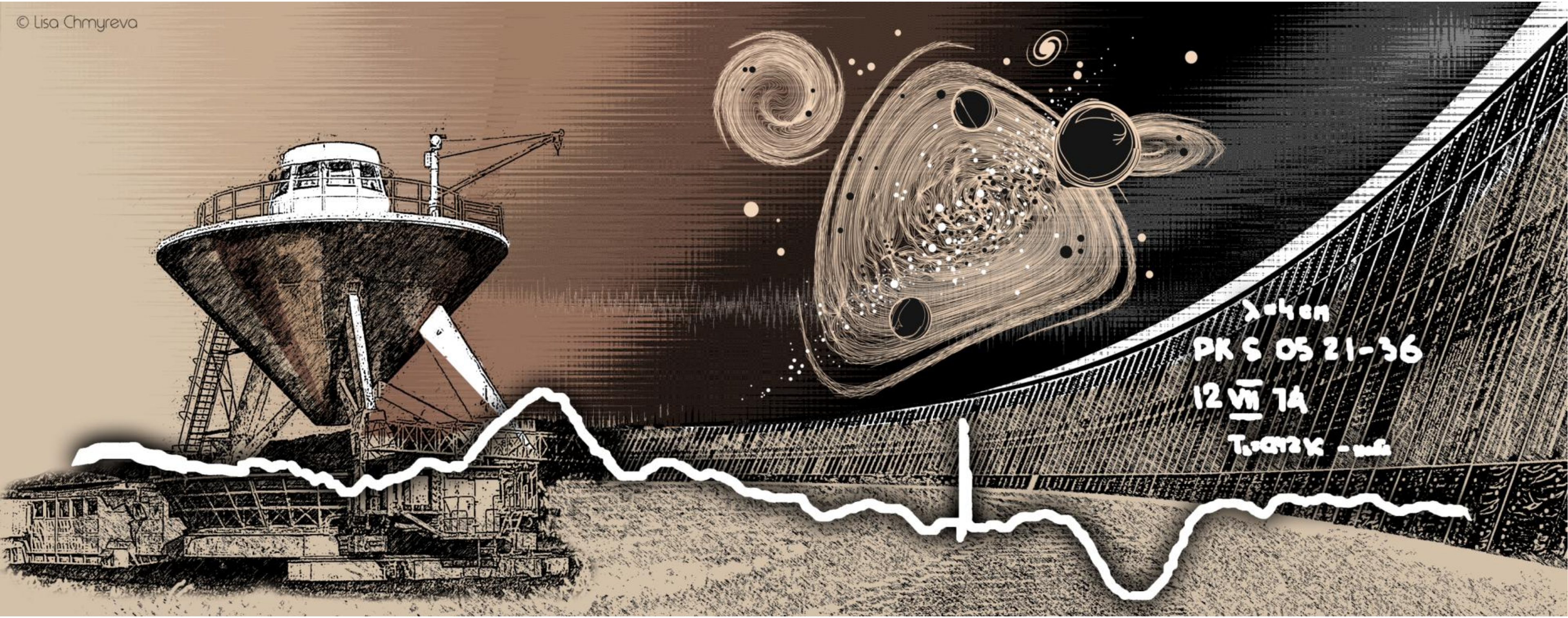
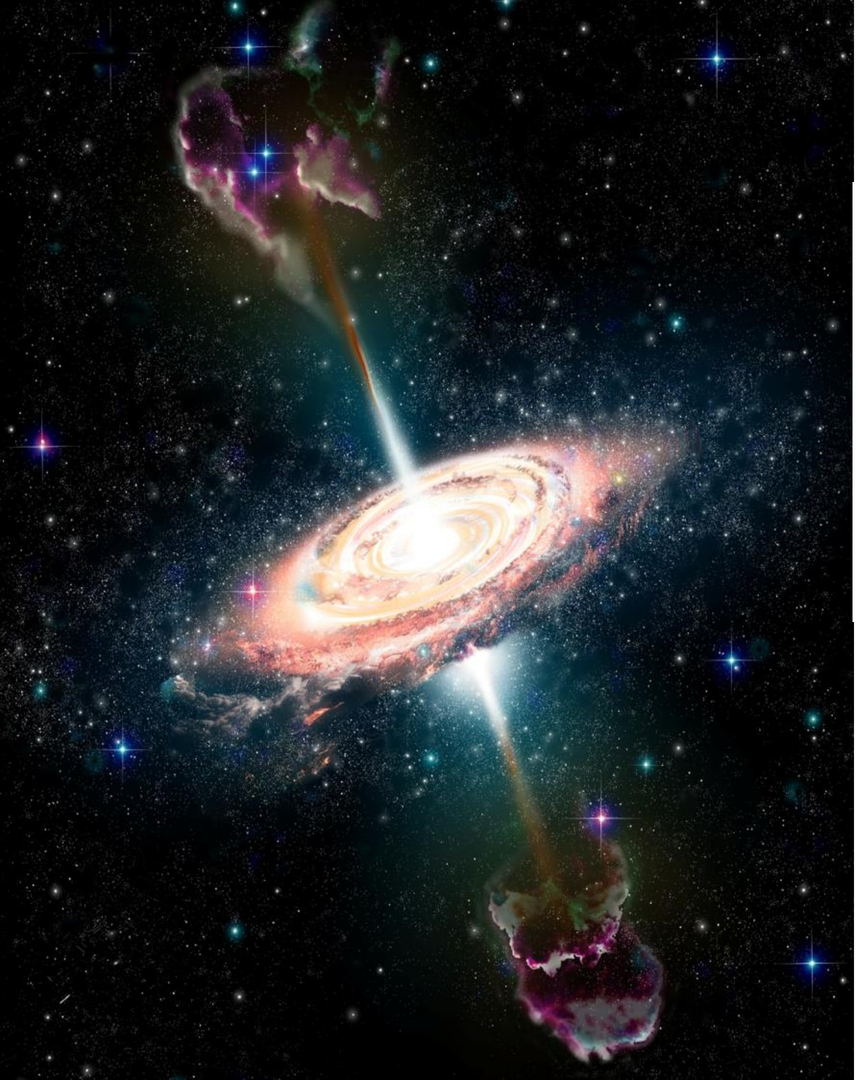
Active galaxies at different scales and wavelengths
SAO RAS 2024

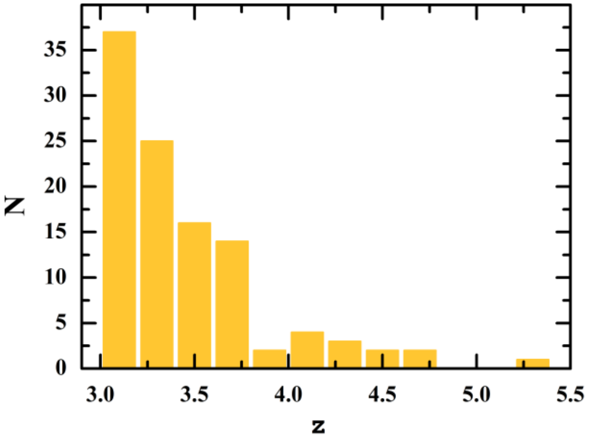


RADIO VARIABILITY OF HIGH-REDSHIFT QUASARS

Sotnikova Yu., Mufakharov T., Mikhailov A., Tao An, Mingaliev M., Semenova T., Kudryavtsev D., Stolyarov A., Khabibullina M., Udovitskiy R., Kovalev Yu., Bursov N., Kudryashova A., Kharinov M., Volvach A.



High-redshift QSOs



Optically selected:

~ 600 AGNs z>5

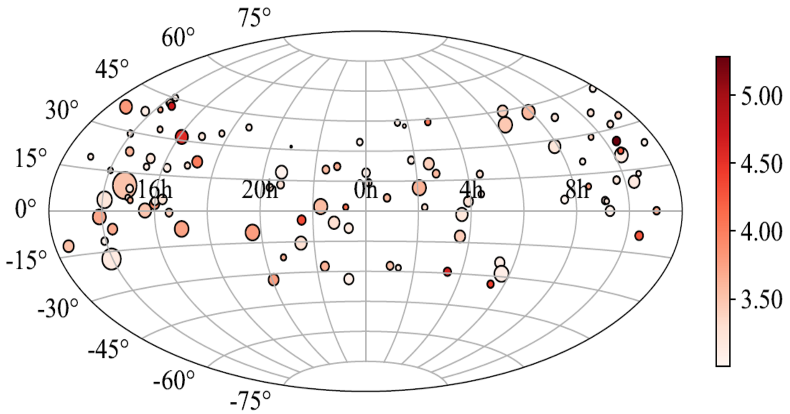
Radio loudness:

R >100

$$R = \frac{S_{\nu,\mathrm{radio}}}{S_{\nu,\mathrm{opt}}}$$

PSO J047.4478+27.2992	6.10	Belladitta 2020
J1427+3312	6.12	McGreer et al., 2006
CFHQS J1429+5447	6.18	Medvedev 2010
PSO J172.3556+18.7734	6.82	Banados 2021
VIK J2318-31134	6.44	Ighina et al., 2021

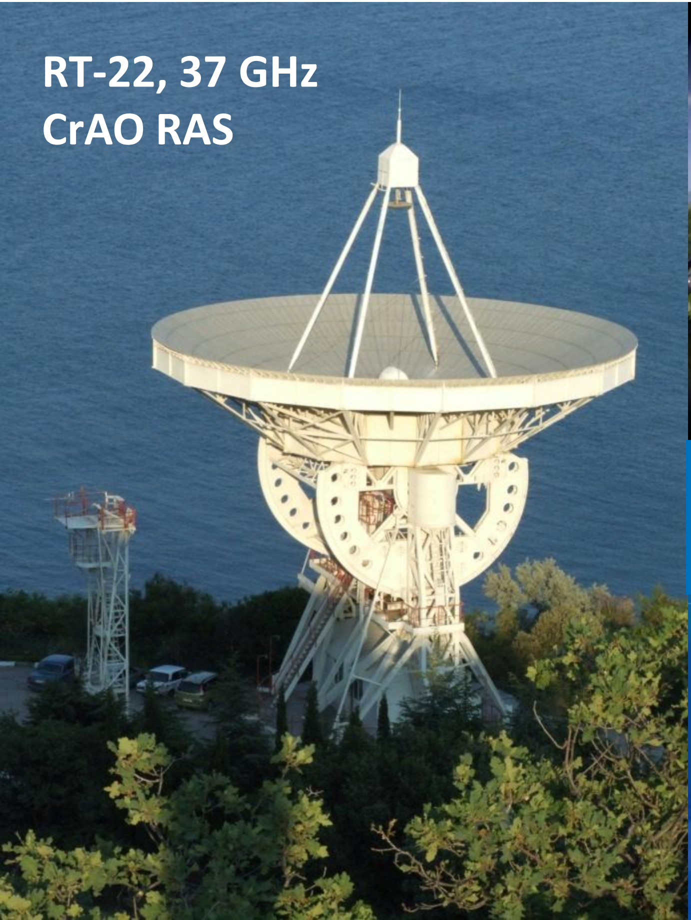
SAMPLE



- 101 radio-loud: $S_{radio}/S_{optical}$>100
- $S_{1.4}$GHz > 100 mJy at -34°<δ<49°
- Spectroscopic redshifts;
- 48 of 101 are identified as blazars in BZCAT (Massaro et al. 2009, 2015) and only 7 have matches in 4FGL (Abdollahi et al. 2020.

NAME	Z	P, W/Hz	INSTRUMENT
PSO J0309+27	**6.10**	$1.9*10^{27}$	R-600, Z-1000
J1702+1301	**5.47**	$1.5*10^{27}$	R-600, BTA
J0906+6930	**5.47**	$3.9*10^{27}$	R-600, Z-1000
J1648+4603	**5.38**	$1.5*10^{27}$	R-600, Z-1000, AS-500/2
B2 1023+25	**5.28**	$1.3*10^{28}$	R-600, RT-32, Z-1000, AS-500/2
J1606+3124	**4.56**	$3.6*10^{27}$	R-600, RT-22, RT-32
TXS 1508+572	**4.31**		R-600
J0646+4451	**3.39**	$2.3*10^{28}$	R-600, RT-22, RT-32, Z-1000, AS-500/2
PKS 1614+051	**3.21**	$1.8*10^{28}$	R-600, RT-22, RT-32, Z-1000, AS-500/2
PKS 2126-15	**3.26**	$2.8*10^{27}$	R-600, RT-22, RT-32, Z-1000, AS-500/2

TELESCOPES


RT-22, 37 GHz
CrAO RAS


RATAN-600, 1-22 GHz
SAO RAS

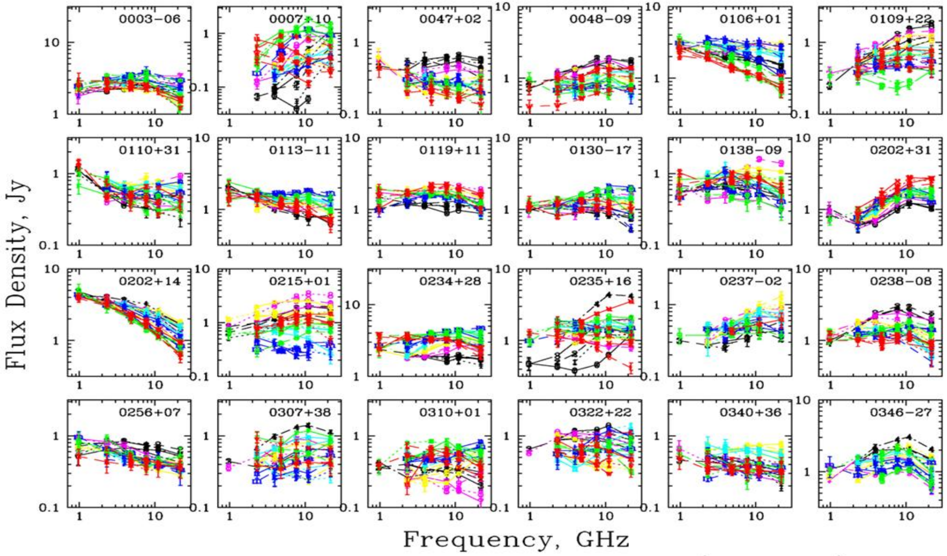

RT-32, 5, 8 GHz
IAA RAS

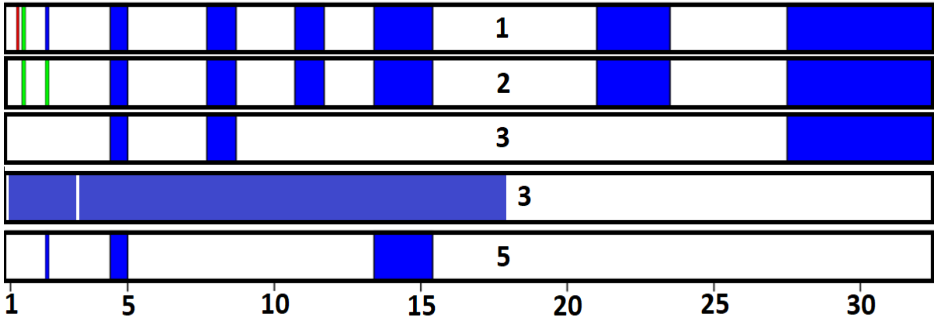

610
Collective use centers
360
Unique scientific facilities
7
Megascience class facilities
Scientific and Technological Infrastructure of the Russian Federation
Core Shared Research Facilities (CSRF) and Large-Scale Research Facilities (LSRF)

RATAN-600 observations 1997-2024

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

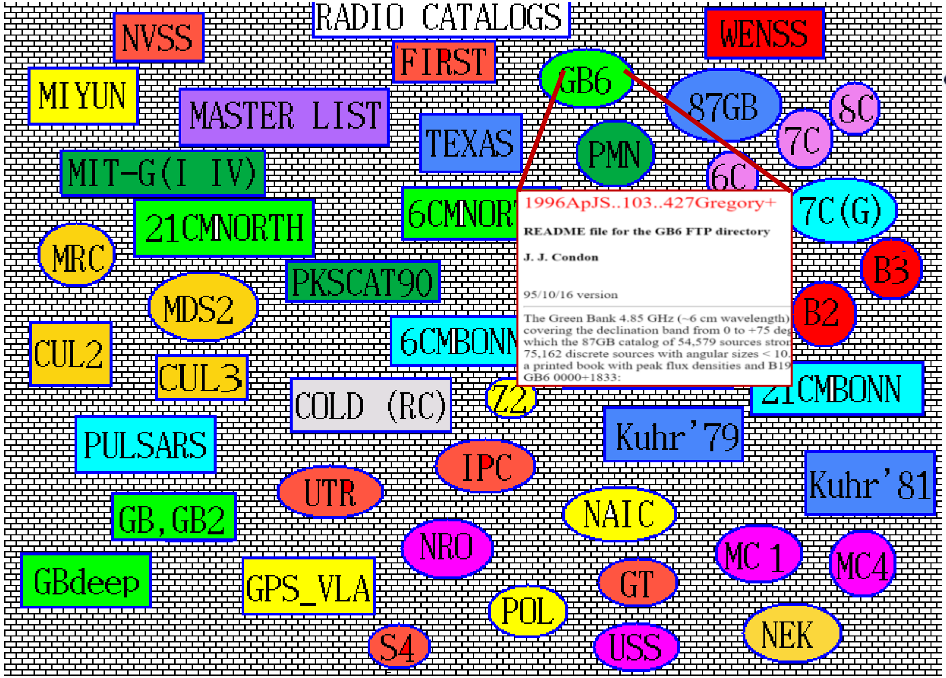
f_0, (GHz)	Δf_0, (GHz)	ΔF, (mJy/beam)	$HPBW_x$, sec	AR, arcsec
22.3	2.5	95	1.5	16.5
14.4	2.0	50	1.6	18
11.2	1.0	30	2.1	23
8.2	1.0	20	2.7	30
4.7	0.6	10	4.8	53





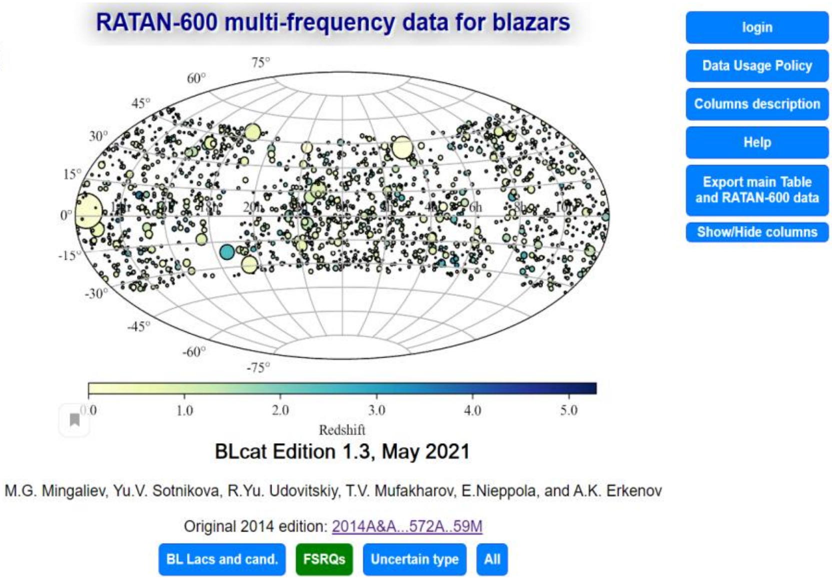
- Multifrequency monitoring of blazar variability on long time scales (SAO RAS, MALBRICS collaboration)
- Monitoring SRGE J170245.3 + 130104 - the most powerful X-ray quasar at z>5 (IKI RAS, SAO RAS)
- Radio spectra and variability of quasars at z>4 (SAO RAS, SHAO)
- Radio properties of the distant quasars at z>3 (SAO RAS)

Search tool: the CATS Database
Astrophysical CATalogs support System
www.sao.ru/cats/



- **radio catalogues;**
- **~630;**
- **Descriptions, software, graphics**

Verkhodanov et al., 1997, 2005, 2009



https://www.sao.ru/blcat

1800 blazars from Roma-BZCAT:

$S_{1.4}$ > 100 mJy, -35° < Dec < 45°.

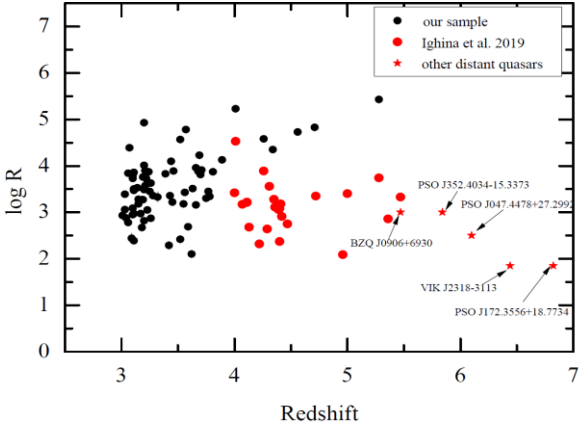
Mingaliev et al., 2014; Sotnikova et al., 2022

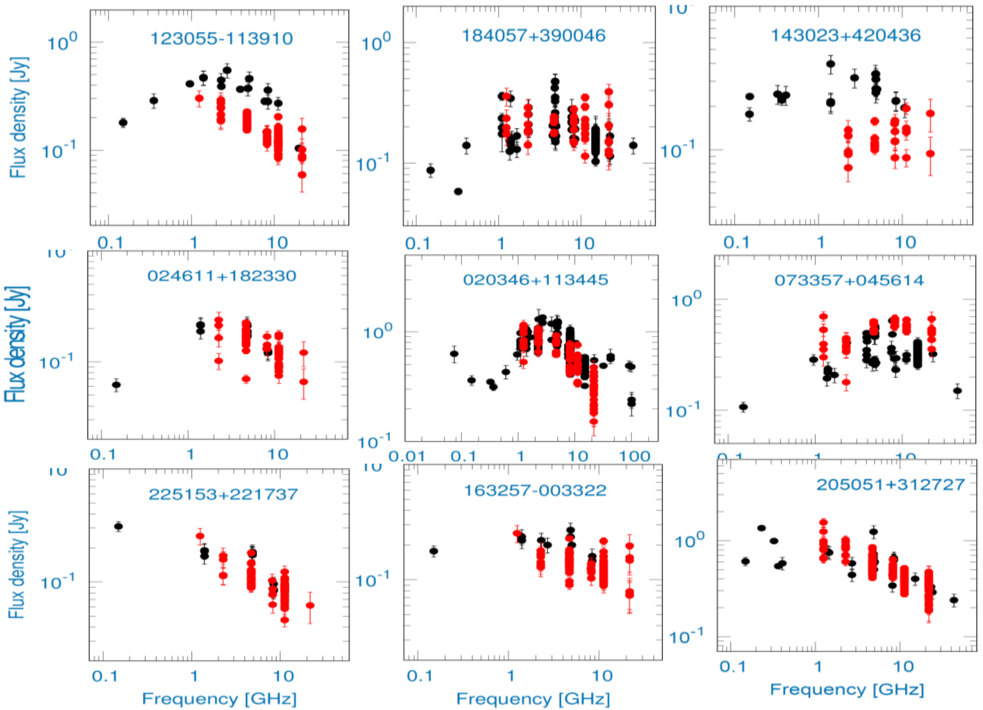
I. HzQSO radio spectra

Sotnikova et al. 2021

2006-2024; Z≥3; $S_{1.4}$>100 mJy; 101 QSO

type	Criteria $S \sim \nu^{\alpha}$	S1; z≥3 %	S2; z≥4 %
PS	$\alpha_{low} > 0$, $\alpha_{high} < 0$	46	43
upturn	$\alpha_{low} < 0$, $\alpha_{high} > 0$	2	8
flat	$-0.5 \le \alpha \le 0$	24	27
steep	$-1.1 < \alpha < -0.5$	15	14
rising	$\alpha > 0$	8	3
ultra-steep	$\alpha \le -1.1$	0	0
complex	two or more min	5	5





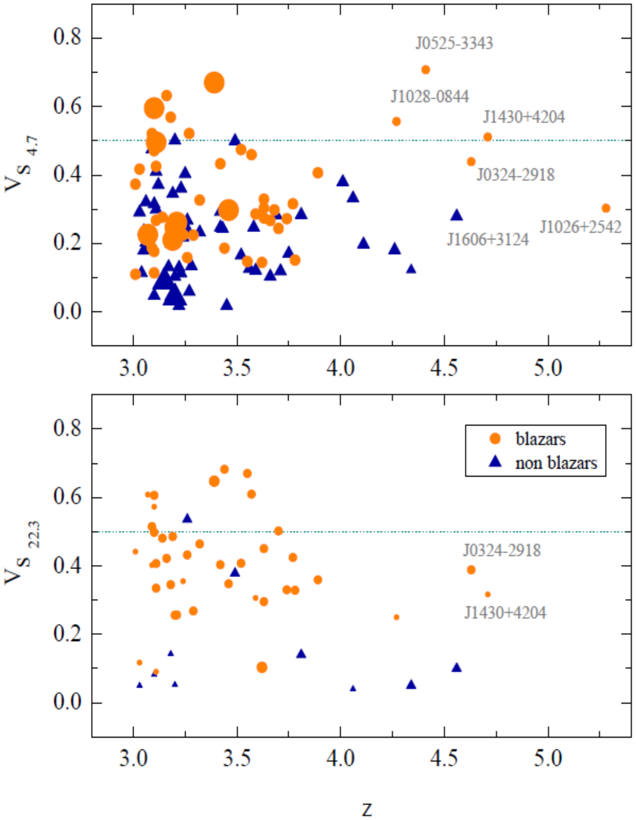
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 508, 2798–2814 (2021) https://doi.org/10.1093/mnras/stab2114

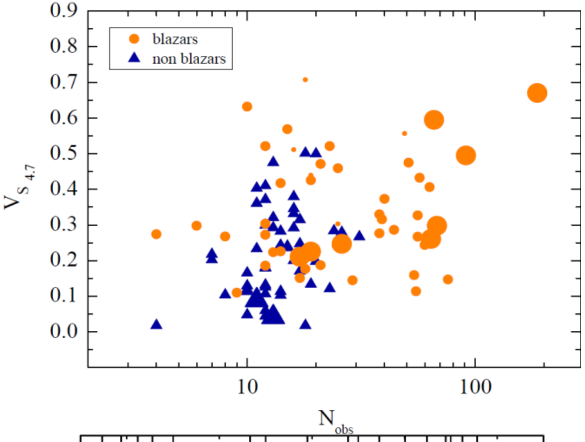
High-redshift quasars at $z \geq 3$ – I. Radio spectra

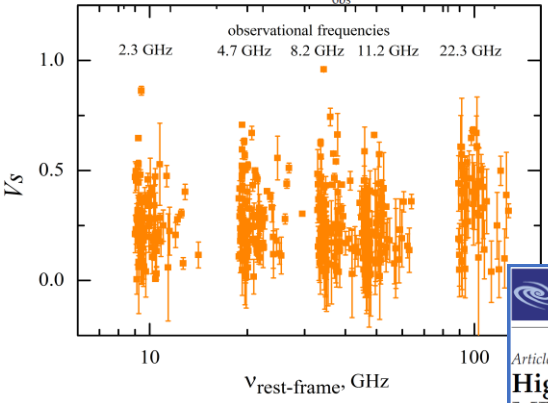
Yu. Sotnikova,[1★] A. Mikhailov,[1] T. Mufakharov,[1,2,3] M. Mingaliev,[1,2] N. Bursov,[1] T. Semenova,[1] V. Stolyarov,[1,2,4] R. Udovitskiy,[1] A. Kudryashova[1] and A. Erkenov[1]

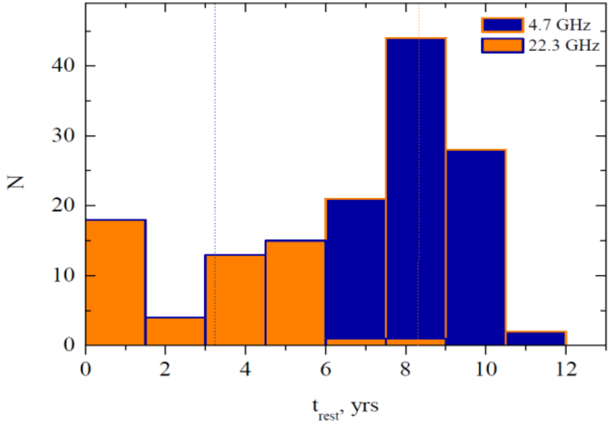
II. Radio variability

Sotnikova et al. 2024









cosmological time dilation

40 yrs → 10-12 yrs

different $\nu_{rest\ frame}$

1-22 GHz → 10-100 GHz

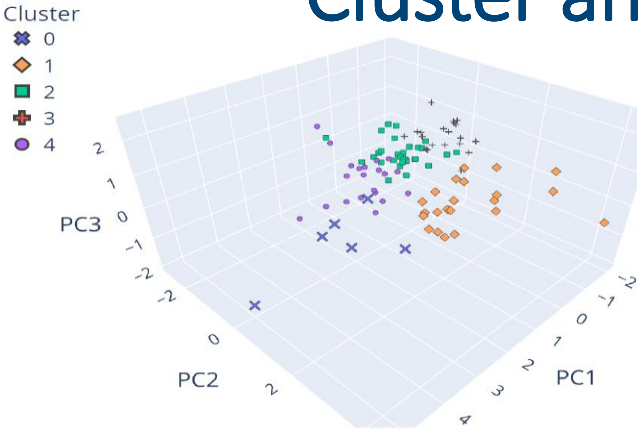
galaxies
MDPI

Article

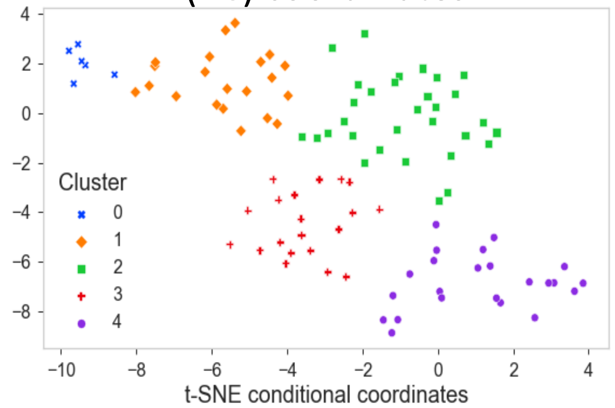
High-Redshift Quasars at $z \geqslant 3$: Radio Variability and MPS/GPS Candidates

Yulia Sotnikova [1,2,3,*], Alexander Mikhailov [1], Timur Mufakharov [1,2,3], Tao An [4,5], Dmitry Kudryavtsev [1], Marat Mingaliev [1,3,6], Roman Udovitskiy [1], Anastasia Kudryashova [1], Vlad Stolyarov [1,7] and Tamara Semenova [1]

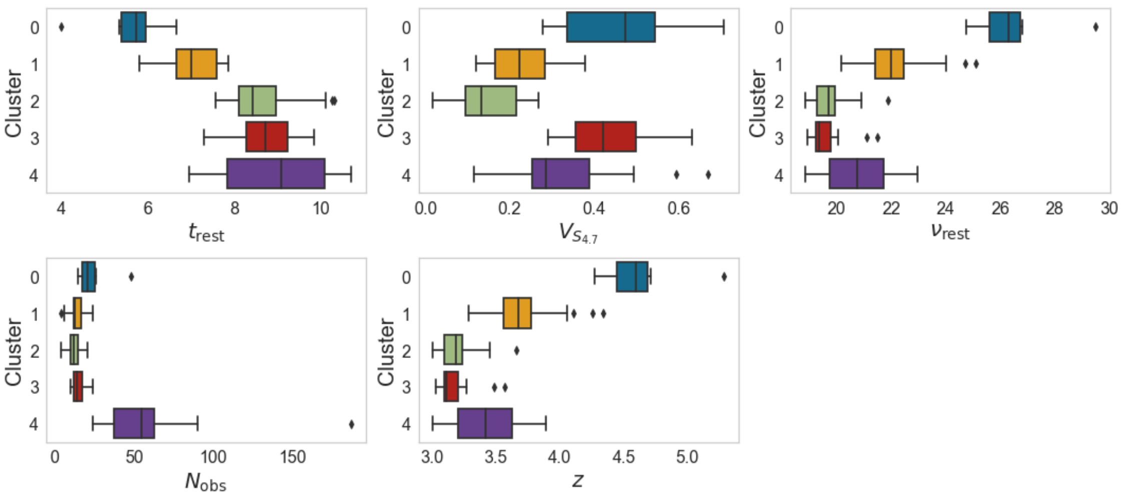
Cluster analysis. PCA k-means + SOM



clusters in the primary component (PC) coordinates



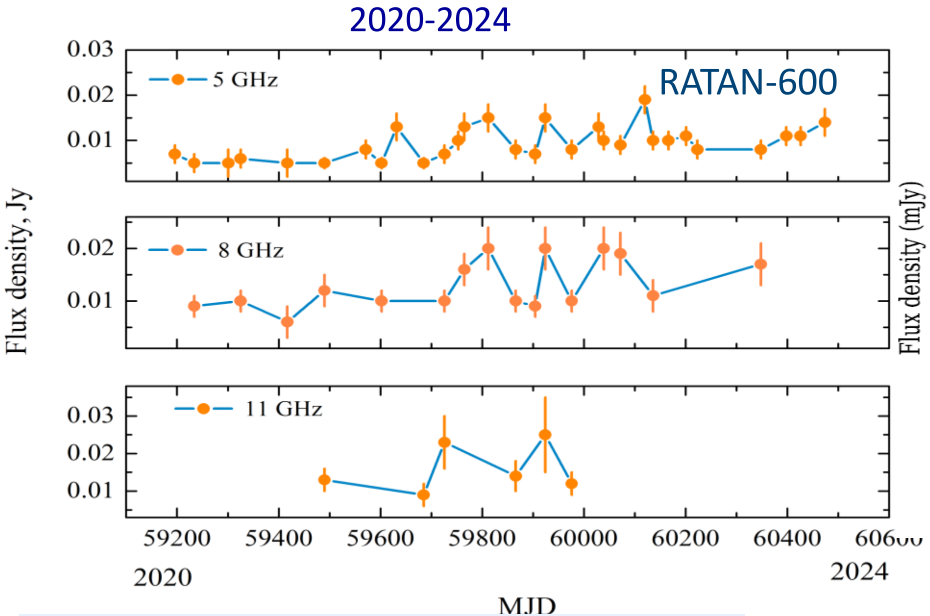
2D t-SNE representation

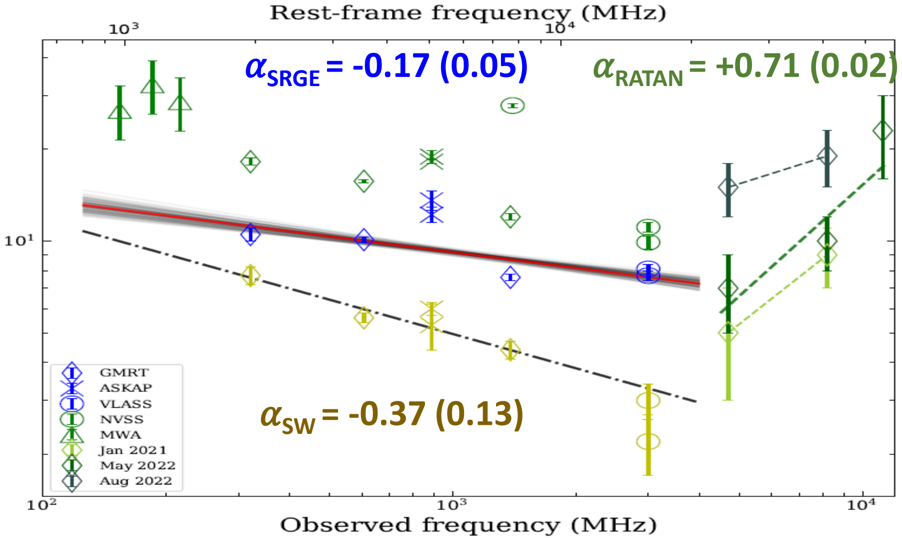


Cluster	N	t_{rest}, yr	V_{S5}	ν_{rest}, GHz	N_{obs}	z
0	6	5.7	0.48	26.3	21	4.6
1	21	7.0	0.22	22.0	13	3.7
2	31	8.4	0.13	19.7	12	3.2
3	20	8.7	0.42	19.3	14	3.1
4	23	9.1	0.29	20.8	55	3.4

SRGE J170245.3+130104 at z=5.5

Khorunzhev et al. 2021; Tao An et al., 2023





Radio spectra J1702+13: MWA, GLEAM-X, GMRT, ASKAP RACS, VLA, NVSS and VLASS, and RATAN-600

$Z = 5.466 \pm 0.003$ (BTA, SCORPIO)

$L_{X\text{-}ray} = 3.6 \times 10^{46}$ erg/s (2-10 keV)

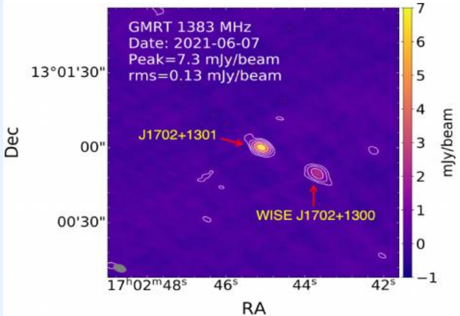
$R > 1100$; $S_{1.4} = 26 \pm 0.9$ mJy

$\alpha_{4.7-8.2} = +0.71\ (0.02)$, $S \sim \nu^{\alpha}$

F_{var}=0.4 (0.04) at 4.7 GHz

0.4 (0.05) at 8.2 GHz

0.4 (0.3) at 11.2 GHz



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 519, 4047–4055 (2023) https://doi.org/10.1093/mnras/stac3774
Advance Access publication 2022 December 22

Is the X-ray bright $z = 5.5$ quasar SRGE J170245.3+130104 a blazar?

Tao An[1,2★], Ailing Wang[1,2], Yuanqi Liu[1], Yulia Sotnikova[3], Yingkang Zhang[1], J. N. H. S. Aditya[4,5], Sumit Jaiswal[1], George Khorunzhev[6], Baoqiang Lao[1,7], Ruqiu Lin[1,2], Alexander Mikhailov[3], Marat Mingaliev[3,8,9], Timur Mufakharov[3,8] and Sergey Sazonov[6]

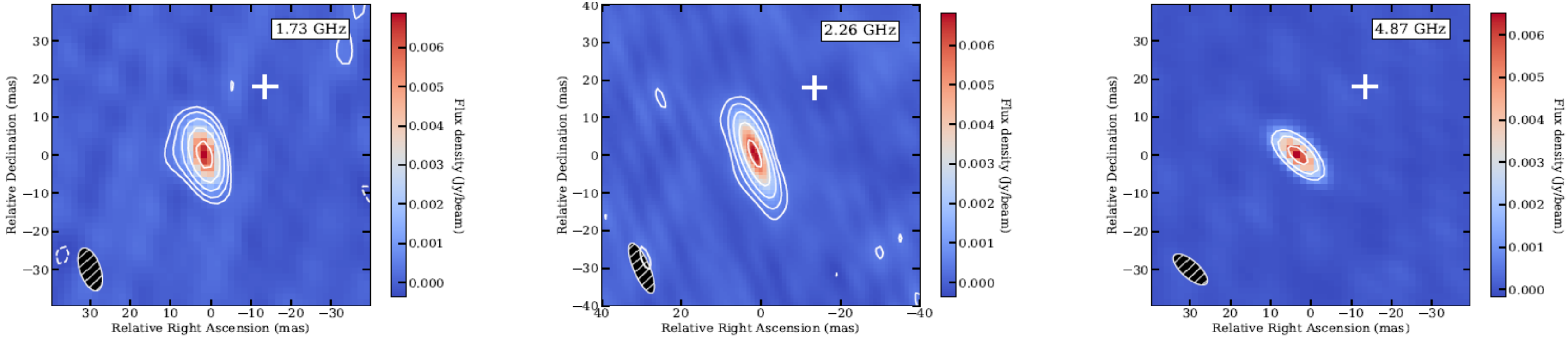
2023MNRAS.519.4047A

SRGE J170245.3+130104 at z=5.5

SAO RAS 14/10/2024

Yuanqi Liu et al. 2024

VLBI 2021



parameters	L band	S band	C band
Epoch	Dec 06	Dec 07	Dec 21
Total observing time, hr	2.75	4	2.75
Central frequency, GHz	1.73	2.26	4.87
Total bandwidth, MHz	256	256	512
Synthesis beam, mas	11.7 x 5.19	9.46 x 5.10	10.91 x 4.46
Image rms noise level, mJy/beam	0.11	0.09	0.42
Peak flux density, mJy/beam	6.77	6.89	6.40
Integrated flux density, mJy	8.35±0.09	7.47±0.08	6.57±0.02
Size, mas	3.28	1.63	0.91
Brightness temperature, 10^9 K	2.0	4.4	2.7

High radio loudness > 1000;
The brightest X-ray blazar;
Flat radio spectra;
Prominent radio variability on timescales of few days in the rest frame.

A&A, 685, A111 (2024)
https://doi.org/10.1051/0004-6361/202449394

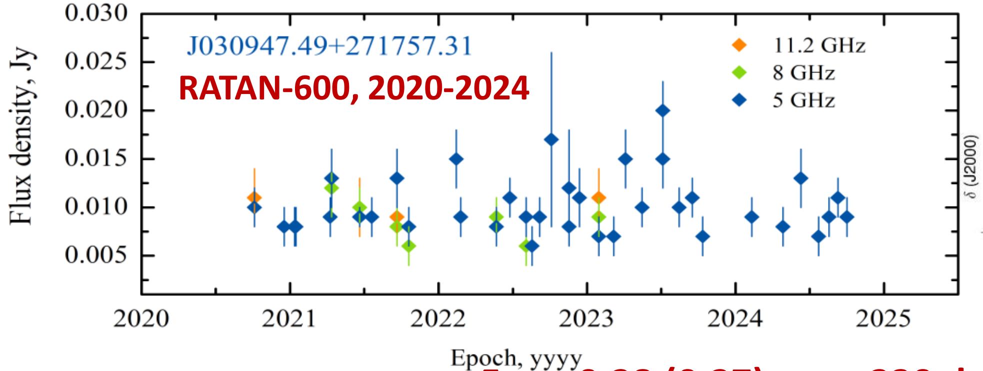
Astronomy & Astrophysics

Very long baseline interferometry observations of the high-redshift X-ray-bright blazar SRGE J170245.3+130104

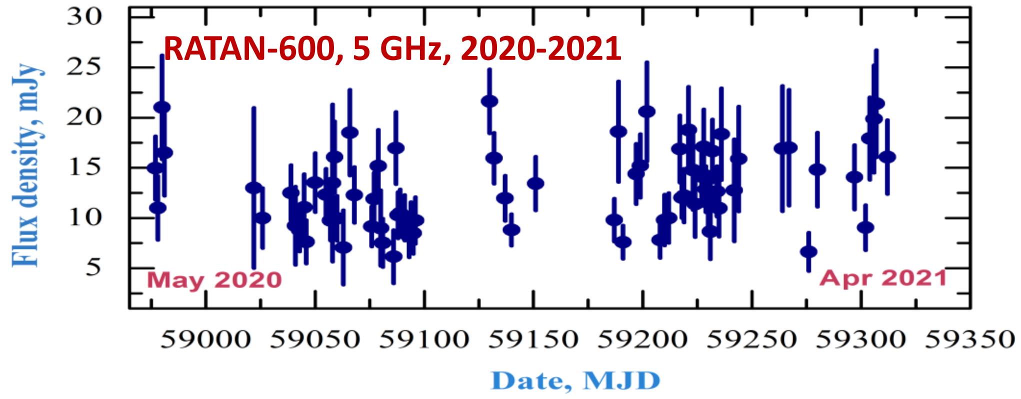
Yuanqi Liu[1], Tao An[1,2,3], Shaoguang Guo[1,2,3], Yingkang Zhang[1,3], Ailing Wang[1,2], Zhijun Xu[1], Georgii Khorunzhev[4], Yulia Sotnikova[5], Timur Mufakharov[5,6], Alexander Mikhailov[5], and Marat Mingaliev[5,6,7]

PSO J0309+27 at z=6.1

Mufakharov et al. 2021



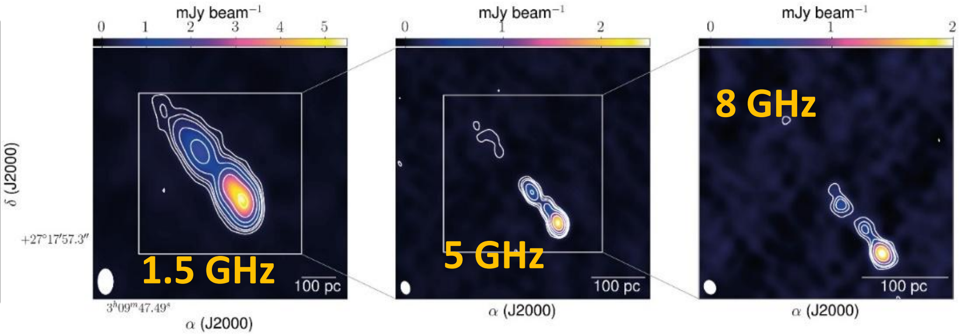
F_{var} = 0.28 (0.27); t_{rest}=230 d



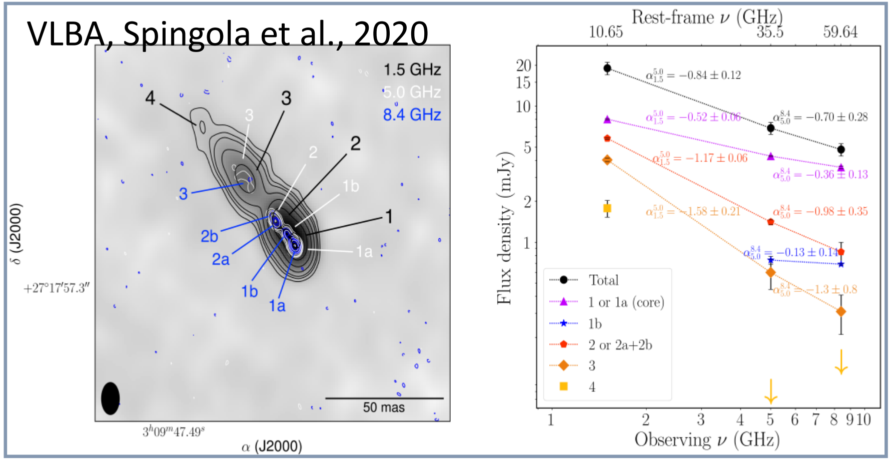
R>10^3; α_{radio} < 0.5; F_{var} = 0.30 (0.02); t_{obs} ~50 d

2021MNRAS.503.4662M

Belladitta et al. 2020

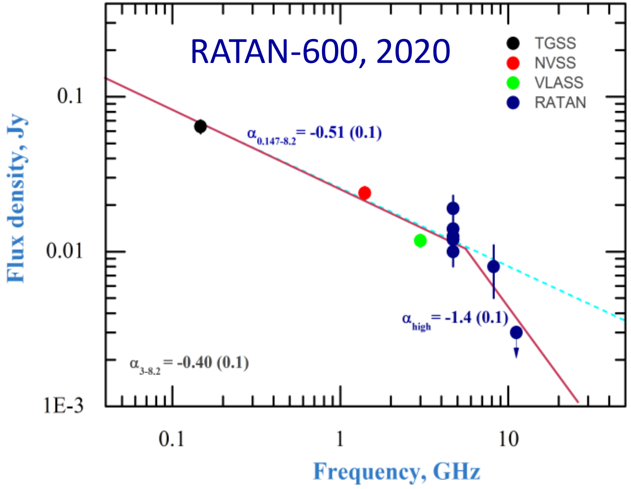


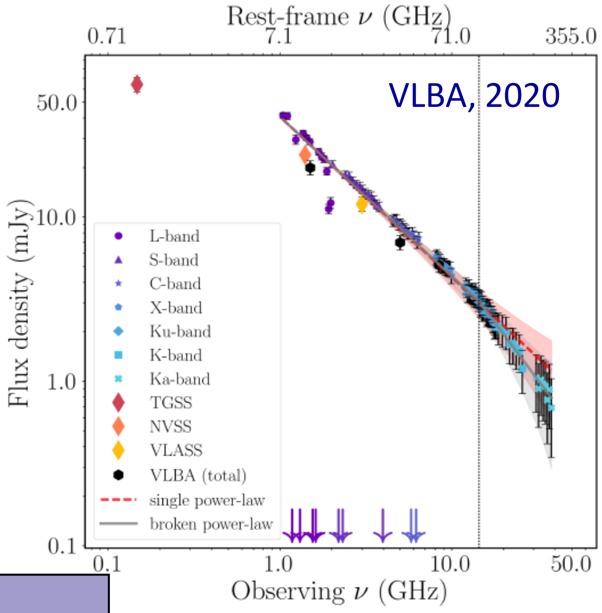
VLBA, Spingola et al., 2020

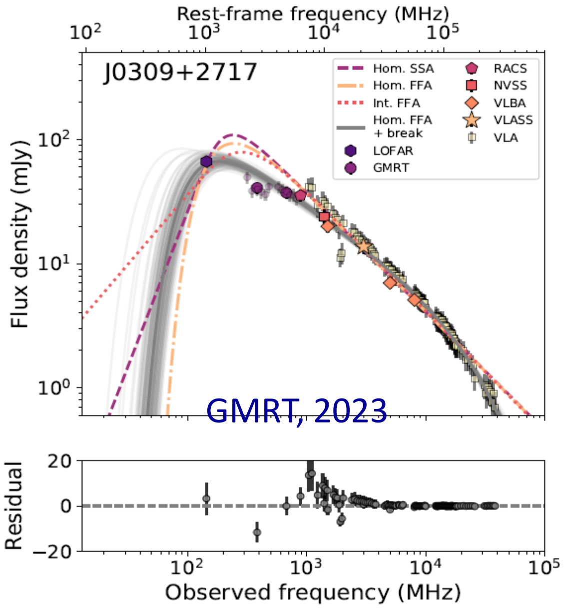


Bright one-sided jet extended for 500 parsec
Brightest X-ray AGN detected at z > 6

Radio spectra PSO J0309+2717 at z=6.1







Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 503, 4662–4666 (2021) doi:10.1093/mnra

Flux-density measurements of the high-redshift blazar PSO J047.4478+27.2992 at 4.7 and 8.2 GHz with RATAN-600

T. Mufakharov,[1,2★] A. Mikhailov,[3] Yu. Sotnikova,[3] M. Mingaliev,[1,3] V. Stolyarov,[1,3,4] A. Erkenov,[3] N. Nizhelskij[3] and P. Tsybulev[3]

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LETTER TO THE EDITOR

Parsec-scale properties of the radio brightest jetted AGN at $z > 6$

C. Spingola[1,2], D. Dallacasa[1,2], S. Belladitta[3,4], A. Caccianiga[3], M. Giroletti[2], A. Moretti[3], and M. Orienti[2]

Astronomy & Astrophysics manuscript no. main ©ESO 2023
September 20, 2023

No strong radio absorption detected in the low-frequency spectra of radio-loud quasars at $z > 5.6$

A. J. Gloudemans[1], A. Saxena[2,3], H. Intema[1], J. R. Callingham[4,1], K. J. Duncan[5], H. J. A. Röttgering[1], S. Belladitta[6,7], M. J. Hardcastle[8], Y. Harikane[9], and C. Spingola[10]

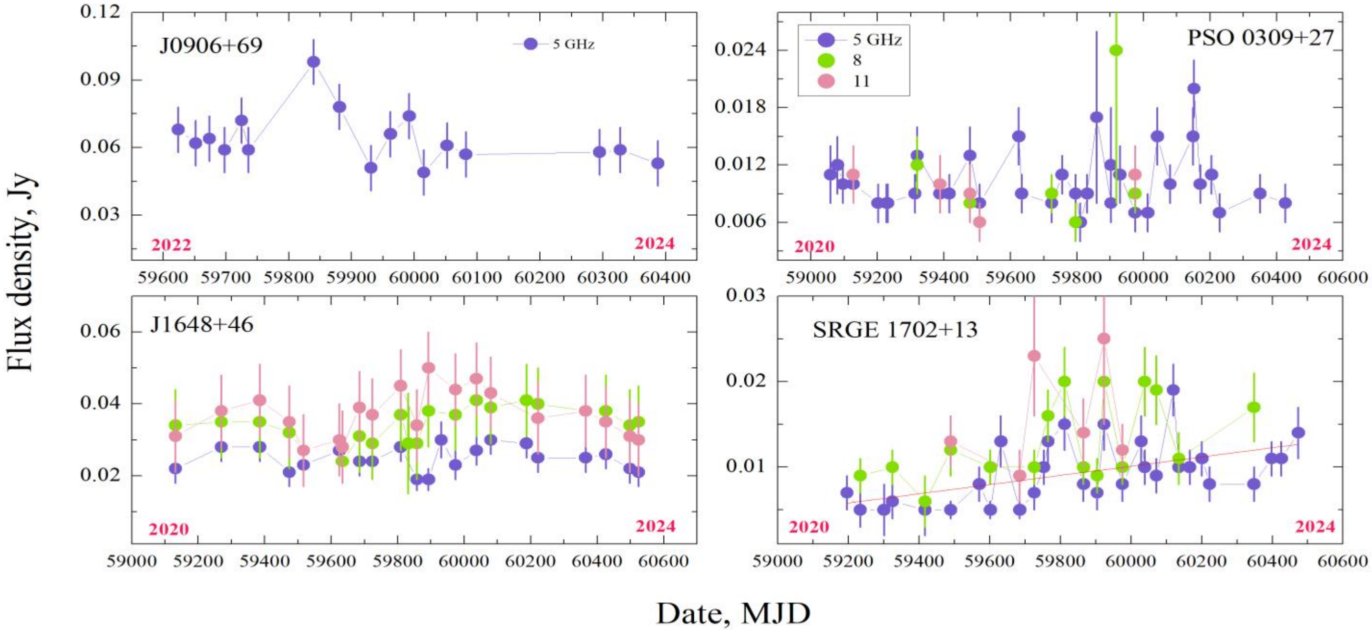
Variability of QSO at the highest z

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

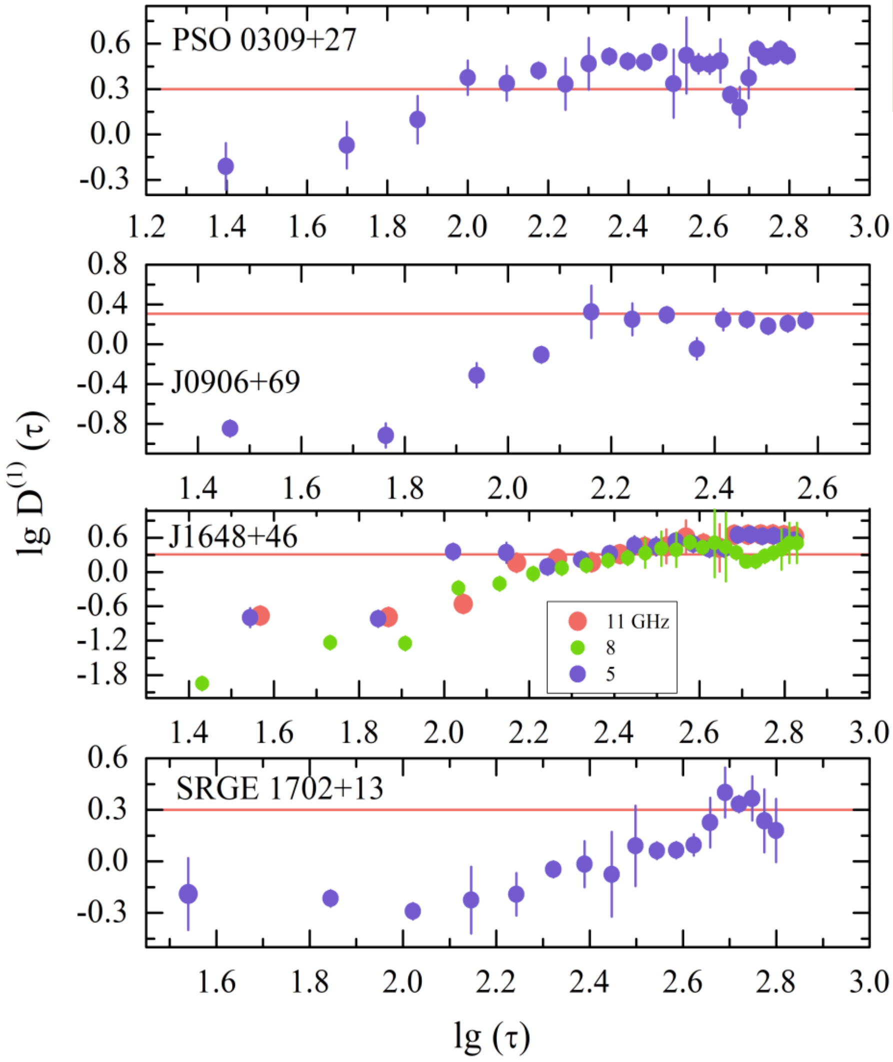
$$F_{var} = \sqrt{\frac{V^2 - \sigma_{err}^2}{\bar{x}^2}}$$

$$\Delta F_{var} = \sqrt{(\sqrt{\frac{1}{2N}}\frac{\sigma_{err}^2}{F_{var} * \bar{x}^2})^2 + (\sqrt{\frac{\sigma_{err}^2}{N}}\frac{1}{\bar{x}^2})^2}$$

name	N	z	V_5	$F_{var,5}$	t_{obs}, yrs	t_{rest}, yrs
J0309+27	32	6.10	0.22	0.28 (0.27)	4	0.6
J1702+13	30	5.47	0.46	0.38 (0.04)	4	0.6
J0906+69	17	5.47	0.20	0.18 (0.01)	3	0.5
J1648+46	23	5.38	0.19	0.19 (0.06)	4	0.6



Variability timescale τ_{rest}



PSO 0309+27; z=6.10; δ=1.6 $R \le c \cdot \tau_{rest} \cdot \delta / (1+z)$

τ_{obs} ~ 112 d =0.3 yr

τ_{rest} ~ 16 d = 0.04 yr

R<0.02 pc

J0906+69; z=5.47; δ=4

τ_{obs} ~ 158 d = 0.4 yr

τ_{rest} ~ 24 d = 0.07 yr

R<0.02 pc

J1648+46; z=5.38

τ_{obs} ~ 250 d =0.7 yr

τ_{rest} ~39 d = 0.1 yr

R<0.03 pc

SRGE 1702+13; z=5.47

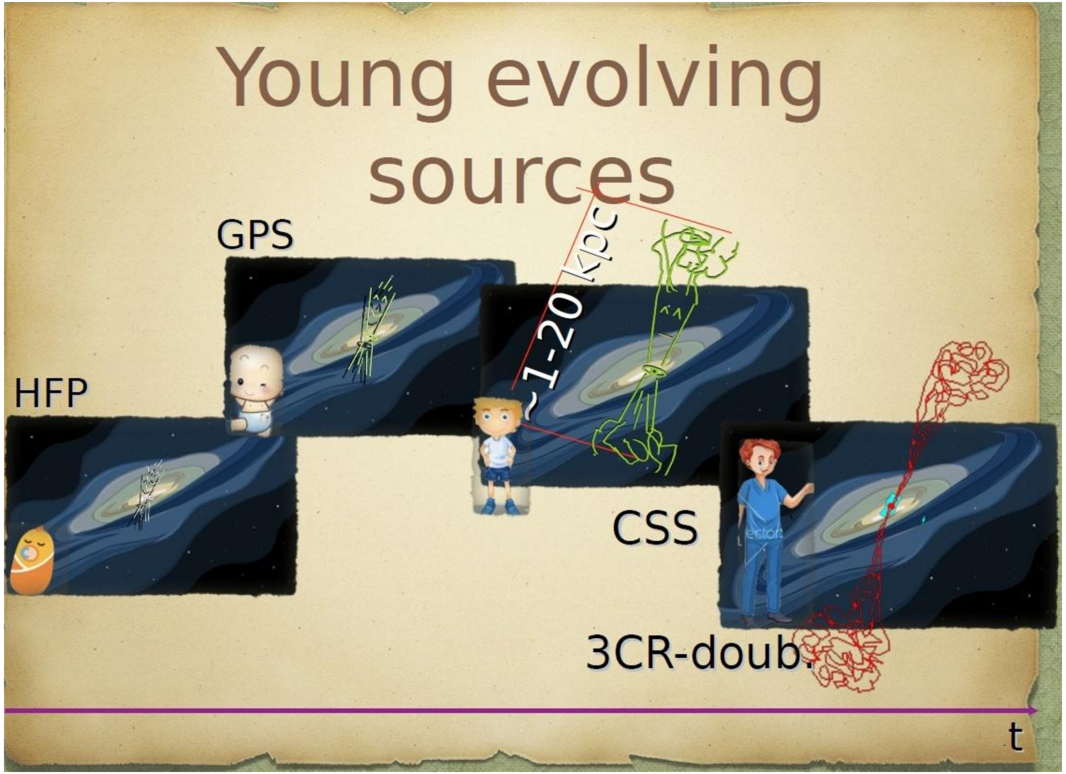
τ_{obs} ~ 250 d =0.7 yr

τ_{rest} ~ 39 d = 0.1 yr

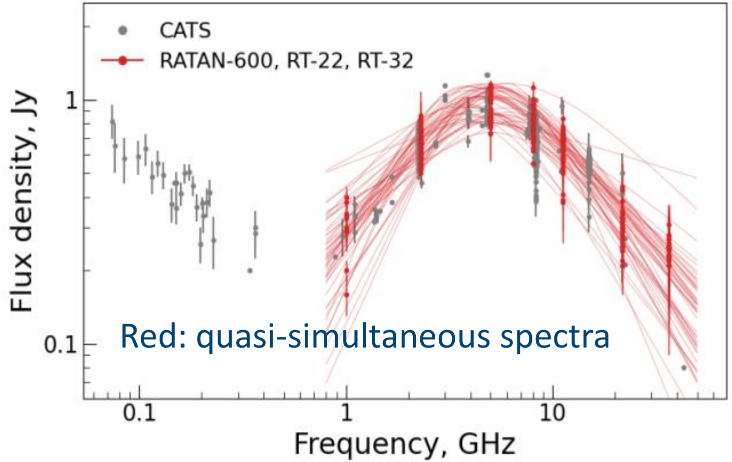
R<0.03 pc

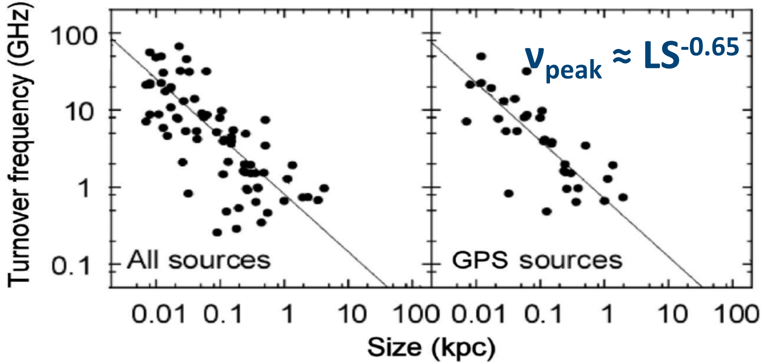
Radio variability of high-frequency peaker PKS 1616+051

Fanti et al., 1990; O'Dea & Baum 1997; Tornikoski et al., 2008

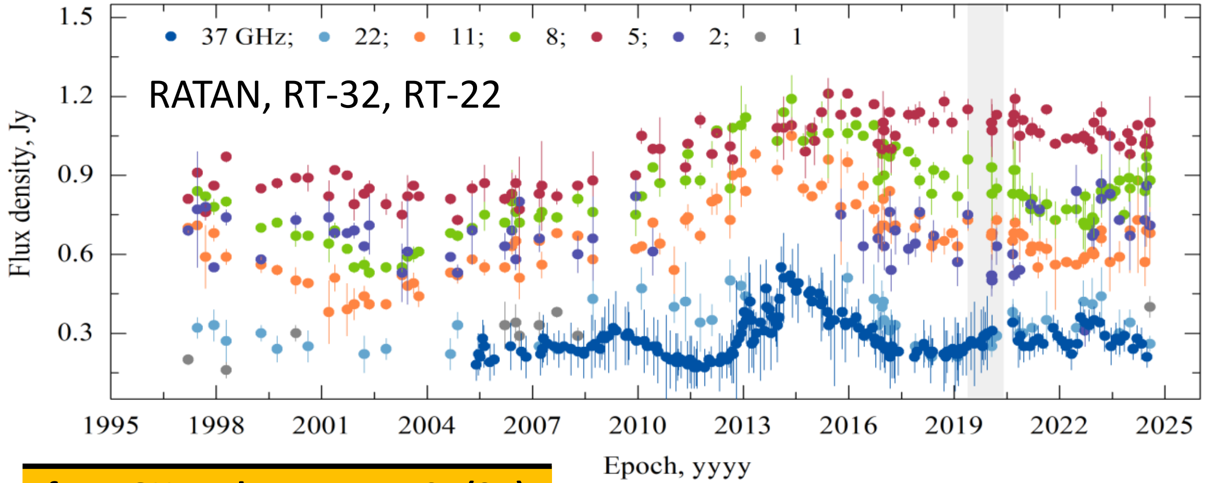


Taken from Vera et al., 2018

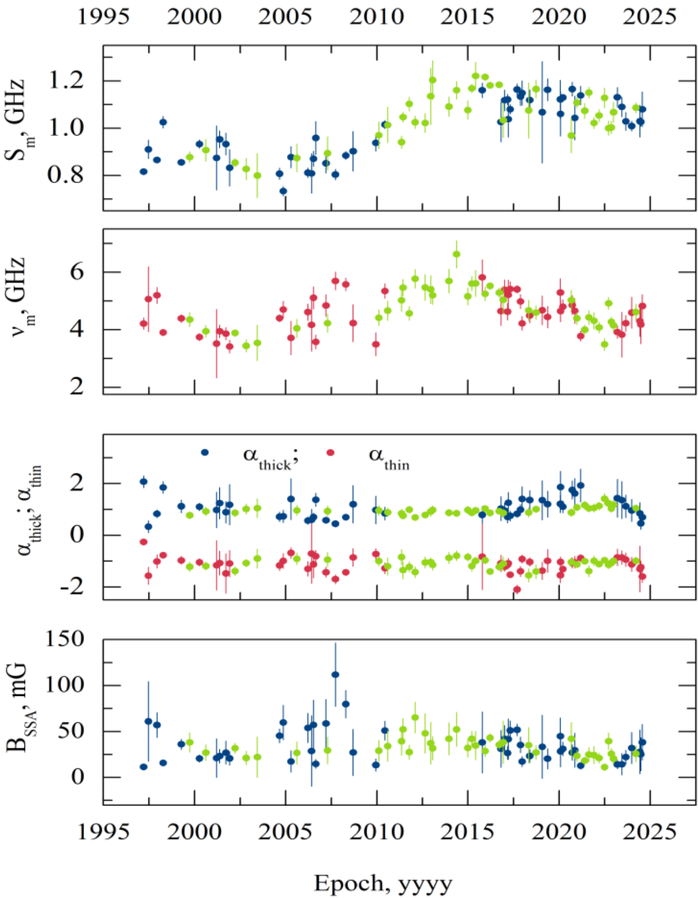




High-frequency peaked PKS 1616+045 at z=3.21



Sotnikova et al. 2024 accepted



freq, GHz	lag, yrs	DCF (2σ)
37 vs 22	0.8	0.64
37 vs 5	1.2	0.38
22 vs 11	3.4	0.68
22 vs 8	2.9	0.73
22 vs 5	6.4	0.61
11 vs 8	0.6	0.86
11 vs 5	2.7	0.81
8 vs 5	4.4	0.84

ν_{peak}: ~5 GHz

F_{var} : 0.1-0.2

SF, τ_{rest}: 0.6-1.8 yrs

DCF, lags: 0.6-6.4 yrs

lag vs frequency ~ -0.6 yr G

Summary

1. Long-term multi-frequency radio measurements are needed for complete HzQSO samples.

2. A significant population of young evolving radio AGNs at z>3.

3. A wide spread of radio variability on any time scale of the measurements ranging 0.02-0.96. Half of the objects exhibit a variability index within the range 0.25-0.50, which is comparable to that observed in blazars at lower redshifts.

4. A small highly variable $V_{5GHz}=0.5$ group of quasars at the highest redshifts, notable by a shorter time scale of monitoring, t_{rest}=~6 yrs.

5. QSOs at z=5-6, J1702+13, J0309+27, J0906+69, J1648+46: prominent radio variability on timescales of weeks to months in the observer's frame which corresponds to very compact size of the emission region.

6. HFP PKS J1616+05: prominent radio variability on timescales of months and years.

2024A&A...685L..11G; 2024Galax..12...25S
2024A&A...685A.111L; 2023MNRAS.519.4047A
2021MNRAS.503.4662M; 2021MNRAS.508.2798S

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SSA / FFA

$$S_\nu = S_m \left(\frac{\nu}{\nu_m}\right)^{\alpha_{\rm thick}} \times \frac{1-\exp\left(-\tau_m\left(\frac{\nu}{\nu_m}\right)^{\alpha-\alpha_{\rm thick}}\right)}{1-\exp(-\tau_m)}, \quad (7)$$

where the optical depth

$$\tau_m \sim \frac{3}{2}\left(\sqrt{1-\frac{8\alpha}{3\alpha_{\rm thick}}}-1\right). \quad (8)$$

$$S_\nu = S_{\rm norm}(p+1)\left(\frac{\nu}{\nu_p}\right)^{2.1(p+1)+\alpha} \times \gamma\left[p+1,\left(\frac{\nu}{\nu_p}\right)^{-2.1}\right], \quad (9)$$

$$B_{\rm SSA} \approx 10^{-5} b(\alpha_{\rm thin})\nu_m^5 \theta^4 S_m^{-2} \delta (1+z)^{-1}, \quad (12)$$