

The Pennsylvania State University
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**TIME SENSITIVE SEARCHES FOR ELECTROMAGNETIC
COUNTERPARTS TO HIGH ENERGY NEUTRINOS**

A Dissertation in
Physics
by
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Abstract

We present the results of multiple electromagnetic searches for counterparts of high energy neutrinos detected by the IceCube and ANTARES neutrino observatories. A long standing problem in astrophysics is the cosmic ray origin problem. Due to their electric charge, cosmic rays deflect in the interstellar and intergalactic magnetic fields, obfuscating their origins. Similarly, the origins of high energy neutrinos are largely unknown, with only one positively identified source, the blazar TXS 0506+056.

Multimessenger astrophysics offers a method to discover the sources of high energy cosmic rays and neutrinos. The mechanisms that produce cosmic rays and neutrinos are very likely to also produce high energy γ -rays. Coincident searches for γ -rays and neutrinos have the potential to reveal the sources of high energy cosmic rays and neutrinos. Such searches have already borne fruit, with the coincident detection of TXS 0506+056.

This thesis details several searches for $\nu+\gamma$ transients, their results, and what they may indicate for future searches. The first search detailed is a blazar flare analysis, looking for neutrinos coincident with TeV γ -rays from several bright northern blazars. This search found a statistical excess of neutrinos during blazar flares, but indicated that the blazar Markarian 421 is a strong candidate for either detecting or limiting neutrino emission from blazars.

The second and third projects utilized the Fermi-LAT γ -ray data to search for electromagnetic counterparts to high energy neutrinos. These searches both looked for a population of subthreshold $\nu+\gamma$ transients, and for an excess of individually high significance $\nu+\gamma$ transients. Using neutrino data from the IceCube 40 and 59 string datasets, we found no evidence of a subthreshold population of $\nu+\gamma$ transients, and no individually high significance events. We did observe a trend for IC59 neutrinos to arrive in regions of the sky that were TeV bright ($p=7\%$) and would like to see if this behavior persists in other neutrino datasets. Our search with archival ANTARES data likewise found no subthreshold population of $\nu+\gamma$ transients.

In parallel with these searches, we also performed X-ray followup to IceCube

detections of likely cosmic neutrinos using the Swift satellite. These searches are important to the field of multimessenger astrophysics as they are what led to the detection of the neutrino emitting blazar TXS 0506+056. Targeted coincidence searches, especially time sensitive searches, are essential to finding more neutrino sources and identifying the sources of high-energy cosmic rays.

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Chapter 1

Introduction

Particle astrophysics probes some of the most extreme environments in the universe. On Earth, we can observe single protons and other nuclei with kinetic energies on the order of macroscopic objects. Understanding where and how such particles originate would allow us to better understand these extreme environments. Unfortunately, the highest energy cosmic rays are all charged particles, and thus are deflected in the Galactic and intergalactic magnetic fields, meaning we cannot pinpoint their origin with sufficient precision to identify individual sources. Fortunately, the acceleration of charged particles to such extreme energies will also produce other particles. Any acceleration of charged particles will always produce photons from thermal emission and synchrotron radiation. Photons can be boosted to high energies through inverse Compton scattering, while pion production and decay will produce both high energy photons and neutrinos. Unlike charged particles, neutrinos and photons can both propagate through space without significant deflection, though photons can be absorbed through interactions with background light and dust.

Neutrinos thus serve as a very useful particle for particle astrophysics. Electrically neutral, neutrinos only interact via gravity and the weak force, which means they propagate through space unaffected by the strong and electromagnetic interactions that can interfere with other particles. But this property also makes them rather difficult to detect. With our current detectors, we have no defined point sources detected through neutrino observation alone. And that is where multimessenger astrophysics come into play.

Multimessenger astrophysics is a new and rising field of study. As cosmic rays do not point back to the source, and there are no solo neutrino sources, the best

bet for finding new sources is to search for temporal and spatial coincidences of multiple messenger particles. Such methods have already borne fruit, most notably in the coincident detection of γ -rays and gravitational waves from GW170817, with significant multi-wavelength followup exploring the subsequent afterglow [1]. Multimessenger observations also led to the observation of a neutrino from the blazar TXS 0506+056 [2].

In this introduction, I will first provide a brief history of particle astrophysics, followed by a discussion of the production of high energy particles, and a discussion on the detection of these particles. The work will present several new searches we made to search for $\nu+\gamma$ coincidences, and some of the work we have done to establish a real-time alert system for $\nu+\gamma$ coincidences.

1.1 A Brief History to Particle Astrophysics

Most scientific discoveries can be traced back to a simple observation and the questions it raised. The story of particle astrophysics begins with the observation that an isolated and insulated electroscope would sometimes spontaneously discharge (see Fig 1.1). This process was first observed in the 18th century, and in 1785, Charles-Augustin de Coulomb observed that this behavior persisted even in a well insulated electroscope [3]. Michael Faraday later confirmed this result in 1835 using superior insulation.

The mystery was partly solved with the discovery of radioactivity in 1896 by Henri Becquerel. Becquerel observed uranium salts emitting penetrating radiation originating from the salts themselves, and could not be attributed to any external effects. Following this discovery, Marie and Pierre Curie (Fig 1.2) began studying this radiation. Using an updated electrometer, Curie observed that the radiation released by uranium caused the air around a sample to conduct electricity. Furthermore, Curie noted that a charged electroscope would quickly discharge when placed near these radioactive materials [3].

Despite this progress, electroscopes far removed from known radioactive sources were still observed to spontaneously discharge. In the early 20th century, it was theorized that the majority of the background radiation originated in the Earth's crust. In 1909 Jesuit priest and German physicist Theodor Wulf developed a more sensitive and portable electroscope, and used it to measure ionization rates at

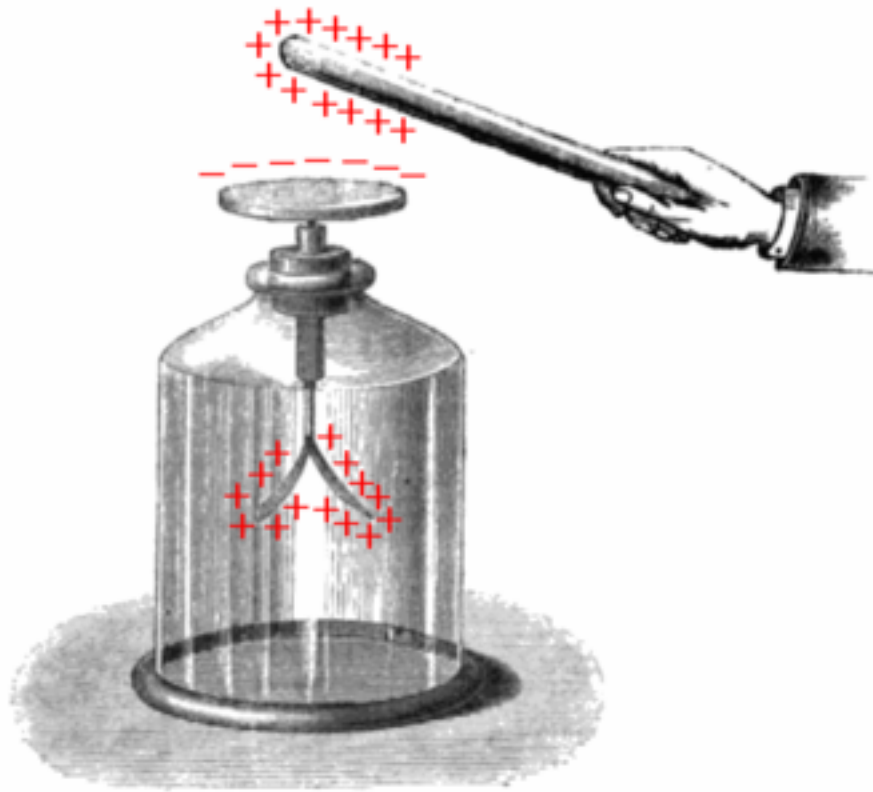


Figure 1.1: Diagram of an electroscope. When a charged object is moved near the plate atop the jar, the induced charge separation causes the metallic foil to separate. Image is public domain.

various locations within Europe. He theorized that if the Earth were the primary source of radiation, moving further away from it would show decreased radiation levels. To this end, he compared ionization rates at the top and bottom of the Eiffel tower in 1910. His results were ultimately inconclusive as although he did measure a decrease in ionization rates at the top of the tower, it was not as much as expected and not statistically significant [4].

As a followup to Wulf's efforts, Victor Hess took several Wulf electroscopes up in a balloon. In a series of flights between 1911 and 1913, Hess made measurements of ionization rates up to an altitude of 5400 m. As seen in Fig 1.4, Hess saw ionization rates hold steady for the first kilometer and then increase to over four times the ground rate [5]. To rule out the Sun as a potential source, Hess took several flights at night and during the solar eclipse of April 7, 1912. Werner Kolhörster later

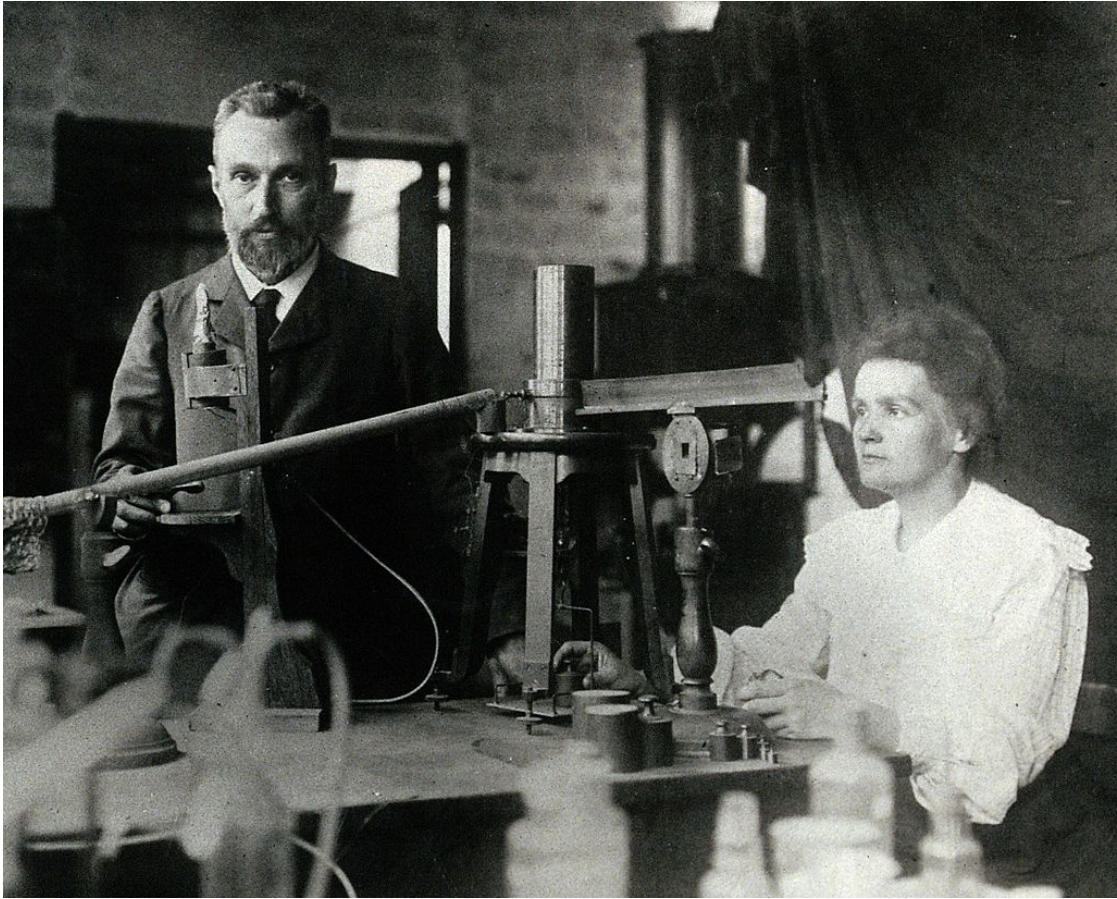


Figure 1.2: Photograph of Marie and Pierre Curie in their lab, circa 1904. Image is public domain.

confirmed Hess's results in 1914, himself flying to an altitude of 9200 m (Fig 1.4, [6]).

Despite the strong evidence provided by Hess and Kolhörster, the extraterrestrial origin of the radiation was not widely accepted at first. Hess himself did eventually get the Nobel prize for his work, in 1936. After World War I interrupted scientific research, serious experimentation on cosmic rays began again in 1926, when Robert Andrews Millikan and Harvey Cameron made radiation measurements at both high altitude and at the bottom of lakes [3]. They concluded that the radiation originated from particles moving through space equally in all directions, and thus should be called cosmic rays. Millikan believed that cosmic rays were primarily γ -rays produced in interstellar space by the fusion of hydrogen [7]. This idea was brought into question when Jacob Clay made measurements of ionization while traveling from Java to Genova. He observed a higher radiation intensity as he



Figure 1.3: Victor Hess (center) returning from one of his balloon flights in August of 1912. Image is public domain.

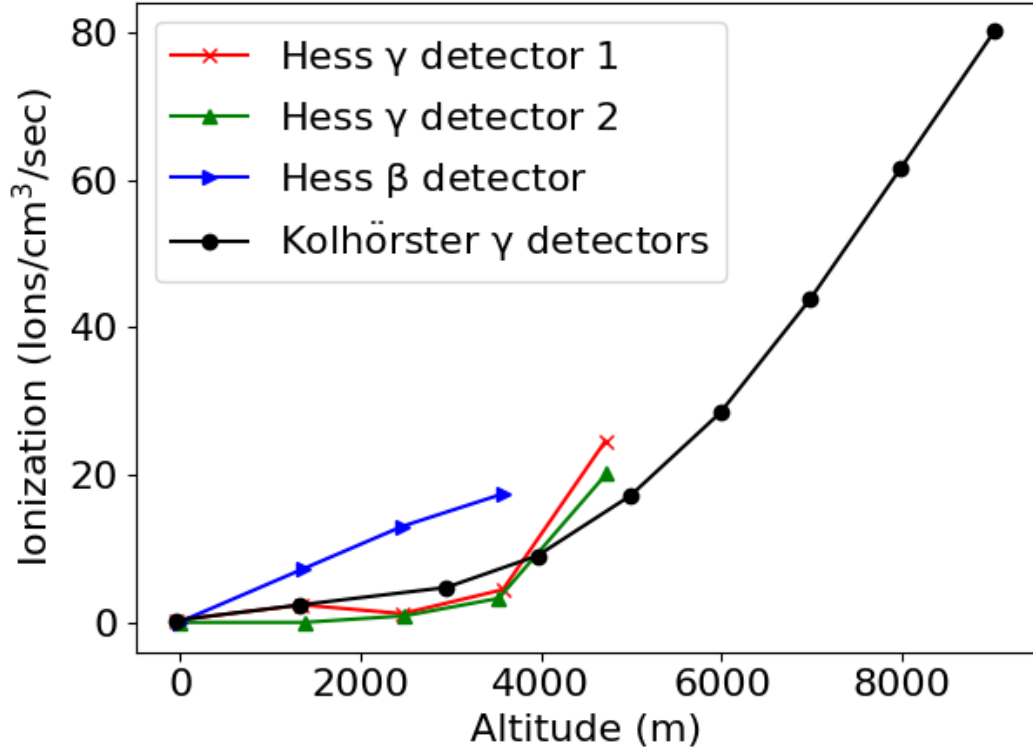


Figure 1.4: Ionization rates as measured by Hess and Kolhörster. Data taken from [6].

moved away from the equator, demonstrating cosmic rays interacting with the Earth's magnetic field [3].

With the development of the Geiger counter in 1928, more evidence confirmed that cosmic rays consisted of charged particles. Several experiments by Bruno Rossi [8], Luis Alvarez, Compton [9], and Thomas Johnson [10] demonstrated that at the equator, more cosmic rays came from the east than from the west, indicating they had a positive charge and were very likely protons [3].

Due to their electric charge, cosmic rays will deflect in magnetic fields and thus do not point back to their point of origin and cannot be used directly to identify the sources of the highest energy particles. However, useful information can still be obtained from their energy distribution, shown in Fig 1.5. Whenever charged particles are accelerated, they will produce electromagnetic radiation. Since this radiation points back to the source, observations of the highest energy gamma ray

sources can be used to try and find cosmic ray sources.

1.1.1 History of γ -ray Astronomy

For much of the early 20th century, scientists were fairly certain the universe contained numerous sources of γ -rays. Cosmic ray interactions, supernovae, and other processes were all theorized as γ -ray sources. The first γ -ray telescope was the Explorer 11 satellite, launched in 1961. Explorer 11 observed fewer than 100 photons in its first year, arriving from all directions.

Gamma Ray Bursts, or GRBs, were discovered by accident in the 1967. Following the Nuclear Test Ban Treaty, the US launched the Vela satellites to search for the γ -ray signature from Soviet bomb tests. Instead of detecting nuclear bombs, the Vela 3 and Vela 4 satellites observed flashes of γ -rays from space [11].

Since the 1960s, numerous satellites have been launched to study the γ -ray sky. Notable satellite missions have been SAS-2, Cos-B, and the Compton Gamma Ray Observatory (CGRO). Currently, the best satellites for surveying the sky are the Swift and Fermi satellites. Swift offers a wide field of view at the hard X-ray energies, with the ability to perform in-depth X-ray and UV/optical followup. Fermi has a wide field of view and the ability to survey the sky over a very wide range of γ -ray energies.

1.1.2 History of Neutrino Astronomy

The neutrino was first mentioned in 1930 by Wolfgang Pauli to explain beta decay. Pauli theorized a very light or massless, electrically neutral particle was carrying away some of the energy, momentum, and angular momentum from the decay. The name neutrino came from the Italian for “little neutral one.” Since the neutrino only interacts via gravitation and the weak force, it remained undetected until 1956 [12].

Atmospheric neutrinos, created by cosmic rays striking the atmosphere, were first discovered in 1965. Solar neutrinos were discovered shortly after in 1968 [13], making the Sun the first identified multimessenger source. But the observation of solar neutrinos created a new problem. The measured solar neutrino flux was only a third of what should be expected based on our understanding of solar physics. This problem was eventually solved with the discovery of neutrino oscillations [14].

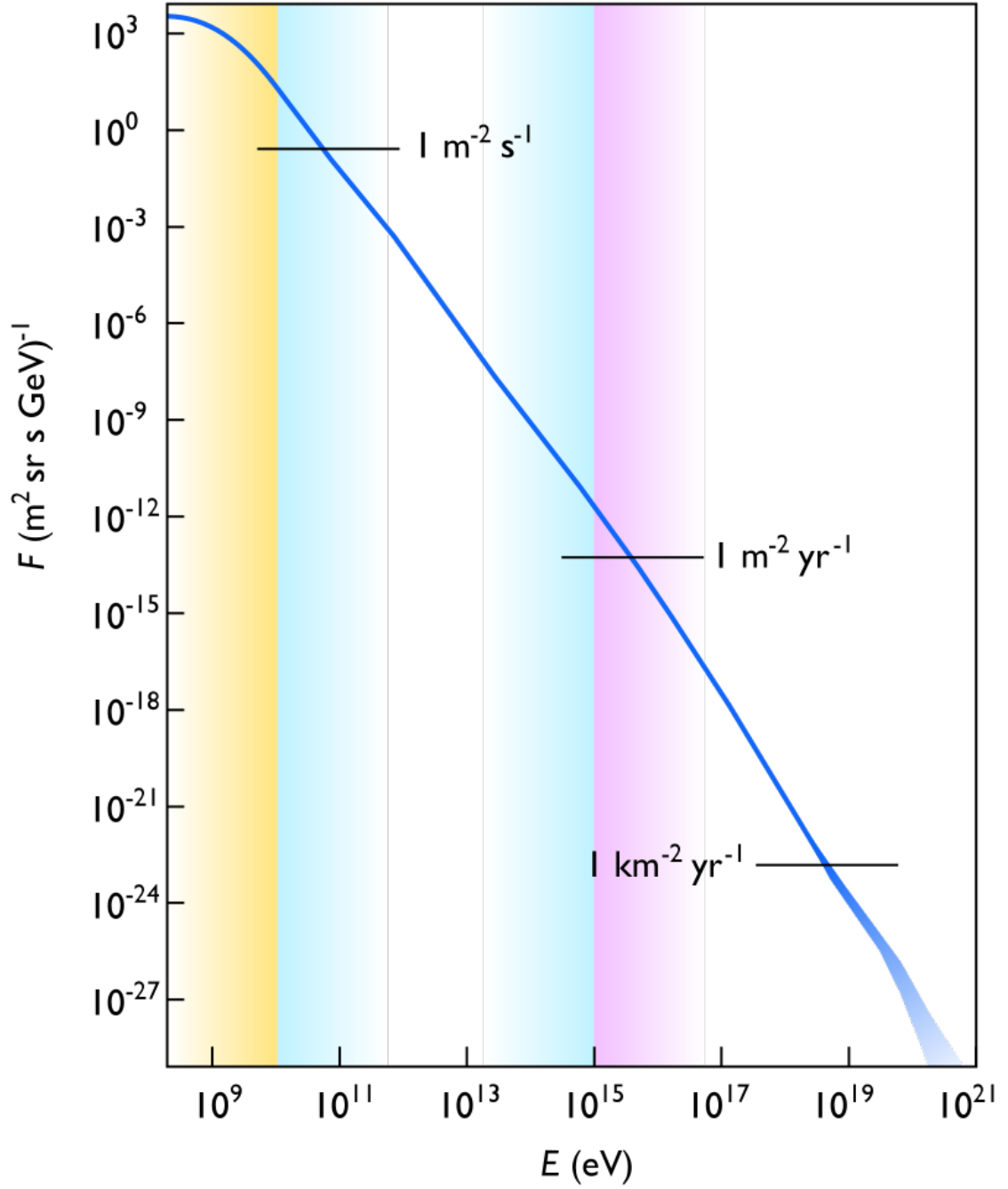


Figure 1.5: Plot of cosmic ray flux vs energy. Image is published under Creative Commons 3 and was taken from [3].

Neutrinos come in three flavors, electron, muon, and tau. As they propagate through space, these flavors are not fixed, and a neutrino will oscillate between flavors.

The supernova of 1987, SN 1987A, was the second ever multimessenger detection. Around three hours prior to the first observation of visible light from the explosion, neutrino detectors across the world recorded a burst of neutrinos. This neutrino burst provided strong evidence for the core collapse supernova model [15].

1.1.3 Multimessenger Astrophysics

There are four fundamental messenger particles in astrophysics, photons, cosmic rays, neutrinos, and gravitational waves. Of these messengers, only photons have provided us with a multitude of well localized sources. Gravitational waves have found numerous sources, but few are well localized, and only one has been observed to have an electromagnetic counterpart. Cosmic rays do not point back to their original source due to their electric charge.

Currently, there are only three known astrophysical neutrino sources. The Sun was the first to be detected, and it remains the best studied persistent neutrino source. The other two sources were detected through multimessenger observations. The first extrasolar neutrino source to be detected was the supernova SN 1987A. The second was the blazar TXS 0506+056, discovered in the X-ray and γ -ray followup of a high energy IceCube neutrino. Multimessenger followup of gravitational wave events lead to another multimessenger source, the neutron star merger GW170817. The subsequent multiwavelength followup gave us a wealth of information on gamma ray bursts and nucleosynthesis.

1.2 Production of High Energy Particles

The γ -ray sky, as shown by CGRO and Fermi, contains a multitude of sources. There are two main models to how a source can produce high energy γ -rays. Leptonic models produce only γ -rays, while hadronic models produce cosmic rays. A significant fraction of these cosmic rays are absorbed either at the source or in the interstellar medium (ISM) around the source and decay to produce photons and neutrinos.

1.2.1 Leptonic Models

Much of the emission from active galactic nuclei (AGNs) and other energetic sources arises from leptonic processes. These models produce an emission spectrum that very closely matches the observed emission spectrum from AGNs [16, 17]. In this model, relativistic electrons and positrons are accelerated in magnetic fields. The acceleration of charged particles will always produce electromagnetic radiation. The radiated power can be described by the relativistic Larmor formula [18]:

$$P = -\frac{dE}{dT} = \frac{2e^2}{3c^3}a^2 \quad (1.1)$$

where e is the electron charge, c the speed of light, and a the acceleration of the particle. Assuming a relativistic particle with a Lorentz factor Γ in a circular orbit, the acceleration becomes $a = \Gamma^2 \frac{v^2}{R}$ where v is the velocity and R the orbital radius. Combining this information [18], we can modify the equation to become

$$-\frac{dE}{dt} = \frac{4}{3}\sigma_T c U_B \Gamma^2 \quad (1.2)$$

where σ_T is the Thomson cross section and U_B the magnetic field density [18].

Photons produced via synchrotron radiation usually have their spectral peak between infrared and X-ray energies, with the exact location depending on the strength of the magnetic field and the Γ factor of the electrons. If the emitting region is dense, the electrons and photons can interact, usually by inverse Compton scattering. In Compton scattering, a photon will elastically scatter off an electron, losing energy in the process, and experiencing a wavelength shift given as [19]:

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos \theta) \quad (1.3)$$

where λ and λ' are the initial and final wavelengths of the photon, h Planck's constant, m_e the electron mass, c the speed of light, and θ the scattering angle. The net effect is the transfer of some of the energy to the electron. However, if the electron is moving, and especially if the motion is relativistic, the inverse of this process can occur. In inverse Compton scattering, an electron transfers some of its kinetic energy to the photon, often greatly boosting the energy of the photon.

These two effects create a double-peaked energy distribution. The low energy

peak is caused by synchrotron emission, while the higher energy peak is caused by some of the synchrotron emission getting boosted by inverse Compton scattering. Both of these processes produce an energy spectrum following a power law distribution. Given a power law index a_e for the parent electron population, the spectral index for the synchrotron and inverse Compton emission will be given by $(a_e - 1)/2$ [18].

1.2.2 Hadronic Models

There is one other set of models for the production of high energy γ -ray, the hadronic models. When protons, nuclei, or other hadrons are accelerated to sufficient energies, collisions with ambient gas, photons or other accelerated hadrons will produce numerous other particles, including charged and neutral pions and kaons. This can occur when cosmic rays interact with the interstellar or intergalactic medium, or other particles close to the source. Neutral pions decay as

$$\pi^0 \rightarrow 2\gamma \quad (1.4)$$

In the rest frame, each photon produced via pion decay will have an energy equal to half the pion rest mass, or 67.5 MeV per photon. Since pions are a spin 0 particle, the photons emission will be isotropic. But since the pions are produced with relativistic velocities, the resulting gamma rays will also have boosted energies. The observed gamma ray energy can be given as

$$E_\gamma = \Gamma E_\gamma^* + \beta \Gamma p_\gamma^* \cos \theta \quad (1.5)$$

where β is the speed as a fraction of the speed of light, γ the Lorentz factor, and p_γ the momentum of the photon. Quantities marked with * are measured in the rest frame.

The decay of charged pions is slightly more complex, with the first decay producing a muon that subsequently decays as well

$$\begin{aligned} \pi^+ &\rightarrow \nu_\mu + \mu^+ \\ \mu^+ &\rightarrow \bar{\nu}_\mu + \nu_e + e^+ \end{aligned} \quad (1.6)$$

In this interaction, each particle will carry approximately 1/4 of the pion

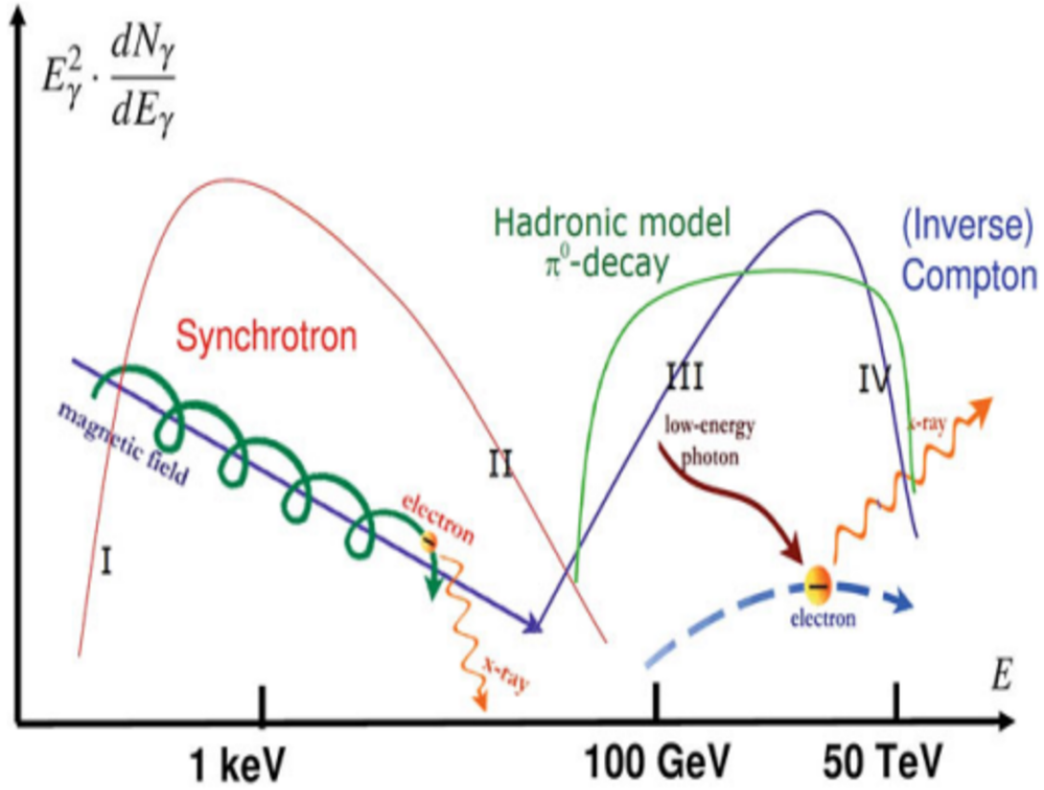


Figure 1.6: Spectral Energy Distribution (SED) for synchrotron emission, inverse Compton scattering, and hadronic pion decay. Image taken from [18]

energy. Taking into account the probabilities of an interaction producing charged vs neutral pions, we find that on average, the γ -ray luminosity will be approximately three times brighter than the corresponding neutrino luminosity [18]. This $\gamma : \nu$ luminosity ratio can range from 2:1 to 4:1 depending on whether the interaction is proton-proton, or proton- γ . Spectra from both processes are shown in Fig 1.6

1.2.3 Production of Cosmic Rays

Excepting the blazar TXS 0506+056, the sources of extragalactic cosmic rays remain unknown, though many have been theorized. The cosmic ray spectrum shows several spectral breaks, where the power law index appears to change. This indicates the presence of several source populations producing cosmic rays at different energies.

The primary theory for the production of cosmic rays is shock acceleration,

also known as Fermi acceleration [20]. In this model, a high velocity shock wave provides energy to particles in its path. A fraction of the particles can bounce across the shock wave multiple times, gaining energy with each bounce. Fermi acceleration produces cosmic rays with a power law spectrum.

1.3 Propagation and Sources of High Energy Particles

As energy increases, the chance for photons to interact with background light increases. The further a γ -ray travels through space, the more likely it is to experience a photon-photon collision with a visible or infrared photon. When this happens, the collision will create an electron-positron pair. This process has the net effect of softening the γ -ray spectrum of any distant sources without changing the integrated energy flux of the source [21, 22].

Cosmic rays also experience attenuation. As energy and travel distance increase, cosmic rays become more likely to interact with other particles in space. At the highest energies, a proton can collide with a photon from the cosmic microwave background as part of the Δ resonance:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

The generated pions will then decay, producing energetic gamma rays and neutrinos. This effect is called the GZK after the scientists who first proposed its existence, Kenneth Greisen [23], Vladim Kuzmin, and Georgiy Zatsepin [23]. The decay of the Δ^+ always produces a pion, with neutral pions decaying into two gamma rays, and charged pions decaying into muon neutrinos and muons, which ultimately decay into electrons, muon neutrinos and electron neutrinos. The net effect of this interaction is to convert some of the cosmic ray flux into γ -rays and lower energy neutrinos [23, 24].

The propagation of cosmic rays and γ -rays also leads to emission from molecular clouds. Molecular clouds are regions of space where the matter density is high enough to permit the formation of molecules. When high energy γ -rays interact with atoms, they can form an electron positron pair. These particles can further

interact with the molecules to produce lower energy γ -rays and sometimes more electrons. Cosmic rays can interact with the clouds producing pions, which will decay to produce photons, electrons, and neutrinos. These processes allow molecular clouds to act as γ -ray and neutrino sources when illuminated by high energy γ -rays and cosmic rays [18].

Despite significant work by numerous collaborations, the sources of high energy neutrinos and extragalactic cosmic rays remain unknown, excepting TXS 0506+056. The vast majority of γ -ray sources in our Galaxy are in the Galactic plane, with the main source classes being supernova remnants, pulsar wind nebulae, and the Galactic center.

Supernova remnants (SNRs) such as the Crab Nebula are left behind after a supernova explosion. One of the most important features of SNRs is the shock wave produced in the supernova. This shock wave can boost particles via Fermi acceleration [20]. SNRs are thought to provide the primary source of galactic cosmic rays. This cosmic ray acceleration has the side effect of creating γ -rays through hadronic processes, meaning SNRs could also be a source of high energy neutrinos, though neutrino emission has yet to be observed from any SNR.

A pulsar wind nebula, such as the Vela pulsar, is a special class of SNR where the core of the supernova explosion has collapsed into a rapidly rotating neutron star. This neutron star emits a narrow jet within the radio frequency, which is visible on Earth as a rapid series of radio pulses. Pulsars have a strong magnetic field which, coupled with their rapid rotation, can power an electron-positron wind at relativistic velocities. Leptonic emission from the wind interacting with the interstellar medium produces majority of the γ -rays [25].

Diffuse γ -ray emission occurs across a range of environments within the Galaxy. This emission can be from pions created from cosmic ray interactions in the interstellar medium (ISM), inverse compton scattering of background photons by electrons or cosmic rays, or from γ -ray interactions in the ISM. Another diffuse source are the Fermi bubbles. Discovered with the Fermi-LAT satellite in 2010, these are extended regions of hard γ -ray emission above and below the galactic plane. The origin of Fermi bubbles is currently unknown [26].

The other relevant sources are extragalactic: Gamma Ray Bursts (GRBs) and active galaxies. GRBs are the most luminous electromagnetic transients ever observed. They come in two flavors, short and long. Short GRBs have a total

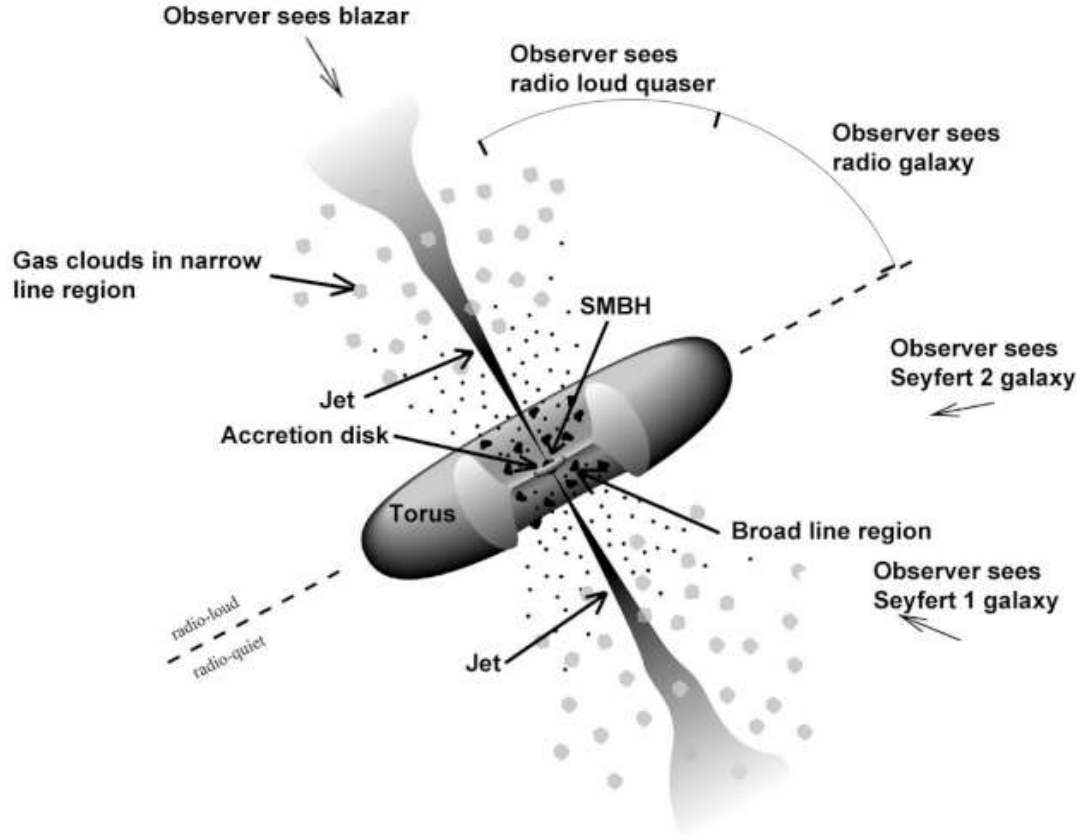


Figure 1.7: Structure of a blazar. From the side, a blazar looks much like any other AGN with a relativistic jet. When the jet is pointed at Earth, we see it as a blazar. Image published by NASA.

duration of less than two seconds. With the gravitational wave detection GW170817, the source of short GRBs was confirmed to be the neutron star mergers [1]. Long GRBs have a duration of greater than two seconds and occur in the aftermath of a core collapse supernova [3]. Both short and long GRBs have been theorized as neutrino sources, but no neutrinos have yet been observed from any GRB. Detection of neutrinos from a GRB or stronger limits on high-energy neutrino production would clarify whether GRBs are sources of high energy cosmic rays. These observations will likely require next generation detection facilities [18].

Active galaxies are a significant source of extragalactic γ -rays, specifically the active galactic nucleus (AGN). In an AGN, the central supermassive black hole is actively accreting matter, forming an accretion disk around the black hole. The emission from the disk is often bright enough to outshine the entire galaxy as

a whole. The disk itself is primarily a thermal source, while the relativistic jet provides strong nonthermal power law emission. The jet emission is thought to be leptonic in origin, but if even a fraction of it is hadronic, the AGN could be a source of both cosmic rays and high energy neutrinos [3, 18]. When the jet is oriented to point at Earth (see Fig 1.7), the AGN is classified as a blazar. Blazars display highly variable broadband nonthermal emission. Blazars are some of the most luminous γ -ray sources known, and have long been considered a good neutrino and cosmic ray candidate source. Neutrino emission was detected from TXS 0506+056 in 2017, confirming at least some blazars are sources of neutrinos [27].

1.4 Detection of High Energy Particles

There are numerous projects and missions crucial to the study of particle astrophysics and multimessenger astrophysics. Broadly speaking, there are two categories for the detectors: space based missions and terrestrial missions. The Earth's atmosphere acts as a shield, absorbing high energy radiation from space. Space based missions observe cosmic sources at these energies from above the atmosphere. Space based missions are used to detect photons in the X-ray and soft γ -ray energy ranges. But at higher energies, these missions lack the detecting area to get good statistics, so we use ground based facilities. Ground based facilities search for the secondary particles produced when high energy particles interact in the atmosphere.

1.4.1 Swift

The Swift mission was launched in 2004 to study GRBs, with a focus on detecting and observing bursts and studying their afterglows. The satellite has three main instruments, the Burst Alert Telescope (BAT), the X-Ray Telescope (XRT), and the Ultraviolet/Optical telescope (UVOT).

The BAT consists of an array of 32,768 CdZnTe detectors arranged in a grid 1.2 x 0.6 m area. A Coded Aperture Mask made of about 54,000 lead tiles sits above the detector array, as shown in Fig 1.8. The BAT can compute an image of the sky by taking a fast Fourier transform of the X-ray shadow the mask casts on the detector array [28].

As part of the original spacecraft design, once the BAT observes a burst, it

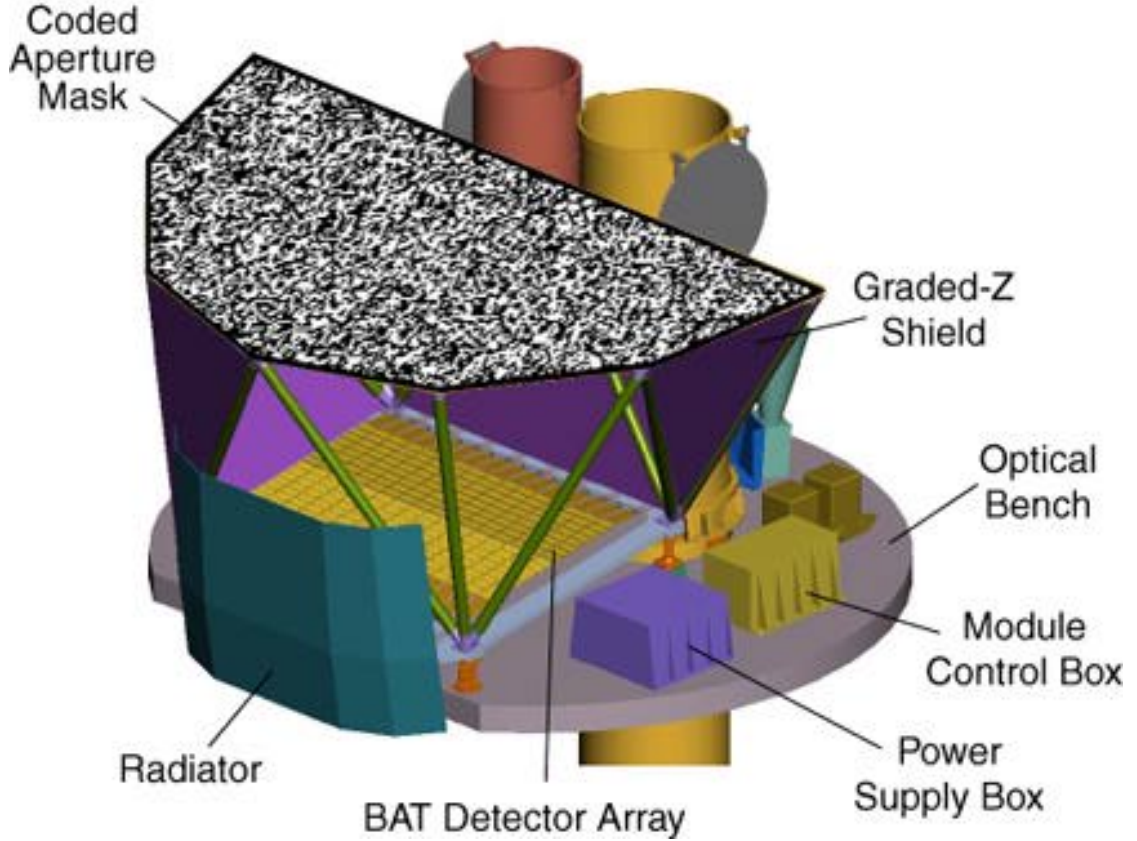


Figure 1.8: Schematic of the Swift-BAT detector showing both the detector array and the Coded Aperture Mask. Image produced by NASA.

can then rapidly slew to point both the XRT and the UVOT to search for an afterglow. The XRT itself uses a mirror configuration built for the Joint European Telescope for X-ray astronomy (JET-X) and a CCD detector similar to the one used for XMM-Newton [29]. The XRT has good sensitivity to X-rays in the 0.2-10 keV band, with a field of view $23.6'$ on each side. The XRT is regularly used as part of the follow-up efforts for astrophysical neutrinos, gravitational wave events, and other potential multimessenger events [30].

1.4.2 Fermi

The Fermi satellite was launched in 2008 to perform all-sky surveys of γ -rays. The satellite has two main instruments, the Large Area Telescope (LAT) and the Gamma-Ray Burst Monitor (GBM).

The LAT detects individual γ -ray photons. To filter the significant flux of cosmic

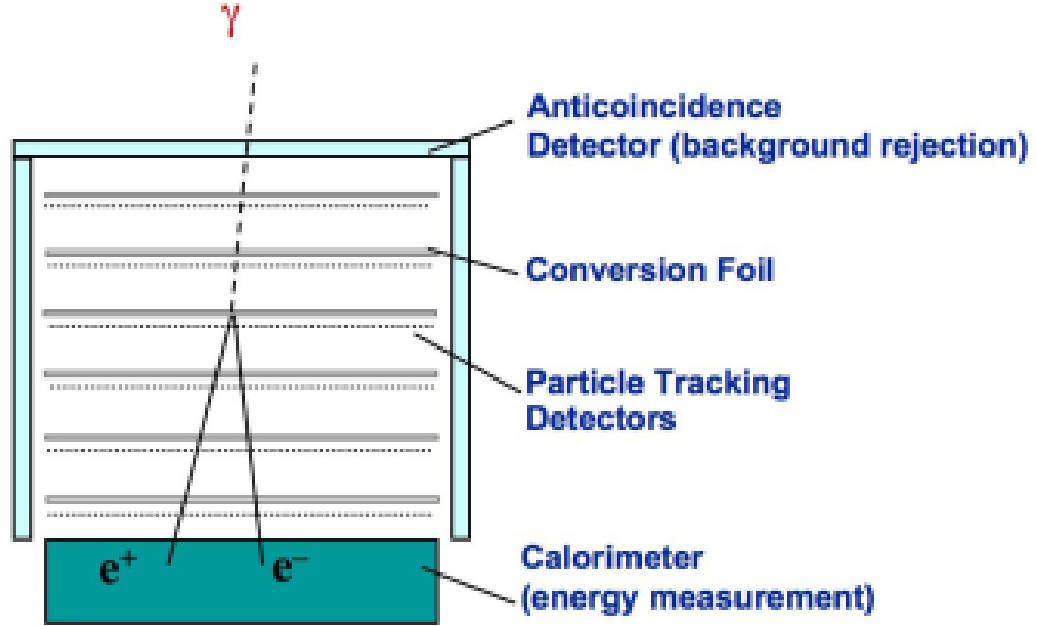


Figure 1.9: Schematic of the Fermi-LAT detector. Image published by NASA.

rays, the LAT is surrounded by an anticoincidence shield. This shield can identify an incoming charged particle with 99.97% efficiency [31]. As shown in Fig 1.9, γ -rays pass through a series of particle trackers coated with tungsten conversion foil. An incoming γ -ray will interact with the foil, producing an electron-positron pair. This pair will continue to propagate through the particle trackers. The LAT has 18 layers of foil-coated silicon strip trackers, each layer alternating its direction in a cross pattern. Once the pair has passed through all the layers, it deposits its energy into the calorimeter. To be classified as a γ -ray, there must be no signal in the anticoincidence shield along the particle track, more than one particle track with the same origin point must exist in the tracker, and a shower of particles needs to be seen in the calorimeter. Any event meeting these criteria can be identified as a γ -ray [31]. The LAT is sensitive to γ -rays with energies between 20 MeV and 300 GeV, and has a 1.2 steradian FOV.

The GBM consists of 12 sodium iodide and two bismuth germanite scintillators. The sodium iodide detectors are sensitive to γ -rays between 8 keV and 1 MeV, while the bismuth germanite detectors are sensitive in the 200 keV to 40 MeV band. The 14 detectors are mounted around the satellite, giving it a total FOV of 8 steradians.

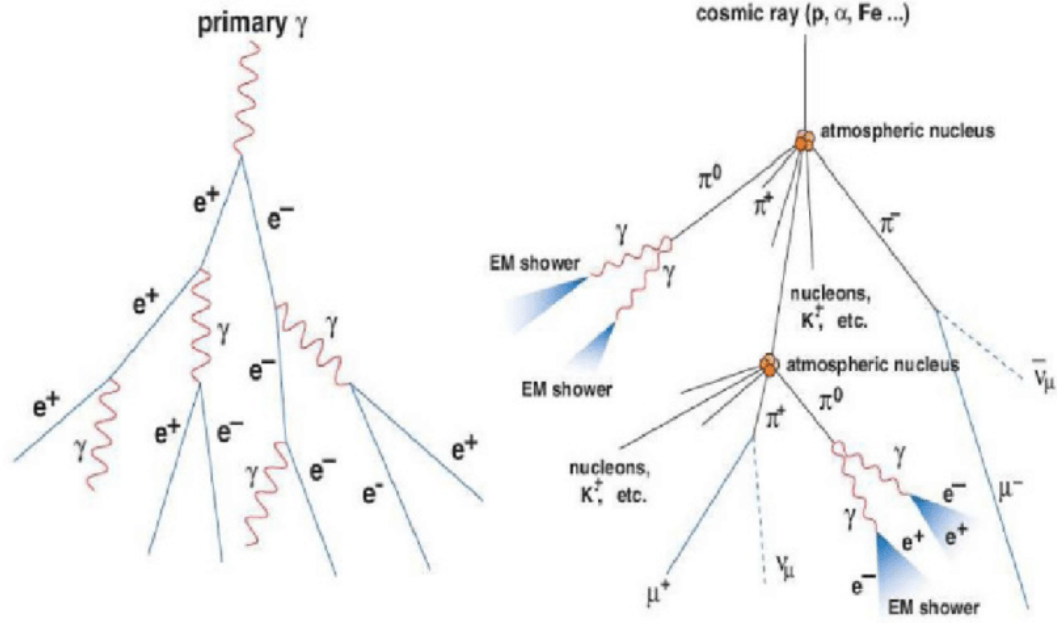


Figure 1.10: Diagram of air showers from γ -rays and from cosmic rays. Image taken from [35]

The GBM searches for any burst-like γ -ray emission [32]

1.4.3 Air Showers

When high-energy particles strike the Earth's atmosphere, they interact and produce secondary particles. This effect was first noticed by Pierre Auger in 1937, when he observed the simultaneous discharge of Geiger counters spread over a large area [33]. This effect is caused by a single, very energetic cosmic ray interacting with air molecules in the upper atmosphere. The interaction produces a cascade of secondary particles, producing an air shower that can be measured over a large ground area. There are two important effects to be considered in the generation of an air shower. The first is pair production, where a high energy photon interacts to produce an electron-positron pair. The second is Bremsstrahlung, where an electron or positron scatters off the electric field, producing x-rays and gamma rays as it loses energy. Both of these processes have the net effect of creating more particles, which results in exponential growth until the energies are low enough that pair production can no longer occur [34]. The process is shown in Fig 1.10.

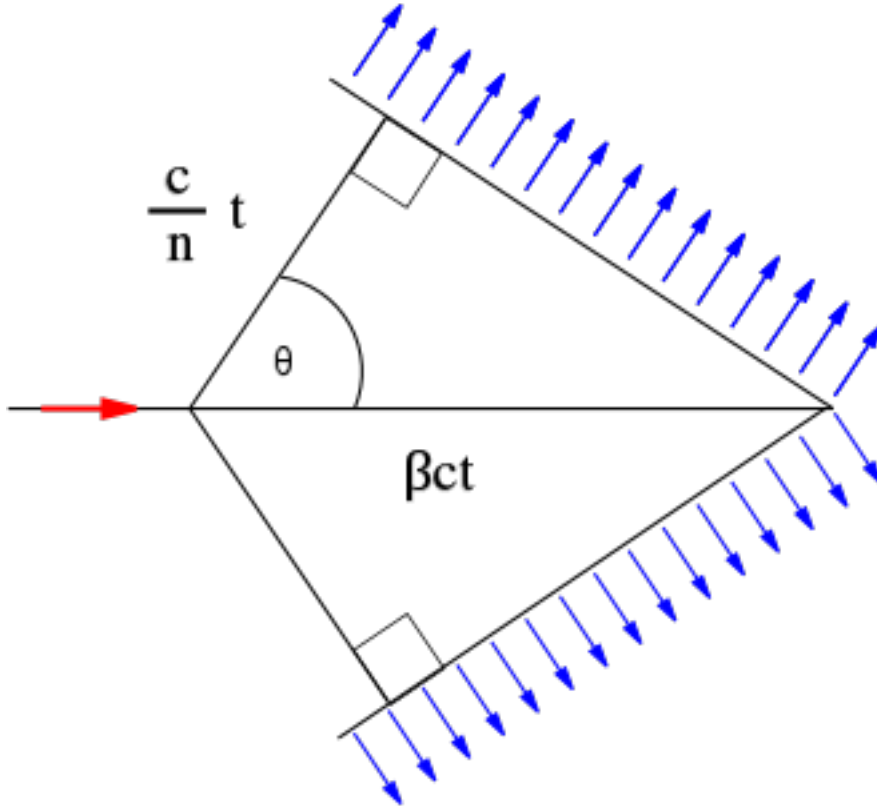


Figure 1.11: Cherenkov emission from a particle with a velocity βc in a material with an index of refraction, n . Image published under Creative Commons 3.0.

While the physics of purely electromagnetic showers are simple, things get more complicated for hadronic showers. When the initial particle is a proton or other atomic nucleus, the shower will also create pions. The decay of neutral pions will create photons that can then induce additional electromagnetic showers. The decay of charged pions will produce muons and neutrinos. The muons make hadronic air showers more complex as their decay can revive a shower.

1.4.4 Air Cherenkov Detectors

When an air shower is initiated in the atmosphere, the resulting secondary particles are all initially moving at very close to the speed of light. One consequence is that their velocities are usually faster than the phase velocity of light in air, which means they will emit Cherenkov radiation. Cherenkov radiation is analogous to a sonic boom generated by objects breaking the sound barrier. When charged particles

move through matter, they disturb the electric fields and polarize the medium. If the particle exceeds the phase velocity of light in said medium, this disturbed field will radiate outward as a cone shaped shockwave. As shown in Fig 1.11, Cherenkov radiation forms a cone. This cone has an angle called the Cherenkov angle:

$$\cos(\theta) = \frac{1}{\beta n} \quad (1.7)$$

where n is the refractive index of the material and βc is the velocity of the particle.

The Whipple 10-meter telescope was the first Imaging Atmospheric Cherenkov Telescope (IACT) to be built. Starting in 1982, the Whipple Collaboration used the telescope to search for the Cherenkov light emitted by air showers. Cosmic ray induced showers can be differentiated from γ -ray induced showers by their shape and ultraviolet excess [36]. The direction of the original particle is reconstructed from the shower, and sources are found by comparing bright spots to the local background [37]. Sensitive to γ -rays with energies between 300 GeV and 10 TeV, Whipple discovered the first TeV emission from the Crab Nebula in 1989 [36].

Following the success of the Whipple telescope, several other IACTs were built. One limitation of Whipple was its physical size. For lower energy γ -rays, the showers are smaller and less luminous, necessitating a larger telescope to be observable. For higher energy γ -rays, the size of the shower can start to become too large for a single telescope to observe. Newer IACTs circumvented this problem by building an array. Several such arrays exist, including the Very Energetic Energetic Radiation Imaging Telescope Array System (VERITAS) [38], the High Energy Stereoscopic System (H.E.S.S) [39], the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) [40], and the Major Atmospheric Cherenkov Experiment Telescope (MACE) [41]. Another relevant IACT is the First G_{APD} Cherenkov Telescope (FACT). Unlike the other new IACTs, FACT consists of one single telescope and is designed to monitor known bright TeV sources rather than discover newer faint sources [42]. The Cherenkov Telescope is currently under construction. Once complete, it will be the largest operational IACT in the world [43].

IACTs are powerful tools, but limited in their operation. They can easily find faint sources, but can only be used on clear, moonless nights. Their field of view is also limited, making it challenging for them to study extended sources of γ -rays such as the diffuse emission from our Galaxy.



Figure 1.12: The HAWC detector in 2016 as photographed by Jordan Goodman.

1.4.5 Water Cherenkov Detectors

A natural complement to IACTs are the extensive air shower arrays. These arrays are designed to more directly detect the secondary particles arriving from air showers, either with scintillation material or water Cherenkov detectors. These detectors can be operated continuously and can survey a wide field of view for any interesting transients. However, their angular and energy resolution is inferior to IACTs. For these reasons, air shower arrays work as the natural complement to IACTs.

Water Cherenkov telescopes work by detecting the Cherenkov light emitted by secondary particles as they pass through large tanks of pure water. As many of the secondary particles are no longer relativistic at sea level, these tanks need to be placed at altitude. The first water Cherenkov telescope was built by the Milagro collaboration. Milagro was the first operational water Cherenkov detector to observe high energy gamma rays, notably observing TeV emission from the extended Geminga region [44].

The largest current water Cherenkov detector is the High Altitude Water Cherenkov Gamma-Ray Observatory (HAWC), as seen in Fig 1.12. Located at an altitude of 4100 m in Mexico, HAWC consists of 300 large tanks each containing

200,000 liters of pure water and four PMTs to detect the Cherenkov light [45]. HAWC is sensitive to γ -rays with energies between 100 GeV and 50 TeV. Plans exist for a less dense array of smaller outrigger tanks to increase the sensitivity of the array to the highest energy γ -rays.

The other major water Cherenkov detector is the Pierre Auger Observatory. Located in Argentina at an altitude of 1400 m, Auger has over 1600 tanks in a hexagonal grid with a 1500 m spacing. Auger was designed primarily to study cosmic rays at the highest energies. Due to the low density of tanks, Auger has very little sensitivity to γ -rays [46].

1.4.6 Neutrino Detectors

Neutrinos are one of the more difficult particles to observe directly. As they only interact with matter via the weak force, they pass through matter unaffected, only rarely interacting. To have a chance to observe neutrinos, a detector needs to be very large in size and strongly shielded from background radiation. There are two high-energy neutrino detectors currently, the IceCube Neutrino Observatory and ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch project).

IceCube is the largest neutrino detector in the world (layout shown in Fig 1.13), consisting of 86 strings of digital optical modules (DOMs) embedded in a cubic kilometer of Antarctic ice. The DOMs range in depth from 1450 m to 2450 m. At the center of the detector is the DeepCore subdetector, which has a higher DOM density and provides greater sensitivity to lower energy neutrinos. IceCube searches for the Cherenkov light emitted from the cascades and tracks caused by both upgoing and downgoing neutrinos. Due to the cosmic ray backgrounds, a higher threshold energy is required for a downgoing neutrino. For upgoing neutrinos, there is an upper limit past which the Earth stops being transparent to neutrinos [47].

The other major neutrino detector is ANTARES. The ANTARES detector is situated about 40 km off the coast of Toulon, France, deep in the Mediterranean Sea. ANTARES uses water as a detection medium. Water has the advantage of providing better angular resolution to the original neutrino direction, with the disadvantages of a higher energy threshold. Natural background light in the water, mainly arising from potassium and numerous biological sources,

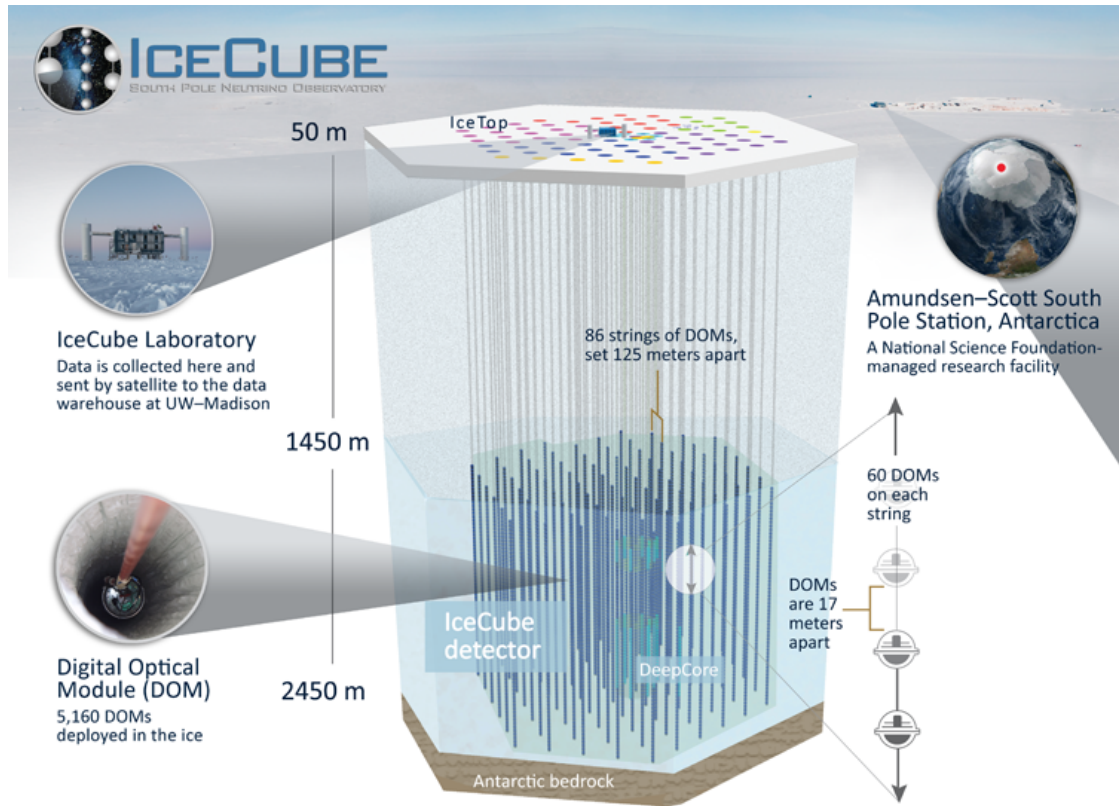


Figure 1.13: Layout of the IceCube neutrino observatory.

also contributes to higher background levels. To ameliorate these effects, ANTARES only studies the upgoing neutrinos [48].

Chapter 2

Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data¹²

We present a targeted search for blazar flux-correlated high-energy ($\varepsilon_\nu \gtrsim 1$ TeV) neutrinos from six bright northern blazars, using the public database of northern-hemisphere neutrinos detected during “IC40” 40-string operations of the IceCube neutrino observatory (April 2008 to May 2009). Our six targeted blazars are subjects of long-term monitoring campaigns by the VERITAS TeV γ -ray observatory. We use the publicly-available VERITAS lightcurves to identify periods of excess and flaring emission. These predefined intervals serve as our “active temporal windows” in a search for an excess of neutrinos, relative to Poisson fluctuations of the near-isotropic atmospheric neutrino background which dominates at these energies. After defining the parameters of an optimized search, we confirm the expected Poisson behavior with Monte Carlo simulations prior to testing for excess neutrinos in the actual data. We make two searches: One for excess neutrinos associated with the bright flares of Mrk 421 that occurred during the IC40 run, and one for excess neutrinos associated with the brightest emission periods of five other blazars (Mrk 501, 1ES 0805+524, 1ES 1218+304, 3C66A, and W Comae), all significantly fainter than the Mrk 421 flares. We find no significant excess of neutrinos from the preselected

¹This paper has been published in the *Astrophysical Journal* as: C. F. Turley, D. B. Fox, & 6 others, the *Astrophysical Journal*, Volume 863, 64 (arxiv:1608.08983)

²Python scripts used in this analysis can be found at <https://github.com/cft114/vic40>

blazar directions during the selected temporal windows. We derive 90%-confidence upper limits on the number of expected flux-associated neutrinos from each search. These limits are consistent with previous point-source searches and Fermi GeV flux-correlated searches. Our upper limits are sufficiently close to the physically-interesting regime that we anticipate future analyses using already-collected data will either constrain models or yield discovery of the second blazar-associated high-energy neutrinos.

2.1 Introduction

The IceCube collaboration has instrumented a cubic kilometer of Antarctic ice at the South Pole with 86 “strings” of photomultiplier tubes, readout electronics, and an internal calibration system so as to detect high-energy ($\varepsilon_\nu \gtrsim 1$ TeV) neutrinos from atmospheric cosmic ray showers and extraterrestrial sources [47]. Operations of the 79-string and full-strength 86-string facilities since 2010 recently yielded discovery of a population of cosmic neutrinos [49–51], validating the experiment’s original motivation and approximate scale [52, 53]. Given the $\gtrsim 10^\circ$ cascade-type (and less frequently, $\sim 1^\circ$ track-type) positional uncertainties and ≈ 1 per month rate of detection for the highest-confidence cosmic events, the absence of any demonstrated association with known γ -ray bursts [50, 51, 54], and the inferred near-isotropic sky distribution [50], the nature of the sources of these cosmic neutrinos remains uncertain and subject to active debate (e.g., [55–58]).

Ultimately, identification of electromagnetic (EM) counterparts to high-energy neutrino sources can proceed by one of two possible paths: Sufficiently variable sources may exhibit correlated variability in their neutrino and EM emissions; or sufficiently bright individual sources may (with time) be identified as *a priori* interesting, astrophysically-plausible EM sources that are coincident with a point-like or extended excess of neutrinos on the sky.

With respect to the first approach, γ -ray bursts (GRBs) have long been considered promising candidates for high-energy neutrino emission [52, 59, 60]. Given the brief timescale for high-energy emission from the typical GRB, and the precision timing of IceCube-detected neutrinos, known GRBs can be readily associated with individual neutrino events even with the limited positional resolution available for the IceCube cosmic neutrinos (mostly cascade events) or associated lower-energy

neutrinos that interact as track events. The relatively relaxed requirements for positional determination also allow use of the full set of detected GRBs from Swift, Fermi, the Interplanetary Network, and other satellites. In spite of this, no coincident high-energy (cascade or track) or low-energy track neutrino interactions have been found in association with any detected GRB [61, 62]. The inferred limit on the fraction of the cosmic neutrinos that are due to GRBs is $<1\%$ [54].

Without the brief temporal window provided by GRBs, identification and confirmation of the neutrino-emitting source population(s) must depend on positional coincidence (particularly via likely-cosmic track-type events) and careful evaluation of the expected flux and spectrum under proposed theoretical models. Proposed source populations currently include star-forming galaxies [58, 63–66], galaxy clusters and groups [64, 67], active galactic nuclei (AGN; [68–72]), and quenched-jet GRBs [73–75]. In addition, it remains possible that a minority of the cosmic neutrinos originate in our own Milky Way Galaxy, either via the Fermi bubbles [26, 76–78], Galactic compact binary TeV γ -ray sources [79, 80] or TeV unidentified sources (such as pulsar wind nebulae or possible hypernova remnants; [81, 82]). All of these scenarios are reviewed by [57].

The γ -ray bright AGN known as blazars represent a particularly intriguing possible source population, as they are the most γ -ray luminous AGN known and the brightest extragalactic sources on the sky at TeV energies, capable of outshining all other TeV sources during some flares. Their γ -ray emission is commonly explained by invoking a leptonic scenario, in which highly-relativistic electrons in the blazar jets generate emission by a combination of synchrotron self-Compton and external inverse Compton processes. This scenario yields minimal high-energy neutrino emission.

However, if or when most of the blazars’ high-energy γ -rays are produced by hadronic interactions in the relativistic jets (with a minority contribution from leptonic emission processes), the lepto-hadronic scenario, some or most of the observed γ -rays will result from cascade emission induced by γ -rays from π^0 decays. In this case, the observed TeV γ -rays will be accompanied by comparable fluxes of $\varepsilon_\nu \gtrsim 1$ TeV neutrinos from decays of coproduced $\pi^\pm$ [17, 83–85]. In a variant of this lepto-hadronic scenario, γ -rays are produced by proton synchrotron radiation without associated high-energy neutrinos [86].

In another alternative possibility, the intergalactic scenario, the γ -rays result

from intergalactic cascades triggered by electron-positron pairs that are produced by ultrahigh-energy cosmic rays escaping from the sources, and photohadronic interactions with the extragalactic background light then lead to a comparable flux in high-energy γ -rays and high-energy neutrinos [87, 88].

Significant neutrino emission is not anticipated in the leptonic scenario [16, 17], nor in the proton synchrotron version of the lepto-hadronic scenario. However, in a general sense we expect protons as well as electrons to be accelerated in blazar jets, and if these AGN are sources of ultrahigh-energy cosmic rays, associated high-energy neutrino emission can be detectable even if the observed γ -rays are dominated by leptonic processes [71]. Carefully-designed searches for neutrino emission from the brightest blazars thus have the potential to constrain source models and important related hypotheses via either detections (possibly providing the first confirmed counterparts for any high-energy astrophysical neutrinos) or upper limits.

While leptonic models have been argued to provide a more natural fit to typical blazar spectra [17], there are unresolved theoretical challenges. For example, blazar γ -ray flares can show fast variability, implying a compact emission region which is hard to reconcile with the non-observation of any high-energy cutoff from $\gamma\gamma \rightarrow e^+e^-$ [89, 90]. The leptonic scenario also struggles to explain the occasional “orphan” TeV blazar flares – flaring emission that is observed at TeV energies without accompanying flaring in the X-ray [91, 92]. Even if prototypical blazar emissions are leptonic, it is still possible that their flares (or perhaps, their orphan TeV flares) reveal a transient and variable contribution from hadronic processes. The June 2002 orphan flare of the blazar 1ES 1959+650 [93, 94] is of particular note in this context. IceCube’s predecessor AMANDA-II detected a single coincident neutrino from the direction of 1ES 1959+650 during the flare, although the *a posteriori* nature of the observation has made it impossible to retrospectively assign a firm confidence level to any claim of association or non-association [94, 95]. Also worth noting is the recent 9.5 month-long GeV outburst of PKS B1424–418, which allowed this blazar to dominate the GeV γ -ray emissions of all catalogued blazars within the 50%-containment region of the $\varepsilon_\nu \approx 2$ PeV “HESE 35” IceCube event when that neutrino was detected, prompting the suggestion that this neutrino was emitted by PKS B1424–418 (estimated p-value of 5%; [96]).

Finally, there is the case of TXS 0506+056, which will be discussed in more

detail in Chapter 5. In September 2017, IceCube detected a high energy neutrino [97]. Followup by Swift and other observatories quickly identified the blazar TXS 0506+056 as the most interesting source candidate [98]. Further investigation by the Fermi-LAT team found that the blazar was in a flaring state at the time of the neutrino alert [27]. Following this, IceCube performed an archival analysis of 9.5 years of neutrino data. Their search found an excess of high-energy neutrinos from the region near TXS 0506+056. This independent 3.5σ neutrino excess supports the case for TXS 0506+056 as the source of IceCube-170922A [99]. This search demonstrated that at least a fraction of high energy neutrinos originate from blazars.

Between April 2008 and May 2009, IceCube ran in a partially-completed “IC40” 40-string configuration. The point-source analysis of this dataset found no evidence for any neutrino point sources bright enough to be distinguished above the atmospheric background [100]. Analysis of data gathered in IceCube’s subsequent “IC59” 59-string configuration (May 2009 to May 2010) and further searches with the full array similarly revealed no point sources, placed upper limits on the neutrino emissions of an array of candidate sources, and reported a null result for both a northern-sky time-dependent search and a Fermi-LAT flux correlated search [101, 102].

The present work extends previous point-source analyses of the IC40 data by explicitly considering the TeV γ -ray behavior of the bright northern blazars which are prime candidates for a first neutrino source detection by IceCube. Modeling the TeV lightcurves of these blazars allows us to select a set of active temporal windows and blazar directions which are (under our assumed conditions) optimal for detection of a neutrino excess over anticipated atmospheric backgrounds. These optimized windows amount in all cases to less than 11% of the full IC40 data collection period, allowing for the possibility of discovering associated neutrino emission below the threshold of previous time-integrated searches.

2.2 Datasets and Analysis

2.2.1 Datasets

The IceCube 40-string dataset (hereafter IC40) was collected between April 2008 and May 2009, a total live time of 375.5 days [100] during which the detector had 40 of the final 86 planned strings deployed. The data (publicly released in September 2011) records a total of 12,877 upgoing neutrino events. Extensive analyses [100, 101] have constrained the intensities of any existing point sources. The IceCube collaboration investigated the accuracy with which they could reconstruct neutrino arrival directions using the cosmic ray shadow of the moon [103], and found their reconstruction uncertainty was 0.7° for the 40- and 59-string configurations.

The six blazars studied in this work are listed with their basic properties in Table 2.1. Publicly-available blazar data (presented in Table 2.2) were collected by the four-telescope Very Energetic Radiation Imaging Telescope Array System (VERITAS; [38]) and (for Mrk 421 historical data only) its predecessor, the Whipple Telescope [37]. Both facilities consist of atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in Arizona, yielding similar effective energy ranges of $0.1 \text{ TeV} \lesssim \varepsilon_\gamma \lesssim 30 \text{ TeV}$ [104], with the exact limits depending on individual observation and analysis parameters such as elevation angle in the sky, analysis parameter cuts, and source spectra. All relevant blazar data are publicly available from the VERITAS website³ Publicly-available historical TeV γ -ray data for Mrk 501 were also used⁴.

2.2.2 TeV Lightcurves

We wish to carry out a targeted search for excess neutrinos when the monitored blazars are relatively bright in TeV γ -rays. This requires defining temporal windows of interest for each blazar. While VERITAS makes discrete measurements, the

³Mrk 421 long-term data [105] are available at <http://veritas.sao.arizona.edu/veritas-science/mrk-421-long-term-lightcurve>. Data for the other blazars are from <http://veritas.sao.arizona.edu/veritas-science/veritas-blazar-spectra> and were not public at the start of this work. The data were initially provided for collaborative use and were published prior to the completion of this work.

⁴Mrk 501 public light curve data presented in [106] and available at http://astro.desy.de/gamma_astronomy/magic/projects/light_curve_archive/index_eng.html.

VERITAS Northern Blazars

Name	R.A.	Dec.	z	L_{TeV} ($10^{44} \text{ erg s}^{-1}$)	F_{TeV} ($10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$)	ε_{th} (TeV)	Γ_{obs}	Γ_{src}	N_{obs}
1ES 0806+524	08:09:59.0	+52:19:00	0.138	0.1	0.2	0.3	3.6	2.7	4
1ES 1218+304	12:21:26.3	+30:11:29	0.182	1.6	1.8	0.2	3.1	2.2	20
3C 66A	02:22:41.6	+43:02:36	0.41	5.8	1.3	0.2	4.1	2.0	17
Mrk 421	11:04:19.0	+38:11:41	0.031	0.4	4.6	0.4	2.2	2.0	93
Mrk 501	16:53:52.2	+39:45:37	0.034	0.1	3.1	0.3	2.7	2.5	15
W Comae	12:21:31.9	+28:13:59	0.102	0.4	1.9	0.2	3.8	3.0	19

Table 2.1: Coordinates are provided in J2000; N_{obs} gives the number of observations during the IC40 observing run. Typical luminosities L_{TeV} and fluxes F_{TeV} are over $0.2 \text{ TeV} < \varepsilon_{\gamma} < 30 \text{ TeV}$. Power-law photon indices for Mrk 421 and Mrk 501 are known to be variable. The redshift of 3C 66A is uncertain, but bounded between 0.33 and 0.44. ε_{th} is the threshold energy for VERITAS observations. Γ_{obs} is the measured γ -ray spectral index, while Γ_{src} is the spectral index corrected for extragalactic background light absorption using the models of [22] and [21]. Blazar properties via TeVCat [107].

Blazar Observations

Name	MJD (d)	Exp. (h)	F_{TeV}		
			Obs. ($10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$)	Unc.	Rev.
1ES 0806+524	54564.179	0.226	2.1	1.5	
”	54566.177	2.554	-0.47	0.72	0.34
”	54567.153	0.562	1.0	1.6	
”	54821.408	0.595	0.52	0.83	
1ES 1218+304	54829.516	1.032	0.92	0.56	
”	54830.524	0.869	3.11	0.67	
”	54838.514	1.037	1.90	0.56	
”	54839.518	0.859	2.14	0.63	
”	54856.459	0.298	3.3	1.1	
”	54862.454	3.072	3.79	0.37	

Table 2.2: Fluxes over $0.2 \text{ TeV} < \varepsilon_\gamma < 30 \text{ TeV}$ (F_{TeV}) are reported as observed (Obs.) with Gaussian uncertainties (Unc.), and with forced-positive revised flux estimates (Rev.) where necessary. Derivation of revised fluxes is described in Sec. 2.2.2. Mrk 421 data were obtained from <http://veritas.sao.arizona.edu/veritas-science/mrk-421-long-term-lightcurve> [105]. Data for the other blazars are from <http://veritas.sao.arizona.edu/veritas-science/veritas-blazar-spectra>. Table 2.2 is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content.

IC40 data were taken continuously, meaning that every detected neutrino must be judged either in or out of sample. We choose to make this judgment by reference to interpolated light curves, which allows us to expand the temporal windows of interest for each blazar beyond the intervals of active VERITAS observation.

This requires us to choose an interpolation approach. We find traditional linear or spline-interpolation approaches not useful, as they result in unrealistic predictions during large data gaps and also (relatedly) because they lack relevant physical underpinning. Since our primary concern is to avoid accepting neutrinos when the blazar flux is low, we seek a conservative interpolation that will revert to a low “baseline” flux in the absence of constraining data, thereby excluding these periods from our detection windows.

Moreover, given the infrequent and non-continuous nature of the γ -ray measure-

ments, we do not find Bayesian Blocks-type approaches as adopted for example by [108], to be appropriate in this case. Rather, we seek to extend observed periods of flaring and excess emission in a realistic and physically-motivated way forward and backward in time, we will be able to accept neutrinos as potential signal when they are detected close to these periods. These concerns lead us to adopt a Gaussian process regression (GPR) [109] as our interpolation approach.

A Gaussian Process Regression, or GPR assumes that every finite collection of random variables has a multivariate normal distribution. For our work, these random variables exist in some domain and their range follows a multivariate Gaussian distribution. This distribution is assumed to have some mean function and covariance function. For this work, we have a matrix of flux measurements

$$\mathbf{y} = (y_1 \cdots y_n)^T \quad (2.1)$$

at times

$$\mathbf{x} = (x_1 \cdots x_n)^T \quad (2.2)$$

where T represents matrix transposition. The gaussian process on this data will be specified by its mean and covariance functions. The mean function, $m(x)$ will be set as a constant, μ_0 for this work. All flux measurements are related by a covariance function, $k(x, x')$, which describes how likely values are to be related based on their temporal separation. For this work, the covariance function is a squared exponential, defined as

$$k(x, x') = \exp \left[\frac{-(x - x')^2}{2l^2} \right] \quad (2.3)$$

where l is the characteristic length scale of the problem.

Using this covariance function, we can build a covariance matrix

$$K = \begin{bmatrix} k(x_1, x_1) & k(x_1, x_2) & \cdots & k(x_1, x_n) \\ k(x_2, x_1) & k(x_2, x_2) & \cdots & k(x_2, x_n) \\ \vdots & \vdots & \ddots & \vdots \\ k(x_n, x_1) & k(x_n, x_2) & \cdots & k(x_n, x_n) \end{bmatrix} \quad (2.4)$$

This matrix establishes the correlation between all pairs of time measurements

in our data. We then can calculate the covariance matrix between an arbitrary intermediate point x_* by calculating the matrix:

$$K_* = \begin{bmatrix} k(x_*, x_1) & k(x_*, x_2) & \cdots & k(x_*, x_n) \end{bmatrix} \quad (2.5)$$

This matrix is written here for one test point x_* but can be expanded into an $n \times n_*$ matrix for multiple test points. The last matrix is the correlation of a test point to itself, and between all test points should there be many.

$$K_{**} = k(x_*, x_*) \quad (2.6)$$

Using these three matrices, we can then write the relation between the flux values, $\mathbf{y}$ and a predicted output f_* . We can also incorporate a noise statistic, σ_n^2 , which is the variance of the Gaussian noise for each measurement. Including this noise, we can then write the full covariance matrix:

$$\begin{bmatrix} \mathbf{y} \\ f_* \end{bmatrix} \sim \mathcal{N} \left(\mu_0, \begin{bmatrix} K + \sigma_n^2 \mathbf{I} & K_*^T \\ K_* & K_{**} \end{bmatrix} \right) \quad (2.7)$$

where $\mathcal{N}(\mu, \Sigma)$ denotes a Gaussian with a mean of μ and a covariance matrix Σ , and $\mathbf{I}$ is the identity matrix.

The probability distribution for predicted values of f_* given the data will follow a Gaussian distribution.

$$y_* | \mathbf{y} \sim \mathcal{N} \left(K_* K^{-1} \mathbf{y}, K_{**} - K_* K^{-1} K_*^T \right) \quad (2.8)$$

The mean and variance of this distribution are then given as

$$\bar{y}_* = K_* K^{-1} \mathbf{y} \quad (2.9)$$

$$\text{var}(y_*) = K_{**} - K_* K^{-1} K_*^T \quad (2.10)$$

Using this method, function values and uncertainties can be calculated for an arbitrary number of intermediate points.

The biggest factor in accurately calculating intermediate values using a Gaussian process is properly selecting the covariance length and other noise hyperparameters. Normally, these hyperparameters are optimized from an initial guess. Optimization

revolves around the log marginal likelihood of the Gaussian process. The log marginal likelihood is defined as

$$\log p(\mathbf{y}|\mathbf{x}) = -\frac{1}{2}\mathbf{y}^T(K + \sigma_n^2\mathbf{I})^{-1}\mathbf{y} - \frac{1}{2}\log |K + \sigma_n^2\mathbf{I}| - \frac{n}{2}\log 2\pi \quad (2.11)$$

For any set of hyperparameters, a log marginal likelihood can be calculated. The optimal hyperparameter set is the one that maximizes the log marginal likelihood. For more details on Gaussian processes, see [109].

As applied by us to VERITAS blazar observations, the GPR works in two passes. In the first pass, it analyzes the data to determine the best-fit mean and covariance hyperparameters. In our case, we precondition the blazar light curves, as described below, so that the mean function is zero, constant and fixed, for each blazar; hence we fit for the covariance hyperparameters only. On the second pass, the GPR uses the hyperparameters and observed data values (ignoring the uncertainties) to predict the maximum likelihood flux (and confidence intervals on that flux) at all intermediate points. Beyond a few correlation lengths, the maximum likelihood flux reverts to the mean value, and the 90%-confidence bounds expand to encompass the full range of the observed data, illustrating the fundamentally conservative nature of this approach.

Our light curve preconditioning begins by replacing negative flux measurements, which are unphysical, with forced-positive replacement values (Table 2.2). These values are calculated from the associated VERITAS flux estimate and uncertainty as follows: Treating the flux estimate and uncertainty as the mean and standard deviation of a Gaussian distribution, we exclude the negative-flux portion of the distribution and use the median of the resulting positive-flux distribution as our replacement value.

Next, we calculate a “baseline flux” F_{base} for each blazar. Under the assumption that measurement uncertainties dominate systematic effects at low flux levels, and that the blazar emission consists of a dominant baseline flux supplemented by occasional periods of excess and flaring emission, we define the baseline flux for each blazar as the mode of the Gaussian kernel density estimator (KDE) for the blazar flux measurements. The KDE mode should be robust to a positive “tail” of excess and flaring emission episodes. We use the `scipy` [110] statistics package implementation. The resulting baseline fluxes are listed in Table 2.3.

In the final step of preconditioning, we divide the blazar flux measurements (and replacement values) by the baseline flux for that blazar and take the natural logarithm. Working in log-space reduces the heteroskedasticity of the flux measurements (which exhibit substantial positive excursions, but have negative excursions bounded to the physical range of non-negative fluxes), making the light curves better suited for GPR analysis. This approach allows us to set the GPR mean to a fixed constant zero for all blazars.

To carry out the GPR hyperparameter fitting and interpolation, we use the python package `pyGPs` [111]. We run the code using the squared exponential kernel with isotropic distances, Gaussian likelihood, exact inference, and a constant mean function, set to zero. The code optimizes the fit by minimizing the negative log marginal likelihood with respect to the hyperparameters. The hyperparameters for Mrk 421 and Mrk 501 were optimized using the extensive historical data. These hyperparameters were then used to generate the light curves from the data concurrent with IC40. All resulting best-fit hyperparameter values are presented in Table 2.3.

Blazars show variability on timescales as small as hours or even minutes. This is reflected in the correlation lengths from the GPR, which are all less than a day, implying flux measurements separated by more than a day are effectively uncorrelated. The correlation length for 1ES 0806+524 was significantly shorter than the other blazars, though due to a small sample size, the value is not well constrained. Better estimates of the correlation length would require more extensive monitoring or historical data, as was used for Mrk 421 and Mrk 501.

The resulting maximum-likelihood GPR-interpolated TeV γ -ray light curves for our six target blazars, which we generate at one hour resolution, are presented in Fig. 2.1. For both Mrk 501 and 1ES 1218+304, there exist short periods where the interpolated curve overshoots the measured flux points. This behavior does not impact the selection of temporal windows of interest; however, if the blazar emission did not actually increase during these intervals, then it will lead to a slight overestimation of the integrated TeV γ -ray fluence in these cases.

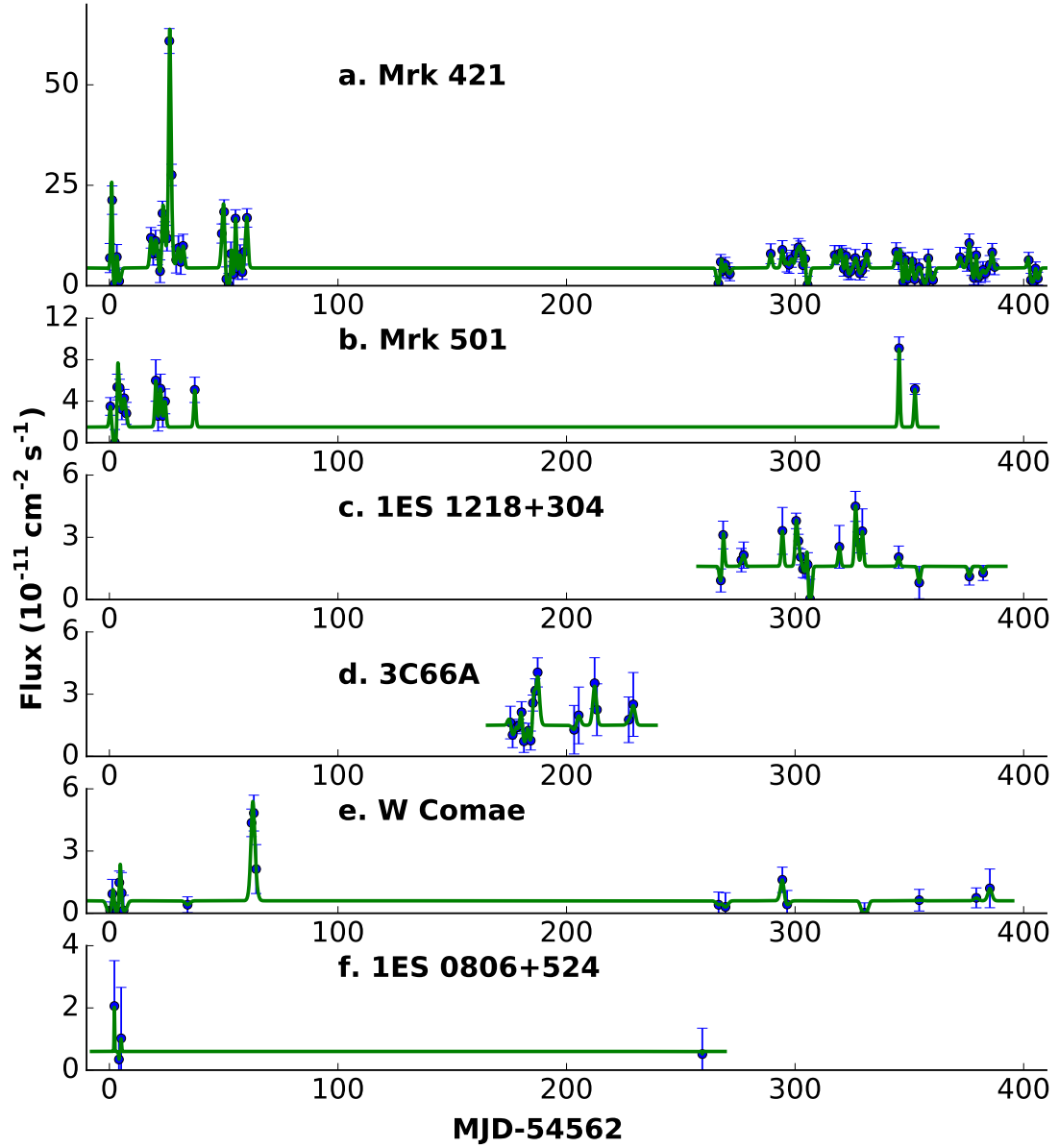


Figure 2.1: VERITAS TeV γ -ray light curves for six northern blazars subject to regular monitoring during the IC40 run, along with the maximum-likelihood interpolation resulting from our Gaussian process regression (Sec. 2.2.2). Time is in days since the start of IC40 (MJD 54562), aligned across all lightcurves.

Results of the Gaussian Process Regression

Blazar Name	N_{obs}	F_{max} ($10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$)	F_{base} ($10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$)	Correlation	Noise		NLML
				Time (d)	Dev.	Dev.	
1ES 0806+524	4	2.1	0.6	0.14	0.81	0.10	4.47
1ES 1218+304	20	4.5	1.6	0.55	1.25	0.08	29.68
3C 66A	17	4.1	1.5	0.89	0.86	0.19	15.56
Mrk 421	93	60.6	4.4	0.61	0.99	0.07	133.96
Mrk 501	15	9.1	1.5	0.52	1.60	0.10	27.44
W Comae	19	4.8	0.5	0.99	1.63	0.10	32.05

Table 2.3: Interpolated curves were generated using Gaussian likelihood, exact inference, a constant mean function and a squared exponential covariance function with isotropic distances. Maximum and baseline fluxes (F_{max} , F_{base}) are over $0.2 \text{ TeV} < \varepsilon_\gamma < 30 \text{ TeV}$. F_{base} is the value of the mean function and was estimated as the mode of a Gaussian kernel density estimator, as applied to the complete set of observations for each source. The covariance function has two hyperparameters, the log of the correlation time and the log of the covariance noise. The likelihood function hyperparameter is the natural log of the standard deviation of the signal noise. The hyperparameters were optimized by minimizing the negative log marginal likelihood (NLML) with respect to the hyperparameters.

2.2.3 Analysis Approach

Before using these interpolated light curves to define (statistically optimal) temporal windows of interest for our search for an excess of associated neutrinos, we need to understand the expected rate of background atmospheric neutrinos. This requires choosing a region of interest (ROI), that is, an acceptance radius (angle) around each blazar position. IceCube has established a 0.7° uncertainty in track event reconstruction [103]. We treat this as the standard deviation for a two-dimensional Gaussian distribution and find that 99.5% of neutrinos should be found within a 2.3° radius of the reconstructed direction. We adopt this 2.3° radius to define the ROI for each blazar.

Selection of the temporal windows of interest begins with the observation that the background atmospheric neutrinos are distributed uniformly in time and near-uniformly on the sky [100, 101]. The chief exception is the excess of events near the horizon owing to atmospheric muons from the southern hemisphere being

(erroneously) reconstructed to low northern declinations. Since none of the targeted blazars have declinations $\delta_{2000} < +25^\circ$, we can safely ignore this effect. Hence, the number of background neutrinos within the 2.3° -radius ROI for any blazar is expected to follow Poisson statistics, with an expected number of 0.023 neutrinos per day (≈ 1 neutrino per ROI per 44 days). (Note that in the next section we test this assumption using Monte Carlo simulations.)

Having generated interpolated light curves in TeV γ -rays for all six monitored blazars, we use their variability to our advantage by selecting the brightest emission periods for our search, maximizing our sensitivity to flux-correlated neutrino emission in excess of the atmospheric background.

Considering the union of the six light curves at one hour resolution, we sort flux measurements (irrespective of target blazar) from brightest to faintest. This sorting yields a one-to-one mapping from any given TeV flux threshold to a corresponding total exposure time (with reduced thresholds implying greater integration times), along with an associated total integrated fluence in TeV γ -rays. The total exposure time, along with the angular size of our adopted ROI, implies an expected number of background atmospheric neutrinos, which in turn implies a minimum number of blazar-associated neutrinos which would have to be present to yield a $>3\sigma$ detection assuming zero detected atmospheric neutrinos. Our optimization is as follows: We select the flux threshold that maximizes the ratio of the integrated TeV fluence to the number of neutrinos needed for $>3\sigma$ detection.

Our prior expectation was that this optimization would yield, for the optimal flux threshold, multiple disjoint temporal acceptance windows across the brightest emission periods of several distinct blazars. In fact, however, when applied to the data for all six blazars, the optimal flux threshold yields acceptance windows totalling ≈ 46 days from Mrk 421 only, which is often the brightest blazar in the sample. These temporal windows of interest are shown in Fig. 2.2 and presented in Table 2.4. The temporal window includes 11% of the IC40 live time, and close to 18% of the live time for Mrk 421, which is close to the 3σ duty cycle calculated in [108]. Though this is the optimal window as defined by our analysis, it completely omits the five remaining blazars. So we choose to carry out two distinct searches for excess neutrino emission: First, a Mrk 421-only analysis (the optimal search, according to our original search criteria); and second, a Mrk 421-exclusive analysis using the light curves from the five other blazars. Optimization of the flux threshold

for the second analysis results in a total ≈ 52 day-long acceptance window including some coverage of each of the five remaining blazars, as shown in Fig. 2.3 and presented in Table 2.4.

Blazar Times of Interest		
Name	T_{start} (d)	T_{stop} (d)
1ES 0806+524	2.138	2.221
1ES 1218+304	268.058	269.266
	276.516	277.766
	293.766	295.141
	299.766	302.849
	304.683	305.433
	318.849	319.891
	325.641	327.766
	328.599	330.099
	345.016	345.641
3C66A	179.687	180.437
	185.104	188.937
	204.979	205.937
	210.854	213.687
	227.729	230.312
Mrk 421	0.116	1.532
	3.199	3.532
	17.324	21.366
	22.616	28.241
	29.157	30.949
	31.449	33.032
	48.449	50.741
	53.116	53.616
	54.699	55.866
	56.866	57.532
	58.949	61.157
	267.574	267.824

	288.741	289.991
	293.699	295.199
	298.074	298.824
	299.907	302.866
	303.741	304.449
	316.782	317.949
	318.824	320.657
	321.949	322.616
	325.991	326.907
	330.657	331.991
	343.574	346.324
	348.241	348.449
	350.866	351.199
	358.241	358.657
	371.741	372.657
	375.199	376.991
	379.032	379.532
	385.574	386.782
	401.616	402.199
Mrk 501	−0.961	0.830
	3.247	8.289
	18.705	25.789
	35.872	38.83
	343.872	347.122
	350.955	353.914
W Comae	4.494	5.036
	61.411	64.327

Table 2.4: Start and stop times (T_{start} , T_{stop}) for the temporal windows of interest are reported in days since the start of the IC40 run (i.e., MJD−54562). Temporal windows for two distinct searches are reported, one using Mrk 421 data only (Mrk 421-only) and one using only data from other blazars (Mrk 421-exclusive); see text for details.

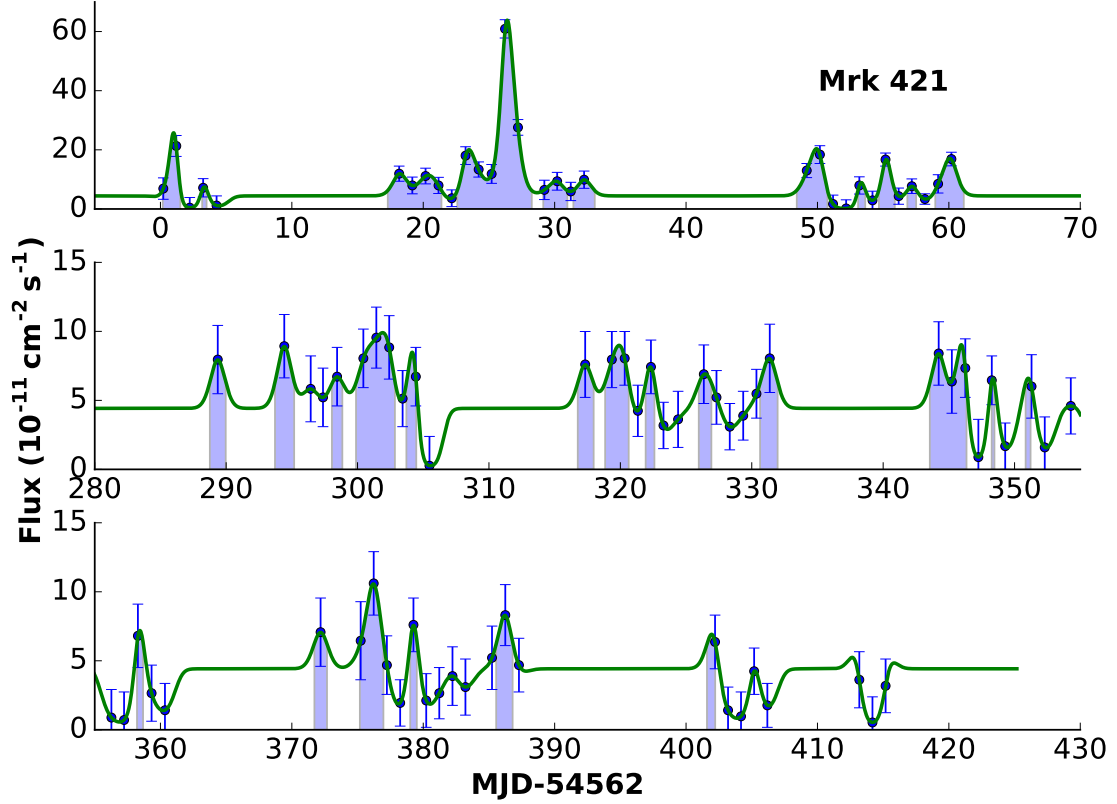


Figure 2.2: Times of interest for Mrk 421 (shaded intervals). These times were selected in our initial optimization as the most sensitive search for associated neutrinos (Sec. 2.2.3). The selection includes 45.6 days with a total TeV γ -ray fluence of 4.1×10^{-4} photons cm⁻² and yields an expected background of 1.03 neutrinos.

2.2.4 Monte Carlo Simulations

We carry out Monte Carlo (MC) simulations to confirm our understanding of the atmospheric neutrino background. Each simulation begins by shuffling the complete list of IC40 neutrino detections, associating each original neutrino ν_i with another randomly-selected neutrino ν_j . In our MC scrambling, the neutrino ν_i retains its original declination and receives the original arrival time of neutrino ν_j , with its new right ascension derived by adjusting the original right ascension for the difference in local sidereal time between the original and new arrival times. In this way, each neutrino retains its original arrival direction with respect to the physical IC40 array, preserving any structure present in detector coordinates. Applying this procedure leads to a new scrambled dataset that retains the original integrated

distributions in time, declination, and arrival direction, while scrambling neutrino positions quasi-randomly in right ascension.

We produce 10,000 MC datasets and search for neutrinos arriving during the predefined ROIs and temporal windows. We then use these results to verify the expected arrival rate and assumption of Poisson behavior for the background atmospheric neutrinos.

Our Mrk 421-only search uses a flux cutoff accepting each lightcurve point brighter than $6.22 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, accounting for 45.6 days in total. The integrated fluence during this temporal window is $4.1 \times 10^{-4} \text{ cm}^{-2}$. From the IC40 data, an average of 1.03 neutrinos should arrive within the 2.3° -radius ROI during the 45.6 days. The 10,000 MC data sets show a Poisson background with a mean of 1.03 and a variance of 1.01. Thus, a $>3\sigma$ detection would require ≥ 5 neutrinos during the temporal acceptance window.

Our Mrk 421-exclusive search uses a flux cutoff of $1.88 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, with 51.6 days above this level, and an integrated fluence of $1.4 \times 10^{-4} \text{ cm}^{-2}$. IC40 data predicts the ROI should see an average of 1.17 neutrinos during the temporal windows. The 10,000 scrambles demonstrated a Poisson background with a mean and a variance of 1.10. Detection at $>3\sigma$ would hence require ≥ 6 neutrinos.

2.3 Results and Discussion

In order to derive physical constraints from our observations, we need to derive expected IC40 neutrino detection rates from the observed TeV γ -ray fluxes of the targeted blazars, using an appropriate model.

We adopt a standard lepto-hadronic model for this purpose. The measured TeV photon fluence for each blazar can be expressed as the integral of the differential spectrum:

$$\phi_i = \int_{\varepsilon_{\text{th}}}^{\varepsilon_2} \frac{N_0}{\varepsilon_\gamma^2} \left(\frac{\varepsilon_\gamma}{1 \text{ TeV}} \right)^{2-\Gamma_{\text{obs},i}} d\varepsilon_\gamma \quad (2.12)$$

where ε_γ is the γ -ray energy, ε_{th} is the threshold energy for that blazar, $\varepsilon_2 = 30 \text{ TeV}$ is the upper energy limit of VERITAS, $\Gamma_{\text{obs},i}$ is the observed power-law photon index for each blazar (Table 2.1), and N_0 is a normalization constant. Once N_0 is known for each blazar, the differential spectrum for neutrinos can be calculated. The number of expected neutrinos is the integral of the neutrino spectrum times

the effective area of IC40:

$$N_{\text{exp},i} = \int_{\varepsilon_1}^{\varepsilon_2} \frac{N_0}{4 \varepsilon_\nu^2} \left(\frac{\varepsilon_\nu}{0.5 \text{ TeV}} \right)^{2-\Gamma_{\text{src},i}} A_{\text{IC40}}(\varepsilon_\nu) d\varepsilon_\nu \quad (2.13)$$

where N_0 is a constant calculated in Eq. 2.12, ε_ν is the neutrino energy, ε_1 and ε_2 bound the calculation over the IC40 effective area $A_{\text{IC40}}(\varepsilon_\nu)$ as presented in [112], and $\Gamma_{\text{src},i}$ is the blazar spectral index after correcting for γ -ray absorption by the extragalactic background light using the models of [22] and [21] (Table 2.1). If $N_{\text{exp},i}$ is larger than the calculated upper limit, non-observation will constrain the fraction of γ -rays produced in lepto-hadronic interactions.

Our Mrk 421-only search yields no neutrinos during the temporal acceptance windows, while ≥ 5 were required for a detection claim. Our non-detection implies an upper limit of 1.27 (2.30 in total, minus 1.03 background) flux-associated neutrinos from Mrk 421 at 90%-confidence. If the TeV γ -ray flux from Mrk 421 during our identified periods of excess and flaring emission were entirely due to hadronic interactions, this would give 0.79 neutrinos. As this is smaller than the upper limit, we cannot constrain the hadronic process for Mrk 421; the relevant figure of merit is $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} < 1.6$.

Our Mrk 421-exclusive search yields one neutrino during the joint acceptance windows for the remaining five blazars; ≥ 6 neutrinos were required in this case for $>3\sigma$ detection. The neutrino arrives from the Mrk 501-specific ROI with an angular offset of 1.5° at MJD 54562.71 (time 0.71 in Figure 2.3 and Table 2.4). With one detected neutrino, we have an upper limit of 2.79 (3.89 total minus 1.10 background) neutrinos at 90%-confidence. Applying our hadronic interaction model to the identified periods of excess and flaring emission from these blazars leads to an expectation of 0.02 neutrinos over the joint acceptance windows with $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} < 140$ as the figure of merit. Note that while the integrated γ -ray fluence from Mrk 421 was roughly three times larger than the fluence from the other five blazars, its expected neutrino fluence was nearly 35 times larger. This is due to the hardness of Mrk 421's spectrum, which yields more neutrinos at higher energies where IceCube is more sensitive. The five other blazars (excepting 3C 66A, which had a much smaller integrated fluence) had softer spectra, yielding more neutrinos at lower energies where IceCube is less sensitive.

A previously published IC40 analysis [100] for Mrk 421 identified and ob-

served two neutrinos, consistent with background, with theoretical neutrino flux calculations yielding a best fit of 2.6 signal events, producing a differential flux limit of $dN/dE \leq 11.71 \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ for muon neutrinos. Additional searches [102] continue to show no correlated neutrinos. Independent analysis of Mrk 421 using γ -ray data from Fermi [113] showed that focusing on blazar flares may be optimal for discovery of correlated $>\text{PeV}$ neutrinos.

While our limits do not suffice to constrain our chosen hadronic interaction model for these blazars, the existence of an additional seven years’ worth of IceCube data, all taken with greater-volume configurations of the detector (including five years’ worth of data using all 86 strings), is encouraging. This should amount to roughly 14 times the effective integration of one year of IC40 data and, in the event of a nondetection, reduce the figure of merit by a factor of ≈ 3.8 . Hence, unless the variability and flaring properties of Mrk 421 and the remaining blazars during IC40 were in some way unusual, we anticipate being able to constrain hadronic models for Mrk 421 with data already in hand at both IceCube and VERITAS, with the anticipated figure of merit (in the case of nondetection) being $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} \lesssim 0.4$. Similarly but less conclusively, we anticipate being able to make a much more sensitive (although potentially, not yet physically constraining) search for excess flux-associated neutrinos from Mrk 501 and the other northern blazars, with $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} \lesssim 32$ as the anticipated figure of merit in the case of non-detection.

2.4 Conclusions

We defined a search for TeV γ -ray flux-correlated neutrinos from six bright northern blazars. The search used publicly-available neutrino data from the IceCube 40-string “IC40” observing run and public TeV γ -ray data from VERITAS. Interpolating the VERITAS light curves with a Gaussian process regression, we isolated temporal windows of interest for two searches: a Mrk 421-only search and a Mrk 421-exclusive search. We confirmed the Poisson behavior of the near-isotropic background with a Monte Carlo simulation using scrambled neutrino datasets.

Our Mrk 421-only search found zero neutrinos compared to a background expectation of 1.03 neutrinos and a requirement of ≥ 5 neutrinos for a $>3\sigma$ detection claim, while our Mrk 421-exclusive search found one neutrino compared to a

background expectation of 1.1 neutrinos and a requirement of ≥ 6 neutrinos for a $>3\sigma$ detection claim.

Both findings are consistent with background expectations, yet they are also consistent with expectations from hadronic blazar models. These non-detections place upper limits of 1.27 neutrinos for Mrk 421 (with a figure of merit $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} < 1.6$) and 2.79 neutrinos for the five other blazars (figure of merit $N_{\nu,\text{obs}}/N_{\nu,\text{exp}} < 140$). These limits are not strong enough to place constraints on the hadronic process for any of the blazars, though the figure of merit for Mrk 421 is close to being physically constraining. However, this search was limited to only the IC40 dataset. The methods developed in Sec. 2.2.3 work equally well for any additional existing data. An interesting future project would be to extend this search to more recent public datasets.

Our analysis showed that Mrk 421 dominates the TeV γ -ray flux from the northern blazars. Mrk 421 is currently monitored in the TeV on a daily or near-daily basis by the High-Altitude Water Cherenkov (HAWC; [114]) and First Cherenkov Telescope using a G-APD Camera for TeV Gamma-ray Astronomy (FACT; [42]) facilities. Since IceCube has been operating at full strength since 2011, it may be fruitful to perform a flux-correlated search on Mrk 421, as even a non-detection will reduce the figure of merit, potentially to a physically constraining value.

As mentioned in Sec. 2.1, TeV orphan flares are a particular candidate for the dominance of hadronic acceleration processes. Using hard X-ray data from the Swift BAT all-sky monitor [115] in tandem with HAWC, FACT, and VERITAS data, TeV γ -ray orphan flares could be isolated from other periods of high TeV flux and used for a distinct, focused search for associated neutrinos.

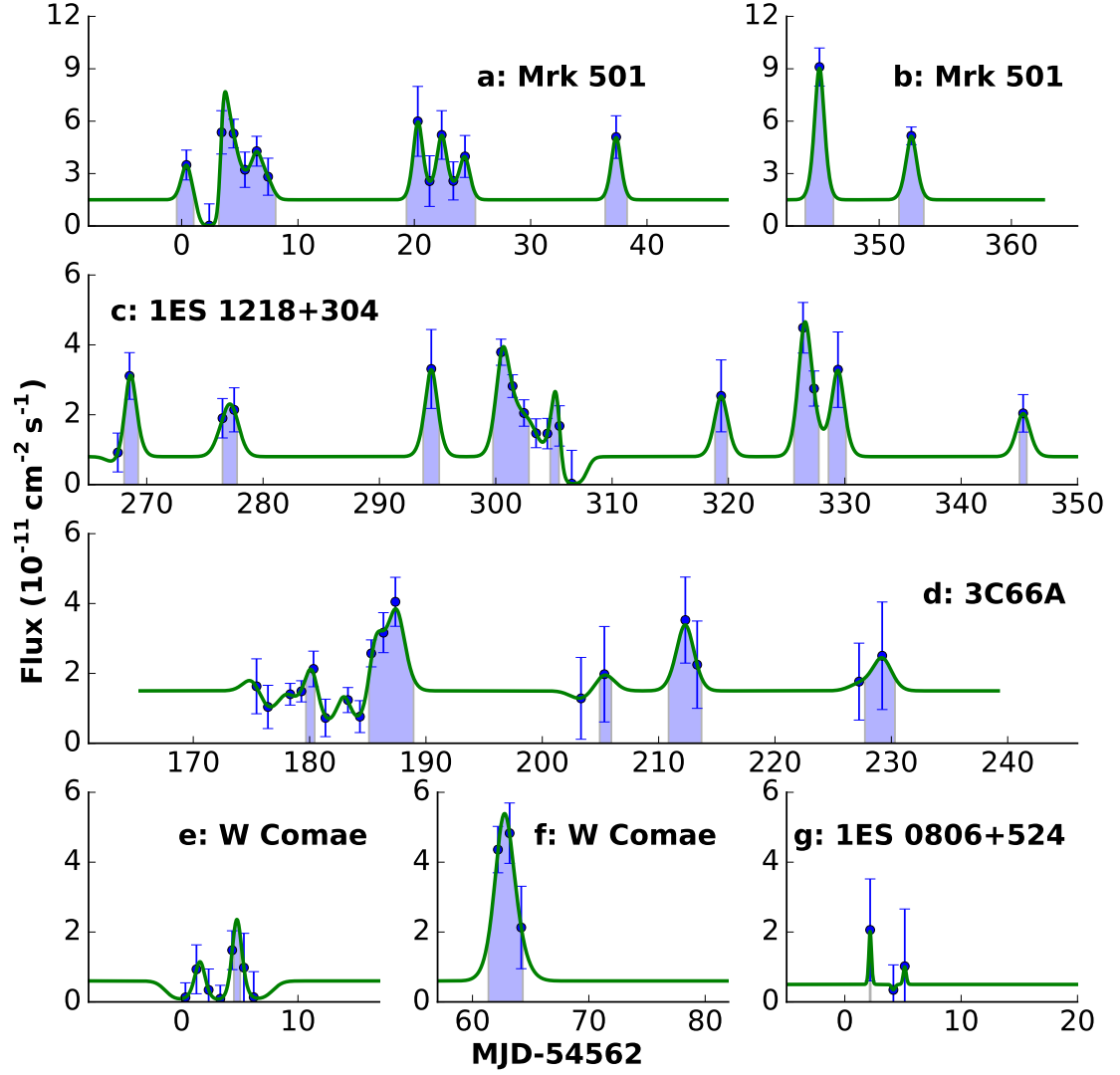


Figure 2.3: Times of interest for Mrk 501, 1ES 1218+304, 3C 66A, W Comae, and 1ES 0806+524 resulting from our Mrk 421-exclusive search (shaded intervals). These times were selected as the most sensitive search for associated neutrinos that excludes data from Mrk 421 (Sec. 2.2.3). The selection includes 51.6 days with a total γ -ray fluence of $1.4 \times 10^{-4} \text{ photons cm}^{-2}$ and yields an expected background of 1.17 neutrinos.

Chapter 3

Search for Fermi-LAT counterparts to IceCube neutrinos¹²

We present results of an archival coincidence analysis between *Fermi* Large Area Telescope (LAT) gamma-ray data and public neutrino data from the IceCube neutrino observatory’s 40-string (IC40) and 59-string (IC59) observing runs. Our analysis has the potential to detect either a statistical excess of neutrino + gamma-ray ($\nu+\gamma$) emitting transients or, alternatively, individual high gamma-multiplicity events, as might be produced by a neutrino observed by IceCube coinciding with a LAT-detected gamma-ray burst. Dividing the neutrino data into three datasets by hemisphere (IC40, IC59-North, and IC59-South), we construct uncorrelated null distributions by Monte Carlo scrambling of the neutrino datasets. We carry out signal-injection studies against these null distributions, demonstrating sensitivity to individual $\nu+\gamma$ events of sufficient gamma-ray multiplicity, and to $\nu+\gamma$ transient populations responsible for $>13\%$ (IC40), $>9\%$ (IC59-North), or $>8\%$ (IC59-South) of the gamma-coincident neutrinos observed in these datasets, respectively. Analyzing the unscrambled neutrino data, we identify no individual high-significance neutrino + high gamma-multiplicity events, and no significant deviations from the test statistic null distributions. However, we observe a similar and unexpected

¹This paper has been published in the *Astrophysical Journal* as: C. F. Turley, D. B. Fox, K. Murase, & 14 others, *The Astrophysical Journal*, Volume 833, 117 (arxiv:1608.08983)

²Python scripts used in this analysis can be found at <https://github.com/cft114/fermice>

pattern in the IC59-North and IC59-South residual distributions that we conclude reflects a possible correlation ($p = 7.0\%$) between IC59 neutrino positions and persistently bright portions of the *Fermi* gamma-ray sky. This possible correlation should be readily testable using eight years of further data already collected by IceCube. We are currently working with Astrophysical Multimessenger Observatory Network (AMON) partner facilities to generate low-latency $\nu+\gamma$ alerts from *Fermi* LAT gamma-ray and IceCube and ANTARES neutrino data and distribute these in real time to AMON follow-up partners.

3.1 Introduction

The IceCube Collaboration has detected the first high-energy neutrinos of cosmic origin [49, 50]. Unlike the atmospheric neutrinos that dominate the observed events at lower energies, the cosmic neutrinos have a harder spectrum, with a current best-fit neutrino power-law index of $\Gamma_\nu = -2.19$ [116]. The sky distribution of high-likelihood cosmic neutrinos is consistent with isotropy, and indeed, no high-confidence counterparts have been identified for any of these neutrinos [102, 117]; however, we note the recent suggestive coincidence between the “Extremely High Energy” muon neutrino IceCube-170922A [97] and a bright and extended GeV-flaring episode of the blazar TXS 0506+056 [27].

In addition to blazars, possible cosmic neutrino source populations include star-forming and starburst galaxies, galaxy groups and clusters, other types of active galactic nuclei, supernovae, and gamma-ray bursts (see [57] for a recent review).

One possible approach to revealing the nature of the source population(s) is to take advantage of the likely-greater number of cosmic neutrinos that must exist within the IceCube dataset at lower energies. For example, using the most recent power-law index and normalization estimates [116], and integrating down to $\varepsilon_\nu \approx 1$ TeV using the facility’s declination- and energy-dependent effective area [102], we find that IceCube should be detecting $r_{\text{cosmic}} \approx 120$ neutrinos of cosmic origin per year, all-sky, below the $\varepsilon_\nu \approx 60$ TeV threshold for individual likely-cosmic events (e.g., those selected as IceCube High Energy Starting Events). If the cosmic neutrino spectrum softens (or becomes dominated by a distinct, softer component) within $1 \text{ TeV} \lesssim \varepsilon_\nu \lesssim 60 \text{ TeV}$ then the number of cosmic neutrinos in this range

could be substantially greater. However, since these lower-energy cosmic neutrinos are individually indistinguishable from the atmospheric neutrino background, some strategy must be employed to identify them before they can be used to study their sources.

One such strategy is illustrated by the IceCube Collaboration’s all-sky and catalog-based point-source searches [102, 117, 118]. These strategies are likely to be optimal in cases where the neutrino sources are persistent, roughly constant, and drawn (respectively) from either unknown or known/anticipated source populations.

Alternatively, for transient or highly-variable source populations, we can take advantage of the neutrino timing and localization to attempt to identify electromagnetic or other non-neutrino counterparts. Any such discovery would have immediate implications for the nature of the sources, whether or not a host galaxy or long-lived counterpart could also be identified.

As reviewed by [57], numerous theoretical models predict the co-production of cosmic neutrinos with prompt and luminous electromagnetic signals. In most such models, protons or other nuclei are accelerated to high energies, often in relativistic jets. Interactions of these accelerated particles with ambient matter or radiation yield copious quantities of pions, with gamma-rays resulting from decay of the π^0 component, and neutrinos from decays of the co-produced $\pi^\pm$. For example, gamma-ray bursts (GRBs) were long considered potential sources of jointly-detected high-energy neutrinos and gamma-rays (e.g., [60, 119, 120]). Although GRBs are now ruled out as the dominant source of IceCube cosmic neutrinos by coincidence studies [121], it remains possible that GRBs supply a fraction of the cosmic neutrinos.

Particular sub-classes of GRBs including “choked jet” events could still provide a partial or even dominant contribution to the cosmic neutrinos [122–124]. Other promising neutrino + gamma-ray ($\nu+\gamma$) transients include luminous supernovae [125], blazar flares (e.g., [126, 127]), and tidal disruption events (e.g., [128–130]).

In this context, the *Fermi* satellite’s Large Area Telescope (LAT; [31]) offers a highly complementary dataset for cross-reference with IceCube neutrino detections. Operating efficiently over the $100\text{ MeV} \lesssim \varepsilon_\gamma \lesssim 300\text{ GeV}$ energy range, the LAT provides instantaneous coverage of roughly 20% of the sky and regular full-sky coverage (under normal operations) every three hours. Its energy range, angular and energy resolution, low background, and sensitivity yield a high-purity sample of

high-energy photons that is almost immediately available (median delay of 5 hours) for real-time cross-correlation with IceCube neutrinos.

The high suitability of the *Fermi* LAT and IceCube neutrino datasets for joint analysis prompted our previous archival search for subthreshold neutrino + gamma-ray ($\nu+\gamma$) emitting sources in the IceCube 40-string (hereafter IC40) public neutrino dataset [131]. This work, carried out under the auspices of the Astrophysical Multimessenger Observatory Network (AMON³; [132, 133]), calculated pseudo-likelihoods for all candidate $\nu+\gamma$ pairs and compared the cumulative distribution of this test statistic to a null distribution derived from scrambled datasets (using the Anderson-Darling test; [134]). The sensitivity of the analysis was calibrated via signal injection, allowing a rough mapping of Anderson-Darling p -value to the number of injected pairs. While the observed test statistic distribution, and the p -value of 4% versus the null distribution, were consistent with the presence of ≈ 70 signal pairs out of 2138 observed coincidences, subsequent vetting tests provided no reason to suspect the presence of a cosmic signal.

The present work can be considered, in part, a continuation and extension of this earlier investigation. First, we revisit the IC40 analysis using the new *Fermi* Pass 8 reconstruction and extend the analysis to the IceCube public 59-string dataset (hereafter IC59), which covers both Northern and Southern hemispheres. Second, we extend the previous test statistic to incorporate the possibility of single neutrino + multiple gamma-ray coincidences, which provides an unbounded statistic suitable for identification of individual high-significance events. Finally, we have divided the *Fermi* bandpass into three energy ranges in our background calculations, which we expect will improve the sensitivity of the analysis for relatively hard-spectrum transients.

3.2 Datasets

This analysis was performed using available IceCube and *Fermi* LAT public data over the period of temporal overlap between the two observatories. The relevant *Fermi* data were the Pass 8 photon reconstructions available from the LAT FTP server⁴. These photon events were filtered using the Fermi Science Tools, keeping

³AMON website: <http://www.amon.psu.edu/>

⁴LAT data located at <ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/photon/>

only photons with a zenith angle smaller than 90° , energies between 100 MeV and 300 GeV, detected during good time intervals (GTI) provided in the LAT satellite files⁵.

The point spread function (PSF) of the LAT is given by a double King function with the parameters depending on the photon energy, conversion type, and incident angle with respect to the LAT boresight [135]. At lower energies (hundreds of MeV), the angular uncertainty can be several degrees, especially for off-axis photons. At $\varepsilon_\gamma > 1$ GeV the average uncertainty drops below 1° , and at $\varepsilon_\gamma \gtrsim 100$ GeV angular uncertainties are better than 0.1° .

Public data from the 40-string (IC40⁶) and 59-string (IC59⁷) configurations of IceCube were used [100, 136]. IC40 ran from April 2008 to May 2009 and contains 12,876 neutrinos over the northern hemisphere. This corresponds to Weeks 9 to 50 of the *Fermi* mission, which has public data available from 4 August 2008. Applying our cuts to the *Fermi* data yield 7.2 million northern-hemisphere photons during IC40, and reduces the IC40 neutrino dataset to 8871 events over the approximately nine-month period of joint operations. IC59 ran from May 2009 to May 2010 and contains 107,569 neutrino events; this period corresponds to weeks 50 to 104 of the *Fermi* mission, and yields 19.4 million photon events passing our cuts. Fig. 3.1 shows neutrino sky maps for IC40 and IC59 in equatorial coordinates.

We adopt a Gaussian form for the IceCube PSF. For IC40, the angular uncertainty for each neutrino is set at 0.7° [103]. Angular uncertainties are provided for the IC59 events, and we use the reported angular uncertainty for each event.

A `healpix` [137] map of resolution 8 (NSide=256, mean spacing of 0.23°) was constructed using the entire *Fermi* data set (weeks 9 to 495 at the time of creation) with the same photon selection criteria used for IC40 and IC59. Using the `HEASoft` [138] software, events were binned into three logarithmically uniform energy bins. Each energy bin was then further binned into a `healpix` map, with the live time calculated via a Monte Carlo simulation. Dividing the counts map by the live time map produced the *Fermi* exposure map. Zero-valued (low-exposure) pixels were replaced by the average of the nearest neighbor pixels. Our three resulting all-sky *Fermi* maps are shown in Fig. 4.2. Due to the additional reconstruction

⁵*Fermi* satellite files located at <ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/spacecraft/>

⁶IC40 data available at <http://icecube.wisc.edu/science/data/ic40>

⁷IC59 data available at <http://icecube.wisc.edu/science/data/IC59-point-source>

uncertainty in the *Fermi* PSF for high-inclination events (inclination angle greater than 60°), three additional maps were generated by further averaging all pixels with their nearest neighbors.

3.3 Methods

3.3.1 Significance Calculation

Our analysis begins by filtering for coincidences between an individual neutrino event and all photons within 5° angular separation and ± 100 s arrival time, as per [131]. The angular acceptance cut corresponds approximately to the maximum 1σ radial uncertainty for *Fermi* LAT photons satisfying our event selection. The temporal acceptance window is chosen to include $\approx 90\%$ of classical gamma-ray bursts [139]. For each coincidence, a pseudo-log-likelihood test statistic, λ , is calculated as follows:

$$\lambda = 2 \ln \frac{(P_{\gamma 1}(\vec{x})P_{\gamma 2}(\vec{x})\dots P_{\gamma n}(\vec{x}))n!(P_\nu(\vec{x}))}{B_1(\vec{x}, E_1, \theta_1)B_2(\vec{x}, E_2, \theta_2)\dots B_n(\vec{x}, E_n, \theta_n)} \quad (3.1)$$

where n is the number of photons coincident with the neutrino, $P_{\gamma i}(\vec{x})$ is the energy-dependent point spread function (PSF) of the LAT at the best fit position, $\vec{x}$, and $P_\nu(\vec{x})$ is the IceCube PSF at the best fit position. Both PSFs have units of probability per square degree. The $B_i(\vec{x}, E_i, \theta_i)$ are the LAT background terms in units of photons per square meter (approximating the *Fermi* effective area) per 200 s (our temporal window) per square degree for each γ_i , given its energy E_i and inclination angle θ_i . In this metric, larger values of λ indicate a higher-likelihood correlated multiplet. This pseudo-log-likelihood statistic is the natural extension of the [131] test statistic to multi-photon coincidences, via the Poisson likelihood of generating an n -fold coincidence from background; in the prior approach, each $\nu+\gamma$ coincidence was treated separately.

The best fit position $\vec{x}$ is determined as the location of maximal PSF overlap. As the overlap of a double King function with a Gaussian function cannot be solved analytically, the best-fit position is found numerically. For single neutrino + multiple photon coincidences, the event photon multiplicity is determined by optimization: We compare the λ value at maximum multiplicity to that which would result if the

photon with the lowest PSF density at the best-fit position were excluded (after recalculating the best-fit position and λ), and iteratively exclude photons until λ no longer increases.

3.3.2 Analysis Definition

We generate a set of 10,000 Monte Carlo scrambled versions of each of our three datasets in order to characterize their null distributions and define analysis thresholds, prior to performing any analysis of the unscrambled datasets. Our scrambling procedure begins by shuffling the full set of neutrino detections, associating each original neutrino ν_i with another randomly selected neutrino ν_j . Each neutrino ν_i retains its original declination and angular error and receives the original arrival time of neutrino ν_j , with its new right ascension derived by adjusting the original right ascension for the difference in local sidereal time between the original and new arrival times, the same approach as in [140]. *Fermi* LAT photons are not scrambled as the LAT data contains known sources and extensive (complex) structure. Coincidence analysis is carried out for each scrambled dataset and λ values are calculated for the resulting $\nu+\gamma$ coincidences via Eq. 3.1.

This analysis presents two discovery scenarios. First, since our test statistic λ is unbounded, the null distribution provides us with threshold values which can be used to identify individually-significant coincidences and estimate their false alarm rates. We define two such thresholds, $\lambda_{\times 10}$, the value exceeded (one or more times) in 1 of 10 scrambled datasets, and $\lambda_{\times 100}$, the value exceeded in 1 of 100 scrambled datasets. For analyses treating a year of observations, these two thresholds would correspond to events with false alarm rates of 1 decade⁻¹ and 1 century⁻¹, respectively.

Under this approach (and without accounting for the trials factor, see below), observation of a single event above $\lambda_{\times 100}$, or two events above $\lambda_{\times 10}$, would constitute evidence of joint $\nu+\gamma$ emitting sources, while observation of two events above $\lambda_{\times 100}$ or four events above $\lambda_{\times 10}$ would enable a discovery claim.

In the absence of any individually-significant events, there remains the opportunity for discovery of a subthreshold population of $\nu+\gamma$ emitting sources. By design, true cosmic coincidences are biased to higher λ values (Fig. 3.3), and a population containing a sufficient number of such signal events can be distinguished from the

null distribution using the Anderson-Darling k -sample test. The k -sample test is used to establish mutual consistency among k observed datasets ($k = 2$ for a two-sample test), testing against the null hypothesis that they are drawn from a single underlying distribution.

Given our choice to make two statistical tests on each of three predefined datasets (IC40, IC59-North, and IC59-South), we apply an $N_{\text{trials}} = 6$ trials penalty to our unscrambled analyses (Sec. 3.4.1).

3.3.3 Signal Injection

To estimate our sensitivity to cosmic $\nu + \gamma$ emitting source populations, we generate signal-like events and inject these into scrambled datasets, comparing the results to the null distribution.

Since we test for γ multiplicity, as part of this process we must adopt a procedure for determining whether each injection is a γ singlet, doublet, or $n_\gamma > 2$ multiplet. To determine the appropriate n_γ distribution, we assume a population of sources emitting one neutrino, with associated photon fluence distributed according to $N(S \geq S_0) \propto S_0^{-3/2}$, where S_0 is a threshold photon fluence and $N(S \geq S_0)$ is the number of events observed with fluences greater than or equal to this threshold; we note that an $S_0^{-3/2}$ dependance is expected for source populations of arbitrary luminosity function distributed in Euclidean space.

Adopting a minimum considered fluence of $S_{\text{min}} = 0.001$ photons, and inverting this relation, we generate the expectation value for the multiplicity of any event as $\langle n_\gamma \rangle = S_{\text{min}} u^{-2/3}$, where u is a uniform random variable. We then generate the observed n_γ by drawing randomly from the Poisson distribution with expectation value $\langle n_\gamma \rangle$. Excluding zero-multiplicity events, we are left with the following n_γ distribution: 93% singlet, 4.8% doublet, 1.1% triplet, 0.5% quadruplet, 0.3% quintuplet, 0.2% sextuplet, and 0.1% septuplet (the highest multiplicity we allow). As an aside, we note that this is (approximately) the unique and universal distribution expected to arise in these cases, for extragalactic source populations extending to modest redshift ($z \lesssim 1$) with weak evolution, and thus distributed in near-Euclidean space.

A signal event of photon multiplicity n_γ is generated by centering the PSF for n_γ LAT photons and an IceCube neutrino at the origin. The neutrino localization

uncertainty is drawn from the full set of IceCube neutrino uncertainties, while the inclination angles and conversion types of the photons are drawn from the full set of these distributions within the *Fermi* dataset. Photon energies are drawn from a power law with a photon index $\Gamma = -2$. The photons and the neutrino are placed randomly according to their respective PSFs. A random sky position is then chosen as the best fit position for this coincidence, and a λ value is calculated following the methods of Sec. 3.3. Since the λ calculation involves maximizing λ by exclusion of outlying photons, many events end up with some of the injected photons excluded. Cumulative distributions for the null and signal-only distributions are shown in Fig. 3.3.

To calculate the sensitivity of our analysis, we inject an increasing number of signal events n_{inj} into a scrambled (null) distribution and compare the signal-injected and null λ distributions using the Anderson-Darling k -sample test. We carry out 10,000 trials for each selected value of n_{inj} and plot the mean resulting p -value against n_{inj} , for each of our datasets, in Fig. 3.4. In this way we estimate the threshold value of n_{inj} that is required to yield a statistically-significant deviation from the null distribution for each of the datasets ($n_{\text{inj},1\%}$ and $n_{\text{inj},0.1\%}$ columns in Table 3.1).

3.3.4 Analysis Sensitivity and Expectations

Carrying out the scrambled analysis on the IC40 and IC59 data produces the null λ distributions shown in Fig. 3.3. Key statistics from these analyses are summarized in Table 3.1. Most of the simulated events with $\lambda > \lambda_{\times 100}$ in IC59-North scrambled runs result from a scrambled neutrino landing in near coincidence with one of two GRBs detected by the LAT during our period of observation. GRB 090902B [141] placed over 200 photons on the LAT, giving a maximum $\lambda = 2560.2$ in a 218-photon coincidence. GRB 100414A [142] placed over 20 photons on the LAT and yields a maximum $\lambda = 91.2$ in a 10-photon coincidence. Excluding all coincidences with either of these GRBs would yield a threshold of $\lambda_{\times 100} = 35$ for the IC59-North data, rather than the GRB-inclusive value of $\lambda_{\times 100} = 49.0$.

Given the number of signal-like $\nu + \gamma$ required to yield a $p < 1\%$ deviation in the Anderson-Darling k -sample test, we estimate our analysis would detect >150 source-like $\nu + \gamma$ coincidences from IC40 ($>13\%$ of the total number of coincidences

Coincidence Search Results

Dataset	$\langle n_{\nu+\gamma} \rangle$	Thresholds				Observed Values		
		$\lambda_{\times 10}$	$\lambda_{\times 100}$	$n_{\text{inj},1\%}$	$n_{\text{inj},0.1\%}$	$n_{\nu+\gamma}$	λ_{max}	$p_{\text{A-D}}$
IC40	1090 ± 30	23.9	27.2	150	210	1128	20.3	63%
IC59-North	4970 ± 65	26.5	49.0	440	570	5046	17.8	16.8%
IC59-South	7072 ± 76	26.8	31.5	565	740	7080	24.4	3.8%

Table 3.1: $\langle n_{\nu+\gamma} \rangle$ is the expected number of neutrinos observed in coincidence with one or more gamma-rays, as derived from 10,000 Monte Carlo scrambled realizations of each dataset. $\lambda_{\times 10}$ and $\lambda_{\times 100}$ are the thresholds above which a coincidence is only observed once per 10 or 100 scrambled datasets, respectively. $n_{\text{inj},1\%}$ and $n_{\text{inj},0.1\%}$ are the number of injected signal events required in simulations to give an Anderson-Darling test statistic of $p < 1\%$ and $p < 0.1\%$, respectively, by comparison to the null distributions for each dataset. $n_{\nu+\gamma}$ is the number of neutrinos observed in coincidence with one or more gamma-rays in the unscrambled data, λ_{max} is the maximum observed λ for each dataset, and $p_{\text{A-D}}$ is the value of the Anderson-Darling test statistic from comparison of the observed λ distribution to its associated null distribution.

in IC40), >440 from IC59-North ($>9\%$), and >565 from IC59-South($>9\%$); see Table 3.1.

3.4 Results

3.4.1 Coincidence Search

Applying our analysis to the three unscrambled neutrino datasets yields the results summarized in Table 3.1. Fig. 3.5, Fig. 3.6 and Fig. 3.7 show the λ distributions for the unscrambled data for IC40, IC59-North, and IC59-South, along with the null distributions, and distributions for signal injections yielding p -values from the Anderson-Darling test of 1% and 0.1%, respectively. All distributions are normalized to the number of coincidences $n_{\nu+\gamma}$ observed in the unscrambled data. No λ values were detected above the $\lambda_{\times 10}$ threshold in any of the analyses. Notably, as seen in Fig. 3.6 and Fig 3.7, the IC59-North and IC59-South data show an excess of lower λ values by comparison to the null distributions, unlike the excess of higher λ values expected from a signal population.

Given our six trials, a minimum observed single-trial $p = 3.8\%$ corresponds to

a trials-corrected value of $p_{\text{post}} = 20.7\%$, which is not significant. However, the similar scale and shape of the residual patterns for IC59-North and IC59-South lead us to seek out possible causes of these residual patterns. To illustrate this point, combining p -values from these two datasets (our most sensitive) by Fisher’s method gives a joint $p = 3.9\%$ (single trial) as the probability of generating two such large deviations by random chance.

We note that we have not conceived of any way for systematic effects to generate the IC59 residuals and low p -values, simply because any errors or simplifications in the analysis (which certainly exist) are replicated across all scrambled datasets. Rather, the only way to generate these effects (if they are not due to random statistical fluctuation) is via spatio-temporal correlation of neutrinos and gamma-rays. Such correlation would imply either cosmic sources, or at a minimum, correlated emission (e.g., enhancement toward the Galactic plane or Supergalactic plane) and hence, require structure in the neutrino sky which has not previously been observed.

We divide our further explorations into two approaches: First (Sec. 3.4.2), we further vet the IC59 data against our original hypothesis, to test for any evidence that short-duration ($\delta t < 100$ s) $\nu + \gamma$ transients are really present in the data. Second (Sec. 3.4.3), we test for longer-duration $\nu + \gamma$ spatio-temporal correlations that might have an effect on our original analysis.

3.4.2 IC59 Vetting

We vet the IC59 datasets to evaluate whether the low p -values and systematic trends in the residual λ distributions that we observe could be due to $\nu + \gamma$ transient sources, as per our original hypothesis, but below the sensitivity of those analyses. We exclude the IC40 dataset from these tests as it is less sensitive to the presence of cosmic sources (see Fig. 3.4 and Sec. 3.3.4).

Specifically, we check for systematic trends or anomalies in the spatial and temporal distributions of the neutrino-coincident photons that might account for the unexpected deviation to lower λ values. We test separately for deviations in the distributions of the photons’ angular and temporal separations from their coincident neutrino, for IC59-North and IC59-South.

With regards to the angular separation distributions, we note that a systematic

underestimation of IceCube neutrino localization uncertainties might cause suppressed λ values relative to simulations, due to the P_ν term in the pseudo-likelihood. In a similar vein, even if all neutrino and gamma-ray localization uncertainties are accurately characterized, a systematically softer spectrum for cosmic $\nu+\gamma$ sources ($\Gamma < -2$) would suppress λ values via the $P_{\gamma i}$ terms in the pseudo-likelihood, since higher-energy LAT photons are better localized.

We construct five-bin histograms of the angular separations of all neutrino-associated photons, with bin boundaries chosen to make the null distribution approximately flat (equal numbers of photons in each bin). We then calculate the χ^2 statistic for the unscrambled data compared to the (flat) null distribution.

Fig. 3.8 (note zero-suppressed y axis) presents our results. Observed IC59-North angular separations are consistent with the (flat) null distribution, exhibiting $\chi^2 = 8.238$ for 4 degrees of freedom ($p = 14.3\%$). IC59-South angular separations, by contrast, show a substantial deficit in the bin at $\delta\theta \approx 3^\circ$ (and modest excesses in the bins to either side), which results in $\chi^2 = 11.502$ for 4 degrees of freedom, giving $p = 4.2\%$. While this deviation is moderately surprising, the absence of any systematic trend to low or high separations suggests it is likely not responsible for the observed deviation in the λ distribution.

Here we note that a systematic trend to small angular separations would suggest the presence of $\nu+\gamma$ sources as per our test hypothesis, while a systematic trend to large angular separations would suggest the presence of $\nu+\gamma$ sources with underestimated localization uncertainties or soft gamma-ray spectra. Neither such trend is observed.

We execute a similar analysis of the temporal separations of coincident photons. In contrast to the angular separations, which are incorporated into our pseudo-likelihood calculation, temporal separations are not considered (apart from the predefined acceptance window), so this analysis serves as an independent test of our original hypothesis. For purposes of trials correction of any subsequent statistics, we therefore add two trials, giving $N_{\text{trials}} = 8$.

Fig. 3.9 (note zero-suppressed y axis) shows our results for temporal separations data in the two IC59 datasets. Neither dataset shows evidence for deviation from the expected flat distribution (illustrated using scrambled datasets), with χ^2 -derived p -values of $p = 73\%$ for IC59-North and $p = 53\%$ for IC59-South.

Examining the angular and timing separations of the neutrinos and coincident

photons at higher resolution thus provides no support for the presence of short-duration ($\delta t \lesssim 100$ s) $\nu+\gamma$ emitting cosmic sources as conceived in our original hypothesis. Since these are not seen, we move on to examine alternative models that might generate $\nu+\gamma$ spatio-temporal correlations in the data.

3.4.3 Tests for $\nu+\gamma$ Correlation

We carry out two tests for spatio-temporal correlations between the neutrino and gamma-ray datasets beyond our original ± 100 s temporal acceptance window.

First, a correlation between neutrino and photon positions on the sky, without any temporal correlation (i.e. in steady state) could suppress λ values relative to the null hypothesis, due to the B_i gamma-ray background terms in our pseudo-likelihood (Eq. 3.1).

To test for positional correlation, we first construct a single *Fermi* background map covering the full energy range. We then measure the background value at the location of every IceCube neutrino in unscrambled data and compute the average photon background for the neutrino map. This average is then compared to the average backgrounds from each of the 10,000 scrambled datasets. The scrambled datasets give an average background of $(1.90 \pm 0.015) \times 10^{-2}$ photons $\text{deg}^{-2} \text{m}^{-2}$ per 200 s for IC59-North and $(2.40 \pm 0.022) \times 10^{-2}$ photons $\text{deg}^{-2} \text{m}^{-2}$ per 200 s for IC59-South. The observed average backgrounds (in the same units) from unscrambled data are 1.91×10^{-2} ($+0.58\sigma$; $p = 28.1\%$) for IC59-North and 2.44×10^{-2} ($+1.67\sigma$; $p = 4.7\%$) for IC59-South. These observed values are presented in the context of the distributions from scrambled data in Fig. 3.10.

This analysis is not an independent test for the presence of $\nu+\gamma$ sources, but rather, an attempt to identify an underlying reason for the trend in λ residuals seen in Sec. 3.4.1. Since the p -value for the separate analyses, as well as their combination ($p = 7.0\%$ by Fisher’s method), are within a factor of two of the p -values from the corresponding λ distribution tests, this provides reason to interpret the latter result as (at least in part) due to the observed tendency of IC59 neutrinos to land on systematically brighter regions of the gamma-ray sky. We reiterate that while this tendency is present in the data, it is not sufficiently strong (in a statistical sense) to support an evidence claim.

As an alternative approach, we check for correlated $\nu+\gamma$ variability on time

scales beyond our predefined ± 100 -second temporal window but shorter than the full extent of the *Fermi* mission. To this end, for each neutrino in our scrambled IC59 datasets, we use the total *Fermi* mission background map to calculate the number of photons expected to arrive within 5° of the neutrino position and $\pm 50,000$ s of the neutrino arrival time (excluding the ± 100 s window used in the original analysis). We then count the number of photons arriving within this spatio-temporal window (again, summing results across our three *Fermi* energy bands). For each neutrino, the observed number of photons within the extended temporal window is expressed as a Poisson fluctuation on the number expected by normalizing against the full *Fermi* mission. We quantify the magnitude of this fluctuation as a p -value and find the equivalent number of σ for a Gaussian distribution, yielding a statistic that we call the local excursion E for that neutrino. The distribution of excursions from all neutrinos in unscrambled data can then be compared to expectations from scrambled data.

We perform the same two tests that we developed in our primary analysis above: First, we check for individual events that exhibit an unusually large excursion, exceeding either the 1 in 10 ($E_{\times 10}$) or 1 in 100 ($E_{\times 100}$) thresholds from scrambled data. Second, we compare the excursion distribution from unscrambled data to the null distribution from scrambled data using the Anderson-Darling k -sample test. Since this analysis involves two further independent tests of the two datasets, we add four trials for purposes of trials correction of any subsequent statistics, giving $N_{\text{trials}} = 12$.

Excursion thresholds for the two datasets are $E_{\times 10} = 614$ and $E_{\times 100} = 1285$ for IC59-North, and $E_{\times 10} = 333$ and $E_{\times 100} = 1075$ for IC59-South. As in our primary analysis, the highest-excursion events in the scrambled data are due to the two GRBs observed in the IC59-North data. Excluding these GRBs would give excursion thresholds of $E_{\times 10} = 575$ and $E_{\times 100} = 1102$ for IC59-North.

Analyzing the unscrambled IC59 datasets reveals no excursions above the $E_{\times 10}$ threshold for either dataset. Performing the Anderson-Darling test on the null and unscrambled distributions yields $p = 55\%$ for IC59-North and $p = 62\%$ for IC59-South. We therefore see no evidence for spatio-temporal correlation of the neutrinos and *Fermi* gamma-rays on the ~ 0.5 day timescale that we probed.

We conclude that the observed tendency of IC59 neutrinos to arrive from brighter portions of the *Fermi* gamma-ray sky, while potentially due to a statistical

fluctuation (single-trial $p = 7.0\%$ for the two hemispheres combined), is both intriguing in its own right and likely explains the systematic trends in λ residuals against scrambled datasets observed for both hemispheres in our original analysis (single-trial $p = 3.9\%$ for the two hemispheres combined). While this p -value cannot support an evidence or discovery claim in the context of our multistage analysis, it nonetheless points the way to interesting future analyses that could make use of eight further years of IceCube data from the 79-string and full-strength (86-string) arrays.

In particular, we note that it is a low-level (single neutrino) correlation between the neutrino and gamma-ray skies that has prompted current interest in the blazar TXS 0506+056 and its possible neutrino IceCube-170922A [27].

3.5 Conclusions

We have carried out an archival coincidence search for neutrino + gamma-ray emitting transients using publicly available *Fermi* LAT gamma-ray data and IceCube neutrino data from its 40-string and 59-string runs, incorporating *Fermi* data from the start of mission in Aug 2008 through May 2010. Our search was designed to be capable of identifying $\nu+\gamma$ transients either as individual high-significance single-neutrino events with high gamma-ray multiplicity, or as a population, via statistical comparison of the observed pseudo-likelihood distributions to those of uncorrelated (scrambled) datasets.

Using Monte Carlo simulations and signal injection, we demonstrated sensitivity to single-neutrino events of sufficient gamma-ray multiplicity. High-multiplicity gamma-ray clusters have been observed throughout the *Fermi* mission in coincidence with bright LAT-detected gamma-ray bursts, including two bursts occurring during our period of study, GRB 090902B (>200 photons; [141]) and GRB 100414A (>20 photons; [142]).

We established sensitivity to subthreshold populations of transient $\nu+\gamma$ sources at the $>13\%$ (IC40), $>9\%$ (IC59-North), and $>8\%$ (IC59-South) level for the three hemisphere-specific neutrino datasets we analyzed ($p = 1\%$ threshold; Sec. 3.3.4). These limits are expressed as the fraction of all neutrinos present in the datasets that are due to $\nu+\gamma$ transient sources ($\delta t < 100$ s), according to our assumptions (Sec. 3.3.3). Expressed as event rates, the limits correspond to >210 (IC40),

>440 (IC59-North), and >565 (IC59-South) gamma-ray associated neutrinos per hemisphere per year. Sensitivity of a joint analysis of the IC59 datasets was not separately established but can be estimated at >850 gamma-ray associated neutrinos per year all-sky. While these limits are well above the conservative limit of $r_{\text{cosmic}} \gtrsim 120$ neutrinos per year all-sky for the full detector array that we derive on the basis of the $\varepsilon_\nu \gtrsim 60$ TeV cosmic neutrino spectrum (Sec. 3.1), that rate could be substantially larger if the cosmic neutrino spectrum softens significantly within the $1 \text{ TeV} \lesssim \varepsilon_\nu \lesssim 60 \text{ TeV}$ range relevant to these data.

Unscrambling the neutrino data, we identify no individual high-significance neutrino + high gamma-multiplicity events, and no significant deviations from the null test statistic (λ) distributions. However, we observe a similar and unexpected pattern in the λ residuals from the IC59-North and IC59-South analyses, our two more sensitive datasets, corresponding to a joint p -value of 3.9% (Sec. 3.4.1). While granting that these residual patterns may be due to statistical fluctuations, we carried out additional investigations in an attempt to determine the origin of the deviations, and whether or not they suggest the presence of $\nu+\gamma$ correlated emission.

We first vetted the IC59 data for short timescale transients (our original test hypothesis) in two ways, checking for systematic trends in the temporal and spatial separations of the neutrino event and its associated gamma-rays. No systematic trends in spatial or temporal separation are evident for either IC59-North or IC59-South (Sec. 3.4.2).

We then checked for $\nu+\gamma$ spatio-temporal correlations on timescales beyond our original ± 100 s window (Sec. 3.4.3). We searched for neutrino-correlated gamma-ray flux excursions within a $\pm 50,000$ s (~ 0.5 day) window centered on the neutrino arrival time, finding no evidence for correlated gamma-ray flux excursions on this timescale. Instead, we find a likely correlation ($p = 7.0\%$, single trial) of IC59 neutrino positions with persistently bright portions of the *Fermi* gamma-ray sky.

This interesting and unexpected finding of our search for cosmic $\nu+\gamma$ sources, a possible signature of gamma-ray correlated structure in the high-energy neutrino sky, should be readily testable using eight years of further data already collected by the 79-string and full-strength (86-string) IceCube.

In particular, if blazars are responsible for a non-negligible fraction of the highest-energy cosmic neutrinos, then – given the brightness of the blazar pop-

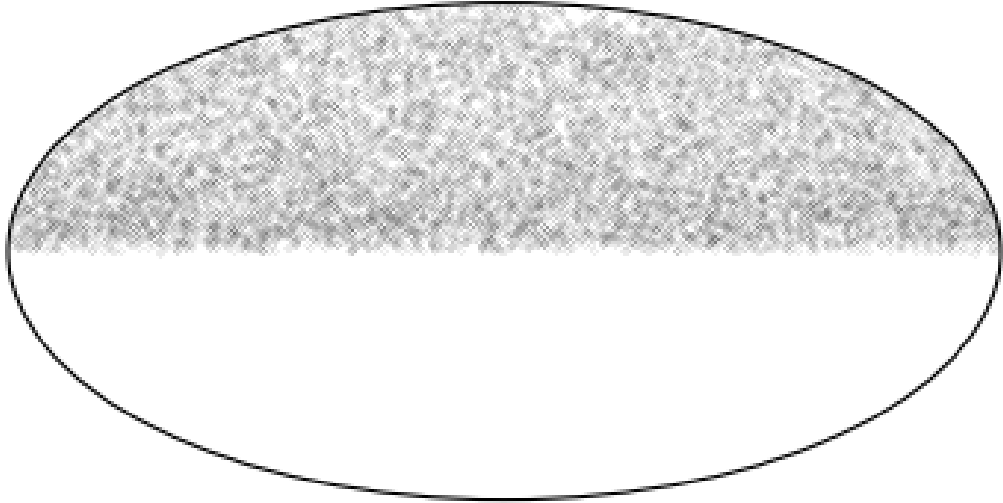
ulation over the $100 \text{ MeV} \lesssim \varepsilon_\gamma \lesssim 300 \text{ GeV}$ LAT bandpass – this would generate correlated structure in lower-energy neutrinos. Blazar associations have been proposed for two likely-cosmic high-energy neutrinos, IceCube-121204 “Big Bird” and IceCube-170922A, thanks to their spatio-temporal proximity to flaring episodes of the blazars PKS B1424–418 [143] and TXS 0506+056 [27], respectively. On the other hand, blazar models are strongly constrained by the IceCube *Fermi*-blazar stacking analysis [144], and by the absence of detected neutrino point sources [145, 146].

In a general sense, some level of correlation between the gamma-ray and neutrino skies is anticipated in models that propose a common origin for the diffuse $\varepsilon_\nu \gtrsim 100 \text{ TeV}$ neutrino and $\varepsilon_\gamma \lesssim 1 \text{ TeV}$ gamma-ray backgrounds [64, 147].

Finally, production of some cosmic neutrinos by Galactic sources, whether compact binaries [80, 148], TeV unidentified sources or hypernova remnants [81, 82, 149], or other source population(s), would naturally lead to correlated structure, given the very prominent Galactic signature in *Fermi* all-sky maps (Fig. 3.2).

Looking ahead, we eagerly anticipate the results of a systematic and comprehensive search for *Fermi* gamma-ray correlated structure in the full IceCube dataset. In addition, having demonstrated its effectiveness on archival data, we will be working with IceCube, ANTARES [150], and other partner facilities of the Astrophysical Multimessenger Observatory Network (AMON) to deploy our neutrino + high gamma-multiplicity search and generate low-latency (delays of ≈ 5 hours) $\nu + \gamma$ alerts from *Fermi* LAT gamma-ray and IceCube and ANTARES neutrino data. These AMON alerts will be distributed in real-time to AMON follow-up partners, prompting rapid-response follow-up observations across the electromagnetic spectrum.

A: IC40



B: IC59

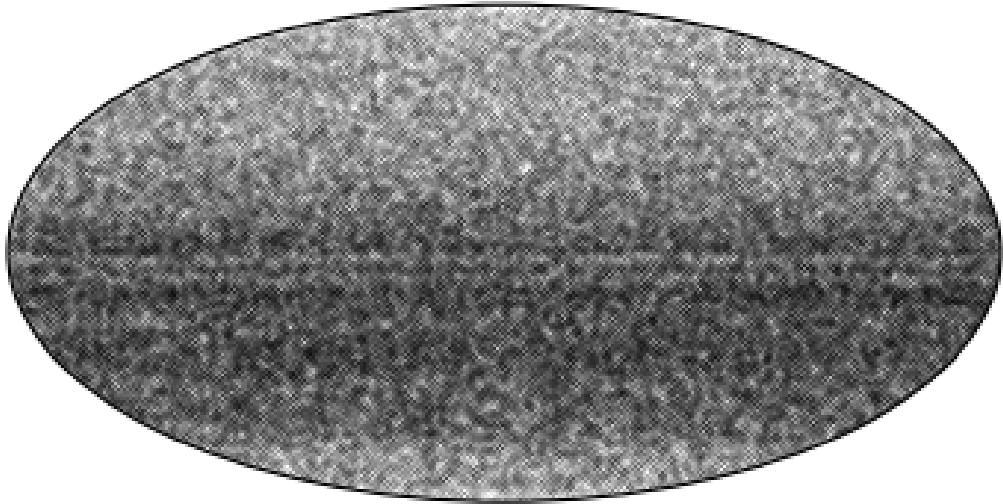
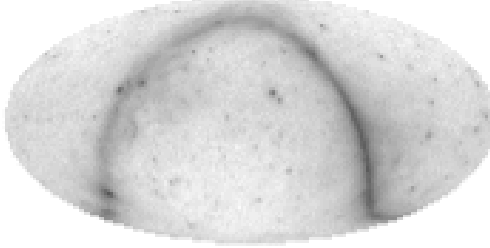
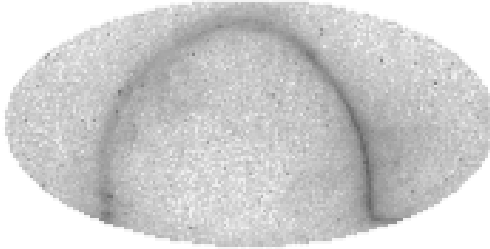


Figure 3.1: Neutrino sky positions from IC40 and IC59. No cosmic structure nor significant point-source detections have been reported from these data [\[100, 136\]](#).

A: 100 MeV - 1.4 GeV



B: 1.4 GeV - 20.8 GeV



C: 20.8 GeV - 300 GeV

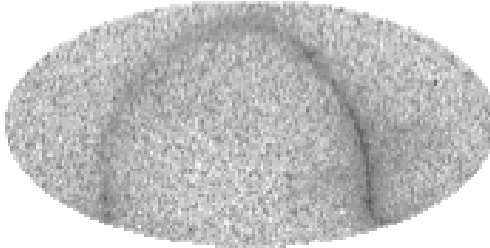


Figure 3.2: *Fermi* LAT all-sky exposure-corrected images. We divide the *Fermi* data into three bins of equal width in $\log \varepsilon_\gamma$ and calculate mission-averaged all-sky images to determine the expected background rate for each photon in the primary analysis. Greyscale intensity units, indicated by the color bars, are photons per 200 seconds per square meter per square degree.

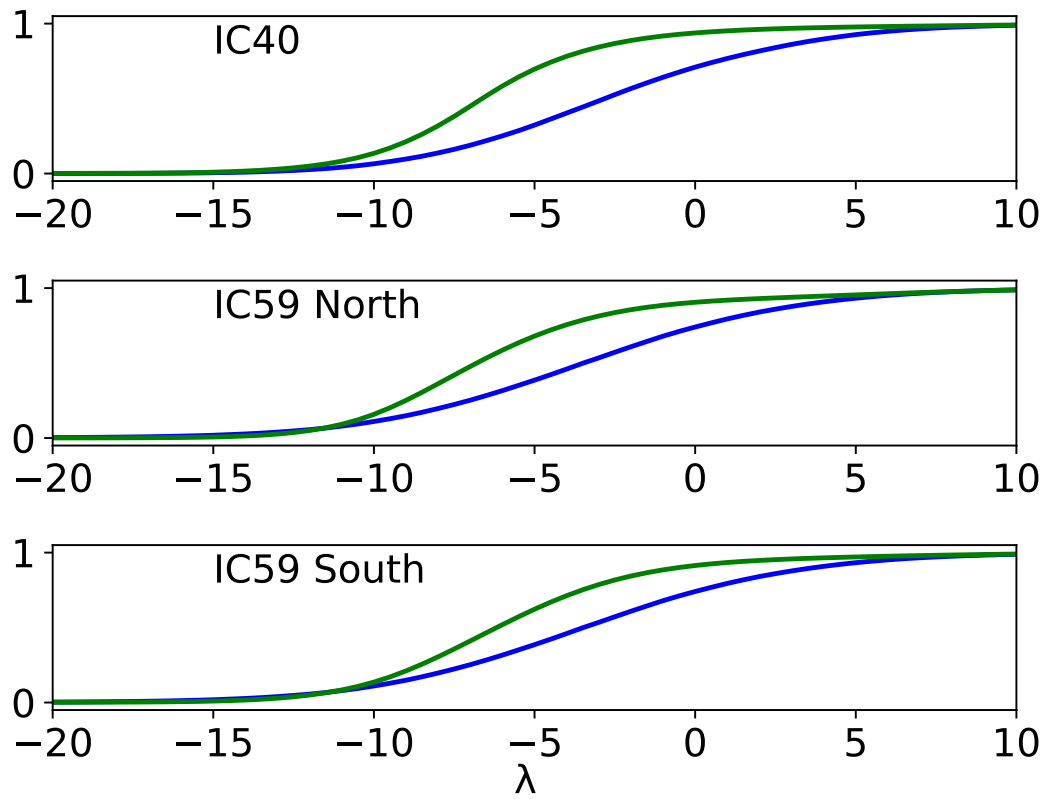


Figure 3.3: Cumulative distribution of pseudo-log-likelihood (λ) values from null/scrambled (green) and signal-only (blue) realizations of the IC40 (top), IC59-North (middle), and IC59-South (bottom) datasets. Note that the tails of the distributions extend far off of the plots

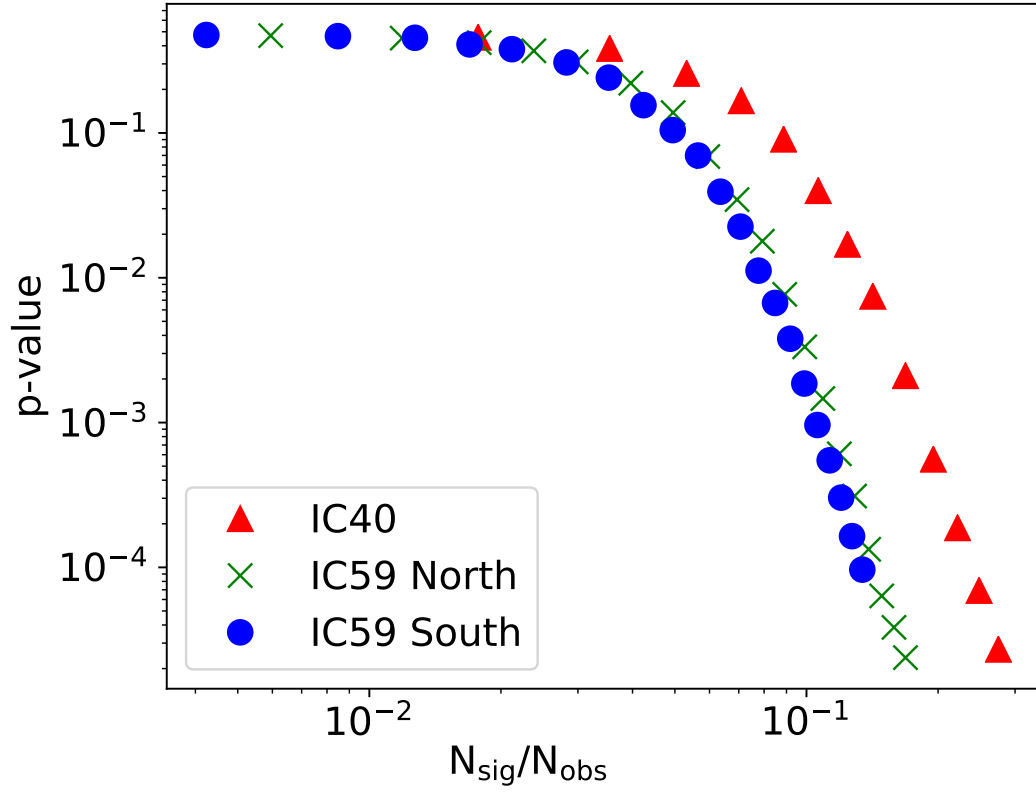


Figure 3.4: Analysis sensitivity, plotted as Anderson-Darling two-sample p -value versus fraction of coincidences that result from signal events, $n_{\text{inj}}/n_{\text{obs}}$. Results for IC40 are plotted in red, IC59-North in green, and IC59-South in blue. As expected, these sensitivities scale roughly as $1/\sqrt{n_{\text{obs}}}$, so that the larger IC59-North and IC59-South datasets provide superior fractional sensitivity than IC40.

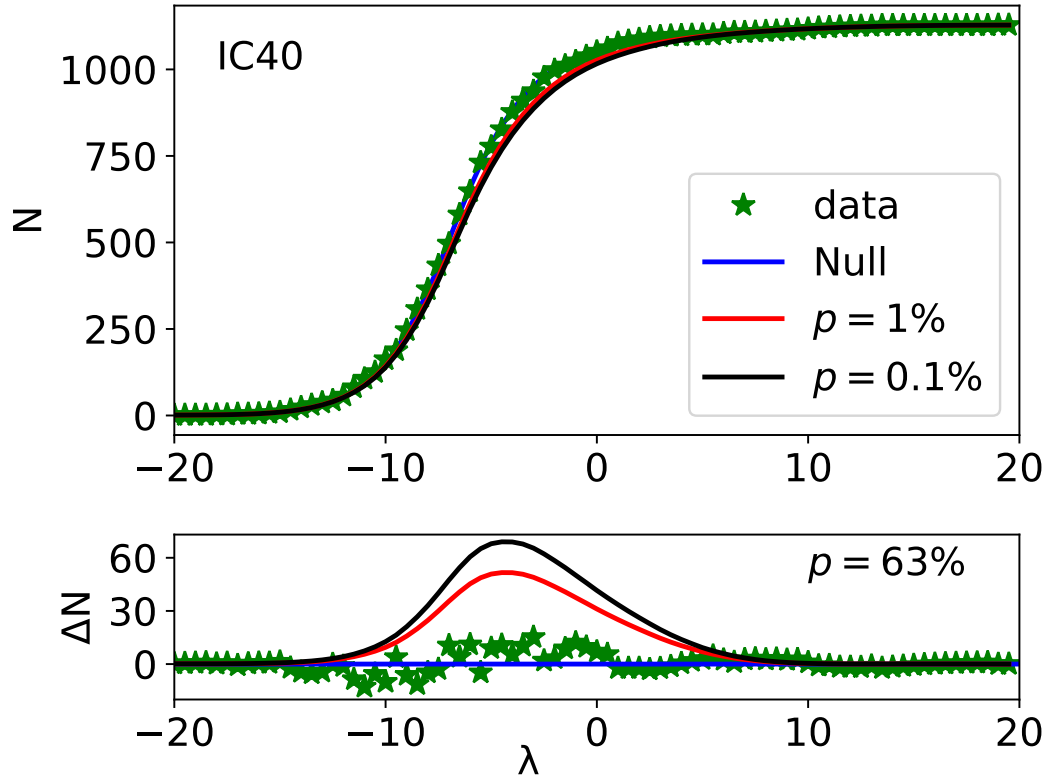


Figure 3.5: Cumulative and residual test statistic (λ) distributions for IC40 ($n_{\nu+\gamma} = 1128$). Upper panel: Cumulative IC40 λ distributions for unscrambled data (green stars), scrambled data / null distribution (blue line), and signal injections yielding $p = 1\%$ (red line) and $p = 0.1\%$ (black line). Lower panel: Residuals, plotted as null minus alternative, for IC40 data (green stars) and the two signal injection distributions (red and black lines).

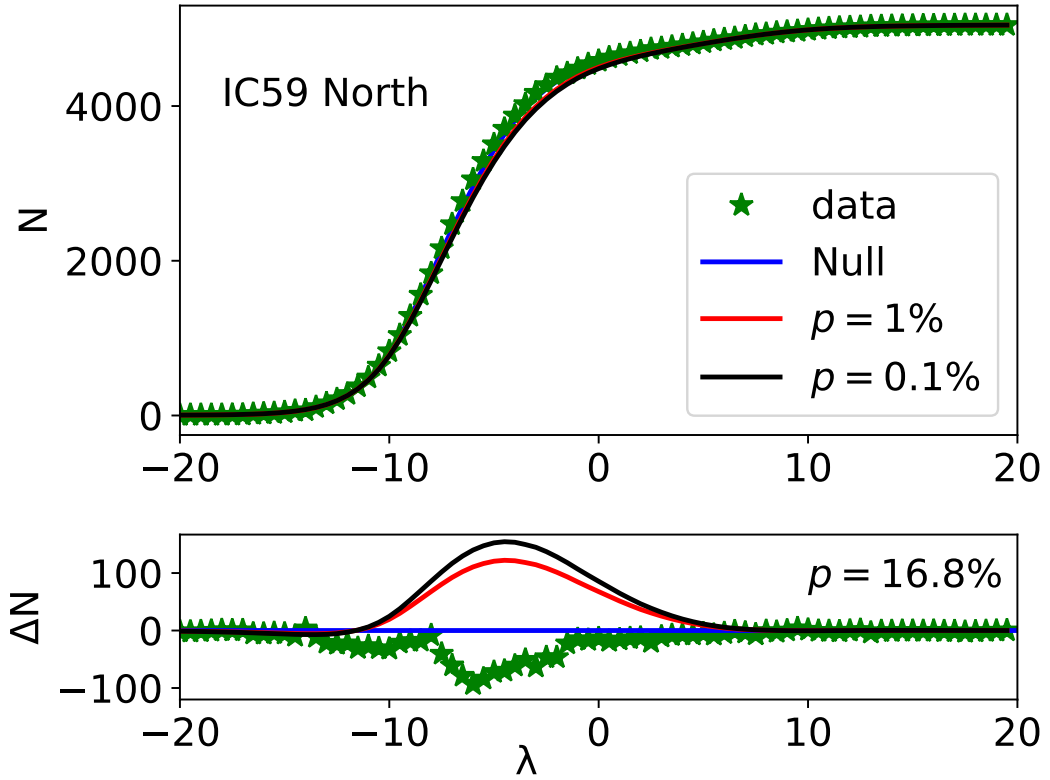


Figure 3.6: Cumulative (upper panel) and residual (lower panel) λ distributions for IC59-North ($n_{\nu+\gamma} = 5046$), including unscrambled data (green stars), scrambled data / null distribution (blue line), and signal injections yielding $p = 1\%$ (red line) and $p = 0.1\%$ (black line). Residuals are plotted as null minus alternative. A similar and unexpected pattern is noted in the residual λ distributions for the IC59-North and IC59-South datasets.

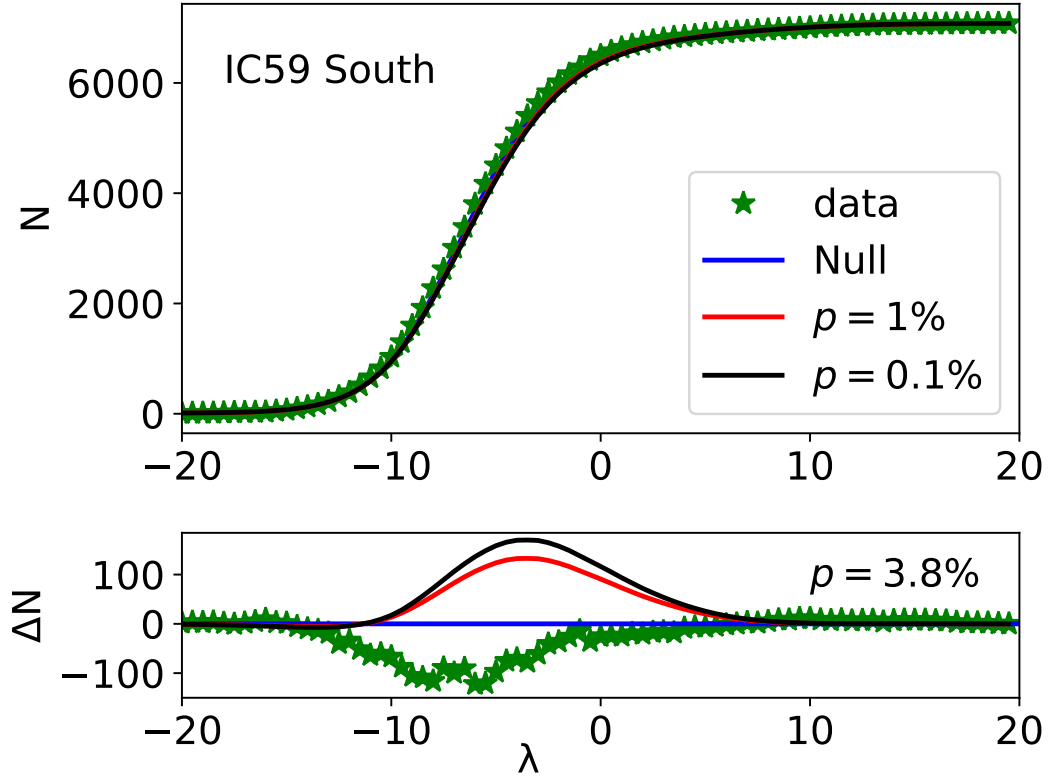


Figure 3.7: Cumulative (upper panel) and residual (lower panel) λ distributions for IC59-South ($n_{\nu+\gamma} = 7080$), including unscrambled data (green stars), scrambled data / null distribution (blue line), and signal injections yielding $p = 1\%$ (red line) and $p = 0.1\%$ (black line). A similar and unexpected pattern is noted in the residual λ distributions for the IC59-North and IC59-South datasets.

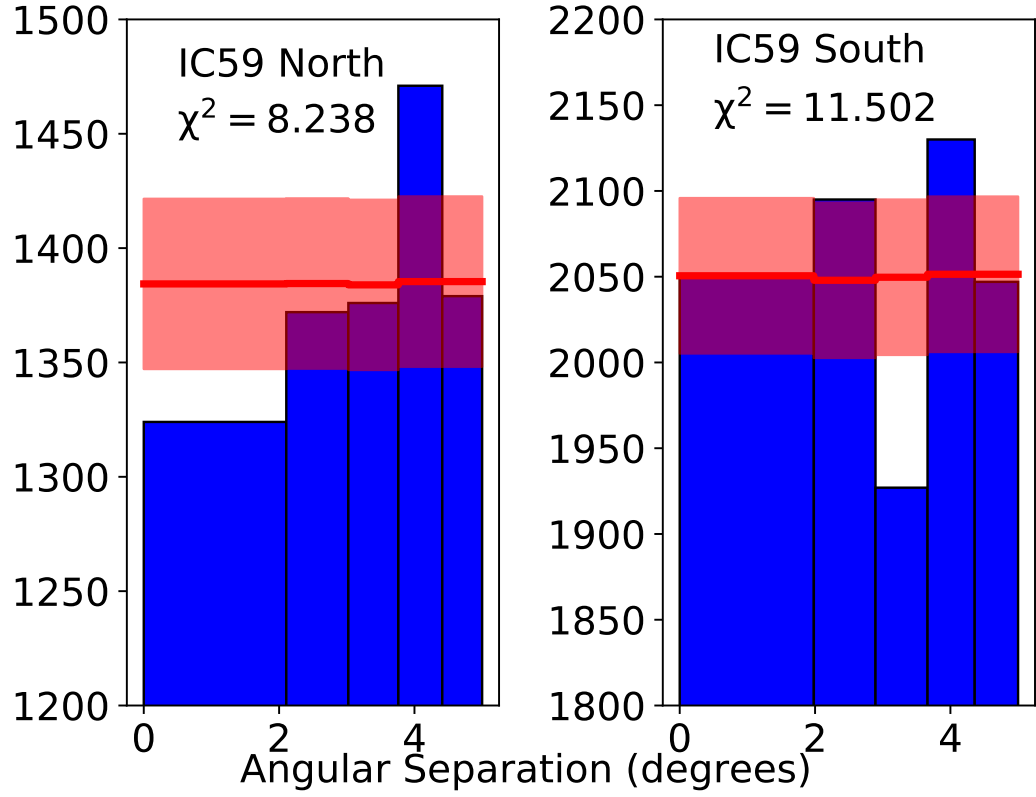


Figure 3.8: IC59 $\nu+\gamma$ angular separations. We test the observed angular separation distribution for neutrino-coincident photons (blue histograms) in IC59-North (left) and IC59-South (right) against the null distribution (red), which is approximately flat by construction (via choice of histogram bin boundaries). The $\pm 1\sigma$ ranges expected for a single dataset on the basis of Poisson uncertainties are indicated as the red range; note zero-suppressed y axis.

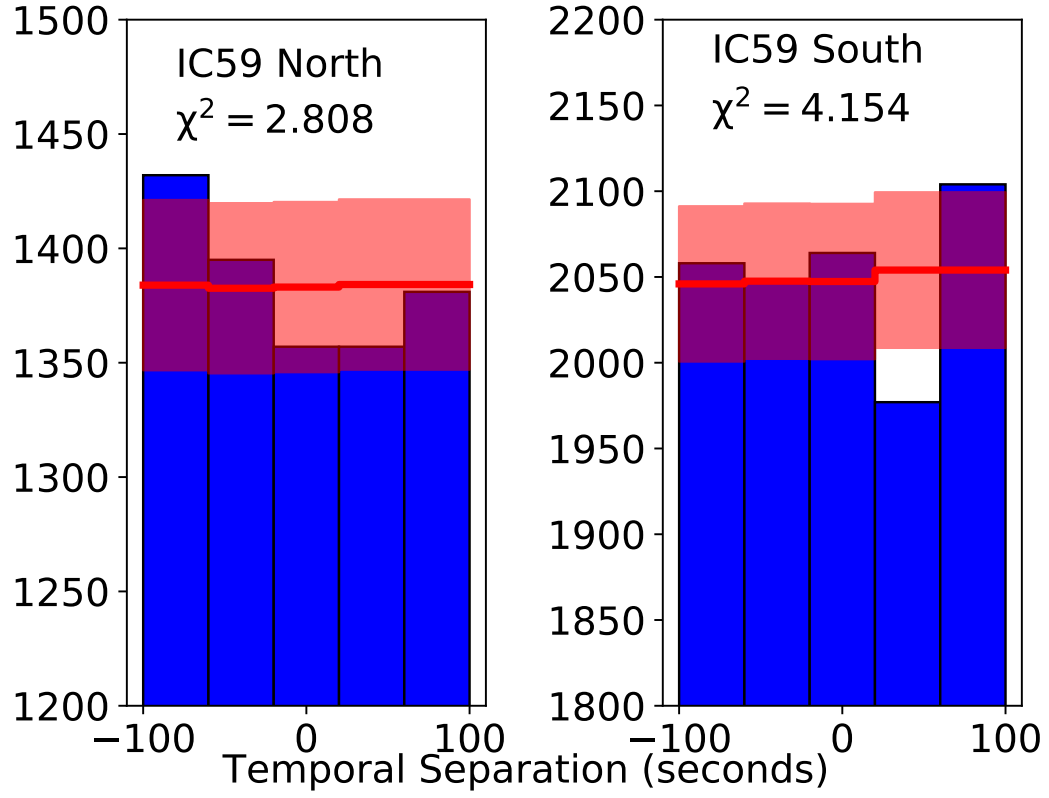


Figure 3.9: IC59 $\nu+\gamma$ temporal separations. We test the observed temporal separation distribution for neutrino-coincident photons (blue histograms) in IC59-North (left) and IC59-South (right) against the approximately flat null distribution (red). The $\pm 1\sigma$ ranges expected for a single dataset on the basis of Poisson uncertainties are indicated by the red range; note zero-suppressed y axis.

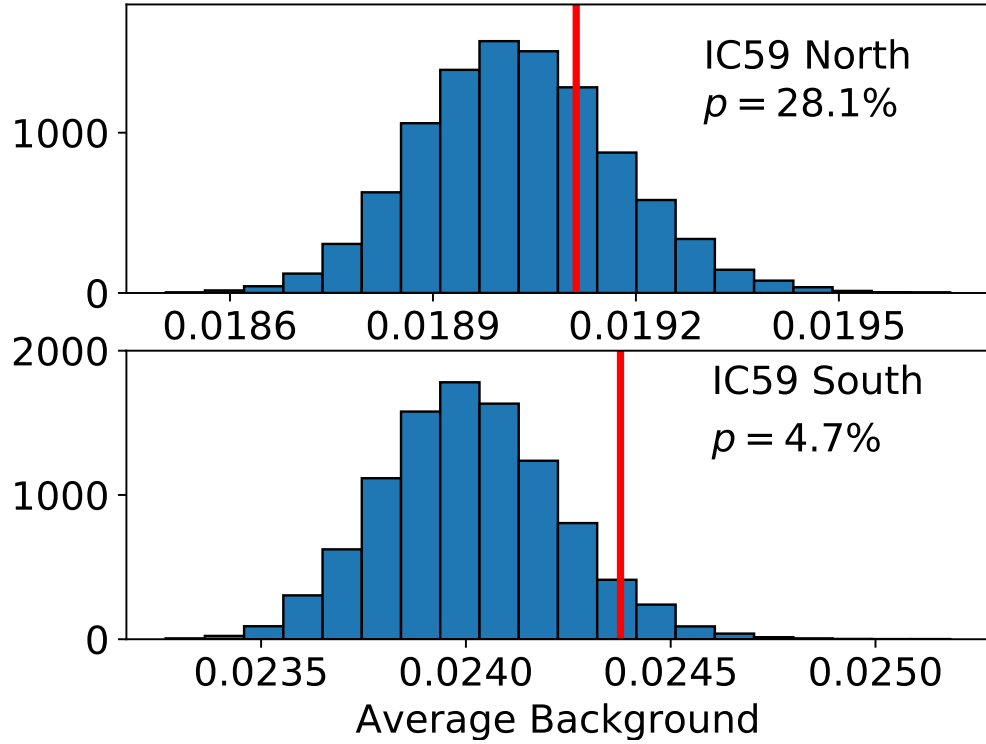


Figure 3.10: Average *Fermi* gamma-ray background rates at the positions of IC59-North (upper panel) and IC59-South (lower panel) neutrinos. In each panel, the histogram shows the distribution from 10,000 Monte Carlo scrambled datasets, while the red line marks the observed background rate for unscrambled data. Background rates are expressed in units of photons $\text{m}^{-2} \text{deg}^{-2}$. Observed neutrino positions show a mild statistical preference for higher-background regions of the *Fermi* gamma-ray sky, with a joint p -value for the two hemispheres of $p = 7.0\%$ by Fisher’s method.

Chapter 4

Search for Fermi-LAT counterparts to ANTARES neutrinos ¹

We analyze 7.3 years of ANTARES high-energy neutrino and *Fermi* LAT γ -ray data in search of cosmic neutrino + γ -ray ($\nu+\gamma$) transient sources or source populations. Our analysis has the potential to detect either individual $\nu+\gamma$ transient sources (durations $\delta t \lesssim 1000$ s), if they exhibit sufficient γ -ray or neutrino multiplicity, or a statistical excess of $\nu+\gamma$ transients of individually lower multiplicities. Individual high γ -ray-multiplicity events could be produced, for example, by a single ANTARES neutrino in coincidence with a LAT-detected γ -ray burst. Treating ANTARES track and cascade event types separately, we establish detection thresholds by Monte Carlo scrambling of the neutrino data, and determine our analysis sensitivity by signal injection against these scrambled datasets. We find our analysis is sensitive to $\nu+\gamma$ transient populations responsible for $>5\%$ of the observed gamma-coincident neutrinos in the track data at 90% confidence. Applying our analysis to the unscrambled data reveals no individual $\nu+\gamma$ events of high significance; two ANTARES track + *Fermi* γ -ray events are identified that exceed a once per decade false alarm rate threshold ($p = 17\%$). No evidence for subthreshold $\nu+\gamma$ source populations is found among the track ($p = 39\%$) or cascade ($p = 60\%$) events. Exploring a possible correlation of high-energy neutrino directions with

¹Python scripts used in this analysis can be found at <https://github.com/cft114/fermant>

Fermi γ -ray sky brightness identified in previous work yields no added support for this correlation. While TXS 0506+056, a blazar and variable (non-transient) *Fermi* γ -ray source, has recently been identified as the first source of high-energy neutrinos, the challenges in reconciling observations of the *Fermi* γ -ray sky, the IceCube high-energy cosmic neutrinos, and ultra-high energy cosmic rays using only blazars suggest a significant contribution by other source populations. Searches for transient sources of high-energy neutrinos thus remain interesting, with the potential for either neutrino clustering or multimessenger coincidence searches to lead to discovery of the first $\nu+\gamma$ transients.

4.1 Introduction

The ANTARES telescope [48] is a deep-sea Cherenkov neutrino detector, located 40 km off shore from Toulon, France, in the Mediterranean Sea. The detector comprises a three-dimensional array of 885 optical modules, each one housing a 10 in photomultiplier tube, and distributed over 12 vertical strings anchored in the sea floor at a depth of about 2400 m. The detection of light from up-going charged particles is optimized with the photomultipliers facing 45° downward. Completed in May 2008, the telescope aims primarily at the detection of neutrino-induced muons that cause the emission of Cherenkov light in the detector (*track-like* events). Charged current interactions induced by electron neutrinos (and, possibly, by tau neutrinos of cosmic origin) or neutral current interactions of all neutrino flavors can be reconstructed as *cascade-like* events [151].

Due to its location, the ANTARES detector mainly observes the Southern sky (2π sr at any time). Events arising from sky positions in the declination band $-90^\circ \leq \delta \leq -48^\circ$ are always visible as upgoing. Neutrino-induced events in the declination band $-48^\circ \leq \delta \leq +48^\circ$ are visible as upgoing with a fraction of time decreasing from 100% down to 0%. While ANTARES has a substantially smaller volume than IceCube, the use of sea water as detection medium (rather than ice) provides better pointing resolution for individual events, especially those of cascade type, and its geographic location enables reduced-background studies of the Southern hemisphere including the Galactic center region. On the other hand, natural light emission in the water leads to higher background levels [152].

Chief scientific results from ANTARES include: searches for neutrino sources

using track- and cascade-like events in data collected between 2007 and 2015 [153], dedicated studies along the Galactic Plane [154], also in collaboration with the IceCube telescope [155], and searches for an excess of high-energy cosmic neutrinos over the background of atmospheric events [156]. No cosmic neutrinos have been positively identified in the ANTARES data. Despite this, by integrating the cosmic neutrino spectrum from [116] over the ANTARES effective area [153], we estimate an expected 6.8 neutrinos of cosmic origin are detected each year, though all but the most energetic will be indistinguishable from the atmospheric background. Among all the possible astrophysical sources, transient sources increase the observation possibilities thanks to the suppression of atmospheric background in a well-defined space-time window. For this reason, the ANTARES Collaboration is involved in a broad multimessenger program to exploit the connection between neutrinos and other cosmic messengers, including: follow-up analyses associated with gravitational wave events [157, 158]; coincidence searches against electromagnetic observations from radio [159, 160] and visible [161] to X- and γ -rays [162]; blazar flare episodes [163]; and the neutrino source TXS 0506+056 [164]. To date, there have been no high-confidence counterparts identified for any ANTARES neutrino event.

In parallel, members of the Astrophysical Multimessenger Observatory Network (AMON²; [132, 133]) have been exploring the possibility of neutrino + γ -ray ($\nu+\gamma$) source identification via coincidence analysis, publishing analyses of *Fermi* Large Area Telescope (LAT; [31]) and public IceCube 40-string [131] and 59-string [165] data. Although no high-confidence $\nu+\gamma$ transients, nor evidence of subthreshold $\nu+\gamma$ source populations, were identified in these works, the latter revealed mild evidence for correlation between IceCube neutrino positions and the *Fermi* γ -ray sky.

Within the last year, a coincidence between the neutrino IceCube-170922A [97] and the flaring blazar TXS 0506+056 [27] led to multimessenger [2] and time-dependent neutrino clustering [99] analyses suggesting this BL Lac-type object as the first known source of high-energy neutrinos and the first identified extragalactic cosmic ray accelerator. Further blazar source identifications can certainly be anticipated; however, the absence of point source excesses in the ANTARES [153] and IceCube [117, 155] time-integrated datasets set strict limits on the fraction of

²AMON website: <http://www.amon.psu.edu/>

the cosmic high-energy neutrinos that can originate in these observed sources.

Possible alternative source populations include star-forming galaxies, starburst galaxies, galaxy groups and clusters, supernovae, and standard and low-luminosity gamma-ray bursts (see [57] for a review). Of these source possibilities, the transient and highly-variable source populations will likely require time-sensitive searches for identification. Hadronic models foresee that neutrinos and γ -rays are co-generated through the production and subsequent decay of mesons, mainly pions. γ -rays then result from the decay of neutral pions, while the decay of charged pions produces neutrinos. Additional processes in dense astrophysical regions can then degrade the energy of individual γ -rays to lower energies while leaving the neutrino energy spectrum almost unaffected, resulting in correlated emission of higher-energy neutrinos and lower-energy γ -rays.

4.2 Datasets

The *Fermi* LAT dataset is highly complementary for cross-reference with high-energy neutrino datasets. The LAT offers a 1.4 steradian field of view, provides all sky coverage every three hours on average, and exhibits good sensitivity over the $100 \text{ MeV} \lesssim \varepsilon_\gamma \lesssim 300 \text{ GeV}$ energy band.

This analysis was performed using publicly available *Fermi* LAT data. The relevant *Fermi* data were the Pass 8 photon reconstructions available from the LAT FTP server³. These photon events were filtered using the Fermi Science Tools, keeping only photons with a zenith angle smaller than 90° , energies between 100 MeV and 300 GeV, detected during good time intervals (GTI) as provided in the LAT satellite files⁴.

The point spread function (PSF) of the LAT is given by a so-called double King function [166] with the parameters depending on the photon energy, conversion type, and incident angle with respect to the LAT boresight [135]. At energies in the hundreds of MeV, the angular uncertainty can be several degrees, especially for off-axis photons. At $\varepsilon_\gamma > 1 \text{ GeV}$ the average uncertainty drops below 1° , and at $\varepsilon_\gamma \gtrsim 100 \text{ GeV}$ angular uncertainties are better than 0.1° .

³LAT data located at <ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/photon/>

⁴*Fermi* satellite files located at <ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/spacecraft/>

The ANTARES data used spans from February 2007 to December 2015. Data from this 8.9 year interval are divided into track and cascade events, all of which are upgoing. According to the selection criteria defined in [153], during this period 7622 track and 180 cascade neutrino candidates were identified. The *Fermi* mission has public data available starting from 4 August 2008. The ANTARES data is coincident with weeks 9 through 396 of the *Fermi* data, with 6774 track-like events and 162 cascade-like events falling within that 7.3 year window. For the ANTARES data, the average PSFs for tracks and cascades are derived from Monte-Carlo simulation, and then interpolated. For track and cascade events, the 90% containment radii for the PSFs are 1.5° and 10° respectively. The ANTARES PSFs are shown in Fig 4.1.

A `healpix` [137] map of resolution 8 (NSide=256, mean spacing of 0.23°) was constructed using the entire *Fermi* data set (weeks 9 to 495 at the time of creation) with aforementioned photon selection criteria. Using the `HEASoft` software⁵, events were binned into three logarithmically uniform energy bins. Each energy bin was then further binned into a `healpix` map, with the live time calculated via a Monte Carlo simulation. Dividing the counts map by the live time map produced the *Fermi* exposure map. Zero-valued (low-exposure) pixels were replaced by the average of the nearest neighbor pixels. Our three resulting all-sky *Fermi* maps are shown in Fig. 4.2. Due to the additional reconstruction uncertainty in the *Fermi* PSF for high-inclination events (inclination angle greater than 60°), three additional maps for analysis of these events were generated by further averaging all pixels with their nearest neighbors.

4.3 Methods

4.3.1 Significance Calculation

Our analysis follows as an extension to the methods presented in [165]. Different from previous work, our analysis allows for coincidences with both multiple photons and multiple neutrinos. Our analysis also covers both the track and cascade events detected by ANTARES. For track-like events, we use an angular acceptance window of 5° , while for cascade-like events, we use a 10° window. For both event types,

⁵HEASoft website: <https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/>

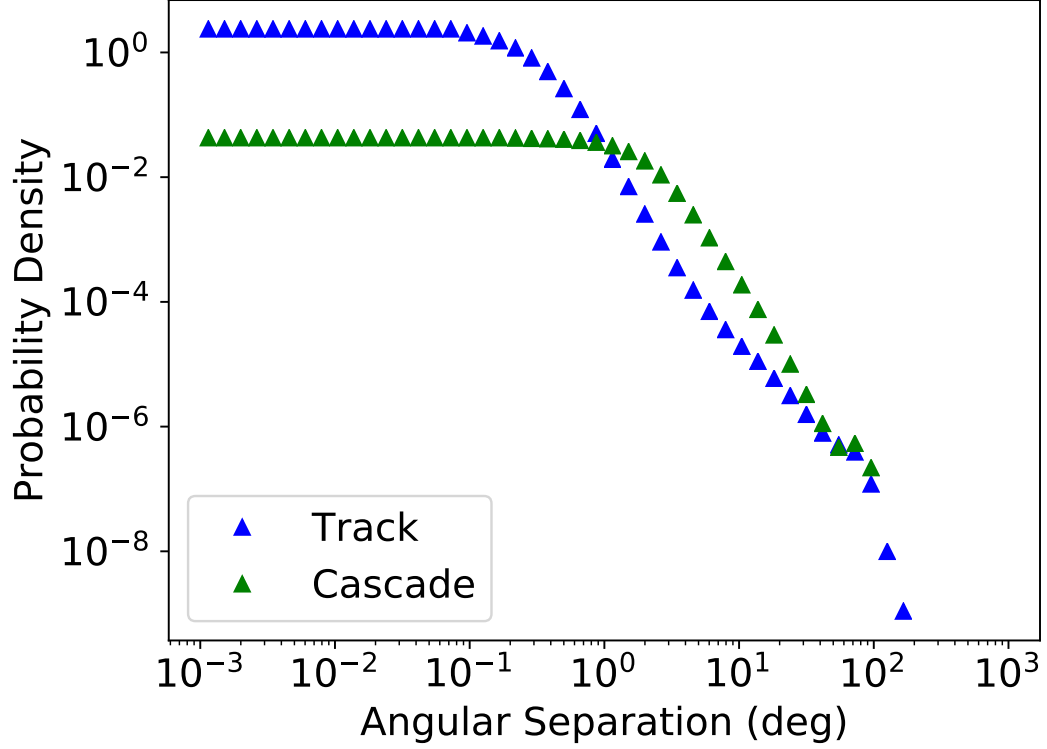


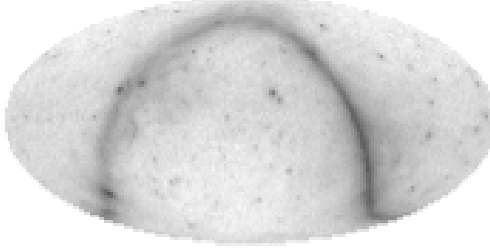
Figure 4.1: PSFs for ANTARES track-like and cascade-like events. Both curves are normalized such that the probability density sums to unity.

the temporal acceptance window is ± 1000 s. Neutrino multiplets are constrained to have each neutrino within both the angular and temporal separation of each other neutrino. Photons must fall within the angular and temporal window as measured from the average neutrino position and time. For each coincidence, a pseudo-log-likelihood test statistic, λ , is calculated as follows:

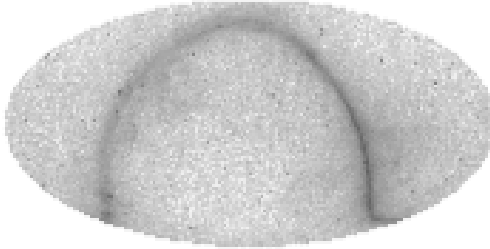
$$\lambda = 2 \ln \frac{P_{\nu\gamma}(\vec{x}) n_{\nu}! n_{\gamma}! \Pi_{\nu,\gamma} \tau(\Delta t_i)}{\Pi_{\gamma} B_{\gamma,i}(\vec{x})} + \sum_{\nu} \ln \frac{1 - p_{c,i}}{p_{c,i}}, \quad (4.1)$$

where $P_{\nu\gamma}$ is the product of the point spread functions (PSF) of each LAT photon and each ANTARES neutrino at the best position, $\vec{x}$, with each PSF normalized to have units of probability per square degree. The LAT PSF for each photon additionally depends on the photon energy, inclination angle, and conversion type. In general, the closer the PSF centers are, the larger the resulting λ value. The n_{ν}

A: 100 MeV - 1.4 GeV



B: 1.4 GeV - 20.8 GeV



C: 20.8 GeV - 300 GeV

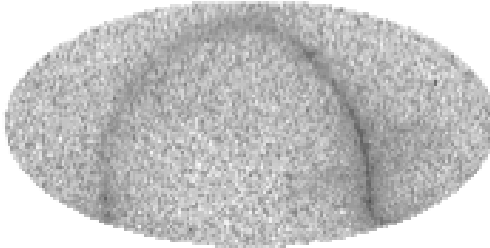


Figure 4.2: *Fermi* LAT all-sky exposure-corrected images in equatorial coordinates. We divide the *Fermi* data into three bins of equal width in $\log \varepsilon_\gamma$ and calculate mission-averaged all-sky images to determine the expected background rate for each photon in the primary analysis. Greyscale intensity units, indicated by the color bars, are photons per 200 seconds per square meter per square degree.

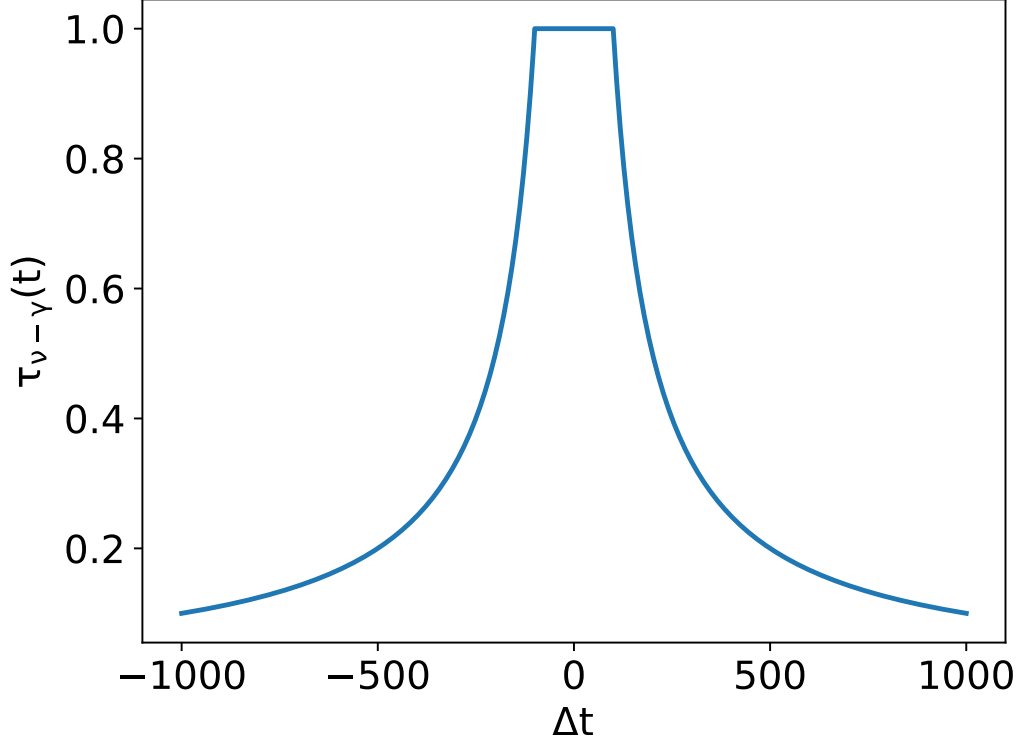


Figure 4.3: Temporal weighting function $\tau(\Delta t)$ used in the analyses. For $|\Delta t| < 100$ s, the function is flat and equal to 1. For $100 \text{ s} < |\Delta t| < 1000 \text{ s}$, the function scales as $1/|\Delta t|$.

and n_γ terms are respectively the number of neutrinos and γ -rays in the coincidence. The $\Pi_{\nu,\gamma} \tau(\Delta t_i)$ term is the product of the temporal weighting function (Fig. 4.3) evaluated for each neutrino and γ -ray in the coincidence. For particles within 100 s of the average arrival time, this function is identically one, and it scales as $1/|\Delta t|$ for times between 100 s and 1000 s. This allows the search to address the possibility of longer-timescale associations (as might result from low-luminosity GRBs) while maintaining a preference for shorter-timescale associations, if and when they are also present.

The $\Pi_\gamma B_{\gamma,i}(\vec{x})$ term is the product of LAT γ -ray backgrounds for each photon at the coincidence location, taken from the background maps shown in Fig 4.2. Together with the factorial terms, this acts like a Poisson probability of observing n_γ photons from background. The p_c factor, similar to the IceCube signalness [167],

is an energy proxy calculated by the ANTARES collaboration. The p_c for a neutrino event is computed on an event-by-event basis using the normalised anti-cumulative distribution of the number of hits from the full ANTARES 2012-2017 neutrino dataset. This probability represents the fraction of ANTARES events with a number of hits larger than that observed for the event: the larger the number of hits, the smaller the p_c value. Overall, larger values of the λ statistic suggest a greater likelihood of a physically associated multiplet from a cosmic source, rather than a coincidence of uncorrelated events.

The best fit position $\vec{x}$ is numerically calculated as the location of maximum PSF overlap. The photon multiplicity of each coincidence is calculated iteratively: Beginning with a coincidence including all photons passing the temporal and proximity cuts, the photon with the lowest PSF density at the best-fit position is removed and a new λ , for the new best-fit position, is calculated. This process is repeated until one photon is left (n_γ iterations), with the iteration yielding the maximum λ selected as the coincidence multiplicity.

This analysis presents two ways to identify a potential signal. First, with λ unbounded, the null distribution provides threshold values which can be used to identify individually-significant coincidences and calculate their estimated false alarm rates. In this work, we use two such thresholds, λ_D and λ_C , corresponding to false alarm rates of one per decade and one per century, respectively. Second, the presence of a subthreshold population of $\nu+\gamma$ emitting sources can be identified by a difference in the cumulative distributions of λ values between the observed and scrambled (null) populations. By design, true coincidences will be biased to higher λ values, and a population containing a sufficient number of signal events can be distinguished from the null distribution via an Anderson-Darling k -sample test [134].

4.3.2 Background Generation

We generate a set of 10,000 Monte Carlo scrambled versions of each of our datasets in order to characterize their null distributions and define analysis thresholds, prior to performing any study of the unscrambled datasets. Our scrambling procedure begins by first converting the coordinates of each neutrino to detector coordinates. The arrival time and azimuthal angle of each original neutrino ν_i are then exchanged

with another randomly selected neutrino ν_j . Each neutrino retains its original elevation. Finally, the coordinates are converted back to the equatorial system. This approach is similar to the method used in our previous work [140], with the primary difference being the use of detector coordinates for the scrambling procedure. *Fermi* LAT photons are not scrambled as the LAT data contains known sources and extensive (complex) structure. Coincidence analysis is carried out for each scrambled dataset and λ values are calculated for the resulting $\nu+\gamma$ coincidences via Eq. 4.1. Thresholds from this analysis for false alarm rates of 1 per decade (λ_D) and 1 per century (λ_C) are presented in Table 4.2.

In contrast to previous work [165], due to the sensitivity to multi-neutrino events and the use of both track and cascade events, we split the analysis into three separate parts. The first part is to detect all coincidences with single-neutrino track-like events. The second looks for coincidences with multi-neutrino track like events. The third and final part is a search for coincidences with all single-neutrino cascade-like events. Multi-neutrino cascades are not considered, as there are no cascade-like events within the temporal acceptance window of each other.

4.3.3 Signal Injection

To estimate the sensitivity of our analysis to subthreshold populations of cosmic $\nu+\gamma$ emitting sources, we generate a population of signal-like events. These events are injected into the scrambled datasets so that the injected distributions can be compared to the null distribution.

We determine the multiplicity of a generated signal event following the methods used in [165]. This method assumes a population of sources emitting one neutrino, with associated photon fluence distributed according to $N(S \geq S_0) \propto S_0^{-3/2}$. In this formulation, $N(S \geq S_0)$ is the number of events observed with a fluence greater than the threshold fluence S_0 . Setting this minimum to 0.001 photons, we can invert this relationship and generate the expectation value for the multiplicity of an arbitrary event in terms of a uniform random variable u as $\langle n_\gamma \rangle = S_0 u^{-2/3}$. The distribution of n_γ is then calculated by drawing randomly from a Poisson distribution with the expectation value $\langle n_\gamma \rangle$. Excluding events with zero photons, this yields the following n_γ distribution: 93.8% singlet, 4.5% doublet, 0.9% triplet, and 0.38%, 0.19%, 0.095%, 0.0567%, 0.0365%, 0.0244%, and 0.0174% for multiplicities four

Coincidence Search Results

Dataset	$\langle n_{\nu+\gamma} \rangle$	λ_D	Thresholds			Observed Values			
			λ_C	$n_{\text{inj},1\%}$	$n_{\text{inj},0.1\%}$	$n_{\nu+\gamma}$	λ_{max}	p_{A-D}	
Tracks, 100 s	2716 ± 36	18.5	25.4	205	260	2734	18.94	39%	
1000 s	"	"	"	220	285	"	"	"	
Cascades	83.6 ± 5.8	8.1	14.6	-	-	80	2.7	60%	
Track Multiplets	0.48 ± 0.69	-	-9.3	-	-	0	-	-	

Table 4.1: $\langle n_{\nu+\gamma} \rangle$ is the expected number of neutrinos observed in coincidence with one or more γ -rays, as derived from 10,000 Monte Carlo scrambled realizations of each dataset. λ_D and λ_C are the thresholds above which a coincidence is observed only once per simulated decade or century, respectively. $n_{\text{inj},1\%}$ and $n_{\text{inj},0.1\%}$ are the number of injected signal events required in simulations to give Anderson-Darling test [134] p -values of $p < 1\%$ and $p < 0.1\%$, respectively, by comparison to the null distributions for each dataset. $n_{\nu+\gamma}$ is the number of neutrinos observed in coincidence with one or more γ -rays in unscrambled data, λ_{max} is the maximum observed λ for each dataset, and p_{A-D} is the Anderson-Darling test p -value from comparison of the observed λ distribution to the associated null distribution. Cells with a ‘-’ could not be calculated, for reasons detailed in the main text.

through ten.

A signal event of photon multiplicity n_γ is then generated by choosing a random right ascension and drawing a random declination from the list of all ANTARES events. These coordinates serve as a sky position for the coincidence. The PSFs for n_γ LAT photons and n_ν neutrinos are then centered on this point, and placed randomly according to their respective PSFs. All photons are chosen to have the same inclination angle, which is drawn from the full set of inclination angles within the *Fermi* dataset. A conversion type for each photon is similarly drawn from the *Fermi* dataset. Photon energies are drawn from a power law with a photon index $\Gamma = 2$. Using the photon background maps, the number of unassociated photons expected to arrive within the temporal and spatial windows for that section of sky is calculated. From this Poisson probability, n_b photons are randomly placed uniformly within the spatial window. Energy and conversion type for the background photons are chosen in the same manner as for the signal photons. All background photons are given the same inclination angle as the signal photons. Each particle is also given an arrival time randomly selected from a uniform distribution. Using this information, a λ value is calculated following the methods of Sec 4.3. Due to the iterative rejection of one or more low-significance γ -rays, events can end up with some of the injected photons excluded.

Because the varied physical models predicting $\nu+\gamma$ coincidences have different characteristic timescales, we generate two sets of signal events for each of the three null distributions. One set draws the timestamps from a uniform distribution 100 s wide, while the other draws from a uniform distribution 1000 s wide.

To calculate the sensitivity of our analysis, we inject an increasing number of signal events n_{inj} and plot the median resulting Anderson-Darling p -value [134] against $n_{\text{inj}}/n_{\text{obs}}$ for the track and cascade data, as shown in Fig. 4.4 and Fig 4.5.

For the tracks, this provides an estimate of the threshold value of n_{inj} that is needed to yield a statistically significant deviation from the null distribution (see columns $n_{\text{inj},1\%}$ and $n_{\text{inj},0.1\%}$ in Table 4.2). For the cascades, the size of each individual scramble is small enough that replacing 100% of the dataset with signal events yields a p -value of 2.8% on average, making it very unlikely that this sample would yield a high-confidence demonstration of an underlying $\nu+\gamma$ source population. At 90% confidence, our analysis is sensitive to >130 source-like $\nu+\gamma$ coincidences in the 100 s track data, >145 in the 1000 s track data, and >60 in the

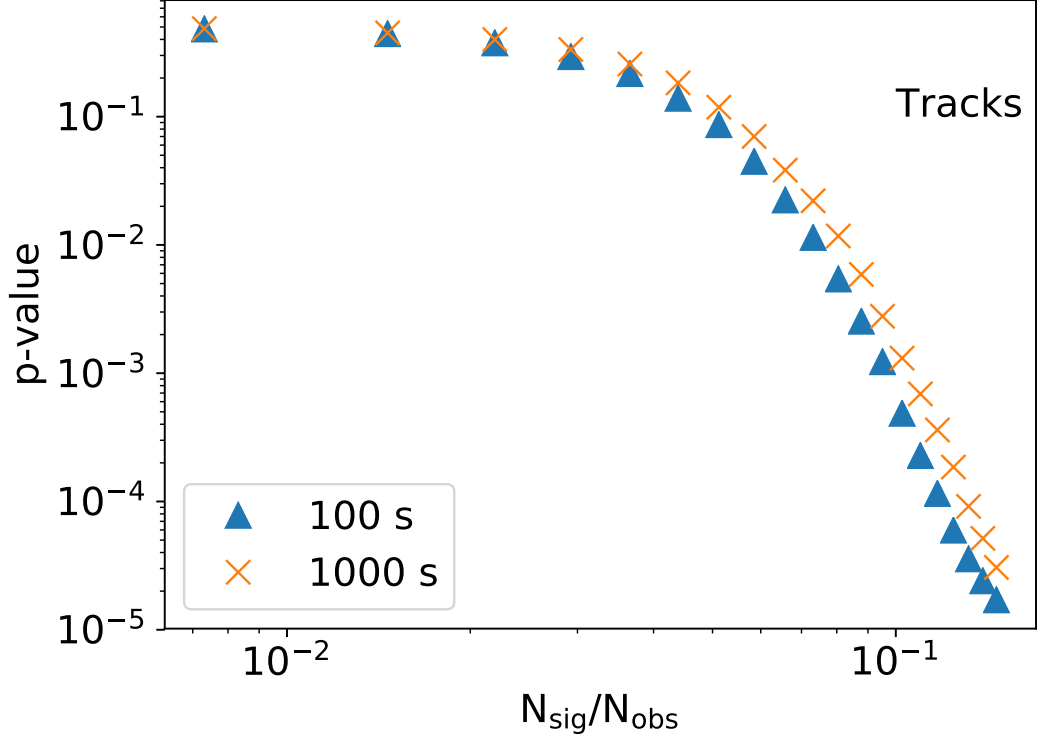


Figure 4.4: Analysis sensitivity, plotted as Anderson-Darling two-sample p -value versus fraction of coincidences that result from signal events, $N_{\text{sig}}/N_{\text{obs}}$. Results from both signal populations are shown.

100 s and 1000 s cascade data. Relevant statistics from these analyses are provided in Table 4.2.

In previous work, [165] found that scrambled neutrinos coincident with LAT-detected GRBs, in particular GRB 090902B [141], yielded λ values well above the λ_{C} threshold. To quantify our analysis sensitivity to GRB + neutrino coincidences, we carried out a Monte-Carlo simulation for each LAT-detected GRB⁶ that occurred within our data collection period. Neutrinos were injected following our signal injection procedures, with the GRB position and trigger time as reference, and with a 1000-second box-window temporal distribution for neutrino arrival times. For each LAT GRB, we carried out 10,000 such neutrino signal injections and calculated the λ value for the resulting association in each instance.

⁶LAT GRB catalog: https://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/

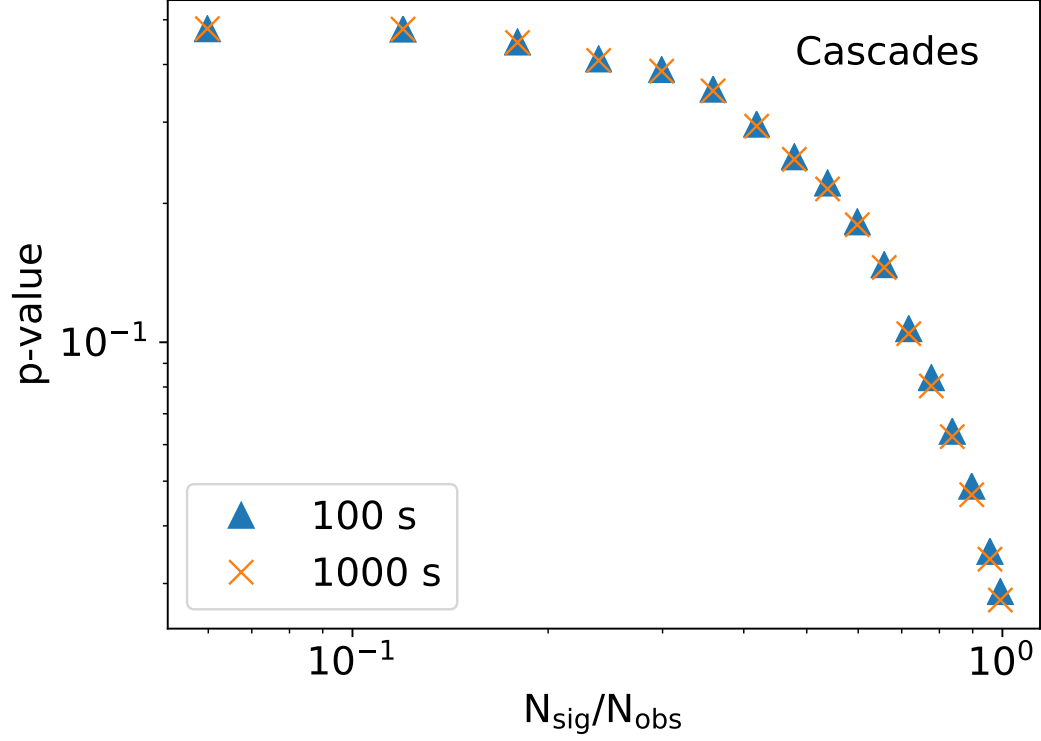


Figure 4.5: Analysis sensitivity, plotted as Anderson-Darling two-sample p -value versus fraction of coincidences that result from signal events, $N_{\text{sig}}/N_{\text{obs}}$. Results from both signal populations are shown.

The maximum λ generated through this search was $\lambda = 3524.5$, resulting from a 368-photon coincidence with GRB 130427A [168]. Of the 128 individual bursts in this simulation, 58 have median λ values from these neutrino injection trials of $\lambda_{\text{med}} > \lambda_{\text{C}}$, and a further five bursts have $\lambda_{\text{C}} > \lambda_{\text{med}} > \lambda_{\text{D}}$.

4.4 Results

Applying our analysis to the two unscrambled neutrino datasets yields the results summarized in Table 4.2. Fig. 4.6 and Fig 4.7 show the λ distributions for the unscrambled data for the track and cascade data, along with the null distributions, and distributions for signal injections (where possible) yielding p -values of 1% and 0.1%, respectively. All distributions are normalized to the number of coincidences

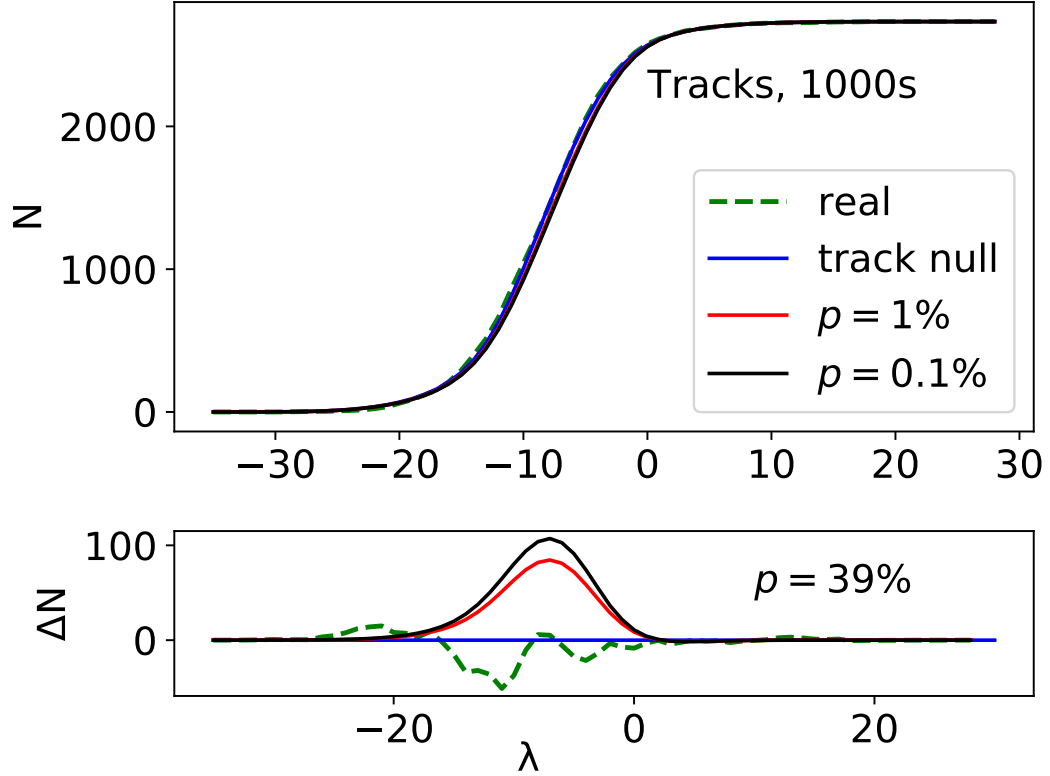


Figure 4.6: Cumulative and residual test statistic (λ) distributions for the track ($n_{\nu+\gamma} = 2734$) data. Upper panel: Cumulative λ distributions for unscrambled data (green dashed line), scrambled data / null distribution (blue line), and signal injections yielding $p = 1\%$ (red line) and $p = 0.1\%$ (black line). Lower pane: Residuals, plotted as null minus alternative, for track data and the two signal injection distributions. The signals were generated with a 1000 s window; curves for injections with a 100 s window look essentially the same. The Anderson-Darling test p -value from comparison of the unscrambled and null distributions is $p = 39\%$ for track events.

in the unscrambled distribution. Note that due to the small size of the cascade coincidence sample, it is not possible to inject enough signal events into a random scramble to differentiate from other random scrambles at better than $p=2.8\%$ (97.2% confidence).

Two coincidences above the λ_D threshold were observed in the track data. From Poisson statistics, two or more such coincidences would be observed 16.6% of the time given the 7.3 year span of the data. Details of these two coincidences are presented in Table 4.1. No λ values above the λ_D threshold were observed in

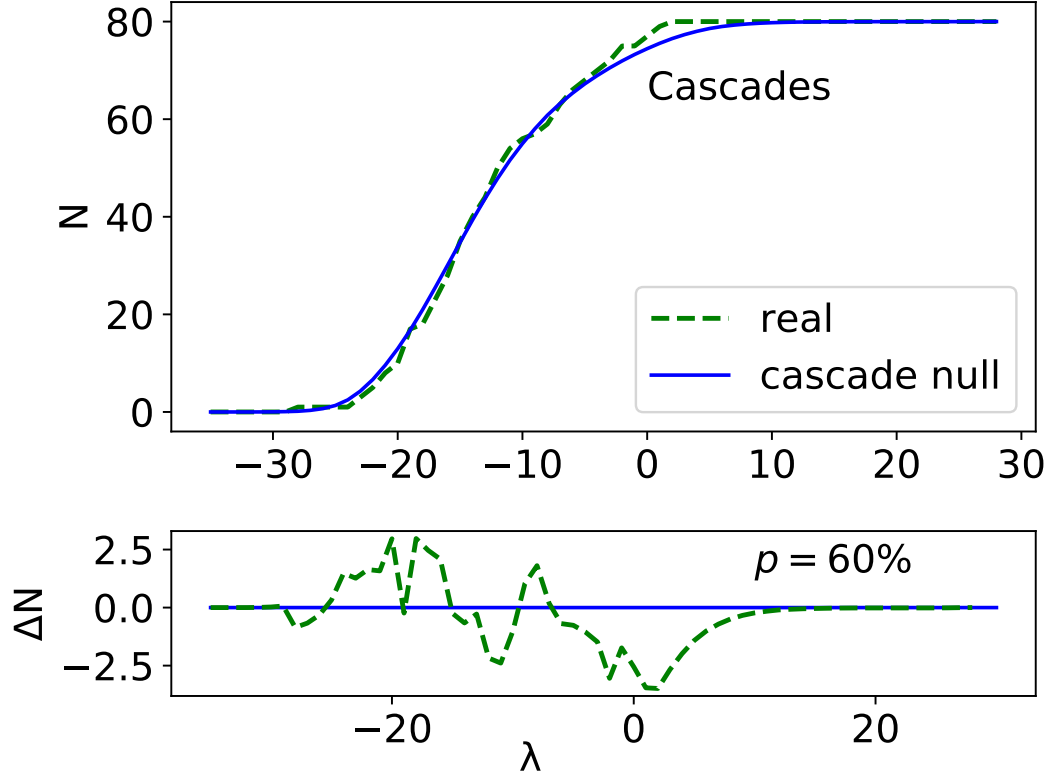


Figure 4.7: Cumulative and residual test statistic (λ) distributions for the cascade ($n_{\nu+\gamma} = 80$) data. Upper panel: Cumulative λ distributions for unscrambled data (green dashed line) and scrambled data / null distribution (blue line). Lower pane: Residuals, plotted as null minus alternative. No signal injection curves are shown for the cascades as even a 100% injection does not allow for discrimination from the null sample for this dataset. The Anderson-Darling test p -value from comparison of the unscrambled and null distributions is $p = 60\%$ for cascade events.

the cascade data. The subthreshold population search demonstrated that both unscrambled distributions were consistent with background, with test statistics of 39% for the tracks, and 60% for the cascades. Results from the track multiplet analysis are not shown as there were, on average, only 0.48 such coincidences per scramble, and none in the unscrambled analysis.

[165] also tested for correlation between neutrino and *Fermi* LAT photon sky positions without any temporal correlation. Repeating this analysis using the ANTARES data, we first construct a single *Fermi* background map covering the full energy range. We then measure the background value at the location of every

High- λ events

Date	Time (UTC)	MJD	Δt (s)	Position (J2000)	$r_{1\sigma}$	N_{ph}	λ	FAR (yr^{-1})
2012 Nov 21	20:19:52	56252.8471	307	248°00, −7°70	2'	1	18.9	0.09
2014 Aug 05	11:13:33	56874.4677	750	279°68, −5°05	3'	2	18.8	0.09

Table 4.2: $\langle n_{\nu+\gamma} \rangle$ is the expected number of neutrinos observed in coincidence with one or more γ -rays, as derived from 10,000 Monte Carlo scrambled realizations of each dataset. λ_{D} and λ_{C} are the thresholds above which a coincidence is observed only once per simulated decade or century, respectively. $n_{\text{inj},1\%}$ and $n_{\text{inj},0.1\%}$ are the number of injected signal events required in simulations to give Anderson-Darling test [134] p -values of $p < 1\%$ and $p < 0.1\%$, respectively, by comparison to the null distributions for each dataset. $n_{\nu+\gamma}$ is the number of neutrinos observed in coincidence with one or more γ -rays in unscrambled data, λ_{max} is the maximum observed λ for each dataset, and $p_{\text{A-D}}$ is the Anderson-Darling test p -value from comparison of the observed λ distribution to the associated null distribution. Cells with a ‘-’ could not be calculated, for reasons detailed in the main text.

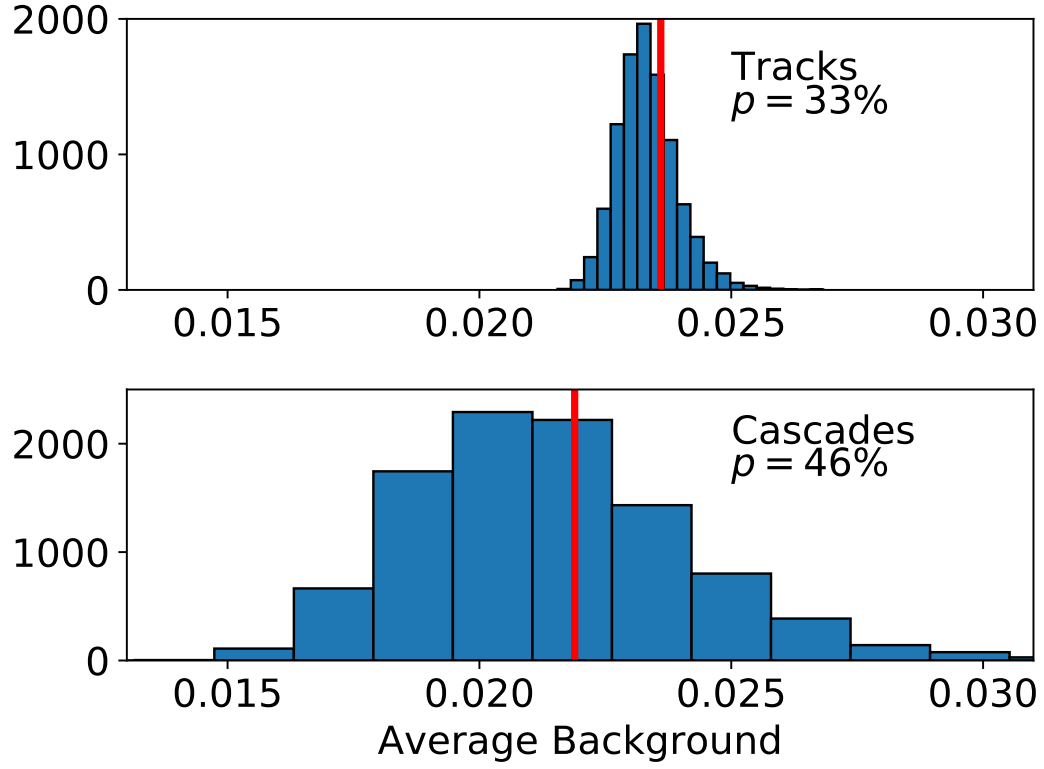


Figure 4.8: Average *Fermi* γ -ray background rates at the positions of track (upper panel) and cascade (lower panel) neutrinos. In each panel, the histogram shows the distribution obtained from 10,000 Monte-Carlo scrambled datasets, while the red line marks the observed background rate for unscrambled data. Background rates are expressed in units of photons per square meter per square degree per 200s. Observed average backgrounds are consistent with background for both datasets.

neutrino in the track and cascade data to compute an average photon background for each neutrino map. Carrying this out on the scrambled neutrino datasets yields an average background of $(2.33 \pm 0.06) \times 10^{-2}$ photons $\text{deg}^{-2} \text{m}^{-2}$ per 200 s for the track data, and $(2.16 \pm 0.36) \times 10^{-2}$ photons $\text{deg}^{-2} \text{m}^{-2}$ per 200 s for the cascade data. The observed backgrounds (in the same units) from the unscrambled data are 2.36×10^{-2} ($+0.44 \sigma$; $p = 33\%$) for the track data, and 2.19×10^{-2} ($+0.09 \sigma$; $p = 46\%$) for the cascade data. Both results are consistent with background (Fig. 4.8.) The dispersion in the cascade background from scrambled datasets is far larger than that for the tracks because of the much-reduced sample size (180 cascade events compared to 7622 track events); however, the two average backgrounds are

consistent, as the mean of the track background is 0.47σ larger than the mean of the cascade background, as measured using the standard deviation of the cascade background distribution. Recalling the IC59 Northern ($p=28.1\%$), IC59 Southern ($p=4.7\%$), and IC40 ($p=58.3\%$) results from [165], we can calculate a unified p -value of 19.7% from these values using Fisher’s method [169].

4.5 Conclusions

We have carried out a search for $\nu+\gamma$ transients using publicly available *Fermi* LAT γ -ray data and ANTARES neutrino data. Our analysis used archival data from both observatories over the period August 2008 to December 2015. As with previous work [165], our analysis was designed to be capable of identifying either individual high-significance $\nu+\gamma$ transients or a population of individually subthreshold events, via statistical comparison to uncorrelated (scrambled) datasets.

Our Monte Carlo simulations demonstrate a sensitivity to single-neutrino events of sufficient γ -ray multiplicity, as demonstrated by signal injection against multiple bright LAT-detected γ -ray bursts. Signal injection against scrambled datasets established our sensitivity to subthreshold populations of transient $\nu+\gamma$ sources at the $>7\%$ level (>180 coincidences) for tracks; however, due to the small sample size, we were not able to place meaningful limits on a subthreshold $\nu+\gamma$ source population within the cascade data. Our limit of >200 coincidences in the full dataset is equivalent to >27 LAT-associated cosmic neutrinos per year in the ANTARES data. Since IceCube estimates of the cosmic neutrino flux and spectrum lead us to expect 6.8 cosmic ANTARES neutrinos per year (Sec. 4.1), our limit is not physically constraining in this context.

Analysis of the observed (unscrambled) data reveals two $\nu+\gamma$ coincidences above a nominal λ_D threshold (false alarm rate $\text{FAR} < 0.1 \text{ yr}^{-1}$; Table 4.1). Due to the 7.3 year span of the data, we anticipate observing two or more $\lambda > \lambda_D$ coincidences 16.6% of the time ($p = 16.6\%$). We observe no statistically-significant deviation of the observed λ distributions from their associated null distributions, with observed p -values of $p = 39\%$ and $p = 60\%$ for the track and cascade events, respectively.

Independently, we performed the first test for correlation between ANTARES neutrino positions and persistently bright portions of the *Fermi* γ -ray sky. Our test

found no significant excess in either the tracks ($p = 33\%$) or cascades ($p = 46\%$). Combining these values with previous results (28.1% for IC59 north, 4.7% for IC59 south, 58.3% for IC40; [165]) by Fisher’s method yields a joint p -value of $p = 19.7\%$.

While our results show no significant evidence of $\nu+\gamma$ coincidences, we look forward to the results of future searches using additional neutrino data. We also continue our work with Astrophysical Multimessenger Observatory Network [132, 133] partner facilities and the Gamma-ray Coordinates Network [170] to generate low-latency $\nu+\gamma$ alerts from *Fermi* LAT γ -ray and high-energy neutrino data. Once these alerts are deployed, they will be distributed in real time to AMON follow-up partners.

Chapter 5

Six Swift Follow-Up Campaigns of Likely Cosmic High-Energy Neutrinos from IceCube

We present results of the first six *Swift* satellite follow-up campaigns seeking to identify transient or variable X-ray or UV/optical sources that might be associated with individual high-energy ($\varepsilon_\nu \gtrsim 1$ TeV) cosmic neutrinos detected by the IceCube Neutrino Observatory. Real-time public alerts providing coordinates and arrival times of likely-cosmic neutrino events have been provided by IceCube, via the Astrophysical Multimessenger Observatory Network, since April 2016. *Swift* responded to two such alerts in 2016 – IceCube-160731A and IceCube-161103A – and to an additional four in 2017 – IceCube-170312A, IceCube-170321A, IceCube-170922A, and IceCube-171106A. Each of these alerts triggered *Swift* X-ray observations to find potential X-ray sources within the targeted region. Excepting the blazar TXS 0506+056 detected in our IceCube-170922A follow-up campaign, no detected X-ray sources are considered likely high-energy neutrino sources. For each campaign, we calculate spectrum-dependent upper limits on the flux of any counterpart within the followup region. We plan to continue pursuit of likely-cosmic IceCube neutrinos, in hopes of identifying additional high-energy neutrino counterpart sources or, in the alternative, establishing robust and useful constraints on physical models for such counterparts.

5.1 Introduction

The detection of high-energy ($\varepsilon_\nu \gtrsim 1$ TeV) astrophysical neutrinos has been reported, and confirmed over five years of data, by the IceCube Collaboration [50, 171]. However, there is to date just one known source of high energy neutrinos, the blazar TXS 0506+056 [27, 99]. This leaves the bulk of the cosmic neutrino sources – potentially also the sources of the highest-energy cosmic rays – unknown. In particular, statistical and stacking analyses show that $\lesssim 20\%$ of the cosmic neutrinos can be from blazars or flat-spectrum radio quasars [172, 173].

Apart from blazars, other possible high-energy neutrino source populations include gamma-ray bursts (GRBs; [52, 174–176]); other types of active galactic nuclei (AGN; [69, 177]); ultra-luminous star-forming galaxies [64, 66]; and low-luminosity GRBs [74, 123, 178–180] or other types of supernova (SN; [181]). In addition, a subdominant fraction of the cosmic neutrinos may originate in Galactic sources, for example, the Milky Way’s “Fermi Bubbles” [182, 183], TeV gamma-ray bright hypernova remnants [81, 82, 184], and the recently discovered Galactic “pevatrons” [185].

If any of the high-energy neutrino source populations are transient, they may well be accompanied by bright electromagnetic emission that could be identified via rapid-response target of opportunity (TOO) observations at X-ray and ultraviolet/optical/infrared or radio wavelengths. The possibility of discovering multimessenger transient sources in this fashion is one of the chief motivations for the Astrophysical Multimessenger Observatory Network¹ (AMON; [132, 186]). One of AMON’s earliest programmatic accomplishments was to work with IceCube to commission real-time public alerts of IceCube likely-cosmic neutrinos so as to enable prompt follow-up searches; the first of these alert streams went live in April 2016.

The “High Energy Starting Event” (HESE) neutrinos were the first IceCube sample shown to include a cosmic component [50], and with many individual HESE neutrinos likely to have an astrophysical origin, they offer a promising sample for follow-up studies. HESE neutrinos interact inside a fiducial volume that is “protected” by the outer layers of the detector, which are used to veto entering muon tracks. The HESE veto increases the signal to noise ratio by removing the largest background, atmospheric muons. The HESE real-time stream triggers on track-like

¹AMON website: <http://sites.psu.edu/amon/>

events from the charged-current interactions of muon neutrinos (and from about one in five tau neutrino interactions). These events have good angular resolution ($\sim 1^\circ$) compared to the cascade-like events that result from other interactions, which have relatively poor resolution in published analyses ($r_{90} \sim 15^\circ$; [50]). The fact that HESE neutrinos interact inside a restricted detector fiducial volume, and satisfy a threshold for high deposited charge, increases the likelihood of these being astrophysical neutrinos, as the great majority of background events (atmospheric neutrinos and atmospheric muons) do not pass these cuts.

The “Extremely High Energy” (EHE) event definition [187], by focusing on the highest-energy throughgoing track events, yields a mostly-distinct sample of likely-cosmic neutrinos, with a rate of track-like events comparable to that of the HESE sample [188]. The EHE stream consists of high-energy induced tracks with energies in the 500 TeV to 10 PeV range, which results in a relatively high-purity sample (comparable to the HESE sample) exhibiting good angular resolution ($< 1^\circ$; [189]).

Broad interest in cosmic neutrino follow-up campaigns prompted IceCube and AMON to implement real-time analysis and triggering for both HESE and EHE event types, with live public alerts through the Gamma-ray Coordinates Network (GCN; [190]) initiated in April 2016 (HESE) and July 2016 (EHE), respectively.

Prior to the identification of these event types as offering enriched samples for studies of the cosmic neutrinos, *Swift* follow-up studies of IceCube neutrino doublets we carried out for several years with no identified counterparts [191]. In 2016, *Swift* observed the location of the IceCube triplet neutrino [192]: Three muon neutrino candidates that arrived within 100 s of each other, and seemed consistent with originating from a single point source in early analyses. No likely electromagnetic counterpart was identified via the resulting follow-up campaigns [192]. Finally, via a distinct program, *Swift* has observed the locations of ANTARES neutrino candidates, with no likely optical or X-ray counterparts found [161].

Since the initiation of the AMON + IceCube HESE and EHE alerts, we have carried out several searches for luminous electromagnetic counterparts to track-like HESE and EHE neutrino events with NASA’s *Swift* satellite [30], analyzing the data gathered via its X-ray Telescope (XRT; [29]) and UV/Optical Telescope (UVOT; [193]). The goal of these observations is to either identify the first EM counterparts to high-energy cosmic neutrinos or to set useful constraints on the nature of any

associated transient or flaring emissions from these sources. An unusual source appearing in the localization region with appropriate timing, energy, and spectral properties, supporting a scenario for joint high-energy neutrino emission, would be a strong EM counterpart candidate. This approach has demonstrated its utility with the extensive followup campaign of IceCube-170922A, when the blazar TXS 0506+056 identified as the first known source of high energy neutrinos and first identified source of extragalactic cosmic rays.

5.2 Observations

From April 2016 through December 2017, the IceCube online system [189] identified eight HESE neutrinos and six EHE neutrinos that were distributed publicly in real-time through AMON and GCN [194–207]. We triggered *Swift* follow-up observations of six of these alerts. Of these six, IceCube-160731A, IceCube-161103A, and IceCube-170312A were classified as HESE alerts while IceCube-160731A, IceCube-170321A, IceCube-170922A, and IceCube-171106A were classified as EHE alerts.

5.2.1 IceCube Data

At the time of these alerts, IceCube distributed two distinct event streams via AMON: HESE and EHE track-like events [207]. HESE cascades have relatively poor resolution in published analyses ($r_{90} \sim 15^\circ$), with the best real-time analyses offering even poorer performance, and so these neutrinos are not distributed. Key parameters reported for both streams include the arrival time, the arrival direction (R.A. and Dec.) and angular error (r_{50} for 50% containment; r_{90} for 90% containment), and the revision number. When refined localizations can be derived promptly (within a few hours of the original alert), they will be distributed as alert revisions, with each such revision having a revision number incremented by +1.

The HESE stream contains two additional event parameters: **charge** and **signal_trackness** [189]. Events with larger **charge** are more likely to have an astrophysical origin: the causally-connected charge (observed within $5\mu\text{s}$ of the event arrival time) is summed and used as an energy proxy; events yielding higher charge are likely to be of higher energy and hence, more likely to be cosmic rather than atmospheric in origin. **signal_trackness**, a number between zero and one,

is intended to reflect the likelihood that the individual HESE neutrino is both signal-like and track-like. Tracks with `signal_trackness` < 0.10 are not well distinguished from cascades in real-time analyses; therefore, only HESE neutrinos having `signal_trackness` ≥ 0.10 are distributed.

The EHE events contain an estimate of the deposited `charge`, an estimate of the neutrino `energy`, and the parameter `signalness`, an estimate of the probability that the event was due to an astrophysical (rather than atmospheric) neutrino [189].

The real-time search of IceCube high-energy neutrinos is enabled by software in-place at the South Pole since April 2016 which provides real-time identification and localization of high-energy neutrinos and rapid ($\sim$ seconds) dissemination of their positions [189].

IceCube-160731A — IceCube-160731A was detected at 01:55:04 UT on July 31, 2016 with `charge` = 15814.74 photoelectrons and `signal_trackness` = 0.91. The initial localization of this HESE neutrino candidate was RA, Dec (J2000) = (215.1090°, -0.4581°) at 01:55:45 UT (41 s after detection) with $r_{50} = 0.42^\circ$ ($r_{90} = 1.23^\circ$). IceCube updated this localization to Ra, Dec (J2000) = (214.5440°, -0.3347°) with $r_{50} = 0.35^\circ$ ($r_{90} = 0.75^\circ$) at 02:35:38 UT on August 1, 2016 (Rev. 1).

This event also triggered the EHE stream at 01:55:58 UT on July 31, 2016 (54 s after detection) with `signalness` = 0.85 and no reported value for `charge`. The EHE localization was reported as RA, Dec (J2000) = (215.0929°, -0.4191°) with $r_{50} = 0.17^\circ$ as Rev. 0. This was updated to Ra, Dec (J2000) = (214.5440° -0.3347°) with $r_{50} = 0.35^\circ$ at 02:35:54 UT on August 1, 2016 (Rev. 1). The value of r_{90} for the EHE stream is not reported in the GCN notice, however an average value of 0.81° has been published by IceCube [189].

IceCube-161103A — IceCube-161103A was detected at 09:07:31 UT on November 3, 2016 with `charge` = 7546.05 photoelectrons and `signal_trackness` = 0.30. The initial localization of this HESE neutrino candidate was reported as RA, Dec (J2000) = (40.8740°, +12.6159°) with $r_{50} = 0.42^\circ$ ($r_{90} = 1.23^\circ$) at 09:08:11 UT (Rev. 0). This was subsequently updated to RA, Dec (J2000) = (40.8252°, +12.5592°) with $r_{50} = 0.65^\circ$ ($r_{90} = 1.10^\circ$) at 14:07:40 UT (Rev. 1).

IceCube-170312A — IceCube-170312A was detected at 13:49:39 UT on March 12, 2017 with `charge` = 8858.64 photoelectrons and `signal_trackness` = 0.78.

The initial localization of this HESE neutrino candidate was reported as RA, Dec (J2000) = (304.73°, -26.24°) with $r_{50}=0.42^\circ$ ($r_{90}=1.23^\circ$) at 13:50:29 UT (Rev. 0). This was subsequently updated to RA, Dec (J2000) = (305.15°, -26.61°) with $r_{90}<0.5^\circ$ at 02:29:21 UT on March 13, 2017 (Rev. 1).

IceCube-170321A — IceCube-170321A was detected at 07:32:20 UT on March 21, 2017 with **charge** = 6214.41 photoelectrons and **signal_trackness** = 0.28. The initial localization of this EHE neutrino candidate was reported as RA, Dec (J2000) = (98.33°, -14.49°) with $r_{50}=0.32^\circ$ (no r_{90} reported) at 07:32:58 UT (Rev. 0). This was subsequently updated to RA, Dec (J2000) = (98.30°, -15.02°) with $r_{90}=1.2^\circ$ at 07:32:58 UT on March 22, 2017 (Rev. 1).

IceCube-170922A — IceCube-170922A was detected at 20:54:30.43 UT on September 22, 2017 with **charge** = 5784.96 photoelectrons and **signal_trackness** = 0.56. The initial localization of this EHE neutrino candidate was reported as RA, Dec (J2000) = (77.2853°, +5.7517°) with $r_{50}=0.25^\circ$ (no r_{90} reported) at 20:55:13 UT (Rev. 0). This was subsequently updated to RA, Dec (J2000) = (77.43 $^{+1.3}_{-0.8}$, +5.72 $^{+0.7}_{-0.4}$)° (uncertainties given are the r_{90} bounds) at 01:09:26 UT on September 23, 2017 (Rev. 1).

IceCube-171106A — IceCube-171106A was detected at 18:39:39.21 UT on November 6, 2017 with **charge** = 15456.10 photoelectrons and **signal_trackness** = 0.75. The initial localization of this EHE neutrino candidate was reported as RA, Dec (J2000) = (340.2500°, +7.3140°) with $r_{50}=0.25^\circ$ (no r_{90} reported) at 18:40:24 UT (Rev. 0). This was subsequently updated to RA, Dec (J2000) = (340.00 $^{+0.7}_{-0.5}$, 7.40 $^{+0.35}_{-0.25}$)° (uncertainties given are the r_{90} bounds) at 22:37:07 UT on November 6, 2017 (Rev. 1).

5.2.2 *Swift* Data

Swift carried out rapid follow-up observations for all six neutrinos. The IceCube-160731A alert triggered both IceCube HESE and EHE alert streams; since the HESE alert arrived earlier than the EHE alert, *Swift* follow-up observations were centered on the initial HESE position. The IceCube-161103A and IceCube-170312A alerts both triggered the HESE stream, while IceCube-170321A, IceCube-170922A, and IceCube-171106A all triggered the EHE stream. All alerts, excepting IceCube-

Neutrino Information

Name	Date	Time (UT)	RA	Dec	Charge	Signal_Trackness
IceCube-160731A	31 July, 2016	01:55:04	$214^{\circ}54^{+0.75}_{-0.75}$	$-0^{\circ}33^{+0.75}_{-0.75}$	15814.75	0.91
IceCube-161103A	3 November, 2016	09:07:31	$40^{\circ}83^{+1.10}_{-1.10}$	$+12^{\circ}56^{+1.10}_{-1.10}$	7546.05	0.30
IceCube-170312A	12 March, 2017	13:49:39	$305^{\circ}15^{+0.5}_{-0.5}$	$-26^{\circ}61^{+0.5}_{-0.5}$	8858.64	0.78
IceCube-170321A	21 March, 2017	07:32:20	$98^{\circ}30^{+1.2}_{-1.2}$	$-15^{\circ}02^{+1.2}_{-1.2}$	6214.41	0.28
IceCube-170922A	22 September, 2017	20:54:30	$77^{\circ}43^{+1.3}_{-0.8}$	$+5^{\circ}72^{+0.7}_{-0.25}$	5784.96	0.56
IceCube-171106A	6 November, 2017	18:39:39	$340^{\circ}00^{+0.7}_{-0.5}$	$+7^{\circ}40^{+0.35}_{-0.25}$	15456.10	0.75

Table 5.1: Information regarding the six neutrinos subjected to follow-up campaigns by Swift. Coordinates are provided in J2000. “S_T” is the IceCube **signal_trackness** of the event, as defined in the main text.

170321A were subjected to a Priority 1 TOO mosaic of 19 *Swift* pointings under our *Swift* Cycle 12 Guest Investigator program (PI A. Keivani). Due to its smaller angular uncertainty, IceCube-170321A was subjected to a 7 pointing mosaic. Excepting TXS 0506+056 in the IceCube-170922A followup, no transient sources were discovered in any of the campaigns [98, 208–212].

Automated analysis of the resulting *Swift* XRT data were carried out at the University of Leicester as the data were received, using the automated reduction routines of [213, 214].

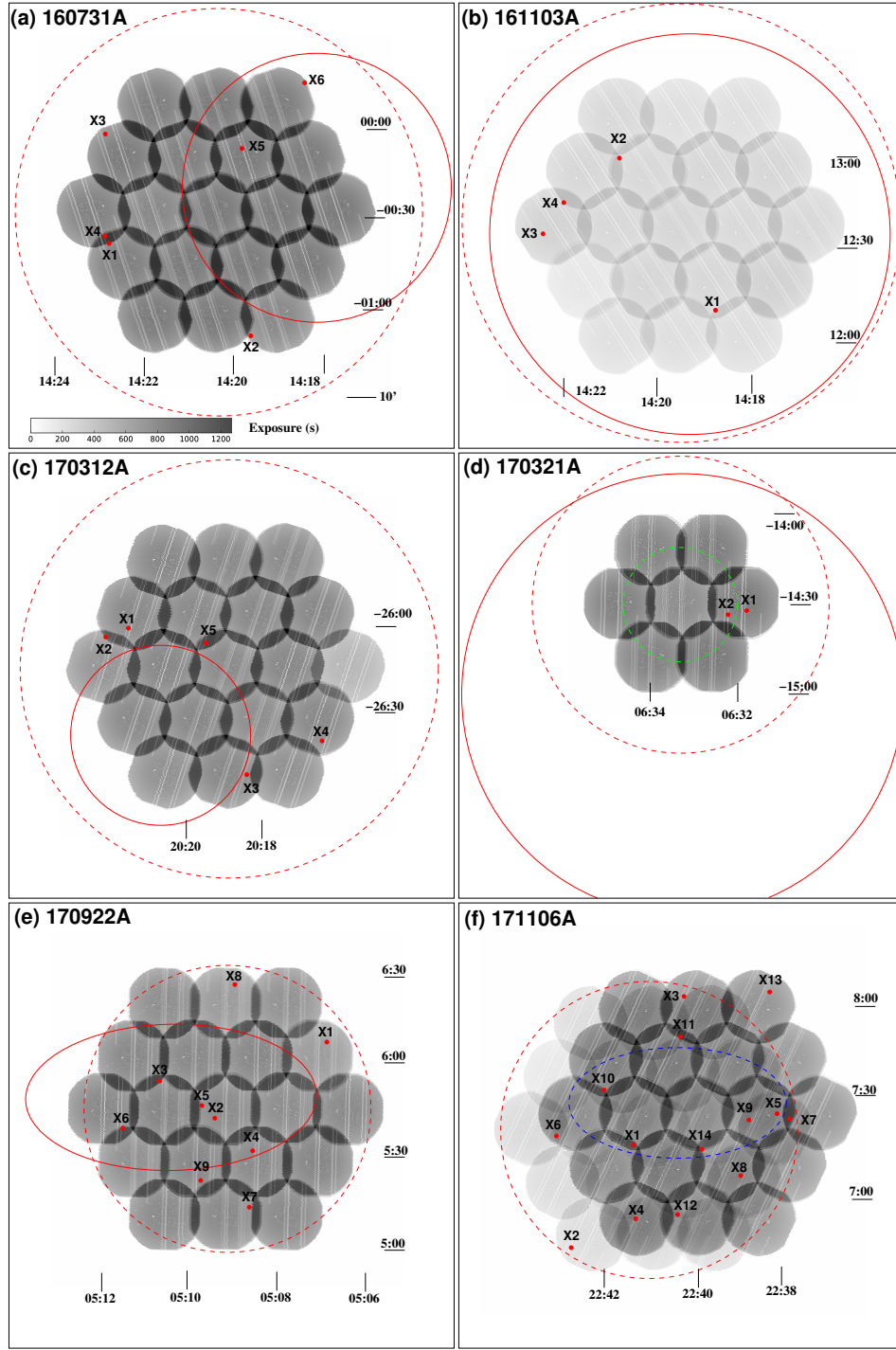


Figure 5.1: *Swift*XRT followup of the six IceCube neutrinos. Each panel shows the X-ray exposure map resulting from the adopted 19-point tiling pattern centered on the initial IceCube neutrino localization (greyscale), and the positions of all detected X-ray sources (red points). Dashed circles show the initial 90%-containment regions (or 50%-containment if the 90% is not available) for each neutrino. Solid circles show the final 90%-containment regions (or 50% if the 90% is not available). Greyscale levels indicate achieved exposure at each sky position, as shown by the color bar. The white streaks are dead regions on the XRT detector caused by a micrometeoroid impact [215].

X-ray sources from the IceCube-160731A campaign

Neutrino	Src	R.A.	Dec.	r_{90}	$R_{X,-3}$	$F_{X,-13}$	
IceCube-160731A	X1	HD 125981	14:22:46.57	−00:38:16.0	4.2''	17(4)	7.3(1.7)
	X2	[VV2006] J141936.0-010840	14:19:36.50	−01:08:45.3	4.9	13(6)	5.6(2.6)
	X3	3XMM J142253.3-000149	14:22:53.44	−00:01:50.7	5.9	22(7)	9.5(3.0)
		QSO J1422-0001					
	X4	1SXPS J142252.8-003553	14:22:53.44	−00:36:00.1	8.1	7(3)	2.9(1.4)
	X5	[VV2006] J141949.9-000644	14:19:50.15	−00:06:45.6	5.5	15(6)	6.5(2.6)
IceCube-161103A	X6	2MASS J14182661+0-14283	14:18:26.81	−00:14:29.2	6.6	15(7)	6.5(3.0)
	X1		02:42:42.34	+12:09:40.0	3.5	39^{+17}_{-13}	$1.6^{+0.7}_{-0.5}$
	X2		02:44:51.43	+12:57:23.4	6.4	38^{+18}_{-14}	$1.5^{+0.7}_{-0.6}$
	X3		02:46:31.73	+12:34:09.1	3.7	35^{+19}_{-14}	$1.4^{+0.7}_{-0.6}$
IceCube-170312A	X4		02:46:07.42	+12:44:11.4	3.0	38^{+18}_{-14}	$1.5^{+0.7}_{-0.6}$
	X1	1RXS J202121.5-260149	20:21:21.41	−26:01:32.3	6.3	28^{+8}_{-7}	$6.3^{+1.9}_{-1.7}$
	X2		20:21:54.52	−26:04:12.0	4.9	21^{+6}_{-6}	$3.4^{+0.9}_{-0.9}$
	X3		20:18:26.48	−26:50:24.6	6.5	10^{+6}_{-4}	
	X4		20:16:34.69	−26:38:56.6	5.8	16^{+6}_{-5}	
IceCube-170321A	X5		20:19:25.94	−26:06:09.9	5.5	$6.4^{+3.5}_{-2.6}$	
	X1	PMNJ0631-1430	06:31:47.52	−14:30:25.8	6.2	11^{+5}_{-4}	
		1SXPS J063147.2-143031					
	X2	2MASS J06321438-1433023	06:32:14.11	−14:33:04.6	4.3	25^{+6}_{-6}	$4.5^{+1.1}_{-1.1}$
		1SXPS J063214.5-14330					

IceCube-170922A	X1	TYC 110-755-1	05:06:53.42	+06:06:55.4	4.3	49^{+11}_{-10}	$10.5^{+2.3}_{-2.1}$
		1RXS J050653.3+060648					
	X2	1SXPS J050925.9+054134	05:09:26.44	+05:41:34.2	1.4	$73.1^{+1.1}_{-1.1}$	$20.4^{+0.3}_{-0.3}$
		TXS 0506+056					
	X3	2MASS J05103912+0554261	05:10:38.74	+05:54:29.4	5.1	15^{+4}_{-4}	
		1RXS J051038.6+055432					
	X4	XMMSL2 J050833.1+053121	05:08:33.39	+05:31:07.8	5.5	32^{+8}_{-8}	$10.1^{+2.7}_{-2.4}$
	X5	HD 33326	05:09:42.99	+05:46:57.1	2.0	$6.5^{+0.4}_{-0.4}$	$1.19^{+0.07}_{-0.07}$
		1SXPS J050942.4+054655					
	X6	PMN J0511+0538	05:11:27.92	+05:38:34.4	3.0	$8.5^{+1.4}_{-1.4}$	$6.0^{+1.0}_{-1.0}$
	X7	V* V1848 Ori	05:08:35.75	+05:12:19.1	6.0	25^{+8}_{-6}	
		XMMSL2 J050836.8+051224					
	X8	1RXS J050857.4+062633	05:08:57.84	+06:26:26.8	5.9	30^{+9}_{-7}	$7.5^{+2.2}_{-1.9}$
	X9	1RXS J050944.9+052219	05:09:44.84	+05:21:50.1	5.7	14^{+6}_{-4}	$2.1^{+0.9}_{-0.7}$
IceCube-171106A	X1	1RXS J224124.3+071253	22:41:24.15	+07:12:57.6	4.1	61^{+9}_{-9}	29^{+4}_{-4}
	X2	HD 215109	22:42:48.20	+06:40:14.2	4.4	82^{+29}_{-24}	
	X3	UGC 12138	22:40:17.12	+08:03:13.6	2.0	410^{+30}_{-30}	126^{+9}_{-9}
		3XMM J224017.0+080312					
	X4	1RXS J224122.2+064851	22:41:20.34	+06:48:58.7	5.4	32^{+9}_{-8}	$8.0^{+2.4}_{-2.0}$
	X5	87GB 223537.9+070825	22:38:10.41	+07:24:12.8	5.2	30^{+8}_{-8}	$9.9^{+2.6}_{-2.67}$
	X6	PMN J2243+0715	22:43:05.82	+07:16:34.7	5.7	9^{+5}_{-4}	
	X7		22:37:54.30	+07:22:02.9	6.8		
	X8	GALEX 2690384041306227301	22:38:59.95	+07:02:43.7	6.3	$4.1^{+4.1}_{-2.5}$	

X9		22:38:47.59	+07:22:24.8	6.1		
X10	WISE J224206.68+073148.3	22:42:06.68	+07:31:52.6	7.4	7_{-3}^{+4}	
X11		22:40:15.96	+07:48:42.2	5.9	9_{-3}^{+4}	$2.58_{-0.93}^{+1.23}$
X12		22:40:26.17	+06:50:14.3	5.9	$3.8_{-2.3}^{+3.7}$	
X13		22:38:21.18	+08:04:20.7	4.9	$3.1_{-2.5}^{+5.0}$	
X14	1RXS J223951.8+071132	22:39:52.53	+07:11:57.1	6.7	9_{-4}^{+5}	$3.7_{-1.5}^{+2.0}$

Table 5.2: R.A. and Dec. are J2000, r_{90} is the 90% confidence error region, $R_{X,-3}$ and $F_{X,-13}$ indicate count rate and energy flux, in units of 10^{-3} cts s $^{-1}$ and 10^{-13} erg cm $^{-2}$ s $^{-1}$, respectively. Fluxes are in the 0.3–10 keV band. Blank values indicate insufficient data to calculate the flux.

IceCube-160731A — *Swift* followed up the first HESE neutrino within about an hour of the neutrino arrival time at the South Pole (01:55:04 UT on July 31, 2016). *Swift* covered a region centered on RA, Dec (J2000) = (215.1090°, -0.4581°), with a radius of approximately 0.8°. *Swift* XRT collected ≈ 800 s per field of PC mode data. The observations were taken between 03:00:46 and 14:51:52 UT on July 31, 2016 and covered 2.1 deg². Assuming a Gaussian form for the neutrino localization, with the r_{90} as specified, the XRT mosaic provides 64% coverage of the localization at greater than 423 s exposure (50% of the nominal achieved exposure per field).

Six X-ray sources were detected in the observations, with all six corresponding to known X-ray emitters or objects catalogued (via SIMBAD; [216]) and from which X-ray emission may be expected. We did not discover any transient X-ray source associated with the IceCube trigger. The 3σ upper limit on the count rate in the rest of the field was 0.01 cts s⁻¹, which corresponded to a 0.3–10 keV flux of 4.3×10^{-13} erg cm⁻² s⁻¹ for a typical AGN spectrum ($N_H = 3 \times 10^{20}$ cm⁻², $\Gamma = 1.7$). Overlaps between the different tiles accounted for 0.5 deg²: in these regions the 3σ upper limit was 0.0071 cts s⁻¹, corresponding to 3.1×10^{-13} erg cm⁻² s⁻¹. Fig. 5.1(a) shows the 19-point tiling pattern centered on the IceCube neutrino, overlaid with the *Swift* exposure map, and the six detected X-ray sources.

Details of the six detected X-ray sources are provided in Table 5.2. All fluxes are 0.3–10 keV and assume the same AGN spectrum as above. Source 1 is 2.4'' from HD 125981 which SIMBAD lists as an A0IV star of magnitude 6.64 (classified by the Michigan Spectral Survey [217]). This may be a spurious detection caused by the high optical flux which can deposit enough charge in the CCD to erroneously register as X-ray events². Source 2 is 6.5'' from [VV2006] J141936.0–010840 which SIMBAD lists as a quasar. Source 3 is 2.2'' from QSO J1422–0001 which SIMBAD lists as a quasar, and 3.1'' from the known X-ray source, 3XMM J142253.3–000149. The observed X-ray flux is consistent with the flux in the 3XMM catalogue [218]. Source 4 has been previously detected by Swift (1SXPS J142252.8–003553 [219]) and the observed flux is consistent with the catalogued values. Source 5 is 5.2'' from [VV2006] J141949.9–000644 which SIMBAD lists as a quasar. Source 6 is 2.3'' from 2MASS J14182661+0014283 [220], which appears to be a late-type star.

No plausible counterparts are found in the UVOT data. All 19 tiling positions

²http://www.swift.ac.uk/analysis/xrt/optical_loading.php

were observed using the U filter. Each UVOT field of view (FOV) covers $17'.1 \times 17'.1$. There is very little overlap of the FOVs in the tiling, but there are small gaps between the FOVs. Twelve of the tilings at least partially overlap with the 90%-confidence IceCube error circle, and in total they cover about 50% of it. Each position was typically observed in four separate exposures, with an average total exposure of 427 s. The average longest single exposure for an individual position averaged 115 s. The limiting sensitivity for finding a new source is about 18.9 mag (Vega system). This accounts for both the sensitivity of UVOT and the depth of the USNO-B Catalog [221] used to reject known sources. X5 is the only XRT source inside the 90%-confidence IceCube error circle that was observed with UVOT, and a source consistent with the position of J141949.9–000644 was detected.

IceCube-161103A — *Swift* followed up the second HESE neutrino within about five hours of the neutrino arrival time at the South Pole (09:08:11 UT, November 3, 2016). The main reason for this delay was due to thermal constraints for the passively-cooled XRT. The observations were taken between 13:58:30 and 18:55:15 UT on November 3, 2016 (i.e. from 17.5 ks to 35.2 ks after the neutrino trigger), and covered 2.1 deg^2 . *Swift* covered a region centered on RA, Dec (J2000) = $(40.8740^\circ, +12.6159^\circ)$, with a radius of approximately 0.8° . *Swift* XRT collected between 150 and 250 s of PC mode data per tile.

Assuming a Gaussian form for the neutrino localization, the XRT mosaic provides 68% coverage of the localization at greater than 114 s exposure (50% of the mean achieved exposure per field).

Four X-ray sources were detected in the observations. None of these are known X-ray emitters, however all are faint, and well below the RASS limits [222], therefore we do not consider any of them to be likely counterparts to the IceCube trigger.

The 3σ upper limit on the count rate in the rest of the field was 0.03 cts s^{-1} , which corresponds to a 0.3–10 keV flux of $1.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for a typical AGN spectrum ($N_{\text{H}}=3 \times 10^{20} \text{ cm}^{-2}$, $\Gamma=1.7$). Overlaps between the different tiles accounts for 0.5 deg^2 : in these regions the 3σ upper limit is 0.02 cts s^{-1} , corresponding to $8.1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Fig. 5.1(b) shows the 19-point tiling pattern centered on the IceCube neutrino, overlaid with the *Swift* exposure map, and the four detected X-ray sources. Details of the four detected X-ray sources are in Table 5.2. All fluxes are 0.3-10 keV and assume the same AGN spectrum as above.

No plausible counterparts are found in the UVOT data. The U filter was used for 16 of the 19 tiling positions, and to avoid excessive count rates from a very bright star the UVW1 filter was used for the other 3 positions. Each UVOT FOV is inside the 90%-confidence IceCube error circle, and in total they cover about 1.54 deg². Each position was observed multiple times, with an average total exposure of 233 s. The average longest single exposure for an individual position is 107 s. The limiting sensitivity for finding a new source in the tilings with the U filter is about 18.9 mag (Vega system). For the observations with the UVW1 filter, the limiting sensitivity for finding sources ranged from 19.6 to 19.9 mag (Vega system), but identifying known sources is more difficult because redder filters were used for the USNO-B catalog. No new sources were found brighter than 19.2 mag in the UVW1 observations.

Six sources brighter than 18.9 mag were flagged as possible new sources in the 16 positions observed with the U filter. Of these, four are Solar System objects: Mallory, 1989 WU2, Albeniz, and Tomhanks. Another appears to be a high proper motion star, and the final one is an artifact due to a very bright star in the FOV. Two of the four XRT sources (Sources 2 and 4) are outside the UVOT images, and there is no evidence for a UVOT source associated with the other two.

IceCube-170312A — *Swift* followed up the third HESE neutrino just over two hours after the neutrino arrival time at the South Pole (13:49:39 UT on March 12, 2107). The observations were taken between 15:51:22 March 12 and 05:04:48 March 13 (7.3 to 54.9 ks after the neutrino trigger) and covered 2.1 deg². *Swift* focused on a region centered on RA, Dec (J2000) = (304.730° - 26.238°) with a error radius of 1.2°, covering 82.3% of the revised r_{90} error region. *Swift* XRT collected between 742 and 839 s of data per tile. Assuming a Gaussian form for the neutrino localization with the r_{90} as specified, the XRT mosaic covers 82.3% of the revised neutrino localization.

Five X-ray sources were detected in the observations. One source, X1, corresponds to a known X-ray source while the other sources were faint objects below the RASS limits [222], and thus not considered likely to be counterparts to the IceCube trigger. The 3σ upper limit on the count rate in the rest of the field was 0.01 ct s⁻¹, which corresponds to a flux of 4.1×10^{-13} erg cm⁻² s⁻¹ in the 0.3–10 KeV band. Overlaps between the different tiles account for 0.5 deg², with a 3σ

upper limit of 0.007 cts s^{-1} , or a flux of $2.9 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$.

IceCube-170321A *Swift* followed up the fourth neutrino within 7 hours of it being detected at the south pole (07:32:20 UT, March 21, 2017). Observations stretched from 14:11:15 UT to 18:02:20 UT on March 21 (23.7 ks to 37.8 ks after the neutrino trigger) and covered 0.8 deg^2 in a seven point tiling. *Swift* covered a region centered on RA, Dec (J2000) = $(98.327^\circ - 14.486^\circ)$ with a radius of 0.32° and collected between 809s and 940s of PC mode data per tile.

Two x-ray sources were detected in the observations, each of which corresponds to a known x-ray emitter catalogued via SIMBAD [216]. The 3σ upper limit on the count rate in the field was $0.0036 \text{ cts s}^{-1}$, which corresponds to a flux of $1.48 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.3-10 KeV band.

IceCube-170922A *Swift* followed up the fifth neutrino just over three hours of it being detected at the south pole (20:54:30.43 UT on September 22, 2017). Observations stretched from 00:08:11 UT to 04:17:14 UT on September 23 (11.6 ks to 26.7 ks after the initial neutrino trigger) and covered a region centered on RA, Dec (J2000) = $(77.285^\circ + 5.752^\circ)$ with a radius of 0.8° . The 19-point tiling covered an area of 2.08 deg^2 and gathered between 659 s and 819 s of PC mode data per tile.

Nine x-ray sources were detected in the observations, all of which correspond to known X-ray sources. One of the sources, X2 on Table 5.2 and Fig 5.1 panel E, the blazar TXS 0506+056, met the afterglow criteria. After Fermi-LAT reported the blazar was flaring above 800 MeV, *Swift* conducted an additional 5 ks of observations beginning on September 27. These observations showed the source brightening and its spectral index softening.

The other eight sources are not considered likely to be counterparts to the IceCube trigger. The 3σ upper limit on the count rate in the rest of the field was $0.0093 \text{ cts s}^{-1}$, which corresponds to a flux of $3.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Overlaps between the different tiles account for 0.5 square degrees and have a limit of $0.0057 \text{ cts s}^{-1}$, which corresponds to a flux of $2.3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$.

IceCube-171106A *Swift* followed up the sixth neutrino within 4 hours of it being detected at the south pole (18:39:39.21 UT on November 6 2017). Observations stretched from 21:51:12 on November 6 to 11:52:10 on November 7 (11.5 ks to

62.0 ks after the neutrino trigger). An updated neutrino position was sent out at 22:37:07 UT on November 6, during the beginning of the *Swift* observations. Due to this update, the entire 19-point tiling was shifted to match the new neutrino position, resulting in a 38-point tiling with 80 to 210 seconds of PC data in the original tiling, and 549 to 636 second of PC data per tile in the updated pointing. The observations cover an area of 2.512 deg².

Fourteen sources were detected in the observations. Nine of these sources correspond to known sources, four of which are known x-ray emitters. The remaining five sources were faint objects below the RASS limits, and thus not considered likely to be counterparts to the IceCube trigger. The 3σ upper limit on the count rate for the rest of the field was 0.01 cts s⁻¹, which corresponds to a count rate of 4.1×10^{-13} erg cm⁻² s⁻¹ in the 0.3-10 KeV band. Overlaps between the tiles account for 0.5 square degrees and have a limit of 0.009 cts s⁻¹, corresponding to a flux of 3.7×10^{-13} erg cm⁻² s⁻¹.

5.2.3 Other reported observations

Our *Swift* campaigns were not the only observations to be carried out in response to the real-time alerts for the six neutrinos. Although this information is all available in detail in the original ATel and GCN circulars, it is summarized here for convenience.

IceCube-160731A — The IceCube-160731A localization was also observed by HAWC [223], FACT [224], MAGIC [225], Fermi GBM [226], Fermi LAT [227], H.E.S.S. [228], Konus-Wind [229], AGILE [230], MAXI/GSC [231], MASTER [232], iPTF P48 [233], LCOGT [234], and ANTARES [235].

AGILE was the only follow-up campaign that reported a possible detection of a γ -ray precursor to the IceCube neutrino [230]. In a recent paper [236], AGILE reports a candidate gamma-ray precursor (AGL J1418+0008) to IceCube-160731A with an excess above 100 MeV between one and two days before the neutrino arrival time which is positionally consistent with the EHE final error region. The post-trial significance of this search is reported as 4σ . The estimated flux of this candidate γ -ray precursor is $F(E > 100 \text{ MeV}) = (3.0 \pm 1.2) \times 10^{-6}$ ph cm⁻² s⁻¹ at $l, b = (344.01^\circ, 56.03^\circ) \pm 1.0^\circ$ (95% stat. c.l. $\pm 0.1^\circ$ (syst.)). There is a possible common counterpart (1RXSJ141658.0–00144) within the error regions of IceCube-

160731A and AGL J1418+0008 with characteristics of a high-energy peaked BL Lac class of blazars [236]. No other observatories have reported a possible EM counterpart to IceCube-160731A.

Konus-Wind also performed a search for a γ -ray transient in a time window before the neutrino's arrival time ($- \sim 5$ days to $+ \sim 1$ day). They found no triggered event and estimated the 90%-confidence upper limit on the 20-1200 keV fluence to $\sim 7.7 \times 10^{-7}$ erg cm $^{-2}$ for a burst with duration less than 2.944 s and with a typical KW short GRB spectrum. For a typical long GRB spectrum, the corresponding limiting peak flux is $\sim 5.8 \times 10^{-7}$ erg cm $^{-2}$ s $^{-1}$ [229].

In X-ray band, in addition to *Swift* XRT, MAXI/GSC scanned the region around the neutrino and found no significant excess X-ray emission. They obtained the 2-20 keV 3σ upper limit of 0.104 photons cm $^{-2}$ s $^{-1}$ for a point source at the neutrino updated position [231].

In optical regime, Global MASTER network, iPTF, and LCOGT performed searches for optical transients. No astrophysical optical transient was detected within 2 deg 2 around the neutrino's location in MASTER searches, however they report a point-like CCD event (MASTER OT J142038.73-002500.1) that is very close to the very bright NGC5584 galaxy. This event is outside of the neutrino's revised error circle [232]. In iPTF searches, two optical transient candidates were found at 1.1 $^\circ$ and 2.0 $^\circ$ from the neutrino candidate position. Their respective host galaxies locate at redshifts of 0.038 and 0.054, respectively. The magnitude of the two transient candidates are 17.25 and 18.71 in Mould R filter [233]. LCOGT observations resulted in no new sources down to 3σ limiting magnitude > 19 [234].

These optical observations can be used to constrain supernovae (SNe) as a progenitor of the neutrino alert. Typically, core collapse and type Ia SNe reach maximum light ≈ 10 days after the explosion. The optical and UV observations of IceCube-160731A took place within a day of the neutrino alert. SN light curves in *R*-band suggest that optical magnitudes at $t + 1$ day are $\Delta M_R \approx 1.8$ mag fainter than peak for type Ibc SNe ([237, 238]), $\Delta M_R \approx 1$ mag for type IIP/L [239, 240], and $\Delta M_R \approx 2$ mag for type Ia ([241, 242]). Thus, the limiting magnitudes from MASTER constrain associated SNe to distances ranging from $D \lesssim 200$ Mpc to $D \lesssim 400$ Mpc. The limits from iPTF similarly constrain SNe to distances of 210 and 275 Mpc. ANTARES found no up-going muon neutrino candidate event detected within 3 $^\circ$ of the IceCube-160731A during a ± 1 h of the neutrino

arrival time. A search on an extended time window of ± 1 day also yielded no detection [235].

HAWC γ -ray observatory searched within 1.5° around the neutrino’s location for both transient and steady sources. The transient search in a time window of about 5 hours including the neutrino’s arrival time resulted in a 1.12σ detection which is not very significant. The steady source search was performed using ~ 16 months of archival data ending ~ 5 months before the neutrino’s arrival time and resulted in a 3.57σ detection. Considering the number of trials in HAWC report, this does not seem to be a significant detection [223].

No significant high-energy γ -ray emission was detected in either of MAGIC [225], FACT [224], or H.E.S.S. [228] observations.

The position of this event was occulted by the Earth for Fermi GBM at the time of detection. But Fermi LAT observed the neutrino’s updated position and placed a > 100 MeV flux upper limits of $< 1 \times 10^{-7}$ ph cm $^{-2}$ s $^{-1}$ at a 95%-confidence level in 2.25 days of exposure (beginning on July 31, 2016 at 00:00 UTC) and $< 0.6 \times 10^{-7}$ ph cm $^{-2}$ s $^{-1}$ in 8.25 days of exposure (beginning July 25, 2016 at 00:00 UTC) [227].

IceCube-161103A — The IceCube-161103A localization was observed by HAWC [243], INTEGRAL [244], Fermi GBM [245], Fermi LAT [246], Konus-Wind [247], CALET [248], MASTER [249], and ANTARES [250].

HAWC searched within 1.1° around the neutrino’s location for both transient and steady sources. The transient search in a time window of about 5 hours including the neutrino’s arrival time resulted in a 1.1σ detection which is not very significant. The steady source search was performed using ~ 16 months of archival data ending ~ 5 months before the neutrino’s arrival time and resulted in a 2.39σ detection. Considering the number of trials in HAWC report, this does not seem to be a significant detection [243].

A search for a prompt γ -ray counterpart of IceCube-161103A was performed using INTEGRAL SPI-ACS and IBIS/Veto. At the neutrino trigger time, the spacecraft was pointing far from the neutrino localization. INTEGRAL did not perform any pointed observations and estimated fluence upper limits for short and long GRB spectra [244].

Fermi GBM placed flux upper limits using the Earth Occultation technique measurements, also performed a seeded search for impulsive emission as well as

a blind search for untriggered impulsive emission. No significant candidate or impulsive emission was found [245]. The position of this neutrino was outside of the Fermi LAT FOV at the time of detection and 5000 s after it [246].

No triggered Konus-Wind γ -ray transient event happened between ~ 11 hours before to ~ 3 days after the neutrino event time [247]. A search for an X-ray and γ -ray counterpart using the CALET Gamma-ray Burst Monitor (CGBM) data shows no on-board trigger around the IceCube event time [248]. MASTER’s auto-detection system did not find any optical transient within the neutrino’s error circle and established limiting magnitudes of 20.2 and 20.5 [249]. These limits constrain SNe to distances of 350 and 400 Mpc respectively.

ANTARES found no up-going muon neutrino candidate events within 3° of the IceCube-161103A during a ± 1 h of the neutrino’s arrival time. A search on an extended time window of ± 1 day also yielded no detection [250].

IceCube-170312A — The IceCube-170312A localization was observed by MASTER. MASTER’s auto-detection software did not find any optical transients within the neutrino error circle. A limiting magnitude of 19.2 was calculated on 13 March using 20 images. Further images taken between 13-19 March have a limiting magnitude of 18.5-19.1 using 16 images [251]. The first limit constrains SNe to a distance of 220 Mpc, while the later limits constrain SNe to distance between 160 and 420 Mpc.

IceCube-170321A — The IceCube-170321A localization was observed by INTEGRAL [252], Fermi-GBM [253], Fermi-LAT [254], Konus-Wind [255], and ANTARES [256].

The IceCube-170321A position was occulted by earth, so Fermi GBM was unable to set any limits on impulsive emission. Using the Earth Occultation technique, GBM was able to place a 3σ limit of 230 mCrab between 12 and 100 KeV between the 18th and 21st of March [253]. The position was outside the Fermi LAT FOV at the time of detection, but entered the FOV after 600 s. The LAT found no significant excess γ -ray emission (0.1 - 300 GeV) within the IceCube-170321A 90% confidence localization and placed an upper limit (95% confidence) of $< 3.2 \times 10^{-7}$ photons $\text{cm}^{-2} \text{s}^{-1}$ in 1 day (beginning 12 hours prior to the T0) and $< 5.5 \times 10^{-8}$ photons $\text{cm}^{-2} \text{s}^{-1}$ in the week preceeding the T0 [254].

Konus-Wind performed a search for a γ -ray transient around the time of the

neutrino detection. They found no triggered event within ± 1000 s of the neutrino and they estimated a 90% confidence upper limit on the 10 keV to 10 MeV fluence of 6.6×10^{-7} erg cm $^{-2}$ for a burst with a duration less than 2.944 s and with a typical KW short GRB spectrum. For a typical long GRB spectrum, the corresponding limiting peak flux is 2.3×10^{-7} erg cm $^{-2}$ s $^{-1}$ [255].

INTEGRAL performed followup starting 31.5 hours after the neutrino detection, with a total of on-target time of 45 ks. IBIS was online for 39.5 ks of this time. No significant new source was found in the JEM-X data between 3 and 35 keV. The IBIS/ISGRI 25-80 keV mosaic image identified an excess with a SNR of 3.9 (3% chance of occurring randomly in the IceCube 90% confidence localization). The upper limit in the 90% confidence region was 4 mCrab between 25-80 keV, and 7 mCrab in the 80-200 band [252].

ANTARES found no upgoing muon neutrino candidate events within an hour of the IceCube event. No events were found upon extending the time window to ± 1 day [256].

IceCube-170922 — The IceCube-170922A localization included the blazar TXS 0506+056, and was observed by a very large number of collaborations. Some of the observations were carried out by HAWC [257], MAGIC [258], VERITAS [259] H.E.S.S. [260] INTEGRAL [261], Konus-Wind [262], Fermi-LAT [27], ASAS-SN [263], MASTER [264], and ANTARES [265]

HAWC searched within 1.3° of the neutrino localization for steady and transient sources. The event was not in HAWC’s FOV at the time of detection. Using the next two transits of the FOV (MJD 58018.35-59018.60 and 58019.35-59019.60), the maximum significance detected is 2.4σ . The steady search was performed using archival data from November 2014 to June 2017. The maximum significance found was 3.5σ [257].

Several IACTs searched for enhanced emission of high energy γ -rays from the direction of the blazar TXS 0506+056. MAGIC detected a $> 5\sigma$ excess of γ -rays above 100 GeV between September 28 and October 3. VERITAS and HESS found no significant excess of γ -rays [259, 260].

INTEGRAL also observed the IceCube-170922A localization and found no significant counterparts. INTEGRAL estimated the 3σ upper limit on the 75-2000 keV fluence for a burst lasting less than 1 second to be 2.8×10^{-7} erg cm $^{-2}$

and the peak flux for a long GRB to be 7.8×10^{-7} erg cm $^{-2}$ s $^{-1}$ on an 8 second timescale [261].

Konus-Wind found no triggered events from 1.7 days before the event to 3.5 days after. They estimated a 90% confidence upper limit on the 10 keV to 10 MeV fluence of 1.0×10^{-6} erg cm $^{-2}$ for a burst with a duration less than 2.944 s and with a typical KW short GRB spectrum. For a typical long GRB spectrum, the corresponding limiting peak flux is 3.1×10^{-7} erg cm $^{-2}$ s $^{-1}$ [255].

Fermi-LAT observed enhanced γ -ray flux above 800 MeV from the blazar TXS 0506+056. Using archival data, the source was found to be in a flaring state with its flux six times brighter than its catalogued value [27]. Following the Fermi alert regarding TXS 0506+056, ASAS-SN observed the blazar and found it to be brighter in the optical band than ever previously measured [263]. MASTER observed the neutrino error region and established a 5σ upper limit of 17.5 mag on single images, and 19.5 on coadd images [264].

ANTARES found no upgoing muon neutrino candidate events within 3° of the IceCube trigger within an hour of the neutrino arrival time. Extending the window to a ± 1 day also yielded no detection [265].

IceCube-171106 — The IceCube-171106A localization was observed by HAWC [266], FACT [267], INTEGRAL [268, 269] Fermi-LAT [270], Konus-Wind [271], Pan-STARRS [272], and MASTER [273].

The neutrino was not in the HAWC FOV at the time of arrival. Searching for steady sources in the 90% confidence region using archival data, HAWC found no significant sources [266]. Fact observed the initial position for 3.26 hours and the updated position for 15.64 hours. The automatic analysis found no significant signal from the observed positions. From these observations, the upper limit flux (99% confidence) was calculated as 0.35 Crab above 750 GeV [267].

The neutrino was 44° from the INTEGRAL spacecraft pointing axis at the time of the alert. INTEGRAL found no significant counterparts within 300 s of the alert. The 3σ upper limit to the 75 keV to 2 GeV fluence is 2.7×10^{-7} erg cm $^{-2}$ for a burst lasting less than 1 s. For a long GRB, the peak flux upper limit in the 75-2000 KeV range was calculated as 3×10^{-7} erg cm $^{-2}$ s $^{-1}$ for 1 s and 8.6×10^{-7} erg cm $^{-2}$ s $^{-1}$ for 8 s [268]. Further followup with INTEGRAL found no new sources in an additional 45 ks of observation time [269].

Fermi-LAT searched for transient γ -ray sources and saw no significant emission between 0.1 and 300 GeV within the 50% confidence region. Upper limits on the photon flux were calculated (95% confidence) as $< 2.0 \times 10^{-7}$ photons $\text{cm}^{-2} \text{s}^{-1}$ in one day of exposure prior to the neutrino arrival time, $< 3.4 \times 10^{-8}$ photons $\text{cm}^{-2} \text{s}^{-1}$ in the week prior, and $< 1.8 \times 10^{-9}$ photons $\text{cm}^{-2} \text{s}^{-1}$ in the eight months prior. Fermi-LAT also investigated the sources detected in the Swift followup and found no significant γ -ray emission consistent with the sources [270].

No triggered Konus Wind event occurred from 6.7 hours before the event to 1.8 days after the event. The 90% confidence upper limit on the fluence in the 10 keV to 10 MeV band is 9.0×10^{-7} erg cm^{-2} for a burst lasting less than 2.944 s assuming a typical short GRB spectrum. For a long GRB type spectrum, the limiting peak flux is 3.1×10^{-7} erg $\text{cm}^{-2} \text{s}^{-1}$ [271].

Pan STARRS observed the neutrino localization starting 37.44 hours after the neutrino arrival time using the i-band and z-band filters. No bright transient sources were found in the field. Seven fainter transients were observed, none of which were known AGN. Three transients are potentially supernova-like candidates, one of which is within 0.7 degrees of the neutrino localization. The other four are nuclear transient candidates. All seven are fainter than magnitude 21 and none can be positively identified as a true transient [272]. MASTER also performed optical followup with several of its robotic telescopes. MASTER-Kislovodsk established limiting magnitudes ranging from 18.9 to 19.3 on 6 November. MASTER-SAAO established limiting magnitudes between 19.9 and 20.6 on 6 November. MASTER-IAC calculated limiting magnitudes between 17.8 and 19.6 on 7 November. These correspond to distance limits ranging from 190 to 420 Mpc. MASTER-Tavrida began its observations after a week and calculated limits between 17.8 and 19.5 on 13 November, corresponding to SNe distance limits between 180 and 500 Mpc. Lastly, MASTER-SAAO calculated further limits on November 29, getting limiting magnitudes between 18.9 and 20. This provides a SNe distance limits ranging from 400 Mpc to 630 Mpc [273].

5.2.4 3FGL Sources

We checked the LAT 4-year point source catalog (3FGL) [274] for possible sources within 90% error region of each of the neutrino localizations. For IceCube-160731A,

the closest 3FGL object was 3FGL J1418.4–0233 with an angular separation of 2.23° , which corresponds to the BL Lac object NVSS J141826–023336. The closest to IceCube-161103A was 3FGL J0239.4+1326, and unclassified object $1^\circ 29'$ away and outside the 90% confidence bounds. Nearest to the IceCube-170312A localization was the unclassified source 3FGL J2025.1–2858 $2^\circ 57'$ away. The closest 3FGL object to the IceCube-170321A localization was 3FGL J0627.9–1517, also known as the blazar candidate NVSS J062753–152003. It was just outside of the 90% confidence localization, with an angular separation of 1.30° and it showed no enhanced γ -ray activity within 24 hours of the neutrino detection [254]. Closest to the IceCube-171106A localization was 3FGL J2234.8+0945, also known as the pulsar PSR J2234+0944. It was $2^\circ 68'$ away from the best fit position.

The only localization to contain a 3FGL source was IceCube-170922A, which contained 3FGL J0509.4+0541. Also known as TXS 0506+056, this source was 0.07° from the best fit position. Additionally, in the weeks prior to IceCube-170922A, TXS 0506+056 demonstrated enhanced γ -ray flux. Extensive followup from various observatories identified this blazar as the likely source of the neutrino.

5.3 Discussion

Here we review reported community follow-up efforts for the six neutrinos, and discuss the results of the follow-up campaigns for each neutrino in light of common transient and variable source scenarios.

5.3.1 Specific source scenarios

Given the broad range of possible sources for the high-energy cosmic neutrinos, and in the interests of brevity, we now explore the physical implications and associated model constraints for a few of these source scenarios.

Blazar flare activity — In a search for neutrino emission from blazars in the second Fermi LAT AGN catalogue (2LAC; [275]), the IceCube collaboration has used three years of neutrino data to constrain the maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to $\sim 27\%$ or less between ~ 10 TeV and 2 PeV [276]. This search assumes a spectral index of -2.5 in a power-law spectrum.

In another study [143], major outburst of blazar PKS B1424–418 occurred in temporal and spatial coincidence of a PeV neutrino. However, this single source has sufficiently high fluence to explain the observed coincident PeV neutrino.

The energy flux threshold on identified or associated blazars from 3FGL is $\sim 3.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. Assuming a fiducial distance of $\sim 10 \text{ Gpc}$, the corresponding luminosity threshold will be $\sim 3.9 \times 10^{46} \text{ erg s}^{-1}$. The energy flux threshold on TeV blazars observed by *Swift* XRT [277] is $\sim 5.0 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. Assuming a fiducial distance of $\sim 10 \text{ Gpc}$, the corresponding luminosity threshold will be $\sim 6.0 \times 10^{46} \text{ erg s}^{-1}$.

Work by [146] placed constraints on the source density of powerful blazar jets such as BL Lac objects ($n_0^{\text{eff}} \sim 5 \times 10^{-9} \text{ Mpc}^{-3}$) and FSRQs ($n_0^{\text{eff}} \sim 2 \times 10^{-12} \text{ Mpc}^{-3}$) suggesting these classes are unlikely to be the dominant sources of IceCube’s neutrinos.

Though not the dominant source of IceCube neutrinos, the identification of TXS 0506+056 as the likely source of IceCube-170922A has demonstrated that they are a source of at least a fraction of the IceCube neutrinos. In the followup to IceCube-170922A, TXS 0506+056 was quickly identified as an interesting source as the closest X-ray and γ -ray bright object near the neutrino best fit position [98]. Further investigation by the Fermi-LAT team found that the blazar was in a flaring state at the time of the neutrino alert and for several weeks leading up to the neutrino alert [27]. Following this, IceCube performed an archival analysis of 9.5 years of neutrino data. Their search found an excess of high-energy neutrinos from the region near TXS 0506+056. This independent 3.5σ neutrino excess supports the case for TXS 0506+056 as the source of IceCube-170922A [99].

GRBs — To evaluate constraints on any associated GRB X-ray afterglows, we make use of a library of 192 *Swift* XRT lightcurves and piecewise power-law fits for *Swift*-detected GRB afterglows, compiled by [278]. Using the power-law fits allows us to calculate fluxes for these afterglows at arbitrary times; since fits exclude intervals of X-ray flaring (e.g. [279]) this approach is conservative with respect to such activity.

Fig. 5.2 shows the median X-ray afterglow flux (black line), and 80%-distribution (light grey) and 50%-distribution (dark grey) ranges on afterglow flux, over the period from $t + 4 \text{ ks}$ to $t + 60 \text{ ks}$ post-burst relevant to our observations (assuming

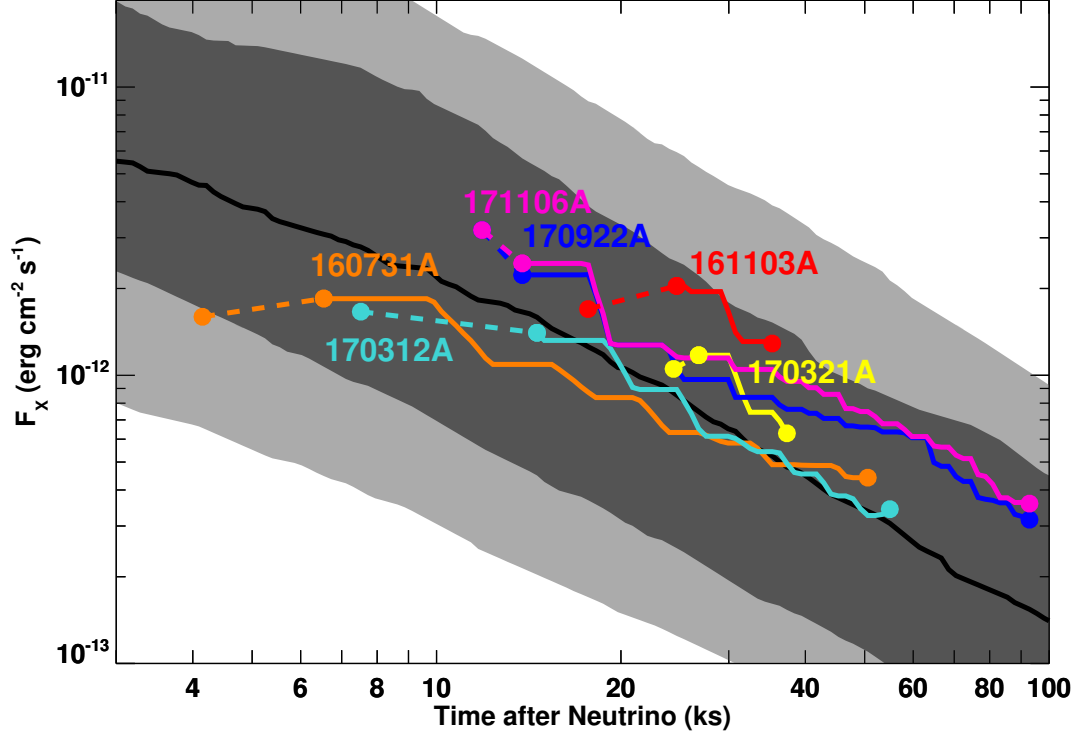


Figure 5.2: X-ray flux limits from *Swift* XRT follow-up campaigns targeting the six neutrinos (IceCube-160731A, orange; IceCube-161103A, red; IceCube-170312A, light blue; IceCube-170321A, yellow; IceCube-170922A, blue; IceCube-171106A, magenta), along with the median flux (black line), 80%-distribution (light grey), and 50%-distribution (dark grey) ranges on afterglow flux for the library of 192 *Swift* XRT afterglow light curves (and piecewise power-law fits) from [278]. Solid lines show average achieved limits from completion of the first observation of the last pointing until the end of the campaign, while dashed lines show flux limits for initial intervals of partial coverage.

the neutrino detection time to be coincident with the GRB). Superposed on the afterglow flux ranges are X-ray flux limits for the six neutrino follow-up campaigns, averaged over the seven or 19 tiles of each mosaic pointing. These limits are derived from the exposure history of these observations using Poisson statistics and a standard XRT afterglow counts to flux conversion factor of $4 \times 10^{-11} \text{ erg cm}^{-2} \text{ ct}^{-1}$. Specifically, the flux limit is defined as the number of source photons required (at any given time) to yield an excess over background with p -value $p \leq 10^{-6}$ in a single source aperture. Given the total FOV of each mosaic, such excesses will occur via

Poisson fluctuation of the background in roughly 10% of 19-tile campaigns (4% of seven-tile campaigns). Our limits indicate that between 30% and 65% of the X-ray afterglows of *Swift*-detected GRBs would be recovered by the follow-up campaigns of these neutrinos, assuming the burst occurred within the FOV of the observations, and ignoring the increased sensitivity provided over regions of pointing overlap (which cover very little sky area). Delay time-based recovery fractions for the six neutrino campaigns are provided in Table 5.3.

These constraints are shown graphically in Fig. 5.2, with a solid line extending from the time when observations of the 19th (final) pointing of each mosaic commenced until the end of the last exposure. Completion of the first exposure of the first pointing of each mosaic is indicated with an additional dot (and dashed line), showing the time when partial-coverage constraints from each campaign begin to accumulate.

Combining the delay time-based recovery fractions ($p_{\Delta t, X}$) and coverage-based recovery fractions ($p_{\Omega, X}$) with the probabilities of cosmic origin (p_S) for each neutrino, as listed in Table 5.3, we find net recovery probabilities (p_{total}) for *Swift*-like GRB X-ray afterglows of 2.6% to 39% for the six campaigns. Taken together, if every single IceCube high-energy cosmic neutrino were accompanied by a *Swift*-like GRB X-ray afterglow, then the probability of observing zero candidate counterparts after these six campaigns would be $p = 18\%$. Hence, further campaigns will be necessary to yield a high-confidence exclusion of this hypothesis from *Swift* follow-up observations alone.

In their previous and independent search, IceCube placed limits on neutrino emission models for neutrinos of all flavors from 807 GRBs [280]. Models with the hypothesis that GRBs are the dominant sources of neutrino flux, e.g. the simplest versions of the fireball model were ruled out. Models surviving IceCube’s constraints in this search required relatively low neutrino production efficiencies. High-luminosity GRBs can still be the sources of Ultra-High Energy Cosmic Rays (UHECRs), if neutrino emission is not correlated with UHECR emission [281]. Another study [282] showed that GRBs with fast time variability without additional prominent pulse structure could be considered as neutrino emitters.

Supernovae — The most useful limits to constrain supernovae (SNe) come from *Swift* UVOT, iPTF, LCOGT, and MASTER observations of the six neutrino

localizations. Specifics of the limiting magnitudes and the respective distance limits are presented in Sec 5.2.3. Supernova limits were established for IceCube-160731A, IceCube-161103A, IceCube-170312A, and IceCube-171106A. No optical follow-up was performed for IceCube-170321A, while the source IceCube-170922A was quickly identified as the blazar TXS 0506+056, excluding them from the supernova discussion.

Over the four optical follow-up campaigns, we calculated distance limits ranging from 160 Mpc to 630 Mpc. IceCube-160731A recieved the most follow-up, with a best limit of 400 Mpc from MASTER. MASTER’s best limit for IceCube-161103A was similarly 400 Mpc. MASTER’s prompt observations of IceCube-170312A established limits of 220 Mpc, with later followup extending that to 420 Mpc. IceCube-171106A was observed by MASTER and Pan STARRS. Initial observations established a best limit of 420 Mpc, while additional followup days later established a stronger limit of 630 Mpc.

Since IceCube is sensitive to multiplets of rare transient sources down to local rates of $\mathcal{R} \lesssim 10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1}$ [283], the absence of such multiplets likely excludes an origin for the cosmic neutrinos in the prompt (core collapse / shock breakout) emissions of core collapse SNe ($\mathcal{R}_{\text{CCSN}} \sim 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$; [284]) or even, jet-driven Ibc SNe / low-luminosity GRBs ($\mathcal{R}_{\text{LLGRB}} \sim 3 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$; [285]). Classical long-duration GRBs ($\mathcal{R}_{\text{LGRB}} \sim 10^{-9} \text{ Mpc}^{-3} \text{ yr}^{-1}$; [286]) are not excluded on this basis; the absence of ν -GRB coincidence events is more constraining [280].

5.3.2 Future efforts

All of the above constraints are subject to a discount factor due to the probability of the IceCube event being an atmospheric neutrino or muon, rather than a track-like interaction of an astrophysical neutrino for the six neutrino events studied. In particular, it is possible that some or all of the events resulted from atmospheric cosmic ray interactions rather than cosmic sources. This is the primary reason why model constraints will have to await the completion of a sustained campaign of follow-up observations of IceCube’s likely-cosmic high-energy neutrinos.

Moreover, given the inevitable delay in commencing high-sensitivity X-ray and UV/optical observations, which have here provided on average 70% coverage, it remains possible that one or even both neutrinos were accompanied by a relatively

Characteristic Probabilities for *Swift*
Neutrino Follow-Up Campaigns

Event	p_S	$p_{\Omega,X}$	$p_{\Delta t,X}$	p_{total}
IceCube-160731A	91%	64%	65%	38%
IceCube-161103A	30%	68%	30%	6.1%
IceCube-170312A	78%	92%	55%	39%
IceCube-170321A	28%	22%	43%	2.6%
IceCube-170922A	56%	79%	46%	20%
IceCube-171106A	75%	98%	45%	33%

Table 5.3: p_S is the probability of the IceCube event being a track-like interaction of an astrophysical neutrino, rather than an atmospheric neutrino or muon. $p_{\Omega,X}$ is the probability of any associated neutrino point source lying within the coverage area defined by the *Swift* XRT follow-up campaign for that event. $p_{\Delta t,X}$ is the probability for an associated *Swift*-type GRB X-ray afterglow to be recovered, given the exposure history for each campaign. p_{total} is the multiplication of the first three probabilities, indicating the total recovery probability for each event, for an associated *Swift*-type GRB X-ray afterglow.

bright EM counterpart that eluded our attempts to capture it.

Table 5.3 shows three different probabilities and their product for each event: the probability of the IceCube event being a track-like interaction of an astrophysical neutrino, rather than an atmospheric neutrino or muon (p_S), the probability of any associated neutrino point source lying within the coverage area defined by the *Swift* XRT follow-up campaign for that event ($p_{\Omega,X}$), the probability for an associated *Swift*-type GRB X-ray afterglow to be recovered, given the exposure history for each campaign ($p_{\Delta t,X}$). The last column shows the multiplication of these three probabilities which is the probability of recovering the source with *Swift* XRT if the emitting object is a long GRB with luminosity drawn from the distribution of GRB luminosities which triggered Swift-BAT. Note that, since the BAT sample is by definition flux limited, a typical GRB will on average be less luminous than a BAT-detected GRB. The average of the total probabilities derived here is 22%. A rough estimate of the minimum required campaigns to establish useful constraints will therefore be 4.5 campaigns.

We plan to continue these searches following up ~ 3 neutrino events with the best localizations and highest p_S per year. Since EHE neutrinos have on average

better localization than HESE, two out of these three planned campaigns will be more likely EHE if they pass the **signalness** cut.

A publishable claim of an electromagnetic counterpart to a neutrino source could potentially be made on the basis of an unusual and a priori unlikely source appearing in the localization region with appropriate timing, energy, and spectral properties supporting a scenario for joint high-energy neutrino emission.

5.4 Conclusions

We have reported the results of six *Swift* satellite follow-up campaigns on likely-cosmic neutrinos detected by the IceCube neutrino observatory, IceCube-160731A, IceCube-161103A, IceCube-170312A, IceCube-170321A, IceCube-170922A, and IceCube-171106A. In observations covering a significant fraction of the 90% containment regions with mean epochs on the order of hours post neutrino, we identified one compelling counterpart: the blazar TXS 0506+056, likely associated with IceCube-170922A [2, 287]. Apart from this detection, we identified no compelling X-ray or UV/optical counterparts for any of the high-energy neutrinos.

For all of the detections, we discuss the limits generated from the non-detection of transient counterparts. We discussed these limits in the context of three potential source models for the cosmic neutrinos: blazars/active galaxies, *Swift*-detected gamma-ray bursts (GRBs), and low-redshift ($z \lesssim 0.1$) SNe.

Our results show that we would need another ~ 5 such follow-up campaigns to reach a significant probability that the source classes discussed could be the EM transient counterparts to the IceCube neutrinos.

Chapter 6

Conclusions

Multimessenger astrophysics is a rising field. While the sources of the highest energy cosmic rays and high energy neutrinos remain unknown from single messenger observations, coincident detection of neutrinos and γ -rays can lead to the positive identification of neutrino sources. Multimessenger searches have already shown their potential, with the coincident detection of a neutron star merger and a GRB, as well as the detection of neutrinos during an outburst from the blazar TXS 0506+056.

As part of my work as a member of AMON, I have worked on several searches for electromagnetic counterparts to high energy neutrinos. In our first project, we searched for a statistical excess of neutrinos from several northern blazars when they were bright in TeV γ -rays. We found no statistical excess, but saw that for Markarian 421 in particular, we were close to being able to place physically meaningful limits on how much of TeV flux could have come from hadronic sources.

Our second and third projects were searches for neutrino coincidences with γ -rays detected by the Fermi satellite's Large Area Telescope. Our search with ANTARES data found no evidence of either a subthreshold population of $\nu+\gamma$ transients, or an excess of high significance coincidences. Our search with IceCube data likewise found no significant excess, but did observe a trend where neutrinos in the IC59 dataset were more likely to arrive from regions of the sky that were γ -ray bright. This trend was not observed in the ANTARES data, but is interesting enough to be worth following up in a future project.

A fourth project has been participating in the Swift followups to IceCube neutrino alerts. This includes followups to IceCube multiplets, such as the followup of the first IceCube triplet [192], and followups to both HESE and EHE neutrinos

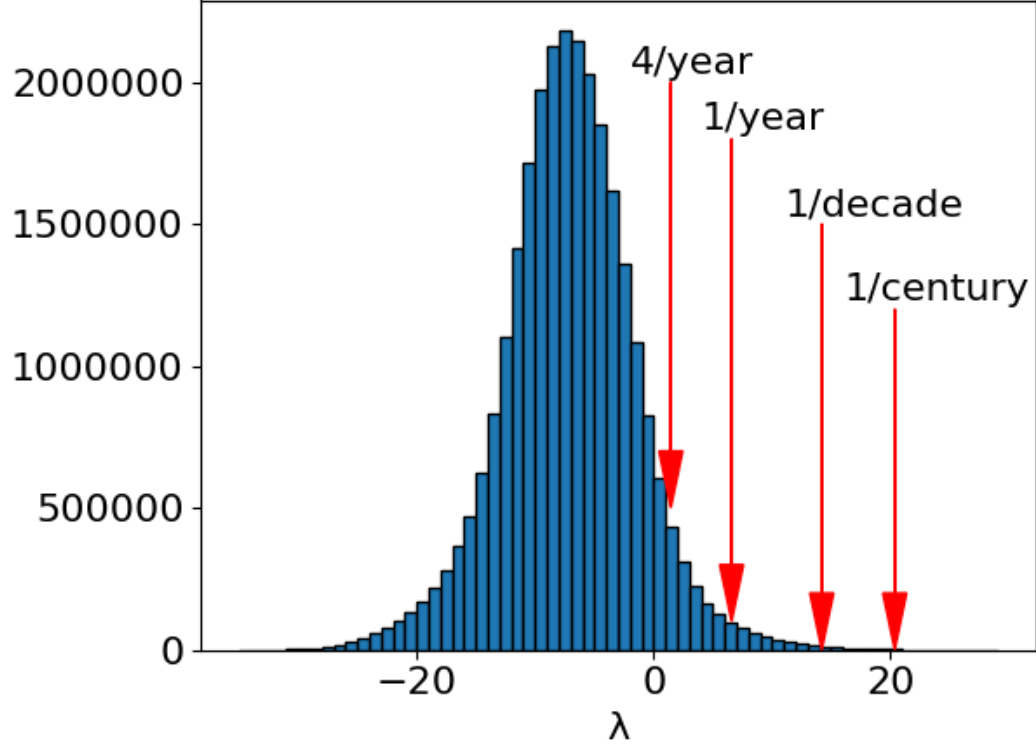


Figure 6.1: Histogram showing the λ distribution used to calibrate the Fermi-ANTARES alert stream. Red lines mark thresholds of 4/year, 1/year, 1/decade, and 1/century.

discussed in Chapter 5.

One offshoot of these archival searches is the development of real time alerts for significant $\nu+\gamma$ transients. The Fermi-ANTARES coincidence stream is currently running and distributing alerts via email while we await the activation of the formal GCN stream. The Fermi-IceCube stream is still undergoing development.

The Fermi-ANTARES stream is currently designed such that it flags any coincidence with a false alarm rate lower than 4/year. Fig 6.1 shows the histogram used to calibrate the real time analysis, including the relevant alert thresholds. Currently, the real time stream has identified a few events above the 4/year threshold, and one coincidence above the 1/year and 1/decade threshold. This last event was a coincidence between a neutrino and two photons, one of which had an energy of 220 GeV. The coincidence had a significance of 1/16.3 years, but

unfortunately was 25° from the Sun, making most followup impossible.

Bibliography

- [1] ABBOTT, B. P. ET AL. (2017) “Multi-messenger Observations of a Binary Neutron Star Merger,” *Astrophys. J.*, **848**(2), p. L12, [1710.05833](#).
- [2] AARTSEN, M. G. ET AL. (2018) “Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A,” *Science*, **361**(6398), p. eaat1378, [1807.08816](#).
- [3] DE ANGELIS, A. and M. J. M. PIMENTA (2013) *Introduction to particle and astroparticle physics: questions to the Universe*, Undergraduate lecture notes in physics, Springer, Milan.
URL <http://cds.cern.ch/record/1529338>
- [4] WULF, T. (1910) “Beobachtungen über Strahlung hoher Durchdringungsfähigkeit auf dem Eiffelturm,” *Physikalische Zeitschrift*, **11**, pp. 811–813.
- [5] HESS, V. F. (1912) “Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten,” *Physikalische Zeitschrift*, **13**, p. 1084.
- [6] HESS, V. (2018) “On the Observations of the Penetrating Radiation during Seven Balloon Flights,” [1808.02927](#).
- [7] MILLIKAN, R. A. and G. H. CAMERON (1928) “The Origin of the Cosmic Rays,” *Phys. Rev.*, **32**, pp. 533–557.
URL <https://link.aps.org/doi/10.1103/PhysRev.32.533>
- [8] ROSSI, B. (1934) “Directional measurements on the cosmic rays near the geomagnetic equator,” *Physical Review*, **45**(3), p. 212.
- [9] ALVAREZ, L. and A. H. COMPTON (1933) “A positively charged component of cosmic rays,” *Physical Review*, **43**(10), p. 835.
- [10] JOHNSON, T. H. (1933) “The azimuthal asymmetry of the cosmic radiation,” *Physical Review*, **43**(10), p. 834.
- [11] PIRAN, T. (1999) “Gamma-ray bursts and the fireball model,” *Phys. Rept.*, **314**, pp. 575–667, [astro-ph/9810256](#).

- [12] COWAN, C. L., F. REINES, F. B. HARRISON, H. W. KRUSE, and A. D. MCGUIRE (1956) “Detection of the free neutrino: A Confirmation,” *Science*, **124**, pp. 103–104.
- [13] DAVIS, R., JR., D. S. HARMER, and K. C. HOFFMAN (1968) “Search for neutrinos from the sun,” *Phys. Rev. Lett.*, **20**, pp. 1205–1209.
- [14] FANTINI, G., A. GALLO ROSSO, F. VISSANI, and V. ZEMA (2018) “Introduction to the Formalism of Neutrino Oscillations,” *Adv. Ser. Direct. High Energy Phys.*, **28**, pp. 37–119, [1802.05781](#).
- [15] BIONTA, R. M. ET AL. (1987) “Observation of a Neutrino Burst in Coincidence with Supernova SN 1987a in the Large Magellanic Cloud,” *Phys. Rev. Lett.*, **58**, p. 1494.
- [16] MARASCHI, L., G. GHISELLINI, and A. CELOTTI (1992) “A jet model for the gamma-ray emitting blazar 3C 279,” *Astrophysical Journal, Letters*, **397**, pp. L5–L9.
- [17] BÖETTCHER, M. (2007) “Modeling the Emission Processes in Blazars,” *Astrophys. Space Sci.*, **309**, pp. 95–104, [astro-ph/0608713](#).
- [18] SPURIO, M. (2015) *Particles and Astrophysics*.
- [19] COMPTON, A. H. (1923) “A Quantum Theory of the Scattering of X-rays by Light Elements,” *Physical Review*, **21**, pp. 483–502.
- [20] FERMI, E. (1949) “On the origin of the cosmic radiation,” *Physical Review*, **75**(8), p. 1169.
- [21] INOUE, Y., S. INOUE, M. A. R. KOBAYASHI, R. MAKIYA, Y. NIINO, and T. TOTANI (2013) “Extragalactic Background Light from Hierarchical Galaxy Formation: Gamma-ray Attenuation up to the Epoch of Cosmic Reionization and the First Stars,” *Astrophys. J.*, **768**, p. 197, [1212.1683](#).
- [22] FINKE, J. D., S. RAZZAQUE, and C. D. DERMER (2010) “Modeling the Extragalactic Background Light from Stars and Dust,” *Astrophys. J.*, **712**, pp. 238–249, [0905.1115](#).
- [23] GREISEN, K. (1966) “End to the cosmic-ray spectrum?” *Physical Review Letters*, **16**(17), p. 748.
- [24] ZATSEPIN, G. T. and V. A. KUZ’MIN (1966) “Upper limit of the spectrum of cosmic rays,” *ZhETF Pisma Redaktsiiu*, **4**, p. 114.
- [25] AHARONIAN, F., L. BERGSTRÖM, and C. DERMER (2013) *Astrophysics at Very High Energies*.

- [26] CROCKER, R. M. and F. AHARONIAN (2011) “Fermi Bubbles: Giant, Multibillion-Year-Old Reservoirs of Galactic Center Cosmic Rays,” *Physical Review Letters*, **106**(10), 101102, [1008.2658](#).
- [27] TANAKA, Y. T., S. BUSON, and D. KOCEVSKI (2017) “Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.” *The Astronomer’s Telegram*, **10791**.
- [28] BARTHELMY, S. D. ET AL. (2005) “The Burst Alert Telescope (BAT) on the Swift MIDEX mission,” *Space Sci. Rev.*, **120**, p. 143, [astro-ph/0507410](#).
- [29] BURROWS, D. N. ET AL. (2005) “The Swift X-ray Telescope,” *Space Sci. Rev.*, **120**, p. 165, [astro-ph/0508071](#).
- [30] GEHRELS, N. ET AL. (2004) “The Swift Gamma-Ray Burst Mission,” *Astrophys. J.*, **611**, pp. 1005–1020, [Erratum: *Astrophys. J.* 621, 558(2005)], [astro-ph/0405233](#).
- [31] ATWOOD, W. B. ET AL. (2009) “The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission,” *Astrophys. J.*, **697**, pp. 1071–1102, [0902.1089](#).
- [32] MEEGAN, C., G. LICHTI, P. N. BHAT, E. BISSALDI, M. S. BRIGGS, V. CONNAUGHTON, R. DIEHL, G. FISHMAN, J. GREINER, A. S. HOOVER, A. E. J. VAN DER HORST, A. VON KIENLIN, R. M. KIPPEN, C. KOUVELIOTOU, S. MCBREEN, W. S. PACIESAS, R. PREECE, H. STEINLE, M. S. WALLACE, R. B. WILSON, and C. WILSON-HODGE (2009) “The Fermi Gamma-ray Burst Monitor,” *Astrophysical Journal*, **702**(1), pp. 791–804, [0908.0450](#).
- [33] AUGER, P. ET AL. (1939) “Extensive cosmic-ray showers,” *Reviews of Modern Physics*, **11**(3-4), p. 288.
- [34] CARLSON, J. and J. OPPENHEIMER (1937) “On multiplicative showers,” *Physical Review*, **51**(4), p. 220.
- [35] LÃSPEZ-ORAMAS, A. (2014) *Multi-year campaign of the gamma-ray binary LS I +61Åž 303 and search for VHE emission from gamma-ray binary candidates with the MAGIC telescopes*, Ph.D. thesis, Barcelona, Autonomia U. URL <https://magic.mpp.mpg.de/backend/publication/show/280>
- [36] WEEKES, T. C. ET AL. (1989) “Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique,” *Astrophys. J.*, **342**, pp. 379–395.

- [37] KILDEA, J. ET AL. (2007) “The Whipple Observatory 10-m gamma-ray telescope, 1997-2006,” *Astropart. Phys.*, **28**, pp. 182–195.
- [38] HOLDER, J. ET AL. (2006) “The first VERITAS telescope,” *Astropart. Phys.*, **25**, pp. 391–401, [astro-ph/0604119](#).
- [39] BERNLÄUHR, K. ET AL. (2003) “The optical system of the HESS imaging atmospheric Cherenkov telescopes, Part 1: Layout and components of the system,” *Astropart. Phys.*, **20**, pp. 111–128, [astro-ph/0308246](#).
- [40] CORTINA, J., F. GOEBEL, and T. SCHWEIZER (2009) “Technical Performance of the MAGIC Telescopes,” [0907.1211](#).
- [41] SHARMA, M., B. CHINMAY, N. BHATT, S. BHATTACHARYYA, S. BOSE, A. MITRA, R. KOUL, A. K. TICKOO, and R. C. RANNOT (2017) “Sensitivity estimate of the MACE gamma ray telescope,” *Nucl. Instrum. Meth.*, **A851**, pp. 125–131, [1701.01120](#).
- [42] ANDERHUB, H. ET AL. (2011) “FACT – the First Cherenkov Telescope using a G-APD Camera for TeV Gamma-ray Astronomy (HEAD 2010),” *Nucl. Instrum. Meth.*, **A639**, pp. 58–61, [1010.2397](#).
- [43] ONG, R. A. (2018) “Cherenkov Telescope Array: The Next Generation Gamma-ray Observatory,” *PoS, ICRC2017*, p. 1071, [1709.05434](#).
- [44] ABDO, A. A. ET AL. (2007) “TeV Gamma-Ray Sources from a Survey of the Galactic Plane with Milagro,” *Astrophys. J.*, **664**, pp. L91–L94, [0705.0707](#).
- [45] DEYOUNG, T. and HAWC COLLABORATION (2012) “The HAWC observatory,” *Nuclear Instruments and Methods in Physics Research A*, **692**, pp. 72–76.
- [46] AAB, A. ET AL. (2015) “The Pierre Auger Cosmic Ray Observatory,” *Nucl. Instrum. Meth.*, **A798**, pp. 172–213, [1502.01323](#).
- [47] ACHTERBERG, A., M. ACKERMANN, J. ADAMS, J. AHRENS, K. ANDEEN, D. W. ATLEE, J. BACCUS, J. N. BAHCALL, X. BAI, and ET AL. (2006) “First year performance of the IceCube neutrino telescope,” *Astroparticle Physics*, **26**, pp. 155–173, [astro-ph/0604450](#).
- [48] AGERON, M. ET AL. (2011) “ANTARES: the first undersea neutrino telescope,” *Nucl. Instrum. Meth.*, **A656**, pp. 11–38, [1104.1607](#).
- [49] AARTSEN, M. G. ET AL. (2013) “First observation of PeV-energy neutrinos with IceCube,” *Phys. Rev. Lett.*, **111**, p. 021103, [1304.5356](#).

- [50] AARTSEN, M. G. ET AL. (2013) “Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector,” *Science*, **342**, p. 1242856, [1311.5238](#).
- [51] AARTSEN, M. G. ET AL. (2014) “Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data,” *Phys. Rev. Lett.*, **113**, p. 101101, [1405.5303](#).
- [52] WAXMAN, E. and J. BAHCALL (1997) “High Energy Neutrinos from Cosmological Gamma-Ray Burst Fireballs,” *Physical Review Letters*, **78**, pp. 2292–2295, [astro-ph/9701231](#).
- [53] BAHCALL, J. N. and E. WAXMAN (2001) “High-energy astrophysical neutrinos: The Upper bound is robust,” *Phys. Rev.*, **D64**, p. 023002, [hep-ph/9902383](#).
- [54] AARTSEN, M. G., M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, D. ALTMANN, T. ANDERSON, C. ARGUELLES, and ET AL. (2014) “Search for Prompt Neutrino Emission from Gamma-Ray Bursts with IceCube,” *ArXiv.org*, **1412.6510**, [1412.6510](#).
- [55] LAHA, R., J. F. BEACOM, B. DASGUPTA, S. HORIUCHI, and K. MURASE (2013) “Demystifying the PeV Cascades in IceCube: Less (Energy) is More (Events),” *Phys. Rev.*, **D88**, p. 043009, [1306.2309](#).
- [56] ANCHORDOQUI, L. A. ET AL. (2014) “Cosmic Neutrino Pevatrons: A Brand New Pathway to Astronomy, Astrophysics, and Particle Physics,” *JHEAp*, **1-2**, pp. 1–30, [1312.6587](#).
- [57] MURASE, K. (2015) “On the origin of high-energy cosmic neutrinos,” in *American Institute of Physics Conference Series*, vol. 1666 of *American Institute of Physics Conference Series*, p. 040006, [1410.3680](#).
- [58] WAXMAN, E. (2015) “The origin of IceCube’s neutrinos: Cosmic ray accelerators embedded in star forming calorimeters,” *ArXiv.org*, **1511.00815**, [1511.00815](#).
- [59] GAO, S., K. KASHIYAMA, and P. MÁŁSZÁROS (2013) “On the neutrino non-detection of GRB 130427A,” *Astrophys. J.*, **772**, p. L4, [1305.6055](#).
- [60] BUSTAMANTE, M., P. BAERWALD, K. MURASE, and W. WINTER (2015) “Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts,” *Nature Communications*, **6**, 6783, [1409.2874](#).
- [61] ABBASI, R. ET AL. (2012) “An absence of neutrinos associated with cosmic-ray acceleration in γ -ray bursts,” *Nature*, **484**, pp. 351–353, [1204.4219](#).

- [62] ADRIAN-MARTINEZ, S. ET AL. (2013) “Search for muon neutrinos from gamma-ray bursts with the ANTARES neutrino telescope using 2008 to 2011 data,” *Astron. Astrophys.*, **559**, p. A9, [1307.0304](#).
- [63] LOEB, A. and E. WAXMAN (2006) “The Cumulative background of high energy neutrinos from starburst galaxies,” *JCAP*, **0605**, p. 003, [astro-ph/0601695](#).
- [64] MURASE, K., M. AHLERS, and B. C. LACKI (2013) “Testing the hadronuclear origin of PeV neutrinos observed with IceCube,” *Physical Review D*, **88**(12), 121301, [1306.3417](#).
- [65] TAMBORRA, I., S. ANDO, and K. MURASE (2014) “Star-forming galaxies as the origin of diffuse high-energy backgrounds: Gamma-ray and neutrino connections, and implications for starburst history,” *JCAP*, **1409**, p. 043, [1404.1189](#).
- [66] SENNO, N., P. MÉSZÁROS, K. MURASE, P. BAERWALD, and M. J. REES (2015) “Extragalactic star-forming galaxies with hypernovae and supernovae as high-energy neutrino and gamma-ray sources: the case of the 10 TeV neutrino data,” *Astrophys. J.*, **806**(1), p. 24, [1501.04934](#).
- [67] MURASE, K., S. INOUE, and S. NAGATAKI (2008) “Cosmic Rays Above the Second Knee from Clusters of Galaxies and Associated High-Energy Neutrino Emission,” *Astrophys. J.*, **689**, p. L105, [0805.0104](#).
- [68] STECKER, F. W., C. DONE, M. H. SALAMON, and P. SOMMERS (1991) “High-energy neutrinos from active galactic nuclei,” *Physical Review Letters*, **66**, pp. 2697–2700.
- [69] HALZEN, F. and E. ZAS (1997) “Neutrino fluxes from active galaxies: A Model independent estimate,” *Astrophys. J.*, **488**, pp. 669–674, [astro-ph/9702193](#).
- [70] ATOYAN, A. and C. D. DERMER (2001) “High-Energy Neutrinos from Photomeson Processes in Blazars,” *Physical Review Letters*, **87**(22), 221102, [astro-ph/0108053](#).
- [71] MURASE, K., Y. INOUE, and C. D. DERMER (2014) “Diffuse Neutrino Intensity from the Inner Jets of Active Galactic Nuclei: Impacts of External Photon Fields and the Blazar Sequence,” *Phys. Rev.*, **D90**(2), p. 023007, [1403.4089](#).
- [72] TAVECCHIO, F. and G. GHISELLINI (2015) “High-energy cosmic neutrinos from spine-sheath BL Lac jets,” *Mon. Not. Roy. Astron. Soc.*, **451**(2), pp. 1502–1510, [1411.2783](#).

- [73] MÉSZÁROS, P. and E. WAXMAN (2001) “TeV Neutrinos from Successful and Choked Gamma-Ray Bursts,” *Physical Review Letters*, **87**(17), 171102, [astro-ph/0103275](#).
- [74] MURASE, K. and K. IOKA (2013) “TeV-PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars,” *Physical Review Letters*, **111**(12), 121102, [1306.2274](#).
- [75] MÉSZÁROS, P. (2014) “Ultra-high Energy Cosmic Rays and Neutrinos from Gamma-Ray Bursts, Hypernovae and Galactic Shocks,” *Nuclear Physics B Proceedings Supplements*, **256**, pp. 241–251, [1407.5671](#).
- [76] AHLERS, M. and K. MURASE (2014) “Probing the Galactic Origin of the IceCube Excess with Gamma-Rays,” *Phys. Rev.*, **D90**(2), p. 023010, [1309.4077](#).
- [77] CROCKER, R. M., G. V. BICKNELL, E. CARRETTI, A. S. HILL, and R. S. SUTHERLAND (2014) “Steady-State Hadronic Gamma-Ray Emission from 100-Myr-Old Fermi Bubbles,” *Astrophys. J.*, **791**, p. L20, [1312.0692](#).
- [78] LUNARDINI, C., S. RAZZAQUE, K. T. THEODOSEAU, and L. YANG (2014) “Neutrino Events at IceCube and the Fermi Bubbles,” *Phys. Rev.*, **D90**(2), p. 023016, [1311.7188](#).
- [79] ABDO, A. A. ET AL. (2012) “Spectrum and Morphology of the Two Brightest Milagro Sources in the Cygnus Region: MGRO J2019+37 and MGRO J2031+41,” *Astrophys. J.*, **753**, p. 159, [1202.0846](#).
- [80] ANCHORDOQUI, L. A., H. GOLDBERG, T. C. PAUL, L. H. M. DA SILVA, and B. J. VLCEK (2014) “Estimating the contribution of Galactic sources to the diffuse neutrino flux,” *Physical Review D*, **90**(12), 123010, [1410.0348](#).
- [81] FOX, D. B., K. KASHIYAMA, and P. MÉSZARÓS (2013) “Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy,” *Astrophysical Journal*, **774**, 74, [1305.6606](#).
- [82] BUDNIK, R., B. KATZ, A. MACFADYEN, and E. WAXMAN (2008) “Cosmic Rays from Transrelativistic Supernovae,” *Astrophysical Journal*, **673**, pp. 928–933, [0705.0041](#).
- [83] MANNHEIM, K. (1993) “Gamma-rays and neutrinos from a powerful cosmic accelerator,” *Phys. Rev.*, **D48**, pp. 2408–2414, [astro-ph/9306005](#).
- [84] GAISSER, T. K., F. HALZEN, and T. STANEV (1995) “Particle astrophysics with high-energy neutrinos,” *Phys. Rept.*, **258**, pp. 173–236, [Erratum: *Phys. Rept.* 271,355(1996)], [hep-ph/9410384](#).

- [85] CERRUTI, M., A. ZECH, C. BOISSON, and S. INOUE (2015) “A hadronic origin for ultra-high-frequency-peaked BL Lac objects,” *Mon. Not. Roy. Astron. Soc.*, **448**(1), pp. 910–927, [1411.5968](#).
- [86] AHARONIAN, F. A. (2000) “TeV gamma-rays from BL Lac objects due to synchrotron radiation of extremely high-energy protons,” *New Astron.*, **5**, pp. 377–395, [astro-ph/0003159](#).
- [87] ESSEY, W., O. E. KALASHEV, A. KUSENKO, and J. F. BEACOM (2010) “Secondary Photons and Neutrinos from Cosmic Rays Produced by Distant Blazars,” *Physical Review Letters*, **104**(14), 141102, [0912.3976](#).
- [88] MURASE, K., C. D. DERMER, H. TAKAMI, and G. MIGLIORI (2012) “Blazars as Ultra-High-Energy Cosmic-Ray Sources: Implications for TeV Gamma-Ray Observations,” *Astrophys. J.*, **749**, p. 63, [1107.5576](#).
- [89] TAVECCHIO, F., J. BECERRA-GONZALES, G. GHISELLINI, A. STAMERRA, G. BONNOLI, L. FOSCHINI, and L. MARASCHI (2011) “On the origin of the gamma-ray emission from the flaring blazar PKS 1222+216,” *Astron. Astrophys.*, **534**, p. A86, [1104.0048](#).
- [90] DERMER, C. D., K. MURASE, and H. TAKAMI (2012) “Variable Gamma-ray Emission Induced by Ultra-High Energy Neutral Beams: Application to 4C +21.35,” *Astrophys. J.*, **755**, p. 147, [1203.6544](#).
- [91] BÖTTCHER, M. (2005) “A Hadronic synchrotron mirror model for the orphan TeV flare in 1ES 1959+650,” *Astrophys. J.*, **621**, pp. 176–180, [Erratum: *Astrophys. J.* 641,1233(2006)], [astro-ph/0411248](#).
- [92] REIMER, A., M. BOTTCHER, and S. POSTNIKOV (2005) “Neutrino emission in the hadronic synchrotron mirror model: The Orphan TeV flare from 1ES 1959+650,” *Astrophys. J.*, **630**, pp. 186–190, [astro-ph/0505233](#).
- [93] KRAWCZYNSKI, H. ET AL. (2004) “Multiwavelength observations of strong flares from the TeV - blazar 1ES 1959+650,” *Astrophys. J.*, **601**, pp. 151–164, [astro-ph/0310158](#).
- [94] SAHU, S., A. F. OSORIO OLIVEROS, and J. C. SANABRIA (2013) “Hadronic-origin orphan TeV flare from 1ES 1959+650,” *Phys. Rev.*, **D87**(10), p. 103015, [1305.4985](#).
- [95] HALZEN, F. and D. HOOPER (2005) “High energy neutrinos from the TeV Blazar 1ES 1959 + 650,” *Astroparticle Physics*, **23**, pp. 537–542, [astro-ph/0502449](#).

- [96] KADLER, M. ET AL. (2016) “Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,” *Nature Phys.*, **12**(8), pp. 807–814, [1602.02012](#).
- [97] KOPPER, C., E. BLAUFUSS, and ICECUBE COLLABORATION (2017) “IceCube-170922A - IceCube observation of a high-energy neutrino candidate event.” *GRB Coordinates Network, Circular Service, No. 21916, #1 (2017)*, **21916**.
- [98] KEIVANI, A., P. A. EVANS, J. A. KENNEA, D. B. FOX, D. F. COWEN, J. P. OSBORNE, and M. W. E. SMITH (2017) “IceCube-170922: Swift-XRT observations.” *GRB Coordinates Network*, **21930**.
- [99] AARTSEN, M. G. ET AL. (2018) “Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert,” *Science*, **361**(6398), pp. 147–151, [1807.08794](#).
- [100] ABBASI, R., Y. ABDU, T. ABU-ZAYYAD, J. ADAMS, J. A. AGUILAR, M. AHLERS, D. ALTMANN, K. ANDEEN, J. AUFFENBERG, X. BAI, and ET AL. (2011) “Search for a diffuse flux of astrophysical muon neutrinos with the IceCube 40-string detector,” *Physical Review D*, **84**(8), 082001, [1104.5187](#).
- [101] AARTSEN, M. G. ET AL. (2015) “Searches for Time Dependent Neutrino Sources with IceCube Data from 2008 to 2012,” *Astrophys. J.*, **807**(1), p. 46, [1503.00598](#).
- [102] AARTSEN, M. G. ET AL. (2014) “Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data,” *Astrophys. J.*, **796**(2), p. 109, [1406.6757](#).
- [103] AARTSEN, M. G., R. ABBASI, Y. ABDU, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, D. ALTMANN, J. AUFFENBERG, and ET AL. (2013) “Observation of the cosmic-ray shadow of the Moon with IceCube,” *ArXiv.org*, **1305.6811**, [1305.6811](#).
- [104] WEEKES, T. C. ET AL. (2002) “VERITAS: The Very energetic radiation imaging telescope array system,” *Astropart. Phys.*, **17**, pp. 221–243, [astro-ph/0108478](#).
- [105] ACCIARI, V. A. ET AL. (2014) “Observation of Markarian 421 in TeV gamma rays over a 14-year time span,” *Astropart. Phys.*, **54**, pp. 1–10, [1310.8150](#).
- [106] TLUCZYKONT, M., E. BERNARDINI, K. SATALECKA, R. CLAVERO, M. SHAYDUK, and O. KALEKIN (2010) “Long-term lightcurves from combined unified very high energy γ -ray data,” *Astron. Astrophys.*, **524**, p. A48, [1010.5659](#).

- [107] WAKELY, S. P. and D. HORAN (2008) “TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy,” in *International Cosmic Ray Conference*, vol. 3, Merida, Yucatan, Mexico, pp. 1341–1344.
- [108] RESCONI, E., D. FRANCO, A. GROSS, L. COSTAMANTE, and E. FLACCOMIO (2009) “The Classification of Flaring States of Blazars,” *Astron. Astrophys.*, **502**, pp. 499–504, [0904.1371](#).
- [109] RASMUSSEN, C. E. and C. K. I. WILLIAMS (2006) *Gaussian processes for machine learning*, MIT Press, Cambridge, Mass.
- [110] JONES, E., T. OLIPHANT, P. PETERSON, ET AL. (2001–), “SciPy: Open source scientific tools for Python,” [Online].
URL <http://www.scipy.org/>
- [111] NEUMANN, M., S. HUANG, D. MARTHALER, and K. KERSTING (2014), “pyGPS: A Package for Gaussian Processes,” [Online; accessed 2016-07-26].
URL http://www-ai.cs.uni-dortmund.de/weblab/static/api_docs/pyGPS/
- [112] ABBASI, R. ET AL. (2011) “A Search for a Diffuse Flux of Astrophysical Muon Neutrinos with the IceCube 40-String Detector,” *Phys. Rev.*, **D84**, p. 082001, [1104.5187](#).
- [113] PETROPOULOU, M., S. COENDERS, and S. DIMITRAKOUDIS (2016) “Time-dependent neutrino emission from Mrk 421 during flares and predictions for IceCube,” *Astropart. Phys.*, **80**, pp. 115–130, [1603.06954](#).
- [114] DEYOUNG, T. and HAWC COLLABORATION (2012) “The HAWC observatory,” *Nuclear Instruments and Methods in Physics Research A*, **692**, pp. 72–76.
- [115] KRIMM, H. A. ET AL. (2013) “The Swift/BAT Hard X-ray Transient Monitor,” *Astrophys. J. Suppl.*, **209**, p. 14, [1309.0755](#).
- [116] ICECUBE COLLABORATION, M. G. AARTSEN, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, I. A. SAMARAI, D. ALTMANN, K. ANDEEN, and ET AL. (2017) “The IceCube Neutrino Observatory - Contributions to ICRC 2017 Part II: Properties of the Atmospheric and Astrophysical Neutrino Flux,” *ArXiv e-prints*, [1710.01191](#).
- [117] AARTSEN, M. G. ET AL. (2017) “All-sky Search for Time-integrated Neutrino Emission from Astrophysical Sources with 7 yr of IceCube Data,” *Astrophys. J.*, **835**(2), p. 151, [1609.04981](#).

- [118] ICECUBE COLLABORATION, M. G. AARTSEN, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, I. A. SAMARAI, D. ALTMANN, K. ANDEEN, and ET AL. (2017) “Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data,” *ArXiv e-prints*, [1707.03416](#).
- [119] WAXMAN, E. and J. BAHCALL (1997) “High Energy Neutrinos from Cosmological Gamma-Ray Burst Fireballs,” *Physical Review Letters*, **78**, pp. 2292–2295, [astro-ph/9701231](#).
- [120] MÉSZÁROS, P. (2015) “Gamma Ray Bursts as Neutrino Sources,” *ArXiv e-prints*, [1511.01396](#).
- [121] AARTSEN, M. G. ET AL. (2015) “Search for Prompt Neutrino Emission from Gamma-Ray Bursts with IceCube,” *Astrophys. J.*, **805**(1), p. L5, [1412.6510](#).
- [122] MURASE, K. and K. IOKA (2013) “TeV-PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars,” *Physical Review Letters*, **111**(12), 121102, [1306.2274](#).
- [123] SENNO, N., K. MURASE, and P. MÉSZÁROS (2016) “Choked jets and low-luminosity gamma-ray bursts as hidden neutrino sources,” *Physical Review D*, **93**(8), 083003, [1512.08513](#).
- [124] TAMBORRA, I. and S. ANDO (2016) “Inspecting the supernova-gamma-ray-burst connection with high-energy neutrinos,” *Physical Review D*, **93**(5), 053010, [1512.01559](#).
- [125] MURASE, K., T. A. THOMPSON, B. C. LACKI, and J. F. BEACOM (2011) “New class of high-energy transients from crashes of supernova ejecta with massive circumstellar material shells,” *Physical Review D*, **84**(4), 043003, [1012.2834](#).
- [126] DERMER, C. D., K. MURASE, and Y. INOUE (2014) “Photopion production in black-hole jets and flat-spectrum radio quasars as PeV neutrino sources,” *Journal of High Energy Astrophysics*, **3**, pp. 29–40, [1406.2633](#).
- [127] GAO, S., M. POHL, and W. WINTER (2017) “On the Direct Correlation between Gamma-Rays and PeV Neutrinos from Blazars,” *Astrophysical Journal*, **843**, 109, [1610.05306](#).
- [128] DAI, L. and K. FANG (2017) “Can tidal disruption events produce the IceCube neutrinos?” *Monthly Notices of the RAS*, **469**, pp. 1354–1359, [1612.00011](#).
- [129] SENNO, N., K. MURASE, and P. MÉSZÁROS (2017) “High-energy Neutrino Flares from X-Ray Bright and Dark Tidal Disruption Events,” *Astrophysical Journal*, **838**, 3, [1612.00918](#).

- [130] LUNARDINI, C. and W. WINTER (2017) “High energy neutrinos from the tidal disruption of stars,” *Physical Review D*, **95**(12), 123001, [1612.03160](#).
- [131] KEIVANI, A., D. B. FOX, G. TEŠIĆ, D. F. COWEN, and J. FIXELLE (2015) “AMON Searches for Jointly-Emitting Neutrino + Gamma-Ray Transients,” *ArXiv.org*, **1508.01315**, [1508.01315](#).
- [132] SMITH, M. W. E. ET AL. (2013) “The Astrophysical Multimessenger Observatory Network (AMON),” *Astropart. Phys.*, **45**, pp. 56–70, [1211.5602](#).
- [133] COWEN, D. F., A. KEIVANI, and G. TEŠIĆ (2016) “AMON: Transition to real-time operations,” in *European Physical Journal Web of Conferences*, vol. 116 of *European Physical Journal Web of Conferences*, p. 10001.
- [134] SCHOLZ, F. W. and M. A. STEPHENS (1987) “K-Sample Anderson–Darling Tests,” *Journal of the American Statistical Association*, **82**(399), pp. 918–924, <https://doi.org/10.1080/01621459.1987.10478517>.
URL <https://doi.org/10.1080/01621459.1987.10478517>
- [135] ACKERMANN, M. ET AL. (2013) “Determination of the Point-Spread Function for the Fermi Large Area Telescope from On-orbit Data and Limits on Pair Halos of Active Galactic Nuclei,” *Astrophys. J.*, **765**(1), p. 54, [1309.5416](#).
- [136] AARTSEN, M. G., R. ABBASI, Y. ABDU, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, D. ALTMANN, J. AUFFENBERG, X. BAI, and ET AL. (2013) “Search for Time-independent Neutrino Emission from Astrophysical Sources with 3 yr of IceCube Data,” *Astrophysical Journal*, **779**, 132, [1307.6669](#).
- [137] GORSKI, K. M., E. HIVON, A. J. BANDAY, B. D. WANDELT, F. K. HANSEN, M. REINECKE, and M. BARTELMAN (2005) “HEALPix - A Framework for high resolution discretization, and fast analysis of data distributed on the sphere,” *Astrophys. J.*, **622**, pp. 759–771, [astro-ph/0409513](#).
- [138] NASA HIGH ENERGY ASTROPHYSICS SCIENCE ARCHIVE RESEARCH CENTER (HEASARC) (2014), “HEASoft: Unified Release of FTOOLS and XANADU,” Astrophysics Source Code Library, [1408.004](#).
- [139] PACIESAS, W. S. ET AL. (1999) “The Fourth batse gamma-ray burst catalog (revised),” *Astrophys. J. Suppl.*, **122**, pp. 465–495, [astro-ph/9903205](#).
- [140] TURLEY, C. F. ET AL. (2016) “Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data,” *Astrophys. J.*, **833**(1), p. 117, [1608.08983](#).

- [141] ABDO, A. A. ET AL. (2009) “Fermi Observations of GRB 090902B: A Distinct Spectral Component in the Prompt and Delayed Emission,” *Astrophys. J.*, **706**, pp. L138–L144, [0909.2470](#).
- [142] TAKAHASHI, H., M. OHNO, and N. OMODEI (2010) “GRB 100414A: Fermi LAT detection.” *GRB Coordinates Network, Circular Service, No. 10594, #1* (2010), **10594**.
- [143] KADLER, M. ET AL. (2016) “Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,” *Nature Phys.*, **12**(8), pp. 807–814, [1602.02012](#).
- [144] AARTSEN, M. G., K. ABRAHAM, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, D. ALTMANN, K. ANDEEN, T. ANDERSON, and ET AL. (2017) “The Contribution of Fermi-2LAC Blazars to Diffuse TeV-PeV Neutrino Flux,” *Astrophysical Journal*, **835**, 45, [1611.03874](#).
- [145] AARTSEN, M. G. ET AL. (2015) “Searches for small-scale anisotropies from neutrino point sources with three years of IceCube data,” *Astropart. Phys.*, **66**, pp. 39–52, [1408.0634](#).
- [146] MURASE, K. and E. WAXMAN (2016) “Constraining high-energy cosmic neutrino sources: Implications and prospects,” *Physical Review D*, **94**(10), 103006, [1607.01601](#).
- [147] FANG, K. and K. MURASE (2017) “Linking High-Energy Cosmic Particles by Black Hole Jets Embedded in Large-Scale Structures,” *ArXiv e-prints*, [1704.00015](#).
- [148] ABDO, A. A. ET AL. (2012) “Spectrum and Morphology of the Two Brightest Milagro Sources in the Cygnus Region: MGRO J2019+37 and MGRO J2031+41,” *Astrophys. J.*, **753**, p. 159, [1202.0846](#).
- [149] AHLERS, M. and K. MURASE (2014) “Probing the Galactic origin of the IceCube excess with gamma rays,” *Physical Review D*, **90**(2), 023010, [1309.4077](#).
- [150] ANTARES COLLABORATION (1999) “A Deep Sea Telescope for High Energy Neutrinos,” *ArXiv Astrophysics e-prints*, [astro-ph/9907432](#).
- [151] ALBERT, A. ET AL. (2017) “An algorithm for the reconstruction of neutrino-induced showers in the ANTARES neutrino telescope,” *Astron. J.*, **154**(6), p. 275, [1708.03649](#).
- [152] AGUILAR, J. A. ET AL. (2005) “Transmission of light in deep sea water at the site of the ANTARES Neutrino Telescope,” *Astropart. Phys.*, **23**, pp. 131–155, [astro-ph/0412126](#).

- [153] ALBERT, A. ET AL. (2017) “First all-flavor neutrino pointlike source search with the ANTARES neutrino telescope,” *Phys. Rev.*, **D96**(8), p. 082001, [1706.01857](#).
- [154] ALBERT, A. ET AL. (2017) “New constraints on all flavor Galactic diffuse neutrino emission with the ANTARES telescope,” *Phys. Rev.*, **D96**(6), p. 062001, [1705.00497](#).
- [155] ALBERT, A. ET AL. (2018) “Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes,” *Astrophys. J.*, **868**(2), p. L20, [1808.03531](#).
- [156] ALBERT, A. ET AL. (2018) “All-flavor Search for a Diffuse Flux of Cosmic Neutrinos with Nine Years of ANTARES Data,” *Astrophys. J.*, **853**(1), p. L7, [1711.07212](#).
- [157] ALBERT, A., M. ANDRÉ, M. ANGHINOLFI, M. ARDID, J.-J. AUBERT, J. AUBLIN, T. AVGITAS, B. BARET, J. BARRIOS-MARTÍ, S. BASA, and ET AL. (2017) “Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory,” *Astrophysical Journal, Letters*, **850**, L35, [1710.05839](#).
- [158] ALBERT, A. ET AL. (2019) “Search for Multimessenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during Its First Observing Run, ANTARES, and IceCube,” *Astrophys. J.*, **870**(2), p. 134, [1810.10693](#).
- [159] CROFT, S. ET AL. (2016) “Murchison Widefield Array Limits on Radio Emission from ANTARES Neutrino Events,” *Astrophys. J.*, **820**(2), p. L24, [1603.02271](#).
- [160] ALBERT, A. ET AL. (2019) “The search for high-energy neutrinos coincident with fast radio bursts with the ANTARES neutrino telescope,” *Mon. Not. Roy. Astron. Soc.*, **482**(1), pp. 184–193, [1807.04045](#).
- [161] ADRIÁN-MARTÍNEZ, S. ET AL. (2016) “Optical and X-ray early follow-up of ANTARES neutrino alerts,” *JCAP*, **1602**(02), p. 062, [1508.01180](#).
- [162] AGERON, M. ET AL. (2012) “The ANTARES Telescope Neutrino Alert System,” *Astropart. Phys.*, **35**, pp. 530–536, [1103.4477](#).
- [163] ADRIAN-MARTINEZ, S. ET AL. (2015) “Search for muon-neutrino emission from GeV and TeV gamma-ray flaring blazars using five years of data of the ANTARES telescope,” *JCAP*, **1512**(12), p. 014, [1506.07354](#).

- [164] ALBERT, A. ET AL. (2018) “The Search for Neutrinos from TXS 0506+056 with the ANTARES Telescope,” *Astrophys. J.*, **863**(2), p. L30, [1807.04309](#).
- [165] TURLEY, C. F., D. B. FOX, A. KEIVANI, J. J. DELAUNAY, D. F. COWEN, M. MOSTAFÁ, H. A. AYALA SOLARES, and K. MURASE (2018) “A Coincidence Search for Cosmic Neutrino and Gamma-Ray Emitting Sources Using IceCube and Fermi-LAT Public Data,” *Astrophysical Journal*, **863**, 64, [1802.08165](#).
- [166] KING, I. (1962) “The structure of star clusters. I. an empirical density law,” *Astronomical Journal*, **67**, p. 471.
- [167] AARTSEN, M. G. ET AL. (2017) “The IceCube Realtime Alert System,” *Astropart. Phys.*, **92**, pp. 30–41, [1612.06028](#).
- [168] ZHU, S., J. RACUSIN, D. KOCEVSKI, J. MCENRY, F. LONGO, J. CHIANG, and G. VIANELLO (2013) “GRB 130427A: Fermi LAT detection.” *GRB Coordinates Network, Circular Service, No. 14471, #1 (2013)*, **14471**.
- [169] MOSTELLER, F. and R. A. FISHER (1948) “Questions and Answers,” *The American Statistician*, **2**(5), pp. 30–31.
URL <http://www.jstor.org/stable/2681650>
- [170] BARTHELMY, S. D., P. BUTTERWORTH, T. L. CLINE, N. GEHRELS, F. MARSHALL, T. TAKESHIMA, V. CONNAUGHTON, R. M. KIPPEN, C. KOUVELIOTOU, and C. R. ROBINSON (1998) “The GRB coordinates network (GCN): A status report,” in *Gamma-Ray Bursts, 4th Hunstville Symposium* (C. A. Meegan, R. D. Preece, and T. M. Koshut, eds.), vol. 428 of *American Institute of Physics Conference Series*, pp. 99–103.
- [171] ICECUBE COLLABORATION (2017) “Observation of Astrophysical Neutrinos in Six Years of IceCube Data,” in *35th International Cosmic Ray Conference (ICRC2015)*, p. 981.
- [172] GLÄNSENKAMP, T. (2016) “Analysis of the cumulative neutrino flux from Fermi-LAT blazar populations using 3 years of IceCube data,” *EPJ Web Conf.*, **121**, p. 05006, [1502.03104](#).
- [173] WANG, B. and Z. LI (2016) “Can FSRQs produce the IceCube detected diffuse neutrino emission?” *Sci. China Phys. Mech. Astron.*, **59**(1), p. 619502, [1505.04418](#).
- [174] WAXMAN, E. (2006) “Gamma-ray bursts: Potential sources of ultra high energy cosmic-rays,” *Nuclear Physics B Proceedings Supplements*, **151**, pp. 46–53, [arXiv:astro-ph/0412554](#).

- [175] DADO, S. and A. DAR (2014) “Origin of the High Energy Cosmic Neutrino Background,” *Physical Review Letters*, **113**(19), 191102, [1405.5487](#).
- [176] TAMBORRA, I. and S. ANDO (2015) “Diffuse emission of high-energy neutrinos from gamma-ray burst fireballs,” *JCAP*, **1509**(09), p. 036, [1504.00107](#).
- [177] MURASE, K. (2015) “Active Galactic Nuclei as High-Energy Neutrino Sources,” *ArXiv.org*, **1511.01590**, [1511.01590](#).
- [178] MURASE, K., K. IOKA, S. NAGATAKI, and T. NAKAMURA (2006) “High Energy Neutrinos and Cosmic-Rays from Low-Luminosity Gamma-Ray Bursts?” *Astrophys. J.*, **651**, pp. L5–L8, [astro-ph/0607104](#).
- [179] KASHIYAMA, K., K. MURASE, S. HORIUCHI, S. GAO, and P. MESZAROS (2013) “High energy neutrino and gamma ray transients from relativistic supernova shock breakouts,” *Astrophys. J.*, **769**, p. L6, [1210.8147](#).
- [180] NAKAR, E. (2015) “A unified picture for low-luminosity and long gamma-ray bursts based on the extended progenitor of llgrb 060218/SN 2006aj,” *Astrophys. J.*, **807**(2), p. 172, [1503.00441](#).
- [181] OFEK, E. O. ET AL. (2013) “X-ray emission from supernovae in dense circumstellar matter environments: A search for collisionless shocks,” *Astrophys. J.*, **763**, p. 42, [1206.0748](#).
- [182] LUNARDINI, C. and S. RAZZAQUE (2012) “High Energy Neutrinos from the Fermi Bubbles,” *Phys. Rev. Lett.*, **108**, p. 221102, [1112.4799](#).
- [183] FANG, K., M. SU, T. LINDEN, and K. MURASE (2017) “IceCube and HAWC constraints on very-high-energy emission from the Fermi bubbles,” *Phys. Rev.*, **D96**(12), p. 123007, [1704.03869](#).
- [184] IOKA, K. and P. MESZAROS (2010) “Hypernova and Gamma-Ray Burst Remnants as TeV Unidentified Sources,” *Astrophys. J.*, **709**, pp. 1337–1342, [0901.0744](#).
- [185] ABEYSEKARA, A. U. ET AL. (2019) “A New Population of Ultra-High-Energy Gamma-Ray Sources Detected by HAWC,” [1909.08609](#).
- [186] AYALA SOLARES, H. A. ET AL. (2020) “The Astrophysical Multimessenger Observatory Network (AMON): Performance and science program,” *Astropart. Phys.*, **114**, pp. 68–76, [1903.08714](#).
- [187] AARTSEN, M. G. ET AL. (2015) “Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube,” *Phys. Rev. Lett.*, **115**(8), p. 081102, [1507.04005](#).

- [188] AARTSEN, M. G. ET AL. (2016) “Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data,” *Astrophys. J.*, **833**(1), p. 3, [1607.08006](#).
- [189] AARTSEN, M. G., M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, D. ALTMANN, K. ANDEEN, T. ANDERSON, I. ANSSEAU, and ET AL. (2017) “The IceCube realtime alert system,” *Astroparticle Physics*, **92**, pp. 30–41.
- [190] BARTHELMY, S. D., P. BUTTERWORTH, T. L. CLINE, N. GEHRELS, G. J. FISHMAN, C. KOUVELIOTOU, and C. A. MEEGAN (1995) “BACODINE, the Real-Time BATSE Gamma-Ray Burst Coordinates Distribution Network,” *Astrophysics and Space Science*, **231**, pp. 235–238.
- [191] EVANS, P. A. ET AL. (2015) “Swift follow-up of IceCube triggers, and implications for the Advanced-LIGO era,” *Mon. Not. Roy. Astron. Soc.*, **448**(3), pp. 2210–2223, [1501.04435](#).
- [192] AARTSEN, M. G. ET AL. (2017) “Multiwavelength follow-up of a rare IceCube neutrino multiplet,” *Astron. Astrophys.*, **607**, p. A115, [1702.06131](#).
- [193] ROMING, P. W. A. ET AL. (2005) “The Swift Ultra-Violet/Optical Telescope,” *Space Sci. Rev.*, **120**, pp. 95–142, [astro-ph/0507413](#).
- [194] GCN/AMON NOTICE (2016), “IceCube-160427A,” https://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon.
- [195] GCN/AMON NOTICE (2016), “IceCube-160731A,” https://gcn.gsfc.nasa.gov/notices_amon/6888376_128290.amon.
- [196] GCN/AMON NOTICE (2016), “IceCube-160806A,” https://gcn.gsfc.nasa.gov/notices_amon/26552458_128311.amon.
- [197] GCN/AMON NOTICE (2016), “IceCube-160814A,” https://gcn.gsfc.nasa.gov/notices_amon/58537957_128340.amon.
- [198] GCN/AMON NOTICE (2016), “IceCube-161103A,” https://gcn.gsfc.nasa.gov/notices_amon/38561326_128672.amon.
- [199] GCN/AMON NOTICE (2016), “IceCube-161210A,” https://gcn.gsfc.nasa.gov/notices_amon/80127519_128906.amon.
- [200] GCN/AMON NOTICE (2017), “IceCube-170312A,” https://gcn.gsfc.nasa.gov/notices_amon/65274589_129281.amon.
- [201] GCN/AMON NOTICE (2017), “IceCube-170321A,” https://gcn.gsfc.nasa.gov/notices_amon/80305071_129307.amon.

- [202] GCN/AMON NOTICE (2017), “IceCube-170506A,” https://gcn.gsfc.nasa.gov/notices_amon/32674593_129474.amon.
- [203] GCN/AMON NOTICE (2017), “IceCube-170922A,” https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon.
- [204] GCN/AMON NOTICE (2017), “IceCube-171015A,” https://gcn.gsfc.nasa.gov/notices_amon/56068624_130126.amon.
- [205] GCN/AMON NOTICE (2017), “IceCube-171028A,” https://gcn.gsfc.nasa.gov/notices_amon/34032434_130171.amon.
- [206] GCN/AMON NOTICE (2017), “IceCube-171106A,” https://gcn.gsfc.nasa.gov/notices_amon/17569642_130214.amon.
- [207] GCN/AMON NOTICE (2016), “Webpage,” <https://gcn.gsfc.nasa.gov/amon.html>.
- [208] EVANS, P. A., J. A. KENNEA, A. KEIVANI, D. B. FOX, G. TESIC, D. F. COWEN, J. P. OSBORNE, M. W. E. SMITH, and F. E. MARSHALL (2016) “Swift follow up of IceCube-160731A.” *GRB Coordinates Network*, **19747**.
- [209] EVANS, P. A., J. A. KENNEA, A. KEIVANI, D. B. FOX, G. TESIC, D. F. COWEN, J. P. OSBORNE, M. W. E. SMITH, and F. E. MARSHALL (2016) “IceCube-161103: Swift-XRT observations.” *GRB Coordinates Network*, **20125**.
- [210] KEIVANI, A., P. A. EVANS, J. A. KENNEA, D. B. FOX, G. TESIC, D. F. COWEN, J. P. OSBORNE, and M. W. E. SMITH (2017) “IceCube-170312: Swift-XRT observations.” *GRB Coordinates Network*, **20890**.
- [211] KEIVANI, A., P. A. EVANS, J. A. KENNEA, D. B. FOX, D. F. COWEN, J. P. OSBORNE, and M. W. E. SMITH (2017) “IceCube-170321: Swift-XRT observations.” *GRB Coordinates Network*, **20964**.
- [212] KEIVANI, A., P. A. EVANS, J. A. KENNEA, D. B. FOX, D. F. COWEN, J. P. OSBORNE, and M. W. E. SMITH (2017) “IceCube-171106: Swift-XRT observations.” *GRB Coordinates Network*, **22115**.
- [213] EVANS, P. A. ET AL. (2009) “Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs,” *Mon. Not. Roy. Astron. Soc.*, **397**, p. 1177, [0812.3662](#).
- [214] EVANS, P. A. ET AL. (2013) “1SXPS: A deep Swift X-ray Telescope point source catalog with light curves and spectra,” *Astrophys. J. Suppl.*, **210**, p. 8, [1311.5368](#).

- [215] ABBEY, T., J. CARPENTER, A. READ, A. WELLS, XMM SCIENCE CENTRE, and SWIFT MISSION OPERATIONS CENTER (2006) “Micrometeoroid Damage to CCDs in XMM-Newton and Swift and its Significance for Future X-ray Missions,” in *The X-ray Universe 2005* (A. Wilson, ed.), vol. 604 of *ESA Special Publication*, p. 943.
- [216] WENGER, M. ET AL. (2000) “The simbad astronomical database,” *Astron. Astrophys. Suppl. Ser.*, **143**, p. 9, [astro-ph/0002110](#).
- [217] HOUK, N., J. SOWELL, and C. M. SWIFT (2000) “The Michigan Spectral Survey of the HD Stars,” in *The Kth Reunion* (A. G. D. Philip, ed.), vol. 18, p. 47.
- [218] ROSEN, S. R. ET AL. (2016) “The XMM-Newton serendipitous survey. VII. The third XMM-Newton serendipitous source catalogue,” *Astron. Astrophys.*, **590**, p. A1, [1504.07051](#).
- [219] EVANS, P. A. ET AL. (2013) “1SXPS: A deep Swift X-ray Telescope point source catalog with light curves and spectra,” *Astrophys. J. Suppl.*, **210**, p. 8, [1311.5368](#).
- [220] SKRUTSKIE, M. F. ET AL. (2006) “The Two Micron All Sky Survey (2MASS),” *Astron. J.*, **131**, pp. 1163–1183.
- [221] MONET, D. G. ET AL. (2003) “The USNO-B catalog,” *Astron. J.*, **125**, pp. 984–993, [astro-ph/0210694](#).
- [222] VOGES, W. ET AL. (1999) “The ROSAT all - sky survey bright source catalogue,” *Astron. Astrophys.*, **349**, p. 389, [astro-ph/9909315](#).
- [223] TABOADA, I. (2016) “HAWC follow up of IceCube 160731.” *GRB Coordinates Network*, **19743**.
- [224] BILAND, A. (2016) “FACT follow-up of IceCube20160731.” *GRB Coordinates Network*, **19752**.
- [225] MIRZOYAN, R. (2016) “MAGIC follow-up observations of IceCube neutrino event 160731A,” *The Astronomer’s Telegram*, **9315**.
- [226] BURNS, E. and P. JENKE (2016) “GBM Observations of IceCube 160731.” *GRB Coordinates Network*, **19758**.
- [227] CHEUNG, C. C., M. W. TOOMEY, D. KOCEVSKI, and S. BUSON (2016) “Fermi LAT Gamma-ray Observations of IceCube-160731,” *The Astronomer’s Telegram*, **9303**.

- [228] DE NAUROIS, M. and H.E.S.S. COLLABORARION (2016) “H.E.S.S. follow-up of IceCube-160731A,” *The Astronomer’s Telegram*, **9301**.
- [229] FREDERIKS, D., S. GOLENETSKII, R. APTEKAR, P. OLEJNIK, M. ULANOV, D. SVINKIN, A. TSVETKOVA, A. LYSENKO, A. KOZLOVA, and T. CLINE (2016) “IceCube-160731A: Konus-Wind limits.” *GRB Coordinates Network*, **19777**.
- [230] LUCARELLI, F. ET AL. (2016) “AGILE follow-up of the neutrino ICECUBE-160731 event,” *The Astronomer’s Telegram*, **9295**.
- [231] NEGORO, H. ET AL. (2016) “MAXI/GSC observations of IceCube-160731A,” *The Astronomer’s Telegram*, **9313**.
- [232] LIPUNOV, V. ET AL. (2016) “Global MASTER net follow up of IceCube-160731A.” *GRB Coordinates Network*, **19748**.
- [233] SINGER, L. P., M. M. KASLIWAL, V. BHALERAO, A. HO, T. BARLOW, S. B. CENKO, E. O. OFEK, N. STROTJOHANN, A. FRANCKOWIAK, M. KOWALSKI, and G. TESIC (2016) “IceCube-160731A: iPTF P48 Observations.” *GRB Coordinates Network*, **19760**.
- [234] ARCAVI, I., G. HOSSEINZADEH, D. GUEVEL, R. KIRPTARICK, S. VASYLYEV, C. MCCULLY, D. A. HOWELL, and S. VALENTI (2016) “LCOGT Optical Followup Observations of IceCube-160731,” *The Astronomer’s Telegram*, **9327**.
- [235] DORNIC, D. and A. COLEIRO (2016) “Search for counterpart to IceCube-160731A with ANTARES,” *The Astronomer’s Telegram*, **9324**.
- [236] LUCARELLI, F. ET AL. (2017) “AGILE detection of a candidate gamma-ray precursor to the ICECUBE-160731 neutrino event,” *Astrophys. J.*, **846**(2), p. 121, [1707.08599](#).
- [237] DROUT, M. R., A. M. SODERBERG, A. GAL-YAM, S. B. CENKO, D. B. FOX, D. C. LEONARD, D. J. SAND, D. S. MOON, I. ARCAVI, and Y. GREEN (2011) “The First Systematic Study of Type Ibc Supernova Multi-band Light Curves,” *Astrophys. J.*, **741**, p. 97, [Erratum: *Astrophys. J.* 753, 180 (2012)], [1011.4959](#).
- [238] GALAMA, T. J., P. M. VREESWIJK, and J. VAN PARADIJS (1998) “Discovery of the peculiar supernova 1998bw in the error box of GRB980425,” *Nature*, **395**, p. 670.
- [239] FARAN, T. ET AL. (2014) “Photometric and Spectroscopic Properties of Type II-P Supernovae,” *Mon. Not. Roy. Astron. Soc.*, **442**(1), pp. 844–861, [1404.0378](#).

- [240] FARAN, T. ET AL. (2014) “A Sample of Type II-L Supernovae,” *Mon. Not. Roy. Astron. Soc.*, **445**(1), pp. 554–569, [1409.1536](#).
- [241] GUY, J., P. ASTIER, S. NOBILI, N. REGNAULT, and R. PAIN (2005) “SALT: A Spectral adaptive Light curve Template for Type Ia supernovae,” *Astron. Astrophys.*, **443**, pp. 781–791, [astro-ph/0506583](#).
- [242] GANESHALINGAM, M., W. LI, A. V. FILIPPENKO, C. ANDERSON, G. FOSTER, E. L. GATES, C. V. GRIFFITH, B. J. GRIGSBY, N. JOUBERT, J. LEJA, T. B. LOWE, B. MACOMBER, T. PRITCHARD, P. THRASHER, and D. WINSLOW (2010) “Results of the Lick Observatory Supernova Search Follow-up Photometry Program: BVRI Light Curves of 165 Type Ia Supernovae,” *Astrophysical Journal, Supplements*, **190**, pp. 418–448.
- [243] TABOADA, I. (2016) “HAWC follow up of IceCube-161103.” *GRB Coordinates Network*, **20120**.
- [244] SAVCHENKO, V., C. FERRIGNO, P. UBERTINI, A. BAZZANO, L. NATALUCCI, S. MEREGHETTI, P. LAURENT, E. KUULKERS, and ICECUBE (2016) “INTEGRAL SPI-ACS and IBIS/Veto observation of IceCube-161103.” *GRB Coordinates Network*, **20122**.
- [245] BURNS, E., A. GOLDSTEIN, P. JENKE, M. S. BRIGGS, and L. BLACKBURN (2016) “Fermi GBM Observations of IceCube-161103.” *GRB Coordinates Network*, **20127**.
- [246] KOCEVSKI, D., N. OMODEI, M. OHNO, and B. CARPENTER (2016) “Fermi LAT Gamma-ray Observations of IceCube-161103.” *GRB Coordinates Network*, **20144**.
- [247] FREDERIKS, D., S. GOLENETSKII, R. APTEKAR, P. OLEYNIK, M. ULANOV, D. SVINKIN, A. TSVETKOVA, A. LYSENKO, A. KOZLOVA, and T. CLINE (2016) “IceCube-161103: Konus-Wind upper limits.” *GRB Coordinates Network*, **20139**.
- [248] KAWAKUBO, Y. ET AL. (2016) “IceCube-161103: CALET Gamma-Ray Burst Monitor upper limits.” *GRB Coordinates Network*, **20162**.
- [249] LIPUNOV, V. ET AL. (2016) “IceCube-161103: MASTER follow-up observations.” *GRB Coordinates Network*, **20121**.
- [250] DORNIC, D. and A. COLEI (2016) “Search for counterpart to IceCube-161103A with ANTARES,” *The Astronomer’s Telegram*, **9715**.
- [251] TYURINA, N. V. ET AL. (2017) “IceCube-170312: MASTER follow-up observations.” *GRB Coordinates Network*, **20903**.

- [252] TYURINA, N. V. ET AL. (2017) “INTEGRAL pointed follow-up of IceCube-170321A.” *GRB Coordinates Network*, **20937**.
- [253] HUI, C. M. ET AL. (2017) “Fermi GBM Observation of IceCube-170321A.” *GRB Coordinates Network*, **20932**.
- [254] BUSON, S. ET AL. (2017) “Fermi-LAT Gamma-ray Observations of IceCube-170321.” *GRB Coordinates Network*, **20971**.
- [255] SVINKIN, D. ET AL. (2017) “IceCube-170321A: Konus-Wind upper limits.” *GRB Coordinates Network*, **20973**.
- [256] DORNIC, D. and A. COLEIRO (2017) “Search for counterpart to IceCube-170321A with ANTARES.” *GRB Coordinates Network*, **20926**.
- [257] MARTINEZ, I. and I. TABOADO (2017) “IceCube-170922A: HAWC follow-up.” *GRB Coordinates Network*, **21924**.
- [258] MIRZOYAN, R. (2017) “First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A,” *The Astronomer’s Telegram*, **10817**.
- [259] MUKHERJEE, R. (2017) “VERITAS follow-up observations of IceCube neutrino event 170922A,” *The Astronomer’s Telegram*, **10833**.
- [260] DE NAUROIS, M. and H.E.S.S. COLLABORATION (2017) “H.E.S.S. follow-up of IceCube-170922A,” *The Astronomer’s Telegram*, **10787**.
- [261] SAVCHENKO, V. ET AL. (2017) “INTEGRAL SPI-ACS observation of AMON IceCube-170922A.” *GRB Coordinates Network*, **21917**.
- [262] KOZLOVA, A. ET AL. (2017) “IceCube-170922A: Konus-Wind upper limits.” *GRB Coordinates Network*, **22281**.
- [263] FRANCKOWIAK, A., K. Z. STANEK, C. S. KOCHANIEK, T. A. THOMPSON, T. W.-S. HOLOIEN, B. J. SHAPPEE, J. L. PRIETO, and S. DONG (2017) “ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity,” *The Astronomer’s Telegram*, **10794**.
- [264] LIPUNOV, V. ET AL. (2017) “IceCube-170922A: First Optical observations of the Neutrino Trigger by MASTER Global Net and 25 IceCube alerts inspection.” *GRB Coordinates Network*, **22942**.
- [265] DORNIC, D. and A. COLEIRO (2017) “Search for counterpart to IceCube-170922A with ANTARES.” *GRB Coordinates Network*, **21923**.

- [266] DICHIARA, S. ET AL. (2017) “HAWC follow-up of IceCube-171106A.” *GRB Coordinates Network*, **22114**.
- [267] BILAND, A. and D. DORNER (2017) “FACT follow-up of IceCube20171106.” *GRB Coordinates Network*, **22120**.
- [268] SAVCHENKO, V. ET AL. (2017) “INTEGRAL observation of IceCube-171106A.” *GRB Coordinates Network*, **22109**.
- [269] SANTANDER, M. ET AL. (2017) “INTEGRAL pointed follow-up of IceCube-171106A.” *GRB Coordinates Network*, **22167**.
- [270] BUSON, S., M. KRETER, and D. KOCEVSKI (2017) “Fermi-LAT Gamma-ray Observations of IceCube-171106A.” *GRB Coordinates Network*, **22132**.
- [271] KOZLOVA, A. ET AL. (2017) “IceCube-171106A: Konus-Wind upper limits.” *GRB Coordinates Network*, **22283**.
- [272] MCBRIEN, O. ET AL. (2017) “Pan-STARRS follow-up of IceCube-171106A.” *GRB Coordinates Network*, **22173**.
- [273] LIPUNOV, V. ET AL. (2017) “IceCube-171106A: MASTER optical observation.” *GRB Coordinates Network*, **22945**.
- [274] ACERO, F. ET AL. (2015) “Fermi Large Area Telescope Third Source Catalog,” *Astrophys. J. Suppl.*, **218**(2), p. 23, [1501.02003](#).
- [275] (2012) “Fermi Large Area Telescope Second Source Catalog,” *Astrophys. J. Suppl.*, **199**, p. 31, [1108.1435](#).
- [276] AARTSEN, M. G. ET AL. (2017) “The contribution of Fermi-2LAC blazars to the diffuse TeV-PeV neutrino flux,” *Astrophys. J.*, **835**(1), p. 45, [1611.03874](#).
- [277] WIERZCHOLSKA, A. and S. J. WAGNER (2016) “X-ray spectral studies of TeV γ -ray emitting blazars,” *Mon. Not. Roy. Astron. Soc.*, **458**(1), pp. 56–83, [1601.07493](#).
- [278] RACUSIN, J. L., E. W. LIANG, D. N. BURROWS, A. FALCONE, T. SAKAMOTO, B. B. ZHANG, B. ZHANG, P. EVANS, and J. OSBORNE (2009) “Jet breaks and Energetics of Swift GRB X-ray Afterglows,” *Astrophys. J.*, **698**, pp. 43–74, [0812.4780](#).
- [279] CHINCARINI, G. ET AL. (2007) “The First Survey of X-ray Flares from Gamma Ray Bursts Observed by Swift: Temporal Properties and Morphology,” *Astrophys. J.*, **671**, p. 1903, [astro-ph/0702371](#).

- [280] AARTSEN, M. G. ET AL. (2016) “An All-Sky Search for Three Flavors of Neutrinos from Gamma-Ray Bursts with the IceCube Neutrino Observatory,” *Astrophys. J.*, **824**(2), p. 115, [1601.06484](#).
- [281] BAERWALD, P., M. BUSTAMANTE, and W. WINTER (2013) “UHECR escape mechanisms for protons and neutrons from GRBs, and the cosmic ray-neutrino connection,” *Astrophys. J.*, **768**, p. 186, [1301.6163](#).
- [282] BUSTAMANTE, M., K. MURASE, W. WINTER, and J. HEINZE (2017) “Multi-messenger light curves from gamma-ray bursts in the internal shock model,” *Astrophys. J.*, **837**(1), p. 33, [1606.02325](#).
- [283] AHLERS, M. and F. HALZEN (2014) “Pinpointing Extragalactic Neutrino Sources in Light of Recent IceCube Observations,” *Phys. Rev.*, **D90**(4), p. 043005, [1406.2160](#).
- [284] TAYLOR, M. ET AL. (2014) “The Core Collapse Supernova Rate from the SDSS-II Supernova Survey,” *Astrophys. J.*, **792**, p. 135, [1407.0999](#).
- [285] LIANG, E., B. ZHANG, and Z. G. DAI (2007) “Low Luminosity Gamma-Ray Bursts as a Unique Population: Luminosity Function, Local Rate, and Beaming Factor,” *Astrophys. J.*, **662**, pp. 1111–1118, [astro-ph/0605200](#).
- [286] WANDERMAN, D. and T. PIRAN (2010) “The luminosity function and the rate of Swift’s Gamma Ray Bursts,” *Mon. Not. Roy. Astron. Soc.*, **406**, pp. 1944–1958, [0912.0709](#).
- [287] KEIVANI, A. ET AL. (2018) “A Multimessenger Picture of the Flaring Blazar TXS 0506+056: implications for High-Energy Neutrino Emission and Cosmic Ray Acceleration,” *Astrophys. J.*, **864**(1), p. 84, [1807.04537](#).

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Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data, 2016, C. F. Turley, D. B. Fox, K. Murase, & 14 others, The Astrophysical Journal, Volume 833, 117 (arxiv:1608.08983)

Multiwavelength follow-up of a rare IceCube neutrino multiplet, 2017, IceCube Collaboration, & 512 others, Astronomy and Astrophysics, Volume 607, A115 (arxiv:1702.06131)

Discovery of a Transient Gamma-Ray Counterpart to FRB 131104, 2016, J. J. DeLaunay, D. B. Fox, K. Murase, & 7 others, The Astrophysical Journal Letters, Volume 832, L1 (arxiv:1611.03139)