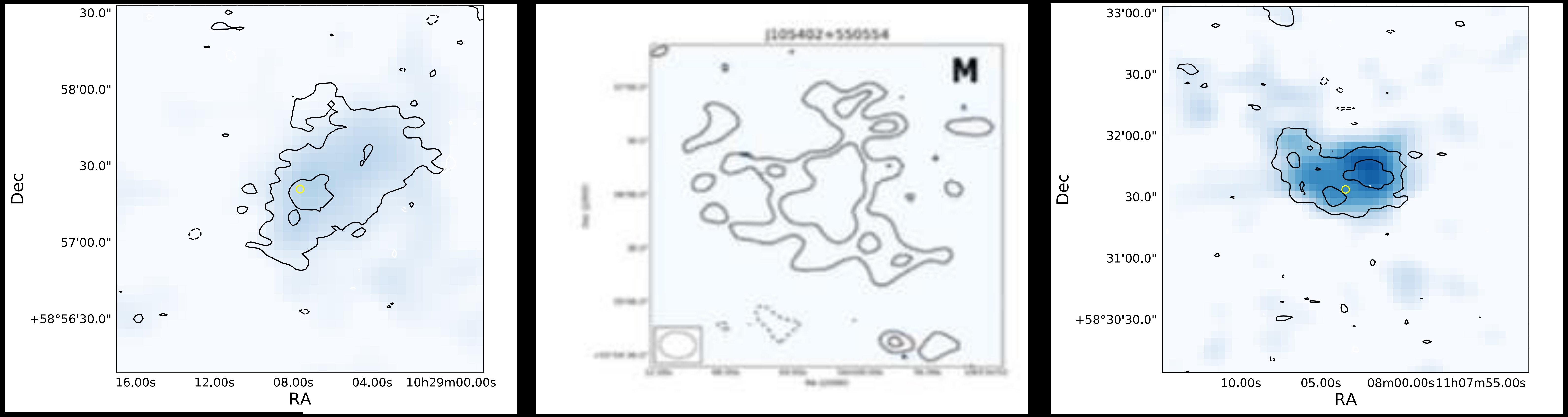


Brienza et al. 2017

Looking for remnant sources in the Lockman Hole (~25 sq deg)

Brienza et al. 2017
Jurlin et al. 2021

LOFAR 150 MHz - 18 arcsec and 6 arcsec



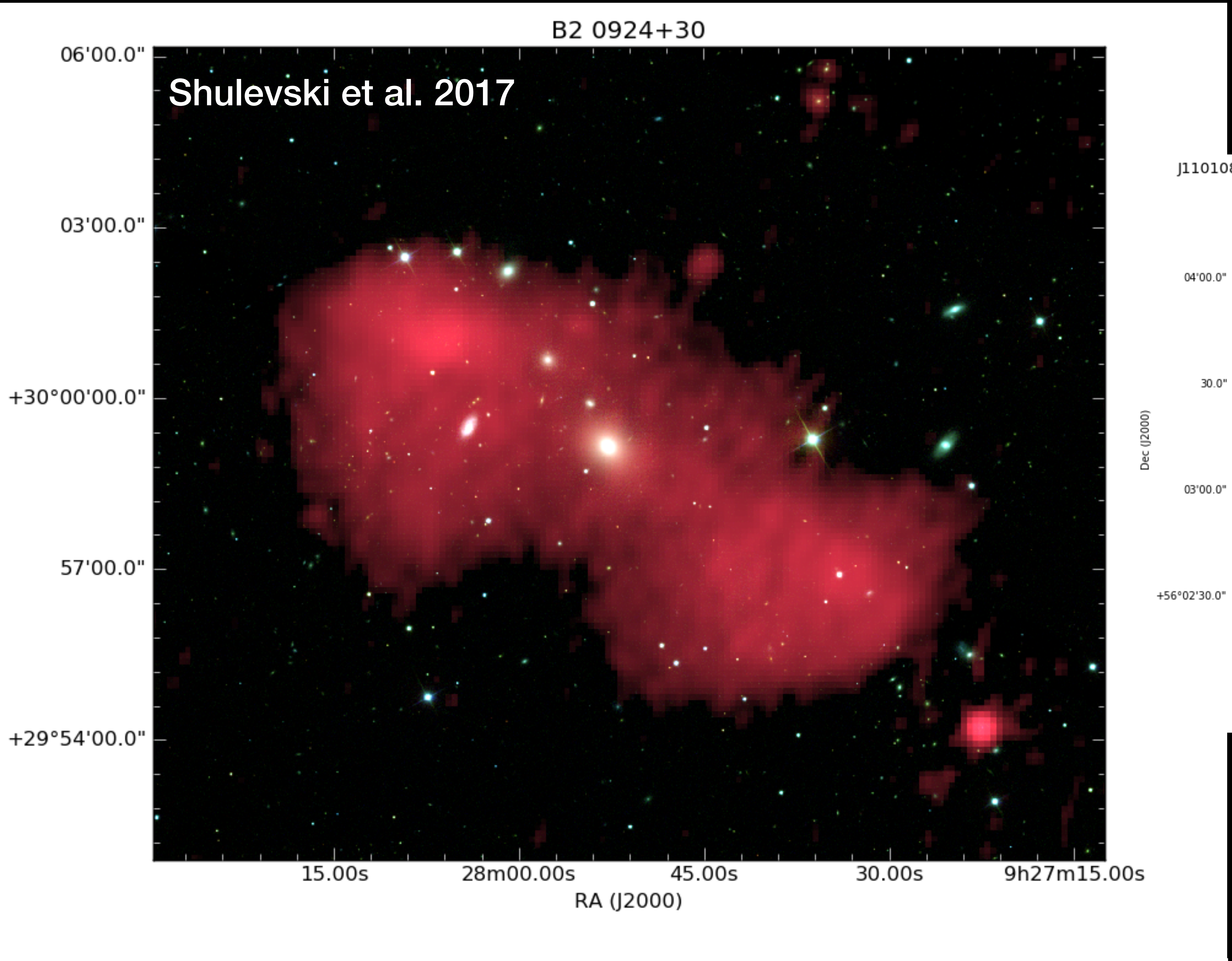
Jurlin et al. 2021

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

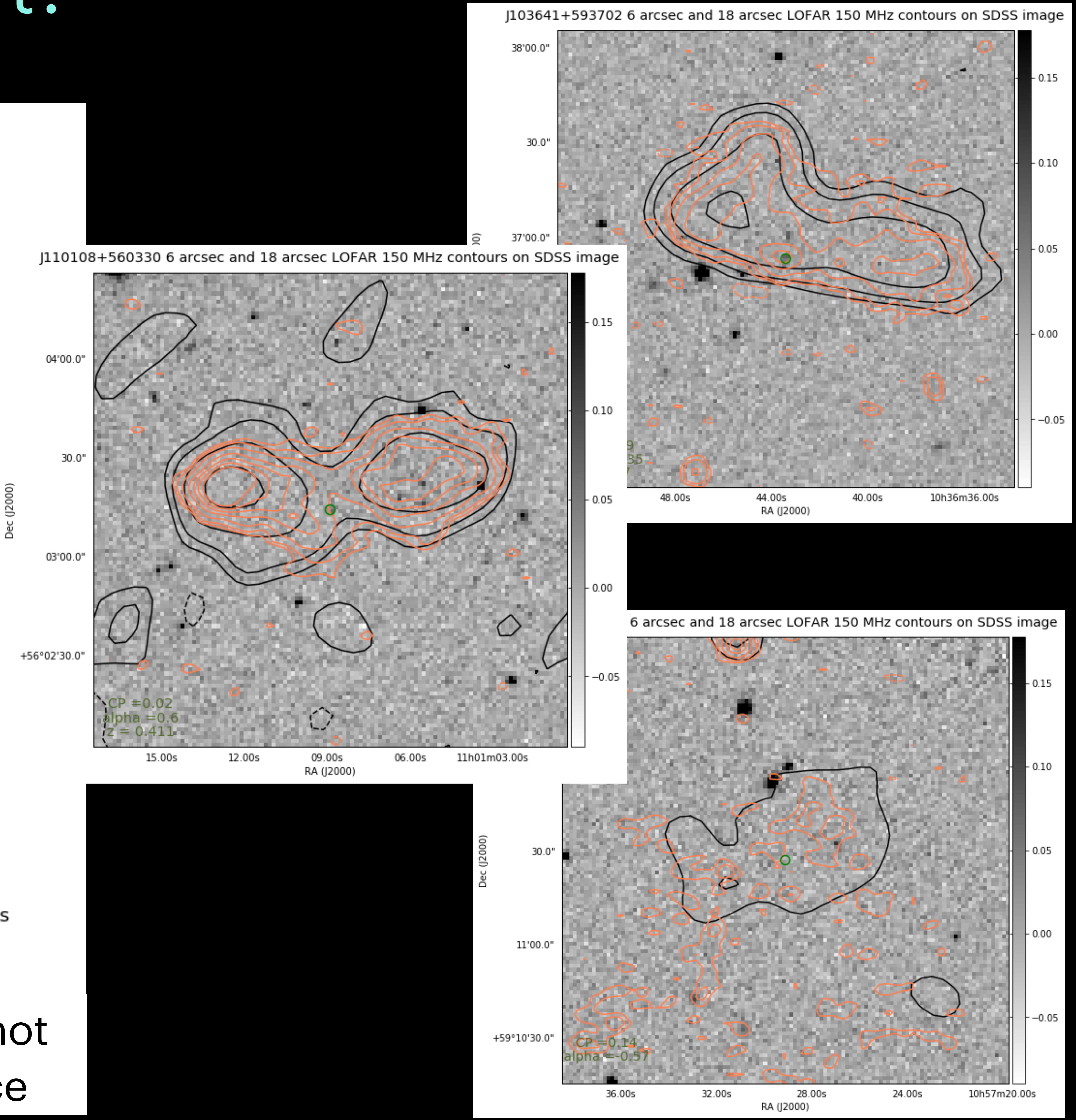
Using all criteria, up to 10% radio sources are remnants (dying radio sources)

How do we characterise them?

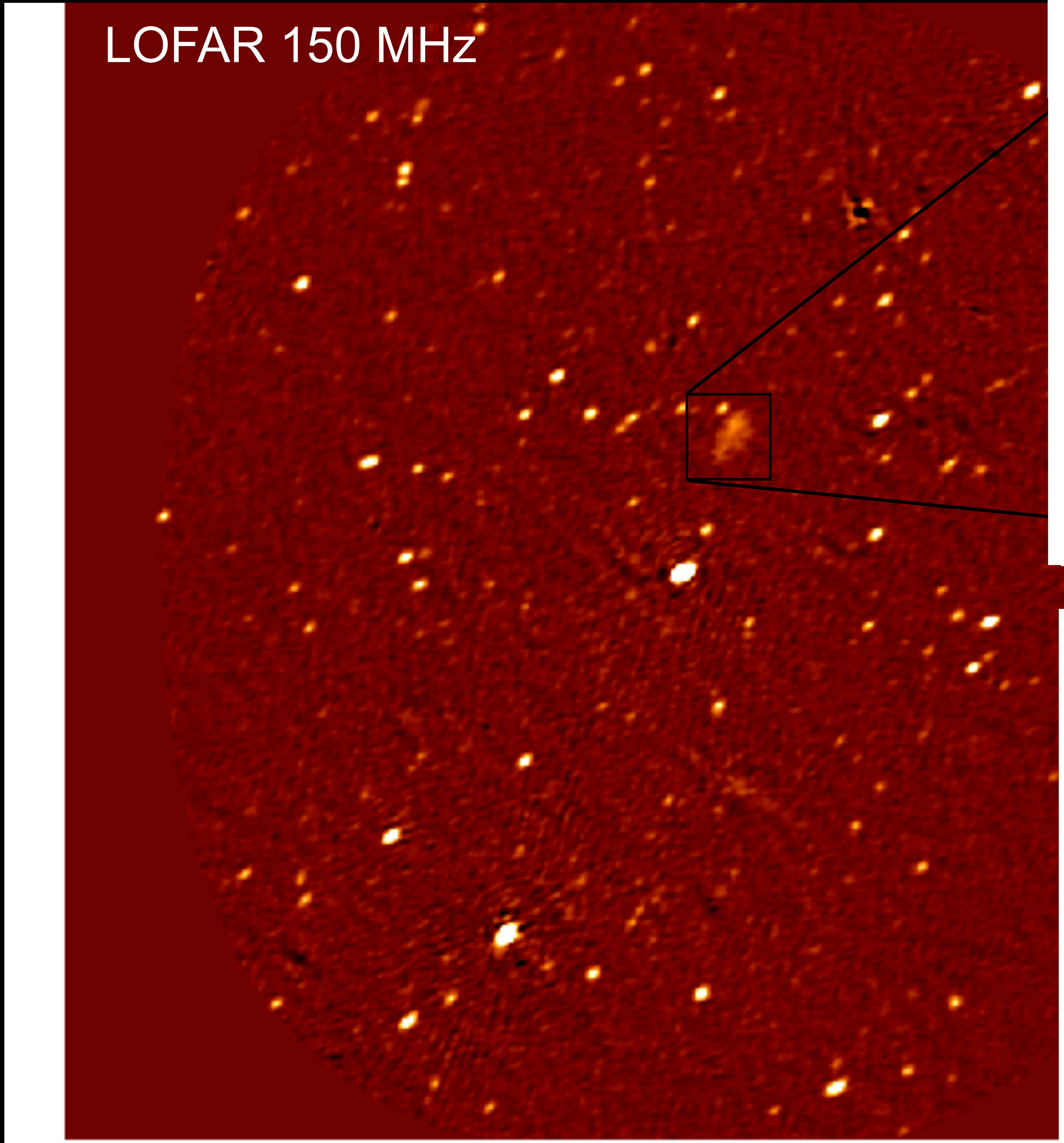
What is the optical counterpart?



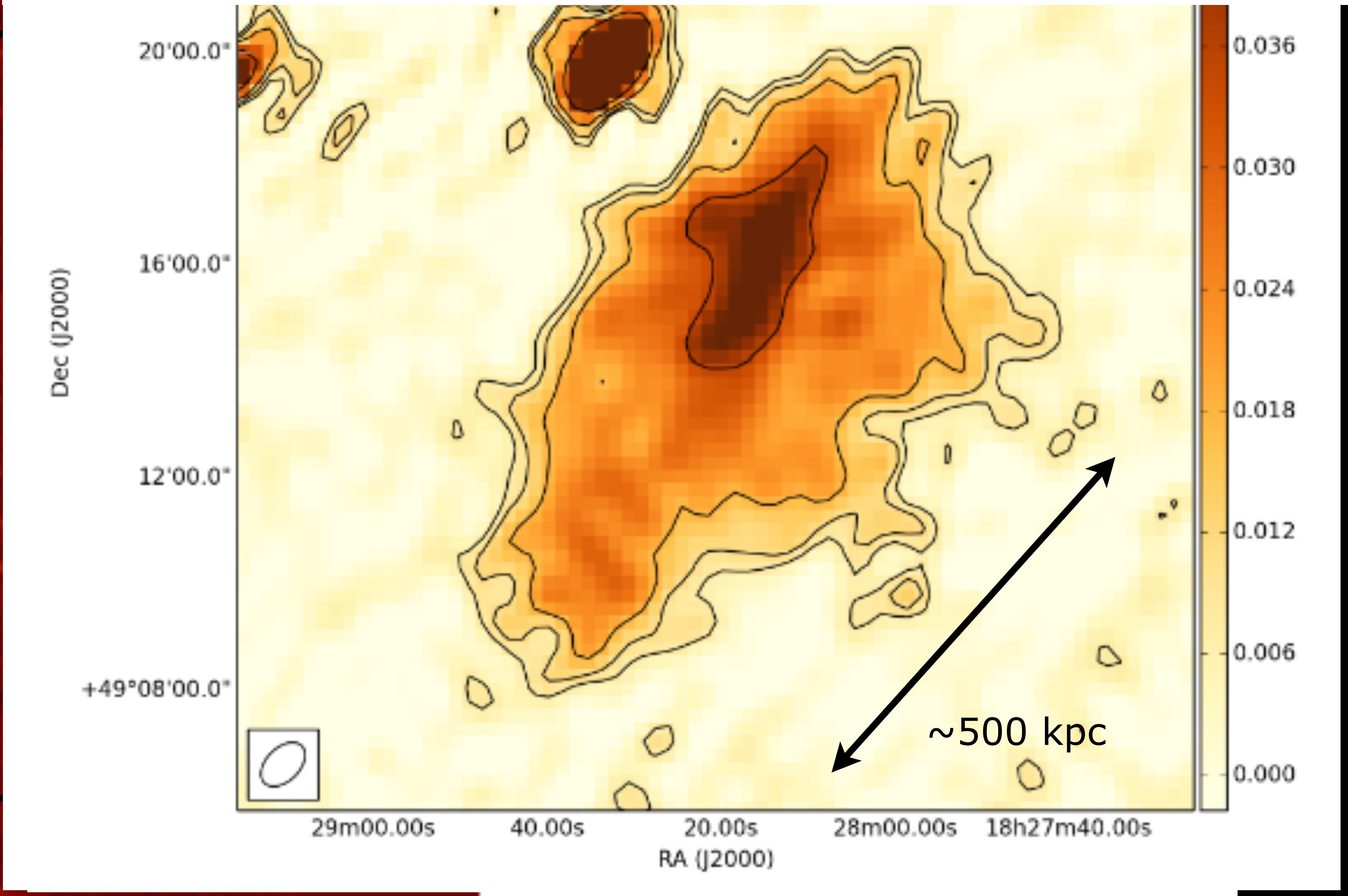
Jurlin et al. 2021

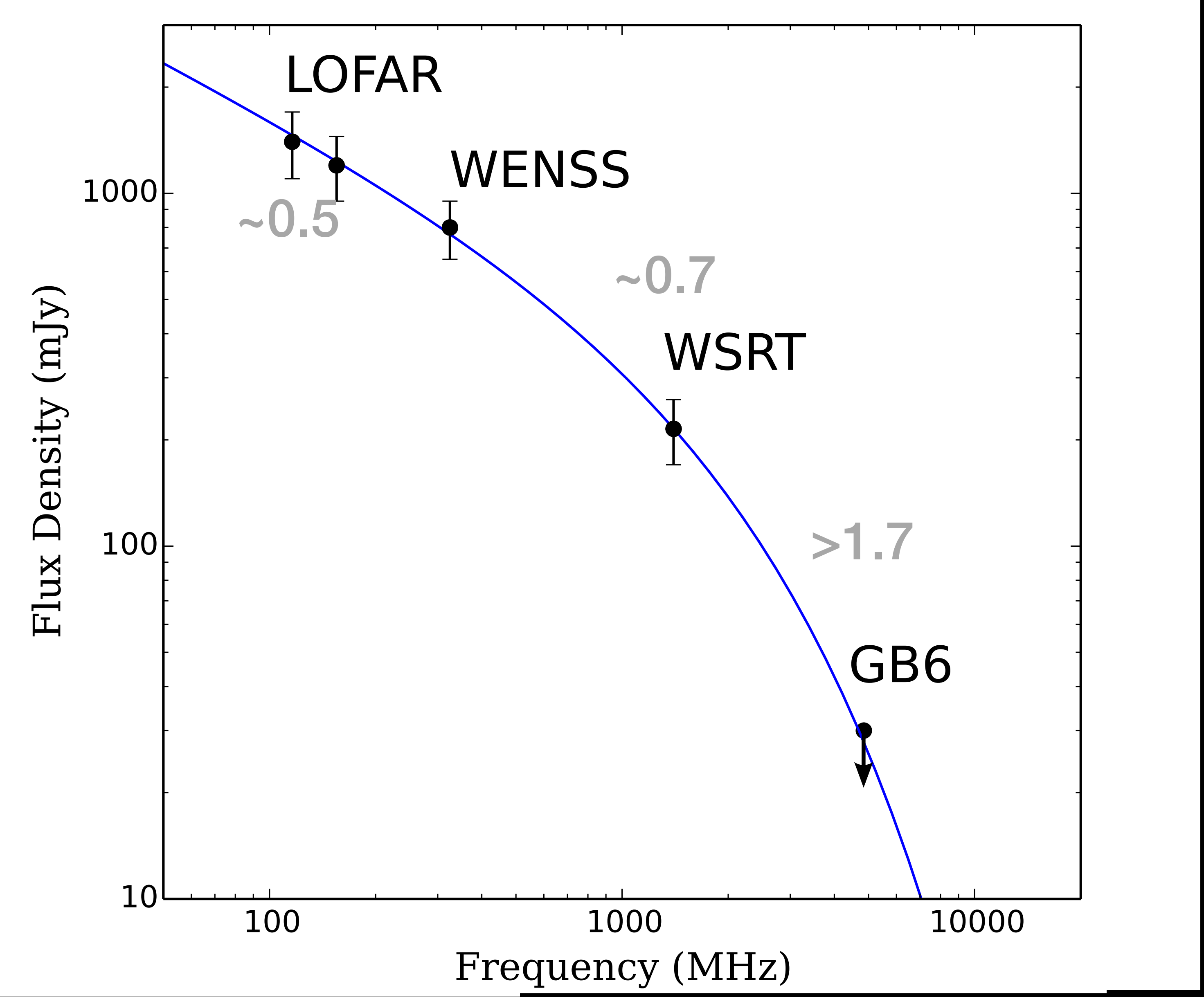


Without optical counterpart (and the redshift) it is not possible to derive the properties of the radio source



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%

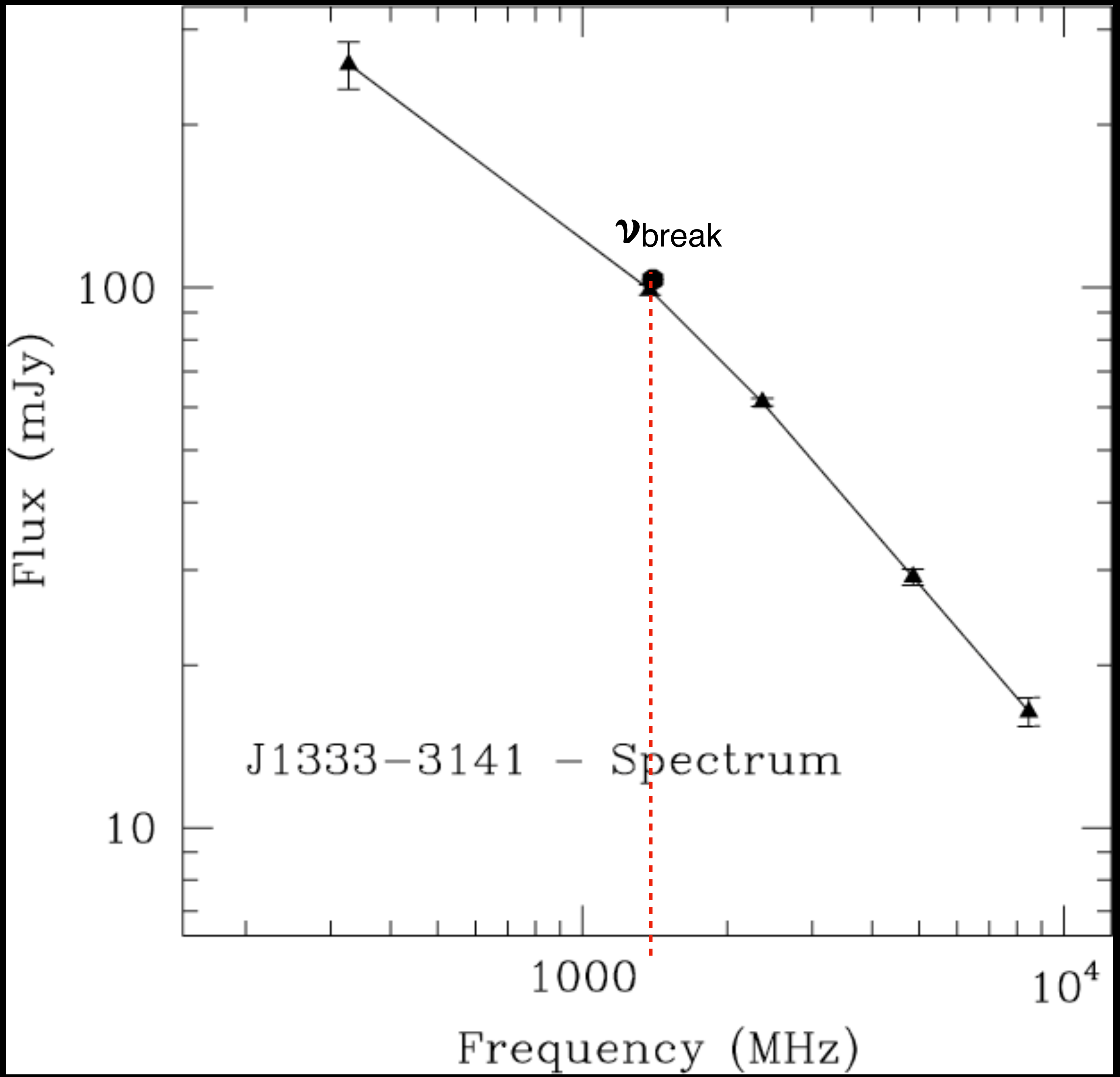
Brienza et al. 2015

important also the availability of high frequencies (from 1.4GHz)

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

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

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

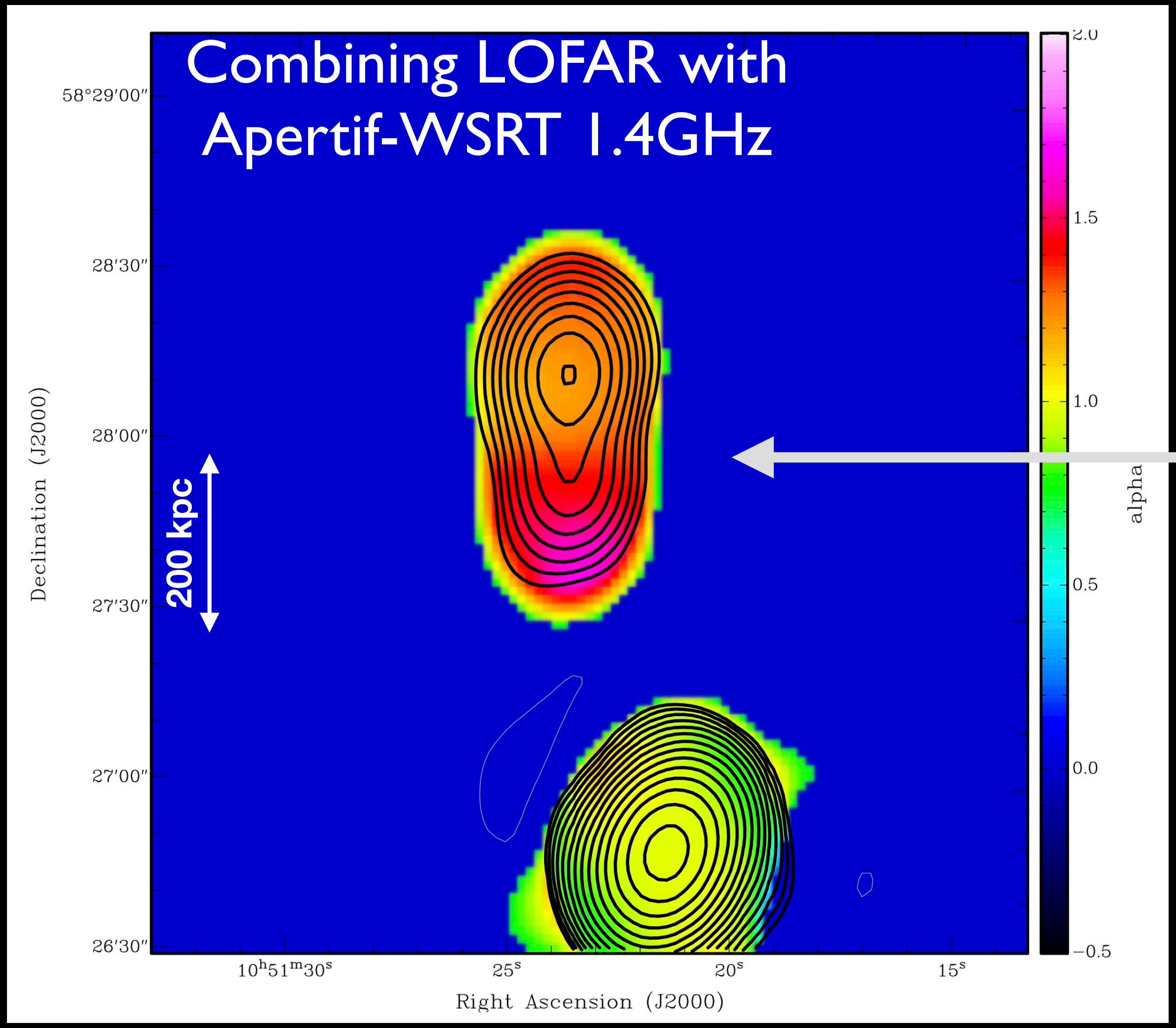
Unless there is re-acceleration in some regions of the radio source!

....from the resolved spectral indices

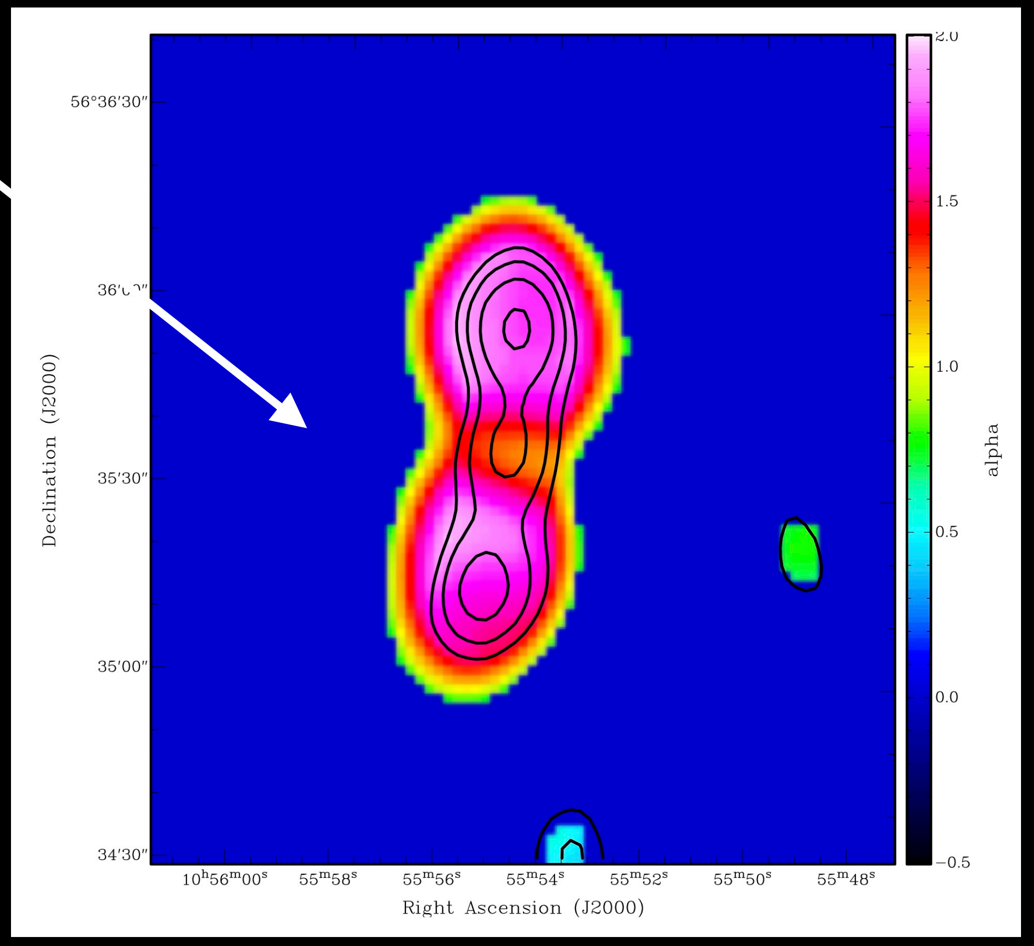
Extended sources with ultra steep spectrum (very old) emission at low frequencies (150-1400 MHz) across the entire source: older remnants

spectral index steeper than -1.8

Morganti+21



Detection **ultra-steep spectrum** emission across the **entire source**



Ages up to 160 - 300 Myr

Frequency break between 600 and 150 MHz, B_{eq} = 3 microG

Modelling of the remnant RG

Brienza, Godfrey, RM et al. 2017

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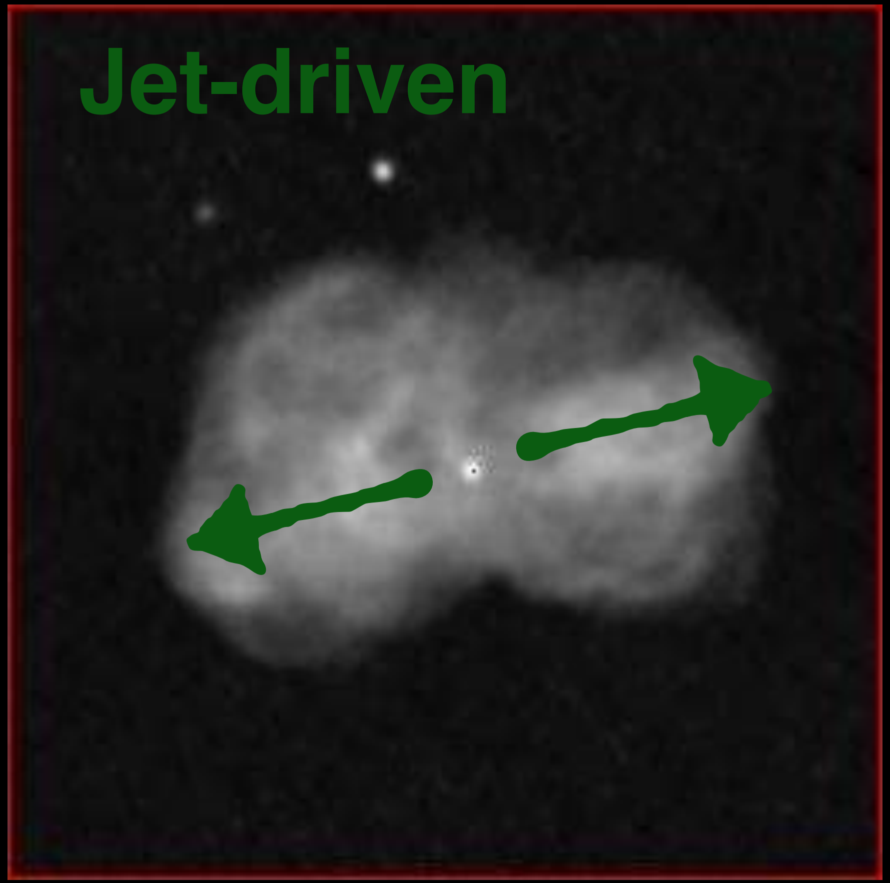

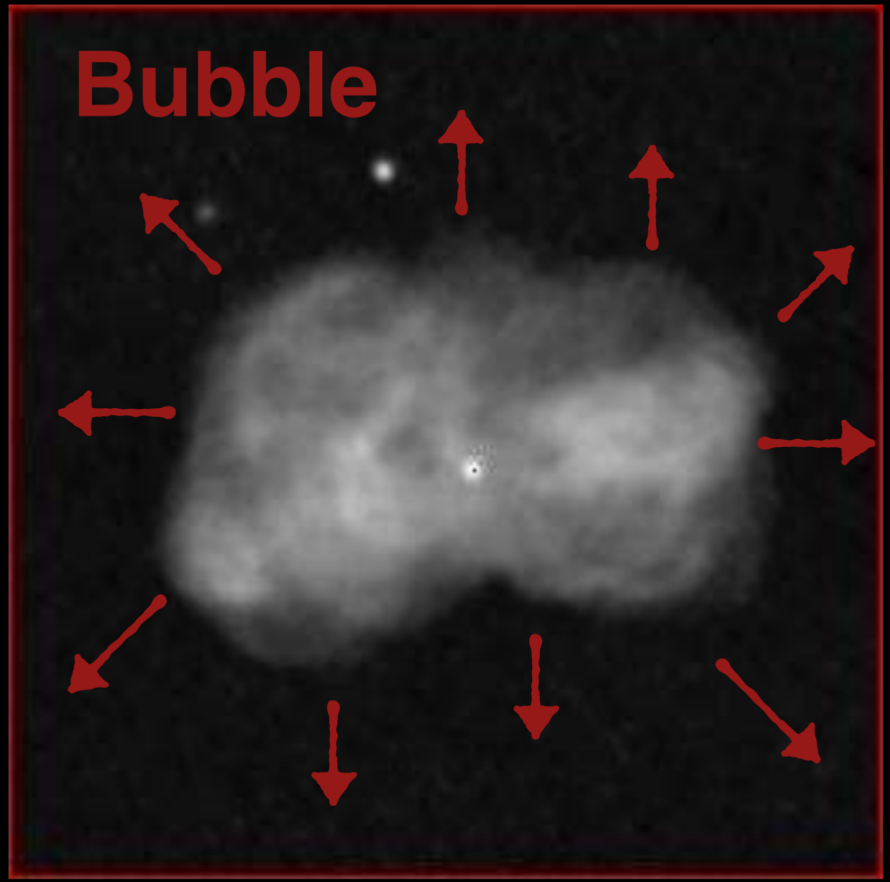

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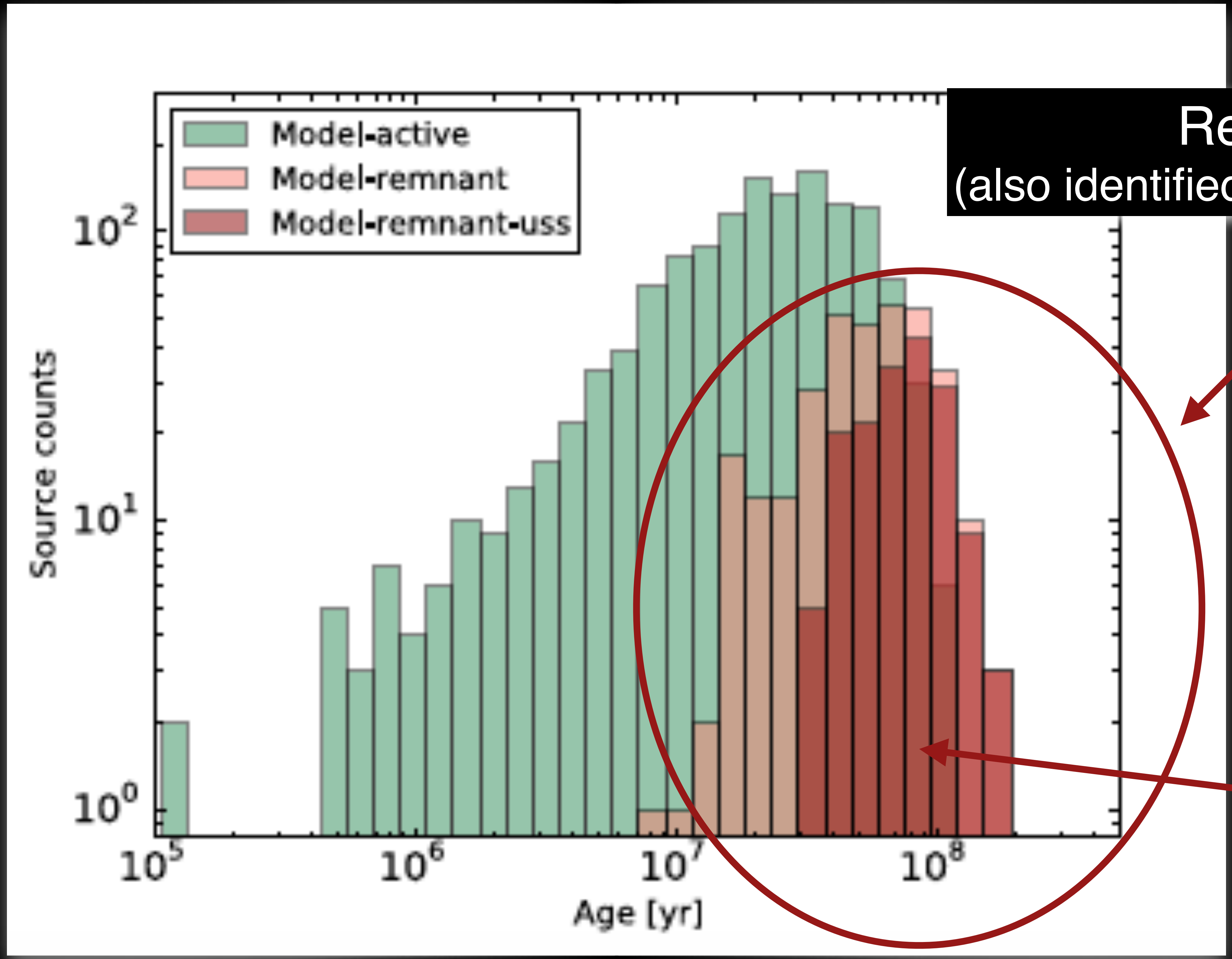
Mock catalogue of remnants
Including radiative losses and adiabatic expansion

Radio lobes are still overpressure (with respect to the ambient medium) when reaching the *off* phase ➔ expansion continue ➔ fast evolution, dimming of the remnant emission



Remnants
(also identified by the morphology)

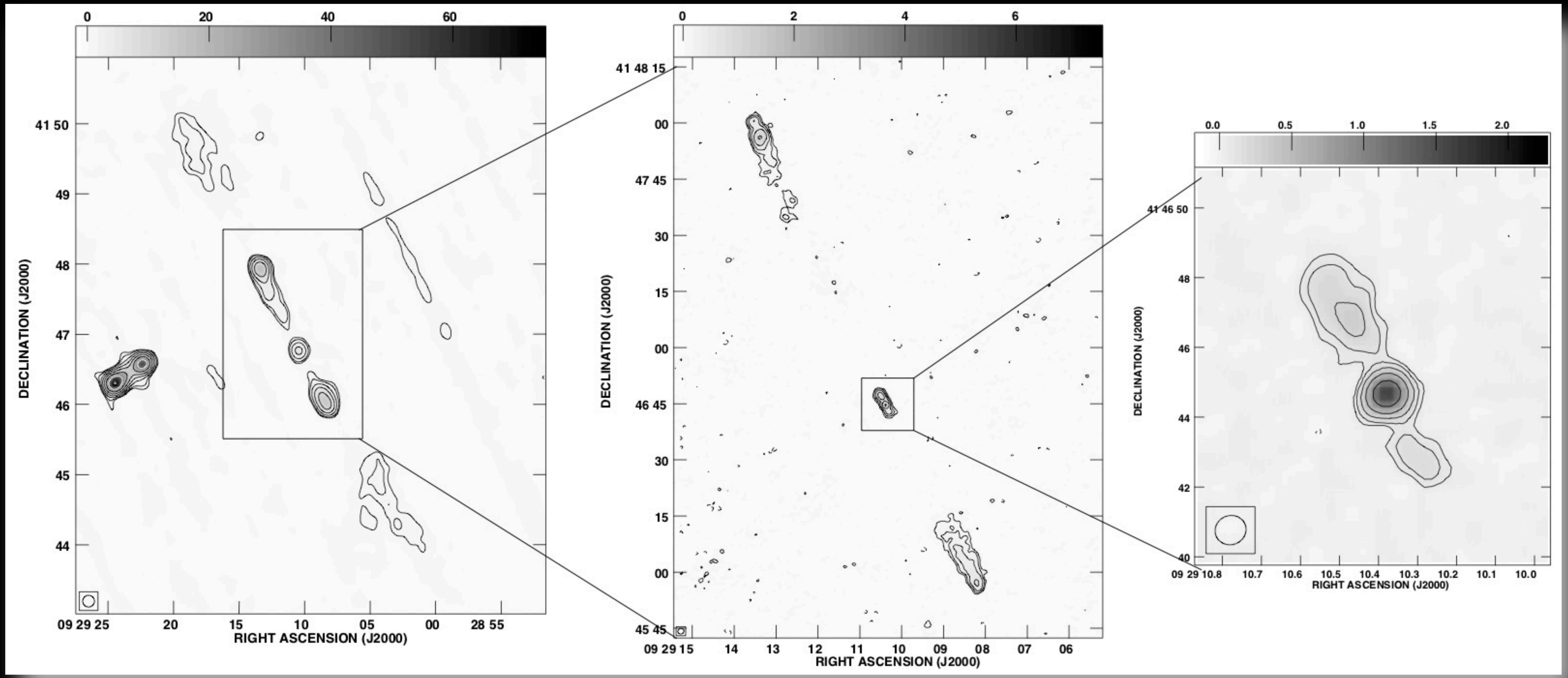
Most of the **remnants are "young"**, i.e. in the phase shortly after the switching off (i.e. **a few x 10^7 yr**)
consequence: low frequency spectrum not yet ultra steep

Remnants selected based on their steep, low frequency spectrum ➔ older remnants in the sky (**ages > 10^8 yrs**)

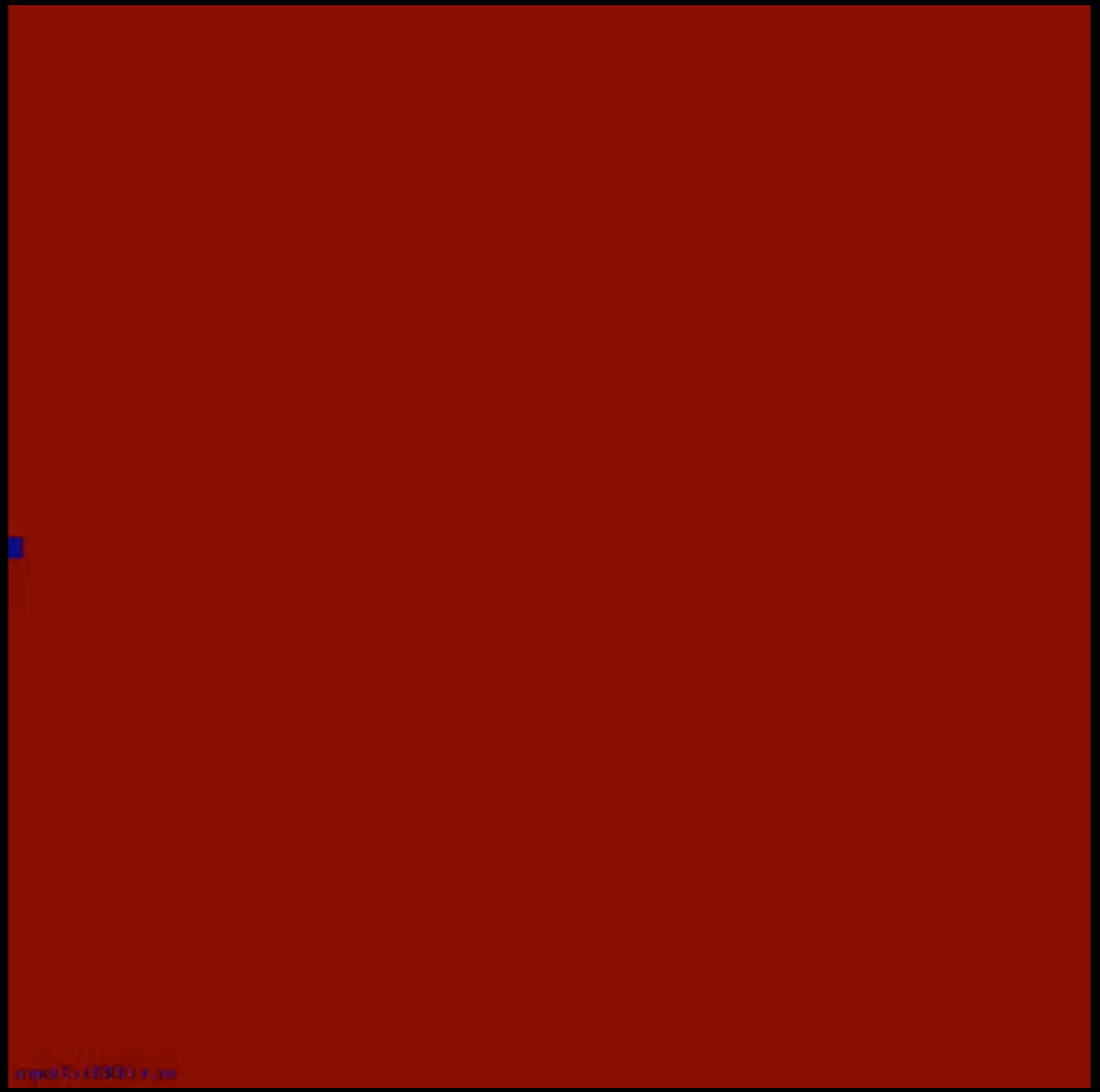
Restarted radio galaxies

more complicated to select these sources, still a lot of work to be done and in progress...

Restarting AGN: double-double radio galaxies



Brocksopp et al. 2007



Simulations Bicknell et al.

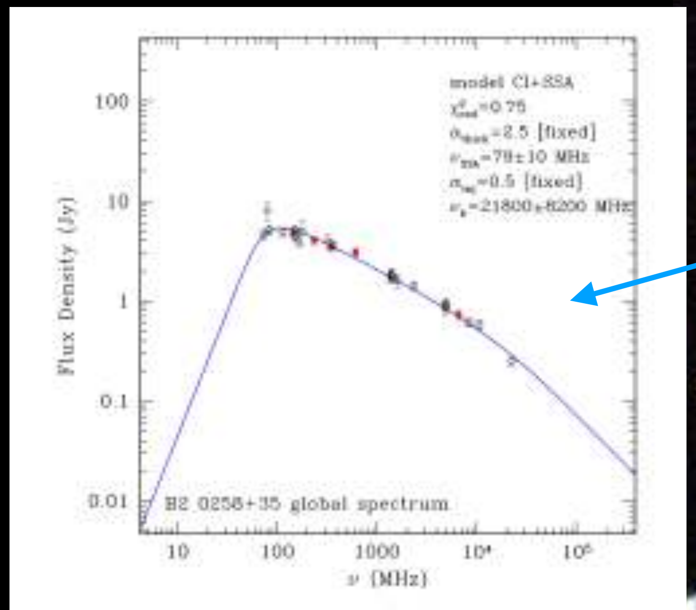
Radio galaxy B0925+420, showing three phases of activity. The images, obtained using the Very Large Array, show three pairs of lobes. The age of the outer lobes was derived to be 25–270 Myr, while that of the inner lobes is 0.4–2 Myr. The supply of energy for the outer lobes ceased 4–70 Myr ago, while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

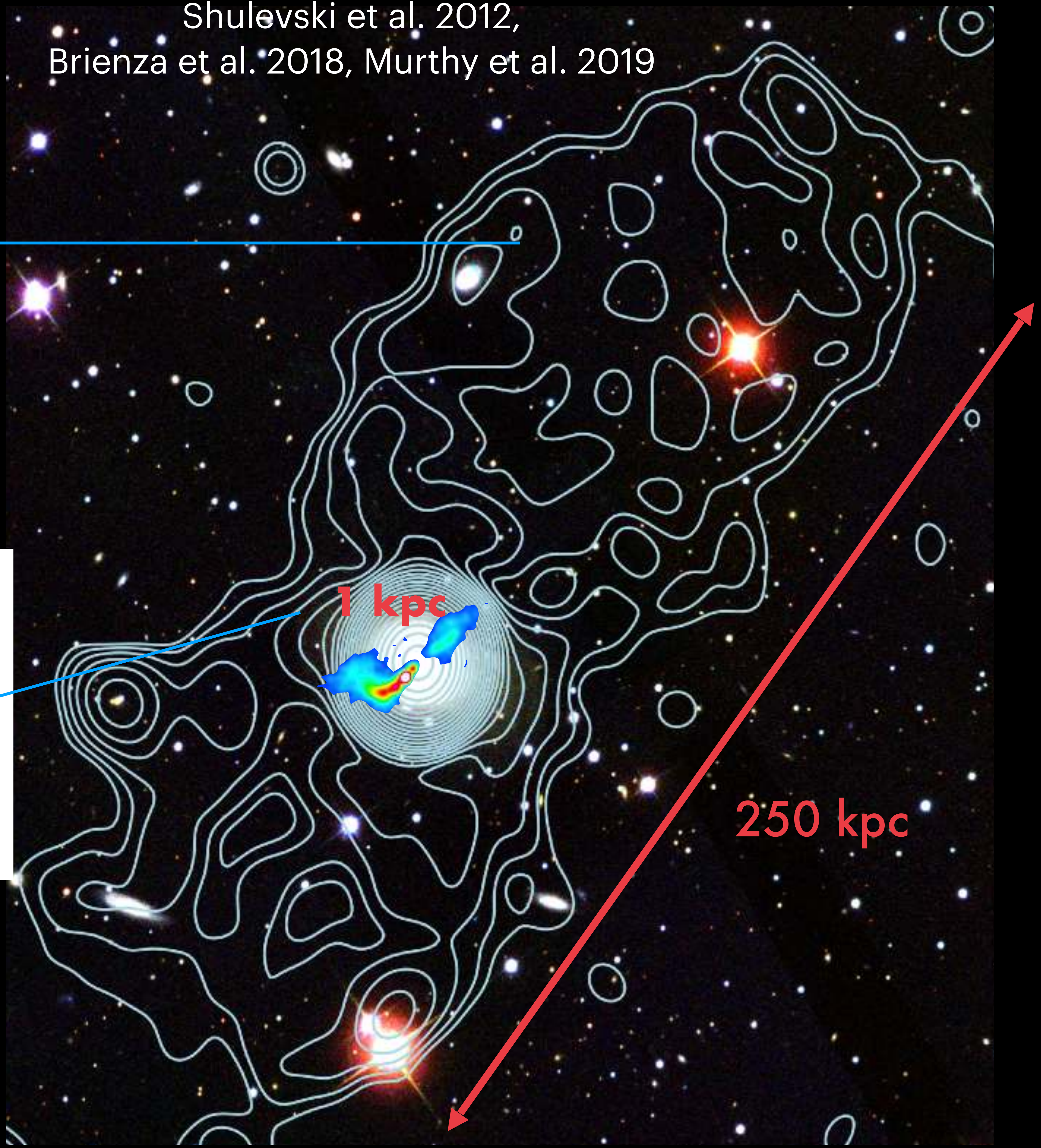
Some of the largest radio galaxies are double-double

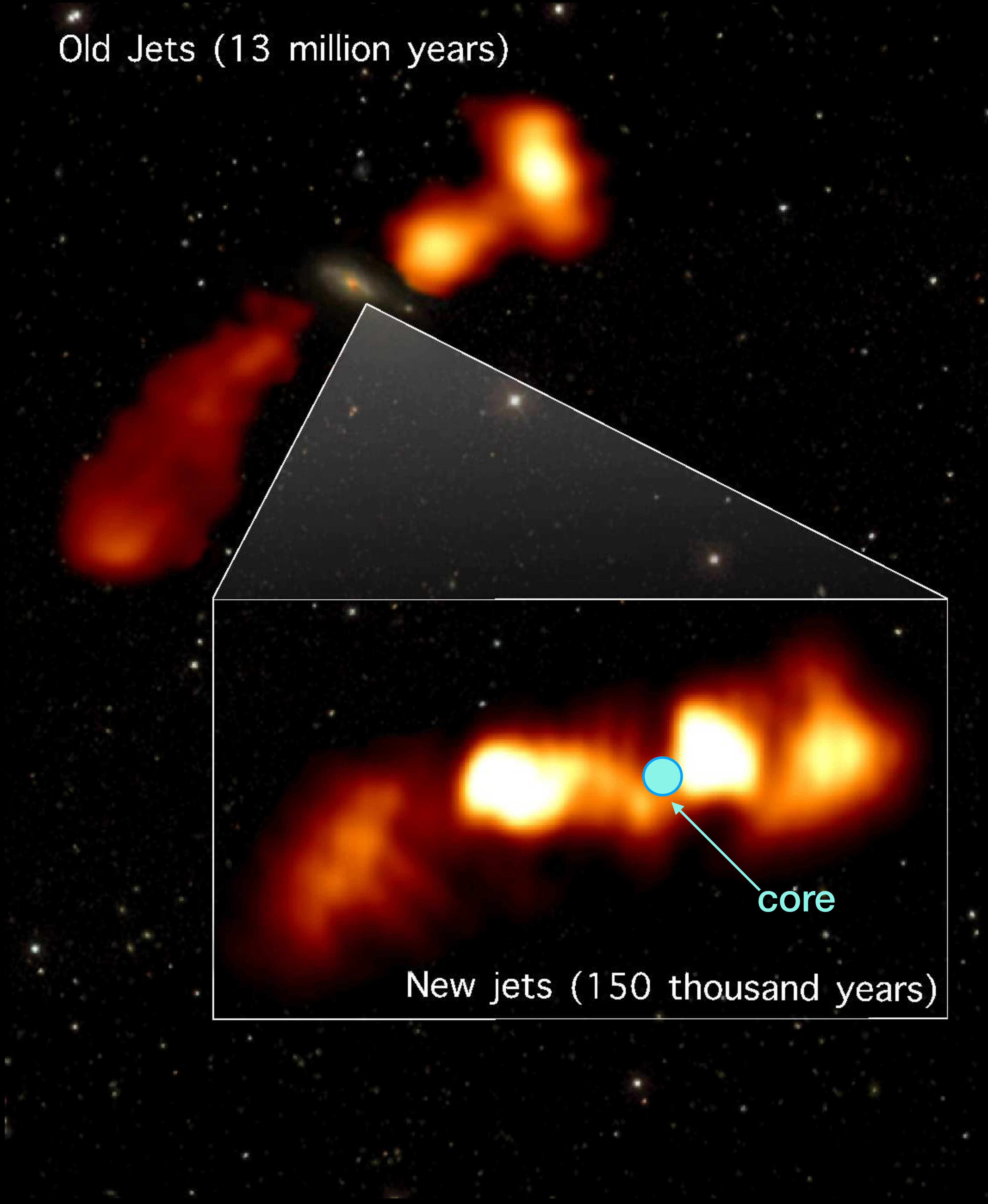
Cases of restarted sources

total age
110 Myr

restarted source
0.4Myr age





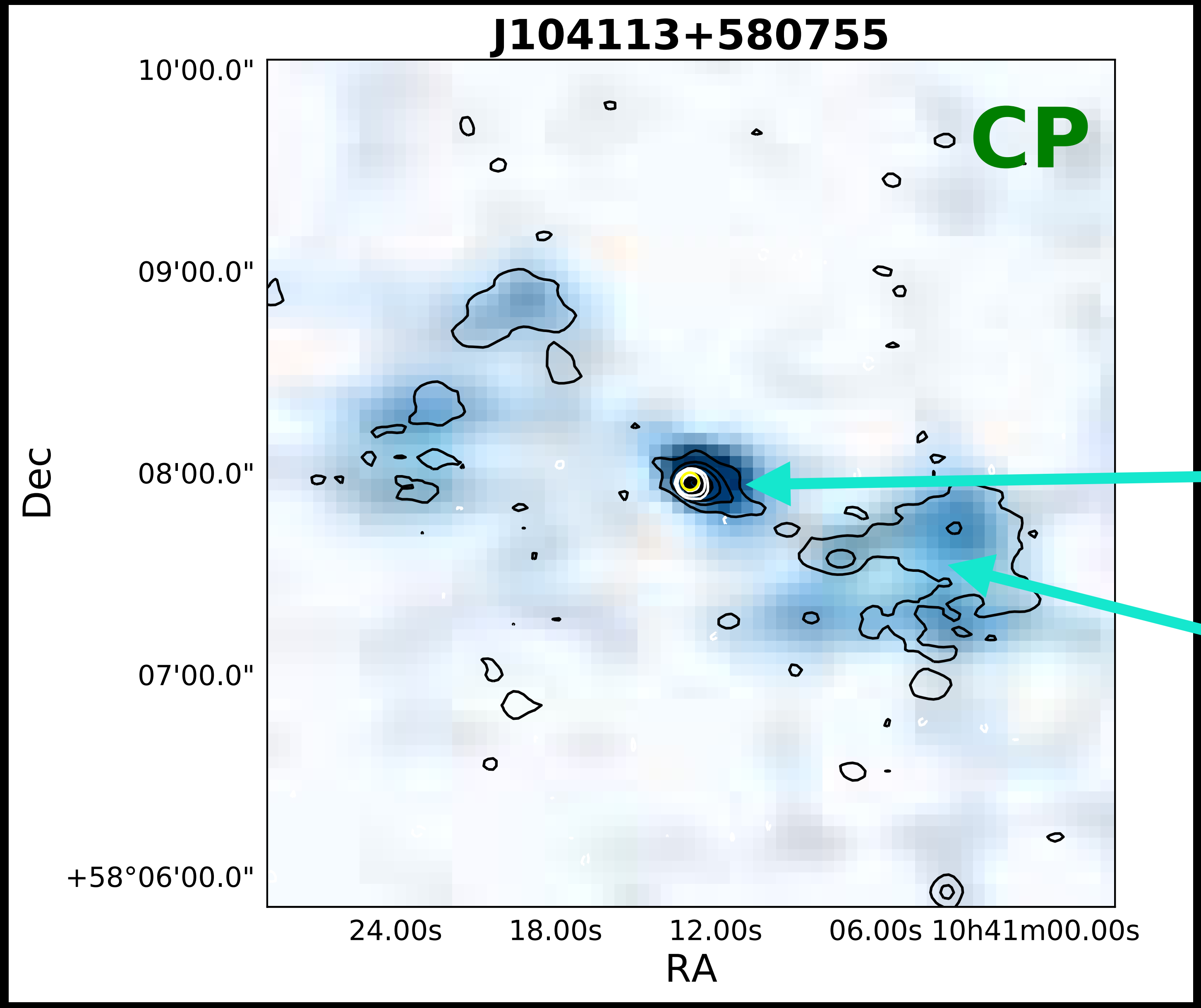


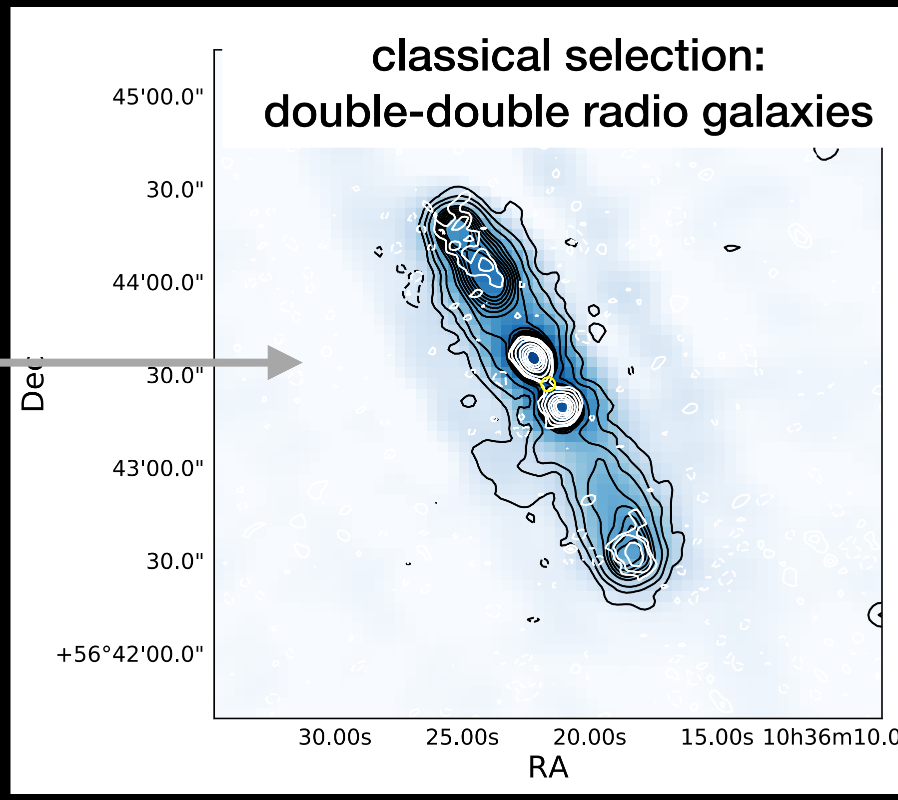
Kukreti et al. 2022

See also Morganti 2017 - Nature Astronomy
Archaeology of active galaxies across the electromagnetic spectrum

Searching for candidate restarted sources using a variety of criteria

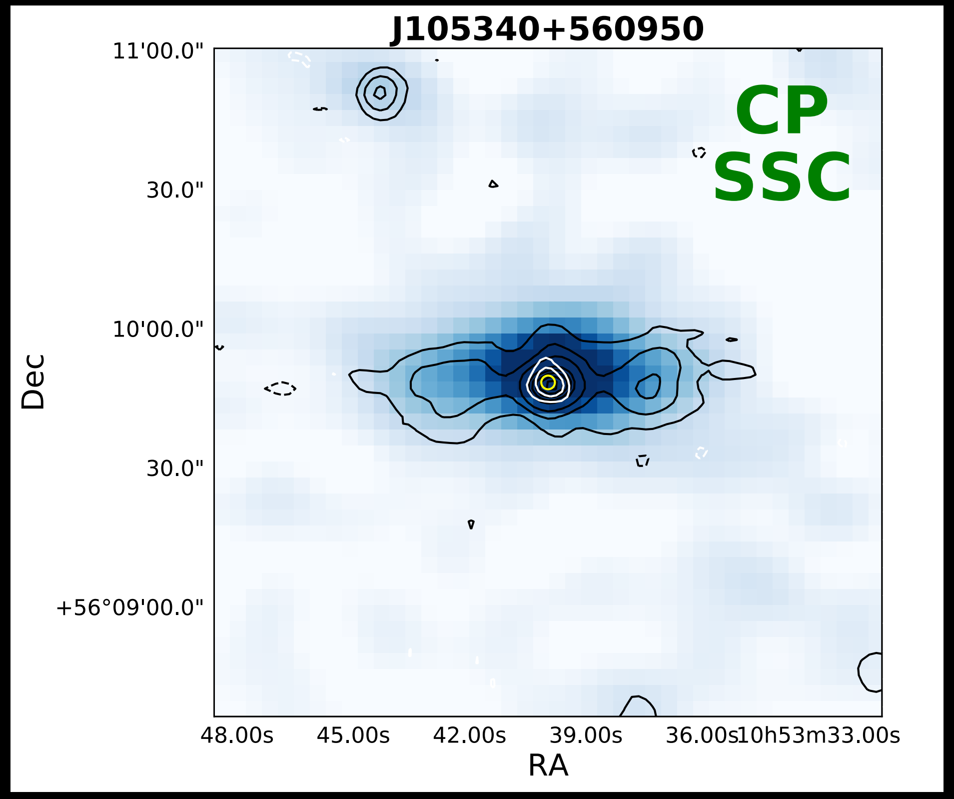
in the Lockman Hole region
Jurlin et al. 2020





Visual inspection (e.g. double-double)

high core prominence:
core relatively bright (CP>0.2)
combined with
low surface brightness extended emission
(comparable to remnants)



steep spectrum core

Up to 15% are candidate restarted radio galaxies!

follow up with LOFAR international baselines to confirm some of them - Jurlin+23

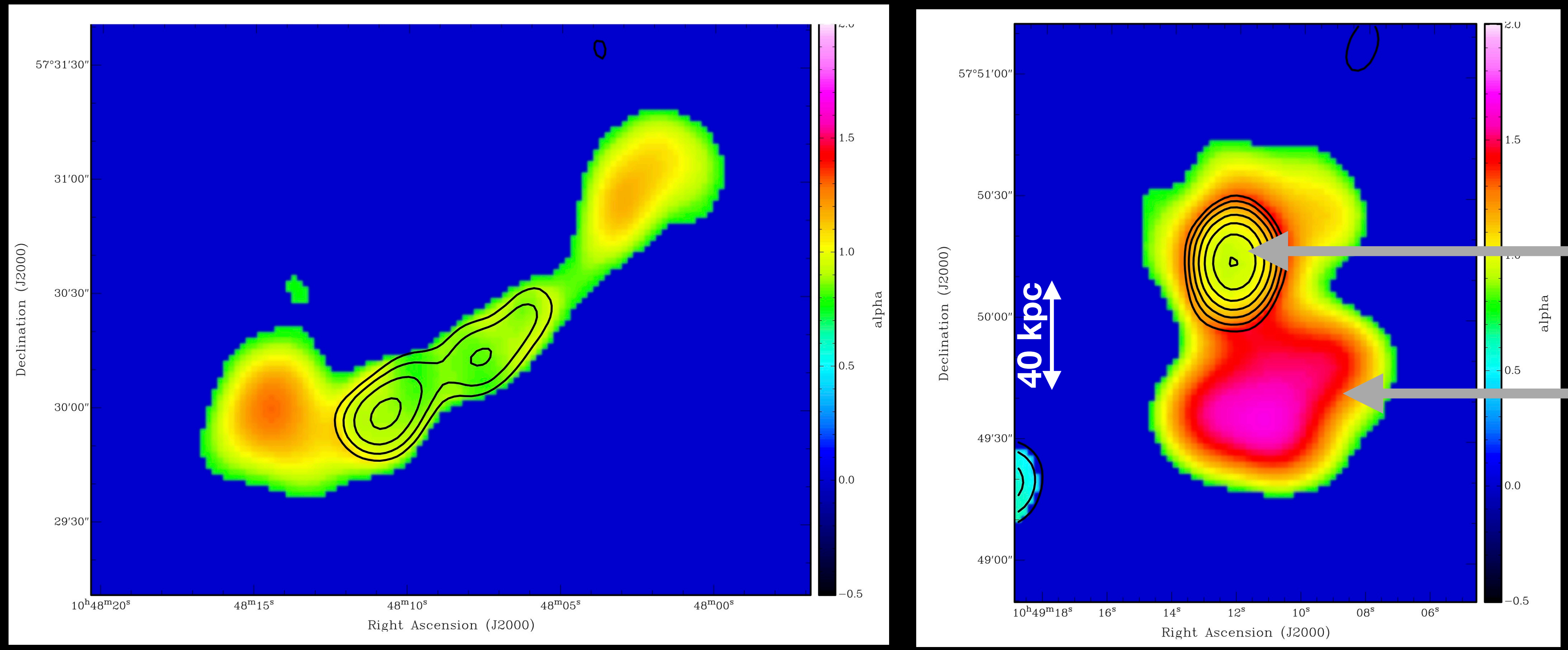
....from the resolved spectral indices: identified restarted inside remnants

Extended sources with USS (very old) emission at low frequencies (150-1400 MHz) and an active central region

(before only one known, 3C388 Roettiger+94 Brienza+2018)

Extended sources with partly USS emission: restarted

Jurlin+21



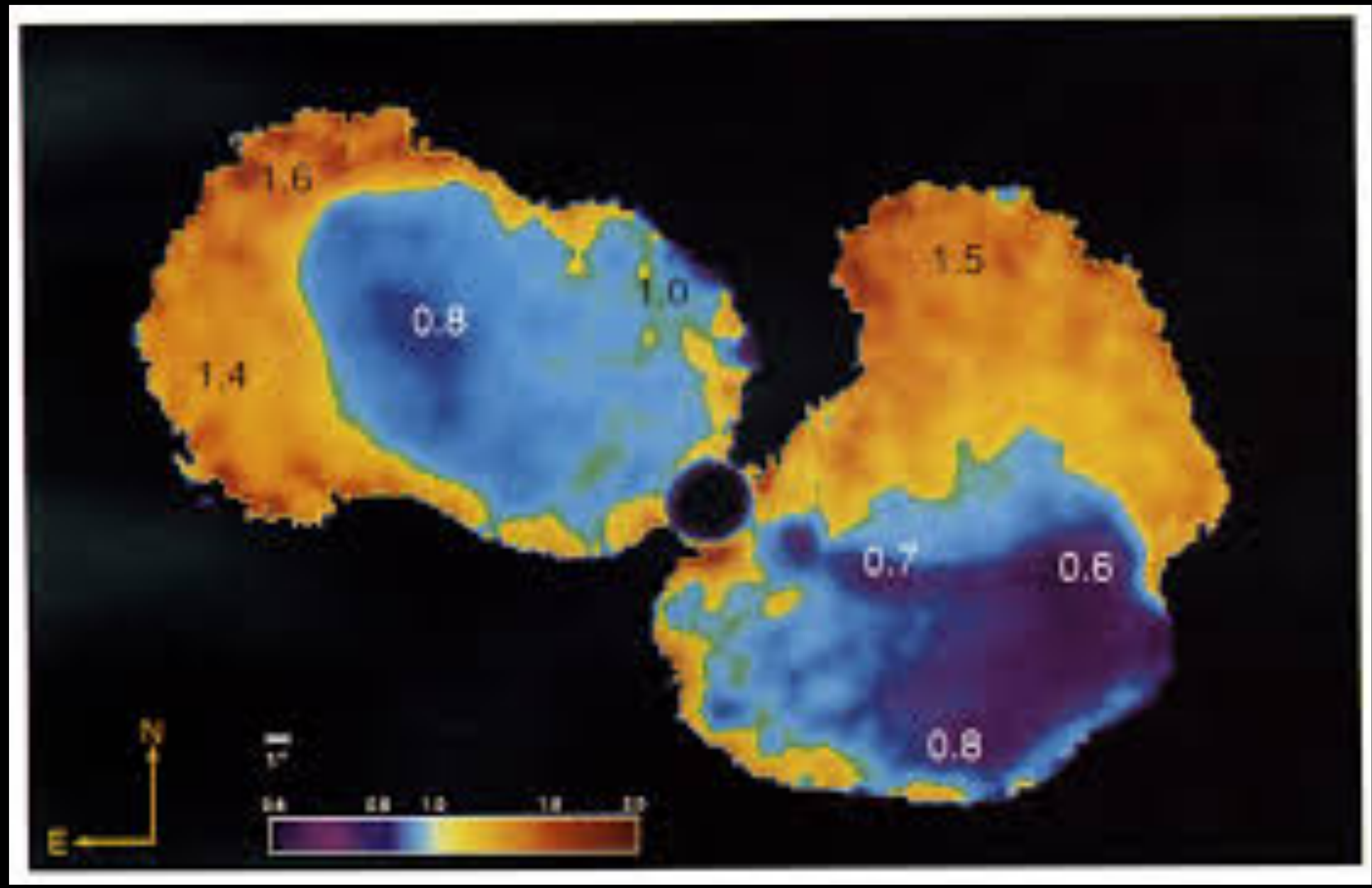
combining LOFAR and Apertif (about 20" res)

Standard SI about -0.8

Spectral index limit
α steeper than -1.5 (i.e. USS)

➔ the existence of these sources suggests the presence of a relatively **rapid duty-cycle**

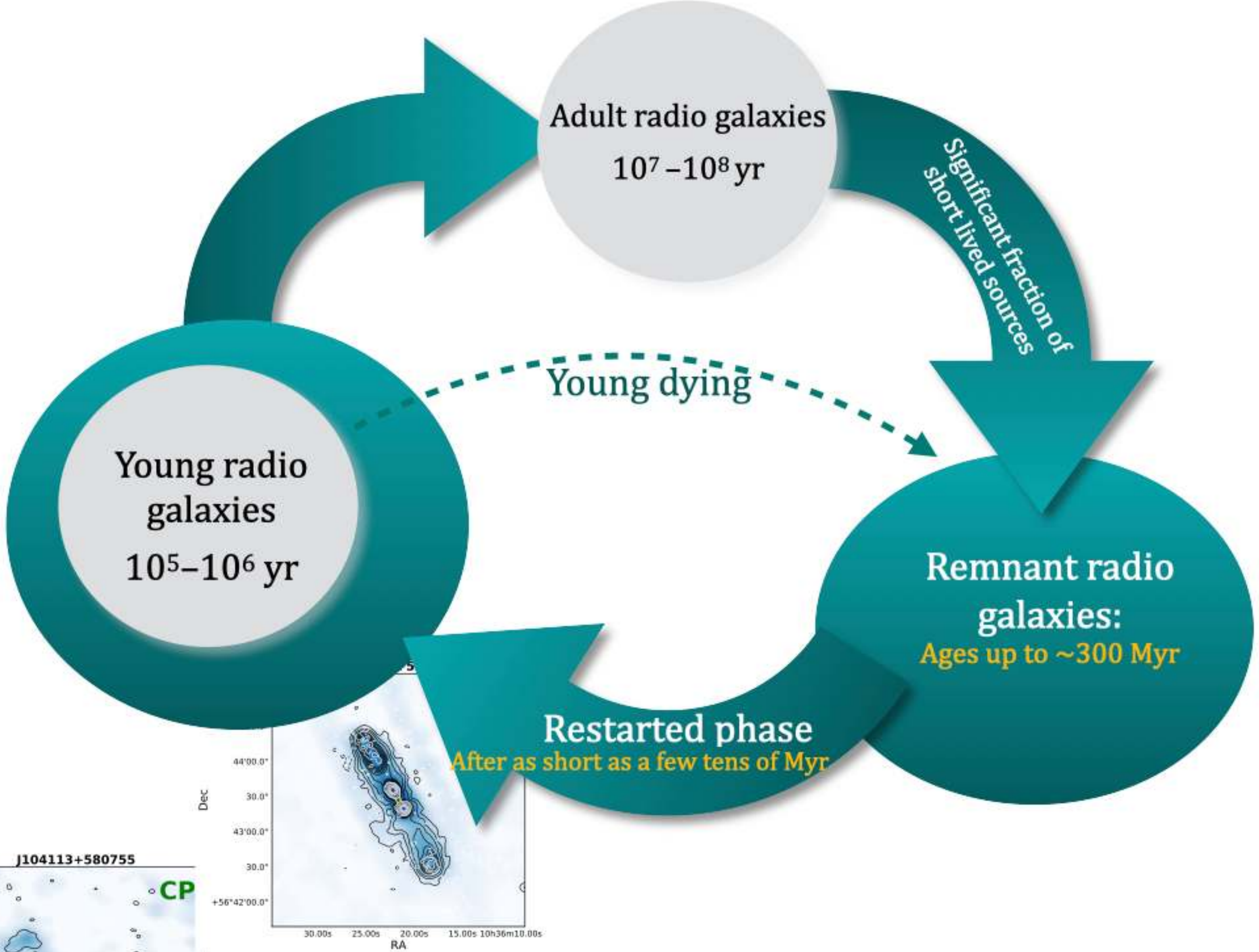
➔ **activity restarted before the remnant emission disappears**

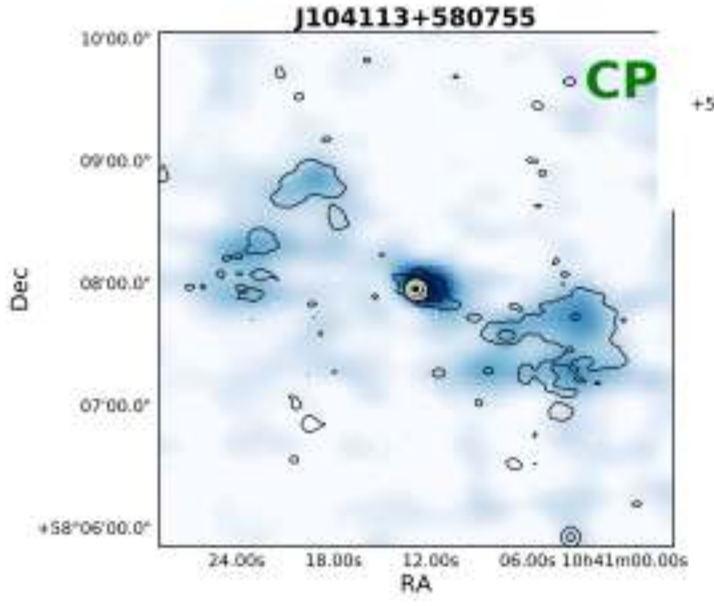


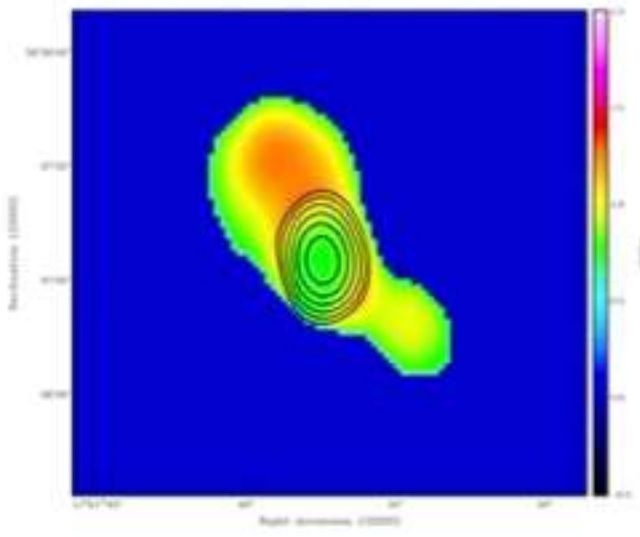
Roettiger et al. 1994), Brienza et al. 2020

...putting all together...

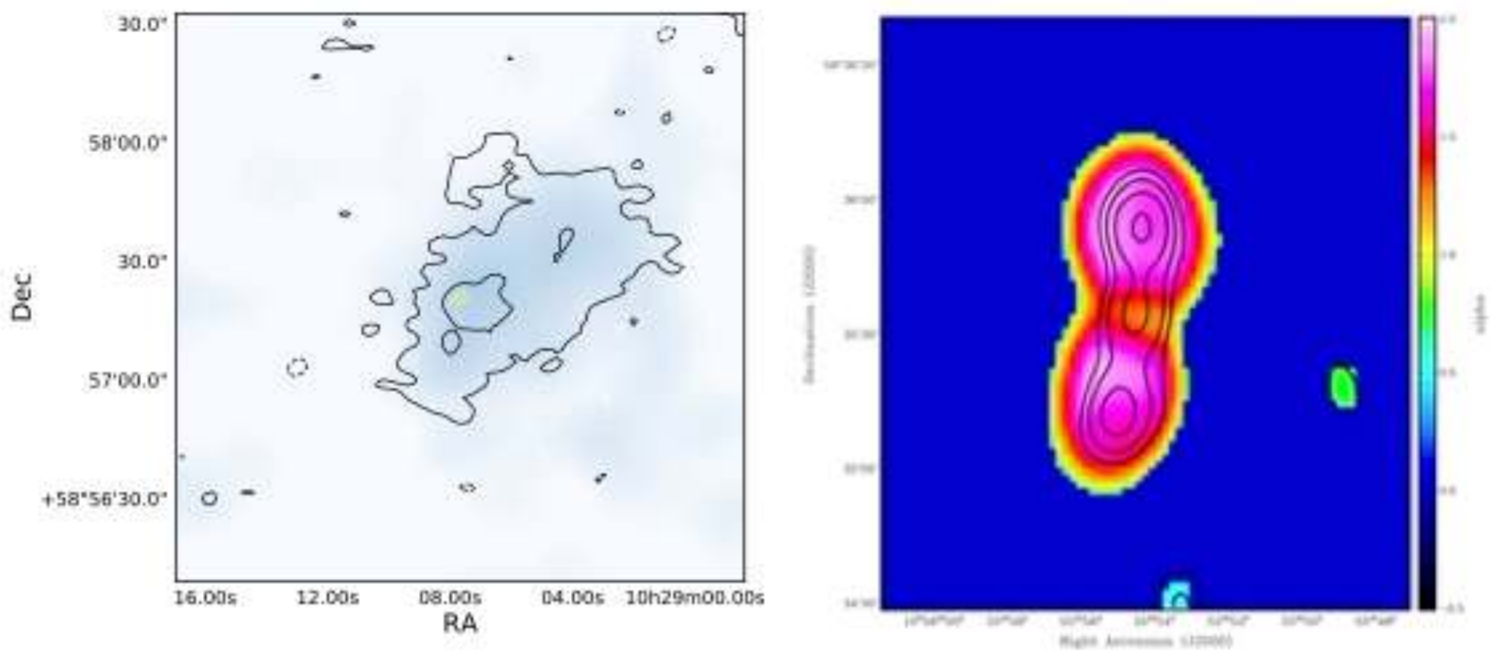
The life cycle of radio galaxies in a nutshell







Candidate restarted radio galaxies selected based on:
double-double morphology (top),
core-dominated(left),
radio spectra dichotomy (bottom)

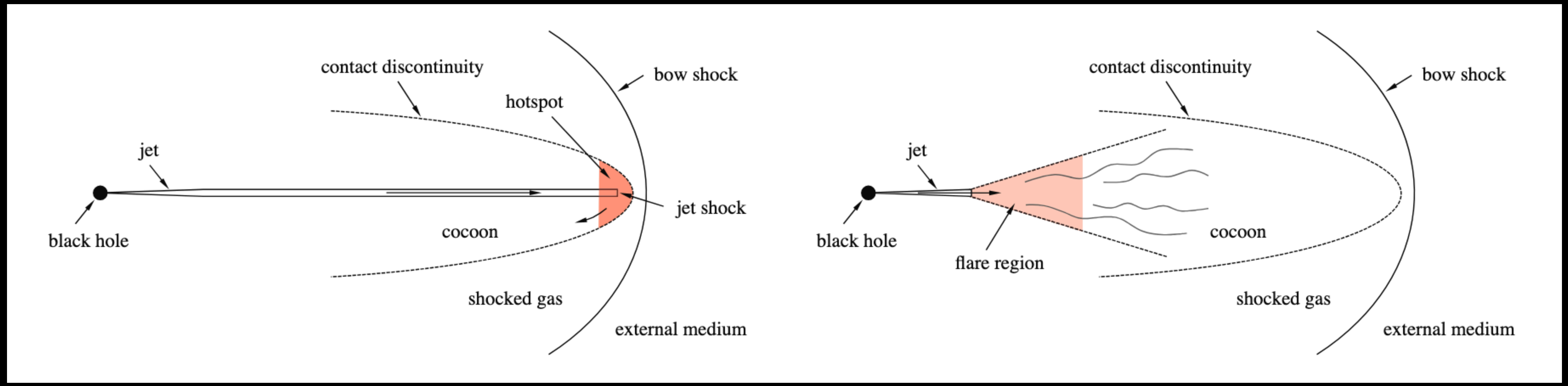


Remnant radio galaxies selected based on the morphology (left) and the extended ultra-steep spectrum emission (right)

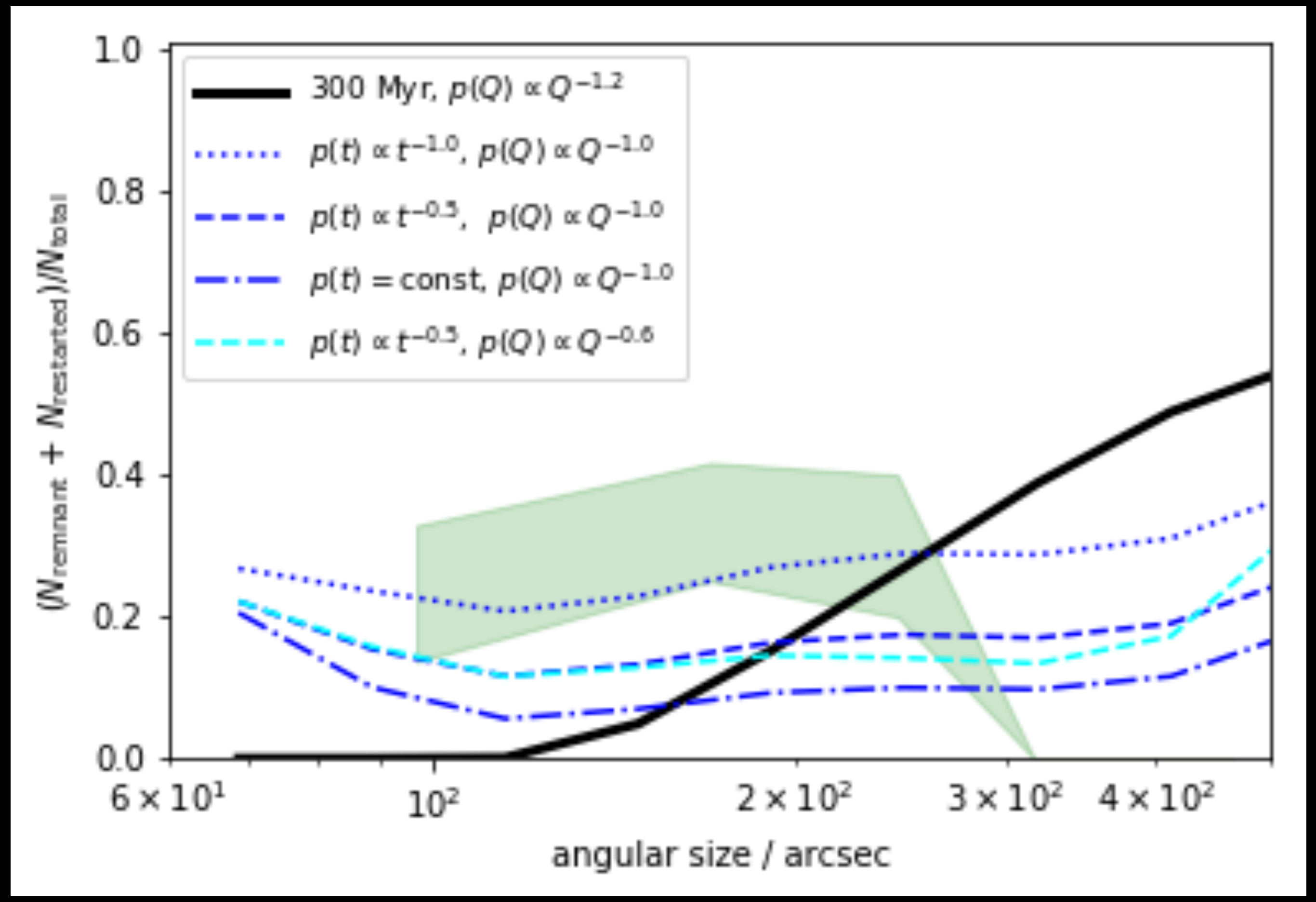
between 7 and 10% of radio galaxies are dying up to 15% are restarted

Note: we have so far looked at radio sources quite luminous and hosted by massive elliptical galaxies

Using observations and simulations to predict the life-cycle of radio galaxies



Using RAiSE (Radio AGN in Semi-Analytic Environments, Turner & Shabala 2015) Simulations: employs outputs of galaxy formation models to quantify jet environments.



Strategy

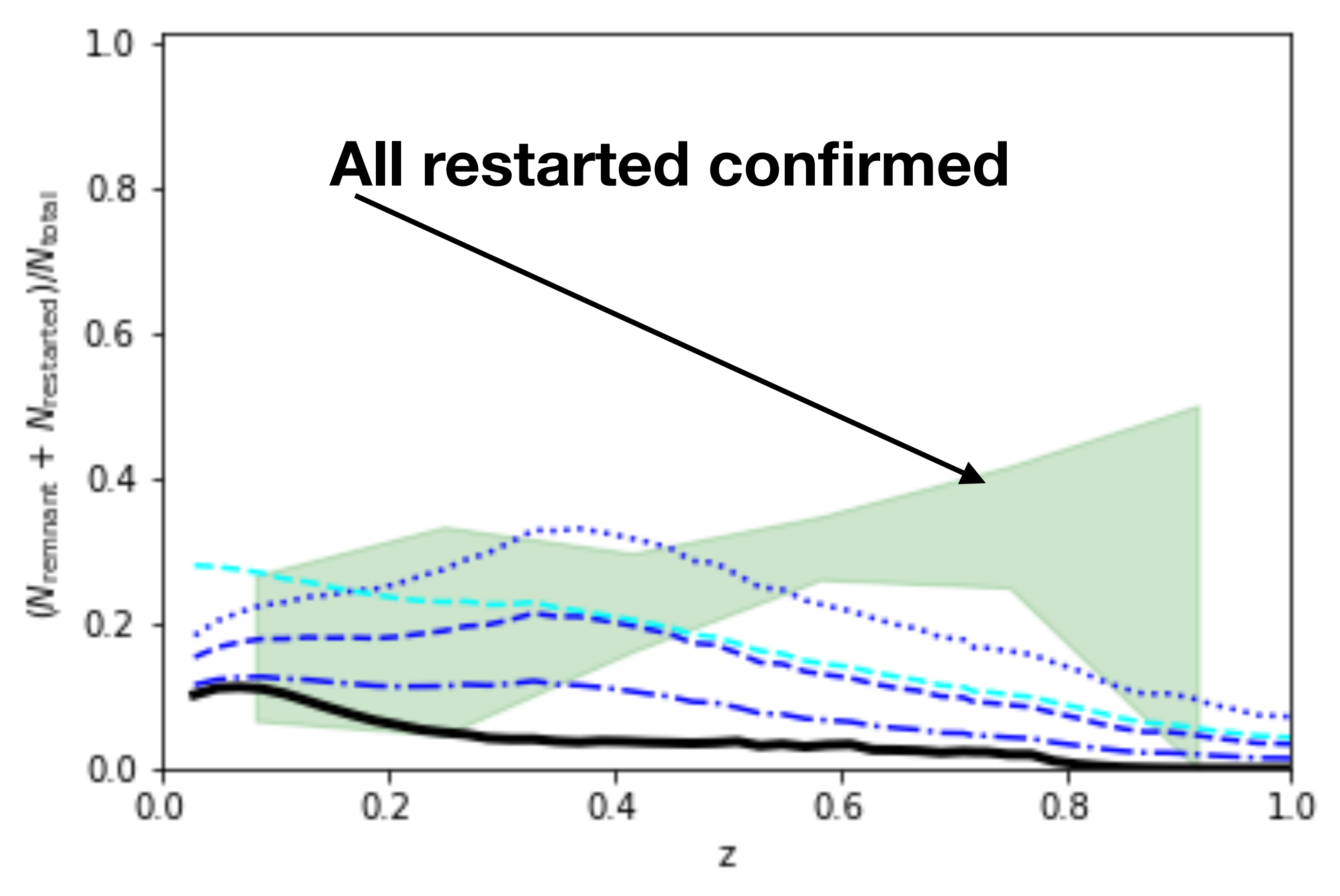
- Sample of active radio galaxies with host information to derive their physical parameters using RAiSE ➜ distribution of physical properties of the radio galaxy population being sampled

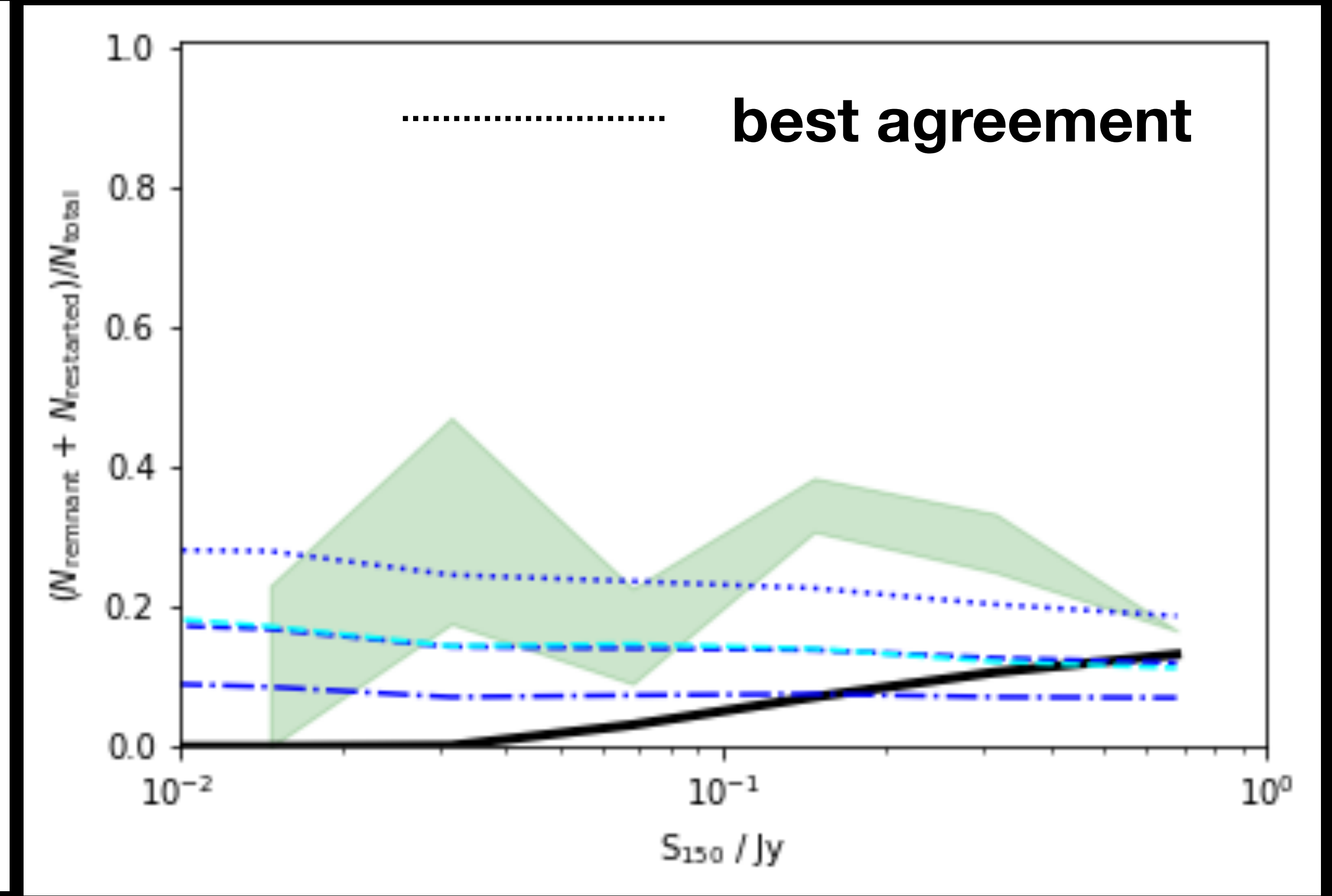
- Use these distributions to make predictions for remnants

Results from the available sample (LH region)

The age distribution of radio galaxies follows a power law: we need short lived sources to get enough remnant lobes which are still visible. Upper end of life time about 300 Myr

Supporting the results obtained from the remnants and restarted





Shabala et al. 2021

what is the relevance for feedback?

every phase injects energy in the ISM/IGM difficult to quantify (jet power not always known)

young and restarted phase are the one with stronger impact on the host galaxy....

we will continue this topic in Les 4