A test of spatial coincidence between CHIME FRBs and IceCube TeV energy neutrinos

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(Dated: November 2, 2022)

We search for a spatial association between the CHIME FRBs and IceCube neutrinos detected in the TeV energy range, by counting the total number of neutrino-FRB pairs with angular separations of < 3 degrees, as well as within the observed neutrino error circle. This number constitutes the total signal events, which is then compared to the total background, corresponding to the null hypothesis of no spatial association. The background was obtained from the total neutrino-FRB matches in off-source angular windows with the same solid angle as the signal window. We do not find any statistically significant excess compared to the background. Therefore, we conclude that there is no evidence for an angular correlation between the IceCube neutrinos in the TeV energy range and CHIME FRBs. For each of these searches, we report 90% Bayesian credible interval upper limits on the observed FRB-induced neutrinos.

I. INTRODUCTION

We search for a statistically significant angular correlation between the Fast-Radio bursts (FRBs) detected by the Canadian Hydrogen Mapping Intensity experiment (CHIME) [1] and neutrinos detected by the IceCube Neutrino Observatory in the energy range between 0.1 to 3 TeV [2]. FRBs are short-duration radio bursts, which were discovered in 2007 [3, 4]. Although the exact nature of FRBs is still unknown (see [5] for a compendium of all FRB models), the recent association between an FRB and a galactic magnetar SGR J1935+2154 [6], has put magnetars as the forefront candidates for FRBs.

Since the origin of the diffuse astrophysical neutrino flux detected by IceCube [7–9] is still a mystery [10, 11], it would be interesting to see if FRBs contribute to the diffuse astrophysical neutrino flux, given the surplus of new FRBs discovered by CHIME. Note however that previous spatial and temporal searches for neutrino emission from FRBs (detected prior to CHIME) using IceCube, have found null results [12–14]. Furthermore, null results have also been reported in searches for neutrinos associated with magnetars from both IceCube and Super-Kamiokande [15–18].

Therefore, we set out to do this search using the first CHIME FRB catalog, using an independent method of estimating the background by counting the observed matches in the off-source regions, where by “off-source” we refer to angular directions far from the putative astrophysical source, wherein any observed neutrinos would be random coincidences and only due to the background. This search is similar to searches for dark matter WIMPs and astrophysical point sources with the Super-Kamiokande experiment [16, 17, 19, 20]. One difference between this search and all other IceCube-based FRB searches is that the previous works carried out both temporal and spatial searches from each of the FRBs. Here, we carry out a stacked search from all the observed FRBs without imposing any time-window around the FRBs. The first CHIME catalog published in Ref. [1] (which we have used for our analysis) contains 18 repeating FRBs. However, the actual number of FRBs which emit bursts multiple times could be larger in case the radio emission happens outside the CHIME duty cycle or when the source is not within the CHIME field of view. Secondly, although hadronic acceleration has been proposed in the regions of the progenitors, there is considerable uncertainty between the radio emission detected in FRBs and any putative neutrino emission [21, 22]. Therefore, in this work we only look for spatial coincidences. Furthermore, one practical consideration for carrying out only spatial searches is that currently there is no temporal overlap between the two datasets. In the future, we shall extend this analysis by also carrying out a temporal search.

This manuscript is structured as follows. The dataset used for our analysis is described in Section II. Our analysis and results can be found in Sect. III. We conclude in section IV.

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II. DATASETS

The public IceCube point source catalog contains 1,134,450 neutrinos spanning a ten year time-span from 6th April 2008 to 8 July 2018 [2, 23]. Each neutrino event is provided with an associated right ascension (RA), declination (DEC), reconstructed muon energy, angular error, and finally the detector zenith and azimuth angle. The reconstructed muon energy provides a lower limit of the parent neutrino energy. The muon energy spans almost nine decades from 10 GeV to approximately 30 PeV. The average angular resolution is 0.85°. The neutrino positions span both the hemispheres. The CHIME FRB catalog contains 491 FRBs, of which 18 are repeaters. These bursts have been detected between 25th July 2018 to 2019 July 1 and measured from 400-800 MHz. Therefore, there is no temporal overlap between the public IceCube catalog and the CHIME FRB dataset. The CHIME collaboration provides 54 attributes for each FRB. The average error in RA and DEC for the CHIME FRBs is about 0.16 and 0.18 degrees, respectively. The FRB catalog mostly covers the Northern Hemisphere and only contains eight FRBs with DEC< 0°. More details on the CHIME FRB catalog can be found in Ref. [1]. We do not make a cut on the declination of the IceCube neutrinos, as we would like to use all of the observed neutrinos for background estimation. We only include IceCube events with angular resolution < 3°. This gives a total of 1,100,993 events, which we use for our analysis. The 3° cut is a conservative choice and is based on a similar study done in Super-K astrophysical neutrinos searches [16]. With this cut we include 97% of the full IceCube dataset. Note that we do not consider the arrival time of the neutrino or the time of the FRB burst, since we are only doing a spatial analysis.

III. ANALYSIS AND RESULTS

A. Coincident searches within 3°

If there is a statistically significant association between the CHIME FRBs and IceCube neutrinos, one should see an excess at small angular (on-source) separations between the FRBs and neutrinos, after stacking all the pairs. Since we do not have redshift measurements for the FRBs, we assume equal weights for each FRB. The total number of pairs within the on-source window should be much greater than the background, which can be obtained by considering the observed matches in the off-source regions at large angular separations. Any excess in the on-source region compared to the background can be regarded as being of astrophysical origin, and can be attributed to FRBs in this case.

We calculate the angular separations between all the FRBs and observed neutrinos, and bin the number of coincident pairs into bins of 3°, as this is the maximum uncertainty in the neutrino direction, because of the cut we have used. At TeV energies, any coincidences between the FRBs and neutrinos at angular separations greater than 3° are chance coincidences and can be considered as background for our search. We do this analysis separately for four energy intervals: 0.1-3 TeV, 1-3 TeV, 3-10 TeV, and finally considering the full dataset.

We first show the full angular distribution between all the FRBs and neutrinos, by binning the data into cosine angle bins of width equal to 0.1. This is an exploratory test, as for any strong angular correlation, one should see a peak in the full angular distribution at close to 0° separations, similar to the peak observed in solar neutrinos, near the direction of the Sun [24]. This distribution can be found in Fig. 1, where the data is binned in cos(\(\theta\)) bins of size equal to 0.1, where \(\theta\) is the angular separation between each pair of FRBs and neutrinos. This distribution is also shown for the full dataset as well as three different equidistant (in log space) energy intervals from 0.1-10 TeV. In the case of a statistically significant association, one should see an excess in the cos(\(\theta\)) bin between 0.9-1 (similar to that seen in solar neutrinos [24]). We do not see such an excess. We however note that the zenith angle distribution is not uniform for some of the energy bins. This is due to a combination of multiple factors. Almost all the FRBs are located in the northern celestial hemisphere. Although, the full IceCube dataset is spread over both the hemispheres, almost all the neutrinos with reconstructed muon energies between 0.1-3 TeV are located in the northern hemisphere. Therefore, there are very few events in the antipodal directions of the FRBs. Therefore, cos(\(\theta\)) shows a downward trend for the second and third panels, as we approach cos(\(\theta\)) = −1. Finally, most of the IceCube events with energies between 3 and 10 TeV show a pile-up near the declination of 0°, with a steeply falling distribution towards 90°. This is then reflected in the zenith angle distribution, which thereby falls off as cos(\(\theta\)) approaches one.

To estimate the background, we bin the cosine of the angular between the neutrino-FRB patches at separations less than 7.35° (corresponding to the angular separation \(\cos \theta \in [0.9,1]\)) into six equidistant (in cos\(\theta\)) bins. This ensures that all the background bins have the same solid angle as the bin containing the signal events. Note that this procedure would emulate the background due to atmospheric neutrinos as well as any non-FRB induced astrophysical neutrinos. This aforementioned plot is shown in Fig. 2. The right-most bin corresponds to an angular separation of 3°, which is where all the signal events would be seen. The background is obtained by averaging the total number of events in the remaining five bins, which correspond to the off-source region. From Fig. 2, we do not see any statistically significant
TABLE I: Results of FRB-neutrino searches within an angular window of 3°, between the FRB and neutrino directions. The signal consists of the total number of coincident pairs within 3°. The background is obtained by averaging the data shown in Fig. 2 for the off-source bins (non-shaded), equally spaced in \( \cos(\theta) \) at angular separations greater than 3°. The error in the background represents the Poisson error. For all the reconstructed muon energy intervals, the expected number of signal events is smaller or comparable to the background, and therefore there is no statistically significant association between the CHIME FRBs and IceCube neutrinos. The last column contains the 90% credible interval flux limits calculated using Eq. 1.

| Muon Energy range | Signal | Background | 90% credible flux limit |
|-------------------|--------|------------|------------------------|
| Full dataset      | 339122 | 340146 ± 583 | 525                   |
| 0.1 - 3 TeV       | 310012 | 310725 ± 557 | 583                   |
| 1-3 TeV           | 146762 | 147143 ± 383 | 442                   |
| 3-10 TeV          | 25135  | 25021 ± 158  | 341                   |

TABLE II: Results of searches within the neutrino error region. The signal consists of the total number of coincident pairs within the neutrino error region. The background is obtained by counting the number of matches within a \( \cos(\delta\theta) \) angular cut, modulo a fixed offset of 5 degrees, where \( \delta\theta \) is the error in the neutrino position. The error in the background represents the Poisson error. Again, the number of signal events is comparable or smaller than the background for all the neutrino energy ranges analyzed. Therefore, we do not find any statistically significant association between the CHIME FRBs and IceCube neutrinos. The last column contains the 90% credible interval flux limits calculated using Eq. 1.

| Muon Energy range | Signal | Background | 90% credible flux limit |
|-------------------|--------|------------|------------------------|
| Full dataset      | 52965  | 53203 ± 231 | 262                   |
| 0.1 - 3 TeV       | 49000  | 49322 ± 222 | 220                   |
| 0.3 - 1 TeV       | 26063  | 26327 ± 162 | 152                   |
| 3 - 10 TeV        | 3363   | 3283 ± 57   | 158                   |
| > 10 TeV          | 453    | 466 ± 22    | 29                    |

excess in the 0-3 degree bin, compared to the off-source bins. Therefore, there is no statistically significant association between the IceCube neutrinos and the CHIME FRBs.

In order to directly compare the observed signal and background, we tabulate the observed signal events and compare them to the expected background obtained, after averaging all the coincident matches in the off-source bins. These results are summarized in Table I. The error in the background corresponds to the Poisson error. As we can see, for all the energy intervals, the number of signal events is smaller or comparable to the background. The only case when the total number of signal events is greater than the background is for the energy range 3-10 TeV where we observe 25135 signal events compared to an estimated background of 25021 events. However this excess is less than 1σ. In order to claim a 3σ detection, we should have seen at least 25495 coincident pairs.

Therefore, from this analysis, we do not find any statistically significant excess between the IceCube neutrinos and CHIME FRBs, when compared to the background. We then calculate 90% credible interval flux limits using Bayesian analyses using the prescription in 2021 PDG [25] for for positive definite signal events corresponding to a Poisson distribution, which can be obtained as follows:

\[
\frac{\int_0^{s_{up}} P(N|s+b)ds}{\int_0^\infty P(N|s+b)ds} = 0.9, \tag{1}
\]

Here, \( s_{up} \) is the desired 90% upper limit, and \( P(N|s+b) \) is the Poisson probability mass function for \( N \) observed events with mean given by \( b+s \), where \( b \) is the observed background. These 90% credible interval upper limits can be found in the last column in Table I.

B. Coincidences within neutrino error region

It is possible that the 3° angle used for the signal window in the previous sub-section is too large, since the average error for the IceCube neutrinos is about 0.9°. This would imply that the 3° angular window is too large and contains significant number background events.
FIG. 1: The angular distribution between of all IceCube neutrinos with respect to the CHIME FRBs for four different muon energy intervals, binned in $\cos(\theta)$ bins of width 0.1.

FIG. 2: Angular separation between the CHIME FRBs and neutrinos in six evenly spaced $\cos\theta$ bins from 0 to $7.35^\circ$. The yellow shaded region corresponds to the signal window corresponding to an angle of $3^\circ$. The remaining five bins are used for background estimation. A tabular summary comparing the signal and background can be found in Table I.
Therefore, as a slight variant of the earlier analysis, we now search for neutrino-FRB matches within the neutrino error circle, which is different for every neutrino. To estimate the background for such a search, we count the number of neutrino-FRB pairs, whose cosine of the angular correlation is within the cosine of the neutrino error circle, modulo an offset of $5^\circ$. In other words, if a given neutrino has an error of $\delta\theta$ and the observed angular separation between the neutrino and FRB is denoted by $\theta_{\nu-FRB}$, a neutrino-FRB coincident pair is considered as background, if it satisfies the following condition

$$|\cos(\theta_{\nu-FRB}) - \cos(5^\circ)| < 0.5[1 - \cos(\delta\theta)]$$

(2)

The factor of 0.5 ensures that the background is estimated within the same solid angle as the signal. Any such pairs at angular separations greater than $5^\circ$ are due to chance coincidences, and hence can be considered as background for this search. A tabulated summary of the results from this search for different neutrino energy ranges can be found in Table II. The error in the background corresponds to the Poissonian error. As we can see, even with this method, the observed number of coincidences within the neutrino error circle is smaller or comparable than the background events. Only for neutrinos in the 3-10 TeV energy range, we find that the total number of signal events is greater than the background. However, in this energy range, the number of excess events (80) is comparable to the error in the background (57), corresponding to an excess of only $1.4\sigma$. We should have observed at least 3454 matches in order to assert a $3\sigma$ detection. Therefore, again we do not find any evidence for any significant angular correlation, between the FRBs and neutrinos, by looking for matches within the neutrino error circle. We again report the 90% credible interval upper limits on FRB-induced neutrinos from this search (using Eq. 1) in Table I. In all the previous searches for neutrinos from FRBs using IceCube, both spatial and temporal searches from individual FRBs were carried out and fluence limits set on each of these FRBs. This is contrast to our analyses where our flux limits are from a stacked time-integrated searches. Therefore, a direct comparison with the previous fluence limits in literature is not possible.

Hence, to summarize, we do not find any statistically significant angular coincidence between the CHIME FRBs and IceCube neutrinos with either of the methods.

IV. CONCLUSIONS

In this work, we have searched for a spatial coincidence between IceCube neutrinos in the TeV energy range and FRBs detected by the CHIME telescope, using background estimation methods, which were used for neutrino astrophysics searches within Super-Kamiokande.

For our analysis, we consider the IceCube neutrinos with error region $< 3^\circ$. We do two searches. In the first search, we look for neutrino-FRB coincident pairs within $3^\circ$. The background for this search was estimated by averaging the coincident pairs in five angular bins between 3 and 7.35$^\circ$, where each bin has the same width in $\cos(\theta)$, which is the angular size of the window used to search for signal from the FRB, viz $3^\circ$. For our second search, we look for coincidences within the neutrino error circle. For the second search, we count the number of neutrino-FRB pairs within the same solid angle as the neutrino error circle, but offset by $5^\circ$, in order to emulate the backgrounds.

Our results from both the searches comparing the observed signal and background events are summarized in Table I and Table II. For both these searches, the number of signal events is comparable to the background. Therefore, we conclude that the observed angular coincidences are consistent with background. For both these searches, we then calculate the 90% credible interval upper limit on the FRB-induced neutrinos, which can be found in the aforementioned tables.

Note that if FRBs are steady state point sources of astrophysical neutrinos in the TeV energy range, their detection significance should increase with additional data. Many other radio telescopes such as uGMRT [26], FAST [27], VLITE [28] continue to discover new FRBs and with the advent of SKA [29] and next generation neutrino telescopes such as IceCube Gen2 [30], one should be able to get a clearer picture as to whether FRBs produce neutrinos in the TeV energy range. In a future work, we shall also carry out temporal searches to supplement the spatial searches implemented in this work, once the public IceCube neutrino catalog is updated.

ACKNOWLEDGEMENT

We are grateful to the CHIME and IceCube Collaborations for making their data publicly available and for thorough documentation of their data products. This work was originally motivated by the preprint arXiv:2112.11375, but has been modified, following the retraction of the preprint by the authors. We also acknowledge encouraging words and feedback from Ranjan Laha, Jonathan Katz, Clancy James, and Zorawar Wadiasingh, after the manuscript was posted.
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