The background of the slide is a deep field image of the universe, showing numerous galaxies of various shapes and sizes, some appearing as bright yellowish-white points of light. Overlaid on this image are several sets of concentric, irregular contour lines in blue and white. These contours represent radio emission from Active Galactic Nuclei (AGN). One prominent set of contours is located in the upper right quadrant, showing a bright central source with several nested loops. Another set is in the lower left, also showing a bright center with surrounding emission. There are several other smaller, less distinct contour sets scattered across the image.

RADIO EMISSION FROM AGN ON ALL SCALES

Scientific prospects for SKA, pathfinders and precursors

Tiziana Venturi
INAF, Istituto di Radioastronomia

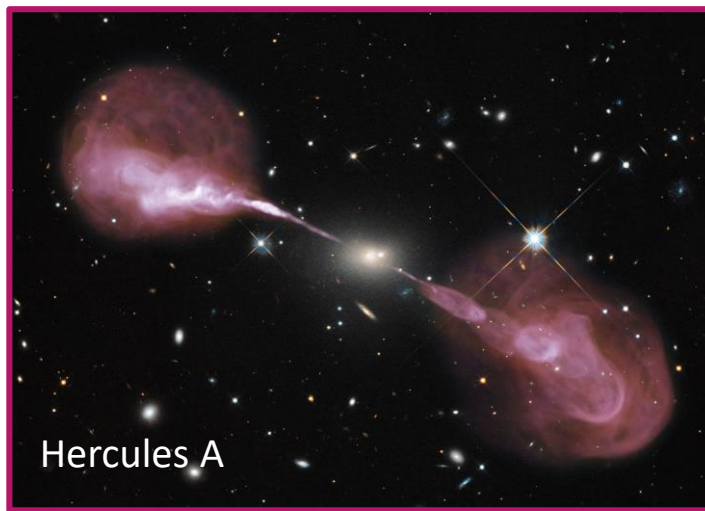
The background of the slide is a deep space image filled with numerous small, distant stars. Overlaid on this are two prominent radio galaxy structures. The upper structure is elongated and oriented diagonally, with a complex pattern of nested blue and white contour lines. The lower structure is more compact and irregular, also featuring blue and white contours. The word 'OUTLINE' is written in large, white, sans-serif capital letters across the upper part of the slide, partially overlapping the top radio galaxy structure.

OUTLINE

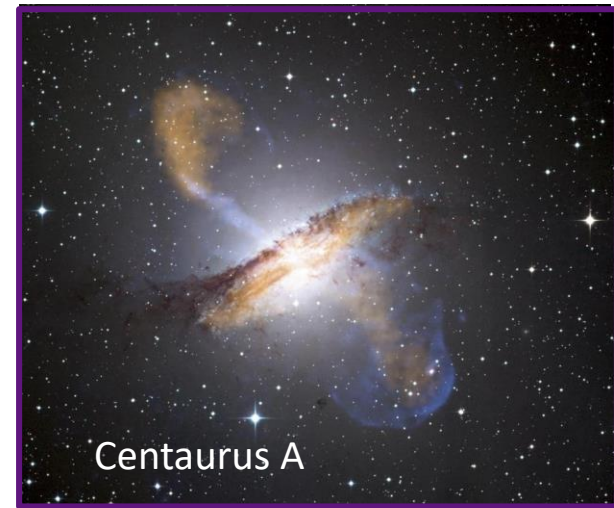
Very limited overview of open questions, new challenges and opportunities in the study of radio galaxies

- **The low frequency end – the extended emission**
- **The high frequency end – the inner regions of AGN**

The relevance of VLBI in the SKA era

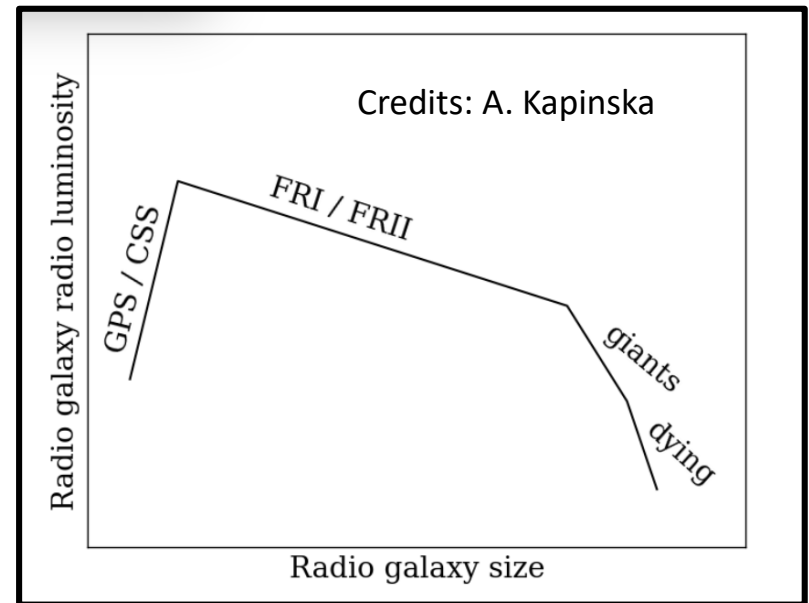
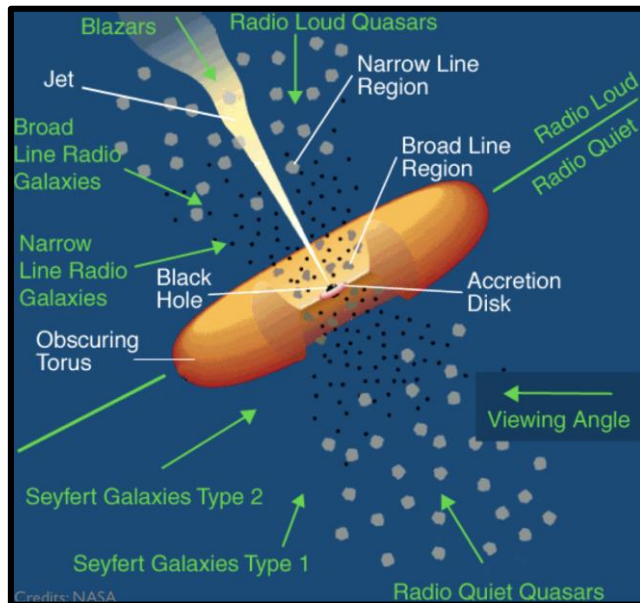


Hercules A

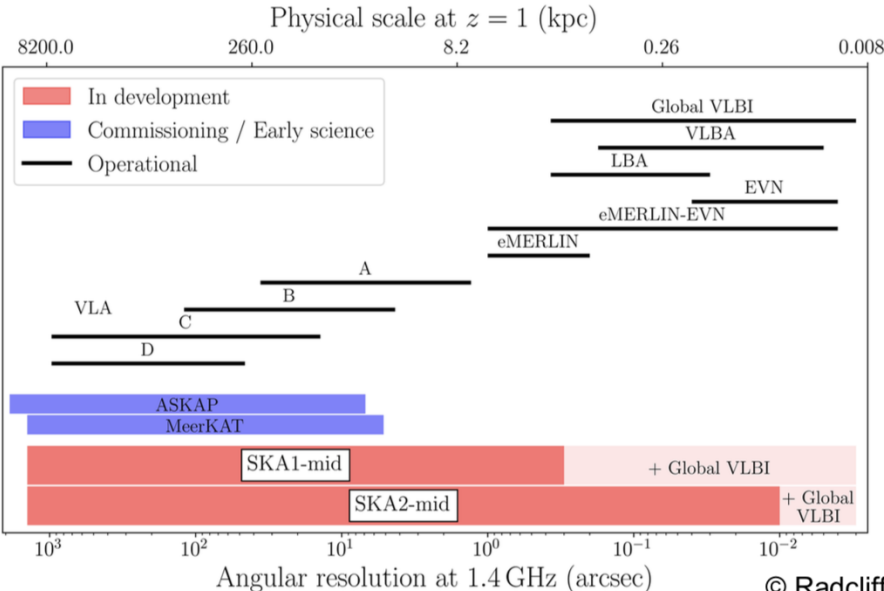
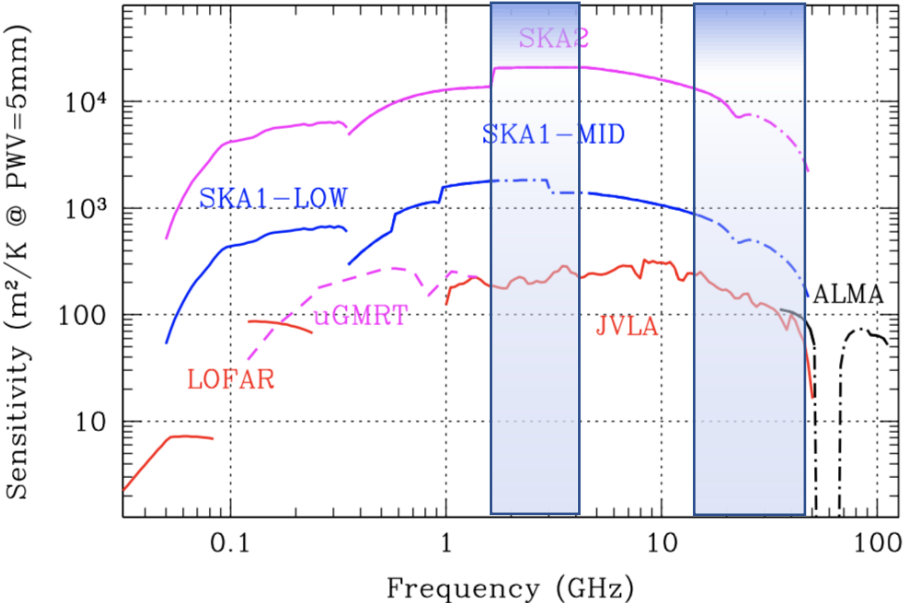


Centaurus A

Science space: Radio galaxies – FRII and FRI – and their nuclear regions



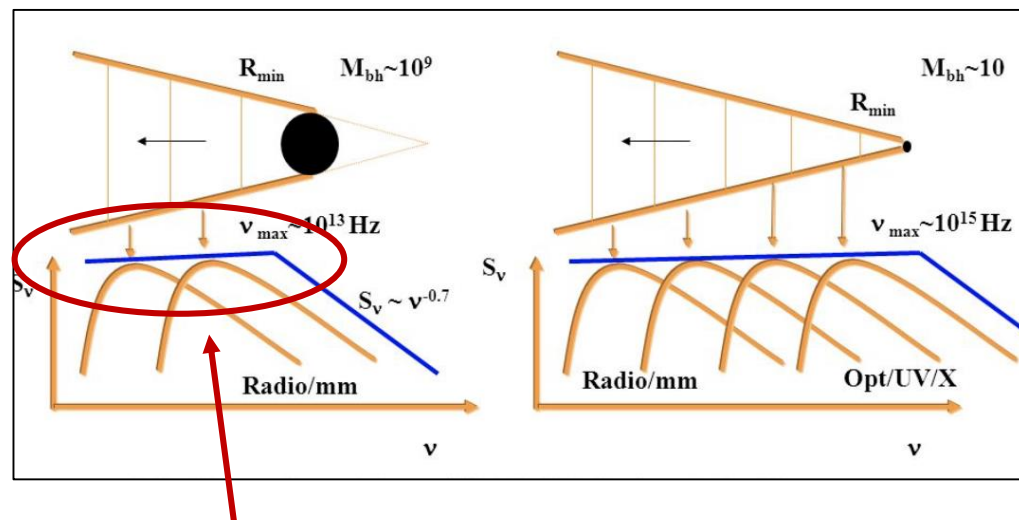
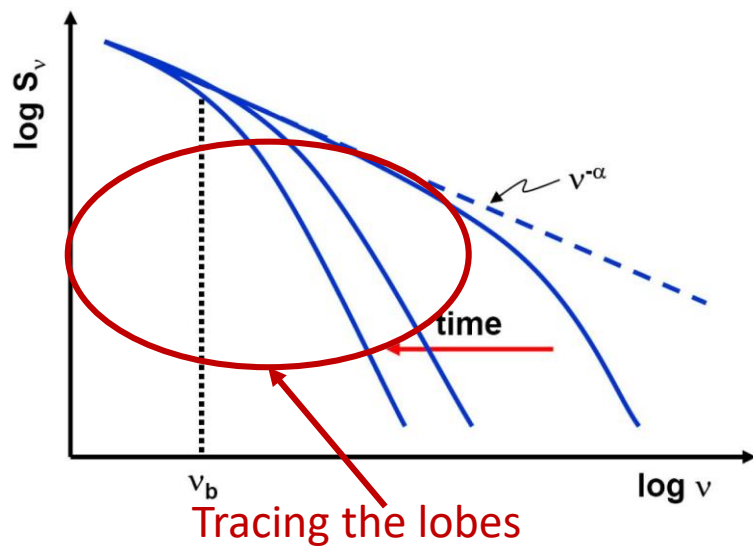
Parameter space



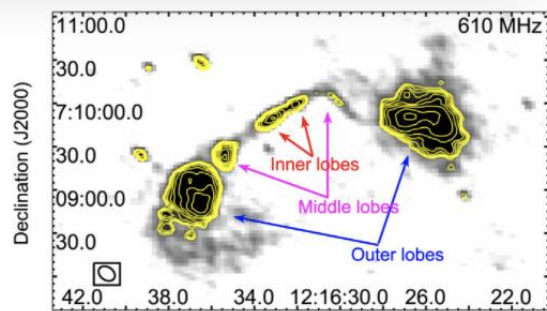
ν_{\min} (MHz)	ν_c (MHz)	ν_{\max} (MHz)	σ_L ($\mu\text{Jy/Bm}$)	σ_c ($\mu\text{Jy/Bm}$)	θ'_{\min} ($''$)	θ_{\min} ($''$)	θ_{\max} ($''$)	θ'_{\max} ($''$)
50	60	69	11050	163	16.4	23.5	1175	3290
69	82	96	3261	47	11.9	17.0	850	2379
96	114	132	1841	26	8.6	12.3	614	1719
132	158	183	1258	18	6.2	8.9	444	1244
183	218	253	973	14	4.5	6.4	321	899
253	302	350	794	11	3.3	4.6	232	650

SKA-TEL-SKO-0000000 2017-10-06

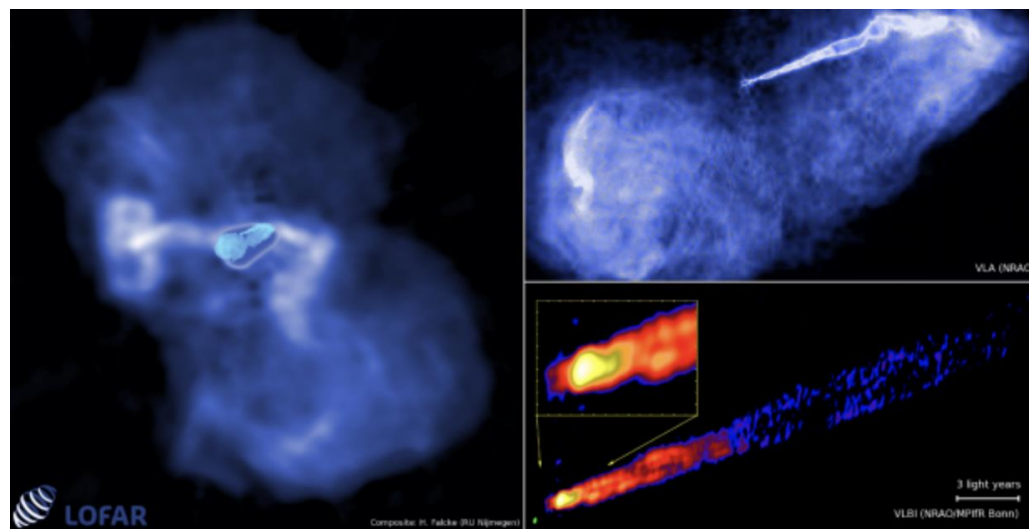
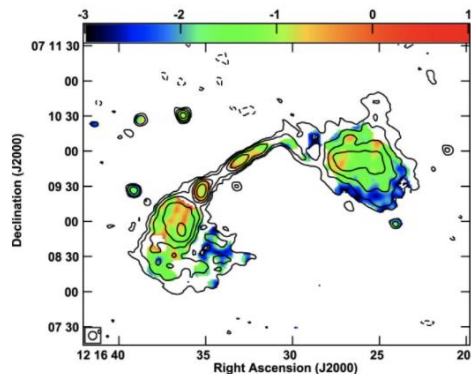
ν_{\min} (GHz)	ν_c (GHz)	ν_{\max} (GHz)	σ_L ($\mu\text{Jy/Bm}$)	σ_c ($\mu\text{Jy/Bm}$)	θ'_{\min} ($''$)	θ_{\min} ($''$)	θ_{\max} ($''$)	θ'_{\max} ($''$)
0.35	0.41	0.48	1176	16.8	1.015	2.031	270.8	541.6
0.48	0.56	0.65	560	8.1	0.745	1.489	198.6	397.2
0.65	0.77	0.89	303	4.4	0.546	1.092	145.6	291.2
0.89	1.05	1.21	186	2.7	0.400	0.801	106.8	213.5
1.21	1.43	1.65	137	2.0	0.294	0.587	78.3	156.6
1.65	1.95	2.25	113	1.6	0.215	0.431	57.4	114.9
2.25	2.66	3.07	99	1.4	0.158	0.316	42.1	84.2
3.07	3.63	4.18	109	1.6	0.116	0.232	30.9	61.8
4.18	4.94	5.70	95	1.4	0.085	0.170	22.7	45.3
5.70	6.74	7.78	89	1.3	0.062	0.125	16.6	33.2
7.78	9.19	10.61	85	1.2	0.046	0.091	12.2	24.4
10.61	12.53	14.46	85	1.2	0.034	0.067	8.9	17.9
14.46	17.09	19.72	91	1.3	0.025	0.049	6.6	13.1
19.72	23.31	26.89	116	1.7	0.018	0.036	4.8	9.6
26.89	31.78	36.67	121	1.8	0.013	0.026	3.5	7.0
36.67	43.33	50.00	209	3.2	0.010	0.019	2.6	5.2



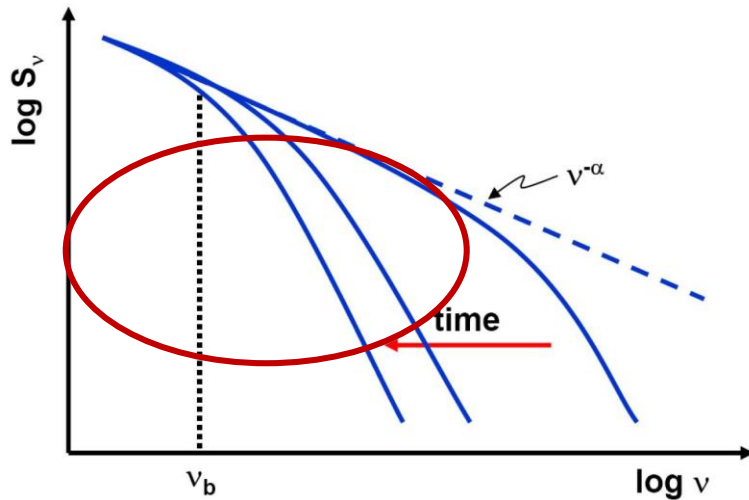
Falcke 2018



Singh et al. 2016 Right ascension (J2000)



Tracing the lobes



High resolution and high sensitivity imaging
at low frequencies (LOFAR, uGMRT)



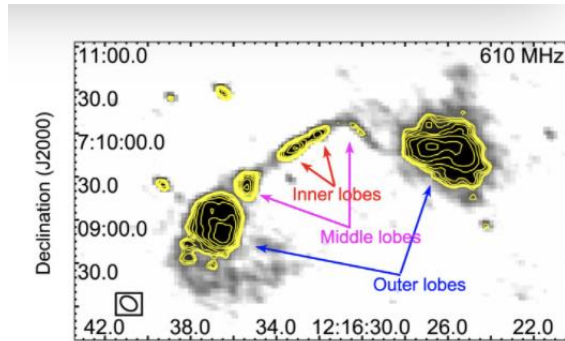
Revision of the size in radio galaxies
Old radio emission



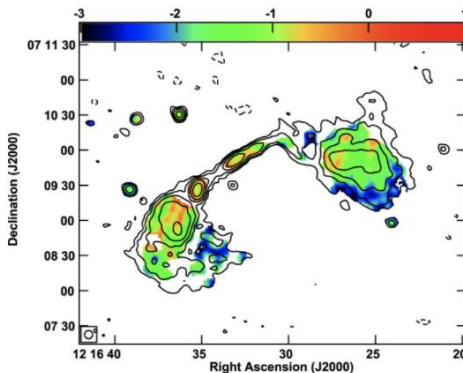
Life cycles of radio galaxies
Restarted emission



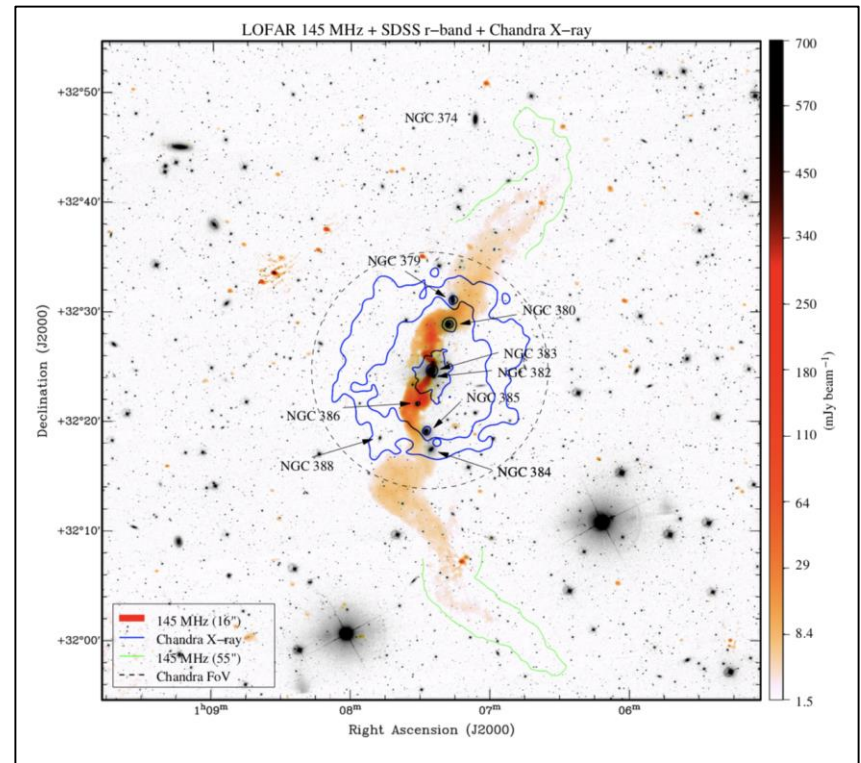
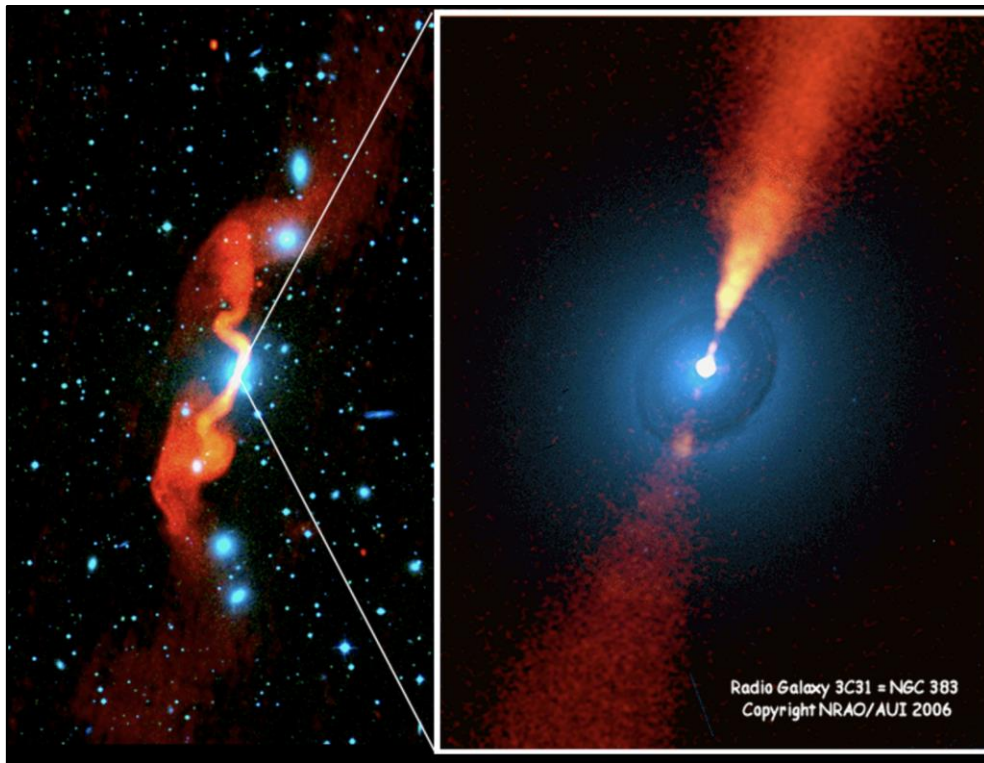
What triggers the radio activity?
Which is the interplay between the
jets and lobes in radio galaxies and the
ICM?



Singh et al. 2016



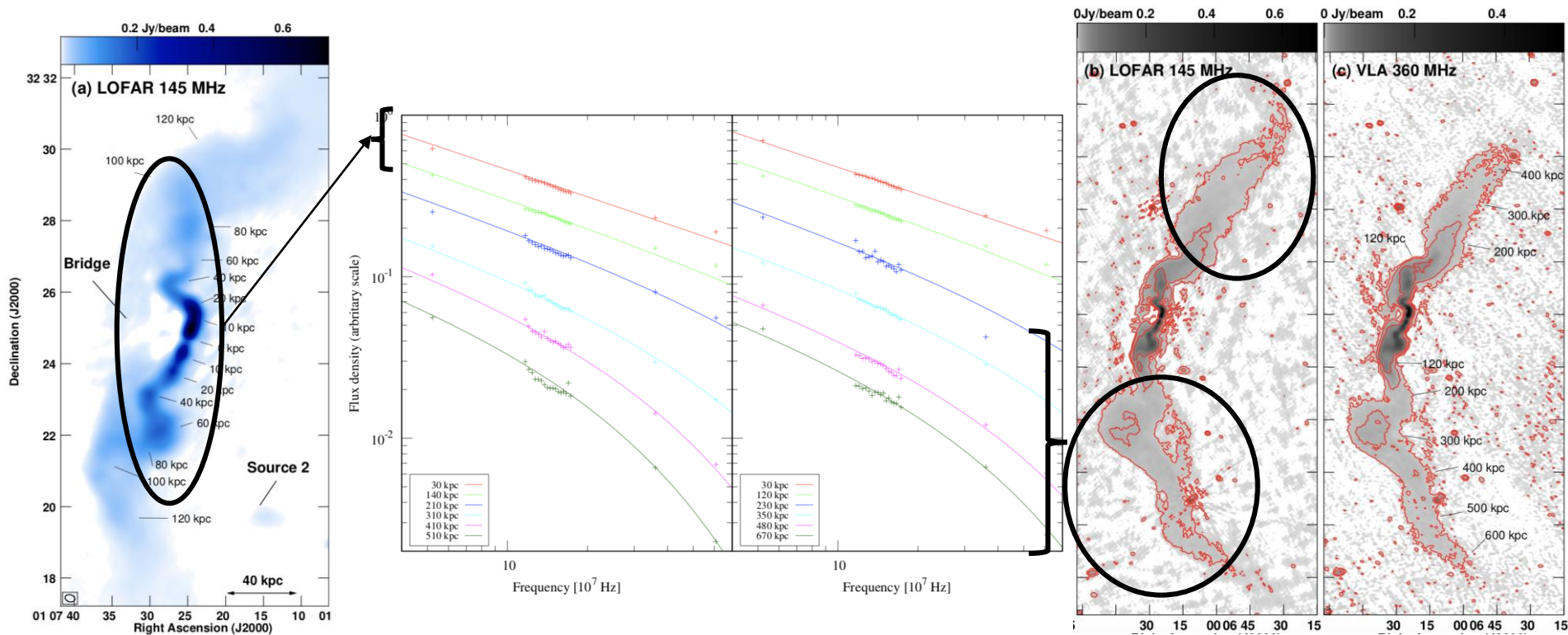
The case of 3C31



Heesen et al. 2018

The case of 3C31

Heesen et al. 2018

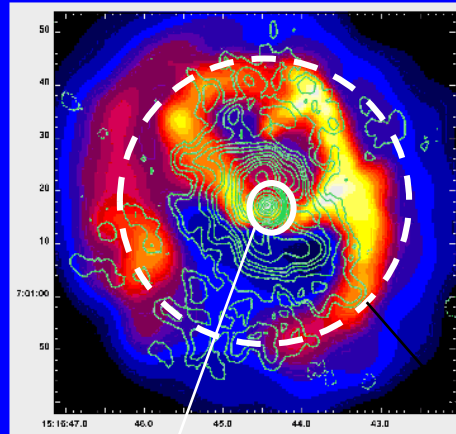


- A nearby ($z=0.0169$) giant radio galaxy (~ 1 Mpc) at low radio frequencies
- Estimated radiative age ~ 200 Myr
- Implications on the expansion on the ICM

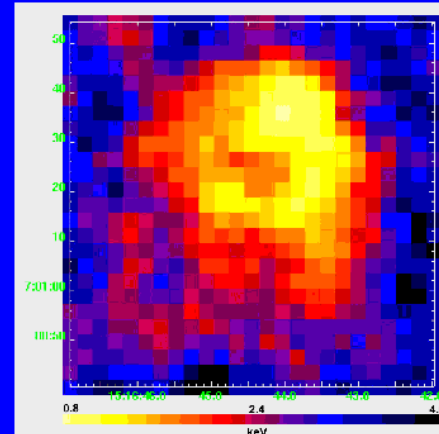
Few cases of
restarted activity
known so far

They seem more
common in dense
environments
(galaxy clusters and
group centres)

Abell 2052



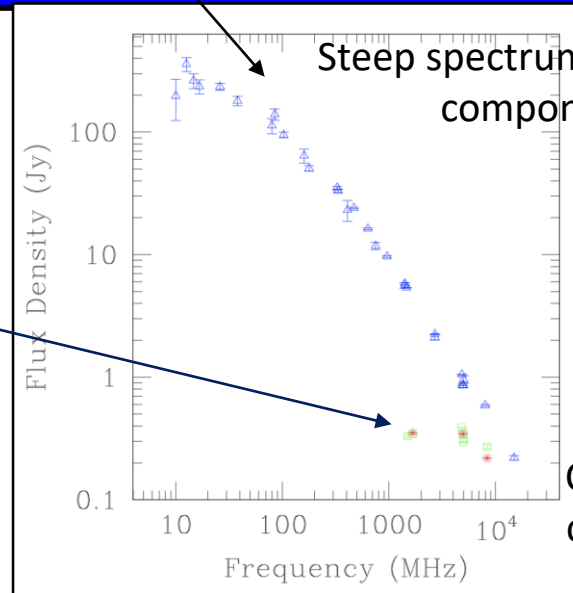
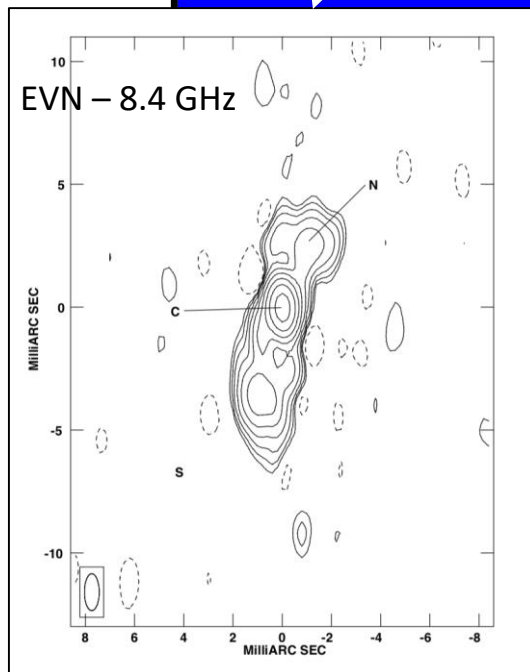
(Radio Contours, Burns [1990])



Chandra ACIS-S3, 36 ksec, $z=0.0348$, $1'' = 1$ kpc

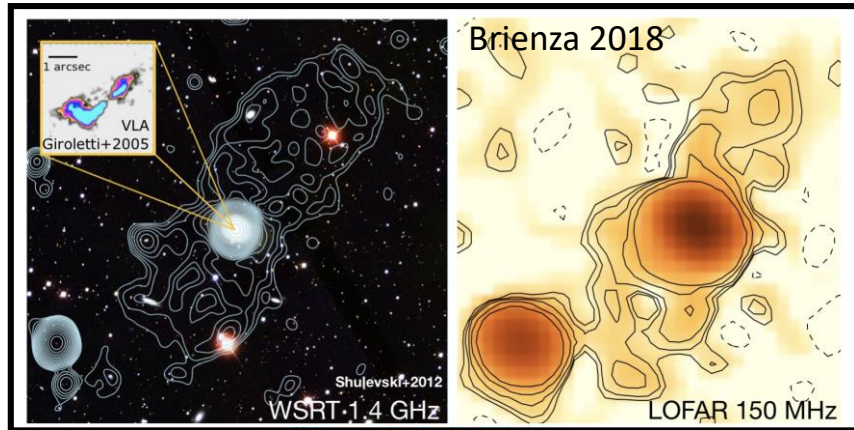
(Blanton et al. [2001,2002])

Major role of
high sensitivity
& high
resolution low
frequency
imaging
combined with
VLBI
observations

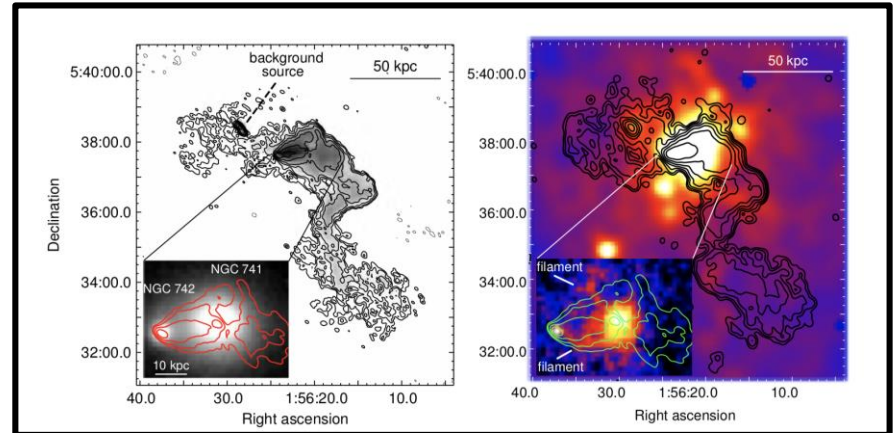


Venturi et al. 2004

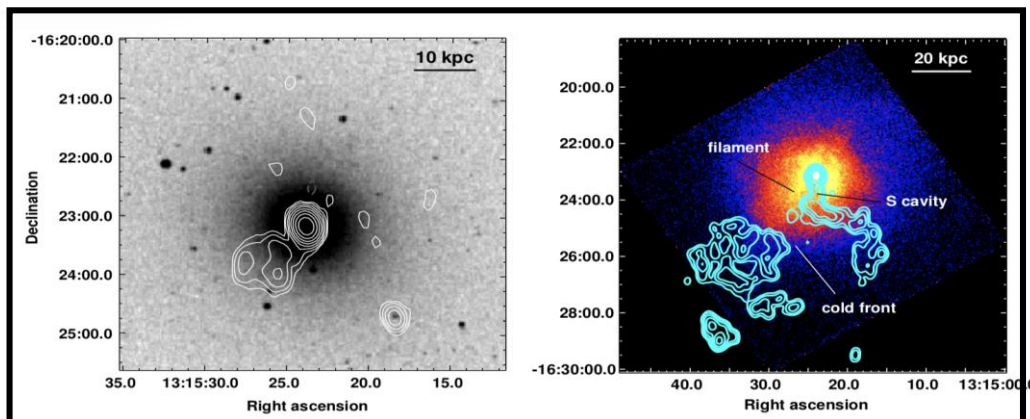
Increasing the statistics on remnant emission from radio galaxies and restarted activity



Restarted activity in B2 0258+35 - The addition of LOFAR to previous studies (Brienza 2018)



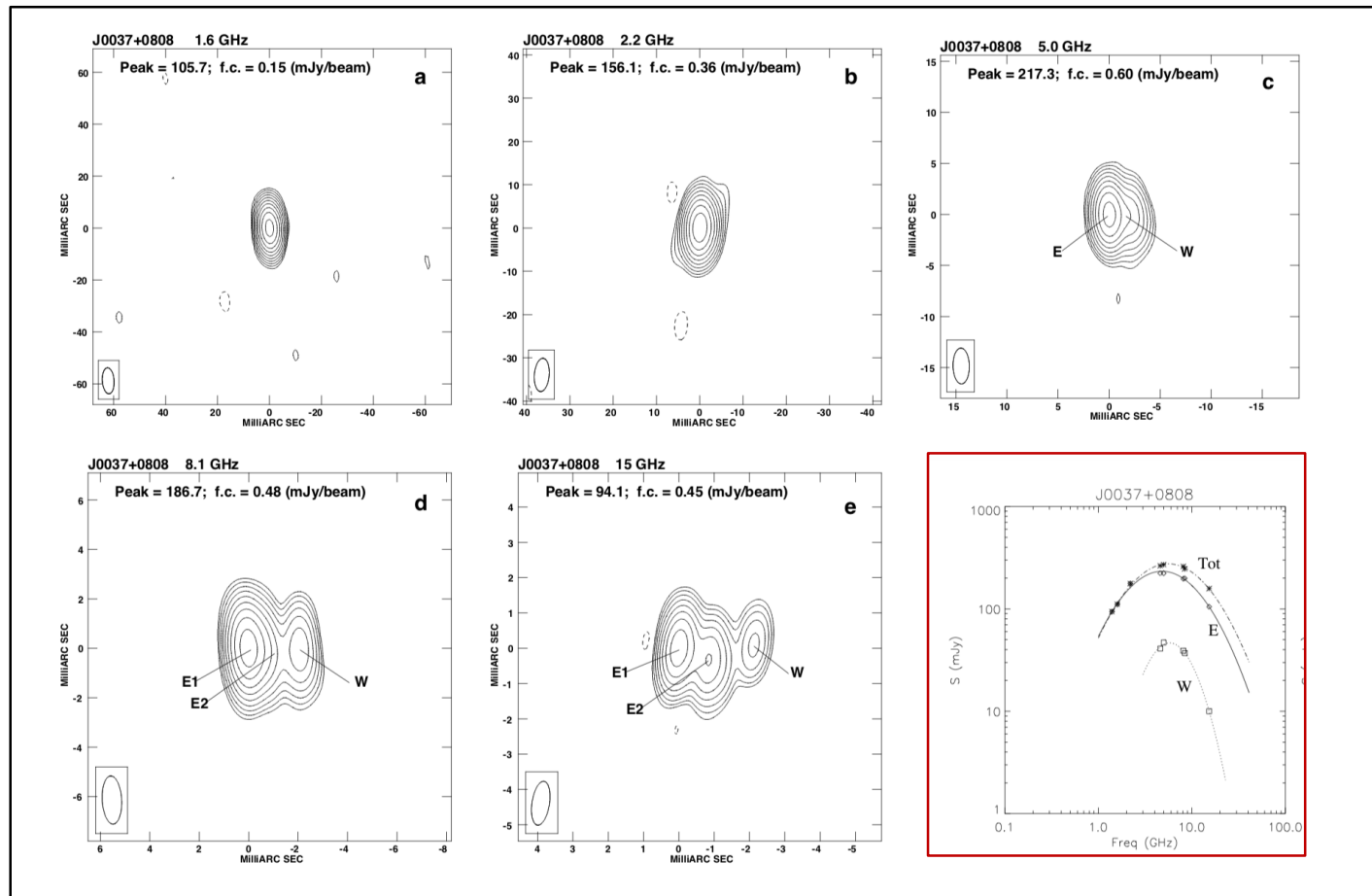
Restarted activity in the galaxy group NGC742 from multiband GMRT imaging (Giacintucci et al. 2011)



Multiple bursts of radio emission in NGC5044 at the centre of a galaxy group from multiband GMRT imaging (Giacintucci et al. 2011)

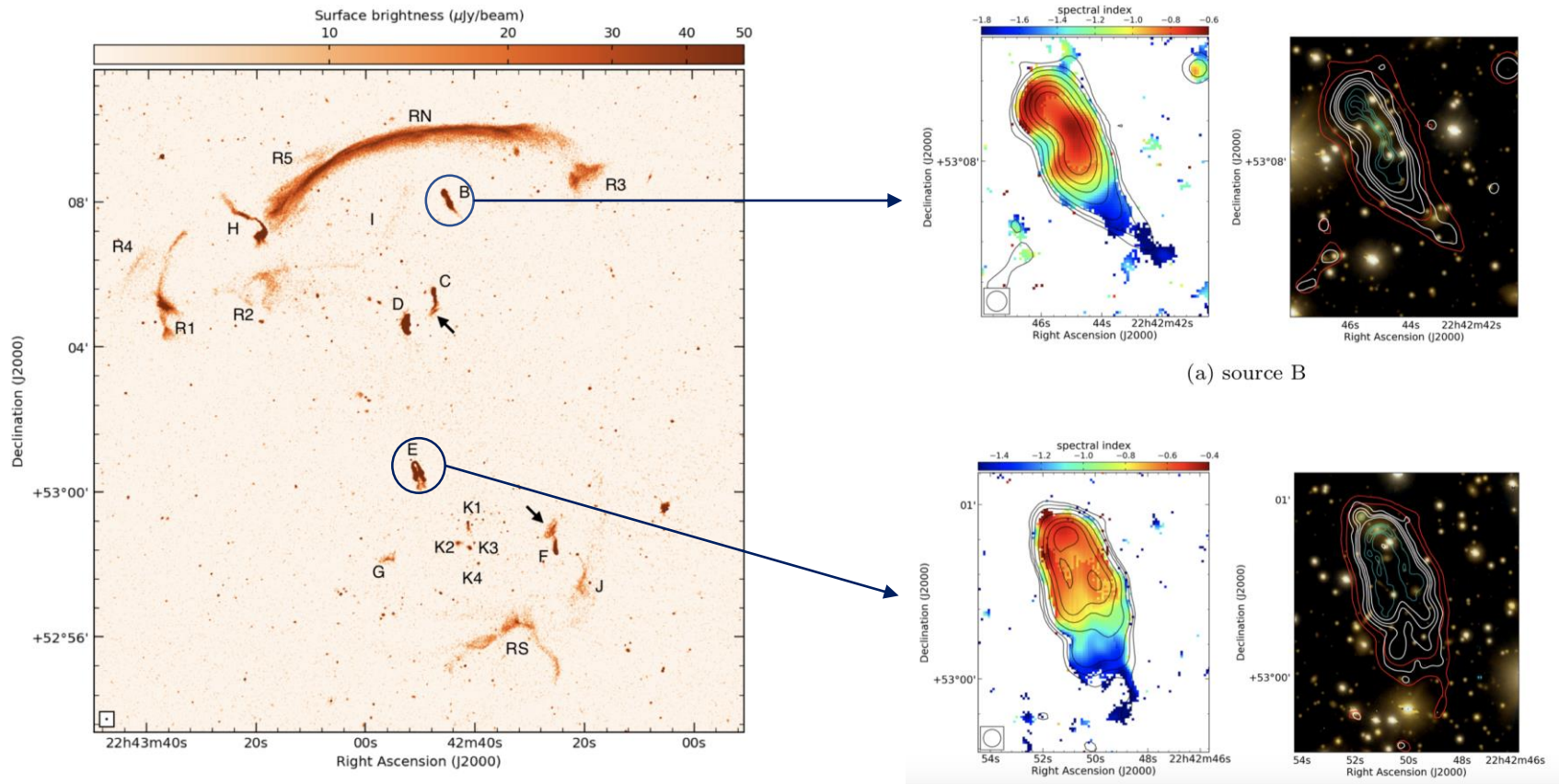
Potentials of the new broad band receivers

- Simultaneous spectra for compact radio sources and nuclear components of radio galaxies



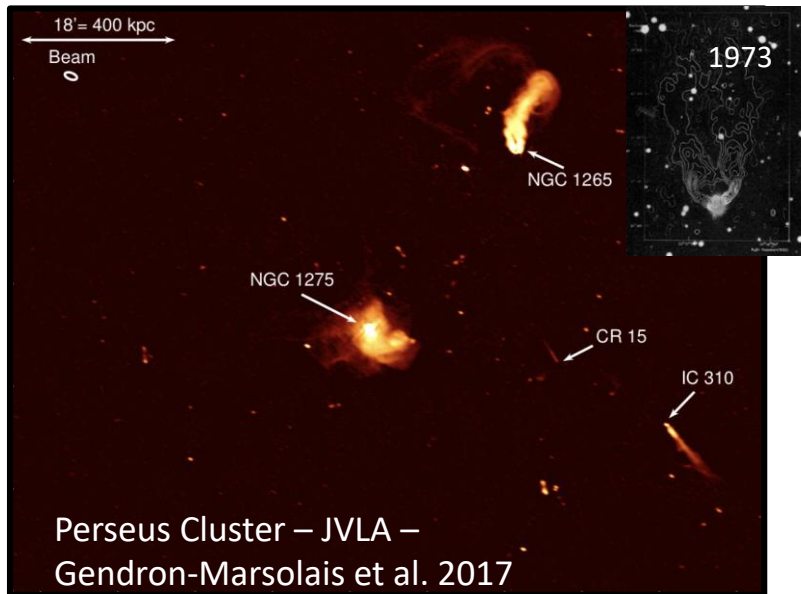
Potentials of the new broad band receivers

- Simultaneous spectral imaging with unprecedented resolution
- Impressive sensitivity at high angular resolution



The Sausage cluster – JVLA 2-4 GHz band – rms 2.3 microJy/b
Di Gennaro et al. 2018

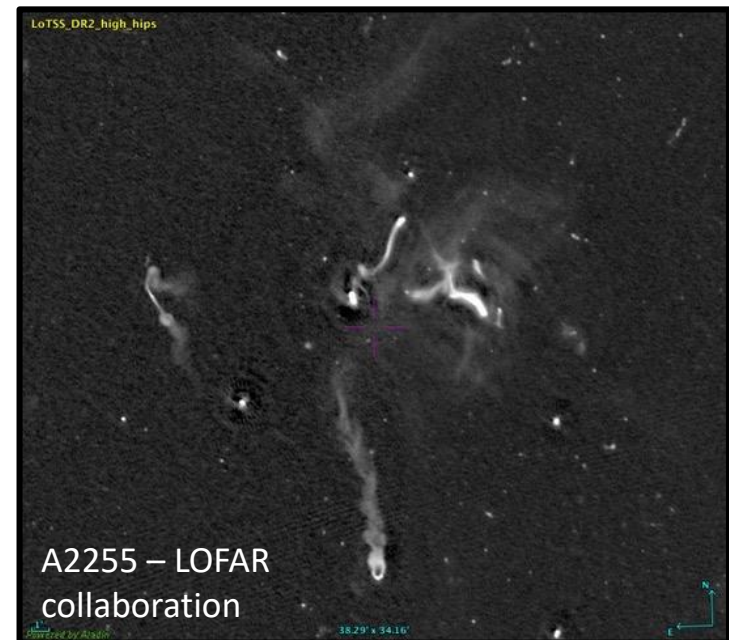
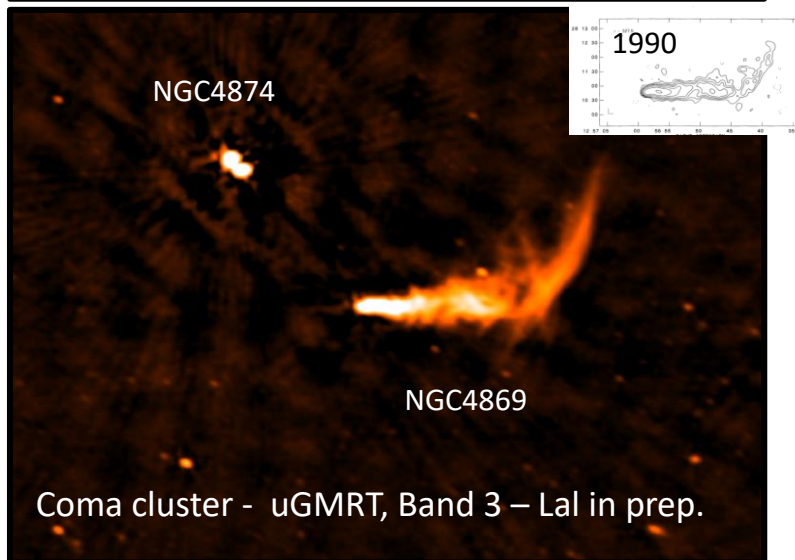
Where AGN science and galaxy cluster science meet



The quality of the present low frequency observations show impressive tails of emission from cluster radio galaxies

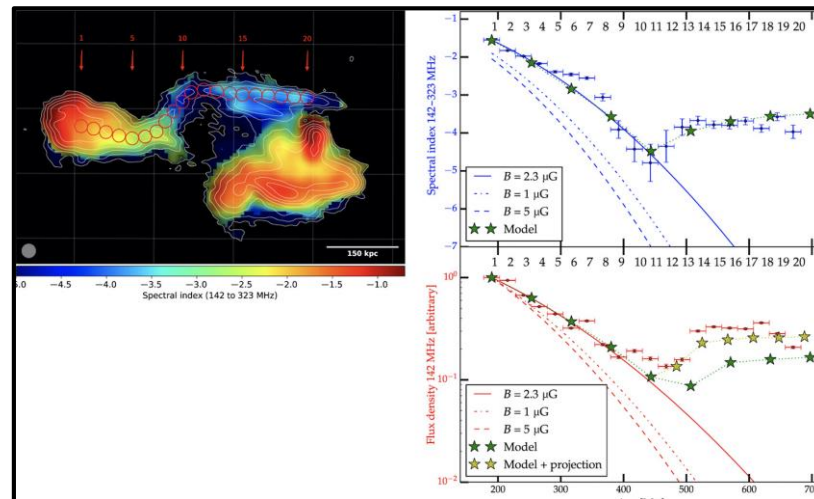
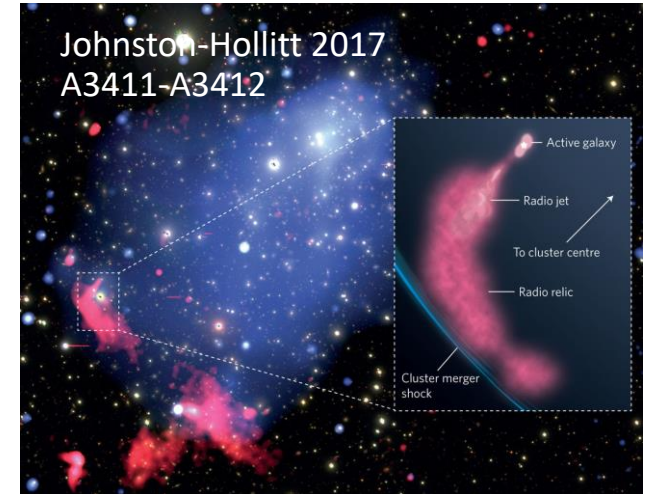
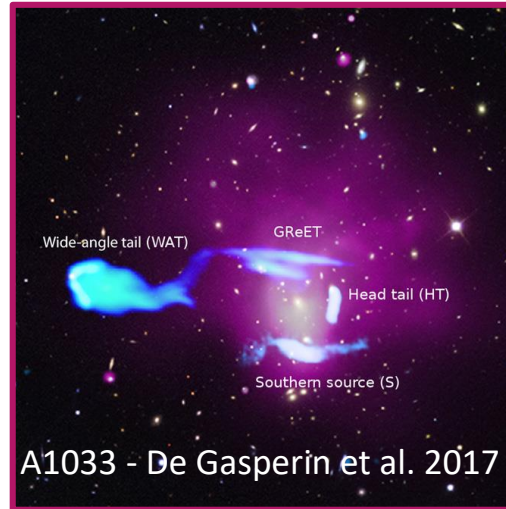
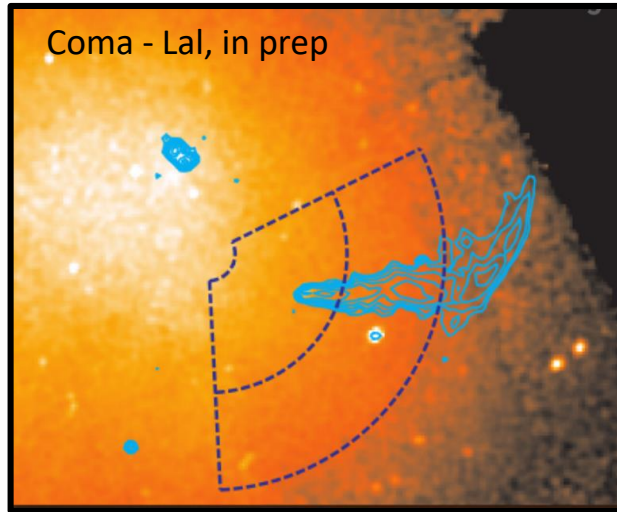


- Radio plasma and ICM interaction
- Trajectories of galaxies in their motion within the cluster



Where AGN science and galaxy cluster science meet

Clear connection between tailed radio galaxies and radio features in galaxy clusters



Tracing the core

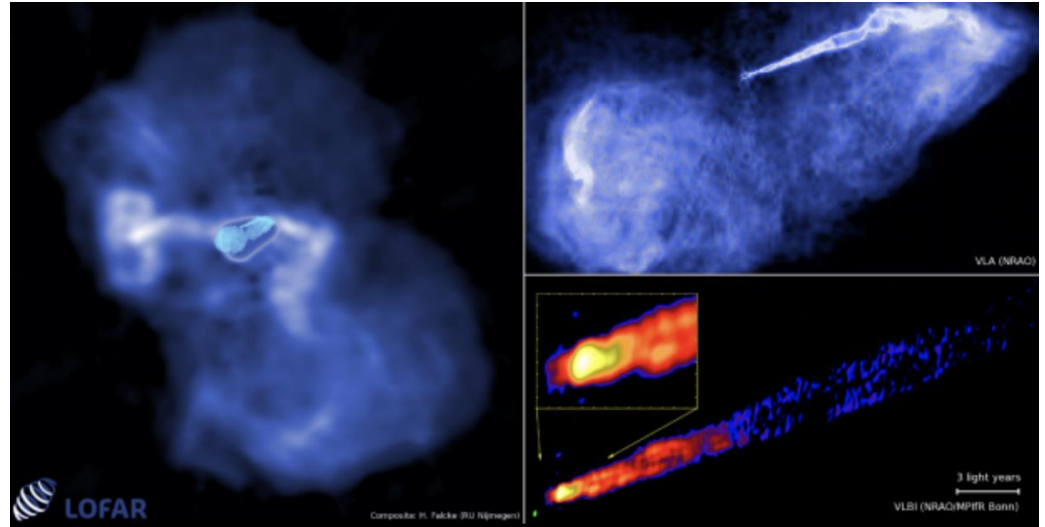
High sensitivity imaging at high frequencies and mas angular resolutions



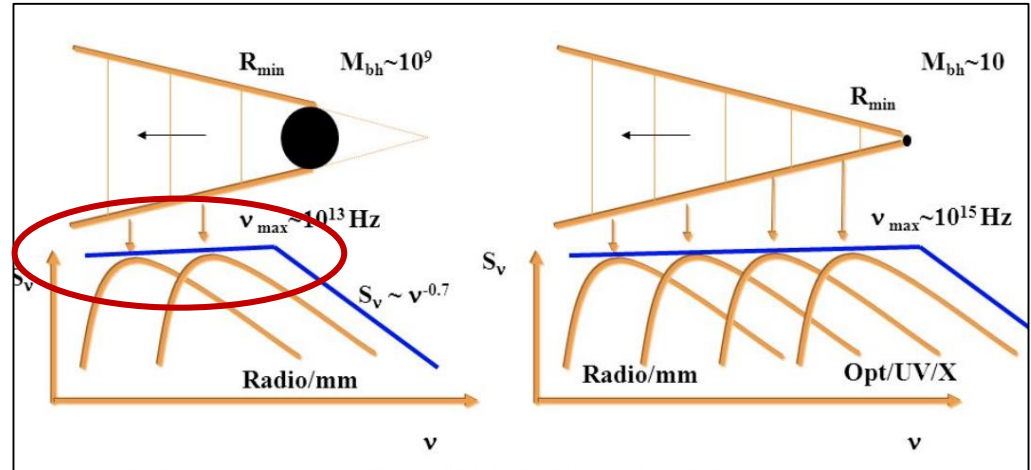
Peering into the innermost regions of AGN

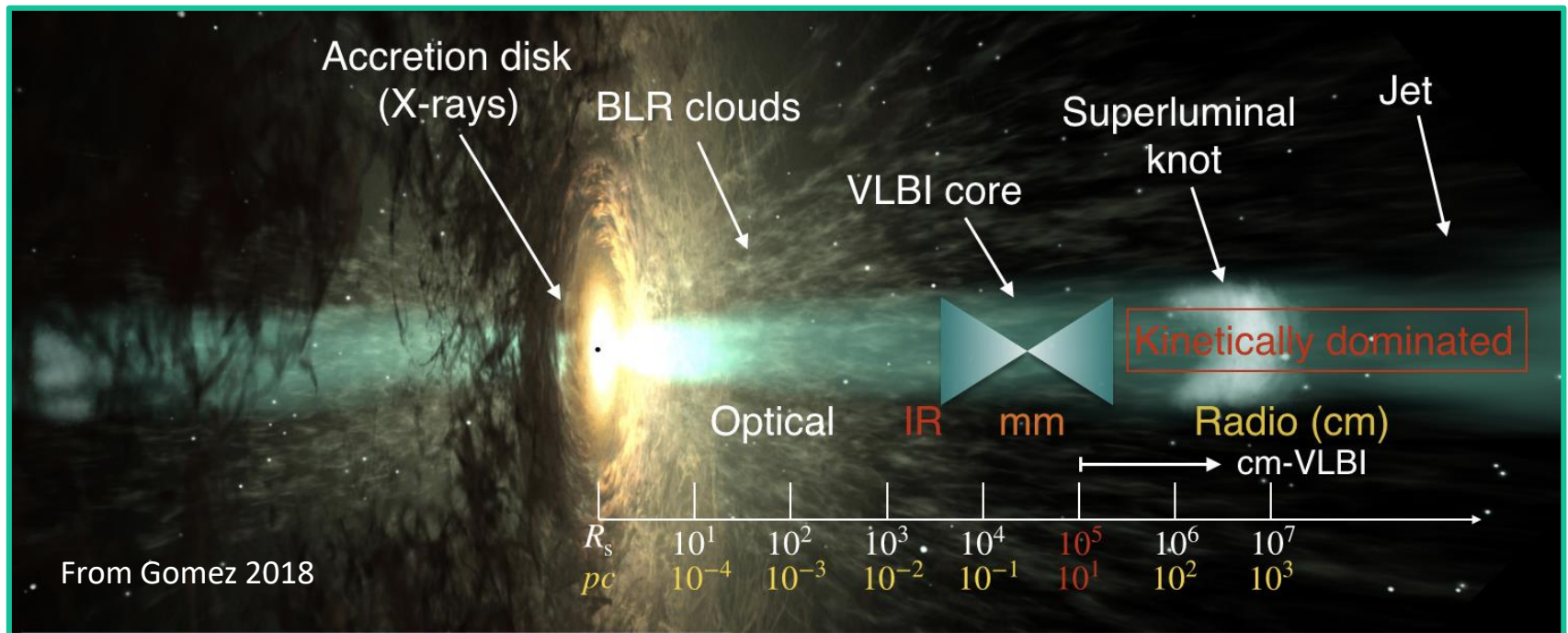


Despite the huge progress in theory, simulations and observing capabilities many questions are still open



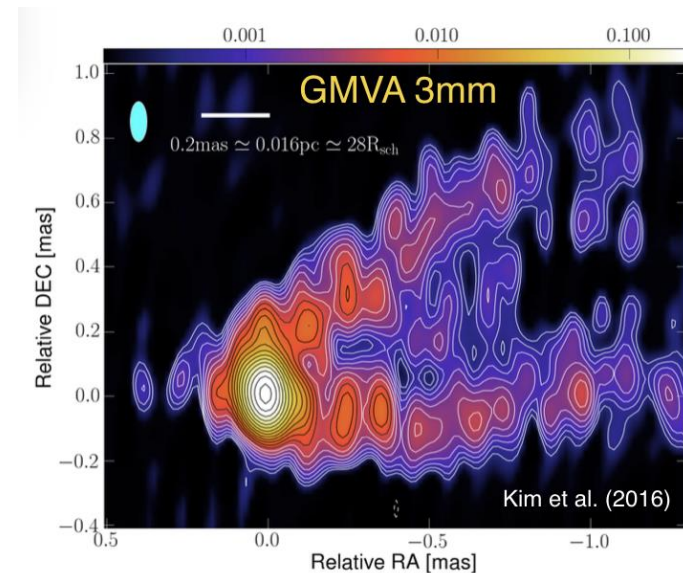
Falcke 2018





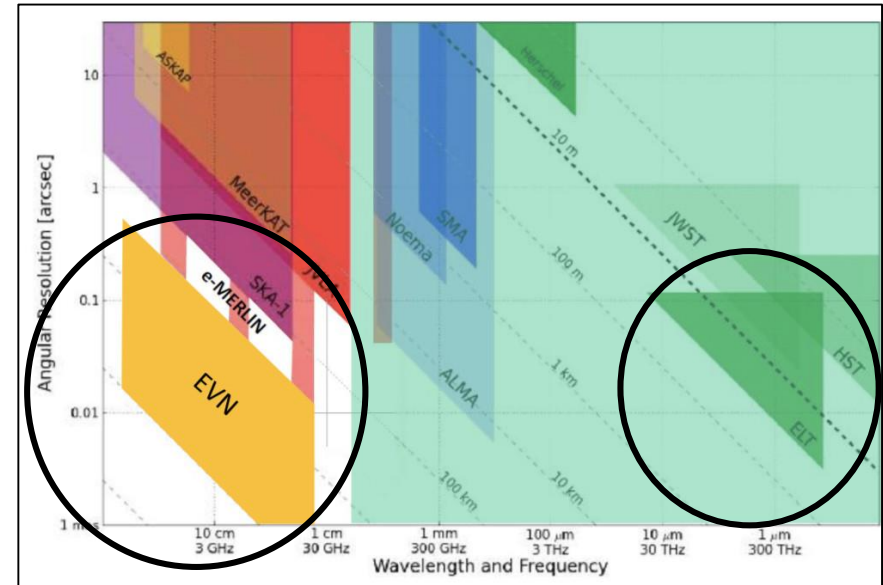
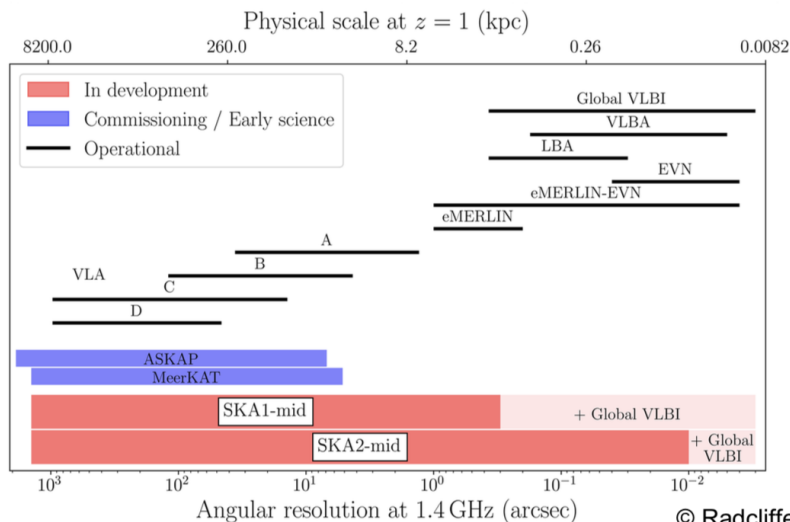
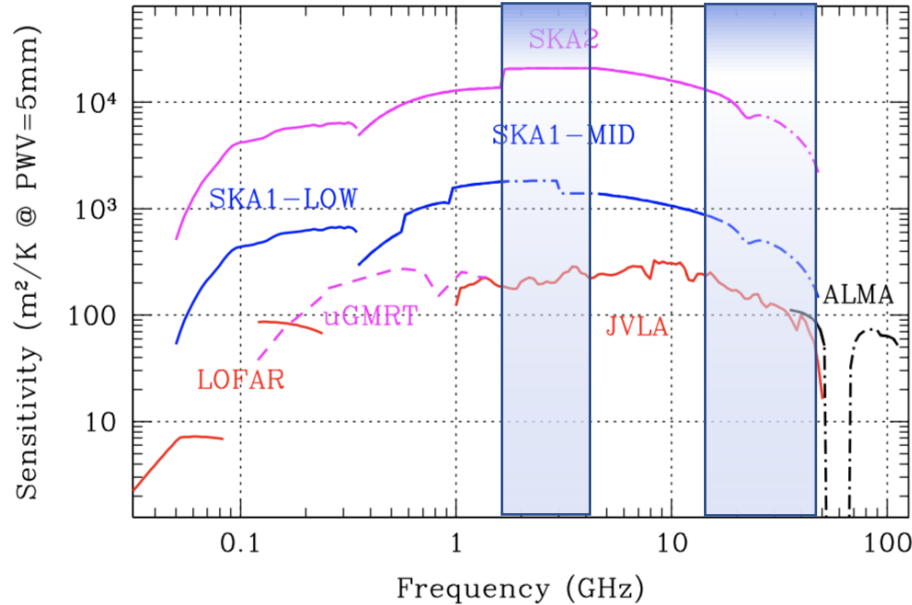
- Which is the launching mechanism for the jets?
- What is the core?
- Where does recollimation occur, and how?
- What determines the accretion mechanism and the jet power?

Very Long Baseline Interferometry
Science



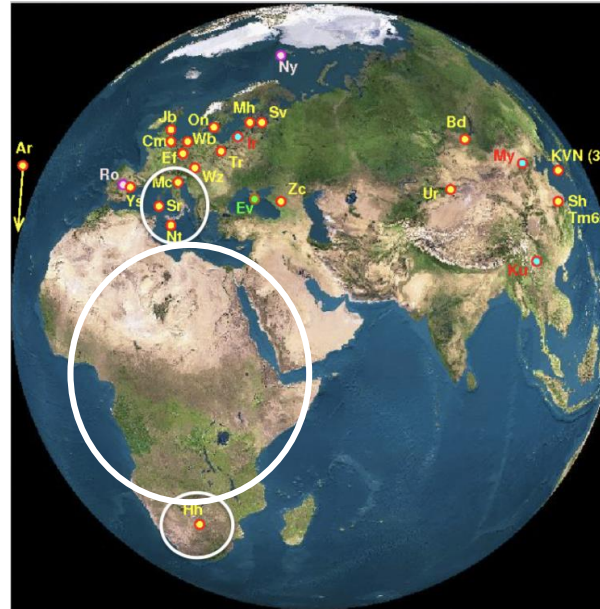
Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	Pulsars	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	Pulsars	High precision timing for testing gravity and GW detection	1/3
6	Pulsars	Characterising the pulsar population	2/3
7	Pulsars	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	Pulsars	Finding pulsars in the Galactic Centre	2/3
9	Pulsars	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	Pulsars	Mapping the pulsar beam	3/3
11	Pulsars	Understanding pulsars and their environments through their interactions	3/3
12	Pulsars	Mapping the Galactic Structure	3/3
13	HI	Resolved HI kinematics and morphology of $\sim 10^4$ M_{\odot} mass galaxies out to $z \sim 0.8$	1/5
14	HI	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	HI	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	HI	HI absorption studies out to the highest redshifts.	4/5
17	HI	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	Transients	Solve missing baryon problem at $z \sim 2$ and determine the Dark Energy Equation of State	$\approx 1/4$
19	Transients	Accessing New Physics using Ultra-Luminous Cosmic Explosions	$\approx 1/4$
20	Transients	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	Transients	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	Cradle of Life	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	Cradle of Life	Characterise exo-planet magnetic fields and rotational periods	2/5
24	Cradle of Life	Survey all nearby (~ 100 pc) stars for radio emission from technological civilizations.	3/5
25	Cradle of Life	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	Cradle of Life	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	Magnetism	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	Magnetism	Detection of polarised emission in Cosmic Web filaments	3/5
30	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	Magnetism	Intrinsic properties of polarised sources	5/5
32	Cosmology	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	Cosmology	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	Cosmology	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	Cosmology	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	Cosmology	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	Continuum	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	Continuum	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	Continuum	Probe the role of black holes in galaxy evolution - I.	3/8
40	Continuum	Probe the role of black holes in galaxy evolution - II.	4/8
41	Continuum	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	Continuum	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	Continuum	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	Continuum	Legacy/Serendipity/Rare.	8/8


Several good reasons for SKA-VLBI operations



- ✓ A large part of the AGN science would remain unaddressed without SKA-VLBI operations
- ✓ Several major SKA science goals would strongly benefit from VLBI
- ✓ Synergy with E-ELT requires milliarcsecond resolution

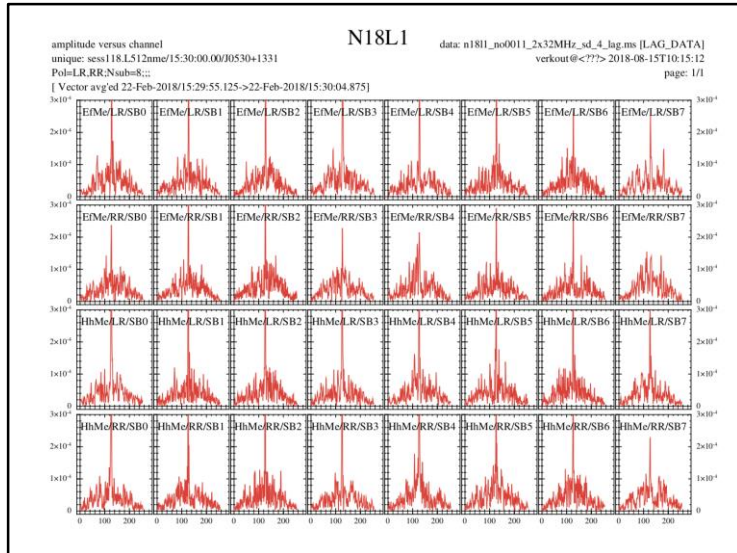
VLBI in the SKA-mid1 era



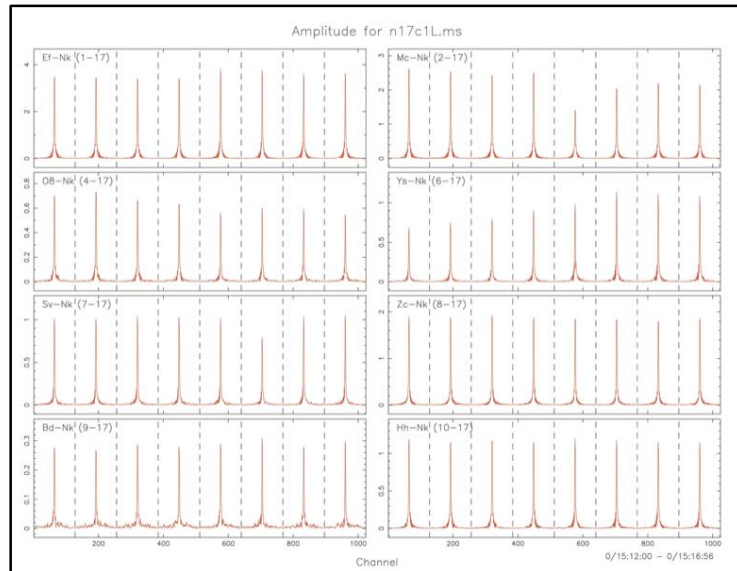
To ensure successful milliarcsecond follow-up of SKA-mid1 sources, and synergy with the E-ELT, the full completion of the African VLBI Network is necessary to ensure the **broadest portion of the sky accessible to all instruments**, and the **best u-v coverage for VLBI**  **Special role of the Italian VLBI Network to ensure continuity between EVN and AVN**

VLBI in the SKA-mid1 era

Integration of the antenna in Ghana and of MeerKAT ongoing



First successful fringe
test between EVN
antennas and
MeerKAT in Session 1-
2018





First successful fringe
test between EVN
antennas and Ghana in
April 2017
(JIVE Press release
07/04/2017)



VLBI in the SKA-mid1 era

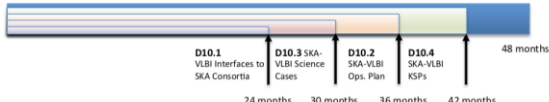
- Focus of one of the WP in the EC-H2020 JUMPING JIVE project (INAF is a partner)

Joining Up Users for Maximising the Profile, the Innovation and the Necessary Globalisation of JIVE
JUMPING JIVE -730884



WP10 Goals and Deliverables

- Make the SKA VLBI compliant
 - Technical requirements, Interfaces
 - Operational model
 - Commissioning plan
- Develop science cases
 - Work closely with the **SKA VLBI Focus Group** and other SKA science WGs
 - Key Science Projects definition
- Deliverables
 - Details on VLBI interfaces to SKA Consortia – **Month 24**
 - Operational plan for inclusion of SKA in Global VLBI – **Month 36**
- Deliverables
 - Portfolio of SKA-VLBI Science Cases – **Month 30**
 - Report on SKA-VLBI Key Science Projects – **Month 42**



Slide from Paragi 2018
JJ Mid-Term Review

Joining Up Users for Maximising the Profile, the Innovation and the Necessary Globalisation of JIVE
JUMPING JIVE -730884



WP9 – Capacity for VLBI in Africa



Slide from Beswick 2018
JJ Mid-Term Review

- Progetto di Grande Rilevanza MAECI-NRF RADIO SKY 2020 (PIs Venturi/Vaccari)

SUMMARY and CONCLUSIONS

- ✓ New potentials in our understanding of radio galaxy evolution are emerging from SKA pathfinders and precursors
- ✓ The radio galaxy science and galaxy cluster science are progressing hand in hand
- ✓ SKA1-mid will complement the current low frequency interferometers in terms of polarization performances
- ✓ The study of radio galaxies would strongly benefit from SKA Band 5 and SKA-VLBI operations

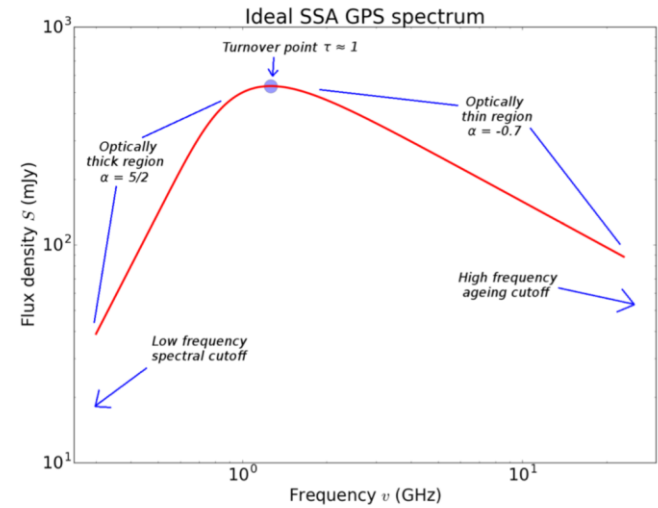
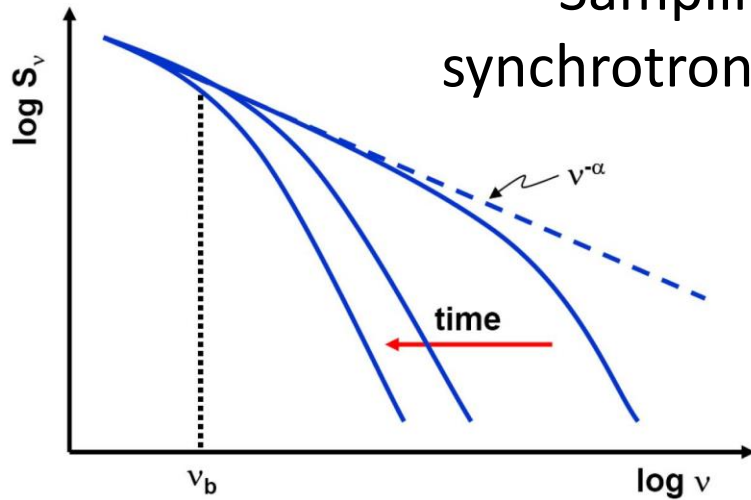
SKA-VLBI operations will be essential:

- In several of the main scientific goals of the SKA
- For a full exploitation of the synergy between SKA and E-ELT
- ❖ Efforts for SKA-VLBI operations in the SKA1 era are in progress and INAF can play a major role

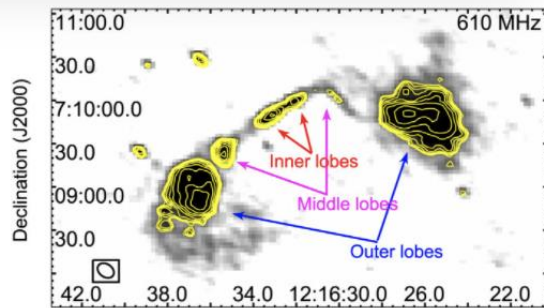
The image is a deep-field astronomical photograph showing a vast field of stars and distant galaxies against a black background. Overlaid on this image are several sets of concentric contour lines in white and light blue. These contours represent intensity levels of a specific signal, likely radio or infrared, and are centered on two primary sources. One source is located in the upper right quadrant, and the other is in the lower left quadrant. The contours vary in density, with the most concentrated areas appearing as bright white lines. The text 'THANK YOU FOR YOUR ATTENTION' is centered in the middle of the image in a white, sans-serif font.

THANK YOU FOR YOUR
ATTENTION

Sampling the synchrotron spectrum



Orienti & Dallacasa 2014



Singh et al. 2016 Right ascension (J2000)

