Supernova Pointing by Neutrino Matter Oscillation

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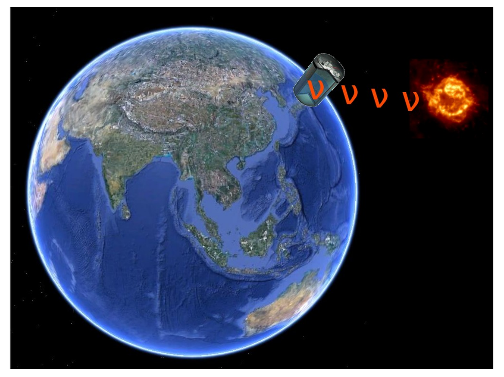
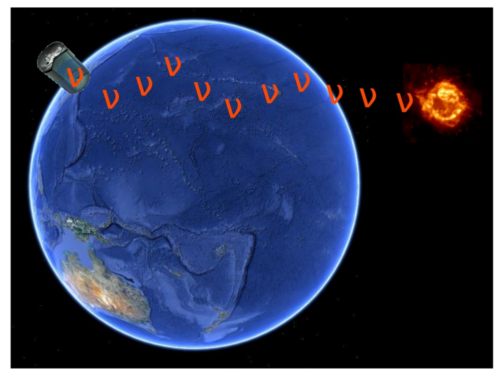
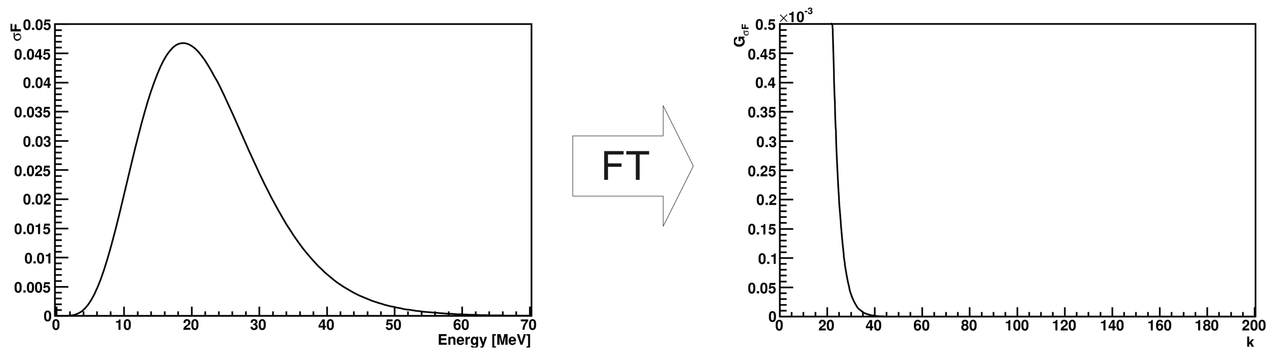
Basic idea

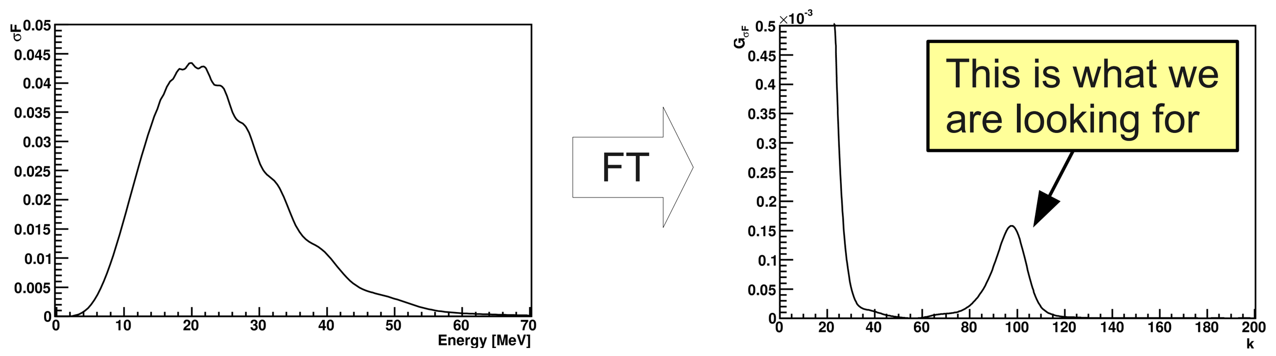
In a core-collapse supernova about 99% of the energy is released as neutrinos. They arrive in pure mass eigenstates at the Earth, but for allowed oscillation parameters they undergo additional oscillations when travelling through Earth matter before reaching a detector (MSW effect). The oscillations can be seen in the energy spectrum and are equidistant in inverse energy y = 12.5/E. A Fourier transformation in y yields a peak. [1,2]



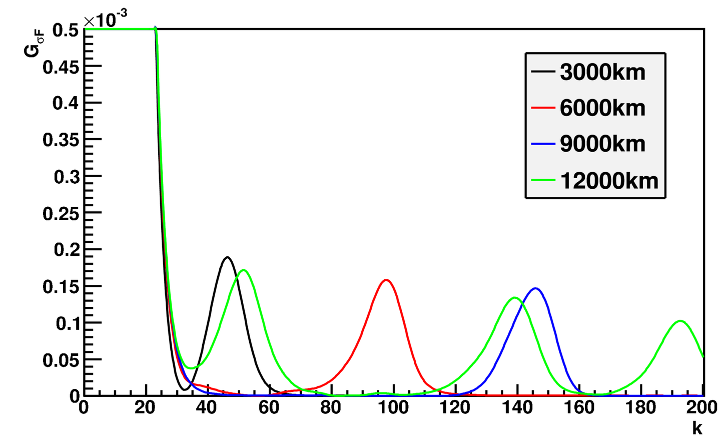




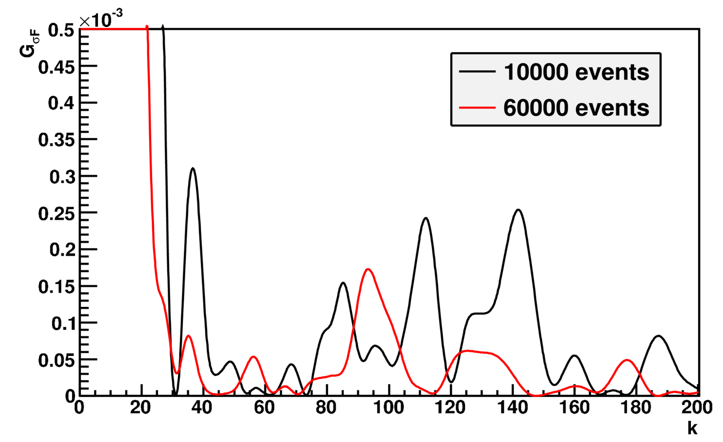
$$G_{\sigma F}(k) = \left|\int_{-\infty}^{\infty} f(y) e^{iky} dy\right|^2$$



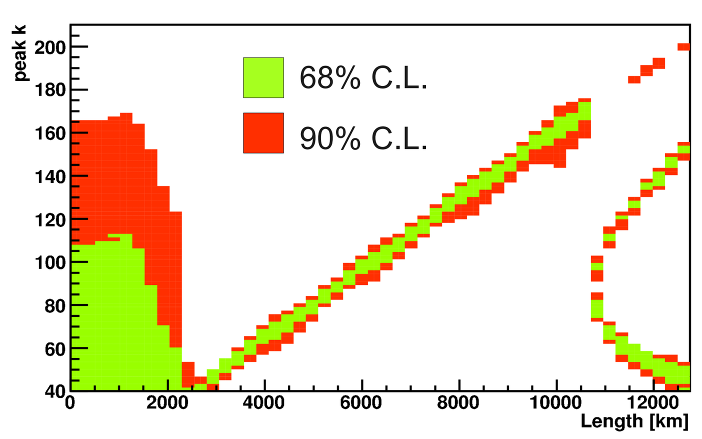
Degrading effects



The peak position in Fourier space depends roughly linearly on the pathlength the neutrinos travel through Earth matter. For large pathlengths they pass the Earth's core. The core's much higher matter density causes multiple peaks to appear, introducing ambiguities [3].



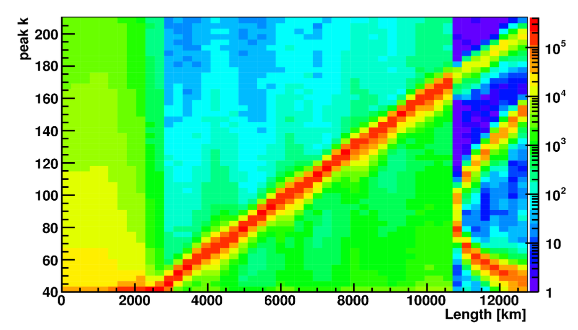
Finite statistics also contribute to quality degradation. This is an example of how the Fourier spectrum gets distorted for 10,000 and 60,000 events, respectively. Low statistics can cause the peak to be shifted and introduce additional ambiguities. The rest of this study is performed assuming 60,000 events.

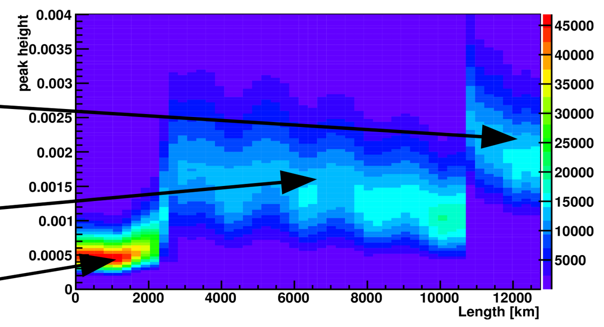


With many simulated finite statistics spectra we can check the distributions of peak k for a given pathlength L. In this Neyman construction one can read off the allowed regions for a measured k by drawing a horizontal line. Especially for low pathlengths, when no oscillation occurs, random noise can easily be misidentified as a peak.

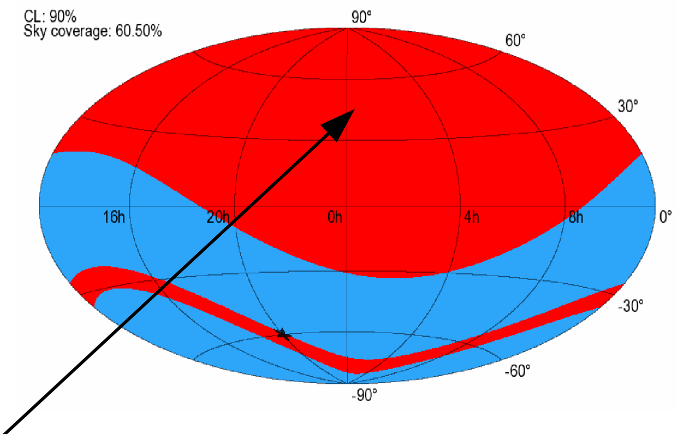
Resolving ambiguities

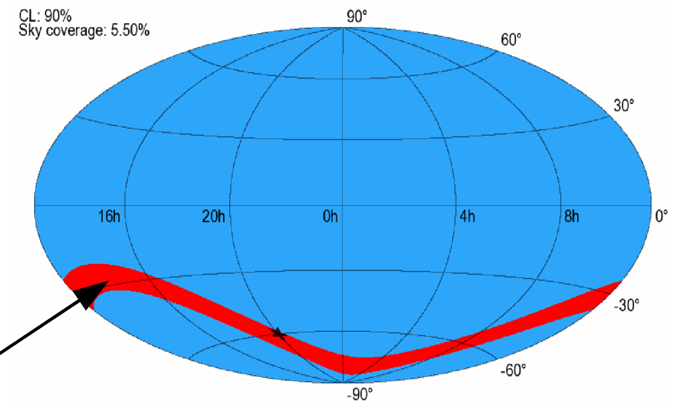
The position of the highest peak is clearly correlated with the pathlength L. There is also information in the height of that peak which especially helps to differentiate between regions of different matter density.





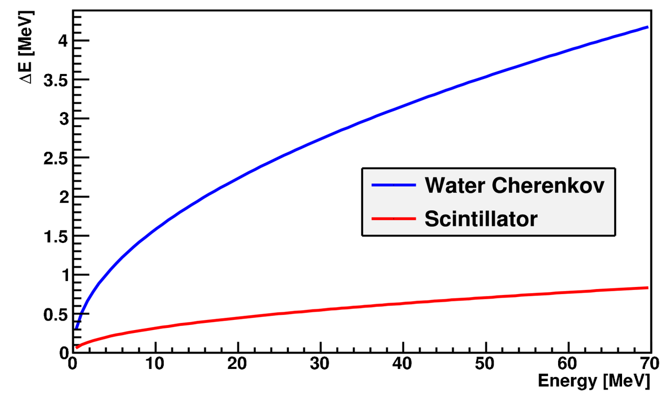
Given a detector location we can map pathlengths allowed by the Neyman construction to allowed areas in the sky within which the supernova is likely to have occurred. Here we see example skymaps in equatorial coordinates for a detector in Finland and a supernova at R.A.=20h, d=-60° at 0:00 GMST showing allowed regions (red) at 90% C.L.



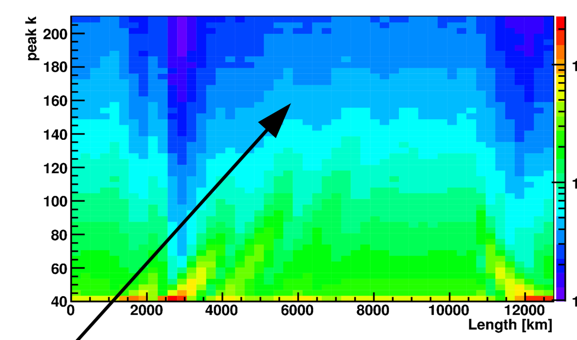


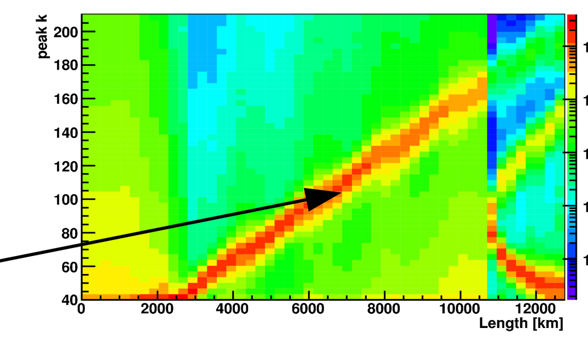
Detector effects

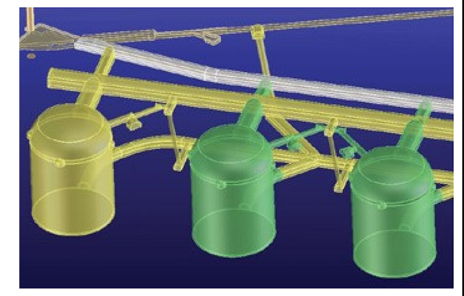
Real detectors do have finite energy resolution; that is they do not reconstruct the energy of each event perfectly. This smears out the measured spectrum, making peaks harder to identify. For each event we assume the measured energy is given by a Gaussian around the real energy, with its width heavily depending on the detector type.



We study our technique for water Cherenkov detectors (such as Super-Kamiokande) and for scintillator-type detectors (such as KamLAND). Due to the weaker energy resolution the distribution of the peak in k is smeared out much more for Cherenkov detectors than for scintillator ones.







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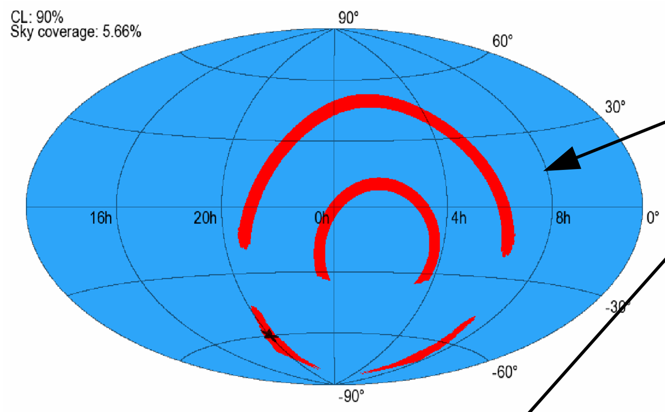
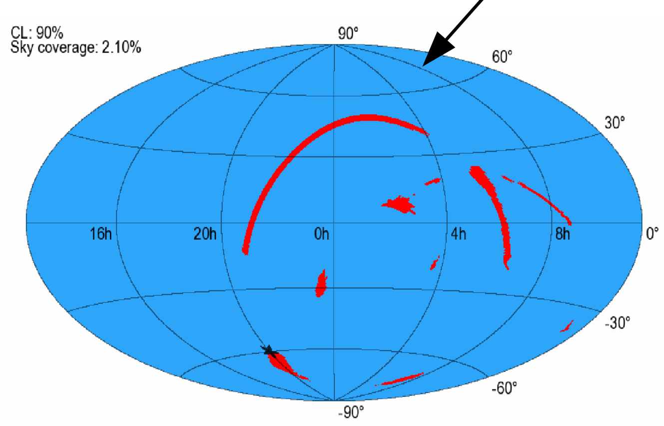
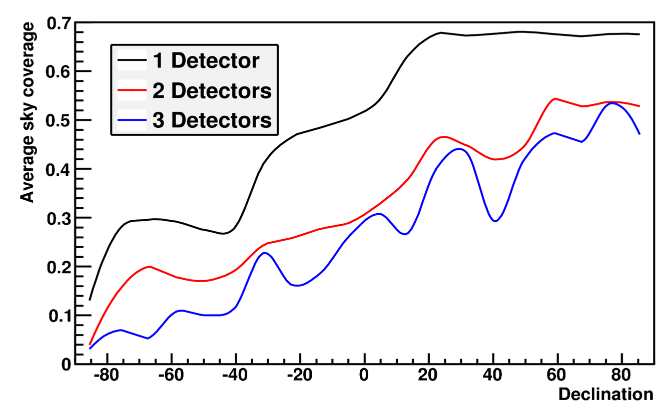
Combining multiple detectors

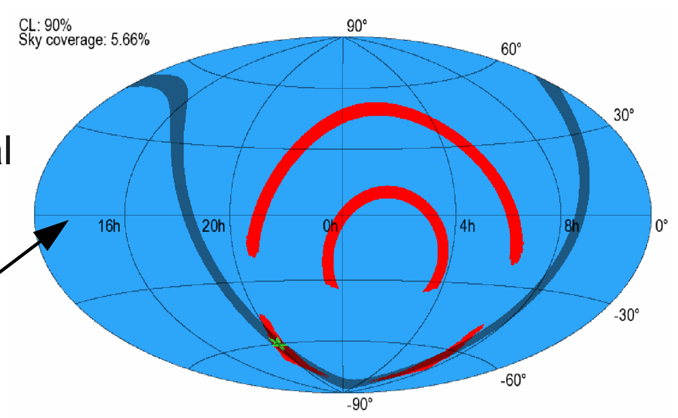
With a single detector only the allowed region can be restricted to a ring in the sky in the best case. With two detectors we can reduce it to two distinct areas, and three detectors can bring it down to one spot. In practice there are still ambiguities because of finite statistics and energy resolution. Technically data of multiple detectors can be combined by doing the Neyman construction in a higher-dimensional space with tuples of pathlengths L_i and tuples of peak positions and heights $(k_i h_i)$.





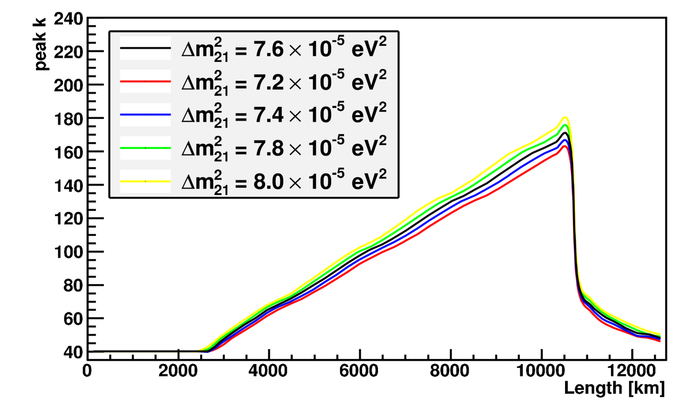


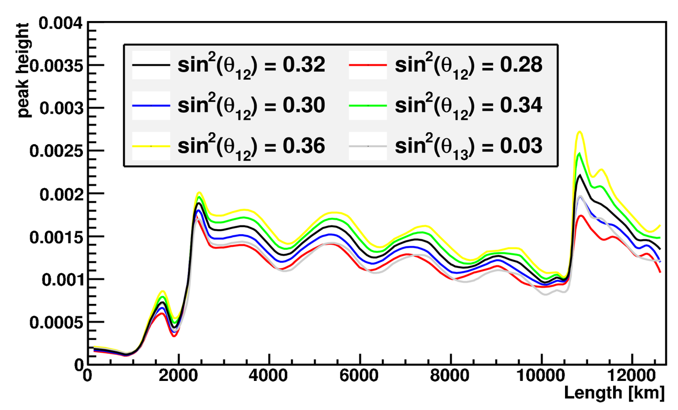
Another means of combining multiple detector data is by relative timing of the neutrino signal. Given the high event count we need for this method anyway this gives a good additional constraint on the supernova position.



Summary

- Need high statistics, O(60,000) events
- Need good energy resolution
- Inferior to water Cherenkov elastic scattering
- Feasible for scintillator detectors
- Combination of multiple detectors improves pointing
- Relative timing can resolve remaining ambiguities
- Good knowledge of oscillation parameters desired





[1] K. Scholberg, A. Burgmeier, and R. Wendell, Phys. Rev. D81, 043007 (2010), 0910.3174
[2] A. S. Dighe, M. T. Keil, and G. G. Raffelt, JCAP 0306, 006 (2003), hep-ph/0304150
[3] A. S. Dighe, M. Kachelriess, G. G. Raffelt, and R. Tomas, JCAP 0401, 004 (2004), hep-ph/0311172