A Gamma-ray View on AGN Variability

Reshmi Mukherjee

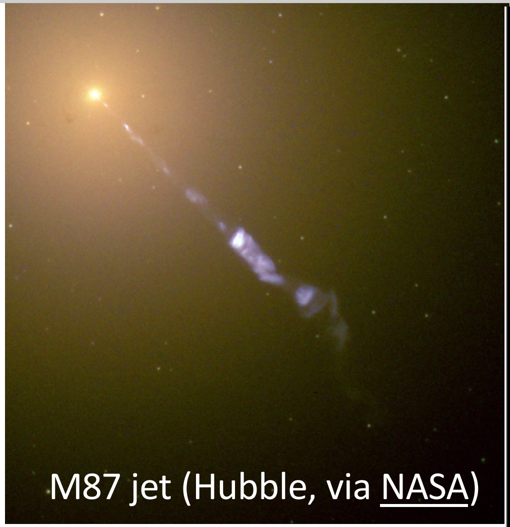
Barnard College, Columbia University, NY

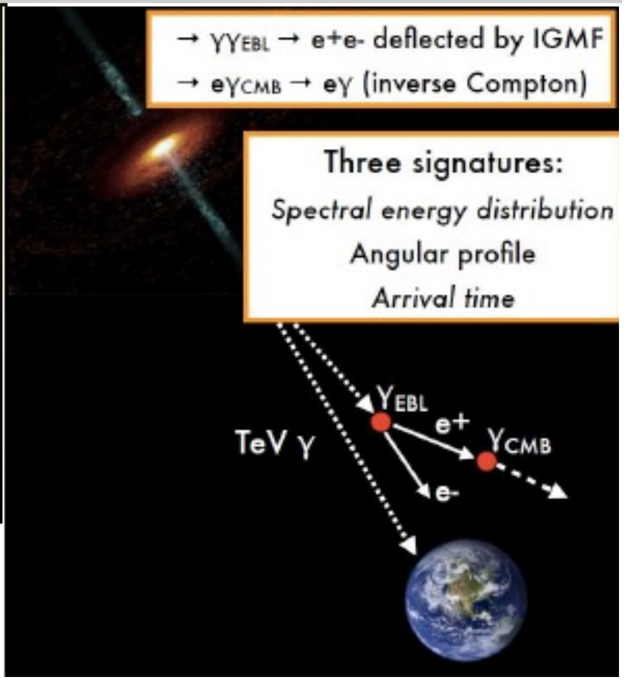
Variability of astrophysical sources across the wavelengths, a tribute to Berrie

November 2025, Pascal Institute, Orsay

Active Galaxies – Unique Probes

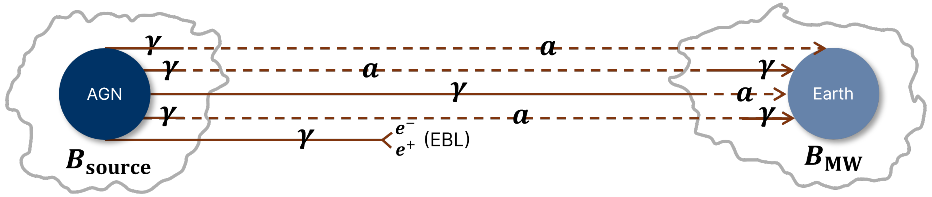
- γ rays are a **product of their source environments**
  - Particle acceleration in extreme astrophysical environments (intense gravitational or magnetic fields)
    - Physics and astrophysics of Supermassive Black Holes.
    - Relativistic outflows with shocks/reconnection (winds, jets)





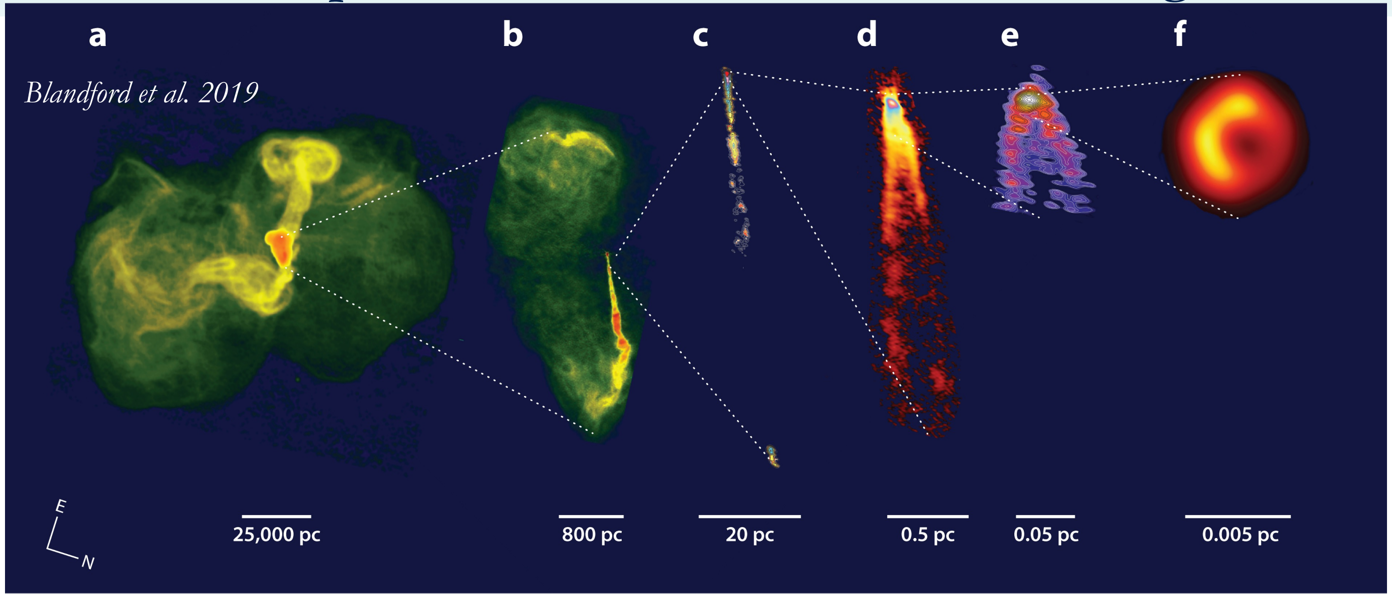
- γ rays **probe the environments they pass through**
  - Explore intergalactic space
    - Extragalactic background light (EBL) measurements
    - Intergalactic magnetic fields

- Exploring **fundamental physics topics**
    - Lorentz Invariance Violation (LIV)
    - Nature of Dark Matter → Mixing with theoretical axion-like particles (ALPs)



Extragalactic Jets: Regime of relativistic plasmas

The pervasive nature of the jet of M 87, one of the closest AGN (20 Mpc) –
BH in M87 - impact observable over 6 decades in length scale

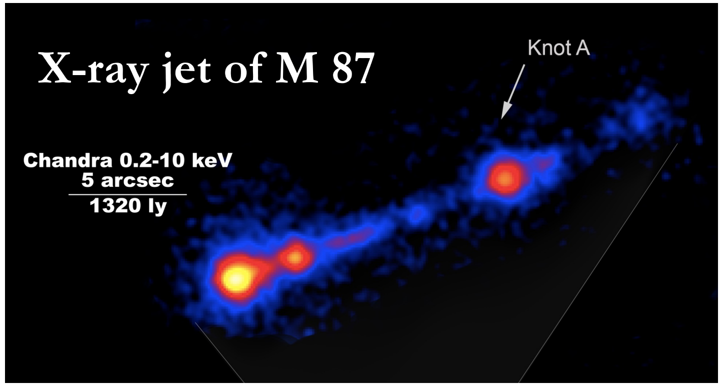


Blandford R, et al. 2019.
Annu. Rev. Astron. Astrophys. 57:467–509

- Resolved radio jets seen in radio galaxies, quasars, and low-frequency peaked BL Lacs
- Origin of fast flares? Physics of particle acceleration & relativistic reconnection? Blazars as neutrino sources?
- Minimum timescales of variability inform different jet emission models
- Brightest flares offer best chances to observe significant rapid variability

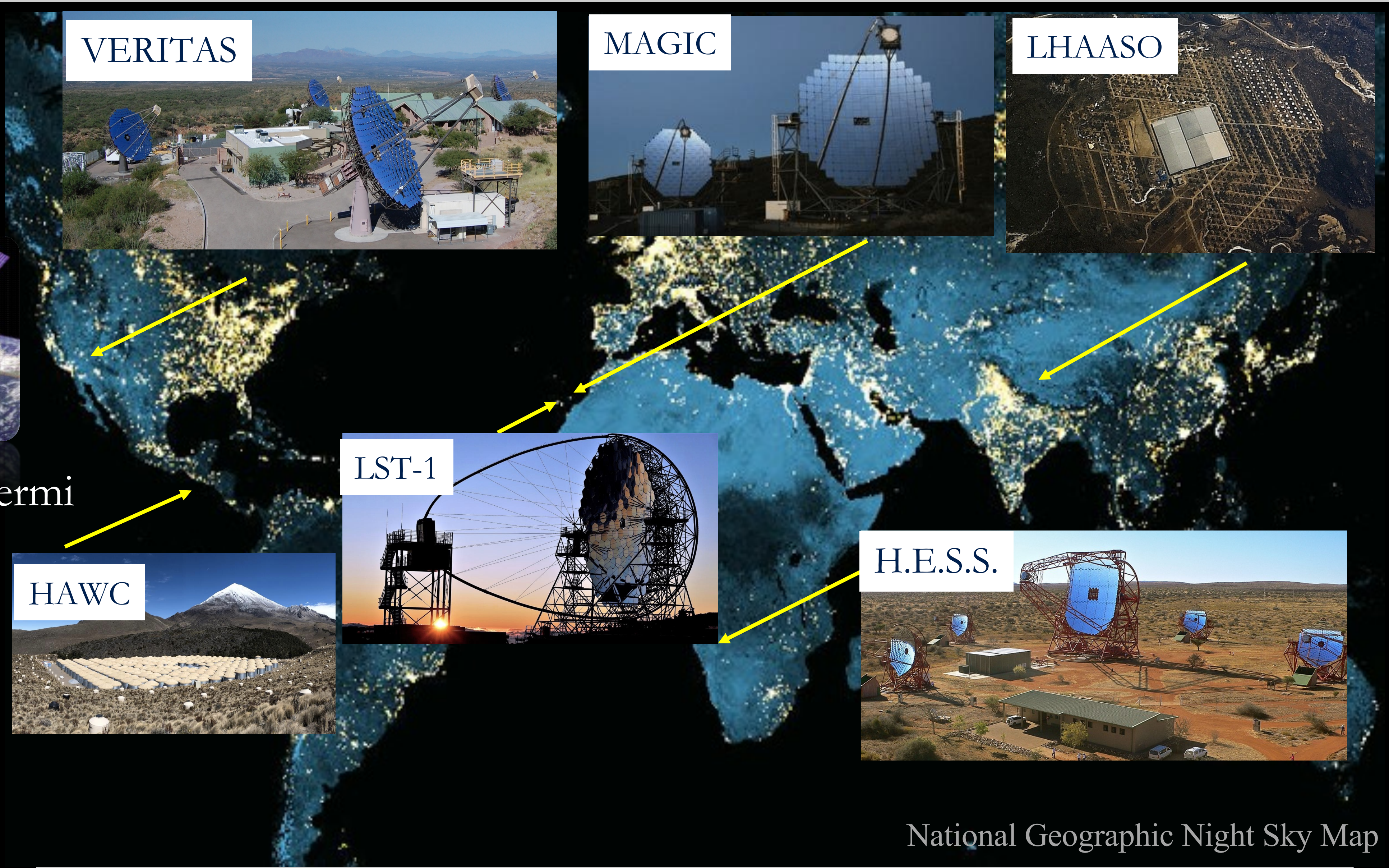
- Large detection areas IACTs ~10^5 m^2 make it possible to sample the γ–ray light curves with ~ min time resolutions
- Correlation studies at mm is important

$$R \leq c\tau_d\delta/(1+z)$$

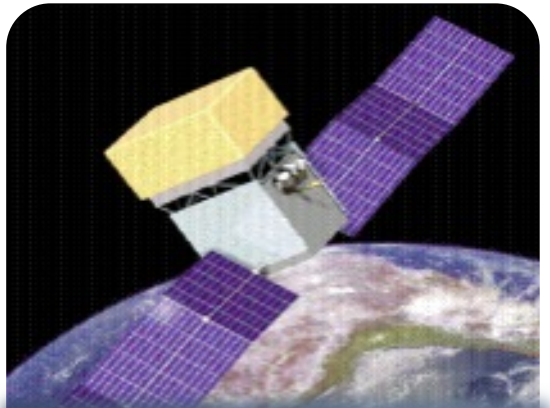


The Gamma-ray Instruments (2025)

Satellites: Fermi



Gamma-Ray Instrument Synergies

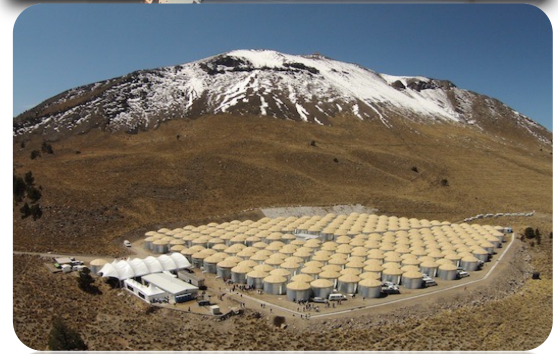


Low-energy threshold - Satellites ~~EGRET~~, Fermi-LAT, ~~AGILE~~: ~20MeV to ~ 300 GeV

Sky survey, transients

High sensitivity – Current IACTs H.E.S.S., MAGIC, VERITAS: 10s GeV to > 30 TeV

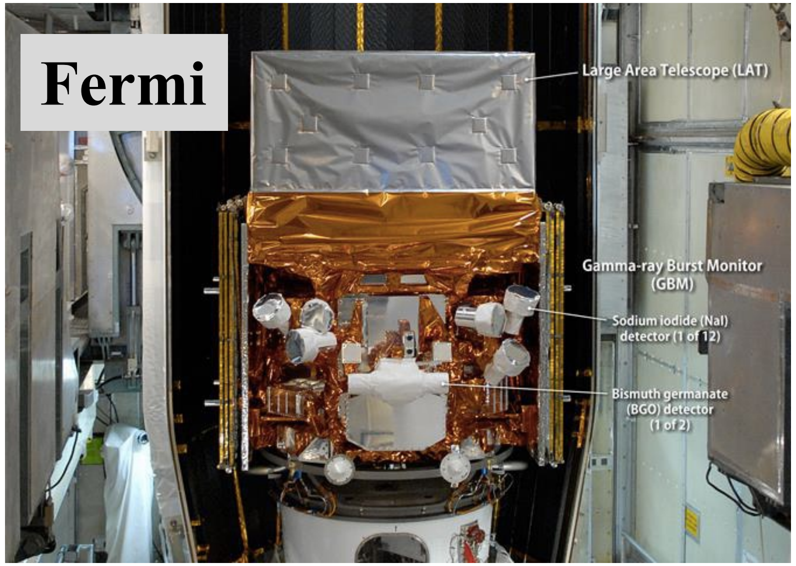
Exceptional sensitivity, but limited field of view, high resolution energy spectra, transients



Large-FoV arrays - HAWC, Tibet ASg, LHAASO: ~ 0.1 to 100 TeV

High duty cycle, extended sources, transients, serendipitous

In Space … Connection to GeV



Fermi:
Large Area Telescope*: 20 MeV ~ >300 GeV
Gamma-ray Burst Monitor: 8 keV – 30 MeV

(At LLR, Berrie led the development of the mechanical structure of the LAT calorimeter, and worked on the early beam tests of the calorimeter at SLAC and CERN)

AGILE: (archival data now)
Gamma-ray imager: 50 MeV – 30 GeV
Hard X-ray imager (18-60 keV)

Fermi-LAT FoV
LAT ~ 2.2 sr
GBM ~ 8.5 sr
Chandra ~ 10^{-4} sr

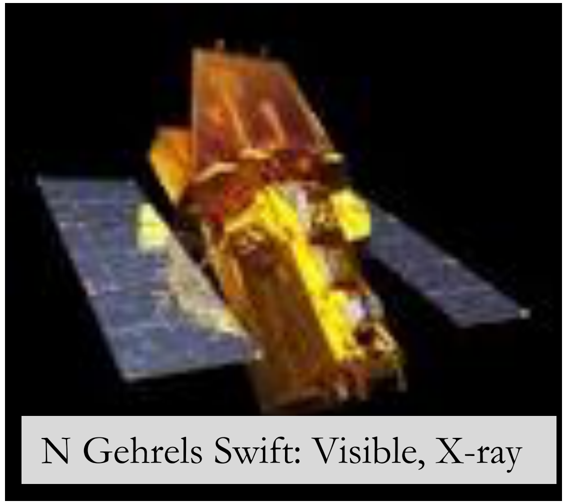
Fermi-LAT PSF
LAT (100 MeV) ~ 12000”
LAT (10 GeV) ~ 360”
Chandra ~ 1”

The Broad Energy Band: 100 MeV – 100 TeV

- Key is the multi-waveband monitoring of sources
- Combined spectrum at GeV-TeV, spectral features, tell us about spectral breaks, particle acceleration
- Particle content of blazar jet: Hadronic vs l
- What is the highest energy emi ource?

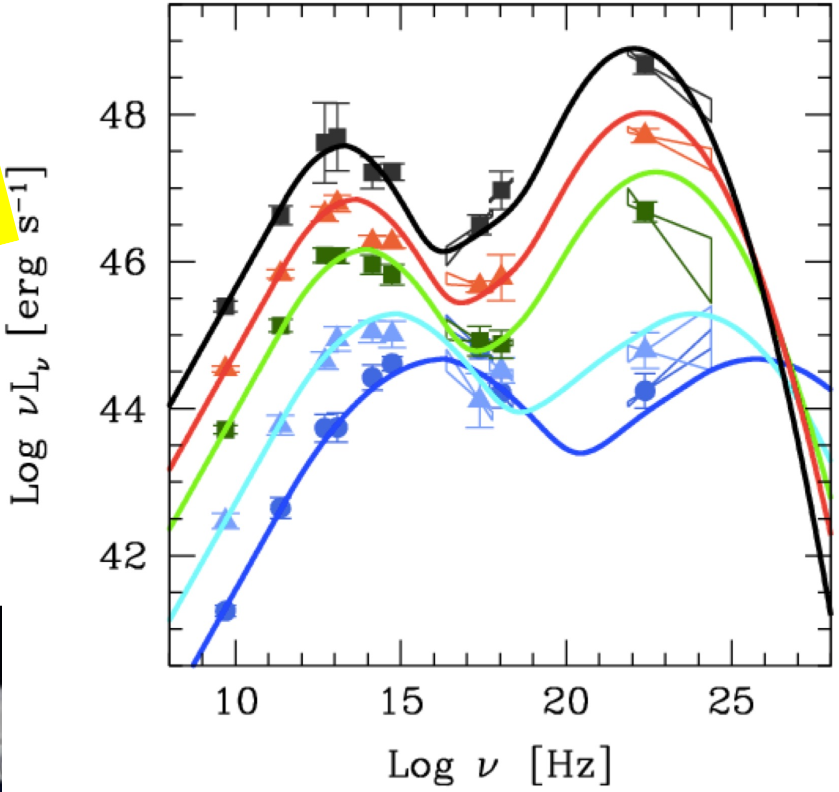
(See Talk by Greg Madejski)

Particularly important to have broad coverage, beyond γ-rays


N Gehrels Swift: Visible, X-ray

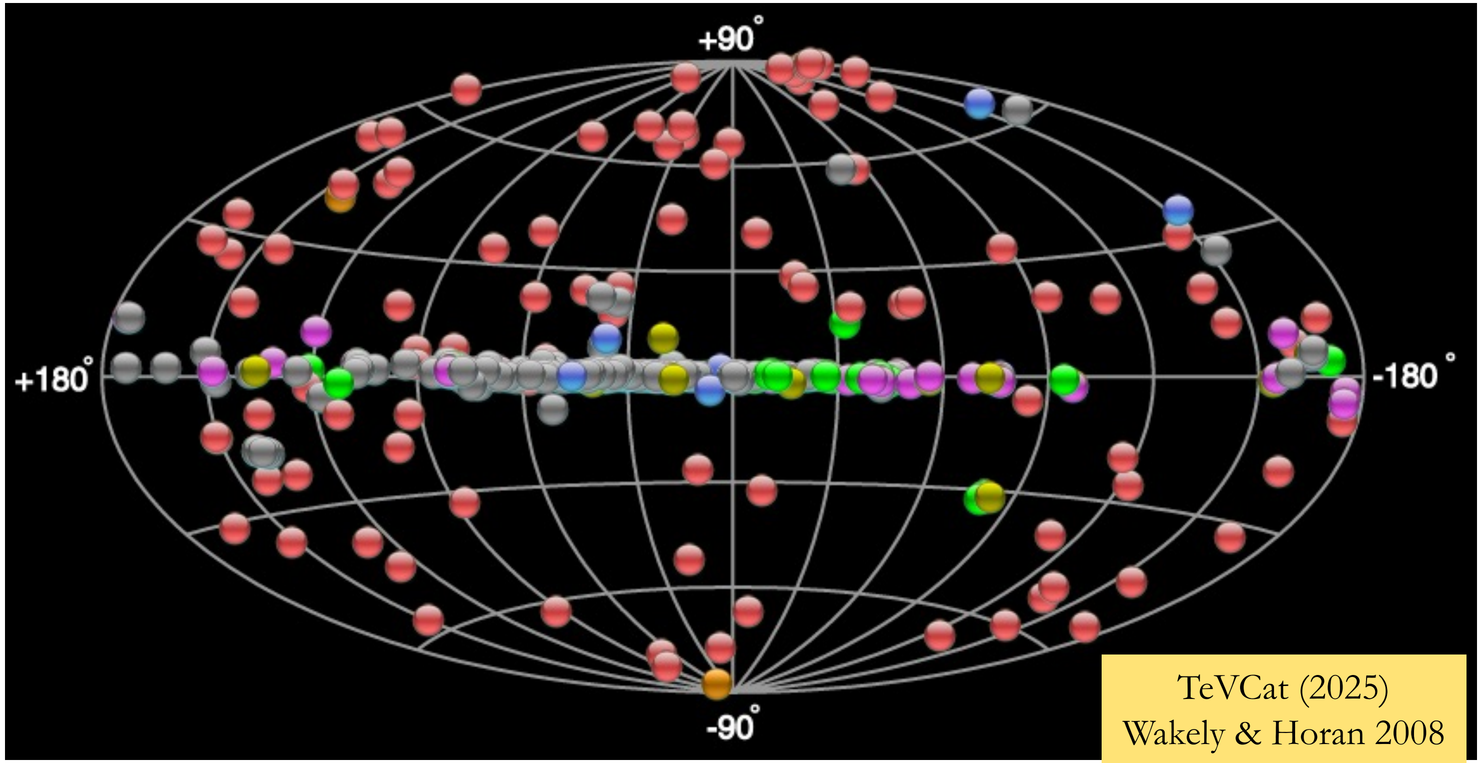

NuStar: 3-79 keV


IXPE: 2-8 keV, Polarimetry



Sambruna 1996; Fossati et al. 1998

VHE (TeV) Gamma-Ray Sky (2025)



Source Types

- PWN TeV Halo PWN/TeV Halo TeV Halo Candidate
- XRB Nova Gamma BIN Binary PSR
- HBL IBL GRB FSRQ LBL AGN (unknown type) FRI Blazar
- Shell Giant Molecular Cloud SNR/Molec. Cloud Composite SNR Superbubble SNR
- Starburst
- DARK UNID Other
- Star Forming Region Globular Cluster Massive Star Cluster BIN uQuasar Cat. Var. BL Lac (class unclear) WR

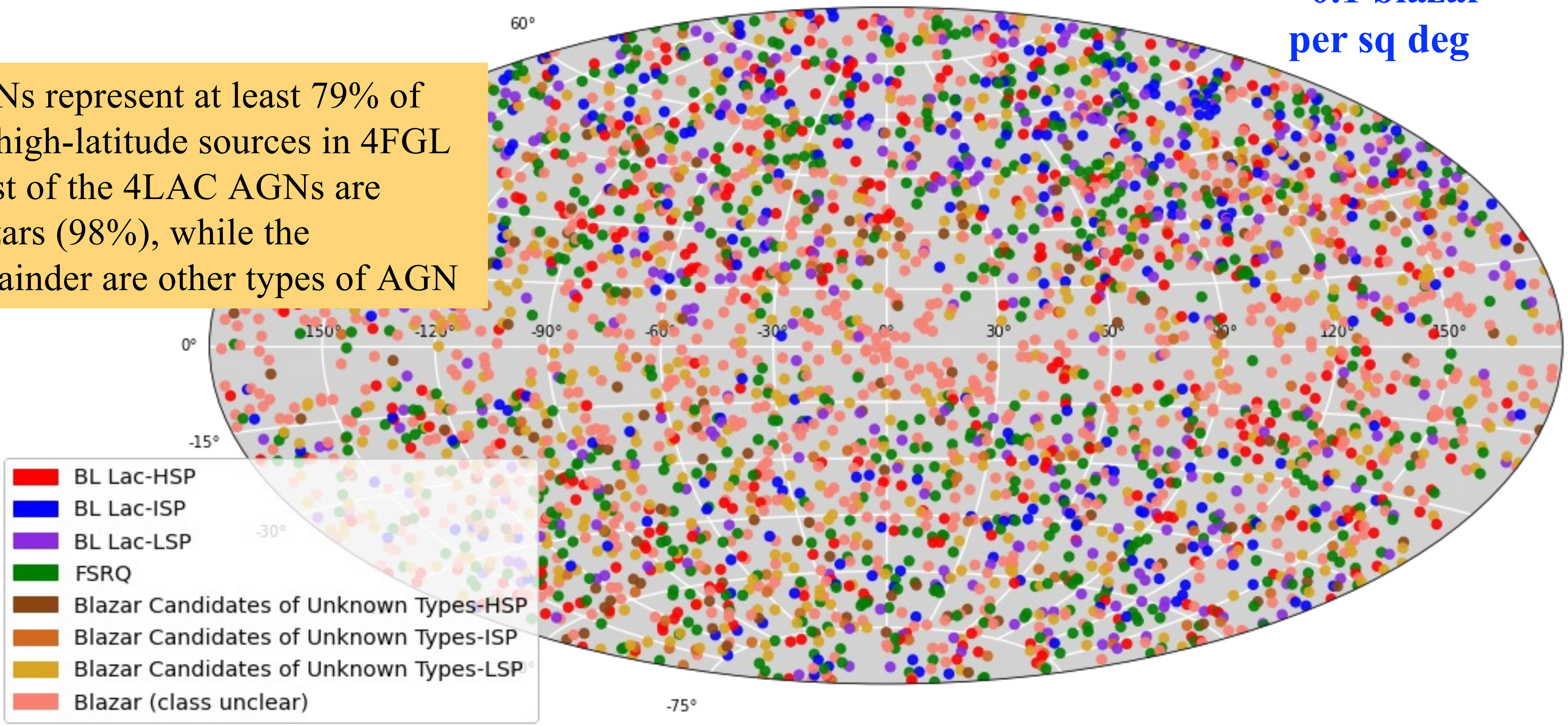
- 10 different source classes, > 300 sources
- More than 90 extragalactic sources
  - Expansion of radio galaxy counts
  - Detection of starburst galaxies
  - **GRBs detected as TeV sources (after a > 15 yr search)**
- Detection of powerful and ultrashort flares of AGN (Fermi, IACTs)

The Extragalactic GeV γ-ray Sky: Blazars

"4LAC" Catalog Fermi-LAT (2020)

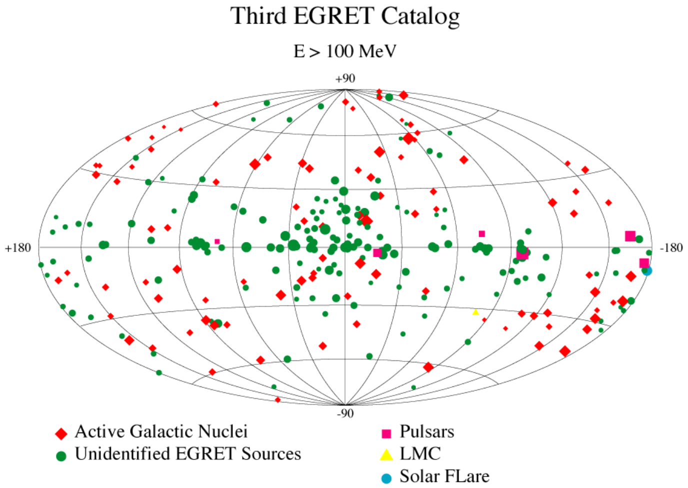
~0.1 blazar per sq deg

- AGNs represent at least 79% of the high-latitude sources in 4FGL
- Most of the 4LAC AGNs are blazars (98%), while the remainder are other types of AGN

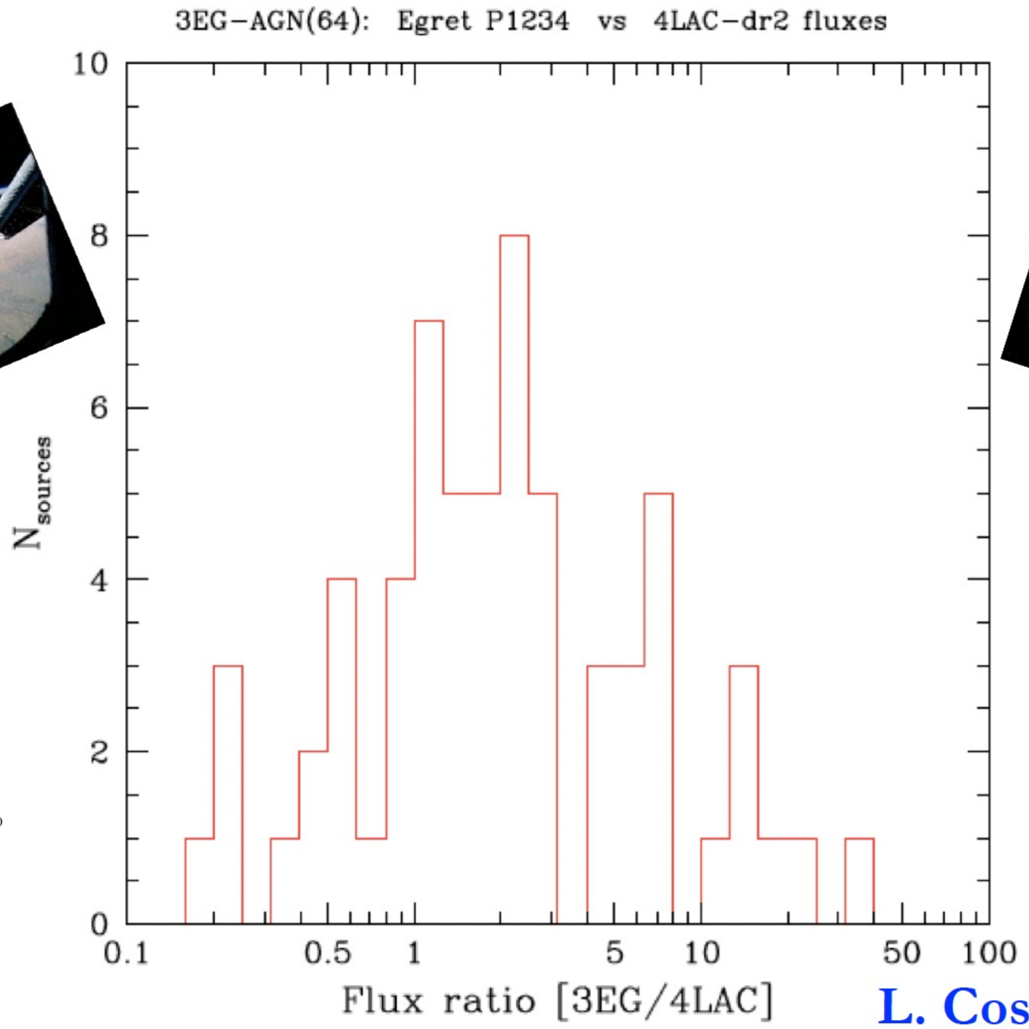


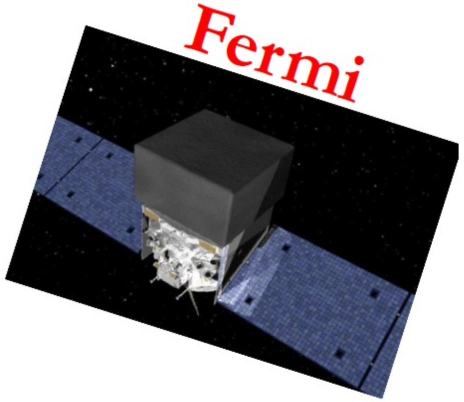
- **Fermi-LAT 14yr (4FGL-DR4): ~ 3900 γ-ray blazars**
- **HESS, MAGIC, VERITAS: ~ 90 blazars**

EGRET - Fermi-LAT : not the same sky



Hartman et al, 1999 ApS



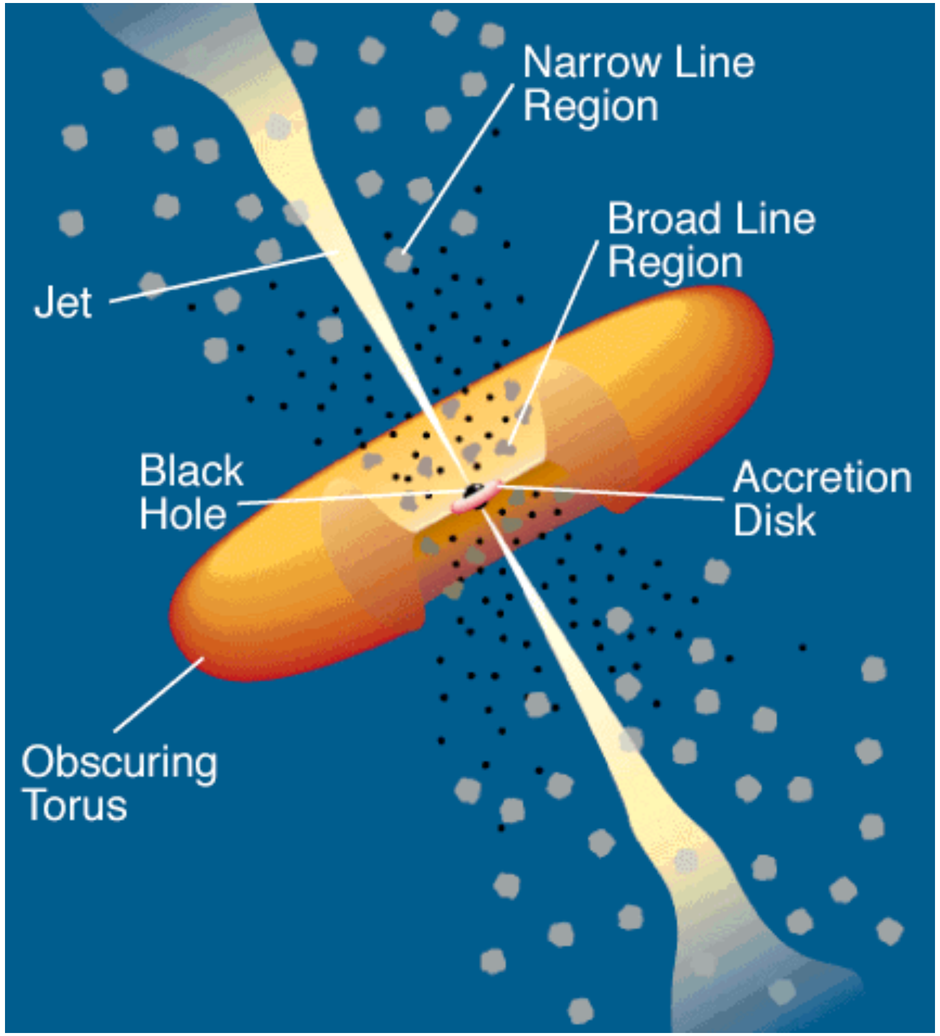


Some sources are ~1-2 orders of magnitude brighter in EGRET than Fermi ➔ Decadal variations from average emission in blazars

L. Costamante, CDY

https://cdy-institute.ie/index.php/events/

Extragalactic γ-ray Sources: Blazars



Urry & Padovani 1995

Physics of Compact Objects: AGN scales

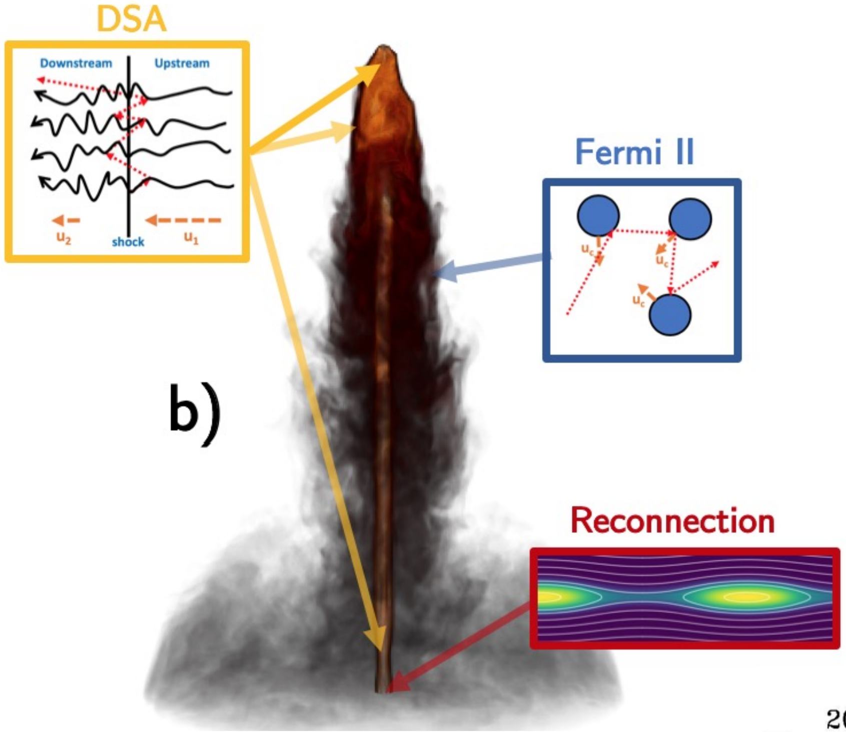
- Active galactic nuclei occupy a tiny fraction of a galaxy
  - $R_G \sim 10^4$ pc
  - $R_{tor} \sim 1$ pc
  - $R_{BH} \sim 10^{-5}$ pc

- Blazars constitute the largest TeV & GeV extragalactic source populations
- May exhibit ultra short time variability (~min scales)
- Could have extremely hard ($>E^{-1.5}$) energy spectra
- Jet power exceeds Eddington luminosity. High γ-ray
- luminosity ~ 10^{48} erg/s (isotropic)

- **GeV-TeV particles are needed to make VHE γ-rays**
- **Doppler boosting allows γ-rays to be detectable from >100 Mpc sources**

Extragalactic γ-ray Sources: Blazars

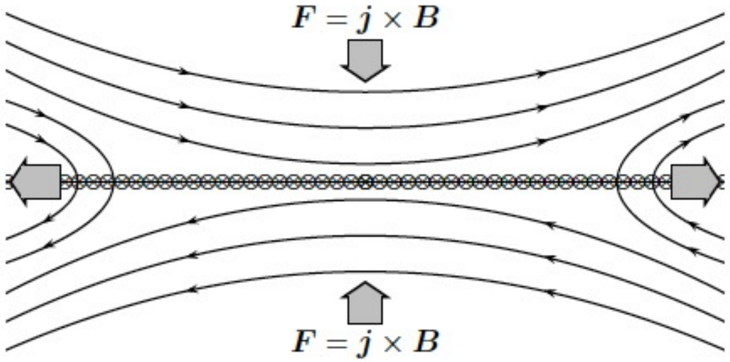
Some possible mechanisms & sites for particle acceleration



Matthews, Bell, Blundell, 2020NewAR..8901543M

- High radiative efficiency
- Dissipative mechanism → powerful accelerator of non-thermal particles

- **Magnetic Reconnection (fully kinetic, PIC simulations)** (e.g. arXiv:2506.02101, Sironi et al.)
- **May be possible to deposit 50 per cent of the dissipated energy into non-thermal leptons as long as the energy density of the magnetic field in the bulk flow is > the rest-mass energy density**

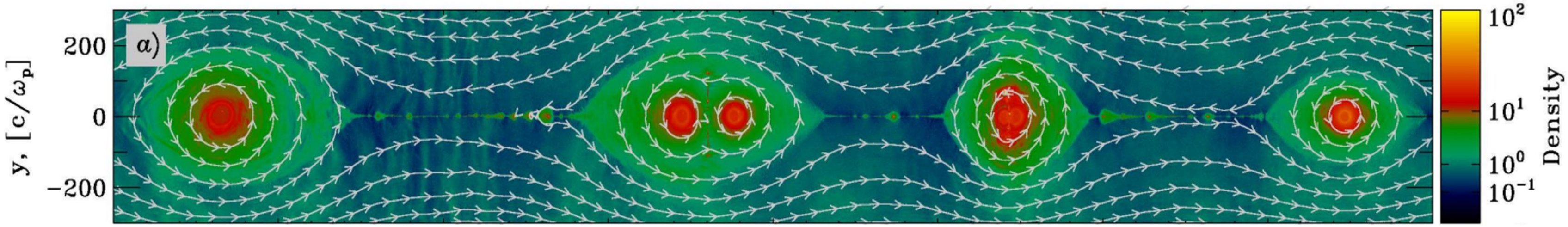


Morris et al. 2019

Magnetization:

$$\sigma = \frac{B'^2}{4\pi n c^2}$$

L. Sironi et al. 2015, MNRAS



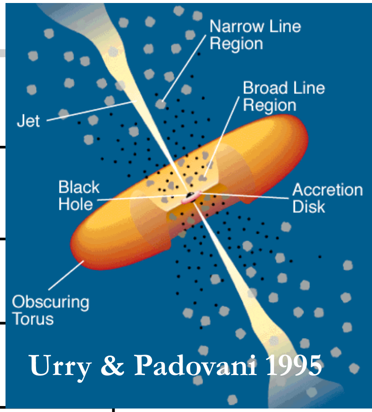
Particle number density with overplotted magnetic field lines

Outline

- **Ultra-fast variability**
- **Long-term variability – Historical light curves**
- **Blazar flares and correlation with mm**
- **Theoretical understanding**

Blazar Variability – Ultra-fast time scales

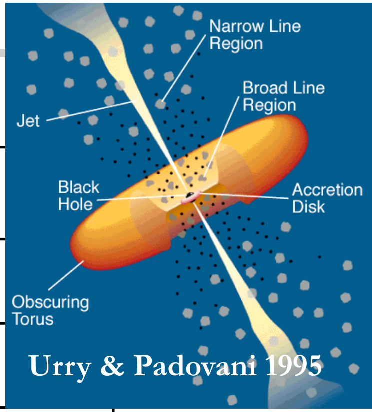
VHE Blazars – Shortest Variability Timescales



Source	Class	Observation Date	Variability Timescale	Telescope	Reference
IC 310	Radio Galaxy	12/13 Nov 2012	~4.8 min	MAGIC	Aleksić et al. 2014
Mrk 421	HBL	7 May 1996	< 15 min	Whipple	Gaidos et al. 1996
		17 Feb 2010	~ 22 min	VERITAS	Abeysekara et al. 2020
		11-19 Apr 2013	~ 30 min	VERITAS/MAGIC	Acciari et al. 2020
PKS 1222+216	FSRQ	17 Jun 2010	~10 min	MAGIC	Aleksić et al. 2011
Mrk 501	HBL	30 Jun, 9 Jul 2005	~2 min ~20 min	MAGIC	Albert et al. 2007
1ES 1959+650	HBL	20 May 2012	~15 min	VERITAS	Aliu et al. 2014
PKS 2155-304	HBL	28 Jul 2006	~5 min	H.E.S.S.	Aharonian et al. 2007
BL Lacertae	LBL/IBL	28 Jun 2011	13± 4 min	VERITAS	Arlen et al. 2013
		5 Oct 2016	~ 36 min	VERITAS	Abeysekara et al. 2018

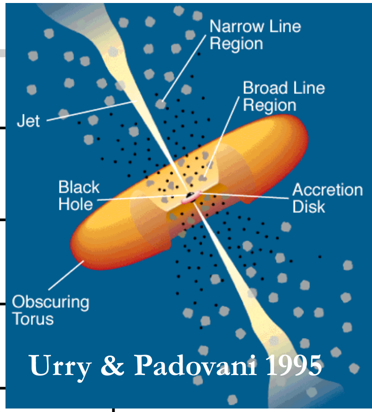
Large amplitude flux variability on 30 min time scales implies that TeV emission originates from small regions of the jets

VHE Blazars – Shortest Variability Timescales



Source	Class	Observation Date	Variability Timescale	Telescope	Reference
IC 310	Radio Galaxy	12/13 Nov 2012	~4.8 min	MAGIC	Aleksić et al. 2014
Mrk 421	HBL	7 May 1996	< 15 min	Whipple	Gaidos et al. 1996
		17 Feb 2010	~ 22 min	VERITAS	Abeysekara et al. 2020
		11-19 Apr 2013	~ 30 min	VERITAS/MAGIC	Acciari et al. 2020
PKS 1222+216	FSRQ	17 Jun 2010	~10 min	MAGIC	Aleksić et al. 2011
Mrk 501	HBL	30 Jun, 9 Jul 2005	~2 min ~20 min	MAGIC	Albert et al. 2007
1ES 1959+650	HBL	20 May 2012	~15 min	VERITAS	Aliu et al. 2014
PKS 2155-304	HBL	28 Jul 2006	~5 min	H.E.S.S.	Aharonian et al. 2007
BL Lacertae	LBL/IBL	28 Jun 2011	13± 4 min	VERITAS	Arlen et al. 2013
		5 Oct 2016	~ 36 min	VERITAS	Abeysekara et al. 2018

VHE Blazars – Shortest Variability Timescales

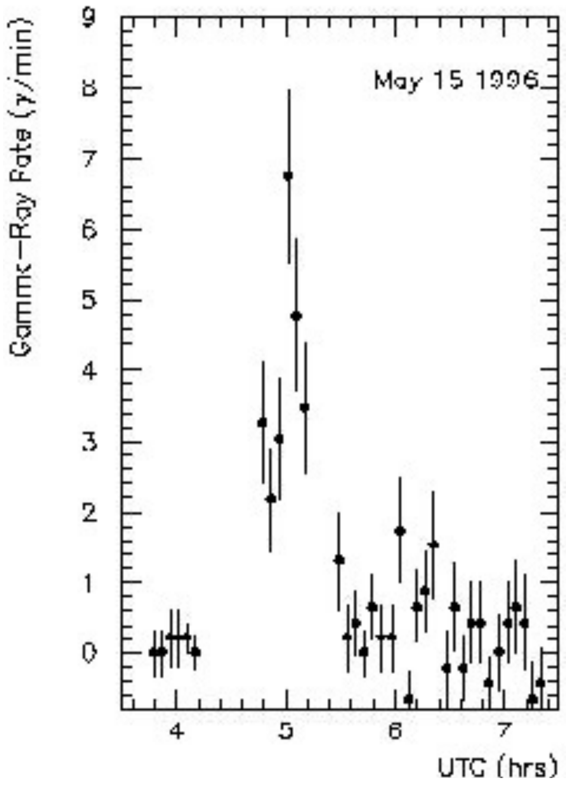


Source	Class	Observation Date	Variability Timescale	Telescope	Reference
IC 310	Radio Galaxy	12/13 Nov 2012	~4.8 min	MAGIC	Aleksić et al. 2014
Mrk 421	HBL	7 May 1996	< 15 min	Whipple	Gaidos et al. 1996
		17 Feb 2010	~ 22 min	VERITAS	Abeysekara et al. 2020
		11-19 Apr 2013	~ 30 min	VERITAS/MAGIC	Acciari et al. 2020
PKS 1222+216	FSRQ	17 Jun 2010	~10 min	MAGIC	Aleksić et al. 2011
Mrk 501	HBL	30 Jun, 9 Jul 2005	~2 min ~20 min	MAGIC	Albert et al. 2007
1ES 1959+650	HBL	20 May 2012	~15 min	VERITAS	Aliu et al. 2014
PKS 2155-304	HBL	28 Jul 2006	~5 min	H.E.S.S.	Aharonian et al. 2007
BL Lacertae	LBL/IBL	28 Jun 2011	13± 4 min	VERITAS	Arlen et al. 2013
		5 Oct 2016	~ 36 min	VERITAS	Abeysekara et al. 2018

Ultrafast variability in blazars is especially intriguing because it cannot originate directly from the central engine, providing insights instead into the physics of nonthermal particle acceleration within the jet

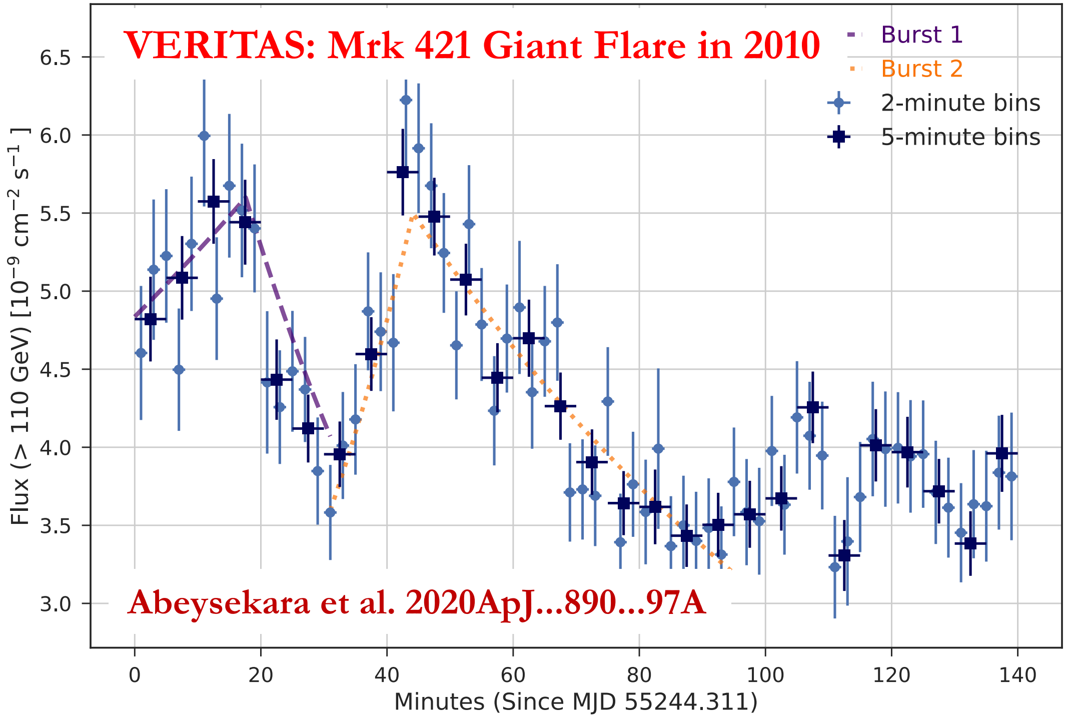
Light Curves: Short Time Scale Variability

Whipple: Gaidos et al. 1998



γ-ray sources often exhibit very short time scale variability

Causality implies that γ-ray variability on a timescale τ is related to the radius of the emission region



For $t_{var} \sim 22$ min →

$$\delta^{-1} R_B \lesssim 3.8 \times 10^{13} \text{ cm}$$

Estimated $\delta_{min} \gtrsim 33$

- $t_{rise} \approx t_{fall} \approx 15\text{min}!$
- $R < ct\delta/(1+z) \approx 10^{-4}\text{pc}$
- For $M = 10^8 M_\odot$ $R_S \equiv 2GM/c^2 \approx 10^{-5}\text{pc}$

γ-ray emission zone may be smaller than the jet-cross section → **flares can be due to large plasmoids created during a magnetic reconnection event**

Mrk 421 – Giant Flare in 2010

Mrk 421 Giant Flare in 2010

For t_{var} ~ 22 min →

$$\delta^{-1} R_B \lesssim 3.8 \times 10^{13} \text{ cm}$$

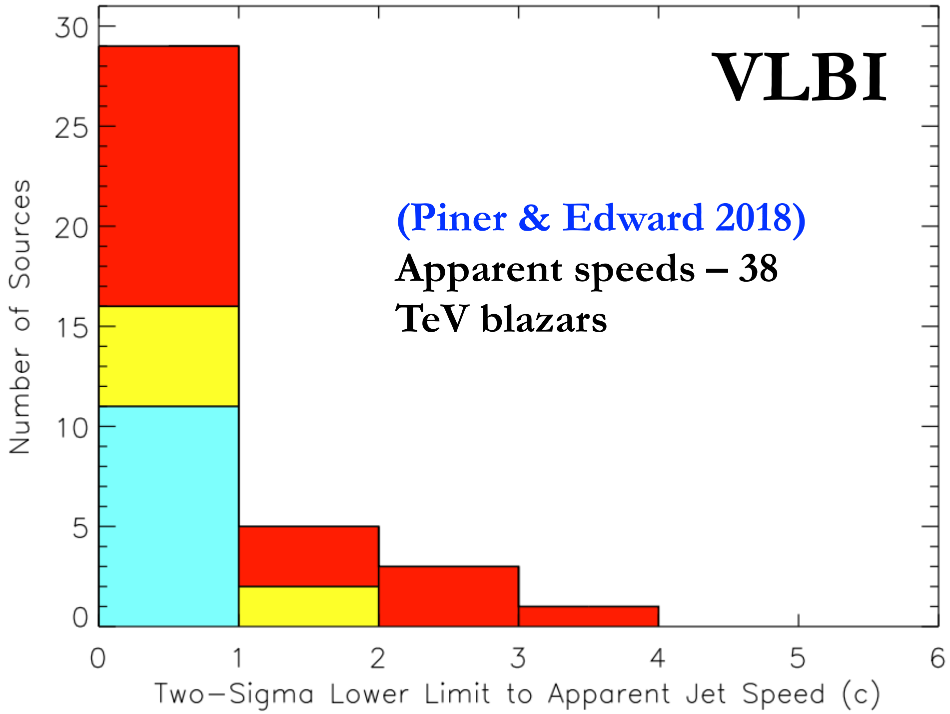
Estimated $\delta_{min} \gtrsim 33$

This can be reconciled with the high Lorentz factors estimated from the high-energy [light curve] data if the jet has velocity structures consisting of different emission regions with different Lorentz factors

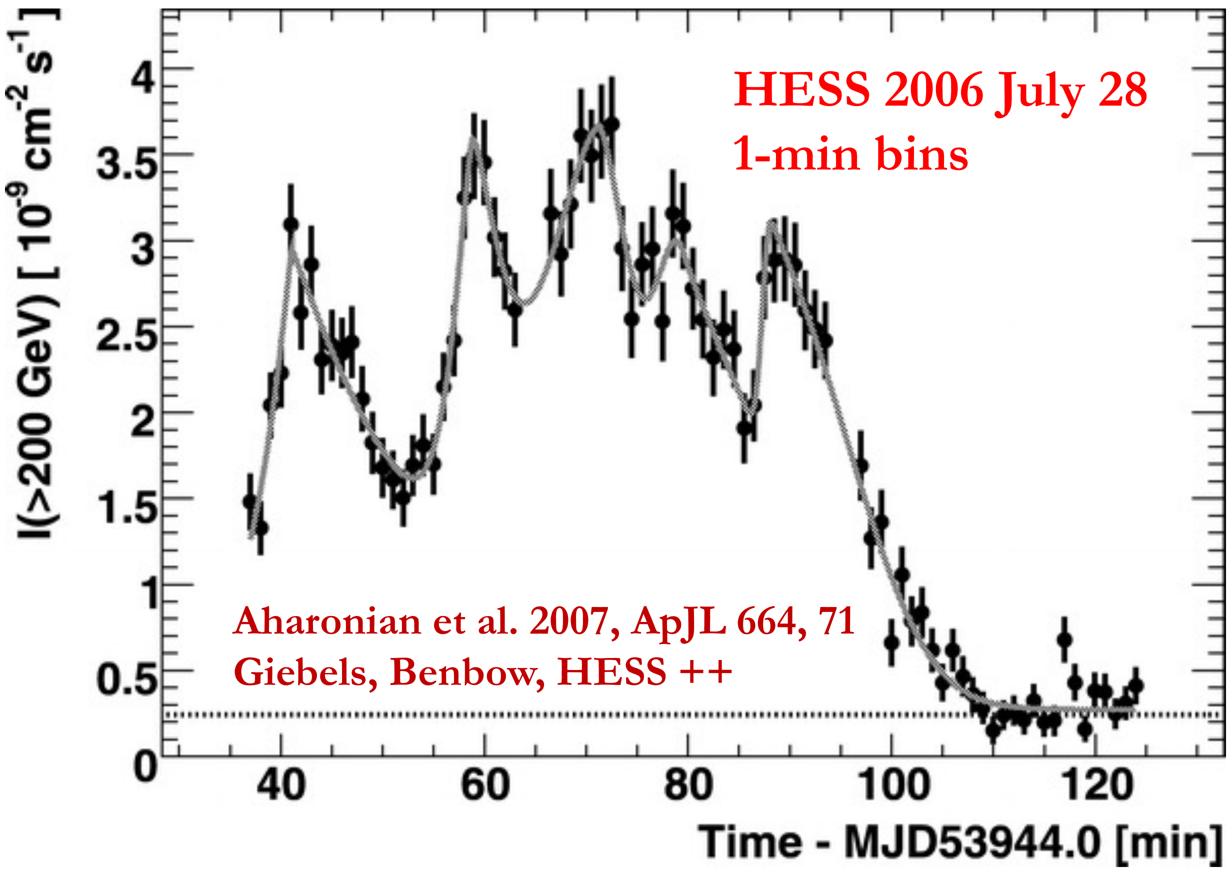
(Piner & Edward 2018)

Fast predicted speed vs low observed speeds: the bulk Lorentz factor crisis

The extremely short variability timescales in the higher-energy bands suggest a much larger Doppler factor (Aharonian et al. 2007) than implied by VLBI observations of the parsec-scale jet



An Exceptional VHE Gamma-Ray Flare of PKS 2155-304



$t_{\rm var} = 173 \pm 28$ s →

$$R\delta^{-1} \leq 4.65 \times 10^{12}\ \text{cm} \leq 0.31\ \text{AU}$$

Mass of the black hole ~ 1-2 X 10^9 M_O

$$M < [c^3 t_{\rm var}\delta/2G(1+z)]\,R_S/R \sim 1.6 \times 10^7\, M_\odot \delta R_S/R$$

→ $\delta \geq (60\text{–}120)\, R/R_S$

- Five overlapping bursts within one hour
- Some flares doubled in intensity in as short a time ~ 3 min
- Peak intensity was some 15 times that of the Crab nebula

News & Views | Published: 15 August 2007

Astrophysics

Photons from a hotter hell

Trevor Weekes

Nature **448**, 760–761 (2007) | Cite this article

226 Accesses | 5 Citations | Metrics

Blazars are massive black holes sending out particle jets at close to the speed of light. Stupendously fast, intense bursts of highly energetic γ-rays indicate that the blazar environment is even more extreme than was thought.

Berrie Giebels - Broad Expertise in the Study of Blazars

A contribution to γ-ray astronomy of GeV-TeV Active Galaxies with *Fermi* and H.E.S.S.

Berrie Giebels

Laboratoire Leprince-Ringuet
Ecole polytechnique, CNRS/IN2P3

Mémoire présenté en vue de l'obtention de

l'Habilitation à Diriger les Recherches de l'Université Paris Sud 11

Soutenue à Orsay, le 20 avril 2011, devant le jury composé de

Réza Ansari, Examinateur
John Carr, Rapporteur
Gilles Henri, Rapporteur
Rene Ong, Rapporteur
Reynald Pain, Président

UNIVERSITÉ PARIS-SUD 11 · LLR · ÉCOLE POLYTECHNIQUE · CNRS IN2P3

Berrie Giebels HDR (2011)

Thesis focuses on exploring the nature of active galactic nuclei, the most luminous objects in the Universe

Scientific impact:

- Understanding the variability of AGN
  - Focusing on PKS 2155-304
  - Exploring power density spectrum
- Studying the broad-band (multi-wavelength) spectrum of AGN
  - Multi-wavelength studies of PKS2155- 304
- Constraining intergalactic radiation fields
  - Propagation of γ-rays from AGN
- Is there flux-dependent spectral variability?

Berrie Giebels – Much more than AGN Variability

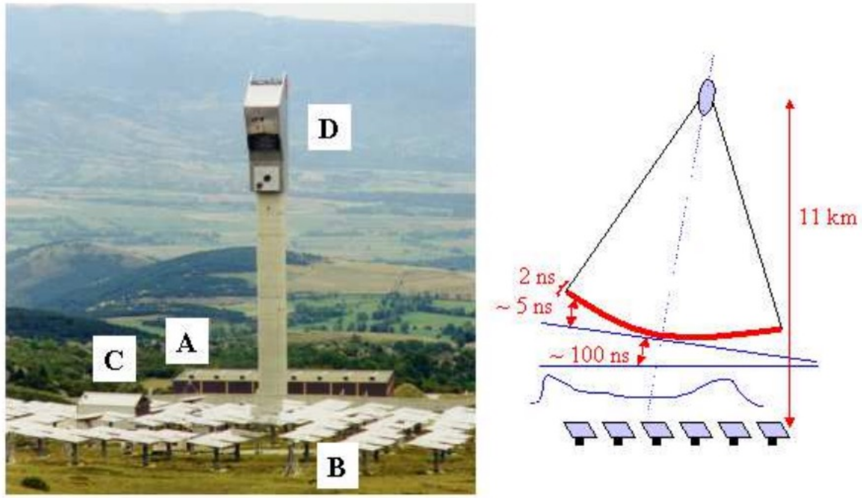


Figure 1: Left: The Thémis solar facility. Beneath A is one of the 7 ASGAT telescopes. B is one of the 18 Themistocle telescopes. C is the hangar housing the CAT imager. D is where the CELESTE secondary optics and counting house were. Right: For a source 20 degrees from the zenith and a heliostat 100 meters from the array center, the wavefront inclination retards the Cherenkov light by ∼ 100 ns, and the wavefront sagitta is ∼ 5 ns. The wavefront thickness (pulse duration) is ∼ 2 ns. The curve is an artist's impression of the Cherenkov density across the light pool, described as an 'Arizona mesa' in the text.

Review of the Solar Array Telescopes David A. Smith Contribution to the proceedings of "Towards a Network of Atmospheric Cherenkov Detectors VII", 27-29 April 2005 - Ecole Polytechnique, Palaiseau, France

Berrie did his PhD from 1995 to 1998 in Bordeaux on the CELESTE experiment

Persistent identifier :	https://www.sudoc.fr/**010656294**
Content and media type :	Texte
Carrier type :	Volume
Title :	Contribution à la reconversion d'une centrale solaire en un vaste détecteur pour l'astronomie gamma / par Berrie Giebels ; sous la direction de Jean Québert Thèse (version d'origine)
Title's alphabet :	Latin
Author(s) :	Giebels, Berrie (19..-....). Auteur Québert, Jean (physicien). Directeur de thèse Université Bordeaux-I (1971-2013). Organisme de soutenance
Date(s) :	1998
Language(s) :	French
Country :	France
Production :	1998
Description :	1 vol. (122 p.) ; 30 cm
French PhD Thesis Number :	1998BOR10553

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

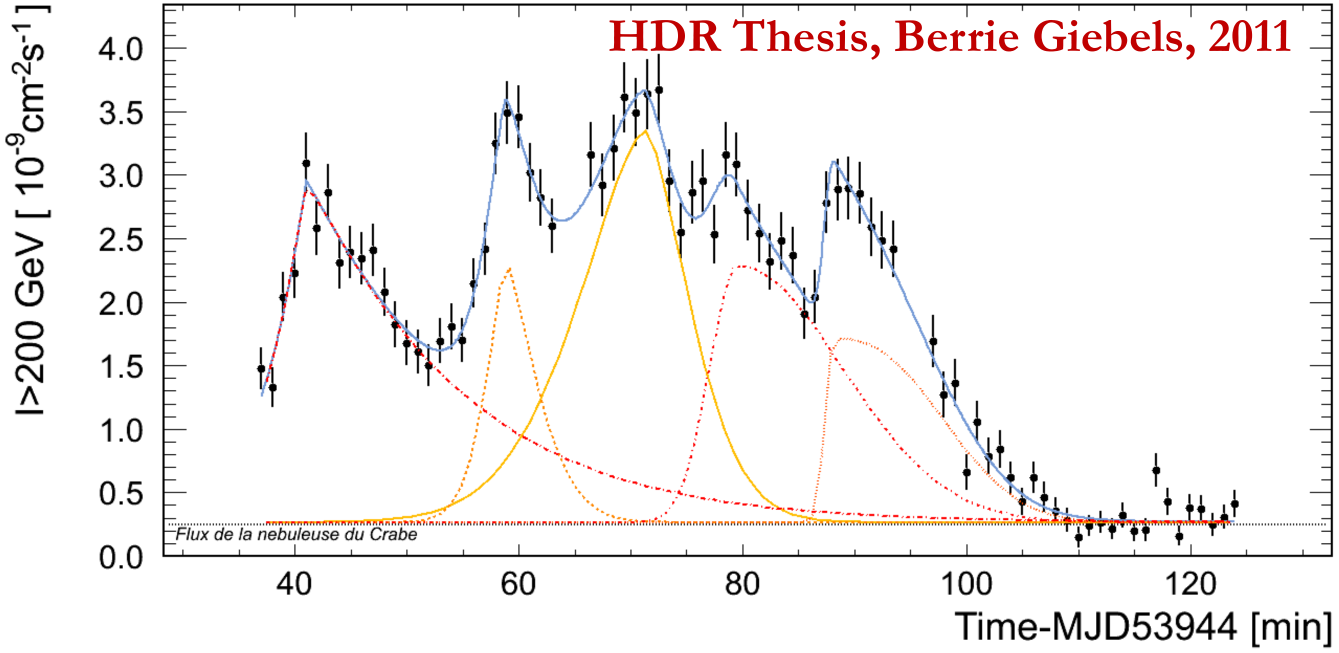
Volume 412, Issues 2–3, 1 August 1998, Pages 329-341

Prototype tests for the CELESTE solar array gamma-ray telescope

B. Giebels a, R. Bazer-Bachi b, H. Bergeret c, A. Cordier c, G. Debiais d, M. DeNaurois e, J.P. Dezalay b, D. Dumora a, P. Eschstruth c, P. Espigat f, B. Fabre d, P. Fleury e, C. Ghesquière f, N. Herault c, I. Malet b, B. Merkel c, C. Meynadier d, M. Palatka g, E. Paré e, J. Procureur a, M. Punch f, J. Québert a, K. Ragan a [1 1], L. Rob h, P. Schovanek g, D.A. Smith a, J. Vrana e [2 2]

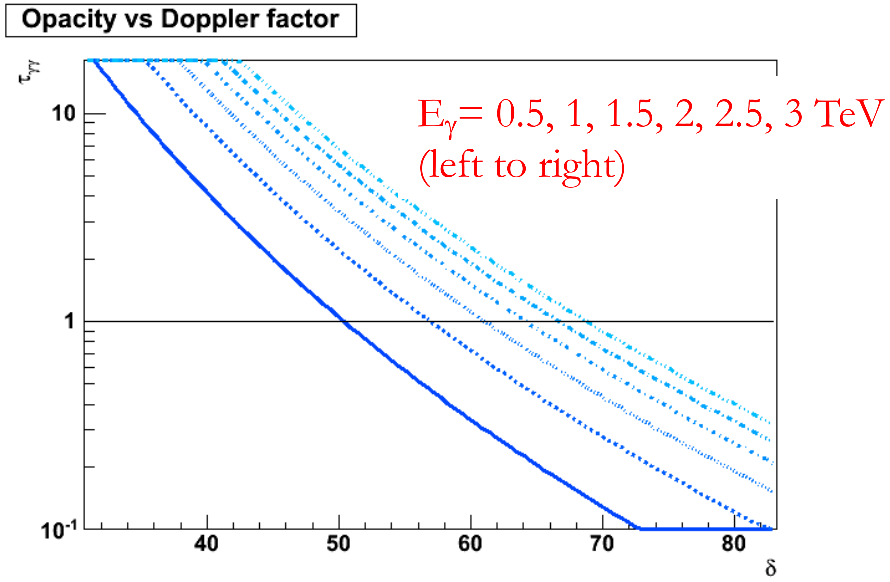
PKS 2155-304 - "Cosmic Rollercoaster"

Observed variability is still among the fastest ever observed from a blazar



Impulsive analysis of the light curve

- Assumed that fast variability is produced by several individual emission regions, rather than fluctuations in one region
- Observed γ-ray emission is the superposition of multiple and independent flares
- Similar to that seen in hard X-ray GRBs

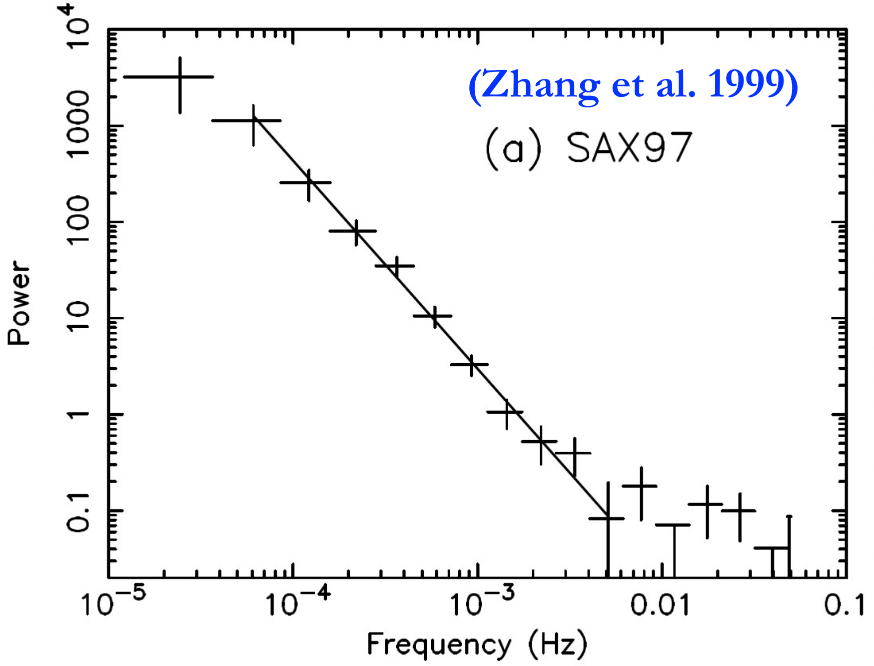


- Sampled at Δt = 60s (~ 3h of observations of the source)
- Superposition of five underlying generalized Gaussians

For E_γ = 500 GeV photons to significantly escape the region, the required Doppler factor is δ > 50, and can be as high as δ > 70 for E_γ = 3TeV
→ *"mini-jets" model, small regions nested in the jet and powered by magnetic reconnections Giannios et al. (2009)*

The Power Spectrum of PKS 2155-304

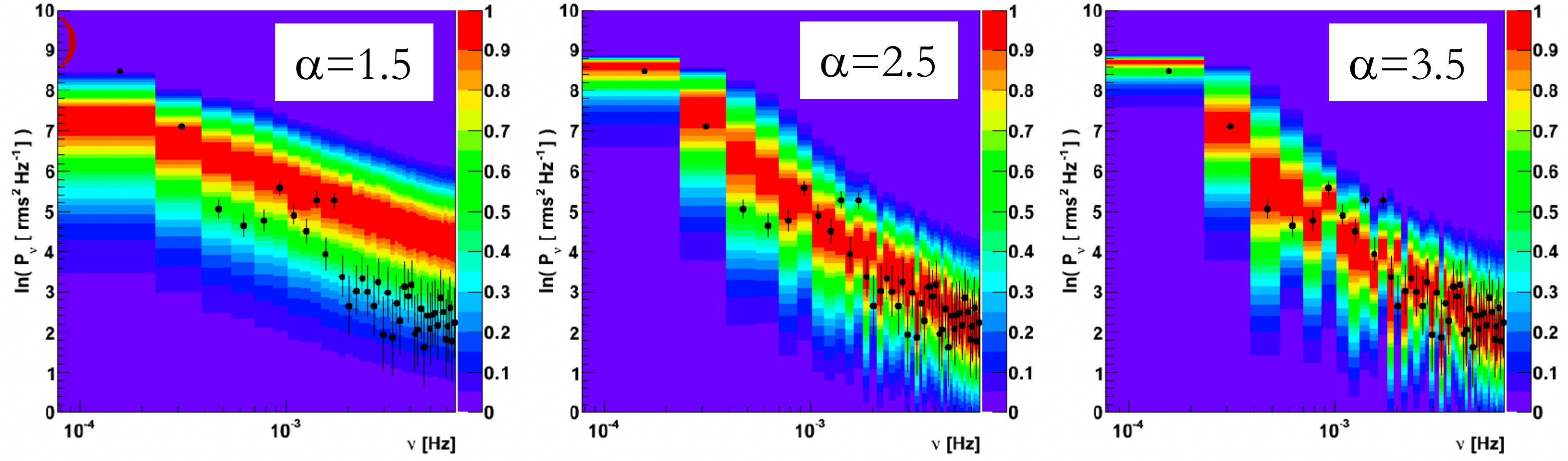
For densely sampled quasi-continuous light curves in the VHE domain it may be possible to probe the properties of the variability itself at different frequencies in in the time domain – Where does most of the variability occur?



X-ray power spectrum of PKS 2155-304 $P(\nu) \propto \nu^{-\alpha}$

Power law behavior of the PSD amplitude of variability decreases when variability timescale decreases

PSD of PKS 2155-304 (HDR Thesis, Berrie Giebels, 2011



Application a likelihood method to the light curve of the "Big Flare" in PKS 2155-304. The intensity levels reflect the probability density derived from 104 simulations of red noise light curves and distorted by experimental effects. The optimal value of α ~ 2.3

Ultra-fast Variability in PKS 1222+21

30-min exposure on PKS 1222+21 with MAGIC (z = 0.432)

- VHE flux > 100 GeV, measured flux ~ 1 Crab Nebula
- 6-min time bins
- VHE flux varies significantly implying a flux doubling time of about 10 minutes → **indicating an extremely compact emission region** with transverse dimensions

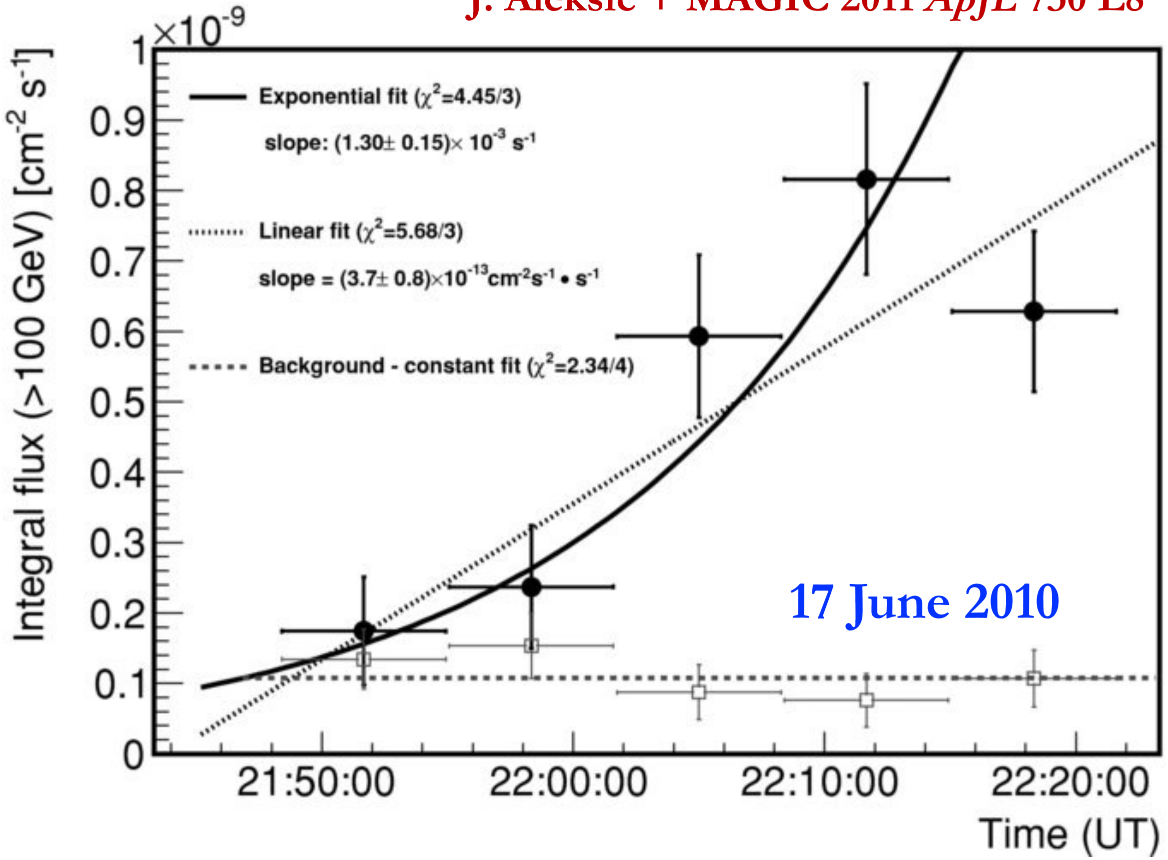
$$R \sim 1.3 \times 10^{14} (\delta/10)(t_{\rm var}/10\,{\rm minutes})\ {\rm cm}.$$

- VHE spectrum - a single power law →

Γ = 2.72 +/- 0.34 (3 – 400 GeV)

- The absence of a spectral cutoff constrains the γ-ray emission region to lie outside the broad-line region (~ 0.1pc)

J. Aleksić + MAGIC 2011 *ApJL* 730 L8



17 June 2010

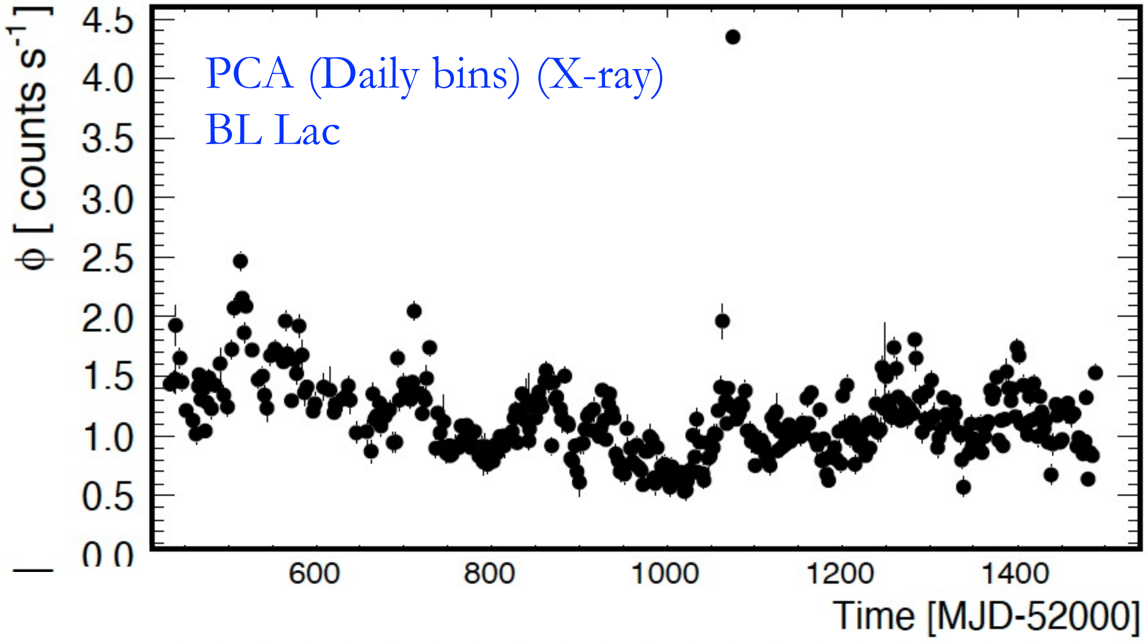
The detection of an ultra-fast TeV flare from PKS 1222+21 puts severe constraints on emission models of blazar jets → invokes the presence of very compact emission regions embedded within a larger-scale jet

Long-Term Light Curves

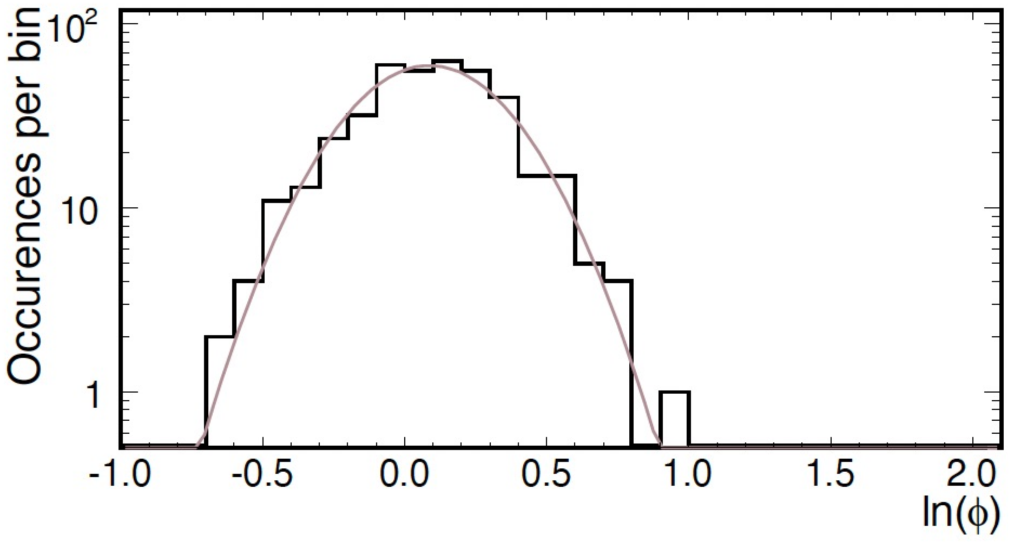
Lognormal Variability in BL Lacertae

Time series characterization is a powerful approach to uncovering the mechanisms driving variability in blazars

BL Lac study in X-rays: First detection of lognormal variability → Is this the imprint of the accretion disk on the jet, linking for the first time accretion and jet properties in a blazar?



Giebels & Degrange 2009A&A...503..797G



Distribution of the logarithm of the fluxes with superimposed Gaussian fit to the data

Linking the variability mechanism causing the X-ray modulation in BL Lac to originating in the accretion disk

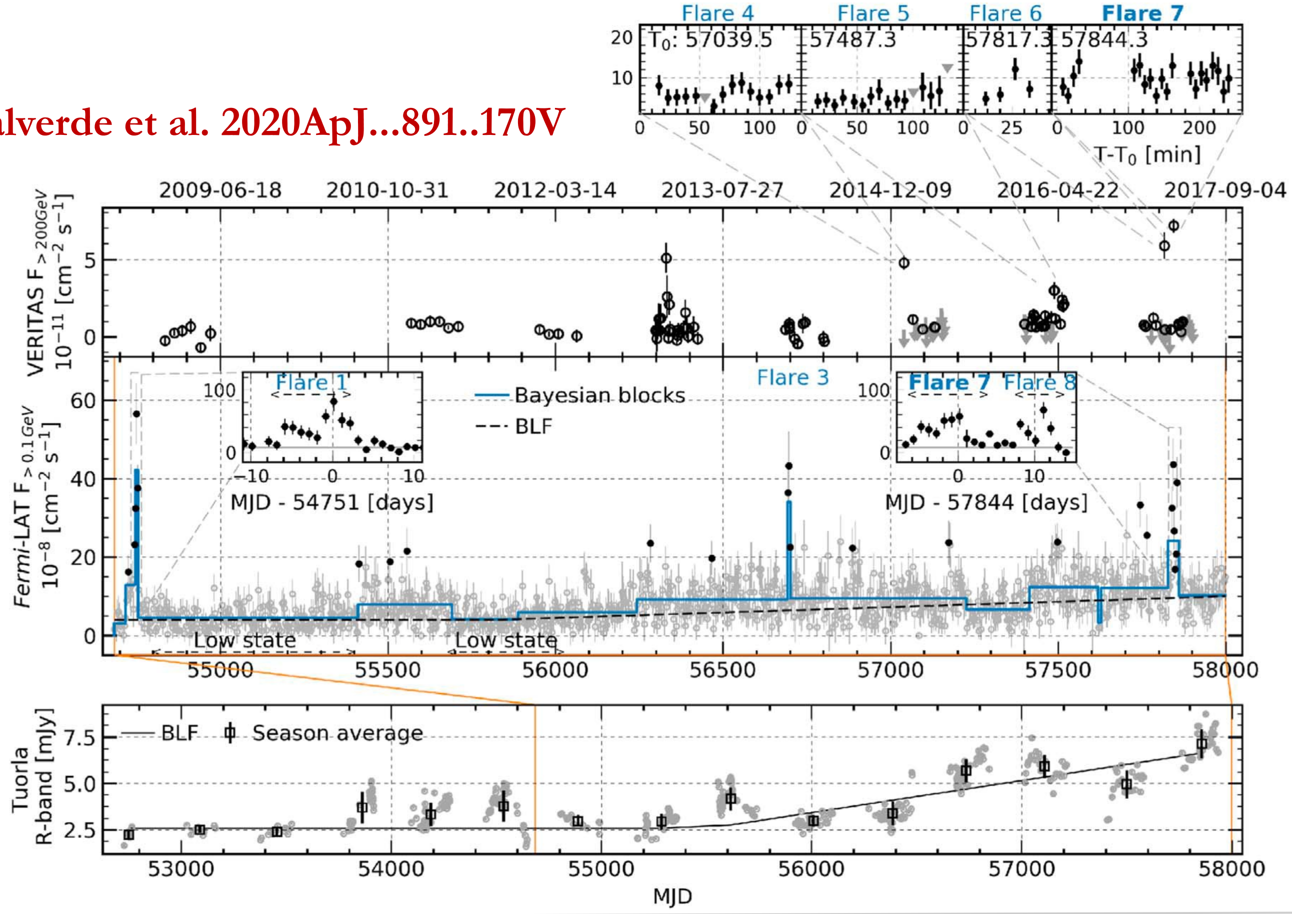
Longterm Study of 1ES 1215+303

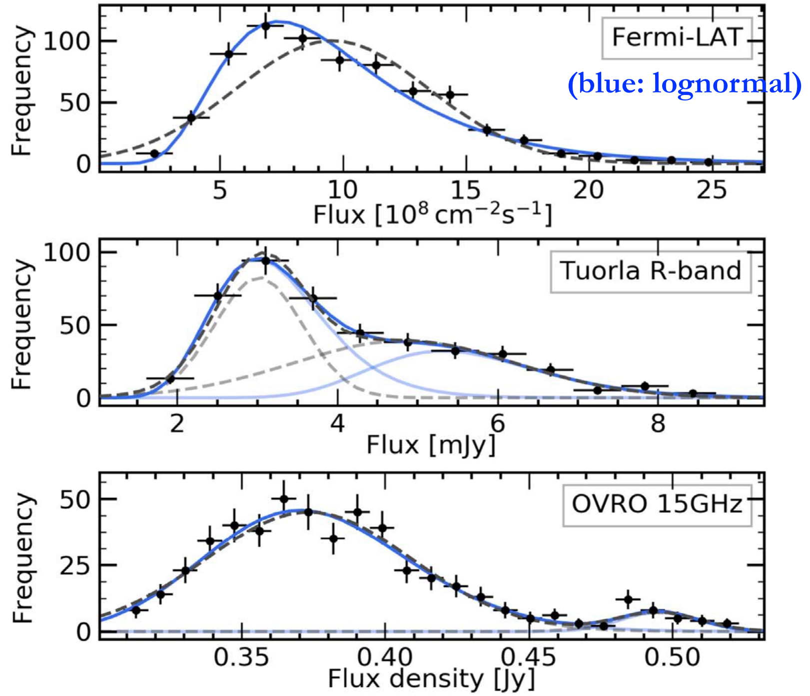
(See Talk by Janeth Valverde)

Decade-long study of gamma-ray emission from 1ES 1215+303 (z=0.130) in the 100 MeV to 30 TeV energy range →

- Multiple strong GeV gamma-ray flares
- Long-term increase in the gamma-ray and optical flux baseline → Lognormal behavior in flux distribution
- Linear correlation between these two bands are observed over the ten-year period

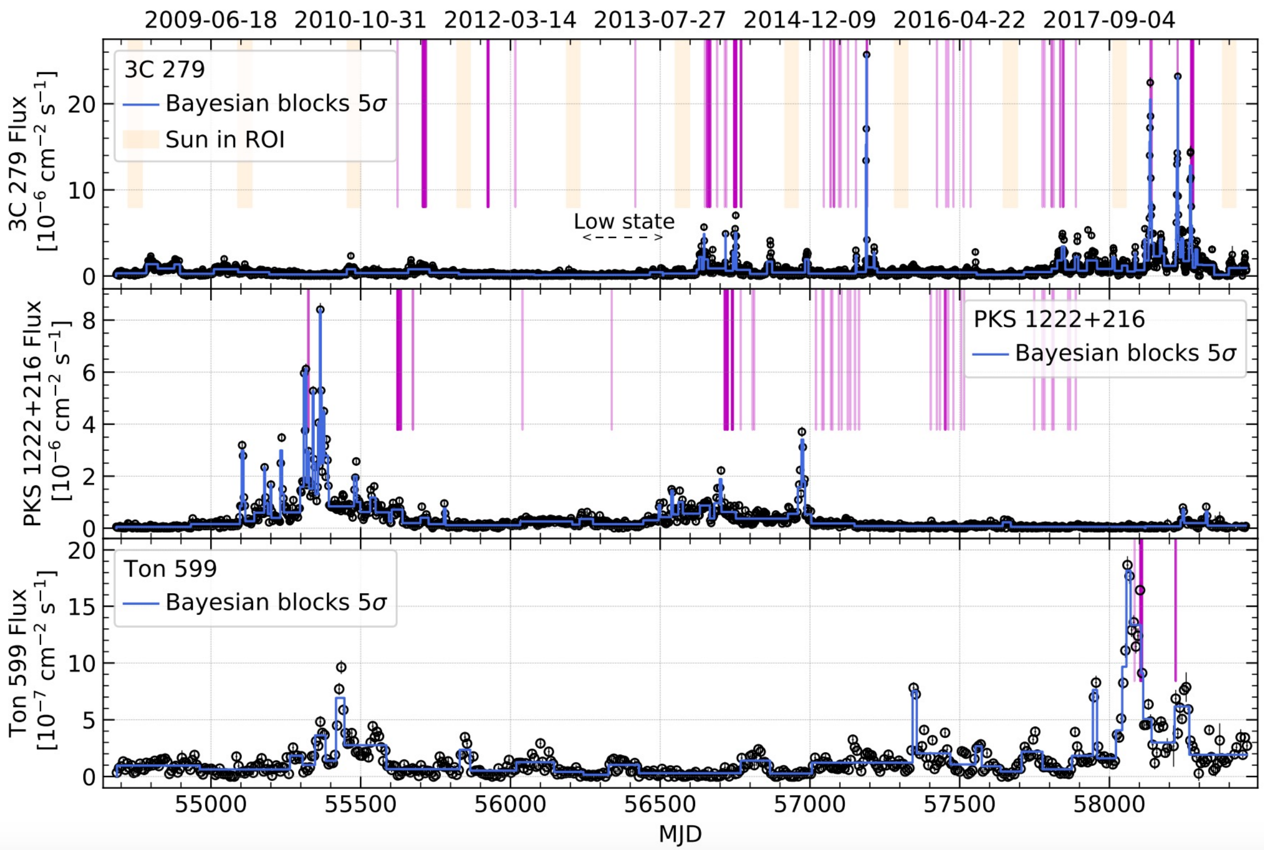
Valverde et al. 2020ApJ...891..170V





Lognormal → e.g. see **Biteau & Giebels 2012A&A...548A.123B could be** contributions of a large number of mini-jets in a jet

Three γ-ray FSRQs Observed by VERITAS & Fermi-LAT



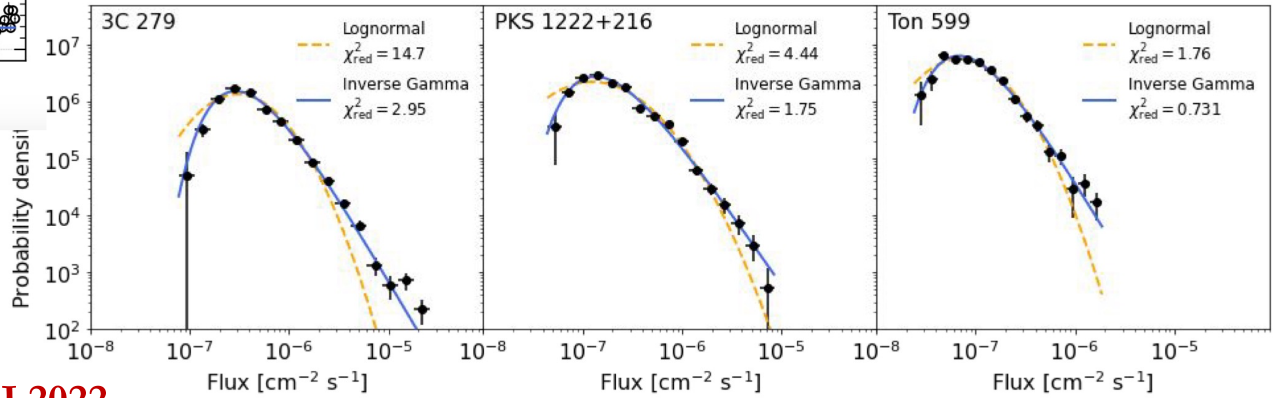
LAT daily and sub-daily light curves for 3 FSRQs

Continuous monitoring over a 10-yr period

- Models for fast flares?
    - Magnetic reconnection?
    - Slower variability explained by shocks

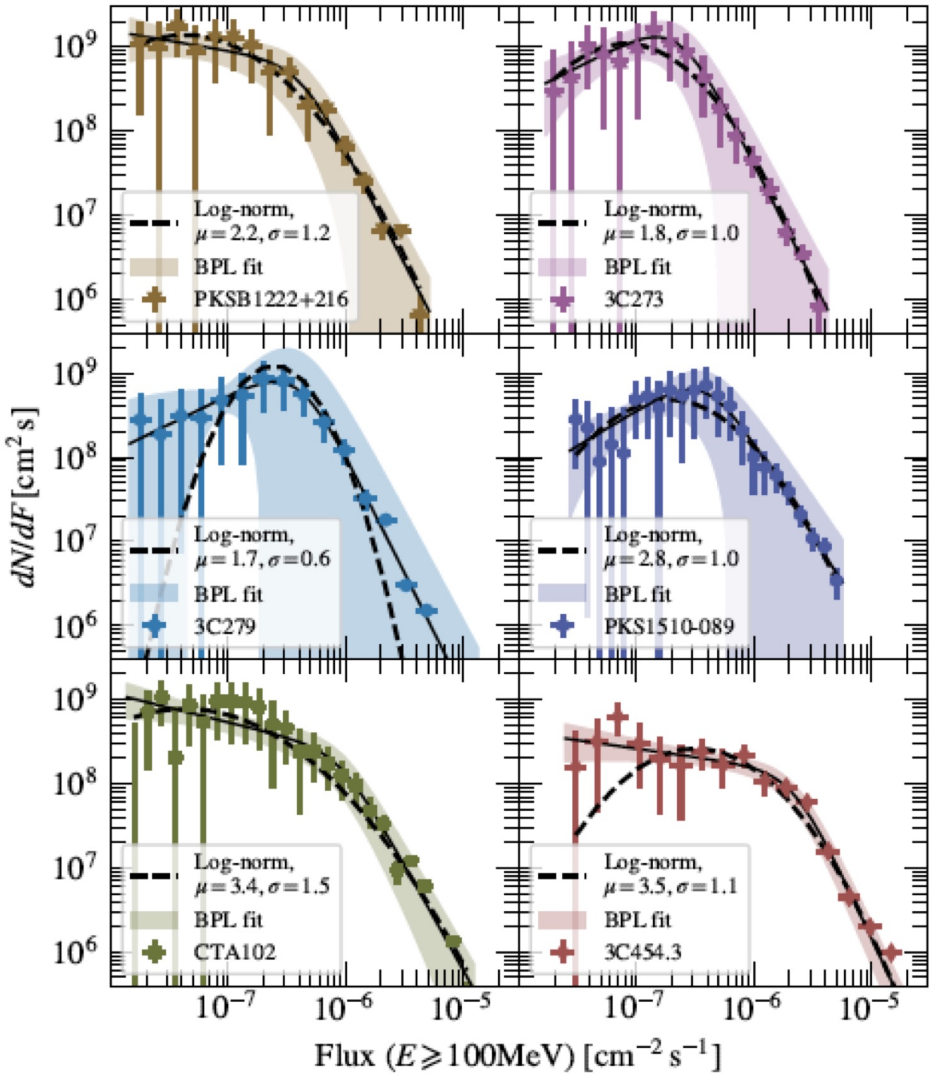
SDE fits to the flux distributions: Values are consistent with variability timescales > 100 r_g/c injected into the jet by magneto-rotational instability in the accretion disk

Comparison of lognormal flux distributions with a model based on a stochastic differential equation (SDE) including both deterministic and stochastic components (Tavecchio et al. 2020) → **Heavier-tailed than lognormal – "Inverse gamma" distribution**



Adams, CB, ++ ApJ 2022

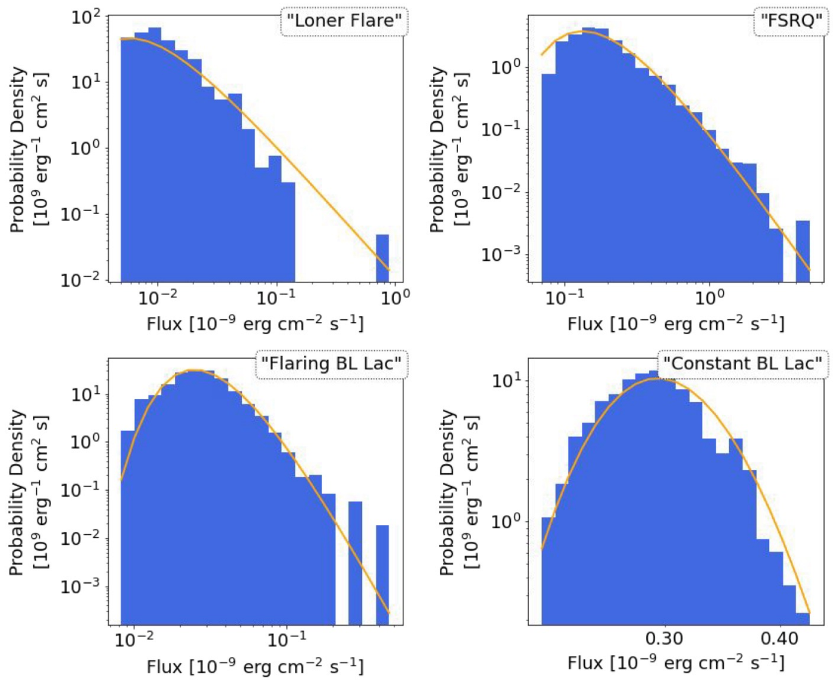
Characterizing Long-Term Variability



Meyer, Scargle, Blandford 2020

Distribution of the fluxes of the weekly 9.5 yr γ-ray light curves for 6 FSRQs: γ-ray outbursts from FSRQs → temporarily the brightest γ-ray emitters in the sky

Lognormal flux distributions are commonly observed for blazars → evidence for a connection between the modulations in the accretion rate and the jet activity (**Giebels & Degrange 2009**)



Also see **Brill, A., ApJ 2022**:

Study of simulated light curves: An autoregressive inverse gamma model of blazar variability: gamma rays are produced in discrete bursts arriving as a shot-noise Poisson process.

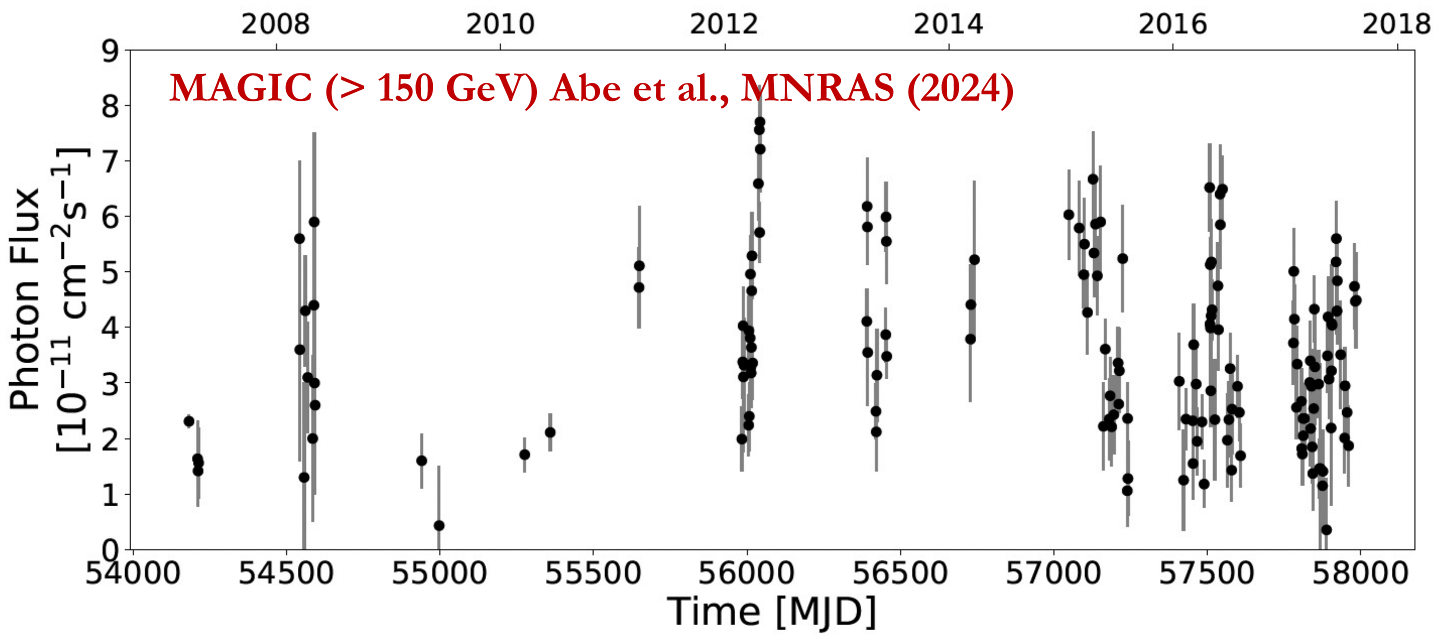
Variability Patterns of PG 1553+113

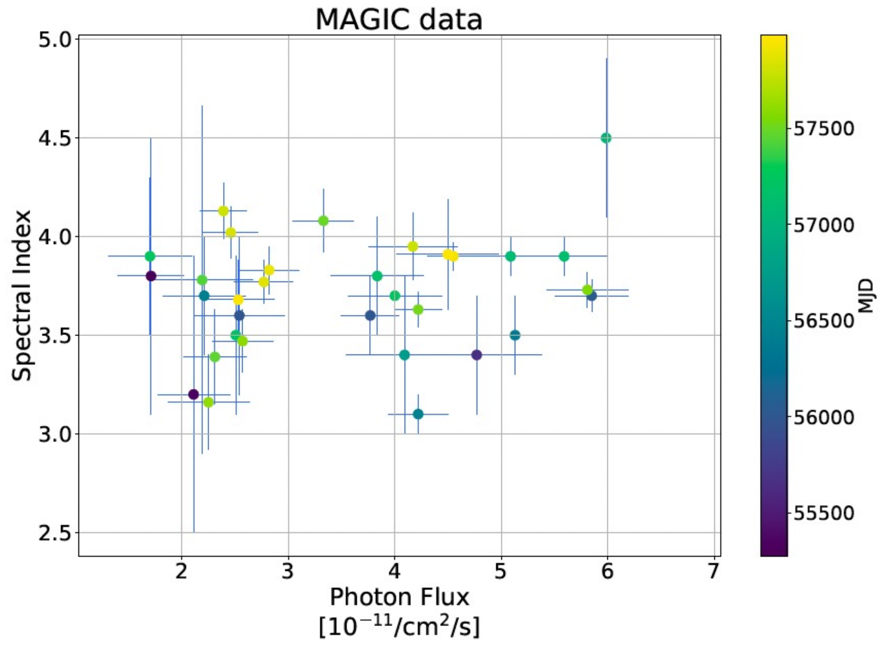
PG 1553: One of the brightest TeV HBLs (0.413 < z < 0.56)

Decade of MAGIC and multi-band observations → one of the few TeV blazars with a convincing quasi-periodic emission in the γ-ray band (2007 – 2017)

Fermi-LAT **continuous monitoring** from 2008 shows a clear signature of periodic modulation of ~2.2 years at E > 100MeV and E > 1 GeV, covering 3.5 cycles (Ackermann et al. 2015) – Optical fluxes correlate with γ-ray emission at 99% confidence

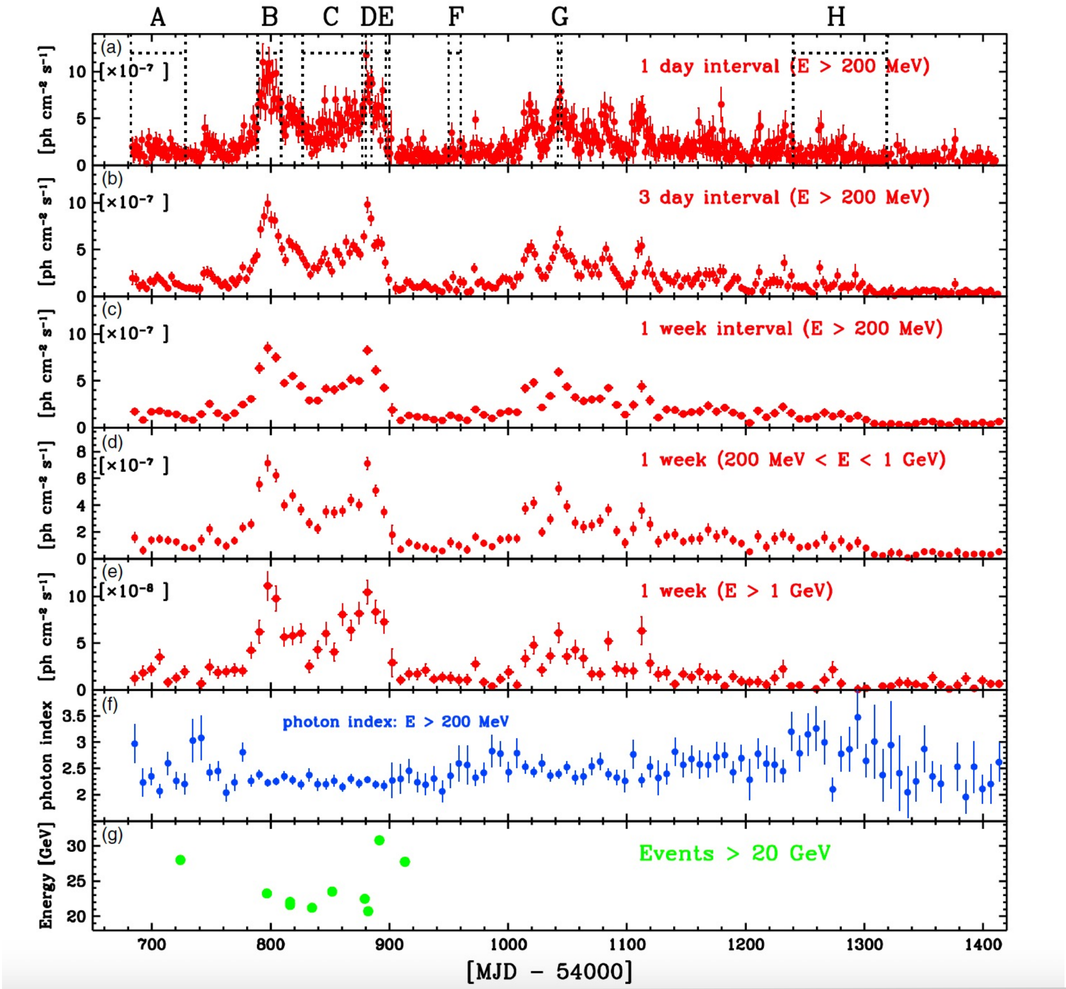
- Optical lightcurve shows evidence for modulation of ~ 2yrs years over 4.5 cycles



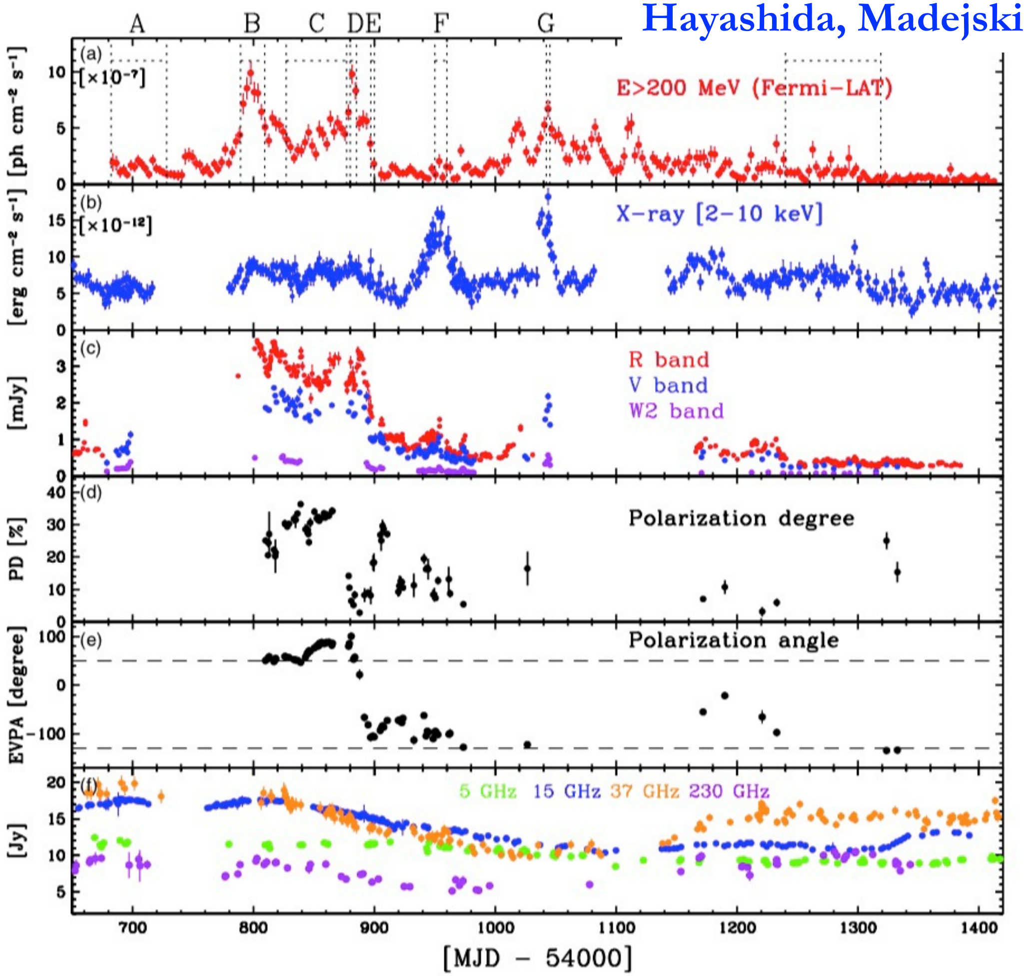


3C 279 – Complex Structure of Variability

Multi-band light curve of 3C279 from Aug 2008 to Aug 2010: Note the complex nature of the variations in the different bands
Variability across bands may or may not be correlated → more than one zone must often be responsible for the emission



Hayashida, Madejski ++ApJ 2012



An Unique Opportunity – 3C 279 with EHT

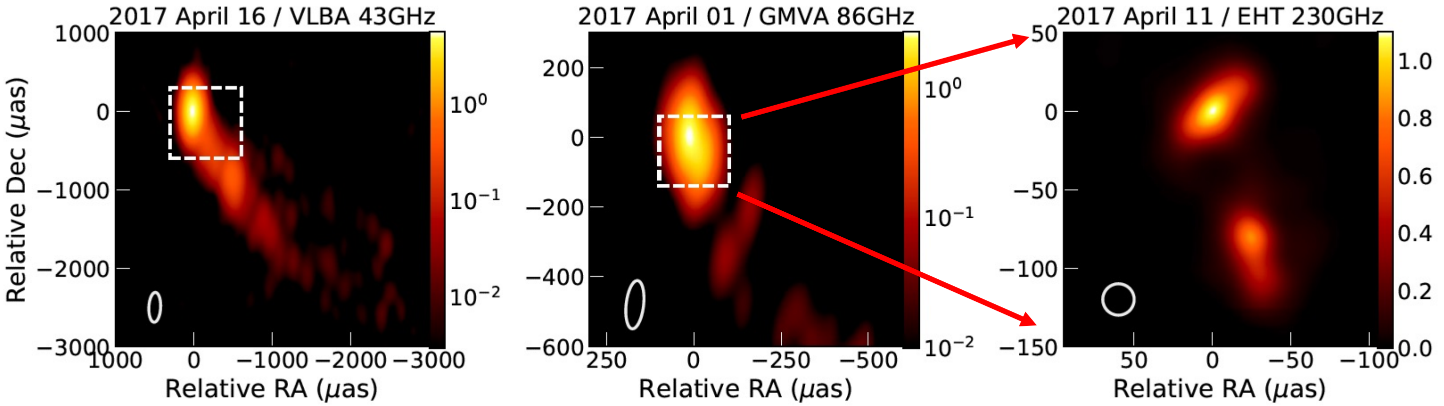
- April 2017 & April 2018: EHT observations with unprecedented angular resolution of 20 μas + radio to the TeV **Principe, G. ++ ICRC 2025**
- Pronounced flaring activity in the UV–optical band. Optical polarization shows substantial variability. Polarization degree ~ 5% to 25%
- EHT data show significant structural variability on daily timescales → systematic changes in the inner jet?
- The elongation observed with the EHT at 230 GHz is oriented nearly perpendicular to the long-term jet direction seen on larger scales

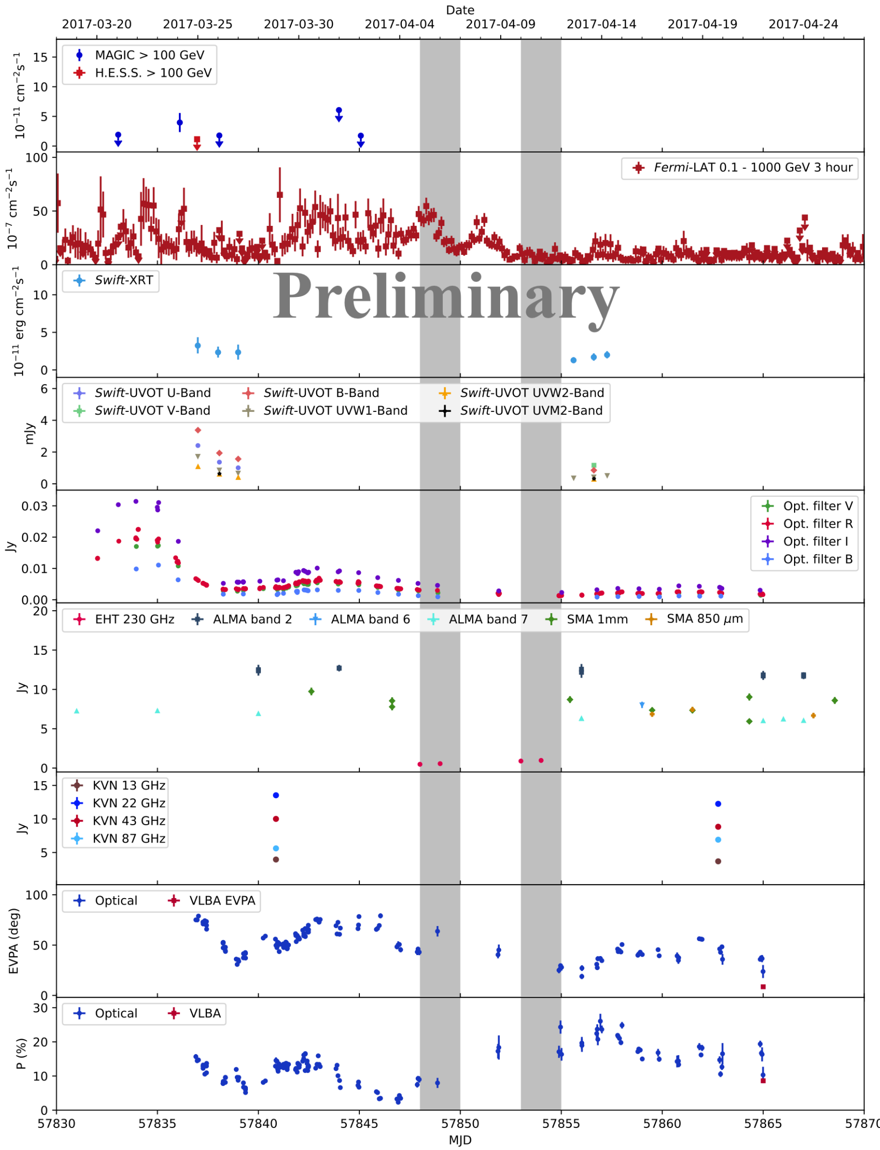
z=0.536

M_{BH} ~ 8 X10^8 M_{sun}

Spatial scale ~ 0.13 pc, ~ 1700 R_{Sh}

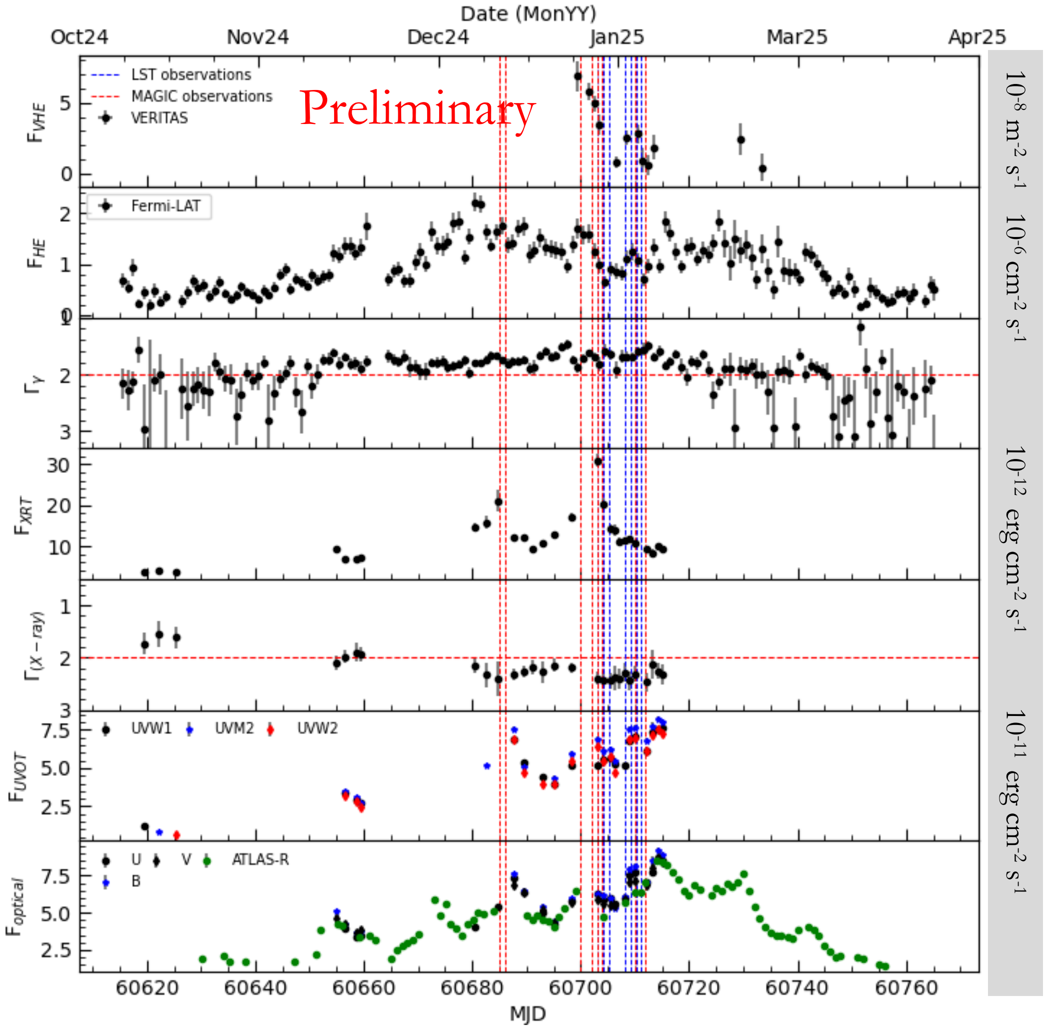
Kim, J.-Y. +, A&A 2020





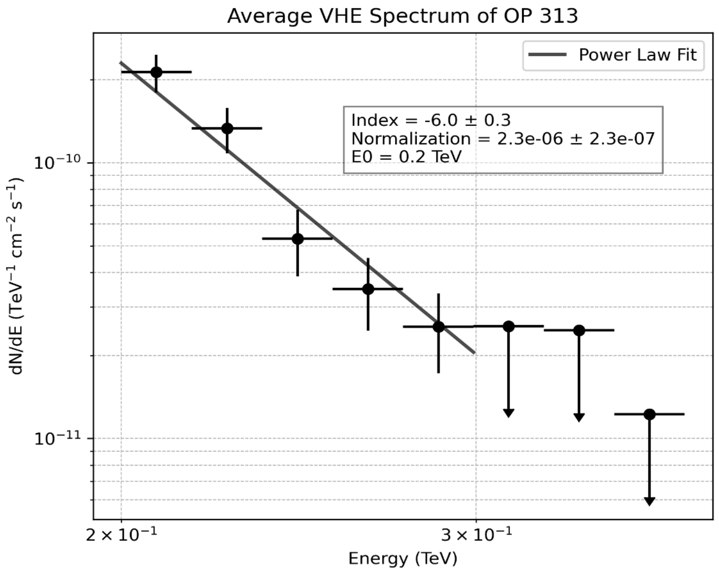
FSRQ OP 313 (B2 1308+326): 2025 Flare

MW study of Jan 2025 flare



- Detection of VHE γ-ray by LST-1 (ATel # 16381) Dec 2023
- Recent GeV γ-ray activity observed by Fermi (ATel #16970)
- VERITAS observations triggered on Jan 24, 2025 (until 27 Feb, 2025) (ATel # 16993)

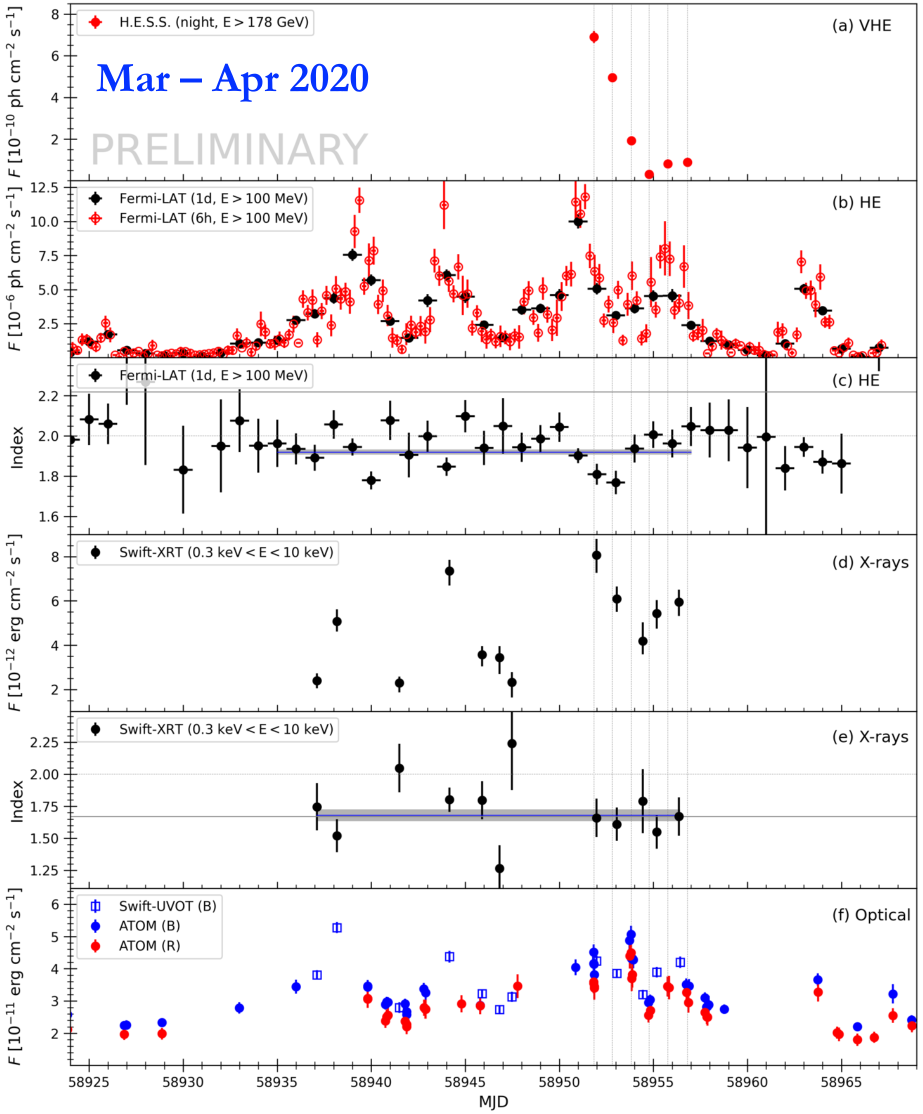
- FSRQ at a redshift of 0.996 (most distant VHE blazar)
- So-called "Changing-look (transitional) blazars"
- VERITAS collected ~ 25 hrs data. Detection at ~ 33 σ



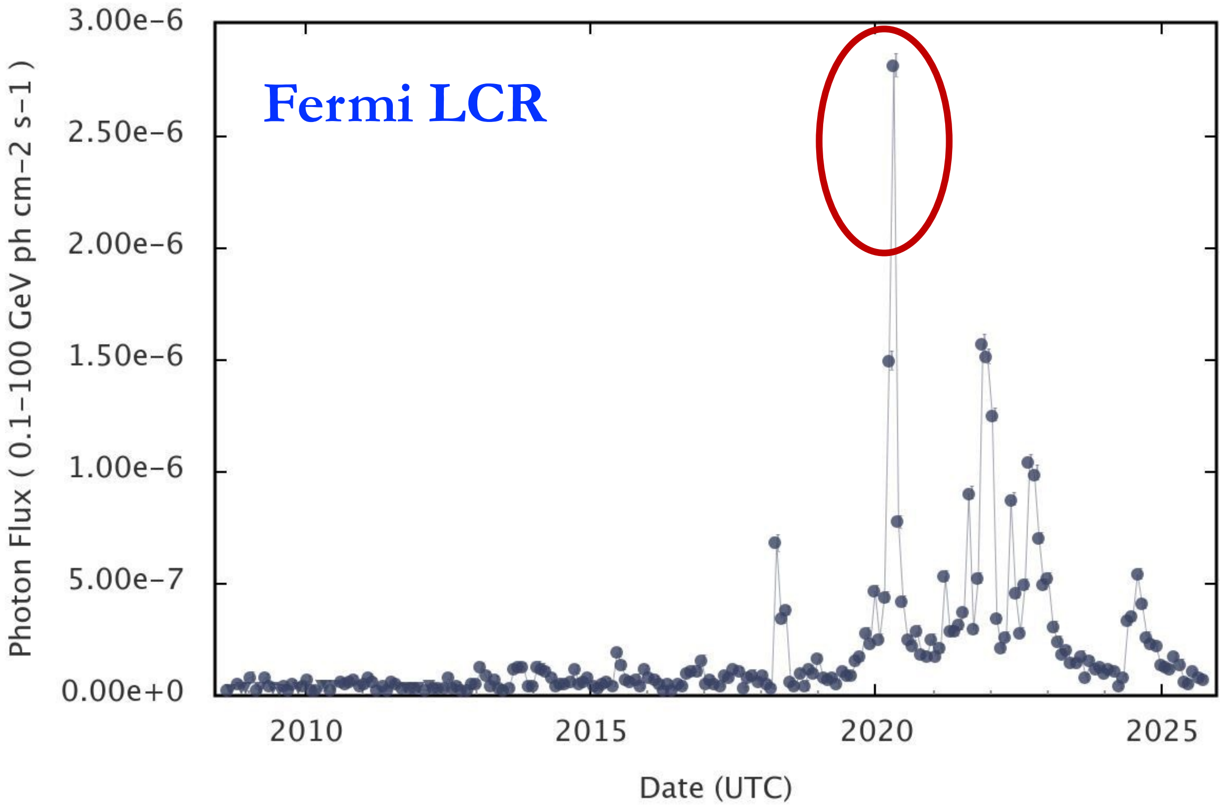
Joint VERITAS, MAGIC, and LST-1 Project
- Physics of SED
- Constrain EBL

Pandey + VERITAS ICRC 2025

Unprecedented γ-ray Outburst of PKS 0903-57

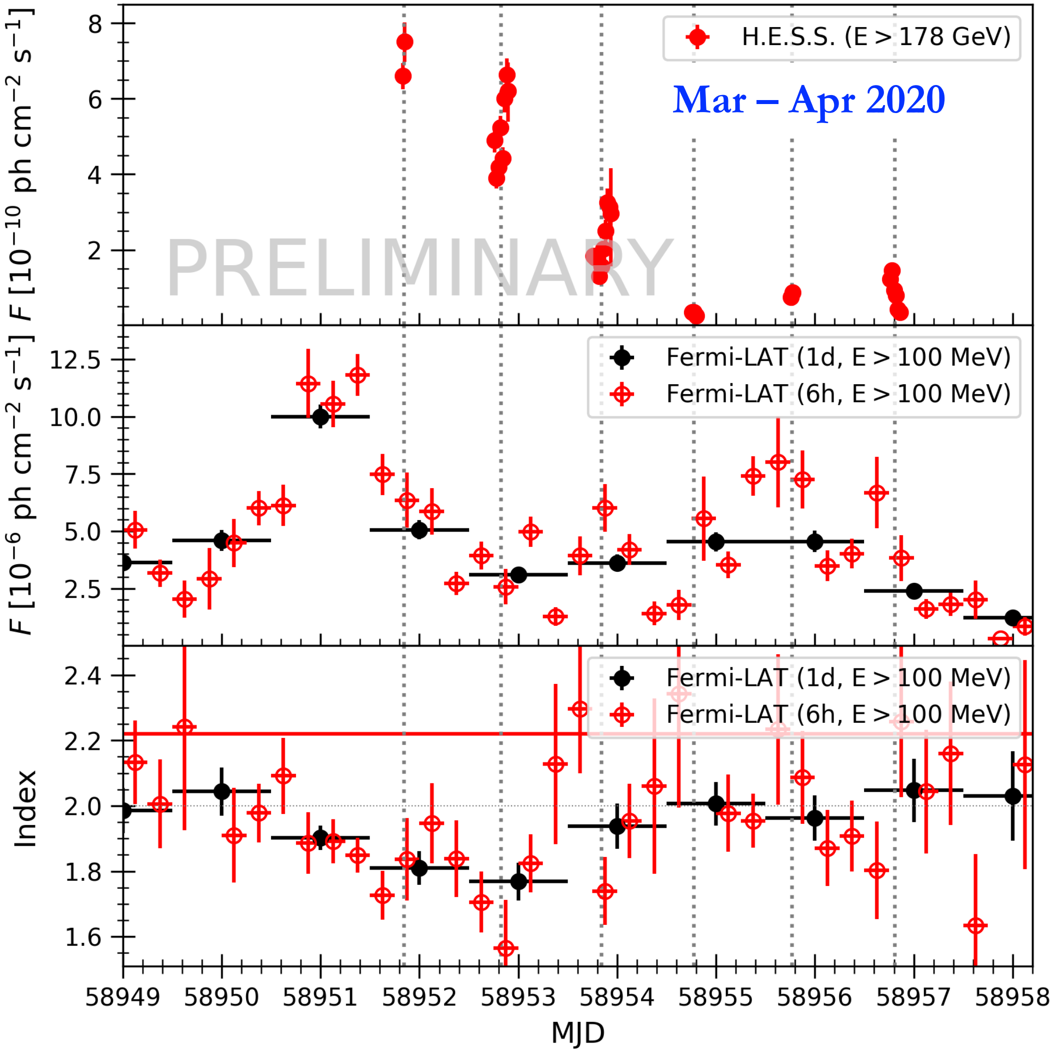


M. Zacharias + H.E.S.S. . GAMMA 24



- Long period of quiescence with Fermi-LAT, followed by activity
- VHE emission detected in coincident with 3rd flare → A striking change in the γ-ray spectrum noted compared to the 4FGL
  → γ-ray peak position shifted from ~ 100 MeV (4FGL) to ~ GeV

H.E.S.S Detection of γ-ray Outburst of PKS 0903-57

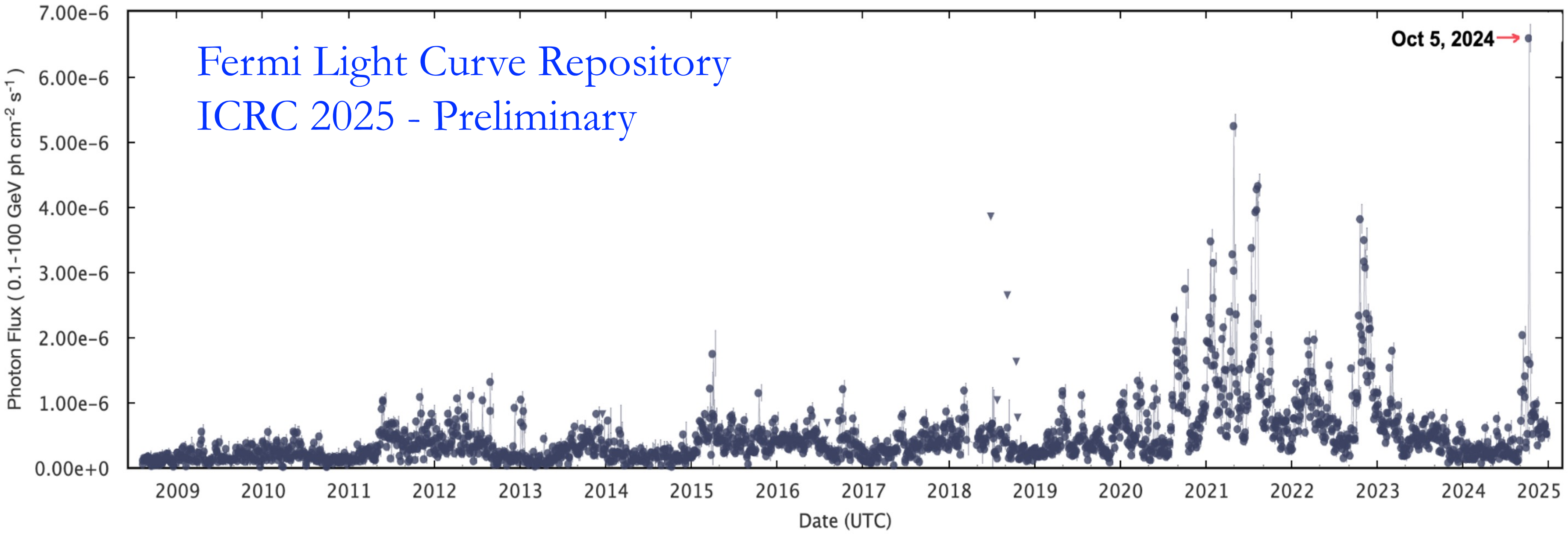


M. Zacharias + H.E.S.S. . GAMMA 24

- H.E.S.S. → Total of ~ 13 h of data, 100 σ > above 160 GeV
- The VHE flux variability time scale is on the order of a few hours
- Evolution of VHE & HE fluxes are different
  → Variability across bands may or may not be correlated

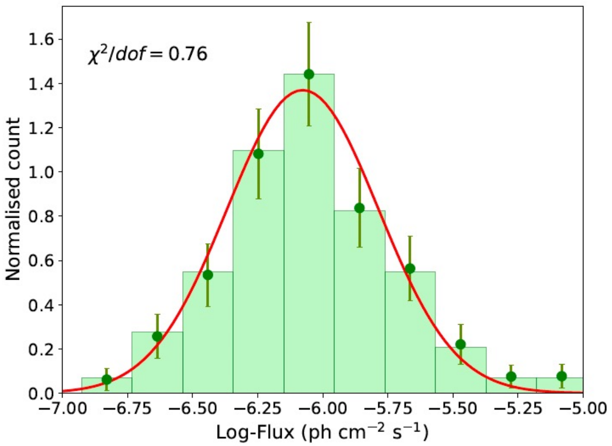
- MWL constraints suggest that the flare probably took place within the dusty torus, possibly powered by shock acceleration

BL Lacertae October 2024 Flare – Highest GeV γ Flux



- Shortest variability timescale?
- Any spectral variations on intranight timescales?

Majumdar, ++ 2025JHEAp..4800402M

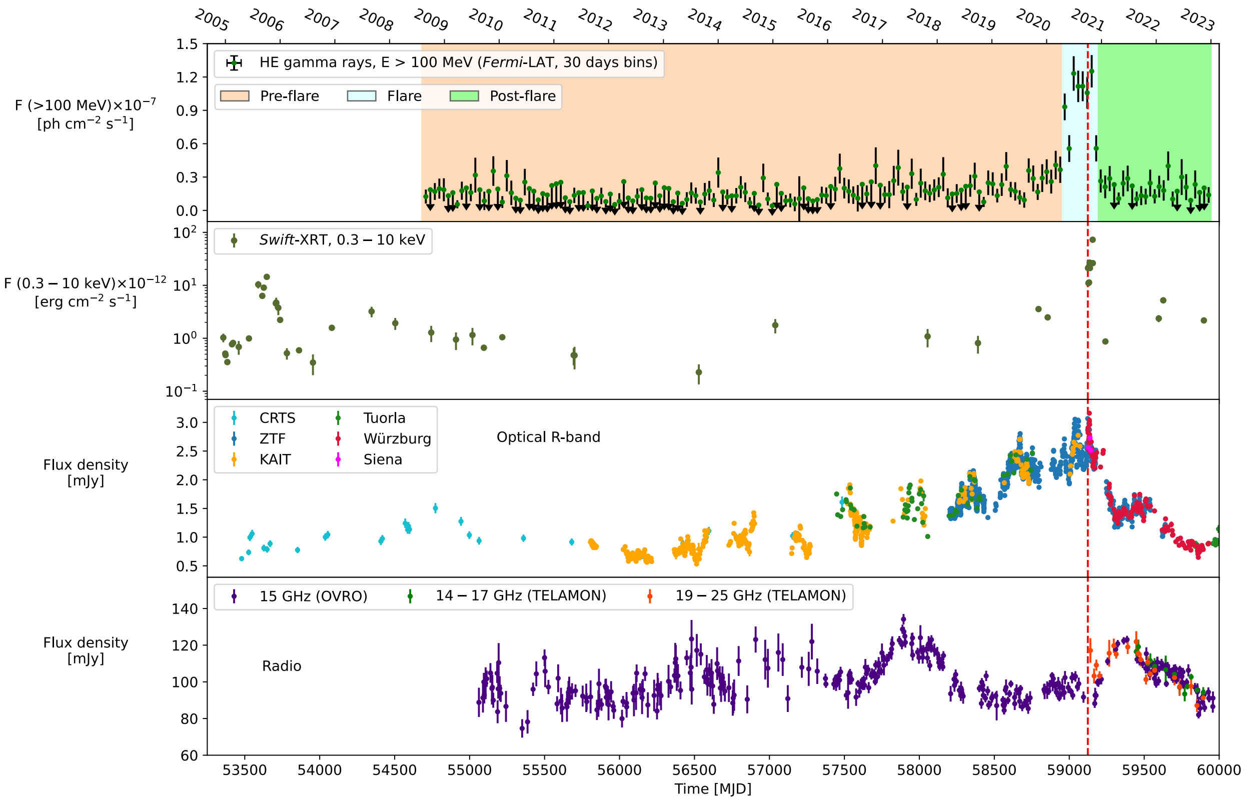


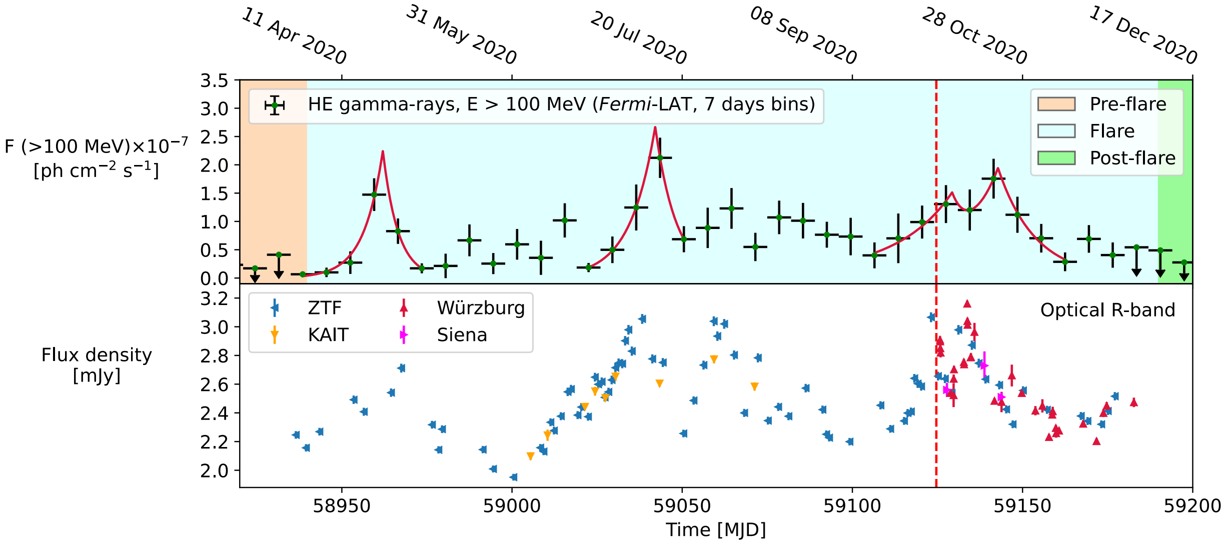
Historically bright γ-ray flux → ~2.59 x 10^{-5} erg cm^{-2} s^{-1}
Detection of a 175.7 GeV photon
Log-normal flux distribution

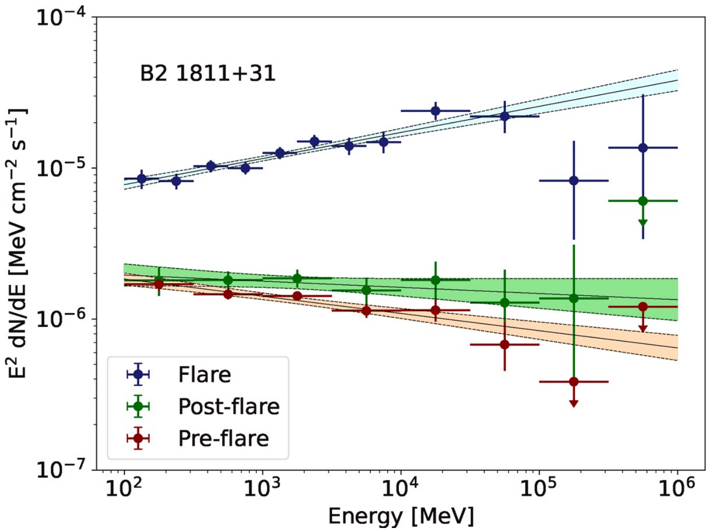
- On Oct 5, 2024, BL Lac exhibits the highest GeV γ-ray flux to date
- Daily-binned 0.1-300 GeV flux ~ 1 × 10^{-5} ph cm^{-2} s^{-1}
- VERITAS observations were triggered using Astro Colibri (https://astro-colibri.science/flaapluc)

B2 1811+31: Blazar Lightcurves Remain a Mystery

Abe, MAGIC ++ A&A, 697, A172 (2025)





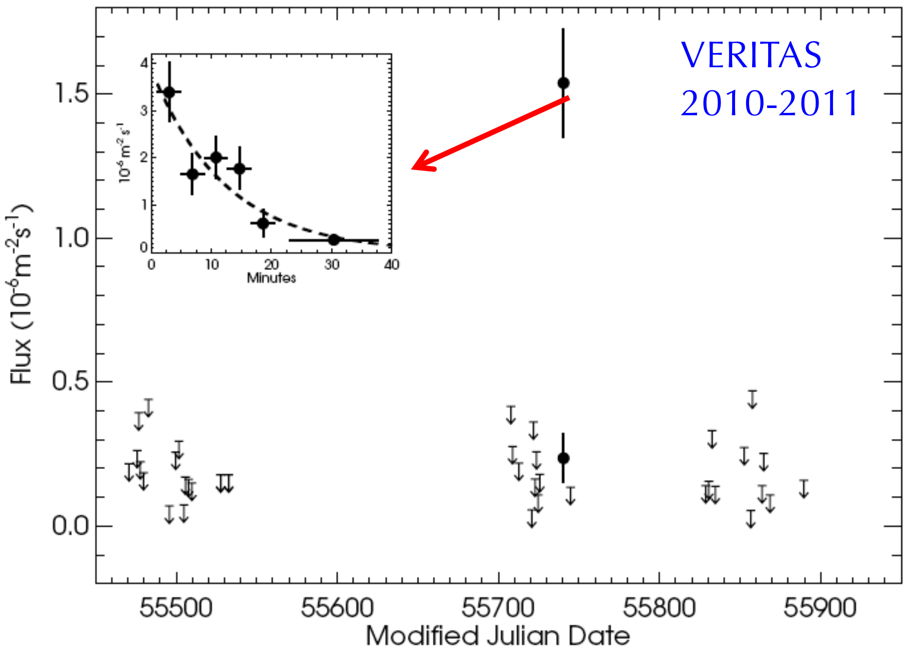


- What causes blazar flares? What is the cadence of blazar flares?
- *Fermi*-LAT B2 1811+31 12-year full dataset light curve, with 1-month bins:
  → Long period of inactivity followed by enhanced state → Fermi-LAT ToO
- MAGIC and VERITAS detections of a flare in B2 1811+31

Fast Flares – Correlation with Radio (mm)

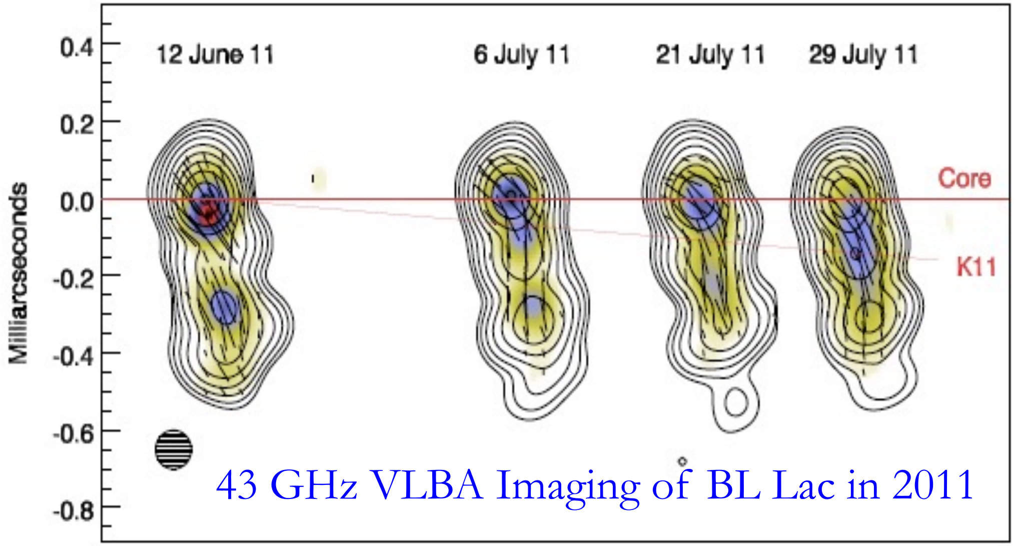
BL Lacertae Flare and Rapid Variability (2011)

Locating the Emission Region in the Jet



VERITAS, Arlen, T. et al. 2013, ApJ, 762,92

New superluminal component near core (43 GHz) – emergence of radio knot linked to γ ray flare

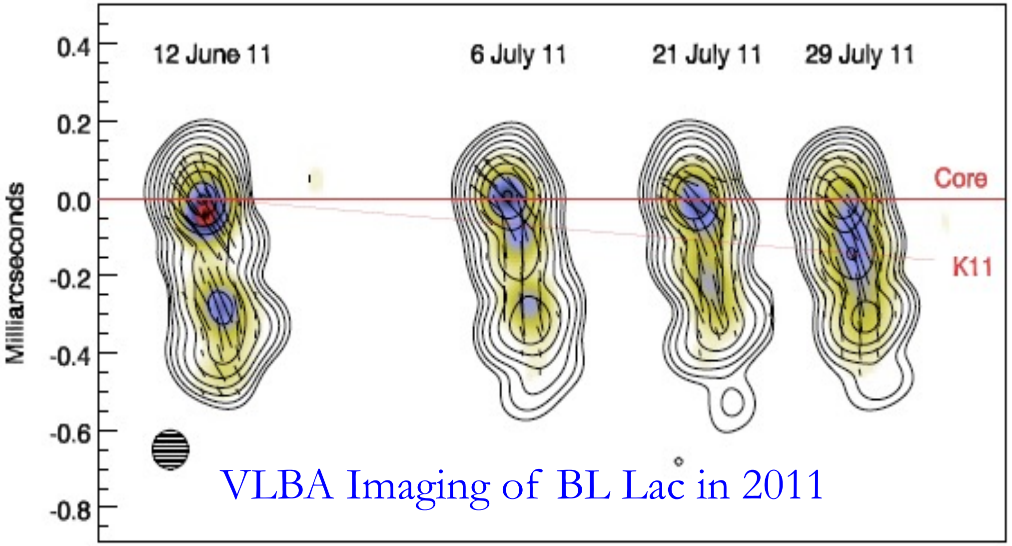


A change seen in the polarization of the core before and after the TeV γ-ray flare (15.4 GHz Mojave)

- Flare on June 28, 2011 picked up by VERITAS monitoring; 125% Crab flux (> 200 GeV); $\Gamma = 3.8 \pm 0.3$
- Flux decayed by factor of 10 in $\tau = 13 \pm 4$ min => Strongly constrains size of emission region ($R < 2.2 \times 10^{13} \delta$ cm)

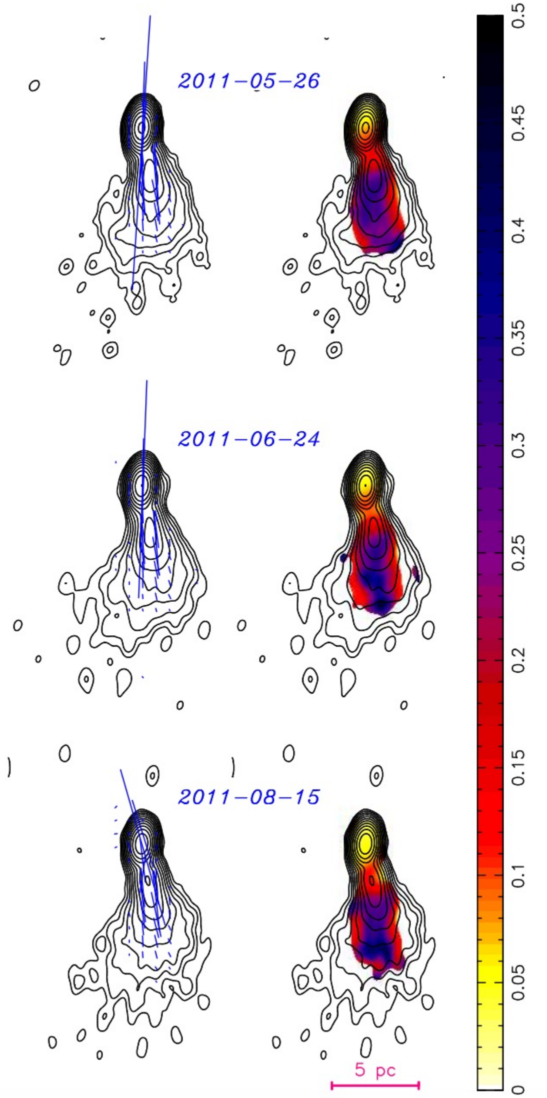
BL Lacertae Flare and Rapid Variability (2011)

Locating the Emission Region in the Jet



43 GHz VLBA

Emergence of superluminal radio knot linked to γ ray flare



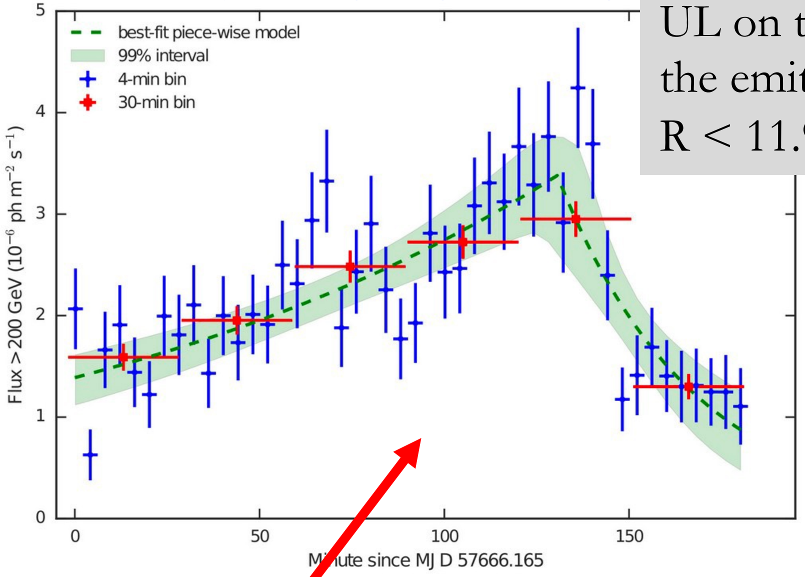
15.4 GHz MOJAVE
Fractional linear polarization 0 to 50%

- Simultaneous changes in optical polarization, X-ray, optical and UV flux + new radio feature: Enables location of emission region
- A change seen in the polarization of the core before and after the TeV γ-ray flare
- No change in the downstream jet polarization
- Emergence of a new component associated with the γ-ray flare

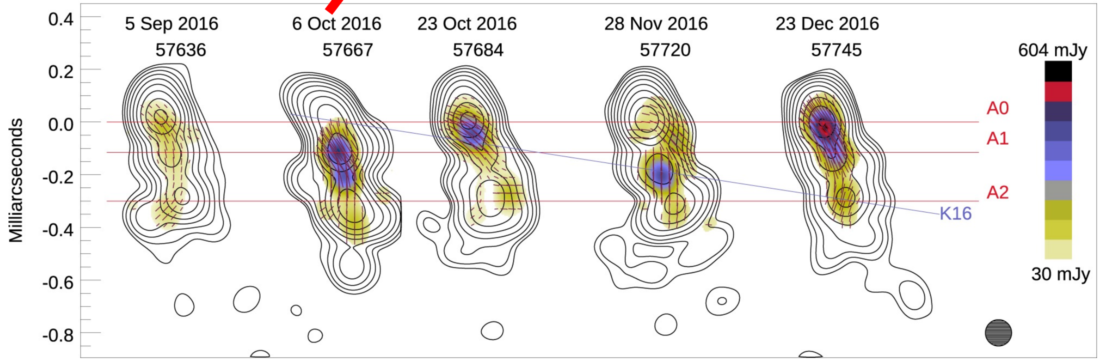
Jorstad, Marscher, Boston U.

BL Lac (2016): γ/VLBI Events – flare simultaneous with ejecta close to the core

BL Lac – Fast TeV Flare



UL on the size of the emitting region: $R < 11.9R_s$



v_{app} measured by VLBI ~ 6c

- Rise ~2.3 hr and a decay time of ~36 min
- Peak flux ~ 180% Crab Nebula
- Contemporaneous variability in X-ray, optical, optical and radio
- Superluminal features at 43 GHz

Also seen in:

- 3C 120 in 2012-2014 (Casadio et al. 2015)
- S4 0954+658 in 2011 (Morozova et al. 2014)
- BL Lacertae 2011 (Arlen et al. 2013, in 2005 (Marscher et al. 2008)
- 3C 454.3 in 2010 (Wehrle et al. 2012)
- OJ 287 in 2009, 2017 (Agudo et al. 2010, VERITAS 2018)
- PKS1510-089 in 2009 (Marscher et al 2010)

Models:

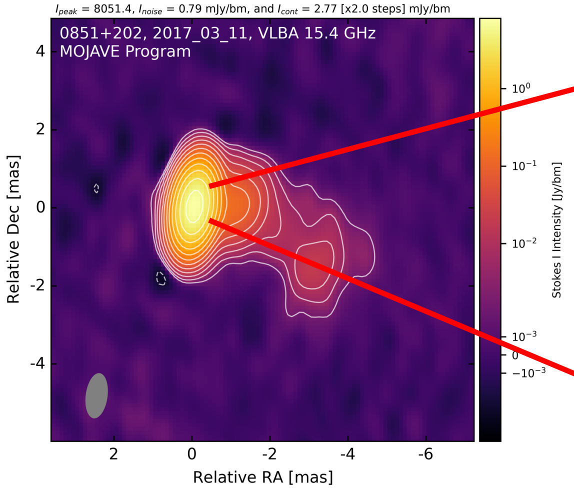
We need an emission zone…

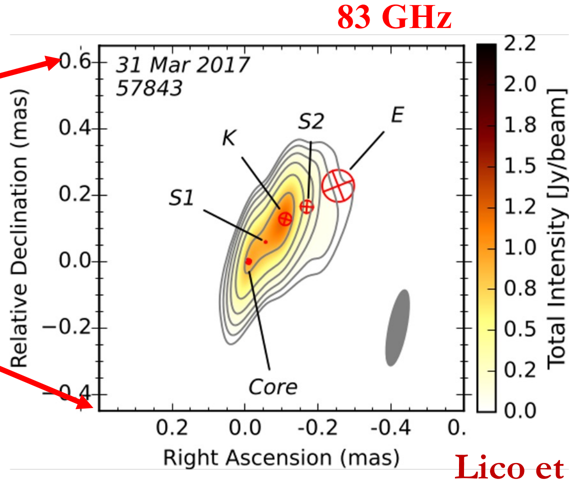
I. relatively small
II. highly Doppler-boosted
III. not too close to the nucleus
IV. in or outside the radio core

Jorstad, Marscher, Boston U.
VERITAS, 2018 *ApJ* 856 95

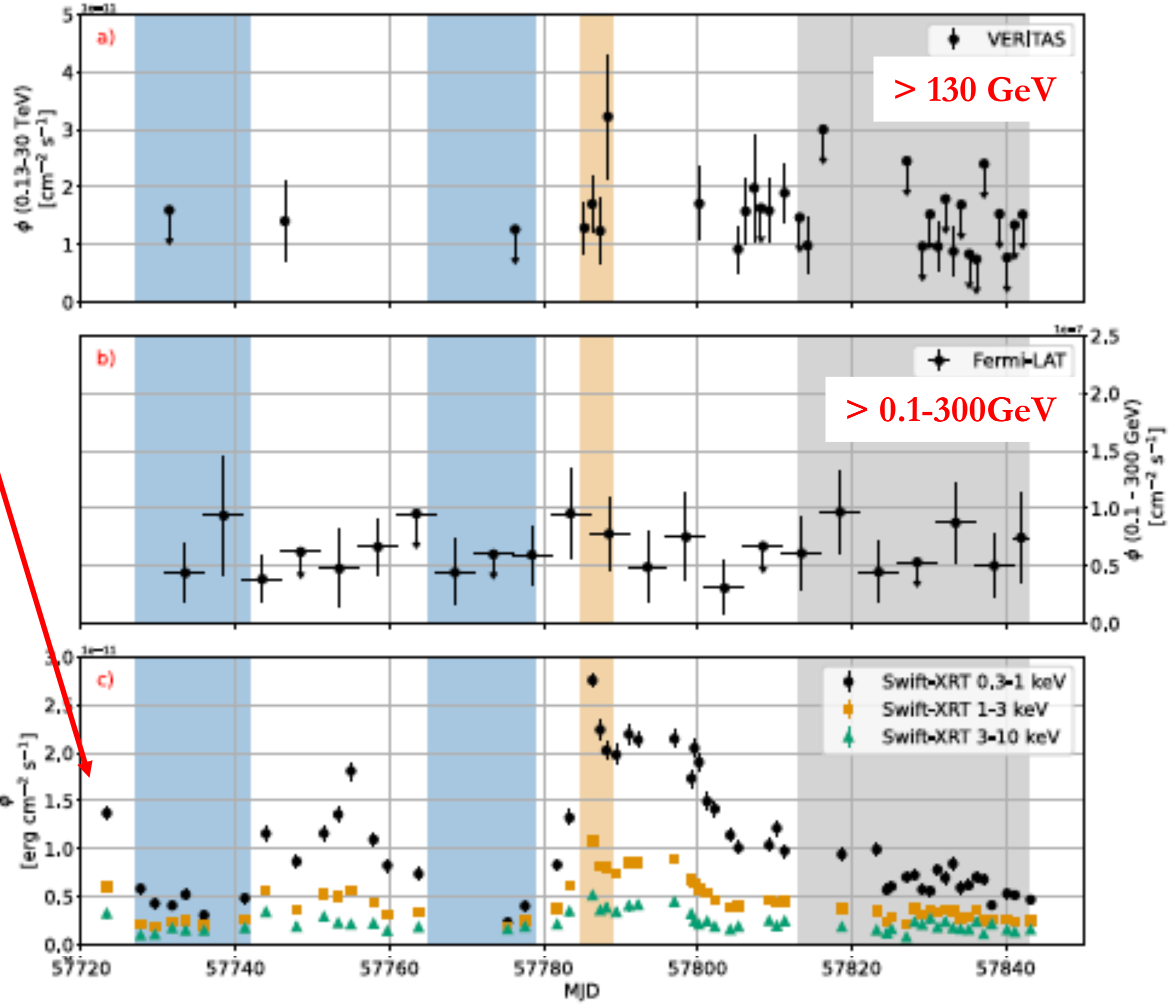
LBL OJ 287
TeV Flare During Historic Soft X-ray Flare

- VERITAS monitoring program on OJ 287 in Dec 2016 (a new historic peak in the soft X-ray)
- VERITAS ToO observations from from 1-4 Feb 2017 → resulted in a > 5σ detection (VERITAS ATel # 10051)
- Observations (83 GHz) of a brightening of the 1st radio knot (S1) before the Feb 2017 flare, and a new radio knot downstream a strongly suggests a flare happening in S1 (~10pc from the core)





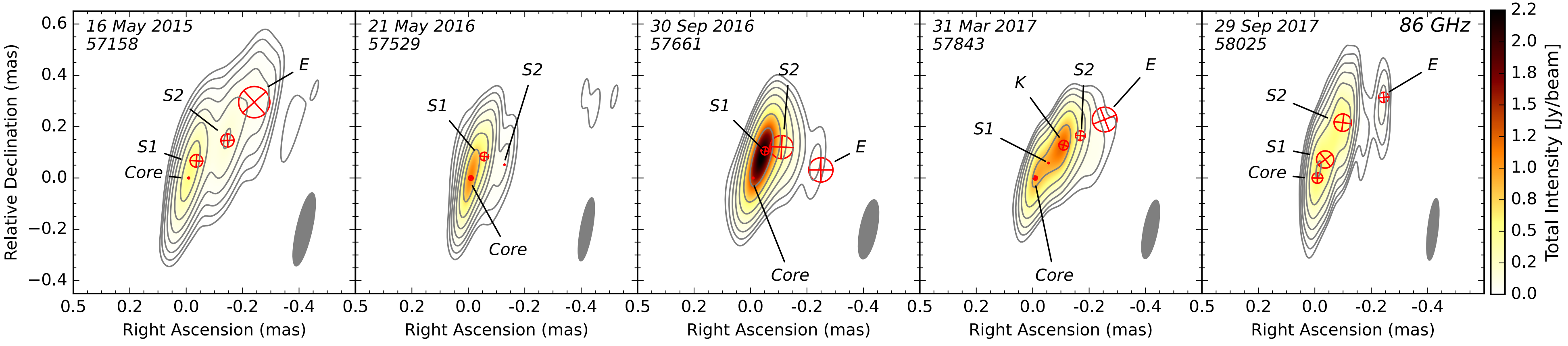
Lico et al. 2022A&A...658L..10L



VERITAS, 2024ApJ...973..134A

Parsec-scale Properties of OJ 287 During TeV Flare

Lico et al. 2022



GMVA: a new jet feature (K) at ~0.2 mas from the core region and located in between two quasi-stationary components (S1 and S2) observed, following the VHE activity

- Parsec-scale source properties investigated via high-res VLBI
- 86 GHz Global Millimeter-VLBI Array (GMVA) observations from 2015 to 2017
- Multiple periods of enhanced activity are detected at different radio frequencies before and during the VHE flaring state
- Recollimation shock. Interaction of S2 & K
- Passage of a new jet feature through a recollimation shock in a region of the jet located at a distance of ~10 pc from the radio core → **Possible trigger for VHE**

VERITAS, 2024ApJ...973..134A

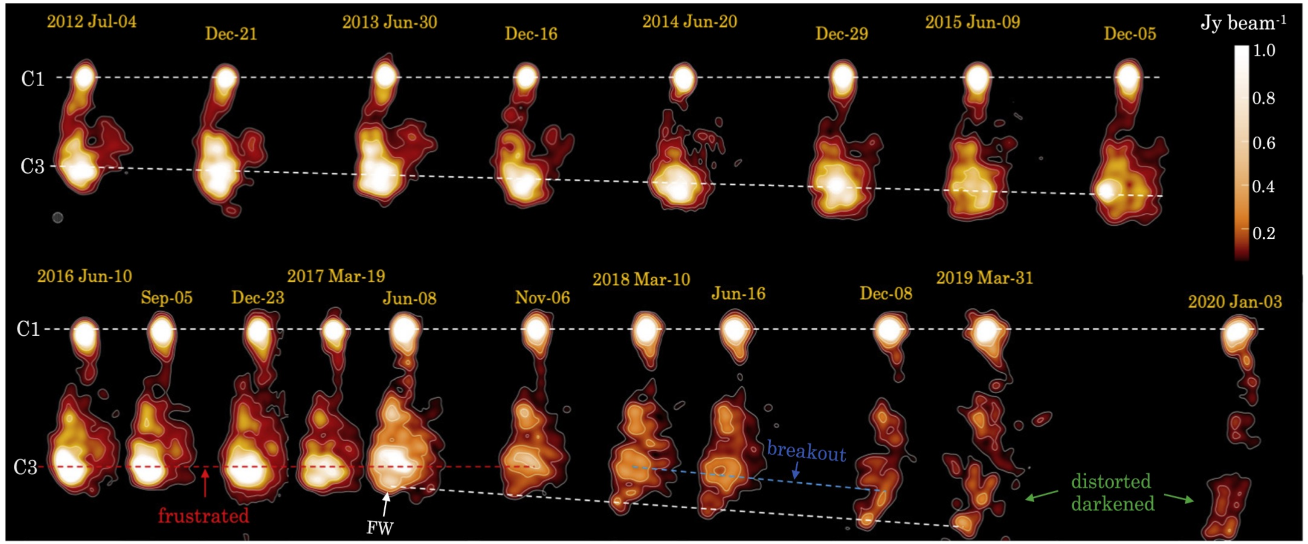
Other Nearby Extragalactic Sources: Radio Galaxies

Radio Galaxies (mis-aligned jets)

Name	Type	Distance
Cen A	FR I	3.7 Mpc
M 87	FR I	16 Mpc
NGC 1275	FR I	70 Mpc
IC 310	FR I/BL Lac	80 Mpc
3C 264	FR I	95 Mpc
PKS 0625-35	FR I/BL Lac	220 Mpc

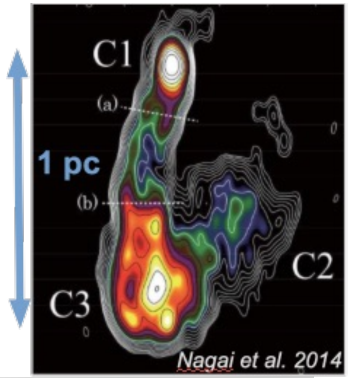
Rieger & Levinson 2018Galax...6..116R

NGC 1275: VLBA image at 43 GHz from 2012 July to 2020 Jan

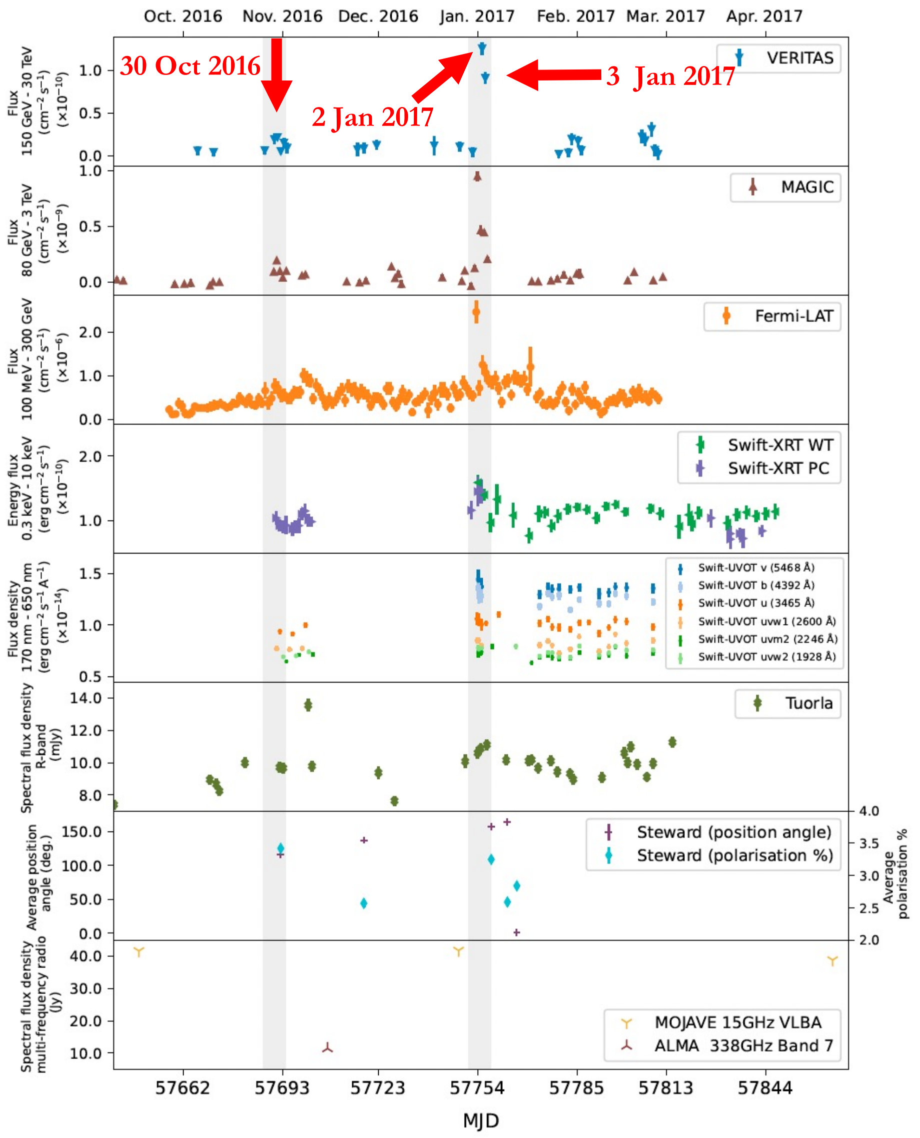


Kino et al. 2021ApJ...920L..24K

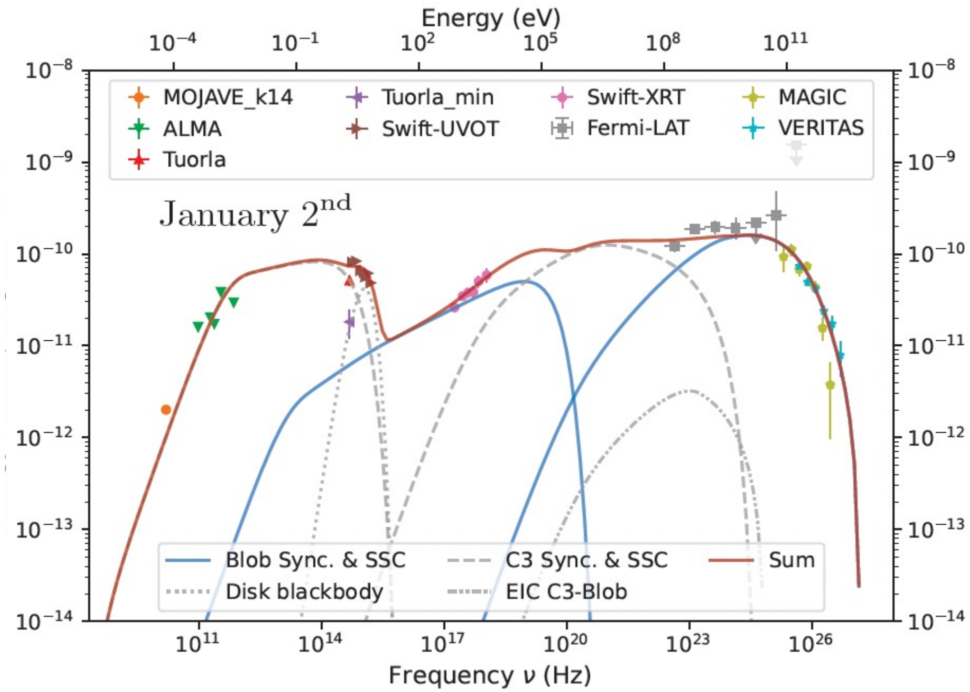
- Radio Galaxies as mis-aligned "blazars" → opportunities for improved understanding of jets VHE emission cannot be produced in same region as mm-band. Need of structured jet model
- Radio image of NGC 1275 shows hotspot associated with C3 entering "frustrated" phase for 1.3 yrs during period of increased γ-ray flux. **C3: brightest component (~3.5 core flux at 15 GHz)**
- New component (FW) seen emerging towards end of frustrated phase 3 months after VHE flare
- Flare interpreted as outcome of a strong relativistic jet perturbation interacting with a slower component in the vicinity of C3



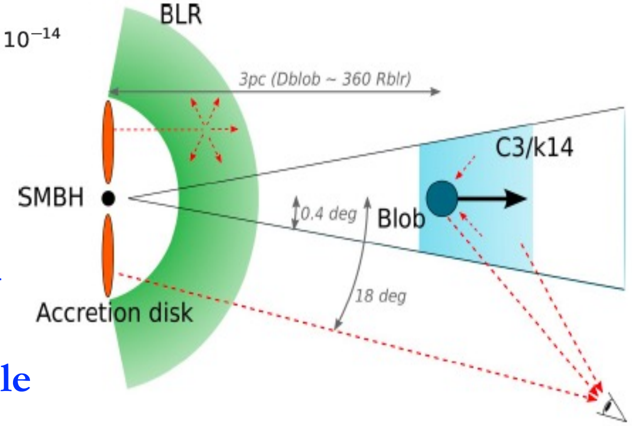
Radio Galaxy NGC 1275: Long term monitoring



VERITAS Collaboration, submitted (2026)



- Jan 2017: MAGIC flare ~150% Crab
- Next day: VERITAS sees ~60% flare
- Multizone blob in jet model can account for ~day-scale evolution of SED
- **Bright, short flares can give insight into particle physics → Limits on ALPs** (VERITAS, PRD 2025) (MAGIC 2024)

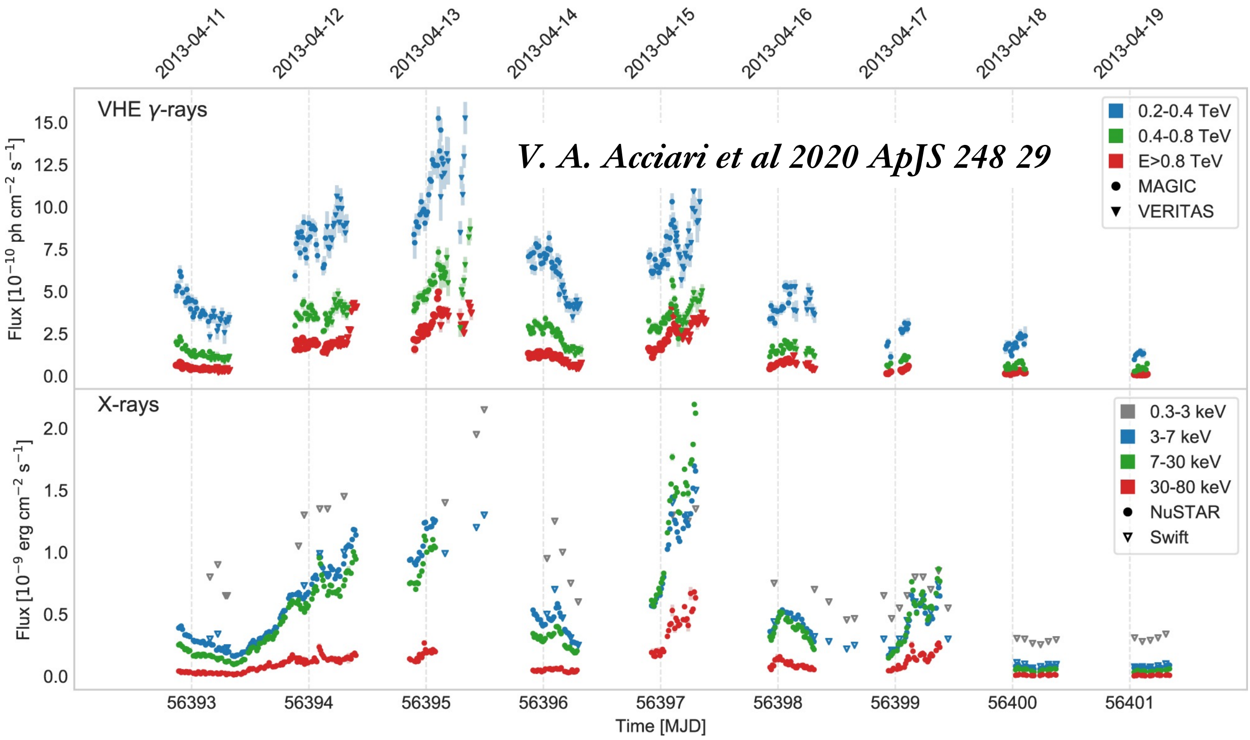


Hervet at al. 2016

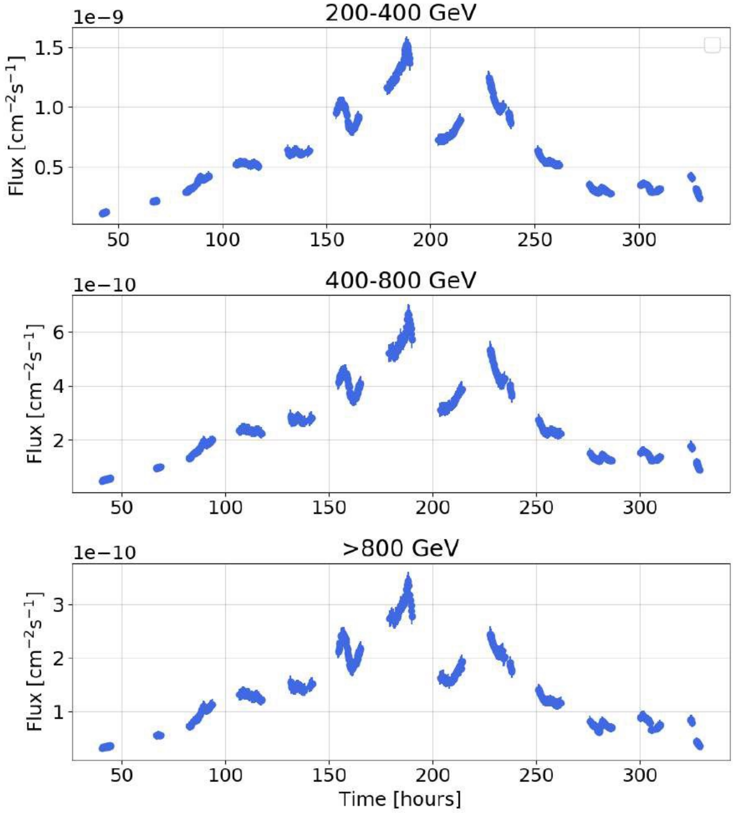
Origin of Fast Flares?

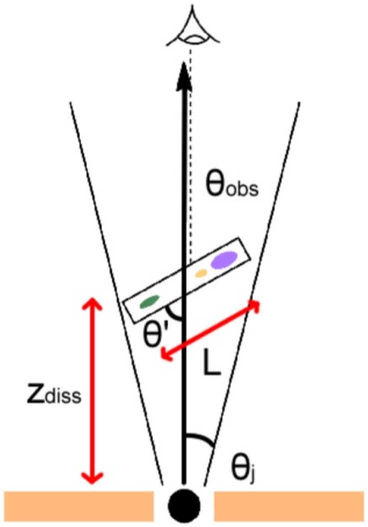
Magnetic Reconnection? Very Fast γ-ray Flares

Mrk 421 during an exceptional flare (2013 April)



Origin of short-duration flares is unknown



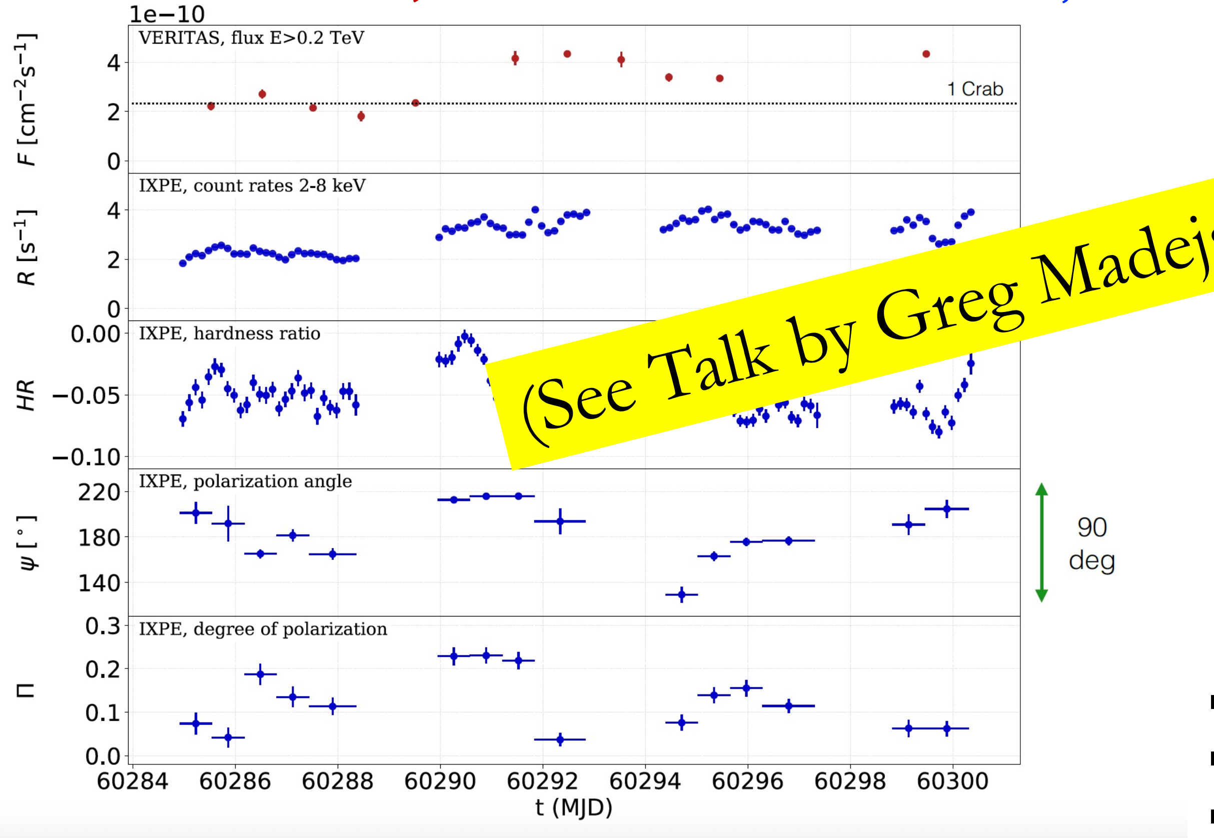


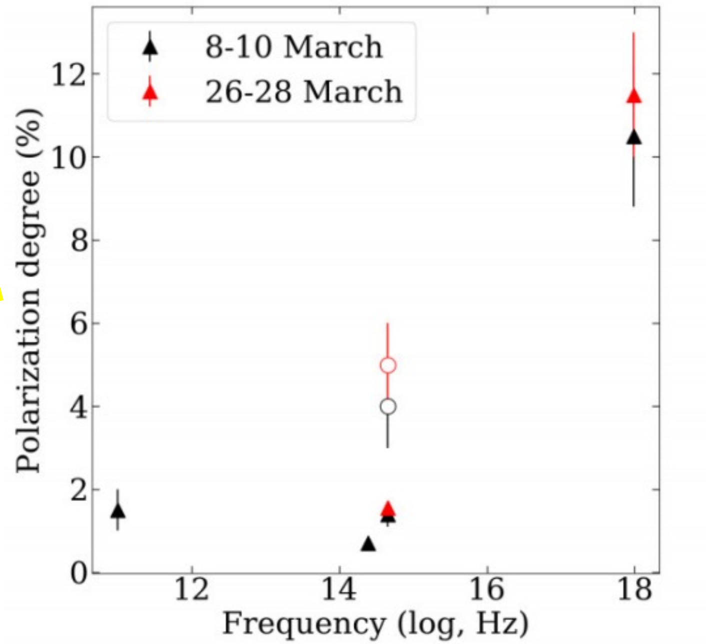
Simulated Mrk 421 light curves
J. Jormanainen A&A 678, A140 (2023)

- Observing campaign with MAGIC and VERITAS in 2013 when the source was flaring
- **Short flares could be due to plasmoids that produce flares with characteristic duration**
- γ-ray emission zone may be smaller than the jet-cross section → flares can be due to large plasmoids created during a magnetic reconnection event
- Variability seen in Mrk 421 2013 light curve could result from several reconnection layers with B = 1 G with different orientations θ

The Connection with Polarization → IXPE

Mrk 421, 2-22 Dec 2023 **Manel Errando, Gamma 2024**





First blazar polarization observation: Mrk 501

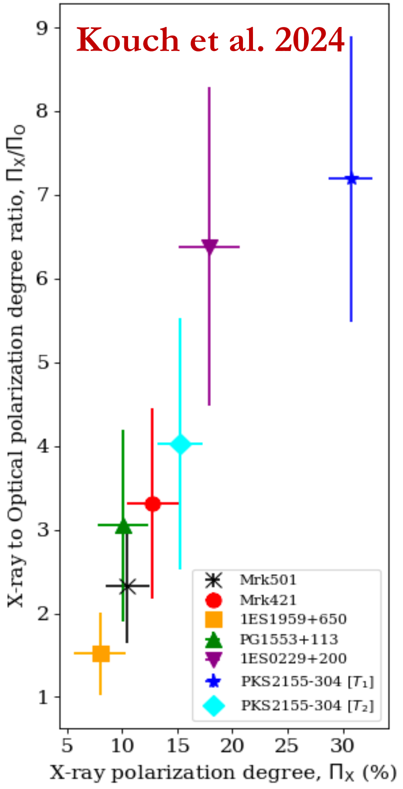
Liodakis, et al. (2022) Nature

Multiwavelength polarization of Mrk 501

- EVPA is aligned with the jet direction
- X-ray polarization is higher than optical polarization
- Polarization angle swings correlated with γ-ray activity
- Emission likely to originate from a localized region in the jet
- Complexity of pol. dynamics favor multi-zone emission region
- Ongoing PIC simulations (e.g. Haocheng Zhang, NASA)

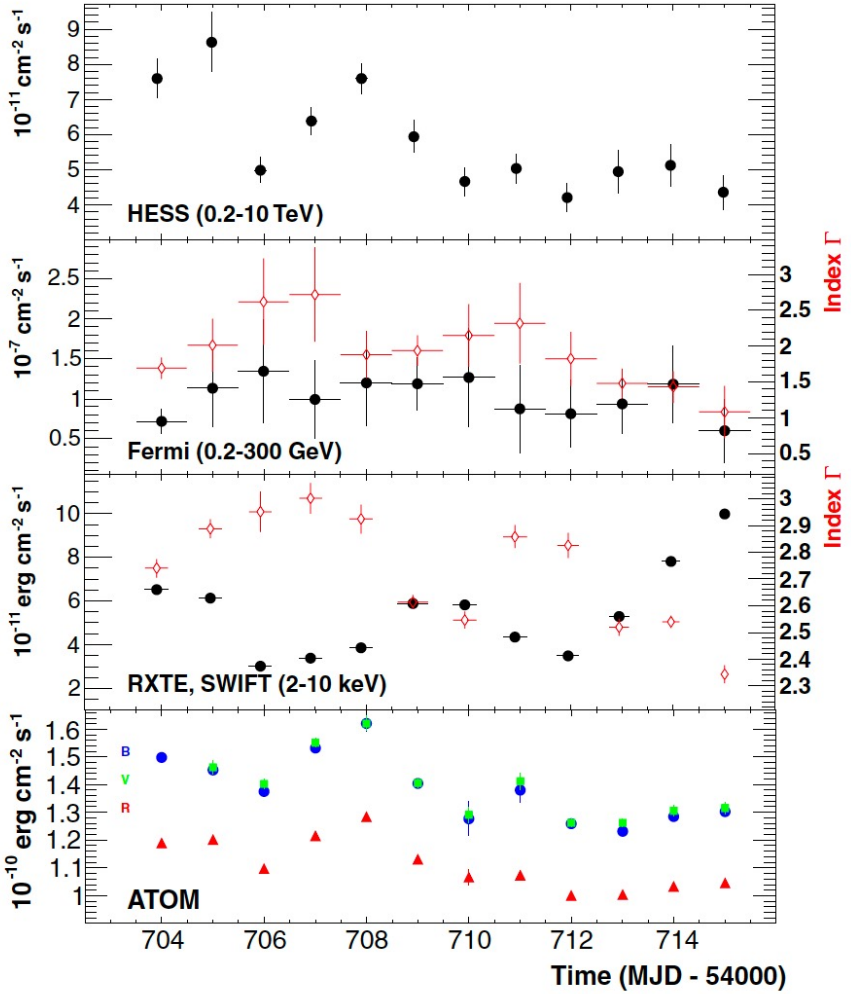
Acceleration of particles to high energies in blazar jets is related to the magnetic field → Can be probed by observations of the polarization of light

PKS 2155−304 → the most highly polarized blazar



- Highest X-ray polarization ~ 30%
- Lack of correlation of temporal variability between the MW polarization properties
- **→ Energy-stratified shock-acceleration scenario in HSP blazars**

H.E.S.S. Collab. Giebels, Chiang ++ 2007

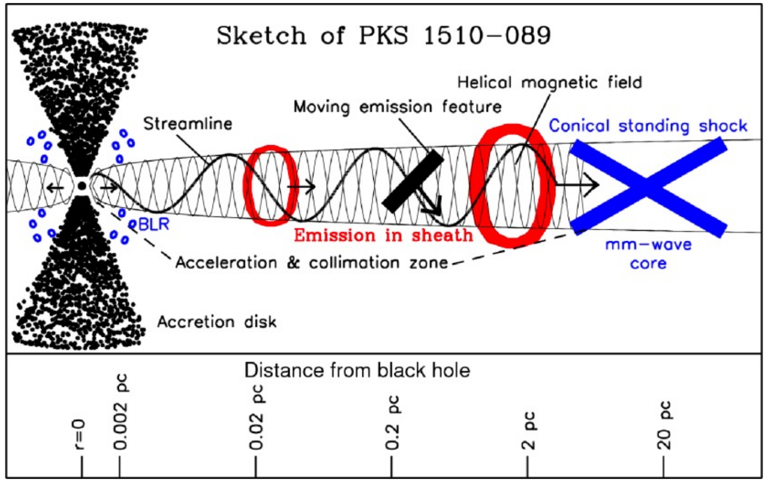


- First simultaneous observations in optical, X-ray, and high-energy gamma-ray (H.E.S.S.) bands of PKS 2155−304
- Clear optical/VHE correlation
- **No correlation between the X-ray and VHE components**
- "Synchrotron self-Compton models are often invoked to explain the SEDs of BL Lac objects → at odds with the correlated variability seen for PKS 2155−304."
- **Consideration of jet-in-jet models, spine-sheath and decelerating flow models**

Understanding Ultrafast Variability in Blazars

Theoretical models suggest →

- Ultrafast γ-ray flares are produced in magnetospheric gaps/current sheets (e.g. Neronov & Aharonian 2007; Ghisellini et al. 2009; Levinson & Rieger 2011; Hakobyan et al. 2023)
- γ-ray flares produced due to the interaction of the jet with an external cloud or a star (e.g., Araudo et al. 2010; Barkov et al. 2012) (however, this scenario requires very large jet power)
- Due to the relativistic random motion of "blobs" in the proper frame of the jet ("jets-in-a-jet" models) (e.g. Giannios et al. 2009; Nalewajko et al. 2011)

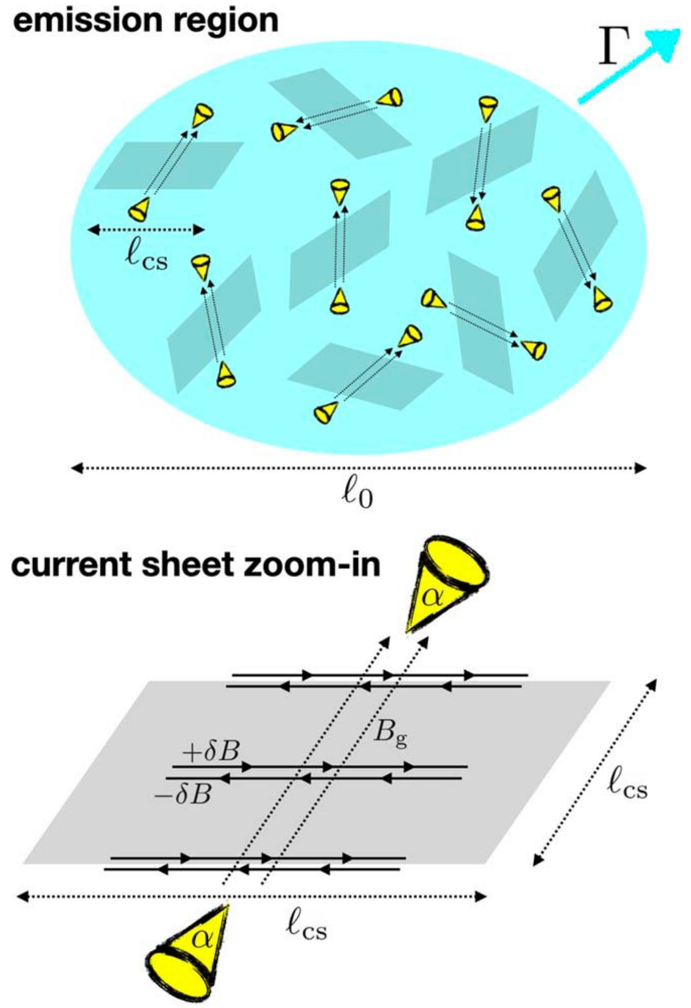


Alan Marsher's model remains very relevant:
Many γ-ray flares occur as "blob" passes through or continues downstream of core, a "steady" feature, e.g., standing (recollimation?) shock

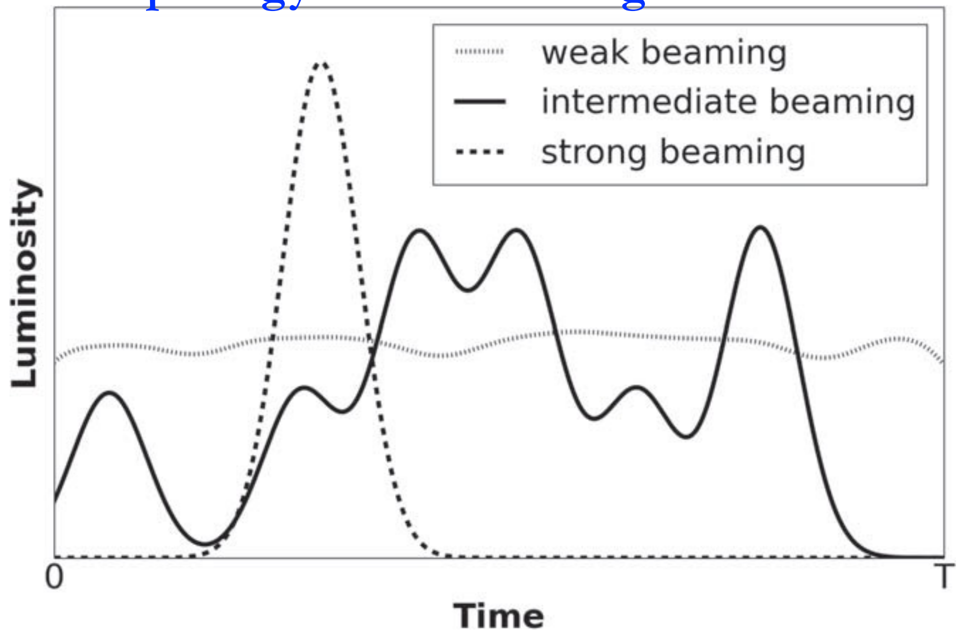
If the jets are highly magnetized, shock acceleration is not effective. Instead, magnetic reconnection could efficiently convert magnetic energy into particle energy (Sironi & Spitkovsky 2014; Sironi et al. 2015)

Ultrafast Variability in AGN Jets: Intermittency and Lighthouse Effect

Cartoon of a scenario: Sobacchi, Piran, Comisso, ApJL 946:L51 (2023)



Morphology of simulated lightcurves



The light curve becomes more variable as the beaming of the radiation from the current sheets increases

- The jet's energy is dissipated via a turbulent cascade. Due to the intermittency of the cascade, the dissipation is concentrated in a set of reconnecting current sheets with a typical size ℓ_{cs}
- Electrons energized by reconnection have a strong pitch-angle anisotropy
- The γ-ray light curve is highly variable as a single beam dominates over the whole emission region when it intercepts the line of sight

Summary

- Observations of fast TeV flares combined with measurements made by VLBI help probe the structure and emission mechanism of blazar jets
- IACTs have detected flares on time scales as short as ~15 min and recorded long baseline > 15 years
- The rapid γ-ray variability observed in TeV blazars implies very compact emitting regions, as well as low γ-ray attenuation by pair production on infrared/optical photons near the emission zone
- In HBLs, variability ➔ large Doppler factors, but low apparent speeds in VLBI jets
- Strong shocks could lead to local jet instabilities and turbulences favor magnetic reconnections ➔ Magnetic reconnection & plasmoids could explain short timescale variability in HBLs
- Direct and indirect observational evidences needed, e.g. through VLBI knot crossing and γ-ray flares → γ-ray flares can occur as "blob" passes through a standing recollimation shock
- **ToO follow ups of blazars as well as HE neutrino alerts continue to be important**

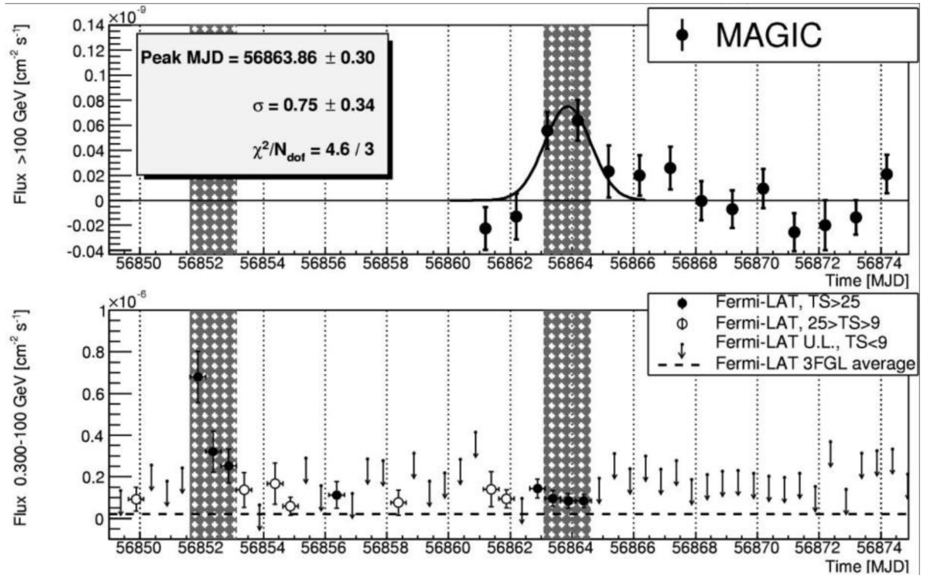
Thank you to Berrie Giebels for advancing our understanding of AGN variability

U.S. National Science Foundation
NASA
Barnard College Columbia University
Nevis Laboratories Columbia University
Columbia | Alliance
Columbia University | École Polytechnique
Sciences Po | Paris 1 Panthéon-Sorbonne
Research Corporation for Science Advancement
VERITAS

Gamma-ray Horizon: Blazar detection at z ~ 1

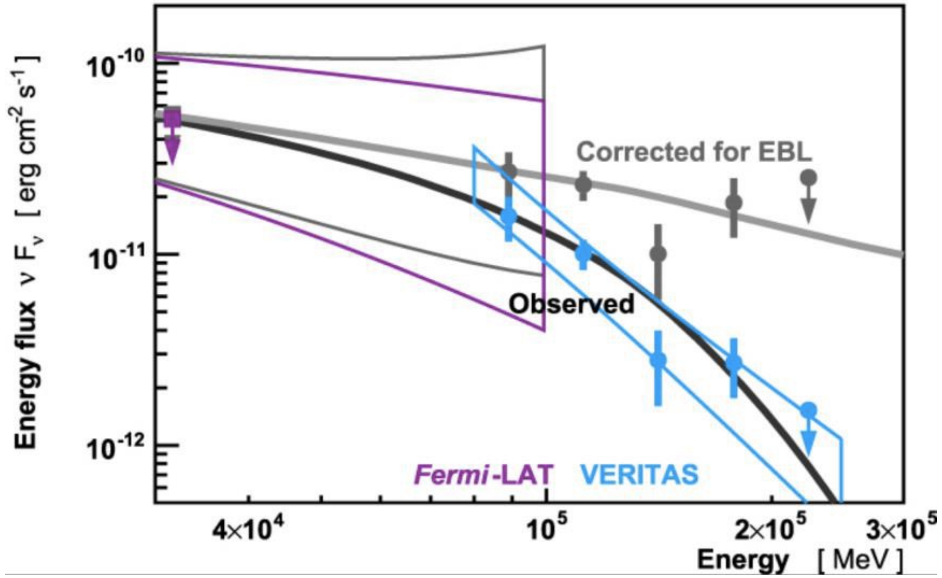
- Quasars are rare at TeV. Detection of 3C 279 by H.E.S.S. and MAGIC during Fermi flare.
- QSO B0218+357 (z=0.96) detected by MAGIC during a gravitationally lensed flaring event.
- Unexpected discovery of FSRQ PKS 1441+25 by MAGIC and VERITAS, z = 0.939.
- Powerful cosmological constraints from a single source, $\gamma + \gamma \rightarrow e^{+} + e^{-}$.

QSO B0218+357



MAGIC Collaboration, A &A, 595 (2016)

PKS 1441+25



VERITAS Collaboration, ApJL, 815 (2015)