Snowmass2021 - Letter of Interest

Trinity: A large Field-of-View Air-Shower Imaging Instrument to explore the UHE-Neutrino Sky down to PeV Energies

Thematic Areas: (check all that apply ☐/■)

■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (NF03) BSM
■ (NF04) Neutrinos from natural sources
■ (NF05) Neutrino properties
■ (NF06) Neutrino Interaction Cross Sections
■ (NF10) Neutrino Detectors

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Abstract: *Trinity* is a proposed observatory sensitive to ultra-high-energy (UHE, 10^6 GeV-10^{10} GeV) neutrinos of astrophysical and cosmological origin. It is a system of static air-shower imaging telescopes that detect Earth-skimming tau neutrinos. The cameras of the *Trinity* telescopes use silicon photomultipliers, which, combined with advances in signal digitization, new mirror technologies, and image analysis, make it possible to reach a sensitivity comparable to that of proposed radio detectors at equal or lower costs. The low threshold of only 10^6 GeV provides a significant overlap in energy with the optical part of IceCube-Gen2. Because both instruments cover similar regions in the sky, exciting opportunities for joint source studies and cross-calibration will arise. *Trinity* will extend the IceCube measured neutrino flux to higher energies, and it will identify steady and flaring UHE neutrino sources in the northern hemisphere, which naturally emphasizes the extragalactic sky. By identifying the first UHE neutrino source, *Trinity* will provide critical measurements to study flavor physics and neutrino cross-sections at energies beyond the reach of accelerators. Any identified UHE neutrino source would be an excellent laboratory for *Trinity* to test physics beyond the Standard Model, such as Lorentz Invariance Violation (LIV).

1 The science case for the *Trinity* UHE neutrino observatory

Trinity is an ultra-high-energy (UHE; $> 10^6$ GeV) tau-neutrino observatory with a low-energy threshold, almost all-sky coverage, and a sensitivity comparable to other proposed experiments. Besides exploring neutrino physics at unprecedented energies, *Trinity* has the potential to contribute fundamentally to astrophysics in many ways, from identifying the sources of ultra-high-energy cosmic rays (UHECR) to gaining insight into the evolution of the universe. The observatory will explore neutrino physics at energies out of reach of accelerators, and the possibility exists to identity new physics beyond the Standard Model of particles[1;2]. The major strengths of *Trinity* are its low threshold of 10^6 GeV and its ability to observe most of the UHE-neutrino sky. These strengths combine to enable a unique science program.

The energy threshold of *Trinity* is lower than in typical UHE radio-detectors because it is an imaging instrument and air showers emit much more energy in Cherenkov light than in the radio. Hence, even when ambient backgrounds are considered too, much more *signal* is available for detection and event reconstruction. Air-shower imaging has also proven to be robust in rejecting events due to artificial light sources, because these are very different from air-shower images and thus easily identifiable.

The almost all-sky coverage of *Trinity* is common to all UHE-neutrino detectors not located close to the north or south pole[3]. Indeed, the sky that *Trinity* observes *above* 1 PeV, is mostly the same sky that the optical part of IceCube-Gen2 observes *below* 1 PeV[4]. Hence, *Trinity* will extend IceCube's measurements of the astrophysical neutrino flux above 1 PeV with neutrinos from the very same sources. The goal for *Trinity* is to identify the origin of these neutrinos by quantifying the flux and constrain and potentially identify a spectral break in its spectrum.

Besides studies of astrophysical neutrinos and cosmogenic neutrinos, which result from the GZK mechanism[5], *Trinity* will search for individual UHE neutrino sources. Sharing the same sky and having significant energy overlap with the optical part of IceCube-Gen2 will allow joint studies of individual sources like TXS 0506+056[6] and cross-calibrate both instruments.

Trinity will observe the Ursa Major cluster, where Telescope Array observes a UHECR excess[7]. *Trinity* will search for a neutrino flux that is correlated with the anisotropy and possibly identify the sources or at least significantly narrow down the potential pool of sources responsible for it.

Trinity, like all Earth-skimming neutrino detectors, is only sensitive to tau neutrinos. This feature could allow for some of the most sensitive flavor studies at EeV energies by combining *Trinity* observations with those of in-ice radio detectors, which are sensitive to all three flavors but do not necessarily have the required flavor resolving power[1;2].

2 Why Trinity now?

UHE-neutrinos present a formidable experimental challenge. Small interaction cross-sections and extremely low fluxes demand huge detector volumes and unprecedented observation times as long as a decade. Keeping systematic uncertainties in check and experiments stable to claim only one neutrino over such extended periods is incredibly hard. A natural approach to mitigate the risks of a false detection by one experiment is to rely on more than one detection technique, a common practice in HEP. That is where *Trinity* plays an essential role because, unlike the large majority of proposed UHE-neutrino detectors, it is not a radio instrument but an air-shower imaging system.

Trinity is a system of six small Cherenkov telescopes located on a mountain 2 km to 3 km above the ground, and that point at the horizon[8]. Frisco Peak in Utah is a possible site. The telescopes image the air-shower that develops when an Earth-skimming tau neutrino interacts inside the Earth, and the generated tau decays in the atmosphere. An offline analysis reconstructs the energy and arrival direction of the neutrino from the recorded images. Air-shower imaging is well established and used by the world's most sensitive VHE gamma-ray and UHECR instruments (Pierre Auger, TA, VERITAS, MAGIC, H.E.S.S. and others)[9–14]. Air-shower imaging has several advantages compared to in-ice UHE neutrino detectors; three important ones are:

Maturity and precision With over forty years in the field, air-shower imaging has earned a reputation of being an incredibly robust technique. Its background suppression is outstanding, systematics is well under control, and the technique shows high immunity to fake events. Imaging yields excellent energy and angular resolution to the point that results from *Trinity* will likely be limited by the neutrino interactions in the Earth.

Low construction costs and operation costs Recent advances in photon-detector technologies – silicon photomultipliers – and readout electronics make new imaging instruments possible that cost about the same as proposed radio instruments while delivering comparable sensitivity[8].

Low Energy Threshold, Air-shower imaging offers a thresholds as low as 10^6 GeV but, in the past, air-shower imaging has not been a favored UHE-neutrino detection technique. This was because costs of Cherenkov telescopes had been high and they could only operate during moon-less nights limiting the duty cycle to $< 10\%$. However, that has changed in recent years. Costs for air-shower imaging instruments have come down thanks to CTA[12] developments, while, at the same time, costs for proposed radio detectors have increased due to more complex setups (beam-forming, phased arrays, large antenna farms, etc). Furthermore, has it been demonstrated that air-shower imaging instruments can have a 20% duty cycle, more than twice as much as was previously possible[15].

The drop in cost for air-shower imaging is due to four significant technological developments: silicon photomultipliers, low-cost signal digitization, novel mirror technologies, and wide field-of-view optics. Of these, the silicon photomultiplier has been a real game-changer. Its ten times higher sensitivity in the red than classical bialkali photomultipliers allows the detection of far-away air showers (100 miles) with telescopes that have functional mirror areas of only $\sim 10\,\mathrm{m}^2$ compared to a $200\,\mathrm{m}^2$ MAGIC telescope[16]. Costs are further reduced with novel mirror technologies developed for CTA and novel $60^\circ \times 5^\circ$ wide-field of view optics[17]. The latter means that *Trinity* requires fewer telescopes, which lowers costs further. Additional savings come from new readout systems[18;19]. All advances combined, *Trinity* is expected to cost less than $5 M when constructed with 360 degrees field-of-view[8].

The MAGIC Collaboration shows regularly that air-shower imaging is a robust technique to search for UHE neutrinos. Although a VHE-gamma-ray instrument, the MAGIC telescopes are regularly pointed at the ocean, searching for UHE neutrino as part of their GRB follow-up program, Target-of-Opportunity programs, or when regular VHE gamma-ray observations are not possible[20;21]. MAGIC has demonstrated that the search for UHE neutrinos is background free close to the trigger threshold[21], but its primary mission is VHE gamma-ray observations. MAGIC thus spends only a small fraction of its annual time for UHE neutrino searches, whereas *Trinity* is fully dedicated to UHE neutrinos and thus 10,000 times more sensitive.

3 Summary

Trinity is a UHE-tau-neutrino observatory with almost all-sky coverage, a low-energy threshold of 10^6 GeV, and a ten-year sensitivity similar to proposed radio UHE-neutrino detectors. New technologies like the SiPM make air-shower imaging attractive for UHE-neutrino detection. *Trinity* capitalizes on that untapped potential and can be operational within five years.

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