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# Could quantum gravity slow down neutrinos?

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In addition to its implications for astrophysics, the hunt for GRB neutrinos could also be significant in quantum-gravity research, since they are excellent probes of the microscopic fabric of spacetime. Some previous studies based on IceCube neutrinos had found intriguing preliminary evidence that some of them might be GRB neutrinos with travel times affected by quantum properties of spacetime, with the noticeable feature that quantum spacetime would slow down some of the neutrinos while others would be sped up. Recently the IceCube collaboration revised significantly the estimates of the direction of observation of their neutrinos, and we here investigate how the corrected directional information affects the results of the previous quantum-spacetime-inspired analyses. We find that there is now no evidence for neutrinos sped up by quantum-spacetime properties, whereas the evidence for neutrinos slowed down by quantum spacetime is even stronger than previously found. Our most conservative estimates find a false alarm probability of less than 1% for these “slow neutrinos”, providing motivation for future studies on larger data samples.

Over the last few years one of the most studied candidate effects of quantum gravity has been in-vacuo dispersion, an energy dependence of the speed of ultrarelativistic particles (see *e.g.* Refs. [1–10] and references therein). This effect could also lead to observably large manifestations, even if, as it appears to be safe to assume [1–7], its characteristic length scale

turns out to be of the order of the minute Planck length, or anyway not much larger than that. Observations of GRBs [1–4], which emit (nearly-)simultaneously photons of different energies and (probably [11–14]) neutrinos, could be well suited for finding a manifestation of the novel energy dependence of the speed.

Some of us were involved in some studies [9, 15–19] of IceCube neutrino data which produced intriguing results: these studies compared observation times and directions of GRBs with those of IceCube neutrinos, finding preliminary statistical evidence of the fact that some of those neutrinos would be GRB neutrinos receiving a contribution to their travel times from quantum-gravity-induced in-vacuo dispersion. A potential weak point of those analyses was that they found comparable statistical significance for neutrinos being slowed down and neutrinos being sped up by in-vacuo dispersion: the most popular quantum-gravity intuition is that [1] all particles with half-integer spin should be affected by the same effect, though a specific model with breakdown of relativistic invariance can accommodate [20] for an effect which has opposite sign for the two helicities of the neutrino (a scenario which might here be relevant since we have no helicity information for IceCube neutrinos).

Recently the IceCube collaboration revised significantly [21] their estimates of the direction of observation of their neutrinos, and we here investigate how the corrected directional information affects the results of the previous quantum-gravity-inspired analyses. We start by quickly reviewing the formalization and parametrization of the model already used in the previous studies of Refs. [15–19]:

$$\Delta t = \eta D(1) \frac{\mathcal{K}(E, z)}{M_P} \quad (1)$$

where  $\Delta t$  is the contribution to the travel time of the neutrino from quantum-gravity-induced in-vacuo dispersion,  $\eta$  is a dimensionless parameter to be determined experimentally,  $M_P$  denotes the Planck scale ( $\sim 10^{28} eV$ , inverse of the Planck length),  $D(z)$  is a function of the redshift  $z$  of the GRB associated to the neutrino<sup>1</sup>

$$D(z) = \int_0^z d\zeta \frac{(1 + \zeta)}{H_0 \sqrt{\Omega_\Lambda + (1 + \zeta)^3 \Omega_m}},$$

and  $\mathcal{K}$  is a function of  $D(z)$  and of the energy  $E$  of the neutrino:  $\mathcal{K}(E, z) \equiv ED(z)/D(1)$ .

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<sup>1</sup>  $\Omega_\Lambda$ ,  $H_0$  and  $\Omega_m$  denote, as usual, respectively the cosmological constant, the Hubble parameter and the matter fraction, for which we take the values given in Ref. [22];  $D(1)$  in Eq.(1) is of course  $D$  evaluated for redshift of 1.

In the data analysis  $\Delta t$  will be estimated in terms of the difference in times of observation<sup>2</sup> between a GRB and a neutrino which can be tentatively described as produced in coincidence with that GRB. Our first task is to find these “GRB-neutrino candidates” [15–19]: neutrinos whose direction is compatible with a GRB direction and whose energy and time of observation render them compatible, according to Eq.(1), with the time of observation of the GRB. As it was clarified in detail in Refs. [15–19] (and will be clear also from the analysis reported here below), for none of our GRB-neutrino candidates we can be certain that it is indeed a GRB neutrino: the correspondence between direction and time of observation can of course also occur accidentally and for the single association between GRB and neutrino our strategy of analysis will inevitably be inconclusive. However, if such associations are numerous enough (and “significant enough”, see below) we could end up in the position of being certain that our data sample contains some GRB neutrinos whose propagation was affected by quantum gravity even though we would not be able to establish which of our GRB-neutrino candidates actually are GRB neutrinos.

Since one of our main goals is to weigh the impact on this sort of quantum-gravity-motivated analysis of the revised estimates [21] of the direction of observation of IceCube neutrinos, for this study we use the same data sample and the same criteria for the selection of GRB-neutrino candidates already used in the previous studies of Refs. [15–19], where the interested reader will find them described in detail. We here just stress that the analyses are confined to neutrinos with energy between 60 and 500 TeV and one has a GRB-neutrino candidate if the GRB and the neutrino were observed at times that differ by no more than 3 days and the angular distance between the direction of the neutrino and the direction of the GRB is within a  $3\sigma$  region, with  $\sigma = \sqrt{\sigma_{\text{GRB}}^2 + \sigma_{\nu}^2}$  (with  $\sigma_{\text{GRB}}$  and  $\sigma_{\nu}$  denoting, respectively, the directional uncertainties for the GRB and for the neutrino).

Taking into account the recently revised estimates [21] of the direction of observation of IceCube neutrinos we only find (see Methods) 3 GRB-neutrino candidates which appear to be “early”, *i.e.* neutrinos which could have been sped up by quantum-gravity effects. And we find (see Methods) that the probability of finding accidentally at least 3 such early neutrinos in our data sample is a whopping 81%. While of course we cannot exclude that

<sup>2</sup> If there were no quantum-gravity effects, a GRB neutrino would be observed (nearly-)simultaneously with the GRB that produced it. We attribute the whole of the time-of-arrival difference to the quantum-gravity-induced  $\Delta t$  of the neutrino, since the photons composing the GRB signal are of much lower energies than our neutrinos and the effect we are studying depends linearly on energy (so any  $\Delta t$  of the photons would be negligible with respect to the  $\Delta t$  of the neutrino).

this might have to be reassessed as more data is accrued, evidently at present the corrected IceCube data provide no encouragement for the hypothesis of quantum-gravity effects speeding up neutrinos. Moreover, the study recently reported in Ref. [23] further disfavours this hypothesis: the rather robust evidence [24] that a neutrino with energy of at least 183 TeV was observed from the blazar TXS 0506+056 strongly constrains “superluminal” neutrinos (the early neutrinos of our analysis) since such superluminal neutrinos should quickly lose energy via electron-positron pair production [23].

Next we look at the hypothesis of “late” GRB neutrinos, where our findings instead are even more intriguing than those previously reported (using erroneous neutrino directions) in Refs. [15–19]. We find (see Methods) 7 GRB-neutrino candidates which appear to be “late”, *i.e.* neutrinos which could have been slowed down by quantum-gravity effects. And we find (see Methods) that the probability of finding accidentally at least 7 such late neutrinos in our data sample is of only 5%. Evidently the case of late neutrinos deserves further investigation. Our 7 late GRB-neutrino candidates are shown in Fig. 1 and have correlation of 0.56.

Going back to the background issues that our selection criteria confront us with, it is important to notice that (see Methods) it is actually likely, with probability of 83%, that at least 1 of our 7 late GRB-neutrino candidates be accidental, and the probability of at least 2 accidental candidates is still a rather high 39% (while the probability of at least 3 accidental candidates goes down to a more bearable 18%). This suggests that, even tentatively assuming the quantum-gravity model is correct, among the data points in Fig. 1 it is likely that there are 1 or 2 which play the role of noise.

We must also stress that in order to produce Fig. 1 one must assign a value of redshift to the GRBs, but only for a minority of GRBs the redshift is known, and in particular only for one of the data points in Fig. 1 the redshift was measured. As stressed in Refs. [15–19] this issue of estimating the redshift for GRBs whose redshift was not measured is rather challenging, also because we can anticipate that the distribution in redshift of GRBs that produce neutrinos will be significantly different from the distribution in redshift of generic GRBs. When more data will be available the distribution in redshift of GRBs that produce neutrinos could be estimated reliably from the analysis itself: one would use the distribution of the GRB-neutrino candidates with known redshift to estimate the redshift distribution of those whose redshift is unknown. With few data points this approach is much less reliable,

but nonetheless we follow again Refs. [15–19] by estimating the redshift of all long GRBs relevant for Fig. 1 on the basis of the single case in which the redshift is known. Only one short GRB is relevant for Fig. 1 and it is of unknown redshift, so (following again Refs. [15–19]) we assign to it redshift of 0.6.

While this research area will undoubtedly benefit from the gradual accrual of knowledge of the redshift distribution of GRBs which are observed in neutrinos, in Methods we show that our findings on the significance of the feature exposed in Fig. 1 depend only weakly on the assumptions made for redshifts.

Also relevant for the understanding of Fig. 1 is the fact that for one of our neutrinos there are three GRBs compatible with it within our temporal and directional window. The same issue was faced in Refs. [15–17], and we follow again those previous studies by selecting the GRB which pairs with that neutrino in the way that leads to the highest overall correlation for the analysis. While the impact of this highest-correlation criterion might have to be scrutinized more carefully if, when more suitable neutrinos are observed, one found several neutrinos pairing with more than one GRB, since our analysis involves only one such neutrino we find (as shown in Methods) that our estimates of the significance of the feature exposed in Fig. 1 depend only weakly on the adoption of this highest-correlation criterion.

The line in Fig. 1 was obtained by best-fitting the data points, which gives  $\eta=21.7$  with  $\delta\eta=4.5$ . Within the model which we are here taking as working assumption the spread of data points around that best-fit line should be interpreted considering that one or two of the points likely are just noise, and for nearly all the points we relied on a rough estimate of redshift.

Our next task is to estimate a “false alarm probability”, *i.e.* estimate how likely it would be for our data sample to produce accidentally (without any intervening quantum-gravity effects) at least 7 late GRB-neutrino candidates with correlation of at least 0.56. Following again what was done in the previous related studies of Refs. [15–17], we do this by performing  $10^5$  randomizations of the times of detection of the neutrinos relevant for our analysis, keeping their energies and directions fixed, and for each of these randomizations we redo the analysis just as if they were real data<sup>3</sup>, including the use of the criterion of

<sup>3</sup> The interested reader can find applications of this method of statistical analysis to cases not involving the study of neutrinos in Refs.[25–29]. The key merit of this approach is that one obtains fully realistic simulated data by just “reshuffling” randomly the real data in a way that only affects the correlation being studied, without modifying other properties of the data. In our case the correlation of interest is between

selecting highest-correlation cases when multiple GRB partners are found for a neutrino. We find that this “false alarm probability” is of only 0.7%, which we feel is our key result for motivating further studies.

Our primary objective has been reached: we established that the revised estimates [21] of the direction of observation of IceCube neutrinos affect strongly the quantum-gravity-motivated analysis: there is now no encouragement for the hypothesis of early neutrinos, while, on the contrary, for late neutrinos the preliminary evidence is significantly stronger than found with the previous incorrect estimates of the directions.

In closing, we focus on one additional task: extending the energy range of the analysis above 500 TeV. As stressed in Refs. [15–19], going below 60 TeV should be useless since most of the additional GRB-neutrino candidates would be background, atmospheric neutrinos. Going above 500 TeV would not pose background problems but it was not done because of the needed size of the time window: the effect grows linearly with energy and therefore, since a 3-day window is needed [15–19] for neutrinos of up to 500 TeV, for a neutrino of, say, 2 PeV, one might have to adopt a 12-day window, in which case the challenge of handling multiple GRB “partners” would grow unmanageably. We here propose a way to include neutrinos with energy greater than 500 TeV that does not require such wide temporal windows: one would still only use the neutrinos with energy between 60 and 500 TeV to estimate a value of the coefficient  $\eta$  of Eq.(1) and then look for candidate GRB-neutrinos with energy higher than 500 TeV which are compatible with that estimate of  $\eta$ .

We find (see Methods) two late GRB-neutrino candidates with energy greater than 500 TeV, which are compatible with  $\eta = 21.7 \pm 9.0$  (we allowed for a  $2\delta\eta$  interval). Also in this case we encounter the multiple-GRB-partner issue, which again we handle by resorting to the highest-correlation criterion. The two resulting GRB-neutrino candidates are shown in red in Fig. 2, together with the seven candidates already shown in Fig. 1. The overall correlation for the nine points in Fig. 2 is a remarkable 0.9997.

This very high value of correlation does not in itself characterize the significance of our findings: also in this case we need a false-alarm probability quantifying how likely it would be for the available neutrinos with energy greater than 500 TeV to accidentally produce the time-of-observation difference  $\Delta t$  and the redshift-corrected energy  $\mathcal{K}$ , and therefore simulated data obtained by “reshuffling” the times of observation would surely not reflect any actual correlation possibly present in the real data. Such simulated data can therefore be used reliably to test how frequently some high values of correlation could be found accidentally even when no true correlation is present.

late GRB-neutrino candidates leading to this high value of correlation, when combined with our late GRB-neutrino candidates with energy between 60 and 500 TeV. We performed  $10^5$  randomizations of the times of detection of the available neutrinos with energy greater than 500 TeV, keeping their energies and directions fixed, and we computed the probability of having at least two late GRB-neutrino candidates with energy greater than 500 TeV which are compatible with  $\eta = 21.7 \pm 9.0$  and produce an overall correlation of at least 0.9997. Also for our simulated data we handle the multiple-GRB-partner issue by selecting the case with highest correlation. We find that the “false alarm probability” is of only 0.005%.

We shall not dwell on the potential significance of this remarkably low false-alarm probability: our investigations started with the goal of studying the impact of Ref. [21] on analyses focusing on the range 60-500 TeV, and the inclusion of events with energy greater than 500 TeV was an afterthought which, while evidently leading to an intriguing result, we feel should not divert attention from the main part of our analysis. Still, combining our findings in the range 60-500 TeV and our findings for energies greater than 500 TeV, there appears to be plenty of motivation for monitoring the evolution of this sort of analyses as more high-energy-neutrino data is accrued.

## METHODS

**Early neutrinos with energy between 60 TeV and 500 TeV.** For the GRBs we use the catalogue that can be found at [icecube.wisc.edu/~grbweb\\_public/Summary\\_table.html](http://icecube.wisc.edu/~grbweb_public/Summary_table.html). For the neutrinos we use the same data sample of Refs. [15–19] and we also follow Refs. [15–19] in focusing on “shower events” with energy between 60 TeV and 500 TeV. Using the selection criteria of Refs. [15–19] (but now relying on the corrected directional data of the more recent Ref. [21]) we find three early GRB-neutrino candidates, which are reported in Table 1.

We estimate the probability that three early GRB-neutrino candidates are found accidentally in our dataset (without any intervening quantum-gravity effect) by generating  $10^5$  simulated datasets, each obtained by randomizing the time of observation of the neutrinos, while keeping their energy and direction fixed, and counting how many times, in these simulated datasets, there are at least 3 neutrinos that find an early GRB-association. We find that this happens in 81% of the cases, and we therefore conclude that our three early

GRB-neutrino candidates are most likely meaningless, just pure background.

**Late neutrinos with energy between 60 TeV and 500 TeV.** We find seven late GRB-neutrino candidates with energy between 60 TeV and 500 TeV, which we report in Table 2. For one of these, with energy of 86.1 TeV, there are three possible associations with a GRB. Only for the GRB associated with the 61.7 TeV neutrino the redshift is known.

By generating  $10^5$  simulated datasets, each obtained by randomizing the time of observation of the neutrinos, while keeping their energy and direction fixed, we find that the probability of obtaining accidentally, without any intervening quantum-gravity effect, at least seven late GRB-neutrino candidates with energy between 60 TeV and 500 TeV is of only 5%.

However, even assuming that some of our seven late GRB-neutrino candidates are “signal” (*i.e.* their propagation times were affected by quantum gravity) it is likely that some of them are “background” (*i.e.* they were picked up in the analysis accidentally). In order to see this we perform an analysis which sets aside our seven selected neutrinos: we randomize the times of observation of the neutrinos which were not selected by our criteria (and therefore should be assumed to be unrelated to any of the GRBs, with or without quantum-gravity effects) and compute how frequently in such randomizations one gets the accidental appearance of late GRB-neutrino candidates. Essentially through these randomizations we estimate which fraction  $\zeta$  of an ensemble of neutrinos that surely does not include GRB neutrinos would accidentally be picked up as a GRB-neutrino candidate. In general, if such an analysis considers  $N$  neutrinos and there are  $M$  true GRB neutrinos, the number  $L$  of GRB-neutrino candidates found clearly will be such that  $N \geq L \geq M$ , and then one can estimate  $M$  (number of GRB-neutrino candidates which actually are GRB neutrinos) through the relationship  $M + \zeta \cdot (N - M) = L$ , in which  $N$  and  $L$  are known, while  $\zeta$  is estimated using the randomizations. Following this procedure we find a probability of 83% that at least 1 of our 7 late GRB-neutrino candidates is a background neutrino, a probability of 39% that at least 2 neutrinos are background, and a probability of 18% that at least 3 neutrinos are background.

Table 2 also reflects the fact that among the 3 possible GRB partners for the neutrino with energy of 86.1 TeV we picked for Fig. 1 the one producing the highest overall correlation.

**Early neutrinos do not even “help” when combined with late neutrinos.** Taking

into account the recently revised estimates [21] of the direction of observation of IceCube neutrinos we found no encouragement for the early-neutrino hypothesis, while we found a noteworthy false-alarm probability for late neutrinos. With the previous (erroneous) version of the IceCube data there was a statistically-significant case separately for early neutrinos and for late neutrino and actually the highest statistical significance was found when combining early and late neutrinos in a single analysis. The most popular quantum-gravity intuition is that [1] all particles with half-integer spin should be affected by the same effect, but there is a model with breakdown of relativistic invariance which can accommodate [20] for an effect which has opposite sign for the two helicities of the neutrino (a scenario which might here be relevant since we have no helicity information for IceCube neutrinos), and therefore it is indeed legitimate to contemplate also the possibility of combining early and late neutrinos in a single analysis.

The fact that (with the corrected IceCube data) we find only 3 early-neutrino candidates, and that we estimate that all 3 are likely background, already suggests that with the corrected IceCube data we should find no encouragement also for this hypothesis combining early and late neutrinos, but it is still interesting to get a quantitative assessment of this point.

We did this by applying the same statistical tools which we applied separately to early and late neutrinos to the combination of all our GRB-neutrino candidates (both early and late). We find that for this case which combines early and late neutrinos the false-alarm probability is of 4.6%. In itself a false-alarm probability of 4.6% would not be discouraging, but the key observation here is that for the late neutrinos on their own we found a false-alarm probability of 0.7%, while adding the early neutrinos to the analysis brings the false-alarm probability to the much higher value of 4.6%. We interpret this as further evidendence of the fact that the presently-available data provide no motivation for the early-neutrino hypothesis, not even in analyses combining early and late neutrinos.

**Late neutrinos with energy above 500 TeV.** We select a shower neutrino with energy greater than 500 TeV as late GRB-neutrino candidate if it satisfies the same angular criterion used for the lower energy neutrinos, and if the difference between its time of arrival and that of the GRB is positive and lies within the range  $|\Delta t - \eta \cdot \mathcal{K}(E, z)| \leq 2\delta\eta \cdot \mathcal{K}(E, z)$ . We find 2 such late GRB-neutrino candidates with energy greater than 500 TeV, and their properties

are given in Table 3. For one of these neutrinos we find three possible GRB partners and we handle this again by selecting the case which leads to the highest overall correlation.

**Weakness of the dependence on the highest-correlation criterion.** As stressed above, one of the neutrinos that play a role in our analysis, a neutrino with energy 86.1 TeV, is compatible with three GRBs within our temporal and directional window. This was handled in our analysis by focusing on the GRB-neutrino pair for our 86.1 TeV neutrino which produces the highest overall correlation. Of course, we used the same highest-correlation criterion also when our simulated data presented more than one GRB paired to the same neutrino. Having adopted the same criterion both to real data and to simulated data ensures that our estimates of false-alarm probabilities are not biased, but still one might wonder whether accidentally our highest-correlation criterion was strongly responsible for the smallness of our false-alarm probabilities.

In order to probe this issue we pair our 86.1 TeV neutrino with GRB120121B, which among the three possible GRB partners is the one producing the lowest correlation, a correlation of 0.53. (As shown in Table II, for our main analysis we paired the 86.1 TeV neutrino with GRB120121A, producing the highest correlation, a correlation of 0.56.) In our simulations we then compared this lowest value of correlation of our true data, with the highest value of correlation for simulated data, thereby giving an “unfair advantage” to the simulated data. Of course, this produces an increase in the false-alarm probability but only rather moderate: from the 0.7% found in our main analysis one gets to a false-alarm probability of 0.9% by giving this “unfair advantage” to the simulated data.

**Weakness of dependence on the assumptions about redshifts.** As stressed above, for GRBs whose redshift is unknown analyses such as ours can estimate that unknown redshift by inferring a redshift distribution for GRBs observed in neutrinos from data itself. While this approach should be very powerful when a large data sample becomes available, at present we are forced to make these estimations on the few data available and surely we must expect that the inferred distribution is very uncertain. However, as we shall here show, our key results, which take the form of some false-alarm probabilities, do not appear to depend strongly on the uncertainties of the redshift distribution.

We are proposing that at present (since indeed few data are available) one should only use for the analysis the average value of redshift of GRBs observed in neutrinos, so a single

value of redshift is estimated and it is attributed to all GRBs of unknown redshift. Of course, we use the same criterion for unknown redshifts also for our simulated data and therefore our estimates of false-alarm probabilities are not biased, but still one might wonder whether accidentally our criterion for handling unknown redshifts happened to be strongly responsible for the smallness of our false-alarm probabilities.

In order to probe this issue we still used our redshift criterion on true data, but instead for simulated data we estimated the redshift of GRBs whose redshift is unknown by choosing the value that produces the highest correlation. We still adjust only a single parameter (the same value of redshift is given to all GRBs in the simulated data whose redshift is unknown), but we adjust that parameter in the way that maximizes the correlation. We are once again giving an “unfair advantage” to the simulated data, and of course this produces an increase in the false-alarm probability but only rather moderate: from the 0.7% found in our main analysis one gets to a false-alarm probability of 1.2% by giving this “unfair advantage” to the simulated data.

**Data availability.** For the GRBs we used the catalogue that can be found at [icecube.wisc.edu/~grbweb\\_public/Summary\\_table.html](http://icecube.wisc.edu/~grbweb_public/Summary_table.html). For neutrinos we used the data reported in Ref. [21].

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## AUTHOR CONTRIBUTIONS

GAC proposed the project. All authors contributed to all the aspects of the analysis, with GAC, GG and GR leading the work on pure theory, GAC, GD, and GG leading the work on statistical methods, MGD, GG and GR leading the numerical work.

## ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to G. A.-C.

## COMPETING INTERESTS

The authors declare no competing interests.

## TABLES

$E_\nu$ [TeV]	$\Delta t$ [s]	z	S/L	GRB
98.5	-113050	-	L	100605A
186.6	-175141	-	L	120224B
66.7	-234884	-	L	140219B

TABLE I. Our three “early” GRB-neutrino candidates. The first column gives the energy of the neutrinos. The second column gives the difference  $\Delta t$  between the time of observation of the neutrino and that of the associated GRB. The third column gives the redshift of the GRB, using “–” when the redshift is unknown (in all these three cases it is unknown). The fourth column specifies whether the GRB is short (S) or long (L). The fifth column specifies the GRB.

## FIGURE LEGENDS/CAPTIONS (FOR MAIN TEXT FIGURES)

**Figure 1. Bla bla bla bla bla bla bla.** The seven late GRB-neutrino candidates with energy between 60 and 500 TeV described in the main text. The blue line was obtained by bestfitting the seven points with the linear relationship between  $\Delta t$  and  $\mathcal{K}$  given by Eq.(1).

**Figure 2. Bla bla bla bla bla bla bla.** Here the red points are for our two late GRB-neutrino candidates with energy greater than 500 TeV. The black points and the blue

$E_\nu$ [TeV]	$\Delta t$ [s]	$z$	S/L	GRB	
98.5	15446	-	L	100604A	*
86.5	160909	-	L	110625B	*
61.7	73690	1.38	L	111229A	*
86.1	200349	-	L	120121C	
86.1	213239	-	L	120121B	
86.1	187050	-	L	120121A	*
186.6	229039	-	L	120219A	*
134.2	135731	-	S	140129C	*
66.7	23286	-	L	140216A	*

TABLE II. In this table we report the seven “late” GRB-neutrino candidates. The first five columns provide the same information as in I. The last column highlights with an asterisk the GRB-neutrino candidates selected by the best-correlation criterion described in the main text.

$E_\nu$ [TeV]	$\Delta t$ [s]	$z$	S/L	GRB	
1035.5	706895	-	S	110801B	*
1035.5	907892	-	L	110730A	
1035.5	1320217	-	L	110725A	
1800	7435884	3.93	L	120909A	*

TABLE III. Selected GRB PeV-neutrino candidates. The columns provide the same information as in Table 2.

line are the same as in Fig. 1.

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