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Trinity: The PeV Neutrino Observatory

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The Trinity Observatory is a proposed UHE-neutrino detector with a core-energy range of 10^6 GeV-10^{10} GeV, bridging the observational gap between IceCube and ultrahigh-energy (UHE) radio detectors. In its final configuration, Trinity is a system of $60^\circ \times 5^\circ$ wide field-of-view air-shower imaging telescopes that detect Earth-skimming tau neutrinos from mountain tops. Trinity's primary science objectives are the extension of the IceCube measured diffuse neutrino flux to UHE energies, detecting cosmogenic neutrinos, and observing neutrino sources. Over a ten-year observation period, Trinity will detect about 60 diffuse UHE neutrinos, provided the IceCube measured diffuse neutrino spectrum does break above PeV energies. Trinity will make critical measurements to study flavor physics and neutrino cross-sections at energies that are out of reach for accelerators. The project's status is discussed here, focusing on the Trinity Demonstrator, a one-square-meter air-shower imaging telescope we deployed on Frisco Peak, Utah, in July 2023. We aim to verify the technology and understand potential backgrounds with the Demonstrator.

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1. Introduction

Multimessenger astrophysics is a powerful approach to unraveling the secrets of the non-thermal universe that photons, neutrinos, and gravitational waves alone cannot deliver because each one probes different regions and energetics of the most extreme celestial objects. Combining all messengers gives us a more complete picture. Multimessenger astrophysics is a relatively young area. The first neutrino and gravitational wave detections took place only a decade ago. Therefore, the potential of multimessenger astrophysics is far from exploited. To fully explore the multimessenger potential, the experimental approach is to increase all instruments' sensitivity and energy reach, including those for neutrino observations [1].

The IceCube Collaboration opened the high-energy neutrino window with the detection of astrophysical neutrinos [2]. With that and a handful of other observations, the IceCube team has impressively demonstrated the powerful and transformational impact of the neutrino window. To date, a diffuse astrophysical neutrino flux, neutrinos from the direction of one blazar and one Seyfert galaxy, and most recently, neutrinos from the galactic plane have been detected with IceCube [2–5].

These tantalizing discoveries are major drivers for extending neutrino observations beyond PeV energies. Observing very-high-energy (VHE, >PeV) and ultrahigh-energy (UHE, >EeV) neutrinos requires techniques capable of covering orders of magnitude larger observing volumes than IceCube with high efficiency to compensate for rapidly falling neutrino fluxes. IceCube observes a large fraction of the sky at TeV energies, but already at VHE and even more so at UHE, the increasing neutrino cross-section restricts the observable sky to a narrow band just below the local horizon, further restricting acceptance.

The Earth-skimming technique is a different approach to detecting VHE and UHE tau neutrinos [6]. It exploits the few hundred kilometer-long interaction lengths of VHE tau neutrinos and the similar long decay length of the tau produced in charged current interactions. The sum of both is equivalent to the extended trajectory of a tau neutrino entering the Earth under an angle of about one degree. For Earth-skimming VHE tau neutrinos, the probability is a few percent that the tau neutrino interacts, and the generated tau decays only after it emerges from the ground. When the tau decays in the atmosphere, it produces an extended particle shower with emission that can be detected in radio and optical.

Of the different approaches developed to explore the > VHE neutrino sky with Earth-skimming neutrinos, Trinity uses the established imaging atmospheric Cherenkov technique to detect the Cherenkov emission from the shower particles [7]. The Cherenkov emission from a VHE-tau-induced shower is so intense that the showers can be imaged with a moderately sized Cherenkov telescope on a mountaintop from more than 100 km distance.

In this paper, we give an update on the development status of Trinity.

2. The Trinity Observatory

Trinity is a proposed system of imaging atmospheric Cherenkov telescopes (IACTs) optimized to view tau-neutrino-induced particle showers [8]. The IACT technique has a long and successful heritage in VHE gamma-ray astrophysics >100 GeV. It reliably separates air-shower images and accidental events caused by fluctuations in the night-sky background based on differences in spatial topology and time development [9, 10]. Light from artificial light sources does not mimic air-shower images. IACTs are, therefore, immune to man-made light. In Earth-skimming neutrino detection, air shower imaging already yields a PeV energy threshold with a ten square meter large light collection area.

Several groups have made attempts to detect neutrinos with Cherenkov telescopes. The MAGIC Collaboration has demonstrated a PeV energy threshold and expected sensitivities by pointing their instrument at the Atlantic [11]. The ASHRA and NTA teams built IACTs dedicated to neutrino observations and pointed their telescopes at Mauna Kea [12, 13]. The Trinity concept varies from these conceptually and in instrument design.

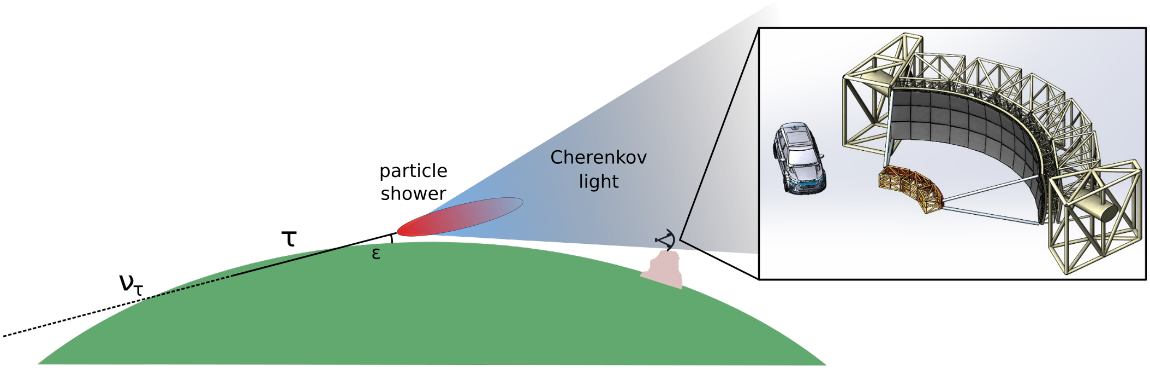

Figure 1: *Trinity* detection concept. Following a tau-neutrino interaction inside the Earth, the resulting tau decays in the air, starting a particle shower imaged with a Cherenkov telescope. The insert shows the conceptual drawing of a Trinity telescope. *Trinity* will consist of 18 such telescopes.

The Trinity concept (see Figure 1) and the detector design are driven by the desire to maximize the detection volume and thus the achievable sensitivity by detecting air showers as far away as possible while at the same time retaining the lowest possible energy threshold. The detection volume is maximized by placing the telescopes on a mountaintop and pointing them at the horizon. At the same time, the lowest possible threshold is achieved with an appropriately sized light collection area and red-sensitive photosensors [7].

The Trinity concept is scalable because each telescope operates independently from the others, and each telescope sees different events. Thus, Scientific observations start with the first telescope without restrictions on event constructability and energy threshold. Adding more telescopes and expanding to different sites increases the acceptance for diffuse neutrino fluxes and point sources. By strategically placing arrays of IACTs at various locations worldwide, it is possible to achieve close-to-all-sky coverage and observe individual sources several hours per day. The Trinity Observatory, in its final configuration, consists of three or more arrays of IACTs. An array comprises up to six wide field-of-view IACTs depending on the local orography, with each telescope observing 60° in azimuth and 5° in vertical [14].

Science operation of Trinity starts with the deployment of the first telescope. Therefore, we plan to develop Trinity in three phases: the Demonstrator Telescope, the Engineering Telescope, and the Trinity Observatory.

3. The Trinity Demonstrator

With the Trinity Demonstrator, we aim to prove the Trinity concept, show remote operation, develop tailored analysis techniques, and study potential sources of background and how to suppress them. In addition, the Demonstrator will observe NGC 1068 and TXS 0506+056, the two sources from which direction IceCube observed neutrinos and other neutrino-source candidates in the 0° to 5° declination range.

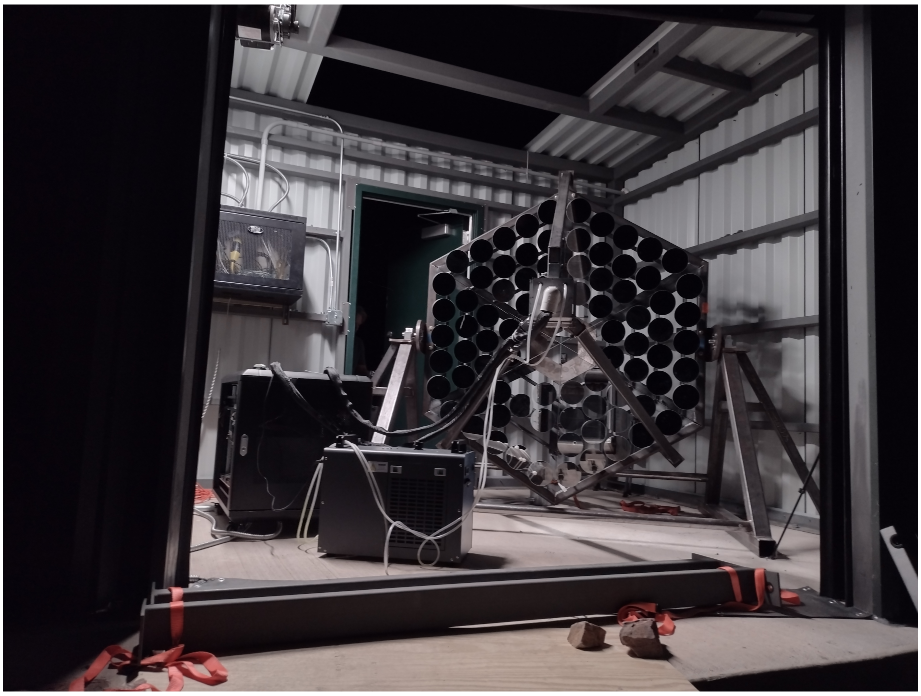

Figure 2: The *Trinity* Demonstrator on Frisco Peak Utah during installation in July 2023.

The Demonstrator telescope is a one square meter class IACT installed on Frisco Peak, Utah; see Figure 2. It is located at N38°31’12", W113°17’16" at an altitude of 2,932 m, about 1,500 m above the surrounding terrain. The optics of the Demonstrator is a classic Davies-Cotton design realized with a tessellated 0.75 square meter light collection surface comprised of 81, 15 cm diameter, and 1.49 m focal length spherical mirrors. The telescope points towards an azimuth of 280° and one degree above the horizon. In this configuration, 3° of the camera Field of View is above, and 2° is below the horizon, matching the solid angle where air shower images from Earth-skimming tau neutrinos are expected [7]. The focal plane is instrumented with a 256-pixel silicon photomultiplier (SiPM) camera. While smaller in scale, the Demonstrators shares the same key characteristics as the future Trinity telescopes, like the same vertical field of view and 0.3° angular resolution, SiPM photosensors, and a 100 MS/s readout.

The SiPM signals are amplified and shaped by MUSIC ASICs [15] and then routed into an AGET readout system [16]. The MUSICs also discriminate the analog signals and provide an OR’d output of the 8 SiPM channels attached to each MUSIC. The discriminator outputs of all 16 MUSIC chips are connected to an FPGA, which instructs the AGET system to start the readout whenever the trigger condition is met. In its present configuration, the trigger condition is met when the signal in one SiPM exceeds the discriminator threshold. Higher-level trigger topologies, e.g., looking for 100 ns time coincidences between neighboring pixels, are implemented in the software.

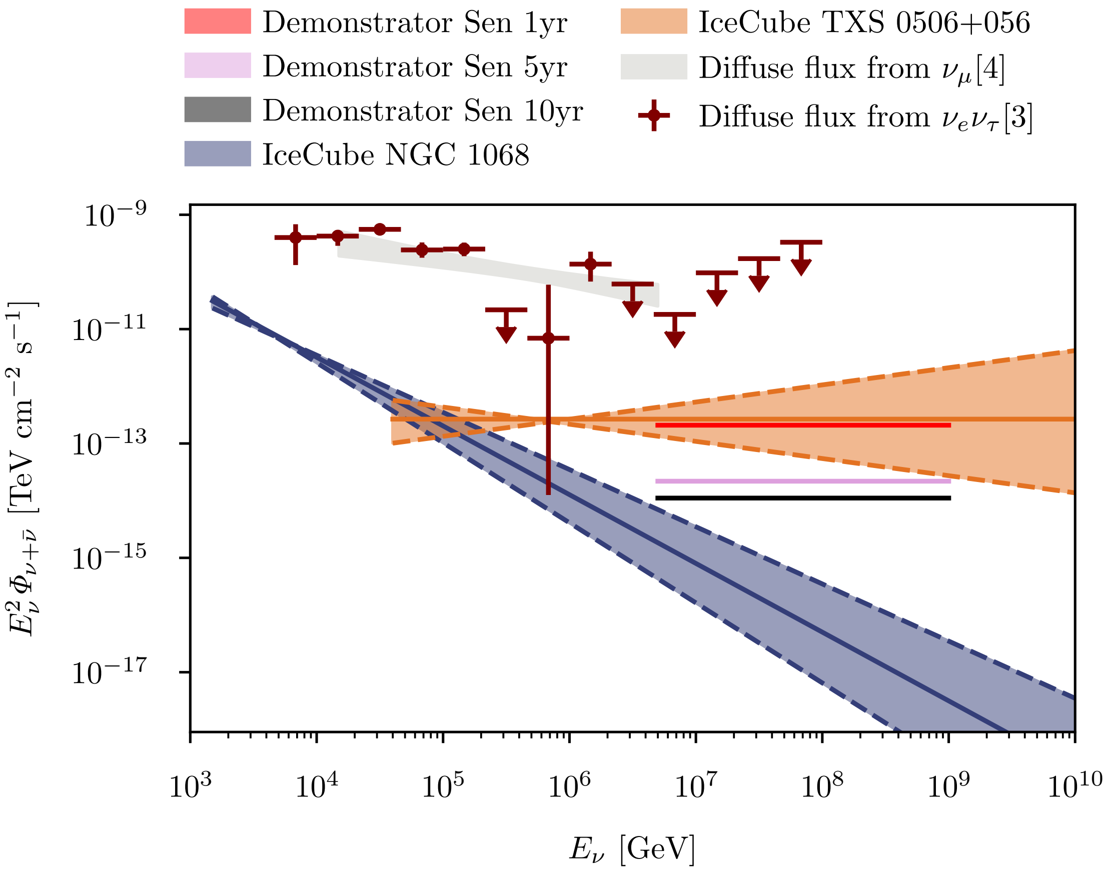

Figure 3: The red horizontal line depicts the expected one-year sensitivity of the Trinity Demonstrator for neutrinos from the direction of TXS 0506+056 and NGC 1068, assuming a power law source with -2 index. The blue and orange bowties show the nine-year average flux of neutrinos from the direction of both sources measured with IceCube. The dashed lines give the uncertainty in the spectral index. The gray bowtie shows the sky-integrated all-sky diffuse flux measured with $\nu_\mu + \bar{\nu}_\mu$ [17], and the red data points are for the same all-sky measurement but with electron and tau neutrinos [18].

The Demonstrator points at 280° azimuth yielding approximately equal annual acceptance for NGC 1068 and TXS 0506+056 of $5.6 \cdot 10^{12}$ cm^2 s. In this configuration, we expect one neutrino from the direction of TXS 0506+056 after two years of observations assuming the averaged multi-year neutrino spectrum published in [4].

To demonstrate the sensitivity of the Demonstrator, Figure 3 has been modified from [4] by showing the extrapolation of the NGC 1068 and TXS 0506+056 best-fit power-law spectrum into the energy range of the Demonstrator and adding the point source sensitivity of the Demonstrator. The Demonstrator's integral sensitivity is indicated by the horizontal lines for a 1, 5, and 10-year observation, assuming a power-law spectrum with a -2 index. Based on the same calculations, Figure 4 shows the expected event distributions after ten years.

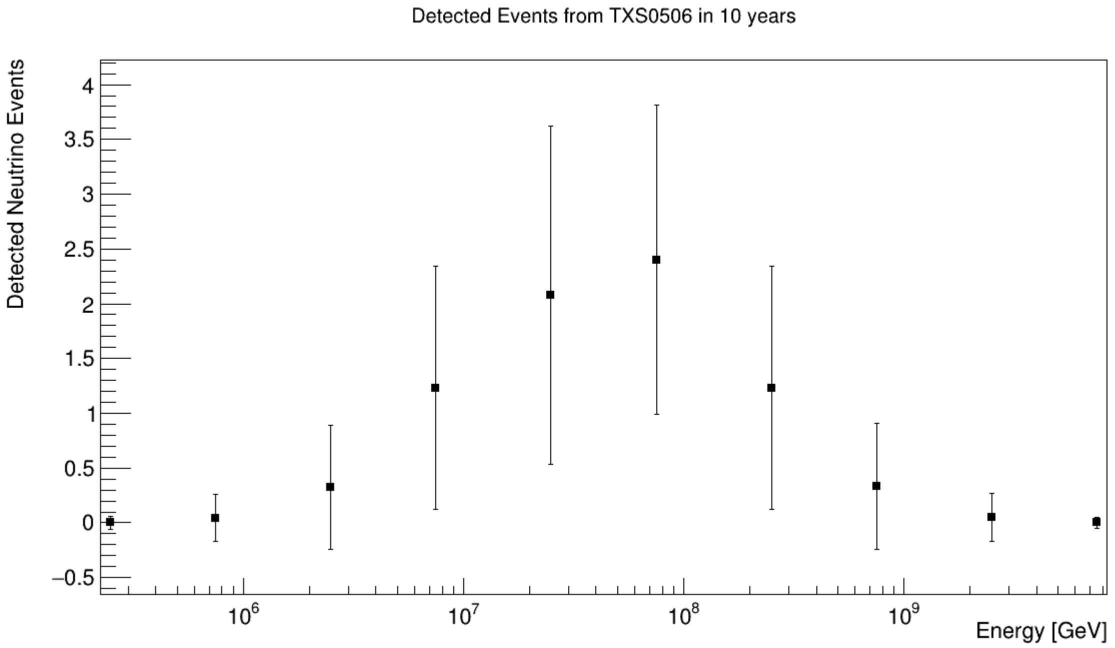

Figure 4: Expected event distribution from TXS 0506+056 in true energy expected with the Trinity Demonstrator after ten years of observation. For the calculation, we assumed that the nine-year average flux measured with IceCube and shown in Figure 3 extends without a change in spectral shape to higher energies.

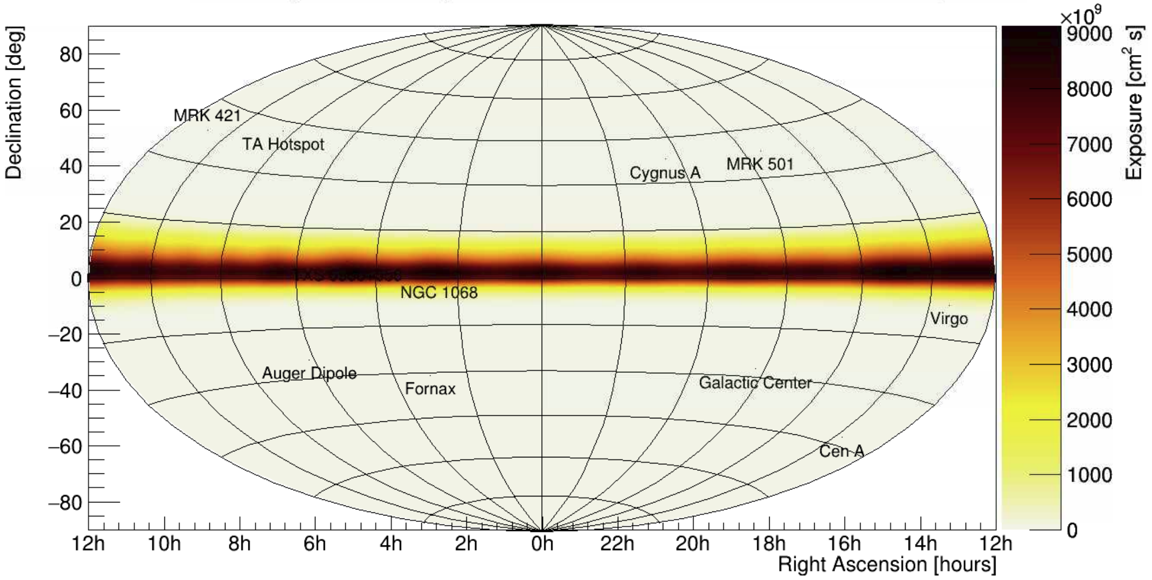

Figure 5: Point-source sensitivity of the Trinity Demonstrator after one year of observing.

NGC 1068 and TXS 0506+056 are not the only sources we will observe with the Demonstrator. While we will not change the pointing direction of the Demonstrator, every potential neutrino source with a declination between 0° and 5° will be in the field of view of the telescope. Figure 5 shows the Demonstrator's annual point source acceptance across the sky for an assumed power-law neutrino spectrum with index -2.

4. Discussion

The advent of neutrino astrophysics at TeV energies with IceCube and the discovery potential at PeV and higher neutrino energies strongly incentivizes the development of instruments detecting VHE and UHE neutrino. While detecting VHE and UHE neutrinos is challenging, Trinity is well-equipped to address it. Once completed, the Trinity IACTs will observe neutrinos from PeV to EeV energies with unprecedented sensitivity providing outstanding capabilities just above the energy band observable with IceCube now.

Trinity will search for the VHE extension of the all-sky extragalactic neutrino flux, cosmogenic neutrinos at VHE and UHE, and neutrino point sources. By being sensitive to tau neutrinos only, Trinity will complement IceCube and other neutrino detectors in measuring the flavor flux ratio, which provides information about the environment in which neutrinos are produced and can test for physics beyond the standard model.

The first phase towards the Trinity Observatory is the Demonstrator, which we have just installed on Frisco Peak in Utah. Operating it will guide the development of the first Trinity telescope, which we will start constructing in 2025. With the Demonstrator, we will observe NGC 1068 and TXS 0506+056 and search for diffuse astrophysical neutrinos.

5. Acknowledgements

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References

[1] M. Ackermann, M. Bustamante, L. Lu, N. Otte, M.H. Reno, S. Wissel et al., *High-energy and ultra-high-energy neutrinos: A Snowmass white paper*, *Journal of High Energy Astrophysics* **36** (2022) 55.

[2] M.G. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J.A. Aguilar et al., *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, *Science* **342** (2013) 1242856 [`1311.5238`].

[3] I. IceCube Collaboration, *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert.*, *Science (New York, N.Y.)* **361** (2018) 147.

[4] R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, *Science* **378** (2022) 538 [`2211.09972`].

[5] R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Observation of high-energy neutrinos from the Galactic plane*, *Science* **380** (2023) 1338.

[6] D. Fargion, A. Aiello and R. Conversano, *Horizontal Tau air showers from mountains in deep valley. Traces of UHECR neutrino tau*, `9906450`.

[7] A.N. Otte, *Studies of an air-shower imaging system for the detection of ultrahigh-energy neutrinos*, *Physical Review D* **99** (2019) 083012 [`1811.09287`].

[8] A.M. Brown, M. Bagheri, M. Doro, E. Gazda, D. Kieda, C. Lin et al., *Trinity: An Imaging Air Cherenkov Telescope to Search for Ultra-High-Energy Neutrinos*, in *Proceedings of Science*, vol. 395, pp. 12–23, Sissa Medialab Srl, sep, 2022, DOI [`2109.03125`].

[9] A.M. Hillas, *Cherenkov Light Images of EAS produced by Primary Gamma Rays*, *ICRC* **53** (1985) 1689 [`arXiv:1011.1669v3`].

[10] E. Aliu, H. Anderhub, L. Antonelli, P. Antoranz, M. Backes, C. Baixeras et al., *Improving the performance of the single-dish Cherenkov telescope MAGIC through the use of signal timing*, *Astroparticle Physics* **30** (2009) 293.

[11] M.L. Ahnen, S. Ansoldi, L.A. Antonelli, C. Arcaro, D. Baack, A. Babić et al., *Limits on the flux of tau neutrinos from 1 PeV to 3 EeV with the MAGIC telescopes*, *Astroparticle Physics* **102** (2018) 77 [`1805.02750`].

[12] S. Ogawa, H. Oshima, R. Nagasawa, M. Sasaki and T. Aoki, *Observation of optical transients and search for PEV-EEV tau neutrinos with ASHRA-1*, in *Proceedings of Science*, vol. 358, p. 970, SISSA Medialab, 2019, http://pos.sissa.it/.

[13] G.W.S. Hou and M. Sasaki, *Neutrino telescope array (NTA): Prospect towards survey of astronomical $\nu\tau$sources*, in *VHEPA2014*, vol. 30-July-20, (Kashiwa, Tokyo), 2015 [`1409.0477`].

[14] J. Cortina, R. López-Coto and A. Moralejo, *MACHETE: A transit imaging atmospheric Cherenkov telescope to survey half of the very high energy γ-ray sky*, *Astroparticle Physics* **72** (2016) 46 [`1507.02532v1`].

[15] S. Gómez, D. Gascón, G. Fernández, A. Sanuy, J. Mauricio, R. Graciani et al., *MUSIC: An 8 channel readout ASIC for SiPM arrays*, vol. 9899, p. 98990G, International Society for Optics and Photonics, apr, 2016, DOI.

[16] E. Pollacco, G. Grinyer, F. Abu-Nimeh, T. Ahn, S. Anvar, A. Arokiaraj et al., *GET: A generic electronics system for TPCs and nuclear physics instrumentation*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **887** (2018) 81.

[17] M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data*, *Physical Review Letters* **124** (2020) 051103 [`1910.08488`].

[18] M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens et al., *Characteristics of the diffuse astrophysical electron and Tau neutrino flux with six years of IceCube high energy cascade data*, *Physical Review Letters* **125** (2020) 121104 [`2001.09520`].