CTAO | LST COLLABORATION

MAGIC

INFN Istituto Nazionale di Fisica Nucleare

Investigating the Emission Mechanism of Blazars S5 0716+714 and Mrk 421 with MAGIC and LST1 in a Multi-wavelength Context

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1. Introduction and motivation

TeV gamma-ray sky

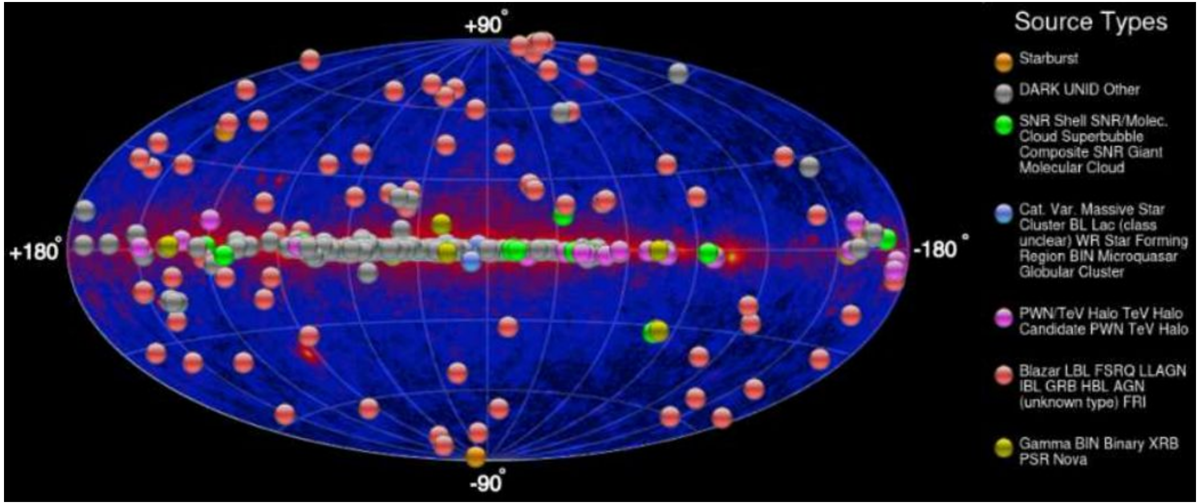


Image source: TeV cat

- Very High-Energy (VHE) gamma-ray astronomy studies the most energetic photons (E > 100 GeV), giving us a direct view of the most energetic cosmic accelerators
- Unlike charged cosmic rays, gamma rays are neutral and travel in straight lines. This allows us to trace them back directly to their sources

TeV gamma-ray sky

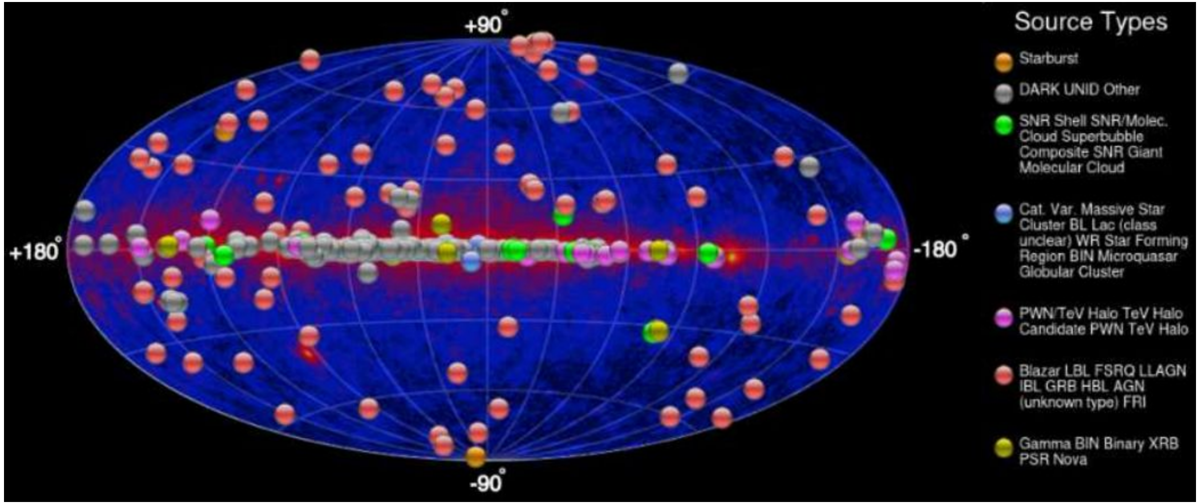


Image source: TeV cat

The field was born in 1989 with the first confirmed detection of Crab Nebula. Today, we know of over 250 sources, revealing a sky populated by diverse and powerful objects

A Sky of Two Halves:

- **Galactic: A rich population of sources concentrated along the plane of our Milky Way (Pulsar Wind Nebulae, Supernova Remnants)**
- **Extragalactic: Sources located far beyond our galaxy, which are dominated by one particular class of objects: blazars**

Blazars as a subtype of AGN

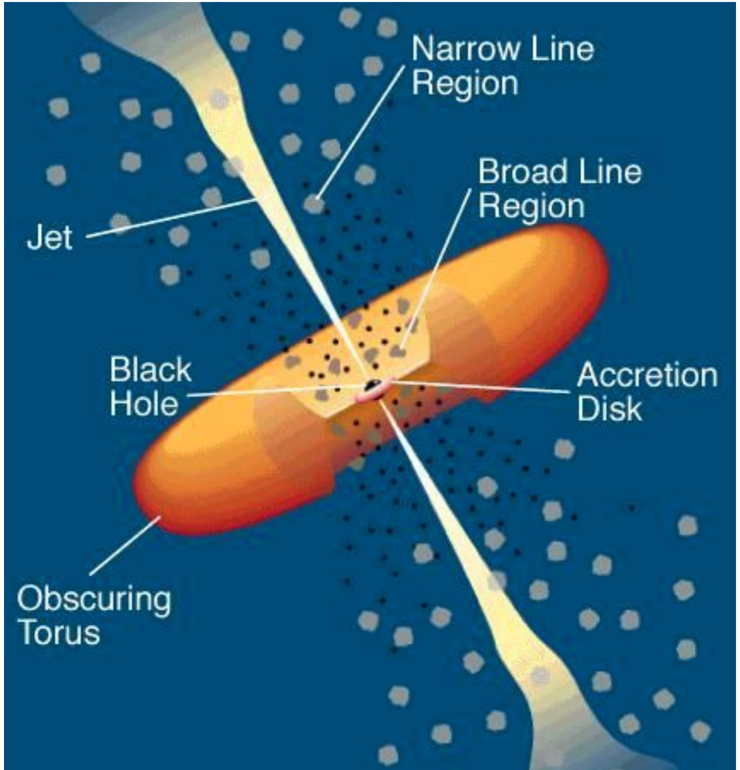


Image source: Urry & Padovani 1995

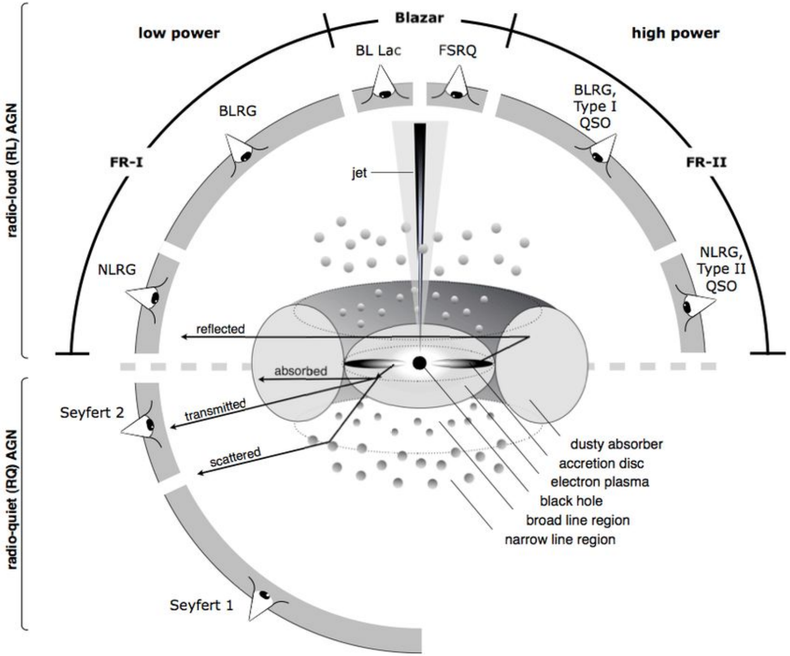
- An Active Galactic Nucleus (AGN) is a compact region at the center of a galaxy that emits a large amount of energy
- The "central engine" is a Supermassive Black Hole (SMBH) with mass ~ 10^6 - 10^{10} $M_{\odot}$
- It is powered by the accretion of matter, which forms a hot, glowing accretion disk as it spirals into the black hole

This central engine is often surrounded by key structures:

- Broad Line Region (BLR): Fast-moving gas clouds close to the disk.
- Dusty molecular torus that can obscure our view of the center.
- In some AGNs, powerful relativistic jets of plasma are launched perpendicular to the disk

Blazars as a subtype of AGN

- The wide variety of observed AGN can be explained by a single "Unified Model," where the main difference is our viewing angle
- The dusty torus acts like a cosmic absorber, hiding the central engine from certain lines of sight
- Pole-on view: We look straight into the center, seeing the bright accretion disk and the Broad Line Region. This gives a Type 1 AGN spectrum
- Edge-on view: Our view is blocked by the torus. We only see the Narrow Line Region further out, resulting in a Type 2 AGN spectrum
- The orientation of the relativistic jet is also crucial. When a galaxy has jets, our angle to the jet determines what we see

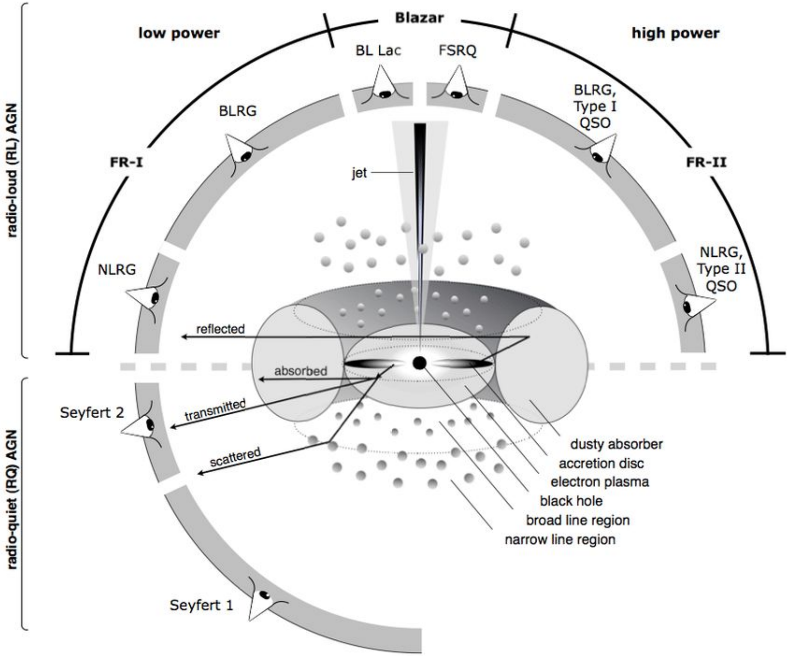


Blazars as a subtype of AGN

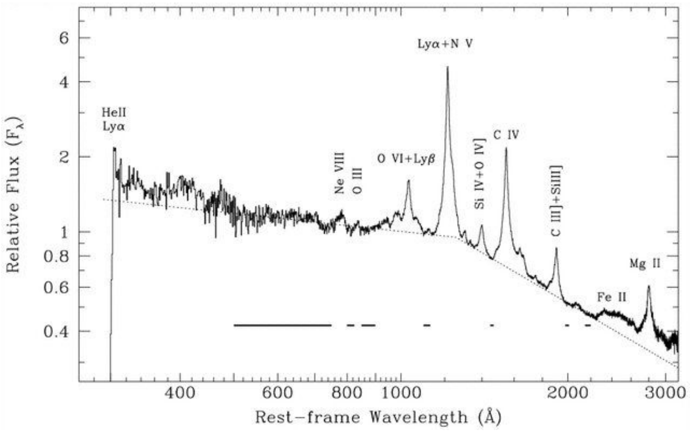
- Blazars are a special class of radio-loud AGN where the relativistic jet is pointed almost directly at Earth (a small viewing angle up to 20°)
- This alignment causes extreme relativistic beaming (Doppler boosting), which dramatically amplifies the jet's emission

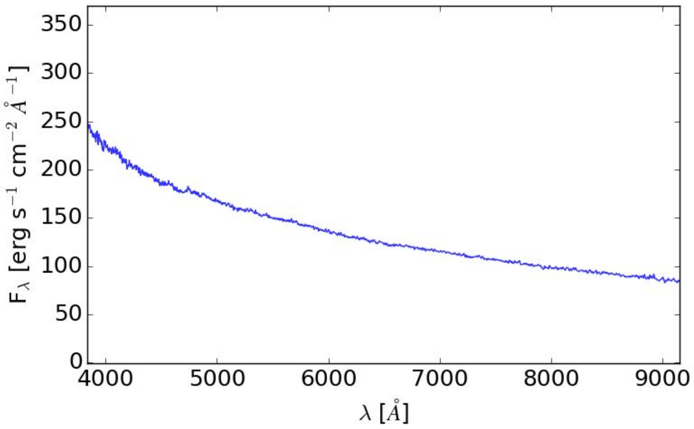
This has profound observational consequences:

- Extreme Apparent Luminosity: The non-thermal jet emission completely dominates the light from the host galaxy and accretion disk
- Rapid & Extreme Variability: Flux changes on timescales from minutes to years, indicating a very compact emission region
- Apparent Superluminal Motion: Blobs of plasma in the jet appear to move faster than the speed of light



Blazars as a subtype of AGN





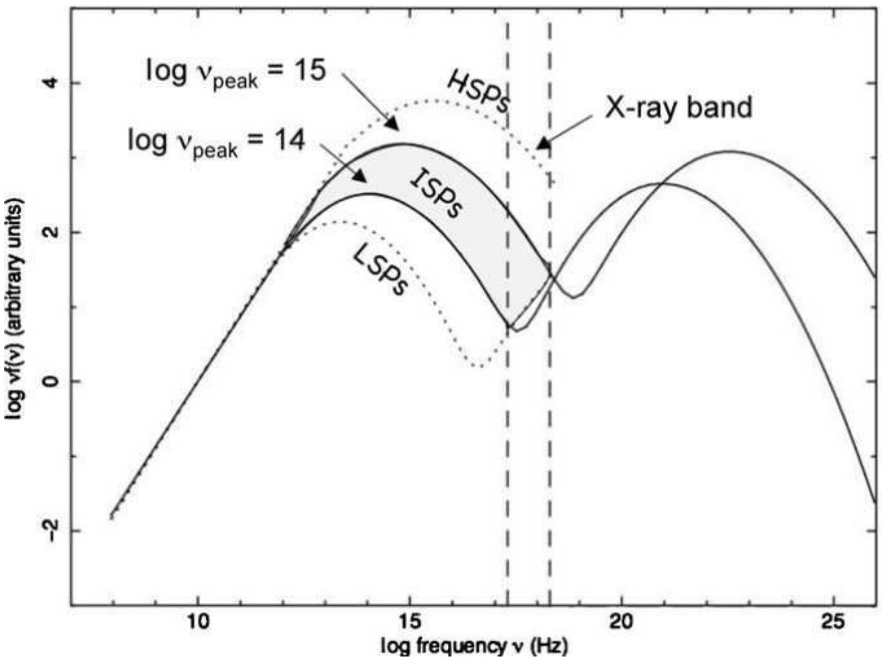
Flat-Spectrum Radio Quasars (FSRQs): Show strong, broad emission lines from the accretion disk and BLR. They are typically the most luminous blazars

BL Lacertae objects (BL Lacs): Have very weak or no emission lines because the featureless jet continuum outshines them. This work focuses on two BL Lacs

Blazars as a subtype of AGN

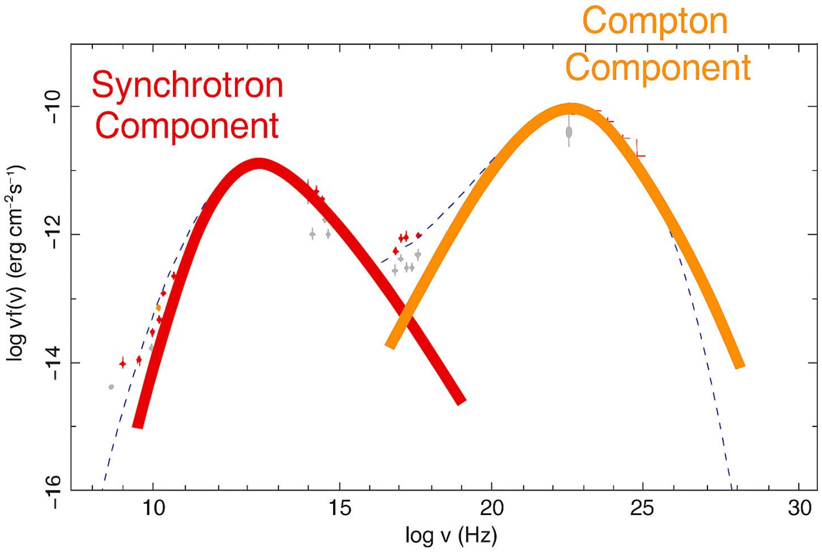
Blazars are also classified by their Spectral Energy Distribution (SED), specifically the peak frequency of the lower-energy synchrotron hump;

- Low-Synchrotron-Peaked (LSP): Peak in the infrared/optical. Includes FSRQs and some BL Lacs
- Intermediate-Synchrotron-Peaked (ISP): Peak in the optical/UV
- High-Synchrotron-Peaked (HSP): Peak in the UV/X-rays. These are prominent VHE gamma-ray emitters, like Mrk 421



The blazar ‘fingerprint’

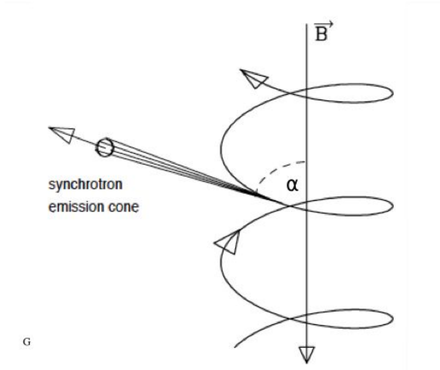
- Blazars emit energy across the entire electromagnetic spectrum, from radio waves to the highest energy gamma-rays
- When we plot this energy output against frequency, we get the blazar's Spectral Energy Distribution, or SED
- The SED is the unique "fingerprint" of a blazar, revealing the physical processes happening inside its powerful jet
- This fingerprint has a characteristic shape: a non-thermal continuum dominated by two broad, distinct humps

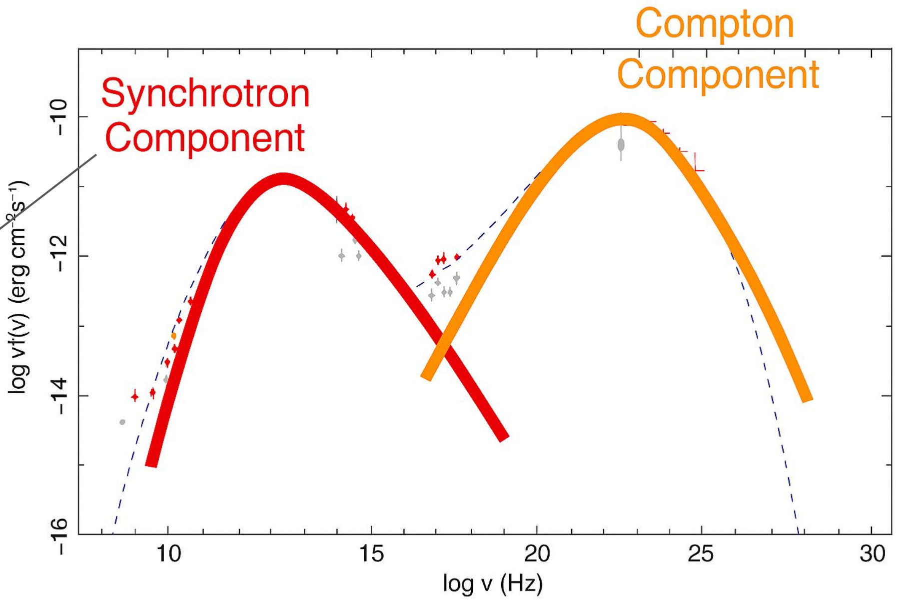


The blazar ‘fingerprint’

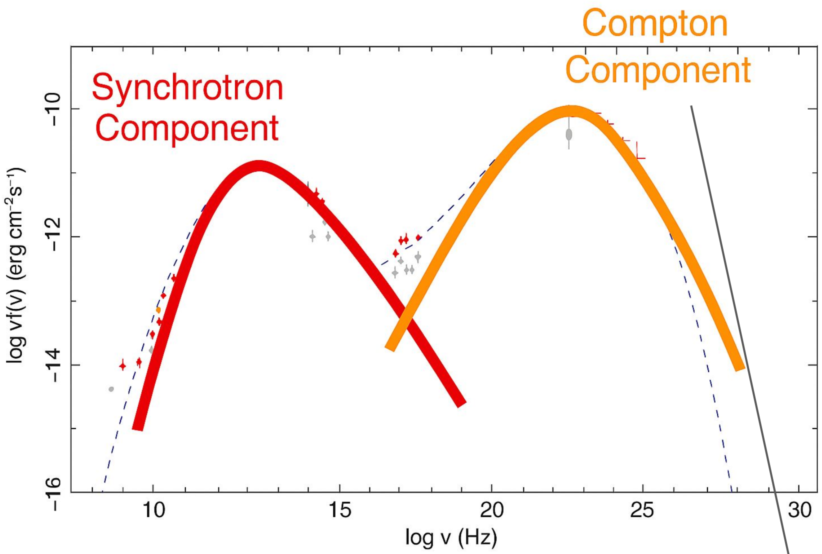
The Low-Energy Hump:

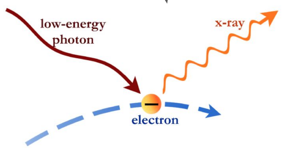
- **This first peak, located from the infrared to X-rays, is well-understood.**
- **It is produced by synchrotron radiation from relativistic electrons spiraling within the jet's magnetic field**





The blazar ‘fingerprint’





The High-Energy Hump: An Open Question

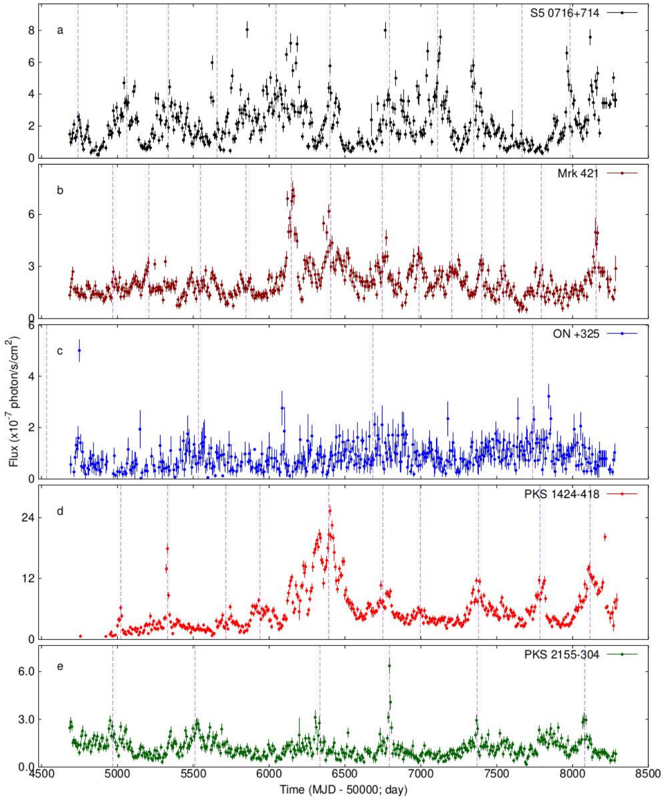
The origin of the second peak, extending to GeV-TeV energies, is one of the biggest unanswered questions in blazar astrophysics

Two main families of models to explain it:

- **Leptonic Models: The same electrons that produce synchrotron light create high-energy gamma rays by up-scattering lower-energy photons via the Inverse Compton (IC) process. This can be Synchrotron-Self Compton (SSC) or External Compton (EC)**
- **Hadronic Models: Propose that accelerated protons are responsible, producing gamma rays through processes like proton-synchrotron or pion decay**

Extreme variability and MWL approach

- Blazars are among the most variable astronomical objects known. Their brightness can change dramatically across the entire electromagnetic spectrum
- These variations occur on a huge range of timescales, from years and months down to hours or even minutes. This is known as intranight variability



Extreme variability and MWL approach

- Because blazars are so variable, observing them with just one instrument gives an incomplete picture. The Spectral Energy Distribution (SED) is not static; it changes as the source brightens and fades
- To truly understand the physics, we need to capture a "snapshot" of the blazar's emission across all wavelengths at the same time. This is the Multi-Wavelength (MWL) approach
- By coordinating observations between ground-based telescopes (like MAGIC and LST for VHE gamma-rays) and space-based observatories (Fermi-LAT, Swift, etc.), we can build a simultaneous SED
- This simultaneous data is essential for accurately testing and constraining our physical models (like the SSC model), allowing us to probe the conditions inside the jet during different activity states

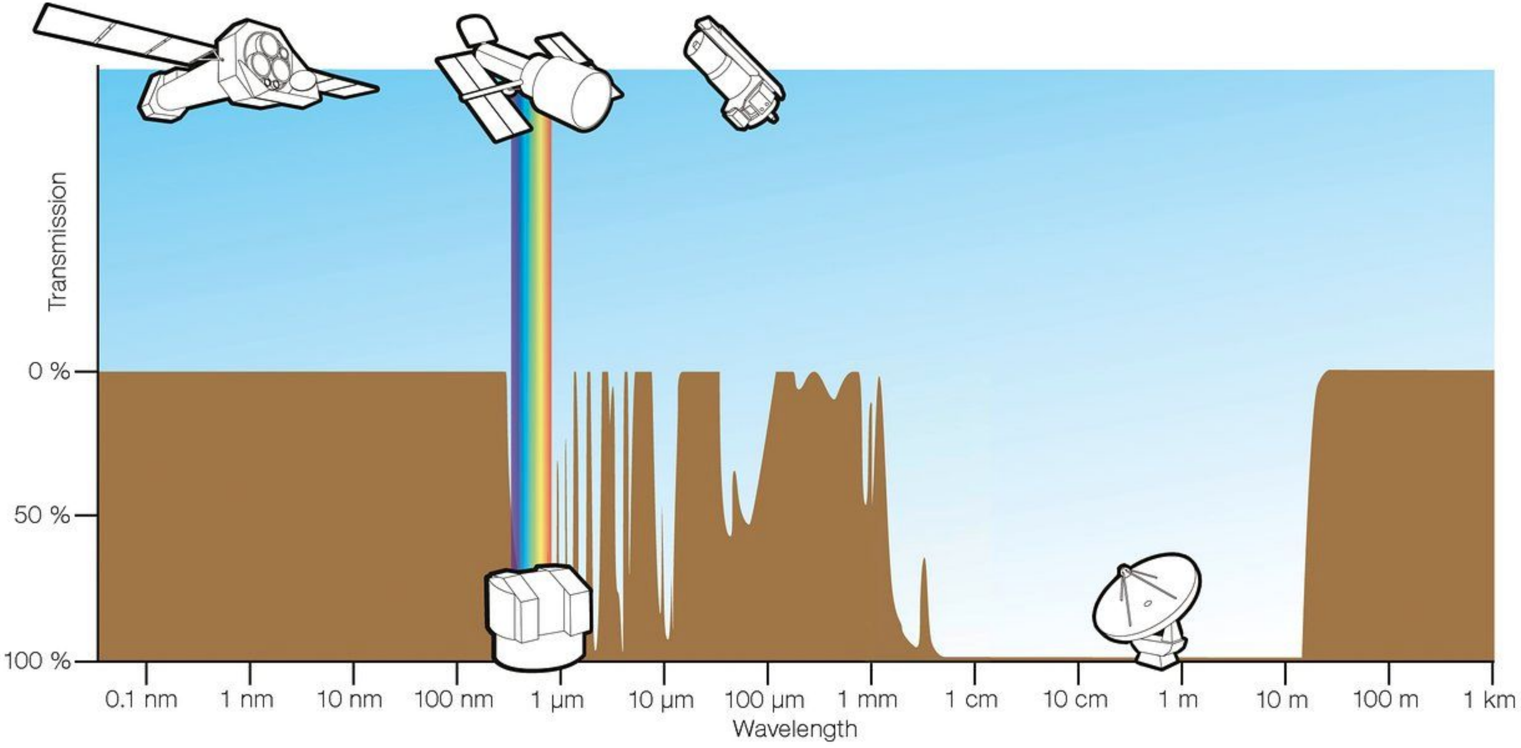
Research goals

This research primary objectives are:

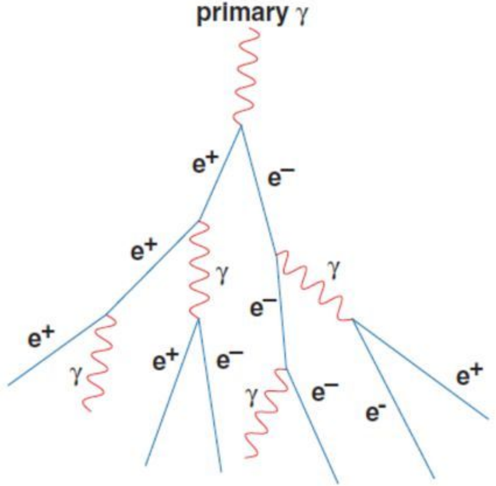
- Characterize the long-term VHE behavior of the blazar S5 0716+714
- Model a historic VHE flare from S5 0716+714 using MWL data to constrain its emission mechanism
- Conduct one of the first science analyses of the blazar Mrk 421 with the new LST-1 prototype telescope

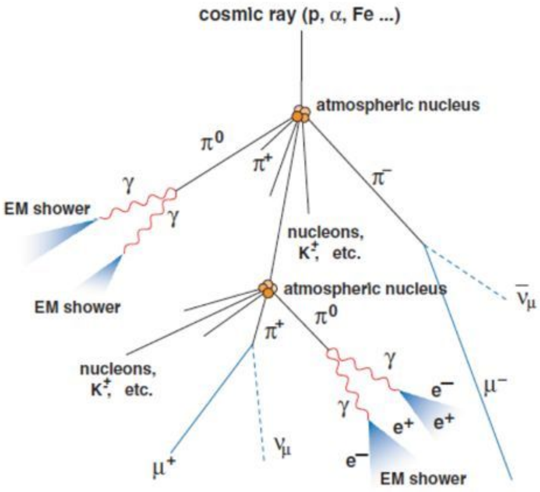
2. Instrumentation and Methods Used

How do we see gamma-rays?



IACT technique





- Extensive air showers (EAS) - cascade of secondary particles created when a single high-energy primary cosmic ray (like a proton, nucleus, or photon) strikes the top of the atmosphere
- The initial interaction triggers a chain reaction, producing a shower of particles that can spread out over several kilometers by the time it reaches the ground
- Three different types: electromagnetic, hadronic, muonic

IACT technique

Cherenkov radiation is a glow produced when a charged particle travels through a medium (like water or air) faster than the speed of light in that medium

As a charged particle passes, it temporarily disturbs the molecules of the medium. If the particle is moving fast enough, these molecules release energy as photons (light particles) when they return to their normal state

Since the particle is moving faster than the light it creates, the light waves bunch up and combine, forming a cone-shaped "shockwave" of light

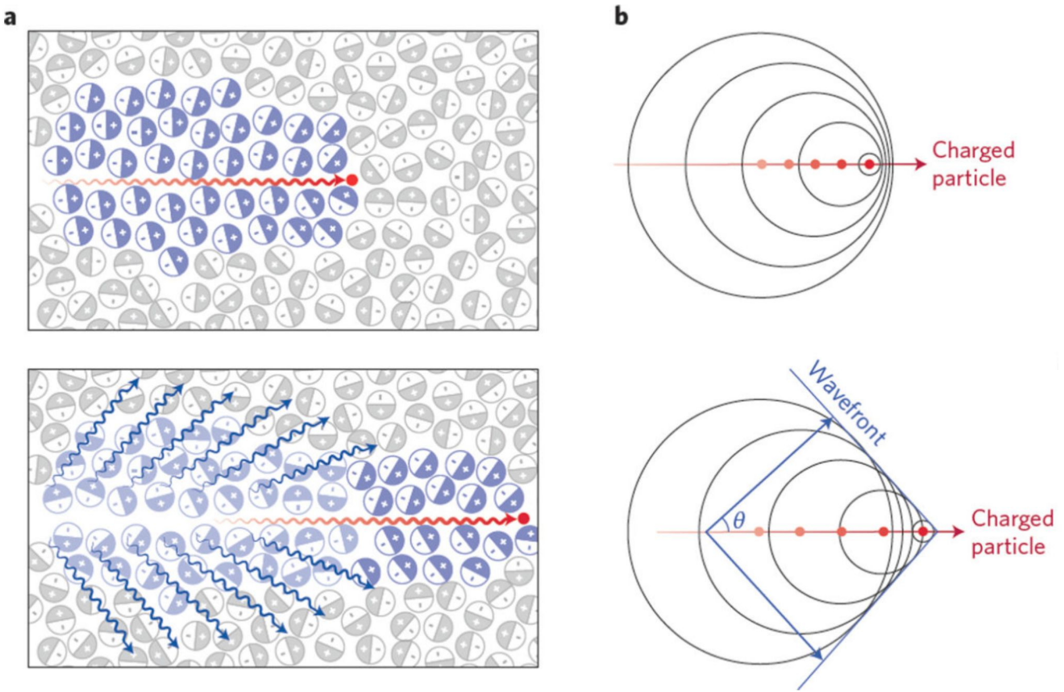
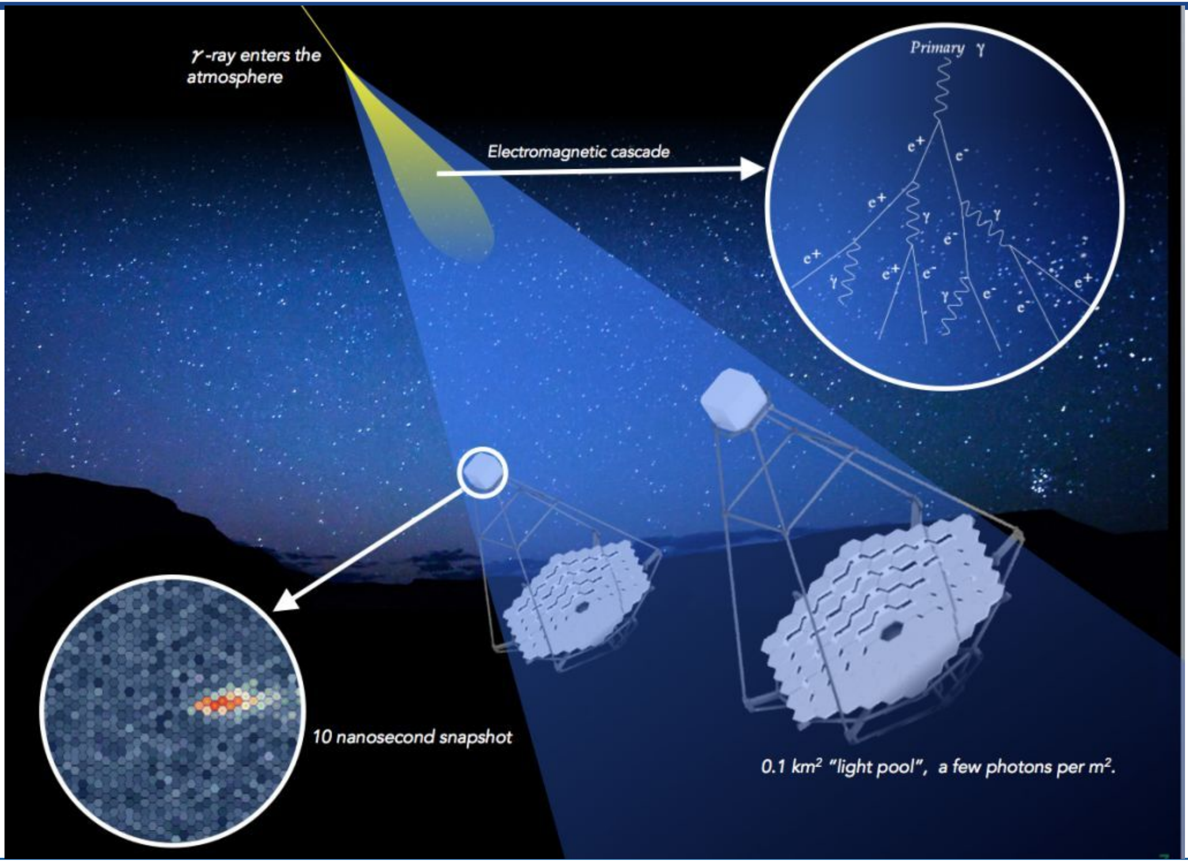


Image from Shaffer et al. (2017)

IACT technique



MAGIC and LST

Major Atmospheric Gamma Imaging Cherenkov (MAGIC)

- A system of two IACTs located at the Roque de los Muchachos Observatory on La Palma, Canary Islands, at an altitude of around 2200m
- Each telescope has a 17-meter diameter dish with total reflective area of ~ 236 m^2
- Each camera has 1039 PMT's with FoV ~ 3.5°
- They are sensitive to gamma rays with energies from 50 GeV to over 30 TeV
- Structure is made from carbon fiber-reinforced plastic tubes - fast repositioning ~ 25 sec

MAGIC and LST

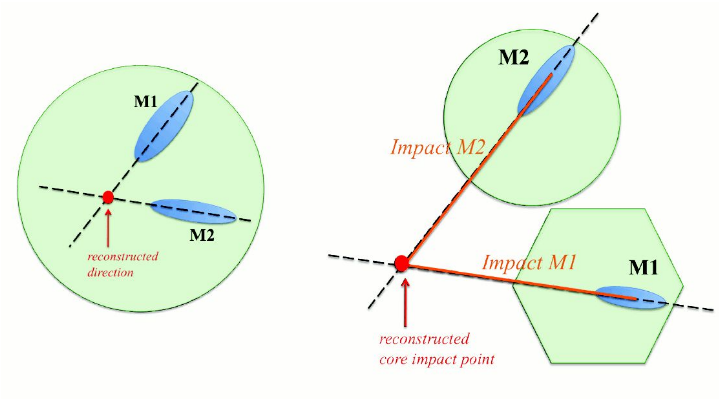
Large Sized Telescope (LST)

- **The largest of three telescope types for the Cherenkov Telescope Array Observatory (CTAO), designed to cover the low-energy gamma-ray spectrum**
- **Dish is 23 meter in diameter with reflective area of ~ 400 m^2**
- **Its energy sensitivity is optimized for the lowest energies, covering a range from 20 GeV to 150 GeV**
- **The camera has 1855 PMT's and it has a field of view of about 4.5°**

Gamma-ray data analysis

Key analysis steps:

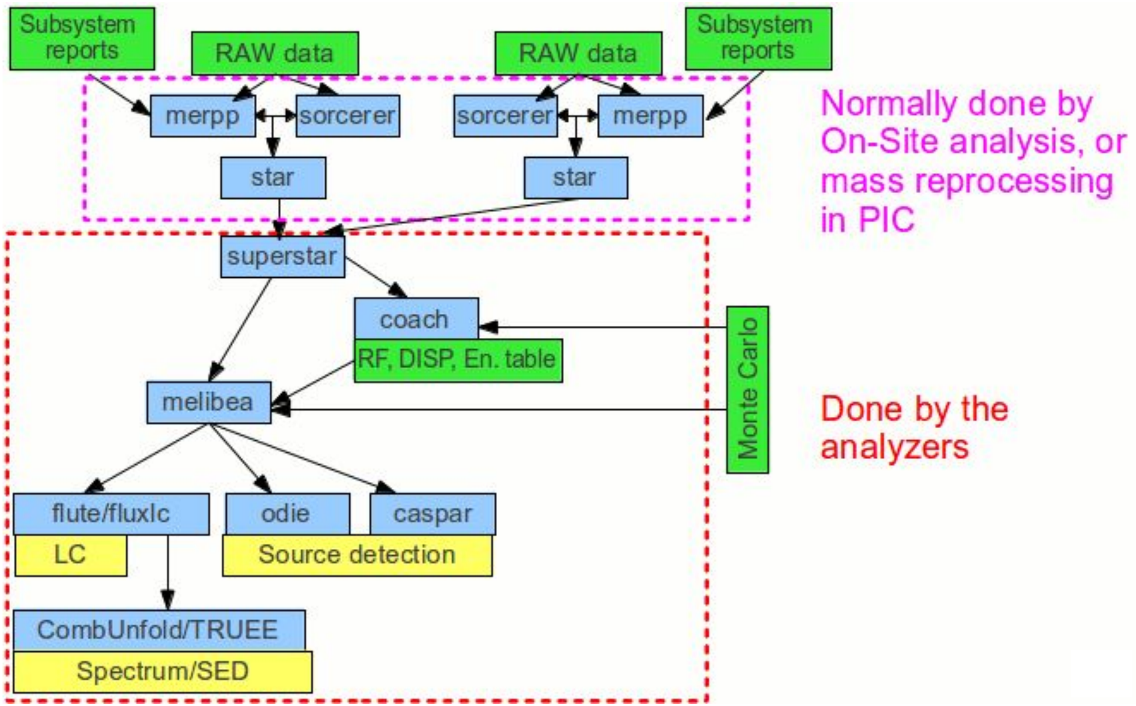
- **Event Reconstruction: Identifying and reconstructing the parameters of individual Cherenkov events, such as arrival time, direction, and energy**
- **Background Estimation: Accurately estimating and subtracting the background noise (primarily from cosmic rays) from the data**
- **Source Detection and Characterization: Identifying and characterizing gamma-ray sources by analyzing the spatial and energy distributions of the detected events**
- **Spectral Analysis: Determining the energy spectrum of the detected gamma-ray sources**



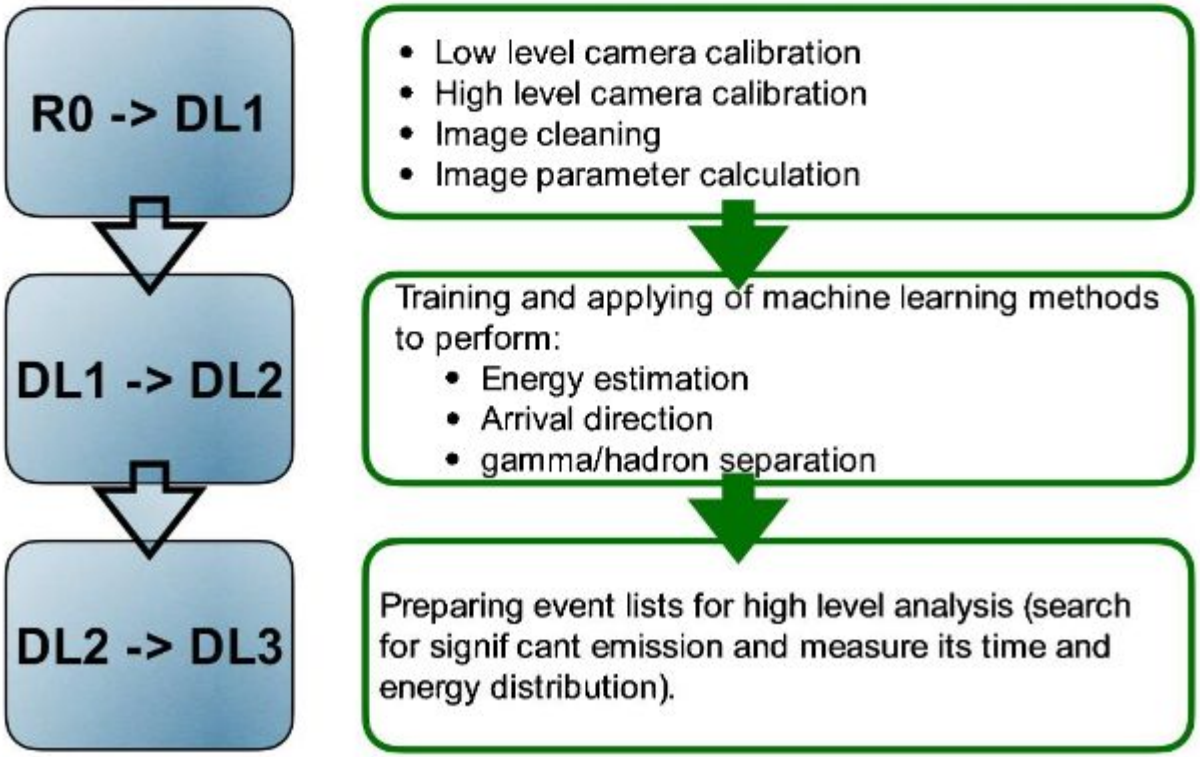
Gamma-ray data analysis

VHE gamma-ray data analysis using data taken by MAGIC is done with program called MARS (MAGIC Analysis and Reconstruction Software)

MARS is a collection of different programs written in C++ and built on ROOT framework

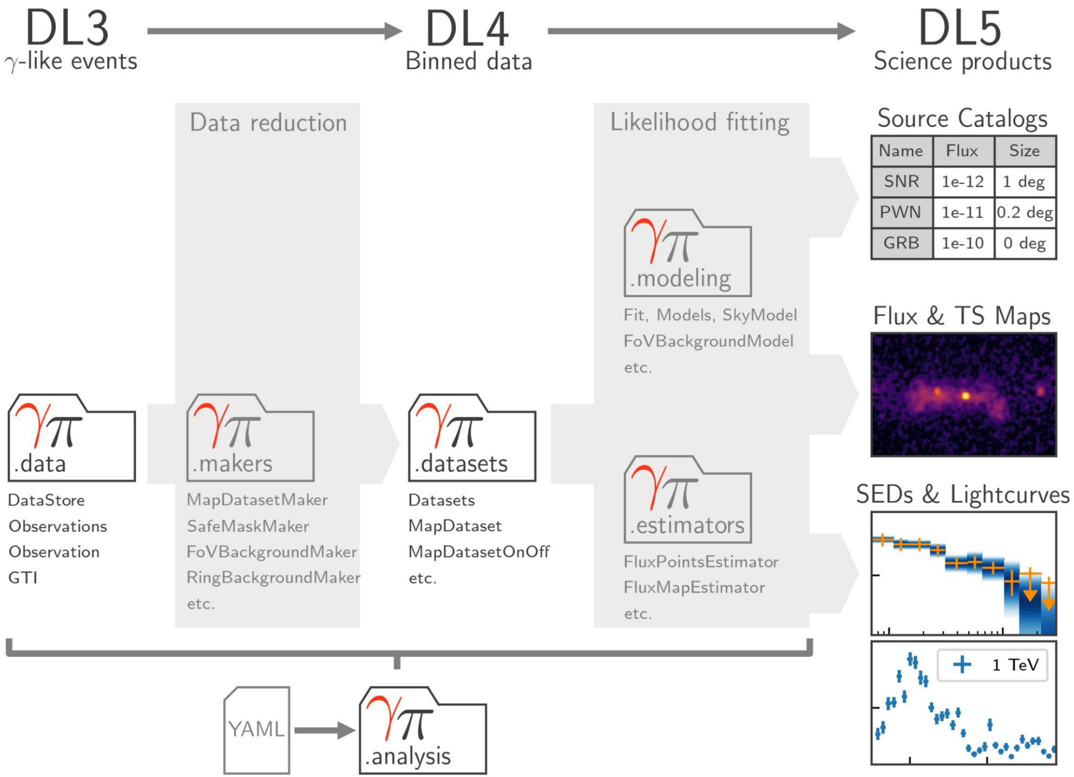


LST data analysis workflow using lstchain software



Gamma-ray data analysis

Post DL3 analysis workflow with Gammapy

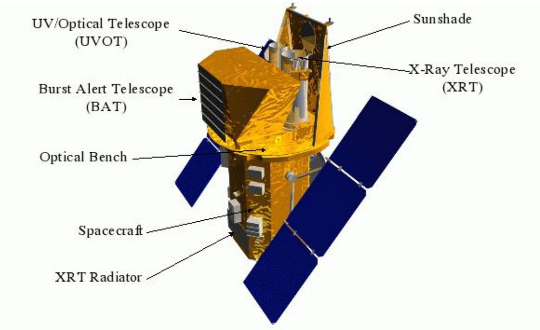


MWL instrumentation

Radio - OVRO

Optical - Calar Alto

Fermi satellite - HE Gamma-rays



Swift satellite - X-ray, UV

3. Results and Discussion

Blazar S5 0716+714 VHE campaign

Blazar S5 0716+714

- Discovered in VHE by MAGIC in 2007
- One of the most variable blazars across all energy bands
- S5 0716+714 is classified as Intermediate-synchrotron-peak BL Lac type object (IBL type)
- It has unknown distance due to the faintness of emission/absorption lines
- Best estimation of distance based on specific assumptions is ~ z=0.23

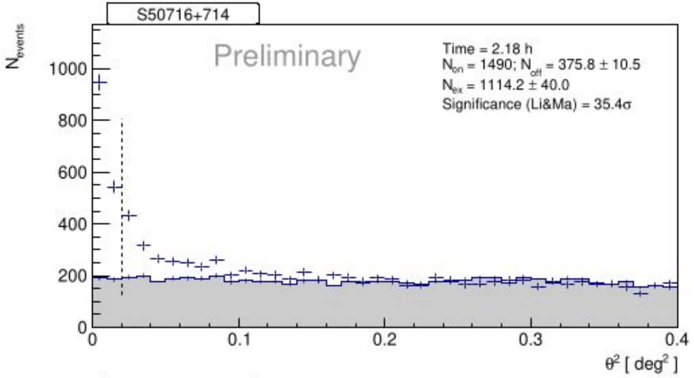
MAGIC VHE observational campaign - from 2015 until 2021

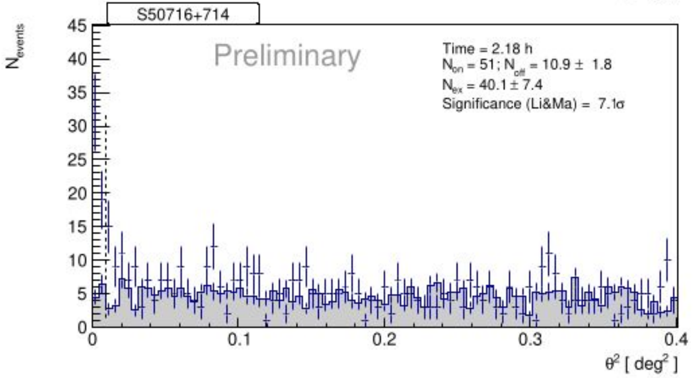
Blazar S5 0716+714 VHE campaign

- Data analysis was split among five different observational periods
- Total effective observation time after quality cuts was 33.29 hours
- In total MAGIC observed source for 34 night, 4 nights were discarded due to the bad weather conditions
- All data was taken under dark conditions
- Zenith angles between 40° and 50°
- Strong flaring state was observed in December 2017

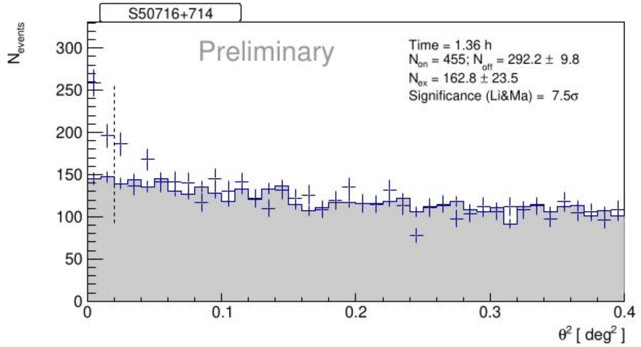
Period	Date	t_{eff}/h	Low energy (σ)	Full range (σ)	Weather
ST_03_06	2015_11_05	0.65	-0.6	0.00	good
	2015_11_12	0.49	1.3	0.00	good
	2015_11_13	-	-	-	bad
	2015_11_14	0.42	1.3	0.23	good
	2016_01_15	-	-	-	bad
	2016_01_16	0.24	-1.5	0.00	good
	2016_01_17	0.38	2.6	0.00	good
ST_03_09	2017_12_28	2.18	35.4	7.1	good
	2017_12_29	1.36	7.5	1.2	good
	2018_01_11	0.97	1.3	-1.4	good
	2018_01_12	0.97	-1.8	-0.6	good
ST_03_11	2018_12_07	0.21	0.4	0.00	good
	2018_12_15	0.78	0.4	0.00	good
	2019_01_29	1.66	-0.7	1.52	good
	2019_01_30	2.31	-0.7	-0.87	good
	2019_02_11	1.35	1.4	-1.25	good
	2019_02_25	1.62	1.4	-0.85	good
	2019_02_27	1.59	2.2	2.45	good
	2019_03_03	1.50	0.2	-0.58	good
ST_03_12	2019_12_29	0.65	1.9	0.00	good
	2019_12_30	0.22	0.5	0.00	good
	2019_12_31	0.07	-	-	bad
	2020_01_01	0.65	2.0	0.00	good
	2020_01_18	0.65	0.70	0.00	good
	2020_01_19	0.65	-0.30	0.00	good
	2020_01_20	0.11	0.30	0.00	good
	2020_01_30	-	-	-	bad
	2020_02_14	2.02	5.2	1.78	good
ST_03_16	2020_12_16	0.77	0.60	0.00	good
	2020_12_20	1.86	-0.50	0.00	good
	2020_12_22	-	-	-	-
	2021_02_15	2.93	0.10	1.61	good
	2021_03_05	2.35	2.30	-0.13	good
	2021_03_12	0.99	1.60	0.00	good

Blazar S5 0716+714 VHE campaign

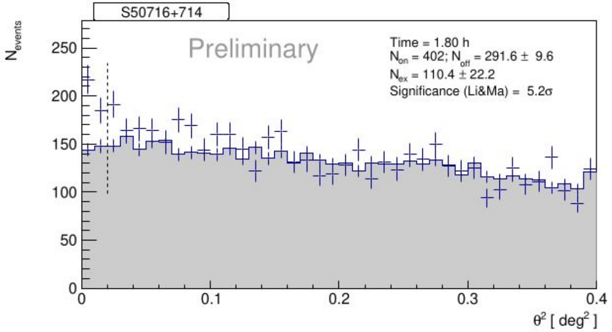




θ^2 plots for 28.12.2017 with HE and FR cuts



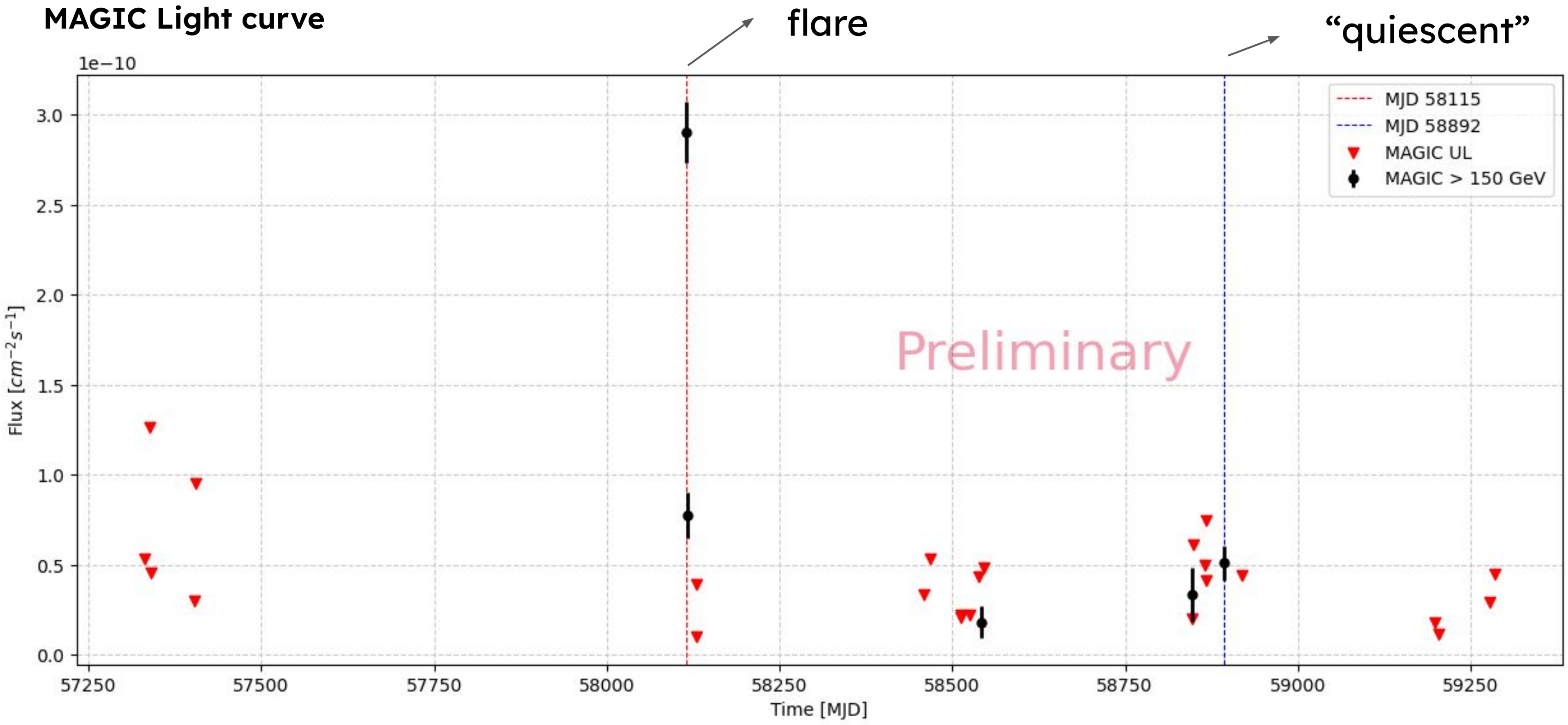
θ^2 plot for 29.12.2017 with LE cuts



θ^2 plot for 14.02.2020 with LE cuts

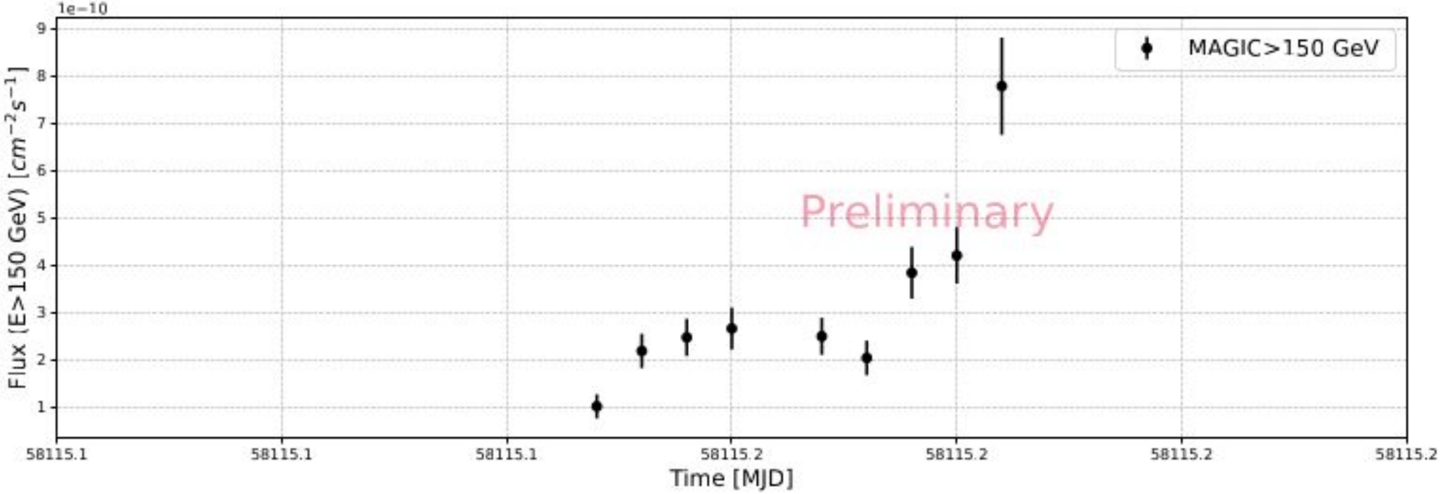
Blazar S5 0716+714 VHE campaign

- **MAGIC Light curve**



Blazar S5 0716+714 VHE campaign

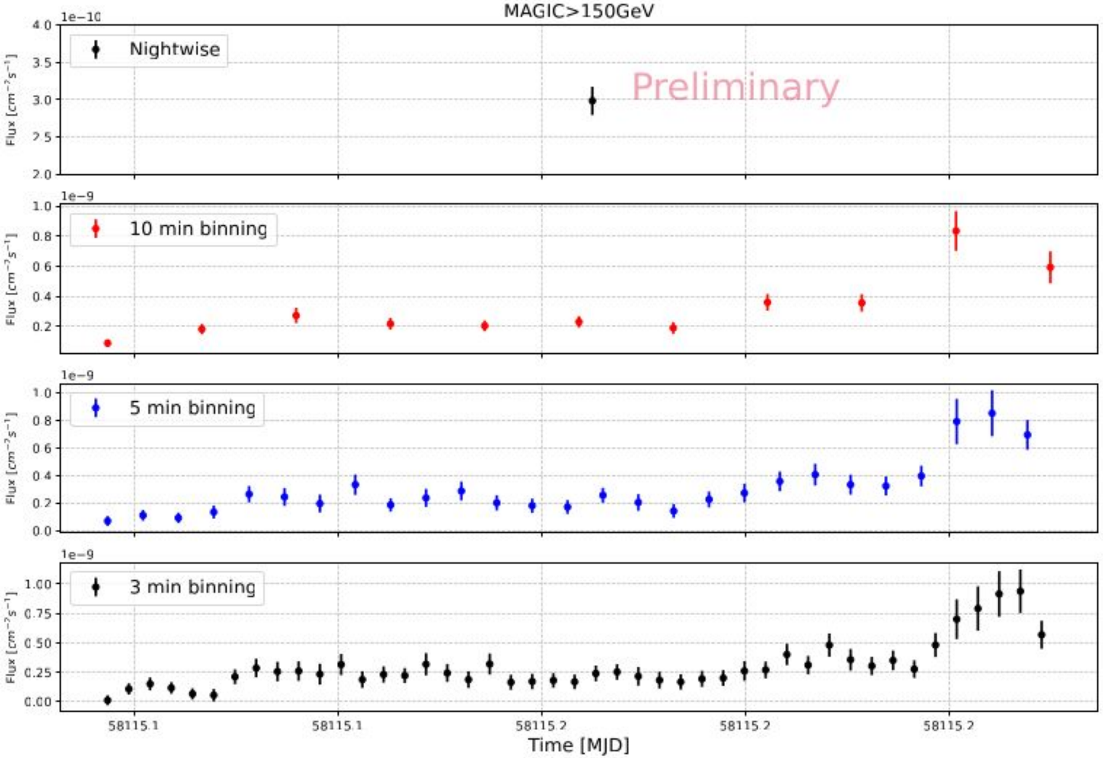
- **During strong flare observed on 28.12.2017 integral flux reached its historical maximum and it was calculated to be $F = 2.93 \times 10^{-10} \pm 1.83 \times 10^{-11}\ cm^{-2}\ s^{-1}$ during 2.18 hours of observation above 150 GeV**



Blazar S5 0716+714 VHE campaign

Since the state of the source was very high and bright in VHE we analyzed data with rebinned sample and calculated the LC with 10 min, 5 min and 3 min binning

Result - intranight variability in VHE gamma-ray band



Blazar S5 0716+714 VHE campaign

Flux doubling time - to characterize rapid flux variations:

$$\tau_d = (t_2 - t_1)\frac{\ln(2)}{\ln(F_2/F_1)}$$

Using MAGIC data, flux doubling time was calculated to be around 57 seconds

Fractional variability - this parameter measures the amplitude of flux variations relative to the mean flux

$$F_{\rm var} = \frac{\sqrt{S^2 - \langle\sigma^2_{\rm err}\rangle}}{\langle x\rangle}$$

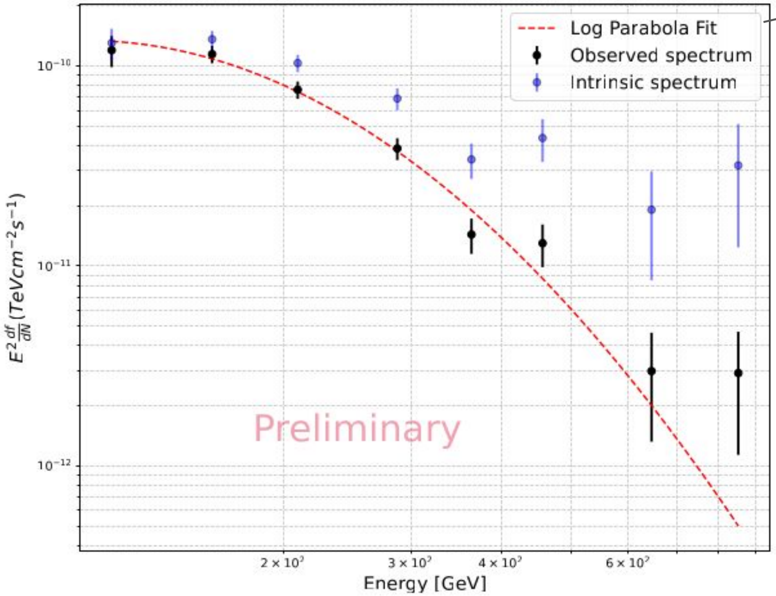
F_{var} = 0.615 ± 0.048

Variability of around 62%

Reflecting rapid and substantial changes in the emission processes within the jet

Blazar S5 0716+714 VHE campaign

Spectral Energy distribution (SED): flaring state



$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-(\alpha+\beta \log_{10}(E/E_0))}$$

Parameter	Symbol	Value
Normalization Constant	N_0	$(3.311\pm^{0.351}_{0.294}) \times 10^{-9}$
(at $E_{\mathrm{norm}} = 184.98$ GeV)		$[\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}]$
Spectral Index	α	$-2.921\pm^{0.241}_{0.247}$
Curvature Parameter	β	$1.060\pm^{0.477}_{0.662}$

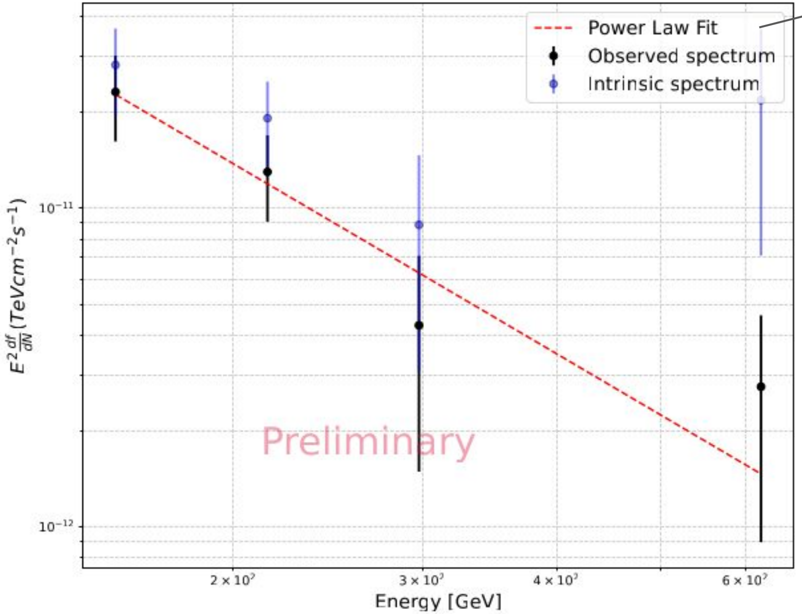
Fit Statistics: $\chi^2/\mathrm{dof} = 11.1631/11$, Probability $= 0.429699$

Energy Range: 110.346 GeV to 8117.54 GeV

Redshift (z): 0.23

Blazar S5 0716+714 VHE campaign

Spectral Energy distribution (SED) : quiescent state



$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_{\text{norm}}} \right)^{\alpha}$$

Parameter	Symbol	Value
Normalization Constant (at $E_{\text{norm}} = 202.82$ GeV)	N_0	$(3.73091 \pm^{0.791546}_{0.809666}) \times 10^{-10}$ [$\text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}$]
Spectral Index	α	$-2.83226 \pm^{0.603989}_{0.602865}$

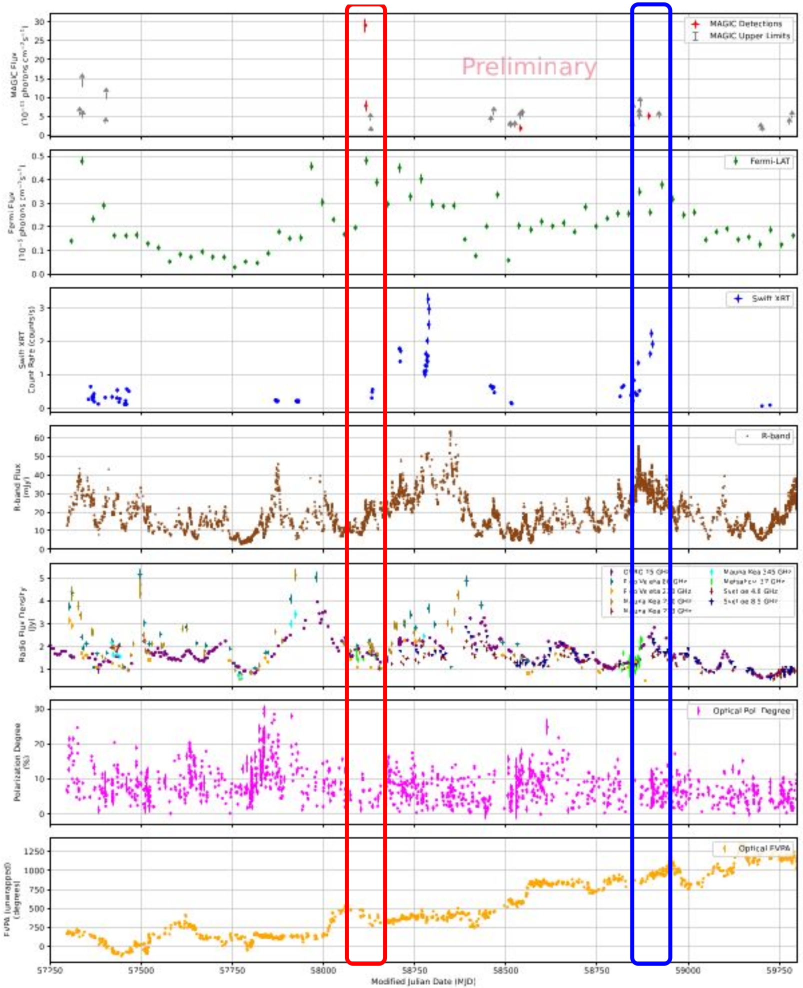
Fit Statistics: $\chi^2/\text{dof} = 15.5536/12$, Probability $= 0.21255$

Energy Range: 155.0 GeV to 1266.5 GeV

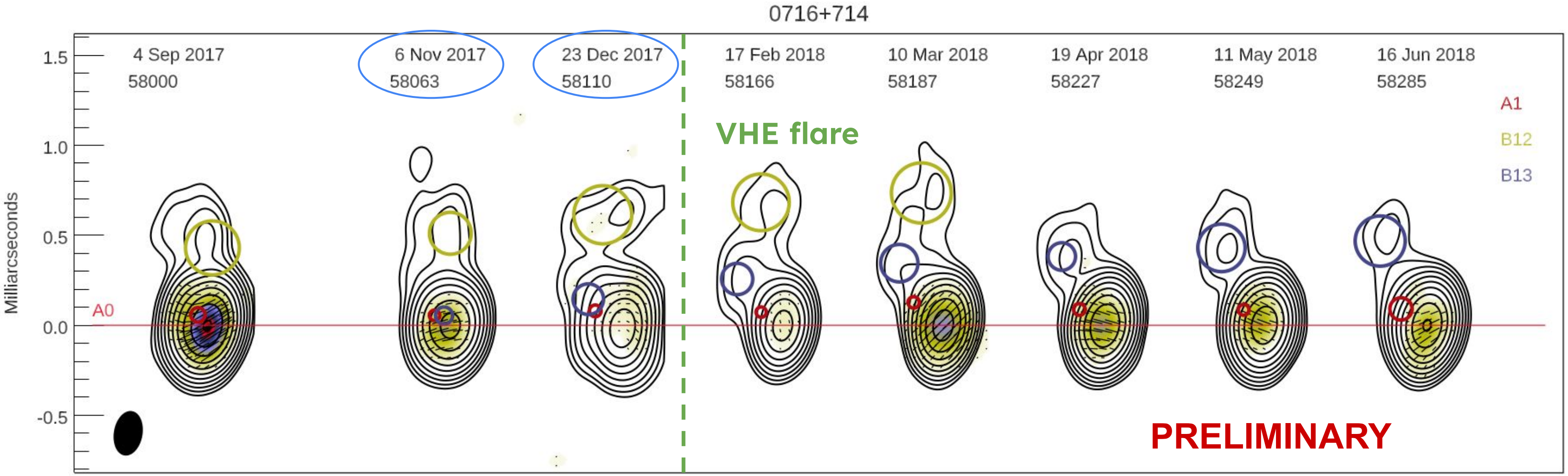
Redshift (z): 0.23

Blazar S5 0716+714
VHE campaign

Multi-wavelength Light Curves



Blazar S5 0716+714 VHE campaign

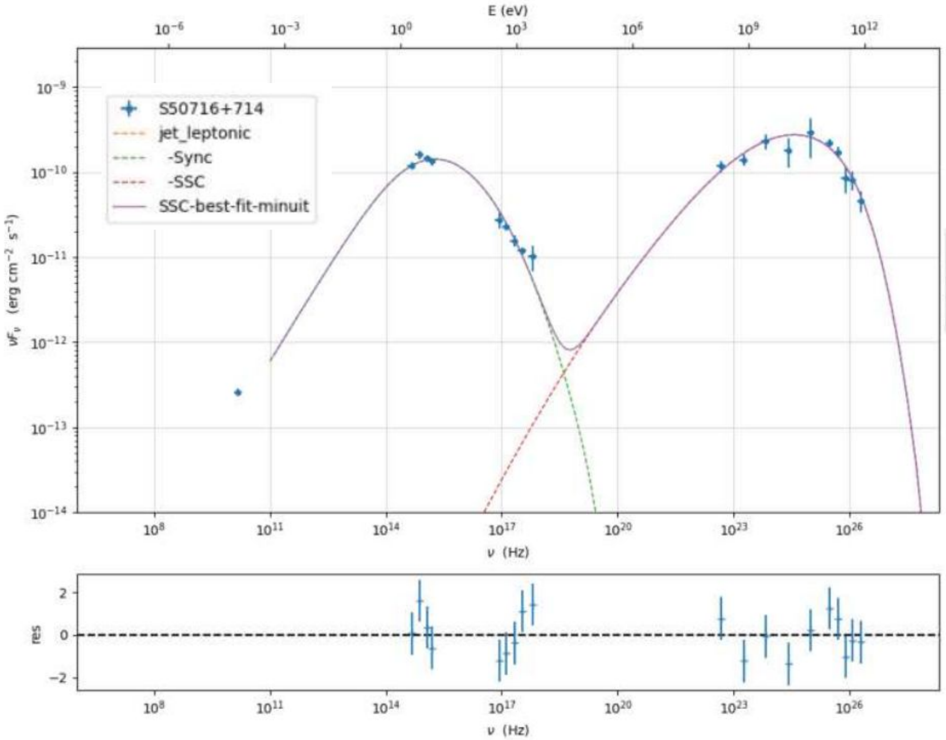


- **Plot shows a sequence of total and polarized intensity images between September 2017 and June 2018 (VHE gamma ray flare happened on 28.12.2017.)**
- **The sequence suggests a possible interaction between moving knot B13 and a stationary feature A1 occurring on MJD 58085±15 (between 06.11.2017 and 23.12.2017)**

Blazar S5 0716+714 VHE campaign

Broadband SED (flaring state) with a leptonic one-zone model (SSC) using jetset

parameter	value	bestfit value	error
gmin	$3.688173 \times 10^{+01}$	$3.688173 \times 10^{+01}$	3.056073×10^{-01}
gmax	$3.081946 \times 10^{+06}$	$3.081946 \times 10^{+06}$	$3.282811 \times 10^{+04}$
N	$1.242681 \times 10^{+00}$	$1.242681 \times 10^{+00}$	7.324461×10^{-02}
gamma0_log_parab	$8.649538 \times 10^{+03}$	$8.649538 \times 10^{+03}$	$5.664751 \times 10^{+02}$
s	$1.514993 \times 10^{+00}$	$1.514993 \times 10^{+00}$	1.902691×10^{-02}
Γ	$1.062287 \times 10^{+00}$	$1.062287 \times 10^{+00}$	5.223439×10^{-02}
R	$1.557365 \times 10^{+17}$	–	–
R_H	$1.000000 \times 10^{+17}$	–	–
B	7.195085×10^{-03}	7.195085×10^{-03}	5.331654×10^{-04}
NH_cold_to_rel_e	$1.000000 \times 10^{+00}$	–	–
beam_obj	$5.000000 \times 10^{+01}$	$5.000000 \times 10^{+01}$	$4.209478 \times 10^{+00}$
z_cosm	2.300000×10^{-01}	–	–



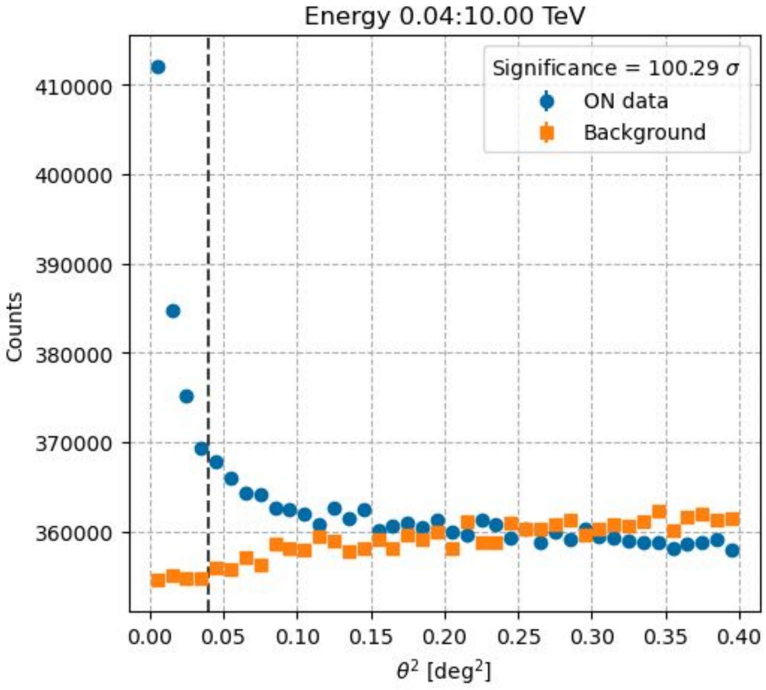
VHE Gamma-ray observations of Mrk 421

Second source in the work is blazar Mrk 421

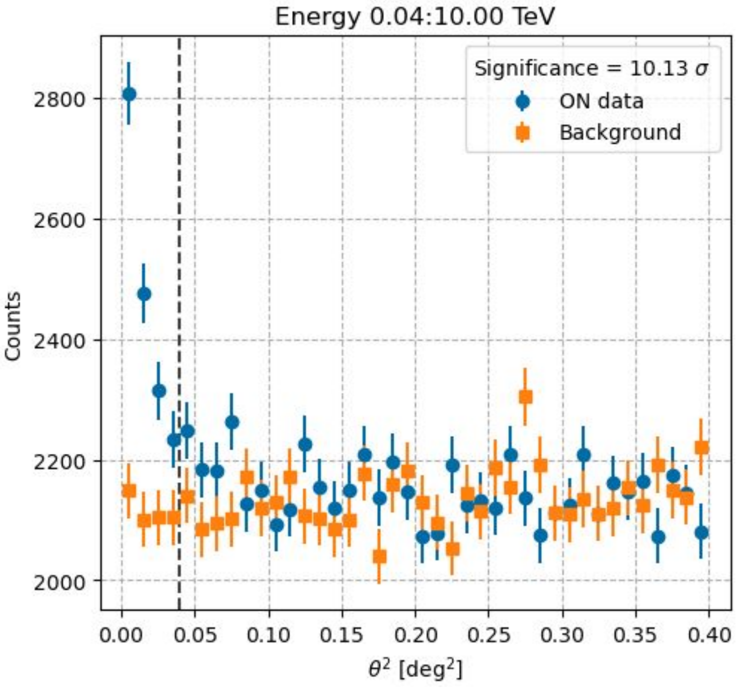
- One of the closest and most luminous blazars at z = 0.031
- It is classified as HSP blazar
- Very well known blazar studied in all energy bands
- Variable in x-ray and VHE band
- Monitored by many instruments

LST observed Mrk 421 between June 2022 and June 2024 - dataset used in this work

VHE Gamma-ray observations of Mrk 421



θ^2 plot for the whole dataset



θ^2 plot for selected high state (MJD 60347 - 7 Feb 2024)

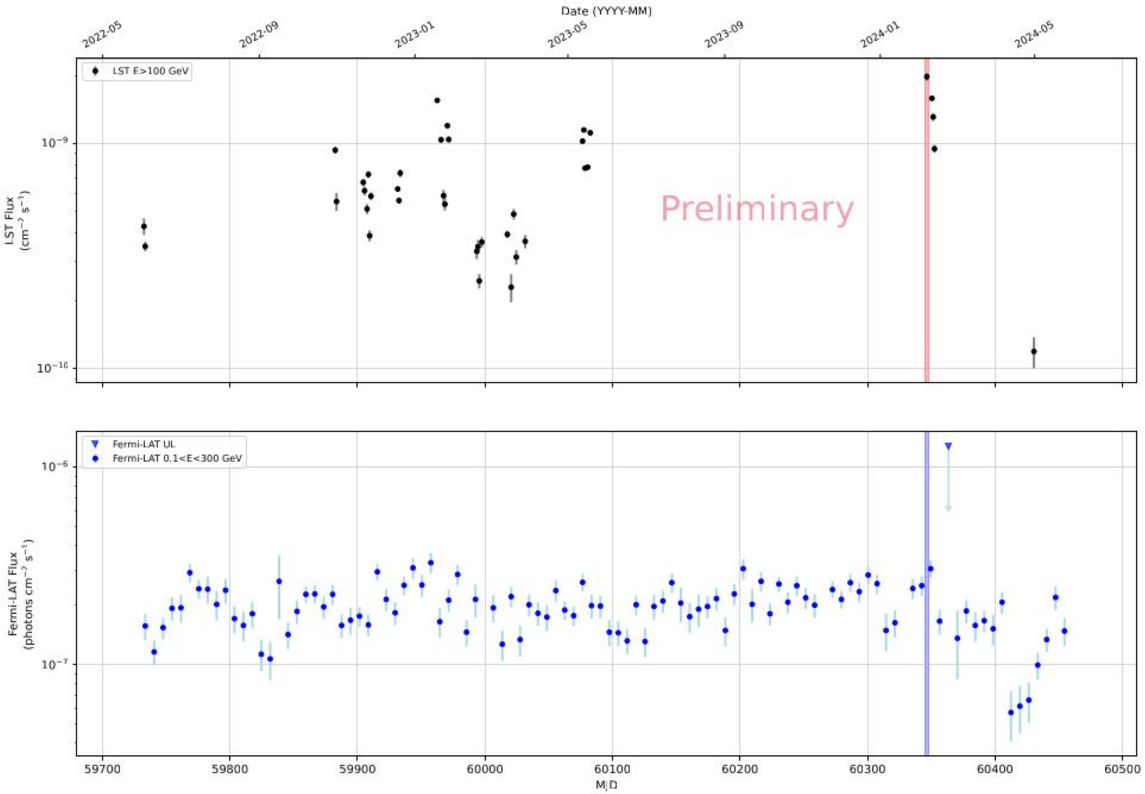
VHE Gamma-ray observations of Mrk 421

Gamma-ray Light curves

(01 June 2022 - 01 June 2024)

LST

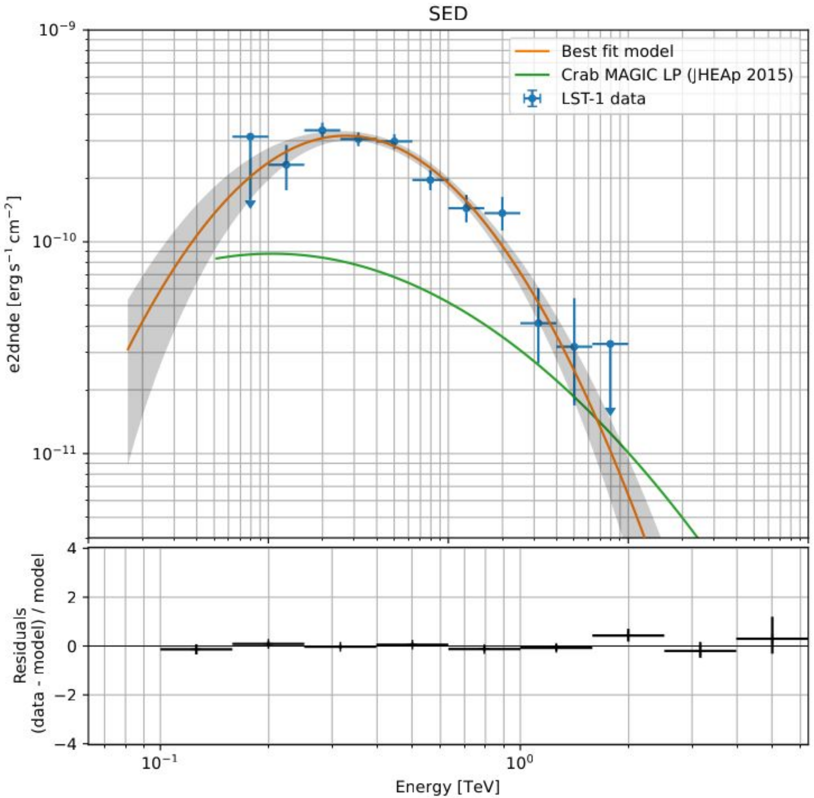
Fermi-LAT



VHE Gamma-ray observations of Mrk 421

SED with LST data for MJD 60347 (7 Feb 2024)

Name	Value	Unit	Error
amplitude	1.1404×10^{-9}	$\mathrm{TeV^{-1}\ s^{-1}\ cm^{-2}}$	5.462×10^{-11}
reference	4.0611×10^{-1}	TeV	-
alpha	2.2461	–	6.991×10^{-2}
beta	2.9885×10^{-1}	–	5.804×10^{-2}



VHE Gamma-ray observations of Mrk 421

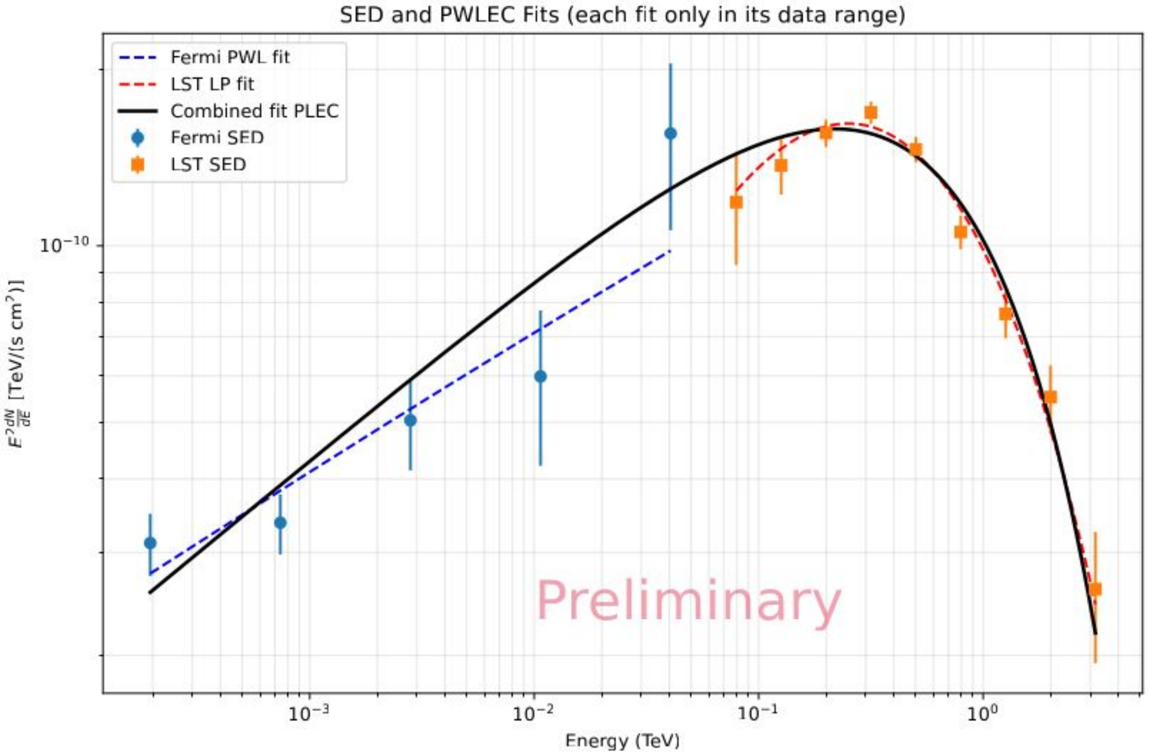
Combined SED:

Fermi-LAT and LST data

(MJD 60347- 7 Feb 2024)

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} e^{-(E/E_0)^b}$$

Parameter	Value	Error
N_0 (log scale)	-9.190	$^{+0.040}_{-0.040}$
α	1.674	$^{+0.029}_{-0.039}$
E_0	6.074	$^{+0.113}_{-0.193}$
b	0.837	$^{+0.254}_{-0.221}$



4. Conclusions and Future Aspects

One-Zone SSC Model Successfully Explains Historic 2017 Flare - S5 0716+714

- In December 2017, the blazar S5 0716+714 underwent a major flaring event, reaching a historical maximum flux in the VHE gamma-ray band
- The broadband Spectral Energy Distribution (SED) of this intense flare, from radio to VHE, was successfully and accurately described using a standard one-zone Synchrotron Self-Compton (SSC) model
- The model fit confirms the classification of S5 0716+714 as an Intermediate BL Lac object, with derived physical parameters (magnetic field, jet power, etc.) consistent with existing literature

Linking Gamma-Rays to Physical Jet Components - S5 0716+714

- VLBI analysis identified multiple moving "knots" or components being ejected from the central core of the jet around the time of the observed gamma-ray activity
- This provides a direct physical context for the gamma-ray production, suggesting that the particle acceleration and subsequent VHE emission are located within these relativistically moving blobs of plasma traveling down the jet
- The flares observed in the gamma-ray and radio bands appear to be linked to these ejections, strengthening the connection between the jet's dynamics and its high-energy radiative output

Discovery of intranight variability - S5 0716+714

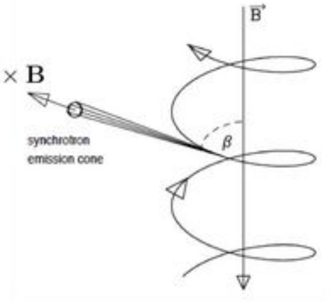
- **The most significant and challenging result from the 2017 flare was the first-ever detection of intranight variability from S5 0716+714 in the VHE gamma-ray band .**
- **The flux was observed to change significantly on timescales as short as three minutes, implying an astonishingly compact and dynamic emission region within the jet**
- **While the one-zone SSC model perfectly describes the time-averaged energy spectrum, it cannot self-consistently explain such rapid changes. The fast variability requires a much smaller emission zone than the one derived from the overall SED fit, creating a significant tension**
- **The one-zone model is a good first approximation, but the discovery of extreme variability proves it is an oversimplification. This result demonstrates the clear need for more complex models—incorporating turbulence, multiple interacting zones, or magnetic reconnection—to fully capture the physics of blazar jets**

Mrk 421 with LST - conclusions

- The observed discrepancy between the HE and VHE activity, with strong VHE flaring and relatively steady HE flux, is a key result of this study.
- the combined HE–VHE analysis of Mrk 421 over two years reveals that strong VHE flares can occur without significant HE counterparts, highlighting the importance of VHE monitoring to investigate the most extreme and dynamic processes in blazar jets.
- Several physical mechanisms can explain this behavior within the framework of the synchrotron self-Compton (SSC) model, which is widely accepted for high-synchrotron-peaked BL Lacs like Mrk 421
- The results presented here demonstrate the power of LST in capturing rapid VHE variability in blazars and provide a new benchmark for the study of HE–VHE connections in Mrk 421
- To further constrain the emission mechanisms, it will be essential to complement these results with additional multi-wavelength data (e.g., optical, radio, X-ray), allowing for full SED modeling and time-dependent analysis. Such studies are in preparation and will take advantage of the unique sensitivity and temporal resolution of LST.

Thank you for your attention

Backup



$$m\gamma\frac{d(\mathbf{v})}{dt} = \frac{q}{c}\mathbf{v}\times\mathbf{B}$$

$$a_{\|} = 0$$

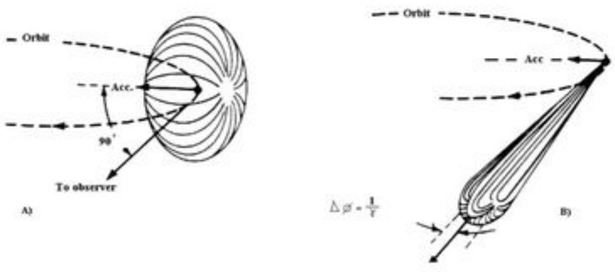
$$a_{\perp} = \frac{evB\sin\alpha}{\gamma m_e c}$$

$$\nu_B = \frac{eB}{2\pi\gamma mc} = \frac{\nu_L}{\gamma}$$

total emitted power

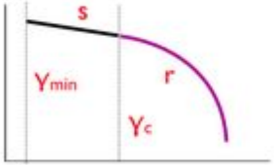
$$P_e = P_e' = \frac{2e^2}{3c^3}a'^2 = \frac{2e^2}{3c^3}[a_{\|}'^2 + a_{\perp}'^2]$$

$$P_S = \frac{2e^4}{3m_e c^3}B^2\gamma^2\beta^2\sin^2\alpha$$



Backup

$N(\gamma) \propto \gamma^{-s}$

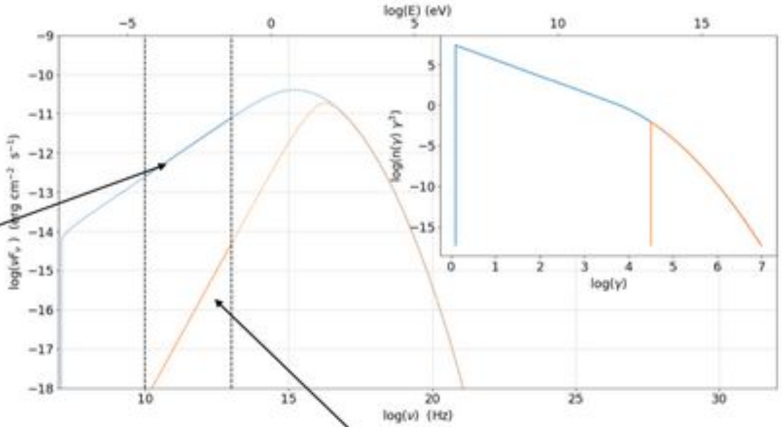


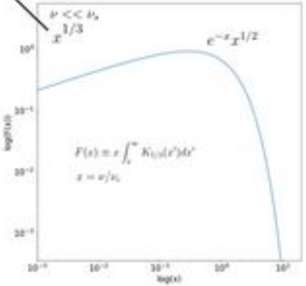
$$j_\nu^S(\nu) = \frac{1}{4\pi}\int_{\gamma_{min}}^{\gamma_{max}} P(\nu,\gamma)N(\gamma)d\gamma \ \propto \nu^{-\frac{s-1}{2}}$$

F_ν	refers to spectral index => SED=	νF_ν
I_ν		νI_ν
L_ν		νL_ν

δ-approx relations $\quad \mathrm{SED} \propto N(\gamma)\gamma^3$

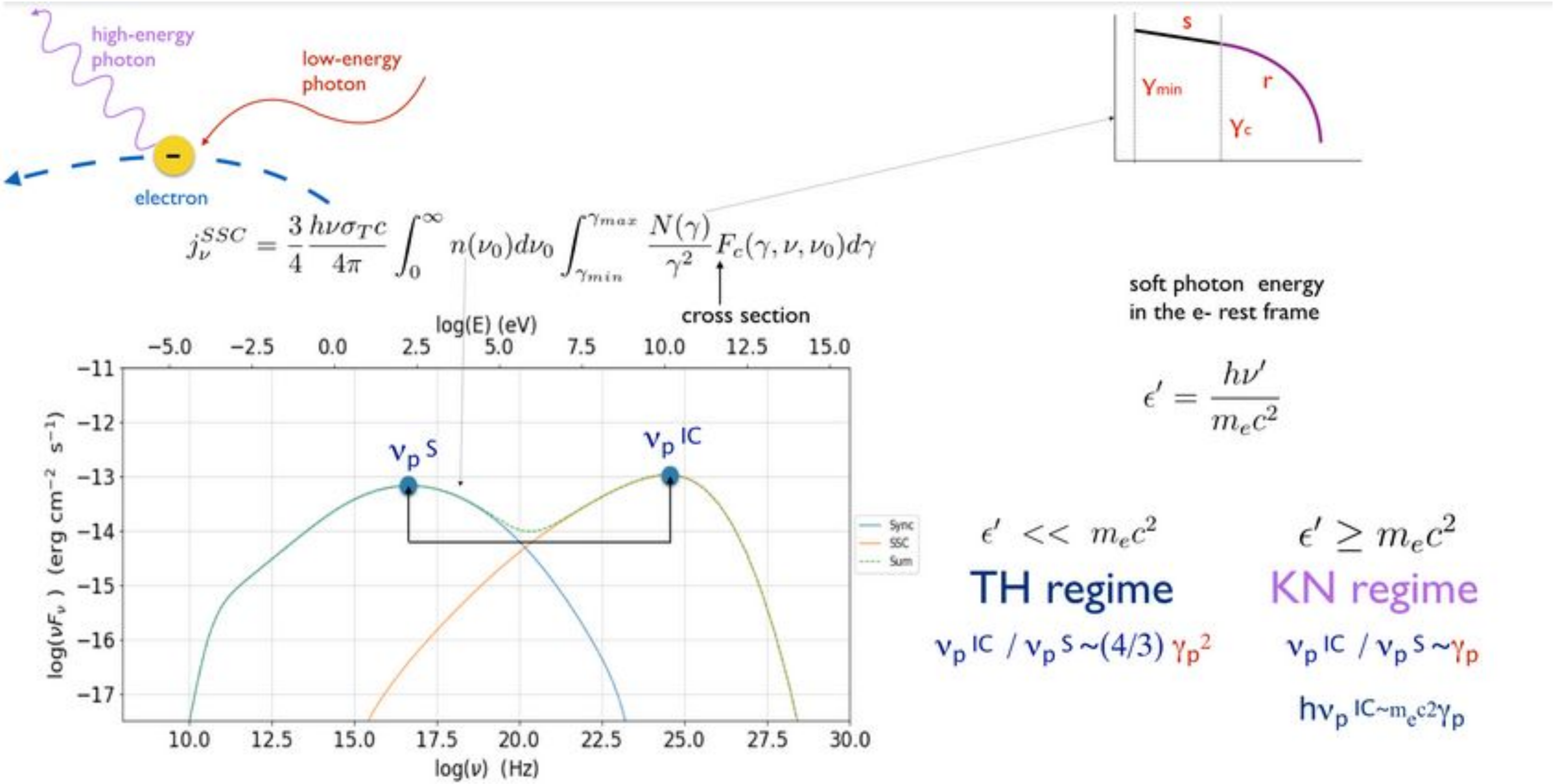
$$S_p^{Sync} \sim \frac{dN(\gamma)}{d\gamma}\gamma_{3p}^3 \ B^2 \ \delta^4 \quad \nu_p^{Sync} \sim 3.2\times10^6 \ (\gamma_{3p})^2 \ B \ \delta$$



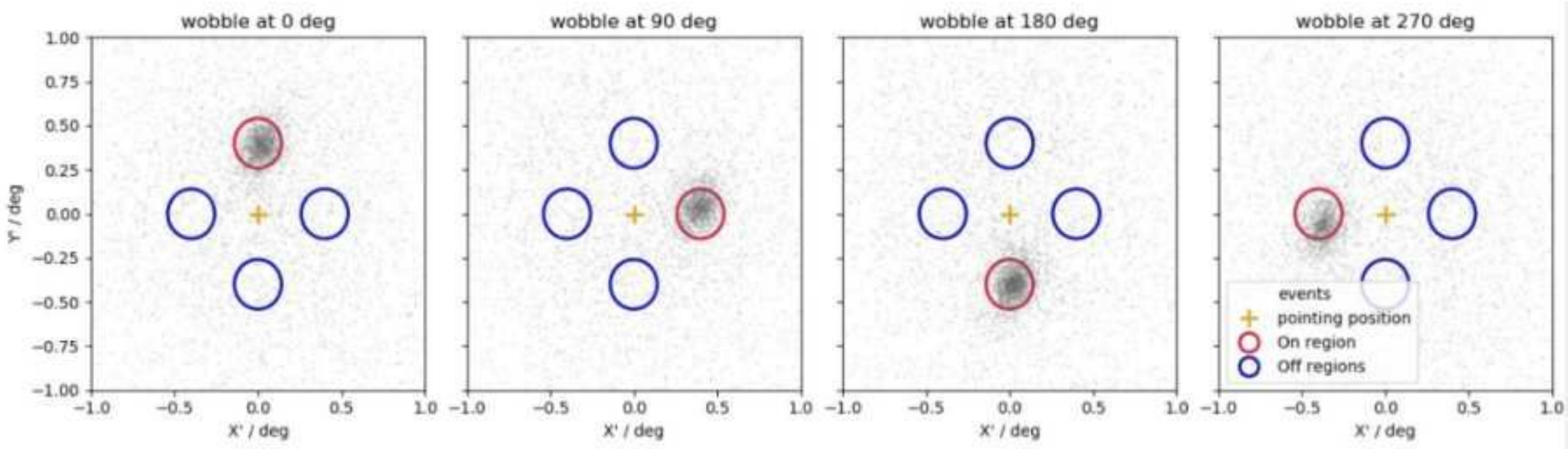


4/3 in SED corresponds to 1/3 in spectral index

Backup


high-energy photon
low-energy photon
electron
$j_\nu^{SSC} = \frac{3}{4}\frac{h\nu\sigma_T c}{4\pi}\int_0^\infty n(\nu_0)d\nu_0 \int_{\gamma_{min}}^{\gamma_{max}} \frac{N(\gamma)}{\gamma^2} F_c(\gamma,\nu,\nu_0)d\gamma$
cross section
s
r
γ_{min}
γ_c
log(E) (eV)
log(νF_ν) (erg cm^{-2} s^{-1})
log(ν) (Hz)
ν_p S
ν_p IC
Sync
SSC
Sum
soft photon energy in the e- rest frame
$\epsilon' = \frac{h\nu'}{m_e c^2}$
$\epsilon' << m_e c^2$
TH regime
$\nu_p^{IC} / \nu_p^{S} \sim (4/3)\gamma_p^2$
$\epsilon' \geq m_e c^2$
KN regime
$\nu_p^{IC} / \nu_p^{S} \sim \gamma_p$
$h\nu_p^{IC} \sim m_e c^2 \gamma_p$

Backup



Theta is the angle between ON/OFF region and center

Backup

Significance calculation

$$S_{LM} = \sqrt{2\left[N_{ON}\ln\left(\frac{1+\alpha}{\alpha}\frac{N_{ON}}{N_{ON}+N_{OFF}}\right) + N_{OFF}\ln\left((1+\alpha)\frac{N_{OFF}}{N_{ON}+N_{OFF}}\right)\right]}$$

Flux calculation

$$F_i(> E_{th}) = \frac{N_{ex,i}}{\langle A_{eff}\rangle(E > E_{th}) \cdot T_{bin,i}}$$

Backup

Emission region

$$R \leq \frac{c t_{\mathrm{var}} \delta}{1+z}$$

$$\delta_D = \frac{1}{\Gamma_b (1 - \beta \cos\theta)}$$

PWL

$$n(\gamma) = k\gamma^{-p}$$

BPWL

$$n(\gamma) = \begin{cases} k\gamma^{-p_1} & \gamma < \gamma_{br} \\ k\gamma^{-p_2} & \gamma \geq \gamma_{br} \end{cases}$$

LP

$$n(\gamma) = k\left(\frac{\gamma}{\gamma_0}\right)^{-(p+q\log_{10}(\gamma/\gamma_0))}$$

Gamma-ray data analysis

- **Low level analysis:**

  usually automatic. A pipeline processes the raw digitized waveforms recorded by each pixel of the MAGIC camera for every triggered event. This involves extracting the integrated charge deposited by the Cherenkov photons, and the precise arrival time of the signal pulse.

- **Intermediate analysis:**

  Study of the datataking conditions and of the quality cuts that need to be applied to the dataset. At this stage, the analyzers decide the final dataset to keep for further analysis, based on the check of LIDAR measurements (for cloudiness), possible presence of calima (dust in the atmosphere). Moreover they can establish how to separate different datasets based on different zenith angles of observations, energy thresholds, sky luminosity (night-sky-background level). After quality cuts, a simulation is performed to take into account the telescope performance and effective area and to estimate the background (Gamma/Hadron separation + Random Forest)

- **High level analysis:**

  The final results that can be used for publications are produced in the high level analysis. Skymaps; θ^2 plots to express the significance of the gamma-ray signal; light curves (integral flux vs. time); differential energy spectrum and spectral energy distributions, both unfolded and corrected for EBL (Extragalactic Background Light absorption).