The compact radio structure of radio-loud NLS1s: the relationship to CSS sources

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5th CSS/GPS workshop

Outline

- Introduction
- Compact radio structure of radio-loud Narrow line Seyfert 1 galaxies
- Summary

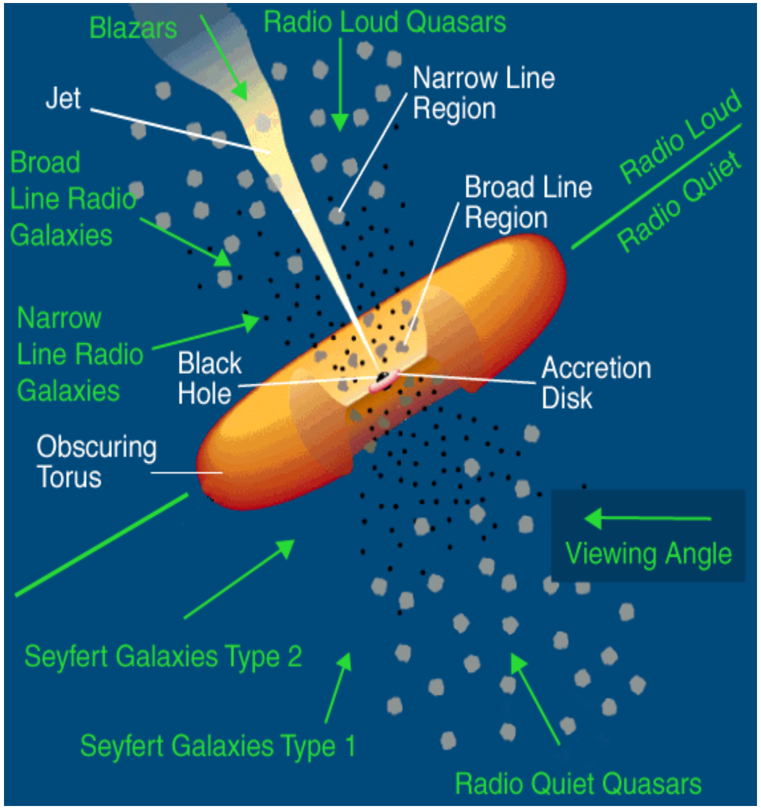
AGN structure and radio-loud

- Radio loudness: $R \equiv L_{\nu 5\ \mathrm{GHz}}/L_{\nu 4400}$,

R>10 radio-loud; <1 radio-quiet;
1<R<10 radio intermediate
(Kellermann et al. 1994)

- Radio luminosity: $P_{6\ \mathrm{cm}} \approx 10^{25}\ \mathrm{W\,Hz^{-1}\,sr^{-1}}$ (Miller et al. 1990)

only 10%–20% were qualified as radio-loud objects in optically selected samples (e.g., Kellermann et al. 1989; Hooper et al. 1995).

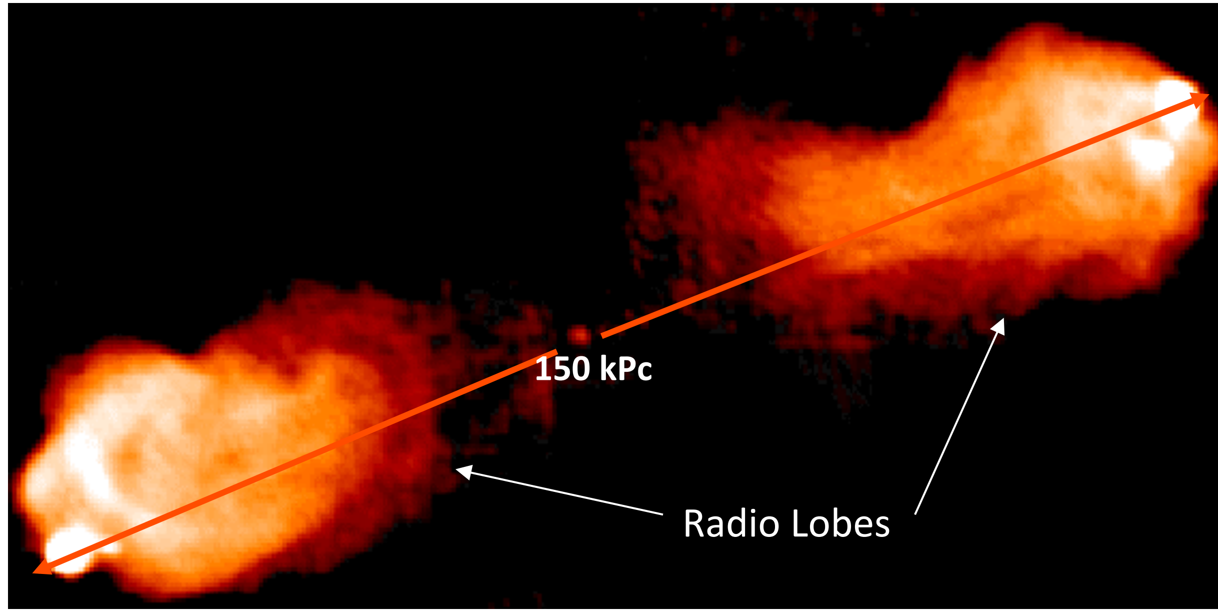


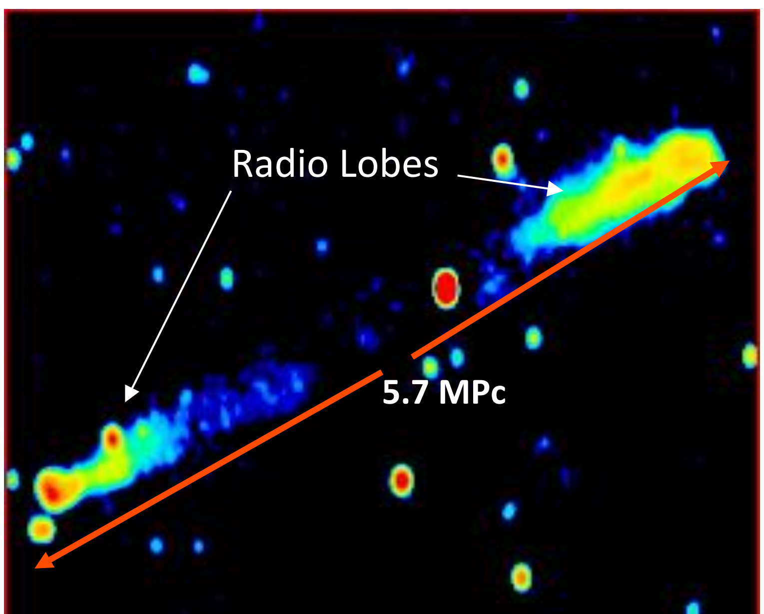
Urry & Padovani (1995)

Radio Galaxies and Jets

Cygnus A →

VLA radio image at 1.4 GHz
the closest powerful radio galaxy
(D=190 Mpc)



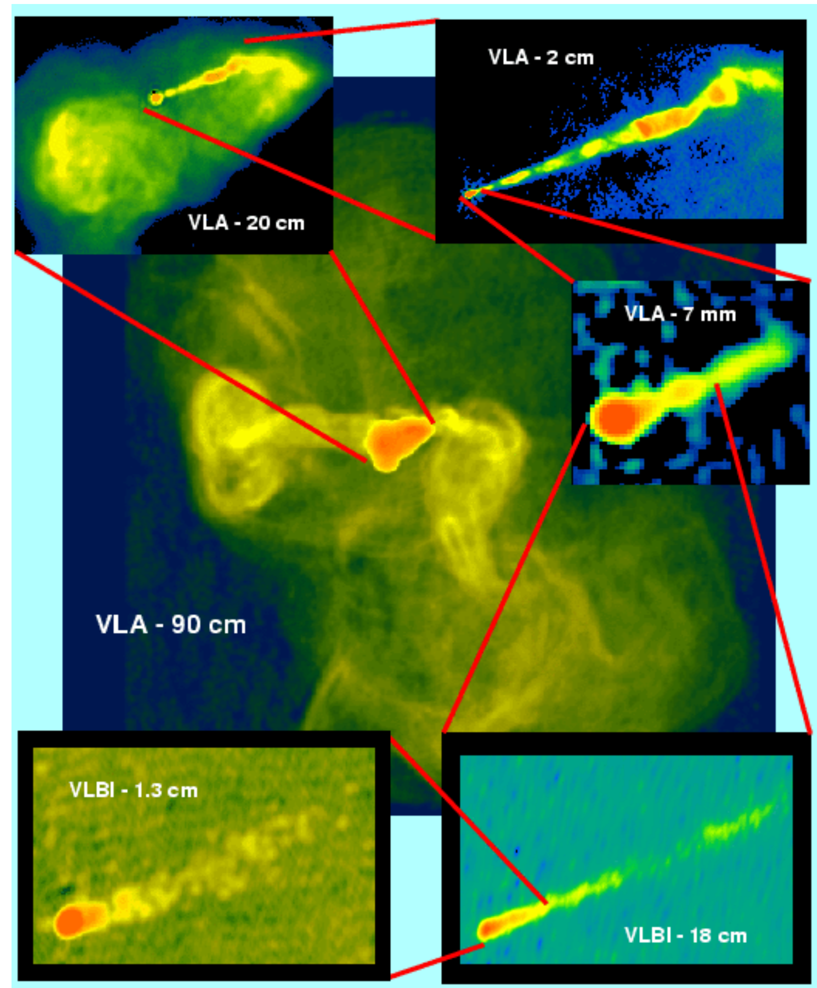


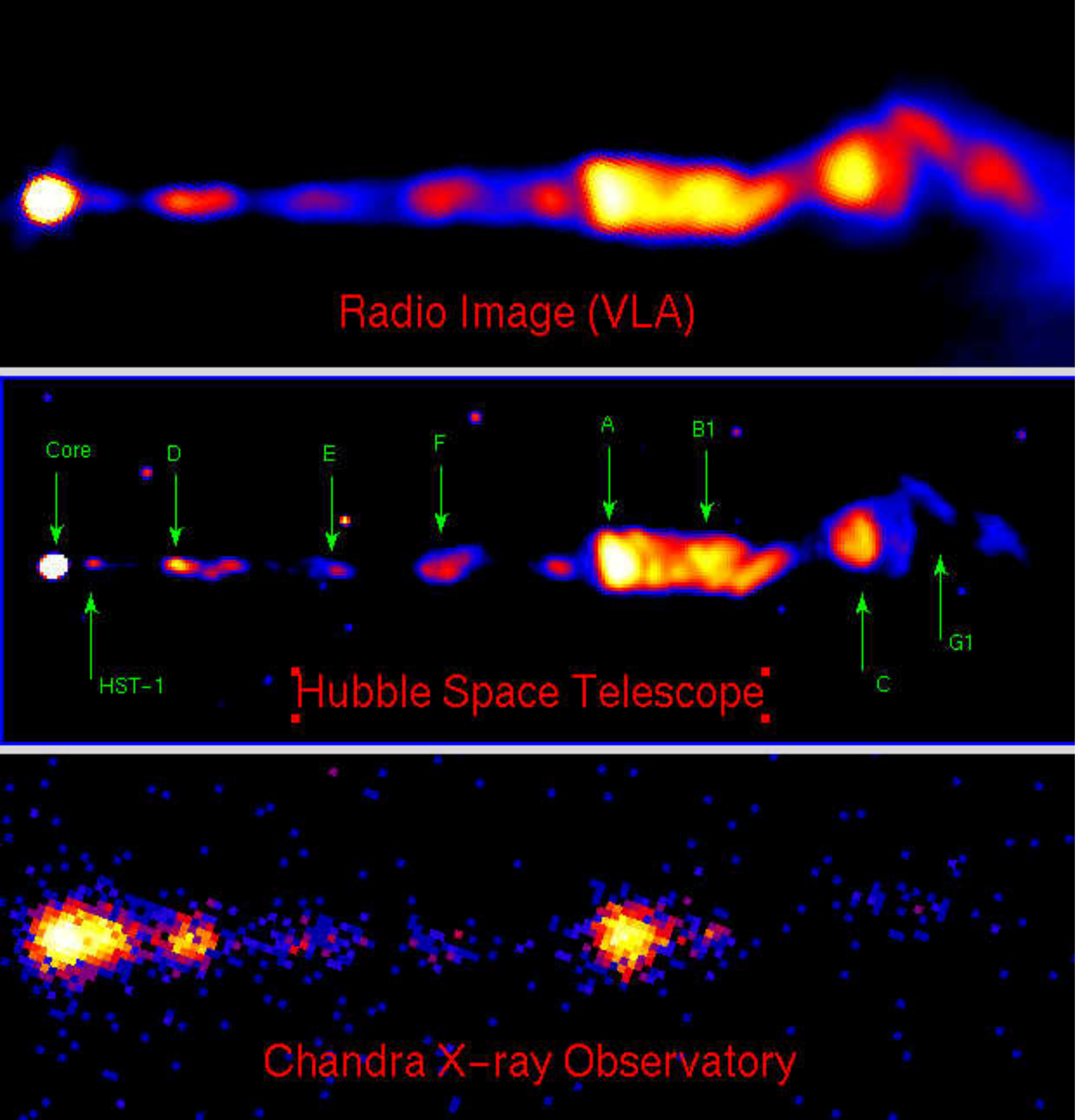
← 3C 236

Westerbrok radio image at 608 MHz – a radio galaxy of very large extent (D=490 Mpc)

M87 (NGC4486; Virgo A): FRI

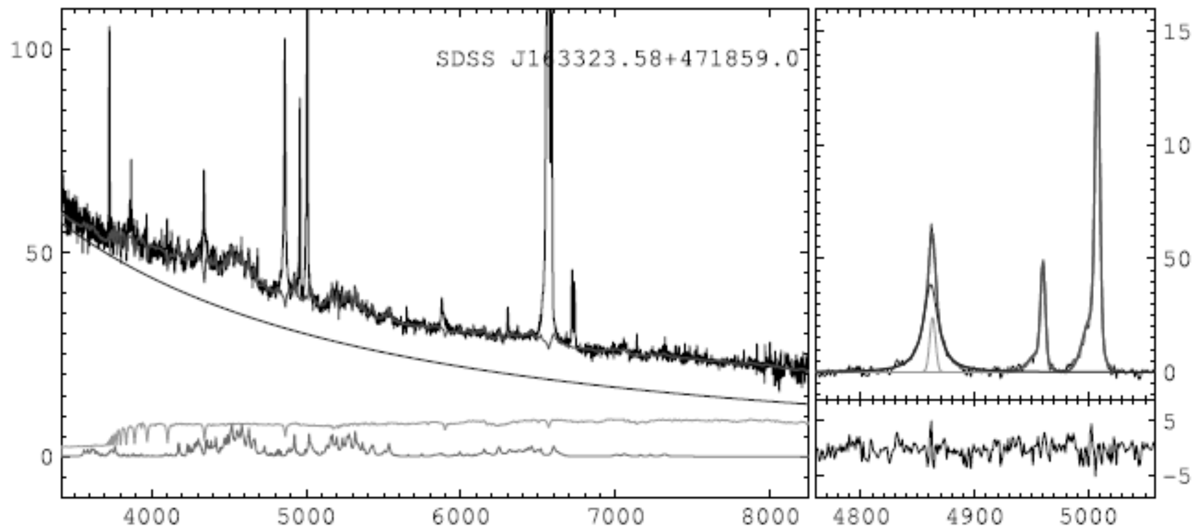
M84, M86, M87 © Royal Observatory Edinburgh/Anglo-Australian Observatory
Photograph from UK Schmidt plates by David Malin

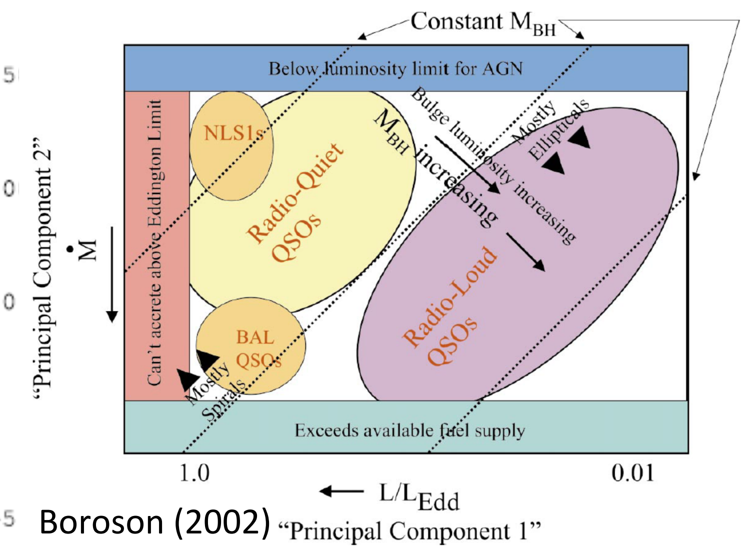



Radio Image (VLA)
Core
D
E
F
A
B1
HST-1
Hubble Space Telescope
C
G1
Chandra X-ray Observatory

M87 jet

Narrow Line Seyfert 1 galaxies (NLS1s)





Boroson (2002)

FIG. 7.—Interpretive diagram showing how PC1-PC2 plane provides basis for classification of AGNs

- Balmer lines broader than forbidden lines but narrower than normal type 1 AGNs (FWHM < 2000km/s)
- Peculiar properties: softer X-ray spectra, fast X-ray variability, strong optical Fe IIs
- Relatively small black hole mass 10^{6-8} $M_{\odot}$(e.g. Collin & Kawaguchi 2004), however still controversial: viewing angle, radiation pressure …
- High accretion rate Lbol >> 0.1 L_{Edd} (up to Lbol/Ledd ~ 1)
- Accretion possible via slim disk (e.g. Abramowicz et al. 1988; Mineshige et al. 2000)

Radio-loud NLS1s (RLNLS1s)

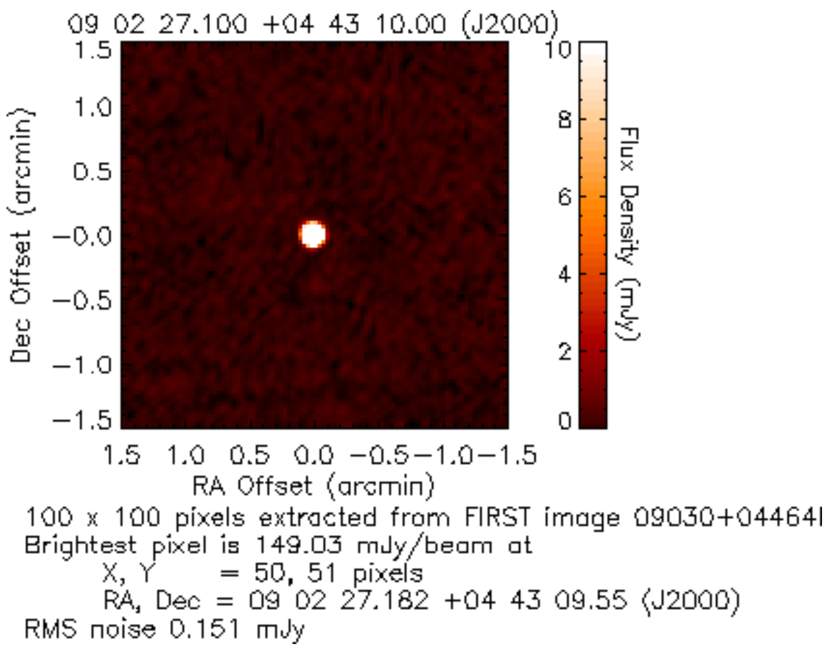
- NLS1s were long thought to be radio-quiet. Radio-loud NLS1s are rare, but they do exist (Siebert et al 1999 ; Grupe et al. 2000; Zhou & Wang 2002; Zhou et al. 2003; Whalen et al. 2006; Komossa et al. 2006; Yuan et al. 2008).
- RL NLS1s sample from SDSS: >100 out of ~2000 NLS1s (Zhou et al. 2006) – RL (R>10) fraction = 7%; very radio-loud (R>100) NLS1s: very rare – 23 from SDSS DR5 (Yuan et al. 2008).

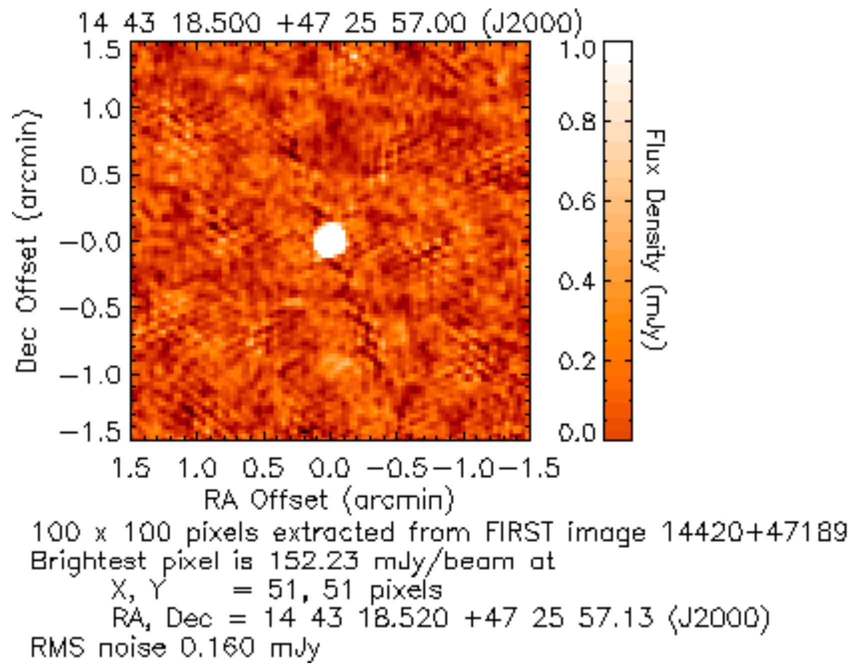
- Komossa et al. (2006): the radio loud NLS1 galaxies are generally compact, steep spectrum sources.

- Several of the radio loudest NLS1 galaxies display blazar characteristics and harbor relativistic jets (Doi et al. 2007; Zhou et al. 2007; Yuan et al. 2008)
- Flat radio spectra, large-amplitude flux and spectral variability, compact radio cores, very high variability brightness temperatures, enhanced optical continuum emission, flat X-ray spectra, and blazar-like SEDs.

Compact at arcsec scale

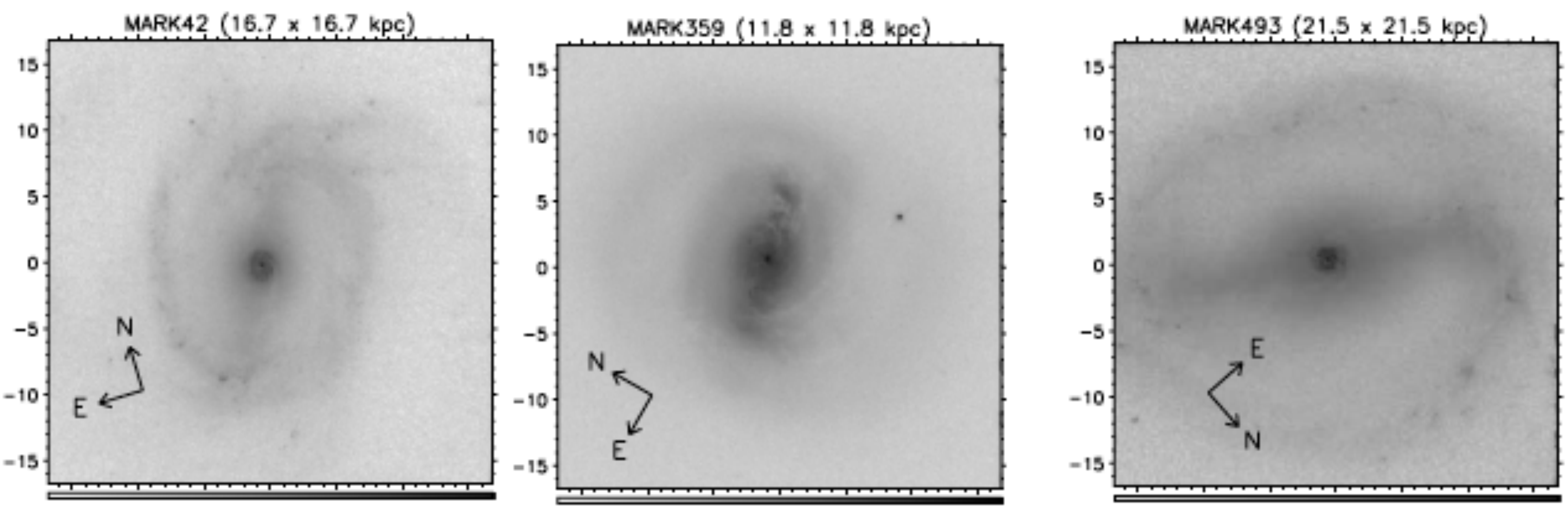
- Arcsecond-resolution observations have resolved the structures of only a few NLS1s because they are generally quite compact (e.g. Ulvestad et al. 1995, Moran et al. 2000, Stepanian et al. 2003, Doi et al. 2012).



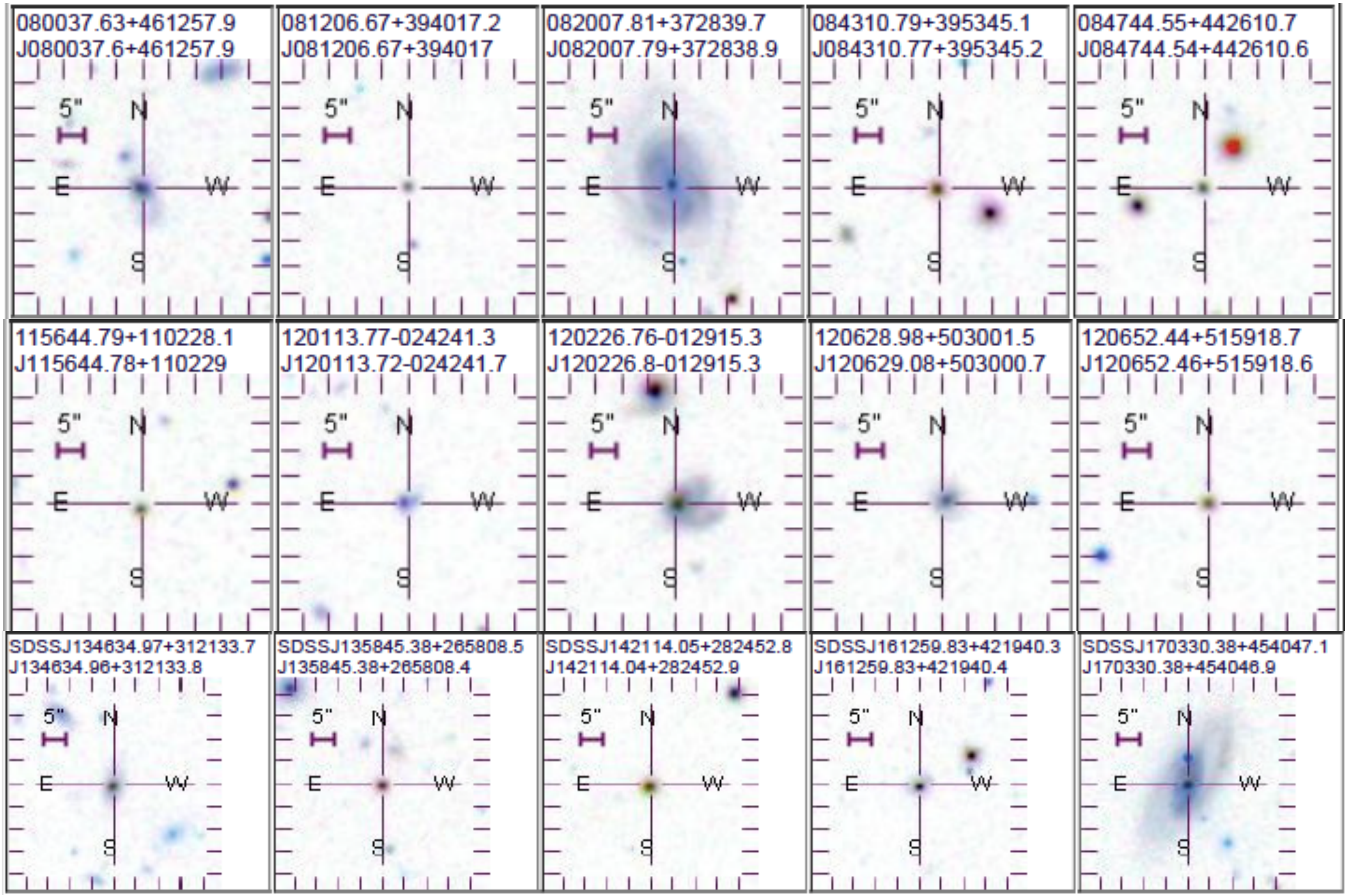


Host galaxies

- Almost all the low redshift NLS1s are hosted by spiral galaxies (Crenshaw et al. 2003, Deo et al. 2006)



Host galaxies of RLNLS1s : unclear



RLNLS1s

- Smaller Mbh, larger accretion rate.
- Two sequences on R - Eddington ratio plane (Sikora et al. 2007).

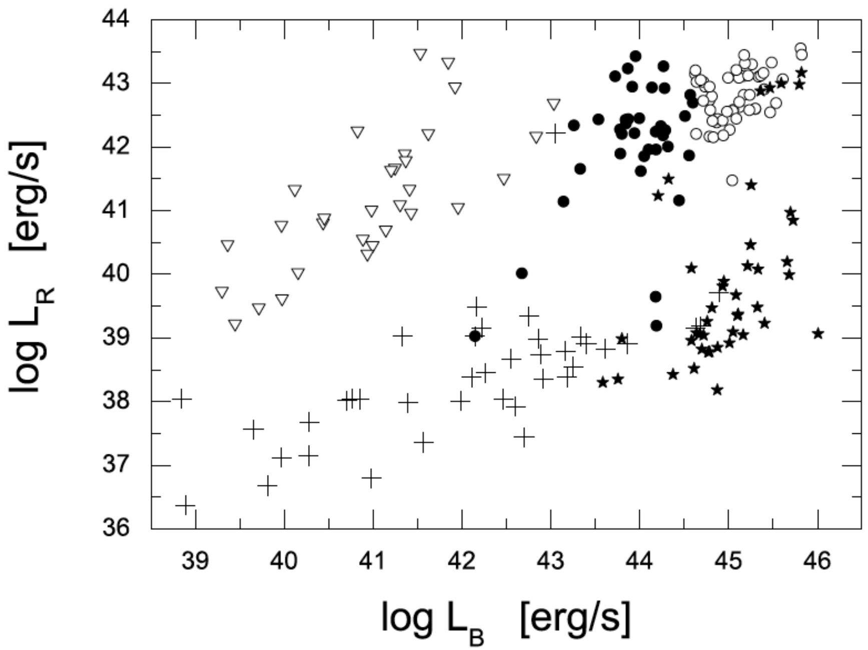


FIG. 1.—Total 5 GHz luminosity vs. *B*-band nuclear luminosity. BLRGs are marked by filled circles, radio-loud quasars by open circles, Seyfert galaxies, and LINERs by crosses, FR I radio galaxies by open triangles, and PG quasars by filled stars.

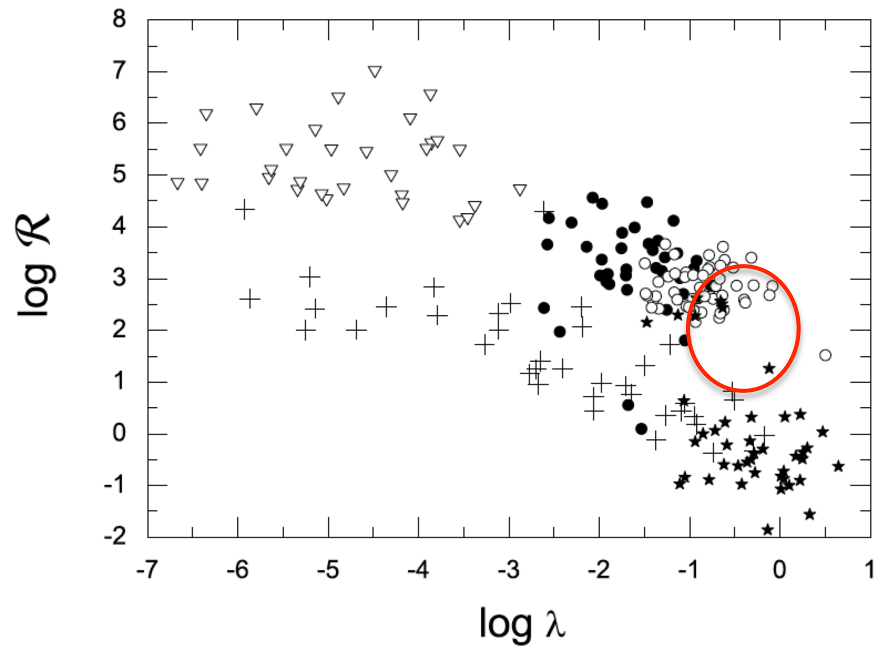
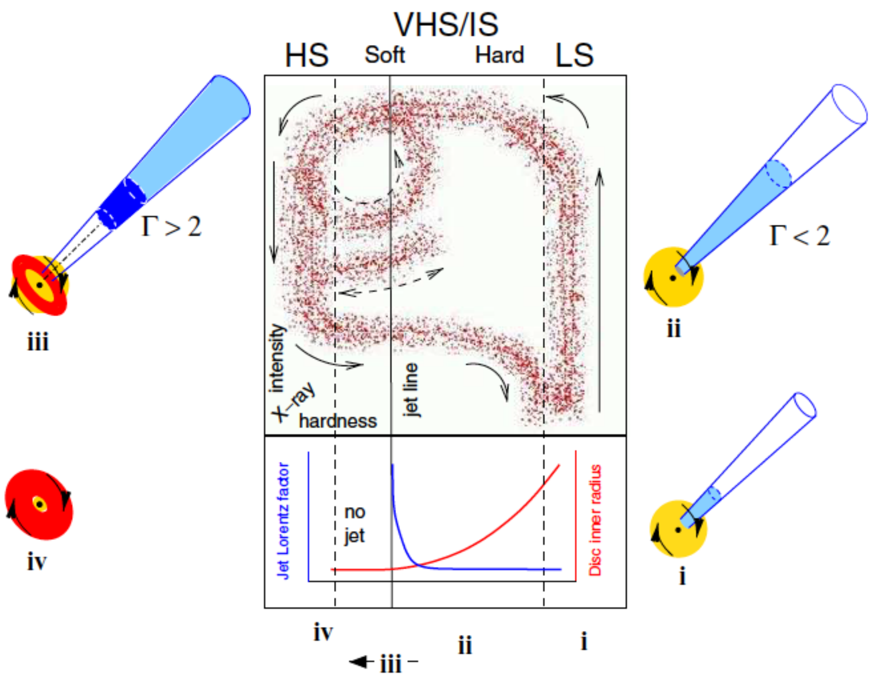


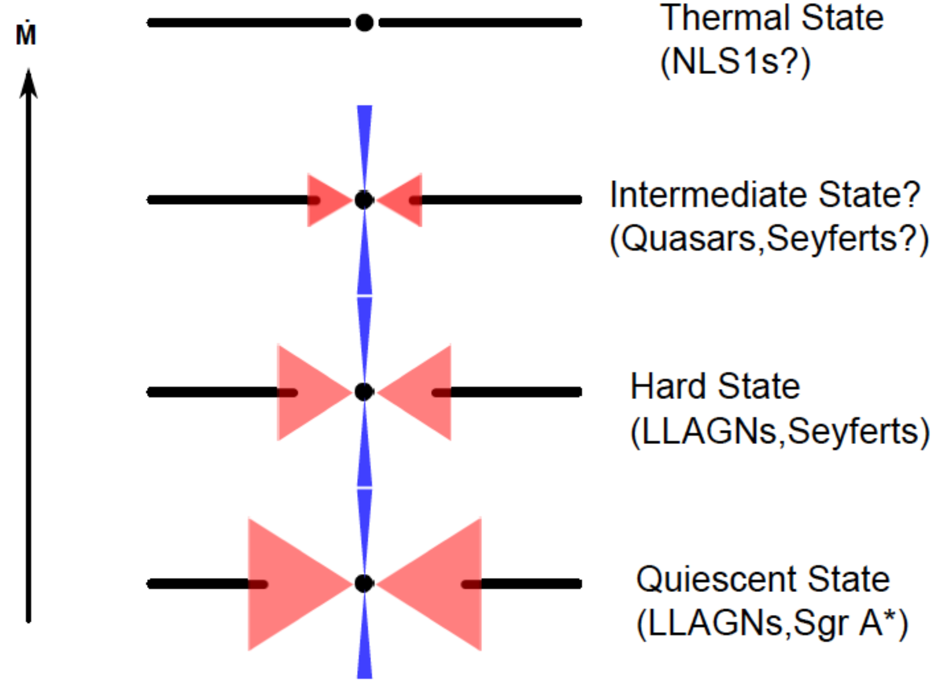
FIG. 3.—Radio loudness $\mathcal{R}$ vs. Eddington ratio λ. BLRGs are marked by filled circles, radio loud quasars by open circles, Seyfert galaxies and LINERs by crosses, FR I radio galaxies by open triangles, and PG quasars by filled stars.

Jets

- Jets in BHB and AGNs: similar ?
- Jet-production related parameters: black hole mass, spin, host galaxy, accretion rate, environments …



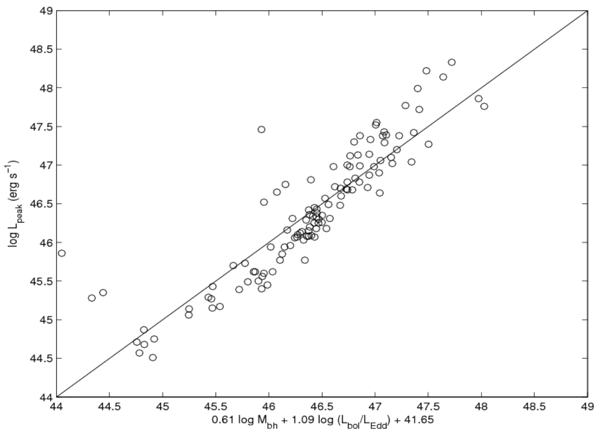
Fender et al. (2004)



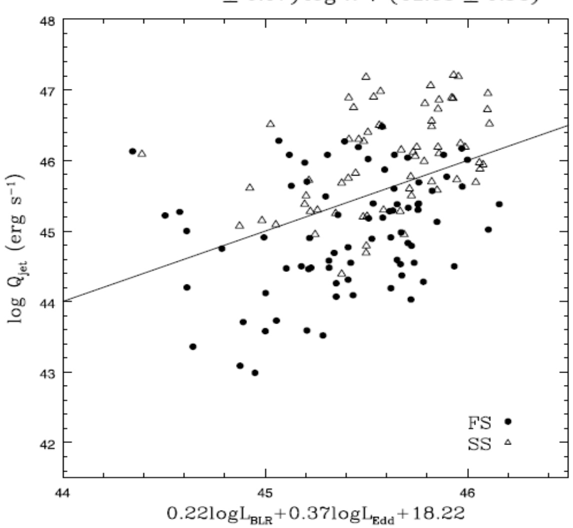
Yuan & Narayan (2014)

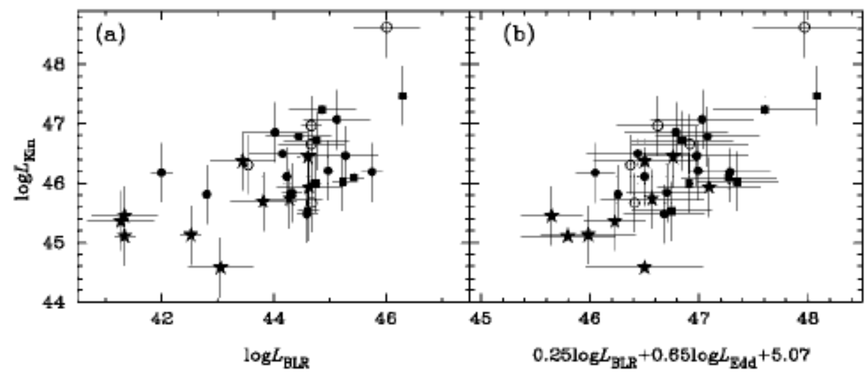
Jet, black hole mass and accretion rate

Gu & Chen (2009) 118 FSRQs; Wang et al. (2004) 35 blazars;
Liu, Jiang & Gu (2006) RLQs; Bian et al. (2008) 306 RLQs



$$\log L_{\rm p} = (0.61 \pm 0.07) \log M_{\rm bh} + (1.09 \pm 0.07) \log \lambda + (41.65 \pm 0.38)$$

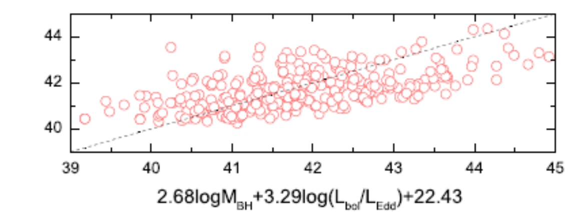


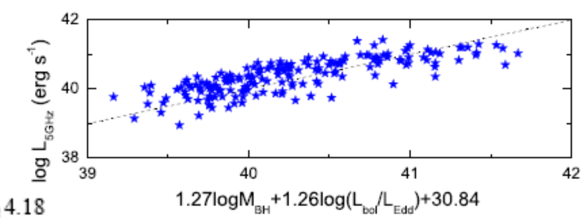


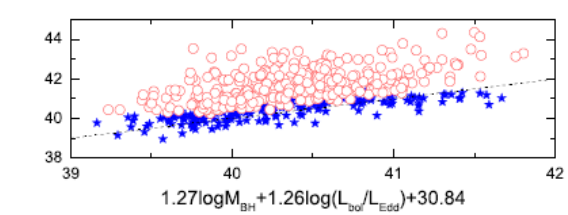
$L_{\rm kin} \propto M^{0.90}_{\rm bh}\ \lambda^{0.25}$,

$Q_{\rm jet} \propto M^{0.59}_{\rm bh}\ \lambda^{0.22}$,

$L_{\rm 5GHz} \propto M^{3.10}_{\rm bh}\ \lambda^{4.18}$







VLBI observations

- Morphologies: core & components - flux density, position angle, angular size, flux variability, proper motion and polarization

- Brightness temperature (Ghisellini et al. 1993)

$$T_{\rm B} = \frac{S_\nu \lambda^2}{2k\Omega_{\rm s}} = 1.77\times10^{12}(\frac{S_\nu}{\rm Jy})(\frac{\nu}{\rm GHz})^{-2}(\frac{\theta_d}{\rm mas})^{-2}, \theta_{\rm d} = \sqrt{\rm ab}$$

$$T_{\rm B}^{'} = T_{\rm B}(1+z)/\delta$$

- Variability brightness temperature: (e.g. Yuan et al. 2008)

$$T_{\rm B,var} \gtrsim \frac{\Delta P_{\nu e}}{2\pi^2 k\nu^2(\Delta t)^2} = \frac{2D_{\rm L}^2\Delta S_\nu}{(1+z)\pi k\nu^2(\Delta t)^2}$$

$$T_{\rm B,var}^{'} = T_{\rm B,var}/\delta^3$$

- Constraints on Doopler factor: equipartition brightness temperature Teq=5×10^{10} K (Readhead 1994); Inverse Compton limit Tb,int ~ 10^{12} K (Kellermann & Pauliny-Toth 1969)

Status of VLBI observations

•Radio-loud NLS1s: RXS J16290+4007, RXS J16333+4718, and B3 1702+457 (VLBA Gu & Chen 2010, Doi et al. 2011, JVN Doi et al. 2007), RX J0806.6+7248 (JVN Doi et al. 2007, VLBA Doi et al. 2011), B2 1111+32 (EVN, VLBA Chen & Gu in prep.).

•gamma-ray NLS1s: compact at kpc scale, but resolved at pc scale (SBS 0846+513, PKS 1502+036 and PKS 2004-447, VLBA D'Ammando et al. 2012, Orienti et al. 2012); SDSS J094857.31+002225.4 (VLBA Doi et al. 2006, Foschini et al. 2011, global e-VLBI Giroletti et al. 2011), 1H 0323+342 (VLBA Zhou et al. 2007), FBQS J1644+2619 (JVN Doi et al. 2007, VLBA Doi et al. 2011).

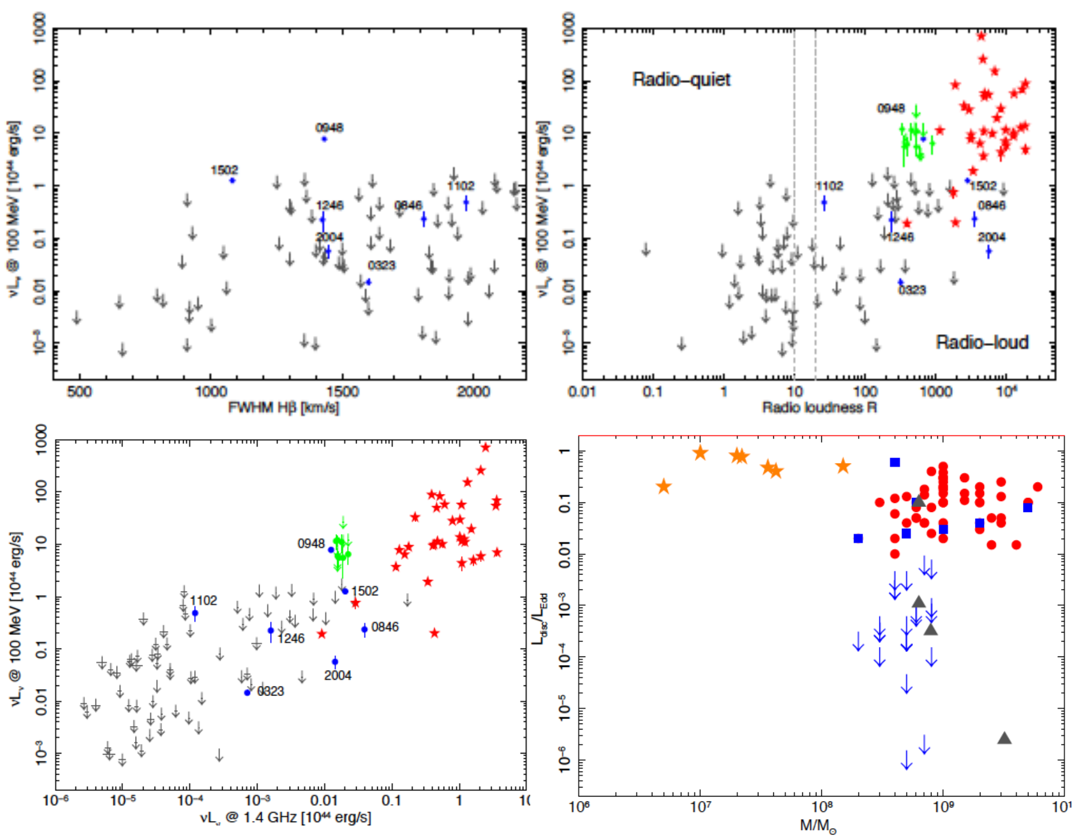
•In total, only 11 RLNLS1s (out of 117) have published VLBI images.

Gamma-ray RLNLS1s

- Foschini (2011)

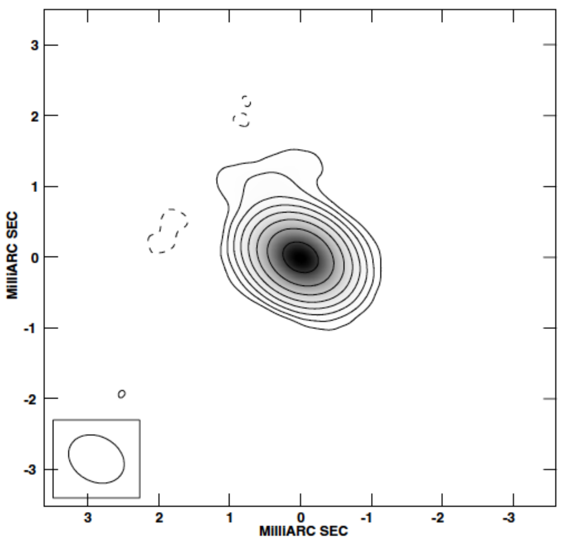
Name	RA	Dec	err(dist)	$F_{0.1-100\ \mathrm{GeV}}$	Γ	TS	$\lvert\tau\rvert$	S/N
1H 0323+342	51.25	+34.20	0.12(0.07)	6.0±0.7	2.87±0.09	164	<2.7	4.0
SBS 0846+513	132.45	+51.19	0.11(0.05)	0.51±0.15	2.0±0.1	52	12±8	4.7
PMN J0948+0022	147.253	+0.385	0.07(0.02)	13.7±0.7	2.85±0.04	1081	<0.8	5.4
FBQS J1102+2239	165.70	+22.63	0.37(0.10)	2.0±0.6	3.1±0.2	32	25±12	2.9
SDSS J124634.65+023809.0	191.83	+2.53	0.47(0.21)	1.7±0.7	3.1±0.3	15	32±15	2.1
PKS 1502+036	226.257	+3.457	0.05(0.02)	7.0±0.6	2.71±0.07	411	1.3±0.5	6.6
PKS 2004−447	302.002	−44.504	0.08(0.07)	1.2±0.3	2.3±0.1	44	6.2±1.7	12

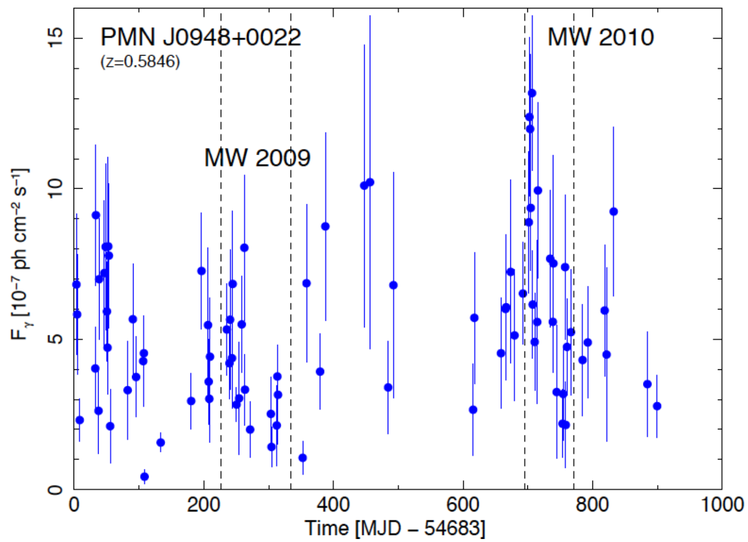
- FBQS J1644+2619 (D'Ammando et al. 2015)

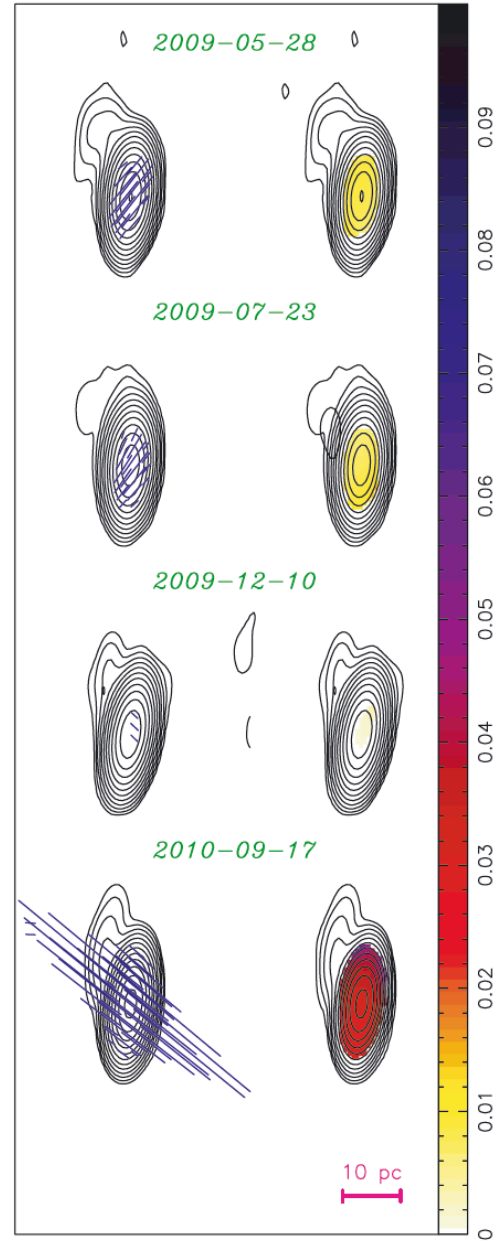


PMN J0948+0022

- A bright and compact component with an inverted spectrum, and a faint jet feature.
- Beaming effect indicated from the variable emission and high brightness temperature.
- First Fermi-detected NLS1s - third class of gamma-ray AGNs.





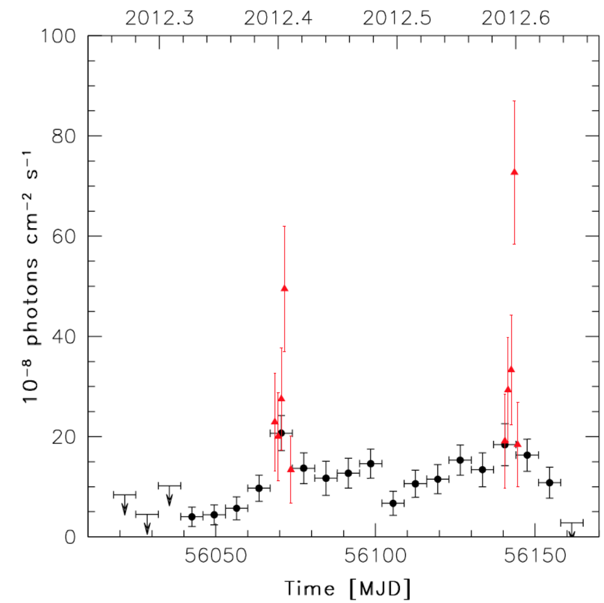


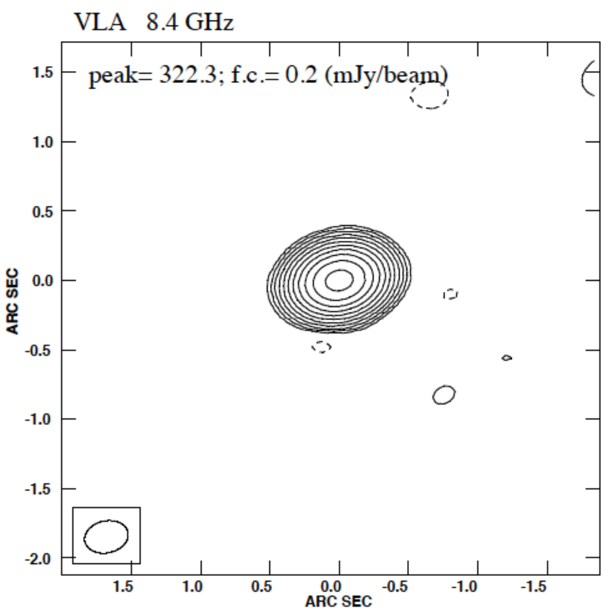
15 GHz VLBA (Foschini et al. 2011)

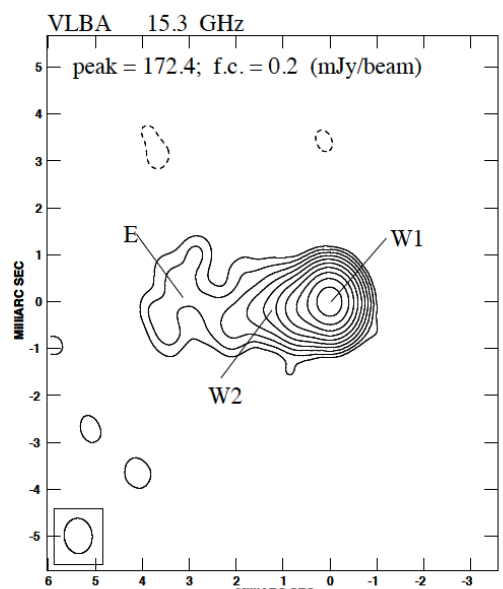
22 GHz global e-VLBI (Giroletti et al. 2011)

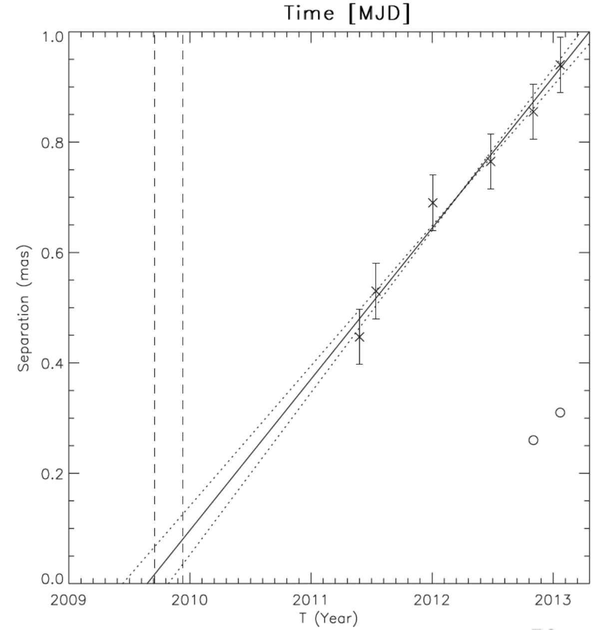
SBS 0846+513 (z=0.5835): (D'Ammando et al. 2013)

- Strong γ -ray flares; an apparent superluminal velocity of (9.3± 0.6)c (MOJAVE).
- Blazar-like; at the low end of the blazar's black hole mass distribution.





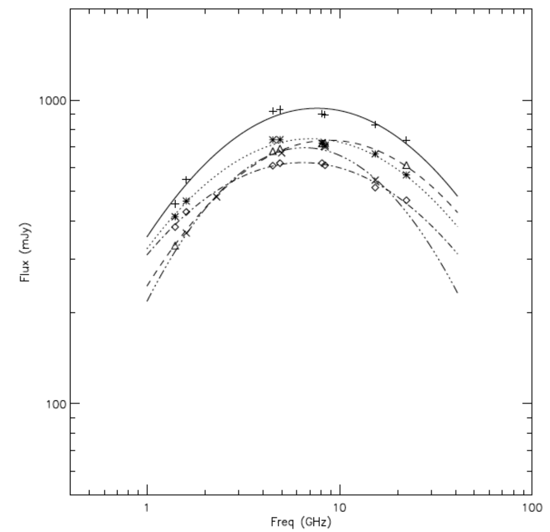


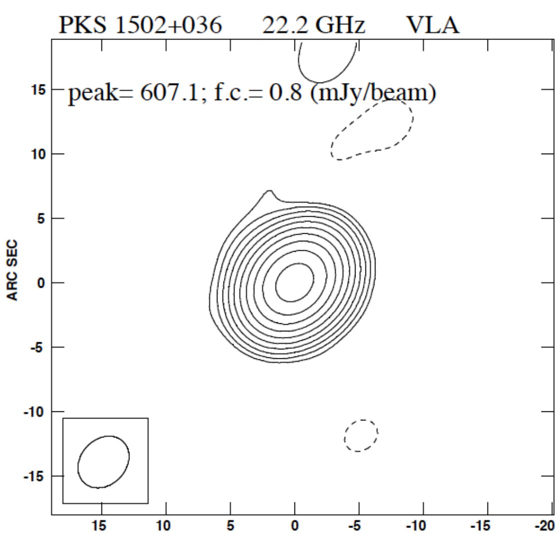


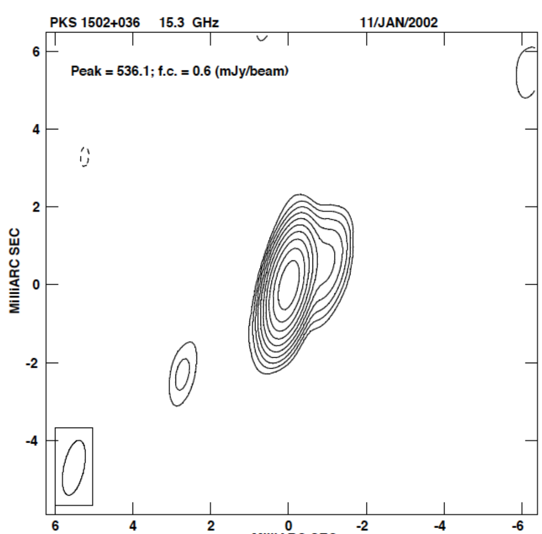
PKS 1502+036

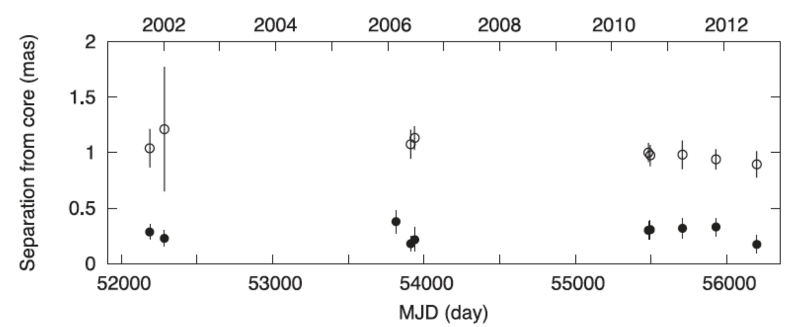
- High frequency peakers (HFPs) selected by Dallacasa et al. (2000), but rejected due to the variability (Orienti et al. 2008).

- No significant proper motion is detected for the jet components (D’Ammando et al. 2013).





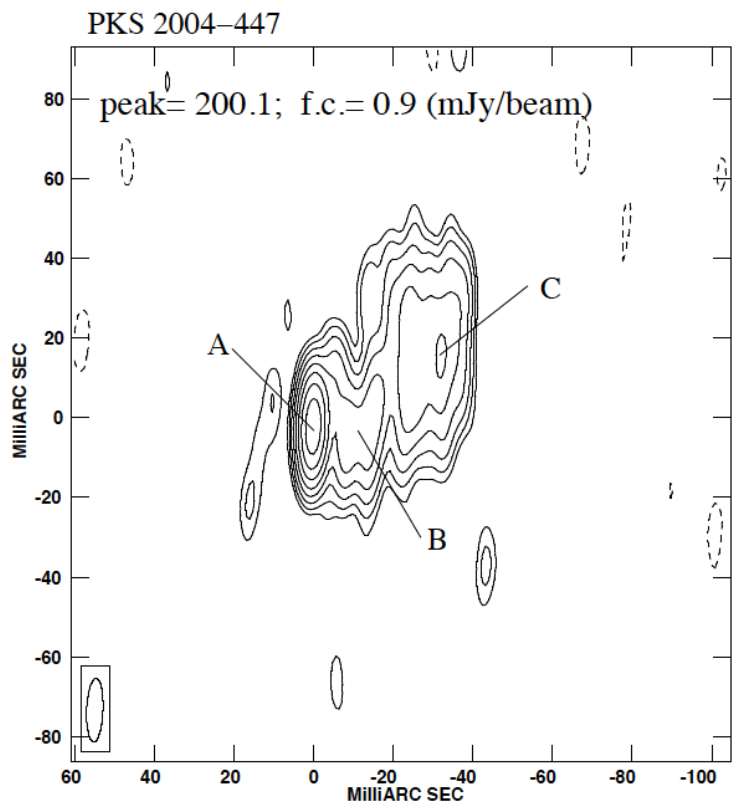




PKS 2004-447

- Compact steep spectrum source: a steep spectrum at high frequency (above 8.4 GHz), the absence of significant flux density variability, and unresolved at arcsecond-resolution (e.g. ATCA) (Gallo et al. 2006).
- Included in the CRATES catalog of flat spectrum objects (Healey et al. 2007) due to its flatter spectrum below 4.8 GHz.

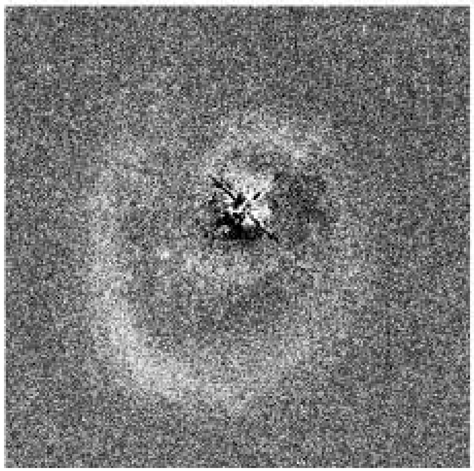
- 1.4 GHz VLBA image (Orienti et al. 2012).



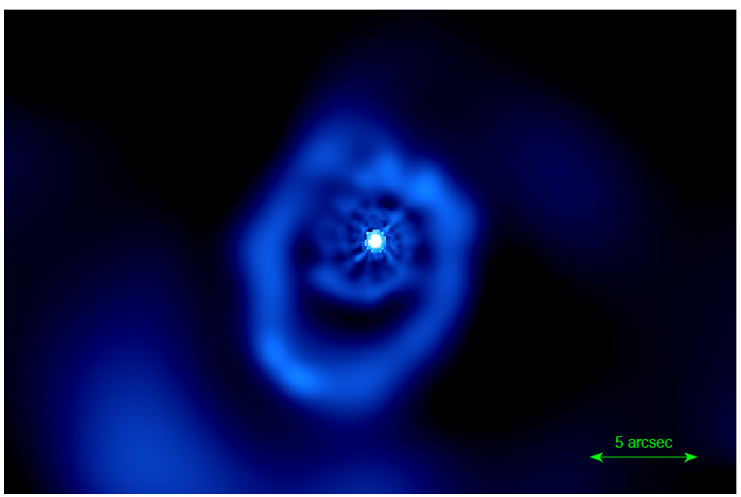
1H 0323+342: hosted in a spiral galaxy
core + weak extended (MOJAVE source, 1.2 pc/mas)

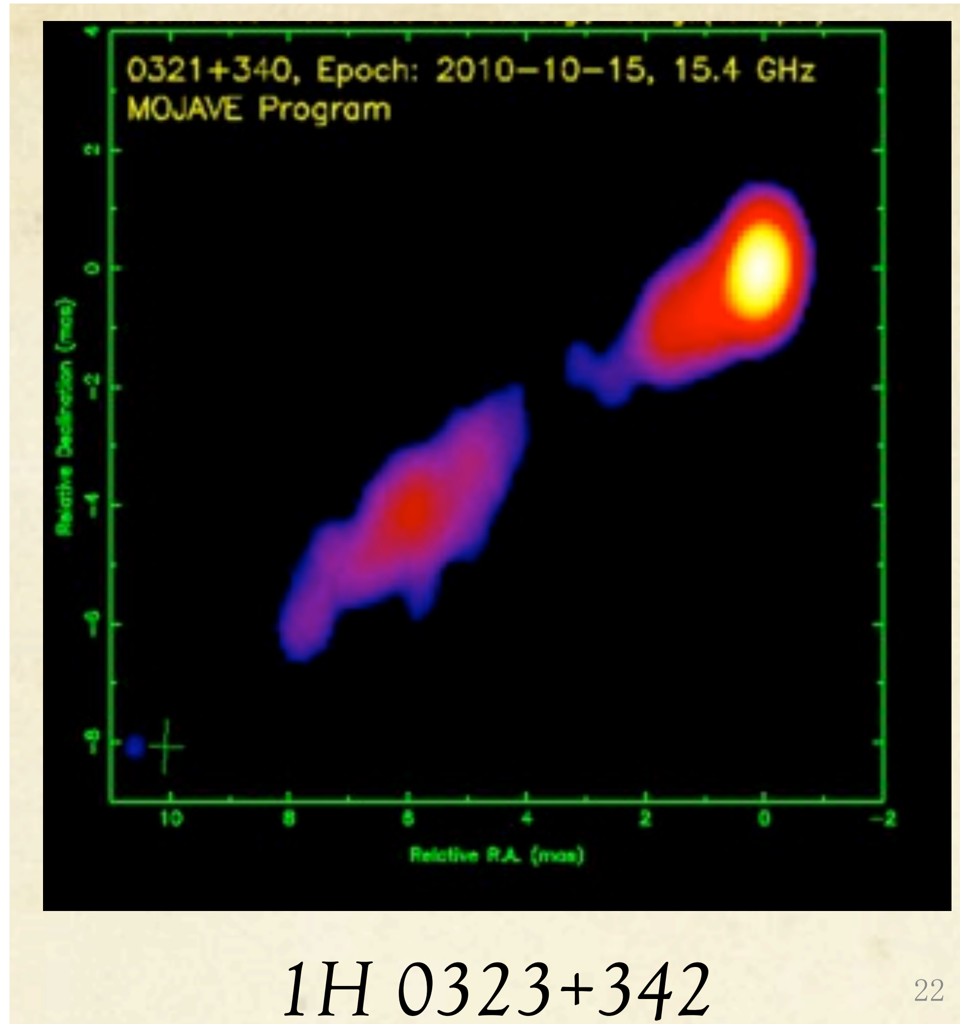
(radio image from Foschini at http://nls1.brera.inaf.it/)

(proper motion: stationary or very low speed, Wajima et al. 2014)



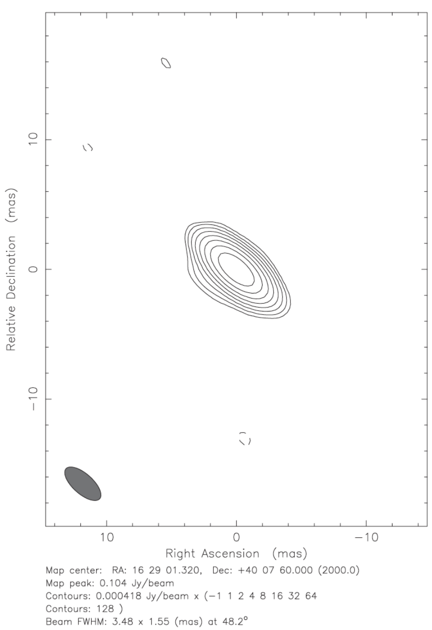
Zhou et al. (2007), Foschini (2011)

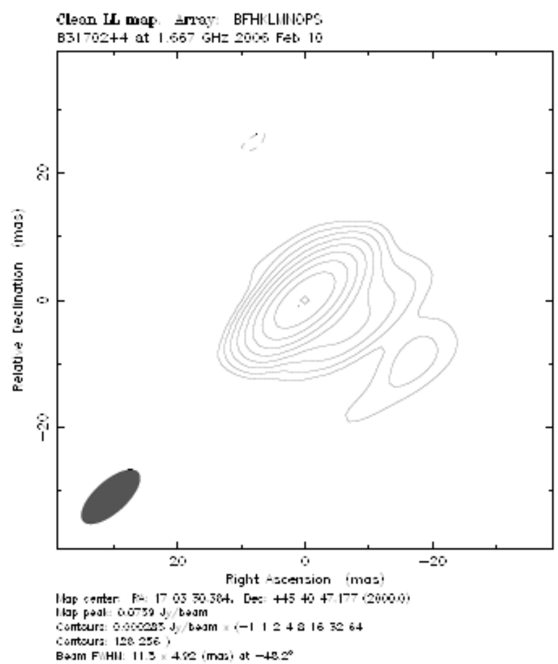


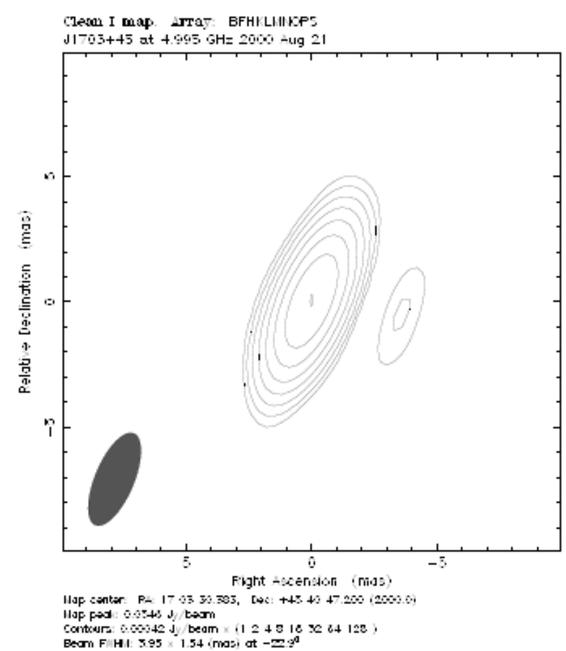


The radio structure of three RLNLS1s (Gu & Chen 2010, AJ)

- Radio loud NLS1s can be either intrinsically radio loud (e.g. B3 1702+457), or apparently radio loud due to jet beaming effect (e.g. RXS J16290+4007 and RXS J16333+4718).







RXS J16290+4007

B3 1702+457

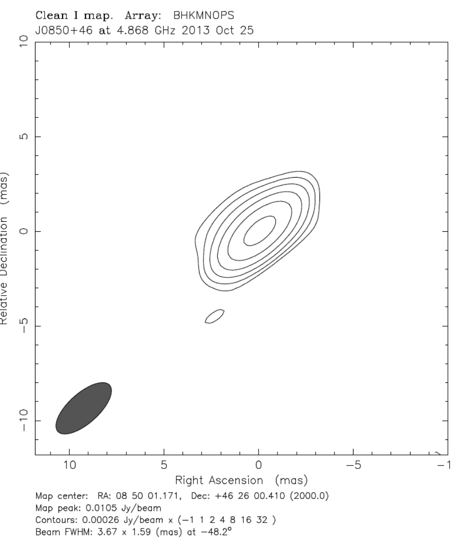
Preliminary results of our observations (Gu et al. 2015, ApJ, to be submitted)

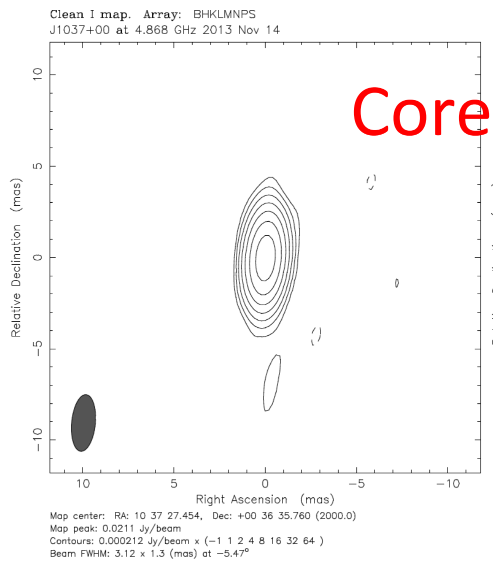
- A largest sample of 117 RLNLS1s (R>10) has been constructed by combining various samples available so far, which are mostly from our own work.
- Fourteen RLNLS1s with FIRST 1.4 GHz flux >10 mJy were observed with a total of 15 hours at 5 GHz using VLBA on Oct. and Nov., 2013.
- This is the first and largest systematic high resolution radio study of RLNLS1s.

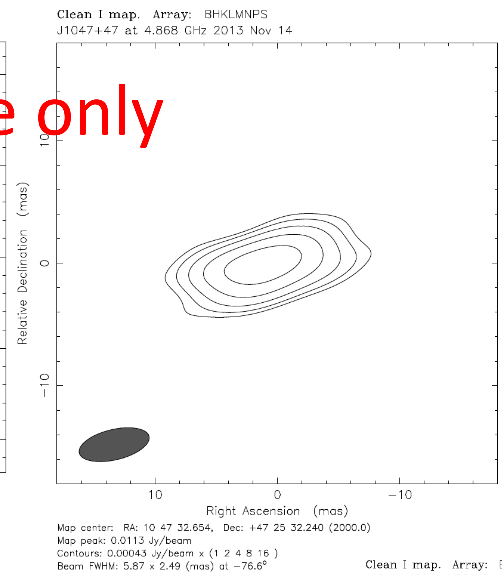
Morphology

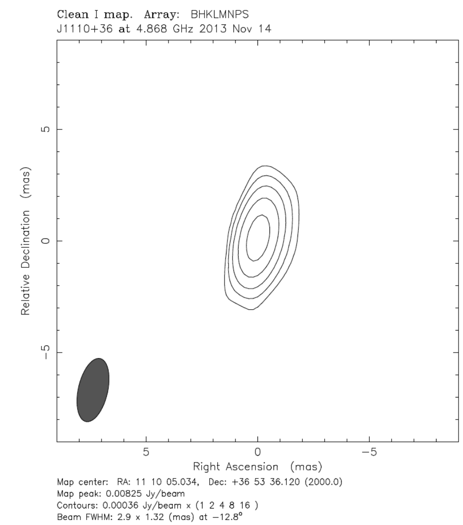
- Generally compact: seven sources show compact core only, and other seven objects have core-jet structure.

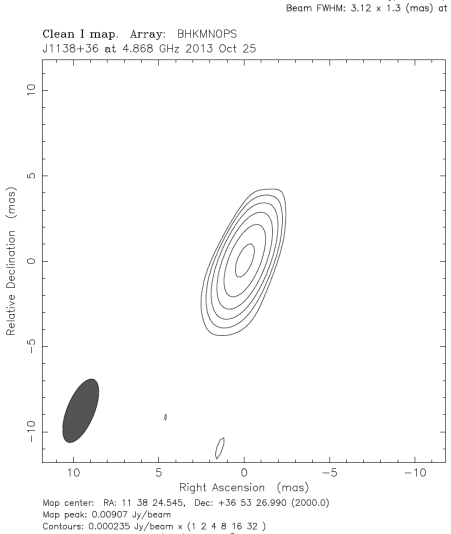
Core only

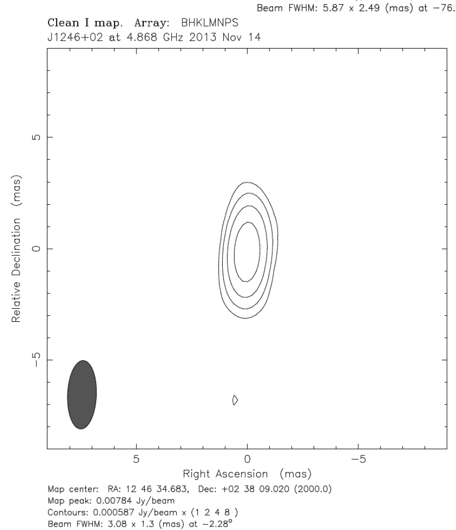


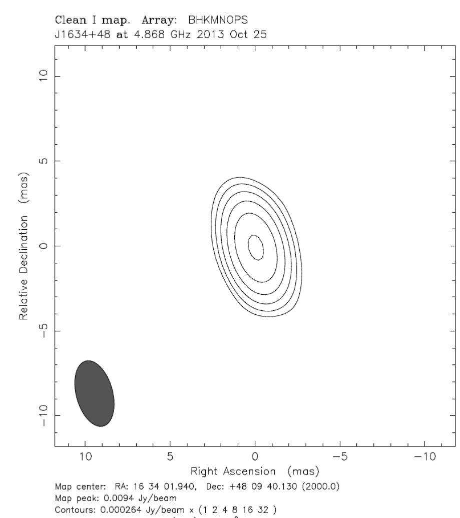


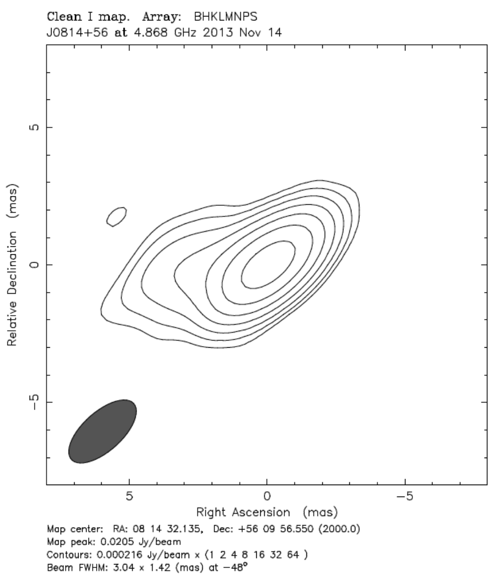


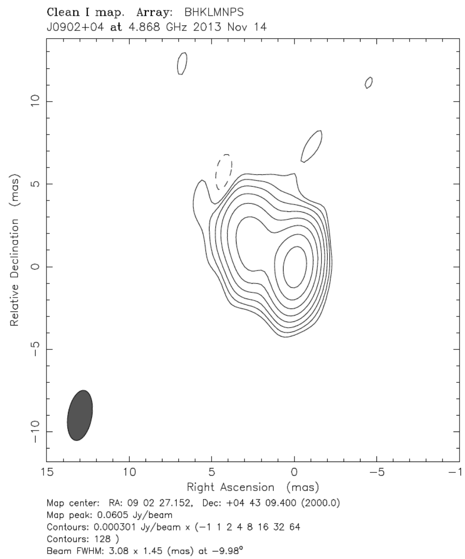


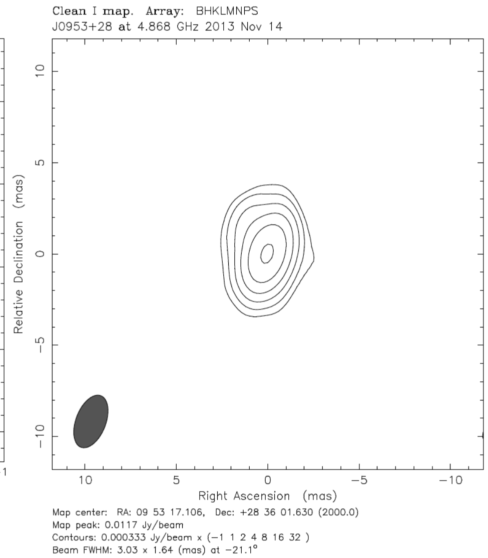


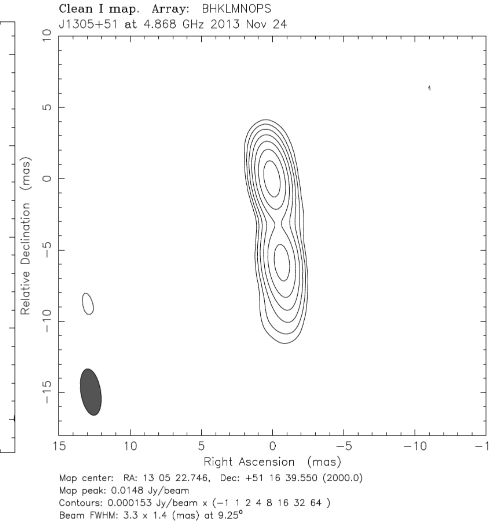


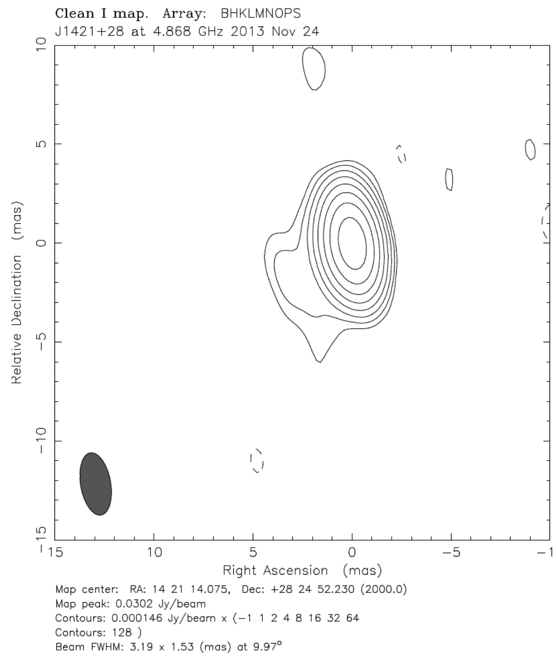



Clean I map. Array: BHKLMNPS
J0814+56 at 4.868 GHz 2013 Nov 14
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 08 14 32.135, Dec: +56 09 56.550 (2000.0)
Map peak: 0.0205 Jy/beam
Contours: 0.000216 Jy/beam x (1 2 4 8 16 32 64)
Beam FWHM: 3.04 x 1.42 (mas) at −48°

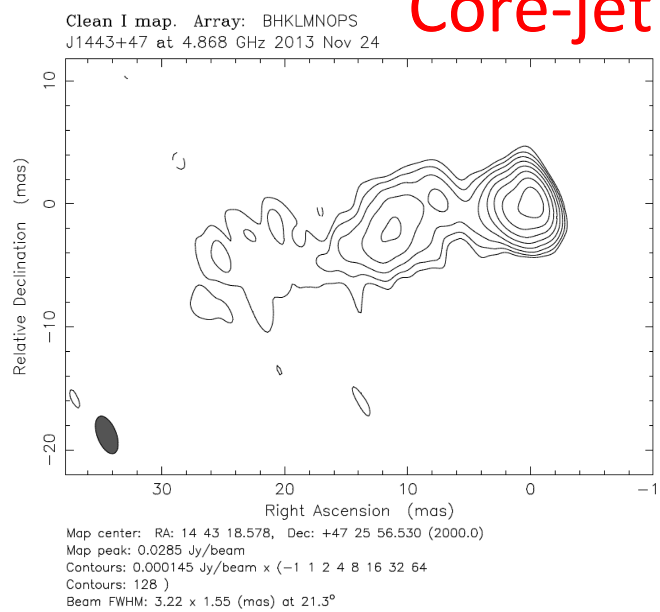

Clean I map. Array: BHKLMNPS
J0902+04 at 4.868 GHz 2013 Nov 14
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 09 02 27.152, Dec: +04 43 09.400 (2000.0)
Map peak: 0.0605 Jy/beam
Contours: 0.000301 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128)
Beam FWHM: 3.08 x 1.45 (mas) at −9.98°

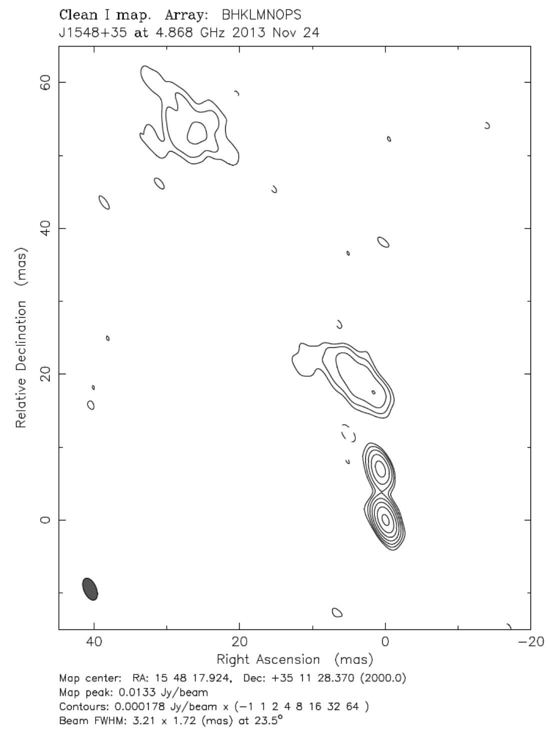

Clean I map. Array: BHKLMNPS
J0953+28 at 4.868 GHz 2013 Nov 14
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 09 53 17.106, Dec: +28 36 01.630 (2000.0)
Map peak: 0.0117 Jy/beam
Contours: 0.000333 Jy/beam x (−1 1 2 4 8 16 32)
Beam FWHM: 3.03 x 1.64 (mas) at −21.1°


Clean I map. Array: BHKLMNOPS
J1305+51 at 4.868 GHz 2013 Nov 24
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 13 05 22.746, Dec: +51 16 39.550 (2000.0)
Map peak: 0.0148 Jy/beam
Contours: 0.000153 Jy/beam x (−1 1 2 4 8 16 32 64)
Beam FWHM: 3.3 x 1.4 (mas) at 9.25°


Clean I map. Array: BHKLMNOPS
J1421+28 at 4.868 GHz 2013 Nov 24
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 14 21 14.075, Dec: +28 24 52.230 (2000.0)
Map peak: 0.0302 Jy/beam
Contours: 0.000146 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128)
Beam FWHM: 3.19 x 1.53 (mas) at 9.97°

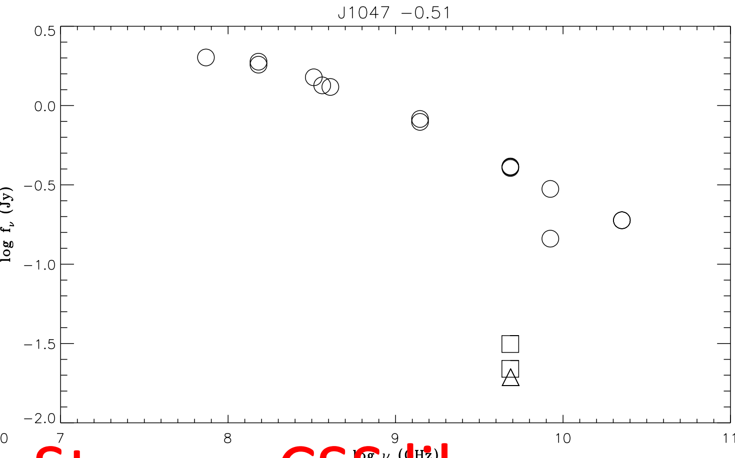
Core-jet

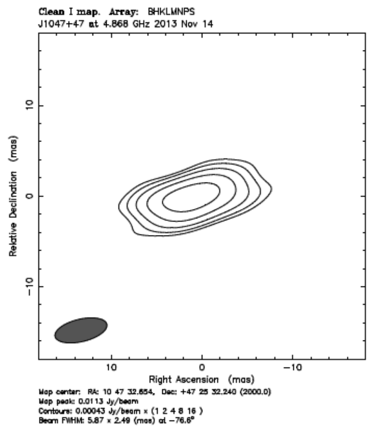

Clean I map. Array: BHKLMNOPS
J1443+47 at 4.868 GHz 2013 Nov 24
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 14 43 18.578, Dec: +47 25 56.530 (2000.0)
Map peak: 0.0285 Jy/beam
Contours: 0.000145 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128)
Beam FWHM: 3.22 x 1.55 (mas) at 21.3°

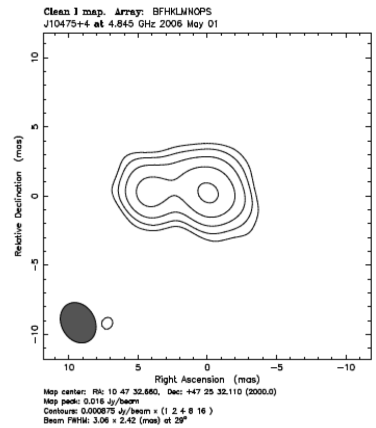

Clean I map. Array: BHKLMNOPS
J1548+35 at 4.868 GHz 2013 Nov 24
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 15 48 17.924, Dec: +35 11 28.370 (2000.0)
Map peak: 0.0133 Jy/beam
Contours: 0.000178 Jy/beam x (−1 1 2 4 8 16 32 64)
Beam FWHM: 3.21 x 1.72 (mas) at 23.5°

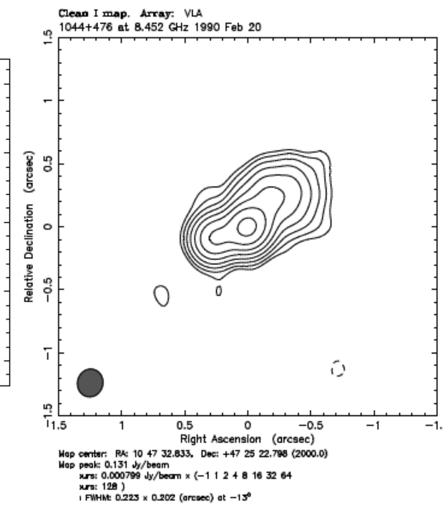
Radio spectra

- In combination with the multi-band data, seven sources show flat or even inverted radio spectra, and steep spectra are found in rest seven objects.

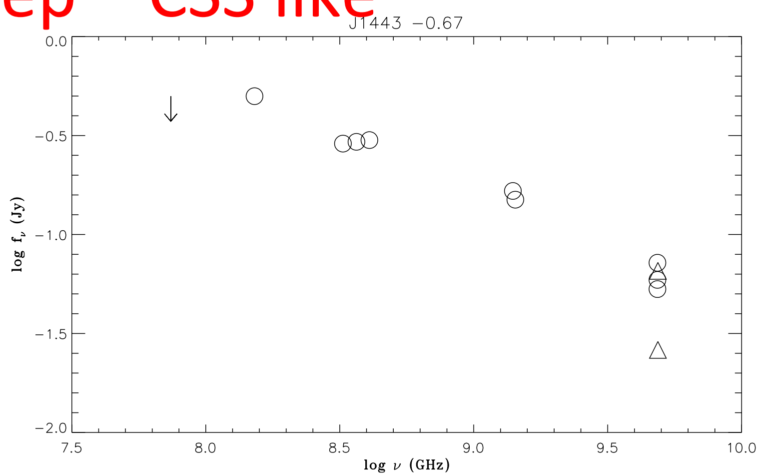


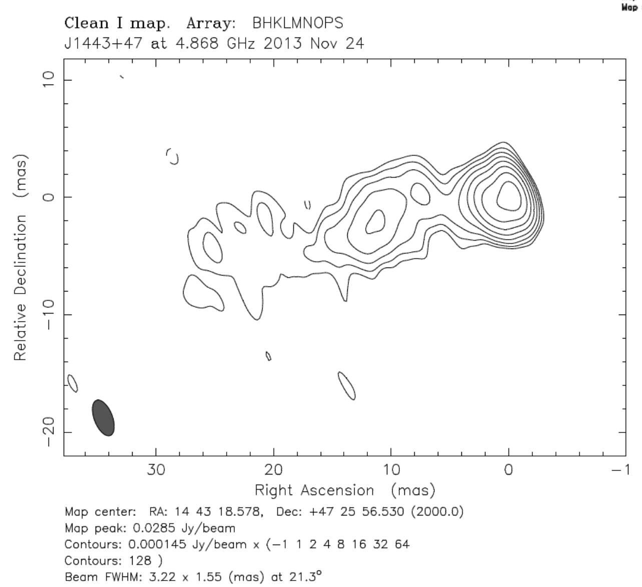




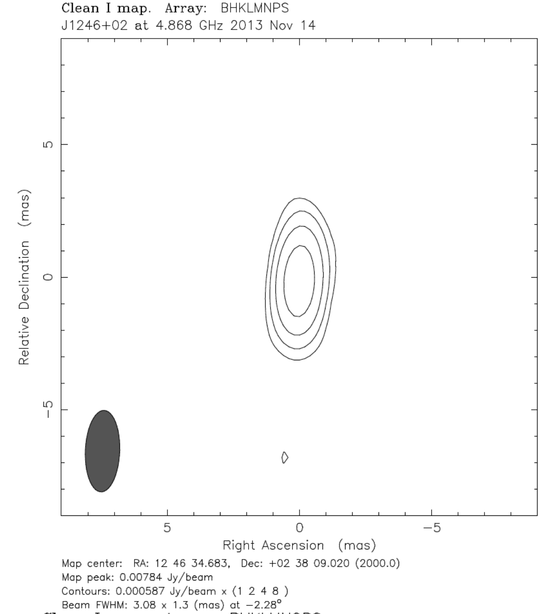


Steep – CSS like

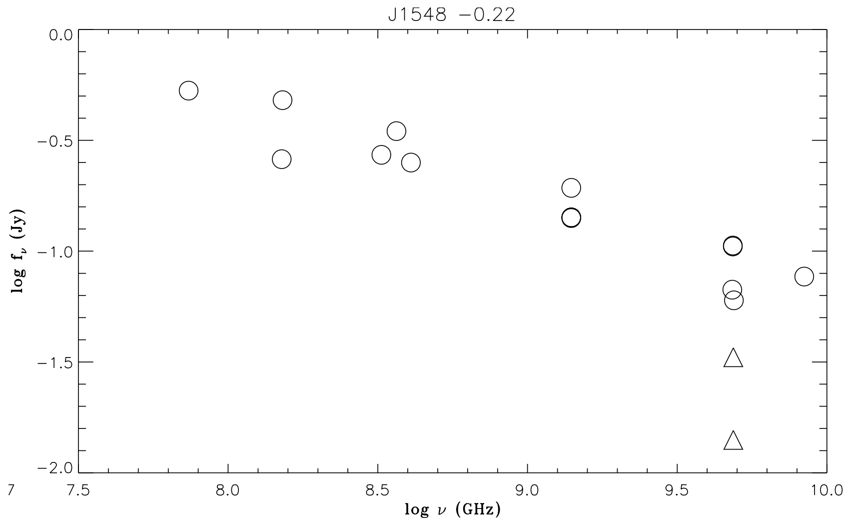


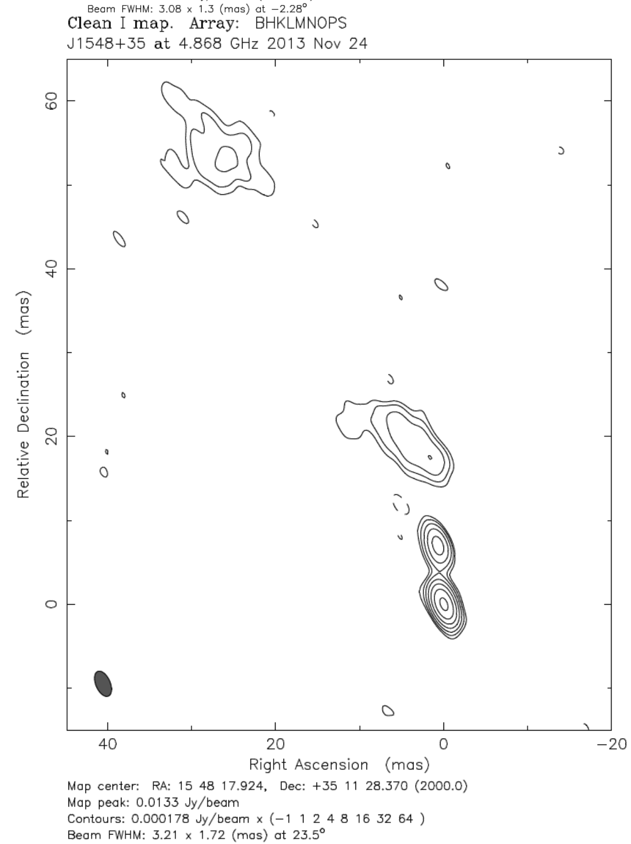


- Fermi detected: J1246+02
- Core only, different from others



Flat

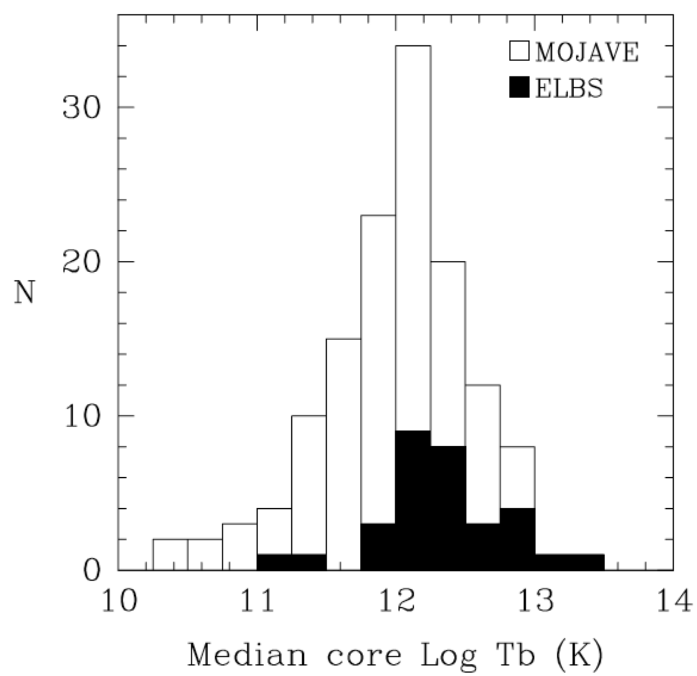




Brightness temperature

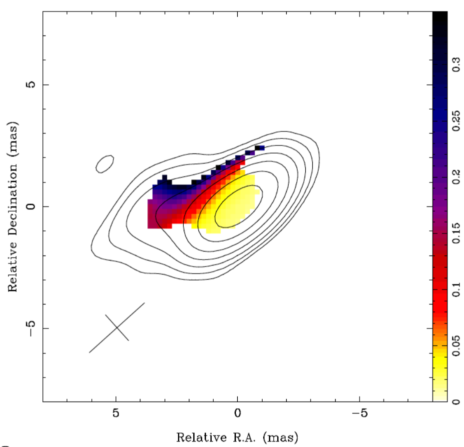
- The brightness temperature of cores range from $10^{\mathbf{8.4}}$ to $10^{\mathbf{11.4}}$ K with a median value of $10^{\mathbf{10.1}}$ K.
- The radio emission is from non-thermal jets, and the beaming effect is generally not significant.
- Typical blazars have 10^{11} - 10^{13} K with a median value near 10^{12} K (Kovalev et al. 2005, 2009).
- The bulk jet speed may likely be low in our sources.

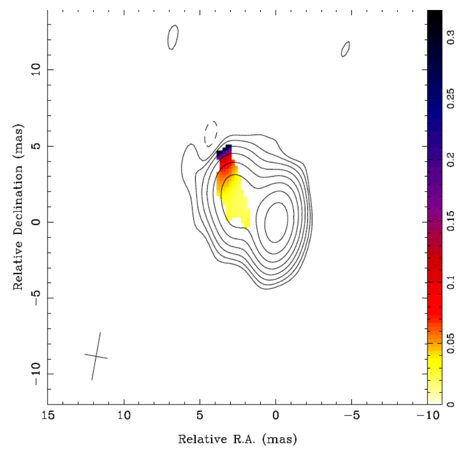
Kovalev et al. 2009

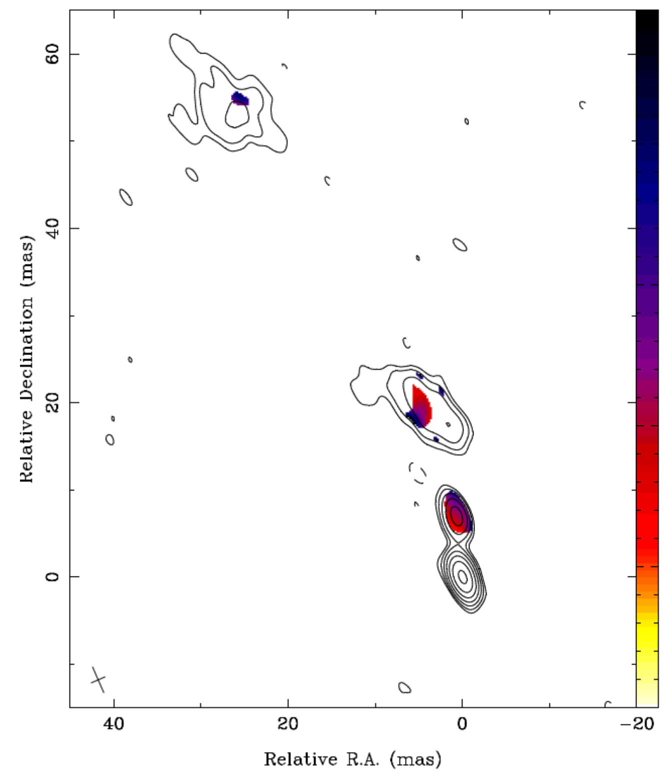


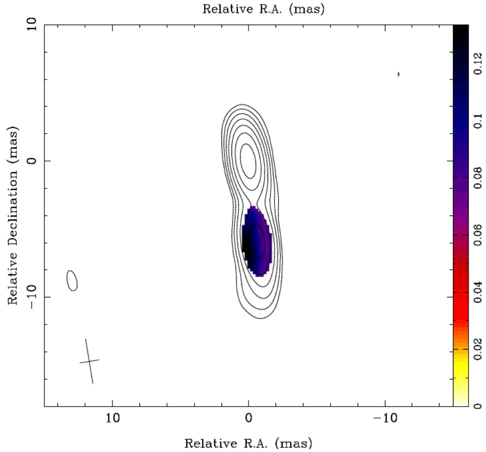
Polarization

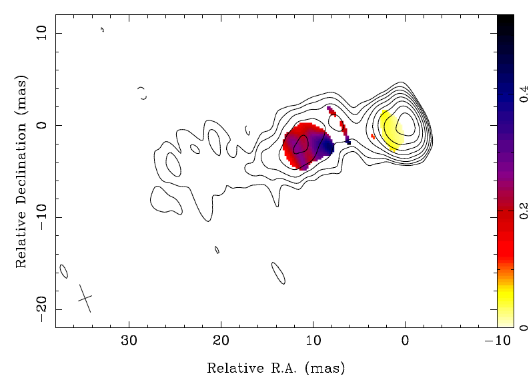
- The higher fractional polarization in jets: the strong Faraday rotation in nuclei region due to the high plasma density, and/or depolarization due to the complex core structure.
- The gradient of fractional polarization along the direction perpendicular to the jet elongation : the jet-ISM interaction at the locations of high fractional polarization because of the jet bulk motion.





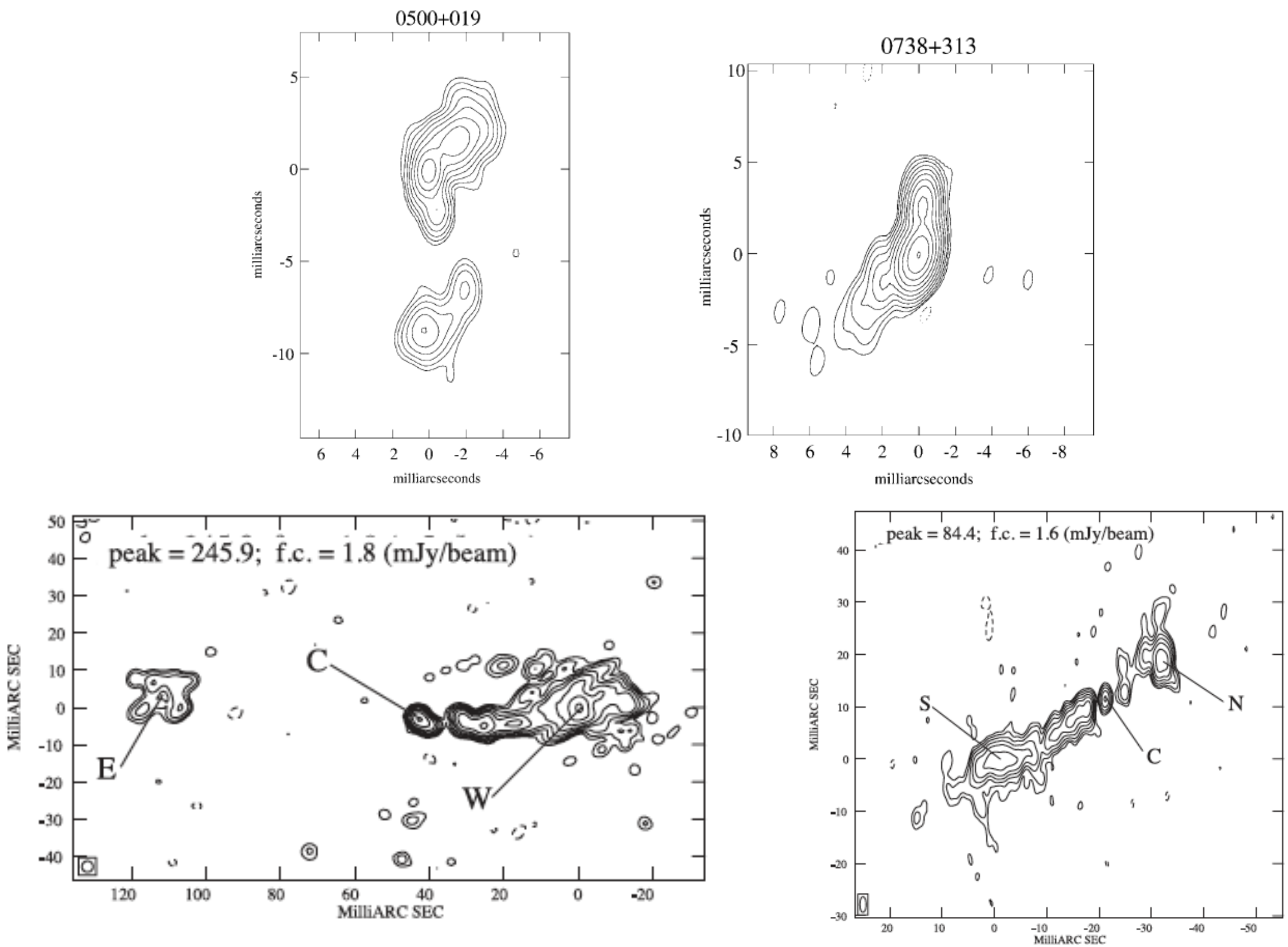






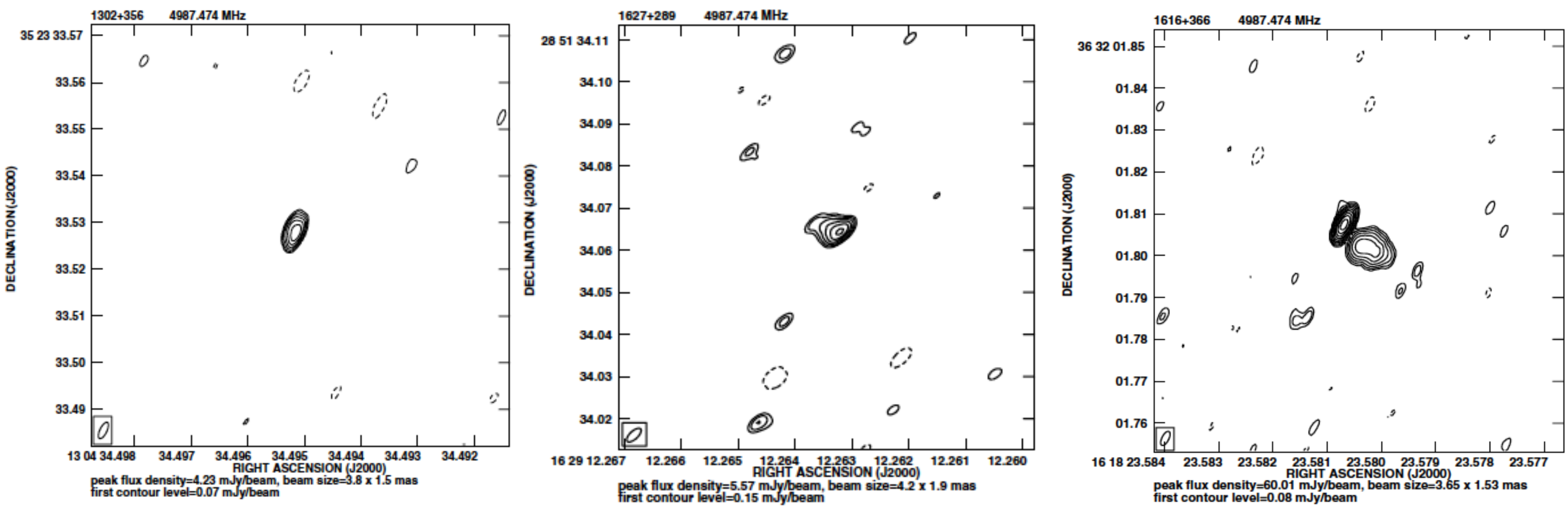
VLBI morphology in typical CSSs

- Most high-power CSSs show double or triple morphologies (O'Dea 1998, Dallacasa et al. 2013)



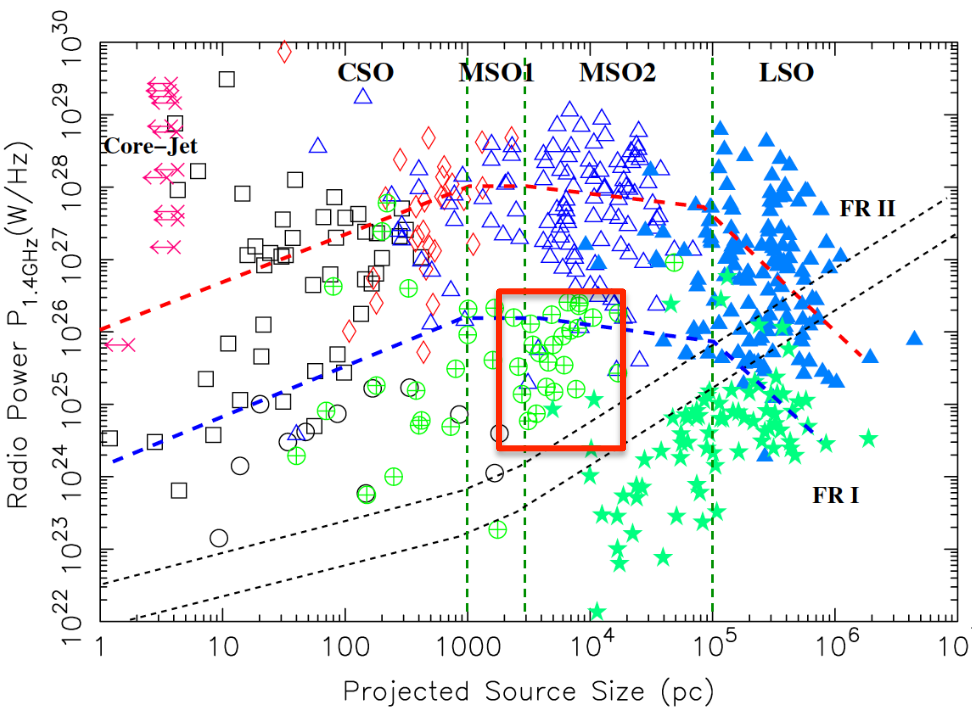
Core, core-jet in low-power CSSs

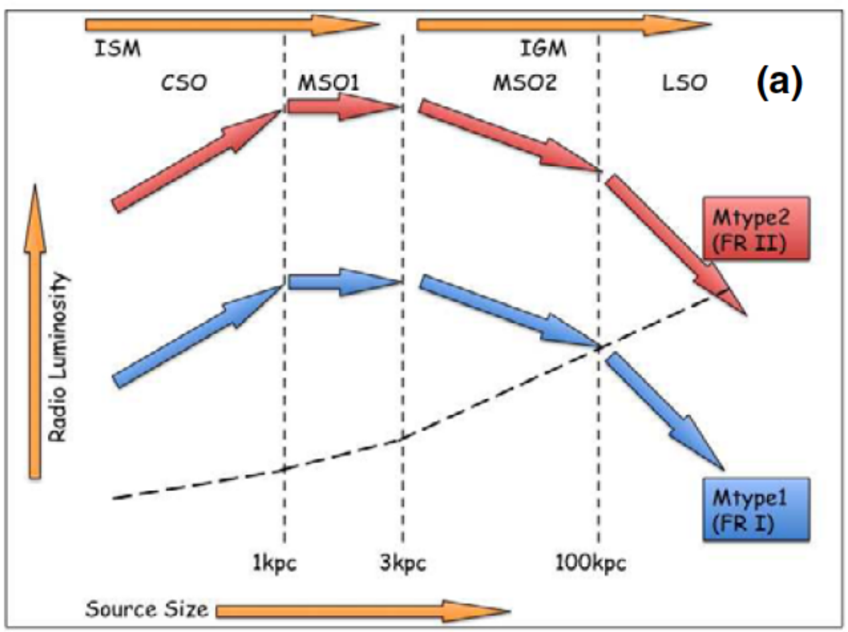
- The compact core only, or core-jet structure have been detected in relatively low-power CSS sources (Kunert-Bajraszewska et al. 2006; Kunert-Bajraszewska & Marecki 2007)



Evolution

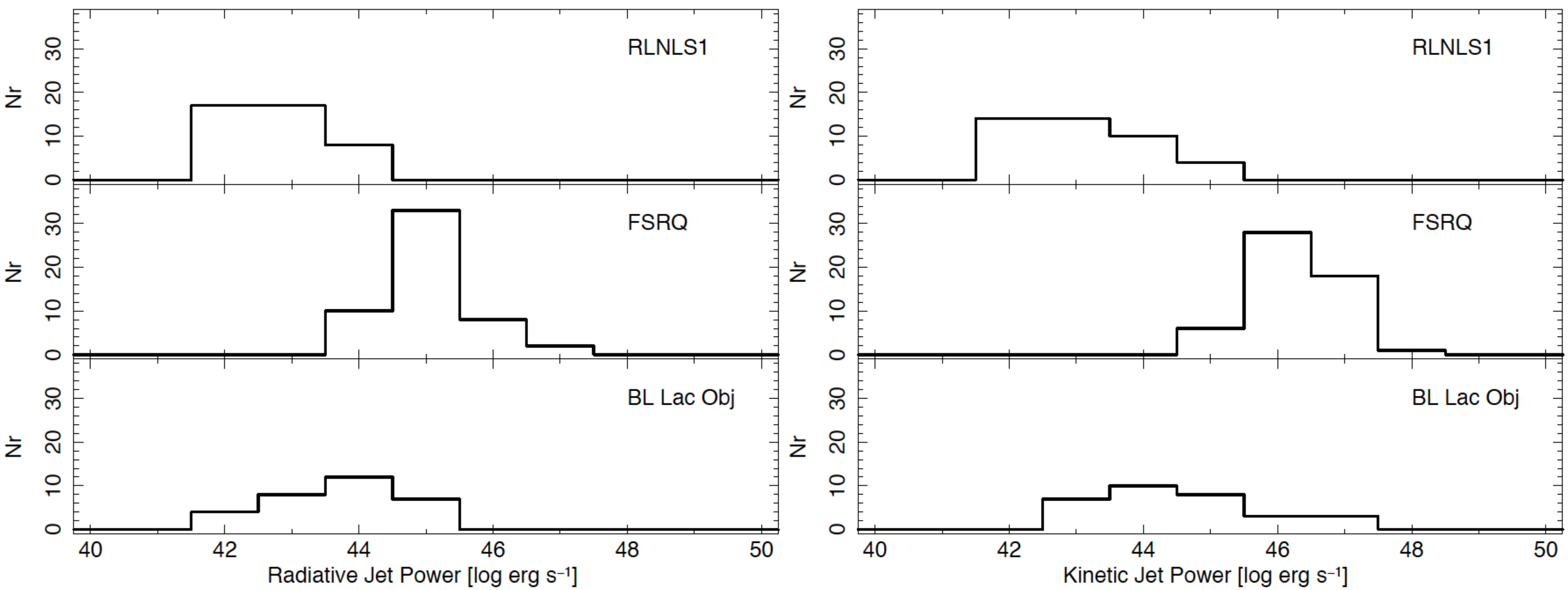
- Our sources occupy the space below the main evolutionary path of radio objects (An & Baan 2012).
- However, the difference is that our sources have small black hole mass and high accretion rate.





Comparison with blazars

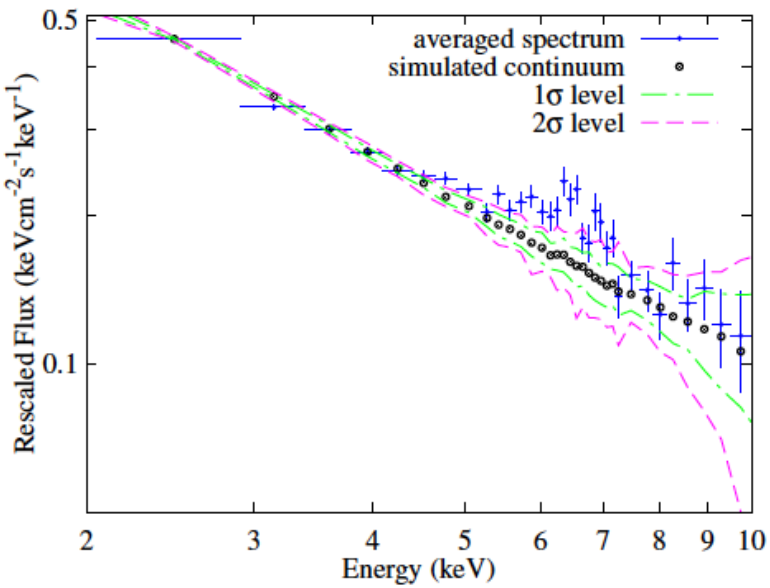
- The central engine of RLNLS1s is quite similar to blazars: the jet power is generally lower than quasars and BL Lacs. However, once normalised by the MBH, the jet power are consistent with each other, indicating the scalability of the jet (Foschini et al. 2014).
- The presence of curvature in the gamma-ray spectrum, similar gamma-ray photon index, and flux variability amplitudes suggest that gamma-ray NLS1s could be similar to low/moderate jet power FSRQs (Paliya et al. 2014).

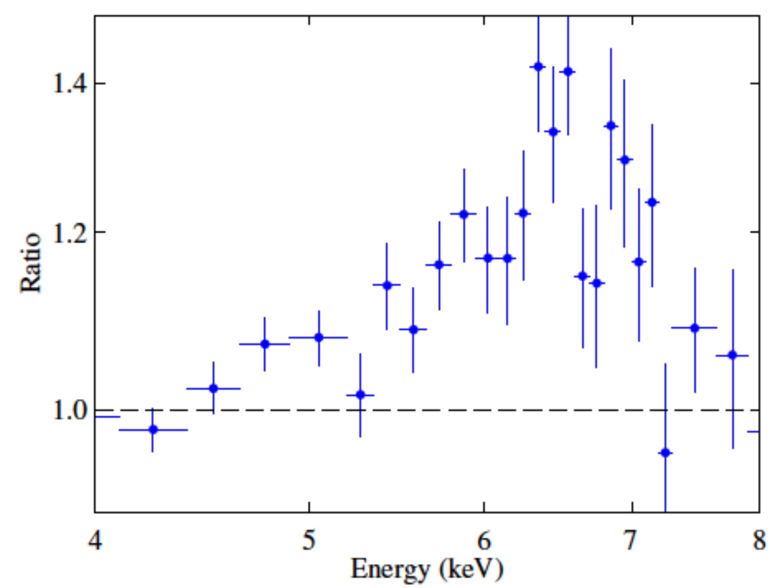


Scenario

- The outflows accelerated from the hot corona above the disk by the magnetic field and radiation force, with high mass loss rate but low speed (Cao 2014).
- (BALQs Tb: 10^9.9 – 10^10.9 with median value of 10^9.6)

- The MBH - Γ correlation: the faster moving jets are magnetically accelerated by the magnetic fields threading the horizon of more rapidly rotating black holes (Chai, Cao & Gu 2012).
- The low jet speed could be due to the low spin, supported by low/intermediate average spins (a < 0.84) from composite broad Fe K line (Liu et al. 2015).





- We have proposed 24 hours VLBA observations for additional 20 RLNLS1s selected with FIRST flux limit >=6 mJy.
- All sources have been observed in Nov. and Dec. 2014, yielding the biggest sample of 45 sources observed with VLBI.

NRAO

Observing Application

Date : Jul, 11 2014
Proposal ID : VLBA/15A-004
Legacy ID : BG232
PI : Minfeng Gu
Type : Regular
Category : Active Galactic Nuclei
Total Time : 24.0

The radio properties of radio-loud narrow line Seyfert 1 galaxies on pc scale

Abstract:

Radio-loud narrow line Seyfert 1 galaxies (RLNLS1s) are very special, because some of them show blazar-like characteristics, while others don't. Relativistic jets were shown to exist in a few RLNLS1s based on VLBI observations and confirmed by the gamma-ray flaring of some of them. These properties are unexpected, in light of the low black hole masses, high accretion rates, and possible spiral hosts of these RLNLS1s, and challenge our understanding of jet formation under such conditions. However, it is far from clear whether relativistic jets are present in all RLNLS1s, and whether they are intrinsically radio loud or not. As a continuation of our previous VLBA observations, we propose 24 hours total of observations with VLBA at 5 GHz (C-band) for 20 RLNLS1s, selected with 1.4 GHz flux density >= 6 mJy, and radio loudness R>=10. The radio morphology and core flux density from the VLBA images will enable us to explore the VLBI properties of these sources. This will allow us to study the nature of their jets, the connections with classical CSSs, and a statistical analysis of the properties of the gamma-ray NLS1s detected with Fermi.

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Anton Zensus	Max-Planck-Institut für Radioastronomie	azensus@mpifr-bonn.mpg.de	

- To constrain the bulk velocity of jets, we proposed 14 hours two-epoch VLBA observations for 10 sources.

Observing Application

Date:	Jan 30, 2015
Proposal ID:	VLBA/15B-015
Legacy ID:	BG234
PI:	Minfeng Gu
Type:	Regular
Category:	Active Galactic Nuclei
Total time:	14.0

Detections on the jet proper motion in radio-loud narrow-line Seyfert 1 galaxies

Abstract:

Radio-loud narrow line Seyfert 1 galaxies (RLNLS1s) are very special, because some of them show blazar-like characteristics, while others do not. Relativistic jets were shown to exist in a few RLNLS1s based on VLBI observations. These properties are unexpected, in light of the low black hole masses, high accretion rates, and possible spiral hosts of these RLNLS1s. Our results from VLBA observations in 2013, show that RLNLS1s are usually compact at pc scale, however the beaming effect is generally not significant, implyinga likely lower jet speed compared to typical blazars. The mildly relativistic jets could likely be explained by either the jet acceleration by the magnetic field and radiation force of the accretion disk, or the low spin in Blandford-Znajek mechanism. To directly constrain the jet bulk velocity, we propose 14 hours two-epoch observations with VLBA at 5 GHz (C-band) for 10 RLNLS1s, including seven well-resolved sources from our observations in 2013, and three gamma-ray objects with resolved structure. The observations will enable us to detect the proper motion of jet components, by combining with our previous and archive observations. This will allow us to strongly constrain the jet bulk velocity, and then to study the nature of their jets.

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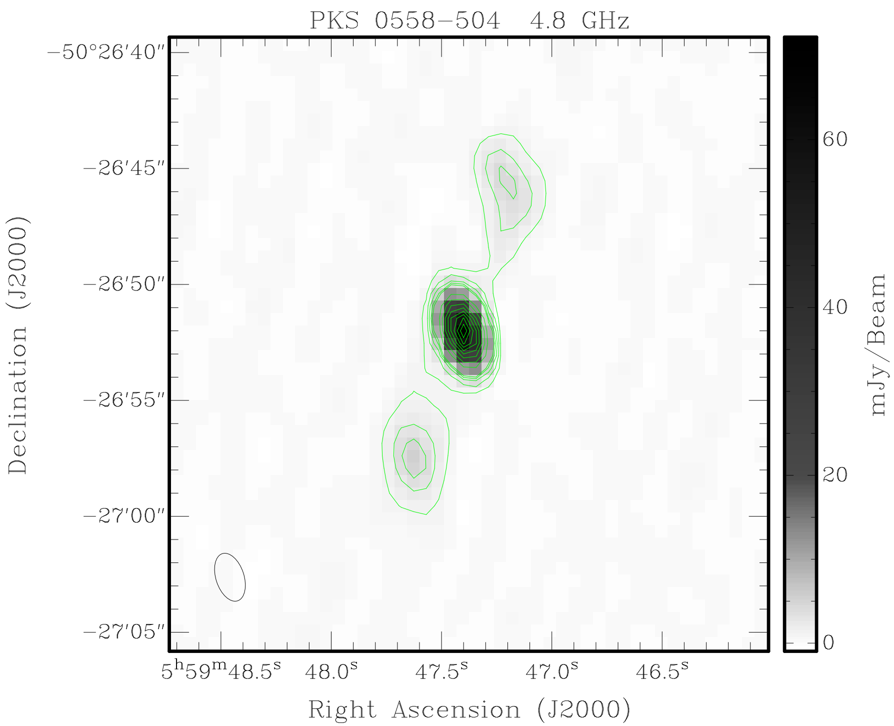
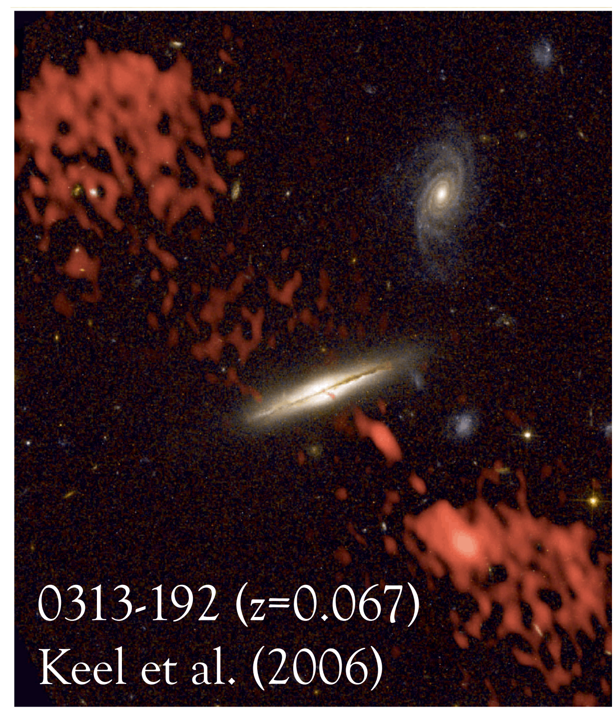
Parent population

- CSS/GPS ? (Yuan et al. 2008, Caccianiga et al. 2014): large viewing angle: CSS/GPS; small viewing angle: blazar-like NLS1s.
- Radio-quiet NLS1s: compact radio structure
- Radio galaxies in spirals ? PKS 0558-504 with large scale 46 kpc double lobes (Gliozzi et al. 2010); double radio source 0313-192 in spiral (Keel et al. 2006); Inskip et al. (2010) for radio sources in disk galaxies.





Summary

- Powerful jets may present in systems with small M_{bh} and high accretion rate, e.g. NLS1s.

- The jet properties of very radio-loud NLS1s (R>100) are diverse on mas scale, in terms of the morphology and spectral shape.

- There may be tight relation between radio loud NLS1s and young radio sources (e.g. CSS).

- The slow jet speed or less relativistic jet, in combination with the low kinetic/radio power, can be responsible for the compact VLBA radio structure in most of sources.

Thanks for your attention !