Supernova detection capabilities of Super-Kamiokande

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Abstract

Super-Kamiokande's capabilities to detect neutrino events from supernovae have been examined. Signal and background rates are examined and compared against each other for three different data sets available in public documents. A brief optimization study is performed as a consistency check. Files have been made available in order that these results can be used for further optimization studies for correlation analyses.

1 Introduction

The purpose of this report is to provide summarized information about background rates and efficiencies for supernova events at Super-Kamiokande (Super-K, SK). This is meant to be used for a joint gravitational wave/neutrino correlation study, as proposed in [1]. Event rates are examined on their dependence on the energy threshold, so that for a given energy threshold (ideally one for which the random gravitational wave/neutrino coincidence rate is low) one can easily determine the corresponding sensitivity and rates at SK.

Three different estimates are made. The first one uses signal and background information from published supernova burst searches [2, 3]. This one does not exactly reproduce their results as information about applied efficiencies is not available. The second one uses background and efficiency information from the search for supernova relic neutrinos [4] and solar neutrinos [5]. The third analysis uses the same data, but without any cuts on the background, assuming 100 % efficiency. This can be useful if there is an external trigger (such as gravitational waves) which can be used as a coincidence criterion. The information here will be useful to evaluate parameters for potential correlation analyses with gravitational waves.

2 Signal

2.1 Expected number of signal events

Fig. 2.4 from [3], replicated in this report in fig. 1, shows the number of events per energy bin for each reaction detected by Super-K for a supernova 10 kpc away from the earth. By summing up all the lines one obtains the total number of events per energy bin. When only looking at events with an energy greater than a given threshold energy, then the total event number in SK is given by the integral over all energies greater than threshold. As the event count decreases rapidly for energies above 60 MeV we use this as an upper integration limit. Figure 3 shows the result as the dashed line.

For the three analyses mentioned in the introduction we applied different efficiencies to the signal. For the one which is supposed to be close to earlier supernova burst searches, no efficiencies were available. We therefore applied the efficiencies shown in figure 2, which were originally applied to solar neutrino searches [5]. For energies higher than 15 MeV, we assumed the efficiency to be 64 %, as the efficiency curve seems to flatten. In addition, we assumed 94 % efficiency for the R_{mean} cut [2, sec. 2.2], as we will be interested in two supernova neutrino events.

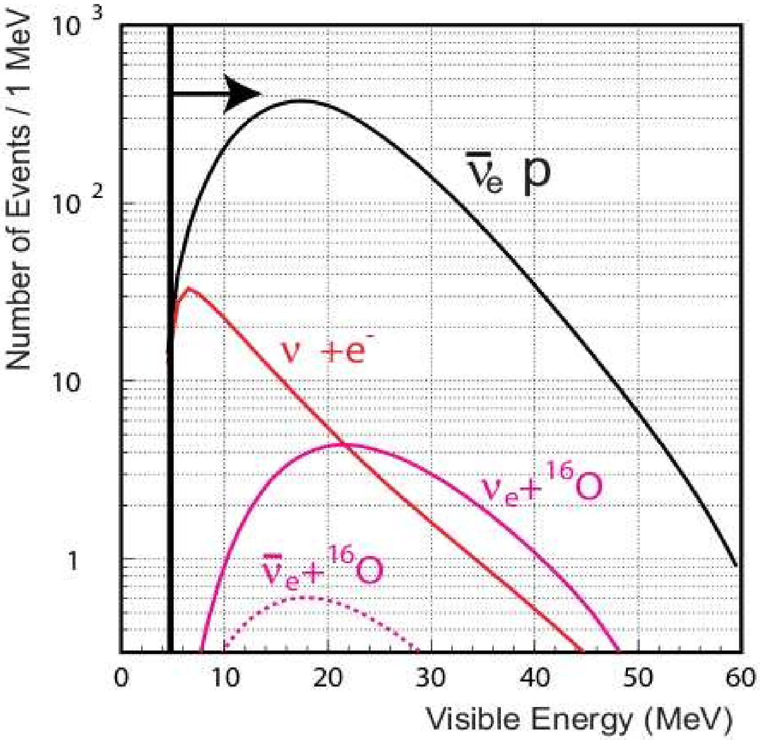

Figure 1: SK neutrino events per energy for a supernova at 10 kpc, from fig. 2.4 from [3].

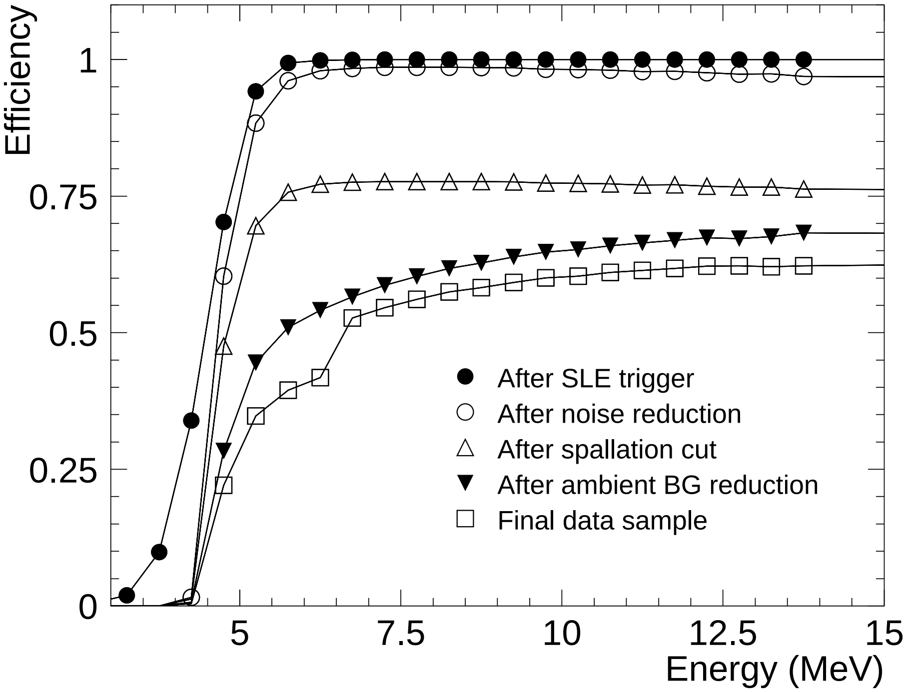

Figure 2: Energy-dependent efficiency after various background reduction steps applied when searching for solar neutrinos, from fig. 28 from [5].

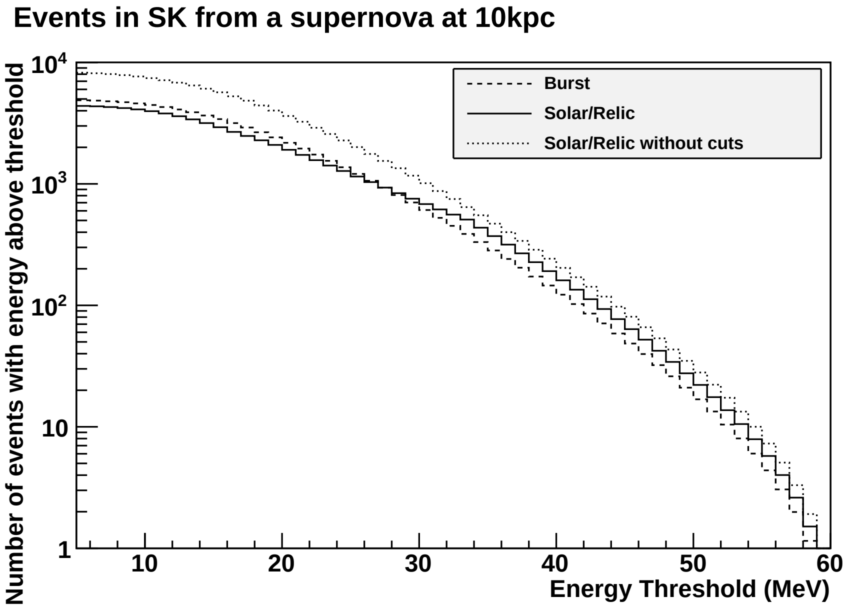

Figure 3: Expected number of SK events with energy greater than a certain threshold for a supernova at 10 kpc. The dashed line uses efficiencies from the burst-based analysis, the solid line uses efficiencies from the solar/relic-based one and the dotted line assumes 100 % efficiency.

For the solar/relic-based analysis, the same efficiencies have been used for energies less than 17 MeV. However, the R_{mean} cut was not applied for these events. Instead, a solar direction cut was applied: All events with $\cos\theta_{\text{sun}} > 0.87$ are assumed to be rejected [4]. Because the signal is expected to be nearly isotropic we apply an efficiency of 93.5 % for this cut. For energies greater than 17 MeV we use efficiencies given in the relic paper: For energies between 17 MeV and 34 MeV (which is where a solar direction cut was performed in the relic neutrino paper), an efficiency of 47 % was applied, and for even higher energies (not including the solar direction cut) 79 % was applied [4].

For the solar/relic-based analysis with no cuts applied, we assume the total efficiency to be 100 %.

2.2 Supernova distance to see one event

As the neutrino flux depends on the distance D as $1/D^2$, we can find the distance at which the mean event count from a supernova is 1 event in Super-K. This is shown in figure 4.

2.3 90 % probability for one event

Assuming Poisson statistics, the probability that we see at least one event in the detector when the mean event count is μ is given by

$$p(\mu) = 1 - \mathrm{e}^{-\mu} \tag{1}$$

Using this relation, we can find the distance at which the probability to see at least one event in the detector is 90 %. This corresponds to a mean event count of $\mu = \log 10 = 2.3$. Figure 5 shows that distance vs. energy threshold.

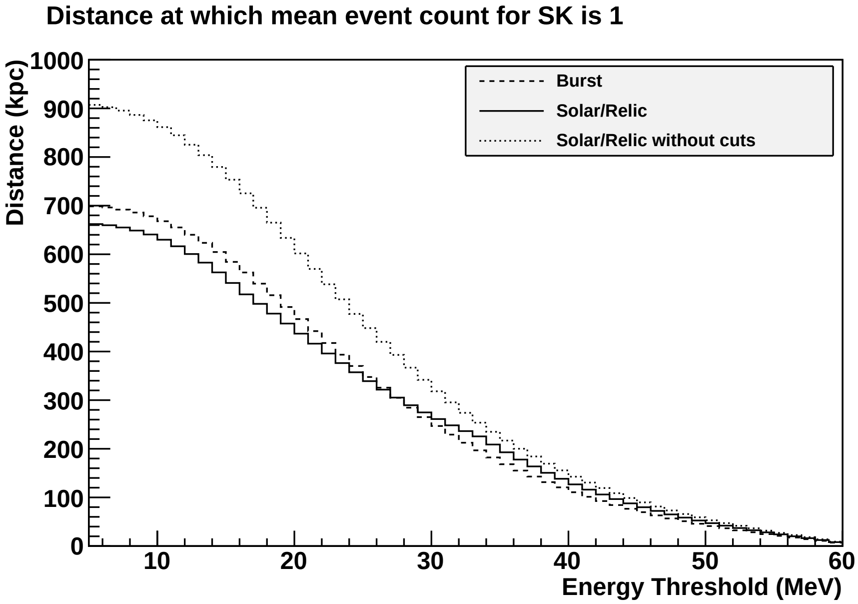

Figure 4: Distance at which the mean event count for a supernova is 1 in SK when only considering events with energy higher than a certain threshold.

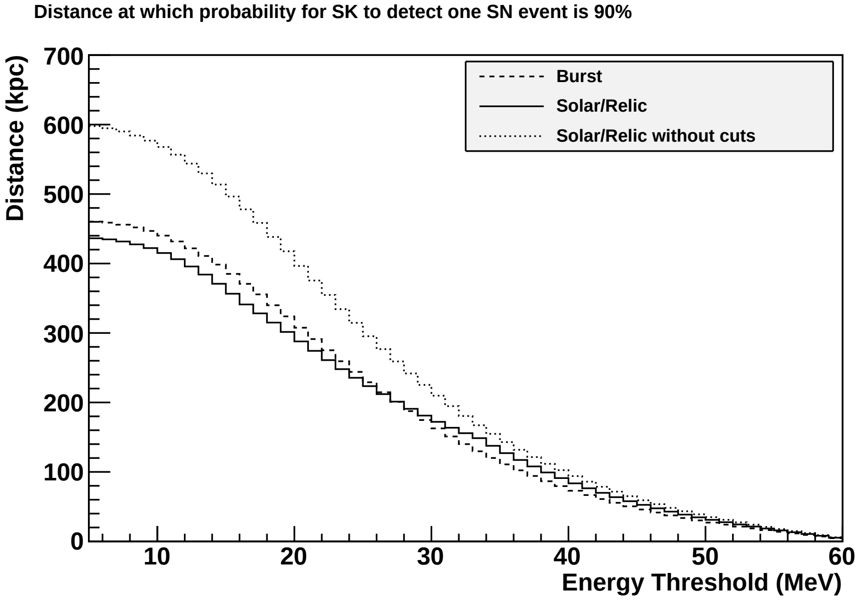

Figure 5: Distance at which the probability to detect one event from a supernova in SK is 90 % when considering events with higher energy than a certain threshold.

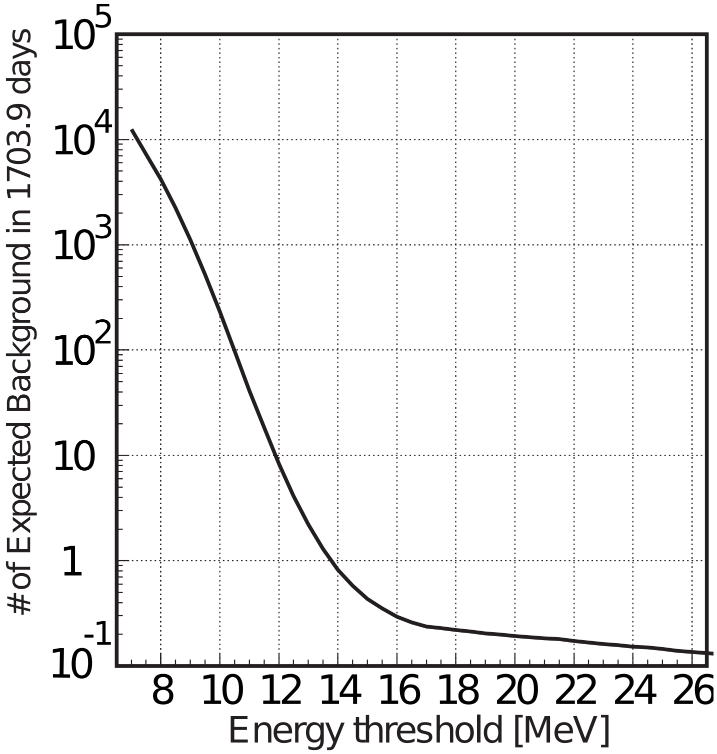

Figure 6: Expected background for supernova burst search. A background event here means two random coincident events within a time window of 20 s in 1703.9 days. The plot is from fig. 3.15 from [3].

3 Background

3.1 Background event rate

For the burst-based analysis, fig. 3.15 from [3], or fig. 6 shows the number of expected chance coincidences as a function of energy threshold, for a period of 1703.9 days. Using the relation

$$C = r^2 T \tag{2}$$

with C being the coincidence rate, r the background event rate and T the time window (20 s in this case), we can find the background rate that was assumed.

For the solar/relic regime, fig. 1 from [4], replicated in fig. 7, shows the differential energy spectrum for energies higher than 20 MeV. For lower energies, fig. 39 from [5], or fig. 8 here, shows expected background rates per energy. It should be noted that the latter data do not include the solar direction cut. However, fig. 40 in the same document (or fig. 9 in this document) shows that about 11.5 % of all background events have $\cos\theta_{sun} > 0.87$ and would therefore be removed by the solar direction cut. The low energy background rates have been scaled accordingly.

Again, we are interested in the integral background rate above a certain energy threshold, as shown in figure 10.

It is noteworthy that the background for the burst-based analysis nearly matches the solar/relic background without cuts. This might mean that for the supernova burst search, a higher (non-reduced) background was assumed than for the solar/relic one. Also, for the burst-based analysis, data were only available between 7 MeV and 26 MeV. For the regions not covered by that, background rates from

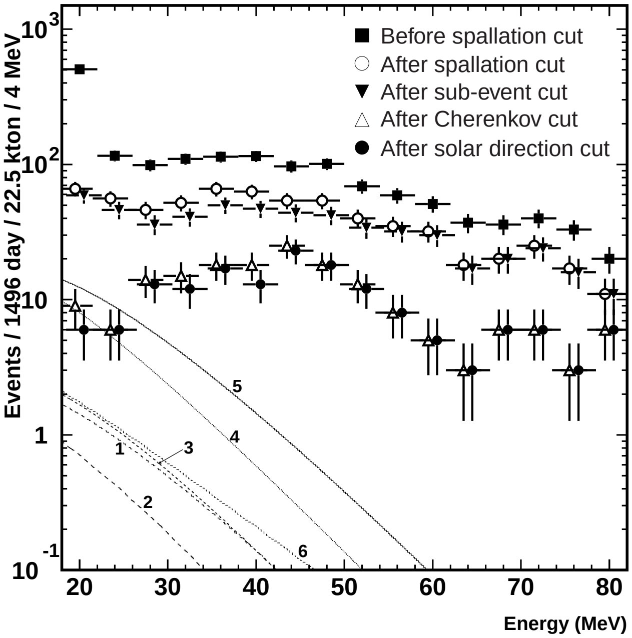

Figure 7: Remaining background events per energy for supernova neutrino events at SK for high energies after various steps of background reduction, from [4, fig. 1].

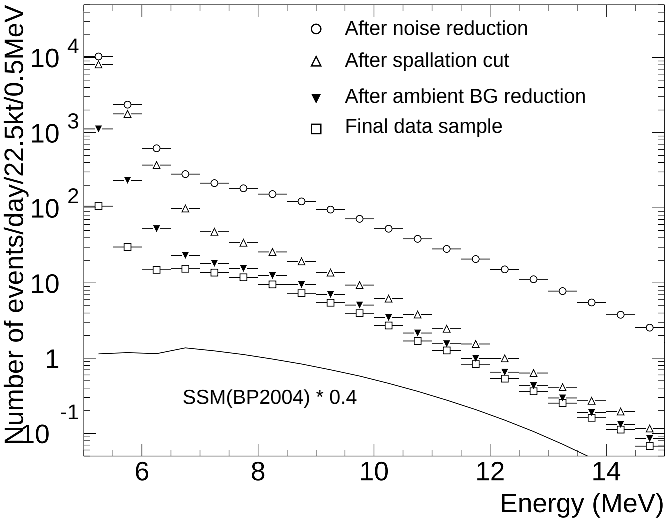

Figure 8: Remaining background events per energy for supernova neutrino events at SK for low energies after various steps of background reduction, from [5, fig. 39].

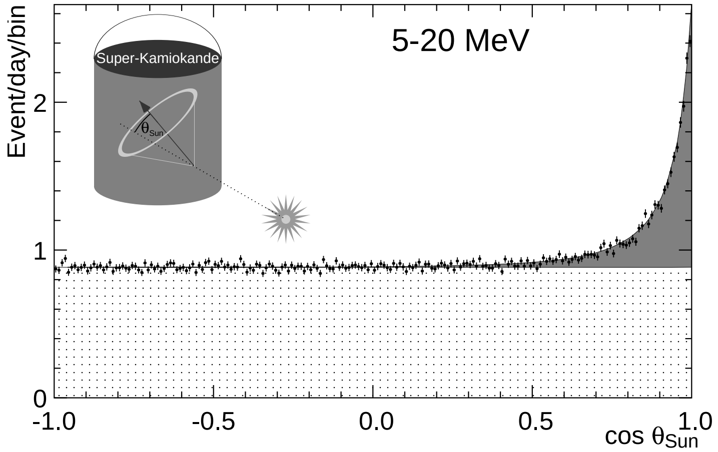

Figure 9: Angular background event distribution, from [5, fig. 40].

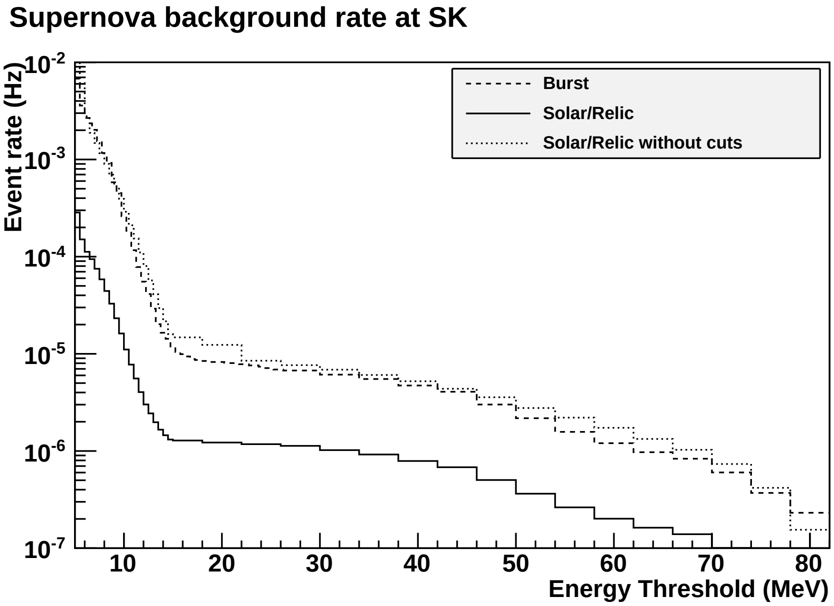

Figure 10: Background event rate for supernova search in SK when considering events with energy greater than a given threshold energy.

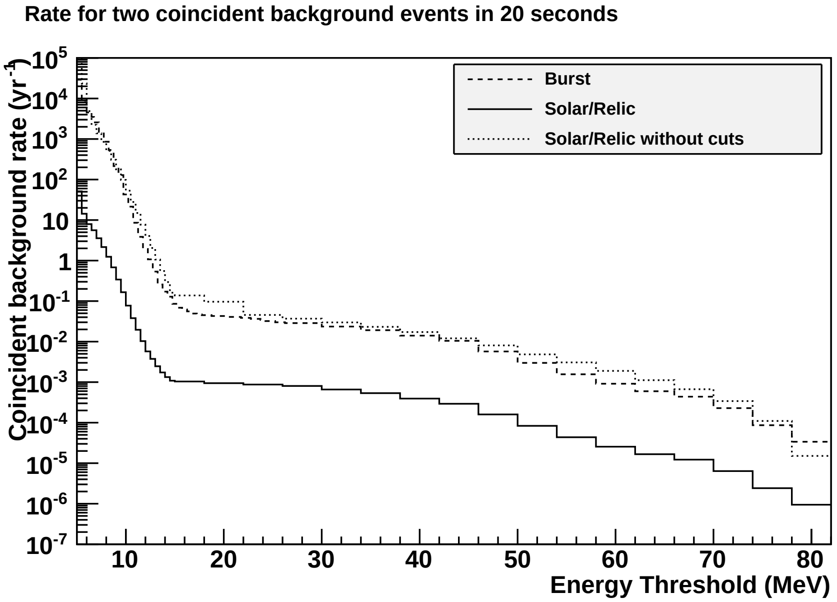

Figure 11: Random coincident rate to see two background events within a time frame of 20 s when only considering events with higher energy than a given threshold energy.

the solar/relic-based analysis have been used, scaled by the ratio of the rates at 7 MeV for smaller energies and the ratio of the rates at 26 MeV for higher energies.

Between the low and high energy regions (from 15 MeV to 20 MeV), no background data were available from the solar/relic-based papers. Therefore the available data were extrapolated into this region. There is still a discontinuity at that point, which may result from having used different data sources for the two regions. However, as this is meant to be a rough estimate only, we do not analyze this effect further here.

3.2 Coincidence interval

A typical time window for supernova neutrino search is 20 s, as this is roughly the time frame in which the neutrinos are emitted. This leads via equation 2 to a coincidence rate (fig. 11), or, if we take the inverse, to a mean interval between two random coincident background events in that time frame, shown in figure 12.

4 Optimization

The following study is not meant as a goal in itself, but rather as a consistency check with similar studies, performed by the Super-Kamiokande collaboration.

4.1 Detection probability over square root of chance coincidences

If we define a signal to be two supernova neutrino events, then a way to find the best energy threshold is to maximize the detection probability of a supernova over the square root of the number of chance coincidences to see two random background events in a short time window of 20 s. The detection probability is again given by Poisson probabilities as $1 - \mathrm{e}^{-N_{sig}} - N_{sig}\mathrm{e}^{-N_{sig}}$, where N_{sig} can be read from figure 3 for 10 kpc and scaled according to the $1/D^2$ law for other distances.

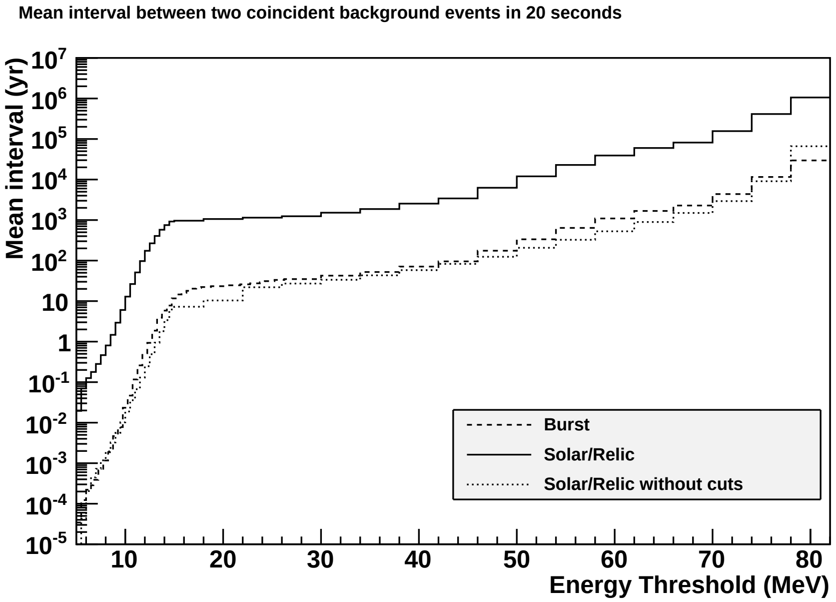

Figure 12: Mean interval between two coincident background events in a time frame of 20 s when only considering events with higher energy than a given threshold energy.

The number of chance coincidences is proportional to the coincidence rate, which is the inverse of the mean interval between two coincident events, as shown in figure 12. Doing this plot, we obtain figure 13.

Using this method, we find slightly different values for the optimal energy threshold. For the burst-based analysis, it is at about 17.0 MeV, for the relic/solar one at 15.5 MeV and for the relic/solar analysis where no cuts were applied we find 24.0 MeV.

These differences are not contradictory. Depending on the background assumed and the cuts applied, the optimal energy threshold is different. It should also be noted that, in general, using this method, the optimal threshold depends on the distance of the supernova. Fig. 13 shows the optimization for a supernova at 300 kpc. However, the dependence on distance is weak. For higher distance, the maxima tend to move a bit to lower energies, and for smaller distances, they tend to move to higher energies.

The Super-Kamiokande collaboration used the same method when analyzing their data to search for supernova neutrino bursts in [2]. They found an energy threshold optimum at 17 MeV, in agreement with our findings.

5 Conclusion

We have examined signal and background rates for supernova neutrino events at Super-Kamiokande when employing an energy threshold. Three cases have been considered, with differences in background rates and efficiencies. Furthermore, we did a brief optimization study – to check consistency with available studies. We found general agreement between our study and [2] for the burst-based analysis, even though we did not know what efficiencies had been applied there.

For the other two cases, we get slightly different values for the best energy threshold, but we do not have anything to directly compare them against. The optimum energy threshold we found in the solar/relic-based analysis is in the same region as the burst-based one (−8.8 %). This suggests that

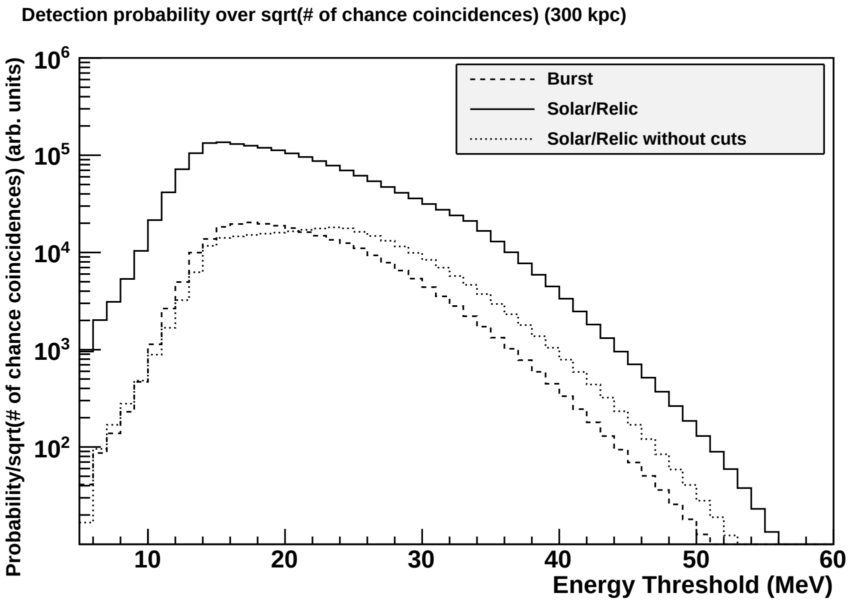

Figure 13: Detection probability of a supernova over the square root of the number of chance coincidences.

this analysis can be used with confidence as well.

The solar/relic-based analysis with no cuts is also provided. Given an external trigger such as a gravitational wave signal it might well make sense to conduct such an analysis on data recorded in the same time frame.

A Plot data files

The data used to create the plots in this report is available on the web.

- For the signal, it is available on `http://phy.duke.edu/~ab260/sn-report/signal_data`. This file contains five columns; the first is the energy in MeV, and the others correspond each to one line in fig. 1 at that energy, in events/1 MeV. No efficiencies have been applied yet on that data.
- For the burst-based analysis, the background data is available on `http://phy.duke.edu/~ab260/sn-report/burst_background_data`. Again, the first column is energy in MeV. The second column contains the corresponding integrated background event rate which has been extracted from fig. 6. For energies lower than 7 MeV, the data from the solar/relic analysis have been used, scaled by the ratio of the background rates at that energy, and likewise with energies above 26 MeV.
- For the solar/relic-based analysis, the background data is available on `http://phy.duke.edu/~ab260/sn-report/solar_relic_background_data`. There are three columns in this file. The first column contains once again energy in MeV; the other two are background event rates per energy in events/1496 days/4 MeV. The second column includes the cuts that were used for the solar/relic-based analysis in this report, including the 11.5 % for the solar direction cut for low energies. The third column contains background rates without any cuts. The information was extracted from fig. 7 and 8 for the corresponding energy regions, respectively. Between 15 MeV

and 18 MeV, it was interpolated between the highest bin of the low energy region and the lowest bin of the high energy region.

- The efficiency data is at `http://phy.duke.edu/~ab260/sn-report/efficiency_data`. It was extracted from fig. 2. Note that these were not the only efficiencies applied; see sec. 2.1 for a complete explanation of the efficiencies applied.

References

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[4] M. Malek et al. Search for supernova relic neutrinos at Super- Kamiokande. *Phys. Rev. Lett.*, 90:061101, 2003.

[5] J. Hosaka et al. Solar neutrino measurements in Super-Kamiokande-I. *Phys. Rev.*, D73:112001, 2006.