PROCEEDINGS OF SCIENCE

Very High Energy Physics and Astronomy with Tau and Photon Probes

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Very-high energy physics (VHEP) is the development of a higher energy frontier complementary to accelerator-based HEP to investigate interactions in space caused by fundamental particles and to study the structure and fundamental interactions of elementary particles. Probing for VHE elementary particles will also enable the discovery of VHE celestial objects and the elucidation of their phenomena. Comparison of VHE neutrino and photon flux spectra from the same object will also allow for fundamental particle physics and cosmological investigations. Neutrinos and photons are well-known elementary particles from the Standard Model (SM) and travel straight in magnetic fields, making them powerful probes for very-high energy physics and astronomy (VHEPA). VHE tau neutrinos skim the earth, are converted to tau, and after decaying in air become an upward air shower at a shallow elevation angle, emitting Cherenkov and fluorescence light. Neutrino oscillations cause neutrino fluxes to homogenize between generations during propagation. Tau neutrino observation should be also tau appearance experiment. Neutrino Telescope Array (NTA) unit is a unique wide-angle, high-precision optical system with an optical bifurcation trigger imaging system, based on Ashra-1, the first Earth-skimming tau search from a celestial object. NTA, consisting of four stations located near the summit of Mauna Loa on the Hawaii Island, simultaneously takes multi-eye images of air shower Cherenkov light and fluorescence above 10 TeV with a high precision pixels of 1 arcmin within a 360 °× 32 ° basic field of view plus a Galactic bulge monitoring field of view. This detection scheme is particularly powerful for the simultaneous monitoring observation of Cherenkov and fluorescence light from VHE tau and photons. NTA's combined VHE tau (E_τ ≥1 PeV) and photon (E_γ ≥10 TeV) probes are expected to open up more comprehensive studies of VHEPA, e.g. search for super-heavy dark matter and clear identification of PeV particle emitters.

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1. Prospects for VHE Physics and Astronomy

The highest energy collider LHC operates at a center-of-mass energy of $\sqrt{s}$ = 13 TeV, which corresponds to a laboratory system energy of p_{lab} = 90 PeV for a fixed target beam. This fact leads us into a new era of synergy between particle high-energy physics (HEP) and very-high-energy (VHE) particle observation. VHE physics (VHEP) can be the development of a higher energy frontier beyond $\sqrt{s} \sim$ sub-PeV that is complementary to HEP to investigate interactions in space caused by fundamental particles and to study the structure and fundamental interactions of elementary particles such as super-heavy dark matter (DM) particle annihilation. Probing for VHE elementary particles with $p_{lab} \leq$ sub-EeV, will also enable to conduct a serious exploration for the discovery of VHE objects and the empirical elucidation of their phenomena, while eliminating vague speculations with reliable data on the nature of the particles and the processes of their interaction.

Neutrinos and photons are fundamental SM elementary particles and travel straight in magnetic fields, making them powerful probes for VHE physics and astronomy (VHEPA). VHE neutrinos and photons can probe super-heavy DM. VHE objects should emit 1st- and 2nd-generation neutrinos with photons from the $p\gamma$ or pp process by accelerated protons, which remain unidentified. Precise comparison of VHE neutrino and photon flux spectra from the same object also allow for fundamental particle and cosmological physics investigations as well as clear identification. Neutrino oscillations cause neutrino fluxes to homogenize between generations during propagation. The observation of taus converted from tau neutrinos can serve as a clear tau appearance experiment.

Neutrino Telescope Array (NTA) [1] is an omni-purpose detector observing shower light caused by VHE taus converted from tau neutrinos and VHE photons with large zenith angles (LZAs).

2. NTA for VHE Tau and Photon Probes

NTA will radially observe shower light in a vast amount of night-time air on the mountain of Mauna Loa within more than π sr field of view (FOV) covered with 1 minute square pixels (Fig. 1).

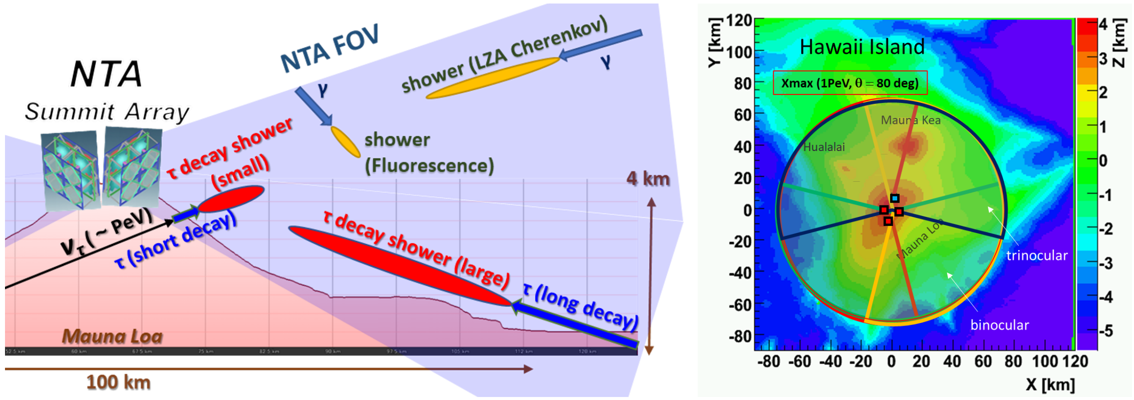

Figure 1: Schematics of "lookout layout" for imaging tau and photon showers with NTA (*left*). The contour map of Hawaii Island is input to our MC simulation (*right*). The radius of the wheel represents the distance to X_{max} of the 1PeV shower coming toward NTA at 80° zenith. Four stations are placed on the mountainside indicated by square marks. One station is responsible for 210 ° azimuth range indicated by four fans.

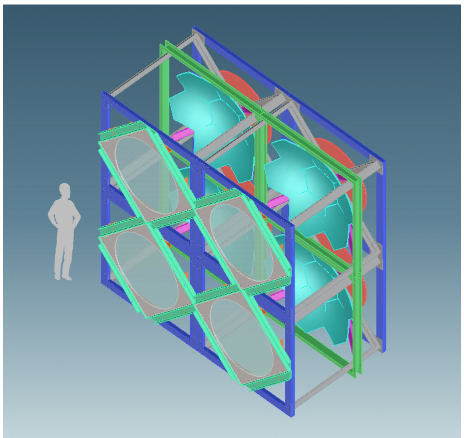

Figure 2: NTA detector unit. The basic design is a 1.5-fold scaled-up version of the Ashra-1 light collector, and four of these collectors are stacked together to form one NTA detector unit with the same FOV.

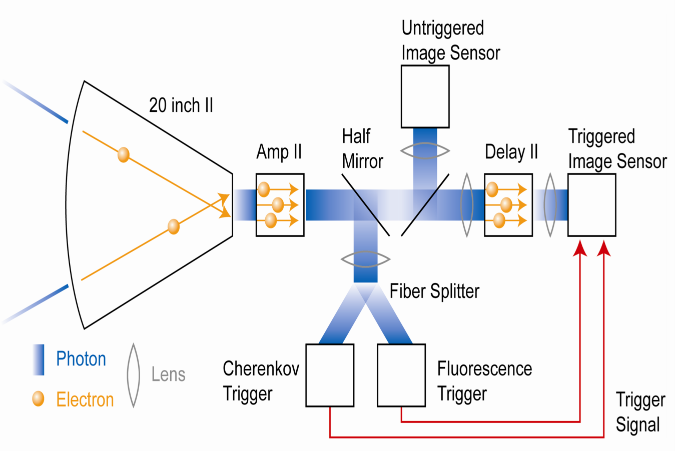

Figure 3: Schematic diagram of Ashra-1 photoelectric image pipeline (PIP); the heart of a multi-messenger approach with a single detection system. The same fine image output from the big imaging tube is sent to multiple triggers and finally read out by the CMOS image sensor.

The lookout layout allows Cherenkov and fluorescence observations over a wide energy range of taus and photons. Four stations will be placed on the mountainside and each station is basically responsible for a FOV of 210° azimuth and 30° zenith, allowing for a high multi-eye observation rate (Fig. 1 *right*). Regarding NTA's view of the southern sky, the FOV is enhanced to always cover the Galactic bulge of the night, considering a high multi-eye observation ratio. Earth-skimming or mountain-hitting tau neutrino are converted to tau in the rock, and tau decays make upward showers [2][3] which are very clear in almost background-free conditions [4]. Downward coming photon showers at LZAs are observed in both Cherenkov and fluorescence light. The Cherenkov light coming from a LZA earns a large effective area (Fig. 4). NTA proto-project, Ashra-1, was placed at the north side of Mauna Loa in 2008.

The basic design is a 1.5-fold scaled-up version of the Ashra-1 light collector with the 42° FOV diameter in Schmidt-type optics [5], and four of these collectors are stacked together to form one NTA detector unit (DU) with the same FOV (Fig. 2). The effective pupil diameter is 3 m, providing good light gathering power. Such a design can also facilitate background passing-through muon rejection, transport and construction on the mountain ground. Note that conventional Davies-Cotton and its subclass of optics have too low accuracy and signal-to-noise (S/N) ratios in the night sky background to be of any use for such wide-angle and fine-resolution observations. The Ashra-1 light collector is a unique hybrid telescope using both light and electrons. 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) [6], which is the world's largest image intensifier, demagnifying to 1 inch at focal surface, enabling high resolution over a wide FOV, i.e. both a 3-minute resolution and a 42° FOV have been achieved (Fig. 5). The following trigger readout Photoelectric Image Pipeline (PIP) (Fig. 3) [7] can image and read out three independent phenomena on different time scales, i.e. shower Cherenkov (ns), fluorescence light (μs), and starlight (s), without sacrificing the S/N ratios. The PIP trigger and readout is the heart of a multi-messenger approach with a single detection system, enabling the first air-shower imaged with a self-triggering fine image sensor with the accuracy

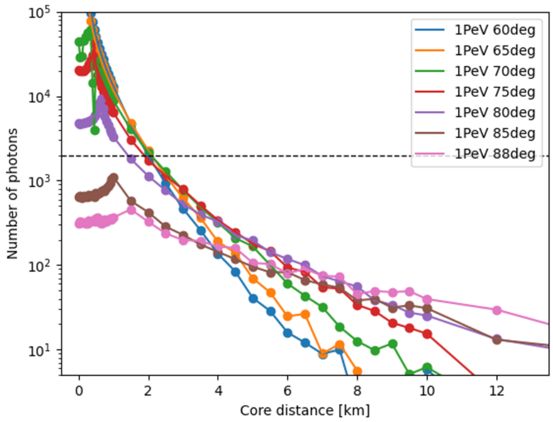

Figure 4: Simulated number of Cherenkov photons from 1-PeV photon showers reaching the pupil of the NTA DU at the core distances as the zenith angle varies from 60° to 88°. Corsika769 with Curved IACT option [9] is used, The threshold of 2000 photons is indicated (*dahed line*).

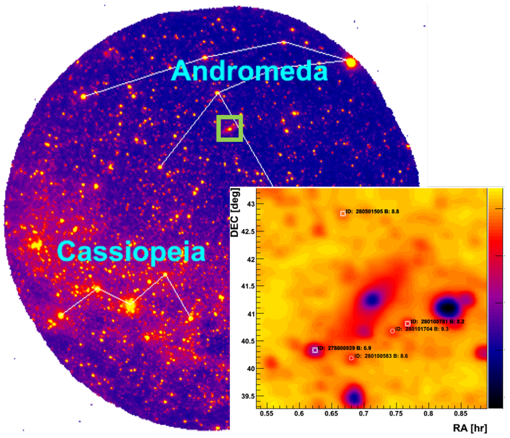

Figure 5: Real star image taken by Ashra-1 with 1 s exposure time and an expanded view around Andromeda galaxy in the square region, demonstrating Ashra-1 imaging performance of a few arcmin resolution in 42° FOV.

of 3 arcmin (0.05°). The Ashra-1 succeeded in the first precision imaging of air-showers with a self-triggered solid state sensor and the first search for PeV-EeV tau neutrinos originating from a GRB [8]. Fig. 6 shows a comparison of diffuse neutrino sensitivity from various VHE neutrino detectors. NTA has the best sensitivity from a few PeV to 100 PeV. The combined observation of LZA air-shower Cherenkov and fluorescence light allows NTA to be sensitive to taus over a wide energy range.

3. Super-heavy Dark Matter Search as VHE Physics

Since DM candidates are considered to be be non-baryonic and non-relativistic from the time of matter-matter collisions, DM must belong to a new particle sector beyond the SM process. Weakly interacting massive particles (WIMPs) are natural DM candidates [11]. The combination of S-matrix unitarity and the dynamics of thermal freeze-out for WIMPs imply an upper limit on the mass of thermal DM of $(m_\chi/110\ TeV)^2 \leq \Omega_\chi/\Omega_{\rm DM} \equiv f_\chi$ [12] using $\Omega_{DM}h^2 \simeq 0.11$ [13]. NTA can provide interesting avenues to explore new VHEP with a combination of tau ($E_\tau \geq$1 PeV) and photon ($E_\gamma \geq$10 TeV) probes.

The number of detectable taus from the Galactic halo DM decaying into neutrinos with NTA is estimated using the effective area $A_{eff}(\Omega, E_{\nu_\tau})$ and the observation time T_{obs}, numerical integration of the DM density ρ_χ along the line of sight (LOS) in a detection solid angle Ω: $N_\tau = (f_\chi\Gamma_\chi/4\pi E_{\nu_\tau})\int d\Omega \int_{LOS} dx\rho_\chi(x)A_{eff}(\Omega, E_\nu)T_{obs}$, where ρ_χ is a cuspy profile described by Navarro-Frenk-White (NFW) [14]; $\rho_\chi(r) = (0.307\ GeVcm^{-3})[r/21\ kpc(1+r/21\ kpc)^2]^{-1}$. T_{obs} is assummed to be 90% of the total moonless night time while the achieved efficiency with Ashra-1 on Mauna Loa was 94%. The estimates of $A_{eff}(\Omega, E_{\nu_\tau})$ are same as used in Fig. 6. The 5-yr sensitivity limits for the DM decay width $(f_\chi\Gamma_\chi)$ at 90 % C.L. for NTA requiring $N_\tau \geq 2.44$ with almost no physics background are illustrated in Fig. 7, comparing with other experiments. Tau

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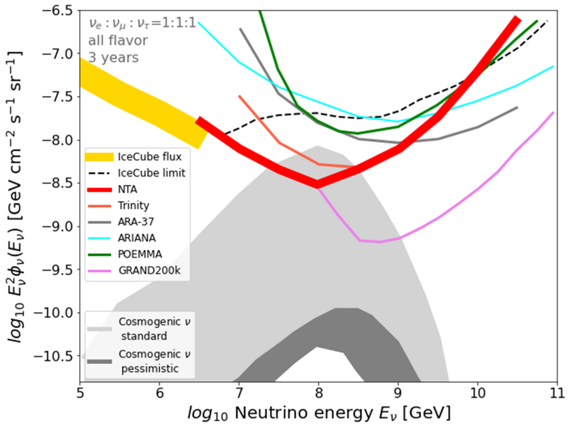

Figure 6: Comparison of diffuse neutrino sensitivities from VHE neutrino detectors and cosmigenic neutrino flux predictions. NTA has the best sensitivities in the sub-PeV region. Figure adapted from [10].

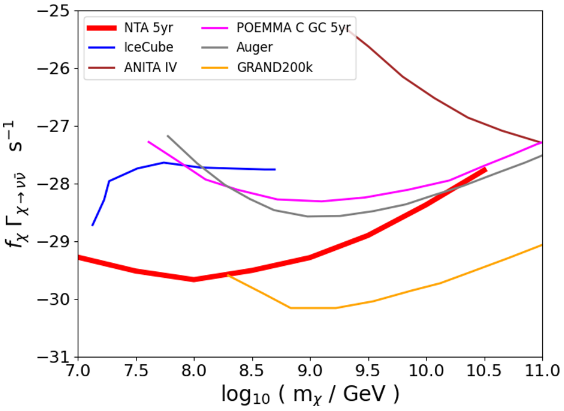

Figure 7: 5-year sensitivities of NTA to DM decay width ($f_\chi\Gamma_\chi$) for $\nu\bar{\nu}$ channels and those of other experiments. NTA has the highest sensitivity in the 10 PeV to sub-EeV region. Figure adapted from [15].

probes by NTA has a dominant search sensitivity to DM WIMP decay neutrinos in the near-energy region of sub-EeV beyond the unitarity limit.

Neutrino signals from DM annihilation and decay are expected to be accompanied by photon signals through W, b and tau channels. NTA can monitor the Galactic Center (GC; Sgr A*) for 980 hr with photon probes annually. This is about 40 times more than tha observing time of H.E.S.S. (254 hr in 10 years) [18]. NTA can monitor the Galactic bulge region (radius 20° from the GC) in its FOV at all times in the night sky. NTA can search for photons originating from 12 % of the total mass of the Galactic halo DM assuming the Einasto profile [14]. NTA also has a vast effective detection area due to the LZA photon shower from the GC at 42° south-central altitude from Mauna Loa, giving it an advantage over time-efficient 2D particle sampling detectors. Fig. 8 shows flux sensitivities of NTA for 5 yr comparing with a possible water Cherenkov survey observatory (0.2 km^2 WCD) and of Cherenkov Telescope Array (CTA) as a function of photon energy E$_\gamma$ for 5 yr and 50 hr of observation of the Galactic halo with the predicted DM annihilation rate into tau pairs [16]. NTA can search for DM WIMPs using both sharp morphology and spectral cutoffs as evidence.

4. VHE Particle Emitter Search as VHE Astronomy

As an important achievement in VHE astronomy (VHEA), PeV particle emitters have been suggested to exist [17]. Moreover, they may be lurking in the GC region [19]. As shown in Fig. 6, NTA can test and unambiguously identify IceCube's PeV emitting sources through high-precision ($\leq 0.1°$) monitoring observations of taus. Fig. 9 shows the expected sensitivity obtained from 5 yr of Cherenkov observations by NTA, H.E.S.S. GC VHE photon measurements, the related results of Auger's limits and the extrapolated photon flux given the quoted spectral indices. NTA has the potential to unambiguously discover and identify very interesting PeV particle emitters in the Galactic bulge region in the still unexplored sub-PeV to sub-EeV energy range, and to measure and test their spectral change or cutoff, if any.

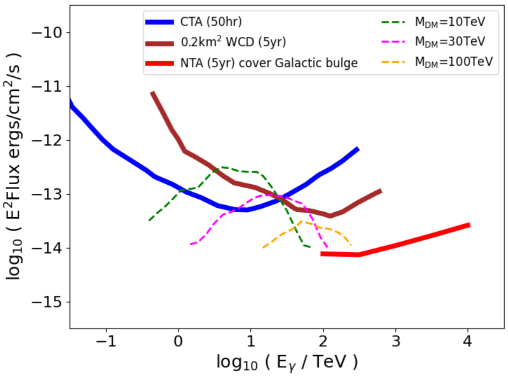

Figure 8: Flux sensitivities of NTA for 5 yr, of a possible 2D observatory (0.2 km^2 WCD) for 5 yr and of CTA for 50 hr observation of the Galactic halo. The predicted DM annihilation rates into τ pairs are indicated. Figure is adopted from [16].

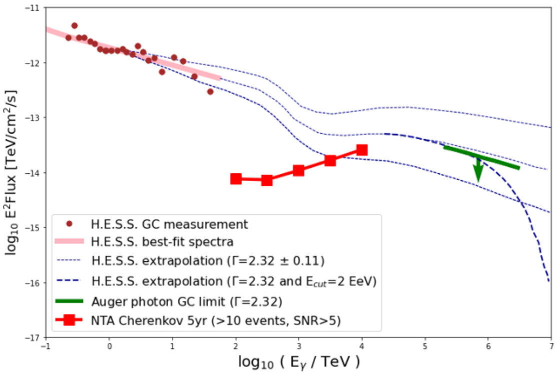

Figure 9: 5-yr sensitivities of NTA to GC VHE photon flux, the related results of H.E.S.S. measurements and Auger's limits and the extrapolated photon flux given the quoted spectral indices. Figure adapted from [20]

5. Conclusions

This is the era of synergy between HEP and VHEPA. NTA's combined VHE tau ($E_\tau \geq 1$ PeV) and photon ($E_\gamma \geq 10$ TeV) probes with FOV more than π sr and 1 arcmin pixel resolution will open up more comprehensive studies of VHEPA, e.g. search for super-heavy DM and clear identification of PeV particle emitters. NTA will take over important results from TeV and pass more developed results to EeV in VHEPA.

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