Radio Loud Black Holes

An observational perspective

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Overview of the second lesson

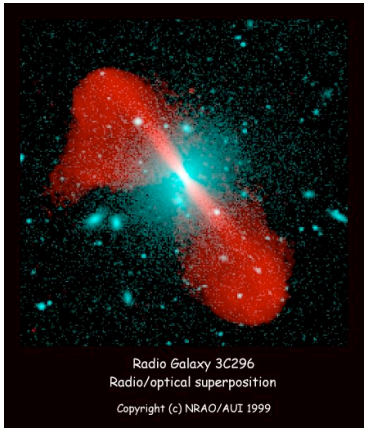
1) Young radio sources and radio galaxy evolution

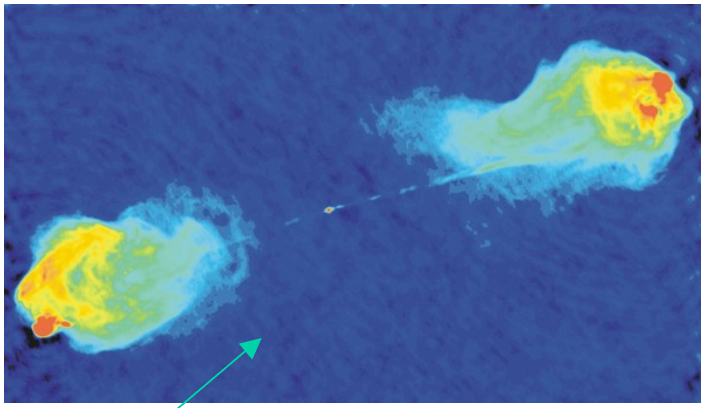
2) Statistics of radio galaxies (luminosity function, radio power vs black hole masses)

3) Instrumental developments in radio astronomy

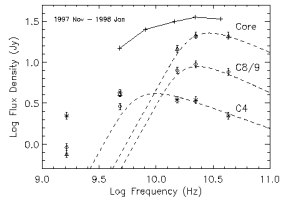
Spectral classification of Extragalactic Radio Sources

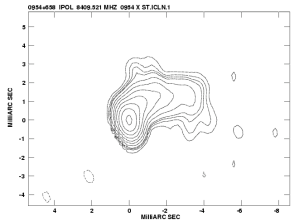
Extended sources whose integrated spectrum is dominated by the steep lobes

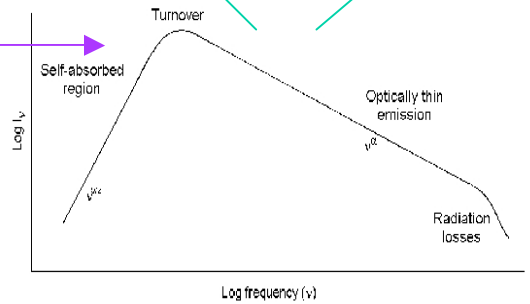




Compact sources with flat integrated spectrum







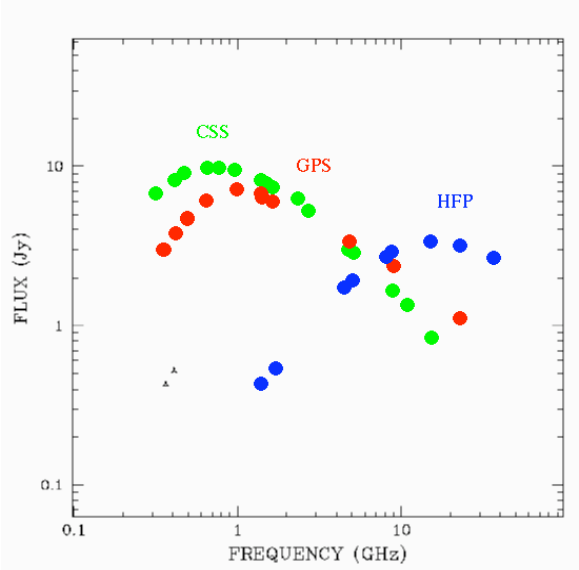
Class of compact *(arcsec)* powerful sources with steep integrated spectrum and turnover around 1 GHz

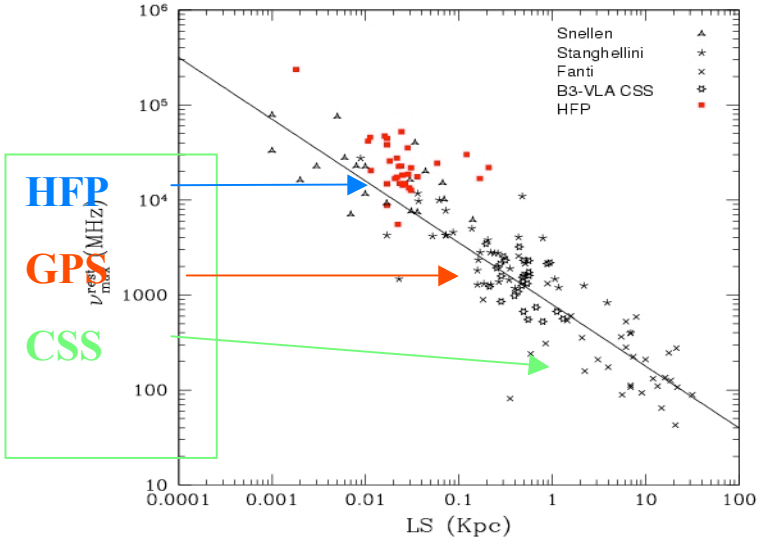
Compact Steep Spectrum Sources

Steep spectra and compact double morphology on the small scale suggests they are not a beamed population of radio sources but rather intrinsically small

What keeps them small? Frustration scenario vs evolutionary scenario

Connection between turnover frequency and dimensions





Stangellini et al.

Dallacasa et al.

Fanti et al.

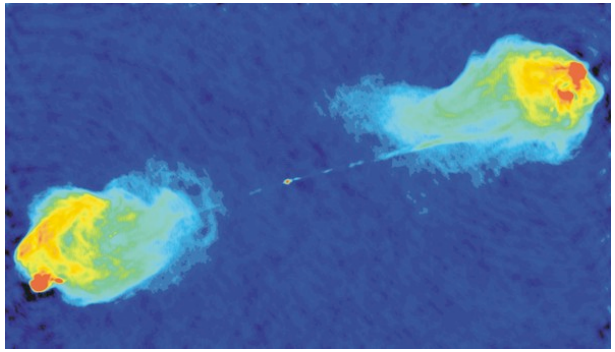
HFP turnover > 10 GHz D < 0.1 kpc

GPS turnover 1 – 5 GHz D 0.1 – 1 kpc

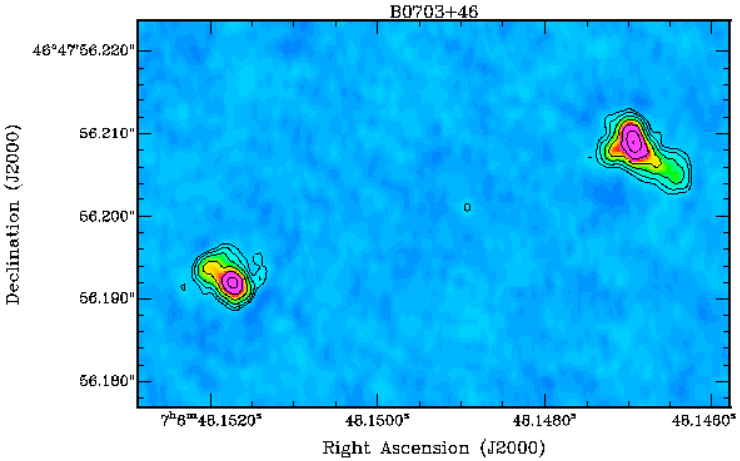
CSS turnover 1 GHz D > 1 kpc

Evolutionary sequence?

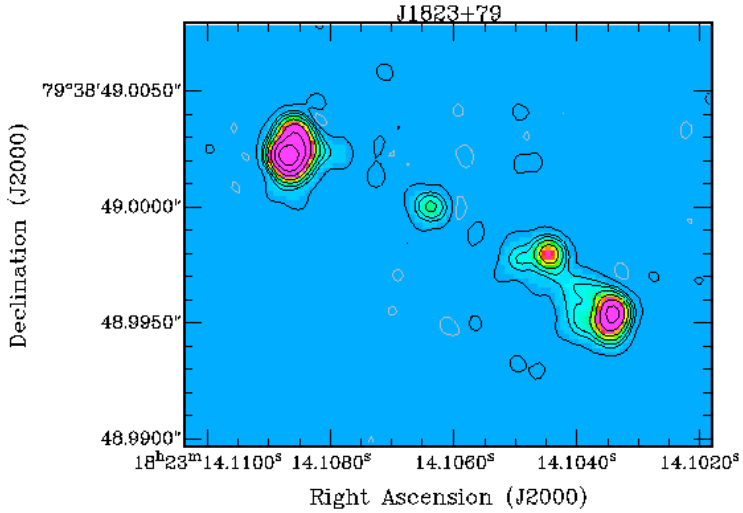
Down sized version of powerful radio galaxies



Hundreds of kpc

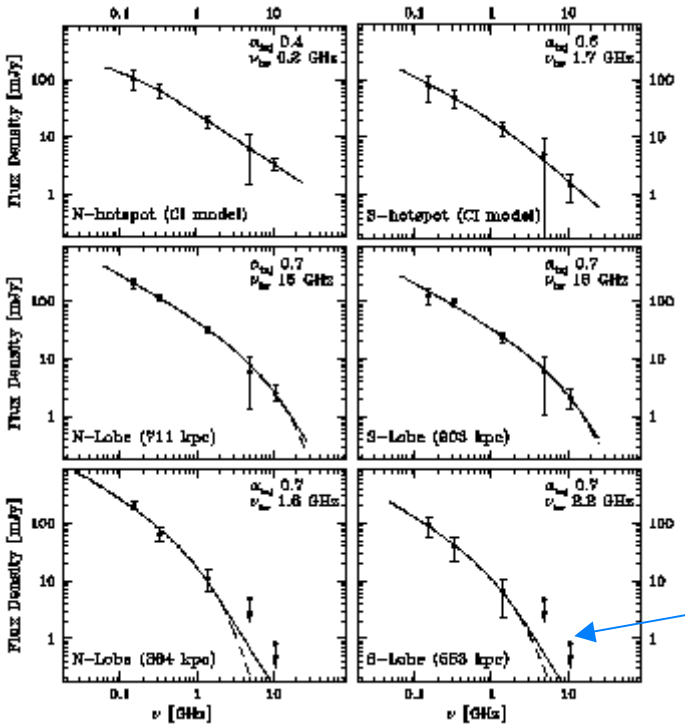


Fraction of kpc

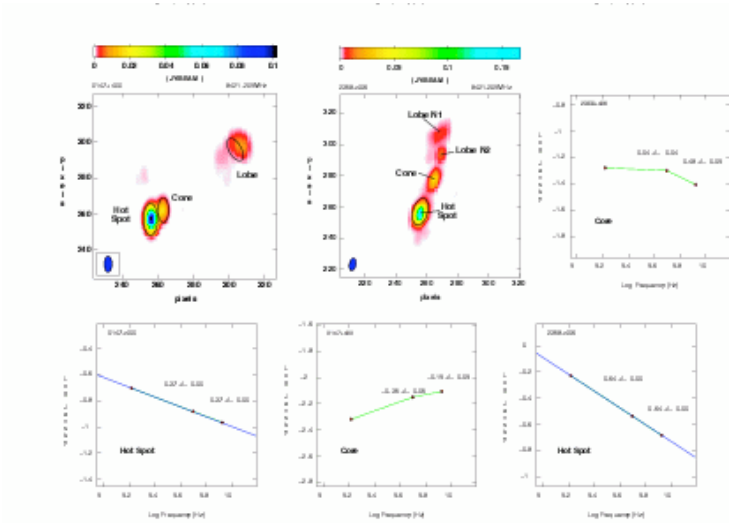


How do we know that they are really young?

Radiative ages and hot spot proper motions



Optically thin spectra with break frequency due to electron aging



Spectra of the individual components in CSS sources

Murgia et al.,

Multifrequency observations show hot spot velocity separation of 0.1 – 0.2c

Radiative age for two sources of about 1500 yrs

Evolutionary sequence from these sources to the large scale FRI and FRII

Radio Loudness and AGN hosts

Radio Loudness parameter defined as:

$$\mathrm{R} = F_{5\ \mathrm{GHz}}/F_{\mathrm{B}}$$

R > 10 *(Kellermann et al. 1989)*

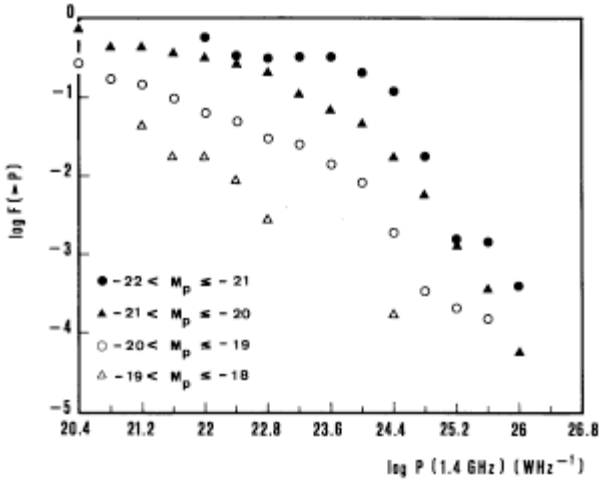
R > 2 – 3 *(Capetti et al. 2006)*

Radio loud AGN are located in elliptical galaxies, but only

~ 10% of such galaxies hosts a radio source of nuclear origin

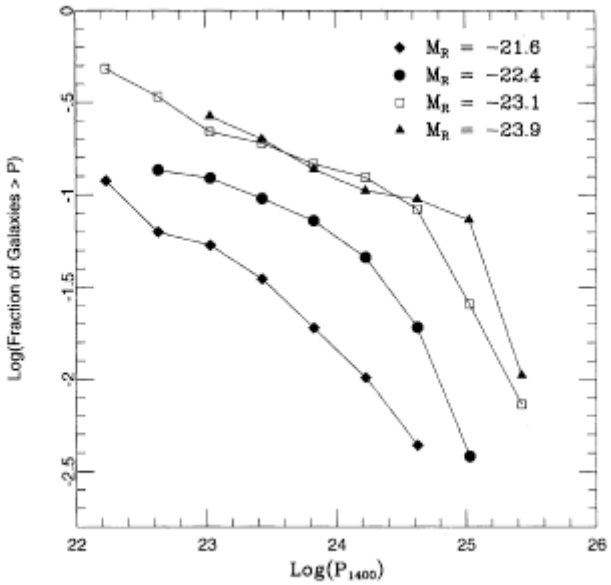
Radio luminosity Functions for E-S0 galaxies (z<0.09)

Field galaxies



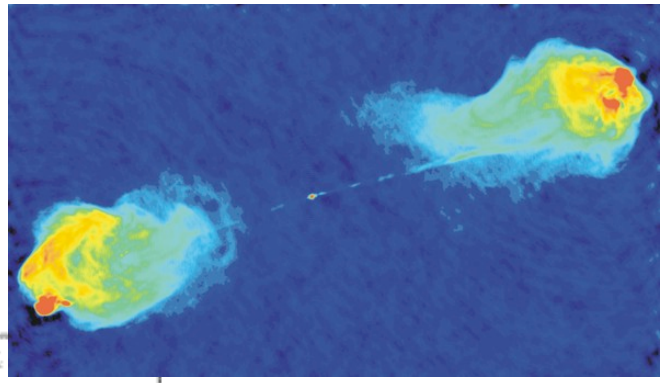
Auriemma et al. 1977

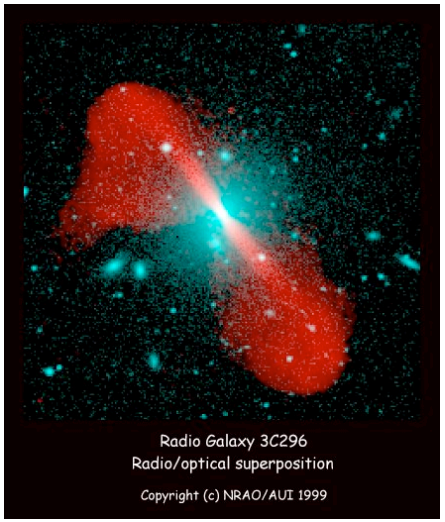
Cluster galaxies

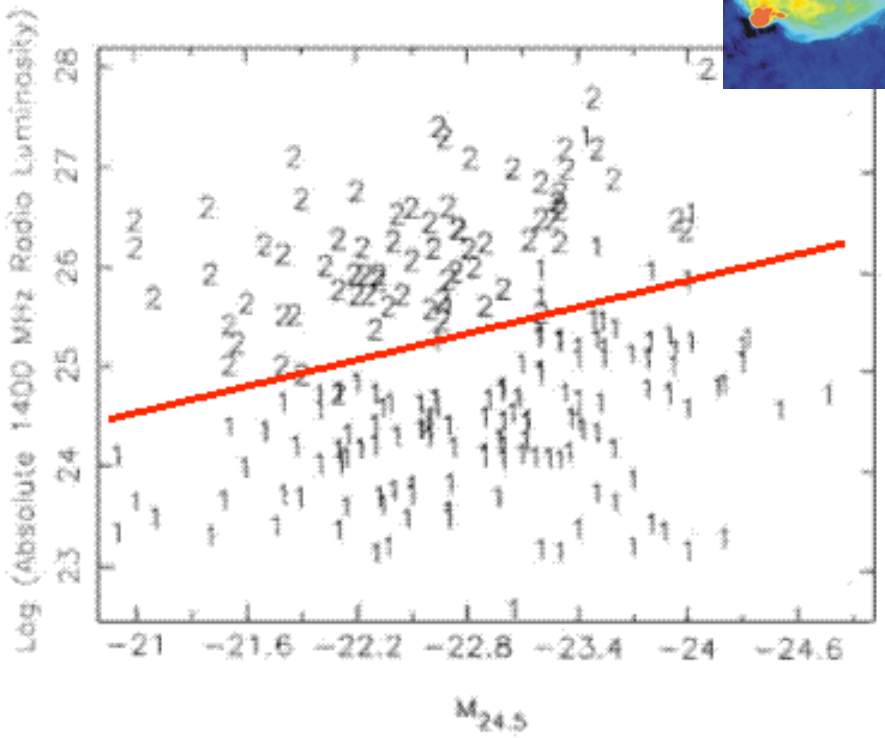


Ledlow & Owen 1996

More luminous galaxies develop more powerful radio sources



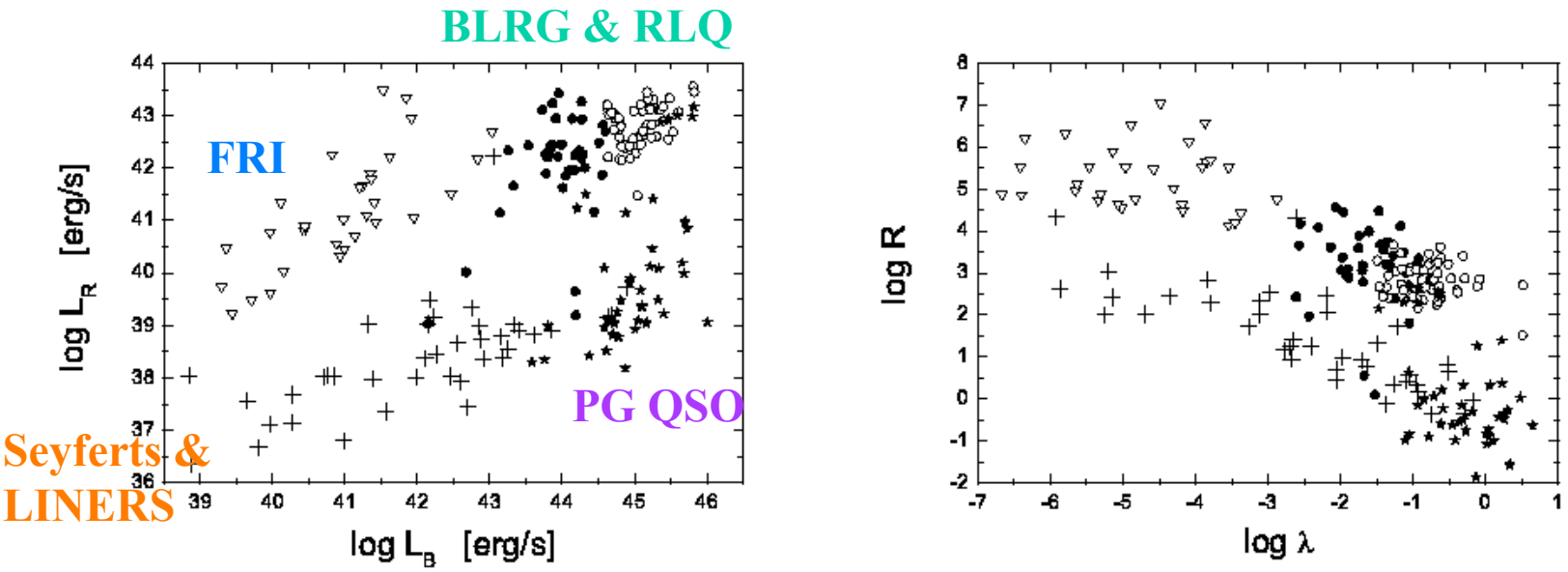




Owen & White 1991

The power transition from FR I to FR II radio galaxies depends on the magnitude of the associated optical counterpart

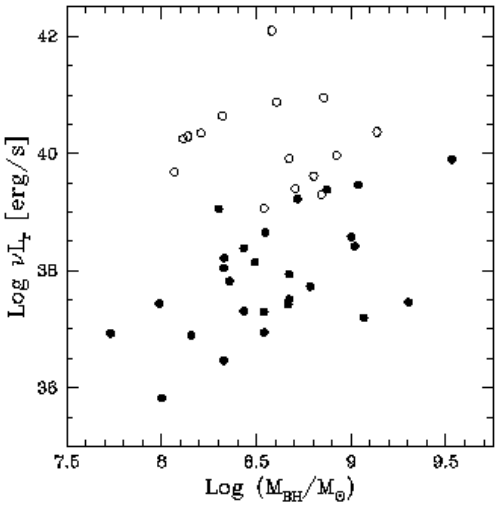
Radio loudness and optical magnitude



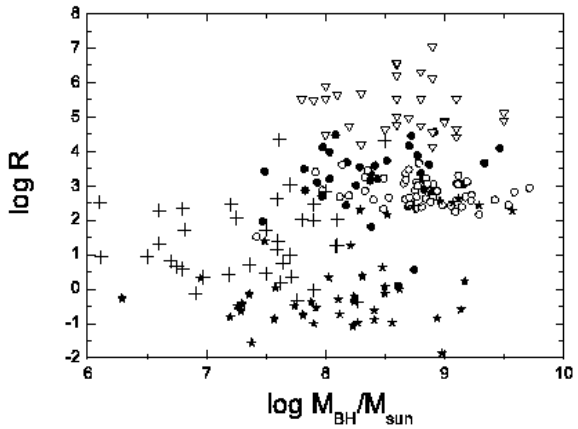
(Sikora et al. 2006)

For any optical luminosity, there are radio loud and radio quiet AGN

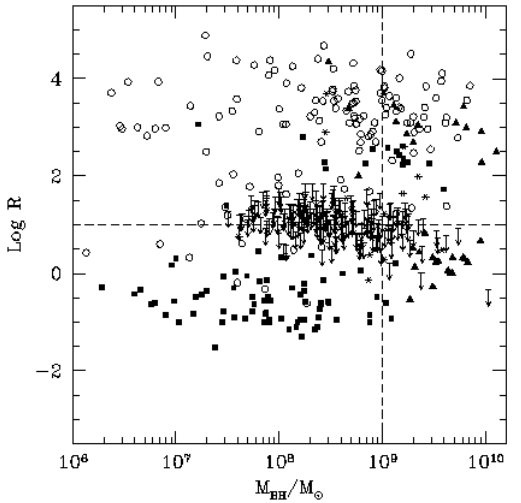
Radio Loudness and Black Hole Masses



Nearby ellipticals
(Balmaverde & Capetti 2006)



FRI,FRII,Seyferts LINERS, PGQSO
(Sikora et al. 2006)



Distant galaxies and QSO
(Urry et al. 2002)

There seems to be no clear link between the radio loudness and the black hole mass for the hosting objects: black hole masses span over three orders of magnitude, radio power over many more

Something else must play a role

Merging events, BH spin…

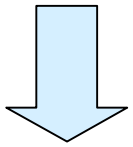
Future perspectives in radio astronomy

Upgrade of existing facilities

e-VLBI

e-MERLIN

e-VLA



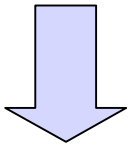
Similar resolution, similar frequencies, higher sensitivity

New instruments in the near future

ALMA

LOFAR

...



New frequencies and hence new research areas

Very Long Baseline Interferometry probes the parsec-scale region in radio loud AGN

European VLBI Network

1.6 GHz – 22 GHz (6 GHz also)

5 to 0.3 mas

z=0.01	->	1 mas = 0.2 pc
z=0.1	->	1 mas = 1.8 pc
z=2	->	1 mas = 8 pc

Very Long Baseline Array

327 MHz – 43 GHz

22 to 0.17 mas

e-VLBI

Same frequencies and same stations connected with optical fiber link

→ Better u-v coverage → Much better sensitivity (microJy level)

→ The faint Universe…

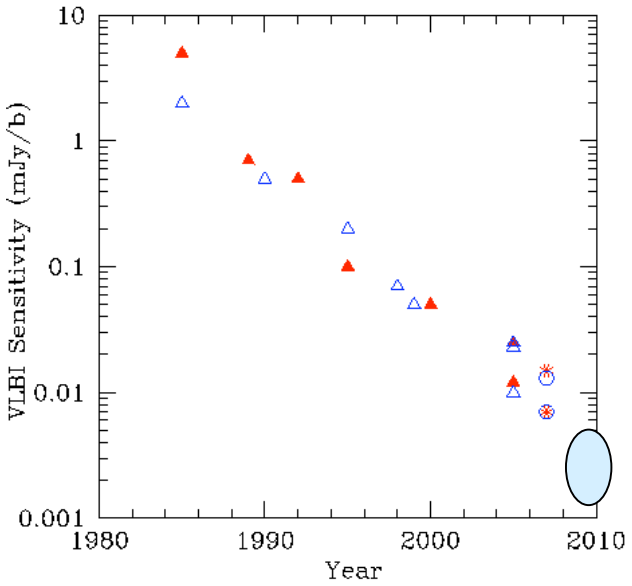
- Nearby LLAGN
- Very distant objects
- AGN/Starburst connection

…

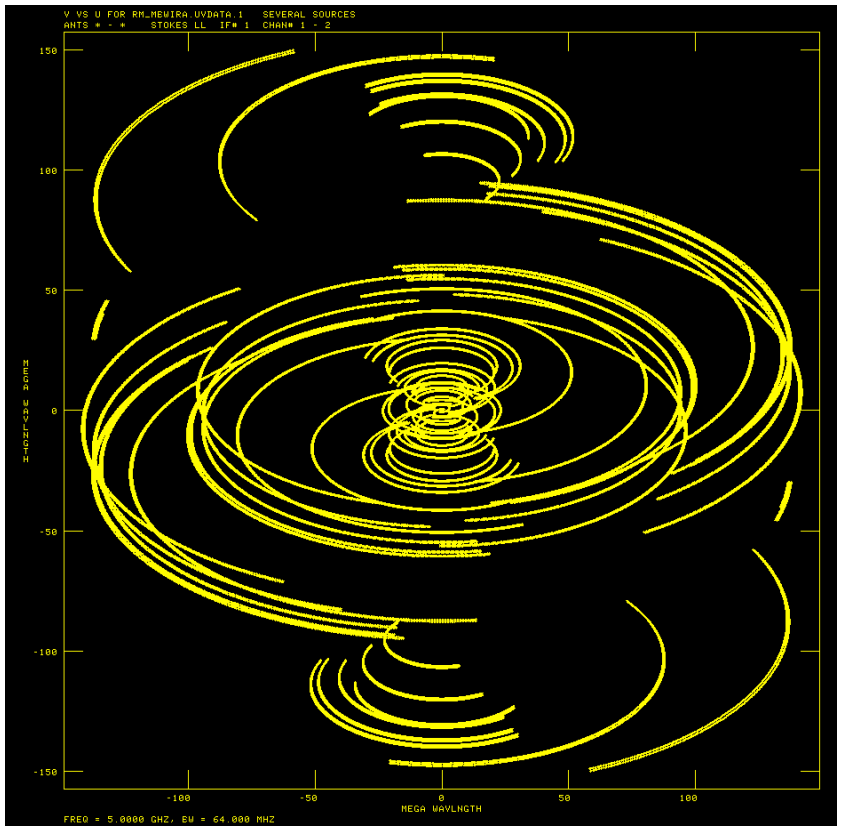
The maximum angular resolution (in milliarcseconds) of some typical EVN and Global VLBI arrays are presented below:

Array	90 cm	18cm	6cm	3.6 cm	1.3 cm	0.7cm
EVN	-	15	5	3	1	0.6
EVN (inc. Sh/Ur)	30	5	1.5	1	0.3	0.15
EVN+VLBA	19	3	1	0.7	0.25	0.13

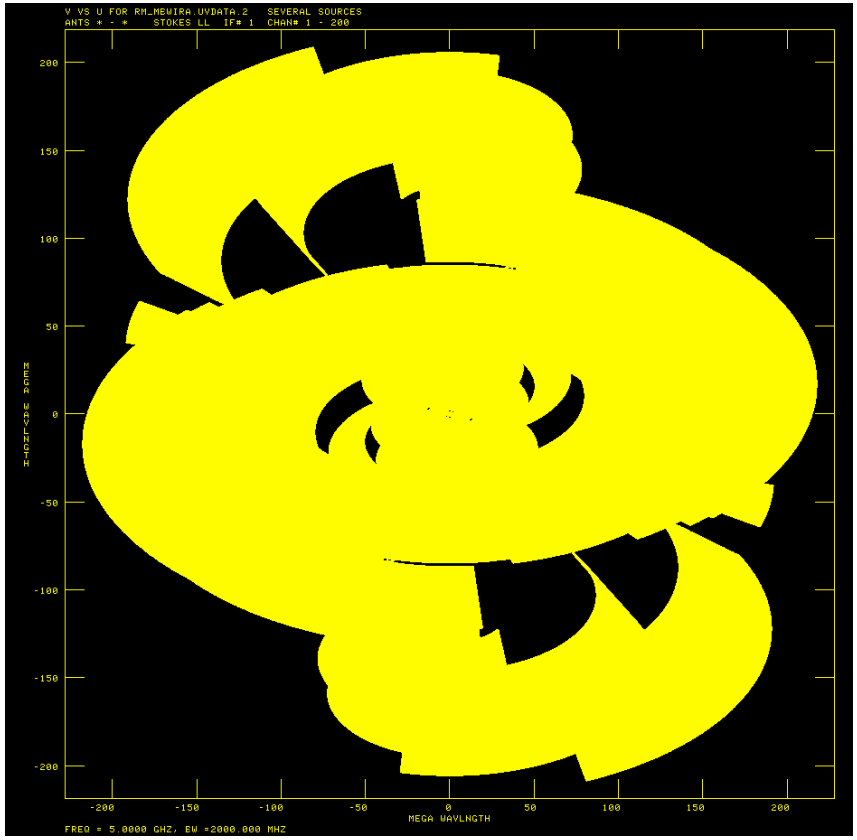
Even higher resolution observations were possible using ground-based arrays together with the Japanese SVLBI orbiting radio telescope, Halca.



eVLBI

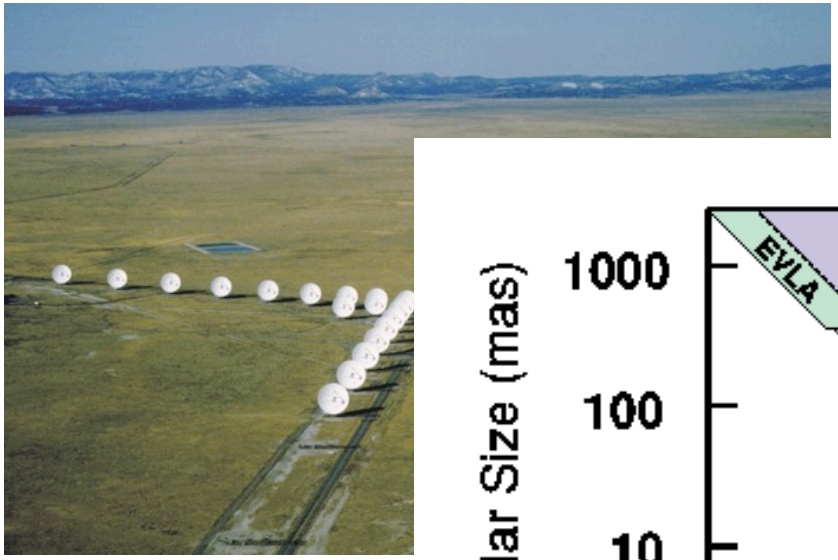


EVN u-v coverage at 5 GHz



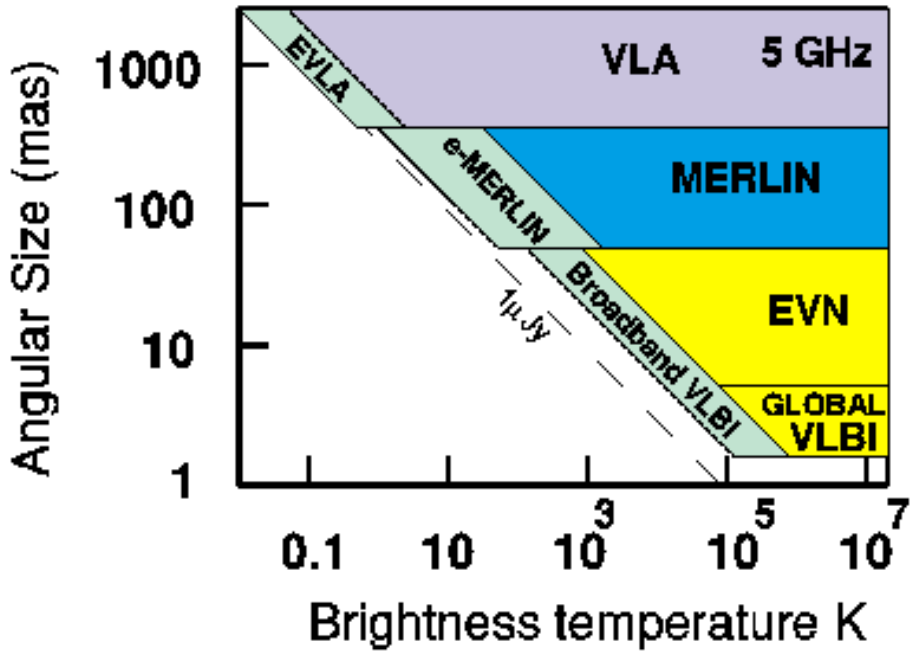
e-EVN u-v coverage at 5 GHz

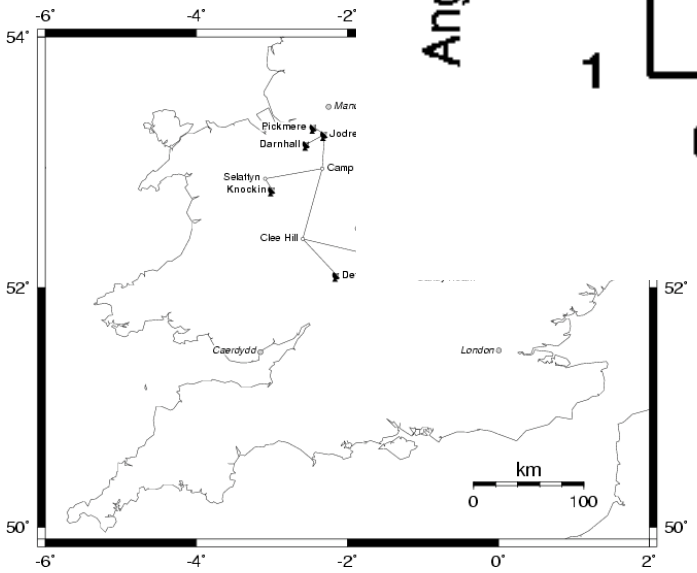
e-VLA & e-MERLIN



EVLA Performance

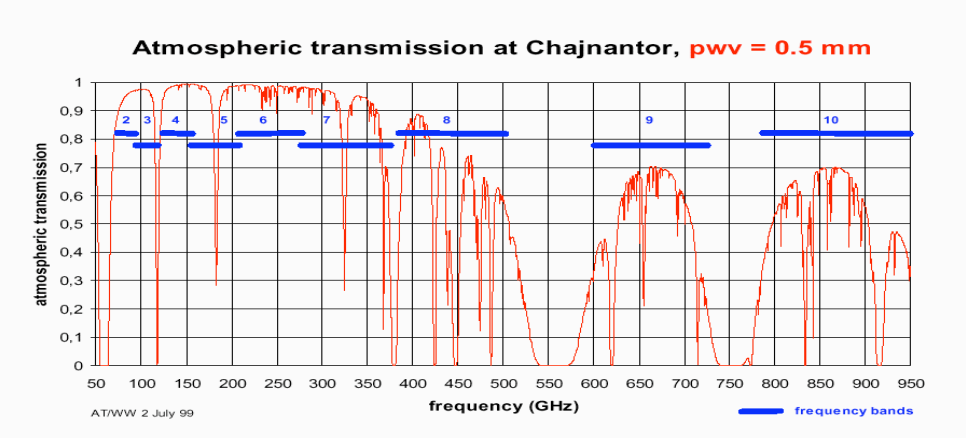
	VLA	Phase 1	Phase 2
Point source sensitivity	10 μJy	0.8 μJy	0.6 μJy
No. baseband pairs	2	4	4
		8 GHz	8 GHz
		16384	16384
		16384 [262144]	16384 [262144]
		~1 Hz	~1 Hz
		75%	100%
		351	666
		0.4"	0.04"

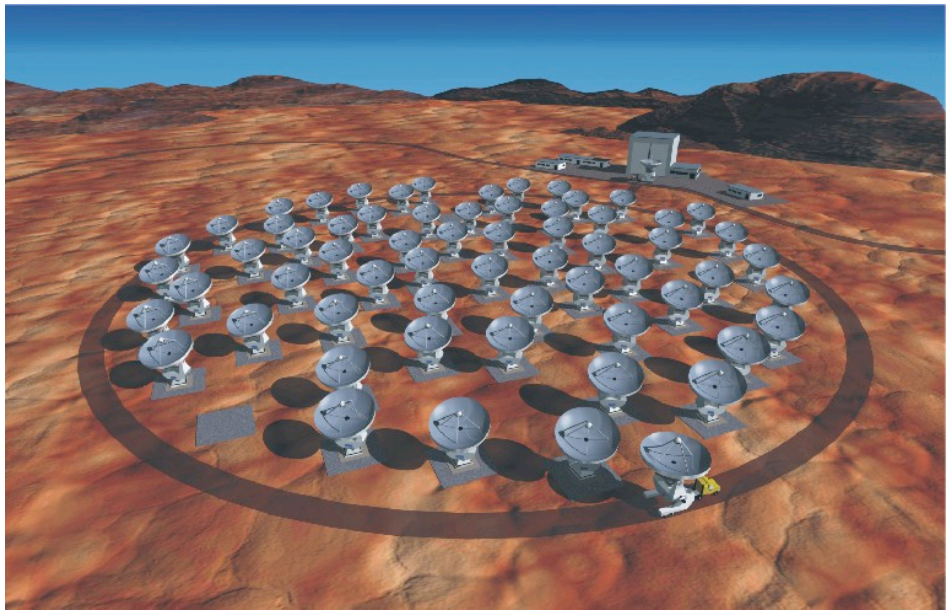




- Simultaneous continuum and multi-line spectroscopy
- Almost complete uv-coverage using MFS
- Sub-milliarcsecond astrometric capability
- Dynamic scheduling and on-the-fly imaging

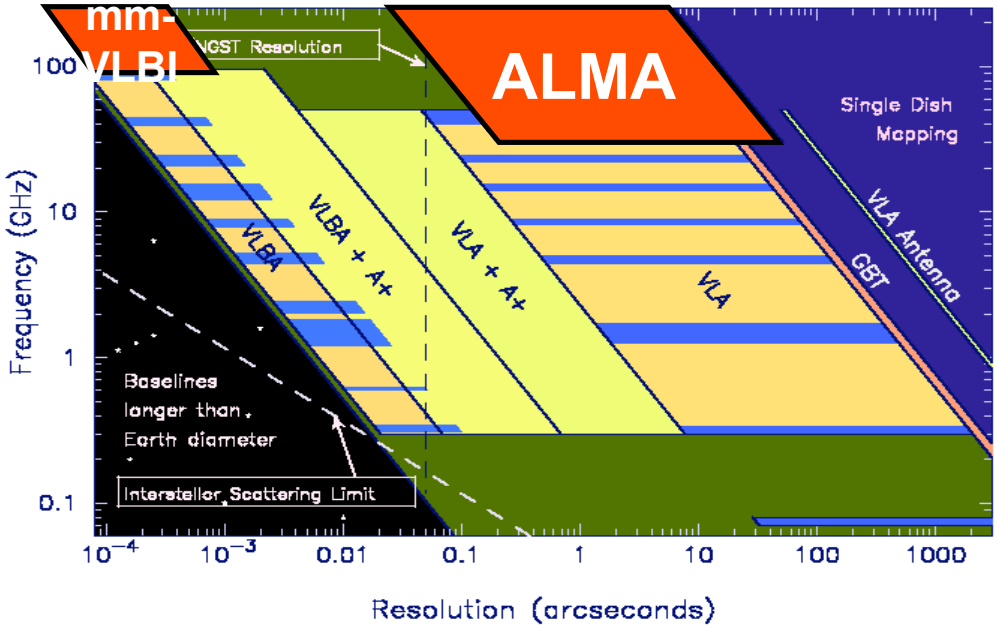
Atacama Large Millimetre Array (ALMA)





9 observing windows between ~40 and ~900 GHz

ALMA sensitivity and resolution



Same resolution of the VLA at much higer frequencies

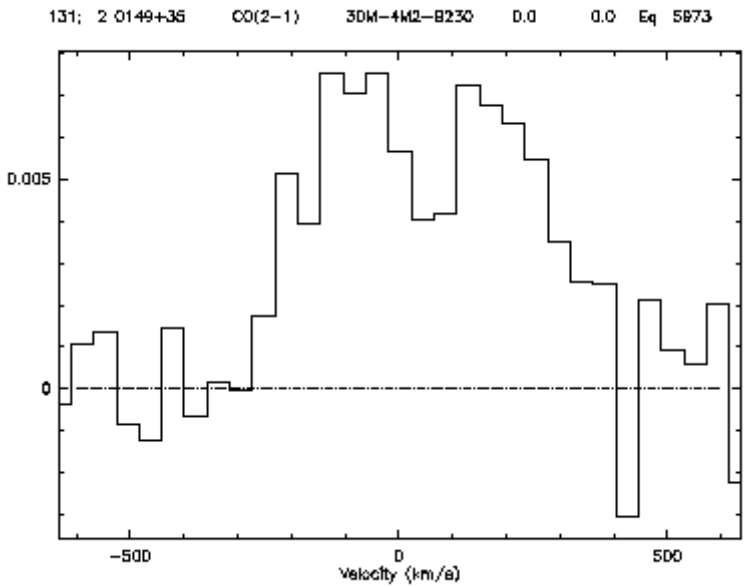
sub-mJy to mJy sensitivity going from the lowest to the highest frequency band

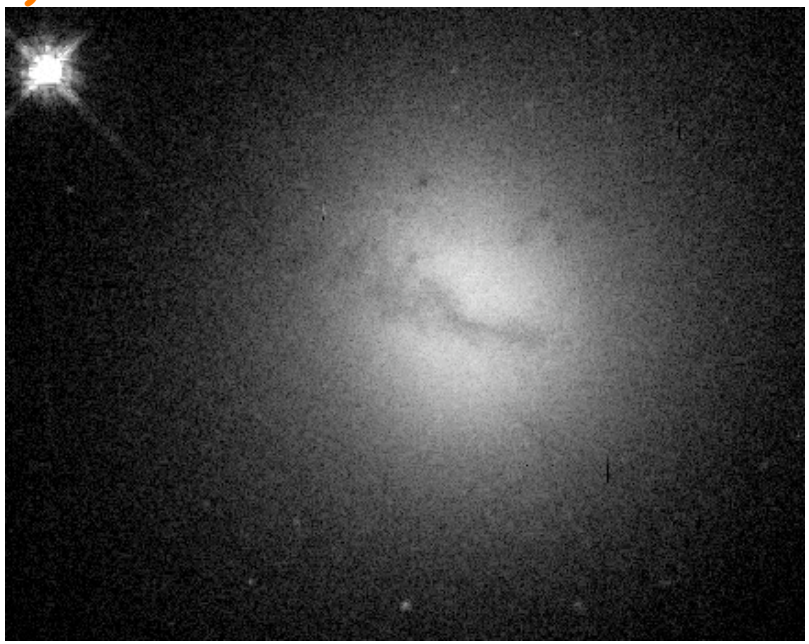
Frequency (GHz)	Continuum (mJy)	Line 1 km s^{-1} (mJy)	Line 25 km s^{-1} (mJy)
35	0.02	5.1	1.03
110*	0.027	4.4	0.89
140	0.039	5.1	1.01
230*	0.071	7.2	1.44
345*	0.12	10.	1.99
490			
675*	0.85	51.	10.2
850	1.26	66.	13.3.

AGN science with ALMA

- The inner AGN jets at very high radio frequencies
- The youngest radio sources (vHFP sources)
- Emission from molecular gas and the medium surrounding the BH
- Primordial dust in high-z objects

CO(1-2) emission in B2 0149+35 (z=0.016)





LOw Fequency ARray LOFAR

Core in the Netherlands with other stations across europe up to 1000 km-baselines

Arcsec to mas resolutions at very low frequency

Low frequency antenna

30 – 80 MHz

High frequency antenna

120 – 240 MHz