Snowmass2021 - Letter of Interest

The Beamforming Elevated Array for COsmic Neutrinos (BEACON)

Thematic Areas:
■ (CF7) Cosmic Frontier: Cosmic Probes of Fundamental Physics
■ (IF10) Instrumentation Frontier: Radio Detection
■ (NF10) Neutrino Frontier: Neutrino Detectors
■ (NF04) Neutrino Frontier: Neutrinos from natural sources
■ (NF06) Neutrino Frontier: Neutrino Interaction Cross Sections
■ (IF4) Instrumentation Frontier: Trigger and DAQ

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Abstract: The Beamforming Elevated Array for COsmic Neutrinos (BEACON) aims to discover ultra-high energy tau neutrinos by searching for the radio emission from upgoing air showers generated by Earth-skimming tau neutrinos. The design takes advantage of the large viewing area available at high-elevation sites, the nearly full duty cycle available to radio instruments, and interferometric techniques to arrive at an efficient, scalable detector. The instrument architecture is based on a compact cluster of radio antennas using beamforming radio techniques, an enabling technology that is expected to permit degree scale pointing resolution, robust background rejection, and enhanced sensitivity. BEACON holds promise to discover both cosmogenic and/or astrophysical neutrinos in a new energy regime.

1 Introduction

Ultra-high energy (UHE, $>$ 100 PeV) neutrinos play an important role as probes of both astrophysics and fundamental physics, as described in several companion LoIs[1–3]. The Beamforming Elevated Array for COsmic Neutrinos (BEACON)[4] is a planned scalable, efficient detector for UHE τ neutrinos, currently under study.

Long expected as the result of cosmic ray interactions with the photon backgrounds[5;6], the flux of cosmogenic neutrinos encodes information about the cosmological evolution and composition of the sources of the highest energy cosmic rays[7]. Observation of these cosmogenic neutrinos would provide important evidence towards identifying the origin of cosmic rays, understanding the underlying acceleration mechanisms, and the evolution of sources over gigaparsec long length scales.

Neutrinos play a key role in multi-messenger astrophysics, a growing field that aims to combine observations from neutrinos, gamma rays, cosmic rays, and gravitational waves to build a complete picture of the highest energy particle accelerators in the universe. Because they are weakly interacting, neutrinos are unique in that they point back to their sources and provide incontrovertible evidence of hadronic particle acceleration from distant corners of the universe. At the EeV energy scale, cosmogenic neutrinos produced during cosmic ray propagation trace the evolution of the highest energy sources and provide key evidence to unravel the decades-long question of the origin of the highest energy particles[8–10]. Astrophysical neutrinos produced at the sources themselves can help us study most complex, non-thermal sources in the universe both through continuous neutrino emission and through flares from explosive transients.

Ultra-high-energy observations of *tau* neutrinos have the unique capability to address outstanding questions in both astrophysics and fundamental physics. While not predicted to be generated at the sources, tau neutrinos result from flavor oscillations over the long baselines expected for cosmogenic neutrinos and for those originating in astrophysical sources, such that the expected flavor ratio at Earth is close to $1\ \nu_e : 1\ \nu_\mu : 1\ \nu_\tau$. Experiments primarily sensitive to ultra-high energy tau neutrinos are therefore uniquely suited to test deviations from this standard scenario for instance through flavor changing processes in a new energy regime[11–21]. Once a flux of tau neutrinos is established, tests of neutrino interactions via cross section measurements can probe both new physics in neutrino-nucleon interactions[22–47] and parton structure[42;44;48;49].

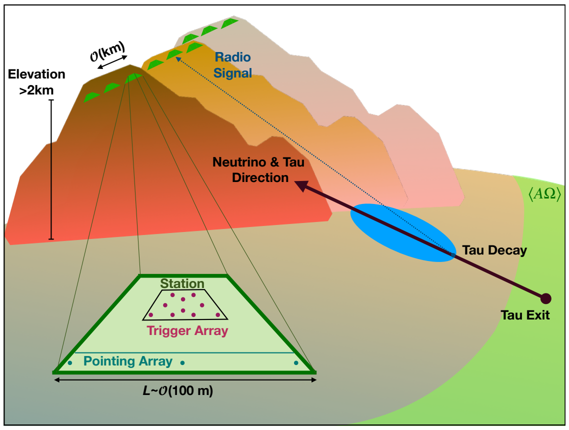

Figure 1: BEACON observes upgoing tau neutrinos from a high-elevation mountain.

2 BEACON Concept and Instrument

The goals of the BEACON, a 100-PeV to EeV scale tau neutrino observatory, are to (1) extend the cosmic neutrino and cosmic tau neutrino spectrum to ultra-high energies and (2) reveal the nature and origin of sources of cosmic neutrinos.

Tau neutrinos can be selectively detected using air shower techniques to search for tau lepton decays in air. Tau neutrinos can have charged current interactions in the Earth to produce a tau lepton that travels through the Earth with relatively small energy loss. If the tau lepton is produced near the surface, it can decay in the air to produce an extensive air shower. If it decays in the Earth it regenerates an additional tau neutrino[50–54]. The combined effects of the moderate decay length of the tau (50 km E/EeV), the large range of the tau lepton in rock, and tau regeneration mean that a detector pointed at the horizon can search for upgoing tau decays with high efficiency[55]. Several current and planned experiments use radio[56–58] and optical instrumentation[59–61;61–68] to search for these upgoing air showers in different geometries.

BEACON is an efficient design meant to search for upgoing tau neutrinos via the radio emission produced by air showers from a high-elevation mountain using beamforming techniques[4]. The design, shown schematically in Fig. 1, uses the high-elevation of a mountain to monitor a large area of the ground for upgoing tau neutrinos. Sites musts be suitably radio-quiet, with a clear 120° view of the horizon. The broadband spectrum of the geomagnetic radio signal from air showers permits both low frequency (30-80 MHz) and higher frequency designs (200-1200 MHz) depending on the radio backgrounds at a given site. Optimization studies of the arrays conclude that the arrays should comprise $\mathcal{O}(10)$ antennas in a phased trigger array to improve sensitivity, signal-to-noise ratio, and background rejection from anthropogenic sources. Interferometric beamforming techniques enable efficient observations of air showers up to 100 km away from the detector, making mountains with 2-3 km prominence ideal sites to search for upgoing tau neutrinos. Outrigger antennas in a pointing array can be arranged to enable degree-scale pointing resolution.

Because the BEACON concept relies on low power (< 50 W), inexpensive, low channel-count instrumentation, the technique is scalable to many stations that can be deployed at one or at many locations around the world. Many high-elevation sites are at mid-latitudes, giving broad sky coverage. With the expected sensitivity of BEACON and enough stations, we expect to be able to constrain the maximum energy of cosmic ray accelerators and to probe extrapolations of the diffuse IceCube neutrino flux into the EeV energy regime. $\mathcal{O}(100)$ stations are needed to improve on existing limits of UHE neutrinos by a factor of ten and $\mathcal{O}(1000)$ to probe pessimistic models of cosmogenic neutrinos assuming a pure iron composition of cosmic rays.

BEACON is expected to be the first experiment of its kind to implement an interferometric trigger on a project designed to search for upgoing tau neutrinos. This type of trigger enables both efficient radio detection in the presence of anthropogenic backgrounds, it has a high duty cycle compared to optical air shower detectors and has been demonstrated to improve sensitivity to weak events in in-ice neutrino experiments[69]. Radio-only triggers on cosmic ray air showers have been demonstrated in the TREND[70] and OVRO-LWA[71] experiments, and an interferometric trigger may improve on the efficiency. A prototype experiment designed to detect cosmic rays through a radio-only interferometric trigger is currently under study at the White Mountain Research Station in Bishop, California[72]. An antenna and view from the mountain is shown in Fig. 2.

Figure 2: BEACON prototype antenna. Credit: S. Devanzo

3 Summary

The BEACON concept targets the highest energy tau neutrinos by searching for radio emission from a high-elevation mountain. The main advantages include: 1) a high duty cycle, 2) significantly reduced resource requirements compared with arrays at lower elevation, and 3) the use of interferometric techniques that enable a high sensitivity implementation that is robust against radio backgrounds. By extending the measurement of the tau neutrino spectrum into a new energy regime, this project can contribute to our understanding of the physics driving the highest energy astrophysical accelerators and their cosmological evolution.

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