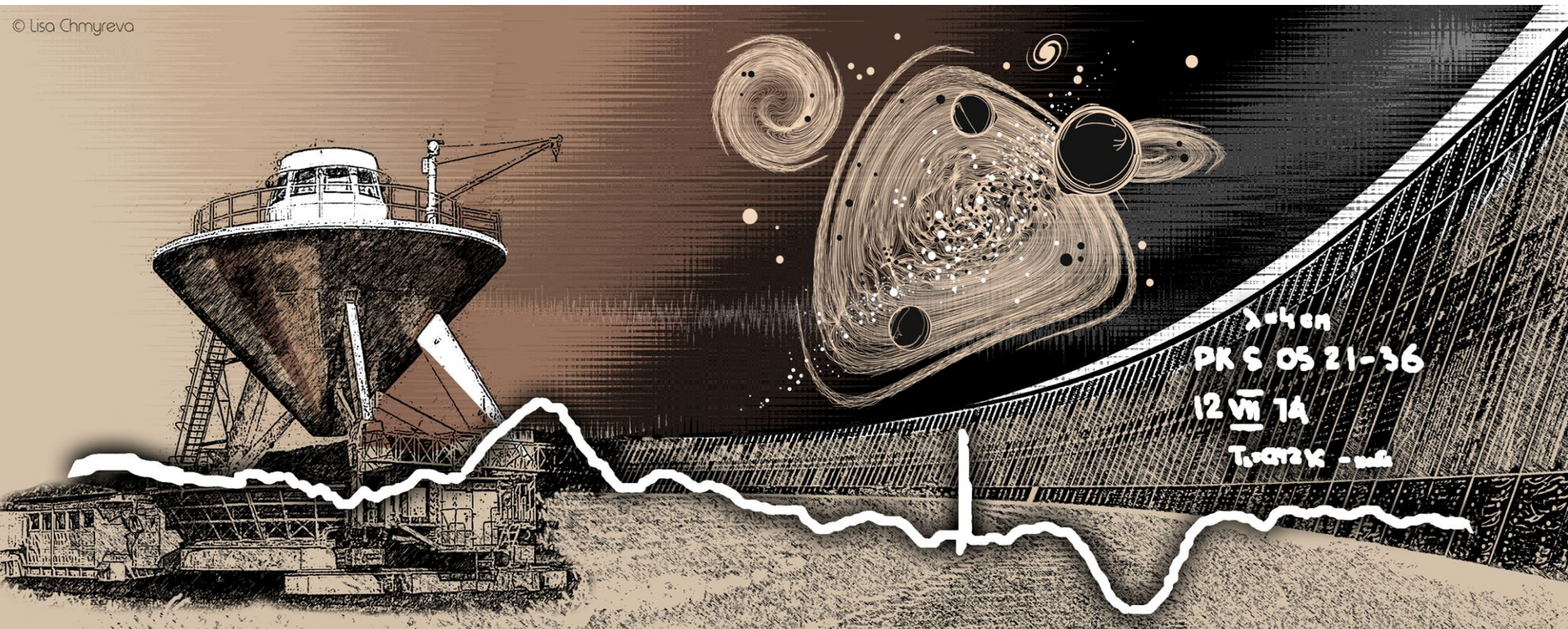


Broadband radio properties of the FR0 radio galaxies

© Lisa Chmyreva



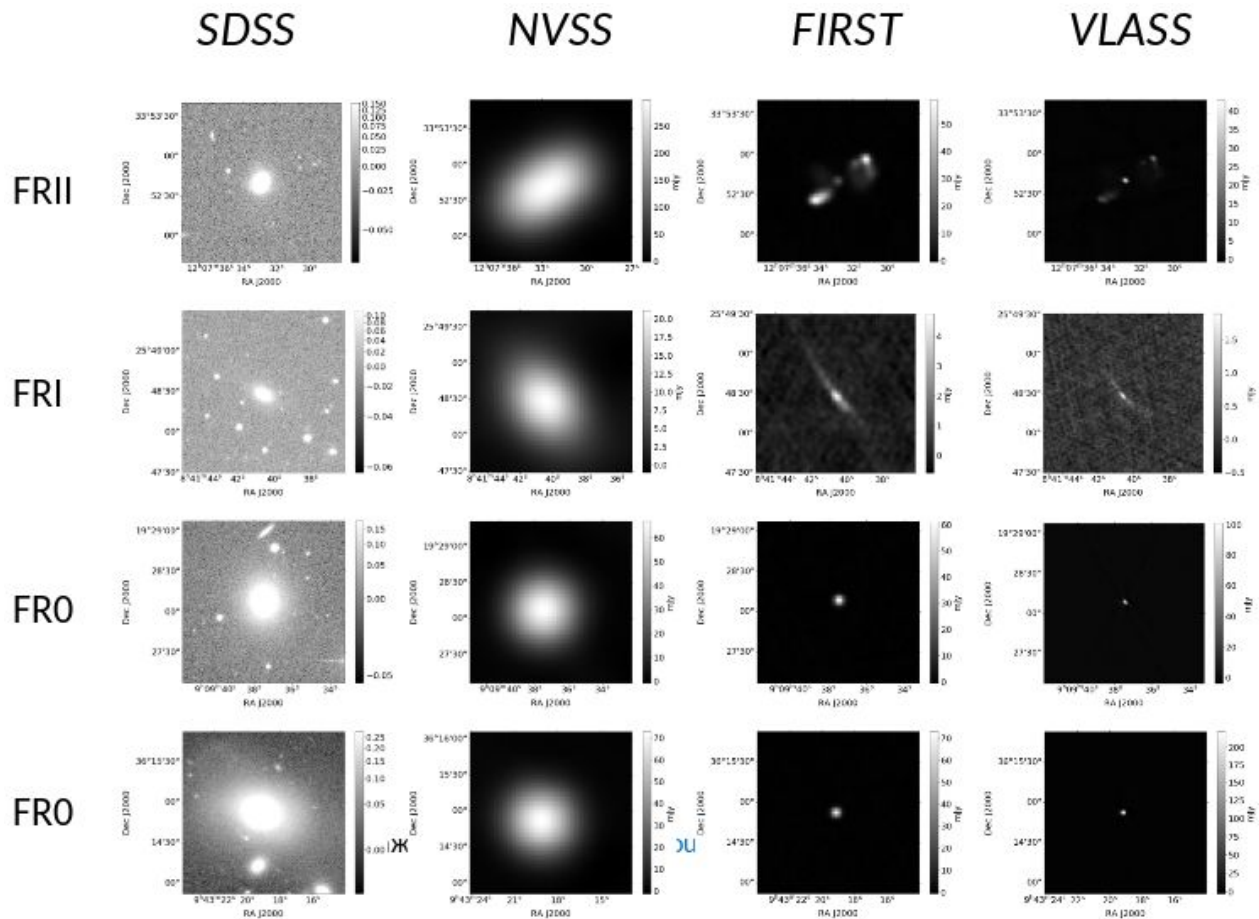
Mikhailov Alexander¹, Sotnikova Yulia¹, Stolyarov Vladislav^{1,2}

¹SAO RAS, ²University of Cambridge

17 October 2024

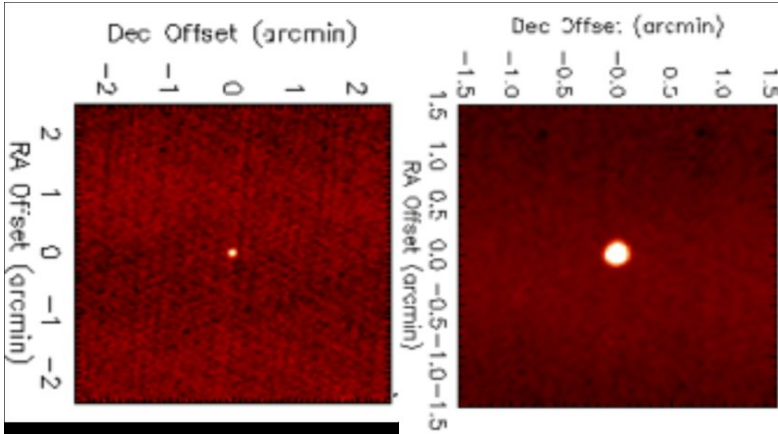
Active galaxies at different scales and wavelengths-2024

Radio galaxies in surveys



FROs in the nearby Universe

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



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

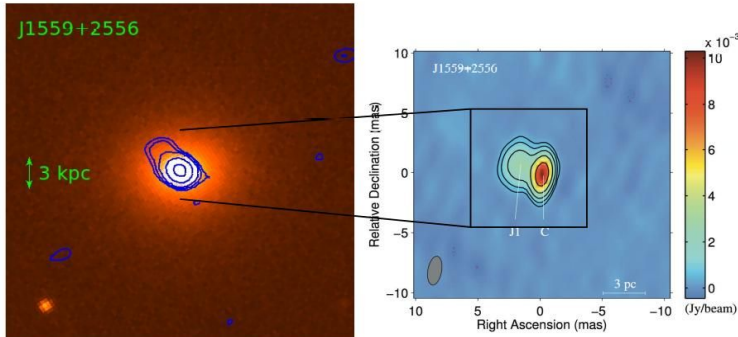


“FRO galaxies”

linear size < 3 kpc

FRO and FRI: space density 5:1

similar properties of host galaxies



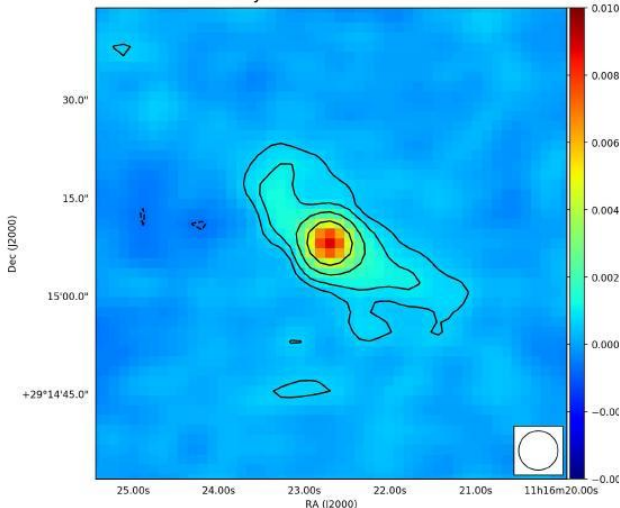
FROs from LoTSS (Capetti et al. 2020)

Detection 66/66

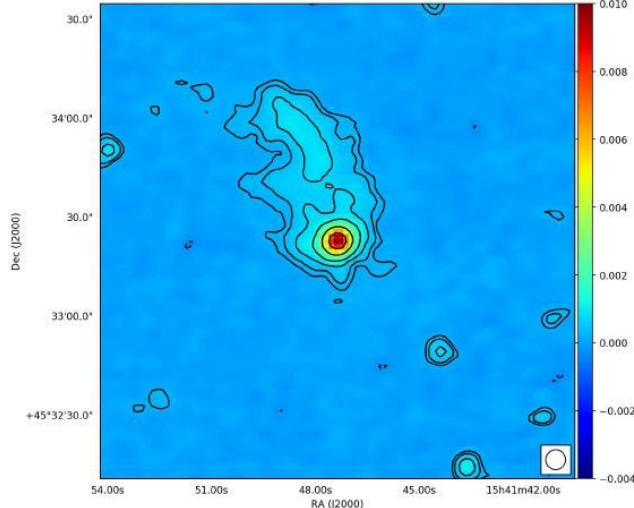
54 point-like sources (linear size < 3-6 kpc)

12 extended sources (15-50 kpc)

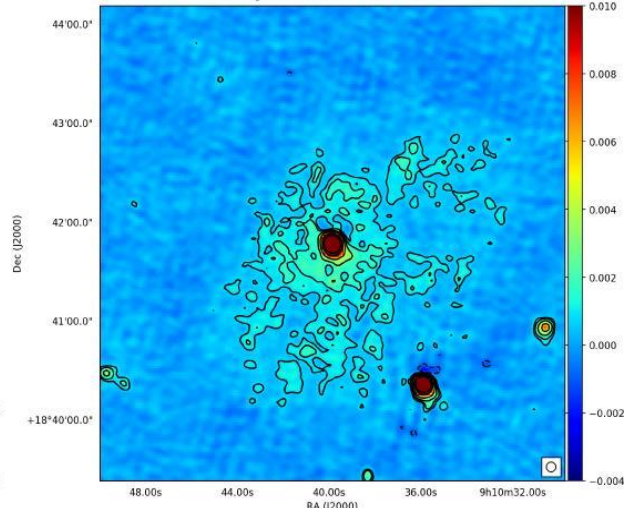
SDSSJ111622.70+291508.2



SDSSJ154147.28+453321.7



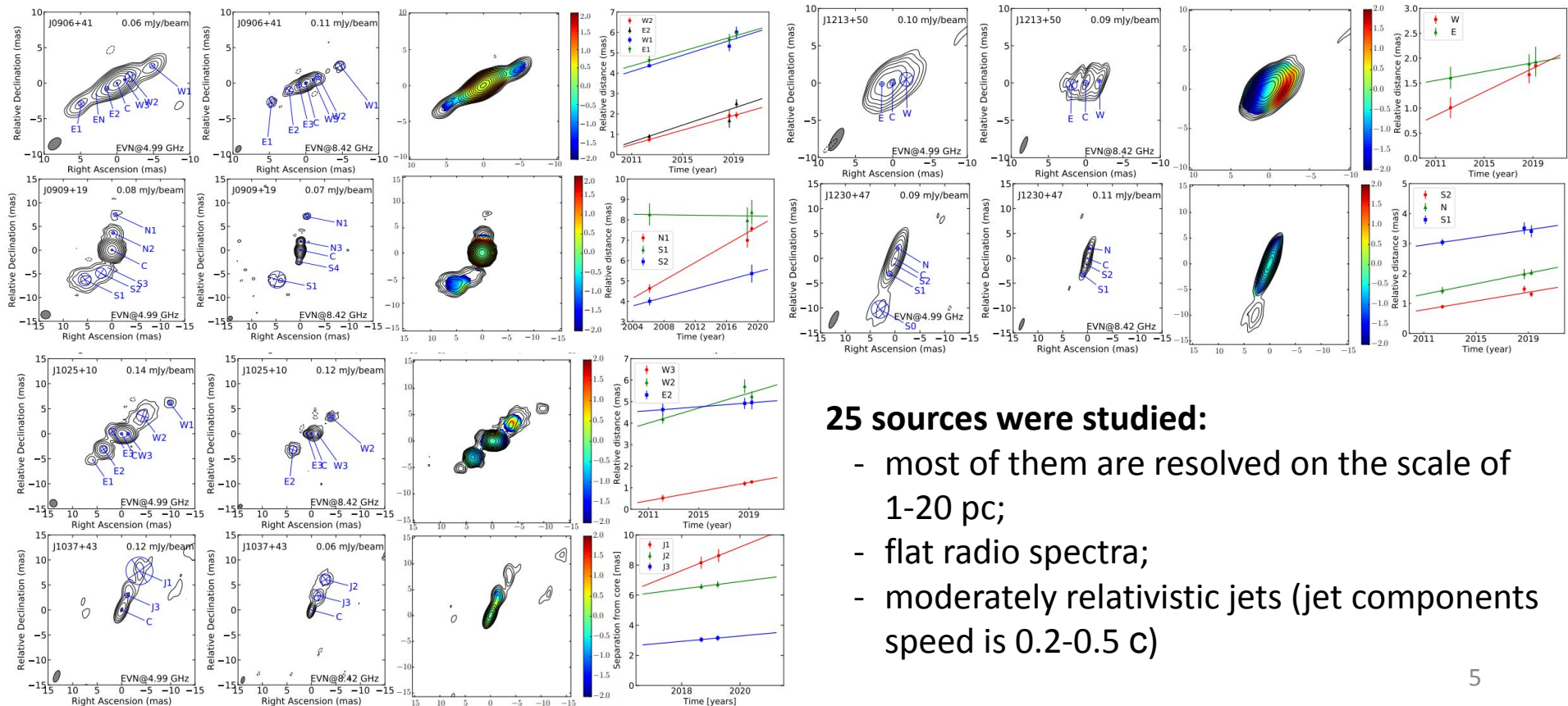
SDSSJ091039.92+184147.6



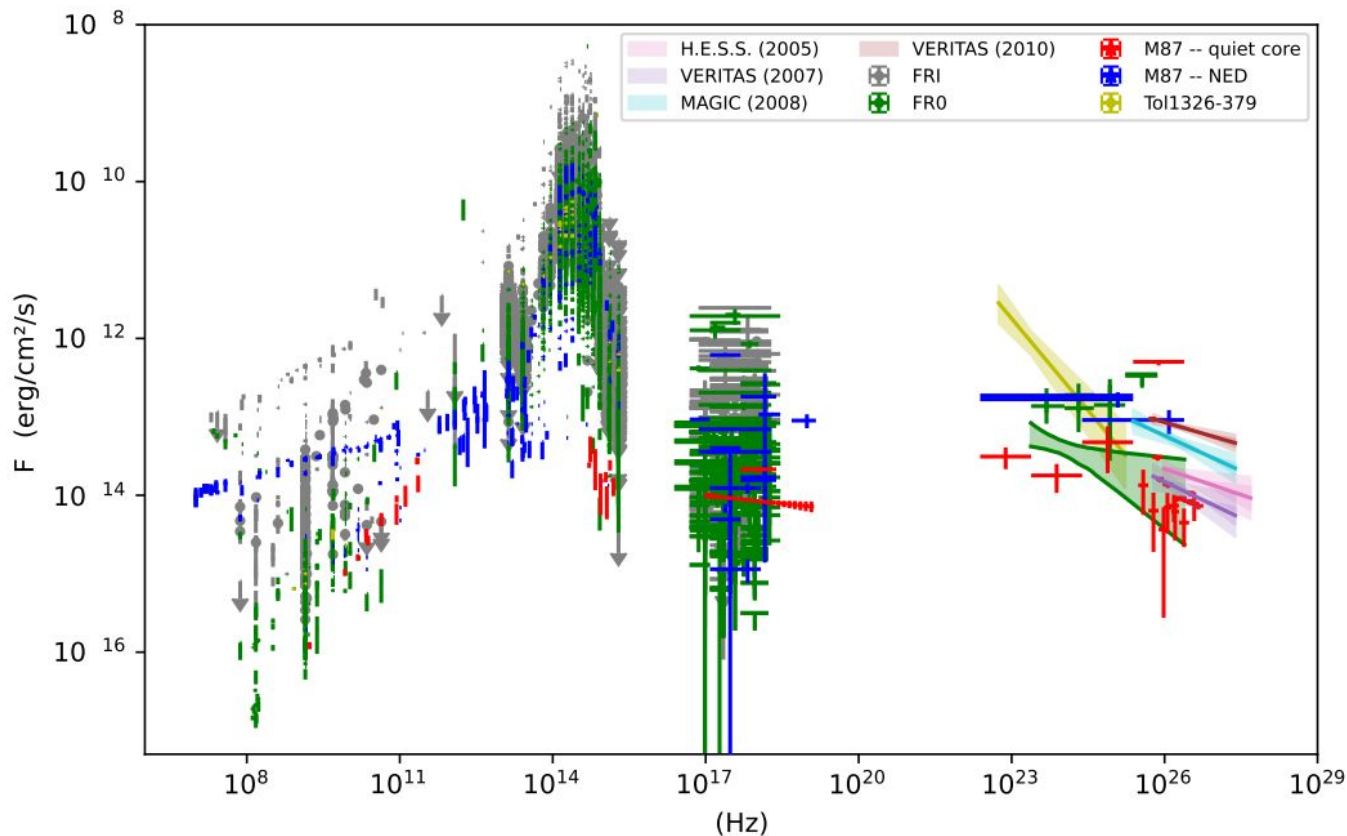
LOFAR observations, 150 M Γ μ
angular resolution 6''

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

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

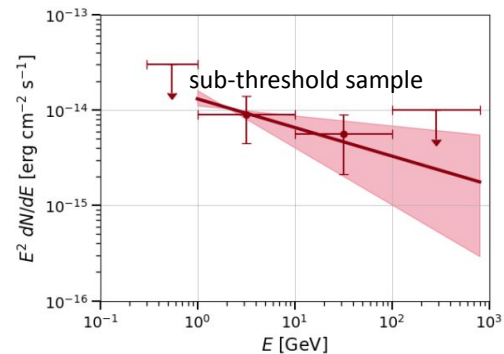
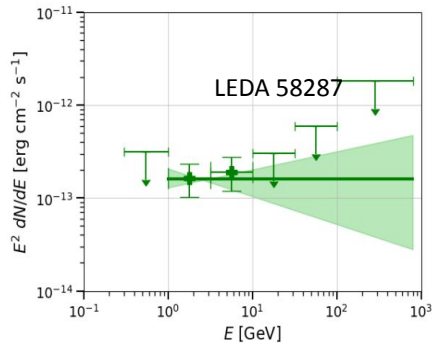
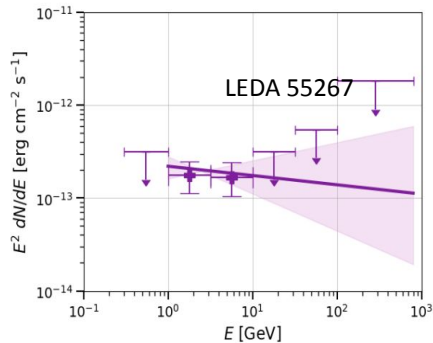
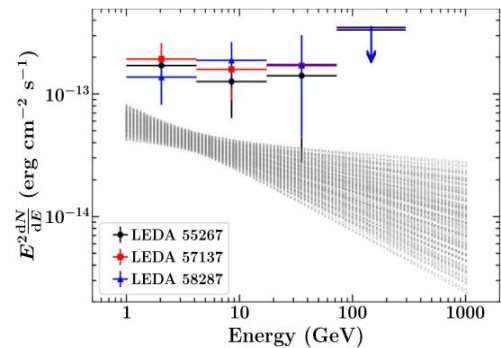


SEDs

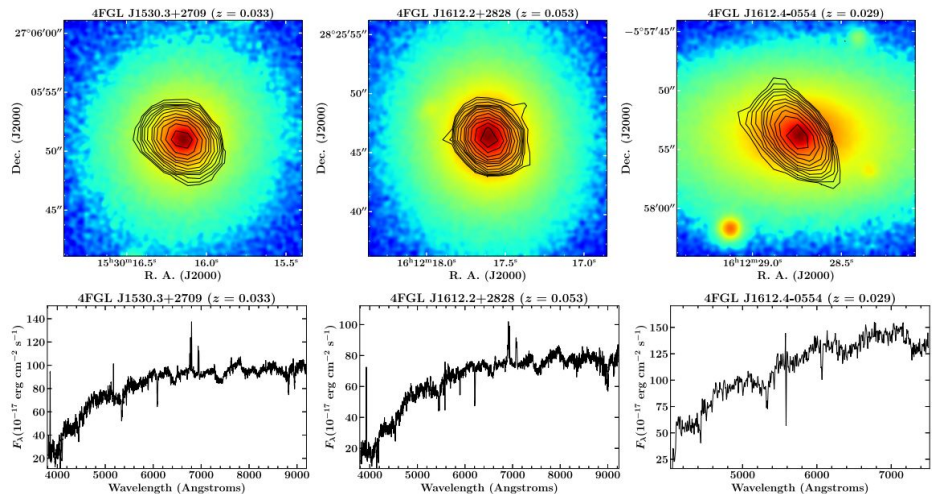


Broad-band spectrum of FR0 almost coincides with spectrum of core M87 (FRI) in a quiet state

γ -ray FROs

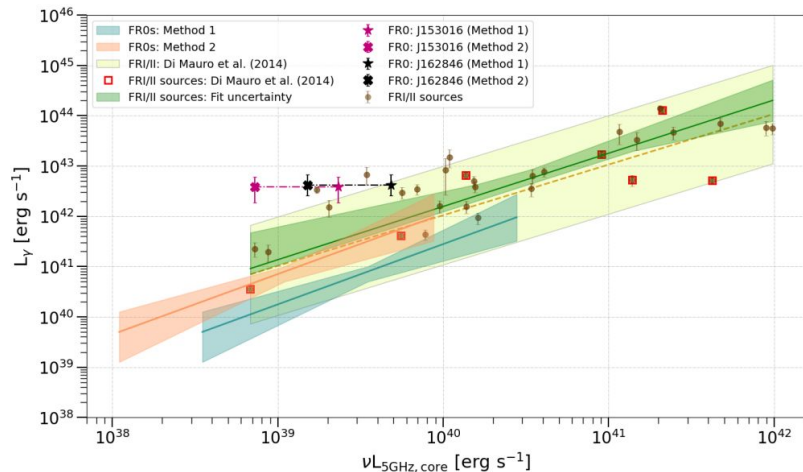


Paliya 2021



Pannikkote et al. 2023

Khatiya et al. 2023



Khatiya et al. 2023

The sample and RATAN-600 observations

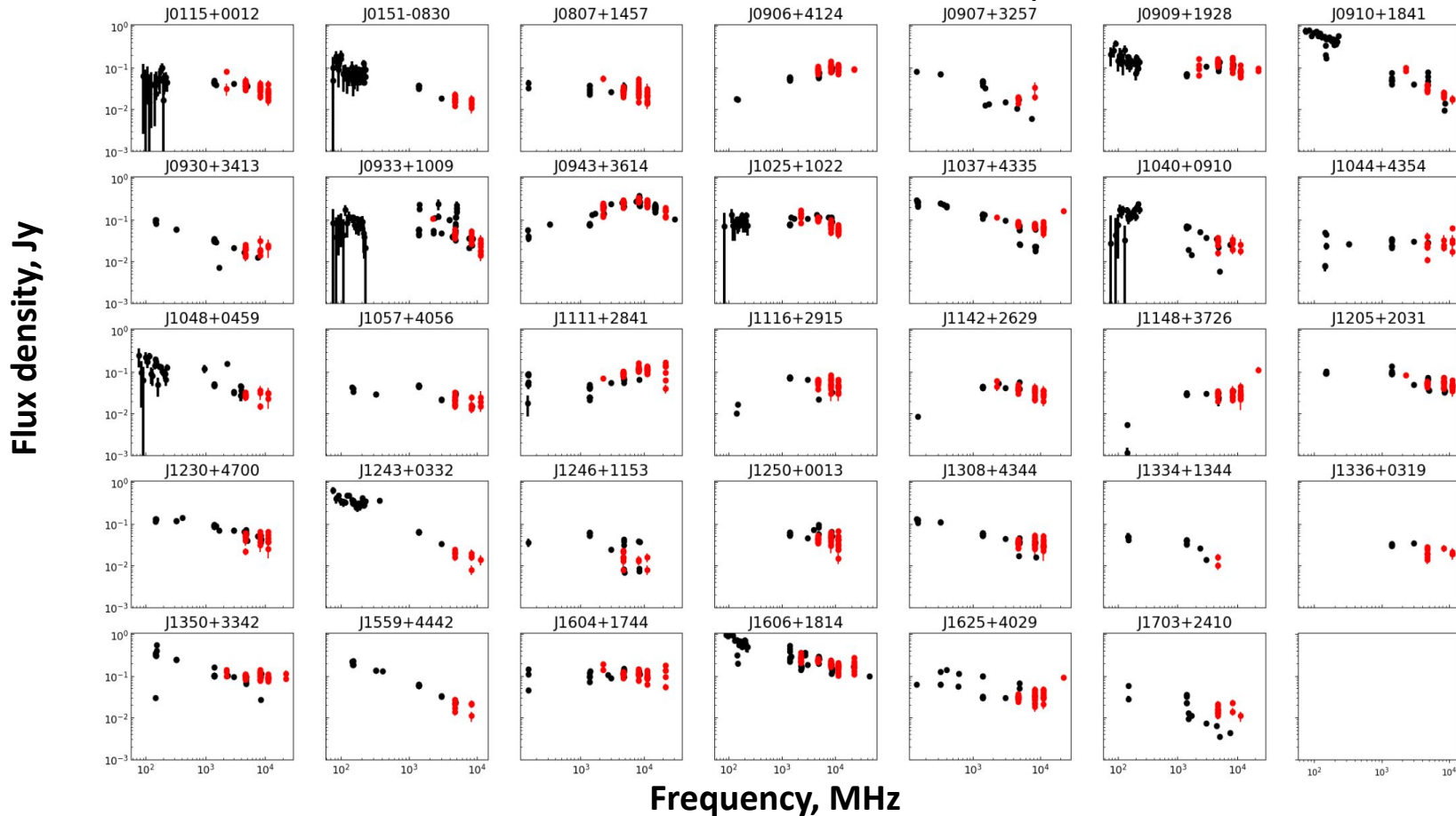
- 34 FROCAT objects from Baldi et al. 2018, $S_{1.4} > 30$ mJy
- $z < 0.05$, $-09^\circ < Dec < 47^\circ$, $01^h < RA < 17^h$
- RATAN-600: 1.28, 2.25, 4.7, 8.2, 11.2, 14.4, 22.3 GHz
- Quasi-simultaneous spectra: the result of records averaging of the source passage at the 7-10 days time scale
- Observations: 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

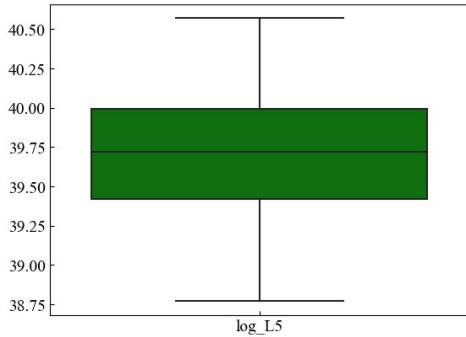
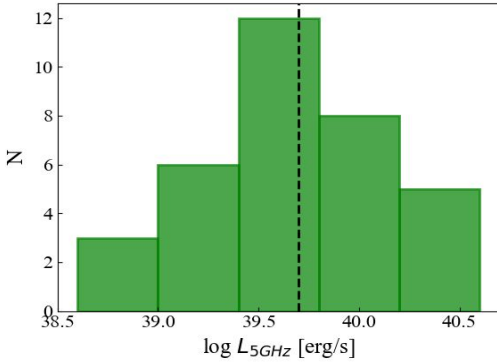
The RATAN-600 measurements - red points



Radio properties

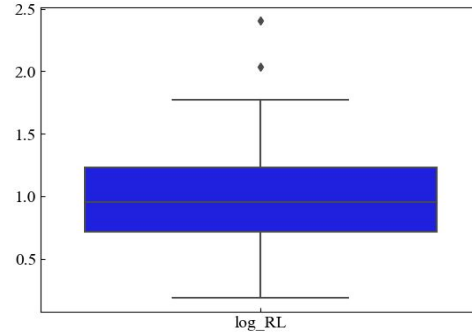
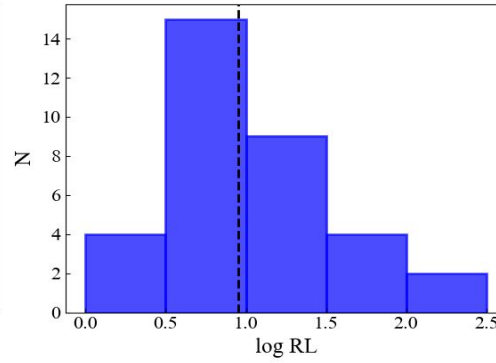
Radio luminosity

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



Radio loudness

$$RL = \frac{f_{5\text{GHz}}}{f_{4400\text{Å}}}$$



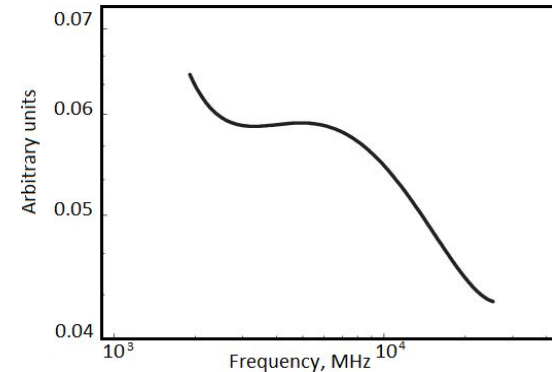
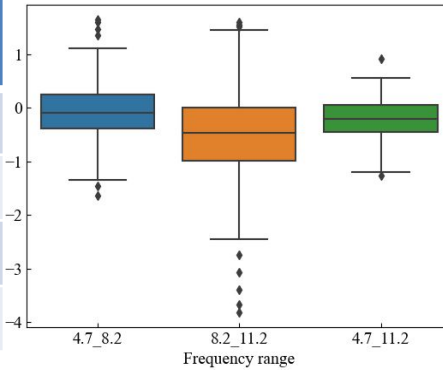
Quasi-simultaneous spectra

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

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



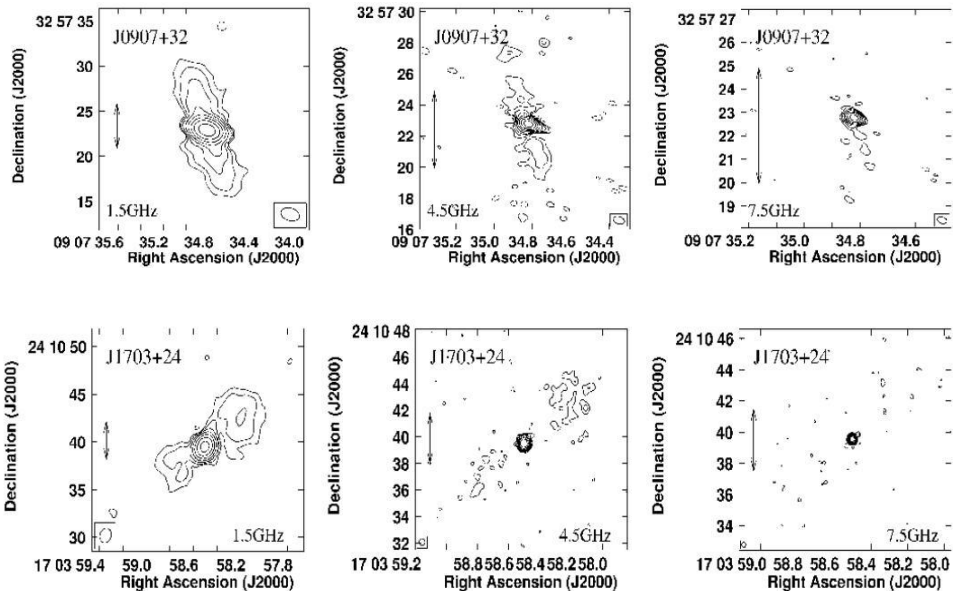
Core dominance parameter

VLA (Baldi et al. 2019):

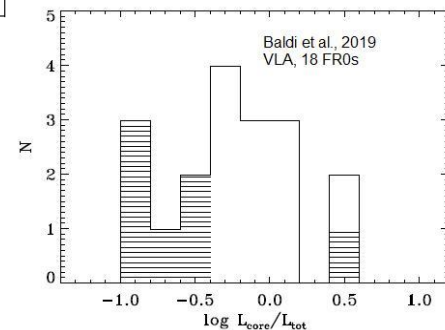
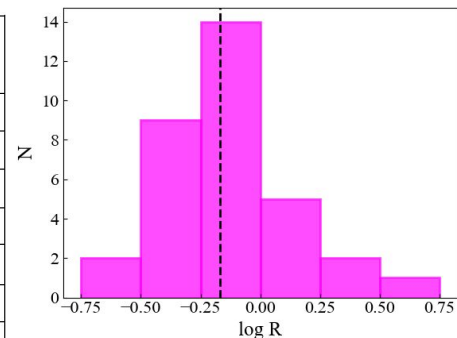
1.5, 4.5, 7.5 GHz, angular resolution ~ 0.3 arcsec,
extended radio structures - 4/18 objects

Mikhailov and Sotnikova 2021

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



Name	$\frac{S_{4.7, R-600}}{S_{4.5, VLA}}$	$\frac{S_{8.2, R-600}}{S_{7.5, VLA}}$
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



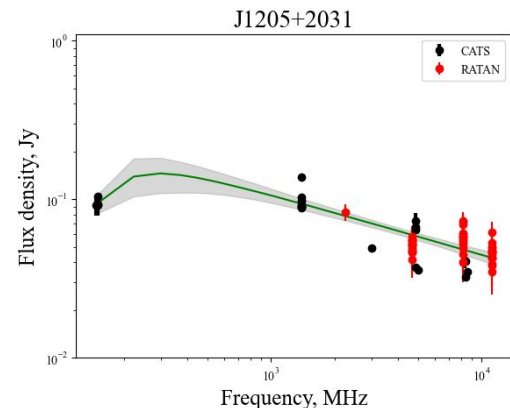
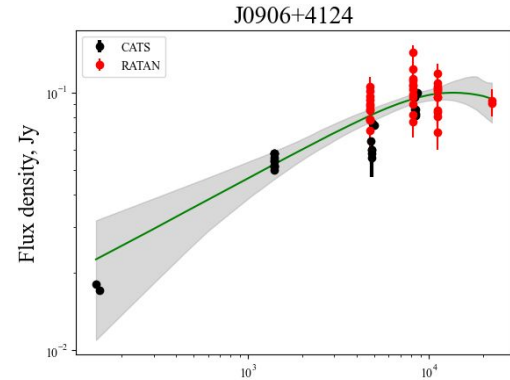
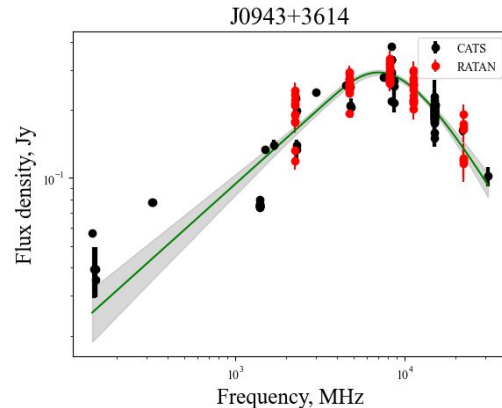
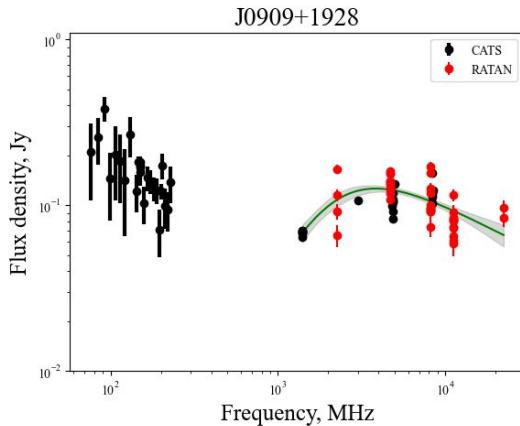
Peaked spectra modeling

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

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

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

some examples



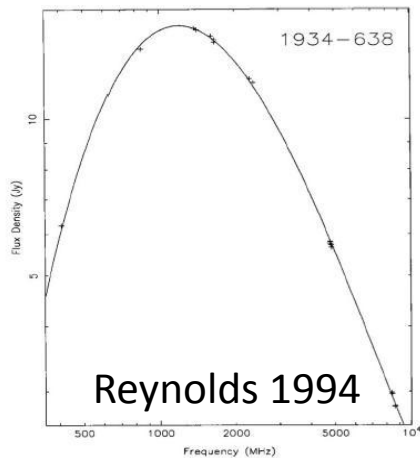
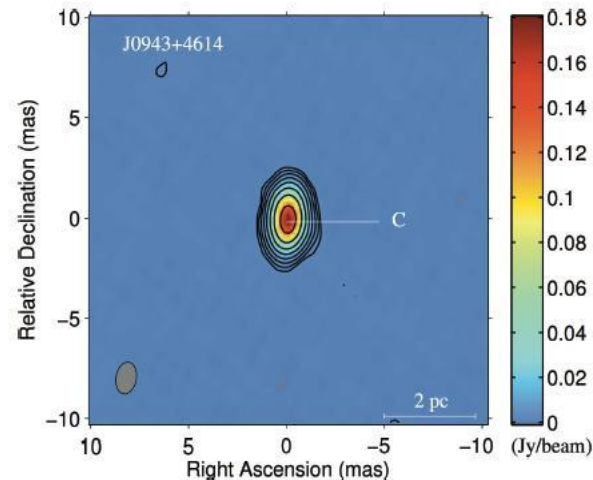
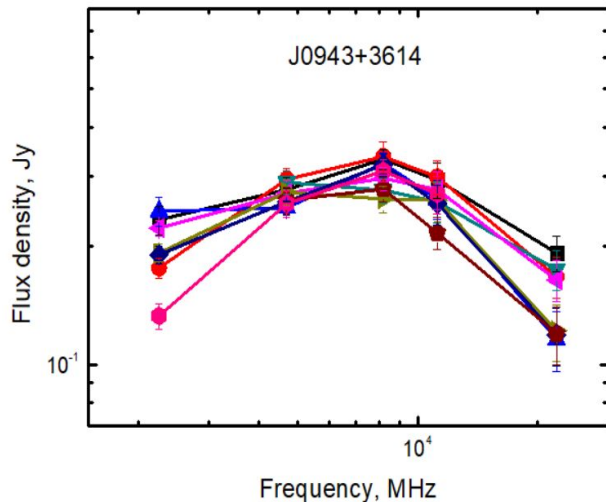
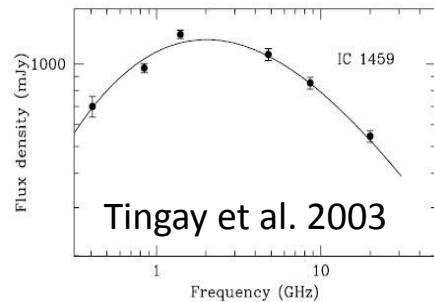
FR0 and GPS

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

$$\alpha_{\text{below}} = +0.5$$
$$\alpha_{\text{above}} = -0.7$$
$$\text{FWHM} \approx 1.2$$

3 candidates among of 34 FR0s

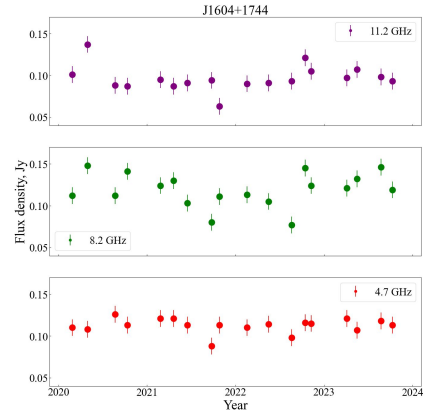
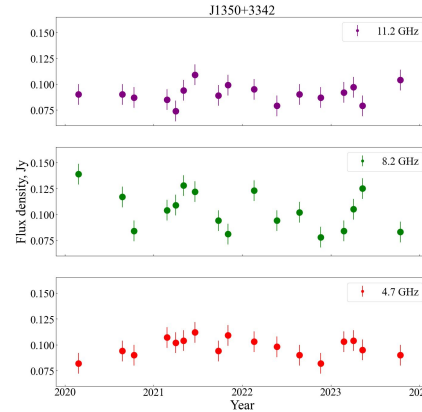
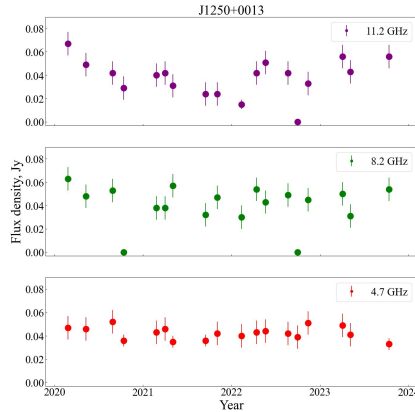
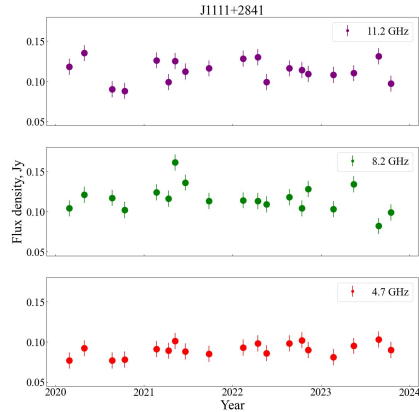
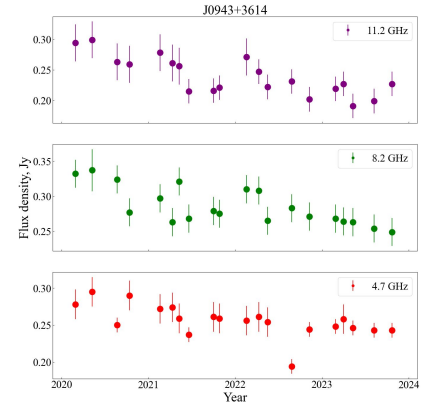
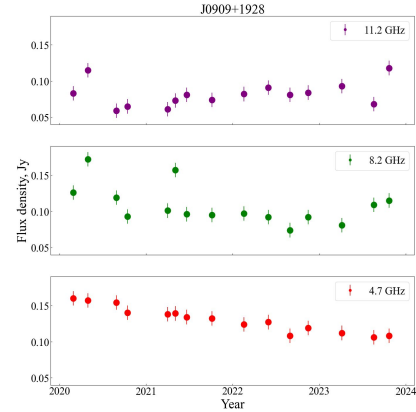
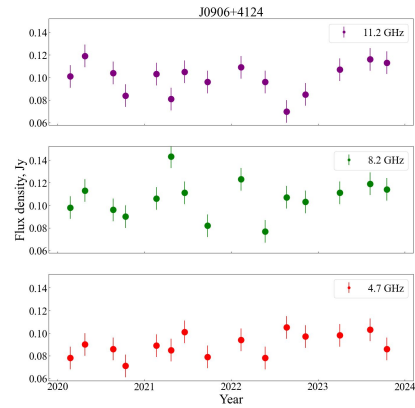
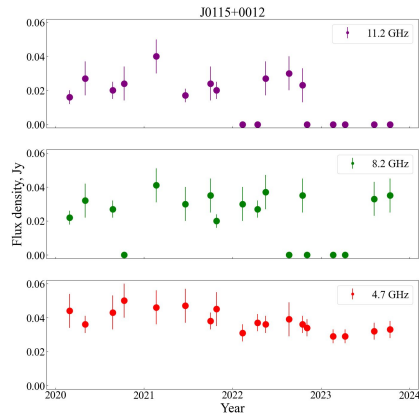
example



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

VLBI image at 8.3 GHz
(Cheng & An 2018)

Light curves (examples)



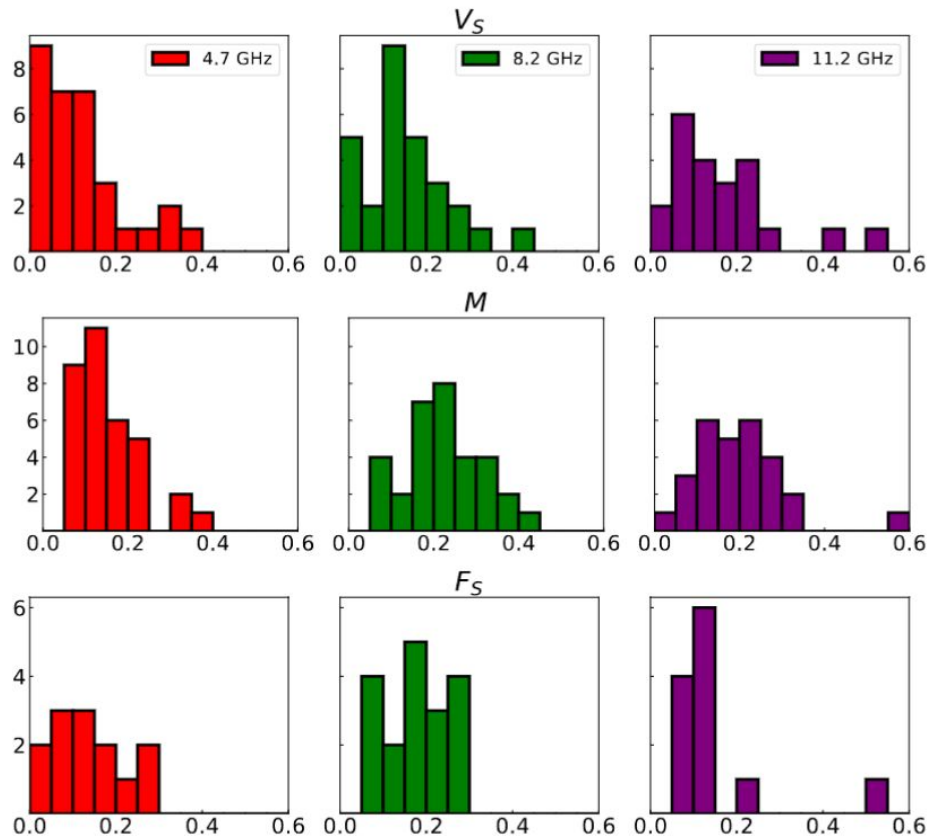
Radio variability level

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

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

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

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



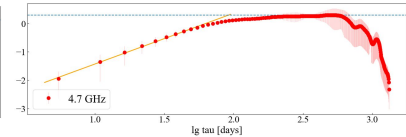
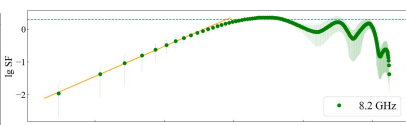
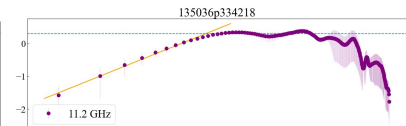
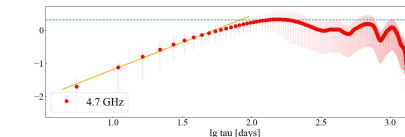
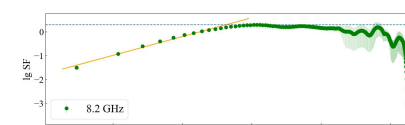
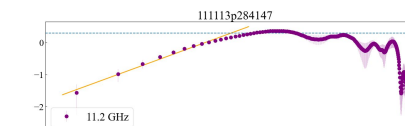
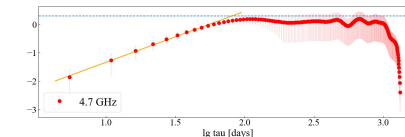
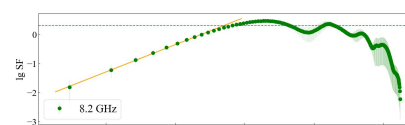
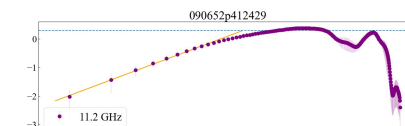
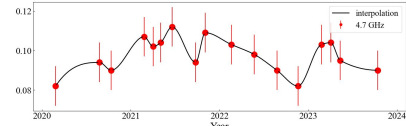
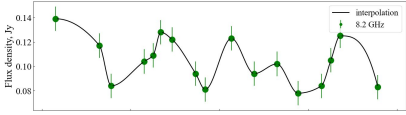
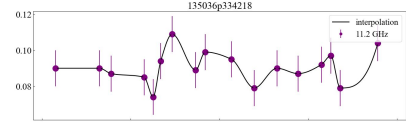
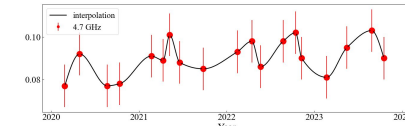
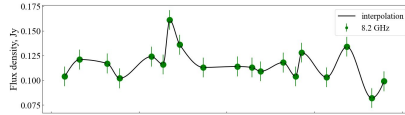
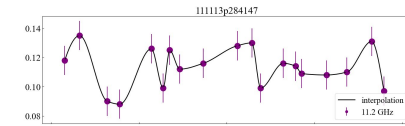
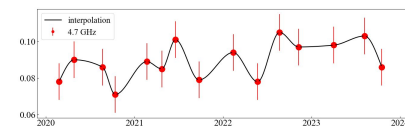
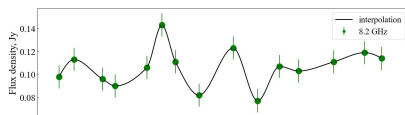
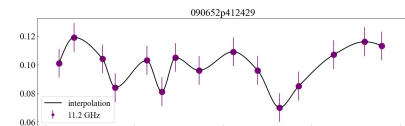
Structure functions (examples)

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

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

Simonetti et al. 1985,
Hughes et al. 1992

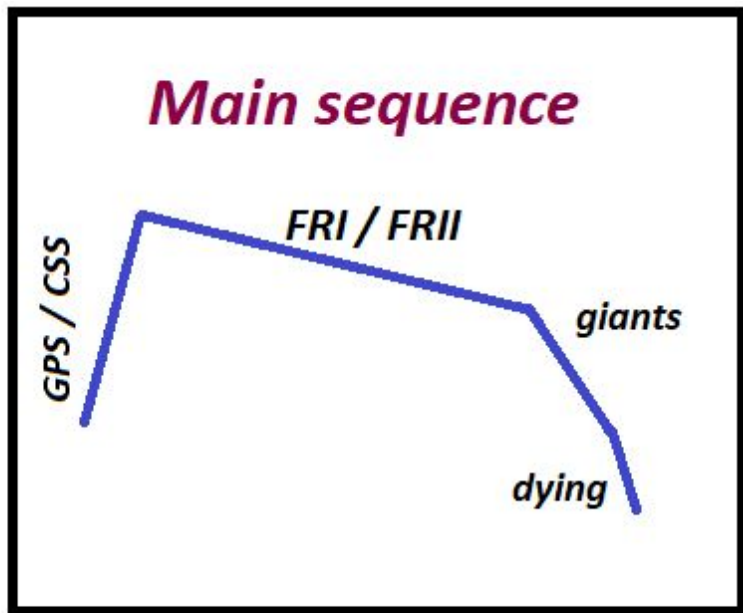
source	frequency					
	4.7 GHz		8.2 GHz		11.2 GHz	
	lg τ	b	lg τ	b	lg τ	b
J0906+4124	2.04	1.80	2.13	1.87	2.41	1.82
J0909+1928	2.93	1.84	2.27	1.61	2.15	1.69
J0943+3614	2.10	1.82	2.32	1.48	2.21	1.80
J1025+1022	2.89	1.63	2.38	1.55	2.33	1.67
J1037+4335	2.10	1.74	2.66	1.78	2.17	1.89
J1111+2841	2.17	1.63	2.01	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 FRO nature

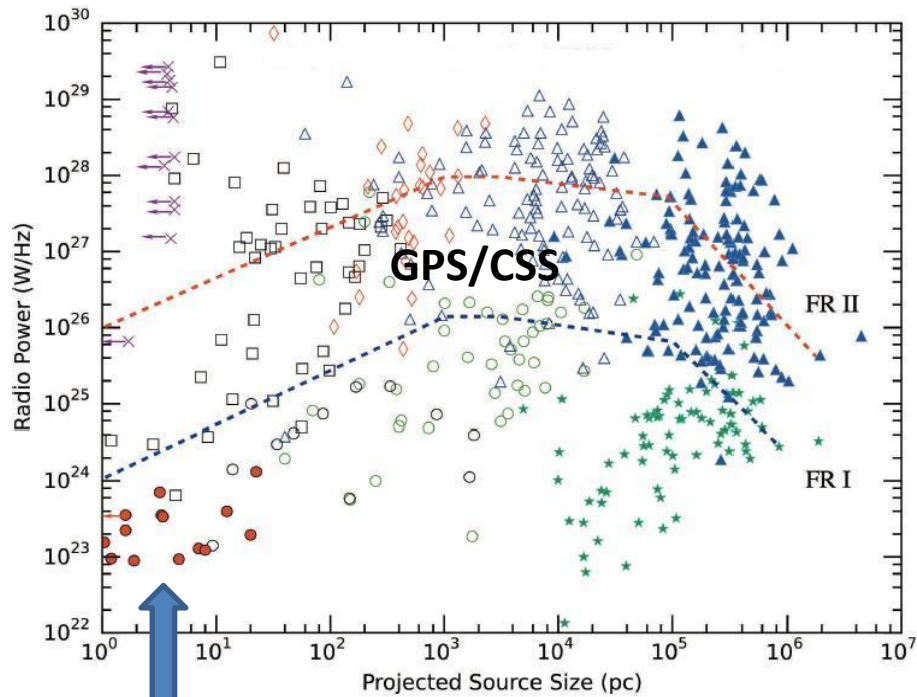
- Young radio galaxies evolving in FRI?
- Short-time accretion stages?
- Low-spin SMBHs?

Radio galaxy radio luminosity



Radio galaxy size

An & Baan 2012



FRO

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