

Short-Wavelength Radio Monitoring of Blazars with Very-High-Energy Emission in Total and Polarized Intensity

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TeV-emitting gamma-ray blazars

- Mainly High-peaked BL Lacs ($\nu_{peak} > 10^{15} \text{ Hz}$) and extreme blazars ($\nu_{peak} > 10^{17.38} \text{ Hz} \triangleq 1 \text{ keV}$)

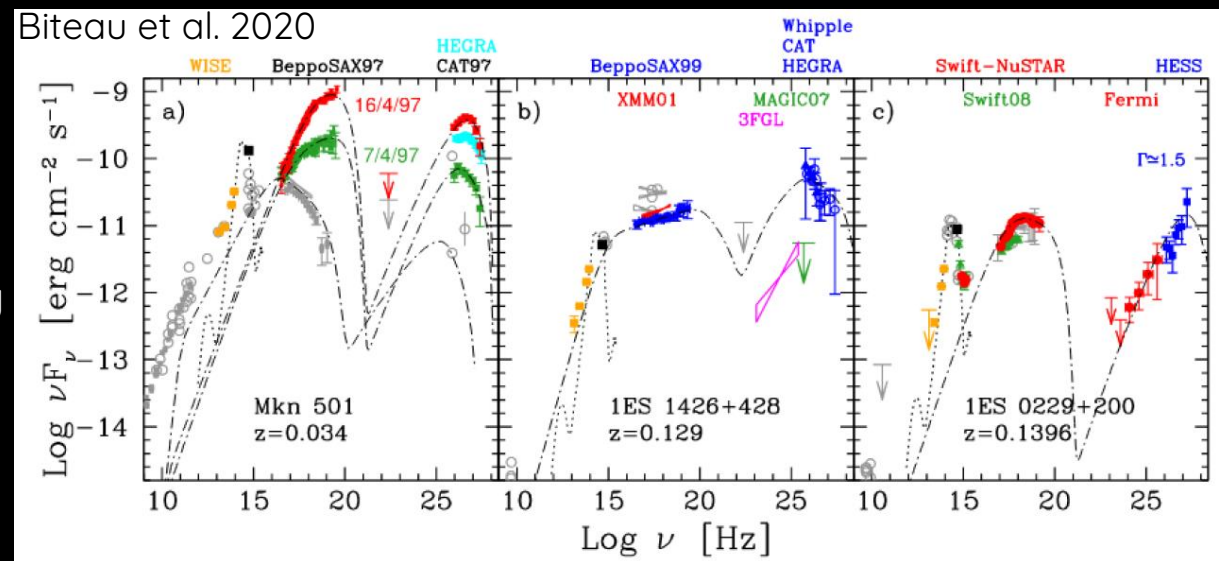
➔ mainly very faint radio sources

- Three classes of extreme behaviour:
 - Extreme during flares
 - Hard synchrotron spectrum w/o persistent TeV-emission
 - Hard gamma-ray spectrum with synchrotron peak in X-ray

- Doppler Crisis

- Very relevant in the upcoming CTA era

- Extreme blazars are suggested to be relevant neutrino sources (e.g., *Tavecchio, Ghisellini & Guetta 2014; Padovani et al. 2015; Giommi et al. 2020*)



TELAMON: TeV Effelsberg Long-term Agn MONitoring

M. Kadler, U. Bach, P. Benke, D. Berge, S. Buson, L. Debbrecht, D. Dorner, P.G. Edwards, J. Eich, F. Eppel, C.M. Fromm, M. Giroletti, A. Gokus, S. Hämmerich, O. Hervet, J. Heßdörfer, A. Kappes, D. Kirchner, S. Kim, S. Koyama, A. Kraus, T.P. Krichbaum, E. Lindfors, K. Mannheim, R. Ohja, G. F. Paraschos, E. Poeschel, L. Ricci, F. Rösch, E. Ros, B. Schleicher, W. Schulga, H. Shetgaonkar, J. Sinapius, J. Sitarek, P. Weber, J. Wilms, M. Zacharias, J.A. Zensus

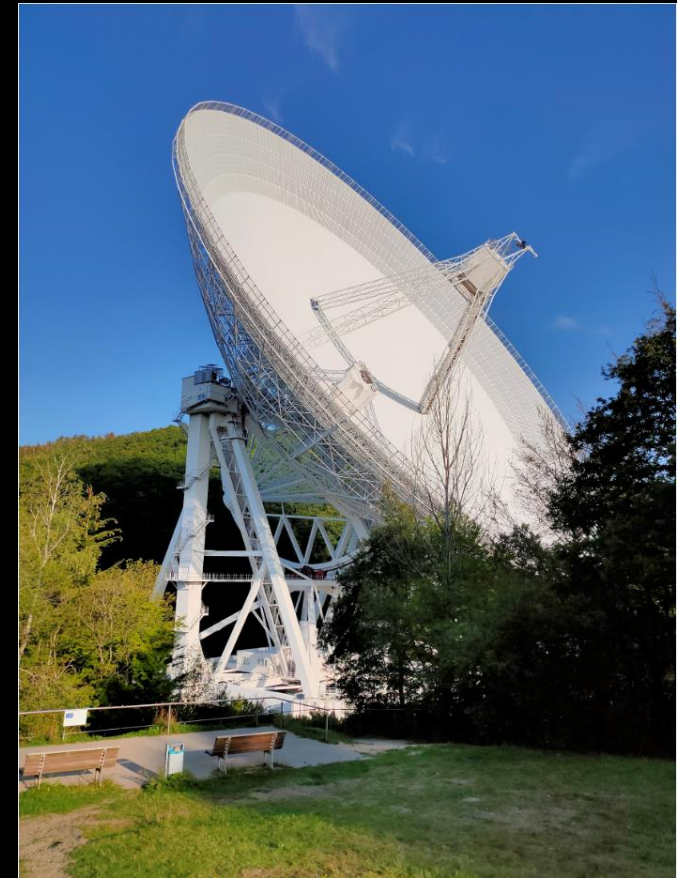
- Monitoring radio spectra of **ALL** 59 TeV detected blazars in the Northern Hemisphere
+ follow-up of Radio Fundamental Catalogue (RFC) sources in small IceCube fields
- **Goals:**
 - Characterize variability and polarization properties to test different emission models
 - Investigate the radio- γ correlation (especially with the upcoming CTA)
 - Pin down neutrino sources by radio flaring activity (e.g., *Plavin et al. 2020/2021*, *Hovatta et al. 2021*)
 - Trace dynamical processes in pc-scale jets related to flares or ν -detections



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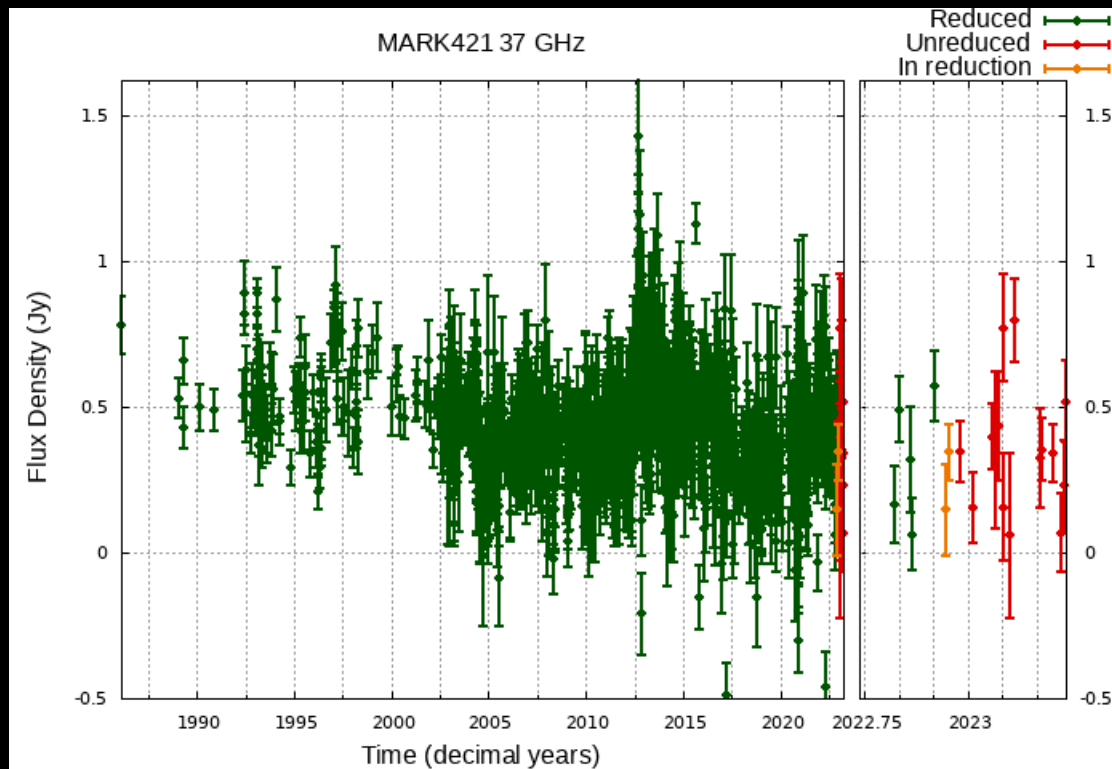
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- Monitoring radio spectra of **ALL** 59 TeV detected blazars in the Northern Hemisphere
+ follow-up of RFC sources in small IceCube fields
- High cadence observations at high radio frequencies
 - Observations every 2-4 weeks since Aug. 2020
 - **Total and polarized** intensity data from 5 GHz to 45 GHz (45mm, 20mm, 14mm, 7mm bands)
- So far, >55 IceCube alerts followed up, observed >170 RFC sources
- Data publicly available on our website
<https://telamon.astro.uni-wuerzburg.de/>



Data Comparison

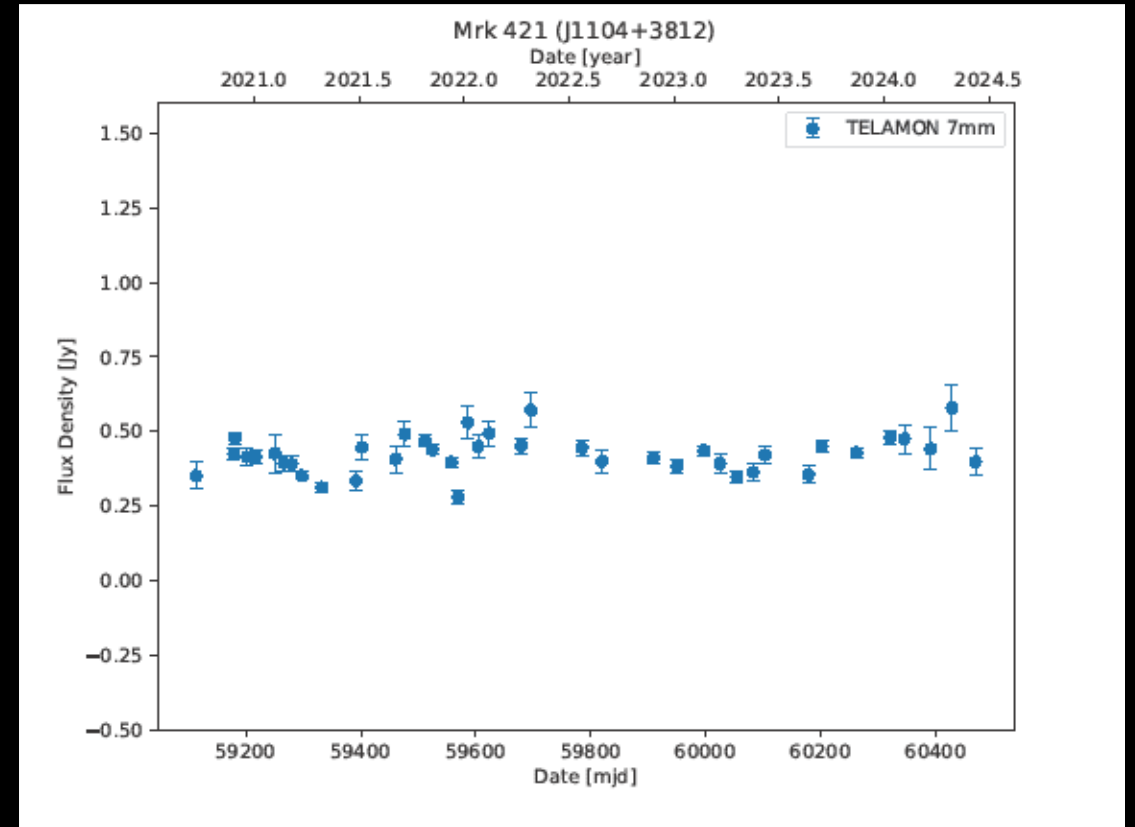
Mrk 421 Metsähovi light curve



14 m dish

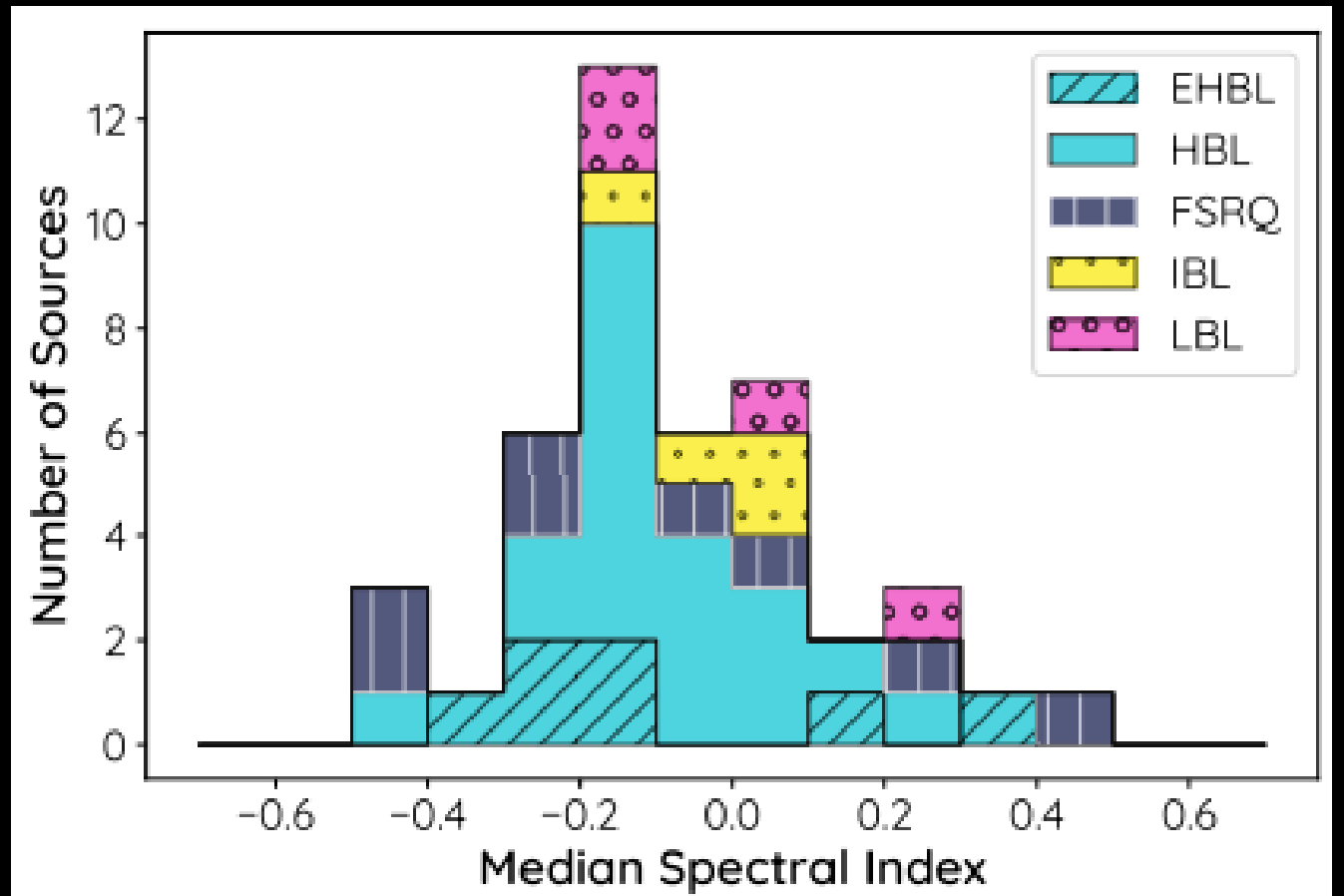
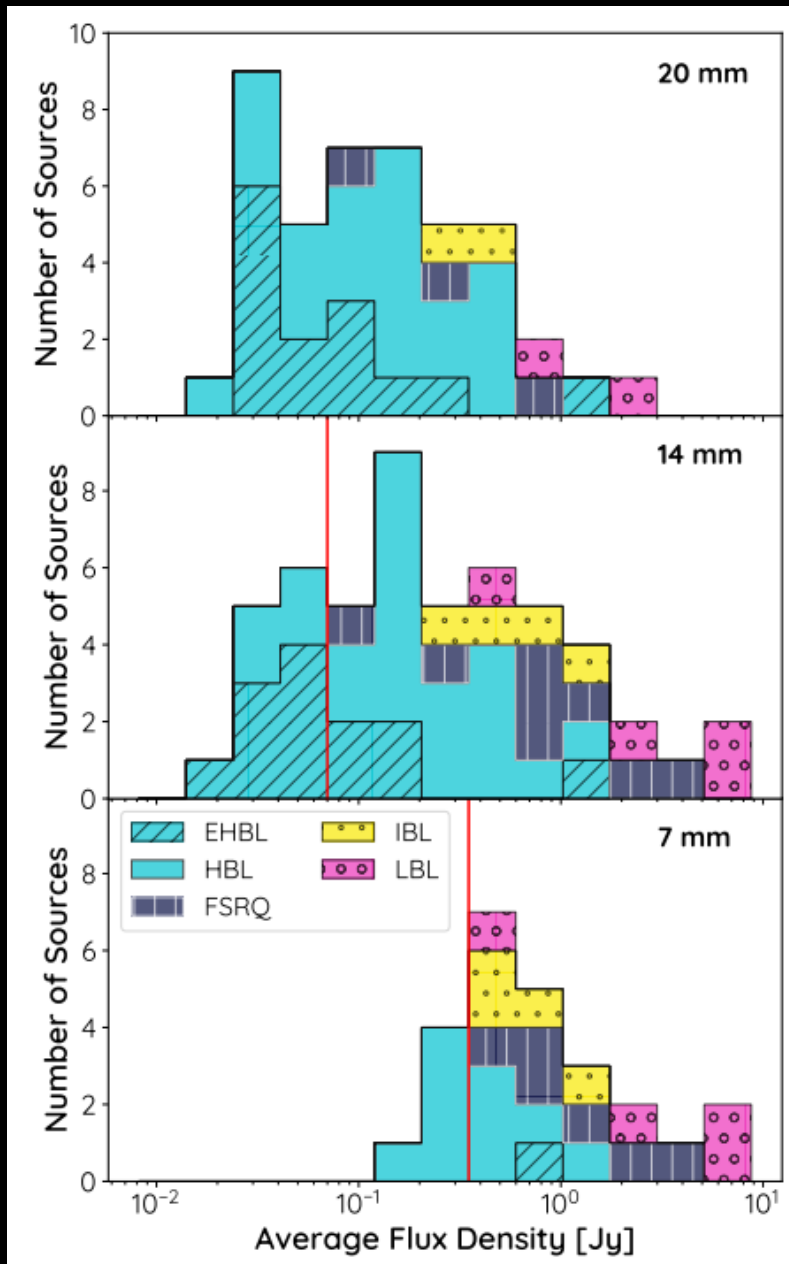
<https://www.metsahovi.fi/AGN/data/>

Mrk 421 TELAMON light curve



100 m dish

Sample Properties

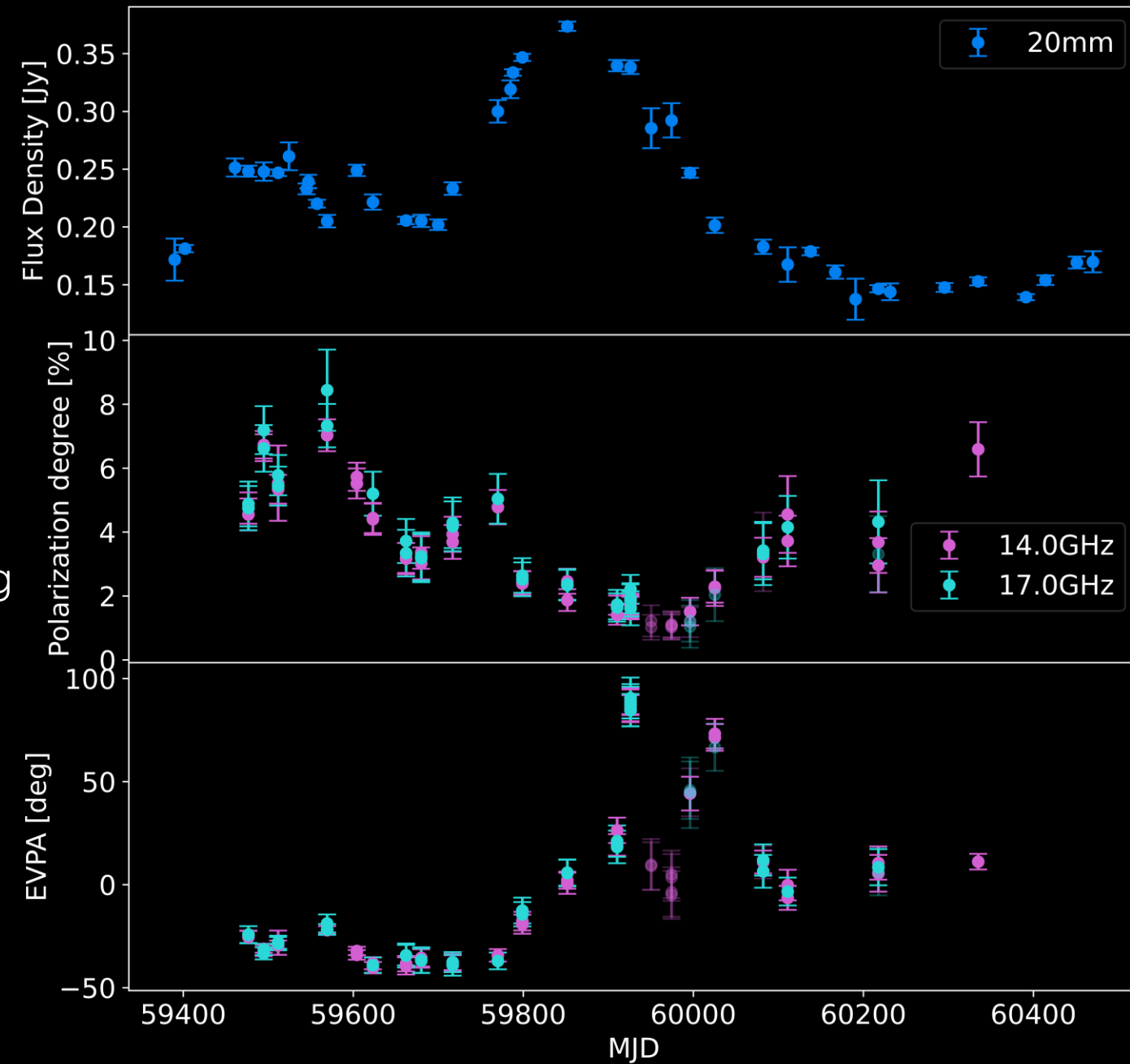


Mean spectral index across all available bands:
 $\alpha = -0.07 \pm 0.20$ with $S \propto \nu^\alpha$

J1443+2501

Heßdörfer et al. in prep.

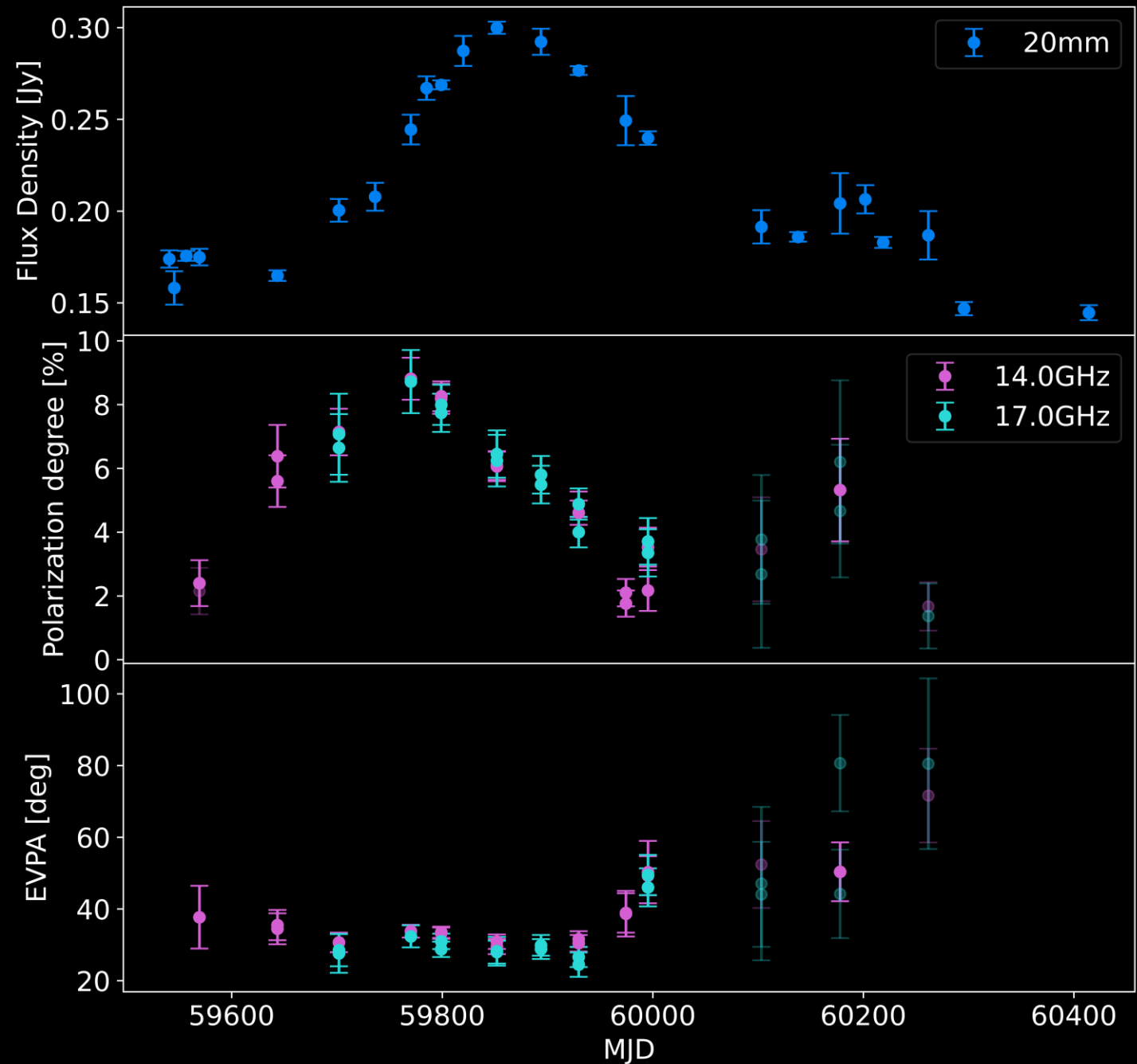
- Flux doubling/halving on time scale of ~150 days
- Polarization flare earlier than total intensity flare flare
- EVPA swing during later epochs



TXS 1801+253

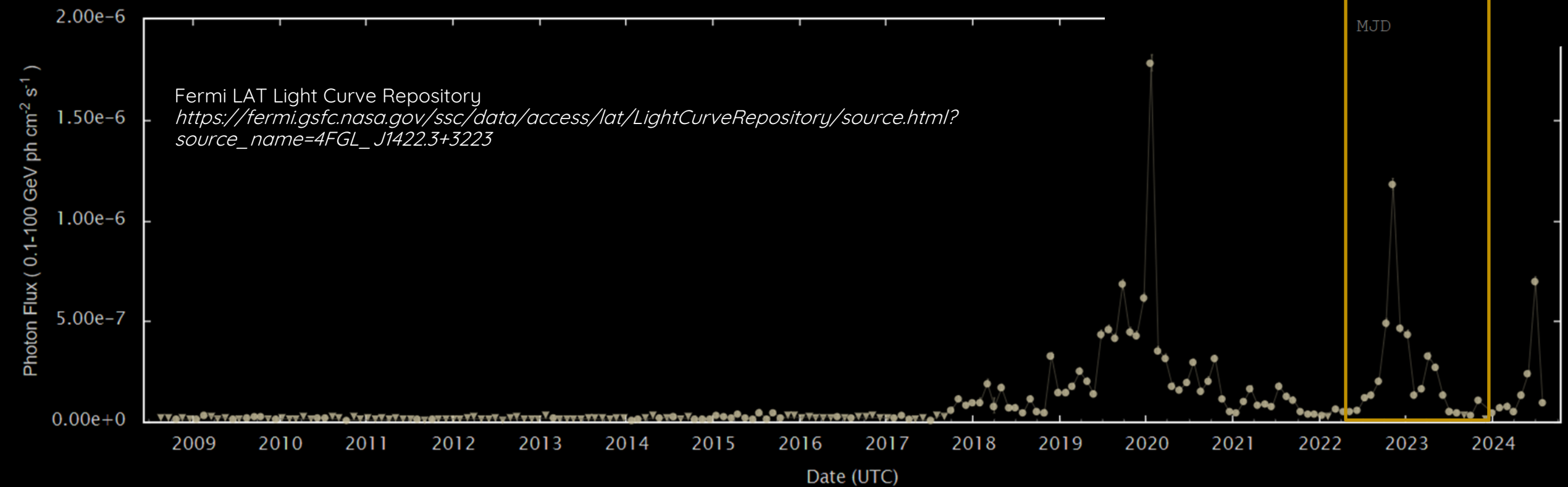
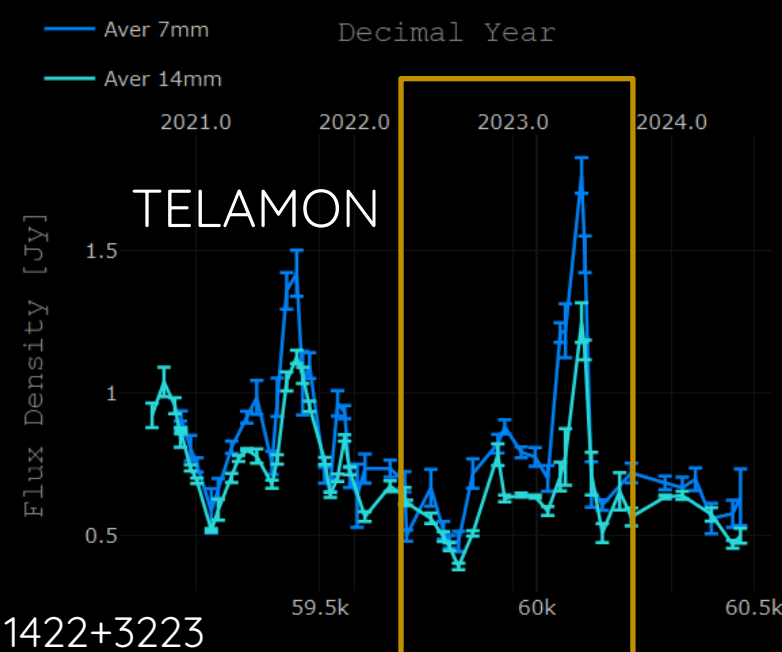
Heßdörfer et al. in prep.

- Flux doubling on time scale of ~ 0.5 yr
- Subsequent flux halving on same time scale
- Polarization flare earlier than total intensity
- Constant EVPA during the flare



What else?

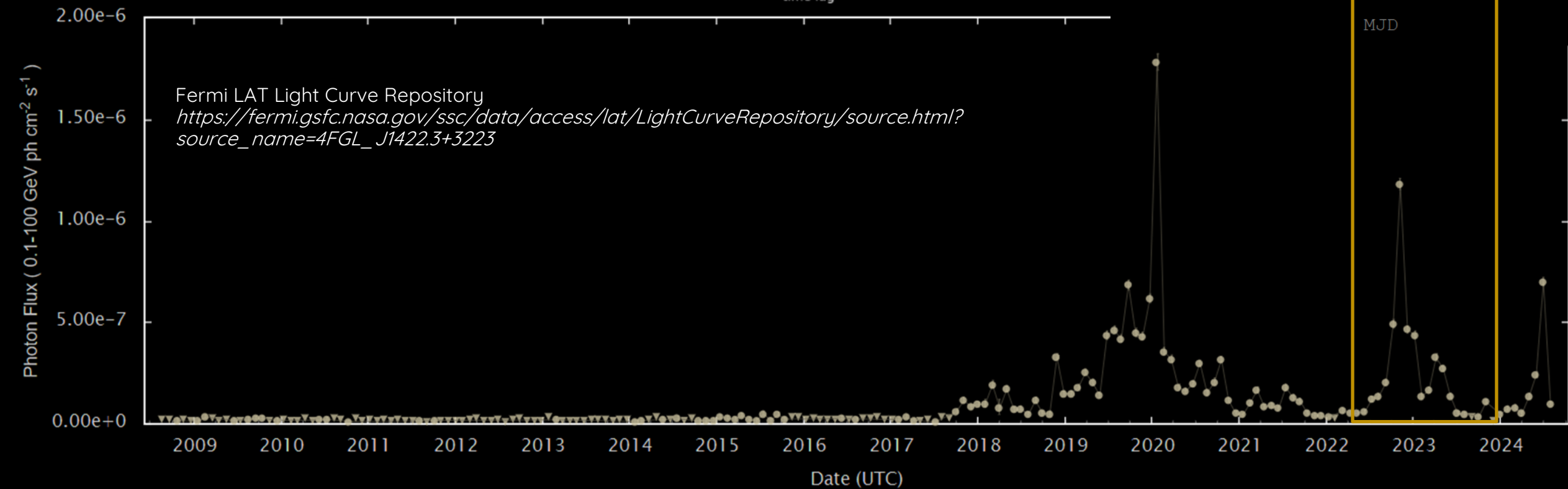
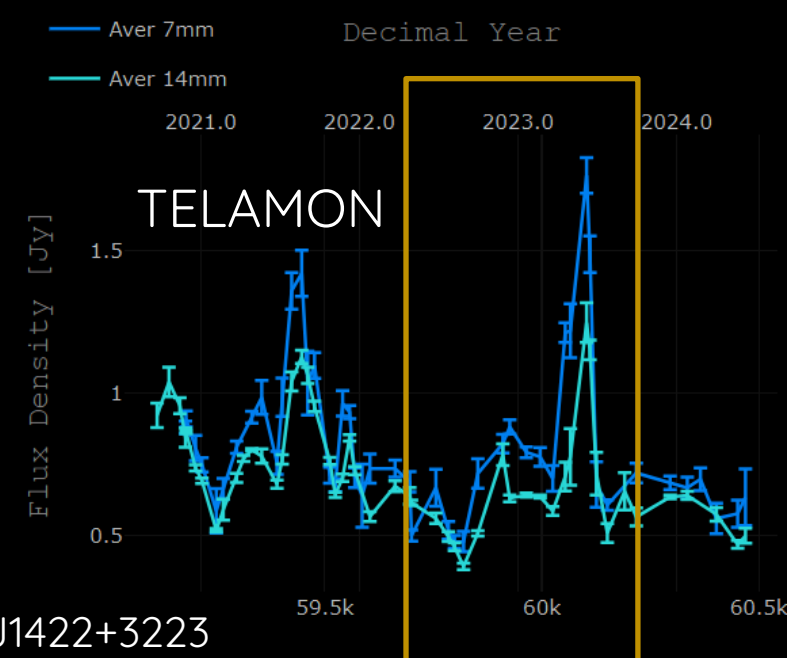
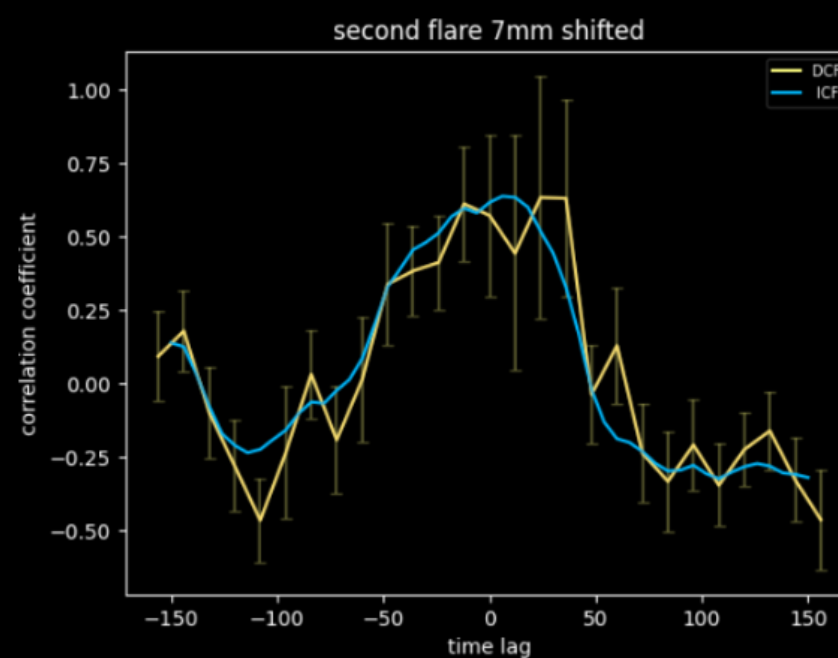
- MWL correlation studies



What else?

- MWL correlation studies

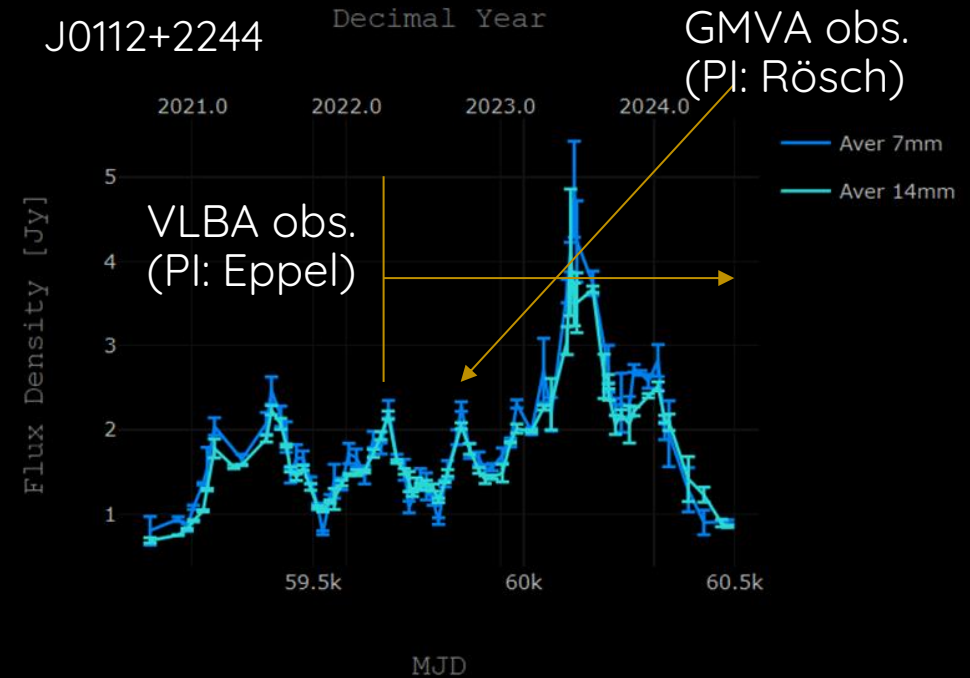
Correlation coefficient ~ 0.64
(γ leads radio by ~ 210 days)



What else?

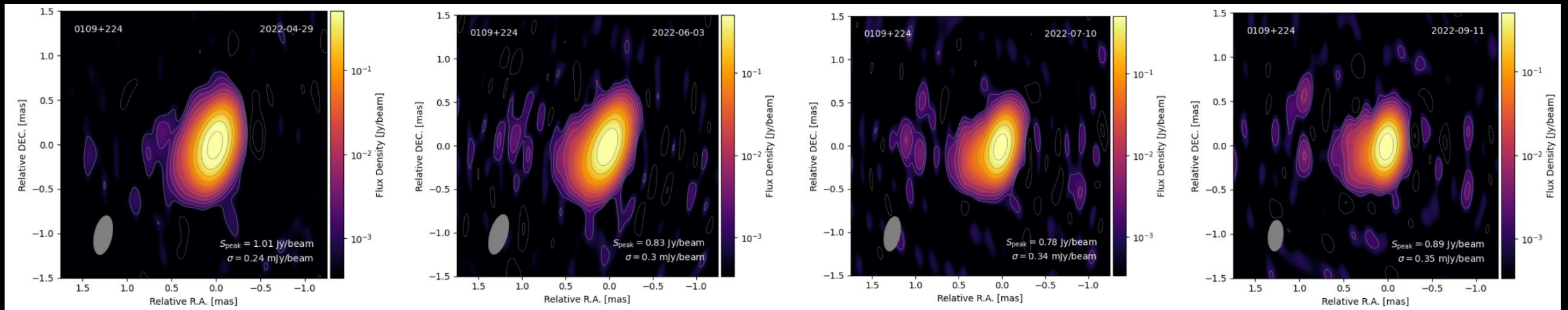
- MWL correlation studies
- VLBI follow-ups

Hint for newly ejected component with $\beta_{app} \approx 5c$



43 GHz VLBA

PRELIMINARY



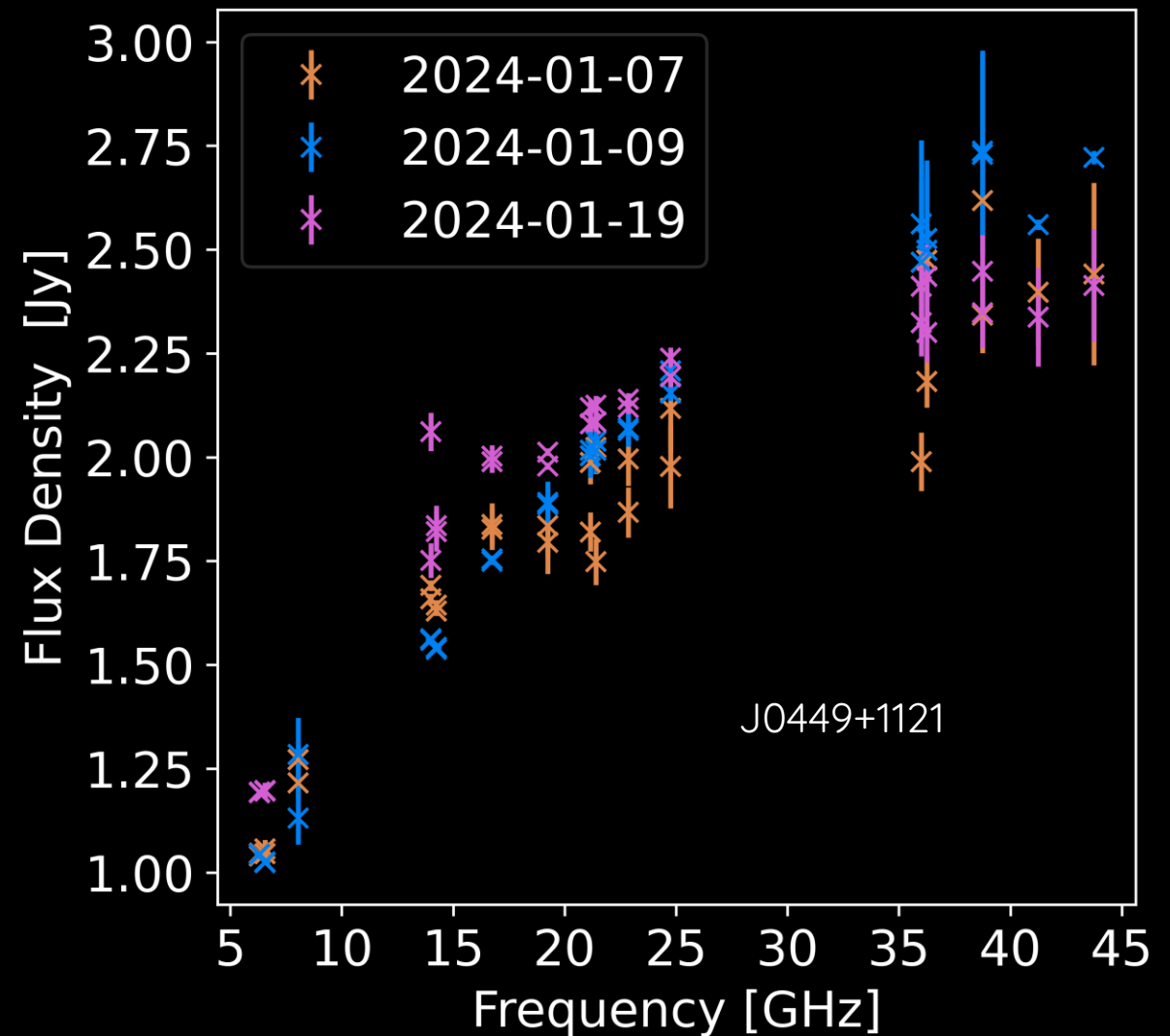
What else?

- MWL correlation studies
- VLBI follow-ups
- Neutrino candidate sources

TELAMON detection of an inverted spectrum and radio flare of PKS 0446+11 coincident with IceCube-240105A

ATel #16399; *F. Eppel (University of Wurzburg), M. Kadler (University of Wurzburg), L. Debbrecht (MPIfR Bonn), J. Eich (University of Wurzburg), A. Gokus (Washington University St. Louis), J. Hessdoerfer (University of Wurzburg), S.-H. Kim (KASI & UST), D. Kirchner (University of Wurzburg), W. Schulga (University of Wurzburg)*
on 10 Jan 2024; 10:37 UT

Credential Certification: Matthias Kadler (matthias.kadler@astro.uni-wuerzburg.de)



$\alpha = 0.523 \pm 0.017$ on 07/01/2024

~1% polarization at all frequencies

What can we do for you?

MWL studies, e.g.,

- G. Di Marco 2022 (M.Sc. thesis): *Very High Energy observations fo the blazar 1ES1959+650 with the Large-Sized Telescope (LST-1) in La Palma*
- M. Splettstoesser 2024 (Poster): *Multiwavelength Modeling Results of Two States of the Distant HBL 1ES 0647+250*
- D. Cerasole et al. 2024 (in press): *Very-high-energy gamma-ray detection and long-term multi-wavelength view of the flaring blazar B2 1811+31*

Put VLBI studies into context (EVPA and total flux scaling), e.g.,

- C. Nanci et al. 2022: *A VLBI investigation of high-energy neutrino emitter candidates*
- F. Eppel et al. 2023: *VLBI Scrutiny of a New Neutrino-Blazar Multiwavelength-Flare Coincidence*

Follow-ups on ATels, e.g.,

- Kadler et al. 2021 (Atel#15105): *TELAMON, Metsahovi, Medicina, OVRO and RATAN-600 programs find a long-term radio flare in PKS0735+17 coincident with IceCube-211208A -> so far 7 follow-up studies*

Conclusion



- TELAMON observes TeV blazars and compact radio sources in IceCube 90% uncertainty regions at high radio frequencies in total and polarized emission in the Northern hemisphere
- Possibility to investigate radio- γ correlation
- TELAMON data can be used to put VLBI and multi-wavelength studies into context
- Our data are publicly available on our website <https://telamon.astro.uni-wuerzburg.de/>

SCAN ME!



A large satellite dish antenna is shown at night, illuminated from below. The dish is a complex structure of white metal, supported by a central tower and several legs. The background is dark, with some trees visible in the foreground. The word "BACKUP" is overlaid in the center of the dish in a bold, yellow, sans-serif font.

BACKUP

Müller Formalism Following Turlo et al., 1985

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

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

- 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

- Use average Müller matrix over all TELAMON epochs for each frequency

TELAMON Neutrino Follow-Up

- Follow-up observations of IceCube bronze and gold neutrino track alerts
- Target positionally coincident compact radio sources listed in the RFC (Radio Fundamental Catalogue, <https://astrogeo.org/calib/search.html>), follow-up depending on the number of sources in the GCN box:
 - <4 (~9 events p.a.): 2 yr monitoring
 - 4-10 (~7 events p.a.): snapshot observation + check-up after half a year
 - >10 (~10 events p.a.): no follow-up, only for sources of special interest
- Goal:
 - Radio flux density monitoring of all sources in these fields to be able to identify potential flaring states
- So far, >55 IceCube events followed up, with >170 RFC sources observed