Neutrino emission during the $\gamma$-suppressed state of blazars

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Despite the uncovered association of a high-energy neutrino with the apparent flaring state of blazar TXS 0506+056 in 2017, the mechanisms leading to astrophysical particle acceleration and neutrino production are still uncertain. Recent studies found that blazars in a $\gamma$-flaring state are too sparse for neutrino production, making the multi-messenger observation of TXS 0506+056 difficult to explain. Here we show that the Fermi-LAT $\gamma$ flux of another blazar, PKS 1502+106 was at a local minimum when IceCube recorded a coincident high-energy neutrino IC-190730A. This suggests the presence of a large target photon and proton density that helps produce neutrinos while temporarily suppressing observable $\gamma$ emission. Using data from the OVRO 40-meter Telescope, we find that radio emission from PKS 1502+106 at the time of the coincident neutrino IC-190730A was in a high state, in contrast to other time periods when radio and $\gamma$ fluxes are correlated. This points to an active outflow that is $\gamma$-suppressed at the time of neutrino production. We find similar local $\gamma$ suppression in other blazars, including the MAGIC flux of TXS 0506+056 and the Fermi-LAT flux of PKS B1424-418 at the time of coincident IceCube neutrino detections, further supporting the above model. Using temporary $\gamma$-suppression, neutrino-blazar coincidence searches could be substantially more sensitive than previously assumed, enabling the identification of the origin of IceCube's diffuse neutrino flux possibly with already existing data.

I. INTRODUCTION

The origin of the isotropic cosmic flux of high-energy neutrinos, discovered by IceCube in 2013, is still unknown [1–3]. The most promising strategy to identify the underlying sources has been multi-messenger observations [4], which were able to rule out rare transients as the primary neutrino emitters [5, 6].

The discovery of a high-energy neutrino in temporal and directional coincidence with an apparently flaring blazar, TXS 0506+056, represented a breakthrough as the first confident identification of an extragalactic neutrino source [4]. However, high neutrino production efficiency necessitates large target photon densities. This in turn renders the source opaque to $\gamma$-rays, in apparent contradiction with the observed blazar flare [7].

In this paper we closely examined the temporal structure of $\gamma$-ray emission from several blazars to resolve this contradiction. We considered blazars with identified neutrino counterparts, namely TXS 0506+056, PKS 1502+106 and PKS B1424418. In particular we present a new analysis of Fermi-LAT data to determine $\gamma$ emission from PKS 1502+106. To probe the underlying mechanism driving the $\gamma$ flux, we examined the radio flux of blazar PKS 1502+106 using archival observations of the OVRO 40-meter Telescope.

II. FERMI-LAT ANALYSIS OF PKS 1502+106

We extracted 12 years of Pass8 Fermi-LAT1 data2, obtained between 2008 August 4 and 2020 June 26 in the energy range from 100 MeV to 300 GeV. The search window was centered at RA$_{J2000} = 226.10^\circ$ and DEC$_{J2000} = 10.49^\circ$ encompassing an area of the sky within $15^\circ$ ROI radius around the central coordinates. We selected event type "front+back" (evtype=3) which is the recommended type for a point source analysis.

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1 https://fermi.gsfc.nasa.gov/science/instruments/lat.html
2 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html
We performed unbinned likelihood analysis of the data utilizing the Fermi-LAT ScienceTools package v11r5p3 with fermipy package 0.17.3. The instrument response function P8R3_SOURCE_V2 was employed altogether with templates of the Galactic interstellar emission model gll_iem_v07.fits and of the isotropic diffuse emission iso_P8R3_SOURCE_V2_v1.txt. We applied the nominal data quality cut (DATA_QUAL > 0) && (LAT_CONFIG==1), and a zenith angle cut $\theta < 90^\circ$ to eliminate Earth limb events.

Our derived counts map of PKS 1502+106 is shown in Fig. 1. We see that PKS 1502+106 is an unusually bright $\gamma$-ray source dominating its environment throughout the 12 years, therefore the input model for the light-curve generation included only PKS 1502+106 and diffuse components.

We show the $\gamma$-ray light curve of PKS 1502+106 in the top panel of Fig. 2. We see that the blazar exhibited larger and smaller flares throughout the Fermi observations. Notably, at the time of the detection of a coincident neutrino neutrino, its $\gamma$ flux was at a local minimum, showing rapid rise during the weeks following the minimum.

### III. RADIO ANALYSIS OF PKS 1502+106

Very long baseline interferometry (VLBI) has revealed the core-jet structure of TXS 0506+056 and PKS 1502+106 [8]. Only those jets are visible by VLBI, that are pointed very close to our line-of-sight, and since neutrino emission in blazars is predicted to be beamed [9–11], VLBI jets are particularly interesting when searching for the sources of neutrinos. Based on 10 years of 2 cm MOJAVE/VLBA data [8], it was argued that the rapid flux density variation of TXS 0506+056 at the time of the detection of neutrino IC-170922A, come from the core at 15 GHz [12, 13]. The small Lorentz factor indicates interactions close to the core of the AGN. Emission from the VLBI core dominated the single dish flux density of TXS 0506+056 measured with the OVRO 40 m Telescope [14]. Based on 7 mm data taken with the VLBA, the flux density increase was exclusively associated with the core at 43 GHz [15]. Interestingly, the VLBI flux density of PKS 1502+106 is also dominated by the core at 15 GHz in PKS 1502+106 at 15, 43 and 86 GHz [16].

We show the flux density curve of PKS 1502+106 obtained by the OVRO 40-meter Telescope [14] at 15 GHz in the lower panel of Fig. 2. We see that, at the time of the observed neutrino, radio emission from PKS 1502+106 was in a high state compared to the flux distribution within our studied time frame.

We also show the correlation plot between the $\gamma$ and radio fluxes of PKS 1502+106 in Fig. 3. Here, we see that until about 2015, the $\gamma$ and radio fluxes are correlated, both for high and for low flux states. After 2015, however, the radio flux stays high while the $\gamma$ flux varies over time. If we consider that outflows from the central black hole are traced by the radio flux that is emitted at smaller radii, this means that the outflow continued to be significant while $\gamma$ emission was suppressed at the time of the neutrino detection from PKS 1502+10.

### IV. $\gamma$ SUPPRESSION IN OTHER BLAZARS

**TXS 0506+056.** IceCube recorded a 290 TeV muon neutrino in temporal and directional coincidence with a 6-months long flare of TXS 0506+056. We show the blazar’s $\gamma$ flux measured by Fermi-LAT and MAGIC in the middle panel of Fig. 4. We see that the Fermi-LAT flux from TXS 0506+056 drops by about 30% from the week prior to the neutrino, and starts rising again within 2 weeks after the neutrino. The picture is also instructive when looking at the MAGIC flux (E $> 90$ GeV). This flux was only measured in the aftermath of the neutrino detection. We see that the MAGIC flux is very low (undetectable) at the time of the neutrino, but then rapidly increases by at least a factor of 10 within 2 weeks [4]. Interestingly, a similar rapid rise was also detected by the MASTER optical telescope in the aftermath of the neutrino detection from the blazar [18].

**PKS B1424-418.** A temporal and directional coincidence was found between the outburst of blazar PKS B1424-418 and a PeV-energy neutrino event (HESE 35, dubbed as "Big Bird") [17]. In the first panel of Fig. 4 we show the gamma-ray light curve of PKS B1424-418 around the time of the neutrino detection [17]. We see that, while there is a longer outburst, at the actual time
FIG. 2: Temporal variation of the $\gamma$-ray and radio brightness of PKS 1502+106. a: Fermi-LAT likelihood light curve integrated between 100 MeV and 300 GeV (marked by black dots with error bars). b: OVRO flux density curve of PKS 1502+106 plotted with light blue dots, that is superimposed by the radio flux density curve binned to the Fermi-LAT light curve (marked with dark blue squares). The detection time of the neutrino IC-190730A is labeled by a vertical purple line.

V. EMISSION MODEL

Comparison of the Fermi-LAT $\gamma$-ray flux and the OVRO 15 GHz flux density suggests that PKS 1502+106 was operating in two modes. In the first mode, the $\gamma$-ray flux correlated with the radio emission both in flaring and quiet phases, with no neutrinos produced. This mode lasted until MJD 56510.17 when the radio flux density was at its lowest ($0.71 \pm 0.01$ Jy). In the second mode the $\gamma$-ray flux decreased while the radio flux density remained high, and at a local minimum of the $\gamma$-ray flux IceCube detected a 300 TeV neutrino from the direction of PKS 1502+106.

The above results suggest that, in the first mode, $\gamma$-rays originate in a transparent source with insufficient target $\gamma$-ray or proton density to produce a detectable neutrino flux. In the second mode a dense proton or $\gamma$-ray target field provides the opportunity to produce neutrinos. At the same time, the target field absorbs of the neutrino there is a sudden suppression in the $\gamma$ flux of the blazar, which then quickly rises again afterwards. Therefore, we find that the neutrino detection coincided with a local $\gamma$ minimum.
high-energy $\gamma$ rays, leading to the minimal flux in the Fermi-LAT data. For instance, for $\gamma\gamma$ interactions the absorption length is two orders of magnitude larger than for $p\gamma$. The $\gamma$ rays that accompany cosmic neutrinos lose energy in the source and emerge at Earth below the Fermi-LAT detection threshold, spread in energy over the longer wavelength electromagnetic spectrum.

In the second mode, a very high cascading contribution from the hadronic $\gamma$-rays is expected, leading to a very high X-ray flux during this time. Checking the Swift-XRT 0.2-10 keV light curve of PKS 1502+106, the flux of this source was indeed increased during this period\(^4\), peaking at about MJD 58100. Interestingly, the Swift X-ray light curve has shown a minimum at about MJD 58700, just like around when the Fermi-LAT $\gamma$-ray flux was at a deep minimum and when IceCube recorded the neutrino event IC-190730A. Though not obvious, the Swift spectrum of PKS 1502+106 was somewhat hardened at about MJD 58000, which would be expected in our scenario. The Swift data being correlated with our modes would imply a cascading of the $\pi^0$ signature down to $\mathcal{O}(10$ keV). This is a scenario that can work as already discussed in [19], but to prove this in detail for PKS 1502+106, detailed theoretical modeling of the multiwavelength data is necessary, which is beyond the scope of this paper.

The radio flux density of both TXS 0506+056 at 15 GHz and 43 GHz and of PKS 1502+106 at 15, 43 and 86 GHz frequencies are dominated by the core [16]. Higher frequencies reveal radio emitting regions closer to the event horizon of the central supermassive black hole in the AGN, therefore the switching between the two modes should happen in the inner jet.

Except at times of neutrino emission, both TXS 0506+056 [20] and PKS 1502+106 are extremely luminous AGN, with the second peaking at $(1.23 \pm 0.03) \times 10^{-6} \text{ ph cm}^{-2}\text{s}^{-1}$. With redshifts of $z = 0.336$ [21] and $z = 1.838$ [22] respectively, we propose that TXS 0506+056 may be the closest of a set of sources that no longer accelerate cosmic rays today.

The model that we present here is fully consistent with multimessenger observations of the extragalactic, diffuse high-energy emission: in order to explain the diffuse high-energy neutrino flux together with the Fermi detection of the extragalactic $\gamma$-ray flux at GeV energies can only be done by either assuming very flat neutrino spectra or taking into account strong gamma-ray absorption in the sources [23].

VI. FUTURE OUTLOOK

We showed that the $\gamma$-ray flux of the three blazars for which a high-energy neutrino counterpart was identified experienced a short-term $\gamma$ suppression at the time of the detected neutrino. Based on these results, the main suggestion of this paper is that the expectation of $\gamma$-flare during the high-energy neutrino emission should be reconsidered or even dropped. In contrast, those blazars that show deep minimums should be the center of studies centered about finding the source of high-energy neutri-
If our model is correct, then it is substantially easier to discover neutrino-blazar connections due to the short allowed time coincidence between $\gamma$-suppressed periods and neutrinos. With this we suggest to revise the strategy to find the origin of the cosmic high-energy neutrinos. It is possible that previously recorded IceCube and Fermi-LAT observations are already sufficient to identify the origin of the bulk of the high-energy neutrinos detected from the Universe.

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