High-frequency polarization studies of high-energy emitting AGN jets

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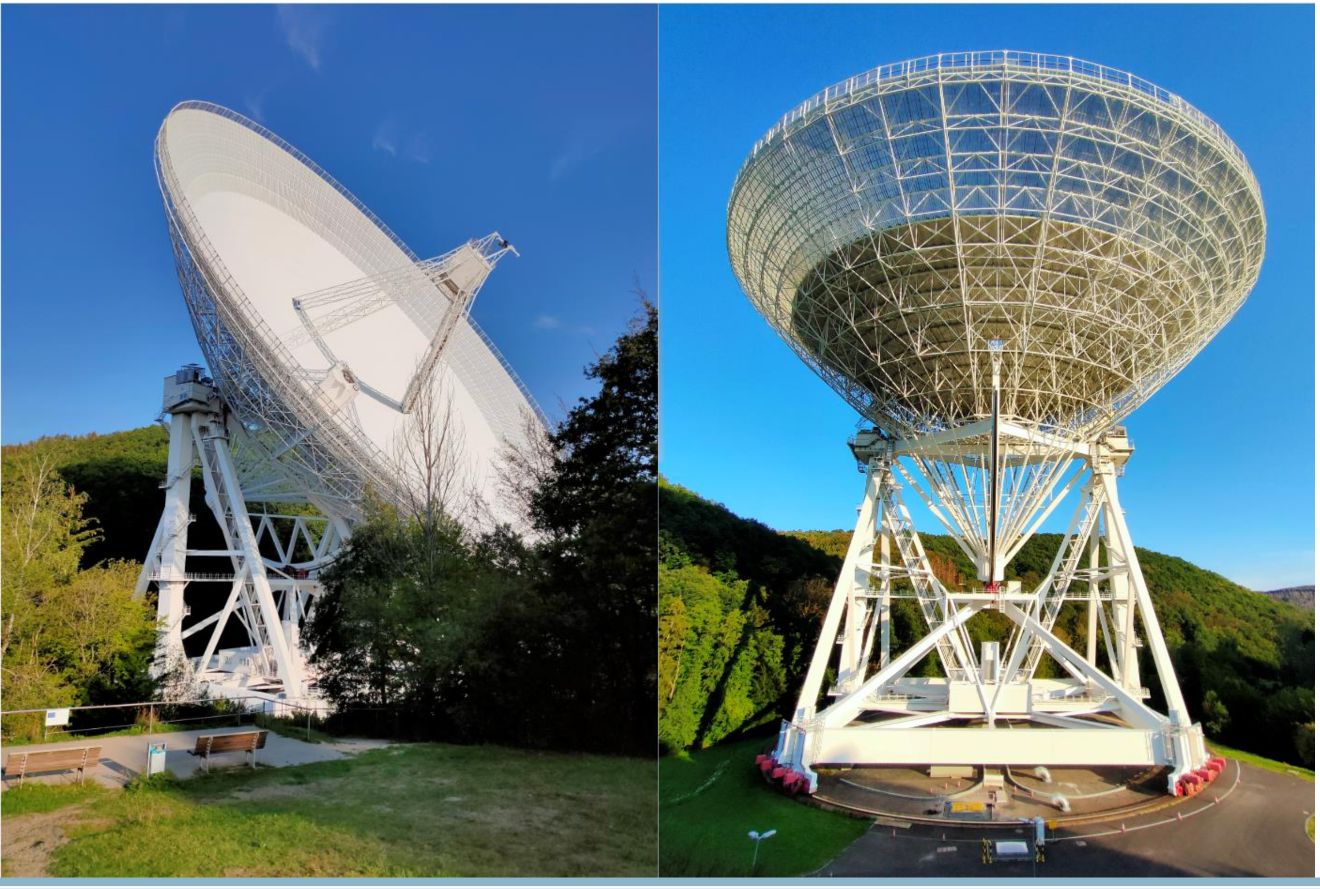
ASTRO WÜRZBURG

Master thesis results



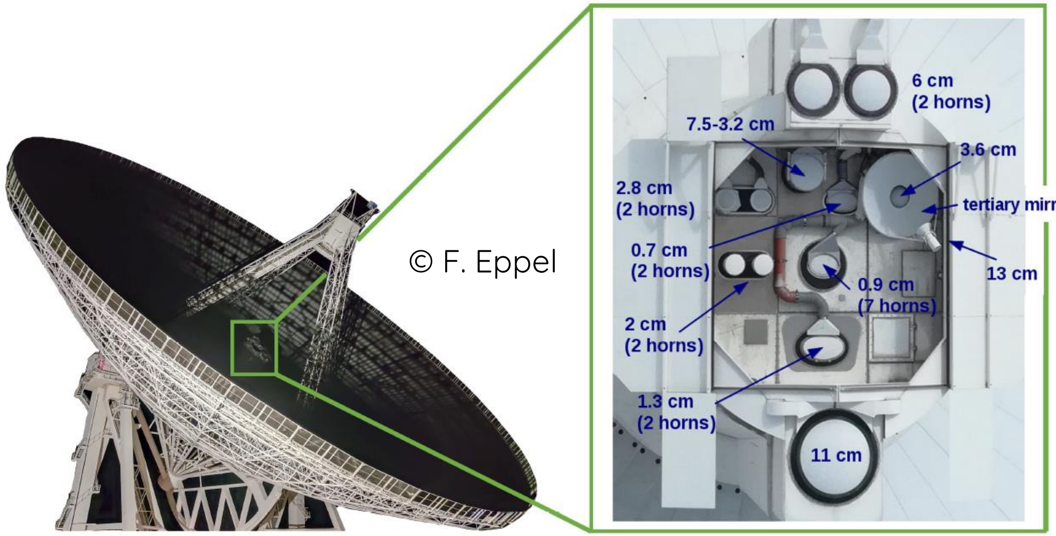
In the framework of the

TELAMON

Program

TeV Effelsberg Long-term AGN Monitoring

- Using Effelsberg 100m telescope and four receivers: 45mm, 20mm, 14mm, 7mm
  - Operated by Max-Planck-Institute for Radio Astronomy in Bonn
  - One of the largest fully steerable radio telescopes in the world
  - Higher sensitivity and angular resolution compared to smaller dishes
- Monitoring radio spectra of TeV-Blazars and candidate neutrino-associated AGN



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➡ Here: Linear polarization study at 14, 17, 36 & 39GHz

TELAMON-Team

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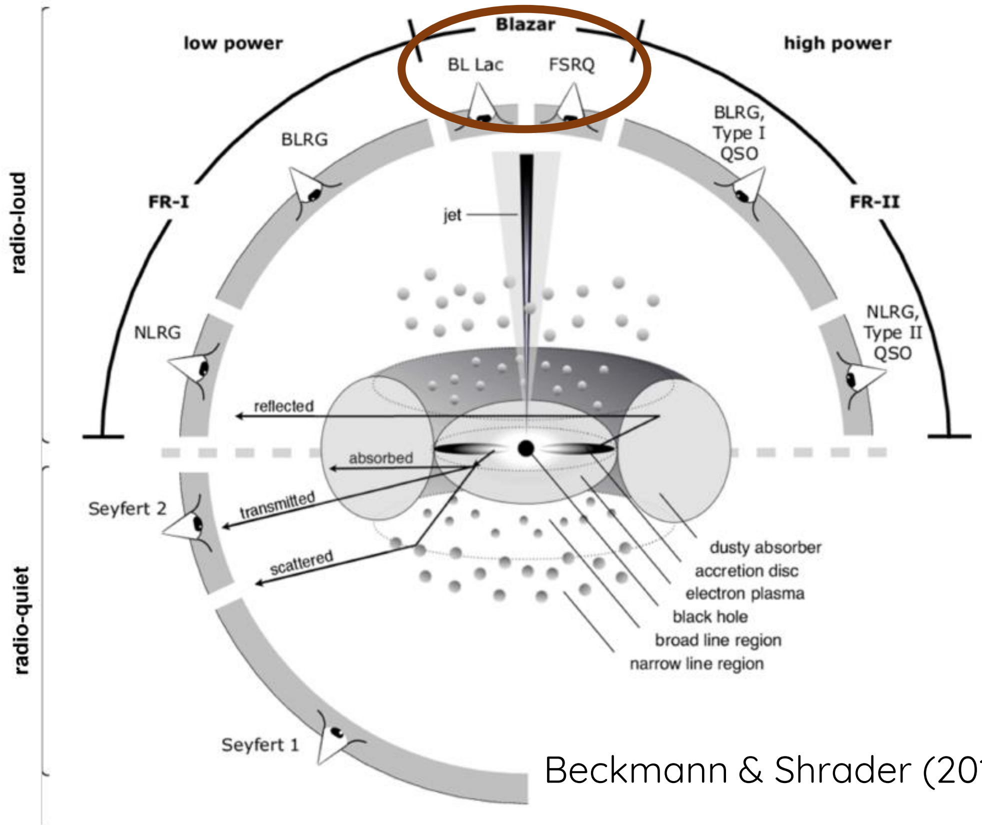
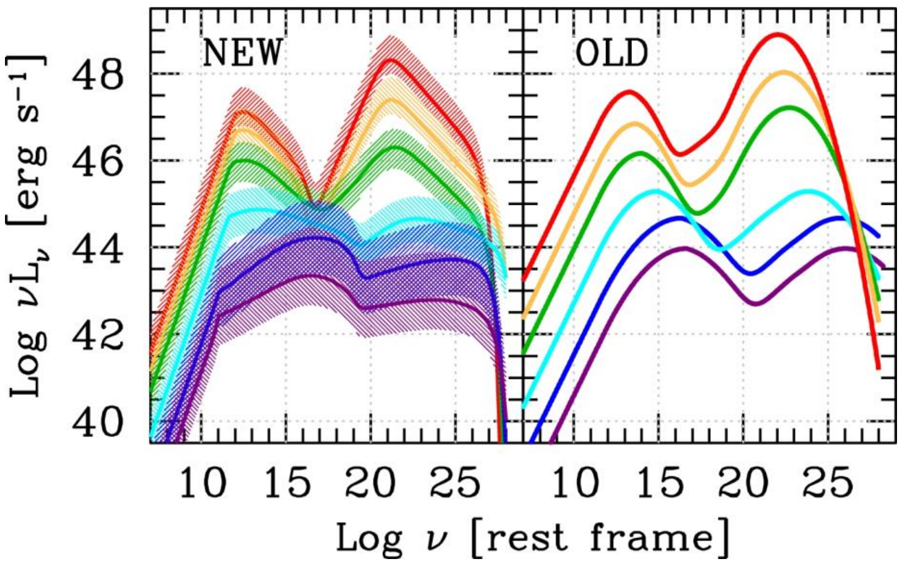
University Würzburg

ECAP

Active Galactic Nuclei



Beckmann & Shrader (2012)



Blazar sequence: Ghisellini et al. (2017)

- Blazars/BL Lacs (& FSRQs): AGN with jets pointed directly towards Earth
- SED: Low-energy hump due to Synchrotron radiation
- Classification according to Synchrotron peak frequency (Padovani & Giommi, 1995):

→ HBLs: $v_{peak} > 10^{15} Hz$

→ Usually very faint radio sources

Synchrotron Radiation

Following Rybicki & Lightman, 1979

- Produced when charged relativistic particles are accelerated in a magnetic field (mostly electrons)
- Considering the two polarization components of the radiation:

$K_X =$ Modified Bessel function of the second kind of order X

$$P_\perp(\nu) = \frac{\sqrt{3}\, e^3 B\ \sin\varphi}{2 m_e c^2}\left[\left(\frac{\nu}{\nu_c}\right)\int_{\nu/\nu_c}^{\infty} K_{5/3}\ (\xi)d\xi + \left(\frac{\nu}{\nu_c}\right)K_{2/3}\left(\frac{\nu}{\nu_c}\right)\right]$$

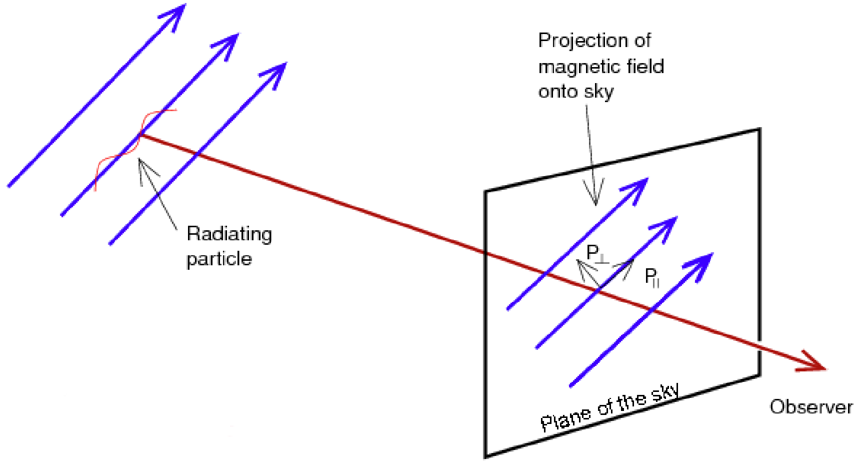
$$P_\parallel(\nu) = \frac{\sqrt{3}\, e^3 B\ \sin\varphi}{2 m_e c^2}\left[\left(\frac{\nu}{\nu_c}\right)\int_{\nu/\nu_c}^{\infty} K_{5/3}\ (\xi)d\xi - \left(\frac{\nu}{\nu_c}\right)K_{2/3}\left(\frac{\nu}{\nu_c}\right)\right]$$

$$P_\nu = P_\perp(\nu) + P_\parallel(\nu)$$

- Degree of polarization for power-law electron distribution:

$$\frac{P_\perp - P_\parallel}{P_\perp + P_\parallel} \sim 70\%$$ (very high!)

- Caveat: Depolarization effects

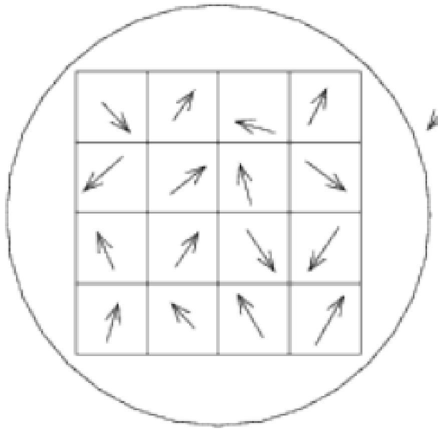


https://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc08/radproc0160.html

Depolarization Effects

- Non-uniformly distributed magnetic fields

➡ Polarization contributions are added vectorially



https://www.web.uwa.edu.au/__data/assets/pdf_file/0007/901267/poln.pdf

- LCP & RCP have different phase velocities in a medium

➡ Rotation of the EVPA → Faraday rotation (internal or external)

$$\Delta\chi = RM \cdot \lambda^2 \qquad RM = 8.1 \times 10^5 \int_L n_e B \cos\theta \, dL$$

Müller formalism

Following Turlo et al., 1985

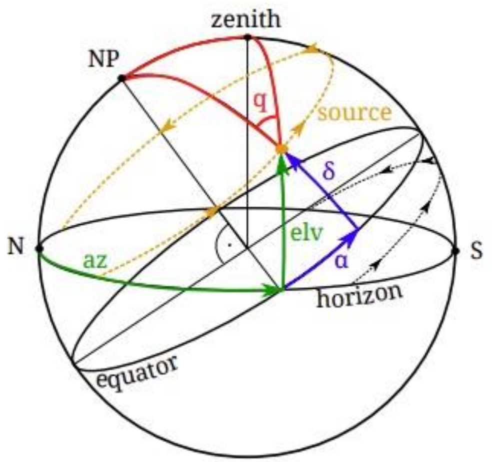
$V \sim 0 \longrightarrow S = \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$

Homan & Lister, 2006

- Measured/Calculated Stokes parameters S_{obs} are not the true parameters S_{true} due to:
  - Parallactic rotation $\longrightarrow$ Described by rotation matrix R
  - Imperfect receiving system $\longrightarrow$ Spurious polarization $\longrightarrow$ Described by Müller matrix M

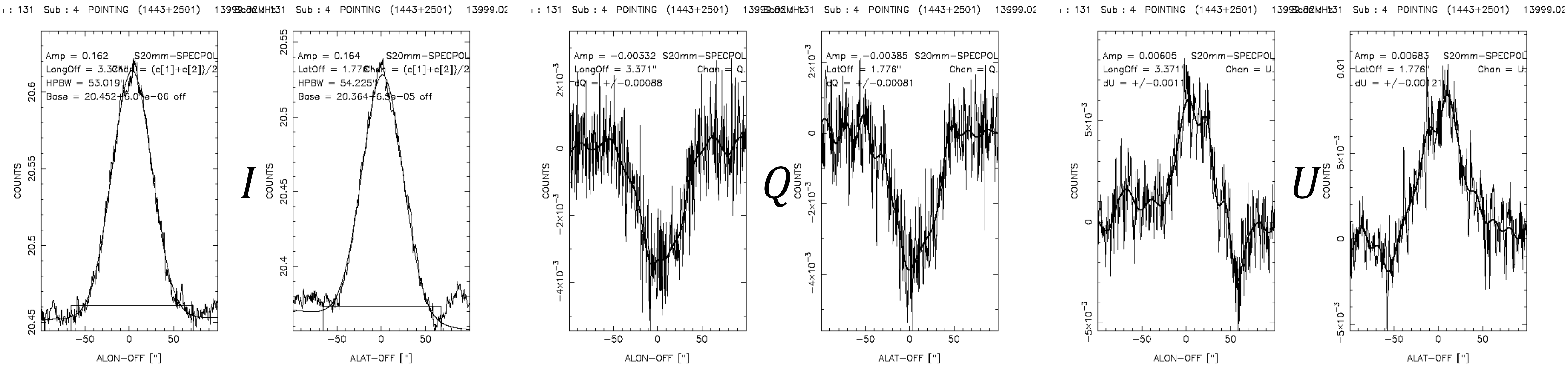
$$S_{obs} = \begin{pmatrix} I \\ Q \\ U \end{pmatrix}_{obs} = M \cdot R \cdot \begin{pmatrix} I \\ Q \\ U \end{pmatrix}_{true} = \underbrace{\begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix}}_{\text{Fitted by observing (polarization) calibrators}} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos 2q & \sin 2q \\ 0 & -\sin 2q & \cos 2q \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \end{pmatrix}_{true}$$

Beuchert, 2013



Parallactic angle $q = \arctan\left(\frac{\pm \cos\phi \sin H}{\sin\phi \cos\delta - \cos\phi \sin\delta \cos H}\right)$

ϕ = geographical latitude of telescope
δ = declination of source
H = hour angle of source

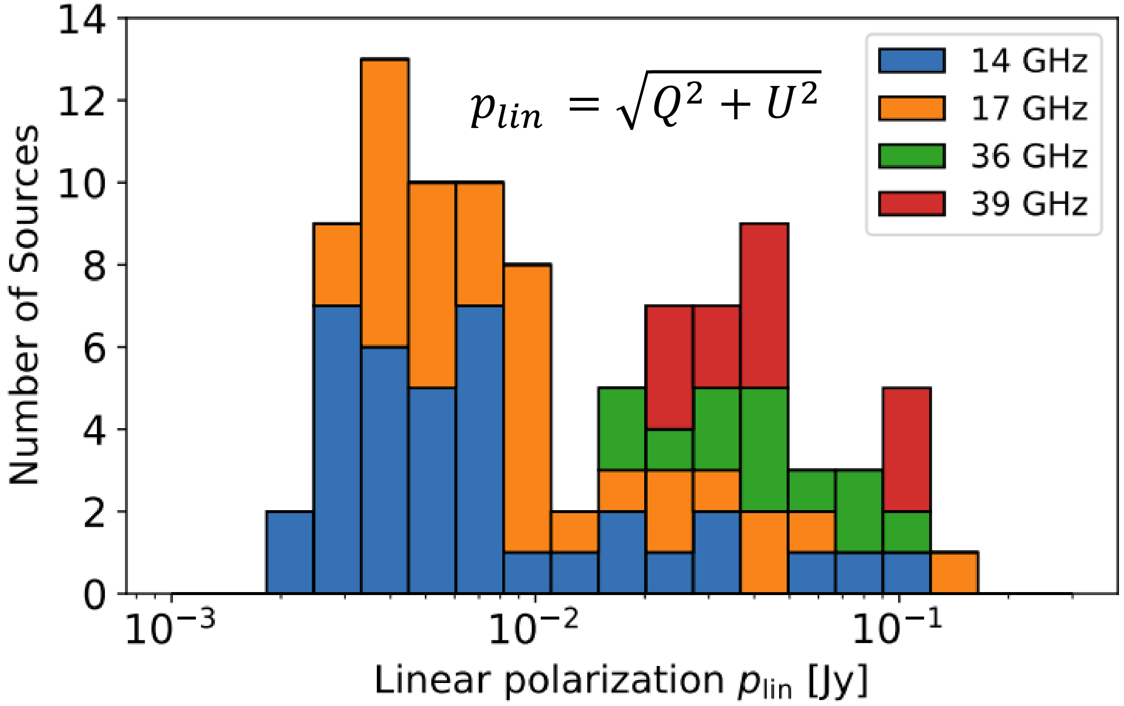


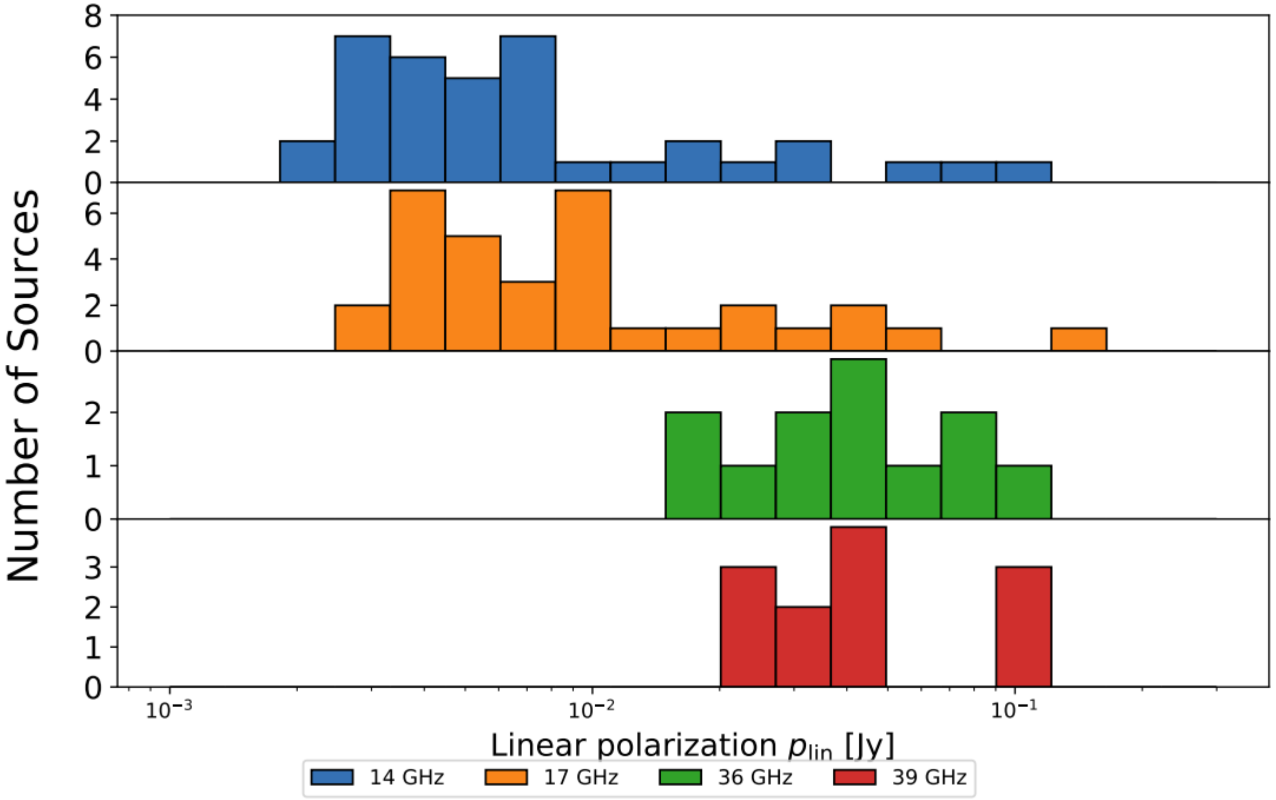
I
Q
U
Amp = 0.162
S20mm−SPECPOL
HPBW = 53.019''
Base = 20.452+6.0 e−06 off
Amp = 0.164
LatOff = 1.776''
HPBW = 54.225''
Base = 20.364+6.5e−05 off
Amp = −0.00332
LongOff = 3.371''
Chan = Q
dQ = +/−0.00088
Amp = −0.00385
dQ = +/−0.00081
Amp = 0.00605
Chan = U
dU = +/−0.0011
Amp = 0.00683
dU = +/−0.00121
COUNTS
ALON−OFF ['']
ALAT−OFF ['']

Linear Polarization

„Significantly polarized“ = $p_{lin} > 2\sigma_{p_{lin}}$

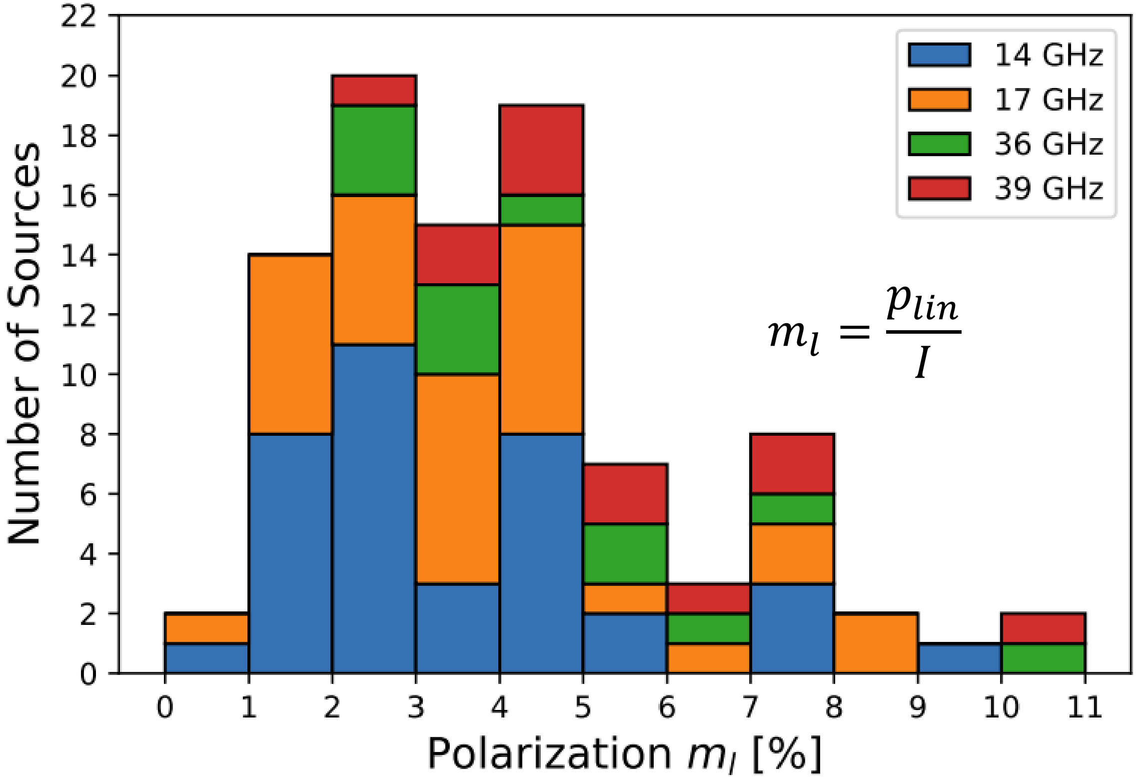
46/87 sources fulfill this criterion

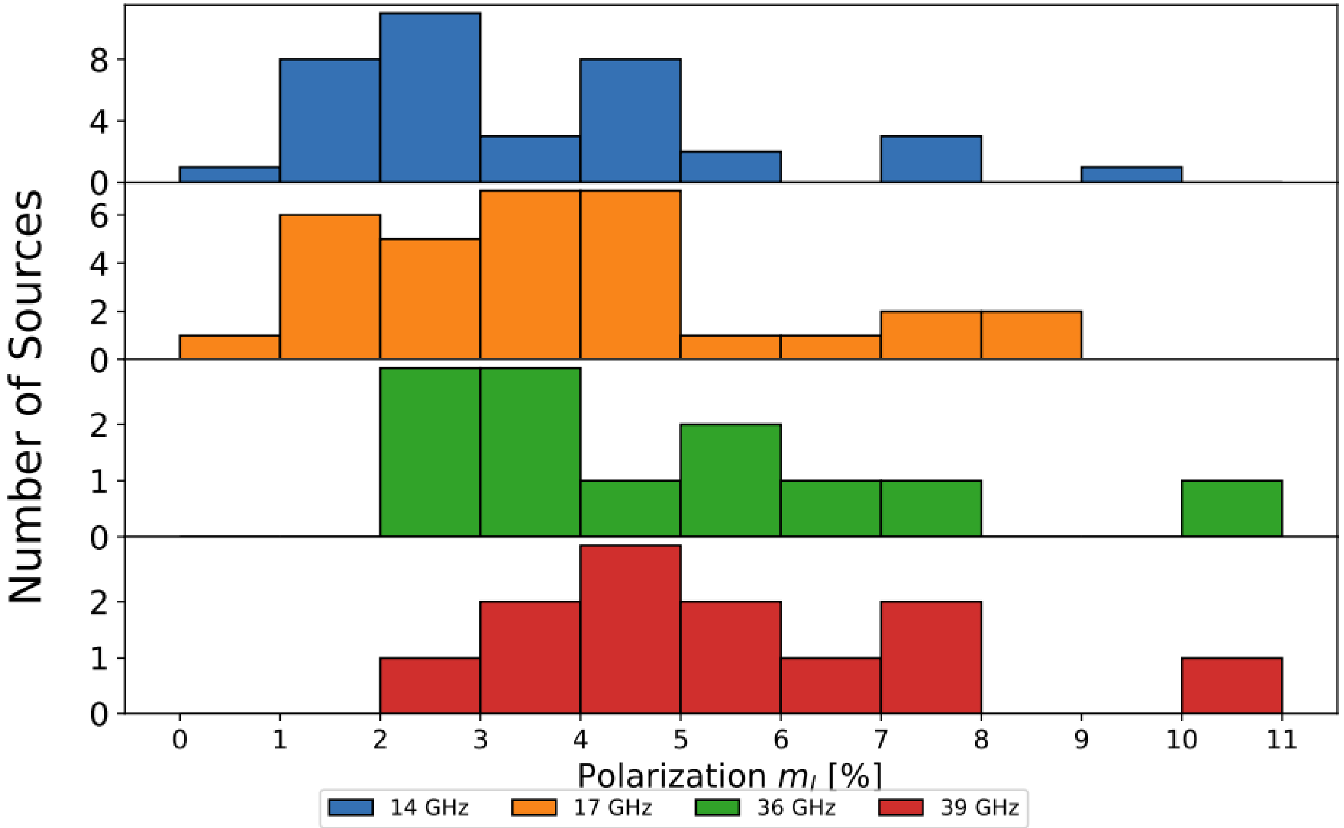




- 20mm: $0.002\text{Jy} \leq p_{lin} \leq 0.01\text{Jy}$
- 7mm: $0.02\text{Jy} \leq p_{lin} \leq 0.1\text{Jy}$

Fractional Polarization



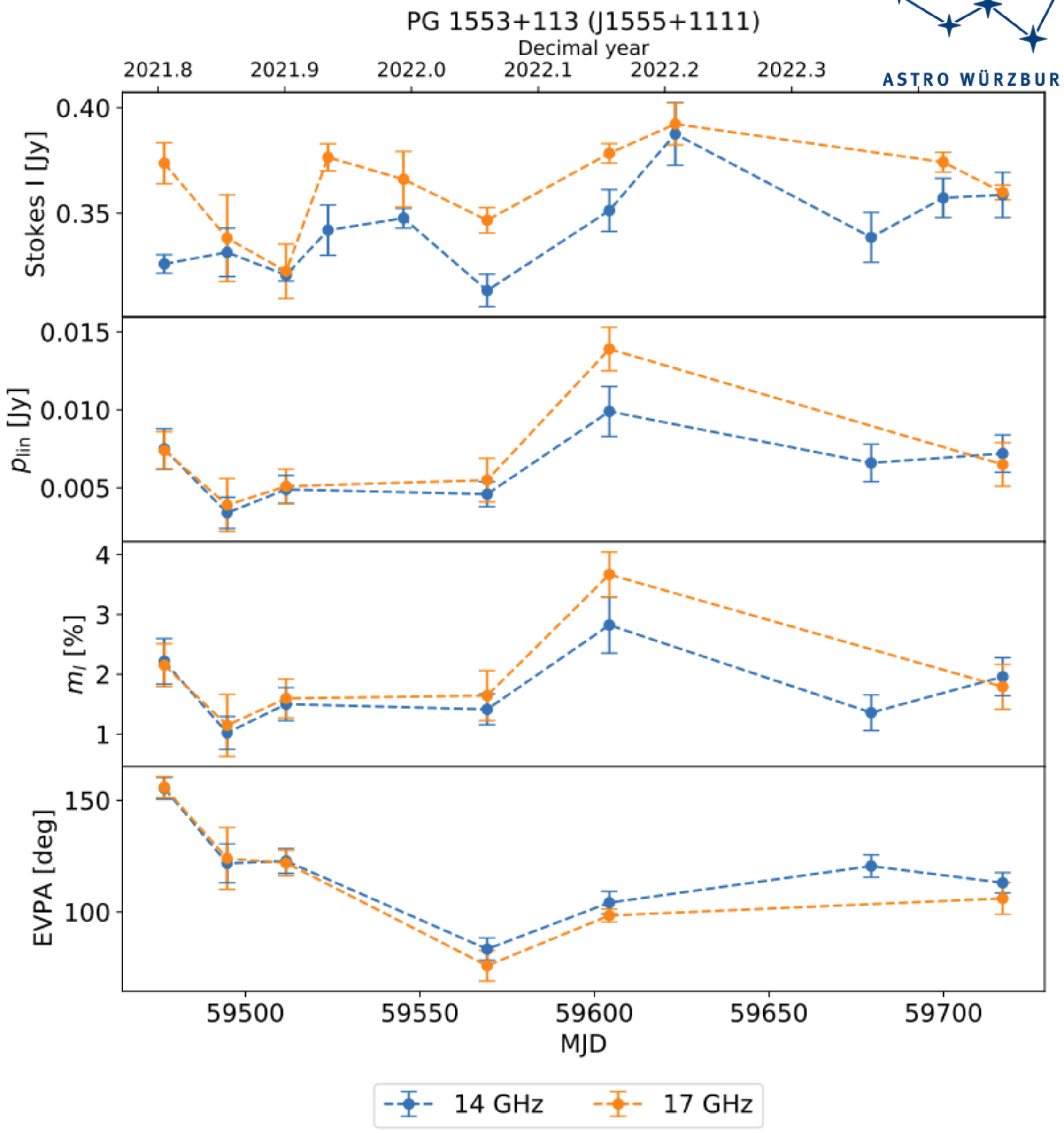


- Most sources have $m_l \leq 5\%$

PG 1553+113

- Shows quasi-periodic gamma-ray emission with a period of ~2.2 yr (Ackermann et al., 2015)
- Strong EVPA variability
  In the optical, swings of > 100° in ~100 days (Blinov et al., 2015) observed
- Shows signs of variability in total and polarized intensity

→ Additional information in EVPA, while other values stay approximately the same



Comparison with MOJAVE

Lister et al., 2018

- MOJAVE uses the VLBA, reaching resolutions ~ 1 mas
- Expect MOJAVE polarizations to be higher, due to depolarization in TELAMON observations
- 30 sources overlapping in TELAMON and MOJAVE source samples
- Compare maximal fractional polarization measured by both programs (at 15GHz)

Name (J2000)	TELAMON frequency [GHz]	TELAMON m_l [%]	MOJAVE m_l [%] at 15 GHz
0112+2244	36	7.3	8.0
0214+5144	14	1.8	4.5
0222+4302	36	6.3	9.0
0303-2407	14	1.7	2.7
0316+4119	14	—	4.1
0509+0541	36	—	4.7
0521+2112	36	—	6.2
0738+1742	14	1.0	4.9
0809+5219	14	3.4	5.6
1015+4926	14	2.6	8.5
1104+3812	39	4.3	3.7
1136+7009	14	5.3	4.2
1145+1936	14	4.9	1.8
1217+3007	36	—	3.1
1221+2813	36	3.9	5.4
1230+2518	36	—	9.6
1415+1320	36	—	0.4
1422+3223	36	2.8	4.3
1427+2348	36	—	4.5
1443+2501	14	7.3	10.9
1518-2731	14	2.7	2.4
1555+1111	14	2.8	3.5
1653+3945	36	2.1	4.4
1728+1215	14	9.6	11.0
1728+5013	14	2.9	6.1
1743+1935	14	2.0	4.3
1751+0938	14	6.2	11.3
1959+6508	14	4.4	4.6
2243+2021	14	2.5	—
2347+5142	14	3.0	4.5

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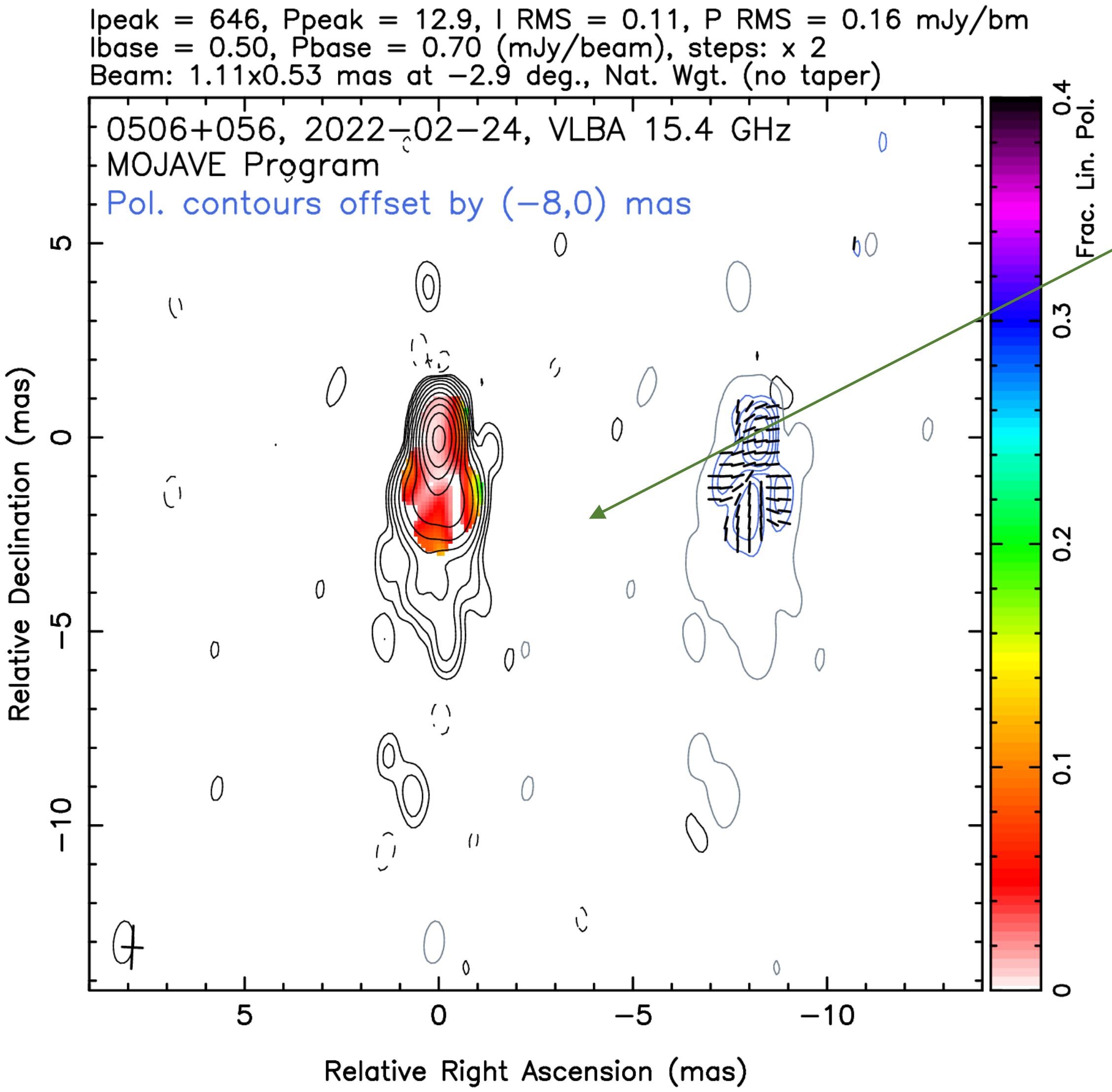

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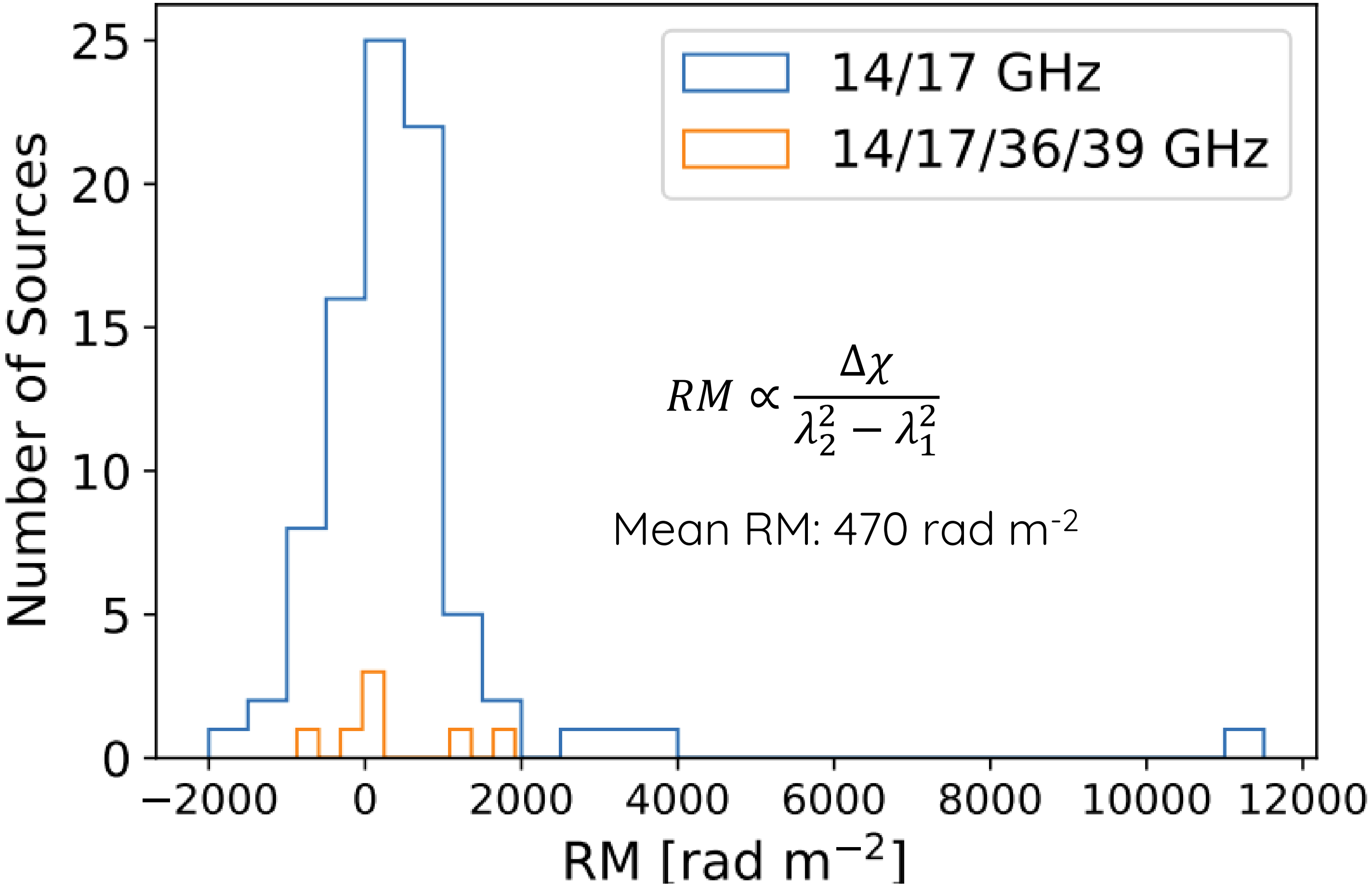
1751+0938	14	6.2	11.3
1959+6508	14	4.4	4.6
2243+2021	14	2.5	—
2347+5142	14	3.0	4.5

Rotation Measures

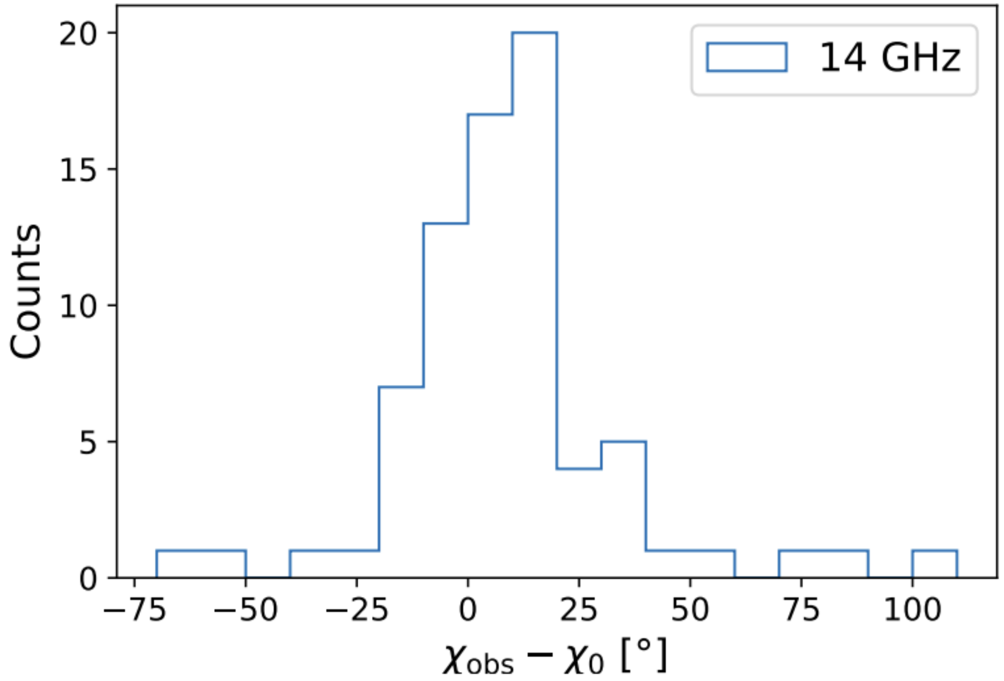
Following Taylor et al., 2009

$$\chi_{obs} = \chi_0 + RM \cdot \lambda^2$$



$$RM \propto \frac{\Delta\chi}{\lambda_2^2 - \lambda_1^2}$$

Mean RM: 470 rad m^{-2}



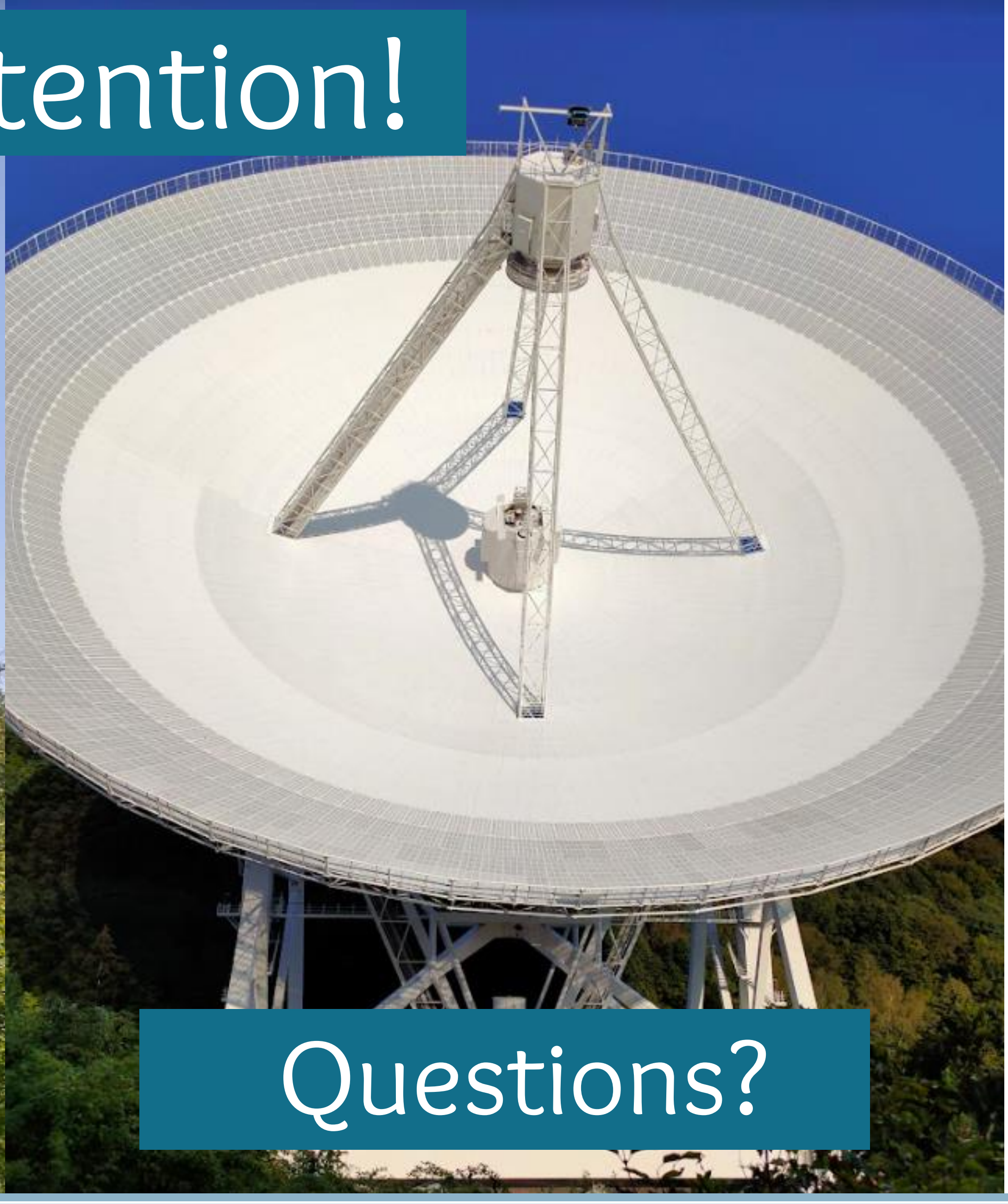
RMs are higher than those found by Taylor et al. (2009) and Myserlis (2015) at 1.4GHz and 10.45GHz, respectively.

But lower than Goddi et al. (2021) at ~100GHz

Summary

- The Effelsberg telescope is superior to other (smaller) telescopes in terms of polarization measurements at high frequencies
- Most TELAMON source are polarized at a level < 5%
- Results are in agreement with earlier studies of brighter sources and expand the discovery space to high-peaked BL Lac objects

Thanks for your attention!



Questions?

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Comparison with F-GAMMA

Angelakis et al., 2019,
Myserlis, 2015

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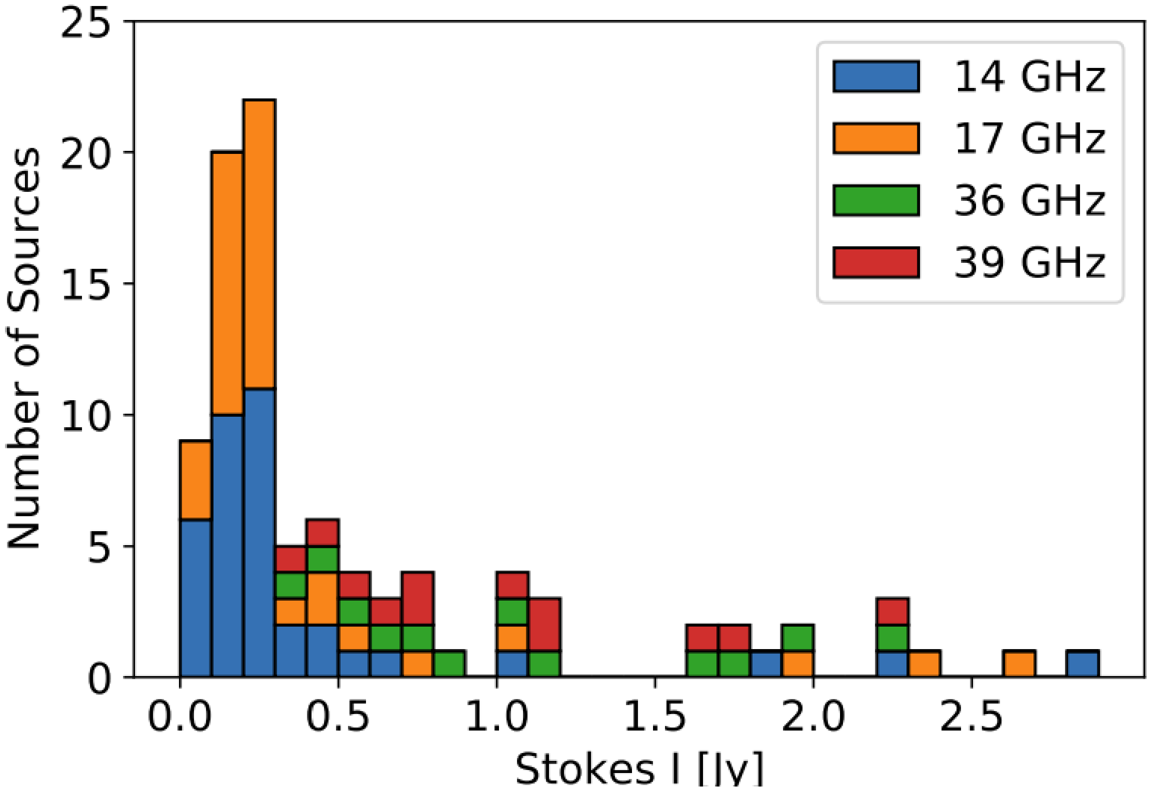
- F-GAMMA observed with the Effelsberg telescope as well, although at slightly lower frequencies
- Their criterion for “significant polarization” is stricter than used in this work
- 15 coincident sources in both samples
- In 8 sources, TELAMON polarization is higher
- In 6 cases, one of the two studies did not detect significant polarization

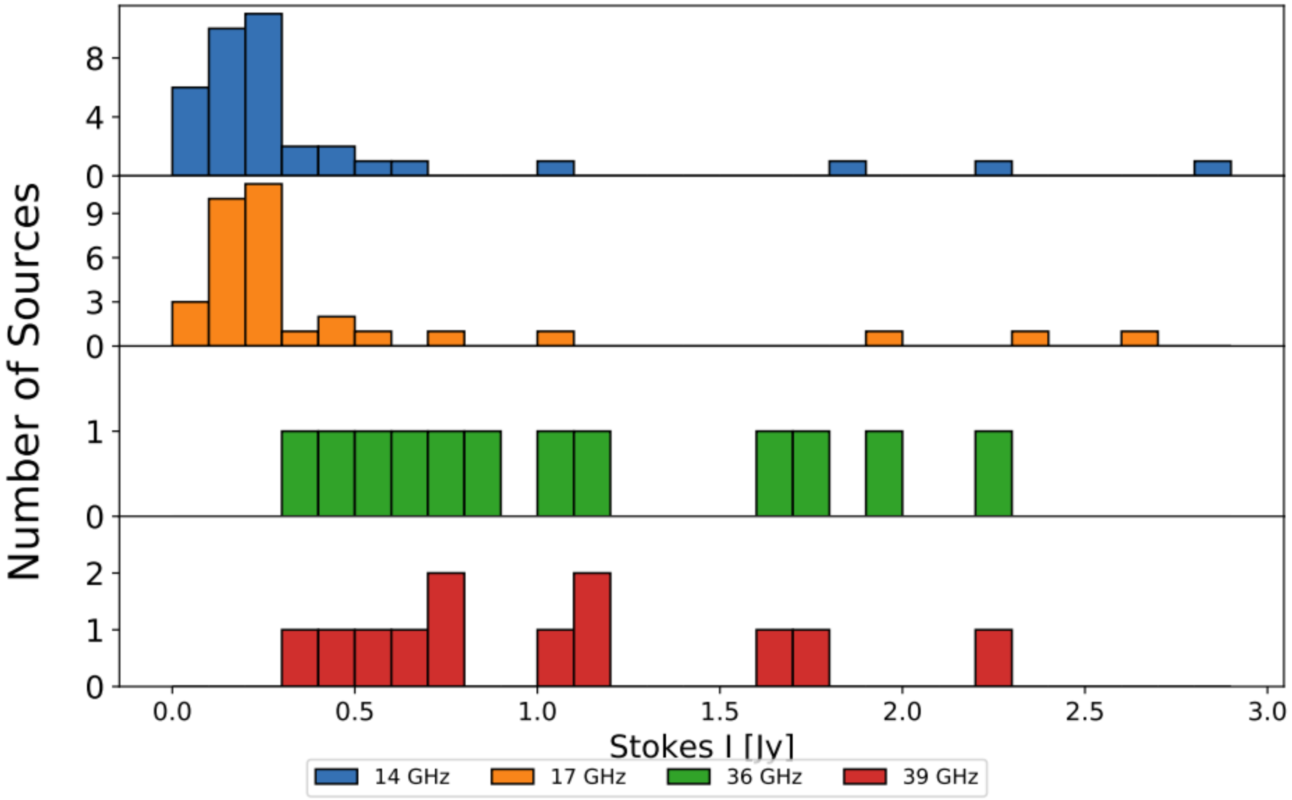
Name (J2000)	TELAMON frequency [GHz]	TELAMON m_l [%]	F-GAMMA frequency [GHz]	F-GAMMA m_l [%]
0217+0144	14	3.0	10.45	2.9
0221+3556	36	10.2	10.45	7.4
0222+4302	36	6.3	10.45	2.1
0738+1742	14	0.6	10.45	2.0
1104+3812	39	4.3	10.45	3.2
1136+7009	14	4.4	8.35	3.8
1217+3007	—	—	8.35	3.3
1221+2813	36	3.9	8.35	2.9
1542+6129	14	2.5	—	—
1555+1111	14	1.6	—	—
1653+3945	36	2.1	10.45	1.6
1751+0939	14	6.0	10.45	3.3
1959+6508	14	3.3	—	—
2158-3013	—	—	2.64	3.0
2347+5142	14	2.1	—	—

Shown are the mean values over all significant detections

Overall good agreement with other studies!

Total Intensity (Stokes *I*)





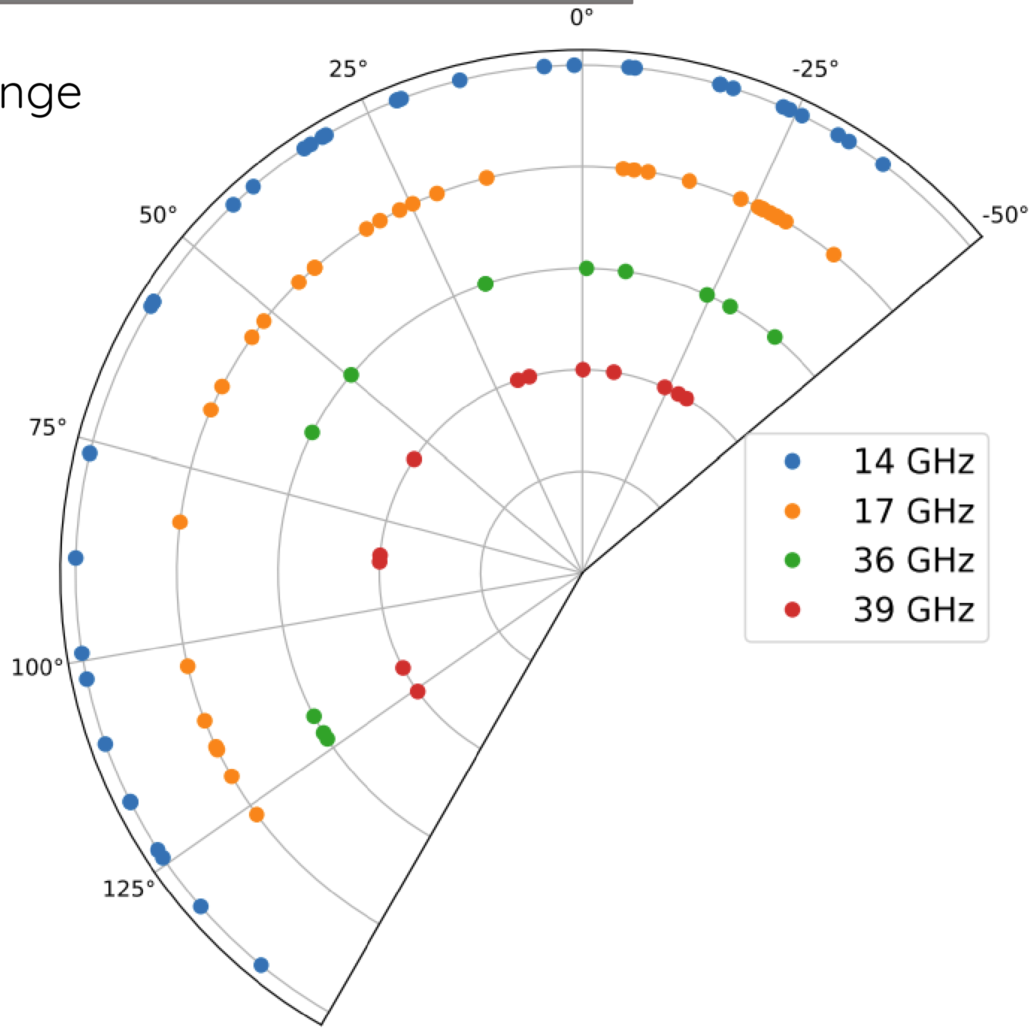
- 20mm: mostly < 0.3Jy

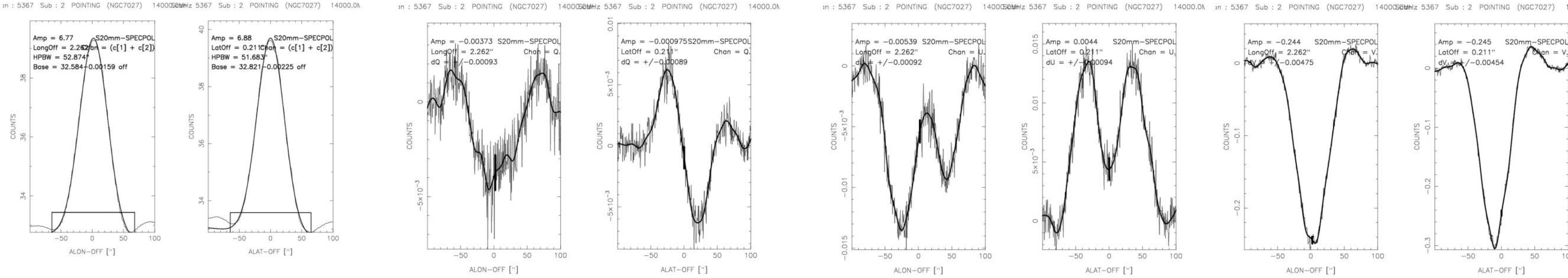
Assuming $m_l = 10\%$ $\longrightarrow$ $p_{lin} < 0.03\mathrm{Jy}$

Polarization Angle (EVPA)

- Distributed in a ~180° range

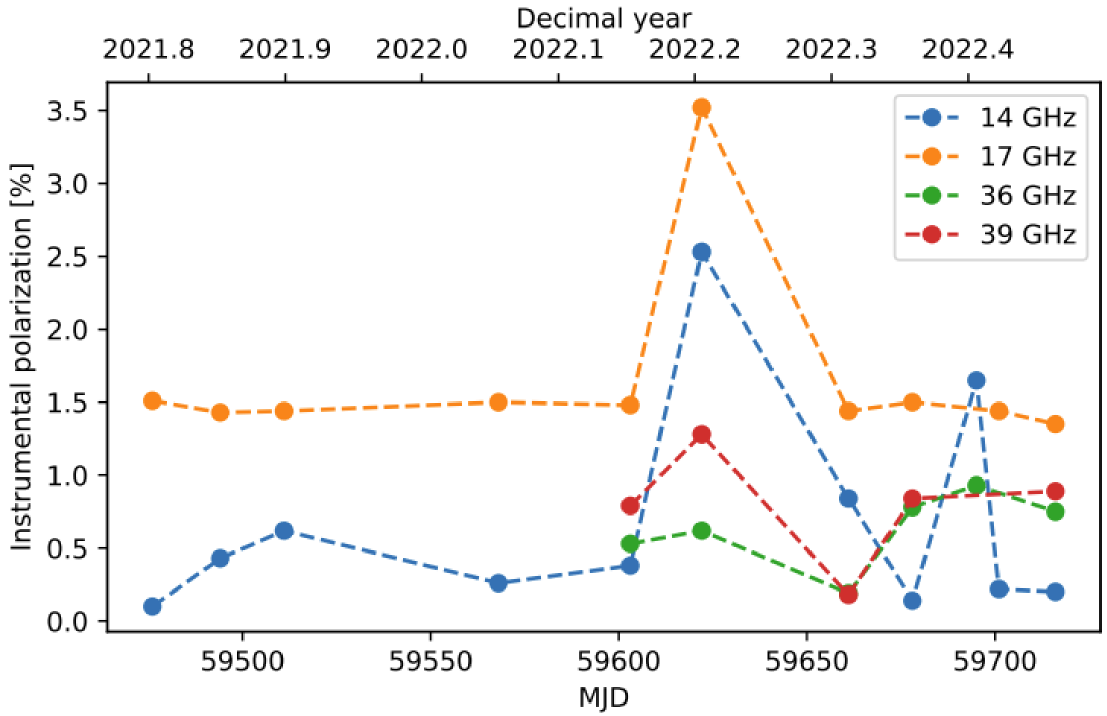
→ $n\pi$-ambiguity



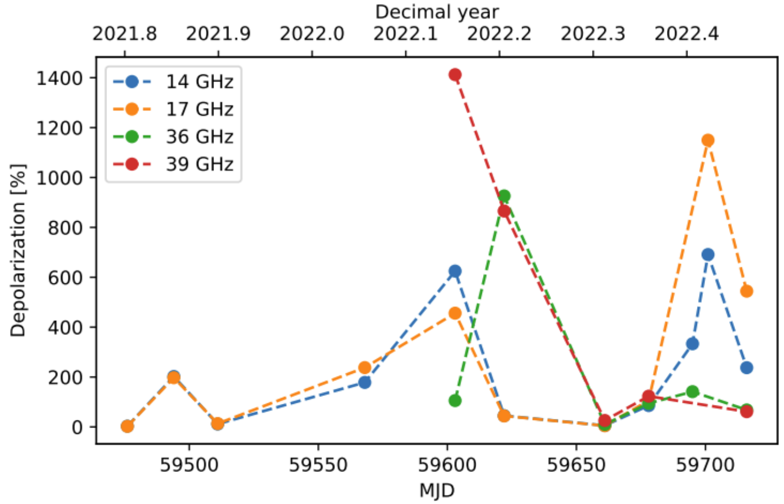

Sub : 2 POINTING (NGC7027) 14000.0
Amp = 6.77 S20mm−SPECPOL
LongOff = 2.262"
HPBW = 52.874"
Base = 32.584 0.00159 off
Chan = (c[1] + c[2])
ALON−OFF ["]
COUNTS
Amp = 6.88 S20mm−SPECPOL
LatOff = 0.211"
HPBW = 51.683"
Base = 32.821 0.00225 off
ALAT−OFF ["]
Amp = −0.00373 S20mm−SPECPOL
LongOff = 2.262"
dQ = +/−0.00093
Chan = Q
Amp = −0.000975 S20mm−SPECPOL
LatOff = 0.211"
dQ = +/−0.00089
Amp = −0.00539 S20mm−SPECPOL
LongOff = 2.262"
dU = +/−0.00092
Chan = U
Amp = 0.0044 S20mm−SPECPOL
LatOff = 0.211"
dU = +/−0.00094
Amp = −0.244 S20mm−SPECPOL
LongOff = 2.262"
dV = +/−0.00475
Chan = V
Amp = −0.245 S20mm−SPECPOL
LatOff = 0.211"
dV = +/−0.00454

Instrumental Properties

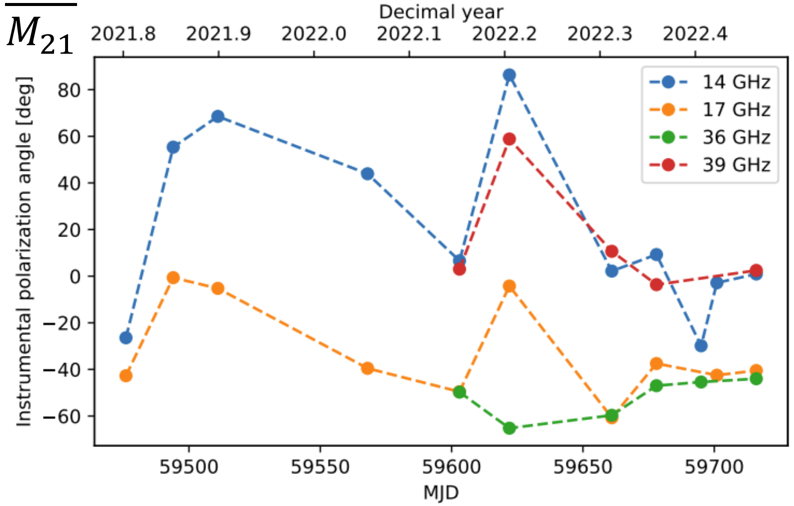
$$p_{inst} = \frac{\sqrt{M_{21}^2 + M_{31}^2}}{|M_{11}|}$$



$$p_{depol} = \frac{\sqrt{M_{12}^2 + M_{13}^2}}{|M_{11}|}$$

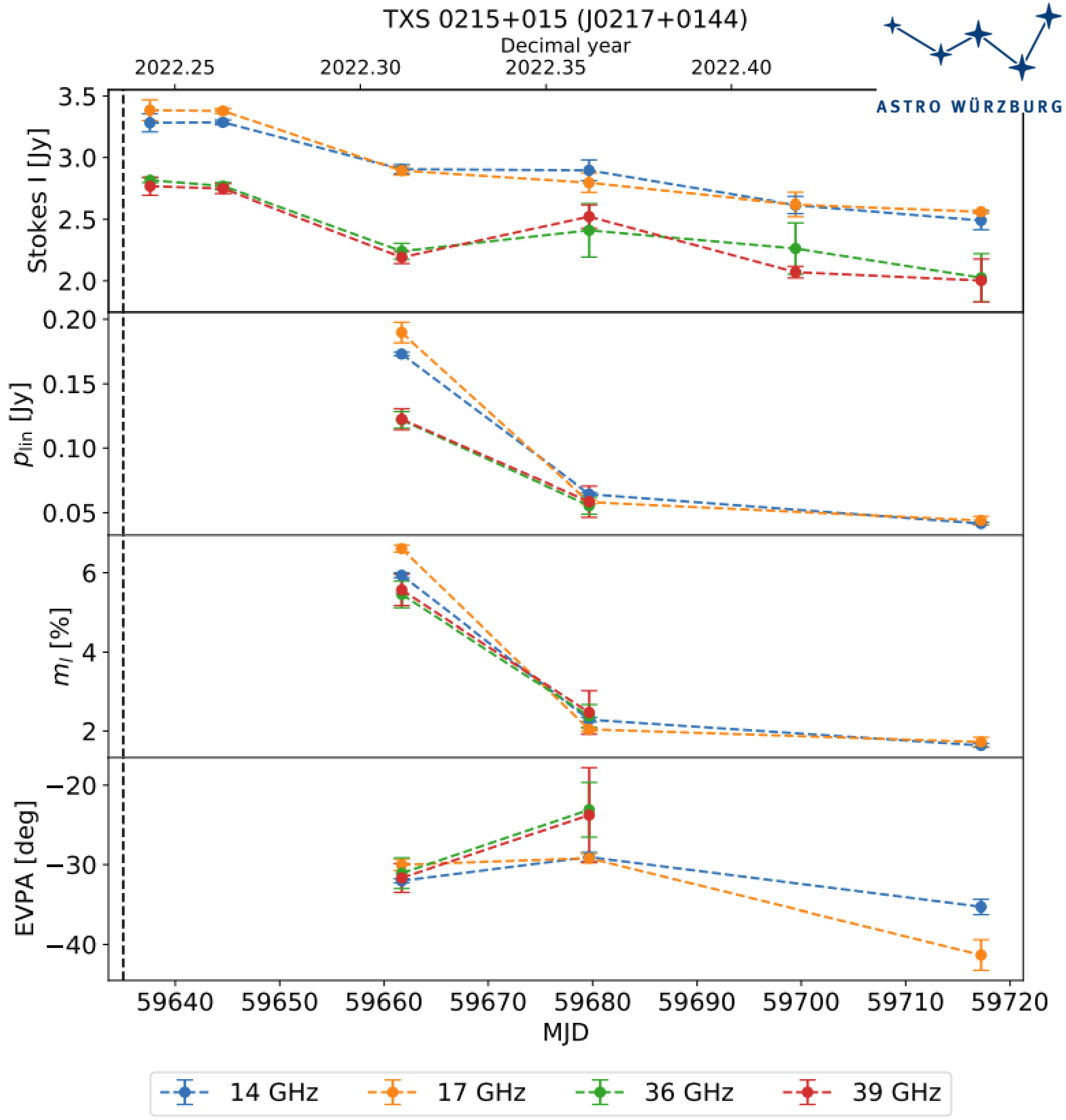


$$\chi_{inst} = \tan^{-1}\frac{M_{31}}{M_{21}}$$

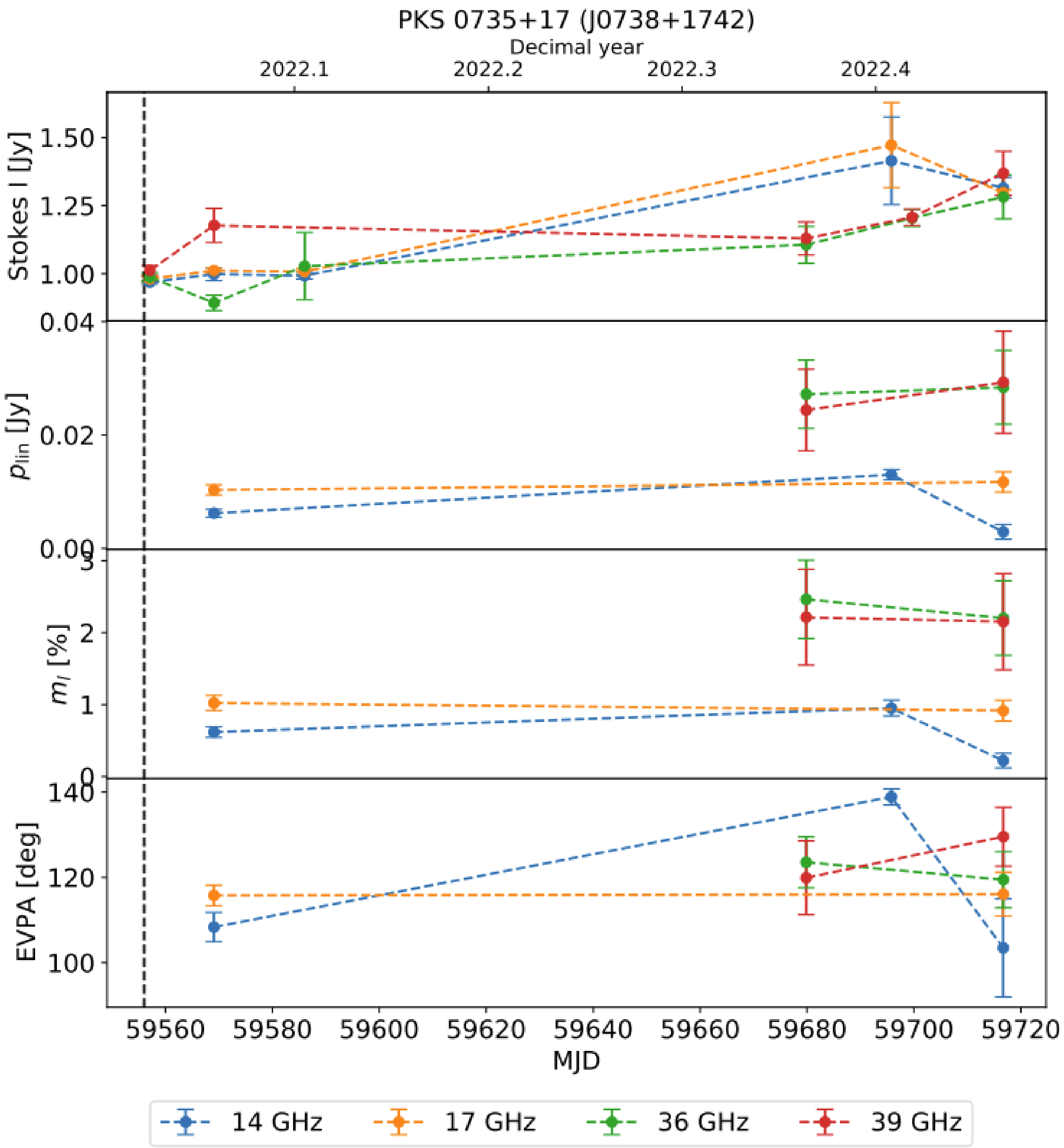


Selected Results

- Associated with IC220225A
- Found to be in an elevated state in gamma- (7 times higher than average), radio- and optical-frequencies
- Potential polarization flare:
  - MOJAVE 15GHz:
    - All time high: 4.0% (Okt. 2011, Feb. 2010)
    - Last published observation: $m_l = 0.3\%, I = 2.9\text{Jy}, \text{EVPA} = -30°$ (Jan. 2022)
    - Latest observation (Apr.2022) not yet published
  - TELAMON 14GHz:
    - $m_l \approx 6\%, I \approx 3\text{Jy}, \text{EVPA} \approx -30°$



- One of the brightest blazars in the 5th Roma-BZCat catalog
- Associated with IceCube, KM3NeT, Baikal & Baksan neutrino detections (Sahakyan et al., 2022)
- Promising neutrino candidate, has similar properties as TXS 0506+056 and other likely neutrino associations
- One of the lowest polarized sources in the sample



- Associated with IC201021A

- Nearly continuous increase in polarization, while total intensity decreases

- One of the highest polarized sources in the sample