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Neutrino Telescope Array (NTA): Multi-Astroparticle Explorer for PeV-EeV Universe

— For Clear Identification of Cosmic Accelerators and Cosmic Beam Physics —

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IceCube has reported detection of three events of neutrinos with energies around 1 PeV and additional events at lower energies, which significantly deviate from the expected level of background events. It is necessary to observe GeV-TeV photon, EeV-ZeV hadron and TeV-PeV neutrino all together, in order to understand hadronic interactions of cosmic rays in the PeV-EeV energy region. It is required to make a step further toward exploring the PeV-EeV universe with high accuracy and high statistics observations for both neutrinos and gamma rays simultaneously, by using the instrument such as Ashra Neutrino Telescope Array (NTA). Wide and fine survey of gamma-rays and neutrinos with simultaneously detecting Cherenkov and fluorescence light with NTA will guide us to a new intriguing stage of recognizing astronomical objects and non-thermal phenomena in ultra-high energy region, in addition, new aspect about the fundamental concepts of physics beyond our presently limited understanding; the longstanding problem of cosmic ray origin, the radiation mechanism of gamma-rays, neutrino and cosmic rays from violent objects like blazars, interaction of gamma-rays and cosmic rays with microwave and infrared background photons, and PeV-EeV neutrinos originated from far places beyond the GZK-horizon.

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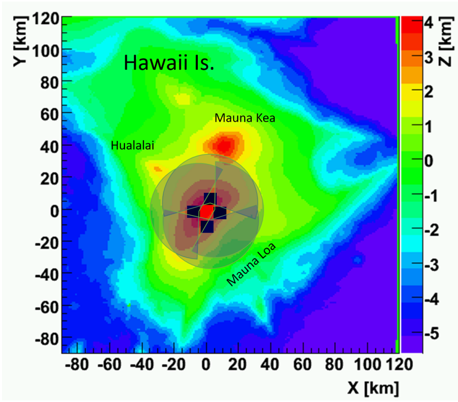

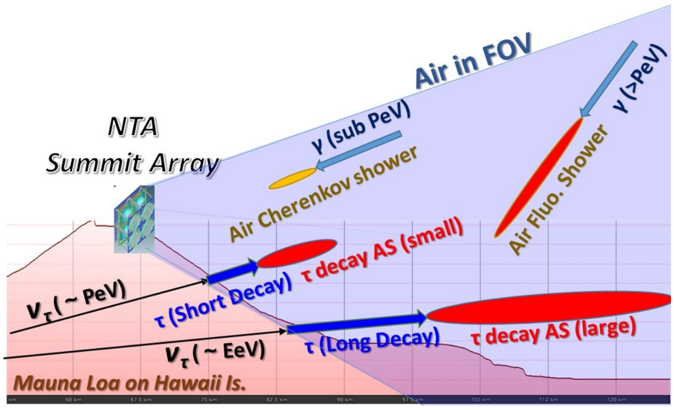

Figure 1: Four candidate observation sites (black boxes) of NTA on Mauna Loa of Hawaii Island (contours) and the sensitive areas (shaded fans) (*left*). Concept of imaging ν_τ and γ air-showers with NTA (*right*).

1. Pevatron Identification with PeV ν's and γ's

IceCube reported the detection of PeV scale astrophysical neutrinos (νs). The origin has not been revealed yet [1]. It is not sure if the detected neutrinos are of extragalactic or Galactic origin, from point-like source or of diffusive origin, this tantalizing situation requesting us to identify the emitting source of the IceCube neutrinos, in other words, to detect and locate the site of accelerating cosmic rays to PeV energies, i.e., PeVatron. On the other hand, ν production is closely related to that of gamma-rays (γ's). Cosmic ray protons produce pions in the reactions: $p+\gamma \to \Delta^+ \to \pi^0 + p,\ \pi^+ + n$; $p + \text{nucleus} \to \pi^{\pm,0} + X$. then, through the decay process of pion, resulting in neutrino emission as well as γs. Thus, we expect a γ flux as intense as neutrino flux emitted from the same site. However, PeV γs from extragalactic sources suffer from serious attenuation of flux due to the absorption in their interaction with infrared and 2.7K photons. A similar amount of γ and neutrino flux is expected only from the PeVatron within our Galaxy. Independent of PeV ν detection by IceCube, HESS has reported γs of energy up to 100 TeV from the region surrounding the supermassive black hole Sgr A* at the Galactic Center [2]. They argue that the γ source is a promising candidate of Pevatron, since the observed hard power-low spectrum of γ's seems to extend likely to PeV energy. Combined detection of PeV ν's and PeV γ's is necessary for knowing the location accurately and clarifying the emission mechanism, providing us with an opportunity of identifying Pevatron. Accordingly, the first step of NTA observation will be to observe the Sgr A* region near Galactic Center. Detection of both PeV neutrino and γ from the region would, if successful, lead to a clear proof for PeVatron existing within our Galaxy. Such a "multi-astroparticle" paradigm detection [3] can be performed uniquely by NTA with a single detector system [8].

Then, NTA can extend its survey, by developing what we shall learn from the investigation work of the Galactic PeVatron candidate, to identify extragalactic PeVatron and accelerators at higher energies: The photo-meson ($p\gamma$) reaction is typically the main ν generation process. Extra-galactic sources like jets and cores of active galactic nuclei (AGN) [5] and γ burst (GRB) jets [6] have been widely studied. Galactic sources such as starburst galaxies (SBGs) and hypernovae may

Figure 2: Ashra-1 Mauna Loa Observation Site (*top*), Ashra-1 light collector (*bottom left*), photo-electric lens imaging tube (*bottom center*) and photoelectric image pipeline (*bottom right*).

emit ν flux mainly through hadro-nuclear (pp) reaction [7].

2. Imaging ν_τ and γ Air-showers

NTA consists of four observation sites at 3000-3500 m a.s.l. on Mauna Loa to watch efficiently the air volume surrounding Mauna Loa above ground or sea (Fig. 1 *left*). The technique of observing earth-skimming tau ν (ES-ν_τ) [10] can enjoys a large target mass by detecting air-showers produced by τ decays in the air (Fig. 1 *right*). In particular, the τ particles are produced by ν_τ's that interact with the Earth matter. They traverse, and emerge out of a mountain or the ground, then decay and generate air-showers. This ES-ν_τ method has a good detection sensitivity for ν's originating from hadron acceleration in astronomical objects in the PeV-EeV region. Additional advantages are perfect shielding of cosmic ray secondaries, precise arrival direction determination, and negligible background from atmospheric ν's [11]. The Ashra detector can efficiently image air-shower Cherenkov and fluorescence light generated from ES-ν_τ and γ air-showers in the effective volume of atmosphere in the field of view (FOV) (Fig. 1 *right*). The unique point is the resolution better than 0.1°, which will yield a high ability of rejecting hadron initiated air-showers and of selecting γ's by analyzing both the fluorescence and Cherenkov light (Fig. 3 *right*).

We will search for deeply-penetrating electron ν (ν_e) and ν_τ (DP-$\nu_{e,\tau}$) as well as ES-ν_τ. Since the decay length of τ with the energy of E_τ is given by 49 m (E_τ/PeV), the target mass of ES-ν_τ is small in the case of E_{ν_τ} below a few PeV. The lower energy sensitivity for ν's below 10 PeV, however, can be compensated by observing air-showers from DP-$\nu_{e,\tau}$. Adding that, we have a

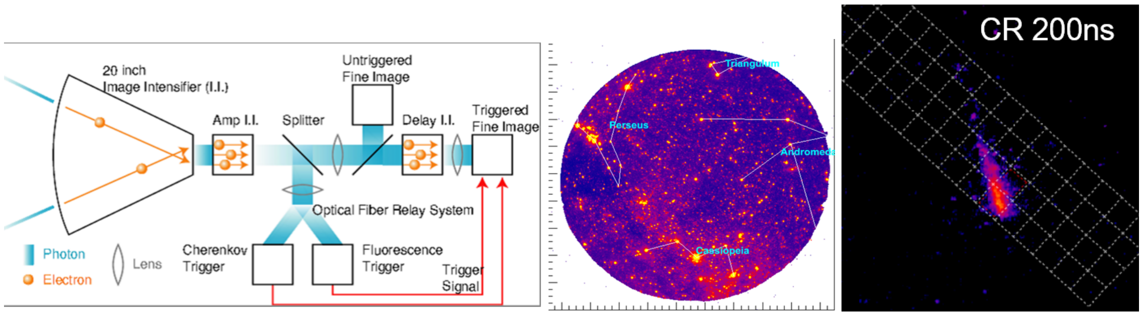

Figure 3: Schematic diagram of Ashra-1 photoelectric image pipeline (PIP) (*left*). A real star image taken by Ashra-1 with 1 sec exposure time without trigger (*center*). Big constellations are indicated on it as guiding eyes. A real air-shower image triggered and read out by Ashra-1 with 200 ns exposure time (*right*).

benefit of searching for ν_e's as well as ν_τ's with the fine imaging detection technique in the energy region in the context of the Glashow resonance [12]. To reject ordinary cosmic ray air-showers, we require the slant depth of the maximum shower size $X_{max} > 1700$ g/cm^2 in the condition of the zenith angle of the arrival shower axis direction $\theta_{zen} > 70^\circ$ [10].

3. From Ashra-1 to NTA

Ashra Phase I (Ashra-1) [4] was developed to achieve very high resolution Cherenkov and fluorescence light images of ν_τ and γ air-showers for very high energy "multi-astroparticle" observation [3] (Fig. 2 *top*). The Ashra-1 light collector as the detector unit (Fig. 2 *bottom left*) achieves a total resolution of ~ 3 arcminutes covering 42° FOV. The key feature is the use of electrostatic rather than optical lenses to generate convergent beams with a 20 inch Photoelectric Lens Imaging tube (PLI) [13] (Fig. 2 *bottom center*), which is the world's largest image intensifier, demagnifying to 1 inch at focal surface, enabling high resolution over a wide FOV [14]. The following trigger readout Photoelectric Image Pipeline (PIP) [15] (Fig. 3 *bottom right*) can image and read out three independent phenomena on different time scales, i.e. air-shower Cherenkov emission (ns), air-shower fluorescence (μs), and starlight (s), without sacrificing the S/N ratios (Fig. 3). The demonstration phase has been operated since 2008 at the Mauna Loa Observation Site at 3300 m asl. on Hawaii Island. Following the alert for GRB081203A given by the SWIFT satellite, Ashra-1 succeeded in the first search for PeV-EeV ν_τ's originating from a GRB with the ES-ν_τ technique setting stringent fluence limits [16].

Based on the performance of Ashra-1, we have planned a new extention, i.g. Ashra Neutrino Telescope Array (NTA), which is an air-shower imaging ν and γ observation system with the following aim/scientific goals [8]: *Clear Discovery and Identification of Non-thermal Hadronic Processes in the Universe, be it Galactic, Extragalatic, or Cosmogenic*. A Letter of Intent for NTA has been published in 2013 [8]. In 2014, a preliminary workshop (VHEPA2014) was held at Kashiwa campus of the University of Tokyo to discuss the design of the project and plans with the colleagues who share common interests. After a workshop in Taipei and an informal meeting to discuss the next post-IceCube detector project at the 34th International Cosmic Ray Conference in The Hague in 2015, we held a workshop as VHEPA2016 at the University of Hawaii Manoa in

January, 2016 to discuss more detailed physics and NTA potential performance, as well as funding requests in each country. We have set up an International Promotion Working Group (IPWG), for reconfirming the basic design of NTA after discussions, editing and publishing White Paper and Technical Design Report in FY 2017.

4. Expected Impacts

There are three stages in the detection procedure; (1) $\nu_\tau \to \tau$ conversion in the earth; (2) τ shower development; (3) detector performance, we evaluate the reconstructed arrival direction of τ air-shower axes to be within 0.1° from the original direction of the PeV-scale ES-ν_τ's and DP-$\nu_{e,\tau}$'s [8, 11]. We have optimized the layout of the NTA stations, mainly enhancing the detection sensitivity for ES-ν_τ's around 1 PeV, in the energy region, where IceCube found the significance of astronomical ν's. Four NTA stations are to be deployed on Mauna Loa at 3000 - 3500 m asl. (NTA Summit Array), watching the air volume surrounding Mauna Loa including the surface of Mauna Loa, which is the world largest volume mountain and works as a large target material, to efficiently detect Cherenkov and fluorescence light generated from τ air-showers with both short and long decay lengths and γ air-showers (Fig. 1). The accurate reconstruction of air-shower images with very fine resolution is a powerful technique not only in the determination of point sources of PeV ν_τ's but also fluorescence observation for γ air-showers above a PeV with large effective area (Fig. 1). Fig. 4 *left* shows the effective detection areas for fluorescence and Cherenkov air-showers induced by ES-ν_τ's and DP-$\nu_{e,\tau}$'s on average over the different elevation angles for the arrival direction between 0° and -30° and between 20° and -5° respectively. It also shows comparisons with those for all flavor ν's with IceCube, IceCube Gen2, and ARA. NTA achieves an effective area similar to that of IceCube at 1 PeV and 10-100 times larger than it above 30 PeV. The sensitivity for ES-ν_τ's with observing Cherenkov light is under study, which may enhance more the discovery potentiality around PeV or the lower energy region. Fig. 4 *right* shows the integral flux sensitivity limits for γ's with NTA for one year observation i.e. 700 hours exposure time comparing with those of other detectors. Fig. 5 shows a simulated image of Earth-skimming tau fluorescence air-shower track with NTA (*left*), the NTA survey FOV for ν's and γ's (*center*), and the annual exposure map for ν's with NTA in the galactic coordinate (*right*). The power of NTA is to survey ν_τ source objects with the best-yet sensitivity in the detection solid angle for ν_τ's defined as $-30^\circ < \theta_{\rm elev} < 0^\circ$ and $0^\circ < \phi_{\rm azi} < 360^\circ$, and for 3 PeV $< E_{\nu_\tau} <$ 30 EeV. By observing DP-$\nu_{e,\tau}$'s, even around the energy of 1 PeV, the total effective area of NTA is competitive with that of IceCube. In the case of γ's, NTA will survey air-shower Cherenkov (fluorescence) light induced by γ's with arrival direction angles below 30° in elevation angle (over half of the sky) for energies between 10 TeV (1 PeV) and several 100 TeV (100 PeV). The geometrical relation of Mauna Loa to NTA detector for detecting air-showers, as illustrated by Fig. 1, gives a large detection area for neutrino and γ's from Galactic Center region as shown in Fig. 4. The unique combination of Cherenkov and fluorescence observations for both ES-ν_τ's and γ's with NTA will truly identify Pevatron(s) and open up new types of search for γ in wide energy range.

The investigation of PeVatron by NTA will give us precious, detailed information about the acceleration phenomenon of cosmic rays in our Galaxy. If a similar amount of fluxes of neutrino and γ's at PeV are not detected from the Galactic Center region, the "negative" result implies a

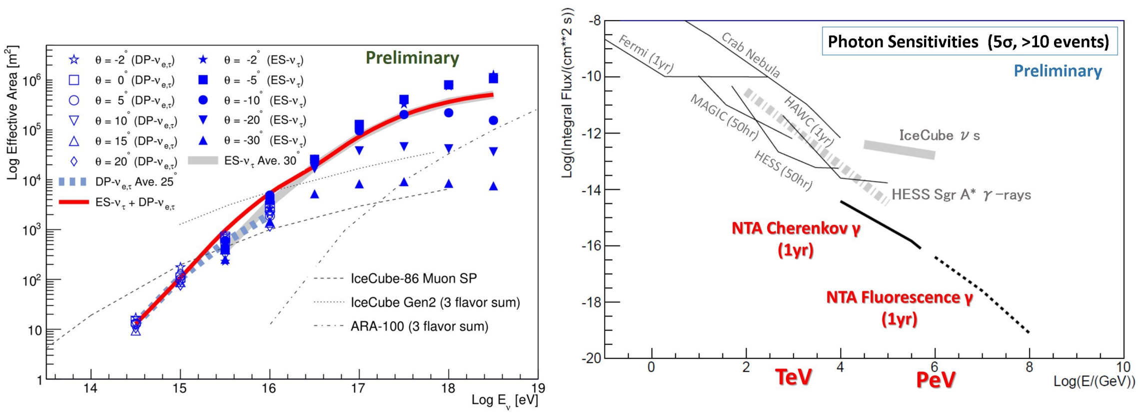

Figure 4: Effective area for ES-ν_τ's and DP-$\nu_{e,\tau}$'s as changing the energies with NTA in comparison with those for all flavor νs with IceCube, IceCube Gen2, and ARA [9] (*left*). Integral flux sensitivity limits (5σ or more than 10 events) for γ's versus the energies with NTA (1yr observation) and other detectors (*right*).

clear statement that IceCube PeV neutrinos are of extragalactic origin NTA has a large detection area in 10 PeV region as demonstrated in Fig. 5, and the next step NTA must take is to confirm extragalactic neutrinos; diffuse flux or emission from point-like objects in the energy region of 10 PeV to EeV. Intensity of γ's around 1-10 PeV suffers from very serious attenuation in the extragalactic space. The intensity of detected ν flux needs to be compared with γ fluxes in a wide energy range down to 100 Ge V and up to EeV. Absorption length of EeV γ's recovers as long as 1 Mpc and the direct comparison between ν and γ may be again made possible in UHE energy region higher than EeV.

For the combined analysis using very high energy multi-astroparticles, the ability to separate γ's from hadron particles is important. Assuming Crab nebula point source, the flux ratio $\Phi_\gamma/\Phi_p \approx 3 \times 10^{-6}(E/\mathrm{TeV})^{0.1}$ which depends on the FOV solid angle. The NTA point-back resolution is so advantaged that $\Phi_\gamma/\Phi_p \approx 0.4$ at 1 TeV with the angular accuracy of 0.1°, which suggests even only the angular cut is useful for the discrimination. In the case of the extended Galactic Center region, where HESS reported the fascinating VHE γ hard spectrum [2], we can estimate $\Phi_\gamma/\Phi_p \approx 10^{-3}(E/\mathrm{TeV})^{0.4}$ in the solid angle of 0.5° radius corresponding to the diffuse γ region, which indicates only the angular cut is not enough for the γ / hadron separation. This γ / hadron particle classification problem in NTA data analysis can be treated with the rapidly-advancing machine learning algorithms applied to fine air-shower images taken by NTA, which have the potential to outperform the traditional simple-cut methods on image parameters. As another training γ / hadron classification method, the Boosted Decision Tree (BDT) method [17] is reported. 54% of the efficiency for the signal γ and 0.7% of background proton is obtained with CORSIKA simulation in comparison with 54% signal and 13% background with the simple-cut method [18]. Fully utilizing NTA's fine imaging capability in the wide FOV, we applied the Multi-Layer (Deep Learning) Convolutional Neural Network (CNN) refer to the method denoted as VGG [19], which is a basic Deep Learning CNN composed by multiple convolution and pooling layers, to the γ / hadron separation. Using the Deep Learning CNN, we obtained the high recognition rate more than 99% on the γ / hadron separation without sacrificing largely the selection efficiencies, which suggests ex-

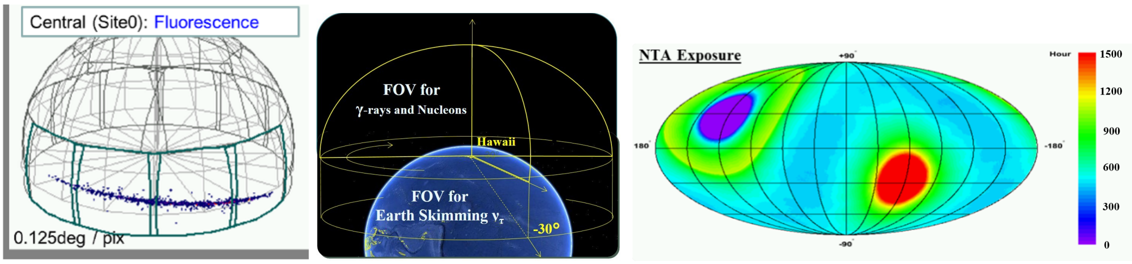

Figure 5: Simulated image of Earth-skimming tau fluorescence air-shower track with NTA (*left*). NTA survey FOV for νs and γs (*center*). Annual exposure map for νs with NTA in the galactic coordinate (*right*).

ploring the VHE universe with multiple astroparticles are realistically effective even for the diffuse extended sources like the Galactic Center. Particularly, the method is useful for testing the Galactic Center as a Pevatron candidate strongly suggested by HESS.

5. New Chapter in Fundamental Physics with NTA

The number of X-ray and γ objects already discovered is quite numerous. We, however in the case of ν, have only two ν-emitting objects as observed, the Sun and SN1987A in the Large Magellenic Cloud, and the energy of detected ν is much less than TeV. The IceCube detection of astronomical ν events of PeV energy declares that a window is now opened to look into high energy ν astrophysics. Then, we expect NTA will open a new chapter of ν and γ phenomena in the energy region of PeV to EeV being described with good sensitivity and good pointing accuracy. The technology is already developed by Ashra-1 and with Hawaii Big Island an excellent site (the largest volume mountain with good astronomy sites) (Fig. 2 *top*).

By using the "cosmic beam of νs and γ's" ejected from the "cosmic hadron accelerators", we may be allowed for reconsidering the principles of the fundamental physics; for examples, the tests of Lorentz invariance [20], extra-dimensions [21], as well as correcting our understanding about cosmic background photon fields [22], as well as PeV γ objects, and so on. NTA has a potential capability to have an impact on fundamental science at the UHE frontier as a complementary to that with "accelerators on Earth".

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