PROCEEDINGS OF SCIENCE

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 UHE radio detectors. Trinity is a system of 60×5-degree 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 neutrino flux to ultrahigh energies and the detection of cosmogenic neutrinos. Over a ten-year observation period, Trinity will detect about 60 diffuse UHE neutrinos if the astrophysical neutrino spectrum does not turn over. Trinity will provide critical measurements to study flavor physics and neutrino cross-sections at energies that are out of reach for accelerators. I present the project's status focusing on the Trinity Demonstrator, a one square meter air-shower imaging telescope we deployed on Frisco Peak, Utah, in July 2023. We the Demonstrator we aim to demonstrate the technology and understand potential backgrounds. In addition, I discuss the discovery potential of diffuse and source UHE neutrinos with the Demonstrator, one Trinity telescope, and the completed system.

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1. Introduction

Multimessenger astrophysics is a powerful approach to unravel the secrets of the non-thermal universe. Photons, neutrinos, and gravitational waves probe different regions and energetics of the most extreme objects in the sky. Combining all the messengers' information gives us a more complete picture of processes than from a single messenger alone.

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 fully exploited.

The experimental approach to fully explore the multimessenger potential 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 up to PeV energies [2]. With just a handful of observations, the IceCube team has impressively demonstrated the powerful and transformational impact of the neutrino window. To date, a diffuse astrophysical neutrino flux, one blazar, one AGN, and most recently, the galactic plane have been detected at high energies with IceCube [2–5].

These tantalizing discoveries are major drivers for extending neutrino observations to higher than PeV energies. Observing very-high-energy (>PeV) and ultrahigh-energy (>EeV) neutrinos requires techniques capable of covering orders of magnitude larger observing volumes 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.

The Earth-skimming technique is a different approach to detecting VHE and UHE tau neutrinos [6]. It uses 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 tau decays after it emerges from the ground. The decay produces an extended particle shower in the atmosphere producing 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 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. The technique robustly 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].

Applied to Earth-skimming neutrino detection, air shower imaging yields a PeV energy threshold with a light collection area as small as ten square meters.

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 pointed their IACTs at a Mauna Kea [12, 13].

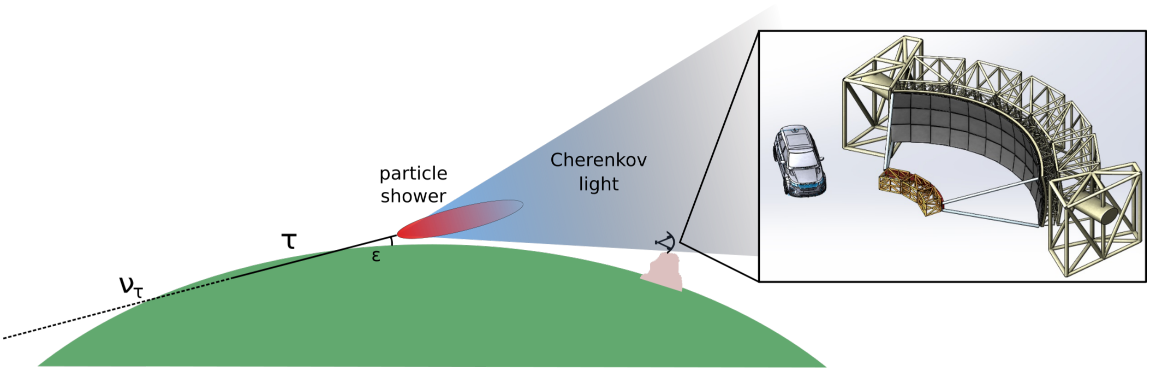

Figure 1: *Trinity* detection concept. Following a tau-neutrino interaction inside the Earth, the resulting tau decays in the air, starting a particle shower imaged with a Cherenkov telescope. The insert shows the conceptual drawing of a Trinity telescope. *Trinity* will consist of 18 such telescopes.

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 detector on a mountaintop and pointing it at the horizon. At the same time, the lowest possible threshold is achieved with an appropriately sized light collection area and photosensors with high red sensitivity [7].

The Trinity concept is scalable by deploying more telescopes on one site and expanding to different sites. By strategically placing arrays of IACTs at various locations, 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 arrays of IACTs. An array comprises six wide field-of-view IACTs, with each telescope observing 60 degrees in azimuth and 5 degrees in vertical [14].

Science operation of Trinity starts with the deployment of the first telescope. For that reason, we plan to develop Trinity in three phases: the Demonstrator, the Prototype, and the Observatory.

3. The Trinity Demonstrator

With the Trinity Demonstrator, we aim to prove the Trinity concept, 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 observed by IceCube.

The Demonstrator telescope is a one square meter class IACT installed on Frisco Peak, Utah 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

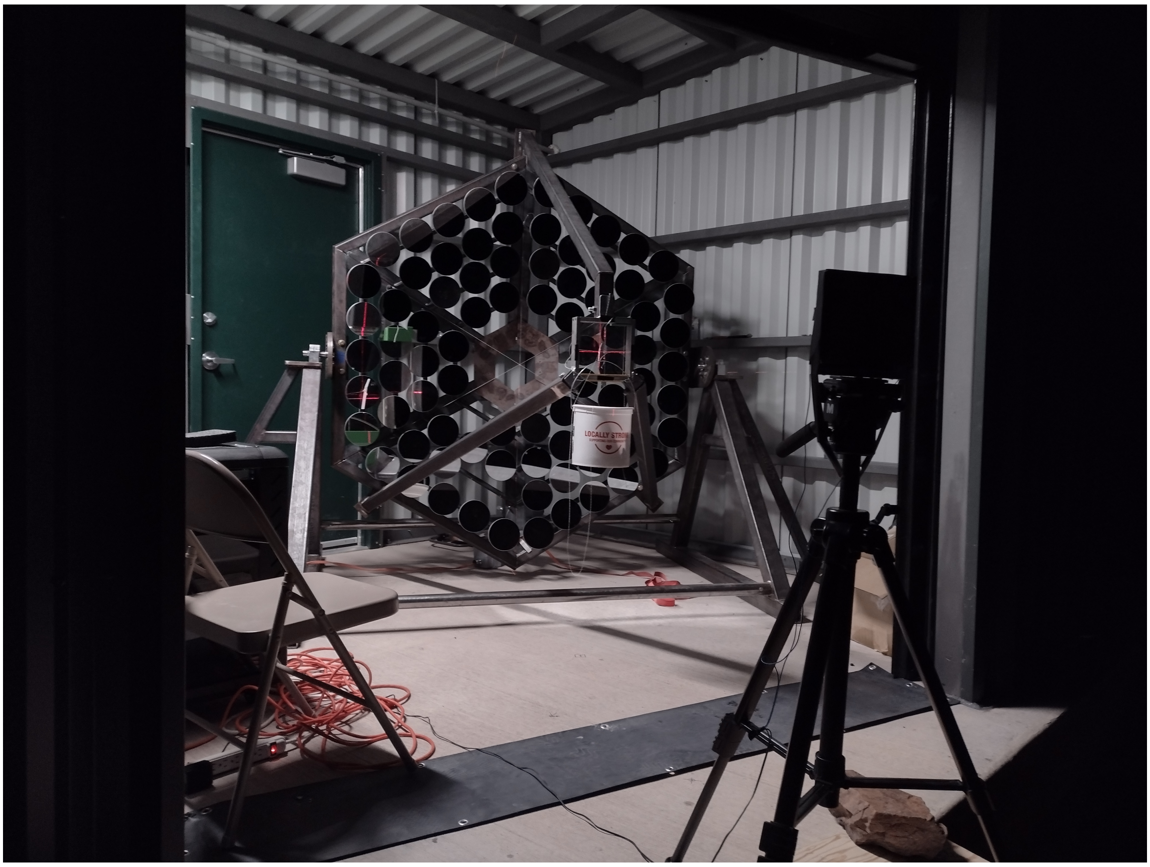

Figure 2: The *Trinity* Demonstrator on Frisco Peak Utah during installation in July 2023.

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 FoV is above, and 2° is below the horizon, thus viewing 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, it shares the same key characteristics as a full-blown Trinity telescope, like the same vertical field of view and 0.3° angular resolution, silicon photomultipliers as photosensors, and a 100 MS/s readout.

The SiPM signals are amplified and shaped by the MUSIC ASIC [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 FPGA triggers the readout if the signal in one SiPM exceeds the discriminator threshold. The software implements higher-level trigger topologies, e.g. looking for 100 ns time coincidences between neighboring pixels.

The Demonstrator points at 280° azimuth yielding approximately equal annual acceptance for NGC 1068 and TXS 0506 of $5.6 \cdot 10^{12}\,\mathrm{cm}^2$ s. That compromise pointing gives one-third of the maximum acceptance would the Demonstrator be pointed at the optimal position of either source.

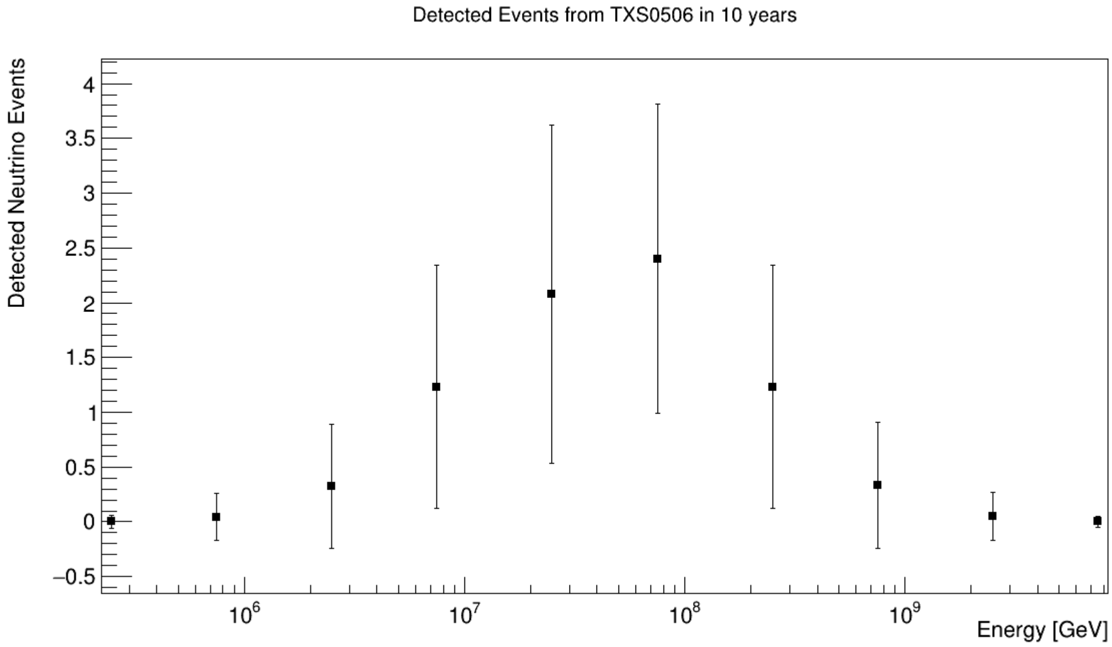

Figure 3: Expected event distribution TXS 0506+056 in true energy.

In this configuration, we expect one neutrino from the direction of TXS 0506 after two years of observations assuming the average 9-year neutrino spectrum published in [4]. Figure 3 shows the expected event distributions after ten years.

Figure 4 is a figure modification from [**?**]. We modified it by extrapolating the NGC 1068 and TXS 0506+056 flux into the energy range of the Demonstrator. The horizontal lines indicate the Demonstrator's sensitivity for a 1, 5, and 10-year observation.

Figure 5 shows a sky plot of the Demonstrator's annual point source acceptance for a power law spectrum with index -2.

4. Discussion

Detecting VHE and UHE neutrinos is a challenging task. The Trinity approach is to image tau-induced particle showers in the atmosphere with Cherenkov telescopes. Once completed, the Trinity Observatory will observe neutrinos from PeV to EeV energies with unprecedented sensitivity.

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 Trinity Prototype, which we will start constructing in 2025. We will also observe NGC1068 and TXS0506 with the Demonstrator and search for diffuse astrophysical neutrinos.

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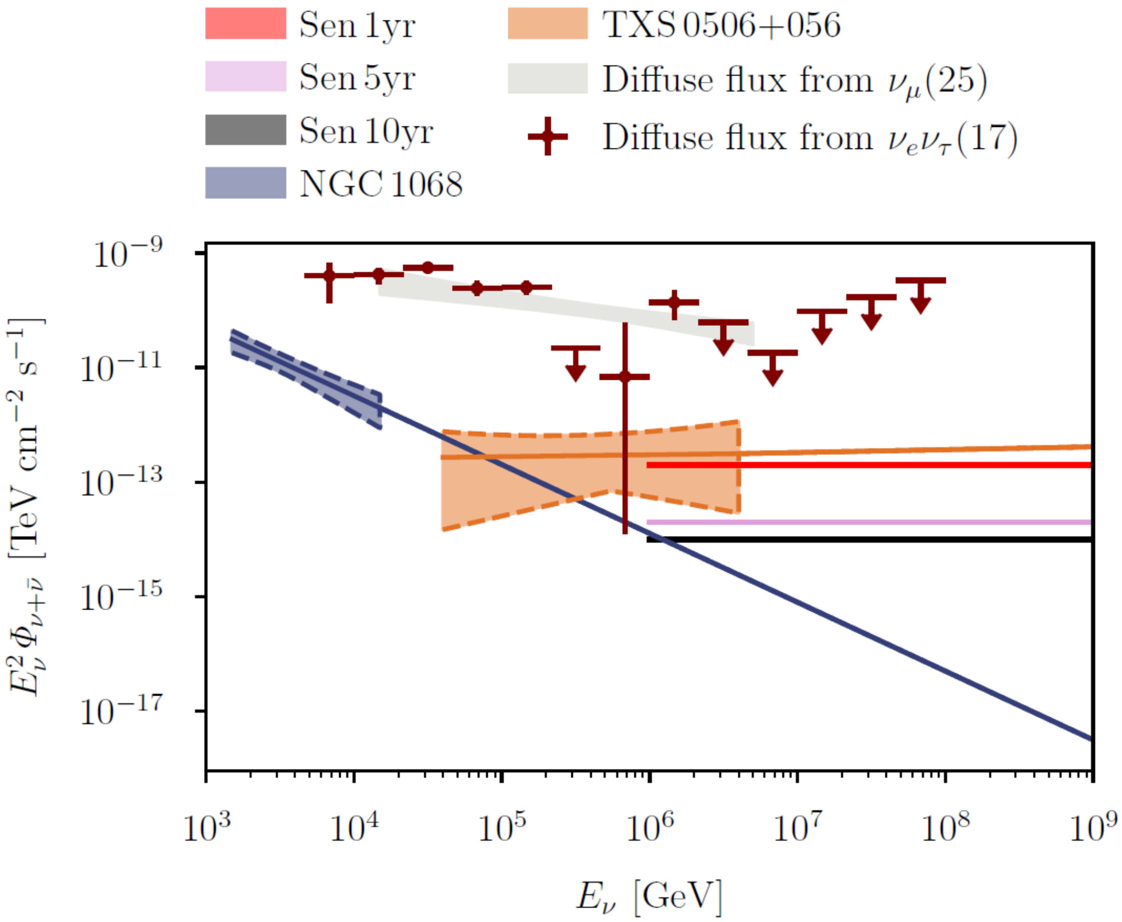

Figure 4: Point source sensitivity of the Demonstrator assuming a power law source with index -2

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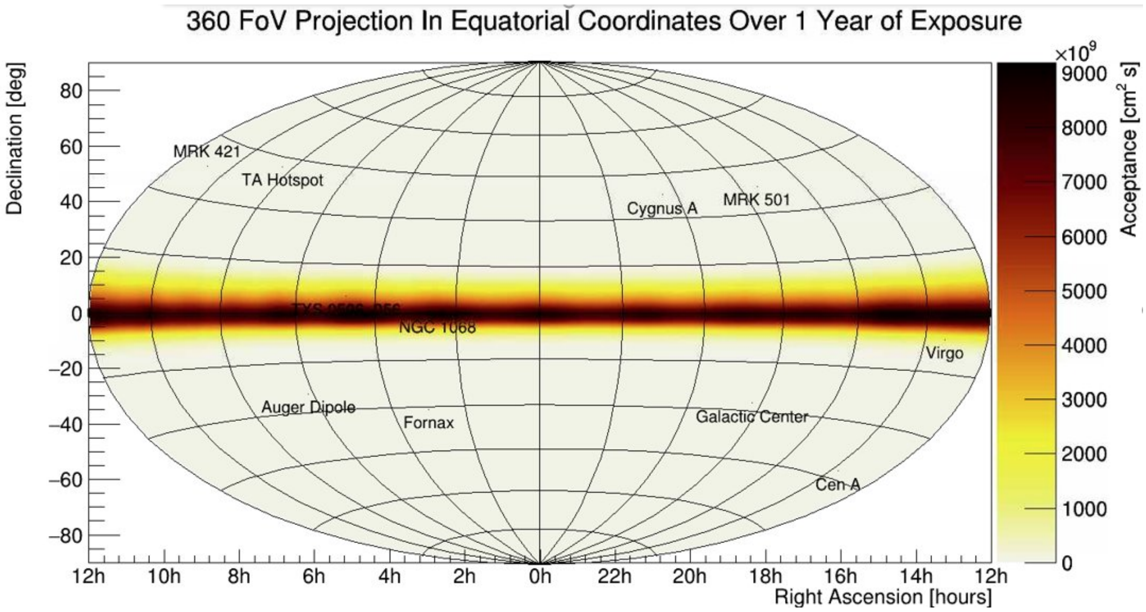

Figure 5: Expected event distribution TXS 0506

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