TeV detection and insights into the emission regions of two gamma-ray fast flaring blazars

Davide Cerasole

University and INFN Bari
davide.cerasole@ba.infn.it

On behalf of MWL collaborators and
the MAGIC and *Fermi*-LAT Collaboration

13th CRIS-MAC 2024
Cosmic-Ray International Studies and
Multi-messenger Astroparticle Conference

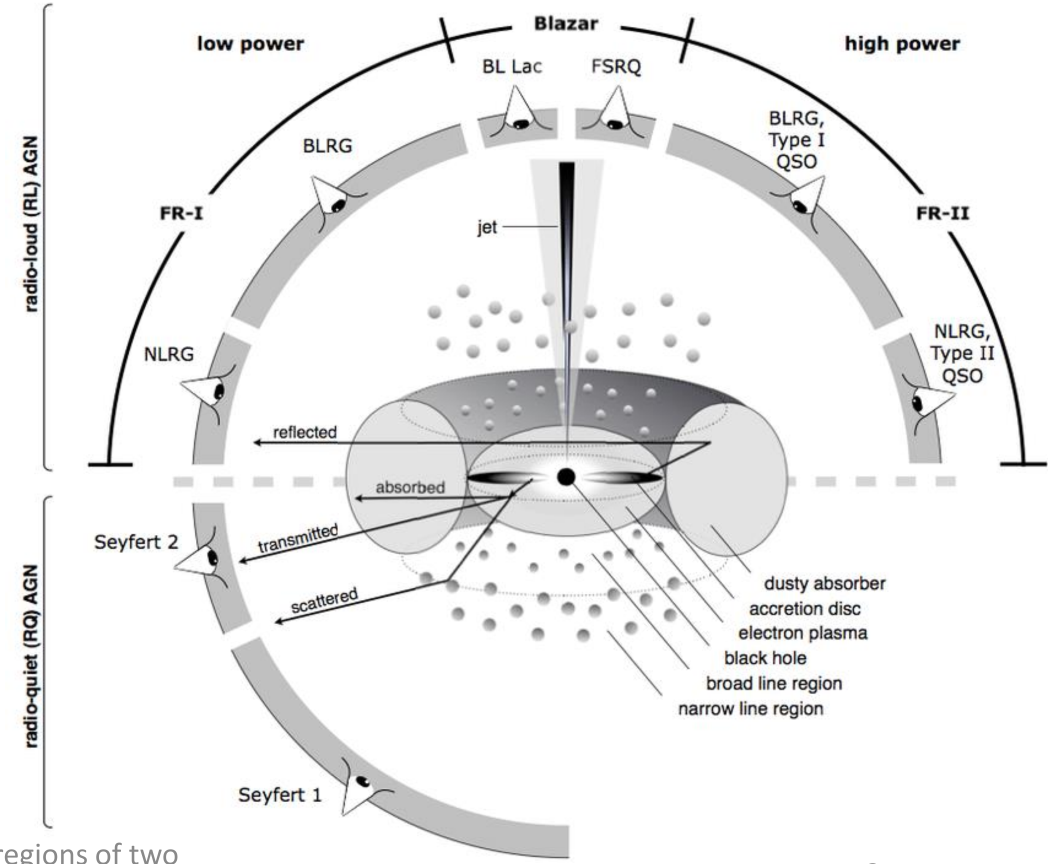
June 20, 2024

Active Galactic Nuclei

- **AGN** are galaxies whose galactic cores outshine the rest of the galaxy, composed of billions of stars
- The galactic core hosts a **supermassive black hole** (SMBH) of $10^6 - 10^{10}\ M_{\odot}$
- 10% of AGNs are radio-loud → **Relativistic jets**
- AGN classification based on
  - AGN orientation with respect to the line of sight from Earth
  - Radio-loudness or quietness

- **Blazars**: AGN with the jet closely aligned with our line of sight
- Sub-classification of blazars
  - Flat Spectrum Radio Quasars (FSRQs): strong optical emission lines
  - **BL Lacs**: no or very weak optical emission lines

Schematic representation of the Unified Model of Active Galactic Nuclei



Blazar MWL SED

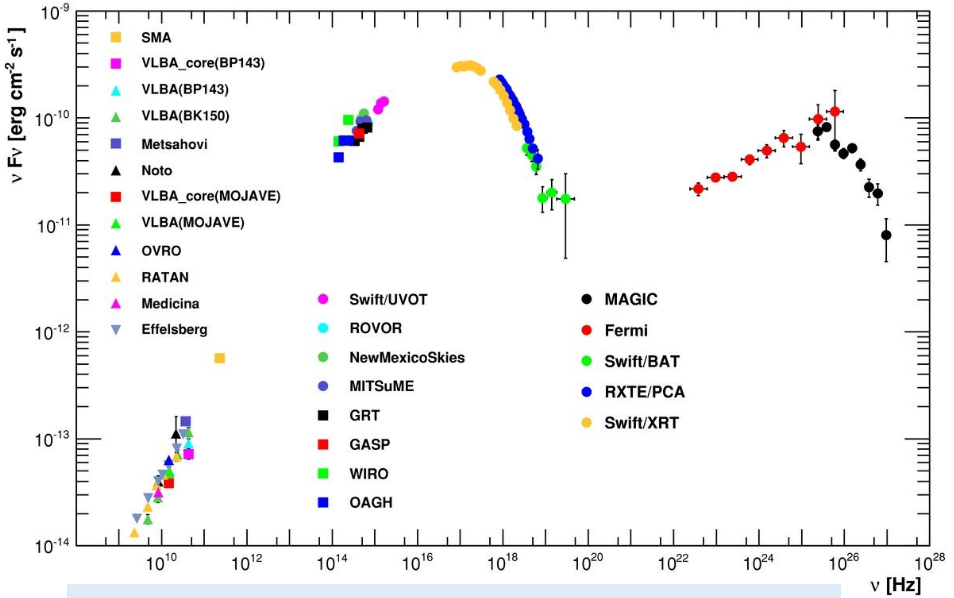
$$\upsilon F_{\upsilon} = E^2 \frac{dN_{\gamma}}{dE}$$

- Blazar MWL Spectral Energy Distribution (SED) shows non-thermal continuum from radio to **Very High-Energy (VHE, 10 GeV < E < 10 TeV)** gamma-rays with two main bumps

1. The first peaks at ν_{synch}, which varies from IR to X-rays. Dominated by synchrotron emission by relativistic electrons interacting with the magnetic field in the jet

• $\nu_{synch} < 10^{14}$ Hz	Low synchrotron-peaked (SP) BL Lacs (**LBL**)
• 10^{14} Hz $< \nu_{synch} < 10^{15}$ Hz	Intermediate SP BL Lacs (**IBL**)
• $\nu_{synch} > 10^{15}$ Hz	High SP BL Lacs (**HBL**)

2. The second bump peaks at energies from MeV to TeV. Less certain origin:
   - Inverse-Compton (IC) scattering of electrons off synchrotron photons (**SSC**), photons external from the jet (EC) (e.g. dusty torus, accreting disk, BLR, CMB…)
   - Proton synchrotron (PS) or γ-rays from $\pi^0 \rightarrow \gamma\gamma$ decay from photomeson production ($p\gamma \rightarrow N\pi$) or proton-proton collisions



Broadband SED of the BL Lac Mrk 421 from a MWL campaign in 2009 (Abdo et al 2011)

Artistic view of a blazar emitting γ-rays and neutrinos (Credit IceCube - NASA - KM3NeT)

The MAGIC Telescopes

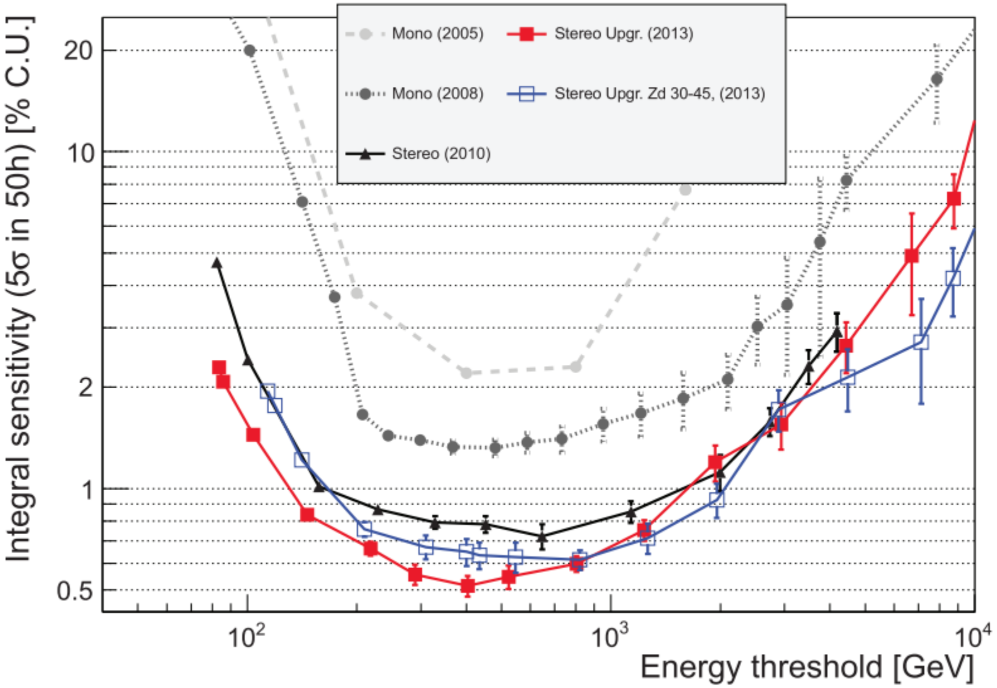
- System of two **Imaging Air Cherenkov Telescopes (IACTs)** located at the Observatorio del Roque de los Muchachos, La Palma Island, Canaries (2200 m a.s.l.)
  - 17 m diameter parabolic aluminum reflectors
  - PMT-based camera of ≈ 1000 pixels
  - Energy range **from 20 GeV** up **to 100 TeV**
  - **3.5° FoV**

- Up to March 2024 (TeVCat), 88 AGNs detected ad TeV
  - 57 HBLs
  - 10 FSRQs
  - 10 IBLs
  - 2 LBLs
  - 4 blazars, 2 AGNs and 2 BL Lac objects of unclear type

Most VHE AGNs are HBLs

Very few LBLs and IBLs are detected at VHEs

Evolution of the integral sensitivity of MAGIC (Aleksic et al. 2016)



TeV detection and insights into the emission regions of two gamma-ray fast flaring blazars

New BL Lacs in the TeV sky

- **B2 1811+31**
  - $z = 0.117$ (Giommi et al. 1991, ApJ, 387, 77, tentative value)
  - **Classified as IBL** in TeVCat
  - ***Fermi*-LAT** observations in HE γ-rays triggered MWL campaign from radio to VHEs

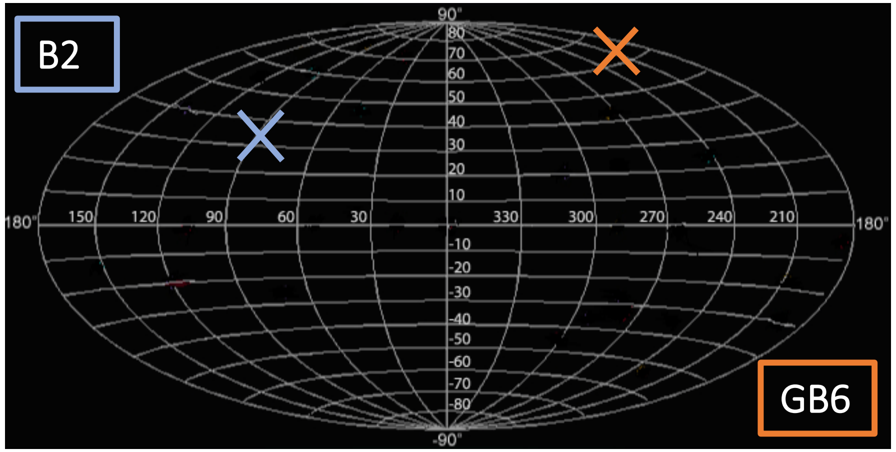
    ATel #14060: *Fermi*-LAT detection of a hard-spectrum GeV flare from the BL Lac B2 1811+31 - 2 October 2020
  - **MAGIC** announced the first detection at VHE γ-rays on 13th October 2020

    ATel #14090: Detection of very-high-energy gamma-ray emission from B2 1811+31 with the MAGIC telescopes

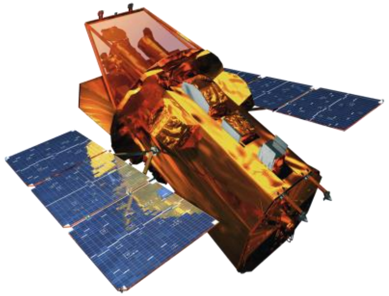
- **GB6 J1058+2817**
  - $z = 0.4793$ (Massaro et al. 2014 AJ, 148, 66, tentative value)
  - **Classified as BL Lac of unclear class** in TeVCat
  - ***Fermi*-LAT** observations in HE γ-rays triggered MWL campaign from radio to VHEs

    ATel #14491: *Fermi*-LAT detection of gamma-ray flaring activity from the BL Lac GB6 J1058+2817
  - **MAGIC** announced the first detection at VHE gamma-rays on 2nd April 2021

    ATel #14506: Detection of very-high-energy gamma-ray emission from GB6 J1058+2817 with the MAGIC telescopes



Fermi satellite



Swift satellite

MAGIC telescopes

New BL Lacs in the TeV sky

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  - $z = 0.117$ (Giommi et al. 1991, ApJ, 387, 77, tentative value)
  - **Classified as IBL** in TeVCat
- Simultaneous MWL campaign in high-state + long-term monitoring
  - **HE** (*Fermi*-LAT) and **VHE γ-rays** (MAGIC)
  - **Optical/UV** (*Swift*-UVOT) and **X-rays** (*Swift*-XRT)
  - **Optical** (CRTS, KAIT, ZTF, Würzburg, KVA, Siena)
  - **Radio** (OVRO, TELAMON)

This presentation!

- **GB6 J1058+2817**
  - $z = 0.4793$ (Massaro et al. 2014 AJ, 148, 66, tentative value)
  - Association with IC130409A, 120 TeV neutrino event (IceCat-1 (Abbasi et al., 2021))
- Simultaneous MWL campaign in high-state + long-term monitoring
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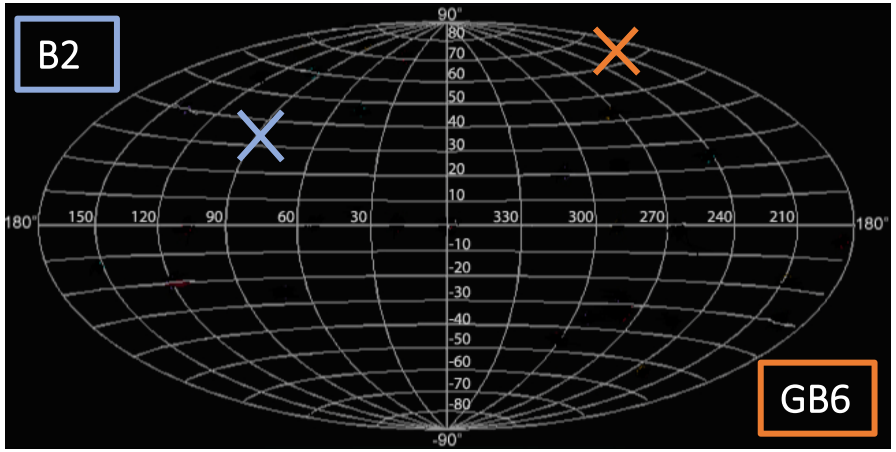
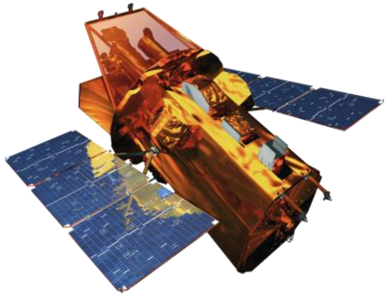



Fermi satellite

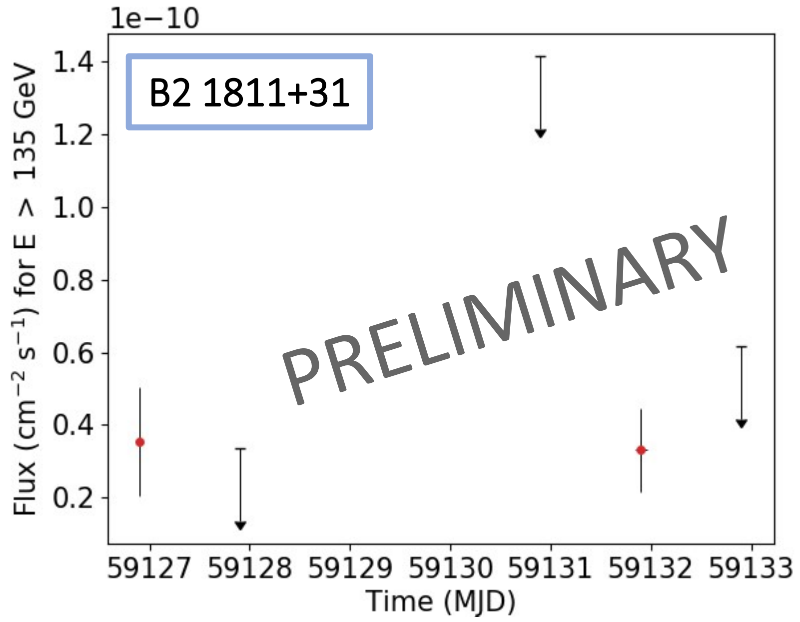

Swift satellite


MAGIC telescopes

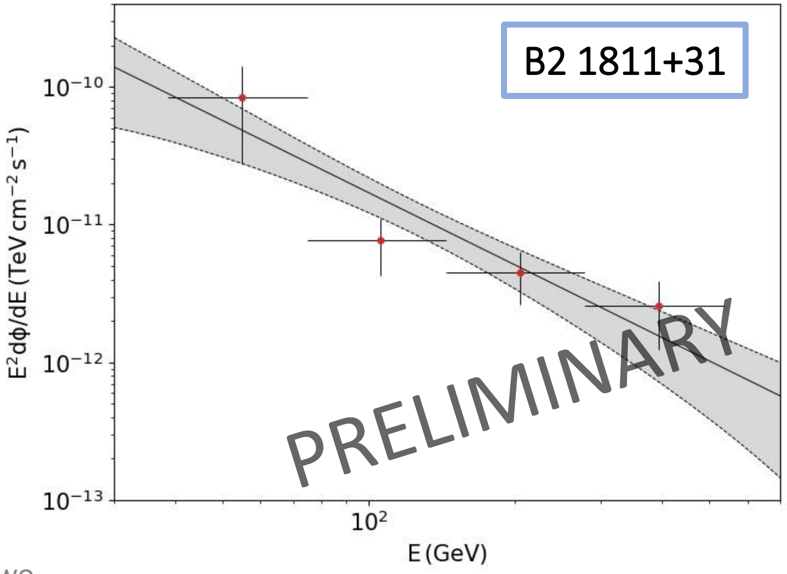
MAGIC detection of VHE emission from B2 1811+31

- Observations from October 5th to 11th, 2020
  - **5 nights of observations**
  - **Detection with 5.3 sigma**
- Night-wise gamma-ray flux for **energies above 135 GeV**
- Data from the last 3 observation nights, 2020 October 9th-11th, combined to evaluate the overall spectrum
  - *Fermi* and *Swift*-UVOT data indicate that the source state during October 5th-6th is different from October 9th-11th (see next slide)
- Unfolding for energy dispersion and correction for absorption by the Extragalactic Background Light (EBL)
- Intrinsic spectrum fitted with a power-law function
  - $\Gamma = 3.75 \pm 0.40$
  - $E_0 = 125.16$ GeV
  - $N_0 = (7.4 \pm 2.0) \times 10^{-10}$ TeV $^{-1}$ cm $^{-2}$ s $^{-1}$
  - $\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$

MAGIC lightcurve



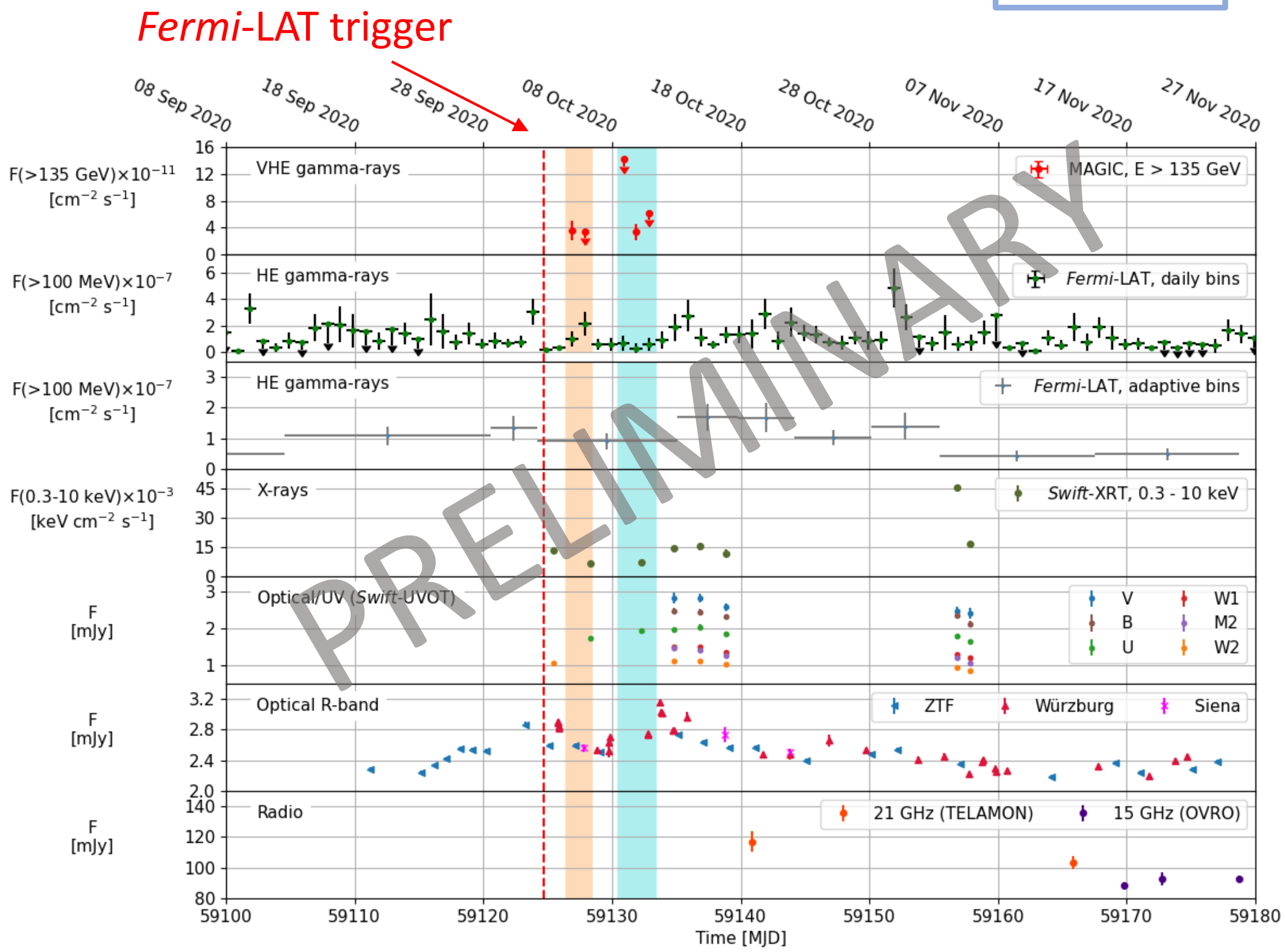
MAGIC SED



2020 Flare MWL lightcurve - B2 1811+31

B2 1811+31

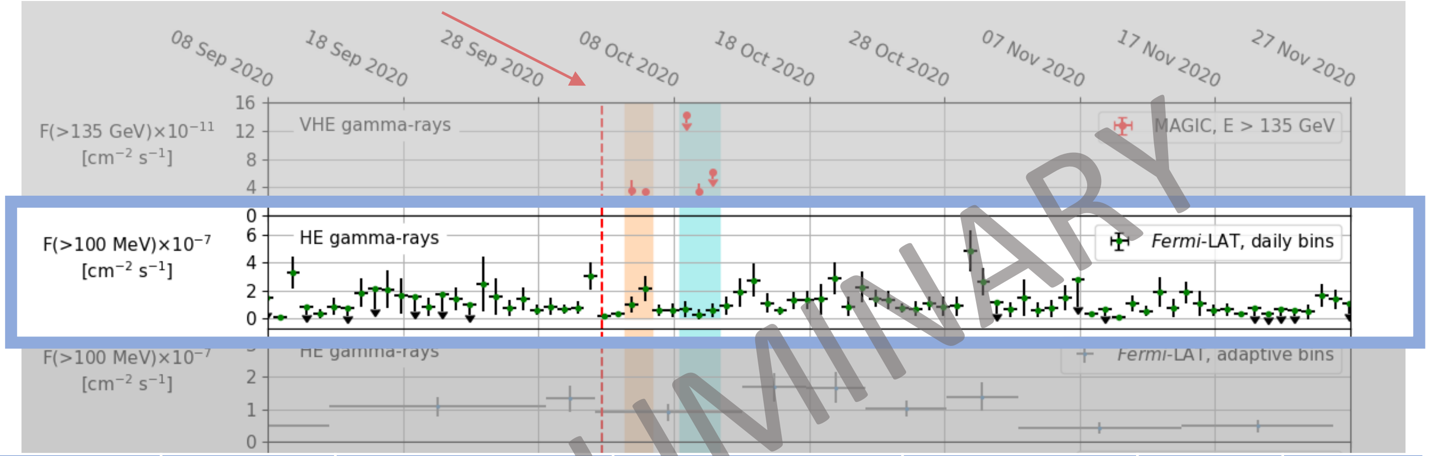
- ***Fermi*-LAT** and ***Swift*-UVOT** data indicate that the source state during the first MAGIC observation nights (**2020 October 5th-6th, reddish band**) is different from that during the last three MAGIC observations (**2020 October 9th-11th, blue band**)
- Dedicated *Fermi*-LAT analyses of 24h-48h-72h of data centered around the MAGIC observation nights confirmed different HE gamma-ray SEDs in the two periods
- **No significant difference** between the ***Swift*-XRT** data in the observations carried out within the two groups of MAGIC observation nights
- The daily gamma-ray variability can be used to set constraints on the size of the emission region responsible for the gamma-ray flare (→ Next slide!)



Fast variability analysis – B2 1811+31

B2 1811+31

Fermi-LAT trigger



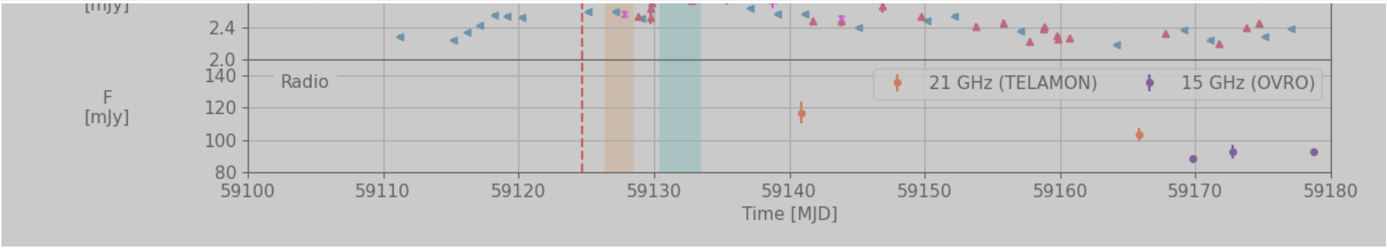
Constraining the emission region size

- Variability timescales of the high-energy gamma-ray flux were estimated from the daily lightcurves using the method in [Foschini L. et al., A&A 530, A77 (2011)](#)
- Scan to find **minimum doubling/halving time** of ***Fermi*-LAT daily light-curve**:

$$F(t) = F(t_0)2^{-(t-t_0)/\tau}$$

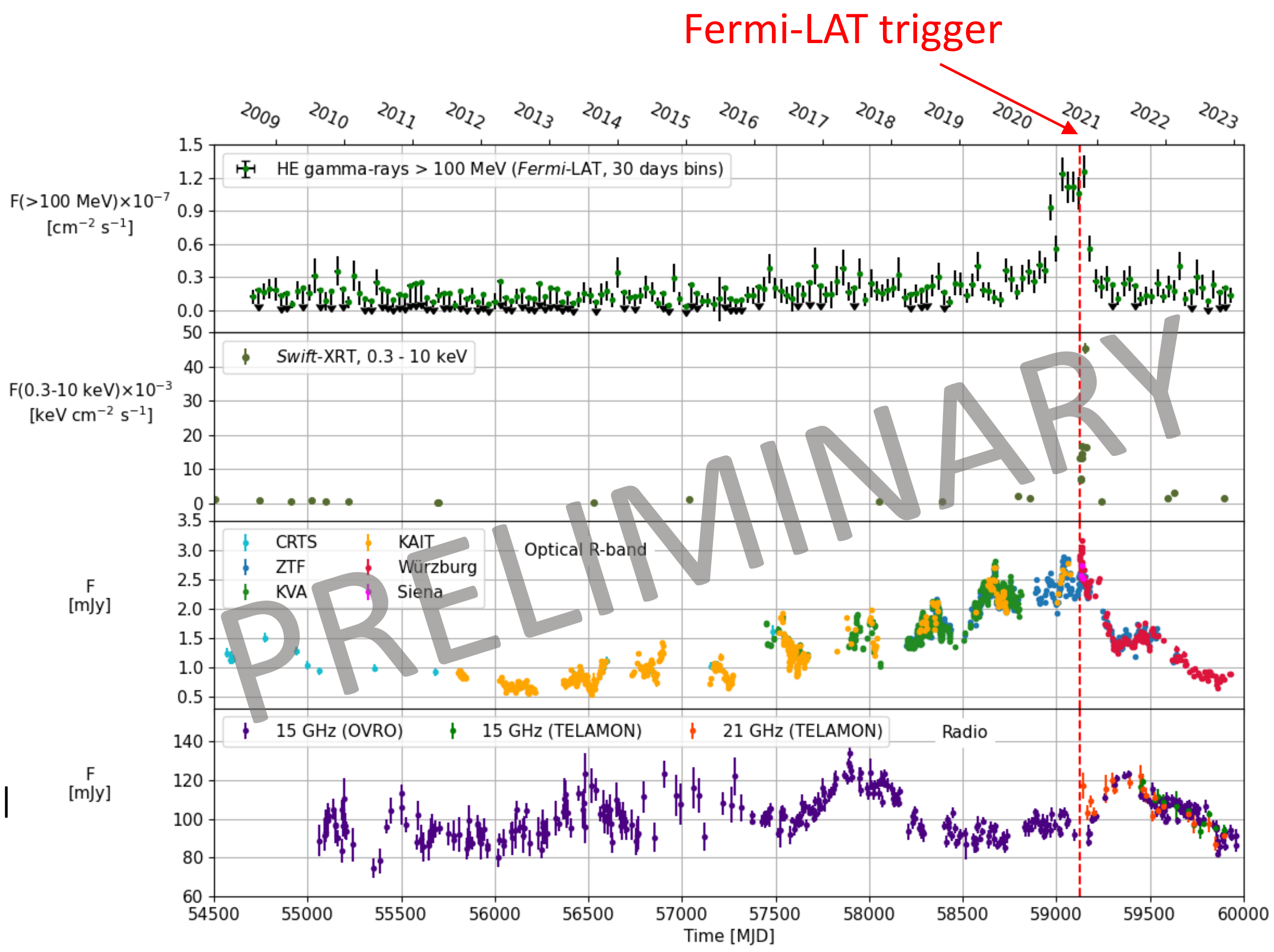
t_0 [MJD]	t [MJD]	$F(t)$ [cm^{-2} s^{-1}]	$F(t_0)$ [cm^{-2} s^{-1}]	Significance	$\|\tau_{UL}\|$	Rise/ Decay
59122.9	59123.9	$(7.8\pm4.4)10^{-8}$	$(3.0\pm1.0)10^{-7}$	2.1	6.1 h	R
59123.9	59124.9	$(3.0\pm1.0)10^{-7}$	$(2.1\pm1.4)10^{-8}$	2.8	3.1 h	D

- Emission size region can be constrained to $R \leq c\Delta t \frac{\delta_D}{1+z}$
- Assuming $\delta_D = 10 - 20$, we find
  - $R_{max} \sim (6-12) \times 10^{15}$ cm for τ_{UL} = 6.1 h
  - $R_{max} \sim (3-6) \times 10^{15}$ cm for τ_{UL} = 3.1 h



Long-term MWL lightcurve - B2 1811+31

- The 2020 HE γ-ray flare occurs at the apex of an increase in the optical activity lasting for several years
- Coherent high-state at HE gamma-rays, X-rays and in optical/UV
- Hint of long-term correlation with no delay of the optical and gamma-ray lightcurves
  - Commonly found for FSRQs, LBLs and IBLs
- Different trend in long-term radio monitoring
  - The bulk of the emission in radio must originate in regions different from those responsible for the optical, X and gamma high state
- Rapid decay of the gamma-ray flux at the final stage of the high-state period in gamma-rays
  - Efficient cooling phase

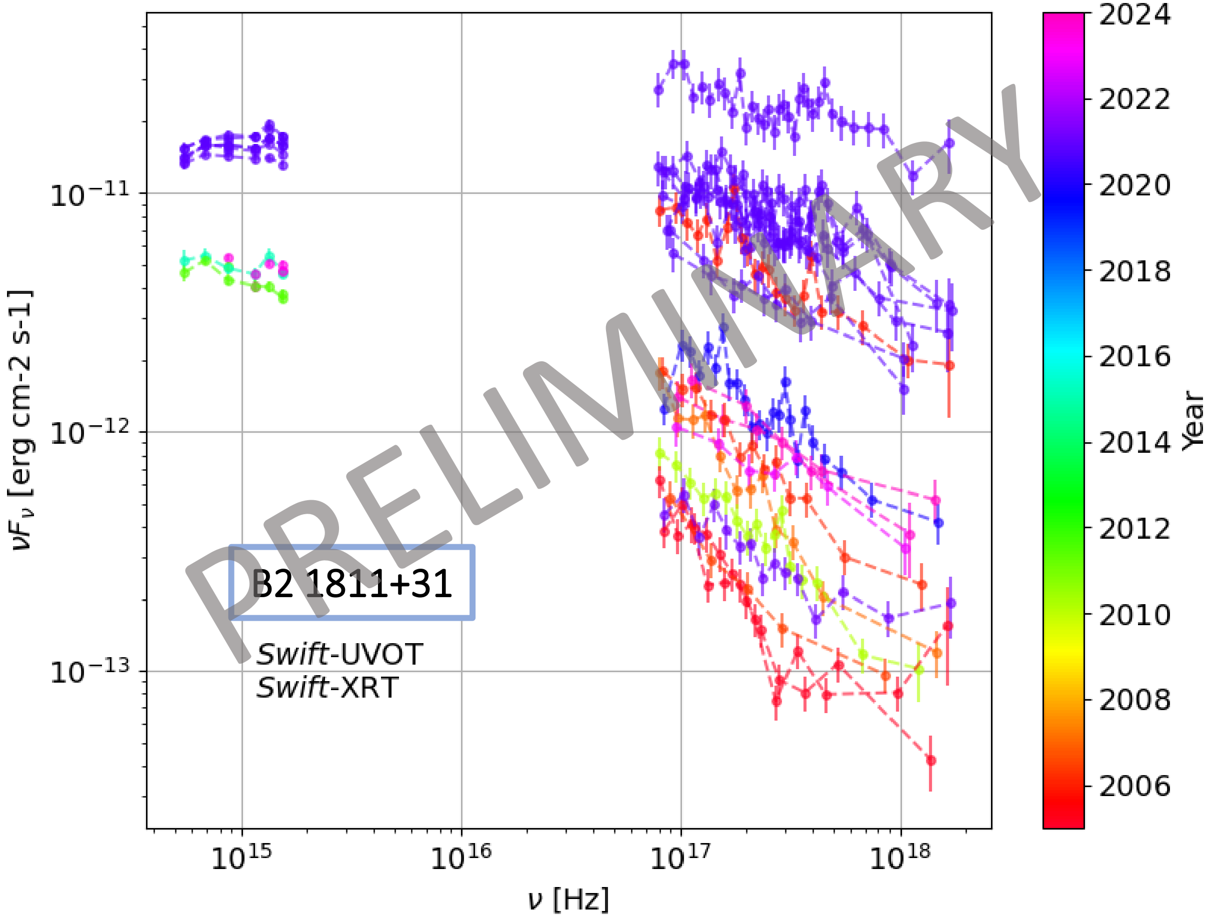


B2 1811+31

Long-term optical-to-X-ray SED evolution

- B2 1811+31 was subject to long-term monitoring by Swift-XRT, for a total of ~100 observations from 2005
- Swift-UVOT performed less frequent observations of this source
- After data quality cleaning, ~70 Swift-XRT and ~20 Swift-UVOT observations spanning over the whole Swift mission were employed to characterize the source SED variability in the optical/UV and X-ray bands
- Simultaneous observations allow for classification of the source states

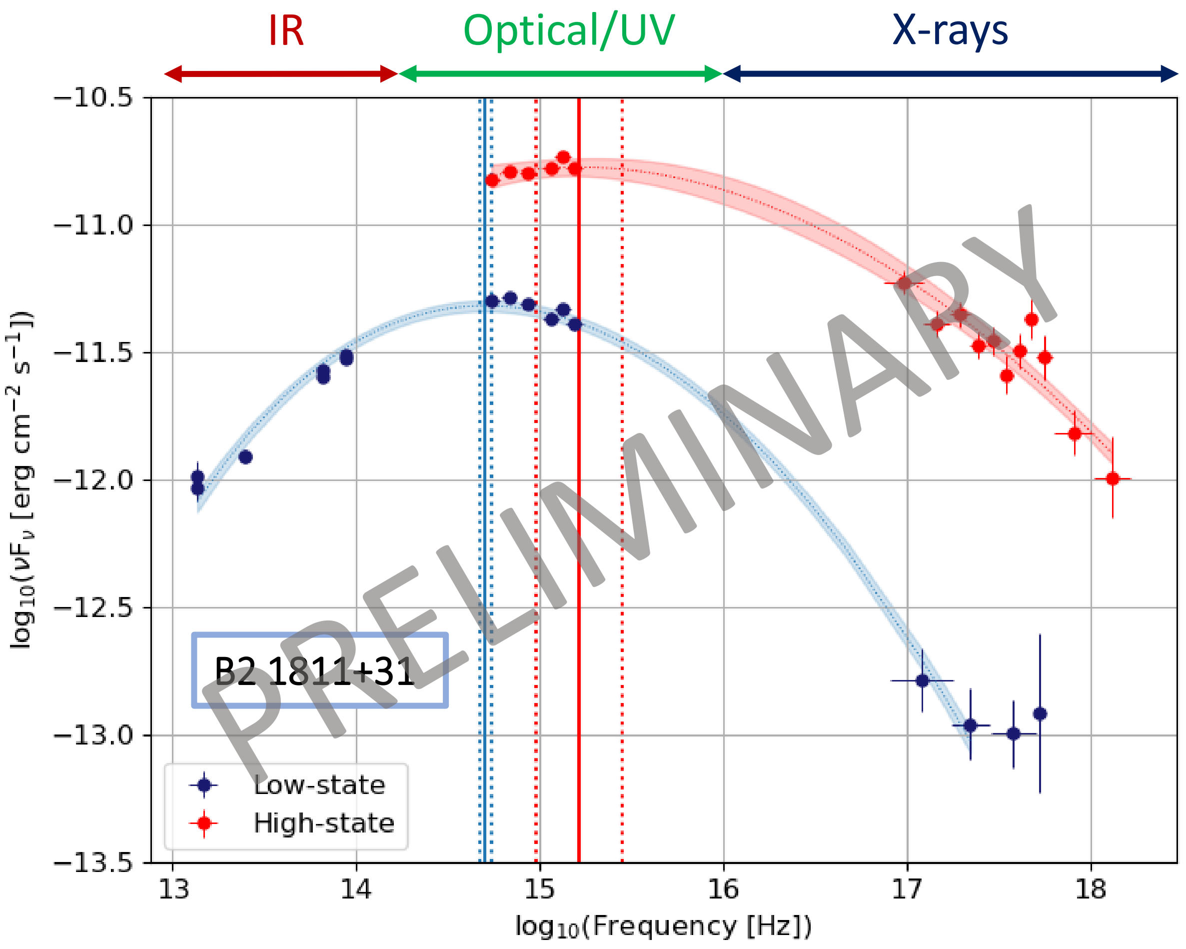
Long-term optical-to-X-ray SED evolution inferred from *Swift*-UVOT and *Swift*-*XR*T observations



Source states classification

- Log-parabola (LP) function
  $$\nu\, F_\nu(\nu) = f_0\; 10^{-b\,(\log_{10}(\nu/\nu_{synch}))^2}$$
- LP fit of IR – X-rays low-state SED
  - WISE (March 2010) +
    Swift-UVOT and -XRT (May 2011, January 2015)
  - $\nu_{synch} \approx 10^{14.71 \pm 0.03}$ Hz
  - IBL during non-flaring state
- LP fit of IR– X-rays flaring-state SED
  - *Swift*-UVOT and -XRT October 6th and 10th 2020
  - $\nu_{synch} \approx 10^{15.21 \pm 0.23}$ Hz
  - Borderline between IBL/HBL during flaring state

Classification of the source low and high states using a log-parabola fit of the infrared-to-X-ray SED

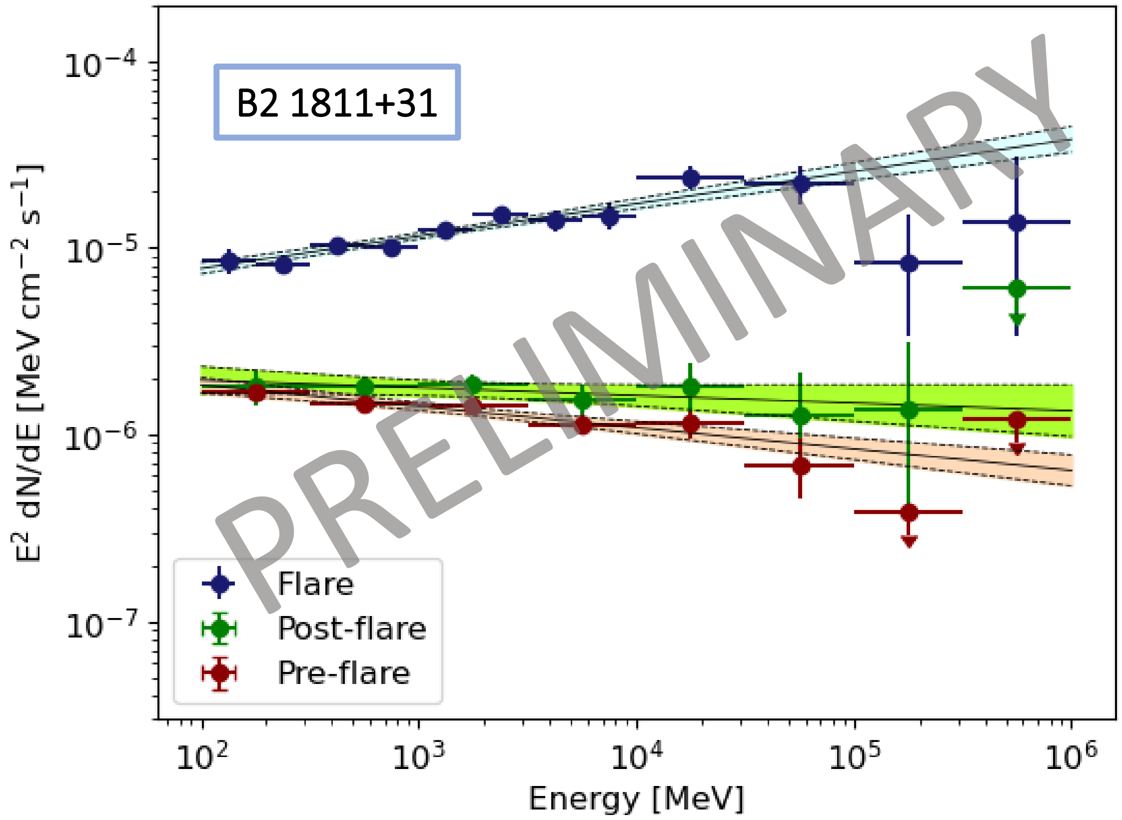


HE gamma-ray SED evolution – B2 1811+31

- Spectral analyses in the 100 MeV - 1 TeV range yield evidence for strong spectral hardening during the high-energy flare period in 2020
- Peak frequency of the **high-energy SED bump shifts** to **higher frequencies during the flare**, with spectral break at tens of GeV
- Signature of freshly accelerated particles produced in the jet

Period	Start [MJD]	Stop [MJD]	Γ_{PL}	F (>100 MeV)$\times 10^{-8}$ [cm^{-2} s^{-1}]
Pre-flare	54682	58940	2.11 ± 0.03	1.7 ± 0.1
Flare	58940	59190	1.83 ± 0.02	9.6 ± 0.5
Post-flare	59190	59945	2.04 ± 0.05	1.9 ± 0.3

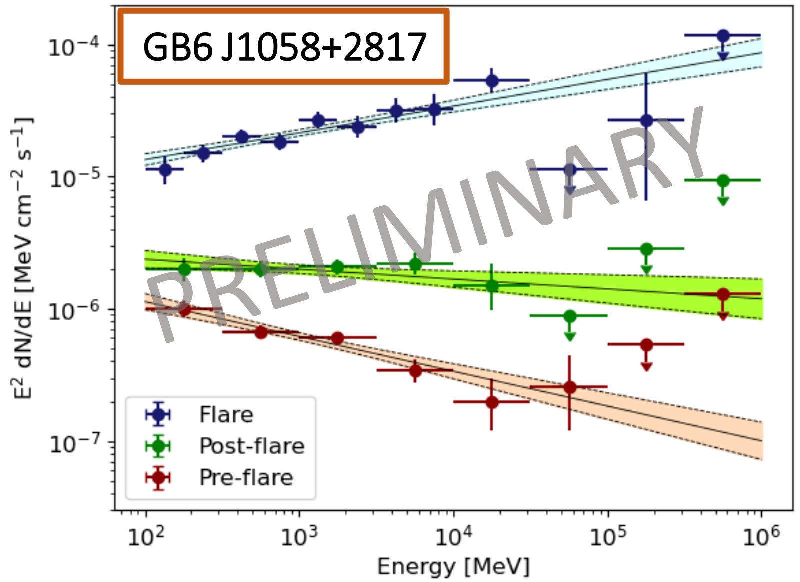
Average high-energy gamma-ray SEDs during the 2020 high-state and in low-state (before and after)



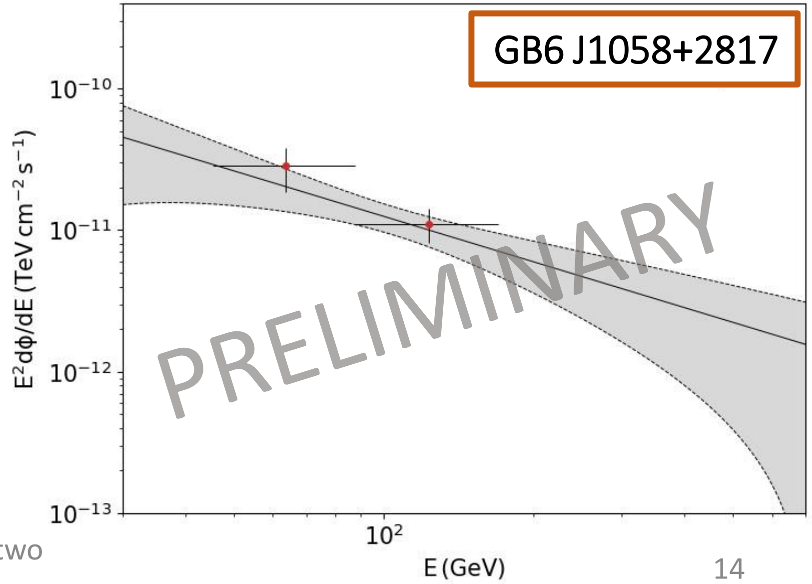
Summary – GB6 J1058+2817

- $z = 0.4793$ (Massaro et al. 2014 AJ, 148, 66, tentative value)
- Association with **IC130409A**, 120 TeV neutrino event (IceCat-1 (Abbasi et al., 2021))
- 4 observation nights from Apr 2nd to 5th, 2021
  - Detection with 5.9 sigma
- Hint of few-hours variability at HE γ-rays, which corresponds to an emission region size of 1×10^{16} cm
- BL Lac of unclear class in 4FGL and TeVCat
- **Estimate of IBL** classification for the source low state
- Strong hardening in the HE gamma-ray band during the high-state

Evolution of the HE γ–ray SED (*Fermi*-LAT)



SED measured by MAGIC during the γ–ray high state



Conclusions and next steps

- **B2 1811+31** and **GB6 J1058+2817** are two blazars that in 2020 and 2021, respectively, entered the catalog of **TeV-detected** sources thanks to the detection by the MAGIC telescopes, triggered by the *Fermi*-LAT
- B2 1811+31 behaved as **IBL in quiet state** and as **borderline IBL/HBL during the flaring state**
    - ISP BL Lacs are rare sources in the TeV sky
- MWL coverage from radio to VHE γ-rays during the high-state and analysis of long-term MWL data provide a unique way to investigate the **dynamics** and **emission mechanisms** of particles accelerated in the jet in both the **steady and flaring states**
- During the **2020 flare**, **both SED bumps** shifted to **higher flux levels** and **higher energies**
- The *Fermi*-LAT lightcurve showed **fast variability of few hours**, providing a constraint of $\approx 6 \times 10^{15}$ cm for the size of the emission zone responsible for the γ-ray flare detected by the MAGIC telescopes
- Hints from **multi-band cross-correlations** can act as guidance to the broad-band SED modelling

- **Next steps**: finalize the modelling of the SEDs of the two sources given the collected MWL info

Thank you for your attention!

MAGIC

Fermi Gamma-ray Space Telescope

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