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Towards Survey of Astronomical ν_τ Sources

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The recent observation of PeV astrophysical neutrino events by IceCube opens a new chapter in neutrino astronomy, calling for increased sensitivity and improved point-back ability, to probe for PeV–EeV neutrino point sources in the gap between IceCube and Auger energies. By separating $\nu_\tau \to \tau$ conversion from τ-shower generation, the Earth-skimming ν_τ method allows for huge target mass and detection volume simultaneously. The Ashra-1 detector, in operation up Mauna Loa on Hawaii Big Island, has demonstrated the feasibility in a 1$^{\rm st}$ search for ν_τ from a GRB. With design based on this experience, a Neutrino Telescope Array (NTA) observatory is being planned, with three site stations watching the air mass surrounded by Mauna Loa, Mauna Kea, and Hualalai, plus a central site station watching the lower night sky. Sensitivities equivalent to > 100 km^3 water and pointing accuracy of $< 0.2^\circ$ can be achieved with Cherenkov-fluorescence stereoscopic observation for PeV–EeV neutrinos that is almost background-free. With the scientific goal of *clear discovery and identification of astronomical* ν_τ *sources* to probe for cosmic proton accelerators, a new international collaboration is being formed.

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1. Introduction: Towards ν-Astronomy

Neutrinos, chargeless and weakly interacting, point back to far away sources. It is no doubt the most penentrating rays from the cosmic accelerators. Looking at the neutrino flux that reaches Earth, the solar neutrinos are "done", we wait for the next nearby supernova, the atmospheric neutrino anomaly [1] taught us near maximal ν_μ–ν_τ mixing, and there is the arching question of GZK neutrinos. But the recent IceCube observation [2] of PeV astrophysical neutrino events begs the question: What if one had better *sensitivity* and accurate *pointing*? Based on the concepts and development of the NuTel and Ashra-1 experiments, cashing in on near-maximal θ_{23}, we propose [3] a new experiment, the Neutrino Telescope Array (NTA), with scientific goal of *Clear Discovery and Identification of Nonthermal Hadronic Processes in the Universe.*

To catch the astrophysical neutrinos from very far away sources, current and developing neutrino telescopes are all $\gtrsim$ "km^3" in size. IceCube [4] has a full km^3 of pristine ice instrumented with more than five thousand 10 inch PMTs. Completed in 2010, the PeV neutrinos have turned our eyes towards very high energy (VHE) neutrino astrophysics. For ultra high energy cosmic rays (UHECR) at and above 10^{18} eV energies, Auger [5] was completed in 2008, covering ~ 3000 km^2. One main targets is the so-called GZK neutrinos, which arise from Δ-conversion of $\gtrsim 10^{19}$ eV cosmic protons by the cosmic microwave background (CMB) radiation. We note, however, that between Auger and IceCube, the gap or window between PeV to EeV (10^{15} eV to 10^{18} eV) still lacks a dedicated experiment, which is quite amazing. The discovery of PeV neutrinos by IceCube suggests a supra-PeV neutrino spectrum, making it imperative to explore this region in earnest.

When protons are accelerated and collide with radiation fields or ambient matter, i.e.

$$p+\gamma \to \Delta^+ \to \pi^0 + p,\ \pi^+ + n; \qquad p + \text{nucleus} \to \pi^{\pm,0} + X, \tag{1.1}$$

νs from $\pi^\pm$ decay would point to the proton accelerators, while γs from π^0 would imply closer-by sources. The search for both νs and γs constitute a multi-messenger approach to the accelerators in the Universe, such as active galactic nuclei (AGN), γ-ray bursts (GRB), and starburst galaxies (SBG). Employing the so-called Earth-skimming ν_τ method that targets the PeV to EeV region, the greater sensitivity and pointing accuracy of NTA could bring us into the era of ν-astronomy.

2. Earth-skimming ν_τ Method

The Earth-skimming (ES) ν_τ method combines quite a few amazing facts: 1) The original $\nu_e : \nu_\mu : \nu_\tau \cong 1:2:0$ from cosmic hadron accelerator turns into $1:1:1$ at cosmic distances by near maximal θ_{23}; 2) VHE ν_τs can convert to τ in Earth/mountain, emerge then decay and shower in air (e from ν_e gets absorbed, while μ from ν_μ does not shower); 3) A UV telescope placed on a mountain a few 10 km downstream can catch the Cherenkov pulse from τ shower (hence the name "NuTel" [6]). Further advantages are: mountain/Earth as shield, precise arrival direction determination, and negligible atmospheric neutrino background.

The magic works for two large mountains separated by a wide valley (see Fig. 1). Hawaii Big Island provides backdrop: Mauna Loa and Mauna Kea each at 4000 m, as excellent sites for astronomy, they are perfect for placing the UV telescope, or up Mt. Hualalai at 2521 m [6]. The NuTel project also illustrates the three stages for event simulation:

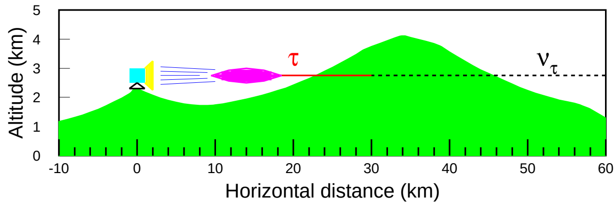

Figure 1: Conversion of $\nu_\tau \to \tau$ inside a mountain and detection technique [6].

⋄ Mountain: $\nu_\tau \to \tau$ conversion cross section, inelasticity, energy loss;

⋄ Shower: τ decay modes, detailed vs fast simulation;

⋄ Detector Performance: light propagation and quantum efficiency, trigger, reconstruction.

The proposal, however, was rejected in 2004, because of low estimated event rate, and the effort, after system tests (in 2009) up 2100 m in Taiwan, eventually petered out.

The ES ν_τ method was also proposed [7] by the Ashra experiment with a fluorescence telescope array, which would be the basic technique for Neutrino Telescope Array, as we will discuss.

3. Ashra-1 and 1$^{\text{st}}$ Search for GRB ν_τ

The All-sky Survey High Resolution Air-shower detector [8] Phase I, or Ashra-1, was developed with the ambitious aim of "multi-messenger astronomy". Fig. 2 shows a Light Collector (LC), and Fig. 3 is the Mauna Loa Observation Site (ML-OS), 3300 m a.s.l. on Hawaii Big Island. Compared with 1° per PMT with 28° coverage per telescope in the late 1990s (HiRes), Ashra-1 has 1.2 arcmin per pixel with potential for all-sky coverage, by use of electrostatic lenses to generate convergent beams. This enables high resolution over a wide field of view (FOV).

The demonstrated electron optics requires: 1) *Wide field precision optics*, modified Baker-Nunn with Schmidt type mirror; 2) *Photo-electric Lens Imaging (PLI) tube* [9], world's largest image intensifier (I.I.) tube converges beams from 20 inch photocathode to 1 inch focal surface for CMOS "video camera" high pixelation readout; and 3) *Photoelectric Image Pipeline* [10] or PIP splits same PLI image to multiple triggers, achieving multi-messenger approach with one detector system to record optical (starlight), fluorescence (μs) and Cherenkov (ns) emissions.

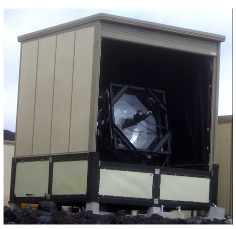

Figure 2: Ashra-1 Light Collector (LC).

Figure 3: The Ashra-1 main and sub stations at Mauna Loa site.

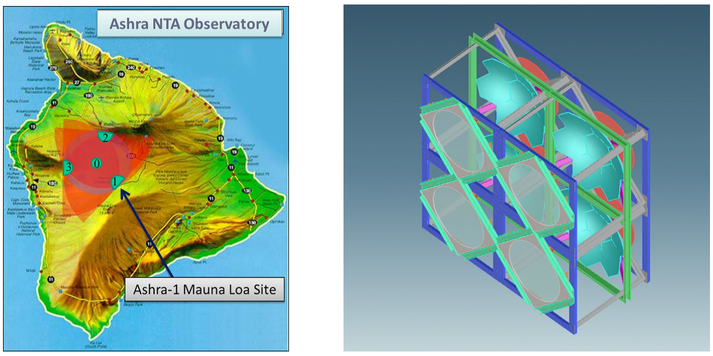

Figure 4: (left) NTA observatory layout on Hawaii Big Island, with overlaid semi-circles to illustrate view from Site1–3; (right) Detector Unit (DU) of 4 LCs scaled up from Ashra-1 design.

Site ID	Location	X [km]	Y [km]	Z [km]	FOV [sr]
Site0	Center	0.000	0.00	2.03	π
Site1	Mauna Loa	9.91	-10.47	3.29	$\pi/2$
Site2	Mauna Kea	4.12	13.82	1.70	$\pi/2$
Site3	Hualalai	-14.02	-3.35	1.54	$\pi/2$

Table 1: Coordinates and FOV of NTA sites, with z-coordinate from topography and y-axis pointing north. Site1 is at ML-OS on Mauna Loa, with Site2 at 25 km distance in the direction of Kilohana Girl Scout Camp.

With alert for GRB081203A given by SWIFT satellite, Ashra-1 succeeded in the first search for PeV ν_τs originating from a GRB [11] with the ES ν_τ technique using one LC. Moreover, Ashra-1 has achieved the best-yet instantaneous sensitivity in the 100 PeV energy region subsequent to a January 2012 trigger upgrade. Ashra-1 continues with technical improvement and demonstration, such as fluorescence detection and multi-messenger exploration of PeV–EeV Universe. With the new impetus of PeV astro-ν observation by IceCube, let us now unfold the NTA project.

4. Neutrino Telescope Array (NTA)

The Neutrino Telescope Array (NTA) is an air shower imaging neutrino detector towards our stated scientific goal. With better than 0.2° pointing accuracy, it would discern the origins of IceCube PeV neutrino events. A Letter of Intent (LOI) is at hand [3], with v2 recently posted.

<u>Site Plan and Size</u>

As shown in Fig. 4 (left), the planned NTA observatory consists of four sites, where coordinates and corresponding FOV are given in Table 1. Site1–3 are the vertices of an equilateral triangle with 25 km sides, and observe the total air mass surrounded by Mauna Kea, Mauna Loa, and Hualalai; the central Site0 can potentially have full-sky coverage.

Recall the ES ν_τ detection, Fig. 1, by separating $\nu_\tau \to \tau$ conversion from subsequent air shower, one preserves the huge target mass required for the initial interaction. Mauna Kea is a mountain equivalent to 10^4 km^3 of ice for converting ν_τ to τ, but it also serves as a shield to CR background. The distance between Mauna Kea and Loa allows a 30 km range for shower development. NTA would augment Ashra-1 performance with fluorescence [7] ability of Site0, plus two

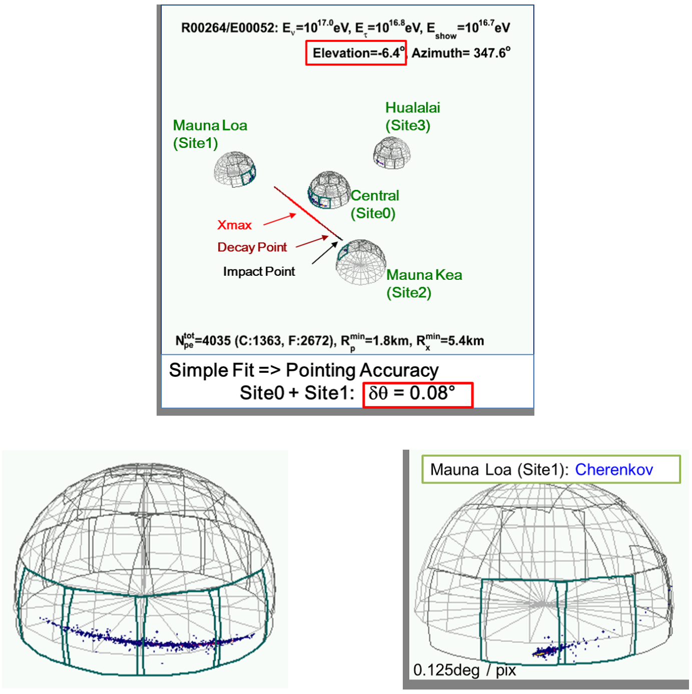

Figure 5: A simulated τ shower event generated by primary ν_τ with $E_{\nu_\tau} = 10^{17}$ eV: (top) Global hit map view; (bottom left) fluorescence shower image taken by Site0, and (bottom right) Cherenkov image taken by Site1. The trigger pixel and fine image pixel FOVs are $0.5^\circ \times 0.5^\circ$ and $0.125^\circ \times 0.125^\circ$, respectively.

other mountain sites. The huge target mass (> 100 km^3), huge atmospheric mass (shower volume, with area > 1000 km^2) and mountain as background shield imply a rather large footprint for NTA.

Each site has a group of DUs composed of 4 LCs (Fig. 4 (right)). The Schmidt optics has pupil of 1.5 m, and FOV of 32° hence 50 cm at focal sphere, but with same trigger and readout. 4 LCs with same FOV and superimposed image give a DU with effective pupil size of 3 m. 12 DUs are needed per π solid angle, so at least 30 DUs are needed. The construction, deployment and operation of these DUs at four distant sites call for an International Collaboration.

Pointing Accuracy

With high pixelation and the ES-ν_τ method, pointing accuracy is the main strength of NTA. Performance studies are based on Ashra-1 experience, and more detail can be found in the LOI [3]. Detailed detector design studies are currently underway. Simulation steps are similar to Sec. 2, except one now also has fluorescence capability. Light propagation and quantum efficiencies are better, but the highlight is the much higher pixelation. We find that the arrival direction of PeV-scale ν_τs is within 0.1° of the direction of the generated hadron air-shower.

Performance and Sensitivity

For NTA detector, we take $32^\circ \times 32^\circ$, $0.5^\circ \times 0.5^\circ$ FOV and $0.125^\circ \times 0.125^\circ$ for DU, trigger pixel and image sensor pixel. From Table 1, Site0 consist of 12 DUs, covering the lower elevation solid angle of π sr. The remaining sites have 6 DUs in the lower elevation $\pi/2$ angle. The bottom edge of the lower elevation angle region is defined to be -9° (below the horizon).

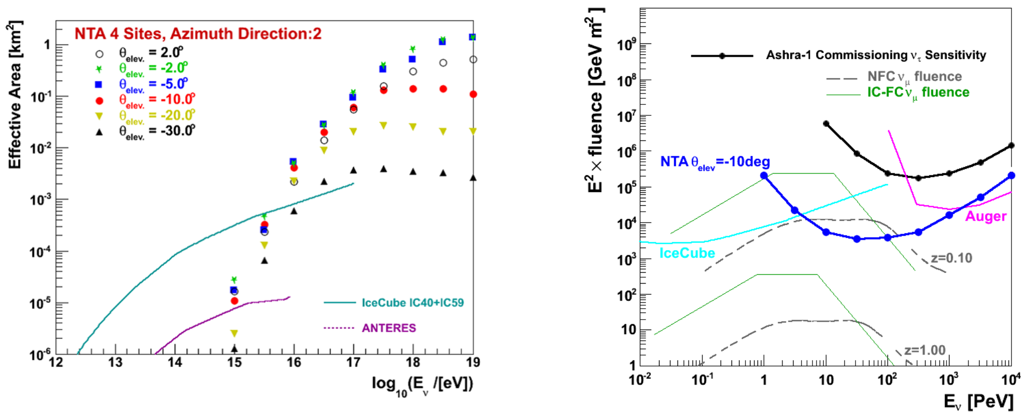

Figure 6: [left] Effective detection area for Site0 with ν_τ arrival towards Mauna Loa (ϕ_2), and dip angles from 2.0° to −30.0°; [right] 90% CL differential sensitivities for $\theta_{\rm elev} = -10°$, in comparison with (earlier) published sensitivities of IceCube and Auger, together with theoretical models (dashed lines for Ref. [13]).

In our simulation, we take density profile of Earth and ν_τ distribution from CTEQ4, input inelasticity parameter and parameterize energy loss. We use τ decay from TAUOLA and air-shower generation of Gaisser-Hillas, and take constant ν_τ energy fraction of 40% from τ decays. For detector simulation, we incorporate light collection and throughput with simplified trigger logic. Event reconstruction is not yet implemented. All candidate events must satisfy trigger conditions: number of photoelectrons per LC > 61; S/N estimated in track-associated 4×64 pixel box (air-shower track included) > 4. A simulated event with primary energy $E_{\nu_\tau} = 10^{17}$eV, elevation angle $-6.4°$ exit from Mauna Kea towards Mauna Loa, is shown in Fig. 5. A combined simple fit to Site0 $\bigoplus$ Site1 gives an error for ν_τ arrival direction at 0.08°. Our estimates for effective detection area for ν_τ from point source is illustrated for Mauna Loa site for various dip angles on left side of Fig. 6 (similar result for Hualalai). The effective detection area turns on sharply above PeV.

The PeV neutrino events call for higher sensitivity searches with more accurate pointing. IceCube events do not [12] preclude additional supra-PeV sources, and "spectrum may not be a power law" (Halzen at EPSHEP). We show on Fig. 6 (right) the differential sensitivity for NTA, compared with IceCube and Auger capabilities. The solid theory curve is ruled out, but subsequent models for GRB neutrino flux, e.g. Ref. [13], can be probed by NTA. Given the IceCube PeV neuntrino events, this search is mandatory. For NTA sensitivity for diffuse ν_τ flux, we refer to the LOI [3].

The power of NTA is to survey ν_τ point source objects with the best-yet sensitivity in the detection solid angle for ν_τ defined as $-30° < \theta_{\rm elev} < 0°$ and $0° < \phi_{\rm azi} < 360°$, and for 10 PeV $<$ $E_{\nu_\tau} < 1$ EeV. Fig. 6 (right) shows that the NTA survey depth can reach $z \lesssim 0.15$, of order 2 billion lightyears. The location of NTA on Hawaii Big Island allows us to survey the Galactic Center (GC) for more than several hundred hours each year, assuming the standard 10–20% duty cycle.

From the IceCube astro-νs at PeV energy, one expects a spectrum to be probed between IceCube and Auger sensitivities. This is precisely where NTA fits in, with great pointing accuracy to pick out point sources within 2 Glyrs. The real target is not the diffuse source, but "nearby" astrophysical Point Sources. Direct observation of such sources with the ES-ν_τ technique would reveal the existence of hadron acceleration mechanisms, and open a new chapter in CR and neutrino astrophysics. Note that PeV neutrinos imply PeV γs, the observation of which would add another group to the Kifune plot (X-ray, GeV γ, TeV γ, ...), which would imply very nearby sources.

5. Towards a New Collaboration

We estimate that a minimum of 30 Detector Units (DUs) are needed for NTA, distributed over four mountain sites on Hawaii Island, assuming $32^\circ \times 32^\circ$ FOV for each DU. The estimated cost per DU (4 LCs plus trigger and readout), based on Ashra-1 experience, is $\sim$ 100M yen. Allowing for some infrastructure and site preparation, but not running and maintenance costs, a crude cost estimate is 5000M yen for the construction of NTA. NTA would eventually be a Collaboration consisting of half a dozen or more countries.

As we design the NTA instruments and explore site options, collaboration organization is still primitive. One would probably need a major funding contribution at more than 50% total cost to start attracting international collaborators, and only then (when some manpower has materialized) would one be able to seriously devise a schedule towards the scientific goal. The time frame for the proposed project will be determined both by budgetary and scientific considerations. A workshop, VHEPA2016, would be held at Hawaii-Manoa in early 2016. Funding efforts would likely take 2 more years. If Japanese core funding is received in time, we hope to start experimental operations using at least part of Site0 and Site1 by 2018. Ashra-1 would continue to run for both testing and scientific purposes. The expected construction time for full NTA would be of order 5 years.

In conclusion, the scientific goal of "*Clear Discovery and Identification of Nonthermal Hadronic Processes in the Universe.*" is reachable. A Collaboration, the NTA, is needed to pin down, and pinpoint, the IceCube PeV astro-ν events.

References

[1] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562 (1998).

[2] M.G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. Lett. **111** (2013) 021103;

[3] M. Sasaki and G.W.-S. Hou, arXiv:1408.6244 [astro-ph.IM].

[4] F. Halzen and S. Klein, December 2014 issue of CERN Courier; Phys. Today **61N5** (2008) 29.

[5] See webpage http://www.auger.org/.

[6] G.W.-S. Hou and M.A. Huang, astro-ph/0204145.

[7] M. Sasaki, Y. Asaoka, and M. Jobashi, Astroparticle Physics 19 (2003) 37.

[8] M. Sasaki, J. Phys. Soc. Jpn. **77**SB (Suppl. B) (2008) 83, presented at VHEPA-3 meeting, 3/2003.

[9] Y. Asaoka, M. Sasaki, Nucl. Instrum. Meth. A **647** (2011) 34.

[10] M. Sasaki, Y. Asaoka and M. Jobashi, Nucl. Instrum. Meth. A **501** (2003) 359.

[11] Y. Aita *et al.*, Astrophys. J. **736** (2011) L12.

[12] M.G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. D **91**, 022001 (2015).

[13] S. Hümmer, P. Baerwald and W. Winter, Phys. Rev. Lett. **108**, 231101 (2012).

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