Dramatic MWL activity of BL Lacertae in 2020—2023

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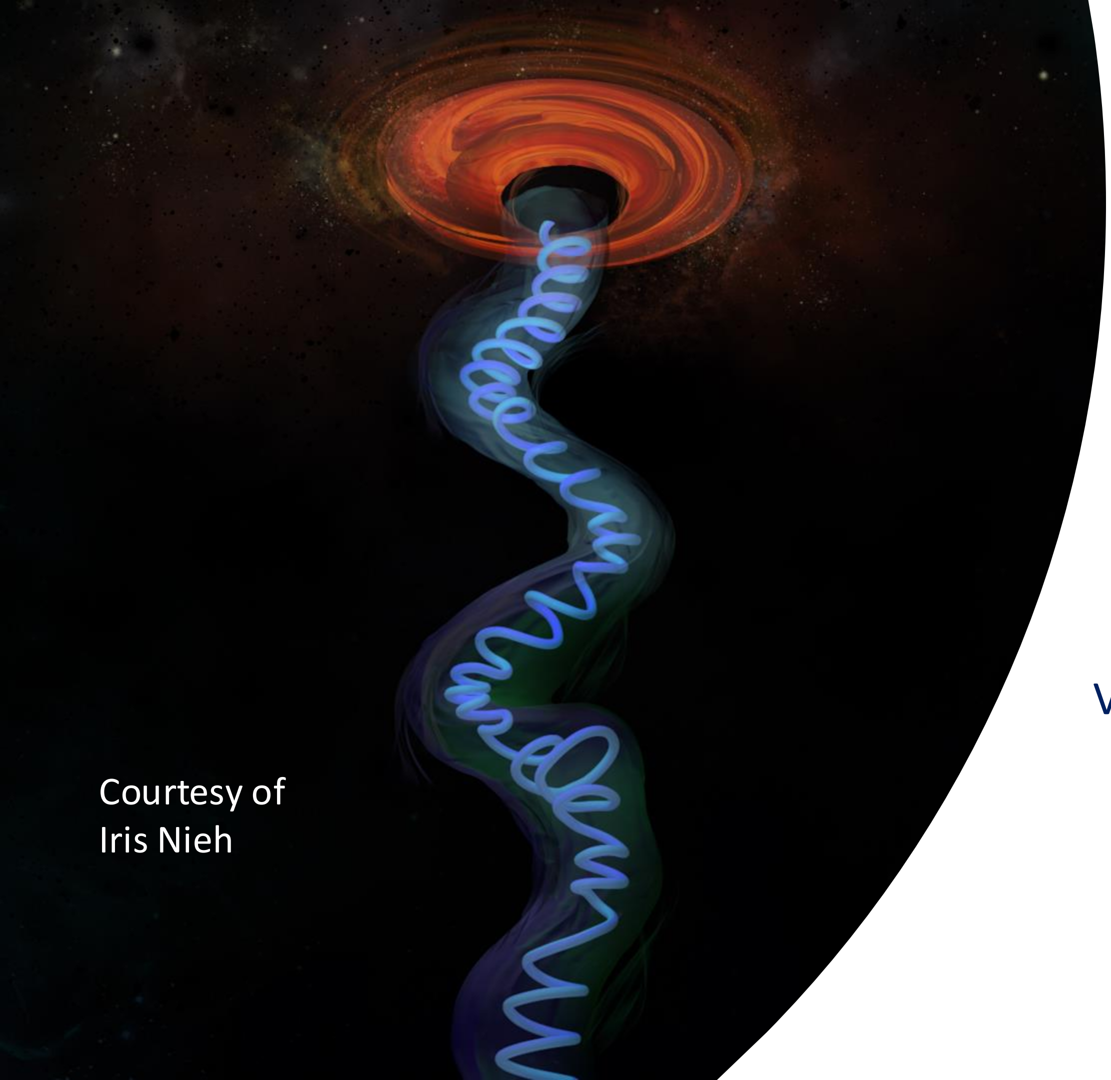
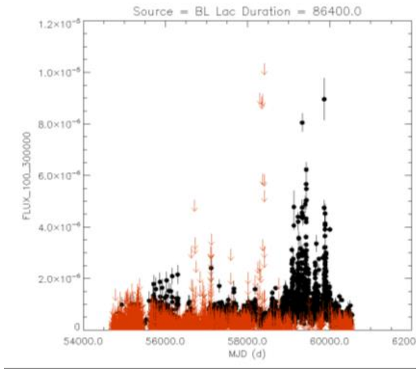


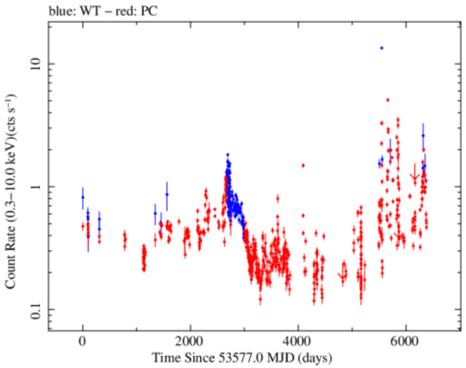
Courtesy of
Iris Nieh

Long-Term MWL BL Lac Light Curves

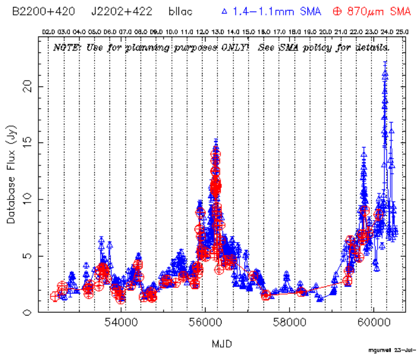
Fermi LAT, 0.1-300 GeV



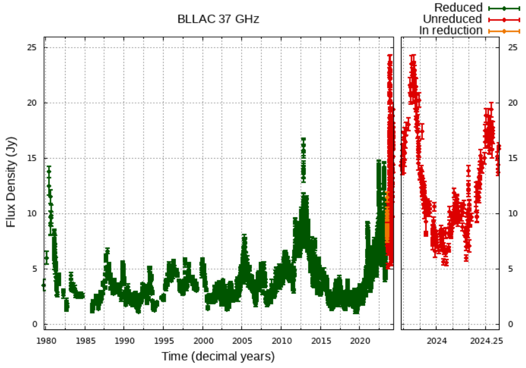
Swift XRT, 0.3-10 keV

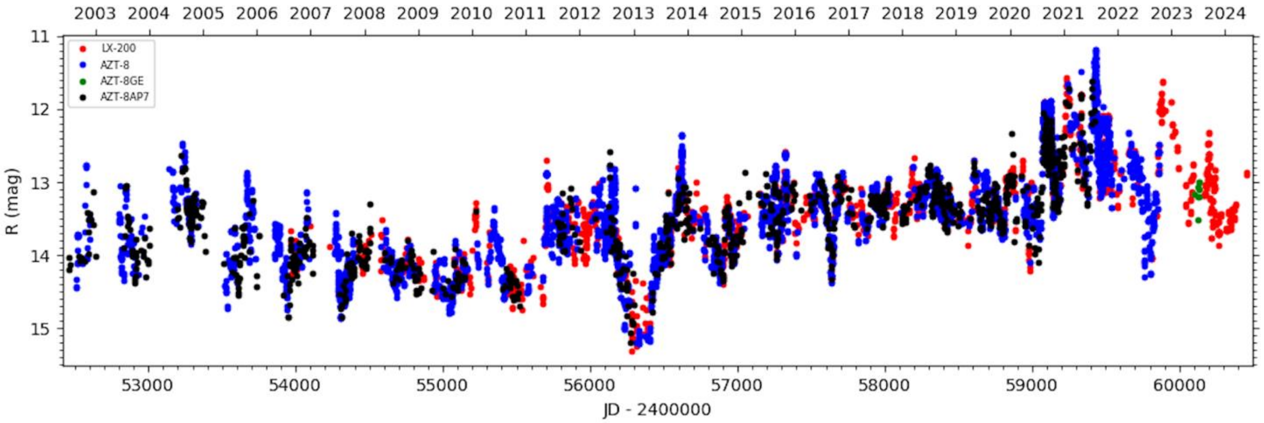


SMA, 1.3 & 0.85 mm



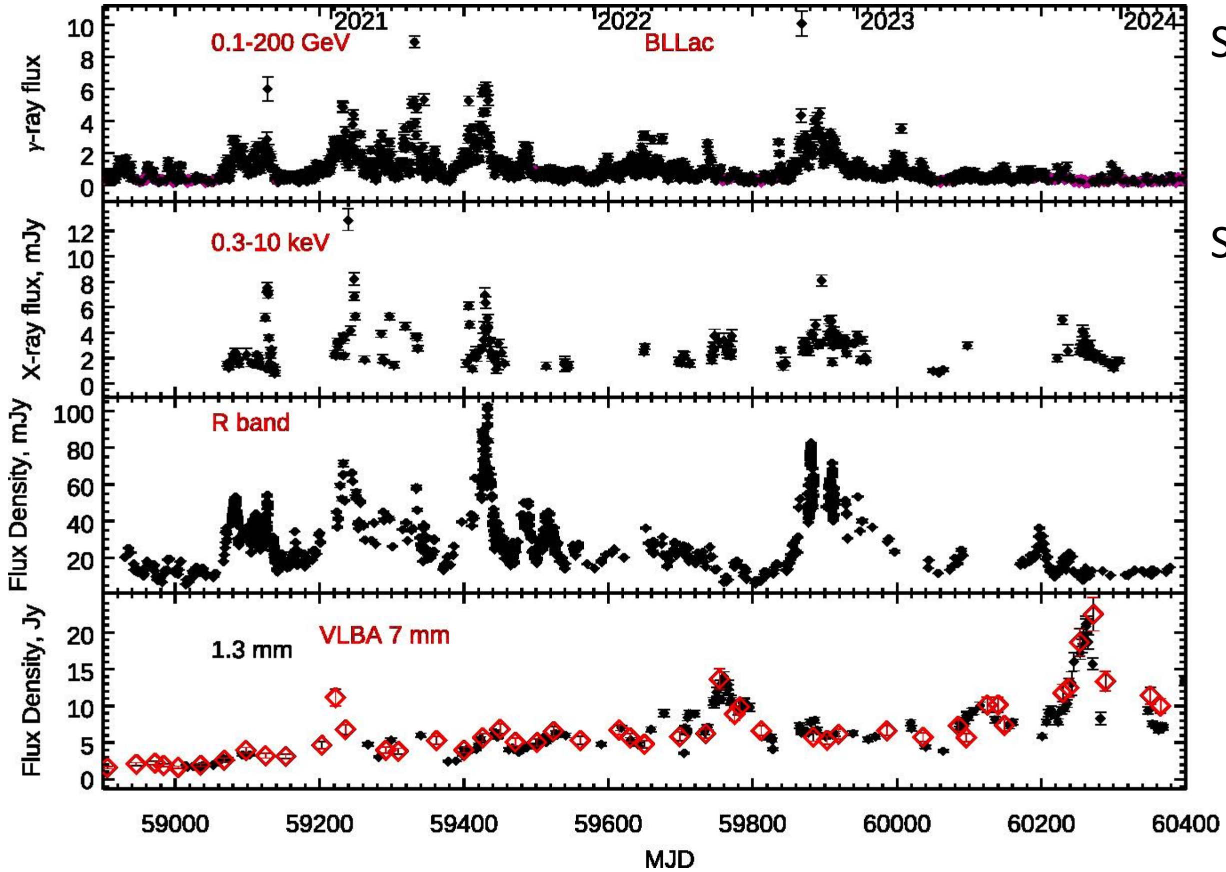
Metsähovi Obs., 8 mm





SPbSU
Optical R band

Different Flaring Events during the 2020-2023 high activity state



S_γ=(1.01±0.08)E-05 ph $s^{-1}cm^{-2}$
MJD:59868, 16 Oct. 2022

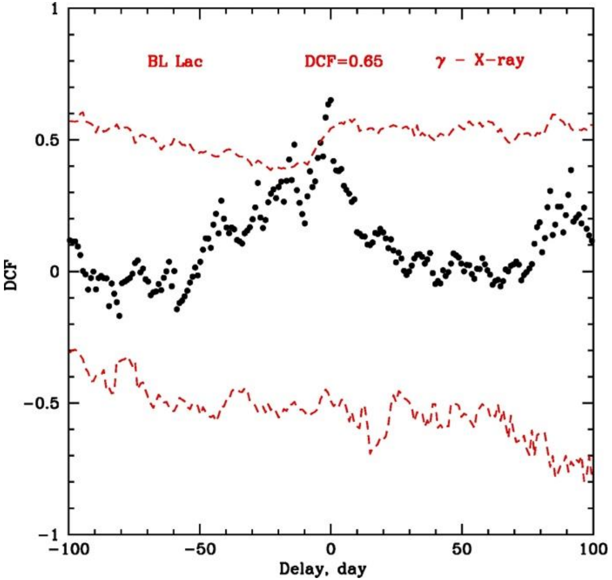
S_X=(1.28±0.09)E-10 erg $s^{-1}cm^{-2}$
MJD:59239.630, 25 Jan. 2021

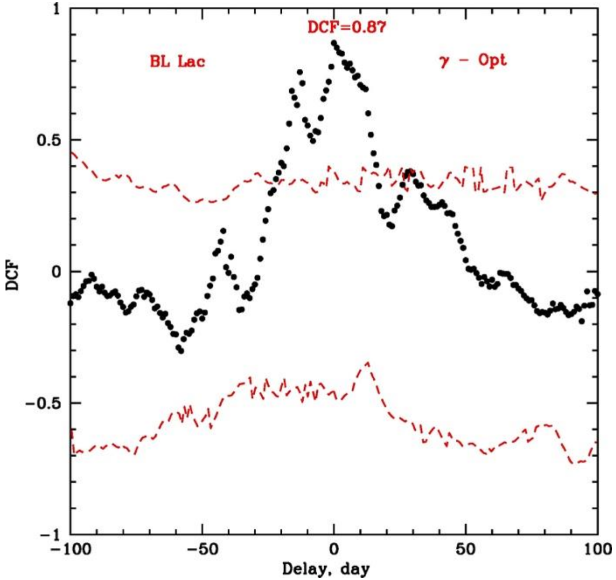
S_R=(102.66±0.95) mJy
MJD:59432.828, 6 Aug. 2021

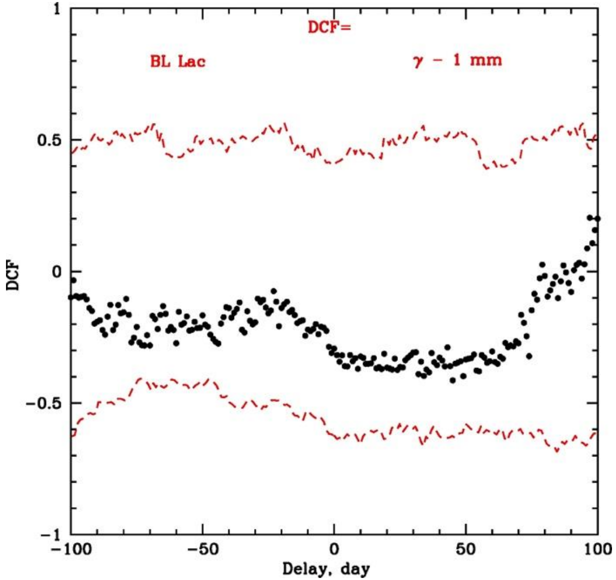
$S_{1.3mm}$=(21.14±1.06) Jy
MJD:60262.129, 14 Nov. 2023

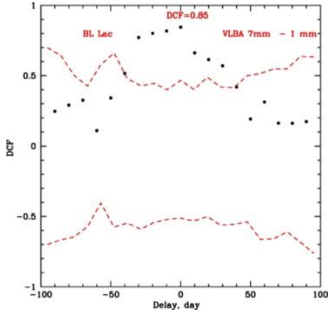
VLBA: S_{7mm}=(22.5±1.3) Jy
MJD:60272, 24 Nov. 2023

DCF Analysis of MWL LC during the 2020-2023 period

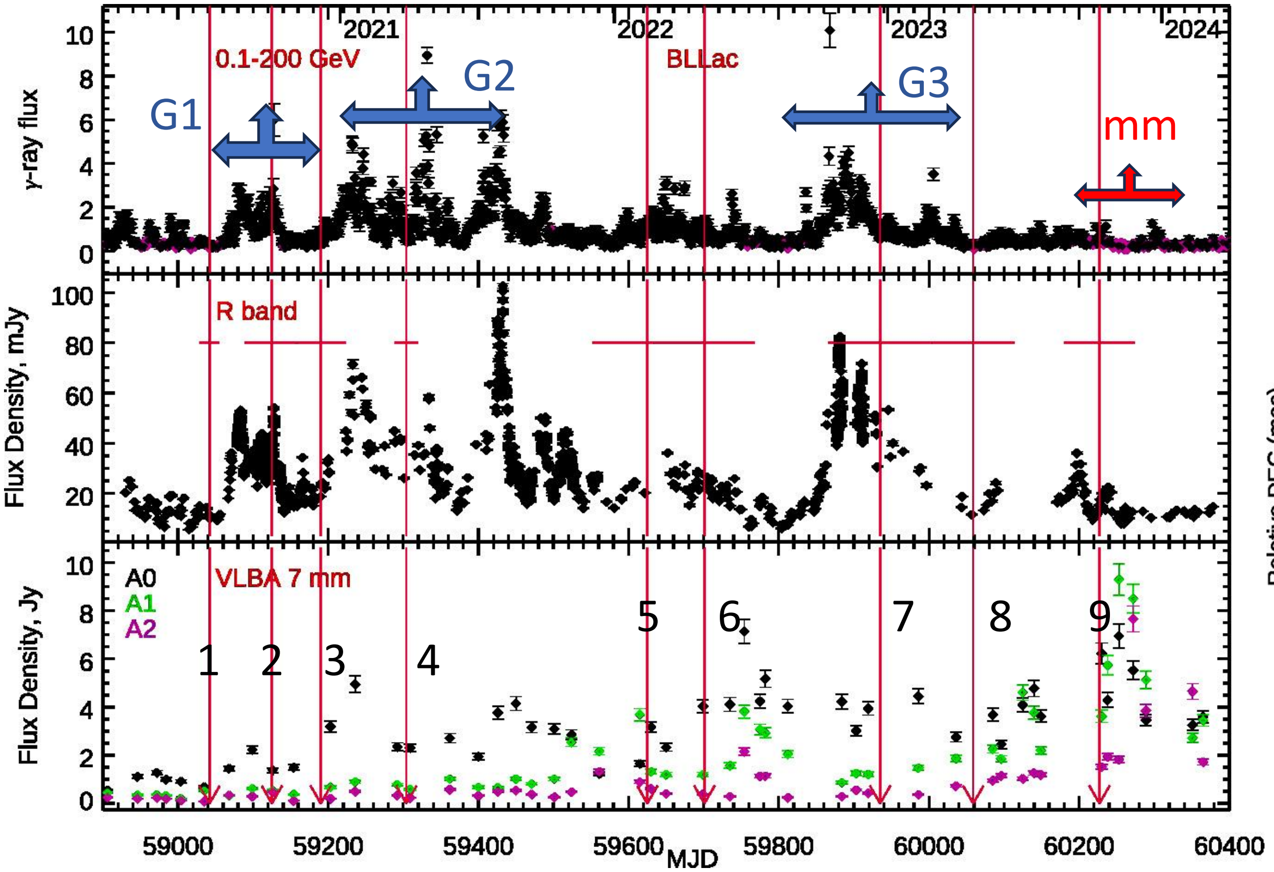




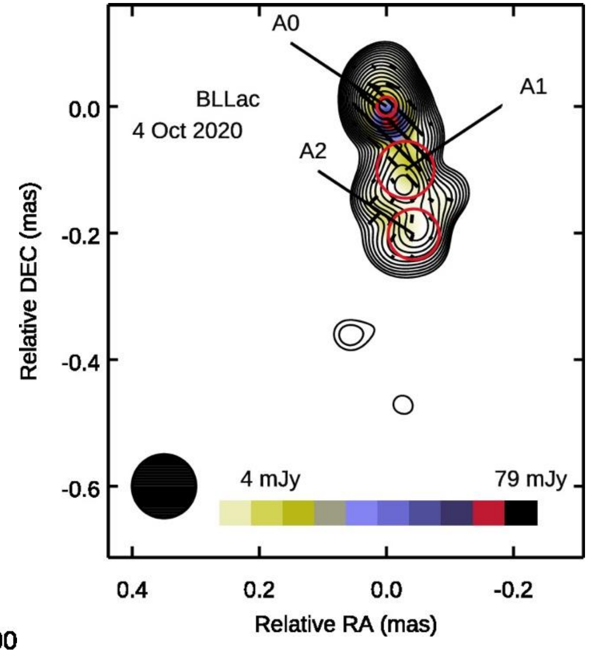




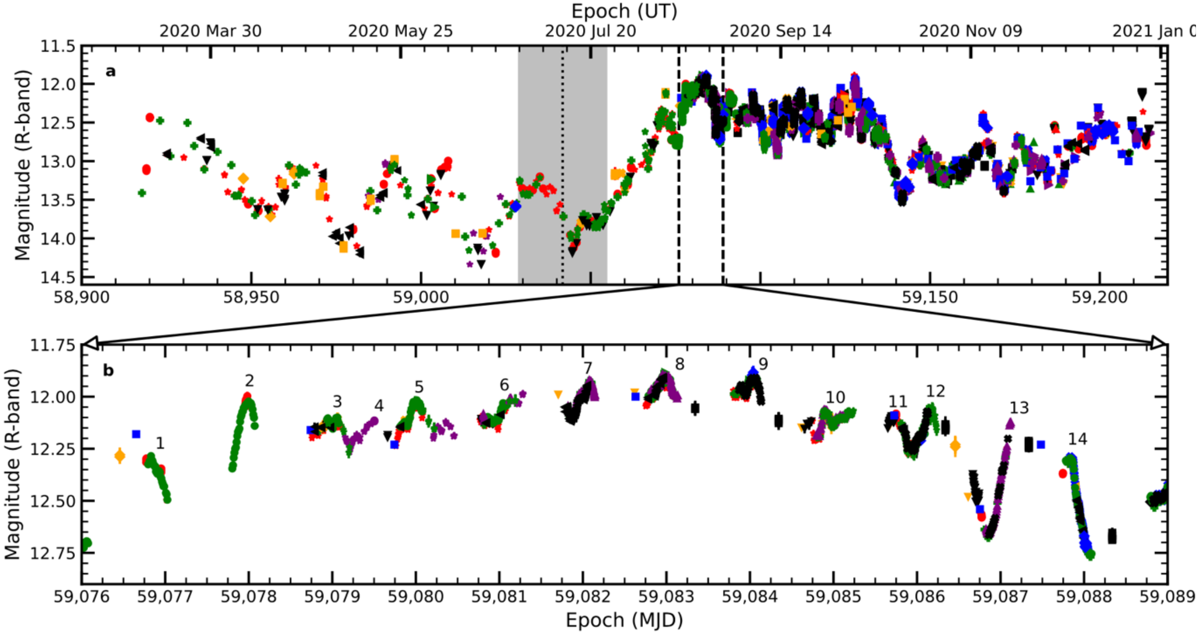
mm-wave Parsec-Scale Jet Behavior and 2020-2023 Activity

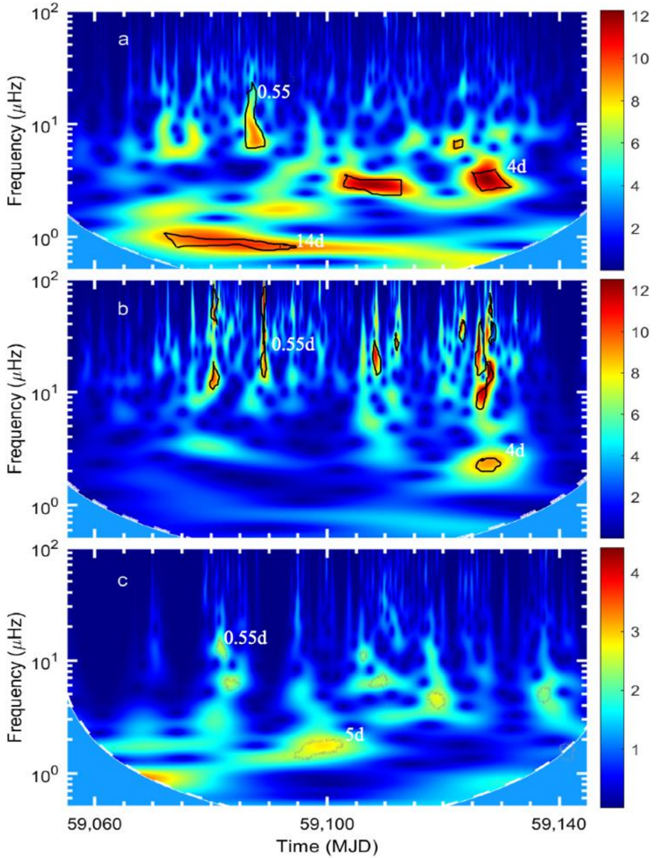


Ejection of 9 superluminal knots with apparent speeds between 15.2 c and 5.5 c.



Optical Brightness Oscillation during the Gamma-ray Event G1

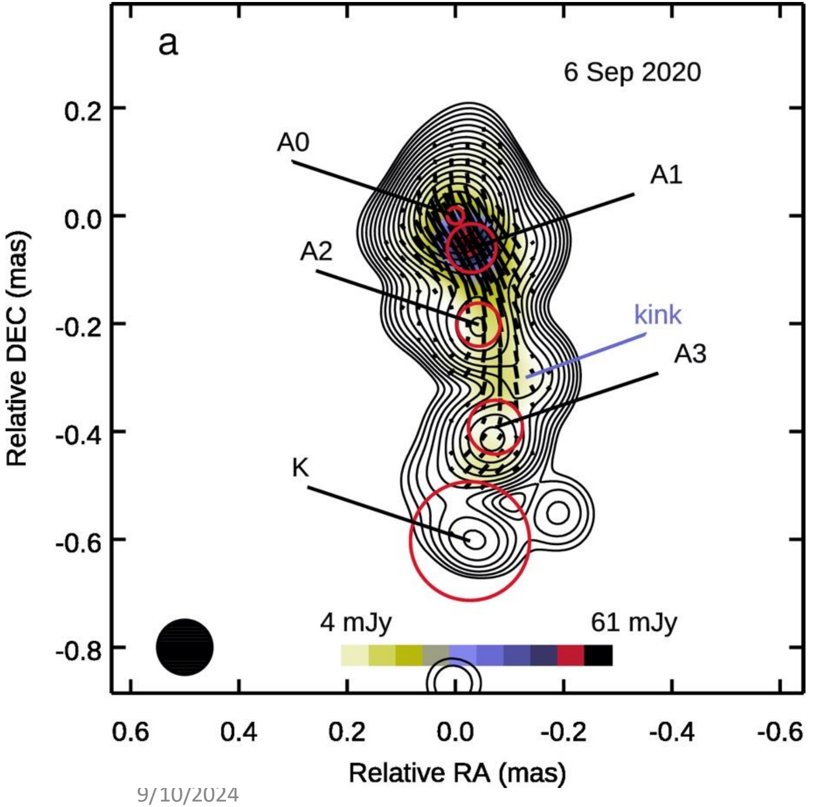


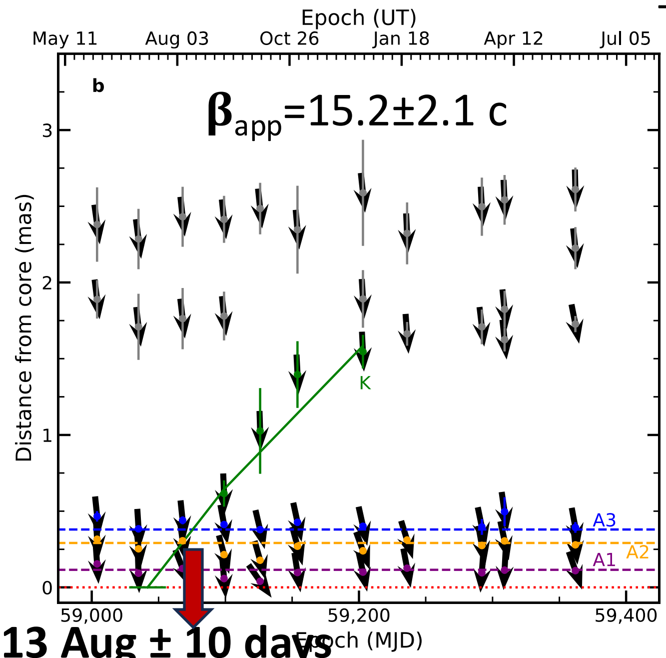


Morlet wavelet with ω_o=6 and
a 1 hr sliding window for data interpolation
MATLAB Wavelet Toolbox v.2021b

Jorstad et al. 2022

Connection between Optical Brightness Oscillation and the Inner Jet Structure

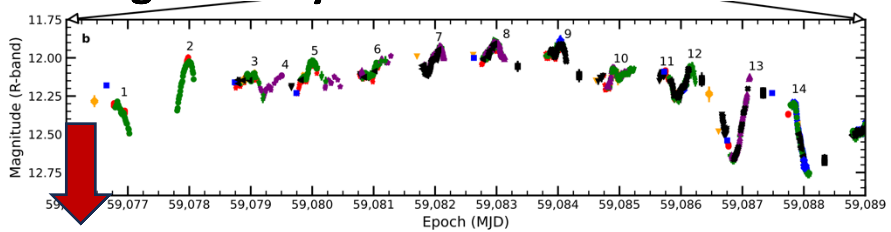




T_o = MJD 59042 ±13

11 July 2020

13 Aug ± 10 days



14 Aug 2020

3DPol Code (Zhang, Chen, & Böttcher 2014) +
+ its upgrade (Zhang et al. 2018; Dong et al. 2020)

Model Parameters:

Γ =15, θ=3.8°, δ=15, α=1.5 ($S_\nu \propto \nu^{-\alpha}$)

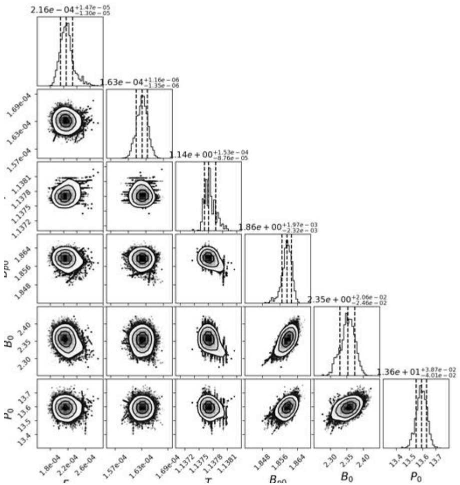
F_{oO} – scaling factor of optical emission

$F_{o\gamma}$ – scaling factor of γ-ray emission

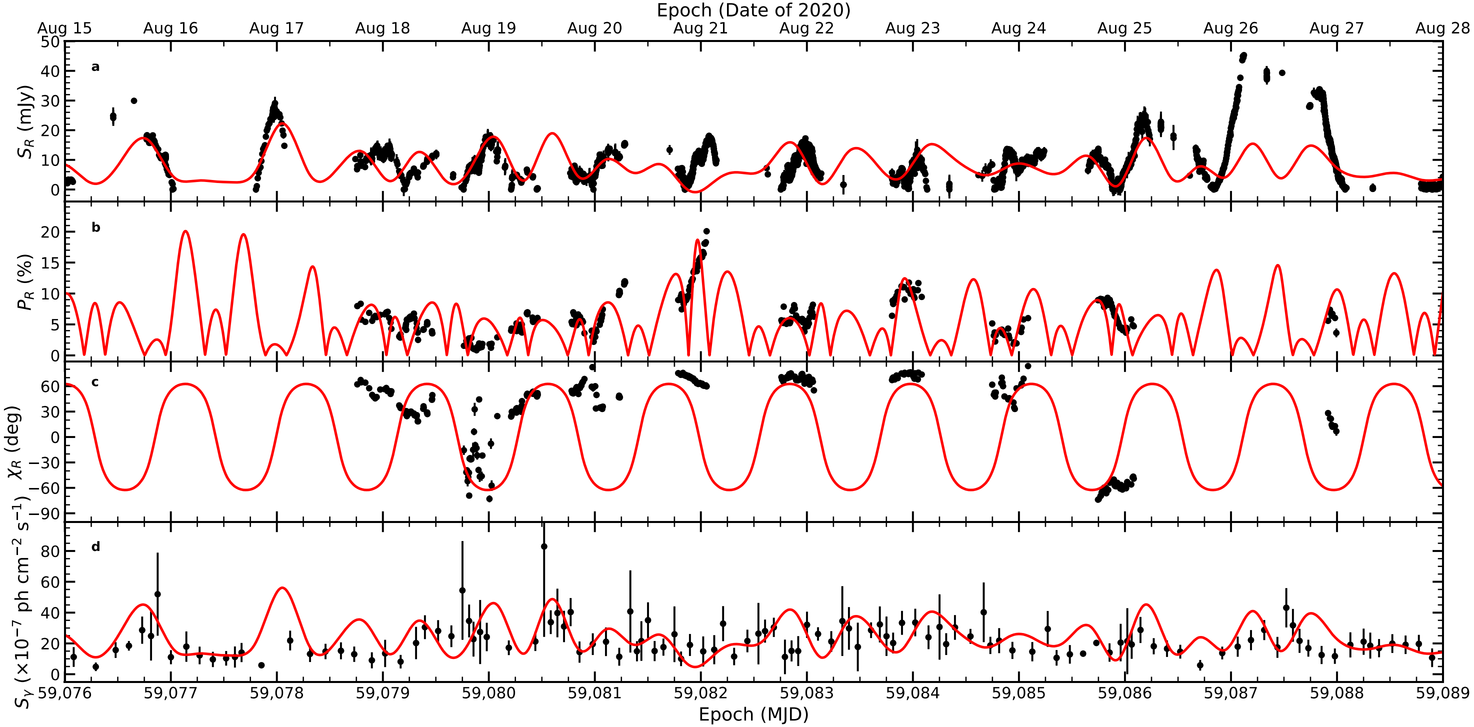
$B_\perp$ =1 G constant toroidal field

$B_\parallel$ - periodically (sinusoidal) fluctuating poloidal field with period T & amplitude B_{po}

B_{tur} – turbulent field with an amplitude B_o and a random component drawn from Gaussian distribution centered on P_o.



Kink instabilities in relativistic jet of BL Lacertae



$\tau \sim 0.55$d

$$\tau \sim \frac{\Delta r(1+z)}{2 v_{\perp} \delta},$$

where Δr – size of a kink,

$v_{\perp}$ - transverse velocity of the kinked region,

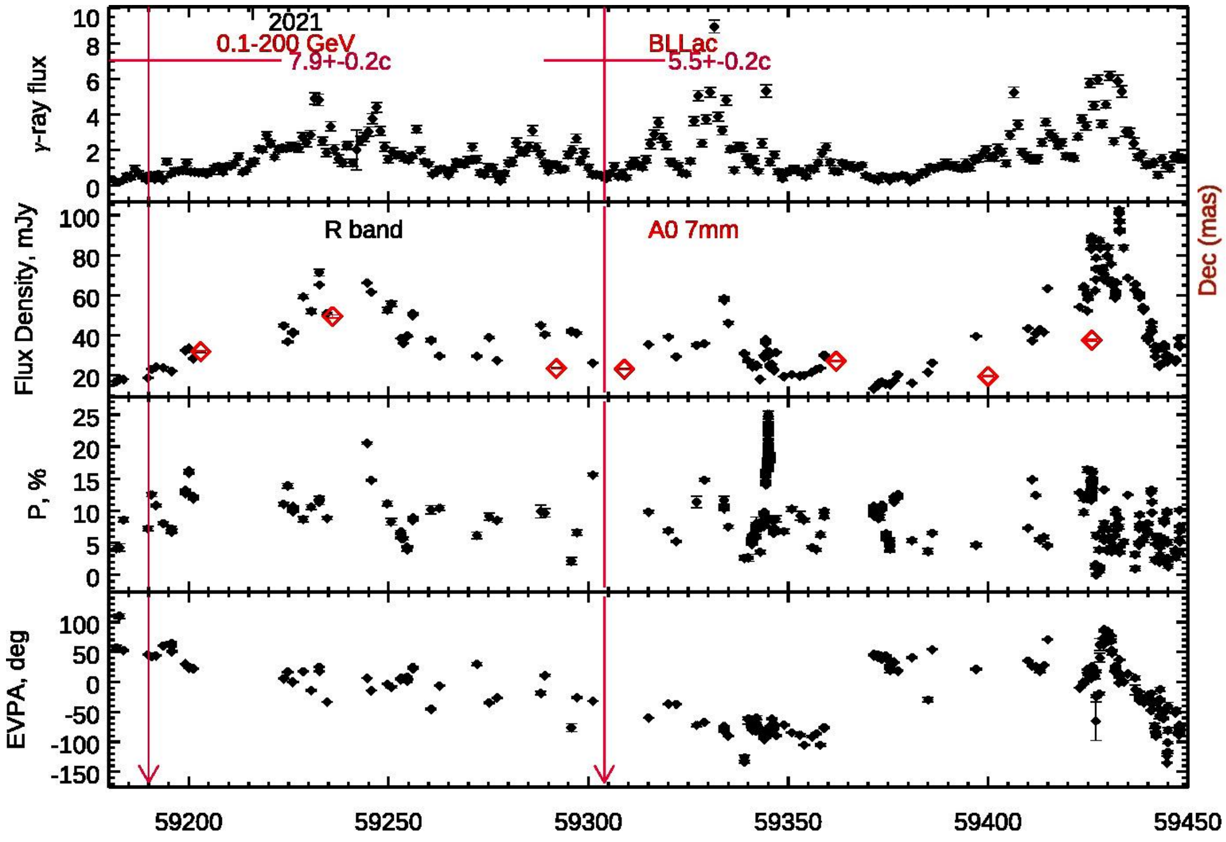
$v_{\perp} \sim 0.1\text{-}0.2c$

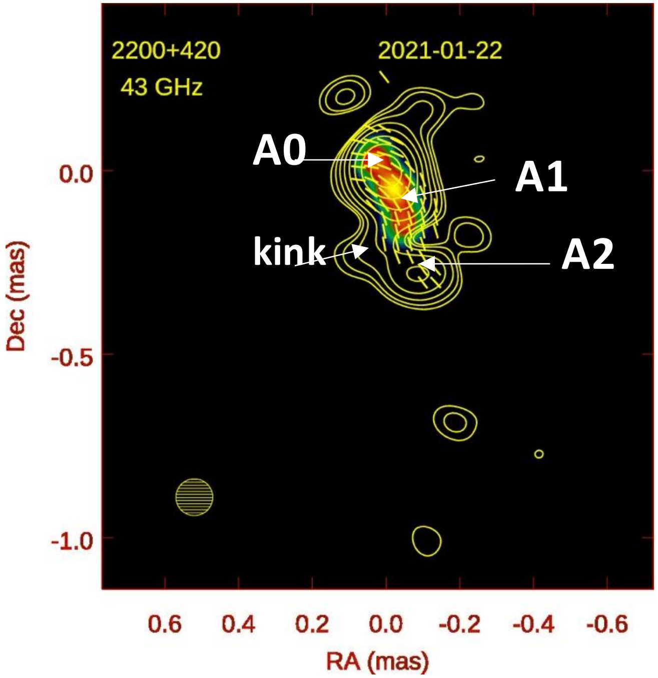
$\delta \sim 15$

$\Delta r \sim 8\times10^{15}$cm ~ 0.003 pc

Model-Data comparison. a) Optical flux densities in *R* band; b) degree of polarization ; c) position angle of polarization; d) γ-ray light curve during the high state of the outburst; black symbols correspond to the data, red solid curves show fitting with MCMC code.

MW behavior during the Gamma-ray Event G2





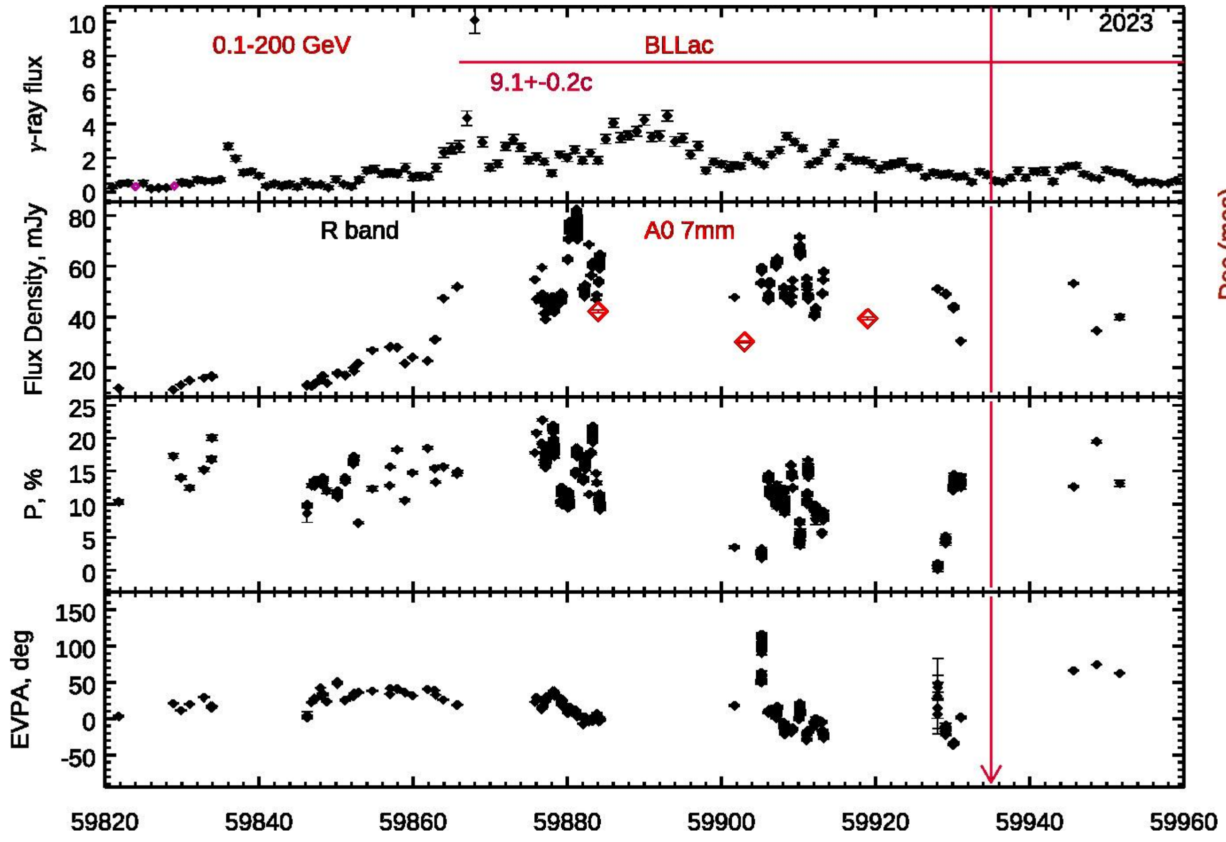
μ=1.71±0.04 mas/yr

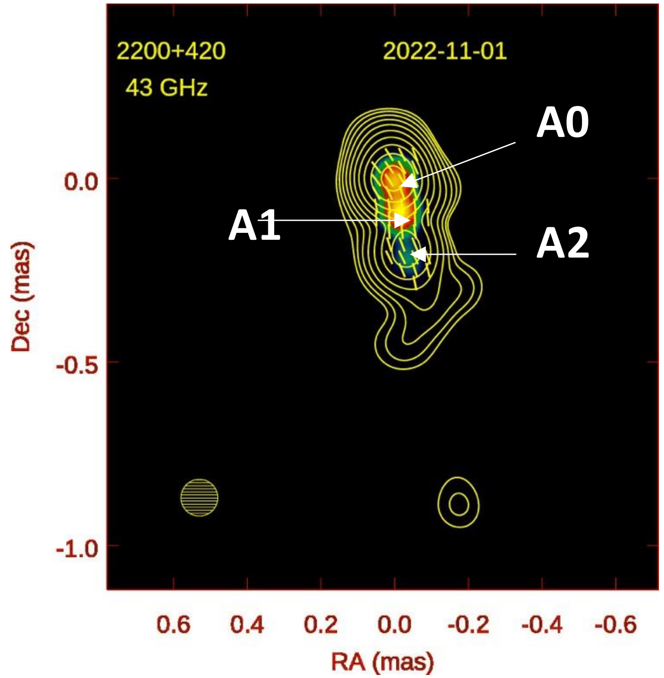
T_o= MJD 59190±33 (6 Dec)

T_{start} =MJD 59220, r~0.14mas (A1)

$\tau \sim$ 4.5d $\delta \sim 8$ $\Delta r \sim 0.012$ pc

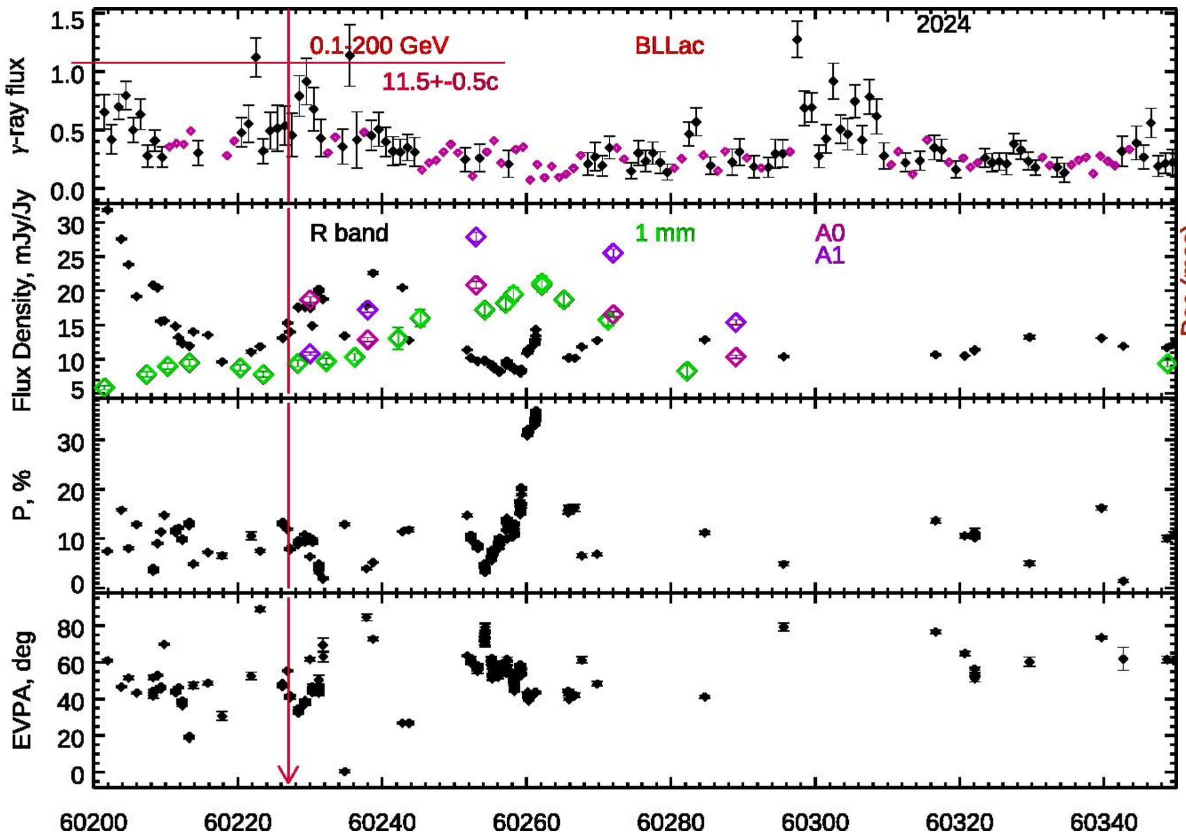
MW behavior during the Gamma-ray Event G3

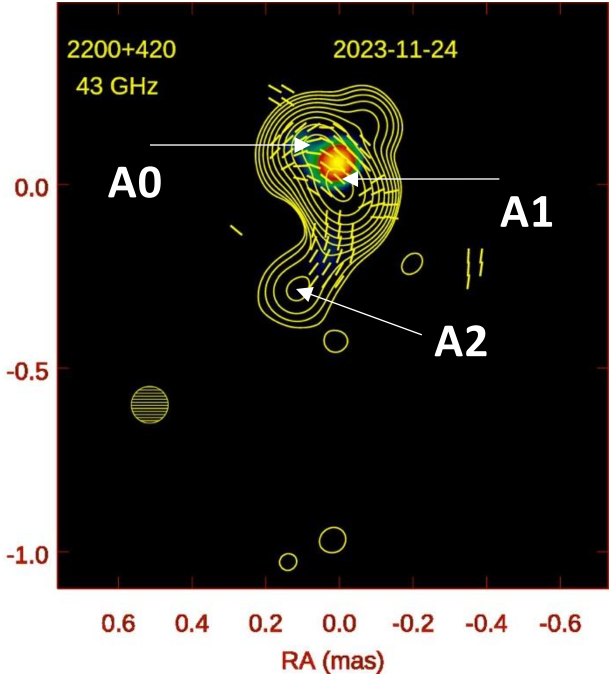




43 GHz total and polarized intensity image of BLLac @ 0.1×0.1 mas^2 with total intensity peak of 3.93 Jy/beam & polarized intensity peak of 0.12 Jy/beam.

MW behavior during the mm-Wave Event





43 GHz total and polarized intensity image of BLLac @ 0.1×0.1 mas^2 with total intensity peak of 10.8 Jy/beam & polarized intensity peak of 0.40 Jy/beam.

Extremely High Optical Polarization + mm-wave Flux Event

Nearly uniform B field perpendicular to innermost jet direction

→ **Unusually strong shock, B ⊥ shock normal**

→ **Not favorable for diffusive shock acceleration of electrons to highest energies (more turbulent B would be more efficient)**

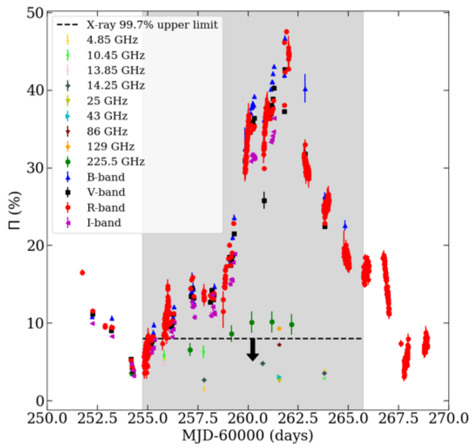
→ **Electrons are mainly accelerated up to ∼1 GeV (e.g., by compression of relativistic electrons in pre-shock plasma), energy distribution steepens at higher energies (Baring+ 2017)**

→ **Modest optical flare from increase in B & weak shock acceleration**

Huge mm-wave flare from increase in B and ≲ 1 GeV electrons

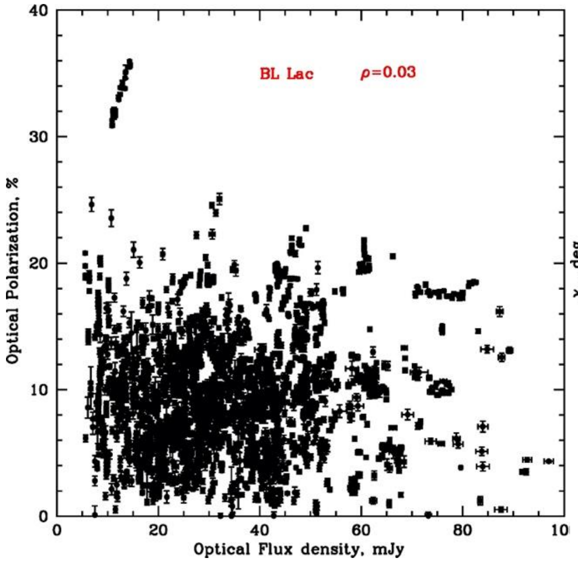
→ **X-ray flare: SSC from electrons up to ∼1 GeV**

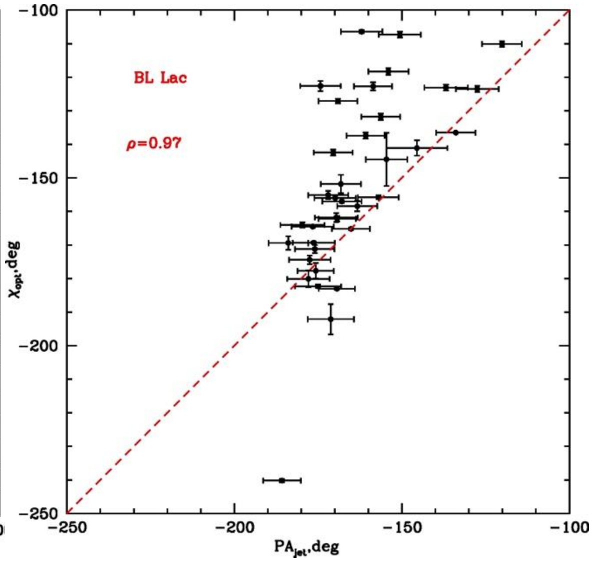
→ **No strong GeV flare: not enough electrons above ∼1 GeV as needed for high-amplitude SSC flare at > 1 GeV**



Agudo et al., submitted.

Localization of Optical Polarized Emission in the Relativistic Jet





1. No correlation between optical flux density and degree of polarization.
2. A statistically significant correlation between optical position angle of polarization and position angle of quasi-stationary feature A1 wrt the core A0.
3. The region of the jet between features A0 and A1 can be the place of the origin of polarized optical emission.

Conclusions

1. Gamma-ray and optical variations correlate exceptionally well during the dramatic MW activity of BLLac in 2020-2023 without a delay > than 12 hrs. This most likely implies the SSC mechanism for gamma-ray production with synchrotron optical photons scattered up to gamma-ray energies.
2. 9 superluminal components were detected in parsec-scale jet during 2020-2023, with their times of ejection coinciding with the start of gamma-ray and/or optical flares.
3. Gamma-ray and optical light curves reveal periods of oscillations on timescales of ~half to several days, which can be caused by current-driven kink instabilities.
4. There is a correlation between the optical EVPA and innermost jet position angle between the VLBI core, A0, and the nearest stationary feature, A1 – the part of the jet which can have almost uniform magnetic field.
5. Multiwavelength light curves and polarimetry, along with fine structure of VLBI imaging, are great tools to unveil blazar physics.