Interpretation of the coincident observation of a high energy neutrino and a bright flare

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On September 22nd 2017, the IceCube Neutrino Observatory reported a muon track from a neutrino with a very good positional accuracy (1). The alert triggered a number of astronomical follow-up campaigns, and the Fermi gamma-ray telescope found as counterpart an object named TXS0506+056 in a very bright, flaring state (2); this observation may be the first direct evidence for an extragalactic source of very high-energy cosmic rays. While this and subsequent observations (3–6) provide the observational picture across the electromagnetic spectrum, answering where in the spectrum signatures of cosmic rays arise and what the source properties must be, given the observational constraints, requires a self-consistent description of the processes at work. Here we perform a detailed time-dependent modeling of these relevant processes and study a set of self-consistent models for the source. We find a slow but over-proportional increase of the neutrino flux during the flare compared to the production enhancement of energetic cosmic rays. We also demonstrate that interactions of energetic cosmic-ray ions result in predominantly hard X-
ray emission, strongly constraining the expected number of neutrinos, and to a lesser degree in TeV gamma rays. Optical photons and GeV-scale gamma rays are predominantly radiated by electrons. Our results indicate that especially future X-ray and TeV-scale gamma-ray observations of nearby objects can be used to identify more such events.

The object associated with the neutrino event is a blazar named TXS0506+056, a specific type of Active Galactic Nuclei (AGN) in which a supermassive black hole powered by accretion of gas spawns a collimated outflow pointing at Earth. Material in these so-called jets moves with nearly the speed of light, and its emission is amplified in the direction of motion, making blazars very prominent sources of radiation that can be observed out to large distances, at considerable cosmic redshifts; see Fig. 1 for illustration. The outflow of matter and radiation should not be so powerful that the surrounding matter is blown away, otherwise the activity of the black hole would be quenched, which for continuous and isotropic emission leads to the so-called Eddington limit. During outbursts or for outflow in a jet the Eddington luminosity may be...
exceeded, because in the former situation the stored energy can still be radiated away and in the latter case the jet does not interfere with the accretion flow.

Blazar emission is widely attributed to radiating electrons, but neutrinos of very high energy are only produced by energetic atomic nuclei usually referred to as cosmic rays. As both the sources of high-energy neutrinos and the origin of cosmic nuclei at the highest energies have not been identified to date, an association between neutrinos and blazars has important implications, that we explore here using a set of time-dependent radiation models. We consider the time evolution and spectral behavior of neutrino and photon emission across the electromagnetic spectrum. Our study is important to infer the physical relation between the observed neutrino and the blazar, to investigate to what degree the findings can be generalized to the entire population of AGN, to determine the relation between their output in photons, neutrinos, and cosmic rays, and to optimize the strategy of future observations.

The emission of very high-energy radiation requires that the radiating particles, electrons or cosmic nuclei, be accelerated to even higher energies. A widely favored acceleration process is Fermi (diffusive) shock acceleration: charged particles gain energy by the frequent and repeated crossing of a shock front, leading to a particle spectrum in the form of a power law ($\propto E^{-\alpha}$) with $\alpha > 1$; similar spectra are indeed observed in nature. Once accelerated, the energetic particles interact and radiate in a region referred to as the radiation zone. The spectrum of electromagnetic radiation from AGN blazars has two characteristic components, a low-energy one arising from synchrotron radiation of energetic electrons, and a high-energy one typically attributed to Compton up-scattering of ambient photons by the same electrons (inverse Compton scattering) $(8, 9)$; see Fig. 2, left panel, for a pictorial example; technical details can be found in the Methods section. Models of this type are collectively referred to as leptonic.

The neutrino emission requires a hadronic scenario instead. Cosmic-ray nucleons at ener-

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1We refer to a public data stream known as Astronomical Telegrams (ATels) until the observational data are published.
Figure 2: **Spectral energy flux from TXS0506+056 flare for two hypothetical scenarios.** The energy spectrum is well reproduced by a purely leptonic model (left panel) with no neutrino production, whereas a simple hadronic model, in which the second hump comes from $\pi^0$ and $\pi^\pm$ decays, overshoots the observed X-ray flux (right panel). Colored bow-ties indicate the observed spectrum with uncertainties (2, 3, 7), and the approximate sensitivity of all current TeV gamma-ray telescopes is indicated by that labeled Imaging Air Cherenkov Telescopes (I.A.C.T.). Colored curves indicate model components as given in the legend. The dashed horizontal green line corresponds to the expected level and energy range of the incident neutrino flux to produce one muon neutrino in IceCube in 180 days, as observed.

A charged pion decays (via a muon) into an electron or positron, which radiates just like any other electron, and three neutrinos that can travel to Earth and are a smoking-gun signature for the acceleration of cosmic nuclei. A neutral pion decays into two photons with similar energy as that of the neutrinos, providing a direct relation between neutrino and photon emission. It is occasionally assumed that hadronic photon emission is responsible for the high-energy component of the spectrum (12), inspired by the case of Mrk 421 which has a different SED that indeed allows this possibility, but a self-consistent analysis of all relevant processes indicates that the synchrotron X-ray emission by secondary electrons would unavoidably overshoot the observed flux (13). For this reason we find that the flare state of TXS0506+056 cannot en-
Energy flux from TXS0506+056 across the electromagnetic spectrum and for neutrinos. Data are represented with their uncertainties as colored bow-ties or as sensitivity curves in the TeV band. Here the energy spectrum is modeled in our hybrid scenario with both leptonic and hadronic contributions. High-energy photons are absorbed during propagation by extragalactic background light, here indicated by the blue shaded region and modeled as in (14).

tirely be reproduced with a hadronic model, see Fig. 2, right panel; an in-depth investigation on hadronic models is available in the Supplementary Information. This leaves the question what the maximal neutrino flux during the flare can be, and what the photon signature of a hadronic model actually is. The same constraint applies to the quiescent state, although it is weaker there. Instead, both the quiescent and the flare state are easily described by a leptonic scenario (see Fig. 2, left panel, for an example).

We propose the hybrid model displayed in Fig. 3, in which the bulk of photon emission is of leptonic origin, and hadronic contributions are as strong as permitted by the X-ray data. Modeling the flare on the basis of an increase in the particle-acceleration power alone will
invariably require a jet power that is in excess of the Eddington luminosity by several orders of magnitude as discussed in the Supplementary Information. While the collimation of the jet permits a power excess, it is probably moderate and within a factor of ten (see, e.g., (15)). A model that satisfies the observational and the power constraints requires the flare to be produced by an increase of electron and proton injection power in a smaller core of the radiation zone. We also allow for an increase of the magnetic-field strength, as that usually goes hand-in-hand with enhanced particle acceleration (16).

Whereas the hadronic contribution to the energy spectrum is clearly visible in the X-ray band, it is also present in the TeV band, but attenuated by pair production with the extragalactic background light. The neutrino emission (red curve) is below that corresponding to one observed neutrino above 100 TeV in 180 days, and it is limited by the observed X-ray emission on account of a correlation between the neutrino response and that in the X-ray band. The GeV-band gamma-ray flare arises from enhanced electron injection. Increasing the proton production only would result in “orphan” neutrino flares coinciding with intense X-ray emission and, likewise, an increase in the electron acceleration power might account for the known orphan GeV/TeV gamma-ray flares (17).

The multi-TeV photon emission is of particular interest in view of a puzzling finding. TeV gamma-ray emission from blazars is partially absorbed in the intergalactic medium on account of interactions with ambient optical and infrared radiation. After correction for this absorption, the spectra of blazars suggest the existence an additional radiation component in addition to that expected with leptonic models (18), which may indicate for the existence of new elementary particles such as axions (19) or blazars emitting a very powerful stream of cosmic rays at the highest energies (20). We posit that the hadronic interactions leading to neutrino emission around 200 TeV offer a simpler and more natural explanation, that predicts time variability in line with that observed.
Figure 4: **Time-dependent simulation of the lightcurve during the flare.** The response is shown for an example period of 90 days. Left panel: Temporal response in 220-TeV neutrinos and various wave bands. Note the scaling variations in the time axis. Right panel: Spectral response of the signals in neutrinos and photons. The dots reflect data taken during the years prior to the flare, and the gray bands represent the observed spread and variation in the earlier flux measurements.

The left panel of Fig. 4 displays the amplification of the signals in various wavebands and in neutrinos for an assumed flare duration of 90 days. Any short-term variations in the particle injection rate would affect the radiation flux with the same response time as shown in the figure, e.g., swiftly in soft X-rays, slower in hard X-rays, and slowest in neutrinos on account of the low energy-loss rate of protons. To be noted are the strong enhancement in the neutrino flux and the flux correlation between neutrinos, hard X-rays, and TeV gamma rays. The neutrinos are produced in interactions with hard X-ray photons and hence their flux receives a synergistic boost due to the increased densities of both, the target photons and the protons. In the case of leptonic emission, some of the gain is lost on account of enhanced energy losses. After the additional injection into the core vanishes, the electrons rapidly cool and consequently the target photon density for the remaining cosmic rays decreases to the quiescent level. The neutrino emission continues at low rate in the larger radiation zone. The right panel shows the spectral...
energy distribution in photons and neutrinos before the flare, at its peak, and late in the cool-off phase. The steeply falling spectrum around the threshold energy of the TeV gamma-ray and soft X-ray telescopes implies that small variations in the injection can lead to sporadic changes in the measured signal, in line with those observed.

Our model allows for 0.23 muon neutrinos per year for energies $E_\nu > 120$ TeV during the flare state, which lasted at least half a year, given the GeV-band lightcurve, and so we expect more than 0.12 neutrino events in that period, implying a probability higher than 10% to actually detect a neutrino. The model describes the dramatic enhancement of the neutrino flux during the entire duration of the flare, and renders the two-week delay between the neutrino detection and the TeV-band activity seen with MAGIC (4) insignificant, likewise that with the later detection with VERITAS$^2$. The late detection in both bands after a few months of GeV-band flaring reflects the slow response predicted by our model. In any case, the time-dependent analysis shows that variability in the band 100 GeV to 1 TeV arises from both leptonic and hadronic contributions. The acceleration of nuclei during quiescence could result in weak neutrino emission, suggesting that other neutrinos from TXS0506+056 might be hidden in the IceCube data, despite the non-detection of other blazars (21).

We have demonstrated that the coincidence of a neutrino with a flare from TXS0506+056 can be described by a significant increase of the injection rates of cosmic nuclei and electrons. This provides evidence for the acceleration of cosmic rays up to energies of about 10 PeV in certain AGN flares, while no conclusion can be drawn about the connection to ultra-high energy cosmic rays at energies above 100 PeV (the consequences of this scenario are outlined in the Supplementary Material). The efficient neutrino production requires either a more compact production region during the flare, such as the denser core of a larger radiation zone, or an injected proton luminosity far in excess of the so-called Eddington limit. Since the production

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of neutrinos necessarily requires the emission of high-energy photons, electrons and positrons, the resulting electromagnetic cascades must be visible in the X-ray (and also TeV gamma-ray) bands – thus constraining the maximally allowed contribution of photo-hadronic interactions and consequently the expected neutrino flux. When taking all constraints into account, we find predicted neutrino rates significantly lower than, but still statistically consistent with one event per year. Our preferred model describes how the neutrino flux, and to a lesser degree also that of hard X-rays, is over-proportionally enhanced during the flare, if that is sufficiently long-lived, explaining why neutrinos are found during such flares and are otherwise statistically not attributable to blazars. Increased injection of cosmic-ray nuclei only would lead to orphan neutrino flares without signal in the GeV band, but an enhancement of the X-ray flux. We note that multi-TeV emission would coincide with neutrino-bright states, that is not easily reproducible with leptonic models and might be mistaken as a signature of new elementary particles such as axions. Our time-dependent modeling of the relevant physics processes provides a self-consistent picture for TXS0506+056 that is based on observations of neutrinos and photons in all spectral bands.

Methods

The time-dependent radiation modeling is performed with the numerical code AM³ (Astrophysical Multi-Messenger Modeling) that has been applied to a similar physical environment and is documented in (13). This Methods section goes into detail on the construction of the spectrum from a publicly accessible data stream called The Astronomical Telegram and the derivation of model parameters.
**Construction of the observed energy spectrum**

Initial information about the IceCube event 170922A has been shared on *The Gamma Coordinates Network* (GCN) notice 21916\(^3\), providing the time, direction, and angular uncertainty of a muon track, a secondary product of a neutrino interacting in the rock and the ice around the detector. The muon track deposited 120 TeV of energy in Cherenkov light, meaning that the true neutrino energy is higher, most probably a few hundreds of TeV and with a small probability above 1 PeV. The purpose of the GCN public data stream is to alert the astronomical community about potential *targets of opportunity*, astrophysical events that might be worth studying across multiple wavebands. The present neutrino event triggered immediate follow-up observations. A six-fold increase, compared to the 3FGL catalog value (22), in the 0.1 – 300 GeV flux from the blazar TXS0506+056 located inside the directional error circle of the neutrino event was noted, and GeV-band flaring had been ongoing for a few months (2). X-ray observations by Swift XRT revealed more sources located within a refined error circle (23), but at that time only TXS 0506+056 was detected in an extraordinarily bright state. A key ingredient for building our model has been provided by a joint Swift XRT and NuSTAR observation (3) of the soft and hard X-ray emission\(^4\). Two weeks after the initial alert the MAGIC telescope detected gamma-rays above 100 GeV with a very soft spectrum (4), whereas the source had been invisible in TeV gamma-rays before (5, 6). Therefore, the spectrum must display a cut-off just above the GeV band and be subject to temporal variation.

In addition to the above listed ATels, we inspected the publicly available light curves of the OVRO 15 GHz radio telescope (24), the ASAS-SN robotic optical telescope network (7, 25) and the Fermi Full Sky Variability Analysis (FAVA) in the sub-GeV and GeV energy ranges (26).

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\(^3\)GCN/AMON notice 21916  https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3 and https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

\(^4\)The X-ray spectrum has been reported twice; ATels 10792 and 10845. Here we use the 10845 since it permits to obtain the break energy, which seems slightly different to what Atel 10792 suggests. We will re-assess the X-ray data after the final analyses have been published
From the visual inspection of the light curves, we conclude that the brightening of the spectrum started in June 2018, reaching peak luminosities close to the date of the neutrino detection, slowly decreasing thereafter without returning to the previously observed quiescent levels. The continuous activity is confirmed by an observation of an additional luminosity spike and spectral hardening six months after the initial observation (27). The light curves are not smooth and show high stochastic variability from one week to the next.

For the temporal evolution study in Fig. 4, we construct the spectrum of the quiescent state from archival observations available from the database of the Space Science Data Center (SSDC)\(^{5}\) and from NASA/IPAC Extragalactic Database (NED)\(^{6}\). These data are not strictly contemporaneous and may be partially contaminated by previous flares. In the optical, we interpret the average of the ASAS-SN V-band flux for dates prior 2017/05/01 as the quiescent state, and likewise the flux average after 2017/09/01 as the flare.

Model parameters are obtained by \(\chi^2\) minimization for the spectral data. To reduce the bias arising from different sparsity of data across the electromagnetic spectrum, each characteristic waveband is represented by a bow-tie, approximate power-law bands corresponding to the integrated flux and the spectral index with their uncertainties. The fit minimizes the integrated flux and the average spectral index of the SED to that observed in each spectral band. Radio data are taken as upper limit, since the radio emission typically arises a much larger region than the radiation zone (12). While this method successfully constrains the parameters, it is based on a simplified representation of the data and does not account for systematic uncertainties. The consequences for the interpretation of the \(\chi^2\) values of our analysis are discussed in the Supplementary Information.

\(^{5}\)http://tools.asdc.asi.it/
\(^{6}\)https://ned.ipac.caltech.edu/
Model for the emission zone

The emission from AGN blazars is dominated by that produced in their jets, on account of the strong relativistic Doppler amplification. The observation of rapid time variability in the observed radiation flux implies a very compact emission region that is tiny compared with the jet. As the escape of radiation from this emission region is typically much faster than acceleration-rate changes and the energy loss of cosmic rays, one neglects the internal structure and models the emission zone as a spherically symmetric, homogeneous blob of radius $R'_{\text{blob}}$ that is filled with gas, photons, magnetic field, and energetic particles. The entire emission zone moves with Doppler factor $\Gamma_{\text{bulk}}'$, and we denote with primes ('') physical variables in the jet rest frame. Electrons and ions are continuously and isotropically injected with power (or luminosity) $L'_{\text{inj}}$, and their injection rate obeys a power law, $d^2n'/d\gamma'dt' = K'\gamma'^{-\alpha}$, where $K'$ is a function of the injection power and $\gamma'$ is the Lorentz factor of the particles that is allowed to take values in the range $\gamma'_{\text{min}}$ and $\gamma'_{\text{max}}$. The emission region is assumed to be filled with a homogeneous, randomly oriented magnetic field of strength $B'$. Energetic particles are allowed to leak out on the time scale $t'_{\text{esc}} = R'_{\text{blob}}/(\eta_{\text{esc}}c)$, where $\eta_{\text{esc}} \leq 1$ is treated as a free parameter.

We model all relevant interactions of the particles, which for electrons include synchrotron emission and absorption, inverse-Compton scattering, and pair production and annihilation. For protons we account for Bethe-Heitler pair production ($p + \gamma \rightarrow p + e^\pm$) and photo-pion production ($p + \gamma \rightarrow p + \pi$). The pions decay to eventually yield neutrinos, electrons, and positrons.

For the hybrid model we model the quiescent state by injecting electrons and protons into the blob until an equilibrium between injection, cooling and particle escape is reached. The injection power of protons is limited by the Eddington luminosity in this phase. The model SED is then fitted to that observed. The flare is initiated in a smaller core in the radiation zone that characterizes the quiescent state, and both contribute to the observed emission in a superimposed...
way, a scenario that mimics localized particle acceleration and subsequent diffusive transport into a larger emission zone (28, 29). The radiation from the core is significantly brighter, revising the presence of the larger (quiescent) zone insignificant. It can be shown that for typical escape parameters the radiation of protons leaking from the core into the outer blob is negligible because of the much smaller radiation density. The transport of electrons from the core into the outer zone contributes less than 16% of the nominal quiescent-state radiation. We increase the injection of electrons by a factor of 3, that of protons by a factor of 10, and the magnetic-field strength by a factor of 20 (see Table 1). Enhanced activity in the smaller core persists for a certain period of time (here $t = 90$ days, which is our conservative example is much less than the total duration of the flare. The stochastic variability seen in the light curves during an extended flaring period may be the result of the fluctuations in the acceleration rate. During the enhanced activity in the core the model allows the total jet power to exceed the Eddington luminosity. This picture is supported by the Fermi GeV-band light curve, which shows that the peak luminosity reported in the original ATel (2) decreases after a few days, while the enhanced emission and variability continues for several more months (27).

**Determination of model parameters**

Most parameters of the hybrid model are obtained through extensive parameter scans using the time-dependent AM$^3$ code. We use the previously described $\chi^2$ optimisation to determine the goodness of fit for a particular SED. The blob size, the Doppler factor, the effective escape velocity, $\eta_{\text{esc}}$, and the maximal proton energy are then adjusted with a view to maximize the neutrino flux in the relevant energy range ($> 120$ TeV) and to minimize the required jet power.

Leptonic or hybrid simulations require the primary electron spectrum to follow a broken power-law: $dN'/d\gamma_e' \propto \gamma_e'^{\alpha_e}$ where $\alpha_e = \alpha_{e,1}$ for $\gamma_{e,\text{min}} < \gamma_e' < \gamma_{e,\text{br}}$ and $\alpha_e = \alpha_{e,2}$ for $\gamma_{e,\text{br}} < \gamma_e' < \gamma_{e,\text{max}}$. For the hadronic model, a single-power-law injection of both electrons
Table 1: Parameters of the models discussed in the main text and shown in Figure 2. Primed quantities refer to the rest frame of the radiation zone (blob). A sizable neutrino rate requires the jet power to exceed the Eddington luminosity during the flare. *We assume a black-hole mass of $5 \times 10^9 M_\odot$, similar to that of the nearby AGN M87.

and protons describes the relevant parts of the spectrum sufficiently well. The determination of the parameter values in Supplementary Table 1 requires deterministic scans of the higher-dimensional parameter space, for which we performed $O(10^8)$ individual AM3 simulations.

For TXS0506+056, we find a good fit for a Doppler-factor $\Gamma_{\text{bulk}} = 28.5$ and estimate 295 TeV as the most probable true neutrino energy that could lie anywhere between 120 TeV and a few PeV (30). The redshift of the host galaxy is known as $z = 0.34$ (31). With the typical simplification that the highest contribution to the neutrino flux originates near the pion-production threshold ($\Delta$-resonance approximation), the proton energy in the observer
The maximal gamma factor of protons in the comoving frame is $\gamma'_p \simeq (E_{\text{obs}}^p/m_p)(1 + z)/\Gamma_{\text{bulk}} \approx 2 \cdot 10^5$. The typical energy of the target photons in $p\gamma$ interactions is $\epsilon'_{\gamma,\text{target}} \simeq E_{\text{threshold}}/(2\gamma'_p) \approx 2.5 \cdot 10^{-6} (0.2 \text{ GeV}) = 0.5 \text{ keV}$. In the observer frame this corresponds to $\epsilon_{\gamma,\text{target}} \simeq \Gamma_{\text{bulk}}\epsilon'_{\gamma,\text{target}}/(1 + z) \approx 15 \text{ keV}$, i.e. hard X-rays. Our full simulation is based on the realistic $p\gamma$ cross section and multi-pion emission at higher energies, yielding for the target photons a wide range of energies in the hard X-ray band. A higher maximum energy of protons leads to a higher peak energy of the neutrino spectrum (even after a possible re-normalization of the injection spectrum), which is incompatible with the current neutrino data as we discuss in the Supplementary Information, and so there is no direct relation between the neutrino event in question and the origin of ultra-high-energy cosmic rays.

### Computation of neutrino rates

For the computation of the expected neutrino event rate in IceCube we use the effective area reported in (32). It is the highest effective area published by IceCube and valid for transient astrophysical sources. The expected atmospheric neutrino background rate is estimated with the numerical code MCEQ (33), the GSF cosmic-ray flux (34), and the SIBYLL-2.3c hadronic interaction model (35); it lies in the range $0.006 - 0.001$ neutrino tracks per year depending on the assumed minimal energy between $120 - 300 \text{ TeV}$ for a solid angle of 1.8 square degrees, commensurate with the 90-% directional uncertainty of the IceCube event (1). Using a probability distribution of true neutrino energies based on (30), the background rate is 0.001 events per year. The hybrid radiation model predicts a reviseoneutrino-event rate at $E_\nu > 120 \text{ TeV}$ of $1.4 \times 10^{-4}$ tracks per year during quiescence and a peak rate of 0.23 tracks per year for the recent flare. By using a signal-over-background definition, the significance for this particular neutrino to originate from the TXS0506+056 flare reaches the $2.8 \sigma$ level for a true neutrino energy $E_\nu > 230 \text{ GeV}$. 


**Data availability**

The historical observations analyzed during the current study are available in the SED Builder Tool of the Space Science Data Center (SSDC) and from the NASA/IPAC Extragalactic Database (NED).

For the recent flare, the optical light curve is obtained from the ASAS-SN Sky Patrol and 15 GHz radio monitoring data from OVRO 40m Telescope databases, respectively. The other bow-ties are constructed based on information from The Astronomers Telegram and the GCN Circulars Archive. The relevant entry numbers are given in the references.

Requests for materials should be directed to S.G. and A.F.

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Author contributions

S.G. performed the numerical modeling and artwork. A.F. extracted and analyzed the data. S.G. and A.F. provided first technical documentation. All authors contributed to the development of the theoretical ideas and the interpretation of the results. The text of the final manuscript was written by M.P., W.W. and A.F. with contributions from S.G.

Competing interests

The authors declare no competing interests.
Supplementary Information

The sparsity and uncertainties of the TXS0506+056 observations will necessarily allow for some model-parameter variations and potentially for degenerate interpretations. The uniqueness of this possible correlation triggered us to check whether other possible interpretations of the observed photon flux and neutrino emission might exist. In this section we discuss a set of scenarios that may all be related to the detection of a correlated neutrino flux.

Concerning the observation, one source of uncertainty can be attributed to the instrumental precision and the data analysis, and another part is related to the non-simultaneity of the measurements. The first type of uncertainty is taken into account as a penalty in the $\chi^2$ minimisation. While a rigorous treatment of the second type of uncertainty is beyond the scope of this work, it is possible to study this aspect using semi-analytical methods.

Concerning the modeling, the large parameter space naturally allows for some degeneracy in the description of the SED. The common scenarios include (1) the favored hybrid model with a limited proton maximal energy, $E_{p,\text{max}}$, (2) a hybrid model using a single radiation zone without core, (3) a leptonic (SSC) model, (4) a hybrid model with $E_{p,\text{max}}$ similar to that of ultra-high-energy cosmic rays (UHECR, about 10 EeV), (5) a fully hadronic model, and (6) a proton-synchrotron scenario.

The preferred hybrid scenario with an imposed limit on $E_{p,\text{max}}$ (1) is comprehensively described in the main text and the Methods section. The leptonic (SSC) model (3) is not explicitly discussed, since there is no neutrino emission. In the next subsections we test the viability of the remaining four scenarios.

Hybrid one-zone model

The SEDs for the quiescent phase and the flare can be reproduced with a single radiation zone, simply by increasing the injection power of particles into the radiation zone. The expected
Supplementary Figure 1: **Time-dependent simulation of the flare with a single radiation zone; As in Fig. 4 in the Main Text, the left panel displays the temporal response and the right panel shows the spectral response.** This model elegantly explains the transition between quiescent and flare SEDs of through a simultaneous increase of injection power of protons and electrons by a factor of three. However, the required power to reproduce the flaring SED and the neutrino observation would strongly exceed the Eddington luminosity.

neutrino flux is higher than in our baseline model and more representative for the IceCube observed flux, and the SED can be nicely reproduced in quiescent and flaring states with similar sets of parameters. As a major drawback, large particle injection luminosities far in excess of the Eddington luminosity for a black hole of $5 \times 10^9$ solar masses ($L_{p,\text{inj}} = \Gamma^2_{\text{bulk}} L'_{p,\text{inj}} = 10^{50.5}$ erg/s in the AGN frame (1), compared to $L_{\text{Edd}} = 10^{47.8}$ erg/s), are required. This interpretation therefore implies an accretion rate exceeding the Eddington luminosity by nearly three orders of magnitude at least during the flare, which is frequently considered to be unlikely for AGN blazars. Note, however, that such high excesses are obtained for other object classes, such as jets from tidal disruptions of massive stars (2).
Supplementary Figure 2: **Hybrid model variant with the presence of UHECR interactions in the source.** The solid curves refer to the hadronic components of the favored model (identical to Fig. 3) with the injection of protons up to $E_{p,max} \sim 4.5$ PeV. The dashed lines show the impact of a proton population that extends up to UHECR energies $E_{p,max} \sim 70$ EeV.

**Hybrid model with UHECR interactions**

The most relevant parameters related to neutrino production are the maximum proton energy, $E_{p,max}$, and the proton injection luminosity, $L'_{p,inj}$. Variation of these parameters results in different spectra of hadronic photon and neutrino emission, but the photon SED may still be compatible with that observed. The choice of the maximal energy is restricted by the number and energy of the observed neutrinos and can be roughly approximated by $E_{p,max} \approx 20 < E_\nu > \simeq 4.5$ PeV. If the maximal energy is computed using the maximum acceleration rate and the light crossing time of the source (as commonly and highly optimistically assumed and known as the Hillas limit), protons may reach UHECR energies, $E_{p,max} = \Gamma_{bulk} (10$ EeV). In a hybrid scenario the proton injection power would be low, $L'_{p,inj} = 10^{43.9}$ erg/s, and Supplementary Figure 2 shows that the photon SED would be well reproduced. The scenario is not acceptable though, because the resulting neutrino flux peaks at a much higher energy, at a few EeV, an energy band in which
Supplementary Figure 3: **Extensive parameter-space scan with a semi-analytical approach.**

Left panel: Four-power-law approximation of the spectral features used for an efficient scan of the hadronic parameters. Right panel: Allowed regions for the model parameters in which the high-energy \( \gamma \)-ray radiation originates from the \( p\gamma \to \pi^0, \pi^\pm \to e.m. \) cascades for one choice the blob-radius, \( R'_{\text{blob}} = 10^{16} \text{ cm} \), and neutrino-energy, \( E^\text{ob}_{\nu} = 250 \text{ TeV} \). The green area with dotted boundary corresponds to constraint (1); blue upper-right region limited by the solid line to constraint (2); yellow area between the dashed parallel lines to constraint (3); the violet lobe formed by dot-dashed boundaries to constraint (4).

All neutrinos are effectively blocked by earth along the path of propagation, since the source is located slightly below the horizon. For a deposited energy of 120 TeV of the muon track in IceCube, the incident neutrino energy \( E\nu \) is expected to lie between 0.12 TeV and 7.6 PeV at 3\( \sigma \) confidence level (3). The expected event rate is only 0.00019/yr within this energy range for UHECR interactions inside TXS0506+056.

**Hadronic model**

The *hadronic* model is defined as the scenario in which the low-energy part of the SED is produced by synchrotron emission of the primary electrons in the jet, whereas the high-energy component arises from hadrons via the process \( p\gamma \to \pi^0 \to \gamma\gamma \) and through synchrotron emission from secondary electrons generated through the reaction chain \( p\gamma \to \pi^\pm \to \mu^\pm \to e^\pm \).
If the target-photon density is high, as is the case here, the gamma rays induce electromagnetic
cascades via pair-production and annihilation, $\gamma\gamma \rightarrow e^\pm \rightarrow \gamma \ldots$. This is the most neutrino-
optimistic scenario of blazar models in which comparable fluxes of gamma rays and neutrino
are expected, since here the hadrons deposit a comparable share of their energy in neutrinos and
photons.

In the main text we describe why this class of neutrino-optimistic models is not applicable
to TXS0506+056. Alternatives are sought by extensively scanning and constraining the pa-
rameter space in a semi-analytical analysis of the spectrum based on the method described in
Appendix A of (4). The following procedure yields contours for the allowed parameter regions:
(1) approximate the entire SED by four power-law spectra (see left panel of Supplementary
Figure 3); (2) choose a blob radius, $R_{\text{blob}}'$, and an observed neutrino energy, $E_{\nu}^\text{ob}$; (3) vary the
comoving magnetic field strength, $B'$, and the Doppler factor of the blob, $\Gamma_{\text{bulk}}$, on a 2D grid
according to the constraints described in the next paragraph; (4) repeat this procedure for each
combination of the parameters, $R_{\text{blob}}' \otimes E_{\nu}^\text{ob}$ (in the present case $10^{15}$ cm $< R_{\text{blob}}' < 10^{19}$ cm
and $10^2$ TeV $< E_{\nu}^\text{ob} < 10^3$ PeV).

The hadronic model requires the following constraints to be met: (1) the synchrotron ra-
diation of protons must not be brighter than the observed emission; (2) the inverse-Compton
up-scattering of synchrotron photons may not dominate the high-energy emission; (3) the syn-
chrotron emission from the hadronic secondaries should peak at $\nu_{\text{peak},2} \sim 10^{23}$ Hz, as observed
(the width of the yellow band is related to the width of $\nu_{\text{peak},2}$); (4) the emission of $e^\pm$ pairs
from the electromagnetic process $p\gamma \rightarrow e^+e^-p$ (Bethe-Heitler) must not exceed that observed
in the X-ray band.

The right panel of Supplementary Figure 3 clearly demonstrates the absence of an overlap of
all the four allowed regions for a specific choice of $R_{\text{blob}}'$ and $E_{\nu}^\text{ob}$. The strongest constraints are
imposed by the compatibility of X-ray data with the predicted emission following the Bethe-
Supplementary Figure 4: **Conditions to be met by a viable proton synchrotron model.** The colored lines are allowed parameters ranges for the maximal proton energy $E_{p,\text{max}}$ and the Doppler factor $\Gamma_{\text{bulk}}$. The arrows point towards the allowed region. The orange region is restricted by the observed deposited energy, red by the presence of TeV gamma-rays, green by requiring a non-excessive magnetic field and blue by the probability to detect a neutrino in IceCube during an assumed 90 days flare period. A higher number of expected neutrinos moves the blue region to the right. The blob size is fixed to $R_{\text{blob}}^\prime = 10^{16}$ cm.

Heitler pair-production process (illustrated by the violet region in the right panel of Figure Supplementary Figure 3). Repeating this analysis for all combinations of $R_{\text{blob}}^\prime \otimes E_{\nu}^{\text{ob}}$, we always find a negative result and hence exclude the hadronic model as a possible explanation for the emission spectrum of TXS0506+056.

**Proton-synchrotron model**

Another possibility to explain the second hump of the SED involves synchrotron emission of protons, hence the name proton-synchrotron model (5). We use an analytical approach, similar to the analysis of the hadronic model.

Here we assume that monoenergetic protons are injected at a characteristic energy $E_{p}^{\text{ob}}$ (ob-
server’s frame). By requiring the proton-synchrotron spectrum to reproduce the observed energy, $E_{\text{psyn}}^{\text{ob}}$, and flux, $F_{\text{psyn}}^{\text{ob}}$, of peak emission, the energy densities of protons in the radiating blob, $u_p'$, and of magnetic field, $u_B'$, can be expressed as functions of the two parameters blob radius, $R_{\text{blob}}'$, and Doppler factor, $\Gamma_{\text{bulk}}$. For the $p\gamma$ interaction we adopt the $\Delta-$resonance approximation. The target photon energy is computed by the threshold condition of $p\gamma$ interactions $\sqrt{s} \sim m_\Delta \sim 1.2$ GeV. The target photon density is computed from a simplified SED as in Supplementary Figure 3. The neutrino peak energy, $E_{\nu}^{\text{ob}}$, and flux, $F_{\nu}^{\text{ob}}$, are subsequently computed, taking into account the possible synchrotron cooling of charged pion and muon secondaries.

To be acceptable, the model has to reproduce the observed spectral distribution and brightness of TXS0506+056, the presence of TeV gamma rays, and a peak neutrino energy in the range 0.12–7600 TeV. Supplementary Figure 4 shows allowed ranges for the $E_{\nu}^{\text{ob}}$ and $\Gamma_{\text{bulk}}$ parameters, given the constrains on these parameters from the above conditions. The parameter scan demonstrates that no viable proton-synchrotron model produces neutrinos in the correct energy range and TeV gamma-rays at the same time. We conclude that this class of models characteristically yields either detectable neutrino fluxes at excessively high energies (EeV range) or a very low neutrino flux at energies compatible with the current observation. Therefore, it is unlikely that a proton-synchrotron scenario can explain the neutrino coincidence with a gamma-ray flare of TXS0506+056.

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