Upgoing ANITA events as evidence of the CPT symmetric universe

Luis A. Anchordoqui[1], Vernon Barger[2], John G. Learned[3], Danny Marfatia[3], and Thomas J. Weiler[4]

[1]*Department of Physics & Astronomy, Lehman College, City University of New York, NY 10468, USA*

[1]*Department of Physics, Graduate Center, City University of New York, NY 10016, US*

[1]*Department of Astrophysics, American Museum of Natural History, NY 10024, USA*

[2]*Department of Physics, University of Wisconsin, Madison, WI 53706, USA*

[3]*Department of Physics & Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA*

[4]*Department of Physics & Astronomy, Vanderbilt University, Nashville TN 37235, USA*

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Abstract

We explain the two upgoing ultra-high energy shower events observed by ANITA as arising from the decay in the Earth's interior of the quasi-stable dark matter candidate in the CPT symmetric universe. The dark matter particle is a 480 PeV right-handed neutrino that decays into a Higgs boson and a light Majorana neutrino. The latter interacts in the Earth's crust to produce a τ lepton that in turn initiates an atmospheric upgoing shower. The fact that both events emerge at the same angle from the Antarctic ice-cap suggests an atypical dark matter density distribution in the Earth.

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The three balloon flights of the ANITA experiment have resulted in the observation of two unusual upgoing showers with energies of (600 ± 400) PeV [1] and (560^{+300}_{-200}) PeV [2]. The energy estimates are made under the assumption that the showers are initiated close to the event's projected position on the ice. These estimates are lowered significantly if the showers are initiated far above the ice. For example, the energy of the second event is lowered by 30% if the shower is initiated four kilometers above the ice [2]. In principle, these events could originate in the atmospheric decay of an upgoing τ-lepton produced through a charged current interaction of ν_τ inside the Earth. However, the relatively steep arrival angles of these events (27.4° and 35° above the horizon) create a tension with the standard model (SM) neutrino-nucleon interaction cross section. In particular, the second event implies a propagating chord distance through the Earth of roughly 7.2×10^3 km, which corresponds to 1.9×10^4 km water equivalent (w.e.) and a total of 18 SM interaction lengths at $E_\nu \sim 10^3$ PeV.[2] Noting that the energy deposited in a shower is roughly 80% of the incident neutrino energy, our cosmic neutrino energy range of interest is $200 \lesssim E_\nu/\text{PeV} \lesssim 1000$. At these energies, the neutrino flux is attenuated by a factor of 10^8 [3]. The ANITA Collaboration concluded that a strong transient flux from a source with a compact angular extent is required to avoid exceeding current bounds on diffuse, isotropic neutrino fluxes [2]. In this Letter we provide an alternative mechanism that produces $\mathcal{O}(100 \text{ PeV})$ τ leptons that exit the Earth's crust.

Neither cosmic ray observatories nor the IceCube telescope have seen any anomalies at comparable energies. So we start with a discussion of how the observation of the anomalous upgoing events at ANITA is consistent with the non-observation of similar events at cosmic ray facilities and IceCube.

Cosmic ray facilities have seen downgoing shower events with energies up to $\sim 10^5$ PeV, but have not reported any anomalous upgoing showers [4]. The IceCube Collaboration has not reported any events above 10 PeV [5, 6]. However, it has been suggested that an upgoing track event from $\sim 11.5°$ below the horizon, with a deposited energy of (2.6 ± 0.3) PeV and estimated median muon energy of (4.5 ± 1.2) PeV [6], could arise from an $\mathcal{O}(100)$ PeV τ lepton [7].

ANITA measures the radio emission from the secondary electromagnetic cascade induced by a neutrino interaction within the Antarctic ice sheet. At a float altitude of 35 km, ANITA has a viewing area of 10^6 km^2 [8]. Cosmic ray facilities have viewing areas that are small compared to that of ANITA. However, transmission losses through the ice and beam efficiency at the detector reduce the average acceptance solid angle of ANITA near the horizon to 3.8×10^{-4} km^2 sr at 10 PeV [9]. Moreover, some cosmic ray experiments have been collecting data for more than 10 years, whereas ANITA has collected data over three balloon flights to yield a total live time of 53 days [2, 10]. Consequently, the exposures of cosmic ray facilities to detect SM neutrino interactions near the horizon exceed that of ANITA by about a factor of 60 [11]. Hence, SM neutrino event rates at these experiments should exceed that of ANITA. We may conclude that an explanation of the unusual ANITA events that depends on an extraterrestrial isotropic flux of high-energy ν_τ's producing τ leptons that decay in the atmosphere is highly disfavored. Leaving aside fine-tuned anisotropic ν_τ fluxes, we also conclude that the exotic ANITA signal must originate inside the Earth. Ground-based cosmic ray facilities only search for quasi-horizontal air showers produced by Earth-skimming neutrinos, i.e., those that are incoming at a few degrees below the horizon [12]. Therefore, if the anomalous events originating inside the Earth are only visible at large angles below the horizon, they escape detection at cosmic ray facilities. Cosmic ray fluorescence detectors are sensitive to upgoing showers emerging at large angles above the horizon, but they operate with a 10% duty cycle.

IceCube looks for shower and track events in their cubic kilometer under-ice laboratory. For showers emerging at $\sim 35°$ above the horizon, the ~ 1 km^2 geometric area of IceCube is

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Email address: `luis.anchordoqui@gmail.com` (Luis A. Anchordoqui[1])

[2]The first event emerged at an angle of 27.4° above the horizon, implying a chord through the Earth of 5.5×10^3 km, which corresponds to 1.5×10^4 km w. e. for Earth's density profile [1].

comparable to ANITA's effective area of ~ 4 km^2 [2]. Then, a comparison of the expected number of events at IceCube and ANITA follows from the product of their geometric volumes and their live times [2, 10, 13]:

$$\frac{\#\ \text{IceCube events}}{\#\ \text{ANITA events}} \sim \frac{1\ \text{km}^3 \times 2078\ \text{day}}{4\ \text{km}^2 \times \text{depth} \times 53\ \text{day}} \simeq \frac{10\ \text{km}}{\text{depth}}\,. \qquad (1)$$

The range of depths at which the shower of an ANITA event is initiated determines the the uncertainty in its energy. It is possible that the second event was initiated between an ice-depth of 3.22 km and a height of 4 km above the ice [2]. We may then expect a comparable number of events at IceCube and ANITA. If the typical depth of shower initiation for ANITA is taken to be 4 km, then IceCube should have seen 5 events. As mentioned above, the 2.6 PeV IceCube event may have its origin in an $\mathcal{O}(100)$ PeV τ lepton. Since the 95% confidence level interval for observing 1 event with no expected background is $[0.05, 5.14]$ [14], IceCube data may not be in tension with ANITA's 2 events.

It is compelling that the two ANITA events are similar in energy and were observed at roughly the same angle above the horizon. We speculate that these two events have similar energies because they result from the two-body decay of a new quasi-stable relic, itself gravitationally trapped inside the Earth. (An alternative new physics interpretation considers a sterile neutrino propagating through the Earth which could scatter with nucleons via mixing to produce a τ lepton [15].)

We frame our discussion in the context of the CPT symmetric universe [16, 17]. In this scenario the universe before the Big Bang and the universe after the Big Bang is reinterpreted as a universe/anti-universe pair that is created from nothing. If the matter fields are described by the minimal extension of the SM with 3 right-handed neutrinos, then the only possible dark matter candidate is one of the right-handed neutrinos, say $\nu_{R,1}$. For this neutrino to be exactly stable the SM couplings must respect the $\mathbb{Z}_2$ symmetry, $\nu_{R,1} \to -\nu_{R,1}$. In the limit in which $\nu_{R,1}$ becomes stable, it also decouples from SM particles, i.e., $\nu_{R,1}$ only interacts via gravity. To accommodate the present-day dark matter density, $\rho_{\rm DM} \approx 9.7 \times 10^{-48}$ GeV^4, the quasi-stable right-handed neutrino must have a mass $M \approx 480$ PeV [16, 17]. Another relevant prediction of the CPT symmetric universe is that the three active neutrinos are Majorana particles as they obtain their masses by the usual seesaw mechanism.

Herein we assume that the $\mathbb{Z}_2$ symmetry is only approximate. Note that in principle the non-gravitational couplings of $\nu_{R,1}$ do not have to vanish, but have to be small enough so that $\nu_{R,1}$ has a lifetime $\tau_{\nu_{R,1}} \gg H_0^{-1} = 9.778\,h^{-1}$ Gyr, where $h \sim 0.68$. This opens up the possibility to indirectly observe $\nu_{R,1}$ through its decay products. For two-body decays, conservation of angular momentum forces the $\nu_{R,1}$ to decay into a Higgs boson and a light Majorana neutrino. The non-observation of a monochromatic neutrino signal from the Galactic center or the Galactic halo sets a lower bound on the lifetime of the quasi-stable right-handed neutrino, $\tau_{\nu_{R,1}} \gtrsim 10^{28}$ s [18, 19]. The decay of the Higgs to $b\bar{b}$ results in a photon flux that is constrained by gamma-ray data. With an appropriate rescaling of energy, the results of Ref. [20] show that the gamma-ray constraint is more than 7 orders of magnitude weaker than the neutrino line constraint.

A dense population of $\nu_{R,1}$ is expected at the center of the Earth because as the Earth moves through the halo, the $\nu_{R,1}$ scatter with Earth matter, lose energy and become gravitationally trapped. An accumulated $\nu_{R,1}$ then decays into a Higgs and an active neutrino that propagates through the Earth and produces a τ lepton near the Earth's surface. The particular angle of the ANITA events is a combination of the dark matter distribution in the Earth, the neutrino interaction cross section, and the τ survival probability. The non-gravitational couplings have to be chosen to produce a long lifetime and the needed abundance of right-handed neutrinos in the Earth to yield the two ANITA events. To achieve a sizable dark matter density in the Earth self-interactions may be invoked.

The event rate integrated over the entire Earth at a particular time is

$$\text{Rate} \equiv \frac{dN}{dt} = 4\pi \int_0^{R_\oplus} r^2\, dr\, \frac{n(r,t)}{\tau_{\nu_{R,1}}}\,, \qquad (2)$$

where $n(r,t)$ is the number density of $\nu_{R,1}$ at time t and $R_\oplus$ is the Earth's radius. The observable rate today ($t = t_0$), as a function of nadir angle θ_n is given by

$$\begin{aligned} A_{\rm eff} \frac{d\,\text{Rate}}{d\,|\cos\theta_n|} &= 2\pi A_0 \times 2\pi \int_{R_\oplus \sin\theta_n}^{R_\oplus} r^2 dr\, \frac{n(r,t_0)}{\tau_{\nu_{R,1}}} \\ &\times \left(e^{-(l_+/\lambda)} + e^{-(l_-/\lambda)}\right) \mathcal{E}(\theta_n)\,, \end{aligned} \qquad (3)$$

where $l_\pm$ are the roots of $R_\oplus^2 + l^2 - 2R_\oplus l \cos\theta_n = r^2$, i.e.,

$$l_\pm = R_\oplus \left(\cos\theta_n \pm \sqrt{\left(\frac{r}{R_\oplus}\right)^2 - \sin^2\theta_n}\right)\,, \qquad (4)$$

and $\lambda = 1.7 \times 10^7/(\sigma/\text{pb})$ km w.e. is the mean-free-path, with σ the neutrino-nucleon charged-current cross section. Here, the effective area $A_{\rm eff} = A_0 \mathcal{E}(\theta_n)$ defines the experimental efficiency $\mathcal{E}$ that includes the target area dependence on θ_n but not the $e^{-l/\lambda}$ suppression which is given explicitly in the integrand. Note that $\mathcal{E}(\theta_n)$ vanishes for $\theta_n < 35^\circ$, peaks at about 75°, and vanishes above 85° [21]. In Eq. (3) we have neglected energy losses due to neutral current interactions and effects from ν_τ regeneration [22]. For $200 \lesssim E_\nu/\text{PeV} \lesssim 1000$, these effects are not important. For a 100 PeV neutrino, $\sigma \sim 4.43 \times 10^3$ pb, the interaction length in rock is $\lambda \sim 10^3$ km, and the average range of the outgoing τ lepton is a few km [23, 24]. Integrating over the duration of an experiment yields the event number as opposed to the event rate.

The fact that for fixed r, we have two special values of l, i.e., $l_\pm$, can be seen from Fig. 1. Of course, if r is too small, then the trajectory at fixed θ_n does not intersect the circle at all; this is the origin of the lower limit in the integration over dr.

The exponential suppression factor in Eq. (3) can be written as

$$\begin{aligned} e^{-(l_+/\lambda)} + e^{-(l_-/\lambda)} &= 2\exp\left(-\frac{R_\oplus \cos\theta_n}{\lambda}\right) \\ &\times \cosh\left(\frac{\sqrt{r^2 - R_\oplus^2 \sin^2\theta_n}}{\lambda}\right)\,. \end{aligned} \qquad (5)$$

The competition between the falling (with increasing θ_n) $e^{-R_\oplus \cos\theta_n/\lambda}$ term and the rising $\mathcal{E}(\theta_n)$ term in Eq. (3) determines the most probable angle of observation. The two unusual ANITA events occur at 27.4° and 35° above the horizon, so we may set the peak of the distribution at $\sim 30^\circ$ above the horizon,

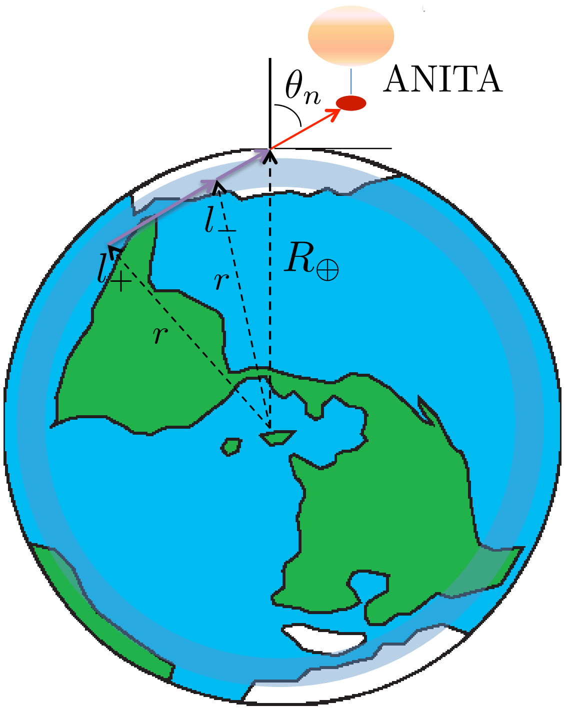

FIGURE 1: The particle's trajectory to ANITA at a given nadir angle.

corresponding to a nadir angle of $\theta_n \sim 60^\circ$. So, taking the view that the event distribution is maximized at $\theta_n = 60^\circ$ by a combination of ANITA's efficiency and the dark matter distribution in the Earth, we require

$$\left.\frac{d^2\,\text{Rate}}{d\,|\cos\theta_n|^2}\right|_{\cos\theta_n=\frac{1}{2}} = 0\,. \tag{6}$$

This result becomes a constraint on the model parameters in Eq. (3).

We end with three observations: *(i)* It is generally assumed that after the dark matter particles become gravitationally bound, they quickly lose their momentum and sink to the core of Earth [25]. We have proposed that ANITA data may be indicating that the dark matter distribution in the Earth may be more complicated. This may result from a recent encounter of the Earth with a dark disk.[3] *(ii)* Quasi-stable right-handed neutrinos will also accumulate in the core of the Sun and the Moon, and on decay will produce a flux of high-energy neutrinos. However, the neutrinos will not escape the Sun or the Moon, and the latter does not have an atmosphere in which the τ leptons can produce showers, so consequently the flux from these sources is unobservable. *(iii)* Data from the fourth ANITA flight is currently being analyzed and may lead to further enlightenment. The second generation of the Extreme Universe Space Observatory (EUSO) instrument, to be flown aboard a super-pressure balloon (SPB) in 2022 will monitor the night sky of the Southern hemisphere for upgoing showers emerging at large angles below the horizon [28]. EUSO-SPB2 will provide an important test both of the unusual ANITA events and of the ideas discussed in this Letter.

[3]Cosmological N-body simulations suggest that a thick dark disk is formed naturally in Milky Way-type galaxies as a consequence of satellite mergers (which usually get dragged into the plane of their host galaxy [26]. This paradigm is consistent with observations [27].

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