EXPECTED PERFORMANCE OF A NEUTRINO TELESCOPE FOR SEEING AGN/GC BEHIND A MOUNTAIN

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We study the expected performance of building a neutrino telescope, which targets at energy greater than $10^{14}$ eV utilizing a mountain to interact with neutrinos. The telescope’s efficiency in converting neutrinos into leptons is first examined. Then using a potential site on the Big Island of Hawaii, we estimate the acceptance of the proposed detector. The neutrino flux limit at event rate 0.3/year/half decade of energy is estimated to be comparable to that of AMANDA neutrino flux limit at above $10^{16}$ eV.

1 Neutrino Astronomy

Neutrino astronomy is still in its infancy. Although neutrinos are abundantly produced in stars, as they live and when they die, one suffers from an extremely low cross section for detection on Earth. Still, it is rather impressive that we already have “neutrino images” of the Sun, as well as neutrino blips of the cataclysmic SN1987A event. At the start of a new century/millennium, we yearn to reach beyond the stars and observe cosmological neutrino sources. Large “km$^3$” ice/water or air shower neutrino “telescopes” are being built, and “the sky is the limit”.

Neutrinos could play an important role in connecting several branches of particle astrophysics. The origin of ultra-high energy cosmic rays (UHECR) is still a great puzzle [1]. Bottom-up theories propose that they originate from energetic processes such as Active Galactic Nuclei (AGN) or Gamma Ray Bursts (GRB). The energetic hadron component could interact with accreting materials near the central black hole and produce neutrinos through the decay of charged pions. On the other hand, top-down theories suggest that UHECR are decay products of topological defects or heavy relic particles. According to these theories, there are more neutrinos than gamma rays and protons [2]. Measurement of the neutrino flux at and above the “knee” region (i.e. $>10^{15}$ eV) provides a good discriminator to distinguish between the two scenarios.

Cosmic gamma rays are attenuated by the infrared, microwave and radio background photons [3]. The recent observation of TeV gamma rays from extragalactic sources such as Mkn421 [4] and Mkn501 [5], however, has aroused some concern. In order to reach the Earth from extragalactic distances, these $\gamma$ sources must have either a much harder spectrum or more powerful mech-
anisms, e.g. electromagnetic (EM) processes such as inverse Compton scattering, or hadronic processes such as $p + X \rightarrow \pi^0 + \ldots \rightarrow \gamma + \ldots$. The former produces few neutrinos, while the latter produces comparable amounts of both neutrinos and photons. Neutrinos therefore provide direct probes of the production mechanism of TeV $\gamma$ rays from extragalactic sources such as AGN/GRB.

Recent results on atmospheric neutrinos add an interesting twist to cosmological neutrino detection. Super-Kamiokande (SK) and Sudbury Neutrino Observatory (SNO) data strongly suggest that muon neutrinos oscillate into tau neutrinos. Below $10^{12}$ eV, the tau decay length is less than 5 mm, and SK and SNO have difficulty distinguishing between showers initiated by electrons and those by taus. Above $10^{15}$ eV, the tau decay length becomes 50 m or more, distinctive enough for identifying the taus. Since cosmic neutrinos are produced via $\pi^+$ decay predominately, one does not expect much directly produced cosmic $\nu_\tau$ flux. Detecting a tau decendent on Earth would not only probe AGN/GRB mechanisms, but would also constitute a tau-appearance experiment.

## 2 A Genuine Neutrino Telescope

Because of the low interaction cross-section, all neutrino experiments resort to a huge target volume. The target volume is usually surrounded by the detection devices in order to maximize detection efficiency. Thus, the target volume is approximately equal to the detection volume. In other words, the cost of building a detector cost varies in proportion to the target/detection volume. Furthermore, to shield against cosmic rays or even high energy atmospheric neutrinos, these detectors often have to be deep underground. For instance, the km$^3$ size ICECUBE project at the South Pole has a price tag of $100M, aims to look for upward going events, and takes years to build. Variants such as sea/ocean or air watch experiments are similarly large and costly. These “telescopes” tend to bear litte resemblance to their EM counterparts.

Some alternative approaches have been proposed, such as using the Earth or a mountain as the target into convert neutrinos to leptons, which will then initiate air showers in the atmosphere. Observing the air showers from a region obscured by a mountain or the Earth can eliminate the contamination of cosmic ray showers. The main difference between this approach and the conventional experiments is that the target volume and the detection volume are different. Moreover, materials in the target volume (mountain, Earth) and the detection volume (atmosphere) are readily available at almost no cost, thus the overall cost (and perhaps schedule) of the
Using an approach similar to that of Vannucci, a Cerenkov telescope sits on one side of a valley opposite a mountain. Energetic cosmic neutrinos, while passing through the atmosphere with ease, interact inside the mountain and produce leptons. Electrons will shower quickly and have little chance of escaping from the mountain. For muons, the decay/interaction lengths are too large to initiate showers inside the valley. The taus have suitable decay length to escape from the mountain and initiate showers inside the valley upon decay. This process is illustrated in Fig. 1. With this design, the telescope is not only a detector for astrophysical and cosmological neutrinos, but also serves as a tau-appearance experiment.

It is interesting to note that this telescope resembles closely usual EM telescopes and a typical particle experiment. The field piece is the mountain, which functions as both a target and a shield, and the subsequent valley is the shower volume. The actual Cerenkov telescope functions as an “eye piece” that focuses the Cerenkov light from a shower emerging from the mountain onto a sensor plane. The sensor could be a MAPMT array, where fast electronics matches the 10 ns Cerenkov pulse and helps discriminate against other background sources. Using two telescopes in coincidence would produce better results. The only drawback, in comparison to a regular EM telescope, is that we cannot move the mountain and would have to rely on the Earth’s rotation to move the telescope.

Besides cost, expected to be far less than ICECUBE or Auger, the most critical issue is the expected count rate. In the following, we choose a potential site (Hawaii Big Island), examine the neutrino conversion efficiency, and then derive the flux limit and sky coverage of the proposed detector.
3 Potential Site

The criteria for choosing a potential site are as follows:

- Reduced artificial lights, dry air and cloudless sky, much like usual optical telescopes.

- Target mountain broad enough for the sake of acceptance.

- Valley wide enough for taus to decay and air showers to develop.

  In the energy range of $10^{14} - 10^{18}$ eV, the depth of shower maximum $\sim 500 - 800 \text{ gm/cm}^2$. At altitude around 2 km, this depth corresponds to a horizontal distance of 4.5 to 7.8 km. Therefore, the width of the valley must be larger than 5 km, but less than the attenuation length of light $\sim 50$ km.

- Good exposure to the Galaxy Center (GC).

  The nearest massive black hole — what may be behind astrophysical neutrinos — is our Galaxy Center.

  Hawaii Big Island, with its perfect weather conditions, has been a favorable site for astronomical (EM) telescopes. The Big Island also has a rather unique configuration. Besides the more sought after Mauna Kea, the other 4 km high mountain, Mauna Loa, has a breadth of approximately 90 km. Across from Mauna Loa to the northwest, Mount Hualalai is $\sim 20$ km away and 2.3 km in altitude. This makes Mauna Loa a good candidate for the target mountain with the detector installed on top of Hualalai. In the following study we assume this configuration.

4 Neutrino conversion efficiency

In this study, the mountain is simplified as a block of thickness $L$. Neutrinos enter the mountain, pass through distance $x$, interact in $x$ to $x + dx$, produce taus, which then survive through the rest of the mountain without decay.

The probability for neutrinos to survive the atmosphere ($P_1$) is taken as 1, which is very close to the actual case. The probability for neutrinos to survive distance $x$ inside the mountain is $P_2(X) = \exp(-x/\lambda_\nu)$, where $\lambda_\nu = 1/(N_A \sigma \rho)$, $\sigma$ is the charged current interaction cross-section $^{11}$, $N_A$ is the Avogadro number, and $\rho$ is the mean density of the mountain. The chance of neutrino interaction in $x$ to $x + dx$ is $dx/\lambda_\nu$. The energy of tau is approximated as $E_\tau = (1 - y)E_\nu$, where $y$ is the fraction of energy carried by
the recoiling (shattered) nuclei or electron, which is in the range of 0.2 to 0.5 with mean $\sim 0.25$, we therefore use $E_\tau = 0.75 E_\nu$.

The probability for taus to survive through the rest of the mountain of distance $L - x$ is

$$P_3(X) = \exp(-(L-x)/\lambda_\tau),$$

where $\lambda_\tau$ is the decay length of tau and equals $(E_\tau/\text{PeV}) 48\,91$ m.

The neutrino conversion efficiency is

$$\varepsilon = \int_0^L \frac{e^{-x/\lambda_\nu} e^{-(L-x)/\lambda_\tau} dx}{\lambda_\nu} = \frac{\lambda_\tau}{\lambda_\nu - \lambda_\tau} \left( e^{-L/\lambda_\nu} - e^{-L/\lambda_\tau} \right),$$

where the integration was done by neglecting the energy loss of tau. The maximum efficiency occurs at $\frac{d\varepsilon}{dL}|_{L = L_{max}} = 0$, i.e.

$$L_{max} = \frac{\ln(\lambda_\nu/\lambda_\tau)}{\frac{1}{\lambda_\nu} - \frac{1}{\lambda_\tau}}.$$  

The conversion efficiencies at five energies are shown in Fig. 2. The efficiency plateaus above $L > L_{max}/2$. This maximal efficiency scales roughly as a power law in energy.

$$\varepsilon_{max} \simeq \frac{\lambda_\tau}{\lambda_\nu} \simeq 3.6 \times 10^{-6} \left( \frac{E_\nu}{\text{PeV}} \right)^{1.4}.$$  

The mean distance traveled by taus inside the mountain is

$$\overline{L}_\tau = \frac{\int_0^L (L-x) e^{-x/\lambda_\nu} e^{-(L-x)/\lambda_\tau} \frac{dx}{\lambda_\nu}}{\int_0^L e^{-x/\lambda_\nu} e^{-(L-x)/\lambda_\tau} \frac{dx}{\lambda_\nu} \lambda_\nu} = \frac{\lambda_\nu}{\lambda_\nu - \lambda_\tau} \lambda_\tau.$$  

Because $\lambda_\nu \gg \lambda_\tau$, $\overline{L}_\tau \lesssim \lambda_\tau$, the mean production point of tau is approximately one decay length inside the mountain. As long as the thickness of mountain is larger than $\lambda_\tau$, $\overline{L}_\tau$ remains unchanged.

5 Acceptance of flux limit

Fig. 3 shows the panoramic view from the top of Mt. Hualalai towards Mauna Loa. The field of view of the detector is the shaded mountain region inside the box. The azimuth angle extends from south to east. The minimum zenith angle of 86.9° is set by the line from the summit of Hualalai to that of Mauna Loa. The maximum zenith angle of 91.5° is set by the line from the summit of Hualalai to the horizon at the base of Mauna Loa. A cross-section of the Big Island along the line from Hualalai to Mauna Loa is shown in Fig. 4.

The acceptance is defined by the effective area multiplied by the effective solid angle. Owing to lateral distribution of air shower, the Cerenkov light
Figure 2. Neutrino conversion efficiency vs mountain thickness (in kilometers) for five energies. The maximum efficiencies are marked with arrows.

Figure 3. The panoramic view from the top of Hualalai. The dash line is the horizon and the shaded region is the field of view obstructed by the terrain of Hawaii Big Island. The region between the horizon and the terrain is the sea to the west of the Big Island.

cone of shower is approximately $5^\circ$ to $6^\circ$. The effective solid angle can be determined by the sensitivity of PMT, the distance from the detector to the
shower maximum, and the Cerenkov light yield of air shower. The number of Cerenkov photons is proportional to the number of secondary particles in the air showers, which is proportional to the tau energy. Also, the lower energy taus decay closer to the mountain, thus farther away from the detector and the Cerenkov light suffers more atmospheric scattering. These two effects reduce the effective solid angle at lower energy. The extend of the effect can be obtained by detailed simulation. To simplify the calculation, we use a constant value of 5°, which yields the effective solid angle

$$\Omega = \int_0^{\theta_c} \sin \theta d\theta d\phi = 2\pi (1 - \cos \theta_c) = 0.024 \text{ sr}$$

The effective area is the cross-section area where tau decays. The mean distance of decay after taus escape from the mountain is still $\lambda_\tau$. So the effective area is

$$a_{\text{eff}}(E) = \int_{\text{FOV}} (r(\omega) - \lambda_\tau(E))^2 d\omega$$

where $\omega$ is the solid angle of each pixel, FOV is the field of view, and $r$ is the distance from the detector to the mountain surface viewed by that pixel. The total acceptance $A(E)$ is $a_{\text{eff}}(E) \times \Omega$ as shown in Fig. 5. Below $10^{17}$ eV, the acceptance is approximately 1 km$^2$ sr, similar to ICECUBE. The sharp decrease in acceptance at $E > 2 \times 10^{17}$ eV is due to the increase in decay length of tau beyond 10 km. The valley $\sim 20$ km is not wide enough to contain these high energy taus.

The target volume is defined as the volume inside the mountain where taus are produced,

$$V = \int_{\text{FOV}} \int_{R_t}^{R_i} r(\omega)^2 dr d\omega,$$
where $R_i$ is the distance from the detector to the mountain surface, and

$$R_f = \begin{cases} 
R_i + W & \text{if } W < \overline{L_\tau} \\
R_i + \overline{L_\tau} & \text{if } W \geq \overline{L_\tau}
\end{cases}$$

where $W$ is the width of mountain in the field of view $\omega$. The target volume is then transferred to the water-equivalent target volume by multiplying the density of rock, $2.65\text{g/cm}^3$. $\overline{L_\tau} \approx \lambda_\tau$ increases almost linearly with energy, so does the target volume. For conventional neutrino telescopes, such as SK or ICE-CUBE, the target volume is identical to the detection volume, therefore the acceptance is proportional to the detection volume. For the Earth-skimming or mountain-valley type neutrino telescopes, the target volume and the detection volume are different. Thus, the acceptance and the target volume do not have any direct relation.

![Figure 5. Acceptance and water equivalent target volume of the potential site in Hualalai.](image)

This study does not consider the effect of energy loss of taus inside the mountain. The effect becomes more serious for energies $> 10^{17}$ eV, where tau energy loss leads to a decrease in decay length of taus, thus increasing acceptance at high energy. When the energy loss of tau is taken into consideration, Eq. (1) cannot be integrated in closed form. At the present stage, we have ignored the energy loss effect for simplicity and treat the results as lower limit of acceptance and upper limit of sensitivity.

Because of the lower light yield and more scattering at lower energy, the acceptance should be lower at lower energy. In view of the two factors
above, the best energy range for this type of detector is approximately in $10^{15} < E < 10^{18}$ eV.

The flux limit is estimated by

$$\Phi(E) = \frac{d^2N(E)}{dT \, dE} = \frac{dN(E)/dT}{A(E)\varepsilon(E)}$$

where $N$ is the number of events, $T$ is the exposure time, $dN(E)/dT$ is the event rate, $dE$ is the bin width of energy which is approximately equal to the energy resolution of detector. The conversion efficiency $\varepsilon(E)$ is calculated by similar process as Eq. (1). The exact zenith angle, the atmospheric pressure, the mountain width, and the curvature of the Earth are all taken into consideration.

In the conversion from $\nu_\tau$ to $\tau$, some fraction of energy ($yE$) are brought out by interacting nuclei. Because this interaction take place inside the mountain, this energy can not be measured. $\sigma_y \sim 0.18$ is the largest source of systematic error in energy. With some uncertainties from detection and reconstruction, a simplified value of half a decade $10^{-0.5} = 0.31$ is assumed as the energy resolution $dE$.

The detector sensitivity is defined as the flux when the event rate is 0.3 event in one year. Based on the acceptance of Hualalai site, the sensitivity of the proposed detector and the recent AMANDA B-10 neutrino limit are shown in Fig. 6. Note that the AMANDA B-10 limit is the integral flux limit from null observation of neutrino in the energy range of $10^{12}$ to $10^{15}$ eV. The null observation in one year of operation of the proposed detector could set an upper limit similar to that of AMANDA B-10, but at $10^{15} < E < 10^{18}$ eV.

6 Sky coverage

The detector is operated at moonless and cloudless nights. We simulate the operation from December 2003 to December 2006. The detector operates when the total time of moonless night is longer than one hour. The total exposure time in three years is 5200 hours, corresponding to a duty cycle of $\sim 20\%$. In reality, some cloudy nights have to be excluded.

According to the field of view specified above, the sky covered by the detector can be calculated. The total exposure hours in $1^\circ \times 1^\circ$ of galactic coordinates are shown in Fig. 7. The galactic center is visible for approximately 70 hours.
7 Discussion

Although the acceptance reaches 1 km$^2$ sr, the optical detection suffers 10\% operation time in each calendar year. There are several ways to improve the acceptance.

- Extending the zenith angle coverage to below the horizon can include the Earth-skimming events, which are not studied in this report. This extension could double the acceptance at $E < 10^{16}$ eV. At higher energy, acceptance does not increase much because of lack of space for taus to
Figure 7. The exposure time in galactic coordinates for the three-year operation from December 2003 to December 2006.

decay.

- If the detector could also detect the fluorescent light from air showers, the current field of view could be triggered by showers initiated by the taus escaping from Mauna Kea and by Earth-skimming from south-west of Mauna Loa. The large increase in solid angle could increase acceptance by a factor of 3 to 10. This is most effective at energy higher than $10^{17}$ eV.

The above improvements can increase the acceptance to 20 km$^2$ sr. The azimuth angle can also be extended to the west side of Hualalai so that the sea-skimming events can be used as well. However, the reflection from waves may create more noise.

The detector should have some coverage of the sky and record cosmic ray events. This can help monitor detector performance, and the cosmic ray flux can be used to cross-calibrate the energy scale with other cosmic ray experiments.

8 Summary

Taking Hawaii Big Island as a potential neutrino telescope site, we calculate the neutrino conversion efficiency. The detector acceptance is approximately
1.4 km² sr. The sensitivity of the proposed detector is close to the AMANDA B-10 limit. The exposure time of the galactic center, where the nearest black hole is located, is approximately 70 hours in three years of operation.

This study shows that a compact neutrino telescope utilizing the mountain for neutrino conversion is capable of achieving a sensitivity similar to that of a big detector. In addition, the cost and construction time is greatly reduced. This type of detector at $10^{15} < E < 10^{18}$ eV could complement conventional neutrino telescopes such as AMANDA aiming at energies $E \lesssim 10^{16}$ eV, and cosmic ray experiments such as Auger aiming at $E \gtrsim 10^{18}$ eV.

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