A Significant Association Between CHIME Fast Radio Bursts and Low-Energy IceCube Neutrinos

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ABSTRACT

Despite numerous studies, the sources of IceCube cosmic neutrinos have hitherto been unidentified. Utilizing recently released IceCube neutrino and CHIME FRB catalogs, we examine the possibility of association between neutrinos and FRBs for both the entire FRB population and individual FRBs using the directional matching method. We report an association between FRBs and low-energy IceCube neutrinos with energies 0.1 – 3 TeV at a significance level of 21.3σ. We also identify 20 FRBs that are candidate association sources of neutrinos, all of which are apparently non-repeating FRBs. This sub-sample of FRBs shows no special properties compared with the whole CHIME FRB sample. We discuss the possible physical origin of such associations within the framework of the magnetar models of FRBs.

1. INTRODUCTION

The source of diffuse cosmic neutrinos observed by the IceCube neutrino observatory (IceCube Collaboration 2013) remains a mystery (Mészáros 2017; Murase & Bartos 2019). In 2018, the IceCube collaboration reported an association between a neutrino event IceCube-170922A and the blazar TXS 0506+056 during a gamma-ray flaring state (IceCube Collaboration et al. 2018a). This has led to the speculation that blazars are the main sources of cosmic neutrinos (e.g. Essey et al. 2010; Kalashev et al. 2013; Kun et al. 2021; Das et al. 2021). However, Luo & Zhang (2020) showed that there is no compelling correlation between blazars and neutrinos in general, nor there is an association between IceCube neutrino flares and gamma-ray fluxes in Fermi-LAT monitored sources. A new analysis by IceCube team with new methods and the newly released 2008–2018 all-sky point-source IceCube data (IceCube Collaboration et al. 2021a) revised the significance of association between TXS 0506+056 and 2014/2015 neutrino flare (IceCube Collaboration et al. 2018b) from 3.8σ to 2.4σ, further undermining this association. Although there are some weak neutrino flare associations reported with several X-ray blazars and tidal disruption events (TDEs) (Rodrigues et al. 2021; Stein et al. 2021; Goswami et al. 2021; Sharma & O’Sullivan 2021; Stathopoulos et al. 2021), they are likely from particular sources with special physical conditions. All these claimed associations are for high-energy neutrinos above 10 TeV. In any case, these potential associations still cannot present a satisfactory explanation to the diffuse cosmic neutrino flux. The sources of cosmic neutrinos, especially those at energies below 10 TeV, remain mysterious (Aartsen et al. 2020a; Smith et al. 2021).

Fast radio bursts (FRBs) are short cosmic radio transients whose origin remains a mystery (Lorimer et al. 2007; Petroff et al. 2019; Cordes & Chatterjee 2019; Zhang 2020). Some early attempts searching for possible associations between FRBs and IceCube neutrinos have been carried out (Fahey et al. 2017; Aartsen et al. 2018, 2020b; Nicastro et al. 2021), but no meaningful results have been obtained thanks to the sparse FRB data available.

Recently, the Canadian Hydrogen Intensity Mapping Experiment (CHIME)/FRB Collaboration released the first catalog, containing a total of 492 FRB sources, among which 18 are repeating sources (The CHIME/FRB Collaboration et al. 2021). The recently released 2008–2018 all-sky point-source IceCube data (IceCube Collaboration et al. 2021b), on the other hand, have 1247308 neutrino events spanning 10 years. The availability of these two large catalogs makes it possible to perform a direct search of associations between the two types of astrophysical events.

In this work, we conduct a search of association between FRBs and neutrinos, for both the entire FRB population and individual FRBs. We report a significant association between FRBs and neutrinos in the 0.1 – 3 TeV energy range in the aforementioned catalogs.

2. NEUTRINO ASSOCIATION TESTS FOR THE ENTIRE FRB POPULATION

We first test the possible association between IceCube neutrinos and the entire CHIME FRB population. Because the CHIME covers the northern hemisphere, we
only consider neutrinos from the northern hemisphere where IceCube also has a better sensitivity. This leaves us 741857 neutrino events and 484 FRBs including 18 repeaters and 466 non-repeaters. We first count the number of neutrinos whose error regions enclose each FRB. The number of matches is calculated this way because FRBs are better localized. After counting the number of matches, we randomly generate the same number of FRBs in the northern hemisphere, and count the number of matches with observed neutrinos in the same way. Then, we compare the observed number of matches with the simulated ones.

A total of 192900 matches are found between CHIME FRBs and IceCube neutrinos in the northern hemisphere. We randomly simulate 484 FRBs in the northern hemisphere for 10000 times. For each realization, we count for the number of matches and obtain a normal distribution to the total number of matches.

![Figure 1](image)

The histograms show the number of matches in the simulations with black line showing fitted normal distribution, while the red vertical lines represent the observed values.

The best-fit parameters for the simulated match distribution has a central value of $\mu = 126030$ and a dispersion of $\sigma = 3056$. Comparing with the observed value of 192900 matches, we find a significant excess of the actual associations, suggesting a $21.9\sigma$ association between neutrinos and FRBs as a population (Fig. 1).

To pinpoint the energy range of neutrino events with the strongest association with FRBs, we split the neutrinos in different energy ranges and redo the significant tests. As shown in 2, the significance exceeds $20\sigma$ for energy ranges $(0.1 - 0.3)$ TeV, $(0.3 - 1)$ TeV, and $(1 - 3)$ TeV, drops to $8.1\sigma$ at $< 0.1$ TeV in the low end and $7.3\sigma$ in $(3 - 10)$ TeV in the high end. The association completely disappears at $> 10$ TeV. Overall, the strongest association occurs in the $(0.1 - 3)$ TeV range.

To test the validity of our method, we also apply the same method to both blazars in the ROMA-bzcat catalog (Massaro et al. 2015) and gamma-ray sources in the Fermi-4FGL catalog (Abdollahi et al. 2020). Again, we only use the sources in the northern hemisphere. This leaves us 2138 blazars and 2302 Fermi Gamma-ray sources respectively. We use the same $0.1 - 3$ TeV neutrino energy range as the main association in FRBs. As shown in Fig. 3, we find no significant associations between neutrinos and these sources. We therefore conclude that the association between low-energy neutrinos and FRBs is genuine.

However, whereas the right ascension (RA) distribution of IceCube neutrinos is uniform because IceCube is located at the south pole, the declination (Dec) distribution is far from uniform, as shown in Fig. 4. As a result, one can argue that the excess of matches between FRBs and neutrinos compared with random FRB locations may be caused by a coincidence in FRB and neutrino distributions instead of a true association, i.e. the FRBs happen to locate in the regions where neutrino events cluster, thus generating more matches compared with the average value from random simulations.

To counter this argument, we randomly generate 200 isotropic source directions between $0$–$10$ degrees in declination and apply the same population match method with neutrino events. The simulation results are shown in Fig. 5a. No excess in number of matches compared with the all-sky random simulation can be observed. While there are more events around $0$–$10$ degrees in declination, those neutrino events also have smaller angular errors (see Fig. 5b), yielding less matches with sources. This cancels out the effect of a higher event density at low declinations.

3. NEUTRINO ASSOCIATION TESTS FOR INDIVIDUAL FRBS

To find out which FRBs contribute most to the general associations between FRBs and neutrino events, we consider simulating match distribution of individual FRBs. For each FRB, the number of matches with neutrinos is first calculated at their original direction. Then, keeping the declination constant, we randomly generate 10000 new RA values for each FRB. The new random RA values and original Dec values combine to form new sets of coordinates. The number of matches with neutrino events is then counted at these random new coordinates. Finally, the distribution of number of matches is compared against the number of matches from the original
Figure 2. Results from the population match simulations in different neutrino energy ranges. The center panel is the IceCube neutrino spectrum in the north hemisphere with five vertical lines at 0.1, 0.3, 1, 3, and 10 TeV, which separate the energy range into six ranges. Other panels present the significance tests for different ranges, with the relevant energy range marked as red-shaded region in the insets. From left to right, up to down and except the middle panel, the energy ranges are <0.1 TeV, 0.1−0.3 TeV, 0.3−1 TeV, 1−3 TeV, 3−10 TeV, >10 TeV, <10 TeV, and 0.1−3 TeV. The strongest association starts at about 0.1 TeV and stops at about 3 TeV.

4. PROPERTIES OF THE CANDIDATE FRBS ASSOCIATED WITH NEUTRINOS

Table 1 shows the properties of the candidate FRBs that are associated with neutrinos. Interesting quantities include width, excess DM values for both the NE2001 (Cordes & Lazio 2002) and YMW16 (Yao et al. 2017) electron density models, and flux. Figure 6 shows the distributions of these FRBs as compared with the respective distributions of the entire FRB population for various parameters. Considering the much smaller sample size than the whole sample, the distributions of the candidate FRBs are consistent with the distributions of the whole sample.

All the 20 FRBs identified with neutrino events are non-repeating FRBs. With 18 repeating and 466 non-
repeating FRBs in the northern hemisphere, this yields a p-value of 0.467. Therefore we are not able to distinguish between repeating and non-repeating FRBs based on their associations with neutrino events.

Table 1. Simulation results and observational parameters for FRBs with p-values smaller than 0.05 in the random RA match simulations.

| FRB name       | RA      | Dec     | p-value | Width(s) | Excess DM(ne2001) | ymwl6 flux (Jy) | Fluence (Jy s^{-1}) | Repeating |
|----------------|---------|---------|---------|----------|-------------------|-----------------|---------------------|-----------|
| FRB20180812A   | 19.3    | 80.8    | 0.0132  | 0.00786  | 722.1             | 708.4           | 0.9                 | 5.0        | No        |
| FRB20180920A   | 78.9    | 28.3    | 0.004   | 0.01475  | 394.9             | 324.9           | 0.9                 | 8.0        | No        |
| FRB20180923A   | 327.6   | 71.9    | 0.0196  | 0.00197  | 119.4             | 92.2            | 0.8                 | 1.2        | No        |
| FRB20181013E   | 307.3   | 69.0    | 0.0439  | 0.00295  | 264.5             | 256.0           | 0.6                 | 2.0        | No        |
| FRB20181203A   | 33.6    | 23.6    | 0.0336  | 0.00295  | 589.2             | 597.3           | 1.7                 | 4.0        | No        |
| FRB20181217A   | 290.5   | 59.8    | 0.0219  | 0.00295  | 1107.4            | 1108.4          | 0.6                 | 1.8        | No        |
| FRB20181222E   | 50.64   | 87.0    | 0.00287 | 0.00393  | 268.1             | 268.2           | 1.1                 | 6.0        | No        |
| FRB20181230B   | 20.8    | 79.7    | 0.0019  | 0.01081  | 1052.4            | 1034.9          | 0.9                 | 10.0       | No        |
| FRB20190101A   | 171.0   | 28.0    | 0.0168  | 0.04227  | 830.3             | 836.0           | 0.6                 | 11.0       | No        |
| FRB20190118B   | 39.7    | 23.6    | 0.0089  | 0.03637  | 620.7             | 627.3           | 0.3                 | 4.0        | No        |
| FRB20190121A   | 354.7   | 78.6    | 0.0405  | 0.00786  | 338.0             | 319.1           | 2.0                 | 11.0       | No        |
| FRB20190201A   | 64.0    | 84.8    | 0.0361  | 0.00098  | 179.6             | 178.5           | 3.0                 | 3.0        | No        |
| FRB20190212C   | 172.6   | 28.14   | 0.0161  | 0.02064  | 994.1             | 997.9           | 0.7                 | 12.0       | No        |
| FRB20190228A   | 183.48  | 22.9    | 0.0405  | 0.03047  | 398.9             | 399.5           | 1.8                 | 36.0       | No        |
| FRB20190403G   | 81.7    | 25.8    | 0.036   | 0.0197   | 700.0             | 620.0           | 0.8                 | 1.6        | No        |
| FRB20190519D   | 164.6   | 42.99   | 0.0237  | 0.00197  | 509.3             | 521.1           | 0.4                 | 0.8        | No        |
| FRB20190621C   | 206.6   | 5.2     | 0.0177  | 0.00098  | 544.6             | 547.8           | 2.0                 | 2.4        | No        |
| FRB20190625D   | 115.02  | 4.87    | 0.0112  | 0.0197   | 616.5             | 587.1           | 5.0                 | 12.0       | No        |
| FRB20190627B   | 256.4   | 40.8    | 0.0407  | 0.00295  | 388.3             | 396.7           | 4.1                 | 10.0       | No        |
| FRB20190630C   | 68.4    | 80.95   | 0.0342  | 0.00393  | 1592.3            | 1586.9          | 0.7                 | 2.3        | No        |

5. CONCLUSIONS AND DISCUSSION

We have discovered a significant association (21.3σ) of IceCube neutrinos between 0.1 – 3 TeV and FRBs from the first CHIME catalog. A closer scrutiny of individual sources led to the identification of 20 individual FRB sources that are candidates for neutrino associations. All candidates are apparently non-repeating FRBs. The observed parameters of this sub-sample of FRBs are consistent with the those of the entire CHIME FRB sample.

Because all CHIME FRBs are located in the northern hemisphere or southern hemisphere with very low declination, and because the majority of neutrino events in the IceCube catalog in the northern hemisphere have energies lower than 10 TeV, we are not able to reliably test the association between FRBs and high energy IceCube neutrinos. The origin of neutrinos with higher energies remains a mystery.

Not all neutrino sources are associated with FRBs and vice versa. This may suggest that there are other astrophysical sources that power cosmic neutrinos, but the ansatz that “all cosmic neutrinos between 0.1 – 3 TeV originate from FRB sources” cannot be ruled out. This is because FRBs are sporadic emitters and bursts have a wide luminosity function (e.g. Luo et al. 2018, 2020; Lu & Piro 2019; Lu et al. 2020). It is possible that all the low-energy neutrinos are from FRB sources but these sources have not been detected to make bursts yet with the current survey observations. It is also possible that all FRB sources emit neutrinos but a significant excess of neutrinos from most of them have not been detected by Icecube yet. Future continued all sky monitoring of both low-energy neutrino sources and FRBs sources will give a better constraint on this ansatz.

The detection of FRB 200425 from the Galactic magnetar SGR J1935+2154 (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020; Li et al. 2020; Mereghetti et al. 2020; Ridnaia et al. 2020; Tavani et al. 2020) places magnetars as the leading candidate source of FRBs. It is possible that all FRBs originate from magnetars, with the apparently non-repeating ones being repeaters with very long waiting times between bursts (e.g. Lu et al. 2020; Zhang 2020). If so, the association between FRBs and IceCube low-energy neutrinos may suggest that magnetars are low-energy neutrino emitters. Indeed, Zhang et al. (2003) have shown that in steady state magnetars are able to make neutrinos with a few TeV characteristic energy through photomeson interaction between accelerated protons and surface X-ray
Figure 3. Results from the population match simulation with Roma-BzCat and Fermi-4FGL catalogs. The histograms show the number of matches in simulations with black line showing fitted normal distribution, while the red vertical lines represent the observed values. Upper: Roma-BzCat, lower: Fermi-4FGL. No significant association is observed.

Figure 4. Declination distribution for IceCube neutrino events. A clear excess can be seen at 0–10 degrees.

Figure 5. Upper: Results from the population match simulation with random source directions between 0–10 degrees in declination. Lower: Declination and angular error distribution of IceCube neutrino events.

Figure 6. Distributions of burst width, flux and excess DM for the candidate FRBs associated with neutrinos and all FRBs in the CHIME catalog.
photons. Murase et al. (2009) showed that new-born magnetars can produce significant high-energy neutrinos through hadronic interactions between accelerated protons and the surrounding stellar ejecta. However, these two emission components either have too low a diffuse flux (Zhang et al. 2003) or too high a neutrino energy (Murase et al. 2009) to account for the discovered association reported here.

Alternatively, neutrinos may be produced during X-ray flaring processes, some of which are associated with FRBs (Lin et al. 2020). Metzger et al. (2020) estimated the neutrino flux within the framework of the synchrotron maser model invoking relativistic shocks and found that the predicted neutrino fluxes are negligibly low. Qu & Zhang (2021), on the other hand, studied photomeson interaction in the near zone regions, either within the magnetosphere or in the current sheet region just outside the magnetosphere. They found that the neutrino flux could be much stronger than the estimation by Metzger et al. (2020). The diffuse neutrino background emission predicted by Qu & Zhang (2021) is indeed in the low-energy range as observed. However, the diffuse flux needs to be enhanced by more than 1000 times in order to match the observed level even for the most optimistic neutrino emission model invoking magnetospheric acceleration of protons. This would be possible if the X-ray bursts not associated with FRBs are more than 1000 more frequent than those associated with FRBs and that all X-ray flares carry baryons and emit low-energy neutrinos. This is probably the best scenario to interpret the reported association. This interpretation also offers support to the acceleration of protons within the magnetar magnetospheres (Zhang et al. 2003; Qu & Zhang 2021), lending indirect support of the magnetospheric origin of FRB emission from magnetars (e.g. Kumar et al. 2017; Yang & Zhang 2018, 2021; Wang et al. 2019, 2021; Lu et al. 2020; Wadiasingh & Timokhin 2019; Wadiasingh et al. 2020; Zhang 2021).

This work is supported by the Top Tier Doctoral Graduate Research Assistantship (TTDGRA) at University of Nevada, Las Vegas.

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