Snowmass2021 - Letter of Interest

An Andean Deep-Valley Detector for High-Energy Tau Neutrinos

Thematic Areas:

■ (NF4) Neutrinos from natural sources
■ (NF10) Neutrino detectors
■ (CF1) Dark Matter: Particle Like
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract: High-energy astrophysical neutrinos, recently discovered by IceCube and observed up to energies of several PeV, opened a new window to the high-energy Universe. Yet much remains to be known. IceCube has excellent muon flavor identification, but tau flavor identification is challenging. This limits its ability to probe neutrino physics and astrophysics. To address this limitation, we present a concept for a large-scale observatory of astrophysical ν_τ in the 1–100 PeV range, where a flux is guaranteed to exist and where the unique properties of ν_τ enhance the observation potential. Its detection would allow us to characterize the neutrino sources observed by IceCube, to discover new ones, and to test neutrino physics at high

energies. The deep-valley air-shower array concept that we present provides highly background-suppressed neutrino detection with pointing resolution $< 1^\circ$, allowing us to begin the era of high-energy tau-neutrino astronomy.

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Introduction.— The last decade has seen the remarkable discovery of an astrophysical flux of high-energy (>10 TeV) neutrinos[1] and the subsequent characterization of their energy spectrum up to several PeV.[3;4;6–8;14] These neutrinos carry unique information about the most energetic non-thermal sources in the Universe, and have the potential to probe fundamental physics at the highest energies. To tap into the full potential of high-energy neutrinos, we require the capability to identify all flavors with comparable efficiency. Yet, so far, our ability to identify high-energy astrophysical ν_τ in neutrino telescopes has been limited.

To address this limitation, we present TAMBO (Tau Air-Shower Mountain-Based Observatory), a detector concept designed to extend observations of neutrinos to higher energies, in the range of 1–100 PeV, using ν_τ. TAMBO is a response to the strategy advocated by the neutrino astrophysics community[11] of a multi-observatory approach that would extend the collective science reach of neutrino observatories.

Present status.— In multi-messenger studies, neutrinos provide unique information since, while propagating to Earth, they are undeflected by magnetic fields and their attenuation length is greater than the size of the Universe. IceCube detects TeV–PeV high-energy astrophysical neutrinos[2;3;13;14], but isolating the ν_τ component is challenging. In neutrino physics, ν_τ has been the least studied neutrino flavor[12;57;58] due to its smaller cross section at lower energies and difficult particle identification. In fact, only after 10 years of observations has IceCube found the first candidate astrophysical ν_τ.[15;17;18] Extending the energy reach to 100 PeV with more than an order-of-magnitude increase in sensitivity would reveal key information about the neutrino sources[11;19;20] and about fundamental high-energy physics.[20–25]

Recent coincident observations of neutrinos with electromagnetic signals from transient astrophysical phenomena have provided the first promising evidence of extragalactic neutrino sources[9;10;59], but we need more coincident observations to make better sense of them. Measuring or constraining the neutrino flux from transient events such as stellar explosions, compact object mergers, and relativistic jets is integral to elucidating the mechanism of astrophysical particle acceleration mechanisms.

TAMBO aims at the unambiguous measurement of the high-energy astrophysical ν_τ flux. The characterization of the ν_τ flux, in combination with the observations of all flavors by IceCube[67], KM3NeT[66], Baikal-GVD[65], and P-ONE[64], will grant us comparable sensitivity to all flavors, and help us to realize the full astrophysics[11;19;20] and particle-physics [21–25] potential of high-energy neutrinos.

TAMBO.— TAMBO is a concept for a deep-valley detector that is most sensitive to 1–100-PeV ν_τ[26] that

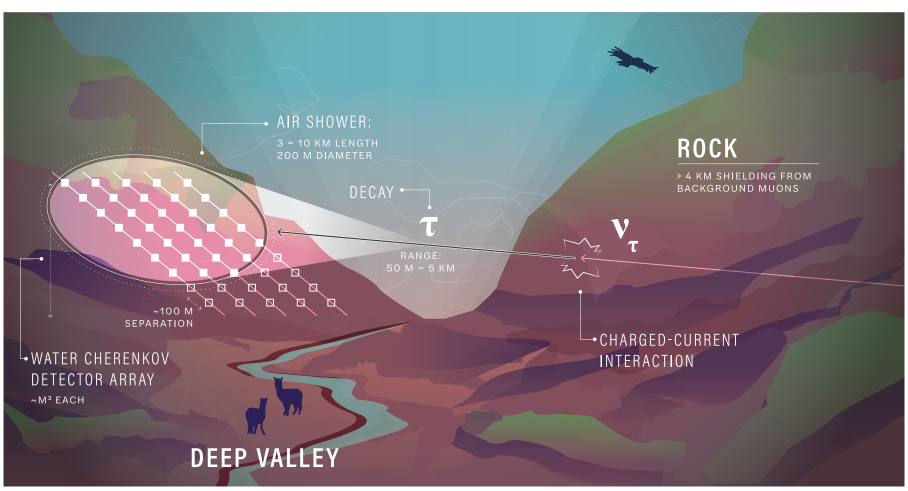

Figure 1: ***Detector concept schematic.*** A ν_τ propagates inside the mountain. In a charged-current interaction, a τ is produced; it travels 50 m–5 km before it decays. If the τ exits into the atmosphere, it decays to produce an air shower whose electromagnetic component extends 3–10 km , with a diameter of ~ 200 m. The shower is detected by an array of water-Cherenkov tanks, with $\sim \mathrm{m}^3$ volume each, separated by ~ 100 m along and across the mountain slope.

could be implemented in the Colca Valley of Peru; see Fig. 1 for an illustration. At these energies, neutrinos propagating in rock have an interaction length of thousands of kilometers[27]. A ν_τ can interact in rock to produce a τ, transferring $\sim 80\%$ of its energy to it. A τ with energy 1–100 PeV travels for 50 m–5 km before it decays. If the underground ν_τ interaction occurs within this distance from a deep valley, the τ is likely to exit into the air, where it decays. Roughly 50% of the τ energy goes into particles that produce extensive air showers. The longitudinal profile of the electromagnetic component of the showers has a characteristic length of ~ 10 km and a diameter of ~ 200 m near the shower maximum. In a deep valley with mountain separations comparable to this length scale, a ground array of small water-Cherenkov detectors, each of approximately 1 m^3 and separated by ~ 100 m, located on the mountain slope, would be highly sensitive to these τ-initiated air showers. The deep-valley topography also provides a significant increase to the geometric acceptance compared to a flat ground array that is sensitive only to Earth-skimming air showers, as used in on-going experiments.[28] The Colca Valley in Peru has been identified as an attractive site to implement this concept.

Main science objectives.— The science objectives of TAMBO are:

1. *Fully characterize the flux of astrophysical 1–10 PeV neutrinos by measuring the ν_τ component.* Measuring the diffuse flux of ν_τ and including ν_τ in the multi-messenger observations of transient astrophysical events would allow us to better understand high-energy neutrino production[11;35] and to more precisely test high-energy neutrino physics.[19;21–25]
2. *Determine whether high-energy neutrino sources continue to accelerate particles above 10 PeV.* This is motivated by the question of whether the sources of high-energy neutrinos have a cutoff at ~ 6 PeV, as suggested in some recent studies[7], and by the future detection of the cosmogenic neutrino flux[60], which is expected to dominate above 100 PeV.[30–34]
3. *Observe the Southern high-energy sky.* Because TAMBO will be located in the Southern hemisphere, it will have a view of the Galactic Center, which hosts an interesting variety of standard sources[62;63] and may be a hot spot for neutrinos from dark matter annihilation.[61]

Design and backgrounds.— In its final design, TAMBO envisions using ∼20,000 detectors with $\sim$ 100 m separation. This represents an exposure of $\langle A\Omega\rangle \geq 400$ m^2 sr $(E/\mathrm{PeV})^{1.5}$ at energies $E = 1$–10 PeV, which is sufficient to detect $\gtrsim 20$ ν_τ events per 3 years, based on the known extraterrestrial neutrino fluxes measured by IceCube. The expected ν_τ energy resolution is $\Delta E/E \leq 100\%$, due to the variance in energy transfer from the ν_τ to the τ in the CC interaction and the energy transfer from the τ to showering particles upon decay. The expected pointing resolution is $\lesssim 1^\circ$, which is typical of air-shower arrays[48–52] and sufficient to make significant advances in neutrino astronomy[11] and studies of fundamental physics.[20;24]

The key aspect of TAMBO is the large signal-to-background ratio when selecting for ν_τ events ($\lesssim 1$ background events for every 20 ν_τ events). High-energy muons, produced either by air showers behind the mountain or by prompt[54] ν_μ interacting in the rock, are largely shielded by the mountains surrounding the valley. For the muons that do make it through to the valley, the probability of an interaction with the atmosphere that results in a sufficiently energetic air shower to trigger the array is $< 0.4\%$, based on AIRES simulations.[55] Other backgrounds, like vertical muons and air showers, are suppressed by requiring coincidence detection in multiple detectors and that the direction of the event be pointed towards the mountains.

Conclusion.— The TAMBO concept is a major observatory for the next decade with the potential to produce a high-purity sample of 1–100 PeV astrophysical ν_τ events for studies in high-energy neutrino astronomy and fundamental physics. It is complementary to other neutrino observatories such as IceCube, KM3NeT, Baikal-GVD, and P-ONE, but with unique capabilities of ν_τ identification. The implementation of TAMBO would provide new discoveries in the under-explored τ-flavor component of the existing neutrino spectrum and extend it to higher energies.

References

[1] IceCube Collaboration, M. G. Aartsen et. al., "First observation of PeV-energy neutrinos with IceCube", Phys. Rev. Lett. 111 (2013) 021103, 1304.5356.

[2] IceCube Collaboration, M. G. Aartsen et. al., "Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector", Science 342 (2013) 1242856, 1311.5238.

[3] IceCube Collaboration, M. G. Aartsen et. al., "Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data", Phys. Rev. Lett. 113 (2014) 101101, 1405.5303.

[4] IceCube Collaboration, C. Kopper, W. Giang, and N. Kurahashi, "Observation of Astrophysical Neutrinos in Four Years of IceCube Data", PoS ICRC2015 (2016) 1081, 1510.05223.

[5] A. Schneider, "Characterization of the Astrophysical Diffuse Neutrino Flux with IceCube High-Energy Starting Events," PoS **ICRC2019** (2020), 1004 doi:10.22323/1.358.1004

[6] IceCube Collaboration, M. G. Aartsen et. al., "Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data", Astrophys. J. 833 (2016) 3, 1607.08006.

[7] C. Haack and C. Wiebusch (IceCube Collaboration), "A measurement of the diffuse astrophysical muon neutrino flux using eight years of IceCube data." PoS(ICRC2017)1005, arXiv:1710.01191

[8] IceCube Collaboration, C. Kopper, "Observation of Astrophysical Neutrinos in Six Years of IceCube Data", PoS ICRC2017 (2018) 981, 1710.01191.

[9] IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403 Collaboration, M. G. Aartsen et. al., "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", Science 361 (2018) eaat1378, 1807.08816.

[10] IceCube Collaboration, M. G. Aartsen et. al., "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert", Science 361 (2018) 147, 1807.08794.

[11] M. Ackermann et al., "Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos," Bull. Am. Astron. Soc. **51**, 185 (2019) [arXiv:1903.04334 [astro-ph.HE]].

[12] S. Parke and M. Ross-Lonergan, "Unitarity and the three flavor neutrino mixing matrix", Phys. Rev. D93 (2016) 113009, arXiv:1508.05095.

[13] M. G. Aartsen et al., "Search for steady point-like sources in the astrophysical muon neutrino flux with 8 years of IceCube data", Eur. Phys. J., C79, (2019), 234, arXiv:1811.07979.

[14] A. Schneider (IceCube Collaboration), "Characterization of the Astrophysical Diffuse Neutrino Flux with IceCube High-Energy Starting Events", PoS(ICRC2019)1004, arXiv:1907.11266

[15] J. Stachurska, "New measurement of the flavor composition of high-energy neutrino events with contained vertices in IceCube," Neutrino2018, Zenodo, 10.5281/zenodo.1301122

[16] J. Stachurska, "New Measurement of the Flavor Composition of High-Energy Neutrino Events with Contained Vertices in IceCube", Talk presented at the TeV Particle Astrophysics (TeVPA) conference, 27-31 August, 2018, Berlin.

[17] J. Stachurska (IceCube Collaboration), "First Double Cascade Tau Neutrino Candidates in IceCube and a New Measurement of the Flavor Composition", PoS(ICRC2019)1015, arXiv:1908.05506

[18] D. Xu and L. Wille (IceCube Collaboration), “Astrophysical Tau Neutrino Identification with IceCube Waveforms", PoS(ICRC2019)1036, arXiv:1909.05162

[19] L. A. Anchordoqui, H. Goldberg, F. Halzen, and T. J. Weiler, “Neutrinos as a diagnostic of high energy astrophysical processes", Phys. Lett. B 621 (2005) 18, hep-ph/0410003.

[20] M. Ackermann et al., “Fundamental Physics with High-Energy Cosmic Neutrinos,” Bull. Am. Astron. Soc. **51**, 215 (2019) [arXiv:1903.04333 [astro-ph.HE]].

[21] C. A. Argüelles, T. Katori, and J. Salvado, "New Physics in Astrophysical Neutrino Flavor", Phys. Rev. Lett., 115 (2015), 161303, arXiv:1506.02043

[22] M. Bustamante, J. F. Beacom, and W. Winter, "Theoretically palatable flavor combinations of astrophysical neutrinos", Phys. Rev. Lett., 115, (2015), 161302, arXiv:1506.02645

[23] R. W. Rasmussen, L. Lechner, M. Ackermann, M. Kowalski, W. Winter, "Astrophysical neutrinos flavored with Beyond the Standard Model physics", Phys. Rev. D 96, (2017), 083018

[24] C. A. Argüelles, M. Bustamante, A. Kheirandish, S. Palomares-Ruiz, J. Salvadó, and A. C. Vincent, "Fundamental physics with high-energy cosmic neutrinos today and in the future", PoS(ICRC2019)849, arXiv:1907.08690

[25] C. A. Argüelles, K. Farrag, T. Katori, R. Khandelwal, S. Mandalia, and J. Salvadó, "Probe Of Sterile Neutrinos Using Astrophysical Neutrino Flavor", arXiv:1909.05341

[26] D. Fargion, A. Aiello, and R. Conversano, “Horizontal Tau air showers from mountains in deep valley. Traces of UHECR neutrino tau", Proceedings of the 26th International Cosmic Ray Conference. August 17-25, 1999. Salt Lake City, Utah, USA. Preprint astro-ph/9906450 (1999)

[27] R. Ghandi, C. Quigg, M. H. Reno, and I. Sarcevic, "Neutrino interactions at ultrahigh energies", Phys. Rev. D, 58, (1998), 093009

[28] F. Pedreira (Pierre Auger Collaboration), "Bounds on diffuse and point source fluxes of ultra-high energy neutrinos with the Pierre Auger Observatory", PoS(ICRC2019)979

[29] M.G. Aartsen, et al., “A Combined Maximum-Likelihood Analysis of the High-Energy Astrophysical Neutrino Flux Measure with IceCube", The Astrophysical Journal, 809, 98, (2015)

[30] K. Kotera, D. Allard, and A. Olinto, “Cosmogenic neutrinos: parameter space and detectability from PeV to ZeV", JCAP **10**, (2010), 013

[31] The Pierre Auger Collaboration, “Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory", JCAP, 04, 038, (2017).

[32] A. Romero-Wolf and M. Ave, “Bayesian Inference Constraints on Astrophysical Production of Ultrahigh Energy Cosmic Rays and Cosmogenic Neutrino Flux Predictions", JCAP **7**, (2018), 025.

[33] R. Alves Batista et al., “Cosmogenic photon and neutrino fluxes in the Auger era", JCAP **01**, (2019), 002.

[34] J. Heinze et al., “A New View on Auger Data and Cosmogenic Neutrinos in Light of Different Nuclear Disintegration and Air-shower Models", ApJ, 873, (2019), 88.

[35] M. Bustamante and M. Ahlers, “Inferring the Flavor of High-Energy Astrophysical Neutrinos at Their Sources", Phys. Rev. Lett., 122, 241101, (2019).

[36] HAWC and IceCube Collaborations, “Combined Analysis of Cosmic-Ray Anisotropy with IceCube and HAWC", Proceedings of Science, PoS(ICRC2017)539, (2017).

[37] IceCube Collaboration, “High Energy Astrophysical Neutrino Flux Measurement Using Neutrino-induced Cascades Observed in 4 Years of IceCube Data", Proceedings of Science, PoS(ICRC2017)968, (2017).

[38] A. Letessier-Selvon, “Establishing The GZK Cutoff With Ultra High Energy Tau Neutrinos", 2001 AIP Conf. Proc. 566, 157, Preprint astro-ph/0009444, (2001).

[39] J. Alvarez-Muñiz et al., “Comprehensive approach to tau-lepton production by high-energy tau neutrinos propagating through the Earth", Phys. Rev. D, 97, 023021, (2018).

[40] Y. S. Jeong, M. V. Luu, M. H. Reno, and I Sarcevic, “Tau energy loss and ultrahigh energy skimming τ neutrinos", arXiv:1704.00050 (2017).

[41] S.I. Dutta, M.H. Reno, and I. Sarcevic, “Secondary neutrinos from τ neutrino interactions in the Earth", Phys. Rev. D **66**, 077302 (2002).

[42] S. Yoshida, R. Ishibashi, and H. Miyamoto, “Propagation of EHE leptons in the Earth: Implications for their detection by the IceCube neutrino telescope", Phys. Rev. D **69**, 103004 (2004).

[43] J. Tseng et al., “The energy spectrum of τ leptons induced by the high energy Earth-skimming neutrinos", Phys. Rev. D **68**, 063003 (2003).

[44] S. Bottai and S. Giurgola, “UHE and EHE neutrino-induced τ inside the Earth", Astropart. Phys. **18**, 539 (2003).

[45] T. Sjöstrand, S. Mrenna, and P. Skands, “A brief introduction to PYTHIA 8.1", Comput. Phys. Comm. 178, 852, (2008)

[46] M. A. K. Glasmacher et al., “The cosmic ray energy spectrum between 10^{14} and 10^{16} eV", Astroparticle Physics, 10 (1999) 291.

[47] F. Fenu et al. (Pierre Auger Collaboration), “ The cosmic ray energy spectrum measured using the Pierre Auger Observatory", Proceedings of Science, ICRC2017 (2017) 486.

[48] A. Walker et al., “Measurement of the angular resolution of an extensive air shower array using a Cherenkov light detector", Nucl. Instrum. Methods A, 301, (1991), 574.

[49] A. Borione et al., “A large air shower array to search for astrophysical sources emitting γ-rays with energies $\geq 10^{14}$ eV", Nucl. Instrum. Methods A, 346, (1994), 329.

[50] C. Bonifazi et al., “The angular resolution of the Pierre Auger Observatory", Nuclear Physics B - Proceedings Supplements, 190, (2009), 20.

[51] I. Tkachev, et al., in: Proceedings of the 31th International Cosmic Ray Conference in Beijing ID, (2011), p. 1311.

[52] R. Abbassi et al., “IceTop: The surface component of IceCube", Nucl. Instrum. Methods A, 700, (2013), 188.

[53] The IceCube Collaboration, “Search for point-like sources in the astrophysical muon neutrino flux with IceCube", Proceedings of Science ICRC2017, (2017) 997.

[54] R. Enberg, M. H. Reno, and I Sarcevic, “Prompt neutrino fluxes from atmospheric charm", Phys. Rev. D, 78 (2008), 043005.

[55] S. J. Sciuto, “AIRES: A system for air shower simulations (Version 2.2.0)", astro-ph/9911331, (1999).

[56] J. Abraham, et al., “Trigger and aperture of the surface detector array of the Pierre Auger Observatory" astro-ph/9911331, NIM A, 613, (2010), 29.

[57] S. A. R. Ellis, K. J. Kelly, and S. W. Li, “Leptonic Unitarity Triangles,” [arXiv:2004.13719 [hep-ph]].

[58] S. A. R. Ellis, K. J. Kelly, and S. W. Li, “Current and Future Neutrino Oscillation Constraints on Leptonic Unitarity,” [arXiv:2008.01088 [hep-ph]].

[59] R. Stein et al., “A high-energy neutrino coincident with a tidal disruption event,” [arXiv:2005.05340 [astro-ph.HE]].

[60] V. S. Berezinsky and G. T. Zatsepin, “Cosmic rays at ultrahigh-energies (neutrino?),” Phys. Lett. B **28**, 423-424 (1969) doi:10.1016/0370-2693(69)90341-4

[61] C. A. Argüelles, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa and A. C. Vincent, “Dark Matter Annihilation to Neutrinos: An Updated, Consistent & Compelling Compendium of Constraints,” [arXiv:1912.09486 [hep-ph]].

[62] M. G. Aartsen *et al.* [IceCube], “Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data,” Astrophys. J. **849**, no.1, 67 (2017) doi:10.3847/1538-4357/aa8dfb [arXiv:1707.03416 [astro-ph.HE]].

[63] A. Kheirandish [IceCube and HAWC], “IceCube Search for Galactic Neutrino Sources based on Very High Energy γ-ray Observations,” J. Phys. Conf. Ser. **1468**, no.1, 012081 (2020) doi:10.1088/1742-6596/1468/1/012081 [arXiv:2001.08524 [astro-ph.HE]].

[64] M. Agostini et al., “The Pacific Ocean Neutrino Experiment,” [arXiv:2005.09493 [astro-ph.HE]].

[65] A. D. Avrorin *et al.* [Baikal-GVD], PoS **ICRC2019**, 1011 (2020) doi:10.22323/1.358.1011 [arXiv:1908.05427 [astro-ph.HE]].

[66] S. Adrian-Martinez *et al.* [KM3Net], J. Phys. G **43**, no.8, 084001 (2016) doi:10.1088/0954-3899/43/8/084001 [arXiv:1601.07459 [astro-ph.IM]].

[67] T. Gaisser and F. Halzen, Ann. Rev. Nucl. Part. Sci. **64**, 101-123 (2014) doi:10.1146/annurev-nucl-102313-025321