Preliminary SN calculations for NOvA

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Started from MiniBooNE note on SN rates and make rough scaling to NOvA

[1] Review what's in MiniBooNE note
[2] Estimates for NOvA

Potential for Supernova Neutrino Detection in MiniBooNE

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The MiniBooNE detector at Fermilab is designed to search for $\nu_\mu \to \nu_e$ oscillation appearance at $E_\nu \sim 1$ GeV and to make a decisive test of the LSND signal. The main detector (inside a veto shield) is a spherical volume containing 0.680 ktons of mineral oil. This inner volume, viewed by 1280 phototubes, is primarily a Čerenkov medium, as the scintillation yield is low. The entire detector is under a 3 m earth overburden. Though the detector is not optimized for low-energy (tens of MeV) events, and the cosmic-ray muon rate is high (10 kHz), we show that MiniBooNE can function as a useful supernova neutrino detector. Simple trigger-level cuts can greatly reduce the backgrounds due to cosmic-ray muons. For a canonical Galactic supernova at 10 kpc, about 190 supernova $\bar{\nu}_e + p \to e^+ + n$ events would be detected. By adding MiniBooNE to the international network of supernova detectors, the possibility of a supernova being missed would be reduced. Additionally, the paths of the supernova neutrinos through Earth will be different for MiniBooNE and other detectors, thus allowing tests of matter-affected mixing effects on the neutrino signal.

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I. INTRODUCTION

As is well-known, about two dozen neutrinos in total were detected from SN1987A in the Kamiokande II, IMB, and Baksan detectors [1]. Even these very limited observations, despite some of their puzzling features, did provide a basic confirmation of the core-collapse supernova mechanism as well as interesting limits on the properties of neutrinos [2]. The Galactic supernova rate is about (3 ± 1)/century (most would be obscured optically by dust) [3], so it is very important that a supernova neutrino signal not be missed because of detectors being down for upgrades or calibrations. This can be accomplished by having as many independent supernova neutrino detectors as possible. Since different detectors use different targets and techniques, having results from several detectors is also very useful for making cross-checks of the data and theory. Additionally, the neutrino paths through Earth will be different, and matter-affected mixing effects on the signal can be significant (see, e.g., Ref. [4]).

The supernova neutrino detection capabilities of various present or near-term detectors are documented elsewhere: Super-Kamiokande (SK) [5], the Sudbury Neutrino Observatory (SNO) [6], Borexino [7], KamLAND [8], the Large Volume Detector (LVD) [9], and AMANDA [10]. SK, once repaired, would expect about 10^4 identified supernova events. The others would expect between a few and several hundred identified events. (The number of identified events in AMANDA is more difficult to quantify since the supernova is seen only as a statistically significant increase in the noise rate). The yields are expected to be larger than from SN1987A in part because the assumed distance is smaller. SN1987A was at a distance of about 50 kpc, in the Large Magellanic Cloud, a small companion of the Milky Way Galaxy. The next supernova will more likely be in our Galaxy proper, and conventionally, a distance of 10 kpc is assumed, approximately the median distance of Galactic stars from Earth. In the case of SK, it is approximately 16 times larger than its predecessor Kamiokande II.

The MiniBooNE detector at Fermilab is designed to search for $\nu_\mu \to \nu_e$ oscillation appearance, using a beam of ~ 1 GeV ν_μ produced by π^+/K^+ decay in flight. These mesons are produced when a proton beam from the Fermilab Booster hits a beryllium target about 500 m away from the detector. The mesons are focused by a magnetic horn system that will allow charge selection and hence running with antineutrinos instead of neutrinos. The beam will operate with the very low duty cycle of 5 Hz of 1.6 μs spills, so only modest shielding from cosmic-ray muons is required. This is provided by a 3 m earth overburden, which nearly eliminates the hadronic component of the cosmic rays (the hadronic interaction length is about 1 m water equivalent). The MiniBooNE experiment will decisively confirm or refute the LSND [11] neutrino oscillation signal; full operations begin in Summer 2002.

We briefly review the basic characteristics of the MiniBooNE detector. A more complete description can be found in Ref. [12]. The detector is a 6.1 m radius steel sphere, filled with mineral oil. The oil has density 0.85 g/cm^3 and its chemical composition is C_nH_{2n+2}, with $n \simeq 30$. At 5.75 m radius, there is a phototube support structure that optically isolates the inner volume from a veto region. The veto region is painted white to maximize light-gathering efficiency (Čerenkov imaging will thus not

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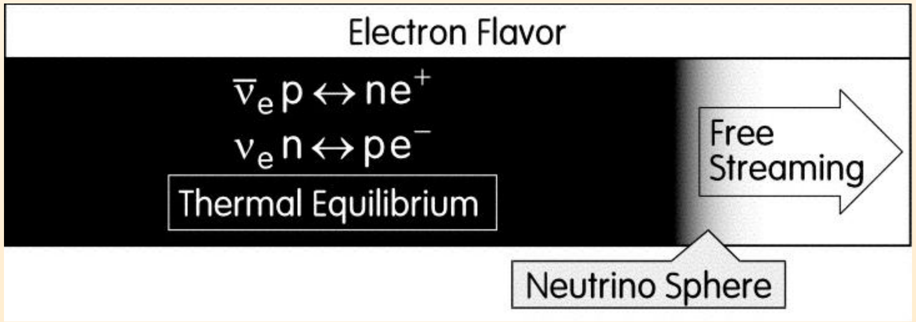
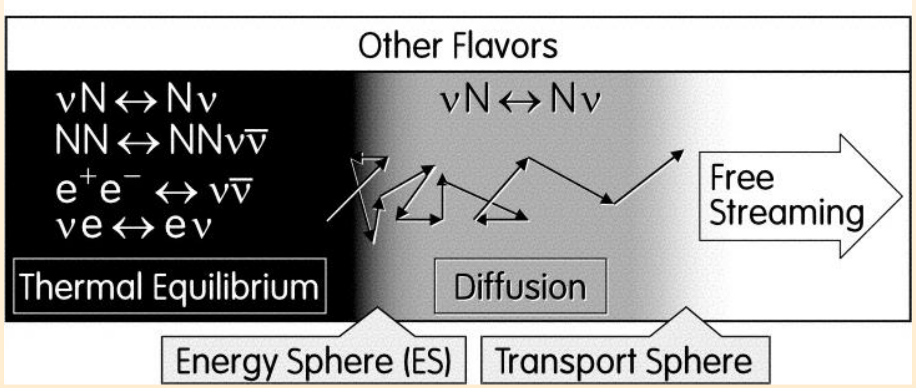
Neutrinos in supernova explosions

- Neutrinos and antineutrinos of all flavors are produced via: $NN \longrightarrow NN\nu\bar{\nu}$, $e^+e^- \longrightarrow \nu\bar{\nu}, \ldots$
- Neutrinos get trapped for some time and reach thermal equilibrium
- Neutrinos eventually escape, each flavor taking away same fraction of energy
- Different neutrino temperatures due to different allowed neutrino interactions:

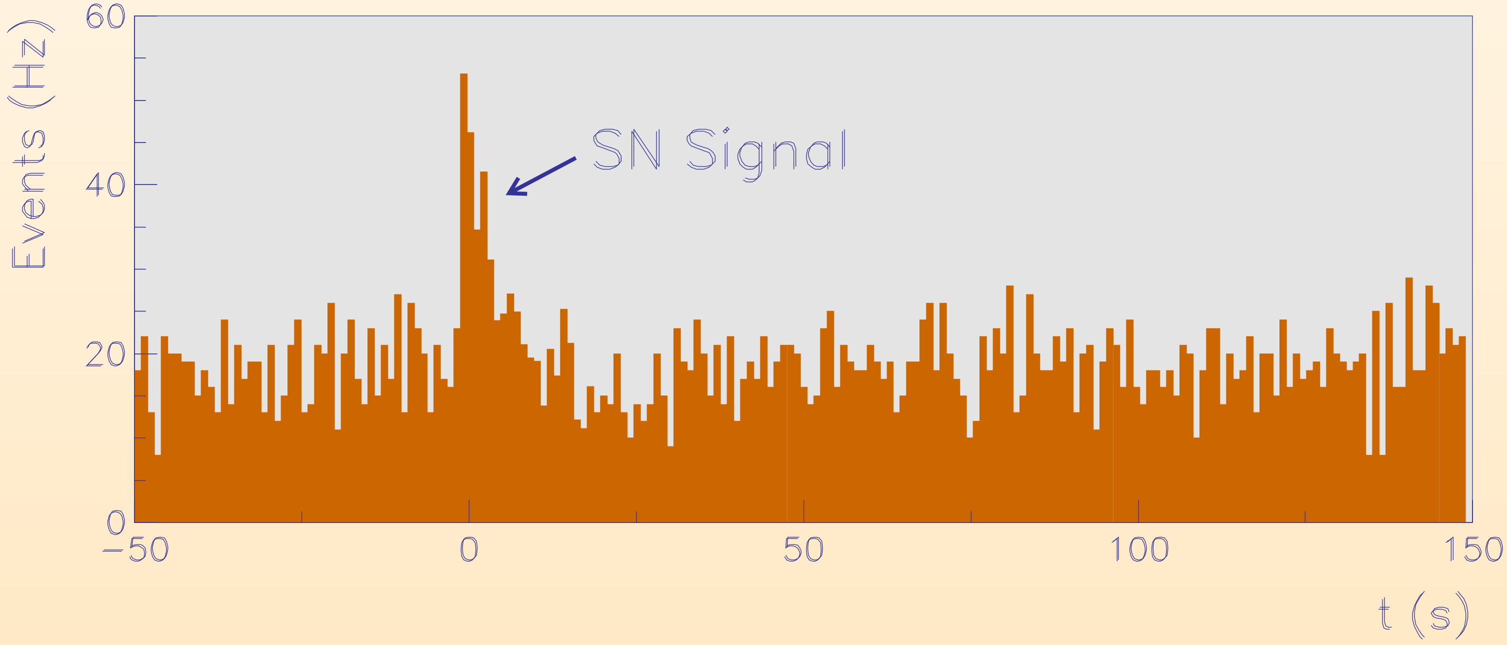




- More interactions $\Leftrightarrow$ larger trapping radius $\Leftrightarrow$ lower temperature
- Duration of neutrino burst: 1-10s

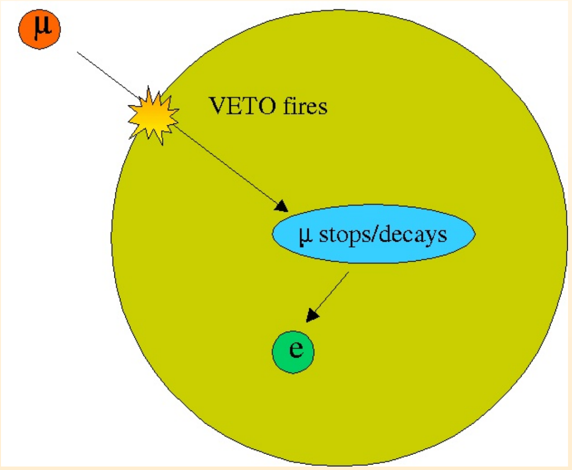
Triggering on a SN

- Selecting only events in the 10MeV $<$ E $<$ 35MeV energy range:
  - 45% of SN signal
  - 20Hz of background Michel electrons, 1-2Hz of background ^{12}B β-decay electrons
- Easy to catch a real SN trigger, while keeping false trigger rate reasonably low
- For a typical, galactic SN signal (sharp rise with τ=3s exponential decay):



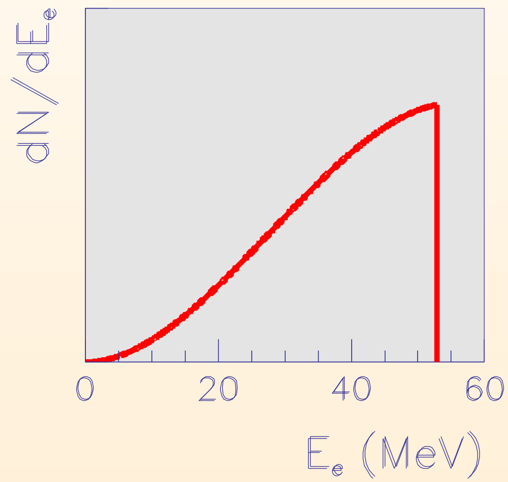
Backgrounds to SN events

- Background due to 10kHz rate of cosmic ray muons entering the detector, 2kHz of which stop inside. Muons typically tagged by veto shield.



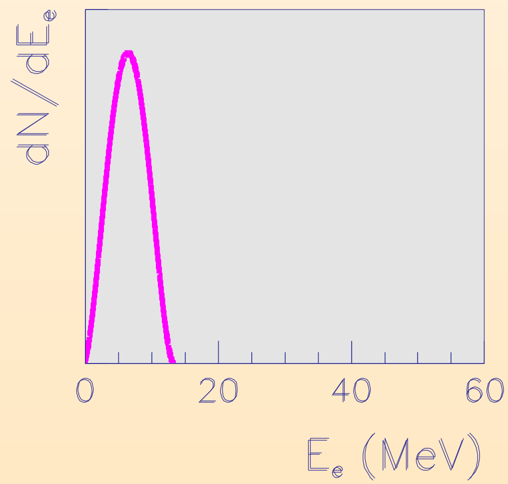
1. Muons decaying

   Signature: "high-energy", Michel electrons



2. Muons capturing on C atoms

   ^{12}B atoms created, which β-decay (long half-life)
   Signature: low-energy, β-decay electrons



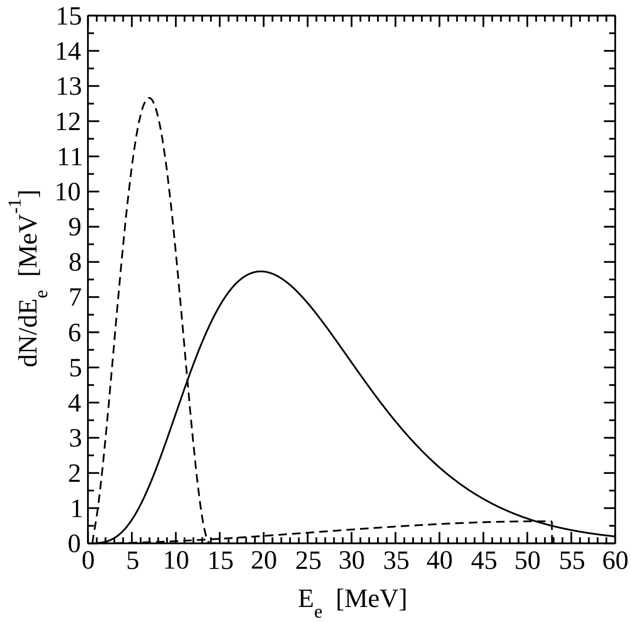


FIG. 1: Spectra of the supernova signal (solid line), ^{12}B decay background (dashed line peaking at low energy), and surviving muon decay background (dashed line peaking at high energy) versus the true electron total energy, over a 10 s interval assumed to contain the full supernova signal. A volume of 0.595 ktons is assumed, though all rates are reduced by 15% to account for the detector deadtime fraction imposed by applying a 15.2 μs holdoff after any muon event. Energy resolution is not included. Below about 5 MeV, backgrounds from ambient radioactivities will dominate over the spectra shown.

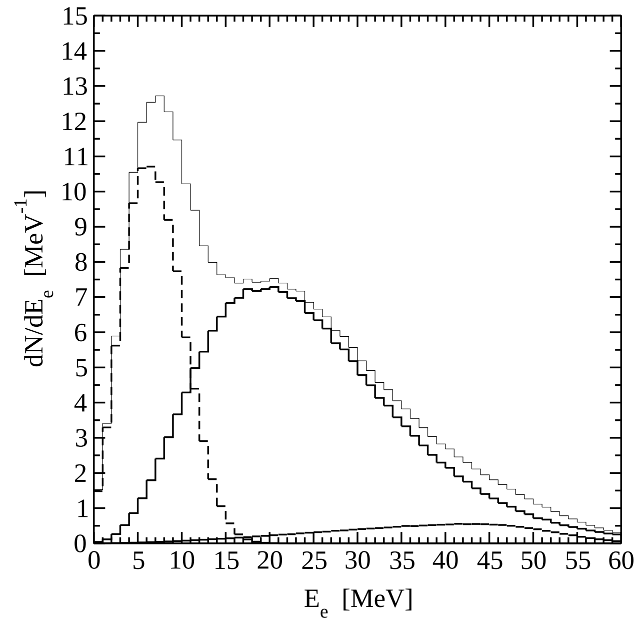


FIG. 2: The same as Fig. 1, except that energy resolution is now implemented as described in the text. The thin solid line indicates the sum spectrum. The curves shown indicate the true spectral shapes. For an actual supernova, there will be Poisson fluctuations on the numbers of events shown in each of the (1 MeV wide) bins.

hit phototubes in the veto region **OR** the main detector volume. We can then impose a 15.2 μs holdoff after any such event. This is over-conservative in the sense that most of these muons will not actually stop and decay in the detector, but the penalty is minor, just a 15% deadtime. With a modest cut at low energies, i.e., requiring a minimum number of hit phototubes, the low-energy radioactivities and a good deal of the ^{12}B beta decays can be cut. In sum, the steady-state rate should be about 4 Hz, easily manageable by the data acquisition electronics.

A candidate supernova can be flagged by a large increase in the data rate, as shown in Fig. 3. A circular buffer can store data for offline evaluation, where it can be examined to see if it has reasonable characteristics (energy spectrum, duration, event positions and directions, etc.). Detailed discussions of supernova trigger for offline evaluation systems were published for Kamiokande [22] and MACRO [23].

V. DISCUSSION AND CONCLUSIONS

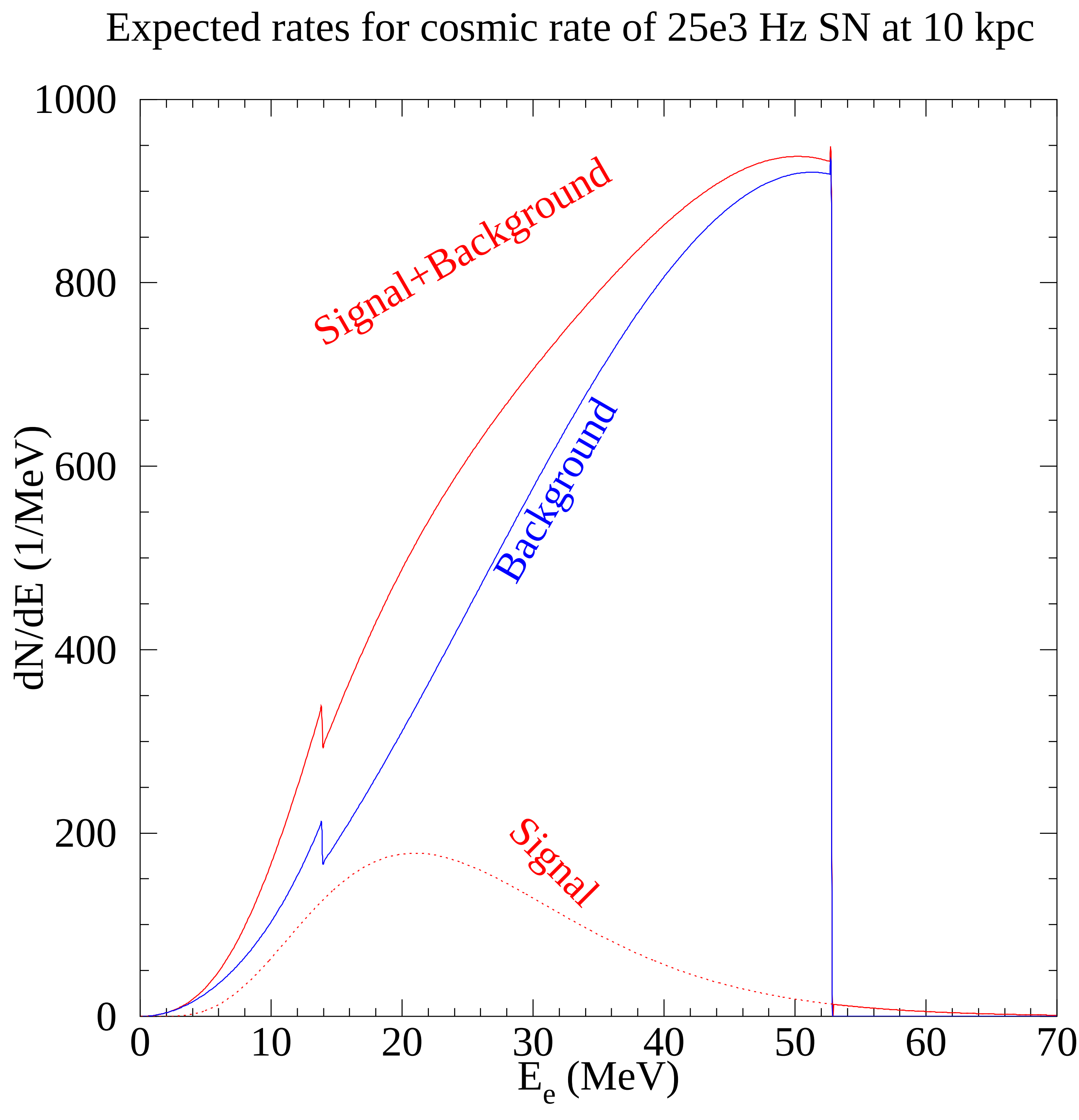
The MiniBooNE experiment [12] will decisively test the neutrino oscillation signal reported by LSND [11]. If the signal is confirmed, it will have a big impact on all of neutrino physics, since simple models with three active neutrinos appear to be inadequate to explain all the data. In addition, several authors have shown that the required mixing parameters would have interesting implications for various aspects of core-collapse supernovae, including the explosion mechanism, r-process production of the heavy elements, and the detected neutrino signal [24].

Our results show that MiniBooNE could be quite useful as a supernova neutrino detector, despite being optimized for much higher energies and being at a shallow depth of only 3 m. With very simple trigger-level cuts, the backgrounds associated with the 10 kHz cosmic-ray muon rate can easily be reduced to a manageable level, as shown in Figs. 1 and 2. The approximately 230 events from a canonical Galactic supernova at 10 kpc can thus be easily identified, with only minimal background contamination. Only about 15% of these events will be lost to detector deadtime as a result of cuts to reduce the muon decay background. This leaves about 190 supernova events, and their spectrum should be well-measured. The steady-state data rate of about 4 Hz in the data acquisition electronics is also easy to handle. The details of implementing a supernova trigger into the MiniBooNE data acquisition system are now being studied. Further, in the very near future, direct measurements of the detector performance and backgrounds will be measured in detail.

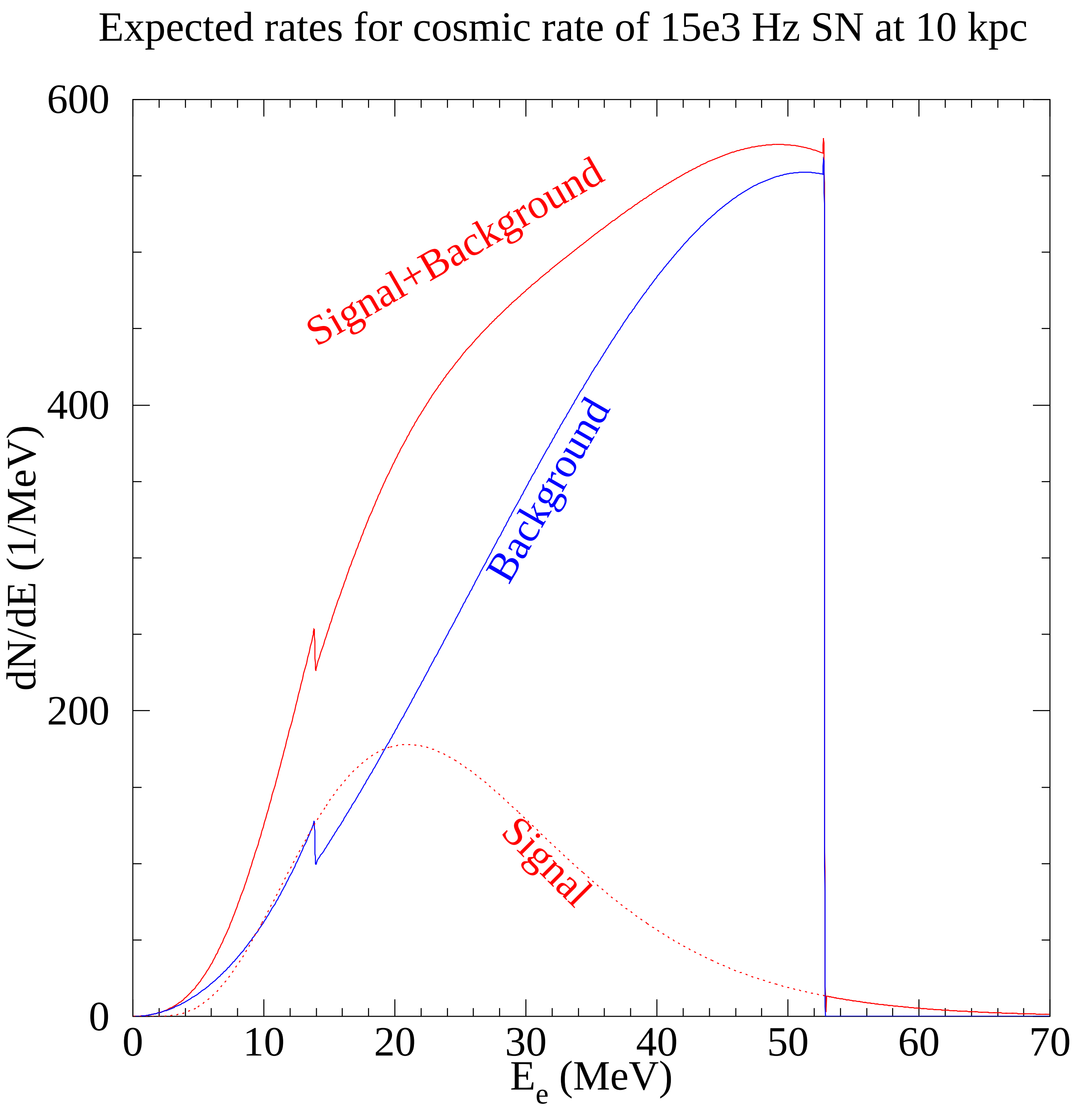
What can MiniBooNE add to the worldwide effort to detect supernova neutrinos? *First*, it is highly desirable to have as many different detectors as possible. This will

Super-nova rates: Scale MiniBooNE to NOVA

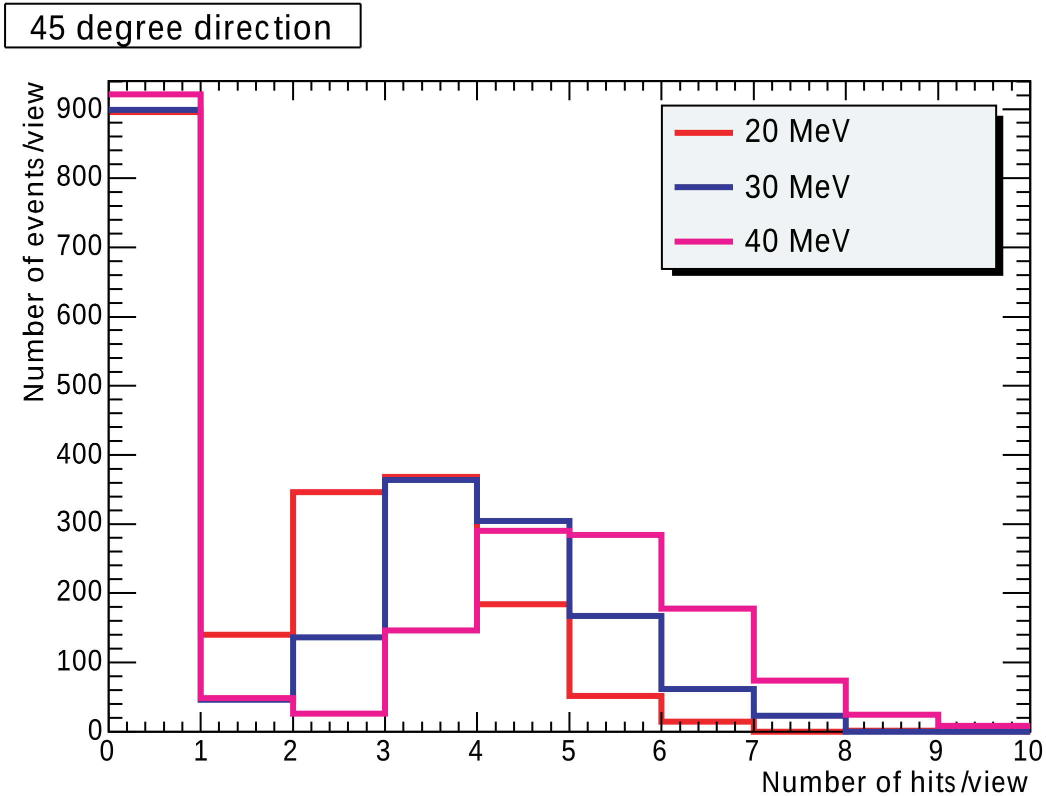
	Miniboone	NOVA	
Mass	0.6	25.0	Kt
Mass Ratio	1	42.0	
Surface Area Ratio	1	12.1	
S/N n+p->e+n events	230	9663.9	(10 kpc S/N event)
Through-going muon rate	8	96.7	Khz
Stopping muon rate	2	24.2	Khz
B12 decays	0.01	0.5	Khz



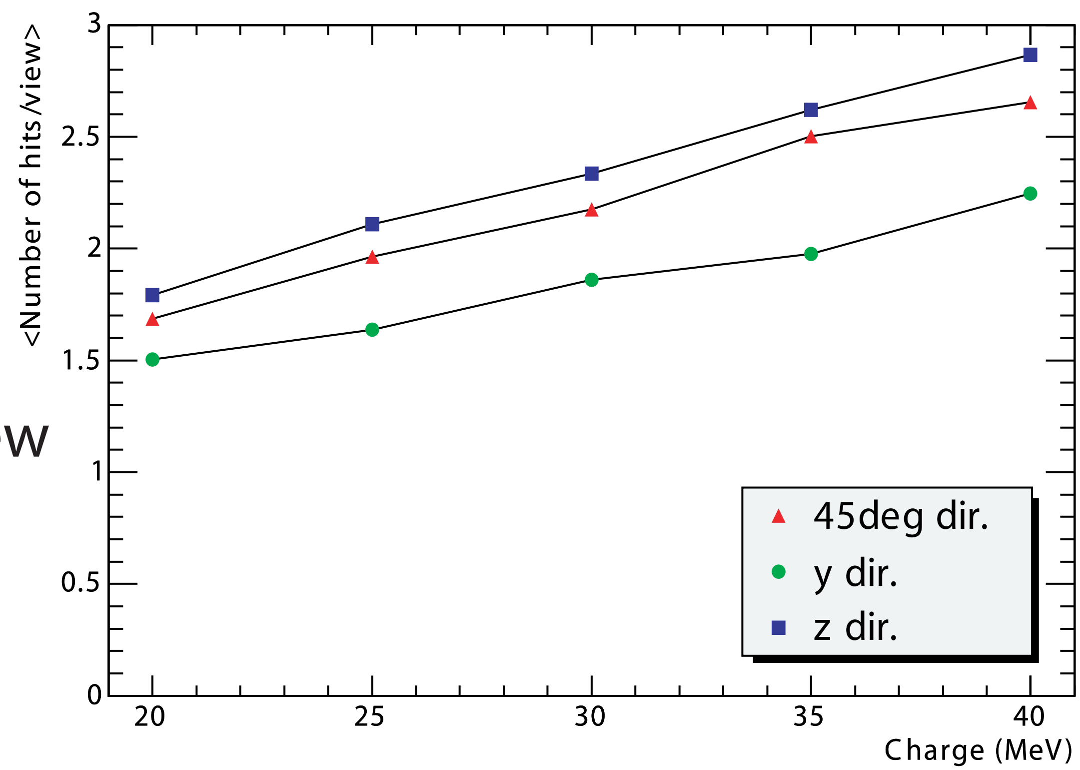
Expected rates for cosmic rate of 25e3 Hz SN at 10 kpc
dN/dE (1/MeV)
0
200
400
600
800
1000
0
10
20
30
40
50
60
70
E_e (MeV)
Signal+Background
Background
Signal



Expected rates for cosmic rate of 15e3 Hz SN at 10 kpc
Signal+Background
Background
Signal
dN/dE (1/MeV)
E_e (MeV)
0
200
400
600
0
10
20
30
40
50
60
70

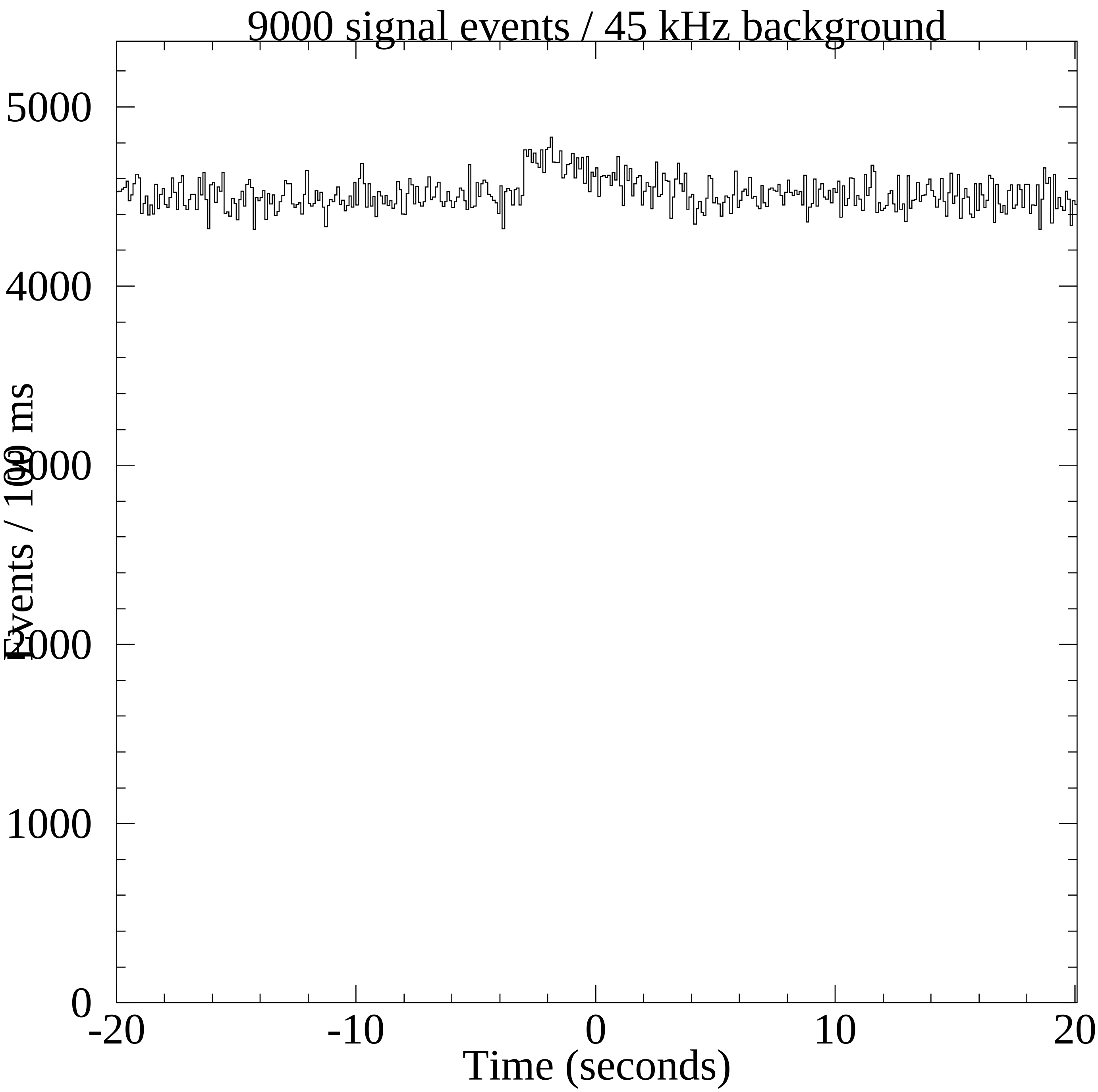


NOvA response between 20-40 MeV

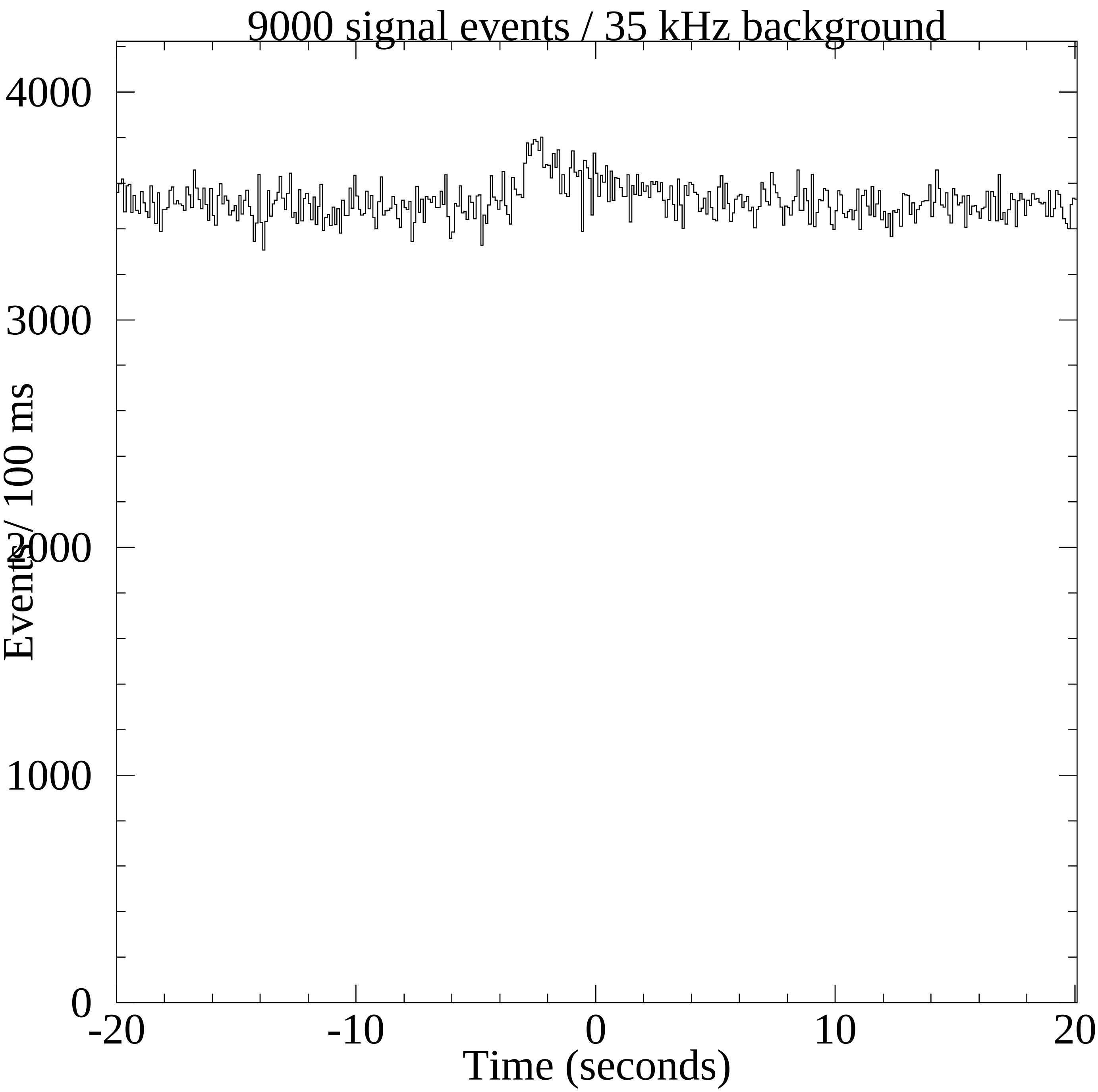


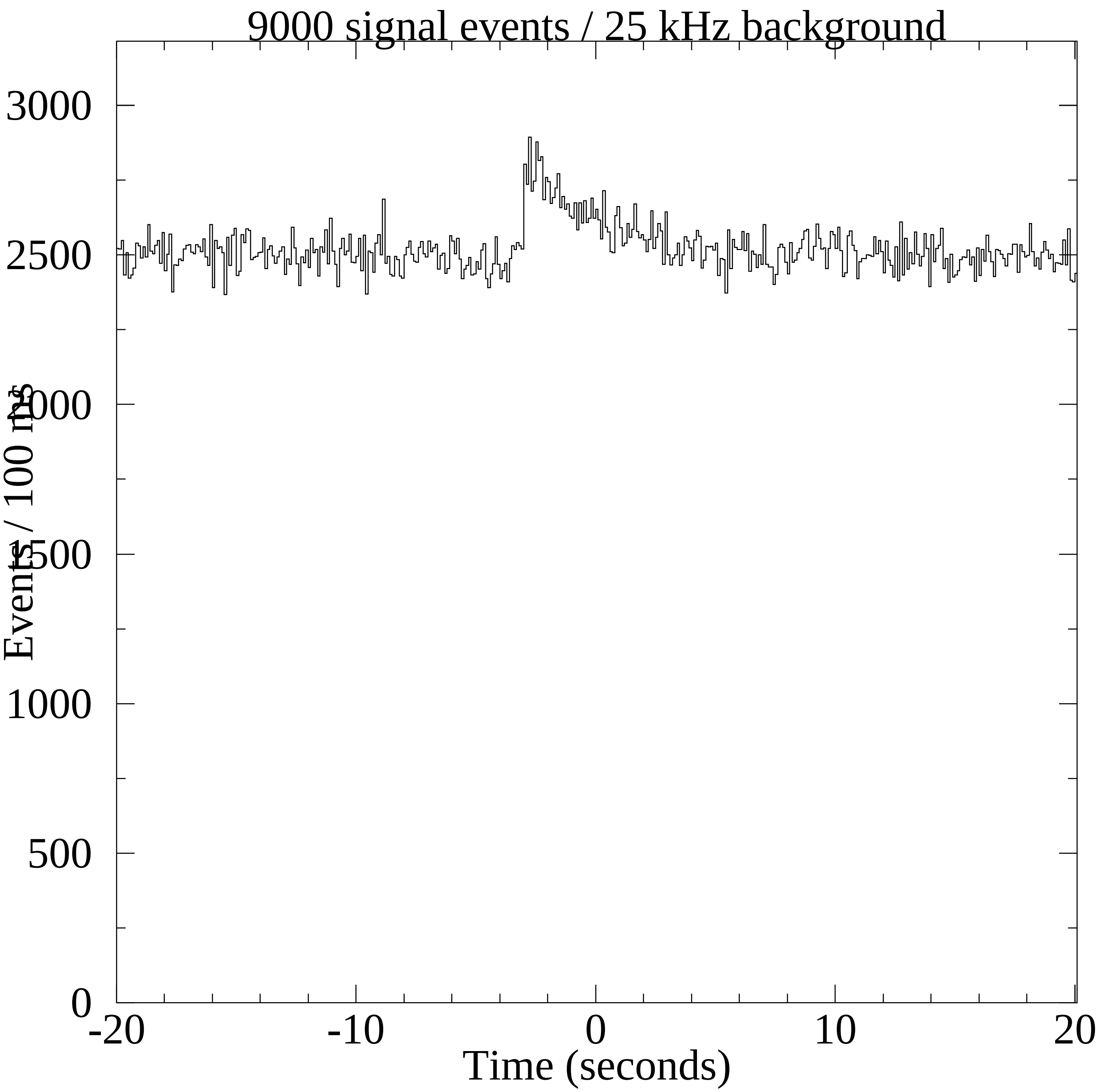
~1 hit/15 MeV/ view

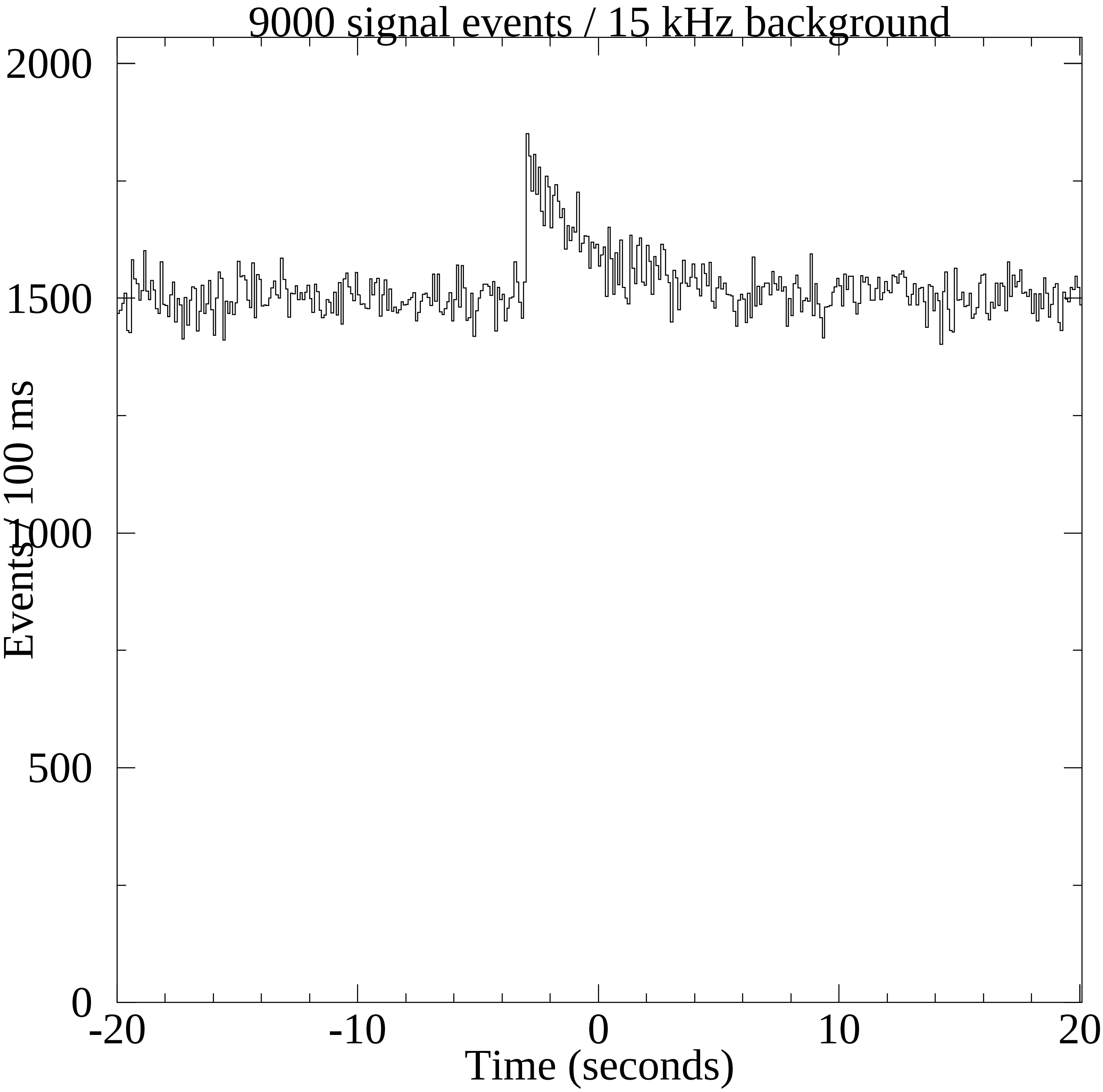
most events have >=2 hits/view



9000 signal events / 45 kHz background
Events / 100 ms
Time (seconds)
0
1000
2000
3000
4000
5000
-20
-10
0
10
20


9000 signal events / 35 kHz background
Events / 100 ms
0
1000
2000
3000
4000
-20
-10
0
10
20
Time (seconds)


9000 signal events / 25 kHz background
Events / 100 ms
Time (seconds)
0
500
1000
1500
2000
2500
3000
-20
-10
0
10
20


9000 signal events / 15 kHz background
Events / 100 ms
Time (seconds)
2000
1500
1000
500
0
-20
-10
0
10
20

Conclusions

-S/N signal: ~9000 events over 10 seconds.
Roughly ½ of these in first second
Roughly ½ of these are in detectable energy range (20-40 MeV)
Looking for burst of ~2.5 kHz in first second

-Signal: Get roughly 1 hit / view / 15 MeV. Most S/N events will give coincidence in adjacent strips in x/y views

-Backgrounds:

1. Radioactive: Dominate below 5 MeV, small in range 20-40 MeV
2. Cosmic mu rate ~100 Hz – should be easy to identify. May ignore top & outside layers of detector (how large is fiducial mass?)
3. Michel electrons: estimate ~25 Hz. May be tagged at cost of live time
4. muon capture (B_{12} decay) rate relatively small above 20 MeV