PROCEEDINGS OF SCIENCE

Tracing Out The Neutrino Sky With TAMBO

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Traditional searches for neutrino point sources have been hindered by the look-elsewhere effect. To address this, TAMBO will generate a catalog of neutrino source localizations - each localization equivalent in size to the square of TAMBO's angular resolution. In doing so, TAMBO will have significantly reduced the available space to be searched by neutrino observatories, thus decreasing the trials factor necessary to elevate a local significance to a global one. In this talk we will present projected sensitivities to various neutrino sources and the effect of a TAMBO event to neutrino source discovery in IceCube. By refining the search through precise source localizations, TAMBO enhances the detection capabilities of observatories like IceCube, paving the way for efficient identification and confirmation of neutrino sources.

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1. Introduction

Astrophysical neutrinos are expected to be produced from the decay of light mesons [1]. Since their conception to their arrival, they are a coherent quantum mechanical superposition of distinct mass states [3]. The specific composition of each of the neutrino flavors in terms of the mass states is given by the neutral-lepton mixing matrix, often known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, measured by Earth-based experiments [4]. Given their production mechanism, we expect that neutrinos maintain their quantum mechanical coherence from production to detection [3]. The study of neutrino flavor conversion from astrophysical neutrinos is of great interest to both particle physics and astrophysics, as it is a highly sensitive probe of new physics phenomena [6–16], can allow for the measurement of the lepton CP-phase [17–20], and can provide unique insights into the production mechanism of neutrinos [21–26].

In this context, tau neutrinos are special, since they are only expected to arise in significant amounts through flavor transitions from initial muon- and electron-flavored neutrinos produced at the source [27]. Though most studies of astrophysical neutrino flavor have focused on distance-independent effects, knowledge of the distance traveled by the neutrino provides access to unique physics. For example, if neutrinos are quasi-Dirac particles [29], where hyperfine mass splittings are present in the neutrino mass spectra, oscillations at very long scales are now present, with oscillation lengths given by $L_{osc} \sim E/\delta m^2$, where δm^2 is the hyperfine mass difference. These new, uncharted oscillation scales can produce signatures on the energy and flavor distribution of high-energy astrophysical neutrinos [34–46]. Generally speaking, the study of the oscillation probability of neutrinos, $P_{\alpha\beta}(L, E)$, for $L \gg L_{\rm Sun}, L_{\rm Earth}$ has the potential to constraint parameter space motivated by quantum-gravity theories and neutrino mass mechanisms.

Measurements of the high-energy astrophysical neutrino spectra already provide us some first insights into the behavior of $P_{\alpha\beta}(L, E)$ in limiting cases, e.g., when the relevant oscillation scale is much smaller source distance scale, this is often summarized in the so-called astrophysical flavor triangles [27]. Less is known about the oscillation probability function for fixed astrophysical neutrino baselines, L, with the notable exception of low-energy supernovae neutrinos observed in SN 1987A and the Sun. This is due to the lack of high-significance source identification, with the current leading significant IceCube-discovered point sources being the blazar TXS 0506+056 [47] and NGC 1068 [48], where these have been measured using high-energy muons. Thus, the measurements of these two sources predominantly yield information on $P_{\alpha\mu}(L, E)$, with $\alpha = e, \mu$, $L_{\rm NGC\ 1068} \approx 14$ Mpc and $L_{\rm TXS\ 0506+056} \approx 1.7$ Gpc, and $E \sim 10 - 100$ TeV, with a subdominant contribution from $P_{\alpha\tau}(L, E)$ due to the contribution of leptonic tau decays in the detector.

It is thus imperative to uncover more sources to explore the distance-energy parameter space of flavor transitions fully. In the rest of this contribution, we will discuss the capabilities of TAMBO to find neutrino sources and the interplay of TAMBO observations with measurements at lower energies from neutrino telescopes such as IceCube or KM3NeT.

2. TAMBO

More than twenty years ago [49, 50], it was noted that very-high-energy neutrinos can be detected by observing the by-products of the on-air tau decays. This method is cost-effective, since

Canyon	**Depth (m)**	**Width (km)**	**Location and Notes**
Yarlung Tsangpo Canyon	~6000	~5–10	Tibet; extremely deep but very remote.
Cotahuasi Canyon	3535	~3	Peru; deep and accessible.
Colca Canyon	3270	~4–5	Peru; deep and accessible.
Kali Gandaki Gorge	~2500	~5	Nepal; very deep but narrow and remote.
Hells Canyon	~2440	~16	USA (Oregon–Idaho); deepest river gorge in North America with steep walls.
Grand Canyon	~1800	~16	USA (Arizona); massive volume and excellent infrastructure.
Tara River Canyon	~1300	~3	Montenegro/Bosnia; Europe's deepest.

Table 1: Subaerial canyons ordered by depth, evaluated as potential sites for Earth-skimming neutrino detection.

at very-high energies, neutrinos are no longer transparent to the Earth, making the predominant signal due to horizontal, Earth-skimming neutrinos. Since then, various methods have been put forward to detect the signature of neutrino-induced tau-showers, which include the detection of particle showers, fluorescence or Cherenkov light, and radio emission. Despite many attempts, the detection of Earth-skimming neutrinos has not been accomplished because the neutrino flux falls steeply with energy, the slow-rising neutrino cross section, and the large backgrounds.

TAMBO [51] is a new, proposed very-high-energy Earth-skimming neutrino observatory that aims to detect neutrinos in the 0.3 PeV to 100 PeV energy range. The detector nominal configuration is expected to be comprised of 5,000 detection units spaced 150 m apart on a triangular grid. To reduce cosmic-ray backgrounds and increase instantaneous sky coverage, we propose using a subaerial deep canyon, where the detector is deployed on one of the mountain sides. There are several subaerial deep canyons that could host TAMBO, see Table 1. The deepest of such canyons is the Yarlung Tsangpo Grand Canyon in Tibet, China; followed by the Colca Canyon and Cotahuasi in Peru. Shallower canyons also exist, notably Hells and the Grand Canyon in the continental US. In the following discussion, we will focus on the Colca Canyon in Peru, which provides a good benchmark to our detector performance and is deemed more accessible than the Yarlung Tsangpo Canyon in China. The final location of TAMBO is still under consideration and will be decided based on a combination of scientific, logistical, and societal considerations.

The canyon depth and width will affect the neutrino detection efficiency and background rejection capability of TAMBO, while its location and orientation determine the instantaneous sky coverage. For example, most of the Colca Canyon follows a north–south orientation, although a smaller segment extends along an east–west direction. If the detector array is deployed in the east–west segment of the Colca Valley, the resulting declination band coverage is approximately $-15.5^\circ \pm 10^\circ$. In contrast, a deployment along the north–south corridor yields a broader coverage of about $15.5^\circ \pm 50^\circ$. These two configurations represent extremes in terms of Galactic Center (GC) exposure. For comparison, a deployment in the Cotahuasi Canyon—which features an

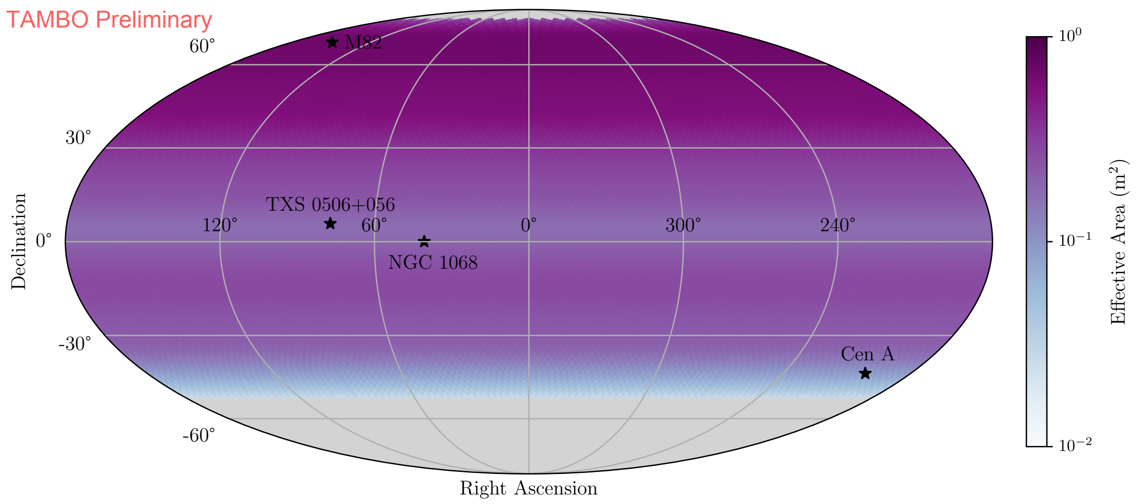

Figure 1: ***Time-averaged TAMBO effective area.*** Notable sources are shown as black stars.

approximately diagonal axis—would result in an intermediate exposure scenario. The width of the canyon is related to the efficiency of detection since it controls the shower development. For example, horizontal PeV showers have a maximum number of particles produced 6–8 km from the shower starting point, making the efficiency of head-on showers slower than horizontal showers.

Fig. 1 shows the 1 to 100 PeV time-averaged effective area of TAMBO in equatorial coordinates for a potential location in the Colca canyon that is laid out along the north-south corridor. Given the detector geometry, the acceptance in declination is very broad. Note the effective area has a minimum around declination of 0°; this is because this corresponds to head-on showers that do not have enough time to fully develop. The efficiency increases for lateral showers and eventually dies off for very lateral showers; the observed asymmetry is due to the valley shape. Fig. 2 shows the instantaneous TAMBO effective area in equatorial coordinates, where again we integrate from 1 to 100 PeV. The TAMBO effective area has two distinct contributions. One contribution is from tau-neutrinos that interact in the mountain (mountain-skimming) opposite to the detector (Fig. 2, left) and another larger contribution that is due to neutrinos that interact in the Earth's crust (Earth-skimming) (Fig. 2, center). The contribution from mountain-skimming neutrinos is provides an approximately 50% additional sky coverage to that given by Earth-skimming neutrinos and is unique to the TAMBO geometry.

3. Source Discovery Potential With TAMBO

To estimate the discovery potential of TAMBO to very-high energy neutrino sources, we simulate the response of the TAMBO array using TAMBOSim [52]. The shower selection criterion is given by the requirement that at least three nearby detection units have hits, and that at least 30 particles have been detected in the entire array. For a reference detector efficiency, we use the reported efficiency from the IceTop Upgrade surface component [53], which follows a similar design as the TAMBO detection units. We also assume that the directional resolution of TAMBO will be comparable to that of IceTop given the similar spacing and array design. Namely, we assume that the angular resolution of the array is 1° in the PeV to 100 PeV energy range. We require that the reconstructed tracks have an overburden of at least 4 km of rock through the mountain to reduce the contamination of penetrating muons. Together with time cuts, the aim is to reduce accidental coincident air-showers, and the expected background is no greater than 10^{-3} events per year.

With the selection described above, the dominant background to detect a candidate source is given by the diffuse, all-sky neutrino emission. For this background, we take the best-fit single power law flux given by the recent IceCube measurement [54], which produces six events in 10 years in the array. To compute the sensitivity and the discovery potential, we consider declination bins comparable with our angular resolution and then bin the remaining right ascension (RA) dimension following the prescription given in Ref. [55], Appendix A. This defines the probability of a background event to be observed in a given bin of RA and declination. Using a Poisson likelihood as a test statistic, we then define the sensitivity and discovery potential in the following way. The sensitivity is defined as the required flux so that the mean test statistic obtained when injecting signal events to be at the 90% tail of the background-only test statistics distribution, while the discovery potential is defined as the flux such that the median test statistic obtained when injecting signal match the $5\,\sigma$ tail of the background-only test statistic distribution. The result shown in Fig. 3 for an E^{-2} source spectrum with a normalization baseline set at 1 PeV.

4. Conclusions

In this contribution, we have presented the sensitivity of TAMBO, a new neutrino telescope optimized for the PeV to 100 PeV energy range, to neutrino point sources. TAMBO is a neutrino telescope that is primarily sensitive to tau neutrino flavors in an as-yet undiscovered energy range. The study of the neutrino oscillation probability for various distances and sources can provide important insights into fundamental physics, including the nature of neutrino masses. TAMBO leverages naturally occurring terrain to reduce background that limits the detectability of mountain-skimming and Earth-skimming neutrino events. The unique geometry of TAMBO allows for these two distinct contributions, which increases the field of view, compared to the Earth-skimming-only contribution by approximately 50%. If deployed on the Colca Canyon on the north-south stretch, the TAMBO instantaneous effective area has a broad declination acceptance band, making it a good

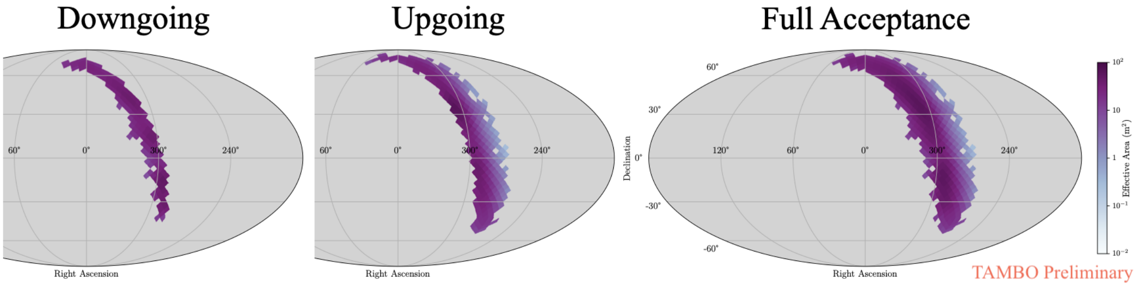

Figure 2: ***Instantaneous TAMBO effective area.*** Left panel shows the aperture for events that go through the mountain opposite to the array (downgoing to horizontal). Center panel shows the aperture for upgoing events that start in the Earth's crust. Right panel shows the full aperture of TAMBO. In all of these figures the color scale is the same and corresponds to the energy-integrated effective area from 1 to 100 PeV.

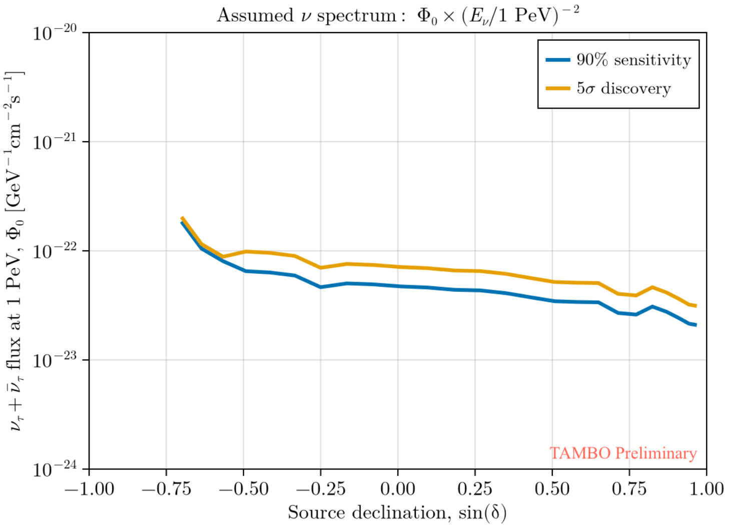

Figure 3: ***Sensitivity of TAMBO to neutrino point sources.*** As a function of the source declination the sensitivity of an E^{-2} spectra source, where the reference normalization, set at 1 PeV, is shown in the vertical axis.

experiment for real-time correlations over a broad range of declinations. Finally, we report the first estimation of the sensitivity of TAMBO to steady-state neutrino sources using a preliminary event selection.

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