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

2) From “radio quiet” to “radio loud”: properties and recent results

Raffaella Morganti

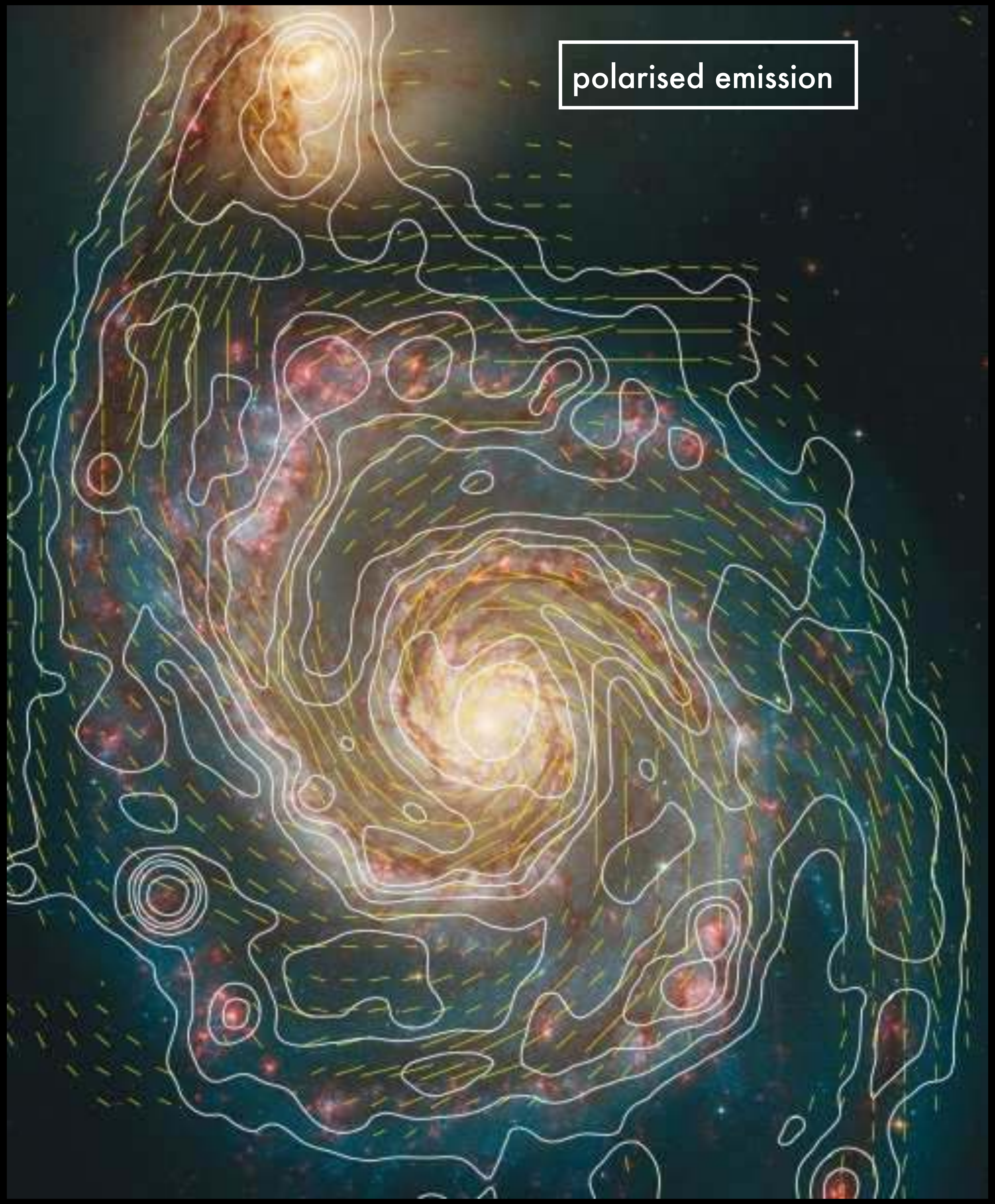
Netherlands Institute for Radio Astronomy (ASTRON)
and
Kapteyn Institute Groningen

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

Where/how radio emission

Radio emission mechanisms: "normal" galaxies

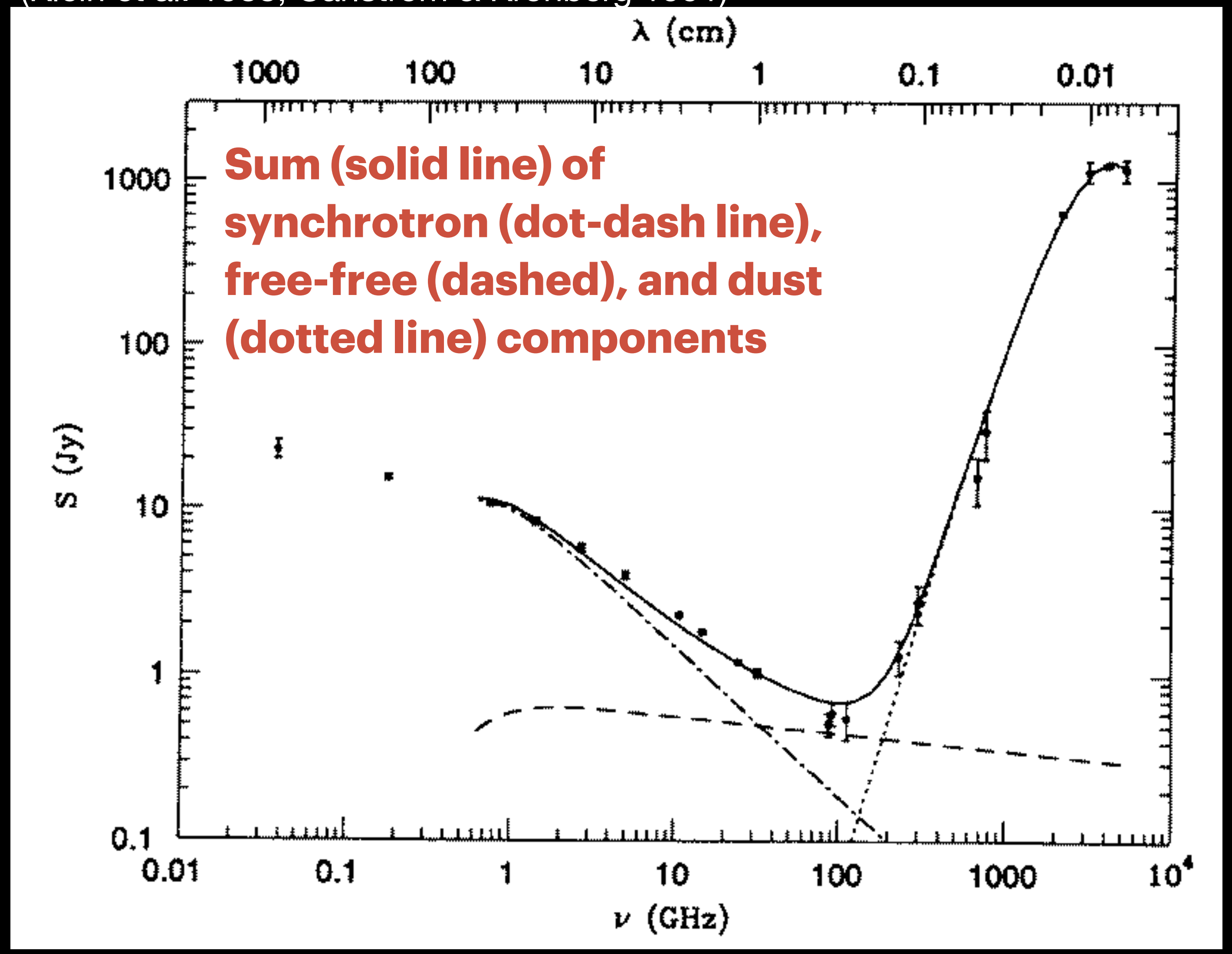


M51 at 48-GHz from VLA and Effelsberg 100-m

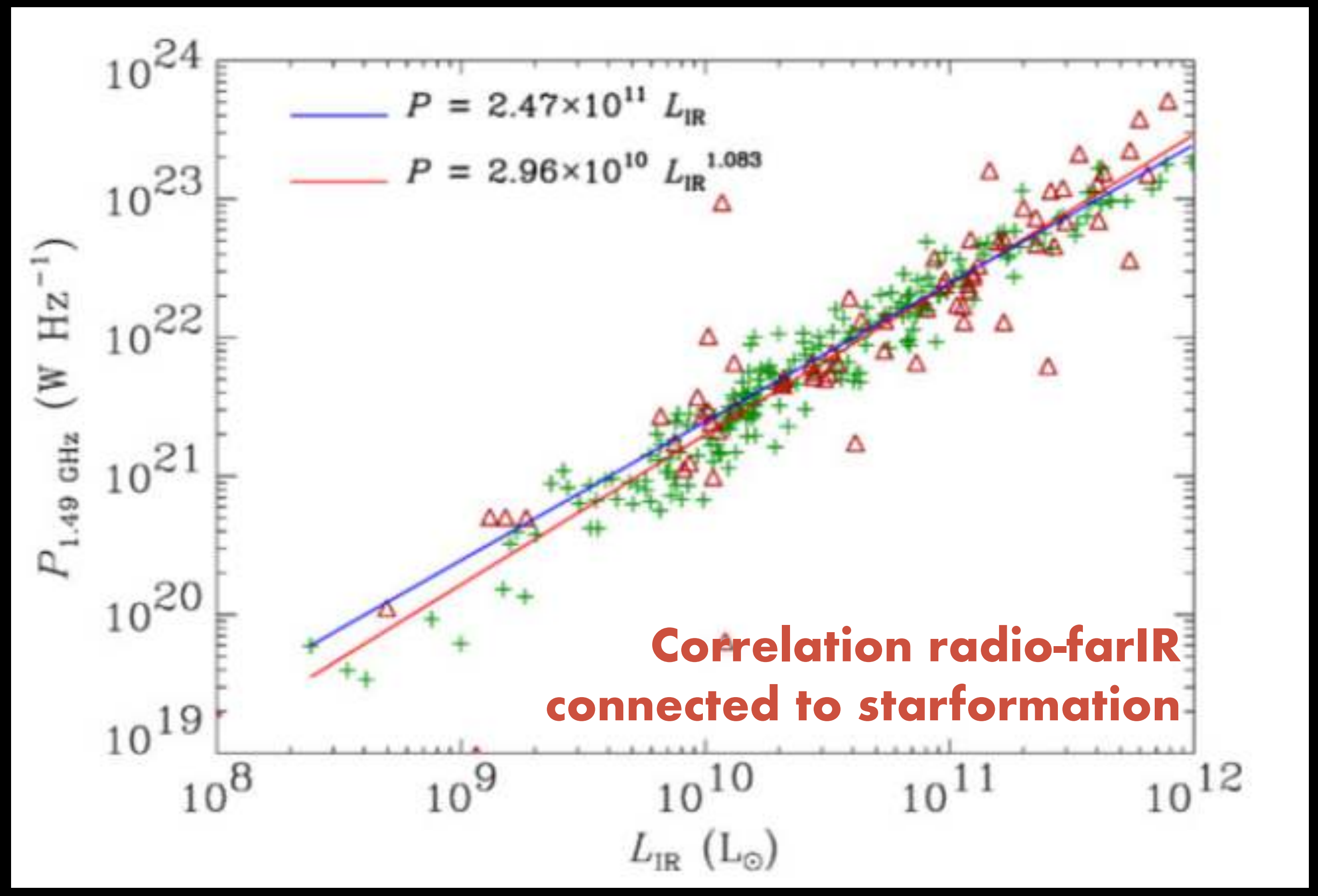
Radio emission from normal galaxies is synchrotron radiation from relativistic electrons and free-free emission from HII regions. Only stars more massive than $M \sim 8\,M_\odot$ produce the Type II and Type Ib supernovae whose remnants (SNRs) are thought to accelerate most of the relativistic electrons in normal galaxies, and these massive stars ionise the H II regions as well. Such massive stars live $\lesssim 3 \times 10^7$ yr, and the relativistic electrons probably have lifetimes $\lesssim 10^8$ yr. Radio observations are therefore probes of very recent star-formation activity in normal galaxies.

Condon J. ARA&A 1992

Observed radio/FIR spectrum of M82
(Klein et al. 1988, Carlstrom & Kronberg 1991)



From the radio emission the SFR can be derived **IF** no contribution of the AGN is present

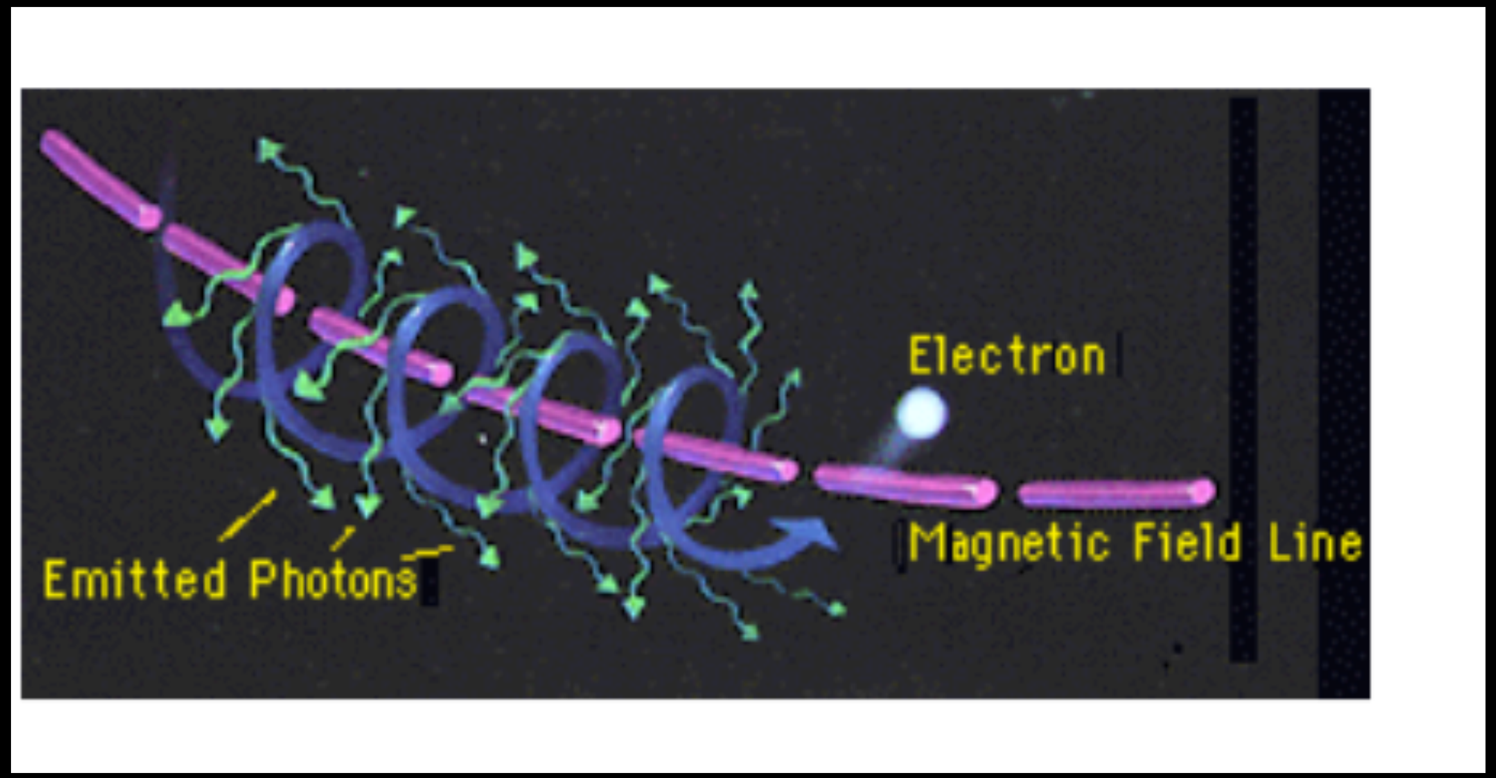


Also line emission - in particular 21 cm HI and molecular gas (ALMA)

Continuum Radio emission mechanisms: "active" galaxies

Dominant mechanism: Synchrotron radiation

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



Energy of the electrons

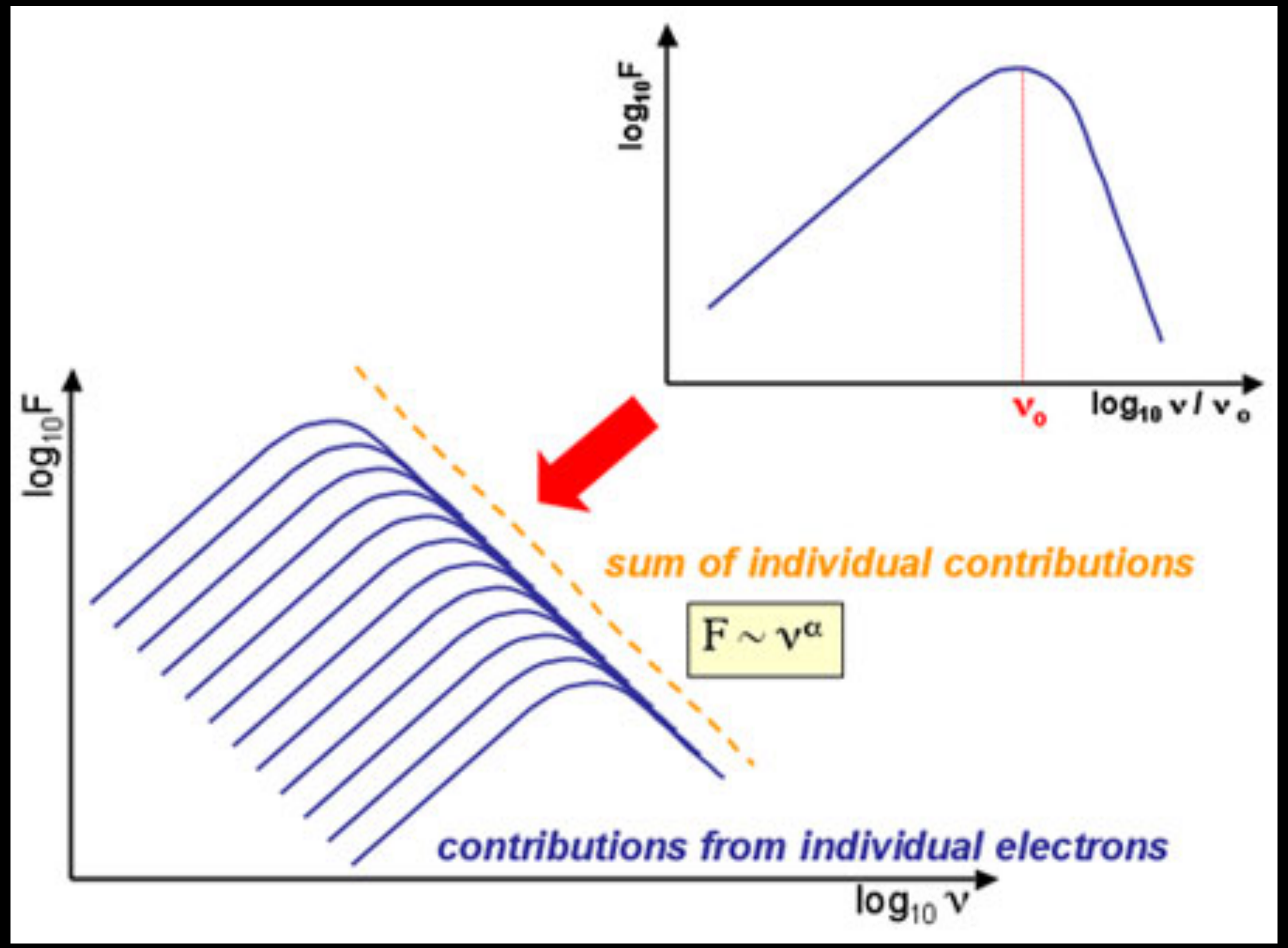
$$E = \gamma m_e c^2$$

Lorentz factor

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

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

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

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

before starting with radio AGN...

Small detour:
what is an AGN?

AGN in a nutshell

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

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Active galactic nucleus

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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".

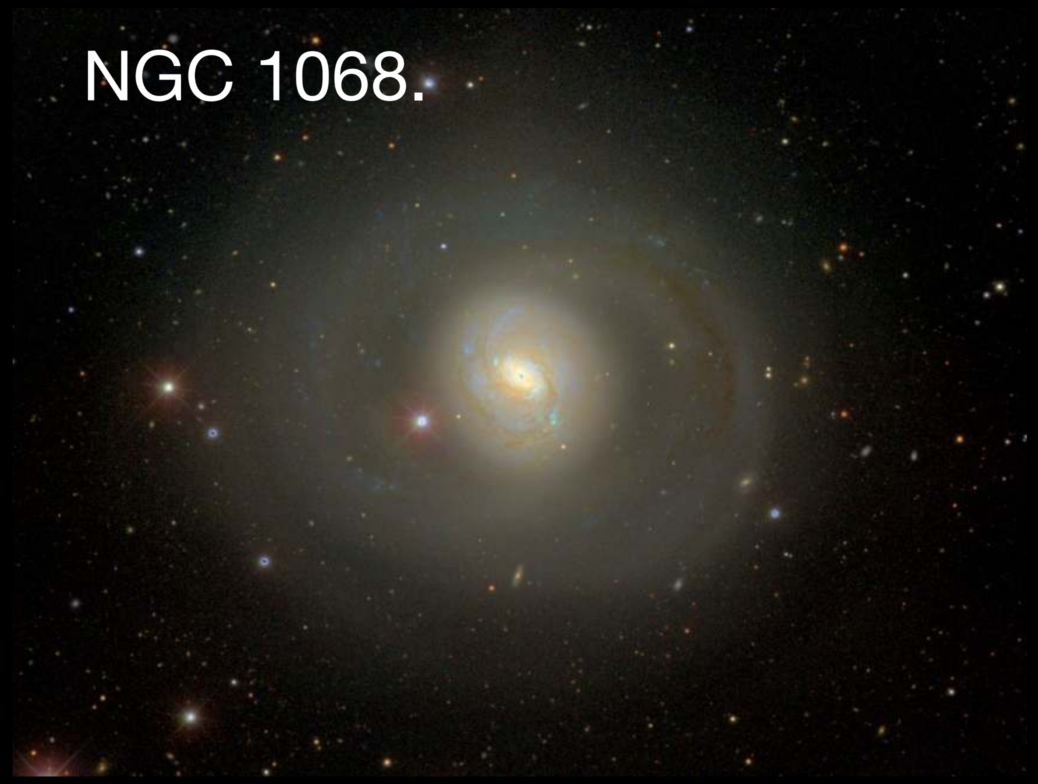
EMISSION NUCLEI IN GALAXIES

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.



* Nuclei are unresolved (<100pc)
* Nuclear mass is very high if emission-line broadening is caused by bound material ($M \sim v^2 r/G \sim 10^{9\pm1}\, M_\odot$)
* 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!

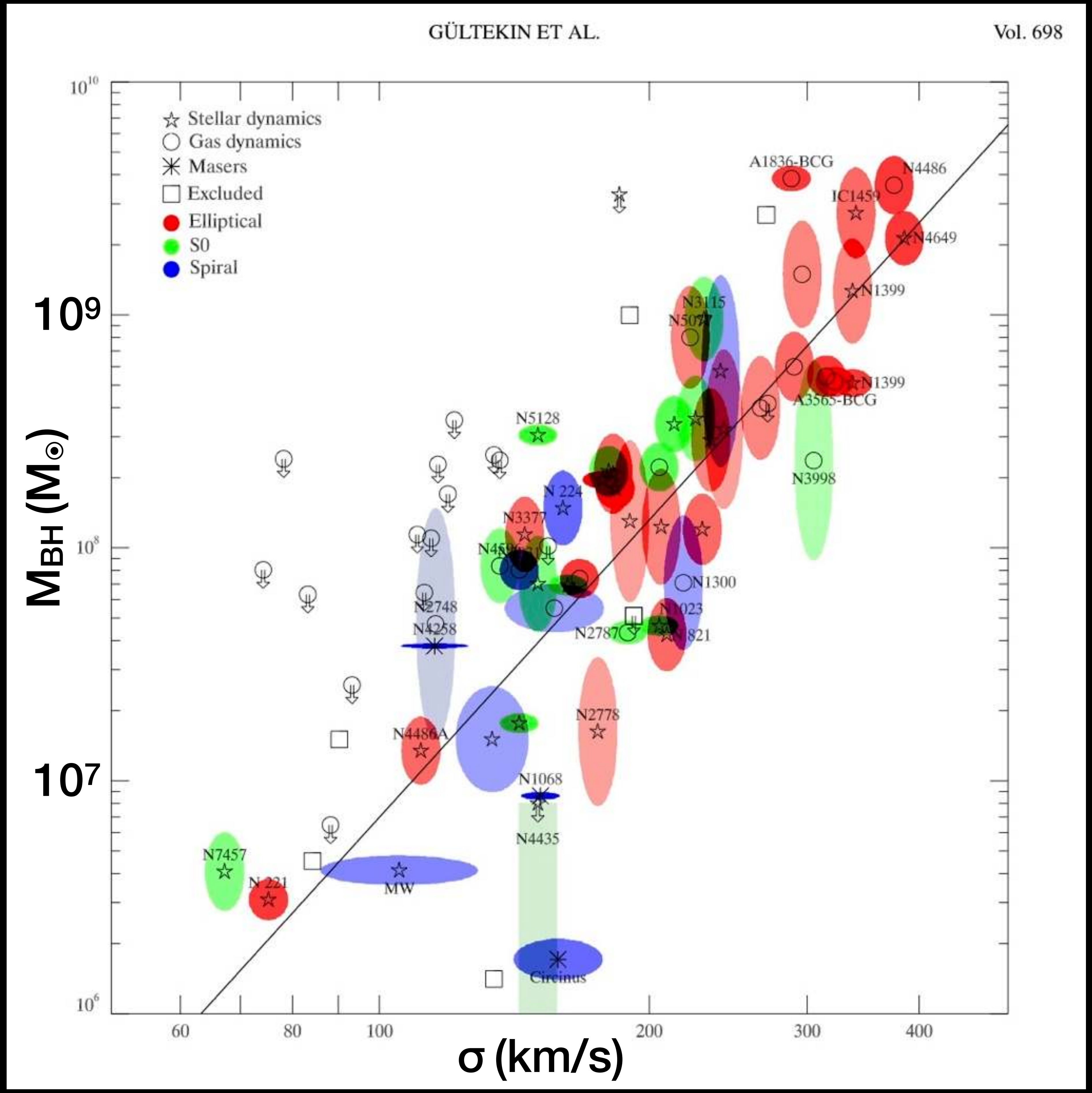
Galaxies and SMBH

All massive galaxies host a supermassive black hole (SMBH)

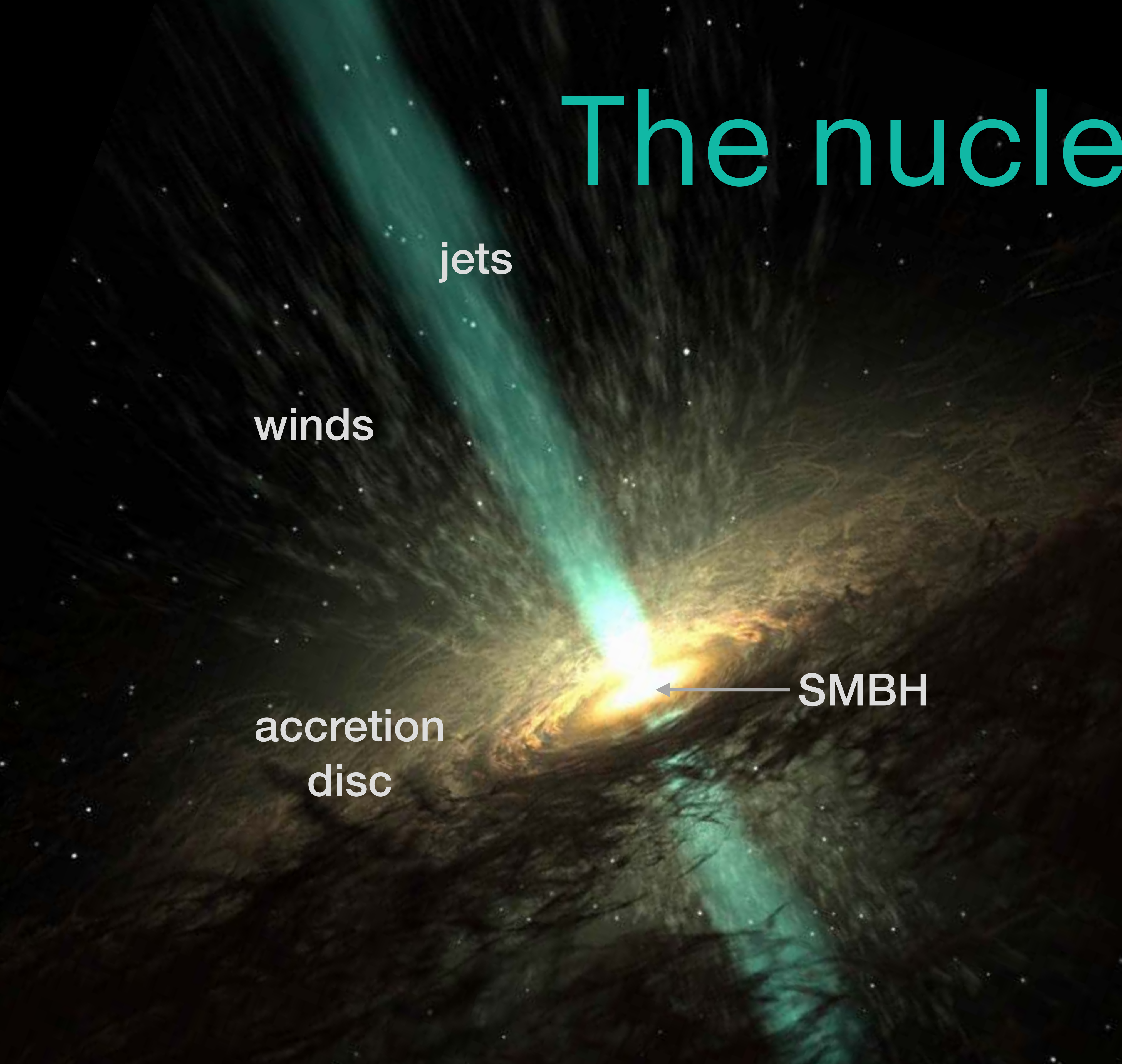
➔ relation M_{BH}-σ velocity dispersion of the stars in the bulge of the galaxy

but not all SMBH are active (right now…)

cycling between "on" and "off" phases, see next Les



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 → minimum central mass for material to be gravitational bound to the centre of the galaxy

$$\frac{GM_{BH}m_p}{r^2} > \frac{\sigma_T S}{c} = \frac{\sigma_T}{c} \cdot \frac{L}{4\pi r^2}$$

$$L \leq L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH}$$

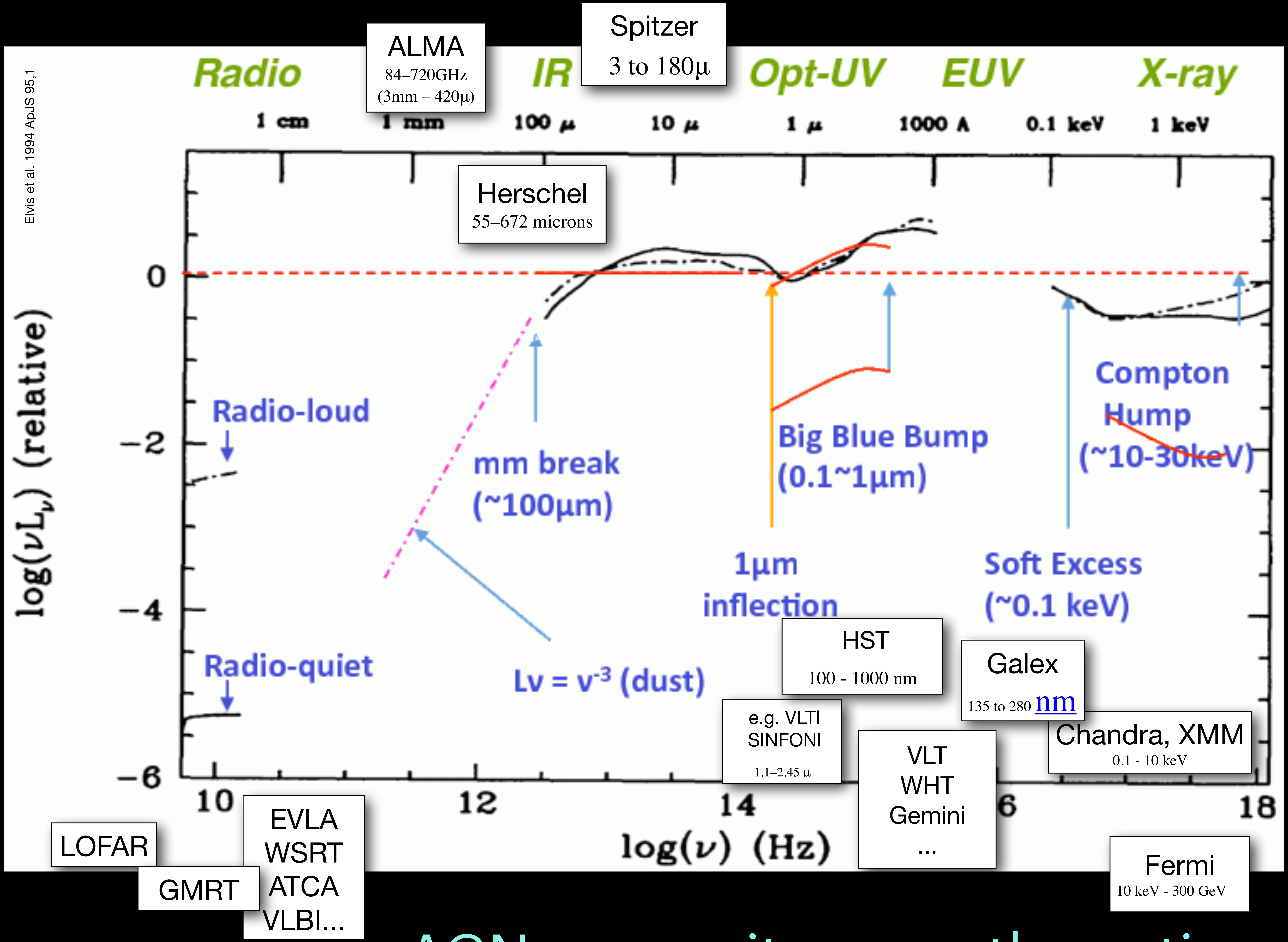
$$L \leq 1.26 \times 10^{38} \frac{M_{BH}}{M_\odot} erg\ s^{-1}$$

σ_T=scattering of photons by free electrons: Thompson scatter
M_{BH}= BH mass
G = gravitation constant
m_p= proton mass

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

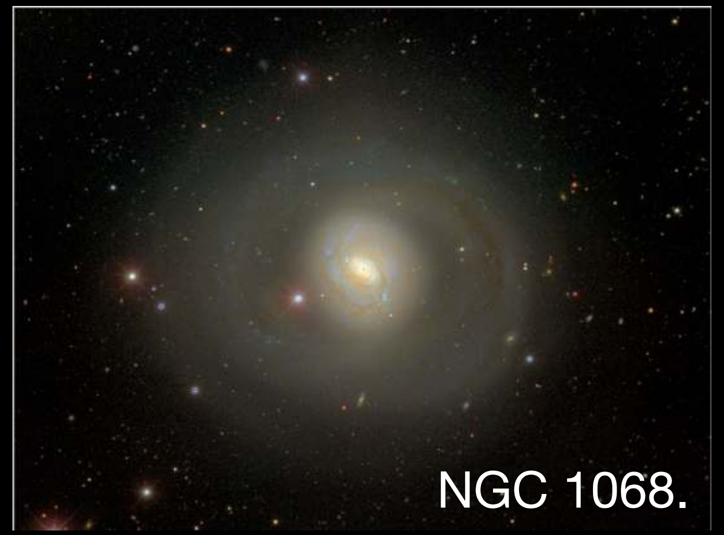
Ratio between Eddington and AGN luminosities → efficiency of the AGN

A variety of processes and emission from the various regions: multi-wavebands phenomenon...



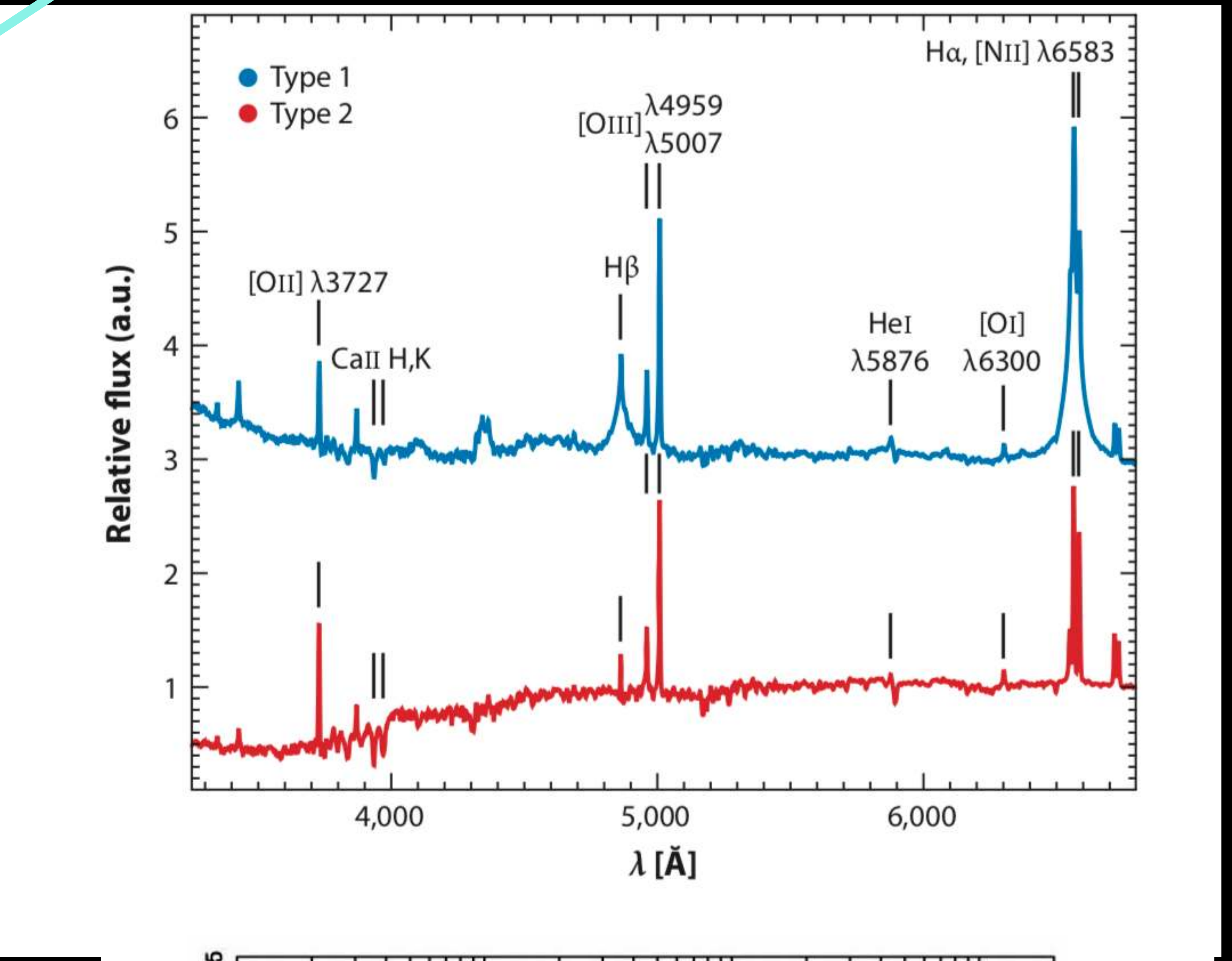
AGN can emit across the entire spectrum

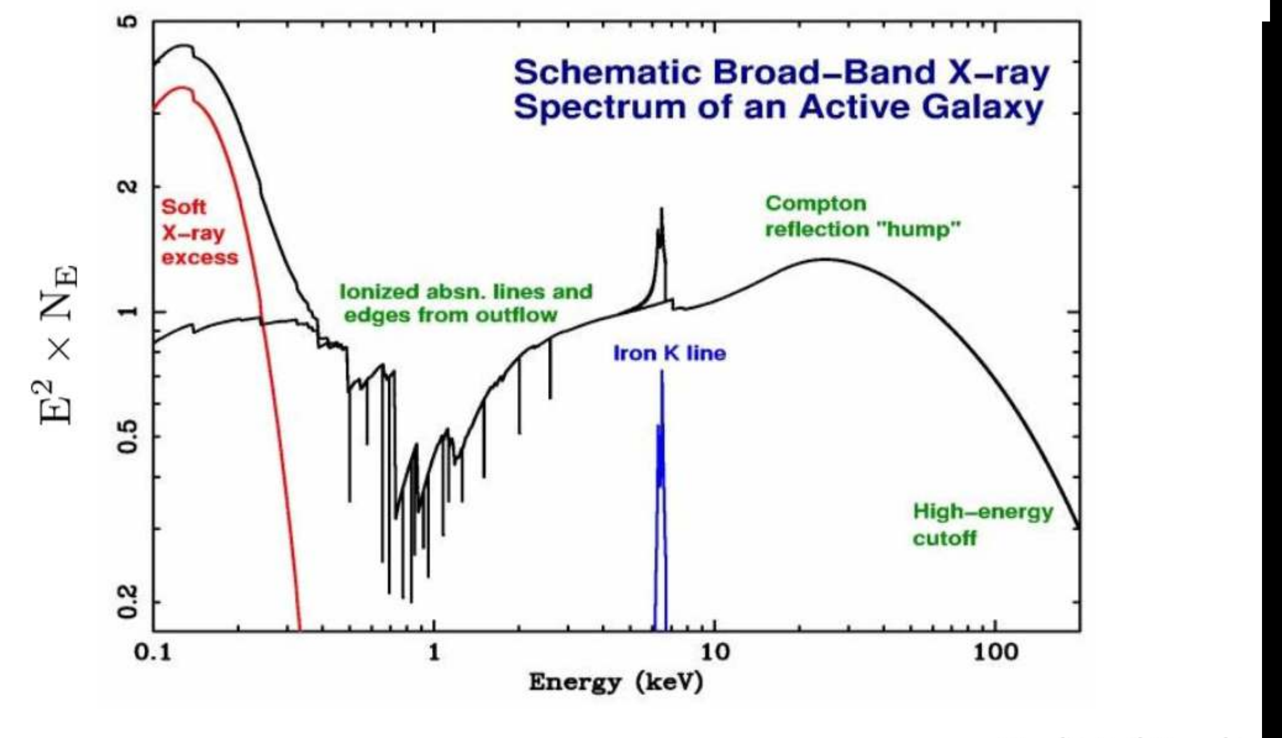
Some of the signatures of an AGN



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)





Credit: Neil Brandt

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

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

⬇

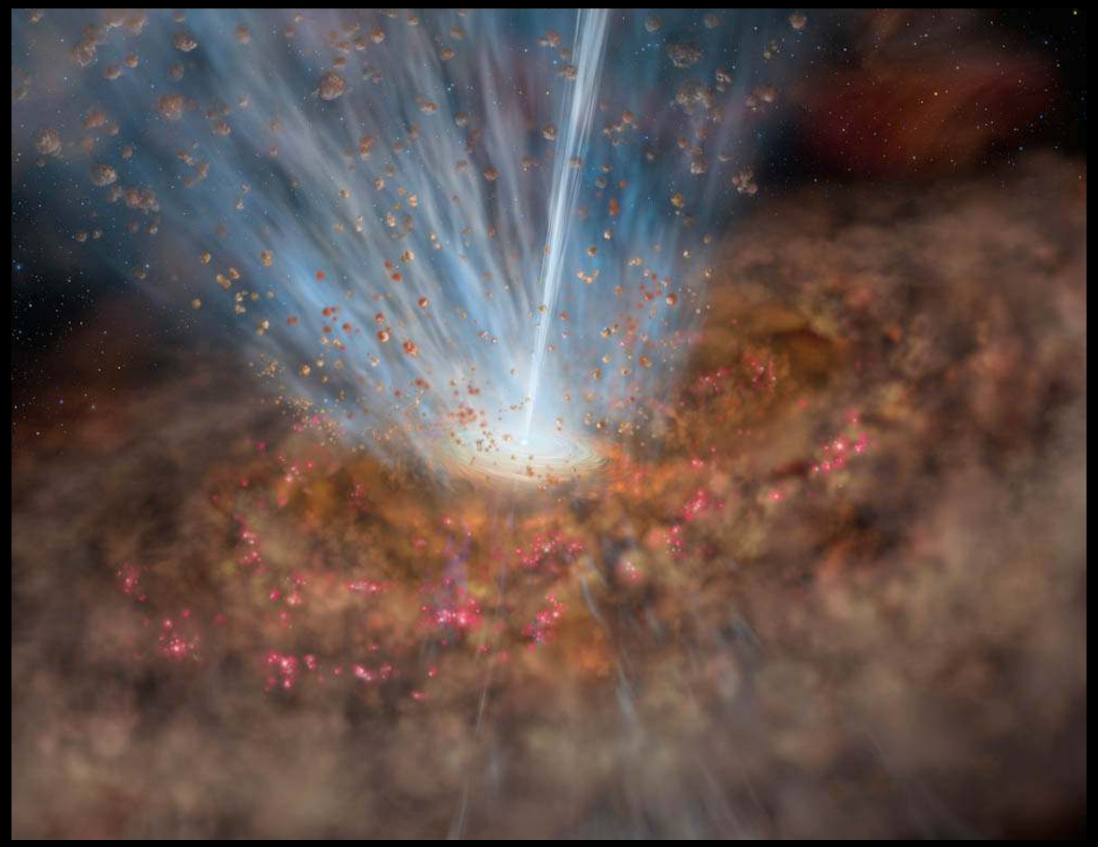
Role in galaxy evolution …

We will get back to this in Les 4

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).

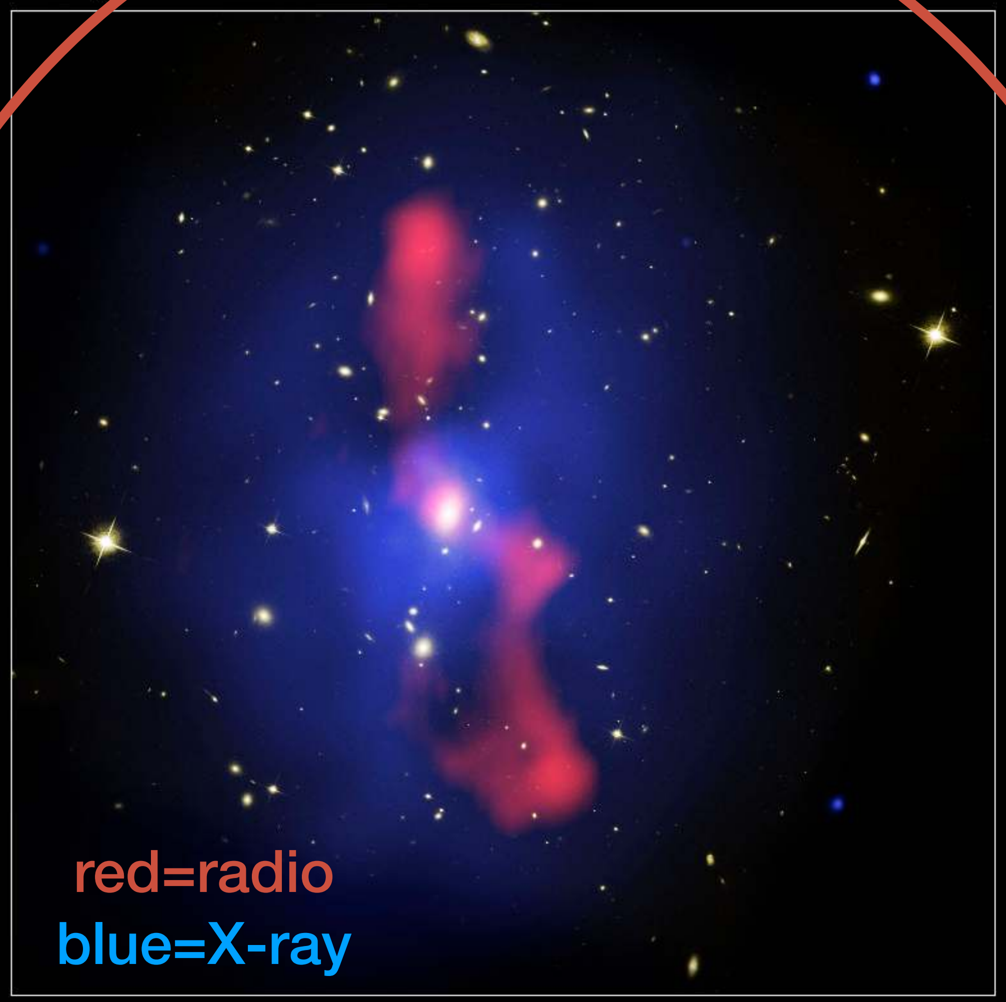
Role of AGN in galaxy evolution: cosmological simulations

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



"Quasar" mode

Galaxy Cluster MS 0735.6+7421



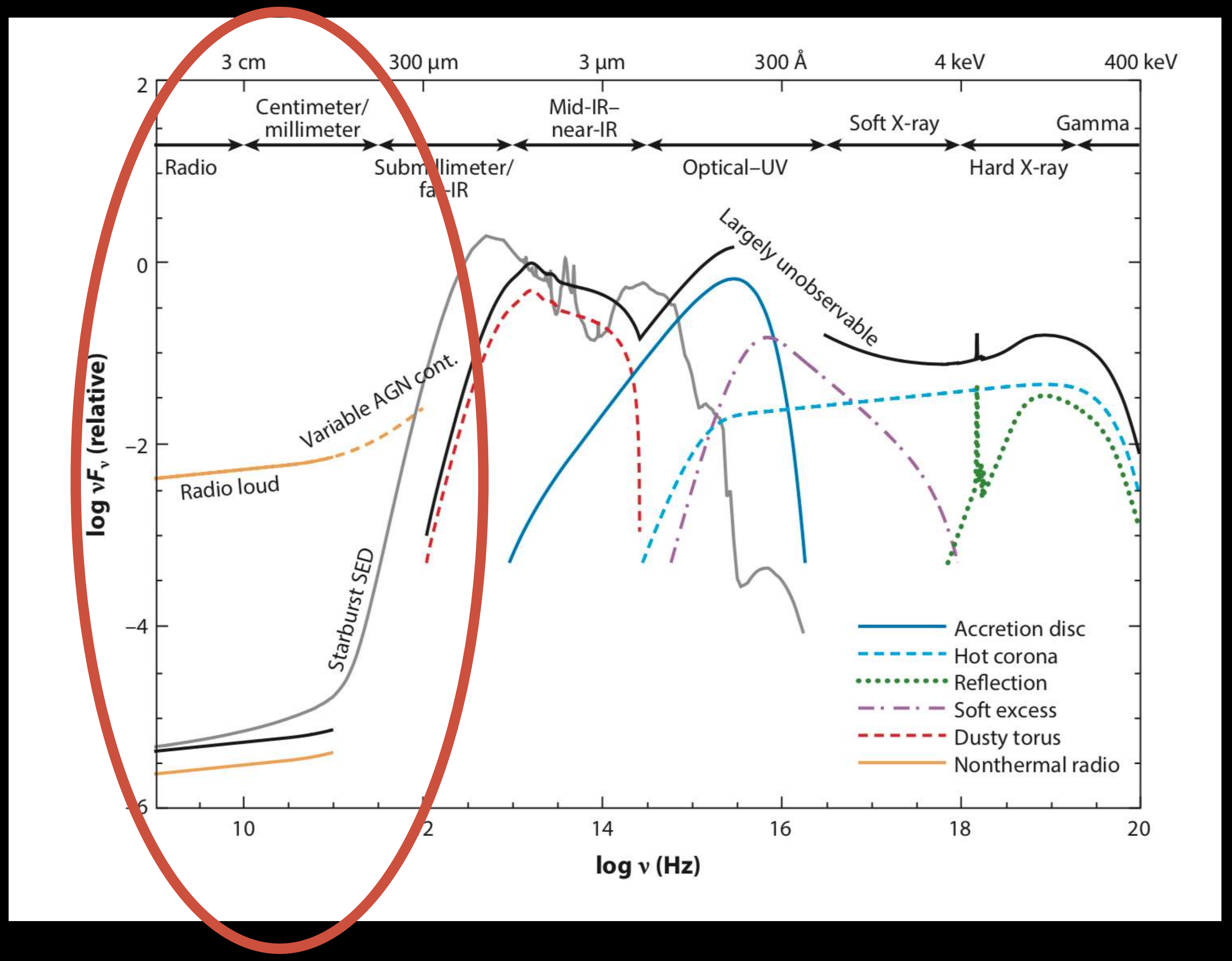
NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

"jet/maintenance" mode
(cluster-scale)

Important role for radio AGN (radio jets)

Questions on this part?

Radio AGN: galaxies where the nuclear radio emission originate from the active nucleus

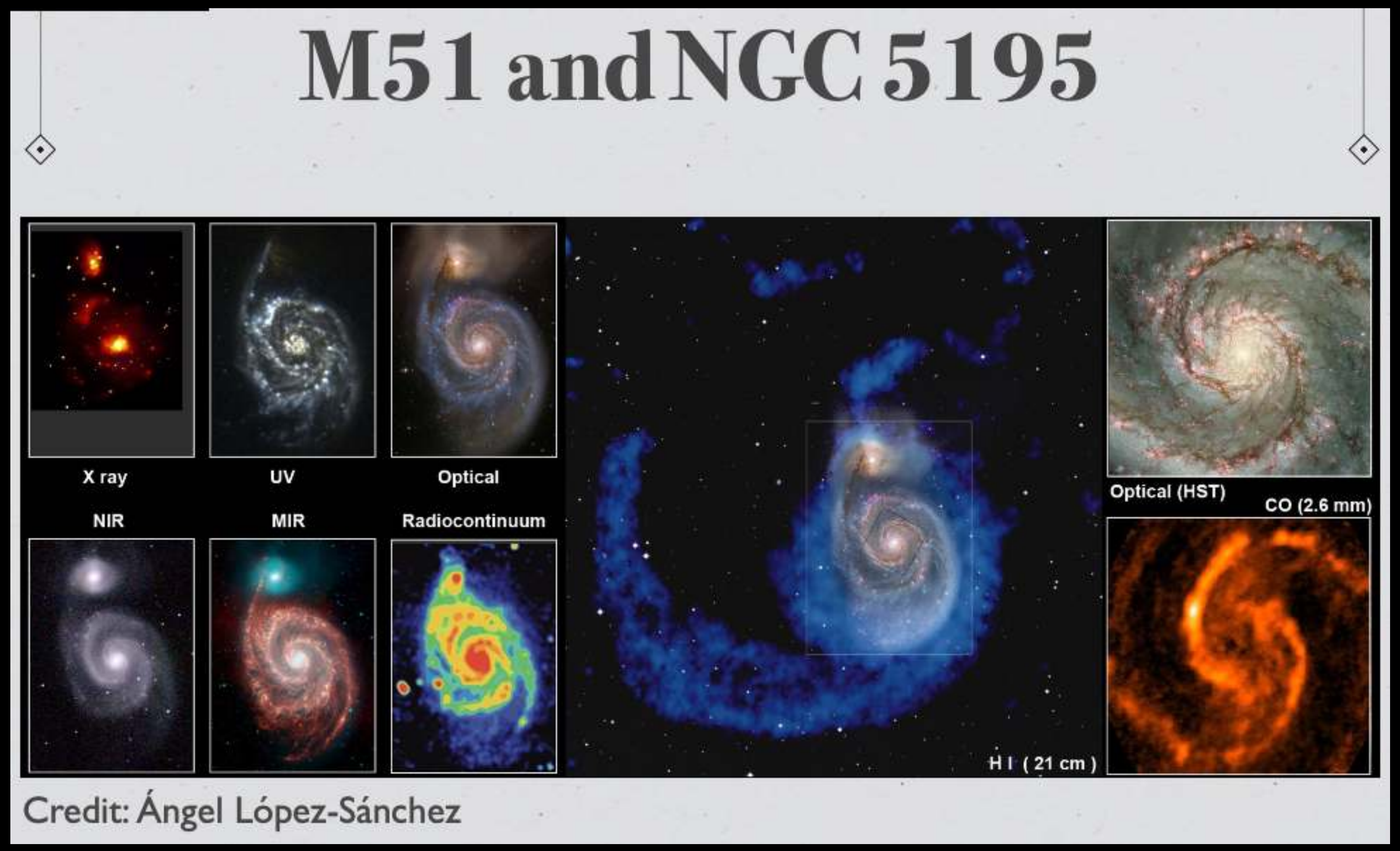


How do we establish this?

Starting point: rule out that the radio originates from starformation

Far-IR - radio correlation

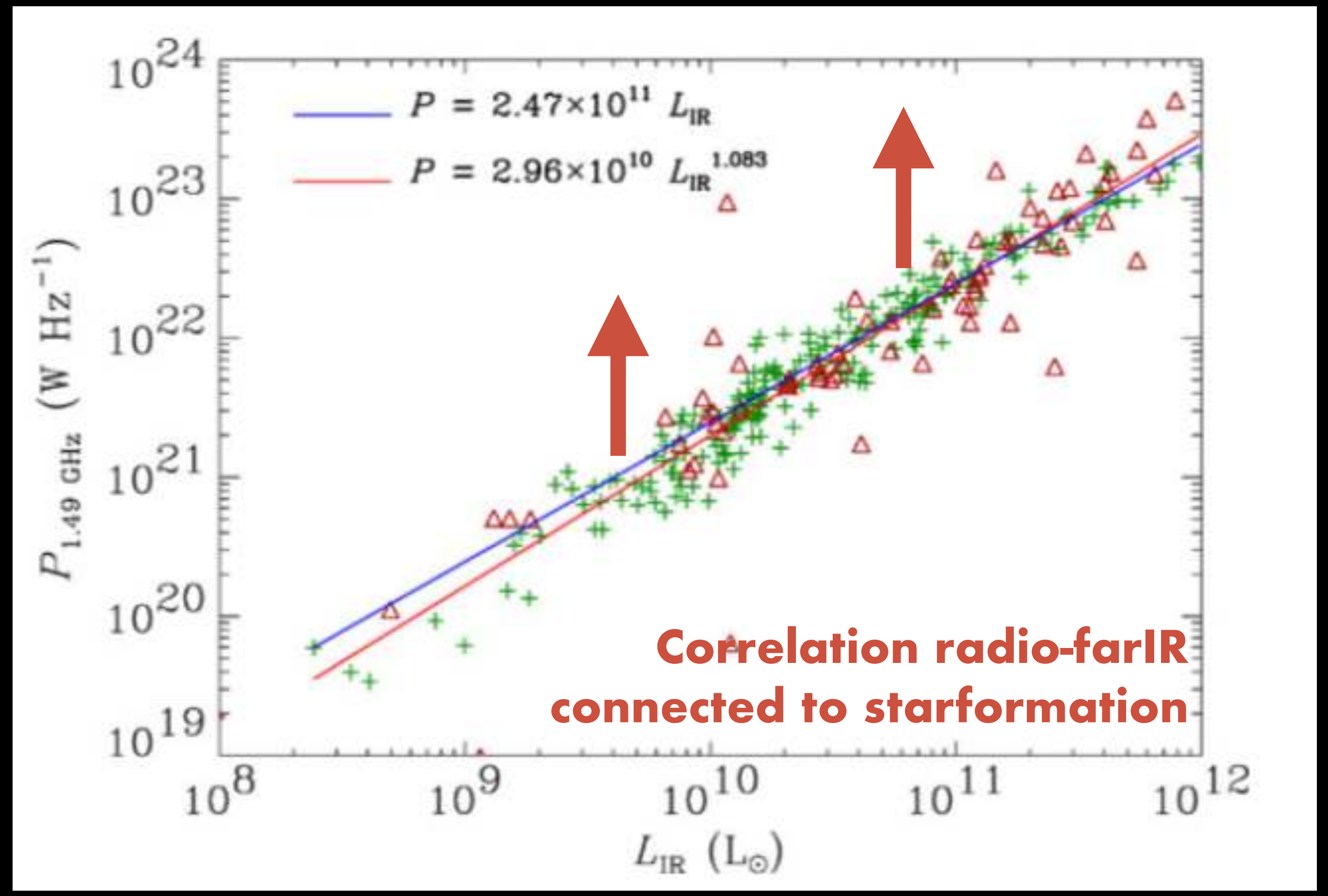
Morphology → following the stellar distribution instead of collimated structures (jet) from the nucleus



but not always easy!

we start with the “historical” idea

(still very much used although a bit misleading)...



Historically: suggested (a relatively arbitrary) radio-dichotomy radio-quiet vs radio-loud

radio-quiet doesn't mean radio silent!

Radio-loudness parameter R, ratio between radio (5GHz) and optical (B-band) monochromatic luminosity (proxy for stars…)
Optically selected AGN have been historically divided in radio-loud or radio-quiet depending on the value of the radio loudness parameter R:

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

or in term of luminosity

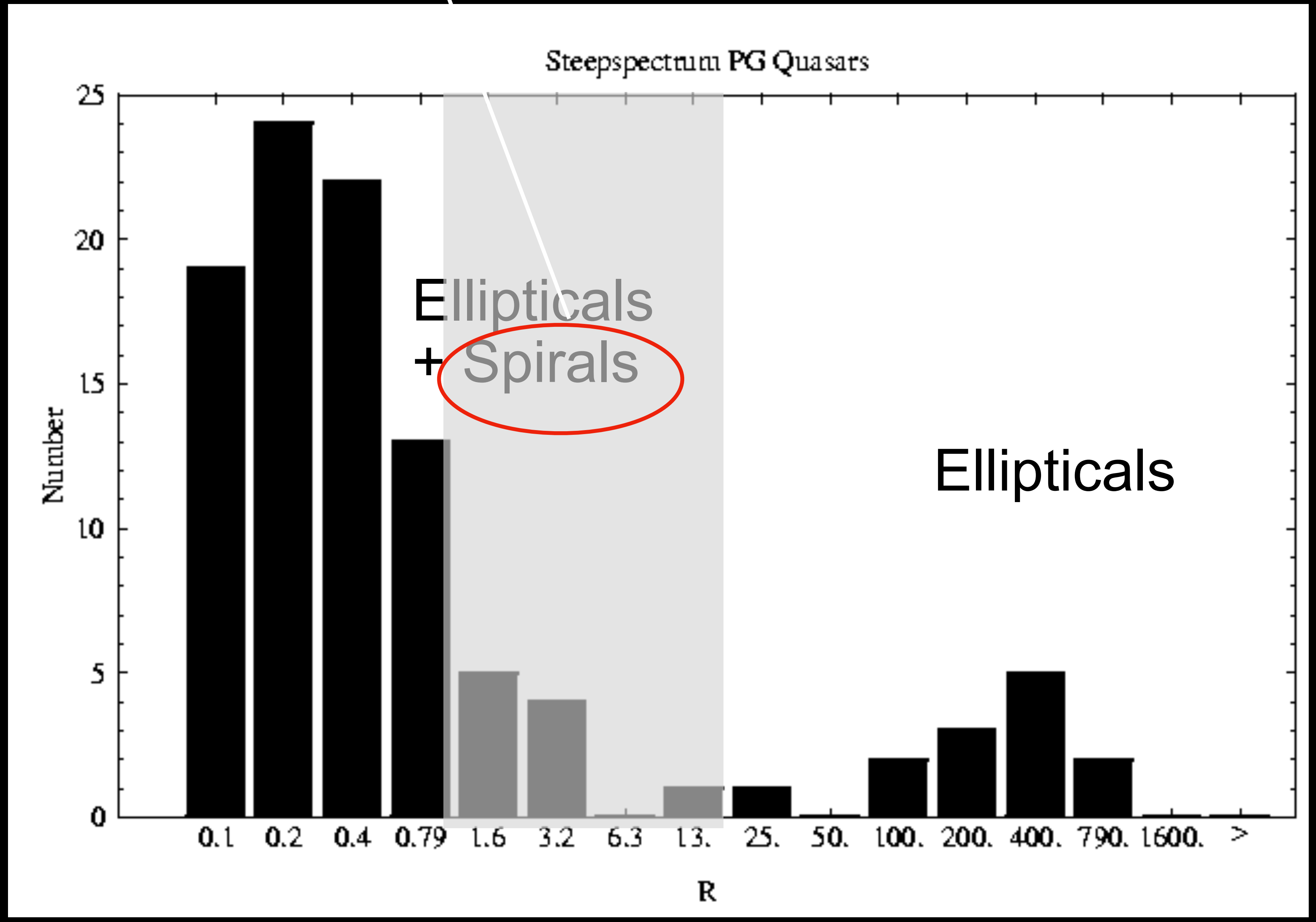
$$R = L_{5GHz}/L_B$$

introduced as a a way to distinguish if the radio emission comes (mainly) from stars or from AGN but too approximate (see later)

Radio-quiet objects show values of R concentrated between 0.1-1, while in **radio-loud sources the R values range from 10 to 100** (Kellerman et al. 1989), so that the boundary between the two classes is normally defined at R = 10 (Visnovsky et al. 1992; Kellerman et al. 1989).

Not really a dichotomy and nature of “radio-quiet” more complex than only star-forming!

spiral galaxies host only low radio luminosity (radio-quiet) AGN

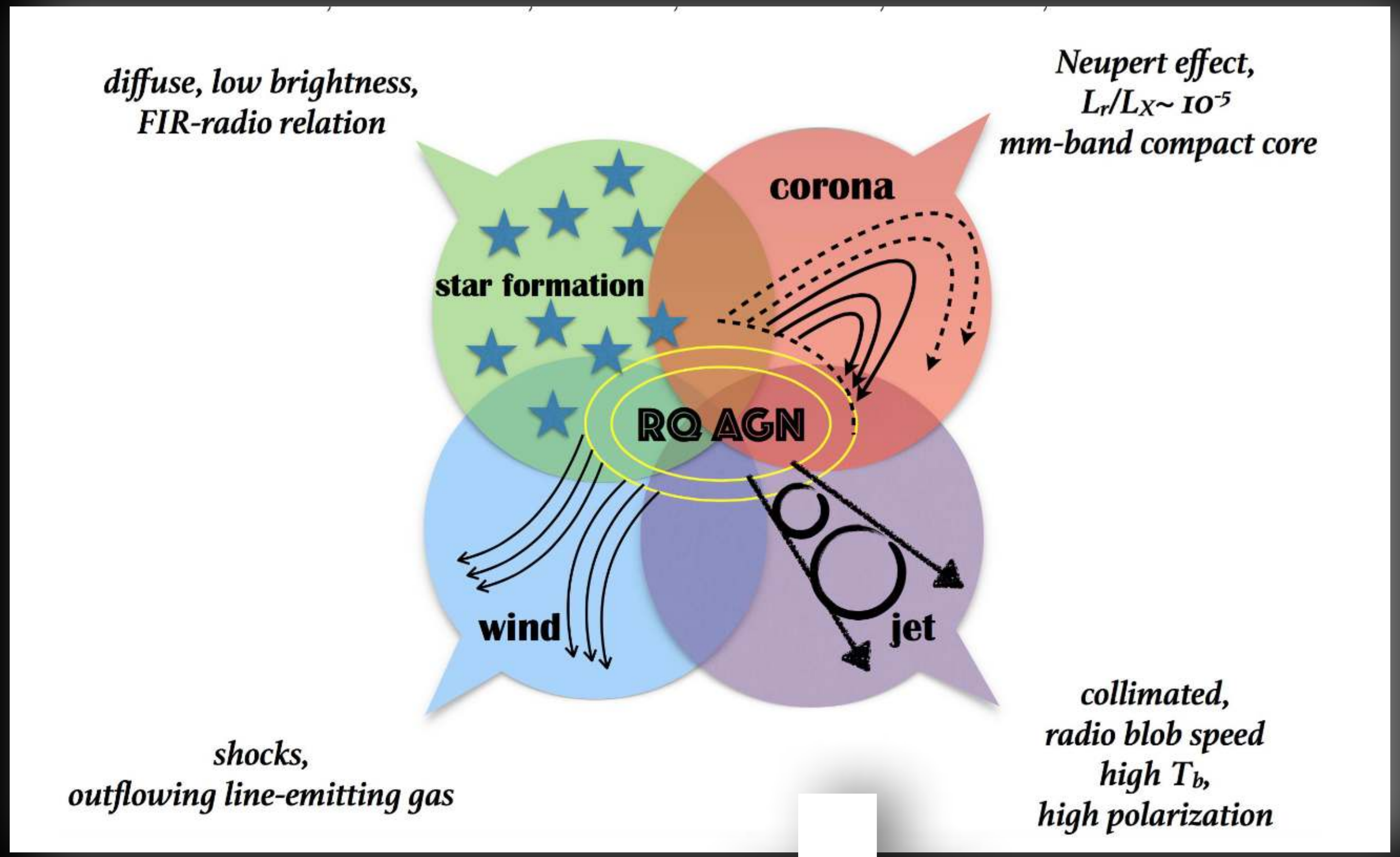


radio-quiet radio-loud

R=radio/optical flux

Kellermann et al. (1989)
Falcke, Sherwood, Patnaik (1996)

- ⋆ Originally suggested to separate radio from star-formation and AGN: indeed many radio-quiet are found in spiral galaxies
- ⋆ Situation more complicated: radio from AGN also in radio quiet, variety of possible origins for the radio emission (including from jets, which is the dominant process in radio-loud)

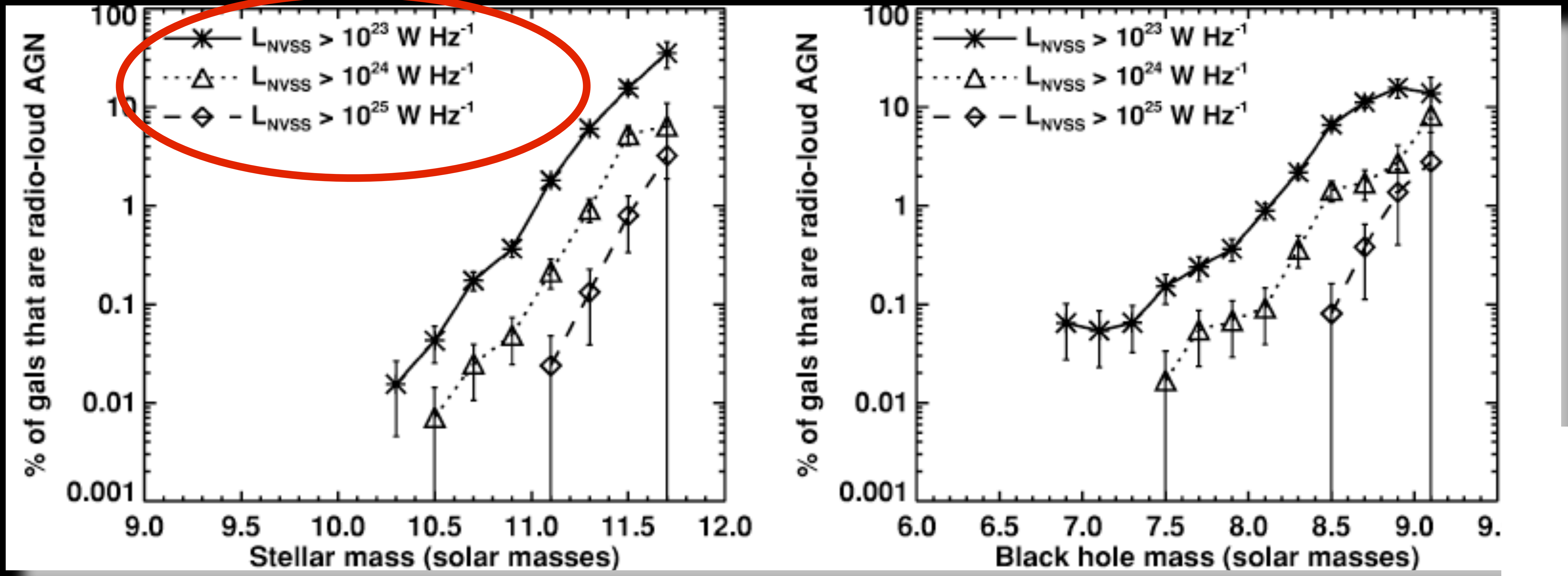


review Panessa et al. 2019

the term “radio-quiet” can be **misleading**: better avoid or being more specific!

Why do we care so much about "radio-quiet" sources?
Because much more common (even if the radio emission less spectacular!)

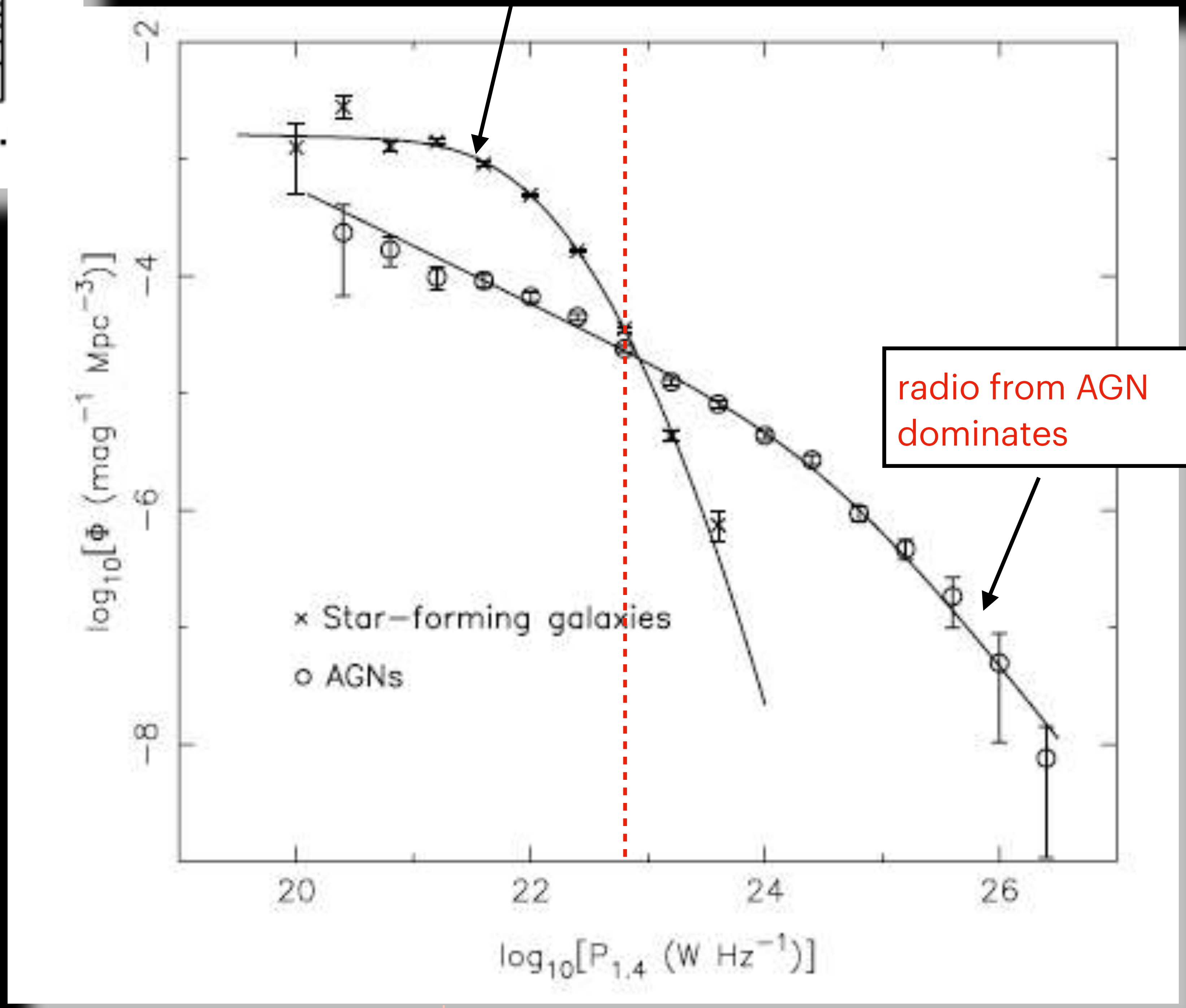
we will see some examples...



Best et al. 2005, Sabater et al. 2019

- ➢ Radio-loud AGN are preferentially hosted by massive early-type galaxies
- ➢ At lower luminosities more sources are hosted by spiral galaxies
- ➢ Fraction of radio AGN increasing with stellar mass of the host galaxy *and with decreasing radio luminosity*:
  for the highest masses, fraction of galaxies that are radio sources >25%

radio from stars and SN dominates



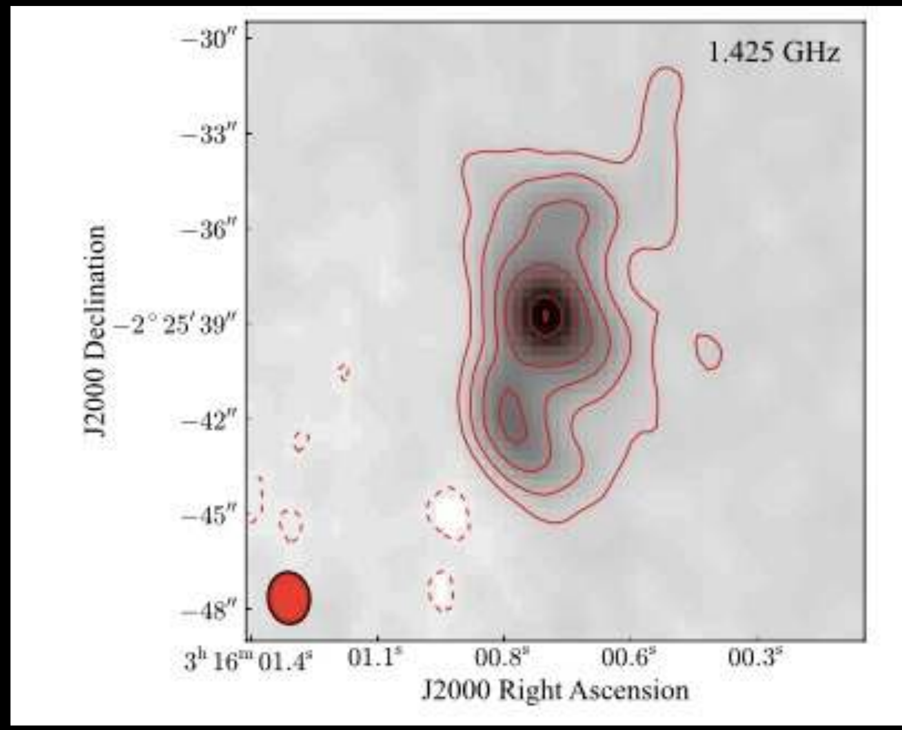
Mauch & Sadler 2007

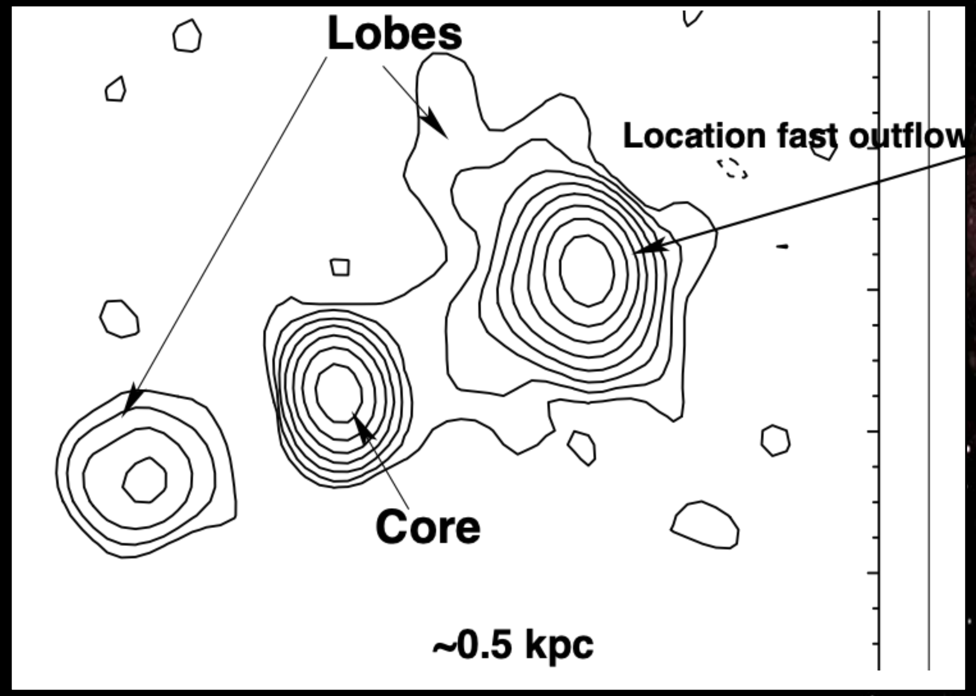
often called “radio-quiet”

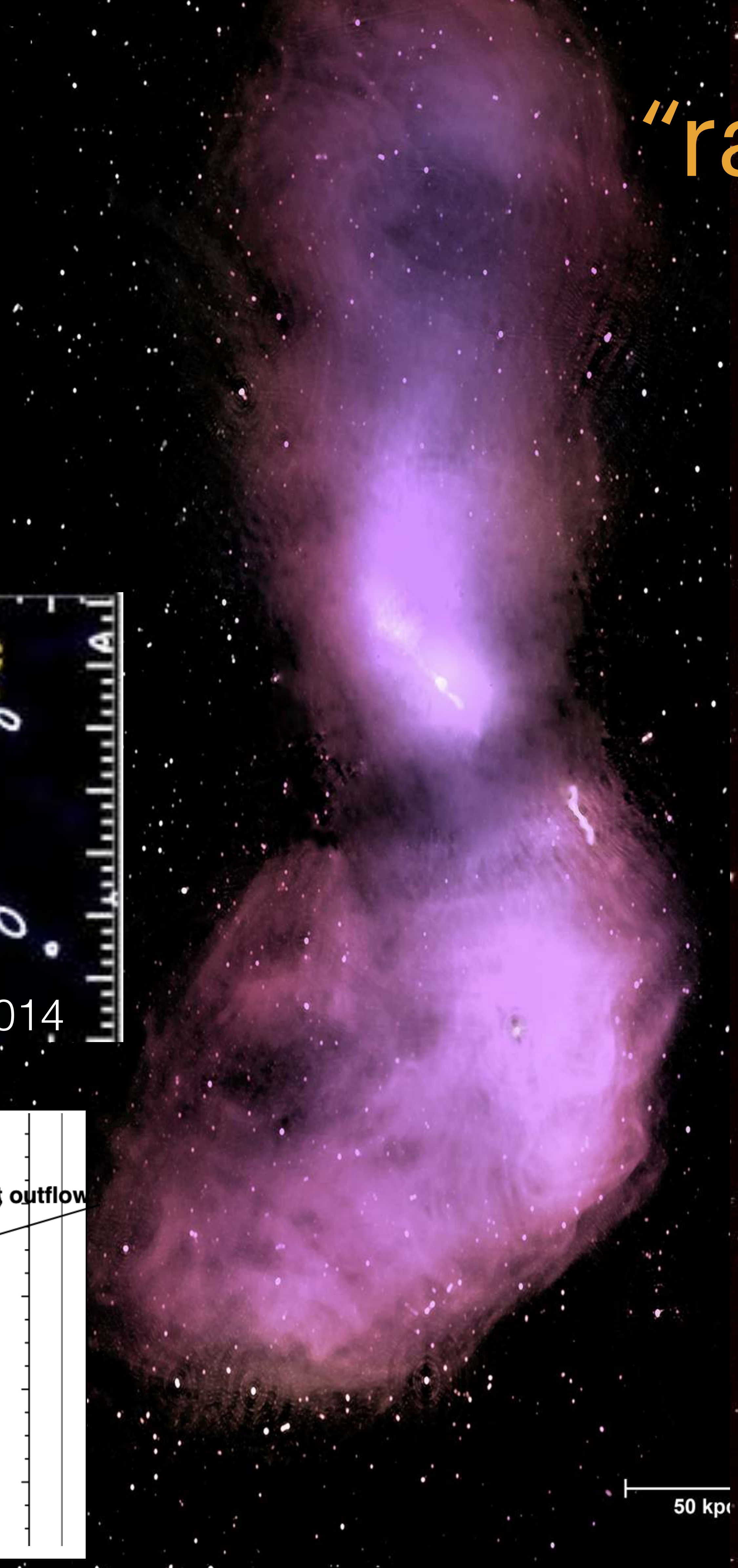
R = L_{5GHz}/L_B <10 (Kellermann et al. 1989)

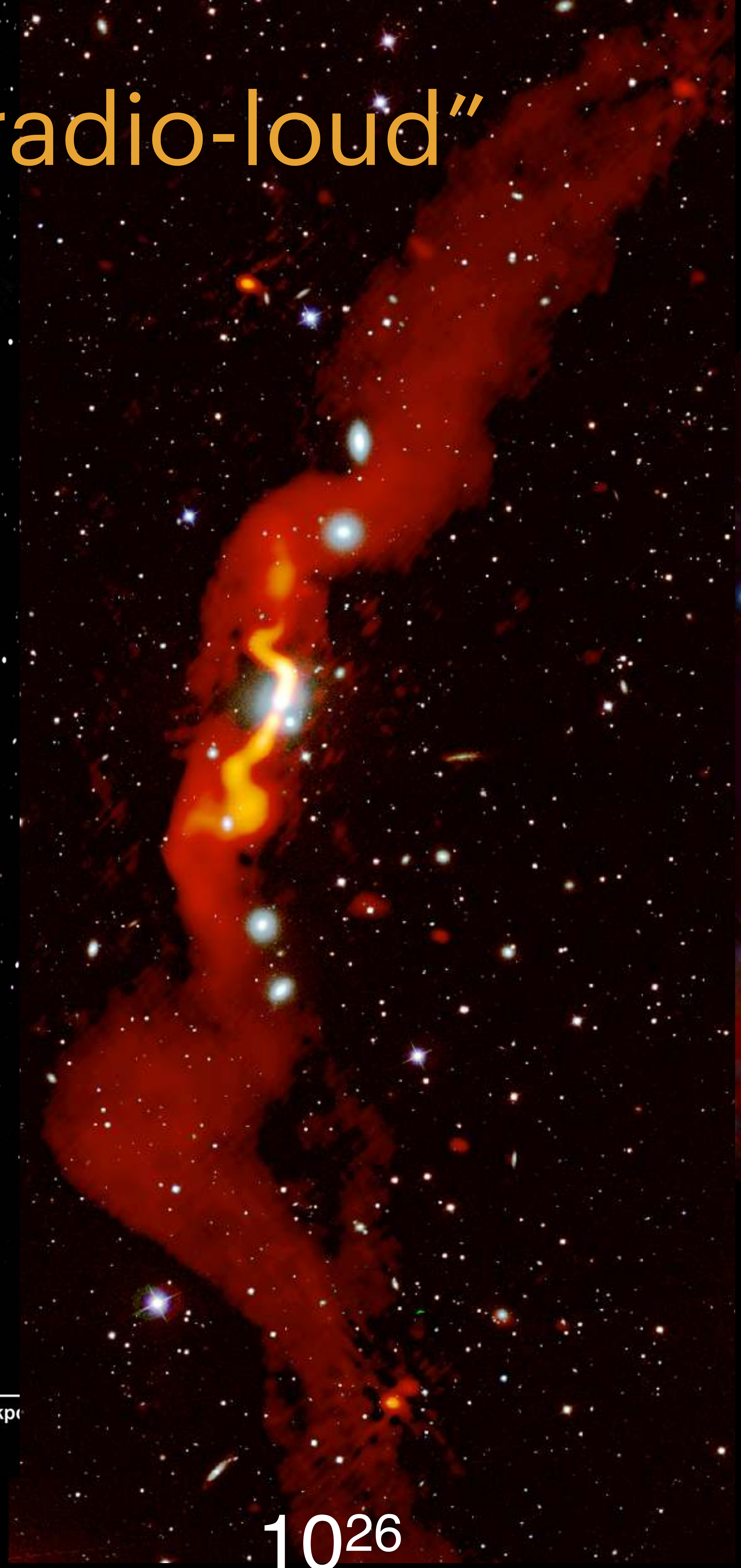
“radio-loud”

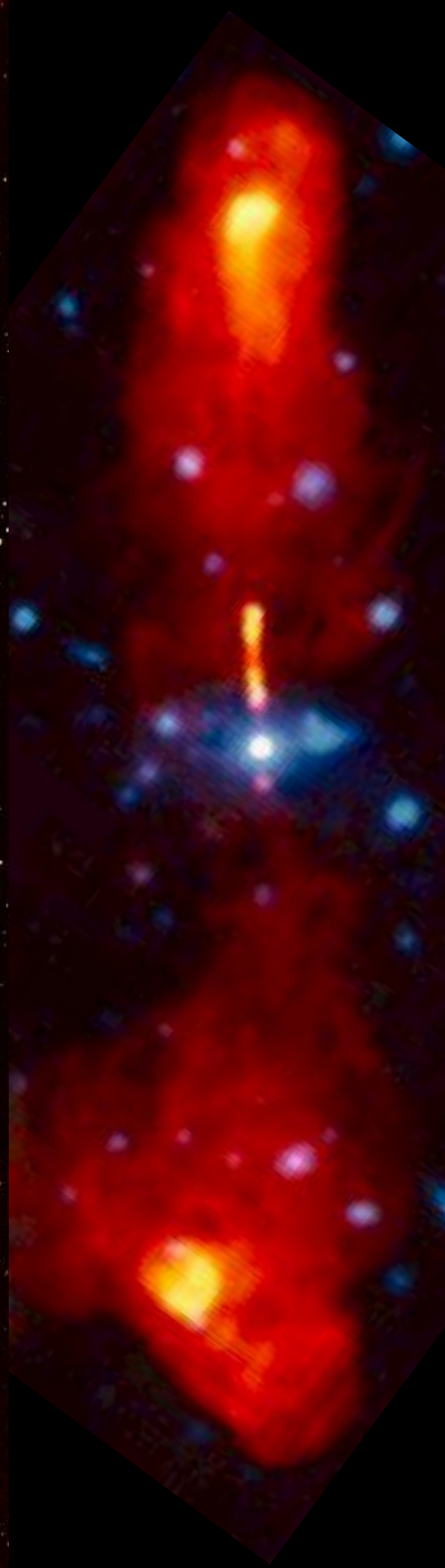
Alatalo et al. 2012











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

radio luminosity

But let's first look at what is the structure of a radio-loud AGN

↓

so that later is clear the difference for radio-quiet...

Radio AGN

(either radio loud or radio quiet)

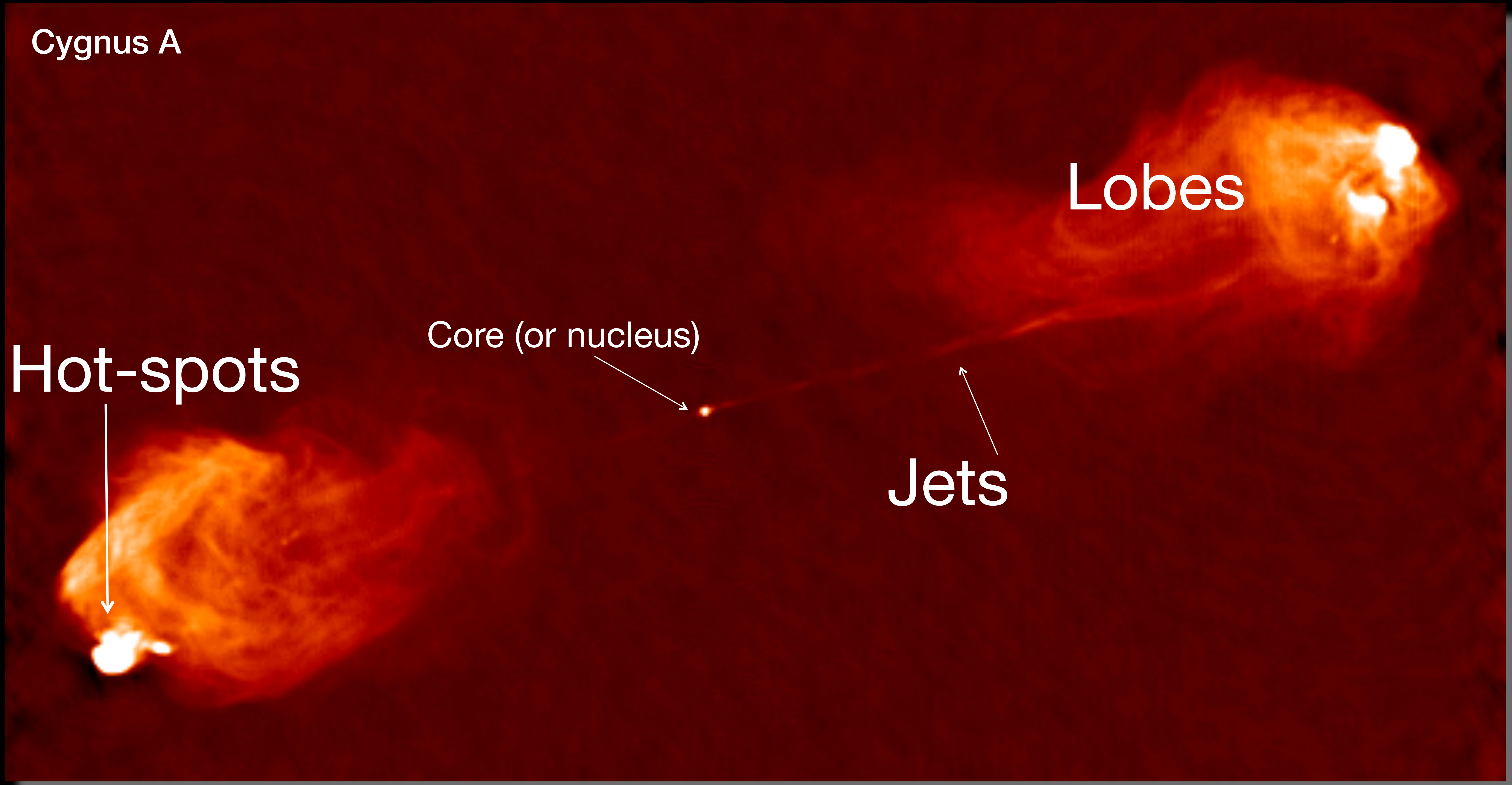
we will call them: **radio galaxies**

... typically early-type galaxies

radio sources = more general (also spirals)

radio quasars = associated with quasar objects...

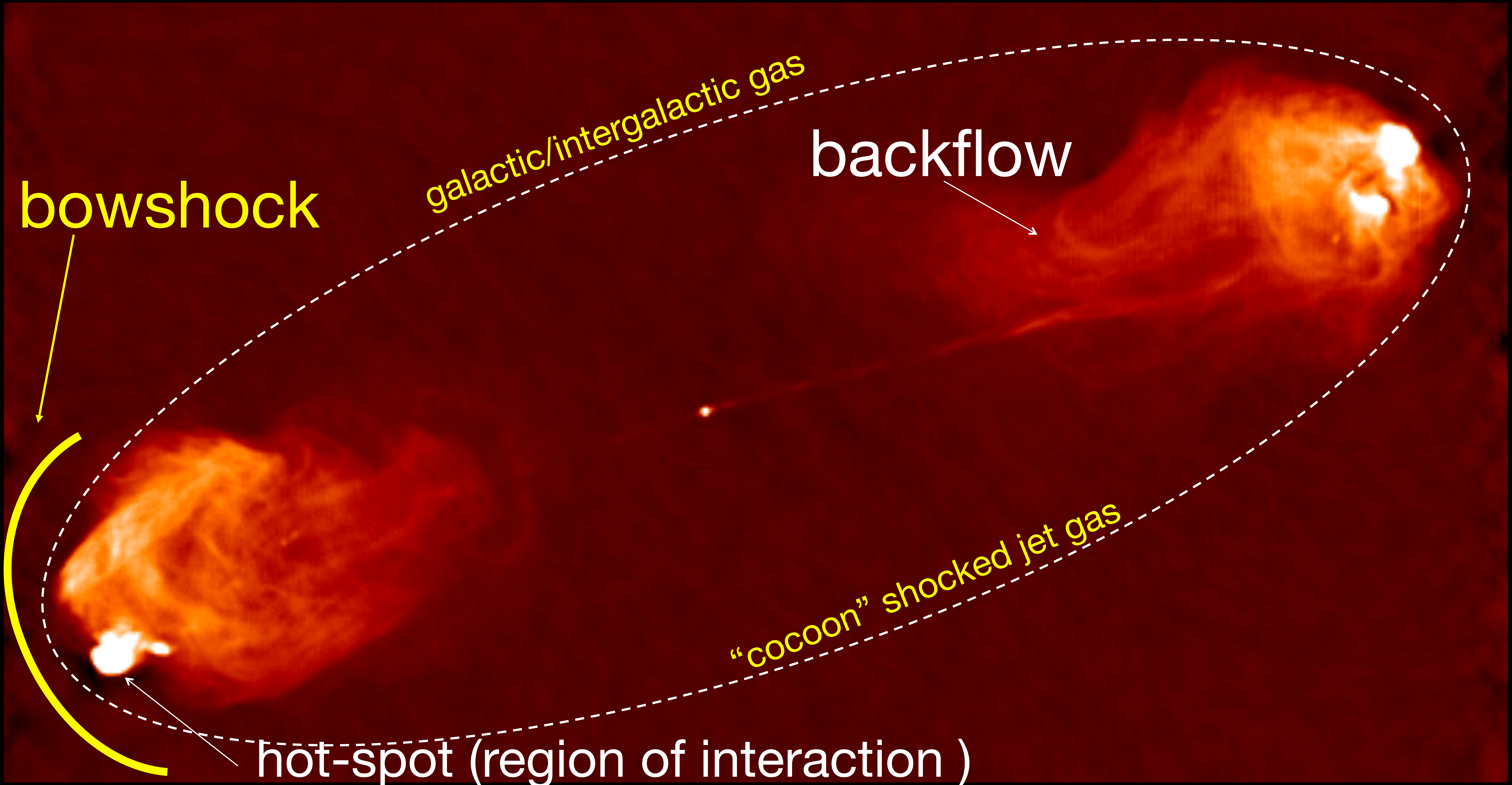
A prototypical (powerful) radio galaxy



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 radio galaxy

Cygnus A



Complex structure getting closer to the SMBH

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

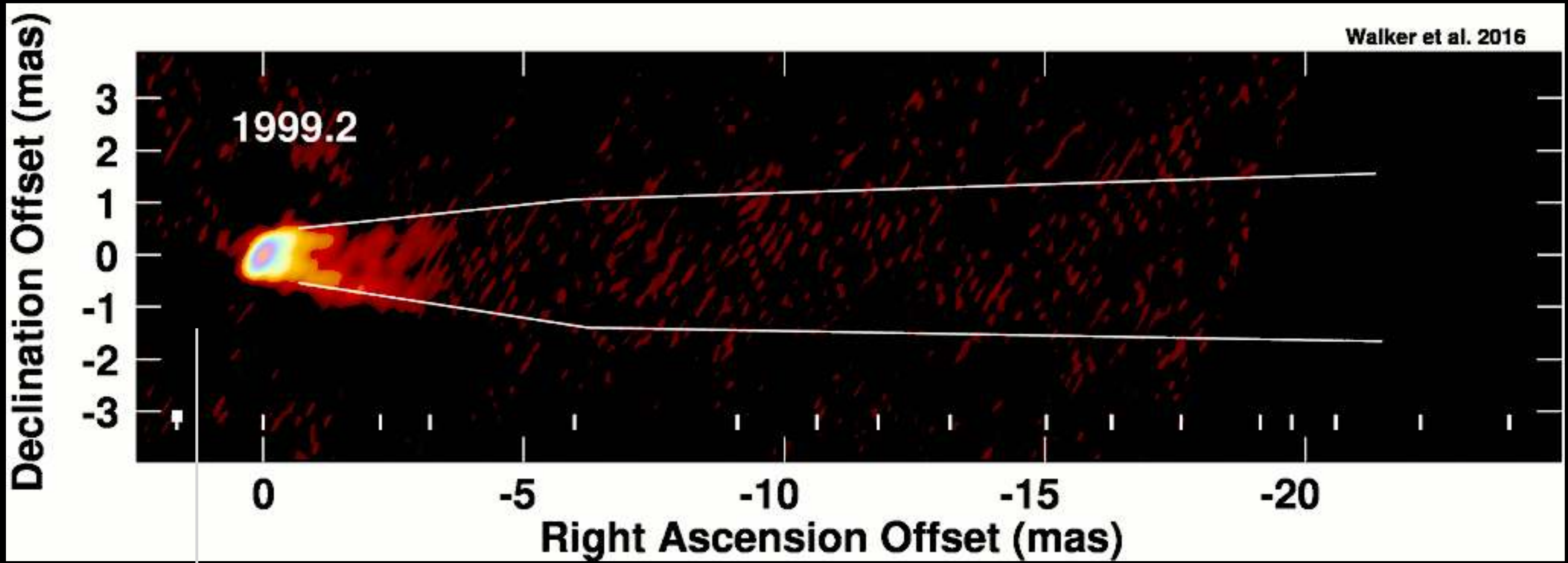
This theory explains the extraction of energy from magnetic fields around an accretion disk, which are dragged and twisted by the spin of the black hole. Relativistic material is then launched by the tightening of the field lines.

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

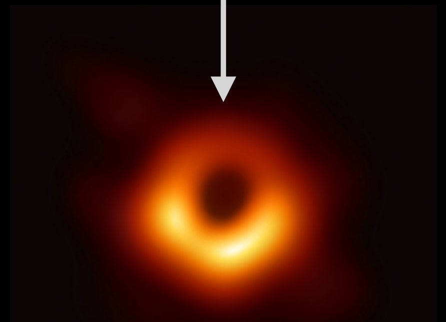
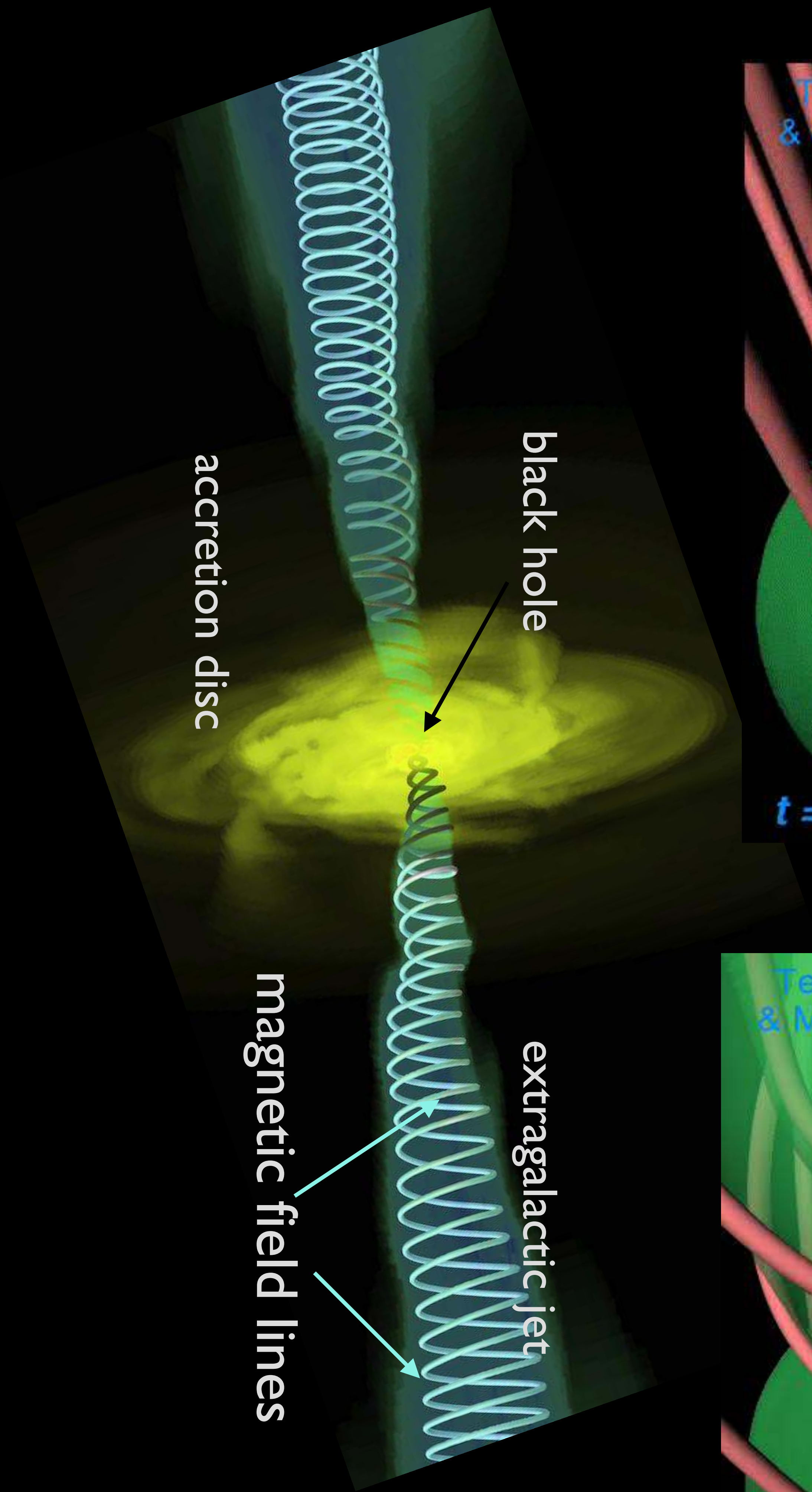
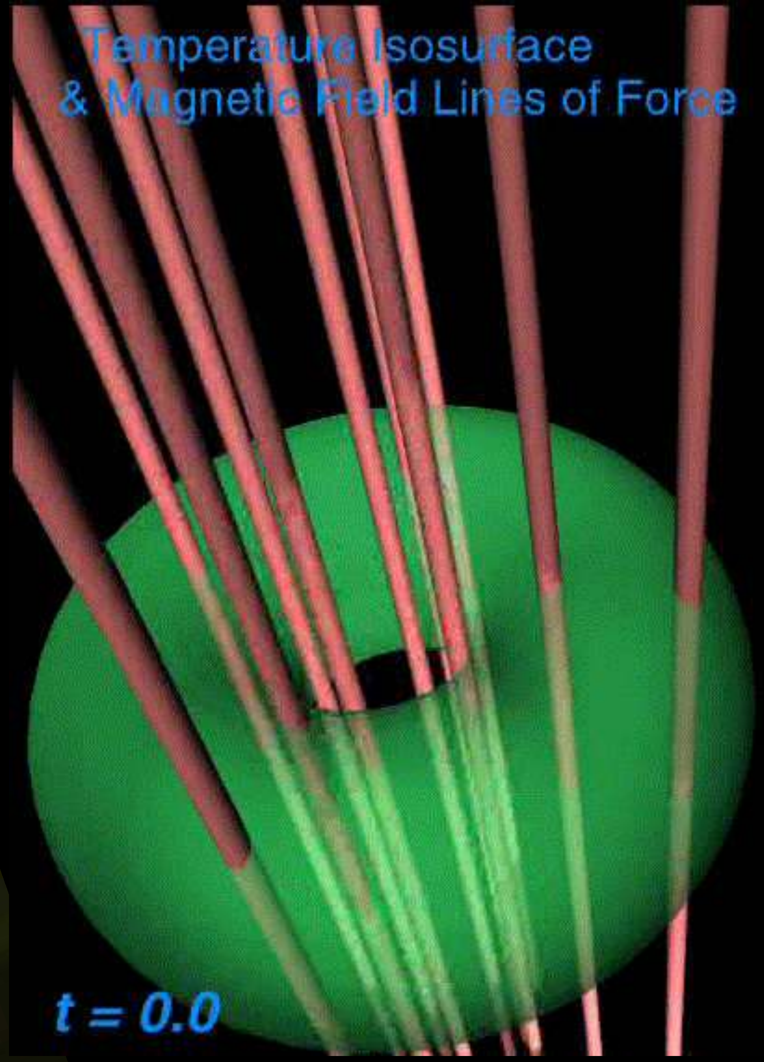
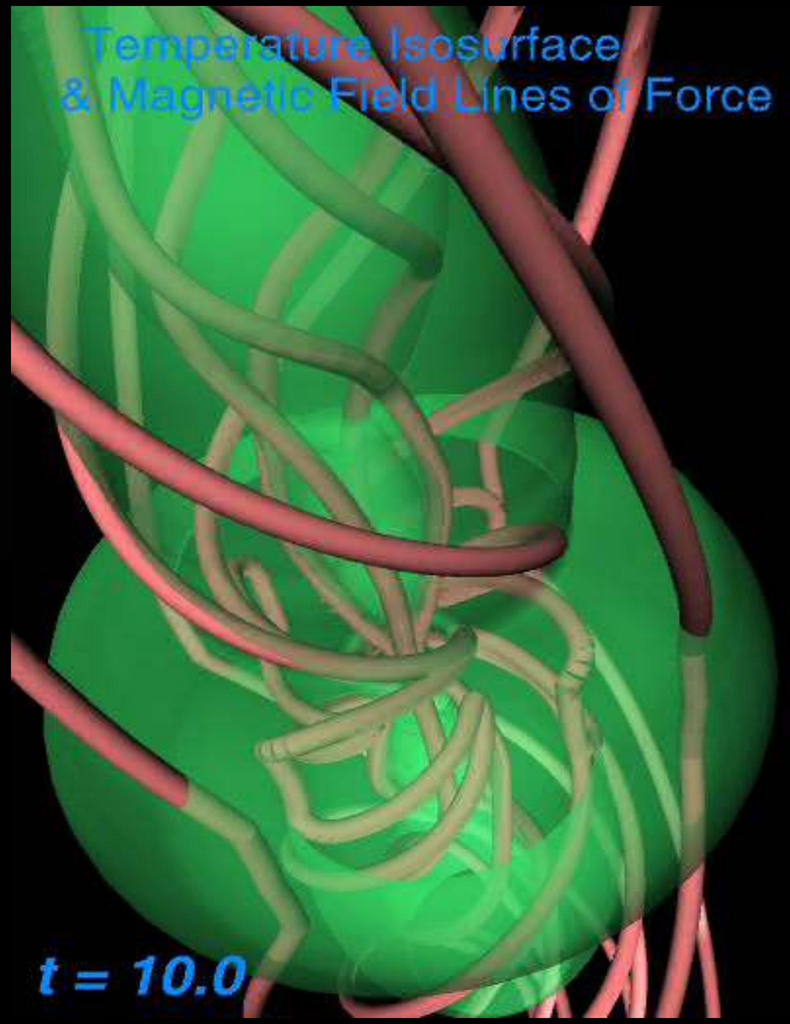


Image from Evnt Horizont Telescope (ETH)



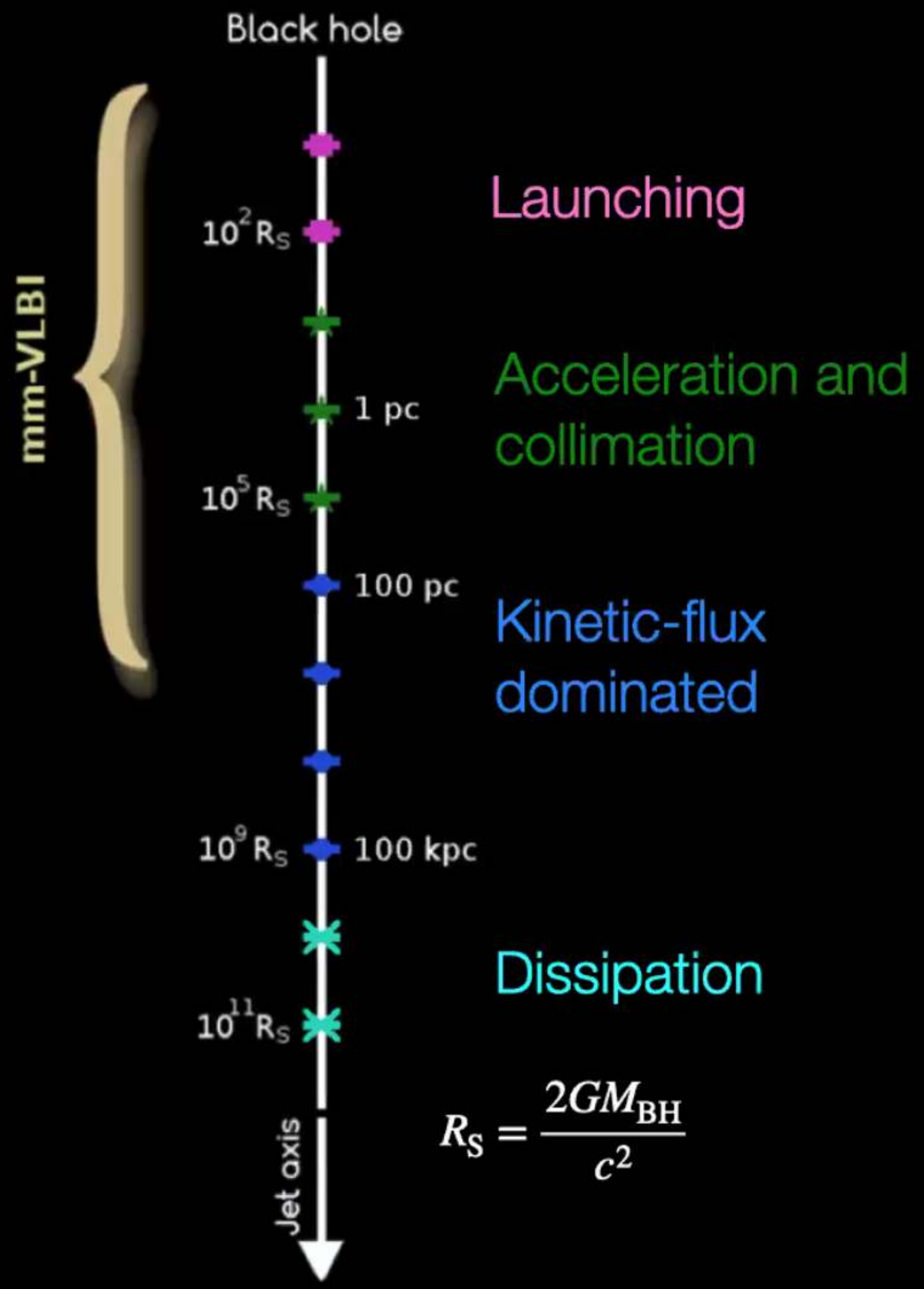




Uchida et al. 1999
Meier et al. 2001

Jets are considered "light": composition mostly electrons, but still not fully clear

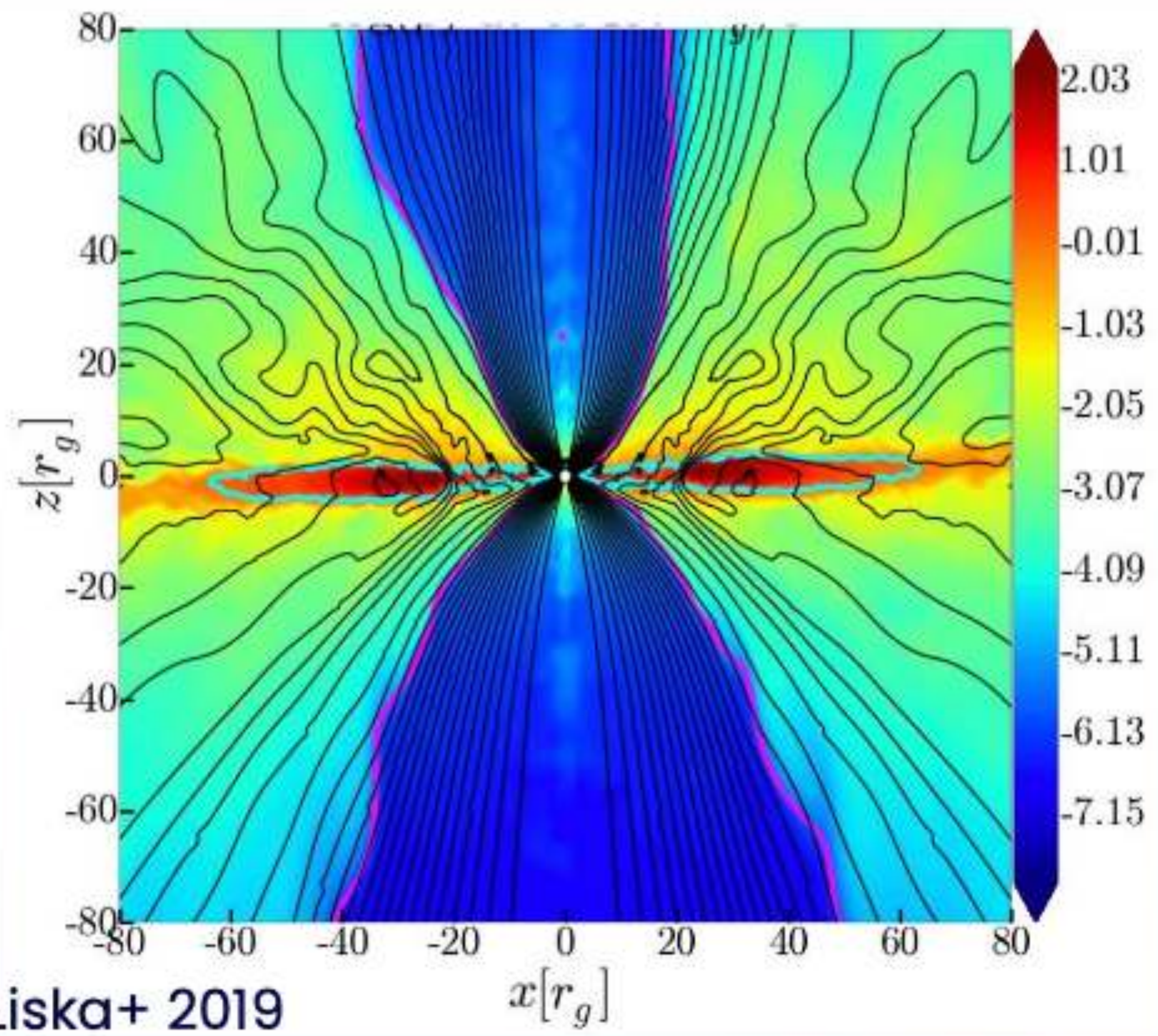
The luminosity of the jet is a fraction of its power ➝ importante for the impact on the host galaxy



$$R_S = \frac{2GM_{BH}}{c^2}$$

Boccardi et al. 2017

Jet power - basics



Liska+ 2019

$$P_{BZ} \propto (BaM_{BH})^2$$

Controlling parameters:
- magnetic flux → accretion rate
- black-hole spin
- black-hole mass

not easy parameters to measure!

empirical relations to estimate the jet power commonly used.

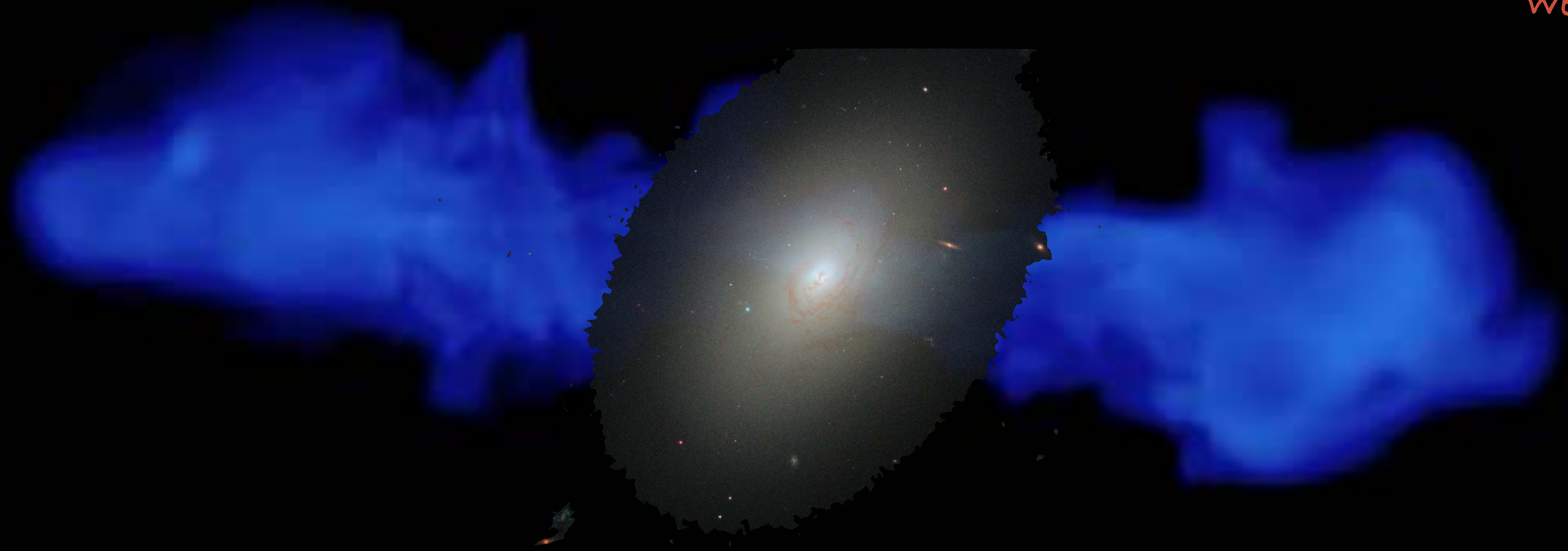
We will get back to this in Les 3

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 can stops and restart

we will see these phases in Les 3



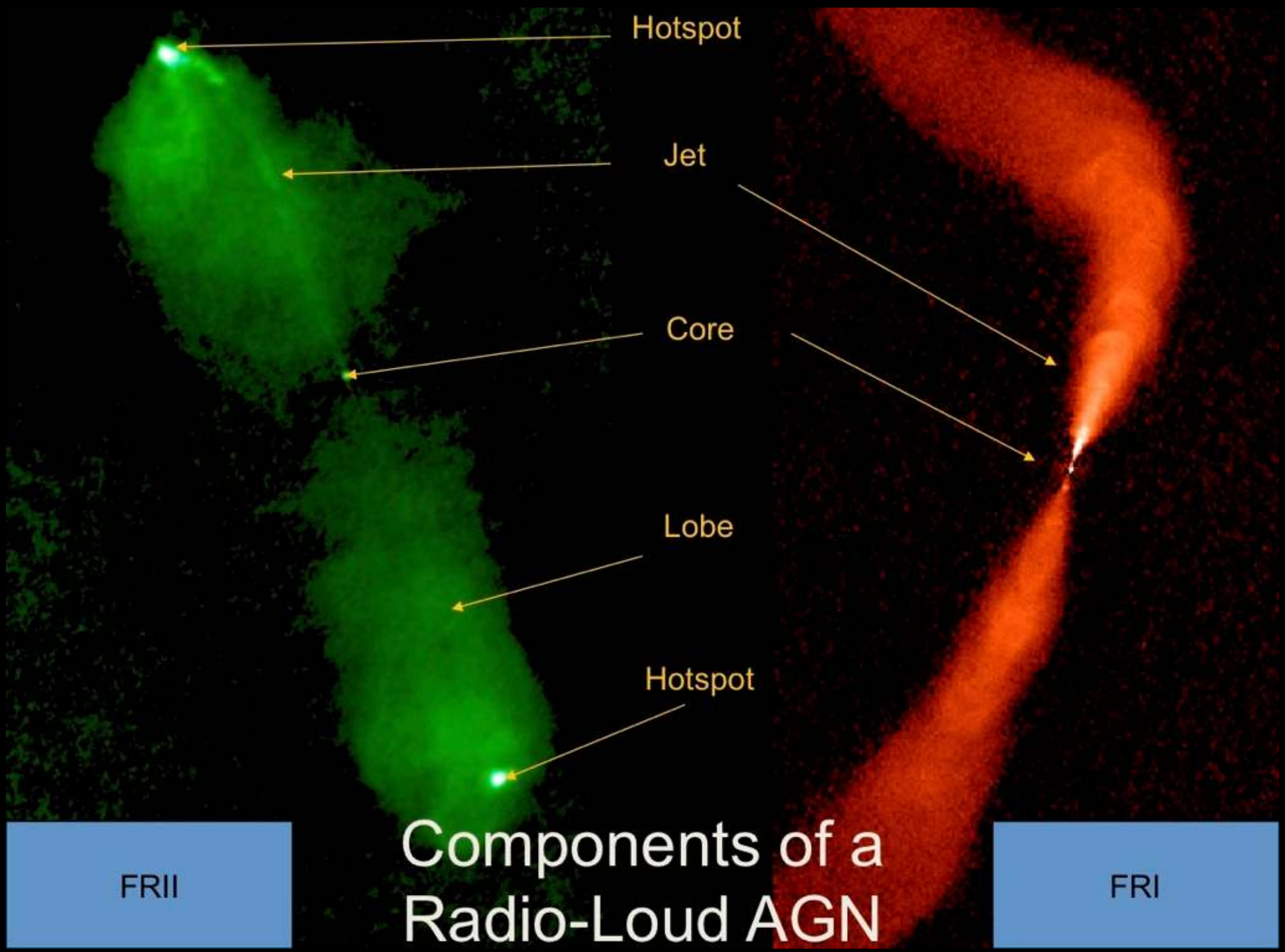
Heinz et al. 2006

Structure of radio 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 larger 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,

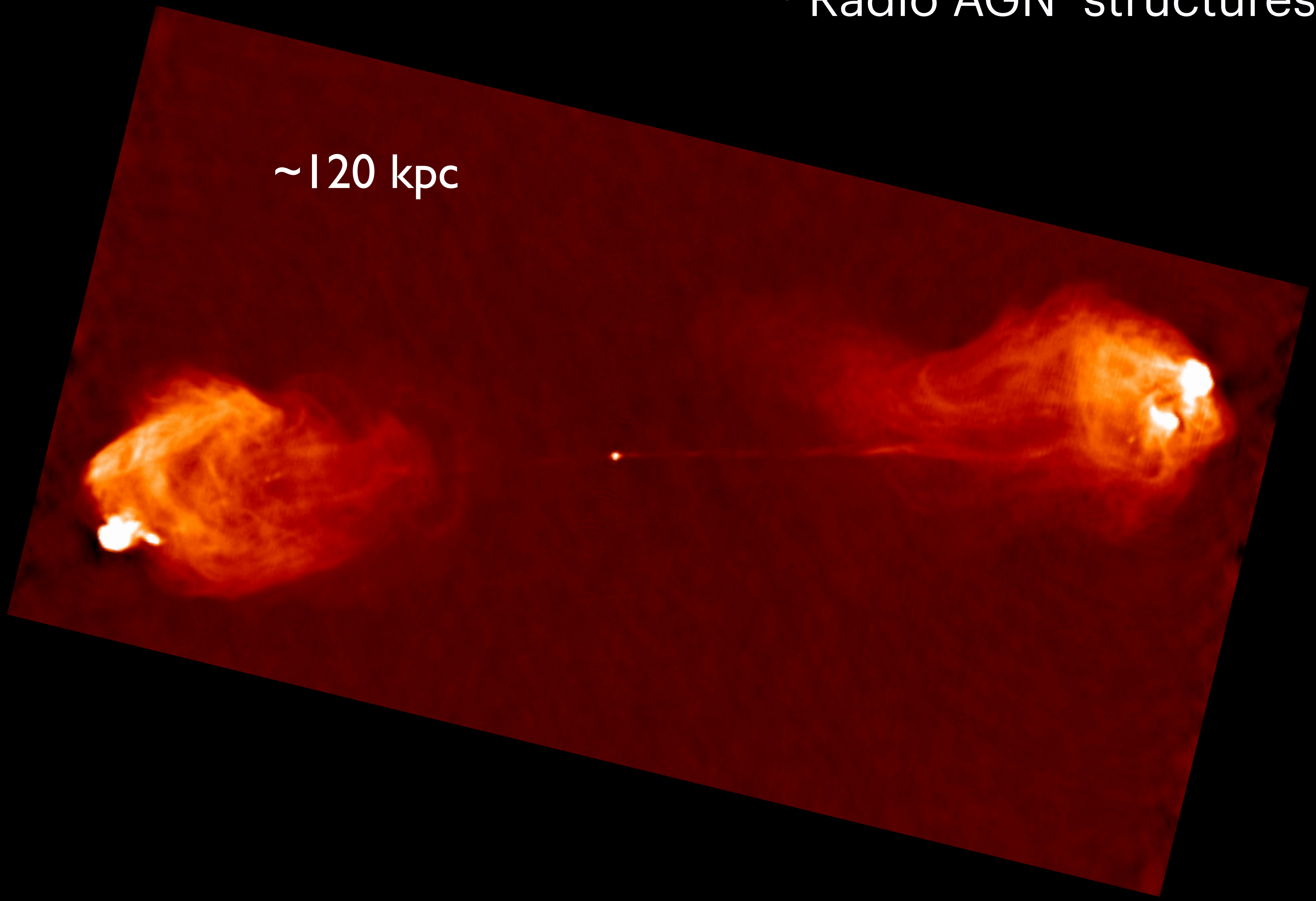
Croston et al. 2018
Mingo et al. 2019

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 - much larger than the optical host galaxy.



Similar morphologies on small and large scales

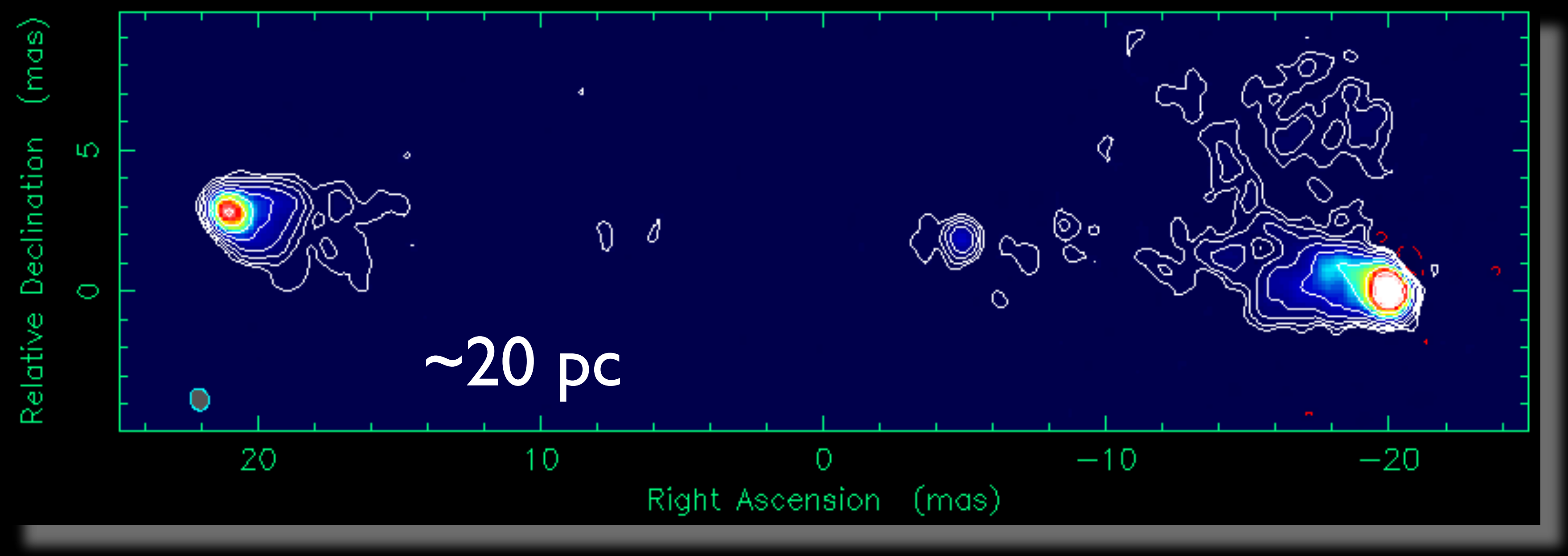
Sizes resulting from:
evolutionary stage (smaller ➔ younger)

but expansion also depends on the interaction with ISM

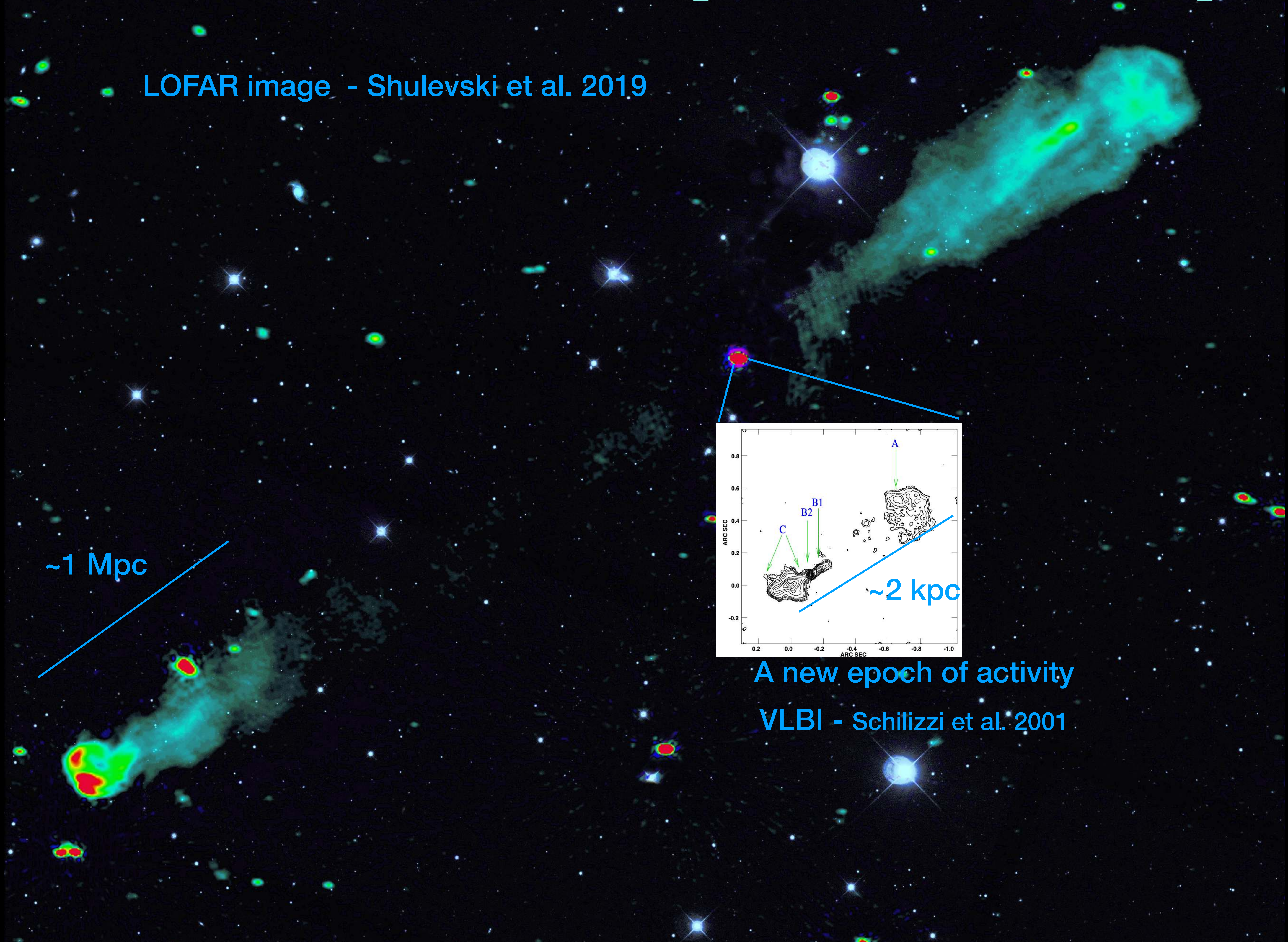
or

orientation effects

... example of giant radio galaxies with LOFAR

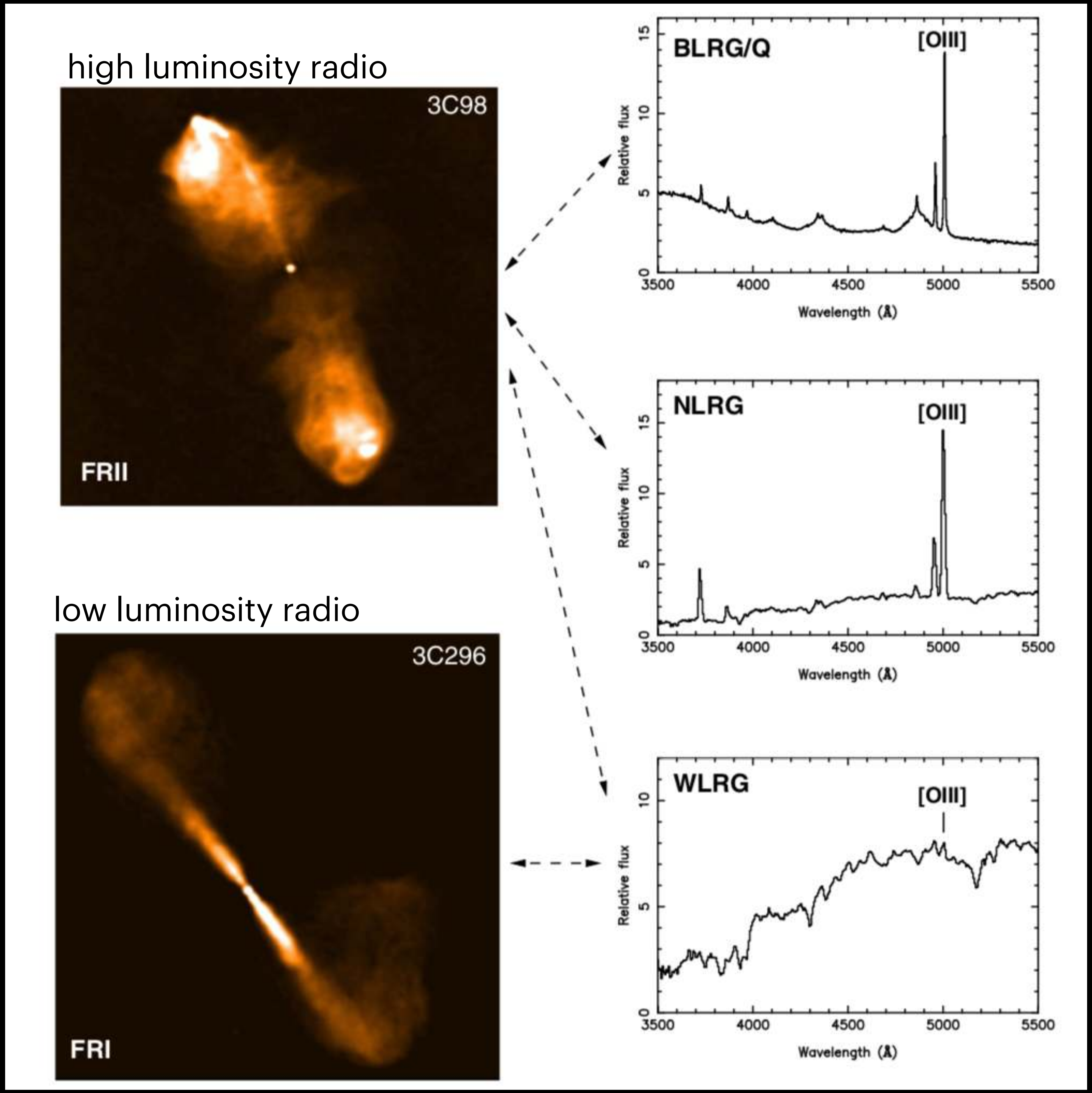


Extreme radio AGN: giant radio galaxies



What type of AGN are the radio galaxies?

From Tadhunter 2016



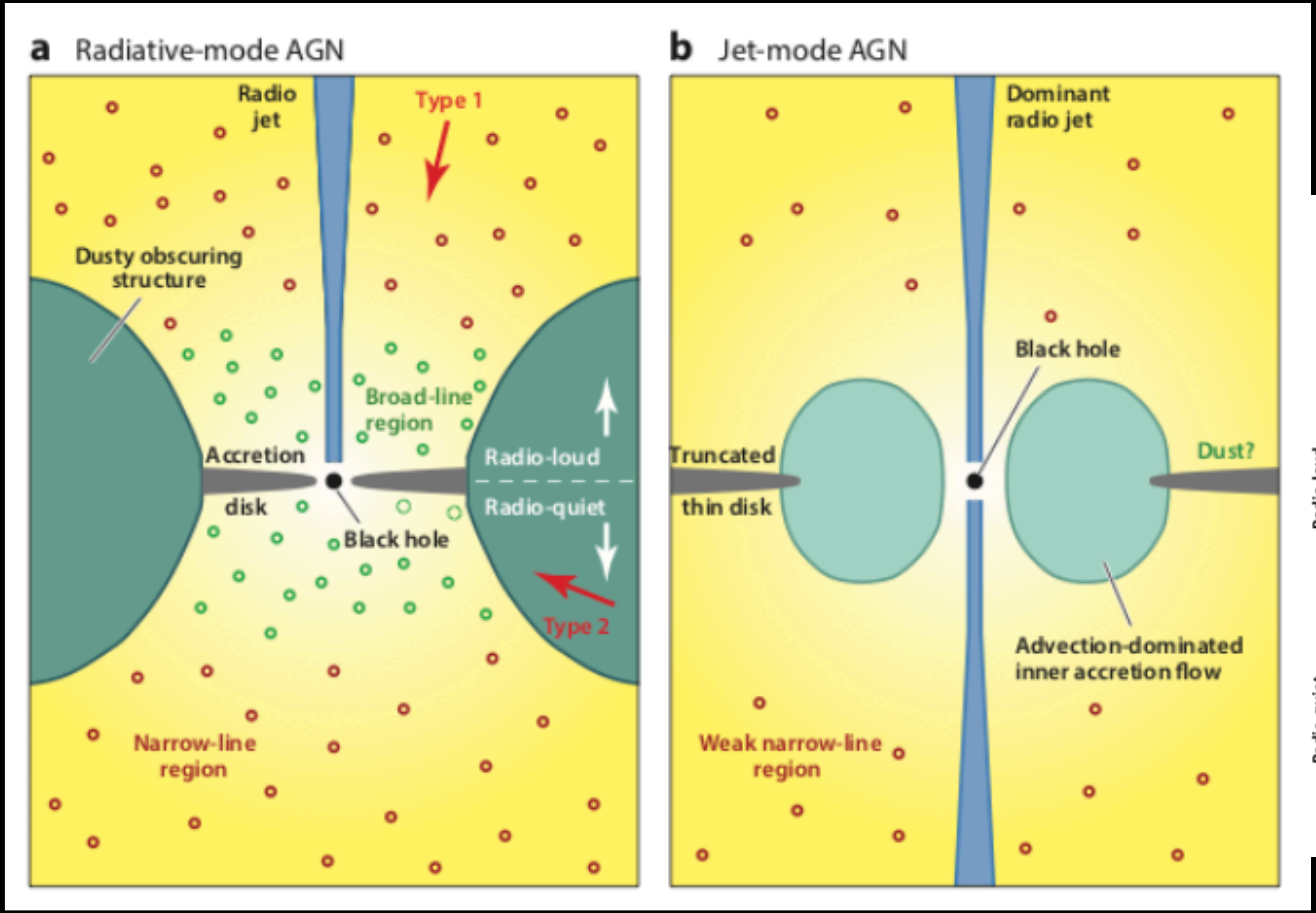
comparison radio and presence of ionised gas

high excitation, broad line RG

high excitation RG

low excitation RG

What makes the difference in ionisation?



Heckman & Best 2014

	$L/L_{Edd} \lesssim 0.01$ — Jet mode	$L/L_{Edd} \gtrsim 0.01$ — Radiative mode: Type 2	Radiative mode: Type 1
Radio-loud	**Low-excitation radio source** • Very massive early-type galaxy • Very massive black hole • Old stellar population; little star formation • Moderate radio luminosity • FR1 or FR2 radio morphology • Weak (or absent) narrow, low-ionization emission lines	**High-excitation radio source** • Massive early-type galaxy • Massive black hole • Old stellar population with some ongoing star formation • High radio luminosity • Mostly FR2 morphology • Strong high-ionization narrow lines	**Radio-loud QSO** Host-galaxy properties like high-excitation radio source, but with addition of: • Direct AGN light • Broad permitted emission lines • Sometimes, beamed radio emission
Radio-quiet	**AGN LINER** • Massive early-type galaxy • Massive black hole • Old stellar population; little star formation • Weak, small-scale radio jets • Moderate strength, low-ionization narrow emission lines	**Type 2 QSO / Seyfert 2** • Moderately massive early-type disk galaxy with pseudobulge • Moderate-mass black hole • Significant central star formation • Weak or no radio jets • Strong high-ionization narrow lines • QSOs more luminous than Seyferts	**Radio-quiet QSO/Seyfert 1** Host-galaxy properties like Type 2 QSO and Seyfert 2, respectively, but with addition of: • Direct AGN light • Broad permitted emission lines • Bias toward face-on orientation
	Light dominated by host galaxy	Light dominated by host galaxy	Direct AGN light

Radiatively efficient AGN

Optically thick (geometrically thin) accretion disks - reaching into the radius of the innermost stable orbit around the central supermassive black hole can be considered cooling-dominated flows: **cooling efficiently** and the energy is **radiated**

Jets are rarer but more powerful

Radiatively inefficient AGN

most of the accretion power is not radiated (no accretion disk) but carried into the black hole (➜ geometrically thick advection-dominated accretion flow, cooling inefficient). The majority of the energetic output is released in bulk kinetic form through radio jets.

radio emission more common but lower power

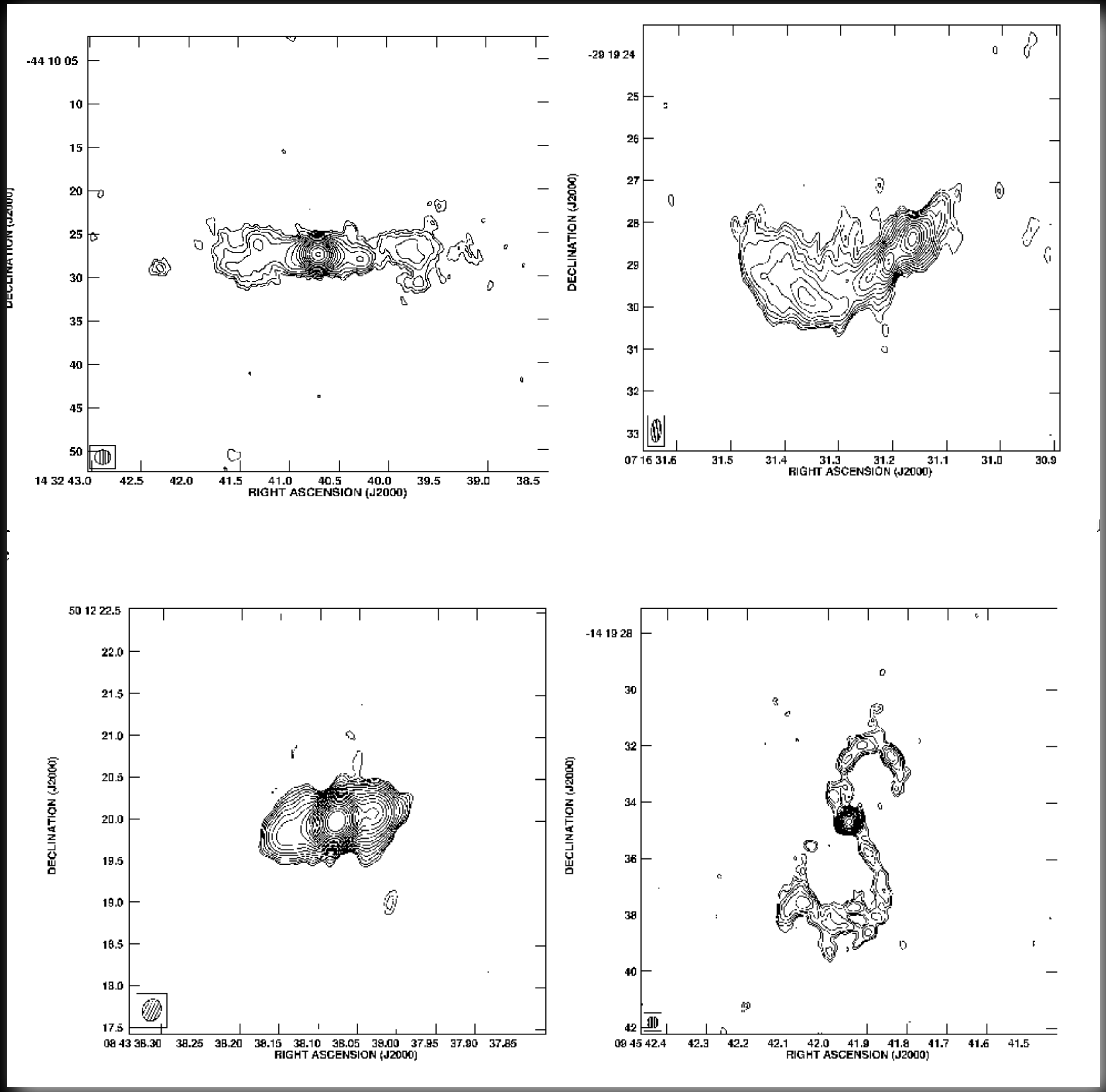
Back to “radio-quiet”
or better low-luminosity radio AGN

Low luminosity/radio "quiet" radio sources

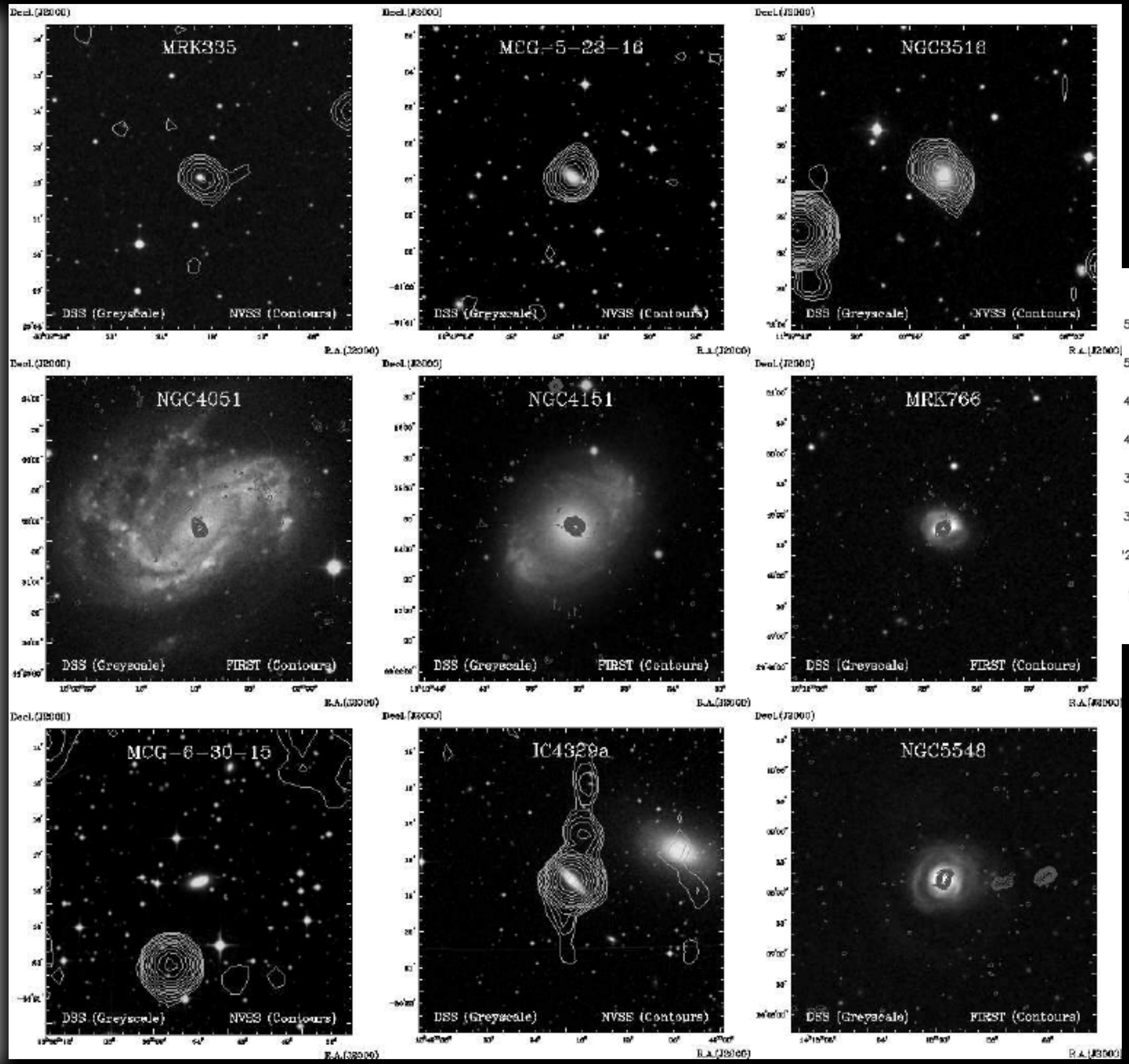
Radio emission: typically small sizes - more complex morphologies

Dominated by entrainment - large fraction of thermal component (not only electrons)....

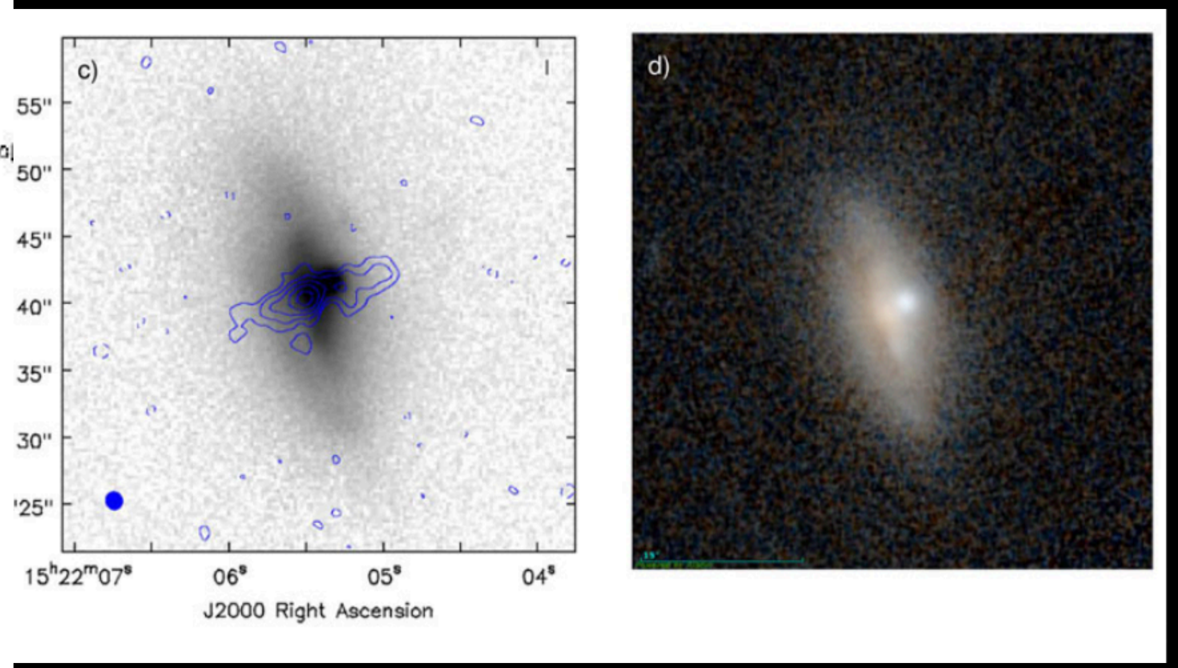
but the distribution of the radio emission can tell you if it is NOT coming from stellar emission but from the AGN



Leipski et al. 2006



Kadler et al. 2004

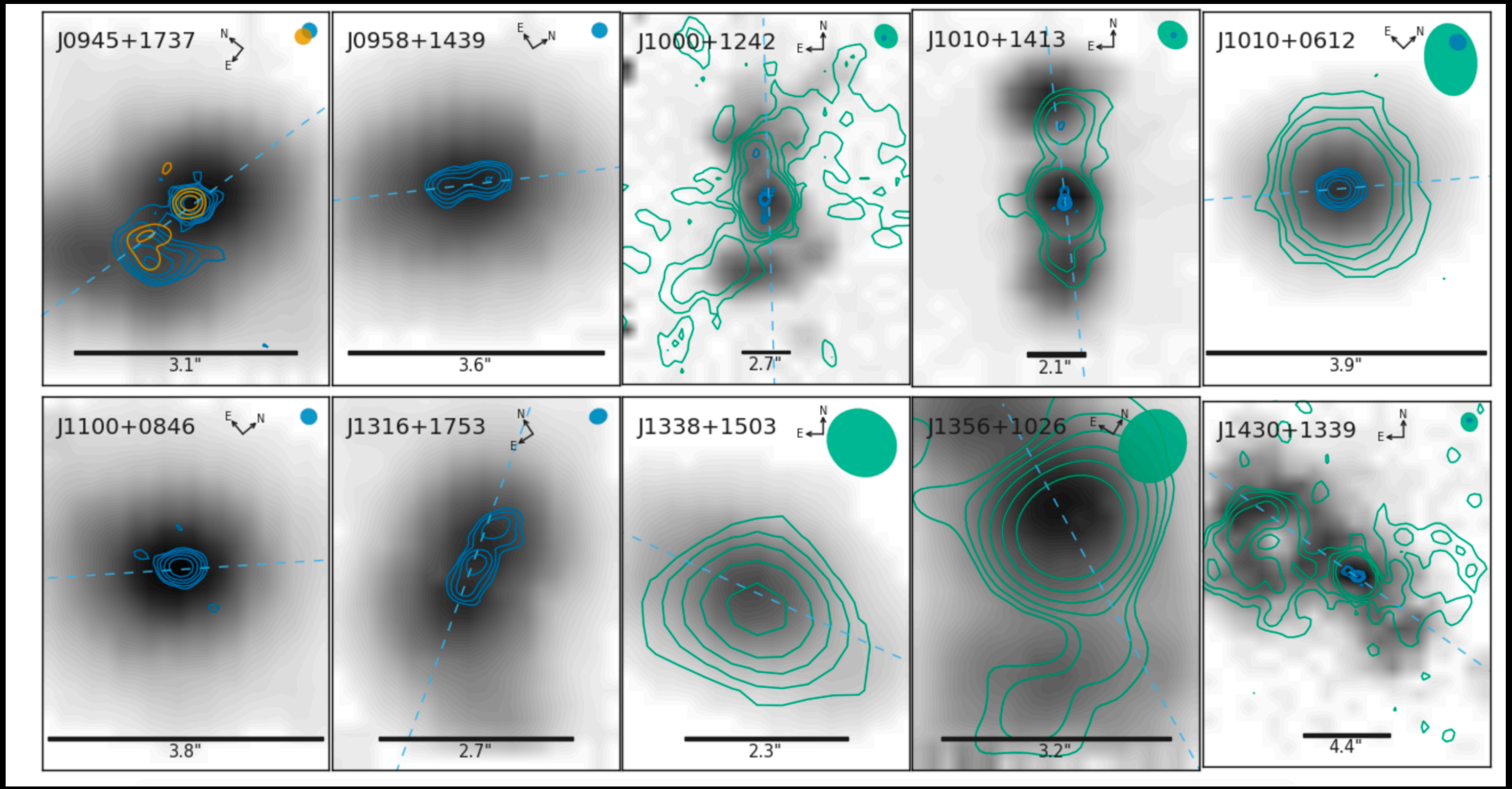


Järvelä et al. 2021

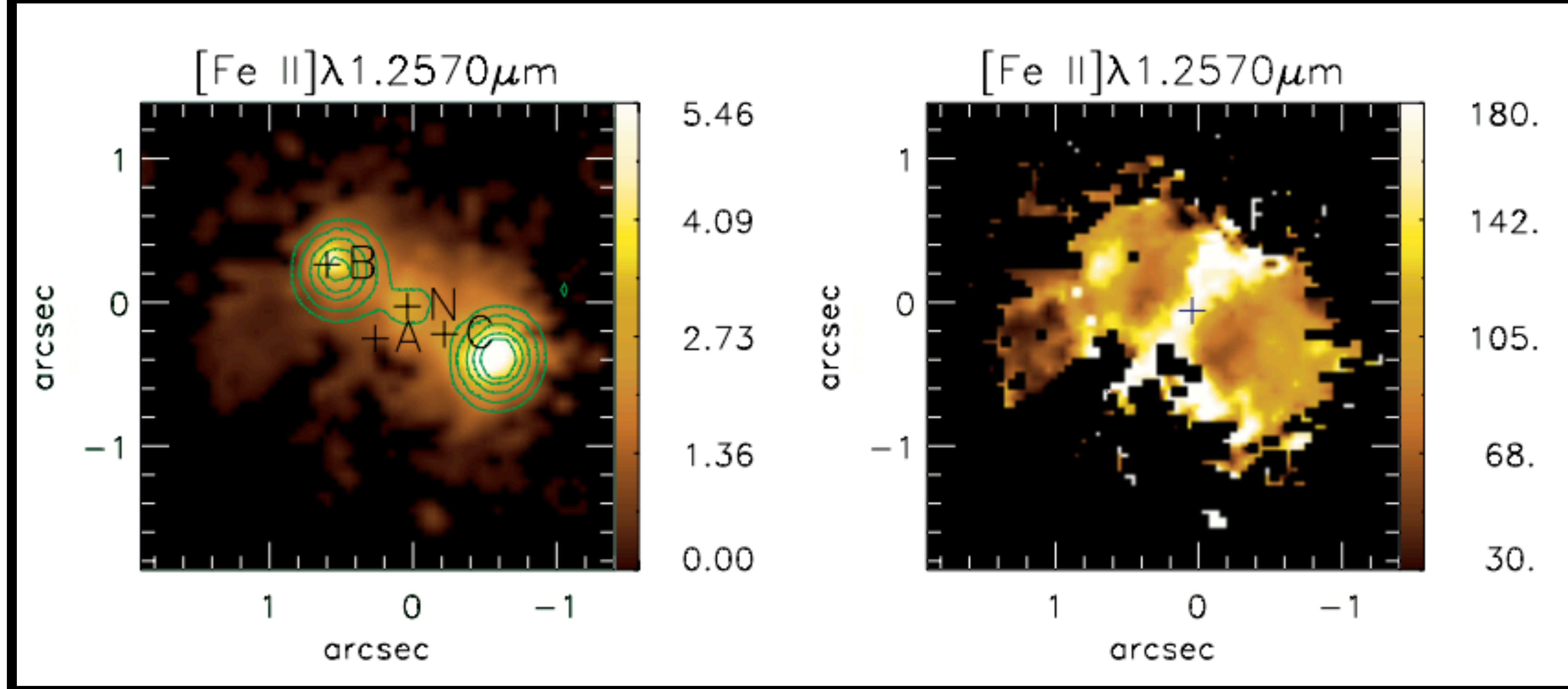
Hot topic: spatial coincidence radio - ionised gas in low luminosity AGN

signature of the radio affecting the surrounding gas?

Jarvis et al 2019



The distribution of [O III] emission (S/N maps) with contours overlaid from the radio images



Riffel, Storchi-Bergmann et al. 2014

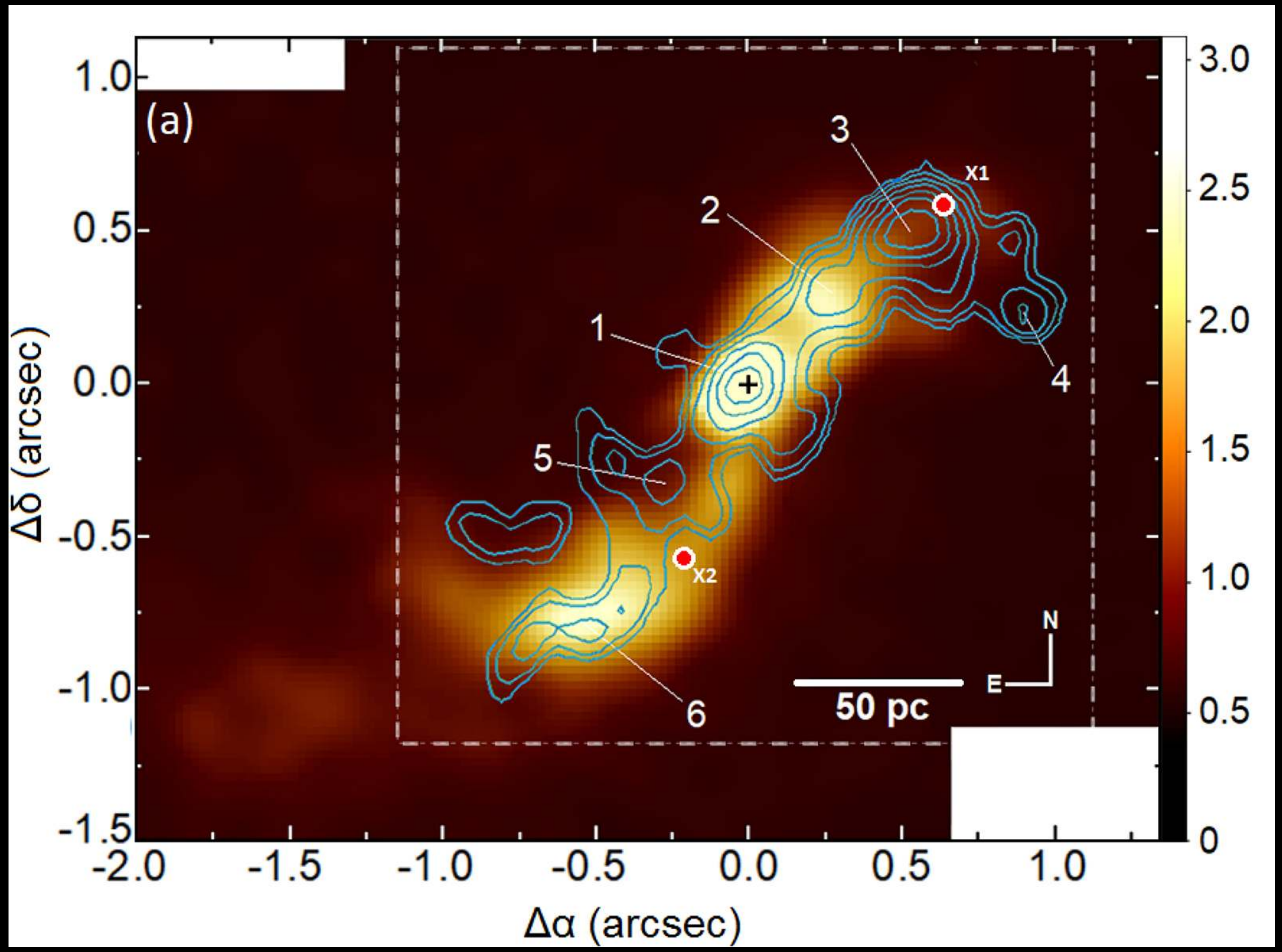
NGC5929 - [Fe II] λ1.25 μm flux distribution with contours of the radio image overlaid (Ulvestad & Wilson 1989)

Radio quiet obscured quasars: ~80–90 per cent of these nine targets exhibit extended radio structures on 1–25 kpc scales. Associated with morphologically and kinematically distinct features in the ionized gas

Hot topic: spatial coincidence radio - ionised gas in low luminosity AGN

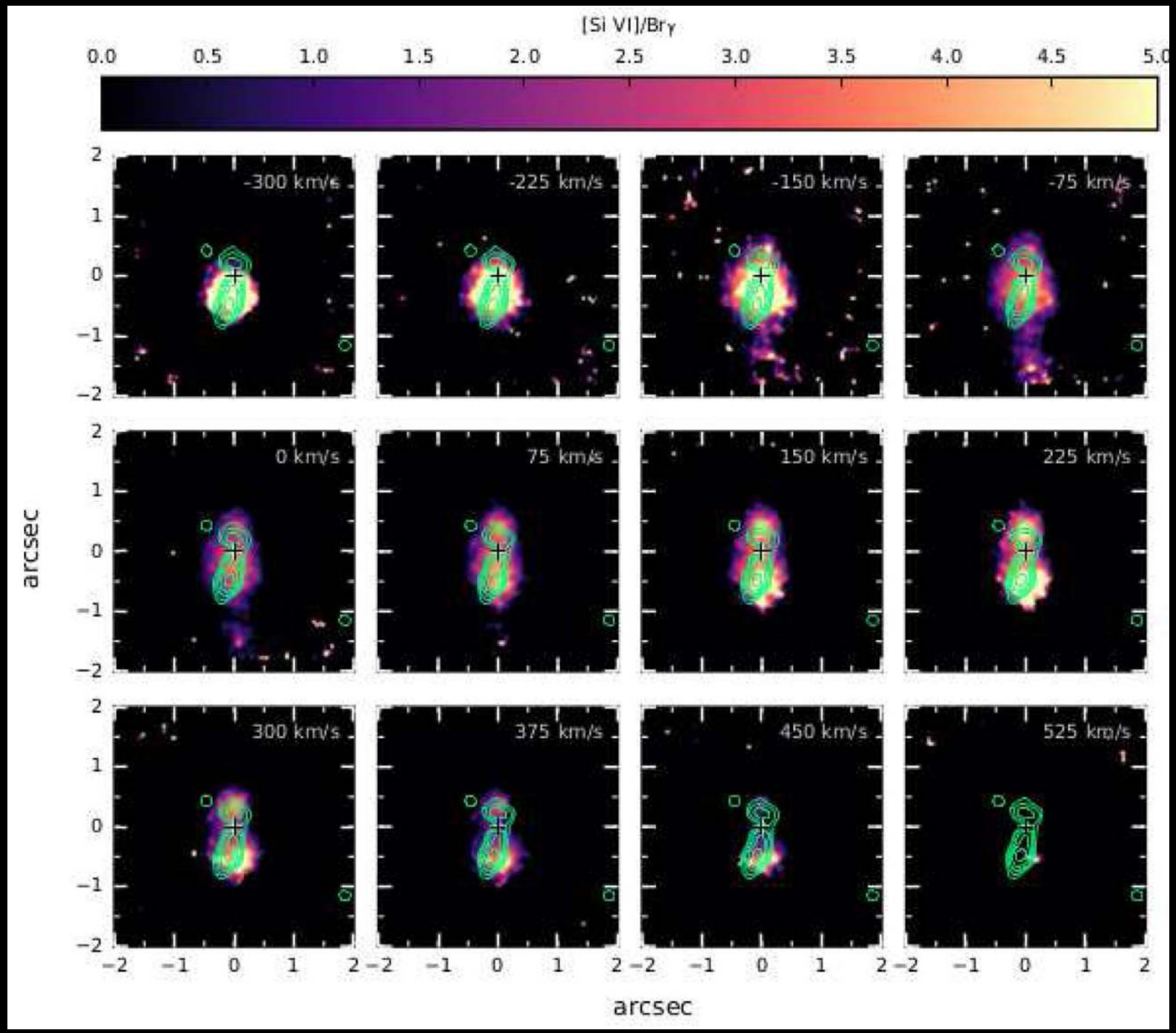
signature of the radio affecting the surrounding gas?

coronal lines

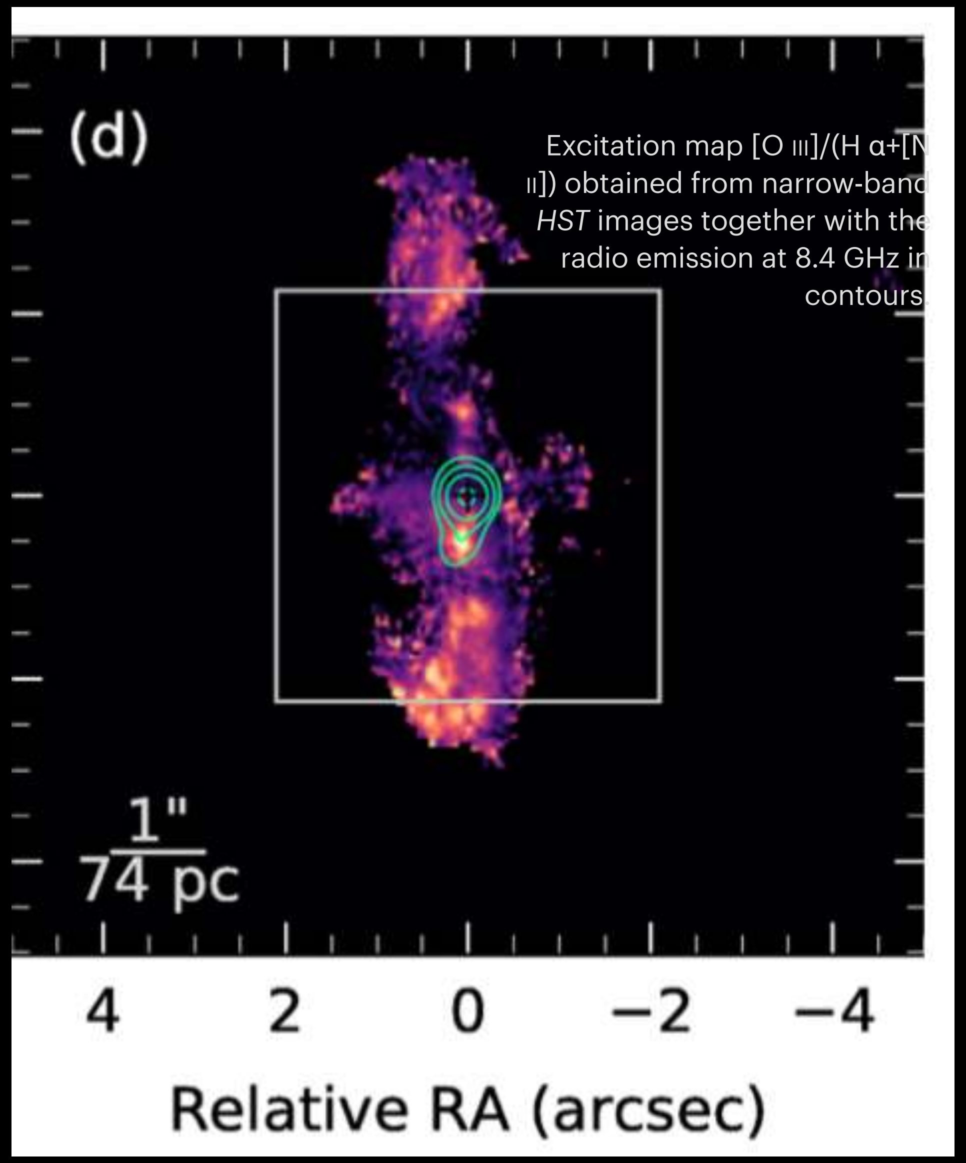


May, Rodríguez-Ardila et al. 2018

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



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.

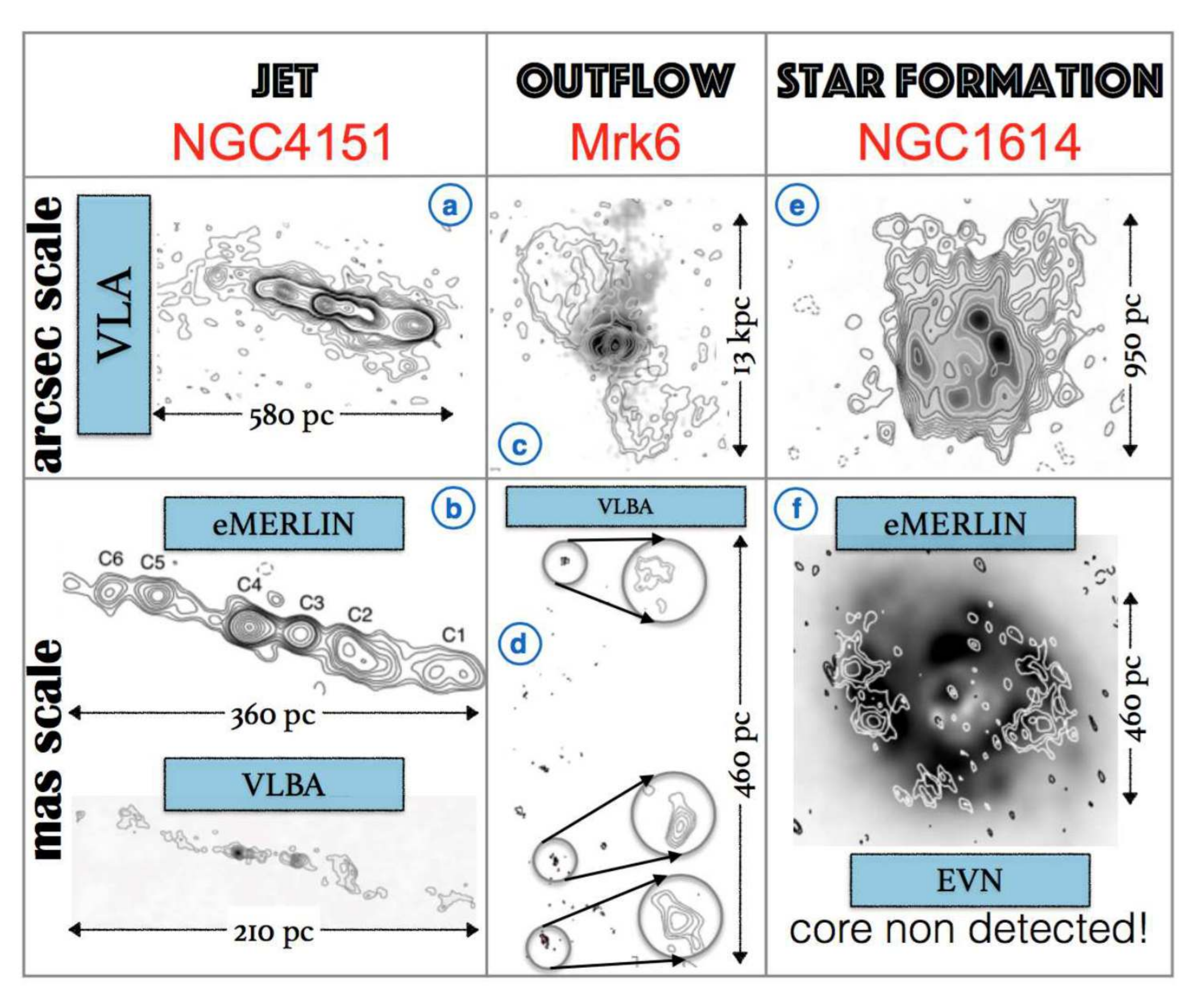


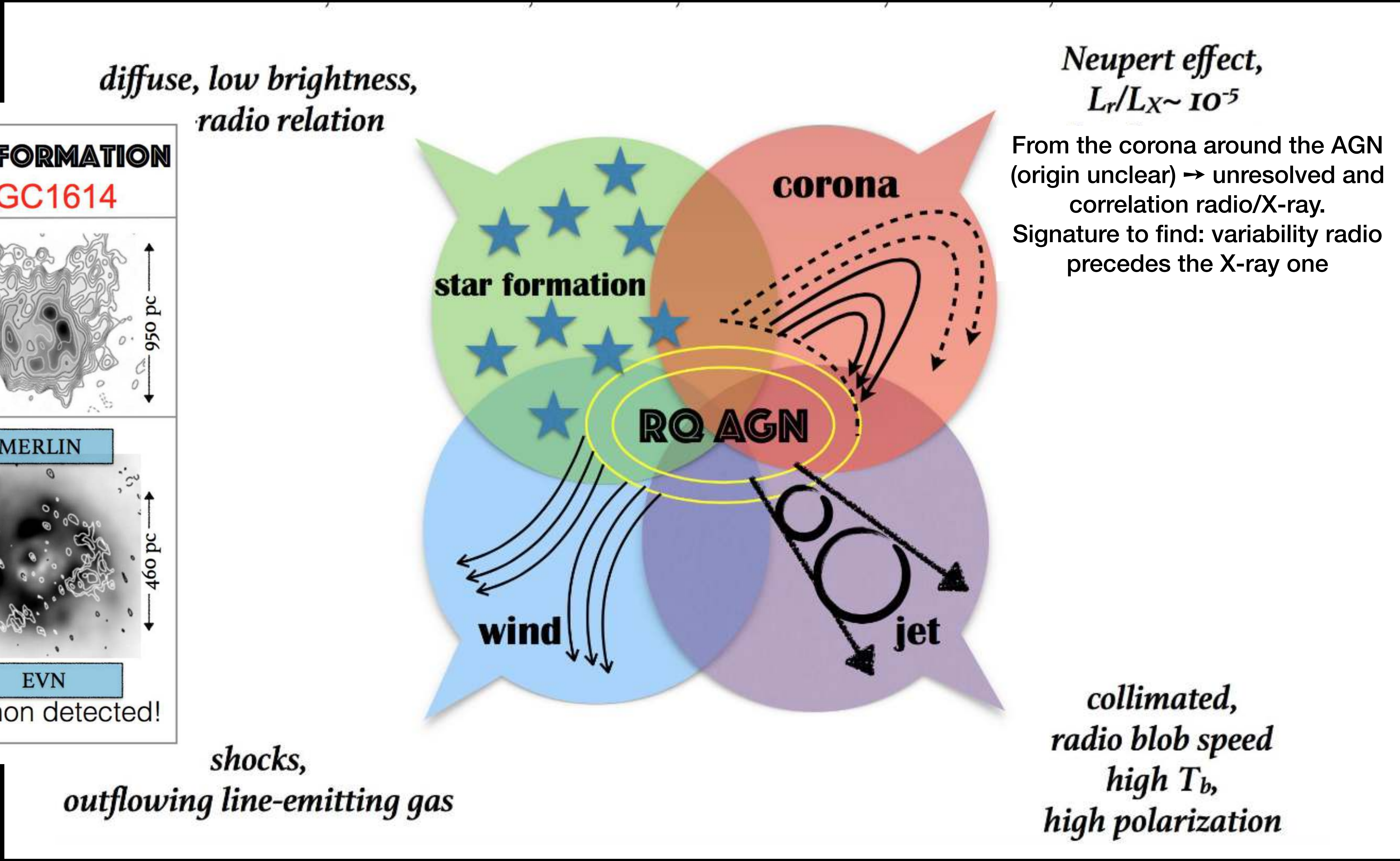
NGC1386 Rodríguez-Ardila et al. 2017

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

We will get back to this in Les 4

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





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

Summary of Les 2

A variety of AGN: multi-wavelengths observations needed for a full characterisation

A variety of mechanisms producing radio emission. At lower radio luminosity, it can be difficult to separate radio from star formation to the emission from an AGN….

The definition of radio “quiet” can be misleading: radio “quiet” doesn’t mean the radio comes from star formation

Radio-loud sources (radio galaxies) have collimated jets: two main morphological classes identified

Connection (to first order) radio - ionised gas….

The main properties of radio sources change with the radio luminosity: this can affect the impact of these jets

Importance of low luminosity radio AGN: **we will see more in Les 4**