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A Search for Coincident Neutrino Emission from Fast Radio Bursts with Seven Years of IceCube Cascade Events

R. Abbasi[1], M. Ackermann[2], J. Adams[3], S. K. Agarwalla[4,65], J. A. Aguilar[5], M. Ahlers[6], J. M. Alameddine[7], N. M. Amin[8], K. Andeen[9], G. Anton[10], C. Argüelles[11], Y. Ashida[4], S. Athanasiadou[2], S. N. Axani[8], X. Bai[12], A. Balagopal V.[4], M. Baricevic[4], S. W. Barwick[13], V. Basu[4], R. Bay[14], J. J. Beatty[15,16], K.-H. Becker[17], J. Becker Tjus[18,66], J. Beise[19], C. Bellenghi[20], S. BenZvi[21], D. Berley[22], E. Bernardini[23], D. Z. Besson[24], G. Binder[14,25], D. Bindig[17], E. Blaufuss[22], S. Blot[2], F. Bontempo[26], J. Y. Book[11], C. Boscolo Meneguolo[23], S. Böser[27], O. Botner[19], J. Böttcher[28], E. Bourbeau[6], J. Braun[4], B. Brinson[29], J. Brostean-Kaiser[2], R. T. Burley[30], R. S. Busse[31], D. Butterfield[4], M. A. Campana[32], K. Carloni[11], E. G. Carnie-Bronca[30], S. Chattopadhyay[4,65], C. Chen[29], Z. Chen[33], D. Chirkin[4], S. Choi[34], B. A. Clark[22], L. Classen[31], A. Coleman[19], G. H. Collin[35], A. Connolly[15,16], J. M. Conrad[35], P. Coppin[36], P. Correa[36], S. Countryman[37], D. F. Cowen[38,39], P. Dave[29], C. De Clercq[36], J. J. DeLaunay[40], D. Delgado López[11], H. Dembinski[8], K. Deoskar[41], A. Desai[4], P. Desiati[4], K. D. de Vries[36], G. de Wasseige[42], T. DeYoung[43], A. Diaz[35], J. C. Díaz-Vélez[4], M. Dittmer[31], A. Domi[10], H. Dujmovic[4], M. A. DuVernois[4], T. Ehrhardt[27], P. Eller[20], R. Engel[26,44], H. Erpenbeck[4], J. Evans[22], P. A. Evenson[8], K. L. Fan[22], K. Fang[4], A. R. Fazely[45], A. Fedynitch[46], N. Feigl[47], S. Fiedlschuster[10], C. Finley[41], L. Fischer[2], D. Fox[38], A. Franckowiak[18], E. Friedman[22], A. Fritz[27], P. Fürst[28], T. K. Gaisser[8], J. Gallagher[48], E. Ganster[28], A. Garcia[11], S. Garrappa[2], L. Gerhardt[25], A. Ghadimi[40], C. Glaser[19], T. Glauch[20], T. Glüsenkamp[10,19], N. Goehlke[44], J. G. Gonzalez[8], S. Goswami[40], D. Grant[43], S. J. Gray[22], S. Griffin[4], S. Griswold[21], C. Günther[28], P. Gutjahr[7], C. Haack[20], A. Hallgren[19], R. Halliday[43], L. Halve[28], F. Halzen[4], H. Hamdaoui[33], M. Ha Minh[20], K. Hanson[4], J. Hardin[35], A. A. Harnisch[43], P. Hatch[49], A. Haungs[26], K. Helbing[17], J. Hellrung[18], F. Henningsen[20], L. Heuermann[28], S. Hickford[17], A. Hidvegi[41], C. Hill[50], G. C. Hill[30], K. D. Hoffman[22], K. Hoshina[4,67], W. Hou[26], T. Huber[26], K. Hultqvist[41], M. Hünnefeld[7], R. Hussain[4], K. Hymon[7], S. In[34], N. Iovine[5], A. Ishihara[50], M. Jacquart[4], M. Jansson[41], G. S. Japaridze[51], K. Jayakumar[4,65], M. Jeong[34], M. Jin[11], B. J. P. Jones[52], D. Kang[26], W. Kang[34], X. Kang[32], A. Kappes[31], D. Kappesser[27], L. Kardum[7], T. Karg[2], M. Karl[20], A. Karle[4], U. Katz[10], M. Kauer[4], J. L. Kelley[4], A. Khatee Zathul[4], A. Kheirandish[53,54], K. Kin[50], J. Kiryluk[33], S. R. Klein[14,25], A. Kochocki[43], R. Koirala[8], H. Kolanoski[47], T. Kontrimas[20], L. Köpke[27], C. Kopper[43], D. J. Koskinen[6], P. Koundal[26], M. Kovacevich[32], M. Kowalski[2,47], T. Kozynets[6], K. Kruiswijk[42], E. Krupczak[43], A. Kumar[2], E. Kun[18], N. Kurahashi[32], N. Lad[2], C. Lagunas Gualda[2], M. Lamoureux[42], M. J. Larson[22], F. Lauber[17], J. P. Lazar[4,11], J. W. Lee[34], K. Leonard DeHolton[38,39], A. Leszczyńska[8], M. Lincetto[18], Q. R. Liu[4], M. Liubarska[55], E. Lohfink[27], C. Love[32], C. J. Lozano Mariscal[31], L. Lu[4], F. Lucarelli[56], A. Ludwig[57], W. Luszczak[15,16], Y. Lyu[14,25], W. Y. Ma[2], J. Madsen[4], K. B. M. Mahn[43], Y. Makino[4], S. Mancina[4,23], W. Marie Sainte[4], I. C. Mariş[5], S. Marka[37], Z. Marka[37], M. Marsee[40], I. Martinez-Soler[11], R. Maruyama[58], F. Mayhew[43], T. McElroy[55], F. McNally[59], J. V. Mead[6], K. Meagher[4], S. Mechbal[2], A. Medina[16], M. Meier[50], S. Meighen-Berger[20], Y. Merckx[36], L. Merten[18], J. Micallef[43], D. Mockler[5], T. Montaruli[56], R. W. Moore[55], Y. Morii[50], R. Morse[4], M. Moulai[4], T. Mukherjee[26], R. Naab[2], R. Nagai[50], M. Nakos[4], U. Naumann[17], J. Necker[2], M. Neumann[31], H. Niederhausen[43], M. U. Nisa[43], A. Noell[28], S. C. Nowicki[43], A. Obertacke Pollmann[17], V. O'Dell[4], M. Oehler[26], B. Oeyen[60], A. Olivas[22], R. Orsoe[20], J. Osborn[4], E. O'Sullivan[19], H. Pandya[8], N. Park[49], G. K. Parker[52], E. N. Paudel[8], L. Paul[9], C. Pérez de los Heros[19], J. Peterson[4], S. Philippen[28], S. Pieper[17], A. Pizzuto[4], M. Plum[12], Y. Popovych[27], M. Prado Rodriguez[4], B. Pries[43], R. Procter-Murphy[22], G. T. Przybylski[25], C. Raab[5], J. Rack-Helleis[27], K. Rawlins[61], Z. Rechav[4], A. Rehman[8], P. Reichherzer[18], G. Renzi[5], E. Resconi[20], S. Reusch[2], W. Rhode[7], M. Richman[32], B. Riedel[4], E. J. Roberts[30], S. Robertson[14,25], S. Rodan[34], G. Roellinghoff[34], M. Rongen[27], C. Rott[34,62], T. Ruhe[7], L. Ruohan[20], D. Ryckbosch[60], S. Athanasiadou[2], I. Safa[4,11], J. Saffer[44], D. Salazar-Gallegos[43], P. Sampathkumar[26], S. E. Sanchez Herrera[43], A. Sandrock[7], M. Santander[40], S. Sarkar[55], S. Sarkar[63], J. Savelberg[28], P. Savina[4], M. Schaufel[28], H. Schieler[26], S. Schindler[10], B. Schlüter[31], T. Schmidt[22], J. Schneider[10], F. G. Schröder[8,26], L. Schumacher[20], G. Schwefer[28], S. Sclafani[32], D. Seckel[8], S. Seunarine[64], A. Sharma[19], S. Shefali[44], N. Shimizu[50], M. Silva[4], B. Skrzypek[11], B. Smithers[52], R. Snihur[4], J. Soedingrekso[7], A. Søgaard[6], D. Soldin[44], G. Sommani[18], C. Spannfellner[20], G. M. Spiczak[64], C. Spiering[2], M. Stamatikos[16], T. Stanev[8], R. Stein[2], T. Stezelberger[25], T. Stürwald[17], T. Stuttard[6], G. W. Sullivan[22], I. Taboada[29], S. Ter-Antonyan[45], W. G. Thompson[11], J. Thwaites[4], S. Tilav[8], K. Tollefson[43], C. Tönnis[34], S. Toscano[5], D. Tosi[4], A. Trettin[2], C. F. Tung[29], R. Turcotte[26], J. P. Twagirayezu[43], B. Ty[4], M. A. Unland Elorrieta[31], A. K. Upadhyay[4,65], K. Upshaw[45], N. Valtonen-Mattila[19], J. Vandenbroucke[4], N. van Eijndhoven[36], D. Vannerom[35], J. van Santen[2], J. Vara[31], J. Veitch-Michaelis[4], M. Venugopal[26], S. Verpoest[60], D. Veske[37], C. Walck[41], T. B. Watson[52], C. Weaver[43], P. Weigel[35], A. Weindl[26], J. Weldert[38,39], C. Wendt[4], J. Werthebach[7], M. Weyrauch[26], N. Whitehorn[43,57], C. H. Wiebusch[28], N. Willey[43], D. R. Williams[40], M. Wolf[20], G. Wrede[10], J. Wulff[18], X. W. Xu[45], J. P. Yanez[55], E. Yildizci[4], S. Yoshida[50], F. Yu[11], S. Yu[43], T. Yuan[4], Z. Zhang[33], and P. Zhelnin[11]
IceCube Collaboration

[1] Department of Physics, Loyola University Chicago, Chicago, IL, 60660, USA
[2] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany

[3] Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[4] Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI, 53706, USA
[5] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
[6] Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
[7] Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
[8] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE, 19716, USA
[9] Department of Physics, Marquette University, Milwaukee, WI, 53201, USA
[10] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
[11] Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, 02138, USA
[12] Physics Department, South Dakota School of Mines and Technology, Rapid City, SD, 57701, USA
[13] Dept. of Physics and Astronomy, University of California, Irvine, CA, 92697, USA
[14] Dept. of Physics, University of California, Berkeley, CA, 94720, USA
[15] Dept. of Astronomy, Ohio State University, Columbus, OH, 43210, USA
[16] Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH, 43210, USA
[17] Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
[18] Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
[19] Dept. of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
[20] Physik-department, Technische Universität München, D-85748 Garching, Germany
[21] Dept. of Physics and Astronomy, University of Rochester, Rochester, NY, 14627, USA
[22] Dept. of Physics, University of Maryland, College Park, MD, 20742, USA
[23] Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy
[24] Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS, 66045, USA
[25] Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA
[26] Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany
[27] Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
[28] III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany
[29] School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, 30332, USA
[30] Department of Physics, University of Adelaide, Adelaide, 5005, Australia
[31] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
[32] Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA, 19104, USA
[33] Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY, 11794-3800, USA
[34] Dept. of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
[35] Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA
[36] Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
[37] Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY, 10027, USA
[38] Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA, 16802, USA
[39] Dept. of Physics, Pennsylvania State University, University Park, PA, 16802, USA
[40] Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, 35487, USA
[41] Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
[42] Centre for Cosmology, Particle Physics and Phenomenology—CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[43] Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI, 48824, USA
[44] Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
[45] Dept. of Physics, Southern University, Baton Rouge, LA, 70813, USA
[46] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
[47] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
[48] Dept. of Astronomy, University of Wisconsin–Madison, Madison, WI, 53706, USA
[49] Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON, K7L 3N6, Canada
[50] Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba, 263-8522, Japan
[51] CTSPS, Clark-Atlanta University, Atlanta, GA, 30314, USA
[52] Dept. of Physics, University of Texas at Arlington, 502 Yates St., Science Hall Rm 108, Box 19059, Arlington, TX, 76019, USA
[53] Department of Physics & Astronomy, University of Nevada, Las Vegas, NV, 89154, USA
[54] Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV, 89154, USA
[55] Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada
[56] Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
[57] Department of Physics and Astronomy, UCLA, Los Angeles, CA, 90095, USA
[58] Dept. of Physics, Yale University, New Haven, CT, 06520, USA
[59] Department of Physics, Mercer University, Macon, GA, 31207-0001, USA
[60] Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
[61] Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK, 99508, USA
[62] Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, 84112, USA
[63] Dept. of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, UK
[64] Dept. of Physics, University of Wisconsin, River Falls, WI, 54022, USA; mkovacevich@icecube.wisc.edu
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[65] also at Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[66] also at Department of Space, Earth and Environment, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[67] also at Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan.

Abstract

This paper presents the results of a search for neutrinos that are spatially and temporally coincident with 22 unique, nonrepeating fast radio bursts (FRBs) and one repeating FRB (FRB 121102). FRBs are a rapidly growing class of Galactic and extragalactic astrophysical objects that are considered a potential source of high-energy neutrinos. The IceCube Neutrino Observatory's previous FRB analyses have solely used track events. This search utilizes seven years of IceCube cascade events which are statistically independent of track events. This event selection allows probing of a longer range of extended timescales due to the low background rate. No statistically significant clustering of neutrinos was observed. Upper limits are set on the time-integrated neutrino flux emitted by FRBs for a range of extended time windows.

Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100); Radio transient sources (2008); High energy astrophysics (739)

1. Introduction

The IceCube Neutrino Observatory, located at the geographic South Pole, is the largest neutrino detector in the world. Encompassing a cubic kilometer of instrumented ice, IceCube is comprised of 5160 digital optical modules (DOMs) situated on 86 read-out and support cables or "strings" to detect the Cherenkov radiation from charged particles created by neutrino interactions in the Antarctic ice (Abbasi et al. 2009; Aartsen et al. 2017). IceCube's instrumentation density is optimized for the detection of neutrinos with energies from 100 GeV to 10 PeV. It contains a higher density subvolume, enabling the detection of neutrinos down to 10 GeV (Abbasi et al. 2012). IceCube has observed a diffuse flux of high-energy astrophysical neutrinos (Aartsen et al. 2013, 2014a, 2015). A study of data collected between 2008 April 6 and 2018 July 10 revealed a 3.3σ inconsistency with background expectations for four sources that include NGC 1068 and TXS 0506+056 (Aartsen et al. 2020b). In 2022, IceCube found further evidence of neutrino emission from NGC 1068 at a significance of 4.2σ (Abbasi et al. 2022). Despite this growing evidence, the origin of the majority of the diffuse astrophysical flux remains unexplained. In this paper, we present a search for time-dependent neutrino emission from various fast radio bursts (FRBs) using seven years of IceCube cascade events and set upper limits on the associated neutrino flux for flares of varying duration.

Transient astrophysical objects are among the primary candidates for producing the astrophysical neutrino flux (Murase & Bartos 2019). The first evidence of neutrino emission from a flaring object came from the blazar TXS 0506+056 (Aartsen et al. 2018a, 2018b). FRBs are a class of transient astrophysical objects that could contribute to the diffuse neutrino flux (Metzger et al. 2020). FRBs are periodic or nonperiodic transient radio bursts that have Galactic or extragalactic origins. To date, hundreds of FRBs across the entire sky have been detected. Recently, FRB 200448 was localized to the Galactic magnetar SGR 1935+2154, suggesting magnetars may be a source of FRBs (Anderson et al. 2020). This has been further supported by the polarization of some FRBs (Wang et al. 2021). While the underlying mechanism that creates FRBs is unknown, it is predicted that this coherent radio emission is the result of an ultrarelativistic shock that propagates into a baryon-filled medium. A by-product of this scenario are TeV–PeV neutrinos that are produced by photohadronic interactions on timescales of varying duration after the FRB (Metzger et al. 2020; Qu & Zhang 2022). Here, we perform a time-dependent stacking search to test if two catalogs of FRBs, one repeating and the other nonrepeating, are producing a statistically significant number of neutrinos.

2. Search for Correlated Cascade Events

The majority of events detected by IceCube can be divided into two topological classes: cascades and tracks. Cascade signatures are produced by charged-current electron neutrino and tau neutrino interactions as well as all-flavor neutral-current interactions. These interactions typically produce electromagnetic and hadronic showers that have a range of 20 m or less; this range scales with energy (Aartsen et al. 2014b). Due to the average DOM spacing and light scattering within the ice, these particle showers lead to cascade events having angular resolutions $\sim$10°–15° (Aartsen et al. 2019). In contrast, track events are the result of muons that are produced by charged-current muon neutrino interactions and have an angular resolution of less than 1° at TeV–PeV energies (Abbasi et al. 2021a). Track events are subject to larger background rates that stem from atmospheric muons. To reduce this, track events below a certain energy threshold are filtered out (Abbasi et al. 2021a). The distinctive topology of cascade events allows our selections to include events that have energies down to hundreds of GeV (Aartsen et al. 2019).

To search for correlations between FRBs and cascade events, the energy, spatial, and temporal information of each cascade event is used with the spatial and temporal information of each FRB. This method is similar to that of IceCube's previous FRB analyses, referred to as Six Year Southern Tracks (Aartsen et al. 2018c) and All-Sky Tracks (Aartsen et al. 2020c), which analysed track data for correlations.

2.1. Data Set and FRB Catalogs

This analysis uses IceCube's Medium Energy Starting Cascade (MESC) data set. A starting event is classified as an event that contains a neutrino interaction vertex in the detector. This data set was originally developed to search for all-sky signatures of potential neutrino sources such as in the Galactic plane (Aartsen et al. 2019). It contains 1,980 cascade events detected from 2010 May to 2017 May. This corresponds to 2428 days of IceCube live time. The first year of data was taken with a 79-string detector configuration and the remaining six years use the complete 86-string configuration. The events in this data set have energies that range between 270 GeV and 1.6 PeV.

This analysis focuses on 48 unique bursts that were detected between 2010 May and 2017 May; the bursts are separated into two catalogs (Petroff et al. 2016). As shown in Figure 1, the first catalog contains 22 nonrepeating FRBs that are located at a

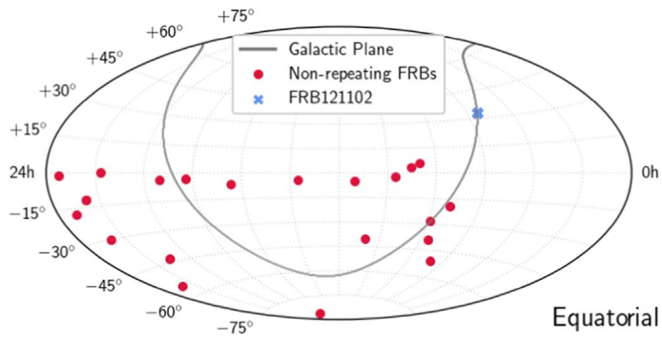

Figure 1. The spatial distribution of FRBs in equatorial coordinates. The 22 unique, nonrepeating FRBs are shown in red and FRB 121102 is shown in blue. FRB 121102 is an extragalactic source located at a decl. of 33°.15 (Spitler et al. 2014).

decl. of six degrees or below. The second catalog contains one repeating FRB (FRB 121102) that produced 26 bursts within the live time of the MESC data set. Since FRBs are an observational class of astrophysical phenomena, nonrepeating and repeating FRBs could be associated with different classes of astrophysical objects. As the underlying physical processes may differ, we treat them in this analysis as independent phenomena. These catalogs are a subset of the FRBs that were analysed in the Six Year Southern Tracks and All-Sky Tracks analyses. This is because the MESC data set has a live time period that does not fully overlap with the track data sets. The catalogs of nonrepeating and repeating FRBs are independently analysed through two time-dependent stacking analyses.

2.2. Analysis Methods

This analysis uses an unbinned extended maximum likelihood method, similar to the previous analyses (Aartsen et al. 2018c). The likelihood is comprised of spatial, temporal, and energy probability density functions (PDFs). These PDFs, similar to those defined in Section 3.1 of Braun et al. (2010), characterize how signal-like or background-like a given cascade is. To test if a cascade and FRB are temporally correlated, a search time window, ΔT, is constructed in the interval $[t_{\rm FRB}, t_{\rm FRB} + \Delta T]$, where $t_{\rm FRB}$ denotes when the FRB was detected. Motivated by Metzger et al. (2020), we test eight different ΔT that are logarithmically spaced from $[10^{-2}, 10^{7}]$ s after the FRB has occurred.[68] The spatial PDF accounts for the angular distance between a given FRB and the reconstructed cascade direction. A 2D Gaussian spatial PDF is used for cascades with an angular resolution less than 7°, while for a resolution greater than 7° a Kent distribution is used. At larger angular resolutions, a Kent distribution characterizes a probability distribution in curved space and cannot be approximated by a Gaussian distribution in flat space. The energy PDF characterizes the neutrino flux in terms of a power law, $E^{-\gamma}$, where γ is the spectral index. We assume a single power law for the energy flux. Using the likelihood ratio test described in Wilks (1938), we construct a test statistic (TS) that encompasses our null and alternative hypotheses,

$$\mathrm{TS} = -2\log\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(n_s, \gamma)}. \quad (1)$$

[68] The Six Year Southern Tracks and All-Sky Tracks analyses searched for neutrino emission in the interval $[t_{\rm FRB} - \frac{\Delta T}{2}, t_{\rm FRB} + \frac{\Delta T}{2}]$.

The null hypothesis represents background expectations ($n_s = 0$) whereas the alternative hypothesis fits for two parameters: the number of signal events, n_s, and γ. The number of events in a given time window can vary according to Poisson statistics. In each ΔT, a small number of events are required to observe a statistically significant correlation. To perform a stacking search, the TS in Equation (1) is additionally summed over each FRB in the catalog.

3. Results

We observed no significant emission in this analysis resulting in TS = 0 for every time window. Upper limits are calculated for both catalogs at the 90% confidence level for the time-integrated flux per FRB for every ΔT (Figure 2). The upper limits assume a flavor ratio (ν_e:ν_μ:ν_τ) of 1:1:1 with equal parts from ν and $\bar{\nu}$. From 10^{-2} to approximately 10^{6} s, the upper limits are relatively constant due to a low background rate. The background saturation occurs 10^{6} s after the FRB.

For the E^{-2} (Figure 2, left) and E^{-3} (Figure 2, right) spectra, we find that the stacked upper limits with cascade events are comparable to the Six Year Southern Tracks and All-Sky Tracks results (Figure 2). For E^{-3}, this analysis offers improved upper limits with respect to the Six Year Tracks. For E^{-2} this analysis is not quite as sensitive as the Six Year Tracks when searching for neutrino emission in ΔT less than 10^{4} s. The flux allowed by the All-Sky Tracks analysis increases by an order of magnitude between ΔT that have durations of subseconds to days. This is due to the rapidly increasing background rate, which requires more signal events to see a statistically significant correlation. As noted above, this is in contrast with cascade events. Finally, we find that for harder spectra, the catalog of nonrepeating FRBs offers slightly more constraining upper limits when compared with FRB 121102. This is in contrast with our upper limits for soft spectra where FRB 121102 has slightly stronger upper limits.

These results are extended to $E^{-2.53}$ to draw comparisons to the measured diffuse flux that has been observed in IceCube's cascade analyses (Aartsen et al. 2020a). The diffuse flux is an all-sky high-energy neutrino flux. Since FRBs are an all-sky phenomenon, these results are relevant. Figure 3 compares the per-burst upper limits for each catalog to the diffuse cascade astrophysical flux by integrating the diffuse flux over both the duration of each ΔT and the entire sky then dividing by the Canadian Hydrogen Intensity Mapping Experiment's (CHIME's) estimated FRB all-sky rate of 820 FRBs per day (Amiri et al. 2021). This assumes that each burst contributes equally to the diffuse all-sky cascades. This flux per FRB is then compared to the $E^{-2.53}$ upper limits from this analysis. Using this method of comparison, we see that the measured diffuse cascade flux establishes the most stringent limit on neutrino emission from FRBs.

4. Conclusion and Future Outlook

In two independent searches for neutrino emission from 22 unique, nonrepeating FRBs and 26 unique bursts from FRB 121102, no significant correlation was found. We provide upper limits on the time-integrated neutrino flux at the 90% confidence level for various spectral indices, as shown in Figures 2 and 3. We also provide estimates on the neutrino flux for FRB catalogs of various sizes (Figure 4). These estimates show that for nonperiodic FRBs that are isotropically

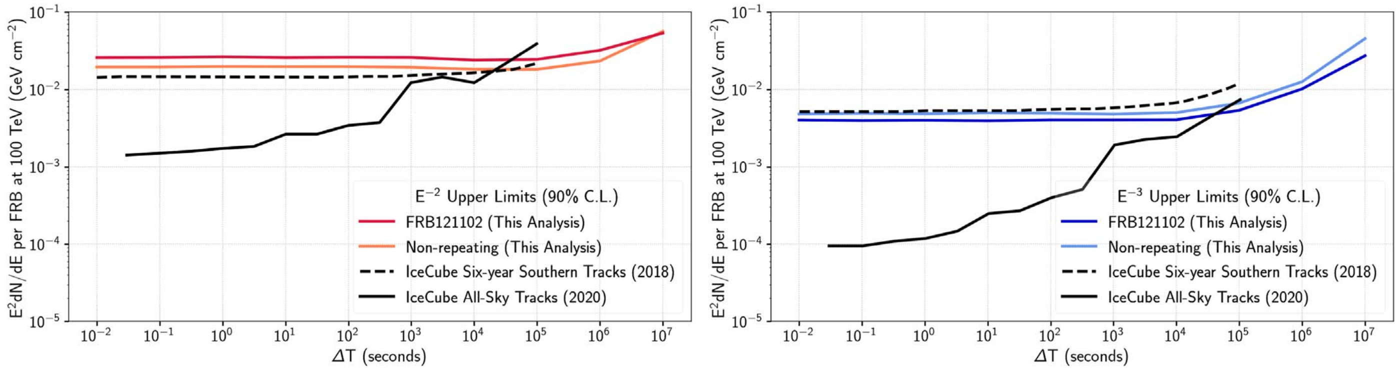

Figure 2. The 90% confidence level upper limits as a function of time-window duration. We assume power-law spectra of E^{-2} (left) and E^{-3} (right) for the time-integrated neutrino fluxes. The Six Year Southern Tracks and All-Sky Tracks analyses used statistically independent events; they are included in addition to our limits. Note that the previous IceCube analyses used symmetric time windows that are centered on the FRB to search for neutrino emission; this analysis only searches for neutrino emission after an FRB has occurred. Hence ΔT is offset by $\frac{\Delta T}{2}$ between this analysis and IceCube's previous analyses and the time windows do not completely overlap.

distributed throughout the southern sky, the neutrino flux per FRB decreases as the catalog size increases. In recent years more FRB observatories, such as CHIME, have come online. This has increased the detection rate of both repeating and nonrepeating FRBs. However, we were only able to analyse a subset of FRBs that overlapped with our data set. New data sets are in preparation that would overlap with 100–1000 FRBs and potentially offer more stringent upper limits (Petroff et al. 2016; Amiri et al. 2021).

Overall, this analysis shows that cascades offer sensitive upper limits when performing transient stacking searches. Given that cascades have a low background rate and are considered independent of track events, IceCube's future analyses would benefit from combining track and cascade events when searching for time-dependent neutrino emission from FRBs. This approach can be extended to IceCube's potential searches that aim to observe transient neutrino emission in real time as well as gamma-ray bursts (Aartsen et al. 2016; Abbasi et al. 2021b). In addition, the next generation of IceCube, IceCube-Gen2, will provide the opportunity to conduct more sensitive searches for neutrino emission from transient sources (Aartsen et al. 2021). In turn, this will allow us to uncover the origin of high-energy astrophysical neutrinos.

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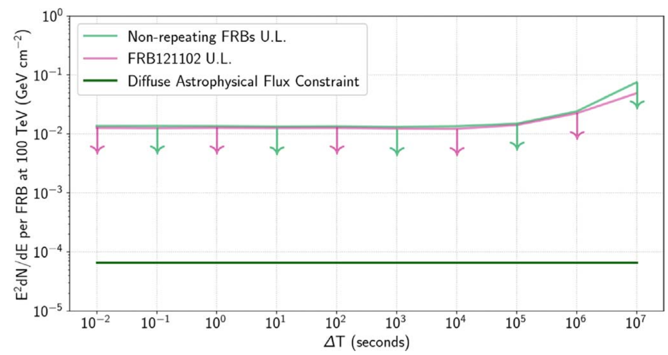

Figure 3. The 90% confidence level upper limits as a function of time windows assuming the best-fit diffuse spectrum ($E^{-2.53}$) measured in cascades (Aartsen et al. 2020a). The "diffuse astrophysical flux constraint" assumes that FRBs are solely responsible for the diffuse neutrino flux. The constraint is calculated by dividing the entire diffuse astrophysical flux equally among 820 homogeneous FRBs. Note that we assume 820 FRBs per day from the CHIME experiment's estimations of the FRB all-sky rate (Amiri et al. 2021).

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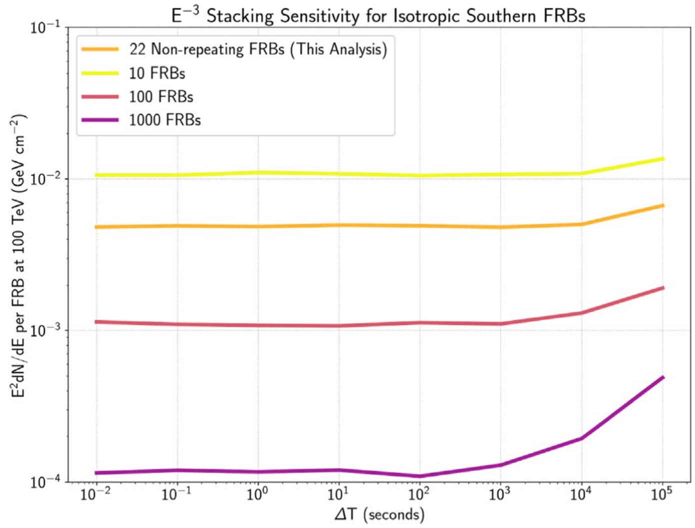

Figure 4. Projected sensitivities for various time-window durations as the number of FRBs in the catalog increases. We assume a power-law spectrum of E^{-3} for the time-integrated neutrino fluxes. Future catalogs are expected to have orders of magnitude more FRBs. The projected sensitivities are calculated at the 90% confidence level and use simulated FRBs that are uniformly distributed in the southern sky.

ORCID iDs

R. Abbasi https://orcid.org/0000-0001-6141-4205
M. Ackermann https://orcid.org/0000-0001-8952-588X
S. K. Agarwalla https://orcid.org/0000-0002-9714-8866
J. A. Aguilar https://orcid.org/0000-0003-2252-9514
M. Ahlers https://orcid.org/0000-0003-0709-5631
J. M. Alameddine https://orcid.org/0000-0002-9534-9189
G. Anton https://orcid.org/0000-0003-2039-4724
C. Argüelles https://orcid.org/0000-0003-4186-4182
S. N. Axani https://orcid.org/0000-0001-8866-3826
X. Bai https://orcid.org/0000-0002-1827-9121
A. Balagopal V. https://orcid.org/0000-0001-5367-8876
S. W. Barwick https://orcid.org/0000-0003-2050-6714
V. Basu https://orcid.org/0000-0002-9528-2009
J. J. Beatty https://orcid.org/0000-0003-0481-4952
J. Becker Tjus https://orcid.org/0000-0002-1748-7367
J. Beise https://orcid.org/0000-0002-7448-4189
C. Bellenghi https://orcid.org/0000-0001-8525-7515
S. BenZvi https://orcid.org/0000-0001-5537-4710
E. Bernardini https://orcid.org/0000-0003-3108-1141
D. Z. Besson https://orcid.org/0000-0001-6733-963X
E. Blaufuss https://orcid.org/0000-0001-5450-1757
S. Blot https://orcid.org/0000-0003-1089-3001
J. Y. Book https://orcid.org/0000-0001-6687-5959
C. Boscolo Meneguolo https://orcid.org/0000-0001-8325-4329
S. Böser https://orcid.org/0000-0002-5918-4890
O. Botner https://orcid.org/0000-0001-8588-7306
M. A. Campana https://orcid.org/0000-0003-4162-5739
C. Chen https://orcid.org/0000-0002-8139-4106
Z. Chen https://orcid.org/0000-0002-2813-7688
D. Chirkin https://orcid.org/0000-0003-4911-1345
B. A. Clark https://orcid.org/0000-0003-4089-2245
A. Coleman https://orcid.org/0000-0003-1510-1712
J. M. Conrad https://orcid.org/0000-0002-6393-0438
P. Coppin https://orcid.org/0000-0001-6869-1280
P. Correa https://orcid.org/0000-0002-1158-6735
D. F. Cowen https://orcid.org/0000-0003-4738-0787
P. Dave https://orcid.org/0000-0002-3879-5115
C. De Clercq https://orcid.org/0000-0001-5266-7059
J. J. DeLaunay https://orcid.org/0000-0001-5229-1995
D. Delgado López https://orcid.org/0000-0002-4306-8828
H. Dembinski https://orcid.org/0000-0003-3337-3850
A. Desai https://orcid.org/0000-0001-7405-9994
P. Desiati https://orcid.org/0000-0001-9768-1858
K. D. de Vries https://orcid.org/0000-0002-9842-4068
G. de Wasseige https://orcid.org/0000-0002-1010-5100
T. DeYoung https://orcid.org/0000-0003-4873-3783
A. Diaz https://orcid.org/0000-0001-7206-8336
J. C. Díaz-Vélez https://orcid.org/0000-0002-0087-0693
H. Dujmovic https://orcid.org/0000-0003-1891-0718
M. A. DuVernois https://orcid.org/0000-0002-2987-9691
P. Eller https://orcid.org/0000-0001-6354-5209
P. A. Evenson https://orcid.org/0000-0001-7929-810X
K. L. Fan https://orcid.org/0000-0002-8246-4751
A. R. Fazely https://orcid.org/0000-0002-6907-8020
A. Fedynitch https://orcid.org/0000-0003-2837-3477
C. Finley https://orcid.org/0000-0003-3350-390X
D. Fox https://orcid.org/0000-0002-3714-672X
A. Franckowiak https://orcid.org/0000-0002-5605-2219
T. K. Gaisser https://orcid.org/0000-0003-4717-6620
E. Ganster https://orcid.org/0000-0003-4393-6944
A. Garcia https://orcid.org/0000-0002-8186-2459
S. Garrappa https://orcid.org/0000-0003-2403-4582
A. Ghadimi https://orcid.org/0000-0002-6350-6485
C. Glaser https://orcid.org/0000-0001-5998-2553
T. Glauch https://orcid.org/0000-0003-1804-4055
T. Glüsenkamp https://orcid.org/0000-0002-2268-9297
S. Goswami https://orcid.org/0000-0002-0373-9770
S. J. Gray https://orcid.org/0000-0003-2907-8306
S. Griswold https://orcid.org/0000-0002-7321-7513
P. Gutjahr https://orcid.org/0000-0001-7980-7285
A. Hallgren https://orcid.org/0000-0001-7751-4489
L. Halve https://orcid.org/0000-0003-2237-6714
F. Halzen https://orcid.org/0000-0001-6224-2417
H. Hamdaoui https://orcid.org/0000-0001-5709-2100
A. Haungs https://orcid.org/0000-0002-9638-7574
K. Helbing https://orcid.org/0000-0003-2072-4172

F. Henningsen https://orcid.org/0000-0002-0680-6588
C. Hill https://orcid.org/0000-0003-0647-9174
W. Hou https://orcid.org/0000-0003-3422-7185
T. Huber https://orcid.org/0000-0002-6515-1673
K. Hultqvist https://orcid.org/0000-0003-0602-9472
N. Iovine https://orcid.org/0000-0001-7965-2252
G. S. Japaridze https://orcid.org/0000-0002-7000-5291
M. Jin https://orcid.org/0000-0003-0487-5595
B. J. P. Jones https://orcid.org/0000-0003-3400-8986
D. Kang https://orcid.org/0000-0002-5149-9767
W. Kang https://orcid.org/0000-0003-3980-3778
A. Kappes https://orcid.org/0000-0003-1315-3711
T. Karg https://orcid.org/0000-0003-3251-2126
M. Karl https://orcid.org/0000-0003-2475-8951
A. Karle https://orcid.org/0000-0001-9889-5161
U. Katz https://orcid.org/0000-0002-7063-4418
M. Kauer https://orcid.org/0000-0003-1830-9076
J. L. Kelley https://orcid.org/0000-0002-0846-4542
A. Kheirandish https://orcid.org/0000-0001-7074-0539
J. Kiryluk https://orcid.org/0000-0003-0264-3133
S. R. Klein https://orcid.org/0000-0003-2841-6553
A. Kochocki https://orcid.org/0000-0003-3782-0128
R. Koirala https://orcid.org/0000-0002-7735-7169
H. Kolanoski https://orcid.org/0000-0003-0435-2524
T. Kontrimas https://orcid.org/0000-0001-8585-0933
L. Köpke https://orcid.org/0000-0001-8530-6348
C. Kopper https://orcid.org/0000-0001-6288-7637
D. J. Koskinen https://orcid.org/0000-0002-0514-5917
P. Koundal https://orcid.org/0000-0002-5917-5230
M. Kovacevich https://orcid.org/0000-0002-5019-5745
M. Kowalski https://orcid.org/0000-0001-8594-8666
A. Kumar https://orcid.org/0000-0002-8367-8401
N. Kurahashi https://orcid.org/0000-0003-1047-8094
C. Lagunas Gualda https://orcid.org/0000-0002-9040-7191
M. Lamoureux https://orcid.org/0000-0002-8860-5826
M. J. Larson https://orcid.org/0000-0002-6996-1155
F. Lauber https://orcid.org/0000-0001-5648-5930
J. P. Lazar https://orcid.org/0000-0003-0928-5025
J. W. Lee https://orcid.org/0000-0001-5681-4941
K. Leonard DeHolton https://orcid.org/0000-0002-8795-0601
A. Leszczyńska https://orcid.org/0000-0003-0935-6313
Q. R. Liu https://orcid.org/0000-0003-3379-6423
E. Lohfink https://orcid.org/0000-0003-3248-5682
L. Lu https://orcid.org/0000-0003-3175-7770
F. Lucarelli https://orcid.org/0000-0002-9558-8788
A. Ludwig https://orcid.org/0000-0001-9038-4375
W. Luszczak https://orcid.org/0000-0003-3085-0674
Y. Lyu https://orcid.org/0000-0002-2333-4383
W. Y. Ma https://orcid.org/0000-0003-1251-5493
J. Madsen https://orcid.org/0000-0003-2415-9959
I. C. Mariş https://orcid.org/0000-0002-5771-1124
R. Maruyama https://orcid.org/0000-0003-2794-512X
F. McNally https://orcid.org/0000-0002-0785-2244
K. Meagher https://orcid.org/0000-0003-3967-1533
M. Meier https://orcid.org/0000-0002-9483-9450
S. Meighen-Berger https://orcid.org/0000-0001-6579-2000
L. Merten https://orcid.org/0000-0003-1332-9895
T. Montaruli https://orcid.org/0000-0001-5014-2152
R. W. Moore https://orcid.org/0000-0003-4160-4700
M. Moulai https://orcid.org/0000-0001-7909-5812
R. Naab https://orcid.org/0000-0003-2512-466X
R. Nagai https://orcid.org/0000-0001-7503-2777
J. Necker https://orcid.org/0000-0003-0280-7484
H. Niederhausen https://orcid.org/0000-0002-9566-4904
M. U. Nisa https://orcid.org/0000-0002-6859-3944
S. C. Nowicki https://orcid.org/0000-0003-2497-8057
A. Obertacke Pollmann https://orcid.org/0000-0002-2492-043X
B. Oeyen https://orcid.org/0000-0003-2940-3164
E. O'Sullivan https://orcid.org/0000-0003-1882-8802
H. Pandya https://orcid.org/0000-0002-6138-4808
N. Park https://orcid.org/0000-0002-4282-736X
E. N. Paudel https://orcid.org/0000-0001-9276-7994
C. Pérez de los Heros https://orcid.org/0000-0002-2084-5866
J. Peterson https://orcid.org/0000-0002-7985-1443
S. Philippen https://orcid.org/0000-0002-0276-0092
A. Pizzuto https://orcid.org/0000-0002-8466-8168
M. Plum https://orcid.org/0000-0001-8691-242X
B. Pries https://orcid.org/0000-0003-4811-9863
C. Raab https://orcid.org/0000-0001-9921-2668
A. Rehman https://orcid.org/0000-0001-7616-5790
E. Resconi https://orcid.org/0000-0003-0705-2770
S. Reusch https://orcid.org/0000-0002-7788-628X
W. Rhode https://orcid.org/0000-0003-2636-5000
B. Riedel https://orcid.org/0000-0002-9524-8943
M. Rongen https://orcid.org/0000-0002-7057-1007
C. Rott https://orcid.org/0000-0002-6958-6033
D. Ryckbosch https://orcid.org/0000-0002-8759-7553
I. Safa https://orcid.org/0000-0001-8737-6825
D. Salazar-Gallegos https://orcid.org/0000-0002-9312-9684
A. Sandrock https://orcid.org/0000-0002-6779-1172
M. Santander https://orcid.org/0000-0001-7297-8217
S. Sarkar https://orcid.org/0000-0002-1206-4330
S. Sarkar https://orcid.org/0000-0002-3542-858X
H. Schieler https://orcid.org/0000-0002-2637-4778
S. Schindler https://orcid.org/0000-0001-5507-8890
J. Schneider https://orcid.org/0000-0001-7752-5700
F. G. Schröder https://orcid.org/0000-0001-8495-7210
L. Schumacher https://orcid.org/0000-0001-8945-6722
S. Sclafani https://orcid.org/0000-0001-9446-1219
A. Sharma https://orcid.org/0000-0001-5397-6777
M. Silva https://orcid.org/0000-0001-6940-8184
B. Smithers https://orcid.org/0000-0003-1273-985X
J. Soedingrekso https://orcid.org/0000-0003-1011-2797
D. Soldin https://orcid.org/0000-0003-3005-7879
G. Sommani https://orcid.org/0000-0002-0094-826X
G. M. Spiczak https://orcid.org/0000-0002-0030-0519
C. Spiering https://orcid.org/0000-0001-7372-0074
R. Stein https://orcid.org/0000-0003-2434-0387
T. Stezelberger https://orcid.org/0000-0003-2676-9574
T. Stuttard https://orcid.org/0000-0001-7944-279X
G. W. Sullivan https://orcid.org/0000-0002-2585-2352
I. Taboada https://orcid.org/0000-0003-3509-3457
S. Ter-Antonyan https://orcid.org/0000-0002-5788-1369
W. G. Thompson https://orcid.org/0000-0003-2988-7998
K. Tollefson https://orcid.org/0000-0001-9725-1479
S. Toscano https://orcid.org/0000-0002-1860-2240
A. Trettin https://orcid.org/0000-0003-0350-3597
C. F. Tung https://orcid.org/0000-0001-6920-7841
M. A. Unland Elorrieta https://orcid.org/0000-0002-6124-3255

N. Valtonen-Mattila https://orcid.org/0000-0002-1830-098X
J. Vandenbroucke https://orcid.org/0000-0002-9867-6548
N. van Eijndhoven https://orcid.org/0000-0001-5558-3328
J. van Santen https://orcid.org/0000-0002-2412-9728
S. Verpoest https://orcid.org/0000-0002-3031-3206
C. Walck https://orcid.org/0000-0002-4188-9219
T. B. Watson https://orcid.org/0000-0002-8631-2253
C. Weaver https://orcid.org/0000-0003-2385-2559
J. Weldert https://orcid.org/0000-0002-3709-2354
C. Wendt https://orcid.org/0000-0001-8076-8877
N. Whitehorn https://orcid.org/0000-0002-3157-0407
C. H. Wiebusch https://orcid.org/0000-0002-6418-3008
M. Wolf https://orcid.org/0000-0001-9991-3923
S. Yoshida https://orcid.org/0000-0003-2480-5105
T. Yuan https://orcid.org/0000-0002-7041-5872
Z. Zhang https://orcid.org/0000-0002-7347-283X
P. Zhelnin https://orcid.org/0000-0002-7347-283X

References

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