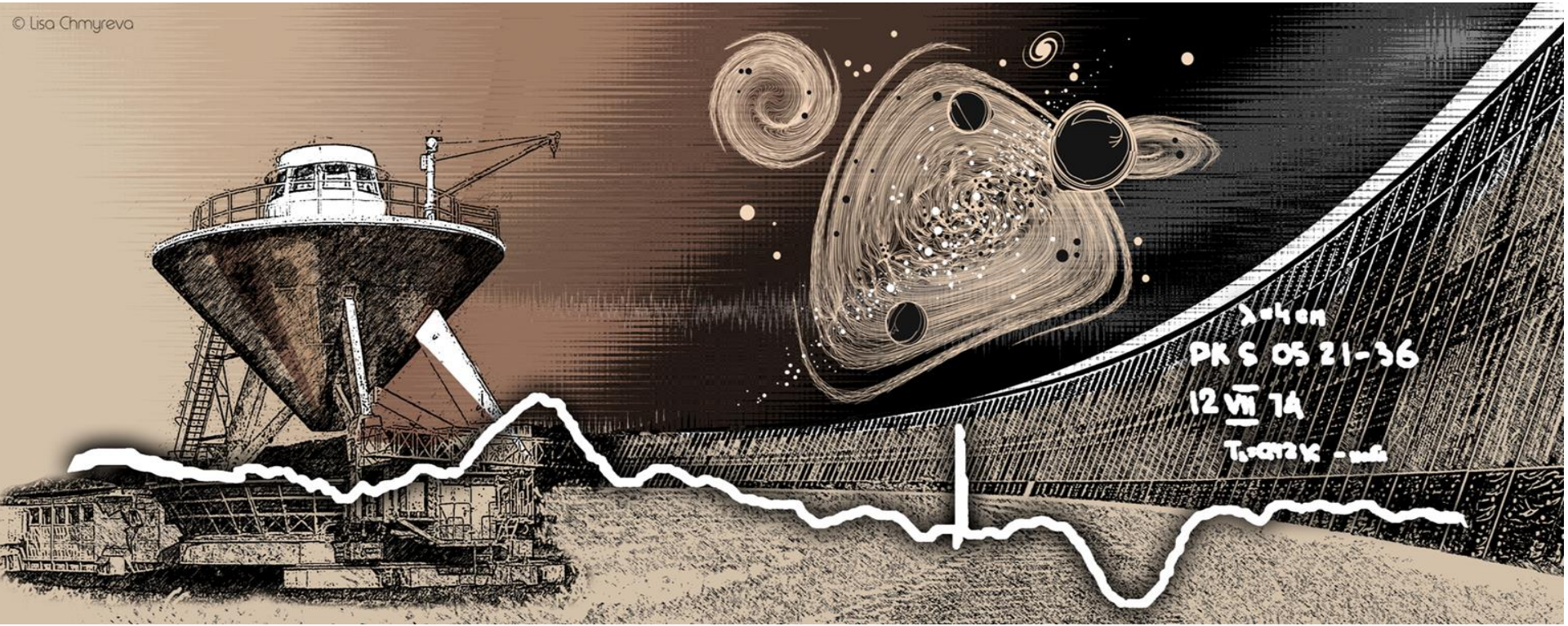
Broadband radio properties of the FR0 radio galaxies



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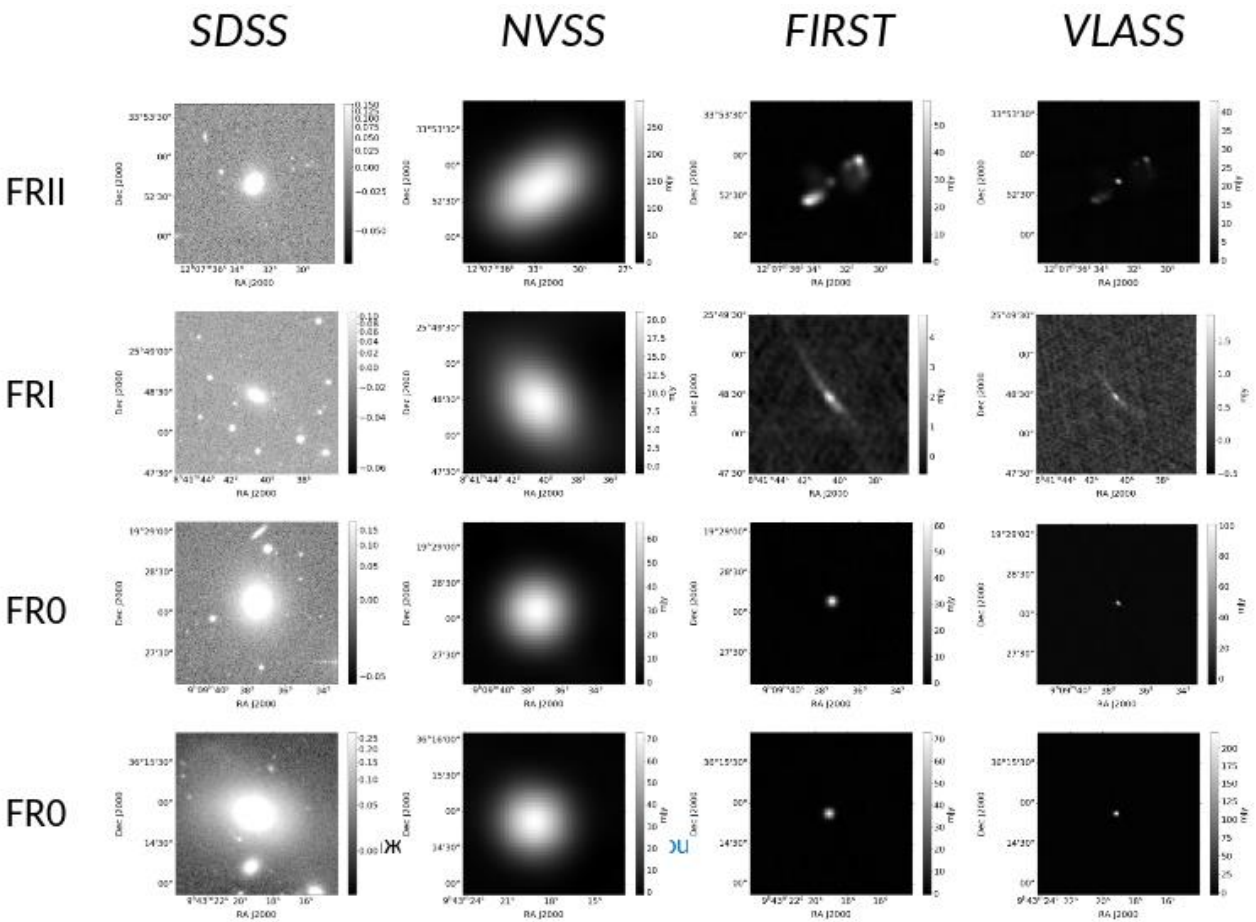
[1]SAO RAS, [2]University of Cambridge

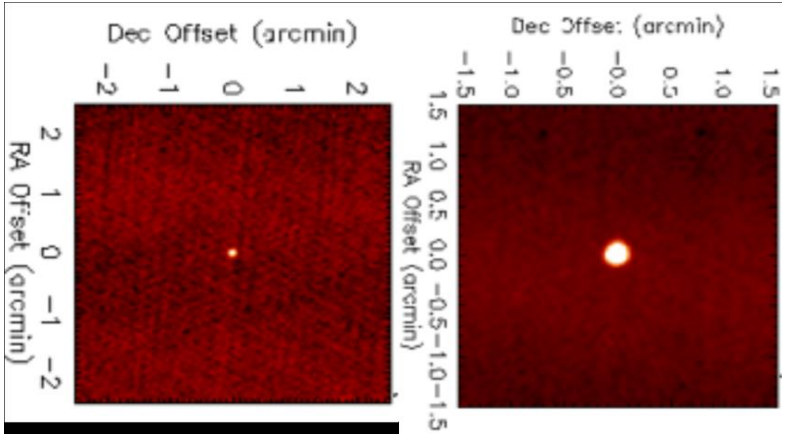
8 October 2024
HEACOSS-2024

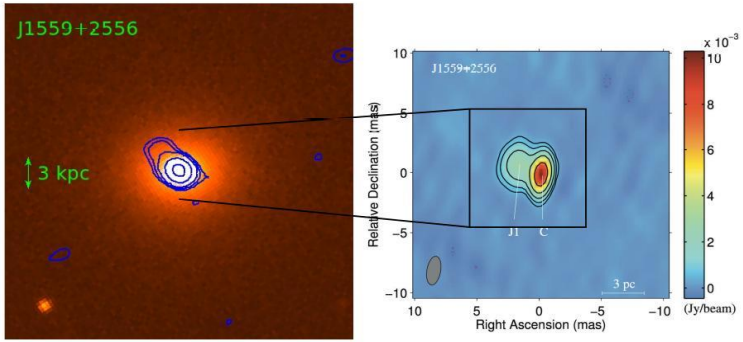
Radio galaxies in surveys



FR0s in the nearby Universe

red elliptical galaxies, M_{BH}~10^8-$10^9 M_\odot$





Best et al. 2005: 2215 objects at z< 0.3,
SDSS + NVSS + FIRST

The most objects have a deficit of extended radio emission compared to classical FRI/FRII
Ghisellini 2011, Baldi et al., 2015, 2018

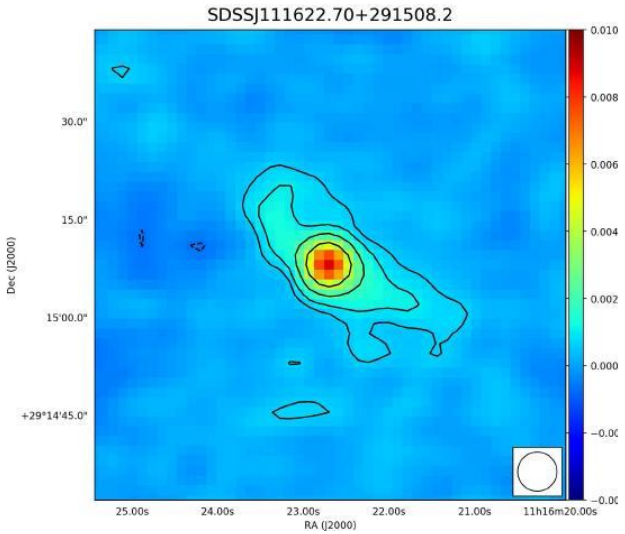
"FR0 galaxies"
linear size < 3 kpc
FR0 and FRI: space density 5:1
similar properties of host galaxies

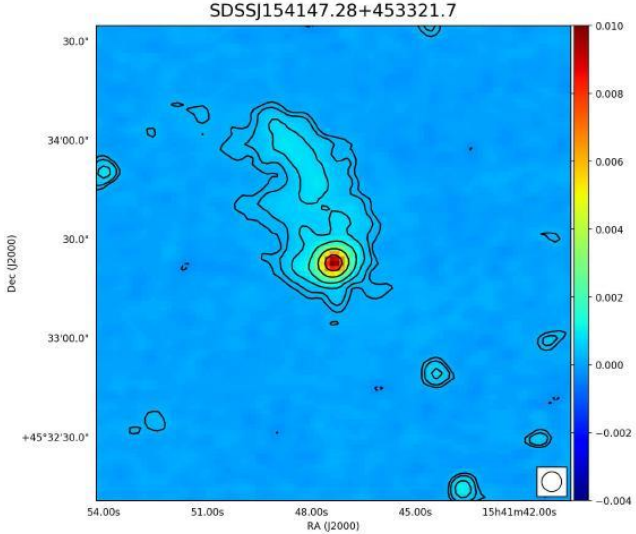
FR0s from LoTSS (Capetti et al. 2020)

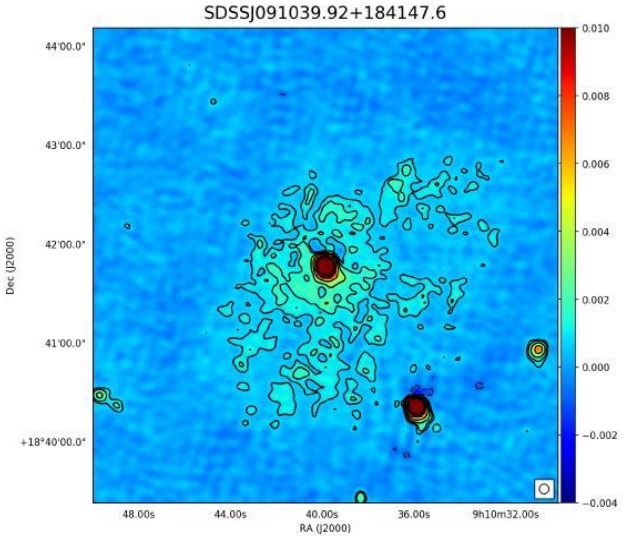
Detection 66/66

54 point-like sources (linear size < 3-6 kpc)

12 extended sources (15-50 kpc)





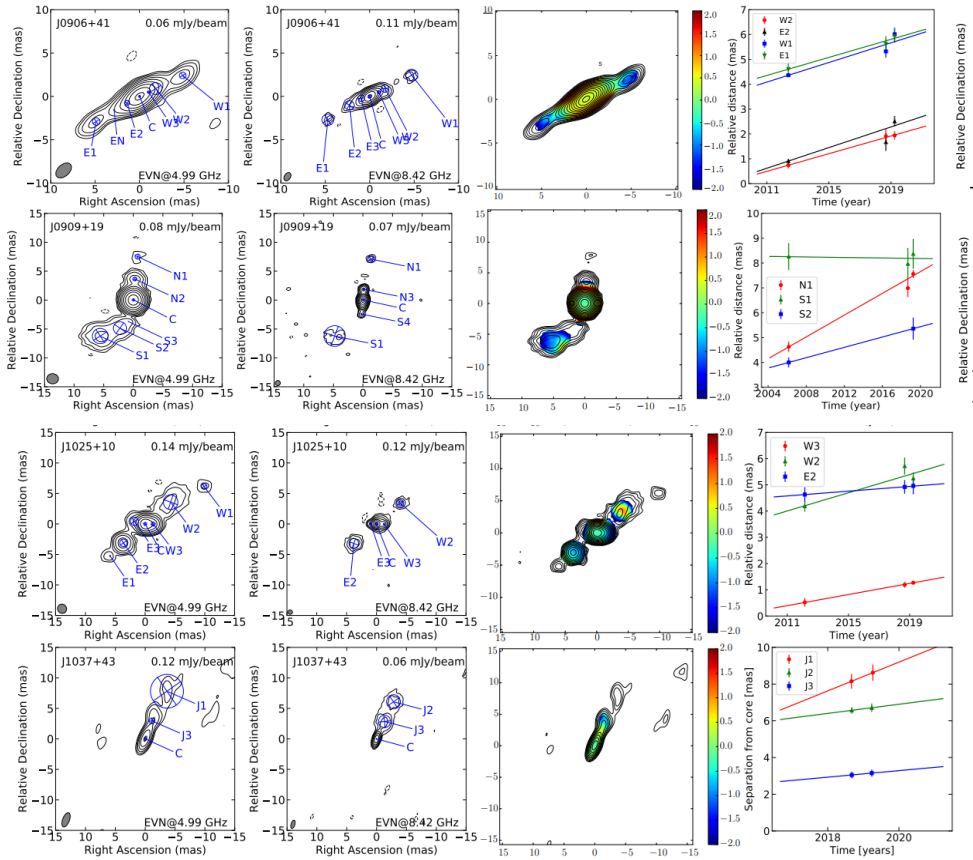


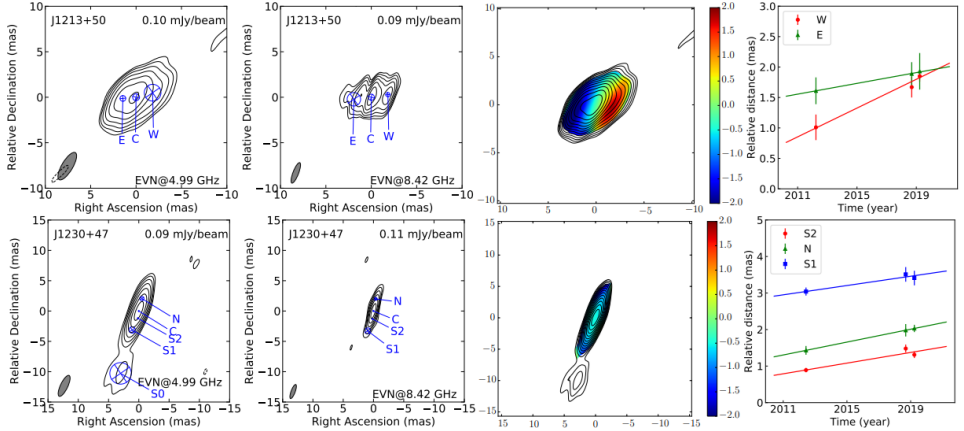
LOFAR observations, 150 МГц

angular resolution 6”

FR0's parsec scale radio morphology (EVN, VLBA)

Cheng & An 2018, Cheng et al. 2021, Giovannini et al. 2023

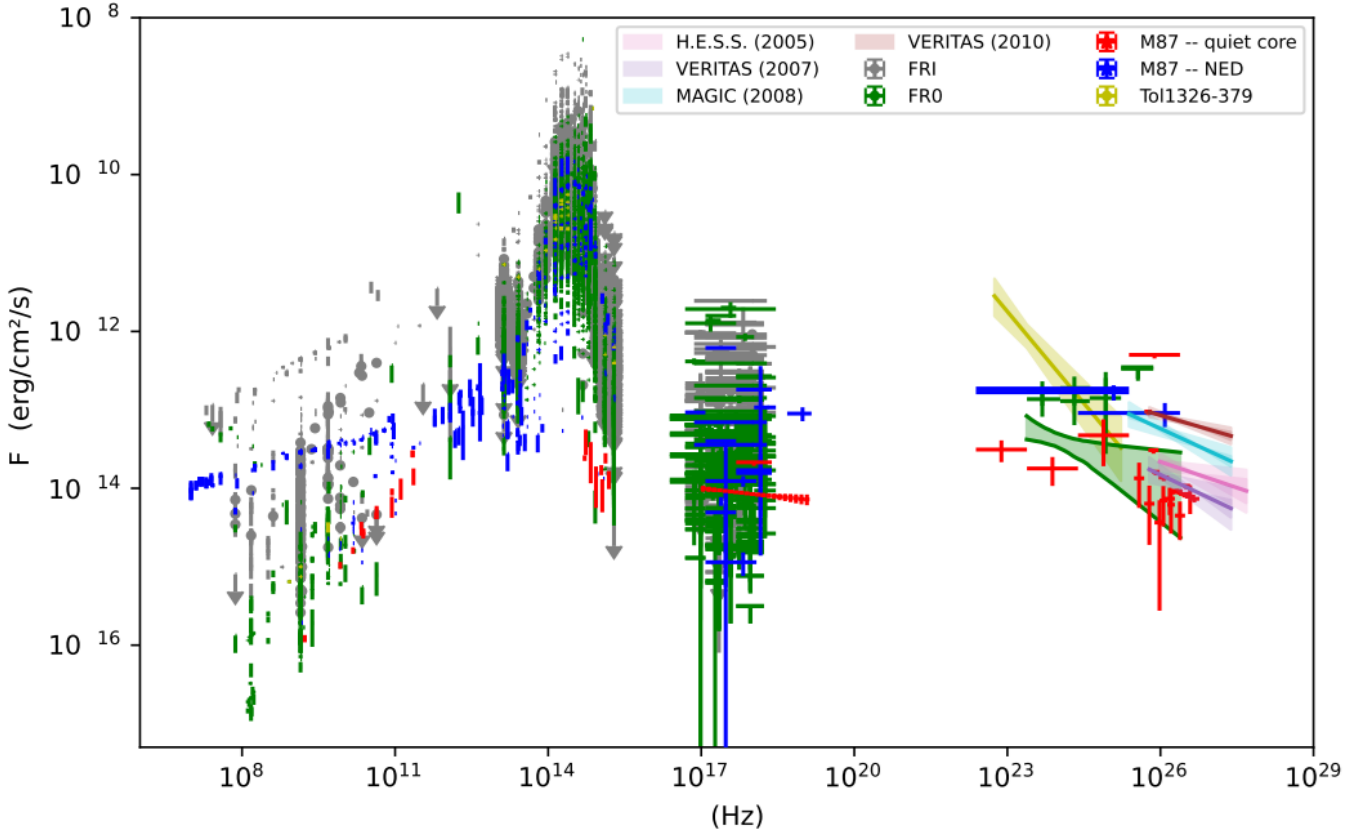




25 sources were studied:

- most of them are resolved on the scale of 1-20 pc;
- flat radio spectra;
- moderately relativistic jets (jet components speed is 0.2-0.5 c)

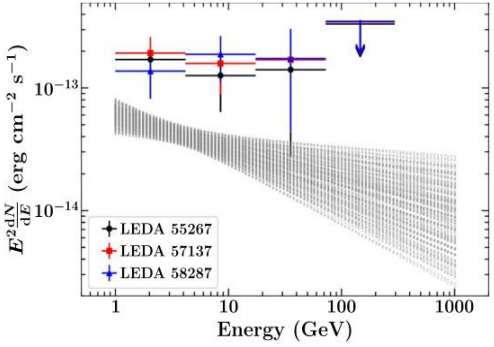
SEDs

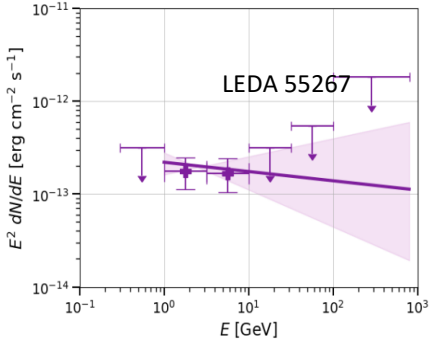


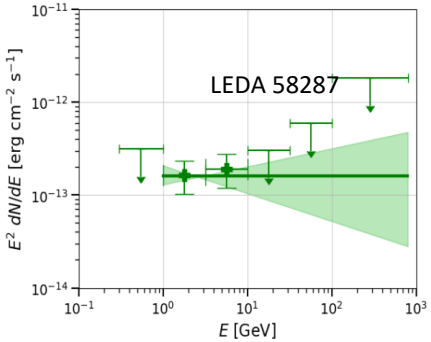
Broad-band spectrum of FR0 almost coincides with spectrum of core M87 (FRI) in a quiet state

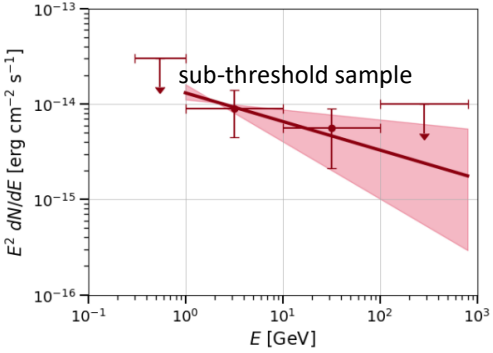
Boughelilba & Reimer 2023

γ-ray FR0s



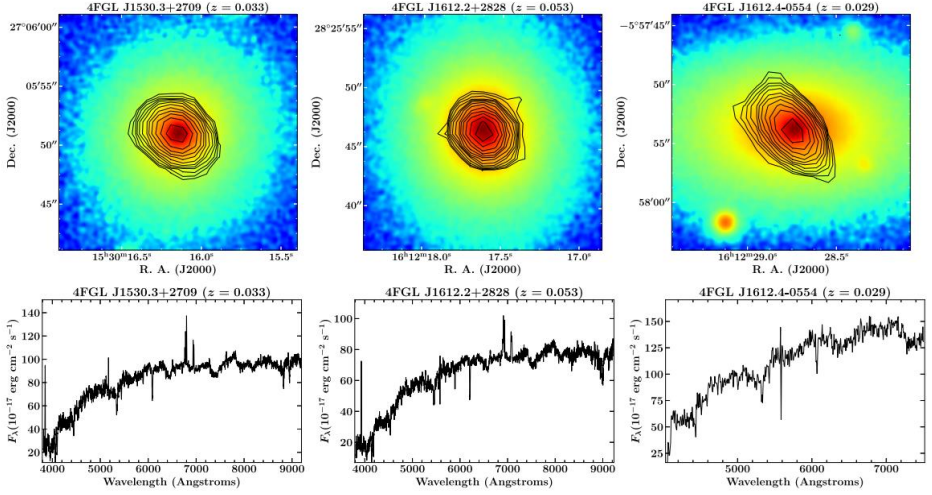




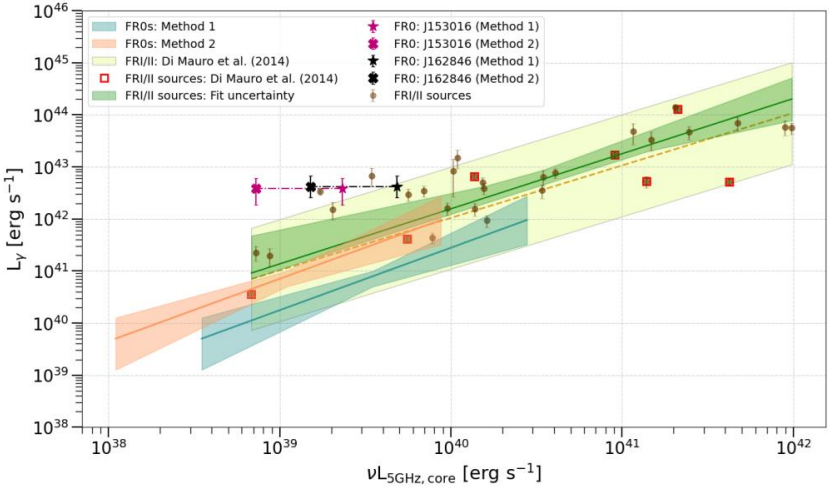


Paliya 2021

Khatiya et al. 2023



Pannikkote et al. 2023



Khatiya et al. 2023

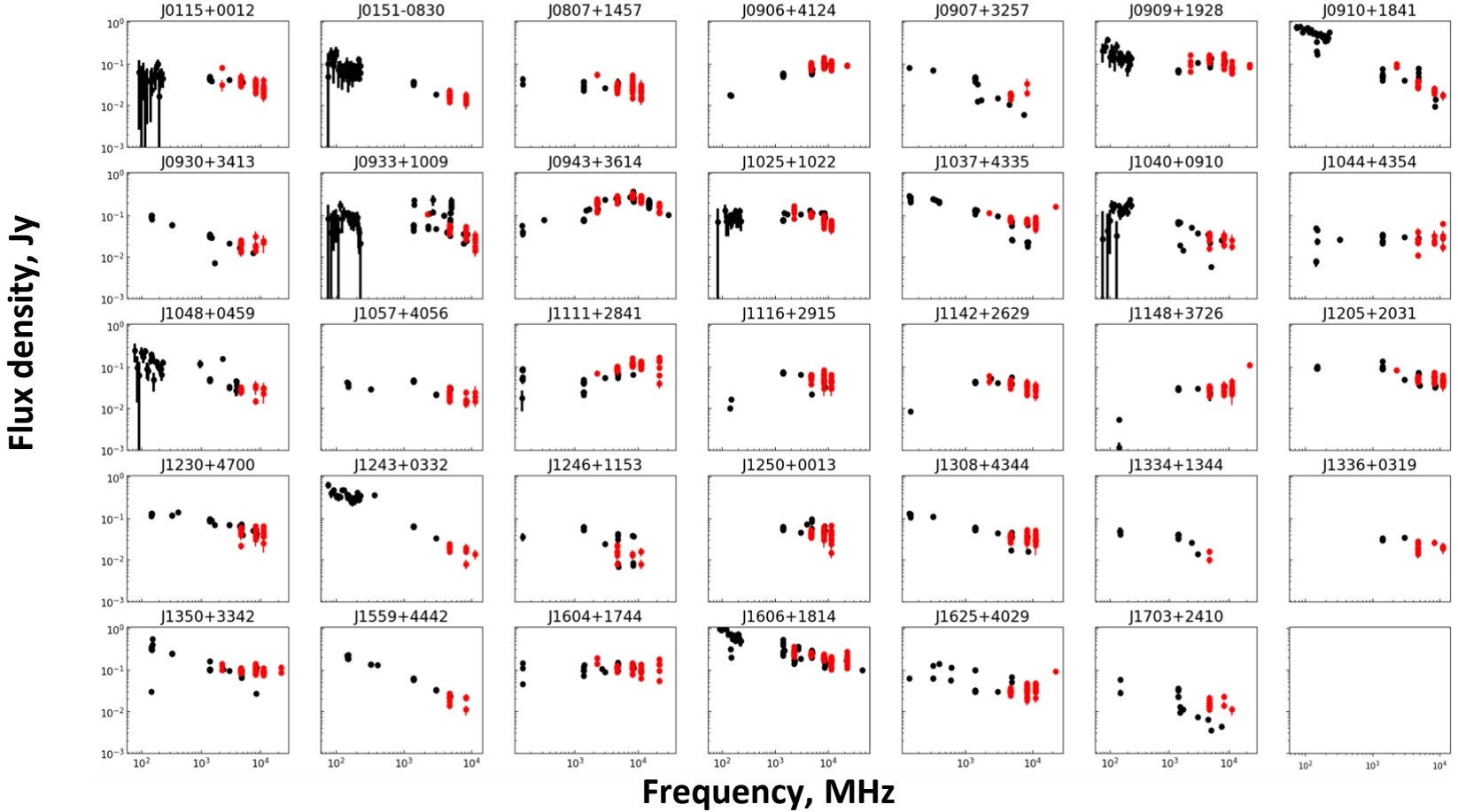
The sample and RATAN-600 observations

- 34 FR0CAT objects from Baldi et al. 2018, $S_{1.4}$ > 30 mJy
- z < 0.05, -09° < *Dec* < 47°, 01^h < *RA* < 17^h
- RATAN-600: 1.28, 2.25, 4.7, 8.2, 11.2, 14.4, 22.3 GHz
- Quasi-simultaneous spectra: the result of records averaging of the source passage at the 7-10 days time scale
- Observations: February 2020 up to the present day
- 7-20 observational epochs for each source

f_0, (GHz)	Δf_0, (GHz)	ΔF, (mJy/beam)	$HPBW_x$, sec	AR, arcsec
22.3	2.5	50	1.0	11
14.4	2.0	25	1.1	13
11.2	1.0	15	1.4	16
8.2	1.0	10	2.0	22
4.7	0.6	5	3.2	35
2.25	0.08	40	7.2	80
1.28	0.06	200	10	110

Radio spectra

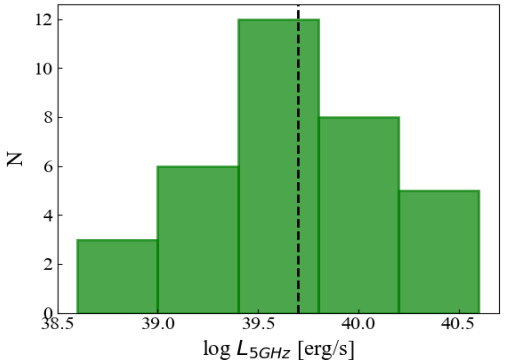
The RATAN-600 measurements - red points

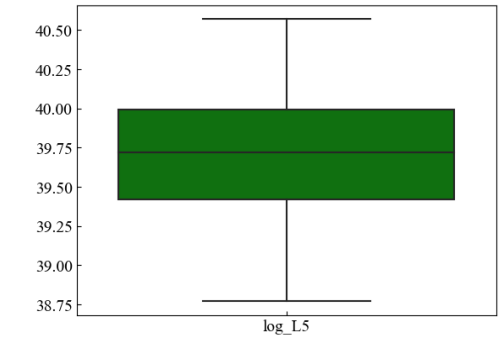


Radio properties

Radio luminosity

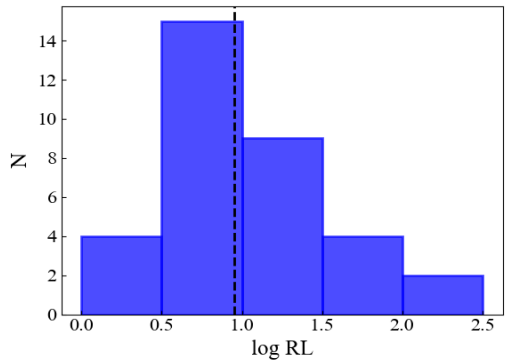
$$\nu L_\nu = 4\pi D_L^2 \nu S_\nu \left(1+z\right)^{-\alpha-1} [erg/s]$$

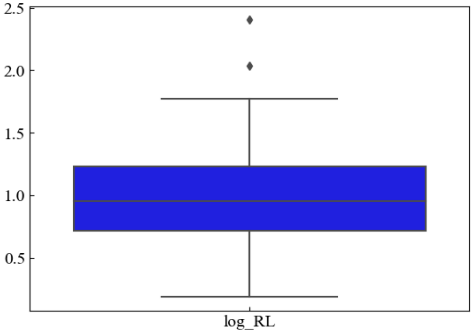




Radio loudness

$$RL = \frac{f_{5GHz}}{f_{4400A}}$$





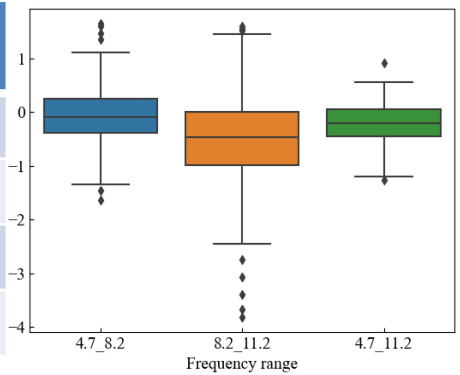
Quasi-simultaneous spectra

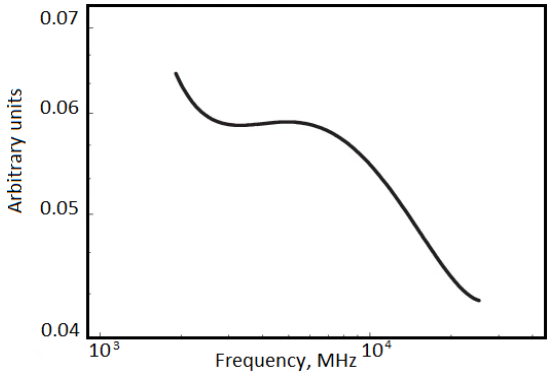
spectral type	%
steep	29
inverted	12
peaked	42
upturn	17

$$S(\nu_j) = \frac{1}{N}\sum_{k=1}^{N}\frac{f_k(\nu_j)}{f_k(1400)}$$

Spectral indices

$$\alpha = \frac{\log S_2 - \log S_1}{\log \nu_2 - \log \nu_1}$$

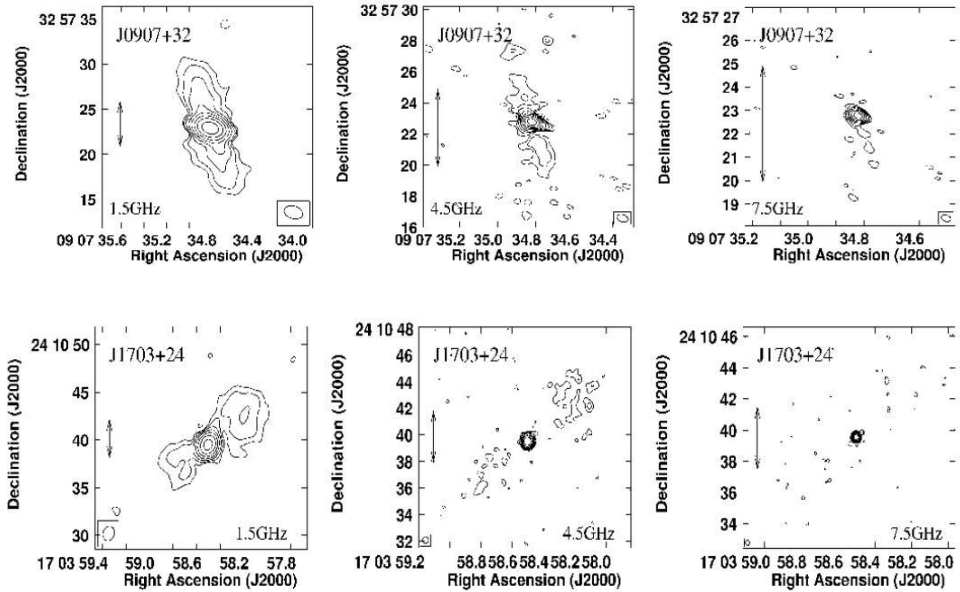




Mikhailov and Sotnikova 2021

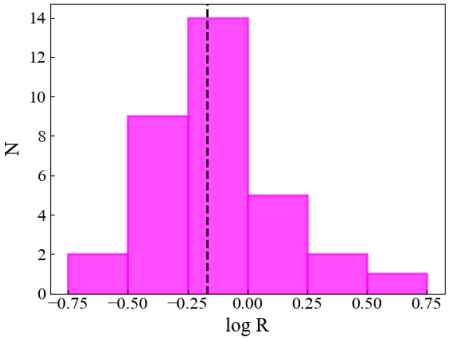
Core dominance parameter

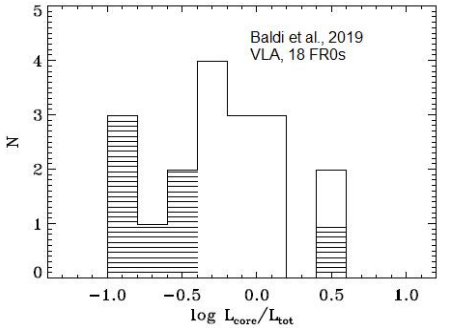
VLA (Baldi et al. 2019):
1.5, 4.5, 7.5 ГГц, angular resolution ~0.3 arcsec,
extended radio structures - 4/18 objects



Name	$\frac{S_{4.7,\text{R-600}}}{S_{4.5,\text{VLA}}}$	$\frac{S_{8.2,\text{R-600}}}{S_{7.5,\text{VLA}}}$
J0907+32*	1.89	3.38
J0930+34	1.25	1.52
J0943+36	1.11	1.19
J1025+10	0.90	0.85
J1040+09	0.88	1.06
J1230+47	0.75	0.72
J1703+24*	2.48	2.56

$$R = S_{8.2} / S_{1.4}$$





Mikhailov and Sotnikova 2021

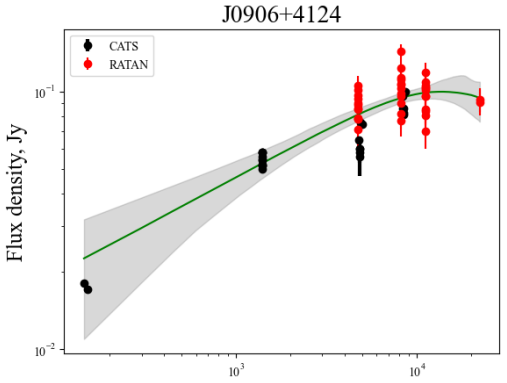
Peaked spectra modeling

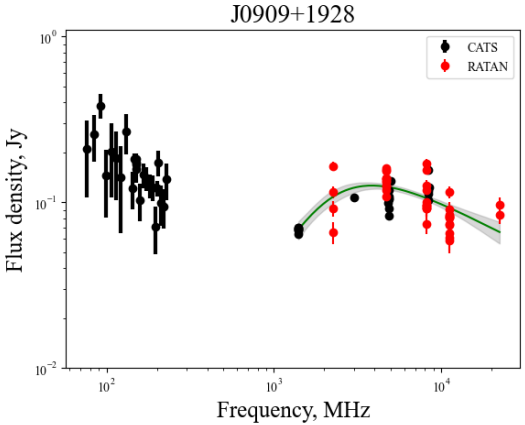
Synchrotron self-absorption (SSA) processes are preferred to free-free absorption (FFA) ones

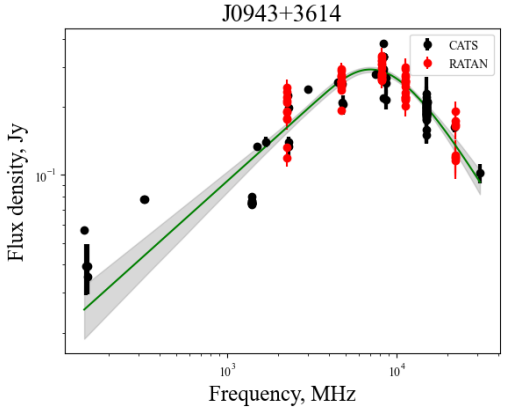
$$S_\nu = S_{\rm peak}\left(\frac{\nu}{\nu_{\rm peak}}\right)^{\alpha_{\rm thick}} \frac{1-\exp(-\tau_m(\nu/\nu_{\rm peak})^{\alpha_{\rm thin}-\alpha_{\rm thick}})}{1-\exp(-\tau_m)}$$

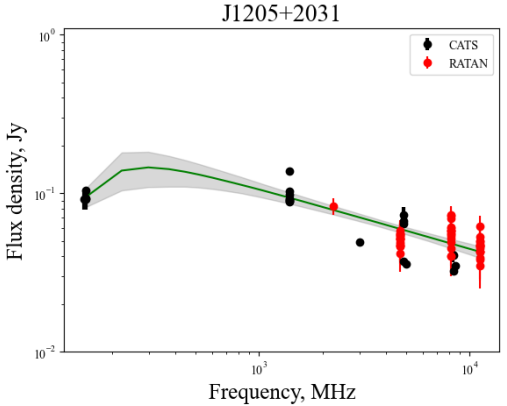
$$\tau_m \approx \frac{3}{2}\left(\sqrt{1-\frac{8\alpha_{\rm thin}}{3\alpha_{\rm thick}}}-1\right)$$

some examples









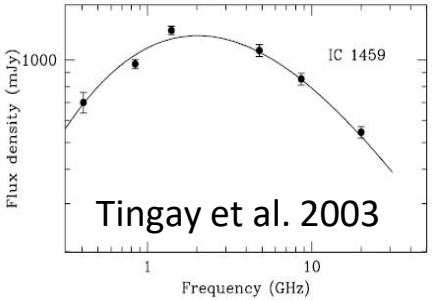
FR0 and GPS

Criteria: O'Dea+ 91, de Vries+ 97

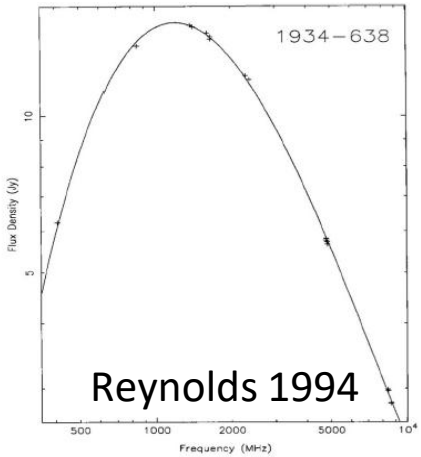
α_{below} = +0.5

α_{above} = -0.7

FWHM ≈ 1.2



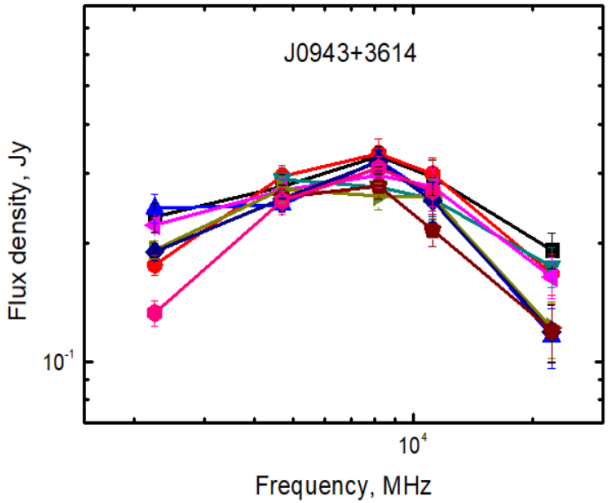
Tingay et al. 2003



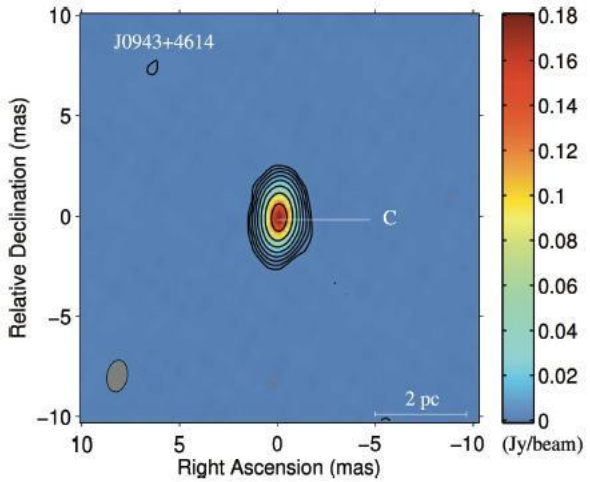
Reynolds 1994

3 candidates among of 34 FR0s

example

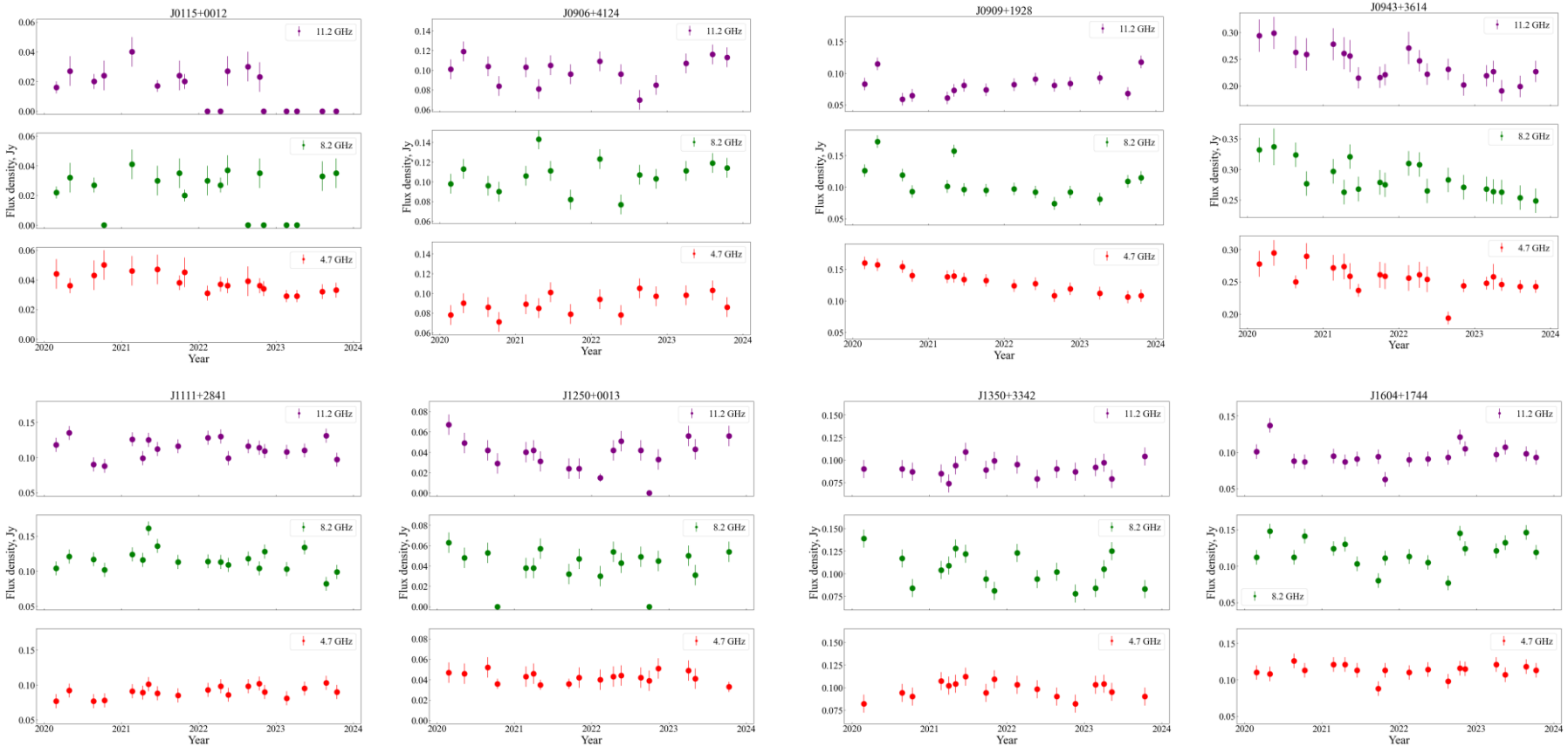


Relatively constant spectral shape, radio variability level ~10 %, Peak frequency is ~8 GHz



VLBI image at 8.3 GHz (Cheng & An 2018)

Light curves (examples)



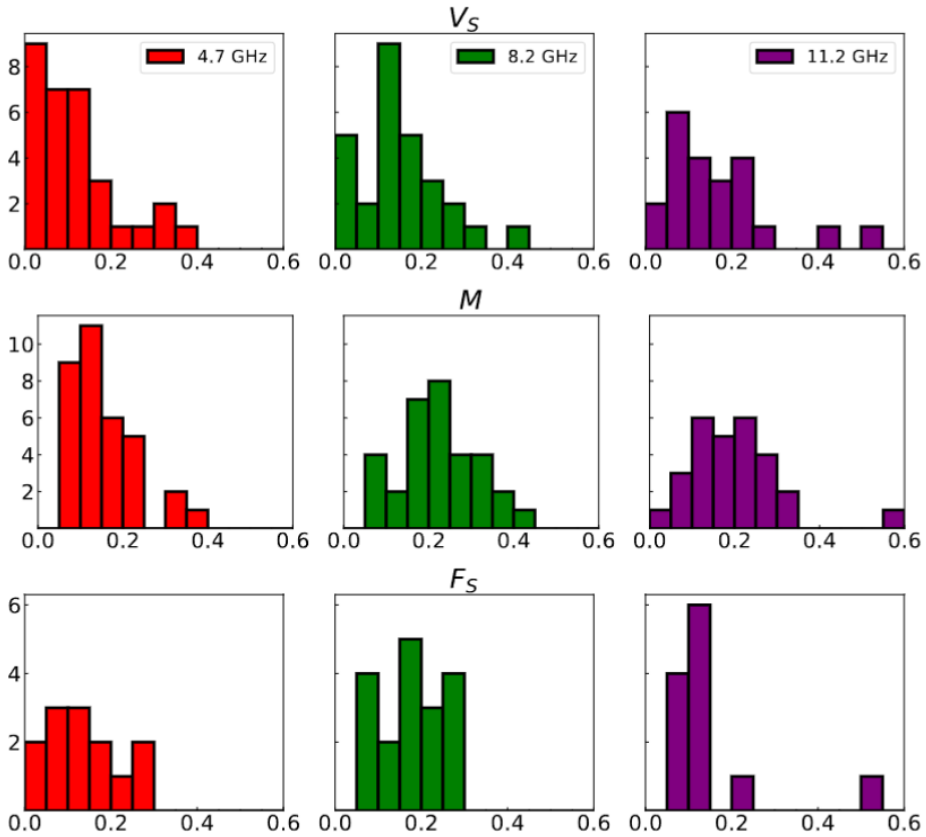
Radio variability level

$$V_S = \frac{(S_{\max} - \sigma_{S_{\max}}) - (S_{\min} + \sigma_{S_{\min}})}{(S_{\max} - \sigma_{S_{\max}}) + (S_{\min} + \sigma_{S_{\min}})}$$ Aller et al. 1992

$$M = \frac{\sigma_S}{\bar{S}}$$ Kraus et al. 2003

$$F_S = \sqrt{\frac{V^2 - \bar{\sigma}_{err}^2}{\bar{S}^2}}$$ Vaughan et al. 2003

frequency	4.7 GHz			8.2 GHz			11.2 GHz		
parameter	V_S	M	F	V_S	M	F	V_S	M	F
N	32	34	15	30	33	18	22	28	12
mean	13	16	12	16	23	18	18	20	16
sd	9	7	8	10	8	7	12	10	12
median	13	14	11	14	22	18	16	19	11
min	1	5	2	0	5	6	2	5	6
max	40	33	27	40	38	29	50	56	50



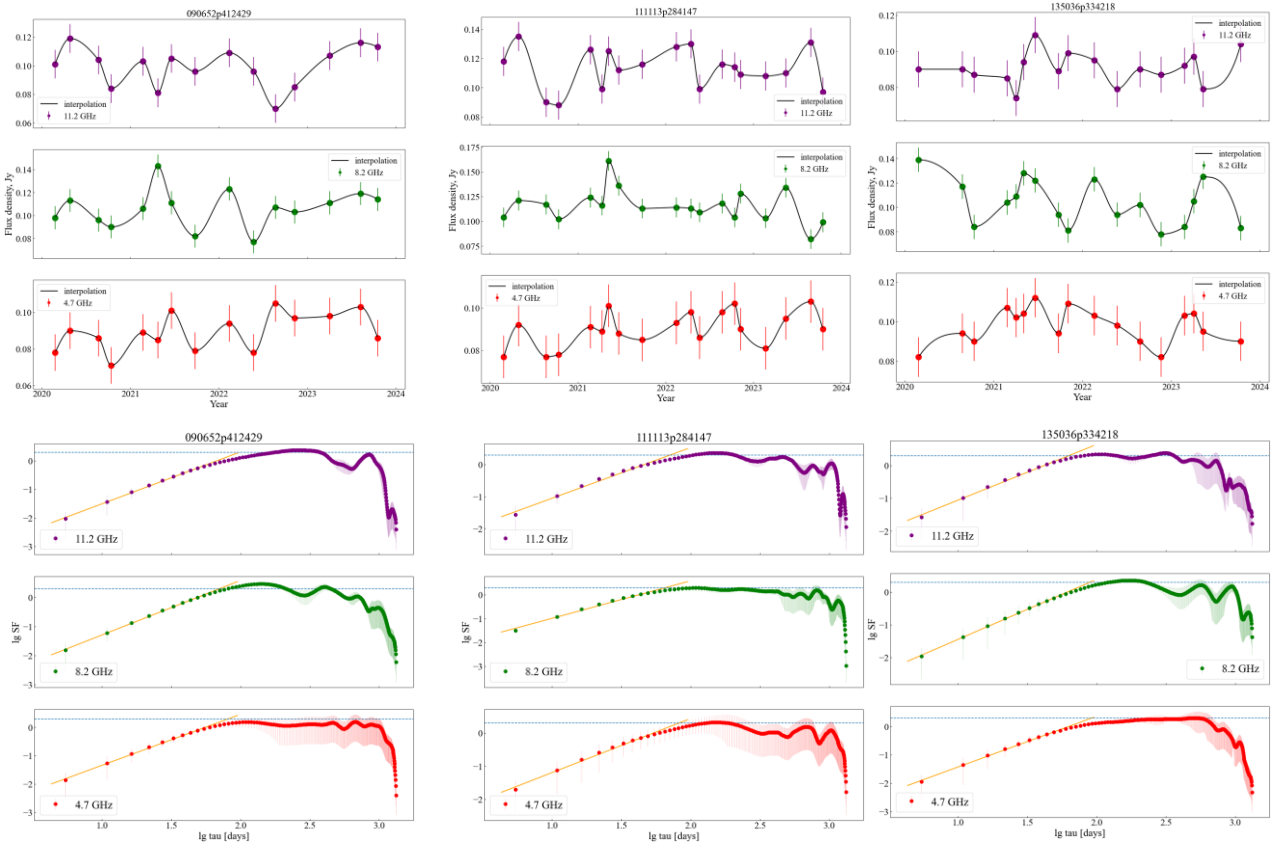
Structure functions (examples)

$$D_1(\tau) = \langle \{[f(t) - f(t+\tau)]\}^2 \rangle$$

$$b = d \log D_1 / d \log \tau$$

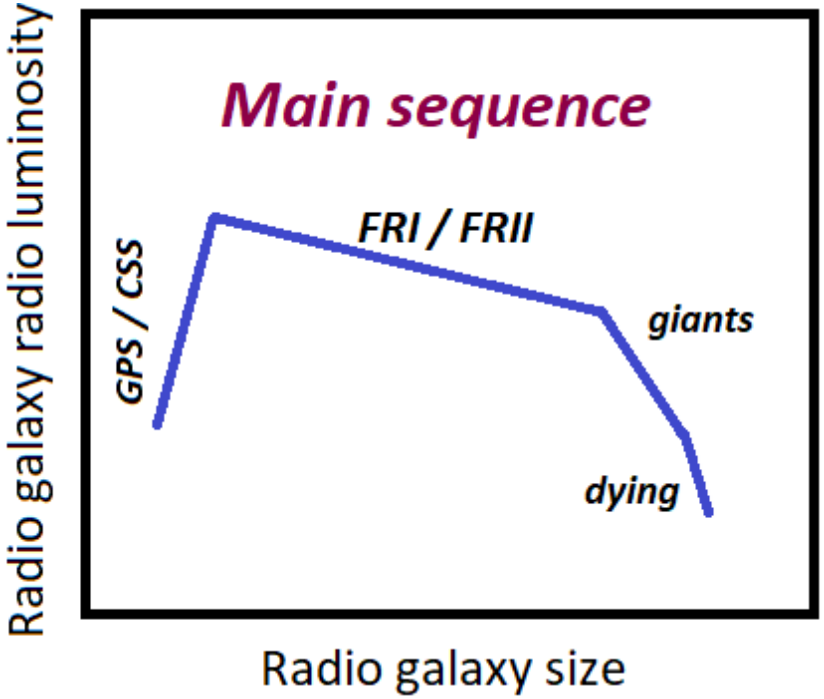
Simonetti et al. 1985,
Hughes et al. 1992

source	frequency					
	4.7 GHz		8.2 GHz		11.2 GHz	
	lg τ	b	lg τ	b	lg τ	b
J0906+4124	2.04	1.80	2.13	1.87	2.41	1.82
J0909+1928	2.93	1.84	2.27	1.61	2.15	1.69
J0943+3614	2.10	1.82	2.32	1.48	2.21	1.80
J1025+1022	2.89	1.63	2.38	1.55	2.33	1.67
J1037+4335	2.10	1.74	2.66	1.78	2.17	1.89
J1111+2841	2.17	1.63	2.01	1.57	2.17	1.58
J1116+2915	2.15	1.72	2.13	1.81	2.23	1.89
J1205+2031	2.27	1.78	2.24	1.75	2.01	1.66
J1250+0013	2.21	1.68	1.94	1.66	2.25	1.81
J1308+4344	2.04	1.68	1.91	1.56	2.32	1.66
J1350+3342	2.38	1.79	2.23	1.83	1.99	1.70
J1604+1744	2.06	1.70	2.12	1.65	2.13	1.66
J1606+1814	2.29	1.66	2.38	1.69	2.36	1.65
J1625+4029	2.27	1.54	2.51	1.68	2.44	1.68



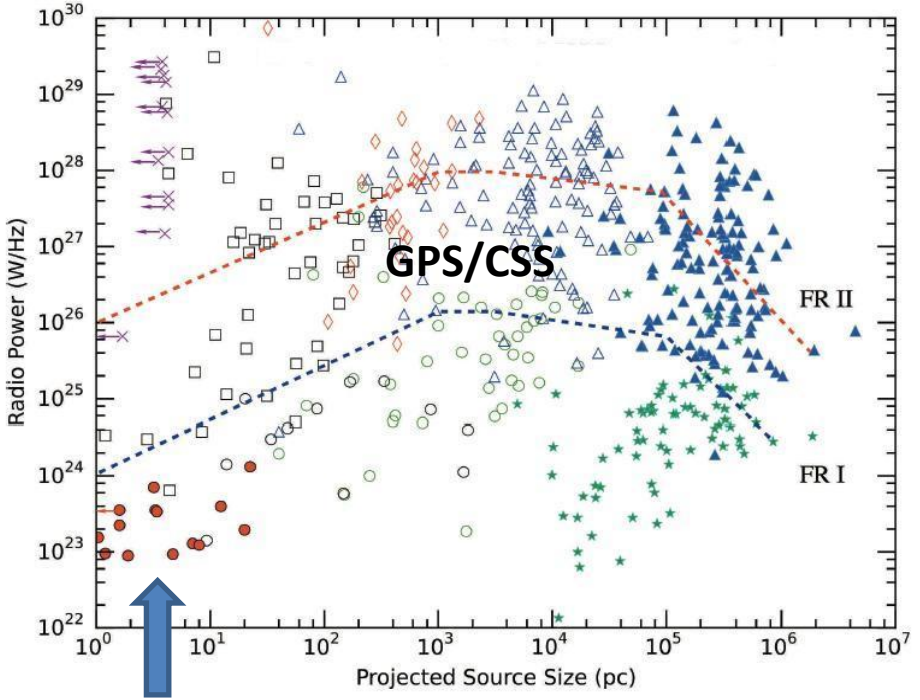
The FR0 nature

- Young radio galaxies evolving in FRI?
- Short-time accretion stages?
- Low-spin SMBHs?



An & Baan 2012

?



FR0

Cheng & An 2018

SUMMARY

- Multifrequency catalog of FR0 measurements at 2-22 GHz, 2020-2024
- Moderate radio luminosity, deficit of extended radio emission was confirmed
- Flat spectrum, contribution of several compact components
- Low luminosity GPS candidates (~10%)
- Characteristic variability level doesn’t exceed 20% at the time scale of ~4 yrs
- Significant contribution to background radiation (from radio to gamma)

QUESTIONS

- Properties of variability at long time scales
- Relationship with other classes of compact (GPS/CSS) and extended radio sources (FRI/FRII)
- Low-contrast extended radio structures