

Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA

P. W. Gorham,¹ B. Rotter,¹ P. Allison,² O. Banerjee,² L. Batten,³ J. J. Beatty,² K. Bechtol,⁴ K. Belov,⁵ D. Z. Besson,^{6,7} W. R. Binns,⁸ V. Bugaev,⁸ P. Cao,⁹ C. C. Chen,¹⁰ C. H. Chen,¹⁰ P. Chen,¹⁰ J. M. Clem,⁹ A. Connolly,² L. Cremonesi,³ B. Dailey,² C. Deaconu,⁴ P. F. Dowkontt,⁸ B. D. Fox,¹ J. W. H. Gordon,² C. Hast,¹¹ B. Hill,¹ K. Hughes,² J. J. Huang,¹⁰ R. Hupe,² M. H. Israel,⁸ A. Javaid,⁹ J. Lam,¹² K. M. Liewer,⁵ S. Y. Lin,¹⁰ T.C. Liu,¹⁰ A. Ludwig,⁴ L. Macchiarulo,¹ S. Matsuno,¹ C. Miki,¹ K. Mulrey,⁹ J. Nam,¹⁰ C. J. Naudet,⁵ R. J. Nichol,³ A. Novikov,⁶ E. Oberla,⁴ M. Olmedo,¹ R. Prechelt,¹ S. Prohira,⁶ B. F. Rauch,⁸ J. M. Roberts,¹ A. Romero-Wolf,⁵ J. W. Russell,¹ D. Saltzberg,¹² D. Seckel,⁹ H. Schoorlemmer,¹ J. Shiao,¹⁰ S. Stafford,² J. Stockham,⁶ M. Stockham,⁶ B. Strutt,¹² G. S. Varner,¹ A. G. Viereggs,⁴ S. H. Wang,¹⁰ and S. A. Wissel¹³

¹*Dept. of Physics and Astronomy, Univ. of Hawaii, Manoa, HI 96822.*

²*Dept. of Physics, Center for Cosmology and AstroParticle Physics, Ohio State Univ., Columbus, OH 43210.*

³*Dept. of Physics and Astronomy, University College London, London, United Kingdom.*

⁴*Dept. of Physics, Enrico Fermi Institute, Kavli Institute for Cosmological Physics, Univ. of Chicago, Chicago IL 60637.*

⁵*Jet Propulsion Laboratory, Pasadena, CA 91109.*

⁶*Dept. of Physics and Astronomy, Univ. of Kansas, Lawrence, KS 66045.*

⁷*National Research Nuclear Univ., Moscow Engineering Physics Inst., Moscow, Russia.*

⁸*Dept of Physics & McDonnell Center for the Space Sciences, Washington Univ in St Louis, MO*

⁹*Dept. of Physics, Univ. of Delaware, Newark, DE 19716.*

¹⁰*Dept. of Physics, Grad. Inst. of Astrophys., & Leung Center for Cosmology and Particle Astrophysics, National Taiwan University, Taipei, Taiwan.*

¹¹*SLAC National Accelerator Laboratory, Menlo Park, CA, 94025.*

¹²*Dept. of Physics and Astronomy, Univ. of California, Los Angeles, Los Angeles, CA 90095.*

¹³*Physics Dept., California Polytechnic State Univ., San Luis Obispo, CA 93407.*

We report on an upward traveling, radio-detected cosmic-ray-like impulsive event with characteristics closely matching an extensive air shower. This event, observed in the third flight of the Antarctic Impulsive Transient Antenna (ANITA), a NASA-sponsored long-duration balloon payload, is consistent with a similar event reported in a previous flight. These events may be produced by the atmospheric decay of an upward-propagating τ -lepton produced by a ν_τ interaction, although their relatively steep arrival angles create tension with the standard model (SM) neutrino cross section. Each of the two events have *a posteriori* background estimates of $\lesssim 10^{-2}$ events. If these are generated by τ -lepton decay, then either the charged-current ν_τ cross section is suppressed at EeV energies, or the events arise at moments when the peak flux of a transient neutrino source was much larger than the typical expected cosmogenic background neutrinos.

The ANITA instrument is primarily designed for the detection of the ultra-high energy (UHE) cosmogenic neutrino flux via the Askaryan effect in ice [1–3], but is able to trigger on a wide variety of different impulsive radio signals. During the first ANITA flight, an unanticipated radio signal was discovered: 16 events due to ultra-high energy cosmic ray (UHECR) air showers were found during a blind search of the data for isolated non-anthropogenic events [4]. ANITA observes UHECR via radio impulses that occur when geomagnetically-induced charged-particle acceleration occurs in the propagation of an extensive air shower in the atmosphere. Conventional down-going ultra-high energy cosmic-ray (UHECR) air showers produce downward-propagating radio impulses that are observed in reflection off the surface of the ice, leading to phase inversion of the signal. UHECR events detected by ANITA also include a subset of horizontally-propagating stratospheric air showers seen just above the horizon, which point directly at the payload, and show no phase inversion of the signal [5]. These observations have established a baseline for identification of events of UHECR origin in ANITA data.

In the ANITA-I flight one such UHECR-like event was observed with characteristics similar to the direct, horizontal cosmic rays, but from a direction well below the hori-

zon, without the phase inversion due to a reflection [5]. The background for this event was estimated to be $\leq 10^{-3}$ events, suggesting the possibility that such events could arise from a high-energy ν_τ charged-current interaction in the ice, leading to a τ -lepton which exits the ice surface and decays, producing an air shower that propagates upward in the atmosphere. However, a possible anthropogenic origin for the ANITA-I event could not be ruled out at sufficient confidence to be conclusive.

The third flight of the ANITA instrument took place from Dec. 18, 2014 through Jan. 8, 2015, with 22 days at float at an altitude of ~ 34 to 38 km. Unexpected strong continuous-wave (CW) interference from geosynchronous satellites limited the effective full-payload exposure to about 7 days of equivalent time. Despite this loss of sensitivity, a set of 20 radio-detected UHECR events were identified in a template-based analysis [6]. Because the polarity of the events was the primary characteristic that would distinguish phase-inverted events from the direct events, including possible upward-going showers, we blinded the event polarity throughout the analysis to avoid bias. The geomagnetic field in Antarctic is predominantly vertical, and thus the Lorentz-force acceleration of the e^+e^- pairs in the shower leads to lateral charge-

separation that produces an almost completely horizontally-polarized (Hpol) signal, with nearly unique temporal and spectral properties compared to anthropogenic background events observed. Despite their small size, the residual horizontal components of the geomagnetic field still provide for a detailed confirmation of the geomagnetic correlation of UHECRs. If we write the geomagnetic field in a local cartesian basis, then $\mathbf{B} = (B_x, B_y, B_z)$, with $B_x, B_y \ll B_z$ as noted above. ANITA's observation geometry also favors air showers with primary particle momenta with zenith angles of 60° or more, and thus their longitudinal velocity will follow $v_x, v_y \gg v_z$ in general.

From Feynman's rule [7], the radiation field per particle will be aligned with the observer's apparent angular acceleration of the charge, which is given by the magnetic portion of the Lorentz force, $\mathbf{F} = q \mathbf{v} \times \mathbf{B}$. Neglecting terms that are second order in the acceleration, and recognizing that the magnetic deflection is nearly perpendicular to the direction of radiation, the observed radiation field vector can be approximated as

$$\mathbf{E} \propto (v_y B_z \hat{x} - v_x B_z \hat{y}) + (v_x B_y - v_y B_x) \hat{z}. \quad (1)$$

The first term in parentheses on the right hand side gives the Hpol component of the field, and because it involves the strongest components of both \mathbf{v} and \mathbf{B} , it is the much stronger of the two radiation fields. The second term gives the vertically-polarized (Vpol) field component, and is significantly weaker because it depends on the much weaker transverse magnetic field vector components. In addition, there is a small contribution from Askaryan emission, but because of the strong Antarctic geomagnetic field, this is limited to about 4% of the total and is neglected here. Because ANITA is designed to do accurate pulse-phase polarimetry with both Hpol and Vpol receiving antennas, the transverse B -field component is readily detectable. Since the geomagnetic field is well-modeled in Antarctica, it provides a strong confirmation of geomagnetic association for a given UHECR impulse, whereas signals of anthropogenic origin are uncorrelated to the geomagnetic field. Fig. 1 shows the geomagnetic-correlated results for the UHECR events selected in ANITA-III. The expected polarization is corrected for the Fresnel coefficient of reflection where appropriate. Measurement errors were determined by measurements of comparable calibration pulses, and include systematics.

The unblinded polarity of the ANITA-III CR events showed that the two above-horizon events among the sample had the expected non-inverted pulse phase, consistent with their origin as stratospheric, atmosphere-skimming air showers. However, as noted above, one of the remaining events also had a clearly non-inverted polarity, inconsistent with a reflection, but in all other ways consistent with UHECR origin. Fig. 2 shows the overlain normalized Hpol waveforms from each of the 20 candidate events, with the 17 inverted-polarity reflected events now un-inverted for direct comparison of the waveform shape. The events have the instrumental response

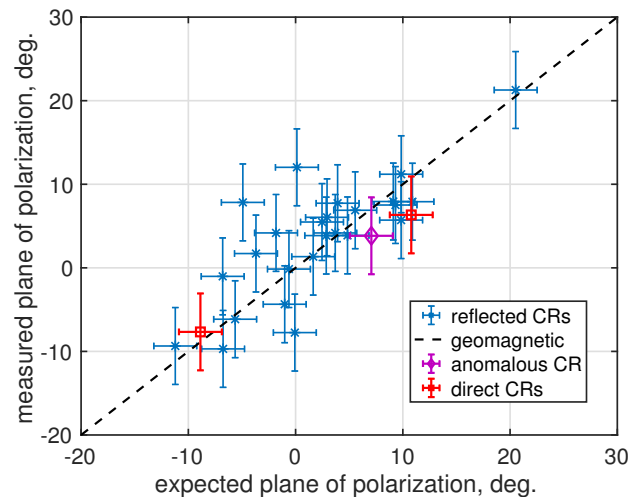


FIG. 1: *Geomagnetic correlation of 20 UHECR events detected in ANITA-III, with event planes-of-polarization determined via Stokes parameters for each event. The two above-horizon non-inverted CRs are shown in red, and the anomalous non-inverted, below-horizon CR-like event 15717147 is shown in magenta.*

deconvolved, and are normalized in amplitude to their maximum magnitude. They are remarkably similar in shape once the inversion is removed.

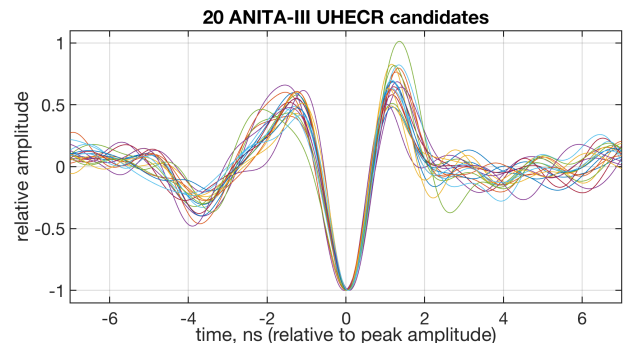


FIG. 2: *Horizontally-polarized waveforms of 20 UHECR events detected in ANITA-III, with the polarity and amplitude all normalized to the peak.*

For the final 20-event UHECR selection, candidates were verified to be spatially and temporally isolated from any other events like them, and showed a high degree of correlation with a waveform template determined by well-established models for UHECR radio emission. We have identified no known physics backgrounds for these events. Potential background comes from anthropogenic radio signals that might mimic the UHECR characteristics, or unknown processes which might lead to non-inverted polarity on reflection from the ice; further investigation of polarity is given in ref. [8]. Two independent background estimates for anthropogenic origin were made. The first, using the likelihood that the event was a statistical outlier of sub-threshold events within its nearby locale, gave a background estimate of $B = 1.2 \times 10^{-3}$ events for the

20-UHECR sample [6]. The second method uses a probability for a single isolated UHECR-like background event, derived from the frequency of UHECR-like events that appeared in known anthropogenic clusters of events and charted bases or camps. Because the rate of actual UHECR events is such that some inevitably do get included (and therefore lost to the analysis) as part of these clusters, this latter estimate provides only an upper limit to the background, $B \leq 0.015$ events, also for the entire 20 UHECR sample. Thus by all indications the resulting selection of events represents a very pure sample of radio-detected UHECRs.

Fig. 3 shows the incident field strength waveforms for all three of the events with non-inverted polarity, along with one of the “normal” UHECR events, chosen because its arrival angle at the payload was similar to that of the anomalous event 15717147. Detailed simulations of the UHECR radio emission process find that the power spectral density (PSD) of the radio signal is dependent on the observer’s viewing angle relative to the axis of the air shower, and the PSD can thus be used, along with other parameters of the shower signal, to estimate the primary energy of the event [10]. To provide more confidence in our estimate, we cross-checked event 15717147 against 12 of the 16 ANITA-I cosmic ray events for which the parameters could be directly compared and scaled. The results are quite consistent, yielding an estimated shower energy of $E = 0.56_{-0.2}^{0.3} \times 10^{18}$ eV for this event, assuming that shower was initiated close to the event’s projected position on the ice sheet. For a shower initiated at a height of 4 km above the ice, the energy is reduced by about 30% to $E = 0.40$ EeV. The errors here are statistical, based on the root-mean-square of the cross-check sample.

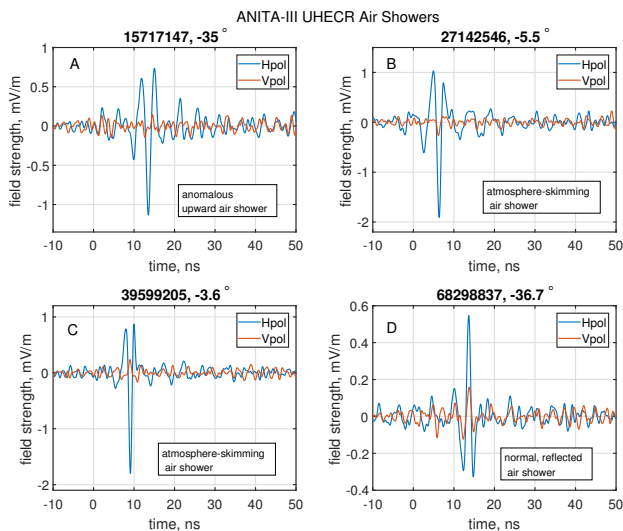


FIG. 3: The three non-inverted polarity events are shown in panels A,B,C. Panel A shows the anomalous event, with the same polarity as the above-horizon events B and C. Panel D shows the waveform for an inverted UHECR that had an upcoming angle close to that of the anomalous CR 15717147. The inversion of the normal reflected CR event is clearly evident.

In addition to the targeted search for UHECR events, we performed two completely independent optimized multivariate blind analyses of all events, favoring impulsive, highly-linearly-polarized events, without consideration of correlation to any UHECR waveform template [17]. In both of these analyses, complete isolation from any anthropogenic source or from any other events was a stringent requirement, and event 15717147 passed in both cases. These two analyses confirm that event 15717147 is unique, impulsive, and isolated, even when not selected by its UHECR-related properties. The *a posteriori* background estimates for both 15717147 and for the similar anomalous event seen in ANITA-I [5] are at the $\gtrsim 3\sigma$ level. There is thus significant evidence for a physical process that leads to direct upward-moving cosmic-ray-like air showers above the ice surface.

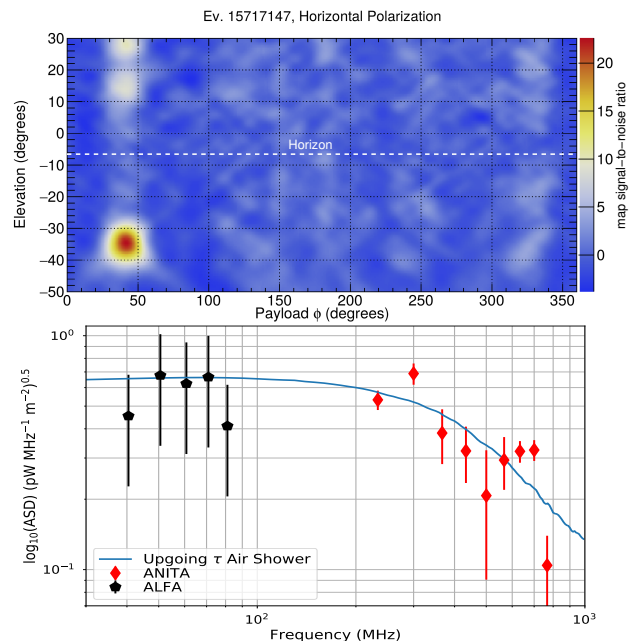


FIG. 4: Top: Interferometric map of the arrival direction of the anomalous CR event 15717147. Bottom: ANITA combined amplitude spectral density (ASD) for the event, from 50-800 MHz, including data from the ANITA Low Frequency Antenna (ALFA). A simulated upward-propagating extensive air shower spectral-density curve is overlain.

For detected radio impulses, the large fields-of-view for the quad-ridged horns used in ANITA allow up to 15 antennas, drawn from up to 5 azimuthal sectors of the payload, to be used for coherent beam forming. Pulse-phase interferometry between these antennas then yields a map of the arrival direction of the radio impulse to typical precisions of 0.25° , 0.65° in elevation and azimuth, respectively [9]. Fig. 4(top) shows the resulting false-color map for event 15717147 in coordinates local to the payload, scaled by the signal-to-noise ratio of the map. Elevation is with respect to the payload horizontal, and the azimuthal angle ϕ is with respect to the payload heading at the event arrival time. Mapping is done for 360° in ϕ to verify that the beamforming solution is unique.

ANITA-III flew a separate low-frequency horizontally-polarized quad-slot antenna, the ANITA low-frequency antenna (ALFA), covering the frequency band from 30 to 80 MHz. ALFA's goal was to provide radio-spectral overlap of ANITA UHECR measurements with ground-based data which generally favors bands below 100 MHz. Roughly 3/4 of the UHECR event sample reported here were also detected in the ALFA, and of those detections, the ALFA data for 15717147 was among the events with the highest signal-to-noise ratio, in this case $\geq 5\sigma$ above the thermal noise. Fig. 4(bottom) shows the combined ASD for this event, including the ALFA data. The overlain curve gives the simulated spectral density expected from a τ -lepton initiated air shower, with characteristics consistent with this event [15]. While similar spectral density would be expected for a normal CR air shower seen in reflection, these data which fit this non-inverted event further strengthen its identification as an anomalous air shower.

An alternative explanation of the similar ANITA-I event as due to transition radiation of an Earth-skimming event has also been proposed [11]. In this model, the plane-of-polarization correlation to geomagnetic angles would be coincidental. Since the event observed in ANITA-III is also well-correlated to the local geomagnetic angle, and both events are consistent within 3-5 degrees of measurement error, coincidental alignment for both appears probable only at the few percent level. The waveform of these events showed a high degree of correlation to radio-detected UHECRs in each flight, which supported their identification as UHECRs. Ref. [11] did not provide any detailed modeling of time-domain waveforms for transition radiation that confirm its similarity to those made by the UHECR emission process. This step appears necessary before this hypothesis can be further evaluated.

TABLE I: ANITA-I,-III anomalous upward air showers.

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon. ⁽¹⁾	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3^\circ, 159.62 \pm 0.7^\circ$	$-35.0 \pm 0.3^\circ, 61.41 \pm 0.7^\circ$
RA, Dec ⁽²⁾	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

¹ Latitude, Longitude of the estimated ground position of the event.

² Sky coordinates projected from event arrival angles at ANITA.

³ For upward shower initiation at or near ice surface.

Table I gives measured and estimated parameters for both of the anomalous CR events, with sky coordinates derived from the arrival direction of the radio impulses.

In our report of the ANITA-I anomalous CR event, we considered the hypothesis that such events could arise through decay of emerging τ -leptons generated by ν_τ interactions beneath the ice surface. However, the interpretation of these events as τ -lepton decay-driven air showers, arising from a diffuse flux of cosmic ν_τ , faces the difficult challenge that

the chord lengths through the Earth are such that the Standard Model (SM) neutrino cross section [18], even including the effect of ν_τ regeneration [12], will attenuate the flux by a factor of 10^{-5} [15, 16]. Event 15717147 emerged from the ice with a zenith angle of $\sim 55.5^\circ$, implying a chord distance through the Earth of ~ 7000 km, or 3×10^4 km water equivalent, a total of 18 SM interaction lengths at 1 EeV. Even with combined effects of ν_τ regeneration, and significant suppression of the SM neutrino cross section above $\sim 10^{18}$ eV, an alternative model, such as a strong transient flux from a source with compact angular extent, is required to avoid exceeding current bounds on diffuse, isotropic neutrino fluxes.

Suppression of the cross section may occur even within the SM for the extremely low values of the Bjorken- x parameter that obtain at ultra-high energies. For example, ref. [19] shows examples where higher-than-expected gluon saturation at $x < 10^{-6}$ causes the UHE deep-inelastic neutrino cross section to saturate at 10^{18} eV, remaining essentially constant above that energy. This yields a factor of 3-4 suppression compared to the SM at 10^{19} eV, approaching an order of magnitude at 10^{20} eV. More recent studies show similar types of suppression are possible, giving factors of 2-3 at 10^{18-19} eV [20, 21]. Such SM-motivated scenarios would certainly decrease the exponential attenuation for the Earth-crossing neutrinos relevant to our case, but unless the suppression is an order of magnitude or more, a large transient point-source flux is likely still required. Thus we consider also a search for potential candidate transients that may be associated with this event.

Under the hypothesis that event 15717147 is a τ -lepton-initiated air shower, the angular error relative to the parent neutrino direction is $\sim 1.5^\circ$, arising from both the width of the emission cone [10], and the intrinsic statistical errors in our estimate of the arrival direction of the RF signal. To investigate this hypothesis further, we point back along the apparent arrival direction, giving sky coordinates shown in Table I. With these parameters, we search existing catalogs for associations with two transient source types for which source confusion is not excessive: gamma-ray burst (GRB) sources, and supernovae. GRBs have been considered as possible UHE neutrino sources for many years, although there are no detections to date. Supernovae (SNe) have also been proposed as UHE sources in a variety of scenarios, both in core-collapse SNe, and more recently even in type Ia SNe, which are believed to originate in the ignition of a white dwarf (WD) progenitor. In the latter case, tidal ignition of a WD by interaction with an intermediate-mass black hole has been proposed as a potential source of UHECRs [23–25].

For the 1.5° radius error circle derived from the angular emission pattern for UHECR events, no concurrent GRBs are observed. A SN candidate is found to be associated: SN2014dz, a nearby type Ia SN at $z = 0.017$, is within 1.19° , well within our expected angular uncertainty on the sky. This relatively bright SN was discovered ~ 7 days before maximum, on 2014-12-20.146 [22]. Our event time follows the initial discovery by just over five hours. Using catalogued SNe discoveries during our flight, and a Bayesian estimator [8], we

find the *a posteriori* probability of a chance association with any confirmed SN, at any redshift, within the estimated likely time period of detectability for this SN, is $P \simeq 3.4 \times 10^{-3}$, or 2.7σ .

If SN2014dz is the source of the putative neutrino candidate, the implied peak isotropic neutrino luminosity must likely far exceed the estimated bolometric luminosity of $L_B = 4.4 \times 10^{42}$ ergs s^{-1} . The lower limit comes already from assuming a much lower cross section than the SM. Alternatively, a beaming hypothesis would significantly relax these constraints.

Both the IceCube [13] and Auger observatories are sensitive to τ -leptons, IceCube through events transiting the detector, or via τ -decay within the detector, and Auger via Earth-skimming τ -decay-initiated air showers within a few degrees of the horizon [14]. In this case, the declination for IceCube implies an additional ~ 4300 km water equivalent column density, but if the SM cross section is suppressed, the ~ 1 km² geometric area of IceCube is still comparable to ANITA's effective point-source geometric area of ~ 4 km² at this arrival angle. Auger has potentially a much larger effective point-source area, but only limited exposure around the time of our event. However if the transient flux was as large as it appears, coincident detections in archival data may be possible.

A search of the projected position given by the similar anomalous event from ANITA-I in 2006 yielded no SNe or any other significant association, but the sky position for this event is within $\sim 10^\circ$ from the galactic plane, and thus extinction leads to low SNe detection efficiency for this region of the sky.

We thank NASA for their generous support of ANITA, and the Columbia Scientific Balloon Facility for their excellent field support, and the National Science Foundation for their Antarctic operations support. This work was also supported in part by the US Dept. of Energy, High Energy Physics Division.

[1] G. A. Askaryan, Excess Negative Charge of an Electron-Photon Shower And Its Coherent Radio Emission, *JETP* **14**, 441 (1962); also *JETP* **21**, 658 (1965).
 [2] D. Saltzberg, P. Gorham, D. Walz, *et al.*, "Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High Energy Particle Cascades," *Phys. Rev. Lett.*, **86**, 2802 (2001).

[3] The ANITA Collaboration, P. W. Gorham, S. Barwick, J. Beatty, *et al.*, "Observations of the Askaryan Effect in Ice," *Phys. Rev. Letters*, (2007) in final revision; <http://arxiv.org/abs/hep-ex/0611008>.
 [4] S. Hoover *et al.*, [ANITA collaboration], *Observation of Ultra-high-Energy CRs with the ANITA Balloon-Borne Radio Interferometer*, *Phys. Rev. Lett.* **105**, (2010).
 [5] P. W. Gorham *et al.*, [ANITA collaboration], *Phys. Rev. Lett.* **117**, 071101, (2016).
 [6] B. Rotter, 2017, unpublished PhD. dissertation, University of Hawaii at Manoa.
 [7] R. P. Feynman, *The Feynman Lectures*, section 34-1.
 [8] See Supplemental Material at [URL will be inserted by publisher] for details on this analysis.
 [9] A. Romero-Wolf, S. Hoover, A.G. Vieregge, *et al.*, *An interferometric analysis method for radio impulses from ultra-high energy particle showers*, *Astropart. Phys.* **60**, 72, (2015).
 [10] H. Schoorlemmer, *et al.* [ANITA Collaboration], *Astropart. Phys.* **77**, 32, (2016); also arXiv:1506.05396.
 [11] P. Motloch, J. Alvarez-Muiz, P. Privitera, and E. Zas *Phys. Rev. D* **95** 043004 (2017).
 [12] F. Halzen & D. Saltzberg *Phys. Rev. Lett.* **81**, 4305, (1998); E. V. Bugaev *et al.* *Astropart. Phys.* **21**, 491, (2004); O. Blanch Bigas, *et al.* *Phys. Rev. D* **78**:063002, (2008).
 [13] M.G. Aartsen *et al.* [IceCube collaboration], *Phys. Rev. D* **93**, 022001 (2016)
 [14] A. Aab, *et al.* [Pierre Auger Collaboration] *Phys. Rev. D* **91**, 092008 (2015).
 [15] J. Alvarez-Muñiz *et al.*, *Phys. Rev. D* **97**, 023021 (2018); <https://arxiv.org/abs/1707.00334>.
 [16] A. Romero-Wolf [ANITA collaboration], 35th Internat. Cosmic Ray Conf., Vol. 301, (2017)
 [17] P. Allison *et al.* [ANITA Collaboration], <https://arxiv.org/abs/1803.02719>
 [18] A. Connolly, R. S. Thorne, D. Waters, *Phys. Rev. D* **83**:113009, 2011.
 [19] E. Henley and J. Jalilian-Marian, *Phys. Rev. D* **73**, 094004 (2006).
 [20] N. Armesto, C. Merino, G. Parente, E. Zas, *Phys. Rev. D* **77**, 013001, (2008);
 [21] A.Y. Illarionov, B. A. Kniehl, & A. V. Kotikov, *Phys. Rev. Lett.* **106**, 231802 (2011).
 [22] <https://wis-tns.weizmann.ac.il/object/2014dz>
 [23] "Ultra-high-energy cosmic ray acceleration in engine-driven relativistic supernovae," S. Chakraborti, A. Ray, A. M. Soderberg, A. Loeb & P. Chandra, *Nature Communications* **2**, Article number: 175 (2011);
 [24] "Tidally disrupted stars as a possible origin of both cosmic rays and neutrinos at the highest energies," D. Biehl *et al.* arXiv:1711.03555 (2017);
 [25] "Ultra-high energy cosmic rays from tidally-ignited white dwarfs," R. Batista & J. Silk, arXiv:1702.06978, (2017).