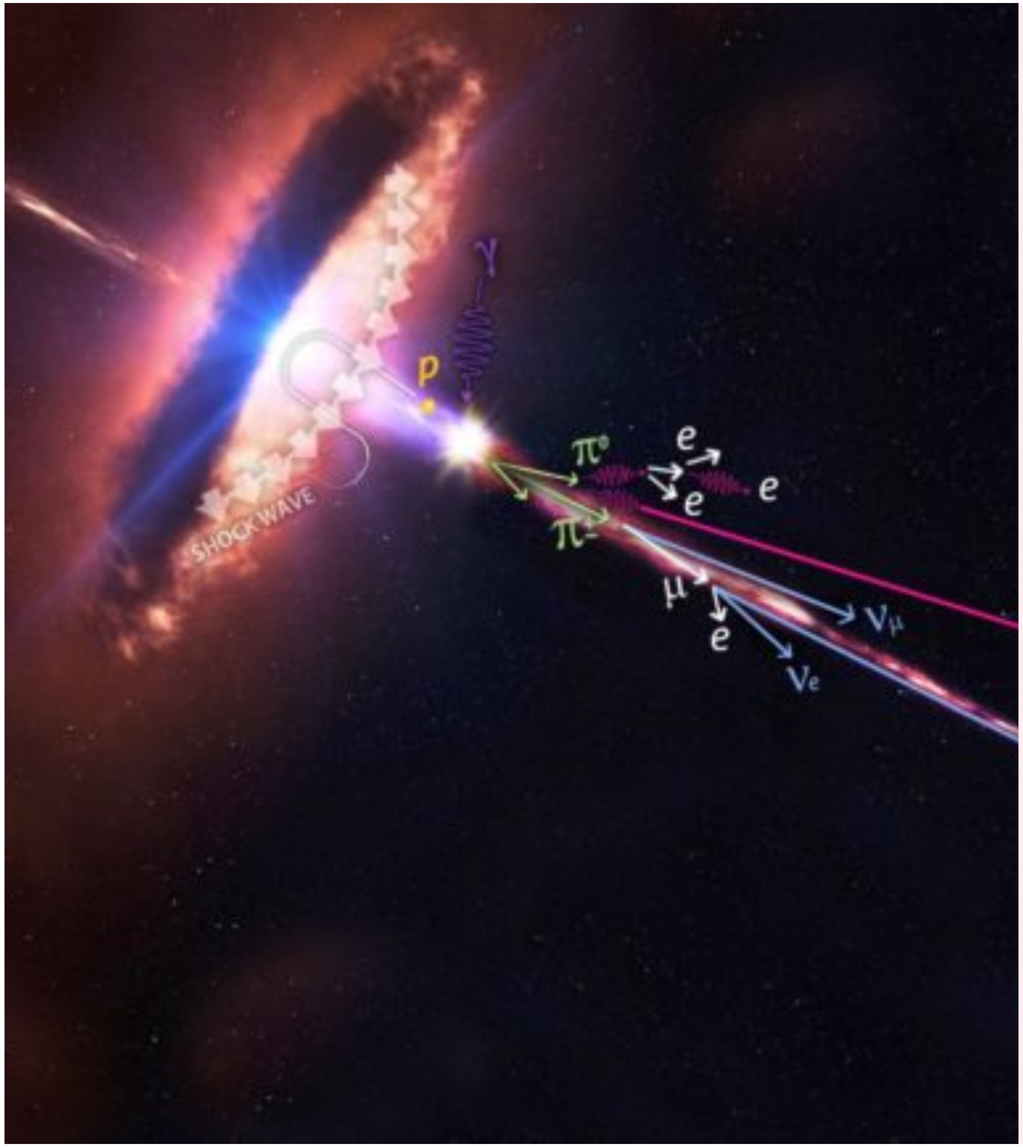


THE BLAZAR TXS 0506+056 ASSOCIATED WITH A HIGH-ENERGY NEUTRINO:

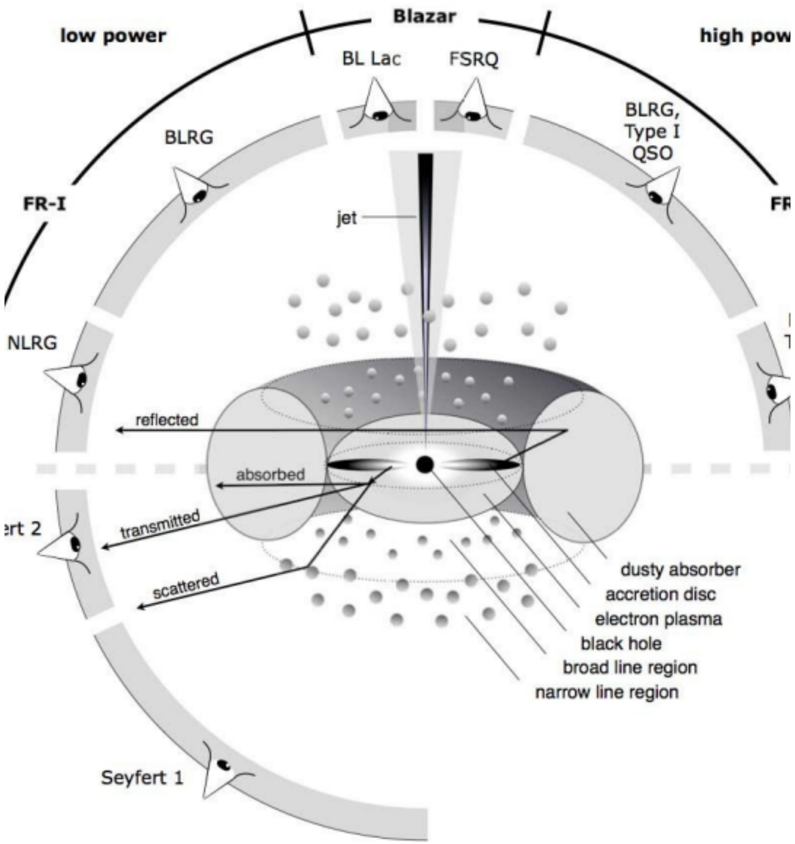
insights into extragalactic jets and cosmic ray acceleration

ABSTRACT

A neutrino with energy of ∼290 TeV, IceCube-170922A, was detected in coincidence with the BL Lac object TXS 0506+056 during enhanced gamma-ray activity, with chance coincidence being rejected at $\sim 3\sigma$ level. We monitored the object in the very-high-energy (VHE) band with the MAGIC telescopes for ∼41 hours from 1.3 to 40.4 days after the neutrino detection. Day-timescale variability is clearly resolved. We interpret the quasi-simultaneous neutrino and broadband electromagnetic observations with a novel one-zone lepto-hadronic model, based on interactions of electrons and protons co-accelerated in the jet with external photons originating from a slow-moving plasma sheath surrounding the faster jet spine. We can reproduce the multiwavelength spectra of TXS 0506+056 with neutrino rate and energy compatible with IceCube-170922A, and with plausible values for the jet power of $\sim 10^{45} - 4 \times 10^{46}$erg s^{-1}. The steep spectrum observed by MAGIC is concordant with internal $\gamma\gamma$ absorption above ∼100 GeV entailed by photohadronic production of a ∼290 TeV neutrino, corroborating a genuine connection between the multi-messenger signals. In contrast to previous predictions of predominantly hadronic emission from neutrino sources, the gamma-rays can be mostly ascribed to inverse Compton up-scattering of external photons by accelerated electrons. The X-ray and VHE bands provide crucial constraints on the emission from both accelerated electrons and protons. We infer that the maximum energy of protons in the jet co-moving frame can be in the range $\sim 10^{14}$ to 10^{18} eV.

Sections:

1. Introduction
2. VHE gamma-ray and broadband emission of TXS 0506+056
3. Interpreting the broadband and neutrino emission
4. Implications for UHECR acceleration in AGN jets
5. Discussion and conclusion



1. Brief Introduction

WHERE DO COSMIC-RAY ORIGINATE FROM?

- Ultra-high-energy cosmic rays (UHECRs) are the most energetic particles known in the Universe with energies exceeding 10^{18} eV.
- From the observed distribution of their arrival directions in the sky, we generally say that they have an extragalactic origin
- Numerous candidate sources have been proposed, but the most promising are active galactic nuclei (AGN) that eject powerful jets of magnetized plasma at relativistic velocities.

⬇

BLAZARS are AGN with their jets oriented in the line of sight of the observer

Typical properties of a blazar and classification

- They typically show a non-thermal spectral energy distribution (SED) consisting of 2 broadly-peaked components:

Low Energy

-peaking in IR to X-ray band
-due to synchrotron radiation by high-energy electrons

High Energy

-peaking in the GeV-TeV gamma-ray range
-due to Inverse Compton scattering of low-energy photons by high-energy electrons

- They can be divided into 2 different subclasses:

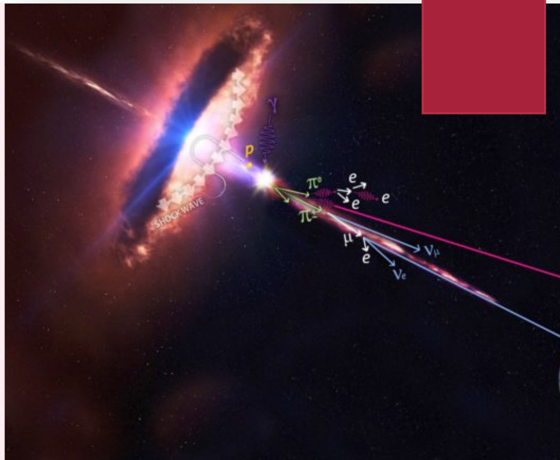
  - FSRQ (Flat Spectrum Radio Quasars) : they are relatively luminous and show strong emission lines in the optical –UV. Their low-energy photons are dominated by thermal photons coming from outside the jet, leading to external Compton emission.

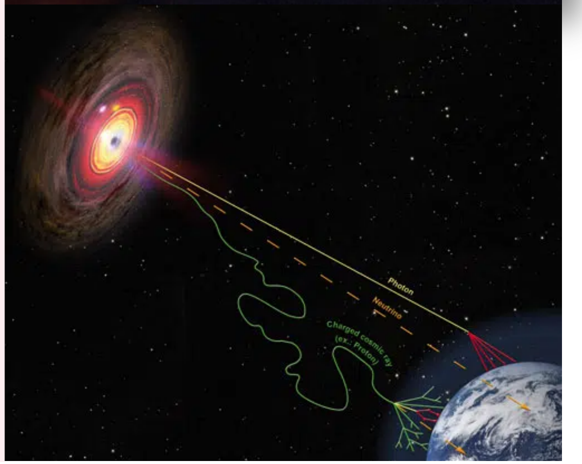
  - BL Lac : they are less luminous and show only weak emission lines. Their low-energy photons are typically synchrotron ones, leading to the synchrotron-self-Compton emission.

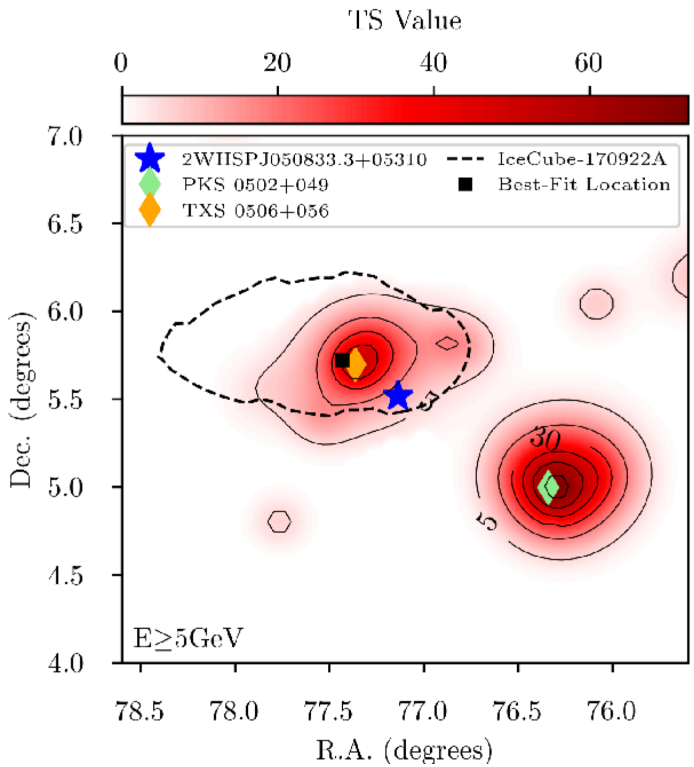
- Charged particles, such as nuclei and protons seem to follow the same acceleration mechanism of an electron.

- They are able to interact with the surrounding matter or with low-energy photons, producing in such a way «neutrinos» or «gamma-ray» .

- Neutrinos can be considered the «smoking-gun» of hadron acceleration. They are expected to point back to their origin in the sky, giving us a lot of information about the sources of cosmic rays.







2. VHE Gamma-Ray and broadband emission

- In September 2017, the IceCube neutrino observatory revealed an event designated IceCube-170922A with 56.5% probability of being a truly astrophysical neutrino. The best-fit reconstructed direction was at 0.1◦ from the sky position of the BL Lac object TXS 0506+0561. Its energy was found to be 290 TeV.

- No additional excess of neutrinos with lower energy was found from the direction of TXS 0506+056 near the time of the alert .

- Observations revealed TXS 0506+056 to be active in all electromagnetic (EM) bands, most notably in GeV gamma-rays monitored by the Fermi-LAT, and in very high-energy (VHE) gamma-rays above 100 GeV, detected for the first time by the MAGIC telescopes.

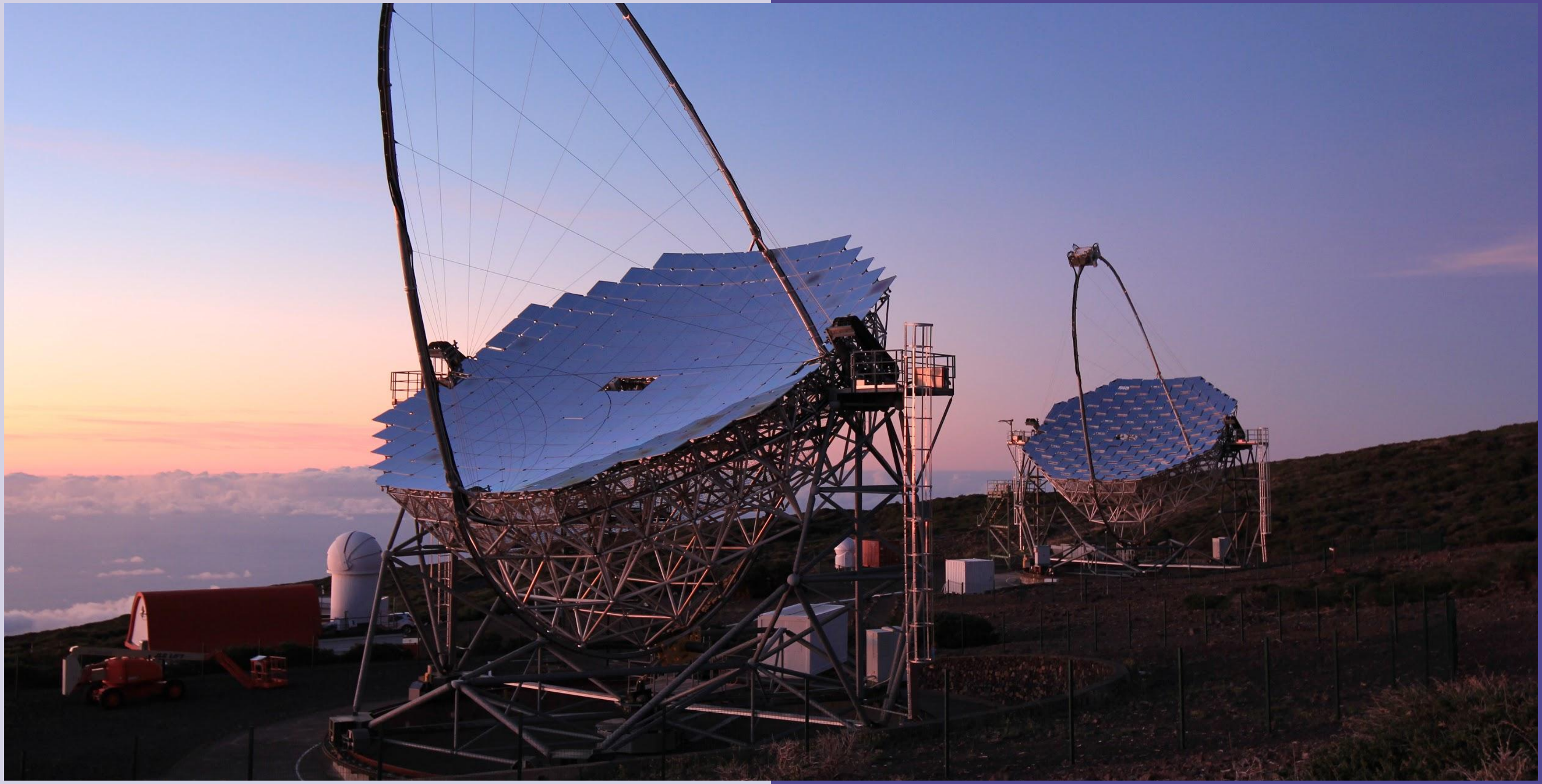
- Its redshift has been recently measured to be z = 0.3365±0.001.

Unique opportunity to explore the interplay between energetic photons, neutrinos and cosmic rays.

From now on what we do is the assumption that the association of IceCube-170922A and the blazar in an active state is genuine, and that the neutrino and EM emission arise from the same region in the object.

A big campaign by many telescopes on ground just begun a few hours after the neutrino alert. Each one was used to have a complete analysis in a specific band of the spectrum, going from Radio frequencies up to VHE (Very High Energy) gamma-rays.

MAGIC (La Palma, Canary Island)



Magic VHE Results

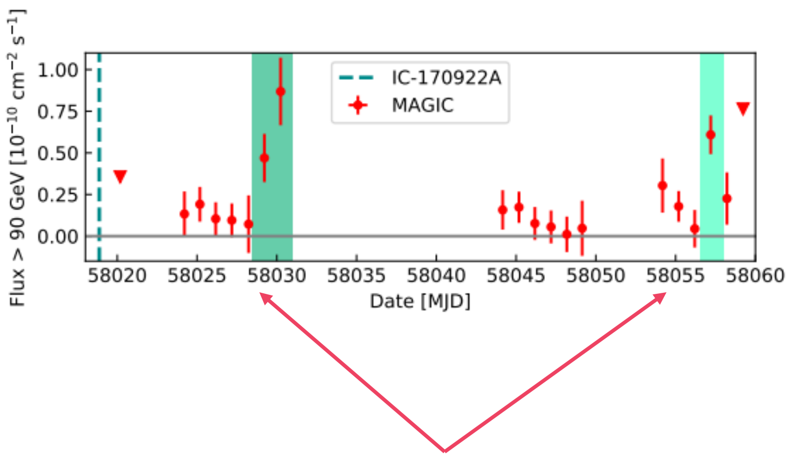
- MAGIC is a system of two IACTs (Imaging Atmospheric Cherenkov Telescope) that record Cherenkov light from shower events in the range between 30 GeV up to 100 TeV within a field of view of ~10 square degrees.

- It made observations of the sky position of IceCube 170922A from September 24 till October 4, 2017

- It made the first detection of a very high energy astrophysical signal which was compatible to the ones coming from the neutrino analyzed.

- We present additional data collected till November 2, giving us a total of 47 hours of exposure (41 selected)

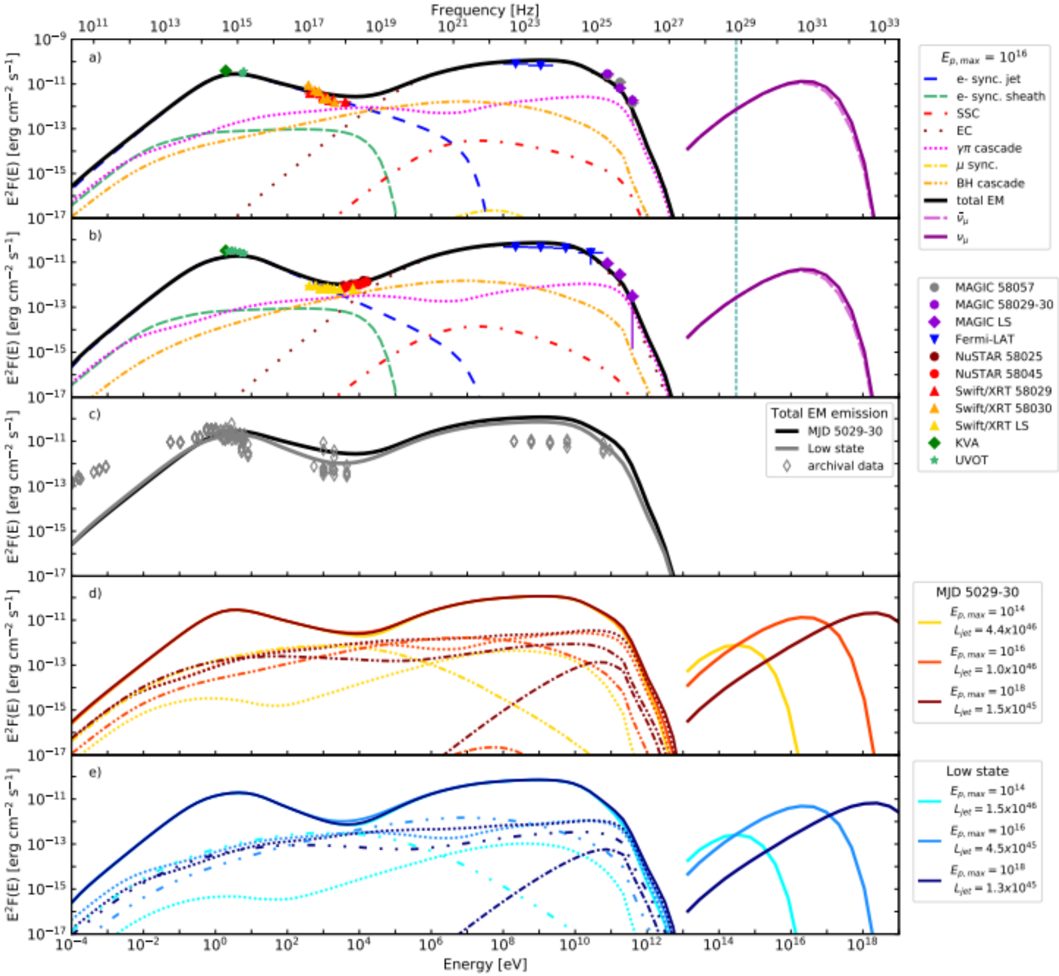
- Parameters cuts obtained comparing with data from the Crab Nebula already known.



two periods of enhanced emission during MJD 58029-30 and MJD 50857.

Date MJD	Effective time [hours]	Flux > 90 GeV [10^{-11} cm^{-2} s^{-1}]
58020.18	1.1	< 3.56
58029.22	1.3	4.7 ± 1.4
58030.24	0.6	8.7 ± 2.0
58056.20	2.3	0.4 ± 1.1
58057.20	2.7	6.1 ± 1.2
58058.22	1.6	2.3 ± 1.6
58059.23	0.3	<7.6

- VHE flux is variable, increasing by a factor of 6% in a day
- Probability of a costant flux is very low, less than 0.3%
- The detection of TXS 0506+ 056 by MAGIC was made also outside these two periods
- The photon spectrum can be described over the range of 80 GeV to 400 GeV by a simple power law dN/dE ~$E↑\gamma$ with a spectral index ranging from (-4.0 ± 0.3) to (-3.5 ± 0.4).
- Significantly steeper than the spectrum measured by Fermi-LAT quasi-simultaneously, with spectral index (-2.0 ± 0.2) in the energy range 100 MeV to 300 GeV.

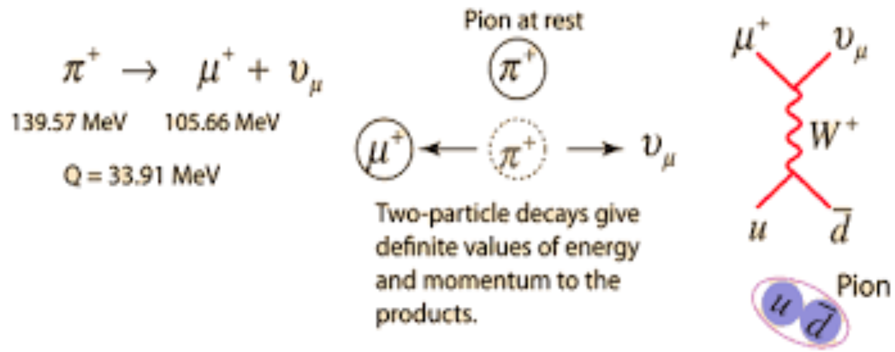


The coverage of TXS is done with other avaible instruments, such as UVOT, XRT on board of Swift, NuSTAR and FermiLAT.

Comparison of the light curve in Figure 1 with that measured by Fermi-LAT suggests the low VHE state to be more representative of the VHE average emission during the six months of enhanced GeV flux.

The obtained SEDs appear typical of BL Lac objects with similar luminosities

3. Interpreting the broadband and Neutrino Emissions



- High-energy neutrino in astrophysical environment are generally made through the decay of charged pions produced in inelastic collisions between high-energy protons and ambient target particles (matter *pp* interactions or low-energy photons $p\,\gamma$ interactions).

- In AGN jets, we generally find the second channel.

- The production of a neutrino with energy E ~ 290 TeV requires interaction between protons with energy E ~ 6 PeV and photons with E ~ 440 eV (UV to soft X-ray band)

- FSRQs are considered promising sources of high-energy neutrinos
- In contrast, BL Lac have always been thought to be inefficient neutrino emitters (low density of UV to soft X-ray synchrotron photons)

The association of high-energy neutrino with TXS 0506+056 is not trivial!

«spine-layer» or *«jet-sheat»* scenario (Tavecchio)

- Structured jets, consisting of a faster core surrounded by a slower sheath (we have sperimental and simulations evidence of this phenomenon)
- Due to the significant relative motion between the two structures, the density of photons arising from the slower sheath appears highly boosted in the reference frame moving with the faster jet
- p γ interactions increase and also neutrinos emission
- Important consequence: associated absorption of gamma-rays via γ γ interactions

sorption above a corresponding threshold. Detection of such a spectral feature constitutes a critical test of photohadronic neutrino production as well as the neutrino-blazar association itself.

Model Description

- In order to describe the broadband EM and neutrino emission from TXS 0506+056, we use the jet-sheath model.
- The radiative output is calculated in the reference frame comoving with the jet flow, assuming an isotropic distribution for electrons and protons and then considering the Doppler shift due to the relativistic motion.
- Let's star by considering all hadronic radiative processes, such as:

  - photon-meson-induced cascade emission
  - Bethe-Heitler pair cascade emission
  - Synchrotron radiation from protons and muons $\longrightarrow$ this is the most important one!

We have to consider also secondary pair cascades due to high energy protons and gamma-rays that give rise to pair production ($\gamma\gamma \longrightarrow e^{+} e^{-}$)

3 components to take in account:

1. Direct products from pγ reactions
2. Secondary pair cascades
3. Hadronic components arising from BH pair production ($p\gamma \longrightarrow p e^{+} e^{-}$)

State	MJD 58029-30	Lower VHE
B [G]	2.6	2.6
$E_{\rm min}$ [eV]	3.2×10^8	2.0×10^8
$E_{\rm br}$ [eV]	7.0×10^8	9.0×10^8
$E_{\rm max}$ [eV]	8×10^{11}	8×10^{11}
n_1	2	2
n_2	3.9	4.4
U_e [erg cm^{-3}]	4.4×10^{-4}	3.6×10^{-4}
U_B [erg cm^{-3}]	0.27	0.27
U_p [erg cm^{-3}]	1.8	0.7
P_e [erg s^{-1}]	2×10^{42}	1.6×10^{42}
P_p [erg s^{-1}]	8×10^{45}	3×10^{45}
P_B [erg s^{-1}]	1.2×10^{45}	1.2×10^{45}

Here's a list of all the parameters calculated in the jet comoving reference frame

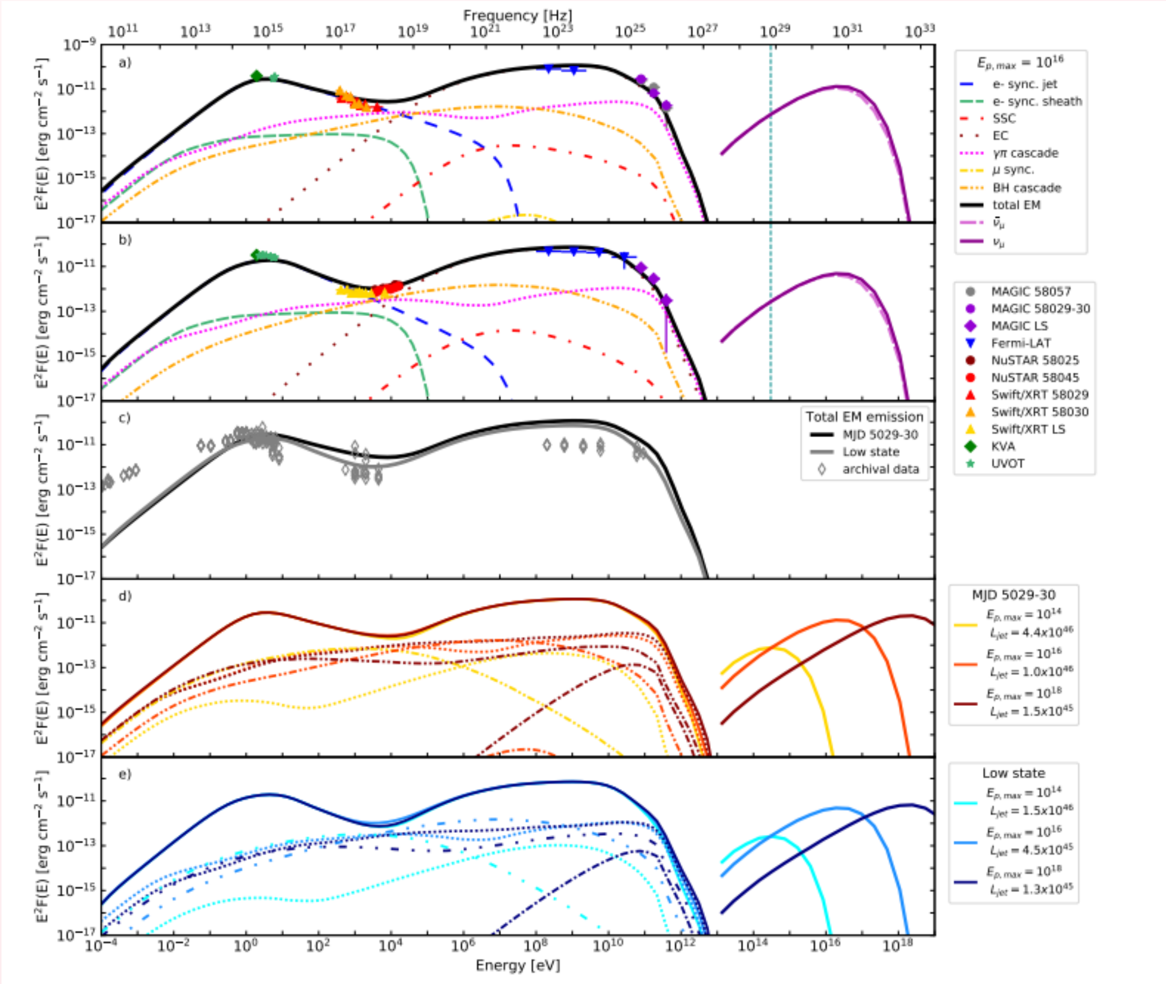
We can see that the most important informations we can deduce from the table are:

- Jet magnetic field B
- Energy densities in relativistic electrons U_e, magnetic field U_B and relativistic protons U_p

Than the jet power can be evaluated as :

$$P_{jet} = \pi R^2 \Gamma^2 c (U_e + U_B + U_p)$$

with $\Gamma_j = 22$, $\Gamma_s = 2.2$ and R = 10^{16} cm (time scale of a day)



Frequency [Hz]
Energy [eV]
E²F(E) [erg cm⁻² s⁻¹]
a)
b)
c)
d)
e)
$E_{p,max}$ = 10^{16}
e- sync. jet
e- sync. sheath
SSC
EC
γπ cascade
μ sync.
BH cascade
total EM
$\bar{\nu}_\mu$
ν_μ
MAGIC 58057
MAGIC 58029-30
MAGIC LS
Fermi-LAT
NuSTAR 58025
NuSTAR 58045
Swift/XRT 58029
Swift/XRT 58030
Swift/XRT LS
KVA
UVOT
Total EM emission
MJD 5029-30
Low state
archival data
MJD 5029-30
$E_{p,max}$ = 10^{14} L_{jet} = 4.4x10^{46}
$E_{p,max}$ = 10^{16} L_{jet} = 1.0x10^{46}
$E_{p,max}$ = 10^{18} L_{jet} = 1.5x10^{45}
Low state
$E_{p,max}$ = 10^{14} L_{jet} = 1.5x10^{46}
$E_{p,max}$ = 10^{16} L_{jet} = 4.5x10^{45}
$E_{p,max}$ = 10^{18} L_{jet} = 1.3x10^{45}

- Strong spectral steepening due to internal γγ absorption is predicted in the VHE band, as a result of photohadronic production of a 290 Tev neutrino

- The fraction of multi-PeV parent protons that undergo pγ interactions is about 10^{-4}. This implies that the γ γ threshold is $E_{\gamma\gamma}=12\ GeV$. So we expect a significant absorption above 100 GeV.

- The MAGIC spectrum matches this expectations , providing a confirmation of the one-zone lepto-hadronic interpretation, as well as the association between the neutrino and the blazar.

- The SED comprise mostly leptonic emissions . In particular, the second SED component peaking in the GeV band is largely accounted for by EC emission. This is in contrast to some earlier studies of neutrino emission from blazars that predicted predominantly hadronic gamma-rays.

- Our models show that neutrino emission can be commensurate with the widely accepted view of primarily leptonic gamma-ray emission from blazars. This implies that the values of the parameters that suitably reproduce the SEDs (in particular magnetic field, Doppler factor, electron density) are in the range commonly derived for BL Lac objects similar to TXS 0506+056 based on purely leptonic models.

- The components of the photo-meson cascade in our model are necessary to explain the very high-energy (VHE) gamma-ray emission and internal $\gamma\ \gamma$ absorption, and thus the predicted neutrino fluxes.

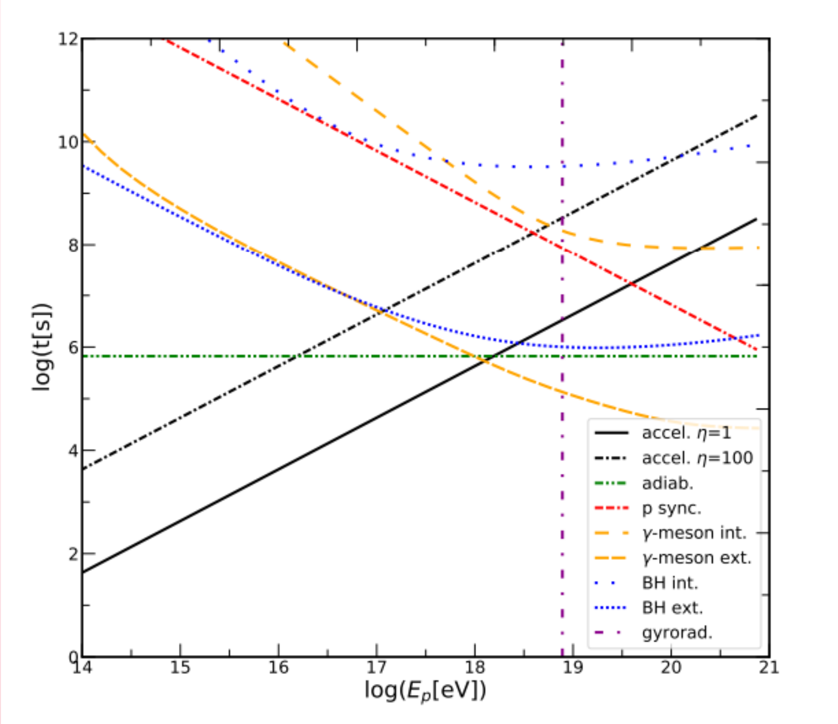
4. Implications for UHECR acceleration in AGN jets

- the multi-messenger observations of TXS 0506+056 can be interpreted by considering the acceleration of electrons and protons in the same region of the jet, which interact with a source of external photons. The detection of the single neutrino may provide the first compelling evidence for proton acceleration in AGN jets, while the MWL observations constrain key parameters.

- Various mechanisms have been proposed for accelerating UHECRs in AGN jets, involving strong shocks, magnetic reconnection, shear flows, etc.
- Indipendently from the acceleration mechanism, the time of acceleration as viewed in the comoving frame of the jet is :

$$t\downarrow acc = 10\eta E \,/\, (\mathrm{ZeBc})$$

Where η is a parameter that characterizes the properties of magnetic disturbances responsable for the acceleration. For relativistic shock we expect a parameter $\eta = 1$.



5. Conclusions

The combined MWL and neutrino observations of TXS 0506+056 can be interpreted in terms of electrons and protons that are accelerated in the same region of the jet and interact with external low-energy photons, originating from the slower sheath surrounding the faster jet spine.

The enhanced luminosity for EC emission relative to the other emission components at small viewing angles is important for adequately reproducing the MWL SEDs. Most notably, the prominent spectral steepening observed at ~100 GeV by MAGIC confirms the internal $\gamma\gamma$ absorption that is expected as a consequence of $p\gamma$ production of a ~290 TeV neutrino.

Jet structure as envisaged in the jet-sheath scenario can be conclusively tested with future very long baseline interferometry (VLBI) measurements with high angular resolution. We note that an alternative source of external photons in BL Lac objects may be provided by radiatively inefficient accretion flows around the central supermassive black holes.