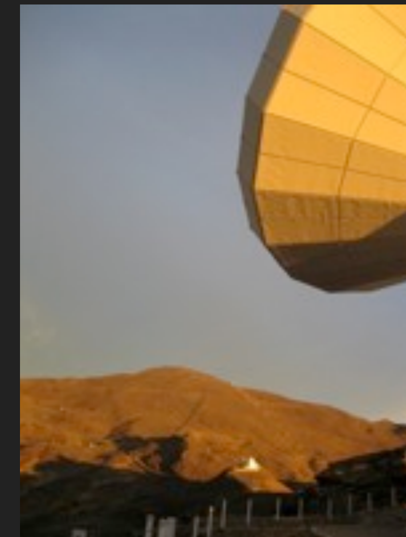
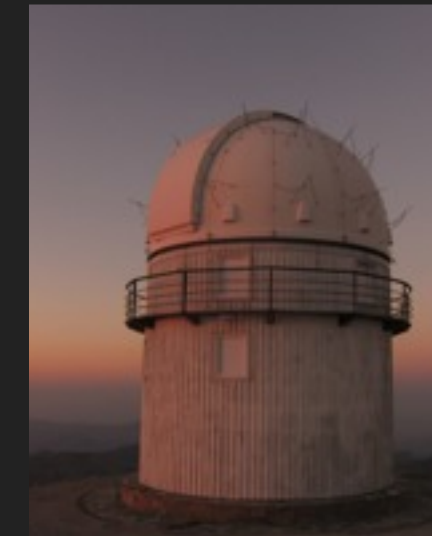





Properties of the radio jet emission of four gamma-ray Narrow Line Seyfert 1 galaxies

E. Angelakis[1] and L. Fuhrmann[1], I. Myserlis[1], N. Marchili[4], L. Foschini[3], V. Karamanavis[1], I. Nestoras[1], J. A. Zensus[1], T. P. Krichbaum[1], H. Ungerechts[2], A. Sievers[2], D. Blinov[5], V Pavlidou[5,6], O. King[7], G. Panopoulou[5], A. Ramaprakash[8]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hgel 69, Bonn 53121, Germany
[2] Instituto de Radio Astronomía Milimétrica (IRAM), Avenida Divina Pastora 7, Local 20, E 18012 Granada, Spain
[3] Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807, Merate, Italy
[4] Dipartimento di Fisica ed Astronomia, Universita di Padova, via Marzolo 8, Padova 35131, Italy
[5] Department of Physics, University of Crete, 71003, Heraklion, Greece
[6] Foundation for Research and Technology - Hellas, IESL, Voutes, 7110 Heraklion, Greece
[7] California Institute of Technology, 1200 E California Blvd, MC 249-17, Pasadena CA, 91125, USA
[8] Inter-University Centre for Astronomy and Astrophysics (IUCAA), Post Bag 4, Ganeshkhind, Pune - 411 007, India

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

F-GAMMA PROJECT

FERMI-GST AGN MULTI-FREQUENCY MONITORING ALLIANCE

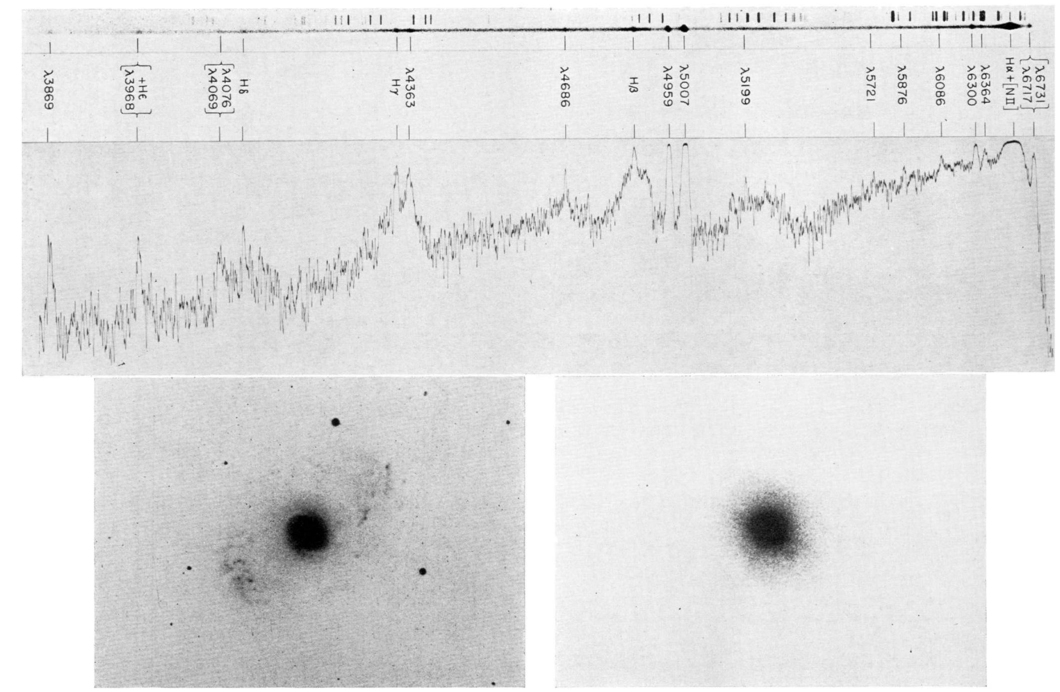
Seyfert Galaxies

General: discovery, properties , characteristics

Seyfert 1943, ApJ...97...28 studied "6 extragalactic nebulae" that were showing:

- "high excitation nuclear emission emission lines superposed on a normal G-type spectrum"
- all lines were Doppler broadened up to **8500 km/s**
- the max width of the Balmer emission increased with the absolute mag of the nucleus and the (light on nucleus)/(total light of nebula)

PLATE I



NGC 4151

Spectrum, microphotometer tracing, and direct photographs. The spectrum is an enlargement from a 325^m exposure taken with the one-prism Cassegrain spectrograph and 10-inch camera at the 60-inch reflector. The photographs (enlargements from a plate taken with the 100-inch reflector) show the weak, amorphous arms on the left and the semistellar nucleus on the right.

- following *Khachikian & Weedman 1974, ApJ...192...581,* they are further classified:
- **Seyfert 1**: HI Balmer lines are **broader** than forbidden lines
- **Seyfert 2**: HI Balmer lines and forbidden lines are **approximately same** width

(typically FWHM for **forbidden** lines **for both** are 300-800 km/s while HI in Seyfert 1's are 1000-6000 km/sec)

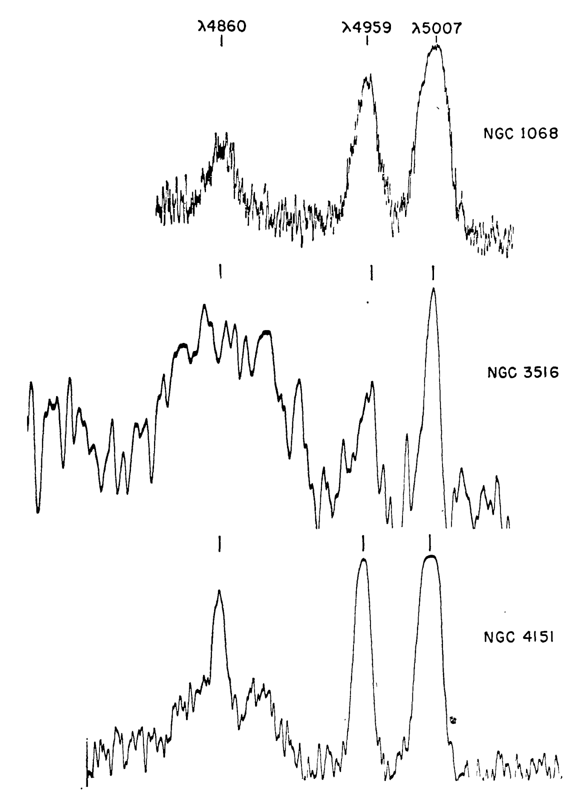
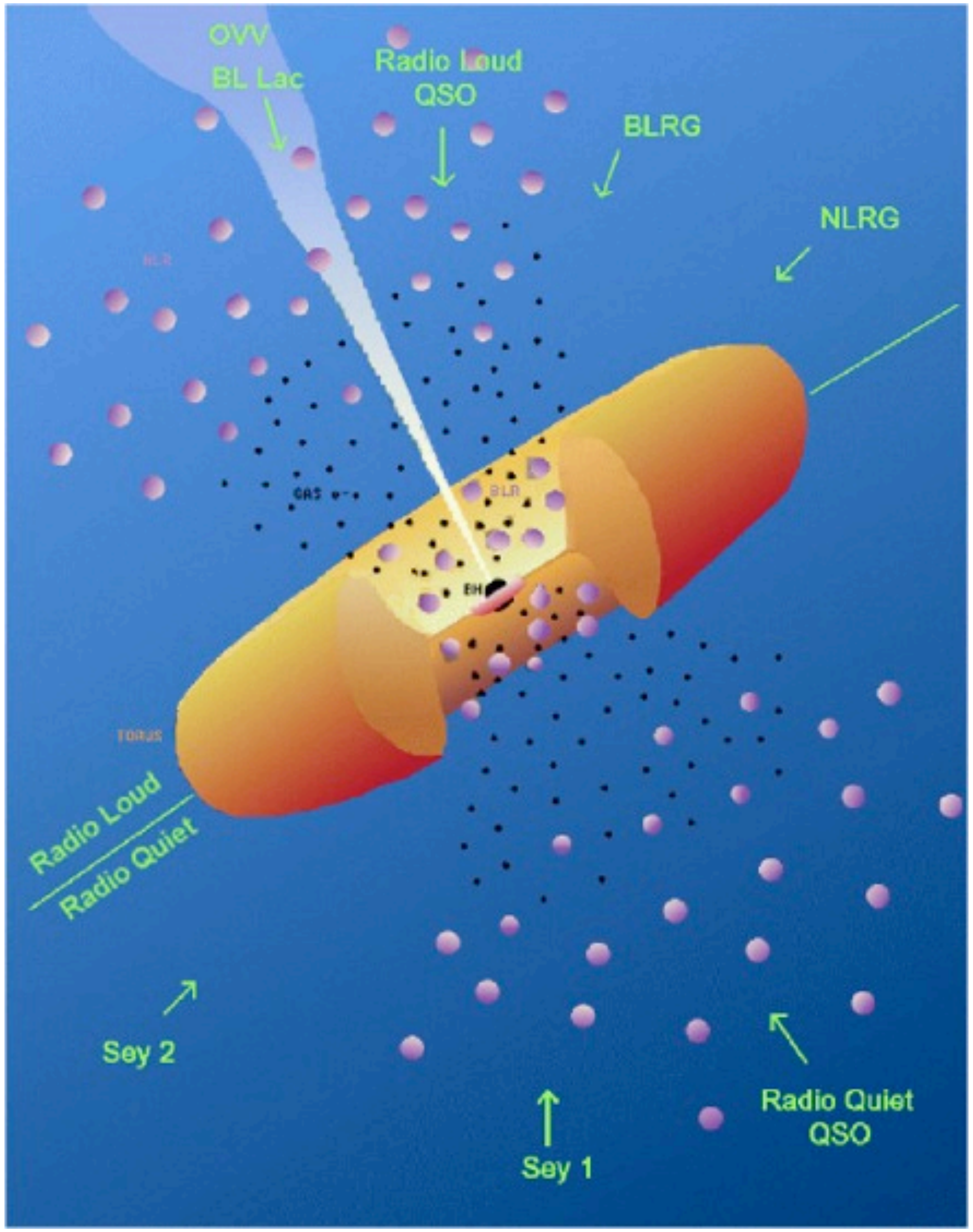


FIG. 1.—Microphotometer tracings of the emission lines λλ 4860 ($H\beta$), 4959 and 5007 [O III] in the nebulae NGC 1068, 3516, and 4151.

Seyfert 1943, ApJ...97...28

Seyfert galaxies then are characterized by:

- extremely bright nuclei
- very bright emission lines
- lines strong Doppler broadened,
- vary fast
- originating near an accretion disc:
  - at the surface of the accretion disk, or
  - at gas clouds illuminated by the central engine in an ionization cone
- narrow lines from the outer part of the AGN
- not varying
- in **Type 2** the broad component is obscured
  - in cases it can be observed in polarized light which is BLR scattered by hot, gaseous halo surrounding the nucleus (*Antonucci & Miller 1985, ApJ...297...621*).



Narrow Line Seyfert 1 galaxies

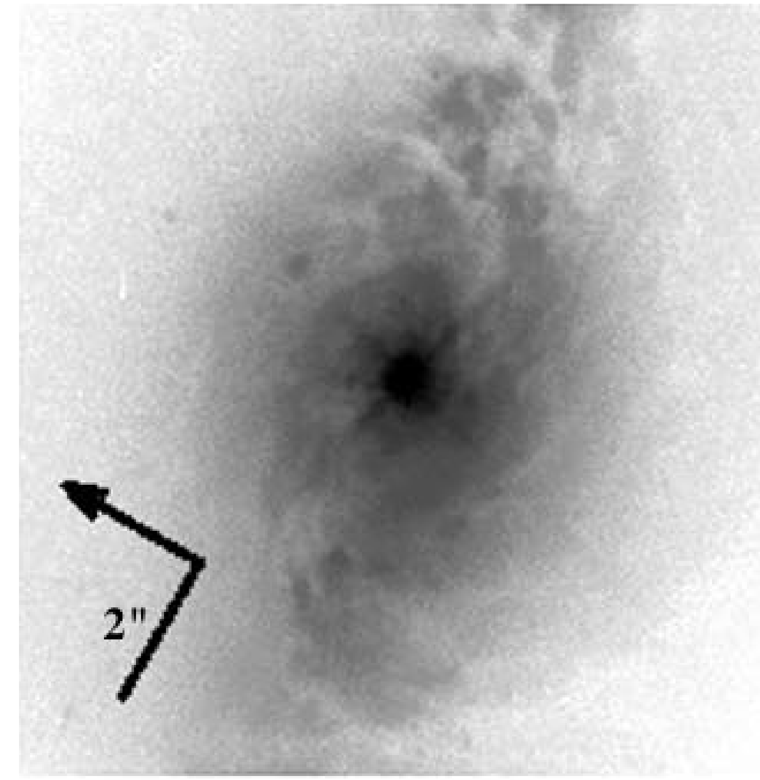
General Characteristics

Davidson & Kinman 1978, ApJ...225...776 noticed that **MRK 359**:

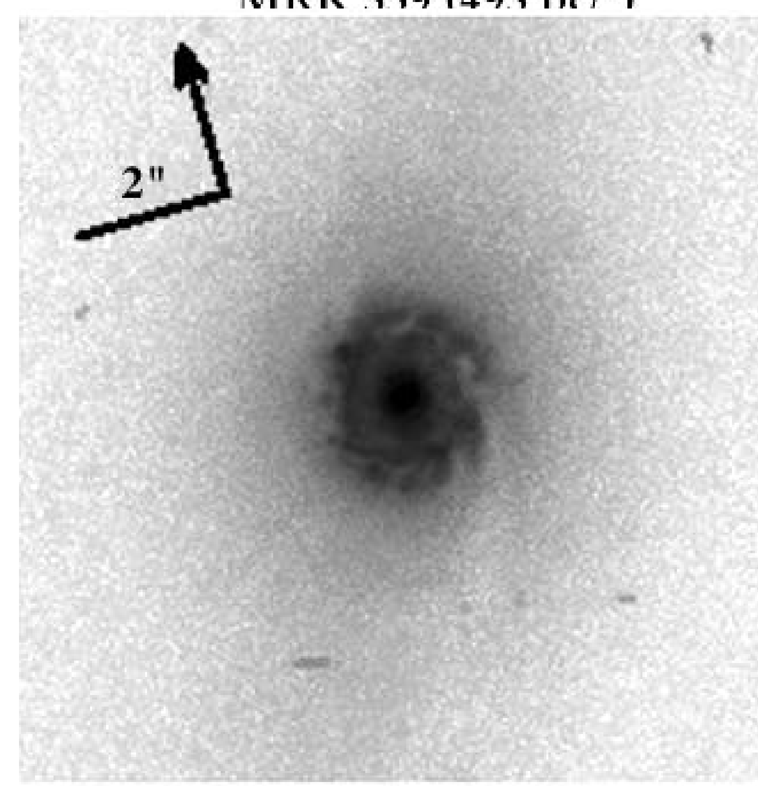
- was lying at the low-end of the line-width distribution
- HI and forbidden lines showed FWHM ~ 300 km/s (similar to Seyfert 2)
- and showed properties common for Seyfert 1's but rare for Seyfert 2's:
    - strong featureless continuum
    - strong high-ionisation lines (e.g. [Fe VII] and [Fe X])

That is: shows a mixture of properties of type 1 and 2 implying a special category that of **"Narrow Line Seyfert 1"** *(Osterbrock & Dahari 1983, ApJ... 273...478)*

Koski 1978, ApJ...223...56 and *Philips 1978, APJL... 38...187* noticed that **MRK 42** showed similar properties with all line-widths to be narrow like in Seyfert 2



MRK 359 (493 pc/")



MRK 42 (696 pc/")

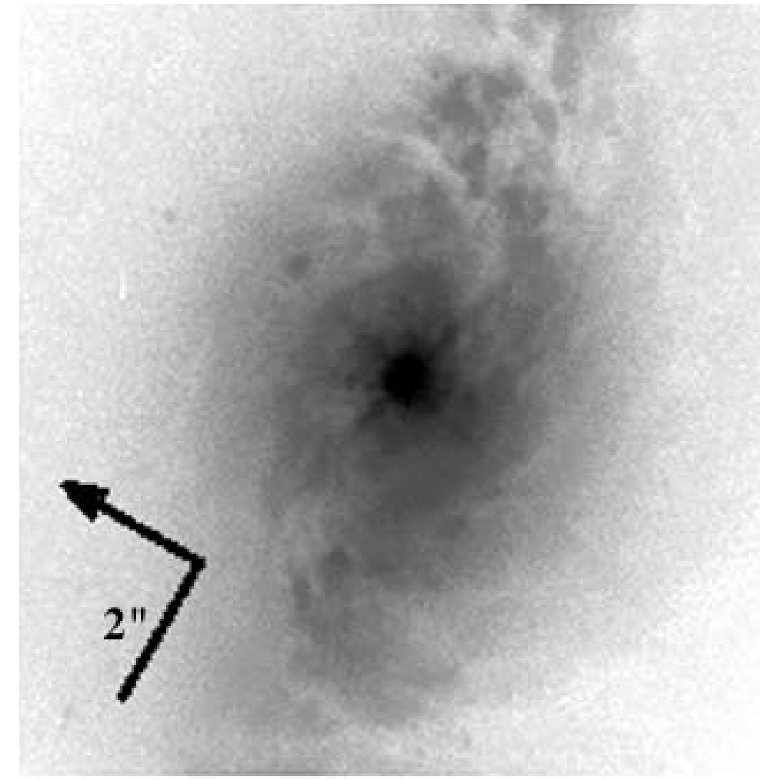
HST image, Malkan, Gorjian & Tam, 1998, ApJ...117...25

Osterbrock & Pogge 1985, ApJ...297...166 then studied a number of such sources that showed:

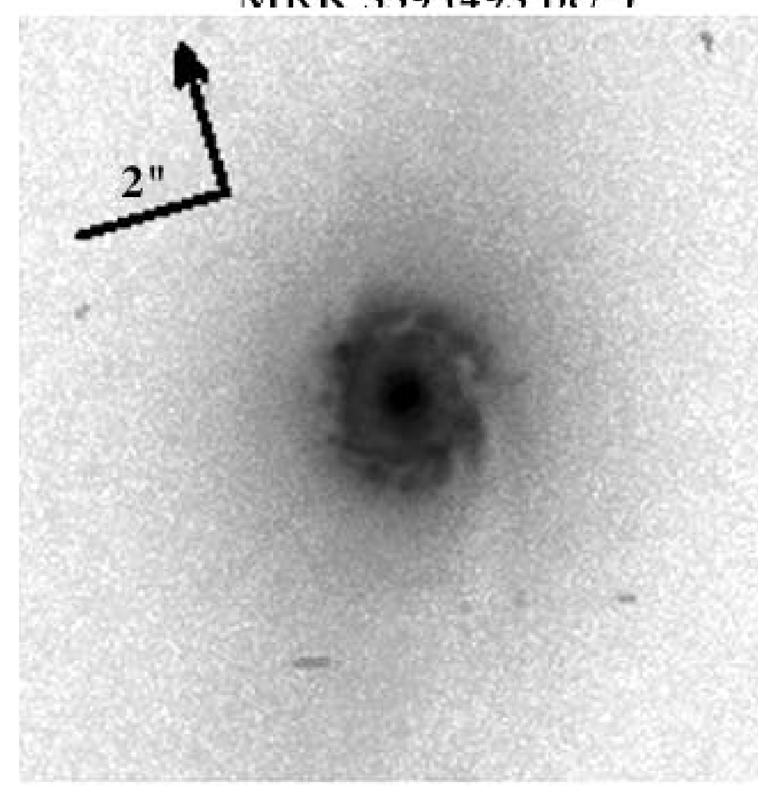
- unusually narrow HI lines
- strong Fe II line
- normal luminosities
- Hβ was slightly weaker than typical Seyfert 1's

Zhou et al 2007, ApJ...658...L13 summarize:

- a narrow width of the broad Balmer emission line: FWHM(Hβ) < 2000 km s^{-1}
- weak forbidden lines: [O III] λ5007/Hβ < 3).



MRK 359 (493 pc/")



MRK 42 (696 pc/")

HST image, Malkan, Gorjian & Tam, 1998, ApJ...117...25

Narrow Line Seyfert 1 galaxies

Radio Observations

Ulvestad, Antonucci & Goodrich 1995, AJ...109...81 studied 7 NLSY1s with VLA:

- the **radio power** at 5 GHz is moderate (10^{20-23} W/Hz)
- the radio emission is **compact** (< 300 pc)

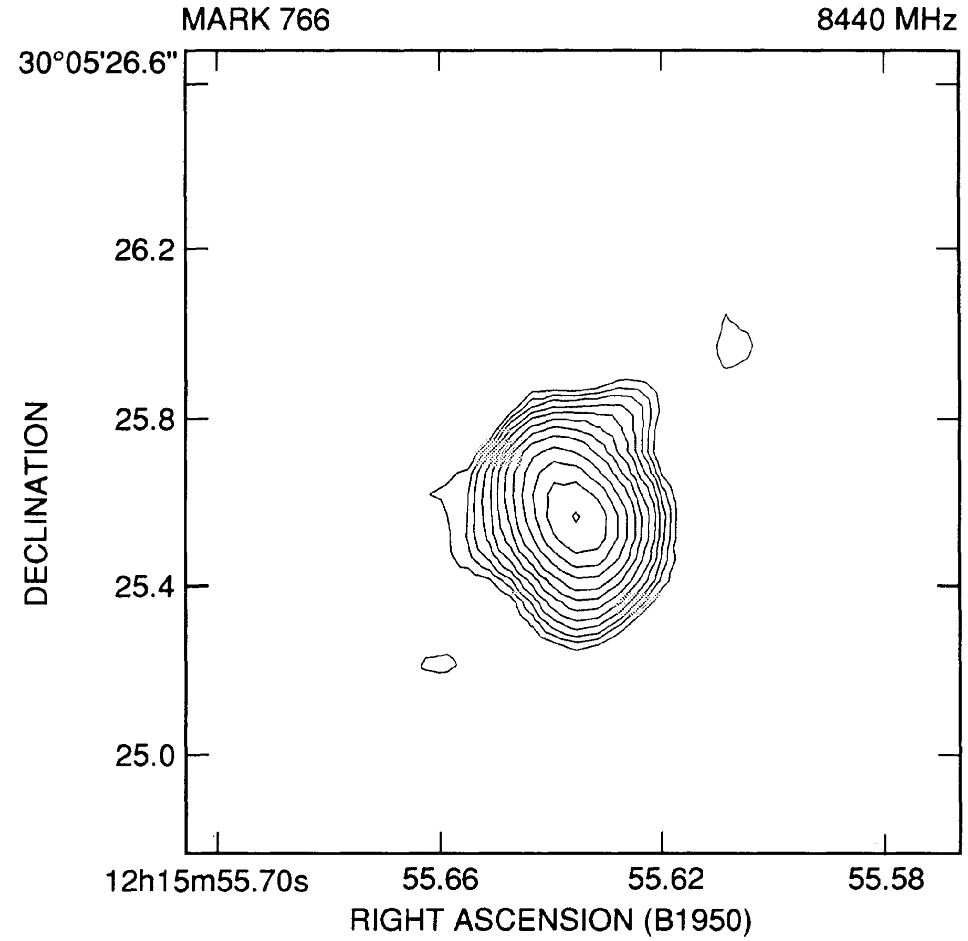
Moran 2000, NewA Rev....44...527 studied 24 NLSY1s with VLA:

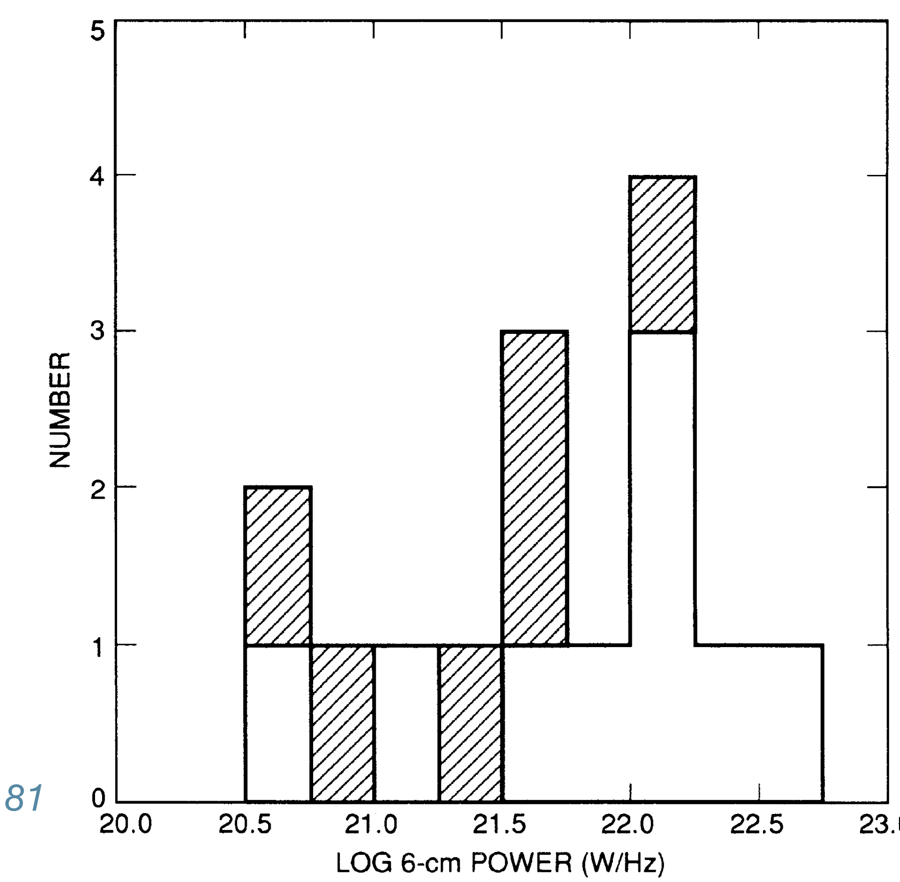
- most of the sources are **unresolved**
- show relatively **steep spectra**

Stepanian et al. 2003, ApJ...588...746 studied 26 NLS1 galaxies and found:

- found 9 radio-detected (FIRST) all **radio-quiet**

Greene, Ho & Ulvestad 2006, ApJ...636...56 observed in radio 19 galaxies with low BH mass and NLS1 spectra and **found only 1**

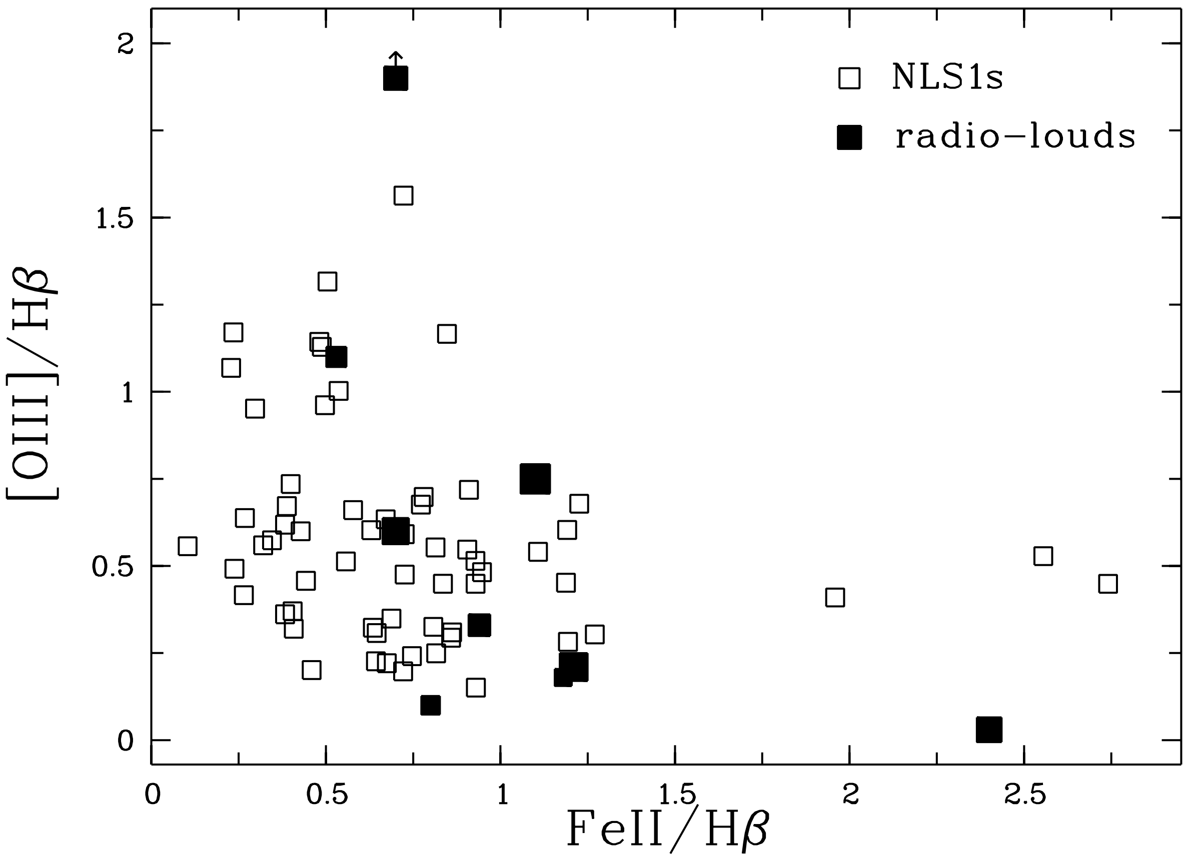


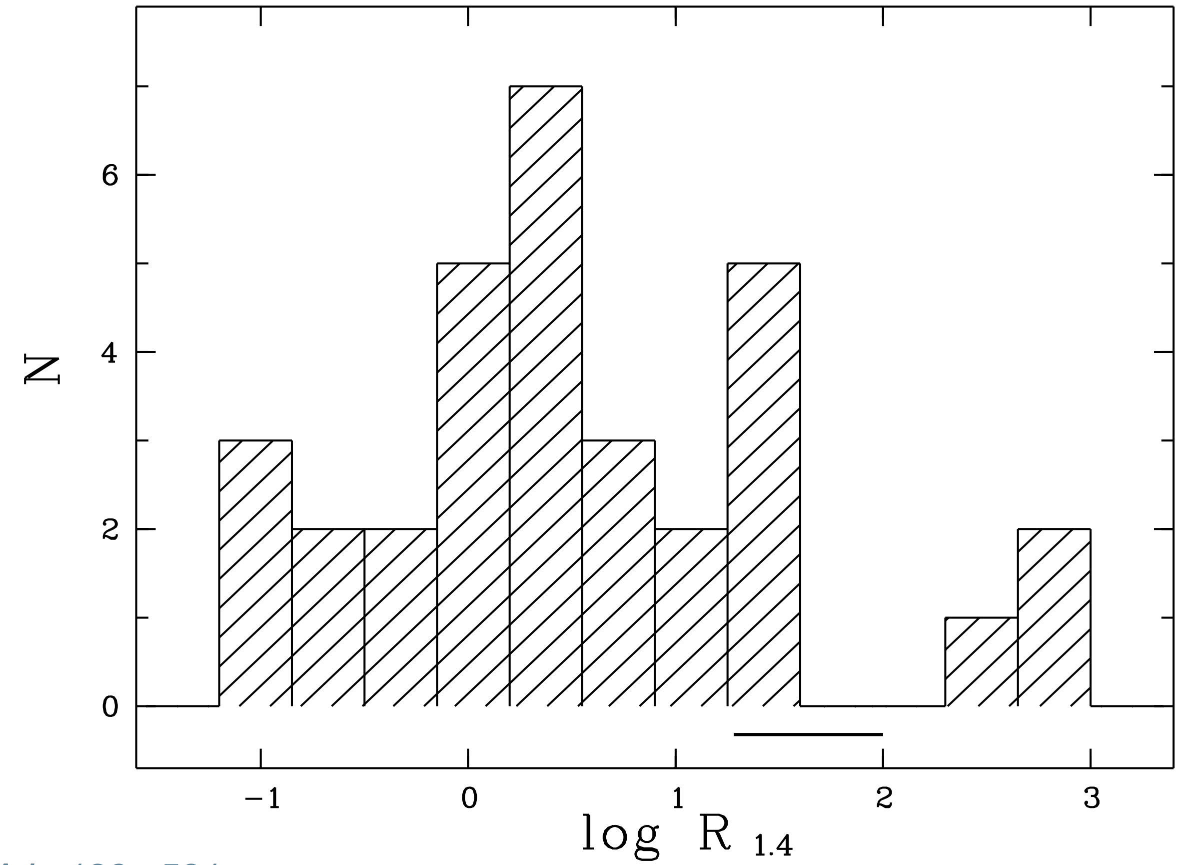


Ulvestad, Antonucci & Goodrich 1995, AJ...109...81

Komossa et al 2006, AJ...132...531 studied a number of NLS1s and found:

- most radio-loud NLS1 are **compact**, **steep**-spectrum, accreting close to or **above the L_{Edd}**
- black hole masses are generally at the upper observed end for NLS1 but still **unusually small**
- index R is distributed smoothly up to the critical value of ~ 10 and covers about 4 orders of magnitude
- ~7% of the NLS1 galaxies are formally radio-loud,
- only 2.5% exceed a radio index R > 100
- morphology similar Compact Steep Spectrum sources (e.g. PKS 2004–447 by Galo et al. 2006, MNRAS...370...245)





Komossa et al 2006, AJ...132...531

RL Narrow Line Seyfert 1 galaxies

the *Fermi* / LAT discovery

Abdo et al. 2009, ApJ...699...976 reports the very first *Fermi*/LAT detection of PMNJ0948+0022

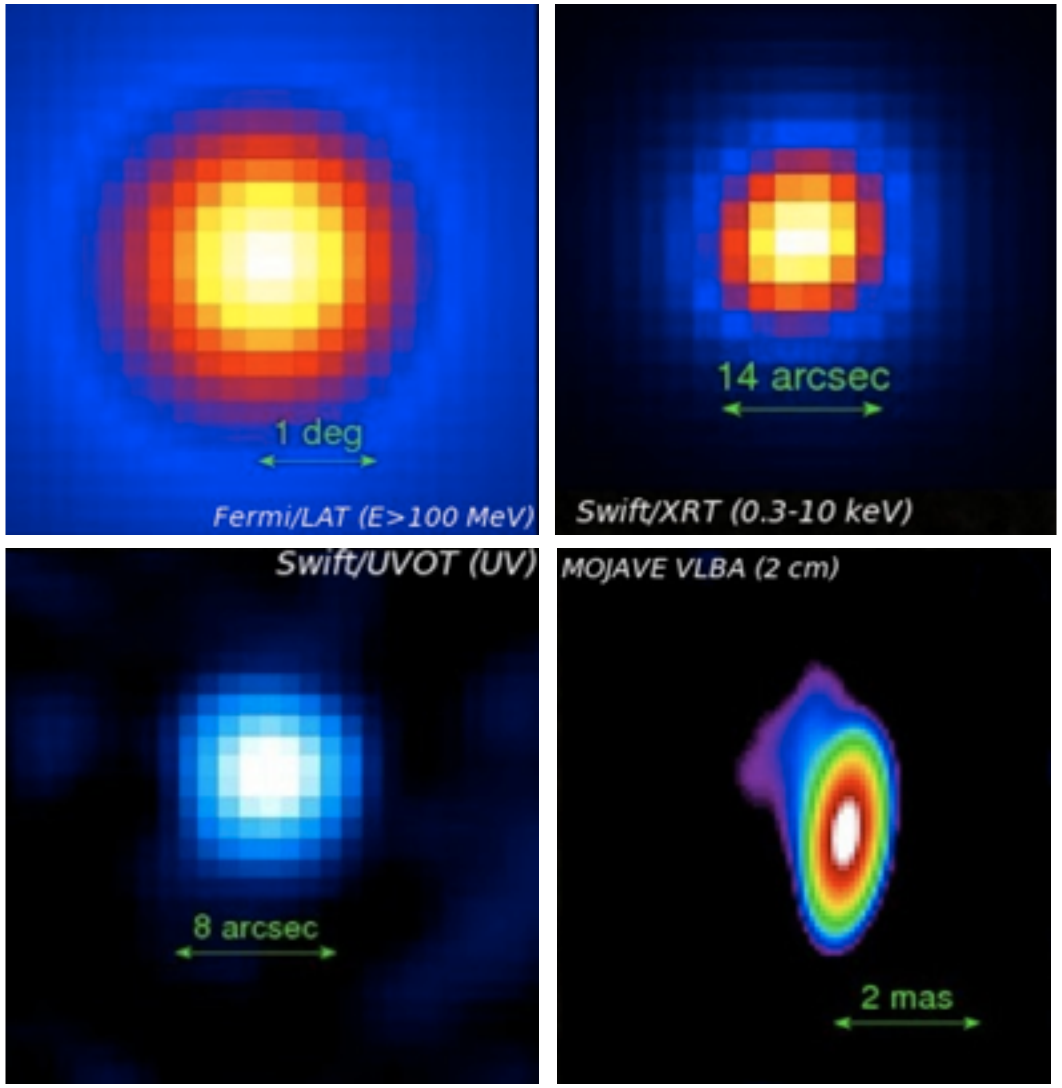
in the first year **4 RL NLSy1** galaxies are detected (*Foschini et al. 2010, ASPC...427...243*):

- 1H0323+342 (z = 0.061)
- PMNJ0948+0022 (z = 0.585)
- PKS1502+036 (z = 0.409)
- PKS2004-447 (z = 0.24)

after 30 months 7 are detected :

- SBS 0846+513 (z = 0.585) (*F. D'Ammando et al. 2012, MNRAS...426...317*)

currently ~dozen **RL NLSy1s** are detected in MeV - GeV ate lower significance (*Foschini et al. 2011, PoS...024 : http://tinyurl.com/gnls1s*)



PMNJ0948+0022 for the July 2010 outburst
Foschini et al. 2010 (image compilation by L. Foschini)

What is so special about RL NLSy1s:

E.g. Foschini et al. 2013, PoS:

- a new class of γ-ray AGN
- show jets similar to blazars although very different in:
  - mass $10^{6-8} M_\odot$
  - high accretion rate 0.1 – $1 L_{Edd}$,
  - host morphology (mostly in spirals)

- **What switches on the jet production**?
- allow us to study a rather unexplored range of low masses ($10^{6-8} M_\odot$):
  - breaking down of the mass requirement of the central accreting object to develop a jet in AGN (*Laor 2000, ApJ...543...L111*)

- RL NLSy1s maybe blazars in a early stage of their life

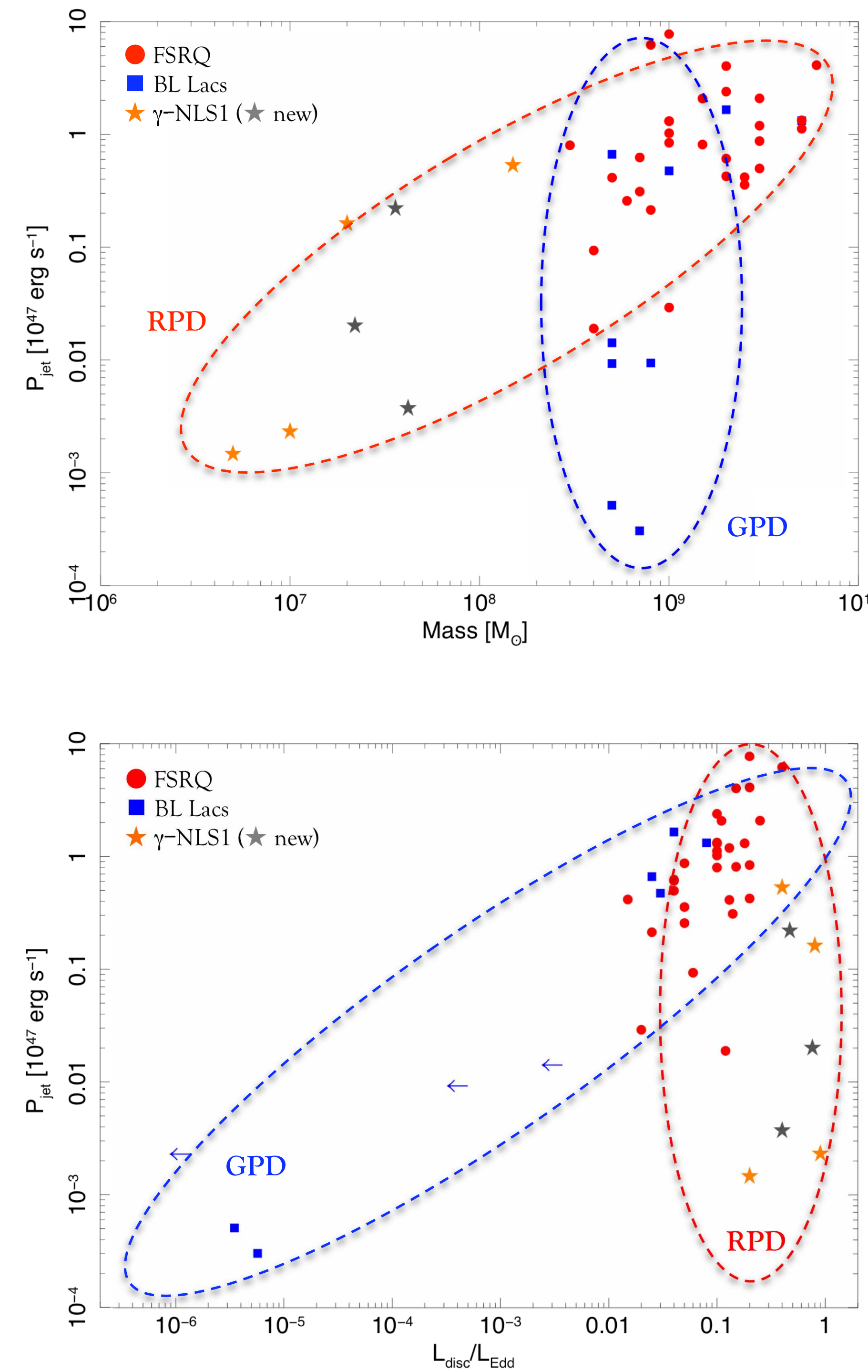


Fig. 3 Jet power vs mass of the central black hole (*top panel*) and the accretion luminosity in Eddington units (*bottom panel*). See the text for more details.

Foschini 2011, RAA....11.1266F

Our monitoring

intro | instruments | tools

F-GAMMA program (*Furhmann et al. 2007, AIPCS... 921...249 ; Angelakis et al. 2010arXiv1006.5610A*):

- Effelsberg 100-m, IRAM 30-m and APEX 12-m
- monitoring ~60 Fermi blazars since January 2007
- at 2.6 - 345 GHz at 12 frequencies, optical and gamma-rays
- linear and circular polarization
- mean cadence 1.3 months

RoboPol program (*Pavlidou, Angelakis et al. in prep.*):

- **optical polarimetry** (first light spring 2013)
- ~100 sources (targets and “control” sample)
- cadence 1/3 days

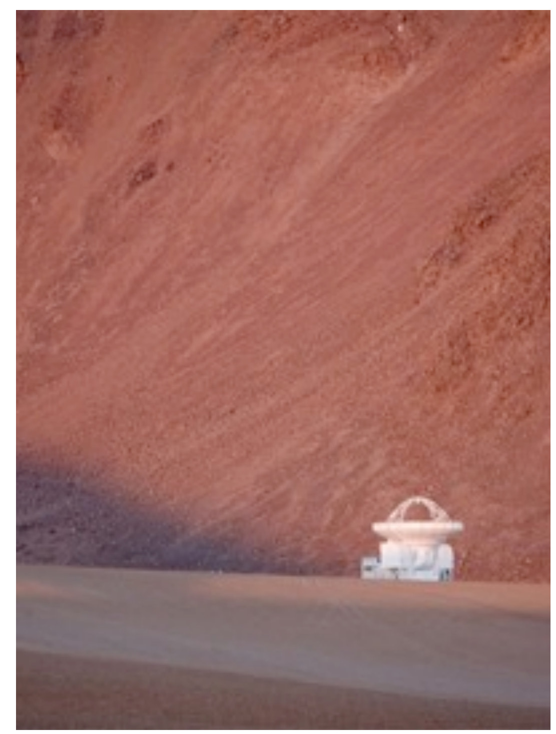
VLBI structural evolution:

- J0324+3410 (*Karamanavis, Furhmann et al. in prep.*)

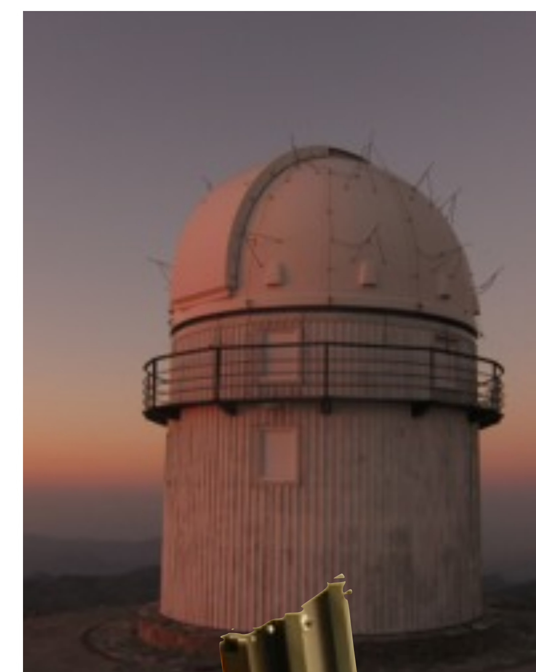
Effelsberg 100-m telescope

IRAM 30-m telescope

APEX telescope



Skinakas 1.3 m telescope

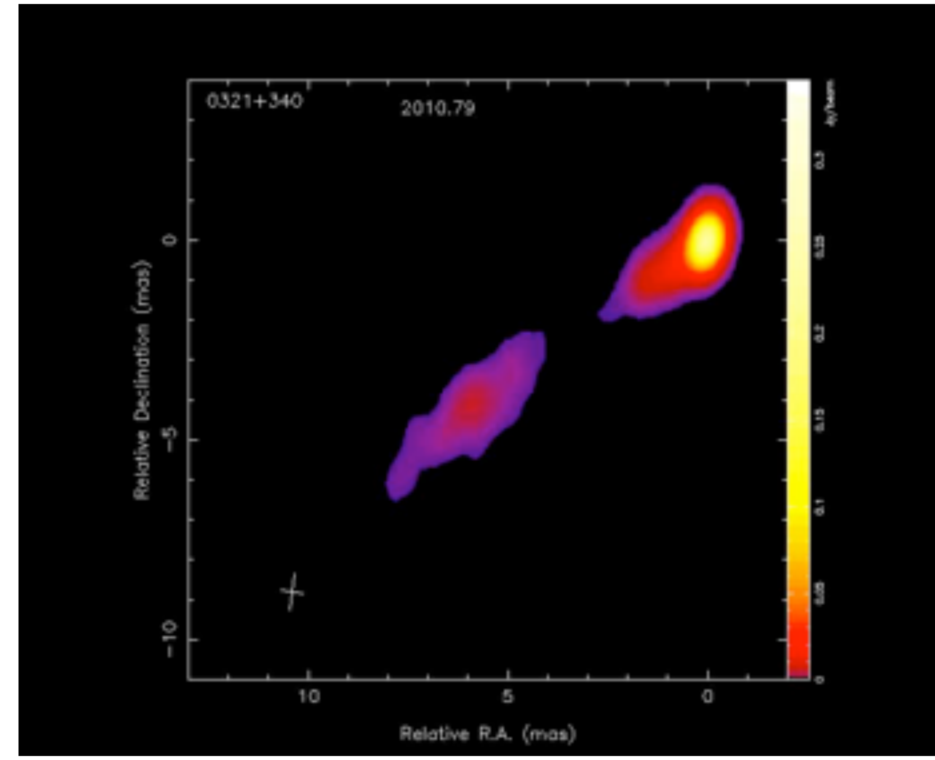


See talk by Prof. V. Pavlidou

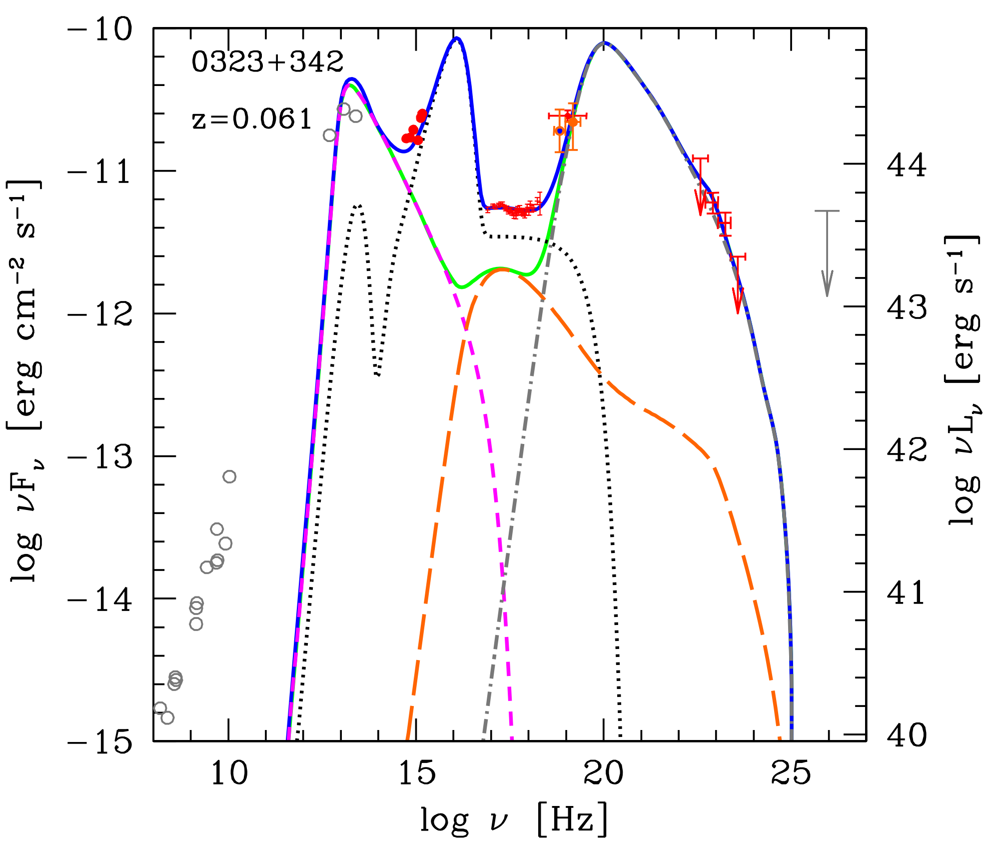
J0324+3410

cm to sub-cm bands | light curves

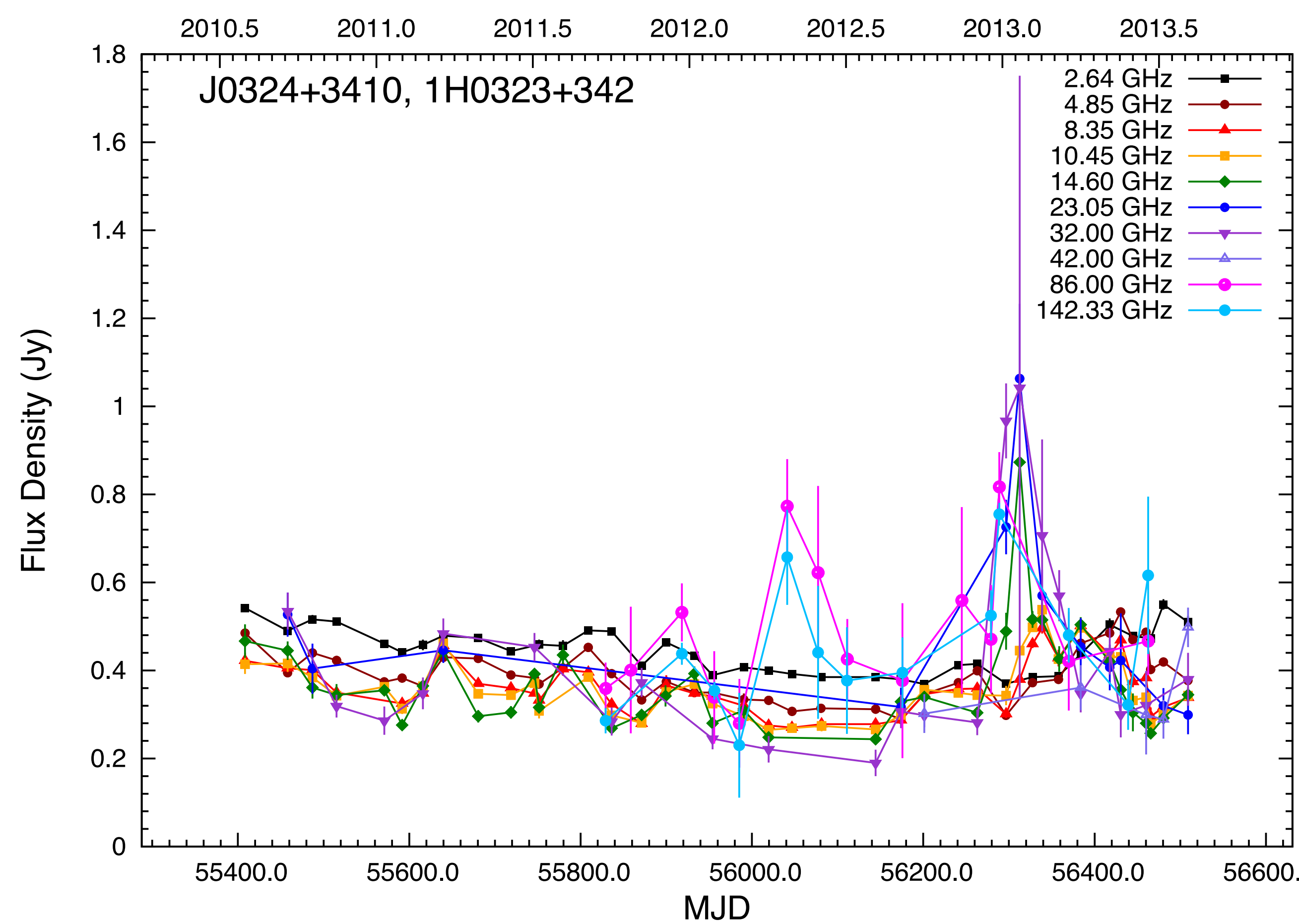
- **mild variability** at low frequencies and intense at high
- short-lived events
- high frequency events absent at low frequencies ! (events not energetic enough?...)
- extended jet apparent even at intermediate frequencies



MOJAVE survey 2cm
scale: 1.162 kpc/" (assumed: Ho = 71, flat universe)



Abdo et al. 2009, ApJ...707...L142–L147

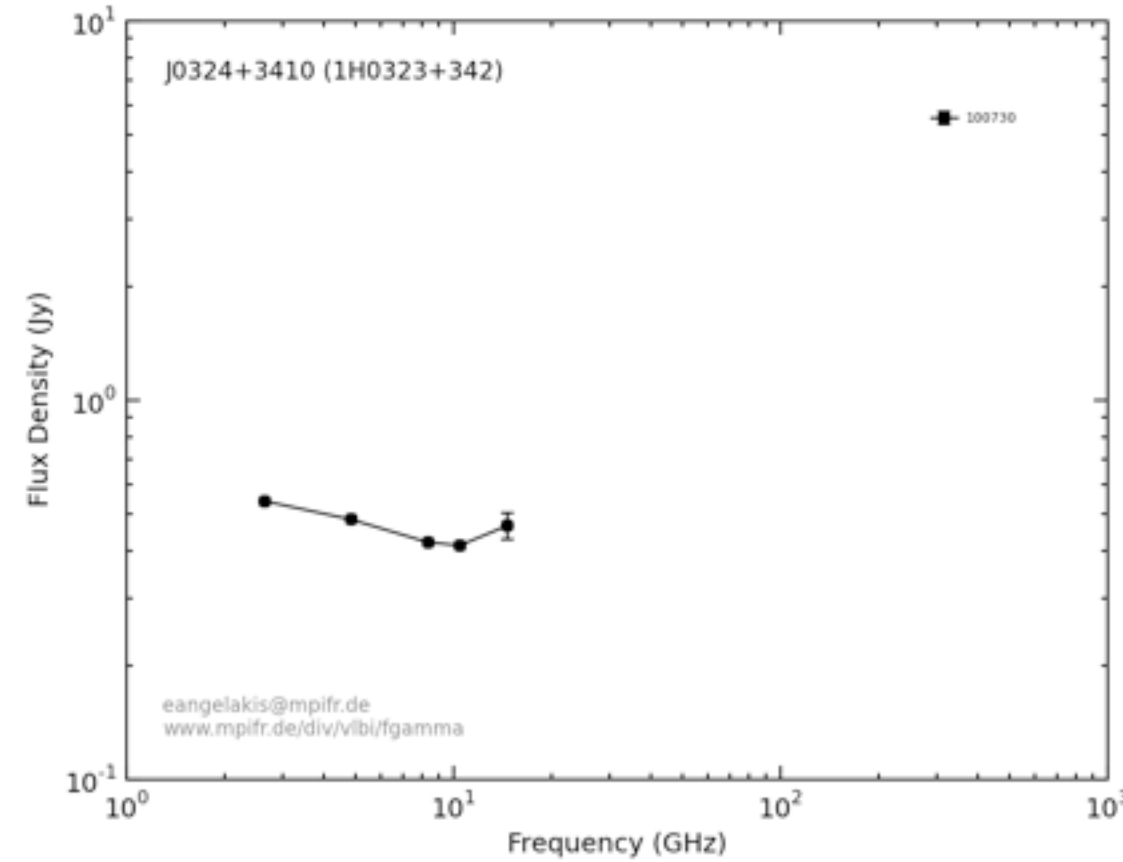


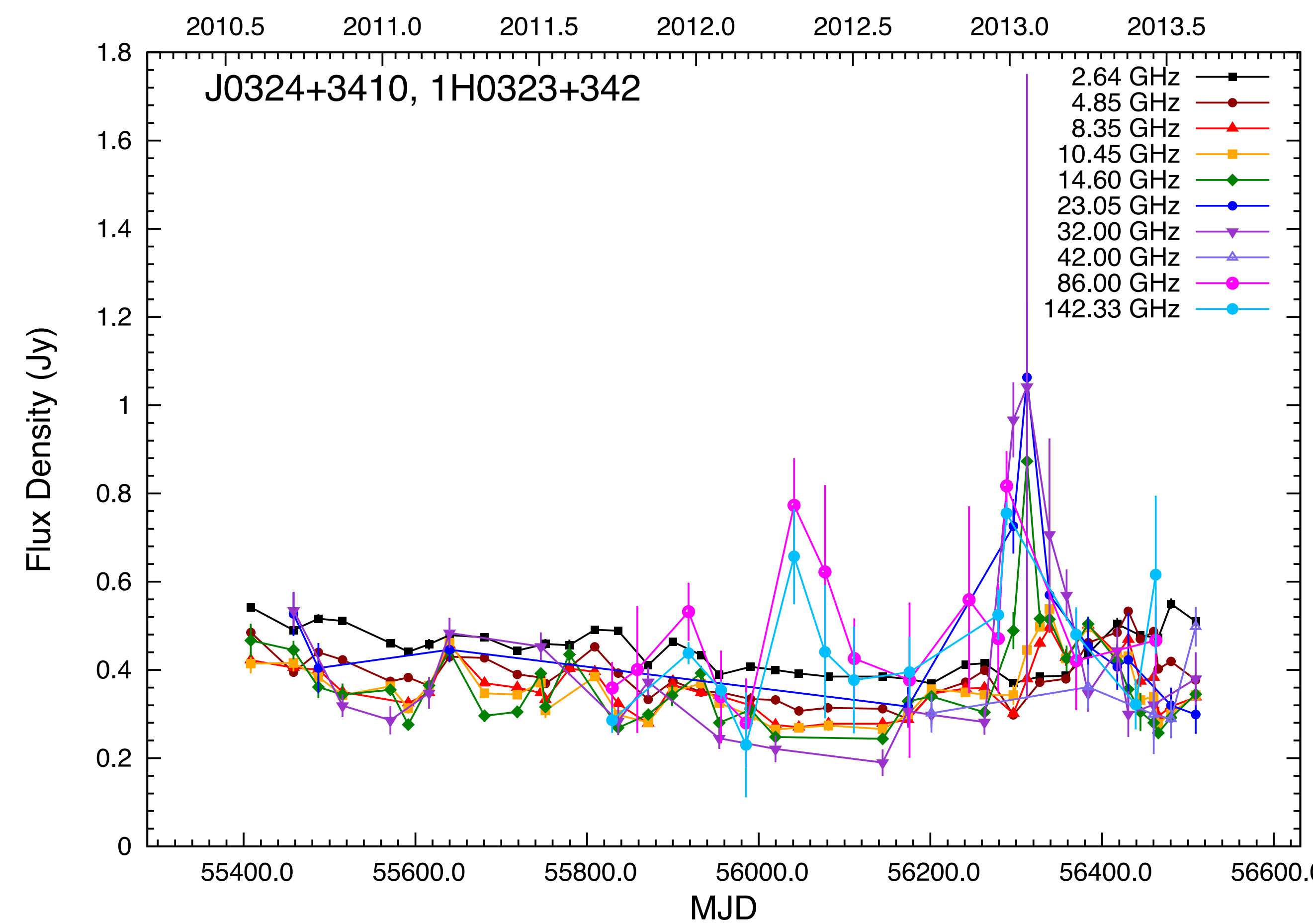
2010arXiv1006.5610A and Angelakis et al. in prep.

J0324+3410

cm to sub-cm bands | radio SED

- **prominent quiescence** spectrum
  - optically thin extended jet : $\alpha_{2.6\text{-}8.4\ \mathbf{min}} \sim -0.5$
- **spectral evolution** at high frequencies $\alpha_{25\text{-}230\ \mathbf{max}} \sim +1.0$
  - very homogenous events
- rapid spectral variability (~month)



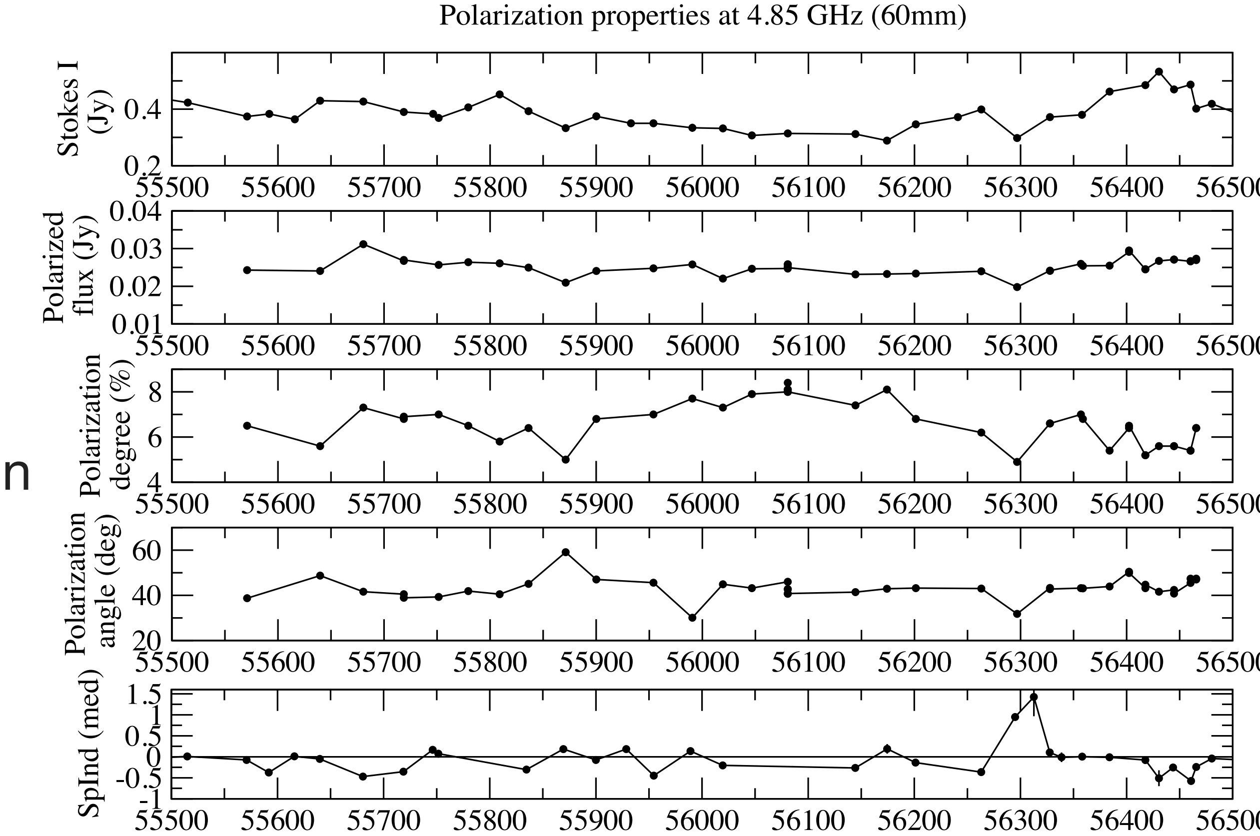


2010arXiv1006.5610A and Angelakis et al. in prep.

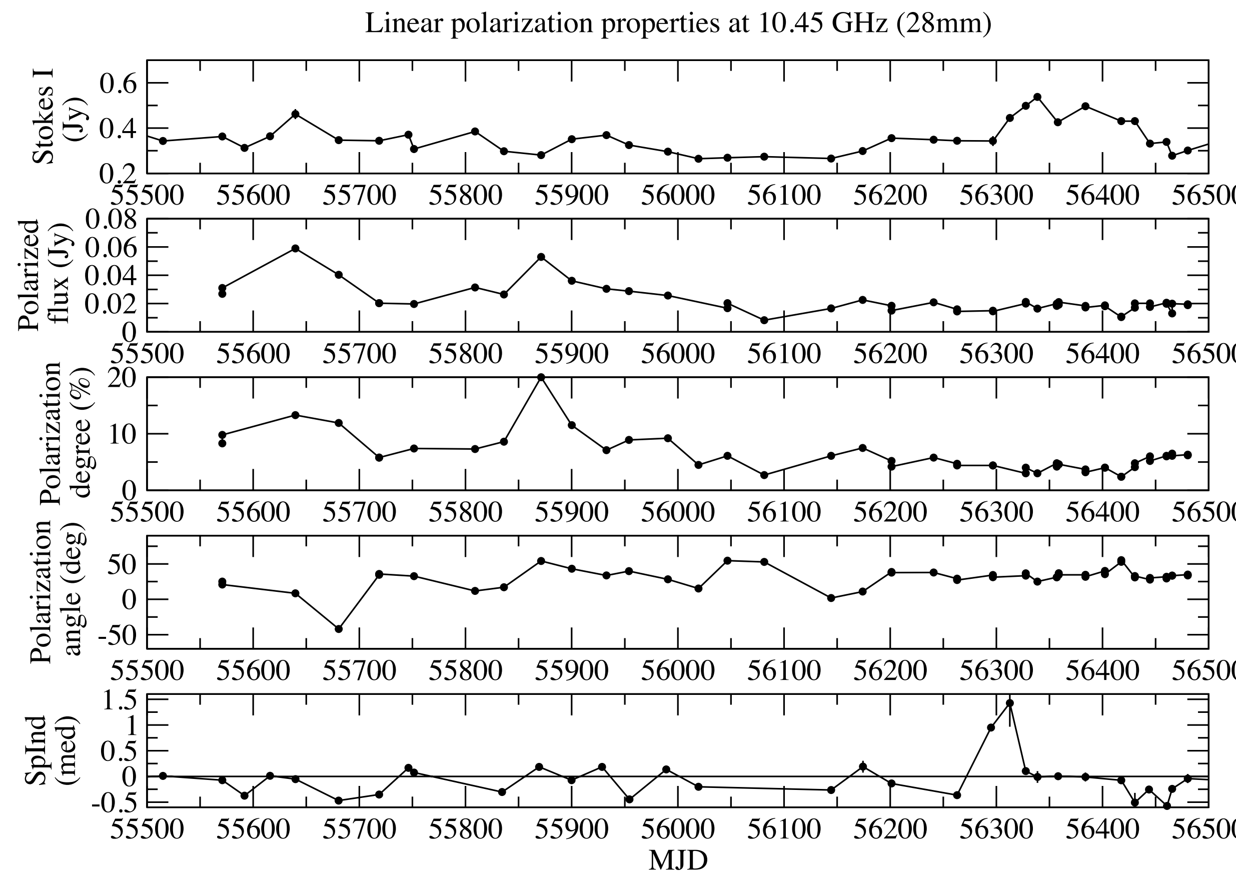
J0324+3410

cm to sub-cm bands | radio polarization

- **highly radio polarized** : signature of a optically thin relic jet
- highly **variable polarization**: indicative of spectral events
- correlated with opacity evolution



Frequency (GHz)	<PD> (%)	StDev	<PA> (deg)	StDev
4.85	6.6	0.97	43	5
8.4	5.8	1.03	35	2
10.45	6	3.15	30	15

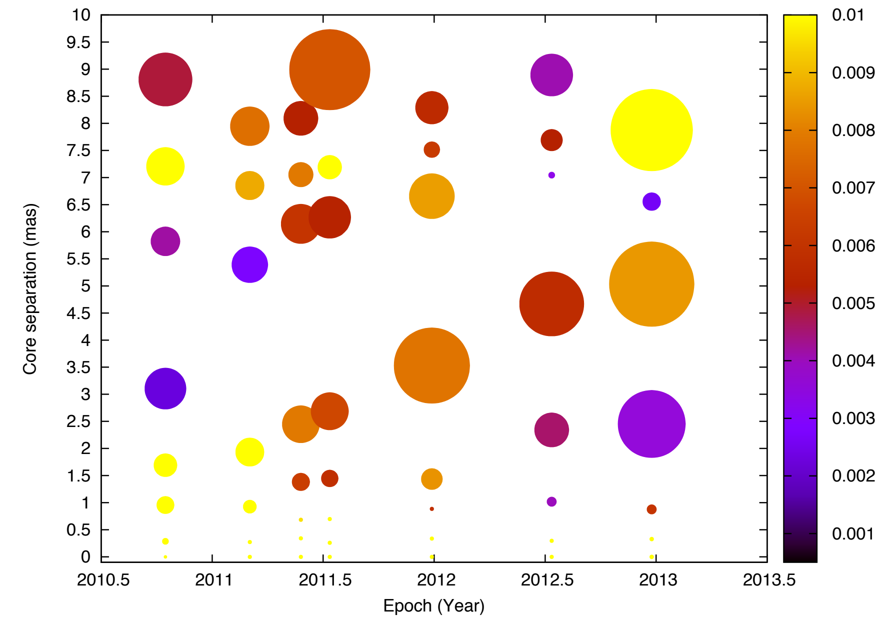


analysis done by I. Myserlis

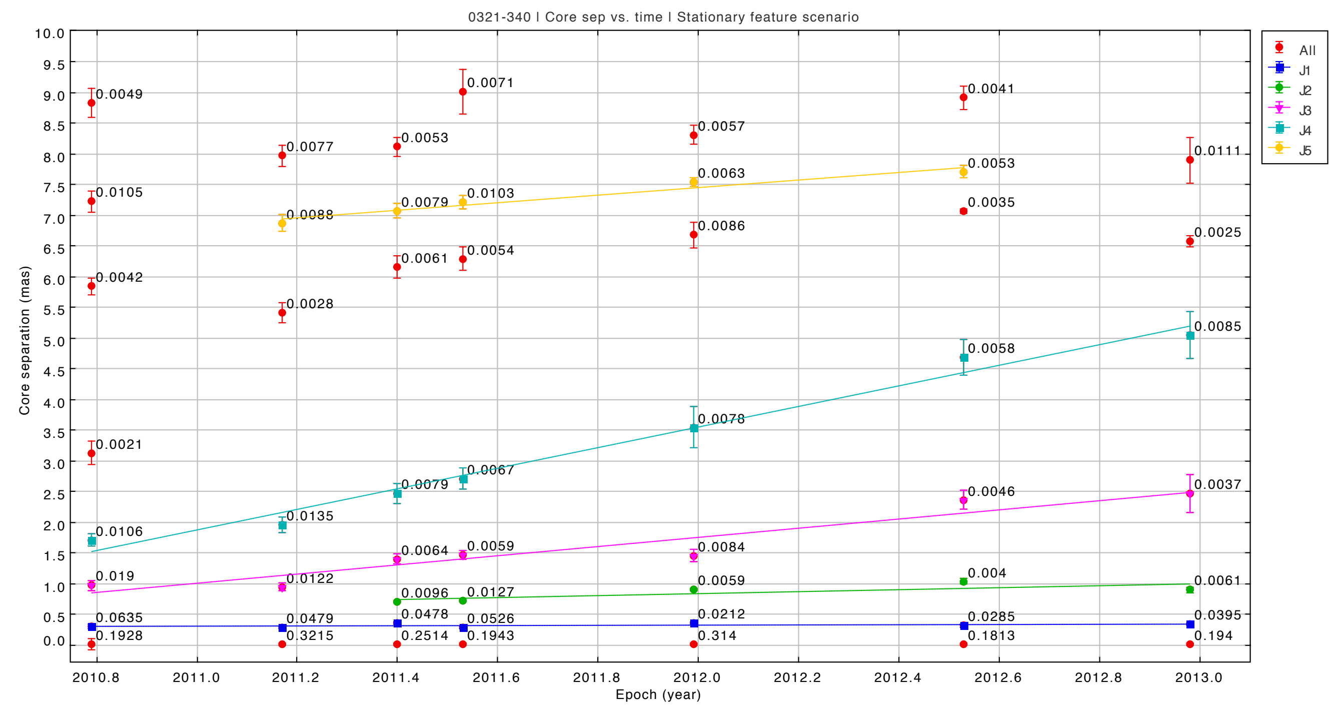
2010arXiv1006.5610A and Angelakis et al. in prep.

J0324+3410

VLBI | structural evolution



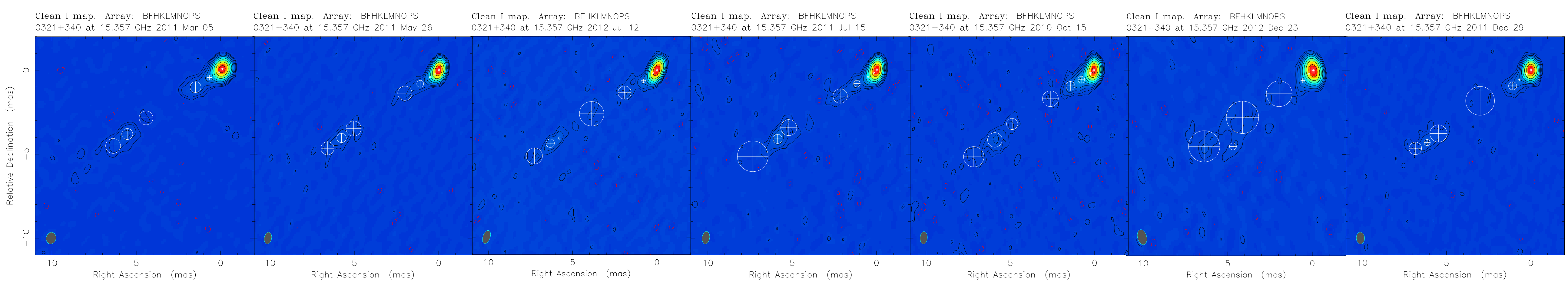
- combine variability D and apparent speeds to extract
  - viewing angles
  - Lorenz factors
- super-c **indicating relativistic jet**



$$u_{\mathrm{app}} = \frac{u_{\mathrm{jet}} \sin\theta}{1 - \frac{u_{\mathrm{jet}}}{c} \cos\theta}$$

$$\delta_{\mathrm{jet}} = \gamma_{\mathrm{jet}} \left(1 - \frac{u_{\mathrm{jet}}}{c}\right)^{-1}$$

Component ID	mas/y	β_{app}	Notes
J1	0.0176	0.071	The stationary feature
J2	0.164	0.658	
J3	0.752	3.017	
J4	1.676	6.723	
J5	0.616	2.471	

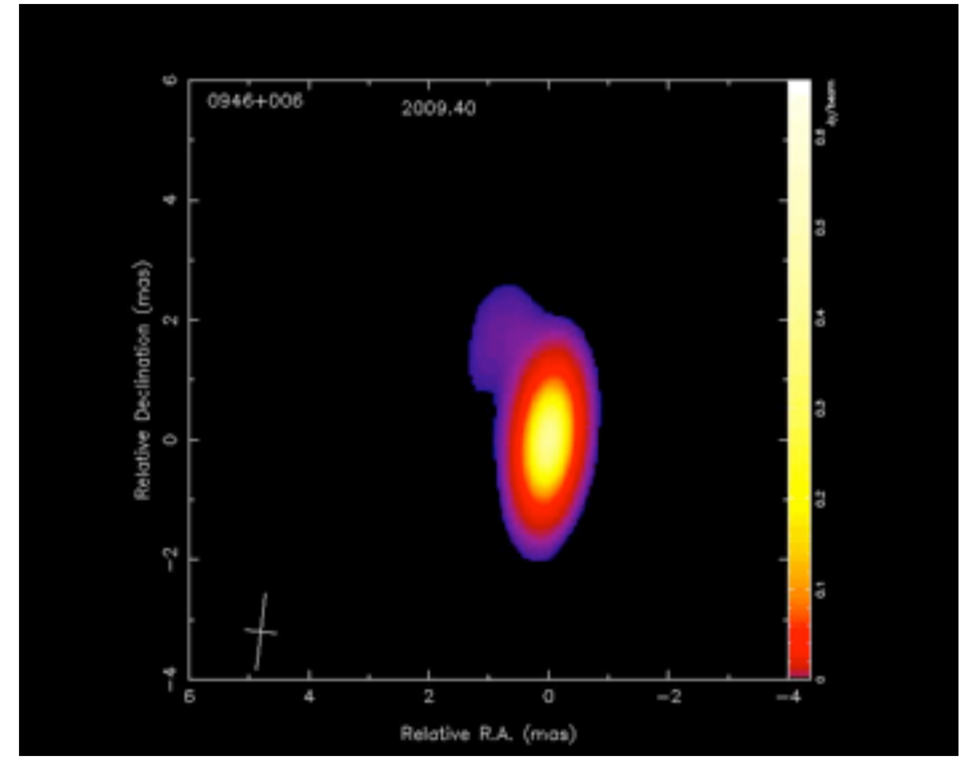


Karamanavis, Fuhrmann et al. in prep.

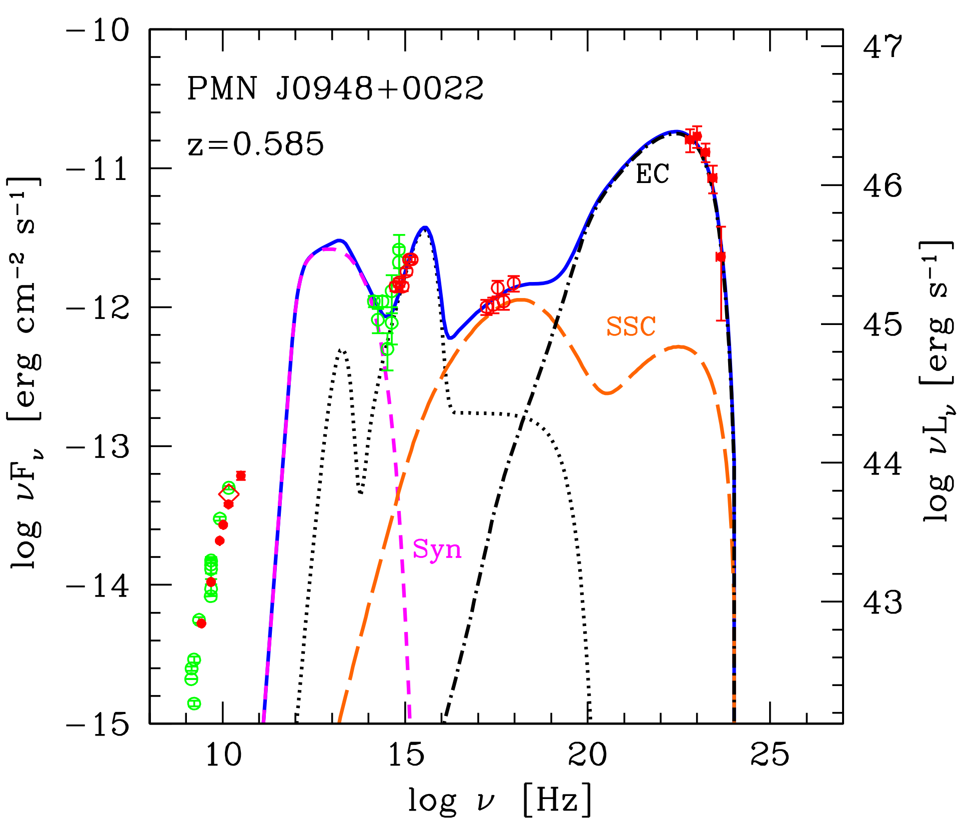
J0948+0022

cm to sub-cm bands | light curves

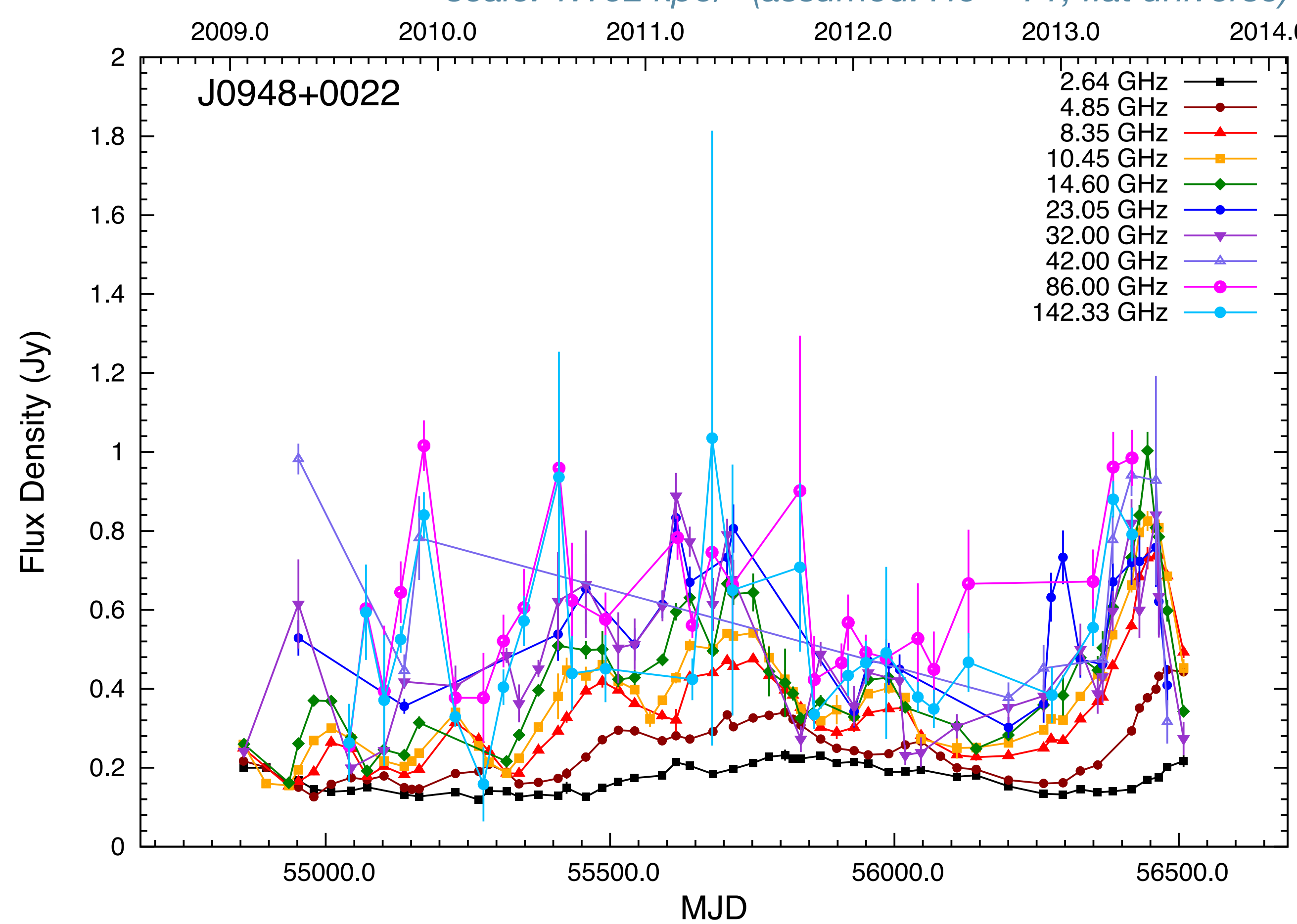
- **intense variability** (factors ~5)
- **short events** with **spectral evolution**
- events propagation in band-pass (energetic enough? ...)



MOJAVE survey 2cm
scale: 1.162 kpc/" (assumed: Ho = 71, flat universe)



Abdo et al. 2009, ApJ...707...L142–L147

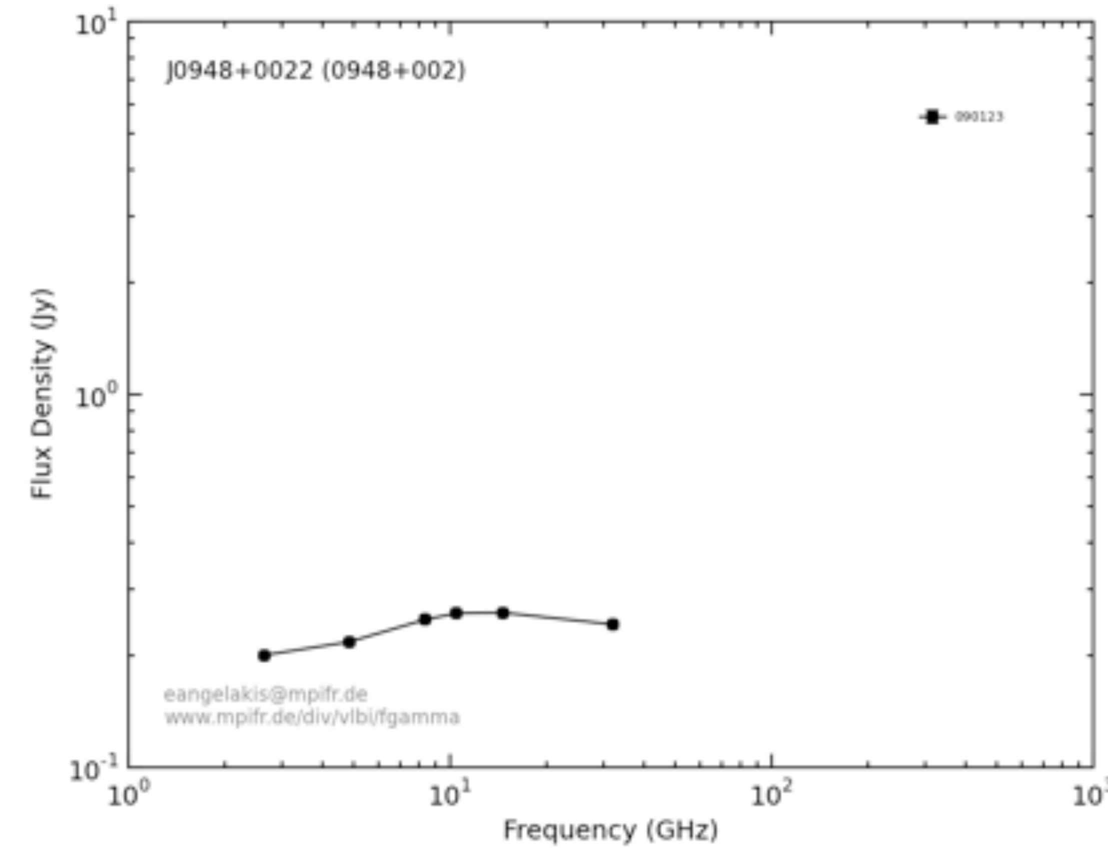


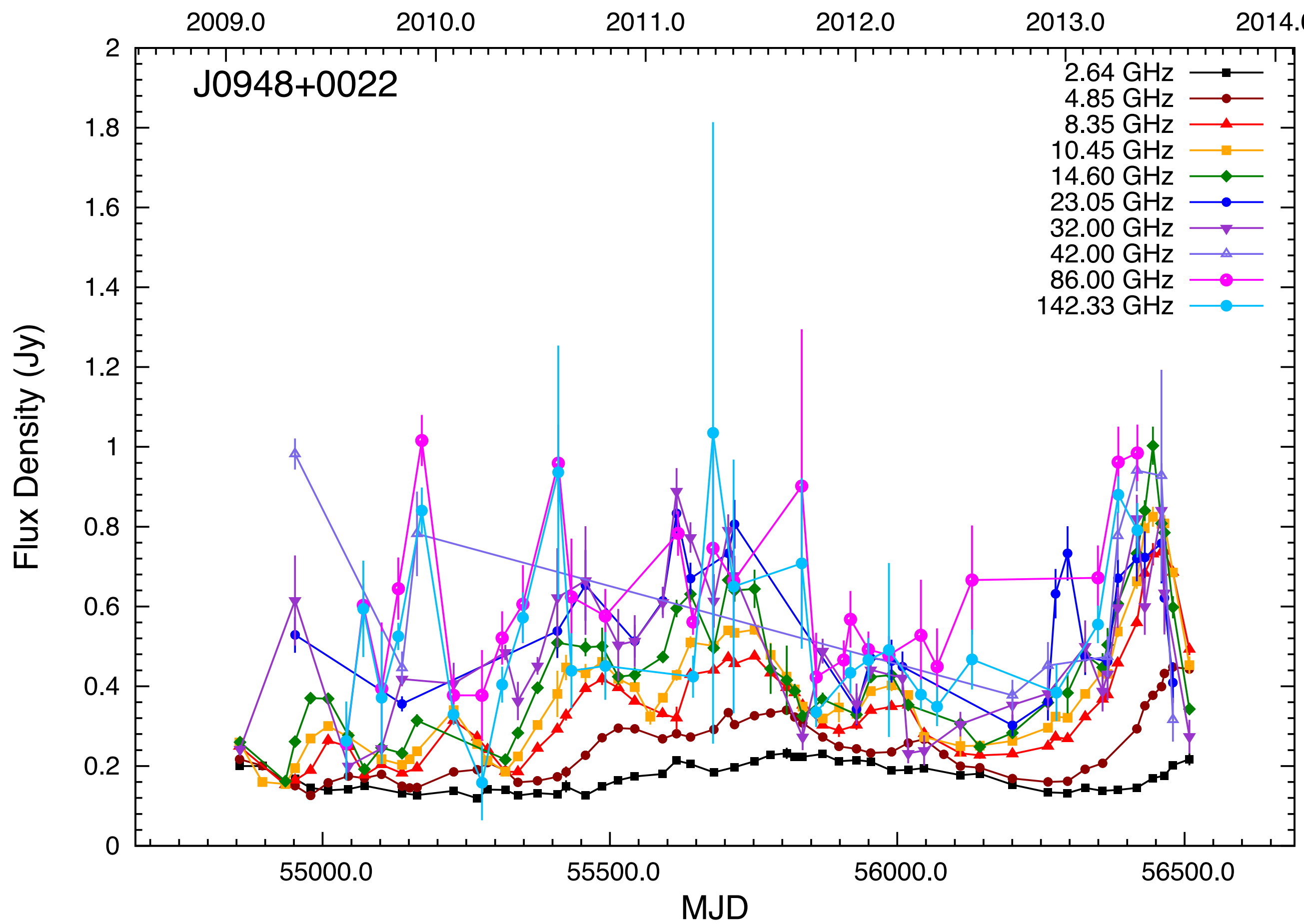
2010arXiv1006.5610A and Angelakis et al. in prep.

J0948+0022

cm to sub-cm bands | radio SED

- absent (?) quiescence spectrum:
  $\alpha_{2.6\text{-}8.4\ \mathbf{min}} \sim$ **-0.13**
- spectral evolution present at all frequencies:
  $\alpha_{2.6\text{-}8.4\ \mathbf{max}} \sim$ **+1.3**
- variability transverses the band-pass
  $\alpha_{25\text{-}230\ \mathbf{max}} \sim$ **+1.6** and $\alpha_{25\text{-}230\ \mathbf{min}} \sim$ **-1.7**
  - homogenous events
- rapid spectral variability





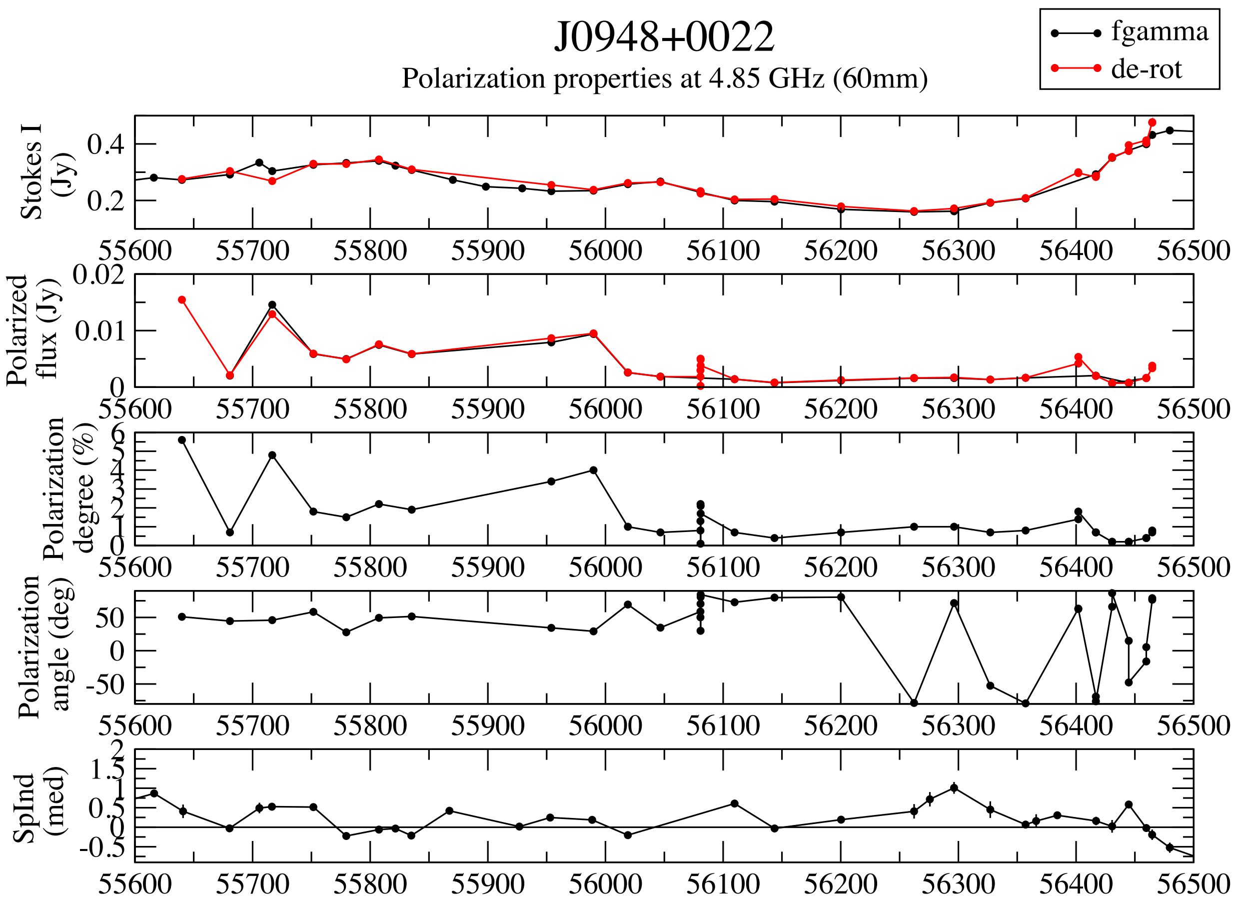
2010arXiv1006.5610A and Angelakis et al. in prep.

J0948+0022

cm to sub-cm bands | radio polarization

- **radio un-polarised** : core dominated, optically thick unpolarised emission
- optical polarization **historical values ~19%**

Frequency (GHz)	<PD> (%)	StDev	<PA> (deg)	StDev
4.85	1.4	1.3		
8.4	1.1	1.1		
10.45	3.3	3.3		

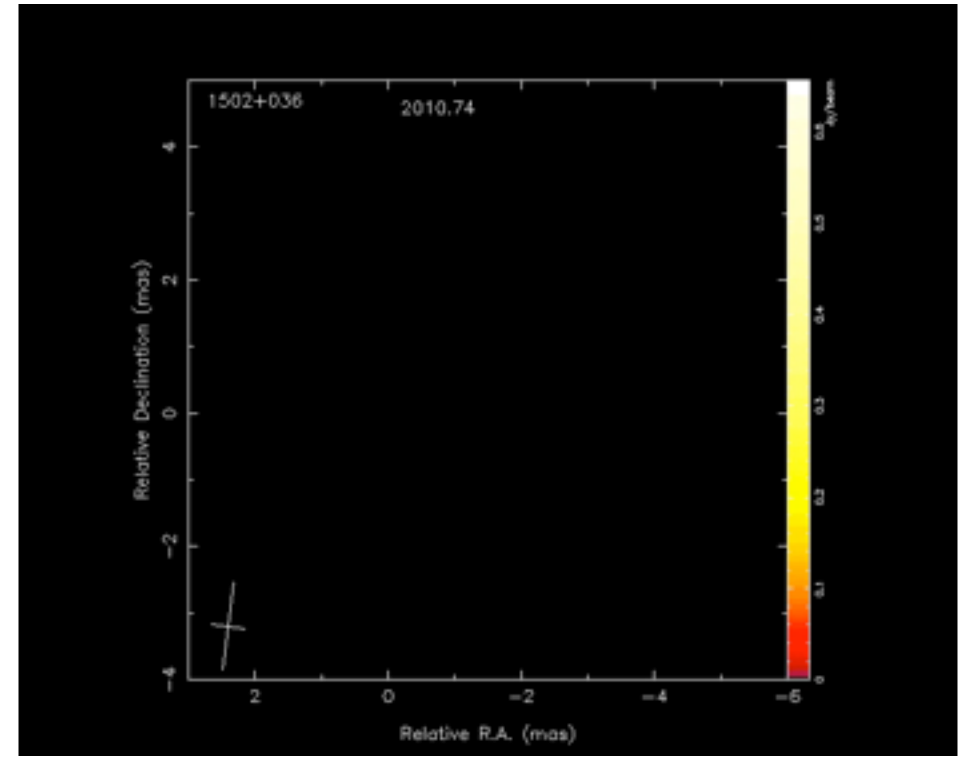


2010arXiv1006.5610A and Angelakis et al. in prep.

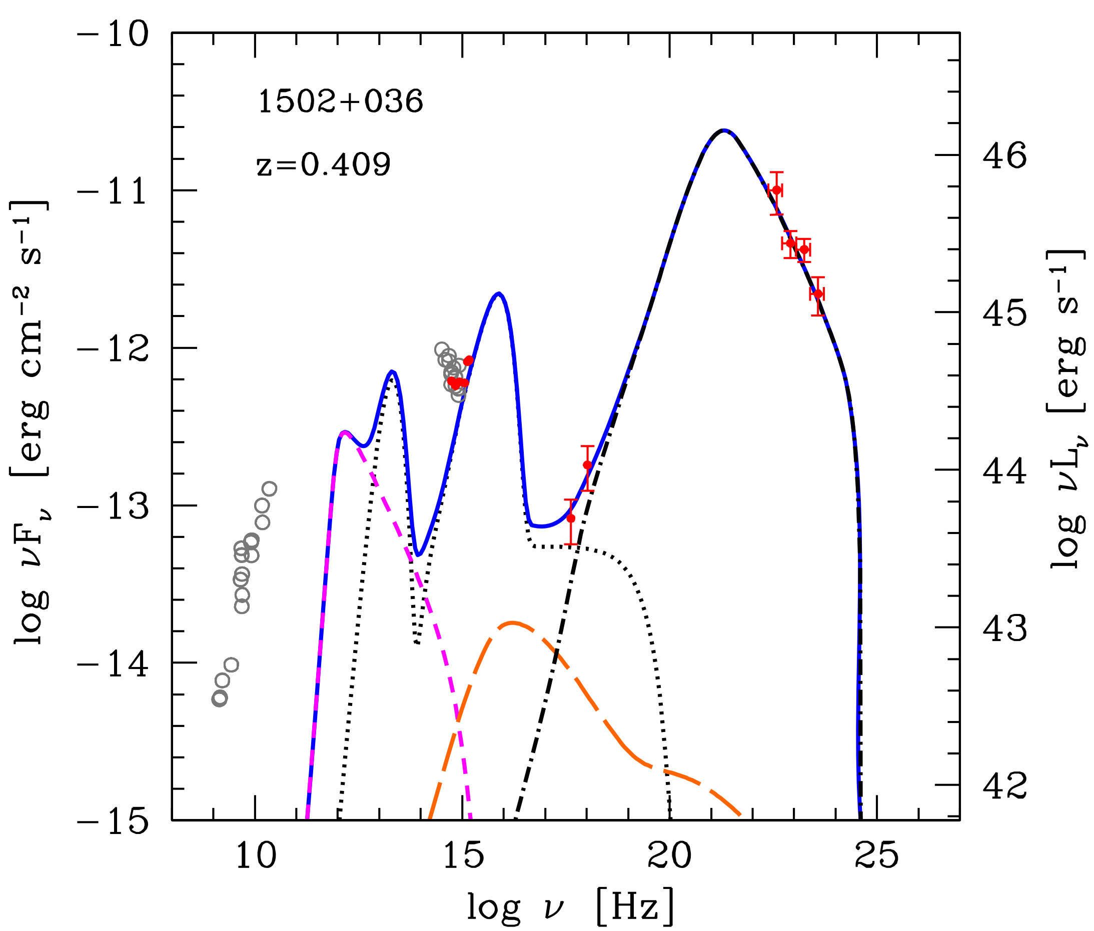
J1505+0326

cm to sub-cm bands | light curves

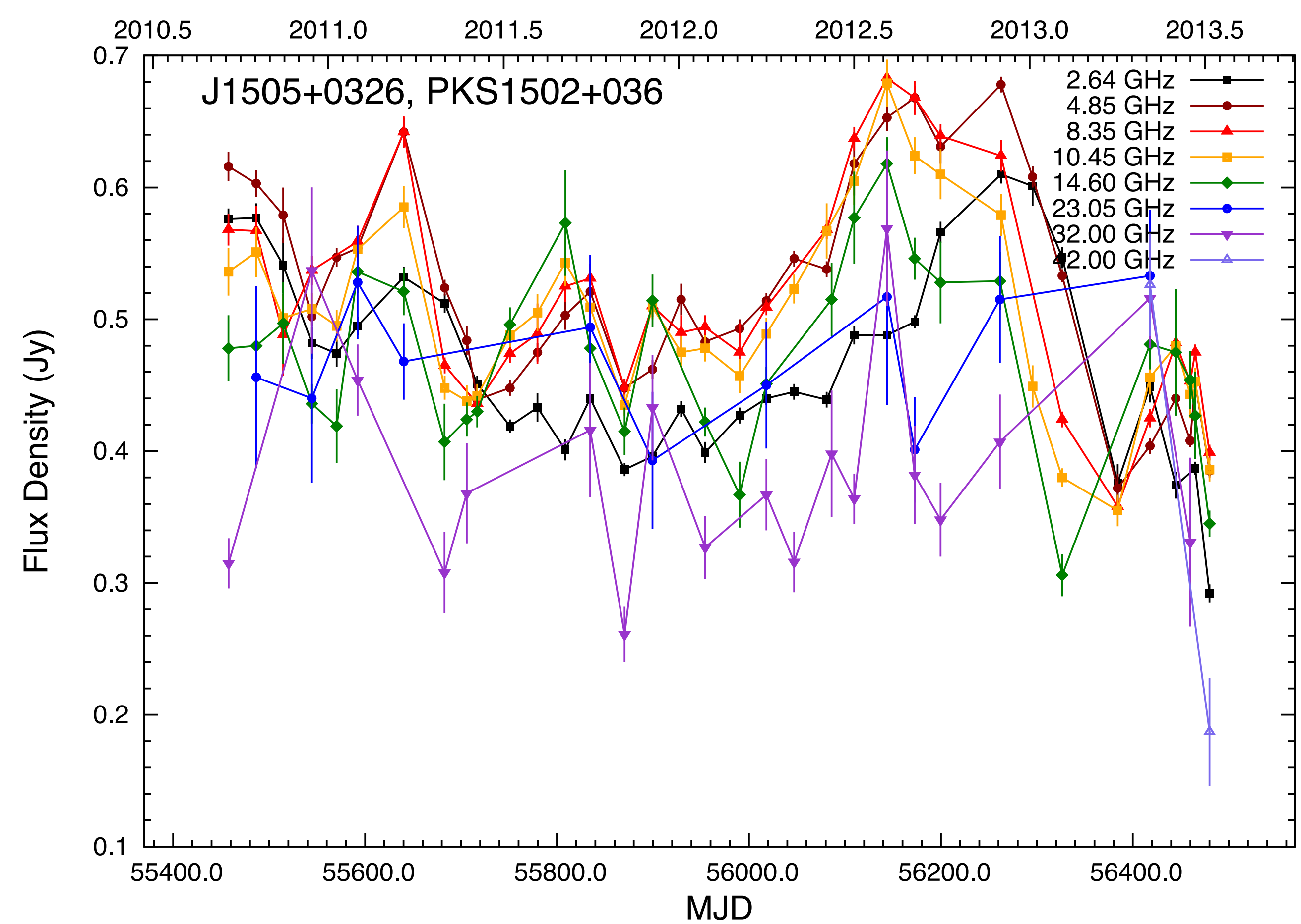
- **mild** variability
- **long** events
- **core** dominated



MOJAVE survey 2cm
scale: 5.416 kpc/" (assumed: Ho = 71, flat universe)



Abdo et al. 2009, ApJ...707...L142–L147

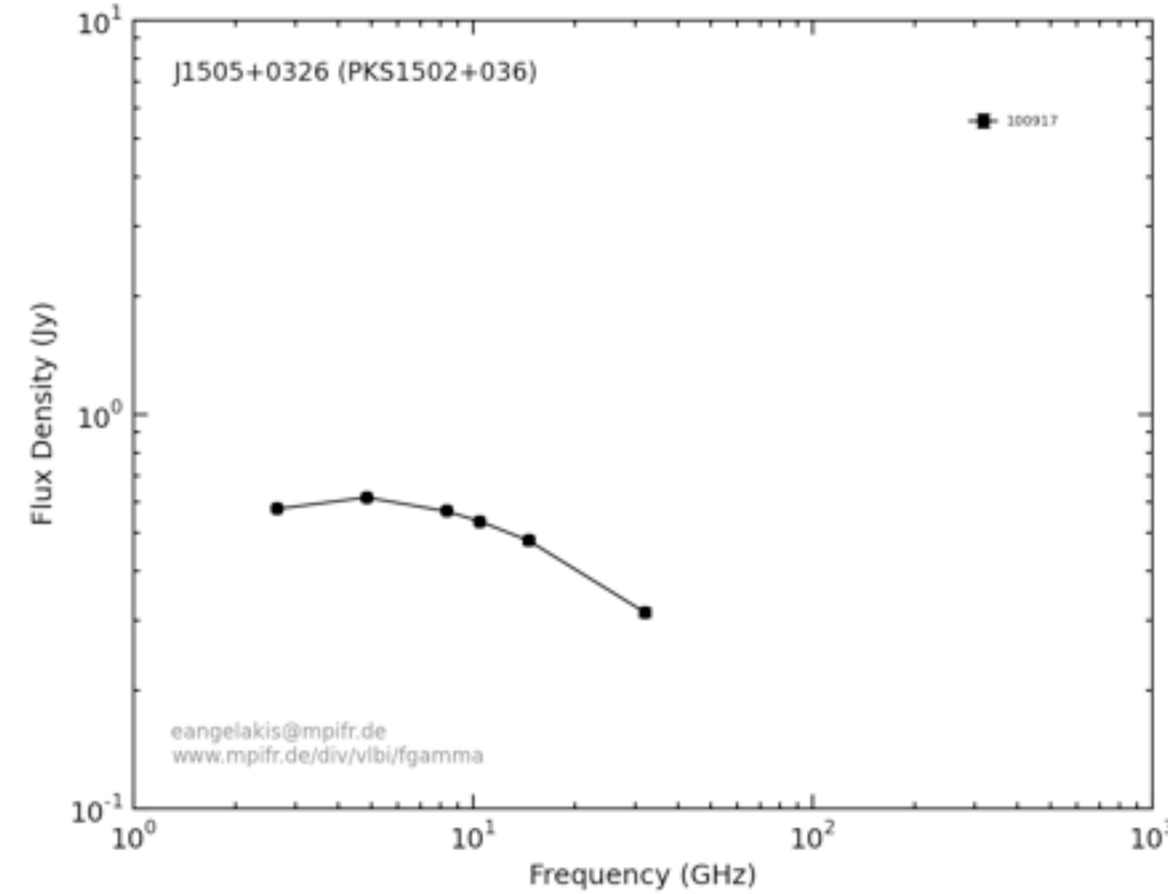


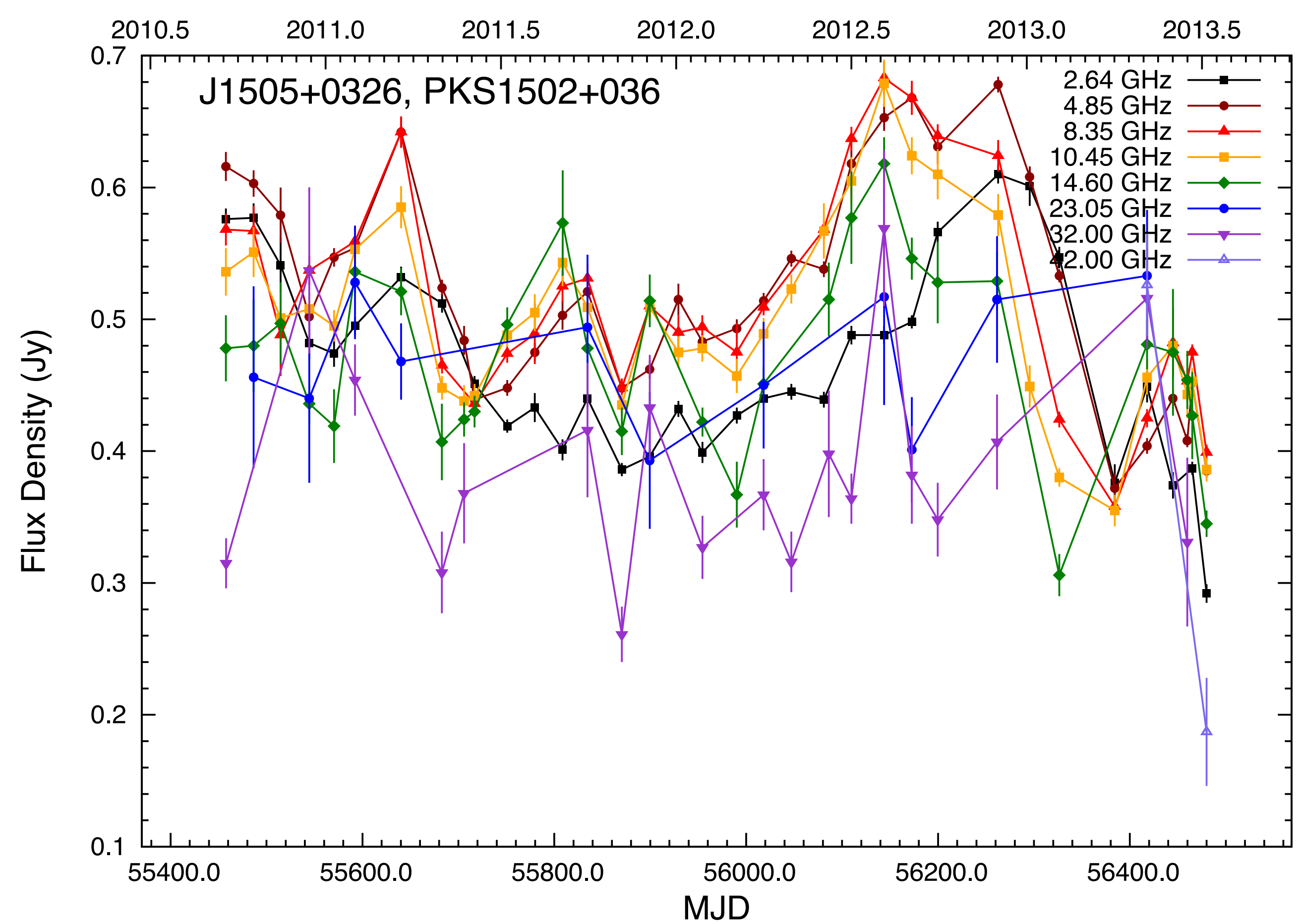
2010arXiv1006.5610A and Angelakis et al. in prep.

J1505+0326

cm to sub-cm bands | radio SED

- mostly convex spectrum
  - $\alpha_{2.6-8.4\ \mathrm{min}} \sim$ **-0.2** and $\alpha_{2.6-8.4\ \mathrm{min}} \sim$ **+0.3**
    $\alpha_{10-25\ \mathrm{max}} \sim$ **+0.2** and $\alpha_{10-25\ \mathrm{min}} \sim$ **-0.5**
- mild spectral evolution
- variability self-similar : semi-achromatic





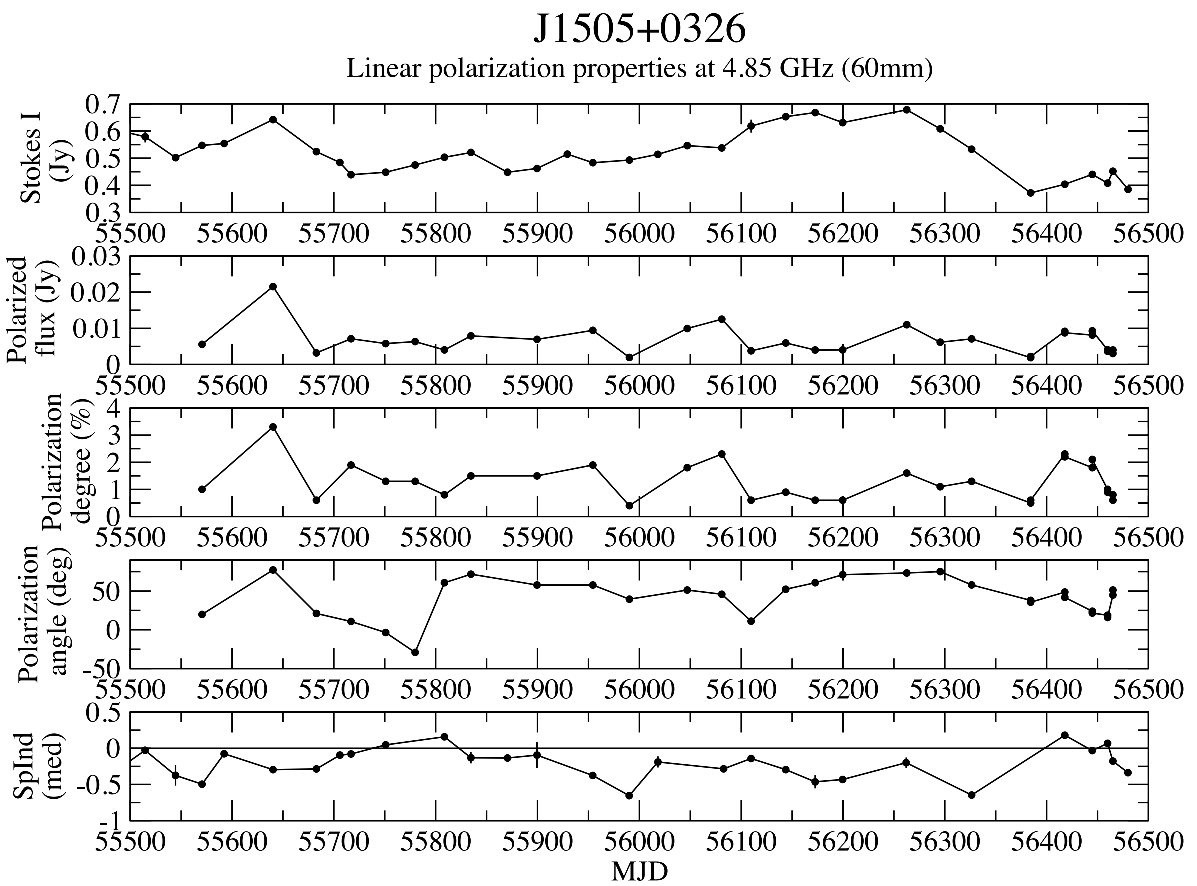
2010arXiv1006.5610A and Angelakis et al. in prep.

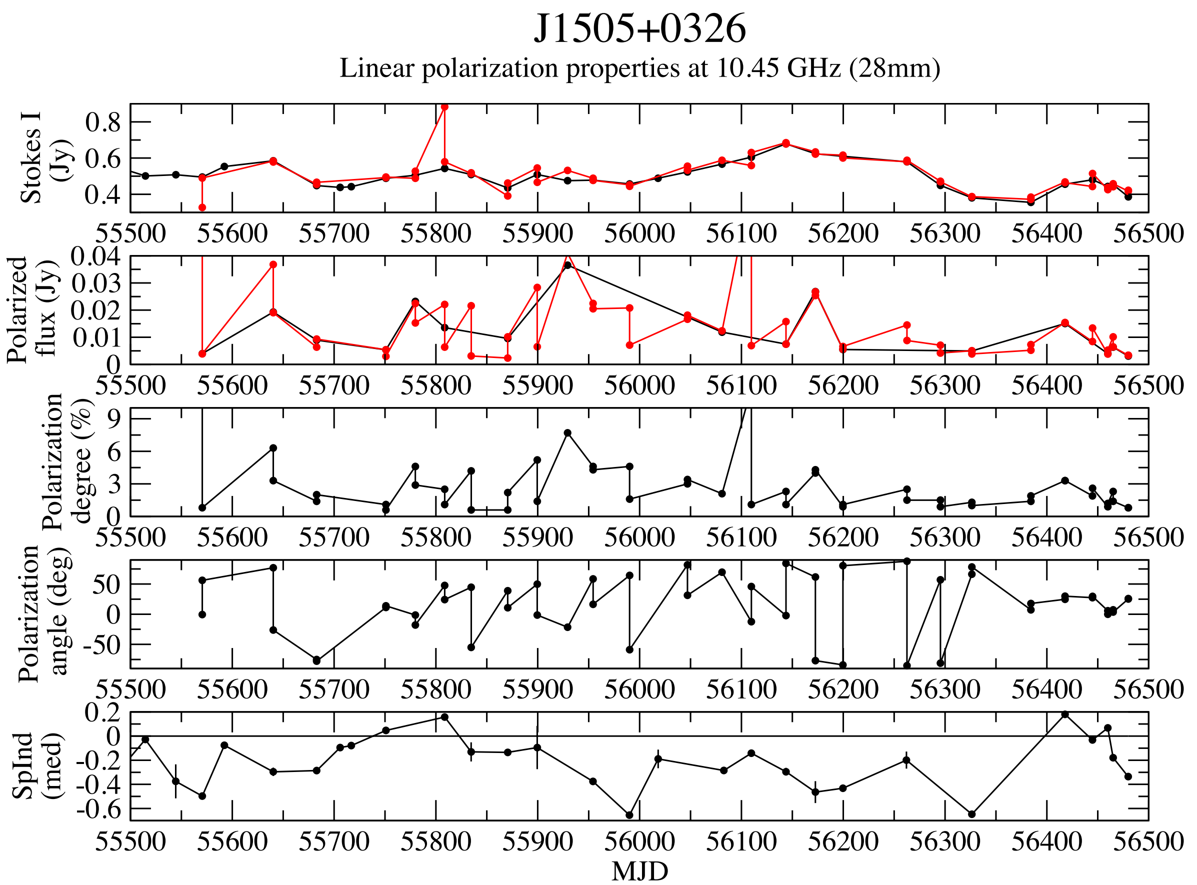
J1505+0326

radio and optical polarization

- **radio rather un-polarized** or **very little** or **variable**: core dominated, optically thick un-polarized emission
- **optically**: un-polarized

Frequency (GHz)	<PD> (%)	StDev	<PA> (deg)	StDev
4.85	1.3	0.7		
8.4	1.3	0.7		
10.45	2.9	3.1		
R band	5.7 +/- 5.3			





2010arXiv1006.5610A and Angelakis et al. in prep.

Putting it all together

variability mechanism | T_B | Doppler factors | jet powers

Variability

TB and Doppler factors

Variability amplitude measures brightness temperature:

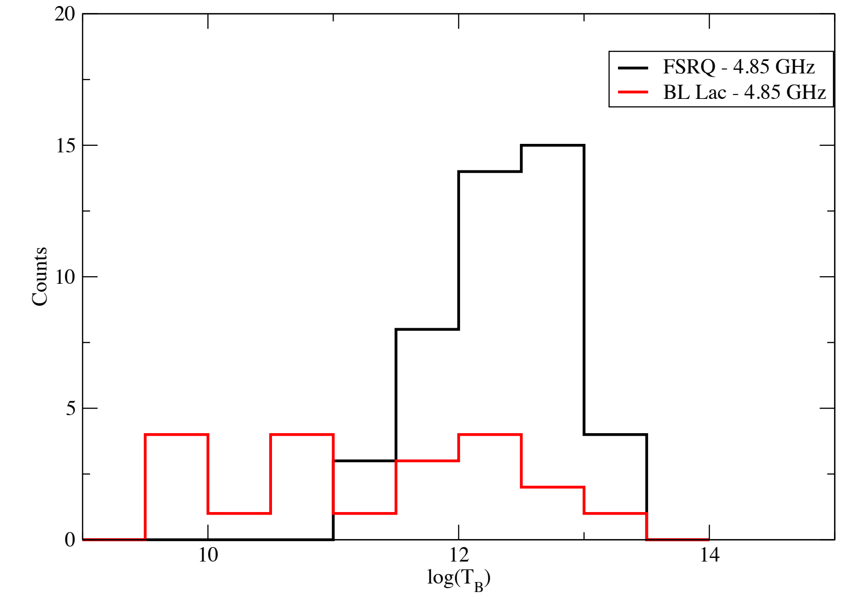
$$T_B = 4.5 \cdot 10^{10} \cdot \Delta S_\lambda \left(\frac{\lambda \cdot d_\lambda}{\Delta t_\lambda \cdot (1+z)^2} \right)^2$$

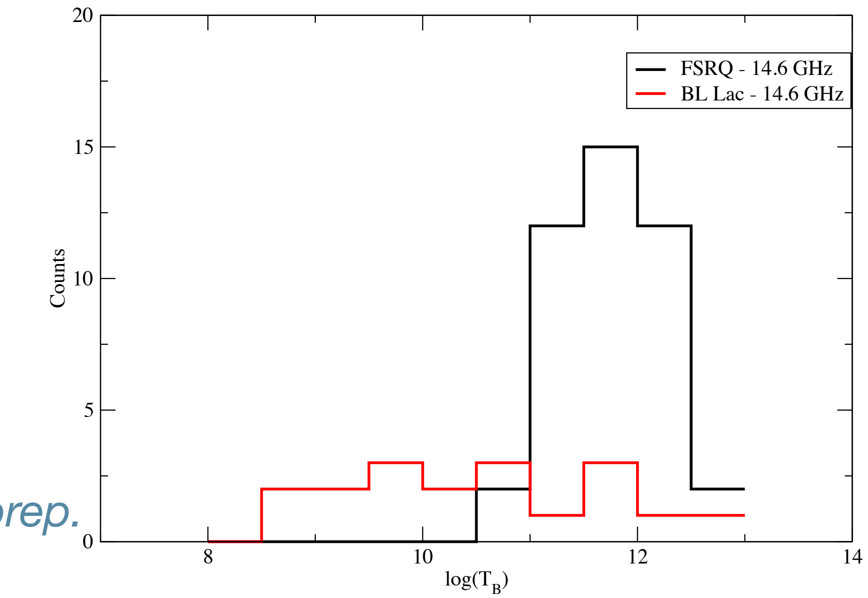
Assuming Equipartition brightness temperature limit:

$$T_B \simeq 5 \cdot 10^{10} \cdot \left(\frac{\delta_{var.}}{1+z} \right)^{3+\alpha}$$

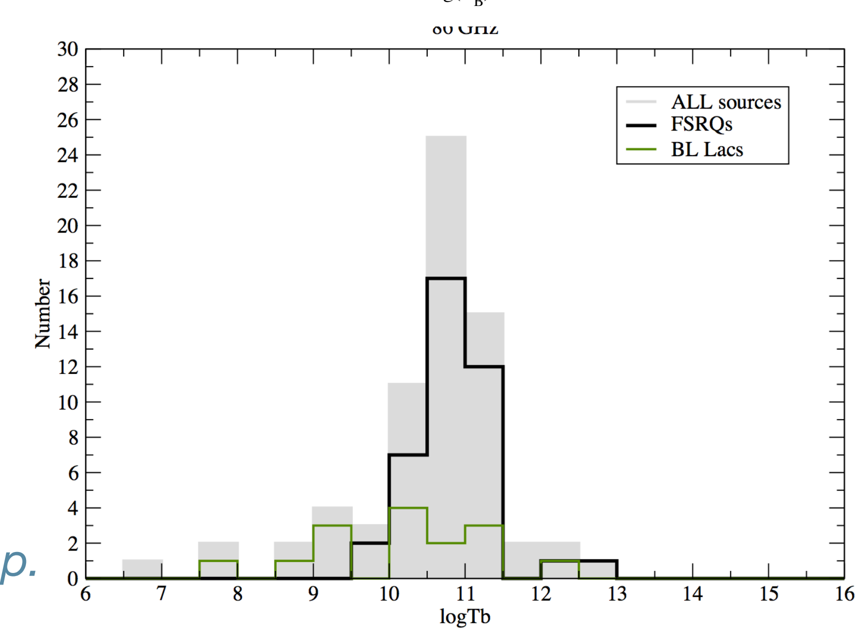
Hence, Equipartition Doppler factor:

$$\delta_{var.} = (1+z) \sqrt[3+\alpha]{T_B / 5 \cdot 10^{10}}$$





Angelakis et al. in prep.

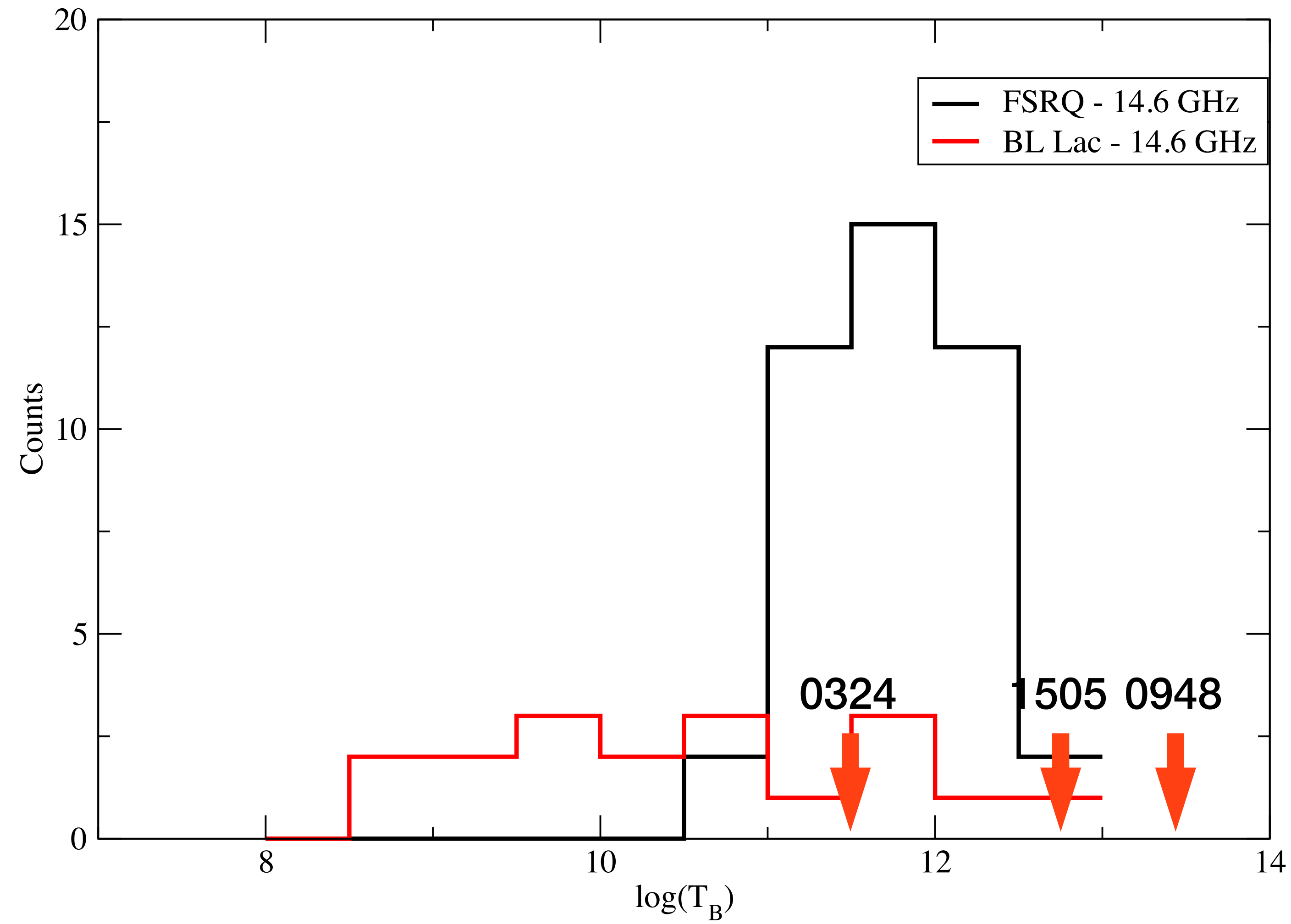


Nestoras et al. in prep.

Variability

TB and Doppler factors

- J0324+3410
  - time scales ~ 40 d
  - $T_{B,15GHz}$: ~ 4.1×10^{10} °K (log=11.6) implying D ~ 0.4
- J0948+0022 *(see also Foschini et al. 2012, 2012arXiv1209.5867F)*
  - time scales ~180 d
  - $T_{B,15GHz}$: ~ $2.3 \times 10^{+12}$ °K (log=13.4) implying D ~ 2.1
- J1505+0326
  - time scales ~120 d
  - $TB_{,15GHz}$: $5.3 \times 10^{+11}$ °K (log=12.7) implying D ~ 1.1



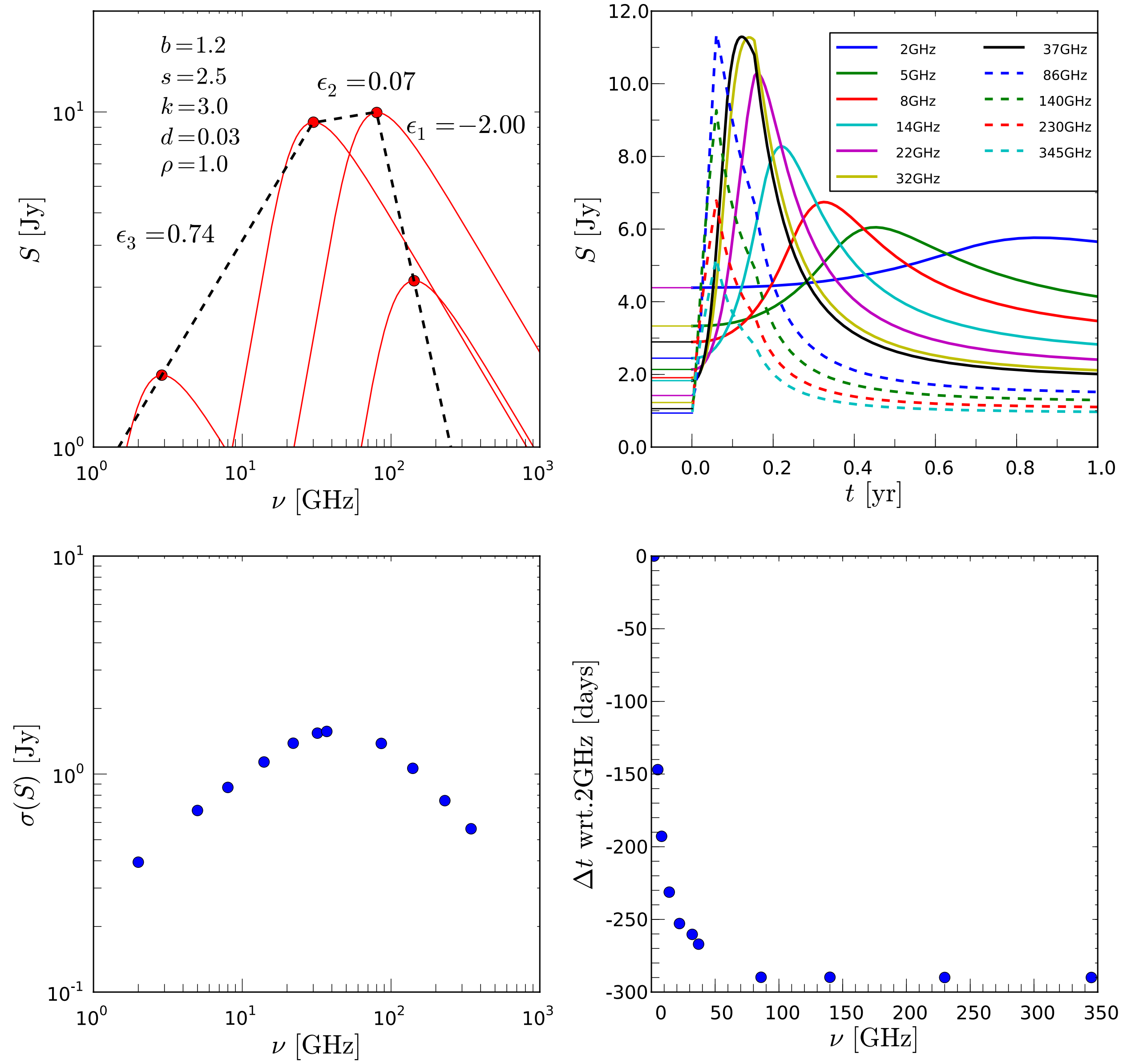
Angelakis et al. in prep.

Fuhrmann et al. 2011nlsg.confE..26F

variability mechanism

intrinsic modulation indices

- shock model (*Marscher & Gear 1985*)
- study case CTA102:
    - a conical jet (p = 1)
    - a toroidal magnetic field (b = 1.2)
    - constant Doppler factor
- if all follow same pattern: increase - max: ~ 60-80 GHz - then plateau -decrease



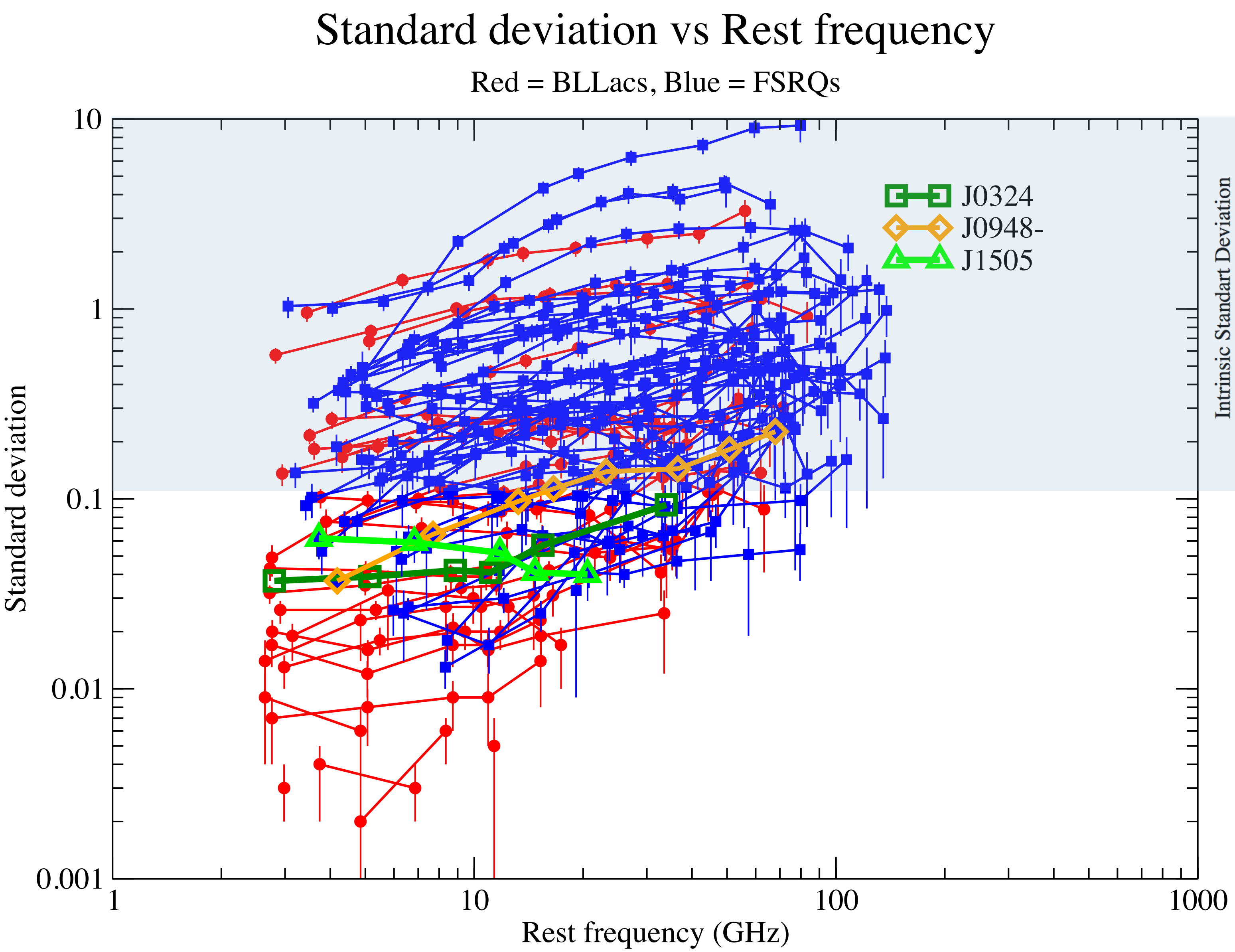
calculations done by C. Fromm

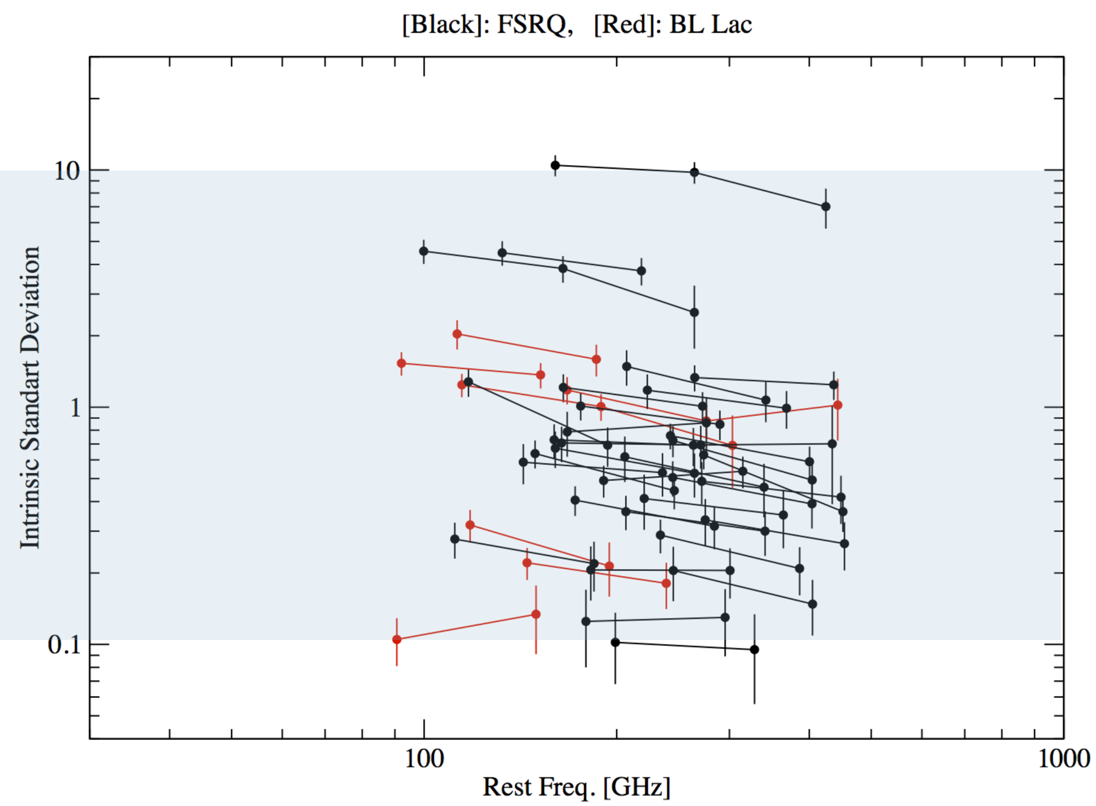
$$\mathcal{L}(\overline{m}) = \int_{\text{all } S_0} dS_0 S_0 \left\{ \left(\prod_{j=1}^{N} \frac{1}{\sqrt{2\pi\left(\overline{m}^2 S_0^2 + \sigma_j^2\right)}} \right) \times \exp\left[-\frac{1}{2} \sum_{j=1}^{N} \frac{(S_j - S_0)^2}{\sigma_j^2 + \overline{m}^2 S_0^2} \right] \right\}$$

Richards et al. 2011, ApJS...194...29R

variability mechanism

intrinsic modulation indices





Nestoras et al. in prep.

Angelakis et al. in prep. | calculations done by V. Pavlidou

jet powers

radiative and kinetic

- jet power calculated according to the model by *Ghisellini & Tavecchio 2009, MNRAS...397...985*
- H0=70 km/s/Mpc
- the physical basis of the correlations are described by *Blandford & Konigl 1979* (found that the radio flux is linked to the jet power)
- radiative and kinetic (electronc+protons +B) jet powers

$$\log P_{\rm jet} = (11 \pm 3) + (0.81 \pm 0.06) \log L_{15\ \rm GHz}$$

Foschini 2011, RAA....11.1266F

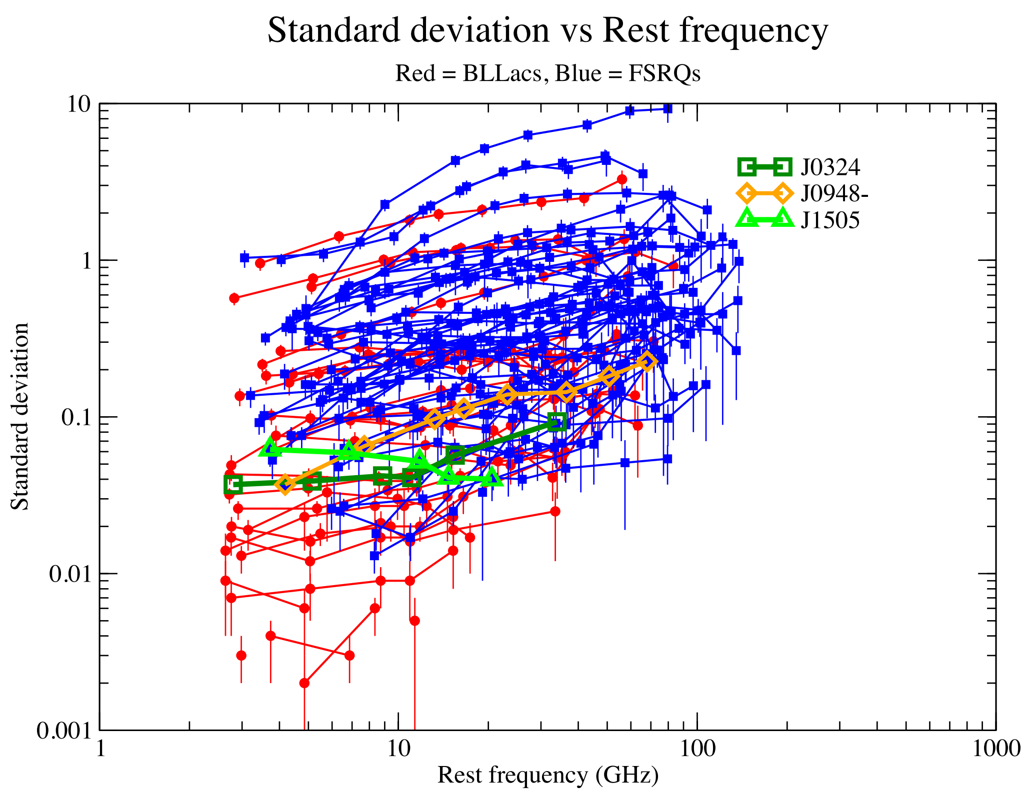
Source	$\log(P_{radiative})$ (log(erg/s))	$\log(P_{kinetic})$ (log(erg/s))
J0324+3410	43.27	43.52
J0849+5108	44.80	45.36
J0948+0022	44.98	45.58
J1246+0038	43.48	43.78
J1505+0326	44.72	45.26

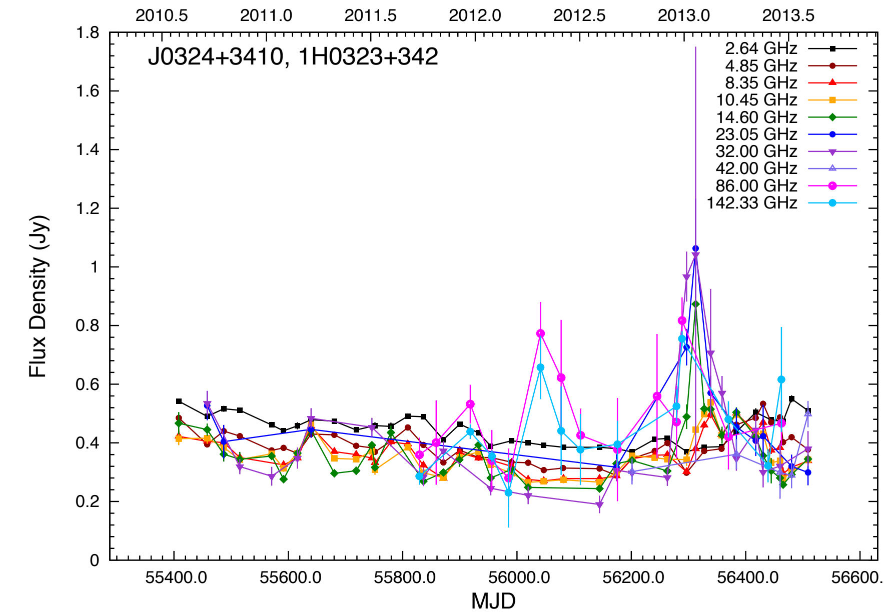
Conclusions

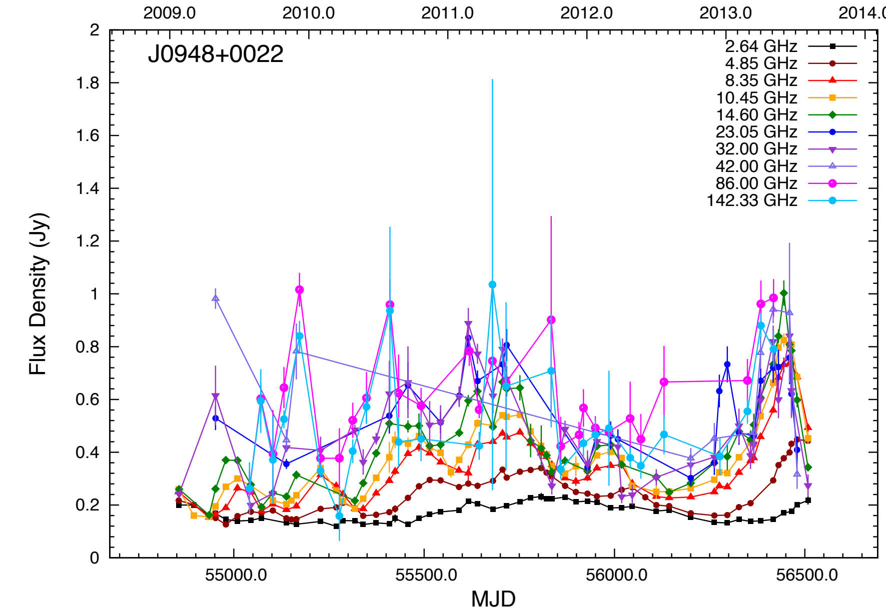
Conclusions

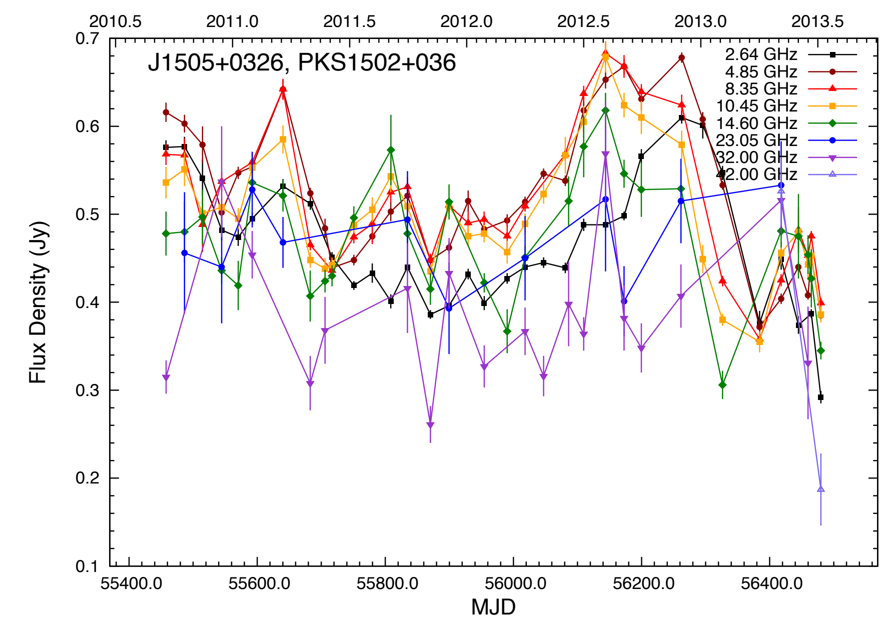
Light curves

- Light Curves
  - 0324 and 1505: **mild variability**
  - J0948: **intense variability** (factors of 5)
  - variability (intrinsic stdev) for J0324, J0948 imitates the **“shock-in-jet”**
    - exception: J1505 behaves otherwise





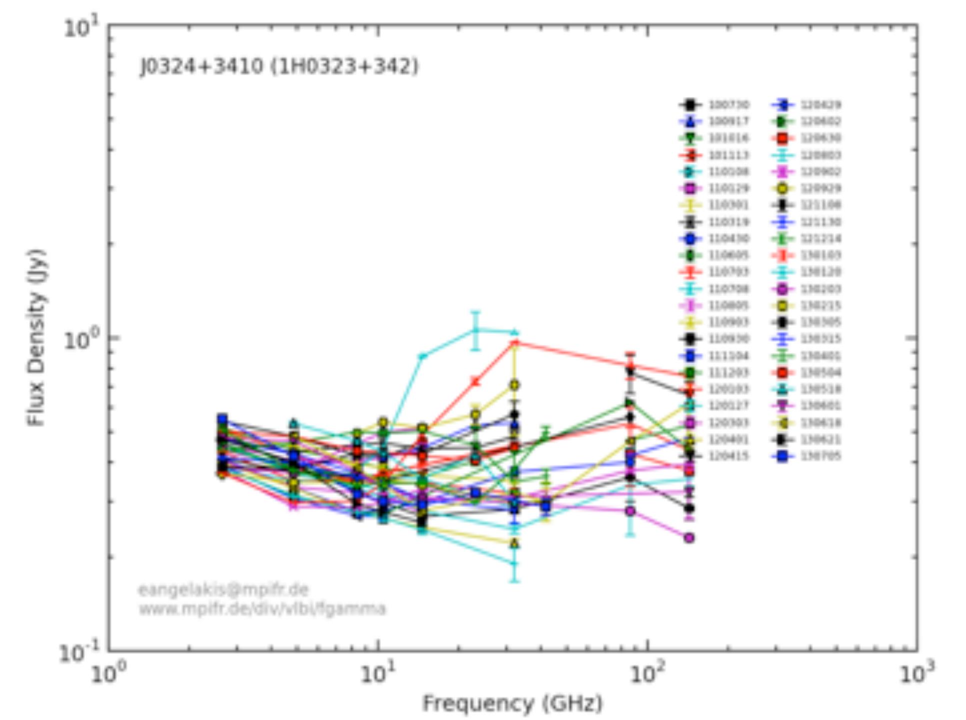


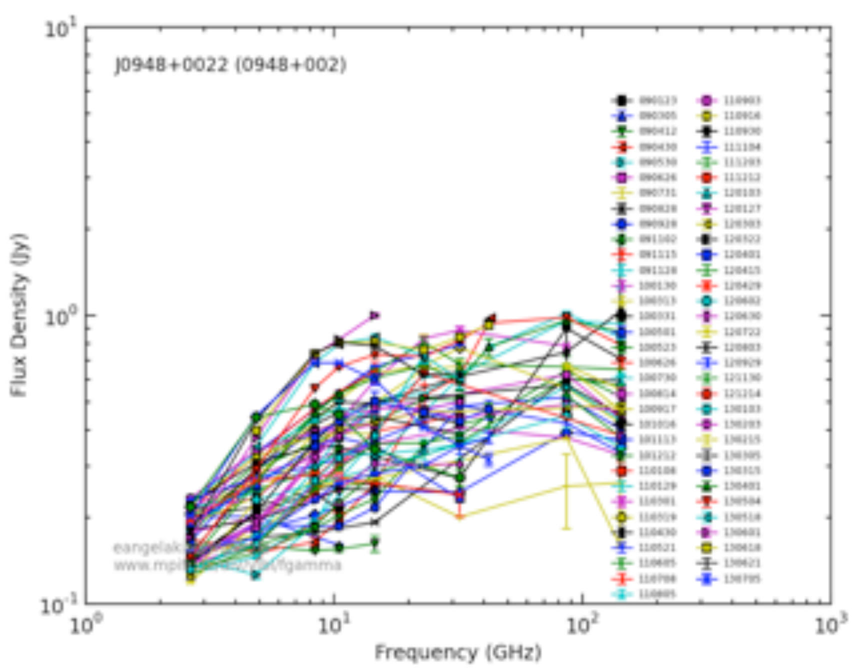


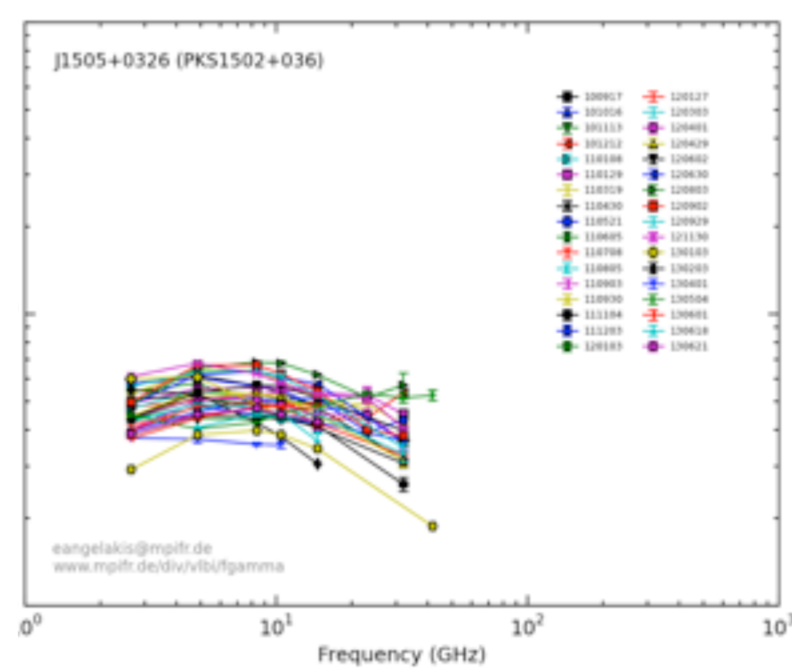
Conclusions

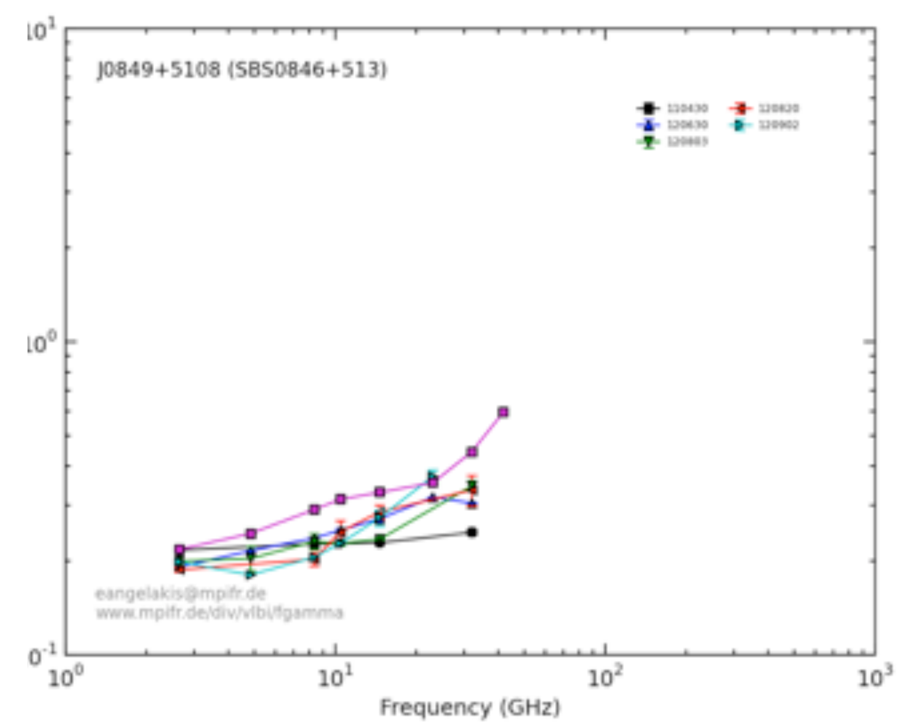
Radio SEDs

- not one flavour
- J0324: **quiescent** present, **mild** evolution, **only high** frequencies
- J0849: **NO quiescent** present, **intense** evolution, **all** frequencies
- J0948: **NO quiescent** present, **intense** evolution, **all** frequencies
- J1505: **NO quiescent** present, **NO** evolution - **achromatic**





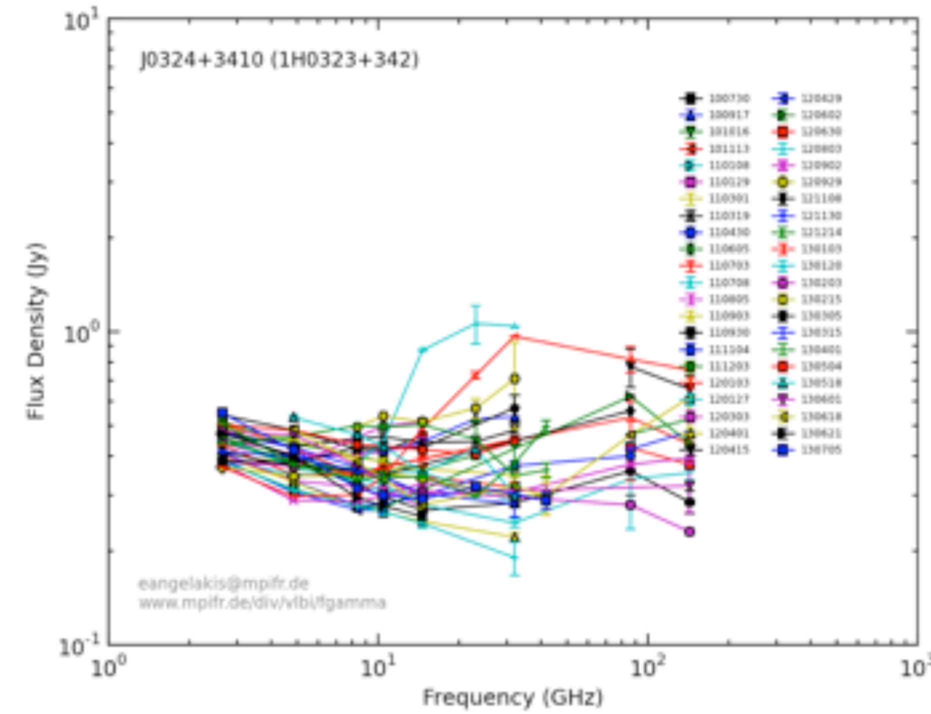


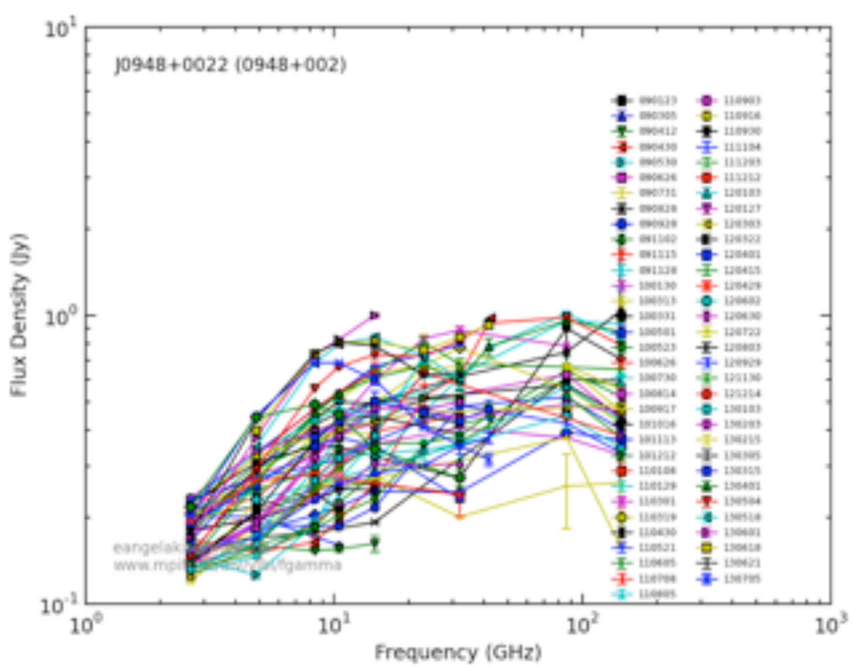


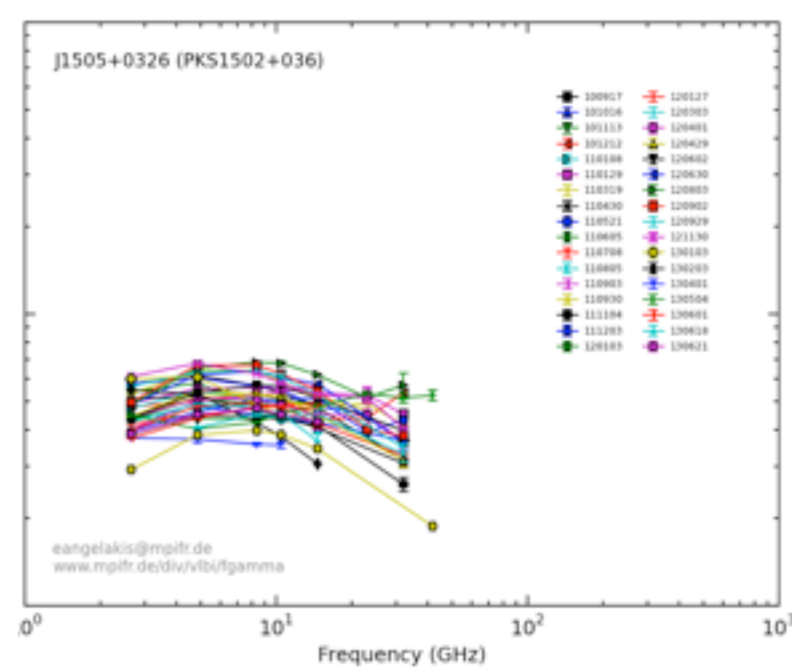
Conclusions

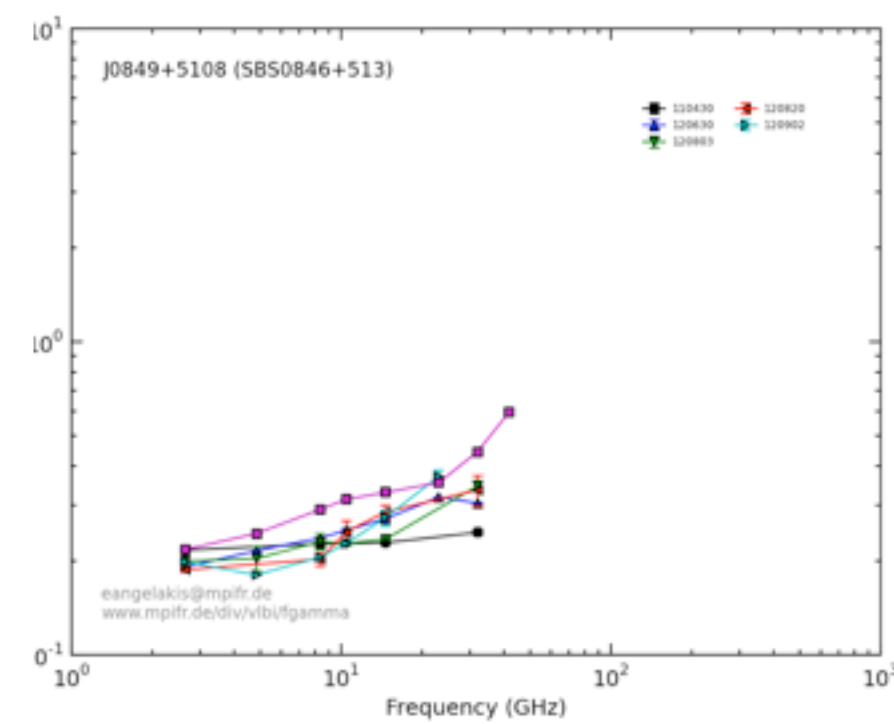
Polarization

- J0324: **radio polarized** (indicative of opt. thin large scale jet.) **- R-band unpolarized**
- J0948: **radio unpolarized - R-band (?)**
- J1505: **radio unpolarized - R-band unpolarized**









Conclusions

- a new class of gamma ray AGNs
- low mass systems ($10^{6\text{-}8}$)
- high accretion ~L_{edd}

- clear indications for presence of a relativistic jet with characteristics (e.g. variability mechanisms) as seen in all other blazars)
  - superluminal motions
  - SBS 0846+513 reaches observed isotropic γ-ray luminosity (0.1–300 GeV) of 1.0×10^{48} erg s^{-1} on daily timescales, comparable to that of luminous FSRQs
  - similar 0948 (Foschini et al 2012)
  - spectral evolution
  - High T_B
  - polarization

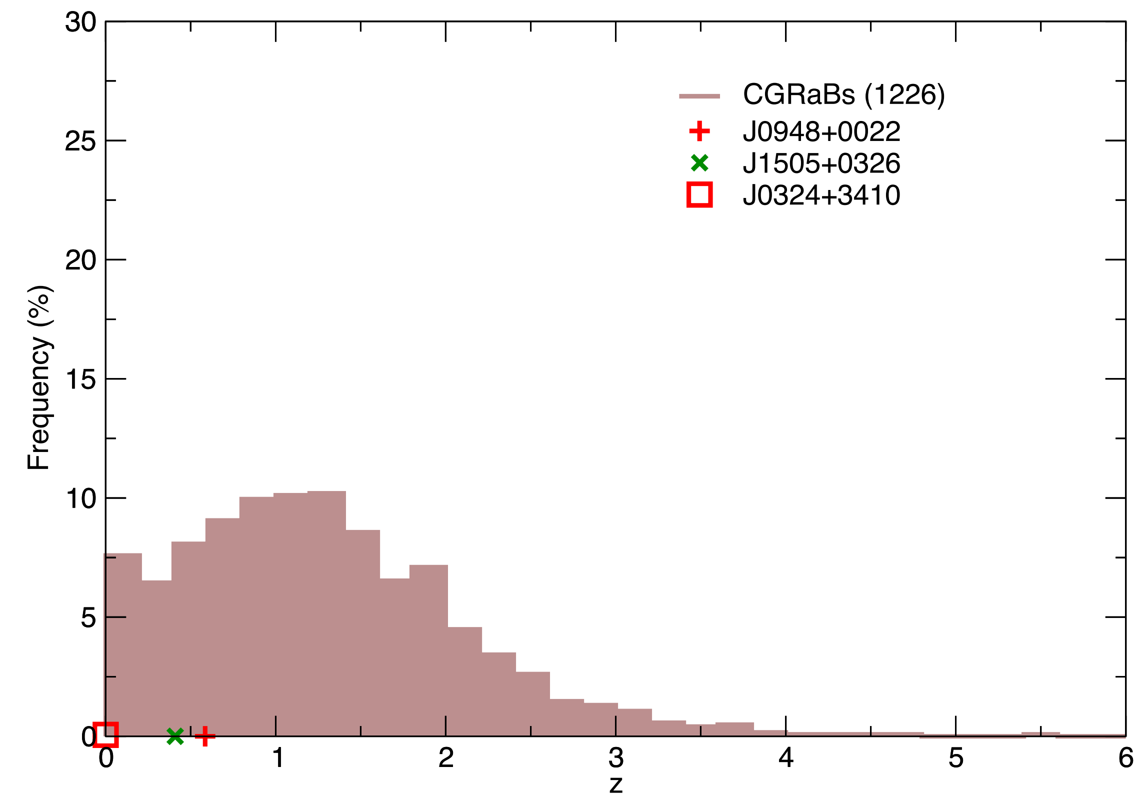
- **what is the key parameter for switching on the jet activity** if not the mass, spin?
- more sources needed
- longer cycle to be observed

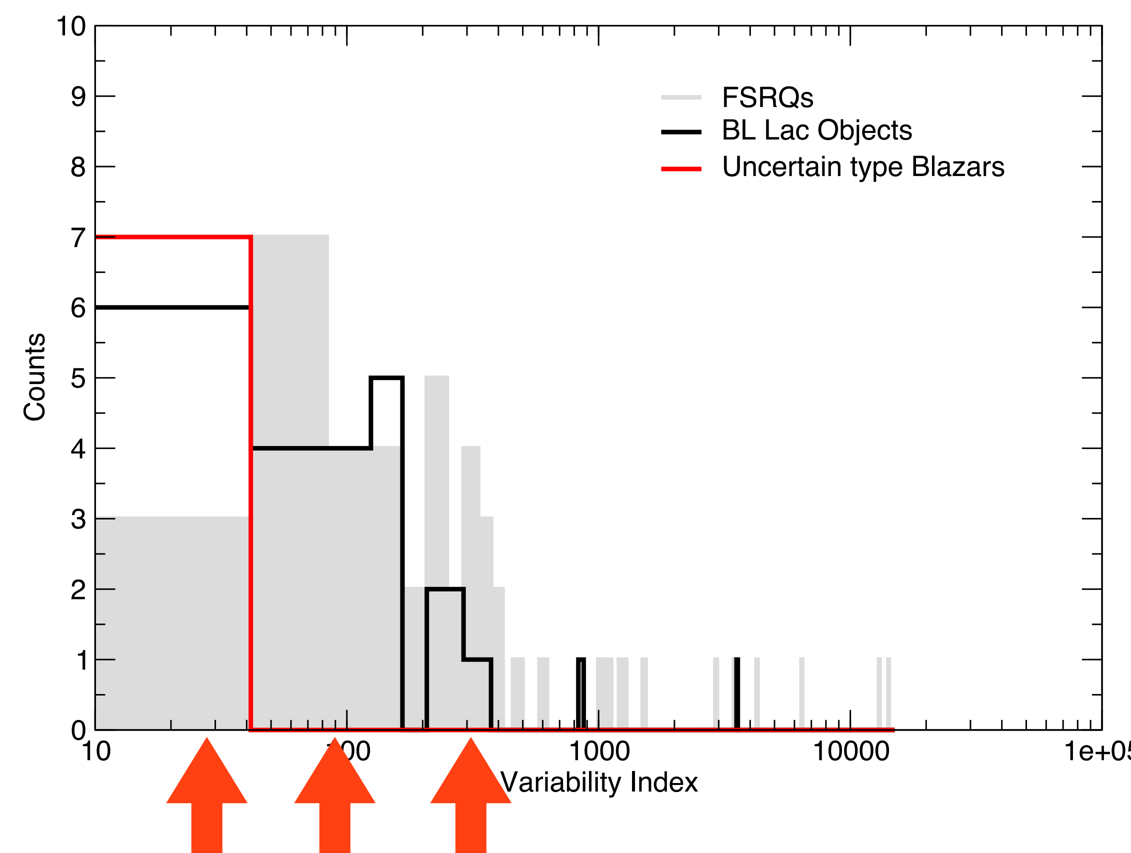
Thank you!

E. Angelakis | Max-Planck-Institut für Radioastronomie

Source	z	Var. Index*	Energy Flux (erg cm^{-2} s^{-1})	Log(R)**
J0324+3410	0.061	90.6	1.42E-11	2.3 (at 5GHz)
J0849+5108	0.584	-	-	3.16
J0948+0022	0.585	326.5	3.89E-11	2.55
J1246+0238	0.363	-	-	2.38
J1505+0326	0.409	27.7	2.05E-11	3.19

* Var. Index: 41.6 => chance of being a steady source of less than 1%
R=f(1.4GHz)/f(4400A) from Yuan et al. 2008, ApJ...685...801





Angelakis et al. in prep.