Status report of the Fermi-LAT analysis of VER J0521+211 during the February 25, 2020, flare

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JRJC 2024
Abbaye de Saint-Jacut-de-la-mer
Côte d'Armor
24-30 Nov 2024

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Outline

- Introduction
  - Gamma-ray astronomy
  - Very Energetic Radiation Imaging Telescope Array System
  - Fermi Gamma-ray Space Telescope
  - Active Galactic Nuclei
- Motivation
- Preliminary results
- Future work

Gamma-ray astronomy

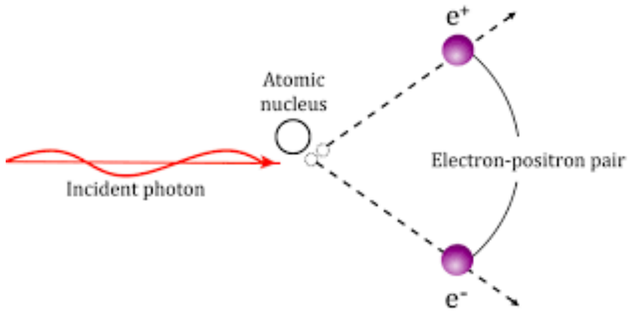
- Gamma rays are the most energetic form of electromagnetic radiation
- Common sources include nuclear reactions, radioactive decay, particle interactions (like annihilation of matter and antimatter), and **astrophysical sources** like supernovae, neutron stars, and **active galactic nuclei.**

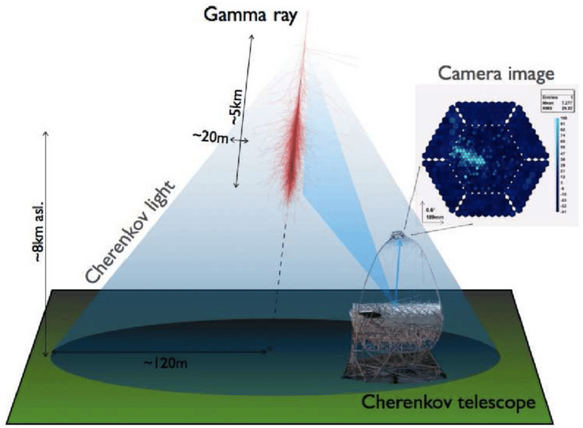
Why study them?

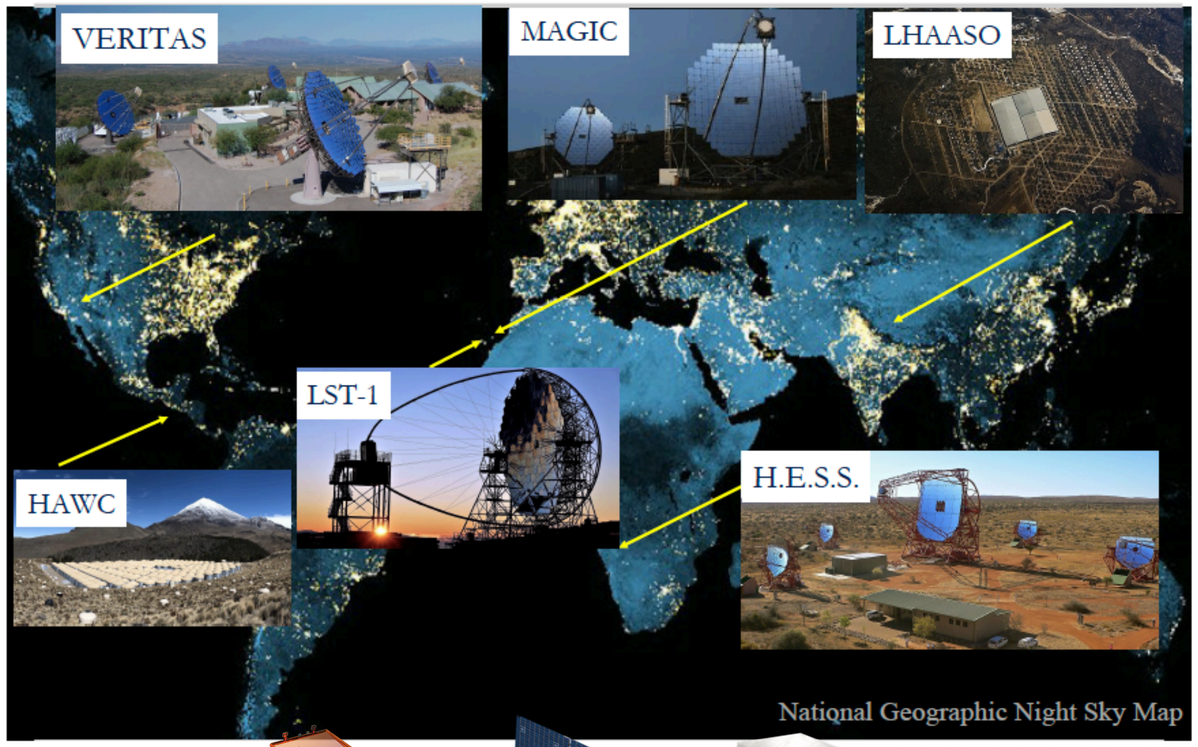
- New Frontiers in Multi-Messenger Astronomy.
- Laboratories of extreme physical environments.

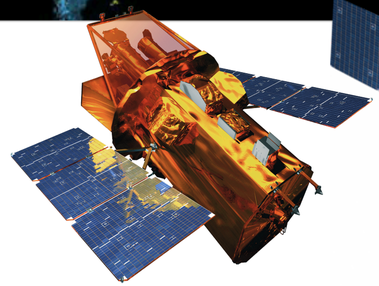
How to study gamma-rays

- Space-based telescopes.
- Ground-based Imaging Atmospheric Cherenkov telescopes.









Neil Geherls Swift Observatory
0.2-150 keV

Fermi Gamma-ray Space Telescope
~20 MeV- up to 1TeV

VERITAS *Very Energetic Radiation Imaging Telescope Array System*

View of the FLWO basecamp and the VERITAS array (Credits: the VERITAS collaboration)

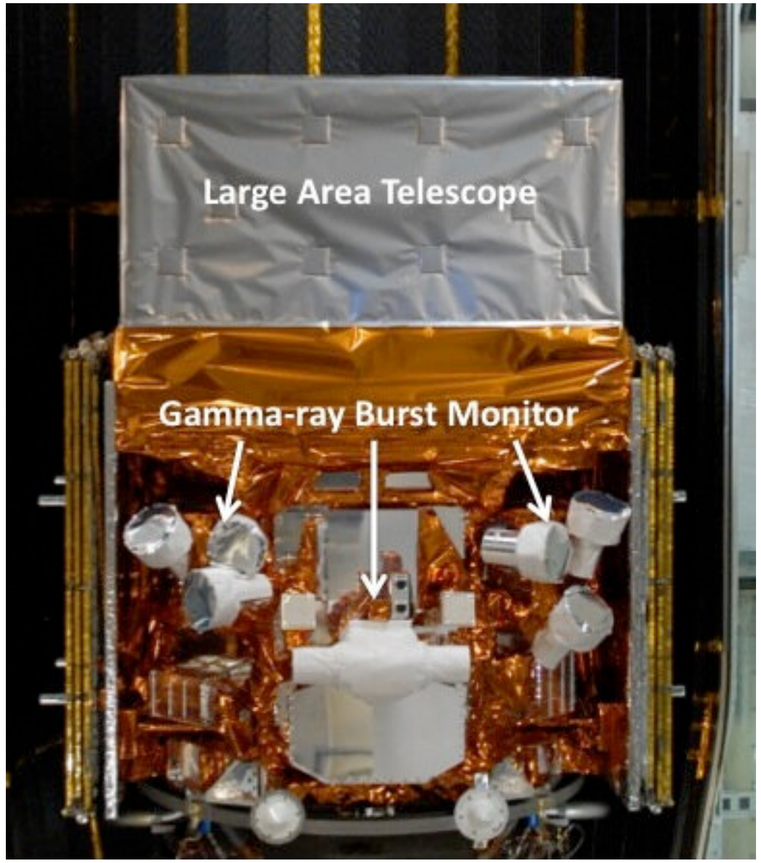
- Ground-based gamma-ray instrument at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona, USA.
- Array of four 12m optical reflectors for gamma-ray astronomy.
- Energy range of 85 GeV to 30 TeV.
- Uses Cherenkov radiation to detect gamma-ray showers produced in the atmosphere.
- Extremely large collection area allows for short-timescale studies of variability in AGNs, probing jet dynamics at high energies.

Fermi Gamma-ray Space Telescope

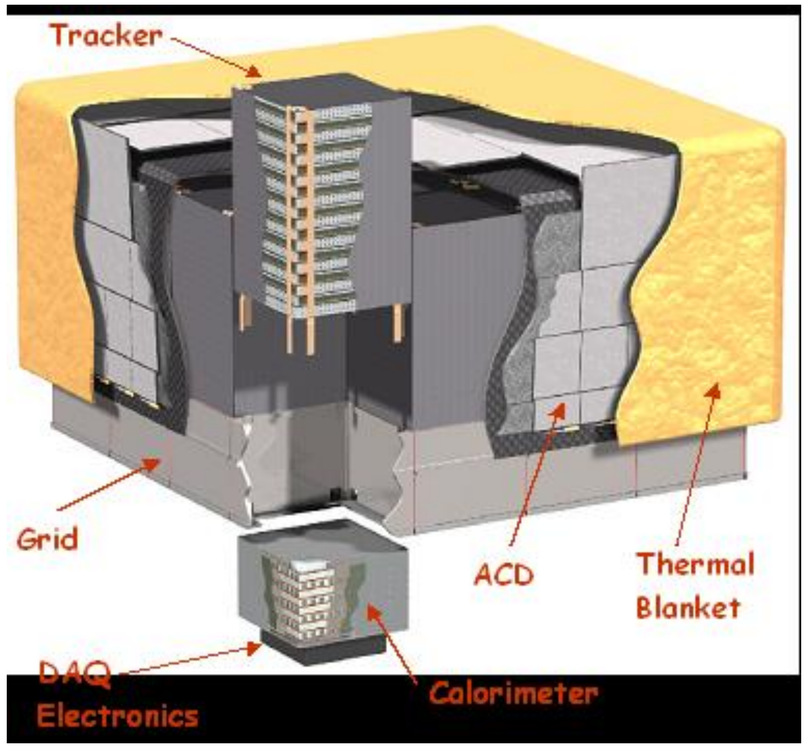
- Launched on June 11, 2008.
- It circles Earth every 96 minutes in a 26° inclination orbit at an altitude of 535 km.
- Fermi Gamma-ray Burst Monitor (GBM): 10 keV - 25 MeV.
- **Fermi Large Area Telescope (LAT)**: 20 MeV - up to 1 TeV.
  - It covers ~20% of the sky at any moment, surveying the entire sky every 3 hours.
  - Ideal for studying gamma-ray bursts, pulsars, active galactic nuclei, and dark matter candidates.
  - Open access to all data.
  - Exploration of the high-energy gamma-ray sky and the investigation of the origin of isotropic diffuse emissions, particle acceleration mechanisms in various astrophysical sources, including active galactic nuclei **(AGNs)**, pulsars, and super-nova remnants, GRBs and other transient sources, contributions to dark matter, **construction of source catalogs.**

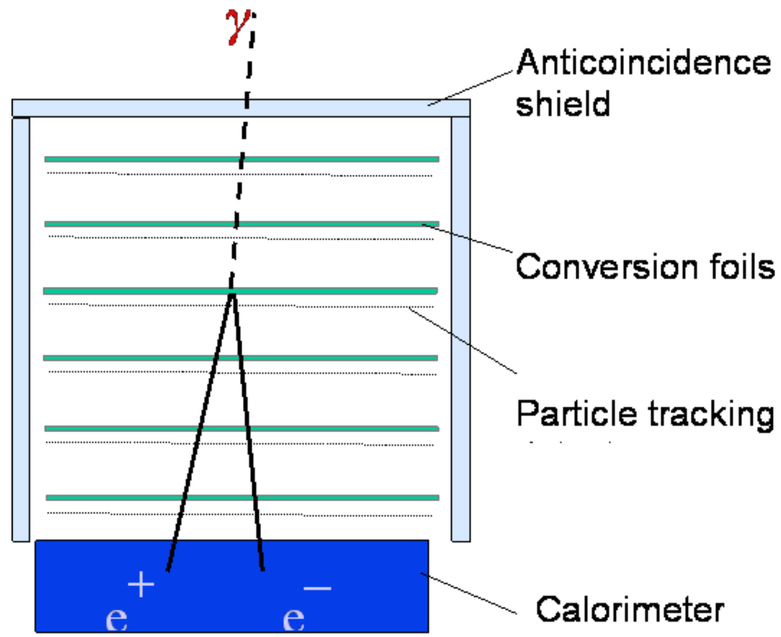
fermi.gsfc.nasa.gov

Fermi Large Area Telescope (Fermi-LAT)



Fermi observatory





Schematic structure of the LAT

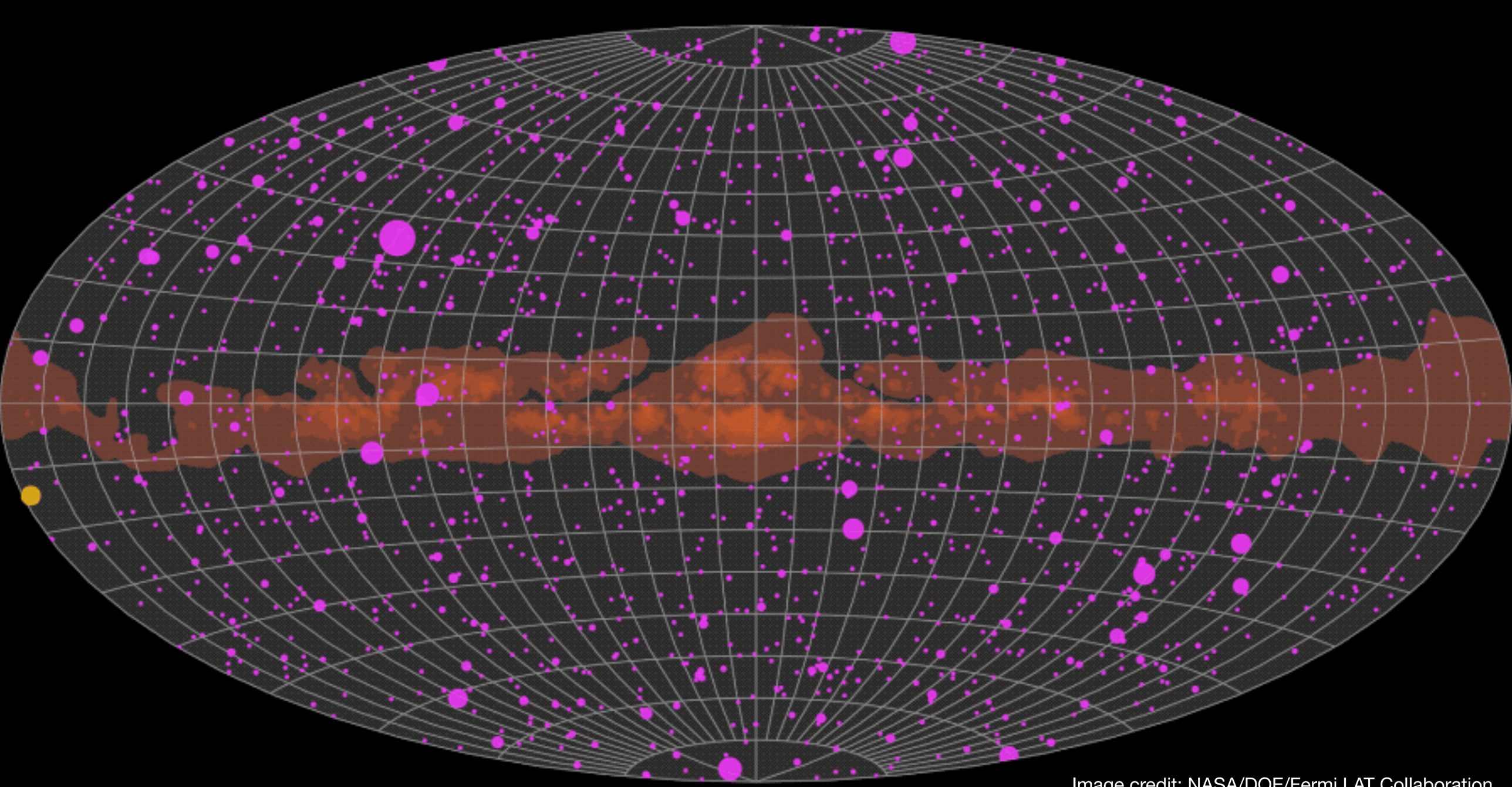
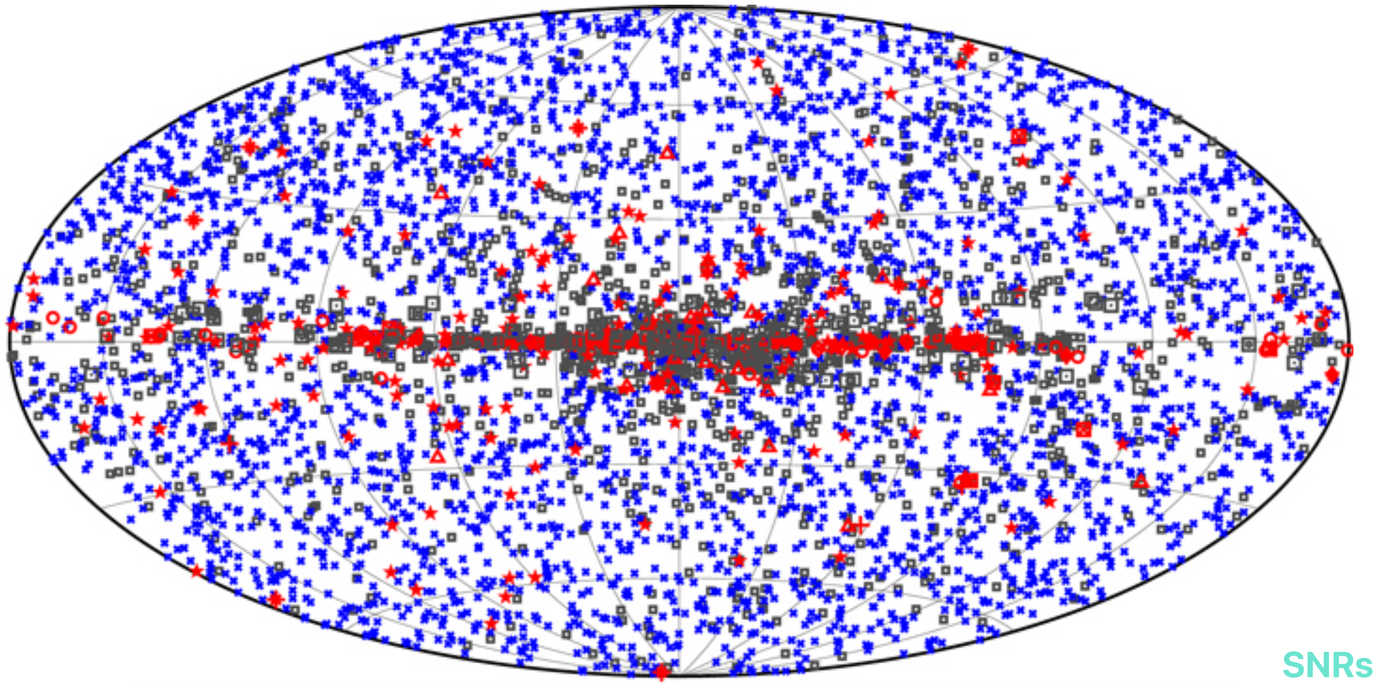
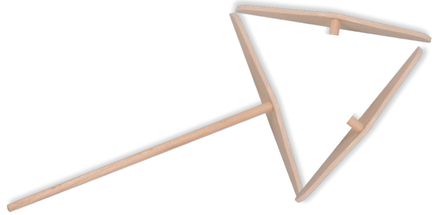
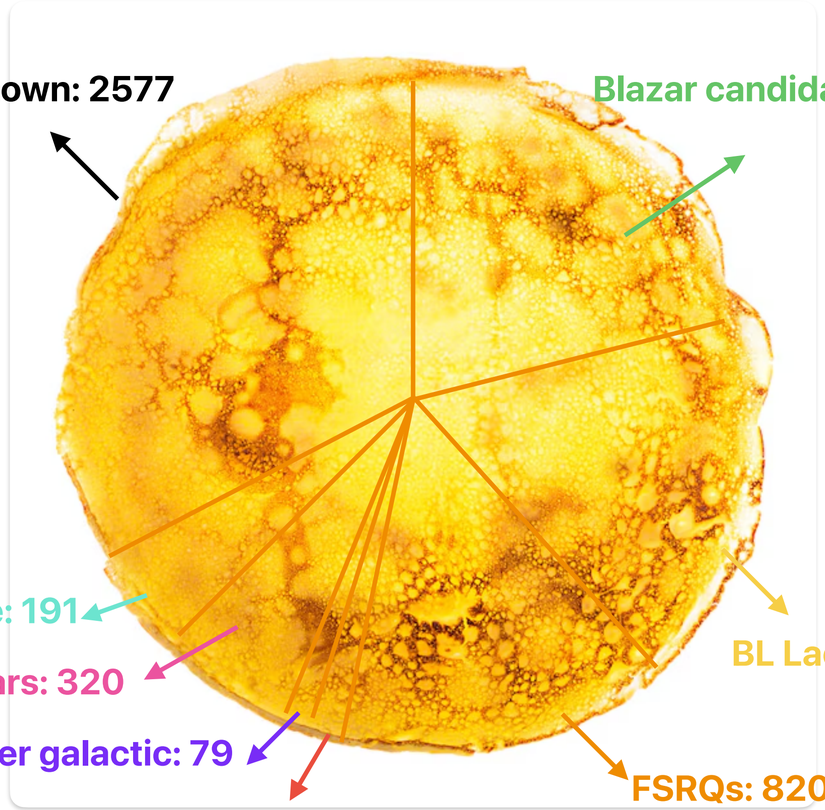


Image credit: NASA/DOE/Fermi LAT Collaboration



No association	Possible association with SNR or PWN		AGN
Pulsar	Globular cluster	Starburst Galaxy	PWN
Binary	Galaxy	SNR	Nova
Star-forming region	Unclassified source		





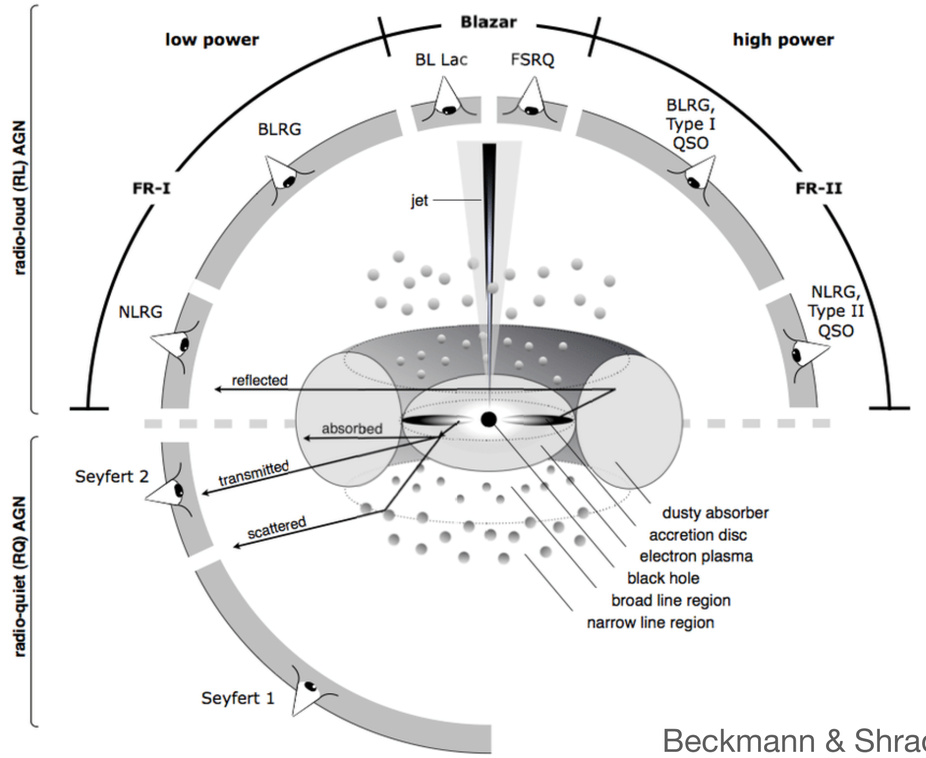
Fermi Large Area Telescope Fourth Source Catalog (4FGL-DR4)

S. Abdollahi *et al* 2020 *ApJS* **247** 33

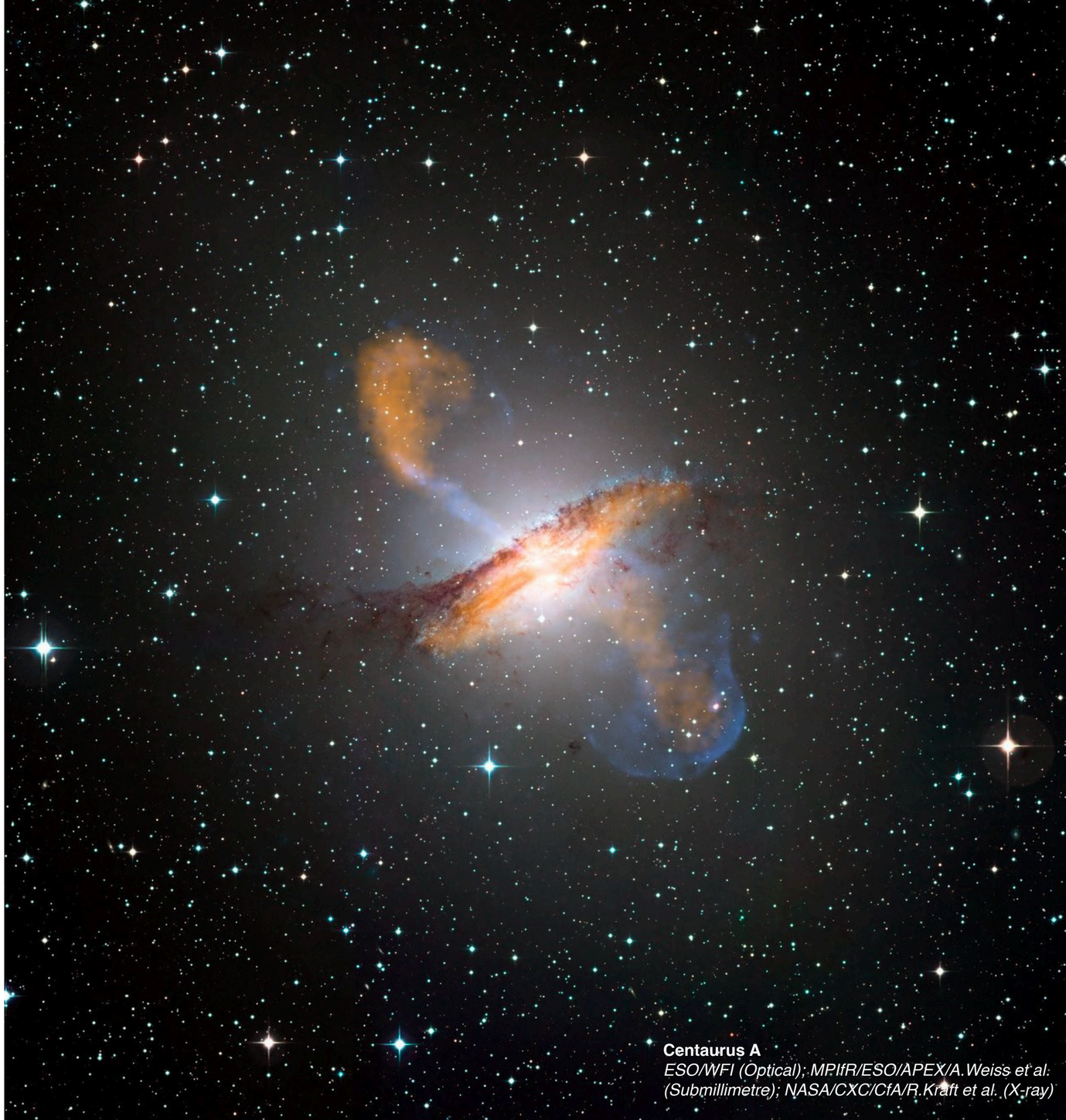
Active Galactic Nuclei

- Extremely luminous regions at the centers of some galaxies are powered by the accretion of matter onto a supermassive black hole.

- High luminosity.
- Multi-wavelength non-thermal emission.
- Strong variability.



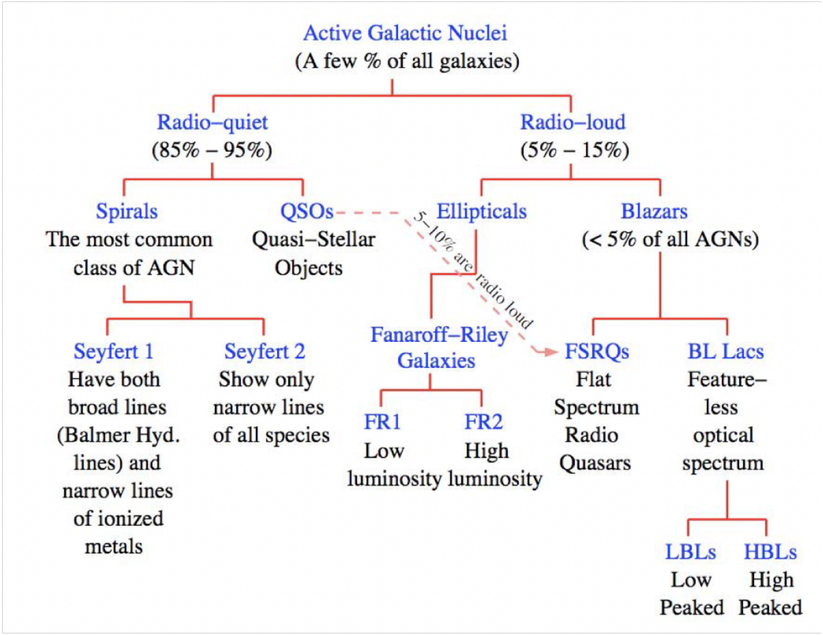
Beckmann & Shrader (2012)

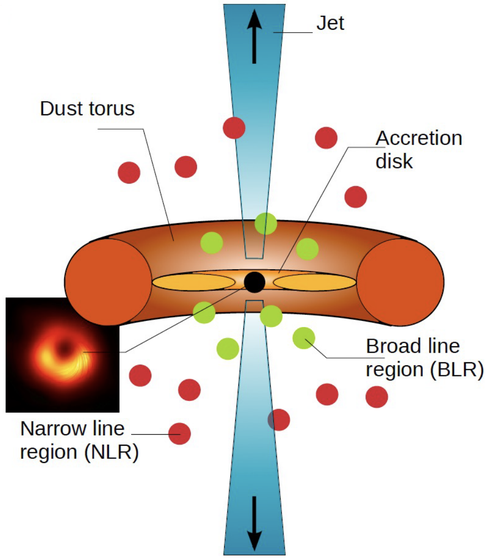


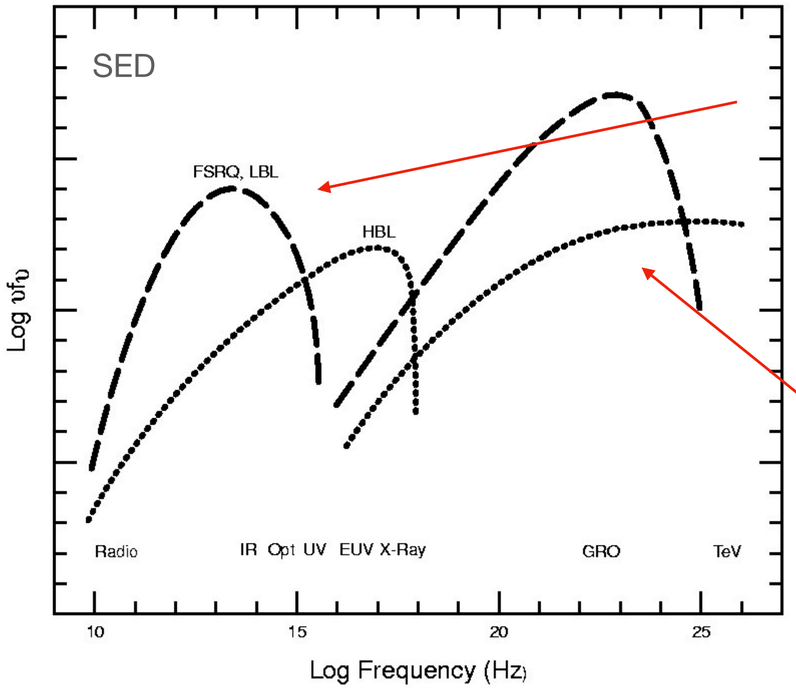
Centaurus A
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

Blazars

- Relativistic jet points nearly directly toward Earth.
- Non-thermal emission.
  - Synchrotron radiation at low energies (X-ray to VHE).
  - Inverse Compton scattering or hadronic processes at high energies (X-ray to gamma-ray).
- Dominant in the high-energy sky, major contributors to the Fermi-LAT gamma-ray catalog.
- Can be classified in flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs).







Lower energy emission due to synch emissions from relativistic electrons in the jet

Higher energy emission could be due to leptonic or hadronic processes

Reshmi Mukherjee, MPIK-CDY Summer School, Heidelberg, 2024.
D. Horan's "Introduction to gamma-ray blazars " Fermi Summer School 2013.

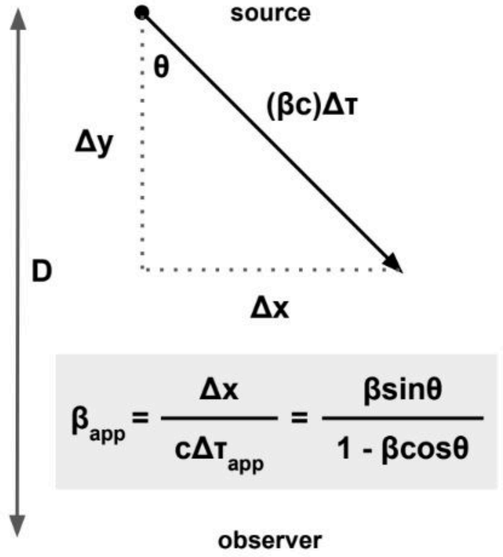
Blazars

Superluminal motion

- Apparent faster-than-light movement of plasma knots

or features in relativistic jets.

- Blobs in jets are tracked over time using very long baseline interferometry (VLBI) radio observations.
- Confirms relativistic jet speeds, supporting the idea that AGN jets are powered by supermassive black holes.



D: distance from an observer at point A

$\nu = \beta c$: actual velocity

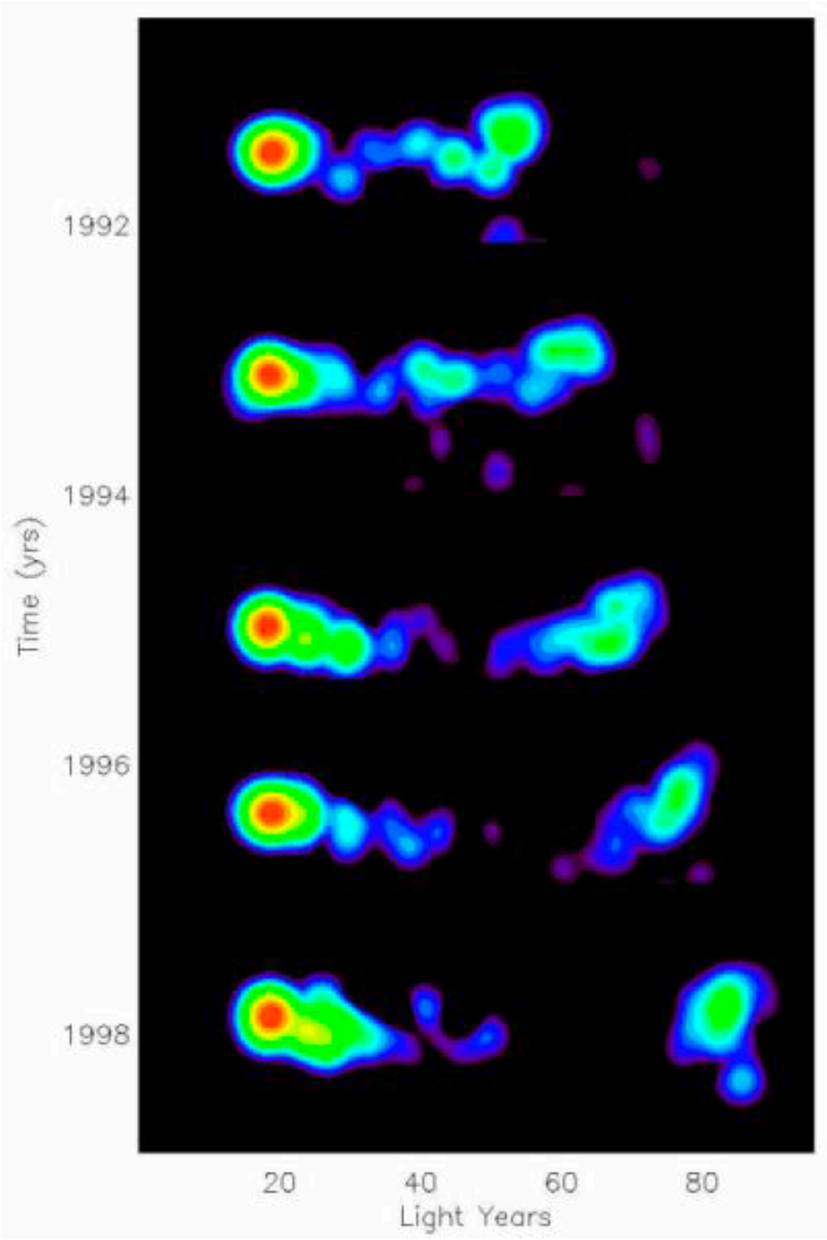
$\Delta\tau$: time to move from point A to B

Δx: transverse motion (what we observe)

$= \nu\Delta\tau\sin\theta$

$= \beta c\Delta\tau\sin\theta$

$\Delta y = \beta c\Delta\tau\sin\theta$: motion towards the observer



Apparently superluminal motion of the radio features in the FSRQ 3C 279

A.Brill, PhD Thesis, Columbia Univ., 2021
Credits: NRAO's Charlottesville, Virginia

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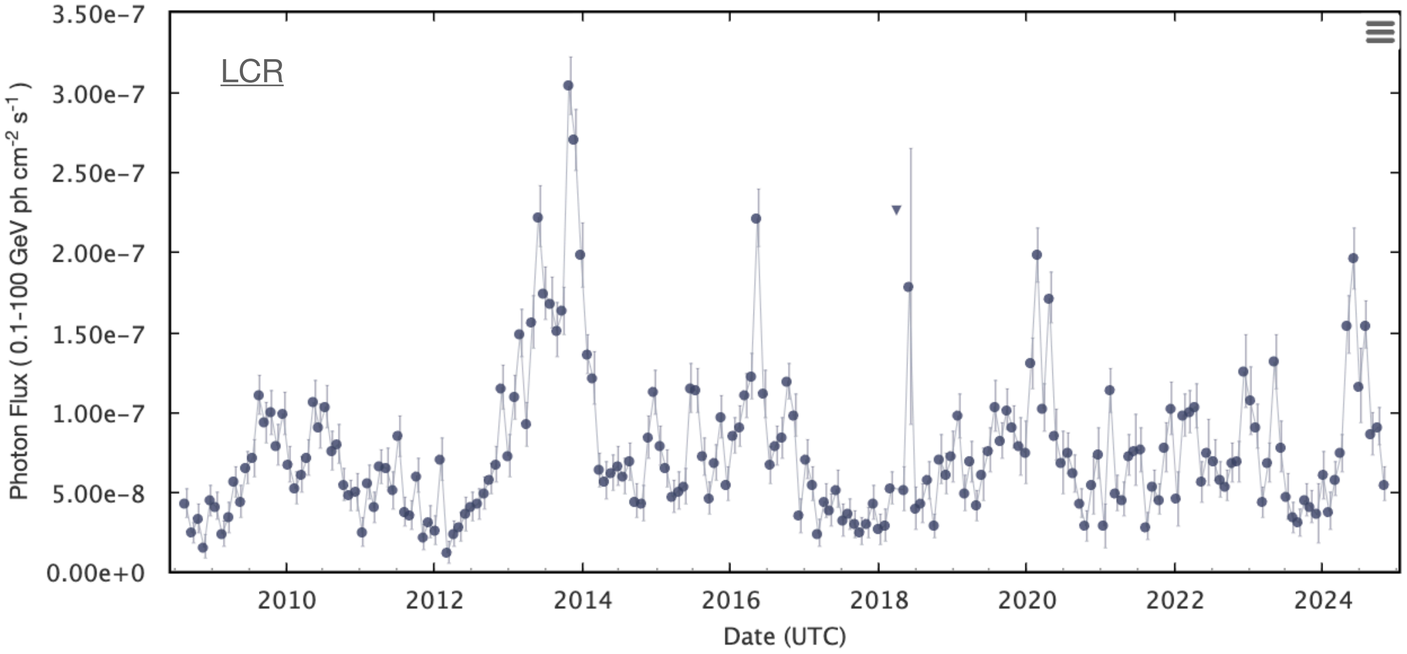
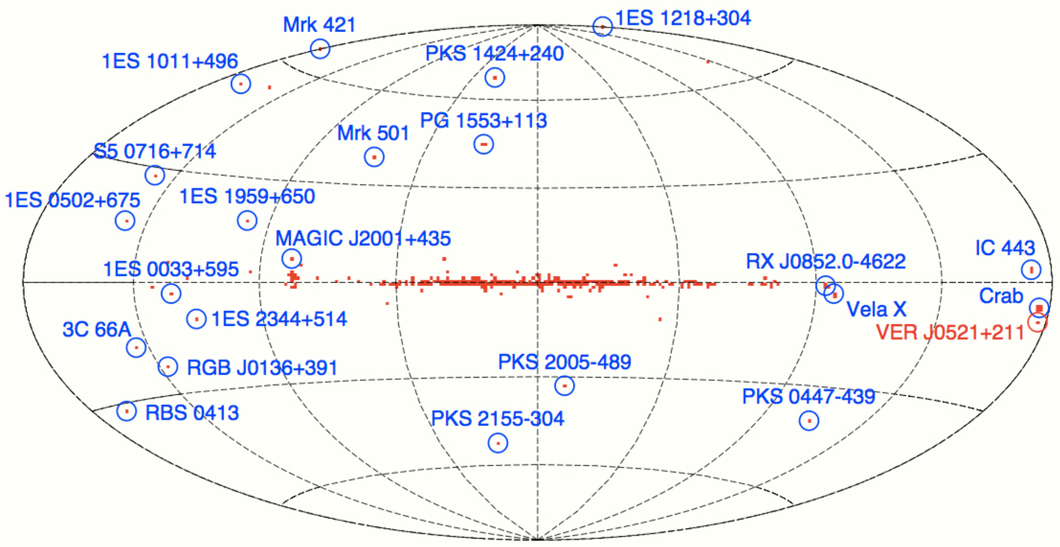
VER J0521+211

- VER J0521+211 is a blazar discovered by VERITAS in October 2009, motivated by a cluster of photons with energies > 30 GeV in the first year of Fermi-LAT observations (ATel # 2260)
- It is classified as an IBL (peak of SED at $10^{14} - 10^{15}$ Hz), but it exhibits a harder X-ray spectrum and HBL-like behavior during flares.
- It is close to the Galactic plane, just 3.08 degrees from the Crab Nebula.





Fermi GI 121074

Astrophys.J. 932(2022) 2

Astrophys.J. 776 (2013) 69

- Association with RGB J0521.8+2112 is strongly supported by X-ray and gamma-ray correlations.
- One of the brightest and most variable TeV IBL.
- An unprecedented VHE flare in February 2020 (no published results yet) triggered the VLBA observations.
- Forms part of the targetted sources in the Fermi GI proposal #12074 “Exploring the connection between superluminal jet components and gamma-ray flares in TeV blazars”

Motivation

- Rare IBL that can be detected at TeV gamma-ray energies on timescales of months.
- Gamma-ray and X-ray bands have exhibited more variability.
- Unprecedented gamma-ray flare from February 2020.
- VLBA observations have shown six moving knots and two superposed quasi-stationary knots.

Objectives

- Carry out data analysis on VER J0521+211, focusing on the gamma-ray flare data set of February 2020.
- X-ray, optical data analysis and TeV correlation.
- High-resolution kinematic study of blobs in radio emission.
- SED modeling.

Previous studies

- Discovery of a new TeV gamma-ray source: VER J0521+211 arXiv:1308.5017 (2013/10).
- Multiwavelength observations of the blazar VER J0521+211 during an elevated TeV gamma-ray state arXiv:2205.02808 (2022/06).
  - Observations between 2012 Nov and 2014 Feb, focusing on the TeV gamma-ray and X-ray behaviors.
- **VERITAS detection of a gamma-ray flare on 25 Feb 2020 (ATel # 13522).**
  - ATels on the February 2020 flare: ATel # 13522, ATel # 13528, ATel # 13532, ATel # 13548, ATel # 13727.

* No published studies so far about this flare.

VERITAS detection of unprecedented gamma-ray flare from the blazar VER J0521+211

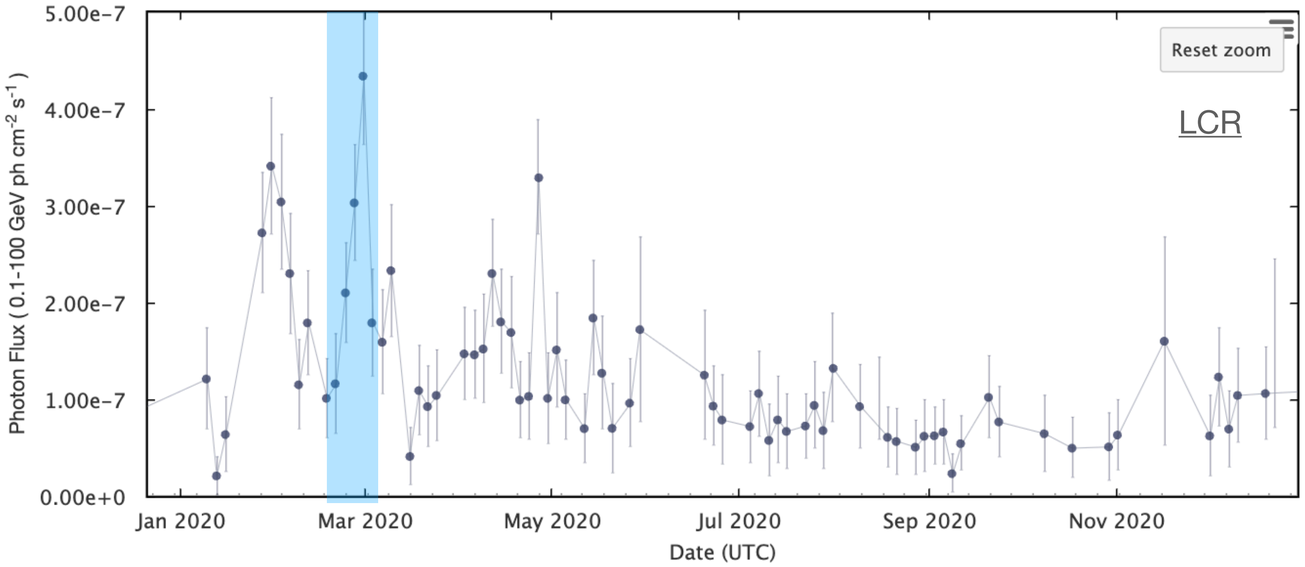
ATel #13522; *John Quinn (University College Dublin) for the VERITAS Collaboration*
on 25 Feb 2020; 20:25 UT
Credential Certification: Deirdre Horan (deirdre@llr.in2p3.fr)

ATel # 13522

Fermi-LAT detection of a hard GeV flare from the TeV source VER J0521+211

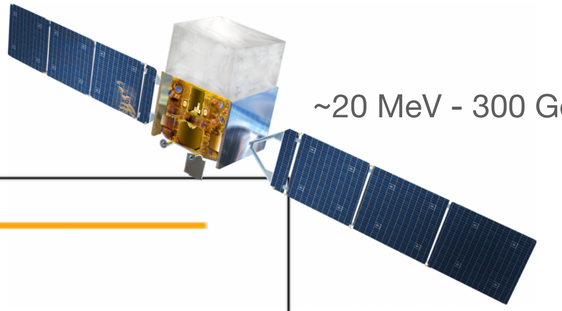
ATel #13528; *J. Sinapius (Univ. of Wuerzburg), R. Angioni (SSDC/INFN), and R. Ojha (NASA/GSFC/UMBC) on behalf of the Fermi-LAT Collaboration*
on 27 Feb 2020; 14:05 UT
Credential Certification: Roberto Angioni (r.angioni90@gmail.com)

ATel # 13528

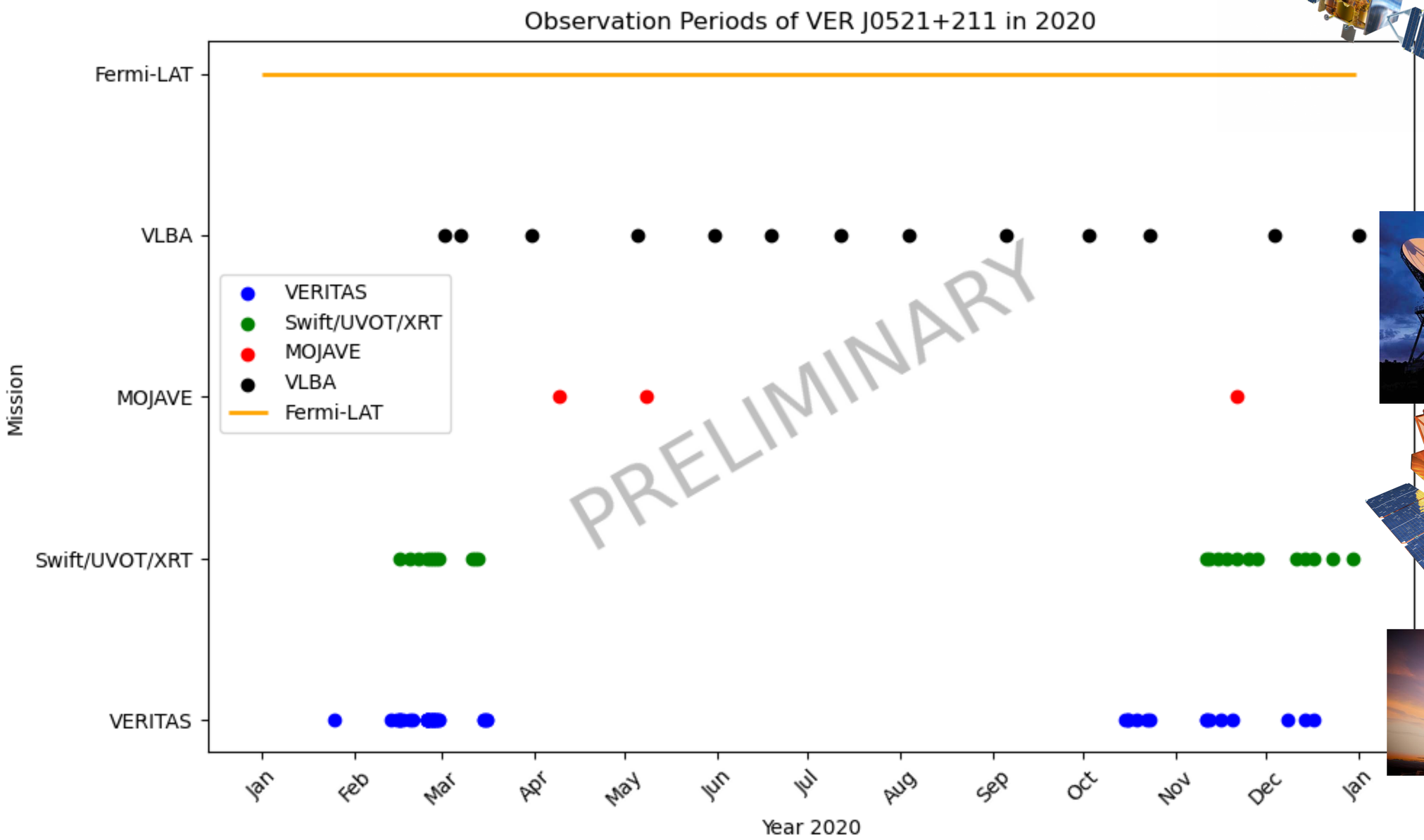


Daily average gamma-ray flux of $(4.2 \pm 1.4) \times 10^{-7}$ **ph cm^{-2} s^{-1}**
4 × 4FGL value
Photon index of 1.5 ± 0.2 (4FGL value 1.92 ± 0.01)

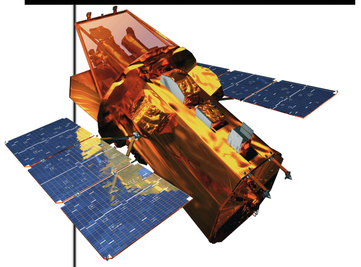
Observation dates



~20 MeV - 300 GeV



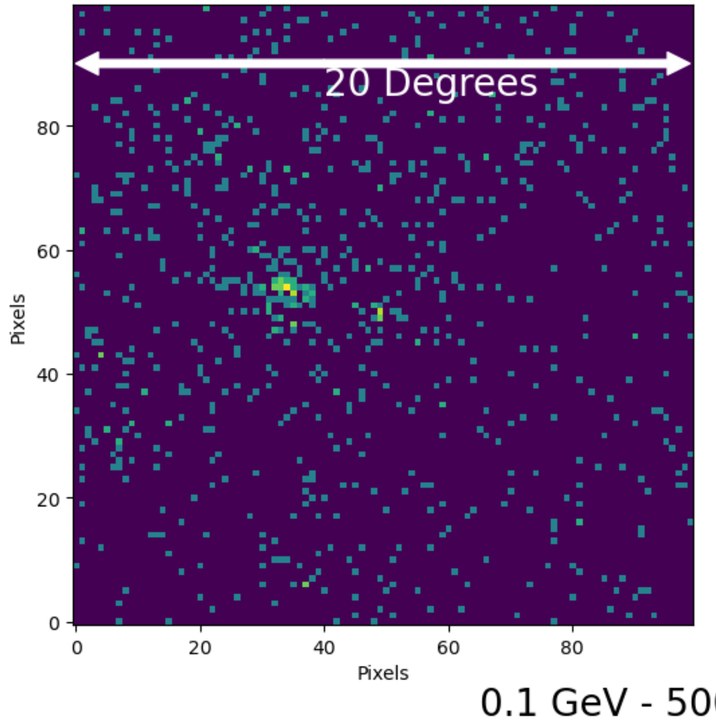
0.3 GHz -96 GHz



~0.2 - 150 keV

~85 GeV - 30 TeV

Fermi-LAT analysis settings

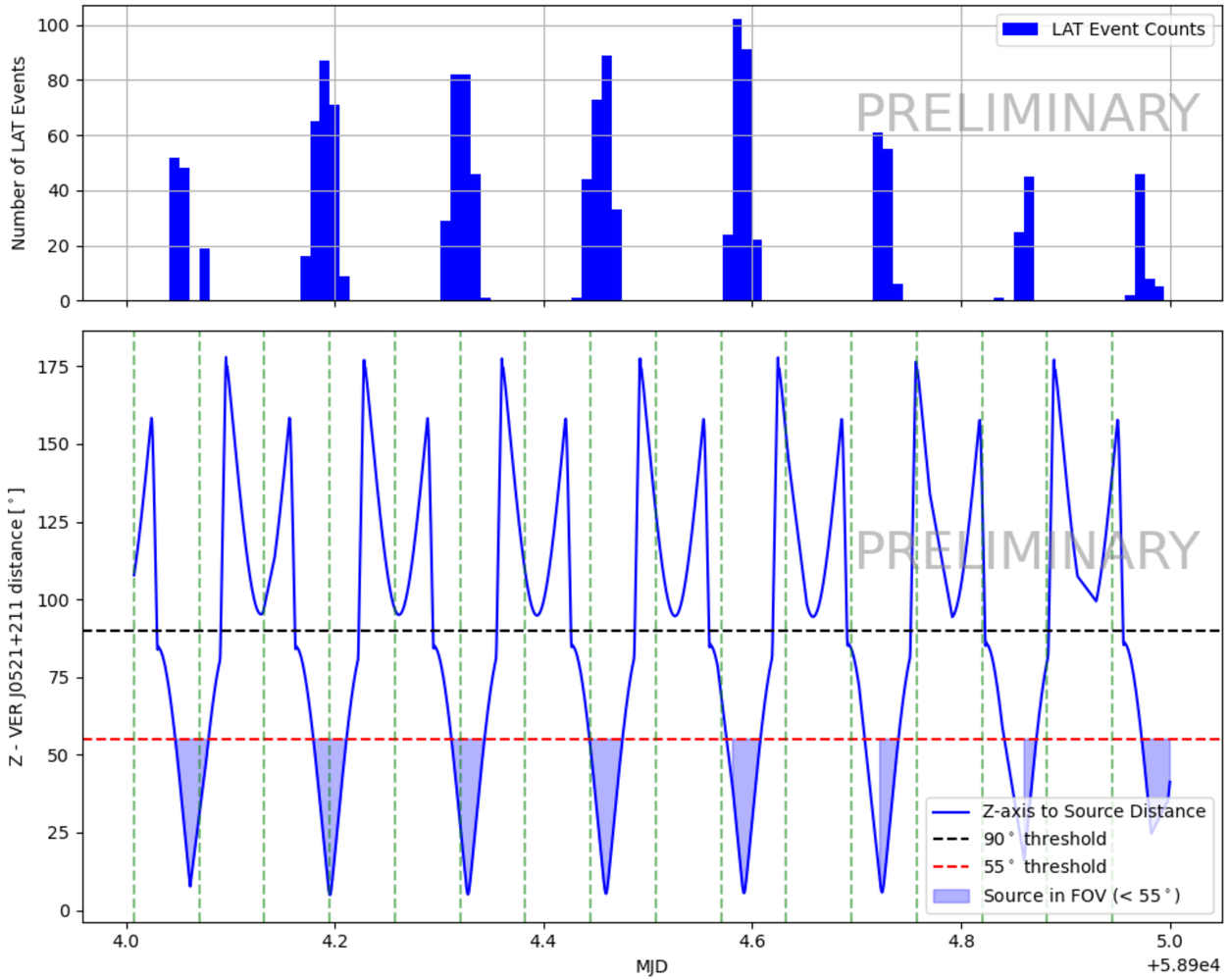


0.1 GeV - 500 GeV

RA: 80.445

DEC: 21.213

ROI size: 20°



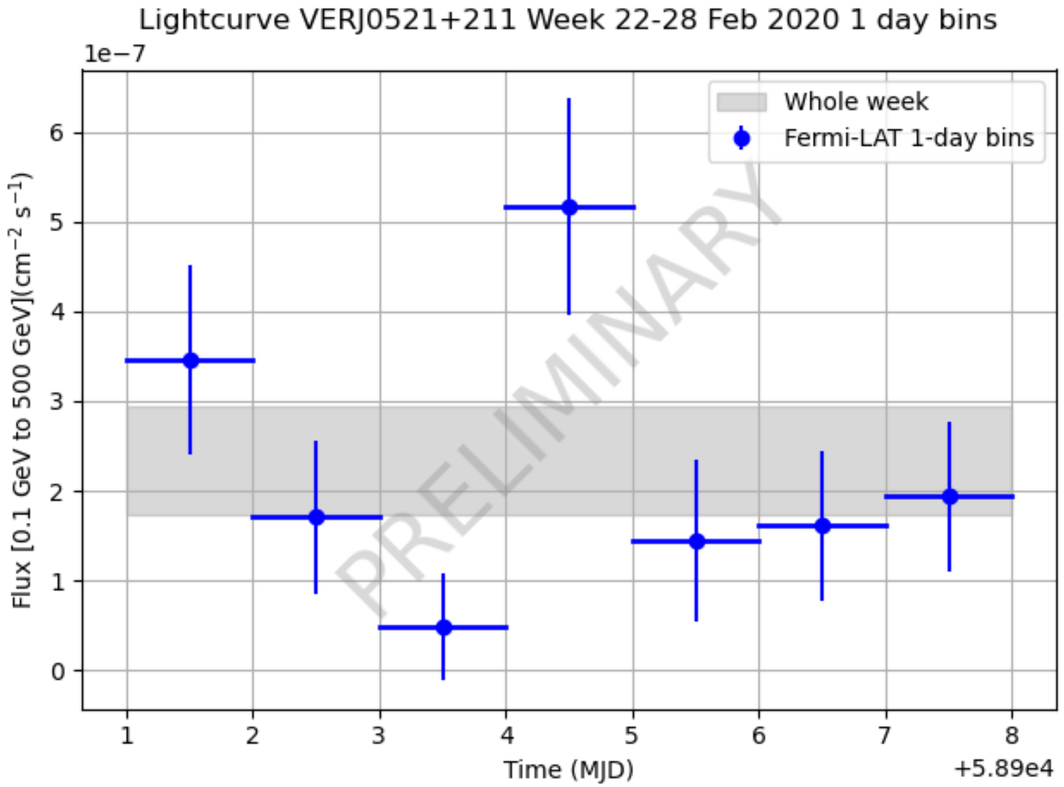
- Name: VER J0521+211.
- Catalog name: 4FGL J0521.7+211 (TXS 0518+211 LCR).
- Data set: Pass 8.
- Event class: 128.
- Energy range: 0.1 - 500 GeV.
- Time interval (light curve) [MET]: 604281605 - 604368004.
- Type: binned likelihood analysis.
- Zenith angle: < 90°.
- Time cuts filter: DATA_QUAL==1 && LAT_CONFIG==1.
- Diffuse emission: gll_psc_v32.xml.
- IRFS: P8R3_SOURCE_V3.
- Optimizer and tolerance: NewMinuit.

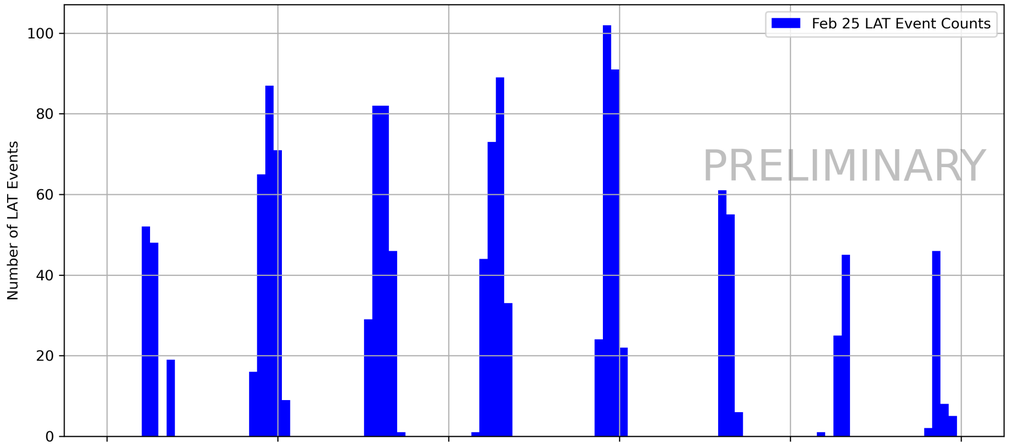
Flare day: Feb 25, 2020

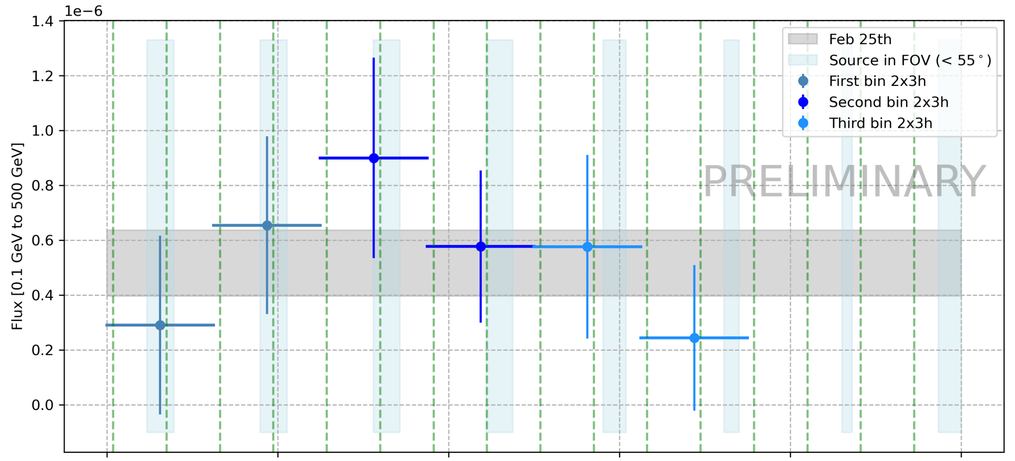
Light curve analysis:
TS = 101.2
Photon flux: $(5.16 \pm 1.20) \times 10^{-7}$ **ph cm^{-2} s^{-1}**

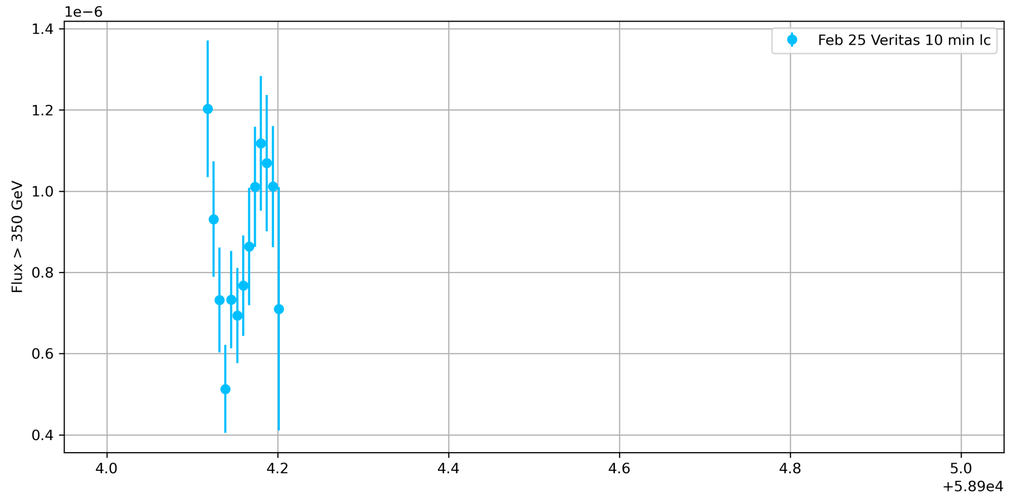
Freeing the spectral index:
TS = 103.94
Photon flux = $(3.72 \pm 1.25) \times 10^{-7}$ **ph cm^{-2} s^{-1}**
Photon index: 1.495 ± 0.161

Reported in ATel # 13528:
Photon flux: $(4.2 \pm 1.4) \times 10^{-7}$ **ph cm^{-2} s^{-1}** (**4** × 4FGL value)
Photon index of 1.5 ± 0.2 (4FGL value 1.92 ± 0.01)

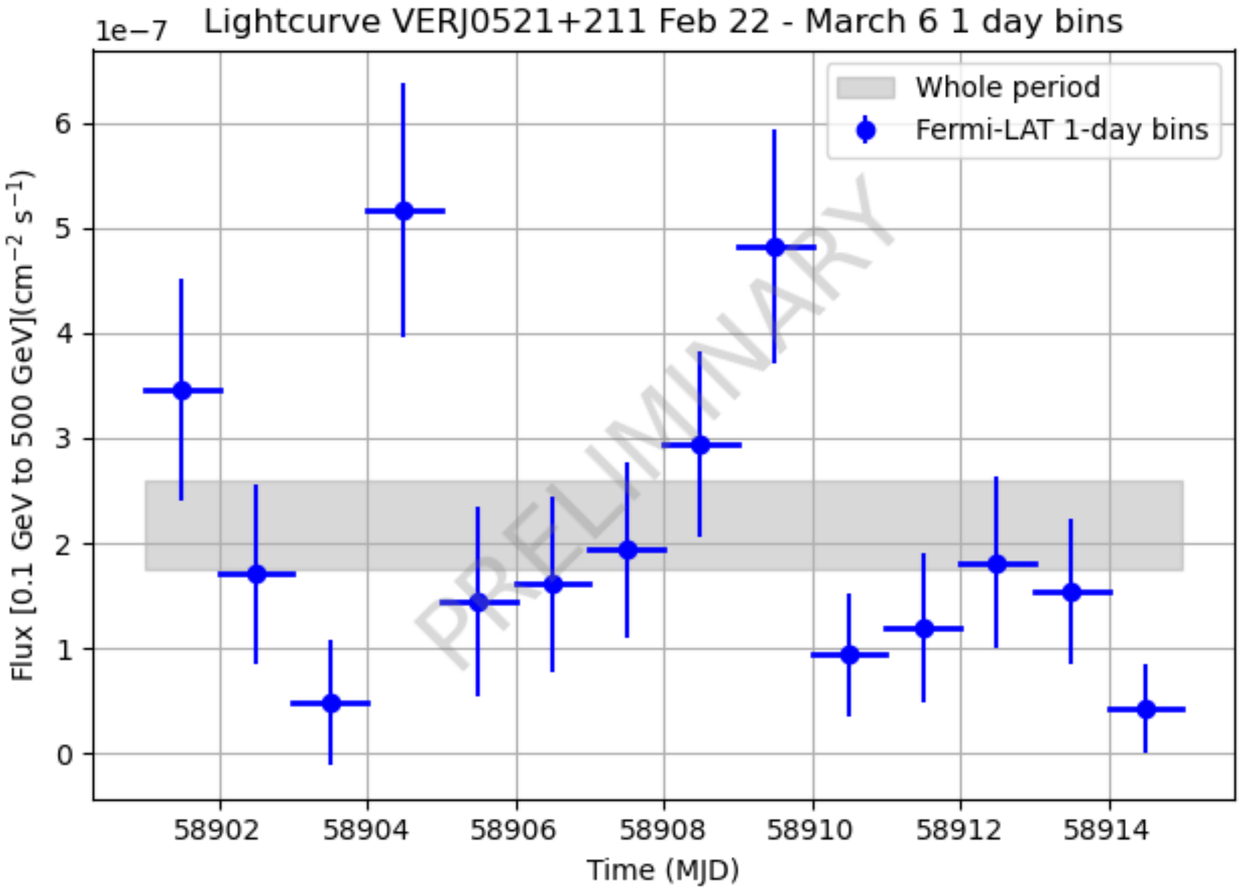


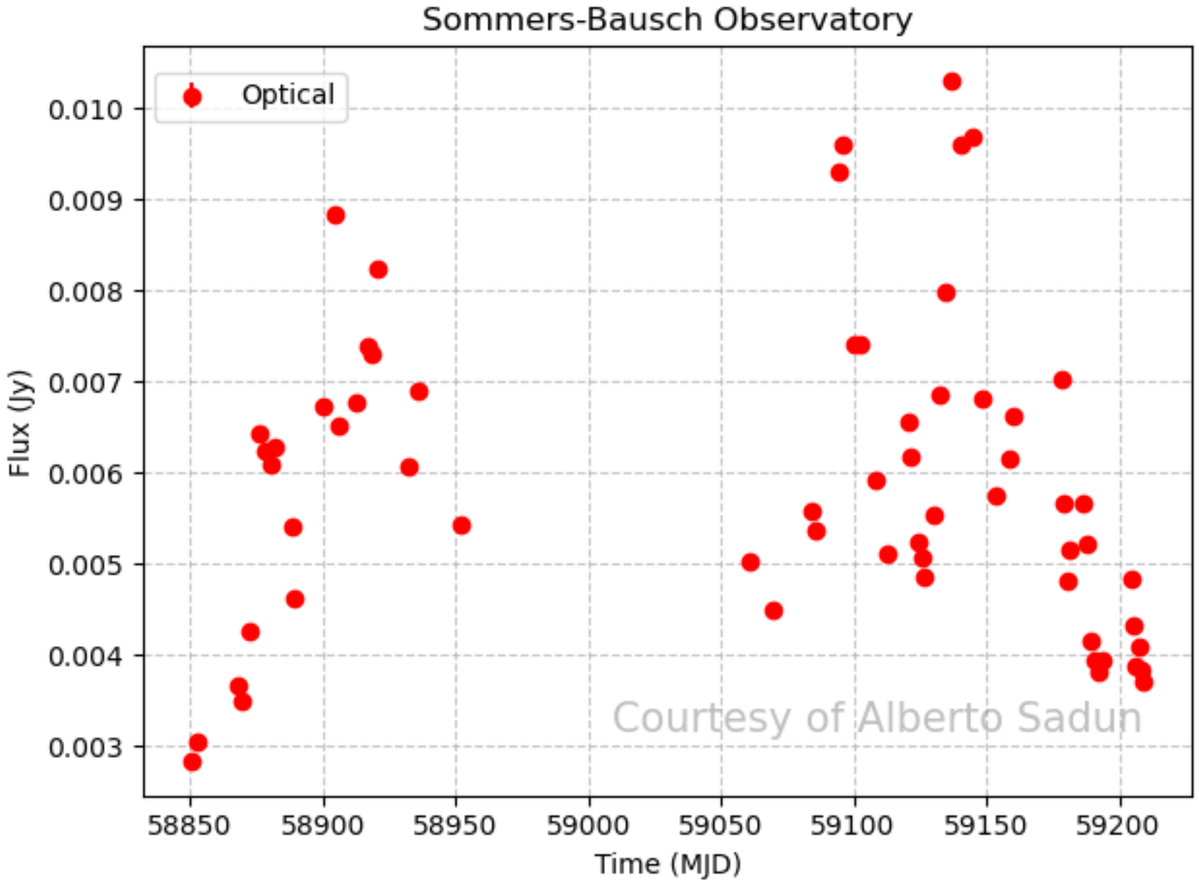






Feb 22- March 6, 2020





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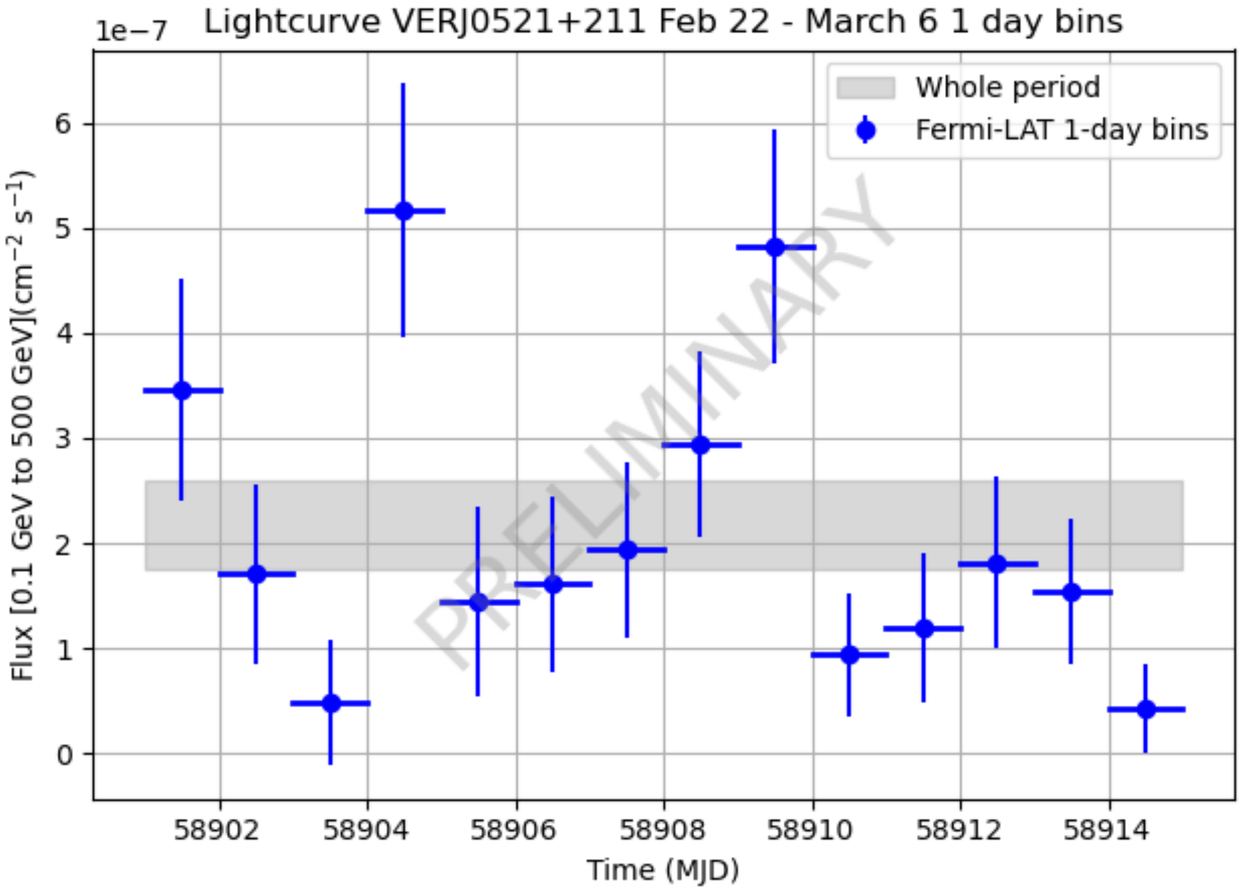

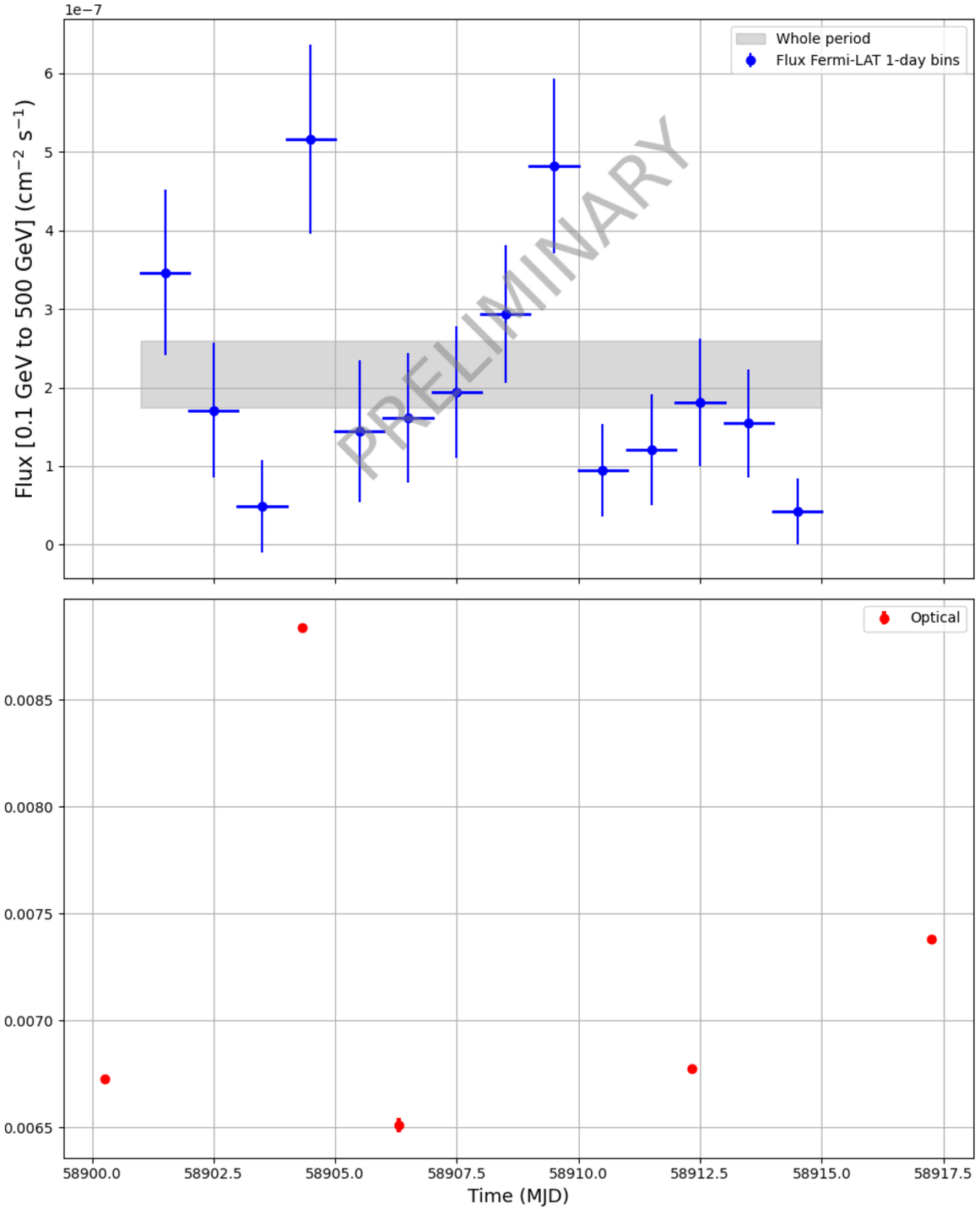

Future work

- Yearly Fermi-LAT light curve.
- VERITAS analysis for 2020 (all year).
- X-ray/Radio/TeV correlation.
- Add Bayesian Block analysis to identify high/low flux states to carry out SED modeling in high/low states.

…still to be determined…

Thank you!

Back-up

- ATel # 13528: Fermi-LAT detection of a hard GeV flare from the TeV source VER J0521+211 (2020/02/27).
  - Flux $(4.2 \pm 1.4) \times 10^{-7}$ ph cm^{-2} s^{-1} (E>100 MeV)
- ATel # 13522: VERITAS detection of unprecedented gamma-ray flare from the blazar VER J0521+211 (2020/02/25).
  - Flux ~130% Crab (E > 100 GeV)
- ATel # 5472: Fermi-LAT Detection of a Bright GeV Flare from VER 0521+211 (2013/10/15).
  - Flux $(1.0 \pm 0.3) \times 10^{-6}$ ph cm^{-2} s^{-1} (E>100 MeV)
- ATel # 2309: VERITAS reports a high gamma-ray flux from VER J0521+211 (2009/11/23).
  - Flux 15-20% Crab (E>100 GeV).
- ATel # 2260: VERITAS discovery of a new VHE gamma-ray source, VER J0521+211 (2009/10/25).
  - Flux ~5% Crab (E>200 GeV).

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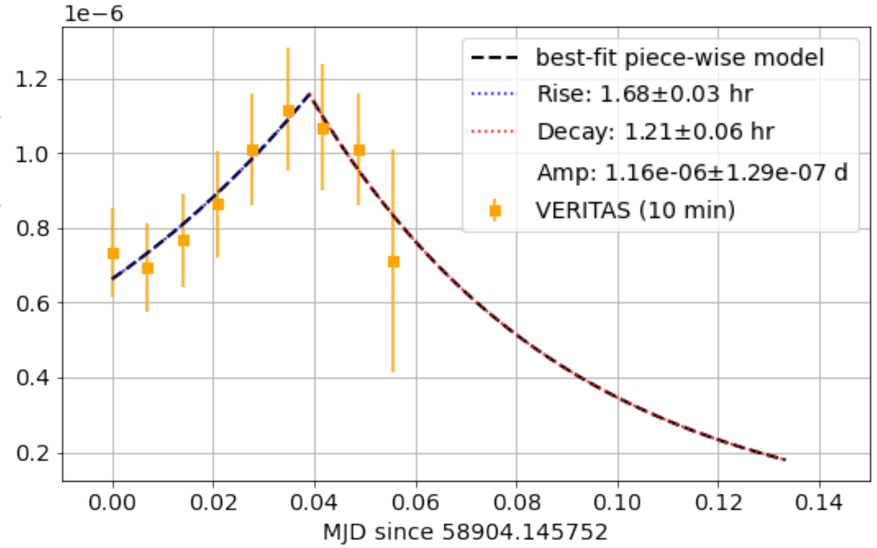
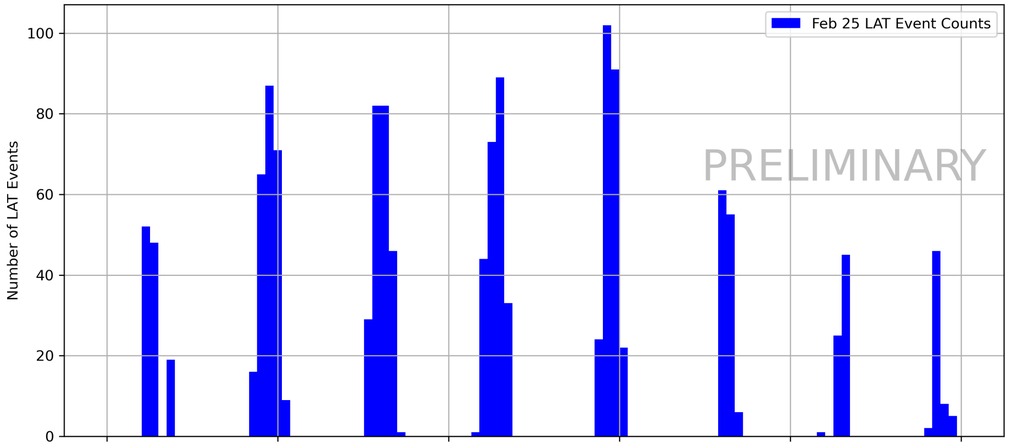
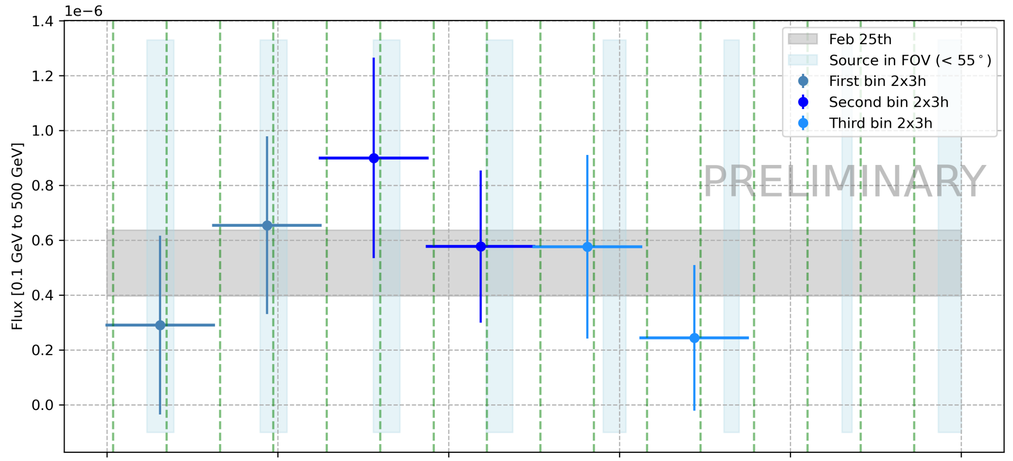
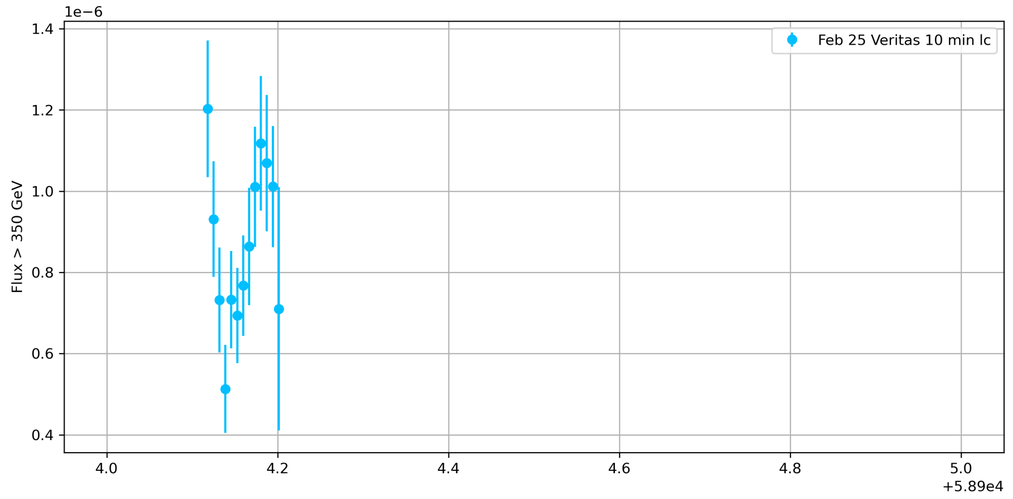


Light curve (**10-minute bins**) showing the integral flux > 350 GeV for VER J0521+211 on **February 25th, 2020**. Start MJD 58904.117975 = 2020-02-25 02:49:53.040 UTC, end MJD 58904.201308 = 2020-02-25 04:49:53.011 UTC. Leela Chari VEGAS 2022 re-analysis.

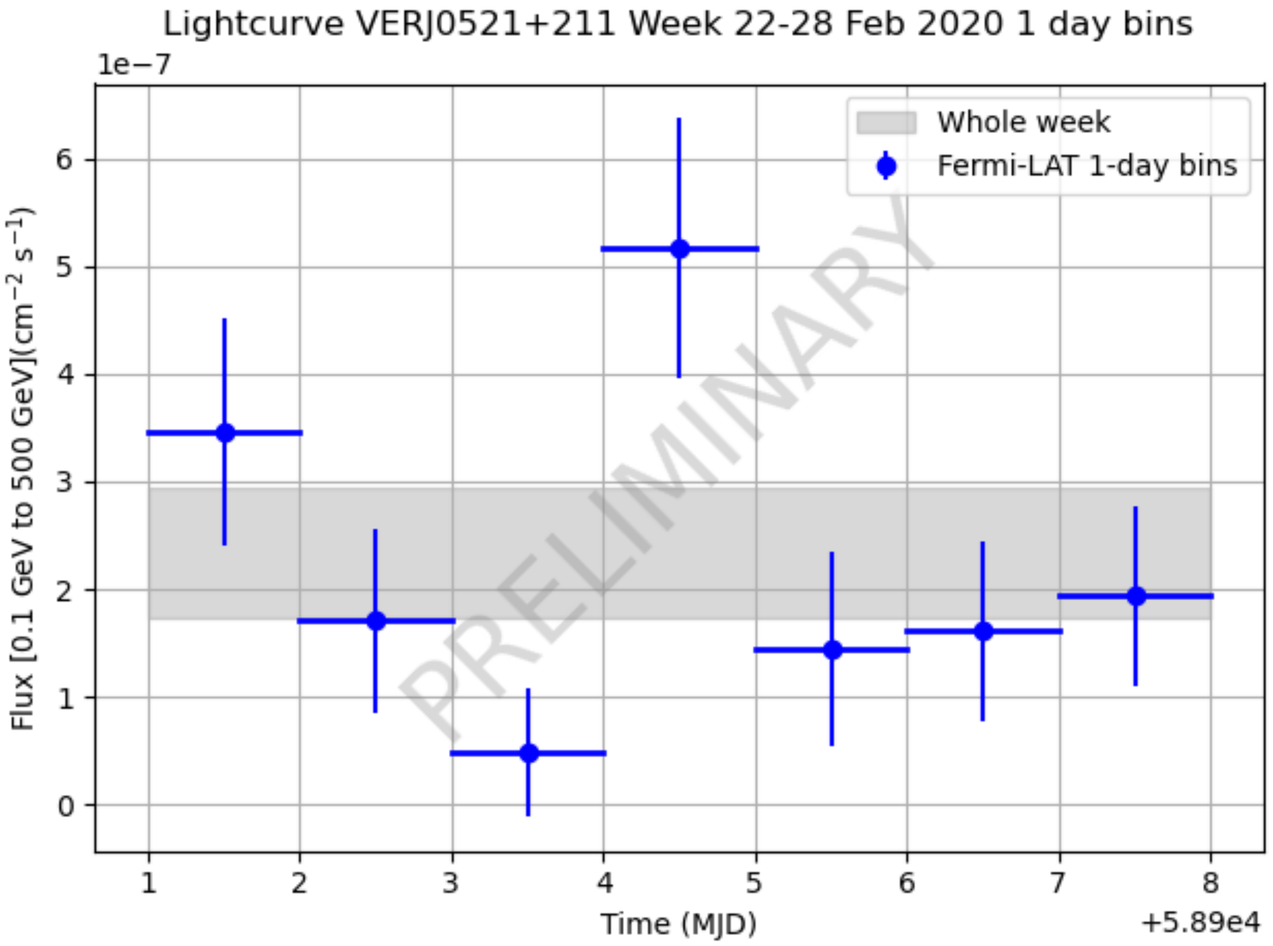
Bin	TS	Flux $(10^{-7}$ ph cm^{-2} s$^{-1})$	Flux_err $(10^{-7}$ ph cm^{-2} s$^{-1})$
1	1.30	2.90	3.26
2	25.69	6.54	3.24
3	**28.33**	**8.99**	**3.65**
4	25.40	5.76	2.77
5	20.78	5.76	3.35
6	2.41	2.441	2.65







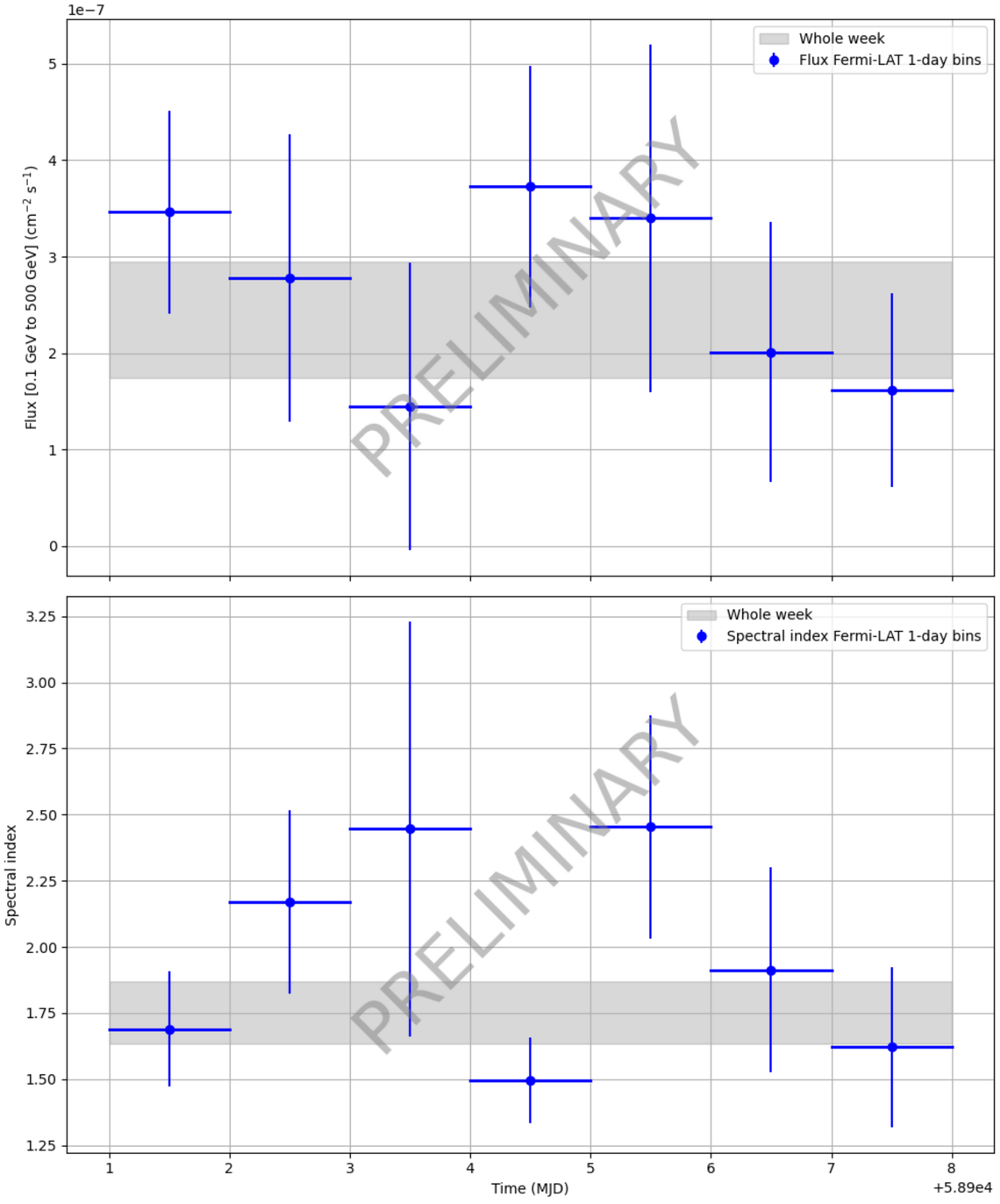
Week of Feb 22-28, 2020



TS = **182.74**

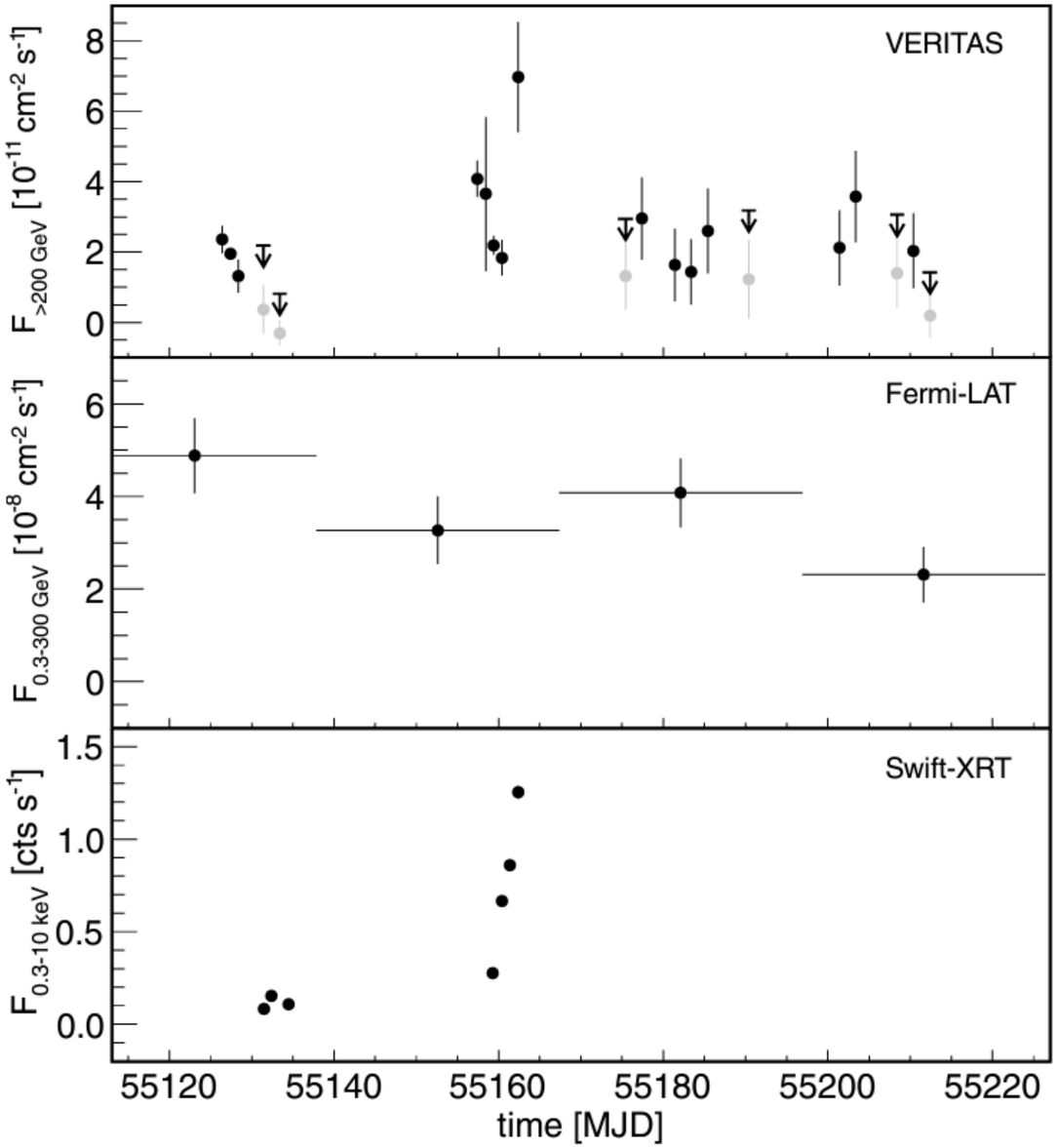
Photon flux: $(2.343 \pm 0.601) \times 10^{-7}$ ph cm^{-2} s^{-1}

Freeing the spectral index of VER J0521+211

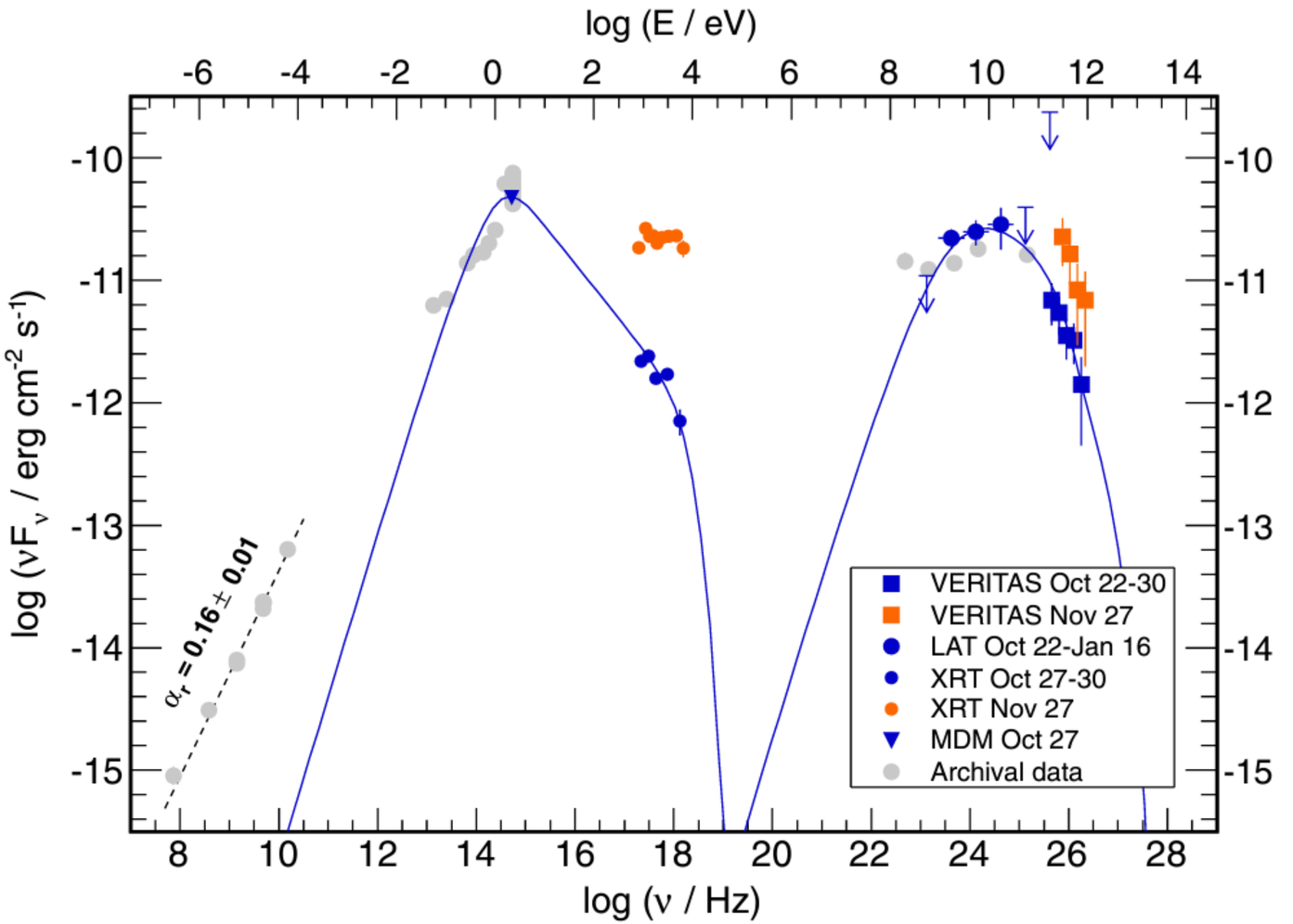


Discovery of a new TeV gamma-ray source: VER J0521+211

- Astrophys.J. 776 (2013) 69 by the VERITAS collaboration and other authors.
- VERITAS detected a new TeV source: VER J0521+211, spatially associated with the radio and X-ray source RGB J0521.8+2112. Follow-up observations in the optical and X-ray bands unambiguously identify VER J0521+211 as a new blazar of the BL Lac type blazar with uncertain redshift, although recent measurements suggest z = 0.108.
- The detected TeV emission is variable on daily timescales with an integral flux of ~0.09 – 0.33 Crab measured between 0.2 and ~1 TeV.
- Observing campaign from Oct 2009 to January 2010. X-ray observations show a trend of spectral hardening with increasing flux, while no significant spectral variability was found at TeV energies.
- With a TeV flux between 0.09 and 0.33 Crab, VER J0521+211 ranks among the brightest known TeV blazars, and can be detected with current ground-based Cherenkov telescopes in less than one hour exposure.



VERITAS (E > 0.2 TeV), Fermi-LAT (0.1-300 GeV), and Swift/XRT (0.3-10 keV) light curves of VER J0521+211. Photon fluxes are calculated in 1-day bins for VERITAS and Swift/XRT, and 29.5 days for Fermi-LAT.



Spectral energy distribution of VER J0521+211 during the VERITAS detection. Optical, X-ray, GeV, and TeV data are shown for the low emission state (blue markers) and for the X-ray and TeV flare on 2009 November 27 (orange markers). A dashed black line shows the fit of the radio data to a power law $F_\nu \propto \nu^{-\alpha}$. The solid blue curve represents a one-zone SSC emission model with parameters adjusted to describe the low-state data, assuming z = 0.1.

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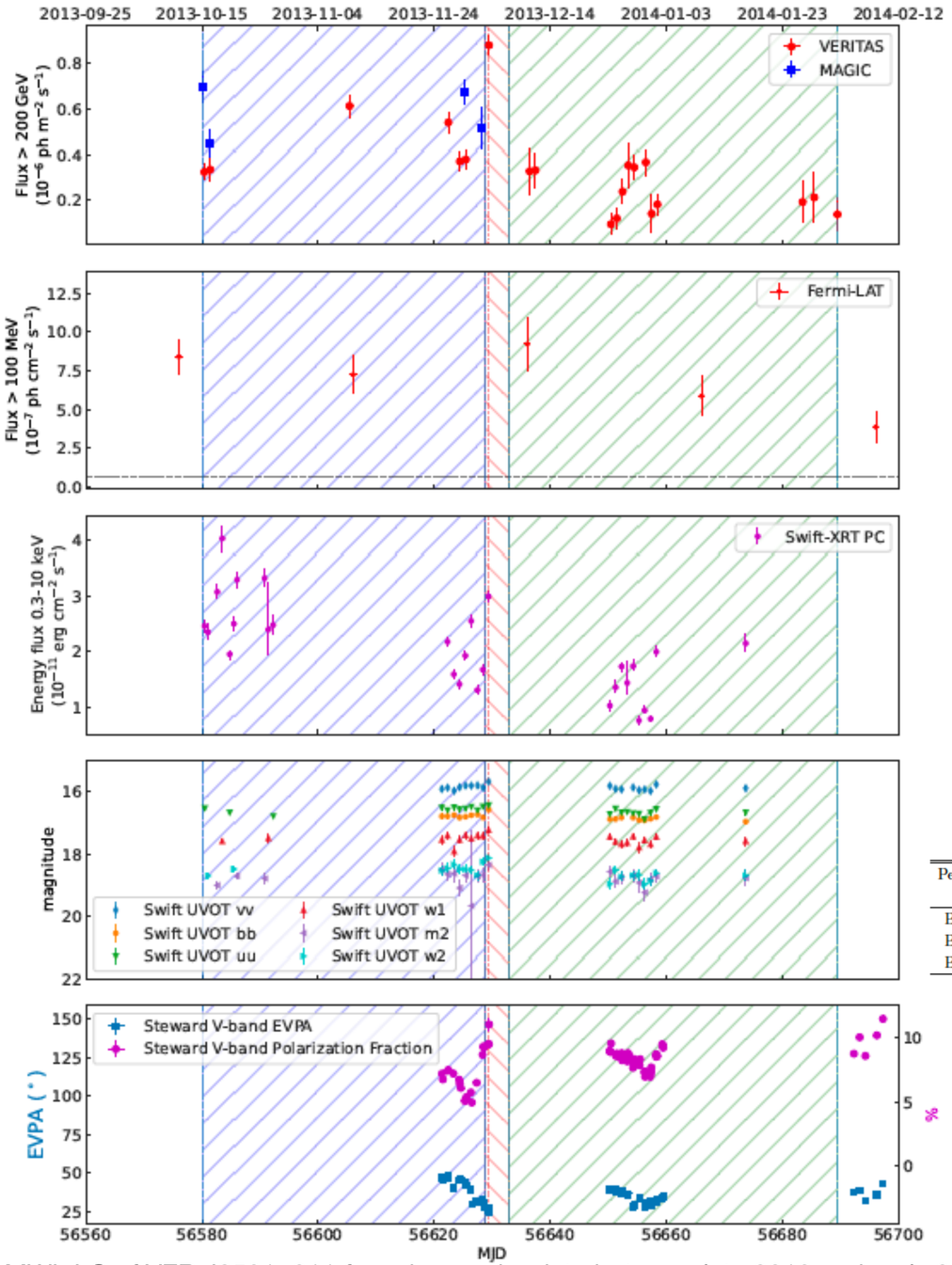
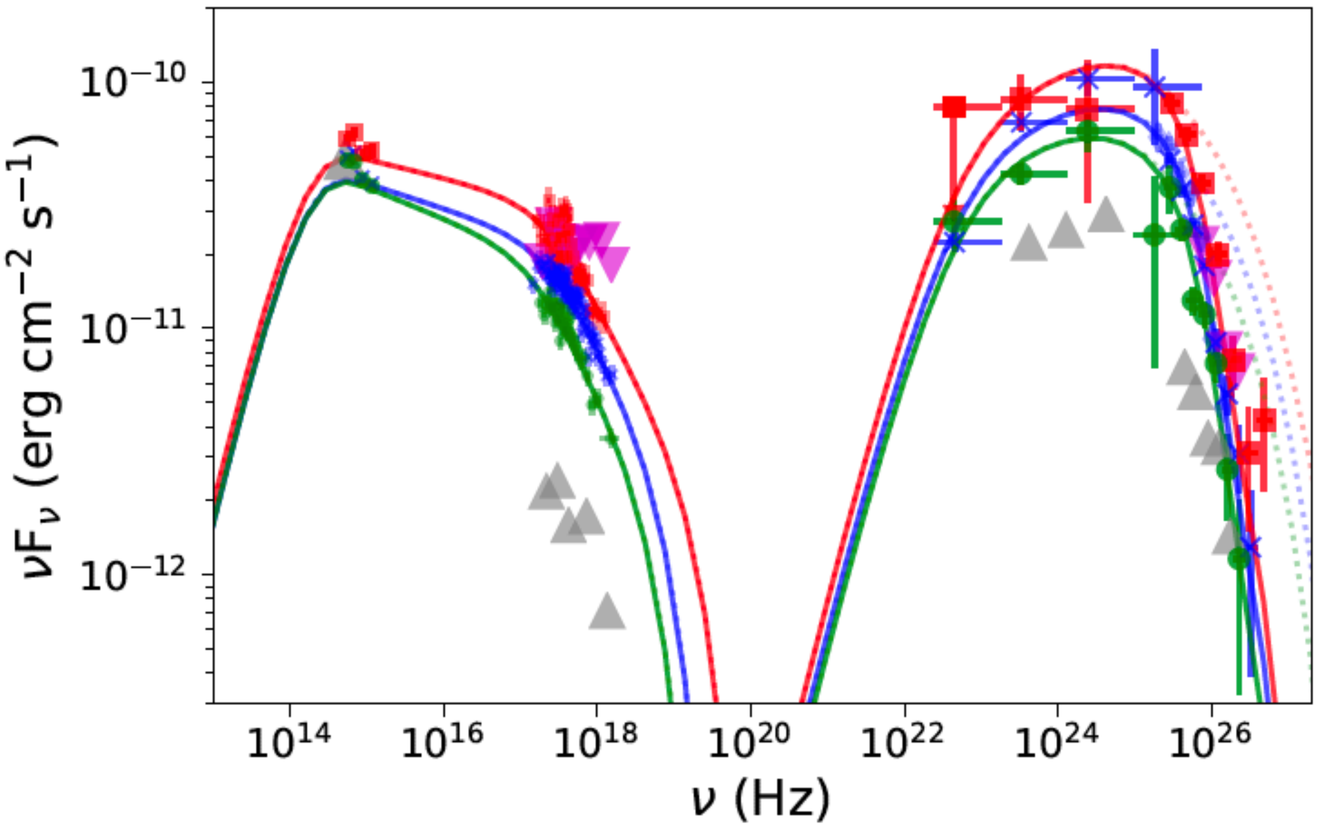
Multiwavelength observations of the blazar VER J0521+211 during an elevated TeV gamma-ray state

- The Astrophysical Journal, Volume 932, Number 2 2022 by the VERITAS and MAGIC collaborations.
- Results from MWL observations between **2012 Nov** and **2014 Feb**, focusing on the TeV (> 200 GeV) gamma-ray and X-ray behaviors.
- Using the gamma-ray spectrum and four models of the EBL, they found an upper limit of $\mathbf{z \leq 0.31}$ (95% CL).
- The peak integral flux above 200 GeV measured with the nightly binned lc is $(\mathbf{8.8 \pm 0.4}) \times \mathbf{10^{-7}}$ ph $m^{-2}s^{-1}$ or $\sim \mathbf{37}\,\%$ of the Crab Nebula flux and the monthly GeV flux above 100 MeV remained higher than **7** times the 3FGL catalog for a period that lasted one year.
- 32 Swift-XRT observations in the period of interest, 28 in PC mode between 2023 Oct and 2014 Feb, and 4 in WT mode in 2012 Nov.
- Swift-UVOT was used in some of the observations during the time period of interest.
- Fermi-LAT unbinned likelihood analysis covering the period of the TeV observations. Sources within 20° only leaving the normalization free for those within 5° from the source and fixed the parameters to the 3FGL catalog.
- Observed by MAGIC on four nights between 2013 Oct and 2013 Dec, ~4.5 hours on Oct 15-16, Nov 29 and Dec 2.
- VERITAS from 2012 Nov to 2014 Feb, ~23.6 h.
- VER J0521+211 was monitored in the V-band by the Steward Observatory. There were 76 observations on 37 nights between 2013 Nov 25 and 2014 April 1 (used publicly available V-band polarimetry results).
- Results point out to the source being an IBL object during the flaring state in 2013.



MWL LC of VER J0521+211 focusing on the data between late 2012 and early 2014 (1σ). The vertical dashed lines and the hatch fills illustrate the three Bayesian blocks [1].

Period	Start MJD	End MJD	Flux (>200 GeV) 10^{-7} photon m^{-2} s^{-1}
BB1	56580.0	56628.5	4.1 ± 0.1
BB2	56628.5	56632.5	8.8 ± 0.4
BB3	56632.5	56689.0	2.7 ± 0.2



Broadband SED during the three Bayesian blocks obtained from the VERITAS lightcurve in the 2013 to 2014 season. Data are from Swift-UVOT, Swift-XRT, Fermi-LAT and MAGIC (only for BB1, blue-filled diamonds) and VERITAS [1].

State	Γ	θ deg	B 10^{-2} G	R 10^{17} cm	w_e 10^{-3} erg cm^{-3}	log $\frac{E_{min}}{eV}$	log $\frac{E_{max}}{eV}$	log $\frac{E_{break}}{eV}$	p_1	p_2
BB1	25	2.2	1.5	1.01	1.32	9.7	12.0	11.25	3.2	4.2
BB2	25	2.2	1.5	1.05	1.45	9.7	12.2	11.25	3.15	4.15
BB3	25	2.2	1.5	1.1	1.0	9.7	11.9	11.15	3.25	4.25
2009[1]	30	-	0.25	4.0	-	10.25	12.0	-	3.0	-

[1] Archambault et al. (2013).

[1] C. B. Adams *et al* 2022 *ApJ* **932** 129