http://www.astron.nl/~morganti

Active Galactic Nuclei and LOFAR

Raffaella Morganti

Netherlands Institute for Radio Astronomy (ASTRON)
and
Kapteyn Institute Groningen
co-Chair of the Low-z AGN and AGN physics LOFAR surveys WG

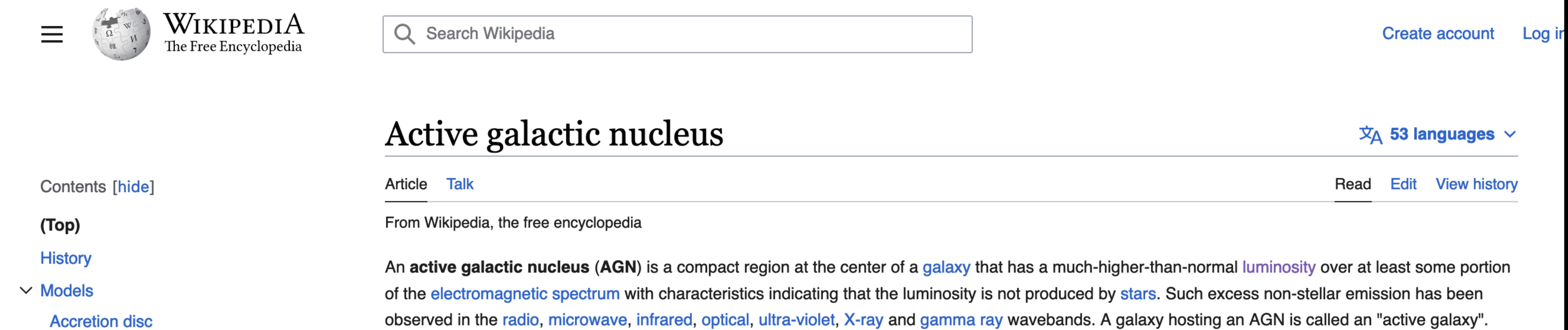
morganti@astron.nl

This lesson

- ❖ Active Galactic Nuclei (AGN) in a nutshell
- ❖ Radio AGN general properties
- ❖ Why is LOFAR important for AGN?
- ❖ Large samples ➔ statistical studies
- ❖ Some highlights on single objects studies

AGN in a nutshell

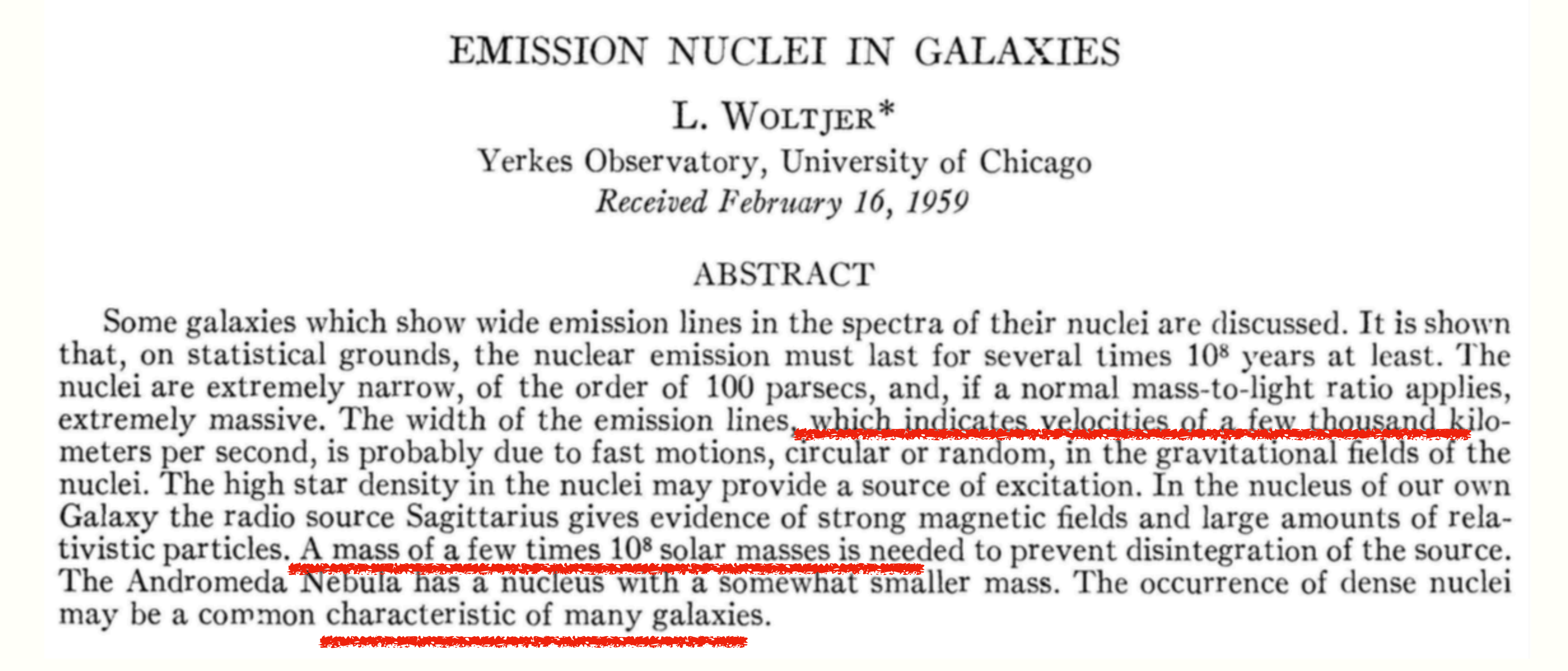
- For an overview: Shields G. "A brief history of AGN" 1999PASP.111..661



Active galactic nucleus

From Wikipedia, the free encyclopedia

An **active galactic nucleus** (**AGN**) is a compact region at the center of a galaxy that has a much-higher-than-normal luminosity over at least some portion of the electromagnetic spectrum with characteristics indicating that the luminosity is not produced by stars. Such excess non-stellar emission has been observed in the radio, microwave, infrared, optical, ultra-violet, X-ray and gamma ray wavebands. A galaxy hosting an AGN is called an "active galaxy".

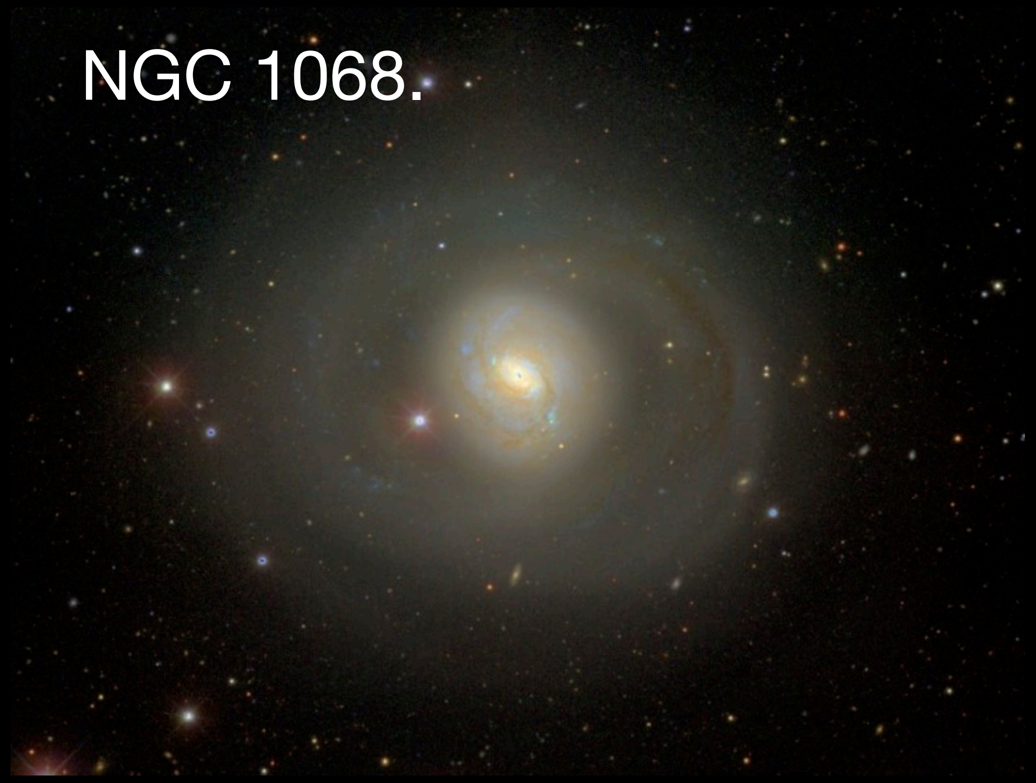


EMISSION NUCLEI IN GALAXIES

L. WOLTJER*
Yerkes Observatory, University of Chicago
Received February 16, 1959

ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

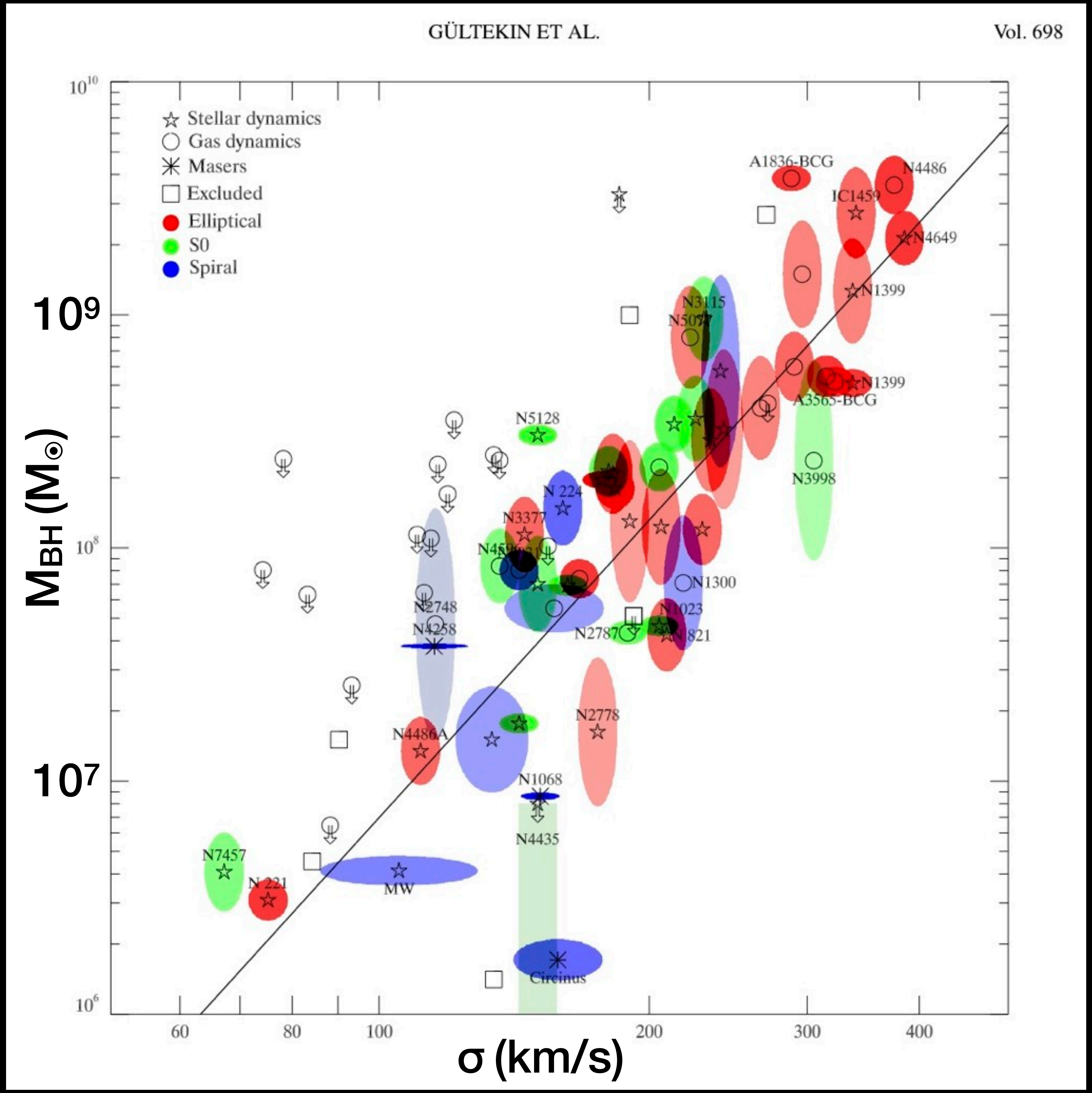

NGC 1068.

* Nuclei are unresolved (<100pc)
* Nuclear mass is very high if emission-line broadening is caused by bound material ($M\sim v^2r/G\sim10^{9\pm1}\,M_\odot$)
* Nuclear emission last for >10^8 years (1/100th spirals is a Seyfert and the Universe is 10^{10} yrs) ➜ assuming all spiral galaxies pass a Seyfert phase!

Galaxies and SMBH

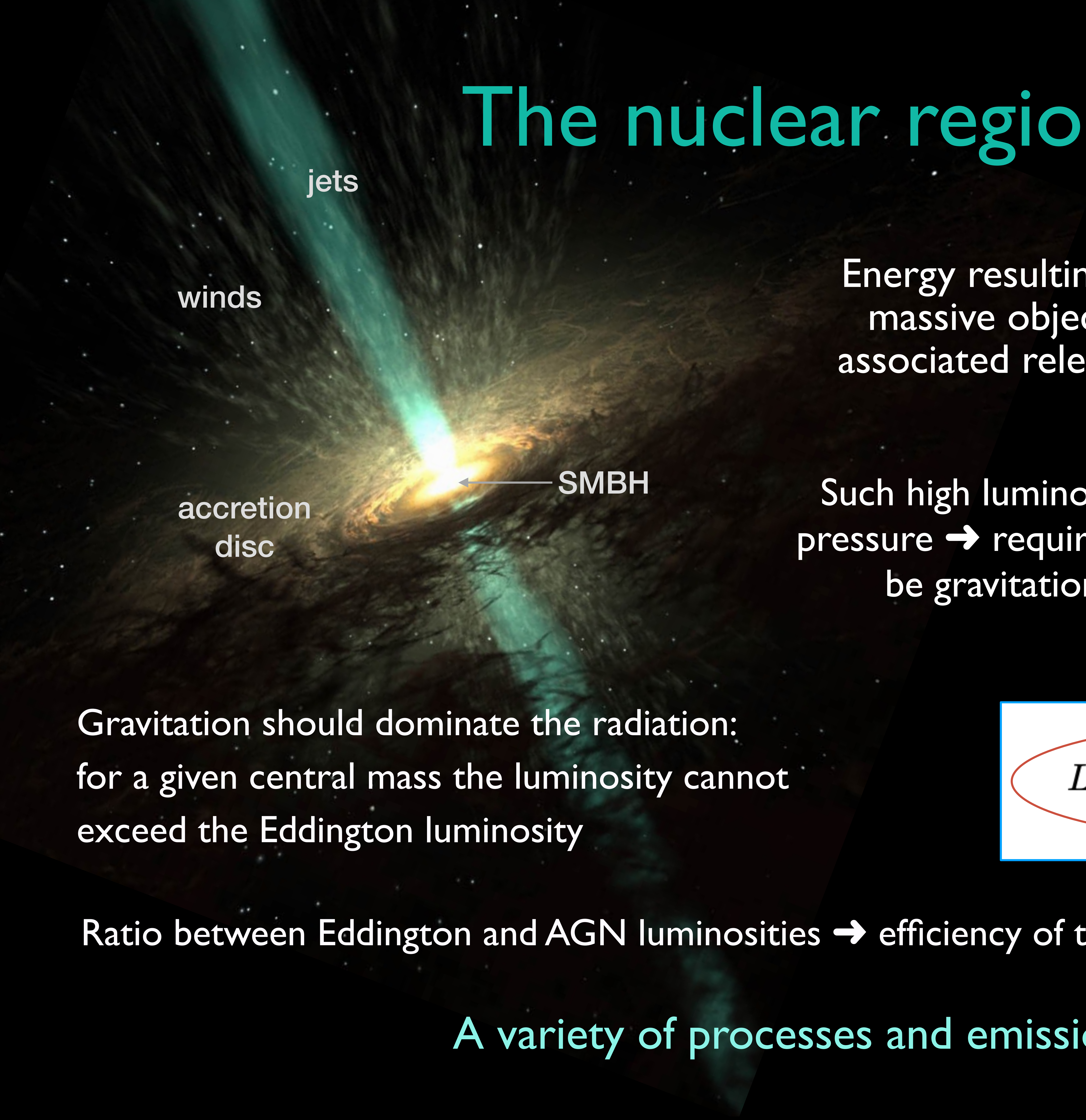
All massive galaxies host a supermassive black hole (SMBH)

➔ relation M_{BH}-σ velocity dispersion of the stars in the bulge of the galaxy



but not all SMBH are active (right now…)

The nuclear regions of an AGN



Energy resulting from accretion onto a compact and massive object (supermassive black hole) and the associated release of the binding gravitational energy

Such high luminosity will produce an enormous radiation pressure ➜ requires a minimum central mass for material to be gravitational bound to the centre of the galaxy

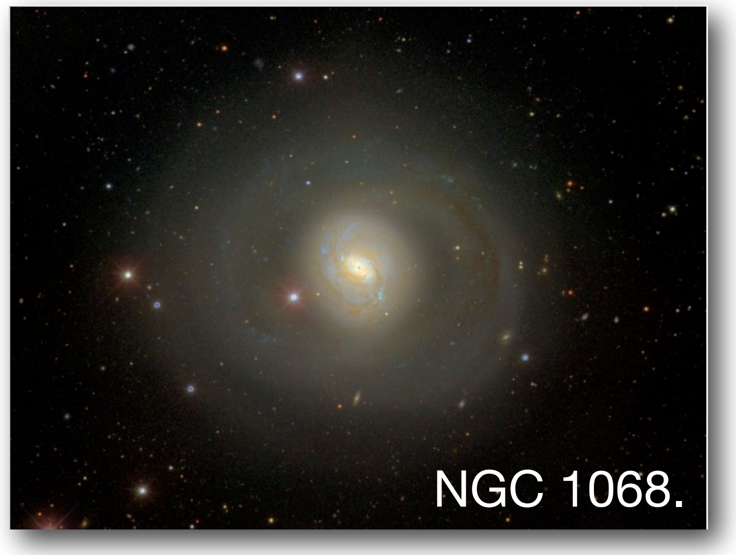
Gravitation should dominate the radiation: for a given central mass the luminosity cannot exceed the Eddington luminosity

$$L \leq 1.26 \times 10^{38} \frac{M_{BH}}{M_\odot} erg\ s^{-1}$$

Ratio between Eddington and AGN luminosities ➜ efficiency of the AGN

A variety of processes and emission from the various regions …

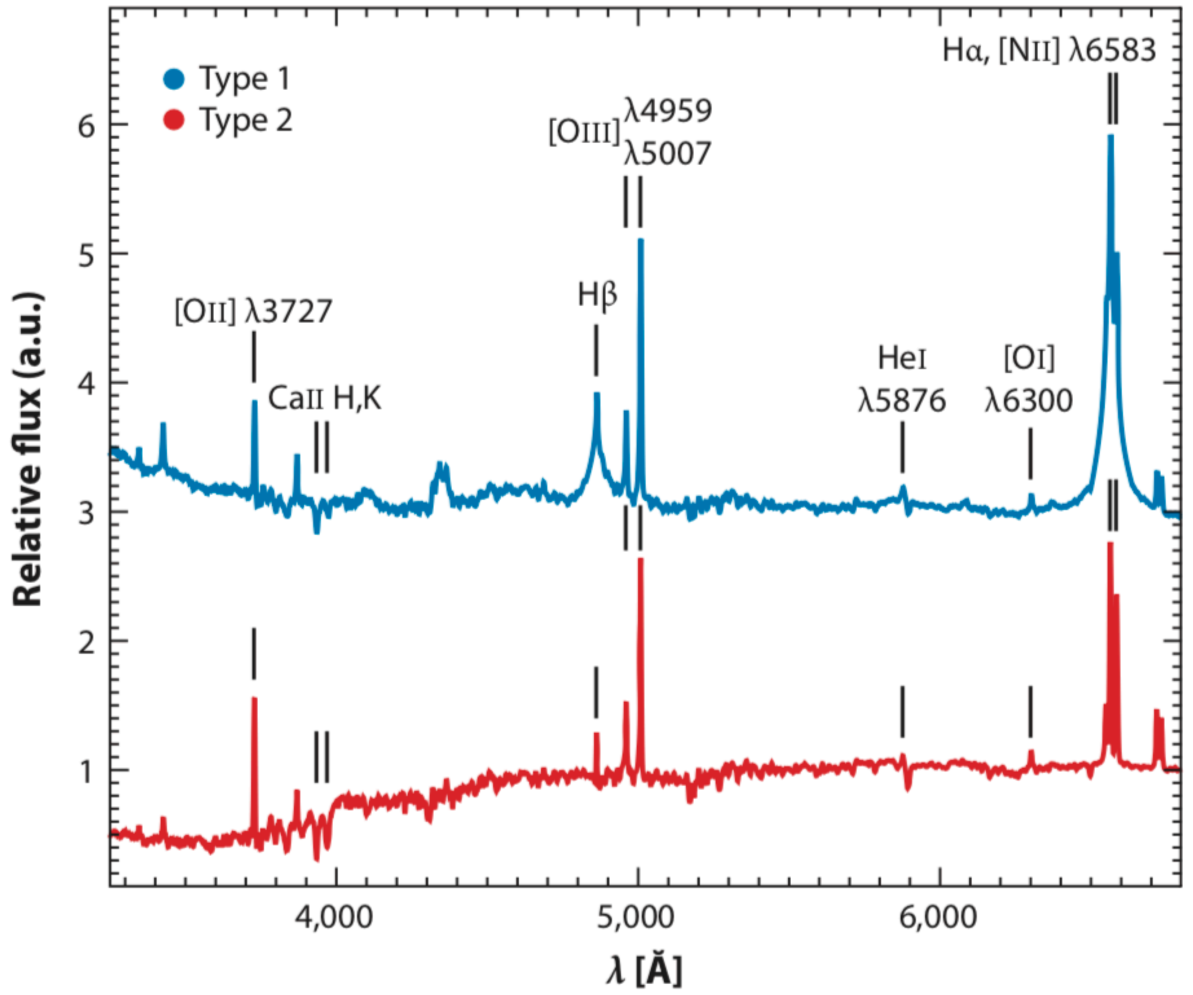
Some of the signatures of an AGN

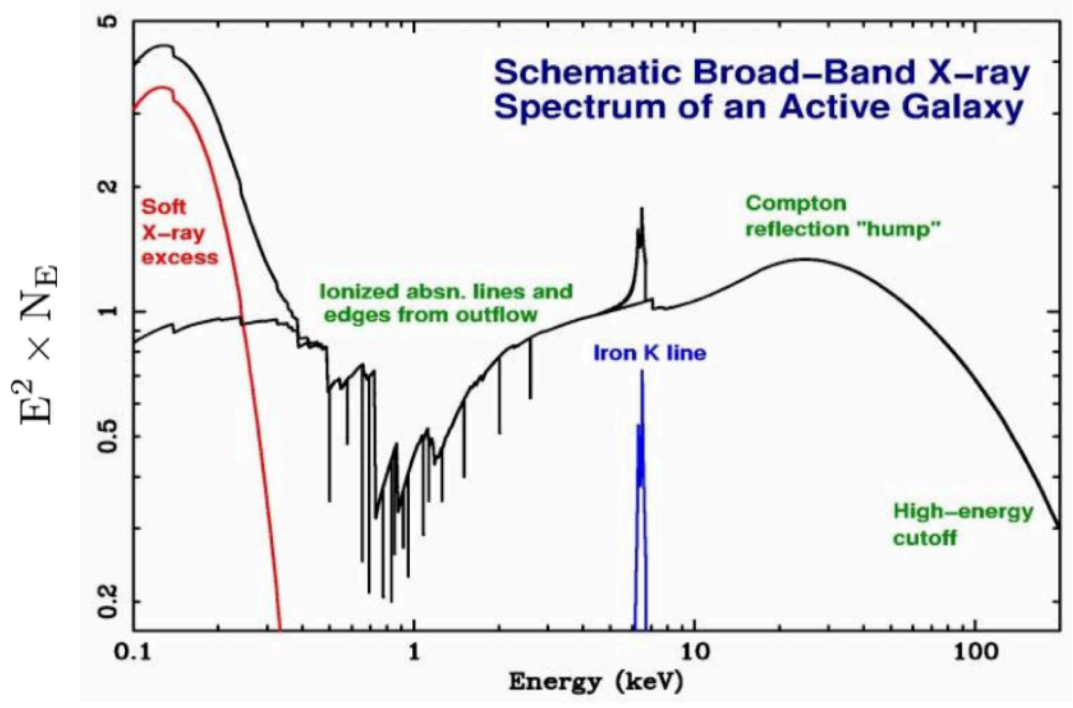


not all simultaneously present!

- Luminous UV emission from a compact region in the centre of galaxy
- Strong emission lines, sometimes highly Doppler-broadened
- High Variability on time-scales of days to months
- Strong Non-Thermal Emission
- X-ray, γ-ray and TeV-emission
- Cosmic Ray Production
- Compact Radio Core
- Extended linear radio structures (jets+hotspots)

because of this variety, AGN means different objects to different people...





Credit: Neil Brandt

Why interesting?

Interesting in their own right - **observed at different wavelengths**

➔ radio - IR/optical - X-ray, ɣ-ray … **variety of phenomena to be explained!**

The energy produced by the growth of the SMBH can exceeds the binding energy of the host galaxy

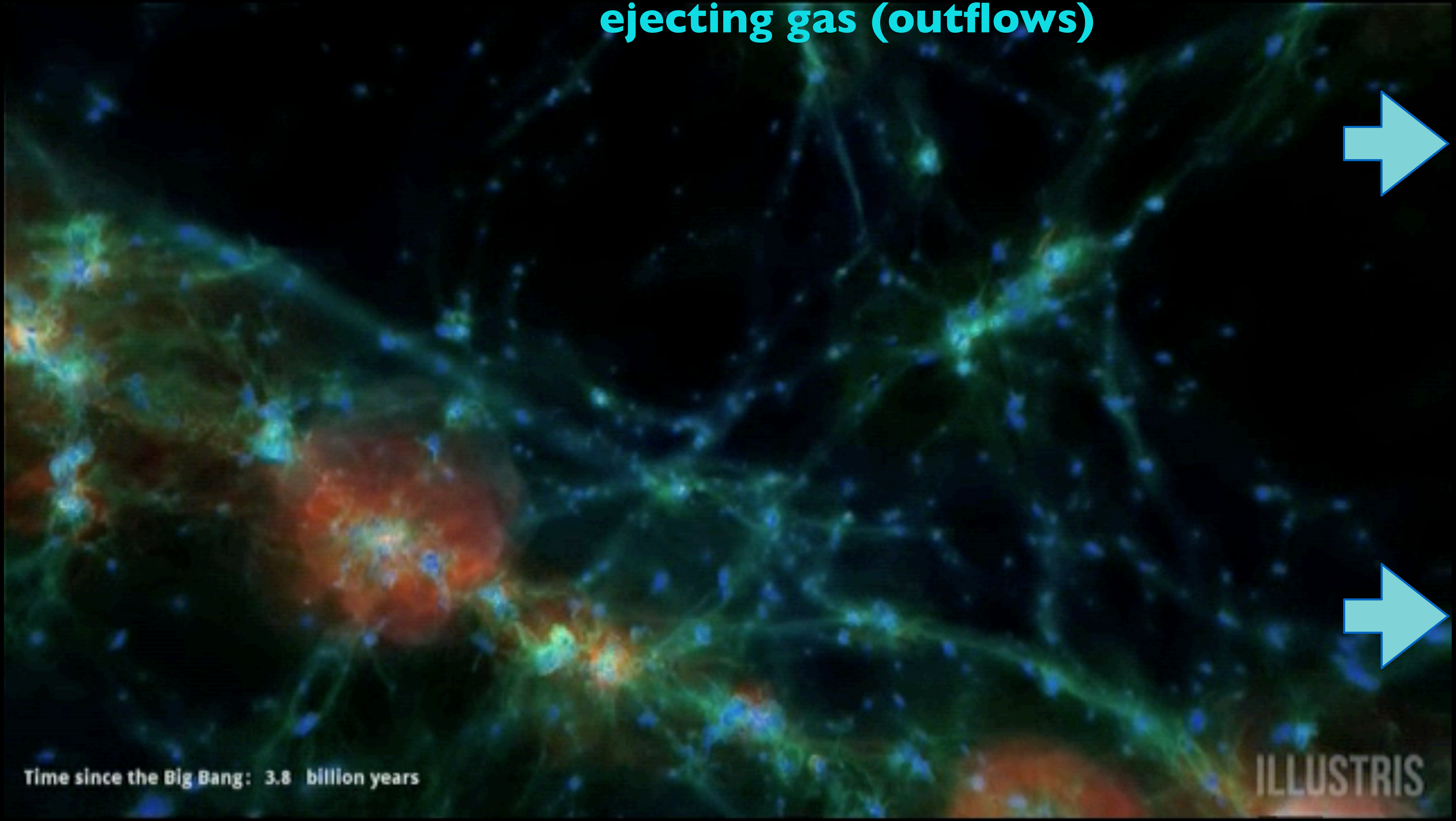
⬇

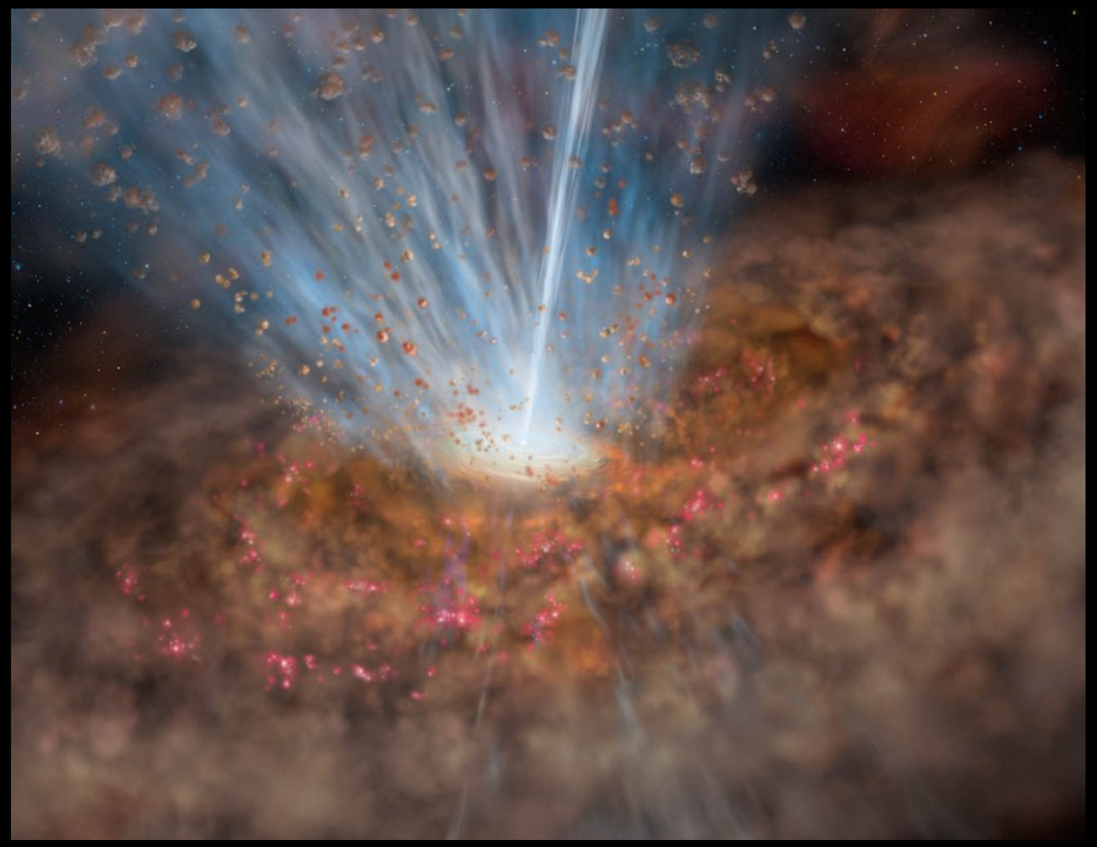
Role in galaxy evolution …

Radiation, winds and jets from the active nucleus of a massive galaxy can interact with its interstellar medium leading to ejection or heating of the gas. This can terminate star formation in the galaxy and stop the accretion onto the black hole. Such **AGN feedback** can account for the observed proportionality between central black hole and host galaxy mass (e.g. review Fabian 2012).

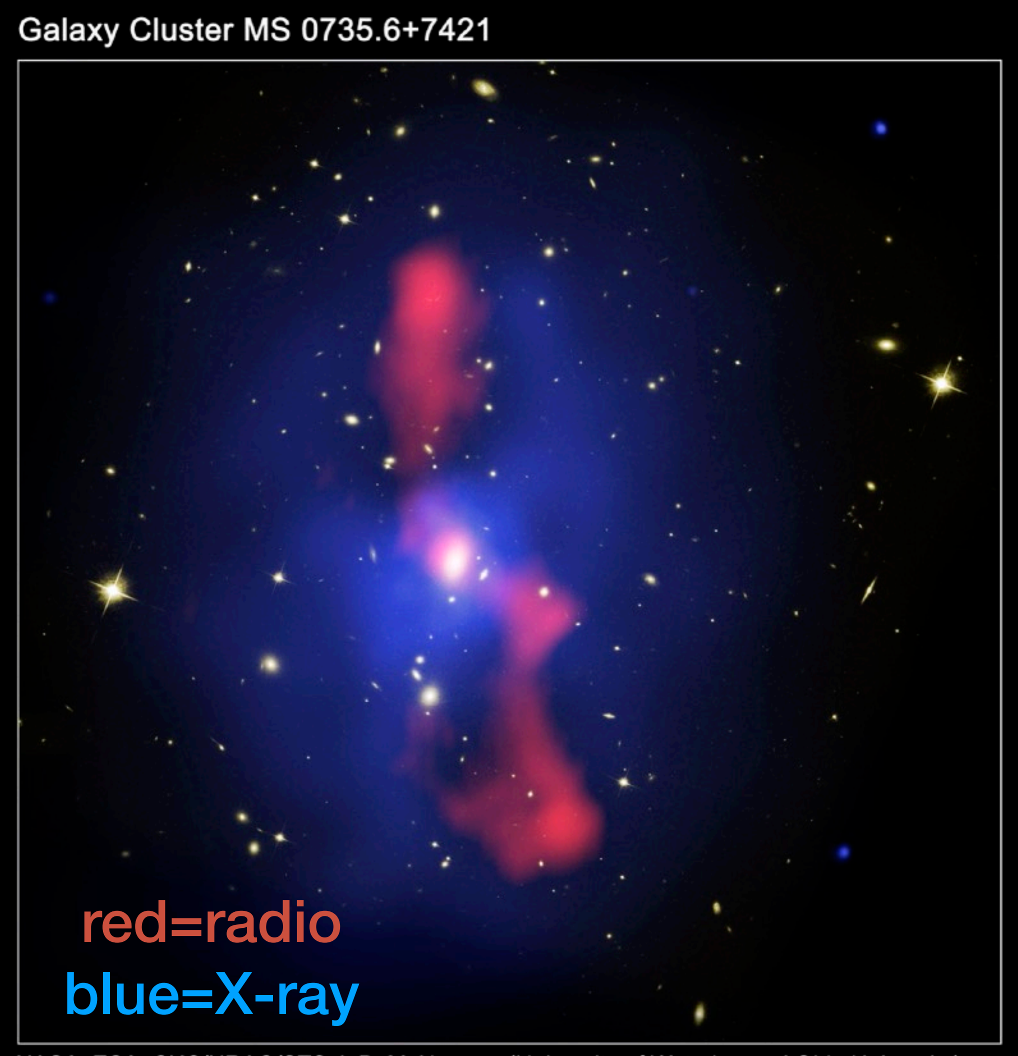
Role of AGN in galaxy evolution: cosmological simulations

Preventing gas from cooling
and/or
ejecting gas (outflows)





“Quasar” mode

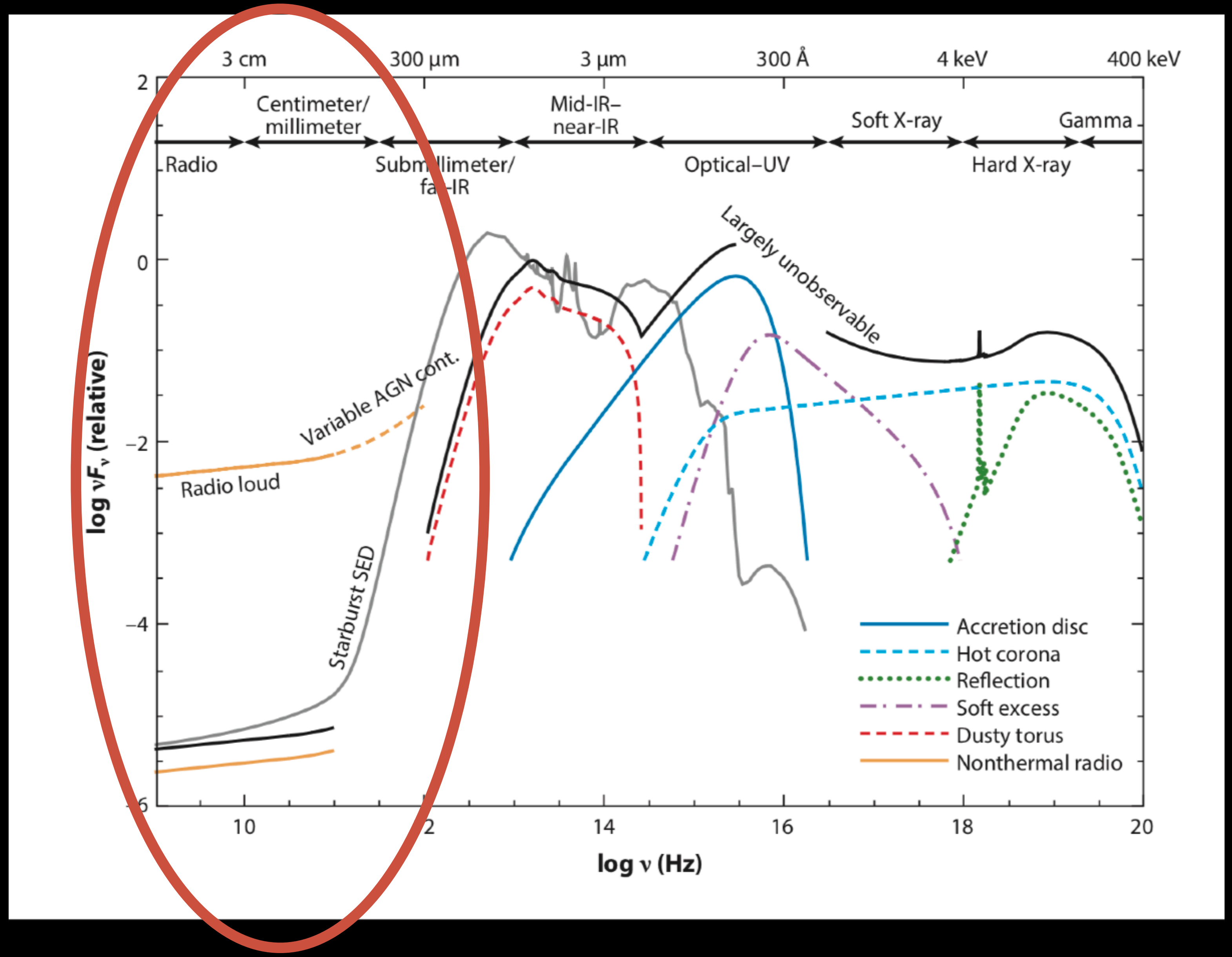


NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

“jet/maintenance” mode
(cluster-scale)

The AGN has to be recurrent to have the required impact on the host galaxy

Radio AGN

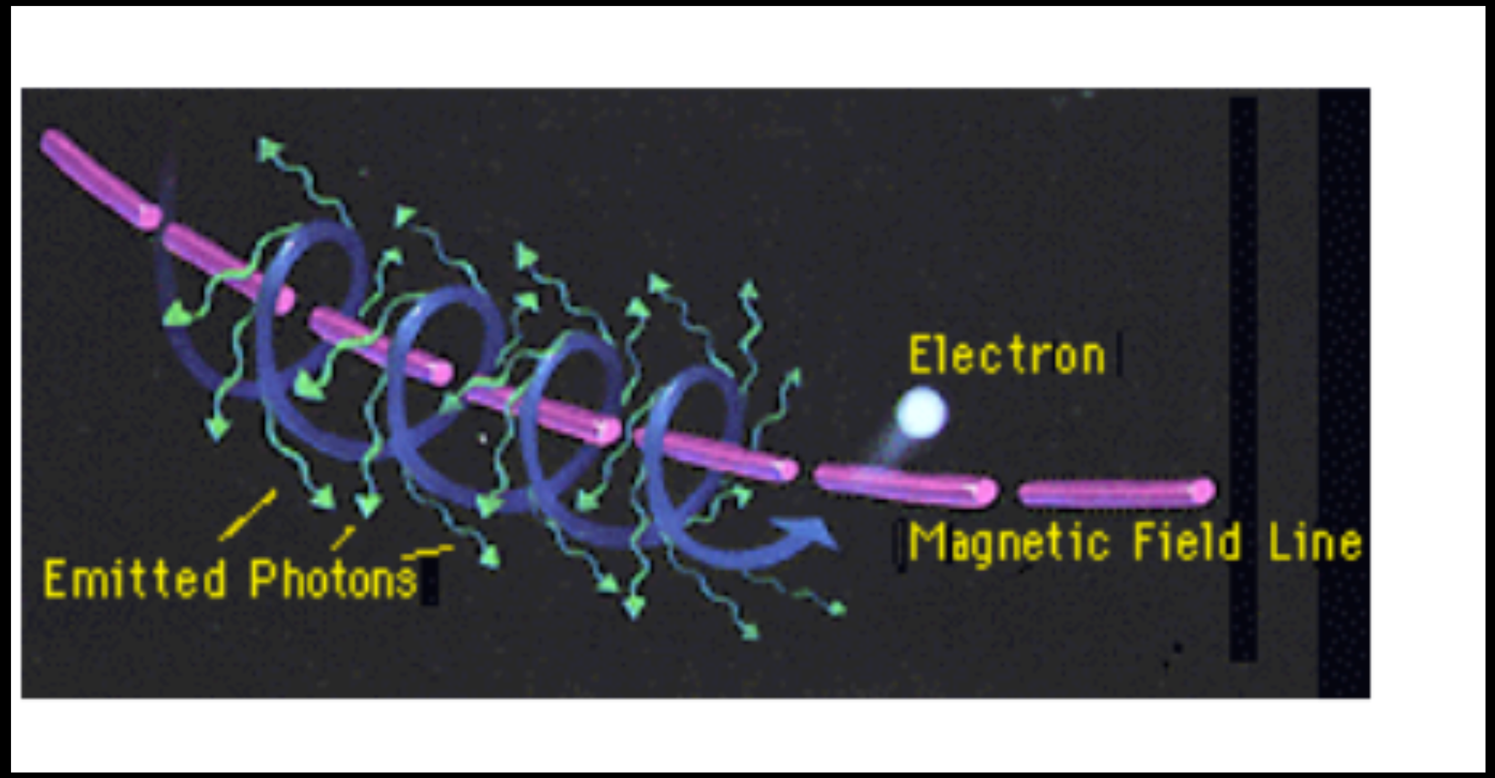


Radio emission originates from
synchrotron emission from relativistic electrons
spiralling along the lines of the magnetic field

p.s. it doesn’t mean that they emit **only** in radio …

Synchrotron radiation

Particle accelerated by a magnetic field will radiate.
Emission but also synchrotron self-absorption
Beamed and polarised radiation



Energy of the electrons

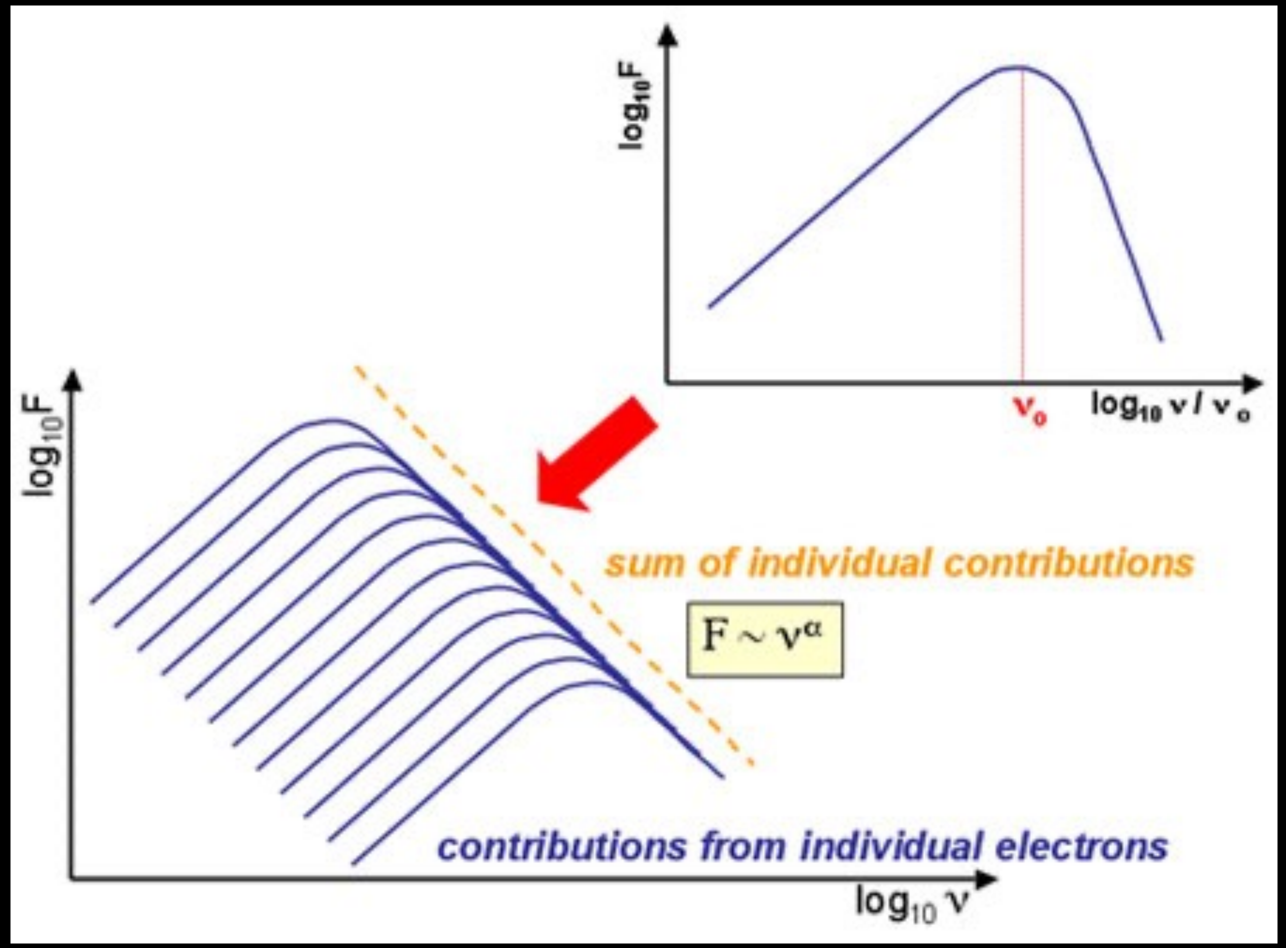
$$E = \gamma m_e c^2$$

Lorentz factor

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

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

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



ensemble of relativistic electrons ➔ power law spectrum (in absence of absorption mechanisms)

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

spectral index

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

emitted flux

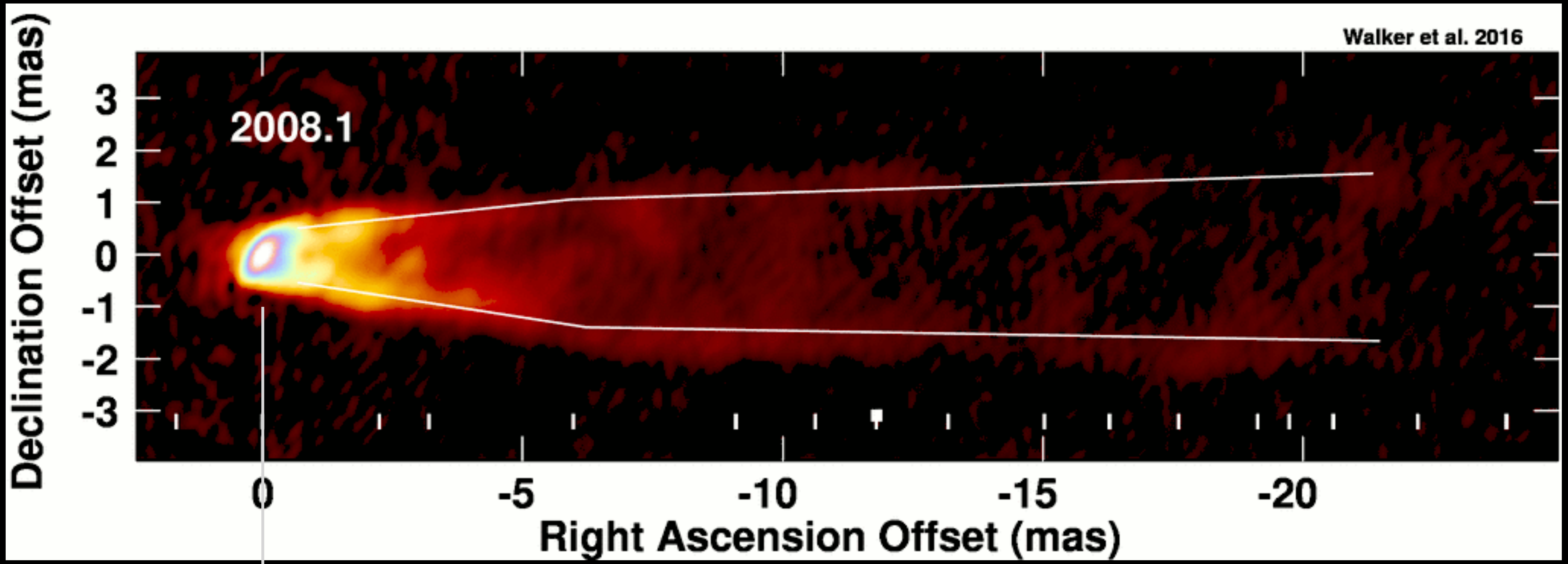
$$F \propto \nu^{-\alpha}$$ ← spectral index

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

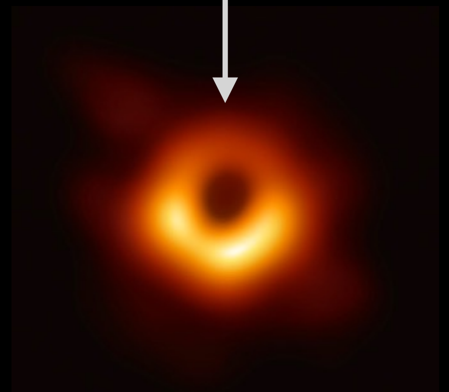
Collimation of the jets

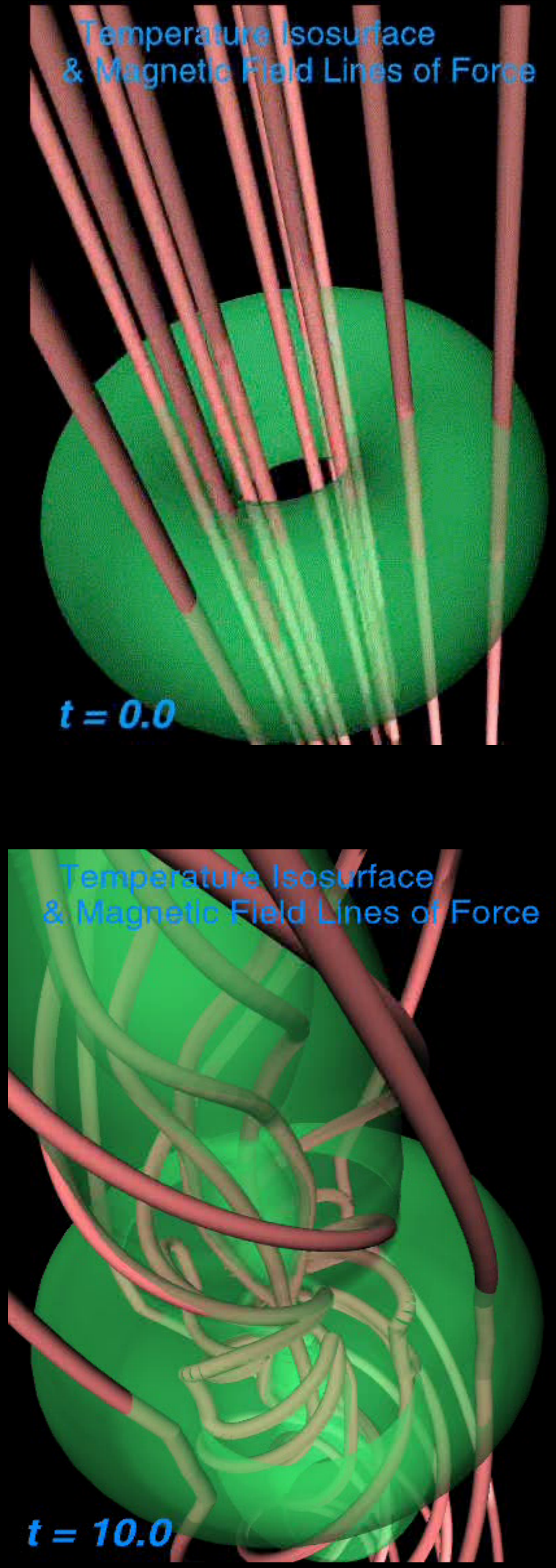
From Craig Walker
Schwarzschild radius of the M87 black hole (2GM/c2) is 7.3 microarcseconds.

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 - Walker et al. 2018
(see also Mertens et al. 2016)

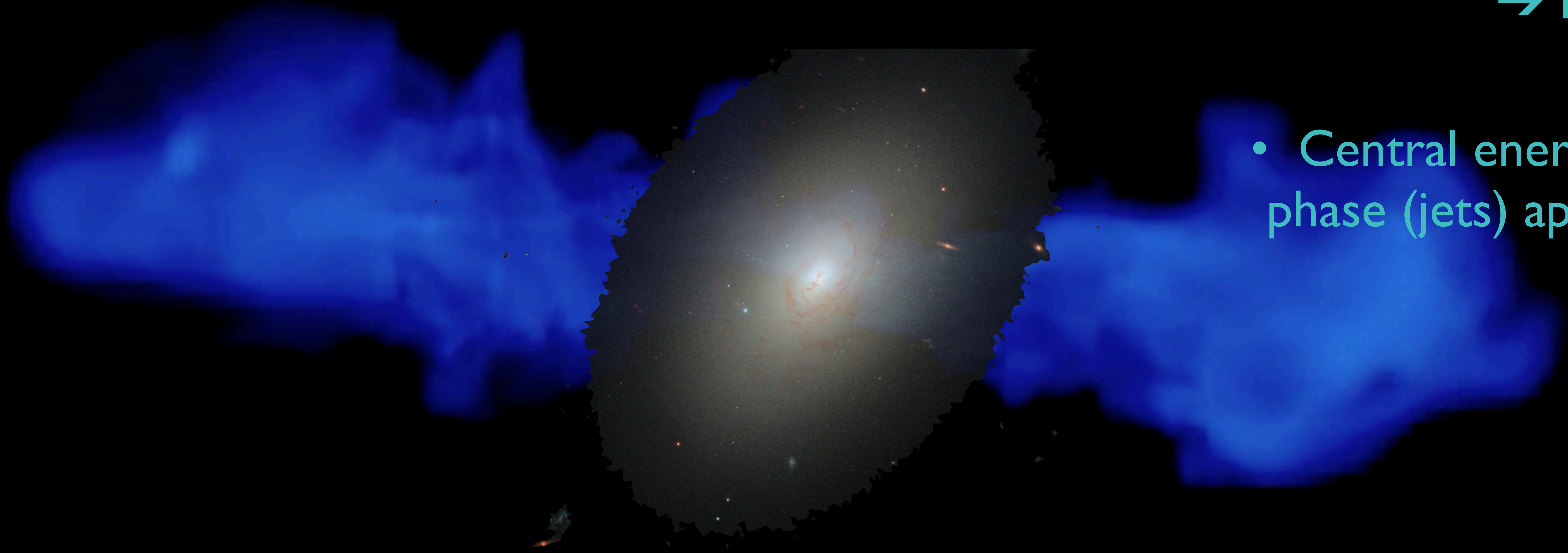




Uchida et al. 1999
Meier et al. 2001

Jets and lobes: evolution of a radio galaxy

- Continuous injection of relativistic electrons: power law spectrum with steepening due to energy losses
- Central energy supply stops: extra steepening of the spectrum, compact features disappear → **remnant** radio galaxies
- Central energy supply can restarted, a new phase (jets) appears → **restarted** radio galaxies



Heinz et al. 2006

Structure of radio AGN

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

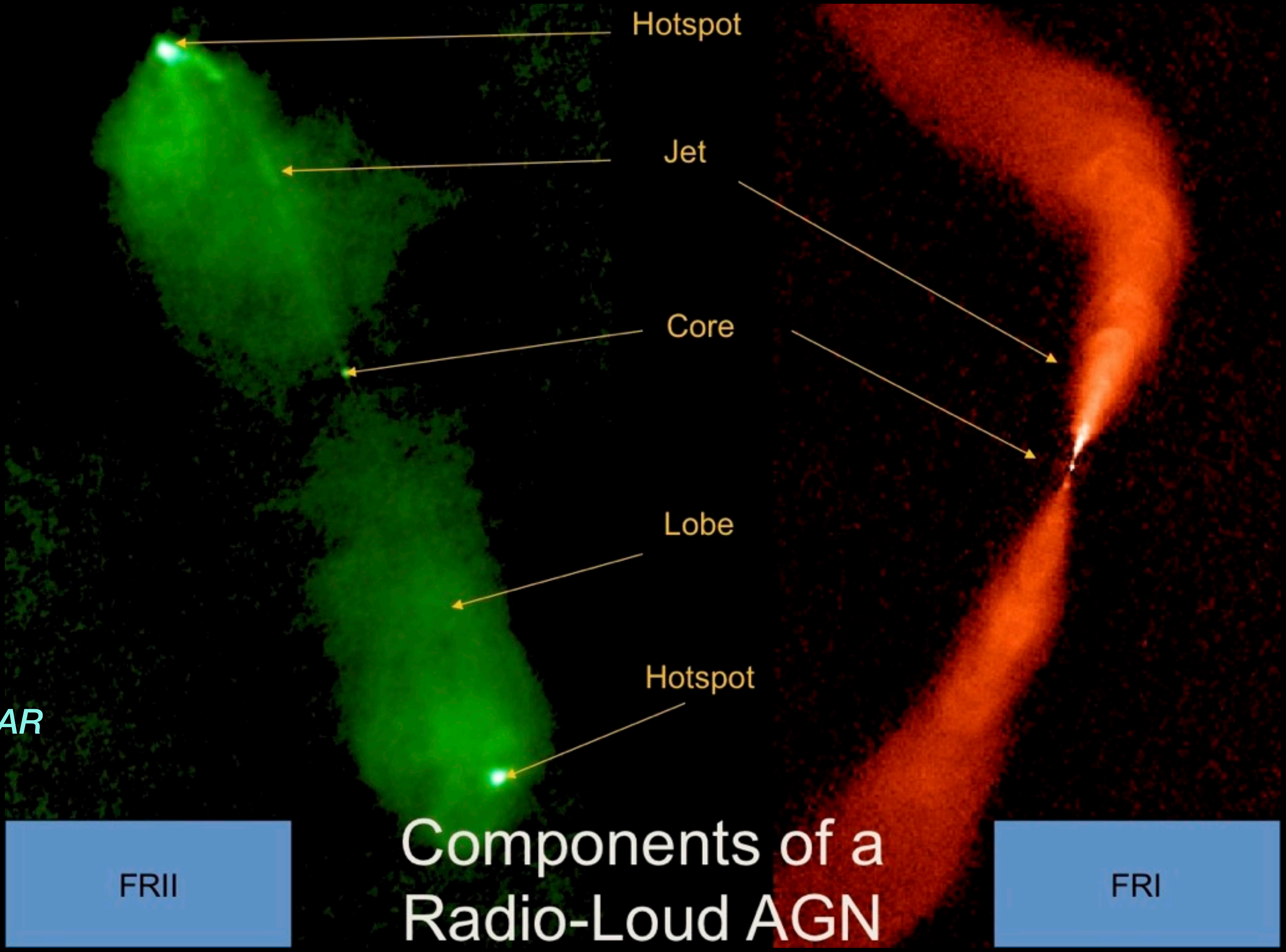
we will see some examples from LOFAR

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

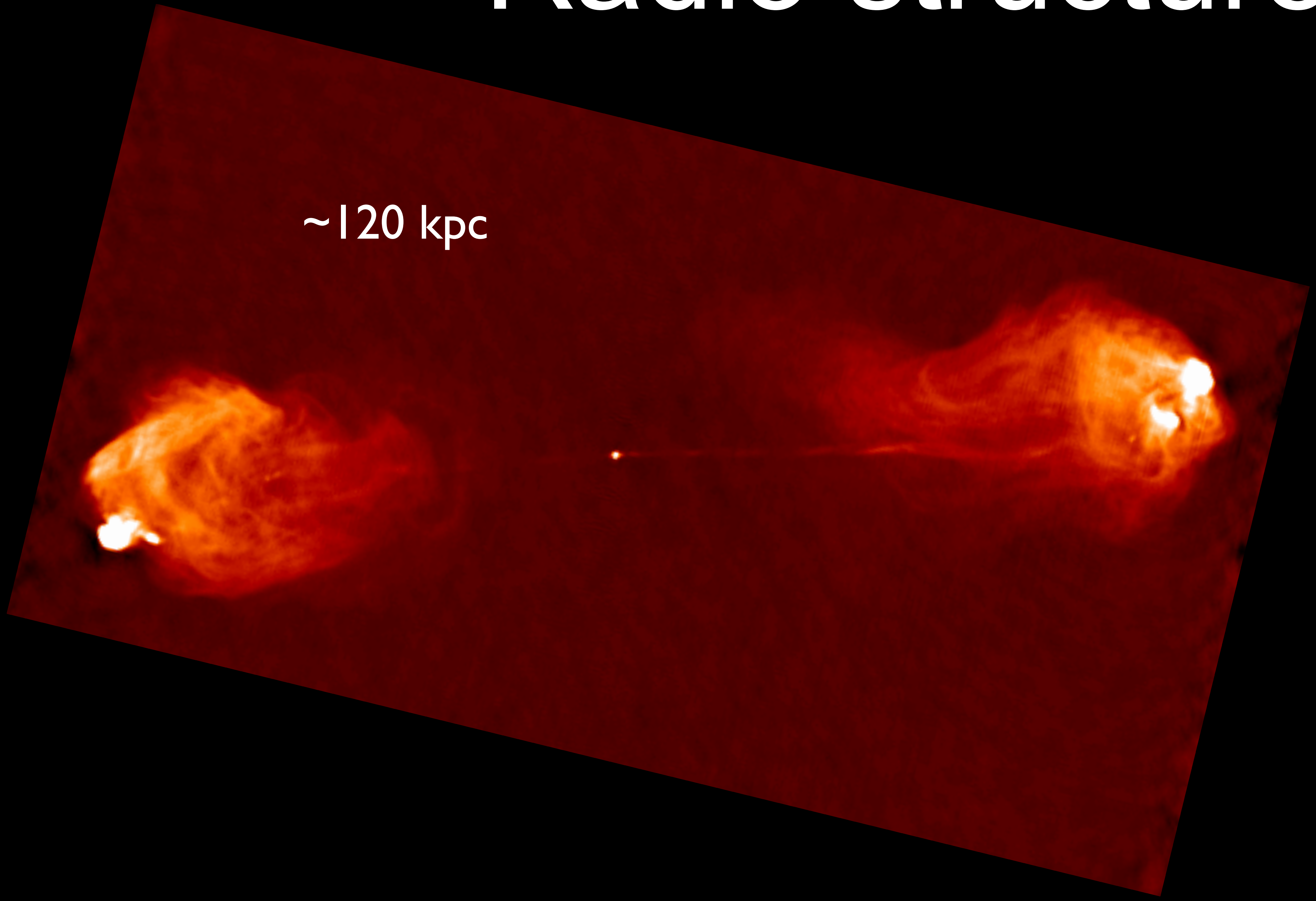
- The type of structure tells us about the properties of the jet (high/low Mach number), environment (dense/cluster or field) efficiency of the central AGN and power of the radio source.

but we will see some new results from LOFAR

- Radio AGN can be of any size - from pc to Mpc sometimes Mpc, much larger than the optical host galaxy.



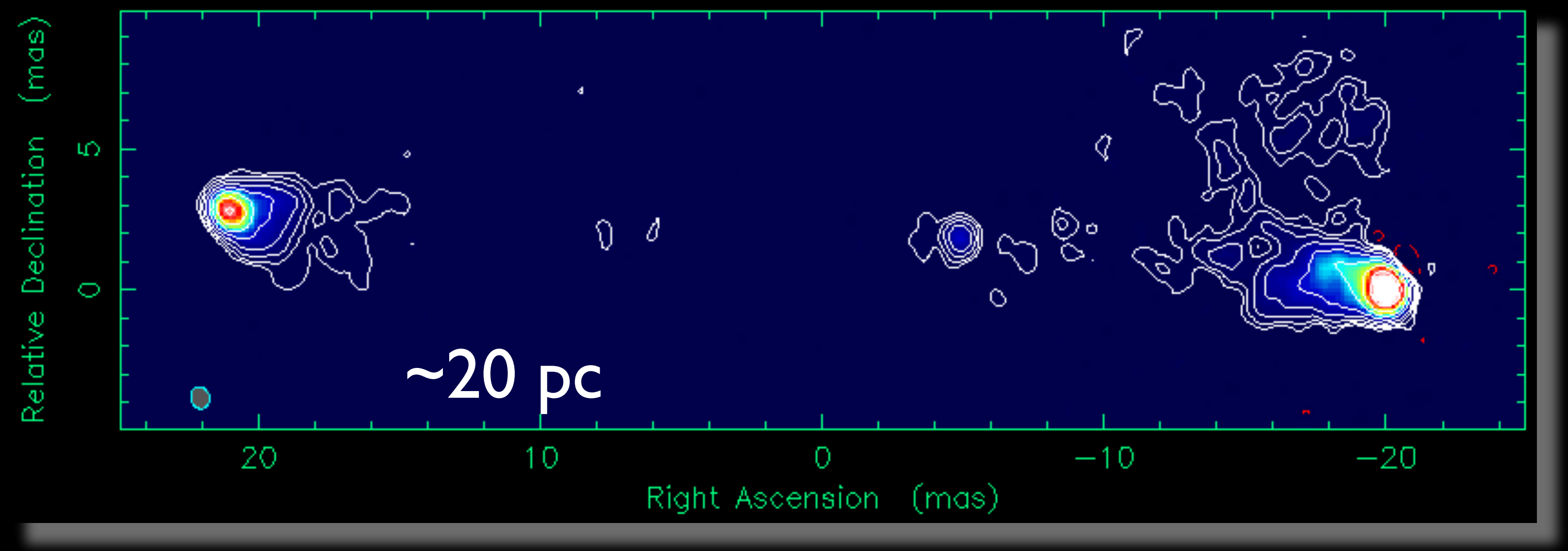
Radio structures from pc to Mpc



Similar morphologies on small
and large scales

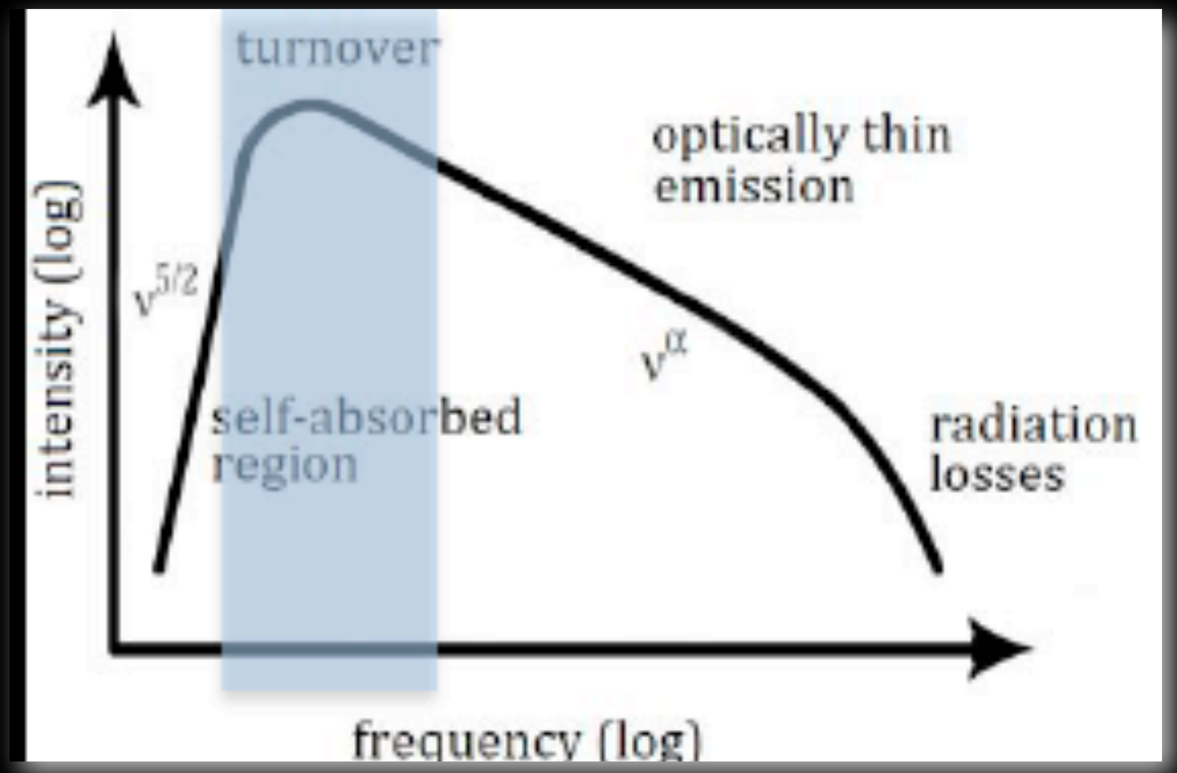
Sizes resulting from:
evolutionary stage (smaller ➔ younger)
but expansion also depends on the interaction with ISM
or
orientation effects

…later some examples of giant radio galaxies
with LOFAR

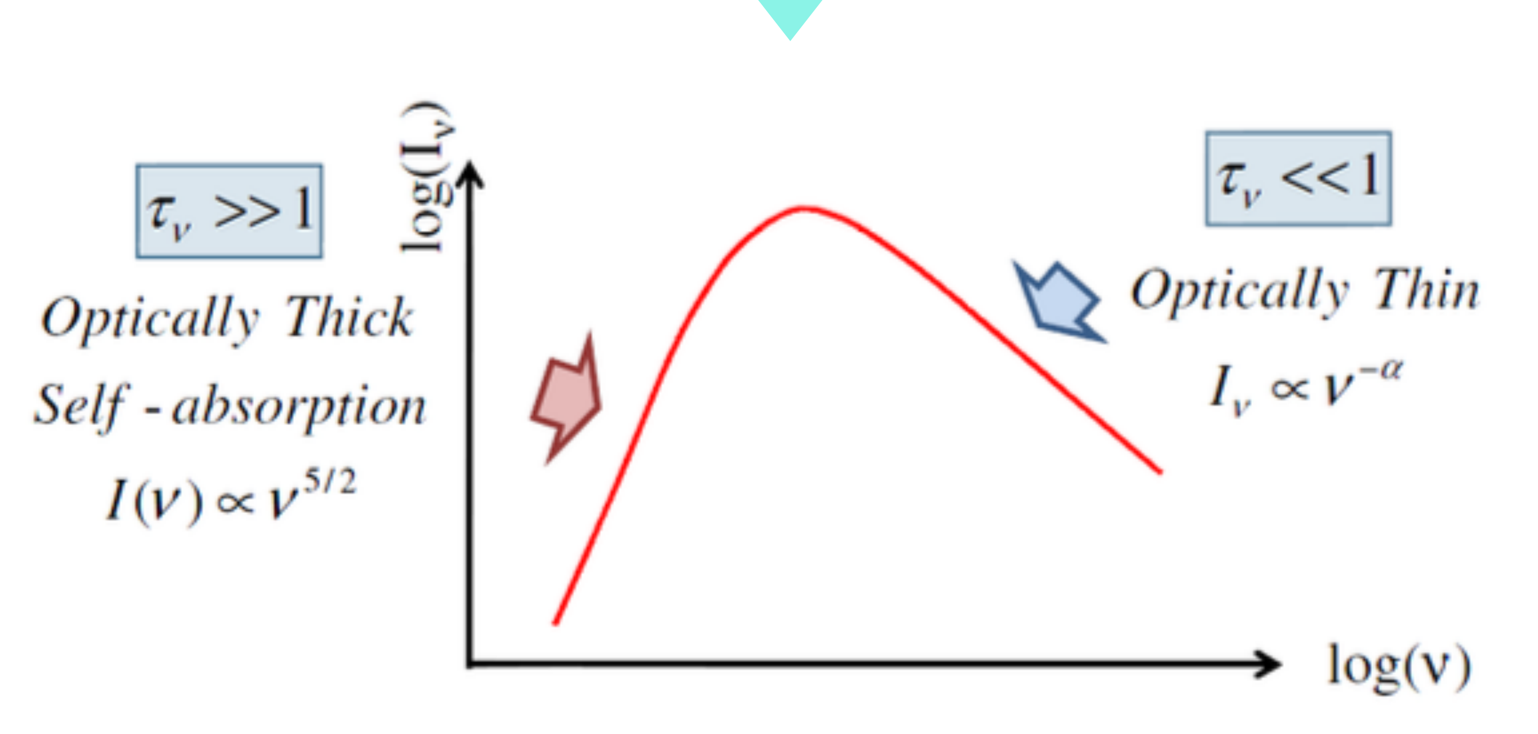


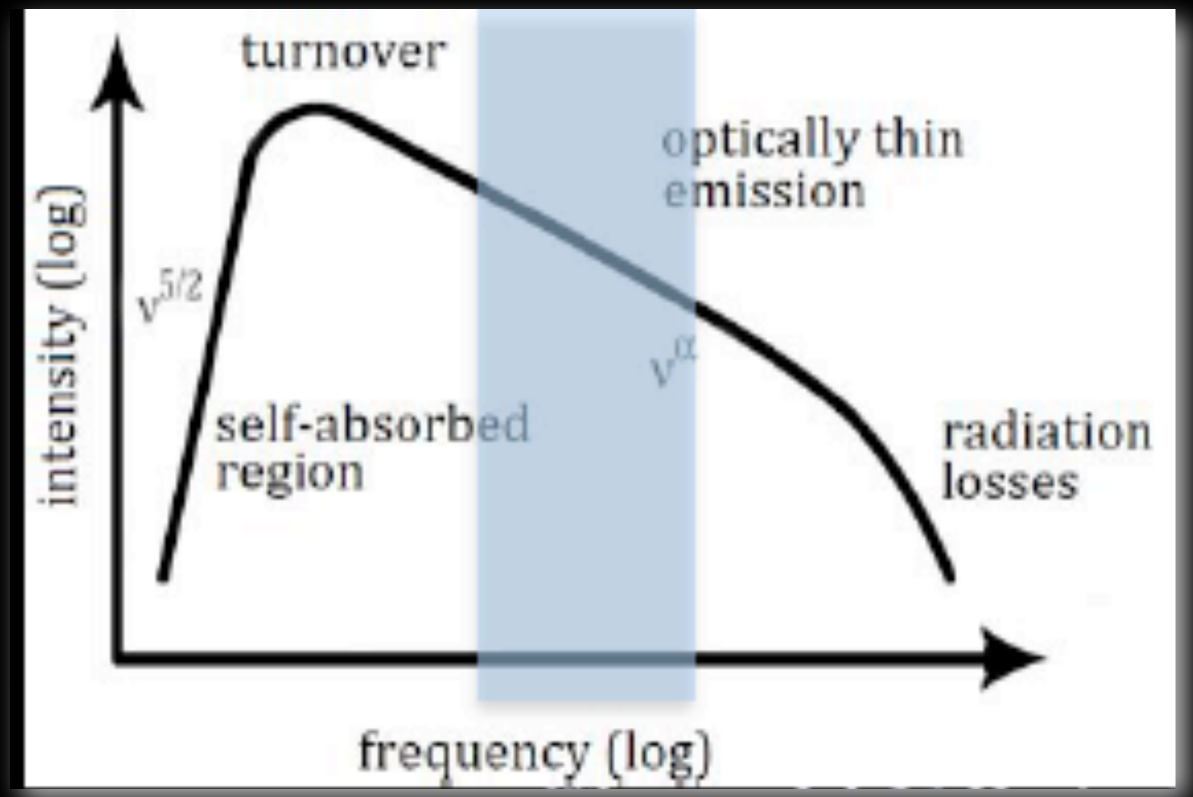
Importance of the spectral index

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

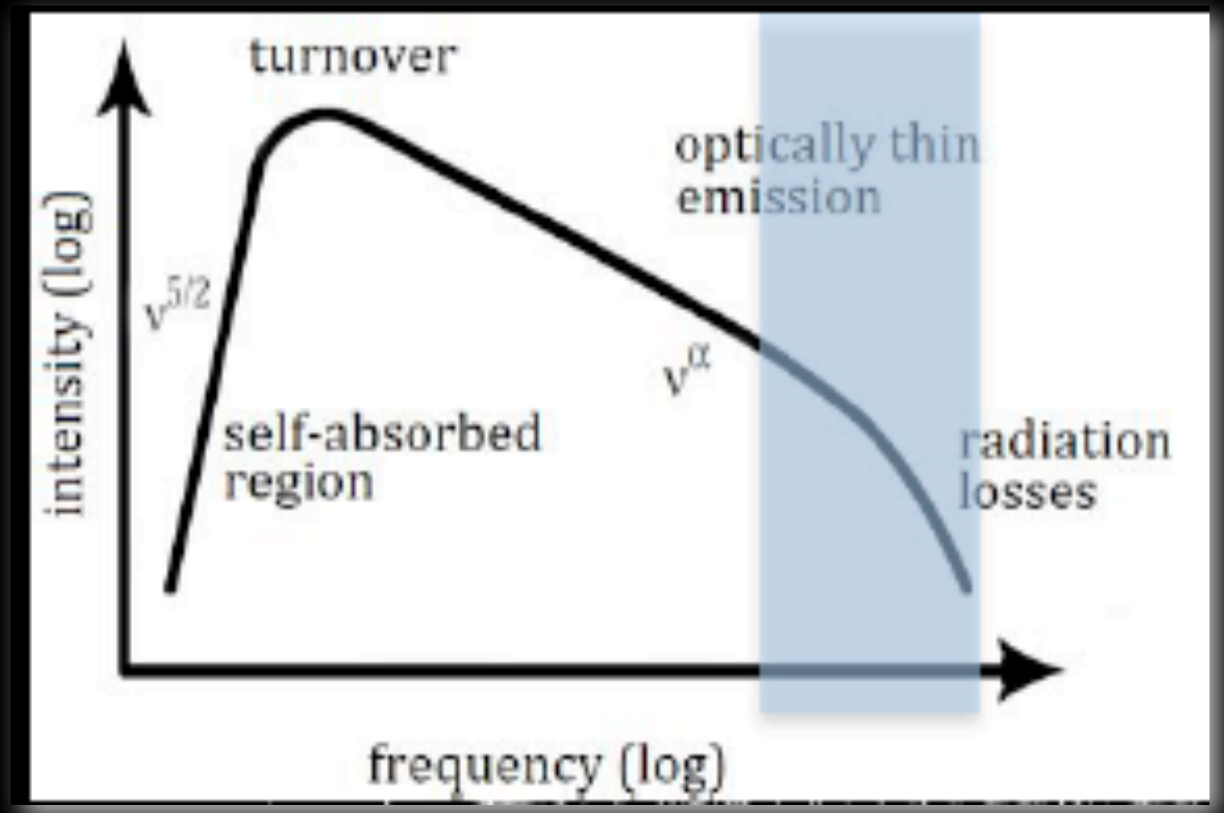


Younger radio galaxies





“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.

Power emitted by an electron

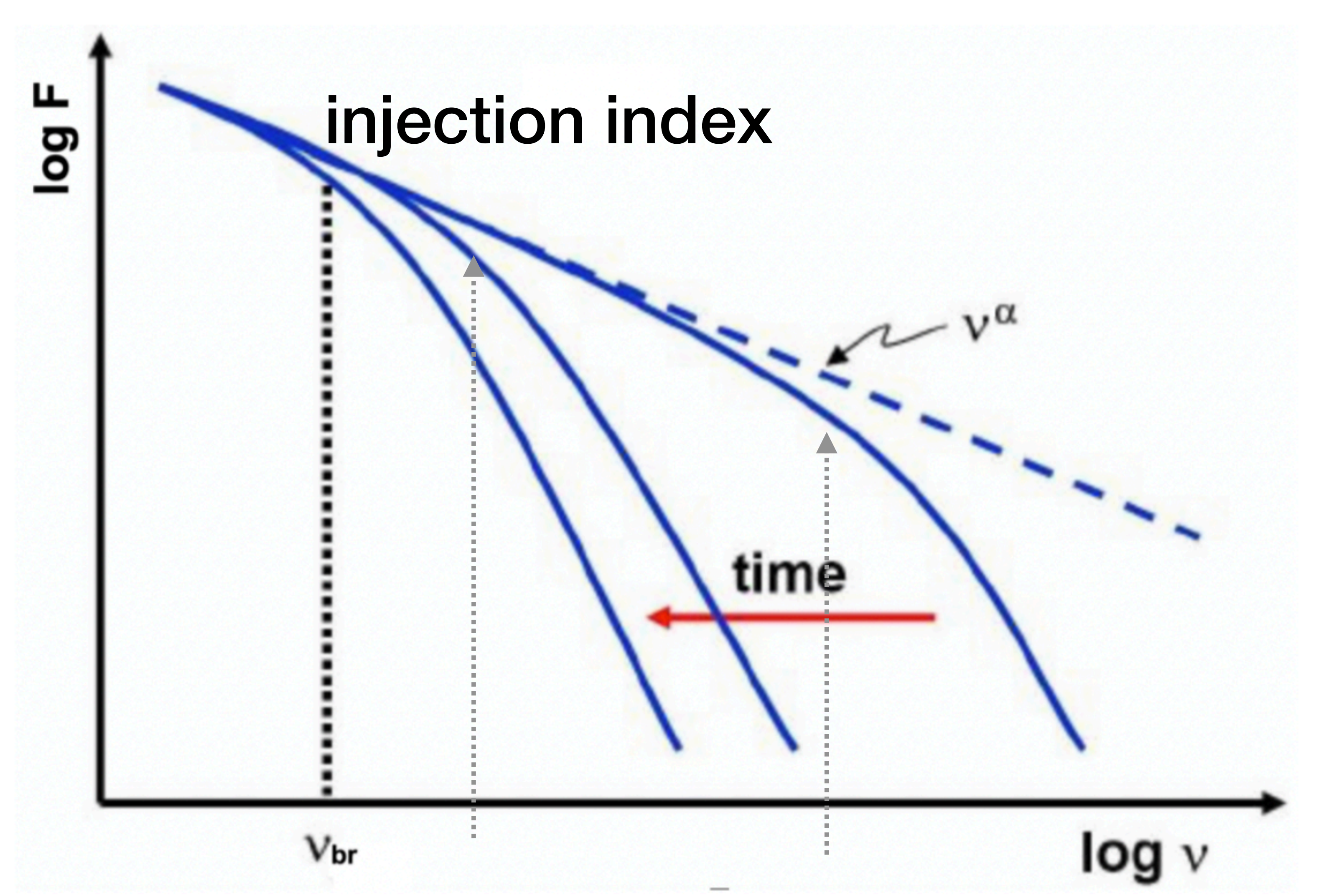
$$P = \frac{dE}{dt} = \frac{4e^4}{9m^2c^3} B^2\gamma^2$$

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)

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

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

Higher B magnetic field and higher ɣ ➔ higher frequency of the emission, higher emitted radiation, shorter tcool



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

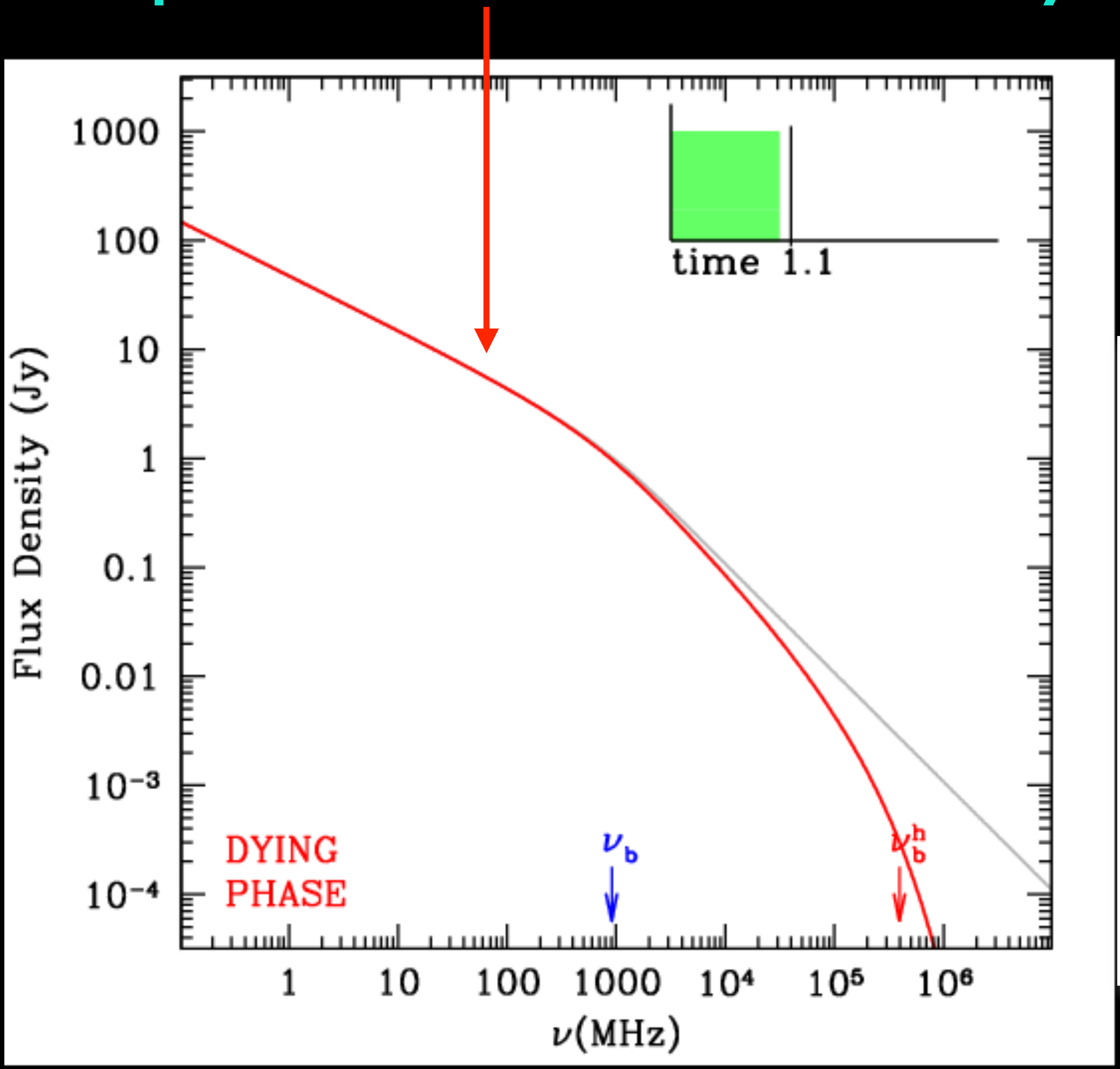
For $\nu < \nu_{break}$ the spectral index remains unchanged
➔ injection index

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

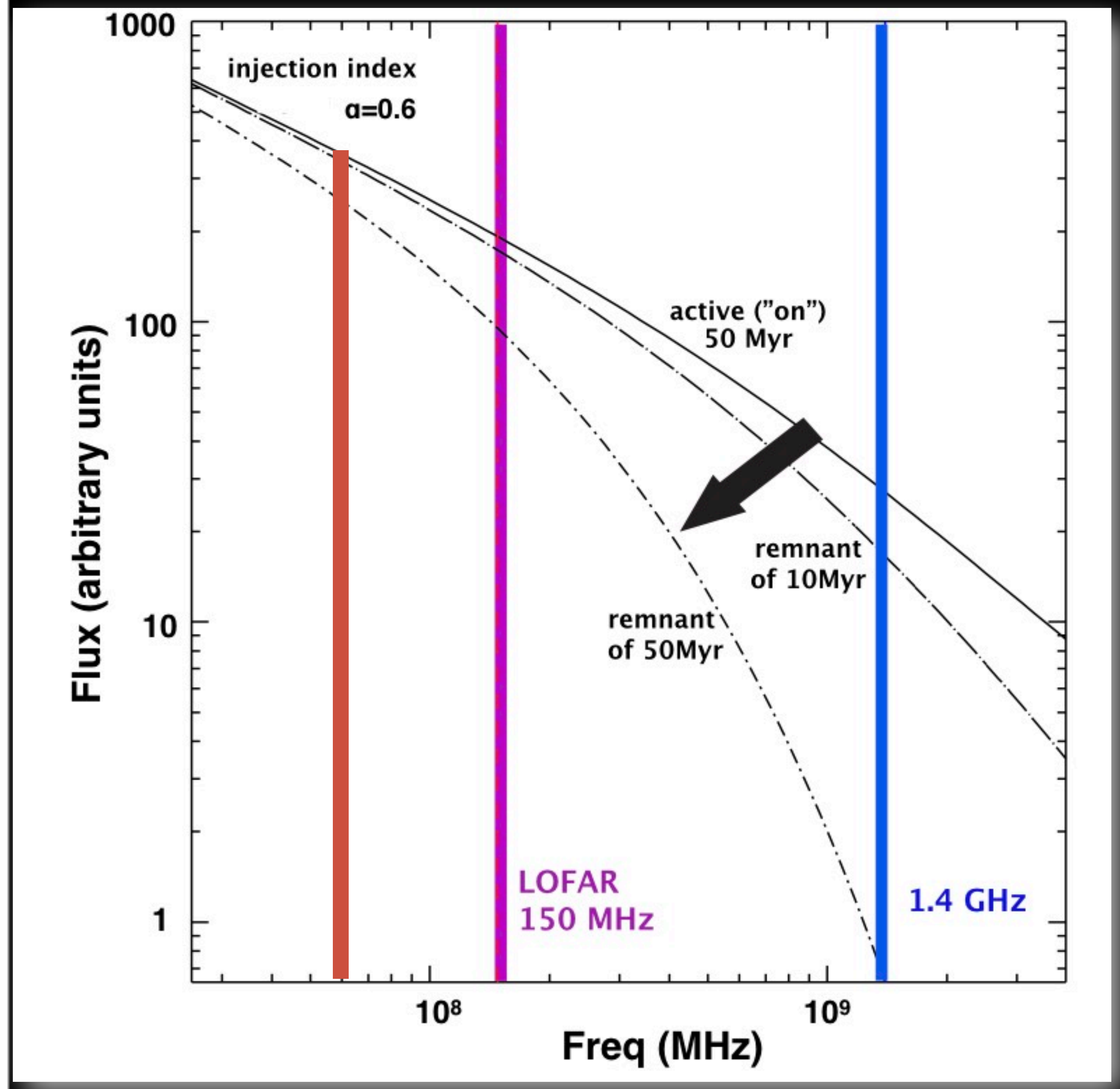
Adding the spectral information
Low frequencies last affected by ageing….

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

Key to have the low frequencies



COURTESY OF M. MURGIA



Morganti 2017

Morphology of the jets and lobes (at different frequencies), luminosity, size, spectral indices (integrated and spatially resolved), polarisation (see lesson from Annalisa Bonafede), energetics

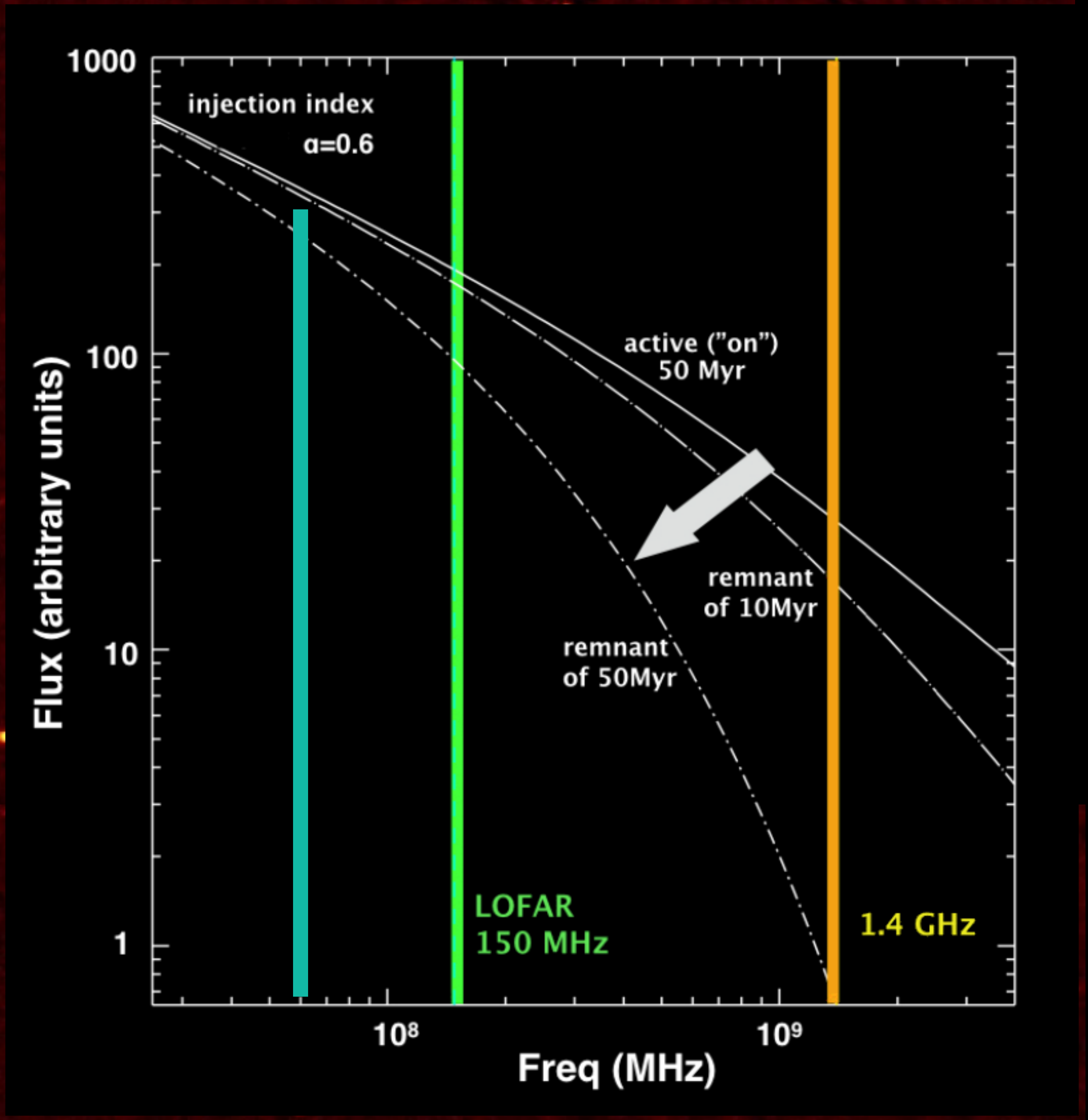
↓

all key parameters to characterise radio AGN -

important to have the optical ID and redshift of the host galaxy

LOFAR: why important for AGN?

LOFAR: why important for AGN?



Very large field of view: HBA about 30 sq deg (LBA even larger)
→ **ideal for searching for rare AGN**

Add the low frequency information at the same resolution as cm
→ detailed spectral index
→ **ideal for timing the history of the radio source**

Sensitivity to low surface brightness structures → **ideal for tracing the morphology, galaxy motion and history**

High spatial resolution (6” HBA, 0.3” international baselines, 15” LBA)
→ **morphological details**

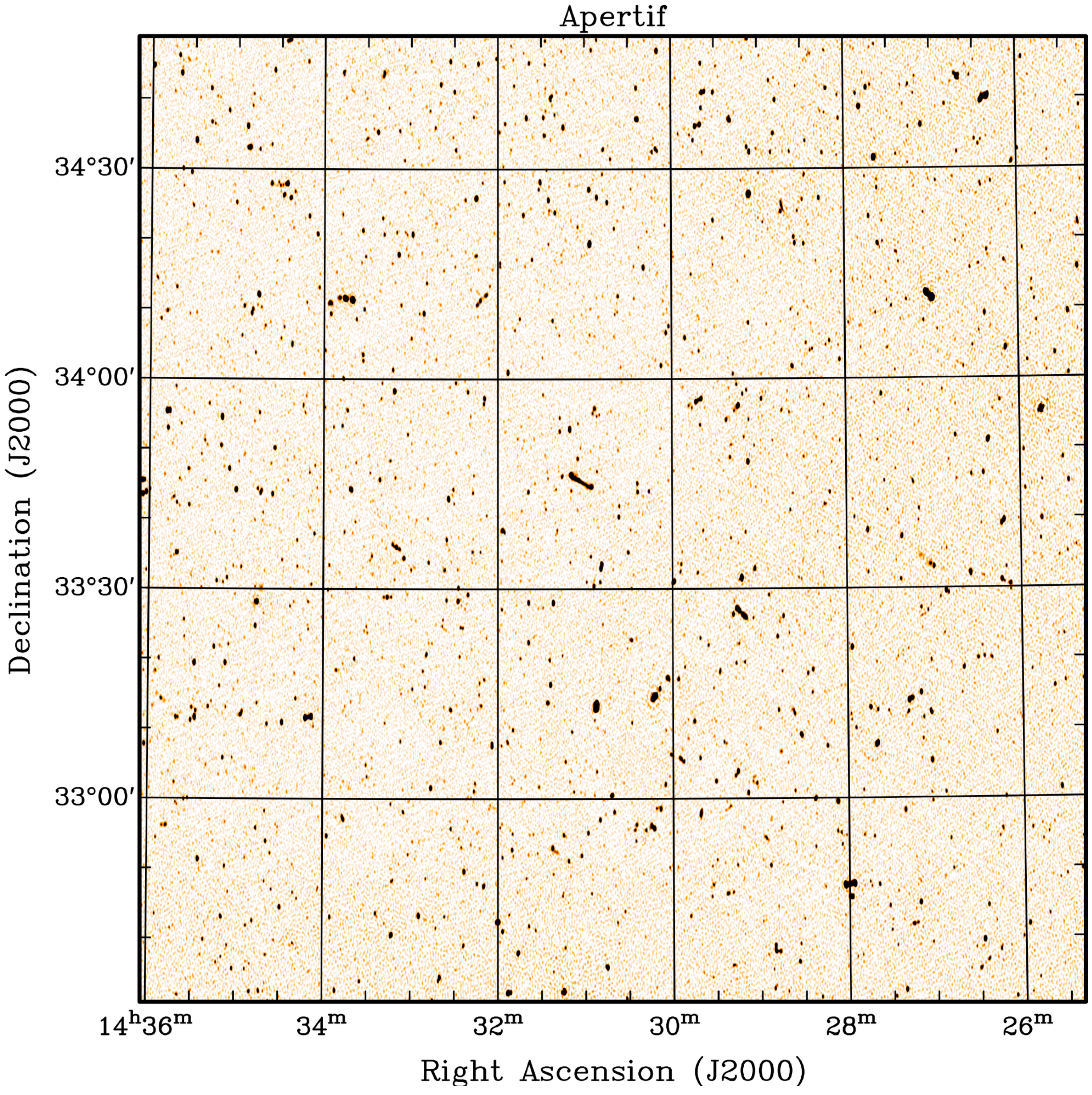
Each LOFAR pointing includes **MANY THOUSANDS** of radio AGN:
mostly unresolved at
6 arcsec resolution, but many showing interesting structures.

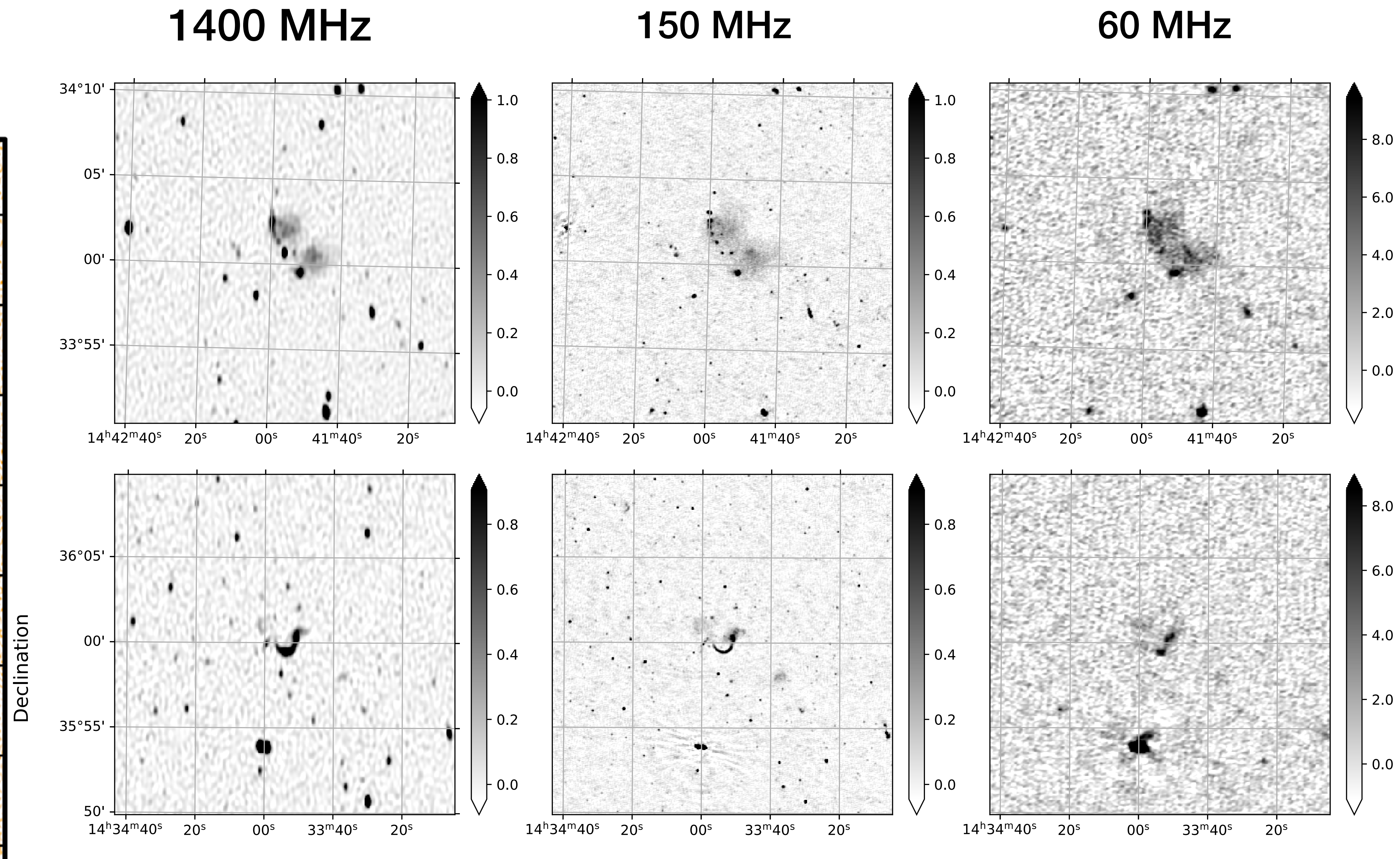
Study of **single objects**
but where LOFAR is particularly strong is the **search for rare objects** and **selection of large samples** of sources:
this includes development of techniques to make such a selection as automatic as possible
key for many studies the availability of the optical identification (redshift, properties of the host galaxy etc.)
as well as have complementary data at high radio frequencies

Lockman Hole region

150 MHz **1400 MHz**

HBA smoothed to Apertif resolution, scaled for $\alpha = -0.7$



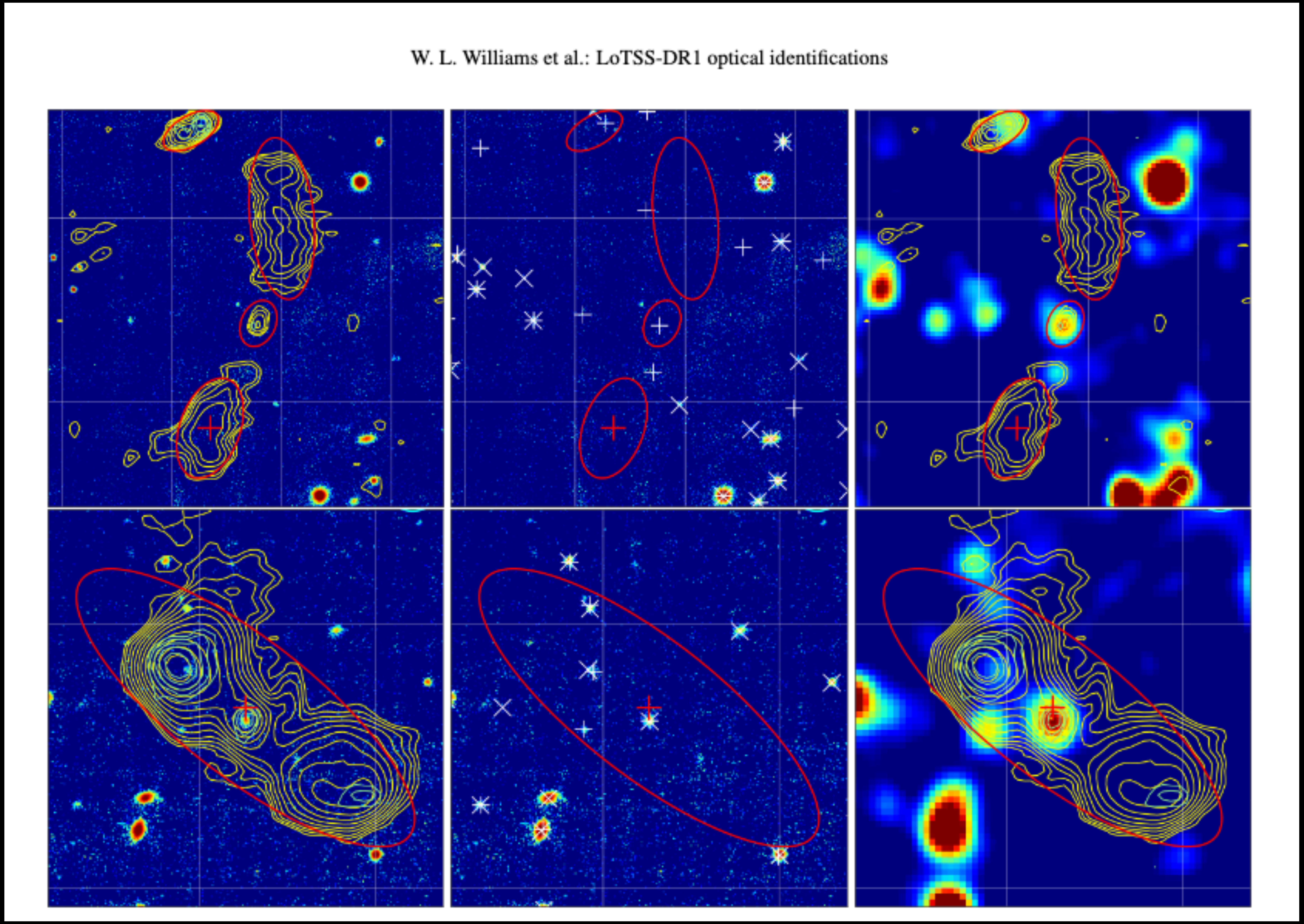


Apertif HBA LBA

- noise 20 - 40 μJy beam^{-1}
- 11.5 x 27 arcsec resolution
- 1.4 GHz

~10x deeper than NVSS, ~2-4x better resolution
better match to LOFAR

Key steps: components association
AND
optical identification


W. L. Williams et al.: LoTSS-DR1 optical identifications

It makes possibile to derive properties of the sources, optical ID, redshift and optical properties of the host galaxy

thanks to the GalaxyZoo with a big effort of Martin Hardcastle and many others

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

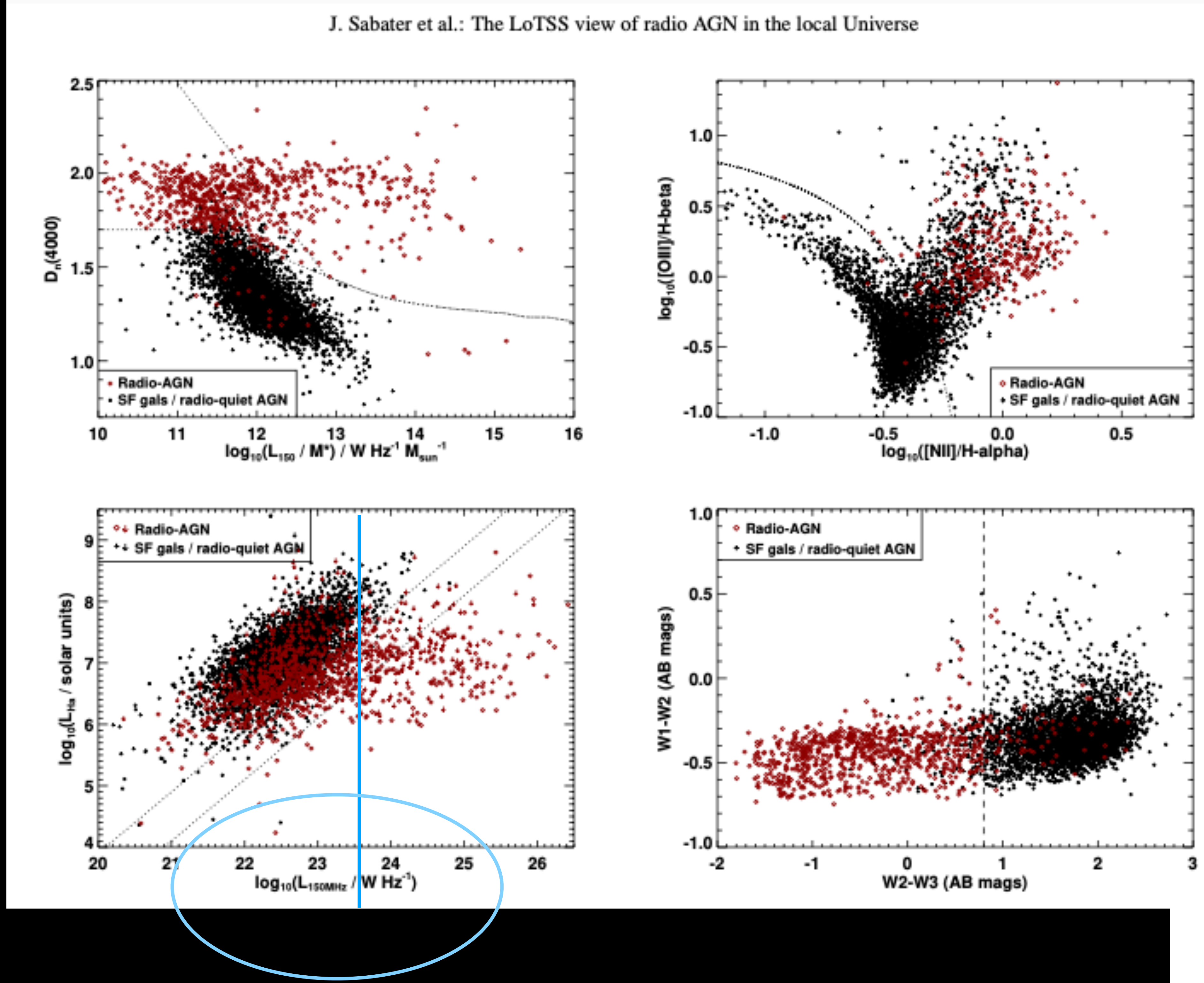
see Williams et al. 2019

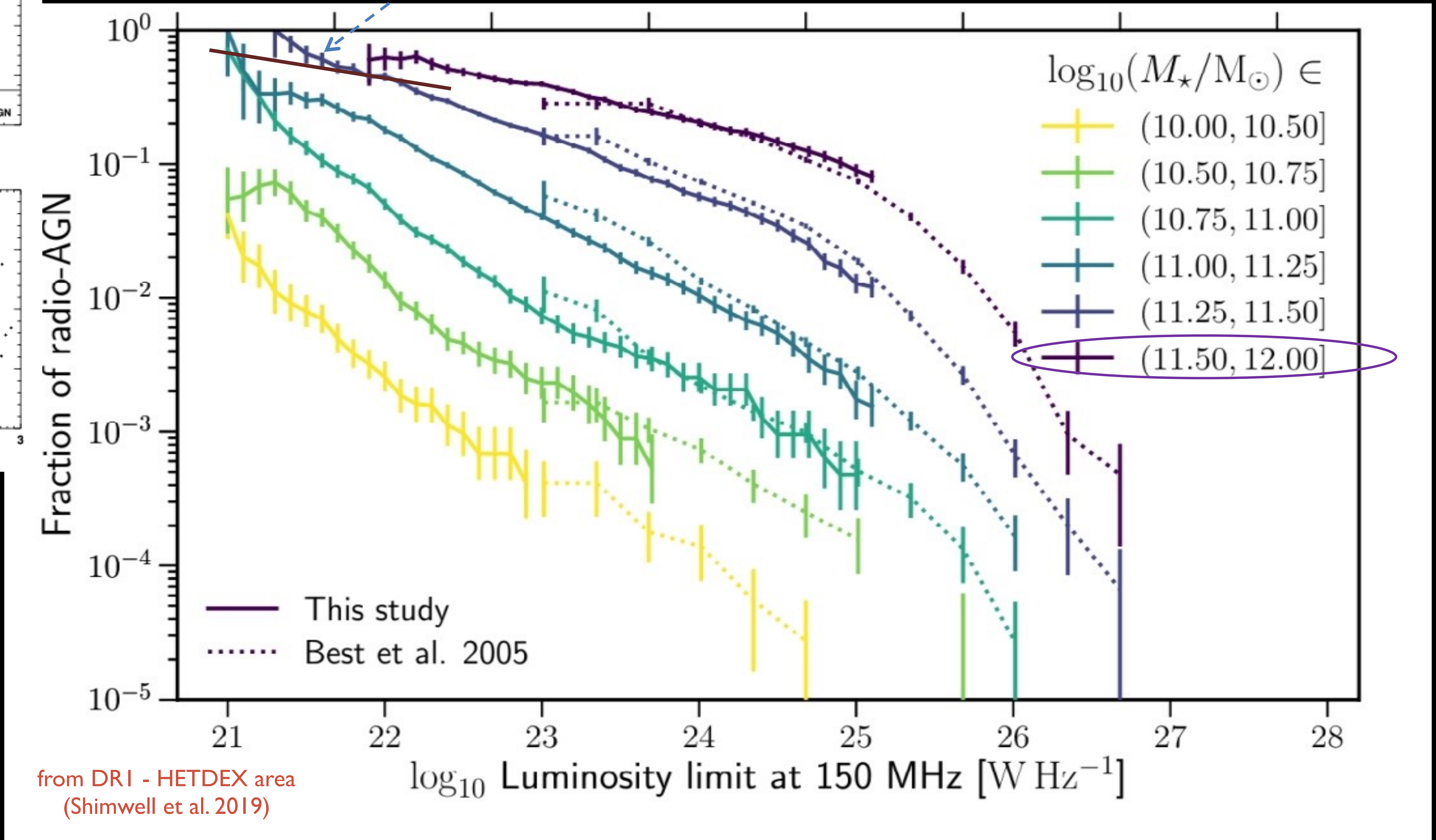
on-going effort to make this step more automatic
(Mostert et al. 2022)

Statistical studies of radio AGN with LOFAR (some highlights)

Determine the fraction of radio AGN

Sabater et al. 2019


J. Sabater et al.: The LoTSS view of radio AGN in the local Universe



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

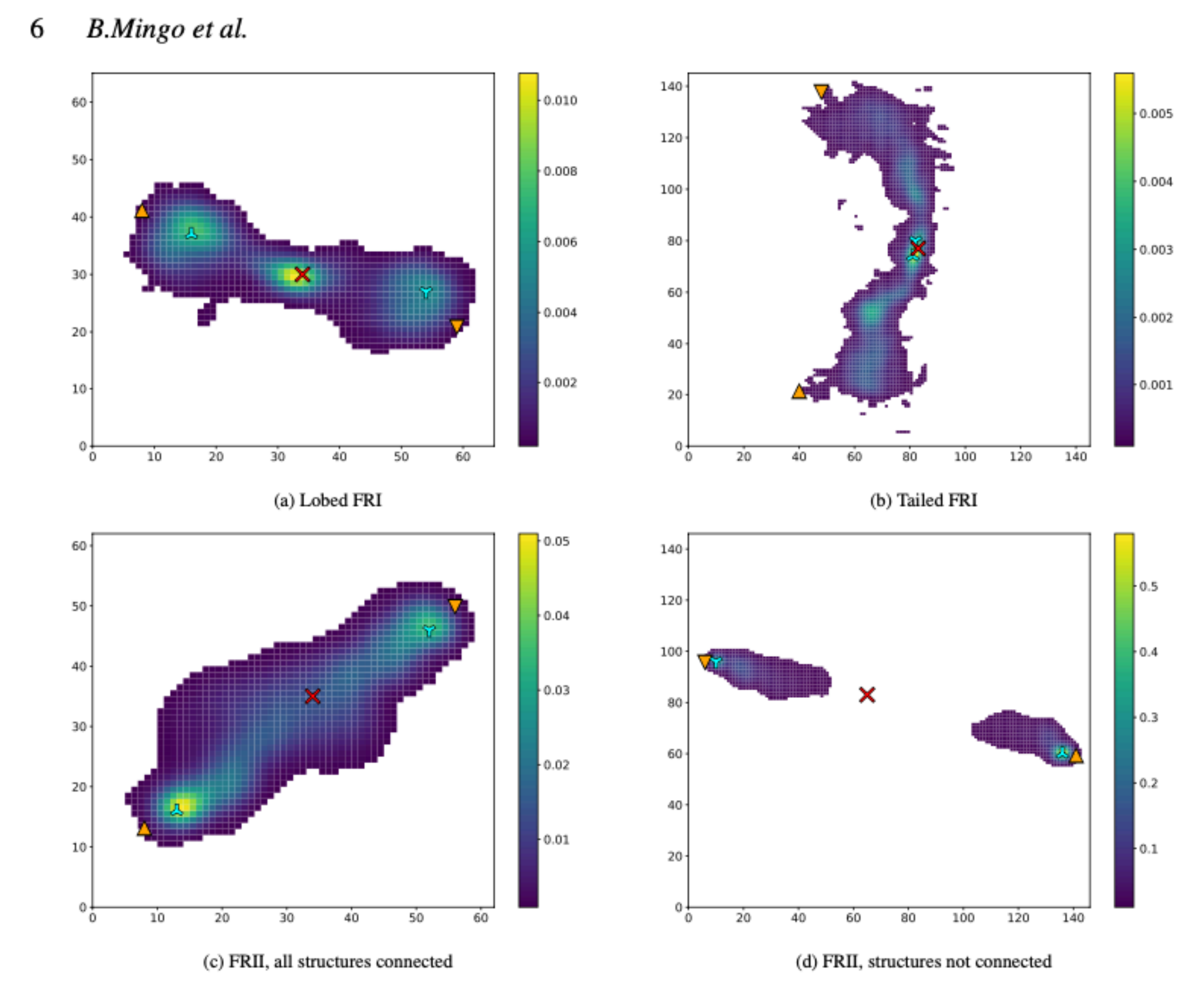
Sabater et al. 2019: **separation AGN and SF down to low radio power.**
Derived the luminosity function of radio AGN - dependence on stellar mass - fraction changing with radio power.
At low power almost every massive galaxy has an AGN: always on?

… but for some different findings see Capetti et al. 2022

FRI/II separation - using automatic tools for the classification

Mingo et al. 2019 develop an automatic way - **LoMorph morphology code -** to classification of FRI and II and they revisit this canonical relationship with a sample of 5805 extended radio-loud AGN from the LOFAR Two-Metre Sky Survey (LoTSS), compiling the most complete dataset of radio-galaxy morphological information obtained to date.

Adopted the traditional definition of FR class (Fanaroff & Riley 1974): if the brightest region is closer to the core (host) than the midpoint of the source on a given side, then it is an FRI; if the brightest region is more distant than the midpoint then it is an FRII.



6 *B.Mingo et al.*

(a) Lobed FRI

(b) Tailed FRI

(c) FRII, all structures connected

(d) FRII, structures not connected

FRI/II separation

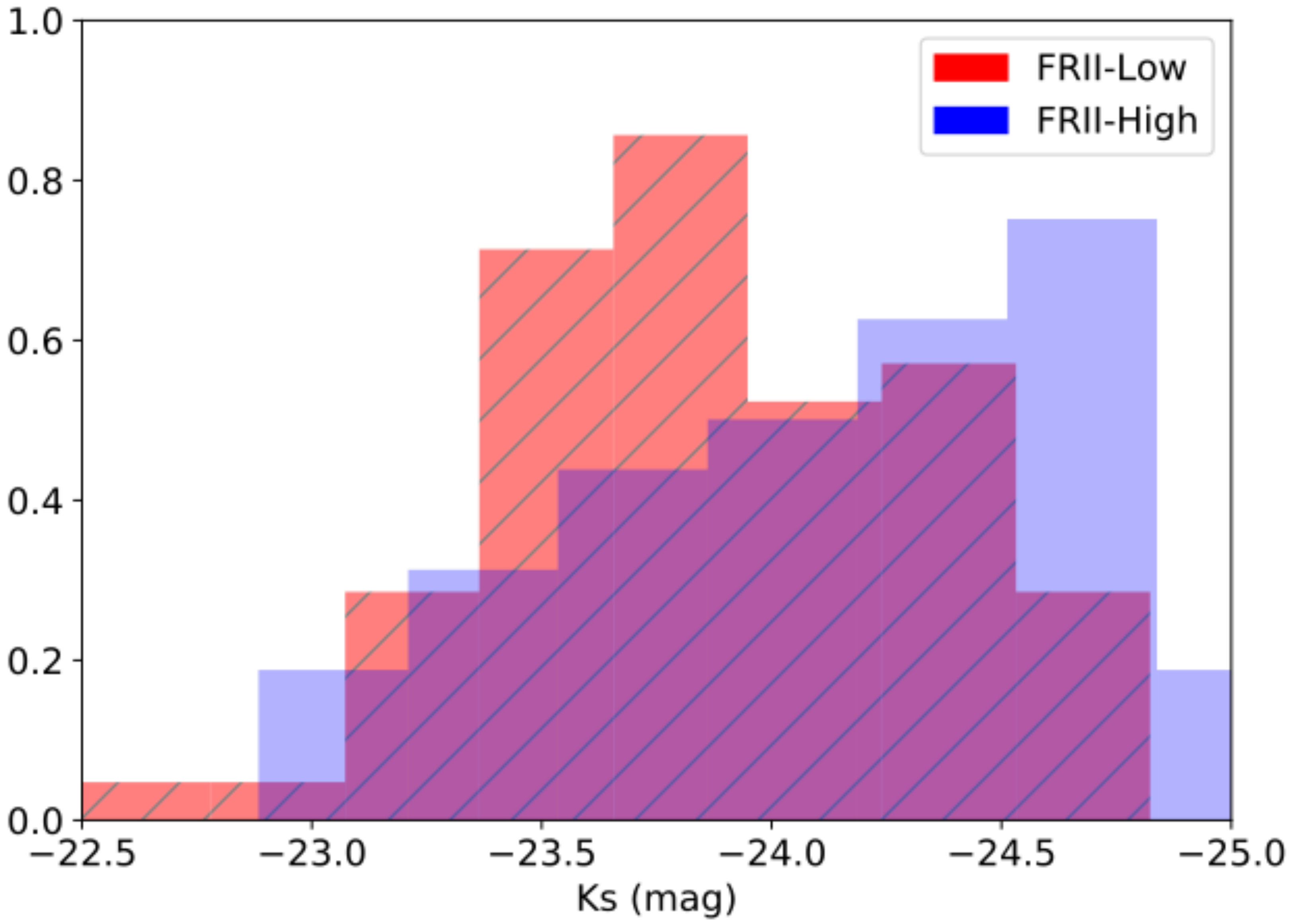
Mingo+ 2019, MNRAS 488 2701

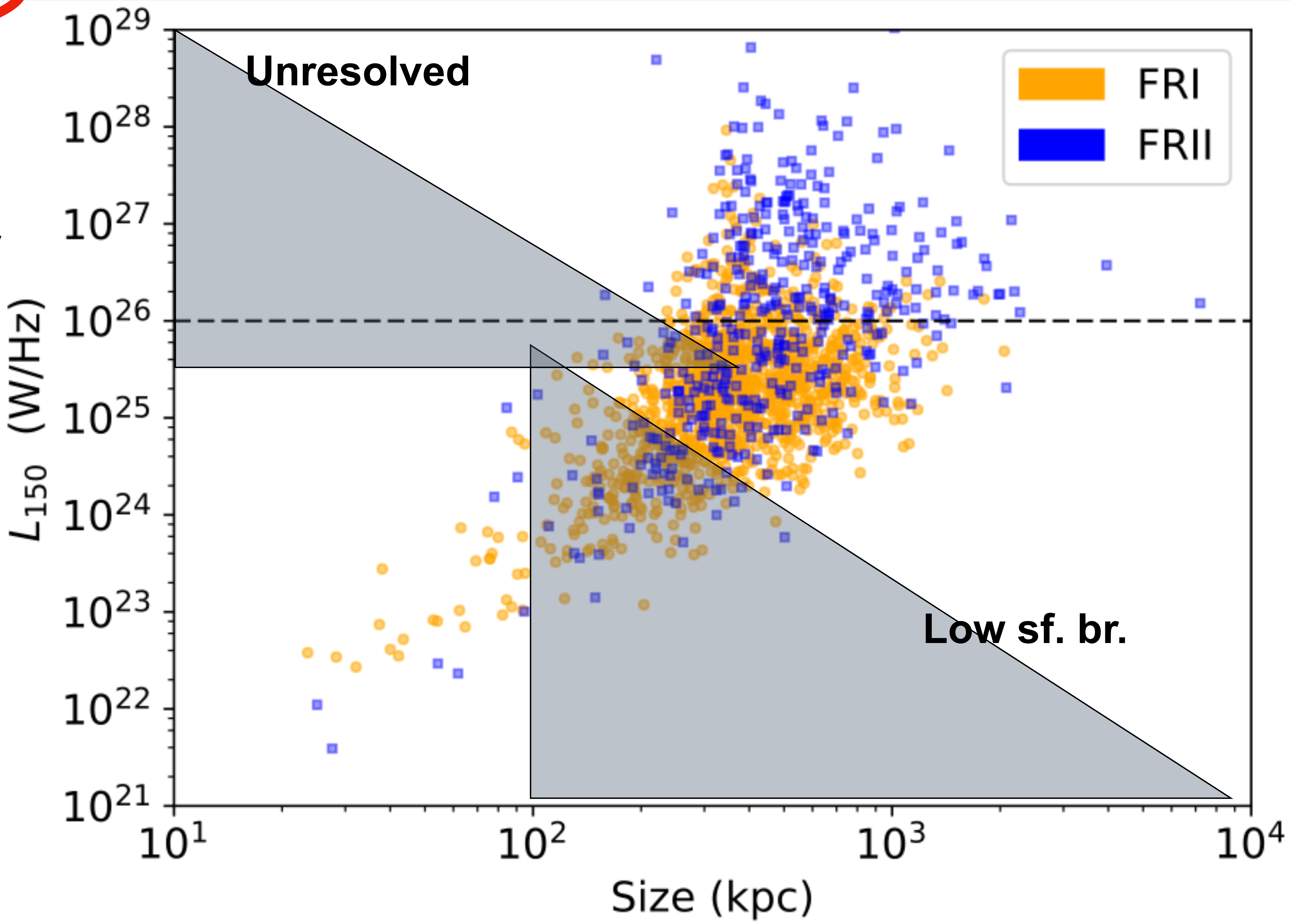
Conclusion: We can no longer rely on just morphology to extrapolate jet power, accretion mode.
A large population of low-luminosity FRIIs exists extending three orders of magnitude below the traditional FR break

New population of low-luminosity ($L_{150}<10^{25}$ W/Hz) FRII

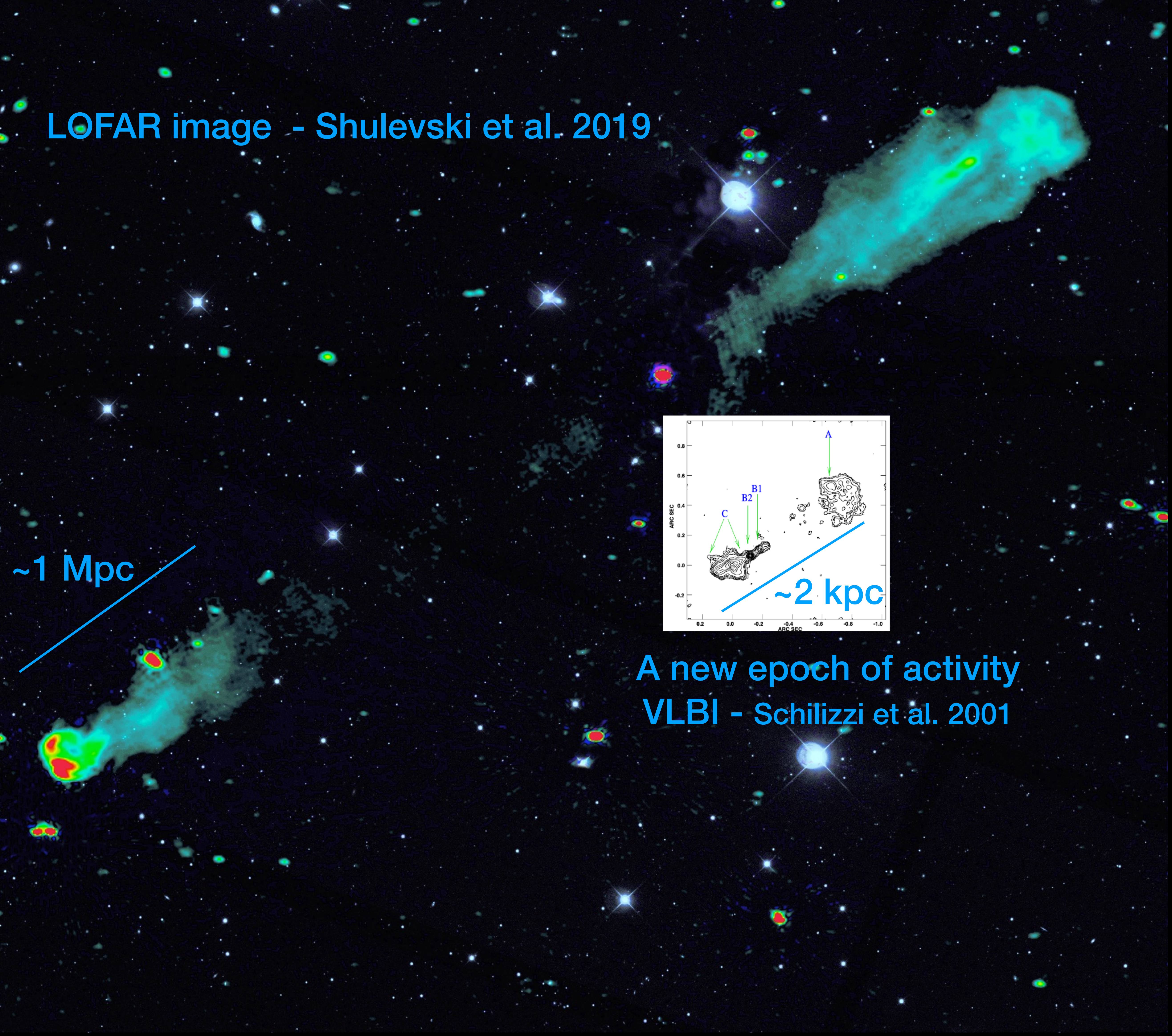
50% of LOFAR FRII below the traditional FRI/II Lum divide

- Possible reasons:
  - **lower mass hosts**
  - Some are old/fading
  - Environments play a role in shaping radio AGN morphology





Extreme radio AGN: Giant radio galaxies


LOFAR image - Shulevski et al. 2019

~1 Mpc

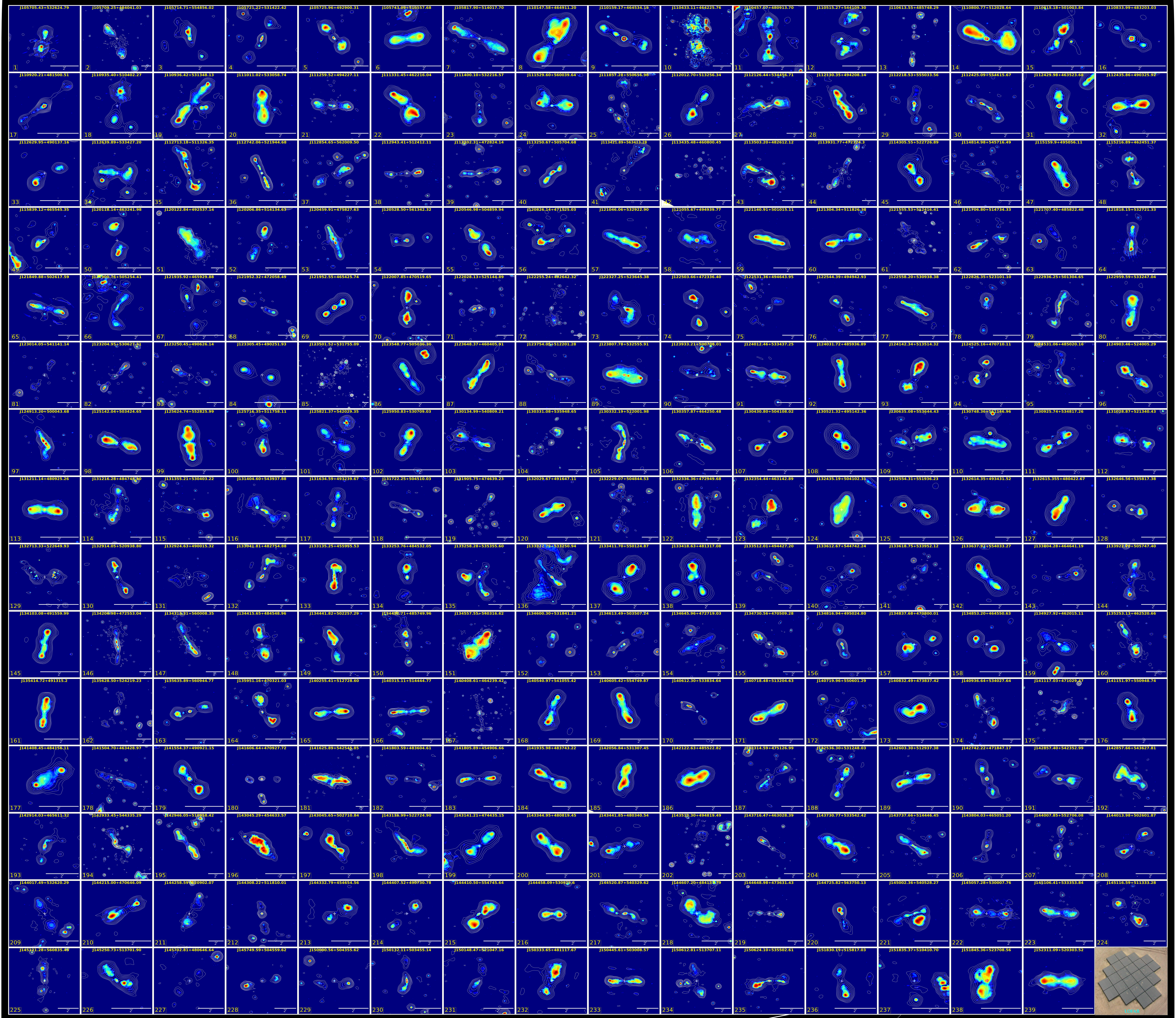
~2 kpc

A new epoch of activity
VLBI - Schilizzi et al. 2001

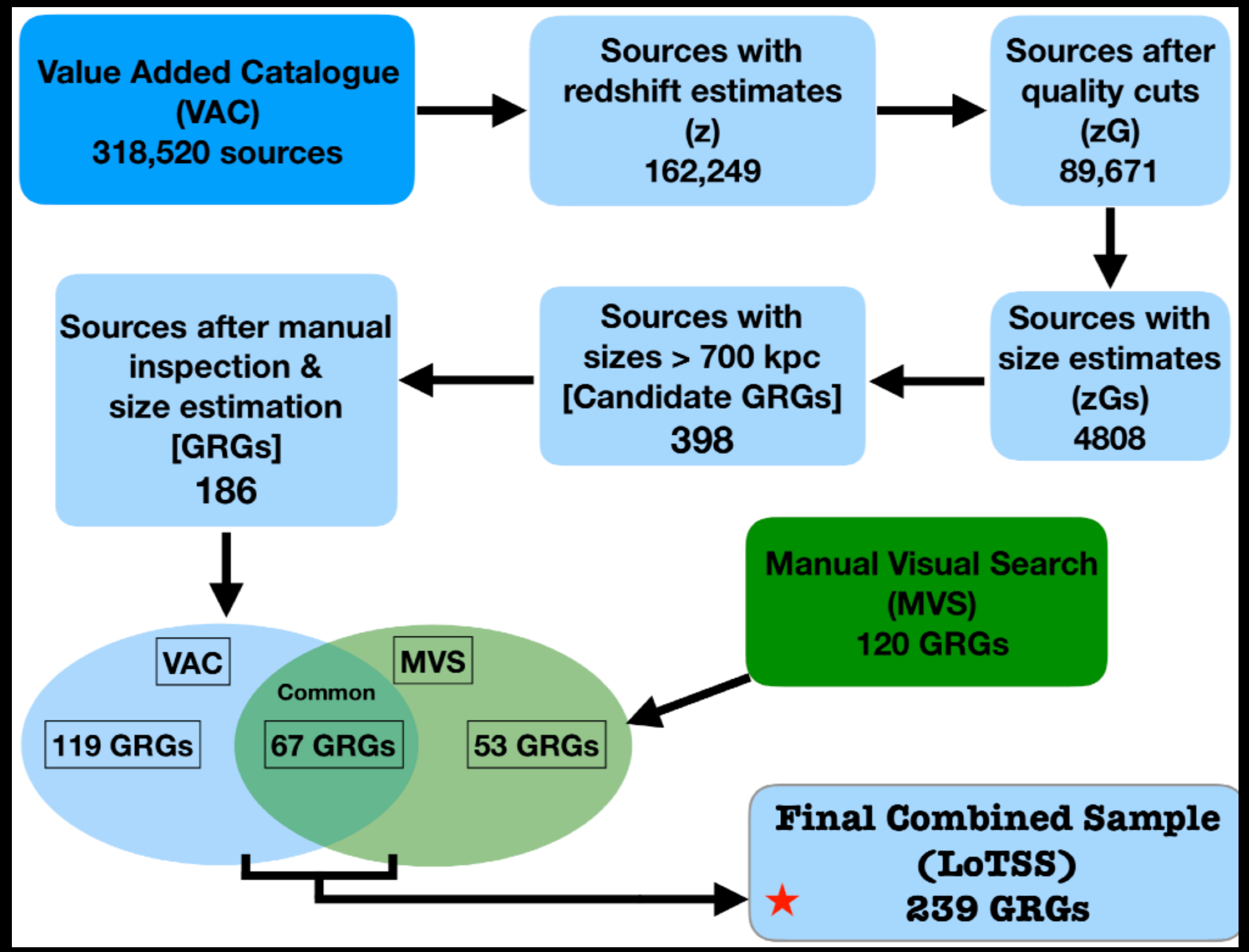
Alcyoneus (giant in the Greek mythology!): the largest known structure made by a single galaxy about 5Mpc

Oei et al. 2022

LARGE SAMPLE OF GIANT RADIO GALAXIES DISCOVERED BY LOFAR



Giant radio galaxies (GRGs) are a subclass of radio galaxies which have grown to megaparsec scales. Shown here are 239 GRGs (of which 226 are new discoveries, Dabhade et al. 2019) with sizes larger than 0.7 Mpc from the 150 MHz LOFAR Two-metre Sky Survey (LoTSS) first data release images that cover a 424 deg^2 (Shimwell et al. 2018)



Value Added Catalogue (VAC) 318,520 sources

Sources with redshift estimates (z) 162,249

Sources after quality cuts (zG) 89,671

Sources with size estimates (zGs) 4808

Sources with sizes > 700 kpc [Candidate GRGs] 398

Sources after manual inspection & size estimation [GRGs] 186

Manual Visual Search (MVS) 120 GRGs

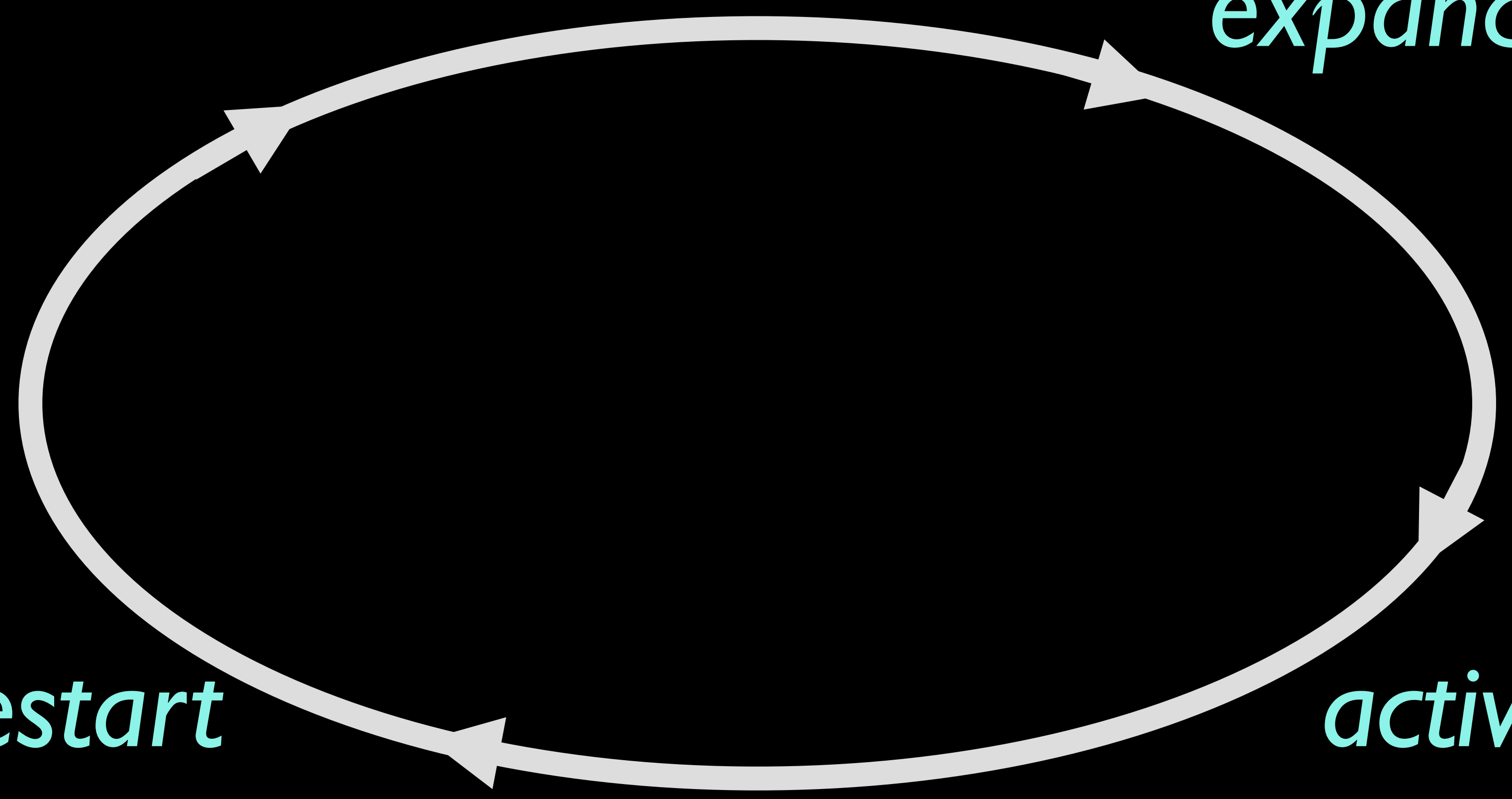
Final Combined Sample (LoTSS) 239 GRGs

Dabhade et al. A&A 2019

Of the 239 GRGs found, 225 are new discoveries. The GRGs in our sample have sizes ranging from 0.7 to 3.5 Mpc and have redshifts (z) between 0.1 and 2.3. The sample contains 40 GRGs hosted by spectroscopically confirmed quasars.

The spectral index of GRGs is similar to that of normal sized radio galaxies, indicating that most of the GRG population is not dead or is not like remnant type radio galaxy. We find 20/239 GRGs in our sample are located at the centres of clusters and present our analysis on their cluster environment and radio morphology.

The evolution and life-cycle of radio sources



expanding adult source
10^7-10^8yr

new born jet
10^5-10^6yr

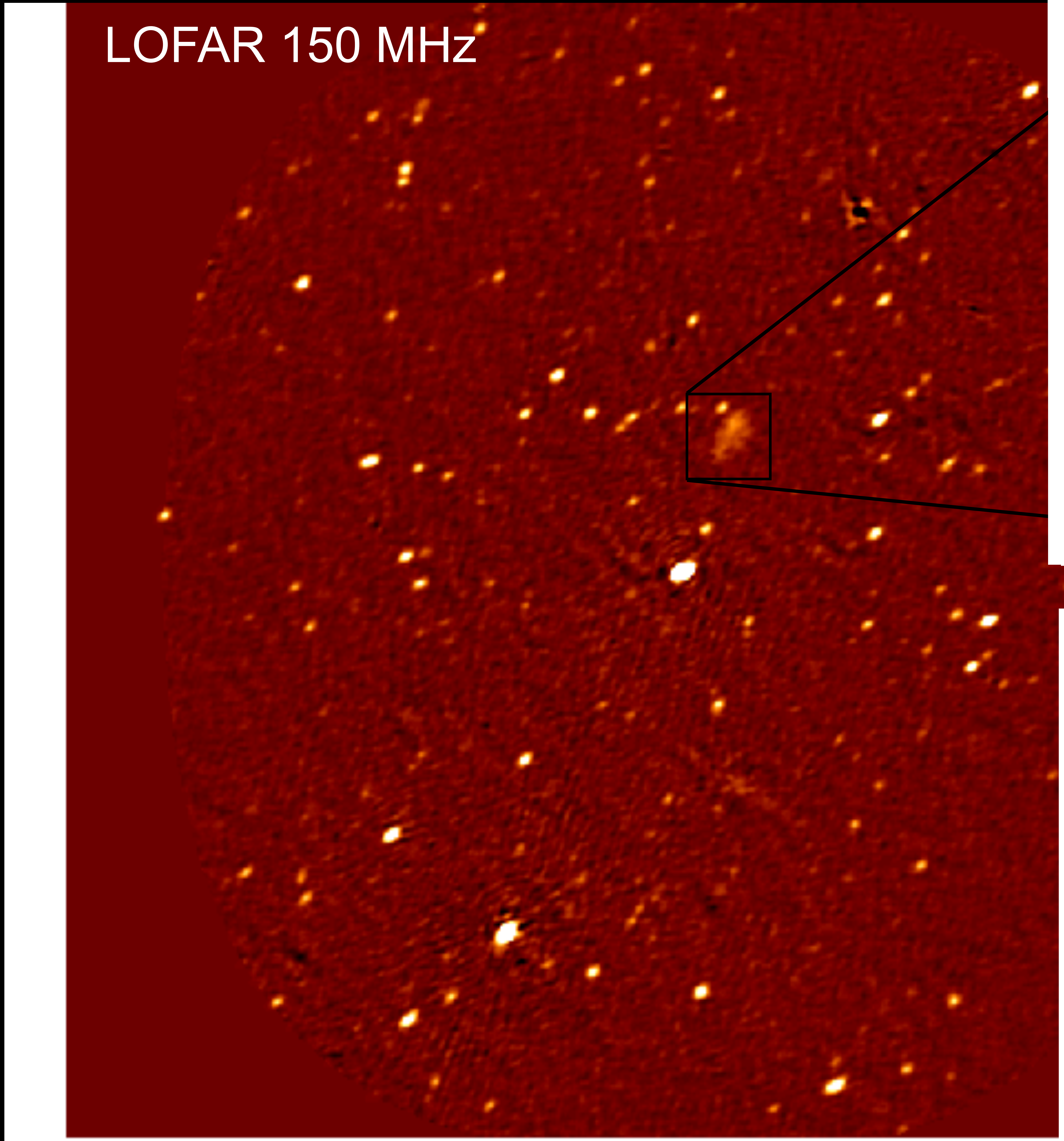
activity restart

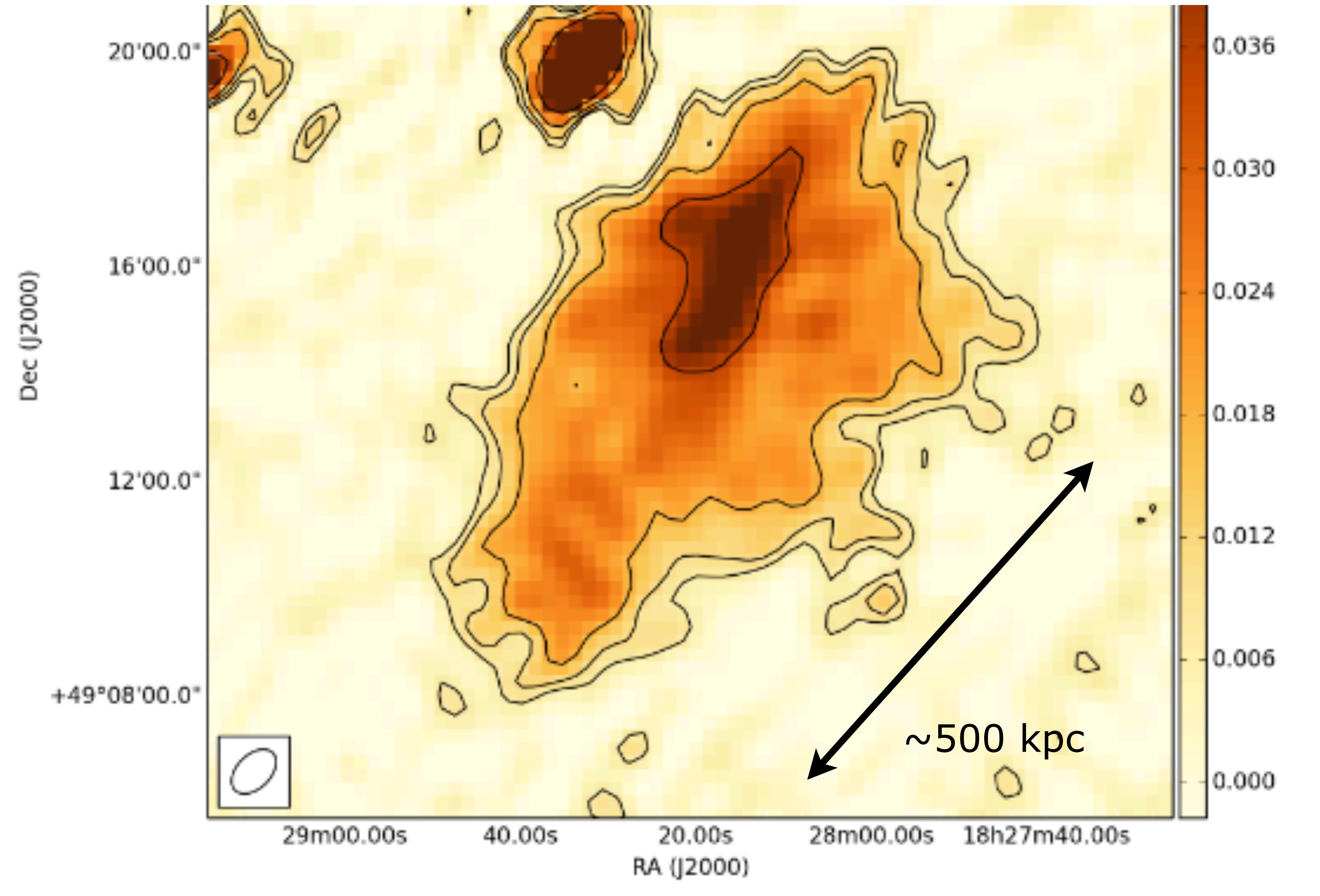
activity stops - remnant

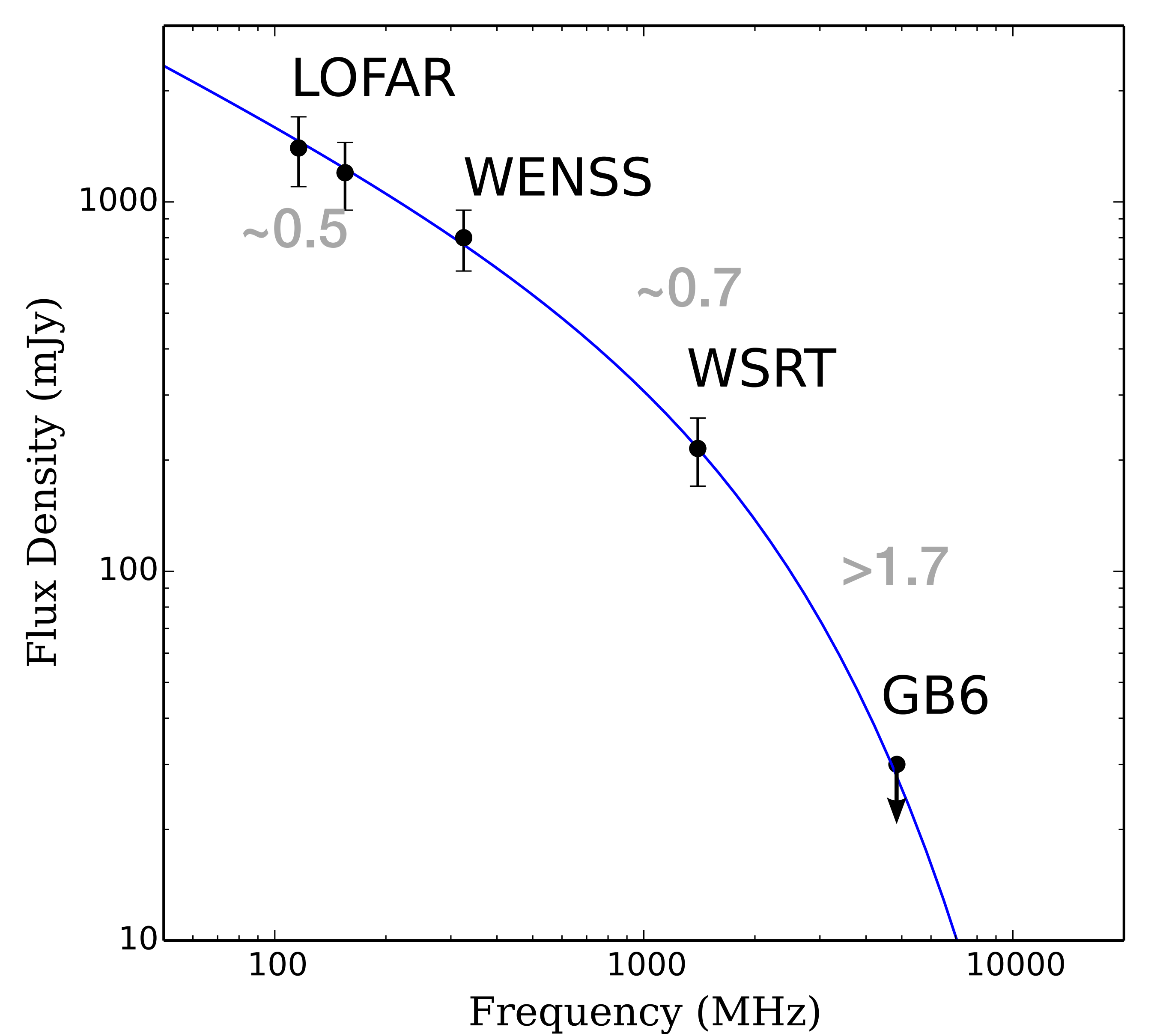
remnant and restarted radio galaxies key for completing the life cycle:
so far mostly selected using one criterium: ultra-steep spectrum for remnants
and double-double sources for restarted …

more possibilities offered by the LOFAR data
(e.g. morphology, presence of bright cores etc.)

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



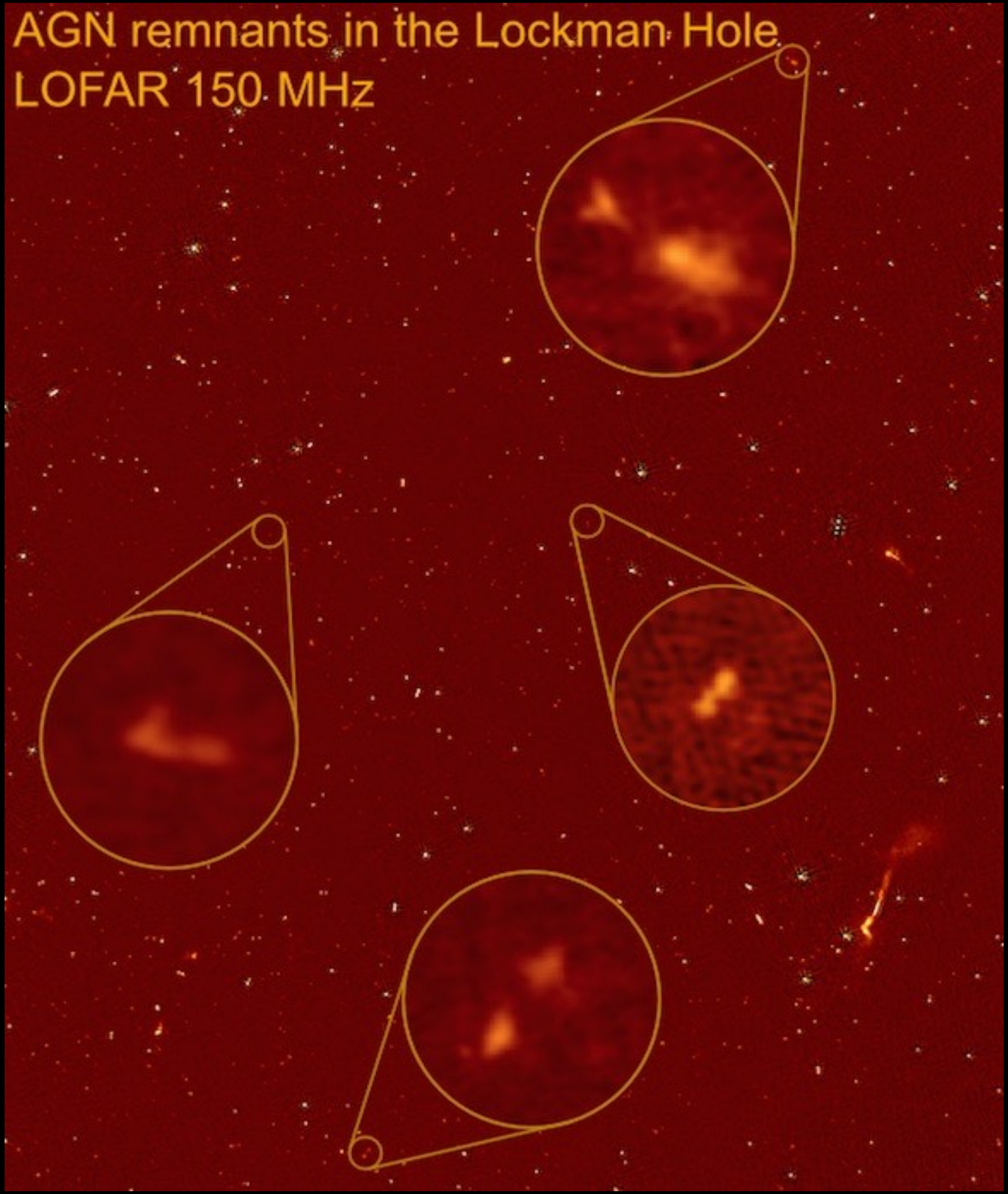




diffuse, low surface brightness emission

Brienza et al. 2015

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



Made possible by LOFAR:
Select remnant radio galaxies
using various criteria

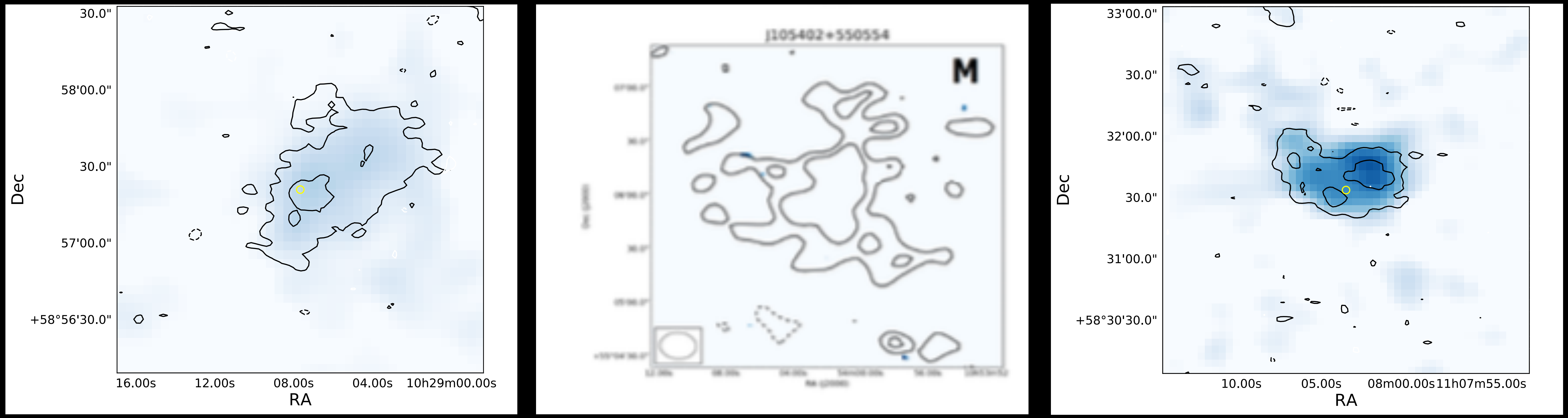
morphology - diffuse
very weak/absent core
ultra steep spectrum

Brienza et al. 2017

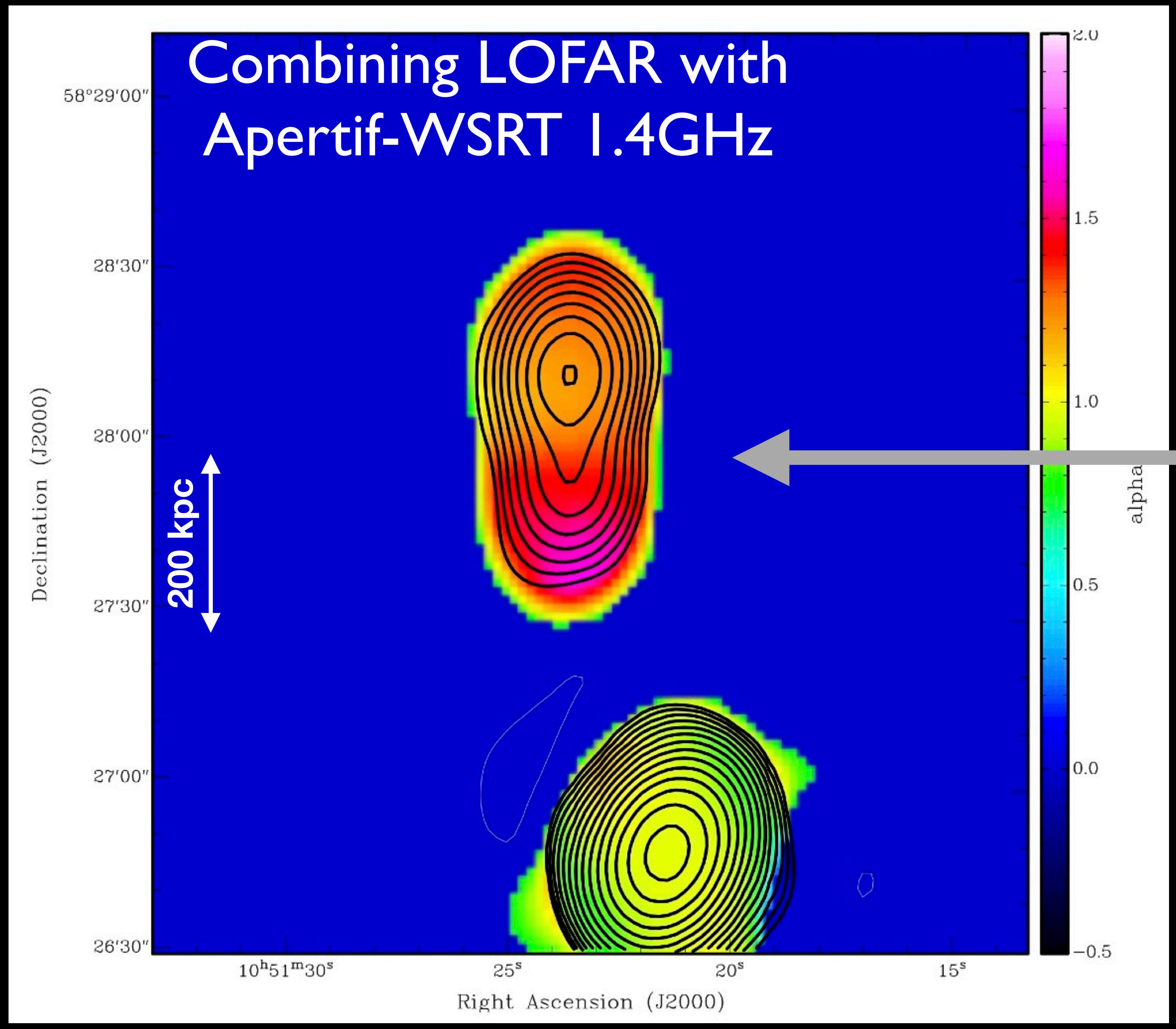
Looking for remnant sources: selection using a variety of properties

Brienza et al. 2017
Jurlin et al. 2020

LOFAR 150 MHz - 18 arcsec



Selection based on morphology
Amorphous, low surface brightness
(10 - 30 mJy arcmin^{-2} @150MHz)
low core prominence



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

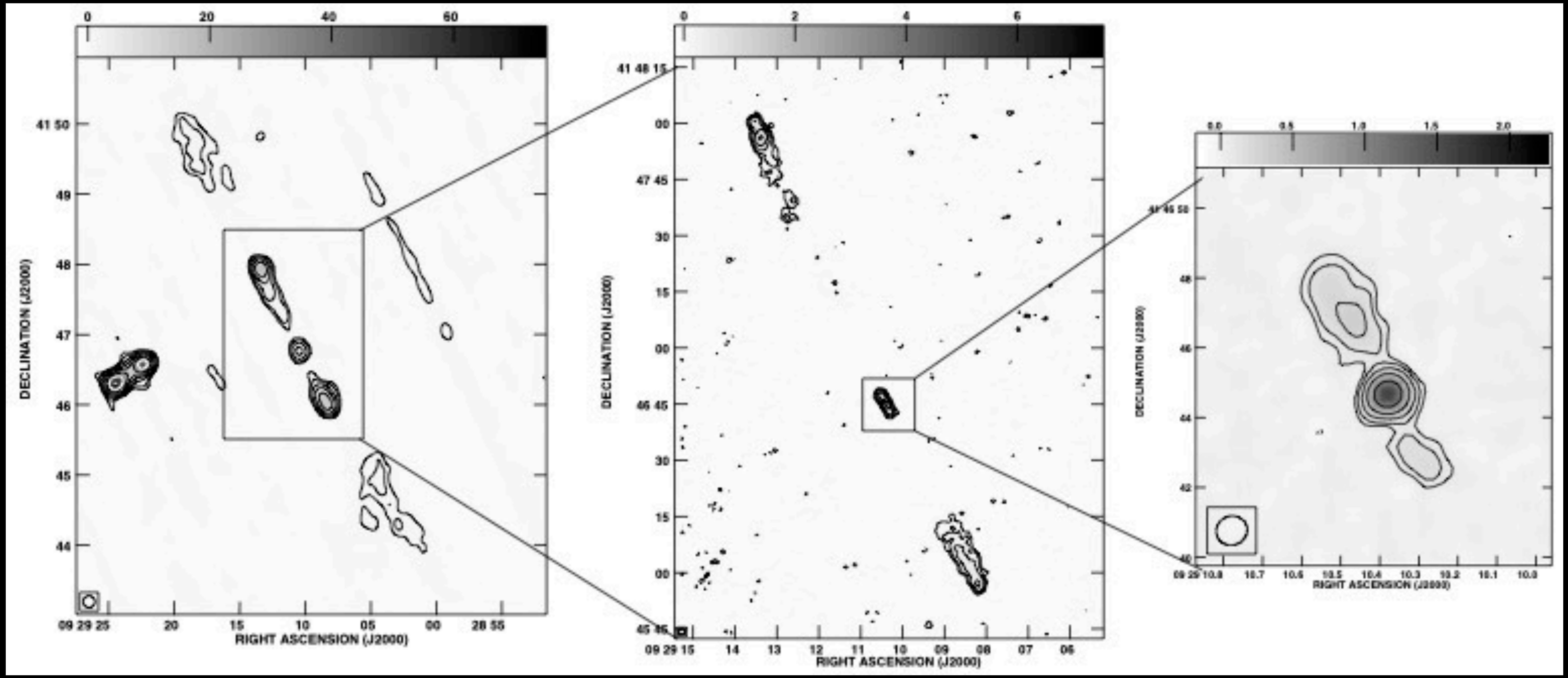
Up to 9% of radio sources are remnants
about 4% are ultra-steep spectrum

Ages up to 160 - 300 Myr
Freq break between 600 and 150 MHz, B_{eq} = 3 microG

The best known restarted radio AGN: double-double radio galaxies

These galaxies display large-scale (many hundred kpc to Mpc) remnant radio plasma in the intergalactic medium left behind by a past episode of active galactic nuclei (AGN) activity, and meanwhile, the radio jets have restarted in a new episode, that can be identified by two pairs of radio lobes

In many cases, extreme stable axis of the ejecta.



Brocksopp et al. 2007

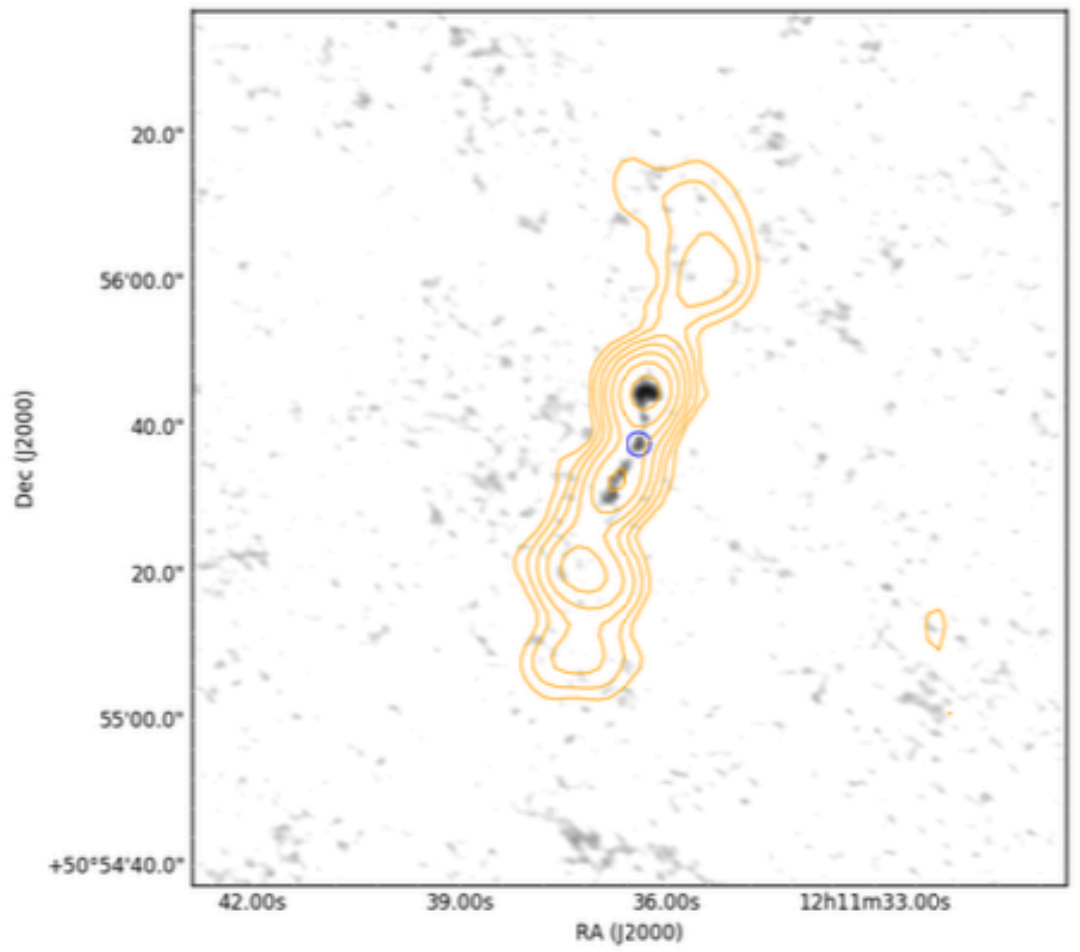
Radio galaxy B0925+420, showing three phases of activity. The images, obtained using the Very Large Array, show three pairs of lobes. The age of the outer lobes was derived to be 25–270 Myr, while that of the inner lobes is 0.4–2 Myr. The supply of energy for the outer lobes ceased 4–70 Myr ago, while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

The best known restarted radio AGN: double-double radio galaxies

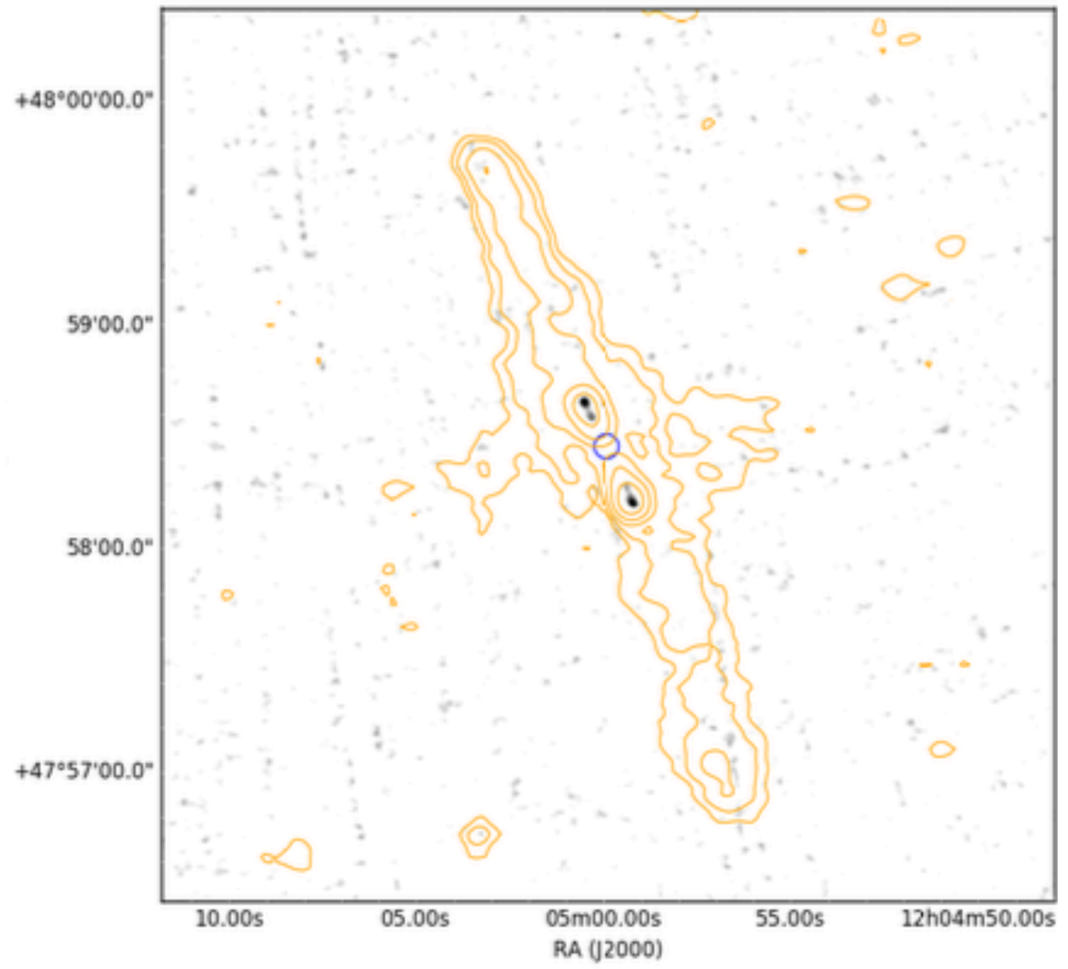
Double-double RG with LOFAR
Mahatma et al. 2019

These galaxies display large-scale (many hundred kpc to Mpc) remnant radio plasma in the intergalactic medium left behind by a past episode of active galactic nuclei (AGN) activity, and meanwhile, the radio jets have restarted in a new episode, that can be identified by two pairs of radio lobes

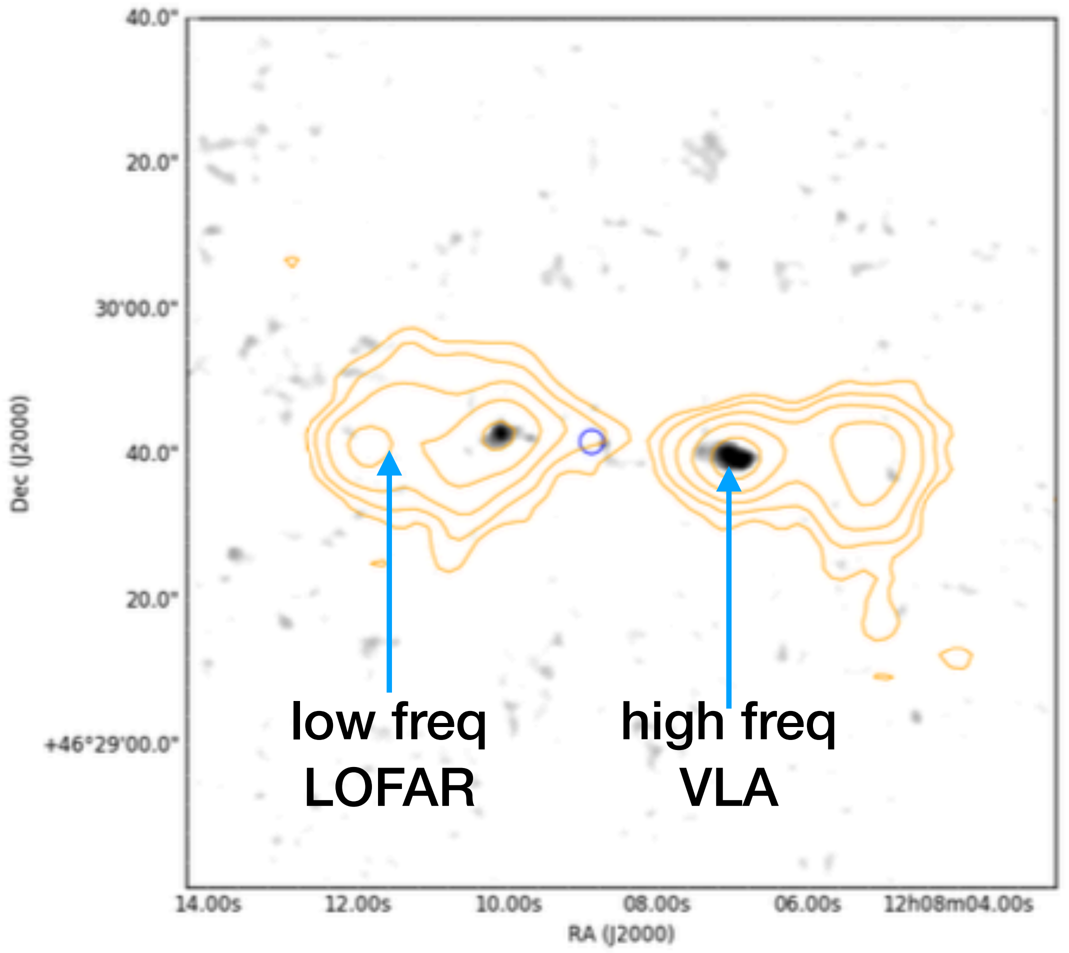
In many cases, extreme stable axis of the ejecta.



A.1. 13 ILTJ121136.54+505537.5
ROBUST: 0.5



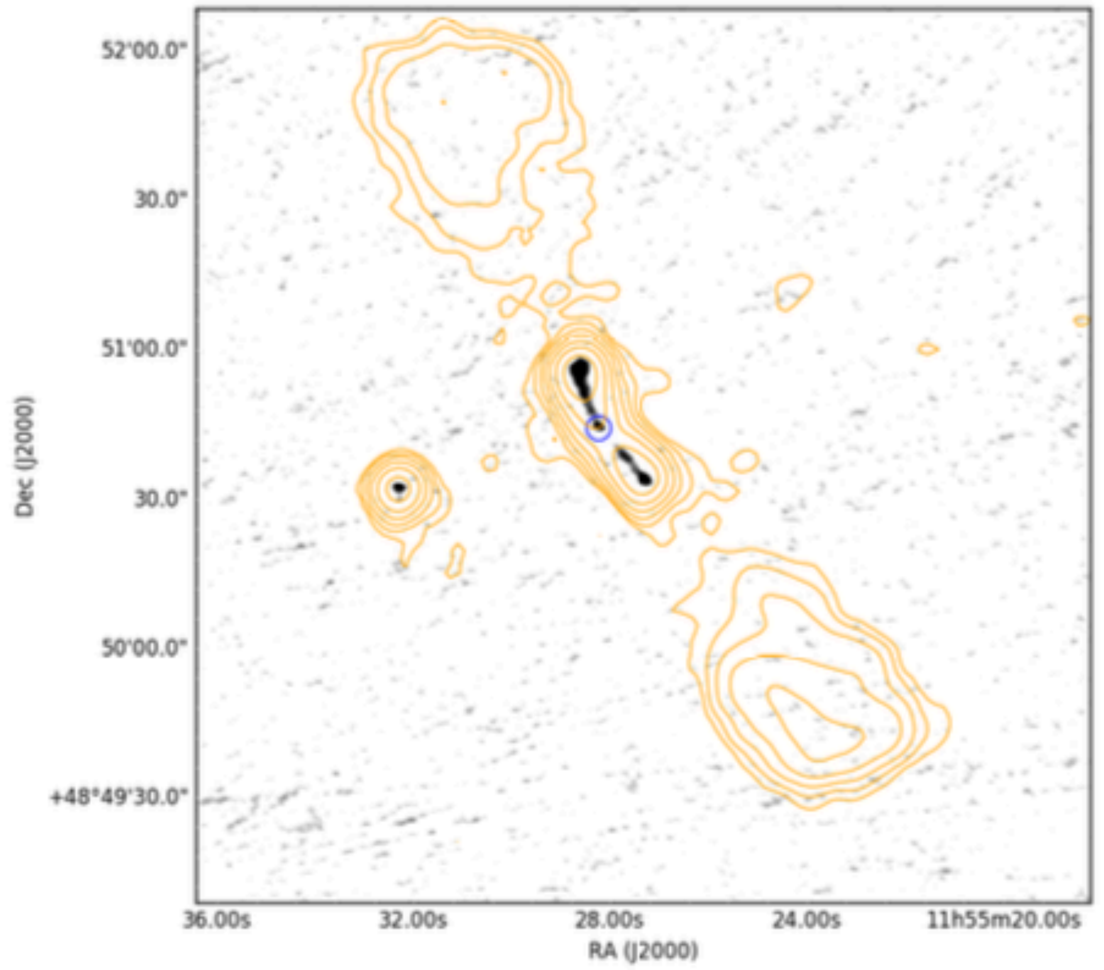
A.1. 11 ILTJ120459.87+475825.4†
ROBUST: -0.5



low freq
LOFAR

high freq
VLA

A.1. 12 ILTJ120808.48+462940.6
ROBUST: 0.5

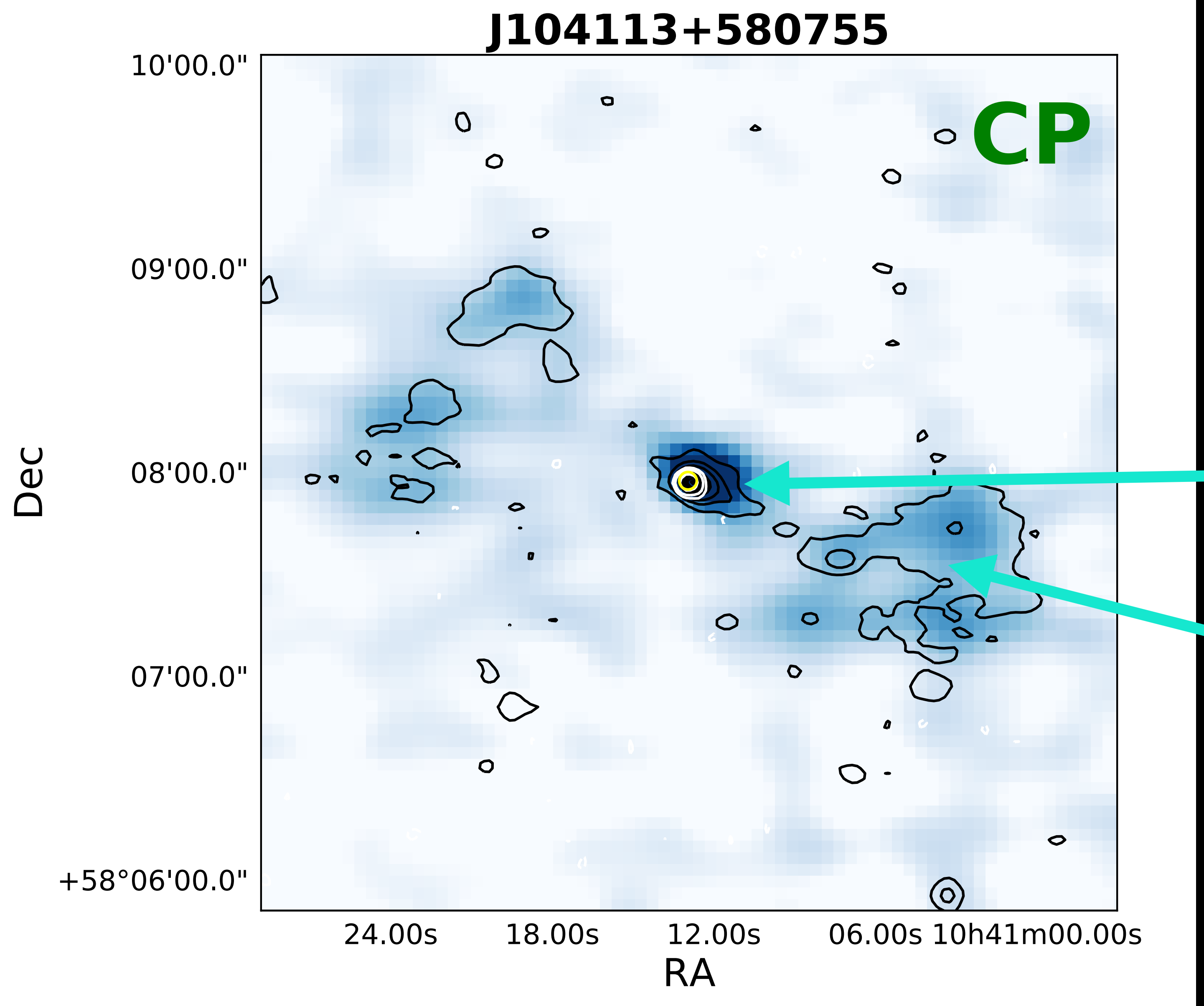


A.1. 10 ILTJ115527.32+485039.0
ROBUST: -0.5

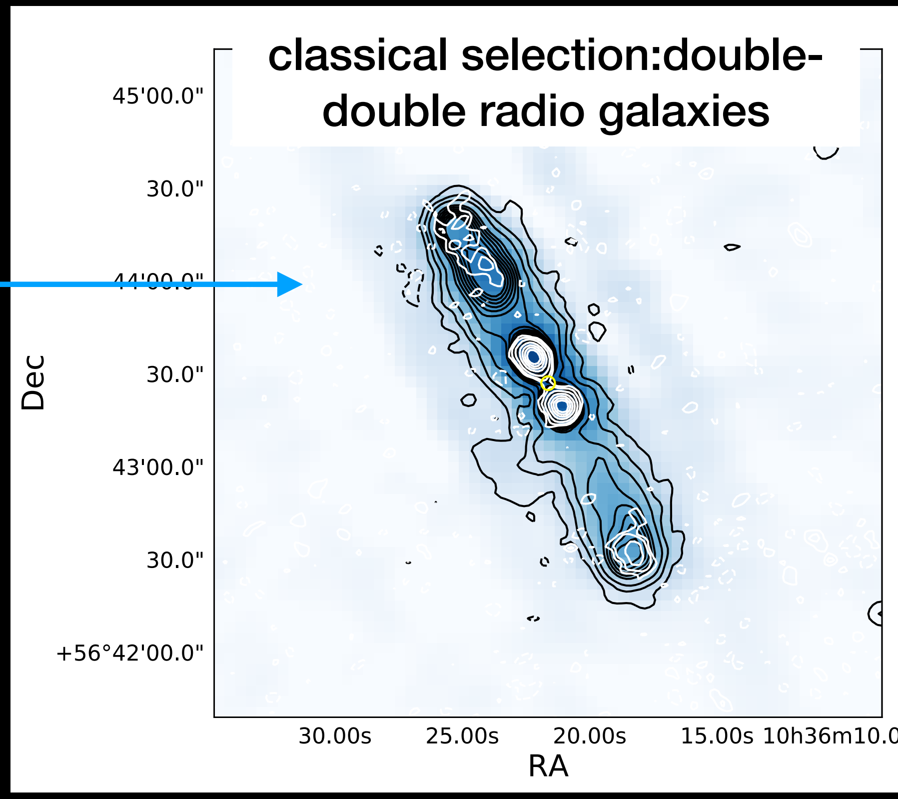
relatively rare objects

Looking for candidate restarted sources: a variety of criteria to select them

Jurlin et al. 2020



Visual inspection (e.g. double-double)

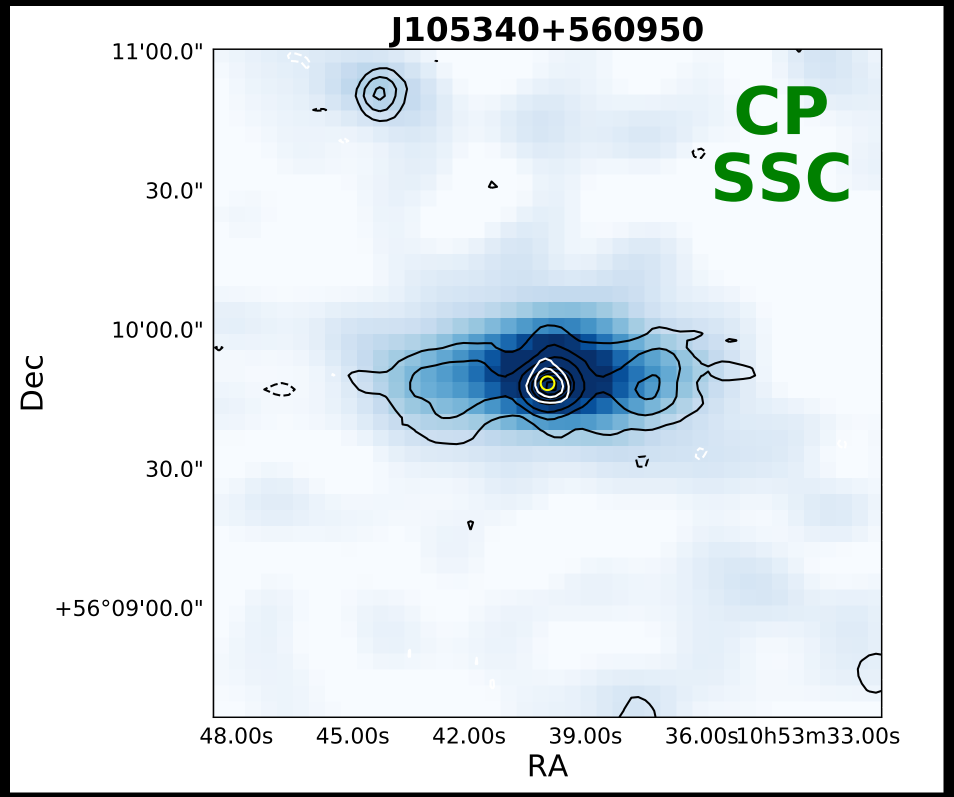


steep spectrum core

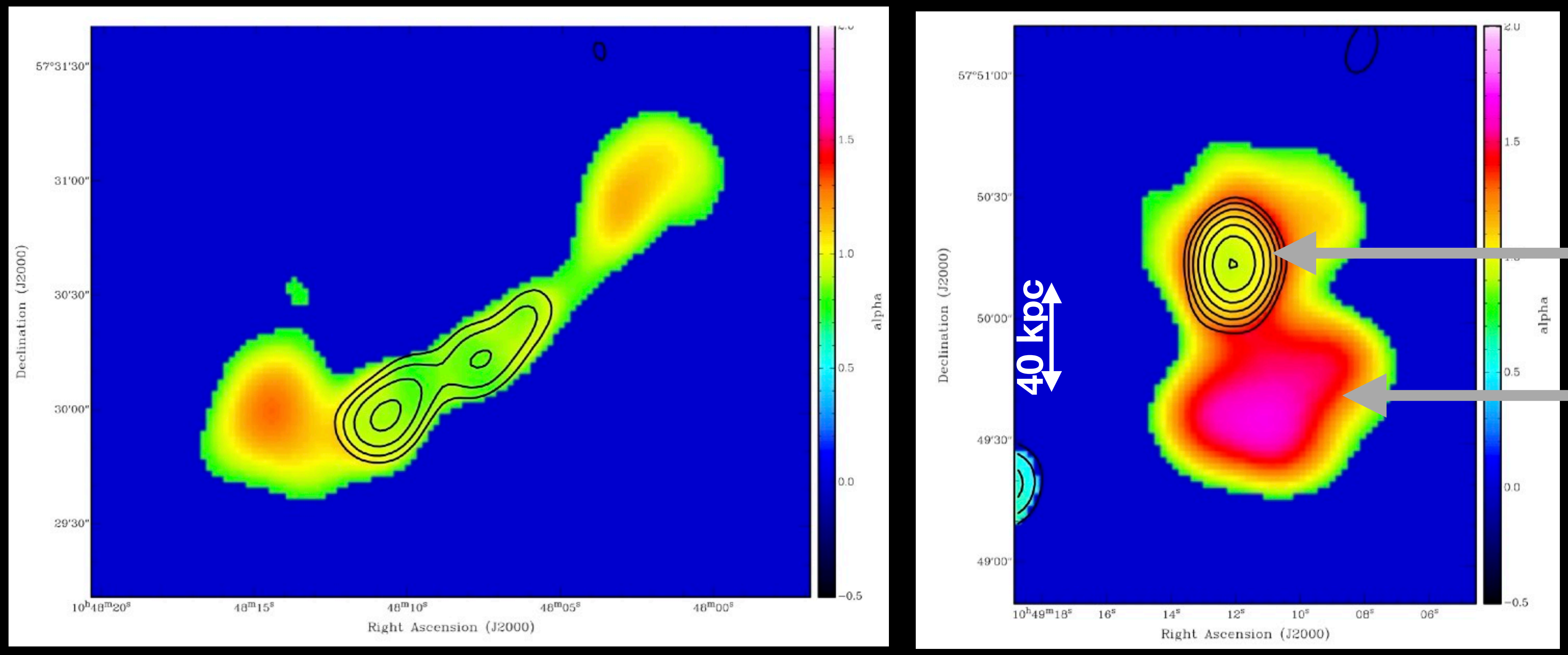
core relatively bright (CP>0.2)

low surface brightness extended emission

(comparable to remnants)



Extended sources with partly USS emission: restarted



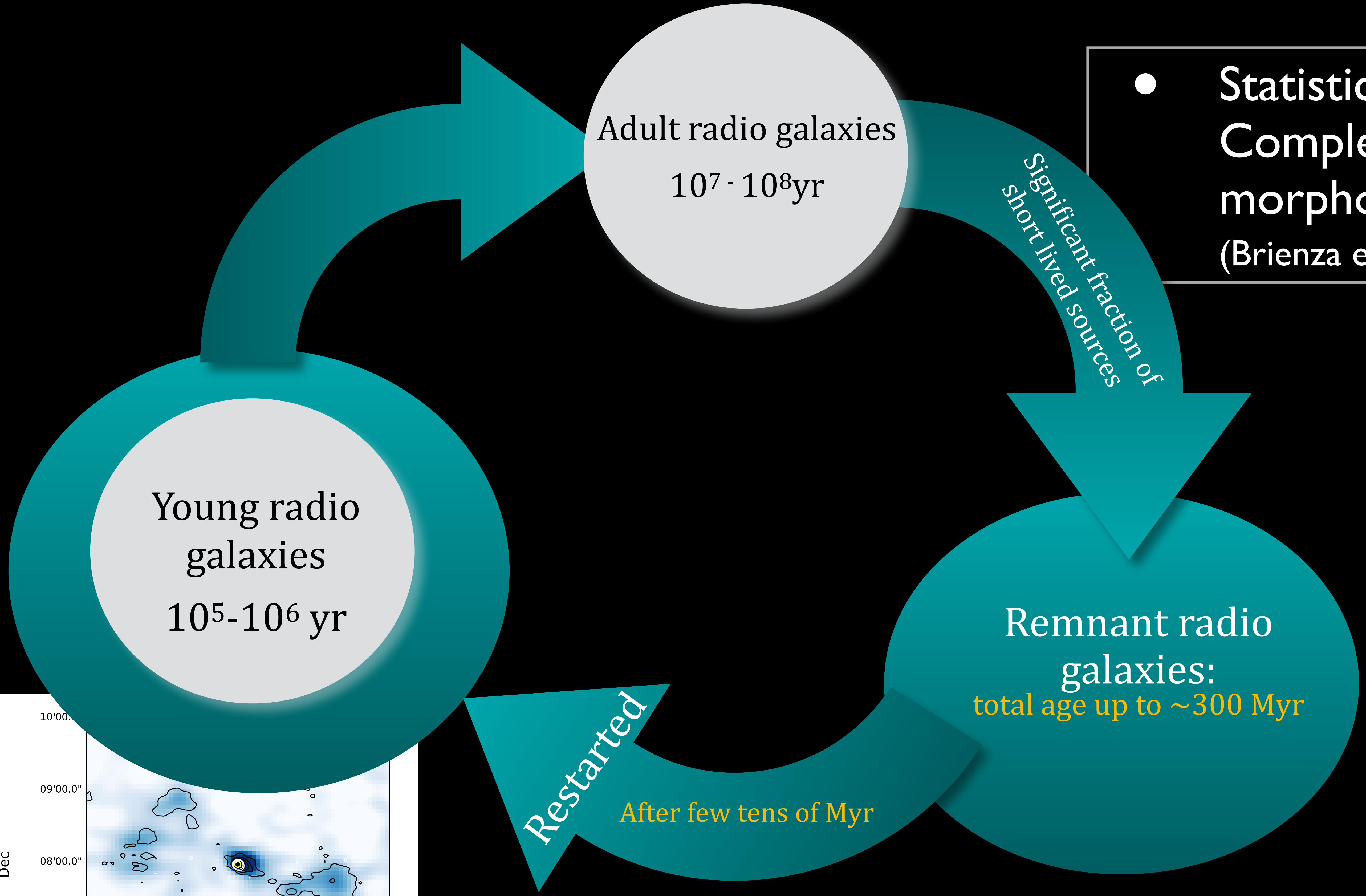
Standard SI ~0.8

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

combining LOFAR and Apertif

Up to 15% are candidate restarted radio galaxies!

The life cycle of radio AGN in a nutshell



Adult radio galaxies

10^7 - 10^8yr

Significant fraction of short lived sources

Remnant radio galaxies:

total age up to ~300 Myr

Restarted

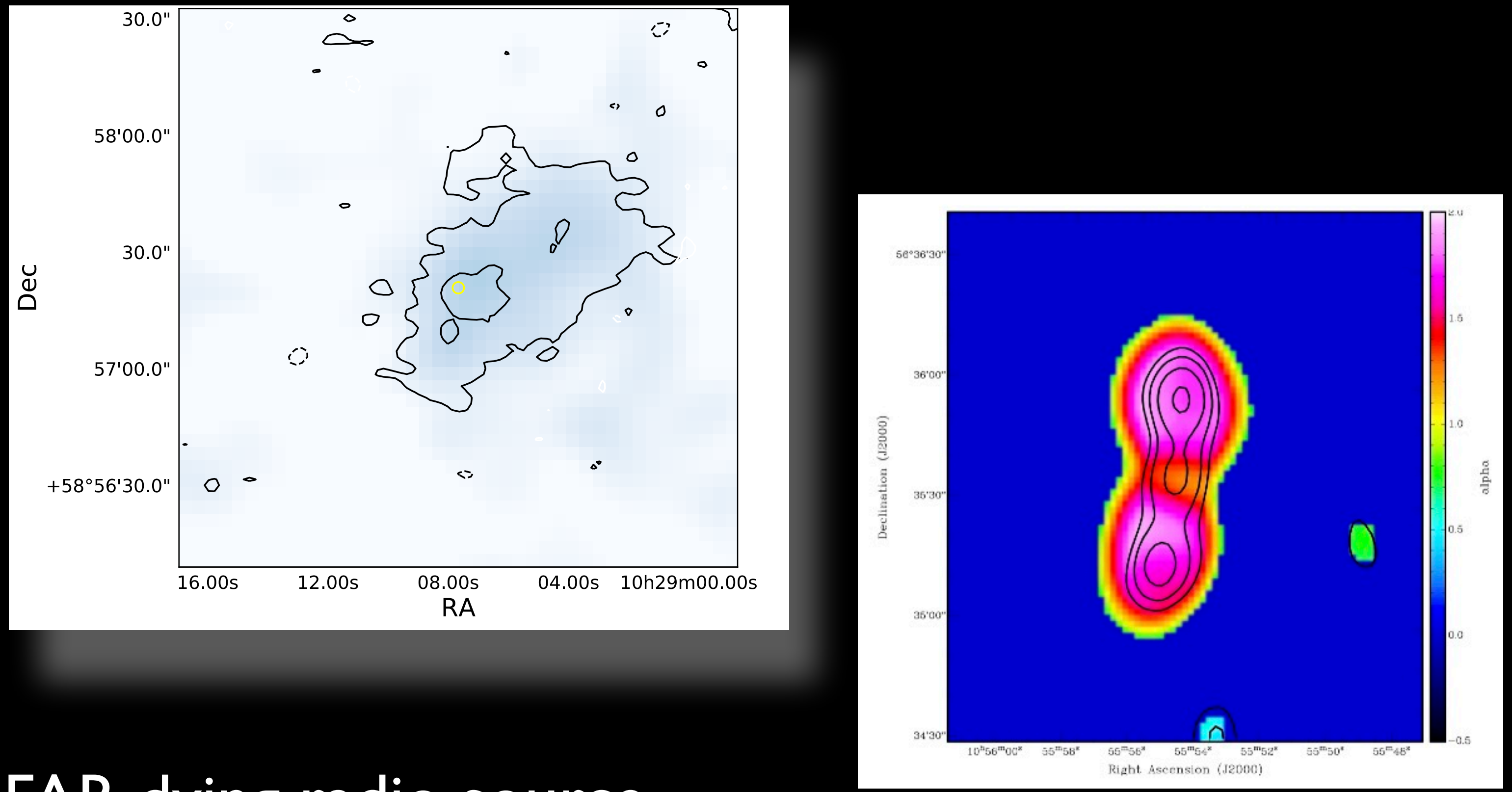
After few tens of Myr

Young radio galaxies

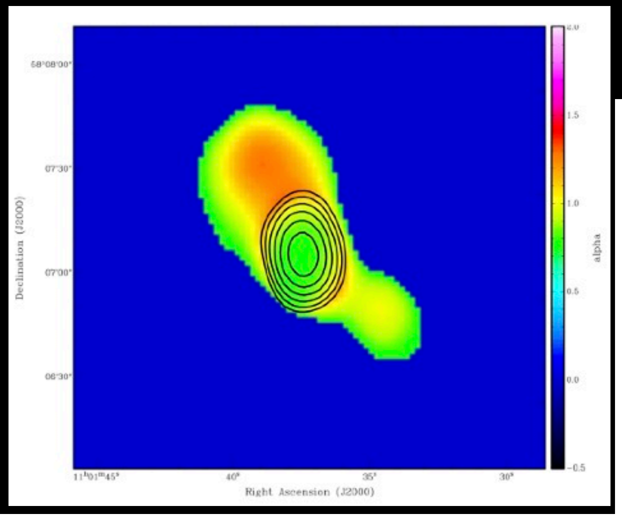
10^5-10^6 yr

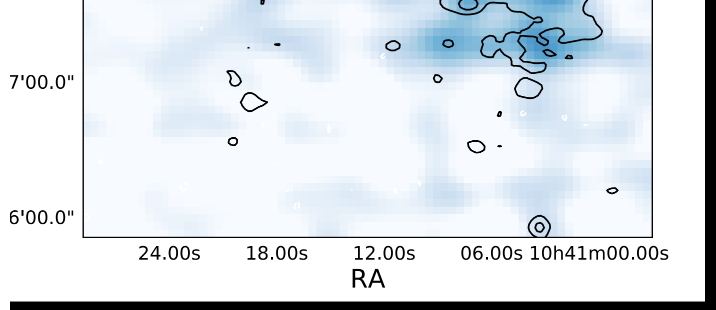
- Statistics of remnants (~9%) and restarted (<15%). Complementing search and statistics based on the morphology (Brienza et al. 2017, Jurlin et al. 2020, Jurlin et al. 2021)

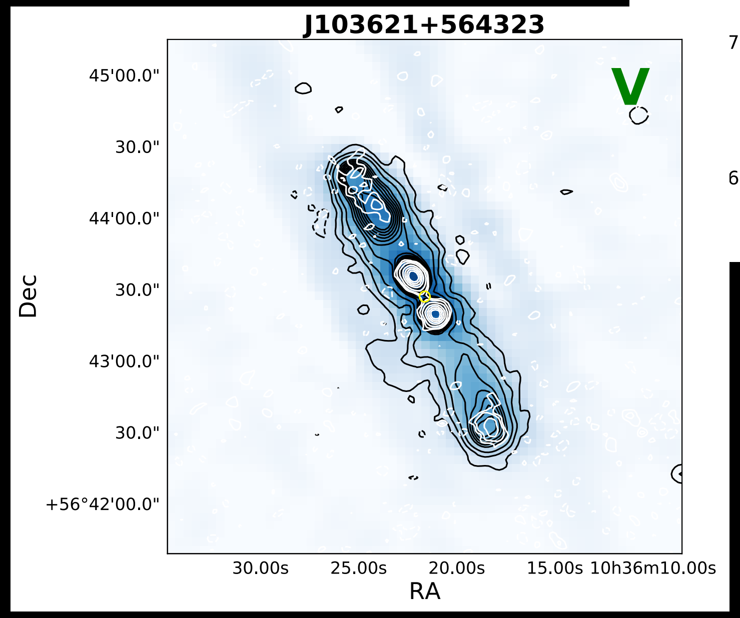
Morganti et al. 2020 A&A https://arxiv.org/abs/2011.08239



LOFAR dying radio source
Brienza et al. 2017, Jurlin et al. 2021





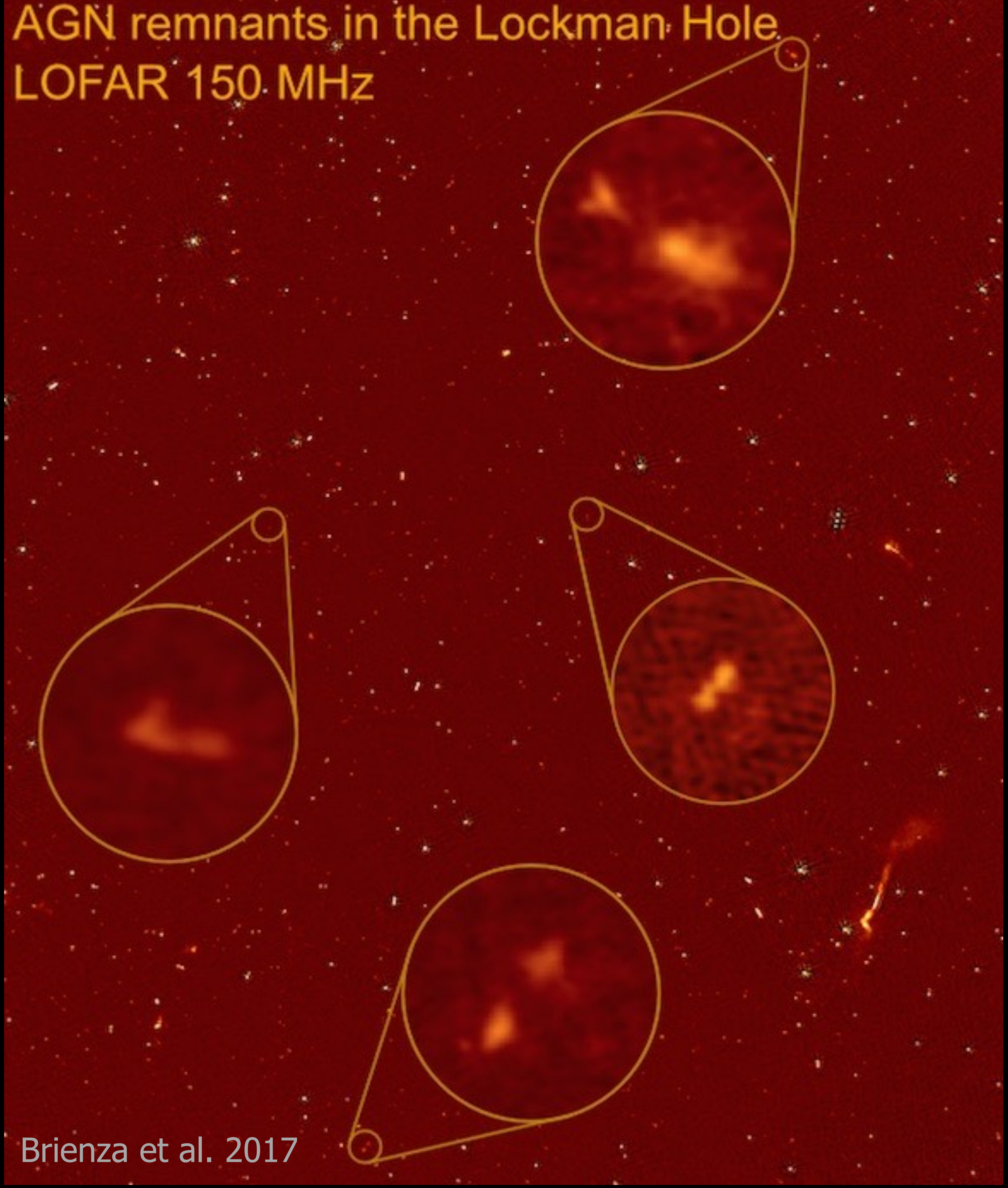


candidate restarted

Jurlin et al. 2020

- 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)

All relevant for the impact of radio AGN in galaxy evolution



Brienza et al. 2017

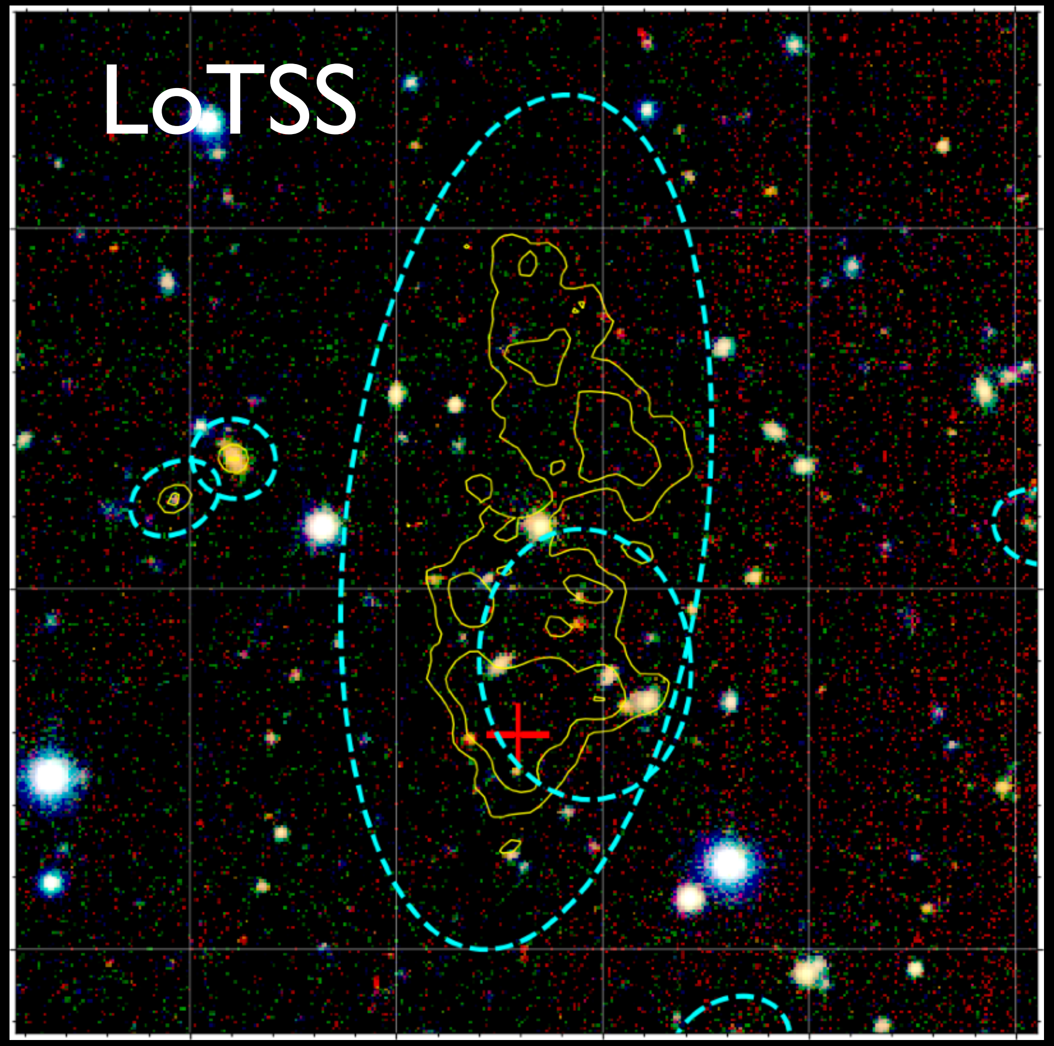
These results were obtained using radio sources in the Lockman Hole (about 30 sq deg)

….but there is much more LOFAR sky now available!

↓

we need to make the selection and analysis more automatic

The next steps: expand the statistics of remnants radio sources

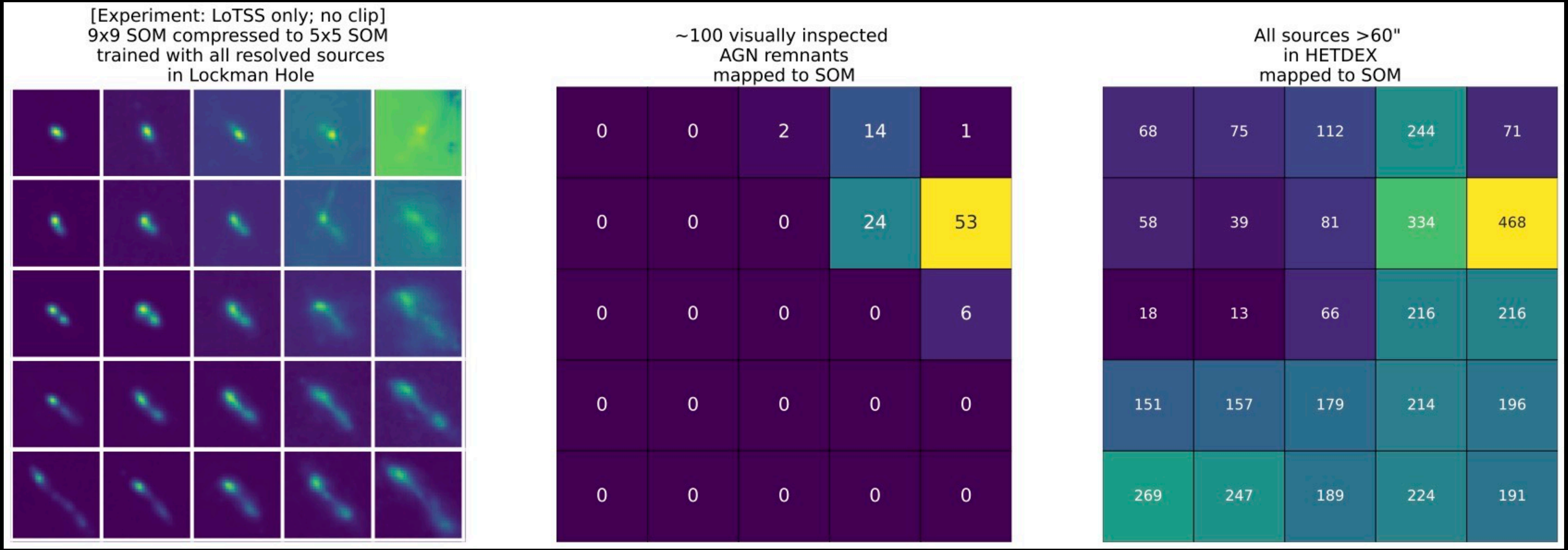


Automatic search for remnants in the LOFAR LoTSS HBA Hetdex area ~400 sq deg

about hundred of candidates already found: selection based on uniform surface brightness distribution (max/median<3)

Brienza et al. in progress

Used as training set in the
Self-organised Map (SOM) - R. Mostert et al. submitted



[Experiment: LoTSS only; no clip]
9x9 SOM compressed to 5x5 SOM
trained with all resolved sources
in Lockman Hole

~100 visually inspected
AGN remnants
mapped to SOM

0	0	2	14	1
0	0	0	24	53
0	0	0	0	6
0	0	0	0	0
0	0	0	0	0

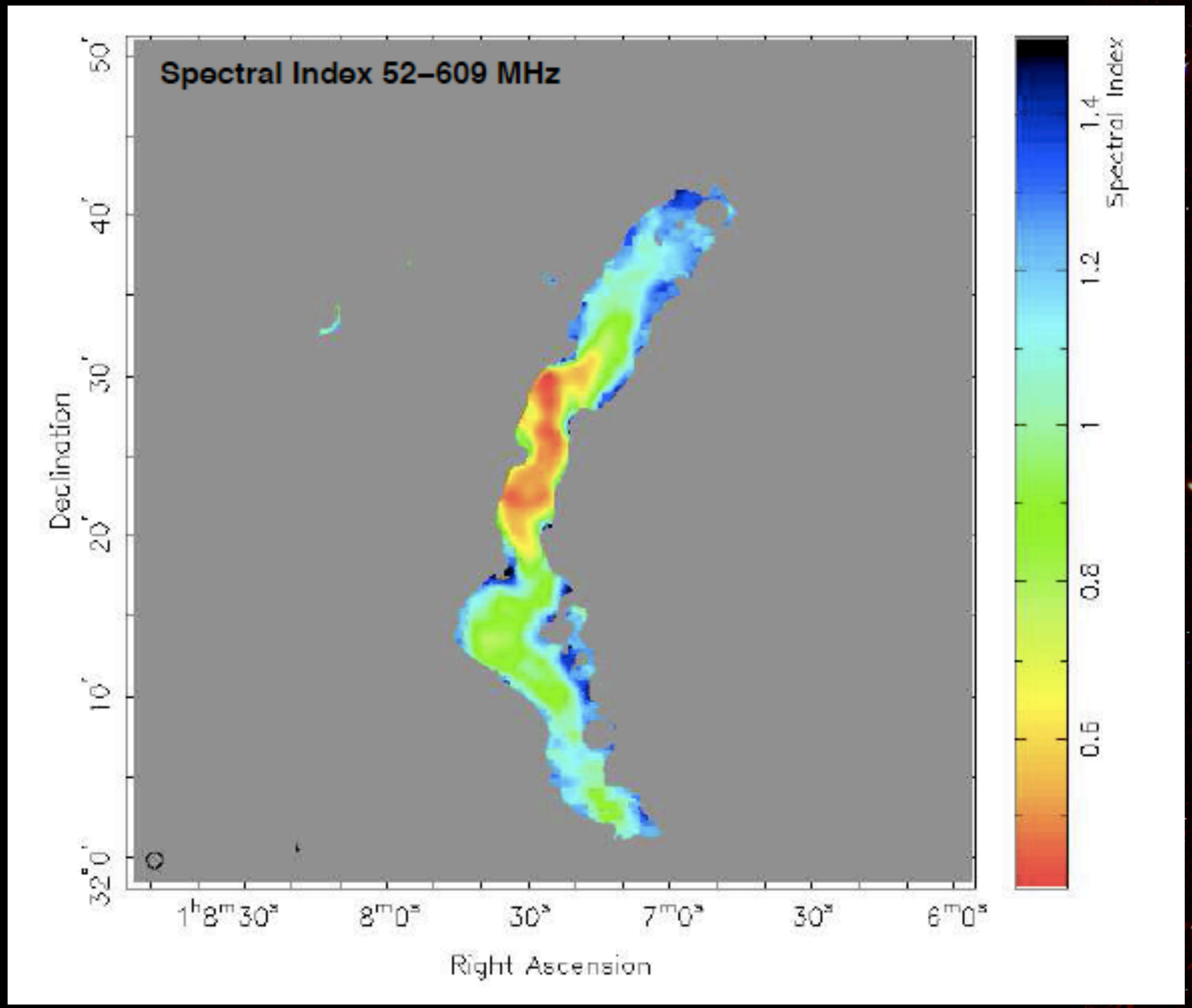
All sources >60"
in HETDEX
mapped to SOM

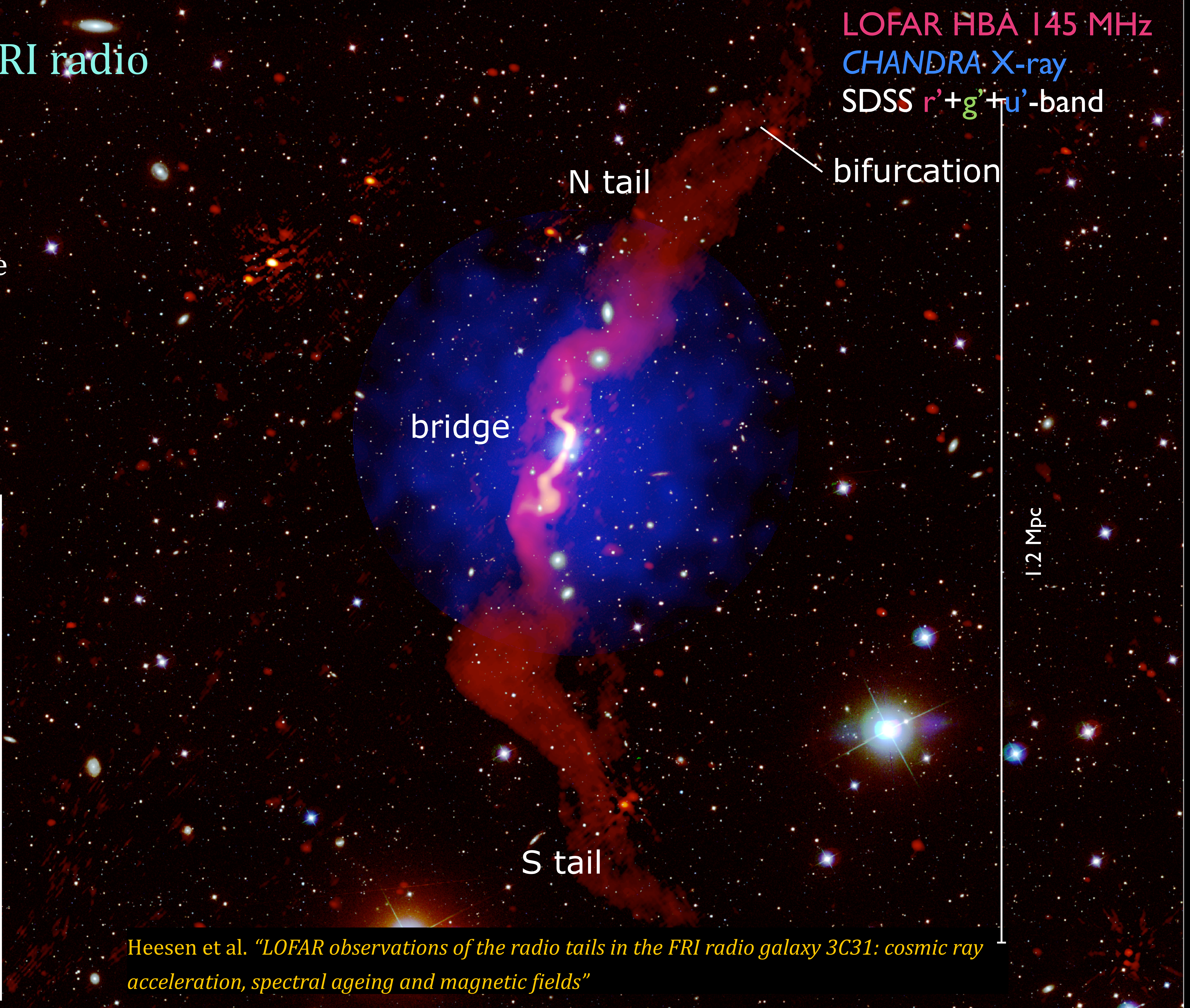
68	75	112	244	71
58	39	81	334	468
18	13	66	216	216
151	157	179	214	196
269	247	189	224	191

… some final other interesting results

LOFAR HBA and LBA of the FRI radio galaxy 3C31

- ✓ Significantly extended the known size
- ✓ Combine LOFAR, GMRT, VLA
  - ➔ importance of frequency coverage
- ✓ Strong entrainment/adiabatic losses
  - ➔ deceleration of the flow
- ✓ effects of ageing in the tails
- ✓ B ~3μG in the tails, ages ~200 Myr

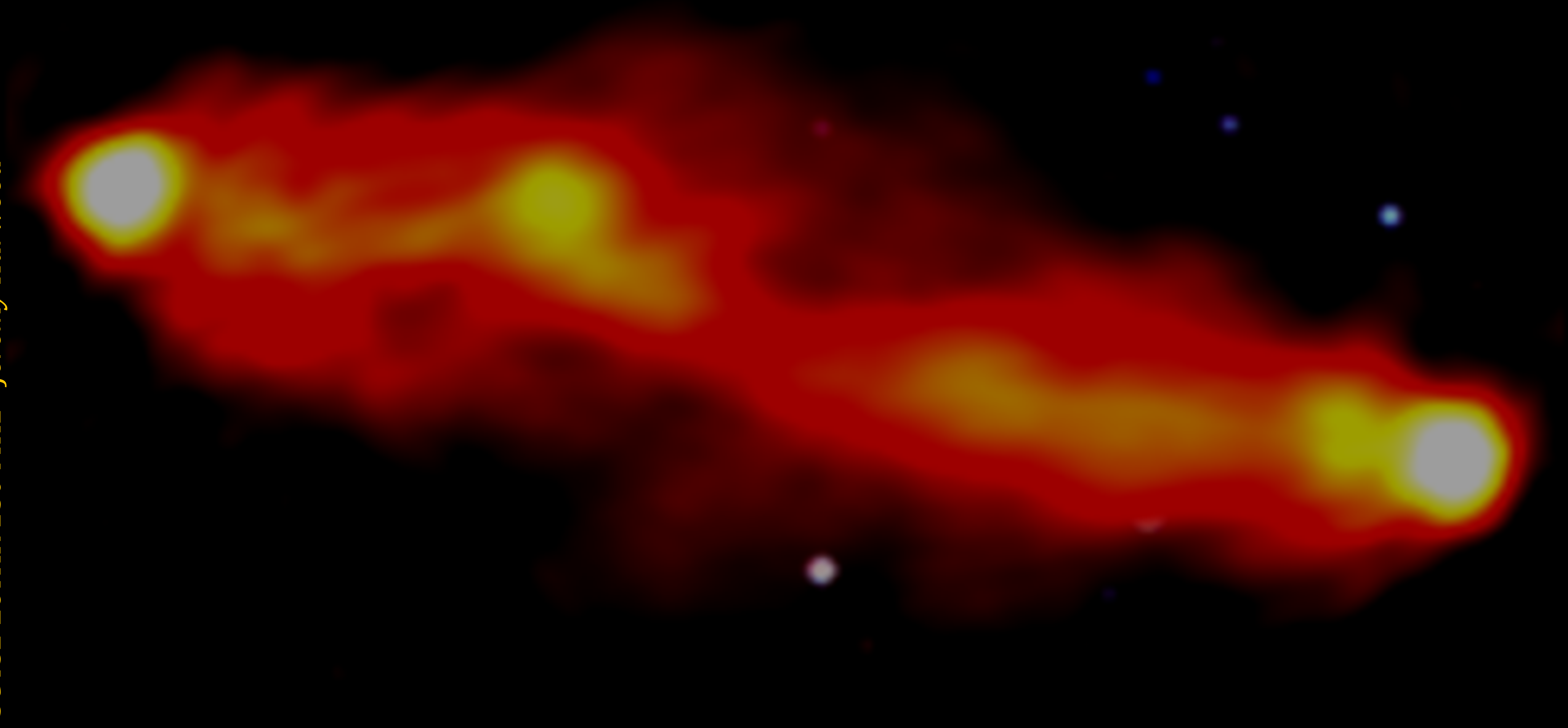




Heesen et al. *"LOFAR observations of the radio tails in the FRI radio galaxy 3C31: cosmic ray acceleration, spectral ageing and magnetic fields"*

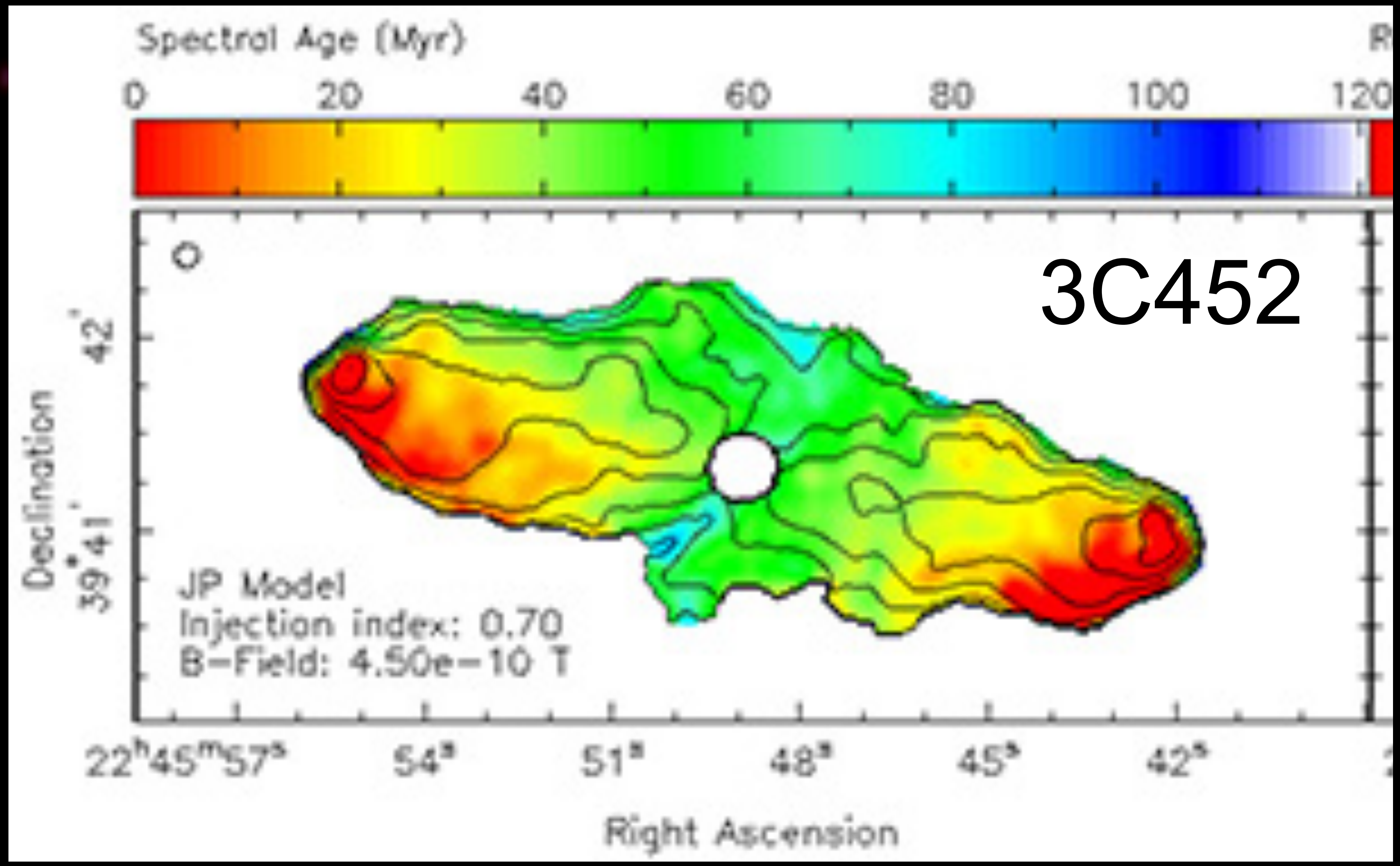
Energetics and morphology of FRII radio galaxies: resolved spectral indices

Better constrained spectrum at low frequencies.
Injection index (as derived from the lobe emission) remains **steeper** than classically assumed values even when considered on well resolved scales at low frequencies ➔ greater amount of energy is contained in the low-energy electron population than previously thought.



3C452 LOFAR 150 MHz - Jeremy Harwood

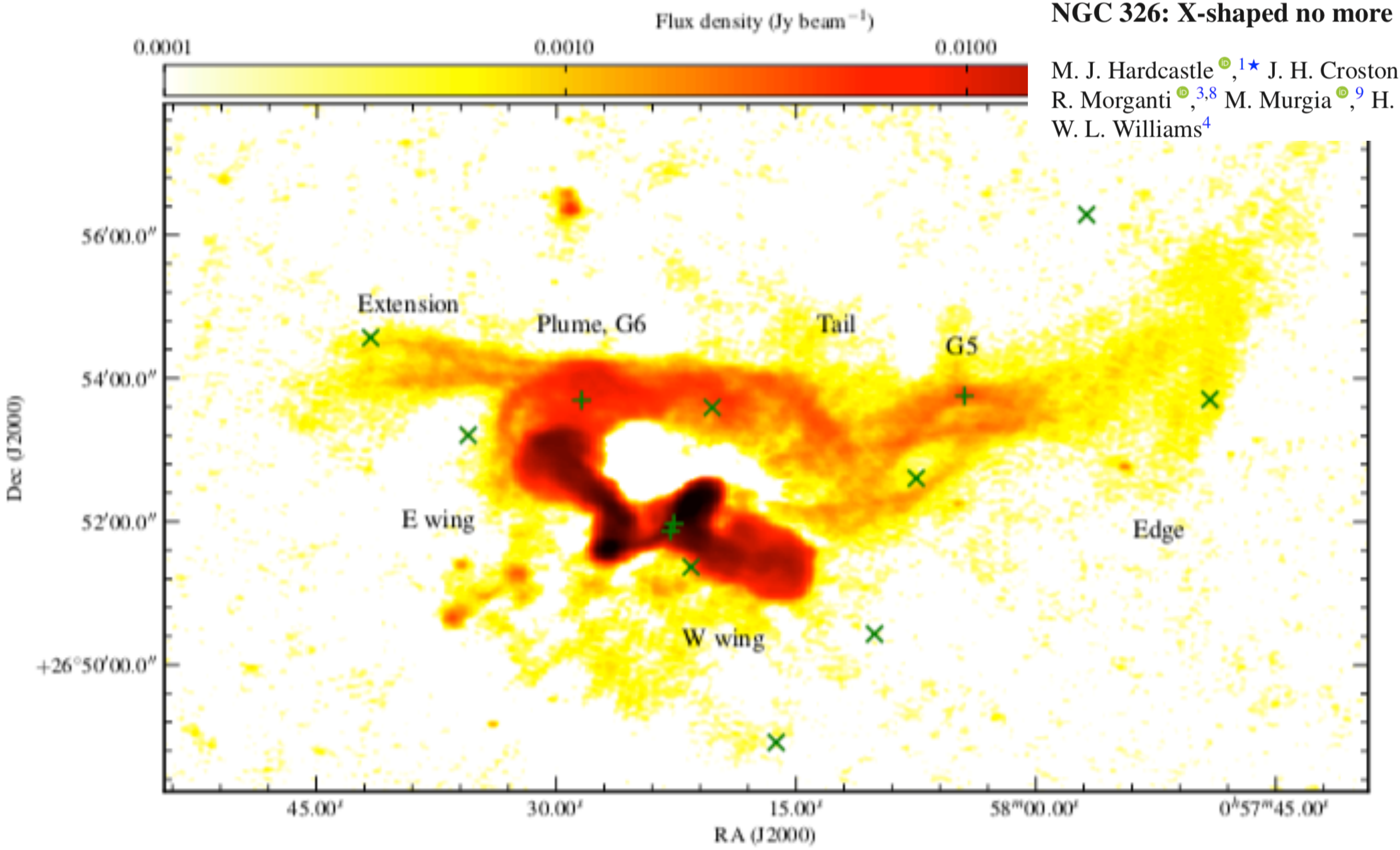
Harwood et al. 2015, 2016



absorption of hotspot emission and/or non-homogeneous and additional acceleration mechanisms

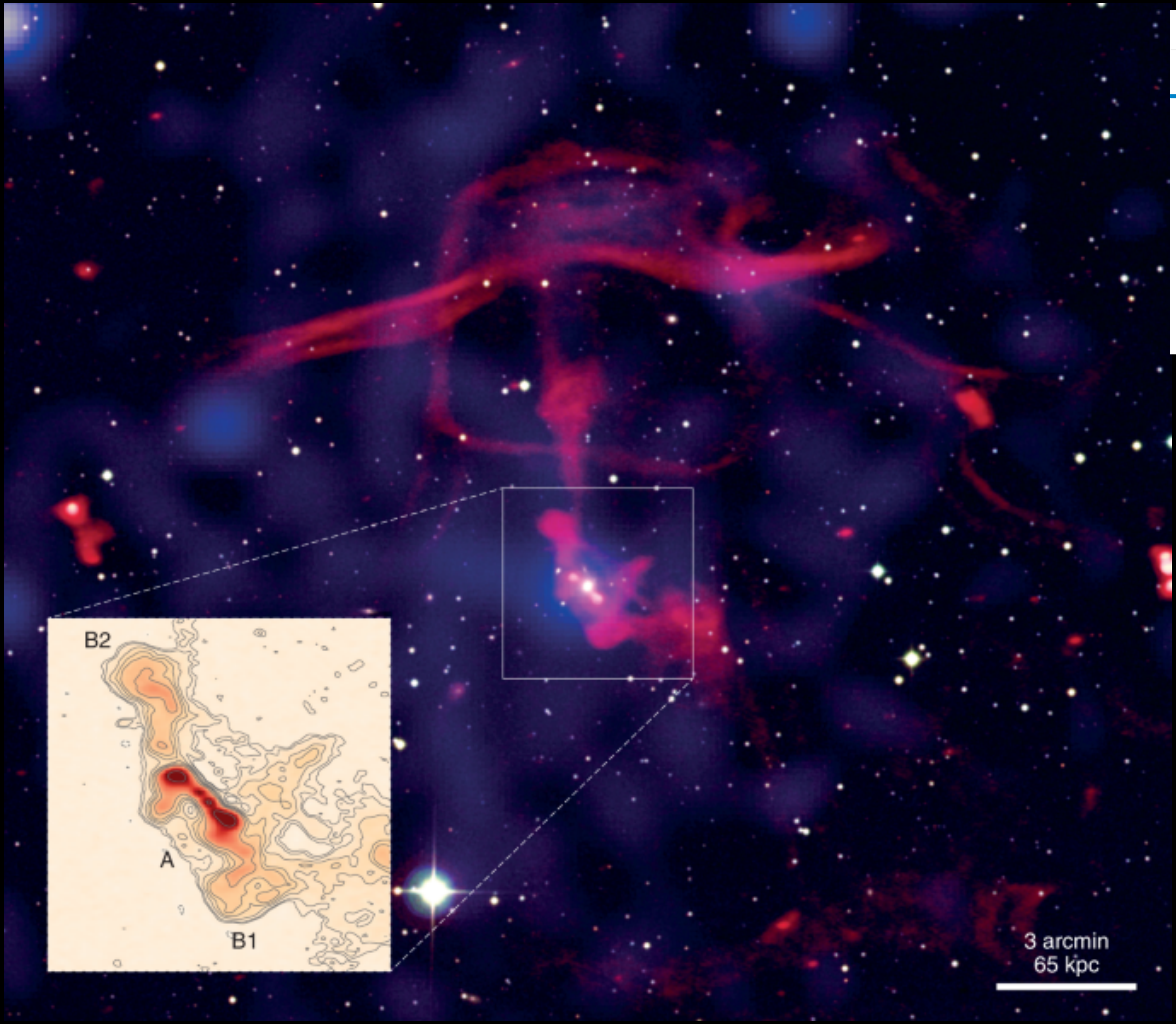
NGC 326: X-shaped no more

M. J. Hardcastle[1]★ J. H. Croston,[2] T. W. Shimwell,[3,4] C. Tasse,[5,6] G. Gürkan[7]
R. Morganti[3,8] M. Murgia[9] H. J. A. Röttgering,[4] R. J. van Weeren[4] and
W. L. Williams[4]



NGC 326, which shows that the formerly known wings of the radio lobes extend smoothly into a large-scale, complex radio structure.

This large-scale radio structure is hard to explain purely in terms of jet reorientation due to the merger of binary black holes, structure is most likely the result of hydrodynamical effects in an ongoing group or cluster merger.



nature > nature astronomy > letters > article

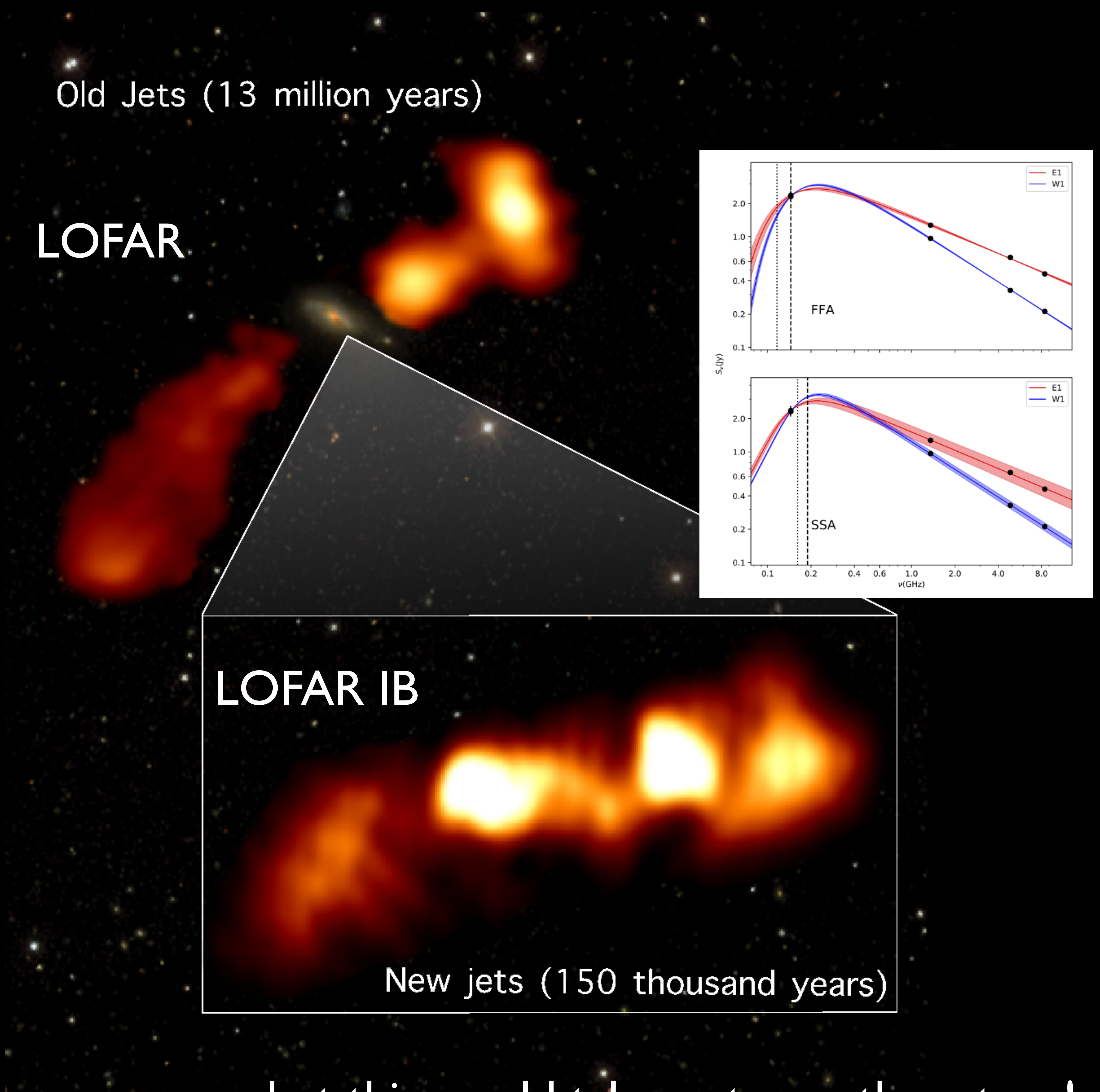
Letter | Published: 18 October 2021

A snapshot of the oldest active galactic nuclei feedback phases

M. Brienza, T. W. Shimwell, F. de Gasperin, I. Bikmaev, A. Bonafede, A. Botteon, M. Brüggen, G. Brunetti, R. Burenin, A. Capetti, E. Churazov, M. J. Hardcastle, I. Khabibullin, N. Lyskova, H. J. A. Röttgering, R. Sunyaev, R. J. van Weeren, F. Gastaldello, S. Mandal, S. J. D. Purser, A. Simionescu & C. Tasse

Active-galactic-nuclei jets inflate cosmic-ray lobes, which can rise buoyantly as light ‘bubbles’ in the surrounding medium: not yet mixed with IGM, effect of magnetic field?

The LOFAR international baselines for nearby AGN



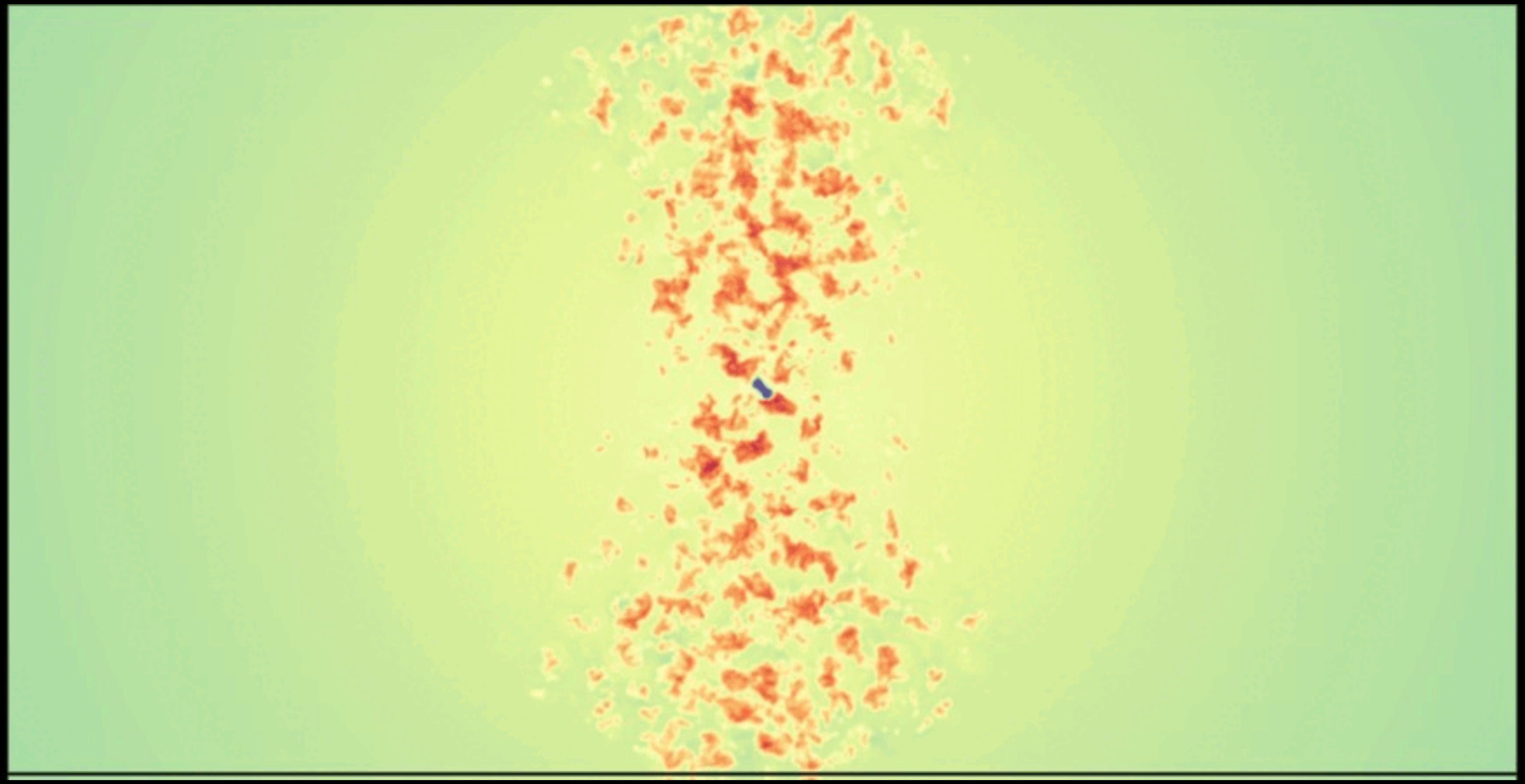
Candidate restarted gas rich and strong interaction jet-ISM.

Turn over spectrum from LOFAR-IB: likely result of free-free

(Kukreti et al. 2021 A&A special issue LOFAR long baselines)

From these spectra one can derive the density of gas around the source

to be compared with the simulations from:
Wagner, Mukherjee & Bicknell 2011,2017



…but this would take us to another story!

LOFAR for radio AGN…

- Great new opportunities given by LOFAR for expanding the study of radio AGN!
- Most of the work so far using HBA but more to come with LBA and the long baselines
- Effort for making more automatic the component association, optical ID and selection of interesting objects
- Combined with other instruments/surveys offers a lot of potential for great science in the northern hemisphere: competitive in the SKA era!

Interested in AGN: Nearby AGN WG ➔ morganti@astron.nl and Martin Hardcastle m.j.hardcastle@herts.ac.uk