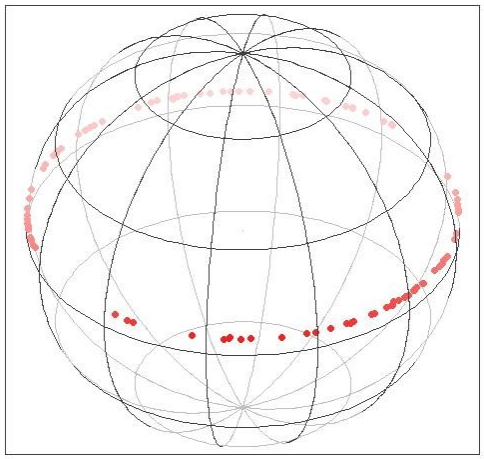
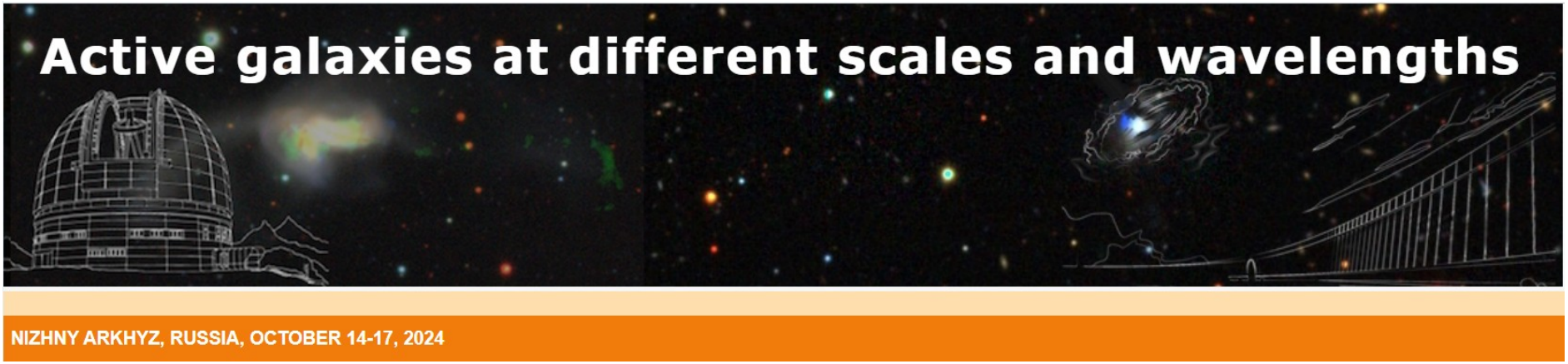


State of the steep spectrum sample of the experiment Cold according to modern sky surveys in the optical and radio ranges

O. Zhelenkova [(1)], Yu. Parijskij, N. Soboleva, A. Temirova [(2)]

(1) SAO RAS; (2) SPb Branch of SAO RAS

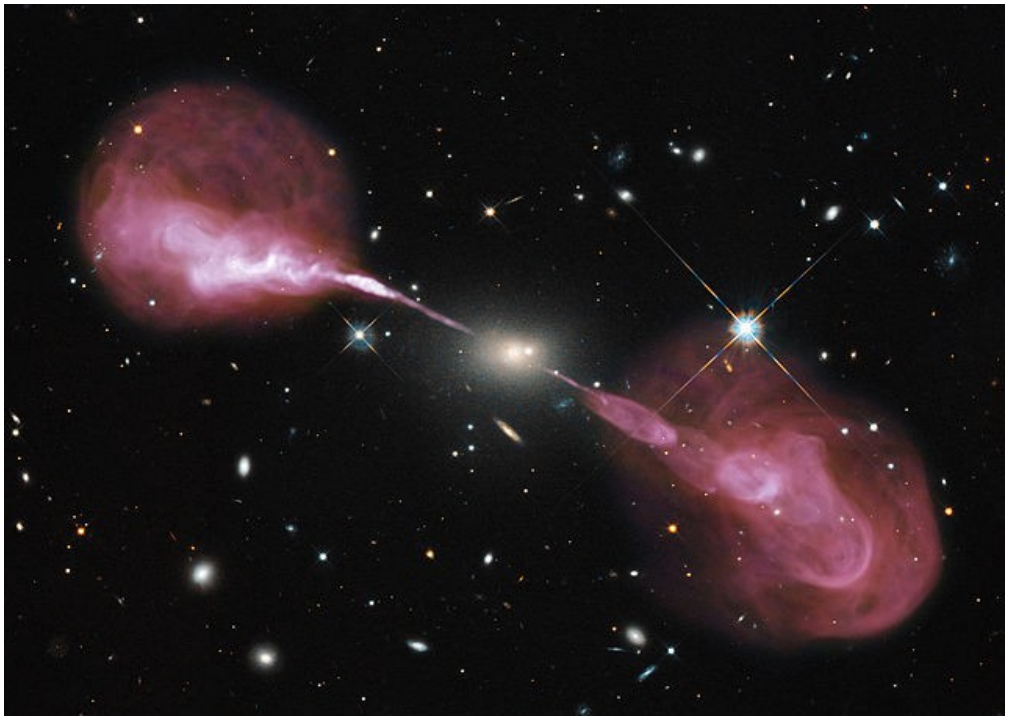


Ragiogalaxies and cosmology

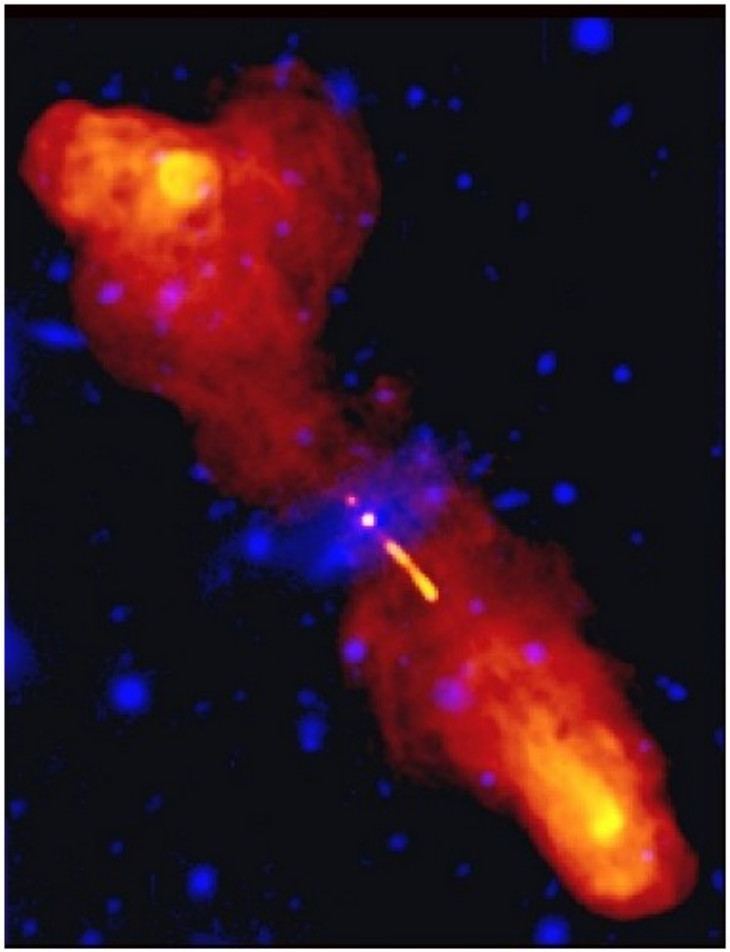
Detecting powerful radio galaxies at high redshifts is a challenging task. However, it should be noted that HzRGs are of particular interest to cosmology for the following reasons:

1. progenitors of local massive elliptical galaxies (Best et al. 1998; De Breuck et al. 2010);
2. the most massive galaxies at their redshift (Overzier et al. 2009);
3. study of the stellar population of the host galaxy, which for quasars is complicated by the high brightness of the active nucleus;
4. often found to be located at the centre of clusters and proto-clusters of galaxies (Pentericci et al. 2000; Miley et al. 2004; Orsi et al. 2016);
5. studies of their environment can give insights into the assembly and evolution of the large-scale structure in the Universe;
6. radio galaxies at $z > 6$, in the epoch of reionization, are of particular interest as they could be used as unique tools to study the process of reionization in detail (Carilli, Gnedin & Owen 2002).

Ragiogalaxies and cosmology



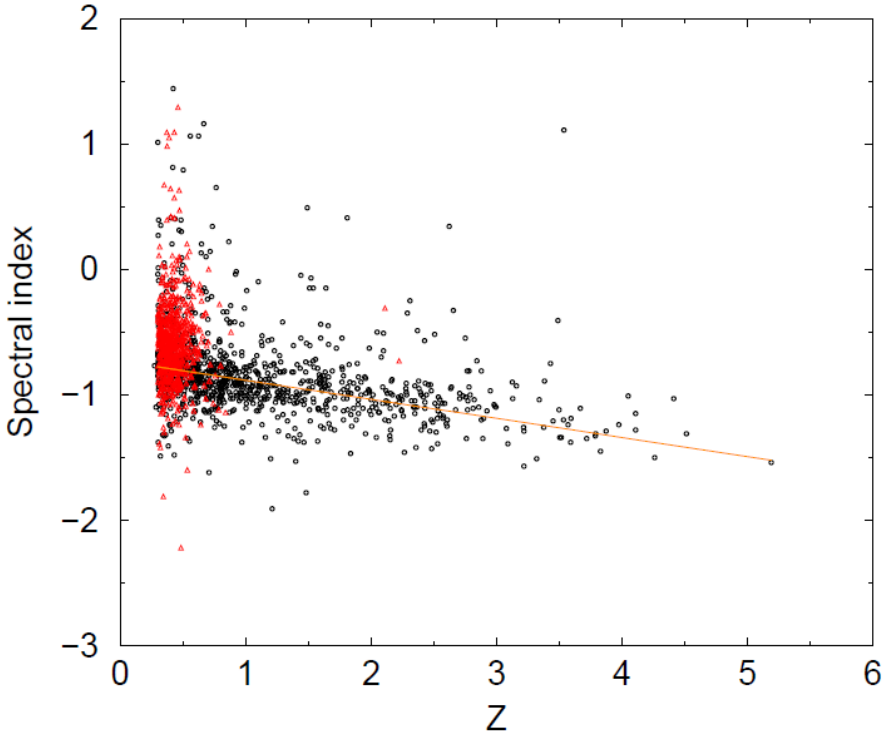
FRI type. Hercules A . The radio emission is imaged in pink and is superimposed on optical image. *Credits: VLA.*



FRII type. 3C 237 radio galaxy. The blue objects are the optical galaxies and stars. *Credits: NRAO*

Ragiogalaxies and cosmology

Blind searches for these rare objects are not effective. In the work of Tielens et al. (1979) it was found that distant sources have steep spectra.



Spectral index (α_{1400}) – redshift diagram for 2442 radiogalaxies (z>0.3). The regression line was drawn using the median spectral indices within bins with a step Δz=0.5. (Verkhodanov et al., 2010).

Although steep spectra are also observed in pulsars and faded and giant radio galaxies, this criterion is often used in the selection of distant object candidates: Roettgering et al. (1994), De Breuck et al. (2000), Broderick et al. (2007), Saxena et al. (2018).

Ragiogalaxies and cosmology

Radio properties of known radio galaxies at z > 4 (from Saxena et al., 2018)

Name	**z**	**S_{150}** mJy	**log L_{150}** W Hz^{-1}	**S_{1400}** mJy	**α_{150}^{1400}**	**Size** kpc	**Reference**
TGSS J1530+1049	5.72	170	29.1	7.5	−1.4	3.5	Saxena+(2018)
TN J0924−2201	5.19	760	29.6	71.1	−1.1	7.4	van Breugel+(1999)
J163912.11 + 405236.5	4.88	103	28.2	22.5	−0.7	−	Jarvis+(2009)
RC J0311 + 0507	4.51	5981	30.3	500.0	−1.1	21.1	Kopylov+(2007)
VLA J123642 + 621331	4.42	undet.	−	0.5	−	−	Waddington+(1999)
6C 0140 + 326	4.41	860	29.4	91.0	−1.0	17.3	Rawlings+(1996)
8C 1435 + 635	4.25	8070	30.4	497.0	−1.2	21.1	Lacy+(1994)
TN J1123 − 2154	4.11	512	29.1	49.3	−1.0	5.5	Reuland+(2004)
TN J1338 − 1942	4.10	1213	29.5	120.8	−1.0	37.8	Reuland+(2004)

RATAN-VLA-BTA (Big Trio) - search for distant radio galaxies using a sample of radio sources with steep spectra

RATAN: Selection sources with ultra steep spectra from RC catalogue. It was obtained from observations of a 40' sky strip survey at declination SS433 δ(1981)=+04º57'±20' (ν=3.94 GHz) and also used UTRAO catalogue (365 MHz);

VLA: morphological structure and precise coordinates of radio sources of the SS sample

BTA: optical identification and obtained spectral redshifts.

Selection criteria for USS-sample (Kopylov et al., 1995):

- $\alpha <= -1.0 \div -0.9$ ($S \propto \nu^{\alpha}$);
- flux density (not brighter than a few hundred mJy at 3.94 GHz);
- FRII type double radio sources;
- small angular size (LAS<20")

RATAN-VLA-BTA - search for distant radio galaxies

1. Parijskij Yu. N.	1. Goss W.M.
2. Soboleva N.S.	2. Pursimo T.
3. Temirova A.V.	3. Nilsson K.
4. Kopylov A.I.	4. Teerikorpi P.
5. Verkhodanov O.V.	5. Sillanpä A.
6. Zhelenkova O.P.	6. Takalo L.O.
7. Bursov N.N.	7. Winn J.
8. Afanas'ev V.L.	8. Fletcher A.
9. Dodonov S.N.	9. Burke B.
10. Moiseev A.V.	10. Conner S.
11. Fatkhullin T.A.	11. Crawford F.
12. Naugol'naya M.	12. Cartwright J.
13. Vitkovskij Val.V.	13. Thomasson P.
14. Komarova V.N.	14. Muxlow T. W. B.
15. Lipovka N.M.	15. Beswick R.
16. Kovalev Yu. Yu.	16. Reich P.
17. Baryshev Yu.	17. Furst E.

RATAN-VLA-BTA - search for distant radio galaxies

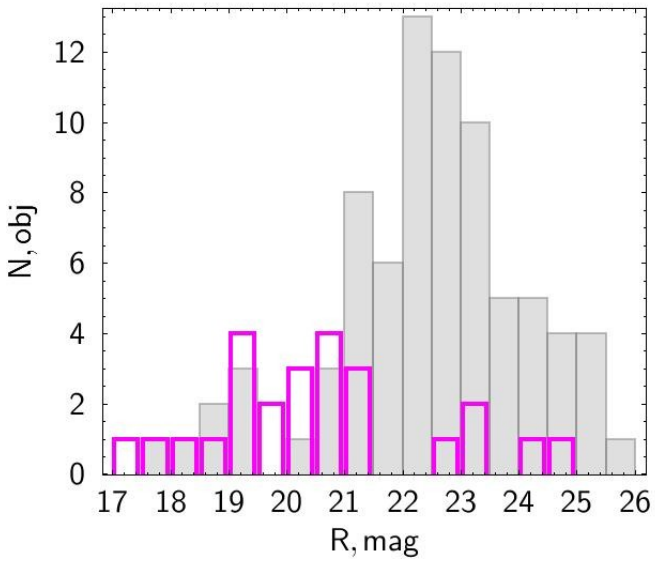
VLA: 300 radio maps were obtained for the Cold sources, including 100 maps for half of the SS-sample sources, at 1.4, 5, 8 and 15 GHz with an angular resolution of 0.1" ÷ 1.5". And 15% of the sources fell into the FIRST survey area (1.4 GHz, 5").

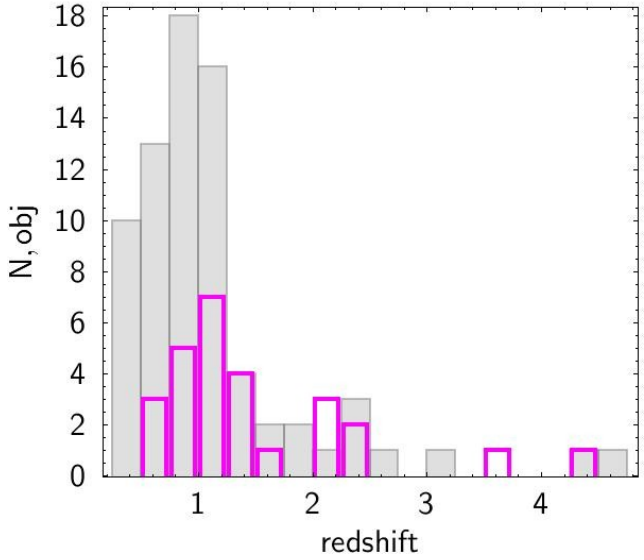
BTA (photometry and optical identifications): observations were carried out from 1991 to 2008 (80 observing nights with θ≈2", 0.75 nights per object);
50% of the time was spent on R-band observations (700 frames, 600 s exposure).
BVI-photometry was performed for half of the objects.
For 22 objects images were obtained (θ≈1") on the 2.56-m NOT telescope (Pursimo et al., 1999).
Optical counterparts were found for 94% of sources.

Photometric redshifts: for 48% of objects photometric redshifts were obtained using BVRI photometry (Verkhodanov+, 2002).

BTA (spectra): Spectroscopic studies of optical candidates were carried out using the SCORPIO focal reducer (Afanas'ev&Moiseev, 2005) from 2001 to 2008 (58 nights, 0.8 nights per object).
For 71 sources spectra were obtained [Dodonov et al. (1999), Afanas'ev et al. (2003), Kopylov et al. (2006), Parijskij et al. (2010)]: 25% - no lines detected, 50% - galaxies (50% with z>1), 25% - quasars (70% - z>1);

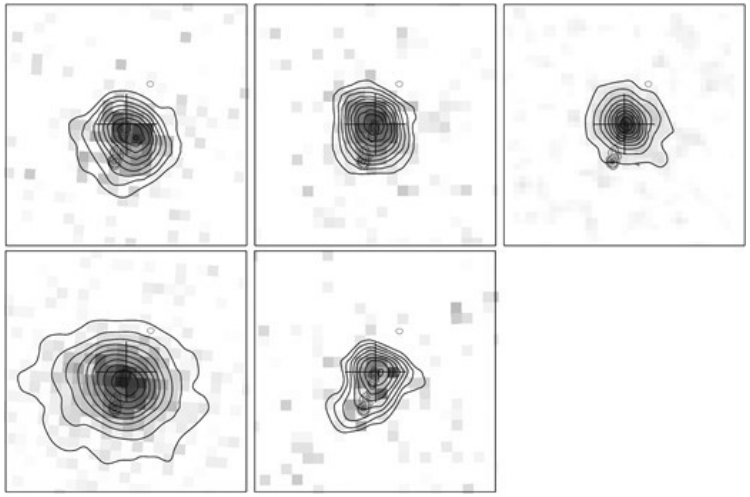
RATAN-VLA-BTA - search for distant radio galaxies



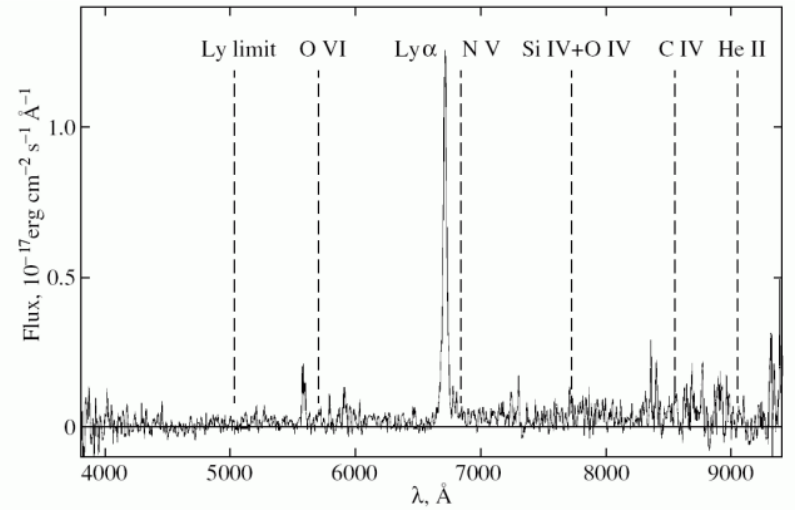


Median characteristics		
α_{365}^{3940}	-1.1	
S_{150}, mJy	1189	42÷6491
S_{3940}, mJy	65	3÷402
LAS, arcsec	11.7	0.1÷122.5
R, mag	22.5	
K, mag	17.7	
W1, mag	16.3	
Z	0.95	
log L_{150}, W/Hz	27.7	25.1÷30.2

The most distant radio sources of the Big Trio program

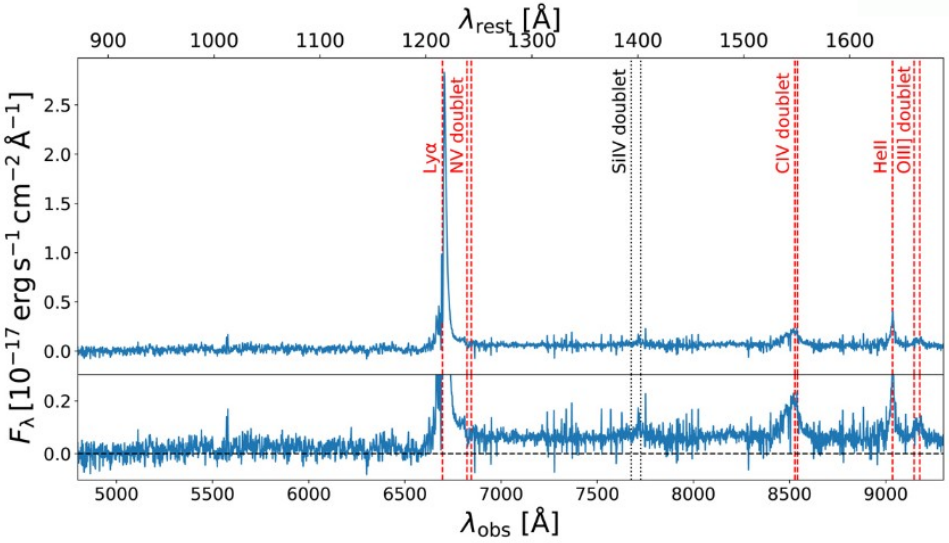


The RC J0311+0507 (4C+04.11) images. From left to right in the top row: the *R*, *I* and *K* bands are shown, in the bottom row: SED 665, SED 707.



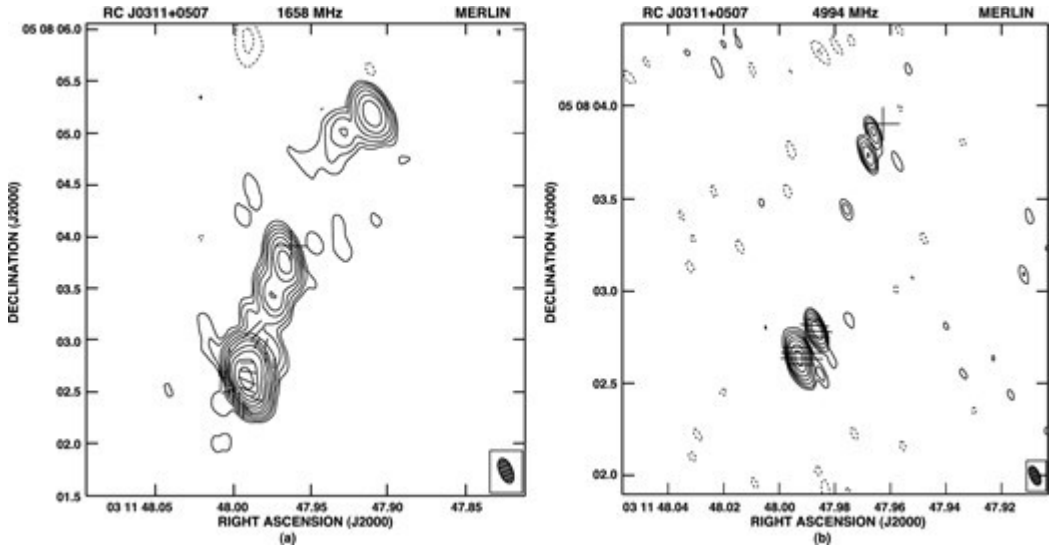
R=22.9

Optical spectrum of the host galaxy of RC J0311+0507. We identify a narrow, intense line at the center. with Lyα 1216 A. z=4.514.

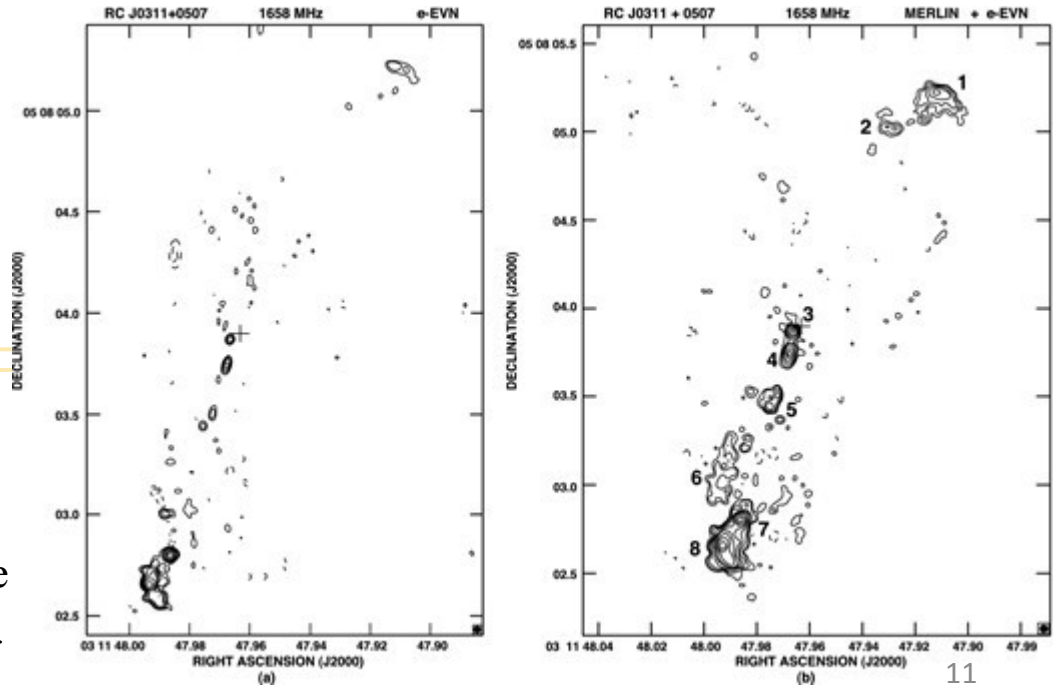


MUSE rest frame UV spectra (Wang+,2021). *Z*= 4.5077

The most distant radio sources of the Big Trio program

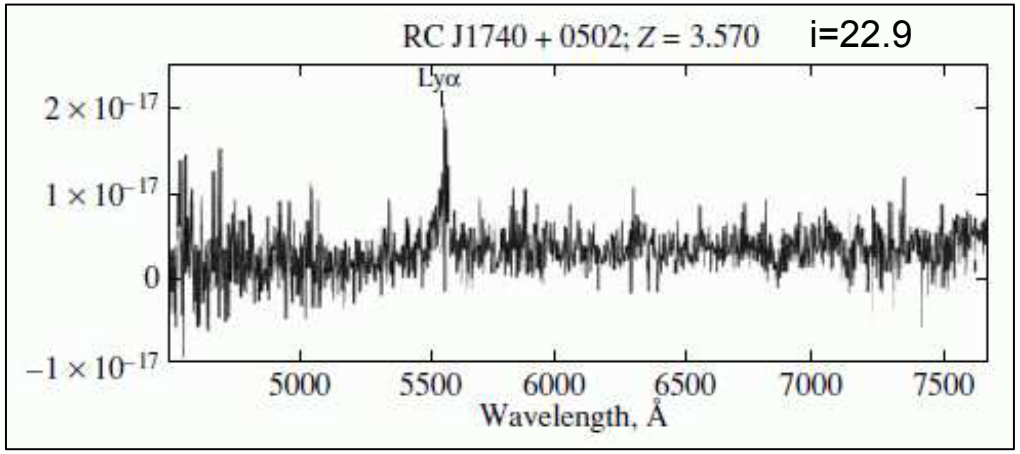


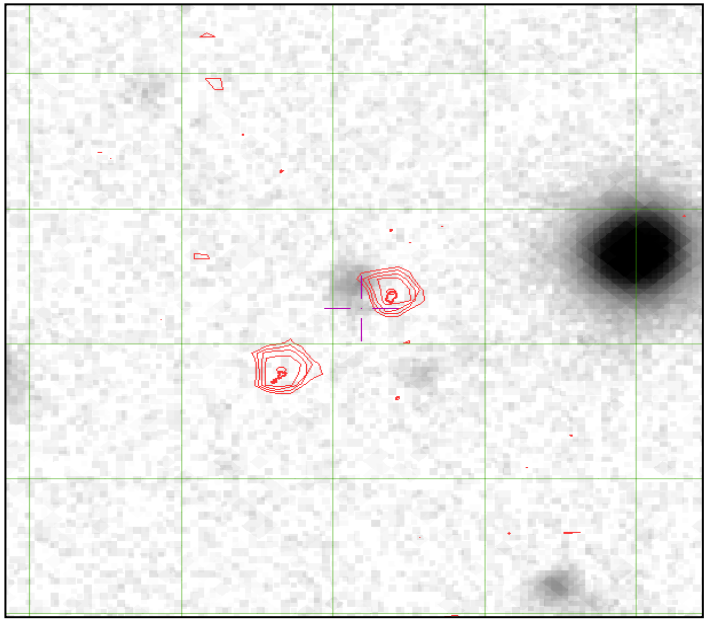
(a) MERLIN (1658 MHz) image with a restoring beam of 0.264" ×0.132 ".
(b) (b) MERLIN (4994 MHz) image with a restoring beam of 0.110"×0.039"

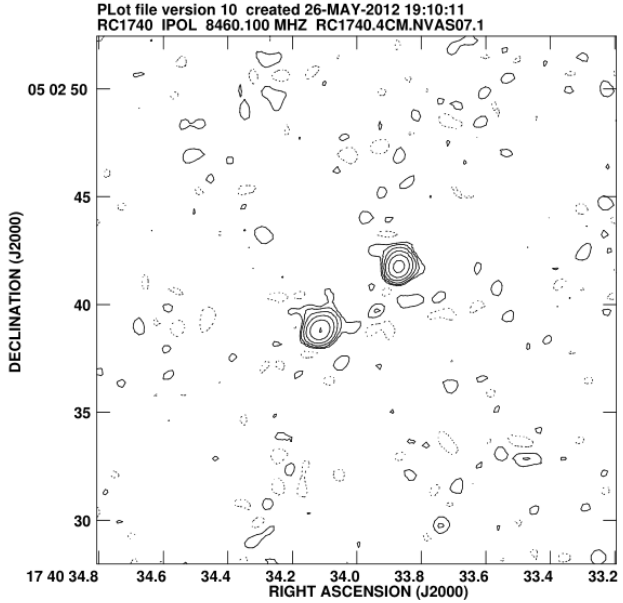


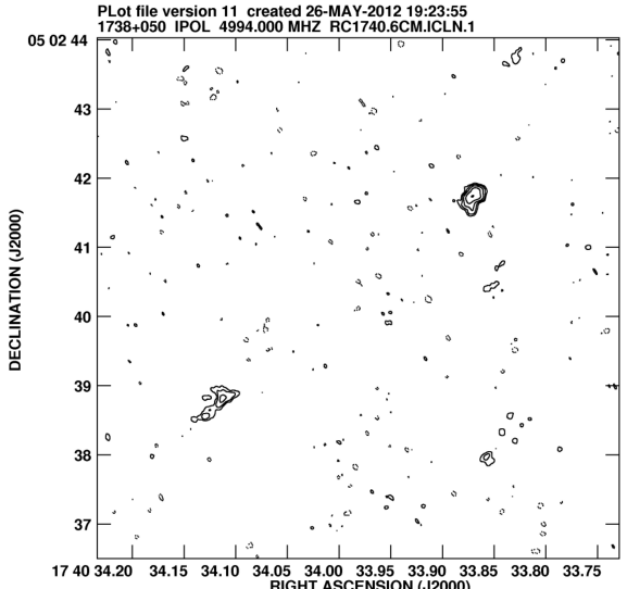
(a) An e-EVN 1658 MHz image of RC J0311+0507 with restoring beam of 0.025" ×0.025"
(b) A MERLIN and e-EVN combined image with a restoring beam of 0.035"×0.035 ".

The most distant radio sources of the Big Trio program

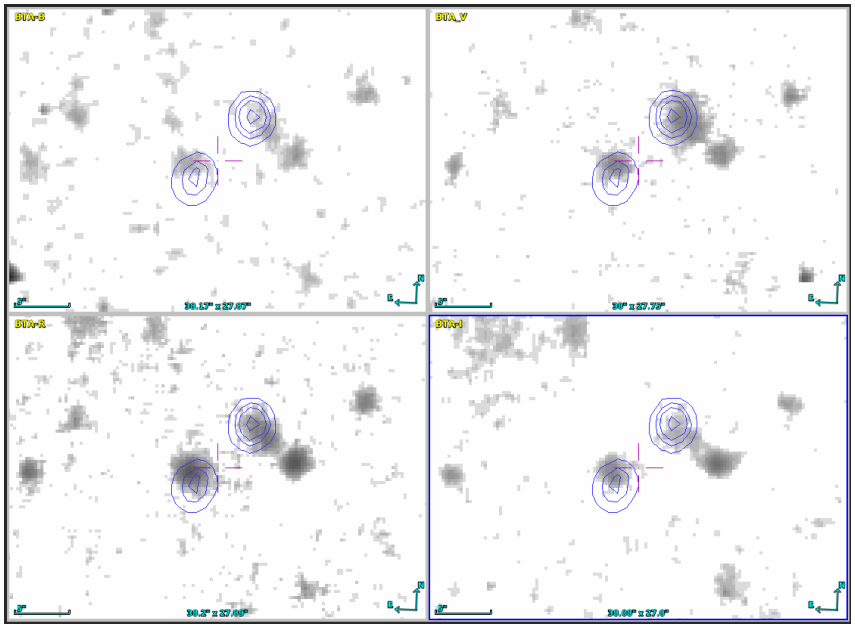


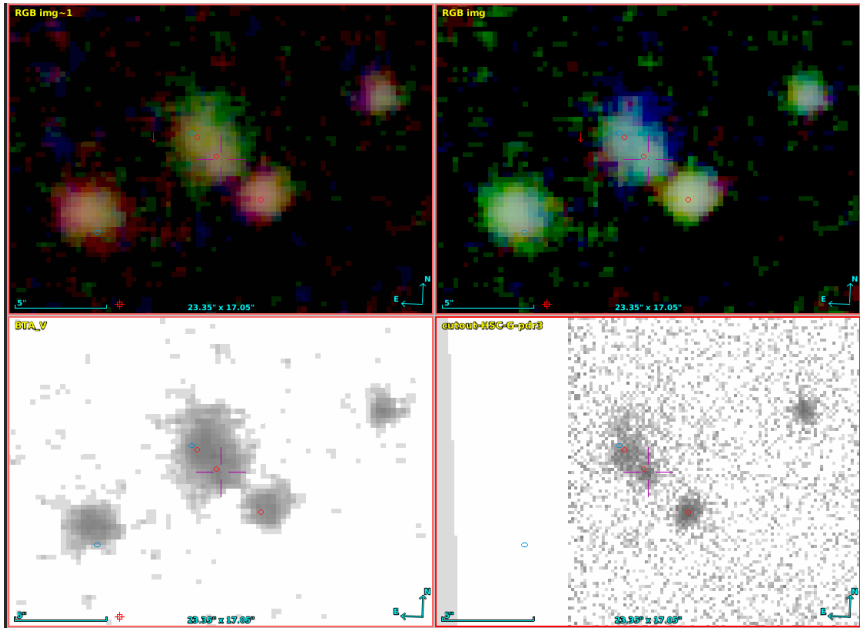


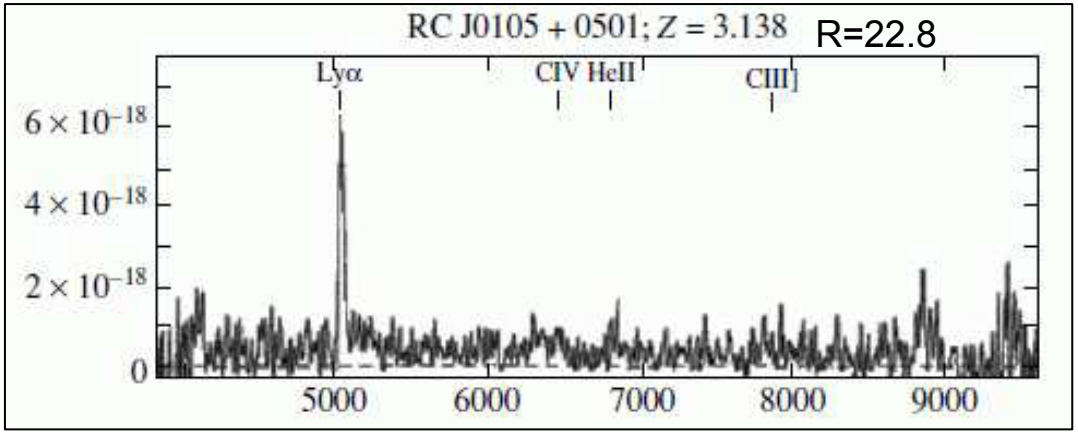


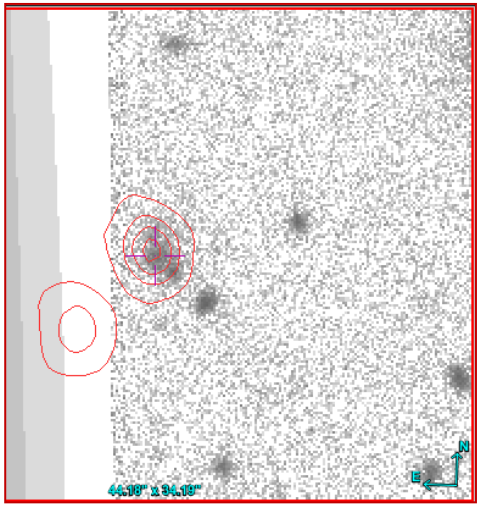


The most distant radio sources of the Big Trio program







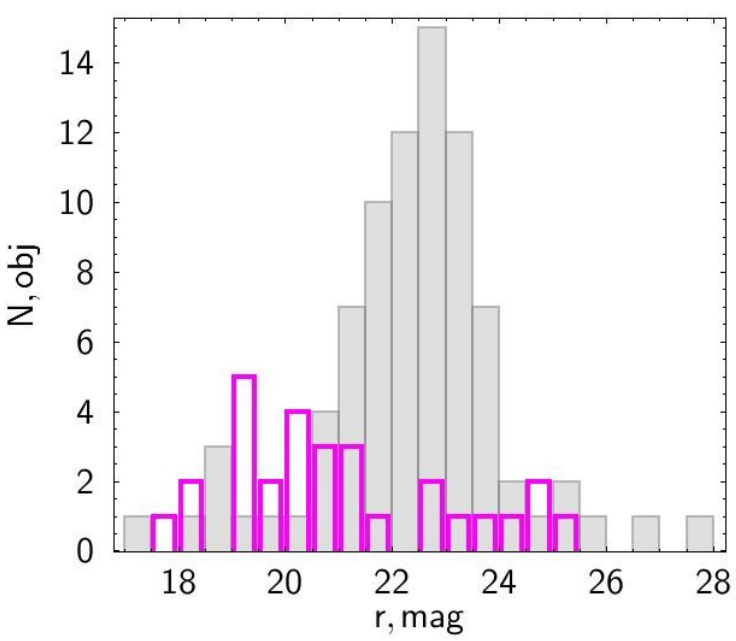


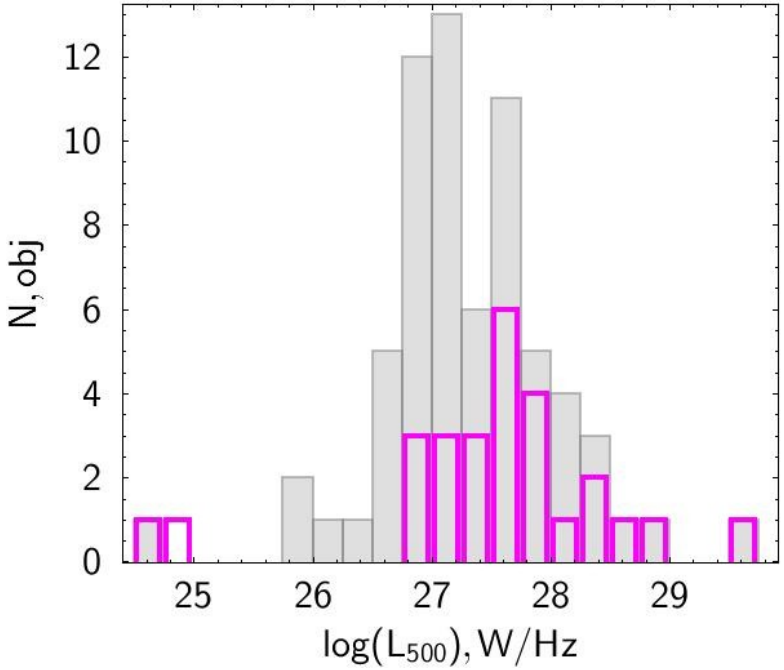
New surveys:

TGSS, GLEAM, WENSS, RACS, VLASS — refinement of the structure of radio sources (for 50% of the sample), refinement of radio spectra;

SDSS, PanSTARRS, WISE, DES, LS, HSC — additional information about host galaxies;

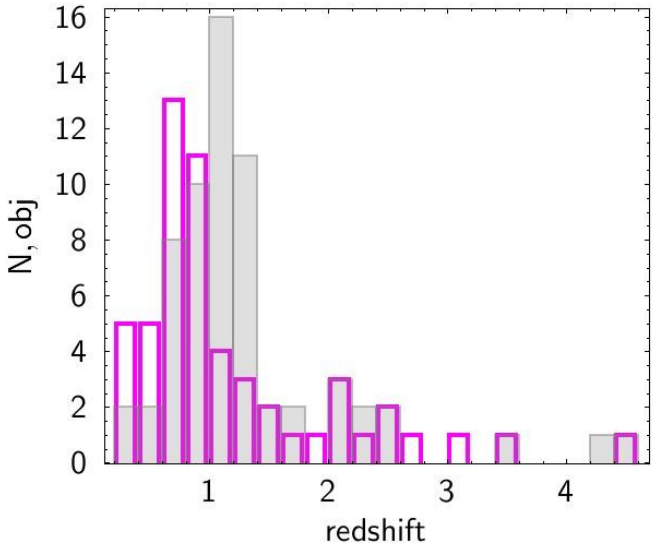
Vizier, Simbad, NED, SDSS, LS, HSC — redshifts of host galaxies.





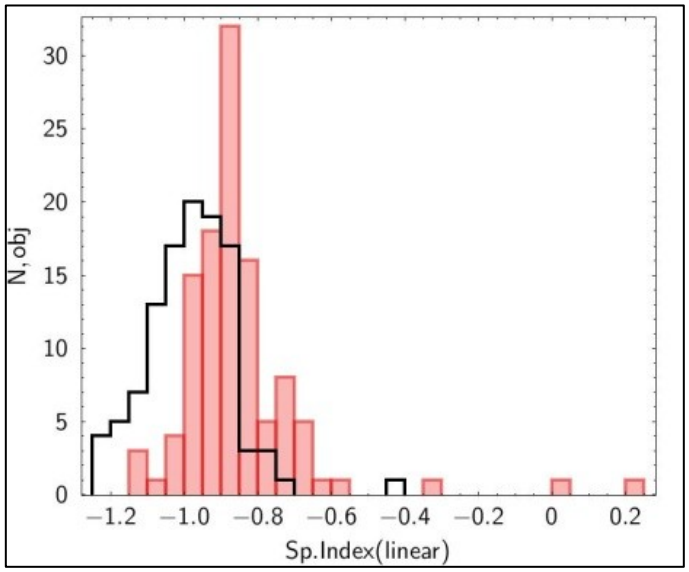
Of 113 sources:

- ❖97% identified;
- ❖80% of galaxies and 20% of quasars (magenta) in the sample.



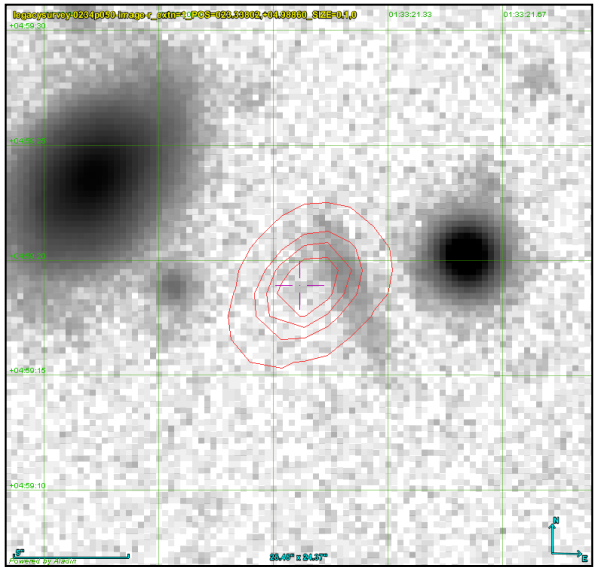
Of 113 sources:

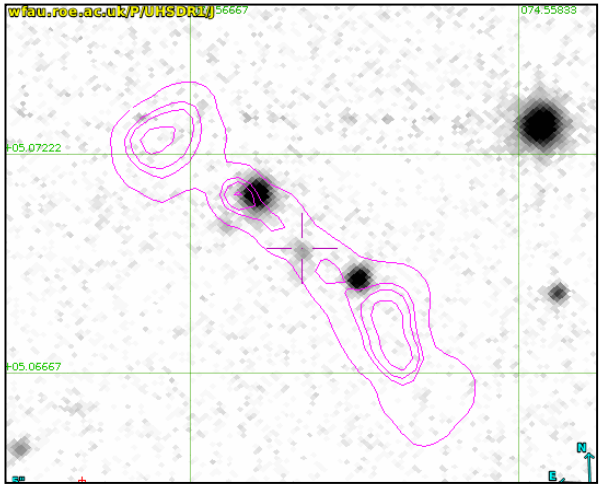
- ❖redshifts known for 88% of sources;
- ❖z_{sp} (magenta) was determined for 55 (48%);
- ❖z_{ph} – 40%;
- ❖from new surveys obtained z_{ph} for 27 sources (23%).



The radio spectra of the SS-sample sources have been refined using new radio surveys. Spectral indices obtained by linear approximation are given, using new (red) and old (black) data.

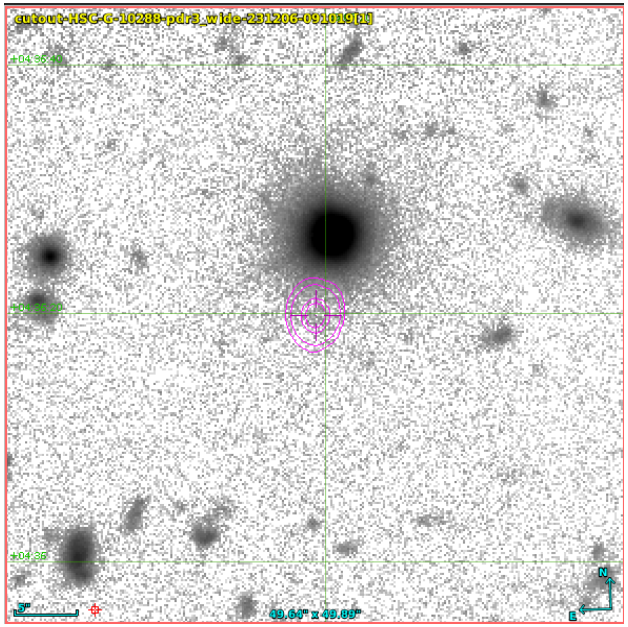
Refinement of optical identifications

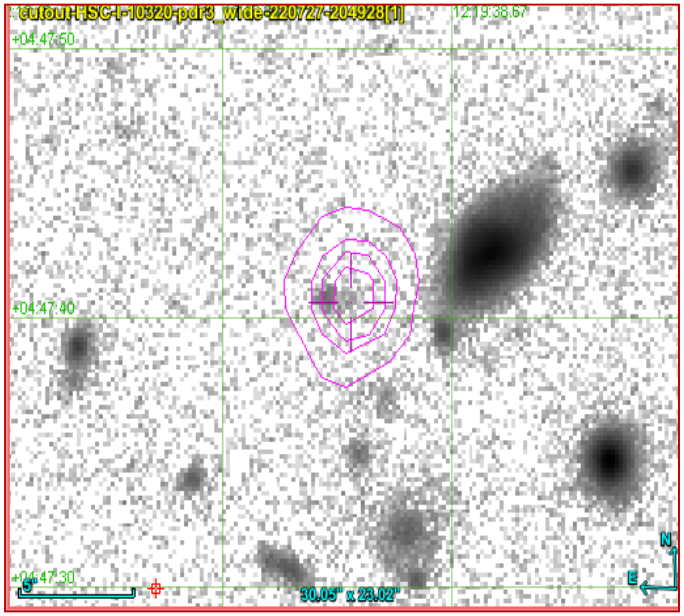




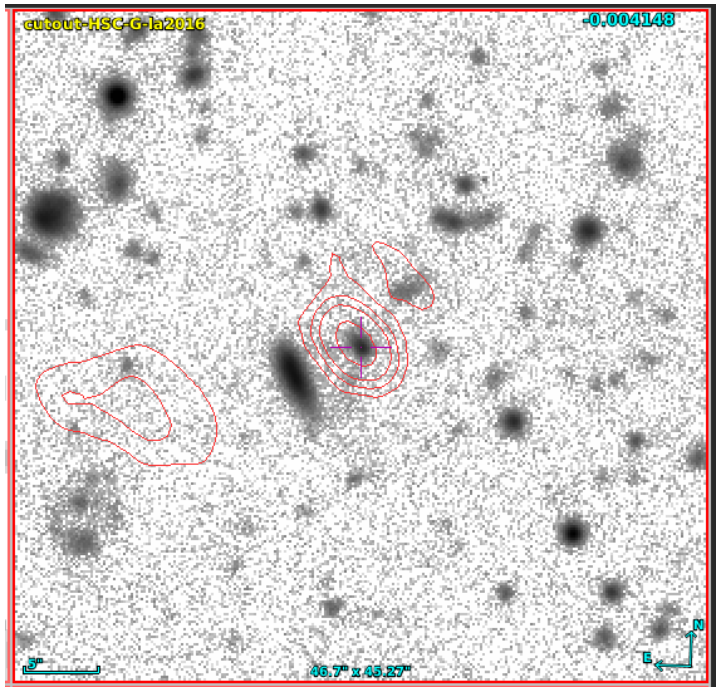
Cutouts from new radio and optical surveys made it possible to refine the identification of radio sources in the sample.

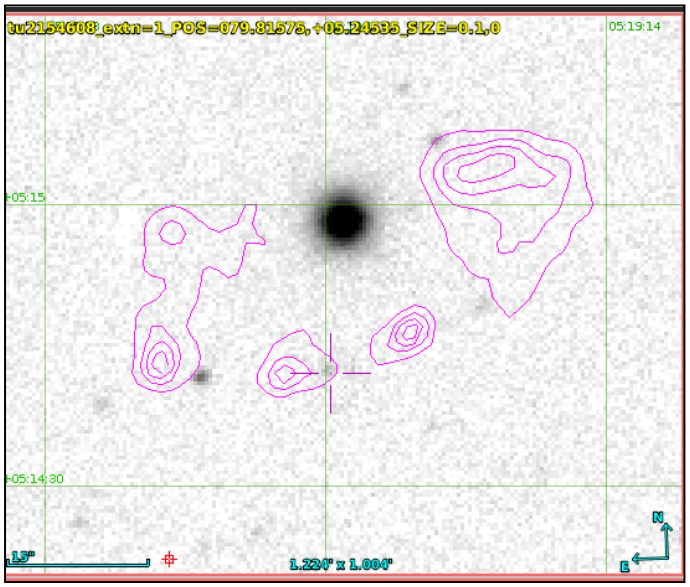
top: RCJ0133+0459, RCJ0458+0456;
bottom:RCJ0907+0439, RCJ1219+0446

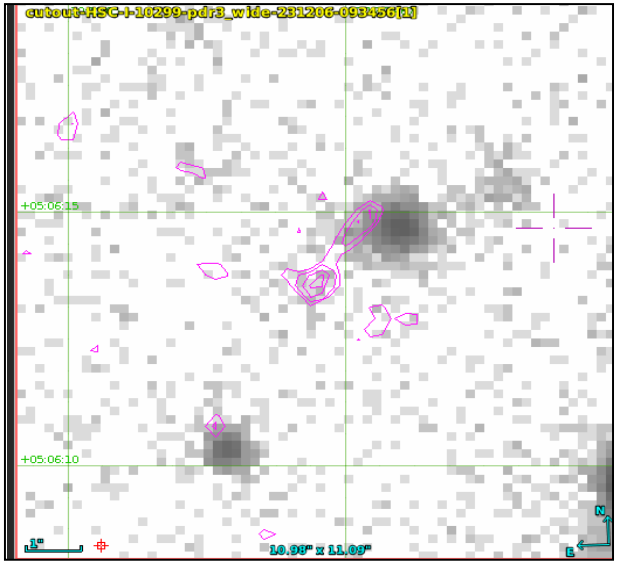


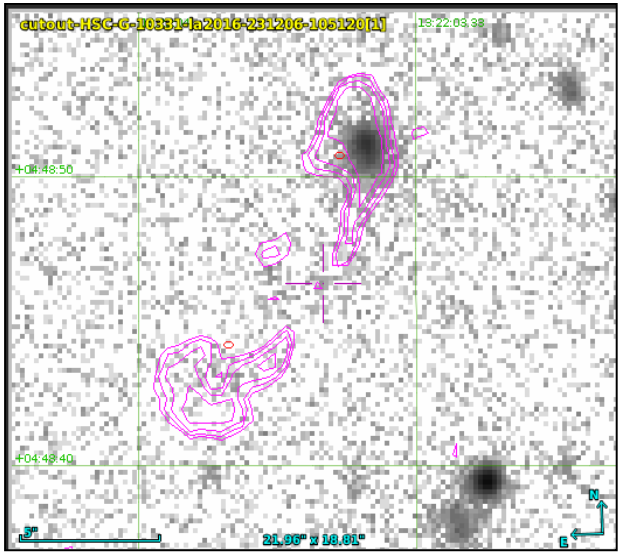


Refinement of optical identifications







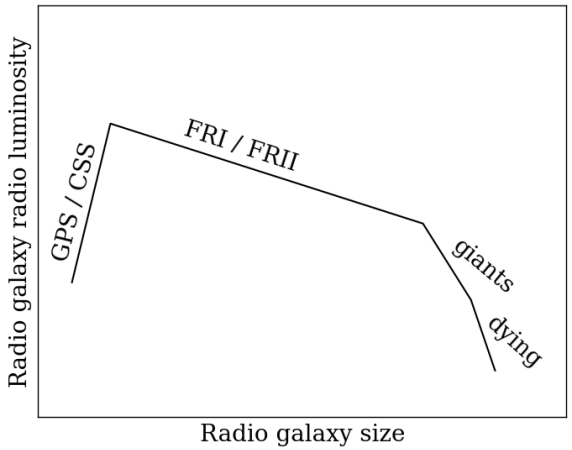


Examples:

top: RCJ0159+0448, RCJ0519+0510

bottom: RCJ1011+0502, RCJ1322+0449.

Evolutionary status of the source: spectral curvature and morphology

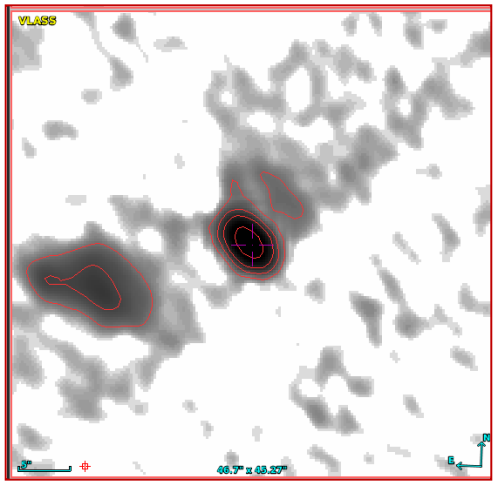


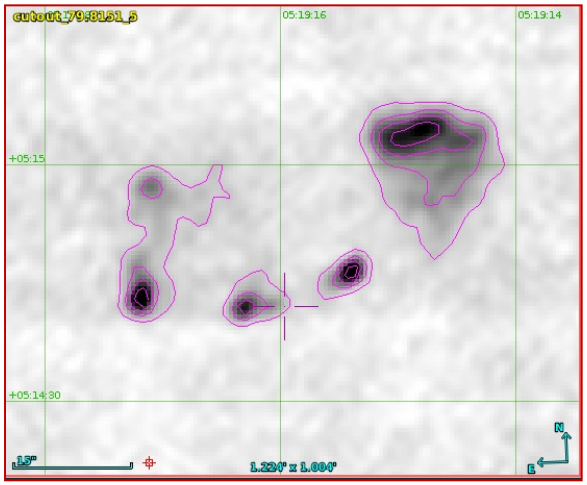
A schematic view of different stages of a radio galaxy life. *Credit: Kapinska.*

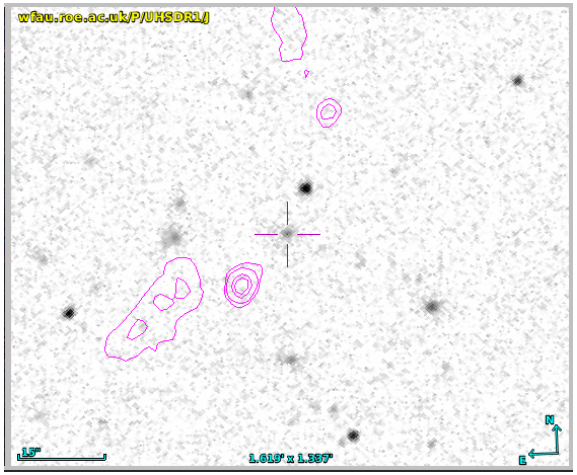
Spectral curvature parameter :
SPC = α_high - α_low ($S \propto \nu^{-\alpha}$) [2011A&A...526A.148M]
SPC>0.5 – faded radio source: ~10%,
SPC<0 – restart of activity in radio range: 15%-17%.
Radio source morphology :
Triple (T), double double (DD) – radio source restart: 20-25%;
There are radio lobes on the NVSS map and no radio lobes on the VLASS map – faded radio source : ~10%.
Small sources CSO, GPS, HFP are considered as young sources [2017ApJ...836..174C]: 10-15%.

Young (10%-15%)	Active (40%-45%)	Faded (10%)	Restart (20%-25%)

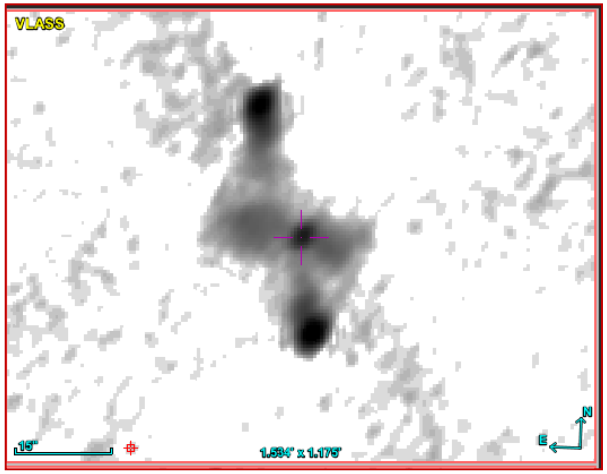
Restart radio sources and wide-angle tailed sources

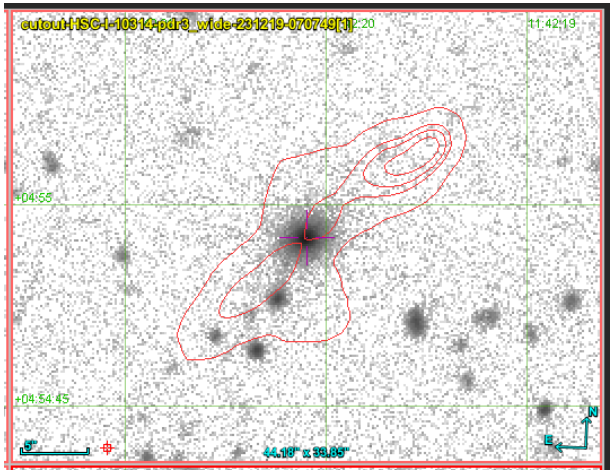


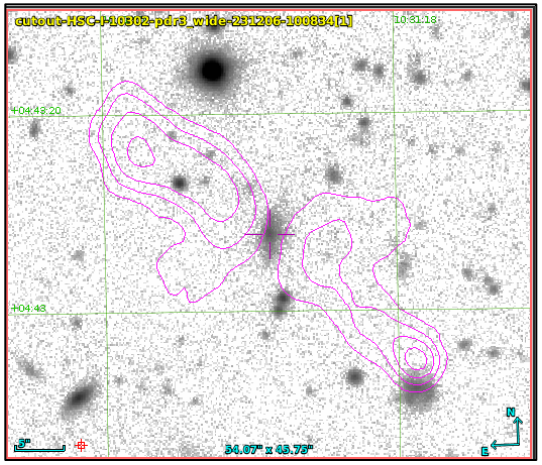




Jet reorientation – X-shaped sources





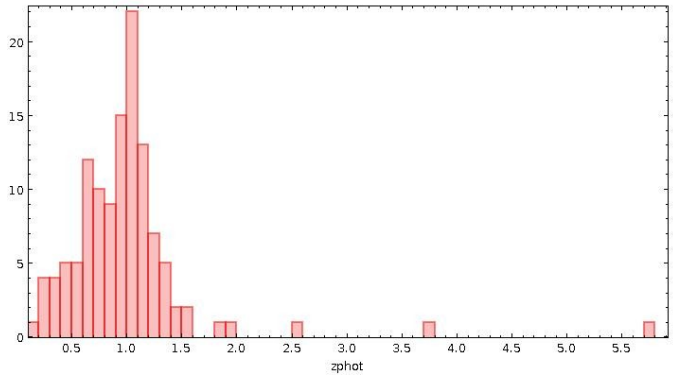


Radio source environment: morphology and photometric redshifts

The deformation of the radio source lobes is an indicator of its environment and/or processes occurring in the immediate vicinity of the AGN.

❖Wide-Angle Tailed, Narrow-Angle Tailed, Head-Tailed [1976ApJ...205L...1O, 2019A&A...626A...8M] sources indicate a cluster or group of galaxies: ~30%.

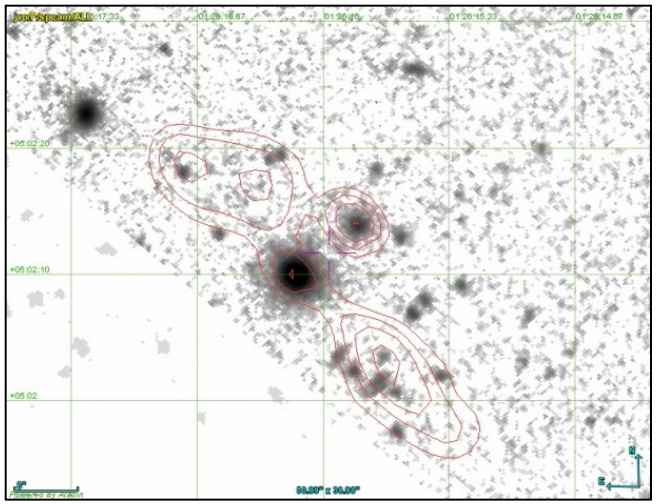
❖The X-, Z-, S-shaped morphology of the radio lobes is explained by a rapid change in the orientation of the jets due to the merger of a small galaxy with a massive elliptical host galaxy, or due to instabilities in the accretion disk. [2004MNRAS.347.1357L, 2019ApJ...887..266J]: ~15%.

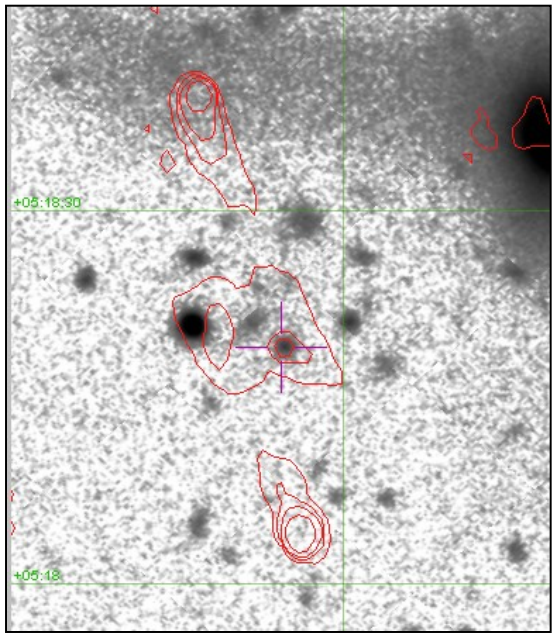


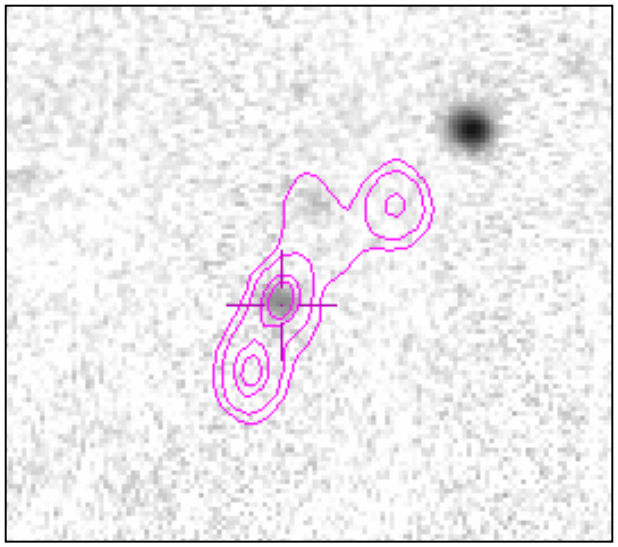
Comparison of photometric redshifts of galaxies in the 1Mpc×1Mpc region around a radio source - half of the sources have neighboring galaxies in photometric redshifts (LS, DataLab).

RCJ0039+0454 (z_LS=1.061±0.092).
Distribution of photometric redshifts (DESI) of galaxies in the 1 Mpc×1 Mpc region around the radio source. Peak at z=1.0-1.1.

Quasar-galaxy pairs







Left: RCJ0126+0502 – a quasar (z_sp=1.008) in a triple source, next to it a point radio source – a galaxy (z_ph=0.934).

Center: RCJ0213+0516 – a radio galaxy (z_sp=0.935) and a quasar (z_sp=0.938) in a group of galaxies.

Left: RCJ0318+0506B (z_ph~0.5).


Thank you for attention!