# Astro2020 Project White Paper

# Expanding the Reach of Tau Neutrino Telescopes with the Beamforming Elevated Array for COsmic Neutrinos (BEACON)

**Topic Areas:** Multi-messenger Astronomy and Astrophysics,
Cosmology and Fundamental Physics

**Stephanie Wissel†,** California Polytechnic State University
**Jaime Alvarez-Muñiz**, Universidade Santiago de Compostela
**Washington R. Carvalho, Jr.,** Universidade de São Paulo
**Austin Cummings**, Gran Sasso Science Institute
**Cosmin Deaconu**, University of Chicago
**Kaeli Hughes**, University of Chicago
**Andrew Ludwig**, University of Chicago
**Eric Oberla**, University of Chicago
**Andres Romero-Wolf**, Jet Propulsion Laboratory, California Institute of Technology
**David Saltzberg**, University of California, Los Angeles
**Harm Schoorlemmer**, Max-Plank-Institüt für Kernphysik
**Daniel Southall**, University of Chicago
**Abigail Vieregg**, University of Chicago
**Enrique Zas**, Universidade Santiago de Compostela

†Corresponding author, swissel@calpoly.edu, (805) 756-7375 July 2019

# 1 Key Science Goals and Objectives

## 1.1 The High Energy End of the Cosmic Neutrino Spectrum

Active galactic nuclei, pulsars, gamma-ray bursts, and galaxy clusters are all implicated as possible accelerators of ultra-high energy cosmic rays that can achieve energies greater than $10^{20}$ eV. The origin of these cosmic rays has confounded the field for decades in part because cosmic rays up to a certain rigidity are unreliable narrators. Such accelerators pump cosmic rays (protons and other nuclei) into the local environment where through $pp$ and $p\gamma$ interactions they can deposit energy into several messengers: neutrinos, gamma rays, and secondary cosmic rays. Cosmic neutrinos can thus identify the sources of the highest energy particle acceleration in the universe. Combined multi-messenger observations can give further insight into the nature of the highest energy accelerators.

Cosmic neutrino production depends on the assumed acceleration mechanism and source types, both of which are informed by observations by the IceCube neutrino observatory in a lower energy range from 100 TeV to 10 PeV [1–5]. IceCube has reported on three main analyses of the cosmic neutrino spectrum. Through-going muon neutrinos indicate a hard spectrum with an index of $E^{-2.13\pm0.13}$ [1]. However, analyses using the all-flavor and high-energy events contained entirely in the detector favor a softer spectral indices of ~ 2.5 [2,6]. Efficient detection of the extrapolations of these fluxes over a large energy range above the 10 PeV scale, requires a detection probability that grows at least as $E$, and such behavior is naturally provided by the Earth-skimming channel, through the rise in the neutrino cross section and the increase of the tau decay length [7].

The difference in measured spectral indices of the neutrino flux can be attributed to the energy threshold of the different analyses, meaning that as with photons, the universe mapped in neutrinos is complex [8]. Different sources contribute the neutrino sky and only through improved event statistics, improved angular resolution, extensions to higher energies, and deeper understanding of the flavor composition can we build a complete map of the neutrino sky [9].

Multi-messenger observations combining neutrino observations with other messengers will permit a deeper understanding of explosive phenomena such as stellar explosions, relativistic jets [10], and compact object mergers [11], among others [9, 12]. The most successful example of this is the recent correlated observation of neutrinos and gamma rays from the blazar, TXS 0506+056 [13, 14]. Neutrino observatories that continuously monitor a wide patch of sky and with a high duty cycle are well suited for such transient searches.

Cosmogenic neutrinos are additionally expected at energies above 1 EeV from the interactions of the highest energy cosmic rays with background photons during cosmic ray propagation [15,16]. Because cosmic rays interact with photon backgrounds within a mean free path of hundreds of megaparsecs and gamma rays are absorbed by the extra galactic background light, cosmogenic neutrinos may provide the only particle probe of the high energy end of the universe at gigaparsec length scales. The long baselines and high energies allow us to probe fundamental physics in otherwise inaccessible energy regimes and length scales [17].

Tau neutrinos, in particular, also have important implications for neutrino astrophysics. A measurement of a tau neutrino flux would confirm the that the tau neutrino flux is astrophysical, because sources are only expected to produce electron and muon neutrinos. The neutrinos produced at the source oscillate as they propagate such that all flavors are expected in even ratios (although deviations from this standard scenario are predicted) [17]. Recent hints in the IceCube data suggest that some events are tau neutrinos [18]. This project can extend the measurement of the spectrum of tau neutrinos into a new energy range, which has important implications for the nature of the highest energy accelerators and fundamental physics.

### 1.2 Goals

High-energy observations of tau neutrinos have the unique capability to address outstanding questions in both astrophysics and fundamental physics, as outlined in several Astro2020 white papers [9–12, 17, 19]. The goals of the Beamforming Elevated Array for COsmic Neutrions (BEACON), a 100-PeV scale tau neutrino observatory are to:

- Extend the cosmic neutrino spectrum to higher energies
- Reveal the nature and origin of sources of cosmic neutrinos, both through direct observations of neutrinos and multi-messenger observations
- Measure the tau spectrum, which can point to different acceleration mechanisms at the sources and possibly beyond-the-standard model physics

With BEACON, we expect to achieve sub-degree scale pointing. We expect to either observe as many as 10-30 tau neutrinos over a five year period or place limits on the maximum energy of cosmic ray accelerators and the extension to the diffuse IceCube neutrino flux. These goals are consistent with the requirements set by two Astro2020 Science Whitepapers [9, 17].

## 2 Technical Overview

### 2.1 Concept

Tau neutrinos can be observed from a high-elevation mountain due to charged current interactions of the neutrinos within the Earth that result in tau leptons. The tau leptons may then emerge from the Earth and decay to produce an particle shower in the atmosphere which can be observed using a variety of air shower detection techniques [20–22].

A promising technique for detecting tau lepton showers looks for radio-frequency (RF) radiation from the particle showers they initiate in the Earth's atmosphere. The signature would be an upcoming broadband radio spark produced by a tau lepton decay in air. Because this channel is practically inaccessible to electron or muon neutrino detection, tau neutrinos present a unique opportunity for studying the neutrino flavor content of the highest energy neutrinos. By maximizing the single detector exposure and by using inexpensive instrumentation deployed in hospitable environments, a high-elevation mountaintop radio detector is a scalable solution to achieving the enormous effective areas necessitated by the expected neutrino flux at > 100 PeV.

BEACON targets the sources and flux of tau neutrino by searching for Earth-skimming, upgoing tau neutrinos. As shown in Fig. 1, BEACON consists of a radio interferometer located on a high elevation mountain. Each station monitors an independent portion of the valley for tau leptons exiting the Earth after being produced by tau neutrinos through a charged current interaction inside the Earth. The sensitivity of each station is maximized by placing the stations on mountain prominences at least 2 km above the valley.

A key aspect of the BEACON concept is the use digital, time-domain interferometry which observes the signal from an air shower on multiple antennas, and coherently delays and sums

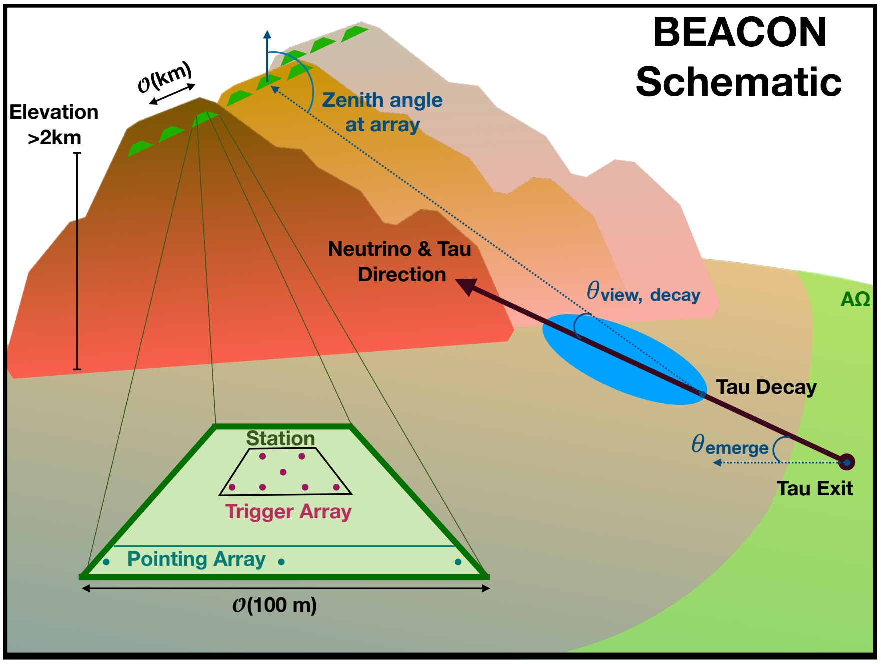


Figure 1: Concept of a high-elevation mountaintop detector.

the signals. Interferometric techniques can improve the angular reconstruction of the signals and enhances background rejection, both at the trigger level and in rejecting backgrounds at the analysis level.

Additionally, by searching for tau neutrinos using a similar technique and in a similar energy regime, but a different environment, BEACON can follow up on anomalous events observed by the ANITA experiment that are observationaly consistent with upgoing particle air showers [23, 24], but inconsistent with an isotropic flux of tau neutrinos [25].

## 2.2 BEACON Architecture

The BEACON detector design is still in the conceptual stage where different choices for the detector design are being weighted against cost, logistical challenges, and performance. We outline the key performance parameters and the trade-offs associated with them below.

The acceptance of a single station to an isotropic tau neutrino flux depends on the elevation of the detector and the combined probabilities that a tau lepton will exit the Earth, that it will decay before reaching the detector, and that the receiver will register the radio signal. A first order estimate of the acceptance of a high-elevation radio receiver, shown in Fig. 2(left), gives insight into how the geometry of this design enhances the sensitivity of each station. Motloch, et al give an analytical estimate of the geometric aperture of a high-elevation, $h$, receiver [26] overlooking a valley where a tau lepton can emerge as the result of a charged current interaction of the original tau neutrino in the Earth. The probability, $P_{exit}$, that the tau exits was calculated by Alvarez-Muñiz, et al [7]. The tau will decay within a decay length $L_{decay}$ = 49 km($E_\tau$/EeV), such that tau leptons emerging at the horizon with energies below 3 EeV with always decay before reaching the mountain ridge. We assume that all such events initiated within a few degrees (1-3$^\circ$) view angle of

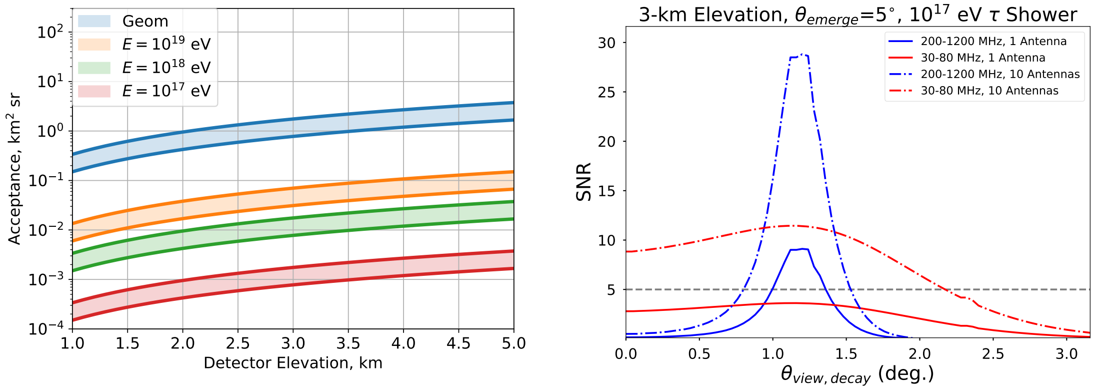


Figure 2: (left) Order of magnitude estimates for the acceptance of a high elevation detector based on the geometric acceptance formula of Motloch, Hollon, Privitera 2014 [26]. We assume a factor of $1/3$ to account for an expected $120^\circ$ field of view. For each energy, we have multiplied the geometric acceptance estimate by the peak $P_{\rm exit}$ values of Alvarez-Muñiz et al. 2018 [7]. (right) A $10^{17}$ eV $\tau$ shower emerging at a $5^\circ$ and decaying at the exit point generates a radio beam pattern shown here as the voltage SNR versus $\theta_{view,decay}$. The radio emission is filtered in the 30-80 MHz (red) and 200-1200 MHz bands (blue) for 1 antenna (solid) and 10 phased antennas (dot-dashed). The SNR is enhanced by $\sqrt{N}$ using $N$ phased antennas.

the neutrino direction are detected via their radio emission, based on the radio beam pattern of an air shower. Because the geometric aperture grows as $h^{1.5}$ [26], the total acceptance increases by a factor of 2.5 going from 1 km to 2 km and by an overall factor of 7 going from 1 km to 4 km.

The radio technique for detecting air showers has matured over the last decade. Ground-based instruments and experiments at accelerators have demonstrated can reconstruct air shower energies with 17% energy resolution [29] and they can accurately model the radio emission [30–32]. The balloon-borne instrument, ANITA, uses interferometric reconstruction [33] to achieve sub-degree angular resolution [34].

The radio beam expected from tau lepton air showers drives the design of the high-elevation antennas in terms of their frequency band and gain. The radio signal is broadband from ~10 MHz to 1 GHz, meaning that various choices can be made about the optimal antenna and frequency band chosen. For instance, as shown in Fig. 2(right), a 30-80 MHz beam is broad, covering a wide range of view angles. Alternatively, the beam in the 200-1200 MHz frequency band can be more strongly peaked at Cherenkov angle, as shown in Fig. 2(right).

Short dipole antennas are readily available in the 30-80 MHz band, typically with gains of 1.8 dBi or better. At higher frequencies, horn antennas and log-periodic dipole antennas can cover a broader range of frequencies and with higher gains. Typical antennas can range from 200 MHz to 1 GHz with gains between 6 dBi and 10 dBi. Incoherent radio backgrounds are dominated by the galactic sky noise in the lower frequency band and by thermal emission from the ground in the higher frequencies. Ultimately, because the acceptance (see Fig. 3) differs by at most a factor of 2 for the two frequency bands considered, the radio backgrounds local to the chosen sites and the angular resolution requirements should determine the final choice of frequency band in the design.

A station architecture based on phased arrays coherently sums the signals from multiple an-

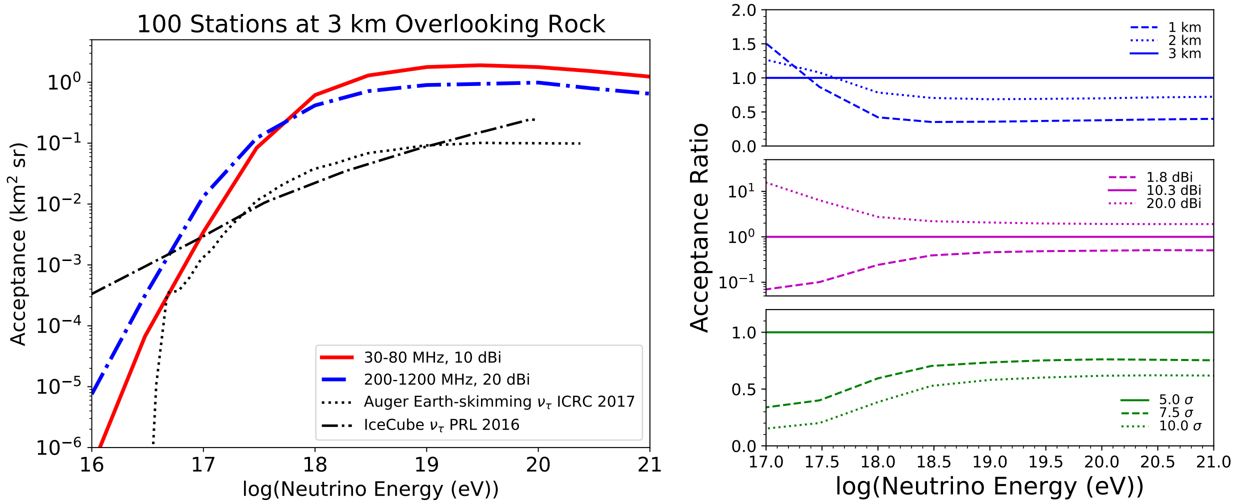


Figure 3: (left) The acceptance of BEACON in two different frequency bands compared with the acceptance of Auger to Earth-skimming tau neutrinos [27] and IceCube [28] to tau neutrinos. The designs assume 100 stations at an elevation of 3 km. The trigger used on each station comprises 7 1.8 dBi antennas in the 30-80 MHz range and 10 10-dBi antennas in the 200-1200 MHz range, both with a threshold of $5\sigma$. (right) The ratio of the acceptance of a 30-80 MHz detector for different: elevations (top), phased array gains (middle), and trigger thresholds (bottom) relative to the design shown on the left.

tennas using formed beams. Multiple beams are formed using time delays pointing in different directions can cover a wide field of view ($120^\circ$) with the higher gain beam formed from $N$ antennas. This has the effect of increasing the voltage SNR by $\sqrt{N}$ as shown in Fig. 2(right), thereby lowering the voltage trigger threshold by the same factor. This technique was first described in the context of neutrino detection by [35] and demonstrated as a successful trigger with ARA [36].

Phased arrays additionally can be used in reconstructing the arrival direction of the tau lepton air shower and in background rejection. The pointing resolution improves with the longest baseline in the array shown in Fig 1, including the outrigger antennas, the bandwidth of the receivers, and the signal strength in in the beam such that one could expect a 10 antenna array of 30-80 MHz receivers separated by 70 m to achieve a pointing resolution of $0.5^\circ$ on $5\sigma$ signal. Additionally, higher frequency, broader band antennas could be used in the pointing array to further improve the angular reconstruction or better constrain the view angle of the events.

Interferometric triggering can additionally be used to reduce triggers from backgrounds produced by man-made sources by masking out directions with strong repetitive sources. This effect was first demonstrated at the analysis level in the TREND experiment [37] and used to trigger on air showers in the OVRO-LWA experiment [38].

## 2.3 Performance Requirements

The optimal design of a high-elevation radio interferometer depends on several factors shown on the right in Fig. 3 including the detector elevation (top), the effective gain of the phased array (middle), and the average trigger threshold on the beam (bottom). The acceptance ratios are referenced

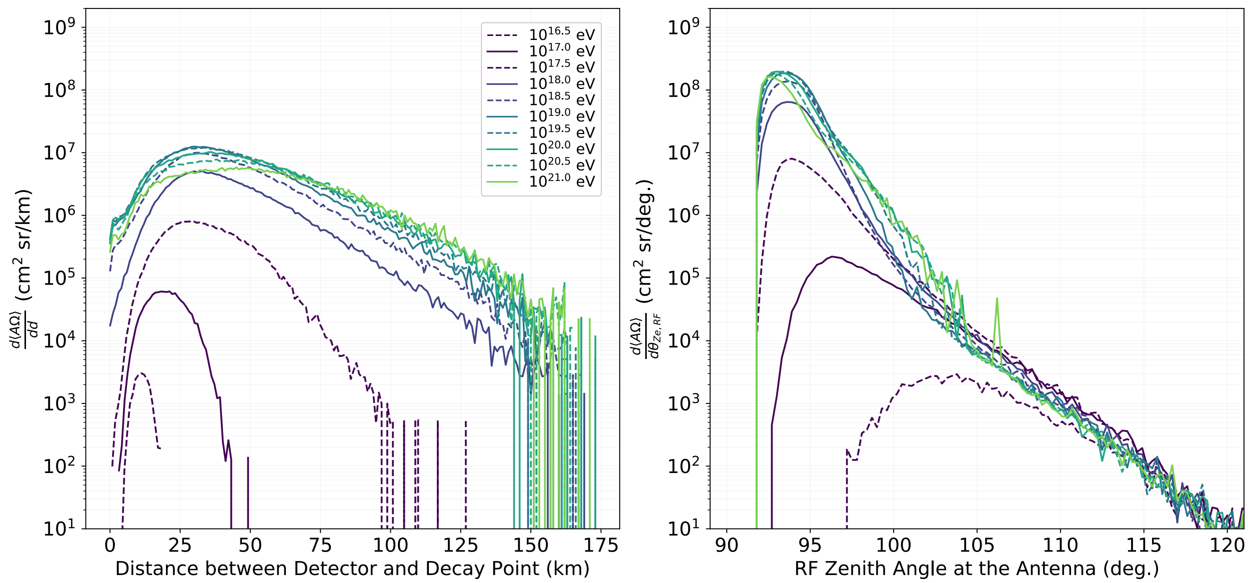


Figure 4: Differential acceptance of the BEACON reference station to isotropoic tau neutrino flux shows the predominant distances between the decay point and the detector (left) and the zenith angles measured at the array (right) for various energies.

to a design of a single BEACON station composed of 7 antennas in the trigger array and 3 additional outrigger antennas each with a gain of 1.8 dBi and a frequency band of 30-80 MHz placed at an elevation of 3 km with a 5$\sigma$ threshold on the beam. These and similar trade studies [39] show that:

- **Frequency Range** The lower frequency design has a higher acceptance for E>$10^{17.5}$ eV, while the higher frequency design yields a lower energy threshold.
- **Number of antennas** The station acceptance linearly increases with the number of antennas up to ~10 antennas, but sub-linearly above that. When increasing the number of stations, however, the acceptance increases linearly regardless of antenna number, assuming that the stations are far apart enough to monitor different regions of the valley.
- **Elevation** The number of expected neutrinos from models that extend to the EeV regime increases linearly with the elevation of the station up to 3 km, while models with cutoffs $E < 10^{18}$ eV are largely insensitive to elevation changes above 1 km.
- **Valley** The number of expected neutrinos is largely insensitive to whether it overlooks rock or ocean, provided it has view out to the horizon. Ocean may still be preferable; however, because manmade noise is more prevalent in the valleys near high-elevation land-locked mountains than over the deep ocean.

Informed by these results, the reference design for BEACON consists of 100 independent stations with 10 phased antennas at 3 km altitude. The BEACON experiment could be composed of many stations either along the same mountain ridge or at multiple sites around the world, thereby scaling up to constrain the UHE neutrino flux and achieve full sky coverage using a technique complementary to optical detectors.

The array layout shown schematically in Fig. 1 balances the need for close-packing of the antennas for triggering and the need for longer baselines between antennas for reconstruction and background rejection. Antennas in the trigger array are closely packed, because phased array triggering is most efficient when all antennas view the same portion of the shower and are a similar distance from the shower. Antennas in the pointing array are separated by a maximum baseline of $\mathcal{O}(100\text{ m})$.

To illustrate the geometry at hand, Fig. 4 that shows that triggered showers are between 10 and 100 km from the detector and that lower energy showers register at closer distances and steeper angles below the horizon. This has two important implications. First, the showers are far enough away that the peak electric field measured by the antennas is degraded by only a few percent, which validates the choice to use interferometric triggering. Second, because the highest energy showers are expected to arrive near the horizon, angular reconstruction better than $0.5^\circ$ is required to reject backgrounds from down-going cosmic rays. An angular resolution of $0.3^\circ$ is achievable with 10 antennas operating in the 30-80 MHz frequency range separated by at most 140 m and triggering events $5\sigma$ above thermal noise in the beams.

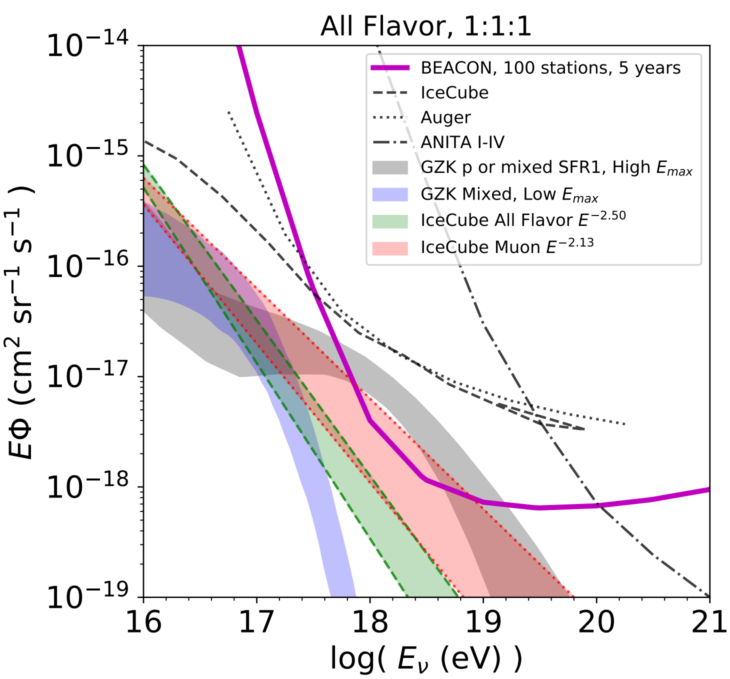


Figure 5: Expected sensitivity of BEACON using the reference design described in the text compared with models of cosmogenic neutrinos, one assuming a high maximum energy in the accelerators (SFR1, p or mixed) [40] and one assuming a mixed composition and a lower cutoff energy [41], as well as extensions to the power law fits of the astrophysical flux observed at lower energies [1,2]. Compared to all-flavor upper limits per decade from IceCube [42], Auger [43], and ANITA [44].

Fig. 5 shows the sensitivity to an isotropic flux of neutrinos with a 1:1:1 flavor ratio expected from 5 years of observation with 100 stations of BEACON. If successfully demonstrated in to perform according to the requirements outline here, such an instrument could measure the ultra-high-energy end of the tau neutrino spectrum or place limits on the cut-offs of the astrophysical tau neutrino flux with a modest number of stations.

## 2.4 Site and Infrastructure Requirements

BEACON detectors can be placed at multiple sites throughout the world to achieve high point source sensitivity and full sky coverage required for searches for neutrinos from explosive transients expected from supernova, gamma ray bursts, blazar flares, and other targets of multi-messenger astrophysics. Different sites view different regions of the sky, and detectors located at mid-latitudes achieve broader sky coverage than those in polar regions. Full sky coverage or a deep exposure towards the galactic center could be achieved through a a thoughtfully designed global network of high-elevation radio instruments.

The high-elevation radio detector concept implies these additional site requirements:

- **High elevation** Mountain prominences of 2 km or higher maximize the detector energy range.

- **Broad azimuthal field of view** A 120° field of view, unobstructed by intervening mountains is preferred to enhance the acceptance of each station.

- **Long mountain ridge** Multiple stations deployed along a mountain ridge need to be separated by a distances of ~ 6 km to be sensitive to independent sets of events originating 100 km away with radio beamwidths of 2°. Multiple stations along the same ridge could act as a veto for man-made radio transients such as airplanes.

- **Radio quiet** An understanding of the RFI at candidate sites is key to assessing the feasibility of a site and the sensitivity of the detector. The electric field threshold – and therefore the energy threshold – can be reliably modeled as some factor ($\sigma$) above the incoherent, thermal backgrounds due to galactic, thermal, and system noise. However, radio-frequency interference (RFI) can increase the unresolved backgrounds, raising the trigger threshold, which can can degrade the instrument acceptance as shown in Fig. 3(right).

The site requirements above point to high mountain ranges in remote areas, such as mountain ranges in California, Nevada, Colorado, and Peru as well as many others. Some of these sites are actively being considered for site surveys. White Mountain Research Station (WMRS) in California reaches an elevation of 3.8 km with a prominence of 2.3 km, overlooking Nevada's Fish Lake Valley and California's Owen's Valley. A radio-quiet region of the Western United States, it has the advantage of hosting a long-standing high-altitude research station run by the University of California. This is the current site of prototypical experiments being conducted in service of the BEACON concept.

# 3 Technology Drivers

This design assumes that each station can efficiently trigger on radio-only signals 5$\sigma$ above thermal noise over a a full 120° field of view with a high livetime over view of rural mountains. While results from the TREND [37] and OVRO-LWA [38] experiments suggest that radio-only triggers on cosmic rays are possible, consistently triggering on impulsive events with a high duty cycle in the presence of radio-frequency interference has yet to be demonstrated. This is the subject of active study with the development of a prototype BEACON station.

A four-antenna interferometer was deployed for 10 months at WMRS using commercially available dipoles designed for the LWA experiment [45] and the same phased array trigger and data acquisition hardware deployed on ARA [36]. The system is designed to automatically adjust the thresholds (defined as power sums relative to thermal noise) in 20 different beams to meet a global trigger rate of tens of Hertz. Prominent sources of RFI would set the threshold to be higher in the beam that points to it. This is evident in preliminary work shown Fig. 6 where two beams maintain high thresholds, while others are lower. After applying RFI rejecting vetos, most beams achieve thresholds between 5 and 20$\sigma$. The antennas in this study were separated by ~10 m, but by using broader baselines, the RFI could be isolated to individual beams. Further exploration into the performance of RFI rejection at the trigger level is on-going. Radio-only triggering in the context of BEACON may be achieved if the trigger and array layout can be designed such that most beams achieve 5$\sigma$ thresholds in voltage.

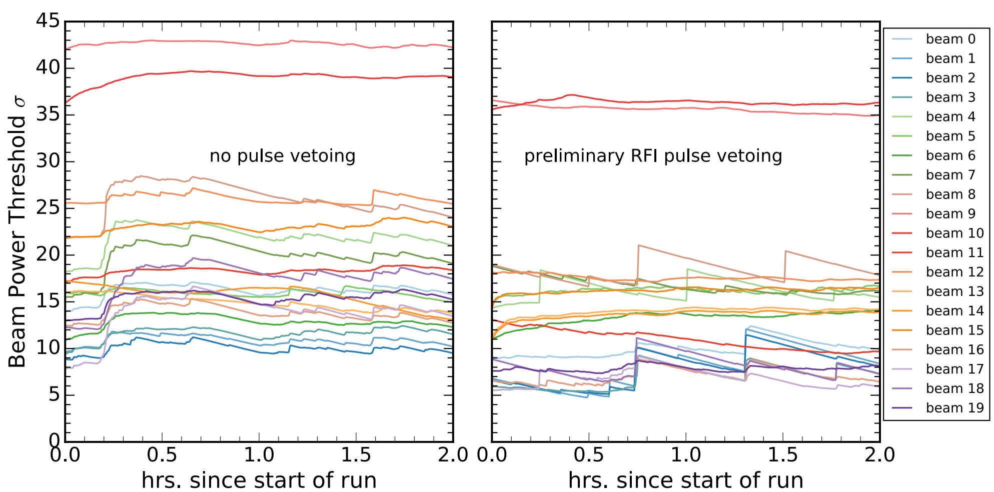


Figure 6: Thresholds referenced to power sums of thermal noise over time in the 20 beams of the 4-antenna interferometer deployed at WMRS in 2018-2019. Two beams maintain high thresholds over the course of the observation, while the rest remain significantly lower. Including RFI vetos in at the trigger level continue to reduce the thresholds further.

We are additionally considering a trigger design based on the scintillation tracks left by through-going muons from the tau lepton showers. Scintillator strip arrays could be mounted such that they face the horizon. Such a trigger could used as the primary trigger or in combination with the beamforming trigger, similar to the radio and scintillator based trigger on LOFAR [46]. Scintillators have long been used to provide the trigger for cosmic ray experiments.

# 4 Organization, Partnerships, and Current Status

The BEACON concept is currently being explored by a consortium of scientists from several institutions around the world. Studies into the hardware requirements, prototypical instrumentation, and site selection are being pursued at the Cal Poly, the University of Chicago, JPL, and UCLA. Comprehensive simulations of the sensitivity of the detector are being conducted by researchers from Cal Poly, JPL, Santiago, São Paulo, MPI, and Gran Sasso. Current team members play leading roles on the ANITA, ARA, Auger, HAWC, and SWGO collaborations and bring complementary experience and expertise to the collaboration. Upon the successful completion of the prototype studies, we expect to expand the collaboration to support the data analysis, logistics, and hardware required to build a full scale array.

# 5 Schedule

This project is currently in the research and development phase, where site selection and instrument performance are being evaluated. We anticipate that within the next 3 years, an estimate of the sensitivity of a prototype station can be made as well as a clear understanding of the amount of time required to deploy and commission each station. However, based on experience with similar systems on ARA and Auger, it is reasonable to presume a deployment schedule of a several (3-5) stations in the first year of deployment followed by 10-20 stations per season in subsequent years.

# 6 Cost Estimates

Each station requires a solar power system, antennas associated front-end electronics, mounts, cables, and a weatherproof enclosure containing data acquisition and triggering electronics, GPS, and networking. Based on the design of the prototypes under consideration thus far, we estimate the total cost per station to be $55k USD, for a total hardware cost for 100 stations of $6M. When including the costs of science personnel, travel and instrument deployment, and logistics brings this into the small ground-based project category, but detailed estimates of these costs are still under consideration.

# 7 Recommendations

The BEACON concept targets the highest energy tau neutrinos by searching for radio emission from a high-elevation mountain. Comprehensive simulation studies and preliminary instrumental studies of the performance of the detector show promise to extend the observation of the neutrino spectrum to beyond 100 PeV within the next decade. 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 as well as the cosmological evolution of the high-energy universe. We recommend that the Astro2020 Decadal Survey Panel support the continued development of this project.

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