TeV Particle Astrophysics - TeVPa Valencia, Spain 2025

Investigation of the extreme activity of Mrk 501 in 2014 and of its intriguing TeV spectral feature

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on behalf of MAGIC Collaboration

Blazars

- Relativistic plasma jet points to our line of sight
- Relativistic effects:

  -An increase in photon energy by δ

  -An increase in energy flux by δ^4

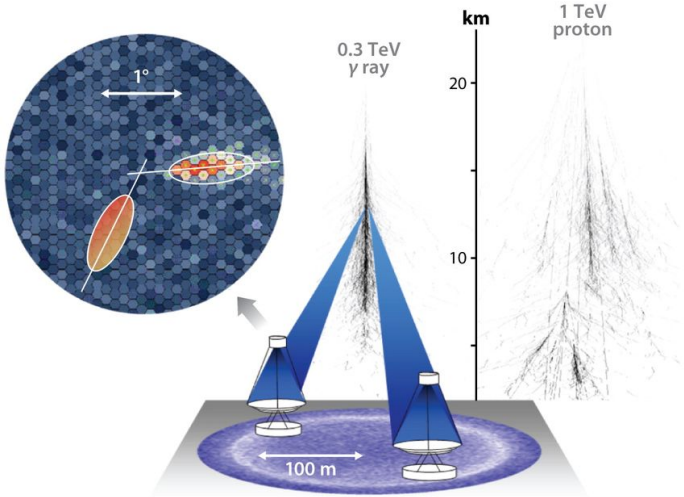
- They can be separated in BL Lacs and Flat Spectrum Radio Quasars (FSRQs) → weak vs strong emission lines in the optical spectra
- Complex MWL emission mechanism → leptonic and hadronic models used for studying it
- Cosmic rays factories?

Credits: NASA, ESA, CSA

MAGIC telescopes

VHE range:
Energies > 100 GeV

VHE gamma-ray detectors aimed at measuring photons with energies between ~50 GeV to ~50 TeV -> imaging atmospheric Cherenkov technique

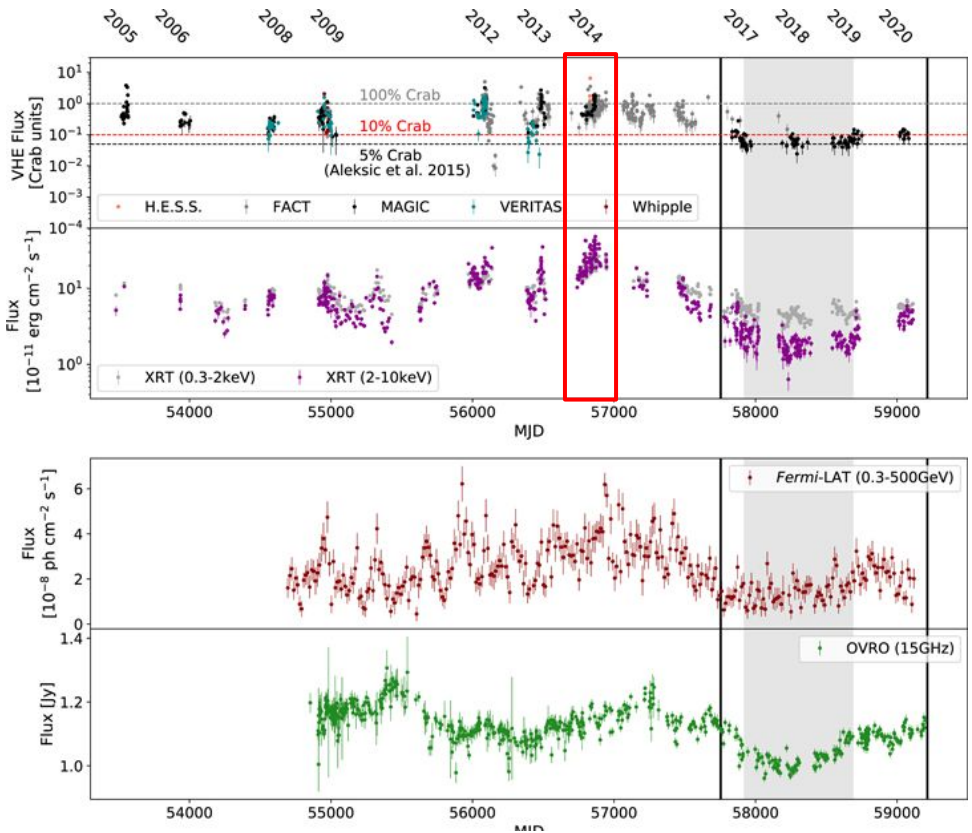


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

Credits: Daniel Lopez, IAC

Ref.:Hinton, J. A., and W. Hofmann. "Teraelectronvolt astronomy." *Annual Review of Astronomy and Astrophysics* 47.1 (2009): 523-565.

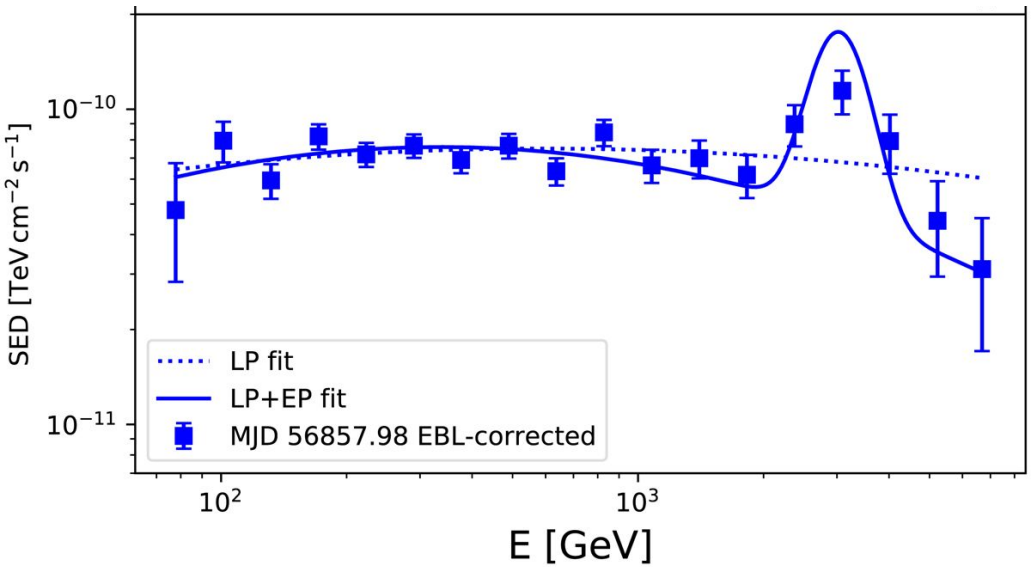
Markarian 501 (Mrk 501) is a nearby blazar -> redshift 0.034!



- 2014: several flares in the VHE gamma-ray band
- 1997: very high activity and many flares as well in the X-ray and gamma-ray bands

Ref.: MAGIC Coll+2023. **Astrophysical Journal, Supplement Series**, v. 266, n. 2, p. 37

Mrk 501's VHE activity in July 19th 2014



Ref.: MAGIC Coll+2020, **Astronomy & astrophysics**, v. 637, p. A86.

The spectra can be described by a log-parabola with a narrow Gaussian-like feature or an exponential log-parabolic shape (Likelihood Ratio Test~3.9-4.5σ)

Physical hypotheses published so far:

- Pile-up of the electron energy distribution [1]
- Additional SSC zone [1]
- Magnetospheric vacuum gap [1,2]
- Pion decay [3]

Refs.: 1. MAGIC Coll+2020, **Astronomy & astrophysics**, v. 637, p. A86.
2. C. Wendel et al. , **Astronomy & Astrophysics** 646, A115 (2021).
3. M. Petropoulou et al., **Astronomy & Astrophysics** 685, A110 (2024).

Investigation of the TeV feature in 2014

May 21st

July 19th

MJD	Flux (eV cm^2 s^{-1})	Flux TeV (eV cm^2 s^{-1})	Γ	b	$\chi^2/d.o.f.$	p value	LRT*
56740.22	0.3±0.07	0.38±0.11	-2.2±0.2	-	4.8/10	0.9	-
56769.15	0.72±0.06	0.48±0.09	-2.28±0.06	-0.82±0.11	9.6/11	0.56	20.9(4.6σ)
56772.09	0.9±0.09	0.5±0.12	-2.59±0.1	-	15.6/12	0.21	-
56782.09	0.81±0.09	0.85±0.15	-2.41±0.11	-	9.2/10	0.51	-
56786.08	0.78±0.1	0.52±0.15	-2.39±0.12	-	11.4/13	0.58	-
56798.11	3.35±0.19	5.46±0.46	-2.07±0.02	-0.49±0.05	10.9/14	0.69	31.9(5.6σ)
56802.0	1.03±0.14	1.34±0.27	-2.33±0.12	-	21.3/13	0.07	-
56802.97	0.98±0.09	0.69±0.14	-2.41±0.09	-	10.7/13	0.64	-
56803.98	0.69±0.07	0.78±0.13	-2.38±0.11	-	15.5/16	0.49	-
56843.05	1.1±0.09	1.0±0.17	-2.37±0.08	-	10.6/13	0.64	-
56845.05	0.78±0.09	1.35±0.21	-2.24±0.14	-	19.3/14	0.16	-
56854.97	1.05±0.09	0.74±0.13	-2.47±0.05	-0.62±0.1	14.0/16	0.6	12.2(3.5σ)
56855.98	1.58±0.12	1.87±0.21	-2.32±0.05	-	20.6/16	0.19	-
56856.91	3.06±0.26	4.16±0.56	-2.21±0.06	-	8.7/13	0.8	-
56857.98	2.51±0.12	3.96±0.27	-2.21±0.04	-	36.5/14	0.001	-
56858.98	3.0±0.21	4.14±0.44	-2.22±0.05	-	11.9/13	0.54	-

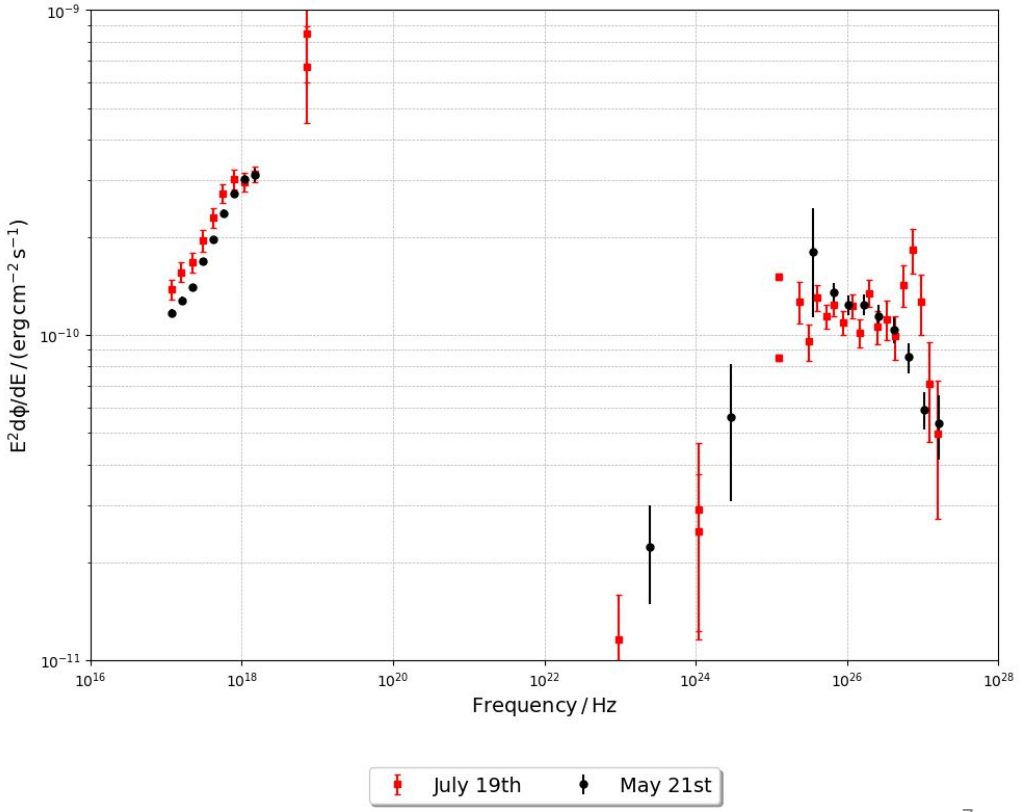
*LRT - Likelihood ratio test

There is more disagreement in the fit of July 19th (p-value of 0.001) than in the other days. The appearance of the spectral feature at this day causes difficulties in fitting properly with analytic functions.

Comparison of the spectra in July 19th with another flaring moment (May 21st)

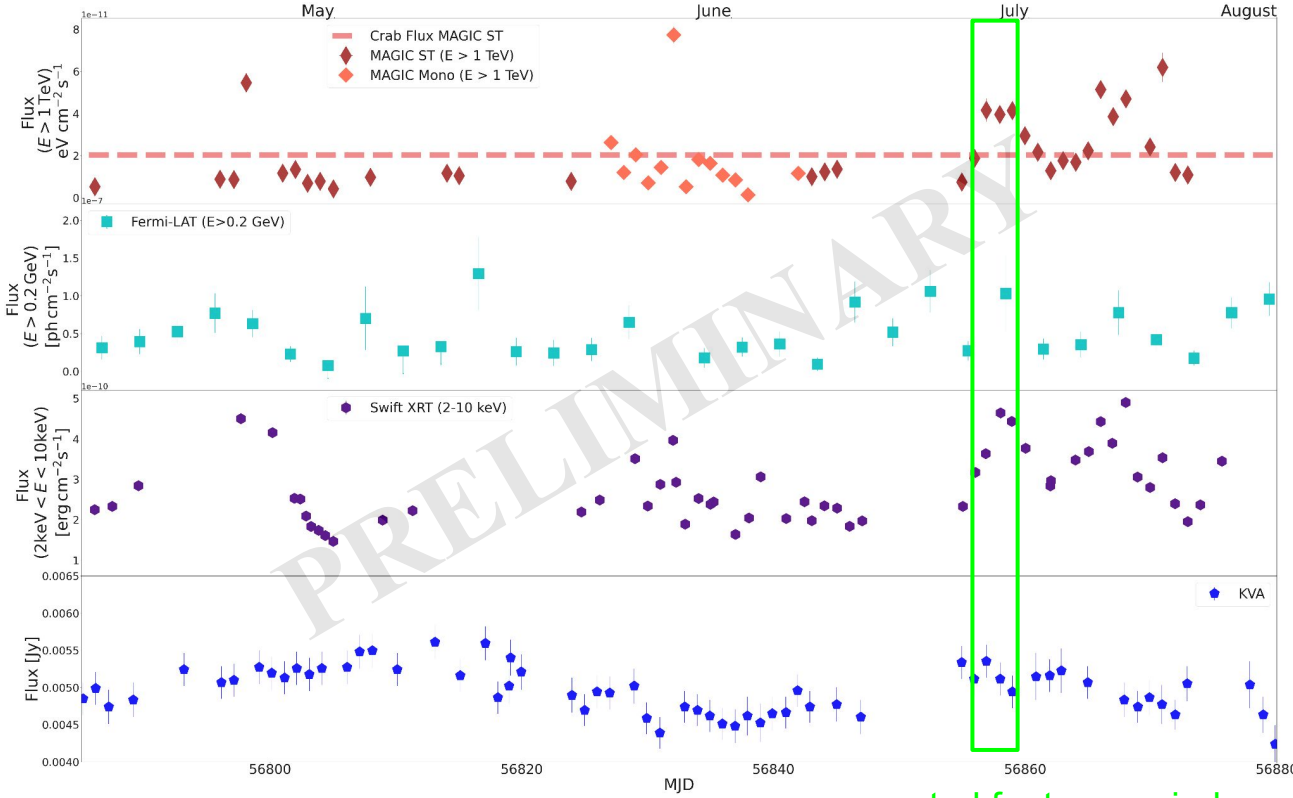
Even in other days with high activity in X-rays and VHE gamma rays, the feature in the SED is not observed!

Is the activity in July 19th caused by a separated process over a general emission?

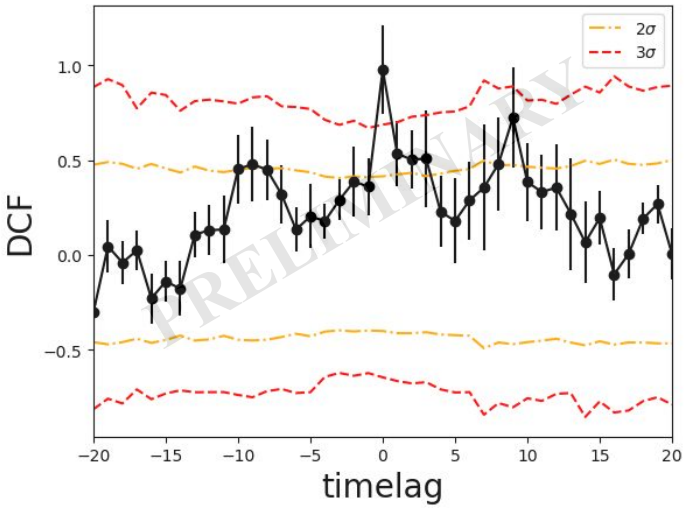


Multiwavelength LC

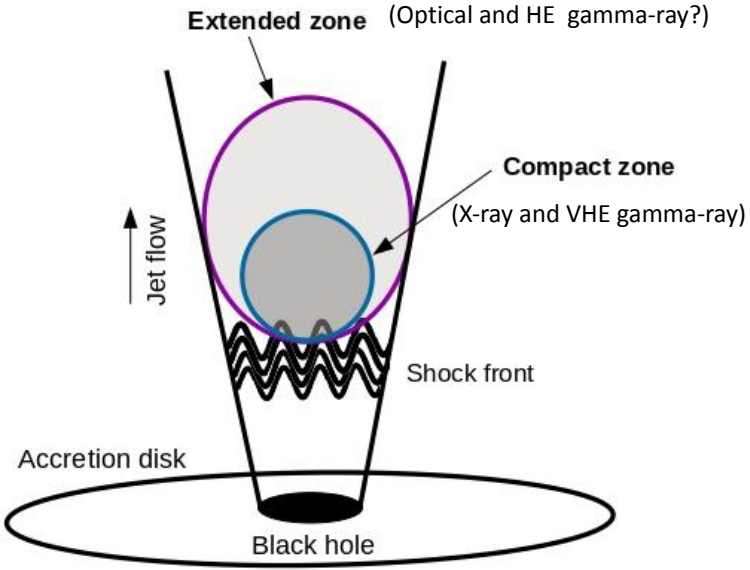
High variability in the X-ray and VHE gamma-ray range!



MAGIC VHE vs XRT X-ray



Simple hypothesis:



Adapted from.:
https://doi.org/10.1051/0004-6361/202348709

Conclusions

- The investigation of the TeV feature of Mrk 501 through other days in 2014 indicates only July 19th with a significant ‘spike’ in the SED-> a radiative /particle acceleration process causing this particular case?

- Initial correlation studies to be further developed indicate the connection between X-ray measured in Swift-XRT and the VHE gamma-ray measured by MAGIC -> a zone close to the supermassive black-hole?

- Article’s draft is almost finished. Stay tuned!

Obrigado!!

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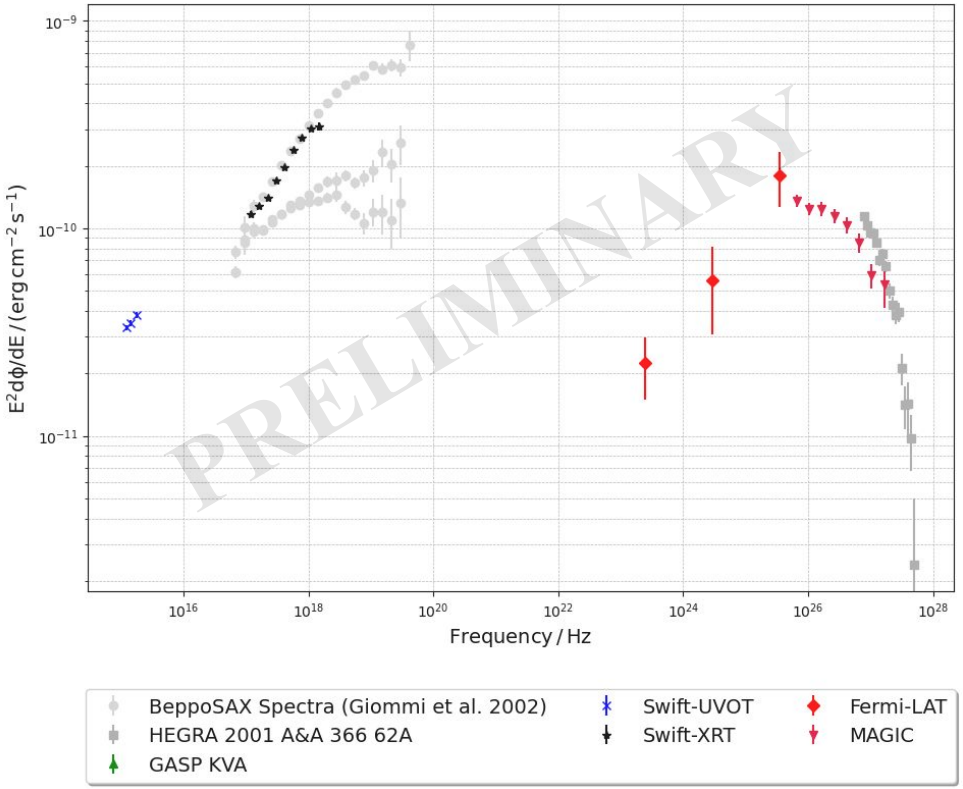
Appendix

SEDs comparison - 1997 x May 21st 2014



Data used from 1997 (taken from 'SSDC SED Builder'):
-BeppoSAX Spectra (Giommi et al. 2002)
-HEGRA_2001A&A_366_62A