Blazar monitoring by the Whole Earth Blazar Telescope (WEBT) Collaboration

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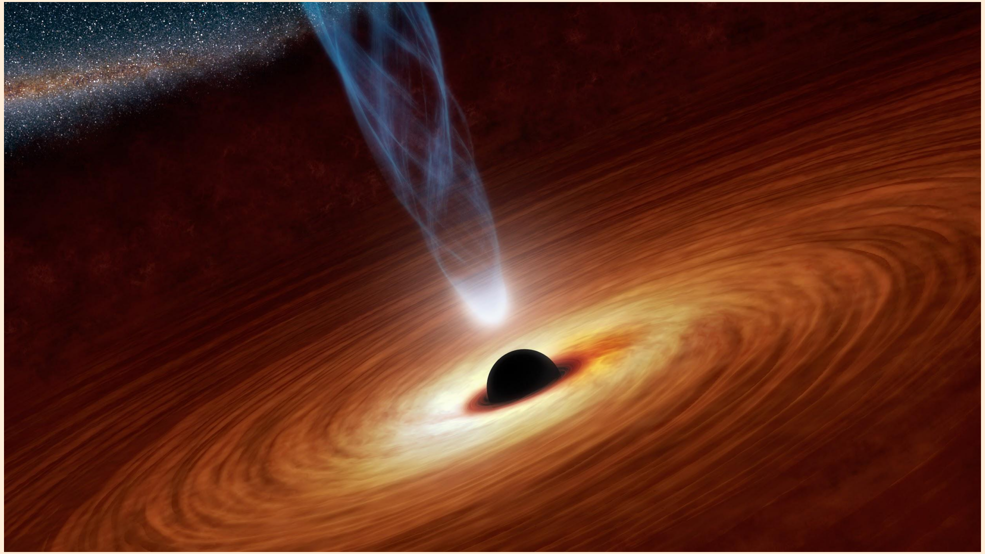


BLAZAR = active galactic nucleus (AGN) with one jet pointing toward us

Jet emission affected by relativistic

effects that depend on the

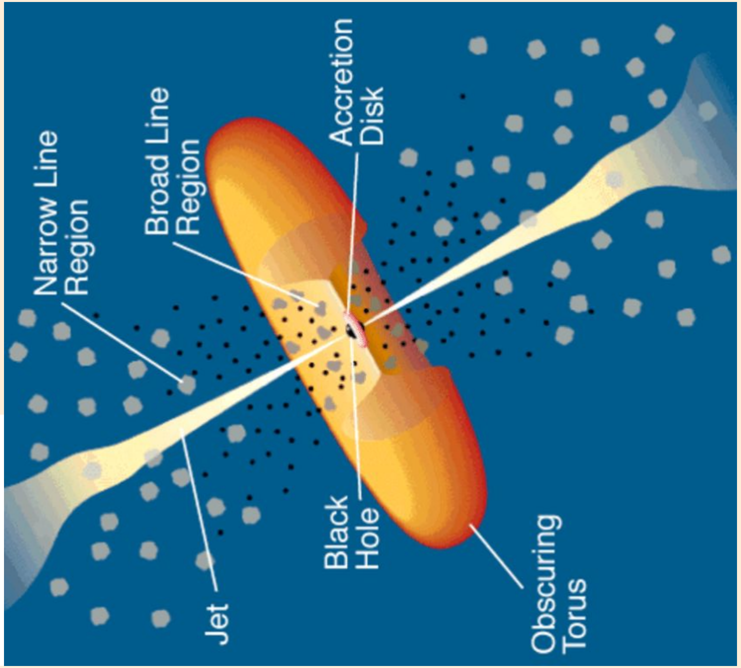
Doppler factor δ

$\delta=[\Gamma(1-\beta\cos\theta)]^{-1}$

θ viewing angle

$\Gamma=(1-\beta^2)^{-1/2}$ bulk Lorentz factor

$\beta=v/c$



Urry & Padovani, 1995, PASP, 107, 803

Consequences of Doppler beaming:

- flux relativistically enhanced $F_\nu(\nu) = \delta^{n+\alpha} F'_{\nu'}(\nu)$
- blue-shift of emitted frequencies $\nu = \delta\, \nu'$ prevailing over cosmological redshift
- shortening of variability time-scales $\Delta t = \Delta t'/\delta$

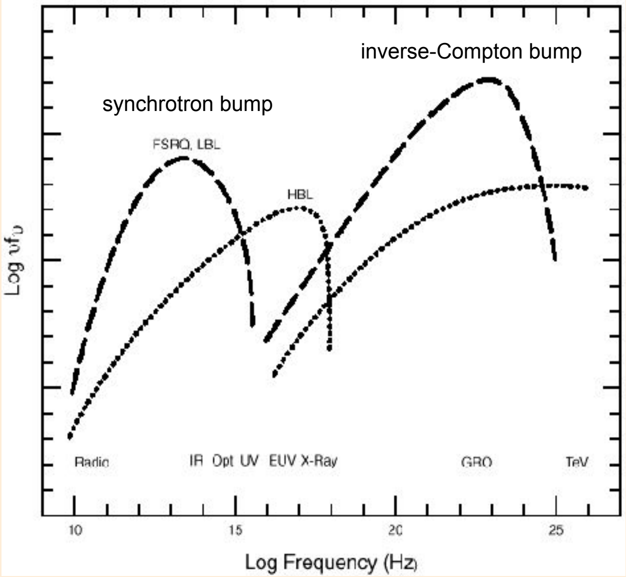
Two types of blazars:

FSRQs (flat-spectrum radio quasars) - strong emission lines

BL Lacs (BL-Lacertae-type objects) - weak or no emission lines

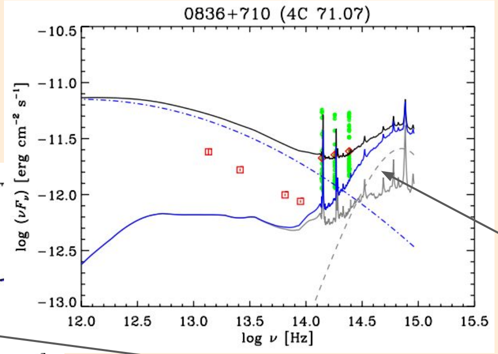
- Low-energy peaked BL Lacs (LBL)
- High-energy peaked BL Lacs (HBL)

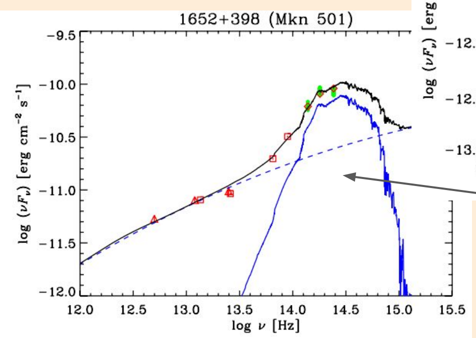
Their spectral energy distribution (SED) is dominated by non-thermal radiation from the jet



But in the optical:

1. synchrotron from the jet - very variable and polarised
2. accretion disc and broad line region (blue) - less variable and not polarised - can dominate in high-redshift FSRQs
3. host galaxy (red) - not variable and not polarised - can dominate in low-redshift BL Lacs





Raiteri et al. 2014, MNRAS, 442, 629

Blazar light curves

Unpredictable variability at all frequencies,

but some (transient) periodicities detected

Time scales from years to minutes

⇨ need for a continuous monitoring

⇨ best if in a multiwavelength (MW) context

Whole Earth Blazar Telescope (WEBT)

https://www.oato.inaf.it/blazars/webt/

A brief outline of WEBT history

1991-2000 Compton Gamma Ray Observatory (CGRO)

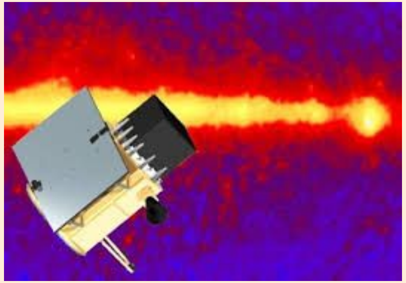
➪ The extragalactic γ-ray sky is full of blazars

1997 birth of the WEBT - John Mattox (BU, USA) President ➪ support to the CGRO observations with continuous optical monitoring

2000 Massimo Villata (INAF-OATo, Italy) President + Claudia M. Raiteri (INAF-OATo, Italy) Executive Officer ➪ +radio+near-IR

2004 radio monitoring at the IRA telescopes in Medicina and Noto (PI: Bach, since 2018 Marchili)

WEBT multiwavelength campaigns on specific objects



2007 birth of the GLAST-AGILE Support Program (GASP) in view of the launch of the AGILE and Fermi γ-ray satellites

➪ 14 (now 15) BL Lacs + 14 FSRQs continuously monitored

Team: ~ 200 observers; more than 150 telescopes (small, medium and large size)

Also high-level amateurs

AFRICA Egypt

AMERICA Argentina,Mexico,USA

ASIA China,India,Japan,Taiwan,Uzbekistan

EUROPE Bulgaria, Crimea, Finland, Georgia, Germany, Greece, Italy, Russia, Serbia, Spain

Deliverables:

- photometry + polarimetry + spectroscopy
- satellite GO observations: XMM-Newton, Swift, TESS
- archive, with data available after publication
- models to explain blazar variability
- 266 papers by the WEBT in the NASA ADS, 135 refereed, including 3 papers on Nature, 2 of which led by the WEBT

Main collaborations:

AGILE, Fermi, MAGIC

Data processing

Common prescriptions for photometric sequence and source calibration (for sources with not negligible host contribution also radii for source and background extraction) on https://www.oato.inaf.it/blazars/webt

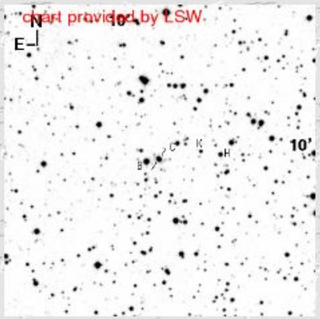
Careful dataset assembling and light curve inspection

Correction for offsets between different datasets

Removal of outliers

Binning of noisy datasets

Coordinates (J2000):
R.A. = 22:02:43.290, Dec. = +42:16:39.98
z = 0.0686



Landessternwarte Heidelberg-Königstuhl

Field of view is 10'x10'

GASP suggested stars: B C H

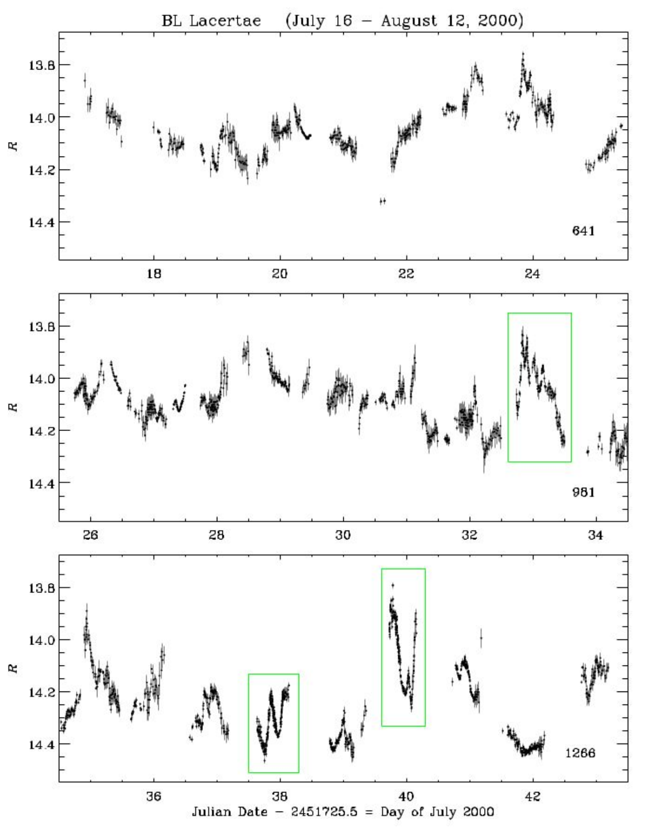
Comparison stars

Star	U	B	V	R	I
B	16.47 (~ 0.07)	14.68 (~ 0.04)	12.90 (0.04)	**11.99 (0.04)**	11.12 (0.05)
C	15.66 (~ 0.06)	15.20 (~ 0.05)	14.26 (0.06)	**13.79 (0.05)**	13.32 (0.05)
H	16.91 (~ 0.09)	15.81 (~ 0.06)	14.40 (0.06)	**13.73 (0.06)**	13.07 (0.06)
K	16.61 (~ 0.08)	16.36 (~ 0.07)	15.47 (0.07)	15.00 (0.07)	14.54 (0.07)

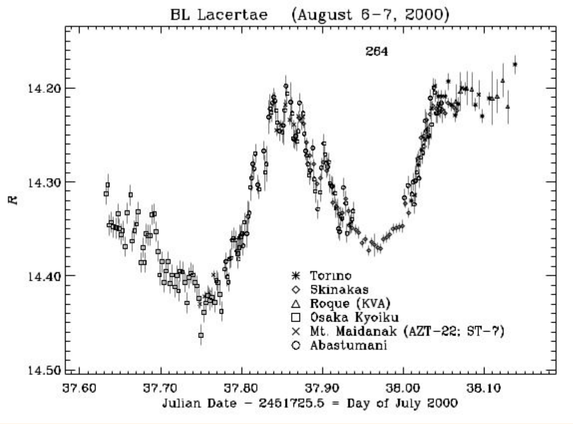
UB from Bertaud et al. (1969, A&A 3, 436)
VRI from Fiorucci & Tosti (1996, A&AS 116, 403)

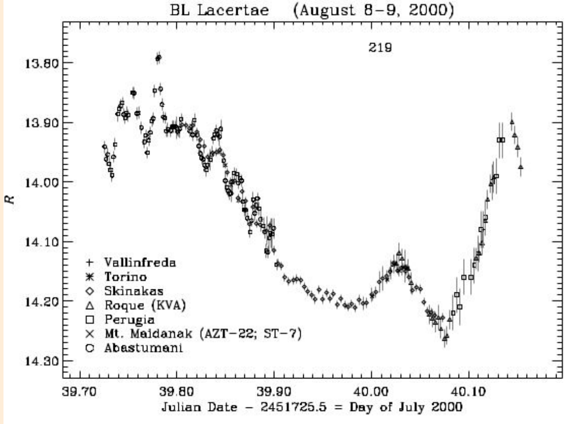
IMPORTANT: As specified since the first campaign targeting BL Lac in 2000, we recommend to use 8 arcsec for the aperture radius, and 10 and 16 arcsec for the radii of the background annulus. This allows us to optimize the subtraction of the host galaxy contribution in the following data analysis.

Optical monitoring with exceptional sampling: past



More than 15000 observations by 24 telescopes in 11 countries

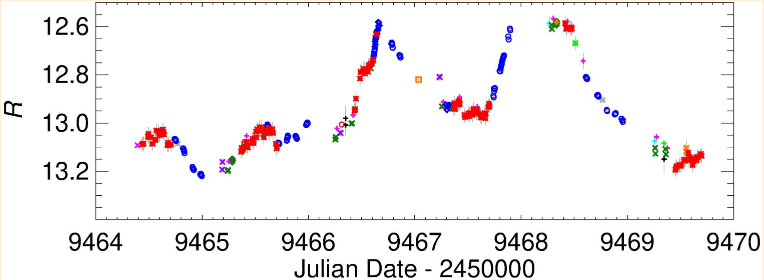




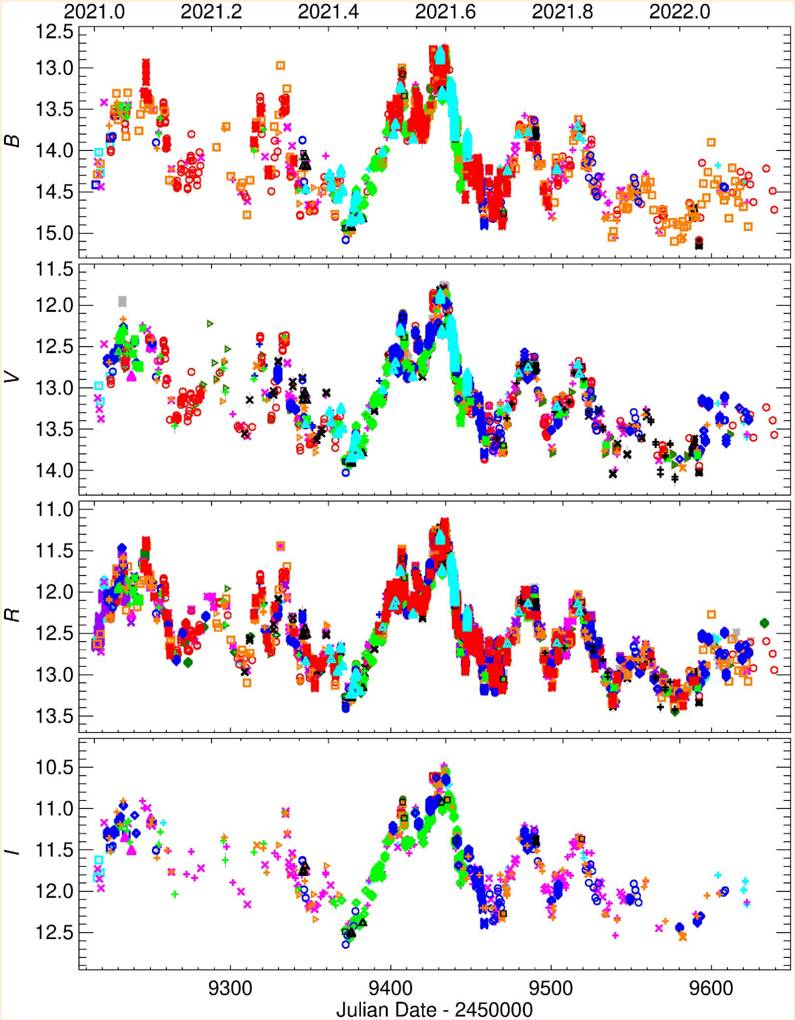
BL Lacertae, Villata et al. 2002, A&A, 390, 407

Optical monitoring with exceptional sampling: present

About 25000 data from 41 telescopes in 14 countries

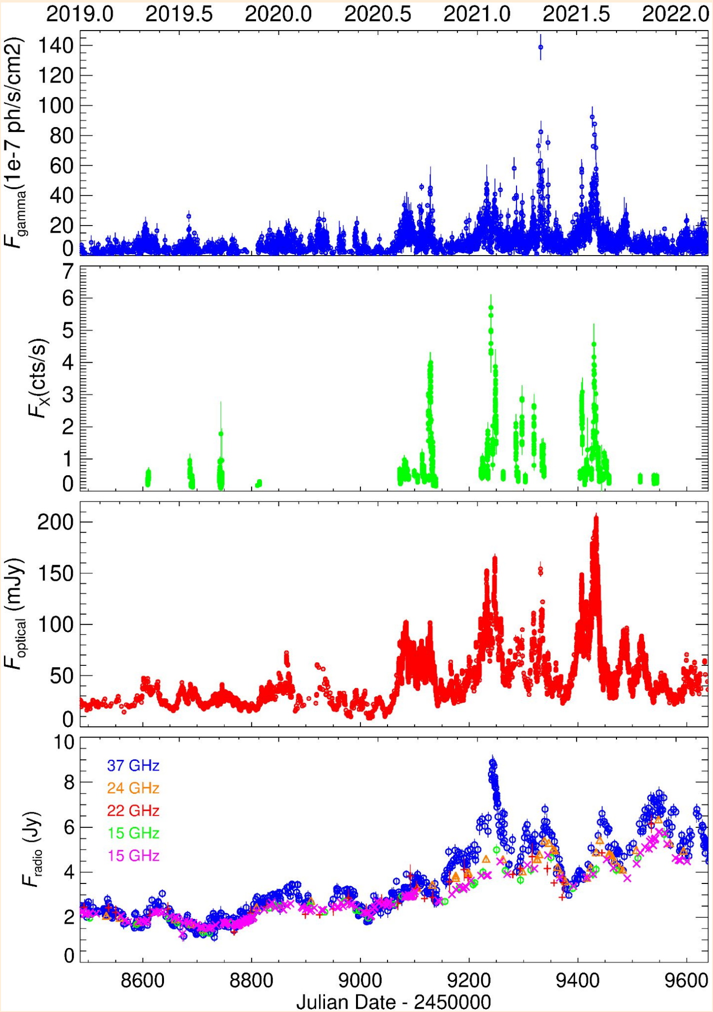


BL Lacertae, Raiteri et al. 2023, MNRAS, 522, 102



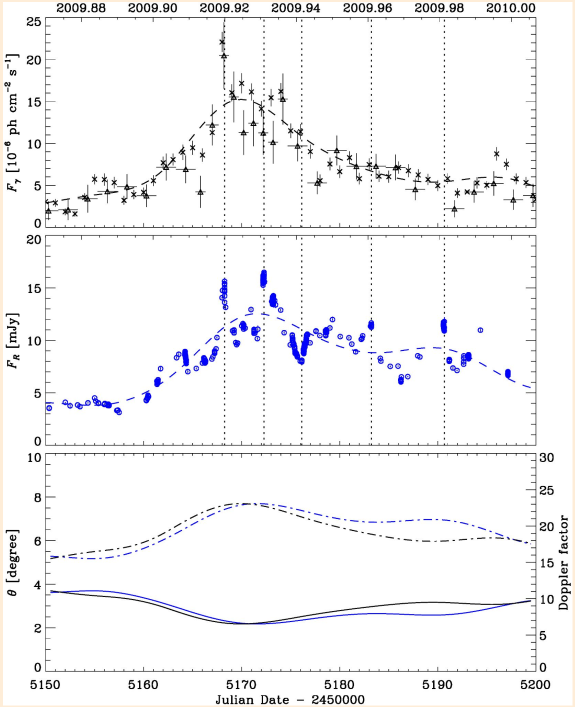
Optical monitoring with exceptional sampling: in progress

35074 data points in the R band in the period 2019-2022 from 54 telescopes in 48 observatories



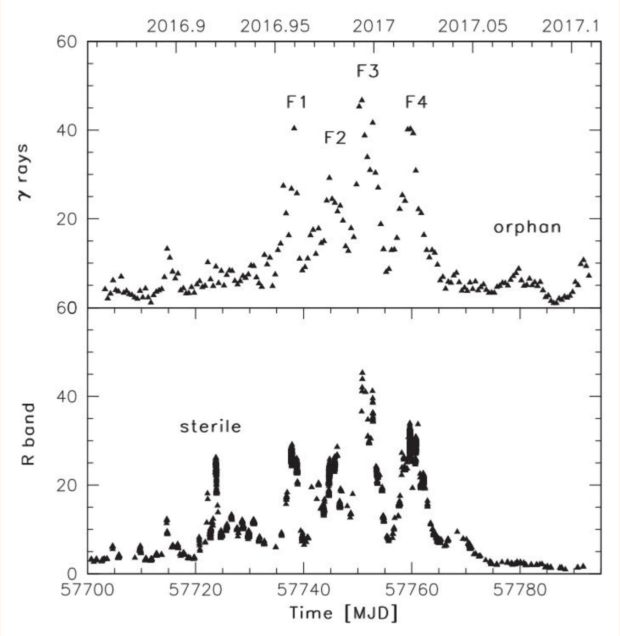
BL Lacertae, Raiteri et al., in preparation

Cross-correlation between gamma and optical

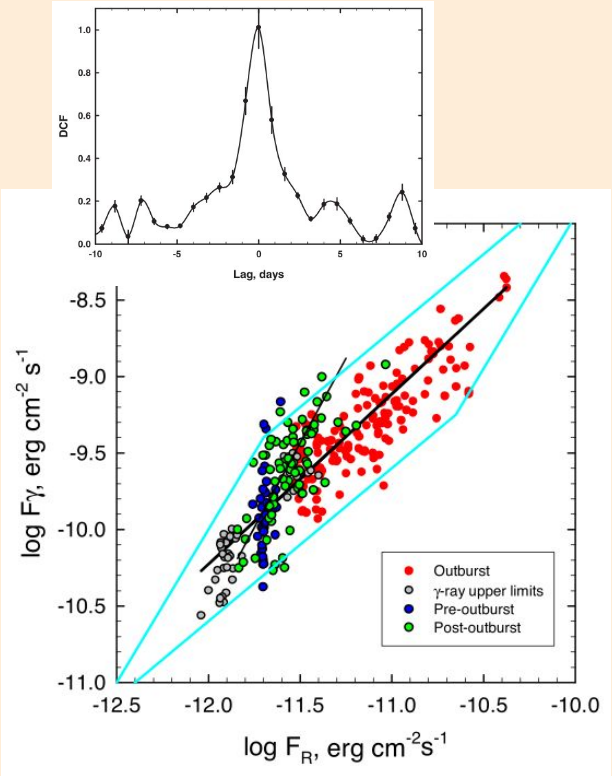


3C 454.3, Raiteri et al. 2011, A&A, 534, A87

General good correlation, but with some differences



CTA 102, D'Ammando et al. 2019, MNRAS, 490, 5300



CTA 102, Larionov et al. 2016, MNRAS, 461, 3047

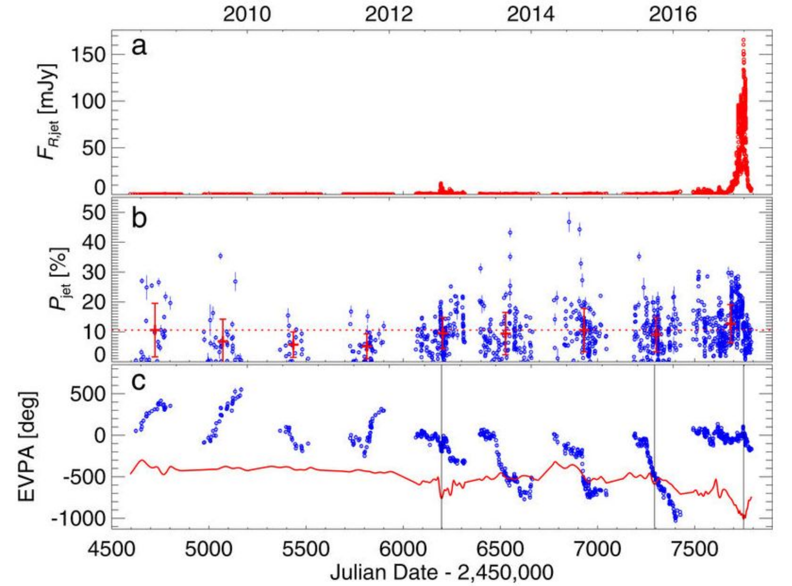
The slope of the correlation changes in different periods

Polarimetric behaviour

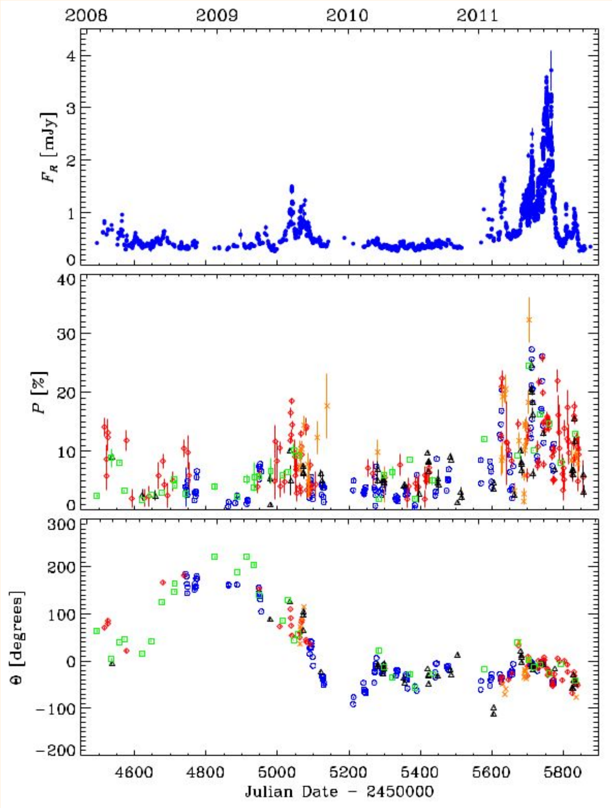
Both polarization degree (P) and angle (EVPA) very variable.

Wide rotations of EVPA: deterministic or stochastic?

Correlation/anticorrelation of P_{jet} with F_{jet}



CTA 102, Raiteri et al. 2017, Nature, 552, 374



4C 38.4, Raiteri, et al. 2012, A&A, 545, A48

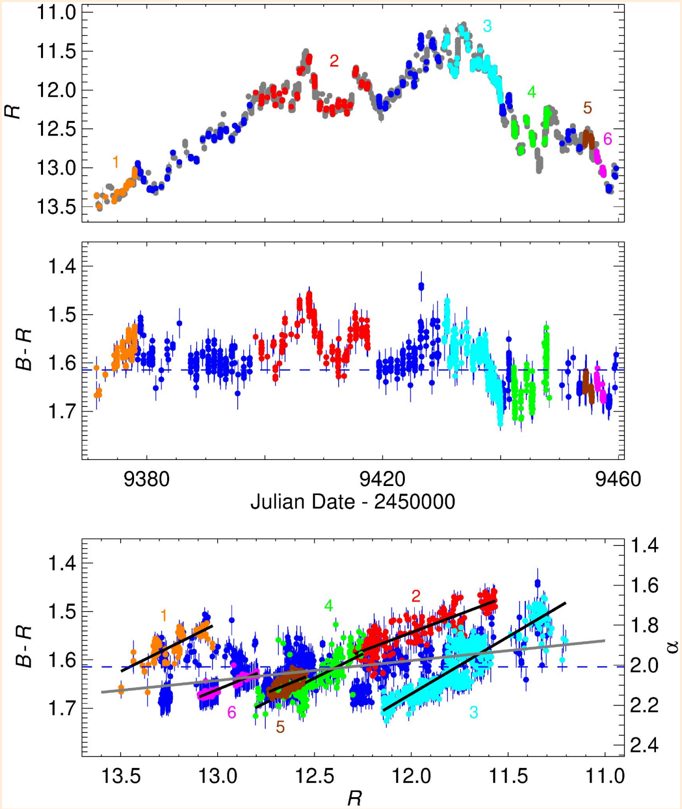
Interpretation of blazar variability

Long-term variability (quasi-achromatic) of **geometrical** origin

(changes in the jet orientation)

Short-term variability (chromatic) due to intrinsic **energetic** processes

(particle injection or acceleration produced by shock waves or magnetic reconnection)



BL Lacertae, Raiteri et al. 2023 (MNRAS, 522, 102)

LETTER

Nature, 552, 374 (2017)

doi:10.1038/nature24623

CTA 102@z=1.037

Blazar spectral variability as explained by a twisted inhomogeneous jet

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Sh. A. Ehgamberdiev[20], C. Espinosa[8], A. Fuentes[4], A. Giunta[19], J. L. Gómez[4], T. S. Grishina[21], M. A.
H. Jermak[23], B. Jordan[24], S. G. Jorstad[21,25], M. Joshi[25], E. N. Kopatskaya[21], K. Kuratov[26,27], O. M. Kur
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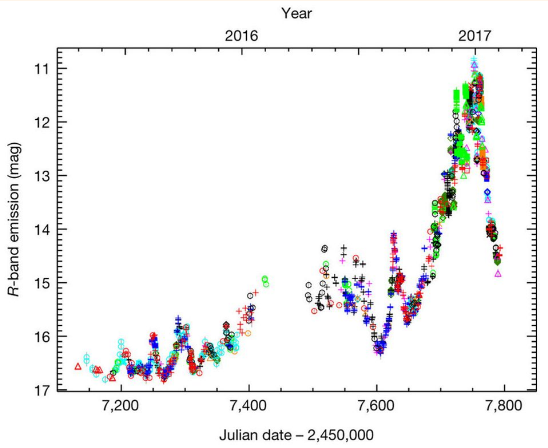
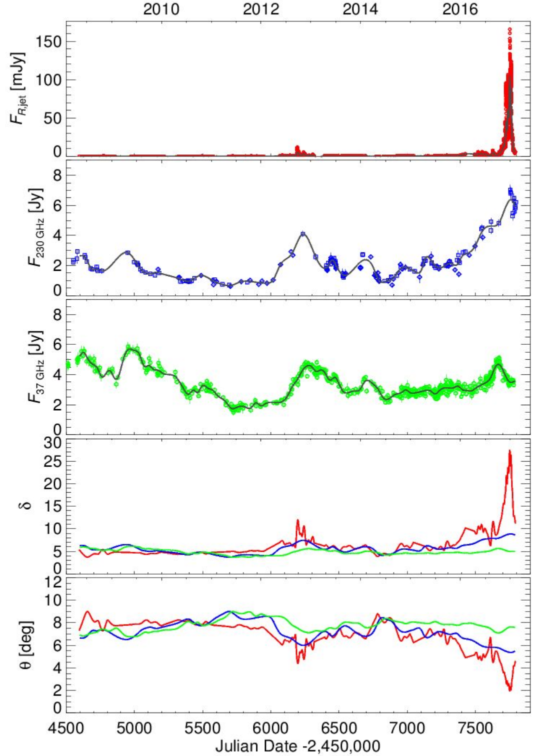
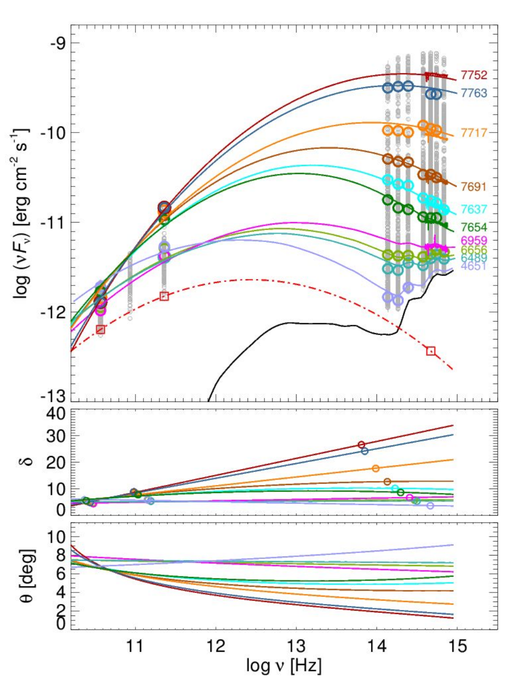
M. P. Malmrose[25], A. P. Marscher[25], K. Matsumoto[35], B. McBreen[36], R. Michel[8], B. Mihov[6], M. Minev
A. A. Mokrushina[5,21], S. N. Molina[4], J. W. Moody[37], D. A. Morozova[21], S. V. Nazarov[7], M. G. Nikolash
D. N. Okhmat[7], E. Ovcharov[10], F. Pinna[2,3], T. A. Polakis[40], C. Protasio[2,3], T. Pursimo[41], F. J. Redondo
G. Rodriguez-Coira[2,3], K. Sadakane[35], A. C. Sadun[43], M. R. Samal[15], S. S. Savchenko[21], E. Semkov[6],
L. Slavcheva-Mihova[6], P. S. Smith[45], I. A. Steele[23], A. Strigachev[6], J. Tammi[32], C. Thum[46], M. Tornik
I. S. Troitsky[21], A. A. Vasilyev[21] & O. Vince[16]







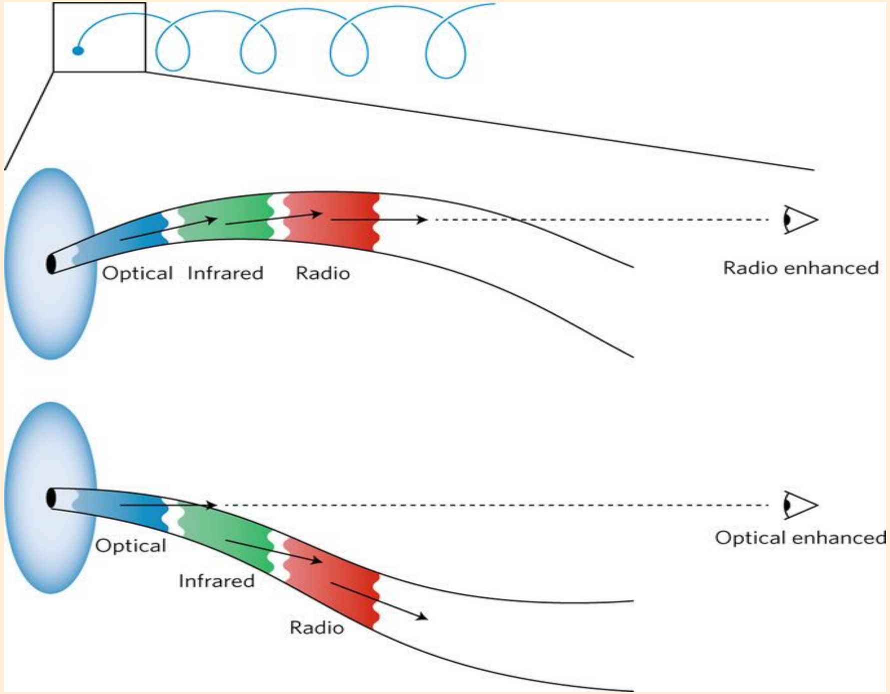
Interpretation of the long-term variability

The ***jet*** is:

inhomogeneous radiation at different frequencies emitted from different regions

curved different emitting regions have different viewing angles

twisting the viewing angle varies in time because of internal (instabilities) or external (orbital motion, precession) reasons



Article

Rapid quasi-periodic oscillations in the relativistic jet of BL Lacertae

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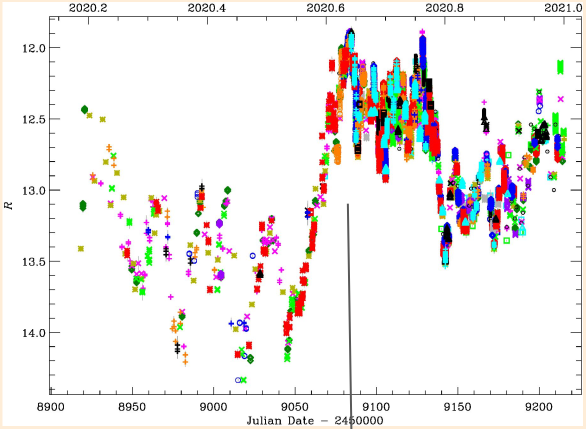
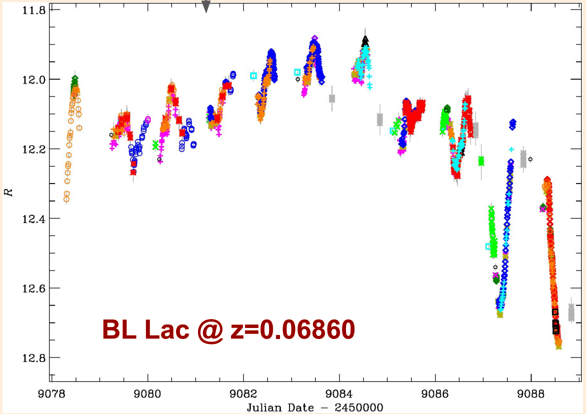


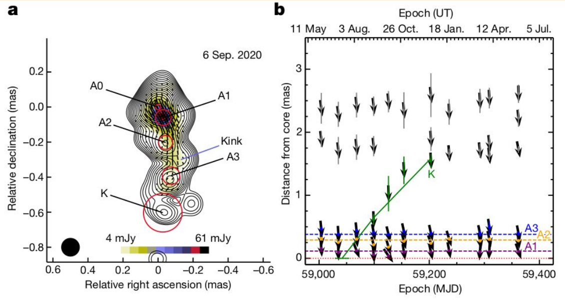


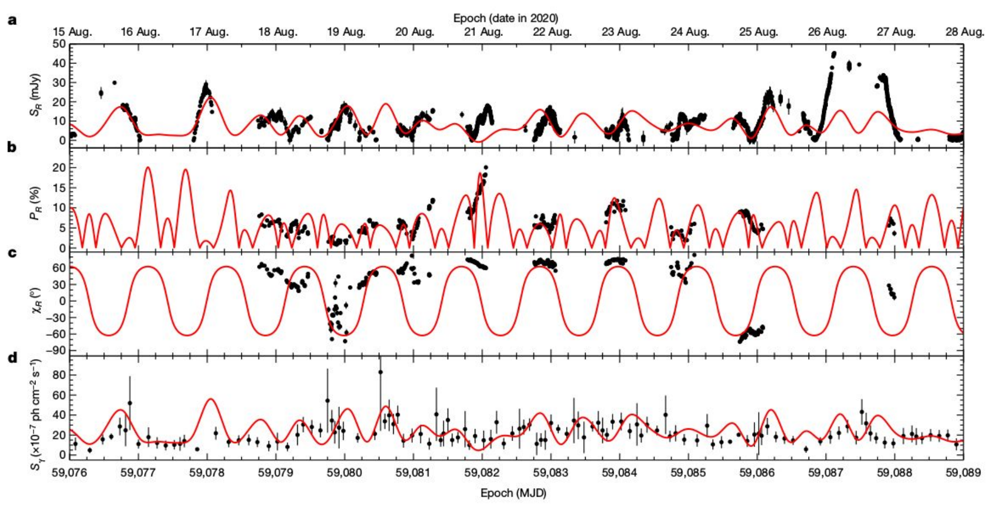
Flux: 37 telescopes in 13 countries; 16497 data points
Polarization: 5 telescopes 1285 measurements

Transient quasi-periodic oscillations (QPOs) with P~13 hr detected in optical flux, optical polarization degree, and gamma-ray flux

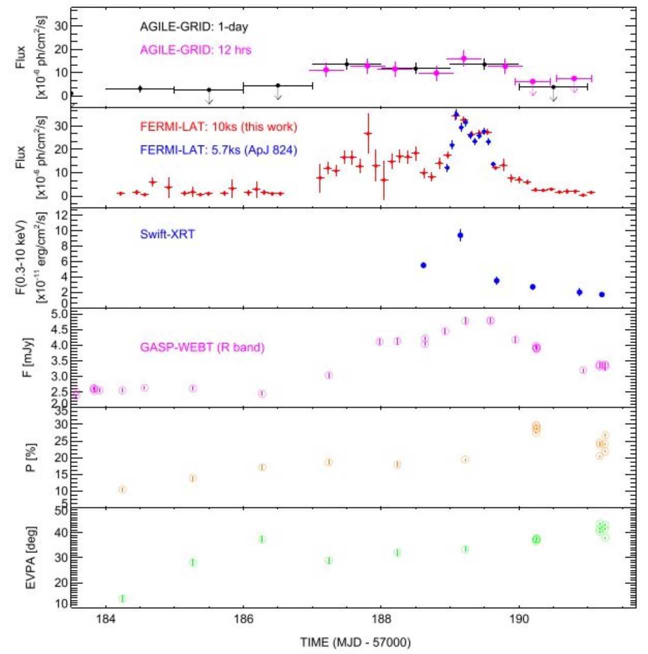
Interpretation of the short-term variability

QPOs triggered by a ***kink instability*** in the jet, when an off-axis perturbation (shock) met a standing shock

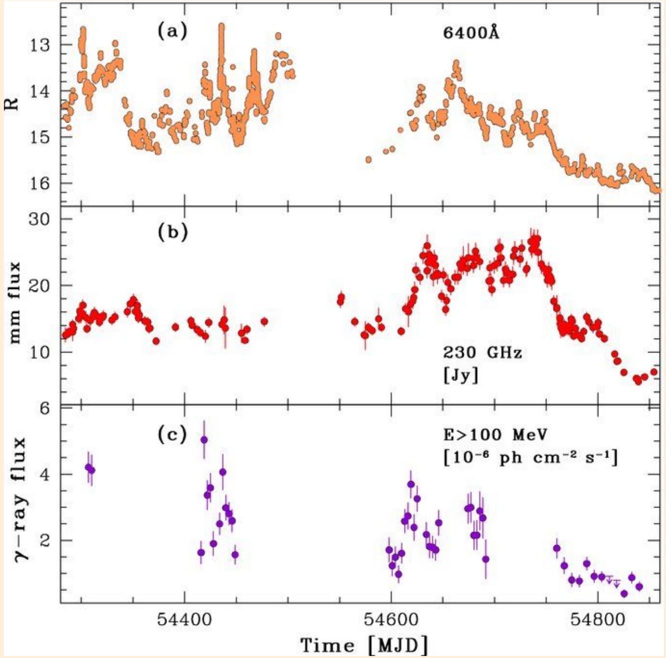




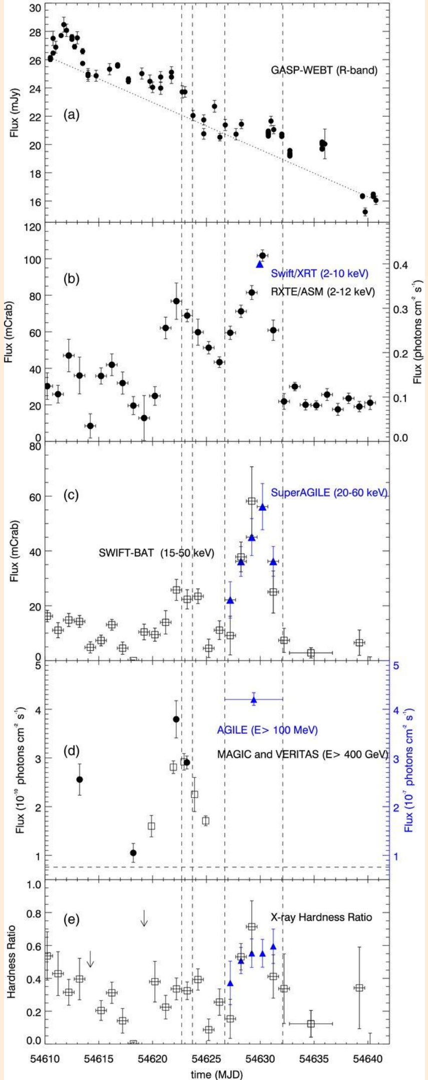
Collaborations with other teams: AGILE



3C 279, Pittori et al. 2018, ApJ, 856,99

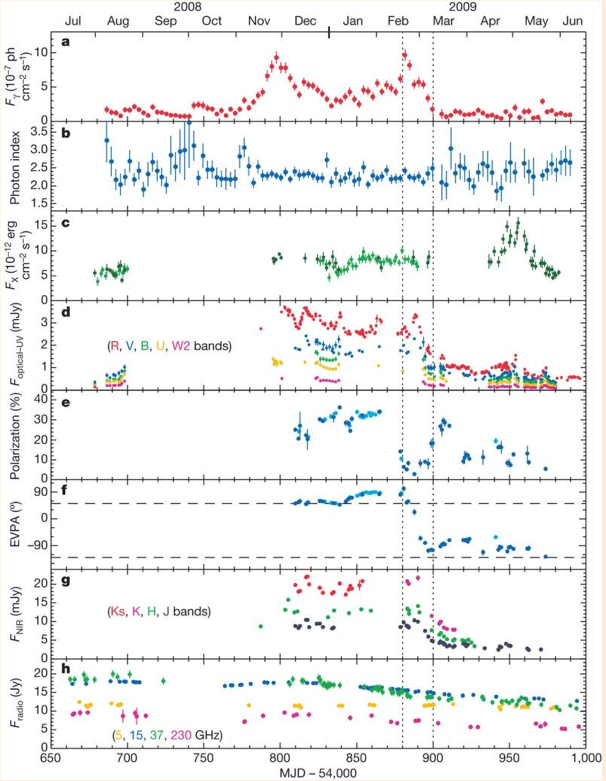


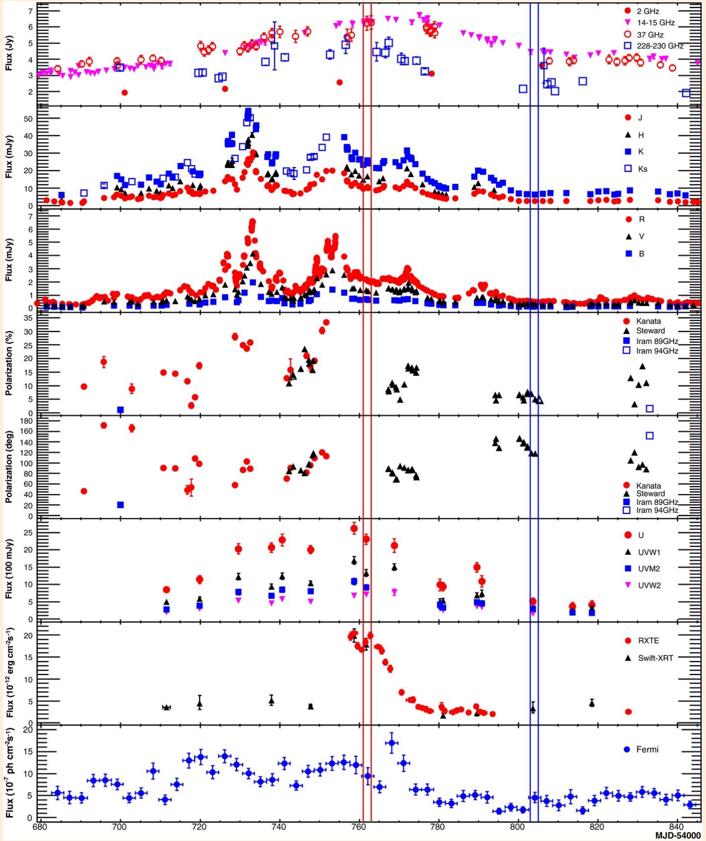
3C 454.3 “The Crazy Diamond”
Vercellone et al. 2010, ApJ, 712, 405



Mkn 421, Donnarumma et al.
2009, ApJ, 691:L13

Collaborations with other teams: Fermi

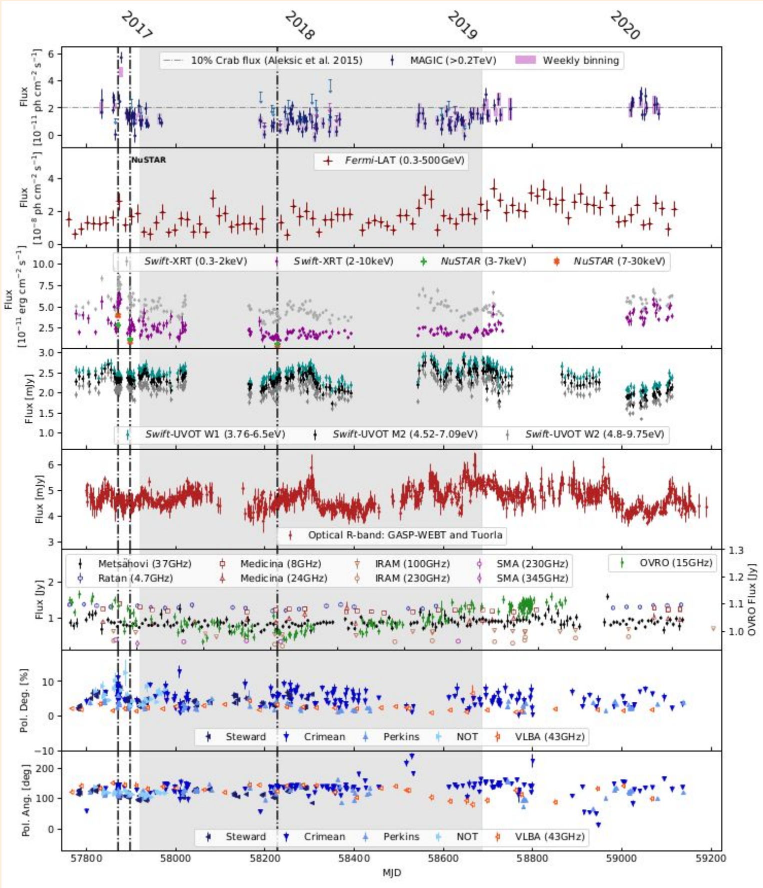




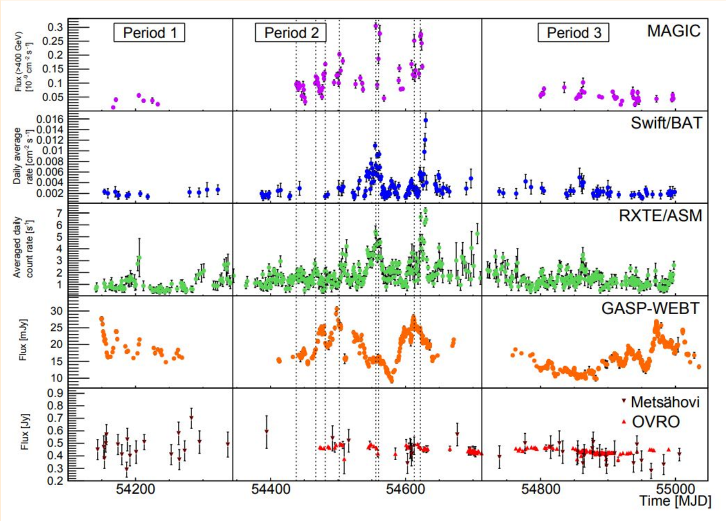
3C 279, Abdo et al. 2010, Nature, 463, 919

AO 0235+16, Ackermann et al 2012 ApJ 751 159

Collaborations with other teams: MAGIC



Mrk 501, Abe et al., ApJS, in press



Mkn 421, Ahnen et al. 2016, A&A 593, A91

Ongoing projects:

S5 0716+714 in 2015-2021
PG 1553+113 in April-May 2022 with TESS
BL Lacertae in 2019
BL Lacertae in 2020
1ES 2344+514 in 2019 -2021
Long-term **Mkn 421** and **Mkn 501** monitoring
Long-term **PG 1553+113** monitoring
Ton 599 involving also XMM-Newton observations in 2019 May and December

Thank you for your attention!